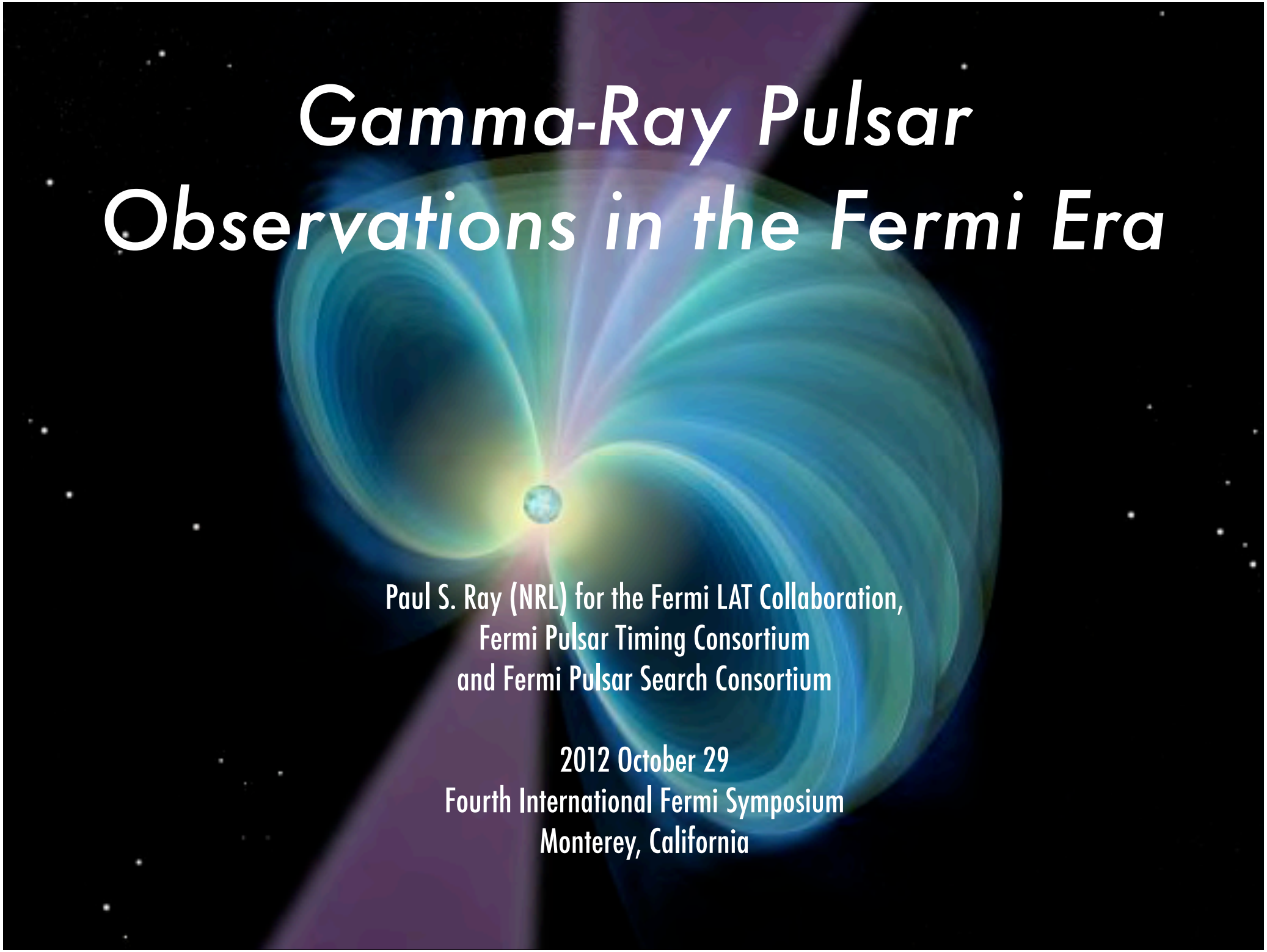


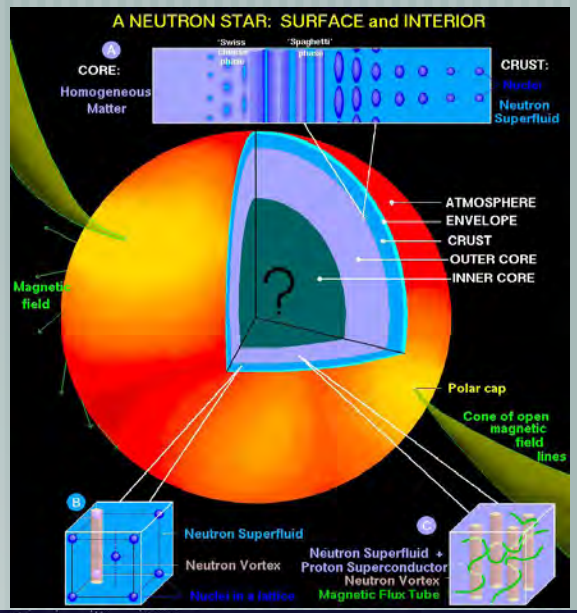
Gamma-Ray Pulsar Observations in the Fermi Era

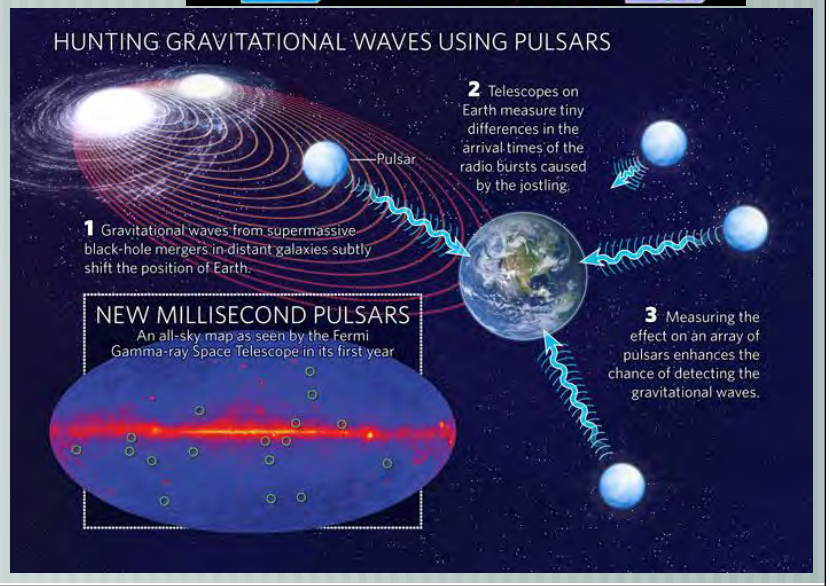
Paul S. Ray (NRL) for the Fermi LAT Collaboration,
Fermi Pulsar Timing Consortium
and Fermi Pulsar Search Consortium

2012 October 29
Fourth International Fermi Symposium
Monterey, California

Pulsars: Probes of Extreme Physics

- Extreme Densities
  - The cores of neutron stars reach super-nuclear densities, where the equation of state is unknown
- Extreme Gravitation
  - Binary pulsars probe many predictions of General Relativity to high precision
  - Pulsar timing arrays should be able to directly detect nHz gravitational waves
- Extreme Magnetism
  - Magnetospheres are central to most pulsar phenomenology
  - Some pulsars have B fields above the quantum critical field ($B \sim 10^{14}$ Gauss in "magnetars")
- Extreme acceleration
  - Acceleration, pair creation, and gamma-ray emission in the magnetosphere
  - Shocks in pulsar winds accelerate particles to >TeV energies
  - Potential sources of cosmic-ray electrons



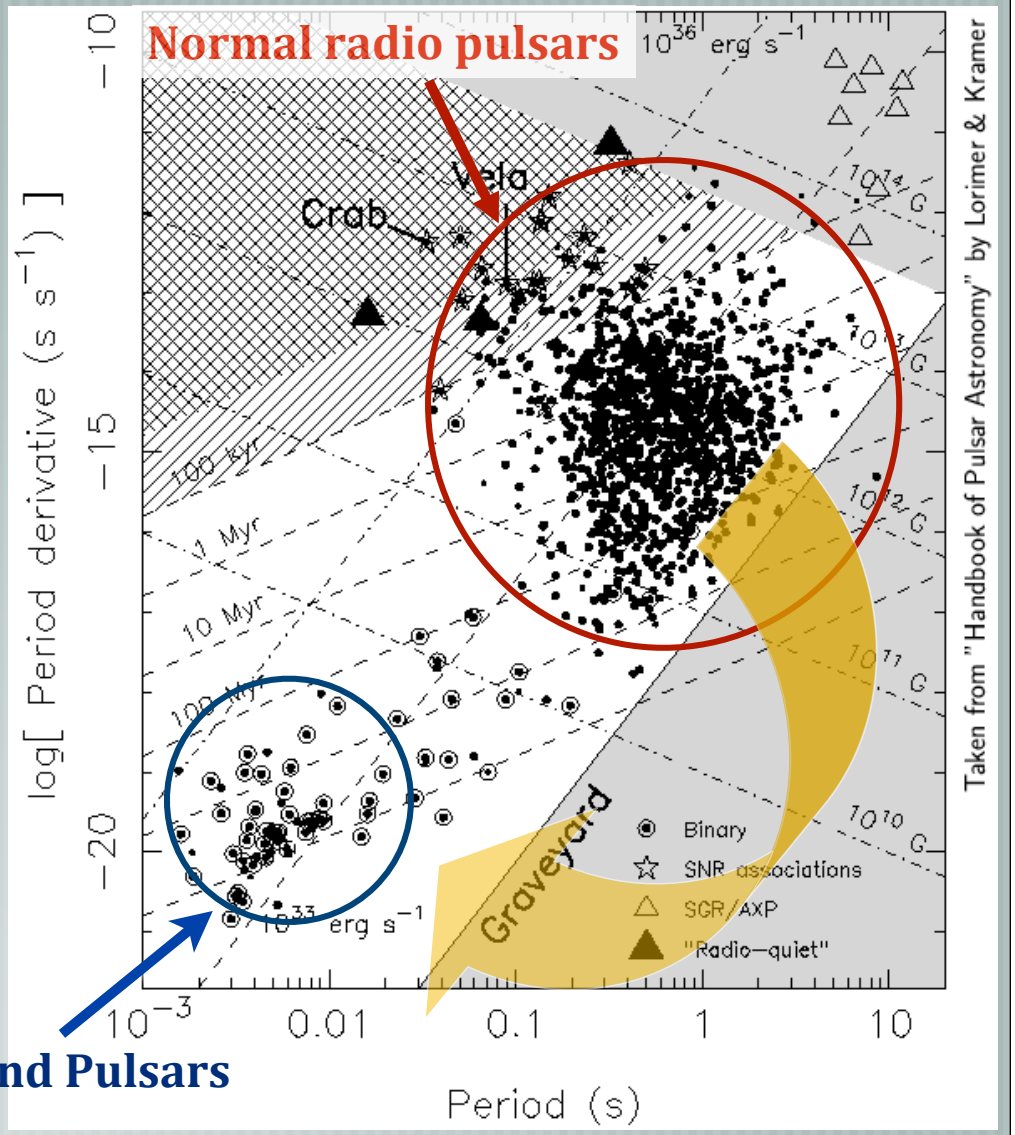


Period and Slowdown

- Rotational energy loss :

$$\dot{E} = 4\pi^2 I \frac{\dot{P}}{P^3}$$

  - I : moment of inertia ~ 10^{45} g cm^2
  - P : rotation period
- 2 classes :
  - Normal Pulsars
  - Millisecond ("Recycled") Pulsars



The Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope

Important Features for Pulsars

- Large area: 8000 cm^2 area (at 1 GeV)
- Broad band: 20 MeV to >300 GeV
- Good localization: 0.6–0.8 deg radius PSF (1 GeV)
- Continuous sky survey mode of operation with wide FOV

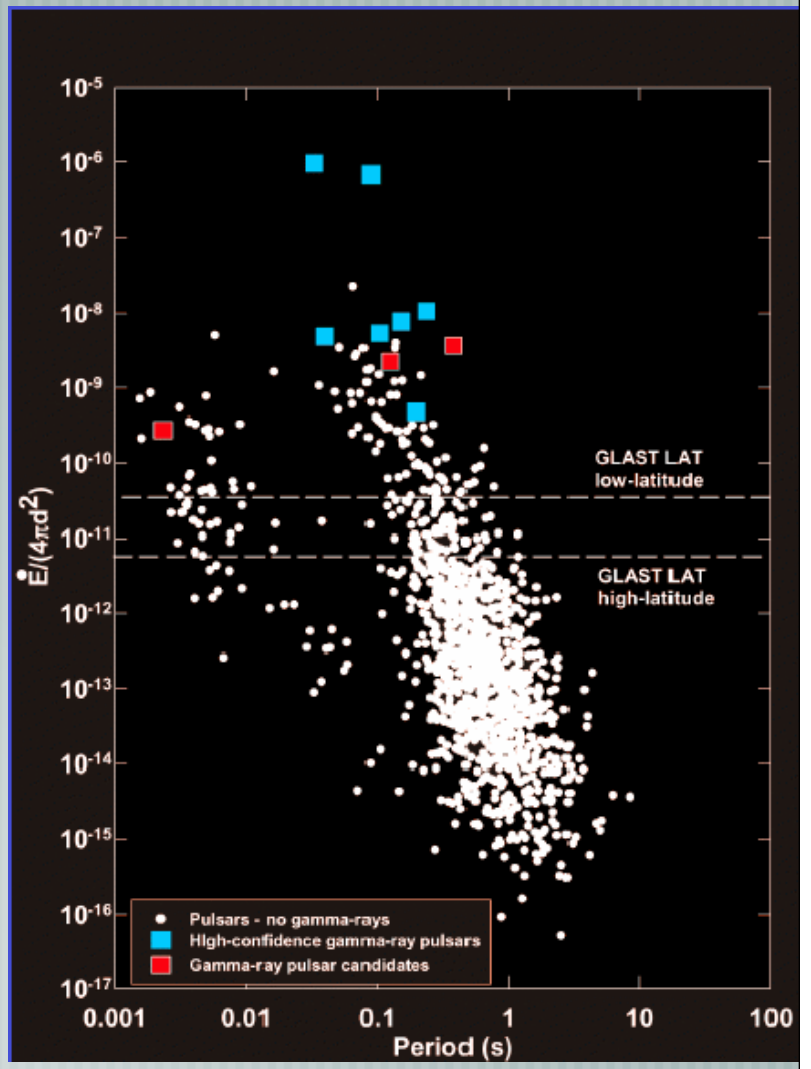
(Atwood et al. 2009, ApJ, 697, 1071)

Previous Observations of Gamma-ray Pulsars

7 detected pulsars (+ 3 candidates) with the Compton Gamma-Ray Observatory

CGRO (with EGRET, COMPTEL, OSSE, BATSE) (1991 – 2000)

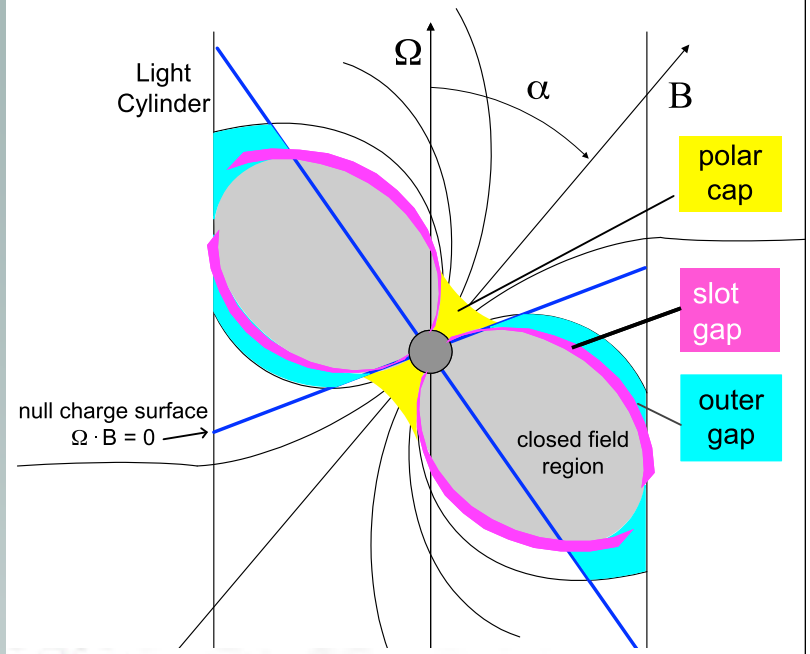
More recently... AGILE (2007 -)

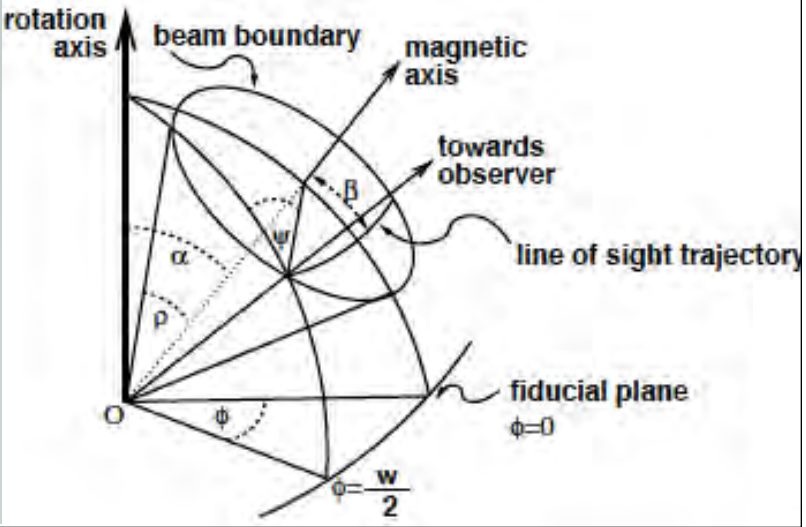


Pulsar Gamma-Ray Emission

- Very significant portion of the energy budget (~10% or more)
  - Visible from many radio-quiet pulsars
- Theoretical models try to explain the observed gamma-ray emission as coming from different regions of the magnetosphere and with different magnetosphere configurations
- Different emission patterns are expected (number of peaks, separation, radio/gamma lag, ratio of radio-loud/radio-quiet) for each model and geometry
- **Gamma-ray observations can help disentangle the geometry of pulsar magnetospheres and emission regions**
  - Need many examples to probe different conditions
  - Extra power when combined with radio polarization

See upcoming talks by Timokhin and Kerr



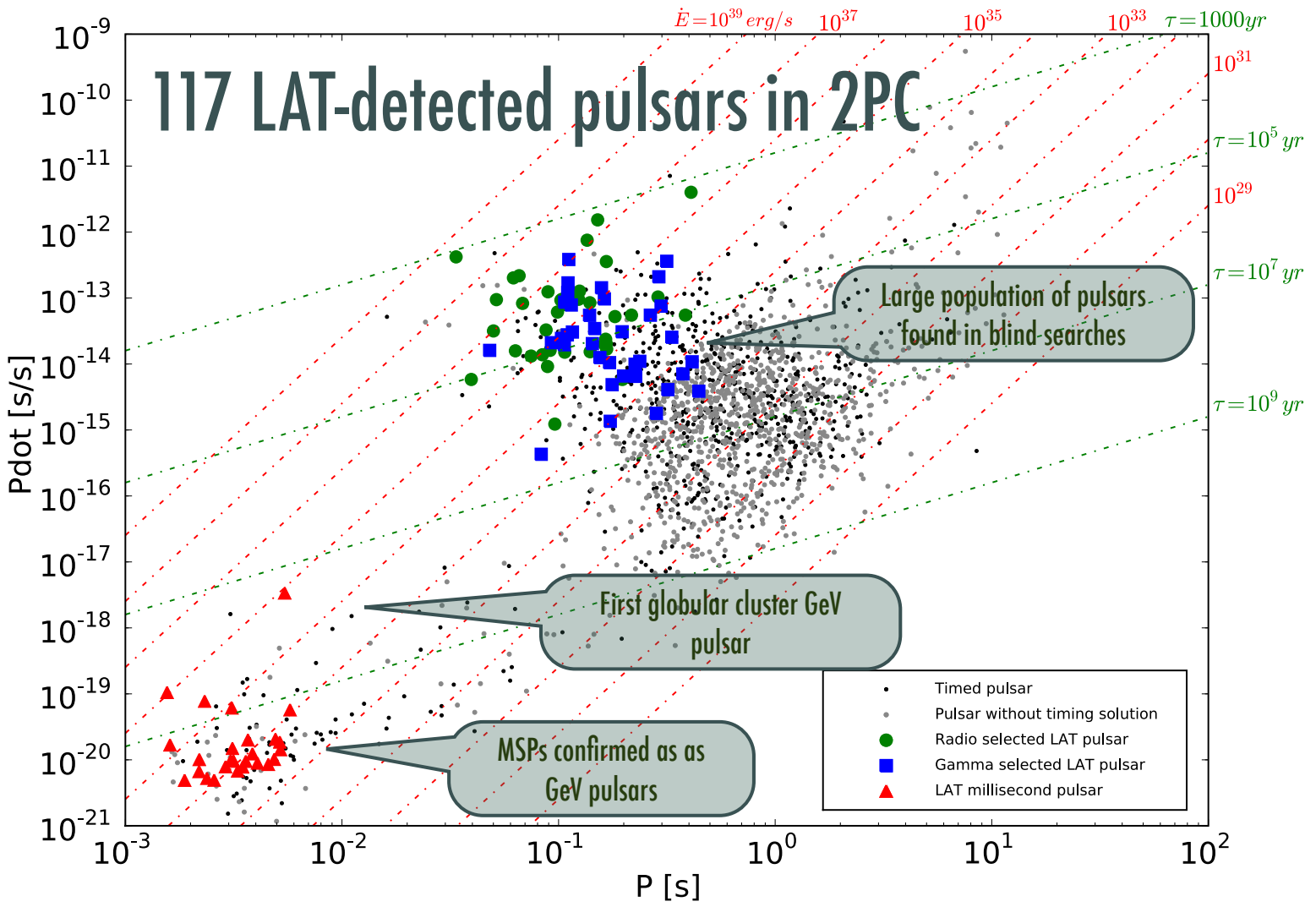


Three+ Ways to Detect Pulsars with the LAT

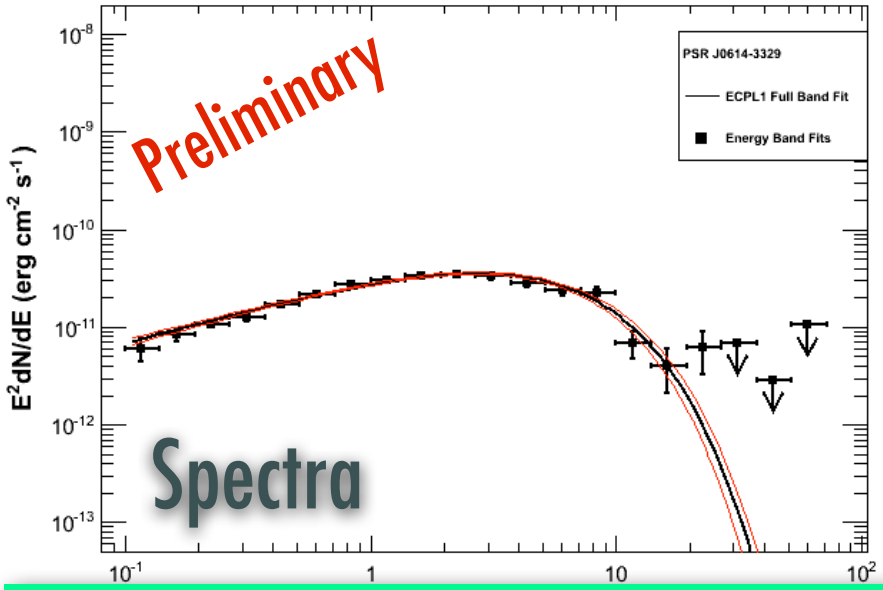
- Folding gamma-ray photons according to a known pulsar timing model, from radio or X-rays
  - All 6 EGRET pulsars were detected this way (but Geminga, Crab and Vela **could** have been discovered in blind searches; Ziegler 2008, Chandler et al. 2001)
- Blind searches for pulsations directly in the gamma-ray data
  - Spectacularly successful for young pulsars
  - **Really** hard for MSPs! See upcoming talk by Pletsch!
- Radio pulsar searches of LAT unidentified sources
  - Sensitivity to MSPs, binaries, very noisy pulsars

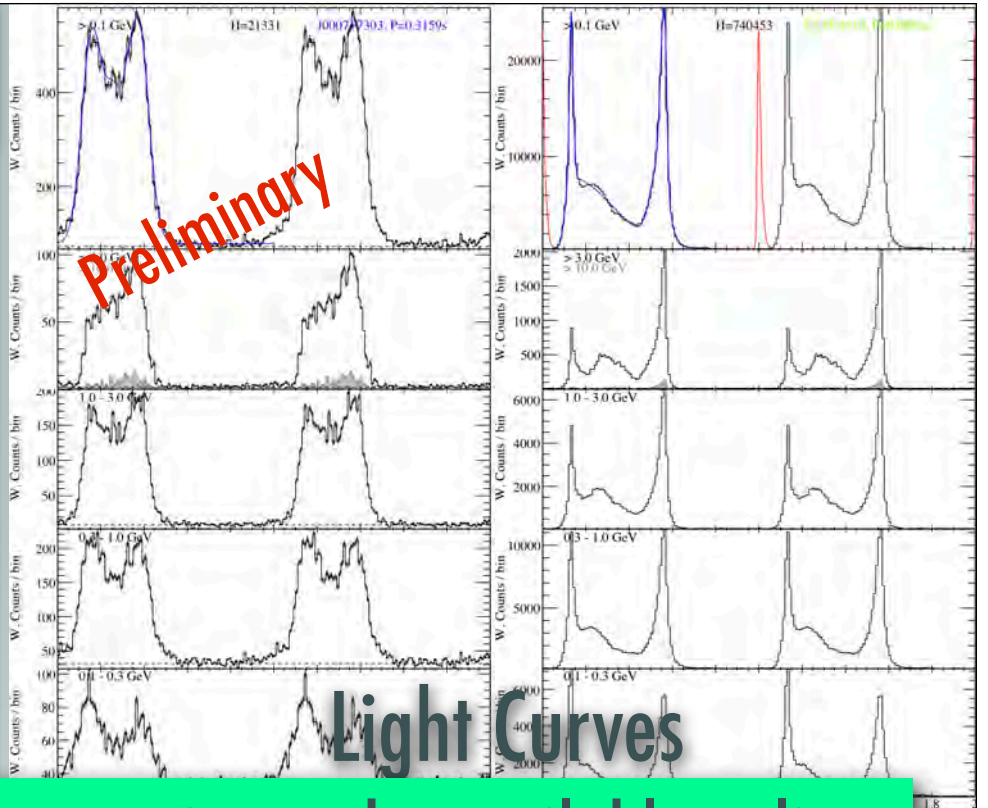
\+ **New**: Optical studies of LAT source locations to find binary pulsar counterparts
  - Still need a blind frequency search to detect pulsations

LAT Pulsar Population Explosion

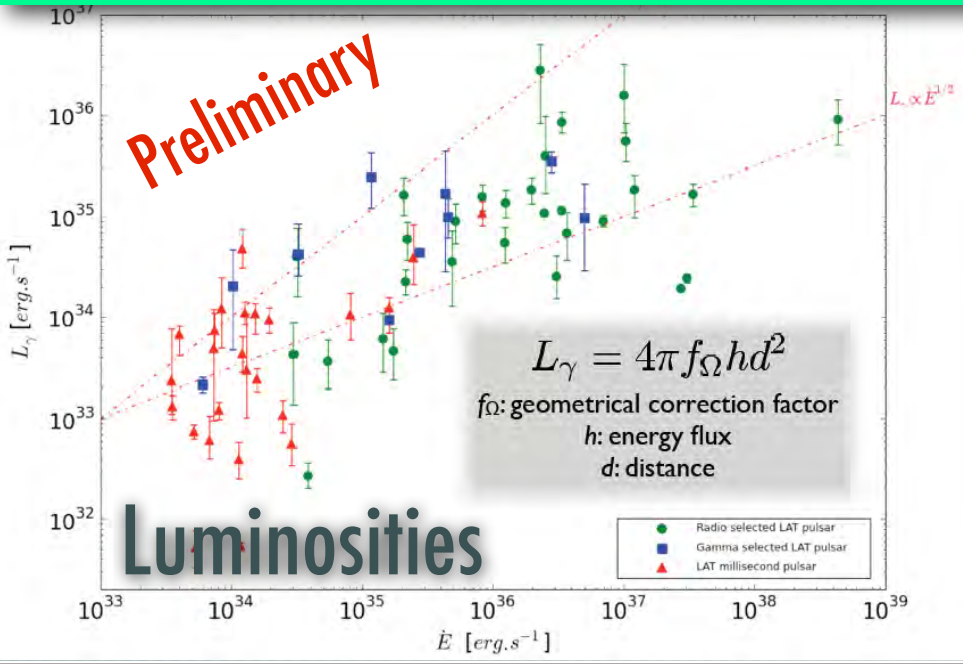


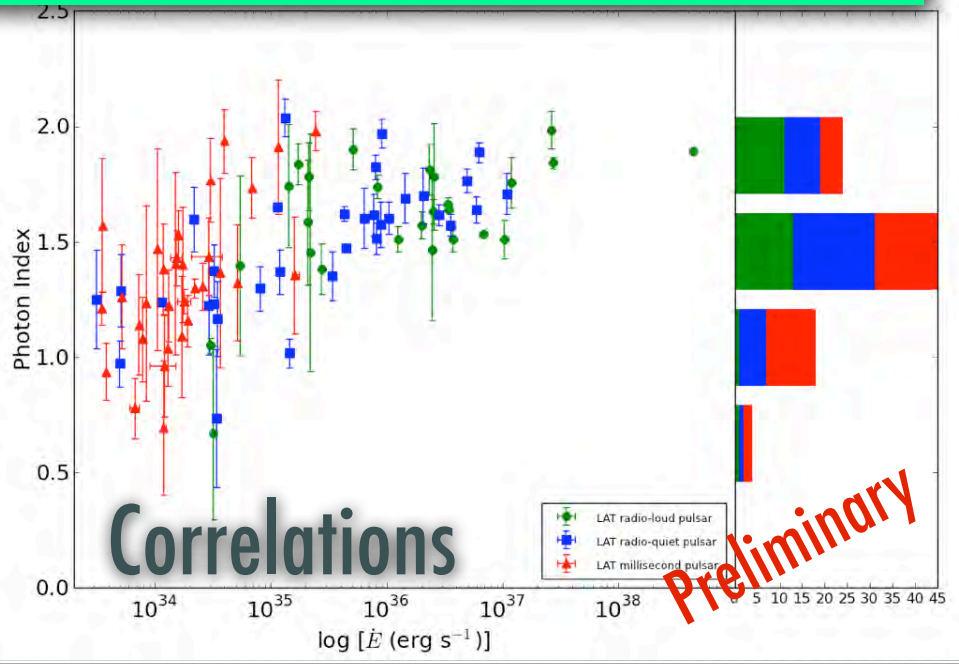
Fermi Second Pulsar Catalog (2PC)



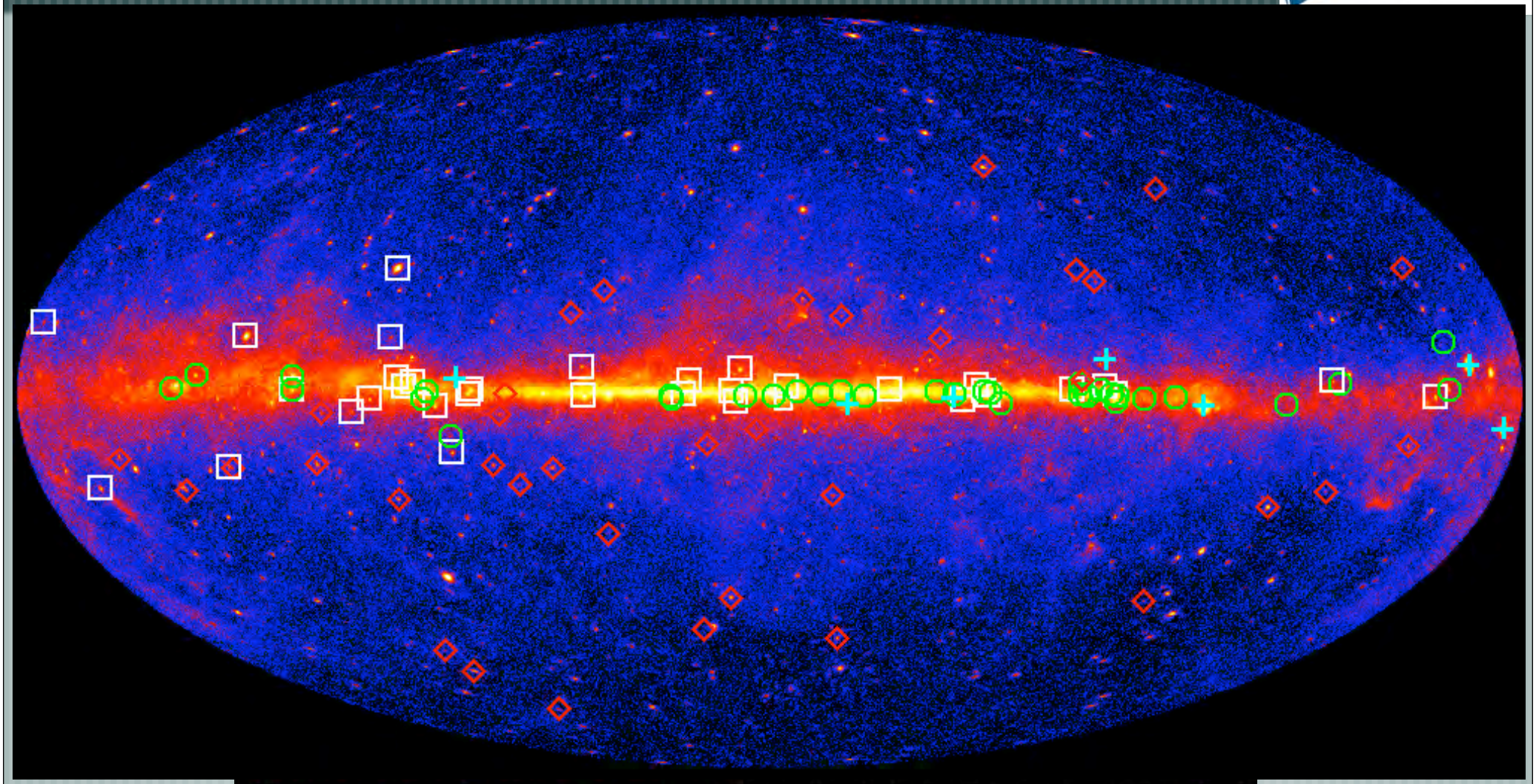


All data, including spectral and light curve points to be available online



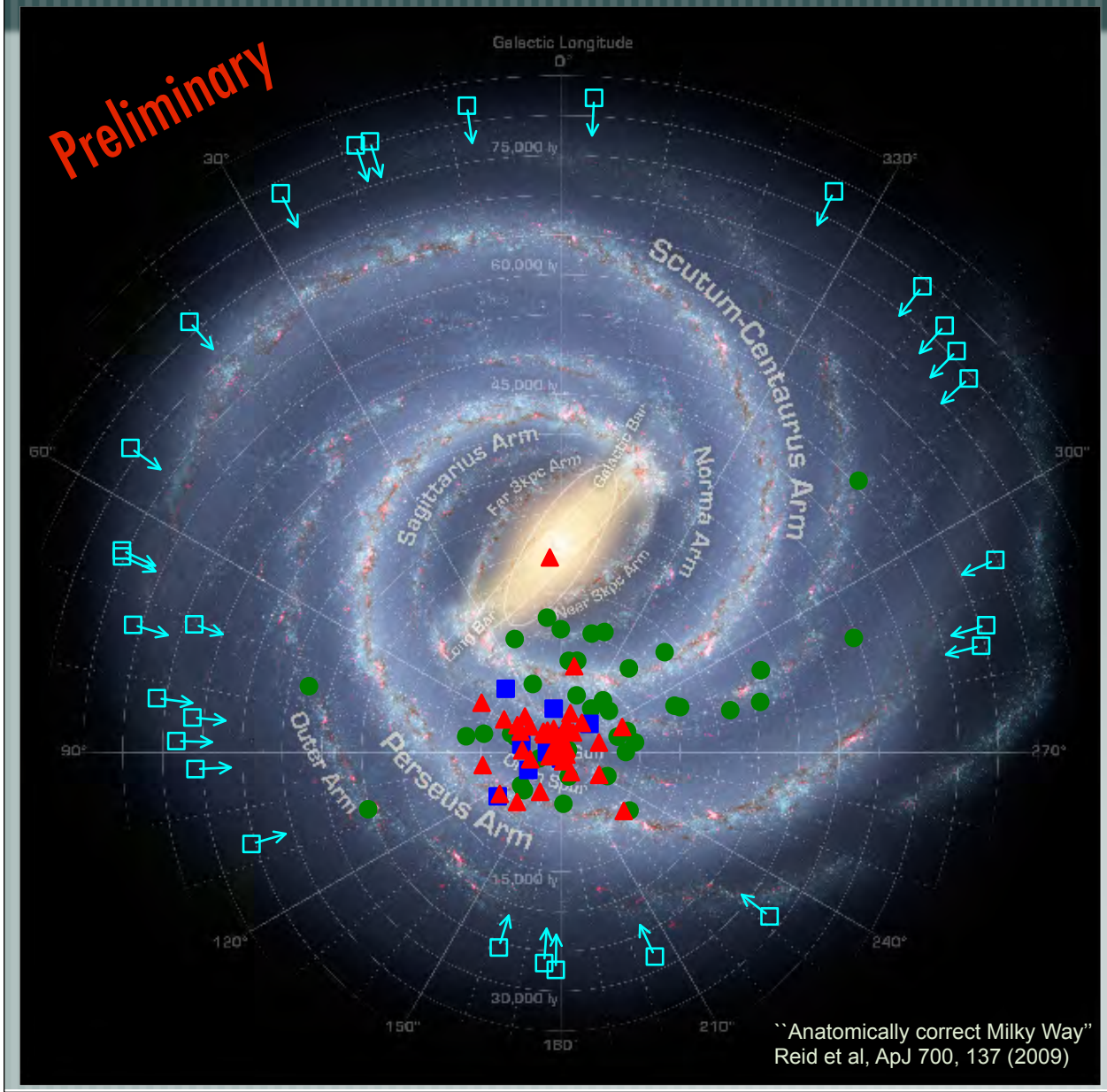


117 Gamma-Ray Pulsars



Shown above are the gamma-ray pulsars detected with the LAT superimposed on the 3 year, front-converting, ≥ 1 GeV sky map: CGRO PSRs(✚), young radio-selected (○), young gamma-selected(□), and MSPs(◇).

Distances



``Anatomically correct Milky Way''
Reid et al, ApJ 700, 137 (2009)

Major effort to evaluate best distances for each pulsar and include Shklovskii effect on measured parameters

Beyond 2PC

- Currently up to 121 publicly-announced detected pulsars

Current list available at:
https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

- Where are the new discoveries coming from?
  - Follow up timing of PSC MSPs
  - New blind search pulsars
  - Faint radio pulsars finally crossing the 5-sigma threshold
  - Multiwavelength studies of LAT unassociated sources

Folding With Known Ephemerides

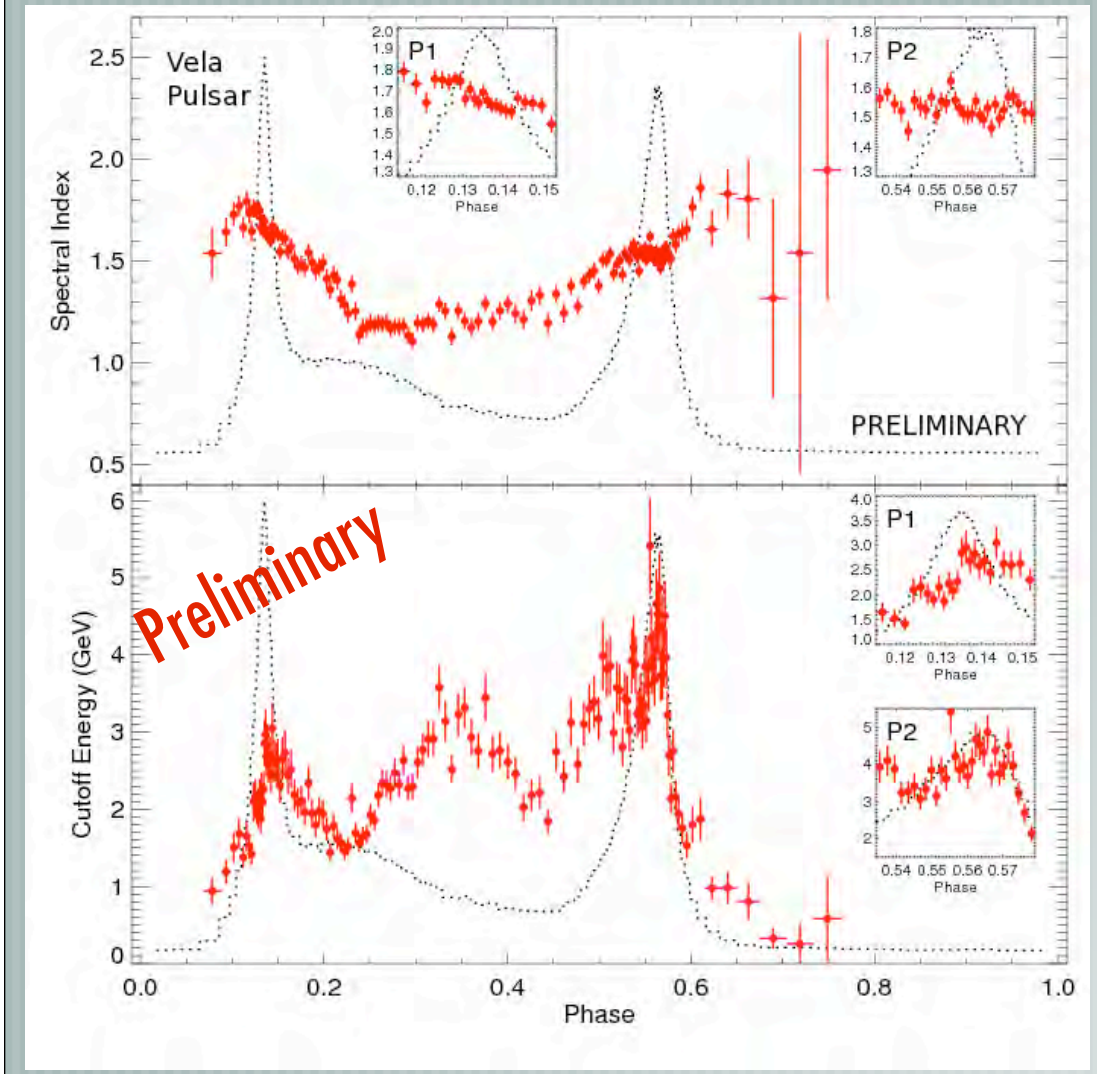




- Large campaign organized to provide radio (and X-ray) timing models for all (~200) pulsars with $\dot{E} > 1 \times 10^{34}$ erg/s (Smith et al. 2008 A&A, 492, 923)
  - Thanks to all members of the Pulsar Timing Consortium!
- Folded LAT photons for 762 pulsars

See talk by R. Shannon in pulsar session

Bright gamma-ray pulsars with Fermi



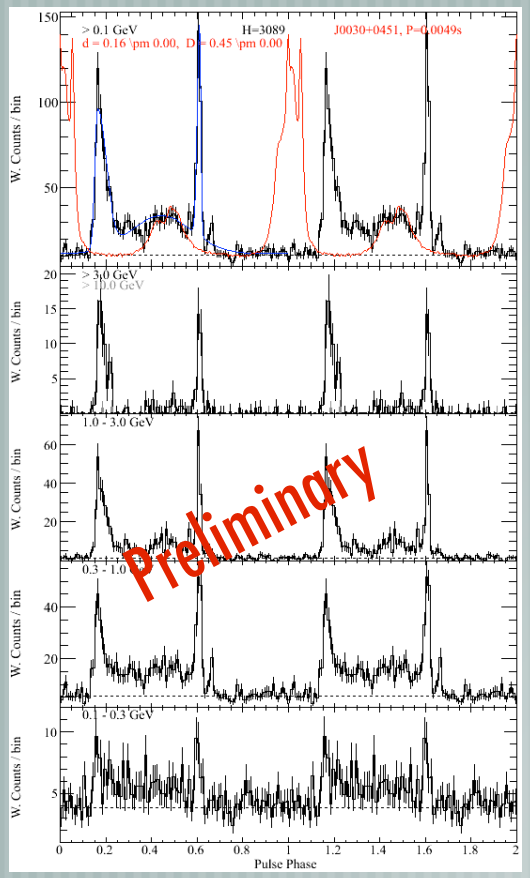
- High signal-to-noise and good timing models allow study of fine features in the light curve and evolution of profile shapes with energy
- Phase-resolved spectroscopy reveals rapid changes is spectral parameters (e.g. cutoff energy) within gamma-ray peaks
- Many pulsars have sub-exponential phase-averaged spectra from superposition of range of exponential cutoffs. **Phase resolved spectroscopy is important for proper modeling.**

See posters by M. DeCesar and N. Renault

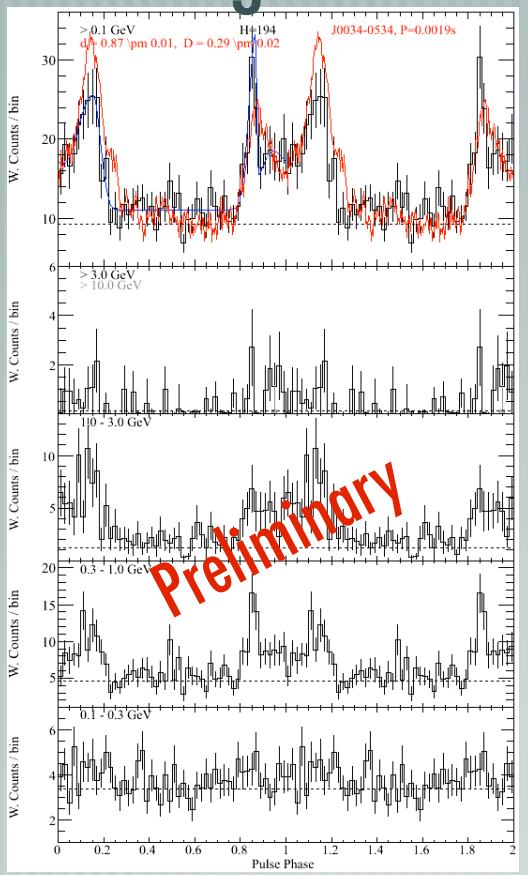
MSPs: A Variety of Pulse Profiles

Fermi Gamma-ray Space Telescope

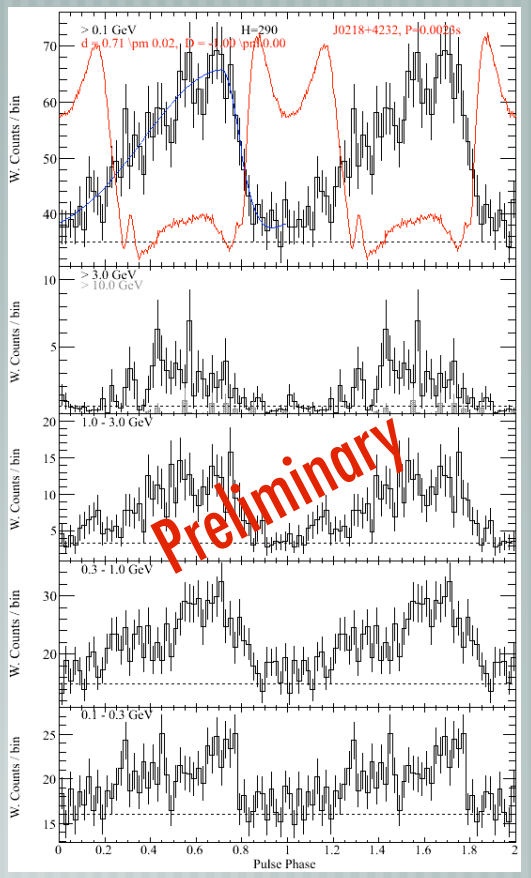
Normal



Aligned



Wide



- Aligned type have the highest magnetic field at the light-cylinder

See posters by T. Johnson and N. Renault
see also Espinoza et al. 2012, submitted

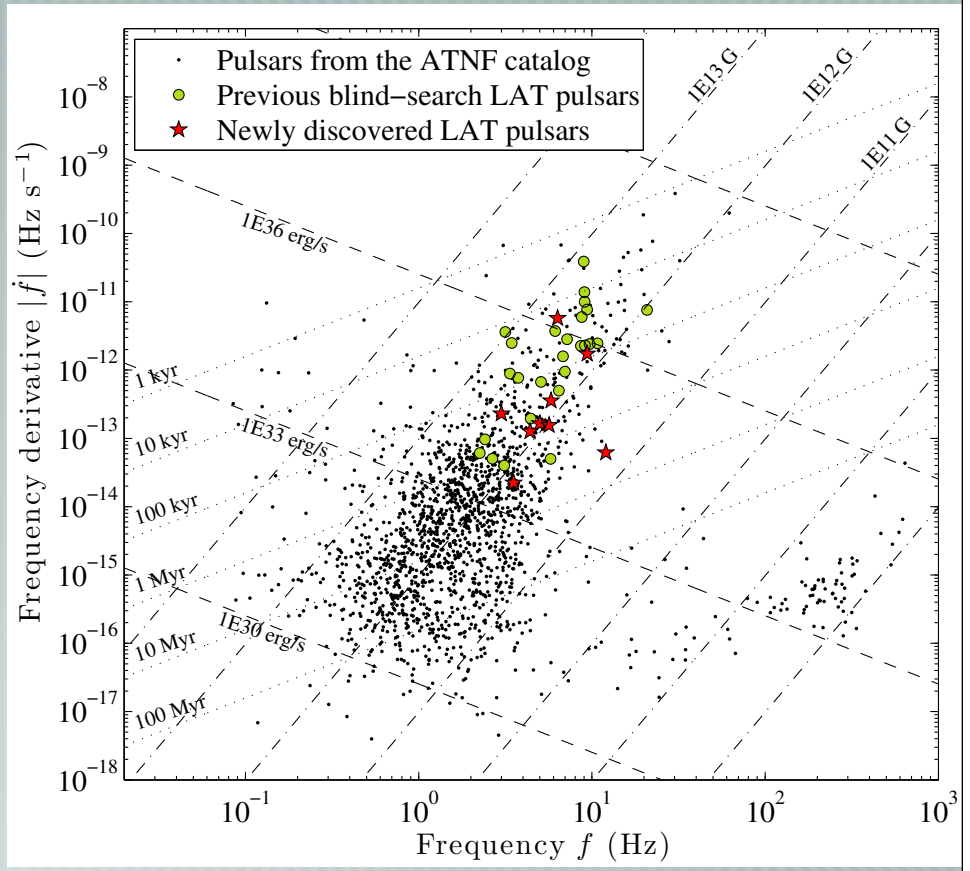
- More degrees of freedom required in light curve fits (PSPC and altitude limited models)

Upcoming Results on Radio Pulsars

- More pulsars crossing 5-sigma threshold
  - Tighter constraints on ` sub-luminous' pulsars
- More counts enabling phase-resolved spectroscopy on more pulsars
- Reprocessed LAT data enables new detections including Globular Cluster MSPs
  - See talks by T. Johnson and J. Wu in pulsar session
- Pushing to low energy for low cutoff pulsars like B1509–58
  - See poster by P. den Hartog

Blind Searches

- Long, very sparse data sets make traditional epoch folding or FFT searches extremely computationally intensive
- Semi-coherent methods have been developed (Atwood et al. 2006; Pletsch et al. 2012) that maintain good sensitivity with greatly reduced computational requirements
- Resulted in 36 discoveries in first 3 years of data (Abdo et al. 2009, Saz Parkinson et al. 2010, 2011; Pletsch et al. 2012a,b)
  - Young to middle age pulsars, $\dot{E} \sim 10^{33.5} - 10^{37}$
- Nearly all (32/36) are undetectable in radio



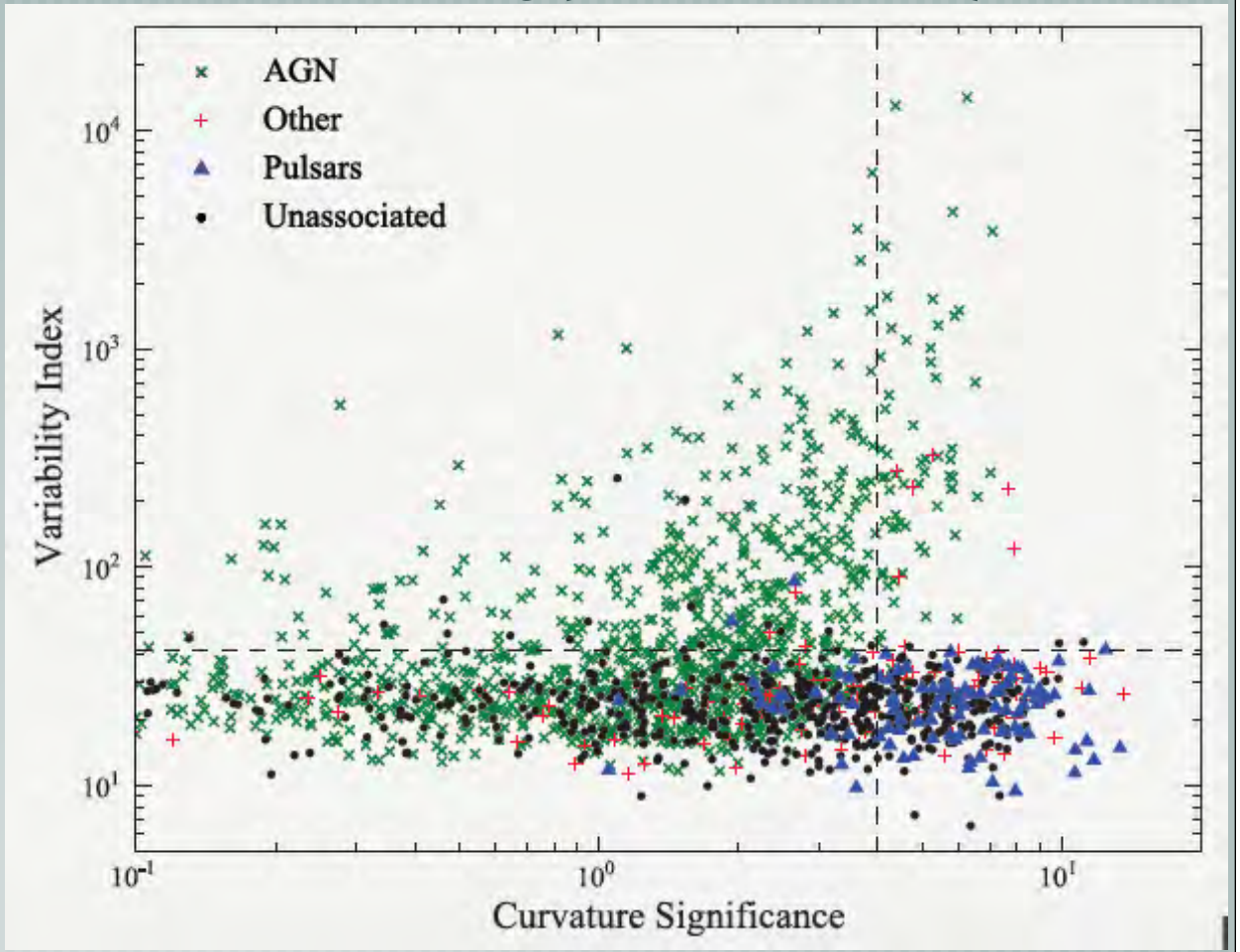
New Territory for Blind Searches

- Millisecond Pulsars
  - See Pletsch talk!
- Galactic Center searches
  - See Saz Parkinson poster
- More integration time for deeper searches
- More computer power/new computational techniques (e.g. fully coherent searches and E@H distributed computing)

Using LAT to Find Radio Pulsars

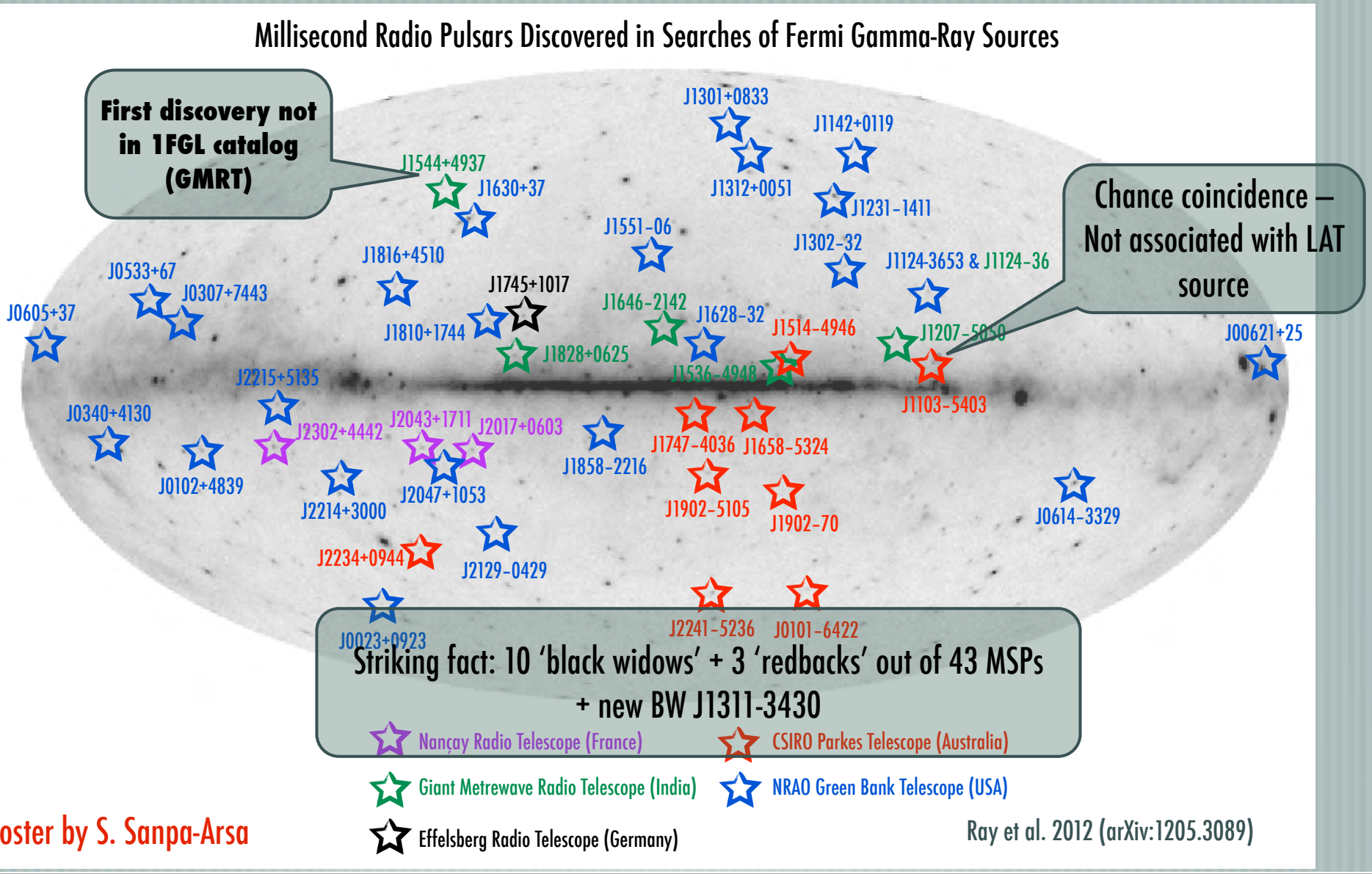
- Best targets are sources with low variability and "pulsar-like" spectra
- Used multiple techniques for ranking sources

2FGL Catalog (Nolan et al. 2012)



More details on ranking of "pulsar-likeness":
Ackermann et al., ApJ 753, 83 (2012)
Lee et al., MNRAS 424, 2832 (2012)

Success! 43+ MSPs found!

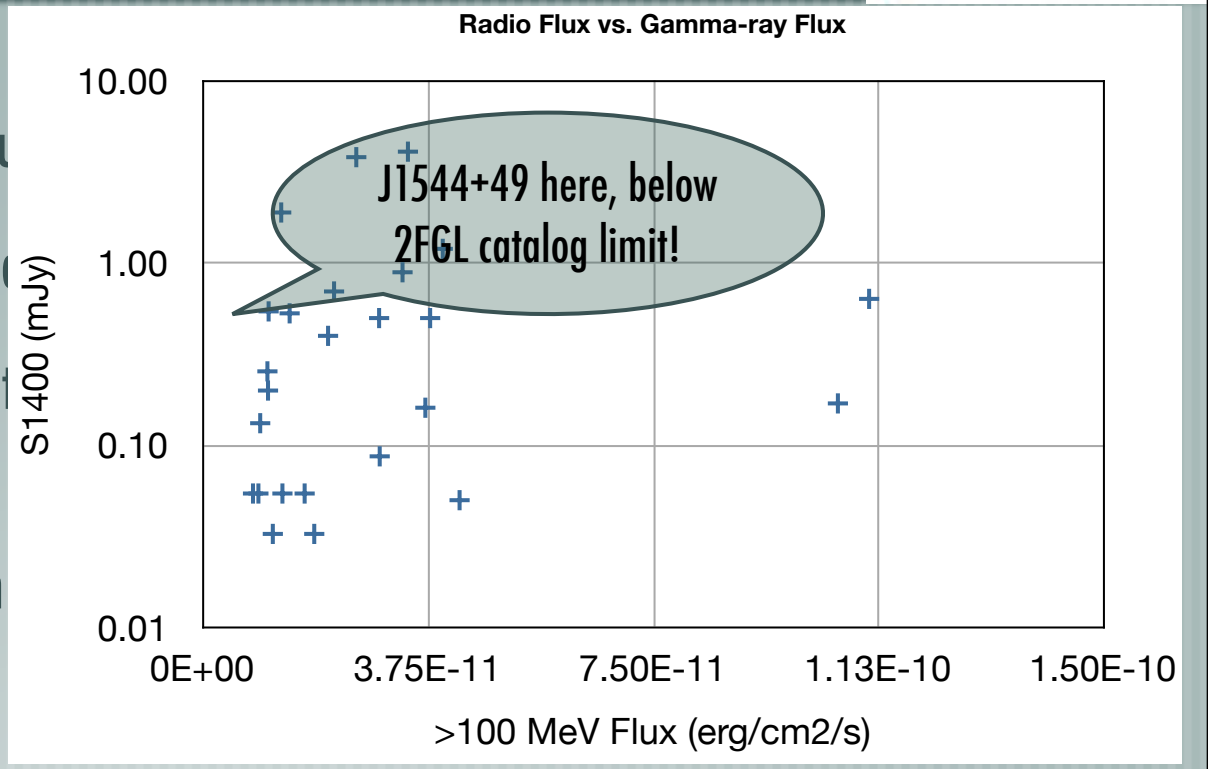


See poster by S. Sanpa-Arsa

Ray et al. 2012 (arXiv:1205.3089)

Prospects

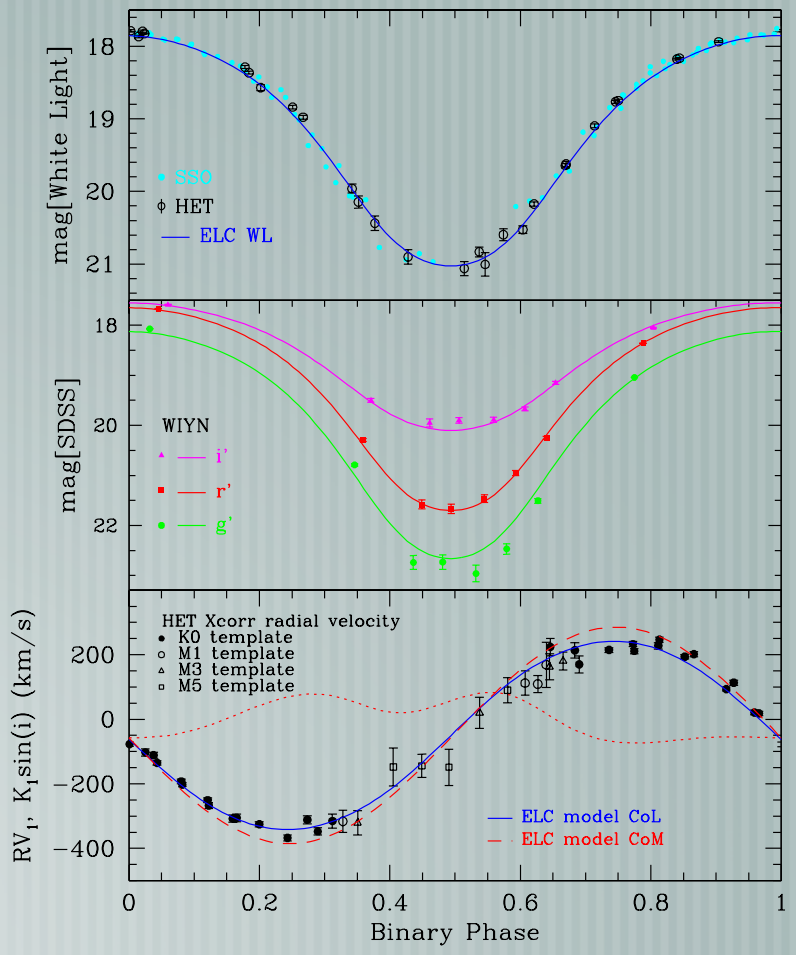
- Searches of LAT unidentified sou
  - Ongoing catalog analysis yiel
  - Re-observations are important pulsar spectra, RFI, etc...
  - Radio flux not correlated with
- Timing results take patience
  - Need about a year to get orbit, position, period derivative
  - Evaluating pulsar timing array potential and getting proper motions (for Shlovskii effect) takes even longer



X-ray + Optical Studies of UNIDs

- Bright unassociated sources subjected to deep X-ray, optical and radio imaging observations to look for likely counterparts
  - Only a handful of bright ones remain
- Recently, two found to be potential radio-quiet MSPs based on optical observations
  - Orbital periods identified in optical
  - J2339+0533 : Porb = 4.6 hours
  - J1311−3430 : Porb = 1.56 hours
- Are there any radio-quiet MSPs?
  - Both have been searched hard for LAT pulsations

J1311−3430

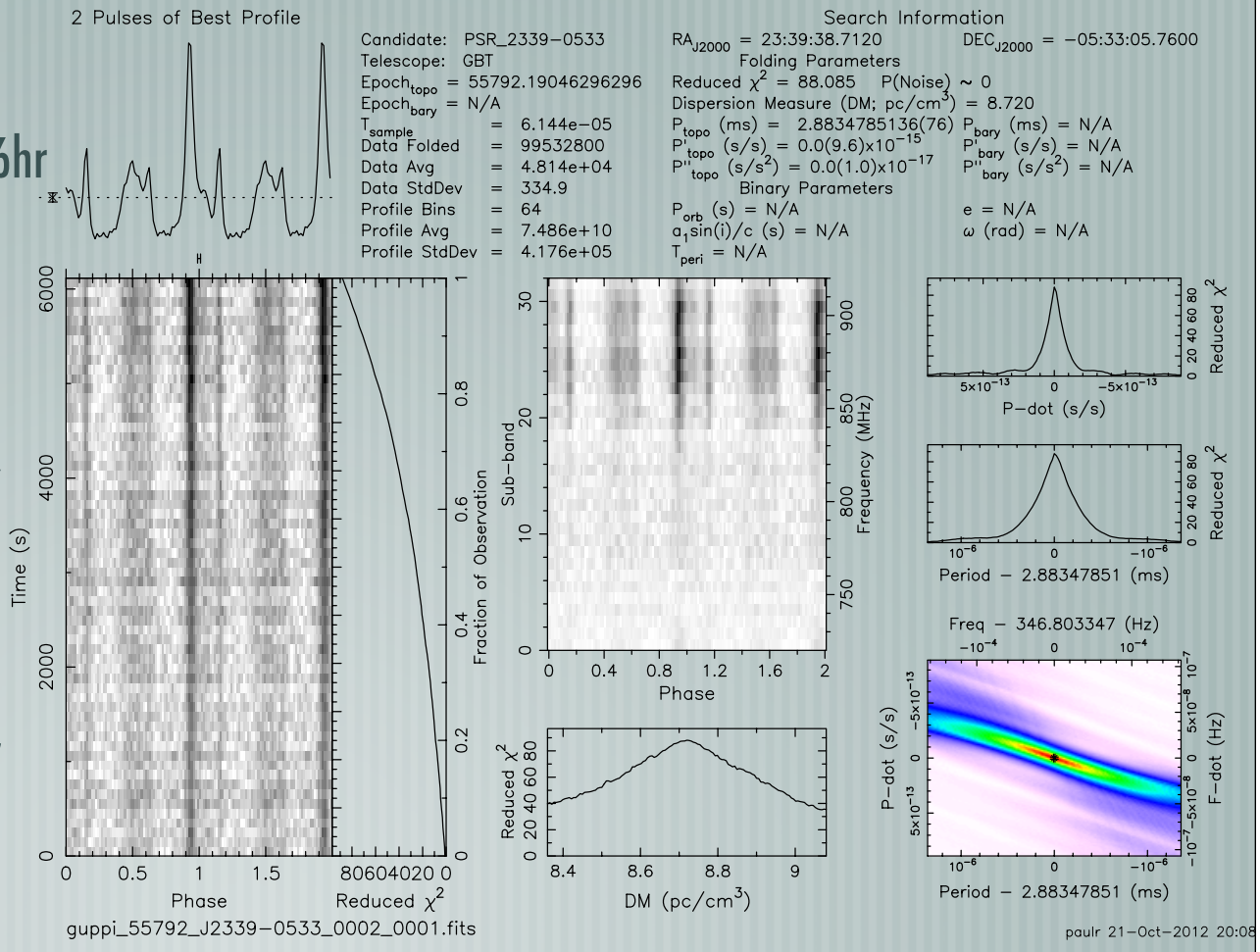


See upcoming talks by Romani and Pletsch and poster by Kataoka

Romani et al. 2011, ApJL, 743, 26

Breaking News: J2339-0533!

- 2.88 ms pulsations discovered in 1.6hr GBT observation at 820 MHz
- DM 8.72 gives D=450 pc
- Measured semimajor axis 0.611 lt-s, larger than expected
  - $M_C > 0.26\ M_\odot$
  - Redback, not black widow



(Ray et al. 2012, in prep)

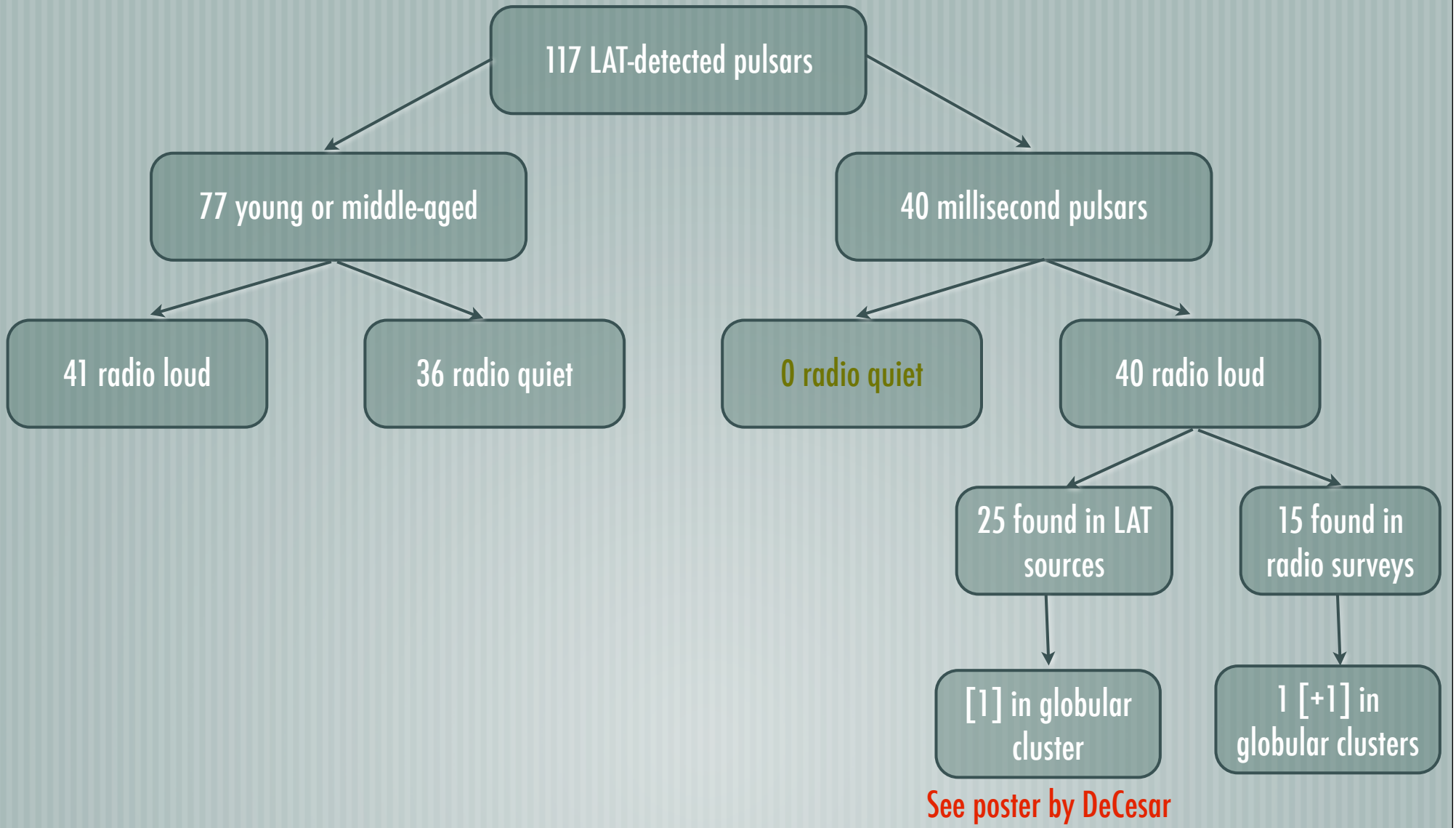
Going Forward

- More detailed multiwavelength studies of J2339 and J1311 and all of the new crop of black widow/redback MSPs that LAT is seeing
  - See Romani talk
- Identification of additional systems through optical and X-ray studies of LAT unassociated sources
  - Several groups pursuing this strategy

Summary

- **2nd Pulsar Catalog near complete with complete details on 117 gamma-ray pulsars**
  - Will be exploited for many follow-up studies of populations, pulse profiles, spectra and much more
- Superb sensitivity has enabled phase-resolved spectroscopy and detailed light curve studies of many pulsars
- Multiple methods have yielded a bounty of pulsars in 3 categories: radio-loud, radio-quiet, MSP
- **Lots more to come:**
  - Blind-search millisecond pulsars
  - More detected radio pulsars
  - More MSPs in searches of LAT sources

Pulsar Varieties in 2PC



Acknowledgements

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