Galaxy Evolution Explorer: Scientific Accomplishments and Impact of Mission Termination

David Schiminovich
Columbia University

Co-I, Instrument Scientist
SODA Lead Scientist/Manager (dev. & early ops.)

Overview

- GALEX has successfully completed its primary mission and is continuing to perform in its extended mission
- GALEX is providing high quality, high impact, near-ultraviolet (NUV) science data
- The recommendation of the 2010 Senior Review was that GALEX continue operations in FY2011, FY2012 with closeout in FY2013
- NASA has instructed the project to terminate operations at the end of FY2011 (September 2011)
- New GALEX observations add significant scientific value to existing survey data and open up new avenues for research
- A bare-bones operational scenario and/or a close-out funding increment will provide high science return

GALEX has successfully completed its primary mission

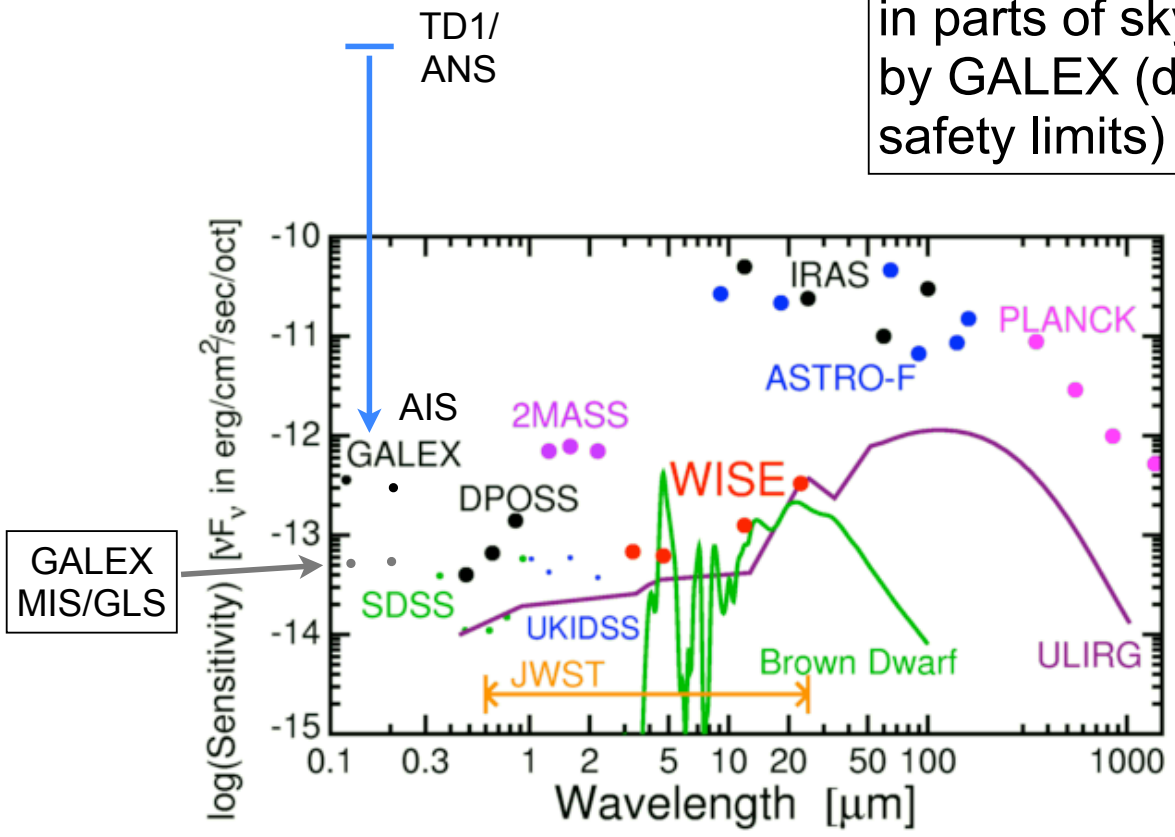
- **Launch:** April 28, 2003
- **Payload:** 50 cm telescope, two wide field photon-counting microchannel plate detectors (FUV, NUV; 1 deg^2 FOV)
- **PI/Team:** Christopher Martin (Caltech); Caltech, JPL, Orbital, GSFC, JHU, OCIW, Columbia, UCLA, UCB, France/LAM, Korea/Yonsei
- **Primary Mission Science Objectives:**
  - Map global history of star formation to determine the star formation rate of the universe between 0<z<2 and determine when and where today's stars and elements originate
- **Primary Mission Implementation (May 2003-September 2007):**
  - Nested surveys: All-sky (80% within detector safety limits), medium deep, deep surveys, some targeted obs. + grism spectroscopy
  - Guest observer program (1/3 available observing time)

GALEX has successfully completed its primary mission: key scientific accomplishments

- **Surveyed the UV sky, reaching flux limits >10,000 times deeper than previous all-sky surveys**
- Produced a standard UV->SFR calibration
- Galaxy “HR” diagram with star-forming main sequence and galaxies transitioning through the “green valley”
- Measured the UV and SFR density of the universe at z<1.5
- Discovery of star formation at low surface densities and in extreme objects (“Lyman break analogs”)

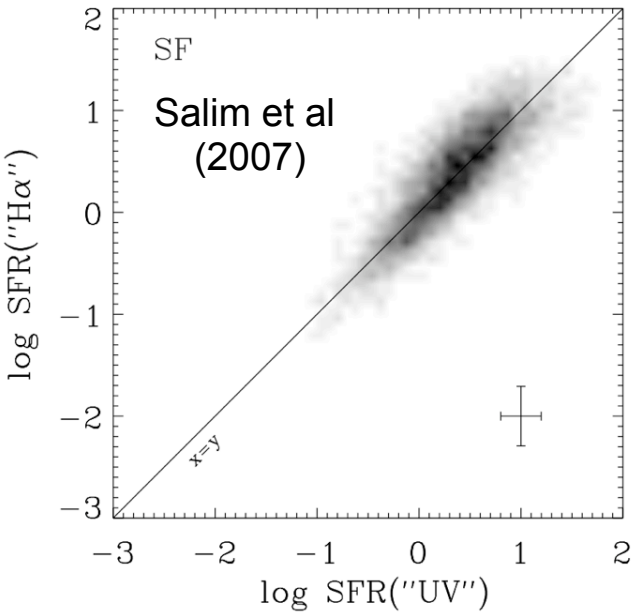
GALEX primary mission: reaches flux limits 10,000x deeper than previous UV all-sky survey

Significant gains still to be made in parts of sky not yet observed by GALEX (due to detector safety limits)



from Ned Wright/WISE
all-sky survey comparison plot

GALEX primary mission: Calibrate UV->SFR



UV STAR FORMATION RATES IN THE LOCAL UNIVERSE

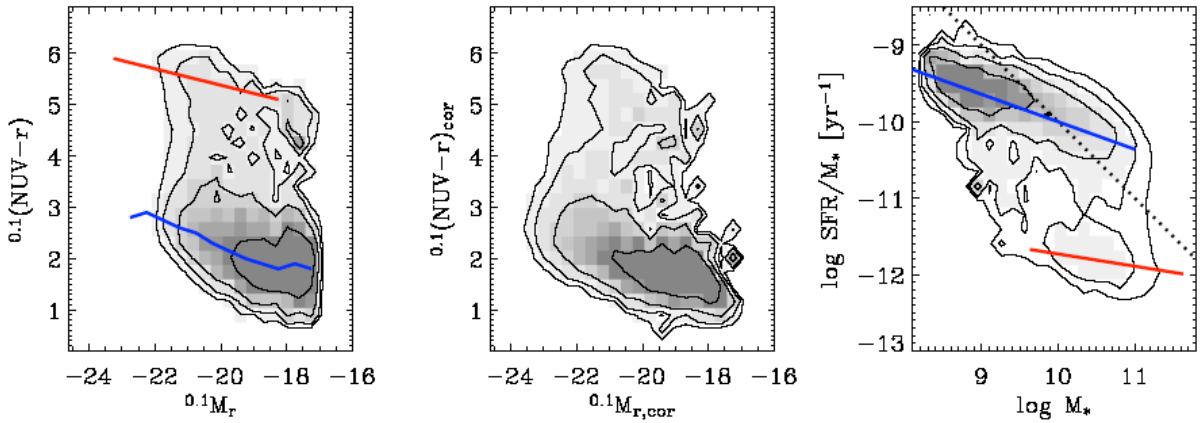
SAMIR SALIM[1,*], R. MICHAEL RICH[1], STÉPHANE CHARLOT[2], JARLE BRINCHMANN[3], BENJAMIN D. JOHNSON[4], DAVID SCHIMINOVICH[4], MARK SEIBERT[5], RYAN MALLERY[1], TIMOTHY M. HECKMAN[6], KARL FORSTER[7], PETER G. FRIEDMAN[7], D. CHRISTOPHER MARTIN[7], PATRICK MORRISSEY[7], SUSAN G. NEFF[8], TODD SMALL[7], TED K. WYDER[7], LUCIANA BIANCHI[9], JOSE DONAS[10], YOUNG-WOOK LEE[11], BARRY F. MADORE[5], BRUNO MILLIARD[10], ALEX S. SZALAY[6], BARRY Y. WELSH[12], SUKYOUNG K. YI[11]

2007 Apr 20 — ApJS Special GALEX Issue

ABSTRACT

We measure star formation rates (SFRs) of ≈ 50,000 optically-selected galaxies in the local universe ($z \approx 0.1$), spanning a range from gas-rich dwarfs to massive ellipticals. We obtain dust-corrected SFRs by fitting the *GALEX* (ultraviolet) and SDSS (optical) photometry to a library of population synthesis models that include dust attenuation. For star-forming galaxies, our UV-based SFRs compare remarkably well with those derived from SDSS-measured emission lines (primarily Hα). Systematic deviations from perfect agreement between these two methods is shown to be due to differences in the dust attenuation estimates. In contrast to measurements based on Hα, UV provides reliable SFRs for galaxies with weak or no Hα emission, and where Hα is contaminated with an emission from an AGN (1/2 of the sample). We use full-SED SFRs to calibrate a simple prescription that uses *GALEX* far-UV magnitude and the UV slope to produce good dust-corrected SFRs for normal star-forming galaxies. The specific SFR (SFR normalized by stellar mass) is considered as a function of stellar mass for (1) star-forming galaxies with no AGN, (2) those hosting an AGN, and for (3) galaxies without Hα emission (the latter two groups forming the bulk of the optical red sequence). We find that the three have distinct star formation histories, with AGN lying *intermediate* between the star-forming and the quiescent galaxies. Normal star forming galaxies (without an AGN) lie on a relatively narrow linear sequence. Remarkably, galaxies hosting a strong AGN appear to represent the *massive continuation* of this sequence. On the other hand, weak AGN, while also massive, have lower SFR, sometimes extending to the realm of quiescent galaxies. We propose an evolutionary sequence for massive galaxies that smoothly connects normal star-forming galaxies to quiescent (red sequence) galaxies via strong and weak AGN. We confirm that some galaxies with no Hα emission show signs of star formation in the UV. We derive a UV-based cosmic star formation density at $z = 0.1$ with significantly smaller total error than previous measurements.

Subject headings: galaxies: evolution—galaxies: fundamental parameters— ultraviolet: galaxies—surveys—galaxies: active

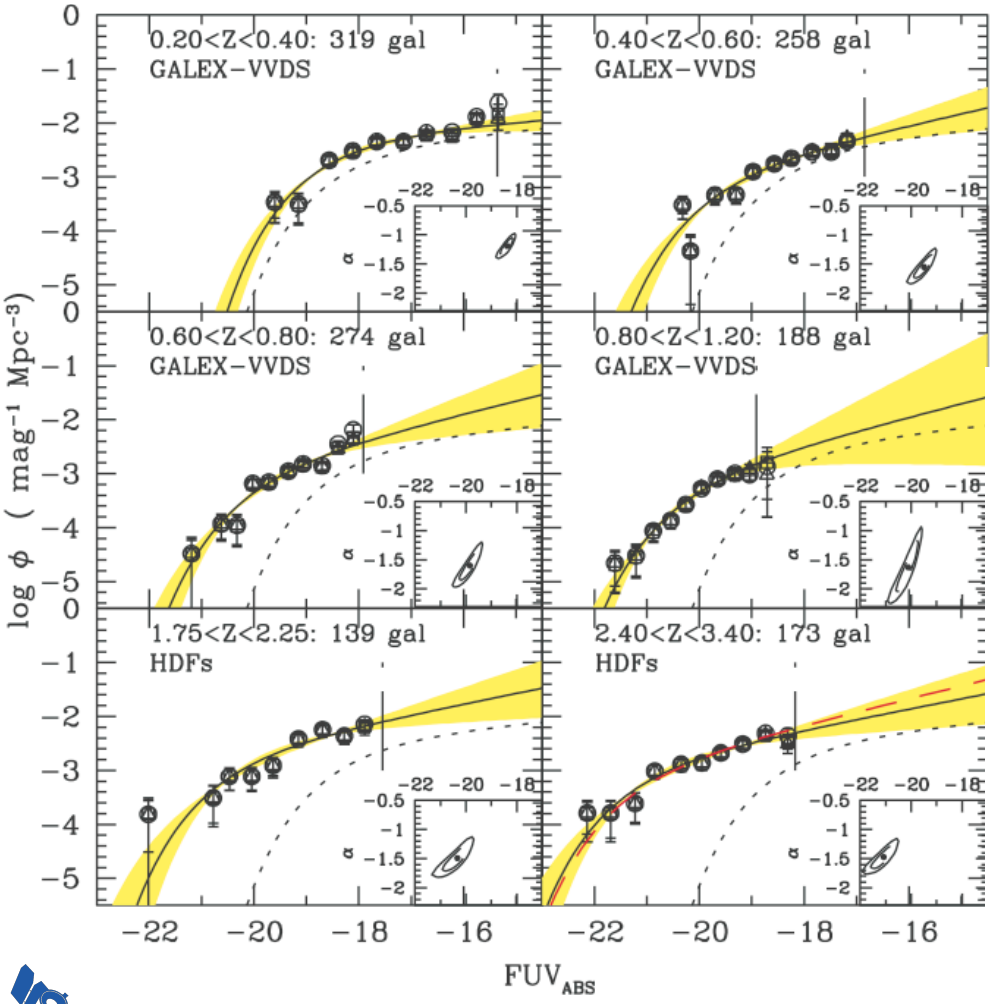


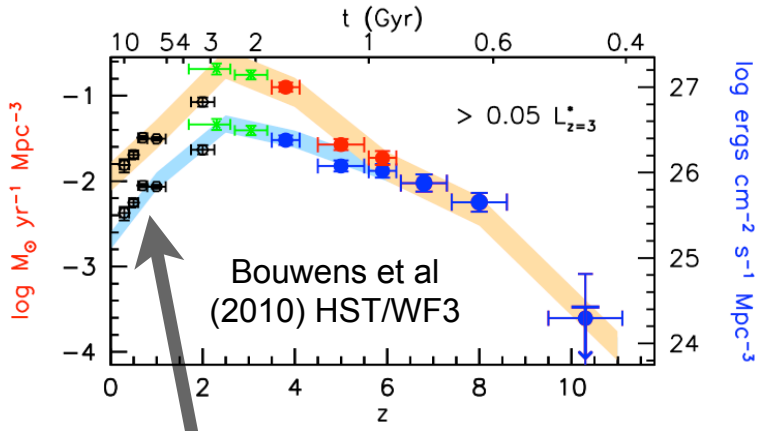
UV-optical color-magnitude diagram converted to specific SFR-stellar mass distribution function

Wyder et al (2007);
Schiminovich et al (2007);
Martin et al (2007);
GALEX ApJS

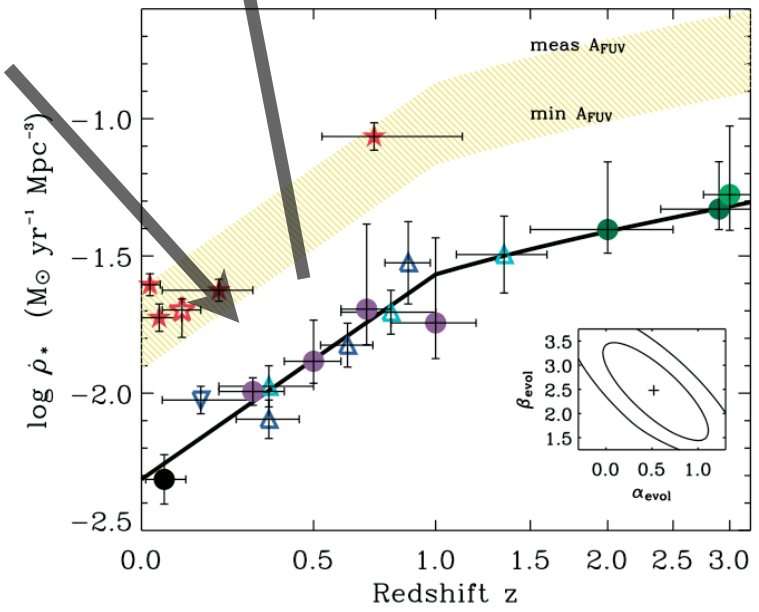
GALEX primary mission: Establish z<2 'anchor' for cosmic star formation history/UV luminosity density

Arnouts et al (2005) GALEX - UV Luminosity function

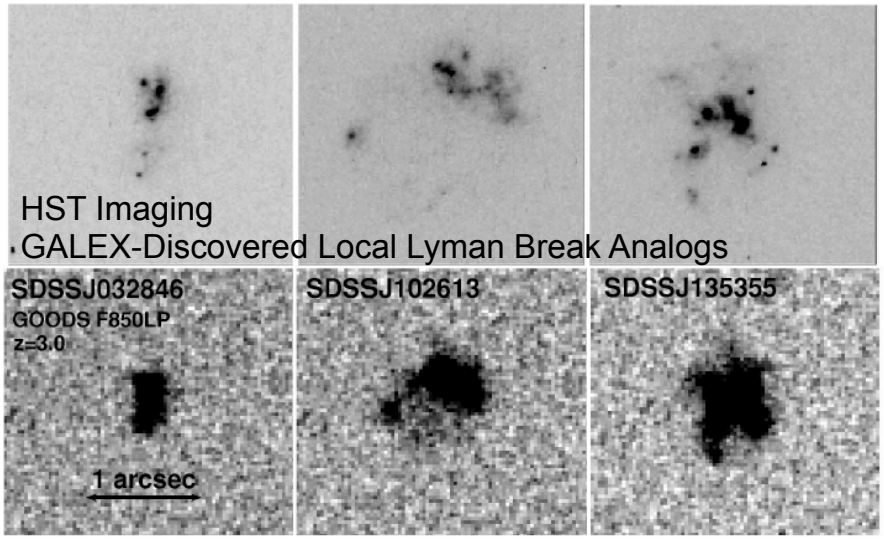


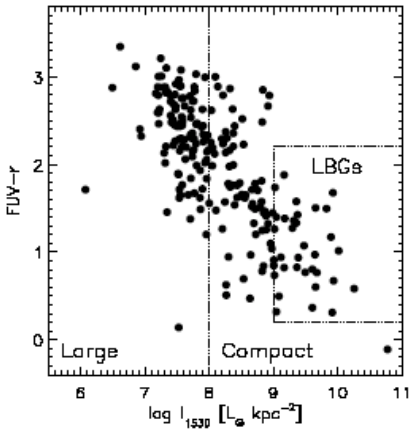


Schiminovich et al (2005) GALEX



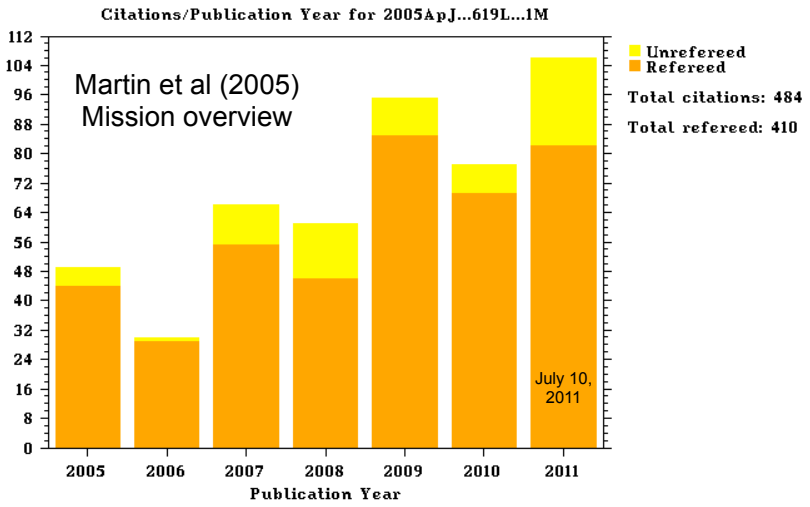
GALEX primary mission: Discovered SF at low density and in extreme local environments

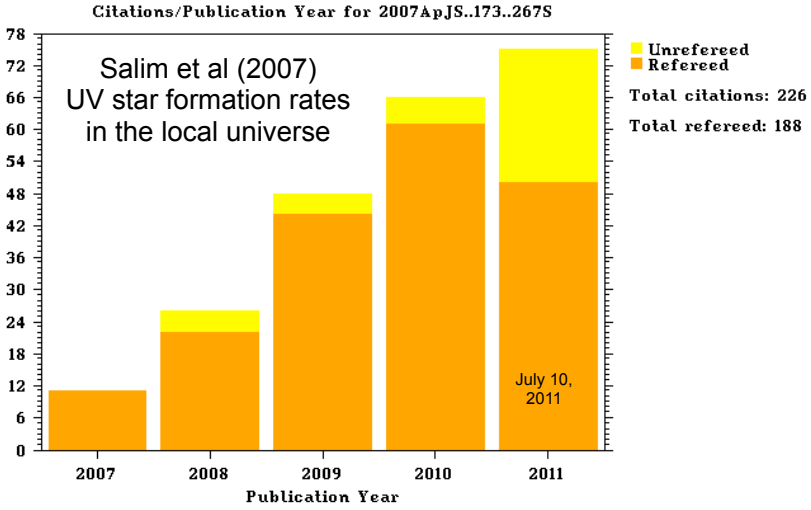


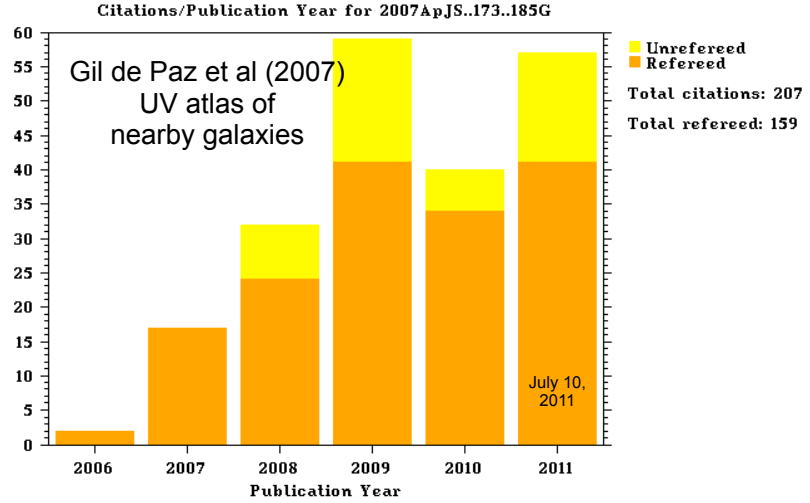


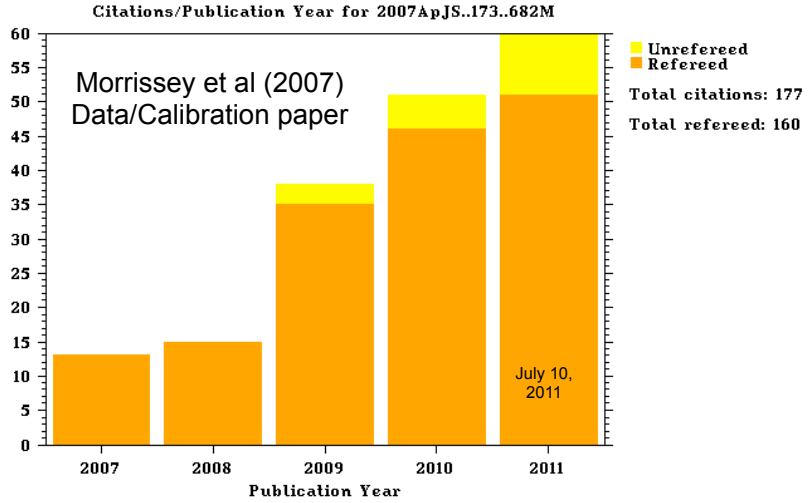
Local Lyman Break Analogs: e.g. Heckman et al (2005), Hoopes et al 2007, Overzier et al (2008)

GALEX primary mission: top-cited science team publications have increasing impact/utility









Also large community base: GALEX in 5% of Jan 2011 AAS science abstracts

GALEX is continuing to perform in its extended mission

- **Extended Mission Objectives (September 2007-present):**
  - Extend star formation history/UV calibration to low stellar mass/low density universe
  - Explore connection between star formation history and other physical properties and determine fundamental drivers of SFH
  - Explore UV Universe into dynamic and low-surface-brightness regimes
  - Extend reach of primary mission surveys
- **Extended Mission Status:**
  - S/C performing nominally
  - NUV detector functioning properly. One year ago electronic drift caused minor degradation in angular resolution but condition has stabilized over past year.
  - NUV Detector count rate limit increased from 30 kcps to 500 kcps
  - FUV detector non-operational during most of extended mission. Possibility for FUV recovery remains, but not risk-neutral.
- **Community and GI input indicates strong interest in GALEX Legacy Survey, Magellanic cloud and Galactic plane survey**

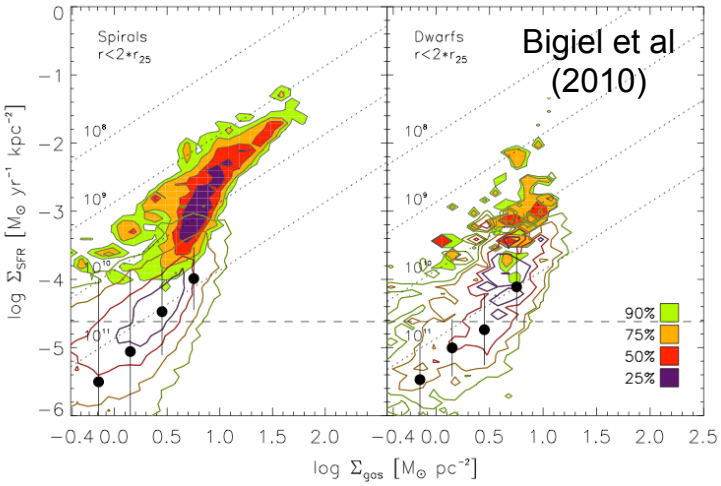
GALEX is providing high quality, high impact NUV science data

- **Extended Mission Implementation:**
  - GALEX Legacy Survey (high-latitude sky to MIS depth---as much as possible)
  - GI program (through FY10)
  - Data Release #6 (GR6) to community in FY11
  - Publication and citation rates increasing
  - Continuing synergy with on-going missions and surveys: HST/COS, Kepler, Spitzer, Herschel, SDSS/BOSS, Pan-STARRS, Wiggle-Z, GAMA, Arecibo HI surveys, WISE

Selected Key Science results

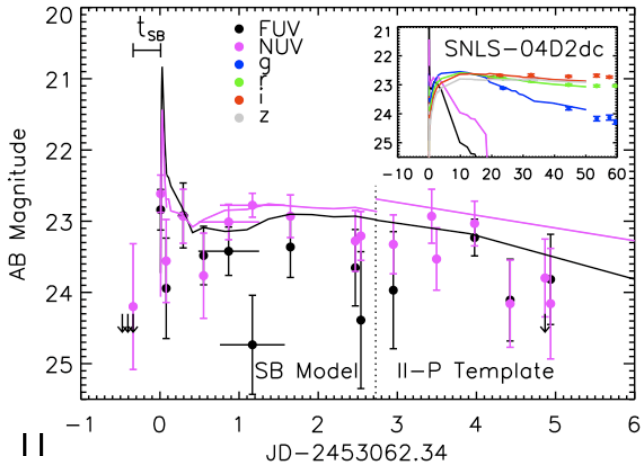
- UV rising flux and residual SF in ellipticals
- UV/Hα: Stochastic SF and variable IMF
- SF-gas connection and inside-out growth of galaxy disks
- Evidence for AGN-galaxy co-evolution
- Mira nebula - spectacular tail
- z~3 QSO candidates: He II Gunn-Peterson
- WiggleZ baryon oscillations using GALEX-selected 0.5<z<1 galaxies

Beyond the Kennicutt-Schmidt relation: new star formation laws



Bigiel et al (2010)

The transient universe: tidal capture flares and SN shock break-out



Gezari et al (2008)

Schawinski et al (2008)

GALEX 2010 Senior Review Proposal

- GALEX was highly ranked 1st, 2nd, 3rd in 2004, 2006, 2008 SR
- SR 2010 proposal included minimal, in-guide and augmented scenarios to continue implementation of GALEX legacy survey
- Proposed minimum mission included elimination of GI program, and relocation of Mission Operations Center to save future cost
- Senior review conundrum ("Marching analysts impact"): how to balance need/ desire for experienced scientific analysts at end of mission close-out vs. cost-saving of streamlined operations staff?
- Additional important extended ops considerations for missions without consumables include: risk management, creative teaming arrangements, and long-term scientific benefit (e.g. current vs. future science/$)
- Ranked 7th in 2010 SR

2010 Senior Review Recommendations

- "**The Committee recommends that the program be continued for two more years and closed out in FY2013.** During this time, the program should emphasize completion of as much of the GLS as possible and the development of software to maximize utilization of the archive. By concentrating on the GLS, the project will map more sky per year, increasing the archival value of the mission accordingly."

- "The Committee feels that moving the Mission Operations Center to Cal Tech which was suggested as a long term cost-saving measure, would introduce unnecessary risk into the mission operations and provide no cost savings given the limited remaining mission lifetime...."

- "The Committee does not recommend funding the GI program nor the execution of the spectroscopic survey."

- **"The SRC recommends that GALAX [sic] receive a budget that is $1M less than in the FY2011 President's budget for FY2011 and FY2012, followed by closeout in FY2013."**

NASA has instructed the project to terminate operations at the end of FY2011

- Project cancellation announced through President's budget release in February 2011.
- Early, non-recoverable, shutdown of working observatory in September 2011, at least one year earlier than SR2010 recommendation. (Project had been projecting operations capability to Feb 2013 using planned FY2012 funds)
- The GALEX team has always been aware that our only expendables are money and luck. While the timing of cancellation was unexpected, we were not surprised by the idea that the mission could end due to termination of funding
- Project has been:
  - Actively exploring end-of-mission scenarios
  - Reducing staff due to tight budgetary constraints
  - Evaluating risk-science-cost trade with new science observations

NASA has instructed the project to terminate operations at the end of FY2011

	FY10 $M	FY11 $M	FY12 $M	FY13 $M
NASA Guideline Feb 2010 (Final Guideline)	7.987 (7.954)	6.951	6.661	-
SR2010 Recommendation		5.951	5.661	"closeout"
FY10-FY14 NASA Guideline Post SR2010		5.321	5.411	0.37
Post-termination guideline		5.321	0.110	-
Re-phased post-termination spending plan (TBD)		4.937	0.494	-
Bare-bones operations plan (% SR2010 budget)			<1.8 (<30%)	0.9 for archiving

Only 2.5% of SR2010 recommended budget

Insufficient for proper archival close-out of mission data

Low-cost operations scenario can provide science/$ boost and savings to NASA

New GALEX observations add significant scientific value to existing survey data

- **Why complete the last 20% of <u>any</u> survey?** Not statistics... for GALEX, observations of each new patch of the sky reach flux limits >10,000x deeper than previous UV surveys w/ significant value as part of a large, homogeneous data set

- **Galactic plane science**:
  - HST/COS targets for ISM absorption line studies,
  - Galactic extinction law investigations
  - Post-MS evolution (stars and nebulae)
  - Activity-age relation in main sequence stars
  - Kepler field

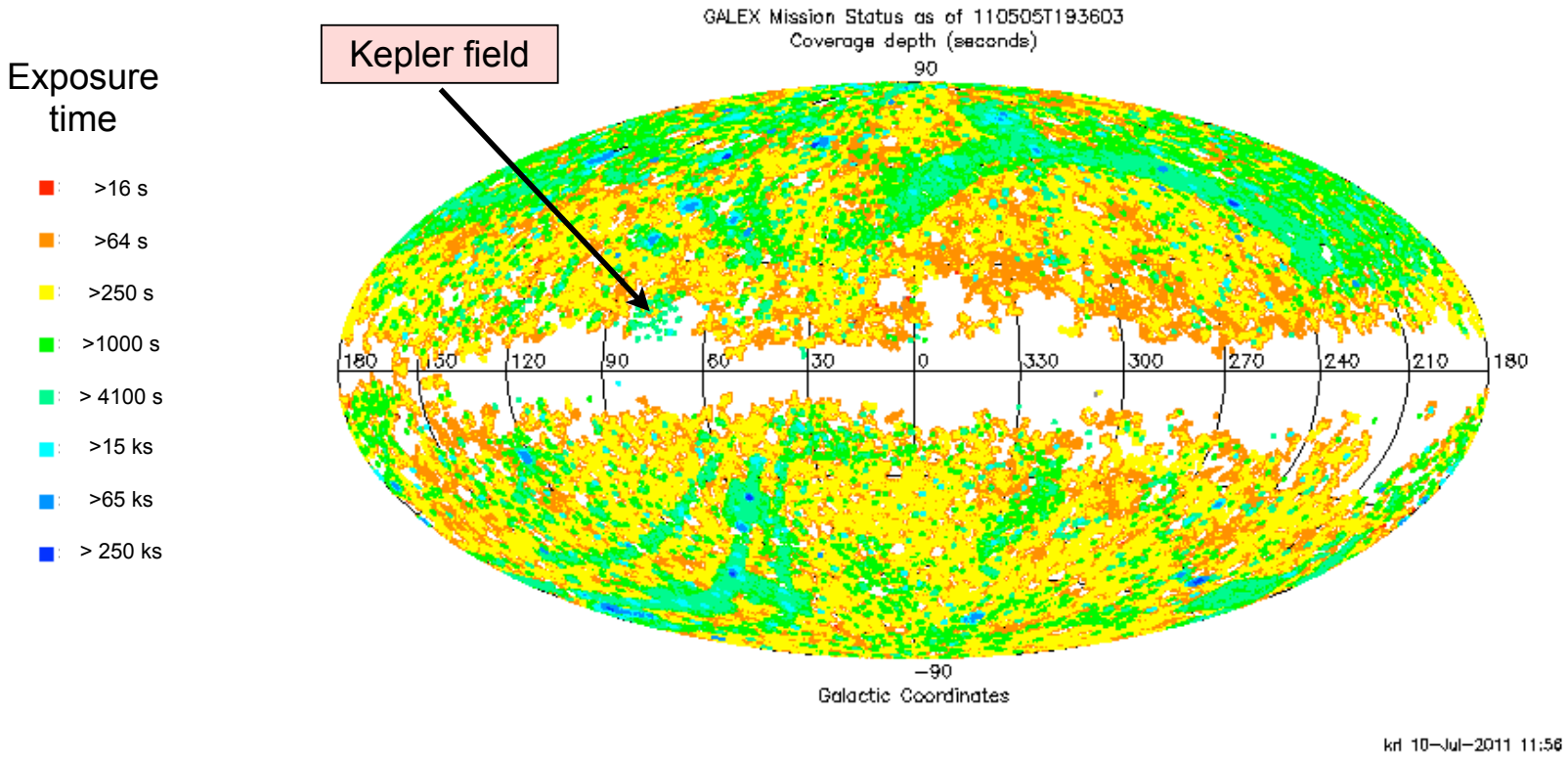
- **Magellanic cloud science**:
  - Star formation laws in resolved regions
  - Feedback and SF regulation
  - Extinction laws and metallicity trends

Findeisen, Hillenbrand & Soderblom (2011) Stellar activity in the Broad-band ultraviolet and the activity age relation in MS stars: "No other activity indicator is as readily available as FUV and NUV photometry"

- **Risk vs. science trade:** Opening up the detector safety limits from 30 kcps to 500 kcps has made it feasible to observe into the Galactic plane and significant portions of the Magellanic clouds. Observations over past couple of months have shown that we can observe these regions with little impact on detector health

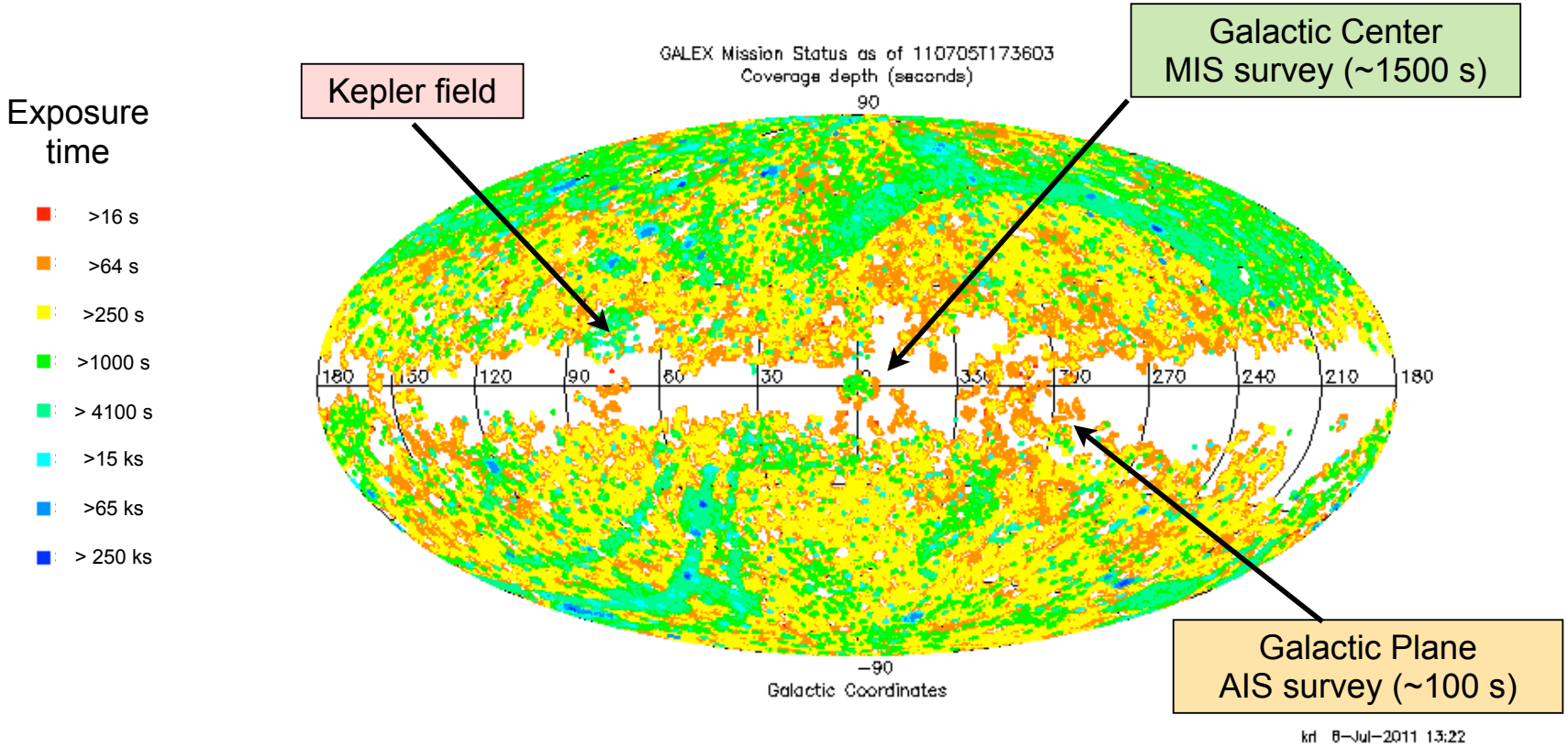
New GALEX observations open up new avenues for research

Sky coverage as of May 5, 2011

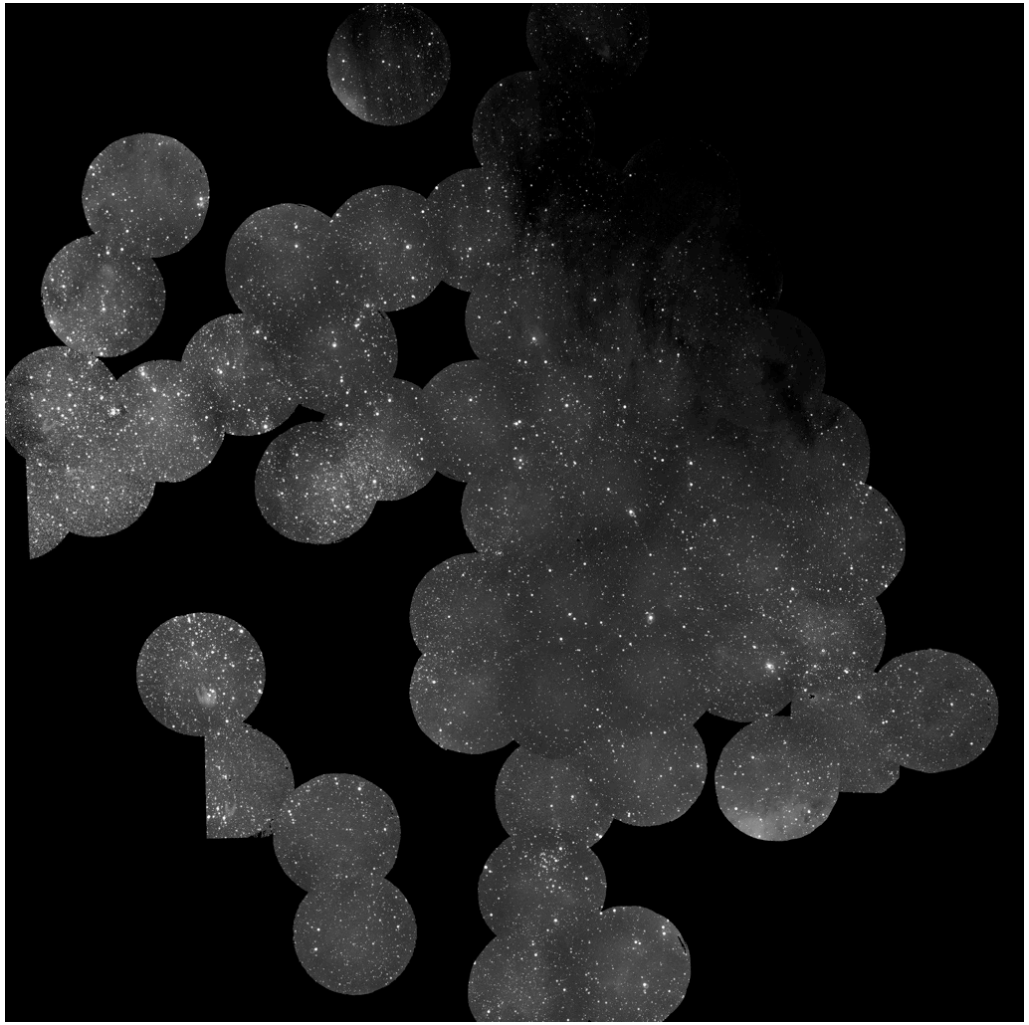


New GALEX observations open up new avenues for research

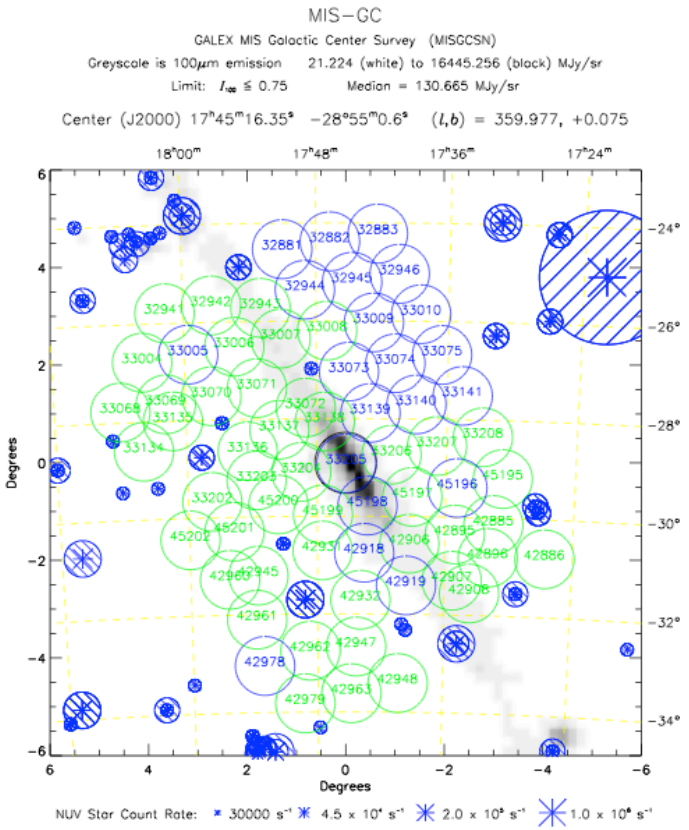
Sky coverage as of July 5, 2011



New GALEX observations open up new avenues for research



New Galactic Center observations



New GALEX observations open up new avenues for research

- AIS Galactic Plane survey - 3500 sq. degrees complete by September 2011
- MIS Galactic Center and bulge survey - 70 sq. degrees in Galactic center, 100 sq. degress in Galactic bulge. GC survey in progress, bulge yet to begin
- SMC and LMC will be fully mapped in August and September if possible
- MIS depth Kepler field survey - goal 2/3 coverage (70 sq. degrees) expected to be completed by September
- Completing observations of the above smaller fields will be tight before planned EOM.
- AIS Galactic plane survey could be completed during FY2012

A bare-bones operational scenario will provide high science return

- We have developed a “bare-bones” plan that would allow us to operate GALEX for <$1.8M per year (or <$5000/day).
- Plan would include:
  - Long-term planning (2-6 month scheduling)
  - Use of existing pipeline for reduction, MAST archiving
  - Simplified ops with no GI program and elimination of TOO, time-critical or re-planned observations
  - Elimination of most university support (universities provide non-costed contribution of effort)
- Plan does not include close-out data analysis effort (next slide)
- In FY2012 GALEX could complete Galactic plane survey (AIS), study Magellanic clouds w/ implications for SF laws, extend GLS, and complement new surveys

A close-out funding increment will provide high science return

- Current close-out plan will result in partially complete final data set (80%) with little documentation
- Ideal scenario would include final calibration, reprocessing and documentation
- Creative teaming arrangements may result in availability of experienced personnel when needed for final processing
- Non-costed effort by university science team members can supplement/match NASA contribution.

- Cost estimates indicate that 0.9 M$ is required to complete task
- We have also developed a low-cost plan for a *recoverable* end of operations (“hibernation”), maintaining ability to de-activate satellite

Summary

- We are grateful for the long and significant support we have received from NASA
- GALEX has successfully completed its primary mission and is continuing to perform in its extended mission. GALEX is providing high quality, high impact NUV science data.
- New GALEX observations add significant scientific value to existing survey data and open up new avenues for research
- The recommendation of the 2010 Senior Review was that GALEX continue operations in FY2011, FY2012 with closeout in FY2013
- NASA has instructed the project to terminate operations at the end of FY2011

We request consideration of:

- A “bare bones” operating mission (<1.8M$/yr) for FY2012
- Funding for final archival close-out of the legacy data set
- “Hibernation” vs. non-recoverable termination