PUEO: The Payload for Ultrahigh Energy Observations

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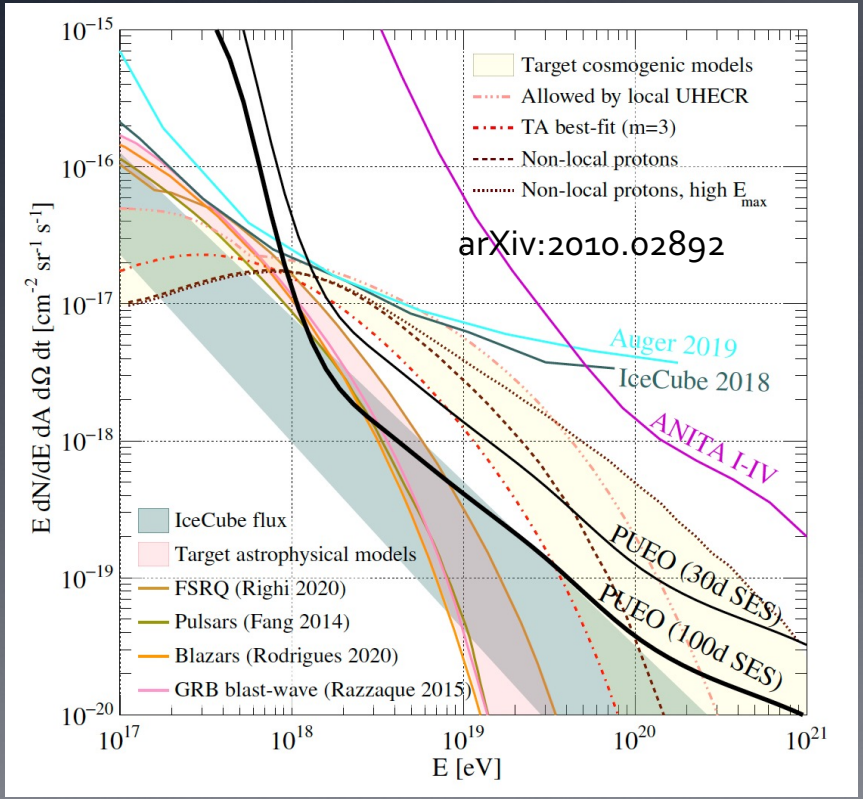
University of Chicago

APAC Meeting June 2021

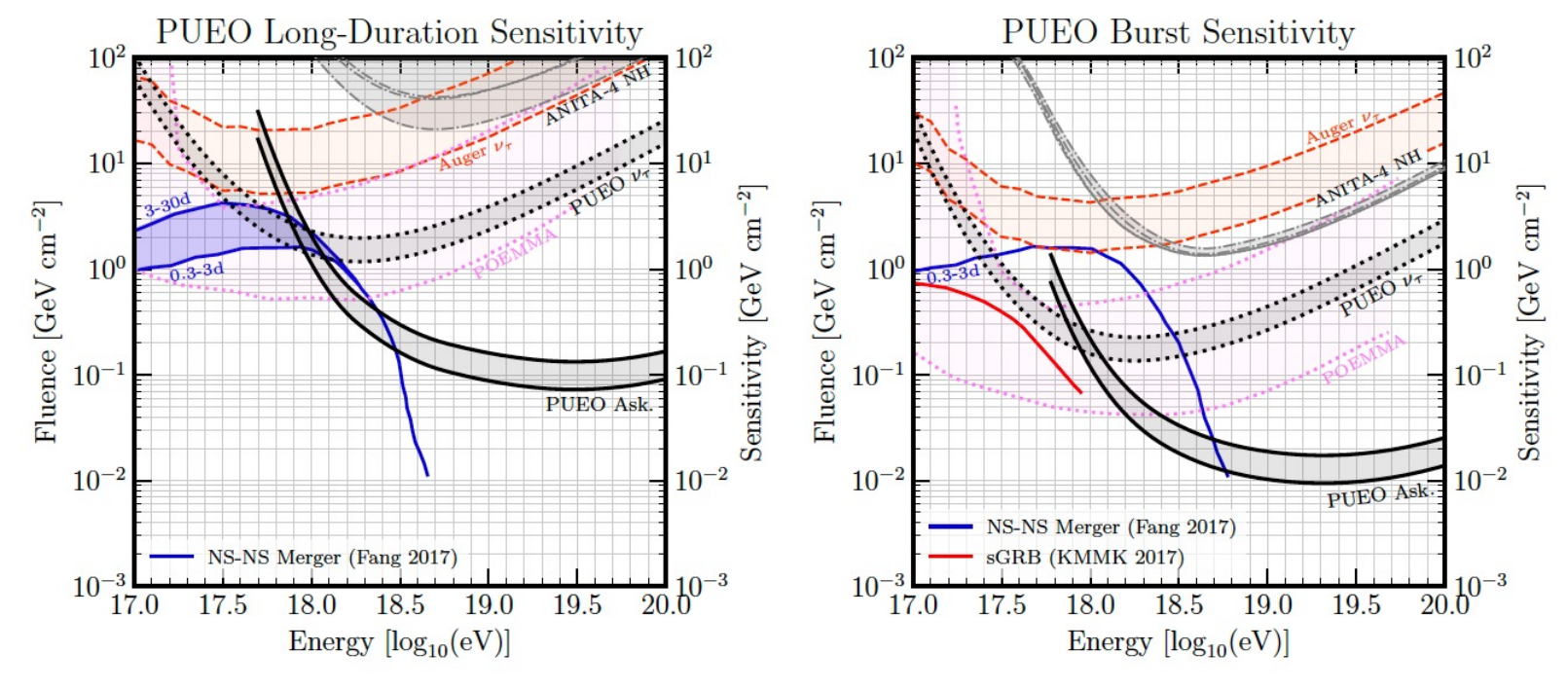
PUEO Science Goals

PUEO Neutrino Sensitivity Projections



- A unique detector for the highest energy (> 10^{18} eV) cosmic particles (neutrinos, cosmic rays, ++ ?)
- Use ultra-high energy neutrinos to constrain the nature of the highest energy astrophysical sources
  - Especially large instantaneous effective volume, for transient, point source, and multi-messenger searches
- Probe fundamental physics in this high-energy regime

Point Source and Transient Multi-Messenger Science



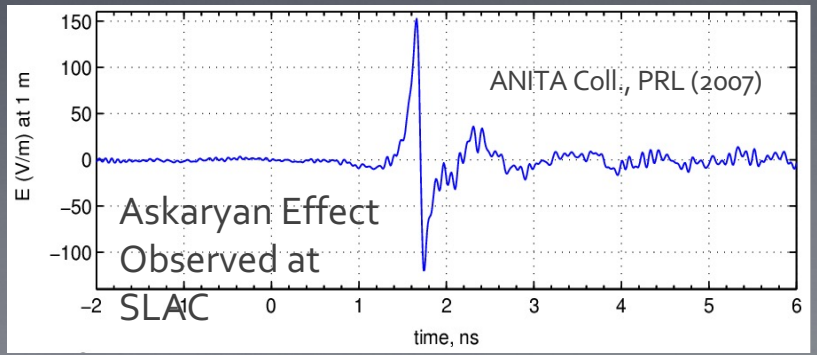
Long: Duration of Flight

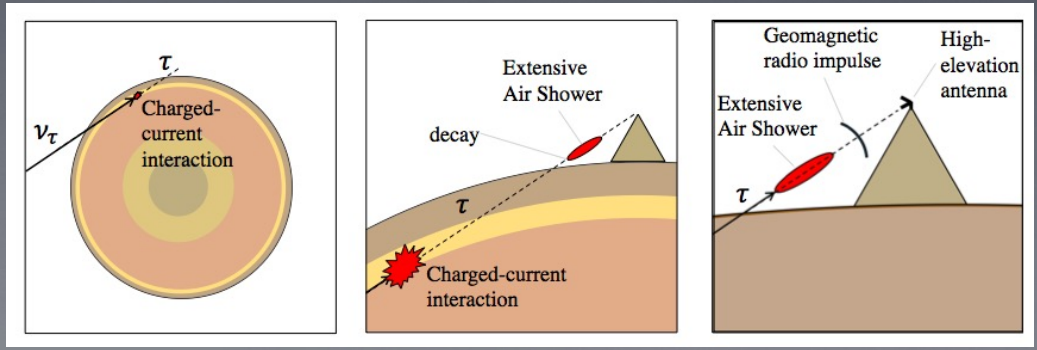
Short: 1000 s

PUEO Detects Radio Emission from Neutrino-Induced Particle Showers

- Method 1: Radio emission from neutrino interactions in a dense material
  - Coherent radio Cherenkov radiation ($P \sim E^2$) if $\lambda >$ Moliere radius
- Method 2: Radio emission from tau neutrino induced air showers
  - Geomagnetic emission from air showers

S. Wissel

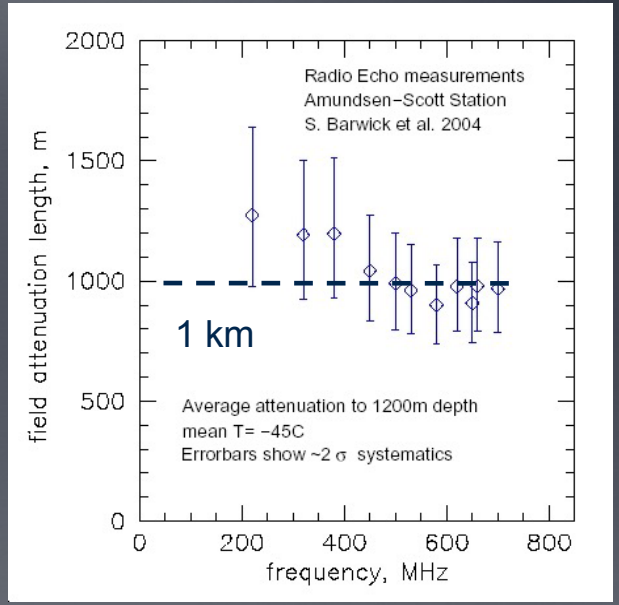




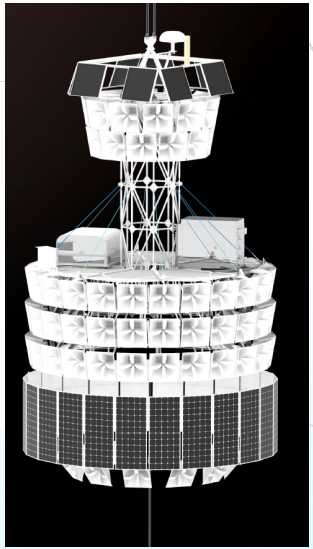
Askaryan Emission Detector Requirements

- ~1 GZK neutrino/km²/year
- L_{int} ~ 300 km
  → 0.01 neutrinos/km³/year
- Need a huge (~100 km³), radio-transparent detector
- Long radio attenuation lengths in ice
  - 1 km for RF (vs. ~100 m for optical signals used by IceCube)

→ Ice is good for radio detection of UHE neutrinos!



1) Neutrino-Induced Askaryan Emission in Ice



Not to scale, angles don't reflect reality

- Signals are vertically polarized

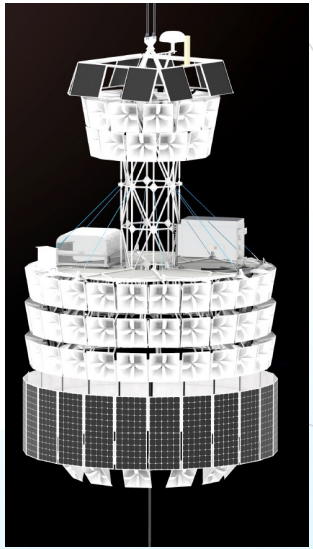
balloon

Ice

Askaryan emission

~EeV ν

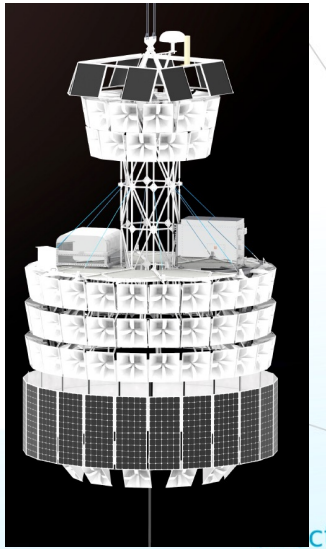
2) Radio Emission from Tau-Neutrino-Induced EAS



Not to scale, angles don't reflect reality

- Signals are horizontally polarized
- Comes from below the horizon

3) Radio Emission from Cosmic-Ray-Induced EAS

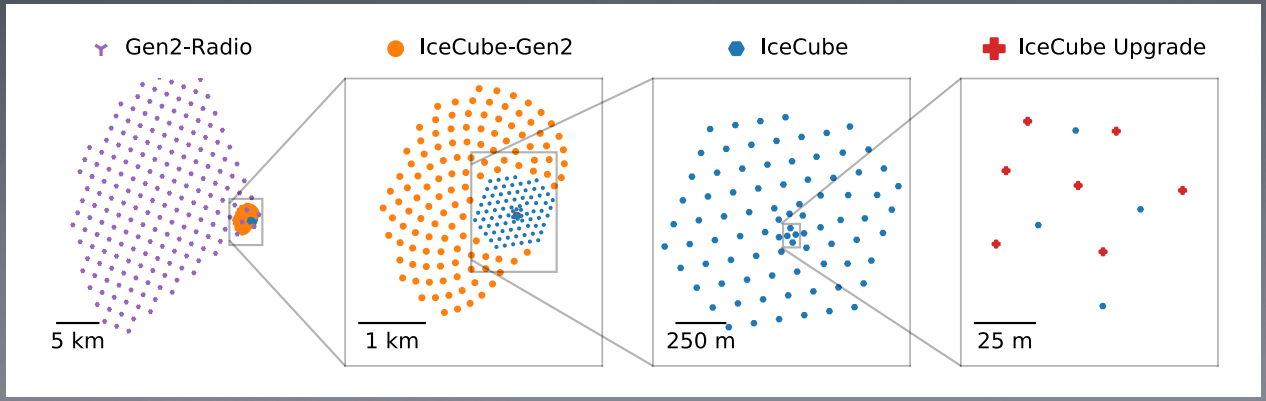


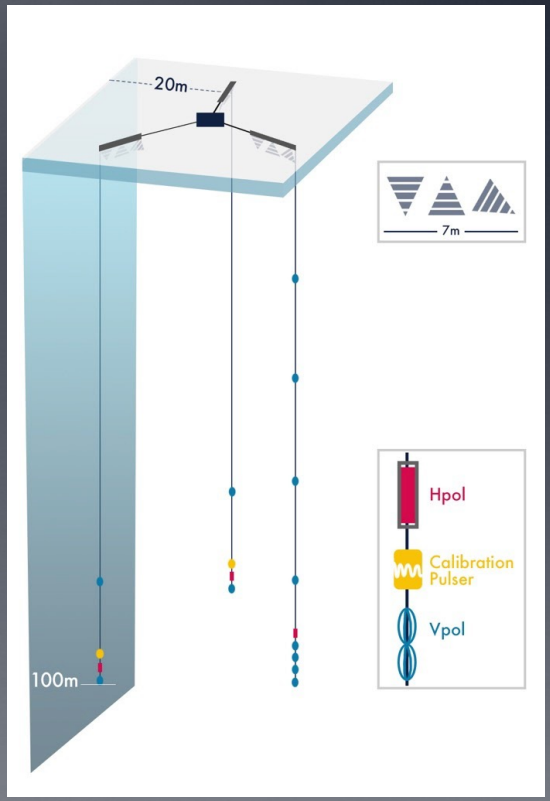
Not to scale, angles don't reflect reality

- Signals are horizontally polarized
- Polarity of reflected (below-horizon) signal is inverted compared to direct (above-horizon) signal and tau neutrino (below-horizon) signal

Complementarity with Ground-Based Experiments

- Ground-based in-ice radio detectors exist (at a modest scale), are being deployed now (at larger scales), and are being planned for the future (at even larger scales).
- IceCube and Auger are also sensitive to high energy neutrinos
- Complementary in energy: PUEO is the best at the highest energies ($> 10^{18.5}$ eV); ground-based detectors are better at lower energies.
- PUEO's instantaneous volume is very large comparatively; good for transient and point source searches
- PUEO can uniquely access both the air shower and in-ice detection channels; good for neutrino flavor ID, cosmic rays, and exotic searches





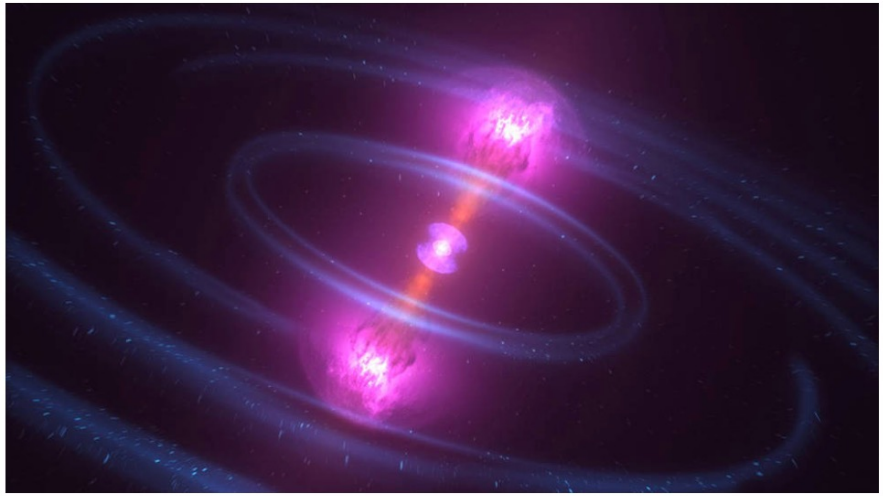
IceCube Gen2 Whitepaper

PUEO Recently Selected for Pioneers Mission Concept Study

Jan. 7, 2021

NASA Selects 4 Concepts for Small Missions to Study Universe's Secrets

NASA has chosen four small-scale astrophysics missions for further concept development in a new program called Pioneers. Through small satellites and scientific balloons, these selections enable new platforms for exploring cosmic phenomena such as galaxy evolution, exoplanets, high-energy neutrinos, and neutron star mergers.



As neutron stars collide, some of the debris blasts away in particle jets moving at nearly the speed of light, producing a brief burst of gamma rays.
Credits: NASA's Goddard Space Flight Center/CI Lab

PUEO is a balloon mission designed to launch from Antarctica that will detect signals from ultra-high energy neutrinos, particles that contain valuable clues about the highest energy astrophysical processes, including the creation of black holes and neutron star mergers. Neutrinos travel across the universe undisturbed, carrying information about events billions of light years away. PUEO would be the most sensitive survey of cosmic ultra-high energy neutrinos ever conducted. The principal investigator is Abigail Vieregg of the University of Chicago.

- A new class of astrophysics mission, including larger, more science capable balloon missions.
- We are currently working on the Concept Study Report, Systems Requirements Review in the Fall.
- PUEO is scheduled to fly in December 2024!!

Building on Heritage from ANITA

NASA Long Duration Balloon launched from Antarctica, four flights (2006,2008,2014,2016)

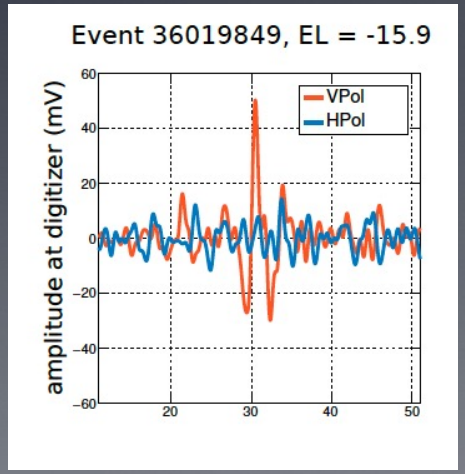
Instrument Overview:

- ~40 horn antennas, 200-1200 MHz
- Direction calculated from timing delay between antennas (interferometry)
- In-flight calibration from ground
- Threshold limited by thermal noise

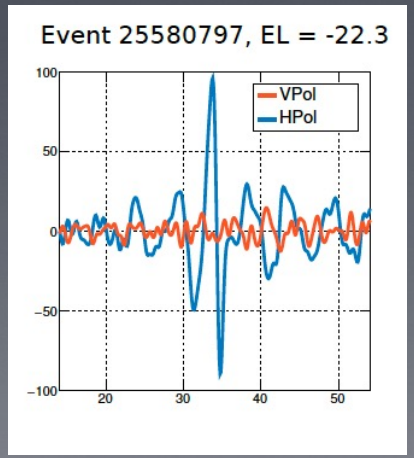
ANITA-III

Summary of Results from ANITA

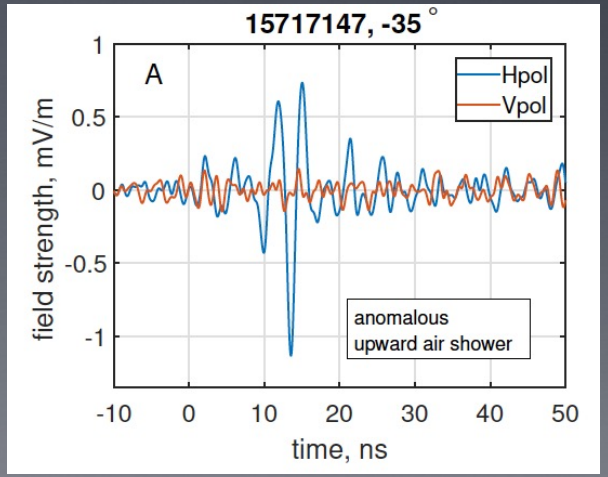
- All ANITA flights have seen 1 or 0 candidate events on a background of ~1 in the main neutrino search (Askaryan channel). No discovery ☹
- ANITA has seen ~100 ultra-high energy cosmic ray events!
- ANITA has seen a handful of "mystery events" that look like cosmic-ray air showers, but are flipped in polarity (consistent with upgoing air showers). The origin of these is unknown.



Example Neutrino Candidate



Example CR Candidate

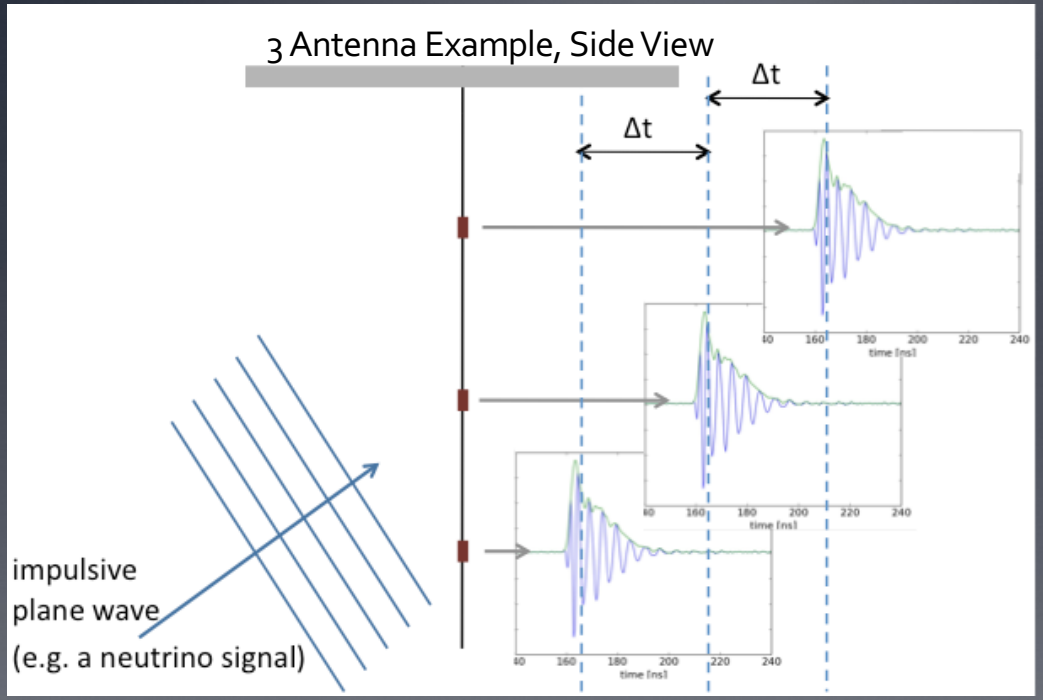


Example "mystery event"

PUEO's Improvements Over ANITA

- Order-of-magnitude improvement enabled by:
  - interferometric phased array trigger
  - real-time digital filtering
  - x2 more antenna collecting area above 300 MHz
  - Improved pointing resolution for better background rejection
  - Addition of low frequency instrument optimized for air shower signals

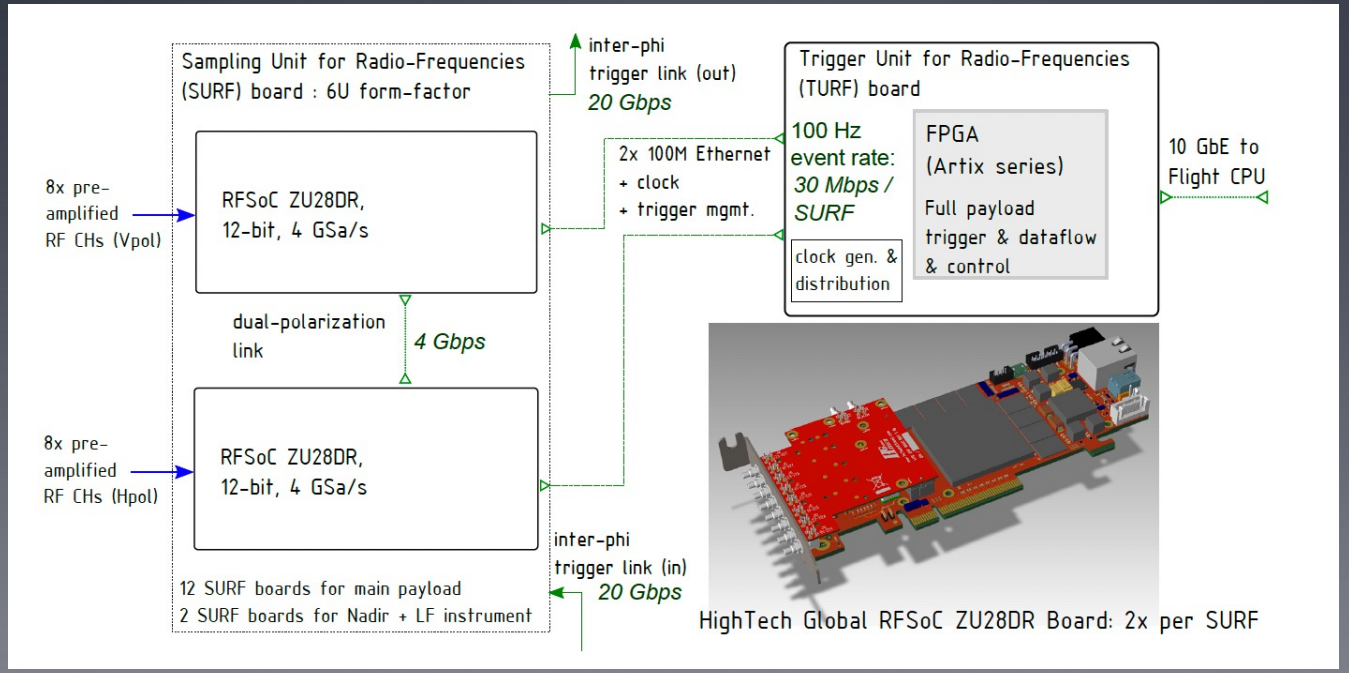
Pushing the Threshold Down and Increasing Sensitivity: A Phased Array



- You know Δt based on the antenna geometry and the speed of light
- Line up signals according to the Δt you know, then sum
- For real neutrino events (plane waves), you a get a higher signal-to-noise sqrt(N) in voltage
- Do this all the time for all possible incoming angles

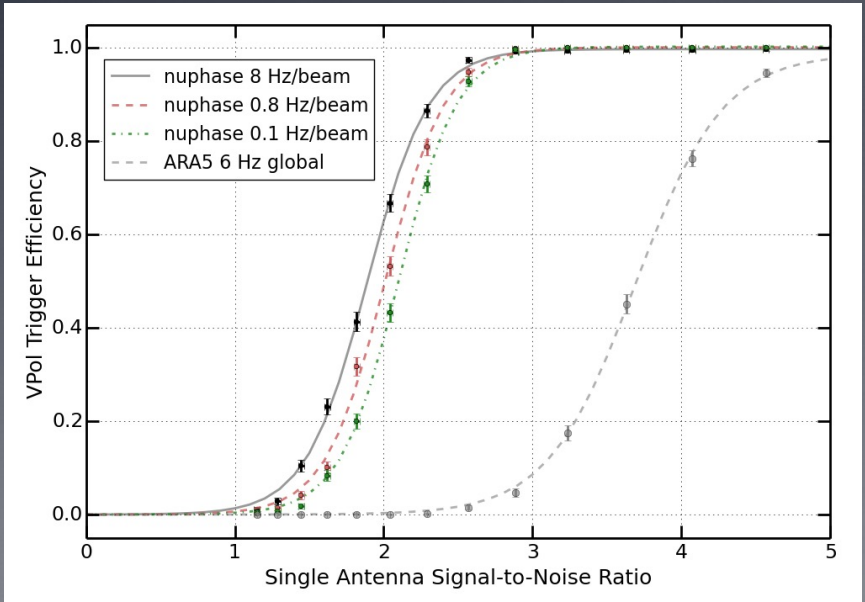
Interferometric Phased Array Trigger for PUEO

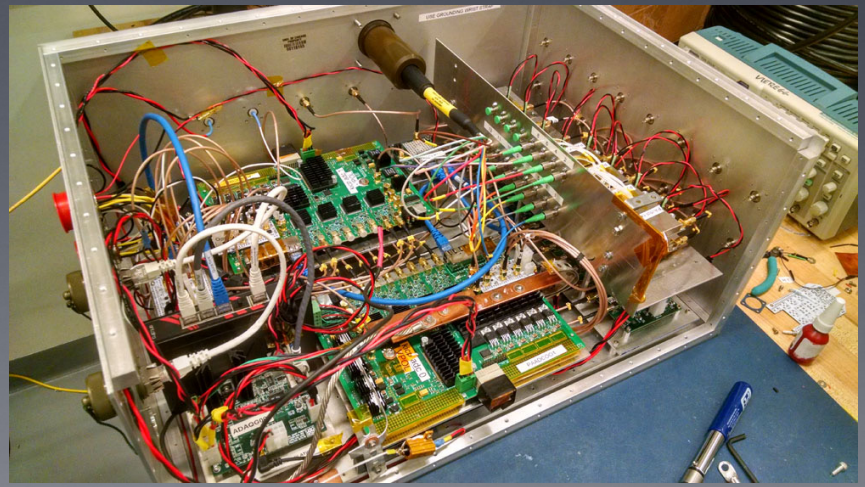
- 8-channel phased array triggering & digitization done using RFSoCs.



A similar system has been demonstrated on ARA @ South Pole

- A real-time interferometric phased array trigger system on ARA5
  - Has been perfectly stable since deployment
  - Trigger performance matches simulations exactly
  - Improvement x2 effective volume achieved already

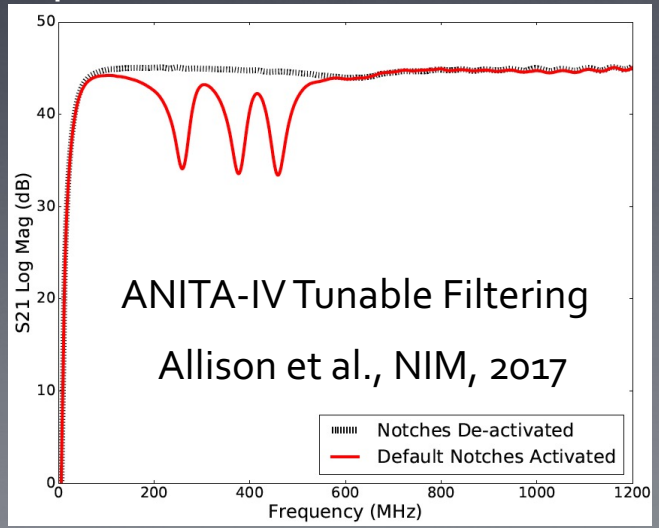




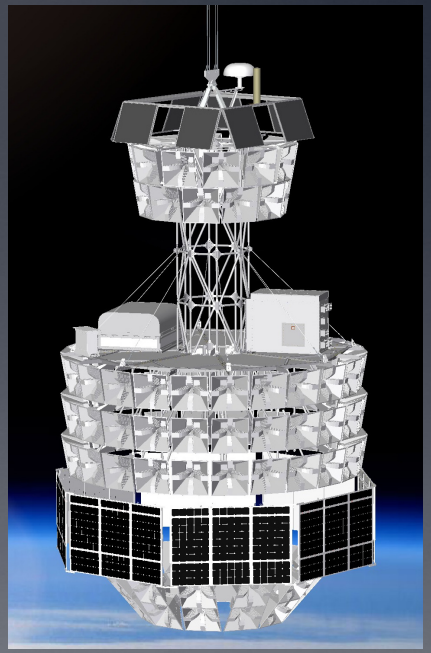
ARA Coll., NIM 2018

Optimized Frequency Range: 300-1200 MHz

- ANITA: 200 MHz high pass, but below 300 MHz, there is a lot of man-made noise
- PUEO: 300 MHz high pass makes antennas 33% smaller in each dimension
- More antennas = more collecting area at frequencies of interest



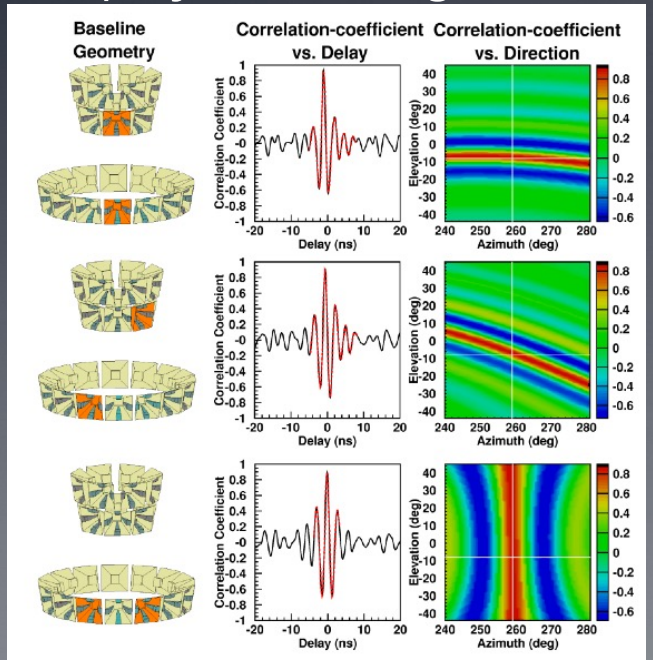
ANITA-III

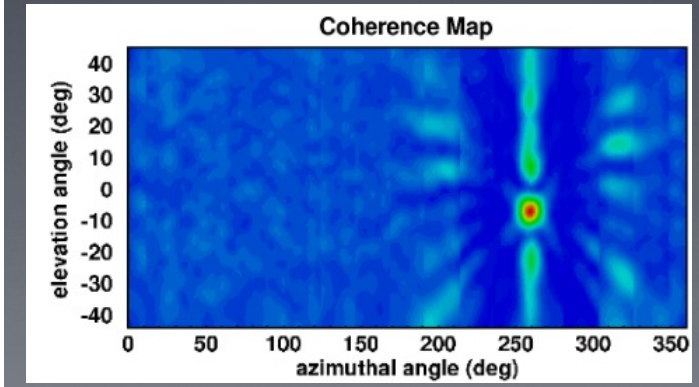


PUEO

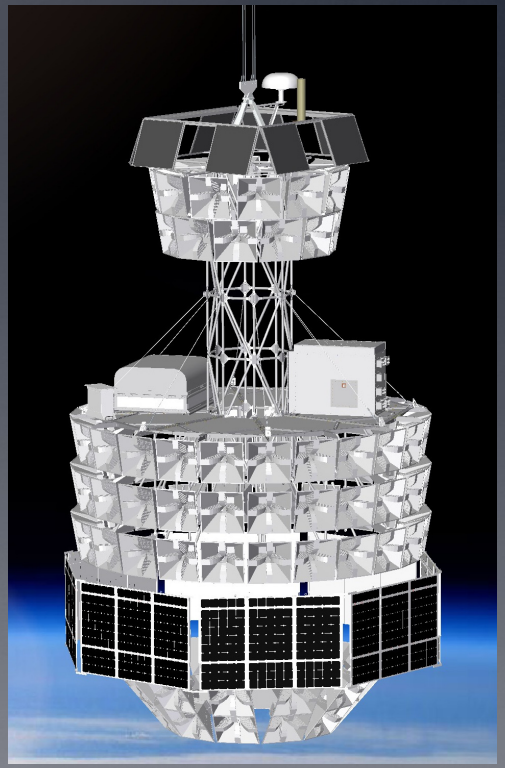
Improved Pointing Resolution in Elevation

- PUEO has longer baselines in elevation than ANITA and an IMU for pitch/roll determination
- Improves background rejection in analysis, since projection of signals onto continent is improved



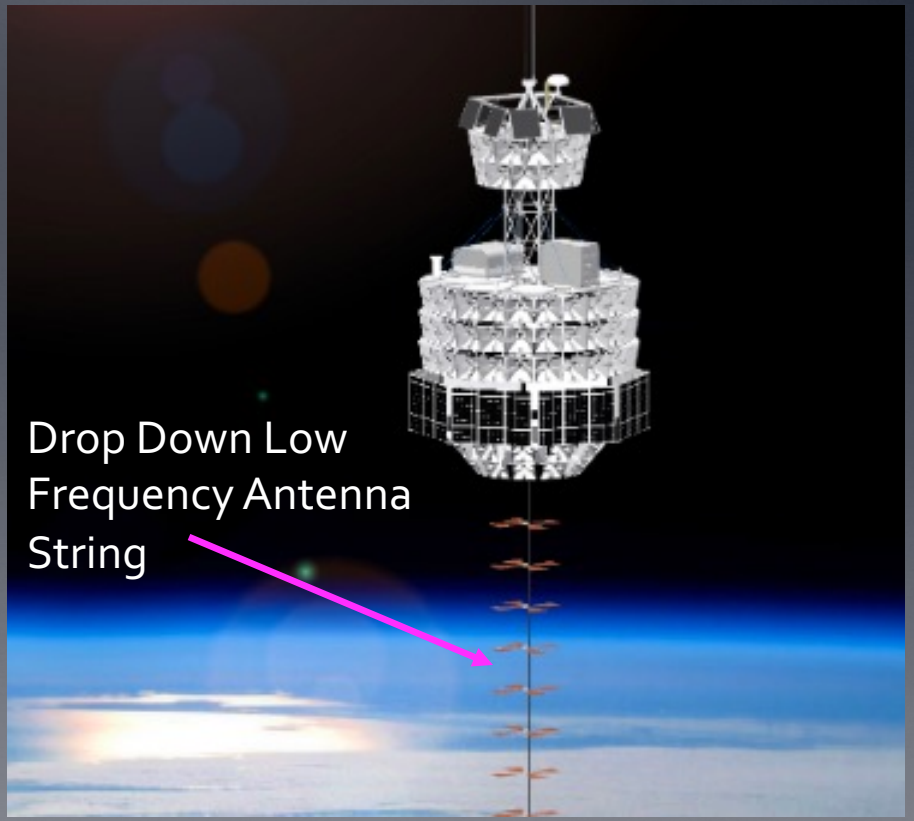


Romero-Wolf et al., JCAP 2015



Low Frequency Instrument

- Air shower signals have lower frequency content than in-ice neutrino signals
- Dedicated LF instrument for characterizing air showers, including the ANITA "mystery events"



PUEO Power and Mass Budgets

- 50% more power than ANITA-IV, to power x2 channels
- Similar mass to ANITA-III

Instrument Subsystem	Pow. [W]
DAQ system	484
RF signal chain	300
Flight computer + Data storage	100
HK & Nav. Sensors	55
Power systems (DC-DC effc. loss)	200
Total CBE	**1139**
Contingency (20%)	228
Total MEV	**1367**
Margin (~19%)	258
Max. Possible Value	**1625**

Instrument Subsystem	Wt. [lbs]
PUEO Instrument box	704
RF signal chain	392
Batteries	160
Antennas + mounting	781
Dropdowns + LF	157
Gondola, mechanical	1423
Total Science CBE	3617
CBE + 10% Contingency	**3979**
CSBF Above Pin	751
CSBF SIP	364
Ballast	350
Total MEV	**5444**
Margin (47%)	2556
Max. Possible Value	**8000**

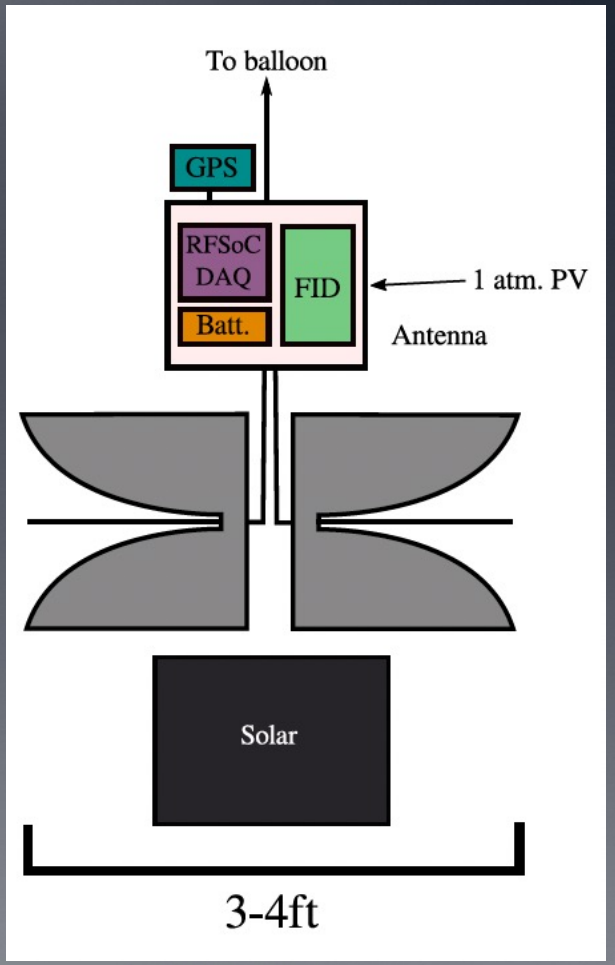
Launch Envelope and Post-Launch Drop-Down

- Similar Launch Envelope to ANITA
- The lower solar panels will drop down after launch
- The ring of nadir-pointing antennas and the LF instrument will be dropped down after launch
- Post-launch drop-downs have been successfully deployed on ANITA

In-Flight Calibration

- A calibration system set up at LDB to send neutrino-like pulses to PUEO
- 2 Deep-field calibration systems (WAIS and Siple Dome have been used in the past), to send neutrino-like pulses to PUEO from low-noise environment, typical for the majority of the flight. Critical for instrument calibration.
- Hi-Cal: a hand-launched balloon following PUEO, with a calibration source on it. Important for reflection studies (cosmic ray science)

Hi Cal Payload Design



PUEO Outlook

- Launch in December 2024
- Order of magnitude (more at low energies where the crossover is with ground-based experiments) improvement over ANITA.
- Especially suited for for high energy transient and point source searches