Table of Contents - APD

3. Astrophysics Division (APD)

3.a. Demographics

3.a.i. Principal Investigators (PIs)

3.a.i.1. Context and Limitations of the Data – APD PIs

26,043 submitted proposals are included in the ROSES 2016-2021 database. Please see Appendix Table 1 to see which programs are included. The total number of proposals submitted and selected for each ROSES year and the total number of proposals submitted to each SMD Division cannot be reported due to the Office of the Chief Scientist's suppression guidelines. See *Yearbook Introduction Section 1.a.ii.1 Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information. The number of proposals rounded to the nearest hundred are included for these two circumstances to provide context. For the Astrophysics Division, there are ~3,600 submitted proposals over all ROSES years: ~3,000 for ROSES 2016-2020 and ~600 for ROSES 2021.

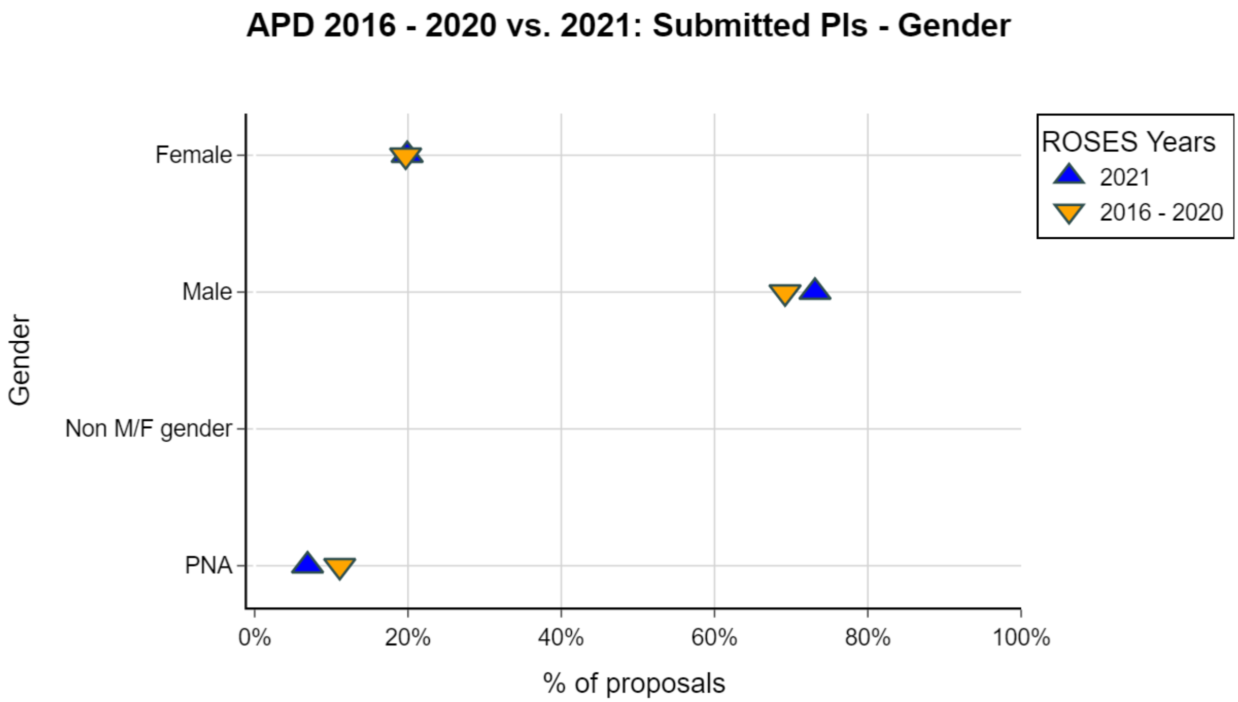
Proposals with PIs who took the survey but selected "prefer not to answer" for all demographic survey questions:

- Submitted proposals: APD 2016 - 2020: 10% | APD 2021: 7%
- Selected proposals: APD 2016 - 2020: 8% | APD 2021: 5%

Unique identifiers in the dataset are not completely unique. Less than 1% of PIs of submitted ROSES 2016-2021 proposals have more than 1 unique ID in the NSPIRES system.

3.a.i.2. Gender – APD PIs

APD PIs: Submitted Gender - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non M/F gender (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: Submitted Gender - Data Table

APD 2016 - 2020 vs. 2021: Submitted PIs - Gender

Gender	APD 2016 - 2020	APD 2021
Female	20%	20%
Male	69%	73%
Non M/F gender	NR	NR
PNA	11%	7%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Selected Gender - Plot

PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non M/F gender (All years), PNA (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

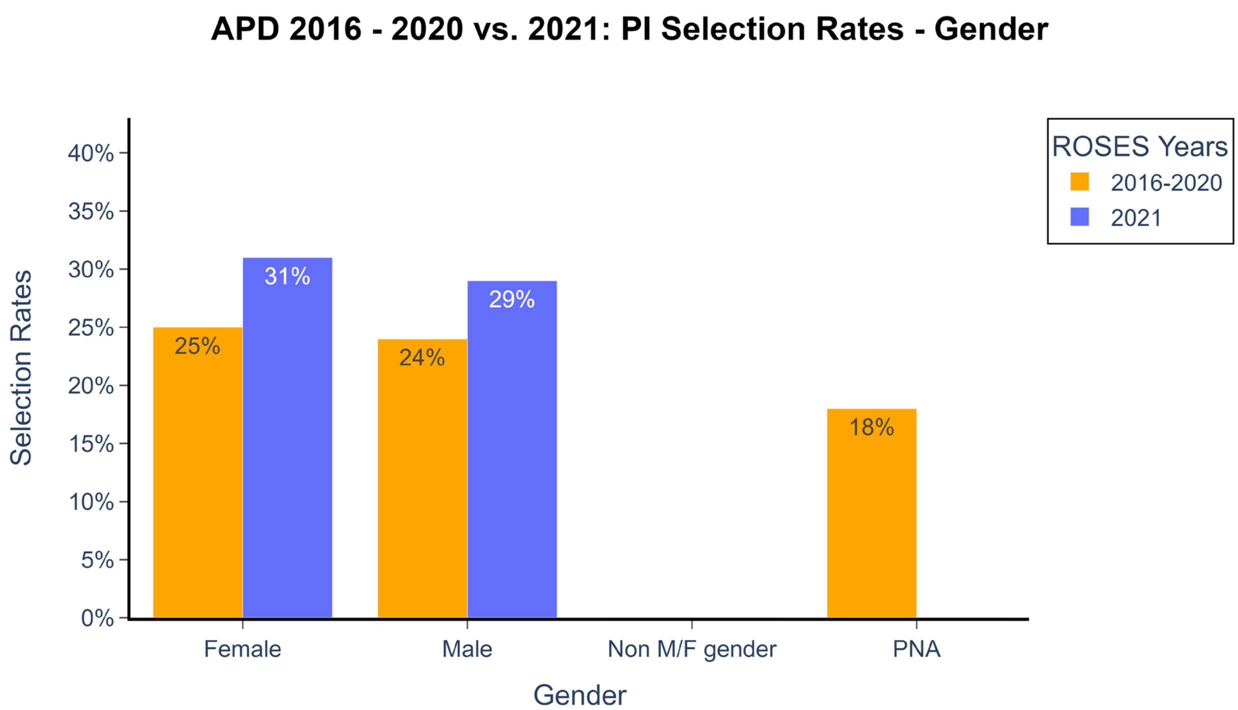
APD PIs: Selected Gender - Data Table

APD 2016 - 2020 vs. 2021: Selected PIs - Gender

Gender	APD 2016 - 2020	APD 2021
Female	21%	21%
Male	70%	73%
Non M/F gender	NR	NR
PNA	9%	NR

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Gender Selection Rate - Bar Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: Non M/F gender (All years), PNA (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: Gender Selection Rate - Data Table

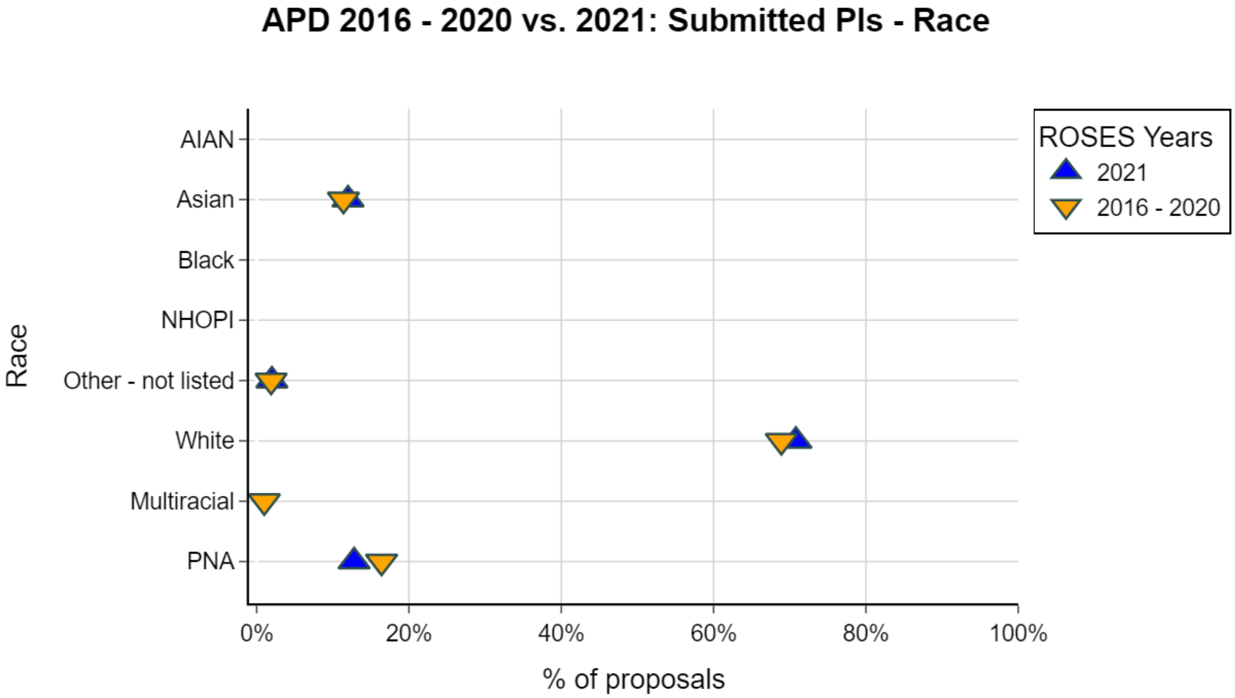
APD 2016 - 2020 vs. 2021: PI Selection Rates - Gender

Gender	APD 2016-2020	APD 2016-2020 Response/All Genders	APD 2021	APD 2021 Response/All Genders
Female	25%	1.09	31%	1.07
Male	24%	1.04	29%	1
Non M/F gender	NR	NR	NR	NR
PNA	18%	0.78	NR	NR
All Genders	23%	1	29%	1

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

3.a.i.3. Race – APD PIs

APD PIs: Submitted Race - Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: AIAN (All years), Black (All years), NHOPI (All years), Multiracial (ROSES 2021).

See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

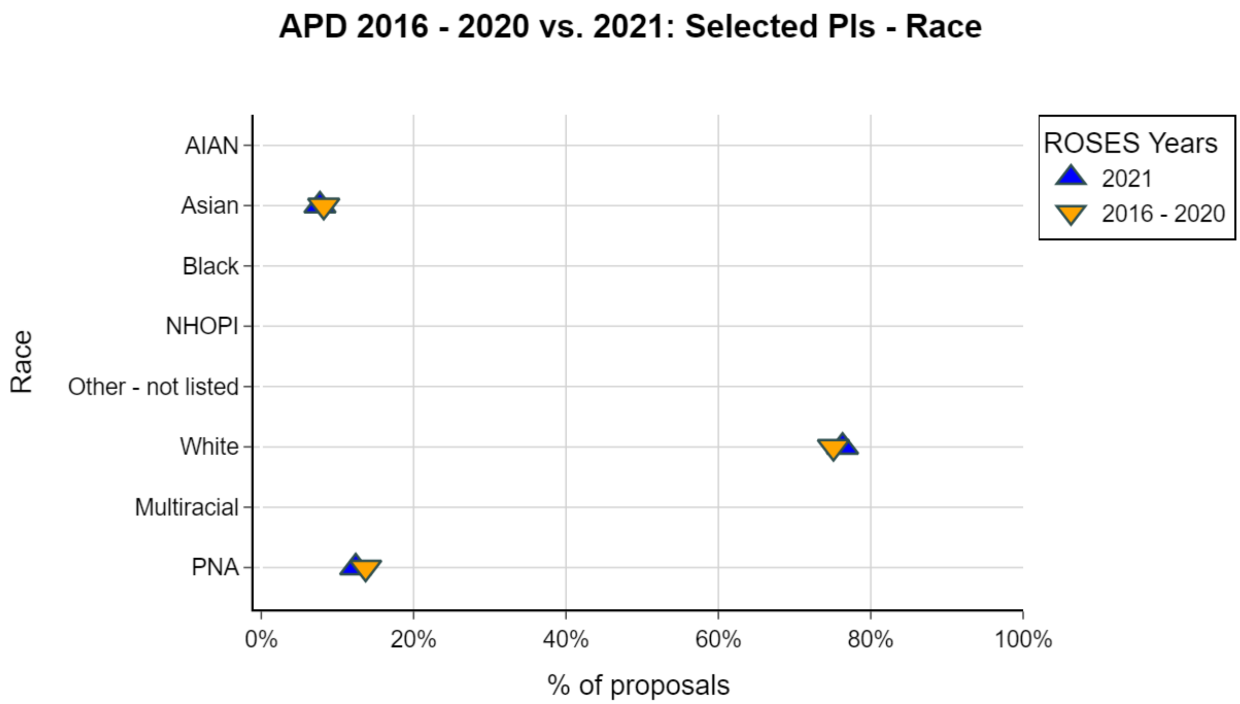
APD PIs: Submitted Race - Data Table

APD 2016 - 2020 vs. 2021: Submitted PIs - Race

Race	APD 2016 - 2020	APD 2021
AIAN	NR	NR
Asian	11%	12%
Black	NR	NR
NHOPI	NR	NR
Other - not listed	2%	2%
White	69%	71%
Multiracial	1%	NR
PNA	16%	13%

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Selected Race - Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: AIAN (All years), Black (All years), NHOPI (All years), Other – not listed (All years), Multiracial (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

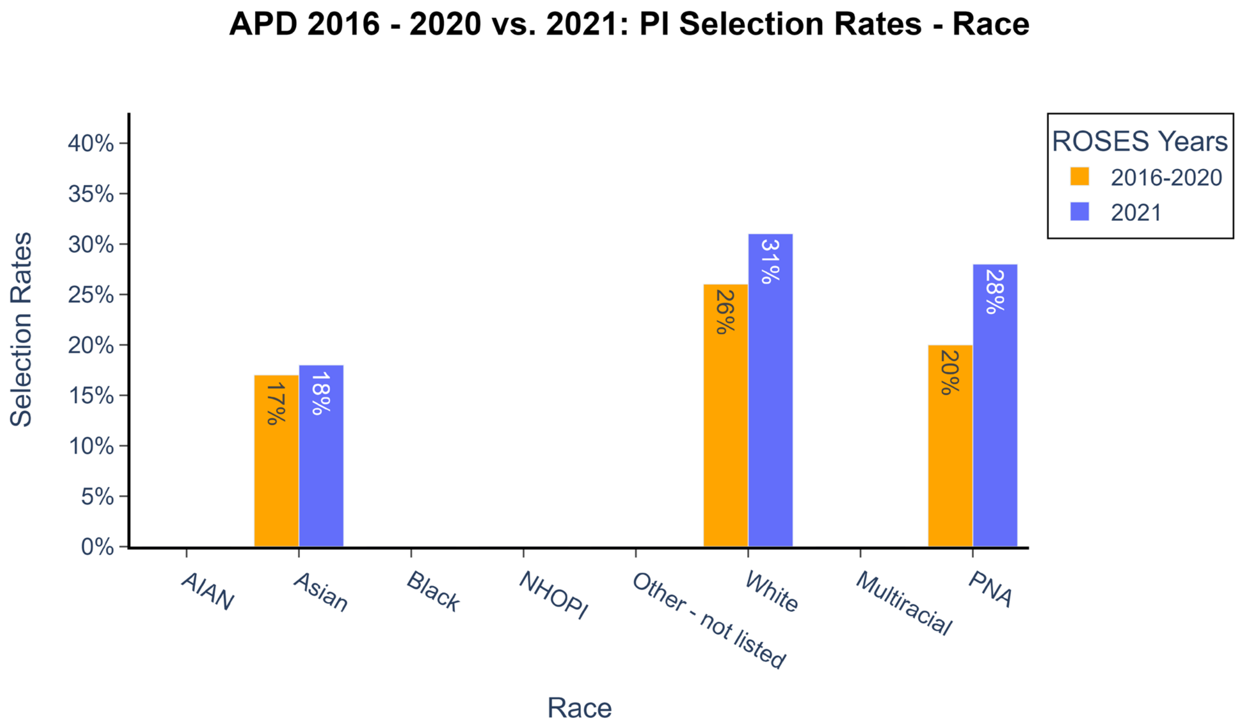
APD PIs: Selected Race - Data Table

APD 2016 - 2020 vs. 2021: Selected PIs - Race

Race	APD 2016 - 2020	APD 2021
AIAN	NR	NR
Asian	8%	8%
Black	NR	NR
NHOPI	NR	NR
Other - not listed	NR	NR
White	75%	76%
Multiracial	NR	NR
PNA	14%	12%

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Race Selection Rate - Bar Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: AIAN (All years), Black (All years), NHOPI (All years), Other – not listed (All years), Multiracial (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: Race Selection Rate - Data Table

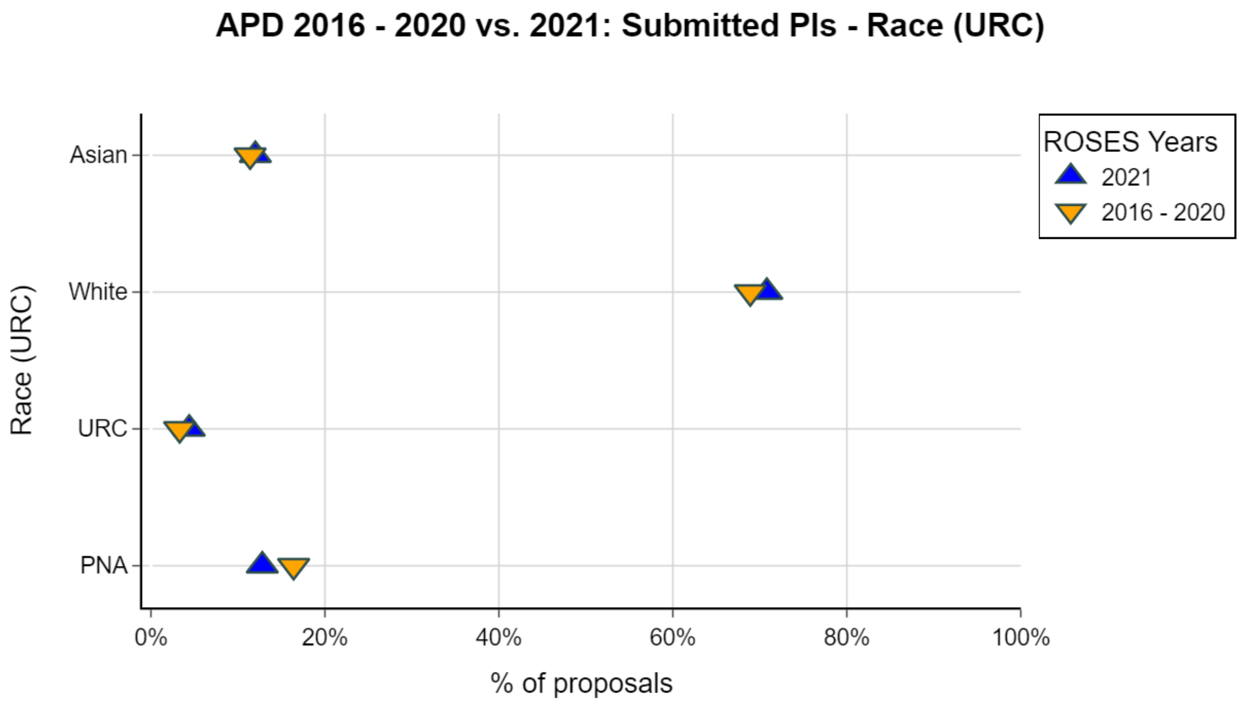
APD 2016 - 2020 vs. 2021: PI Selection Rates - Race

Race	APD 2016-2020	APD 2016-2020 Response/All Races	APD 2021	APD 2021 Response/All Races
AIAN	NR	NR	NR	NR
Asian	17%	0.74	18%	0.62
Black	NR	NR	NR	NR
NHOPI	NR	NR	NR	NR
Other - not listed	NR	NR	NR	NR
White	26%	1.13	31%	1.07
Multiracial	NR	NR	NR	NR
PNA	20%	0.87	28%	0.97
All Races	23%	1	29%	1

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

3.a.i.4. Race using Under-Represented Community (URC)– APD PIs

APD PIs: Submitted Race (URC) - Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

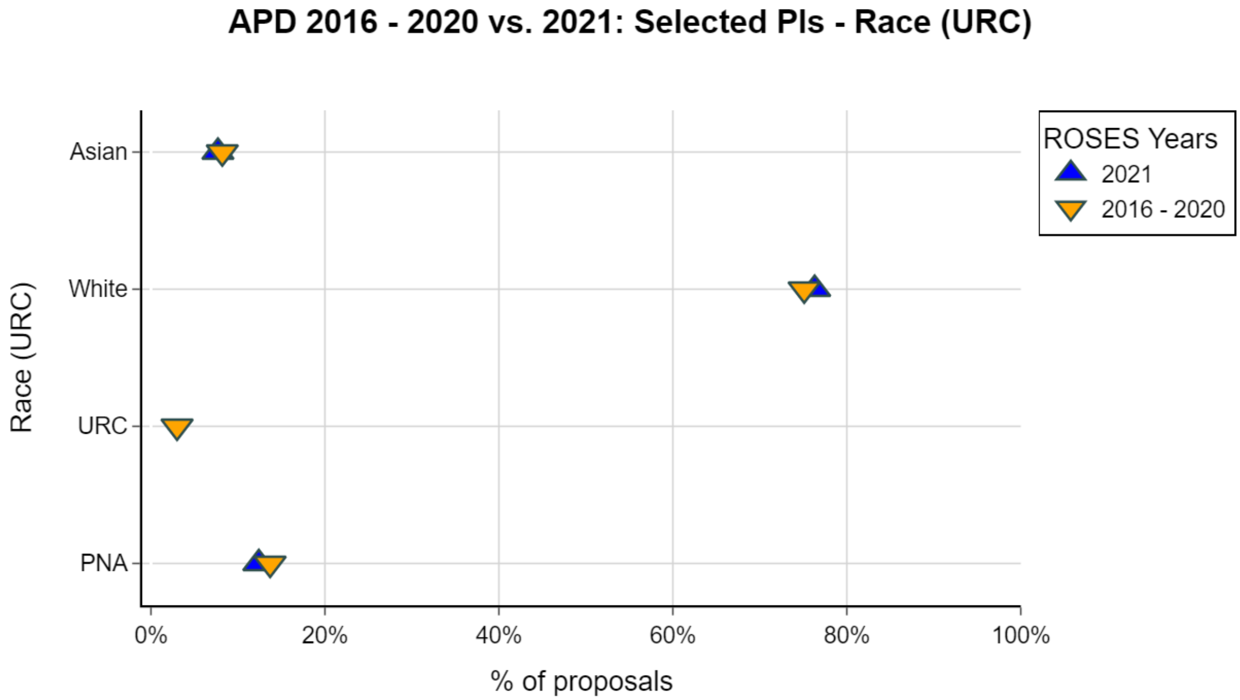
APD PIs: Submitted Race (URC) - Data Table

APD 2016 - 2020 vs. 2021: Submitted PIs - Race (URC)

Race (URC)	APD 2016 - 2020	APD 2021
Asian	11%	12%
White	69%	71%
URC	3%	4%
PNA	16%	13%

Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Selected Race (URC) - Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: URC (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

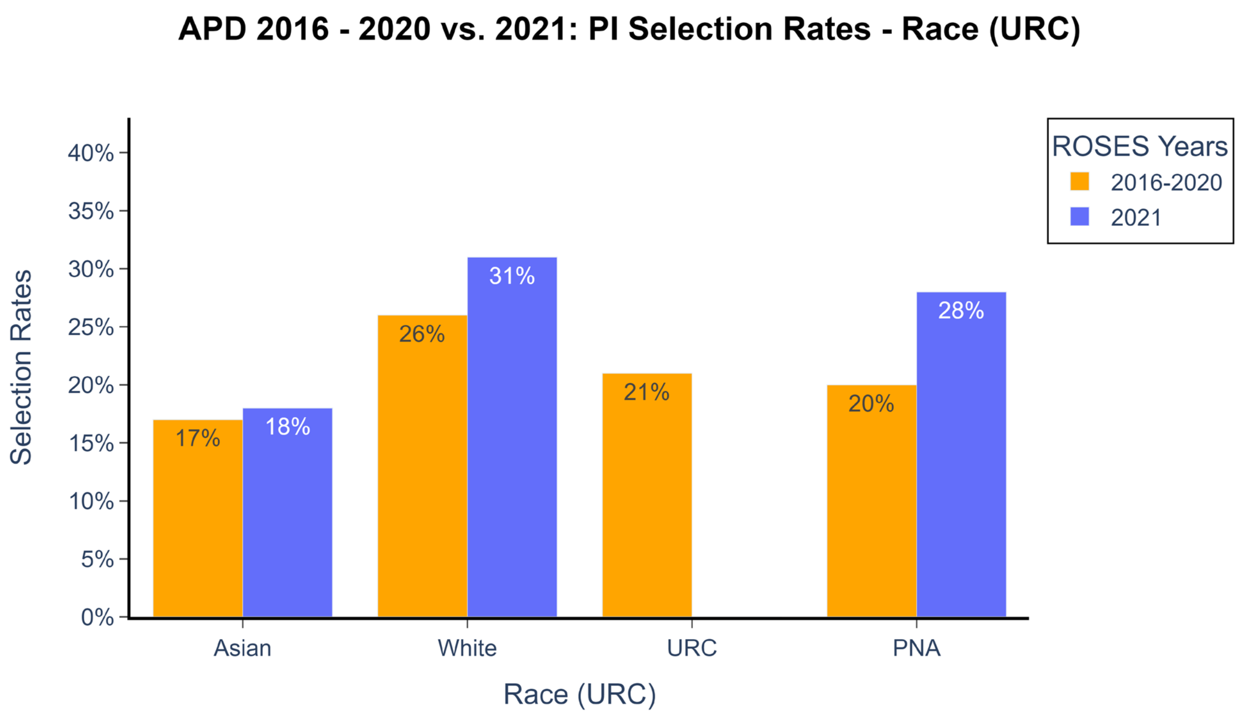
APD PIs: Selected Race (URC) - Data Table

APD 2016 - 2020 vs. 2021: Selected PIs - Race (URC)

Race (URC)	APD 2016 - 2020	APD 2021
Asian	8%	8%
White	75%	76%
URC	3%	NR
PNA	14%	12%

Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Race (URC) Selection Rate - Bar Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: URC (ROSES 2021)
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: Race (URC) Selection Rate - Data Table

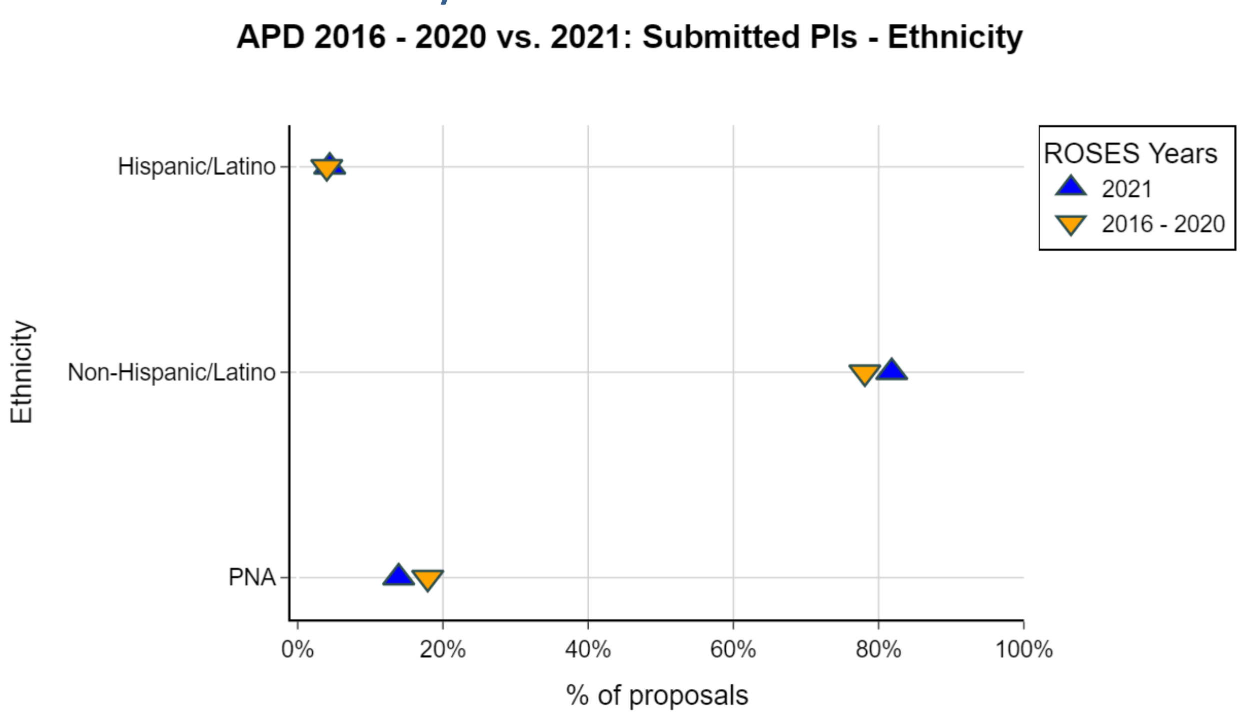
APD 2016 - 2020 vs. 2021: PI Selection Rates - Race (URC)

Race (URC)	APD 2016-2020	APD 2016-2020 Response/All Races (URC)	APD 2021	APD 2021 Response/All Races (URC)
Asian	17%	0.74	18%	0.62
White	26%	1.13	31%	1.07
URC	21%	0.91	NR	NR
PNA	20%	0.87	28%	0.97
All Races (URC)	23%	1	29%	1

Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

3.a.i.6. Ethnicity – APD PIs

APD PIs: Submitted Ethnicity - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

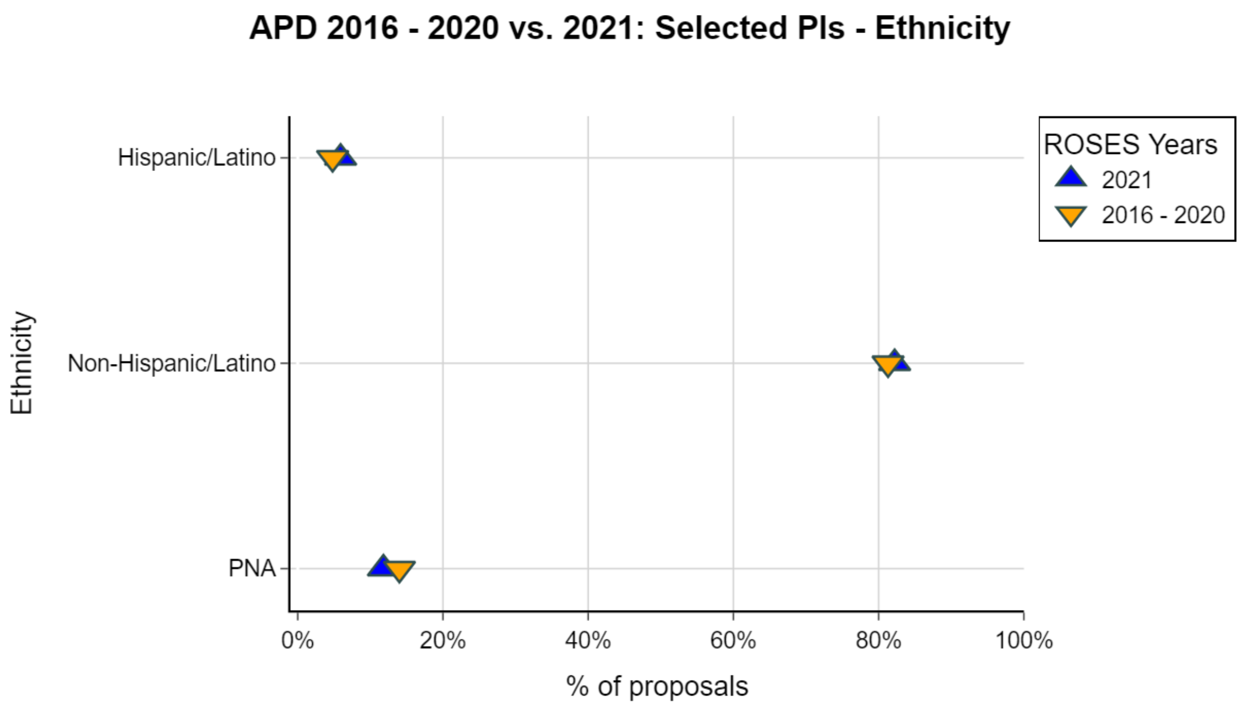
APD PIs: Submitted Ethnicity - Data Table

APD 2016 - 2020 vs. 2021: Submitted PIs - Ethnicity

Ethnicity	APD 2016 - 2020	APD 2021
Hispanic/Latino	4%	4%
Non-Hispanic/Latino	78%	82%
PNA	18%	14%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Selected Ethnicity - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

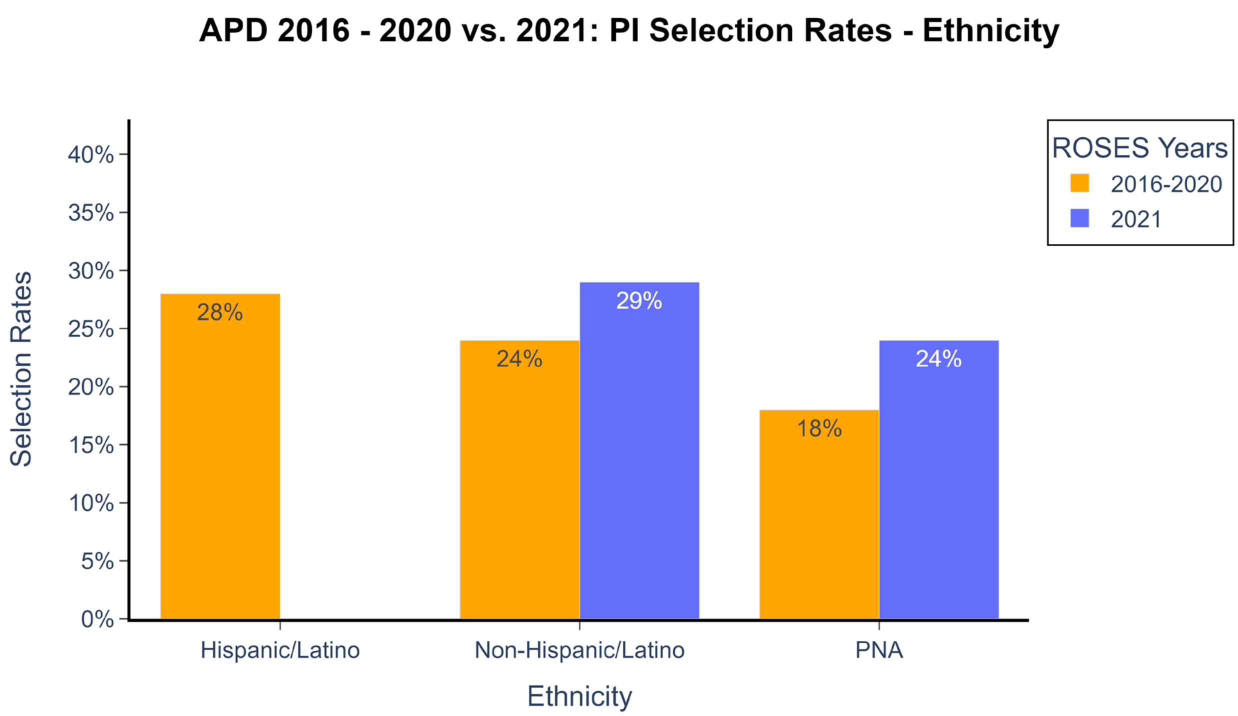
APD PIs: Selected Ethnicity - Data Table

APD 2016 - 2020 vs. 2021: Selected PIs - Ethnicity

Ethnicity	APD 2016 - 2020	APD 2021
Hispanic/Latino	5%	6%
Non-Hispanic/Latino	81%	82%
PNA	14%	12%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Ethnicity Selection Rate - Bar Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: Hispanic/Latino (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: Ethnicity Selection Rate - Data Table

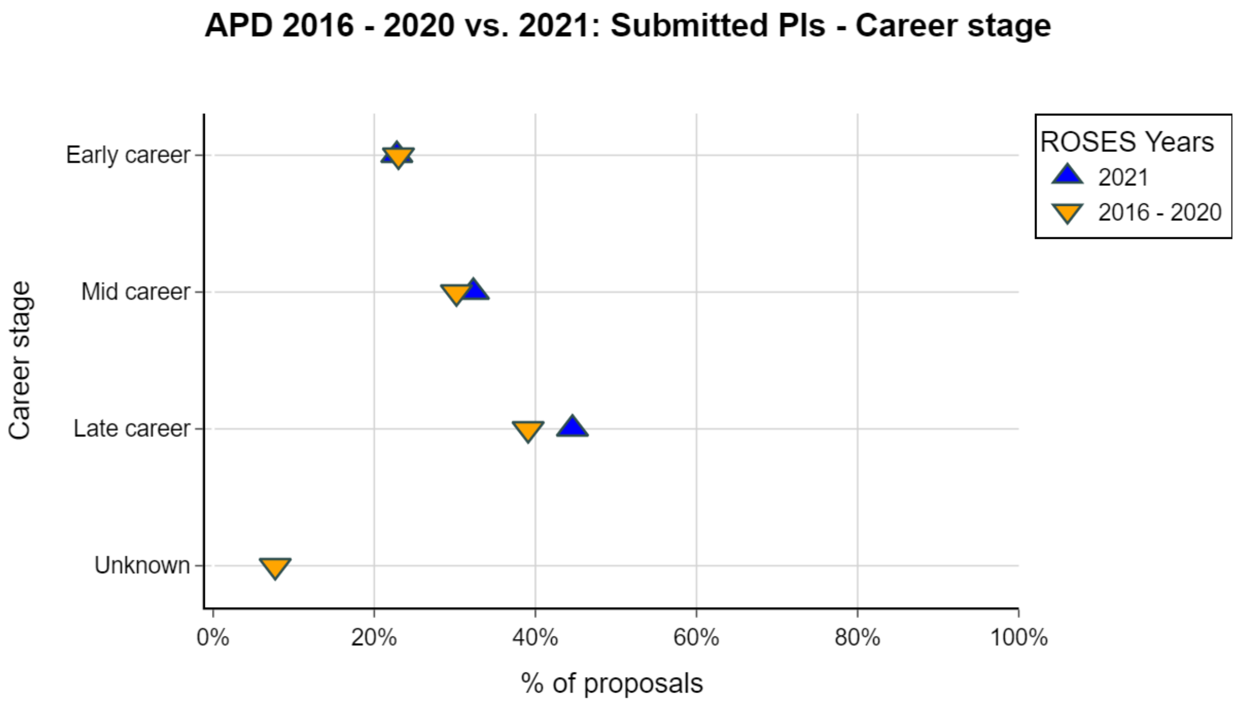
APD 2016 - 2020 vs. 2021: PI Selection Rates - Ethnicity

Ethnicity	APD 2016-2020	APD 2016-2020 Response/All Ethnicities	APD 2021	APD 2021 Response/All Ethnicities
Hispanic/Latino	28%	1.22	NR	NR
Non-Hispanic/Latino	24%	1.04	29%	1
PNA	18%	0.78	24%	0.83
All Ethnicities	23%	1	29%	1

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

3.a.i.6. Career Stage – APD PIs

APD PIs: Submitted Career Stage - Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Unknown (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

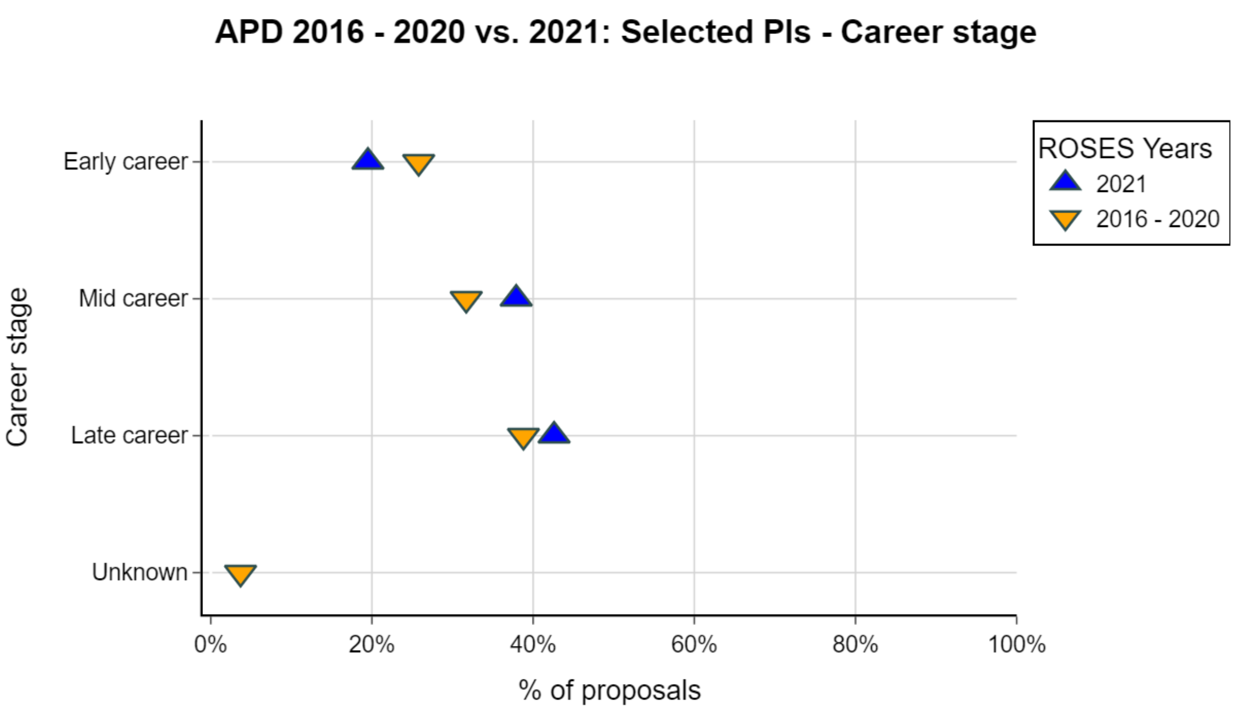
APD PIs: Submitted Career Stage - Data Table

APD 2016 - 2020 vs. 2021: Submitted PIs - Career stage

Career stage	APD 2016 - 2020	APD 2021
Early career	23%	23%
Mid career	30%	32%
Late career	39%	45%
Unknown	8%	NR

Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Selected Career Stage - Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Unknown (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

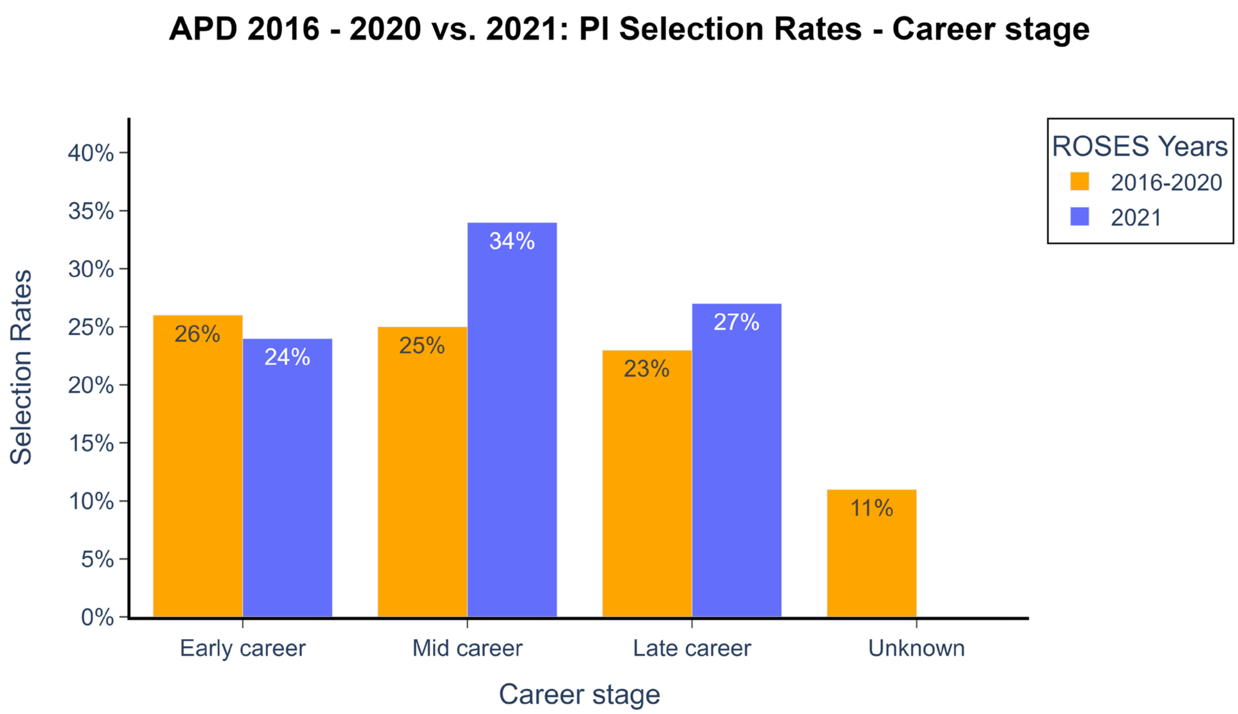
APD PIs: Selected Career Stage - Data Table

APD 2016 - 2020 vs. 2021: Selected PIs - Career stage

Career stage	APD 2016 - 2020	APD 2021
Early career	26%	20%
Mid career	32%	38%
Late career	39%	43%
Unknown	4%	NR

Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Career Stage Selection Rate - Bar Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: Unknown (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: Career Stage Selection Rate - Data Table

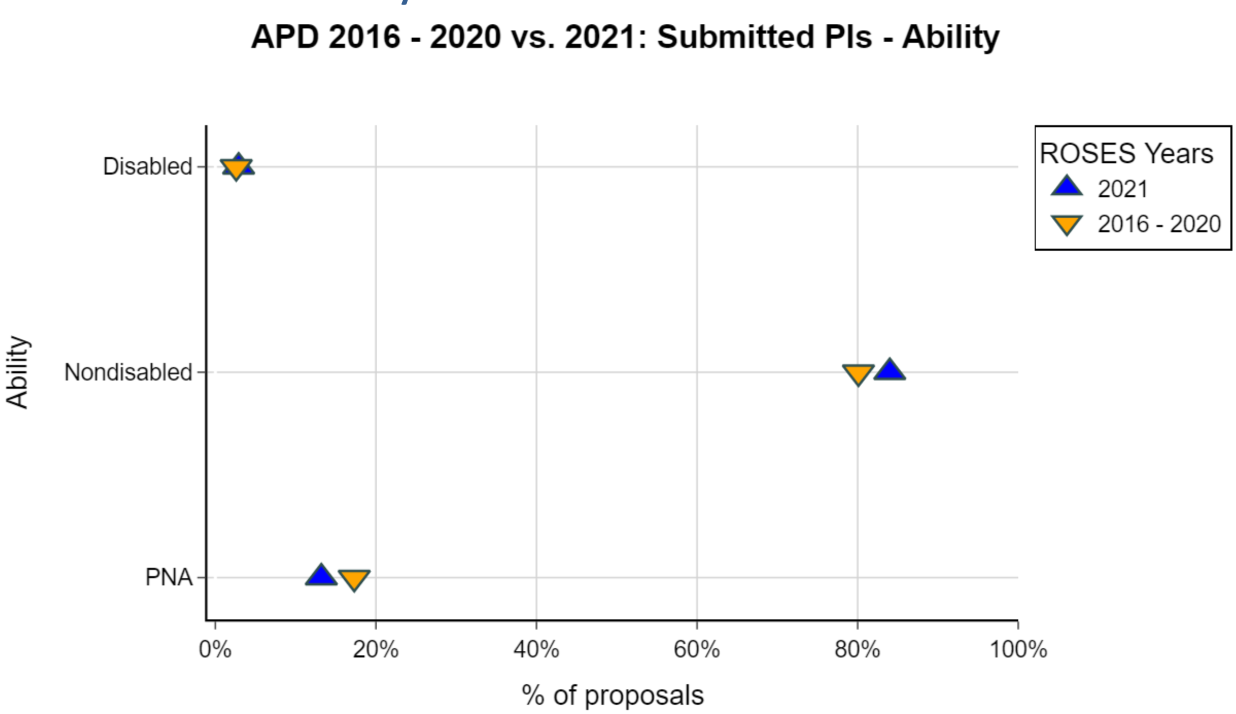
APD 2016 - 2020 vs. 2021: PI Selection Rates - Career stage

Career stage	APD 2016-2020	APD 2016-2020 Response/All Career stages	APD 2021	APD 2021 Response/All Career stages
Early career	26%	1.13	24%	0.83
Mid career	25%	1.09	34%	1.17
Late career	23%	1	27%	0.93
Unknown	11%	0.48	NR	NR
All Career stages	23%	1	29%	1

Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

3.a.i.7. Disability Status – APD PIs

APD PIs: Submitted Ability - Plot



Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

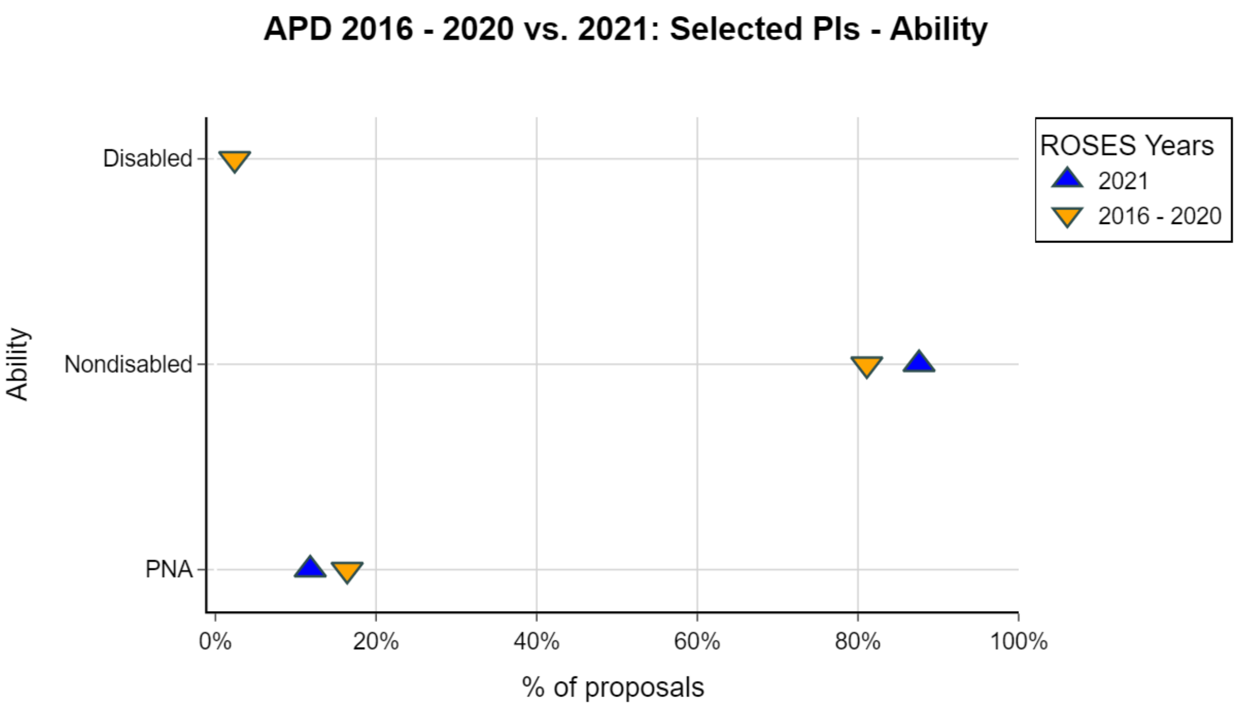
APD PIs: Submitted Ability - Data Table

APD 2016 - 2020 vs. 2021: Submitted PIs - Ability

Ability	APD 2016 - 2020	APD 2021
Disabled	3%	3%
Nondisabled	80%	84%
PNA	17%	13%

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Selected Ability - Plot



Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Disabled (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

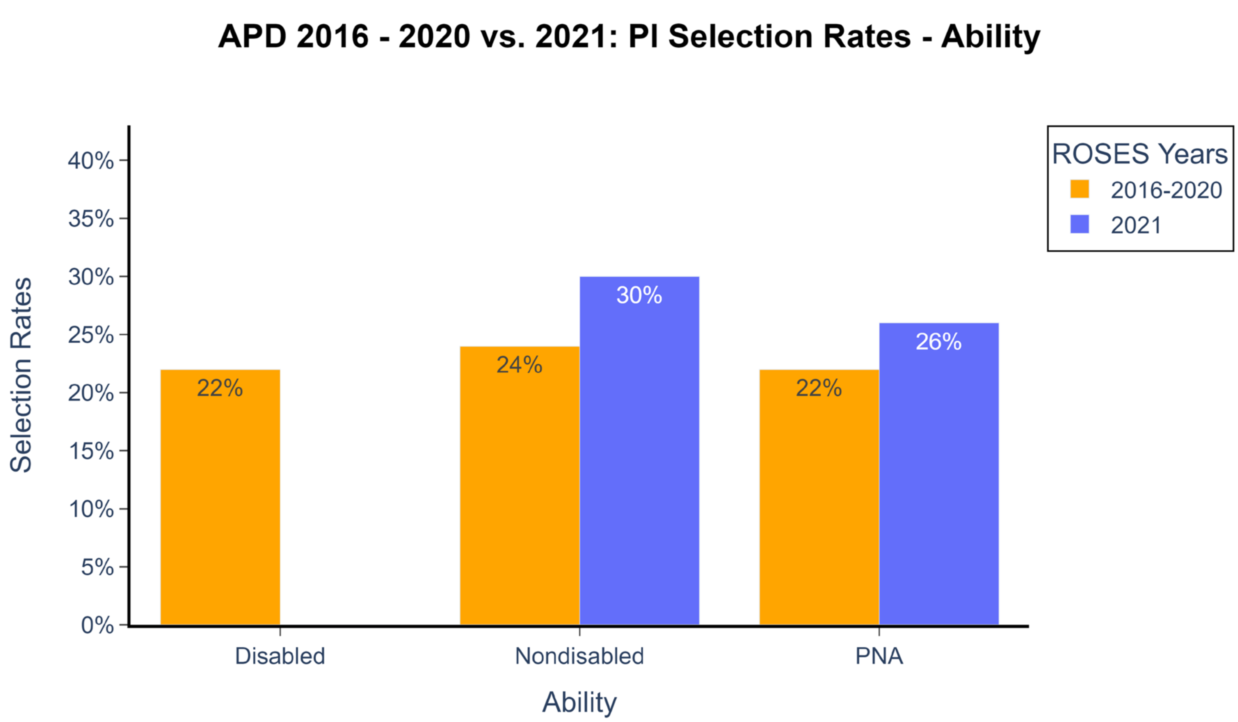
APD PIs: Selected Ability - Data Table

APD 2016 - 2020 vs. 2021: Selected PIs - Ability

Ability	APD 2016 - 2020	APD 2021
Disabled	2%	NR
Nondisabled	81%	88%
PNA	16%	12%

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Ability Selection Rate - Bar Plot



Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: Disabled (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: Ability Selection Rate - Data Table

APD 2016 - 2020 vs. 2021: PI Selection Rates - Ability

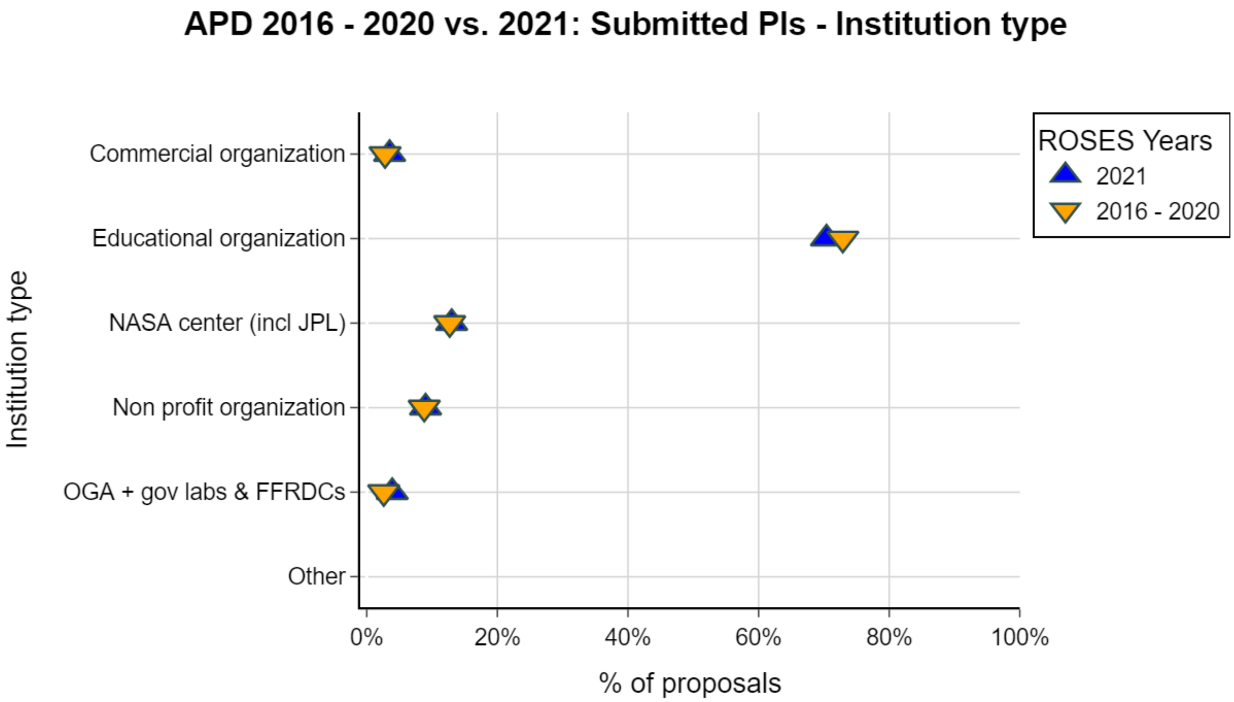
Ability	APD 2016-2020	APD 2016-2020 Response/All Abilities	APD 2021	APD 2021 Response/All Abilities
Disabled	22%	0.96	NR	NR
Nondisabled	24%	1.04	30%	1.03
PNA	22%	0.96	26%	0.9
All Abilities	23%	1	29%	1

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

3.a.i.8. Institutional Analysis

3.a.i.8.a. Institution Type – APD PIs

APD PIs: Submitted Institution Type - Plot



OGA: Other Government Agency | FFRDCs: Federally-Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Other (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

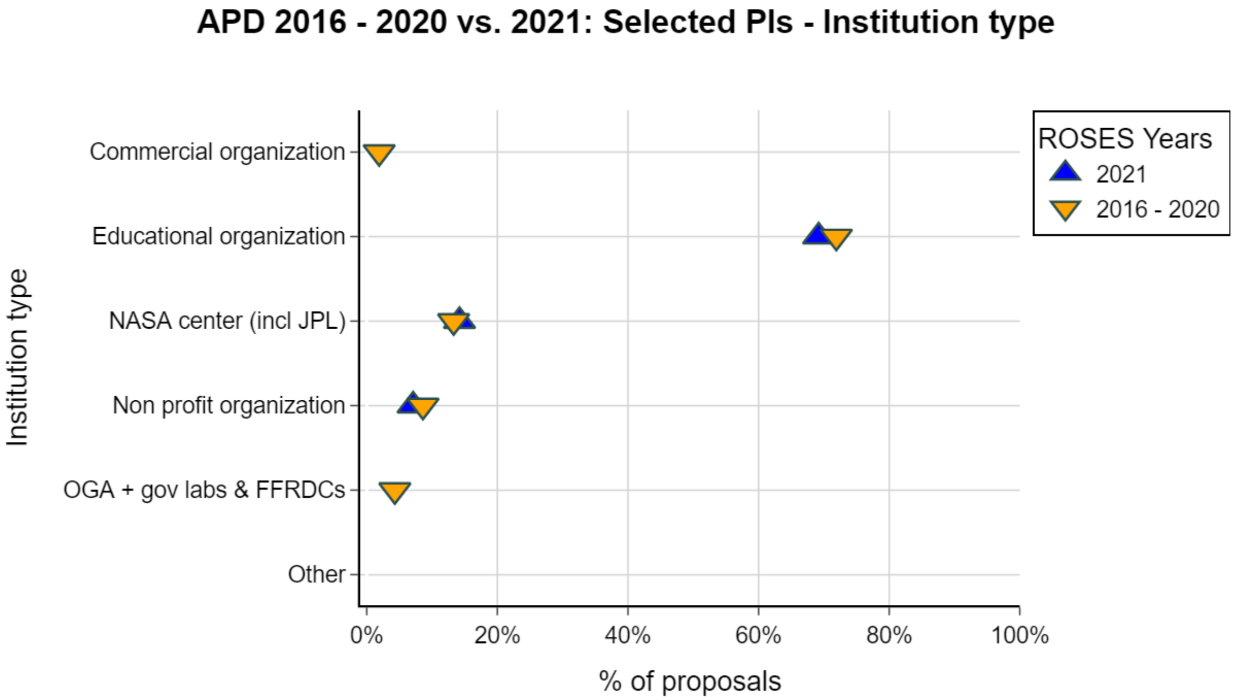
APD PIs: Submitted Institution Type - Data Table

APD 2016 - 2020 vs. 2021: Submitted PIs - Institution type

Institution type	APD 2016 - 2020	APD 2021
Commercial organization	3%	4%
Educational organization	73%	70%
NASA center (incl JPL)	13%	13%
Non profit organization	9%	9%
OGA + gov labs & FFRDCs	3%	4%
Other	NR	NR

OGA: Other Government Agency | FFRDCs: Federally-Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Selected Institution Type - Plot



OGA: Other Government Agency | FFRDCs: Federally-Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Commercial organization (ROSES 2021), OGA + gov labs & FFRDCs (ROSES 2021), Other (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

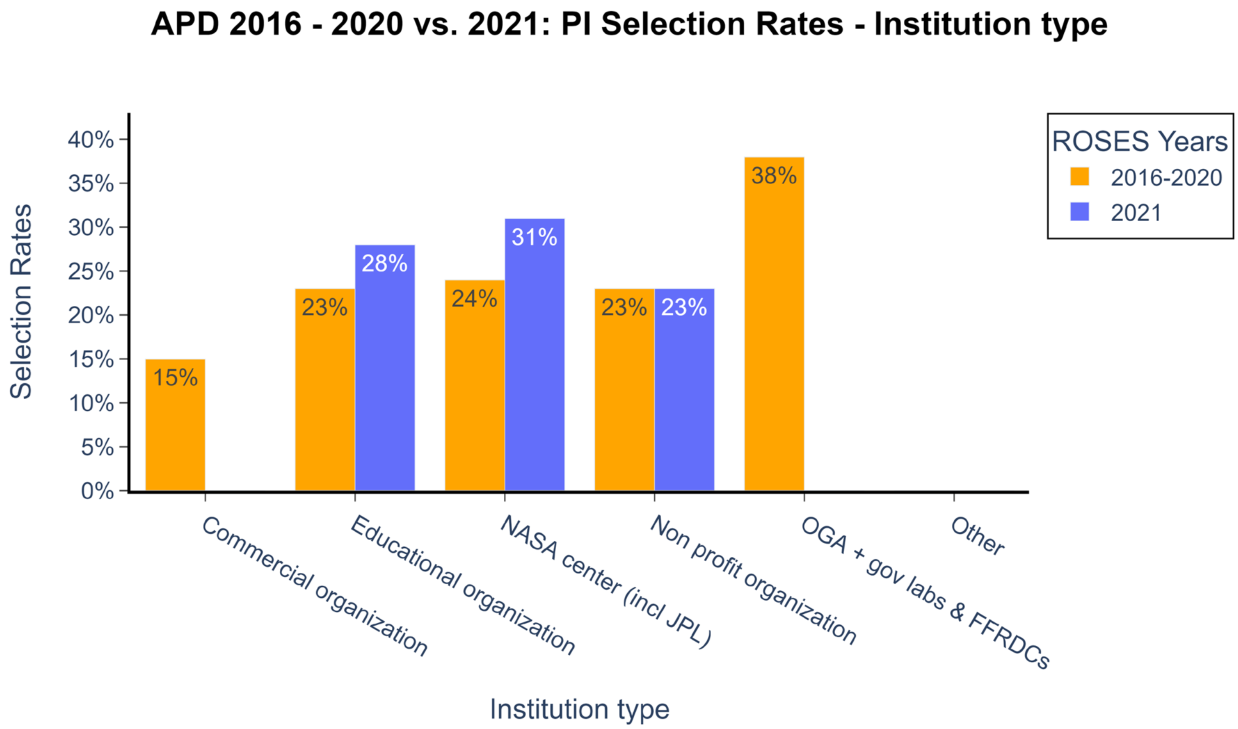
APD PIs: Selected Institution Type - Data Table

APD 2016 - 2020 vs. 2021: Selected PIs - Institution type

Institution type	APD 2016 - 2020	APD 2021
Commercial organization	2%	NR
Educational organization	72%	69%
NASA center (incl JPL)	13%	14%
Non profit organization	9%	7%
OGA + gov labs & FFRDCs	4%	NR
Other	NR	NR

OGA: Other Government Agency | FFRDCs: Federally-Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Institution Type Selection Rate - Bar Plot



OGA: Other Government Agency | FFRDCs: Federally-Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: Commercial organization (ROSES 2021), OGA + gov labs & FFRDCs (ROSES 2021), Other (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: Institution Type Selection Rate - Data Table

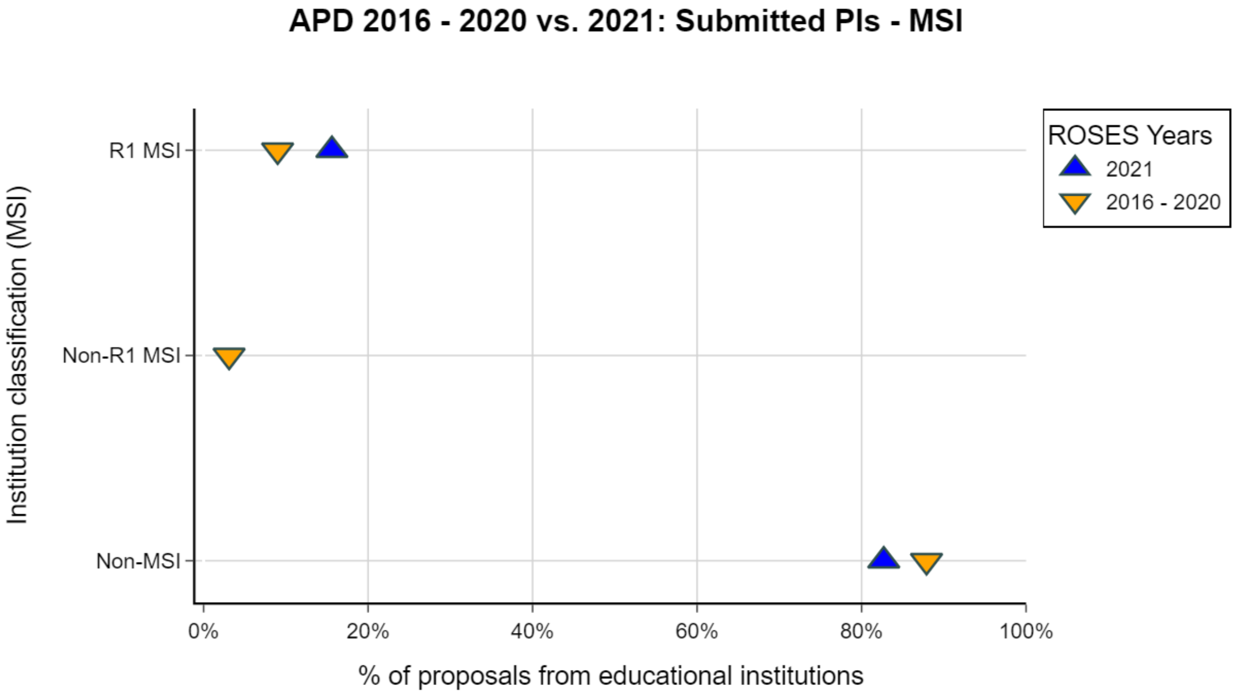
APD 2016 - 2020 vs. 2021: PI Selection Rates - Institution type

Institution type	APD 2016-2020	APD 2016-2020 Response/All Institution types	APD 2021	APD 2021 Response/All Institution types
Commercial organization	15%	0.65	NR	NR
Educational organization	23%	1	28%	0.97
NASA center (incl JPL)	24%	1.04	31%	1.07
Non profit organization	23%	1	23%	0.79
OGA + gov labs & FFRDCs	38%	1.65	NR	NR
Other	NR	NR	NR	NR
All Institution types	23%	1	29%	1

OGA: Other Government Agency | FFRDCs: Federally-Funded Research and Development Centers | Other: State, Local or Federally Recognized Tribal Government Agency & Unaffiliated Individuals | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

3.a.i.8.b. Minority Serving Institutions (MSIs) – APD PIs

APD PIs: Submitted MSI - Plot



MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non-R1 MSI (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

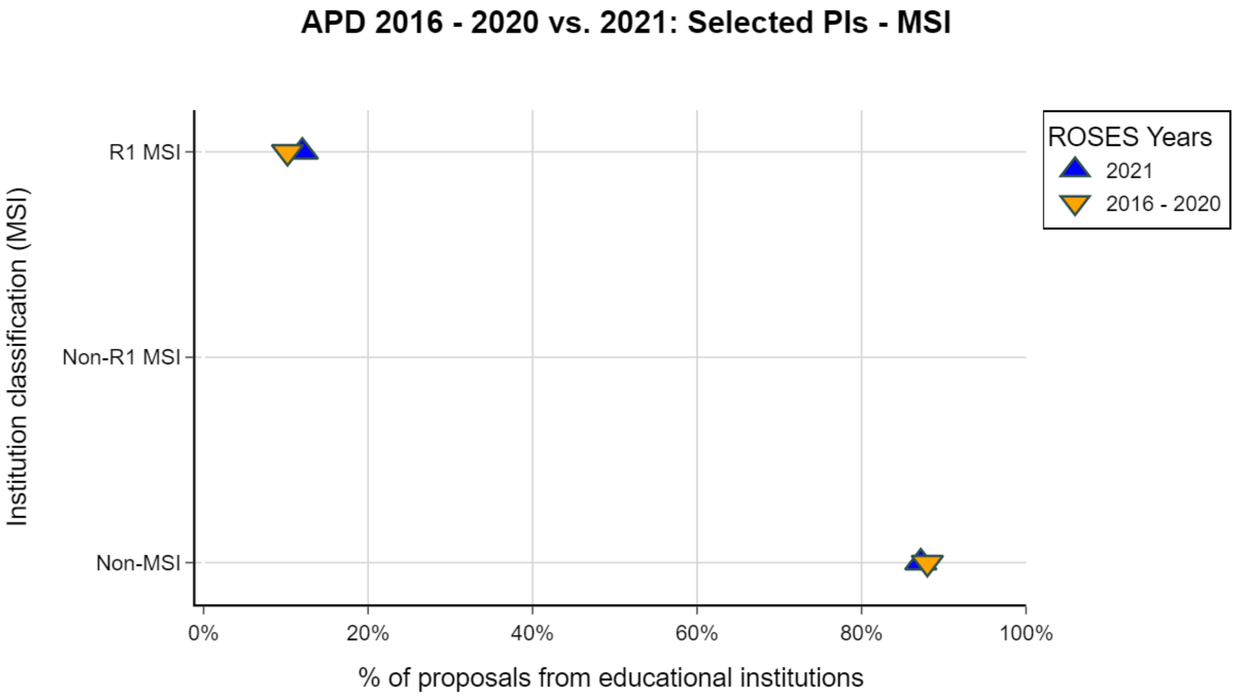
APD PIs: Submitted MSI - Data Table

APD 2016 - 2020 vs. 2021: Submitted PIs - MSI

MSI	APD 2016 - 2020	APD 2021
R1 MSI	9%	16%
Non-R1 MSI	3%	NR
Non-MSI	88%	83%

MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Selected MSI - Plot



MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non-R1 MSI (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

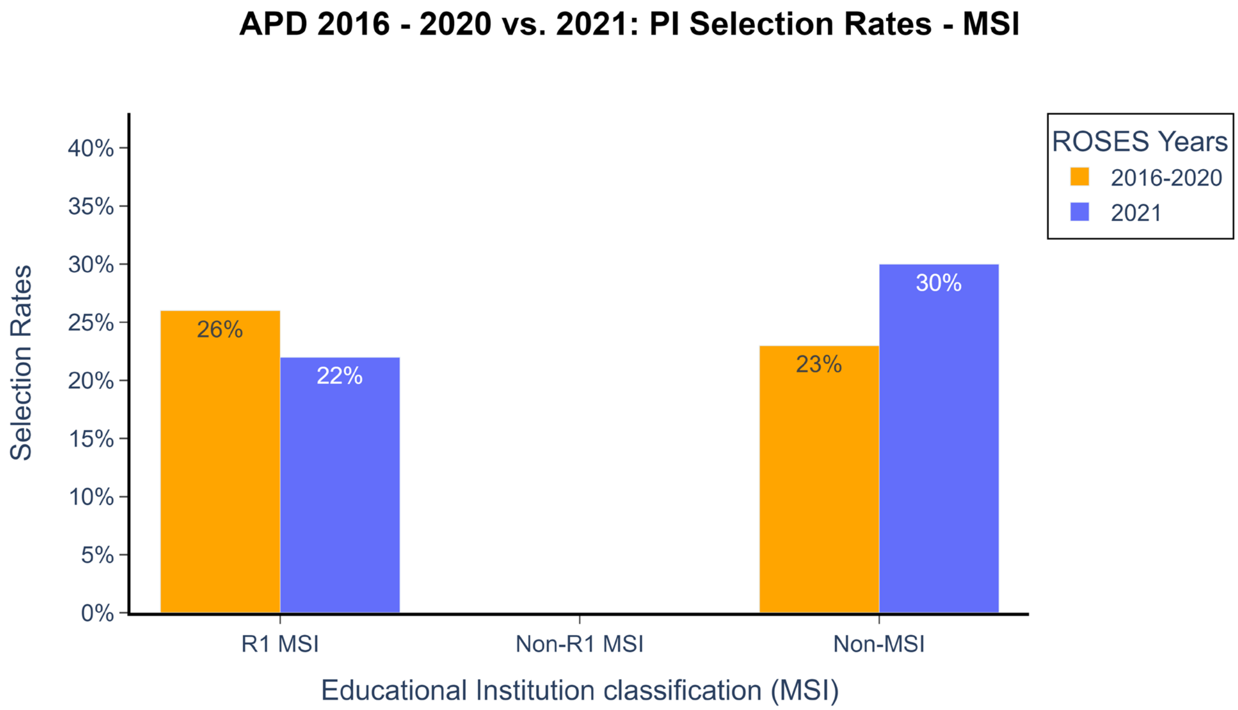
APD PIs: Selected MSI - Data Table

APD 2016 - 2020 vs. 2021: Selected PIs - MSI

MSI	APD 2016 - 2020	APD 2021
R1 MSI	10%	12%
Non-R1 MSI	NR	NR
Non-MSI	88%	87%

MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: MSI Selection Rate - Bar Plot



MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: Non-R1 MSI (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: MSI Selection Rate - Data Table

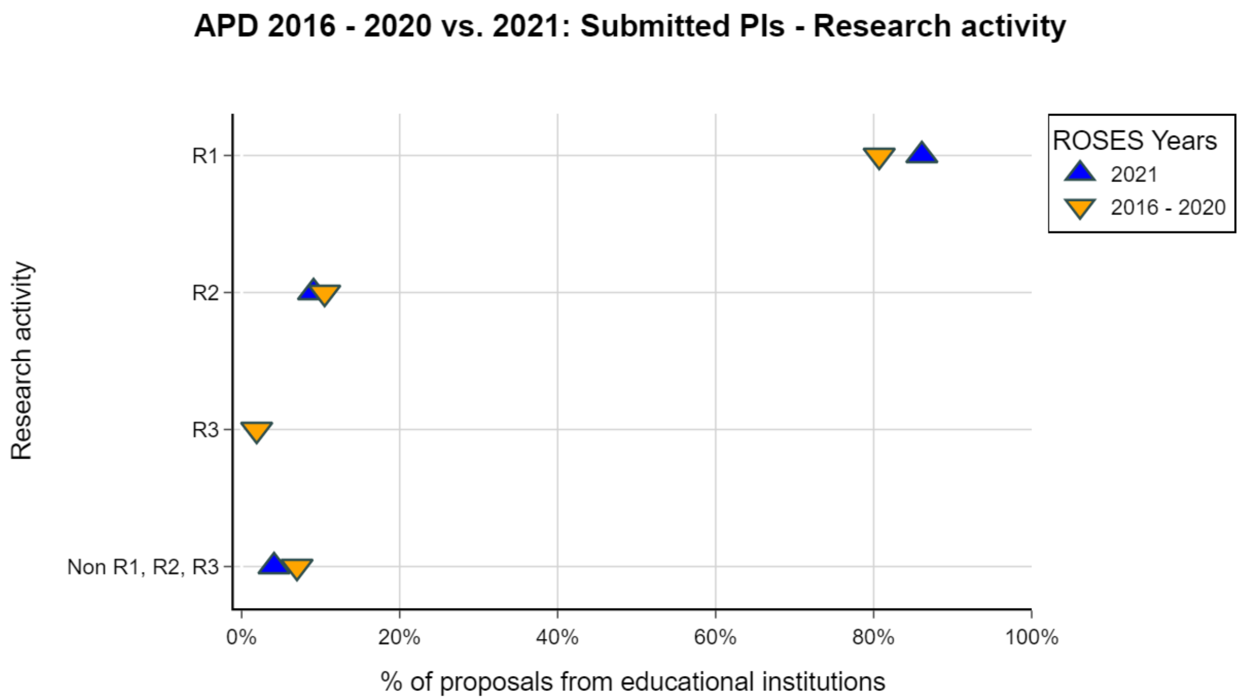
APD 2016 - 2020 vs. 2021: PI Selection Rates - MSI

MSI	APD 2016-2020	APD 2016-2020 Response/All Educational Institutions	APD 2021	APD 2021 Response/All Educational Institutions
R1 MSI	26%	1.13	22%	0.79
Non-R1 MSI	NR	NR	NR	NR
Non-MSI	23%	1	30%	1.07
All Educational Institutions	23%	1	28%	1

MSI: Minority Serving Institution | R1: Doctoral university - Very high research activity | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

3.a.i.8.c. Carnegie Classification of Research Activity – APD PIs

APD PIs: Submitted Research Activity - Plot



R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: R3 (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

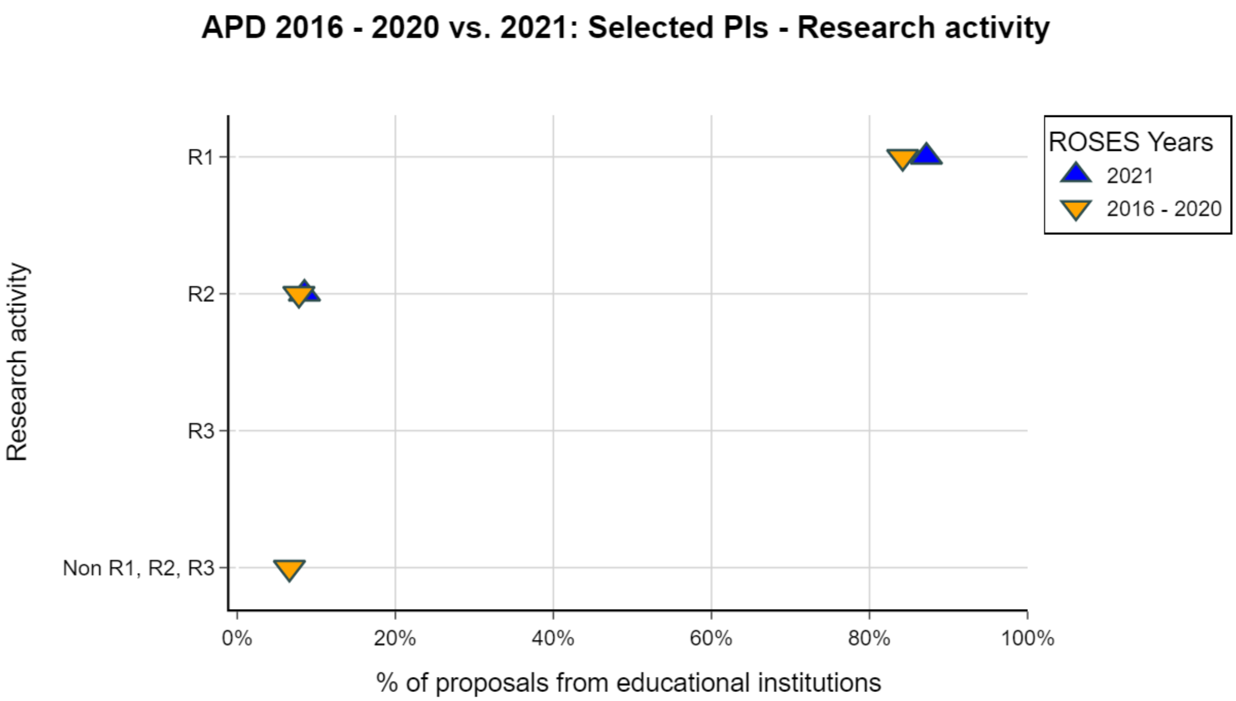
APD PIs: Submitted Research Activity - Data Table

APD 2016 - 2020 vs. 2021: Submitted PIs - Research activity

Research activity	APD 2016 - 2020	APD 2021
R1	81%	86%
R2	10%	9%
R3	2%	NR
Non R1, R2, R3	7%	4%

R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Selected Research Activity - Plot



R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: R3 (All years), Non R1, R2, R3 (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

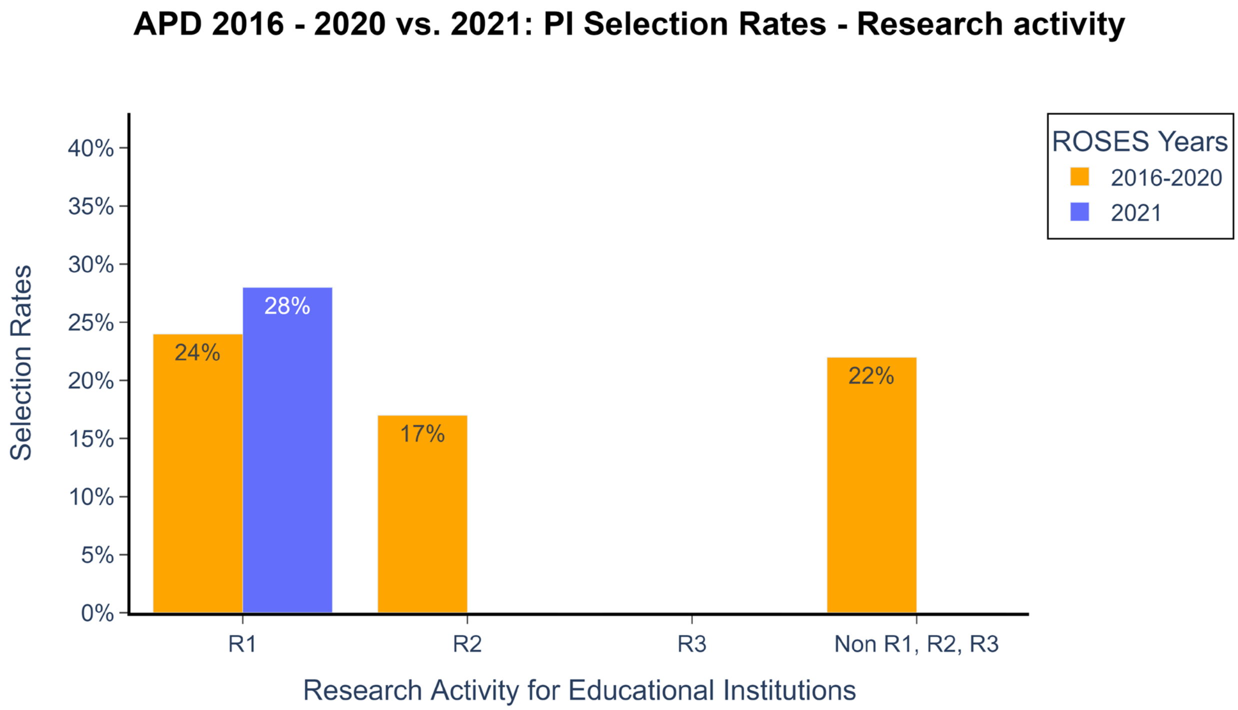
APD PIs: Selected Research Activity - Data Table

APD 2016 - 2020 vs. 2021: Selected PIs - Research activity

Research activity	APD 2016 - 2020	APD 2021
R1	84%	87%
R2	8%	8%
R3	NR	NR
Non R1, R2, R3	7%	NR

R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD PIs: Research Activity Selection Rate - Bar Plot



R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

Suppressed categories: R2 (ROSES 2021), R3 (All years), Non R1, R2, R3 (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD PIs: Research Activity Selection Rate - Data Table

APD 2016 - 2020 vs. 2021: PI Selection Rates - Research activity

Research activity	APD 2016-2020	APD 2016-2020 Response/All Educational Institutions	APD 2021	APD 2021 Response/All Educational Institutions
R1	24%	1.04	28%	1
R2	17%	0.74	NR	NR
R3	NR	NR	NR	NR
Non R1, R2, R3	22%	0.96	NR	NR
All Educational Institutions	23%	1	28%	1

R1: Doctoral university - Very high research activity | R2: Doctoral university - High research activity | R3: Doctoral/professional university | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated. | Selection rate = # of selected proposals with PIs from a demographic response group/ # of submitted proposals with PIs from the same demographic response group

3.a.ii. Science Team

3.a.ii.1. Context and Limitations of the Data – APD Science Team

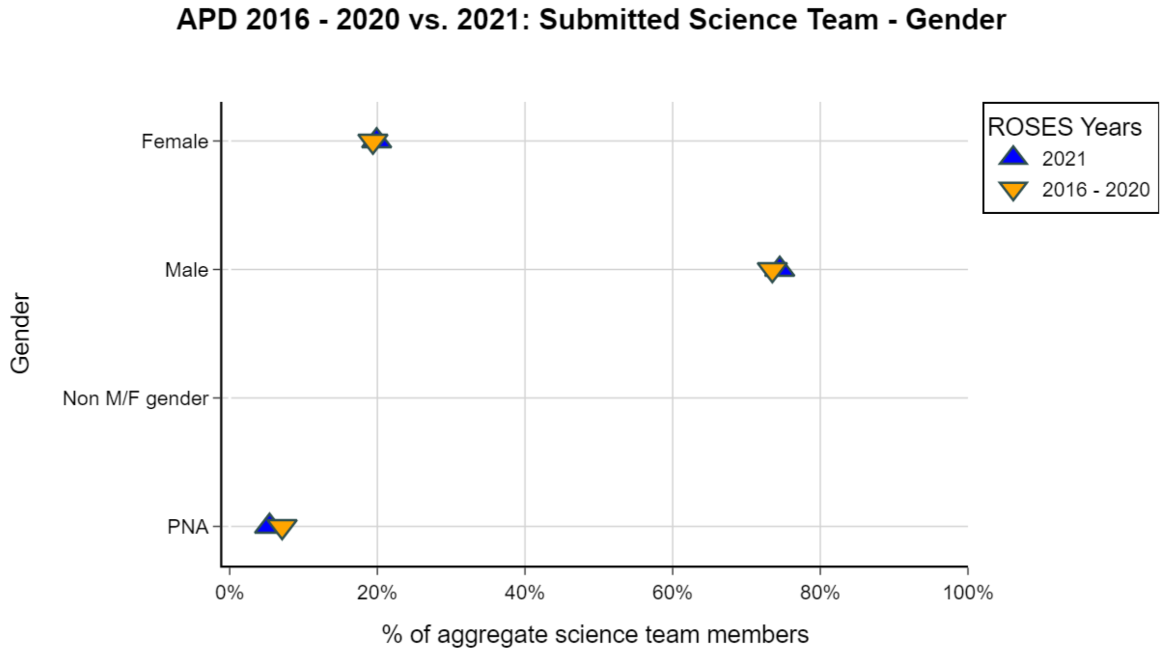
26,043 submitted proposals are included in the ROSES 2016-2021 database. Please see Appendix Table 1 to see which programs are included. The total number of proposals submitted and selected for each ROSES year and the total number of proposals submitted to each SMD Division cannot be reported due to the Office of the Chief Scientist's suppression guidelines. See *Yearbook Introduction Section 1.a.ii.1* *Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics* for more information. The number of proposals rounded to the nearest hundred are included for these two circumstances to provide context. For the Astrophysics Division, there are ~3,600 submitted proposals over all ROSES years: ~3,000 for ROSES 2016-2020 and ~600 for ROSES 2021.

Instances in the science team member dataset where a science team member took the survey but selected "prefer not to answer" for all demographic survey questions:

- Submitted proposals: APD 2016 - 2020: 6% | APD 2021: 5%
- Selected proposals: APD 2016 - 2020: 6% | APD 2021: 5%

3.a.ii.2. Gender – APD Science Team

APD Science Team: Submitted Gender - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non M/F gender (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

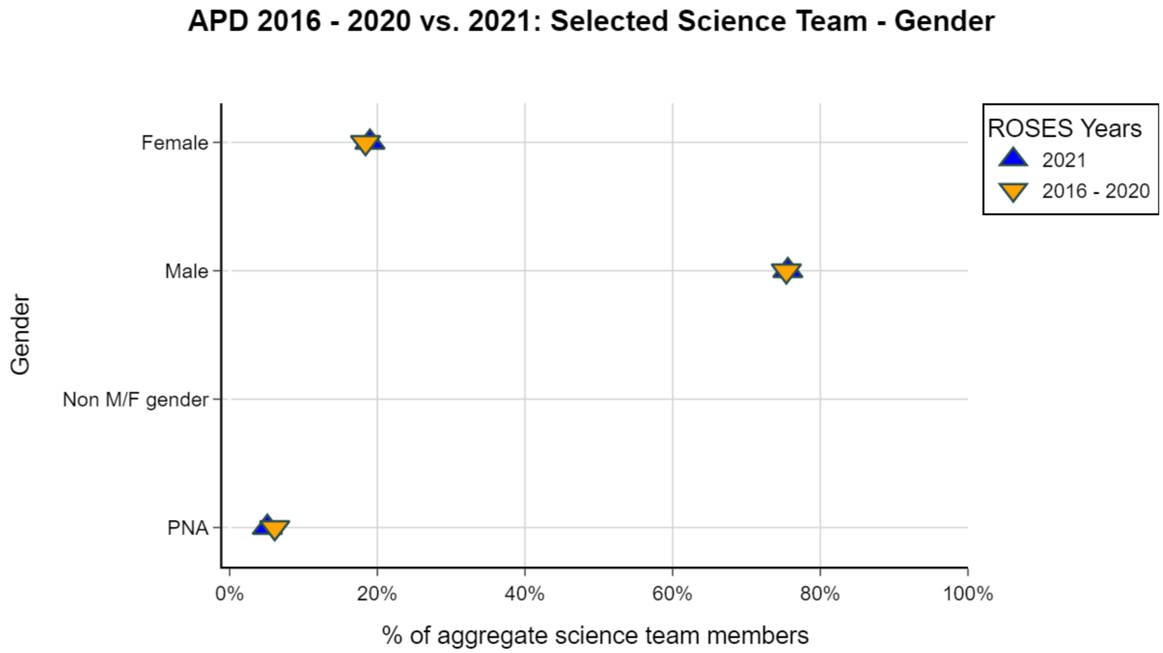
APD Science Team: Submitted Gender - Data Table

APD 2016 - 2020 vs. 2021: Submitted Science Team - Gender

Gender	APD 2016 - 2020	APD 2021
Female	19%	20%
Male	74%	74%
Non M/F gender	NR	NR
PNA	7%	5%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD Science Team: Selected Gender - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Non M/F gender (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

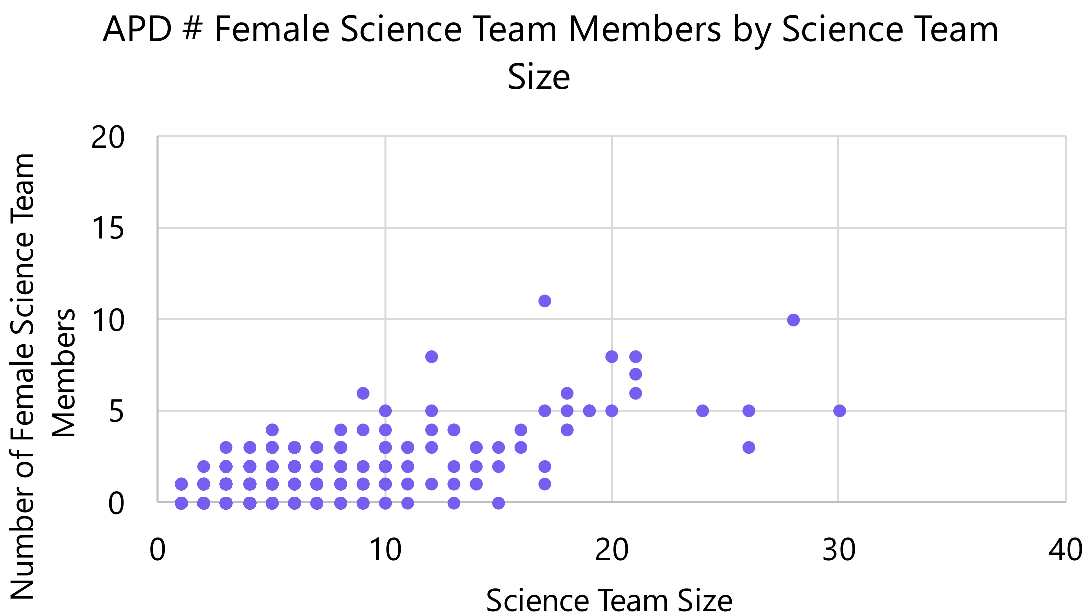
APD Science Team: Selected Gender - Data Table

APD 2016 - 2020 vs. 2021: Selected Science Team - Gender

Gender	APD 2016 - 2020	APD 2021
Female	18%	19%
Male	75%	76%
Non M/F gender	NR	NR
PNA	6%	5%

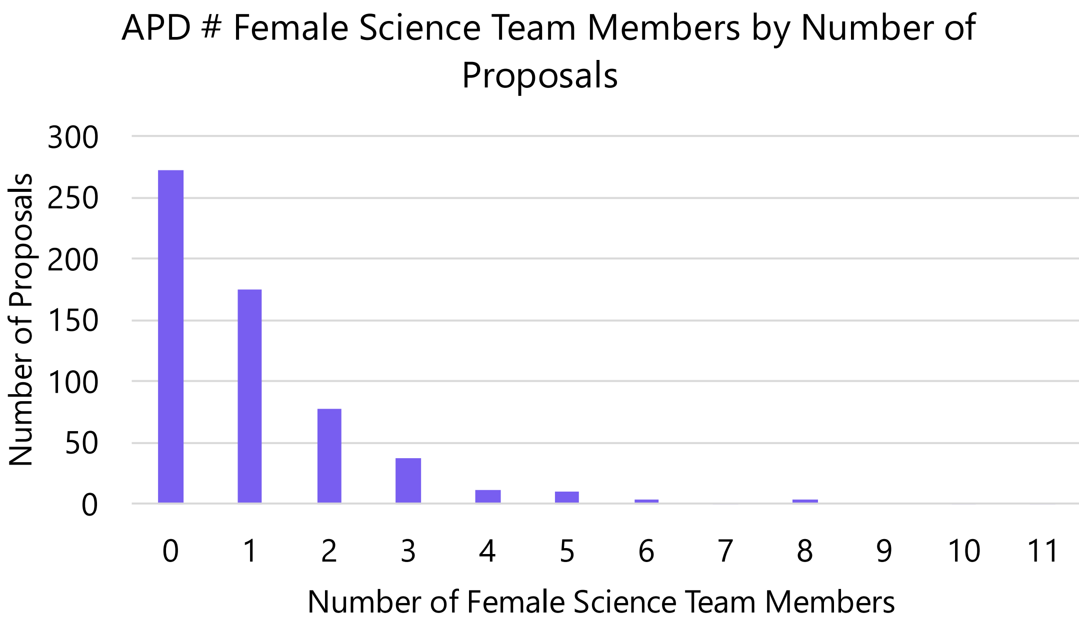
PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD ROSES 2021 Science Teams: Female Science Team Members by Science Team Size – Scatter Plot



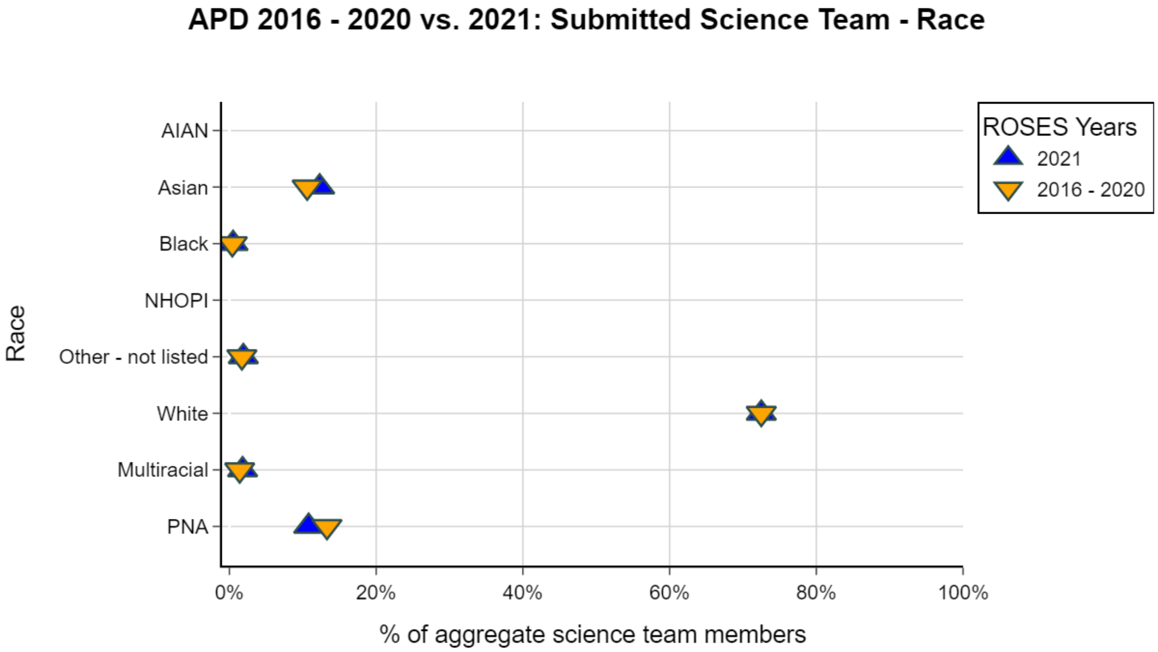
Note: 46% of proposals submitted to ROSES 2021 Astrophysics programs did not include female researchers in their science team. 12% of proposals submitted to ROSES 2021 Astrophysics programs only included the PI as the science team.

APD ROSES 2021 Science Teams: Female Science Team Members by Number of Proposals – Bar Plot



3.a.ii.3. Race – APD Science Team

APD Science Team: Submitted Race - Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: AIAN (All years), NHOPI (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

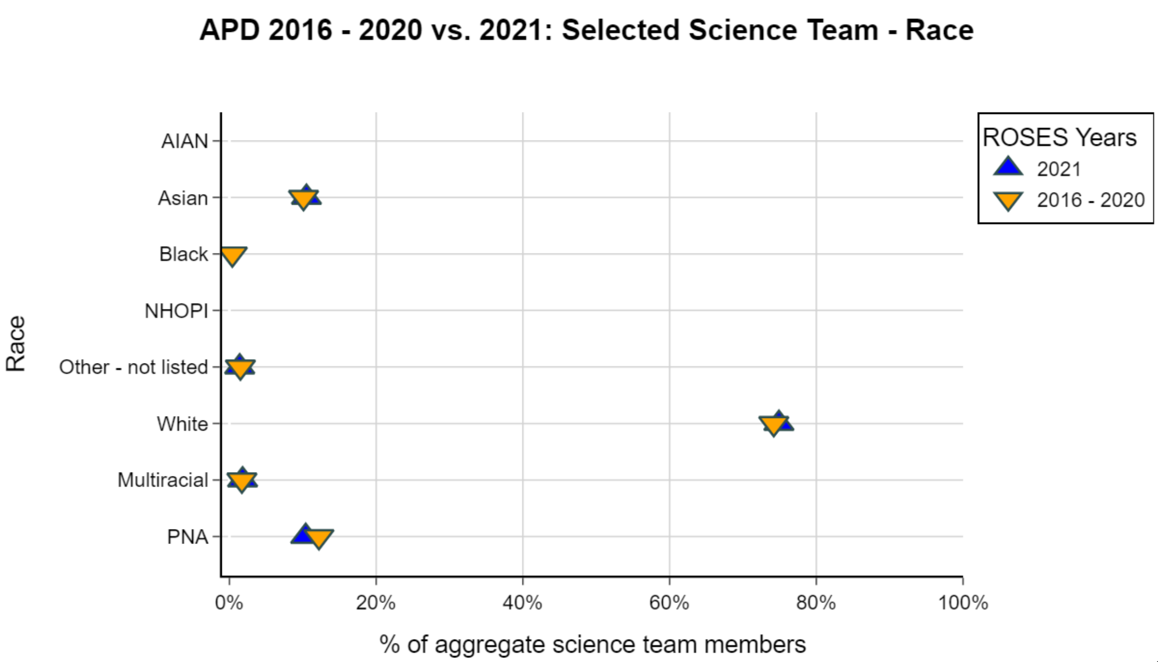
APD Science Team: Submitted Race - Data Table

APD 2016 - 2020 vs. 2021: Submitted Science Team - Race

Race	APD 2016 - 2020	APD 2021
AIAN	NR	NR
Asian	11%	12%
Black	< 1%	< 1%
NHOPI	NR	NR
Other - not listed	2%	2%
White	72%	72%
Multiracial	1%	2%
PNA	13%	11%

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD Science Team: Selected Race - Plot



AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: AIAN (All years), Black (ROSES 2021), NHOPI (All years).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

APD Science Team: Selected Race - Data Table

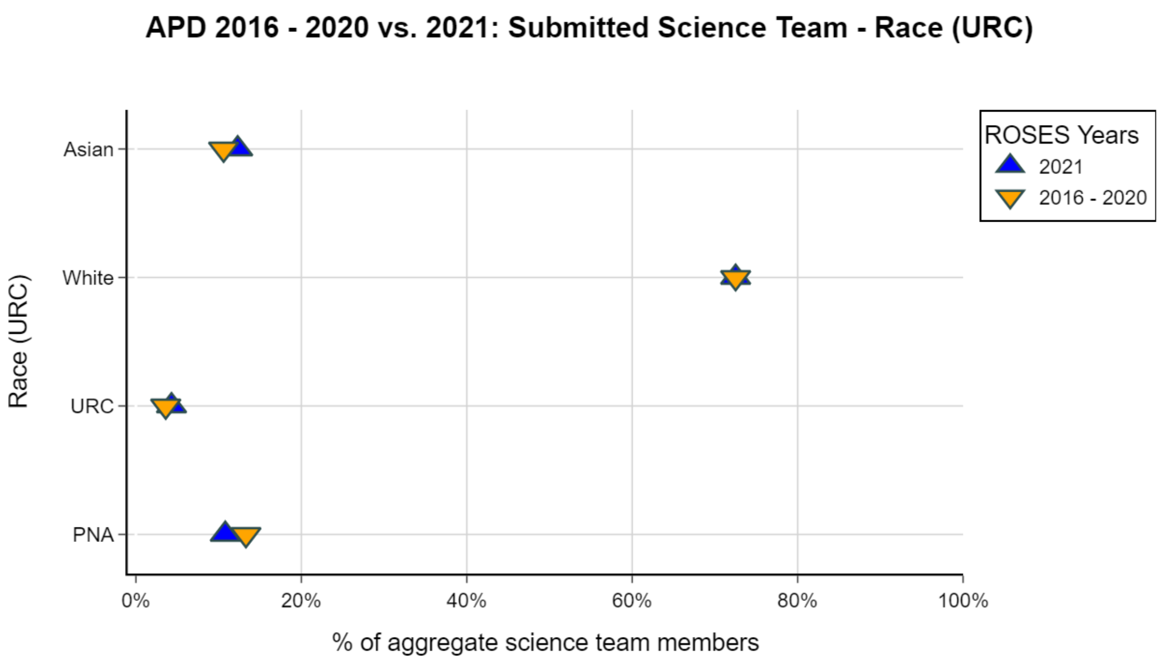
APD 2016 - 2020 vs. 2021: Selected Science Team - Race

Race	APD 2016 - 2020	APD 2021
AIAN	NR	NR
Asian	10%	10%
Black	< 1%	NR
NHOPI	NR	NR
Other - not listed	2%	1%
White	74%	75%
Multiracial	2%	2%
PNA	12%	10%

AIAN: American Indian and Alaska Native | NHOPI: Native Hawaiian and Other Pacific Islander | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

3.a.ii.4. Race using Under-Represented Community (URC) – APD Science Team

APD Science Team: Submitted Race (URC) - Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

APD Science Team: Submitted Race (URC) - Data Table

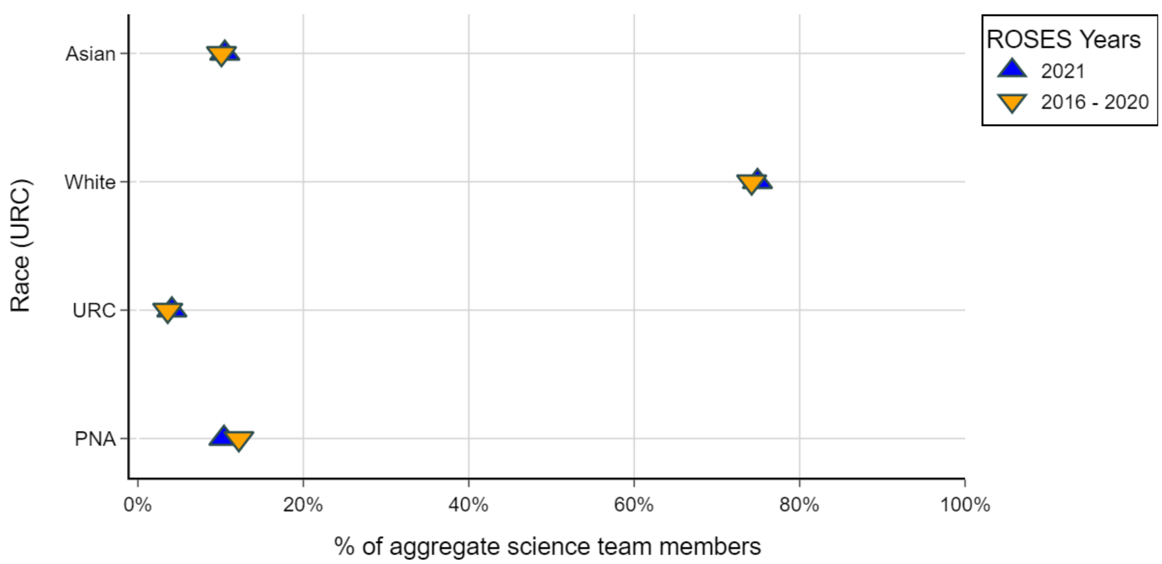
APD 2016 - 2020 vs. 2021: Submitted Science Team - Race (URC)

Race (URC)	APD 2016 - 2020	APD 2021
Asian	11%	12%
White	72%	72%
URC	4%	4%
PNA	13%	11%

Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD Science Team: Selected Race (URC) - Plot

APD 2016 - 2020 vs. 2021: Selected Science Team - Race (URC)



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

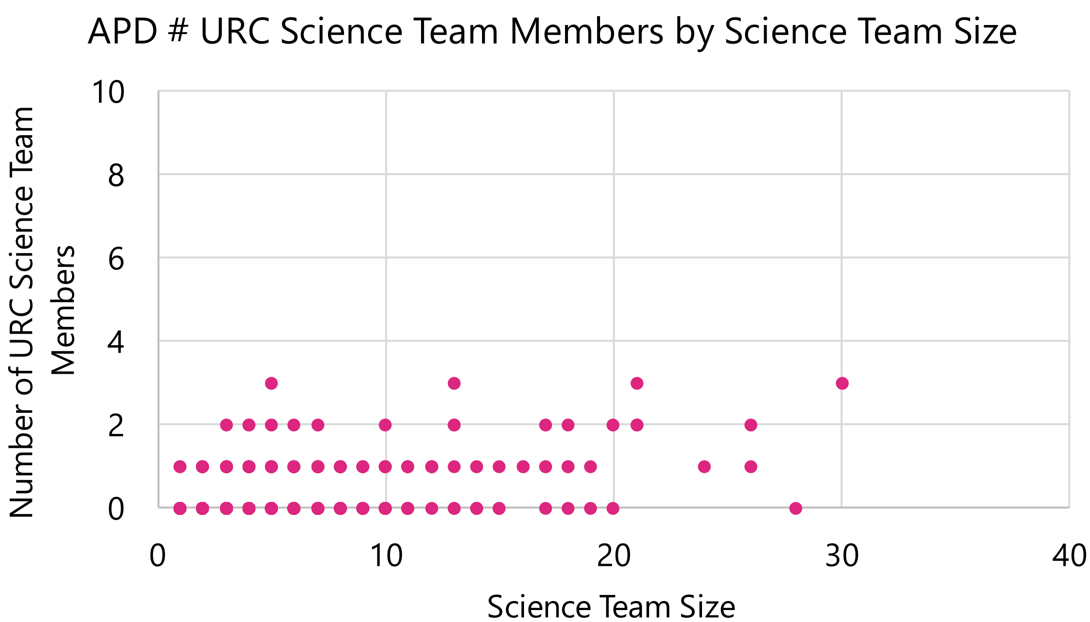
APD Science Team: Selected Race (URC) - Data Table

APD 2016 - 2020 vs. 2021: Selected Science Team - Race (URC)

Race (URC)	APD 2016 - 2020	APD 2021
Asian	10%	10%
White	74%	75%
URC	4%	4%
PNA	12%	10%

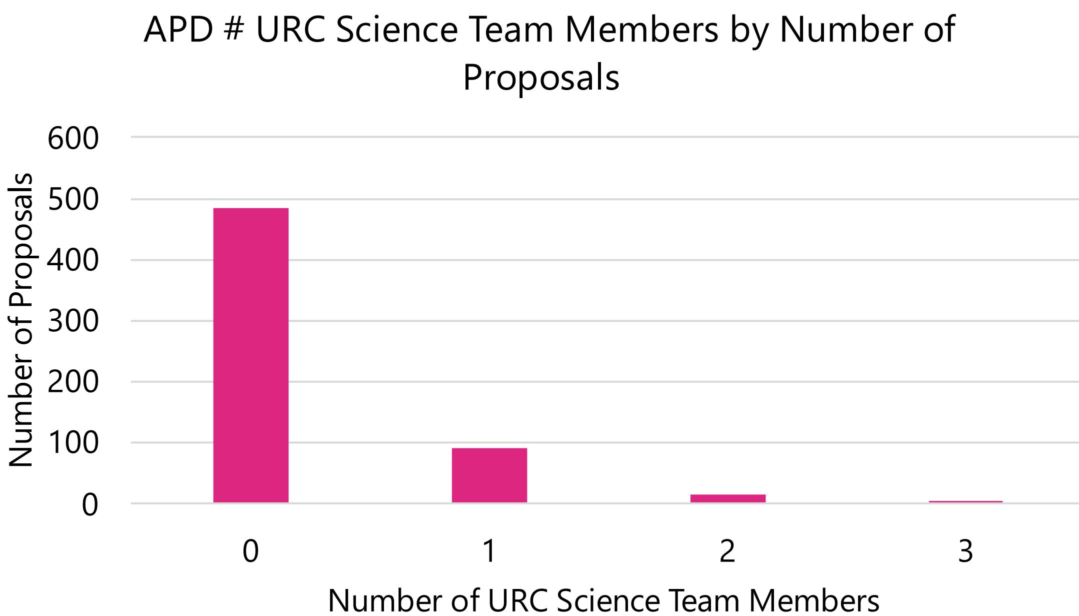
Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD ROSES 2021 Science Teams: URC Science Team Members by Science Team Size – Scatter Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other. | Note: 82% of proposals submitted to ROSES 2021 Astrophysics programs did not include URC researchers in their science team. 12% of proposals submitted to ROSES 2021 Astrophysics programs only included the PI as the science team.

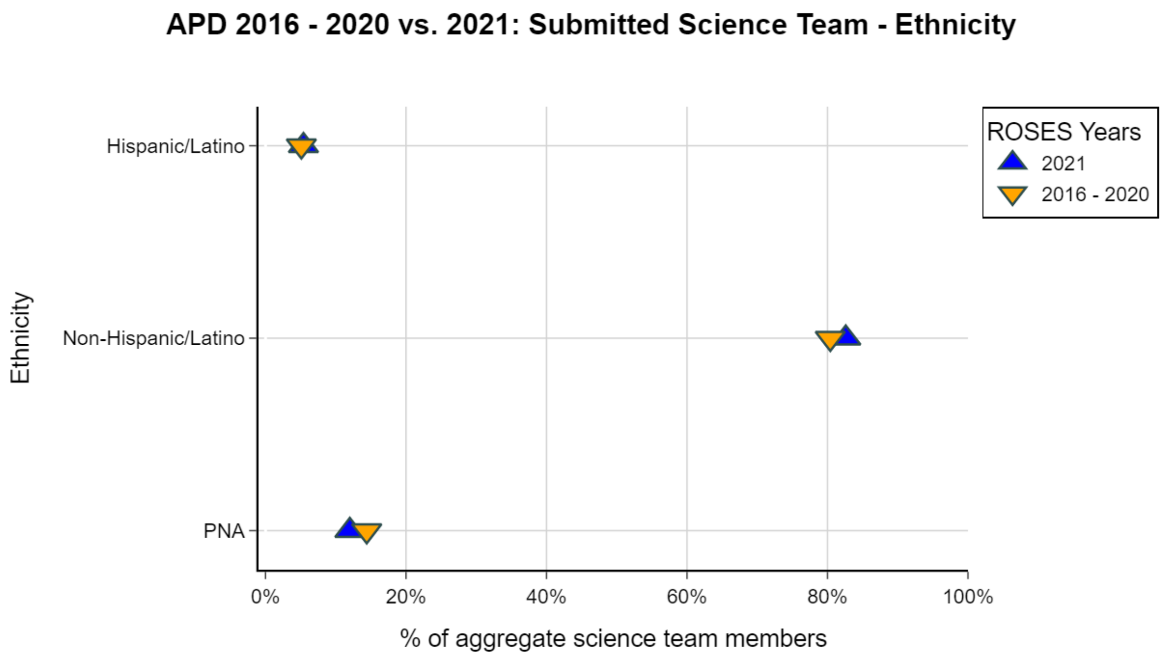
APD ROSES 2021 Science Teams: URC Science Team Members by Number of Proposals – Bar Plot



Under-Represented Community (URC) includes American Indian & Alaska Native, Black, Native Hawaiian & Other Pacific Islander, Multiracial, and Other.

3.a.ii.5. Ethnicity – APD Science Team

APD Science Team: Submitted Ethnicity - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

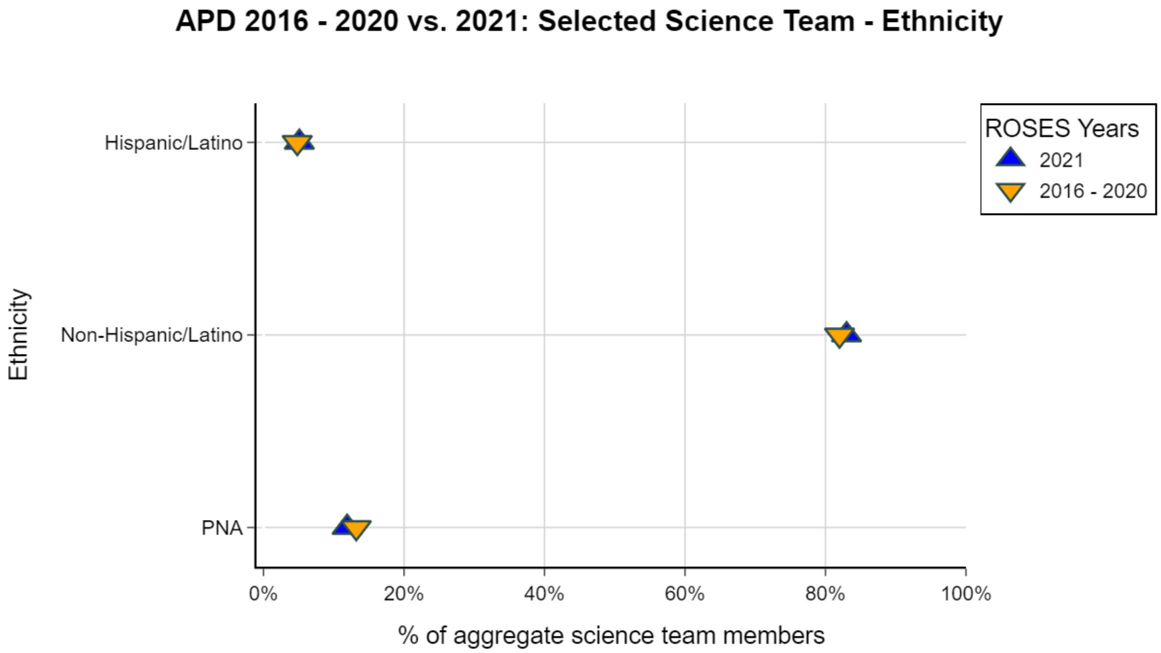
APD Science Team: Submitted Ethnicity - Data Table

APD 2016 - 2020 vs. 2021: Submitted Science Team - Ethnicity

Ethnicity	APD 2016 - 2020	APD 2021
Hispanic/Latino	5%	5%
Non-Hispanic/Latino	80%	83%
PNA	14%	12%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD Science Team: Selected Ethnicity - Plot



PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

APD Science Team: Selected Ethnicity - Data Table

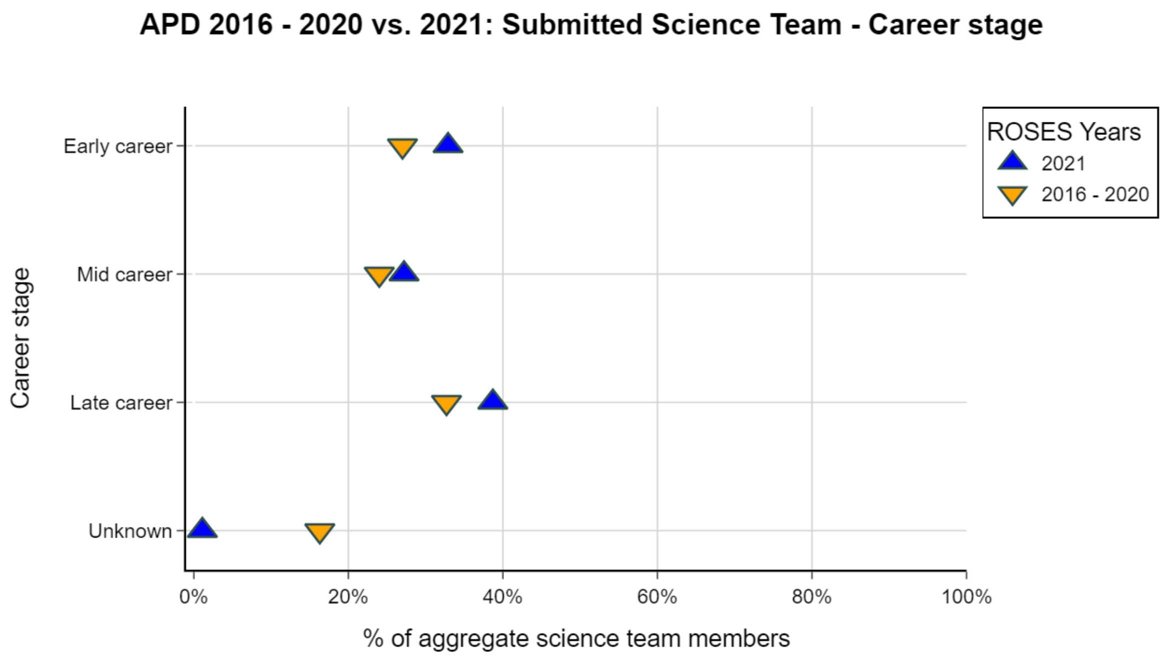
APD 2016 - 2020 vs. 2021: Selected Science Team - Ethnicity

Ethnicity	APD 2016 - 2020	APD 2021
Hispanic/Latino	5%	5%
Non-Hispanic/Latino	82%	83%
PNA	13%	12%

PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

3.a.ii.6. Career Stage – APD Science Team

APD Science Team: Submitted Career Stage - Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated. APD Science Team: Submitted Career Stage - Data Table

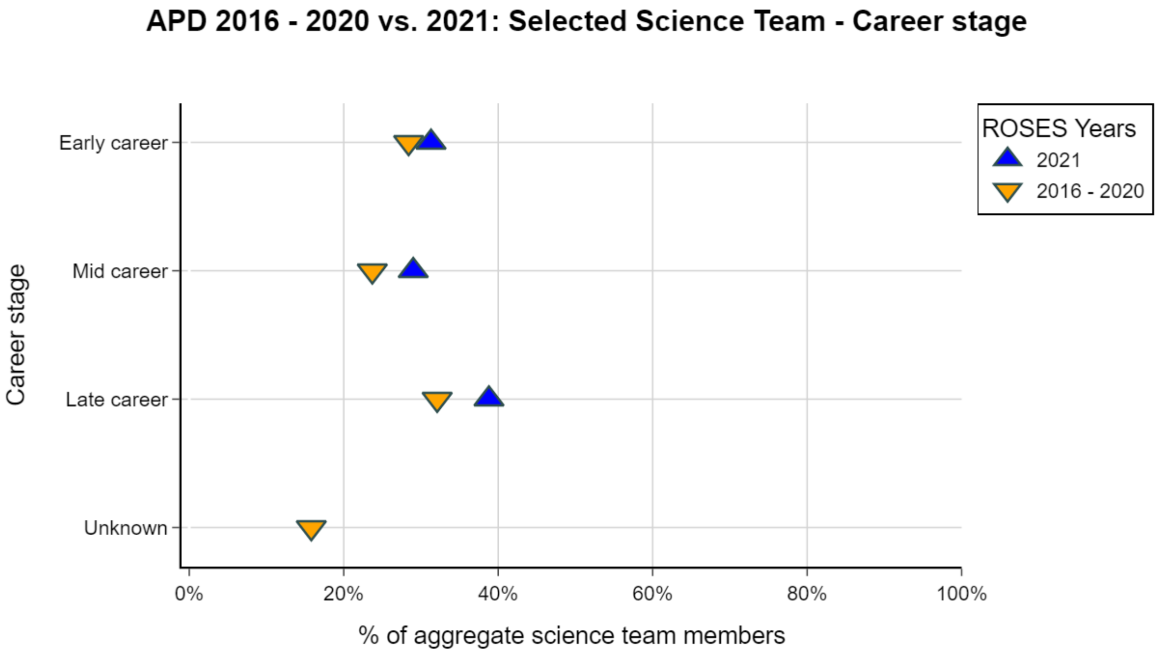
APD Science Team: Submitted Career Stage – Data Table

APD 2016 - 2020 vs. 2021: Submitted Science Team - Career stage

Career stage	APD 2016 - 2020	APD 2021
Early career	27%	33%
Mid career	24%	27%
Late career	33%	39%
Unknown	16%	1%

Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD Science Team: Selected Career Stage - Plot



Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | ROSES 2016-2020 proposal data are aggregated.

Suppressed categories: Unknown (ROSES 2021).
See Yearbook Introduction Section 1.a.ii.1. Office of the Chief Scientist (OCS) Suppression Guidelines for self-reported demographics for more information.

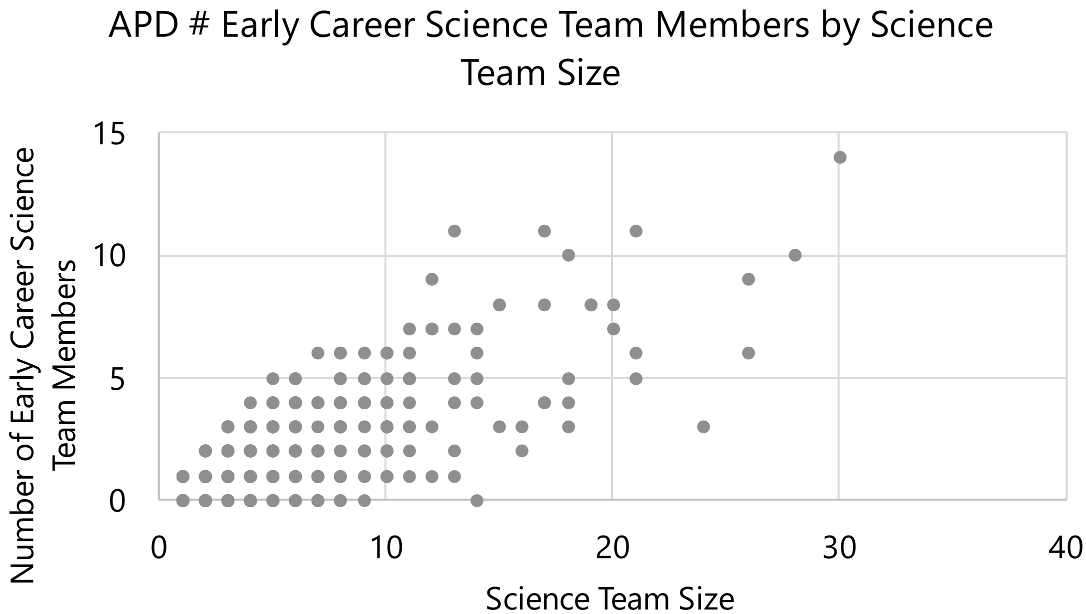
APD Science Team: Selected Career Stage - Data Table

APD 2016 - 2020 vs. 2021: Selected Science Team - Career stage

Career stage	APD 2016 - 2020	APD 2021
Early career	28%	31%
Mid career	24%	29%
Late career	32%	39%
Unknown	16%	NR

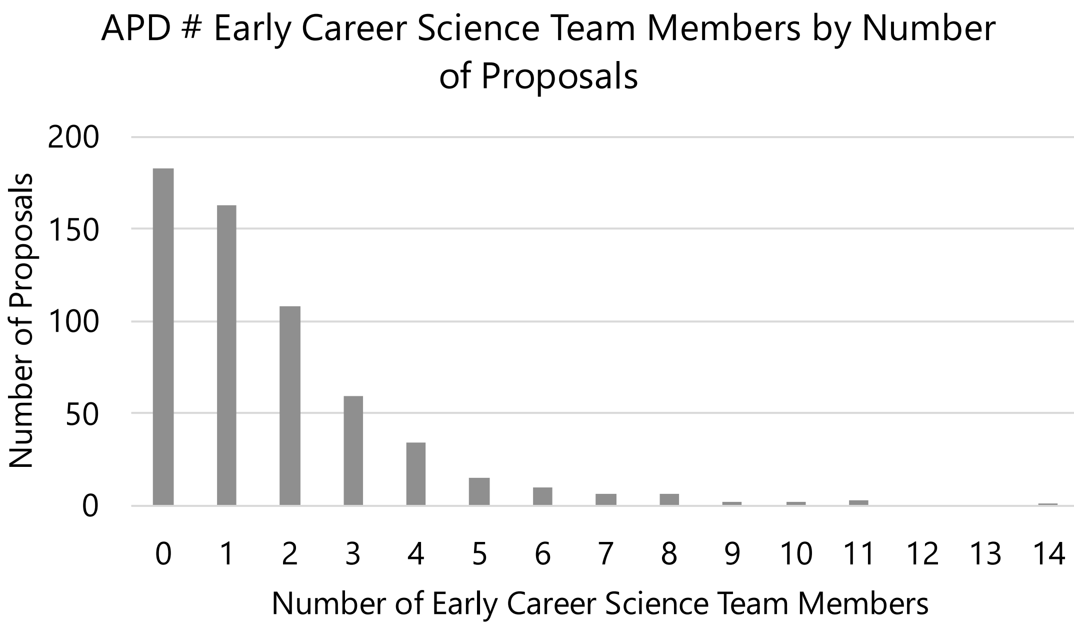
Early career: < 10 years since earning final degree | Mid career: 10 - 19 years since earning final degree | Late career: 20+ years since earning final degree | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD ROSES 2021 Science Teams: Early Career Science Team Members by Science Team Size – Scatter Plot



Early career: < 10 years since earning final degree | Note: 31% of proposals submitted to ROSES 2021 Astrophysics programs did not include early career researchers in their science team. 12% of proposals submitted to ROSES 2021 Astrophysics programs only included the PI as the science team.

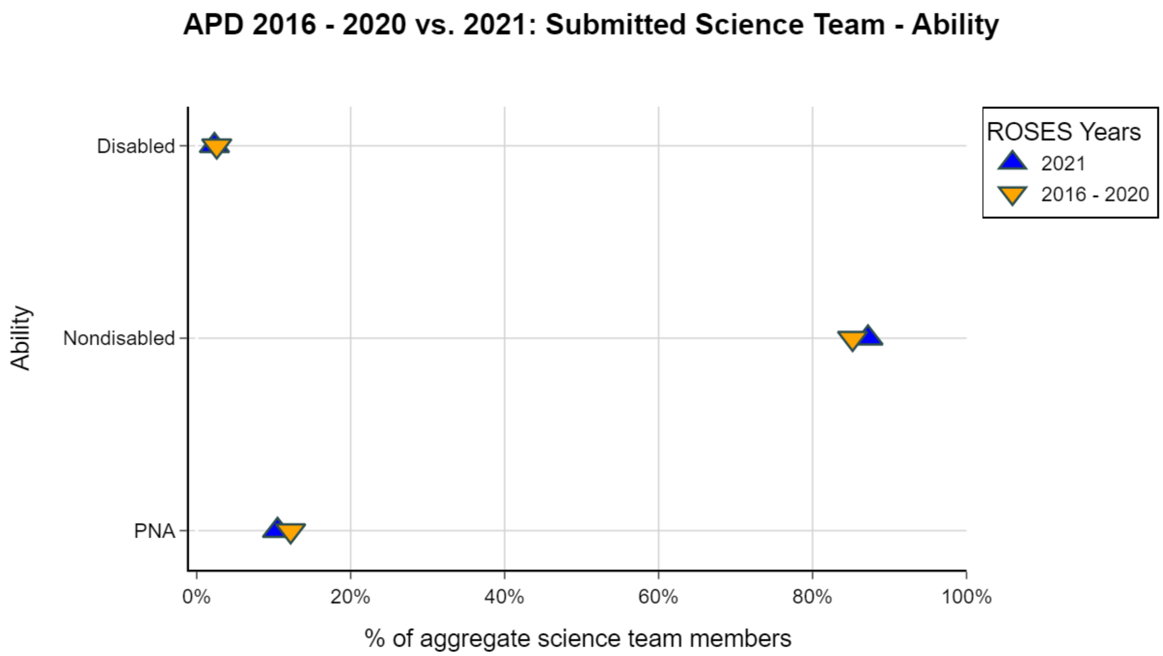
APD ROSES 2021 Science Teams: URC Science Team Members by Number of Proposals – Bar Plot



Early career: < 10 years since earning final degree

3.a.ii.7. Disability Status – APD Science Team

APD Science Team: Submitted Ability - Plot



Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

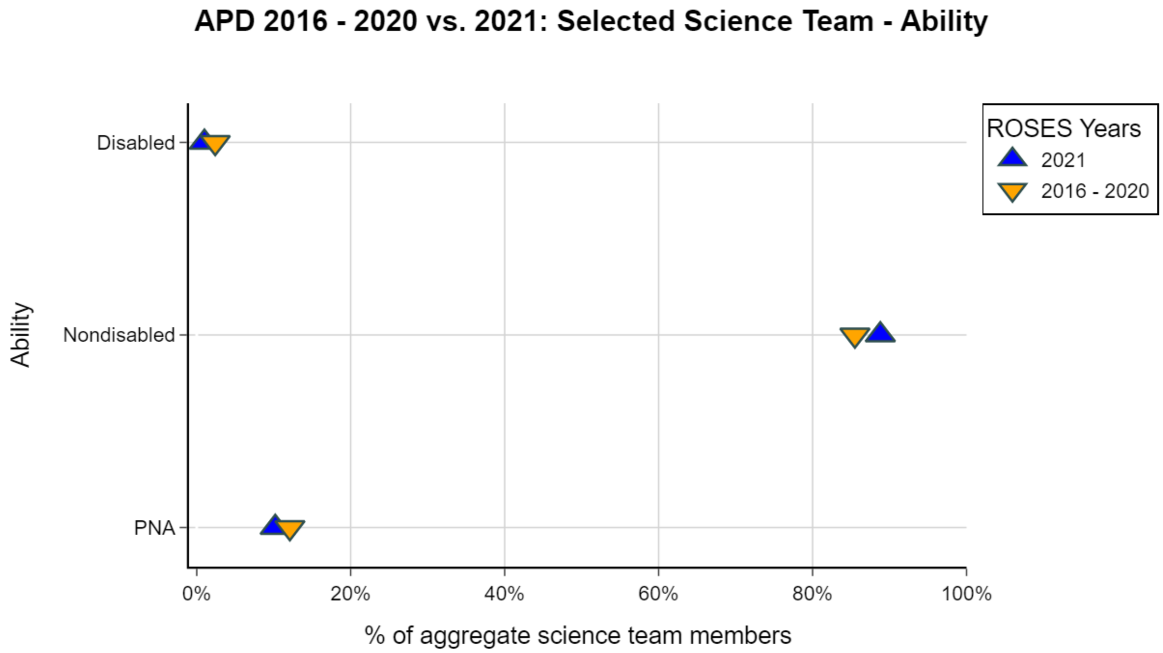
APD Science Team: Submitted Ability - Data Table

APD 2016 - 2020 vs. 2021: Submitted Science Team - Ability

Ability	APD 2016 - 2020	APD 2021
Disabled	3%	2%
Nondisabled	85%	87%
PNA	12%	10%

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

APD Science Team: Selected Ability - Plot



Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | ROSES 2016-2020 proposal data are aggregated.

APD Science Team: Selected Ability - Data Table

APD 2016 - 2020 vs. 2021: Selected Science Team - Ability

Ability	APD 2016 - 2020	APD 2021
Disabled	2%	1%
Nondisabled	86%	89%
PNA	12%	10%

Disabled includes hearing, visual, mobility/orthopedic, and other impairment. | PNA: Prefer not to answer | NR: Not reportable | ROSES 2016-2020 proposal data are aggregated.

3.b. Proposal Data

3.b.i. New PIs – APD

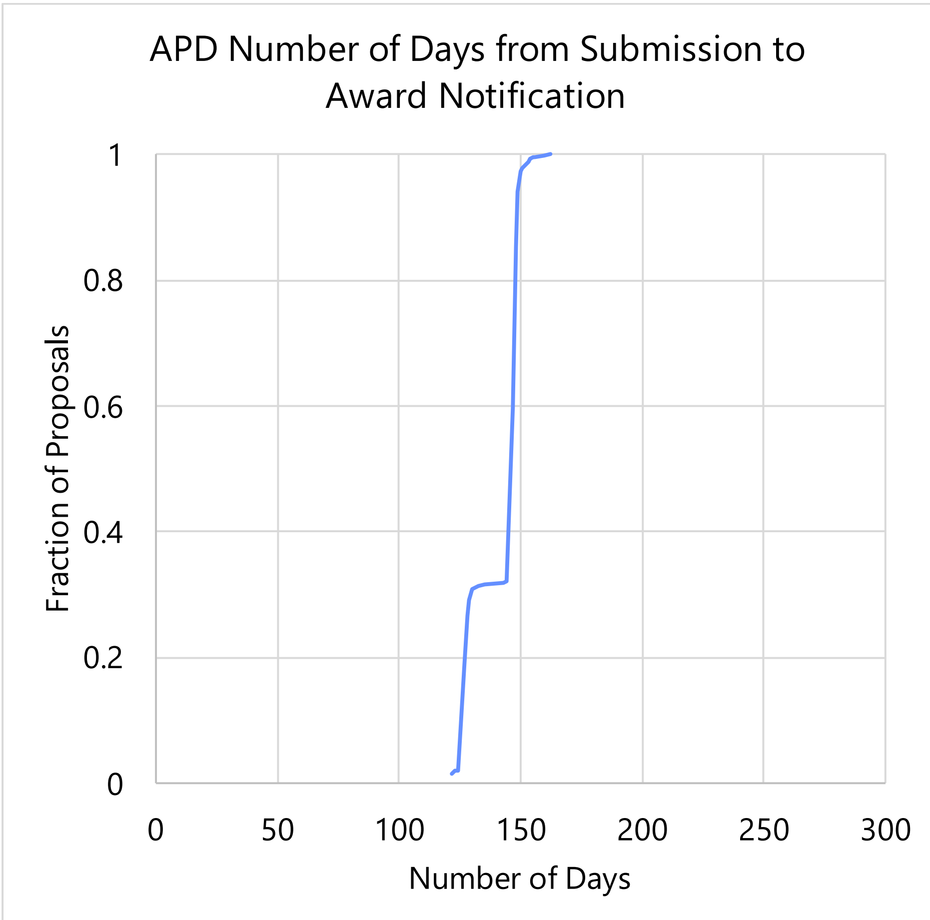
Comparison of Proposal Statistics of New PIs and Unique PIs for ROSES 2021 – Data Table

APD 2021	New PIs	Unique PIs	New PI %
Selected	91	162	56%
Submitted	358	510	70%
Selection Rate	25%	32%	

New PI (Division): A PI that was selected by any program in the given SMD Division in ROSES 2021 but was not selected by any program in that SMD Division in the previous five ROSES years.
New PIs Submitted: an individual submitting a proposal that would be a new PI if the submitted proposal were selected.
Unique PIs: participation of individuals and not proposals.

3.b.ii. Time from Proposal Submission to Award Notification for ROSES 2021 – APD

Number of Days from Proposal Submission to Award Notification for APD - Empirical Distribution Function



Note: Number of days from proposal submission to 80% of award notifications for APD is 148 days. SMD Policy Document SPD-22A applied to proposals submitted to ROSES 2016-2021 and included this statement: "Proposers shall receive a status notification from the Program Officer concerning their proposal no later than 150 days after the proposal due date, if selections have not yet already been made and announced."

3.c. ROSES 2021 Selection Announcements

Appendix D. Astrophysics Division

Appendix	Program Element Name
D.2	Astrophysics Data Analysis
D.3	Astrophysics Research and Analysis
D.4	Astrophysics Theory Program
D.5	Neil Gehrels Swift Guest Investigator Cycle 18
D.6	Fermi Guest Investigator Cycle 15
D.7	Strategic Astrophysics Technology
D.9	NuSTAR General Observer Cycle 8
D.10	TESS General Investigator Cycle 5
D.11	NICER Guest Observer Cycle 4
D.15	Astrophysics Pioneers

Astrophysics Data Analysis Program (ADAP21)
Abstracts of Selected Proposals
(NNH21ZDA001N-ADAP)

Below are the abstracts of proposals selected for funding for the Astrophysics Data Analysis Program (ADAP21). Principal Investigator (PI) name, institution, and proposal title are also included. Two hundred and seventeen (217) were received in response to this opportunity. On November 21, 2021, forty-one (41) proposals were selected for funding. On January 27, 2021, seven (7) additional proposals were selected for funding.

Steven Allen/Stanford University
The Next Stage of X-ray Reverberation: Mapping a Sample of Supermassive Black Holes

In the past few years, the detection of X-ray reverberation from the inner regions of accretion disks in active galactic nuclei (AGN) has added a further dimension to the study of the extreme environments around supermassive black holes, but we are just beginning to understand how to interpret these observations. Time delays have been measured in a sample of AGN between variations in energy bands corresponding to the continuum emission and the reflection that is observed from the inner accretion disk. These reverberation time lags are interpreted as the light travel time between the X-ray emitting corona and the disk. The nature of these analyses, however, has been largely qualitative, lacking detailed statistical analysis and modelling of the data, and has been carried out independently of constraints from the X-ray spectrum.

We propose to conduct a detailed, systematic study of X-ray reverberation in AGN using archival data from XMM-Newton, Suzaku and NuSTAR. We will develop a new statistical framework to apply self-consistent models simultaneously to measurements of the reverberation time delays and spectroscopic measurements of the reflection observed from the accretion disk. We will determine the correlations between the reverberation time lags and the fundamental parameters describing the disk reflection spectrum, the black hole and inner accretion flow to confirm the validity of the reflection and reverberation model. We will then obtain the most precise measurements of the location and geometry of the corona across the sample of AGN in which reverberation has been detected. These measurements of the corona will overcome a key systematic uncertainty in measuring the spins of supermassive black holes with enhanced knowledge of how the inner accretion disk is illuminated by the X-ray continuum. We will study how the corona and accretion disk vary across the sample of black holes, to understand the relationship between the corona and the mass, accretion rate and environment of the black hole, as well as studying the variation of the coronae with time in the individual AGN, to begin to piece together the mechanism by which the corona is powered and energy is released in the accretion process onto supermassive black holes.

Gaspar Bakos/Princeton University
Image Subtraction Light Curves For All Stars Down to T = 16 Mag in the Archival TESS Full Frame Images

Objectives:

The objective of the proposed research program is to derive, and make public for the first time, high-precision trend-filtered image-subtraction-based light curves and periodogram information for the hundreds of millions of stars with T < 16 mag that are in the NASA Archival Full-Frame Images from the TESS mission.

Methods:

The NASA TESS mission has completed a three year optical time domain survey of most of the sky. Full-frame images were collected at 30 minute cadence, or 10 minute cadence, with 28 days of coverage for regions near the ecliptic plane, increasing to a year of coverage at the ecliptic poles. Time-series photometry can be extracted from these images with sufficient precision to detect transiting Super-Earth-size planets around bright Sun-like stars. We propose to to analyze these data with an image subtraction reduction pipeline that has previously been developed and used to produce light curves for the hundreds of thousands of known star cluster members included in these observations. This method performs very well in crowded fields, producing very high precision light curves. Here we propose to use these tools to generate light curves for *all* of the stars down to T = 16 mag contained in the archival images, apply a variety of detrending methods to the light curves, optimally stitch together light curves from multiple sectors, calculate a variety of periodograms for these light curves, and make the light curves and relevant peak periodogram values public for all of these stars. This will increase by more than an order of magnitude the number of stars with publicly available high-precision TESS light curves that can be searched for transiting planets and other stellar variability signals.

Perceived Significance:

FFI light curves have been made public for stars with T < 13.5 mag, H < 10 mag, and/or distances less than 100 pc by the NASA SPOC and MIT QLP groups. While many bright stars are included in these releases, vast numbers of transiting planet systems and other interesting variable sources do not have public light curves from the TESS Full Frame Images. Moreover, the image subtraction approach that we will use will enable higher precision and more accurate photometry for the many blended sources in the TESS images. Producing such a data product will be of high value for the community, with expected significant impacts on the fields of exoplanets, stellar astrophysics and studies of the structure and history of the Milky Way. We expect this project to enable the discovery of thousands of transiting planets around stars that have not been searched at high precision to date, to provide observations of tens to hundreds of thousands of pulsational and rotational variable stars, and vast numbers of eclipsing binaries. Many other exotic variable phenomena may also be investigated using the light curves that we produce through this effort.

Antara Basu-Zych/University of Maryland Baltimore County
The Nature of High Ionization Emission Line Galaxies Near and Far: A Reckoning of All the Energetic Processes From Stellar Populations to Shocks

The Epoch of Reionization and Cosmic Dawn, at ($z>6$) is the next big frontier for galaxy studies. However, understanding which sources are relevant to ionization at these great distances requires a more detailed investigation of star formation in young, very low-metallicity regions. Spectroscopic observations of ($z>2$) galaxies reveal high ionization emission lines similar to those also seen in a unique local sample of young, star-forming regions: He II emitters (He IIs), selected via signal-to-noise > 5.5 in He II 4686A emission. In both the high-z galaxies and He IIs, the high-ionization line ratios challenge our understanding about the energetic sources capable of producing such emission lines. Specifically, stellar population synthesis models are unable to reproduce the observed line ratios, and recent studies found inconclusive evidence regarding the significance of X-ray binaries to the He II emission. Additionally, stellar winds and supernovae in young star clusters can produce fast (v_s > 1000 km/s) shocks, potentially traced by X-ray emission and capable of ionizing He II in ~1 kpc nebulae for several Myr. Yet fast shocks have not been explored as yet in He IIs. Therefore, in this proposal, we aim to address:

* How important are HMXBs and/or fast shocks in He IIs?
* Can HMXBs, shocks and O/WR stars explain the He II emission and high-ionization line ratios?

To answer the first question, we will develop X-ray color diagnostics to measure the shape of the underlying SED to differentiate between HMXBs and/or fast shocks. These diagnostics will be applied to the 37 He II regions in the Chandra (and XMM) archival data, and yield X-ray luminosity distributions and limits on the He II-ionizing flux from each source for use in the next step, the photoionization and shock modeling.

In addition to the X-ray analysis, we will use GALEX, Swift, SDSS photometric, Spitzer and WISE archival data for the He IIs to carry out UV-to-IR spectral energy distribution (SED)-fitting, using a state-of-the-art MCMC Bayesian fitting code. The posterior distribution functions from the SED-fits (e.g., star formation histories, metallicities, and stellar SEDs), and the X-ray emission constraints (e.g., L_x and X-ray SEDs) will serve as inputs to the photoionization (including shock) modeling in order to estimate the stellar contribution to the ionizing budget.

The novel aspect of this proposed work is that we will self-consistently model all the potential He II-ionizing sources to determine whether the combination of these sources can account for the observed He II emission or if additional source and/or more exotic stellar models are required.

By accounting for all the ionizing emission from O/WR stars, XRBs, and fast shocks, we will explore the origin of the ionizing flux in these nearby high-ionization galaxies, particularly those responsible for heating and reionizing the early (z > 6) Universe. These are the galaxies expected to be targeted by upcoming JWST observations. Along with catalogs containing all measured and derived SED-fit parameters and L_X distributions for all 37 He IIs, we will make the template X-ray SEDs for the He IIs publicly available. We expect these may be useful in a number of studies, e.g., (1) modeling the X-ray emission from high-z galaxies, which is relevant to interpreting the 21-cm fluctuations measurable by next-generation interferometers, and, (2) modeling shocks in young, low-metallicity, star forming regions, which is another potential JWST science focus utilizing the mid-IR spectroscopic emission lines.

Nicholas Battaglia/Cornell University
Enhancing the Planck Sunyaev-Zel'dovich Galaxy Cluster Catalog and Revisiting their Cosmological Constraints

Over the past two decades cosmological observations have successfully probed the linear regime and described these observations by a simple 6-parameter, LambdaCDM cosmological model. The new frontier for cosmology is to look for departures from this LambdaCDM model, which pushes future probes and measurements into the quasi-linear and non-linear regimes, for example measurements of the late-time growth of structure. Redshift dependent measurements of galaxy cluster abundances are powerful probes of the late-time growth of structure and are recognized as important cosmological probes by the National Research Council 2010 decadal survey.

Galaxy clusters are identified across a spectrum of wavelengths, commonly ranging from millimeters (or microwave frequencies) to sub-nanometers (or X-ray energies). Measurements of secondary temperature fluctuations in the cosmic microwave background (CMB) that arise from the thermal Sunyaev-Zeldovich (tSZ) effect are emerging as a powerful tool to count clusters, since tSZ-selected cluster samples have well-behaved selection functions. However, the current published Planck satellite results for the cosmological constraints from tSZ galaxy cluster abundances differ from the Planck primary CMB anisotropy constraints at 95% confidence. Extensions to our ›CDM cosmological model, like non-minimal neutrino mass, allow for these two probes of the amplitude of matter fluctuations to differ between redshift 1100 (CMB measurements) to today (tSZ cluster measurements). It is unclear whether these differences provide evidence for new extensions to our cosmological model or for systematics in the mass calibration of the Planck tSZ cluster sample.

We propose to reanalyze the Planck tSZ cluster abundances and re-calibrate their masses to address whether these differences between the parameters derived from the Planck tSZ cluster abundances and the Planck primary CMB anisotropies are due to new physics or systematics. Our reanalyses will include: the development of a new tSZ cluster likelihood that will maximize the cosmological information that we can extract from the tSZ catalog; new weak-lensing mass calibrations of Planck clusters that will be included in our new tSZ cluster likelihood; and an updated and enhanced Planck tSZ cluster catalog, which we will provide to the astronomy community.

Cara Battersby/University of Connecticut, Storrs
3-D MC: Mapping Circumnuclear Molecular Clouds from X-ray to Radio

We combine the rich legacy of NASA space astrophysics mission data from Chandra, Herschel, and Spitzer in a novel way that exploits natural X-ray tomography to produce 3-D maps of molecular clouds (MCs, the birthplaces of stars) in the Central Molecular Zone (CMZ) of our Galaxy for the first time. While standard observations are limited to a 2-D view (plus one dimension of velocity for spectral line data), numerical simulations reveal that MCs have rich and complex 3-D structures, which cannot be accurately represented by 2-D projections. Our new maps enable the first 3-D measurements of the physical properties of MCs (including measures of their internal turbulence), which are topics of particularly intense interest and heated debate in our extreme CMZ.

This pioneering modeling of MCs in 3-D is now possible thanks to decades of Chandra X-ray observations, which can be combined and compared with archival Herschel and Spitzer data. Past X-ray events from SgrA* propagate radially outwards and produce X-ray echoes when the light interacts with the surrounding molecular gas. Different epoch Chandra observations slice through the 3-D structure of the MCs along the light s path, illuminating different parts of the cloud over time, akin to X-ray tomography in medical science. We combine these multi-epoch Chandra X-ray data with archival Herschel Far-IR and Spitzer Mid-IR data, complemented by ground-based radio spectral line data, to map the MCs in 3-D for the first time. Using these unprecedented maps, we measure the physical and turbulent properties of MCs in the CMZ. Additionally, since the observed X-ray echoes are a convolution of SgrA* s past light curve and the properties of the reflecting clouds, the proposed study will provide key constraints on the previous flaring activity of SgrA*.

We benchmark the success of our program by the accomplishment of three key goals:

1) Goal I: Generate 3-D maps of MCs in the CMZ. By combining the Chandra time lags with identified cloud structures in Herschel and Spitzer, we will model the 3-D distribution of each MC.

2) Goal II: Measure the turbulent and physical properties of MCs in 3-D. Using these novel 3-D maps of each MC, we will measure and report on their physical (size, axis ratio, and orientation) and turbulent properties (using the Spatial Power Spectrum and Density Probability Distribution Function) in 3-D.

3) Goal III: Constrain previous SgrA* flaring activity. By correlating the X-ray echoes with our measurements of the 3-D cloud structure and distribution, we will constrain the outburst history of SgrA*.

The proposed study capitalizes on the complementary strengths of three NASA space astrophysics missions in a novel way to directly address the fundamental nature of MCs in 3-D and to help constrain the past outbursts from our Galaxy s central supermassive black hole, SgrA*.

Charles Bennett/Johns Hopkins University
Leveraging Planck and WMAP Data to Address Open CMB Foreground Issues

We propose a detailed analysis of data from the Planck and WMAP missions to address pressing issues relating to modeling and removal of synchrotron and dust as CMB foregrounds. Our work will answer three questions: (1) How much variation is there in the high-latitude polarized synchrotron spectral index? (2) Can an independent reanalysis of Planck power spectra and dust cleaning shed light on the lensing anomaly? (3) How do foreground modeling differences impact consistency of Planck and ground-based data?

First, we propose to revisit the determination of the polarized synchrotron spectral index through use of WMAP 23 and 33 GHz maps, Planck 30 GHz, and lower frequency data. The CMB is only linearly polarized at the level of a few percent, and emission from Galactic synchrotron and thermal dust dominates the total observed polarized sky signal even at frequencies where the foreground emission is lowest. Accurate characterization and removal of these foregrounds is therefore a critical step in current and future CMB studies, particularly in the effort to detect the inflationary B-mode polarization signal. Previous studies combining 2.3 GHz observations with WMAP and Planck frequencies have noted significant variation in the synchrotron spectral index at high Galactic latitudes. Our analysis will augment these studies with the inclusion of 1.4~GHz polarization data, the addition of newly released Faraday depth maps, and a rigorous treatment of potential low-level non-astrophysical WMAP and Planck modes that may affect the spectral index value derived at high latitudes.

Second, we propose to reanalyze the Planck temperature maps, focusing on dust cleaning for the 217 GHz channel and the persistent preference for the phenomenological lensing amplitude parameter, A_L, to exceed the physical value of unity, the stand-out unexplained feature in the Planck dataset. We will improve upon existing results by incorporating multiple higher frequency maps for the cleaning process (e.g., 545 GHz and 857 GHz), exploring the impact of different algorithms for determining cleaning coefficients on cosmological constraints, and allowing variation in the cleaning coefficients with multipole. We will perform new consistency checks based on splitting the sky area in two by Galactic or ecliptic coordinates to probe the spatial localization of A_L or any other features. We will explore different strategies for constructing both Galactic and point source masks and propagate these choices through to final parameters.

Third, we propose to augment the Planck cosmological likelihood with high-resolution ground-based data from the ACT and SPT telescopes to construct and test a unified high-multipole foreground model. This will resolve the discrepancy between the current Planck and SPT cosmic infrared background (CIB) foreground models, and provide a more powerful consistency test between these state-of-the-art datasets. Our joint likelihood will adopt common templates in the frequency and angular domains for the CIB and Sunyaev Zel'dovich (SZ) components, testing the ability of the combined data to discriminate between existing models, and exploring the impact of template choices on important cosmological results, including the A_L parameter and kinematic SZ detection or limits.

Many recent papers have carefully considered characterization of the CMB foregrounds. We propose to build on these results and to improve quantification of the foregrounds in select areas where further advances are both needed and possible. This work will increase the scientific legacy of WMAP and Planck, and pave the way for future experiments.

Joel Bregman/University of Michigan, Ann Arbor
Resolving the Hot Halos to the Virial Radius and Beyond in the Local Universe

About half of the baryons lie inside virialized structures (galaxies, groups, clusters) and are hot, with temperatures near the virial temperature. This gas is heated by accretion shocks, AGN, and supernovae, which determines the radial temperature and density distribution. All of the baryons would be retained at low feedback rates, while highly energetic feedback can drive mass loss from the system, such as in the form of winds. Most of this hot gas mass lies at large radii (> 0.2R_200), so studying the outer regions is crucial yet challenging.

Hot gas can be measured by the thermal Sunyaev-Zel'dovich (SZ) effect, where the surface brightness is proportional to the line of sight pressure integral, while the entire signal is proportional to the product of the gas mass and the average temperature. SZ studies are particularly powerful for resolved systems, where the signal is detectable throughout the virial volume, either for individual nearby objects or stacks of objects. The public SZ map (y-map) from the Planck Collaboration demonstrates feasibility to this approach, but it has a number of shortcomings. It uses an early data release (ver. 2) and a map-making algorithm that suppresses power for resolved targets. Significantly better, but not optimal maps have now been produced, using Planck data release 4 plus WMAP and map-making algorithms that recover the signal of resolved systems.

We will produce optimized maps and use them to study spatially resolved SZ signals of nearby galaxy groups/clusters and nearby galaxies, including the Milky Way and M31. Maps will be optimized for different regions of the sky (including with significant dust emission) and for both small and large angular scales. In addition to targeted studies, we will produce an all-sky catalog of resolved sources, and make our optimized y-maps publicly available.

For galaxy clusters/groups, preliminary studies show that some nearby systems have very good SZ signals (Centaurus, Fornax) to at least R_500. When combined with X-ray data, this work will lead to definitive measures of the radial distribution of mass and metallicity. Stacks of nearby groups and clusters will lead to improved signals at larger radii, ~3R_500. One published stack showed a signal at large radii that is indicative of the complex internal-external accretion shock systems. We propose to produce a significantly larger stack to define this outer region to higher S/N, which will best define this crucial region.

A stack of 12 nearby L* galaxies (D < 10 Mpc) demonstrate that extended hot halos lie around normal spiral galaxies. We will improve on this result by making a stack of resolved galaxies within 40 Mpc, yielding a higher S/N gaseous mass distribution at 0.4-1.5 R_200. This will determine if the baryons in the average L* galaxy lie within $R_200 or have been pushed further out by feedback processes. There are also nearby galaxies that can be studied individually with our optimized maps (e.g., Sombrero), but for the two closest systems (M31, MW), special map-making is required. M31 is close enough to the Galactic plane that we will develop an algorithm that is optimized for dust contamination. For the Milky Way, maps will be constructed that are suited to a large angular scale Galactic signature. Our preliminary results, from non-optimized maps, finds a signal for both M31 and the Milky Way. The final result will inform the mass and extent of these hot halos, as well as the metallicities, when compared to available X-ray data.

Adam Burgasser/University of California, San Diego

Infrared Gold: A Student-Centered Program to Extract, Analyze, and Disseminate 20 Years of IRTF/SpeX Point-Source Spectroscopy

The recently released IRTF IRSA Data Archive and IRTF Legacy Archive contain nearly 20 years of observations made with instrumentation on NASA s InfraRed Telescope Facility. These data include over 1.7 million exposures (40 TB) of spectral data obtained with the SpeX imager/spectrograph. While several libraries and catalogs of IRTF/SpeX data focused on specific types of sources (stars, brown dwarfs, asteroids) have been published, the full scientific potential of these data has been limited by the lack of science-grade spectral data products in the public archive. We propose to (1) develop and release an open-source, python-based data reduction pipeline for IRTF/SpeX; (2) reduce and analyze all SpeX data in the IRTF IRSA Data and IRTF Legacy Archives, comprising over 50,000 sources; (3) release science-grade reduced data products to the community spanning a broad range of science domains; and (4) engage and train a diverse student cohort in astronomical research and science skills. We will release to the public both the pipeline reduction code and the final data products, the latter through the IRSA Data Archive and NASA Open Data Portal. We will also conduct science verification tests of data products through research projects conducted by undergraduate students from diverse backgrounds. The projects will be designed by experienced SpeX users and supported through a training program in basic astronomy concepts, infrared spectroscopy, python programming, data science, and scientific literacy and communication. This data archive program addresses several of NASA s strategic goals and objectives, enabling scientific discovery across a wide range of astrophysical fields, facilitating the search for life beyond Earth through improved characterization of exoplanet host stars, and safeguard- ing Earth through expanded spectral information of Near Earth Objects and other minor bodies in the Solar System. This program also addresses national challenges by actively recruiting, training and mentoring future physical scientists from traditionally underrepresented populations.

Daniela Calzetti/University of Massachusetts, Amherst
1,000 Star Formation Histories in Nearby Galaxies

The current understanding of the physical underpinning of star formation processes and of how spirals form and evolve in galaxies heavily relies on the quantification of the differential star formation rates between spiral arms and interarm (diffuse) regions. The star formation rates (SFRs) are usually measured using empirical `recipes' that employ a single or two luminosities, e.g., ultraviolet and infrared (UV+IR) or optical and infrared (Halpha+IR). Recent investigations have underscored that these recipes can overestimate the actual SFRs in the interarm regions, thus posing a challenge for any attempt to compare observations with either models or simulations.

We propose to overcome this limitation by deriving SFRs from fits of multi--wavelength spectral energy distributions (SEDs), rather than from one--or--two--bands recipes. This approach has been shown in the literature to mitigate the issues related to the recipes, through the leveraging of the full SED for deriving internally--consistent physical parameters. We will combine imaging data for 34 nearby (<20 Mpc) spiral galaxies from four NASA Archives (GALEX, 2MASS, Spitzer, Herschel) and from ground based surveys (e.g., SDSS) to produce 0.15 micron to 500 micron SEDs of galaxy regions at 1-1.5 kpc scale. The >= 20-band SEDs will be run through the publicly available MAGPHYS fitting code to derive, for each region, stellar masses, SFRs, and star formation histories (SFHs) over the most recent 2 Gyr. The galaxies will each be divided into tens to hundreds of sightlines, thus yielding several thousand of independent SFHs across the full range of spiral morphologies.

When combined with a careful arm/interarm region separation for each spiral galaxy, the stellar masses and SFHs will be used to achieve the following goals: (1) quantify the amount of current star formation occurring in the diffuse, interarm regions of spiral galaxies and investigate the arm/interarm SFR ratio as a function of morphological type and presence/absence of bars; (2) provide updated prescriptions for SFR recipes, by leveraging the results from the first goal to quantify the amount of non-SFR luminosity included in the standard UV+IR and Halpha+IR indicators; and (3) interpret the distribution of stellar masses and SFHs in light of spiral arms theories. For this latter goal, we will generate specific SFRs (SFR/stellar mass) over several timescales to test predictions from models and numerical simulations that spiral arms have the sole role of gatherers of material, rather than triggerers of star formation. While numerical simulations provide a common picture, observations have so far yielded conflicting results, mainly due to the predominant use of recipe SFRs.

Beyond our specific applications, the stellar masses and SFHs produced as part of this project lend themselves to numerous additional applications, including, but not limited to, tests of star formation theories when our maps are combined with gas maps. For this reason, we will release our maps of derived parameters via stable archives (IRSA, MAST), for access by the broader community.

Tzu-Ching Chang/Jet Propulsion Laboratory
Intensity Mapping Cross-Correlation Tomography with COBE and Planck

The Extragalactic Background Light (EBL), the integrated intensity from all sources of emission throughout the history of the Universe, is a cornerstone cosmological measurement that encodes the history of galaxy assembly from the first stars to the present day. The EBL spectrum is a key constraint on all models of galaxy formation and evolution, and provides an anchor that connects global radiation energy density to star formation, metal production, and gas consumption. Yet, we have not determined the brightness of the extragalactic sky over the full range of the electromagnetic spectrum with sufficient accuracy to establish the radiative content of the Universe. Applying novel measurement techniques to the COBE and Planck datasets, we propose to conduct new measurements of EBL fluctuations from the near-infrared (NIR) till the far-Infrared (FIR).

The EBL spans the observable electromagnetic spectrum from gamma-rays to the radio over 20 decades in wavelength. In this proposal, we zoom in on the NIR to FIR wavelength range of 1 1000 ¼m, where the EBL captures the redshifted energy released from stars and galaxies, integrated throughout the cosmic history. It is the repository of all energy released by nuclear and gravitational processes since the epoch of recombination. As motivated by the EBL observed structures spectral energy distribution (SED), EBL is often decomposed for convenience into the Cosmic Optical Background (COB) in the optical and NIR wavelengths (more appropriately from 0.1 ¼m but for the scope of this proposal we focus from 1 ¼m and above) and the Cosmic Infrared Background (CIB) in the mid-infrared (MIR) to FIR. The COB emission, with a radiation spectrum peaking at 1 ¼m, is thought to be dominated by starlight in galaxies through direct emission, while the CIB, peaking at 100 ¼m, is dominated by reprocessed starlight through absorption and reradiation by dust with an intensity comparable to the COB. Together, the COB and CIB contain more than 5% of the total radiative energy of the Universe, and hold the key to the fossil records of galaxy assembly history.

The recent release of new datasets and the development of novel analysis techniques motivate our program. Planck released its final legacy full-sky maps. When combined with novel all-sky HI4PI HI survey they led to large dust-cleaned FIR EBL (CIB) maps. Numerous well characterized LSS surveys cover large area with redshifts up to z ~ 2. Novel analysis techniques such as line intensity mapping and cross-correlation enabled new discoveries.

All these elements put together lead us to propose to revisit and extend the COBE insights on the EBL. For this program, we propose novel use of the COBE Diffuse Infrared Background Experiment (DIRBE) and COBE Far-Infrared Absolute Spectrometer (FIRAS) maps in conjunction with Planck and LSS tracers. We will use Planck, the third generation CMB satellite to extract more signals from COBE, the first generation CMB satellite.

Our program is articulated along four projects. (1) We will cross-correlate publicly available SDSS, BOSS, and eBOSS galaxy and quasar catalogs with DIRBE to measure the NIR and MIR EBL fluctuation on large-scales. (2) Using publicly released Planck and HI4PI based CIB maps, we will measure the cross-correlation between FIR and NIR-MIR EBL fluctuations. This measurement will uniquely constrain NIR, MIR, and FIR EBL models. (3) Jointly analysing these measurements performed, we will extend current models to coherently model and interpret NIR-MIR-FIR EBL fluctuations. (4) Using the increased frequency resolution of FIRAS, we will cross-correlate FIRAS maps with LSS surveys to detect or constrain extragalactic [CII] line intensity fluctuations and infer the [CII] cosmic luminosity density at $0.2 < z < 2$.

Lennox Cowie/University of Hawaii, Honolulu
A Comprehensive FIR Catalog of the Hubble Frontier Fields: A Herschel Based Tool for Deep Searches for High Redshift Galaxies

More than half of the star formation in the universe is obscured by dust and can only be directly probed using far-infrared and submm/mm observations. Many of the most luminous star-forming galaxies are completely missed in rest-frame UV-selected samples. Determining the redshifts and properties of far-infrared/submm-selected galaxies, particularly those with the highest star formation rates, is therefore critically important to obtain a full understanding of the history of star formation.

One of the best ways to study galaxies at both optical/near-infrared and far-infrared wavelengths is by observing sources lensed by massive foreground clusters. Lensed sources are magnified at all wavelengths, and their images benefit from enhanced spatial resolution. The present proposal aims to to provide a definitive far-infrared catalog based on Herschel images of the six intensively studied Hubble Frontier Field clusters. The Herschel satellite obtained extremely deep images of these fields at 100 and 160 micron (PACS) and at 250, 350, and 500 micron (SPIRE) which combined with ground-based submm and mm data, provide a powerful means of determining the spectral energy distributions of dusty star-forming galaxies over the full rest-frame far-infrared. However, because of Herschel's low resolution, and hence large positional uncertainties and confusion, techniques are required to deblend the fluxes from overlapping neighboring galaxies. This has usually been done using the source positions of Spitzer 24 micron samples, but this approach misses and misidentifies galaxies in the longer wavelength Herschel bands.

We propose to use deep, moderate resolution 450 micron data from ground-based SCUBA-2 observations, together with Spitzer 24 micron and available ALMA submm/mm data, to improve the completeness and accuracy of the deblending of the Herschel data in the Hubble Frontier Fields. Including the longer wavelength priors will improve our interpretation of the information from Herschel and allow us to probe to the highest redshifts.

We will measure fluxes and colors from the optimally deblended Herschel data. We will identify, when possible, optical/near-infrared counterparts using the ultradeep HST data and also look for counterparts in X-ray and radio data, which may indicate active galactic nuclei. We will use the extensive lensing models to determine magnifications and publicly available codes (GRASIL, MAGPHYS, CIGALE, SED3FIT) to obtain the best fits to the optical through submm/mm spectral energy distributions. We will estimate photometric redshifts and star formation rates from the fits, and to use the various codes to estimate systematic uncertainties. We will obtain spectroscopic redshifts from the literature, from the KOA archive, or from new Keck observations, to check the photometric redshifts.

The rich space-based and ground-based datasets on these heavily studied fields will provide key information on the range of spectral energy distributions in far-infrared/submm-selected galaxies and on the contribution of dusty galaxies to the star formation history, particularly at the highest redshifts. This is critical to NASA's goal of mapping the history of galaxy formation in the universe and will provide valuable inputs to planning observations with the James Webb Space Telescope. We will release on a dedicated website our far-infrared catalog with optimal deblended Herschel fluxes, redshifts, and other properties.

Xinyu Dai/University of Oklahoma, Norman
Multi-Wavelength and Time-Scale Study of AGN Variability in the TESS and ASAS-SN Era

Variability is a powerful tool to better understand the nature of AGN, because it is a major challenge for the standard accretion disk model and a unique tool to geometrically constrain the AGN central engine.

The combined TESS, Swift-BAT, RXTE, and ASAS-SN data is ideal to study variability of bright AGN to extract multi-wavelength and multi-timescale light curves to better characterize the variability properties and their dependence on AGN parameters, such as the black hole mass and spectral type.

We propose to achieve the following research goals.

1) Measure AGN optical variability up to four orders of magnitude in the frequency space by combining TESS and ASAS-SN data for a large sample (10,000) of bright AGN (R<15), search for high frequency break in the power spectrum and micro-variability.

2) The large dynamical frequency range provided by the sample allows PI's team to measure the PSD break timescale more accurately than previous studies, and the team expects to accurately measure the scaling relationships between variability characteristics and AGN parameters, such as between the break timescale and black hole mass to 4--8% and to even better accuracies for relations involving the variability amplitude.

3) Joint optical and X-ray variability analysis of bright AGN using TESS, RXTE, Swift, and ASAS-SN light curves will allow PI's team to correlate optical and X-ray variability characteristics for the first time using a large sample and reveal new AGN physics.

4) Compare AGN variability from different AGN types and parameters, especially between Type I and II AGN, and perform simulations to constrain the torus model.

These variability studies will yield rich astrophysical constraints for AGN and supersede previous AGN optical variability studies and surveys. The proposed research will result in legacy products for the AGN community such as the cleaned light curves from 10,000 AGN, because these bright AGN are favorite targets for other AGN studies such as reverberation mapping, polarimetry, and multi-wavelength variability studies. The analysis results will guide the AGN community to study the AGN variability in the LSST era and provide a complement sample since LSST is limited to only fainter targets.

Ashkbiz Danehkar/Eureka Scientific, Inc.
Black Hole Spin Survey of Radio-quiet AGN

High energy X-ray spectra of active galactic nuclei (AGN) emitted from accretion flows around supermassive black holes (SMBH) offer a novel means to study the general relativistic strong-field gravity impacts of black holes. Nearby Seyfert type I active galaxies contain the best known radio-quiet AGN for an X-ray survey due to low levels of obscuration. In particular, highly ionized gaseous outflows measured from H-like and He-like iron absorption lines in AGN are mostly emitted from the areas close to the innermost stable circular orbit (ISCO) regions of the accretion disk around the SMBH, which are affected by general relativistic strong-field gravity of the spinning supermassive black hole. Relativistically broadened fluorescent K-alpha iron lines emitted from nearby ISCO regions can be used to constrain the black hole spins, which will help us understand how SMBHs impact on their host galaxies and formation of large-scale galactic outflows. We have not yet fully investigated whether physical and kinematic properties of highly-ionized ultra-fast outflows are correlated with SMBH angular momenta as predicted by the theory of general relativity.

We therefore propose to advance our understanding of the physics of supermassive black holes in radio-quiet AGN by constraining the black hole spins of a sample of radio-quiet Type I AGN (Seyfert 1.0, 1.2, and 1.5) with well-identified highly-ionized ultra-fast outflows based on H-like and He-like Fe absorption lines, and to explore possible correlations of the kinematic and physical conditions of X-ray ultra-fast outflows with black hole spins measured from relativistically broadened K-alpha iron lines at 6.4 keV (rest frame) and Compton reflection humps above 10 keV. A recently developed relativistic disk reflection model will allow us to accurately constrain the spin parameters of SMBHs in these objects. Our SMBH spin measurements will be released in an online database and their results will be discussed in details in our peer-reviewed publications. Our final goal is to compile a spin database, together with the black hole masses recently determined from the reverberation mapping campaigns, that can be used to explore possible correlations of the SMBH angular momenta with kinematic and physical properties of ultra-fast outflows. This study will be implemented using X-ray archival data collected by NuSTAR (NASA mission), Suzaku (NASA & JAXA joint mission), and XMM-Newton space telescopes over the past decade.

Kathryne Daniel/Bryn Mawr College
Wrinkles in Time: Linking Stellar Ages to Kinematic Ridges

High resolution simulations of disk galaxies ubiquitously have multiple generations of transient spiral patterns. It is generally accepted that these transient spirals play a critical role in driving disk evolution, where the duty cycle for transient spiral arms is positively correlated with the degree of their influence. However, the history of transient spirals affecting the Solar Neighborhood is unknown. To date there has been no attempt to observationally characterize the duty cycle of transient spirals, thus leaving a substantial gap in our empirical understanding of how the Milky Way disk has evolved.

This study brings together the expertise of specialists in galactic dynamics (PI: theoretical modelling & Gaia+GALAH analysis) and emerging techniques for stellar age determination (co-I/Science PI: stellar rotation & gyrochronology) to place constraints on the local duty cycle for transient spirals through the analysis and interpretation of data from TESS Cycles 1 and 2. The motivation for our program is a groundbreaking analysis of Gaia data, which revealed a rich pattern of previously undetected corrugations , or wrinkles, when local stellar phase-space positions are projected into action-space, natural coordinates for orbits (Trick+19). Each wrinkle is thought to be the signature of a single spiral pattern as it drives stars at the Lindblad resonances into highly eccentric orbits (measured by radial action) in on order a dynamical time. Since orbits otherwise only steadily become more eccentric over many dynamical times, young stars are not otherwise expected to populate these regions of action-space. Therefore, wrinkles can only be as old as their youngest stellar members. NASA s Transiting Exoplanet Survey Satellite (TESS) has ushered in a golden age for stellar age determination using gyrochronology, a well-established technique where rotation is used as a proxy for age. Gyrochronology with TESS data is well suited for determining the ages of the youngest stars in each of these wrinkles, since the stars of interest are dwarf stars younger than ~2Gyr with distances less than ~300 pc, thus placing a timestamp on the passage of a transient spiral arm.

The observational sample will be based on Gaia identified wrinkle members cross-correlated with GALAH in order to obtain more accurate radial velocities and chemistry. A cut will be made to include only stars with high radial action in order to minimize contamination from non-resonant, young disk stars. From these, a subset of rapidly rotating late-type dwarfs will be selected from the TESS near field sample (g <~ 13, d <~ 300 pc). Preliminary estimates indicate over 100,000 stars may fit these criteria, which is more than sufficient to place a timestamp, and thus duty cycle, on the 7-14 wrinkles identified in the Gaia field. Rotating stars from amongst the wrinkle members will be identified through analysis of TESS photometry, using a combination of Lomb-Scargle periodograms and the autocorrelation function. Rotation periods and errors will be measured using Gaussian processes with the open-source code exoplanet. Ages can then be inferred using the open-source code stardate, which combines gyrochronology and isochrones. Further analysis using galpy, a Python based code for modeling galactic dynamics, will be used to interpret the TESS data and infer the lifetimes and duty cycles of transient spiral arms in the Solar Neighborhood.

This project will be the first study of its kind, both providing an estimate for the duty cycle of transient spiral arms in the Solar Neighborhood and establishing a novel technique for determining the formation time for Galactic kinematic structures. This application of precision age determination using gyrochronology from TESS data in combination with kinematic surveys may be used as a stepping stone to larger studies that include additional methods for age determination, like astroseismology, and data from ZTF, LSST and K2.

Megan Donahue/Michigan State University
Baryonic and Weak Lensing Properties of a Volume-Limited Sample of Clusters of Galaxies

This proposal seeks support for a uniform analysis of archival X-ray data on the LoVoCCS clusters, a nearby, volume-limited sample of 143 clusters of galaxies with halo mass 10^14--10^14.5 solar masses. Its primary goal is to characterize and interpret the *deviations* of individual galaxy clusters from the usual scaling relations between a cluster's observable properties and its underlying halo mass, which encode information about the cluster's mass-assembly and star-formation histories. The LoVoCCS project is currently gathering high-quality weak lensing data that will deliver lensing masses and substructure maps for all of these clusters, along with star-formation histories based on optical photometry. This parallel X-ray analysis will establish how deviations of a cluster's baryonic gas properties from the usual scaling relations correlate with deviations in stellar mass, star-formation history, and mass substructure. It will build upon and extend a population statistics model previously applied to LoCuSS, a smaller sample of higher mass clusters. Improvements to that model will enable halo-mass measurements of unsurpassed accuracy in this mass range and will provide a unique window into the links between mass assembly, star formation, and feedback processes in massive galaxies. The work will further NASA's efforts to discover the secrets of the universe and reveal the astrophysics of how the universe transformed dark matter and baryons into galaxies. It will support the development of statistical tools for the much richer datasets to emerge from eROSITA, the Nancy Roman Telescope, XRISM, and Athena.

Jacqueline Faherty/American Museum of Natural History, The
Uncovering Ultracool Benchmarks in a WISE to Gaia Search

One of the most important surveys for brown dwarf science has been NASA s Wide-field Infrared Survey Explorer (WISE) mission which unveiled a population of extremely cold brown dwarfs right in our backyard, including the 3rd and 4th closest systems to the Sun. The WISE-only detected brown dwarfs are treasures for comparative exoplanet studies. Their atmospheres strongly resemble Jupiter s yet their isolated nature (lacking a host star) challenges our definition of the word planet . The coldest brown dwarfs could only be discovered in WISE because they emit the majority of their flux at 4.5 microns (or across WISE s W2 band). Consequently measuring fundamental parameters for these objects is limited in scope as only the Spitzer and Hubble space telescopes as well as a handful of large ground based facilities can meaningfully observe them.

One way to obtain much needed parallaxes, ages, metallicities and applicable compositional information for these objects is to utilize symbiotic science and find the brown dwarf co-moving with a well-calibrated main-sequence star or white dwarf. The release of 1.4 billion parallaxes and proper motions (including ~300,000 objects within 100 pc) in the Gaia eDR3 release is the exact seed needed to find benchmark brown dwarf systems. To date, no team has attempted to match Gaia to NASA s WISE catalogs in search of co-moving benchmarks leaving a missed opportunity for breakthroughs in brown dwarf science.

The goal of this proposal is to find those missed WISE-detected brown dwarfs co-moving with a bright Gaia-detected object (star or white-dwarf), as well as the coldest brown dwarf members of nearby moving groups. Based on expected companion frequencies and extensions of the mass function into the cold brown dwarf regime, this ADAP proposal should yield thousands of new discoveries. We will use the sample of benchmarks discovered to (1) calibrate the relation between fundamental parameters of the ultracool dwarf population, such as age and metallicity, and the observed photometry and spectroscopy (2) investigate higher-order multiplicity as well as companion statistics, and (3) examine the distribution of binding energies for systems of different mass ratios and separations. Using newly discovered members of young moving groups, we will also go after the holy grail in star formation studies: an investigation of the initial mass function from the highest-mass stars, down to isolated planetary-mass objects.

Steven Finkelstein/University of Texas, Austin
Leveraging Spitzer to Investigate Reionization and the Growth of Massive Cosmic Structures over 10 deg^2

Our proposed work uses Spitzer/IRAC observations over 10 deg^2 in two legacy fields to cover two key goals of NASA s Cosmic Origin program:

i) The evolution of the reionization process. Lyman-alpha emission is one of the most promising tracers of reionization, and the paucity of detectable Lyman-alpha emission at z > 7 may indicate a predominantly neutral intergalactic medium (IGM). However, we know that the interstellar medium (ISM) must also play a strong role as at z~2-3, where galaxies have been much better studied and the IGM is certainly fully ionized, Lyman alpha is only detected spectroscopically from ~20-30% of galaxies. The internal properties of galaxies are ignored in reionization analyses as the dependance of Lyman-alpha line strength on those galaxy properties measurable at high redshift (e.g., stellar mass, dust attenuation, star-formation rate) is not known. We propose to fund an effort to use several thousand hours of archival Spitzer/IRAC imaging in the North Ecliptic Pole (NEP) and COSMOS fields to measure the correlations between intrinsic Lyman alpha emission and galaxy physical properties for a new sample of ~500,000 galaxies at z~2-3.5. These galaxies have their Lyman-alpha emission constrained via two large IFU spectroscopic surveys of these fields from the Hobby Eberly Telescope Dark Energy Experiment (HETDEX). Critically, the IRAC imaging in these fields allows robust constraints on the photometric redshifts and stellar masses, and the breaking of the age-dust degeneracy, while the redshift range probed by this spectroscopy allows us to measure the Lyman-alpha properties of galaxies free from IGM attenuation, and subsequently decipher which physical properties correlate best with strong Lyman-alpha emission. This will mitigate systematic effects common in previous Lyman-alpha based reionization studies (which assume most/all galaxies should be emitting Lyman-alpha), unlocking the potential of Lyman-alpha emission to be used to pin down the evolution of the end of reionization, constraining the nature of the reionizing sources.

ii) The growth of massive cosmic structures. This proposal focuses on developing observational techniques to characterize the physical evolution of galaxies in their large scale environment before the peak epoch of cosmic star-formation. We aim to answer: (A) When and how do galaxies inside cluster environments assemble their mass? Is the stellar mass of cluster galaxies built before, during, or after coalescence? (B) Do protoclusters themselves experience episodic bursts triggered by the collapse of large scale (~10 comoving Mpc) filaments? Or is their growth fueled through gradual halo mergers on smaller scales? This work will establish criteria for the detection and characterization of new protoclusters from the ongoing VIRUS surveys in the NEP and COSMOS fields. Grounded in work from cosmological simulations, we will use the size of overdense structures, traced by their Lyman-alpha emitters, and the stellar masses of individual galaxies within those structures to infer eventual z=0 cluster masses, then study the characteristics of constituent galaxies as a function of total halo mass. New protocluster discoveries will be cross-correlated with existing Herschel submillimeter datasets to characterize the relative abundance of rare galaxy populations (dusty starbursts and quasars) in overdensities.

The full photometric and spectroscopic dataset will be made available to the Euclid team, providing a significant resource to the Euclid photometric redshift calibration effort in this Euclid deep field.

Eric Gawiser/Rutgers University, New Brunswick
Constraining the Regulation of Galaxy Growth with Star Formation Histories

One of the key unanswered questions in understanding the formation and evolution of galaxies is how galaxies assemble their stellar populations over time. There is significant evidence that this process of galaxy growth is regulated by interactions between galaxies and the gas surrounding them on timescales from 5-1000 Myr, but the dominant mechanism remains unclear. The investigators will combine broad-band rest-frame ultraviolet-through-near-infrared photometry from HST and Spitzer with Chandra X-ray imaging and ground-based emission-line spectroscopy. Novel methodology will enable a comprehensive measurement of the stochasticity of galaxy star formation histories in >50,000 galaxies with stellar masses down to 10^7 M_sun at 0.3 < z < 6 in the Chandra Deep Fields and additional CANDELS/3D-HST fields.

The investigators will

1. Use smooth, non-parametric star formation histories to perform Spectral Energy Distribution fitting on rest-frame ultraviolet-through-near-infrared photometry to obtain stellar masses and average star formation rates since the Big Bang;
2. Calibrate hard-band X-ray luminosity as a 1000 Myr star formation rate estimator by utilizing its sensitivity to long-lived low-mass X-ray binaries;
3. Probe star formation rates on 5, 100, and 1000 Myr timescales via Balmer line spectroscopy, near-ultraviolet plus far-infrared luminosity, and hard X-ray luminosity, respectively;
4. Analyze the resulting diagrams of short-term star formation rates versus each galaxy's average star formation rate since the Big Bang;
5. Measure the redshift evolution of the normalization, slope, and intrinsic scatter of the correlations seen in these diagrams;
6. Compare these observational results with the predictions of cosmological simulations that model galaxy formation; and
7. Use this comparison to identify the physical processes responsible for regulating star formation in galaxies on timescales ranging from 5-1000 Myr.

The database of measured star formation rates over multiple timescales will be made public to enable a wide range of analyses by the astronomical community. This research will support the Ph.D. theses of two graduate students.

Anjali Gupta/Eureka Scientific, Inc.
Holistic View of the Milky Way Diffuse X-ray Emission: The eROSITA/Fermi Bubbles and the Extended Halo

The galactic halo, or the circumgalactic medium (CGM), is an important component of a galaxy and it serves as a gas reservoir with accretion from the intergalactic medium (IGM) and outflows from the Galactic disk (star-formation and/or AGN induced). Recently discovered eROSITA bubbles, and well-known Fermi bubbles, provide a great channel to understand the effects of the feedback by Galactic winds on the Milky Way (MW) CGM. We propose to analyze the Suzaku archival observations to characterize the diffuse X-ray emission of these magnificent Galactic bubbles and the extended halo. Our program has four primary components:

1. Characterizing X-ray Emission Along The Fermi and eROSITA Bubbles.
   The MW halo is interacting with the ``Fermi and eROSITA bubbles" towards the center of Galaxy. We will use Suzaku observations to constrain the thermal structure of the

Galactic bubbles and will study the spatial distribution of X-ray emission within and around the bubbles. Once we characterize the thermal parameters of the bubbles, we will use these parameters to accurately measure the bubbles energetics and age and will compare them with the models of the past AGN/starburst activity including outflows.

2. Characterizing the Warm-hot Gas in the MW Galactic halo.
   To estimate the energetics and age of the Galactic bubbles require knowledge of the density and temperature distributions of the extended CGM because it determines the shape and speed of any shock travelling through it. We will characterize the emission parameters of the ubiquitous warm-hot gas in the MW halo using Suzaku spectra and will constrain its density and temperature distribution models.

3. How Ubiquitous Are the Hot Component and/or enhanced abundances in the MW Halo?
   Recent works have detected super-virial temperature (hot) gas and/or non-solar abundances in the MW halo along a few sightlines distributed over the sky. With our proposed program we will systematically search for the signature of recently discovered super-virial temperature gas and/or non-solar abundances in the MW halo. This will be the first attempt to map the sky with the emission from the hot component and non-solar abundances in the MW halo.

4. Probing OI Contamination in the Suzaku Observations.
   Suzaku spectra taken after 2011 are contaminated by OI fluorescent line due to the increase in solar activity. To achieve the goals noted above (1-3) we will carefully quantify the OI fluorescence line contamination. We will also study the variation of OI with solar activity and time of observation. Understanding OI emission is not only important for the archival Suzaku observations, it is also vital for future missions. Our results will be especially useful for the upcoming XRISM mission that will begin observing during a period of high solar activity.

The results from our proposed program will provide insights on the heating, chemical enrichment and mixing of the MW CGM and provide important inputs to the models of galaxy formation, evolution, and feedback. Ultimately, we will present a holistic view of the MW CGM that will inform theoretical models of structure formation. The proposed study will be a major advance over previous studies and will be a lasting legacy of the Suzaku mission.

Philip Kaaret/University of Iowa, Iowa City
Final Archive of the HaloSat data

We propose to enhance the HaloSat archive by providing high-level data products from an analysis of the full HaloSat data set. These products will include the results of spectral modeling fitting and derived parameters such as the oxygen line fluxes for each halo field and will be made available at the HEASARC for use by the broad community. The products will enable inclusion of HaloSat results in multiwavelength studies of the circumgalactic medium of the Milky Way. In support of this goal, we will improve the instrument calibration via studies of the evolution of the spectral response and effective area of the instrument over the full mission duration and improve the data filtering and background modeling. The updated response matrices, reprocessed low level data files, and the analysis note describing the data filtering and background estimation procedures will be made available at the HEASARC.

Erin Kara/Massachusetts Institute of Technology

Bridging the Gap Between X-ray and UV/Optical Disk Reverberation Mapping in Active Galactic Nuclei

In the field of physics, black holes are the ultimate test of general relativity. In the field of astrophysics, they are another fundamental piece in our cosmic understanding, as they are the most efficient means of converting matter into energy, releasing up to 42% of the rest mass energy of hot gas that plunges towards the event horizon. Supermassive black holes at the centers of galaxies are typically 1000 times less massive than the galaxies in which they reside, and yet it is widely thought that the energy produced via accretion onto these black holes can dictate how their entire host galaxy evolves. Most of the power output from an active galactic nuclei (AGN) is released in the innermost region, and thus studying the accretion flow, at the intersection of gas inflow and energy outflow, is essential for understanding how AGN grow and affect their surrounding environments.

In recent years, there have been two breakthroughs in how we probe the AGN inner accretion flow, through the development of X-ray Reverberation Mapping on short timescales (largely using XMM-Newton, NuSTAR and NICER), and UV/optical Disk Reverberation Mapping on longer timescales (largely with Swift, HST and optical/NIR photometry from the ground). The goal of both of these reverberation mapping techniques is to search for time delays between the X-ray light produced closest to the AGN and light that is reprocessed off the gas inflowing towards the central object. X-ray reverberation measures short time delays that corresponds to distances of tens of gravitational radii in the inner accretion disk, while UV/optical disk reverberation mapping finds time delays that correspond to distances of hundreds to thousands of gravitational radii, mapping the outer accretion disk to the broad line region.

While the ultimate goal of both techniques is the same (to understand the structure, dynamics and energetics of gas in the vicinity of the black hole), the fields have been largely developed in parallel, with little cross-talk in development of analysis methods, modeling or interpretation of results. This disconnection exists mainly because these two new reverberation mapping techniques require different telescopes and different campaign durations and cadences.

The main goal of this proposal is to bridge the gap between studies of X-ray reverberation from the inner accretion disk to longer wavelength reverberation mapping of the outer accretion disk to broad line region, with the ultimate purpose of understanding the AGN fuel supply and the causal connection between these spatially distinct regions. This will be accomplished in two ways:

-- We will develop Fourier-resolved timing techniques (that have been fruitful in X-ray reverberation studies) for UV/optical reverberation, in order to isolate the reverberation signature from other physical processes, e.g., absorption and scattering.
-- We will build the first broadband reflection and reverberation model from optical/UV to X-rays to simultaneously model reverberation across different wavebands. Incorporating the entire SED self-consistently will enable reliable disk and black hole parameter estimates.

This ADAP proposal will use publicly accessible data from several NASA-funded telescopes (Swift, HST, XMM-Newton, NICER, NuSTAR) and ground-based telescopes. We will develop and make available tools that will become pivotal to both reverberation mapping communities, and will disseminate models for broadband SED modeling that will have a range of applications to the wider AGN community.

By applying new techniques and models to archival datasets, we will put strong constraints on the geometry and energetics of gas flows around black holes, which is essential for making robust measurements of fundamental black hole parameters, (e.g., mass and spin). This is crucial and timely work for reaching NASA Astrophysics/SMD goals to probe the nature of black holes and explore the evolution of galaxies.

Jeyhan Kartaltepe/Rochester Institute of Technology
Toward a Uniform and Complete Keck Spectroscopic Archive for the COSMOS Legacy Field

We propose an in-depth analysis of galaxies over the full COSMOS 2 sq. degree field by performing a uniform reduction and public release of all Keck LRIS, DEIMOS, NIRSPEC, and MOSFIRE data in the public NASA Keck Observatory Archive (KOA). We aim to produce fully reduced two-dimensional (2D) and one-dimensional (1D) spectra for all targets on all masks. We will then associate detected objects with existing deep legacy field photometry, including serendipitously-detected objects, and run these data products through already supported routines to determine redshifts for sources and measure emission line fluxes, equivalent widths, and kinematic information. We will then create an interactive online database to provide these data to the larger astronomical community. These data will be used to:

1) Calibrate photometric redshifts in Dark Energy Surveys, to a bias precision of 0.2% in order to constrain the dark energy equation of state.

2) Perform an environmental study of galaxy properties and the intergalactic medium (IGM) surrounding large scale structure during the universe's peak growth epoch at $1.5<z<4$, combining measurements of galaxy overdensity with IGM tomography (out to $z\sim2.8$).

3) Extract kinematic information (rotation velocity and velocity dispersion) and identify potential mergers in order to investigate kinematic properties of galaxies both on and off the star forming main sequence.

4) Measure the Lyman alpha luminosity function and escape fraction at z>5 to constrain possible sources of reionization.

5) Create a comprehensive spectroscopic catalog of 0<z<9 galaxies in COSMOS which will serve as a tremendous extragalactic NASA legacy dataset and enable the selection of sources for follow-up observations with facilities such as the James Webb Space Telescope and ALMA.

The COSMOS legacy field will be a major calibration field for surveys of the future, such as those conducted by Euclid and WFIRST. The public database that we are proposing to build will significantly amplify the value of the Keck Observatory Archive (KOA) to the greater NASA extragalactic and cosmology communities, while directly addressing many of the goals laid out in the Cosmic Origins and Physics of the Cosmos programs.

Alexander Kashlinsky/Science Systems And Applications, Inc.
Precision measurement of source-subtracted cosmic infrared background from new Spitzer data

The cosmic infrared background (CIB) is the integrated infrared light originating in all extragalactic sources over all cosmic time, and thus encodes unique clues to the history of galaxy evolution. In deep infrared mosaics, after individually detected sources are excluded, the remaining signal (the ``source-subtracted CIB") reflects the cumulative emission from objects that by necessity are inaccessible to direct telescopic observation. These objects can be characterized by measuring the spatial fluctuations of the source-subtracted CIB. Indeed, over the past fifteen years, studies of source-subtracted CIB fluctuations in deep 3.6 and 4.5 mic Spitzer mosaics at sub-degree angular scales imply the existence of hitherto unknown populations of sources, too faint to be individually detected. This has significant implications for cosmology, and for our understanding of how galaxies evolved.

Thus far, the CIB fluctuation studies have used the deepest available datasets, the Spitzer narrow and deep extragalactic surveys. Their limited angular extent makes them unable to probe large angular scales, an unfortunate limitation because that is exactly where the contributions of the unknown populations is strongest and their spatial structure is diagnostic of their epochs. The proposed project will fill this gap by analyzing new moderately-deep Spitzer mosaics data covering approximately 18 square degrees across two separate fields at 3.6 and 4.5 mic in order to isolate, with good sampling and high significance, the source-subtracted CIB fluctuations to angular scales as large as 3 deg. At smaller angular scales these data will be used to measure with high precision the contribution from known galaxies and provide much improved constraints on the fluctuations that arise from the extrapolation of these known galaxies beyond the individual detection limit. This would lead to significant leaps in understanding the nature of both the known and new populations that contribute to the source-subtracted CIB fluctuations, a subject that is currently debated.

The new Spitzer data mosaicking, fluctuation analysis, and source counts to be carried out by the team for this project will provide a precision measurement of the fluctuations contributed by the remaining known galaxies and extend the measurement of the CIB to the critical angular scales where one can distinguish between the currently proposed cosmological explanations of the fluctuation signal. Specifically, the project will achieve the following novel science results with the high fidelity CIB maps constructed here: 1) high-precision determination of the CIB fluctuation contribution from the known remaining galaxy populations and their progression by magnitude, and 2) the probe of the significant excess CIB power on angular scales >1 deg, which is critically important for cosmological interpretations.

Joel Kastner/Rochester Institute Of Technology
Understanding Our Nearest Youngest Neighbors: NASA Archival Studies of Young Stars Near the Sun

The past two decades have seen dramatic progress in our knowledge of the population of young stars of age <100 Myr that lie within ~120 pc of the Sun, i.e., closer than the nearest well-studied star-forming clouds. Such nearby, young stars provide unique tests of pre-main sequence stellar evolution and the late stages of evolution of protoplanetary disks, and represent the best targets for direct imaging searches for giant exoplanets. In the past few years, Gaia data have provided the raw material for exhaustive investigations of the nearby field star population in search of candidate young stars, yielding several thousand new candidates. We propose a well-rounded investigation of data contained in NASA's 2MASS, WISE, GALEX, XMM-Newton, TESS, and Spitzer archives, combined with selective ground-based spectroscopy, that is aimed at exploring and exploiting this treasure trove. Our main goals are to test the ages of candidate nearby, young stars that are suggested by their positions in Gaia color-magnitude diagrams; characterize the evolution of rotation and magnetic activity for stars in the age range ~5-100 Myr; and, for those stars that display mid-IR evidence for warm circumstellar dust, constrain the structure and chemistry of protoplanetary and debris disks in their terrestrial planet formation regions.

Our testbed will be the (~50) known and (~100) newly identified members of the epsilon Cha Association, which, at a mere ~5 Myr of age, represents the youngest known stellar group within ~100 pc. The proposed research will firmly establish the epsilon Cha Association and (by extension) other NYMGs as benchmarks with which to calibrate and interpret Gaia color-magnitude diagrams of young clusters in the context of the wealth of NASA multiwavelength archival data available for cluster members. In so doing, our ADAP-funded study of the epsilon Cha Association will provide a battery of essential tests for pre-main sequence evolutionary models and theories of planet formation.

Mukremin Kilic/University of Oklahoma, Norman
An Ultraviolet to Infrared Survey of Single and Double White Dwarfs with GALEX and WISE

We propose to take advantage of the unique datasets made available by NASA's Galaxy Evolution Explorer (GALEX) and the Wide-Field Infrared Survey Explorer (WISE) to characterize the local white dwarf population in the Galaxy. The Montreal White Dwarf Database (MWDD) includes all spectroscopically confirmed white dwarfs known, as well as all white dwarf candidates within 100 pc.There are 41,543 white dwarfs in the MWDD with spectral types, including 33,694 objects where MWDD has an optical spectrum available. Out of the 41,543 white dwarfs with spectral types, 27,513 have GALEX and 11,019 have WISE photometry available.

By exploiting the full range of the electromagnetic spectrum available from these missions, we will constrain the physical parameters of all spectroscopically confirmed white dwarfs in the solar neighborhood, including the 100 pc sample, and we will

1- verify the accuracy of the photometric method by expanding our wavelength range from optical only, i.e. SDSS and Pan-STARRS, to UV and mid-infrared through GALEX + WISE + ground-based infrared surveys like 2MASS. A comparison between model fits using optical data only and fits based on UV + optical + IR data will enable us to constrain any systematic differences between the two methods. If there are any systematic differences found, we will provide correction functions for the physical parameters of each object (based on optical data) as a function of temperature and mass.

2- provide a detailed model atmosphere analysis that will significantly improve the temperature and mass estimates for all spectroscopically confirmed white dwarfs in the solar neighborhood, constrain the amount of pile-up of massive white dwarfs in the crystallization sequence, and verify if the current evolutionary models including the latent heat of crystallization are able to match the significance of the pile-up.

3- identify UV-excess objects, specifically double degenerate systems.

4- identify IR-excess objects, and significantly increase the number of known white dwarfs with low-mass stellar and substellar companions.

5- use the TESS Full Frame Imaging data, with 10 or 30 min cadence, to perform a variability survey of all of the spectroscopically confirmed white dwarfs in the MWDD.

Our survey will be the most comprehensive UV-to-infrared white dwarf survey ever done, and it will provide an ultraviolet, optical, and infrared catalog of the solar neighborhood white dwarf population detected by GALEX and WISE. It will provide the best constraints on the mass and temperature distribution of nearby white dwarfs, and the frequency of stellar and substellar companions, and debris disks around white dwarfs and their progenitor main-sequence stars.

Chip Kobulnicky/University of Wyoming

Lifting the LID on the Nature of Extraplanar Galactic Dust Using Line-of-sight Incremental Dereddening.

Extinction and reddening by interstellar dust taint astrophysical signals, frustrating precision measurement of cosmological standard candles and electromagnetic components of multimessenger transient signals. Dust leaves its imprint on the signals from all distant Galactic and extragalactic targets, including the Cosmic Microwave Background polarization. Although an average Milky Way disk reddening curve is empirically defined and plausibly interpreted in terms of a power law distribution of interstellar dust grain sizes, significant deviations are also documented. These variations with location in the Galaxy are not well understood in terms of physical causes and are not even well mapped. In particular, the nature of dust above the Galactic Plane is poorly probed. Extraplanar dust may resemble dust in the halos and extraplanar regions of other galaxies where populations of supernova, gamma-ray bursts, and electromagnetic transients from gravitational wave sources preferentially reside. Documenting the nature and origins of extraplanar dust in the Milky Way in true three-dimensional detail, as informed by local physical influences, is now both possible and pressing. Understanding the nature of this dust holds the promise of improving dereddening within other galaxies.

This proposal describes an investigation to measure the reddening curve and investigate the nature of dust in the Milky Way outside one gas/dust scale height at z>150 pc above the Plane. The program leverages new Gaia distances to stars of known temperature/gravity/metallicity having broadband ultraviolet, optical, and infrared photometric measurements from 0.15--4.5 microns. We will employ Line-of-sight Incremental Dereddening (LID) to remove the effects of foreground dust that would otherwise veil the signature of potentially extreme non-standard dust far from the Plane. Results from a pilot study show how line-of-sight averaging without foreground subtraction will unwittingly mute the true variations in dust grain size/composition that can now be linked to specific physical causes along each sightline. We propose an all-sky study of the reddening curve at large z heights starting from a spectroscopic base sample of over 400,000 stars. Archival WISE, Spitzer, GALEX, and IUE datasets will provide reddening curves toward each source. The analysis will compare the high-z reddening curve within 30'x30' tiles to established Galactic curves and characterize the dust in terms of the standard ratio of total-to-selective extinction, R_V. We will produce tabular data holding extinction curves and maps of R_V as a function of Galactic coordinates, z height, and proximity to physical features that may be responsible for shaping dust grain size distributions, including OB associations, HII regions, interstellar bubbles, galactic fountains, and high-velocity clouds.

Michael Koss/Eureka Scientific, Inc.
Piercing through the Torus: A 15 Year X-ray Variability Survey of BAT AGN

The Swift-BAT all sky survey has made a major contribution to our understanding of the hard X-ray sky (14-195 keV), detecting over 1000 active galactic nuclei (AGN) in more than 400 refereed publications. In the NASA senior review, Swift received the highest rating with the work extending the BAT survey, as we are proposing here, specifically identified as a critical area for additional funding. The BAT AGN Spectroscopic Survey (BASS) provided the first large and complete census of the key physical parameters of the supermassive black holes (SMBHs) that power the local AGN population, including the black hole mass, line-of-sight obscuration, bolometric luminosity, and accretion rate. In the 2nd data release (DR2), 850 Swift-BAT AGN were studied with high quality X-ray spectra for the entire sample, and optical/NIR spectra and black hole masses for over 95% of the sample. Despite this wealth of data, however, there has been very little study of the temporal behavior of BAT-detected AGN.

Hard X-ray emission (>10 keV) from the corona of AGN can probe the innermost parts of the central engine of these systems. Although the temporal behavior of this emission may carry unique signatures of changes to these physical components, it has yet to be fully explored. One of the critical advantages of the hard X-rays (over UV/optical) is that it can find and trace large changes of obscuration (NH>10^22-10^25 cm-2) in obscured systems. This project proposes to use the largest available datasets for hard X-ray selected AGN, drawn from the Swift BAT legacy all-sky survey and a multitude of other facilities, to address the following key questions: (1) What can the hard X-ray monitoring tell us about the structure of the obscuring medium around AGN? (2) What are the hard X-ray signatures of AGN that experience dramatic changes in their accretion flow and/or circumnuclear structure as seen in the X-rays and IR?

Specifically, we will: (1) use new multi-epoch spectroscopy of 55 Compton-thick (CT) AGN, over baselines of months to greater than years, to constrain the existence of and properties of the non-varying reflection/reprocessed component. This will be the first large study of variability in CT AGN, increasing the number studied with multi-epoch NuSTAR spectroscopy above 10 keV from merely 4 to more than 40 and for the first time combine this study with WISE variability. We will also directly correlate eclipsing events with changes in IR emission from NEOWISE. (2) Use the 15-year light curves of Swift BAT for 1014 unbeamed AGN, to identify and characterize the occurrence rate of large variability events in the BASS sample, and associate them with changes in the accretion disk emission or eclipsing events using complementary WISE and MAXI/Swift XRT data, based on the accompanying changes in the IR, soft X-rays, and optical.

This proposal links with NASA s Strategic Plan to "Improve understanding of the origin and destiny of the universe, and the nature of black holes." The goal of this NASA proposal is to radically transform our understanding of AGN using variability studies into the nature of the obscuring material near the supermassive black hole, the elusive nuclear torus . This study will for the first time survey and map AGN tori using the time variable X-ray obscuration from several NASA satellites to reveal the torus geometry and thickness that was impossible to determine before a program of this type. The ROSES guidelines also state: answer questions that would be difficult, if not impossible, to address through an individual observing program . The primary data we are using includes months/years from Swift BAT, NuSTAR, XMM, WISE, and MAXI which have no associated funding programs for this type of large archival investigation.

Laura Lopez/Ohio State University
Investigating the Hot Gas Outflows of Starburst Galaxies

We propose an archival program to analyze XMM-Newton and Chandra observations of sixteen nearby, edge-on, star-forming/starbursting galaxies to investigate the nature and role of hot, 10^7 K gas in galactic outflows. Tremendous advances have been made regarding the cold and warm gas in starburst disks and outflows, but the hot gas remains the most poorly constrained gaseous component. Without knowledge of the amount and role of the hot gas in outflows, large uncertainties plague galaxy formation simulations and undermine their predictive power.

Using deep XMM-Newton and Chandra data toward our sample much of which has never been analyzed in the context of galactic outflows we will map the diffuse, hot gas in outflows and compare their distribution to the cool and warm phase medium, measure the hot gas properties using spatially-resolved spectroscopy, evaluate the presence of charge exchange and non-thermal emission associated with the outflows, and compare the results to galactic wind models to ascertain wind properties (e.g., wind geometry, mass loading, metal loading, and energy thermalization) and their dependence on galactic parameters (e.g., stellar mass, star-formation rate). Using this approach, we bridge theory and observations as well as exploit the wealth of high-quality, multiwavelength data available now on these sources. This proposal is timely and important given the upcoming launch of XRISM, and it will foster a complete view on the multi-phase nature of galactic outflows.

Derck Massa/Space Science Institute
Understanding Wind Variability in Hot Stars and Its mplications

Accurate mass loss rates are required for astrophysical applications ranging from the evolution of the elements to the dynamics of the interstellar medium. Consequently, a firm understanding of the nature of stellar winds and the uncertainties involved in measuring mass loss are essential to many fields.

This proposal seeks to apply the Sobolev approximation with exact integration (SEI) model to repeated observations of OB star wind lines (from the \iue\ and \fuse\ archives), in order to quantify the variability seen in wind line fluxes in physical terms and to investigate its origin. Studying these variations is important it two respects.

First, changes in the apparent radial optical depth of the wind, determined by the SEI models, is directly proportional to differences in the inferred mass loss rate measured by ANY model. Consequently, the wind line variability places a limit on the intrinsic accuracy of mass loss rates derived from a single observation of UV wind lines.

Second, the results will provide clues about the underlying nature of the variability. These can be gleaned by examining the radial dependence of the wind optical depth and how it changes. Another important parameter obtained from the fits to doublets is the best fit ratio of oscillator strengths (f-ratio). This parameter can be interpreted as a proxy for the fraction of the line of sight to the photosphere that is covered by optically thick structures, furnishing important information about the nature of the wind flow. Initial results for one series, reveals a relation between the f-ratios and optical depths which, if verified, has important consequences concerning the structure of OB star winds.

Daniel Masters/California Institute of Technology
Mapping the Galaxy Color-SFR Relation with Spitzer and Herschel Stacks

We propose to measure the empirical relation between galaxy star formation rate (SFR) and broadband optical/near-IR colors, using an innovative stacking analysis of Herschel PACS/SPIRE and Spitzer MIPS imaging. SFR is generally considered difficult to estimate accurately without spectroscopic diagnostics or far-infrared (FIR) photometry, both of which are prohibitive to obtain for large numbers of faint, high-redshift galaxies. Meanwhile, upcoming large-scale surveys of the 2020s (Rubin, Euclid and Roman) will present us with billions of faint galaxies for which we only have broadband images in ~6-8 optical/near-IR filters. The question arises: how well can we measure SFR from the broadband colors alone? Our proposal seeks to answer that question, with significant implications not only for upcoming surveys but for existing deep fields as well, for which broadband photometry must be relied on to derive SFR for the majority of galaxies.

We will use an innovative manifold learning technique known as the self-organizing map, or SOM, to stack galaxies in bins of observed broadband colors. This procedure will ensure that our Herschel PACS/SPIRE and Spitzer MIPS stacks are built from galaxies with similar intrinsic physical properties. A key point of this proposal is that we will be able to test directly the correlation of the optical-NIR colors with FIR properties. With the stacked FIR measurements made across the galaxy color space, we will be able to accurately constrain the empirical SFR-color relation, thereby overcoming the limitations of template fitting that result from uncertainties in the reddening, initial mass function (IMF), emission line evolution, and star formation histories.

Our proposal will thus leverage archival Herschel and Spitzer data to substantially improve SFR estimates for faint sources in existing deep fields, as well as maximize the information from large-scale imaging surveys happening in this decade. In addition to providing calibrated SFRs for nearly all galaxies in the deep fields to i~25, we will use our results to investigate the evolution of the galaxy main sequence for low-mass galaxies to high redshift and put new constraints on the cosmic star formation history.

Smita Mathur/Eureka Scientific, Inc.

Understanding the Chemical Enrichment and Heating of the Circumgalactic Medium of the Milky Way

The stellar disks of spiral galaxies stand out in optical images. This is where new stars form, stars explode in supernovae when they die, and next generation of stars are born again. The actual size of a galaxy, however, is about 20 times larger, and is filled with dark matter that binds a galaxy gravitationally. The vast space between the stellar disk and the outer radius of a galaxy is also filled with gas; this gaseous medium is called the circumgalactic medium (CGM). Theoretical simulations suggest that when matter from the intergalactic medium (IGM) enters the dark matter halo, it is heated up to a temperature that depends on the total gravitational mass of a galaxy. This is about a few million degrees for galaxies like our Milky Way. When the gas from the CGM cools, it falls down on the galactic disk, and takes part in the next generation of star formation. When the stars die, supernovae throw the enriched material back into the CGM.

Thus the CGM is an important component of a galaxy, being ``a fuel tank, a waste dump and a recycling hub" all in one. Naturally, the CGM has attracted attention in recent years from theorists and observers alike. In the past decade, a lot of observational effort has gone into detecting and characterizing the CGM. Because of our special vantage point, most successful studies have been for our own Milky Way (MW). The MW CGM has been detected unambiguously along several directions in both absorption and emission. We now understand that its temperature is a few million degrees, it is extended to a large radius, has low density, and it contains a huge amount of baryonic mass; all this is as expected from theoretical models. And then came new discoveries that rattled our understanding.

Deep XMM-Newton observations toward a blazar revealed several interesting surprises recently. In addition to the million degree gas, 10 million degree gas was also detected in absorption in the grating spectrum. Neon abundance was found to be super-solar relative iron. Neon to oxygen and nitrogen to oxygen ratios were also found to be non-solar. The emission spectrum of the CGM around this sightline revealed another warm-hot component. All these results were robust, but surprising. If these are the general properties of the MW CGM, they provide unprecedented insights into the chemical and thermal history of the CGM. How is the CGM heated to such high temperatures; what leads to multiple-temperature hot components; what kind of supernova feedback is responsible for enriching the CGM with metals; is oxygen depleted?

Before we can start answering these questions, it is imperative to know whether the blazar sightline noted above is somehow unique or whether the hot temperatures and non-solar abundance ratios are the general properties of the CGM. We will find out with four classes of extragalactic targets distributed all across the sky and three different projects using over 21Ms of XMM-Newton data. We will further disentangle the location of the gas by comparing the extragalactic sightlines with Galactic sightlines with over 12Ms of data. This will be a major step forward in our understanding of the thermal history and chemical enrichment of the CGM. Our proposed program is designed to yield guaranteed science results with far-reaching consequences toward understanding galaxy evolution, and the role of feedback.

This will be a lasting legacy of XMM-Newton and will provide the necessary ground work for future missions. Thus, our proposed program is scientifically important, well defined, and forward looking, a win-win-win.

Travis Metcalfe/White Dwarf Research Corp
Asteroseismic Calibration of the Empirical Activity-Age Relation

Understanding the evolution of stars and their planetary systems requires a reliable method of determining their precise ages and masses. In young stars, both rotation and magnetic activity are empirically correlated with the stellar age. Beyond the middle of their main-sequence lifetimes, this correlation appears to break down for rotation, but it persists for magnetic activity. We propose to recalibrate the empirical activity-age relation, by combining published chromospheric activity measurements of bright stars with asteroseismic ages and masses derived from data obtained by the Transiting Exoplanet Survey Satellite (TESS).

Our target list is drawn from hundreds of bright stars with published multi-year data on chromospheric activity from the Mount Wilson and Lowell surveys, the California Planet Search, as well as smaller samples from other surveys. Asteroseismic analysis relies on short-cadence (2-minute or 20-second) observations, for which target pixel files and light curves have been delivered by the Science Processing and Operations Center (SPOC). Light curves optimized for asteroseismology are available through the TESS Asteroseismic Science Operations Center (TASOC). From a power spectrum of these short-cadence light curves, we will determine the global oscillation properties and/or individual mode frequencies for each of our targets. Asteroseismic radii, masses and ages will be derived from grid-based and detailed modeling, using the observational inputs obtained from TESS data along with spectroscopic constraints gathered from the literature and luminosities from Gaia EDR3.

The proposed work will establish a new tool to determine reliable ages for older stars and their planetary systems, where methods based on rotation begin to break down. Spot modulations in older stars are notoriously difficult to detect, both because active regions become smaller and rotation periods grow longer. By contrast, spectroscopic signatures of magnetic activity become weaker but more constant in time, so a single measurement is more likely to be representative of the mean activity level. Such measurements are a natural byproduct of radial velocity follow-up programs, and our new tool will allow these same data to yield the age for fainter targets where asteroseismology is not feasible.

Richard Miller/Johns Hopkins University
MeV Astrophysics via Planetary Occultation

We will address several diverse topics in MeV astrophysics (0.1-10 MeV) by leveraging new observing capabilities enabled by previously deployed planetary exploration assets. Specifically, our proposed effort will utilize archived datasets acquired by gamma-ray spectrometers aboard NASA s Lunar Prospector (LP) and Mars Odyssey (MO) missions, and JAXA s Kaguya, to survey, monitor, and characterize astrophysical sources at nuclear energies. This research program builds on first light detections made from the Moon and Mars using these datasets, benefits from extensive operational experience in planetary orbits, leverages well-understood archived datasets, and employs the validated Lunar Occultation Technique (LOT) detection methodology.

Our approach challenges the status quo by leveraging time-domain measurements made in benign, slowly changing background environments to increase sensitivity at MeV energies. Non-imaging gamma-ray spectrometers in orbit about airless planetary bodies are the single instruments required for, and time resolved spectra are the sole data product needed to perform, LOT-based analyses.

Comprehensive multiyear gamma-ray spectrometer datasets (LP-GRS, MO-GRS, K-GRS, respectively) are the foundation of our astrophysics data analysis effort and have been archived in the Planetary Data System (PDS). Although originally intended for orbital planetary geochemistry, when used in conjunction with the LOT these spectrometers fill an important capability gap in MeV astrophysics, a direct consequence of the well-characterized slowly changing planetary backgrounds, ~100% operational duty cycle, near-uniform sky coverage and wide field-of-view afforded by the LOT.

The basic tenets of the LOT methodology have been validated from orbits about the Moon and Mars. Proof-of-principle investigations led to the successful detection of the first high-energy astrophysical sources detected from the Moon and Mars. Demonstration of the LOT s effectiveness to monitor and characterize both persistent and time-variable targets over extended periods of time were key outcomes of these proof-of-principle studies.

Our goals fall into two broad categories, targeted astrophysical searches and all-sky survey. Within each category, gamma-ray energy selections (individual nuclear lines, broadband continuum) and temporal cadence (persistent, nuclear transient, variability) provide intrinsic flexibility and are driven, in part, by theoretical and/or phenomenological considerations appropriate to specific searches.

The LOT is a paradigm changing technique uniquely enabled by our nearest celestial neighbors. Future programmatic opportunities may leverage this methodology to enhance NASA astrophysics, and this proposal supports that goal, in part, by providing an intriguing, useful and overdue probe of the cosmos at MeV energies.

Maryam Modjaz/New York University (Inc)

Meta-study of UV-through-NIR Explosive Transients for the Roman Space Telescope and Beyond

We are undergoing a revolution in time-domain astronomy. Classes of objects that are rare yet astrophysically important have become increasingly well-observed via innovative surveys, but our knowledge and inference of their physical parameters lags behind. In particular, blue transient phenomena, including infant core-collapse SNe (CCSNe), Superluminous SNe (SLSNe) and Fast Blue Optical Transients (FBOTs) have been recently discovered and well-observed, and all of them are important tools for many fields of astrophysics as well as fascinating objects with many outstanding questions.

What is needed for such a systematic study of these blue transients is an up-to-date multi-wavelength (UV to NIR) archive coupled with population studies and modeling. The relatively rare and costly nature of space-based observations means that these events tend to get studied on a case-by-case basis, and are rarely compiled into a cohesive whole.

Here we propose to aggregate, analyze, and model the large and multi-wavelength dataset of CC SNe, SLSNe, and FBOTs, including Hubble & Swift UV data,(approximately 150 objects, depending on the precise sample definition), which have been become available only recently, to improve their usage for cosmology, to enable efficient follow-up of future objects detected by the Roman Space Telescope and Rubin Legacy Survey of Space and Time (LSST), and to constrain their mysterious progenitors and hotly debated explosion mechanisms. We will name it the Comprehensive Archive of Astronomical Transients (CAAT).

In addition we propose to make available to the community a number of products including:

1) Template lightcurves for object classes using cutting edge multi-dimensional gaussian process techniques.
2) Bolometric corrections using UV-NIR data, both spectroscopically and photometrically (to the extent the data allows)
3) Physical parameter inference from model grids for well sampled classes of transients with consensus models.

This is the most opportune time to do the proposed work, given recent and upcoming publications of data by many of the major SN and transient groups (Berkeley, Carnegie SN Project, CfA, PanSTARRS, PTF, ASAS-SN, DES, ZTF), such that the data are begging to be analyzed and to be used for important purposes as a whole. The results of this work will have high impact on a number of fields: high-precision cosmology, transient surveys, and our understanding of the most powerful explosions of massive stars. Thus, this proposal is a low-risk, high-impact project}.

In summary, we are proposing to enable legacy studies for the Roman Space Telescope and future transient surveys by aggregating, analyzing and modeling these scientifically important explosive events. In addition, we will answer crucial questions about the explosion and powering mechanism for certain transient types, including Stripped CCSNe and SLSNe Ic.

Elena Orlando/Eureka Scientific, Inc.
Characterizing the Galactic Diffuse Emission

Current observations from radio to gamma rays are offering an amazing and unprecedented view of the sky, unveiling properties of the diffuse emission in the Milky Way mostly associated with cosmic rays and magnetic fields. Indeed, recent observations at the opposite frequencies of the electromagnetic spectrum, such as microwaves with Planck and gamma rays with Fermi LAT, have revealed diffuse emission from the Milky Way, which is produced by cosmic rays interacting with the interstellar medium and magnetic fields during their acceleration and propagation in the Galaxy. Many regions of unexplained enhanced emission show up as Galactic large-scale features, which sometimes seem to partially overlap at different frequencies. However, these features depend on the model assumption for the distribution and density of cosmic rays and magnetic fields across the Galaxy, which are poorly known. An explanatory example of these features is the famous Fermi Bubbles seen in gamma rays, two large lobe-like structures likely extending ~10 kpc from the Galactic center, possibly being a signal of the past activity of the Milky Way s black hole. The Fermi Bubbles can potentially be connected to the Haze, and/or Loops and Spurs seen in microwaves, and whose origin is still unknown.

By analyzing publicly available NASA data, we propose to investigate the large-scale distribution and density of cosmic rays and magnetic fields in the Galaxy producing diffuse emission. We also propose to spatially and spectrally characterize the unexplained diffuse features of publicly available data from radio to gamma rays.
Results for a variety of NASA space missions will be made available to the scientific community for reproducibility and for further studies, with the effect of enhancing the outcome of the ADAP program in particular, and the NASA missions in general.

Terry Oswalt/Embry-Riddle Aeronautical University, Inc.
Assessing the Empirical Rotation-Age Paradigm Using Wide Stellar Binaries

Accurate stellar ages constrain a host of astrophysical questions of interest ranging from the habitability of planets to the Galaxy's star formation history and age. Gyrochronology, an empirical relation between rotation and age, is believed to be competitive with or better than most other methods of stellar age determination for lower main sequence stars. We propose to test competing rotation-age models using wide noninteracting binaries. The Kepler, K2 and TESS fields contain hundreds of thousands of such pairs. Because components of each pair are coeval and share the same metallicity, such a large sample offers the opportunity for unique leverage on quantifying what is really a "rotation-metallicity-age relation" for main sequence stars. Moreover, wide binaries span a much broader range in age and metallicity than stellar clusters, which may have mixed populations and dynamically lose low mass stars.

Kepler and TESS are ideal for measuring stellar rotation via modulation of light curves as active regions (spots) rotate through the line of sight. TESS has much broader sky coverage, brighter targets with high photometric precision, and nearly continuous time windows near the ecliptic poles. Kepler, however, provides a much longer time window needed for detection of longer rotation periods typical of stars older than the Sun. Using archival data from these missions, supplemented by ground-based follow-up observations on selected pairs, our proposed study will probe the rotation-age paradigm in two ways:

1. Components of pairs consisting of two main sequence stars are expected to have the same rotation age.
2. Pairs with a white dwarf component provide an independent age estimate age for the system from cooling theory, which should be commensurate with the rotation age of its main sequence companion.

Jennifer Patience/Arizona State University
A Benchmark Survey of Substellar Companions -- a Critical Test of Formation and Evolution Models

Brown dwarfs represent the low-mass end of the IMF, and the most extreme mass ratio stellar binaries. It is expected that while the stellar IMF drops off moving toward lower masses, a separate distribution belonging to giant planets becomes more frequent as mass decreases. Recent radial velocity studies of this brown dwarf desert, however, suggest it only holds at very small separations (<100 days), and there is no evidence for a desert at wider separations probed by direct imaging. However, given the relative rarity of brown dwarf companions, it is difficult to trace this relationship in detail with a limited number of detections. The companion fraction and orbital architectures provide empirical constraints on formation models for both stellar and substellar systems. Detection of younger brown dwarfs requires only a few minutes of integration time with large ground-based telescopes equipped with adaptive optics (AO). We propose to perform a comprehensive, volume-limited search for stellar and substellar companions by utilizing the extensive set of multi-epoch high resolution imaging observations in the NASA Keck and HST archives, many of which have not been published to date, and the all-sky survey of WISE for the widest companions. From this uniform analysis, drawing upon the extensive NASA archives of both ground-based high resolution and space-based high sensitivity images, we will expand our list of candidates, and finalize any characterization of the companion properties with limited follow-up observations. Finally, we will generate contrast curves and completeness to companions for every star to determine the population-level properties of brown dwarf companions to high-mass stars. This sample will be over three times as large as previous surveys for stellar and substellar companions to B and A stars and will search an additional three decades in separation coverage compared to current substellar companion searches. In conjunction with previous surveys, this project will allow us to understand the demographics of brown dwarf companions to high-mass stars at several orders of magnitudes in separations, from 10 to >1000 AU from these data, which in the next few years we will be able to combine with Gaia detections of brown dwarfs from 1-10 AU around higher mass stars, a regime unprobed by radial velocity surveys, as A stars are not amenable to precision radial velocity observations. By comparing this population of brown dwarf companions to high mass stars to the equivalent population around solar-type stars, we can, for the first time, understand how this low-mass end of the binary population evolves with stellar host mass. Given the limited lifetimes of more massive stars, brown dwarfs that are companions also form a critical set of benchmark brown dwarfs which can be used to calibrate brown dwarf formation and evolution models in a way that the isolated field population cannot.

Joshua Peek/Space Telescope Science Institute
Taming the Sharks: Dynamics and Dust in the High-Latitude 3D ISM With GALEX

Looking at the diffuse Galactic ISM from below, in radio or infrared emission, we see a cacophony of magnificent structures. The clouds of neutral gas that stretch across the high-latitude sky vary in temperature, velocity, morphology, and composition. They could be newly accreted cool gas from the halo, the swept up edge of a supernova-driven super bubble, or bundles of coherent magnetized filaments. But while this area of sky provides the clearest and most detailed view of the diffuse ISM, we have little concept of its geometry. We know the Sun resides in a local cavity, and that most of the dust-bearing column begins at least 100 pc away. We know that the scale height of the neutral medium is ~400 pc, fading off murkily into the hotter disk-halo interface. But tools for determining the 3D structure of the ISM depend on substantial reddening of starlight, which the thin, high-latitude ISM does not provide.

In this project we will develop a wholly new technique for the 3D reconstruction of the ISM based on the nearly all-sky maps from the GALEX satellite. GALEX images, especially in the far-ultraviolet (FUV), are rich with dozens of large-scale, complex reflection nebulae, stemming from the scattering of FUV starlight off of small dust grains. Our analysis shows that these bright FUV nebulae are clearly identified with cold neutral medium (CNM) structures above the Galactic plane. Recent progress in our physical understanding of the CNM and newly created algorithms for HI data analysis have provided mechanisms for extracting these CNM features across the high-latitude sky. The key to uniting the FUV and HI representations of the CNM, and finding the distance to each cloud, is the stars. With Gaia DR2 we now have very accurate distances to all of the bright FUV-emitting stars above the plane. These stars emit a radiation field that is both quite patchy, due to the rarity of bright FUV emitters, and is reflected by dust dramatically closer to the plane, due to the forward-scattering nature of small grains and the short scale height of hot stars. These effects together allow us to reconstruct the 3D structure of much of the cold ISM above the plane.

We will focus our scientific analyses of these 3D dust maps on two specific areas: the dynamics above the disk plane and the variation of dust scattering properties. Since our structures have radial velocities from HI, we will be able to study material upwelling and inflowing, the physical scale of coherent velocity structures, and the relationship between vertical kinetic energy of the gas and potential energy. At greater distances above the disk we can test hypotheses of angular momentum exchange with the halo through a fountain flow, and the amplitude of Galactic ISM rotational lagging with height far above the disk.

The variation of dust scattering properties in this data set allows us to test theories of dust evolution in the ISM. If grain evolution is driven by gas density, we expect scattering to change with the measured thermal state of each cloud; if grains are processed by shocks, we will see variation with velocity. Perhaps grain evolution depends on the origin and history of large-scale ISM structures, and we will find cohesion in dust properties structure by structure. By using NUV and FUV data together, we can build a more detailed picture of grain evolution across these environments in both small silicate and carbonaceous grains, probed by NUV and FUV scattering, respectively.

Our 3D ISM database, contributed back to MAST along with GALEX maps specifically processed for reflection nebulae and enhanced FUV star catalogs, will be a powerful tool in its own right for astronomers studying everything from cosmic microwave background foregrounds to reddening map distortions to 3D dust scattering statistics in star-forming galaxies. Like heavily referenced, low-latitude 3D ISM maps, our data products will be a resource for years to come.

Ylva Pihlstrom/University of New Mexico
Infrared Circumstellar Shell Emission of Galactic AGB Stars: Mass-Loss Rates, luminosities and Distances

Understanding the asymptotic giant branch (AGB) mass-loss processes and how they depend on fundamental stellar parameters have implications on galaxy evolution scenarios. Many studies have focused on AGB samples where a distance is known, for example AGBs in the Magellanic Clouds, while similar studies in the Galaxy have been hampered due to few distance estimates along with most stars in the bulge being heavily obscured. We address this with a statistically significant sample of AGB stars in the Galactic plane and bulge. We propose to use cross-matched infrared (IR) data of a sample of ~35,000 AGB stars to construct Spectral Energy Distributions (SEDs), and fit models calculated from radiative transfer codes to the SEDs. Properties like mass-loss rates and bolometric luminosities will be inferred from the modeling after distance matching. These properties, when combined with kinematics, location, and other physical characteristics, will provide new insights into the population of AGB stars in the central Galaxy.

The sample is based on the IRAS color-color diagram for variable stars, which effectively can select for evolved stars. As IRAS was confused in the plane, the IRAS color-color selection has been mapped to the MSX color regime, resulting in a sample of ~35,000 IR bright, periodically variable AGB stars. The sample is cross-matched with existing NASA IR catalogs (1-70um regime) covering the plane partly or fully. IR SEDs are formed and extinction corrections are applied. The resulting SEDs are fitted to radiative transfer models of cool stellar envelopes. Mass-loss rates and bolometric luminosities are henceforth derived for the sample. The methods proposed are statistical, implying some uncertainties in derived values for an individual source may exist, but for a sample of 35,000 stars resulting luminosity and mass-loss rate distributions will be representative of the stellar populations overall. Moreover, we explore a new method to provide distance estimates to all these stars. This cannot be achieved by missions like Gaia, as a large fraction of AGB stars are heavily obscured in the optical.

The data analysis includes comparing the mass-loss rates and luminosity functions to the lower metallicity AGB populations in the LMC and SMC, as well as to existing theoretical models of AGB evolution. By including period information for a subset of the proposed sample, relations between period, luminosity, mass-loss rate and colors will be quantified for Galactic conditions. The data will be used to tease out age populations in the mid-plane of the Milky Way disk, and how they relate to the Galactic bulge and bar structure.

The main deliverables to the community will be the model-independent cross-matched data and distance estimates for each source, along with our model-derived properties. Providing the comprehensive raw data set allows other researchers to apply different methods for deriving similar parameters using their model of choice for those few properties that are more heavily model dependent.

The proposed sample is unique as it covers a very wide range of AGB evolutionary stages and/or ages (initial masses), and is focused on the Galactic bulge and plane region where much data is missing due to optical obscuration. With a statistical approach, details of the Galactic AGB populations is addressed. The proposed research addresses the analysis of archival data from NASA space astrophysics missions, deriving information from the targets by the combined use of several missions. This could not be done via single observing programs, and increases the scientific return of the NASA missions. This elaborate and extensive data set will be instrumental to new research on AGB stars in the Milky Way and feature the opportunity and niche of the combined NASA missions for future research.

Troy Porter/Stanford University
Multi-Messenger 3D Modeling of the Interstellar Medium of the Milky Way

The interstellar medium (ISM) and the processes that occur within it are crucial in shaping the evolution of galaxies. The collapse of massive gas clouds composed of molecular hydrogen and heavier elements leads to the formation of stars. As stars evolve along the main sequence, the radiation they emit is absorbed and re-emitted by dust in the ISM, affecting the astro-chemical distribution and balance between molecular, atomic, and ionized hydrogen. Supernova (SN) explosions at the final stage of evolution of massive stars accelerate cosmic rays (CRs), which in turn ionize the gas in the ISM and influence the galactic nucleosynthesis and star-formation rate.

CR propagation and the feedback effects in the ISM is a complex and fundamental problem in modern astrophysics. The CRs are subject to various energy losses due to their interactions with the other components of the diffuse ISM: the interstellar gas, radiation and magnetic fields. SN create turbulent magnetic fields, which affect the propagation and escape of CRs from a galaxy. CRs also generate turbulence and drive galactic winds, resulting in outflows of material enriching circumgalactic space. In the case of star-forming galaxies, the energy density in the radiation and magnetic fields, CRs, and turbulent motions of the interstellar gas are similar, so all of these components influence the others.

Meanwhile, the cohesive ``big picture" view of the mutual effects of CRs on and between the other ISM components is currently missing. The objective of this proposal is to provide this big picture through developing detailed data-driven models of the interstellar gas, radiation and magnetic fields, and CRs in the Milky Way. Our proposal utilizes data from a number of successful NASA missions, or missions with significant NASA involvement: WMAP, Planck, INTEGRAL, COMPTEL, Fermi-LAT, Spitzer, IRAS, Herschel, and COBE. The combination of the data with the advanced modeling and analysis methods that we are proposing will result in state-of-the-art 3D models for all major components of the ISM in the Milky Way.

These models will be used to investigate the deep connections between the following important properties related to the evolving ISM: 1) the CR heating and pressure; 2) the observed radio/infrared/gamma-ray relation (the empirical correlation between the thermal infrared dust emission, non-thermal CR electron synchrotron emission from ongoing star-formation, and high-energy gamma-ray emissions produced by CR nuclei interacting with gas); and 3) the spatial distribution of carbon monoxide and its relationship to molecular hydrogen through the often used XCO parameter.

The results of our proposed work will also have other uses besides our immediate scientific objectives. The interstellar gas, radiation, and magnetic field distributions are the major foregrounds for cosmology experiments. Our models for these ISM components can be utilized to provide state- of-the-art estimates for interpreting the cosmological data. The diffuse ultraviolet/far-infrared and CRs are critical ingredients for modeling the molecular chemistry in the ISM.

Further application of the advanced models that we will develop includes self-consistent multi- wavelength analysis of the Galactic center (GC) region: the gamma-ray excess at the GC has been discussed in many papers and interpreted as originating from dark matter annihilation or due to unresolved point sources. They will enable unveiling the true nature of the excess, its relevance to the enigmatic WMAP/Planck ``Haze'' at microwave frequencies, as well as to the activity of the central supermassive black hole, and possible link with the ``Fermi Bubbles''.

All models, data products, and code improvements resulting from our proposed work will be made freely available to enable studies by other researchers.

Blagoy Rangelov/Texas State University-San Marcos
Multi-wavelength Classification of X-ray Sources in Spiral Galaxies

The census of extragalactic X-ray sources plays a vital role in tackling a large number of astrophysical questions, ranging from binary stellar evolution to star formation history of galaxies. Yet, the majority of extragalactic X-ray sources lack proper classification. For example, even though ~3,000 X-ray sources are cataloged in the Andromeda (M31) and Triangulum (M33) galaxies, only a small fraction (less than <1/4) of those have reliable astrophysical classifications. The goal of this proposal is to study the X-ray source populations in seven nearby galaxies using a robust, systematic methodology. To achieve this goal, the we will utilize modern machine-learning (ML) methods to classify thousands of X-ray sources automatically and obtain classification confidences for all objects.

Archival data from the Hubble Space Telescope (HST) and the Chandra X-ray Observatory Chandra will be used to cross-correlate the positions of X-ray sources with those of their possible low-energy counterparts, and to extract the multi-wavelength (MW) parameters for thousands of X-ray sources. The MW parameters will be supplied to the ML algorithm to classify X-ray sources, utilizing a training dataset constructed from already classified X-ray sources. The feasibility of this novel approach has already been demonstrated as described in the proposal.

The primary scientific outcomes of this project will be 1) development of an automated classification ML tool for extragalactic purposes, 2) classification of thousands of previously unidentified extragalactic X-ray sources, and 3) comparison of the X-ray source populations of seven nearby galaxies (including M31 and M33). Given the vast amount of data accumulated in data archives, there is a clear demand for more robust automated classification tools in astronomy. This project will support the development of ML applications for astronomical data and training of astrophysicists in modern computer science methods. Therefore, the impact of this project goes beyond the immediate scope of this program.

James Reeves/Catholic University of America
A Definitive Test of Accretion Disk Wind Models in AGN

Black holes, once viewed as an exotic theoretical possibility, are now known to be present at the centers of most galaxies, including our own. Their masses correlate with galaxy bulge mass and even more tightly with the velocities of stars in the bulges of galaxies. This implies a co-evolution of Supermassive Black Holes (SMBHs) and their host galaxies. An important clue to the mecha- nism responsible for this co-evolution came with the discovery of ultra fast X-ray outflows, which are launched near the SMBHs powering luminous quasars. Indeed, these outflows are predicted when black holes accrete near to their maximum possible Eddington rate. Such outflows may have provided the necessary mechanical feedback that both controlled the formation of stellar bulges in galaxies and simultaneously regulated black hole growth. Thus as black holes grow and their Eddington rate increases, more material is swept outwards through the galaxies by the black hole wind, reaching a critical point whereby matter is expelled from the galaxy bulges and subsequently quenching new star formation in the process. Evidence for this is seen from large scale galaxy out- flows, which are observed in the form of molecular gas at distances up to a kilo-parsec from the black hole.

This proposal aims to study the powerful black hole winds which help to regulate the growth of black holes and of the galaxy around them. In particular we will study an extensively observed quasar called PDS 456, whereby matter accretes onto the SMBH at the Eddington limit and emits large amounts of high energy radiation. This radiation can push material outwards in the form of a fast wind, reaching speeds of up to a third of the speed of light. This study will then be extended to the extensive archival X-ray observations available for a sample of active galaxies, selected to have strong winds, obtained by the X-ray telescopes onboard XMM-Newton and NuSTAR. From developing and utilizing a dedicated suite of wind models, we will infer the properties of the outflows, the rate at which material is pushed outwards and its mechanical power. This will enable us to deduce how important the outflows are and, more generally, their role in regulating the growth of black holes and their effects on the galaxy that surrounds them. The models developed here will act as a pathfinder for predicting the wind signatures that may be observed with the next generation of X-ray calorimeter instrumentation.

This study supports NASA s strategic goal within the Astrophysics Research Program, to dis- cover how the universe works: specifically, to understanding accretion onto supermassive black holes and the feedback of material from the central engine to the host galaxy.

Armin Rest/Space Telescope Science Institute
SynDiff: Bayesian Difference Imaging for Optimal TESS Light Curves

The origins, physical mechanisms, and diversity of supernovae (SNe) and other explosive transients remain shrouded in mystery. The high-cadence lightcurves of TESS with unprecedented precision provides critical early time data, probing a window that is inaccessible to traditional ground-based SN surveys. However, these investigations of transient and variable sources look for small bumps and wiggles in the light curves - the subtle signatures of astrophysical processes. These signatures can be very similar to instrument and reduction artifacts, which also cause correlated noise in the light curves. These instrument and reduction artifacts are the fundamental limit on extracting science from TESS light curves, and must be corrected. We propose to resolve this problem with SynDiff: a novel approach that leverages deep ground-based observations at high spatial resolution to correct these artifacts and obtain optimal TESS light curves, together with an innovative web-based Python interface for scientific studies. With the exquisite TESS lightcurves in combination with the ground-based follow-up, we will be able to (1) determine the types of companions to progenitors of SNe Ia using features in the early lightcurves; (2) explore the explosion physics of SN using subtle features during their rise; (3) constrain the radius and properties of progenitor stars of core-collapse SNe using the signatures of shock break-out; and (4) constrain the light curves of exotic and rare events like superluminous SNe, tidal disruption events, kilonova, and fast transients. Not only is TESS ideal to search for worlds that may be inhabited by extraterrestrial life through its primary exoplanet detection mission, but TESS combined with SynDiff will also be a powerful tool for understanding the Universe.

Raghvendra Sahai/Jet Propulsion Laboratory
Searching for Bloated Stars: A Study of the Early Evolution of Massive Stars

SCIENCE: Understanding the formation and early evolution of high-mass (8 Msun) stars is of fundamental importance in astrophysics. A key difference between the formation of high- and low-mass stars is due to the effect of accretion. Swollen stars are high-mass young stellar objects in a crucial evolutionary phase of active accretion -- when the stellar surface is expanding because of the accretion of matter on to the star. These stars, unlike typical O-type stars on the main-sequence, have a relatively low effective temperature and low ionizing flux, and thus are highly deficient in radio emission. While this phase of massive star formation is firmly predicted by theory, observational data to test this theory is sorely lacking. For example, there were no clear examples of O-type stars identified in such a phase, until a recent discovery of IRAS19520+2759 [28]. This object is the best "bloated star" candidate so far, based on its luminosity (>10^5 Lsun), optical spectrum and very weak centimeter radio emission. Even though bloated stars must constitute a stage prior to the ultra-compact HII region phase, their relationship with other signposts of massive star formation, such as the presence of a hot molecular core or the association with powerful and collimated outflows, is not clear -- as a class bloated stars remain very poorly explored from the observational point of view. We therefore propose to make an extensive survey for candidate bloated star objects based on the study of IRAS19520, that can be used to test models of such stars and establish their relationship with other signposts of massive star formation (e.g., presence of a hot molecular core or association with powerful and collimated outflows).

OBJECTIVES AND PLANNED DELIVERABLES: We will use surveys of compact OH maser-line emission sources found in surveys of the Galactic plane (e.g., with the VLA or ATCA) that are (i) associated with far-infrared point-sources (in the Akari/WISE/IRAS/ MSX point-source catalogs, supplemented by Herschel or Spitzer imaging data when available), (ii) have a 25-to-12 micron flux ratio F25/F12>1.4 (in order to exclude most AGB stars). Additional luminous objects such as red supergiants and post-AGB objects will be eliminated from the resulting list using near-to-mid IR color-color criteria. We will then cross-correlate our candidate list with continuum radio surveys such as FIRST[9], RMS [40], CORNISH [30], and the ongoing VLASS[22], then then extract sources with very weak or undetectable radio emission (as a fraction of the bolometric flux) as bloated star candidates. Our preliminary search of a list of 300 OH maser-line sources finds 10 bloated star candidates, demonstrating that our proposed study will likely yield few x 100 bloated-star candidates.

We will use 2MASS, MSX, WISE, Akari, Spitzer, and Herschel archives to obtain the full near- to far-IR SEDs of our bloated-star candidates, and a 2-D dust radiative transfer code [31] to fit these with 2D dust models in order to constrain basic physical parameters such as the stellar mass and effective temperature, luminosity, envelope and disk mass. We will extract from published literature ancillary diagnostic data (or if absent, get new data) -- high-frequency radio (e.g., using VLA/ATCA), (sub)millimeter-wave and optical/near-IR spectroscopy, observations -- for a key subsample of the 25 best bloated star candidates (highest luminosities, lowest fractional radio fluxes) to search for the presence of outflows and central disks (key features of the bloated-star evolutionary phase) enabling us to estimate the outflow mass-ejection rates/ lifetimes and accretion rates and constrain theoretical models. Our final list of bloated stars, together with their physical properties, will provide an invaluable data set for understanding a transitory, but very important phase in the lives of massive stars, leading to an improved understanding of all aspects of our Universe.

Yue Shen/University of Illinois, Urbana-Champaign
TESS Exploration of Quiescent and Low-Activity Supermassive Black Holes

This project will exploit the precision photometry, high-cadence/multi-year baseline, and all-sky coverage of TESS in the search for tenuous nuclear supermassive black hole (SMBH) accretion in the local galaxy population compiled in bright galaxy catalogs (e.g., NGC galaxies). The unique combination of TESS capabilities makes it the ideal facility for identifying and characterizing low-level SMBH accretion in the local universe. Based on TESS-detected nuclear variability, the project will identify SMBHs at the centers of NGC galaxies, and measure their variability properties. TESS photometry provides competitive sensitivity to detect SMBHs accreting at extremely low accretion rates, and the nearly all-sky coverage will provide a complete census of NGC galaxies, which is impossible with any other facilities. The measured variability power spectrum density down to hourly timescales can be used to constrain accretion flow models and even the mass of the black hole. As a byproduct, this project will also study the TESS light curves of a nearly complete collection of optically bright AGN and highly variable blazars to unprecedented temporal coverage, sample size and light curve quality.

Sridharan Tirupati Kumara/Smithsonian Institution/Smithsonian Astrophysical Observatory
The Galactic Life Cycle: The Gum Nebula Cometary Globules and Molecular Clouds

The central processes in galaxy evolution are the life cycles of stars and the interstellar medium (ISM). ISM evolution is less well understood than stellar evolution . Throughout their lives, stars provide feedback into the ISM, causing its disintegration, destruction and dispersal, through outflows, radiation, stellar winds and supernovae. This feedback influences further star formation, sweeps up and collects the dispersed material and possibly triggers star-formation, to restart the process. The ISM evolves through multiple phases and structures in this process - the diffuse ionized and neutral phases and the dense neutral phase which includes the clumps and cores from which stars form. The details of these processes are poorly understood. This proposal addresses such feedback in the Gum Nebula, a setting where all the steps of the cycle are active, the destruction of the dense phase being the current dominant process. We propose to study the young stellar and dense ISM components and structures in the region, specifically - the system of Cometary Globules (CGs), and the associated IRAS Vela Shell (IVS), small molecular clouds, and Young Stellar Objects (YSOs). We will employ a variety of NASA and other archival data and tools.

The Gum Nebula is one of the largest regions of ionized hydrogen emission in the Milky Way. It hosts the nearest O-type star, zeta Puppis, with a runaway high velocity, possibly of past supernova origin. Additional massive stars - the gamma2 Velorum binary, the Vela OB2 association and the Vela supernova remnant are present in the region circumscribed by an annular system of small molecular clouds, many of which have a head-tail cometary morphology and bright rims facing the central region - the Cometary Globules (CGs). This system of CGs and the shell of infrared emission marking its inner periphery (the IVS), are expanding at ~ 12 km/s. Preliminary evidence exists for enhanced star-formation in the system. Thus, the region exhibits multiple indications of the effects of stellar feedback spanning a few million years

A key piece of information needed for a full understanding of the system - reliable distances to the molecular clouds - is missing, while the distances to the central energizing stellar sources are available. Recently developed high reliability methods to estimate distances to large molecular clouds have heralded a fundamentally new understanding of their distribution in the solar neighborhood. The proposed work would refine and adapt these techniques to smaller clouds in the first year. Combining the new distances thus obtained and the known velocities for ~ 100 small molecular clouds in the Gum Nebula region, their 4D distribution will be constructed. This enables, for the first time, the 3-D visualization of the system and the energizing stars, providing a basis for their spatial and dynamical interrelations to be studied. Models can then include detailed individual relative locations, as opposed to past treatments as a general system. Such modeling, and a study of the YSOs in the region, identified using the 2MASS and WISE catalogs, will be pursued in the second year. A subset the YSOs with parallax distances will be tied to individual clouds with the newly derived distances. Their locations, incidence rates , and expanding motions in a smaller subset with proper motion data, will be studied to reveal evidence for triggered star-formation.

These advances would provide the foundations for a comprehensive picture of the the Galactic lifecycle in the Gum Nebula to be developed. The techniques developed have broader applications to study the distribution of Bok globules and other small molecular clouds in the solar vicinity enabling a better picture of our neighborhood.These studies use existing NASA archival data (2MASS, Herschel, Planck and WISE) to create new knowledge, leveraged by the newly developed methods and additional data from other sources.

Panayiotis Tzanavaris/University of Maryland Baltimore County
Narrow and Broad Fe K Emission in Galactic Black Hole Spectra

*The Problem

Fluorescent Fe K line and associated scattered ("reflected") emission from neutral matter in Galactic Black Hole X-ray Binary (BHXRB) spectra can arise either in the accretion disk around the central black hole (observed as a "broad" line) and/or in more distant matter (observed as a "narrow" line). Relativistically broadened lines can be modeled to measure BH spin.

" Broad line modeling is ubiquitous in XRBs. In contrast, only recently and only a few systems have been modeled with narrow lines using the latest narrow-line physical modeling.

" Active Galactic Nuclei (AGN) work has shown that sometimes previously modeled broad lines can be modeled with narrow lines due to continuum modeling effects. This issue is to date virtually unexplored in BHXRBs.

" A census of how many existing BHXRB spectra and states can or cannot be modeled with narrow lines is lacking. Such an assessment is key for identifying the best candidates for spin measurements with present and future X-ray missions and data.

" Issues such as highly supersolar iron abundances, pile-up effects, whether the Innermost Stable Circular Orbit (ISCO) is truly accessible and discernible in X-ray spectra, and ranges of derived BH spin values, remain debatable for BHXRBs.

*This Proposal: Key Statement

We propose to assess the observational signature of Fe K± line and associated reflected continuum emission in 24 Galactic BHXRBs. Using the latest models, we will model broadband X-ray spectra as required with (1) narrow lines, deducing information on the level of obscuration and X-ray reprocessing in the surrounding medium far from the central BH, or (2) broad lines, aiming to constrain black hole spin in the strong gravity regime.

*Research Strategy

We will model 282 individual observations with NuSTAR broadband X-ray data, key for constraining high-energy reflection continua. We will measure observed and intrinsic X-ray luminosities, and, depending on narrow- or broad-line modeling, column densities in and out of the line-of-sight, covering factors, and spin. For a subset of observations we will also model contemporaneous observations with XMM-Newton and Chandra, as a cross check for Fe K line properties. All measurements will be associated to spectral states of different observations.

*Proposal Significance

This proposal fills a gap in BHXRB analysis to date. We propose the first systematic analysis of these data aiming to assess first and foremost how often it is possible to employ narrow-line modeling in BHXRBs, using the latest physically motivated models for narrow-line and associated reflection continua. Measuring BH spin has far-reaching implications, as it probes the strong gravity regime and the history of angular momentum distribution from which the BH formed, and how much this has impacted the surrounding medium; it is directly related to the production of relativistic jets. Thus, both cases where only narrow-line modeling is warranted and those where narrow-line modeling is not possible are extremely important for assessing the state of the field. In particular, cases where narrow line modeling is not successful will provide support to existing BHXRB spin measurements, and also be of the highest priority for future investigations. In contrast, cases where narrow-line modeling is possible will provide independent measurements of iron abundances, levels of obscuration in and out of the line of sight, and how these correlate with spectral states in the BHXRB environment.

*Proposal Relevance

We propose original research in the Research Area Collapsed Objects and Transient Phenomena, with eligible archival data from three NASA missions, thus addressing the goals of the D.2 Program Element in ROSES-2021.

George Younes/George Washington University
Energy-Dependent Pulse Profile Diagnostics from Magnetar Atmospheres

Neutron stars (NSs) represent ideal laboratories to study matter under extreme density, gravity, and magnetic field conditions. Magnetars constitute the most extreme manifestations of NSs, possessing the strongest dipole magnetic fields ever measured. The energy reservoir encapsulated in these large B-fields is the prime culprit for their bright persistent soft X-ray emission, with luminosities $L_[0.5-8 keV]~1.0e32-1.0e36 erg/sec often exceeding their rotational energy losses. This quasi-thermal light is believed to emanate from their hot stellar surface, with effective blackbody temperatures kT~0.5 keV. Persistent hard X-ray emission above 10 keV is also seen from around ten magnetars at similar luminosities. Magnetars are also the most variable sources of the class of NSs. They exhibit unique bright millisecond X-ray bursts that may occur in isolation or in a burst storm when hundreds are emitted in matter of minutes. This year, in a unique occurrence to date, a fast radio burst was observed in coincidence with an X-ray burst from one Milky Way magnetar. Concurrent with X-ray bursts, magnetars often enter an outburst epoch where their persistent soft and hard X-ray fluxes increase by factors of a few up to 1000 times the quiescent level. These outbursts are often accompanied by drastic changes in the spectral and temporal properties of the persistent signals. Such ephemeral conditions last anywhere from months to years, during which the overall source properties slowly relax back to their pre-outburst levels. The photospheric-like soft X-ray emission from magnetars most likely originates from an extended, highly-magnetized atmosphere, and is an optimal resource for probing the physics of these elusive sources.

Over the years, soft X-ray observations of magnetars' persistent and outburst emission below 10 keV have yielded a large library of high signal-to-noise data. The combination of such rich datasets with the theoretical advances in modeling radiative processes in high B-field regimes now permits a more complete understanding of these topical compact objects, unattainable otherwise. Hence, here we propose an archival study of XMM-Newton, Chandra, and NICER data from 17 magnetars, during persistent and outburst epochs, fitting their energy-resolved pulse-profiles with a state-of-the-art model for anisotropic soft X-ray emission from magnetar atmospheres. The pulse-phase-dependent spectroscopic model is obtained from a detailed Monte Carlo simulation of polarized X-ray transport in fully-ionized magnetar atmospheres. This code integrates over the entire surface, from pole to equator, addressing arbitrary local zenith angles for the field direction, thereby encapsulating a wide range of local radiation anisotropies. Accurately treating the variation of such anisotropies across the surface is essential to enabling energy-dependent pulse profiles to be used as powerful diagnostic tools for magnetars. The extensive magnetar sample for this project spans a range of field strengths and spin down ages, allowing us to determine variations in the surface emission locale as a function of these two parameters, as well as differences between outburst and persistent emission stages. The study will also allow us to constrain the value of the inclination angle between the magnetic and spin axes, and probe its change with age in the population; this objective has important implications for evolutionary trends of magnetars, including helping identify the significance of magnetic field decay with age. Finally, by incorporating general relativistic effects, we plan to determine how much the pulse-profiles depend on the mass-to-radius ratio for the star, potentially informing neutron star equations of state.

Astrophysics Research and Analysis
Abstracts of Selected Proposals
(NNH21ZDA001N-APRA)

Below are the abstracts of proposals selected for funding for the Astrophysics Research and Analysis program. Principal Investigator (PI) name, institution, and proposal title are also included. 155 proposals were received in response to this opportunity. On May 13, 2022, 48 proposals were selected for funding.

Steven Allen/Stanford University
X-Ray Speed-Reading: Integrated Readout Technology for Fast, Very Low-Noise, Megapixel X-Ray Imaging Detectors

The most recent biennial Physics of the Cosmos Program Annual Technology Report identifies "fast, low-noise, megapixel X-ray imaging arrays" as a top-priority technology development need for future PCOS strategic astrophysics missions. The Astro2020 Decadal Survey further recommended "an X-ray mission designed to complement the European Space Agency (ESA) Athena mission" as the joint top priority for a new line of Probe Class missions. Here, sensitive, high spatial resolution (<1″ half power diameter; HPD) X-ray imaging across a wide field of view likely represents the most natural complement to Athena, although high spectral resolution (R~7500) measurements utilizing dispersive grating spectroscopy offer another route. In either case, translated to the detector focal plane array, these features require thick (>100µm), fully depleted, small pixel size X-ray detectors with a combination of fast readout rate, low noise, high spatial resolution and large pixel number, which cannot be furnished by currently mature technologies.

Despite recent progress in X-ray detector technology, significant improvements are still needed. In particular, state-of-the-art X-ray CCDs cannot deliver the frame rates required for future strategic missions such as the Advanced X-ray Imaging Satellite (AXIS), a probe-class mission concept conforming to the recommendations of Astro2020. At Stanford, we have recently developed advanced integrated readout electronics - the MIT CCD readout chip (MCRC) - which, by virtue of fast amplifiers and minimal parasitics, can increase the per-output pixel readout rate of X-ray CCDs to 5M pix/sec, while maintaining the required excellent low noise performance. The MCRC design complements the CCD technology being developed by the MIT Kavli X-ray group and MIT Lincoln Laboratories, which is a clear candidate for the focal plane instrumentation of AXIS and other potential probe class X-ray missions. The first prototype of the MCRC readout electronics has been submitted for manufacture and will be tested over the coming year. Further improvements are necessary, however, to advance the TRL of the combined detector-plus-readout system to the point that it is suitable for a full flight instrument.

In our previous efforts, we have also studied a novel CCD output stage concept dubbed the Single electron Sensitive ReadOut (SiSeRO). We have recently demonstrated the first proof-of-principle operation of such a device, as well as the potential for sub-electron noise performance, and have integrated a SiSeRO-suitable drain readout input into the first prototype MCRC readout chip. Further development is now needed to support the development of detectors incorporating multiple SiSeRo devices and establish more firmly the potential of this new detector device class.

Specifically, in this proposal we aim to make the following improvements to the MCRC readout platform: 1) hybrid integration with external, multichannel, highly integrated, high performance ADCs; 2) integration of a CMOS high voltage (~12 V) clock driver for the output stage reset pulse, to minimize the time required for reset; 3) integration of detector bias generators into the ASIC; 4) improved housekeeping and monitoring functions through the addition of a simple ADC; 5) capturing temperature and detector bias conditions at the front end; 6) performance improvements to the MCRC drain readout scheme, including the extension of that capability to JFET-based CCDs.
The development is structured into two ASIC manufacturing submissions, where the first one will include test structures for features and performance improvements that will be integrated into the existing MCRC V1.0 padframe, so every one of its 8 channels would test a different component, for efficient testing in the existing test systems. The second submission would use the best candidates from the previous submission and produce a new MCRC V2.0 chip with enhanced capabilities.

Emily Barrentine/NASA Goddard Space Flight Center
μ-Spec Integrated Spectrometers for Far-Infrared Spectroscopy in Space

Astrophysical observations of the far-infrared (far-IR) red-shifted emission lines (CO, CI, CII, NII, OI, OIII) from the cold molecular gas of galaxies, and star forming regions, trace the environments and dynamics of star and structure formation over the history of our universe, from the period of reionization until recent times. To observe the full range of emission lines over this cosmic timeline, broadband cryogenic spectrographs in space are required, which feature unprecedented background-limited sensitivities, and which can meet the low size, weight and power (SWAP) requirements of a space mission.
μ-Spec is an integrated spectrometer, which realizes a far-IR grating-analog spectrometer on a 2D silicon chip, using superconducting microstrip transmission lines. In doing so, it reduces instrument size by an order of magnitude compared to a free-space grating. Several aspects of the μ-Spec design approach also provide the high performance that is needed for these future space spectrographs, including high efficiency, high spectral purity, high immunity to stray light and cross-talk, and via integrated superconducting kinetic inductance detectors (KIDs), near background-limited sensitivity. The μ-Spec technology has been demonstrated at a spectral resolution, $R=\lambda/\Delta\lambda = 64$ at 500-750 μm, and currently a $R=512$ μ-Spec design, operating from 555 - 714 μm, is in fabrication for the EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) balloon mission. In the proposed APRA-ROSES development program we will advance the μ-Spec spectrometer technology towards the shorter-wave performance that will be required for future space missions.

The objective for our proposed APRA program is to extend the spectral coverage of the spectrometer architecture down to optical wavelengths of 273 µm. Our current spectrometer design approach, implemented with niobium (Nb) microstrip lines, allows for designs operating down to 475 µm (the superconducting gap wavelength of Nb). In the first year of this program, we will refine niobium-titanium-nitride (NbTiN) films and patterning processes, and integrate these into the spectrometer fabrication process, which will allow us to implement the spectrometer design in NbTiN microstrip transmission lines, enabling operation down to optical wavelengths of 273 µm. We will redesign the current spectrometer component designs and the R=512 spectrometer grating design, to operate down to optical wavelengths of 273 µm. In the second and third years of our program we will fabricate and complete the full optical characterization of these NbTiN µ-Spec spectrometers.

The demonstration of a µ-Spec design operating to 273 µm will be a significant advancement for the science capability of the µ-Spec technology. It will enable future far-IR balloon and space science missions, to employ these low-SWAP integrated spectrometers, and provide new access to key emission lines. This includes for a balloon mission the ability to measure and map CII and NII emission lines over an expanded redshift range from z=4 to 1, to probe star formation as a function of redshift. For a future space mission, it will enable the ability to measure NII and OIII emission lines, and their ratio, to trace metallicity back to the period of reionization, while signifcantly reducing mission SWAP.

Steven Boggs/University Of California, San Diego
Radiation Damage Effects and Charge Trapping Correction Techniques in the COSI Germanium Detectors

The Compton Spectrometer and Imager (COSI) is a wide-field gamma-ray (0.2-5 MeV) imager and spectrometer utilizing germanium strip detectors. COSI had a successful super pressure balloon flight from New Zealand in 2016 (COSI-APRA), producing results on polarization of Gamma-Ray Bursts (GRBs), positron annihilation emission from the Galactic Center, measurement of the ^{26}Al flux from the Galactic Center, and detections of other celestial gamma-ray sources. COSI has recently been selected for a SMEX mission (COSI-SMEX) for launch in 2025.

We are now proposing a 3-year program focused on radiation damage effects and correction techniques in our cross-strip GeDs developed for the COSI program. This work will focus on detector modeling of charge trapping effects, characterization of charge trapping resulting from radiation damage, and finally development of a detailed algorithm for correcting the effect of radiation damage to optimize and maintain the excellent spectral performance of these detectors.

Objective 1: Significantly improve our physical modeling of charge transport in the COSI-APRA GeDs to include charge trapping effects. This work will allow us to better understand the effects of radiation damage on charge collection, and ultimately spectral performance.

Objective 2: Perform proton beam irradiations on the COSI-APRA detectors at fluences comparable to those expected in LEO to characterize the effects of radiation damage on both the hole and electron collection. These measurements will allow us to benchmark the detector simulations for moderate-to-severe radiation damage.

Objective 3: Use the detector simulations to develop detailed techniques for correcting the effects of charge trapping on the spectral response of the detectors. These techniques will be demonstrated on the radiation-damaged COSI-APRA detectors.

Objective 4: Annealing the COSI-APRA detectors to characterize the effectiveness in repairing the proton radiation damage.

Objective 5: Repeat the modeling and beam tests on a non-flight version of the COSI-SMEX detectors, enabling us to develop data analysis methods that incorporate the correction techniques for optimal spectral performance for the COSI-SMEX detector geometry.

Objective 6: Perform detailed background simulations of the COSI-SMEX detectors in their LEO environment to identify characteristics in the background data that we will be able to utilize to characterize the radiation damage effects and optimize the correction technique while on orbit.

The proposed work covers fundamental detector physics focused on radiation damage in germanium cross-strip detectors. The correction algorithms that we develop will be useful for optimizing the spectral performance for the COSI-SMEX detectors over the lifetime of the mission. This work is not part of the funded technology line for COSI-SMEX.

Gregory Brown/Lawrence Livermore National Laboratory/Dept of Energy
Multi-Channel, High-Resolution Measurements of X-ray Emission following Dielectronic Recombination in Support of High Energy X-ray Astrophysics

The scientific return from measurements using the Chandra and XMM-Newton high-resolution X-ray grating spectrometers, followed by a collection of significant results published following the analysis of the broad-band spectrum of the Perseus cluster measured by Hitomi’s quantum calorimeter have solidified the power of high-resolution X-ray spectroscopy for diagnosing hot astrophysical sources. The high spectral resolution, high signal-to-noise X-ray spectra provided by these instruments have also driven the terrestrial-based laboratory astrophysics community to produce higher accuracy results, and to develop and build improved capabilities of isolating and measuring X-ray emission from atomic processes taking place in hot astrophysical sources. The additional interplay between atomic theory and experiment, coupled with revolutionary advances in satellite-based diagnostics, has pushed these fields to achieve new levels of accuracy and completeness. With the launch of the Resolve calorimeter spectrometer on the X-ray Imaging and Spectroscopy Mission (XRISM), the next decade will surely see this synergy play out again. One of the processes that, in many cases, still requires more attention before it reaches the standard of accuracy demanded by Resolve,

is dielectronic recombination (DR). At its most basic, DR involves the resonant population of a doubly excited state, which can then relax via radiative or Auger decay. The resonant nature of the recombination process means DR can significantly affect a plasma's charge balance and is a highly sensitive temperature diagnostic. DR plays a significant role in the study of multi-temperature sources and non-equilibrium sources. While many studies of DR have been completed, those have generally only focussed on the primary, high-energy decay paths that produce K-shell satellites. The X-ray emission following decay of the satellite electron, for example, for high-n DR resonances, is not typically measured. Here we propose to measure all the X-ray radiative decay paths following DR of highly charged ions of astrophysically relevant elements. The measurements will be completed using the Lawrence Livermore National Laboratory's EBIT-I electron beam ion trap coupled with a high-resolution calorimeter spectrometer built at NASA/GSFC and high-resolution crystal and grating spectrometers. This well developed suite of instruments makes it possible to create DR resonant excited levels and measure all the significant X-ray radiative decay paths, as well as improve on the accuracy of previous DR studies. These data will help interpret existing observations of a variety of sources, and are particularly important for interpretation of new high-resolution observations by the calorimeter instruments to be flown on XRISM.
We have an equipment upgrade request.

Kerri Cahoy/Massachusetts Institute of Technology
High-order Wavefront Control for High-contrast Imaging on Space-rated Processors

Introduction: "Coronagraph contrast stability" is an identified Tier 1 gap for Exoplanet Exploration (ExEP) in NASA's 2019 Astrophysics Biennial Technology Report. This proposal investigates the performance of advanced wavefront control algorithms on space-rated processor equivalents (D.3 1.2.3). NASA class-A missions, such as the IR/O/UV telescope recommended by the Astro2020 decadal survey, will incorporate radiation-hardened processors and potentially Field-Programmable Gate Arrays (FPGAs). "Adaptive wavefront control algorithms" have not been tested on radiation-hardened components, although Astro2020 identified them as one of the "high-priority technologies to mature".

Onboard high-order wavefront sensing control (HOWFSC) was initially planned for the Roman Space Telescope (RST) Coronagraph Instrument. However, it was de-scoped due to time and budget constraints. The ground-in-the-loop approach used for RST is suboptimal for future missions that will likely require control updates on much shorter time scales. We propose to advance the Technology Readiness Level (TRL) of onboard HOWFSC to 3, before the mission hardware selection process that typically occurs several years before launch.

There are uncertainties in performance associated for HOWFSC on radiation-hardened processors and/or FPGAs. Radiation-hardened component performance significantly lags off-the-shelf components. Even the next generation of radiation-hardened processors might not be powerful enough to run state-of-the-art HOWFSC algorithms. FPGAs can be customized to improve performance, but their functionality heavily depends on implementation details. Porting HOWFSC to radiation-hardened processors and FPGAs may be further impaired by the rigid coding and testing practices required by a class-A mission (particularly when machine learning is involved in HOWFSC algorithms). The proposed work is crucial for assessing these risks long enough before the hardware selection process for the IR/O/UV large telescope so that technology gaps can be identified and mitigated.

Approach: We will implement several HOWFSC algorithms on equivalents to radiation-hardened processors and FPGAs. An optical model relevant for the IR/O/UV Large Strategic Mission will be run on a separate machine and receive control inputs from the space-rated processors. We will document the performance of space-rated components and any challenges in porting HOWFSC algorithms to them. We will make predictions for the development effort necessary to ensure that HOWFSC computation consumes less than 5% of mission time with an optical setup consistent with that expected for the IR/O/UV telescope.

Expected Results: 1) Improved time and resource consumption estimates for state-of-the-art HOWFSC algorithms on hardware relevant to the IR/O/UV Large Strategic Mission. 2) Identification of potential risks, for example, long execution times, limited radiation-hardened random-access memory, and incompatibility of algorithms with FPGAs. 3) Comparison of alternative HOWFSC approaches and processing architectures, assessing the impact on science yield, taking into account their performance as well as computation time.

Significance of Results: This work will lead to an improved understanding of the risks associated with wavefront control onboard a space coronagraph. We will assess how class-A mission processing and software requirements impact exoplanet yield. We will identify technology gaps that need to be addressed and matured to enable onboard HOWFSC for an IR/O/UV telescope mission.

Brandon Chalifoux/University Of Arizona
Aligning High-Resolution X-Ray Telescope Mirrors Using Adjustable-Height Spacers

Future high-resolution high-throughput X-ray telescopes will require nanometer-accurate alignment of up to tens of thousands of thin optical components. The assembly must be made in a reasonable amount of time and must survive launch. Current approaches, which either kinematically constrain or over-constrain the mirrors, have not been shown to meet all three requirements simultaneously. In contrast to current approaches where spacer dimensions are tuned before bonding, we propose to adjust mirror alignment after bonding by creating strain within glass spacers using an ultrashort pulsed (USP) laser. We propose a process comprising three steps: 1) fabricate spacers using USP laser-assisted chemical etching, 2) bond the spacers and mirrors together into mirror modules, and 3) adjust spacer dimensions using USP laser-generated strain. The mirror modules will use glass and silicon mirrors supplied by Goddard Space Flight Center. They will be tested using an interferometer to detect figure changes during alignment, and the relative alignment between mirrors will be measured using a Hartmann test operating in visible light. The mirror alignment performance will be tested in an X-ray beamline at Marshall Space Flight Center. This project will advance assembly and alignment technology to enable future high-resolution X-ray telescope missions.

Renata Cumbee/University of Maryland, College Park
Charge-exchange X-ray Emission Calculations for XRISM Spectral Modeling: Hydrogen- and Helium-Like Highly-Charged Ion Emission

While the X-ray spectroscopic mission Hitomi was short-lived, it did give us a tantalizing glimpse of a high-resolution universe for 3-7 keV photon energies. In particular, it demonstrated from observations of the Perseus cluster that high-lying H-like Lyman lines and the He-like triplet could be readily resolved allowing for detailed studies of local emission mechanisms. As X-ray astronomers anxiously await the launch of XRISM, and planning continues for Athena, it has been realized that much of the necessary atomic data for highly charged ions are of insufficient reliability or completely lacking. Here we propose to focus on charge exchange of highly charged ions colliding with atomic H and He using a variety of complementary theoretical approaches. We will consider collisions of incident bare and one-electron ions of Si, S, Ca, and Fe, predict their n,l,S-resolved cross sections, and simulate their X-ray emission spectrum. For this problem, we will bring to bear the following approaches: quantum and semiclassical molecular-orbital close-coupling, atomic-orbital close-coupling (AOCC), classical trajectory Monte Carlo, and multichannel Landau-Zener. Well-tested codes relevant to the problem are available within our team for all methods except for AOCC, which currently can only treat one-electron transitions within a Slater-type orbital basis for charged ions less than 11+. As a consequence, we also propose to evolve the AOCC code to treat two-electron systems in a Gaussian basis which will allow for studies of double electron capture. Relevant atomic structure, e.g. double-excited states, will be computed with Autostructure and the Flexible Atomic Code. Theoretical data will be benchmarked to available experimental Electron Beam Ion Trap experiments to verify reliability. These benchmarks will be combined with existing CX spectrum models to provide updated models of charge exchange emission, available to the community to immediately make use of these results in spectral analysis tools such as XSPEC.

Susana Deustua/National Institute Of Standards & Technology
CANDLE: Calibration using an Artificial star with NIST-traceable Distribution of Luminous Energy. An Engineering Demonstration Unit for Astrophysics

The Astro 2020 Decadal Survey (DS) lays out an ambitious suite of programs to address key 21st Century astrophysics in its three themes, noting that the data archives from these programs are also an invaluable resource in their own right. It also unequivocally states that calibration is essential: “the most complex and precise measurements would mean nothing without pipelines to calibrate and process the raw data...”

Because the science requirements to address some of the most fundamental questions of 21st Century Astrophysics e.g. the nature of dark energy? - are demanding, it is essential that calibration activities support the accurate measurements of the signals from astronomical sources. Dark energy investigations need absolute flux calibration with a precision that is 10 times better than achieved to date. Two general approaches to establishing fundamental flux calibrations are a) use stars whose spectral energy distributions are accurately determined and b) project a calibrated light source into the instrument.

A solution to calibration that supports the Decadal Survey's science objectives is a NIST-traceable calibrated light source that behaves as an artificial star and is accessible to our space based observatories like JWST, The Roman Space Telescope and future IR/VIS/UV telescopes or ground-based systems like Rubin Observatory and the planned extremely large telescopes. This points to a calibration payload that could piggy-back on a star shade or be deployed as an independent payload in a suitable orbit for space-based observatories, or placed in an Earth-orbiting satellite like ORCAS and accessible to ground-based telescopes.

We propose to design, build and test an SI-traceable, artificial star engineering demonstration unit (EDU) designed to fit in a volume less than 12U (1U=1000cc), where the technology readiness levels of its components can be raised to at least TRL 4. CANDLE (Calibration using an Artificial star with NIST-traceable Distribution of Luminous Energy) will provide calibrated light between 0.4 and 2.5 microns to match the wavelength range of planned surveys for dark energy studies with Roman and Rubin Observatories. Further, to enable cross-checks and mitigate systematic effects, CANDLE will consist of at least two complementary modes: single mode fiber lasers and reflected sunlight. A possible third mode is a programmable spectrum mode that mimics celestial source spectral energy distributions. The EDU will enable the calibration of the output beam profiles, characterization of the error budget, and establish performance parameters for the trade space between different orbits.

The project will provide a path for achieving the flux calibration precision and accuracy that will support not only the immediate objectives of the Decada Survey's key science but will also ensure that the vast data archives from NASA's astrophysics missions can maximize science well into the future.

Alex Drlica-Wagner/University Of Chicago
Development of Skipper CCDs for Robust Single-Photon Measurements in Future NASA Missions

The 2020 Decadal Survey on Astronomy and Astrophysics (Astro2020) identifies several compelling scientific opportunities that require ultra-low-noise detectors operating at ultraviolet (UV) to infrared (IR) wavelengths. Foremost among these is the search for signatures of life on planets outside the solar system through direct imaging and spectroscopy of Earth-like planets in the habitable zones of solar-type stars. This ambitious goal drives the highest ranked mission in Astro2020, a large

infrared/optical/ultraviolet (IR/O/UV) space telescope. However, no specific detector technology has been identified that can provide single-photon counting with high quantum efficiency (QE), large dynamic range, linear response, and tolerance to the harsh space radiation environment over the duration of plausible mission lifetimes.
We propose a comprehensive program to advance the technology readiness of silicon Skipper CCDs for ultra-low-noise measurements in space. Skipper CCDs use a floating-gate amplifier coupled with a low-capacitance sense node to achieve deeply sub-electron readout noise through multiple, non-destructive measurements of the charge in detector pixels. Our group has recently demonstrated that Skipper CCDs can achieve readout noise of < 0.05 e- rms/pix at optical and near-IR wavelengths (~400nm to ~1.1μm). Since this ultra-low-noise capability is achieved through a relatively minor modification to the CCD readout structure, Skipper CCDs are expected to retain the well-studied characteristics of thick, fully depleted, p-channel CCDs: high QE at visible and near-IR wavelengths, excellent linear response over a large dynamic range, extremely low dark current and clock-induced charge, and excellent radiation tolerance. However, to date, Skipper CCDs have not been demonstrated for astronomical applications.
In collaboration with Fermilab and NASA Goddard Space Flight Center, we propose to demonstrate the performance of Skipper CCDs for future space-based astrophysics missions. We will utilize recently fabricated Skipper CCD detectors and readout electronics to provide a cost-effective demonstration of this novel detector technology. Our project has the following specific goals: (1) Verify the radiation tolerance of Skipper CCDs through exposure to high particle rates at the Fermilab Irradiation Test Area. (2) Explore hardware, firmware, and software strategies to perform faster detector readout. (3) Study backgrounds that are intrinsic to silicon detectors operating in the single-photon regime to assess unforeseen risks to future space missions. (4) Demonstrate the performance of Skipper CCDs for astronomical observations using the 4.1-m SOAR Telescope.

This project will expose Skipper CCDs to the full complexity of astronomical observing scenarios including readout modes that would be used in space. This experimental demonstration of critical function and science performance will advance Skipper CCDs to technology readiness level (TRL) 5. Together with other work at Fermilab and NASA Goddard, this project is a stepping stone toward achieving TRL 6 prior to the start of mission formulation.

Manel Errando/Washington University
Polymer Actuators For High-Resolution X-ray Optics

The development of thin, segmented, grazing-incidence X-ray optics has the potential to enable future large-area X-ray missions with sub-arcsecond angular resolution. We propose to continue the development of a novel class of low-voltage thin-film actuators based on electroactive polymers to address the need for adjustable mirror figure control in future high-resolution X-ray missions. Electroactive polymers produce high strains at low voltages, being able to correct the deformations that submillimeter-thick mirror shells experience during mounting an assembly of the optical system. Fabrication of polymer thin films is a low-cost, scalable technology that can be easily translated to production by industrial partners. With fabrication temperatures below 140 degrees Celsius, electroactive polymer films can be deposited on mirror substrates inducing minimal thermal and coating stress.

This proposal is the successor of APRA-funded effort 80NSSC19K0372 with title "A novel actuator for adjustable X-ray optics based on plastic electroactive polymers". We propose to continue the development of this technology building on our current success in fabricating polymer actuators on flat silicon substrates. This proposal has four main aims:

i) Demonstrate absolute correction of figure errors induced by mounting stress on a 4in-diameter flat silicon substrate.
ii) Verify that functionality of actuators on flat substrates is stable and reproducible after thermal cycling tests.
iii) Develop and optimize a fabrication protocol to deploy polymer actuators on curved substrates.
iv) Characterize typical shell deformations and fabricate asymmetric electrode arrangements that correct the expected deformation modes with minimal complexity.
This effort leverages state-of-the-art device fabrication infrastructure at the Institute for Material Sciences and Engineering at Washington University in St Louis and optical metrology facilities at the University of Iowa, as well as the expertise of the proposal team and technical and engineering support at both institutions. The ultimate goal of our effort is to deliver a mission-enabling deformable mirror technology that removes risk from the mounting and assembly process of large-area high-resolution X-ray optics while minimizing the complexity of the actuator array system. This proposed research will advance polymer actuators for deformable X-ray optics to TRL 3.

Adam Fleisher/National Institute Of Standards & Technology
Comb Spectroscopy for the Critical Evaluation of Molecular Line Lists: The Astrophysical Molecule HCN

Hydrogen cyanide (HCN) has been observed in dense interstellar clouds, star-forming regions, comets, and exoplanetary atmospheres. When present with its isomer hydrogen isocyanide (HNC), their respective abundances act as indicators of local temperature and chemistry, and HNC is suggested as a tracer to identify proto-brown dwarfs. Furthermore, their relative abundances and isotopic composition are useful chemical clocks for star formation. Each of these areas of astrophysical exploration relies upon spectroscopic reference data to dependably model observations.

Here we will propose a critical experimental evaluation of a newly published ab initio line list for HCN. The results will give confidence to conclusions inferred from infrared and microwave observations. Proposed work will include the accurate measurement of transition intensities across the 1-5 μm wavelength region, including of hot bands and stable isotopic substitutions (e.g., $H^{13}CN$) using direct frequency comb spectroscopy. Uniquely, we propose to rigorously compare interferometric and dispersive comb spectroscopy methods (dual-comb spectroscopy and cross-dispersed comb spectroscopy) for their utility in providing accurate spectral reference data. Furthermore, we will propose new measurements of H_2 and He pressure-broadening coefficients to resolve a discrepancy in the literature. Preliminary measurements at NIST using dual-comb spectroscopy at a wavelength of 1.55 μm suggest good agreement between experiment and theory, but broadband laser-based measurements will be proposed to benchmark theory across a wide range of relevant conditions. Finally, we will explore spectroscopic measurements of HNC at high temperatures.

An experimentally validated line list will directly service several NASA missions, including SOFIA, TESS, and JWST. The results will establish observational consistency across the electromagnetic spectrum (e.g., between JWST and ALMA) by ensuring an accurate HCN/HNC potential energy surface and dipole moment surface – both of which are required to model radiative transfer in extreme astrophysical environments.

Brian Fleming/University Of Colorado, Boulder
Mapping Feedback From Massive Stars with the INFUSE and MOBIUS Integral Field Spectrographs

We propose a five year sounding rocket program to investigate star-formation and feedback processes using integral field ultraviolet (UV) spectroscopy.

The INtegral-Field Ultraviolet Spectroscopic Experiment (INFUSE) sounding rocket-borne instrument is a new class of far-UV (100 - 180 nm) integral-field spectrograph nearing completion under a predecessor APRA award. INFUSE will map the shocked interfaces between expanding supernovae and the ambient interstellar medium (ISM) at arcsecond scales to study how the energetic deaths of massive stars shape the evolution of the host galaxy. We propose to extend the objectives of the original award by launching INFUSE two additional times, first to study the Vela supernova remnant Shrapnel D as a compliment to the original science investigation of the Cygnus Loop, and then to study the influence of massive stars and feedback in the closest and best-studied “green pea” analog galaxy, NGC 2366. “Green pea” galaxies have extremely ionized interstellar mediums, and have been shown to be likely ionizing radiation emitters. INFUSE will map the UV continuum and highly ionized features (O VI, C IV) in the closest analog to JWST targets at the Epoch of Reionization. This program will comprehensively demonstrate the advanced INFUSE optical design, eLiF mirror coatings, and large-format cross-strip MCP detectors for use on future NASA orbital missions, including the large UV/O/IR mission recently endorsed by the 2020 Decadal Survey.

We will then build on the scientific and technical success of INFUSE by developing in parallel the Multi-Octave Bandpass Integral-field Ultraviolet Spectrograph (MOBIUS) instrument. MOBIUS leverages advances in optical design, grating fabrication, and near-UV (180-320 nm) detector technologies, all developed under previous and existing NASA APRA/SAT programs, to add a second spectral octave to the INFUSE architecture with no loss of far-UV efficiency. We propose to launch MOBIUS once under this award to obtain a 3-dimensional (x, y, λ) ultraviolet data cube of the low-redshift Seyfert galaxy NGC 1068. The INFUSE and MOBIUS instruments will serve as flight demonstration platforms for advanced mirror coatings, large-format cross strip anode microchannel plate (MCP) detectors, large-format sealed tube MCP detectors, etched silicon gratings, and advanced micro-optical fabrication techniques, helping raise the TRL of each of these NASA-ROSES sponsored technologies in preparation for the orbital missions of the 2020s and 2030s.

The INFUSE and MOBIUS development is accomplished in the framework of a robust educational program where the training of new undergraduate, graduate, and postdoctoral scholars is paramount. The principal investigator, lead postdoctoral scholar, and two additional co-investigators at the University of Colorado are all early career (less than 10 years from receipt of their PhD). Graduate students lead the day-to-day activities of the program, including mentorship of undergraduate students, fabrication, calibration and testing of the instrument, and science data analysis. This strong commitment of the INFUSE/MOBIUS team to education and training, as well as technology development and science, ensures that a new and diverse generation of instrument scientists, technologists, and principal investigators will be prepared to lead future NASA flight programs.

This program has a five year period of performance, beginning October 2022, however the budget for the first year is only for six months of activity. This is to ensure funding continuity for our April 2023 INFUSE launch, which falls at the end of the predecessor award period of performance, as well as to rephrase the project to the government fiscal year calendar.

Javier Garcia/California Institute of Technology
Relativistic Accretion Disk Reflection Models for the New Era of X-ray Astronomy

Since the first discovery of a black hole, Cygnus X-1, X-ray astronomy has offered a unique probe into the nature of compact objects. Vast amounts of high energy photons are emitted in the regions close to the black hole, producing distinct features in the X-ray spectra that carry crucial physical information of the compact object and the interaction with its surrounding. The detailed modeling of these observables, referred to asX-ray reflection spectroscopy, has been used for the last three decades with great success to study accreting compact objects, and most importantly, to determine the black hole spins. Our group has produced a framework of models called RELXILL, which is the most advanced tool for X-ray reflection including relativistic effects. Our software is open source and publicly available, and has become the state-of-the-art in treating X-ray reflection. Fitting our spectral models to observed X-ray data involves the use of statistical algorithms which scan the space of parameters and determine which set provides the best representation of the data. This process thus requires the evaluation of the model many thousand times as different sets of physical parameters are tested. Having now received ample feedback from the X-ray community, there is a clear requirement for the models to include additional physics, increasing their complexity. Likewise, the new generation of X-ray observatories will deliver data with far superior sensitivity and spectral resolution. There is thus a sorely need for the optimization and acceleration of our codes in order to handle large datasets in a timely fashion. Our plan is to advance the RELXILL framework following three strategic steps:

• Restructure, optimization, and acceleration of the RELXILL routines. This includes a reorganization of the codes, a new I/O paradigm, and modules for cloud computing.
• Documentation and training for users and developers. This includes the publication of a complete of user's and developer's guides, and the organization of training workshops and scientific conferences.
• Scientific improvements and extensions. This includes developing a new model flavor to treat returning radiation, and adding new modules for different coronal geometries.

This proposal seeks funding for the further development and enhancement of a suit of numerical models for the calculation of the X-ray reflected spectrum near black holes. Specifically, these models will be brought up to the standards of the new observational facilities, such as XRISM, Athena, and Lynx, which are expected to deliver vast amounts of data with unprecedented quality. Thus, our models need to become more physically accurate, faster to run, and more efficient in handling very large amounts of data. These future challenges can only be faced with the incorporation of advanced numerical techniques, radical enhancements for software efficiency and scalability, and shifts of the current paradigm of work flow, such as incursion into centralized software through the use of virtual machines, dock containers, and cloud computing.

Jonathan Grindlay/President and Fellows of Harvard College
Development of a Through Silicon Via (TSV)-enabled HREXI Detector Module (HDM)

We propose to continue our APRA program to optimize the development of a High Resolution Energetic X-ray Imager (HREXI) with a new generation of CdZnTe (CZT) detectors, each read out by NuSTAR ASICs (NuASICs) with Through Silicon Vias (TSVs) rather than fragile wire bonds (WBs). We have designed and built an optimal close-tiled Detector Crystal Array (DCA) board composed of 2 × 2 close-tiled 2 × 2 × 0.3cm CZTs. We have designed and are ready to fabricate a DCA controller board that will also serve as a prototype for the FPGA Mezzanine Board (FMB) that will provide full control, commanding and high speed readout of a 2 × 2 close-tiled array of DCAs. We have developed the first robust implementation of TSVs in NuASICs with a leading 3-D interconnects firm (Micross) that will allow minimal gap CZT tiling (lower backgrounds), lower noise (than WBs; as we have demonstrated), and flip-chip bonding for more robust and simplified integration and testing than with the 87 WB connections on each ASIC for data, commanding and power as flown on NuSTAR. The Micross TSV ASIC fabrication revealed high inter-TSV leakage which will be fixed by increased thickness of barrier layers on each TSV and/or possibly by fabrication of NuASICs on higher resistivity NuSTAR Si wafers.

We now propose to design and build the final module of a larger imaging CZT array: the FPGA Mezzanine Board (FMB) to command, control and read out 2 × 2 DCA boards. This hierarchical design (only 2 boards high) enables much larger total area and lower power imagers as required for our ultimate goal: a 1024 cm^2 CZT array consisting of 4 × 4 FMBs that interface to a single Detector Mother Board (DMB) for prompt burst image processing of a coded aperture imaging telescope with a 0.87 sr Field of View to provide prompt ~20″ source positions for GRBs and transients with the current NuASIC (600μm pixels) and ~10″ positions with the proposed 300 μm pixel ASIC being developed by our Caltech partners. This HREXI detector plane would provide the first broad band (3 - 300 keV) time-resolved spectra from stacked images.

We propose to build and test 1 fully populated FMB (with 2 × 2 DCAs) under this APRA proposal. The first two DCAs (Yr 2) will employ WB-NuASICs for initial tests as we eliminate Micross TSV leakage with thicker TSV barrier layers or higher resistivity Si wafers for fabrication of TSV-NuASICs. A second pair of DCAs follows (Yr3) equipped with TSV-NuASICs. Both types of DCAs will be fully tested (TVAC and shake tests) simultaneously while mounted together to an FMB to bring the electronics and TSV technology to TRL 6 within 3 years. This enables a full test of TSV vs. WB readouts to fully demonstrate TSV-NuASICs are as reliable as WB-NuASICs, which are flight-proven by NuSTAR. This would enable development of the compact wide-field (0.87 sr), broad band (3 - 300 keV) X-ray telescope on a SmallSat platform. This will do impressive new science (below) to achieve NASA and Astro2020 priority objectives in Time-domain Astrophysics (TDA) and would enable a future continuous full-sky, broad-band, time-domain hard/soft X-ray imaging survey with a Constellation (8 - 12 SmallSats) mission as the 4π X-ray Imaging Observatory (4πXIO). Such a mission, possible as an "Incremental Explorer" (launched 2-4 at a time) or a low-cost Probe mission, would address numerous key NASA and Astro 2020 objectives, from Exoplanet habitability from rates of X-ray flares from M dwarf host stars, to the study of the Early Universe revealed by high-*z* GRBs, physics and evolution of black holes (on all scales), and high resolution <10″ source positions (with the future 300μm pixel ASIC) and spectra for TDA and Multi-messenger Astrophysics for, particularly, LIGO/VIRGO/KAGRA GW events.

Christopher Groppi/Arizona State University
Metamaterial Filters and Low-Mass Focusing Optics for Millimeter, Sub-millimeter and Terahertz Applications

Large-aperture far-infrared filters are an essential component for virtually all far-infrared, submillimeter and millimeter wave instruments, from space observatories to ground based experiments. But currently, high performance large-aperture filters are available from only a single non-US source. In addition, extensive work over the past decades have reduced the mass, power and volume required for terahertz detectors and their associated backend electronics and cryogenics. Optical elements, however, remain largely untouched by this improvement. Particularly for smallsat applications, the mass and volume of antennas and optical elements provide significant restrictions. We propose to develop very thin, lightweight planar filters and focusing optics based on metamaterial structures to address this performance and availability gap. Quasioptical filters based on stacks of metal screen sandwiched between dielectric layers are commonly used in terahertz instruments. Our concept is based on a similar idea, but uses a different fabrication technology. The optics will be made using lithographic techniques at the Arizona State University Flexible Display Center, founded to fabricate liquid crystal displays on flexible dielectrics. The ASU FEDC process uses spin cast polyimide to generate high quality dielectric layers, with in situ metal layer deposition and etching. Circuits are built up one layer at a time, optically registered to the previous layer with each deposition, guaranteeing micron level alignment. Their fabrication technology is well matched to THz optics of this type with a minimum trace and space of 2-3µm on dielectrics down to 3µm thickness. Their technology can fabricate structures in 150mm diameter circular or 370 mm × 470 mm rectangular formats, allowing the fabrication of a wide variety of optics. This technology allows for the straightforward fabrication of filters, but also allows the fabrication of metamaterial focusing optics. A lens or mirror can be thought of as a phase transformer with a radially varying phase transformation. We divide the surface of the optic up into sub-wavelength cells and optimize the transmission line in that cell to provide the desired phase shift, while simultaneously optimizing transmission through the stack. Focusing optics can either be transmissive (a lens) or reflective (a mirror). In the transmissive case, the anti-reflective coating is “built in” to the design of the metamaterial optic. The FEDC process allows micron accuracy alignment of each layer, ensuring the features of each transmission line cell are aligned throughout the optic. A complete THz optic (with ~10 layers) is under 0.3mm thick. We propose to fabricate two generations of 150mm diameter planar filters, lenses and mirrors using the FEDC 150mm prototyping process on Kapton dielectric. In addition we will investigate the use of two novel low loss dielectrics in our designs: a proprietary low loss alumina film from Corning Inc., and cyclic olefin copolymer, a spin castable dielectric with loss comparable to polypropylene.

Sonia Hernandez/Continuum Space Systems, Inc.
Mission Classes and Technological Advances in Orbit Determination and Clock Precision to Enable Space-Based Imaging of Supermassive Black Holes

This Supporting Technology proposal targets algorithm and technology development to enable new missions designed to image event horizons of nearby supermassive black holes (SMBHs). SMBHs reside at the heart of most galaxies, and the evolution and growth of galaxies and SMBHs are thought to be closely linked. Further, SMBH event horizons and inner regions of their accretion disks offer unparalleled opportunities to probe fundamental physics and astrophysics. Over the past decade, the international Event Horizon Telescope (EHT) project has demonstrated the potential return from imaging M87*, the SMBH in the center of M87.

The Earth’s diameter constitutes a fundamental limit to the current EHT. At the frequencies used (~230 GHz), a network of telescopes employing very long baseline interferometry (VLBI) can only obtain an angular resolution sufficient to image M87* and SgrA*, the SMBH in the center of the Galaxy. Extending the EHT to include space-based antennas would expand the sample of SMBHs and enable testing (i) the extent to which the spins of SMBHs encode the history of their growth and interactions with their host galaxies (relevant to the Cosmic Origins Program); (ii) the extent to which General Relativity provides an adequate description of SMBHs; and (iii) the

magnetohydrodynamics by which relativistic jets can be launched from the immediate environs of SMBHs (relevant to the Physics of the Cosmos Program).
The RadioAstron mission has demonstrated the feasibility of space-based VLBI. However, a space-based EHT requires frequencies an order of magnitude higher. Technological developments enabling spaced-based VLBI are ongoing (e.g., deploying large dishes in space), however, there is a gap in technology needed to achieve precise orbit determination and timing. The four main investigation areas of this study are:

1. Mission Classes: Development of mission design algorithms to determine optimal orbit configuration to obtain images of potential SMBHs. The types of orbits can vary from Earth-centered, to Moon-centered, to orbits in the stable Lagrange regions in the Earth-Moon and Sun-Earth systems. Number of spacecraft can range from a single antenna to a constellation of multiple spacecraft. We will create mission design tools using JPL's Mission-analysis Operations & Navigation Toolkit Environment (MONTE) software to develop broad types of orbits that can quickly assess uv-coverage distribution based on specific input parameters, such as number of spacecraft and type of orbit.

2. Orbit Determination: In low-Earth orbit, the state-of-the-art for orbit determination (OD) is at centimeter-level precision. However, OD accuracy in deep space is no better than several meters. Realizing an effective space VLBI mission requires characterizing the possible OD uncertainties in the context of the algorithms used. A recent meeting at the Keck Institute for Space Studies identified orbits at geosynchronous and above as most promising for substantial improvements in event horizon imaging; there is a compelling need to develop a thorough parametric understanding of the OD requirements necessary to support future spaced-based EHT science. Leveraging MONTE, we will develop the algorithms to assess OD requirements for different mission classes

3. Clock Precision: Each spacecraft requires a clock for precise time-keeping in order to align wavefronts in phase. Hydrogen masers, used on the ground and for RadioAstron, are too massive and may not have sufficient performance for space-based VLBI. We will develop the requirements on clock phase coherence time and compare this to the performance obtained by existing space clocks, as well as new or emerging clock technologies that might be used in a space EHT mission.

4. Simulated Images: Using orbit simulations and incorporating uncertainties, we will produce simulated EHT images to demonstrate the imaging capabilities and science goals that can be achieved with each mission class.

Seyedeh Sona Hosseini/Jet Propulsion Laboratory
Astrophysics Miniature UV Spatial Spectrometer (AMUSS)

Mapping the distribution of diagnostic UV (FUV) emission lines (from atomic, ionic, and molecular species) is critical to understanding the structure and evolution of galaxies, including our own. Many astrophysical objects that produce these FUV emission lines, such as the interstellar medium of our Galaxy and the circumgalactic medium around nearby galaxies, are angularly-extended, diffuse and very faint. It has often been challenging to observe such targets because traditional slit-spectrographs lack the sensitivity to disperse the low photon flux into a large number of spectral resolution elements (*R*~100,000) and cannot detect the faint FUV emission spectra from these important astrophysical targets without the need to large aperture telescopes.

The proposed technology maturation for the Astrophysics Miniaturized UV Spatial Spectrometer (AMUSS) is based on an interferometric technology called Spatial Heterodyne Spectrometer (SHS) that enables AMUSS to obtain ultra-high sensitivity data from angularly-extended, faint diffuse targets such as the interstellar medium of our Galaxy and the circumgalactic medium around nearby galaxies over a targeted narrow wavelength range. AMUSS is configurable for various spectral lines with a very narrow bandpass anywhere from the FUV to the visible region. For the purpose of this project, AMUSS is configured to target the C IV doublet at 1541 Å and 1556 Å at high spectral resolution (*R*> 100,000). For that reason, this concept applies to more than one mission and is capable of meeting multiple science objectives.

This APRA project matures our existing TRL 3 SHS module to TRL 4.
The low-mass, compact configuration of AMUSS enables sensitive, high-resolution spectroscopy from SmallSat missions. SmallSats and rideshare opportunities are increasingly playing a more significant role in NASA and provide the benefits of low cost, low risk, but are challenging because of their requirement for a low payload mass. Current investigations to study faint, diffuse astrophysics targets are accomplished by large instruments with considerable demands on spacecraft resources (mass, power, volume). AMUSS is based on a different technique design that reduces the mass, size, and power requirements by orders of magnitude while increasing the spectral resolution and sensitivity to address targetted fundamental science objectives in astrophysics as well as solar space weather research.

AMUSS's specifications and objectives fall under the High-performance spectral dispersion component/device priority table in the Cosmic Origins annual technology report. AMUSS will provide a unique high sensitive spectroscopic UV platform in space for studying line emission from diffuse and major astrophysical constituents of our Universe. These studies address the fundamental Cosmic Origins Program question, "How did the Universe originate and evolve to produce the galaxies, stars, and planets we see today?" which is directly relevant to NASA's overarching Astrophysics goal of addressing: "How did we get here?"

Carolyn Kierans/NASA Goddard Space Flight Center
Balloon Flight for the Compton Pair Telescope

A future medium-energy gamma-ray (MeV) mission will address many questions posed in the recent Astro2020 Decadal survey in both the New Messengers and New Physics and the Cosmic Ecosystems themes. In particular, the MeV range provides uniquely information for electromagnetic counterparts to multimessenger events.

Here we propose an augmentation to compensate for unavoidable COVID-delays for the Compton Pair (ComPair) telescope project. The ComPair prototype instrument was first funded through a 2015 APRA (PI: McEnery) to raise the Technology Readiness Level (TRL) of key components required for a future MeV Medium explore-scale mission. Over the past five years, the ComPair team has designed and built a prototype instrument that consists of 4 detector subsystems: a double-sided silicon strip detector (DSSD) tracker, a novel high-resolution Frisch-grid cadmium zinc telluride (CZT) calorimeter, and a high-energy hodoscopic cesium iodide (CsI) calorimeter, all of which are surrounded by a plastic scintillator anti-coincidence detector. These subsystems together detect and characterize photons via Compton scattering and pair production, and are a proof-of-concept for a MeV space telescope with the same architecture.

The goals of the initial ComPair proposal were 1) to develop the necessary technologies to enable a future medium energy gamma-ray mission, and 2) to design, build, and test a prototype instrument in a beam test and balloon flight. By the end of FY22, the ComPair team will have achieved all of the original APRA goals, with the exception of the balloon flight; significant delays due to the COVID-19 pandemic have pushed the ComPair launch date from Fall 2021 to Fall 2023. This proposal is an augmentation for an additional 17 months to provide the path to the ComPair balloon flight and a completion of the originally proposed goals.

The GSFC-led team has a strong heritage in designing and building gamma-ray telescopes; however, maintaining that capability is an important aspect of this program. In additional to TRL advancement, this proposed research is provides valuable experience to early career members of the GSFC and NRL groups. The ComPair program provides necessary hands-on training to the early-career ComPair management, postdocs, graduate students, and early-career engineers. This proposal will enable the completion of the ComPair balloon flight, providing a critical career milestone for the junior scientists and engineers working on the ComPair Project.

Sungho Kim/Jet Propulsion Laboratory
CMOS Integrated Comb Generator for Large Format MKID Arrays

Microwave kinetic inductance detectors (MKIDs) are sensitive superconducting devices that can be easily multiplexed for large-array telescopes, successfully demonstrated by MAKO, a 432-pixel photometer, and the Multiwavelength Submillimeter kinetic Inductance Camera (MUSIC), a 576-pixel photometer. Because of the high atmospheric absorption of submillimeter waves, space telescopes have an insurmountable advantage over ground-based ones. Currently, the biggest bottlenecks in developing large-array MKID space telescopes come from the absence of power efficient and radiation-tolerant readout electronics.

The readout electronics for a typical MKID system are composed of three main functional blocks: a comb generator, an RF block for the frequency conversion and signal conditioning, and a digital spectrometer backend. Current state-of-the-art electronics for ground-based instruments are built with FPGAs and discrete RF components, the combination consuming large amounts of power, greater than 160 W for 8,000 pixels. A recently developed commercial alternative, the Xilinx RF System-on-a-Chip (RFSoC), in which analog-to-digital converters (ADC) and digital-to-analog converters (DAC) are embedded directly with the FPGA, has recently been adopted for MKID readout. The RFSoC improves on the power efficiency of earlier MKID readouts, supporting 8,000 pixels with 56 W of power, but still relies on external RF frequency conversion and signal conditioning circuitry. In addition, for a space-borne submillimeter imaging instrument, a hardware solution needs to be both power-efficient and radiation tolerant. Unfortunately, even though the RFSoC has demonstrated great promise for ground-based experiments, there is no path for dealing with its radiation softness. In conclusion, no viable solution is available for low-power, radiation tolerant readout electronics necessary for large format MKID arrays.

Application specific integrated circuits (ASICs) are an attractive solution for realization of a power efficient, radiation tolerant MKID readout. An ASIC solution supporting all functional elements, including the RF signal conversion and conditioning using an advanced CMOS process (28 nm) for 8,000 pixels would require about 5 W. Of the three main components, an ASIC spectrometer has already been demonstrated in 65 nm technology consuming sub-W of power. The design of the RF components is straightforward and pose little risk to the overarching goal of producing a single chip MKID readout ASIC. The comb generator, however, is unique to newly emerging technologies such as MKID arrays and Quantum Computers, and as such has not been demonstrated. In this work we propose to design and implement a comb generator for 8,000 pixels with a multiplexing technique. The chip produced by the proposed effort, supporting the baseband comb generation, will consume 0.5 W for 8,000 pixels and will be implemented in 28 nm. Furthermore, directly targeting a space-borne instrument, the ASIC will be developed incorporating radiation hardening by design (RHBD) techniques.

The ASIC-based electronics proposed in this effort will pave the way for a low-power, radiation tolerant, single chip solution for the large format MKID array. It will offer a power reduction of an order of magnitude (x12 including the RF block), as well as size and mass benefits of several orders of magnitude (bulky system to a single chip) from integrating several previously discrete functions into a single ASIC. Its radiation tolerant design will enable the commissioning of MKID arrays comprised of thousands of pixels for space-borne far-infrared imaging instruments.

Fabian Kislat/University of New Hampshire, Durham
Transition Edge Sensor Arrays For High-Energy X-Ray And Gamma-Ray Astronomy

Hard X-ray imaging spectroscopy with NuSTAR has provided new insights into a broad range of astrophysical phenomena. Several technological breakthroughs enable an extremely powerful follow-up mission. Members of our team fabricated a 256-pixel transition edge sensor (TES) microcalorimeter array with microwave multiplexed superconducting quantum interference device (SQUID) readout. The excellent energy resolution (55 eV Full Width Half Maximum, FWHM) all the way up to 100 keV is about

20 times better than the CZT detectors used on NuSTAR. Used on a balloon-borne or space-based observatory these detectors enable exciting new gamma-ray spectroscopy measurements.

We propose a 3-year detector development program with the goal of developing focal plane instrumentation for a next-generation hard X-ray telescope up to 100 keV. Building on recent progress in the development of TES gamma-ray detectors and readout systems, we will: develop a detector array with thicker absorbing structures to enhance quantum efficiency; optimize the TES design in order to improve energy resolution; and develop a method to attach absorbers to the TES using metal bonding in order to improve the response time of the detectors. We will also carry out proof-of-concept experiments as a first step to developing an entirely new method of TES absorber fabrication using electroforming of the absorbing structures. These developments will be accompanied by a rigorous test program to evaluate energy resolution and spatial uniformity of the devices, linearity of the energy response, and signal timing.

We envision to follow up on the work presented here with a proposal for a full-size balloon-borne hard X-ray prototype telescope that will not only be used to flight-test the detectors developed here, but also deliver exciting new scientific results from observations of the ^{44}Ti lines in Cassiopeia A.

Henric Krawczynski/Washington University
Development of a 511 keV Gamma-Ray Camera

The origin of the 511 keV gamma-ray emission from the galactic center region is still uncertain. The emission may be produced by the annihilation of positrons, resulting from the decay of dark matter particles, with electrons from the interstellar medium, and may thus be connected to one of the most important puzzles of current astrophysics research: the nature of dark matter. Perhaps more likely, the positrons are created by astrophysical sources, involving exclusively standard model physics. We propose here the development of the technologies for a 511 keV gamma-ray camera called 511-CAM (511 keV gamma-ray CAmera using Micro-calorimeters) that can be used in the focal plane of a pointed gamma-ray telescope. The 511-CAM has a projected 511 keV energy resolution of 270 eV Full Width Half Maximum or better, and improves by a factor of at least 16 on the performance of state-of-the-art Ge-based Compton telescopes, and by a factor of 3 or higher on the best possible Fano-factor-limited performance of a single-crystal high-purity Ge detector. With the unprecedented energy resolution and sub-arcmin angular resolutions of Laue lens or channeling optics, such an experiment could make substantial contributions to identifying the origin of the 511 keV emission by measuring the line-of-sight velocities of the emitting sources, and by identifying and characterizing point sources. The proposed two-year research program includes extending the upper energy reach of the SLEDGEHAMMER microcalorimeter gamma-ray detectors from 210 keV to beyond 511 keV by fabricating and testing SLEDGEHAMMER detectors with thick Sn, Ta, Bi, and BiSn absorbers in the first year of the program. In the second year of the program, we will build and test a dual-layer prototype detector of the 511-CAM. A full-sized 511-CAM (to be built in a follow-up research program) will be made of a stack of

~8 layers of SLEDGEHAMMER detectors that absorbs >90% of the incident 511 keV gamma-rays. The experimental program will be complemented by detailed detector simulations. The comparisons of the experimental and simulated data will allow us to fine tune the detector simulations. The fine-tuned simulations will in turn be used to optimize the design of the full 511-CAM. The R&D will allow us to design and propose 511-CAM-based balloon-borne and satellite-borne missions to future NASA announcements of opportunity.

John Krizmanic/NASA Goddard Space Flight Center
Continued Development of nuSpaceSim: Modeling of Extensive Air Shower Signals from Cosmic Neutrinos for Space-based Experiments

We propose to continue the development and increase the fidelity of the nuSpaceSim simulation package, which has been developed (currently funded under NASA proposal 17-APRA17-0066: "Modeling of the Air Shower Signals from Cosmic Neutrinos for Space-based Experiments") as a comprehensive end-to-end simulation software bundle to model the optical and radio signals from extensive air showers (EAS) induced by cosmic neutrino interactions. The initial results from nuSpaceSim have demonstrated that sub-orbital and space-based measurements of these distinctive signals of upward-moving EAS sourced from neutrino interactions within the Earth have unique sensitivity to the astrophysical and the cosmogenic neutrino flux. For the optical Cherenkov signals, the neutrino sensitivity starts at the PeV energy scale for a square meter area telescope and has a strong component from muon-induced EAS from muon neutrino interactions in the Earth. The nuSpaceSim software package is based on a vectorized, multi-thread/core Python framework using a sampled library approach to efficiently generate simulated neutrino-induced EAS signals at a specific location where the detector response module records the events. nuSpaceSim is being developed with the anticipation that it will be used by the community as a tool to determine an instrument's neutrino sensitivity. Thus, current and future NASA experimental efforts in space-based cosmic neutrino detection, including ANITA, PUEO, EUSO-SPB2, and the POEMMA Astrophysics Probe, will or have benefited from the results of nuSpaceSim development. The initial nuSpaceSim work effort has been focused on the modeling the signals generated by tau-neutrino interactions within the Earth that lead to upward-moving EAS created by the tau-lepton decay and the proposed development will include EAS from VHE and UHE muons. The nuPyProp software package that models the tau-lepton (from tau neutrinos) and muon (from muon neutrinos) Earth-emergence probability distributions was publicly released in the summer of 2021 and is available on the HEASARC (https://heasarc.gsfc.nasa.gov/docs/nuSpaceSim/). A publicly beta-version of nuSpaceSim has been available via github since October 2021. nuSpaceSim is based established software standards are being used, including XML format for simulation and detector parameter input, HDF5 format for library and data files, Pip/Conda for Python dependency management, and the use of docker containers for software distribution to minimize cross-platform dependency issues. The baseline nuSpaceSim modules include event and celestial geometry definition, sampling the tau-lepton Earth-emergence probability distributions, generation of the tau-lepton decay products, sampling of EAS profile libraries, generation of the optical Cherenkov and radio EAS signals, propagation of the signals thru the atmosphere, modeling the detector response, and generation of event-by-event analysis variables. nuSpaceSim includes a number of utility packages, such as interpolation routines, and a beta-version using a HEASARC interface for using the MERRA-2 database to generate cloud distribution libraries has been implemented. The proposed nuSpaceSim development will increase the fidelity of the physics modeling, including the modeling of transient neutrino sources, leptons from the hadronic products of deep-inelastic neutrino scattering, instrument modeling, including photo-detector variability, and modeling of atmospheric attenuation/scattering of the EAS optical Cherenkov signals using a data-driven approach (such as ozone and aerosols from MERRA-2). The proposed development will also increase the fidelity of tau-lepton induced EAS while also including a stochastic VHE muon-induced EAS model, and the modeling of the optical Cherenkov and radio signals from the copious muons generated in the EAS from hadron decays.

Aigen Li/University Of Missouri, Columbia
JWST and PAHs in Protoplanetary Disks: Placing Constraints on PAH Properties

The 3.3, 6.2, 7.7, 8.6 and 11.3 micron emission features of polycyclic aromatic hydrocarbon (PAH) molecules have been detected in protoplanetary disks (PPDs) around Herbig Ae/Be stars and T Tauri stars. PAHs are present at the disk surfaces and even in the cavity or gaps from which large grains are missing. They play an important role in the thermal budget and chemistry of the gas in PPDs, by providing photoelectrons for heating the gas and large surface areas for chemical reactions. Stochastically heated by a single UV/visible photon, PAH emission is spatially more extended than large grains and therefore, PAH emission can resolve PPDs more easily and is a powerful tracer of the disk structure.

Due to their limited sensitivities, it was not possible for ISO or Spitzer to spatially resolve PAH emission in PPDs. Indeed, so far almost all spatially-resolved observations of PAH emission were made by ground-based telescopes. Also, the low detection rate of PAH emission in T Tauri disks is probably related to their faintness. With its unprecedented sensitivity, JWST is expected to detect and spatially resolve PAH emission at all the major bands in a much larger sample of Herbig Ae/Be and T Tauri disks. This will enable far more detailed band analysis than previously possible.

To facilitate the analysis, interpretation and modeling of the incoming JWST data (as well as existing data from ISO, Spitzer and ground-based observations) of PAH emission in PPDs, we propose to develop a PAH spectral and band-ratio (i.e., $I_{6.2}/I_{7.7}$, $I_{11.3}/I_{7.7}$) library. This library will serve the JWST community as a quantitative diagnostic tool for determining the PAH size and ionization fraction from the observed band ratios of the PAH emission features at 6.2, 7.7 and 11.3 micron.

We will calculate the IR emission spectra of both neutral and ionized PAHs of various sizes, located at various radial distances (from the central star) in PPDs around stars of a wide range of spectral types and of several representative luminosities. We will create a library of PAH model emission spectra and model band ratios and generate a series of diagrams of $I_{6.2}/I_{7.7}$vs. $I_{11.3}/I_{7.7}$. To demonstrate the effectiveness of this diagnostic tool}, we will apply the model $I_{6.2}/I_{7.7}$ vs. $I_{11.3}/I_{7.7}$ diagrams to infer the PAH size and ionization fractions of a number of PPDs of representative properties (for all of which PAH emission has been detected and spatially resolved by ground-based observations).

The model spectra and the band-ratio diagrams will be made publicly available and will serve as a valuable "library" for JWST whose high spatial resolution and high sensitivity will revolutionize PPD and PAH studies. Our proposed work lies precisely within APRA's Laboratory Astrophysics mission to produce "computational efforts to explore the spectroscopic properties of atoms and molecules and particulate matter" and "support the determination of fundamental atomic, molecular, nuclear and solid-state parameters that are essential for analyzing and interpreting data from NASA Astrophysics missions" (e.g., JWST, Spitzer).

Maxim Markevitch/NASA Goddard Space Flight Center
Normal-Incidence Mirror For Narrow-Band X-Ray Imaging Of Circumgalactic Medium

We propose to develop a novel normal-incidence X-ray mirror for E=0.5 keV using multilayer coating. This is the energy of the elusive Oxygen VII line emitted by warm circumgalactic gas halos – one of the major "discovery areas" identified by the 2020 Astrophysics Decadal Survey. Our mirror would reflect in a narrow (few-eV) energy interval and, for example, help separate the faint redshifted OVII line from the much brighter, but not redshifted, OVII line originating in the Milky Way. For incidence angles close to 90 deg (similar to optical telescopes), such a mirror can have few-arcsecond angular resolution over a significant field of view, potentially providing sharp, narrow-band imaging at low cost. The coating would consist of many layers of contrasting-density materials that must be very sharp to achieve a useful Bragg reflectivity. While normal-incidence multilayer mirrors have been built for far UV and very low-energy X-rays (E=0.1 keV), it has not been possible to go to higher energies, because the layer period becomes very small – 1.1nm for our energies of interest, the size of a few atoms. We will employ Atomic Layer Deposition (ALD) – a technique that is currently experiencing fast development in many industries – to deposit layers of the requisite sharpness. ALD is a self-limiting chemical reaction that results in depositing strictly one molecular layer of the material on the surface, free of the random-shot error of the traditional techniques that becomes intolerable for the small layer thickness that we need. Our preliminary trials have been encouraging, but more material pairs and ALD variants must be tried. We propose to pursue several ALD methods in-house and use commercial expertise where efficient. The team includes scientists from Goddard and University of Texas.

Christopher Martin/California Institute of Technology
FIREBALL-2: The Next Generation of UV Science, Technology, and Leadership

The Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall-2, FB-2) is designed to discover and map faint emission from the cool-warm circumgalactic medium of low redshift galaxies ($0.3<z<1.0$). FIREBall-2 will detect emission from hydrogen Lyα in the CGMs of nearby galaxies and quasars, providing the first census of the density and kinematics of this material for low *z* galaxies and opening a new field of CGM science. The Astro2020 Decadal Survey Panel on Galaxies specifically recommended "Mapping the Circumgalactic Medium and Intergalactic Medium in Emission" as a key Discovery Area in understanding Cosmic Ecosystems over the next decade (Table 2-2, Astro2020 Decadal Report). FB-2 is the only ultraviolet (UV) telescope currently in operation that can tackle this ambitious goal.

FB-2 also tests and validates key technologies and science strategies for a future space mission to accomplish its primary science mission: to map emission from CGM and IGM baryons. FIREBall-2 successfully launched in 2018 from Ft. Sumner, New Mexico. The team accomplished extraordinary feats during both campaigns to perform the complex maneuvers and focusing sequences required for FB-2, and the instrument performance worked better than required – with <0.5″ rms/sec/axis with 3-axis guidance (RA, DEC, rotation). FIREBall-2 demonstrated the first delta-doped EMCCD UV detector and UV multi-object spectrograph, paving the way for both technologies to be used in future space applications. Future flights of FB-2 will fly key technologies that further the Astro2020 Decadal recommendation for Technology Maturation ahead of NASA's Great UVOIR Observatory post-Roman. FB-2 will fly brand-new technology advances that further improve UV CCDs for future Great Observatories, including customizable anti-reflection (AR) coatings, visible light-blocking filters for UV instruments, and the future of EMCCD technology – the Teledyne-e2v 311 silicon wafer model. In addition, UV coatings and filters play an important role in the Great Observatories Technology Maturation program, for which FB-2 plans to develop and fly customized narrow-band UV filters that can be incorporated into future UV imagers or spectrographs. FB-2 also provides key technology validation for NASA's next Great Observatory, the Roman Space Telescope, by flying the Roman-CGI EMCCD controller, Nuvu v3, for the first time.

Due to a mission-ending balloon failure which started at the beginning of our science window, FB-2 was unable to observe any CGM target fields above the minimum altitude for its UV transmission window at 200 nm in 2018. Because of a nighttime termination of the mission, the instrument also experienced higher-than-expected winds upon landing, which dragged and damaged key components of FB-2. While repairs to all aspects of the instrument have been very successful, the COVID-19 pandemic severely hampered our progress to re-vamp the program post-build. While we are on-track to re-fly FB-2 in the fall of 2022, the recommendations by the Astro2020 decadal survey make it clear that additional flights of FB-2 are warranted, both from scientific and technological aspects. We will request two additional flights of FB-2 past its upcoming 2022 campaign, one in Ft Sumner, NM (2024) and another in Alice Springs, Australia (2026).

FB-2's future flights will continue to provide important training for the next generation of space astrophysicists working in UV and other wavelength instrumentation. FB-2 provides a unique and highly efficient training ground for early career scientists to lead mission-critical systems and oversee the full build-up of a space-based mission, on a scale similar to that of a full-fledged space satellite. Many of FB-2's previous Project Scientists, roles in which postdocs take on, go on to pursue their own space astrophysics programs.

Christopher Materese/NASA Goddard Space Flight Center
Quantifying the Radiolytic Stability of Aromatic Nitrogen Heterocycles

Aromatic hydrocarbons are believed to be abundant in the interstellar medium and specific compounds as small as benzene have been identified in space. Despite ongoing efforts, heterocycles where nitrogen atoms replace C–H groups in the aromatic ring (called nitrogen heterocycles or N-heterocycles) have not been definitively identified. One possible explanation for their non-detection is a difference in radiolytic stability relative to their aromatic hydrocarbon counterparts. To date, no laboratory experiments have systematically characterized the radiolytic stability of small (monocyclic) aromatic hydrocarbons with (0 to 3) nitrogen atoms. Importantly, the number of nitrogen atoms, their positions in the aromatic ring, and the presence of other abundant extraterrestrial ices likely all influence the radiolytic stability of these molecules and consequently their survival in space.

We propose to quantify the radiolytic stability of aromatic hydrocarbons with a focus on N-heterocycles. Specifically, we will measure the rate constants and half-lives for the radiation induced destruction of monocyclic N(0-3)-aromatic molecules under conditions relevant to the interstellar medium. The proposed work would be the first systematic quantification of the kinetics of the radiolysis of monocyclic aromatic N-heterocycles. The results of this work will reveal the survivability and likelihood of detection of these compounds in different interstellar environments and could be used in astrochemical reaction networks. Additionally, the results of this work will motivate and guide observational efforts relevant to current and future observational assets including among others, the James Webb Space Telescope (JWST), and the Next Generation Very Large Array (ngVLA) recently prioritized in the decadal survey.

We will study the radiation (~0.8 MeV p+) driven destruction of monocyclic N(0-3)-aromatic molecules under conditions relevant to the interstellar medium. High-level objectives of this research include: (O1) Determining the impact that the incorporation of nitrogen atoms has on the radiolytic stability of aromatic molecules. (O2) Ascertaining whether the positions of nitrogen atoms impact the radiolytic stability of a molecule. (O3) Characterizing how the presence of other interstellar ices such as H_2O or CO_2 impacts the radiolytic stability of these aromatics. (O4) Using the information gained from this work (O1-O3) to assess the survivability of these molecules in interstellar environments. The radiolysis will be monitored in situ using transmission infrared (IR) spectroscopy. Our results will be quantitative and based on measured absorbed energy, making it easier to apply them to different astrophysical environments. Note: The refractive indices (*n*) and densities (ρ) of many of the compounds selected for this proposal are not available in the literature under astrophysically relevant conditions. To address this, our lab will provide a complete end-to-end analysis starting with measurements of *n* and ρ and culminating in radiolytic stability determinations.

John Mates/National Institute Of Standards & Technology
Next Generation Bolometric Microwave SQUID Multiplexer

In the coming decades, satellite missions in the mm/sub-mm/FIR will require instruments with > 10^4 background-limited sensors, for which transition-edge sensor (TES) bolometers are a proven, mature technology. However, the scalability of the technology is practically limited by the capabilities of SQUID-based multiplexing readout. We propose to develop microwave SQUID multiplexers (umux) capable of meeting the demands of the next generation of ultra-sensitive cameras. Current microwave SQUID multiplexers for bolometry achieve a multiplexing factor of approximately 10^3, which is a factor of ~5 larger than that of other technologies. Yet underutilization of the RF bandwidth leaves room for improvement in channel count. We propose multiple avenues of research to better optimize umux for bolometric applications: 1) To develop umux at lower frequencies, enabling narrower resonator bandwidths, 2) to develop a post-fabrication resonator editing technique to improve frequency scatter, enabling tighter frequency packing, and 3) to develop multi-SQUID resonators for hybrid multiplexing that combines signals from multiple bolometers in each resonator. Together, these research efforts should enable an order of magnitude improvement in the multiplexing factor. As a concrete target, we propose a design capable of reading out 3,200 bolometers in an octave of bandwidth, which may be expanded by use of hybrid multiplexing. The output of the research program would be a dramatic increase in the scalability of TES-based focal planes, which is highly relevant to NASA instruments such as the Galaxy Evolution Probe (GEP) and the Probe of Inflation and Cosmic Origins (PICO).

Benjamin Mazin/University Of California, Santa Barbara
Approaching the Fano Limit with UV, Optical, and Near-Infrared MKIDs

Microwave Kinetic Inductance Detectors, or MKIDs, are the most capable superconducting detectors for UVOIR astronomy. Unlike conventional semiconducting detectors, MKIDs can determine the energy and arrival time of each incoming photon without read noise or dark current. They are the only UVOIR superconducting detector technology that have been demonstrated in ground-based astronomical applications with arrays of up to 20,000 pixels. Recent breakthroughs have enabled us to more than double their spectral resolution, to R=33 at 400 nm. In this proposal we lay out a plan to improve spectral resolution of these UVOIR MKIDs to near the Fano limit, R>80 at 400 nm, while also addressing other requirements for future NASA missions like integrating anti-reflection (AR) coatings for improved QE.

Dan McCammon/University Of Wisconsin, Madison
Sounding Rocket Investigations Of Diffuse X-Rays

Current models suggest that almost half the normal matter in the Universe exists in the form of diffuse gas at temperatures near one million degrees and above. Much of this material is thought to be divided between an intergalactic "web" of matter collected around dark matter filaments and a "circumgalactic medium" surrounding individual galaxies. Learning the nature of this circumgalactic medium is essential to understanding the evolution of galaxies and following cosmological structure formation down to the scale of individual galaxies and groups.

The CGM and IGM, which must account for the bulk of this diffuse hot material are observationally difficult and their investigation will require a combination of absorption and emission measurements. The proposed ARCUS mission would represent a tremendous advance in absorption data, while serious emission studies will require a probe-class mission.

In the meantime, the far brighter hot gas emission from the Galactic disk and lower halo is accessible to suborbital missions and quite interesting in its own right as central to stellar feedback, metal distribution, and the earliest steps toward star formation. The eROSITA sky survey will provide information on the spatial distribution of Galactic hot gas in unprecedented detail, but the spectral resolution is not adequate to disentangle multiple components along the line of sight, particularly for gas temperatures near 1 million degrees.

We propose first to analyze our data on the Galactic center soft X-ray bulge from our XQC rocket instrument on its long-delayed flight from Australia, to be launched during the final days of the predecessor grant. This instrument will then be "retired" to Oak Ridge National Laboratories, where it will serve as the detector for an experiment to measure charge exchange X-ray production on the merged-beams facility there under a NASA-funded Laboratory Astrophysics program.

The XQC instrument used the same first-generation microcalorimeter technology employed on Hitomi/XRISM. While its 7-8 eV energy resolution does a reasonable job of isolating individual lines at the 2-4 million degree temperatures of the Galactic soft X-ray bulge, it is entirely inadequate for the much more crowded region at 150-300 eV, where the bulk of the emission from 1 million degree gas lies. This cooler material fills much of the large void in which the Sun is embedded, and is expected to be common throughout the Galactic disk as well as in the CGM and IGM. So we will continue with the development of a new rocket instrument employing 2nd-generation TES microcalorimeters with the 1-2 eV resolution required for resolving individual lines and disentangling the local hot bubble emission from foreground Solar wind charge exchange and $1 \cdot 10^6$ K gas in the halo.

We need to design and test specialized magnetic shielding to accommodate the large field of view required along with our continuing detector development. We are not proposing to fly the instrument during the period of this grant. We are discussing the required readout with other groups, but optimizing detectors and readout hinges on details such as how slow we can make the detectors and how many there should be. We expect these issues to be better pinned down in the first year or so of this grant, and before it ends we should have made detailed arrangements with a collaborating group for the readout and we will bee ready to submit a proposal to complete a flight instrument starting from a high TRL level and with a solid schedule.

We will continue the development of a pulsed laser calibrator that is essential for testing these low-energy, high-resolution detectors and calibrating them in flight. We will work on evaluating their usefulness for in-flight calibration of major X-ray missions such as Lynx or LEM.

Stephan McCandliss/Johns Hopkins University
Rocket and Laboratory Experiments in Astrophysics -- Off-Axis FORTIS

We submit herein a proposal describing plans for the development of an Off-Axis version of FORTIS (Far-UV Off Rowland-circle Telescope for Imaging and Spectroscopy). OAxFORTIS represents an evolution in our sounding rocket borne pathfinder to explore the scientific utility of multi-object spectroscopic surveys over wide angular fields in the far-UV as enabled by newly maturing technologies. Our efforts are directly relevant to realizing the Pathways to Discovery – under the Themes of Cosmic Ecosystems, and Worlds & Suns in Context – that will be explored by the large infrared/optical/ultraviolet space telescope (IOU-ST) recently prioritized by the Astro2020 Decadal survey. Here we will concentrate on globular clusters with a goal to to identify the progenitor populations of the HHB in three globular clusters (M13, M10, and M3), with similar ages and [Fe/H] abundances, in an effort to shed light on the “second parameter problem.”

The move to an off-axis configuration for the largely matured FORTIS is enabled by new state-of-the art advances in LiF/Al mirror coatings, single crystal silicon diffraction gratings, and third generation programable micro-shutter arrays (MSA-3G). These respective technologies are under development by our collaborators in the Optics Branch of the Goddard Space Flight Center (GSFC), the electron beam lithography group at Pennsylvania State, and our Co-Investigators in the MSA-3G group at GSFC. They were all baselined in the NASA commissioned flagship mission studies known as LUVOIR and HabEx, which were key drivers of the Decadal’s decision to prioritize IOU-ST. They also appear as Tier-1 and -2 Gaps in the Astrophysics Biennial Technology Report (2019), and as such, the raising of their technical readiness is a high priority.

Our sounding rocket program provides an avenue for assessing the robustness of these new technologies to survive the integration & testing, fielding, launch and operation in space mission environment, while gleaning a peek into their potential to advance scientific discovery. It also supports early career researchers in the form of undergraduate and graduate students, providing hands-on experience with all aspects of in the development of a space science mission. Our efforts are part-and-parcel of the foundational activities required to advance science, mature technologies, and develop a sustainable and diverse workforce that is essential to carrying forward the ambitious program outlined by Astro2020 for UV astrophysics in the coming decades.

Jeff McMahon/University Of Chicago
A Sub Millimeter Integral Field Spectrometer Optimized For Space

We propose to develop and demonstrate the first large-format mm-wave Integral Field Spectrometer (IFS). This architecture can realize 432 spatial pixels, each coupled to an $R = 100$ spectrometer covering an octave of bandwidth in a 150 mm diameter package. We will concentrate our initial development on the 90 and 150 GHz atmospheric windows, which are sensitive to multiple orders of carbon monoxide (CO) emission from redshifts $z = 1$-4. We will also test the scalablity of this IFS up to 600 GHz. This project will provide a laboratory demonstration of this technology in stages, starting with completing the design of the underlying technology, then fabricating a complete detector unit consisting of many spectrometers coupled to a compact horn array, and finally a 2-D array of multiple working detector units read out simultaneously.

High-sensitivity mm-wave spectrometers are key to understanding the evolution of the Universe and the birth of stars and galaxies during the first billion years of its history. They will soon enable dedicated line intensity mapping (LIM) surveys, which use observations of atomic and molecular spectral lines from unresolved galaxies to map large-scale structure and star formation rate in 3 dimensions. IFS technology will enable instruments with > 1000 spectrometers that densely sample a telescope’s focal plane, producing images and taking spectra with 25 times the mapping speed of present-generation instruments, per unit focal plane area. The scientific possibilities of future satellite missions will be transformed by dramatically reducing the mass and volume of the IFS. This will enable new measurements of the yet-unexplored first billion years of our universe when structures and stars first formed, and improve the precision of cosmological constraints over those from CMB and optical galaxy surveys. The proposed lab demonstration of a dense array of sensitive, multi-pixel, on-chip spectrometer units is a key milestone toward future large-scale LIM and spectral distortion surveys from balloons and space.

Christopher Mendillo/University Of Massachusetts, Lowell
PICTURE-D: Planetary Imaging Coronagraph Testbed Using a Reusable Experiment for Debris Disks

Planetary Imaging Coronagraph Testbed Using a Reusable Experiment for Debris Disks (PICTURE-D) is a balloon-borne suborbital research program to directly image several debris disks of nearby star systems in reflected visible light. The mission aims to characterize warm dust close to the host stars, examine planet-dust interactions and determine dust background levels for future exoplanet imaging missions. PICTURE-D is a follow-on to the PICTURE-C mission, which developed all of the required key technologies and established a functional direct-imaging balloon platform. PICTURE-C consists of a self-aligning, unobscured telescope feeding a vector vortex coronagraph. It includes adaptive optics systems for wavefront stabilization and high-contrast imaging.

PICTURE-C successfully performed its first engineering flight in September, 2019 from Ft. Sumner, NM and was prepared for a second science flight in October, 2021. Unfortunately, the mission had 6 scrubbed launch attempts in 2021 due to bad weather and launch safety concerns and could not launch before the end of the campaign. The flight has been rescheduled for fall of 2022.

PICTURE-D will maintain a strong heritage to PICTURE-C, reusing all of the same hardware with a few strategic upgrades to increase scientific yield. The mission will also reuse the Wallops Arc Second Pointer (WASP) pointing system and gondola from PICTURE-C. The greatly reduced development time will result in the opportunity to perform multiple science flights. The five year mission will consist of three conventional balloon flights, nominally from Ft. Sumner, NM, but with the possibility of a southern hemisphere flight from Alice Springs, AUS. Over the course of these three flights, PICTURE-D will observe 6-10 debris disk and exoplanetary systems. It will characterize these systems using 5-band photometry over a 20% visible bandpass (540-660 nm) and at a raw contrast level of $< 1\cdot10^{-7}$.

PICTURE-D will upgrade the detector system, vortex coronagraph, and wavefront control algorithms of PICTURE-C to advance new technologies and enable new scientific endeavors. The existing detector will be upgraded from a traditional CCD to an Electron Multiplying CCD (EMCCD) to drastically improve the signal-to-noise ratio of the science images. To enable dust polarimetry measurements, PICTURE-D will advance the TRL of new vortex coronagraph architectures, including the double/triple grating vortex and possibly the scalar vortex. The key advantage of these designs over the vector vortex coronagraph flown on PICTURE-C is they both allow high contrast imaging in two orthogonal polarizations simultaneously. Finally, PICTURE-D will implement Multi-Star Wavefront Control to observe dust populations in binary star systems. This is purely a software upgrade in the wavefront control system, no new hardware is required.

PICTURE-D will advance Goal 1 listed in the 2018 National Academy of Science report entitled, Exoplanet Science Strategy – to understand the formation and evolution of planetary systems as products of the process of star formation, and characterize and explain the diversity of planetary system architectures, planetary compositions, and planetary environments produced by these processes. PICTURE-D, takes the first observational steps towards several of the recommended findings from this report. PICTURE-D will also play a major role in technology maturation for a future flagship IR/Optical/UV exoplanet imaging mission, as was designated with the highest priority in the Astro2020 decadal survey.

The PICTURE-D team includes several graduate and undergraduate students as well as early career scientists and technologists who will advance future exoplanetary studies such as LUVOIR and HabEX long after honing their skills on a pathfinding program.

Igor Moskalenko/Stanford University
Self-consistent Modeling of Multi-messenger and Multi-wavelength Galactic Emissions in Support of Past, Current, and Future NASA Missions

Our proposed work aligns well with the priorities underlined in the Astro2020 Decadal Survey, which calls for the development of numerical models and interpretation of multi-mission data. The Survey emphasizes the need for self-consistent models of multi-messenger and multi-wavelength emissions praising such models to be as important as the development of new experiments.

This is a successor proposal of a highly successful two-decade-long effort funded by the NASA's APRA Program through the sub-topic 'Laboratory Astrophysics.'
The last decade brought spectacular advances in astrophysics of cosmic rays (CRs) and gamma-ray astronomy. Launches of forefront missions were followed by a series of discoveries even in the energy range that deemed as well-studied. Among them PAMELA, Fermi-LAT, AMS-02, NUCLEON, CALET, DAMPE, ISS-CREAM, and more mature missions, such as ACE-CRIS operating in the L1 Sun-Earth Lagrange point, and Voyager 1, 2 operating in the interstellar space. High-resolution CMB data are provided by WMAP and Planck. Indirect observations of CRs are done by X-ray and gamma-ray telescopes: INTEGRAL, Fermi-LAT, HAWC, LHAASO, H.E.S.S., MAGIC, VERITAS. Under construction are CTA and SKA. The reached level of precision demonstrates that we are on the verge of major discoveries. However, taking full advantage of the high quality data requires numerical models of comparable accuracy. Our main research tool is the state-of-the-art fully numerical GALPROP framework, which has 25 years of development behind it, it is consistently updated to keep up with ever increasing amount and precision of experimental data. GALPROP provides a self-consistent interpretation and combines in a single framework the results of individual experiments in physics and astronomy spanning in energy coverage, types of instrumentation, and the nature of detected species (CR species and thermal and non-thermal photons). Its range of physical validity extends from sub-keV--PeV energies for particles and from μeV--PeV for photons. It has proven to be invaluable tool in sophisticated analyses in many areas of astrophysics including numerous searches for new phenomena. We are proposing considerable improvements of the GALPROP framework that include the following interconnected tasks: (i) development of a comprehensive model of diffuse Galactic multi-wavelength and multi-messenger emission; (ii) development of a self-consistent model of the Galactic magnetic field and incorporation it into a full 3D model of the interstellar medium (ISM) including hydrogen gas (H_2, HI, HII), dark neutral medium, and thermal interstellar radiation field (radio, IR, optical); (iii) development of a self-consistent GALPROP HELMOD framework for Galactic and heliospheric propagation of CRs (MV-TV); (iv) improvement of the isotopic production cross sections for astrophysical applications; and (v) further development of the GALPROP code and its optimization. The new work proposed in this study will represent a dramatic step forward for astroparticle physics, studies of radio/IR/gamma-ray emissions and their relationships in starforming galaxies, astrophysics of CRs, X-ray and gamma-ray astronomy, and CMB-related analyses. The improved GALPROP framework will be publicly available as was the case with previous versions of the code.

Angela Olinto/University Of Chicago
EUSO-SPB2 (Extreme Universe Space Observatory on a Super Pressure Balloon 2nd Generation) from Flight to Science Results

This proposal is to support the flight campaign, data acquisition, data analysis, and dissemination of the science results of the Extreme Universe Space Observatory on a Super-Pressure Balloon 2nd generation (EUSO-SPB2). Supported by NASA under 16-APRA16-0113, EUSO-SPB2 is currently under construction. The main science goals of EUSO-SPB2 are to detect, for the first time from sub-orbital altitudes, fluorescence and optical Cherenkov signals generated by ultrahigh energy cosmic rays (UHECRs) and search for very high energy astrophysical neutrinos from a target-of-opportunity campaign following alerts of energetic transient events, such as a binary neutron-star coalescence. EUSO-SPB2 is a pathfinder for a future space mission capable of multi-messenger observations of astrophysical neutrinos from transient events and UHECRs, such as POEMMA.

EUSO-SPB2 consists of two 1m diameter aperture wide-field of view telescopes: a Fluorescence Telescope (FT) and a Cherenkov Telescope (CT). The two Schmidt telescopes are being assembled for field tests in the Spring of 2022 and the full payload will be integrated for the hang test in the Fall of 2022. Following the hang test, the payload will be shipped to Wanaka, New Zealand for a flight campaign in early 2023. This proposal is to fund the EUSO-SPB2 team from flight campaign to science results starting on January 1, 2023, to December 31, 2025.

The EUSO-SPB2 is designed to observe extensive air-showers (EAS) generated by cosmic rays and neutrinos via the air-shower's fluorescence and optical Cherenkov signals. The FT covers a 37.4×11.4 square degrees field of view with a camera of MAPMT (6912 pixels) that takes images in microsecond timescales. The FT records the longitudinal development of an EAS from UHECRs with energies above 1 EeV. The CT optics covers 12.8×6.4 square degrees field of view with a bifocal mirror design for background rejection. The CT camera has 512 SiPM pixels and takes images in 10 nanosecond timescales (built under APRA 80NSSC19K0627). The CT design is optimized for detecting the Cherenkov signal from EAS generated either above the Earth's limb by cosmic rays or below the Earth's limb by tau-neutrinos that interact as they cross the Earth and generate a tau-lepton that decays producing an upward going EAS. The threshold energy of the CT for detection of both cosmic rays and neutrinos is around a PeV.

The EUSO-SPB2 team in this proposal is composed of the University of Chicago, the Colorado School of Mines, the City University of New York, Lehman, Goddard Space Flight Center, and the University of Iowa. This team includes experienced researchers who were involved in the EUSO-SPB1 flight from Wanaka, New Zealand, in 2017. The team includes the addition of experts from Goddard Space Flight Center and the University of Iowa, who will lead the prioritizing and coordinating of target-of-opportunity searches for possible neutrino transients and the public release of the mission science data. Built with lessons learned from SPB1 and significant advances in telescope design and modeling of the multi-messenger target of opportunity capabilities, the science payload for EUSO-SPB2 will provide pioneering and ground-breaking data to advance the fields of cosmic ray and neutrino astrophysics.

Jeremy Perkins/NASA Goddard Space Flight Center
BurstCube Operations

In 2017 we proposed to design, build, and fly BurstCube: a small CubeSat with the aim to detect and characterize short gamma-ray bursts that are counterparts of gravitational wave sources. BurstCube is a '6U' CubeSat (each 'U' is approximately 10 cm × 10 cm × 10 cm so that a '6U' is approximately10 cm × 20 cm × 30 cm) with a '4U' instrument package. The instrument consists of four CsI scintillators read out by arrays of Silicon Photo-multipliers. It will detect photons from approximately 50 keV to 1 MeV and roughly localize gamma-ray transients on the sky, rapidly sending alerts to the ground which will enable follow-up at other wavelengths and at greater sensitivity. The BurstCube project began in the Fall of 2017 with a period of performance of 5 years. It currently has a projected launch readiness date of 2022. BurstCube has completed all major design reviews, the instrument is assembled, calibrated, and tested and will be integrated with the spacecraft soon. We are currently manifested for a launch with NanoRacks in late 2022 or early 2023. The COVID pandemic caused an approximately 1 year delay to the BurstCube mission and operations will begin after the period of performance of the original grant ends. In this proposal we request support for two years of BurstCube operations.

Jonathan Pober/Brown University
Foreground Removal for Space Based Neutral Hydrogen Cosmology

Observations of the highly-redshifted 21 cm line of neutral hydrogen are one of the last frontiers in cosmology. Vast volumes of the observable Universe can be probed via this technique, including redshifts higher than ~ 30 (i.e. prior to the formation of the first stars). At these very high redshifts, the hydrogen traces the cosmic density field, ultimately promising orders of magnitude more information than could ever be extracted from the Cosmic Microwave Background. However, at these high redshifts the rest-frame 21 cm signal has shifted to very long radio wavelengths, emission that is blocked by the Earth's ionosphere. Accessing this cosmological treasure trove requires space-based observations.

At moderately high redshifts (e.g. $z \sim 7$), the hydrogen signal can still be observed from the ground, and multiple experiments are underway targeting a first detection. These experiments have taught the community many lessons about the challenges of this technique: foreground radio emission swamps the 21 cm signal by 5 orders of magnitude. The foregrounds can, in principle, be separated based on their spectral behavior, but the radio telescope must be modeled with extremely high precision to enable such techniques.

The challenge is even greater for space-based missions. At the highest redshifts, the foregrounds can exceed the 21 cm signal by as much as 8 or 9 orders of magnitude. Furthermore, the mapping between radio frequency and cosmological redshift has moved to a fundamentally different regime. For instance, a 1 MHz radio-frequency bandwidth centered at 30 MHz ($z \sim 45$ in the 21 cm line) spans a redshift range almost forty times larger than a 1 MHz bandwidth centered at 180 MHz ($z \sim 7$). The repercussions of this fact are significant: frequency structure introduced by the instrument contaminates many more modes of the 21 cm signal at high redshifts than at low. Because of this relationship, the preferred ground-based technique of "foreground avoidance" (where only modes of the 21 cm signal that cleanly separate from the foreground emission are used to make cosmological constraints) cannot be used at high redshifts. Techniques focused on "foreground subtraction" must be employed for a space-based neutral hydrogen cosmology experiment to be successful.

PI Pober's previous APRA award ("A Science-Driven Performance Specification Framework for Space-Based Neutral Hydrogen Cosmology Experiments") developed software to simulate mock data for space-based radio telescopes and enable design studies and planning for optimal observing strategies. This software – pyuvsim – provides ultra-precise, fully polarized, horizon-to-horizon simulations, which ultimately are necessary to capture all the subtleties in extracting a 1-part-in-10^8 signal. This successor proposal aims to use pyuvsim to aid in the development of foreground removal algorithms for space-based missions. The final products of this research will be two-fold: (1) an updated version of the publicly-available 21 cm cosmology package FHD ("Fast Holographic Deconvolution") which has been demonstrated to successfully remove foreground emission and recover the 21 cm signal from pyuvsim simulations of space-based neutral hydrogen cosmology missions; and (2) a suite of publicly-available pyuvsim simulations exploring a range of space-based neutral hydrogen cosmology mission concepts that can enable "data challenges" and other technique development for these experiments. Having this software in-hand will maximize the impact of space-based low-frequency radio astronomy instruments that can serve as pathfinders for future 21 cm cosmology focused missions.

David Rapetti/Universities Space Research Association, Columbia
Modeling and Analyzing Low Radio Frequency Observations from the Lunar Surface in Pursuit of the Dark Ages

The Dark Ages is an unexplored era of the early Universe which represents THE discovery area in cosmology as identified by the Astro2020 Decadal Survey. Due to the absence of astrophysical sources, this epoch provides a purely cosmological probe and unprecedented opportunities to investigate new physics of the cosmos. To pursue a first detection of the Dark Ages via the hyperfine line of primordial neutral hydrogen, we propose to utilize low radio frequency observations from two experiments, ROLSES and LuSEE, manifested for flight within NASA's CLPS program to land on the lunar surface in 2022 and 2025, respectively. The primary goal of this proposal is to characterize the systematics associated with lunar-based low frequency measurements. For this, we will build modeling sets to describe challenging systematics including the beam-weighted foreground, which is much larger than the signal, and those from the receiver, gain and temperature offset, as well as sets for the signal based on a variety of dark matter models. These modeling sets are inputs to our well-developed data analysis pipeline, which can robustly extract the signal from systematics using Bayesian statistical techniques and modeling sets that encompass precise and accurate possible variations for each of the data components. ROLSES, located on the lunar nearside, will be employed to observationally constrain the sky at low frequencies (1-30 MHz) and investigate the interactions of the antenna beam with the subsurface. With LuSEE data from the radio-quiet lunar farside over 1-80 MHz, we will be able to achieve higher precision measurements of the beam-weighted foreground at the level to either potentially detect the Dark Ages global 21-cm signal or construct solid systematic foundations for follow-up CLPS instruments to attain this long-sought-after, revolutionary measurement.

Brian Rauch/Washington University
SuperTIGER-2: Data Analysis and Interpretation, Payload Recovery, and Assessment for Future Flights

The SuperTIGER Collaboration with members at Washington University in St. Louis, the NASA Goddard Space Flight Center, the California Institute of Technology, and the University of Maryland Baltimore County are proposing analysis and interpretation of data from the SuperTIGER-2 (ST2) flight separately and in combination with the data from the first flight (ST), and to complete recovery of the payload and assess it for future flights. ST2 flew for 32 days on a stratospheric balloon launched from McMurdo Station, Antarctica on December 15, 2019, through termination on January 17, 2020, followed by recovery of high priority items on January 22, 2020. This recovery included the data vault, which unfortunately did not have a complete record of the data due to a network switch failure midway through the flight. This Antarctic season the flight computers have been recovered from the field, which when returned will provide the complete data set from the flight for analyses of rare ultra-heavy Galactic cosmic ray (UHGCR) abundances of elements above 28Ni and energy spectra of the more abundant elements below. The UHGCR measurements will address the Astro2020 priority in multi-messenger observations “to constrain sites of r-process nucleosynthesis,” and will help determine the relative contributions of neutron star mergers and core collapse events like supernovae. The atmospheric propagation corrections previously used will be complemented with new atmospheric transport corrections, and GALPROP will be upgraded to model UHGCR to complement the nested leaky box model currently used. Results of ST2 analysis and interpretation individually and in combination with ST will be presented in conferences and published in journals. We plan to complete the recovery of ST2 in December 2022 - January 2023 in compliance with the Antarctic Treaty, and after the payload is returned by vessel its condition will be assessed for future flights.

Karwan Rostem/NASA Goddard Space Flight Center
Ultra-Low Noise Transition-Edge Sensor Bolometers for Far-Infrared Astronomy

Advances in superconducting detector technology are essential to enabling national science priorities in mid- and far-infrared (IR) astrophysics. Specifically, superconducting ultra-low noise detectors are required for implementing the Astro2020 Decadal Survey recommendation of a far-IR Probe mission beginning in 2030. The importance and need for these detectors in large-format arrays is recognized as a Tier-1 technology gap by the NASA Cosmic Origins Program (COR). We propose to develop absorber-coupled transition-edge-sensor (TES) bolometer arrays to address the need of future far-IR missions in space. The absorber-coupled TES technology has been employed in numerous pioneering sub-orbital far-IR and millimeter instruments. Absorber-coupled TESs can be used to efficiently detect light across the entire mid- and far-IR wavelength range.

The typical detector requirements for a far-IR astrophysics mission concept are summarized as follows: (1) Highly sensitive detectors with performance approaching 10 zW/√Hz for background-limited operation in telescopes with cold optics. (2) A detector time constant in the millisecond range. (3) Optically efficient pixel architecture that is scalable to a kilo pixel format with uniform detector characteristics. (4) Compatibility with operation in the ionized particle radiation environment.

This proposal seeks to implement and validate a unique TES bolometer design that promises 10 zW/√Hz sensitivity with a high (>70%) pixel filling fraction. The approach can be tailored to provide a sensitivity across 1000 to 10 zW/√Hz range, therefore enabling and enhancing the science potential of future sub-orbital and spaceborne far-IR imaging and mid-resolution spectroscopy instruments.

The approach is based on engineering the thermal conductance of a bolometer with a coherent phononic filter, a structure which utilizes sub-wavelength features to reduce phonon transmission through coherent (Bragg) reflections. An absorber-coupled TES bolometer with phononic thermal isolation can simultaneously provide a high sensitivity and optical efficiency due to the compact nature of the phononic filter. Filters ~50 µm in length could achieve a sensitivity of 10 zW/√Hz for the most demanding spectroscopic instruments, while filters ~10 µm in length have been designed for 100 zW/√Hz sensitivity, which is suitable for the imager and spectrometer instruments on the Galaxy Evolution Probe concept.

We propose a three-year effort to fabricate and test phononic-isolated TES arrays suitable for background-limited operation in a cryogenic space telescope. We have all the elements in place to succeed in this effort, including phononic filter designs, in-house state- of-the-art fabrication facilities, demonstrated mechanical robust pixels with phononic filter isolation structures, and a dark test environment. Our effort addresses the APRA solicitation for advancing detector design and operation towards highly sensitive, compact, and robust characteristics.

Kevin Ryu/Massachusetts Institute of Technology/Lincoln Lab
Development of Next-Generation Wiring Capability for Advanced X-Ray Microcalorimeters

Microcalorimeters offer exciting opportunities for X-ray astronomy, with energy resolution that is about a factor of 100 better than the silicon CCDs, which is the current work-horse detector technology being used in X-ray imaging spectrometer satellite missions such as Chandra and XMM. The recent astrophysics decadal survey endorsed an X-ray mission as one of the three new NASA Great Observatories (NGO) missions that should proceed in development through the next decade. This is a proposal to further develop X-ray microcalorimeter technology, continuing to work in close collaboration with the X-ray microcalorimeter group at NASA's Goddard Space Flight Center, with a view to providing an instrument with even greater capabilities than have ever been envisaged before, and potentially with properties that could help reduce the estimated cost of the future X-ray NGO. This will be a direct follow-on to an existing APRA program. GSFC will collaborate with this development as part of a GSFC astrophysics work package titled, "Advanced X-ray Microcalorimeters".

One of the main limitations on the achievable microcalorimeter array size had been the challenge of fabricating high-density, high-yield microstrip superconducting wiring between all the pixels in the array. Utilizing decades of investment in infrastructure and process development at MIT/LL for superconducting electronics, a new approach was developed to solve this problem. In this approach, MIT/LL fabricated the base-layer multi-level superconducting wiring layer, and GSFC fabricated and tested the microcalorimeter arrays, integrating with the MIT/LL wiring. The approach successfully demonstrated a prototype 50 kpixel array for transition edge sensors (TESs) and a 100 kpixel array for magnetic microcalorimeters (MMCs). In this program we propose to take this development to the next step, providing even greater advances in detector array fabrication capability.

We propose to investigate advanced next-generation wiring capabilities for X-ray microcalorimeters that may enable a microcalorimeter instrument to meet most of an X-ray NGO observatory's instrument requirements. The following aspects of the superconducting metal lines will be developed: 1. Smaller features to enable smaller pixel pitch. 2. Additional wiring layers. 3. Larger regions with high density wiring. Currently the metal line width and spacing of 400 nm has been demonstrated. In this proposal, we will reduce this to 300 nm line and space definition to enable higher wiring density. Second, additional metal layers will enable additional shielding and inductance in a given area, which can help with the array design and performance. Third, we have demonstrated the 400 nm metal line features for the central 22 × 22 mm region of the wiring wafer. By either stitching or using another DUV lithography tool with a larger exposure field, we can increase the central region which has fine features. This will enable patterning a detector array that can cover a wider field of view.

The additional wiring capabilities have the potential to enable new array capabilities with pixel pitches of 0.3 arc-seconds or less, a field-of-view of one arc-second pixels that is greater than ten arc-minutes, and some pixels with resolving powers greater than 5000. If this research is successful, an X-ray NGO that will enable us to reveal the hidden universe could become significantly more stream-lined and less expensive than the Lynx observatory design submitted to the astrophysics Decadal Survey.

Phillip Stancil/University Of Georgia, Athens
Rovibrational Collisional Excitation of Diatomic and Triatomic Molecules by Quantum Computations and Machine Learning for Modeling of Infrared Observations

Refractory elements are deemed to be incorporated into interstellar dust grains, but their observed presents in the gas-phase suggests the grains reside in turbulent environments, e.g. intense ultraviolet radiation fields or high-velocity shocks. To aid in the understanding of observations of refractory molecules, we propose to compute accurate collisional excitation rate coefficients for rotational and vibrational transitions of NaCl, AlCl, AlO, SiS, SH, and H_2S due to H and H_2 impact. This work, which uses fully quantum mechanical methods for inelastic scattering and incorporates full-dimensional potential energy surfaces (PESs), pushes beyond the state-of-the-art for such calculations, as recently established by our group for rovibrational transitions in full-dimension. All the required PESs will be computed as part of this project using ab initio theory and basis sets of the highest level feasible and particular attention will be given to the long range form of the PESs. The completion of the project will result in 12 new interaction PESs. The state-to-state rate coefficients for a large range of initial rovibrational levels for temperatures between 1 and 3000 K will be computed and extended to higher excitation using artificial neural network and gaussian process regression approaches. The chosen collision systems correspond to cases where data are limited or lacking, include less-studied refractory elements, and will provide observable emission/absorption features in the infrared (IR). The final project results will be important for the analysis of a variety of interstellar and extragalactic environments in which the local conditions of gas density, radiation field, and/or shocks drive the level populations out of equilibrium. In such cases, collisional excitation data are critical to the accurate prediction and interpretation of observed molecular IR emission lines in protoplanetary disks, star-forming regions, planetary nebulae, embedded protostars, and photodissociation regions. The use of the proposed collisional excitation data will lead to deeper examination and understanding of the properties of many astrophysical environments, hence elevating the scientific return from the soon-to-be-launched JWST, as well as from current (SOFIA, HST) and past IR missions (Herschel, Spitzer, ISO), and from ground-based telescopes.

Daniel Swetz/National Institute Of Standards & Technology
Highly Scalable Transition-Edge Sensor Arrays For Optical To Near-Infrared Astronomy

For the past few decades, charge-coupled devices (CCDs) have been a dominant technology in optical to near-infrared (NIR) astronomy, but more recently, instruments incorporating superconducting detector technologies, particularly microwave kinetic inductance detectors (MKIDs), have been built for a number of astronomical applications. MKIDs have multiple advantages over CCDs in the optical to near-IR regime, including single photon detection with microsecond timing, broadband wavelength coverage, and intrinsic energy resolution. These qualities are critical for observations of multi-wavelength, time-variable sources, such as compact binaries, exoplanet transits, and millisecond pulsars. MKIDs can also be naturally read out using frequency division multiplexing (FDM) techniques that are standard in the telecommunications industry, enabling large detector arrays.

Another type of superconducting detector technology, the transition-edge sensor (TES), shares in many of these same advantages, but because TES performance is less sensitive to fabrication processes and additional material layers, the per pixel performance (energy resolution and quantum efficiency) of a TES can be much simpler to improve. This can be seen, for example, in the detector quantum efficiency, where near unity efficiency at 1550 nm has been demonstrated in TESs. Reading out TES devices has traditionally involved the use of superconducting quantum interference devices (SQUIDs), which are not innately straightforward to multiplex for microsecond scale signals. Due to this limitation, we instead propose to multiplex optical to near-IR TESs using the novel kinetic inductance current sensor (KICS). The KICS utilizes a resonator fabricated with high kinetic inductance superconductors and geometries, allowing it to exploit the kinetic inductance's quadratic current dependence. By coupling a TES with such a device, photon events that cause a change in the TES current can be measured as shifts in the resonant frequency of the readout resonator, and a large number of devices can be multiplexed using FDM techniques in much the same way as MKIDs.

This program will comprise of three main research thrusts. First and foremost, we will develop and optimize KICS devices to read out integrated optical/NIR TES arrays, with the goal of multiplexing a kilopixel scale array through a single microwave transmission line. Next, we will improve TES energy resolution, primarily by reducing the superconducting critical temperature and dynamic range of existing devices, and by fabricating devices on membranes and phonon barriers. Finally, we will optimize optical stacks to maintain high photon quantum efficiency across a broader wavelength band. All in all, by the end of this program we aim to demonstrate the multiplexed readout of kilopixel scale integrated array of optical/NIR TES detectors with resolving power approaching 90 at 1550 nm and quantum efficiency > 90 % between 400 nm to 2000 nm. Upon further development, optical to near-IR TES arrays would not only be significant for general purpose instruments for multi-wavelength, time domain astronomy, but they could be groundbreaking in the study of exoplanets, a focus area of the recent decadal survey. Here, a large array of TESs with high efficiency and resolution paired with a large space telescope could be used for the search of biosignatures in exoplanet atmospheres.

Peter Timbie/University Of Wisconsin, Madison
Modeling and Testing Kinetic Inductance Detectors (KIDs) for Astrophysics

Kinetic inductance detectors (KIDs) are used in a growing number of applications for sensing electromagnetic radiation, from mm-wavelengths to X-rays. They are relatively easy to fabricate and to read out. Background-limited performance in arrays of thousands of devices has been demonstrated from the ground, even at very low power levels, as in high-resolution spectroscopy.

KIDs are made from superconducting thin films in which absorbed radiation splits Cooper pairs into quasiparticles, a process that changes the film's inductance. The films are patterned into microresonators whose resonance properties respond to the inductance change and can be monitored by measuring the complex transmission of a microwave signal in an adjacent, coupled readout line. Multiple sensors can be formed with distinct resonant frequencies and read out simultaneously using a frequency comb of microwave probe tones.

Models for KIDs have been developed that agree with many measurements. Nevertheless, these models have significant limitations and are difficult to use for optimizing designs for applications. In particular, the heating of quasiparticles by the readout signal and the diffusion of quasiparticles in the microresonator are two important pieces of physics that are not yet well understood and strongly affect device performance. We propose to develop a model for KIDs that includes these effects and test the model over a targeted parameter space that includes a range of detector volumes, optical power, and readout power. A particularly important goal of the modeling is to understand and demonstrate the large dynamic range expected from MKIDs when using tone tracking and power tuning in the readout system. Test devices will be made from superconducting films, TiN and Al, at the University of Wisconsin, and cryogenic tests will occur there and at NASA/Goddard. Our investigation will advance understanding of the fundamental operational aspects of KIDs. The basic detector physics results from our tested model will be made available in published software that can be used by other groups as they design KIDs for specific applications. This code will allow instrument designers to anticipate KID performance in the focal planes of future missions from mm to visible wavelengths.

Sylvain Veilleux/University of Maryland, College Park
Miniature Photonic Filters, Spectrometers, and Nulling Interferometers for Astrophysics and Space Science

We seek to build on our expertise in astrophotonics – photonics applied to astronomical instrumentation – to develop an exciting new technology for future NASA missions. Under our current APRA grant, we have replaced the bulky optics of conventional near-infrared filters and spectrometers with miniature (~1 cubic-centimeter) photonic devices imprinted using buried silicon nitride ("nano-core") technology, the leading solution for low-loss waveguides at 1 - 1.7 µm. We have perfected the design of the waveguides, improved the deposition method of the cladding material (silica), and reduced the scattering losses with the use of a new high-precision (a few nm instead of ~8 nm) electron beam writer, resulting in ultra-low propagation losses of only 0.018 dB/cm at 1.6 µm (instead of 0.25 dB/cm before the APRA-funded effort). We have fabricated complex photonic filters with improved and reproducible transmission profiles thanks to a new double-spiral design that results in a compact footprint of only 1.5 mm diameter which reduces non-uniformity in the fabrication of these filters. We have put these

photonic filters between two 2 × 2 multi-mode interferometers (MMIs) to make use of both the transmitted and reflected spectra, without dispersing the light, for exoplanet science applications. Finally, we have successfullly fabricated and tested two types of polarization splitters, one that makes use of MMIs and another one based on bent directional couplers, to address the polarization dependence of our devices.
Here we wish to apply what we learned over the past four years to fabricate and test (1) a new generation of high-throughput, high-resolving-power (> 50,000), polarization-combining, multi-input on-chip spectrometers based on a three-stigmatic-point design with flat focal surfaces to ease coupling with near-infrared detectors, and (2) new on-chip cascaded nulling interferometers that will make use of up to three thermally- or piezoelectrically-tuned MMIs in series to fine tune both the phase and power balance between the signals to deliver suppression ratios of 50-80 dB (10^5 - 10^8). The performances of these photonic devices will exceed those of conventional instruments. All of these devices will be optimized, fabricated, and tested in-house by our trained graduate students using the state-of-the-art facilities of the Maryland NanoCenter and AstroPhotonics Lab as part of their PhD theses. Up to three undergraduate students will also be involved with this research.

This effort directly addresses one of the technology gaps identified in the 2019 Astrophysics Biennial Technology Report, namely the need to develop "high-performance spectral dispersion components / devices." Astrophotonics is also explicitly cited in the Astro2020 report as a "potentially revolutionary strategy for the next generation of astronomical instruments." A wide swath of astrophysical research, from spectroscopic studies of the distant universe to searches for biosignatures in the atmospheres of exoplanets, stands to benefit from these miniature devices on board future NASA-funded balloon, CubeSat, Explorer, Probe-class, and Flagship missions.

Scott Wakely/University Of Chicago
HELIX - the High-Energy Light Isotope eXperiment

This proposal seeks support for the continuation of a new suborbital program (HELIX; the High-Energy Light Isotope eXperiment), designed to make measurements of the isotopic composition of light cosmic-ray nuclei from ~200 MeV/nuc to ~10 GeV/nuc. Past measurements of this kind have provided profound insights into the nature and origin of cosmic rays, revealing, for instance, information on acceleration and confinement time scales, and exposing some conspicuous discrepancies between solar and cosmic-ray abundances. The most detailed information currently available comes from the ACE/CRIS mission, but is restricted to energies below a few 100 MeV/nuc. HELIX aims at extending this energy range by over an order of magnitude, where, in many cases, no fully resolved measurements exist, and where relativistic time dilation affects the apparent lifetime of radioactive clock nuclei. The HELIX measurements will provide essential information for understanding the propagation history of cosmic rays in the galaxy. This is crucial for properly interpreting several intriguing anomalies reported in recent cosmic-ray measurements, pertaining to the energy spectra of protons, helium, and heavier nuclei, and to the anomalous rise in the positron fraction at higher energy.

HELIX employs a high-precision magnet spectrometer to provide measurements of light isotopes with excellent mass resolution. The superconducting magnet, originally used for the HEAT payload in five successful high-altitude flights, has been combined with state-of-the-art detectors to measure the charge, time-of-flight, magnetic rigidity, and velocity of cosmic-ray particles with high precision. The instrumentation, currently undergoing integration on the payload at Chicago, includes plastic scintillators, a high-performance gas drift chamber, and a ring-imaging Cherenkov counter employing aerogel radiators and silicon photomultipliers. A proposed single-layer silicon strip detector layer will further enhance performance.

To reduce cost and technical risk, the HELIX program is structured in two stages. The first stage, which is the subject of this proposal, focuses on the construction of the main HELIX instrument, as well as LDB flights to perform measurements of key light isotope ratios from ~200 MeV/n to ~3GeV/n. A future stage 2 will build on this work, incorporating evolutionary enhancements to the instrumentation to extend the energy reach into the challenging ~10 GeV/n range. The stage 1 instrument achieves a maximum detectable rigidity of ~850GV and charge range from Z=1 to Z=10. The high field of the magnet will make it possible to reach the required mass resolution dm/m = 2.5% over the energy range of concern with very small systematic limitations due to multiple Coulomb scattering in the thin tracker. This is a decisive advantage over the current AMS-02 instrument which employs a permanent magnet with an average field ~7 times smaller than that of HELIX.

The primary scientific goals of the full HELIX program are:
- a high-statistics measurement of the ^{10}Be/^{9}Be ‘clock ratio’ to ~10 GeV/nuc
- a high-statistics measurement of the ^{3}He/^{4}He ratio to ~12GeV/nuc
- the first measurements of ^{22}Ne/^{20}Ne above 1 GeV/nuc
- the first mass-resolved measurements of ^{7}Li/^{6}Li, and ^{10}B/^{11}B above 1 GeV//nuc

A number of secondary goals will also be pursued including the measurement of several other isotopic and elemental abundance ratios and fluxes,
The proposed work will be conducted by a team of US scientists and engineers with extensive experience in cosmic-ray observations on balloons or in space, and, specifically in magnet spectroscopy, with the SMILI, P-BAR, and HEAT programs. Significant participation from a crew of more than 10 graduate, post-graduate, and undergraduate students forms an important educational element of the program.

Scott Will/NASA Goddard Space Flight Center
Computationally Efficient Adaptive Wavefront Control For Coronagraphy Using Algorithmic Differentiation

Wavefront sensing and control using deformable mirrors is a critical technology for achieving direct imaging of Earth-like exoplanets and circumstellar dust clouds using future space-based observatories, a key scientific target of the primary mission recommended by the Astro2020 Decadal Survey. In recent work, Will, Groff and Fienup (JATIS, 2021) showed how formulating the focal-plane wavefront control problem as a nonlinear optimization problem, and computing the necessary derivatives using

algorithmic differentiation, enables deformable mirror commands to be obtained without computing a control Jacobian matrix. This greatly reduces the computational resources (CPU time and memory) compared to conventional methods. Later, Will et al. (Proc. SPIE, 2021) demonstrated this approach experimentally using the High Contrast Imager for Complex Aperture Telescopes (HiCAT) coronagraphy testbed, showing equivalent performance in coronagraph contrast to current Jacobian-based approaches.
We propose to extend on this work by implementing and experimentally testing adaptive control capabilities, in which experimental data is used to improve the performance of the control loop by tuning the computer model used by the control algorithm to better reflect reality. Our approach will build upon our Jacobian-free control framework to bring its computational benefits to existing Jacobian-based adaptive control methods (Sun et al., JATIS, 2018), which have been shown to improve the convergence rate of the control loop. This, in turn, reduces the overheads associated with wavefront sensing and control, leaving more time for scientific observations and ultimately increasing scientific yield.

Benjamin Williams/University of California, Los Angeles
Quantum-Cascade Local Oscillators Beyond 5 THz

Many molecular species that comprise the interstellar medium have strong spectral features in the terahertz range, and the high spectral resolution provided by heterodyne spectroscopy is required to obtain ~km/s velocity resolution to resolve their complicated lineshapes and disentangle them from the background. Understanding the kinetics and energetics within the gas clouds of the interstellar medium is critical to understanding star formation processes and validating theories of galactic evolution. THz quantum-cascade (QC) lasers are candidates for local oscillators that deliver high-powers sufficient to pump large arrays of heterodyne mixers, particularly above 2 THz where electronic techniques provide diminishing output power. To date, THz QC-lasers have been deployed as local oscillators on two heterodyne instruments (upGREAT/SOFIA and GUSTO) to map the [OI] line at 4.74 THz. However, there exists no viable local oscillator above 5 THz, which is needed to access important spectral lines including [OIII] at 5.79 THz and [NIII] at 5.23 THz. Previous observations have shown that oxygen and nitrogen lines often dominate the emission from galactic HII regions, and originate from regions rich with activity: early-type stars in the process of formation, shocks and supernova remnants.

The proposed work would develop the underlying technology for THz QC-laser local oscillators in the 5-6 THz spectral range. Such heterodyne receivers may find future use in a future far-IR probe mission, or balloon platform, SmallSat, or Explorer-class mission. To date, operation of THz QC-lasers at frequencies above 5 THz has proven especially difficult because of increased losses and reduced gain associated with to the proximity of the laser frequency to the polar-optical-phonon resonances within the III-V semiconductor gain medium. This project will address these issues through fundamental research to develop advanced active regions that mitigate this degradation above 5 THz. In addition, the QC-laser will be implemented using a new architecture previously developed by our team: the QC vertical-external-cavity-surface-emitting-laser (QC-VECSEL). QC-VECSELs have excellent beam quality, and are capable of single-frequency output tunable over as much as 20% of their center frequency – an asset for a frequency agile local oscillator. Furthermore, the output power from a QC-VECSEL is scalable from sub-milliwatt levels (suitable for few-pixel instruments on power constrained platforms) to over 10 milliwatts of output power (suitable for pumping future large format heterodyne array instruments of 100 pixels (or more) for rapid mapping of the interstellar medium).

Our research goal in this proposal is to develop quantum-cascade laser local oscillator sources that operate above 5-6 THz for the first time. We present a multi-themed research plan that spans from (a) fundamental development of the QC laser material, (b) its implementation in a frequency-agile metasurface QC-VECSEL, and (c) frequency stabilization of the QC-VECSEL and its insertion in a practical heterodyne receiver testbed as a proof-of-concept demonstration. We choose 5.23 THz and 5.79 THz as specific demonstration frequencies, so as to correspond with the aforementioned [NIII] and [OIII] lines. At the outcome, we expect to demonstrate QCL local oscillators in the region, which exhibit fine tuning to enable spectral alignment with the lines of interest. Particular attention will be paid to exploring the trade-offs between output power, wall-plug efficiency, operating temperature, and power consumption, with a mind to meeting power budget requirements of future SmallSat and balloon missions.

Michael Zemcov/Rochester Institute Of Technology
Composing the History of Near-IR and Optical Light Production with the Cosmic Infrared Background Experiment-2 (CIBER-2)

The Cosmic Infrared Background ExpeRiment-2 (CIBER-2) is a sounding-rocket borne instrument designed to measure anisotropy in the extragalactic background light in 6 broad bands covering the optical and near-infrared. Using high-sensitivity, wide-angle, multi-color anisotropy measurements, CIBER-2 will elucidate the history of interhalo light (IHL) production and carry out a deep search for extragalactic background fluctuations associated with the epoch of reionization (EOR). The instrument had its first flight in June 2021, and our preliminary analysis demonstrates generally good performance in all three science channels. Having now characterized the system in space, our team requires support to refurbish and fly CIBER-2 to realize the scientific promise of a program NASA has invested in heavily over the past 5 years.
CIBER-1, Spitzer, and AKARI all observed fluctuations at near-IR wavelengths that appear to be extragalactic, highly correlated between different instruments, and not associated with known galaxy populations. Models of IHL associated with the assembly of cosmic structure are consistent with the data and suggest that IHL may represent a major branch of light production at near-IR wavelengths. Probing the history of IHL through improved anisotropy measurements using multiple bands and correlating with other tracers of large-scale structure is essential to understand this population's importance in the cosmic history of star formation. In addition to the low-redshift IHL signal, the search for fluctuations in the near-IR background arising from UV emission from the first generation of stars and their remnants continues. The total luminosity produced by EOR sources is uncertain, but a lower limit can be placed assuming a minimal number of photons to produce and sustain reionization. This 'minimal'

extragalactic background component associated with reionization is detectable in fluctuations at the design sensitivity of CIBER-2, and will provide an important constraint on sources of ionizing photons in the $z < 8$ universe.
CIBER-2 has been optimized for IHL-EOR component separation through maximizing its sensitivity to surface brightness and deliberate design of its wavelength coverage. In particular, and uniquely, CIBER-2 will simultaneously observe EBL anisotropy from the optical to deep into the near-IR, providing a long lever to cleanly distinguish and separate the different components of the extragalactic background. The instrument consists of a 28.5 cm wide-field telescope operating in 6 spectral bands covering 0.5 to 2.5 microns, cooled to 80 K with a liquid nitrogen cryostat. Three focal plane assemblies operating H2RG detector arrays generate 1.1 × 2.3 square degree images of the sky. In addition, 3 linear variable filter bands provide continuous coverage over the near-IR to permit absolute photometry of the background light. Our successful first flight demonstrates the readiness of the instrument, but additional flights are necessary for the instrument to reach its full scientific potential.

In this program, we request funding to support 2 recovered flights and to analyze these flight data to final science products. We will study the history of IHL production by implementing a multi-band cross-correlation analysis, and use this information to search for a reionization component. We will also combine multi-band CIBER-2 data with weak lensing maps and galaxy redshift catalogs to fully elucidate the history of IHL production through spectral cross-correlations. CIBER-2 will pathfind these techniques using real flight data ahead of the SPHEREx MIDEX mission, and help train a diverse workforce ready to push the boundaries of IR astrophysical science and instrumentation.

Astrophysics Theory Program
Abstracts of Selected Proposals
(NNH21ZDA001N-ATP)

Below are the abstracts of proposals selected for funding for the Astrophysics Theory Program (ATP21). Principal Investigator (PI) name, institution, and proposal title are also included. One hundred and eighty-four proposals (184) were received in response to this opportunity. On November 3, 2021, forty-four (44) proposals were selected for funding. On February 11, 2022, three (3) additional proposals were selected for funding.

Matthew Baring/William Marsh Rice University
Modeling Hard X-ray Bursts and Giant Flares from Magnetars

Magnetars are neutron stars of extreme magnetization, the most magnetized objects known in the Universe. They are among the most topical sources in high energy astrophysics, being discovered in 1979 when their emission of intense flares of non-thermal hard X rays was first detected. Pulsed modulation of the signal in a single giant flare forged the interpretation of a neutron star origin. Yet in the intervening 35 years, we still do not know precisely what emission mechanisms are acting in their magnetospheres to produce such signals. Nor do we know how the much more common `regular' bursts from magnetars arise. Notwithstanding, the observational database for magnetars has expanded dramatically over the last 2 decades, and we now know of nearly 30 confirmed magnetars. Last year elicited the exciting discoveries of the detection of a fast radio burst from a Galactic magnetar during an X-ray bursting epoch, and the detection of a giant flare from a magnetar in the nearby Sculptor galaxy. NASA's Fermi mission featured in both these discoveries, and has enhanced magnetar science through the observation of prolific bursting activity from select sources using the Gamma-Ray Burst Monitor (GBM). The GBM has clearly demonstrated that magnetar spectra are non-thermal with a quasi-exponential cutoff, a so-called Comptonized form. The intensities of magnetar bursts and giant flares strongly suggests that their emission zones are highly optically thick to Compton scattering.

This program will perform detailed numerical computations of the establishment of hard X-ray spectra of transient magnetar signals using a Monte Carlo approach. We plan to develop state of the art models for both burst and giant flare emission signatures using Monte Carlo simulations of radiation transport and particle dynamics in magnetar magnetospheres, assembled using several existing well-tested codes. The dominant process will be Compton scattering, with polarizations of photons being tracked, since they are integral to determining the scattering probabilities. The Compton cross section will include the details of cyclotronic resonances that are sampled at higher altitudes and enhance overall opacity. It is planned to first model an evolving Comptonizing cloud that expands in closed field regions of the magnetosphere, adding the important radiation processes of magnetic photon splitting, and magnetic one-photon pair creation for giant flares. Given an impulsive injection of energy at either equatorial or polar locales, the transport of radiation and energy exchange between pairs and photons will be tracked, using observations to provide diagnostics on the lepton injection/acceleration site. A prime objective is to determine what physical processes limit the emission to less than a few hundred keV in energy. Polarization characteristics will be ascertained to serve as a guide for science agendas of planned future hard X-ray/soft gamma-ray polarimeters such as LEAP and AMEGO. The simulation will be adapted to define a dynamical outflow model for the spectral shape and pulsation properties of the initial spike and temporal tail of magnetar giant flares. The outflow zone will be fed radiation from an equatorial fireball zone. One goal here is to ascertain whether a super-Eddington polar outflow can explain the observed pulsation amplitude in giant flare tails, and if so, how it can constrain the geometry and energetics of these rare events. Another agenda is to calibrate the pair density so as to assess how it loads the outer magnetosphere with plasma, an influence that might account for the alteration of magnetar spin-down rates observed subsequent to giant flares.

Nicholas Battaglia/Cornell University

A Novel Approach to Maximize the Astrophysical and Cosmological Information Extracted from Thermal Sunyaev-Zeldovich Maps

Over the past two decades we have built a simple 6-parameter cosmological model, LCDM, that describes current cosmological observations. More recent observations have hinted that departures from our ΛCDM model may be required to reconcile measurements of the cosmic microwave background (CMB) and late-time probes of the large-scale structure (LSS) growth. However, the relative precision of these differences is not yet of sufficient statistical significance to be clear evidence for new extensions. In this proposal we will develop a method that uses secondary temperature fluctuations in the CMB to assess whether these differences are real and extensions to our cosmological model are necessary.

As CMB photons propagate through the expanding universe they are scattered by energetic electrons in the intracluster medium and circumgalactic medium, resulting in secondary fluctuations which are the dominant temperature anisotropies on arcminute scales. The thermal SZ (tSZ) effect is the increase in energy of CMB photons due to scattering off hot electrons and probes the integrated pressure along the line-of-sight. Measurements of the tSZ effect are sensitive to baryonic effects like feedback and how LSS grows over time.

The statistical tSZ estimator that probes all the statistical tSZ moments (and almost all the information) for a given scale is the probability distribution function (PDF) of a tSZ map. This is an underutilized estimator and excellent candidate to provide the precision needed to determine whether extensions to our cosmological model are necessary. The tSZ PDF has been measured and used to constrain growth of structure parameters. Despite these tSZ PDF measurements being highly statistically significant, their cosmological constraints were comparable to those from other tSZ observables. The limiting factor for these tSZ PDF analyses were in the theoretical modeling and methods.

Approximations were necessary to analytically write out the likelihood. And multi-scale tSZ PDF analyses have not been utilized because of the non-trivial covariance matrix computations required. We will undertake this work in the proposed investigation, by developing a novel method to optimally extract cosmological and astrophysical information from multi-scale tSZ PDF measurements, which will enable the full utilization of the tSZ signal to place competitive constraints on extensions to our current LCDM cosmological model.

Mitchell Begelman/University Of Colorado, Boulder
Strongly Magnetized Disks: A Paradigm Shift in Black Hole Accretion Physics

The amount of vertical magnetic field threading an accretion disk is a fundamental second parameter in accretion disk physics, of comparable importance to the accretion rate. Even modest amounts of net magnetic flux can drastically change the vertical structure of the disk, catalyzing the creation of a strong toroidal (horizontal) field whose pressure thickens the disk and broadens the accreting zone. The resulting faster inflow rates and lower densities can in principle resolve numerous shortcomings of standard accretion disk theory, by explaining outburst timescales and variability in cataclysmic variables (CVs), X-ray binaries (XRBs), and active galactic nuclei (AGN); spectral and thermal anomalies in XRBs and AGN; state transitions in XRBs; and the absence of thermal instabilities in the high-soft state. Magnetic elevation could also prevent or limit gravitational fragmentation in the outer disks of AGN. The extreme limit of flux accumulation, in so-called magnetically arrested disks (MADs), appears necessary to explain the creation of powerful jets and is supported by recent observations with the Event Horizon Telescope.

Although magnetic field is a key disk parameter for the reasons cited above, we do not understand how it is distributed in accretion disks or how it evolves either theoretically or observationally. Through this project, we aim to reduce the uncertainty surrounding the magnetic field configuration by using first-principles general-relativistic magnetohydrodynamical (GRMHD) simulations of accretion disks around black holes. We will address the competition between advection and diffusion of magnetic flux within a disk, how the disk structure evolves in response to accumulated flux as a function of radius, and the observational signatures by which these magnetic effects can be detected and studied.

Specifically, we will:

1) Determine the conditions under which a disk can become strongly magnetized by dragging in flux from the environment. We will carry out a systematic survey over thermal scale height and initial magnetization, in order to see when field can be captured and advected toward the black hole and when it diffuses away. By running simulations for longer durations and to larger radii than in previously published models, we will attain sufficient dynamic range to study field transport under

conditions approaching those in AGN and XRBs, and to determine whether the flux distribution can reach a steady state or not.

2) Analyze the simulations to extract analytical models for the vertical structures of strongly magnetized disks, and to understand the basic physical processes responsible for these structures such as instabilities, buoyancy, dynamo effects and large scale torques.

3) Post-process the simulations and use the analytical models to extract basic-level radiative features that might be observable, and their dependence on both magnetization and accretion rate. We will further use radiation GRMHD simulations to study the survival or collapse of strongly magnetized hot accretion flows as a function of sub-Eddington luminosity. Effects to be studied will include coronal structure, the emergent spectrum and polarization, and transitions between optically thick and optically thin behavior that might characterize disk state transitions, especially in XRBs and changing-look quasars.

Results from this study will have a direct impact on the interpretation of radiation from accreting black holes across the electromagnetic spectrum, both from existing NASA facilities and upcoming missions such as the Imaging X-ray Polarimetry Explorer (IXPE).

Andrei Beloborodov/Columbia University
Magnetic Dissipation and Radiation from Compact Objects

The project will investigate the process of magnetic energy conversion into electron-positron plasma and radiation around neutron stars and black holes. This process plays a fundamental role in the observed bursting activity of compact objects, which are studied by NASA missions. The proposal builds on existing kinetic plasma simulations of two known dissipation mechanisms: magnetic reconnection and Alfven wave turbulence cascades. The new kinetic simulations will be coupled to a radiative transfer code that tracks the emission/absorption of photons and their conversion to electron-positron pairs. This will lead the project to the next milestone: a first-principle model for emission from magnetic reconnection and turbulence damping. The new simulation tools will also be used to explore a novel dissipation mechanism described in the proposal. This mechanism is activated in strong low-frequency electromagnetic waves. In contrast to common belief that such waves silently escape, the proposal demonstrates that the waves must dissipate in the vicinity of the compact object, creating powerful electron-positron fireworks around it. The main outcome of the proposed work is a theoretical framework that will allow one to predict emission spectra from first principles and compare them with observations. This framework will be instrumental in understanding the mechanism of magnetar X-ray bursts, fast radio bursts, electromagnetic precursors of neutron star mergers, and hard X-ray emission from accreting black holes.

Lars Bildsten/University Of California, Santa Barbara
Massive Star Envelopes and Explosions: 3D Simulations and Observational Consequences

Massive stars are at the forefront of astrophysical research, both due to their rapid, and sometimes dramatic, evolution on the main sequence, and soon thereafter, when they explode due to the emergence of a strong shock from the collapsed core. Prior to explosion, they are luminous enough to approach the Eddington limit and receive increasing hydrostatic support from radiation pressure. Our proposed efforts are 3D radiation hydrodynamic (RHD) simulations with Athena++ to reveal the unique properties of convection, radiative transfer and turbulence in astrophysical regimes immediately applicable to current and upcoming observations.

Some distant stars unambiguously reveal their 3D nature to the observer, such as seen in images of nearby RSGs (e.g. Betelgeuse), whereas other stars exhibit phenomena which we attribute to physics that is intrinsically multi-dimensional, such as conventional convection. It has been a theoretical challenge to realistically model stars in 3D due to the obvious computational hurdles. This is especially true in cases where radiative transfer must also be simultaneously solved through a highly turbulent medium with large density variations over optical depths ranging from far above unity down to the radiating photosphere. However computational capabilities have now reached the level where physically realistic 3D RHD models can be run for long enough to reach a local steady-state solution which can then be diagnosed and compared to observations.

With this proposal we will perform 3D RHD simulations of near-Eddington stars, identify when the structural impact of the 3D nature of the RHD cannot be accurately represented by 1D predictions, and, where possible, allow for meaningful updates to 1D models such as those in Modules for Experiments in Stellar Astrophysics (MESA). An equally critical goal is to perform and diagnose specific 3D RHD models of observational relevance. The first observational connection is to the outer 25% of convective envelopes of stars on the main sequence (OB stars) heavier than 20 times the mass of the sun, where recent TESS observations are finding surprising temporal variability. The second observational context is nearly whole star convective models of luminous red supergiants at the end of their lives. The structure of their outer envelopes is manifest when observed prior to explosion and impacts the early part of the supernovae light-curves, especially the shock breakout signatures first seen by GALEX and expected to be studied in detail by the planned ULTRASAT UV mission.

Simeon Bird/University Of California, Riverside
A Cosmological Emulator in 11 Dimensions for the Roman Space Telescope

With the arrival of NASA s WFIRST (Nancy Grace Roman Space Telescope) telescope, an unprecedented amount of information will be available to constrain cosmological parameters even on small scales where structure growth is non-linear. However, realising this potential will require the construction of large, accurate, computational models for structure growth. These models take the form of emulators: computer codes which interpolate between cosmological simulations. This proposal will build and publicly release a new theoretical model for the matter power spectrum with increased parameter coverage over an extended cosmological model with 11 parameters. We will use the multi-fidelity cosmological emulation technique, which reduces the number of high resolution simulations required to build an emulator by a factor of > 4. A large number of low resolution simulations, which map out the dependence of the power spectrum on cosmology, are combined with a few high resolution simulations, which correct for resolution in a cosmology dependent fashion. Compared to previous emulator projects, our new emulator will increase the number of parameters simultaneously emulated to 11 and will have accurate modelling of massive neutrinos. Our emulator will include the 5 parameters of the base cosmological model and 6 parameters covering all currently popular ΛCDM extensions. These will include parameters with the potential to alleviate the current tensions in the cosmological model, the H0 and S8 tensions. The effects of baryons will initially be included using a baryonification recipe. Pending the completion of separate work, hydrodynamic simulations will be incorporated as a higher fidelity rung of our emulator to directly model the effect of galaxy physics.

Omer Blaes/University Of California, Santa Barbara
Accretion Disks around Supermassive Black Holes with Realistic Opacity

In marked contrast to models of accretion disks around stellar mass black holes, neutron stars, and in cataclysmic variables, existing theoretical models of accretion disks around supermassive black holes do a very poor job of explaining, never mind predicting, the observed properties of luminous active galactic nuclei (AGNs). We contend that a primary reason for this is that luminous AGN accretion disks contain regions that lie in a very different physical regime, a regime that happens to be very similar to the envelopes of massive stars. They are hugely radiation pressure dominated, and they have temperature sensitive Rosseland mean opacity enhancements due to iron, as well as enhanced opacities due to partially ionized helium. In massive stars, these opacities can drive vigorous convection and also highly time-variable outflows. Local simulations of magnetohydrodynamic turbulence in gas pressure dominated accretion disks have already demonstrated that opacity driven convection can directly alter the turbulent stresses in highly time variable ways. We expect that such effects will only be stronger in the radiation dominated environment of a luminous AGN disk.

We propose to carry out radiation magnetohydrodynamic simulations of specific radial regions of AGN accretion disks where iron opacity is likely to affect the dynamics of the disk, as well as regions further out where helium opacity may drive outflows through continuum radiation pressure. We will explore how these effects depend on black hole mass, accretion rate, and metallicity. We anticipate that these opacities will drive highly time variable convection which will affect the vertical heat transport and even the vertical hydrostatic support because of large convective turbulent kinetic energy densities. We also anticipate that the convection will interact with the magnetohydrodynamic turbulence to alter the angular momentum transporting stresses, potentially affecting the radial temperature and density profiles of the disk. We believe that this variability is likely to play an important role in explaining the characteristic time scales measured in damped random walk models of observed optical/UV variability, and may also play a role in the changing look AGN phenomenon. The helium opacity region is likely to be cospatial with the launching zone of line-driven winds, as well as the region where existing models predict the disk to be self-gravitating. Our simulations will therefore hopefully provide a better physical picture of the disk in these important regions.

In addition to running and analyzing these simulations, a major objective will be to build a new, flexible and observationally testable model of the optical/ultraviolet emitting regions of AGN disks, as a replacement to the standard alpha disk model which is so problematic. Informed by the simulation results, we will parameterize the dependence of turbulent stresses, vertical turbulent pressure support, vertical convective heat transport, variability amplitudes, and continuum opacity-driven mass loss rates as a function of black hole mass, accretion rate, radius, and metallicity. That this will be possible is due to the fact that the dynamics here rests on well-characterized atomic physics underlying the continuum opacities. By doing this we hope to shed light on numerous, unexplained aspects of luminous AGN phenomenology, including their spectra, their stochastic variability, and the existence of changing-look quasars.
The simulation code we will be using is mature, and we will hire a postdoctoral researcher to assist in running the simulations on NASA supercomputers, and analyzing the results to elucidate both the physics and the observational implications. This will provide invaluable training in modern computational radiation magnetohydrodynamics, as well as in applying simulation results to an important astrophysical problem.

Laura Blecha/University Of Florida, Gainsville
Bridging the Gap from Galactic Scales to Black Hole Accretion Flows in a Multiphase ISM

Supermassive black holes (BHs) are fundamental to many aspects of galaxy evolution, and they are the next frontier in gravitational wave (GW) astronomy. Pulsar timing arrays may very soon detect nanoHertz GWs from BH binaries, and the Laser Interferometer Space Antenna (LISA) will be able to detect BH mergers out to z ~ 20. Currently, however, essentially everything we know about BHs beyond the local Universe comes from electromagnetic observations of gas accretion onto BHs, seen as active galactic nuclei (AGN). Even in the coming era of low-frequency GW astronomy, electromagnetic observations of BH accretion will be a crucial complement to GW observations in order to distinguish between theoretical models of BH formation and evolution.

This underscores the urgency of addressing a major outstanding problem in astrophysics: how BH fueling occurs in the supermassive regime. The vast dynamic range involved in bringing gas from cosmological to accretion disk scales presents a formidable computational challenge. Most numerical studies of BH accretion focus on either small-scale simulations of accretion disks or large-scale simulations of galaxies and cosmological volumes. The former are limited by the inability to model the dynamical processes that drive gas inflows to fuel accretion disks, and the latter must rely on sub-grid prescriptions to model physics on unresolved scales. This sub-grid physics includes not only BH fueling and feedback, but also star formation, stellar feedback, and the evolution of the multiphase interstellar medium (ISM).

We propose a novel study of gas inflows in galactic nuclei that will bridge this critical gap in our understanding of BH accretion. For the first time, this regime will be explored using a broad suite of cosmological zoom and idealized galaxy and galaxy merger simulations, both with and without AGN feedback, using a state-of-the-art numerical framework. This framework, employed in the AREPO magnetohydrodynamics code, brings together (i) a new explicit model (SMUGGLE) for a self-regulating, multiphase ISM and (ii) a method for achieving ultra-high resolution near multiple BHs, enabling us to resolve the scales of BH gas capture at reasonable computational cost.

The following closely related projects have been designed to address the fundamental question: how do the characteristics of nuclear gas inflows and BH accretion depend on galactic environment?

1. We will quantify the impact of a multiphase ISM on nuclear gas inflow rates and angular momenta in a range of galactic environments.
2. We will examine the dependence of AGN variability and duty cycles, including dual AGN lifetimes, on galactic environment and on accretion and feedback models.
3. We will characterize the nature of early BH growth at high redshift, during the epoch of initial galaxy assembly.
4. We will use the above results to develop an improved sub-grid scheme for BH accretion that can be employed in future galactic- and cosmological-scale simulations.

This investigation will constitute a significant step forward in understanding the electromagnetic signatures of BH accretion, BH growth over cosmic time, and BH/galaxy co-evolution. The proposed sub-grid BH accretion model development will enable a broad range of future studies of BH and galaxy evolution, including GW source predictions. These questions are especially pressing now, as we prepare for a wealth of new high-redshift AGN data from JWST, Athena, and Lynx, as well as the next frontier of GW astronomy in the low-frequency regime.

Michael Boylan-Kolchin/University Of Texas, Austin
Cosmological Assembly of Galactic Disks and Bulges

The origin of thin galactic disks and their connection to thick disks and bulges is a stubbornly outstanding issue in galaxy formation modeling. While our general picture of angular momentum acquisition via tidal torques from large-scale structure -- implying that some galaxies will be supported by angular momentum -- has been in place for several decades, a consensus model of how, when, and why thin disks form and survive has not emerged. The spin-up of baryonic material leads to a broad distribution of angular momentum, both in terms of amplitude and orientation, which means that the emergence of thin disks requires further processing beyond simple spin-up and angular momentum conservation during cooling. The subsequent survival of thin disks in a hierarchical universe is also somewhat surprising, at first blush. Finally, connections among the formation of thin disks, thick disks, and galaxy bulges remain murky: are thick disks often heated remnants of early thin disks, or are thick disks precursors to the formation of thin disks? Does bulge material come from stars and gas with high initial angular momentum support that is later scrambled by mergers or secular processes, or can bulges be formed directly from turbulently supported gas or the migration of giant gaseous clumps at high redshifts?

Using state-of-the-art cosmological simulations of Milky-Way-mass galaxies, our work will explore the connection between angular momentum acquisition and galaxy morphology as a function of time. We will explore the structure of disks at high redshift, their evolution to low redshift, and the processes that drive morphological changes along the way. Through chemodynamical analysis at z=0, we will compare to ongoing surveys of galaxies in the local Universe to understand the origins of their present-day structure. By making mock James Webb Space Telescope (JWST) images of our simulated galaxies at high redshift, we will provide paths for using JWST data to differentiate among current models of disk galaxy formation. A subset of our simulations will include black hole feedback models, enabling us to understand the role of AGN feedback in disk galaxy evolution. Finally, we will explore the circumgalactic medium s role as the mediator of cosmological inflow (providing the baryonic fuel for galaxy formation) and stellar feedback (establishing the turbulence and clumpiness of disks). This work will result in a theoretical framework that will help interpret data from NASA missions, including JWST, and will contribute to NASA Science Mission Directorate's strategic objective to understand the Universe and the Astrophysics Division's goal of exploring the origin and evolution of the stars and galaxies that make up the Universe.

Blakesley Burkhart/Rutgers University, New Brunswick
The Cosmic Origins Spectrograph as a Probe of AGNFeedback in the Low Redshift Lyman Alpha Forest

Recent observations of the low redshift Lyman-± forest have challenged our theoretical understanding of neutral gas in the intergalactic medium (IGM), as the statistics of the observed and numerically simulated Lyman-± forest spectra do not agree (Kollmeier et al. 2014; Gurvich et al. 2017; Tonnesen et al. 2017; Viel et al. 2017). We will use simulations to perform the first comprehensive analysis of the impact of AGN feedback and the galactic UV photon escape fraction on the low-redshift Lyman-± forest. Both these physical processes are of critical importance for the wider field of galaxy formation. In particular, AGN feedback is a poorly understood process which can control the star formation rate in massive galaxies The power of NASA's Hubble Space Telescope s (HST) Cosmic Origins Spectrograph observations of the low-redshift Lyman-± forest arises as they directly measure the effect of AGN feedback on neutral gas surrounding galaxies, allowing detailed constraints of AGN feedback models. In order to guide future observations in differentiating our models, we will also generate predictions and forecasts for potential future space-based UV missions. Our research uses data from a current NASA mission and provides a science case for future NASA missions and is thus within the scope of the astrophysics theory program. Our theoretical work will address the following key science questions:

What constraints can be placed on cosmic ultraviolet background models at low redshift by HST/COS observations, and what does this mean for the average galaxy UV photon escape fraction? To what distance does AGN feedback heat the neutral IGM, and what are the observable effects on the low-redshift Lyman-± forest? How are the statistics of the Lyman-± forest, such as the flux power spectrum, column density distribution function (CDDF) and b-parameter distribution affected by the feedback prescription?

The proposed observations can only be taken in the UV and thus require space-based missions (e.g. HST COS). In order to guide future observations in differentiating our models, we will also generate predictions and forecasts for potential future space-based UV missions. As our research involves a combination of multiple NASA missions it is thus within the scope of the astrophysics theory program.

Luca Comisso/Columbia University
Self-Consistent Particle Anisotropy Transforms our View of Synchrotron High-Energy Sources

Synchrotron emission from high-energy electrons powers virtually all astrophysical non-thermal sources. Synchrotron light curves, spectra, and polarization measurements allow us to shed light on the dissipation and emission processes of high-energy astrophysical sources. However, despite the enormous observational progress, our current understanding and modeling of synchrotron emission are limited by the use of ad hoc assumptions for the particle momentum distribution in the emission region. The key and commonly-adopted assumption of isotropic particles has been recently challenged by fully kinetic particle-in-cell (PIC) simulations, which arguably represent the most powerful tool for studying from first principles the physics of particle acceleration. Given that the synchrotron power per particle depends on the "pitch" angle between particle velocity and magnetic field, synchrotron emission may be severely suppressed in plasmas with anisotropic particle distributions, as compared to the commonly-adopted isotropic case. The vast majority of models neglect the effect of anisotropy, and so they miss a key ingredient to interpret the observed emission.

With this proposal, we argue that we need to go "back to the drawing board:" a self-consistent treatment of particle anisotropy is of paramount importance to model astrophysical high-energy emission, and may help to solve the most puzzling mysteries of non-thermal sources. Our main goal is to perform first-principles PIC simulations of magnetized plasma turbulence, including cooling losses (synchrotron and inverse Compton, via both external Compton and synchrotron self-Compton) as well as pair production. With a physically motivated description of non-thermal particle acceleration in turbulence --- both regarding the particle spectrum, as well as the energy-dependent pitch-angle anisotropy --- we will be able to produce reliable radiative models, with a predictive power missing in current approaches. The research program tackles three outstanding questions in modeling high-energy astrophysical sources. (i) The GeV flares from the Crab Nebula; (ii) The "orphan" gamma-ray flares in BL Lacs; (iii) The source of internal dissipation in GRB jets, which gives rise to the so-called "prompt" emission. Our first-principles simulations will produce synthetic light curves and spectra that can be reliably compared with the wealth of available observations.

Zachariah Etienne/University Of Idaho, Moscow
superB: Numerical Relativity for LISA & 3G Detectors

Numerical relativity (NR) solves Einstein's equations of general relativity (GR), in full, on the computer. Improvements to the algorithmic and mathematical underpinnings of NR codes have recently culminated in a coming-of-age for the field, moving it beyond proof-of-principle calculations and into the realm of predictive astrophysics. Over the past five years, NR-based theoretical predictions of gravitational waves (GWs) have formed the foundation for analyses aimed at uncovering the binary parameters in all GW observations of binary black holes (BBHs).

Despite NR's successes in these early years of gravitational wave (GW) astronomy, one need not scratch far beneath the surface to uncover challenges that limit or threaten the potential science gain from future GW observations. In short, the unprecedented sensitivity promised by LISA/3G GW detectors will not translate into unprecedented science gain unless NR codes become far more accurate and efficient.

Among various new NR infrastructures in development, one of the most promising for advancing LISA and 3G detector science is BlackHoles@Home. BlackHoles@Home is a new NR code for the consumer-grade desktop that leverages recent algorithmic and mathematical advances in NR to solve the GR field equations on dynamical multiple-patch, bispherical-shaped, numerical grids. Such grids are optimized for the BBH problem, and have resulted in factors of ~10-100 boosts in efficiency over current NR codes, along with far greater accuracies that come with 10-100x less numerical noise in its GW predictions. In short BlackHoles@Home has brought the BBH problem from the supercomputer to the desktop.

However, the goal of BlackHoles@Home is not to generate NR-based GW predictions as quickly as possible, but to maximize throughput in their generation over the timescale of years. Looking ahead, it is quite possible that LISA and 3G detectors observations of loud GWs from BBHs will usher in a new age of GW data analysis, in which rapid, focused NR-based GW follow-ups are a requirement. BlackHoles@Home's focus on efficiency over speed rules out rapid follow-up NR simulation campaigns, as well as the ability to (in a reasonable time) model high mass ratio or long inspiral BBHs that LISA may detect.

To this end, we propose to develop superB: a highly scalable, supercomputer-ready fork of the BlackHoles@Home NR code, built atop the Charm++ infrastructure.

The development of superB will take place in stages, with the goal of achieving two key performance Milestones. The first Milestone aims to improve speed such that a 20 orbit simulation of a 70:1 mass ratio BBH can be performed on a supercomputing cluster within one month, by the midway point of the proposal period. The second milestone aims to improve performance on supercomputers by at least another factor of 2, to achieve the same duration simulation for a 100:1 mass ratio BBH, by the end of the proposal period.

JiJi Fan/Brown University
Cosmological Probes of Scalar Dynamics

Quantum field theories of scalars have played an important role in the development of theoretical cosmology studies. They have been applied widely to model different stages of cosmic history and address some of the most challenging questions in cosmology, such as: how does the transition from inflation to the thermal big bang happen? what are the nature and cosmic history of dark matter? The proposed research aims at developing new scalar field models for cosmic particle production and axions, and exploring their novel cosmological and astrophysical probes. It consists of two concrete tasks: 1) develop new observables of preheating and particle production in general, and explore a new mechanism that could improve the depletion of the inflaton energy density by several orders of magnitude compared to canonical preheating mechanisms in the literature; 2) examine under-explored astrophysical sources and measurements that could probe and constrain the axion's couplings to the standard model particles, study the cosmological evolution of axion dark matter which obtains its mass from interacting with Abelian gauge fields instead of non-Abelian gauge fields, and improve the models with the axion as an early dark energy component to alleviate both the Hubble and S8 tensions simultaneously.

The proposed research is at the interface of multiple neighboring fields: particle physics, cosmology and astrophysics. It will employ both analytical and data-driven approaches. On the one hand, these tasks will apply theoretical tools in quantum field theory (e.g., symmetries and non-perturbative dynamics) to enhance our understanding of cosmic scalar field models and sharpen their predictions for astrophysical observables. On the other hand, they will open up new avenues to interpret the rapidly growing cosmic data.

This proposal addresses NASA's astrophysics objective to understand how the universe work and the underlying scientific principles. The two tasks focusing on different aspects of cosmic scalar dynamics complement each other and will both contribute to building up a full cohesive history of our universe.The proposal will utilize rapidly improving data from existing NASA experiments such as the Hubble space telescope, Chandra X-ray Observatory, WMAP and Planck, as well as future missions and projects such as PICO, SPHEREx, PIPER and LCRT.

Claude-Andre Faucher-Giguere/Northwestern University, Evanston
The Physics of the CGM and its Role in Galaxy Evolution

This project focuses on the physics of the circumgalactic medium (CGM) and its role in galaxy evolution. The proposed work is motivated by evidence that the CGM holds the key to answering several of the outstanding central questions in galaxy formation, as well as by recent advances in galaxy formation simulations. The project will use a new generation of cosmological zoom-in simulations from the FIRE project, which include a comprehensive model for stellar feedback and have sufficient resolution to self-consistently capture interactions between the ISM and the CGM. The new simulations also include previously-neglected but important physical processes: magnetic fields, cosmic rays, and multi-channel AGN feedback.

In the first part, we will carry out a detailed analysis of the cosmic baryon cycle in the new simulations by identifying and tracking different types of gas flows based on their full history (inflows, outflows, recycling flows, ...). We will expand on previous work on the baryon cycle in three major ways: (i) a quantification of how the baryon cycle depends on the new magnetic field/cosmic ray/AGN physics; (ii) a comprehensive analysis of the angular momentum evolution of gas in different channels and the implications for how galaxies assemble; and (iii) predictions for how abundance patterns trace different parts of the baryon cycle, which will enable observations to better constrain the feedback processes involved, including core collapse vs. Type Ia SNe.

In the second part, we will focus on the role of CGM virialization in driving critical transitions in galaxy evolution. Recent work predicts that inner CGM virialization (ICV) plays a key role in explaining multiple transitions experienced by galaxies around L*: (i) the emergence of large, long-lived galactic disks; (ii) the transition from bursty to steady star formation; (iii) the suppression of star formation-driven galactic winds around Milky Way-mass galaxies; and (iv) the accelerated growth of supermassive black holes and the onset of strong AGN feedback. We will first use controlled simulations in which galaxy and CGM physical parameters can be varied independently to identify the causal mechanisms involved in these transitions, as well as to explicitly test the predictions of ICV against competing theories. We will then use cosmological simulations to develop new statistical predictions necessary to test the proposed physical picture in observations. We will in particular predict how CGM properties relate to the formation of disk galaxies, the onset of AGN feedback, the quenching of star formation, and the formation of ``red and dead'' massive ellipticals.

This project will enable the interpretation of major discoveries made by several of NASA's observatories, including HST and Chandra, about the CGM and galaxy evolution. The project will also produce predictions testable by future observations of galaxy evolution with JWST and Roman, and of the hot CGM by future X-ray and CMB missions.

Robert Fisher/University Of Massachusetts, Dartmouth
The Physics of Turbulence-Driven Detonation Initiation in Type Ia Supernovae

Type Ia supernovae (SNe Ia) are among the most common and most luminous events in the transient cosmos. SNe Ia play a crucial role in astrophysics as sources of momentum and energy, turbulence, cosmic rays, and enriched isotopes for the interstellar medium. SNe Ia serve as standardizable candles for cosmology, and therefore they play a critical role as both probes of dark energy and in a possible Hubble constant tension between early and late universe physics. Yet, despite their importance, the stellar progenitors and explosion mechanisms of SNe Ia remain largely unknown.

This proposed research effort addresses the SNe Ia stellar progenitor and explosion mechanism problems by directly tackling the physics of the central engine of SNe Ia, detonation. Researchers have recently developed an experimentally validated first-principles theory of the turbulence-driven deflagration-to-detonation transition (tDDT) in realistic, unconfined media. Under the auspices of this proposal, we will build upon these recent advances to construct subgrid models for incorporation into global full-star hydrodynamical simulations of SNe Ia. We will undertake an extensive set of global full-star simulations of leading near-Chandrasekhar mass (M_Ch) and double- degenerate progenitor channels. In close collaboration with leading theorists and observers, we will compute nucleosynthetic yields along with synthetic spectra and light curves from these models, and will widely disseminate these.

The resulting investigations for the first time will incorporate a first-principles, experimentally-validated DDT mechanism into SNe Ia models, with potentially transformative impact on the outstanding questions of stellar progenitors and explosion mechanisms of SNe Ia. We will make nucleosynthetic yields, synthetic spectra, and light curves generated from our models widely available to observers and modelers. This work will be of key relevance to current and upcoming NASA missions, including HST, JWST, Chandra, the Nancy Grace Roman Space Telescope, and the JAXA/NASA Hitomi replacement XRISM. Large-scale simulations will make it possible to address whether double-degenerate binary white dwarf mergers are able to account for normal SNe Ia, and improve our insight into a crucial probe of the nature of dark energy and the Hubble tension.

Francois Foucart/University of New Hampshire, Durham

Models of Kilonova and Gamma Ray Burst Sources with Monte-Carlo Neutrino Transport

Over the next few years, observations of neutron star-neutron star (NSNS) and black hole-neutron star (BHNS) mergers are expected to provide us with information about a wide range of open questions in physics and astronomy. By observing these mergers, we can improve our understanding of the properties of dense nuclear matter, the origin of heavy elements, the mass and spin distribution of black holes and neutron stars, and the mechanism powering short gamma-ray bursts, among other topics. NASA missions will play a crucial role in this process, as long as we can rely on accurate models for the electromagnetic signals powered by these events.

BHNS/NSNS mergers and their post-merger remnants are complex systems that can only be accurately studied through general relativistic simulations evolving Einstein's equations, the relativistic equations of (magneto)hydrodynamics, and neutrino radiation transport. Due to their high cost, however, these simulations are not used directly to analyze observations. Instead, we rely on semi-analytical models of observable signals calibrated to the results of a small number of simulations. Existing models are severely limited by insufficient parameter space coverage and incomplete physics in simulations. The main objectives of this proposal will be to perform merger and post-merger simulations aimed at addressing some of the main remaining model uncertainties. We will in particular leverage the Monte-Carlo radiation transport code recently implemented in the SpEC merger code to accurately determine the mass and composition of the matter outflows emitted during merger, and over the long-term viscous evolution of the remnant disk. Advanced neutrino transport algorithms are crucial to the determination of the composition of matter outflows, which in turn sets the outcome of r-process nucleosynthesis in mergers and greatly impact the properties of kilonovae. Our simulations will be the first large scale study of BHNS/NSNS systems with full neutrino radiation transport, including both 3D merger simulations and axisymmetric simulations of black hole-disk and neutron star-disk remnants. We will then use the result of our simulations to improve existing outflow models, and address potential biases in kilonova models due to the use of simulations with approximate transport algorithms.

We will additionally use SpEC to study one of the most important division of the BHNS parameter space: the exact location of the boundary between disrupting BHNS mergers (which produce bright electromagnetic counterparts) and non-disrupting BHNS mergers (which don't). This boundary plays a major role in our interpretation of electromagnetic signals from BHNS mergers, yet it has so far largely been extrapolated from simulations of disrupting BHNS binaries. To address potential biases due to that extrapolation process, we will perform a suite of simulations directly exploring the location of the boundary between disrupting and non-disrupting binaries, and use them to improve models of matter outflows in BHNS mergers.

Finally, we will take advantage of the availability of Monte-Carlo radiation transport in SpEC to study energy deposition due to neutrino-antineutrino annihilation in black hole-accretion disk systems. Pair annihilation could play an important role in the production of short and long gamma-ray bursts. Our simulations will for the first time study this process through general relativistic evolution of an accretion disk including radiation transport and viscosity.

Steven Furlanetto/University of California, Los Angeles
A New Window into Galaxy Physics and Environments During Cosmic Dawn Through Cross-Correlations

In the next few years, several new NASA missions will provide exquisite measurements of the high-z Universe, from detailed photometry and spectroscopy of individual galaxies (James Webb; JWST), to wide-field surveys targeting bright galaxies (Roman), to statistical fluctuations in the diffuse near-infrared background (SPHEREx). Though each facility constitutes a major advance on its own, the most compelling science will require a synthesis of each disparate observable into a cohesive model of galaxy formation and cosmic reionization. This is a major modeling challenge, as the properties of individual galaxies depend on their large-scale environments, while the large-scale ionization environments in turn depend on, and influence, the properties of galaxies. Capturing all relevant scales and physics in a single volume is thus beyond the reach of even state-of-the-art simulations.

In order to provide context to the relatively small fields targeted by JWST with the large-scale information accessible to Roman and SPHEREx, we first propose to build what we will hereafter refer to as a hybrid simulation pipeline. This pipeline will meld together semi-numerical algorithms, which relate the properties of entire galaxy populations to the large-scale density, to semi-analytic modeling techniques, which relate galaxy properties to the detailed formation histories of their host dark matter halos. In this framework, N-body simulations are designed to resolve only the halos that host galaxies bright enough to be detected in upcoming surveys, leaving all unresolved populations to be modeled via the semi-numerical approach. This frees up computational resources that can then be used to dramatically increase the simulation volume, which results in predictions that are well-matched to the wide areas of upcoming surveys with Roman and SPHEREx, ensuring that galaxies in a wide variety of environments are captured by the model.

We will focus on two main applications of this new modeling pipeline. First, we will calibrate techniques for inferring the large-scale environment of galaxies from upcoming surveys, which will allow observers to compare galaxy samples in different environments, provide predictions for the signatures of assembly bias and feedback from reionization, and guidance for stacking analyses in comparable environments to constrain sources beyond survey magnitude limits. It will also open up the possibility of constraining the reionization history in individual regions of the Universe. Second, we will make predictions for cross-correlation signals between Roman and SPHEREx, as well as current and future probes of reionization via CMB and 21-cm telescopes. Such investigations are uniquely enabled by our large-volume hybrid simulations, and will provide guidance for, e.g., how to constrain the escape fraction of ionizing radiation in high-z galaxies, as well as the magnitude (or equivalent halo mass) at which the galaxy luminosity function turns over -- neither of which are easily accessible via galaxy surveys alone.

Our research program will provide valuable modeling tools and mock datasets for theorists and observers. All software used to generate mock catalogs in JWST, Roman, and SPHEREx filters will be made publicly available, as will the mocks themselves. This is complementary to large ab initio simulation efforts, as we can afford to run hundreds of models with different assumptions, rather than presenting only a few best guess scenarios. Doing so is essential for understanding the combined results from several upcoming NASA missions, and thus will significantly increase their return-on-investment.

Vera Gluscevic/University Of Southern California
Cosmological Signals of Light Dark Matter: New Predictions and Connections

Dark matter is a major constituent of the Universe, but its physical nature remains a mystery, and the leading candidate is a new particle whose fundamental properties are unknown. In context of current null results from direct detection searches, a broad landscape of compelling candidate models has emerged, in particular involving light (sub-proton-mass) particles that could easily evade detection in a laboratory. Such candidates are readily accessible with cosmological probes.

We propose to develop a theoretical framework that will enable simultaneous inference of two fundamental properties of dark matter particle---its mass and strength of interactions with normal matter---using cosmological information relevant for the Big Bang Nucleosynthesis, cosmic microwave background (CMB) anisotropy, and substructure in the local Universe, self--consistently, avoiding reference to specific particle models. Such a framework will dramatically improve sensitivity of the CMB and other structure-based probes to light dark matter in all thermal-relic scenarios.
It will also allow exploration of completely novel dark matter paradigms. Finally, it will enable future analyses to integrate out assumptions about the high-energy behavior of dark matter and focus on constraining its fundamental properties robustly, with a combination of data sets.

We set the following goals: i) provide model-independent and self-consistent predictions for primordial element abundances, linear matter power spectrum, and CMB primary anisotropy for interacting light dark matter; ii) enable forward-modeling of substructure in cosmologies featuring light dark matter scattering with baryons; iii) critically re-assess and improve bounds on dark matter particle mass and interactions with standard particles, using CMB anisotropy and Milky Way satellite abundance.

The proposed work will have profound implications to human understanding of the fundamental nature of dark matter, aligned with NASA's mission. Our results and products will directly facilitate analysis and interpretation of CMB data from present and future NASA missions; in particular, the proposal directly helps to expand the science scope of Planck and PICO (NASA mission under study). Theoretical formalisms we propose to develop facilitate exploration of dark matter signals using all probes of structure in the Universe, and therefore directly align with the mission of SPHEREx, the Roman Space Telescope, and more broadly, to the science goals of DES, DESI, Simons Observatory, CMB-S4, and the Vera C. Rubin Observatory.

Sebastian Heinz/University Of Wisconsin, Madison
Heat Pumps in the Heart of Galaxy Clusters: Black-Hole Mitigated Conduction in Cool Core Clusters.

Objectives:

The physics of cool core galaxy clusters plays a key role in our understanding of cosmic structure formation and evolution. The necessary fine balance between heating and cooling in these systems poses challenges both for our understanding of microphysical processes in the hot ionized medium within the cluster (cosmic ray transport, thermal conduction, and turbulence) as well as the physics of black hole accretion and jet formation. While thermal conduction had been discounted as a possible mechanism to provide the fast yet gentle heating required for feedback to work, recent work suggests that jets driven by the accreting central supermassive black hole can drive large scale flows that transport low entropy gas from the cluster core into thermal contact with the vast thermal heat bath of the outer cluster, in effect acting like a heat pump. In theory, this new path can increase the efficiency of AGN heating well above 100%, even if thermal conduction is strongly suppressed below the Spitzer value. At the same time, new approaches to modeling particle transport in simulations of AGN jets and new methods of analyzing the X-ray emission from clusters (in particular, the ability to measure X-ray intensity power spectra) afford us with the opportunity to develop new connective tissue between the observational and computational study of cool core clusters.

We will investigate the physics of AGN feedback in cool core clusters with a focus on testing the hypothesis that AGN jets can act like heat pumps. We aim to quantify the efficiency gain and heating rate of clusters subject to AGN-driven entropy transport and thermal conduction. We will derive new diagnostics of current and past AGN activity and develop tools for visualizing thermal and non-thermal emission from cool core clusters, with a focus on current and future X-ray obseratories in the NASA portfolio.

Methods:

We will use the FLASH code to perform high-resolution MHD simulations of jet propagation in cool core clusters, focusing primarily on the Perseus cluster as a well-defined test case. The simulations will have sufficient numerical resolution to preserve large temperature gradients induced by bulk transport of cluster gas ahead of and in the wake of the jet-inflated cavities. Carefully controlled resolution experiments will control the effects of numerical mixing that otherwise plague large scale simulations of clusters and mask the action of thermal conduction. To facilitate efficient and accurate computational modeling of anisotropic thermal conduction, we will develop a two-moment method to treat anisotropic thermal conduction module for FLASH in order to ensure that the simulations could be performed at very high resolutions and at much reduced CPU costs compared to the expectations based on simulations performed using standard approaches to include heat transport. We will continue to develop power-spectral analysis tools that allow spatially masked calculation of intensity fluctuation spectra and compare them directly to X-ray observations of the Perseus cluster and other clusters. We will use an implicit particle transport solver to accurately model the spectral evolution of the non-thermal synchrotron and inverse Compton emission from the jet and radio lobe plasma.

Significance to NASA objectives:

The study of the X-ray cooling of clusters and their heating by supermassive black holes directly maps to the Physics of the Cosmos objectives and the core science objectives of current and future X-ray telescopes operated wholly or in part by NASA, such as Chandra, XMM, Hitomi, XRISM, and Athena. Specifically, our study will address the themes "How Did We Get Here--The History of Galaxies" and "How Does the Universe Work--Revealing the Extremes of the Universe" of the NASA Road Map "Enduring Quests, Daring Visions".

Tina Kahniashvili/Carnegie Mellon University
Gravitational Waves as a Probe of the Early Universe

In the first fractions of a second after the Big Bang, the extremely energetic and dense environment of our universe would have sourced a strong gravitational radiation. This radiation is expected to survive in the universe today as a stochastic gravitational wave background. Gravitational wave missions such as the Laser Interferometer Gravitational-Wave Observatory (LIGO) are currently searching for this signal, and the upcoming Laser Interferometer Space Antenna (LISA) will extend the search by several orders of magnitude in sensitivity. A detection of this primordial gravitational radiation will open a window onto the early universe, thereby allowing us to explore the composition and dynamics of the universe at an epoch that remains inaccessible to laboratory experiments.

We propose to study the generation of gravitational radiation from various early-universe sources. A primordial gravitational wave background that's detectable by LIGO or LISA cannot arise from the Standard Model of particle physics and cosmology alone, but rather it would be strong evidence for new physics. We propose to analyze well motivated models of axion-driven inflation and cosmological phase transitions (involving physics beyond the Standard Model and including but not exclusively first order ones). We are especially interested in the imprints of possible parity violation in the early universe which will result in the non-zero circular polarization of the stochastic gravitational waves background. Another focus of our research will consist of investigating primordial plasma dynamics and its effects including generation of acoustic (sound waves) and/or turbulent motions in the early universe (without being limited by non-relativistic description). The gravitational waves from parity violating inflationary sources can leave an imprint on the cosmic microwave background anisotropies (birefrigence, parity-odd cross correlations), while the gravitational waves from realistic early-universe turbulent sources possibly present around the electroweak energy scale are within the reach of LISA. We propose phenomenological and numerical studies of physical processes in the early-universe to determine the initial conditions for viable gravitational waves source generation and development.

The successful completion of this work will furnish the astrophysics community with (i) robust predictions for gravitational wave spectra from early universe sources, (ii) guidance for distinguishing different potential sources given the data, and (iii) clear understanding of how new physics can be probed with gravitational wave observations. Overall this work advances NASA's agenda to explore the origin, evolution, structure, and destiny of the universe itself.

Constantinos Kalapotharakos/University of Maryland, College Park
Exploring the Foundations of Pulsar High-Energy Emission

This proposal seeks to advance studies to address outstanding problems in pulsar science and non-thermal astrophysics, particularly acceleration of the highest energy particles in pulsars. Its goals are driven by the >13-year accumulation of Fermi data and the imminent release of the Fermi Third Pulsar Catalog, reports of >100 GeV pulsed emission by MAGIC and HESS-II, and the beginning of operations by the Cherenkov Telescope Array. Pulsars are a special class of astrophysical objects because of the broad variety of physical processes (e.g., non-ideal MHD effects, particle acceleration, broadband emission, pair-production) that take place in their highly magnetized environments. The gamma-rays dominate energetically and thus provide the best constraints on the pulsar current structure, electric fields, and dissipation location. In the last decade, observational and theoretical advancements have set the stage to provide a compelling description of the pulsar phenomenology but also to explore the underlying microphysical foundations. Yet, the plasma generation and acceleration of the highest energy GeV/TeV particles remains an open research question.

The proposed work will expand on state-of-the-art MHD (ideal and dissipative), particle-in-cell (PIC), and radiation codes of pulsar magnetospheres to include physically consistent injection of pairs and study their effects on the global magnetosphere structure; our goals are an account of the Fermi phenomenology as evidenced by the newly-discovered Pulsar Fundamental Plane , detailed models of pulsar pulse profiles, and insights in pulsar plasma creation and acceleration of particles for TeV gamma-rays. The proposed investigation will place the study of extant pulsar magnetosphere models on much more secure footing and solve several outstanding current issues by its inclusion of (i) microphysics of pair formation locally and globally and (ii) broadband phase-resolved spectral studies that span infrared to TeV energies. The methods of the proposed study are state-of-the-art, ranging from local PIC codes that capture small-scale microphysical properties to efficient 3D MHD and PIC codes that provide the large-scale global magnetospheric properties. Importantly, we propose a cohesive way of combining these approaches to obtain realistic magnetospheric structures and synchronous pulse profiles and spectra that can be tested against data.

The results of our studies will lead to robust constraints and a deeper understanding of the mechanisms behind broadband pulsar emission. More specifically, our study will uncover the role of various emission mechanisms (i.e., curvature radiation, synchrotron, inverse Compton, and synchrotron-self-Compton) and their contribution in the various parts of the spectrum. This will enable unprecedented insight into the machinery of pulsars as high-energy accelerators and generation of the cosmic rays from them and set the stage for the Cherenkov Telescope Array and future proposed NASA observatories in the MeV band, such as AMEGO/AMEGO-X.

Changgoo Kim/Princeton University

Star Formation Regulation and Wind Driving in Numerical Simulations of the Interstellar Medium with Supernovae, Stellar Winds, Radiation and Cosmic Rays

Galactic star formation is notoriously inefficient, proceeding at a rate two orders of magnitude below the maximum. The inefficiency of gas consumption has been attributed to the effects of energetic feedback from massive stars. Feedback restores energy lost to dissipation and radiation, thereby maintaining the overall force balance between pressure and gravity. Feedback also drives galactic outflows that transfer mass and metals from galactic disks to halos, with the associated energy from hot gas and cosmic rays reheating the circumgalactic medium. Star formation, feedback, and its effects in the interstellar medium (ISM) is a multi-physics, multi-scale problem; highly localized collapse and stellar feedback of several forms dynamically interact with gravity, magnetic fields, and turbulence, subject to the complex microphysics of the multi-phase ISM.

The proposed project aims to develop a state-of-the-art numerical framework for modeling the star-forming ISM at high spatial resolution including all the major feedback agents: supernovae, stellar winds, UV radiation, and cosmic rays. The proposed work will make use of recently developed physics modules and couple them with a highly efficient magnetohydrodynamics code. Our framework includes:

- An adaptive ray tracing module for UV radiation transfer to follow photo-ionization, photo-dissociation, photo-electric heating, and radiation pressure;
- A two-moment cosmic ray module for transport with advection, streaming, and diffusion including a self-consistent calculation for varying scattering coefficient in different gas phases;
- A photochemistry module coupled with the computed UV radiation field and low-energy cosmic ray density to track species abundances and cooling/heating.

The new simulation framework will allow us, for the first time, to systematically and quantitatively assess the role of different feedback mechanisms in regulating star formation rates and driving multiphase galactic winds. We will focus on two representative galactic conditions (one similar to the solar neighborhood and the other typical of nearby star-forming disk galaxies) at high resolution with full physics. We will run a set of restart control models to study the impact of different feedback mechanisms. We will also run a set of simulations with varying metallicity to understand the effects of reduced cooling on star formation and galactic outflow rates, and on thermal phase balance. Finally, we will run simulations in which cosmic rays are fully active, affecting gas dynamics and ionization and self-consistently setting the scattering rate coefficient. The proposed program will make substantial progress toward comprehensive numerical modeling of the star-forming ISM, and will provide theoretical underpinning for observed links between ISM properties, star formation rates, and wind outflow rates identified by several NASA missions.

Alexei Kritsuk/University Of California, San Diego
Simulations of the Turbulent Interstellar Medium for Future CMB Experiments

The search for the imprint of gravitational waves on the cosmic microwave background (CMB) through precision measurements of the CMB polarization is an ambitious endeavour. It holds the potential to reveal information about the first fractions of a second of our Universe. However, polarized galactic emission is brighter than the signal from the early Universe at all frequencies, even in the cleanest patches of the sky. Thus, being able to remove galactic emission is of crucial importance for the quest to detect gravitational waves from the early Universe.

To facilitate the removal of foregrounds, experiments observe the sky at a range of frequencies. The set of frequencies and the sensitivity at each frequency must be identified when the experiment is designed, long before the first data is taken. Future experiments will be as much as two orders of magnitude more sensitive than current experiments so that existing data is only of limited use. As a consequence, the optimization of the design requires simulations of the sky that are as realistic and representative as possible.

The anisotropies in dust and synchrotron emission are currently typically simply approximated as Gaussian fluctuations with an amplitude that reproduces the desired level of polarized foregrounds, and a simple frequency dependence like a power law for synchrotron radiation and a modified black body spectrum for dust. The foregrounds in the real sky are, of course, highly non-Gaussian and display a more complex and spatially varying spectral dependence.

The PI and Co-I propose to perform ab initio simulations of the multiphase magnetized interstellar medium (ISM) that will allow to generate self-consistent maps of polarized galactic emission over the full range of frequencies and angular scales relevant for the search for gravitational waves from the early universe. These maps will be shared with the CMB community. As such, the proposed research falls within the science goals of NASA's space-astrophysics program and is directly relevant for future ground-based experiments like the South Pole Observatory, Simons Observatory, as well as CMB-S4, and for space-based CMB experiments like LiteBIRD as well as next-generation space-based CMB experiments like PICO.

This work will lead to multiphase magnetized ISM simulations that will be a significant improvement over earlier simulations through higher order accurate numerical methods and increased resolution, which will allow to extend the inertial range from degree scales relevant for the recombination peak to arcminute scales relevant for delensing, and through the inclusion of dust particles in the simulations, which will allow to study how well dust emission in the higher frequency bands is expected to correlate with dust in the CMB bands.

The simulations will also help to answer some fundamental questions of critical importance to a better understanding of multiphase MHD turbulence, such as how energy is transferred from large to small scales, whether there is a conservative Kolmogorov-like energy cascade, and which mass-weighted variables can properly capture the energy transfer physics. The simulations will help to understand the energy exchange between Alfv\'en and fast and slow magnetosonic modes and whether or not it leads to energy equipartition between the modes. The simulations will be used as a testbed for the emerging reconstruction techniques of the interstellar magnetic field topology from polarimetric observations.
Finally, the simulations have the potential to generate transformative approaches to both star formation and compressible MHD turbulence, e.g. in galaxy formation modeling in cosmological context, where stellar feedback plays an important role.

Yuan Li/University Of North Texas
Connecting Galaxies and Supermassive Black Holes: Meso-scale Simulations of Multiphase Accretion Flows

Most supermassive black holes (SMBHs) in the local universe are accreting at rates much below the Eddington limit, yet they generate enough feedback power to maintain the quiescent state and suppress cooling flows in massive galaxies and galaxy clusters. How gas flows from the galaxy onto the SMBH is far from clear. NASA's Chandra X-ray observations of nearby SMBHs challenge the classical Bondi accretion model. Optical and radio observations further suggest that in many systems hosting powerful radio jets, the central region is multiphase with a much cooler component in addition to the hot X-ray gas. We propose to study the multiphase SMBH accretion flows in these systems from galaxy-scale to horizon-scale. We will focus on the meso-scale accretion flows from the Bondi radius to hundreds of Schwarzschild radii, predicting the mass flux of different phases, as well as their angular momentum and magnetic flux.

The proposed research will serve as an important step towards a complete picture of the SMBH feeding-feedback cycle in the low-redshift universe. Our proposal takes advantage of a newly developed nested zoom-in technique that has been successfully used in studies of the hot accretion flow onto the SMBH in our own Milky Way. This technique allows us to initialize higher-resolution, smaller-scale simulations with conditions drawn from larger-scale simulations. We will simulate three representative systems with varying masses, from the central galaxy of a massive galaxy cluster to a typical group central. Out of the three systems, we will first focus on M87, the central galaxy of the nearby Virgo cluster, which now has rich observational data available from galactic scales all the way down to the event horizon. We will examine the physical properties of the meso-scale accretion flows, and how they depend on the mass of the system and the stage of the SMBH feedback cycle. Our proposed research will bridge a gap in our current theoretical understanding of SMBH accretion and will provide realistic initial conditions for horizon-scale GRMHD simulations. The findings will also be used to inform galaxy-scale simulations and large-scale cosmological simulations of galaxy formation and evolution.

The proposed theoretical work is tightly connected to observations. In particular, it bears direct relevance for the observations of several NASA space missions, including Chandra and the Hubble Space Telescope. It will provide theoretical guidance on the interpretation of existing observations related to SMBH accretion, black hole mass measurements, and SMBH variability studies, as well as making predictions for future missions.

Matthew Liska/President and Fellows of Harvard College
Simulating Luminous Black Hole Accretion Disks and Coronae

Most black holes (BHs) in our galaxy were discovered when they underwent dramatic outbursts, in which their luminosity increased by multiple orders of magnitude and they transitioned through a `luminous-hard' state. The physics of such luminous disks is of crucial importance to understanding the growth of supermassive black holes (SMBHs) through cosmological time since such disks drive most of the mechanical and radiative black hole feedback. However, the 'luminous-hard' state is perhaps the least understood black hole accretion state, because radiation, magnetic fields, and strong-field gravity all play dynamically-important roles and cannot be neglected. To make matters worse, the accretion timescale in the inner parts of the accretion disk is so short that the radiation emitting electrons thermally decouple from the ions. This causes the geometrically thin 'cold' outer disk to transition into a geometrically thick 'hot' inner disk consisting out of hot ions and cold electrons. The morphology, dynamics and emission processes of such 'transitional' disks are poorly understood. In addition, we often expect the equatorial plane of the gas accreting onto a spinning BH to be misaligned with the BH equator, which can lead to severe disruption of 'transitional' accretion disks.

The non-linearity of the governing equations, including the possible occurrence of thermal and viscous instabilities in the disk, severely limits the ability of semi-analytical models to make accurate predictions and warrants first principle numerical simulations in order to properly interpret observational data. The primary difficulty for simulating such `transitional' disks numerically is the need to dynamically resolve the extremely small angular thickness of the disk as it moves through the computational grid: this requires the usage of highly efficient numerical simulations featuring adaptive mesh refinement.

Using the GPU accelerated general relativistic magnethodynamics (GRMHD) code H-AMR the field recently succeeded in simulating a 'transitional' accretion disk. As the 65 degrees tilted disk evolved, it tore apart through the warping of space-time and started to precess. Precession provides arguably the most compelling explanation for low frequency quasi periodic oscillations (QPOs) observed in X-Ray Binary (XRB) lightcurves.

The main thrust of this proposal is to carry out, analyze and ray-trace the next generation of GRMHD simulations of accretion disks in the 'luminous-hard' state. In contrast to previous simulations, which used an over-simplified analytical model to mimic radiative cooling, we will use our newly developed radiation GRMHD code that, in addition to radiation, also takes into account thermal decoupling between ions and electrons in the plasma. In addition, using a separate set of GRMHD simulations incorporating our newly developed resistivity and viscosity schemes, we will test the effects of a non-standard magnetic Prandtl number on accretion disk turbulence. These next generation GRMHD simulations are expected to lead to a vastly improved understanding of luminous black hole accretion including the morphology of the mysterious corona, the formation of radiation driven outflows and the (non-)occurrence of thermal and viscous instabilities. The proposed ray-tracing analysis performed by a to-be-hired postdoc will allow us to generate first-principle lightcurves and spectra from such simulations. This will significantly improve our theoretical understanding of data obtained by NASA-funded missions such as NICER, Chandra, Hubble and JWST.

Andrew MacFadyen/New York University (Inc)
Orbital Evolution and Multi-Messenger Signatures of Binary Black Holes with Circumbinary Disks

The goal of this proposal is to elucidate the long-term orbital evolution, as well as the accompanying electromagnetic and gravitational wave signatures, of black hole binaries (BHBs) with circumbinary gas disks.

This requires a detailed understanding of the hydrodynamical reaction of the disk to the orbital motion of the BHBs, as well as the back-reaction of the disk on this orbital motion, while treating the coupled system self-consistently. This is an exceptionally well-posed problem, whose clean solution will yield the answers to fundamental questions, such as: (i) How long does a BHB take to coalesce? (ii) How efficiently are the individual BHs fueled during the coalescence process? (iii) What are the basic characteristics of this accretion and the emerging electromagnetic (EM) emission?

In order to answer these questions, the proposed research will follow a multi-pronged, systematic approach, combining analytic calculations with one-, two- and three-dimensional, high-resolution hydrodynamical simulations. The results from this proposal will be applied to interpret observations of (i) the stochastic gravitational wave (GW) background and of any individual supermassive BHBs by Pulsar Timing Arrays (PTAs), (ii) periodicities in quasar light-curves in large time-domain EM surveys and (iii) stellar-mass BH binaries detectable by LIGO and Virgo. Our results will also be needed to interpret EM counterparts of inspiraling BH binaries discovered by the planned space-based GW detector LISA, in which NASA is invested as a partner.

The proposed work will directly support NASA's Strategic Plan via its Strategic Goal 1: "Expand Human Knowledge Through Scientific Discoveries," Strategic Objective 1.1: "Understand the Sun, Earth, Solar System, And Universe," including the core context "Discovering the Secrets of the Universe."

Mathew Madhavacheril/University Of Southern California
Inflation Physics from Cosmic Velocities with Joint Galaxy and CMB Simulations

The main objective of this project is to enable the tightest constraints on multi-field inflation to date by using cross-correlations of the cosmic microwave background (CMB) and galaxy surveys. This requires measuring cosmic velocities with the kinetic Sunyaev-Zeldovich (kSZ) effect, an imprint in the CMB that can be extracted jointly with galaxy surveys. This recently proposed application holds great promise because analysis of upcoming galaxy and CMB data is forecast to reach an uncertainty in the amplitude of primordial local non-Gaussianity, fNL, below sigma(fNL)~1, bringing observations to the regime where models of inflation involving an additional spectator field can be discriminated. Currently, theoretical predictions are inadequate for application to upcoming observations, due to an insufficient understanding of the systematic effects inherent to this new probe of the early universe. Detailed verification with a set of numerical simulations that models primordial non-Gaussianity as well as relevant survey systematics -- with correlated large-scale structure for CMB and galaxy observables -- will be crucial for putting inflation physics from kSZ on a robust footing. We propose to develop a novel approach for jointly simulating large-scale structure and the correlated CMB, resulting in the only available simulated dataset of the kind required to measure the kSZ effect through cross-correlations of large-scale structure observatories like SPHEREx, Euclid, Rubin and Roman with CMB surveys like Simons Observatory and CMB-S4. In addition, the simulations will be publicly available to the community and allow pan-experiment collaboration for joint cosmological analyses with a wide array of observables. The novel techniques developed will enable simulations to be produced efficiently, paving the way for combining multiple observational probes through likelihood-free or simulation-based inference. Our joint sky simulation framework will satisfy a key theoretical requirement for making discoveries in fundamental physics from cosmic velocity measurements using galaxies and the CMB.

Katarina Markovic/Jet Propulsion Laboratory
Leveraging Weak Gravitational Lensing - Redshift Space Distortions Cross-Correlations

The growth of cosmic structure on large scales has the potential to serve as a powerful discriminator between models of dark energy and modified gravity. Multiple experiments have successfully measured large-scale growth with two powerful probes: weak gravitational lensing (WL) and redshift-space distortions (RSD) in the distribution of galaxies. WL and RSD measurements are primary science targets for next generation Stage IV surveys including NASA s Nancy Grace Roman Space Telescope, ESA/NASA Euclid Mission, the NSF/DOE Rubin Observatory s Legacy Survey of Space and Time (LSST) and the NSF/DOE Dark Energy Spectroscopic Instrument (DESI). WL and RSD constraints from these experiments have the potential to trigger a paradigm shift in our canonical cosmological model.

The observed anisotropic clustering of galaxies in redshift-space, called RSD, is a combination of the isotropic clustering of galaxies in real space and the apparent distortion of this signal due to peculiar velocities. Both the clustering of galaxies and their velocities are correlated with the underlying distribution of large scale dark matter structure in the Universe. The same cosmic scaffolding induces a coherent distortion in the observed ellipticities of background galaxies measured in WL studies. This implies that WL and RSD are extremely covariant and ideally suited to a combined analysis. Yet, the two probes have never been combined in an optimal way because RSD is a 3D signal in redshift space while WL is inherently a projected observable.
A correctly combined RSD WL analysis could yield some of the most competitive and systematics-free constraints on cosmological parameters, modified gravity and dark energy by breaking the degeneracies between cosmological and nuisance parameters, constraining highly uncertain nonlinear RSD models, increasing the signal-to-noise, and acting as an important consistency check. Our aim is to forecast the science returns from a joint RSD WL analysis and develop the theoretical models to fully exploit the physical covariance between the two signals for the first time.

To combine RSD and WL we will use the latest developments in estimator theory, halo occupation distribution modeling, emulation and data compression, and will use some of the largest suites of N-body simulations over cosmological parameter space to date. With the eventual aim of performing a joint RSD WL analysis using these data sets, the goal of this program is twofold:

Objective 1: Forecast the science returns from a joint RSD WL analysis of Stage IV data and, Objective 2: develop a joint model for the RSD WL signal and covariance matrix, and optimally extract information from the cross-correlation.

At the conclusion of our program we anticipate that we will have developed the theoretical tools necessary to perform a combined RSD WL analysis on early Stage IV data releases.

Brian Metzger/Columbia University
The Role of Shocks in Classical Novae

Classical and recurrent novae are eruptions on the surfaces of white dwarfs powered by runaway nuclear burning of hydrogen-rich material accreted from a stellar companion. Although conventionally thought to be powered directly by the thermal energy released from the nuclear burning, a variety of evidence suggests that shocks play a key role in powering nova emission across the electromagnetic spectrum. The high densities in classical novae ejecta imply the dynamical importance of radiative cooling, i.e. the shocks are ``radiative'' with respect to both thermal and non-thermal particles. Hydrodynamical simulations of radiative shocks reveal a rich multi-dimensional picture of the shock-front structure and post-shock gas, which could have a significant impact on the thermal (UV, optical, X-ray) emission as well as the relativistic particle acceleration and non-thermal emission (radio, X-ray, gamma-ray).

The proposed research will develop new multi-dimensional models of radiative shocks and their radiation, allowing the rich multi-wavelength observations to be combined into a coherent description of the nova phenomenon. High resolution MHD simulations of radiative shocks will explore the effects of the upstream magnetic field on the growth of thin-shell instabilities and the implications of magnetic pressure on the post-shock compression. The simulation data will be processed to determine, as a function of the upstream shock parameters, the (1) thermal UV/X-ray emission from the host post-shock gas; and (2) non-thermal radio to gamma-ray emission. These local simulations will be complemented by separate global 2D and 3D hydrodynamical simulations of the shock collision between fast and slow outflows in novae, with the goal of making predictions for: (1) the synchrotron radio light curves and global ejecta geometry inferred from thermal radio imaging; (2) clumping of the gas due to radiative cooling instabilities behind the shock and the resulting implications for observed dust and molecule formation.

The proposed work on shocks in novae will have implications for a variety of topics in high energy astrophysics, including: relativistic particle acceleration and magnetic field amplification at shocks; physical processes giving rise to mass ejection from binary interaction and nuclear burning on white dwarfs (and implications for the single degenerate channel of Type Ia supernovae); hydrodynamical instabilities at radiative shocks; non-thermal emission processes; formation of cosmic dust; and the origin of shock-powered astrophysical transients more broadly. Our results will impact predictions for NASA observatories (Fermi, Swift, NuSTAR, HST) and well as ground-based facilities (VLA, VLBA, ALMA, IceCube, VERITAS, CTA).

Igor Moskalenko/Stanford University
Modeling the Radio/Infrared/Gamma-Ray Correlation at Sub-Galactic Scales for the Milky Way and Starforming Galaxies

Star-forming galaxies constitute a majority of galaxies in the Universe. Until recently they were only observed in radio, infrared, and optical wavelengths. Thanks to the Fermi Large Area Telescope mission, a dozen of such galaxies are now observed in gamma rays. Through these observations, empirical relationships were established between the star formation rate and radio, infrared, and gamma-ray luminosities that holds over many orders of magnitude from dwarf galaxies up to starburst systems.

The basic idea of a connection between the star formation rate that can be scaled through the thermal infrared emission, and non-thermal radio- and gamma rays seems to be clear. Massive stars both heat infrared emitting dust and end their lives as supernovae, whose remnants accelerate cosmic rays, the electron component of which produces synchrotron emission in the magnetic field of the galaxy. Gamma rays with energies >100 MeV are the result of electron bremsstrahlung, inverse Compton scattering off of the interstellar photons, and the hadronic emission produced in inelastic interactions of cosmic ray nucleons with gas. Though this framework constitutes a physical basis for the correlation, its persistence over diverse interstellar environmental conditions is still a mystery. Modern galaxy evolution simulations have included some of these processes, but have a number of hidden parameters that undermine the reliability of their results. Moreover, their steady-state solutions are suitable for unresolved systems, but do not allow to accurately describe spatially resolved details that are observed in the Local Group galaxies.

The objective of this proposal is to elucidate the nature of the widely-employed empirical radio/infrared/gamma-ray correlation, and its extension to sub-galactic scales. We will do this by modeling the thermal and non-thermal emissions from the Milky Way and Local Group galaxies. We are proposing to develop detailed models for the electromagnetic emission due to stars and dust in star-forming regions and entire galaxies. We will simulate the cosmic-ray transport and cosmic-ray-induced emissions from these galaxies by including all relevant processes in the interstellar medium. In the case of star-forming galaxies, the energy density in the radiation and magnetic fields, cosmic rays, and turbulent motions of the interstellar gas are similar, so all of these components should be included self-consistently. Our proposed study will provide the critical insights for breaking the impasse that the galaxy evolution modeling efforts have to properly include cosmic rays into the current frameworks.

Michelle Ntampaka/Space Telescope Science Institute
Precision Cluster Cosmology with Interpretable Machine Learning

The modern cosmological model describes how tiny density fluctuations in the early Universe evolved into today's cosmic web of overdense dark matter filaments, sheets, and halos. The most massive dark matter halos host galaxy clusters containing hundreds or thousands of galaxies and a hot intracluster medium. Galaxy clusters populate the high mass (>10^14 Msolar) tail of the halo mass function, and the abundance of clusters is sensitive to the details of the underlying cosmological model.

Though the modern cosmological model is successful in characterizing the formation of these massive structures, it still has unanswered questions and unexplained tensions. One of these tensions is a disagreement between large-scale structure and the cosmic microwave background's constraints of the amplitude of density fluctuations, sigma8, a cosmological parameter that describes how the matter in the Universe is distributed. As measurements of sigma8 have improved, error bars have shrunk but the tension has remained. Early-time measurements predict a larger sigma8 and more massive clusters, while late-time measurements of sigma8 are smaller and predict fewer massive clusters.

Cosmology is in a golden age for addressing this tension. Rich archival data and upcoming huge observational surveys can be compared to suites of cosmological volume simulations with modern, flexible data analysis techniques. The proposed research will create data analysis methods to take advantage of astronomy's richest data sets and answer open questions in the modern cosmological model. This research will address this opportunity with the following science products:

-- Improved cluster mass estimates with interpretable machine learning: Precise cluster masses are an essential ingredient for most cluster-based cosmological analyses. This research will build on encouraging preliminary results from neural networks to produce a low-scatter mass proxy that is a ~15% improvement over the current state of the art.

-- Galaxy cluster mass accretion as a function of cosmology: Cosmological parameters inform galaxy cluster environment, which in turn affects the cluster merger and mass accretion history. This research will identify measures of mass accretion to constrain cosmological models.

-- Signatures of cluster mass accretion history with convolutional neural networks: The mass accretion history of galaxy clusters leaves subtle imprints on cluster dynamics and cluster outskirts. This research will develop a machine learning image analysis approach for inferring accretion history from multi-wavelength cluster observations.

This research is possible because of recent advancements in three separate fields: 1. planned huge observational surveys that complement existing archival data (e.g., the upcoming, exquisitely detailed Roman Wide Field Instrument High Latitude Wide Area Survey, which will include spectroscopic observations of galaxies in and around clusters), 2. recently released suites of realistic simulations (e.g., the AbacusSummit N-body and Magneticum hydrodynamical simulations), and 3. innovations in modern, flexible, and interpretable machine learning data analysis methods (e.g., deep convolutional neural networks for image recognition).

Stanley Owocki/University Of Delaware
3D MHD Modeling of Obliquely Rotating Massive-Star Magnetospheres

Modern spectro-polarimetry has revealed that a subset of O, B and A-type stars harbor large-scale, organized (predominantly dipolar) magnetic fields, ranging in surface strength from a few hundred to tens of thousand Gauss. Such fields can trap the radiatively driven, ionized winds of hot stars, giving rise to large, corotating, circumstellar magnetospheres. These intricate structures can be detected at multiple wavelengths, with available diagnostics at X-ray, ultraviolet, visible, near-infrared, and radio wavelengths, each probing a distinct magnetospheric component. Building on an extensive formalism developed over the past two decades, the project here will add key new extensions, based on full 3D MHD simulations, together with generation of these synthetic diagnostics, to develop physics-based, observationally constrained 3D models of such massive-star magnetospheres (MSMS). The results will be directly applicable to observations from NASA missions such as Chandra, HST, and TESS. But a potentially broader impact will be the relevance of this study of well-constrained MSMS models as testbeds for magnetospheric processes in other remotely observed magnetized systems, e.g., pulsars and magnetars, or magnetized accretion in protostars, binary systems, and even QSO/AGNs. Finally, utilization of modern virtual reality (VR) visualization to aid physical insight into the complex 3D structure will also offer public outreach opportunities, allowing viewers to ``fly through magnetospheres'' with goggles tuned to a range of spectral bands from X-ray to radio.

Alexander Philippov/Princeton University
First-Principles Simulations of Black-Hole Magnetospheres

A range of long-standing problems in black-hole astrophysics have recently become accessible to detailed investigation by the advent of general-relativistic and radiation methods for particle-based kinetic plasma simulations, as well as GPU-accelerated three-dimensional general-relativistic magneto-hydrodynamics codes. We propose to use our unique, state-ofthe- art computational tools to study (a) the behavior of black-hole magnetospheres in which plasma is supplied by self-consistent pair creation and radiative signatures of pair discharges near the event horizon; (b) dynamics and radiative output of reconnection-powered flares in magnetically arrested accretion flows; (c) the global evolution of accretion-disk coronae with both spacetime curvature and radiation effects, and (d) X-ray emission powered by radiative magnetic reconnection in the coronae of thin accretion disks. This research has broad relevance to NASA science, as it principally aims to understand X-ray and gamma-ray observations by Chandra, NuSTAR, and Fermi. We expect this work to have a broad impact on the field, from stimulating further technical developments in ever more realistic astrophysical plasma simulations, to aiding the interpretation of observations of individual sources.

Anthony Pullen/New York University (Inc)
Characterizing Galaxy Evolution from Line Intensity Mapping

NASA has invested in numerous observatories with the mission to characterize the physics of galaxy evolution across cosmic time. Historically this has included galaxy observations from Hubble, Spitzer, and others. Recently, NASA funded line intensity mapping (LIM) surveys that seek to probe galaxy evolution. While galaxy surveys are fundamentally limited to only the sources that are bright enough to detect, LIM can map the emission from populations of much fainter yet more numerous star-forming galaxies, revealing a more global picture of galaxy evolution and star formation across cosmic time. In order to interpret spectra from both galaxy surveys and LIM, models are required to connect emission observables to galaxy properties such as metallicity and star formation rate (SFR). Cosmological simulations using numerical hydrodynamics or more computationally efficient semi-analytic techniques provide a means of connecting physical processes as well as physical properties with a wide variety of observables. However, numerical simulations are much too expensive to run over the large volumes that will be probed by LIM with the required dynamic range. Semi-analytic models (SAMs) have recently been used to create pilot LIM forecasts, demonstrating the promise of this technique. However, there is no existing rigorous framework for mapping the measurements of multiple line emissions to galaxy properties across cosmic time. In particular, performing a rigorous inference procedure in the high-dimensional space of the direct SAM parameters is computationally infeasible.

We propose to construct an analytic framework that maps a set of galaxy properties to a set of line emission luminosities, enabling upcoming LIM surveys to infer key physical quantities such as the cosmic molecular gas mass and cosmic SFR densities from LIM observables using Bayesian Inference. Unlike the empirical models that have been presented in the literature, this framework will be based on physical a priori models of galaxy evolution and line emission, using semi-analytic models and the IllustrisTNG cosmological hydrodynamic simulation. First, we will combine a model for dense clouds and HII regions in the interstellar medium with the Santa Cruz SAM and the IllustrisTNG simulations to simulate an array of dark matter halos over a range of masses and redshifts populated by galaxies. We will couple each galaxy's cloud properties with spectral synthesis codes (Cloudy/DESPOTIC) to create a library of luminosities for several key lines that will be measured with upcoming LIM experiments, including CO rotational lines, CI, [CII], H-alpha, and [OIII]. Next, using the SAM and TNG, we will construct the Conditional Galaxy Property Distribution (CGPD), which characterizes the N-dimensional distribution of galaxy properties conditioned on halo mass and redshift, and the Line Luminosity Relation (LLR), which characterizes the luminosity of line i based on the set of galaxy properties. We will use dimensionality reduction techniques to find the minimal set of galaxy properties that preserves the most information. Finally, we will combine the CGPD and LLR with a standard halo model to predict LIM observables such as the integrated intensity, auto- and cross-power, and Voxel Intensity Distribution. We will develop an inference framework that provides constraints on the posterior of the CGPD based on a desired set of observations, as well as the global cosmic molecular gas mass and cosmic SFR density. We will publicly release our simulated halo and galaxy catalogs as well as our analysis code. Our results will yield insights into the physical processes of galaxy formation while preparing future NASA missions for LIM and galaxy surveys to probe the physics of galaxies and large-scale structure.

Brant Robertson/University Of California, Santa Cruz
Decoding the Physics of Cosmological Structure Formation from the Intergalactic Medium

The properties of the "cosmic web'", the large-scale filamentary distribution of matter in the universe, are critical probes for constraining cosmological physics including the nature of dark matter and the sum of the neutrino masses. Absorption line signatures of neutral hydrogen gas (the "Lyman-alpha Forest'") in the intergalactic medium (IGM) provide among the best constraints available from the cosmic web, but interpreting such observations requires detailed cosmological hydrodynamical simulations that cover an enormous range of physical models. James Webb Space Telescope, to be launched later this year, will revolutionize this field by providing a census of the time-dependent emissivity from galaxies and active galactic nuclei that ionize and photoheat the IGM. The forthcoming JWST observations further drive an urgent need for sophisticated, high-resolution simulations of the Lyman-alpha Forest that can simultaneously capture the impact of both galaxy emission and cosmological physics on the post-reionization properties of the IGM.

This program will perform an unprecedented study using cosmological simulations powered by the the public, GPU-native, MPI-parallelized code Cholla to model the cosmological formation of large-scale baryonic structures with unmatched detail. A primary scientific advance of this program will be to model the range of physics that influence the observed properties of the Lyman-alpha Forest. During Year 1 of the research plan, simulations will be used to constrain simultaneously the possible mass of warm dark matter candidates while accounting for the allowed range of strength and timing of photoheating from active galactic nuclei and galaxies. Year 2 expands the project to constrain additionally the sum of neutrino masses and the running of the spectral index. Years 2-3 of the project explore the impact of galaxy formation and AGN feedback on the Lyman-alpha forest.The simulations will provide a new window on how galaxies like those discovered by James Webb influence the intergalactic medium, and how the cosmological physics revealed by the properties of the IGM govern the formation of galaxies.

Study of the fine-grained gaseous structures of the intergalactic medium requires cosmological simulations with consistently high resolution maintained throughout a statistical volume of the universe. Cholla has remained at the forefront in this space, and community development has improved its performance by 10x over the last year. The current performance of the code fully enables the proposed scientific plan as demonstrated by the presented scaling tests.

Carl Rodriguez/Carnegie Mellon University

Stellar Dynamics and Stellar Collisions in Star-by-Star Models of Nuclear Star Clusters

Nuclear star clusters (NSCs), found in the centers of most galaxies, are the densest stellar environments in the Universe. These extreme densities are thought to be responsible for many otherwise rare dynamical events, such as physical collisions, tidal disruptions, high-energy transients, gravitational-wave captures, and more. But the births of these leviathans at high redshifts remain shrouded in mystery. Were these systems formed from globular clusters that spiraled into the centers of their host galaxies, from in situ star formation, or both? Did the seeds of super massive black holes that inhabit (some) of these clusters form through repeated mergers of stars and compact objects, or were they already present, forged in some more exotic process? Does the excess of blue light seen in many of these clusters arise from stellar collisions? The upcoming launch of JWST will provide us with an unprecedented view of star cluster formation at high redshifts, making a theoretical understanding of these dynamical environments and their stellar collisions a top priority.

To that end, we will create the first star-by-star N-body models of NSCs with 10^6 to 10^8 stars, realistic stellar evolution, and central massive black holes, in order to understand both the nascent phases of proto-NSC formation and their evolution and growth into the NSCs we observe today. To understand the implications of the many stellar collisions and mergers that occur in these environments, we will simultaneously create a series of low- and high-resolution hydro models of stellar collisions with realistic stellar structures and initial conditions taken directly from our N-body simulations. This will allow us to explore the formation of "super" blue stragglers, intermediate mass black holes, and many other exotic stellar systems and transients that are expected to form in NSCs. This proposal has direct relevance to observations of NSCs at high redshifts (JWST) and in the local universe (HST, Chandra). The N-body tools and hydro prescriptions for stellar collisions will be publicly released as stand-alone modules at the end of this project, allowing the broader theory community to independently model these unique dynamical environments.

Evan Schneider/University Of Pittsburgh
From Feedback to Galactic Winds: The ISM-Halo Connection

In the cold dark matter paradigm, gravitational collapse of dark matter and gas leads to the formation of galaxies, but the galaxies we observe contain far fewer baryons than their cosmic share. A solution to this puzzle is feedback   the process by which star formation leads to the subsequent ejection of gas from galaxies, and thus moderates future star formation. In particular, the hot gas generated by supernovae has been explicitly linked to driving outflows in observations of nearby galaxies, demonstrating that stellar feedback is a key component of galaxy evolution. However, connecting the physics of individual supernova explosions to outflows on a galactic scale has proven challenging.

Numerical simulations of feedback on small scales have led to robust models of supernova bubble evolution, and demonstrated that the temporally and spatially correlated nature of explosions in a cluster can create sufficient hot gas to drive a wind. Meanwhile, cosmological simulations have demonstrated that the global properties of these winds must correlate with global properties of galaxies, such as halo potential and star formation rate. But simulations that can link these two scales are still missing. Until now, no simulation has had the resolution necessary to capture both the driving physics in the interstellar medium (ISM) and the formation and evolution of outflows on a galactic scale.

We propose a suite of such simulations. Using the GPU-native code Cholla, we will run a series of galaxy-scale simulations with a constant resolution of 2pc or less. This scale is sufficient to both a) resolve the hydrodynamic interactions between hot and cooler gas phases that set the properties of winds and b) capture the global properties of these winds as they escape the disk and expand into the surrounding halo. These simulations will answer many specific questions about the nature of multiphase galactic outflows and their connection to the properties of the ISM in which they arise. In particular, we will be able to describe: how local ISM properties like gas surface density affect the properties of the resulting outflows; how global outflow properties scale with global star formation rate and galactic potential; the breakdown of mass, momentum, and energy outflow rates by phase, and how this scales with local or global galaxy properties; and the time variability of these processes.

To do so, we will add star formation and feedback modules to the open-source Cholla code. We will draw on physically-motivated techniques from ISM simulations with similar resolution, creating stellar sink particles based on local ISM properties, and implementing feedback on a local scale that resolves both the thermal and kinetic components of supernova feedback. Self-consistently capturing the process of star formation and feedback in the interstellar medium is critical, as the environment in which supernovae explode has been demonstrated to change their effectiveness in driving winds.

In addition to answering the theoretical questions posed above, we will use the results of these simulations to aide in the interpretation of existing observations of outflows by NASA facilities such as HST and Chandra, as well as future observations by JWST. With a sophisticated radiative transfer post-processing technique, we will create emission maps that can be directly compared to observations, allowing us to place better constraints on observed outflow rates and morphological properties. Both the source code and data generated by the simulations will be made public, and will provide a resource that the astrophysics community can continue to use to study outflows in future investigations.

Sarah Shandera/Pennsylvania State University
Astrophysical Implications of Dissipative Dark Matter: Mom Gravitational Waves to Large-Scale Structure

Mapping the distribution of dark matter is a key science goal of the Nancy Roman Space Telescope, the James Webb Space Telescope and the Euclid mission. Ultimately, this data will be used to understand the still unknown particle physics relevant for 85% of the matter in the universe. Together with advances in the theory and modeling of both dark and baryonic effects, the observations may provide evidence that dark matter has a more complex particle nature than the standard cold dark matter scenario assumes. Intriguingly, dark matter that is not only self-interacting but also dissipative can give rise to a diverse array of structures all the way down to compact objects and black holes formed from dark matter. In that case, gravitational wave data from mergers of compact objects provides a new, complementary set of constraints as well as a possible discovery channel.

Our goal is to develop some of the necessary analytic and numerical tools to test non-trivial dissipative dark matter models with data from cosmic structure on many scales. For that, we employ a model of dissipative dark matter, ``atomic'' dark matter, which is simple enough be done in detail, but complex enough to produce a rich spectrum of structures. In this model, we will predict correlated signatures for large-scale structure, galactic structure, and ultra-compact object abundance and mergers.
While some aspects of this model have been studied before, our work will be the first to include the molecular processes that are essential for understanding cooling and compact object formation. We will (i) Include the full chemistry network into simulations of dark matter halos and subhalos, and make predictions for lensing signatures of dissipative dark matter; (ii) Numerically study the collapse and fragmentation of small gas clouds of dissipative dark matter to more accurately predict populations of black hole binaries formed from dark matter; (iii) Reinterpret existing and future large-scale constraints on dark matter interactions, generally presented in terms of a cross-section, in a framework suitable for dissipative dark matter. We will do this using the temperature-dependent cooling function, which allows large-scale constraints to be usefully combined with complementary constraints from compact object abundance; (iv) Develop a framework for using gravitational wave data on binary black hole mergers to constrain two distinct populations of compact objects: an astrophysical population and a dark matter population, which generically extends into the sub-solar mass regime; and (v) Generalize what we

learn from the specific ``atomic" dark matter model to determine which extensions to more complex particle physics will be both consistent with current constraints and most testable by future gravitational wave observations.

Jonathan Slavin/Smithsonian Institution/Smithsonian Astrophysical Observatory
Dust Destruction in the Inhomogeneous Interstellar Medium

Interstellar dust is both a tracer of galaxy evolution and plays an active role in that evolution. The presence of dust accelerates star formation by catalyzing molecule formation, which leads to rapid cooling and condensation of gas. At the same time star formation and the accompanying feedback leads to dust destruction. Supernovae are central players in both the creation of dust and its destruction as well as in galaxy evolution via energy input. As is now widely acknowledged, the heating and cloud disruption created by supernova shocks is necessary to prevent rapid consumption of gas by star formation. The fact that there is ongoing star formation in present day galaxies is due to supernova feedback. The complex interplay of supernovae and dust is thus clearly important for understanding galaxy evolution.

There have been many studies of dust destruction by supernova shocks, however the full context of those shocks has not been fully explored. The interstellar medium is known to be inhomogeneous on a wide range of size scales ranging from sub-pc to hundreds of pc and that can have a profound influence on supernova remnant (SNR) evolution. In particular SNR evolution is strongly affected by taking place in either a cloudy medium or within a pre-existing cavity. The effectiveness of SNR shocks in destroying dust can similarly be strongly affected by the inhomogeneities in the medium. This aspect of SNR shock dust destruction has yet to be fully explored and the goal of this proposal is to model dust destruction in that context. We will simulate SNR evolution in cloudy media and cavities including the destruction of dust using numerical magneto-hydrodyanamics coupled with grain sputtering and shattering calculations. We will include observational diagnostics including UVOIR emission lines and X-ray emission. We expect to significantly improve our understanding of dust destruction, which is a crucial facet of galaxy evolution.

Glenn Starkman/Case Western Reserve University
Searching for the Topology of the Universe

"How did the Big Bang unfold?" However phrased, NASA's strategic plans have consistently asked this question. We seek the stage on which it unfolded. Over a century ago, Karl Schwarzschild analyzed the available data to find the shape of the Universe. Our objective is to create the analytic and software infrastructure needed to extend that search as far as it can be taken -- to establish the topology and geometry of the universe, the connectivity and dimensions of space, and our location within our "fundamental domain." Some argue that inflation would have stretched any interesting topology beyond observability, but that depends on the number of e-folds of inflation. The observed low-l multipoles of the CMB temperature exhibit multiple anomalies, for which cosmic topology may be a context for a comprehensive explanation. In particular, for angles greater than 60 degrees, there is a near complete absence of two-point temperature correlations on the CMB sky despite the non-vanishing of the low-l angular power spectrum. This requires covariance among different low-l multipoles of the CMB. The only known context in which such covariance arises (while preserving the fundamental underlying origin of fluctuations in quantum processes during inflation) is non-trivial spatial topology on a scale of order the size of the last scattering surface (LSS).

Regardless, Schwarzschild's observational question deserves an observational answer. Previous searches for cosmic topology have extended nearly to the LSS, but they have been applied only to a subset of possible fundamental domain shapes and observer locations. Moreover, given the level of homogeneity of the observable Universe, the dynamics that led to that homogeneity almost certainly operated out to scales well beyond the LSS, and so topology somewhat beyond the LSS should still be discoverable.

After first placing the existing search results in the context of the full set of possible fundamental domains, we will translate existing or easily extended analytic work to software capable of producing simulated primordial fluctuations in the universe. We will then produce simulated observations of observables like the cosmic microwave background (CMB) anisotropies, galaxy distributions, and intensity maps. These simulated observations will be used to attempt to identify promising signatures of topology, both analytically and using machine learning trained on ensembles of these simulations. They will also be used to try to infer candidate topologies from known CMB anomalies. This preparatory work is key to an anticipated future search of existing and anticipated data for the shape of the universe.

A finite universe would force us to rethink inflation, and profoundly influence string/M-theory, quantum gravity and quantum cosmology. More broadly, it would be as monumental as the discovery that the Earth is round. Having found cosmic topology, we could know all of the Universe, not just the corner in which chance has placed us.

Jamie Tayar/University Of Florida, Gainsville

Modeling Red Giants: A Fundamental Diagnostic for Ages Across the Universe

Red giant stars are often used as a diagnostic of galactic histories because they are bright, plentiful in all galaxies regardless of current star formation rate, and particularly visible in wavelengths not obscured by dust. In the future, NASA s JWST mission intends to expand these studies of how galaxies form and evolve to a wider range of galaxies across cosmic time. However, all of this work relies on accurate models of red giant stars that can convert the observed light into estimates of compositions and ages. Unfortunately, work by NASA s Kepler, K2, and now TESS missions studying stars in the nearby universe have demonstrated that current models of red giant stars are significantly offset from reality. Using a combination of asteroseismic masses and radii as well as ground-based spectroscopy, fundamental parameters are now available for thousands of red giant stars. Preliminary work comparing these results to model predictions has demonstrated that these offsets between models and data are age and metallicity dependent, which raises concerns for future extrapolations of these models to lower metallicity galaxies earlier in cosmic time as well as our ability to accurately estimate ages for even the most well studied stars.

We therefore propose to:

- Identify the current discrepancies between published grids of models, document these differences as a function of mass and metallicity, and provide an easy to use open source tool to estimate current uncertainties on the inferences of ages from observational data
- Leverage the existing open source stellar evolution code MESA to thoroughly explore how uncertainties in stellar physics cause variation in commonly used diagnostics such as the temperature of the giant branch, the location of the red clump, the luminosity of the red giant branch tip, the location of the red giant branch bump, and the chemical mixing at the first dredge up.
- Use currently available data to generate publicly available calibrated models that are significantly more consistent with the properties of real red giant stars than any current models.

These better models will then represent a tool for a wide variety of astrophysical studies to interpret data from our own Milky Way (Kepler, K2, TESS, SPHEREx) and in other galaxies (HST, JWST) through data from both individual stars and through stellar population synthesis.

Francis Timmes/Arizona State University
Probing The Interior Composition Of White Dwarfs

Background and urgency: Photons emitted from stellar surfaces and neutrinos released from stellar interiors may not directly reveal all that we want to know about the internal constitution of the stars. For example, a direct view of the chemical stratification from the core to the surface is hidden. These interior abundance profiles matter: they impact a star's opacity, thermodynamics, nuclear energy generation, and pulsation properties. The stellar models, in turn, are used to interpret the integrated light of stellar clusters and galaxies, decipher the origin of the elements, predict the frequency of merging neutron stars and black holes, and decipher the population(s) of exploding white dwarfs that underlay Type Ia supernova cosmology.

Fit and relevance: The interiors of white dwarfs encapsulate their stellar evolution history, especially the nuclear reactions and rotational mixing that take place during the helium-burning stage. The pulsation properties of variable white dwarfs are sensitive to their mechanical, thermal, and composition structures, and hence white dwarf seismology offers the potential to probe the interior composition of white dwarfs, and by extension, the nuclear reaction rates responsible for the chemical stratification. The proposed research program has three interwoven focus efforts that will leverage the 6-7 digits of precision in the observed pulsation periods of variable white dwarfs from NASA's Kepler and TESS missions to open a new frontier on constraining their interior abundance profiles.

A vision of the future and a road map: The goal of this proposal is to reveal the interior mass fraction profiles of pulsating white dwarfs. To reach this goal, we will bind the following into a tightly coupled, bi-directional closed loop: seismology data of variable white dwarfs from NASA's Kepler and TESS missions, nuclear data from the Facility for Rare Isotope Beams and other laboratories, stellar evolution models from MESA, stellar pulsation calculations from GYRE, and a machine learning technique aimed at connecting the observed white dwarf pulsation data with the stellar models. Specifically, the nuclear physics experiments and astronomy observations will provide essential input for the dynamic stellar models. The stellar pulsation models, coupled with a random forest regressor machine learning technique, will then provide guidance to the nuclear physics experiments (e.g., which reaction rates to measure or refine) and enable predictions of new features for white dwarf seismology observations to close the loop.

Outcomes: The major outcomes of this research program will be (1) potentially groundbreaking new constraints on the interior composition of white dwarfs; (2) an open-source random forest regressor software instrument for extracting reaction rate and rotational parameters of the stellar models that produce white dwarfs from the observed g-mode pulsation periods and other properties of white dwarfs; (3) increasing the diversity of white dwarf seismology researchers. The resulting products of the research will be freely shared in support of NASA science activities.

Paul Torrey/University Of Florida, Gainsville
Direct Modeling of Interstellar Dust in a Cosmological Framework

Almost every extragalactic ultraviolet through near infrared observation in the Universe is impacted by interstellar dust. The importance of dust cannot be overstated: Our community's entire understanding of the cosmic evolution of the star formation rate density, galaxy stellar mass functions, and active galactic nuclei luminosities depend directly on our understanding of and correction for the extinction and attenuation properties of dust in galaxies. And yet, a foundational theory describing the origin of galaxy extinction curves, attenuation laws, and their variation evades us. In this proposal, we will develop advanced models for co-evolving dust with state-of-the-art galaxy formation physics in cosmological simulations to date. Our newly developed methodologies will allow us to self-consistently predict the dust content in and around galaxies, including grain size distributions, in galaxies over cosmic time. These advances in simulation methodology that we propose will enable us to make significant progress in the following areas:

- The Origin of Dust Extinction Laws in Galaxies: We will employ a newly developed technique for simulating galaxies at high resolution in a cosmological context in order to develop a general model for the variability of extinction laws within galaxies. We will develop the first cosmological model for the origin of variations in observed extinction laws in the Galaxy and Magellanic Clouds, including slope and 2175 Angstrom bump strength variations.

- A General Model for Dust Attenuation Laws in Galaxies: Dust attenuation folds in the physics of dust extinction with the complexities of star-dust-geometries. As such, attenuation is critically important for SED fitting and the derivation of galactic physical properties. We will combine our cosmological simulations -- that include resolved spatially and temporally varying extinction laws -- with dust radiative transfer models to develop the most robust model for attenuation law variations to date. This will enable us to develop a general theory for the origin of observed relationships in attenuation laws, such as the bump-slope correlation. Moreover, we will use our simulation results to help inform priors that can be used within popular SED fitting codes.

- The Dusty Circumgalactic Medium: In our final year, we will holistically review the distribution of dust within out simulated volumes to assess how dust is wrapped up in the galactic baryon cycle, and the role circumgalactic dust plays in the long standing missing-metals problems in galaxies.

Regner Trampedach/Space Science Institute
Non-LTE 3D Spectral Synthesis for Large-Scale Stellar Surveys, Asteroseismology and Galactic Archaeology

The ability to determine precise and accurate elemental abundances of stars is crucial for a number of lines of inquiry in astronomy. On the galactic scale it can tell us about different stellar populations, whether they merged from dwarf galaxies being tidally torn apart by the Milky way; formed in the colliding gas from a larger merger with our Galaxy; or a giant molecular cloud coalesced from its own gravity forming an open cluster of stars. This latter scenario is probably how our Sun got its start. With sufficiently accurate abundances and the kinematics of two billion stars provided by the GAIA mission, there is a real chance of finding our Sun's siblings, now fully mixed with other populations after about 21 orbits around the Galaxy.

To obtain stellar abundances the emergent spectrum of light is computed for atmosphere models of the observed stars, adjusting the composition of the models to match the observed spectrum. Most such analyses are based on one-dimensional atmosphere models and assume local thermodynamics equilibrium (LTE) in modeling the interactions between radiation and matter. Both greatly reduce the computational cost of the problem, but they also affect the results, with systematic and largely unknown biases and giving conflicting abundances from different spectral lines of the same element.

The proposed project will develop methods for computing radial and temporal averages of 3D atmosphere simulations, that can be used in modified 1D spectral synthesis calculations to exactly reproduce the line strength and profile of the full 3D non-LTE (NLTE) calculation. All the costly calculations will be performed as part of this project, while the spectroscopist user can compute a line profile for just a few times the cost of a 1D LTE calculation. Crucially, these averaged quantities can be interpolated between simulations of a grid, to enable line synthesis for any star with atmospheric parameters that fall within the ranges of the grid. The full 3D NLTE calculations will have to be carried out for the hundreds of simulations of the grid, but can be applied to millions of stars in large-scale surveys like SDSS-APOGEE, GALAH, GAIA and the upcoming 4MOST and WEAVE, to name a few. These NLTE calculations will be for hundreds of specific lines of about 10 elements, and we will prioritize commonly used diagnostic lines. We also anticipate the database to be expanded as part of future projects as need and opportunities arise. This project will nicely complement a current project for computing averages for 3D LTE line synthesis, but for arbitrary lines from the first three ions of any of 27 elements. This combination will revolutionize stellar spectroscopy by being much more realistic, abandoning free parameters, and produce less ambiguous matches to stars enabling new inquiries to realize the full potential of modern stellar surveys.

This work will greatly improve the analysis of all stellar spectroscopic observations, including surveys in support of NASA's TESS mission, and the past Kepler/K2 missions (both for asteroseismic targets and planet hosts). Combining this with the now ubiquitous Gaia parallaxes will provide unprecedentedly strong constraints on all fundamental parameters of stars, and sharpen our view of the stars, their populations in our Galaxy and our place in it.

Dmitri Uzdensky/University Of Colorado, Boulder
Nonthermal Particle Acceleration, Electron Heating and Radiation in Hot Black Hole Accretion Flows: From First-Principles Kinetics to GRMHD Simulations to Observations

Proposal summary

Dramatic new discoveries in black-hole (BH) astrophysics, like the imaging of the M87 supermassive BH s shadow by the Event Horizon Telescope (EHT), are revolutionizing our understanding of these fascinating objects. The light outlining the BH in M87 or at the Galactic Center (Sgr A*) comes from accreting gas just outside the event horizon, where it is heated to tremendous energy before being swallowed. The behavior of this plasma just outside a BH, and its radiation, is the main theme of this proposal.

These magnetized plasma accretion flows are routinely studied with global 3D general-relativistic magnetohydrodynamic (GRMHD) simulations, which have provided an accurate large-scale view of the flow dynamics. However, while these MHD can accurately describe the plasma s energy content and pressure, which is dominated by the ions, they do a poor job of modeling the detailed behavior of the electrons   which emit virtually all of the radiation. This is because these plasmas are collisionless, the electrons and ions are thermally decoupled, and their temperatures may differ wildly; furthermore, the electrons may be highly nonthermal. Not understanding the electron kinetics thus puts us at a great disadvantage for understanding the internal physics and the observed radiation from BH accretion flows, even if GRMHD models provide a correct basic accounting of the overall flow morphology, dynamics, and energetics.

Some GRMHD studies include schemes for evolving electron fluid properties, incorporating the effects of advection, adiabatic compression, and radiative cooling. So far, however, these models have been at best only rudimentary, and often ad hoc, ways to account for electron heating by collisionless turbulent plasma processes.

Developing rigorous, first-principles methods for calculating electron thermal and kinetic properties near BHs is the main goal of our proposal. These methods will be based on relativistic kinetic theory and state-of-the art relativistic particle-in-cell (PIC) simulations of electron-ion plasmas in the semirelativistic (ultrarelativistic electrons but nonrelativistic ions) regime.

We will specifically investigate two types of processes: (a) kinetic turbulence, in connection with persistent synchrotron emission, and (b) magnetic reconnection, a leading candidate for powering intense flaring emission, e.g., infrared and X-ray flares from Sgr A*. To study these processes in the context of BH accretion flows, we will pursue three Research Thrusts:

i. Analyzing GRMHD simulations to measure fluid-level properties of plasma turbulence or current-sheet parameters in local, mesoscopic boxes.
ii. Compiling a library of PIC-based subgrid prescriptions for electron heating, nonthermal particle acceleration, and radiative signatures, as functions of the MHD-level parameters.
iii. Incorporating these prescriptions back into GRMHD simulations to evolve the electron plasma component and compute the resulting radiation.

This project will thus create a two-way information-flow infrastructure for connecting global GRMHD models with first-principles electron kinetic physics. This will provide a rigorous theoretical and computational framework for studies of collisionless, turbulent, relativistic plasmas accreting onto BHs, including Sgr A* and M87, and will enable accurate and direct calculation of the persistent and flaring emission from these systems. By providing a crucial link between GRMHD models and BH observations, this project will greatly advance our understanding of how astrophysical BHs interact with their environments.

This project has strong astrophysical motivation and is made timely by recent advancements in radiative GRMHD and PIC codes and growth in computing resources.

Eli Visbal/University Of Toledo
Modeling Supermassive Black Hole Seed Formation and Growth on Cosmological Scales

Quasar observations imply that billion solar mass supermassive black holes existed within less than a billion years after the Big Bang. Currently, it is not understood how these black holes formed so rapidly. In the simplest picture, they would grow from black hole remnants of the first stars. However, one of these black hole seeds would need to constantly accrete at the Eddington limit from nearly the start of the universe to reach the observed black hole masses. Many effects make this unlikely, including feedback from accretion onto the black hole. One possible alternative explanation is that the first supermassive black holes were seeded by approximately 100,000 solar mass black holes formed through runaway collapse of gas in the early universe. These so-called direct collapse black holes (DCBHs) are only thought to form in special environments with very low metallicity and suppressed gas cooling. The larger mass of DCBH seeds would allow them to more easily grow through gas accretion and mergers into the first supermassive black holes.

While we currently lack definitive observational evidence of DCBHs, a number of upcoming or proposed instruments such as JWST, Lynx, and LISA will soon have the ability to probe DCBH formation. However, to maximize the scientific return of these observations, improved theoretical models are required. Current models cannot accurately determine the cosmic abundance of DCBHs because of the vast dynamic range in spatial scales involved in the problem (i.e. the importance of small dark matter halos where the first stars form within the large cosmic volume containing a single high-redshift quasar). We propose to (i) develop a new semi-analytic framework based on cosmological N-body simulations that solves the dynamic range issue; (ii) run hydrodynamical cosmological simulations of individual DCBHs to accurately calibrate the framework; and (iii) utilize the results to make a range of observational predictions. This work will be used to guide and interpret observations completed through NASA missions including JWST, Lynx, and LISA. We will predict observational signatures of DCBHs which when compared against data will reveal whether DCBH formation is the solution to the puzzle of the first supermassive black holes. This will advance NASA's goal of understanding the history and evolution of galaxies and supermassive black holes.

Nicolas Yunes/University Of Illinois, Urbana-Champaign
Overcoming Systematics in Gravitational Wave Tests of General Relativity with LISA

This proposal is focused on (i) the study of systematics that may hinder tests of general relativity with the Laser Interferometer Space Antenna (LISA), and (ii) the development of methods to overcome these systematics. We propose to explore systematics induced by mismodeling of waveforms (in the inspiral, in the merger and in the ringdown of comparable-mass massive black holes), by astrophysical effects (such as superposition of signals and environmental effects), and by instrumental effects (such as calibration uncertainties and data gaps) in single events and after stacking many events. We will investigate which tests of general relativity are affected by these systematics, modeling either generic deviations (using the parameterized post-Einsteinian framework) or specific deviations (in a given set of theories). For those tests that are hindered by systematics, we will develop methods to ameliorate their effect, by modeling the systematics and then marginalizing over them.

The proposed work is of direct relevance to NASA's strategic mission to better understand the universe through observation, and to NASA's mission of discovery and knowledge. The region of the universe where gravity is very strong and dynamically changing (the extreme gravity universe) is one of the last un-turned stones. This is in part because extreme gravity objects, like black holes, are difficult to resolve due to their size and distance from Earth. NASA's investment in space-borne gravitational wave astrophysics as a partner to the European Space Agency is aimed at resolving such objects and, for the first time, exploring the extreme gravity universe in detail. The focus of this proposal is to aid in this endeavor by ensuring that tests of general relativity and any inferences drawn about theoretical physics from LISA data are robust to systematic uncertainties that will be encountered when real data is collected.

Neil Gehrels Swift Guest Investigator Cycle 18
Abstracts of Selected Proposals
(NNH21ZDA001N-Swift 21)

Below are the abstracts of proposals selected for funding for the Neil Gehrels Swift Guest Investigator Cycle 18 program. Principal Investigator (PI) name, institution, and proposal title are also included. 140 proposals were received in response to this opportunity. On February 8, 2022, 33 proposals were selected for funding.

Marco Ajello/Clemson University
SWIFT CHARACTERIZATION OF PERIODIC-EMISSION BLAZARS

Blazar emissions are characterized by high variability in their Gamma-ray emission, property extended to other wavelengths, enclosing the entire electromagnetic spectrum. This variability also is observed in different timescales, ranging from years to minutes. Some blazars present predictable temporal behavior, having periodic patterns in their emissions. This proposal will observe 3 blazars with $\leq 5\sigma$ periodicity in their Gamma-ray emissions. The Swift observations will help to determine the relationship between the Gamma-ray fluxes and the X-ray and ultra-violet fluxes in these periodicity blazars. Characterizing the multiwavelength properties of these blazars will unveil the mechanisms underlying this phenomenon, for instance, the presence of binary supermassive black holes.

Marco Ajello/Clemson University
THE LEGACY OF SWIFT-BAT: THE HARD X-RAY SKY

Large-scale time-domain surveys have lead to the identification of new types of extreme variability in active galaxies, called changing look" active galactic nuclei (CL-AGNs, hereafter). These extreme variations are not only characterized by orders-of-magnitude changes in the optical, UV, and X-ray luminosity of the source, but also a rapid transition between spectral states. The primary goal of this program is to capture and densely monitor the earliest phases of a new (TOO) CL-AGN event, at optical, UV, and X-rays with Swift UVOT and XRT, in order to provide the critical information on how this phenomenon is triggered and how AGN central engine works.

Marco Ajello/Clemson University
PHOTOMETRIC REDSHIFTS FOR FERMI BLAZARS WITH SWIFT/UVOT

The class of AGNs called blazars, are prominent members of Fermi detected sources. The study of blazar evolution with redshift is important as they also provide a powerful diagnostic tool to study the evolution of the Extragalactic Background Light (EBL). Using blazars as cosmological probes requires knowledge of their redshift. We propose to jointly use Swift-UVOT and SARA-CT/ORM, a 0.65m and 1m telescope in Chile and Spain respectively, to derive photometric redshifts for sources above z~1.3. This method makes use of 10 UV-nIR filters, which allows for reliable redshift measurements. This project will deliver measurements of the Spectral Energy Distributions for 20 3FGL blazars and establish photometric redshifts for those with z > 1.3.

Katie Auchettl/University Of California, Santa Cruz
PROBING THE EARLY UV AND X-RAY EVOLUTION OF TDES

When a star wanders too close to a supermassive black hole, it can be ripped apart and consumed by the black hole. However, exactly the mechanism in which a black hole can rip apart stars and consume them and why they destroy stars is currently not well known. Here we use Swift to shed light on what happens to the stellar debris, and how the black hole devours it by studying the light emitted in optical, UV, and X-ray from this extreme event to piece together the final stages of this star's life

We will take advantage of Swift X-ray Telescope to take multiple snapshots of the evolution of a star that was recently disrupted and devoured by a supermassive black hole. Using the corresponding multiwavelength light curves which will be combined with ground-based spectroscopy we will analyze this data in unison to piece together the properties and nature of both the star and black hole and how the star is accreted.

This proposal utilizes the unique ToO and multiwavelength capability of Swift, which has been revolutionary in studying the transients of all phenomena, especially tidal disruption events (TDEs), the subject of this proposal. These data will place constraints on the early-time energetics of TDEs, which are critical for breaking the degeneracies in current TDE emission models as we continue to explore the TDE phase space and better understand the demographics of our local black hole population.

Katie Auchettl/University Of California, Santa Cruz
BRIGHT OPTICAL TDES AND THEIR FINAL STAGES OF EVOLUTION

When a star wanders too close to a super massive black hole, it can be ripped apart and consumed by the black hole. However, while most studies focus on the very early stages of these extreme events, very little is known about what happens in the final stages of the star being devoured. Here we use Swift to shed light on what happens to the stellar debris many years after the star was initially disrupted.

We will take advantage of Swift X-ray Telescope to take multiple snapshots of the evolution of a star that was recently disrupted and devoured by a supermassive black hole. Using the corresponding multiwavelength light curves which will be combined with ground-based spectroscopy we will analyze this data in unison to piece together the properties and nature of both the star and black hole and how the star is accreted.

This proposal utilizes the unique multiwavelength capability of Swift, which has been revolutionary in studying the transients of all phenomena, especially tidal disruption events (TDEs), the subject of this proposal. The proposed data will fill a current void in our understanding of the very final stages of a star being devoured and will provide detailed late time optical/UV/X-ray light curves for a majority of TDEs, which is currently sorely missing.

Dennis Bodewits/Auburn University
WHY WAS COMET C/2017 K2 ACTIVE AT RECORD-SETTING DISTANCES FROM THE SUN AND WHAT HAPPENS WHEN IT REACHES THE INNER SOLAR SYSTEM?

We propose to use Swift/UVOT to characterize the activity of comet C/2017 K2 (PanSTARRS) as it passes the H2O snowline for the first time. This comet was discovered to be already highly active as far as 25 au from the Sun, where only hypervolatiles like CO, N2, and O2 can sublimate. Using a combination of UVOT imaging and grism spectroscopy, we will follow the chemical composition, volatile and dust mass loss rates of this object. The proposed Swift observations will resolve whether this comet is a rare, CO-rich comet, or whether it belongs to the hyperactive comets that spew out icy grains. These findings address the chemical composition of comets, are directly relevant to the study of storage and release of volatiles in icy moons, and for the study of the distribution of volatiles through our solar system in general, constraining planetary
formation models.

Slavko Bogdanov/Columbia University
SWIFT MONITORING OF NEARBY X-RAY BINARY-MILLISECOND PULSAR TRANSITION OBJECTS

The identification of three binary millisecond pulsars transforming between accreting and rotation-powered states has finally closed the evolutionary missing link between low-mass X-ray binaries and recycled pulsars. These discoveries imply that their parent population, redbacks, may also be recycled pulsars that sporadically revert to/from a low-luminosity accreting phase. We propose a continuation of the dedicated Swift X-ray and UV monitoring campaign of all such nearby binary radio millisecond pulsars aimed at catching them in the act of switching to/from an accreting state. This effort would greatly aid in constraining key aspects of the poorly understood transition process of pulsars between accretion and rotation power.

Alessandra Corsi/Texas Tech University, Lubbock
A SEARCH FOR BL-IC SNE WITH X-RAY AFTERGLOWS USING ZTF+SWIFT

The rare class of massive-star explosions dubbed broad-lined (BL) Type Ic supernovae (SNe), estimated to constitute only 5% of the Ib/c (stripped-envelope core-collapse) SN population, is of special interest due to its relation to gamma-ray bursts (GRBs). What makes some BL-Ic SNe produce GRBs remains a mystery. Two key questions are yet to be answered: (i) Why do only a fraction of BL-Ic SNe have relativistic ejecta powering radio/X-ray afterglows? (ii) Are low-luminosity GRBs beamed? Our proposal aims to answer these questions via follow-up observations of SNe discovered by the Zwicky

Transient Facility (ZTF), using the Neil Gehrels Swift observatory and the Jansky VLA. This program capitalizes on the overlap between Cycle 18 of Swift and years 1.5-2.5 of the 3-yr-long Phase II of ZTF.

Simone Dichiara/Pennsylvania State University
SEARCHING HIGH AND LOW FOR ELUSIVE GRB

We propose a follow-up program dedicated to the search for the optical/NIR counterparts of short duration (< 2s) gamma-ray bursts (sGRBs) using our accepted programs on space-based and ground-based telescopes. We will use photometric and spectroscopic measurements to estimate the redshifts of these sGRBs, study their afterglows and identify any signatures of a radioactive-powered kilonova. The proposed work is critical for identifying the population of high redshift (z >1) sGRBs and rare nearby (z <0.1) events. It will greatly enhance the science return of *Swift* observations, and provide a vital complement to gravitational wave astronomy.

Yize Dong/University Of California, Davis
HIGH CADENCE UV LIGHT CURVES OF EXTREMELY YOUNG SUPERNOVAE

In the hours after explosion, supernovae (SNe) provide clues about their progenitor star systems and their explosion mechanisms. We are conducting a 12-hour cadence SN search of nearby galaxies (D<40 Mpc; the DLT40 Survey), directly tied to ground-based imaging and spectroscopy for immediate followup. Our survey has found 13 SN Ia, 3 SN Ib/c and 10 SN II and one kilonova during the last three years, 15 within 2 days of explosion. During the next Swift cycle, even younger SNe will be found as we have brought a second search telescope online in Australia, making our program more robust to weather and allowing for a sub-day cadence search. In several instances, DLT40 and its ground-based follow-up have revealed early light curve features (which vary on several hour time scales) that point to shock breakout, CSM or companion star interactions. One of the main limitations is the cadence of the accompanying Swift UV observations, which start 1-2-days after the request, and have typical cadences of 1 day. Here we request early, very high cadence (6 hours) UV photometric light curves of all young DLT40 SNe which have nondetections within 24 hours of discovery. This legacy dataset of 5 SNe, when combined with our ground-based follow-up campaigns, will point to the progenitor system and its environment.

Ryan Foley/University Of California, Santa Cruz
PROBING THE PROGENITOR METALLICITY OF TYPE IA SUPERNOVAE WITH EARLY-TIME UV SPECTROSCOPY

Ultraviolet (UV) observations of Type Ia supernovae (SNe Ia) are useful for understanding pro- genitor systems and explosion physics. Theory suggests that progenitor metallicy differences have little effect on optical SN data, but significantly change UV spectra. To address this problem, Swift has obtained UV spectra of 40 SNe Ia at peak brightness, the largest such sample to date. With this sample, we confirm theoretical predictions and also find that SN Ia UV spectra a week before peak appear to be much stronger metallicity indicators. However, the current early-time sample is too small for statistical analyses. We propose to obtain UV spectra of 6 SN Ia >1 week before peak to better investigate the metallicity effect and improve the cosmological precision of SNe Ia.

Ryan Foley/University Of California, Santa Cruz
EXTREMELY YOUNG TRANSIENTS

Observations of supernovae (SNe) and other transients within hours of explosion provide unique data about the exploding star, its circumstellar (CS) environment, and companions. Swift observations can look into a rare window where we see the system before and while the SN overruns its CS material (CSM) and companion. In particular, X-ray and UV observations probe the interac- tion between a SN and nearby gas/companion stars. The UV observations of a young SN within hours of explosion provide additional information about the size of the progenitor star, the density of its outer layers, and how the star exploded. We aim to observe all discovered young transients, regardless of survey, providing a legacy for Swift and the entire transient community.

Jonathan Gelbord/Spectral Sciences, Inc
EXTENDED MONITORING OF THE DRAMATICALLY-VARYING AGN MRK 817

Mrk 817 is currently the subject of an ambitious 15-month, multi-observatory intensive reverberation mapping campaign, yielding constraints on the accretion disk and revealing new obscuration with dramatic variability. More time is needed to constrain the physical extent of the reprocessing region, apply new tests to separate the signals of the accretion disk and the broad line region, monitor the physical changes and the response they provoke, and explore the surprisingly weak correlation between X-rays and longer wavelengths. We propose a Swift Key Project to extend monitoring with 365 1-ks observations over two years. Supporting ground-based data (already approved) would extend year-round coverage to near-IR wavelengths. These data will provide a lasting Swift legacy for years to come.

Jeroen Homan/Eureka Scientific, Inc.
INVESTIGATING SHALLOW HEATING IN NEUTRON STAR CRUSTS

Neutron stars are the densest directly observable stellar objects in our universe and serve as astrophysical laboratories to study matter under extreme physical conditions. The composition and structure of their ~1 km thick crust is responsible for many observable properties of neutron stars. The curst also plays a fundamental role in the emission of gravitational waves and the evolution of the stellar magnetic field. Low-mass X-ray binaries (LMXBs), in which matter is transferred from an solar-type star and accreted on to a neutron star, offer powerful means to investigate the properties of neutron star crusts.

Monitoring the thermal response of the crust to accretion-induced heating and subsequent cooling can be used to infer the dense matter physics of the crust. In the past decade crustal cooling has been monitored for 10 transiently accreting neutron star LMXBs. Comparing the observations with ever-improving heating/cooling simulations has provided unique insights into the properties of neutron star crusts. A major unexpected outcome of crust cooling studies is that in almost all systems, significantly more heat appears to be released in the crust than can be accounted for by current nuclear heating models. This extra heat manifests itself at a shallower depth than the expected deep crustal heating and is released early in quiescence. For the 10 neutron star LMXBs for which the cooling has been monitored it was found that typically a contribution between ~1 and ~3 MeV per accreted nucleon by the unknown shallow heat source was needed to explain their early cooling evolution. It was also found to be of variable strength in single sources.

In order to investigate the nature of the shallow heat mechanism, we propose to study the final decay and the early (< 50 days) crust cooling curve of a neutron-star transient that has exhibited an outburst of more than a month. Crustal cooling has been studied in 10 neutron-star LMXBs and each source has provided unique insights into neutron star crustal properties. However, only three of those sources have good coverage of both their final decay and early quiescence, which is needed to optimally constrain the shallow heating. In order to better understand the observed diversity of shallow heating behavior our long-term goal is to at least double the sample of sources for which both the final decay and early quiescence are observed in detail. The opportunities for this are relatively rare and it is imperative that we seize every one of them. To this end we will use a series of Swift ToO observations to monitor a regular neutron star LMXB transient during and after its decay from outburst to quiescence. Our program consists of 16 individual 3 ks observations at a cadence of 1 observation every 3-4 days.

Once a suitable target has been identified we will trigger our Swift program. Observations will be analyzed as soon as they are available on the quick-look data page. Spectra and light curves will be analyzed to judge whether the source is still decaying or has reached quiescence; once quiescence has been reached we will trigger accompanying Chandra and/or XMM-Newton programs for deeper observations that will follow the long-term cooling of the source.

The quiescent spectra will be fitted with a neutron-star atmosphere model. The resulting temperatures will be used to construct a cooling curve, likely in combination with data from Chandra and/or XMM-Newton. The cooling curves will be fit with the latest cooling code (a 2D successor to the frequently used NSCOOL model), which will take into account the outburst profile, including Swift data obtained during the decay. These models will provide us with an estimate of the shallow heating.

This proposal addresses Objective 1.1 in NASA's Strategic plan: "to understand the Sun, Earth, Solar System, and Universe".

Jeroen Homan/Eureka Scientific, Inc.
OBSERVING THE EARLY RISE OF X-RAY TRANSIENTS WITH SWIFT

A large fraction of low-mass X-ray binaries (LMXBs) are transient. They spend most of their time in quiescence and occasionally go into outburst, during which their luminosity can increase by factors of more than a million. These outbursts are difficult to predict and are generally first noticed by all-sky monitors or wide-field cameras, like MAXI, Swift/BAT, and IBIS/ISGRI onboard Integral. However, given the limited sensitivity of such instruments, a transient's flux is typically already a factor of 1e3-1e4 above its quiescent level when it is first detected, and follow-up observations with more sensitive instruments often do not start until the flux has risen by an additional factor of 5-10. As a result, the early rising phase of LMXB outbursts (below ~1e36-1e37} erg/s remains relatively poorly studied.

The Faulkes Telescopes have detected the initial onset of several outbursts in the optical, but these onsets were often noticed too late. The main reason for this was the lack of an automated pipeline that analyses the data in real-time. Instead, the incoming data had to be analyzed manually. This has limited the scientific impact of the Faulkes Telescopes LMXB monitoring program, as we were often not able to alert the X-ray binary community to the opportunity of follow-up observations in a timely manner. Recently, this shortcoming has been addressed with the development of an innovative pipeline named the "X-ray Binary New Early Warning System" (XB-NEWS). This pipeline will identify optical outbursts as soon as they begin, allowing us to trigger multi-wavelength campaigns at a very early stage.

The ongoing monitoring of ~40 transient LMXBs with the Faulkes Telescopes, combined with the new XB-NEWS pipeline, allows us to catch the rise of X-ray transients, not only in the optical, but with triggered observations at other wavelengths as well. We aim to follow-up the optical detection of an outburst rise with a Swift X-ray and UV monitoring campaign. The optical data from Faulkes and the X-ray and UV coverage provided by Swift will allow us to better understand how and where outbursts are triggered in LMXBs. Additionally, the Swift data will be used to search for absorbing structures in the accretion flow and for detailed studies of the X-ray spectral/variability evolution during the rise.

After XB-NEWS indicates the start of a new outburst we will trigger our Swift program as soon as possible, with a "high" trigger urgency (<24 hr). The source will then be observed for 20 days, with 2 ks of exposure per day. Our program will likely cover a short period before the transient is detected in X-rays and/or UV; daily observations during this phase allow us to constrain the start of the outburst in X-rays and hence accurately measure the delay between optical and X-ray emission. Our Swift program will also cover a substantial part of the rise, although we realize there may be occasional gaps of a few days due to observing constraints. The Swift data will be analyzed by PI Homan, using Swift-specific tools in HEASOFT and other software. The analysis will focus on 1) the X-ray and UV spectral and variability evolution during the rise of the triggered sources and 2) a detailed comparison of the the optical, UV, and X-ray outburst light curves of the sources.

This proposal addresses Objective 1.1 in NASA's Strategic plan: "to understand the Sun, Earth, Solar System, and Universe"".

James Jackman/Arizona State University

UNDERSTANDING THE DISCONNECT BETWEEN NUV AND WHITE-LIGHT FLARE EMISSION FROM LOW-MASS STARS WITH CR DRA

The near-ultraviolet (170 320nm; NUV) emission of M stars is pivotal to our understanding the habitability of terrestrial exoplanets. NUV flux can impact the abundance of biosignatures such as ozone and water, yet the same photons may drive prebiotic chemistry on the surfaces of these planets, chemical processes that can lead to abiogenesis. Yet, these cool stars may not provide the necessary NUV flux in their quiescent state for these processes. An alternative pathway for this emission may be via stellar flares, intense bursts of irradiation caused by magnetic reconnection events. Flares can increase the NUV flux from low-mass stars by orders of magnitude. Therefore, in order to fully assess the habitability of exoplanets around low mass stars, accurate knowledge of the possible NUV energies and occurrence rates of their flares is essential.

However, measuring UV flare rates of individual stars of interest is an expensive task, requiring several orbits of the Hubble Space Telescope (HST). To get around this scarcity of measured NUV flare rates, current habitability studies often use white-light measurements to predict the NUV effects of flares. These white-light measurements are used to calibrate a chosen empirical flare model, which is then extrapolated into the NUV. However, the accuracy of these white-light calibrated UV predictions are poorly constrained. Models used by these studies often ignore the contributions of emission lines and changing flare temperatures. Yet, despite their importance, we do not know how exactly these features depend on each other, and thus their exact contribution to the UV and total energy budgets of flares.

We will simultaneously observe the highly active bright M binary CR Dra with the Swift UVOT grism and TESS to study the NUV spectra of white-light flares. We will build a framework to reduce and analyse the NUV spectra of flares, and build a catalogue of quiescent and flare spectra of CR Dra. Each of these spectra will have simultaneous optical photometry from the 20-second cadence mode of TESS. We will use this catalogue of NUV spectroscopy to constrain the contribution of emission lines to the energy budget of flares, study how this contribution changes with temperatures measured from the flare continuum, and test the accuracy of modelling the NUV activity of low-mass stars from TESS data alone. By performing tests with simultaneous NUV spectra and optical spectroscopy, we will study how the flux contribution changes with flare phase (e.g. at the peak versus during the decay phase of a flare) and assess how the accuracy of literature flare models changes with phase. We will be able to measure correction factors for models, which can be applied to flare observations for individual stars of interest, such as those hosting habitable zone rocky exoplanets (e.g. TRAPPIST-1). Our results will provide a vital resource for the construction of future flare models, and future habitability studies.

James Jackman/Arizona State University
DO OPTICALLY QUIET M STARS SHOUT IN THE NUV?

The near-ultraviolet (NUV) emission of M stars is one of the most important factors of our understanding the habitability of terrestrial exoplanets. The amount of NUV flux influences the formation of hazes and the abundance of biosignatures in the atmospheres of these planets. Atmospheric hazes complicate the searches for these biosignatures via transmission spectroscopy, meaning inactive M stars that lack flares in their optical lightcurves have become preferred targets for follow up observations with next-generation instruments such as JWST.

However, the optical lightcurves used for exoplanet discovery (e.g. with TESS) typically probe the longer wavelengths of flare emission, where the contrast between the flare and quiescent spectrum is minimised. This contrast is increased in the NUV, allowing for the detection of more regular lower energy flares. Therefore, stars that lack optical flares may flare regularly in the UV where their effects on exoplanet atmospheres are most important. NUV observations of optically quiet M stars are required to test whether these stars are as amenable to transmission spectroscopy as previously thought.

We will obtain Swift NUV lightcurves of five optically quiet M star planet hosts, to search for NUV flares. This will using Swift UVOT with the UVM2 filter. Each of these targets hosts a planet that has been highlighted for follow up atmospheric characterisation with transmission spectroscopy using JWST. We will build a framework to reduce and analyse the NUV lightcurve of each star, to search for and characterise flares. We will use our framework to measure the average NUV flare rate of optically quiet low-mass stars. We will also perform flare injection and recovery tests to characterise the detection efficiency for all UVOT lightcurves, to constrain which UV flare energies and rates can be ruled out for each star, in the event we do not detect any flares. These tests and results will allow us to assess the high energy environments of planets around optically quiet M stars.

We will also apply our framework to archival Swift UVOT observations of active low-mass stars such as Proxima Centauri, AD Leo and EV Lac, to measure the average NUV flare of active low-mass stars. We will use both datasets to compare the average flare rates of active and inactive low-mass stars, and test whether both show the same relative flare behaviour and whether NUV flare rates can be scaled according to the quiescent magnetic activity of a given M star.

Amanpreet Kaur/Pennsylvania State University
EXPLORING UNPROBED X-RAY VARIABILITY IN M87 DURING THE 2022 EVENT HORIZON TELESCOPE (EHT) MULTIWAVELENGTH CAMPAIGN USING SWIFT

Understanding the accretion flows and the radiative output seen from the jets in active galactic nuclei are fundamental to our understanding of accreting black holes. As an AGN with a prominent jet visible in various energy regimes, M87 is a unique source to conduct these studies. The proposed investigation is to obtain Swift X-ray observations during the upcoming 2022 Event Horizon Telescope campaign collaborating with various facilities from radio to gamma-rays. Our goal is to capture the intrinsic variability in the X-ray emission throughout this campaign, which would be utilized to constrain the models explaining the observed spectral energy distribution for M87*. We request one observation (1ksec each) every day for 4 weeks during the entire length of the EHT campaign of 4 weeks.

Jamie Kennea/Pennsylvania State University
KEY PROJECT: THE DETECTION AND MONITORING OF ELECTROMAGNETIC COUNTERPARTS OF GRAVITATIONAL WAVE SOURCES WITH SWIFT IN O4

We seek to identify and observe EM counterparts to GW events during the next LIGO/Virgo/KAGRA observing run (O4"). We request deep follow-up observations at high priority in order to monitor and characterize EM candidates detected by Swift or other observatories. Based on lessons learned during O2 and O3, we also propose to greatly enhance the Swift GW follow-up program with new initiatives. These include optimizing the follow-up strategy and trigger criteria, enhancing tran- sient detection abilities by utilizing pre-imaging surveys, searching for prompt emission in BAT data, and refactoring the Swift observing plans for the higher rates and smaller localizations O4 will yield.

Jamie Kennea/Pennsylvania State University
RAPID SWIFT FOLLOW-UP OF FAST RADIO BURSTS IN CYCLE 18

We seek to identify high-energy counterparts to Fast Radio Bursts, for which the progenitor sys- tems and emission mechanism remain unknown. We propose extremely rapid response follow-up observations with XRT and UVOT for exceptionally bright and low dispersion measure (nearby) events and to save the BAT event data when the FRB position is within the BAT FOV. This proposal takes advantage of new enhancements to Swift s fast-response capability, and will leverage an MOU with the CHIME team to trigger on FRBs within seconds of detection, providing the earliest and deepest constraints on non-radio emission from FRBs, as well as the greatest chance of finding a counterpart. This will significantly enhance the science return of Swift, and help solve the mystery of FRBs.

Sibasish Laha/University of Maryland Baltimore County
CAUGHT IN THE ACT: A SWIFT TOO CAMPAIGN ON CHANGING-LOOK AGN

Large-scale time-domain surveys have lead to the identification of new types of extreme variability in active galaxies, called "changing look" active galactic nuclei (CL-AGNs, hereafter). These extreme variations are not only characterized by orders-of-magnitude changes in the optical, UV, and X-ray luminosity of the source, but also a rapid transition between spectral states. For example, sources initially exhibiting AGN type-2 characteristics (i.e., optical/UV dominated by the host galaxy and narrow emission lines only) have transitioned to a type-1 state, displaying strong broad emission lines, and vice versa. The drastic changes seen in CL-AGNs in such short timescales (a few months to years) are challenging the simplest form of the AGN unification framework which predicts that such changes occur over far longer timescales [6,11]. It seems likely that CL-AGN events are driven by surprisingly rapid and extreme changes in the accretion disk around the super-massive black hole (SMBH) and/or by a change in the amount of dense circumnuclear gas along the line-of-sight, which would explain the sudden appearance of broad emission lines, but the nature of this new population is still poorly understood. The primary goal of this program is to capture and densely monitor the earliest phases of a new (TOO) CL-AGN event, at optical, UV, and X-rays with *Swift* UVOT and XRT.

Methods: X-ray and UV spectroscopy of the evolving source (pre and post flare). We will have a total of ~50 observations of Swift and each of them will need careful spectral modeling. The temporal evolution will also be interesting.

Daniel Lawther/University Of Arizona
CAPTURING THE RE-IGNITION OF THE BROAD LINE REGION IN MRK 590

Mrk 590 is an extremely variable Changing Look Active Galactic Nucleus that has been in a repeat flaring state since 2017. These flares occur near the theoretical continuum luminosity threshold for an accretion disk state transition. The broad emission lines typical of Type 1 AGN activity are observed to vary with continuum luminosity. The physical nature of the broad-line emitting gas in AGN is not currently well understood. In particular, the observed rapid changes in accretion rate and disk luminosity during changing-look events is not explained by our current theory of AGN accretion, and the necessary conditions for production of broad emission lines (based on source geometry, bulk gas dynamics, and photoionization physics) are largely untested. The current flaring state of Mrk 590 provides an excellent `laboratory' for studying these issues for supermassive black hole accretion. To further our understanding of the accretion flows and broad-line emitting regions in AGN, we aim to capture the evolution of Mrk 590 from a very faint state with no broad emission lines, to a typical Type 1 AGN state with prominent broad emission lines, as the accretion rate increases. To this end, we ask for regular monitoring observations with Swift XRT and UVOT, along with a ToO monitoring run to be triggered when Mrk 590 reaches a low-luminosity state and then re-ignites. This monitoring serves as a trigger for related ToO programs with HST and VLT. As a bonus, it will extend our record of the X-ray variability behavior since 2017; the currently available X-ray lightcurves display a possible quasi-periodic signal at a circa 2 sigma significance, and predict a strong flare during Cycle 18 which would confirm the quasi-periodic behavior.

This Swift program will result in 46 visits, including monitoring observations every ~2 weeks throughout Cycle 18, and an additional high-cadence ToO monitoring run. In this Phase 2 proposal, we ask for funding to support the processing and subsequent analysis of the Swift monitoring and ToO observations. The funds requested will support the PI, Dr. Daniel Lawther (hereafter DL) as a postdoc at University of Arizona for 17 weeks (including salary, benefits and overheads) while calibrating the Swift data and performing the analysis tasks required to reach our science goals. We ask for salary funding for DL to perform four tasks, as follows. 1) The data processing of the incoming Swift observations, and triggering / coordination of the ToO observations based on the Swift monitoring, in collaboration with associated program PIs. 2) Spatial and spectral modeling of the host galaxy of Mrk 590, in order to isolate the emission of the central AGN for further analysis. 3) Modeling of the accretion disk emission and its dependence on the varying accretion rate. 4) An X-ray and UV-optical timing analysis, to confirm the quasiperiodic nature of the flaring behavior, or to test alternative hypotheses (e.g. tidal disruption events) if the flares do not follow the previously observed periodicity during Cycle 18. The accretion disk and timing studies will be published in peer-reviewed journals; we do not seek funding for publication costs here.

We note that we asked for funds ($800) to attend a conference in our Phase 1 budget narrative. Due to UA-mandatory increases in DL's salary and benefits during Cycle 18, we have removed this item from our Phase 2 budget to allow the analysis tasks to be fully funded.

Dacheng Lin/Northeastern University
TWO UNIQUE SOURCES IN A ROW: ESO 243-49 HLX-1 AND A NEWBORN HARD TIDAL DISRUPTION EVENT

We request 52x1 ks weekly snapshots of two very special neighboring objects simultaneously in *Swift* GI Cycle 18: the strong intermediate mass black hole (IMBH) candidate ESO 243-49 HLX-1 and a newborn rare hard tidal disruption event (TDE). For HLX-1, these data will be crucial to further understand 1) how the outburst separation time (likely tracing the aperiodic orbital period) evolves and 2) what the ultimate fate of the system will be (e.g. donor ejection). For the new TDE, we want to 1) search for new giant fast X-ray flares as seen in the past for this event and 2) constrain its long-term UV and X-ray evolution.

Thomas Maccarone/Texas Tech University, Lubbock
THE SWIFT GALACTIC BULGE
MONITORING SURVEY: FOURTH EPOCH

We propose to survey a 16 square degree region of the Galactic Bulge, every two weeks during the part of the year when the survey region is observable to Swift. This will allow us to detect new very faint X-ray transients -- objects bright enough that they must be X-ray binaries, but too faint to be detected by all sky instruments. These objects are likely to dominate the total number of X-ray binaries, but they are still known in small numbers due to their faintness. We expect to substantially increase the number of know VFXTs, while also obtaining detections outside the hard-to-follow-up Galactic Center region where most of the currently known VFXTs have been found.

Meredith MacGregor/University Of Colorado, Boulder
A SWIFT AND ALMA VIEW OF THE ORIGIN AND IMPACT OF M-DWARF FLARES

Many of the exoplanets considered prime candidates to host life orbit M dwarf stars. However, these stars exhibit extreme activity and flaring that can erode a planet's atmosphere and potentially damage surface life. Recent observations of Proxima Cen suggest that millimeter and UV emission trace each other closely during stellar flares. We have been given access through private consultation to upcoming ALMA ACA Cycle 8 observations (~10 hours on-source per target, 72 hours total with overheads) of the four closest mid M-dwarfs spanning various ages and activity levels. Here, we propose to obtain simultaneous UV/X-ray coverage with Swift to constrain the high-energy emission of flares and their potential impact on planetary habitability. This proposed multi-wavelength study will demonstrate whether the millimeter-UV flare correlation is a universal property of mid-M dwarfs regardless of age. By deriving a scaling relation between millimeter & UV emission, we will have a powerful new tool to determine the UV/X-ray environment of stars and their potential to host habitable planets, capitalizing on all-sky millimeter cosmology surveys.

Raffaella Margutti/University of California, Berkeley
A SWIFT INVESTIGATION OF FAST BLUE OPTICAL TRANSIENTS

Fast and Blue Optical Transients (FBOTs) are a new class of stellar explosions. With extremely rapid time scales of evolution and luminous emission, FBOTs probe the extremes of the explosion parame-ters and/or stellar progenitor properties, and are hard to reconcile within the traditional supernova models. Alternative scenarios include strong shock interaction with a dense medium, or the presence of a central engine (e.g. BH or magnetar formed by the explosion). Here we propose a focused inves-tigation of the closest FBOTs (d<300 Mpc) with Swift as part of our extensive multi-wavelength monitoring program (radio to X-rays). By densely sampling the UV and X-ray properties of FBOTs with Swift, our overarching goal is to advance our understanding of their intrinsic nature.

Alan Marscher/Boston University
COMBINED SWIFT AND IXPE OBSERVATIONS OF BLAZARS

The investigators propose to observe with the Swift XRT and UVOT blazars whose X-ray linear polarization will be measured by IXPE. The Swift observations will specify which blazars are bright enough to be detected during an IXPE visibility window, and will provide X-ray and UVOT continuum spectra during the IXPE observations. This is part of an overall program to determine the contemporaneous polarization (at mm, optical, and X-ray frequencies) and radio to gamma-ray spectral energy distribution of blazars. Such information will determine the mechanism and location (relative to lower frequencies) of the X-ray emission, neither of which has been determined thus far. It will also test models for particle acceleration that results in high-energy emission in the relativistic jets of blazars.

Dheeraj Pasham/Massachusetts Institute of Technology
CAPTURING QUASI-PERIODIC OUTFLOWS FROM A FUTURE AGN OUTBURST USING XRT AND UVOT MONITORING

Ultrafast outflows (UFOs) with an enigmatic quasi-periodic variability of 8.5 days have recently been identified from an AGN X-ray outburst. The physical origin of these quasi-periodic outflows (QP-Outs) is unclear but time-resolved X-ray spectral analysis suggests that they are driven by quasi-periodic changes in the apparent strength of absorption by the UFOs. Following the discovery of this new AGN phenomenon, we propose XRT+UVOT monitoring (500 s each for 150 d; 50 ks) of a carefully selected future AGN outburst. Our goals are to 1) expand on the pilot study and understand the frequency and duty cycle of such events, and 2) understand the accretion disk's role with simultaneous UV monitoring. The science objectives require X-ray and UV monitoring which can only be facilitated by Swift.

Dheeraj Pasham/Massachusetts Institute of Technology
TRACKING THE LONG-TERM EVOLUTION OF QUASI-PERIODIC ERUPTIONS FROM THE NUCLEUS OF A PASSIVE GALAXY USING XRT MONITORING

Quasi-Periodic Eruptions (QPEs) are high-amplitude, repeating X-ray flashes from external galaxies. They are a promising new phenomenon which could provide novel insights into accretion instabilities and/or interactions of orbiting bodies with AGN accretion flows. We request for 2 sets of high-cadence XRT monitoring observations (15 visits/day for 5 days per set) of QPEs from eRO-QPE1 discovered by NICER. Our goals are to 1) track the evolution of QPE properties, i.e., mean time between eruptions, amplitude, and coherence over a time span of 3 years, and 2) validate the current evidence for a 2:3:4 period resonance seen in existing Swift and NICER data. Our science goals require high-cadence X-ray monitoring and currently Swift is ideally-suited to perform such observations.

Richard Plotkin/University Of Nevada, Reno
BLACK HOLE JET LAUNCHING PHYSICS: TRIGGERING JWST WITH SWIFT

Despite approximately 50 years of compact object studies in the Galaxy, the physics of relativistic jet launching remains an active and open field of research. Luckily, with the impending launch of JWST, a new parameter space is opening up in the field of jet physics, allowing for the study of the spectral break above which the jet becomes optically thin on sub-second time scales, providing a crucial link between light and plasma properties. We are proposing to use the rapid X-ray follow-up capabilities of Swift to monitor the outburst decay of a Galactic Low-mass X-ray binary, ensuring it is in a jet-dominated state in order to trigger an already in-place JWST program to study the jet break at high time resolution.

Juan Santander/University Of Alabama, Tuscaloosa
PINGING DOWN NEUTRINO-BLAZAR EMITTERS WITH SWIFT

Given their extremely energetic emission, gamma-ray blazars have long been suggested as sources capable of accelerating cosmic rays, and that therefore may also produce neutrinos. The detection of an IceCube high-energy neutrino in temporal and spatial coincidence with a flaring blazar has strengthened the case for these sources to be responsible for at least part of the high-energy astrophysical neutrino flux observed by IceCube. As hadronic models most often predict high X-ray fluxes, the Neil Gehrels Swift Observatory is uniquely positioned to test this hypothesis by performing follow-up observations of promising neutrino source candidates. These observations are therefore crucial in understanding the multiwavelength properties of blazars as candidate hadronic sources.

Michael Siegel/Pennsylvania State University
A SWIFT/UVOT STUDY OF RR LYRAE IN M62 AND M5

RR Lyrae stars have enormous pulsations in the near ultraviolet (NUV). UV photometry is uniquely sensitive to the properties of RR Lyrae stars -- particularly temperature and surface gravity -- and gives unique insight into the astrophysics of pulsating stars -- particularly the role of the hydrogen ionization front and the presence of shocks. We propose a survey of RR Lyrae stars in two relatively metal-rich clusters that host abundant populations of RR Lyrae, including numerous first overtone pulsators which are ripe for further exploration in the NUV. They are ideal targets for exploring the properties of first overtone pulsators, the effects of reddening on RR Lyrae, the astrophysics of pulsating stars and the connection between period, metallicity and NUV luminosity.

Kirill Sokolovsky/Michigan State University
IN SEARCH OF SHOCKS IN NOVAE

The theory predicts that shocks that power GeV gamma-rays in novae should emit most of their energy as X-rays. However the predicted bright X-ray emission was never observed. Whether this lack points to something fundamental about the shock physics, or is simply an issue of small-number statistics, is unclear. We request Swift monitoring (40 ks split across 10 epochs) and NuSTAR snapshot (40 ks single epoch) of a newly discovered bright Galactic nova to expand the sample of gamma-ray novae with exquisite X-ray light curves. The resulting data will be interpreted alongside multi-wavelength observations to better understand shocks in novae, particularly characterize the luminosity, duration, temperature, location, and absorbing column associated with these shocks. Understanding shocks in novae may be relevant for extragalactic shock-powered transients.

Fermi Guest Investigator - Cycle 15
Abstracts of selected proposals
(NNH21ZDA001N-Fermi GI - Cycle 15)

Below are the abstracts of proposals selected for funding for the Fermi Guest Observer Cycle 15 program. Principal Investigator (PI) name, institution, and proposal title are also included. Eighty-two (82) proposals were received in response to this opportunity. On July 22, 2022, 34 proposals were selected for funding.

Marco Ajello/Clemson University
SEARCH FOR LONG-TERM VARIABILITY IN BLAZARS

Blazar emission is highly variable at different wavelengths, becoming a periodic behavior in some cases. However, periodicity detection is still an open issue but crucial to improve the understanding of the blazars. To improve the study about periodicity, we will use 14 years of gamma ray data provided by the Fermi Large Area Telescope (LAT) to systematically study the light curves of more than 3000 blazars. Recently, a long term flux raising trend has been detected in the emission of PG 1553+113, which can be interpreted as an evidence of a binary supermassive black. Consequently, we will perform the first systematic search for long term trends in the same sample. This study will provide the first detection and characterization of long term trends in Fermi LAT blazars

Marco Ajello/Clemson University
THE COSMIC HISTORY OF LIGHT

The extragalactic background light (EBL) encodes the emission of every star, galaxy and black hole that was ever active in the observable Universe. It is thus of critical importance to understand galaxy evolution and stellar activity, but as of today it remains still highly uncertain. This program leverages state-of-the-art tools to provide a measurement of the EBL optical depth at ~24 epochs across the $0<z<4.3$ redshift range. This measurement will be used together with luminosity and mass density galaxy data, the fraction of neutral hydrogen and TeV EBL optical depths to obtain a precise characterization of the EBL evolution. This program will measure the UV background shortly after the re-ionization and the star-formation rate up to $z\sim10$.

Marco Ajello/Clemson University
A LEGACY ANALYSIS OF THE MILKY WAY DWARFS

Upper limits (ULs) on the dark matter (DM) annihilation cross section from gamma-ray searches in the Milky Way dwarf spheroidal satellite galaxies (dSphs) remain one of the most robust and stringent constraints from indirect DM searches. Specifically, they are crucial for constraining DM interpretations of the Galactic center excess. Due to the accumulation of over 14 years of data (at the start of Cycle 15), an improved LAT dataset, a larger number of dwarfs, and a robust analysis pipeline, now is an ideal time to conduct a comprehensive legacy analysis of the dSphs. Compared to the last comprehensive analysis of all confirmed and candidate dSphs, we expect that below ~100 GeV the statistical sensitivity of the ULs will be improved by a factor of ~3.

Marco Ajello/Clemson University
CHARACTERIZING THE GAMMA-RAY EMISSION FROM LOW-LUMINOSITY AGN

A majority of the active galactic nuclei (AGN) in the local Universe are classified as low-luminosity AGN (LLAGN). Although gamma-ray emission is predicted from both the jets and disks of LLAGN, to date only 4 significant sources have been detected. We therefore propose to conduct a stacking study of the subthreshold LLAGN from the Palomar survey, as well as a detailed SED modeling for all sources. Our preliminary analysis shows that our program will result in a brand new detection of a significant source, as well as a significant detection of the subthreshold population. Moreover, our program will very likely establish a radio-gamma scaling relationship that may extend a similar relationship in FR I and FR II radio galaxies by ~100 times lower in radio luminosity.

Marco Ajello/Clemson University
MEASUREMENT OF THE ISOTROPIC DIFFUSE GAMMA-RAY BACKGROUND

The isotropic diffuse gamma-ray background (IGRB) comprises all extragalactic diffuse emission and is found to be approximately isotropic on large angular scales. The primary goal of this work is refinement of the IGRB measurement, employing 8 years of pass8 Fermi data and the 4FGL source catalog. A reduction of the systematic uncertainties arising from the DGE emission will be achieved through improved modeling of this emission, as well as a careful selection of analysis regions. A few other improvements including, wider energy range (between 50 MeV - >1 TeV), larger dataset, more powerful fitting techniques etc., will also be achieved in the current analysis.

Matthew Baring/Rice University
Comptonizing Winds in Magnetar Giant Flares

Fermi's Gamma-Ray Burst Monitor (GBM) has enhanced magnetar science via observations of their bursting activity. This legacy includes the exciting discovery in 2020 of an extragalactic magnetar giant flare (MGF) from NGC 253. This proposal addresses these topical transients, simulating radiative transfer in an evolving electron-photon cloud, modeling the establishment of soft gamma-ray spectra in MGFs using a Monte Carlo approach. The guaranteed high Thomson opacity seeds polarization-dependent anisotropic Comptonization. Given a

prompt injection at the polar surface, magnetospheric radiation
transport and energy exchange between pairs and photons will be tracked
on open field lines, using the evolving Fermi-GBM spectra for GRB 200415A
to constrain the energetics and dynamics.

Regina Caputo/NASA/GSFC
A Search For Dark Matter in Ultra-Dense Black Hole Environments

The identity of the dark matter (DM) remains an open question. To address this problem, we propose searching for a DM particle whose annihilation signal appears as two gamma-rays. Ultra-dense DM environments formed around supermassive black holes (SMBH) increase the probability of DM annihilation, which leads to a stronger signal flux occurring around these objects. We will conduct a stacking analysis of radio-quiet elliptical galaxies: these objects are numerous, host SMBHs, and represent an ideal environment with little gamma-ray background. We estimate that we can set constraining upper limits on the DM annihilation cross section, which are competitive with those set by the dwarf Spheroidal galaxies, by stacking only 22 elliptical galaxies. Anything learned about DM carries high significance for both astrophysics and high energy particle physics.

Paolo Coppi/Yale University
AGILE + FERMI: SHORT-TIMESCALE GEV VARIABILITY IN BLAZARS AND ITS CONNECTION TO OPTICAL AND TEV VARIABILITY

Extreme variability is a hallmark of the blazar phenomenon, yet many published Fermi analyses rely on daily or weekly lightcurves despite the fact that both GeV and TeV blazars now have demonstrated variability on timescales as short as ~5 min. Integrating over such variability, if present, masks the underlying physical emission mechanisms and can lead to apparently unphysical spectra that cannot be fit by standard models. We aim to carry out the most rigorous analysis to date of short-term gamma-ray variability in blazars, from ~100 MeV to GeV (and TeV, if available) energies and compare it to variability at Optical/NIR energies. To remedy orbital coverage gaps in Fermi and combat systematics, we will carry out a simultaneous analysis with AGILE using a new aperture photometry pipeline.

Milena Crnogorcevic/University of Maryland
Light at the end of the tunnel: search for ALP dark matter in precursor emission of lGRBs

Axion-like partilces (ALPs) are a well-motivated candidate for constituting a significant fraction of cold dark matter. They can be produced in core-collapse supernovae (CCSNe) and converted into gamma-rays in the Galactic magnetic field. The ALP emission precedes that of the jet outbreak after a collapse of a massive star. With the observationally suggested causal connection between CCSNe and long gamma-ray bursts (lGRBs), a spectral analysis of the Fermi-observed lGRBs with precursor emission provides an unexplored venue in the context of ALP searches. In this project, we propose a comprehensive analysis of lGRB precursors to inform whether their origin can be explained with ALPs. In case no excess signal is reported, our approach allows for a computation of a stringent limit on the ALP-photon coupling. The analysis proposed relies on statistical tools developed in Meyer & Petrushevska (2020) and Crnogorcevic et al. (2021), as well as the legacy code developed by the Fermi team. The data analyzed will span the Fermi Large Area Telescope (LAT) observations of lGRBs since its launch in 2008 to day. In addition to the standard analysis regularly used in the high-energy community, our analysis will include an additional LAT Low Energy (LLE) technique, which allows for an increased sensitivity in energies relevant to ALP investigations. We predict that the results pertaining to the physical properties of ALPs (i.e., their mass and the coupling to the photons) will be competitive to those currently reported in literature.

Paul Duffell/Purdue University
Numerical Modeling of Off-Axis GRB Jets

Understanding gamma ray bursts (GRBs) is among the primary goals of Fermi. Off-axis GRBs provide a powerful new handle on constraining GRB scenarios. We propose to build a set of numerical tools to construct off-axis GRB outflows "from engine to afterglow". By performing relativistic hydrodynamics simulations coupled with radiative transfer calculations post-processing the hydrodynamical output, we will produce off-axis light curves and spectra based on any hydrodynamical initial conditions. We propose to compute light curves and spectra from these simulations and compare with observed off-axis GRB afterglows such as GRB170817A. These models will be valuable for interpreting GRB prompt and afterglow data from multi-messenger events.

Abe Falcone/Pennsylvania State University
SYSTEMATIC SEARCH FOR X-RAY COUNTERPARTS OF NEW 4FGL-DR3 UNASSOCIATED SOURCES WITH SWIFT: NEW BLAZARS, PULSARS, AND MORE

We propose to use Swift to find X-ray and UV/opt. counterparts of new unassociated 4FGL-DR3 Fermi-LAT sources. Prior programs led to Swift observations of 261,199, 600, & ~750 Fermi unassociated sources from prior 1,2,3,4FGL catalogs respectively. Likely X-ray counterparts are found in ~1/3 of these. We propose >200(!) new observations of 4FGL-DR3 unassociated sources. These new data will determine properties, and ~5 arcsec positions, of all detected X-ray sources in the LAT regions, contributing to identification, classification, and follow-up. This proposal supports the large analysis and interpretation task, which will require additional data reduction software. The Swift PI commits to the Swift observing time. Reduced data will be made publicly available for all to analyze.

Ke Fang/University of Wisconsin-Madison
Unveiling the GeV Counterparts to Ultrahigh Energy Gamma-ray Sources with Fermi-LAT

A dozen ultrahigh-energy (UHE; exceeding 100 TeV) gamma-ray sources have recently been discovered by air shower observatories. Most of them are unidentified sources that either enclose or reside near a pulsar. We propose to analyze the off- pulse Fermi-LAT data to search for lower-energy counterparts to the observed UHE gamma-ray sources. We will compare physical models with the multi-wavelength observation of individual sources to investigate the origin of the gamma-ray emission. We will also carry out a population study based on the properties of the UHE emission and gamma-ray pulsars. This project will advance the understanding of particle acceleration and interaction in pulsars and wind nebulae, and increase our knowledge about the newly discovered UHE gamma-ray sky.

Adam Goldstein/Universities Space Research Association
Improving GBM Localizations with the InterPlanetary Network

We propose to maintain Fermi GBM in the 3rd InterPlanetary Network (IPN) of Gamma-Ray Burst (GRB) detectors through Cycle 15 and provide improvements to GBM localizations using IPN localization annuli. This effort facilitates identification of GRBs with associated gravitational-wave, neutrino, VHE, and other multi-wavelength signals, and aids multi-messenger and multi-wavelength follow-up observations. By maintaining Fermi GBM in the IPN, ~50% of GBM localizations can be improved, and IPN localizations utilizing multiple spacecraft aid GBM in studying systematic uncertainty of localizations and detector responses. Furthermore, the time-tagged event data that Fermi GBM provides is of crucial importance to the IPN effort of multi-instrument localization.

Thomas Humensky/Goddard Space Flight Center
Exploring Shock Acceleration in Novae at High and Very High Energies

Novae are sudden visual outbursts powered by runaway nuclear burning on the surface of a white dwarf accreting from a stellar companion. Although traditionally novae were thought to be powered directly by the energy released from nuclear burning, it is now known that shock interaction plays an important role in powering nova emission across the electromagnetic spectrum. Evidence for shocks includes multiple velocity components in the optical spectra; hard X-ray emission starting weeks to months after the outburst; and an early sharp maximum in the radio light curve on timescales of months, in clear excess of that expected from freely expanding photo-ionized ejecta. However, the most striking indicator of shocks in novae is the discovery by Fermi-LAT of >100 MeV gamma rays, observed at times coincident within a few days of the optical peak and lasting a few weeks. Current observations are consistent with the hypothesis that many, and possibly all, novae produce shocks and >100 MeV gamma-ray emission. Most of the LAT-detected novae are distinguished only by their relatively close distances. In one particularly well-characterized nova, ASASSN-16ma, the gamma-ray emission is tightly correlated with the optical emission, suggesting that the optical emission is also powered by shocks.

The recurrent nova and symbiotic binary RS Ophiuchi underwent a new outburst in August 2021, 15 years after its last eruption. This event triggered observations over the whole electromagnetic spectrum, including in the very high energy (VHE; E > 100 GeV) gamma-ray range, and yielding, for the first time, a detection of a nova in VHE gamma rays (by the H.E.S.S. and MAGIC telescopes). This event establishes novae as a new class of TeV sources which provide an additional probe of the physics of shocks and relativistic particle acceleration in the novel physical regime of dense and partially neutral shocks, complementary to the conditions of other astrophysical accelerators involving collisionless shocks.

This project aims to build on these earlier observations by systematically analyzing Fermi-LAT data for all optically detected novae in the Galaxy, and by monitoring recurrent-nova system T Coronae Borealis (T CrB), a system physically similar to RS Ophiuchi that is only half as far away. T CrB erupts roughly every 80 years, most recently in 1946, and is due for an eruption in the coming years; it has recently shown an increased level of activity, possibly a harbinger of an imminent eruption. Thus, for this project:

1. We will use a transient alert system we have developed, in addition to following ATels, to identify candidate novae. Our alert system is subscribed to receive real-time or near-real-time alerts from NASA-GCN, (e.g. alerts from the Swift, Fermi and INTEGRAL satellites), GAIA photometric alerts, ASAS-SN and ALARRM. We use AMPEL, an analysis framework designed for high-throughput surveys, for the light curve analysis.

2. We will perform a Fermi-LAT analysis for all candidates and report the results promptly to the community via Astronomer's Telegrams.

3. We will specifically monitor the symbiotic recurrent nova T CrB via a dedicated daily and weekly analysis of the Fermi-LAT data in case it goes into outburst.

4. We will request VERITAS ToO observations for promising events: 10 hrs initially, with an additional 10 hrs if the initial observations show evidence of a VHE signal.

Peter Jenke/NSSTC
ENHANCEMENTS AND OPERATION OF AN ACCRETING PULSAR PROGRAM USING GBM DATA

Since Cycle 1, the entire sky has been monitored for accreting pulsar using Fermi GBM data.
Pulsars with spin frequencies in the 1 mHz to 2 Hz range (to 16 Hz starting in cycle 7) are monitored and frequency histories and pulsed fluxes (8 50 keV (up to 1000 keV upon request) are published on a public website. A daily blind search for previously unknown
or quiescent pulsars is also performed. Source specific analyses to track the evolving pulse frequencies of all detected pulsars results in time histories of the pulse profile, pulsed flux, and frequency of these sources. Through a public website and ATels, quick-look estimates of pulsed flux and frequency are published. These are crucial for multi-wavelength observations. We propose, for Cycle 15, to provide a utility to estimate the posterior distributions for standard accretion torque model parameters and binary orbital parameters. For the first time, there will be a versatile, easily used standard for estimating orbital and torque parameters for accreting binary systems.

Svetlana Jorstad/Boston University
Study of Blazar High Energy Events with Optical Polarimetry and Photometry

We propose to monitor optical linear polarization and flux (BVRI bands) of 52 gamma-ray AGN 8-10 nights per month at the 1.8m Perkins telescope to build a database of polarization parameter behavior during gamma-ray quiescent and flaring states. We will construct gamma-ray and optical light curves and polarization curves to search for correlations between gamma-ray and optical flux and polarization variations, analyze spectral index evolution, and study magnetic field properties in optical emission regions at different gamma-ray activity states. We will include new sources in the sample based on Fermi, VHE, and neutrino alerts. This information will lead to important insights into the particle acceleration mechanisms and locations of gamma-ray emission sites in AGN.

Oleg Kargaltsev/
CLASSIFICATION OF 4FGL SOURCES WITH 4XMM AND MULTIWAVELENGTH SURVEYS

More than 50% of 4FGL-DR3 sources with |b|<10 deg are not firmly identified, of which 257 have X-ray coverage in a comprehensive 4XMM-DR11 catalog. We will explore the nature of particle accelerators in these gamma-ray sources using multiwavelength classification approach, which combines gamma-ray/X-ray/optical/NIR/IR/radio data and feeds them into machine-learning pipeline. The pipeline will make use of already existing training dateset expanded to gamma-rays, IR, and radio. We expect to (1) increase the fraction of identified 4FGL sources, (2) determine a fraction of gamma-ray sources which are ``dark" at other wavelengths, (3) learn more about the particle accelerators in gamma-ray sources, and (4) classify all X-ray sources within the selected 4FGL fields.

Jamie Kennea/Pennsylvania State University
IMPROVING THE LOCALIZATION OF GBM GRBS WITH SWIFT/BAT EVENT DATA IN CYCLE 15

We seek to improve the localization of \fermi/GBM detected GRBs. Utilizing GBM alerts, \swift\ is commanded to dump BAT event data, usually discarded on board, to the ground. These data will be analyzed for evidence of a co-detection of the GRB by BAT. If detected, then we will utilize BAT data either to localize the GRB to $\sim$arc-minute resolution (if within BAT FOV), or if outside the BAT coded FOV, combine information from GBM and BAT to significantly reduce the GBM error region. We estimate obtaining arc-minute localizations for 15 GBM GRBs per year, in addition to those co-detected by BAT, and many more will allow us to significantly reduce the GBM error region. This is vitally important for the upcoming O4 GW detector run which overlaps Fermi Cycle 15.

Matthew Kerr/Naval Research Laboratory
Building the Fermi Pulsar Timing Array

Fermi has been incredibly successful at finding pulsars: the count is now over 280, and more than 130 of these are millisecond pulsars (MSPs). (Before Fermi, there were fewer than 10 gamma-ray pulsars known.) The haul has advanced our understanding of the pulsar emission mechanism, evolution of low-mass binaries, and Galactic populations of neutron stars. Each pulsar, particularly each MSP, also provides an astrophysical clock, the best of which rival terrestrial time standards. Monitoring pulses from these pulsars can reveal subtle signatures, including binary companions, post-Newtonian effects, and low-frequency gravitational waves from merging supermassive black holes.

Traditionally such work has been done using large, radio telescopes. Building on previous work, we have recently demonstrate that Fermi-LAT is also surprisingly sensitive to low-frequency gravitational waves. One prominent advantage of using gamma-ray data is that, unlike radio waves, it is not affected by propagation through the ionized interstellar medium. In this project, we propose to improve the search for gravitational waves by optimizing the way in which we carry out the search with Fermi-LAT data. In particular, for each pulsar, we will determine the best possible set of photons which maximizes the significance of the pulsed signal. We will further implement modifications to the software we have developed to include MSPs with strong variations in the orbital period. Finally, we will work with radio astronomers to understand any differences between radio pulsar timing array data sets and gamma-ray pulsar timing data sets, both globally and for each pulsar. With these improvements, and the accrual of additional data, the Fermi-LAT sensitivity will probe the intriguing candidate signals recently detected by radio PTAs and potentially confirm or refute their interpretation as originating with a gravitational wave background.

Daniel Kocevski/
The Fermi Light Curve Repository

We propose to further develop the Fermi LAT light curve repository, consisting of a public library of light curves for variable Fermi LAT sources on a variety of timescales. The Fermi LAT light curve repository aims to provide publication quality light curves on timescales of days, weeks, and months for over 1500 sources deemed variable in the 4FGL-DR2 catalog. We propose to implement a range of supplemental time-series analyses to characterize the long-term gamma-ray variability of the sources currently tracked by the repository. This includes developing a flare detection method and an algorithm to distinguish the flux attributed to flaring activity from the flux in the quiescent background (QB) of a source to estimate a baseline emission for the sources in the sample.

Daniel Kocevski/
Developing an Open Source Coherent Sub-threshold Targeted Search of GBM Data

We propose to implement a version of the GBM targeted search as an open source tool which would be made available to the community. The new version would make use of the newly available GBM Data Tools, which provide a comprehensive and modern application programming Interface for GBM data. The use of the Data Tools would provide a means by which the targeted search could be applied to GBM-like data from other instruments, including a range of SmallSats funded to fly in the coming years. We also propose to extend the joint likelihood analysis underlying the search to be used with data collected across multiple missions, combining the sensitivities of all GBM-like detectors to form a truly coherent multi-mission sub-threshold search to provide a ever deeper search of the gamma-ray sky. (

Matthew Lister/Purdue University
Investigating Gamma-Ray Emission From Young Radio Galaxies

We propose a joint Fermi-VLBA study to investigate small scale jet structure and high energy emission in a sample of ten young AGN jet systems. The sample AGN are distinguished from other known young radio galaxies by their atypically flat radio spectra and unusually bright radio cores, and two have already been detected by Fermi LAT. Our study will lead to a better understanding of AGN life cycles, as well as the gamma-ray emission mechanisms in misaligned AGN and newly emergent relativistic jets.

Raffaella Margutti/University of California at Berkeley
A coordinated Fermi-VLA view of the most extreme mass-loss events from massive stars

The recent GeV detection of SN iPTF14hls at d=150 Mpc opened up a new window of investigation on the most extreme mass-loss events. Thus motivated we propose a systematic search for GeV emission from nearby (d<150 Mpc) SN shocks interacting with a dense environment. GeV emission is predicted to originate as the SN ejecta crash into dense shells of material previously ejected by the progenitor star. We capitalize on the synergy of Fermi/LAT and VLA observations with three goals: (i) Test the supernova shock breakout through a dense wind model using GeV observations. (ii) Constrain the cosmic rays acceleration at shocks formed by the collision between the SN ejecta and the CSM shell. (iii) Deliver the first predictions of the neutrino emission associated to ordinary interacting SNe and superluminous SNe.

Brian Metzger/Columbia University
FROM GEV TO TEV GAMMA-RAY EMISSION IN NOVAE

The discovery by Fermi LAT of GeV gamma-rays from classical novae illustrates that shocks and high energy particle acceleration are common in nova outflows. We will extend our recent multi-dimensional simulation work on radiative shocks in novae to calculate their multi-wavelength emission up to the highest energy gamma-rays. By combining the distribution of inclination angles across the shock front relative to the upstream magnetic field with the results of particle-in-cell simulations, we will predict the particle acceleration efficiency and compare to those observed. Particular focus will be placed on calculating the maximum particle energy, to address the recent H.E.S.S discovery of TeV emission from RS Oph.

Brian Metzger/Columbia University
Gamma-Rays from Magnetar-Powered Supernovae

Stellar explosions have been discovered with peak luminosities too high to be powered by traditional energy sources. A popular model for such "superluminous supernovae" (SLSNe) and "fast blue optical transients" (FBOTs) posits the birth of a magnetar engine. We will develop and apply a Monte Carlo radiative transfer model for magnetar-powered supernovae which self-consistently accounts for radiative processes in their wind nebula and ejecta and makes predictions for the late-time escape of non-thermal gamma-ray emission. Our results will be compared to observations of SLSNe/FBOTs with Fermi-LAT and Air Cerenkov telescopes in order to test the magnetar model. The same model will be applied to predict gamma-ray emission from long-lived magnetar remnants in binary neutron star mergers.

Kaya Mori/Columbia Astrophysics Laboratory
A GeV survey of pulsar wind nebulae and TeV halos: probing the origin of Galactic PeVatrons and positron excess

The proposal seeks a unique opportunity to collect legacy Fermi-LAT data and explore pulsar wind nebula (PWN) astrophysics at the deepest level, in conjunction with recently obtained X-ray and TeV data. Our targets represent a diverse class of PWNe: 6 middle-aged PWNe (including PeVatron candidates detected by LHAASO and HAWC) and 6 new TeV halos associated with relic PWNe. Given 14 years of the LAT data, we can reach sufficient sensitivity to test multi-wavelength SED models for the PWNe (with GeV spectral data uniquely determining their intrinsic electron energy distribution) and to detect GeV counterparts of the new TeV halos. The proposed Fermi-LAT analysis will allow us to probe the particle acceleration mechanisms in the middle-aged PWNe and the origin of the positron excess.

Michela Negro/University of Maryland Baltimore County
SEEKING THE BROAD LINE REGION OF FERMI-LAT BLAZARS

Blazars are a class of radio-loud AGN with a powerful jet oriented close to the line of sight. FSRQ are a class of blazars for which the quasar core" emission can dominate the optical spectrum, overwhelming the jet emission. A recent work targeting the FSRQ 4C 71.07, found evidence for an outflow emission, observing clearly blueshifted broad lines. The known orientation of blazars disc represents a unique advantage in the study of the outflows that is not available in general for AGN. We propose to study of a sub-sample of the Fermi- LAT FSRQ that show a prominent nuclear emission. We will look for outflow signatures in the broad lines and correlate possible line variability with the LAT gamma-ray emission to determine the role of the jet in the photoionization of the BLR.

Jeremy Perkins/NASA/GSFC
STUDYING THE EARLY-TIME EMISSION OF GAMMA-RAY BURSTS USING FERMI AND HAWC DATA COHERENTLY

The Fermi-LAT telescope has detected photons from Gamma-Ray Bursts (GRBs) up to 95 GeV and discovered the emergence of a high-energy spectral component above 100 MeV. Very-high-energy (VHE) emission from GRBs has been confirmed by MAGIC and HESS. However, due to slewing constraints, they miss the onset and peak of the VHE emission, critical for understanding the environment of GRBs, the acceleration mechanisms, and the jet and central engine properties. HAWC is a VHE observatory well suited to study the early-time emission from GRBs thanks to its wide field-of-view and continuous monitoring, filling this important gap. This proposal looks to capitalize on recent improvements to HAWC event reconstruction and data analysis to perform a joint study with Fermi data. This will better constrain theoretical models and help us understand the physics responsible for the highest energy photons produced in GRBs.

Judith Racusin/NASA/GSFC
CHARACTERIZING GAMMA-RAY EMISSION FROM PULSAR WIND NEBULAE WITH THE FERMI-LAT

Pulsar wind nebulae (PWNe) are some of the brightest and most energetic sources detected in the Milky Way Galaxy, defining the majority of TeV sources detected by Cherenkov Telescopes. As such, PWNe provide a direct view to some of the most extreme Galactic environments, which may be responsible for the production of particles to cosmic ray energies. Taking advantage of the latest event reconstruction update for Fermi, we propose a systematic search for MeV-GeV PWNe targeting the locations of known PWNe identified in other wavelengths. A second approach searches for new PWNe in the off- pulse phases of Fermi-detected pulsars. New detections will be combined with available multiwavelength data and semi-analytic modeling to determine the underlying relativistic particle spectra.

Paul Ray/Naval Research Laboratory
NEW SEARCHES FOR RADIO MILLISECOND PULSARS IN FERMI SOURCES WITH THE 4FGL-DR3 CATALOG

Fermi has had a spectacular impact on pulsar research, especially for millisecond pulsars (MSPs). Since 2008, Fermi has led to the discoveries of 115 MSPs in targeted radio searches of unassociated sources. We aim to continue this amazing MSP discovery pace using the Green Bank Telescope (GBT) and the most up-to-date LAT point source catalog, the 4FGL-DR3, which covers 12 years of LAT data and contains over 2000 unassociated sources. We have identified 34 sources as especially strong MSP candidates, based on comparisons between their gamma-ray spectral and variability characteristics and those of the known radio+gamma-ray MSP population. We request 51 hours of GBT time to search these sources for radio pulsations.

Frank Schinzel/University of New Mexico
REVEALING A MISSING POPULATION OF GAMMA-RAY PULSARS

More than 300 neutron stars, so called pulsars, were detected in the gamma-rays by Fermi. The pace of pulsar discoveries has remained unabated even though it has long been assumed that there are few new radio-loud pulsars to be found in the Galactic plane (GP). The latest Fermi/LAT point souce catalog, 4FGL-DR3, presents a doubling in the number of pulsar-like unassociated gamma-ray sources (UAS) to about one quarter of all detected GP sources. UAS are Fermi/LAT detected point sources that have no plausible multi-wavelength counterpart and which nature is unknown.

It is our hypothesis that the growing population of UAS in the GP are in fact missing radio-loud young, energetic pulsars that are hidden from standard pulse searches by interstellar scattering. We propose to overcome this limitation by observing with the Karl

G. Jansky Very Large Array a large sample of steep-spectrum radio sources found in UAS to detect circular polarization, which is a clear signature for pulsars.

This will allow for a concentrated follow-up of promising candidate, both in the gamma-rays and at radio wavelengths, to confirm their nature and to characterize their physical properties. This will continue to increase the importance of Fermi/LAT detections for the discovery of pulsars and provide insights into the physical properties of the population of young energetic pulsars in the GP.

Jay Strader/Michigan State University
Uncovering Fermi Galactic Binaries with Optical Spectroscopy

Support is requested for a spectroscopic program to discover and characterize Galactic compact binaries among unassociated Fermi sources. Intriguing systems have already been found, new subclasses of pulsar binaries with red giant companions and a "missing link" proto-white dwarf--millisecond pulsar binary. The regular observing cadence and optical spectroscopic resources constitute a unique opportunity to add value to the Fermi mission through ground-based correlative observations.

Louis Strigari/
Searching for Inverse Compton Emission from Globular Clusters with Fermi-Lat and HAWC

The motivation for the proposal is searching for evidence of a high-energy emission component due to inverse Compton scattering (ICS) in the spectra of a globular cluster (GC) sample. The proposed sample will consist of 35 and 76 GCs in the field-of-view of Fermi-LAT and HAWC, respectively. Most GCs are known to have millisecond pulsars (MSPs) as the primary source of gamma-ray emission. However, it is currently unknown if these MSPs will also have TeV halos or extended TeV emission; and how much the ICS contributes to the gamma-ray emission.

Zorawar Wadiasingh/University of Maryland College Park
Towards First-Principles Models of Magnetar Burst Fireballs

Fermi GBM has a catalog of many hundreds of magnetar bursts. Recent reports of rotational-phase selection of magnetar short bursts in SGR 1830-0645 and SGR 1935+2154 strongly suggest a fixed and low altitude emission locale for magnetic flux tubes which confine the Comptonized fireball during magnetar bursts. At such low altitudes, gravitational lensing can be important and a second lensed image can result for bursts behind the neutron star for the observer. This lensing can imprint not only flux changes, but time delays and spectroscopic variation of bursts at particular rotational phases. We propose to develop the first magnetar burst fireball models accounting for curved spacetime, radiative transport in strong magnetic fields, and photon splitting.

Strategic Astrophysics Technology (SAT)
Abstracts of Selected Proposals
(NNH21ZDA001N-SAT)

Below are the abstracts of proposals selected for funding for the Astrophysics Research and Analysis program. Principal Investigator (PI) name, institution, and proposal title are also included. 40 proposals were received in response to this opportunity, whereas 39 proposals were found to be compliant. On May 12, 2022, 12 proposals were selected for full funding and 2 for partial funding.

Marshall Bautz/Massachusetts Institute of Technology
Extremely Low-noise, High Frame-rate X-ray Image Sensors for Strategic Astrophysics Missions

X-ray imaging sensors for future strategic missions will require relatively small pixels (≤16 μm) with relatively large depletion depths (~100 μm), with excellent soft X-ray performance at high (20-100 frames/sec) readout rate. Achieving physics-limited performance in these devices requires a large number of parallel, fast output amplifiers to achieve the required frame rate and very low readout noise to achieve the required spectral resolution and soft X-ray quantum efficiency. Low noise is critical because charge packets produced by low-energy photons will diffuse to be collected in multiple pixels, some of which contain very small (a few dozen electrons or less) amounts of charge. Reliable detection and accurate measurement of such small charge packets is essential for both good spectral resolution and low-energy quantum efficiency, and requires very low noise (~2.5 electrons RMS or less). Current flight technology achieves read noise levels of a few electrons RMS at pixel rates of 50 - 100 kHz per output. To mature the detector technology required for future strategic missions we propose to extend our current Strategic Astrophysics Technology work, which has demonstrated a single-channel pJFET CCD output amplifier with < 3 electrons RMS noise operating at 2 MHz. We propose to demonstrate a multi-output CCD with noise < 2.5 e- RMS per read, and with technical characteristics (output rate, output pitch, pixel size and depletion depth) and spectral resolution meeting the requirements of the AXIS X-ray probe, a mission concept conforming to the recommendations of Astro2020. To do this we will i)fabricate a version of our current test CCD equipped with 16 of our best current pJFET amplifiers and test it with a multi-channel ASIC readout under development in our current program; ii) optimize the design of our existing pJFET amplifier for even lower noise and iii) further develop and test a new, high-responsivity amplifier design, the Single-electron Sensitive ReadOut (SiSeRO), which in our recent measurements of proof-of-concept devices shows the potential for sub-electron noise. We will achieve the latter two objectives by means of two additional versions of the multi-output CCD, one each equipped for development of pJFET and SiSeRO amplifiers, respectively. Our access to fabrication facilities at MIT Lincoln Laboratory and the design, device simulation, and test capabilities of our team allow all of these elements to be addressed efficiently within the scope of our proposed program. Successful completion of this work will raise the technology readiness of this sensor architecture very close to TRL 4, and facilitate rapid achievement of TRL 4 in a follow-up program.

Douglas Bennett/National Institute Of Standards & Technology
Microwave SQUID readout technology development for future X-ray astrophysics missions

Microwave SQUID multiplexing (umux) provides the best opportunity to achieve the low noise levels and large readout bandwidth necessary for future NASA X-ray microcalorimeter missions. We propose to develop robust and scalable integration of umux devices with the X-ray focal planes, by designing, fabricating, and testing new microwave SQUID multiplexers that have a reduced footprint, are integrated into the X-ray focal plane via indium bump bonds, and use back side metallization of the chip to effectively enclose it in its own grounded cage, shielding it from the external microwave environment. This work should enable a large-format X-ray focal plane assembly to advance to TRL 5 ahead a potential transition into a potential Great Observatories Mission and Technology Maturation Program in the second half of this decade. Additionally, we propose to leverage our group's existing time-division SQUID multiplexing development for Athena and the other work in this proposal, to deliver time-division multiplexer designs suitable for integration into the focal plane of a Probe or Explorer class x-ray mission.

Charles Bradford/Jet Propulsion Laboratory
Ultrasensitive Far-IR Kinetic Inductance Detector Arrays: Maturation for Flight Year 1

We propose a program to retire the key technical risk of far-infrared space astrophysics missions recently recommended by Astro2020. We will demonstrate large arrays of kinetic inductance detectors (KIDs) with the sensitivity and format required to deliver the massive scientific potential of spectroscopy aboard cryogenic space-borne observatories, whether a near-term probe-class facility like the Galaxy Evolution Probe (GEP) or a future Far-IR Great Observatory (FIRGO) similar to Origins. We will build on APRA development and ground-based and balloon-borne arrays to build packaged focal planes that can be directly inserted into phase A/B designs for these mission. We will demonstrate two arrays at wavelengths which bound the envisioned far-IR range: 25 μm and 350 μm, with pixel pitch, readout density, and size informed by these concept studies. Our full program will yield two full-size arrays will meet all of the essential performance and system-level requirements imposed by a near-term probe:

1. a per-pixel noise equivalent power (NEP) below 1×10^{-19} W /sqrt(Hz).
2. provide 65% optical efficiency relative to a light incident on the pixel's coupling optic,

3. can maintain high scientific utility in the face of cosmic-ray interactions in space, and
4. are packaged into a flight-ready housing with at least 8000 pixels demonstrating >80% yield and acceptable cross talk.

Our work in year 1 will be to design the KID pixels and coupling structures for the two waveband, and demonstrate them in single pixels and/or small arrays. Success will be measurements showing compliance with requirements 1 and 2 above for both bands. The work to meet this milestone includes a) electromagnetic design beginning with incident radiation atop the horn or lens through to absorption in the KID inductor/absorber , b) construction of small prototype arrays (~50–few hundred pixel) which include coupling structures; and c) performance verification of these with our existing small-array setups. Also in year 1 we will study the full array design, incorporating the latest instrument-level requirements from probe concept studies (primarily pixel layout and input f/#).

Kerri Cahoy/Massachusetts Institute of Technology
Adaptive High-order Wavefront Control Algorithms for High-contrast Imaging on the Decadal Survey Testbed

Introduction: This work will increase the TRL of continuous high-order wavefront sensing and control (HOWFSC) systems for space-based coronagraphs. NASA exoplanet missions need to reach a contrast of 1e-10 and maintain it for many-hours-long observations to detect and characterize exoplanets. Coronagraph contrast stability" is a tier 1 gap for Exoplanet Exploration (ExEP) in NASA's 2019 Astrophysics Biennial Technology Report. The Astro2020 decadal survey identified adaptive wavefront control algorithms that are more efficient and improve tolerance to instabilities" as one of the high-priority technologies to mature" for the recommended IR/O/UV Large Strategic Mission.

The Coronagraph Instrument (CGI) on the 2.4-meter Roman Space Telescope (RST) plans to mitigate contrast instability by slewing to a bright reference star several times a day for re-calibrating. However, this introduces its own instability as the solar angle of the telescope changes, affecting thermal distribution. Slewing to a reference star is still feasible with RST's target contrast, but may be infeasible for the larger Astro2020-recommended 6-meter IR/O/UV telescope with 2-3 orders of magnitude higher contrast. High-order wavefront perturbations would need to be continuously controlled (dark hole maintenance) on time scales of minutes. In experiments on the High-contrast Imager for Complex Aperture Telescopes (HiCAT) at the Space Telescope Science Institute, dark hole maintenance rejected artificially-introduced time-dependent wavefront aberrations at the 1e-8 contrast level, at TRL 3. We propose increasing the TRL to 4 by demonstrating advanced HOWFSC algorithms at the 1e-9 to 1e-10 contrast on the Decadal Survey Testbeds (DST) at JPL.

Approach: We will explore the trade space of dark hole maintenance (DHM) on HiCAT at 1e-8 contrast, so that we optimize our time on DST for a true TRL 4 demonstration. On

HiCAT, we will first run our basic DHM scheme for a large space of parameter such as wavefront drift magnitude and photon flux. We will then compare our experimental results to theory and simulation of HiCAT. In order to improve agreement between the three, we will implement advanced algorithms such as modal DHM (to improve performance relative to theory) and system-identification (to improve match with simulations). We will then bring basic DHM to TRL 4 by demonstrating it on DST at 1e-10 contrast and comparing its performance to theory. We will also validate the advanced algorithms on DST.

Expected Results: 1) TRL 4 for continuous contrast maintenance via demonstration in a vacuum laboratory at a contrast level necessary to detect Exo-earths and analysis of (closed-loop) contrast degradation in the presence of various wavefront instabilities. 2) Assessment of the benefits of using advanced/adaptive algorithms, including modal wavefront control and system identification techniques. 3) Observing scenario data package (similar to OS 9 for Roman Coronagraph) scaled to represent the IR/O/UV mission's baseline.

Significance: This work will lead to an improved understanding of the risks and rewards associated with wavefront control on a space coronagraph. We will assess how well we can maintain contrast in the presence of wavefront instabilities in an environment relevant to the IR/O/UV telescope. New HOWFSC approaches will lead to better contrast stability and higher science yield, and reduce missions cost and risk as larger structures in the observatory would not need to be as stable.

Michael Hoenk/Jet Propulsion Laboratory
High Performance FUV, NUV, and UV/Optical CMOS Imagers

We propose the development and maturation of high efficiency, large format, low noise, FUV, NUV, and broadband complementary metal oxide semiconductor (CMOS)-based detectors that address the needs of future NASA missions particularly the large IR/O/UV observatory that is recommended by the Astro2020 decadal.

Our proposed objectives for this development are tied to the technology gaps identified by Technology Development for Cosmic Origins (TCOR) and the large telescopes technology requirements of the large Astro2020-recommended IR/O/UV observatory recommended by NASA flagship mission concepts studies, especially the LUVOIR while recognizing that the Astro2020 recommends a significantly smaller approach that will place even more exacting requirement on the high signal to noise ratio needed at the detector end. We have identified several of the key and driving detector requirements of NASA flagship mission workhorse instruments such as LUVOIR High-Definition Imager (HDI) and LUVOIR Ultraviolet Multi-Object Spectrograph-Near Ultraviolet (LUMOS-NUV) and plan to address these in a focused, stepwise approach. These instruments need high performance detectors in large format (10's megapixel), low noise (<2.5 e-), small pixels (5-10 µm), high quantum efficiency (>50%), and tailorable spectral response in a large (multi gigapixel) mosaic focal plane array (FPA).

This proposed effort combines advanced CMOS design develop in industry (Teledyne-e2v, SRI, and RVS) including low noise stitchable scalable arrays, 3D-stacked, hybrid buttable CMOS detector technologies with performance of superlattice (SL) doping and delta doping (i.e., 2D-doping) processes and integrated, multilayer antireflection (AR) coatings and visible rejection filters. Using LUVOIR-HDI and LUMOS-NUV as guiding requirements, we will demonstrate and develop 2D-doped, low noise scientific CMOS detector arrays with integrated multilayer coatings for broadband NUV-NIR response as well as for the NUV range. Key performance parameters to be addressed include QE, PRNU, and noise. Additionally, these detectors will be evaluated for astrophysics applications, e.g., precision photometry and astrometry using JPL's astronomical scene emulator.

Our team comprises members with complementary expertise in materials, detectors, characterization, instruments, and observational science. Multiple members of our team were involved in the LUVOIR STDT and design team and have first-hand understanding of the requirements of LUVOIR and the TCOR technology gap. Furthermore, this development paves the way for demonstration and TRL advancement through suborbital flights.

Amir Jahromi/NASA Goddard Space Flight Center
Development of a 30 mK ultra-low temperature Continuous Adiabatic Demagnetization Refrigerator (CADR) with a continuous 700 mK intermediate stage for heat intercept

Several past, and many future, astronomical instruments require cooling to sub-Kelvin temperature to obtain high sensitivity. In many cases, large arrays of cryogenic detectors will be required. The cooling systems associated with these detectors will require performance surpassing the limits of present flight sub-Kelvin coolers. We have begun to address this technology gap with an SAT-funded refrigeration system that will come to a conclusion in FY 2022. We propose to extend that development of a compact cooling system to provide significant cooling at even lower temperature, lifting significant heat continuously at temperatures down to 30 mK and reject the heat to a cryocooler at 4.5 K, simplifying the overall cryogenic system. We will also develop a new continuous cooling stage at 0.7 K to intercept heat, which is crucial for low temperature detector harnesses, optics, as well as the lower stage coolers (30 mK) of our proposed system.

Our proposed system will exceed the requirements of all currently conceived cryogenic detector arrays, including flagship and Probe missions recommended by the 2020 Astrophysics Decadal Committee: the Far-IR Probe, Inflation Probe, X-ray Probe, and possibly the HabEx/LUVOIR flagship with far-IR sub-Kelvin detectors.

Multi-stage ADRs offer great flexibility. The same refrigerator can be operated at any temperature within the range of 30 to 300 mK. The 0.7 K heat intercept stage could be regulated at other temperatures between 300 mK and 1 K to suit the cooling requirements of a detector system. Continuous stages could be added at other temperatures to provide cooling to, for example, Superconducting Quantum Interference Device arrays for Transition Edge Sensors (TES) or High Electron Mobility Transistors (HEMT) for Microwave Kinetic Inductance Detectors (MKID).

Now is the time to pursue this effort. Our team completed the end-to-end design, build, and flight qualification of the Hitomi ADR. Launched successfully in February 2016, the ADR provided a stable 50 mK on-orbit detector array temperature for over one month until the untimely demise of the spacecraft. We have delivered a similar 3 stage ADR for the replacement mission, XRISM. The SAT awarded to our team in 2017 has resulted in a fully assembled unit about to be tested and vibration qualified at the system level. This proposal builds on that successful effort utilizing the same experienced team. In short, the team is ready now to make this technology mission-selectable by 2025.

We will set new standards in sub-Kelvin spaceflight cooling. At the conclusion of this work, NASA will have a TRL-6 magnetic cooling system ready for missions in the coming decades.

Randall McEntaffer/Pennsylvania State University

Ultraviolet Spectroscopy for the Next Decade Enabled Through Nanofabrication Techniques

The recently released Astro2020 Decadal Survey identified an IR/O/UV large strategic mission as the number one priority in the next decade. A main science focus for UV spectroscopy is understanding stellar impacts on their environments. UV radiation from low mass stars can greatly influence planetary habitability by altering chemistry of atmospheres while magnetic activity can drive atmospheric loss. Furthermore, understanding winds from massive stars through their UV spectra will constrain models of stellar mass loss and their dependence on stellar characteristics such as mass and metallicity. UV spectra of stars can also help us understand binary evolution, galactic spectra, photoionization rates, and impacts on protostellar disks.

Astro2020 also prioritized an ambitious course of technology maturation specifically for supporting the IR/O/UV strategic mission. This proposal aims to develop UV diffracting optics, a key technology for future UV spectrographs. These efforts leverage heavily from a previous SAT program, which developed viable fabrication techniques for improving echelle gratings and creating custom groove shapes on curved surfaces. The continuation of these studies will increase the performance of UV gratings to reach requirements for future missions. In addition to using performance testing to verify the fabricated optics, they will be incorporated into existing suborbital rocket programs for technology readiness maturation in the real-world conditions of a flight instrument.

High-efficiency, UV echelles and custom-groove, curved-substrate gratings are enabled through a combination of electron-beam lithography (e-beam) and subsequent etching processes. This SAT program will utilize the world-class Nanofabrication Lab within the

Materials Research Institute at Penn State University. The e-beam tool writes each groove individually and can be programmed to create custom groove directions with sub-nanometer resolution. Once the precision patterns are written, dry and wet etch processes can transfer the pattern into the substrate. These fabrication methods have been used successfully in the previous SAT study to create medium-fidelity echelles and curved-substrate prototypes. The new SAT program will extend these efforts to create high-fidelity echelles and full-sized, curved-substrate, flight-like gratings.

Shouleh Nikzad/Jet Propulsion Laboratory
High Efficiency, UV/Optical Photon Counting Detectors

In this one-year effort and under partnership with Teledyne-e2v we will take steps toward the development of high efficiency and tailorable UV (with red rejection) and UV/Optical photon counting detectors. We will incorporate techniques that were demonstrated in a recent APRA funded task for atomic layer deposition graded coatings and detector-integrated metal dielectric filters. These techniques will be demonstrated on standard electron multiplying CCDs (EMCCDs) and potentially deep depletion EMCCDs—the latter for response extension into near infrared. Completed devices will be characterized for photon counting, red rejection, and in-band quantum efficiency (QE).

Manuel Quijada/NASA Goddard Space Flight Center
Advanced Al mirrors with passivated LiF for environmentally stable 1-meter class UV space telescopes

The recently released 2020 Decadal Survey on Astronomy and Astrophysics has prioritized a large (≈ 6 m aperture) infrared/optical/ultraviolet (IR/O/UV) space telescope as the next NASA flagship mission with the scientific goal of searching for signatures of life on planets outside of the solar system in addition to perform other critical astrophysical observations using the same platform. The report observes that the outstanding science discoveries that this mission is proposed to accomplish will only be feasible if critical technologies reach TRL 6 or above in the next 5 years. Among the technology needs mentioned, the IR/O/UV telescope requires improvements in the mirror optical coatings. This proposal will address these needs.

Our team at the Goddard Space Flight Center (GSFC) has recently developed a new reactive Physical Vapor Deposition (rPVD) process (Quijada et al., Mirror Tech Days 2021) that consists in fluorination/passivation of thermally evaporated Al mirrors protected with a LiF overcoat. These coatings offers the highest ever reported Far-Ultraviolet (FUV) reflectance performance while exhibiting a remarkable environmental stability. This new coating technology also satisfies all the reflectivity requirements as specified in the Large UV-Optical-Infrared Surveyor (LUVOIR) Science and Technology Definition Team (STDT) report. Moreover, the entire coating process is carried out at ambient temperature and a technology readiness level (TRL) of up to 3 has been demonstrated at a small scale.

This proposal effort will advance the TRL of this mirror coating process to 5-6 by performing two tasks. First, we will transfer this rPVD process to our largest 2-meter chamber at GSFC in order to enable the coating of a 1-meter diameter class mirror. Secondly, we will validate this process by coating the primary mirror (0.5 meter diameter) and gratings (150 x150 mm2) of the Far-UV Off Rowland-circle Telescope for Imaging and Spectroscopy (FORTIS) sounding rocket (PI: S. McCandliss) that is being developed at John Hopkins University. This instrument concept will be operating in the FUV (90-150 nm) spectral region to carry out laboratory experiments and design studies.

A parallel effort in this proposal will be to conduct a comprehensive study to better understand the environmental stability observed in mirror coatings produced with the rPVD process. Although the outstanding stability of these coatings have been demonstrated in the lab, the fundamental physics that ultimately drive this behavior is not fully understood to enable optimization and an informed strategy for preflight hardware processing. Thus, we propose to combine the optical coatings expertise at GSFC with the expertise in materials analysis at Brigham Young University (Prof. David Allred), which has recently studied the optical, microscopic and structural changes of bare LiF thin films exposed to humid air. We will establish a collaboration to perform a similar study on these Al+xeLiF mirrors fabricated through the rPVD process. A better understanding of the degradation mechanisms on Al+LiF mirrors will help to further improve its performance, particularly in the range of 91.2-100 nm.

Karwan Rostem/NASA Goddard Space Flight Center
Advancing Readout of Large-Format Far-IR Transition-Edge Sensor Arrays

Advances in superconducting detector technology are essential to enabling national science priorities in far-infrared (far-IR) astrophysics. The 2020 Decadal Survey recommendation for a far-IR Probe mission beginning in 2030 clearly emphasizes the need for technology development. A key area identified by the Cosmic Origins Program (COS) as a Tier-1 technology gap is cryogenic multiplexing of tens of thousands of superconducting detectors, which requires a unique low power, low noise and scalable solution. To address this challenge, this proposal focuses on the development of time-domain multiplexing for superconducting Transition-Edge Sensor (TES) bolometers. The TES bolometer is a mature detector technology that has been employed in numerous pioneering sub-orbital millimeter and far-IR instruments. Specifically, the absorber-coupled TES bolometer is uniquely versatile. It can be used to efficiently detect light across the entire 1-1000μm range and is the most promising candidate for achieving ultra-low noise operation with high optical coupling efficiency in the infrared. A new generation of two-dimensional time-domain multiplexer (2dMUX) array will be designed, fabricated, and tested that permit significantly higher multiplexing factors (≥128) over current implementations. The circuit and physical design of the multiplexer unit cell has improved greatly through existing efforts to build 2dMUXs for the X-ray

Integral Field Unit on the Advanced Telescope for High Energy Astrophysics (ATHENA L-Class ESA mission), which uses an array of 3,168 TES micro-calorimeters. The advances made in the design and performance of the 2dMUX for X-IFU are immediately applicable to the multiplexing of far-IR TES bolometers. For example, the latest innovation is a two-level row address switch that dramatically reduces the number of wires needed to address the readout. A reduction in the number of wires directly translates to a lower dissipation at the coldest stage of a cryogenic focal plane and longer cryogenic hold time. Further improvements in the physical layout of the multiplexer unit cell promises will lead to a 30% reduction in the 2dMUX array size, which translates to a reduction in size of the focal plane assembly. The new generation of 2dMUX arrays will have better noise performance, dissipate less power, and require significantly less row address wires. The first year of the program will focus on the design and integrating two-level switching into an array format. In the second year, two 32(row)×16(col) 2dMUX arrays will be hybridized to a fanout board and read out as a 64(row)×16(col). The end-to-end performance of the multiplexer chips will be assessed with an array of 1024 low-noise TES pixels that will be placed on the fanout board.

Babak Saif/NASA Goddard Space Flight Center
Ultra-stable Telescope Metrology Development for High-contrast Exoplanet Detection

We propose to advance the technology of several ultra-stable structure test bed technologies and metrology methods, particularly picometer spatial metrology and calibration methods, ULE mirror ultra-stable control, and ultra-stable composite stability. These technologies and metrology methods are key needs to enable a 6 meter Infra-Red Optical Ultra-Violet (IROUV) space telescope as recommended in the Decadal Survey on Astronomy and Astrophysics 2020 report “Pathways to Discovery in Astronomy and Astrophysics for the 2020s” (hereafter, Astro2020): “the mission the survey puts forward will combine a large, stable telescope with an advanced coronagraph.” A telescope of this type can support both general class astrophysics and high contrast imaging though the driving telescope technological need is for the primary mirror to be stable to approximately 10 pm RMS over control bandwidths ranging from minutes to hours.

Mark Schattenburg/Massachusetts Institute of Technology
Technology maturation for a high-sensitivity and high-resolving power x-ray spectrometer

With NASA support, MIT is developing a revolutionary type of lightweight, high efficiency and high resolving power x-ray spectrograph called the critical angle transmission (CAT) x-ray grating spectrometer (CAT-XGS) that addresses specific science elements within the Astro2020 Decadal Review. Concentrated technology development has produced nanofabricated grating elements assembled into prototype spectrometers with an unprecedented combination of resolving power and diffraction efficiency. Technology has advanced to the point where it was selected for the Lynx design reference mission reviewed by the Decadal committee, and also the Arcus x-ray spectrometer proposed for a NASA MidEx mission. A series of prototype flight grating spectrometers using CAT gratings have been built and x-ray tested, meeting Arcus mission requirements and passing environmental tests. This technology is targeted to Explorer class as well as and X-ray Probe and Strategic missions called for in the Astro2020 Decadal Review.

Effort to date has primarily addressed basic issues of grating design, manufacturability, metrology, alignment, assembly and test of prototype components that, while meeting the requirements of Explorer missions, fall short of the requirements for probes or strategic missions where improvements of resolving power, diffraction efficiency and the sheer number of gratings required for missions place stringent demands that go beyond current capability.

We propose to address technical issues impeding progress, specifically to increase the grating bar aspect ratio using advanced technology including new Enhanced Silicon-on-Insulator (E-SOI) wafers now coming onto the market. Tall, thin, and vertically aligned grating bars are essential for high spectrometer efficiency and resolving power. We propose to address challenges in nanofabrication technology that will enable improved spectrometer performance meeting strategic requirements, while reducing the cost and complexity of the manufacturing steps.

Johannes Staguhn/Johns Hopkins University
Demonstrating Large Low Noise Transition Edge Sensor Arrays for Future FIR Space Missions

The 2020 Decadal report explicitly recommends two potential FIR missions. One of those will be a competed FIR Probe that, according to the report, could be launched as early as 2030. This probe mission requires a very fast and focused detector development program to mature current detector technologies that potentially can meet the sensitivity and pixel number requirements of such a mission- from currently TRL level 3 to level 6 not later than in 2025. It is evident that it is mandatory for the technology development for such a mission to begin now rather than only once the mission formulation has begun. While not yet defined, the detector requirements for the Probe mission can be expected to be close to the parameters required for the FIR Probe GEP, which is the FIR Probe proposed to the Decadal survey. In terms of detector noise requirements, this translates into detector NEPs just below 10^{-18} W/sqrt(Hz) for the low spectral resolution imaging instrument GEP-I. In terms of pixel numbers, both GEP instruments require a few times 10^4 pixels, but with individual detector arrays with ~1,400 pixels each for GPI-I, and ~ 6,000 pixels each for GPI-S.

Here we propose to build and demonstrate tileable individual kilopixel arrays with an architecture that can meet the few 10^4 pixel requirements for both GEP instruments, and which can meet the noise requirements for GEP-I with slightly modified optical parameters. These arrays will be based on an architecture we have developed and demonstrated in a prior SAT. The architecture demonstrated there is optimized for the use of the latest 2-D time domain SQUID multiplexers developed and produced at NIST, together with a high density fanout scheme developed by our team for a separate SAT. The noise requirements will be achieved by using a pixel design our group has successfully developed and demonstrated for the HIRMES Transition Edge Sensor (TES) based high resolution spectrometer arrays, but with a potential minor reduction of the transition temperature Tc that will be be enabled by the available cooling power provided by space certified ADRs, such as the one flown on HITOMI. Our array design will also be compatible with future lower NEP TES designs that are currently investigated by members of this team and other groups.

In summary, we propose to use a combination of an already demonstrated array architecture with an existing TES pixel design plus high-density readout schemes designed to read out those arrays with 2-D SQUID multiplexers designed by NIST. This will be an end-to-end demonstration of large TES-based arrays capable of meeting the requirements for the low spectral resolution imaging instrument of the FIR probe mission GEP, which can be considered as a template for the actual low-resolution instrument expected to be proposed for a future FIR probe, which is called for in the Decadal report.

J. Wallace/Jet Propulsion Laboratory
Dual-purpose coronagraph masks for enabling high-contrast imaging with an IR/O/UV flagship mission

The recently released Astronomy Decadal report is impressive in its endorsement of the search for and detection/characterization of exoplanets. In particular, the report endorses a flagship, space-based telescope to specifically address this ambitious science goal.

However, we should be mindful that there are serious technical challenges presented by the ambitious goal of high-contrast imaging. In particular, optical quality and stability of the full optical beam train of the observatory   from collecting aperture to science focal plane   is required. Specifically, the total contribution of the wavefront errors must be stable at the 10 pm level over the several tens of minutes. This is very difficult.

Thankfully there is good news. Over the past decade, NASA has been investing resources into the technical development of wavefront sensing in support of high-contrast imaging, and it has yielded great success. In particular, the Zernike Wavefront Sensor (ZWFS) has been integrated into the focal plane mask of a stellar coronagraph to enable low-order wavefront sensing (ie., pointing jitter, focus, astigmatism). This low-order ZWFS has been demonstrated to meet the sensing and control requirements using faint photon fluxes typical of many science observing scenarios. Separately, a dedicated ZWFS has also been demonstrated to measure mid- to high-spatial frequencies with exquisite sensing capabilities at the picometer level, with precision limited only by the quantum fluctuations of photon-noise.

Here we propose to extend this technology in the following way: the Zernike wavefront sensor will be modified to work: 1) with photons not in the science band 2) to measure both low- and high-spatial frequencies and 3) to do so contemporaneously with high-contrast science observations. The dual-purpose focal plane mask (combining wavefront sensing and coronagraphy) will greatly relax the observatory requirements. Using this dual-purpose focal plane mask capability, we fundamentally change the picometer wavefront requirement from being a stability problem to being a sensing and control problem. This affords a significant relaxation in the observatory requirements.

Our plan is to develop dual-purpose focal plane masks, experimentally demonstrate these masks first for high-contrast imaging, then subsequently for wavefront sensing, and finally for contemporaneous science and sensing with active, closed-loop wavefront control. The goal being to maintain high-contrast in the science focal plane while sensing and controlling wavefront quality using out-of-band photons.

NuSTAR General Observer Cycle 8
Abstracts of Selected Proposals
(NNH21ZDA001N-NuSTAR)

Below are the abstracts of proposals selected for funding for the NuSTAR General Observer Cycle 8 program. Principal Investigator (PI) name, institution, and proposal title are also included. 168 proposals were received in response to this opportunity. On August 8, 2022, 39 proposals were selected for funding.

Marco Ajello/Clemson University
PROBING AGN OBSCURATION VARIABILITY WITH NUSTAR AND NICER

Active galactic nuclei (AGN) are powered by accreting supermassive black holes, surrounded by a torus of obscuring material. Recent observations have detected variability in the line of sight column density, giving rise to the 'patchy torus' hypothesis. Other observations, however, fail to find the variability expected from a patchy torus in Sy2 galaxies. Here, we propose to monitor a Sy2 galaxy, with confirmed yearly column density variability, but that shows no variability in timescales of days. We need additional observations on timescales of months to properly constrain the obscurer properties. The number of sources for which a monitoring campaign (i.e. > two observations) has shown variability is only a handful, making the addition of every possible source vital.

Marco Ajello/Clemson University
UNVEILING MASQUERADING BL LAC OBJECTS

Masquerading BL Lacs are an elusive class of blazars, which comprises of FSRQs appearing as disguised BL Lac objects. In this work, we will unveil a potential target in an attempt to understand the nature of these sources and how they fit in the blazar population. We propose this source to be observed with {\it NuSTAR} and XMM-Newton to help us construct a multiwavelength Spectral Energy Distribution. This will assist us in revealing some essential characteristics of this intriguing object. As the recent detection of high-energy neutrinos by IceCube in the direction of TXS 0506+056 shows, these masquerading BL Lacs may be responsible for the astrophysical IceCube neutrino flux, proving that there is more to them than meets the eye.

Steven Allen/Stanford University
The relationship between the corona and jet in the radio-loud Seyfert galaxy IRAS 17020+4544

We propose the first hard X-ray study of the radio-loud narrow line Seyfert 1 galaxy IRAS 17020+4544. This AGN shows strong evidence for X-ray reflection and reverberation from the inner regions of the accretion disk, which can be used to measure the location and geometry of the coronal X-ray source. We request a 300 ks NuSTAR observation of IRAS 17020+4544. This will allow us to unambiguously characterize the reflected X-rays from the inner accretion disk. Modelling the reflection spectrum from the inner accretion disk will enable measurements of the location and structure of the corona, the properties of the inner accretion flow, and the spin of the black hole, to better understand how the central engines of radio-loud AGN differ from their radio-quiet counterparts.

Steven Allen/Stanford University
Completing hard X-ray observations of the iron K reverberation sample of Seyfert galaxies

We request 200 ks NuSTAR observations of the AGN MS 22549-3712 and PG 1244+026, the two remaining members of the sample of Seyfert galaxies in which iron K reverberation time delays have been significantly detected that have not yet been observed by NuSTAR. The primary objective is to measure the spectrum of the X-rays reflected from the accretion disk that are expected to give rise to these time delays. These measurements will be important to validate the X-ray reverberation model, to determine the consistency between the X-ray spectrum and the observed time lags, and to enable the tightest constrains on the structure of the corona and the spin of the black holes.

Ralf Ballhausen/University of Maryland, College Park
Searching for New Cyclotron Lines in Transient Pulsars

Cyclotron resonant scattering features (CRSFs or cyclotron lines) are the only direct way to measure the B-field close to the surface of an accreting neutron star and probe the physics in the accretion column. Here we propose a 50ks ToO observation of a CRSF candidate source in outburst at a flux of 50mCrab or higher to discover new CRSF sources. The current sample of known CRSF sources underrepresents the huge parameter space of B-fields, luminosities and geometries and therefore any new discovery is valuable to provide insight in the physical conditions necessary to form an observable line. NuSTAR is the most sensitive instrument to date to discover new CRSFs and constrain their energy and profile.

William Brandt/Pennsylvania State University
The Corona-Jet Connection of RLQs in Light of NuSTAR

We propose NuSTAR observations (with 200 ks total exposure) of two high-redshift radio-loud quasars that launch among the most powerful relativistic jets with FR II type morphologies and have radio-loudness parameters of R=3000-7000. These NuSTAR observations, combined with archival X-ray data below 10 keV, can detect the expected high-energy cutoff of the hard X-ray power law up to 200-300 keV. Measuring the cutoff of the X-ray spectra of RLQs will not only shed light on the nature of their hard X-ray emission but also reveal how the corona is linked to the relativistic jets.

Ilaria Caiazzo/California Institute of Technology
CONSTRAINING AXIONS WITH ZTF J1901+1458

We propose a 100-ks observation of the recently discovered young and strongly magnetized white dwarf ZTF J1901+1458 to constrain the coupling of axions to nucleons, electrons, and photons for a large range of axion masses. Because of the high temperature in the core of the white dwarf, nuclei of iron-57 are excited thermally and can produce 14.4-keV axions as they decay; additionally, axions can be produced through axion bremsstrahlung. These axions can convert to 14.4-keV X-rays (or to a thermal continuum in the case of axions from bremsstrahlung) while traveling through the intense magnetic field surrounding the white dwarf. A detection with NuSTAR would be revolutionary for our understanding of fundamental physics, but even if no hard X-rays are detected above the background, the proposed observations will yield better constraints than the CAST experiment for all axion masses and constraints more stringent (by an order of magnitude) even than the proposed IAXO experiment for low-mass axions.

Stephen Cenko/NASA Goddard Space Flight Center
Probing the high-energy infrared connection for 4U 0142+61

The primary goal of this project is to obtain a timing solution of the magnetar 4U 0142+61 simultaneous with the JWST observation of the source. This timing solution will be used to search for pulsations in the JWST data. We will jointly fit the phase integrated NIR to hard X-ray spectrum of 4U 0142+61 to elucidate the nature of the IR emission and to search for connections between the hard X-ray and IR emission (e.g., differentiating between a reprocessing fallback disk or magnetospheric emission). This has direct implications for the formation of magnetars. We will also fit the phase-resolved NuSTAR spectrum of 4U 0142+61. If IR pulsations are detected by JWST we will compare the pulse profiles observed by NuSTAR and JWST to look for differences. We will also fit the IR to hard X-ray phase-resolved spectra. Lastly, we will compare our results to those reported from the previous NuSTAR observation to look for long term evolution in the pulse profile and spectrum.

Laura Chomiuk/Michigan State University
Understanding the Gamma-Ray Production Mechanism in Nova Shocks

We propose a 60ks observation of a new bright (V < 7.5) nova likely to be detected in gamma-rays. The observation will probe shocks within the nova ejecta, constrain the non-thermal particle acceleration and gamma-ray production mechanisms. We will put an upper limit on the particle acceleration efficiency by comparing thermal X-ray and optical to GeV luminosity and search for predicted non-thermal X-rays. Understanding shocks in novae is relevant for other shock-powered transients including Type IIn supernovae, tidal disruption events and stellar mergers. NuSTAR is the only instrument capable of detecting hard X-rays from novae simultaneously with the GeV emission. The observations should be conducted now to take advantage of the simultaneous operations with Fermi and XMM.

Francesca Civano/Smithsonian Institution/Smithsonian Astrophysical Observatory

The First Time Domain NuSTAR and JWST Survey

The JWST Deep Time-Domain Field in the NEP (NEP DTDF) is a GTO target that will have excellent 8-band deep (m~28) imaging and grism spectra in the NIR by JWST and already has exquisite multiwavelength data. As JWST is now at its L2 location, the NEP observations are planned to start in June/July and will repeat every 90 days. Given the interesting results from Cycle 5+6 NuSTAR programs, we request 855 ks (3 epochs simultaneous with JWST) for monitoring the NEP in the hard band to focus on variability, 0.3-24 keV spectroscopy through simultaneous XMM observations, the faint end of the AGN population at >8 keV, the obscured fraction, and a variable z>1 FSRQ. Combining Cycle 5+6+8 data, we will get the deepest NuSTAR survey, with 65-70 sources in 3-24 keV, and ~20 single epoch detections.

Thomas Connor/Smithsonian Institution/Smithsonian Astrophysical Observatory
BREAKING THE LENS: AGN CUTOFF ENERGY ABOVE REDSHIFT 3

This proposal is to observe a high-redshift quad-lensed quasar with joint NuSTAR+XMM observations, with the goal of using the full X-ray spectrum to constrain the cutoff energy in the quasar's X-ray power-law emission. This value is related to the temperature of the X-ray corona and, in combination with previous Chandra observations measuring time delays between individual lensed images, will enable one of the highest-redshift measurements on the coronal temperature -- compactness plane. We will use X-ray spectral modeling, using both XMM and NuSTAR spectra, to the level of complexity enabled by the total photon counts in order to constrain E_Cut for appropriate assumptions. These observations will provide one of the earliest looks at coronal behavior, constraining how early AGN evolve and how similarly systems in the peak of AGN activity are to better-studied local Universe analogs.

Xinyu Dai/University Of Oklahoma, Norman
MICROLENSING SIZE OF AGN HARD X-RAY EMISSION

We propose to measure the size the AGN hard X-ray emission with microlensing for the first time to the X-ray brightest lensed quasar, RXJ1131-1231, providing a physical constraint on the temperature gradient of the corona and the reflection component. This will provide a crucial independent test of the emerging paradigm for the reflection model for Type I AGN, where the reflection is dominated by regions close to the black hole with strong relativistic and light bending effects. This will further constrain the environment immediately around the black hole, which is essential to accurately measure black hole spins and understand the cosmic X-ray background.

Konstantin Getman/Pennsylvania State University
X-ray Driven Chemistry In The Protoplanetary Disk of DQ Tau

X-ray flares are expected to induce time-variable ion-molecular chemistry in young protoplanetary disks. DQ Tau is a young, high eccentricity stellar binary that exhibits X-ray/optical/mm-band flux increases near periastron and offers a unique laboratory for gas-phase ion disk chemistry. We won ALMA program to observe the reaction of molecular line emission to an increase in ionizing radiation of DQ Tau. We propose joint NuSTAR/Swift observations near periastron of DQ Tau to measure non-thermal hard- and thermal soft-band X-ray fluxes as inputs to a state-of-the-art time-resolved physical-chemical disk model. The model and ALMA data will provide unique estimates of disk density distribution that have far-reaching implications for understanding evolution of disks and formation of planets.

Lindsay Glesener/University Of Minnesota
Expanding the Science of Solar Flare-Accelerated Particles with Multi-Messenger Co-Observations

A multi-messenger approach to the study of solar flare accelerated particles provides important opportunities for connecting the activity on the Sun and in the heliosphere. In recent years, the Parker Solar Probe (PSP) perihelia, in which the spacecraft approaches the Sun at a distance 15 times smaller than 1 AU, have defined intervals in which many observatories, including NuSTAR, simultaneously observe the Sun. NuSTAR's sensitivity to hard X-rays (HXR) is unique among solar observers and has made substantial contributions towards understanding the nature of microflare-scale phenomena. To extend this effort, this proposal seeks to utilize NuSTAR's significant capabilities in the HXR range to study solar flare particle acceleration, heating, and propagation via organized co-observations with a cohort of solar instruments. With a multi-messenger approach, in which remote-sensing measurements are paired with in-situ measurements of particles and plasma flows, the understanding of how flares accelerate particles and eject them throughout the heliosphere will be maximized through its joint-science opportunities.

Brian Grefenstette/California Institute of Technology
WHAT BROKE THE CLOCKED BURSTER?: GS 1826-238 IN THE SOFT STATE

We propose a NuSTAR observation to constrain the hard X-ray spectrum of GS 1826-238, the Clocked Burster," which has been in a largely unstudied soft state since roughly 2015. Stray light observations with NuSTAR show that the source is now disk-dominated with infrequent Type I X-ray bursts. We propose a 40-ks observation with NuSTAR to extend spectroscopy beyond what can be done using stray light and to search for any evidence of reflection in the spectrum.

Amruta Jaodand/California Institute of Technology
Chasing the X-ray Afterglows of Gravitational-Wave Events

Significance:
Many astrophysical questions regarding NS mergers still remain open. What fraction of them have central engines and how long do they operate? What is the maximum mass for

a stable NS remnant? How much energy do mergers release? Do all mergers produce successful relativistic jets and short GRBs? Broadband X-ray observations (Using soft and hard X-ray observations) of diverse NS merger events (especially in conjunction with radio observations) will be able to answer many of these questions. In LIGO O4 we expect about 2--7 GW events with electromagnetic counterparts, and therefore arc-second localizations. NuSTAR's broadband coverage and ability to look close-to/at the Sun will crucial for following-up these neutron star gravitational wave mergers.

Since the discovery of the first binary black hole (BBH) merger in 2015, the LIGO-Virgo observatories have leveraged a new messenger, gravitational waves (GWs), to study the Universe. Subsequently, a new era of multi-messenger astronomy has begun with the detection of GWs and photons from the binary neutron star (BNS) merger GW170817, which yielded a scientific bonanza in fields as wide-ranging as gravitational physics, nucleosynthesis, extreme states of nuclear matter, relativistic explosions and jets, and cosmology. These objectives align well with NASA's focus on compact object physics as highlighted in Astro2020 decadal survey. GW170817 is currently the only GW event with a definitive electromagnetic (EM) counterpart. GW170817 provided an excellent confirmation of some previous predictions of merger EM signals while also presenting some surprises. LIGO-Virgo-KAGRA are expected to start their year-long O4 run at the end of 2022. The median distance for the mergers will be 110 170 Mpc for the BNS and 200 300 Mpc for NS-BH. The sky localizations are expected to be <20 50 deg2 substantially smaller than those for the LIGO-Virgo O3 run. We expect <2-7 highly significant GW events for BNS/NS-BH with electromagnetic counterparts and arcsecond localizations. These will be the promising events for follow up with NuSTAR. We aim to follow-up an event which falls under one of the following criteria: 1) a rare, very-luminous BNS merger event, 2) a bright BNS merger within flux range of 5 with peak flux during Sun constraint for other X-ray observatories since NuSTAR is currently the only observatory which can look close to or at the Sun. The NuSTAR observation would be triggered only if an EM counterpart with arc-second localization exists.

Work Plan

Based on extensive simulations of outflows from merger events and their interaction with the environment we have produced synthetic X-ray light curves which show peak flux being reached in ~5-20 days. Hence, optimally we would obtain NuSTAR observations within this time to study highly relativistic outflows and/or bright magnetar emission. Follow-up observations at 1 3 months and 3 6 months will further allow us to study late time X-ray emission. The BNS event will be easily detectable by NuSTAR with 70-100 ks observation epochs.

We will use most updated versions of NuSTARDAS and NUSkybkgd with most recent CALDB files to rapidly reduce the data and commence the analysis. Our team has experience in working with archival NuSTAR datasets from GW170817 and short GRBs. We will use spectral and temporal analysis pipelines developed in these projects along with XSPEC to rapidly analyse observations. As soon as initial results are prepared for each observation, we would rapidly disseminate them to the wider astronomy community via Gamma-ray Coordination Network (GCNs) given the high interest in following-up

EMGW objects. We will also publish these results in a timely manner to high impact factor journals.

Michael Koss/Eureka Scientific, Inc.
A Survey of the Most Luminous X-ray Selected Obscured Quasars at z=0.2-0.4

Nearby powerful AGN provide the best way to understand the growth of supermassive black holes and their effect on galaxies. Most recently, the BASS survey has identified a sample of 12 highly luminous obscured AGN (5e44-1e46 ergs/s) at 0.2<z<0.4, that have never before been observed in the X-rays outside of short Swift XRT exposures. NuSTAR observations enable accurate X-ray spectral modeling of of NH, Fe Ka, and intrinsic X-ray luminosity to test models of Eddington limited feedback. This survey would form a complete census of the 17 most luminous obscured AGN at z<0.6 detected in the ultra-hard X-rays, providing a template of high luminosity luminosity obscured AGN emission above 10 keV.

Michael Koss/Eureka Scientific, Inc.
Using Variability to Study the Size of the Absorber in Compton-thick AGN

For more than 30 years, it has been assumed that a pc-scale torus produces a constant Compton reflection component in heavily obscured AGN. The 157-month Swift BAT processing has recently been finished and nearly all (87%, 14/16) of the brightest Compton-thick AGN are variable in the 20-50 keV band. We propose a variability study of two CT AGN with large NH variability detected in multi-epoch spectra showing changes from reflection to transmission dominated or Compton-thick to thin or vice versa, to place constraints on the size of the variable absorber. These observations will test the size and patchiness in the absorbing material that is the chief component of the AGN unified model.

Gerard Kriss/Space Telescope Science Institute
DECIPHERING EVOLUTION OF CHANGING-LOOK AGN NGC 3516

The main goal of this NuSTAR proposal is to ascertain how the remarkable changing-look phenomenon in NGC 3516 has evolved, which helps us in addressing the outstanding questions on the origin and the impact of the poorly-understood changing-look behavior in active galactic nuclei (AGNs). In Mehdipour et al. 2022 (ApJ, 925, 84) we reported on the X-ray characteristics of the spectral transformation of NGC 3516 in its new "low-flux state". The upcoming joint observations with NuSTAR and XMM-Newton (obtained in this NuSTAR proposal) are aimed to observe the AGN in its "transition state" between the low-flux and the high-flux states. In order to carry out this investigation and achieve the scientific objectives of our proposal, the following tasks need to be carried out by the postdoc (Dr. Mehdipour) on the NuSTAR and XMM-Newton data, requiring 6.7 months of effort in total:

(1) Data processing and reduction: The new NuSTAR and XMM-Newton are processed and reduced. The final spectral products are produced, ready for analysis and modelling.

Also, the light curves during the observations are created for our examination, as part of our variability study.
[0.4 month of effort]

(2) Deriving the spectral energy distribution (SED): For modeling the changing absorption by the AGN outflows, and properly disentangling the absorption components from the continuum components, the model for the broadband SED is required. We establish the SED model using XMM-Newton/OM in the optical/UV band, and XMM-Newton/EPIC and NuSTAR in the soft and hard X-ray bands, respectively. By comparison with the Swift monitoring of NGC 3516, the long-term variability of the SED is established.
[1.0 month of effort]

(3) X-ray spectroscopy of the Fe K-alpha line and the X-ray reflection component: Using the NuSTAR and XMM/EPIC spectra we model the Fe K-alpha line and the Compton hump to ascertain how the X-ray reflection has changed as a result of the changing-look phenomenon in NGC 3516. By comparing with previous measurements, constraints on the uncertain parameters of this X-ray reprocessing region are obtained.
[1.0 months of effort]

(4) Spectroscopy of the soft X-ray broad-line region (BLR) and the narrow-line region (NLR): A consequence of the changing-look phenomenon via accretion activity may be changes in the emission by the X-ray BLR and NLR. The high-resolution spectroscopy with XMM/RGS allows us to measure changes in the parameters of these regions, by modeling the broad O VIII and the narrow O VII emission lines.
[1.1 months of effort]

(5) X-ray spectroscopy of absorption by the AGN ionized outflows (i.e. the warm absorbers): We model the X-ray absorption by the ionized outflows using XMM-Newton and NuSTAR. The new XMM/RGS spectrum allows for the first time soft X-ray absorption lines to be detected via the increased continuum flux during the transition-state of NGC 3516. W establish how the ionized outflows have responded to the changing-look transformation of NGC 3516.
[1.1 month of effort]

(6) Accretion and photoionization/wind modeling: By using the SED and the absorption models derived above, we carry out photoionization modeling. This photoionization modeling enables us to establish how the ionization parameters of all ionized gases in NGC 3516 have evolved, thus establishing the changes in the accretion of NGC 3516 and their physical impact on the BLR, NLR, and the outflowing winds.
[1.1 month of effort]

(7) Journal paper and conference preparations: The results of the above analysis and modelling will be further discussed and iterated on with the rest of the team to produce a global picture of the long-term transformation of NGC 3516. We proceed to write and

prepare material (figures and tables) for one journal paper, and also prepare and present results in a major international X-ray conference, which will take place in Europe.
[1.0 month of effort]

Samuel Krucker/University of California, Berkeley
USING DISK-OCCULTATION TO STUDY NON-THERMAL PROCESSES IN SOLAR FLARES WITH NUSTAR AND SOLAR ORBITER/STIX

The aim of this proposal is to search for X-ray bremsstrahlung signatures, produced by non-thermal electrons within solar flares, in the solar corona. Such electrons are accelerated during the release of coronal magnetic energy. The X-ray signatures of these events are the smoking guns" necessary to understand magnetic energy release and particle acceleration in solar flares. However, these events can generally not be detected as they are overwhelmed by the much brighter X-ray emissions from the chromosphere and lower corona. Here we propose to use the solar disk as a natural occulter ('coronagraph') to shield NuSTAR from the intense flare emission lower down and thus reveal the much fainter non-thermal signatures from the corona. To also capture the main flare emissions that are not visible to NuSTAR, we will use Solar Orbiter STIX hard X-ray observations taken from a different vantage point than Earth. The time frame for observing occulted flares is ideal in Cycle 8, as solar activity is rising with moderately bright flares that are most suitable for NuSTAR occulted solar observations.

Daniel Lawther/University Of Arizona
ToO observations of a re-awakening AGN: Exploring the physics of Changing-Look AGN

After a 10-year hiatus, Mrk 590 has partially re-ignited, with repeated major X-ray and UV flareups captured by Swift monitoring. We wish to seize this rare opportunity to document the onset of AGN activity as it occurs, since this can lead to significant insight on the long-standing issue of how AGNs are triggered and fueled. We will use ongoing Swift XRT monitoring to trigger up to 4 single-visit observations with NuSTAR, of which 3 are joint with XMM (or NICER) observations. Together, these data will probe signatures of the build-up of a standard (optically thick) accretion disk at low and high accretion rates. We will obtain tight constraints on the strengths of a soft X-ray component, a high-energy reflection component and any potential intrinsic absorption at each flux level. As a bonus, the data are also ideal for testing the recent prediction that quasi-periodic eruptions can explain the flux changes seen for Mrk 590.

This is a multi-year ToO proposal (NuSTAR Cycles 8 and 9). We ask for funding during NuSTAR Cycle 9 only, as the analysis work can only proceed once the data are collected.

Felicia McBride/Bowdoin College
Blazar X-rays and neutrinos: Investigating the most promising IceCube neutrino alerts

We propose to perform two 40 ksec target of opportunity follow-up observations of X-ray luminous sources that we identify in association with two separate "gold"-quality IceCube high-energy neutrino alerts. These alerts are likely to be from astrophysical neutrinos. The first identification of an astrophysical source of high-energy neutrinos occurred in 2018, following IceCube-170922A and the BL Lac-type blazar TXS 0506+056. X-ray follow-up of likely-cosmic neutrino alerts has thus proven its utility for identifying possible neutrino counterparts, and most importantly to measure the hadronic contribution to the high-energy emission. We aim to use this approach to identify more such sources and calculate their neutrino flux.

Michael McDonald/Massachusetts Institute of Technology
ZWCL 1856.8: CAPTURING A DOUBLE RADIO RELIC IN THE NUSTAR FIELD OF VIEW

We propose a 30 ks NuSTAR observation to study an early stage-post first core passage merger ZWCL 1856.8+6616. This galaxy cluster hosts one of the 12 known double radio relics in the universe. NuSTAR is the best instrument on board to study the non-thermal phenomena associated with the radio relics. Since these structures are generally observed in cluster outskirts, their faint nature and the scattered light background of NuSTAR make it difficult to constrain the inverse Compton (IC) emission. Radio relics of this cluster are curiously enclosed within the field of view of NuSTAR, as well as the central bright intracluster emission. With this proposal, we aim to study the shock features that are indicated by relics, the cluster temperature structure, and search for IC emission.

Jon Miller/University Of Michigan, Ann Arbor
MEASURING THE SPIN OF FUTURE BLACK HOLE TRANSIENTS

NuSTAR is unrivaled in its ability to measure disk reflection in stellar-mass black holes, and to infer the spin of the black hole using the shape of this component. Particularly in the era of gravitational wave events, which deliver an independent angle on black hole spin, it is important to obtain as many spins from X-ray binaries as possible. This program seeks to obtain spins in a number of stellar-mass black holes, to facilitate comparisons between the X-ray binary and gravitational wave populations. Only bright black hole transients will be targeted, and a number of models will be tested to ensure robust spin results, as free as possible from systematic errors and model dependencies.

Jon Miller/University Of Michigan, Ann Arbor
A LOOK INTO THE HEART OF A TIDAL DISRUPTION WITH NUSTAR

This program will observe a bright tidal disruption event, leverage the unique capabilities of NuSTAR to study the disk and any outflows. When and how an accretion disk forms, and how much of the disrupted star is bound to the black hole versus ejected, are open questions. NuSTAR is ideally suited to detecting the formation of an accretion disk through relativistic reflection, reverberation, and quasi-periodic oscillations. Its spectral resolution is sufficient to detect strong ultra-fast outflows, like the winds seen in PDS

456. These outflows are anticipated if the mass accretion rate exceeds the Eddington limit.

Kaya Mori/Columbia University
NuSTAR ToO observations of Swift X-ray transients in the Galactic Center

We propose NuSTAR ToO observations of new X-ray transients and recurrent outbursts from the known VFXTs (very faint X-ray transients), detected by Swift-XRT, at r < 50 pc from the Galactic Center. Broad-band X-ray spectral and timing data obtained by NuSTAR will provide the useful diagnostic tools of identifying X-ray transients in the Galactic Center. NuSTAR will play a unique role in investigating the nature of X-ray transients in the central parsec region as demonstrated by the discovery of a transient magnetar in 2013 and the black hole spin measurements from two new black hole transients in 2016. Detecting and characterizing new X-ray transients, together with investigating quiescent X-ray binaries, will allow us to explore the population and formation of X-ray binaries near Sgr A*.

Kaya Mori/Columbia University
Probing the star cluster origin of PeV cosmic-ray accelerators in the Milky Way

Massive star clusters have been lately recognized as potentially a primary class of the most extreme particle accelerators in our Galaxy. Westerlund 2 is one of the PeVatron star cluster candidates that powers a gigantic gamma-ray cocoon extending over ~300 pc. Given its clean environment with no other TeV sources or bright X-ray sources causing background contamination, Westerlund 2 is best suitable for a NuSTAR investigation of the star cluster origin of Galactic PeVatrons. The proposed NuSTAR observation will (1) confirm the putative non-thermal X-ray emission suggested by Suzaku observations, (2) distinguish between the leptonic and hadronic SED models, and (3) determine the maximum energy of cosmic-rays accelerated in the star cluster.

Reshmi Mukherjee/Barnard College
SEARCHING FOR NEUTRINO-EMITTING BLAZARS IN HARD X-RAY BAND

We propose NuSTAR target-of-opportunity (ToO) observations of a candidate neutrinoemitting blazar, triggered by the combination of an IceCube neutrino alert and detections of a spatially coincident blazar by Fermi-LAT and Swift-XRT. We request 40 ks of initial NuSTAR observation within 24 hours, on a best-effort basis, after the trigger. If the hard-X-ray flux from the initial observation is > 1.5

Joseph Neilsen/Villanova University
X-RAY JETS & BH SHADOWS: NUSTAR, EHT, CHANDRA, AND SWIFT ON M87

With a large, well-studied jet and the second largest event horizon on the sky, the radio galaxy M87 is one of the primary targets for the Event Horizon Telescope. In light of the incredible success of the 2017 campaign, we are eagerly planning for observations in

2023. To this end, we request 100 ks of NuSTAR time on M87 to be coordinated with Chandra. In addition to the potential tests of GR, coordinated NuSTAR/EHT observations offer an incredible opportunity: a chance to a chance to observe structures near the event horizon while tracking their high-energy variability. In synergy with Chandra, NuSTAR spectra of M87 (and multiwavelength SEDs) will place tight constraints on the energetics and acceleration of particles near the event horizon of this supermassive black hole.

Sean Pike/California Institute of Technology
RAPID FOLLOW-UP OF UNKNOWN MAXI SOURCES NEAR THE SUN WITH NUSTAR

Each year, the Monitor of All-sky X-ray Image (MAXI) aboard the International Space Station (ISS) produces dozens of rapid notices to the astronomical community, alerting scientists to transient events and newly discovered sources across the X-ray sky within minutes of detection. This is accomplished using a pair of wide-field instruments -- the Silicon Slit Camera (SSC) and the Gas Slit Camera (GSC) - which scan nearly the entire sky once every 92 minutes (the orbital period of the ISS). Many MAXI alerts represent outbursts from known or newly discovered X-ray binaries including black hole candidates and accreting neutron stars, while others are produced in response to brightening of white dwarfs, active galactic nuclei, Supergiant Fast X-ray Transients, and other sources, some of which remain uncategorized. Previously unknown sources make up about 20% of MAXI alerts, with an average of about 15 such triggers each year. While MAXI's wide field of view, exhaustive sky coverage, and internet connection aboard the ISS make it a powerful tool for detection and rapid reporting of X-ray transients, its large PSF 1.5 degrees, spectral resolution (18% at 5.9 keV), and short exposure time per source due to its nature as an all-sky survey mean that it has limited capacity for localization and hard X-ray spectral analysis. Follow-up with focused X-ray observatories is instead necessary to gain a better understanding of a newly discovered MAXI source.
The goal of rapid follow-up can often be achieved with the Swift observatory. However, the region of the sky within 47 degrees of the Sun is not accessible to Swift. The same restriction holds for many other X-ray telescopes due to the increased risk of damaging sensitive instruments when pointing near the Sun. NuSTAR, however, is uniquely capable of observing sources close to the Sun. In fact, the observatory has performed a number of direct observations of the Sun. In practice, astronomical observations near the Sun are primarily limited by X-ray emission from the Sun itself, which becomes a strong source of background (via absorbed stray light) at Sun angles of less than 10 degrees. Therefore, we propose rapid follow-up observations of up to 3 unknown MAXI X-ray transients which lie between 10 and 40 degrees of the Sun using NuSTAR for in order to tile the corresponding MAXI error region, localize the source, and perform spectral analyses for the purpose of source classification.

Richard Plotkin/University Of Nevada, Reno
PROBING RAPID VARIABILITY IN BLACK HOLE X-RAY BINARY JETS

Despite ~50 years of compact object studies in the Galaxy, the physics of relativistic jet launching remains an active and open field of research. Luckily, with the recent successful launch of JWST, a new parameter space is opening up in the field of jet physics, allowing for the study of the spectral break above which the jet becomes optically thin on sub-second time scales, providing a crucial link between light and plasma properties. We are proposing to use the unique combination of high time resolution and hard X-ray coverage of NuSTAR to study the outburst of two BH-LMXBs in a jet-dominated hard state. We will probe evolving, rapid, sub-second variations, and, for the first time ever, we will search for correlated variability with mid-infrared spectral observations with JWST.

Gayathri Raman/Pennsylvania State University
NuSTAR STUDY OF THE QUIESCENT STATE SPECTRAL AND TIMING PROPERTIES OF MAXI J1409-619

The proposed study aims to carry out detailed timing and spectral studies of a very unique X-ray pulsar, MAXI J1409-619. X-ray observations of this target will be carried out during its low intensity state using NuSTAR in the upcoming observing cycle. MAXI J1409-619 harbors a neutron star (NS) compact object accreting from a massive stellar companion. It undergoes transient outbursts separated by long periods of quiescence. Outbursts are typically characterized by increased accretion and high luminosities. However, very little is understood about these systems when they accrete at low luminosities. Such pulsars, in all their different intensity states, present a unique laboratory to test various theories of accretion onto magnetized NS.
In recent years, the broadband spectral capabilities of NuSTAR have proven to be invaluable to characterize the quiescent state spectra of X-ray pulsars. Signatures of steady accretion from a cold-accretion disc have been proposed to include a dramatic transition from typical power-law with exponential cutoff spectrum at high luminosities to a two-component spectrum. There are at least three additional pulsars that exhibit this behavior. The proposed NuSTAR observations will examine these models for MAXI J1409-619.

In addition, MAXI J1409-619 has exhibited the cyclotron resonant absorption spectral line exclusively during its low intensity state.The detection of a cyclotron line energy is extremely crucial because it serves as a direct probe of the surface magnetic field of the NS. The target has also displayed timing signatures of instabilities near the NS magnetosphere in the form of quasi periodic oscillations (QPOs). Measurement of the frequency of these QPO signatures allows for constraining the properties of the accretion flow near the disk-magnetospheric boundary, an independent measure of the NS magnetic field can be obtained.

The key objectives of the proposed study are the following: i) to unambiguously identify the cyclotron scattering feature and possible higher harmonics in the X-ray spectrum, which serve as a direct diagnostic of the magnetic field of the neutron star, ii) to study the quiescent state X-ray spectral contributions in the broad NuSTAR energy band of 3-79 keV and iii) to search for signatures of instabilities around the NS magnetospheric boundary in the form of QPOs in the power spectrum. With a large photon collecting area and good spectral resolution of NuSTAR, the proposed observations will for the first time provide a unique opportunity to study the high-energy spectrum of this target in great detail.

The proposed NuSTAR observations will be processed using the standard NuSTAR Data Analysis Software (nustardas) provided under the latest version of the High Energy Astrophysical Software (HEASOFT) and its the corresponding calibration database. Once processed, timing and spectral products from both the FPMA and FPMB detectors will be extracted for further analysis. Light curves will be examined for possible signatures of quiescent state variability. PDS will be constructed to identify possible low and high frequency QPO features. The 3-79 keV energy band will be modeled using the standard XSPEC fitting package. A search for cyclotron absorption features will be carried out near the previously reported energies.

The members of the analysis team have well documented expertise on X-ray data analysis. The P.I will supervise the direction of the entire project and will perform data analysis along with help from the Co-Is. The data analysis is expected to be completed in a total of 6 months, after which a manuscript will be drafted for publication in a peer reviewed journal.

The proposed study has a broader impact towards better understanding accretion flow properties at the lowest luminosity states in X-ray pulsars. The project is in line with NuSTAR's primary science objective of broadband X-ray characterization of high energy astrophysical phenomena.

James Reeves/Catholic University Of America
HEADING INTO THE WIND: A HARD X-RAY NUSTAR VIEW OF PG 1126-041

We propose a hard X-ray look at the mini-BAL QSO, PG 1126 041 with NuSTAR (120 ks), complemented in soft X-rays with XMM-Newton (90 ks), to study the physical properties of its accretion disk wind. This will be the first ever hard X-ray observation of this AGN, whose line of sight intercepts multiple phases (ultraviolet, soft X-ray and Fe K) of a variable wind originating on accretion disk scales. Detailed studies of AGN disk winds are rare, here PG 1126 041 resembles PDS 456, the archetypical luminous AGN with a powerful accretion disk wind. The observations will: (i) measure the Fe K and hard X-ray wind profile, allowing the fast wind energetics to be accurately derived, (ii) probe rapid wind variability on timescales of tens of ks in the innermost disk and (iii) link all the phases of the wind from the UV to hard X-rays.

Benjamin Safdi/University of California, Berkeley
X-RAY SIGNATURES OF AXIONS FROM RX J1856.6-3754

We propose a 40 ks NuSTAR observation of the nearby isolated neutron star (NS) RX J1856.6-3754 to search for evidence of a hypothetical particle of nature called the axion. From Chandra and XMM-Newton observations it was previously thought the NS is a thermal emitter at temperatures ~100 eV. However, a recent study analyzed the archival data between 2-8 keV and found evidence for a hard X-ray spectrum consistent with the existence of an axion, which would be produced within the NS core, escape the star, and convert to X-rays in the NS magnetosphere. If the signal is from axions then the X-ray spectrum will peak in the NuSTAR energy range and may be detected by our observation. If it is not, we will further characterize the excess to converge on an explanation of the signal.

John Tomsick/University of California, Berkeley
Spin and Reflection in a Black Hole Transient

Abstract from the science proposal: We propose a joint 50 ks NuSTAR and 5 ks NICER TOO observation of a transient black hole (BH) X-ray binary source during outburst. Using NICER monitoring to determine the source state, we will trigger the primary joint NuSTAR/NICER observation when the source transitions from the hard state to its intermediate state. Modeling reflection features in the source spectrum will be used to measure the BH spin, as well as constrain the innermost environment of the accretion disk. We will only target sources that have not yet been observed by NuSTAR during outburst, whether that means an entirely new transient BH candidate or a previously known BH X-ray binary that has been in quiescence since the launch of NuSTAR. Examples of well-known sources include GRO J1655-40 and XTE J1550-564.

Claudia Urry/Yale University
UNCOVERING THE MOST POWERFUL JETS AT THE DAWN OF COSMIC TIME

With this proposal, we will observe 11 high redshift blazars with NuSTAR. These are supermassive black holes that are actively accreting gas from their surroundings and are also capable of accelerating particles almost up to the speed of light, which are collimated into cones called jets. Powered by billion solar mass black holes, these jets can shine as bright as 100 billion suns and they are all found at a stage when the universe was barely 1-2 billion years old, making them the most powerful sources of their class. All of the proposed sources, however, crucially lack hard X-ray measurements hampering the physical understanding of these jets and their black holes. NuSTAR data will allow us to accurately detect jet emission in the hard-Xray band up to 50 keV. This will be fundamental to determining the position of the high-energy peak, hence confirming that it falls in the MeV band. Further, NuSTAR will enable us to determine the power of the jet, deriving the underlying electron population responsible for the emission and measuring the location of the emission region. Multi-wavelength follow-up of these sources will enable us to detect the emission surrounding the central black hole and infer its mass.

All newly acquired data will be analyzed by a graduate student supported by the funds obtained with this proposal during the academic year 2022-2023. Multiband data will also be gathered as simultaneously as possible from other ground- and space-based facilities by the CO-I Marcotulli (a postdoc) to determine the entire panchromatic spectral energy distribution of the sources. Besides fitting a phenomenological model to the X-ray data, we will apply a physical model to extract the jet parameters and the black hole masses of these sources. A workstation for the graduate student will be sufficient to perform the proposed data analysis and run the model for physical interpretation. The results will be submitted for publication in a high-impact journal (such as the Astrophysical Journal).

The proposed blazars are some of the most powerful persistent objects in the universe. Thanks to extreme beaming in their jets, they enable us to study the high-redshift universe and unveil the growth and formation of supermassive black holes, as well as its connection to a jetted phase of an AGN. It is therefore paramount to find and study more such sources, and NuSTAR excellent capabilities are ideal for this science.

Daniel Wik/University of Utah, Salt Lake City
THE FASCINATING MERGER OF ABELL 3266

The most energetic events in the Universe since the Big Bang have been galaxy clusters merging. In rare cases, multiple subclusters have been observed merging together. Abell 3266 is one such cluster. As the subclusters merge, shock fronts form and can be distinguished with telltale signs like a surface brightness edge. Such an edge was observed in this cluster with eROSITA, however it is located in a complex temperature environment with multiple hot regions that is difficult to constrain with that telescope. NuSTAR's ability to probe hard X-ray energies can provide key insights into this region and allow us to constrain the Mach number of the shock as well as potential inverse Compton scattering that may occur from the reacceleration of electrons by the shock.

Shuo Zhang/Bard College
Joint NuSTAR and EHT Probe of Sgr A*: Flares, Black Hole Shadows and a New Hard X-ray Source

Following the successful joint NuSTAR/Chandra/EHT observation campaigns during 2017-2018, we propose a 100 ks NuSTAR exposure to overlap with the EHT observation window in spring 2023 during NuSTAR AO Cycle 8. Our primary science goals include: 1) Detect bright X-ray flares, determine flare start/stop time and X-ray variability during a flare, to feed to the EHT analysis; 2) Enlarge the existing NuSTAR Sgr A* flare sample by detecting and characterizing new flares, and test the trend that brighter X-ray flares have harder spectra than fainter flares. A secondary science goal is to monitor a new hard

X-ray source newly revealed by archival NuSTAR data, which is located only 1 pc from Sgr A*.

Xiurui Zhao/Smithsonian Institution/Smithsonian Astrophysical Observatory
Constraining the properties of AGN coronae using a sample of luminous, high-redshift quasars with NuSTAR

The primary X-ray emission observed in Active Galactic Nuclei (AGN) is believed to be produced from a tiny region surrounding the supermassive black hole (SMBH), namely the corona. A critical coronal compactness versus temperature threshold is predicted above which any increase in the source luminosity would then generate positron-electron pairs rather than continue heating the coronal plasma. Current observations show that all local AGNs populate the region below this critical line. However, these models have rarely been probed by sources in the high-luminosity regime where the tightest can be made on the coronal models. We proposed four high-luminosity quasars (z~1-2) to more than double the current sample size of high-luminosity quasars to constrain the coronal models and thus better understand the physics of AGN coronae.

NICER GO Cycle 4 - List of Accepted Proposals

Prop #	Title	PI Name	Abstract
5001	THE FIRST X-RAY POLARIMETRY AND SPECTROSCOPY OBSERVATIONS OF TRANSIENT BLACK HOLE X-RAY BINARIES	FIAMMA CAPITANIO	We propose 3 joint NICER+NuSTAR ToOs observations of transient black hole X-ray binaries to be taken in coordination with IXPE, a NASA-ASI mission that will be launched on Dec,9,2021.The first year IXPE observing plan includes up to 3ToO of TBHXB in outburst.Each ToO includes one long exposure in the hard state and another in the soft(> 300ks). We propose(for each ToO) two 30ks NICER+NuSTAR exposures during the hard state IXPE pointing and one 20 ks NICER+NuSTAR exposure during the soft state IXPE pointing. This will provide an unprecedented combination of X-ray polarimetry, high resolution spectroscopy and timing; yielding unique information on coronal geometry, blackhole spin and role of the jets
5005	MONITORING X-RAY PULSARS FOR GRAVITATIONAL WAVE SEARCHES	WYNN HO	We propose monitoring campaigns for five radio-quiet X-ray-only pulsars (PSR J0058-7218, J0537-6910, J1412+7922, J1811-1925, and J1849-0001), all of which can only be done with NICER observations. These data allow computation of an accurate phase-connected timing model for each pulsar, which enable LIGO/Virgo/KAGRA to perform the most sensitive gravitational wave searches from these young, fast-spinning, and potentially strong gravitational-wave emitting pulsars. We request multi-year observations since contemporaneous data are needed and the next gravitational wave observing run is scheduled to begin in mid/late 2022 and run for one year until mid/late 2023. High cadence observations of PSR J0537-6910 will also further refine and test this pulsar's unique glitch behaviors.
5006	OBSERVING THE NEXT X-RAY BINARY - RADIO MILLISECOND PULSAR TRANSITION WITH NICER	SLAVKO BOGDANOV	In recent years, three millisecond pulsar binaries have been observed to switch between accreting and rotation-powered pulsar states, thereby unambiguously establishing the long-suspected link between low-mass X-ray binaries and "recycled" pulsars. In the low-luminosity accreting state, they exhibit X-ray and optical variability unlike anything observed in other X-ray binaries. We propose a continuation of the NICER Cycle 1 and 2 Target of Opportunity program to trigger on the next nearby binary recycled pulsar transformation to an accretion disk state. This would result in an improved understanding of the peculiar phenomenology of these systems, which, in turn, may shed light on the little-understood physics of the quiescent regime in NS X-ray binaries.

Prop #	Title	PI Name	Abstract
5014	BLACK HOLES TRANSITIONS: NICER AND MULTIWAVELENGTH	TOMASO BELLONI	Black hole X-ray binaries (BHXBs) cycle through different accretion states rapidly, providing a time-resolved view of how matter behaves in a strong gravity environment. Simultaneous multi-wavelength observations are the optimal tool that exposes this view. However, these campaigns (connecting the evolving accretion inflow and jet outflow) have been rarely achieved. We request a TOO consisting of five 10ks NICER visits of a BHXB as it transitions from the hard to the soft state to complement Astrosat/INTEGRAL/HXMT coverage. Our target list contains 15 candidates. We target the transition to reveal both the rapid orbit-to-orbit X-ray variability and the slower X-ray variability that characterize the significantly changing accretion disk (derived from X-ray spectra and timing).
5015	NICER TIMING OF THE TRANSITIONAL PULSAR PSR J1023+0038: A UNIQUE TESTBED FOR LOW-LEVEL ACCRETION PHYSICS	SLAVKO BOGDANOV	In 2013, PSR J1023+0038 transformed from a rotation-powered radio millisecond pulsar state to an accretion-disk-dominated X-ray pulsar state, where it has remained since. In its current accretion-disk state it shows coherent X-ray pulsations, suggestive of active accretion onto the neutron star surface at very low luminosities (~10^33 erg/s). Using these pulsations we have found that in the X-ray state the pulsar is spinning down ~25% faster than in the radio state. We propose to extend our long-term timing solution with NICER through an impending state transition in the near future, which would be immensely helpful for understanding how tMSPs undergo sudden state transitions and enable us to constrain accretion models.
5019	A NICER VIEW OF BLACK HOLE X-RAY BINARY OUTBURSTS IN THE SOFT X-RAY BAND	JIACHEN JIANG	We request a monitoring program of one of six black hole transients with low Galactic reddening when in outburst, consisting of 20 observations each with 6 ks exposure. With our proposed observations, we will be able to study the inner accretion process during an outburst, such as the inner radius and the temperature of the disk. In particular, we will measure the inner disk density and compare the densities in different states. Previous tests for the high density disk model focused on sources with moderate Galactic column density. No soft X-ray observations without pile-up effects for our proposed transients are available in the archive. Our observations will be triggered by the MAXI and Swift-BAT monitoring program.

Prop #	Title	PI Name	Abstract
5020	FOLLOW-UP HARD X-RAY TRANSIENTS IN THE MAGELLANIC CLOUDS	GEORGIOS VASILOPOULOS	The Magellanic Clouds (MCs) harbor a large sample of Be/X-ray binaries at a moderate and well known distance with low Galactic foreground absorption. However, their transient nature complicates observations in X-rays. We propose five triggered NICER observations of new or unexplored high-mass X-ray binaries (HMXBs) in the MCs. Our goal is to study their spectral and temporal properties, and build-up a large sample of pulsars in order to study their demographics in the MC system.
5021	CATCHING THE NEXT OUTBURST OF IGR J00291+5934	PETER BULT	We propose to observe the next outburst of the AMXP IGR J00291+5934 with NICER. Specifically, we request a total of 150 ks in observing time to monitor the full 2-week outburst at high cadence. We expect that this monitoring campaign will yield a rich data set that allows for multi-faceted investigation of this accreting pulsar; including a study of the long-term neutron star spin evolution and torquing mechanisms driving it; the binary evolution of AMXPs; and the magnetospheric interactions between the variable accretion flow and the neutron star itself.
5025	MONITORING THE NEXT OUTBURST OF IGR J17480-2446 (TERZAN 5 X--2): A LAB FOR STUDYING THERMONUCLEAR BURNING REGIMES	GIULIO MANCUSO	During its first and only outburst in 2010, the 11 Hz accreting pulsar IGR J17480-2446 became one of the most prolific X-ray bursters known to date, showing all type of bursting regimes, in qualitative agreement with theoretical models of thermonuclear burning, but showing also substantial deviations from them. Here we propose 240 ksec ToO observations to monitor the next outburst of the source. These observations will allow us to study, among others, the interaction between the accretion disk and the flux coming from the X-ray bursts; the spin-up evolution of the NS as a function of the accretion rate and the connection between the accretion rate and the marginally stable burning.

Prop #	Title	PI Name	Abstract
5026	THE DISCOVERY OF THE NEW SOURCE WITH MILLIHERTZ QUASI-PERIODIC OSCILLATIONS	GIULIO MANCUSO	Quasi-periodic oscillations (QPOs) at frequencies of millihertz (mHz) have only been reported in a few neutron star (NS) systems since their discovery. Given their close relation with the occurrence of type I X-ray bursts, numerical simulations strongly suggest that mHz QPOs are due to a special mode of burning, called "marginally stable nuclear burning". However, even though model predictions agree well with the observations, there are still many open questions. Here we propose, after having detected the mHz QPOs with any instrument, and within the next few days, 50 ksec ToO observations to study the mHz QPOs in the next NS system that shows them. These observations will allow us to test whether the oscillations can be described as temperature fluctuations originating on the NS surface.
5030	FAST MULTI-WAVELENGTH VARIABILITY FROM A BH	THOMAS MACCARONE	We propose 12 observations of a black hole transient of 3.6 ksec each with NICER to be made simultaneously with VLT fast-timing measurements in the infrared. These data will be used to understand the evolution of the IR/X-ray cross-correlation function, the lags in which give fundamental information about the speed of the relativistic jets in these systems. NICER will allow high throughput and access both to the geometrically thin and geometrically thick spectral components in the accretion flow. By observing the evolution of this cross-correlation function we will be able to make the first observational study of the evolution of the jet speed in X-ray binaries.
5031	FOLLOWING THE PULSE EVOLUTION OF IGR J17062-6143	PETER BULT	We propose to observe the AMXP IGR J17062 for a total exposure of 150 ks during the NICER cycle-4 GO program. With these observations we will be able to measure the small pulse amplitude of this source at two epochs, thereby verifying if its recent oscillatory evolution persists. This allows us to provide valuable guidance to the theoretical efforts trying to model this unique accreting millisecond pulsar, and potentially help come to a better understanding of the interplay between the stellar magnetosphere and the influence of mass accretion.
5033	MONITORING ACCRETING MILLISECOND X-RAY PULSARS IN OUTBURST	PETER BULT	We propose a general purpose monitoring campaign of the next outburst of any AMXP, known or unknown. We request a total of 50 ks observing time to be spread over the typical 2 - 3 week duration of such an outburst, so that we can follow the properties of the pulsations as a function of flux. Additionally, this even sampling of the full outburst will also allow us to characterize the non-pulsating emission through a spectroscopic and timing study.

Prop #	Title	PI Name	Abstract
5035	NICER OBSERVATION OF X-RAY BRIGHT TIDAL DISRUPTION EVENTS	YUHAN YAO	We propose high-cadence NICER observations of two tidal disruption events (TDEs). First, we will test if features observed in stellar mass black holes (BHs) exist in massive BHs, such as the rapid evolution of disk temperature and power-law slope, quasi-periodic oscillations, and reverberation lags. For non-jetted TDEs, this program will confirm the scale (in)variance nature of the underlying physics governing the accretion onto stellar mass BHs and massive BHs. For relativistic TDEs, the observations will shed light on the power mechanism of TDE jets. Second, by combining NICER with contemporaneous UV/optical observations, we will study the interplay between the X-ray emitting disk and the reprocessed emission in the optical, and constrain the origin of the reprocessing layer.
5044	CORRELATED RADIO/MM-X-RAY TIMING OF CYGNUS X-1	THOMAS MACCARONE	We propose to observe Cygnus X-1 with NICER simultaneously with millimeter band observations. These data will provide a time lag for the mm emission from the X-ray emission, helping to understand the structure of the jet, following up on a previous result which indicates that either there is strong acceleration in the part of the jet from which the radio emission comes, or the size scale of the jet is not linearly proportional to the wavelength.
5051	NICER FOLLOW-UPS OF RARE AGN IGNITION AND SHUTDOWN EVENTS DETECTED WITH EROSITA	MIRKO KRUMPE	eROSITA, successfully launched in mid-2019, performs multiple all-sky X-ray surveys. By monitoring roughly half a million AGN, eROSITA identifies rare, accretion ignition/shut-down events as they occur. We request 5 ToOs each totalling 60 ks (2 ks roughly every day for 30 days) to explore how the X-ray coronae in AGN respond to a sudden, major change in accretion rate. The NICER data will also deliver the first medium signal-to-noise benchmark spectrum to which later spectra can be compared. They will reveal the evolution of the photon index, the possible intrinsic absorption, and the flux. This data set, combined with high-cadence optical monitoring, will give valuable insights into how accretion flows evolve during AGN ignitions/shut-downs.

Prop #	Title	PI Name	Abstract
5054	CATCHING X-RAY TRANSIENTS ON THE RISE WITH XB-NEWS AND NICER	JEROEN HOMAN	Observing campaigns of black hole and neutron star transients have long relied on triggers from X-ray all-sky monitors or wide-field cameras. However, due to the limited sensitivity of these instruments, the early rising phase of outbursts is typically missed. Here we propose a NICER monitoring program of known transient LMXBs that is triggered by detections of optical outburst activity with the Faulkes Telescopes/XB-NEWS. This allows us to catch transients as they emerge from quiescence in X-rays. With our program with aim to test the disk-instability model in LMXBs, follow the early X-ray spectral/ variability evolution of an outburst, and search for extended absorbing structures. We request monitoring campaigns for two transients, each with daily 2 ks observations for 20 days.
5055	USING NICER TO STUDY THE SOLAR-WIND INTERACTION WITH THE RARE, CO-RICH COMET C/2017 K2	DENNIS BODEWITS	We request 94 ksec of NICER observing time to study the solar-wind interaction of comet C/2017 K2 at 4 distinct epochs along its orbit. C/ 2017 K2 is a long-period comet on a highly eccentric orbit that will bring it to its first perihelion in December 2022. K2 is a particularly notable comet because it showed activity at a record-setting distance from the Sun on approach, suggesting a peculiar chemical composition, likely very rich in CO ice. We will test theoretical predictions of the effect of comet chemistry on charge-exchange emission spectra, study the spectral evolution of K2 as its activity evolves and is exposed to different solar wind conditions, and investigate the source of poorly understood cometary 1 -2 keV emission features.
5057	ORBITAL EVOLUTION OF ULTRACOMPACT WHITE DWARF BINARIES	TOD STROHMAYER	The ultracompact white dwarf systems HM Cnc and V407 Vul represent unique opportunities to probe binary evolution driven by gravitational radiation and mass transfer. NICER observations to date have provided new, precise frequency measurements in both systems, and the first measurement of an orbital frequency second derivative in an ultracompact binary. We propose observations of both sources to continue to extend their temporal baselines, enabling new, unique probes of their orbital evolution.

Prop #	Title	PI Name	Abstract
5059	PROBING THE X-RAY VARIABILITY IN GX 1+4 AND A SEARCH FOR COMPTON SHOULDER WITH NICER	PRAGATI PRADHAN	We request 30 2ks (total 60 ks) NICER snapshots - distributed any way as long as they are spaced out by more than a day - of the symbiotic LMXB GX 1+4 to (i) explore the NH and iron line variability at different intensity states and thereby understand the physical origin of these states. We will also (ii) measure the equivalent width of iron line with spin phase and probe any anisotropy in matter distribution around the pulsar. Finally, we will (iii) search for possible Compton recoil feature (to Fe kalpha line) in high NH states when the conditions are highly conducive for the formation of a Compton shoulder. Since our goals require frequent visits to the source with an instrument of large area and good spectral resolution, NICER is the only facility to make this possible.
5065	NICER CONSTRAINTS ON BLACK HOLE BINARY ACCRETION PHYSICS	RILEY CONNORS	A number of open questions persist in our understanding of the accretion flow properties of outbursting black hole binaries: principally the inner disk radius location, the disk density, iron abundance and inclination, and black hole spin. The superior spectral/timing resolution of NICER, and the high energy coverage provided by NuSTAR, present a golden opportunity to get constraints on these key quantities. We propose simultaneous NICER and NuSTAR ToO observations of any one of the 18 listed transient black hole X-ray binaries. We request a total of 8 ks of NICER time, split into four 2 ks exposures, each simultaneous with a 20 ks NuSTAR exposure (total of 80 ks NuSTAR time), to be spaced within a week of one another.
5067	IDENTIFYING NEWBORN COMPACT OBJECTS IN FAST, BLUE OPTICAL TRANSIENTS USING NICER'S SUPERIOR TIMING OBSERVATIONS	DHEERAJ PASHAM	NICER has recently identified a ~225 Hz quasi-periodic oscillation (QPO) from the fast, blue optical transient (FBOT) AT2018cow. This has been interpreted as a signature of fallback accretion onto a new born compact object in a supernova. Following this success we are proposing for high-cadence monitoring observations of a new FBOT in cycle 4. Our main goals are to 1) identify a similar QPO in a future FBOT, 2) search for coherent pulsations, and 3) study the evolution of such a signal with time, dependence on source luminosity and multi-wavelength properties. Identifying more such systems has the potential to open up a new area of science of study of compact objects right at birth. The key to this program is high time resolution in X-rays and currently only NICER has such a capability.

Prop #	Title	PI Name	Abstract
5069	FAST TRANSITIONS OF X-RAY VARIABILITY IN BLACK HOLE X-RAY BINARIES	LIANG ZHANG	Fast X-ray variability, e.g. quasi-periodic oscillations (QPOs), is a distinct characteristic of black hole X-ray binaries. Fast transitions between different types of QPOs or broadband noise are sometimes observed with significant spectral changes. The study of the fast transitions can provide important evidence on what triggers a QPO and on the physical origin of the QPO, which help us understand the mechanism responsible for the state transitions. NICER's superb time resolution and large effective area below 2 keV make it an ideal mission to study the fast transitions, especially on how the disk changes during the transitions. In this proposal, we ask for 120 ks NICER observations of next black hole candidate showing fast transitions to fully probe the spectral changes.
5070	TOO MONITORING OF A FUTURE STELLAR TIDAL DISRUPTION EVENT	DHEERAJ PASHAM	We propose ToO monitoring observations (2x300s per day for 200 d~120 ks) of a future stellar tidal disruption event (TDE). Our main goals are 1) to identify and study accretion states, transitions and accompanying corona formation around a supermassive black hole (SMBH) in a TDE. This follows NICER's recent success in doing so for the TDE AT2018fyk. 2) to search for the precession period of a newly formed accretion disk in soft X-rays to measure the SMBH spin. This is motivated by theoretical studies and NICER's detection of a 1.34 d quasi-periodicity in ASASSN-18EL: a changing-look AGN likely triggered by a TDE. Both our goals require excellent maneuverability, monitoring capability and a large soft X-ray effective area. At present, only NICER has all these capabilities.
5071	REGULAR MONITORING OF THE DRASTIC IRON-LINE PROFILE TRANSITION OF CIR X-1 AT THE PERIASTRON	MAYU TOMINAGA	Cir X-1 is the youngest known binary system in our Galaxy, hosting a neutron star. A NICER AO2 observation was carried out to cover the entire Cir X-1 orbit with 99 regular snapshots. Three iron emission/absorption lines were observed near the periastron (phase=0) at 6.4 keV, 6.7 keV and 7.0 keV. In particular, the highly ionized Fe lines at 6.7 keV and 7.0 keV switched from emission to absorption between the orbital phases 0.93 and 0.96. We hope to clarify these line production mechanisms by studying orbit-by-orbit variation/stability of the emission/absorption line strengths and the transition phase. We concentrate on the orbital phase-period when the emission lines switch to the absorption lines (0.85-1.05) and propose to monitor this phase-period over the AO4 duration.

Prop #	Title	PI Name	Abstract
5074	ACCRETING MILLISECOND X-RAY PULSARS WAVEFORM MODELING AND THE EQUATION OF STATE OF NEUTRON STARS	ALESSANDRO PAPITTO	Modelling of the waveform of the X-ray pulsations of accreting ms pulsars (AMSP) is one of the most promising ways to constrain the equation of state of neutron stars. However, it requires an extremely high number of counts to break the degeneracy between the many parameters that shape the X-ray pulse profiles. The polarimetric information granted by the forthcoming IXPE mission will measure the geometry of the hot spots independently, easing the requirement. We propose a 350 ks NICER ToO observation of the next outburst of an AMSP to measure the pulsar ephemeris and fold simultaneous IXPE data and derive a high statistics energy-resolved pulse profile. The proposed observation will measure the mass and the radius with an accuracy of a few per cent.
5075	RAPID OPTICAL AND X-RAY TIMING OBSERVATIONS OF NEUTRON STAR XRBS WITH OPTICAM AND NICER	ANGEL CASTRO	High-speed, multi-wavelength observations are essential to understand the underlying physics of the accretion process in the sub-second range in XRBs exhibiting short periods of X-ray and optical activity called outbursts. To study the causes of these sudden outbursts, the variability scales in the different wavelengths and the changes in the geometry of the emitting zone, we propose anticipated observations of 6 outbursts with NICER, strictly simultaneous with optical ground-based follow-up. We will make extensive use of the new OPTICAM triple-band optical instrument that already has 14 nights of guaranteed observation time during the period coinciding with AO4. Observations will also be made with optical telescopes to which our team have access.
5076	MAGNETAR OUTBURSTS AS A CLUE FOR UNDERSTANDING MAGNETIC ENERGY DISSIPATION AND FAST RADIO BURSTS	TERUAKI ENOTO	Magnetar X-ray outburst is sporadic dissipation of magnetic energy via short bursts, giant flares, and persistent emission enhancement. The physics underlying this process is still an open question. Follow-up NICER observations of transient magnetars have provided clues for this question, as shown by recent successful NICER ToO programs: the radio-loud XTE J1810-197, the Galactic fast radio burst (FRB) source SGR 1935+2154, high-B pulsar / magnetar Swift J1818.0-1607, a new source SGR 1830-0645, and the long-term active Swift J1555.2-5402. Prompt X-ray observation is becoming more and more critical after discovering the FRBs from the Galactic magnetar SGR~1935+2154 in 2020. Here we propose NICER ToO observations of magnetar outbursts in soft X-rays.

Prop #	Title	PI Name	Abstract
5078	NOVAE IN OUTBURST AS SUPERSOFT X-RAY SOURCES	MARINA ORIO	We ask to monitor the next two luminous classical or recurrent novae in outburst. The eruptions occur on shell burning white dwarfs undergoing a thermonuclear runaway; after the initial flash and a following radiation pressure driven wind, the white dwarf's atmosphere shrinks to almost pre-eruption radius with a very thin layer above the burning shell, reaching extremely high effective temperature - up to a million K. The white dwarf is observed directly as a luminous supersoft X-ray source (SSS). NICER is ideal to study the SSS, because of its response in the soft range and timing capabilities. Several novae in the SSS phase, as well as permanently burning SSS, also show puzzling modulations with periods around a minute, and NICER is extremely useful in their investigation.
5079	FOLLOWING A NEW MAGNETAR OUTBURST WITH NICER AND NUSTAR	ALICE BORGHESE	Isolated neutron stars powered by the instabilities and decay of their huge magnetic field, magnetars are characterized by a distinctive high-energy flaring phenomenology: short bursts of X-/gamma-rays, often accompanied by enhancements of the persistent X-ray luminosity, referred to as outbursts. Magnetar-like activity was discovered from isolated neutron stars with a broad range of magnetic field strengths. Moreover, the recent detection of a FRB-like burst from a Galactic magnetar has strengthened the belief that at least a sub-group of FRBs can be powered by magnetars. Here, we propose to follow two new outbursts from a known or a new source with NICER and NuSTAR to gather new physical insights on magnetar surface, field configuration and magnetosphere.
5083	IS THE MAGNETAR IN WESTERLUND 1 A LOW-B MAGNETAR?	ALICE BORGHESE	After two major outbursts in 2006 and 2011, CXOU J164710.2-455216 entered a multi-outburst phase in 2017 May, during which three flux enhancements were registered. The latest occurred in 2018 February and since then, the source flux is slowly decaying towards the quiescent level. An intensive multi-instrumental campaign found that the magnetar rotational properties had changed following the latest bursting event, adding J1647 to the small group of low-B magnetars. With the monitoring campaign proposed here, we will be able to infer the dipolar magnetic field strength during a non-active state and to test the untwisting-bundle scenario for magnetar outbursts.

Prop #	Title	PI Name	Abstract
5087	NICER FOLLOW-UP OF AN EXTREME NUCLEAR TRANSIENT	ERIN KARA	X-ray observations of extreme accretion episodes provide a unique probe of the physics feedback from supermassive black holes. Whether due to some unknown disc instability, a stellar tidal disruption event or an encounter with an orbiting low mass compact object, such events change the accretion flow over timescales of weeks to months. X-rays are an essential part in understanding these extreme accretion episodes since they probe the regions closest to the black hole. NICER, in particular, is ideally suited for X-ray follow-up because it has flexible scheduling, a large effective area, good spectral resolution and lack of pile-up. We request to follow-up one bright extreme nuclear transient event for 150~days every 3~days for 1.5~ks (for a total of 75ks).
5091	CAPTURING QUASI-PERIODIC OUTFLOWS FROM A FUTURE AGN OUTBURST	DHEERAJ PASHAM	NICER has recently identified Ultrafast outflows (UFOs) with an enigmatic quasi-periodic variability of 8.5 days during an AGN outburst. The physical origin of these quasi-periodic outflows is unclear but time-resolved X-ray spectral analysis suggests that they are driven by quasi-periodic changes in the UFO's absorption. Motivated by the discovery of this new AGN phenomenon, we propose NICER monitoring (2x500 s for 150 days) of a future AGN outburst with an outflow. Our primary goal is to expand on the pilot study and build a sample to understand the frequency and duty cycle of such events. A large collecting area, good spectral resolution and the ability to monitor for months is necessary to achieve our science goal. As a result NICER is the only facility that can carry out this study.
5093	MONITORING MAGNETARS WITH NICER	GEORGE YOUNES	Magnetars are young highly-magnetized isolated neutron stars with emission peaking in the X-ray band. The decay of their super-strong magnetic fields fuels their high energy radiation. Here, we propose a yearly monitoring program of six magnetars with NICER to establish their spectral and phase-coherent timing properties. Such a campaign will refine our understanding of these unique sources by discovering new glitches and revealing their relative strengths and recovery times, identifying new spin-down glitch events, and revealing magnetars burst and outburst activity. In the process, we will also refine our knowledge on magnetars variability and the correlations between the spectral and temporal properties in quiescence and in outburst.

Prop #	Title	PI Name	Abstract
5094	CHARACTERIZING X-RAY EMISSION OF A WHITE DWARF PULSAR CANDIDATE DISCOVERED IN THE ZTF OPTICAL SURVEY	KAYA MORI	We propose to observe a white dwarf (WD) pulsar candidate ZTF J185139.81+171430.3 with NICER and NuSTAR. The first WD pulsar system, AR Sco, is one of the rare astrophysical manifestations on how a magnetically interacting binary system can accelerate particles in the magnetosphere and generate broad-band non-thermal synchrotron radiation from radio to X-ray band. ZTF observations revealed a 12.37-minute highly-modulated, coherent periodicity from our target. This is a unique feature previously detected from AR Sco. Alternatively, the source could be an AM CVn star or an accreting intermediate polar with unusually high optical modulation. The proposed NICER + NuSTAR observations will explore the nature of this peculiar CV by investigating its X-ray spectral and timing properties.
5096	TRACKING THE HIGHLY VARIABLE X-RAY OBSCURER IN MRK 817 WITH NICER	EDWARD CACKETT	Knowledge of the structure and kinematics of gas around supermassive black holes is vital to understanding accretion and thus AGN feedback. To this end, Mrk 817 is currently the subject of an ambitious 15-month multi-observatory intensive disk reverberation mapping campaign. However, both UV and X-ray observations have revealed the presence of new obscuration that displays dramatic variability. NICER monitoring has been key to tracking the changes in the X-ray obscurer. Optical monitoring of Mrk 817 will continue during NICER Cycle 4, and we propose for NICER monitoring with a 2-day cadence in order to continue to track the variability of this obscuring gas and, combining with longer wavelength data, to better understand its nature and location.
5097	NICER TOO OBSERVATIONS OF SWIFT/XRT DEEP GALACTIC PLANE SURVEY (DGPS) SOURCES	CHRYSSA KOUVELIOTOU	We propose a ToO follow up program linked to the ongoing Swift/XRT Deep Galactic Plane Survey. Phase-I covered 10 deg<|l|<30 deg and|b|>0.5 deg and has detected ~300 sources, of which 150 are new/unclassified transients. Phase-II is covering 30 deg<|l|<50 deg and |b|>0.5 deg, which similarly to Phase-I, aims at mapping X-ray sources with good depth and coverage to enable source identification and multi-wavelength followups. Source identification strongly depends on timing and spectral information to accurately measure time variability and X-ray flux. NICER observations are, therefore, pivotal in source classification. We request 5 ToOs, 10 ks each (total of 50ks), of new sources found in Phase-II observations, which will be provided to us through private consultation.

Prop #	Title	PI Name	Abstract
5099	LF-QPOS IN BH-LMXBS: EXPLORING THE ROLE OF COMPTONISATION WITH NICER AND NUSTAR	FEDERICO GARCIA	BH LMXBs show prominent low-frequency QPOs in their power-density spectra, with fractional amplitudes that increase with energy and complex lag spectra. The question about their physical origin remains unanswered. Quasi-simultaneous observations with NICER and NuSTAR in the soft and hard X-ray bands will allow us to probe the radiative mechanism that modulates the energy-dependent timing properties of these LF QPOs. This information is crucial to unveil the physical mechanism that produces these QPOs, both dynamically, either connected to Lense-Thirring Precession or through instabilities in the hot accretion flow, and radiatively, via Compton amplification in the corona where the observed spectral-timing properties are imprinted onto the X-ray emission.
5104	INVESTIGATING THE ACCRETION-EJECTION INTERPLAY IN THE NS X-RAY BINARY 4U 1820-30 WITH NICER	ALESSIO MARINO	The persistent neutron star X-ray binary 4U 1820-30 displays a 170 d accretion cycle, evolving between phases of high and low X-ray luminosity. Over this cycle, dramatic changes are observed in both the X-ray spectral-timing properties (related to the accretion flow) and the radio spectral shape (related to the jet). Interestingly, the jet evolution seems to be triggered by the accretion rate rather than the spectral state. The aim of the proposal is to progressively track the spectral and timing evolution of the accretion flow over a cycle with a NICER+NuSTAR monitoring campaign. 9 NICER observations of 10 ks each, 3 of them paired with 20 ks NuSTAR visits, are requested. This campaign will be coupled with radio and IR observations to trace the accretion/ejection coupling mechanism.
5105	THE ORIGIN OF SUB-SECOND MULTIWAVELENGTH VARIABILITY IN BLACK HOLE BINARIES	JOHN PAICE	Over the past few years, successful multiwavelength campaigns on a handful of Galactic Black Hole (BH) X-ray Binaries have revealed remarkable sub-second variability and significant optical/infrared-vs-X-ray correlations, with some arising in the first acceleration zone at the base of a compact, relativistic jet. But what drives these variations, and are they really as stable as they sometimes appear? Here we propose up to 10 individual anticipated ToO observations on 1--2 hard state outbursts, strictly simultaneous with optical/infrared timing. We will probe rapid, sub-second photometric variations and search for inter-band time delays to disentangle the jet/disc/coronal components using spectral-timing, and probe these systems on theory-critical, unprecedented scales.

Prop #	Title	PI Name	Abstract
5106	NICER AND NUSTAR FOLLOW-UP OBSERVATIONS OF GAMMA-RAY FLARING BLAZARS	FILIPPO D'AMMANDO	There are many open questions related to the nature of the high-energy emission and the physics of jets which need to be addressed, such as the radiative processes producing the high-energy emission, the parameters of the emitting region(s) and the jet composition. Radiative models need to be tested against MWL simultaneous SED. We propose to trigger 1 ToO observation with NICER and NuSTAR if gamma-ray flaring activity from a blazar is detected by Fermi-LAT and a high X-ray flux has been confirmed by a rapid Swift follow-up observation. The goal is the study of the broadband SED and MWL light curves for putting constraints on the physics of relativistic jets from super-massive black holes, and on the acceleration and radiation mechanisms at work in such extreme environments.
5107	MEASURING HMXB WINDS WITH NICER OBSERVATIONS OF CYG X-1 NEAR ORBITAL PHASE 0	MICHAEL NOWAK	Cyg X-1 is in a 5.6 day orbit around a High Mass X-ray Binary that donates mass to the black hole system via ``focused wind accretion''. Near orbital phase 0, or line of sight to the inner accretion flow passes through this wind, and allows X-rays from the black hole to probe the wind's structure. Historically, we see ``dips'' associated with both highly ionized absorption and colder, denser near neutral absorption. NICER, with its large effective area, superb soft X-ray response, and low background is uniquely suited to study this dipping behavior on time scales potentially as fast as 0.1 s. We will use modeling of light curves, time-dependent color-color diagrams, and spectra at different color/flux levels.
5108	NICER CHARACTERISATION OF OUTBURST REFLARES IN LMXBS	ARIANNA ALBAYATI	Reflaring events have been seen to occur after the outbursts of LMXBs. They are several orders of magnitude fainter than the main outburst, and each last from a few days to up to two months. These reflares are observed only for some sources and, in the same source, only for some outbursts. NICER has recently allowed for the first detailed spectral studies of reflares, uncovering full state transitions which exhibit hysteresis loops, one of which was in an unusual clockwise direction. However, the cause of reflaring, and why there is such variety in their manifestation, is still unknown. To explore this, we propose to observe the next source which shows reflares at the end of the outburst every other day for a total of 120 ksec with NICER to follow the reflare's evolution.

Prop #	Title	PI Name	Abstract
5111	NEUTRON STARS MULTI-WAVELENGTH FAST VARIABILITY: PROBING DISK-JET CONNECTION	FEDERICO VINCENTELLI	Simultaneous X-ray/optical-infrared observations of black hole X-ray binaries have shown to be one of the best ways to probe the jet in its innermost regions. Nonetheless neutron star X-ray binaries, which are clearly dominated by the jet at IR wavelength, have almost never been studied with this approach. Here we propose to observe with NICER the Neutron Star Low Mass X-ray binary 4U 0614+091 simultaneously with already approved fast IR HAWK-I@VLT observations. We ask to perform a 8 ks observation. This data will allow to study the disk-jet interaction in accreting neutron stars in great detail, as already done extensively in black-hole X-ray binaries.
5114	TRACKING THE EVOLUTION OF X-RAY QUASI-PERIODIC ERUPTIONS FROM A QUIESCENT GALAXY	RICCARDO ARCODIA	Quasi-Periodic Eruptions (QPEs) are extreme soft X-ray bursts of unknown nature recurring on the timescale of hours. So far only four such sources have been found. One of these, eRO-QPE1, can only be monitored with NICER. We want to know i) if QPEs are still ongoing and if the period has changed since discovery, ii) if there is evidence of a decrease, resonances and/or possible modulations, iii) the physical cause of these bursts. To achieve this, we ask for 4 sets of observations, each with a baseline of 7 days with 14 visits per days, each visit with exposure of 250s (for a total of 98ks).
5115	MONITORING THE VARIABILITY OF "QUIESCENT" SWIFT-BAT BLAZARS WITH NICER	SERGIO MUNDO	A recent 5-month NICER monitoring campaign of 4 "quiescent" Swift-BAT blazars reveals that variations in the 0.3-2 keV band are detected on three distinct timescales, but that the fractional variability is <25% and decreases on longer timescales, implying low-amplitude variability for all sources and showing very little to no variability on monthly timescales, which is in stark contrast to previous studies that show that blazars are highly variable in the X-rays over a wide range of timescales. As a follow-up to this campaign, we propose multi-cycle NICER observations of these 4 BAT blazars as well as of 2 additional blazars whose variability is not detected by the BAT, in order to characterize the long-term variability, search for flares, and obtain high-quality time-averaged spectra.

Prop #	Title	PI Name	Abstract
5117	A COHERENT TIMING SOLUTION FOR THE "MAGNIFICENT SEVEN" ISOLATED NEUTRON STAR RBS 1774	ADRIANA MANCINI PIRES	Among thermally emitting isolated neutron stars, RBS 1774 appears particularly hot in X-rays and strongly magnetised. Recent XMM-Newton and eROSITA observations reveal unexpected variations in its timing behaviour (a decrease in pulsed fraction and higher spin down), as well as evidence of multiple absorption lines and a cooler thermal component. We propose coordinated NICER observations to derive a precise timing solution and perform phase-resolved spectroscopy. These will allow us to determine the high value of spin down hinted by analysis of existing data, which places the source closer to a magnetar than any other M7 INS. The NICER campaign will likewise provide invaluable information on the geometry and orientation of the emitting region and spin-dependence of the spectral features.
5118	RELATIVISTIC REFLECTION AND REVERBERATION MAPPING IN A BLACK HOLE BINARY	JINGYI WANG	Black hole astrophysics can be regarded as a fundamental tool in studying the accretion and ejection physics in the strongest gravity regime in the Universe. Reflection spectroscopy studies the time-averaged flux-energy spectrum, providing constraints on properties in the accretion disk and the corona, but degeneracies take place in problems such as the truncation level of the disk. Reverberation mapping is a timing technique revealing the disk-corona geometry in the innermost regions, which could help break degeneracies. With recent cutting-edge developments in physical spectral-timing models, the main goal in this proposal is to find clues on the state transition mechanism, and the coupling between the disk, corona and jet in black hole binaries.
5126	MONITORING THE EVOLUTION OF NASCENT ACCRETION DISCS FORMED IN TIDAL DISRUPTION EVENTS	ADAM MALYALI	During its ongoing all sky survey, SRG/eROSITA is rapidly detecting a large number of Tidal Disruption Events (TDEs), identified through their ultra-soft, large amplitude flares from previously quiescent galaxies. We request NICER monitoring of 6 X-ray bright TDEs to be discovered by eROSITA in Cycle 4. The NICER data will be used to: i) search for quasi-periodic modulations in these X-ray light curves from precessing nascent accretion discs, ii) characterise the X-ray variability of TDEs over short and longer timescales after the initial eROSITA detection.

Prop #	Title	PI Name	Abstract
5130	THE UNUSUALLY SLOW FREQUENCY CHANGE OF RXJ0806.4-4123	GEORGE PAVLOV	A NICER timing campaign of 2019-2021 on the isolated neutron star RX J0806.4-4123 showed that its frequency derivative is unusually small. It is in fact so small that there still is the possibility for its positive as well as negative values despite the tight NICER constraints on the timing solution. The proposed additional observation will reduce the uncertainty of the frequency derivative by a factor of five. This can answer the question whether RX J0806.4-4123 spins down or up. The spin-up could be due to accretion from a fallback disk while a very slow spin-down would mean an unexpectedly low spin-down power of this isolated neutron star.
5131	THE OBSCURED STATE OF GRS 1915+105	JOSEPH NEILSEN	GRS 1915+105 is a black hole binary known for its unique variability, strong winds, jets, and BH spin. After 20+ years in outburst, NICER detected a huge change in this iconic source: the X-ray flux dropped by 100x! Spectra suggest a large obscuring shroud, but what is this obscuring gas? The "obscured" state is highly variable, with flares that reveal strong winds and highly-ionized absorption. We propose to study its long-term evolution with 35 weekly exposures of 2.7 ks in Cycle 4. NICER is the only mission capable of frequently monitoring this important new state. We also request a 25 ks NuSTAR ToO to constrain scattering and wind photoionziation. These observations will also grow a NICER legacy archive of obscured variability in GRS 1915+105.
5133	NICER+FAST SIMULTANEOUS TOO OBSERVATIONS OF THE REPEATING FAST RADIO BURSTS 121102 AND 180301.	SIBASISH LAHA	The fast radio bursts (FRBs) are milli-second duration radio transients, the origin of which is still unknown. Possible mechanisms that could generate these highly coherent radio emission from FRBs involve a) neutron star magnetospheres and/or b) relativistic shocks far from the central energy of the source. Polarization signatures in radio band can distinguish between the two scenarios. Detection of emission in X-rays (with a measure/limits on the efficiency $\eta ~E_{Radio}/E_{X-ray}$) are therefore crucial to establish/confirm if indeed the emission mechanisms are the same as those predicted by radio polarization angle measurements. We propose to observe the sources FRB~180301 and FRB~121102 each with a total exposure of $\sim 50\ks$ with NICER+FAST during their bursting-phases.

Prop #	Title	PI Name	Abstract
5134	LEGACY OBSERVATIONS OF ACCRETION DISK WINDS IN BHXRBS	NOEL CASTRO SEGURA	BHXRB viewed at high inclinations display wind signatures in their X-ray spectra. These features are the signatures of powerful, hot and equatorial accretion disk winds being driven from these systems in their luminous soft states. Remarkably, blue-shifted absorption lines have recently also been discovered in optical and NIR recombination lines. These features must also be produced in an outflow, but the physical conditions traced by these outflows are different. It is unclear if they are associated with driven by different mechanisms or simply with different regions/phases within the same outflow. We propose to answer this question by carrying out simultaneous time-resolved spectroscopy of the next black-hole transient in the X-ray and optical bands, throughout a full outburst.
5135	DEFINING THE VARIABLE X-RAY SPECTRUM OF GAMMA2 VEL, THE NEAREST WC-BINARY	MICHAEL CORCORAN	We propose monitoring observations of of the nearest WC+O binary, Gamma2 Vel with NICER around 2 orbits during AO4. This will provide the best measure ever obtained of the change in flux, emission measures, temperatures and column densities as the X-ray emitting shock recovers from periastron passage. The derived variations in column density, temperature and X-ray flux will be compared to simulated data from detailed hydrodynamic models to constrain the shock structure in 3-D. We will also propose for ground-based monitoring of the C~III 5696 emission line and other emission lines. We will compare X-ray and available optical spectra variations to WR~140 and other WC+O binary stars to explore shock cooling and differences in dust formation from Gamma2 Vel and other WC+O binaries.
5136	CATCH THE NEXT OUTBURST: NICER FOLLOW-UP OF THE CHANGING-LOOK AGN MRK 1018	ROISIN BROGAN	Mrk 1018 is one of only two changing-look AGN ever observed to change type twice. The AGN was discovered mid-transition and has a rich range of multi-wavelength data available, primarily covering the faint 1.9 type state. During this faint state it changes its energy output unpredictably. In 2020, an outburst so large that it could be regarded as a changing-look event by itself was observed. We request that a ToO monitoring program over 6 months be put in place. This will track the evolution of the X-ray flux during outburst and provide four spectral X-ray snapshots to compare spectral parameters with the faint phase. The optical monitoring program will also be increased to a similar cadence for a unique multi-wavelength picture of the response to drastic accretion changes.

Prop #	Title	PI Name	Abstract
5139	A SEARCH FOR PULSATIONS FROM NEW CANDIDATE ISOLATED NEUTRON STARS	MEGAN DECESAR	The ROSAT All-Sky Survey discovered the Magnificent 7 (M7), seven slowly-rotating, highly magnetized X-ray dim isolated neutron stars (XDINS) with thermal X-ray emission. All but one of the M7 have pulsed emission, with quasi-sinuosoidal light curves and pulsed fractions between 1.5-18 percent. Their nearly-pure thermal spectra, along with absorption features detected in most of the M7, provide a mechanism to probe their atmospheric composition and magnetic and emission geometries. The thermal emission also provides a unique probe of the neutron star equation of state. Four new M7-like XDINS candidates were recently identified in the 4XMM Data Release 10 (4XMM-DR10). We propose to search for X-ray pulsations in the brightest two of these sources.
5140	MEASURING BLACK HOLE SPIN AND MASS THROUGH X-RAY REFLECTION SPECTRA AND REVERBERATION LAGS	GUGLIELMO MASTROSERIO	X-ray reflection in accreting black holes probes the inner region of the accretion disc, and proper modelling of the spectral and timing properties of this emission enables measurement of the black hole mass and spin. The unique combination of NICER s soft and NuSTAR's hard coverage provide the broad bandpass, high count rates and energy and timing resolution required to constrain models of the time averaged energy spectrum and the reverberation lag energy spectrum on different timescales. We propose to observe any black hole transient, known or unknown, exceeding 30 mCrab during the bright hard state for 30 ks with simultaneous NICER and NuSTAR observation in order to access unprecedented characterisation of black hole spin and mass.
5141	SEARCHING FOR CLOSE SUPERMASSIVE BLACK HOLE BINARIES WITH EROSITA, NICER, AND XMM-NEWTON	MIRKO KRUMPE	eROSITA is performing multiple all-sky X-ray surveys and monitoring almost half a million AGN every six months. It has the capability to identify exceptional AGN with periodic X-ray flux signals. These objects are potential supermassive black hole binaries (SMBHB). We request ToO monitoring campaigns for up to three eROSITA-selected candidate periodic AGN. Each ToO consists of six individual pointings, 10 ks each, spaced roughly four weeks apart. The campaigns are needed to track the flux modulation waveform on a monthly time-scale, accurately determine the period, and to determine the details of follow-up observations to confirm the binary nature. The most convincing case will be the target of a pre-approved 100 ks XMM-Newton observation.

Prop #	Title	PI Name	Abstract
5146	CONSTRAINING THE X-RAY VARIABILITY PROPERTIES OF THE QUIESCENT BLACK HOLE V404 CYG	MARK REYNOLDS	The quiescent state is the dominant accretion mode for black holes on all mass scales. Our knowledge of the nature of the quiescent accretion flow is limited due to the characteristic low luminosity in this state. Here, we propose 100 ks of \textit{NICER} monitoring observations of the quiescent stellar mass black hole V404 Cyg. These observations will allow us to characterize the quiescent accretion flow variability (spectral \& timing) at the viscous timescale, associated with the optically thick disc/ADAF interaction region, around a stellar mass black hole.
5147	NICER STUDIES OF AGN CLOUD OCCULTATION EVENTS DETECTED WITH EROSITA	MIRKO KRUMPE	Understanding the sub-structure of the torus in AGN is requisite for understanding the radiative and mechanical processes occurring in AGN central engines, and recent works point to tori composed of clumps. eROSITA is currently performing multiple all-sky X-ray surveys, including monitoring the brightest ~80 AGN for spectral changes, though 2023. eROSITA is thus in a position to detect rare transits of torus clouds across the line of sight. For up to 2 objects, we request ToO campaigns consisting of 7 visits each, with each visit 10 ks (total request of 140 ks), to systematically trace the smoothness of torus clumps and illuminate the sub-structure of clumpy tori in AGN.
5152	THE RISING OF WR 140	MICHAEL CORCORAN	Eccentric, massive colliding wind binaries are laboratories to study collisionless shocks in astrophysical settings. The best example of such a shock laboratory is WR 140, where wind-wind interactions generate variable emission from the X-ray to radio bands including dust formation. NICER monitoring will allow use to sensitively measure the physical changes of the hot shocked gas and fill in an important gap in the variation of column density. NICER provides the best measure of the colliding wind X-ray spectrum free of systematic uncertainties which occur when comparing data from different instruments. We propose to extend the NICER observations of WR 1140 with weekly monitoring through Cycle 4 as the X-ray emission begins to increase towards periastron passage in 2024.

Prop #	Title	PI Name	Abstract
5158	X-RAY AND RADIO SIMULTANEOUS MONITORING CAMPAIGN OFNEARBY REPEATING FAST RADIO BURSTS IN THE SOUTHERN HEMISPHERE	TERUAKI ENOTO	The origin of fast radio bursts (FRBs) remains mysterious. The most plausible candidate is the magnetospheric phenomenology of neutron stars, but this still includes multiple scenarios, involving magnetar bursts that release magnetic energy and giant radio pulses that originate from rotational energy. In any plausible scenario for FRBs, the energy emitted incoherently at high energies is orders of magnitude larger than the radio; thus X-ray measurements offer one of the strongest constraints on the FRB engine. Here we propose simultaneous radio and X-ray observations of nearby extragalactic repeating fast radio bursts (FRBs) in which radio bursting activities are confirmed within 10 Mpc in the southern hemisphere.
5160	COORDINATED MONITORING OF NGC 4051 BY NICER AND TESS TO TEST THE X-RAY REPROCESSING PARADIGM	MICHAEL FAUSNAUGH	Recent measurement of AGN accretion disk sizes rely on the interpretation of UV/optical continuum time delays as light-travel times, which assumes that X-ray variations drive the UV/optical variations. This "X-ray reprocessing" model requires that X-ray heating of the accretion disk produces an X-ray reflection spectrum that is closely correlated with the UV/optical variations. We propose testing this model by searching for correlations of the X-ray reflection spectra in NGC 4051 with optical variations. We will use NICER to produce a time series of high SNR X-ray reflection spectra that are concurrent with a nearly continuous TESS light curve. Correlated variations wills strongly support the X-ray reprocessing paradigm, and a lack of correlation will constrain alternative models.
5161	TIME-RESOLVED SPECTROSCOPIC AND POLARIMETRIC STUDIES OF 4U 1626-67 WITH NICER AND IXPE	MASON NG	4U 1626-67 is an unusual low-mass ultracompact X-ray binary with a ~42 minute orbital period which hosts a ~7.7 s pulsar with a strong magnetic field of B ~ 3e12 G. It has exhibited two episodes of torque reversals in 1990 and 2008, and it is currently in the sustained spin-up state. We propose a 40 ks observation, quasi-simultaneous with the Imaging X-ray Polarimetry Explorer (IXPE), slated for launch on 12/09/2021. Joint NICER and IXPE observations will provide us with a level of unprecedented synergy that will enable accurate spectropolarimetric analysis designed to constrain the emission region geometry, to discern the distinct behavior between the spin-up and spin-down states, and to understand the flaring behavior that occurs only in the spin-up state.

Prop #	Title	PI Name	Abstract
5165	CONTINUUM-FITTING SPIN MEASUREMENTS OF BRIGHT BLACK-HOLE TRANSIENTS	JAMES STEINER	Stellar-mass black holes in X-ray transients undergo months-long outbursts during which they explore wide-ranging accretion rates and spectral-timing states. Following transitioning to the thermal/soft state, the black hole undergoes a protracted thermal decline. The pristine thermal/soft state contains only minor contribution from the nonthermal components; most of the emission comes from the thermal accretion disk continuum. Accordingly, this state is the gold-standard for spin measurements via X-ray continuum fitting. We request 10x2ks observations during the thermal phase of the outburst, to monitor a bright black-hole transient in decline, in order to determine its spin. We request up to two triggers over the next cycle, for a maximum of 40ks.
5167	SOFT X-RAY EXCESS VARIABILITY IN THE REPEAT-FLARING CLAGN MRK 590	DANIEL LAWTHER	The changing-look AGN Mrk 590 lost its soft X-ray excess as it transitioned to Type 2 around 2010. After partial re-ignition in 2017, it is now in a repeated (and possibly quasi-periodic) X-ray and UV flaring state, with an accretion rate `flickering' near the threshold to sustain a geometrically thin, thermal disk. Here, we ask to use the excellent soft X-ray sensitivity of NICER to monitor its X-ray luminosity variations, and in particular the variability of the soft X-ray excess component, during these flares. This will test the warm-Comptonization model for soft excess, providing a high dynamic range in UV and X-ray luminosities. The observations also provide X-ray SED monitoring to support a broad-scoped, multi-wavelength investigation of the current flaring activity.
5170	STUDYING THE PERSISTENT DISK WIND IN GX 13+1	JEROEN HOMAN	We propose a NICER monitoring campaign of the luminous neutron-star LMXB GX 13+1, with the aim of studying how the persistent disk wind in this source changes with variations in the mass accretion rate. Due to the high inclination of the source the latter is difficult to measure directly. Instead we will use changes in the hardness-intensity tracks as a proxy for changes in the accretion rate. We request four sets of 4 x 4 ks observations (64 ks total) to achieve this goal. The individual NICER exposures are long enough to accurately track changes in the density and ionization of the disk wind.

Prop #	Title	PI Name	Abstract
5171	A STUDY OF M DWARF FLARES USING SIMULTANEOUS MULTI-WAVELENGTH DATA	RISHI PAUDEL	We propose to obtain NICER X-ray data of four nearby active mid-M dwarfs simultaneously with the Atacama Large Millimeter Array radio and the Neil Gehrels Swift Observatory UV data. These stars are spectral analogues of another flaring mid-M dwarf with a planetary system - Proxima Cen - and span a wider range of ages and activity levels. Such data will enable us a) understand the physical mechanism associated with M dwarf flares, b) examine if the correlation between millimeter and UV emission found in a previous study of Proxima Cen flare extends into X-ray wavelength and is a universal property of mid-M dwarfs regardless of age and activity level. Our results will be significant inputs to models that estimate the impacts of strong flares on the atmospheres of planets orbiting M dwarfs.
5172	THE PROPERTIES AND EVOLUTION OF ACCRETION DISKS IN BLACK HOLE BINARIES	JAVIER GARCIA	We request 10ks of NICER and 100ks of NuSTAR time to trigger Target of Opportunity (ToO) observations of a new or known black hole transient during the end of the outburst, after the source has entered the low-hard state. We aim to obtain high signal-to-noise data during this fainter phase in order to measure the level of disk truncation using X-ray reflection spectroscopy. We will also provide measurements for the disk inclination, ionization and iron abundance. These observations will provide crucial constraints to support a large-scale data analysis program for these sources.
5175	NICER MONITORING OF ETA CARINAE X-RAY EMISSION CYCLE 4: FROM APASTRON TO APASTRON WITH NICER.	DAVID ESPINOZA-GALEAS	We request 52 ksec of observation time in NICER AO4 to continue monitoring the X- ray emission from the massive colliding wind binary Eta Carinae (η Car). NICER started to observe η Car s X-ray emission as part of NICER Observatory Science Program and continued in cycles AO1, AO2, and AO3. If accepted the NICER AO4 will complete a whole cycle from apastron to apastron (∼5.54 years) of monitoring program. The NICER AO4 will cover η Car s orbital phases between ∼4.37 and ∼4.55 providing time-resolved spectrometry of η Car s at apastron. Flux observations from NICER AO4, together with observations from NICER AO3, will be compared with RXTE observations at the same orbital phases to show changes in the mass loss of the stars.

Prop #	Title	PI Name	Abstract
5176	X-RAY REVERBERATION IN BILLION MASS BLACK HOLES	VENKATESSH RAMAKRISHNAN	The Event Horizon Telescope (EHT) observations of the supermassive black hole (SMBH) in M87, has provided a powerful experimental testbed for strong gravity. Hence the SMBHs in several nearby systems, including the SgrA*, are all potential candidates to enhance our understanding of gravitation in such extreme environments. However, providing strong constraints on several aspects of the accretion and jet physics in active galaxies that are possible through multiwavelength observations, is vital for the convergence of theoretical simulations of accretion processes. We thus propose a NICER monitoring campaign of three nearby galaxies, probing for the orbital variability time-scale. Besides, we also seek to address the role of the magnetic field based on the turbulence of the light curves.

Astrophysics PIONEERS21
Abstracts of Selected Proposals
(NNH21ZDA001N-PIONEERS21)

Below are the abstracts of proposals selected for funding for the Astrophysics PIONEERS21 program. Principal Investigator (PI) name, institution, and proposal title are also included. 15 proposals were received in response to this opportunity. On July 27, 2022, one proposal was selected for funding.

Brian Rauch/Washington University
The Trans-Iron Galactic Element Recorder for the International Space Station, TIGERISS, an Exceptional Nucleosynthesis Pioneer

We will propose the Trans-Iron Galactic Element Recorder for the International Space Station (TIGERISS), a new mission evolved from the LDB TIGER and SuperTIGER missions and the Heavy-Nuclei Explorer SMEX. TIGERISS will measure ultra-heavy Galactic cosmic ray (UHGCR) nuclei resulting from neutron-capture nucleosynthesis in heavy stars, supernovae, and neutron-star mergers. Current model predictions of supernova and neutron-star merger r-process neutron-capture nucleosynthesis of UHGCR nuclei vary considerably in expected production, in large part because of the need for better data to constrain them. TIGERISS will supply data that will both challenge and improve these models. Compared to its predecessors, TIGERISS will have a greatly improved capability to definitively identify UHGCR nuclei, as demonstrated in component accelerator tests at CERN. The geometry factor for TIGER was 0.6 m2 sr, while for TIGERISS we estimate it to be ~1.5 m2 sr based on the expected Kibo attachment point. Thus, in one month of TIGERISS operation, we would observe a data set equivalent to the two TIGER LDB flights, which will be more than sufficient to demonstrate that the instrument is working correctly after it is tuned. During its primary mission, TIGERISS will measure abundances relative to 26Fe for every element from 5B to 82Pb, a large range unprecedented with a single, active detector, allowing it to probe for potential r-process source signatures in the heavy elements. Furthermore, taking UHGCR measurement outside the atmosphere eliminates the need to correct for charge-changing interactions and energy losses that occur above balloon instruments, allowing it to reach higher in charge with lower systematic error than SuperTIGER. The TIGERISS configuration and materials have been optimized to maximize the effective geometric acceptance per unit active area and ensure mission success within the constraints of the ISS platform. Recent SuperTIGER results show that the OB-association model that explained the GCR abundances for 40Zr and below is not adequate for the elements above it through 56Ba, suggesting a possible new r-process source. In one year of observation, TIGERISS is expected to measure comparable UHGCR statistics to SuperTIGER through 56Ba with the dynamic range to measure through 82Pb without atmospheric corrections and scintillator saturation effects, which will address the questions raised by SuperTIGER and seek signatures of new r-process sources. TIGERISS will be built by the exceptionally successful SuperTIGER collaboration, with their decades of experience being leveraged to support and encourage opportunities for students and early-career researchers, and simultaneously draw in a new generation of diverse scientists.