The *Fermi* Large Area Telescope View of Gamma-ray Pulsars

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on behalf of the *Fermi* Large Area Telescope Collaboration and the Pulsar Timing and Search Consortia

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The *Fermi* Gamma-ray Space Telescope

NASA/DOE + numerous international agencies and universities.
Launched 11 June 2008.
<u>2 Instruments</u>:

Large Area Telscope (LAT) (Atwood+ '09)
- 20 MeV – > 300 GeV
- ~7000 cm^2 @ 1 GeV, on-axis
- ~0.7° 68% containment radius @ 1 GeV
- 2.4 sr field of view (~20% of the sky)
- Event times accurate within < 1μs
- See talk by Eric Charles on Thursday.

Gamma-ray Burst Monitor (Meegan+ '09)
- ~8 keV – ~40 MeV
- Sees full, unocculted sky

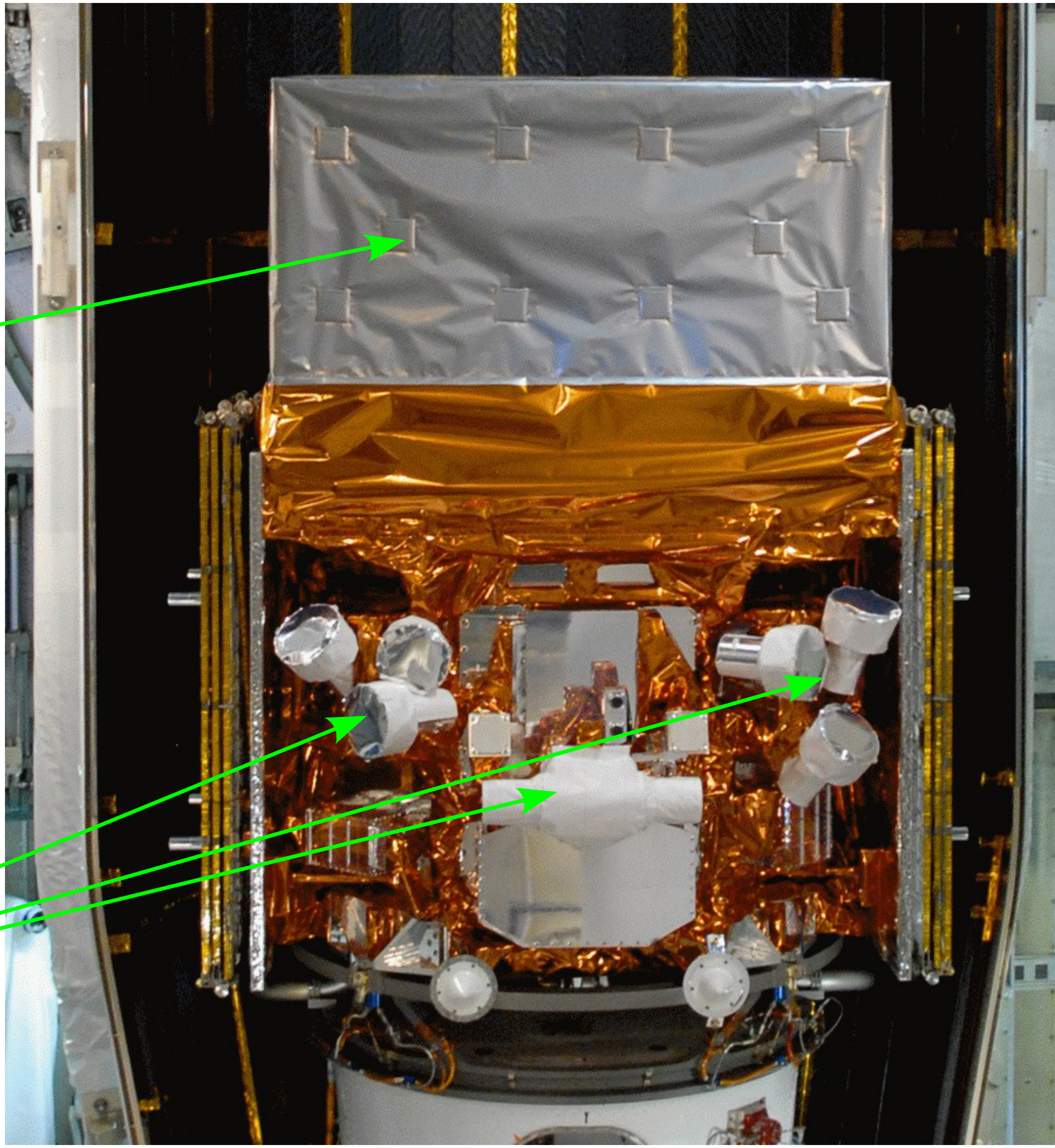


Photo Credit: NASA

Gamma-ray Pulsars

Charges pulled from the surface.

- Accelerated along magnetic field lines in vacuum gaps → curvature radiation.
- Expect non-variable phase-averaged flux (but see talk by Luigi Tibaldo).
- Exponentially cutoff power-law spectrum:

$$\frac{dN}{dE} \propto E^{-\Gamma} e^{-\left(\frac{E}{E_{Cut}}\right)}, E_{Cut} \propto \frac{\gamma_{CR}^3}{\rho_c}$$

Low-altitude models (polar cap) predict sharper cutoff due to photon splitting on strong near-surface field.

- Disfavored by LAT observations as primary source of gamma rays.
- Observed gamma rays predominantly from the outer magnetosphere.

Proposed Emission Models

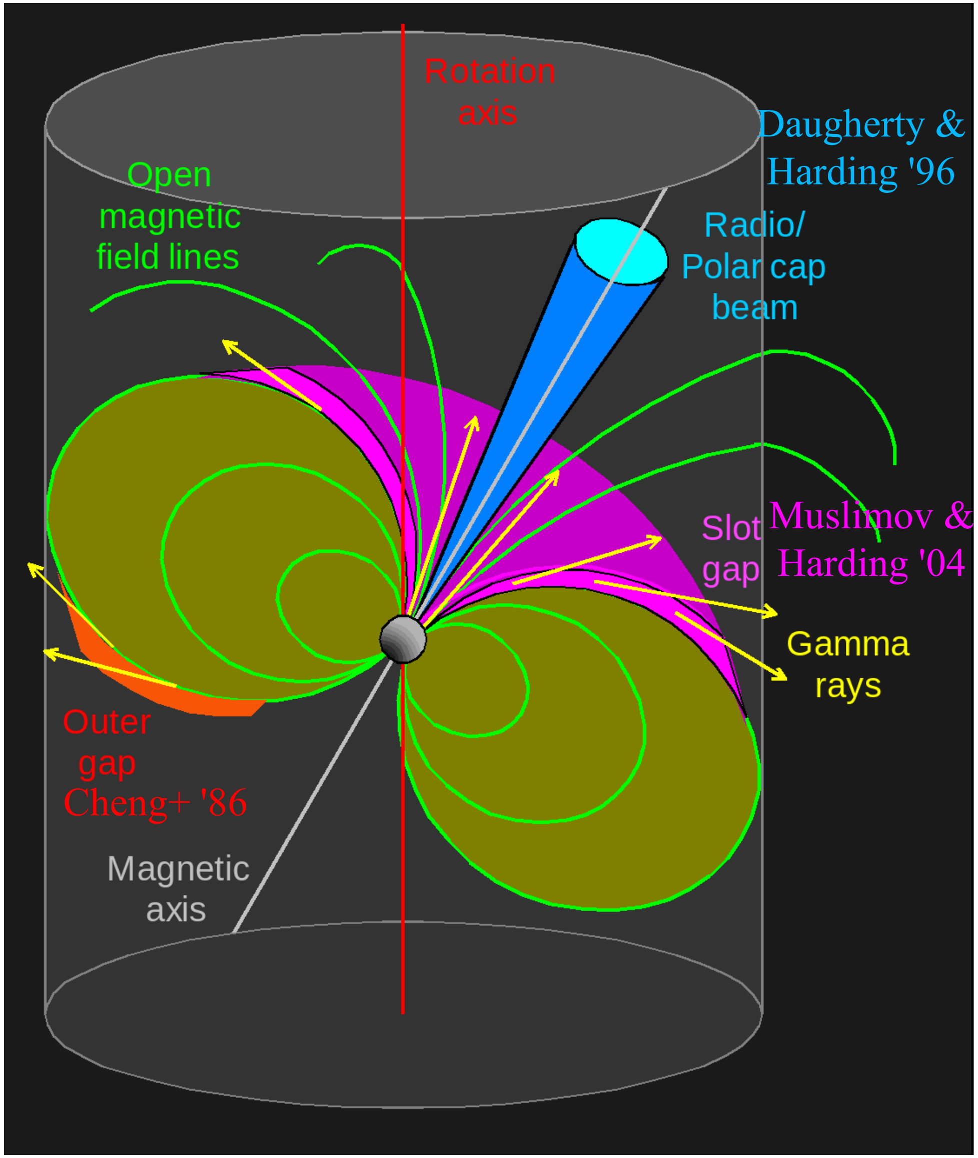
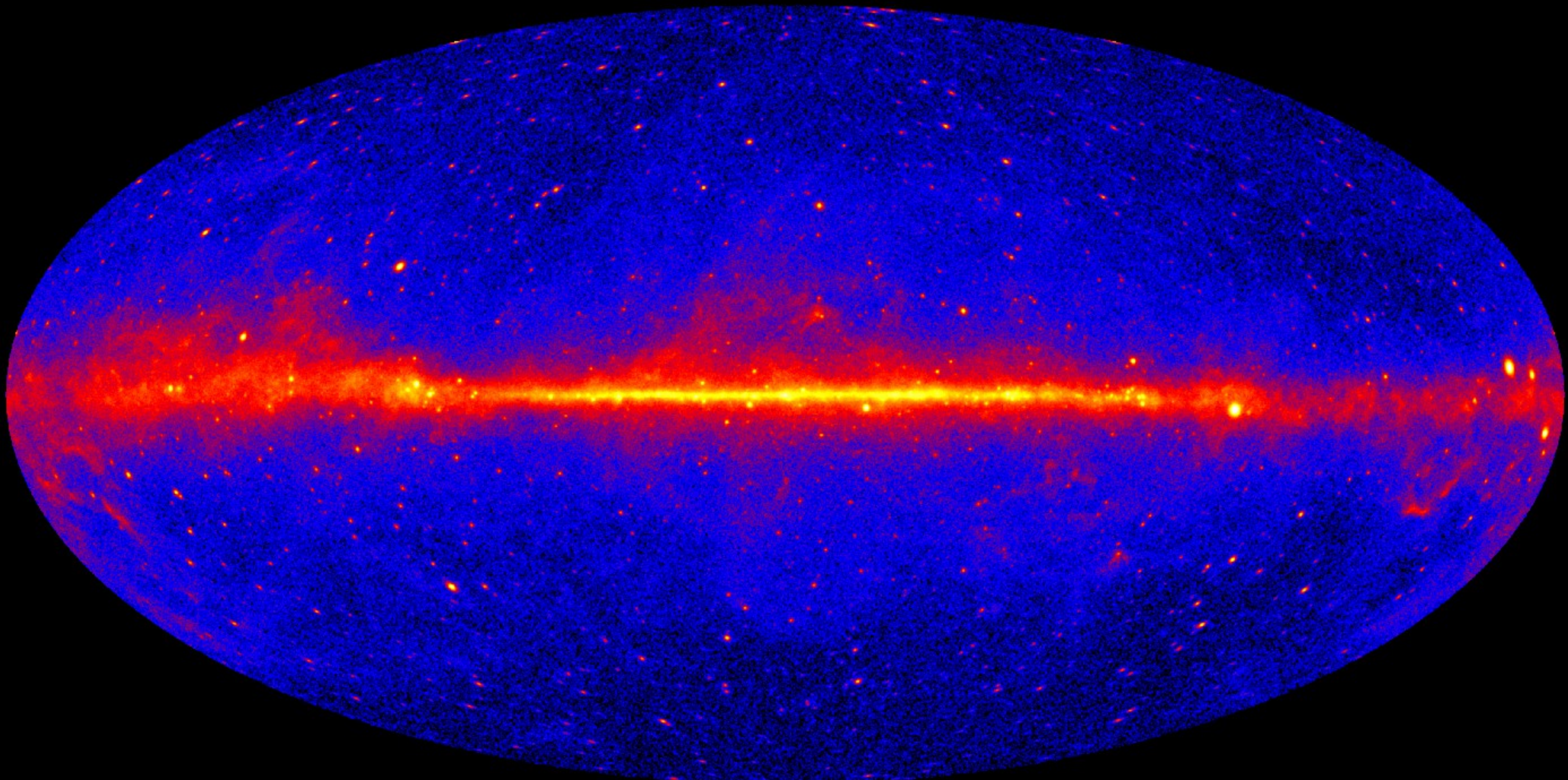


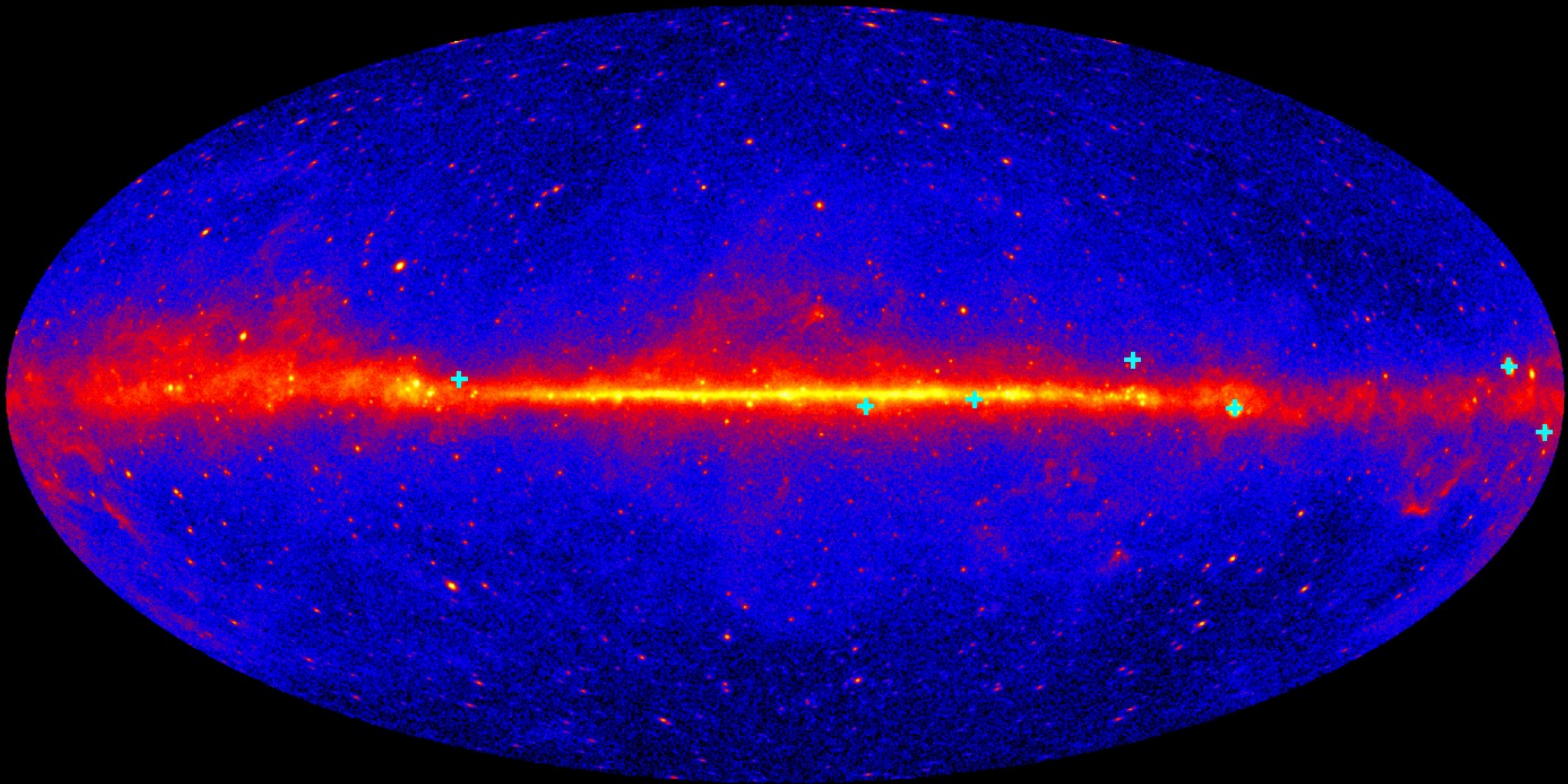
Figure Credit: Alice Harding

The LAT Sky



LAT-5 year sky map (front-converting events, ≥ 1 GeV)

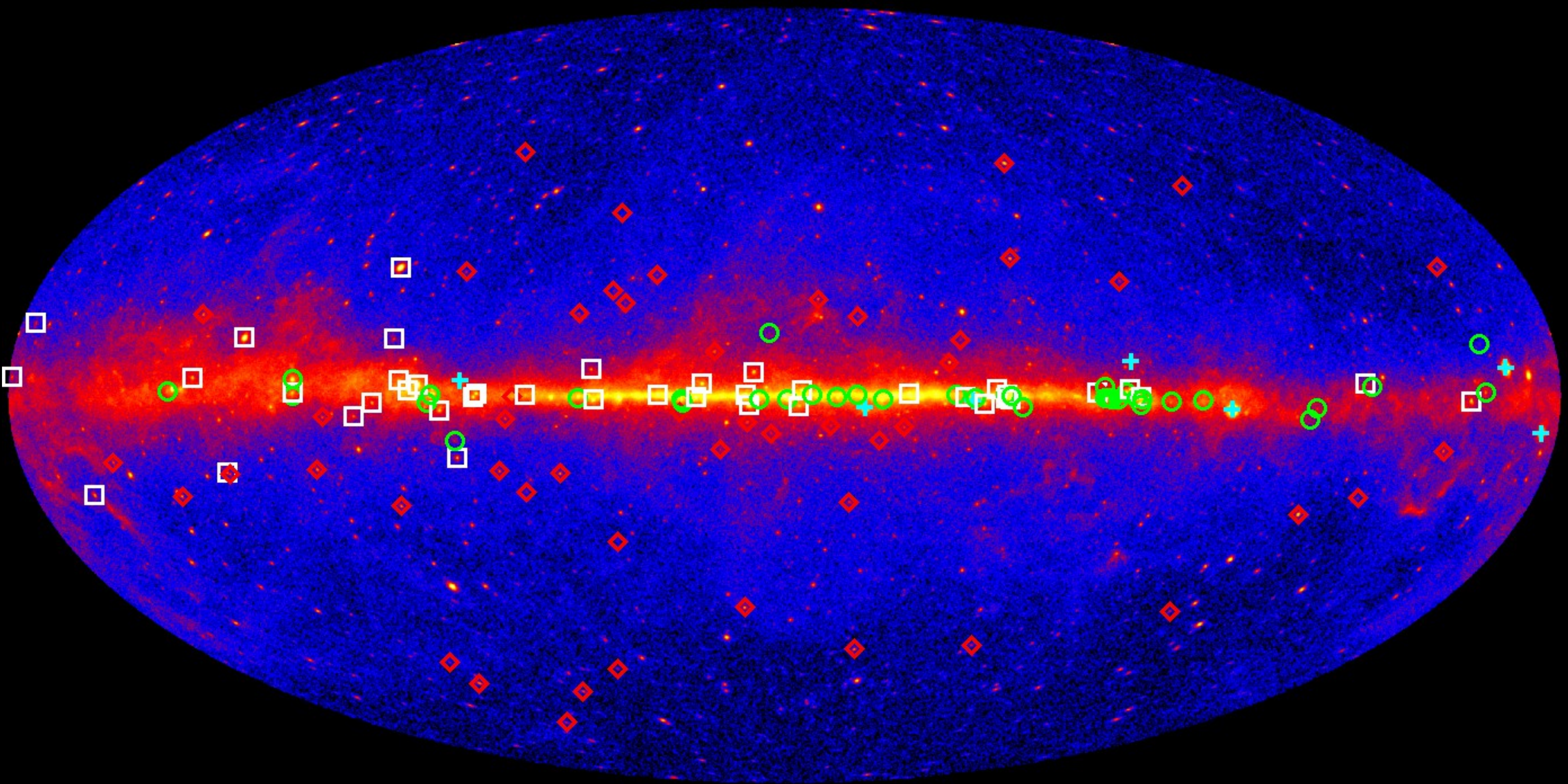
Before *Fermi*



LAT-5 year sky map (front-converting events, ≥ 1 GeV)

Compton Gamma-Ray Observatory pulsars (✚)

136 Gamma-ray Pulsars



LAT-5 year sky map (front-converting events, ≥ 1 GeV)

CGRO PSRs (✚), young radio-selected (○), young gamma-selected(□), and MSPs(◇)

For an up-to-date list see: http://tinyurl.com/fermipulsars

Current Pulsar Count

136 detected gamma-ray pulsars:

85 young, non-recycled pulsars:

42 radio-selected, 39 X/gamma-ray selected

4 new radio-quiet pulsars found using Einstein@Home (Pletsch+ '13)

51 millisecond (recycled) pulsars:

1 pulse period discovered first in gamma-rays (Pletsch+ '12)

1 mildly-recycled pulsar (PSR J0737-3039A; Guillemot+ '13)

2 globular cluster MSPs (Freire+ '11; Johnson+ '13)

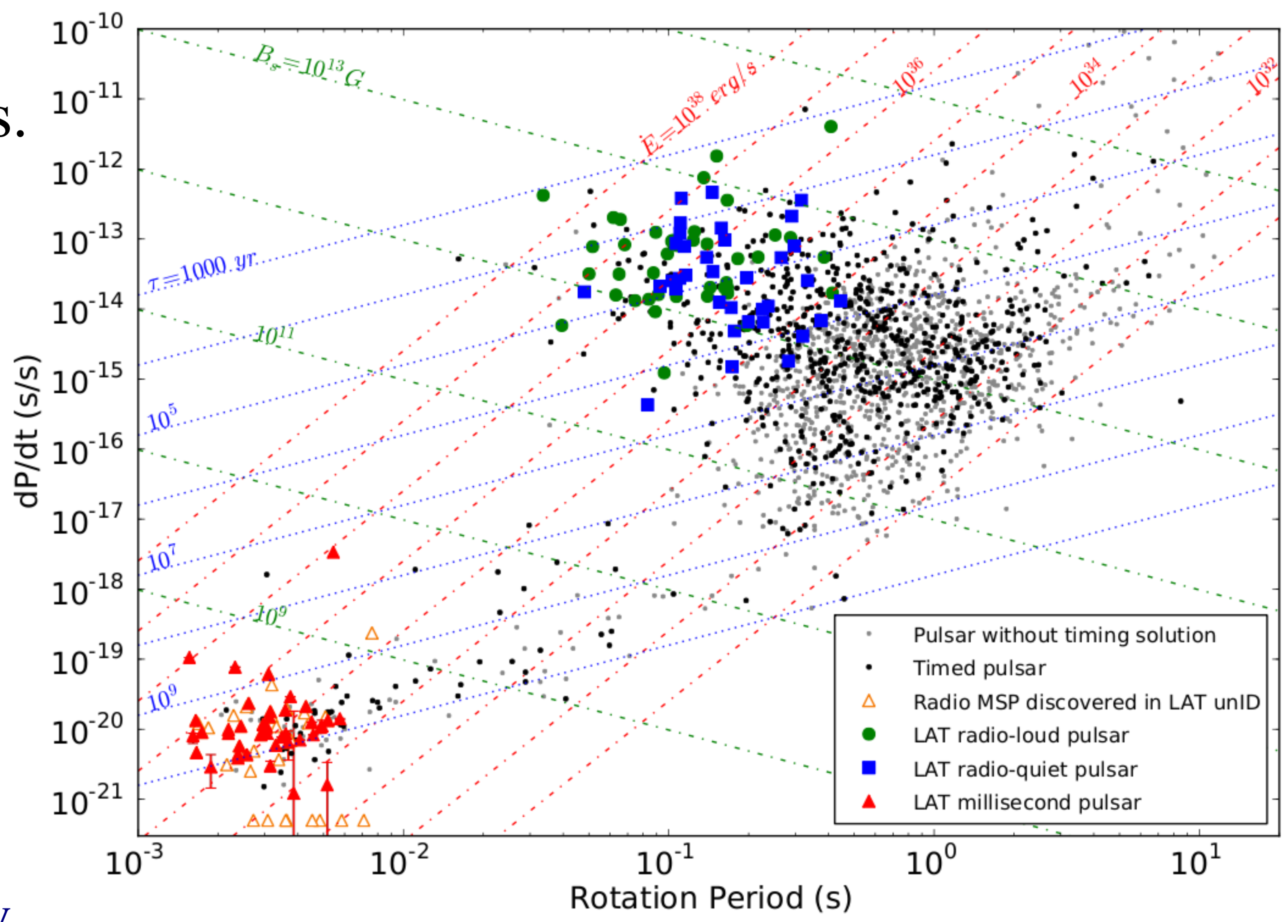
The 2nd LAT Pulsar Catalog

117 pulsars with significant (≥5σ) LAT pulsations in 3 years.

- Abdo+ '13
- 77 young pulsars:
  - (42 radio-loud)
  - (35 radio-quiet)
- 40 millisecond pulsars (MSPs)

Catalog (2PC) includes:

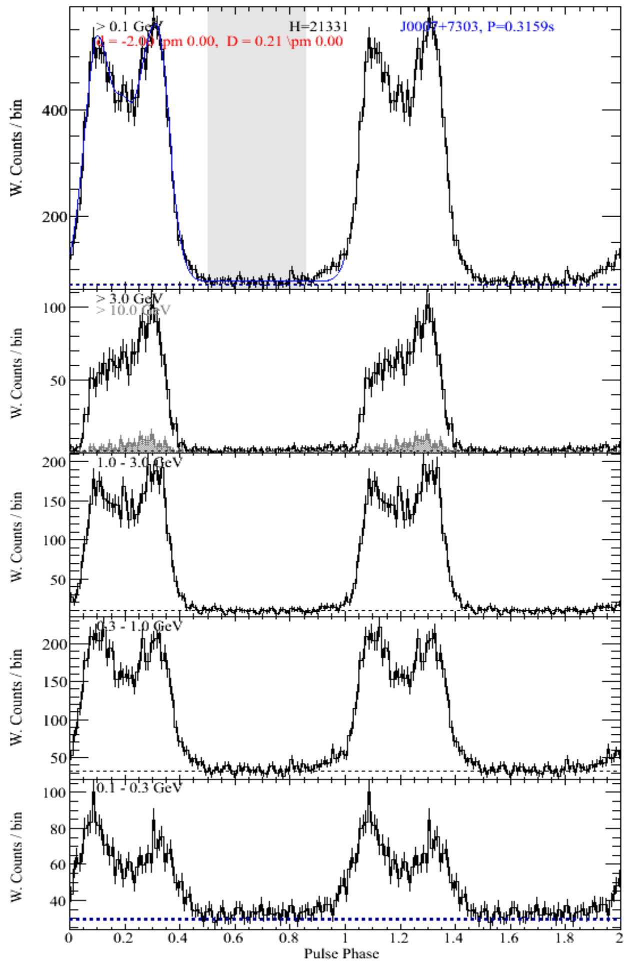
- Gamma-ray spectral and light curve characterizations,
- Radio flux density,
- X-ray and optical characteristics,
- Estimate of pulsar flux sensitivity over the sky.



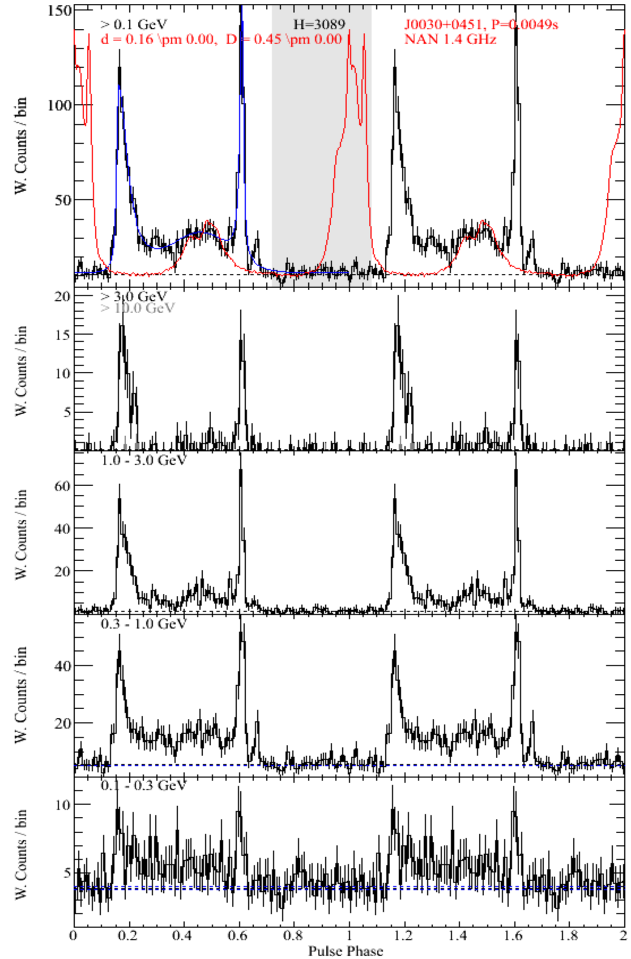
For data files, figures, and timing solutions, see: http://tinyurl.com/fermi2pc

LAT Pulsar Light Curves

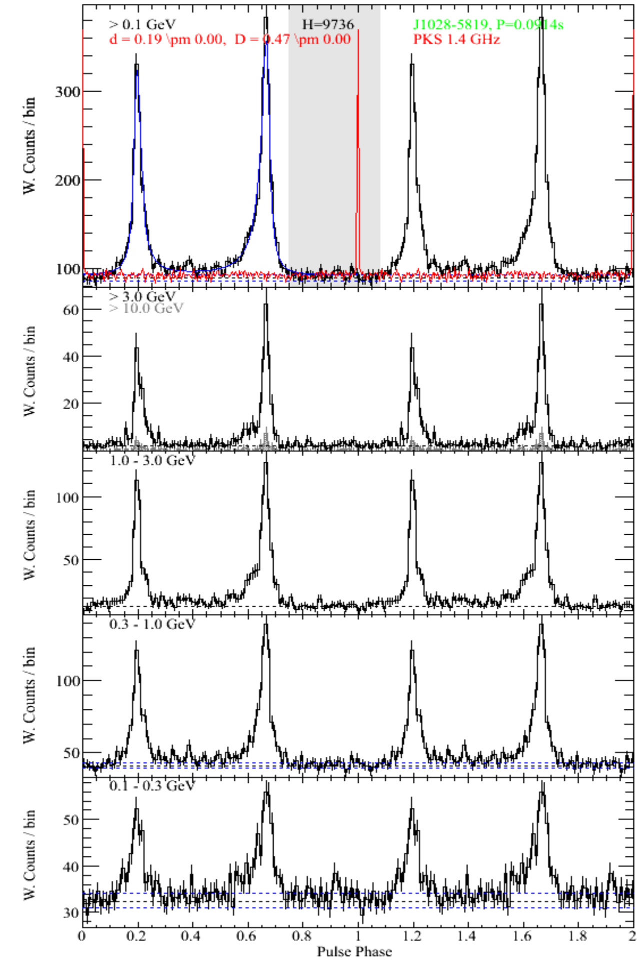
PSR J0007+7303



PSR J0030+0451



PSR J1028-5819



Large variety of pulsar light curves, if radio detected usually significant lag, except for Crab and growing class of MSPs (6 to date) with aligned radio and gamma-ray peaks.

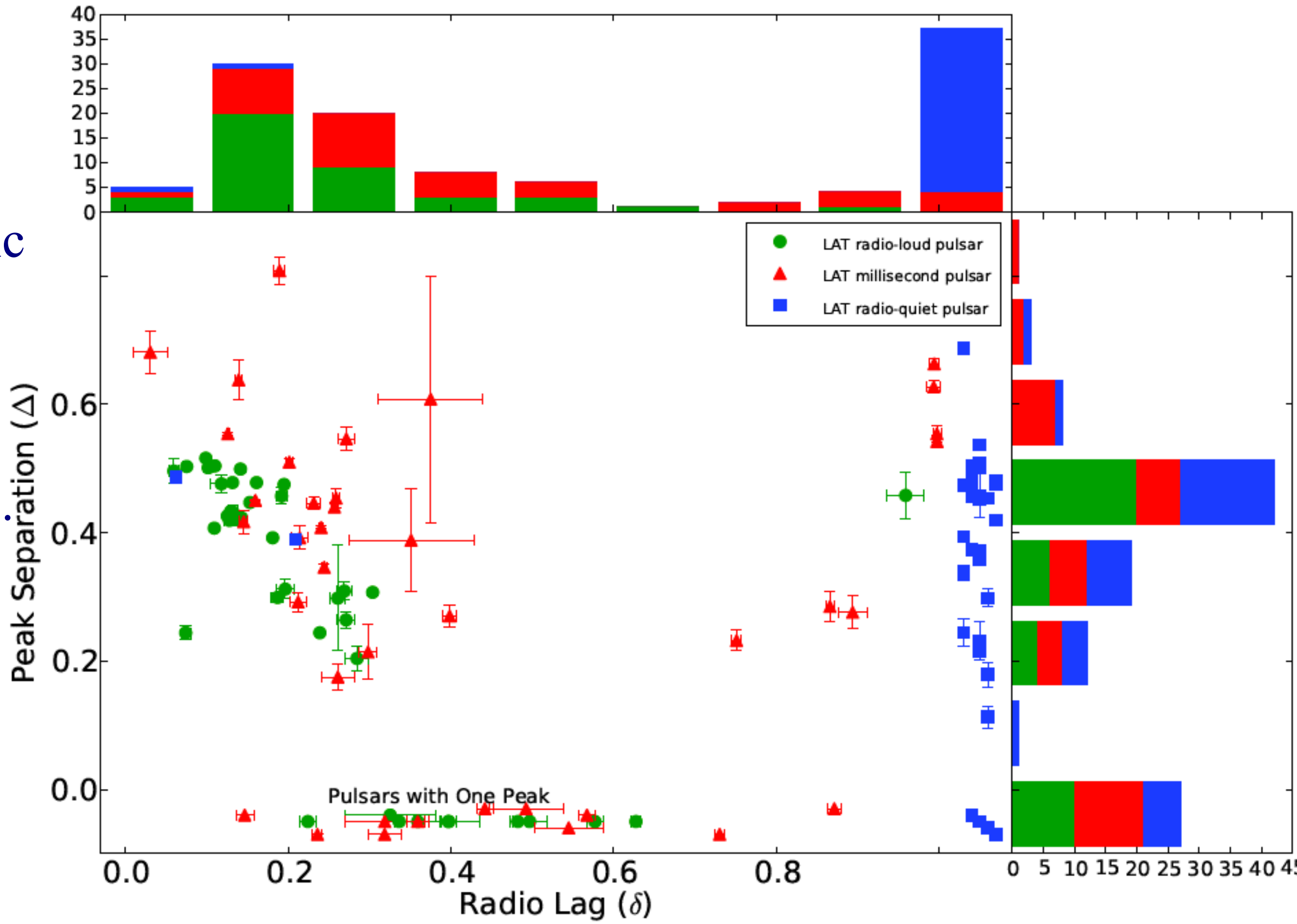
Peak Separation

Gamma-ray peak separation vs. radio lag.

- ≈phase difference between 1st gamma-ray peak and magnetic axis
- Important discriminant for emission models (e.g., Watters & Romani '11).
- More scatter for MSPs (smaller light cylinders).

Radio lag.

- Vacuum vs. charge-filled magnetosphere (e.g.; Kalapotharakos+ '12).

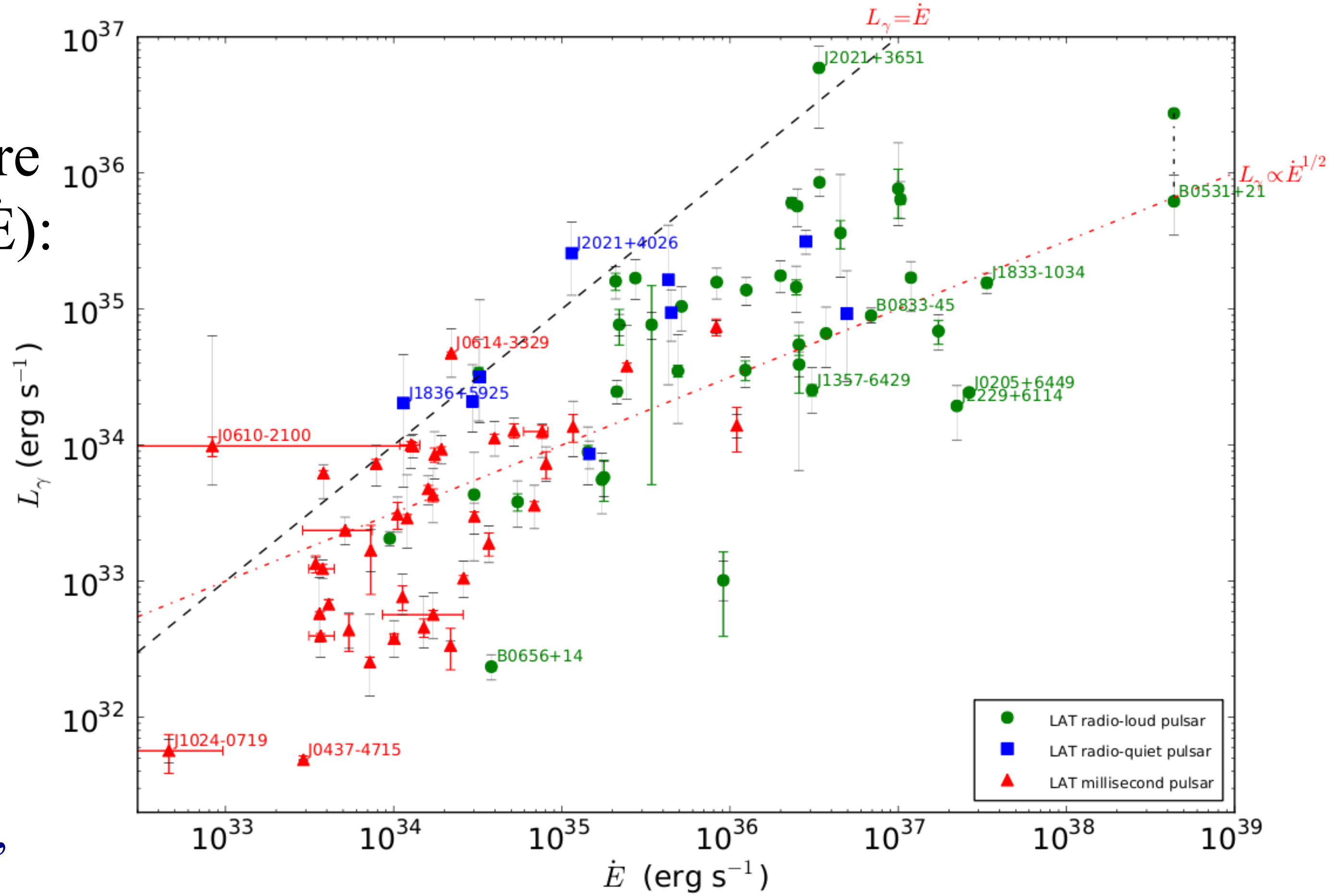


Gamma-ray Luminosity

$$L_\gamma = 4\pi d^2 f_\Omega G_{100} \propto V \propto \sqrt{\dot{E}}$$

Expect gamma-ray luminosity to scale as square root of spin-down power ($\dot{E}$):

- f_Ω a beaming factor (set to 1 for 2PC),
- d pulsar distance typically large uncertainty,
- G_{100} LAT energy flux,



Break needed at low $\dot{E}$:

- ~few × 10^{34} erg/s.
- Different model predictions, still unclear.

Multi-wavelength Properties

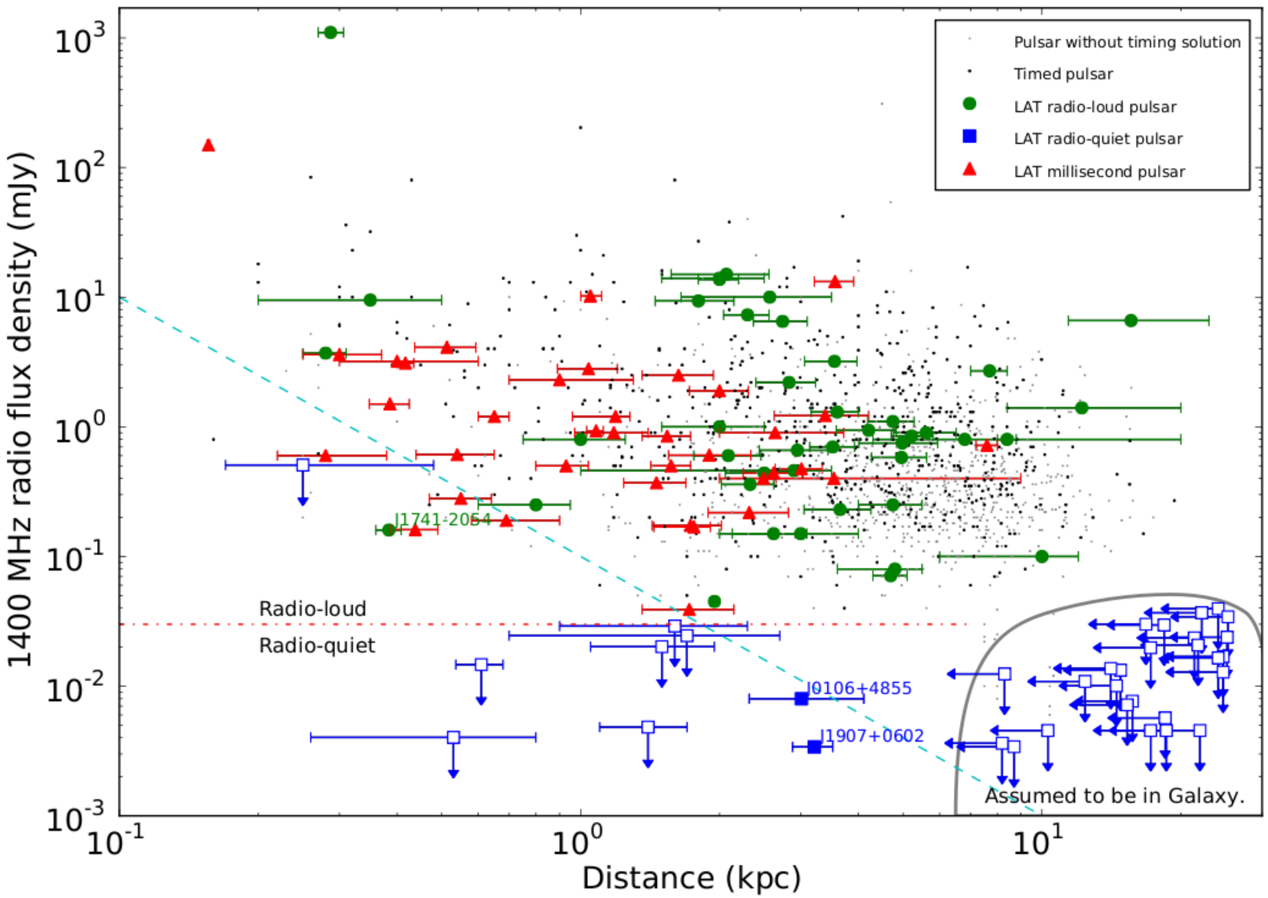
No correlations.

Faint gamma-ray pulsar can be bright radio pulsar.

Gamma-ray energy flux always greater than optical.

Young radio-quiet pulsars tend to have lower X-ray fluxes than radio-loud pulsars.

See also Marelli '12.



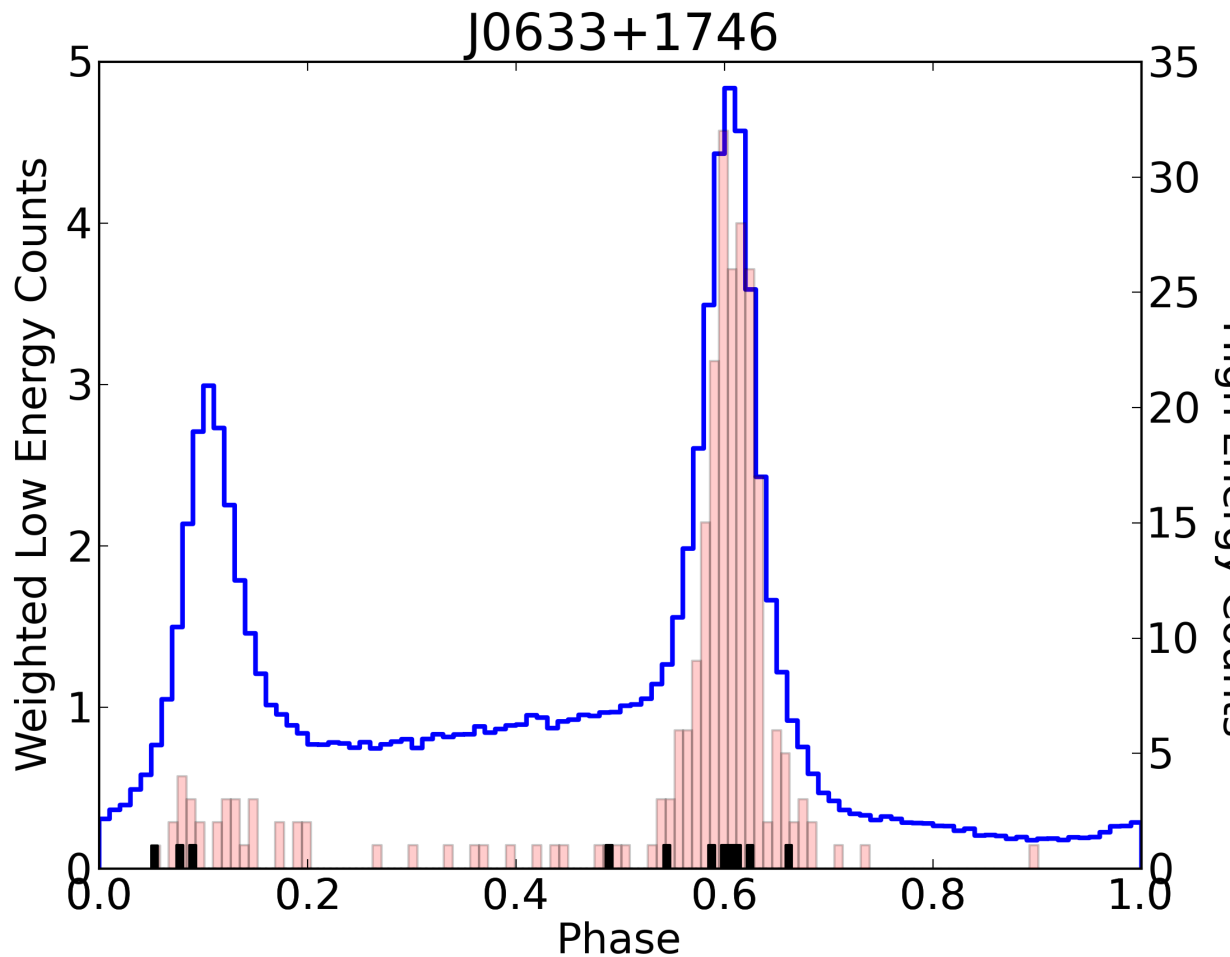
Pulsars above 10 GeV

Detection of pulsations from the Crab above 100 GeV (e.g.; Aliu+ '11).

- Can't be curvature radiation, additional or different mechanism (e.g., Lyutikov '12).

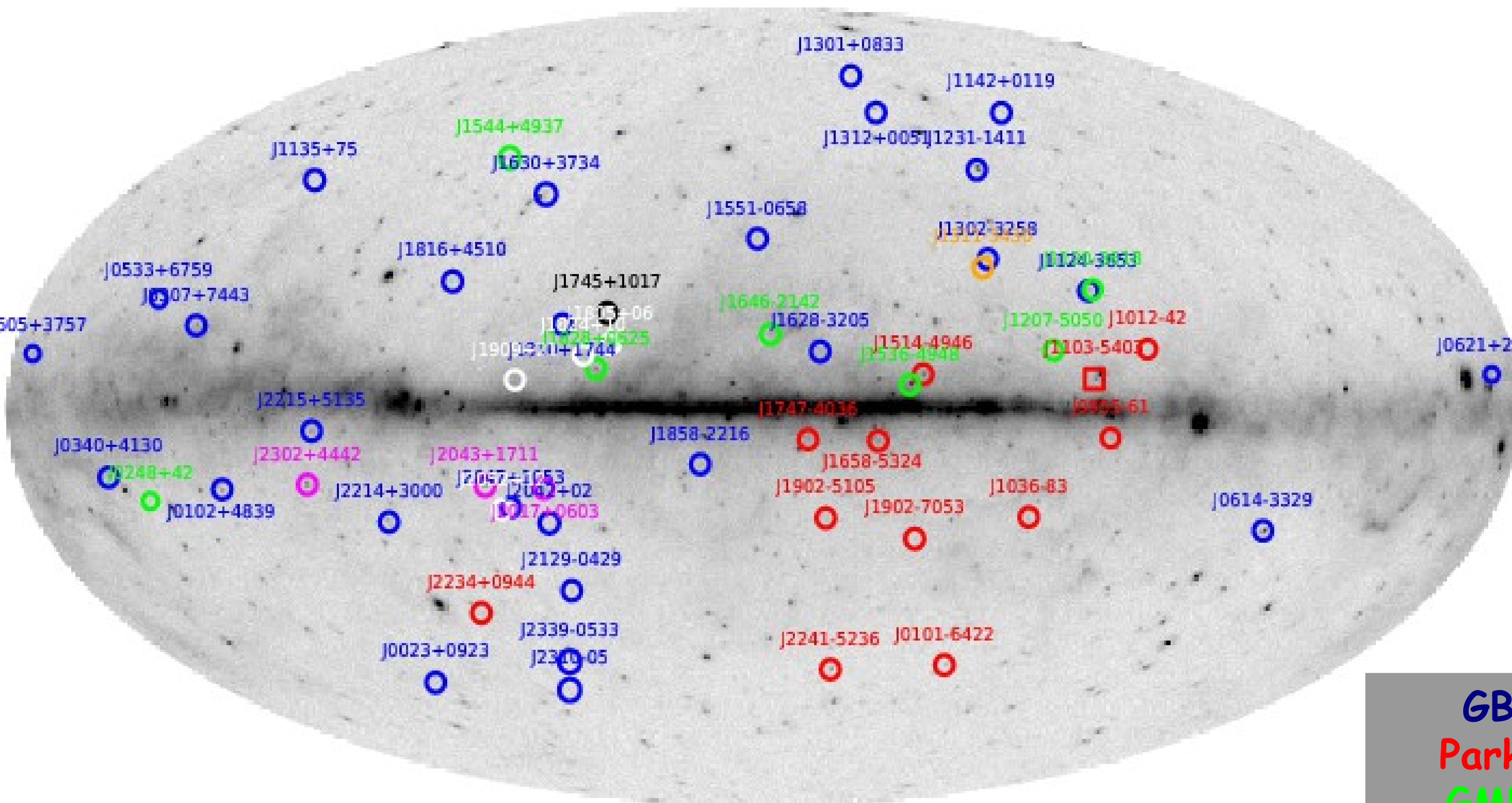
First *Fermi* LAT catalog of ≥10 GeV sources (1 FHL, 3 years, Ackermann+ '13).

- 28 pulsars pulsing above 10 GeV.
- 13 above 25 GeV.
- Spectral characterization limited by statistics.
- Ongoing investigation.



Blue: ≥ 100 MeV
Pink: ≥ 10 GeV
Black: ≥ 25 GeV

An MSP Treasure Map



GBT
Parkes
GMRT
Nancay
Effelsberg
Arecibo
LAT

An MSP Treasure Map

Radio observations of LAT unassociated (with pulsar-like characteristics) sources have led to the discovery of >55 new MSPs (e.g., Ray+ '12).

- LAT error circles comparable to radio beam sizes, know where to look, stare longer.
- Gamma-ray pulsations from more than 20.
- ~20 waiting for better timing solutions, a few chance coincidences.

One blind search gamma-ray MSP (Pletsch+ '12).

- But not radio-quiet (Ray+ '13).

~15 new black widow and redback systems (Roberts '13).

- Proves these are not primarily restricted to globular clusters (as suggested by King+ '03).

No radio-to-gamma-ray flux correlation, several bright radio MSPs

- ~15-20% of the new MSPs have been added to pulsar timing arrays (PTAs) to detect gravitational waves (see parallel session tomorrow 11:00 am – 12:30 pm).

Conclusions

Observations with the *Fermi* LAT have revolutionized gamma-ray pulsar science.

- Number of known gamma-ray pulsars increased by a factor of almost 20.
- Clearly established outer magnetosphere as dominant source of gamma rays.

Helped increase the population of Galactic field MSPs by ~50%.

- Targeted searches, no radio-to-gamma-ray flux correlation.
- Population of field black widows and redbacks (potentially more ~2$M_\odot$ neutron stars).
- Have added to PTAs, fraction of eclipsing systems limits this somewhat.

Future:

- More candidates for several tens of GeV pulsations.
- Pushing down on the "gamma-ray death line".
- Polar cap gamma-ray contribution?

References & Acknowledgments

Abdo, A. A., et al. 2013, ApJS, 208, 17
Ackermann, A. et al. 2013, ApJS, 209, 34
Aliu, E. et al. 2011, *Science*, 334, 69
Atwood, W. B., et al. 2009, ApJ, 697, 1071
Cheng, K. S., et al. 1986, ApJ, 300, 500
Daugherty, J. K. & Harding A. K. 1996, ApJ, 458, 278
Freire, P. C. C., et al. 2011, *Science*, 334, 1107
Guillemot, L., et al. 2013, ApJ, 768, 169
Johnson, T. J., et al. 2013, ApJ, 778, 106
Kalapotharakos, C., et al. 2012, ApJ, 754, L1
Lyutikov, M. 2012, ApJ, 757, 88
Marelli, M. 2012, PhD thesis, Univ. Insubria (arXiv:1205.1748)
Meegan, C., et al. 2009, ApJ, 702, 791
Muslimov, A. G. & Harding, A. K. 2004, ApJ, 606, 1143
Pletsch, H. J., et al. 2012, *Science*, 338, 1314
Pletsch, H. J., et al. 2013, ApJL, *accepted* (arXiv:1311.6427)
Ray, P. S., et al. 2012, Proc. of the 3rd *Fermi* Symposium (arXiv:1205.3089)
Ray, P. S., et al. 2013, ApJ, 763, L13
Roberts, M. S. E 2013, IAU Proc., 291, 127
Watters, K. P. & Romani, R. W. 2011, ApJ, 723, 123

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