
# *Gamma-ray observations of pulsars with the Fermi LAT*

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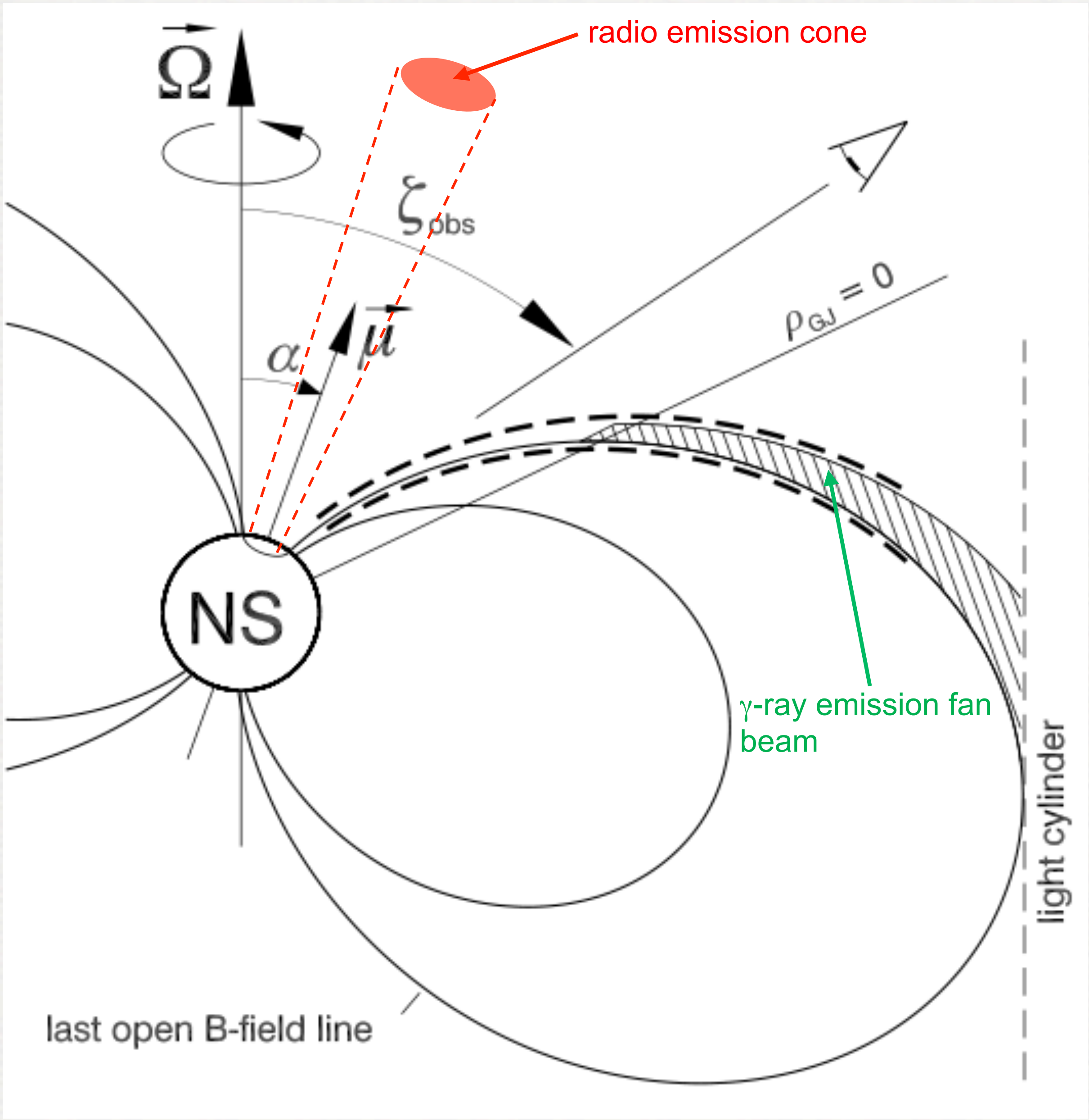
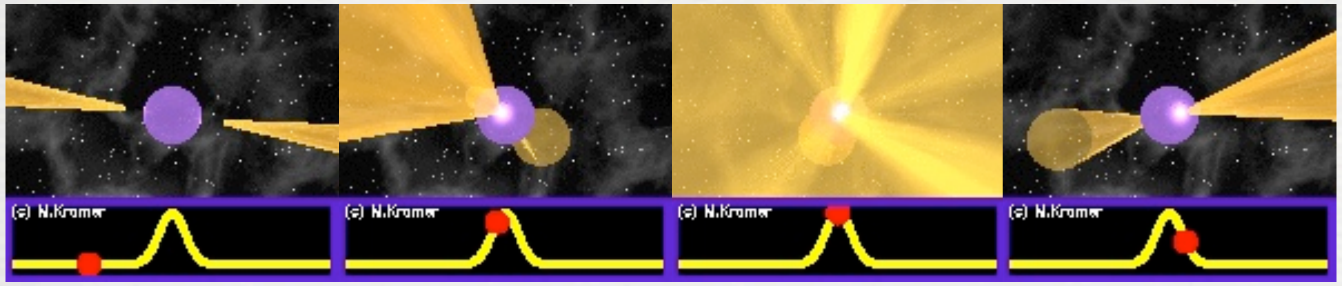
Realtime Astroparticle Physics, Bonn

05/02/2013

# Pulsars




Pulsars are rapidly rotating highly magnetized neutron stars, born in supernova explosions of massive stars.

Typically: M ~1.4 $M_\odot$ and R ~ 10 km

Dense plasma co-rotating with the star.

Magnetosphere extending to the "light cylinder", where $\Omega \times R_{LC} = c$.

Emission (radio, optical, X-ray …) produced in beams around the pulsar.

Pulsars are cosmic lighthouses!

# Period and spin-down

Kinetic energy loss rate:

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

⇒ Pulsars spin down.

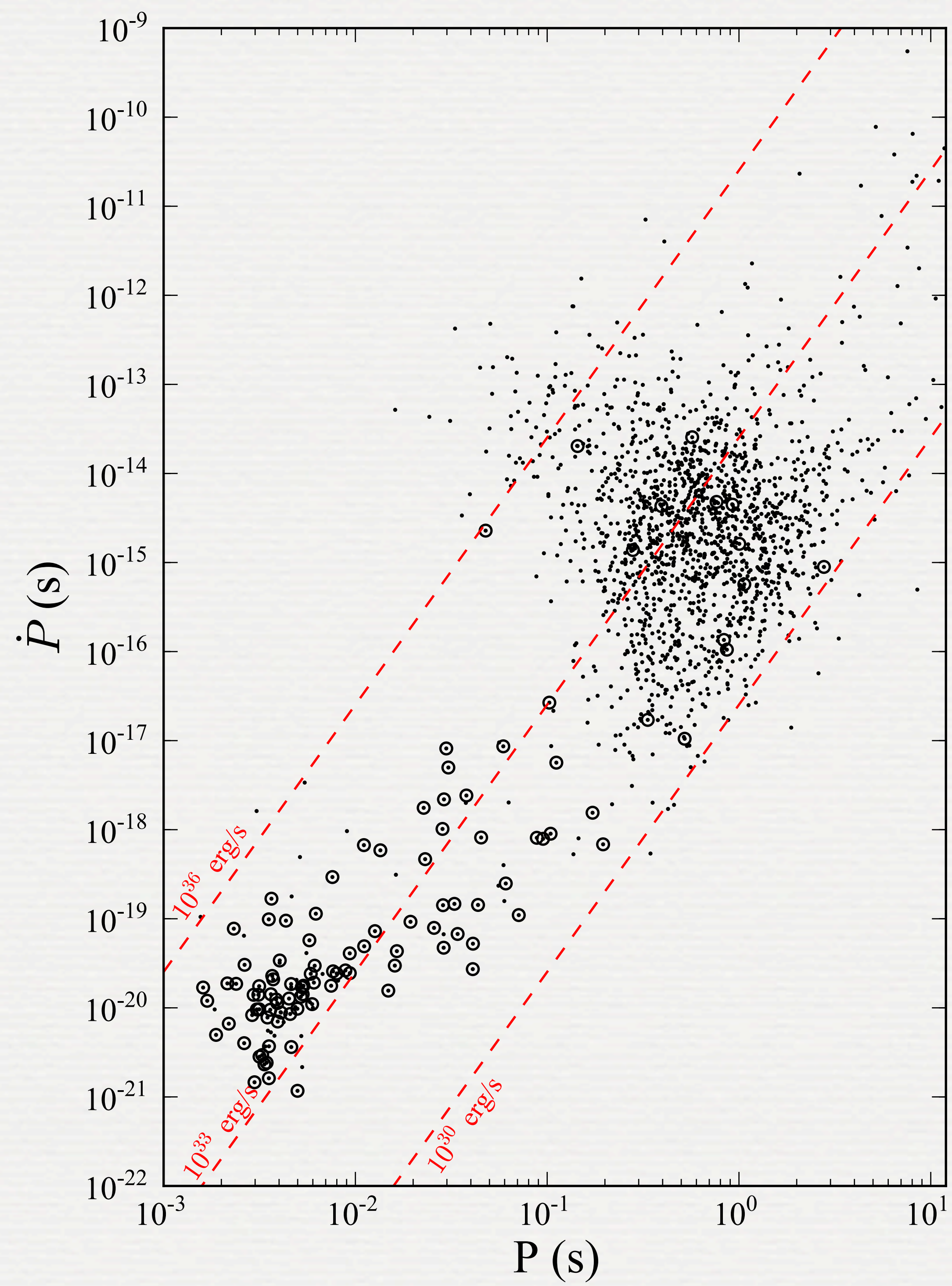
Two main pulsar families:

- “normal”: P = 0.1-10 s, $\dot{P} = 10^{-18}$-$10^{-12}$
- “millisecond” (MSPs): P ≤ 0.1 s, $\dot{P} < 10^{-18}$

Most MSPs are in binary systems (circles), for evolutionary reasons.

About 2000 pulsars known today.

Vast majority in radio only!



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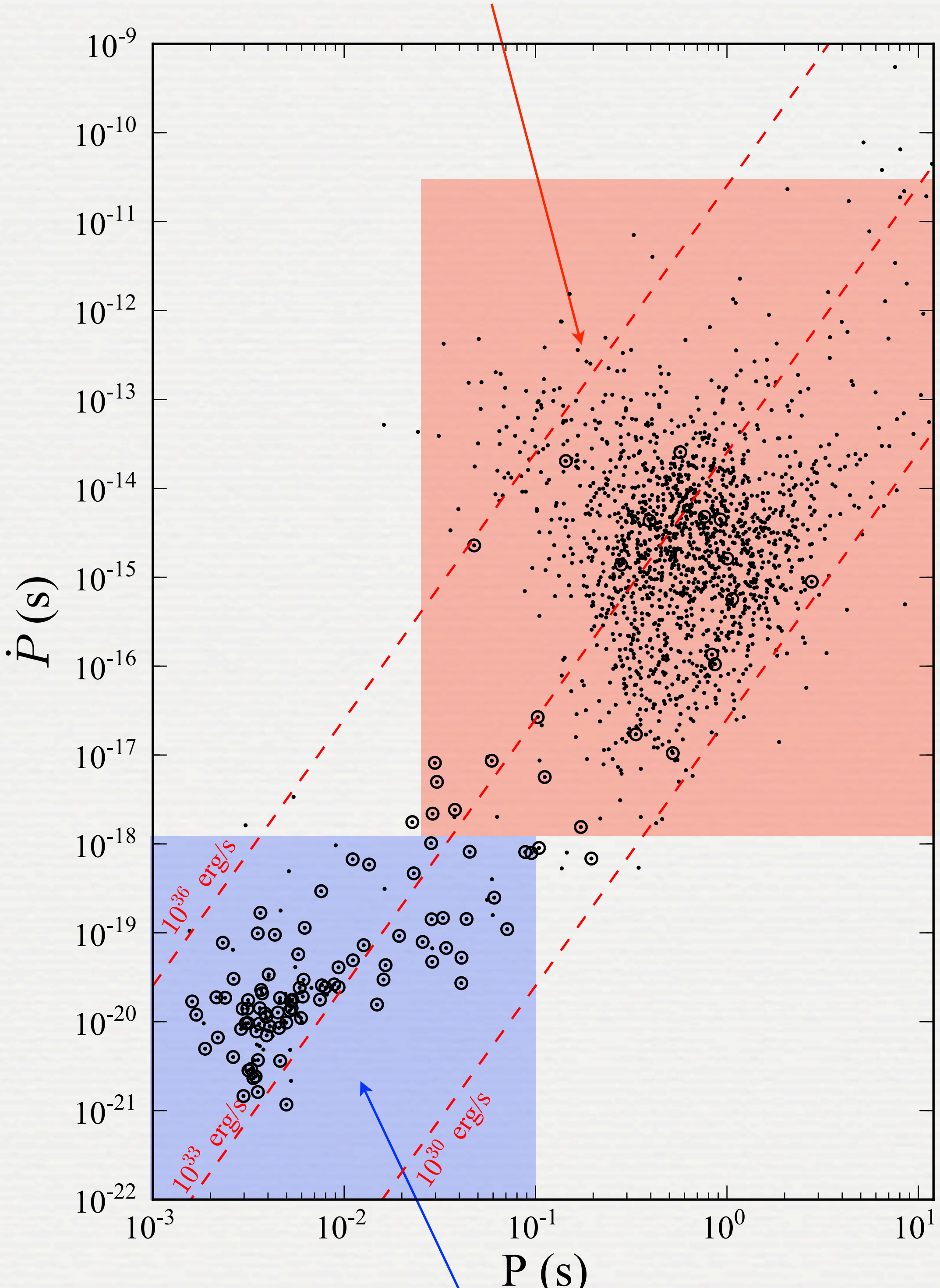
~1800 "normal" pulsars




~200 Galactic and globular cluster MSPs

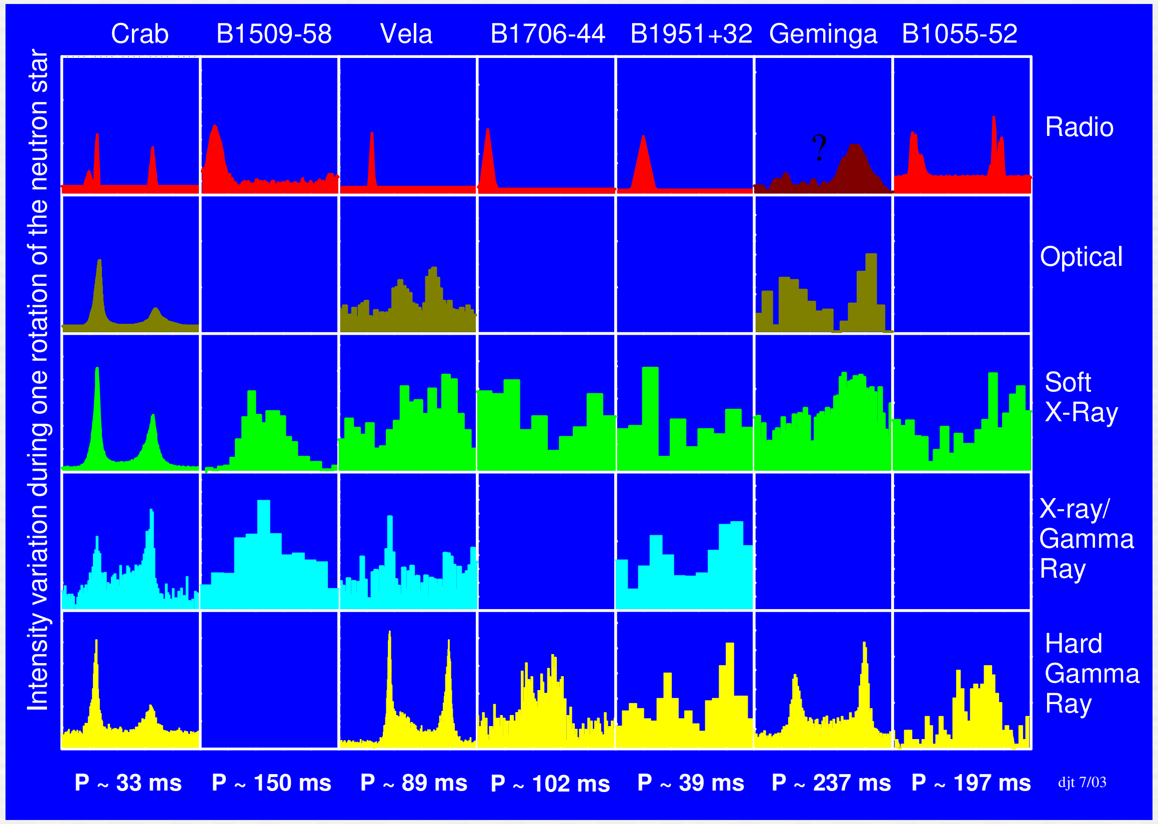
# Why γ rays?

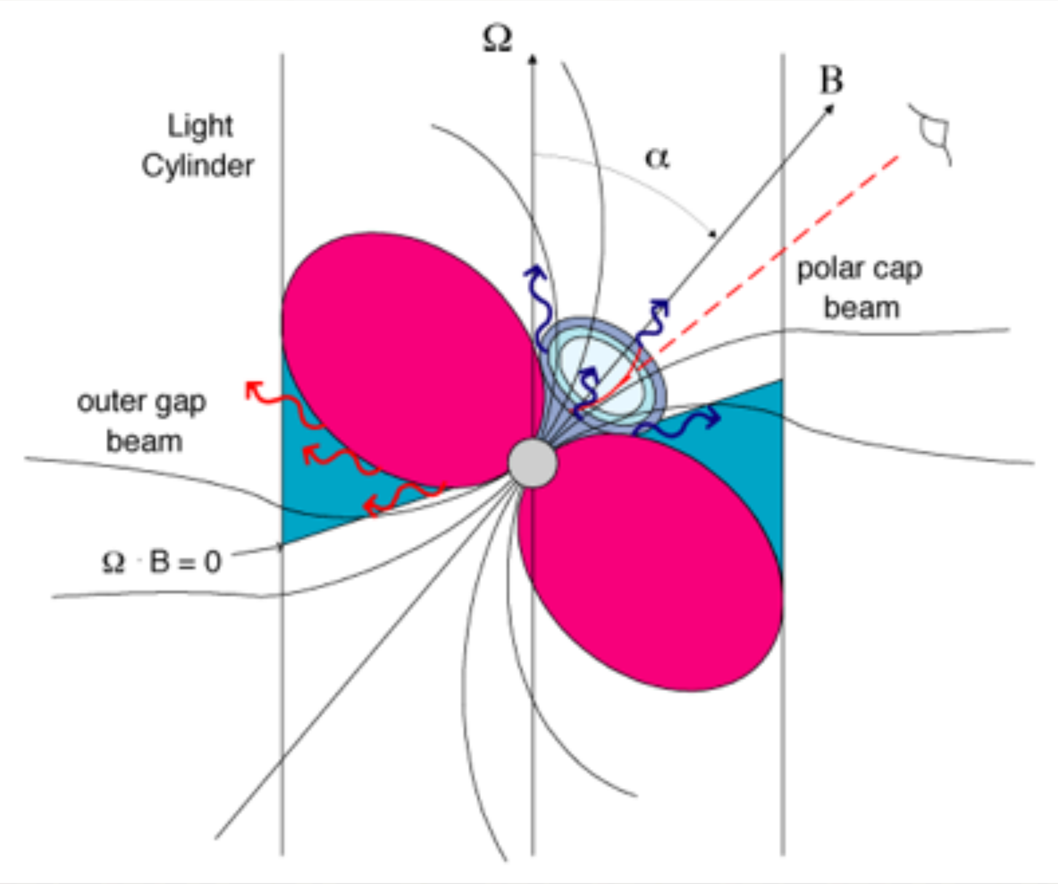
Radio emission represents a negligible fraction of the energy output.

In contrast, EGRET measured γ-ray efficiencies as high as ~10% (e.g. Thompson 2007). γ rays are a probe of fundamental particle acceleration processes in the magnetosphere.

Also, γ rays are beamed along magnetic field lines with small pitch angles. γ rays thus track the structure of the magnetic field.

In addition, radio and γ-ray beams have very different structures. γ-ray observations give access to different pulsar populations.



# The *Fermi* Gamma-ray Space Telescope

***Fermi*** = Large Area Telescope (LAT)

\+ Gamma-ray Burst Monitor (GBM)

Launched on 11 June 2008. Will operate through 2016, and could continue beyond.

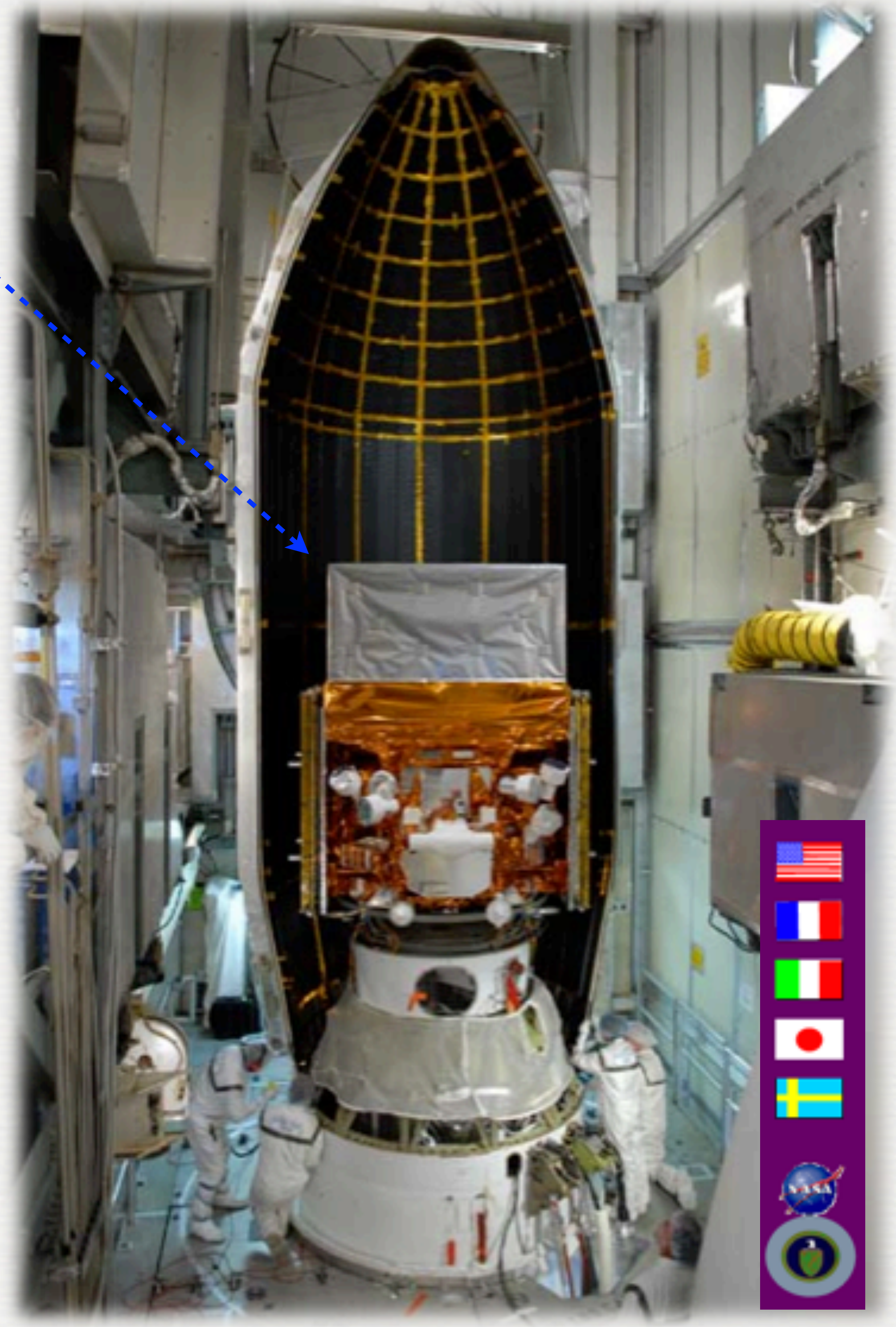
Energy range: 20 MeV to > 300 GeV (including unexplored 10 - 100 GeV).

Area of 8000 $cm^2$, viewing angle of 2.4 sr.

Survey strategy. Entire sky seen every 3h.

Timing accuracy < 1 μs.

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



# Observing pulsars with the *Fermi* LAT

**Principle:** phase-fold the *Fermi* LAT data with a timing model accounting for <u>every single pulsar rotation</u> over a given interval.

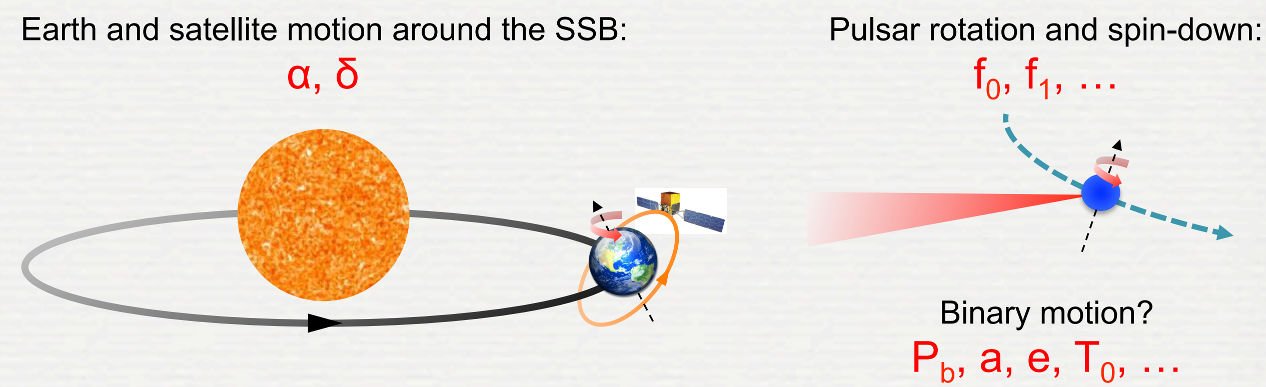
(typical exposures: $10^8$ - $10^{11}$ rotations)

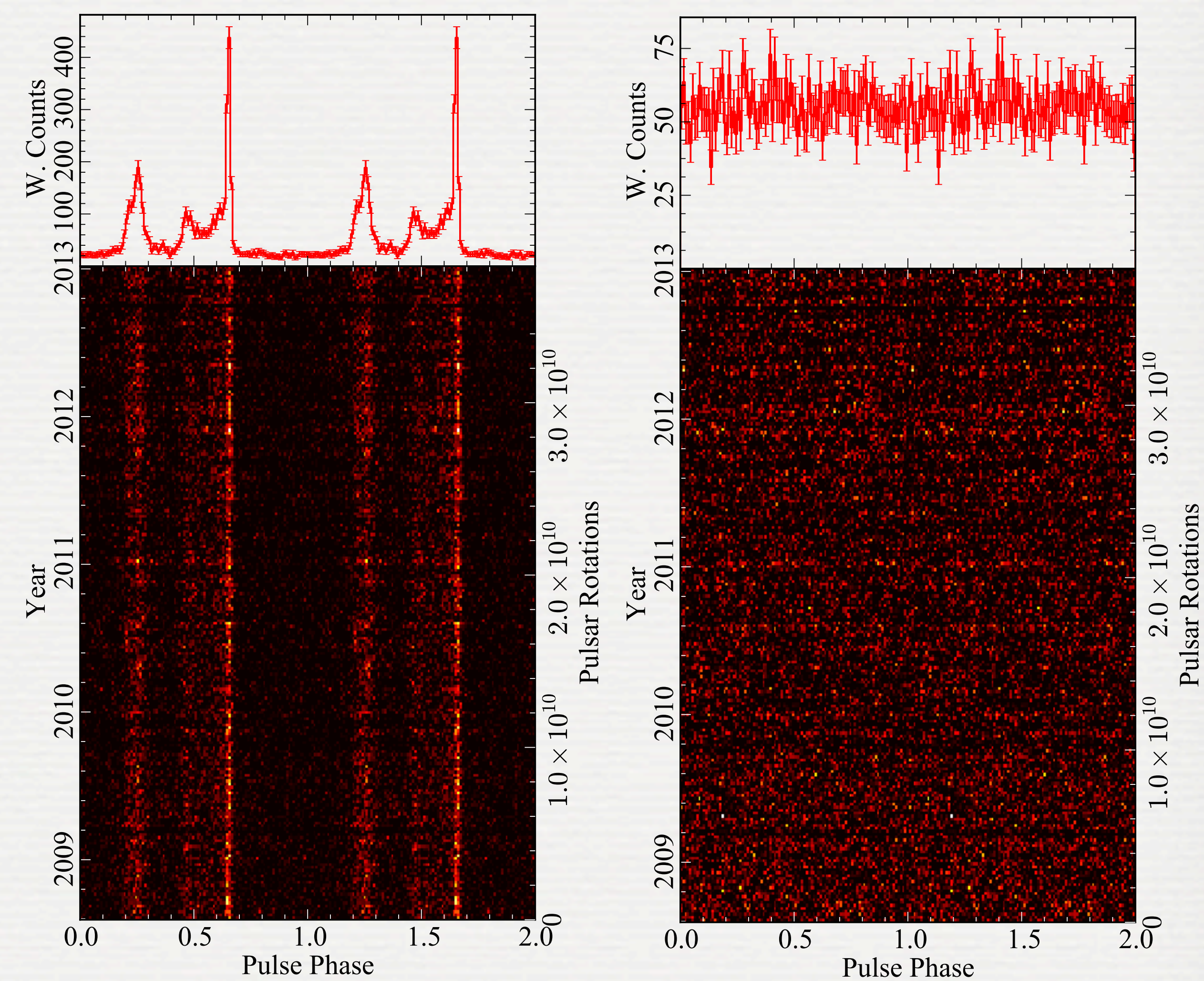
**Parameters:**

- right ascension α and declination δ, for converting the photon times to the Solar System Barycenter (SSB).

- rotational frequency and time derivatives: $f_0$, $f_1$, ...

- orbital parameters for pulsars in binary systems.



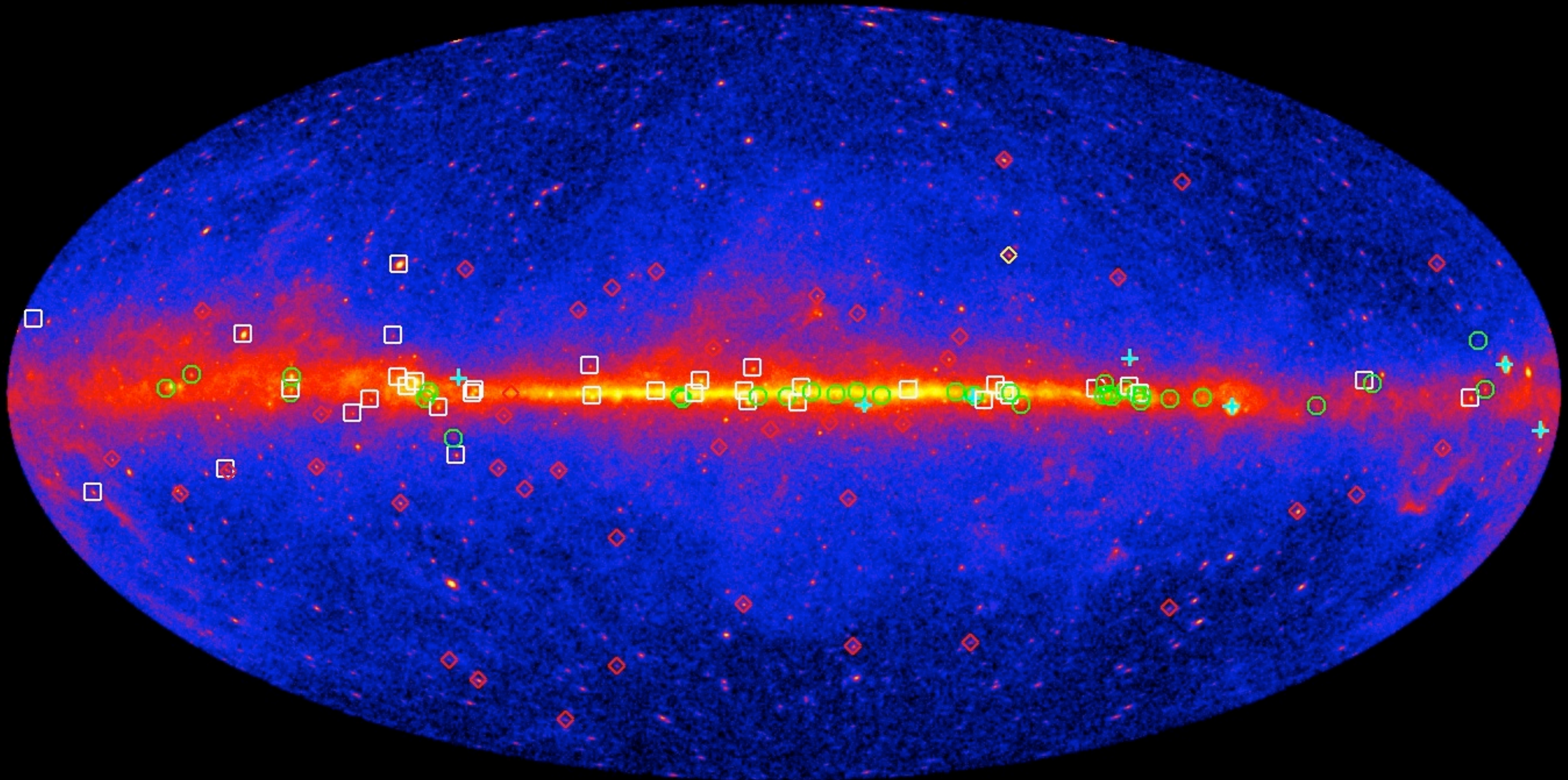

PSR J1231-1411 (P = 3.684 ms), with correct timing model (left) and wrong timing model (right)

# Observing strategies

- Folding the LAT data using known pulsar timing models, obtained from radio or X-ray timing measurements
  - ➡ EGRET pulsars all detected this way, although blind searches could have discovered the Geminga, Crab and Vela pulsars.
  - ➡ Large pulsar timing campaign, allowing pulsation searches for >700 pulsars! (See Smith et al., A&A 492, 923, 2008).
- Blind pulsation searches, directly in the LAT data
  - ➡ Only way of finding radio-quiet objects.
- Multi-wavelength observations of LAT unidentified sources
  - ➡ Pulsation searches in radio (sensitivity to MSPs, binary systems).
  - ➡ Optical and/or X-ray studies can locate binary companions and constrain orbital parameters.

# 121 γ-ray pulsars!

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



41 young radio- and X-ray-selected (green circles, cyan crosses)

36 young γ-ray-selected (white squares)

43 radio-selected MSPs (red diamonds) + 1 γ-ray-selected MSP (yellow diamond)

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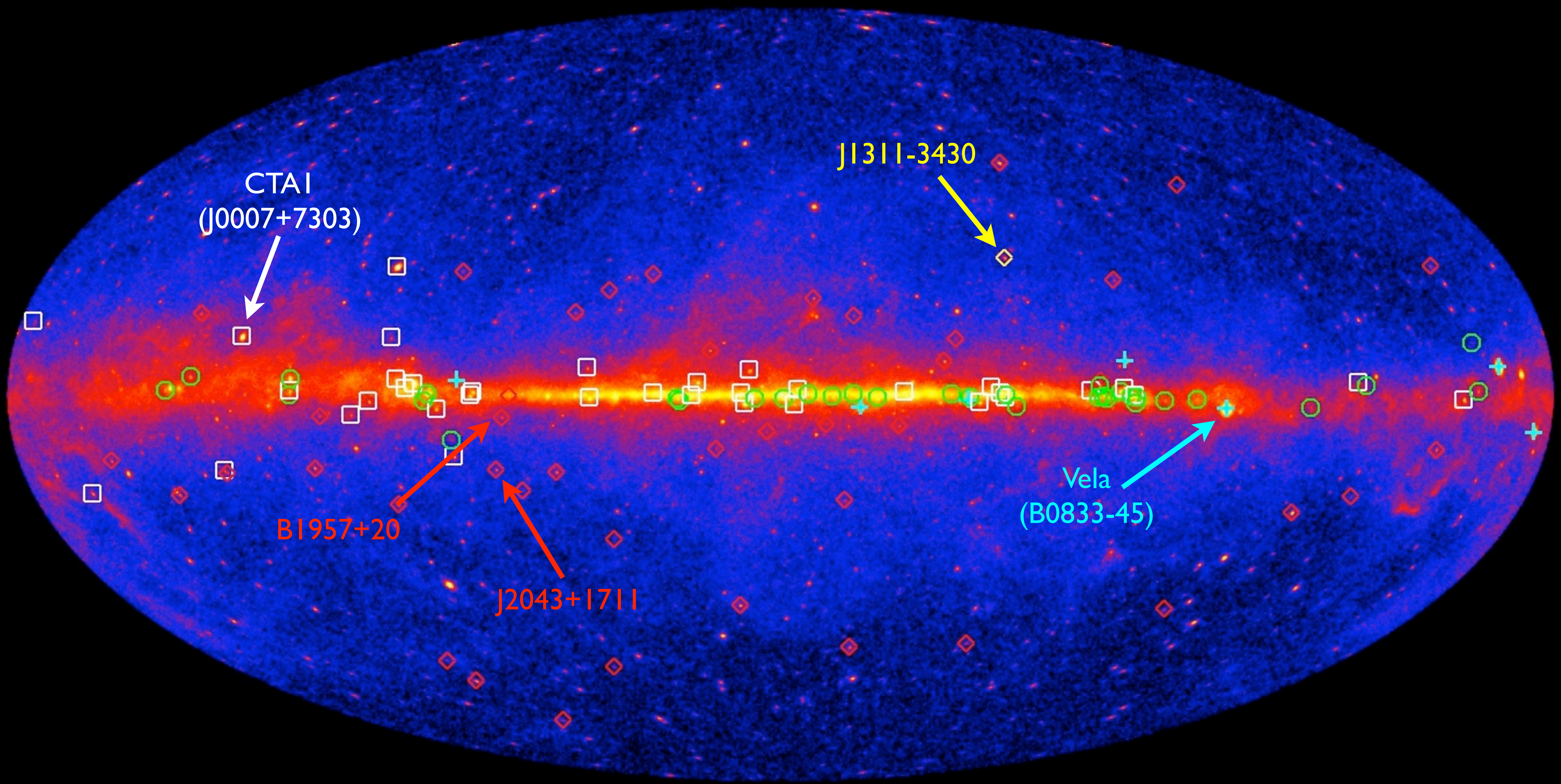


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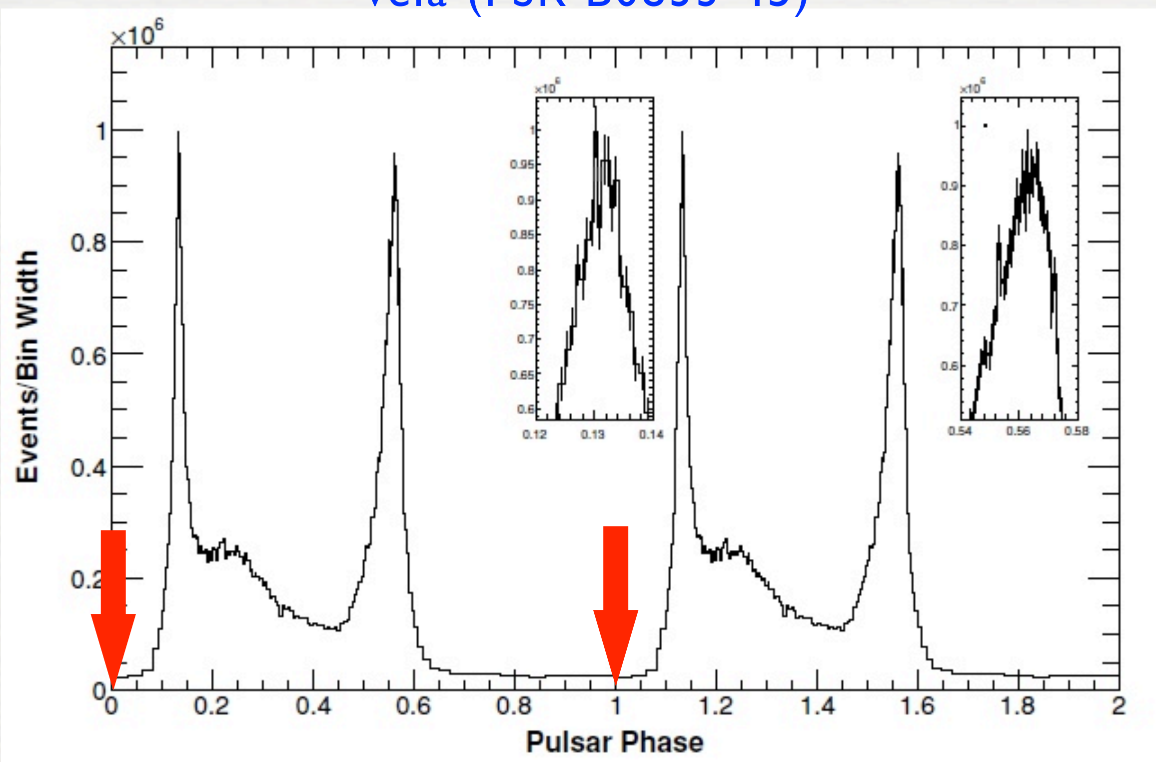
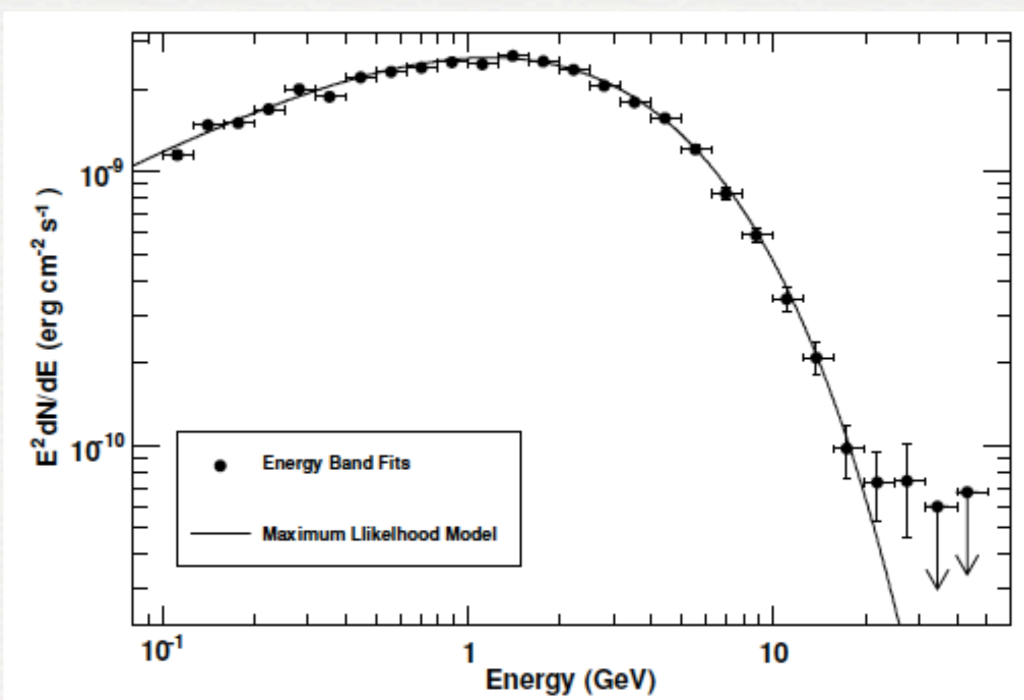
# EGRET pulsars in exquisite details

Vela (PSR B0833-45)




Spectral energy distribution for the Vela pulsar, with 1 yr of data (see Abdo et al., ApJ 713, 154, 2010)

EGRET pulsars are detected by the LAT with very high signal-to-noise, allowing detailed studies of their light curves and spectral properties as a function of energy.

Vela = archetypal γ-ray pulsar. Two sharp peaks separated by ~0.4 rotations, with the first peak offset from the radio emission by 0.1-0.2 rotations.

Spectrum well modeled by an exponentially cut off power law, of the form:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-\Gamma} \exp\left(-\frac{E}{E_c}\right)^{\beta}$$

Strong variations of the spectral properties with phase, caused by varying emission altitudes and particle populations.

Common properties among γ-ray pulsars.

# γ-ray MSPs

A good fraction of MSPs have γ-ray light curves resembling those of normal pulsars.

More exceptions to the archetypal Vela γ-ray light curve in the MSP population.

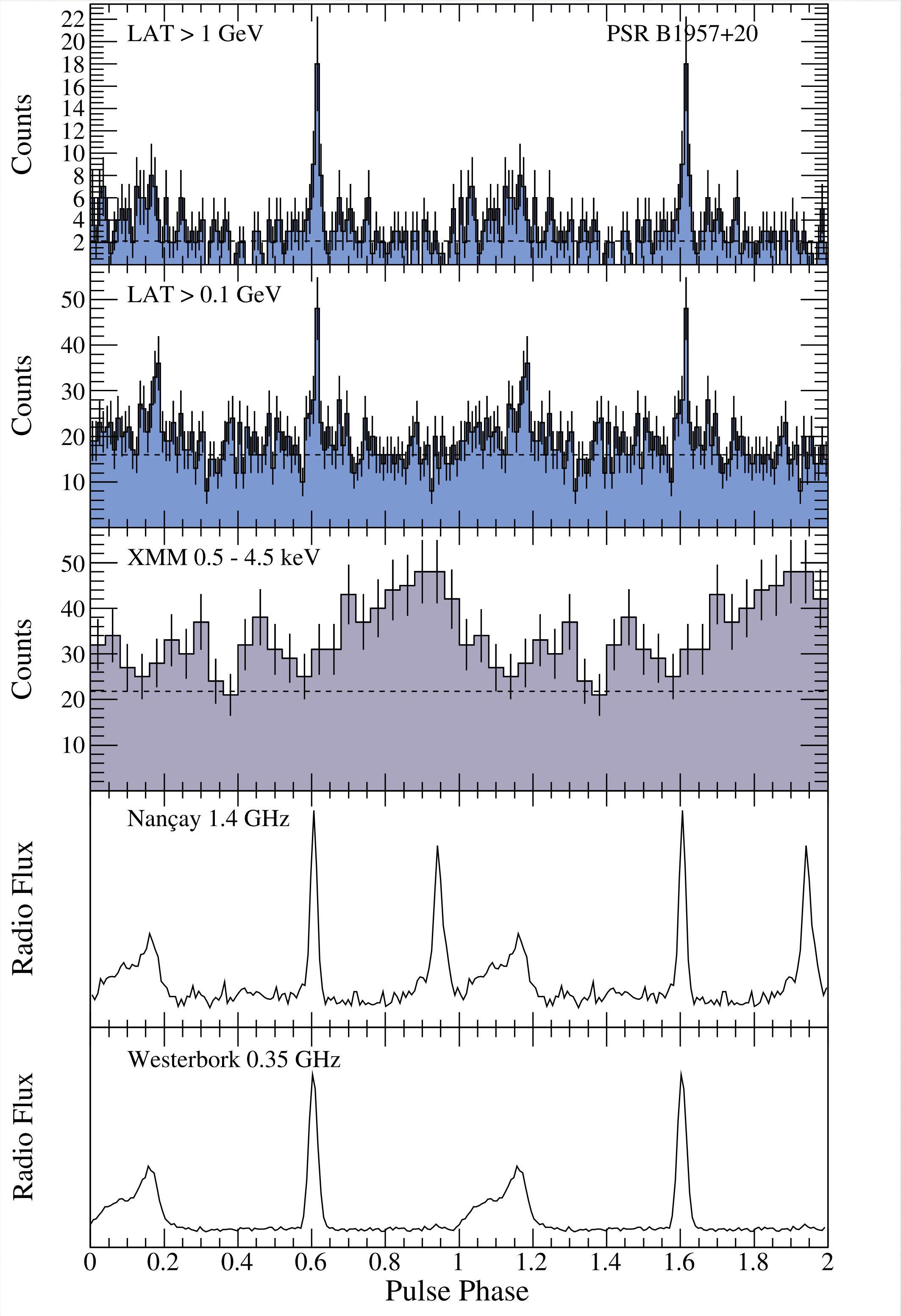
- Triple peaks (J1231-1411)

- Aligned radio and γ-ray peaks (J0034-0534, B1937+21, B1957+20, J1823-3021A, J1902-5105).

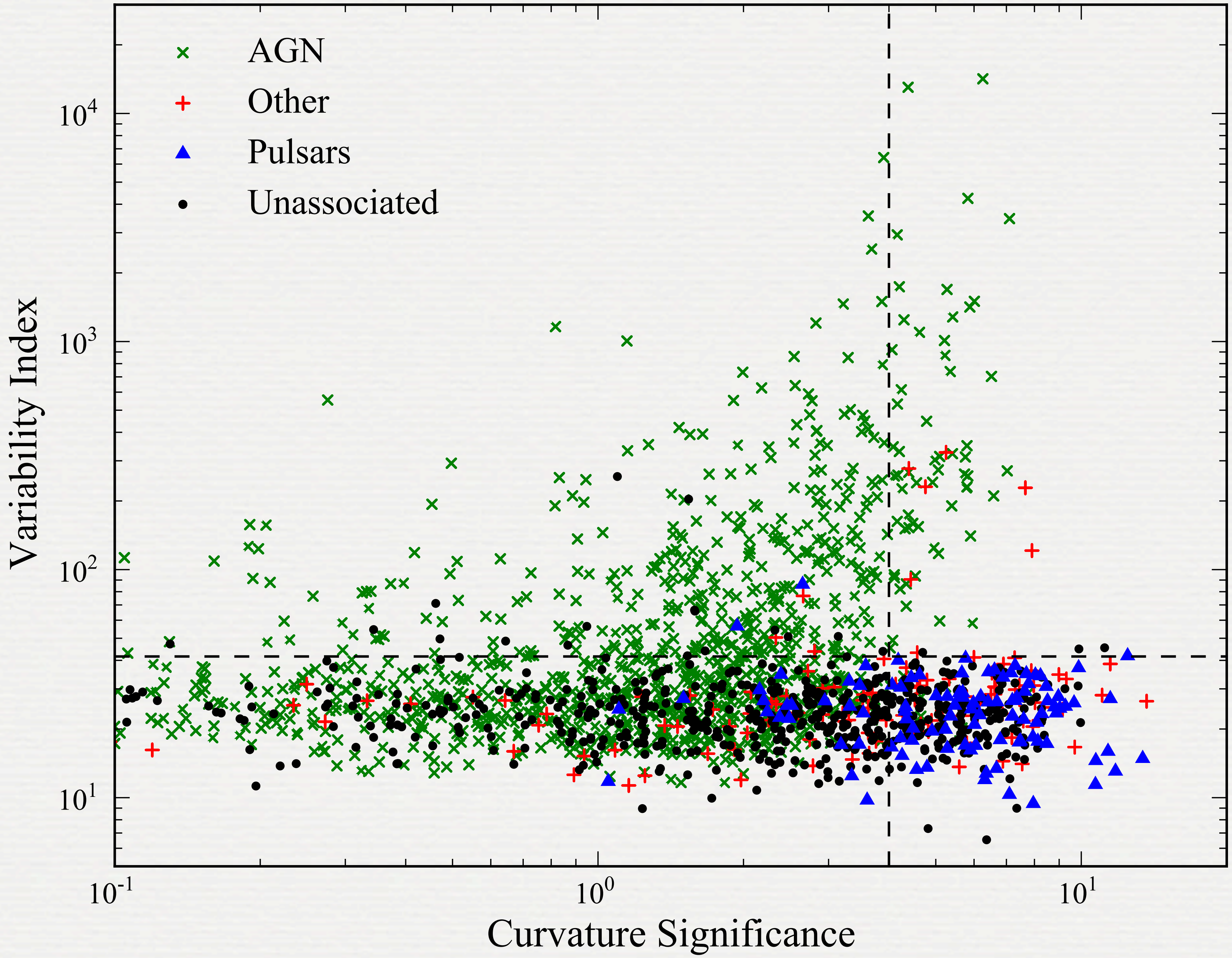
Alignment suggests that the radio emission and the γ-ray emission are co-located in the outer magnetosphere.

MSPs: important γ-ray pulsar population (currently >33% of all γ-ray pulsars).

PSR B1957+20, Guillemot et al. ApJ 744, 33 (2012)



# Finding unknown pulsars with the LAT




Based on the 2FGL Catalog, Nolan et al. ApJS 199, 31 (2012).

Best targets have pulsar-like properties: low variability indices and curved spectra.

Techniques used for ranking sources: visual inspection of light curves & spectra, or statistical studies of populations (cf. Ackermann et al., 2012; Lee et al. 2012; Mirabal et al. 2012)

# Blind pulsar searches

Long & sparse datasets such as LAT data make coherent searches very computationally intensive.

Semi-coherent methods maintaining sensitivity while reducing computational costs have been developped.

(Atwood et al. ApJL 652, 49, 2006, Pletsch et al. ApJ 744, 105, 2012)

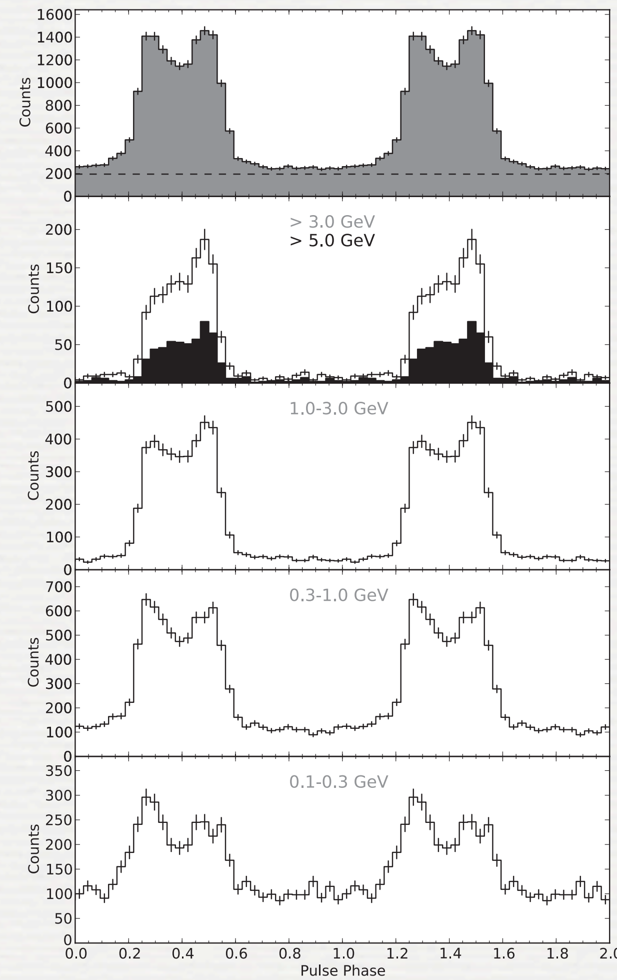
Searches have been spectacularly successful: 36 new pulsars found in the first 3 years of LAT data.

(Abdo et al. 2008, 2009, Saz Parkinson et al. 2010, 2011; Pletsch et al. 2012a,b)

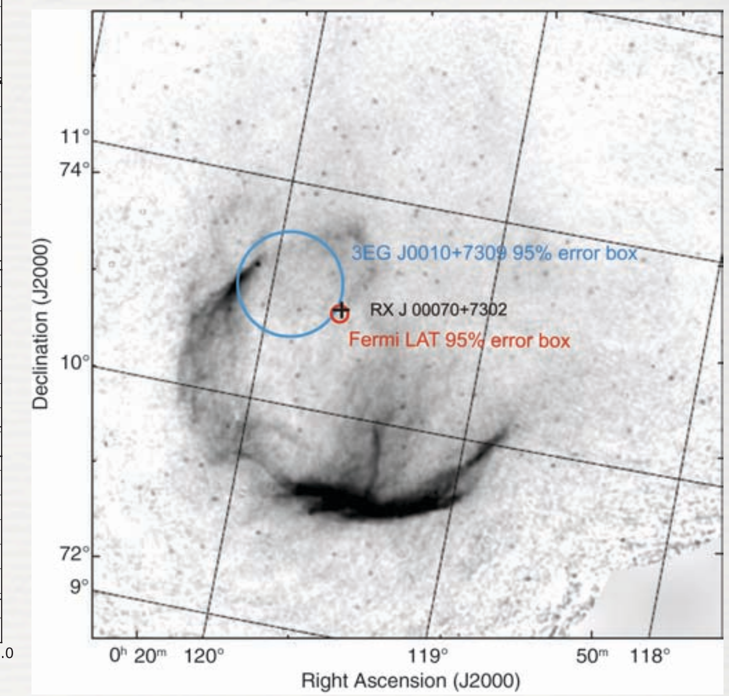
1st discovery: J0007+7307 in the supernova remnant CTA1.

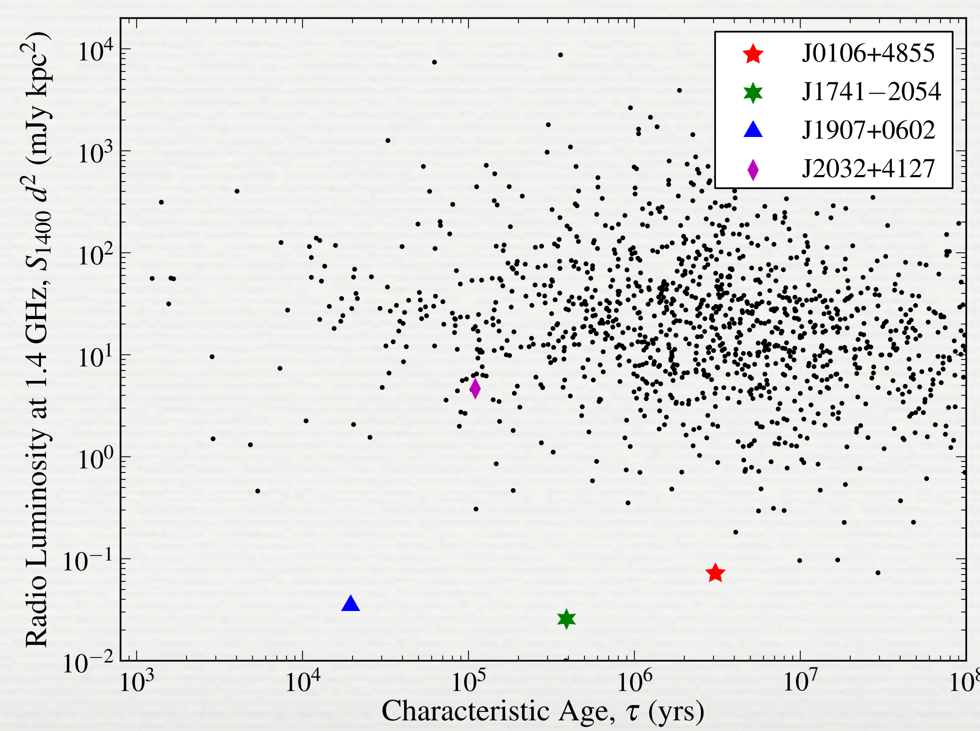
Only 4 detected in radio so far, 3 of them with very low radio luminosities.

What does radio-faint mean?




J0007-7303, in CTA1 (Abdo et al., Science 322, 1218, 2008, & Abdo et al., ApJ 744, 146, 2012)



# Finding unknown radio pulsars with the LAT

Searches for pulsars in EGRET unidentified sources had modest success, because of poor source localization.

Typical localization accuracy (95% CL): <10'.

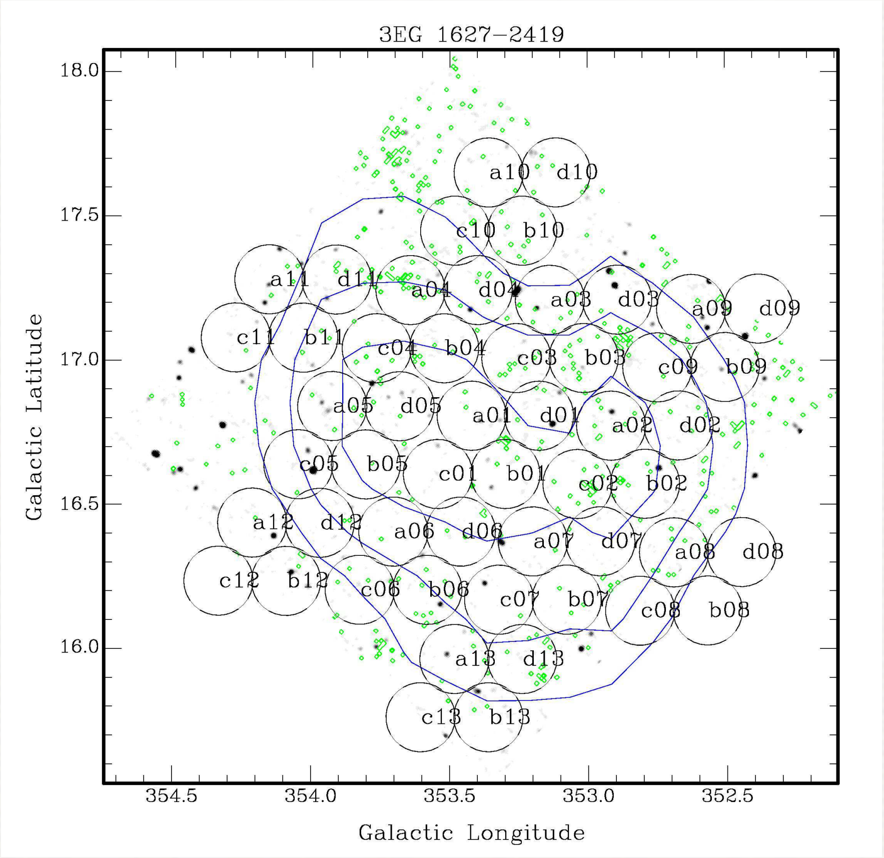
⇒ same size as radio telescope beams!

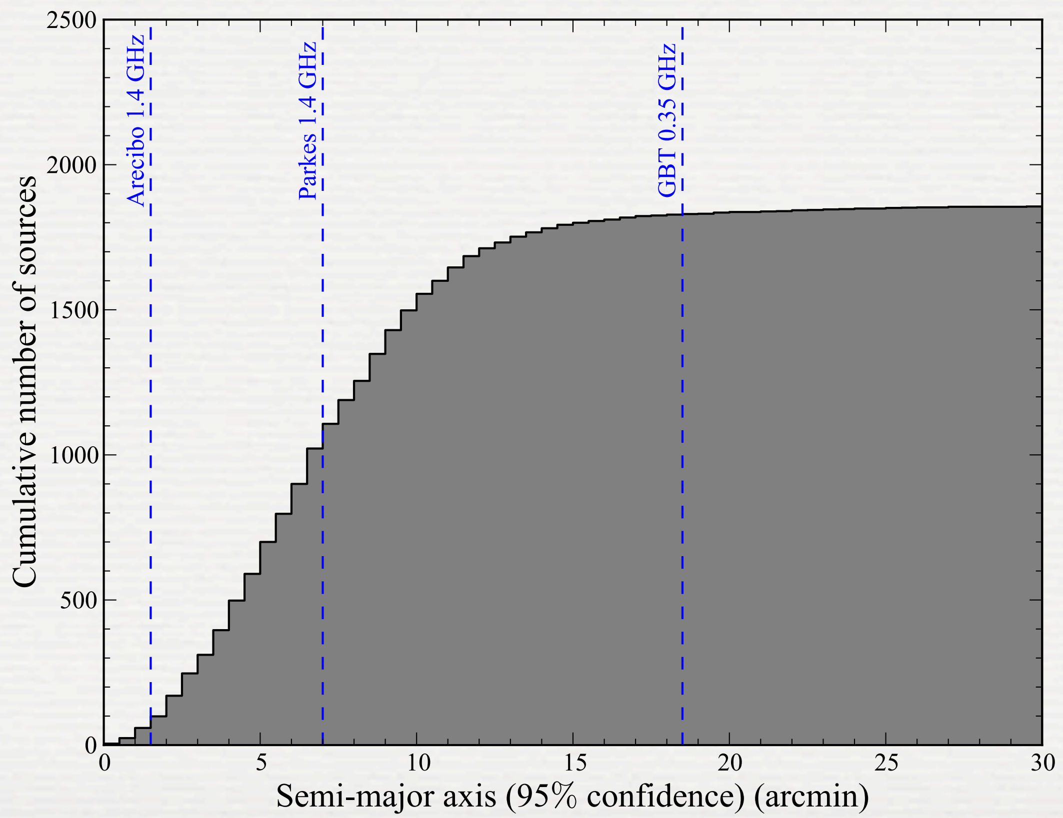
Pulsars can be missed in radio surveys for several reasons: sensitivity, binary motion, dispersion & scintillation, eclipses, insufficient sky coverage...

Top: radio pointings required to cover 3EG 1627-2419.

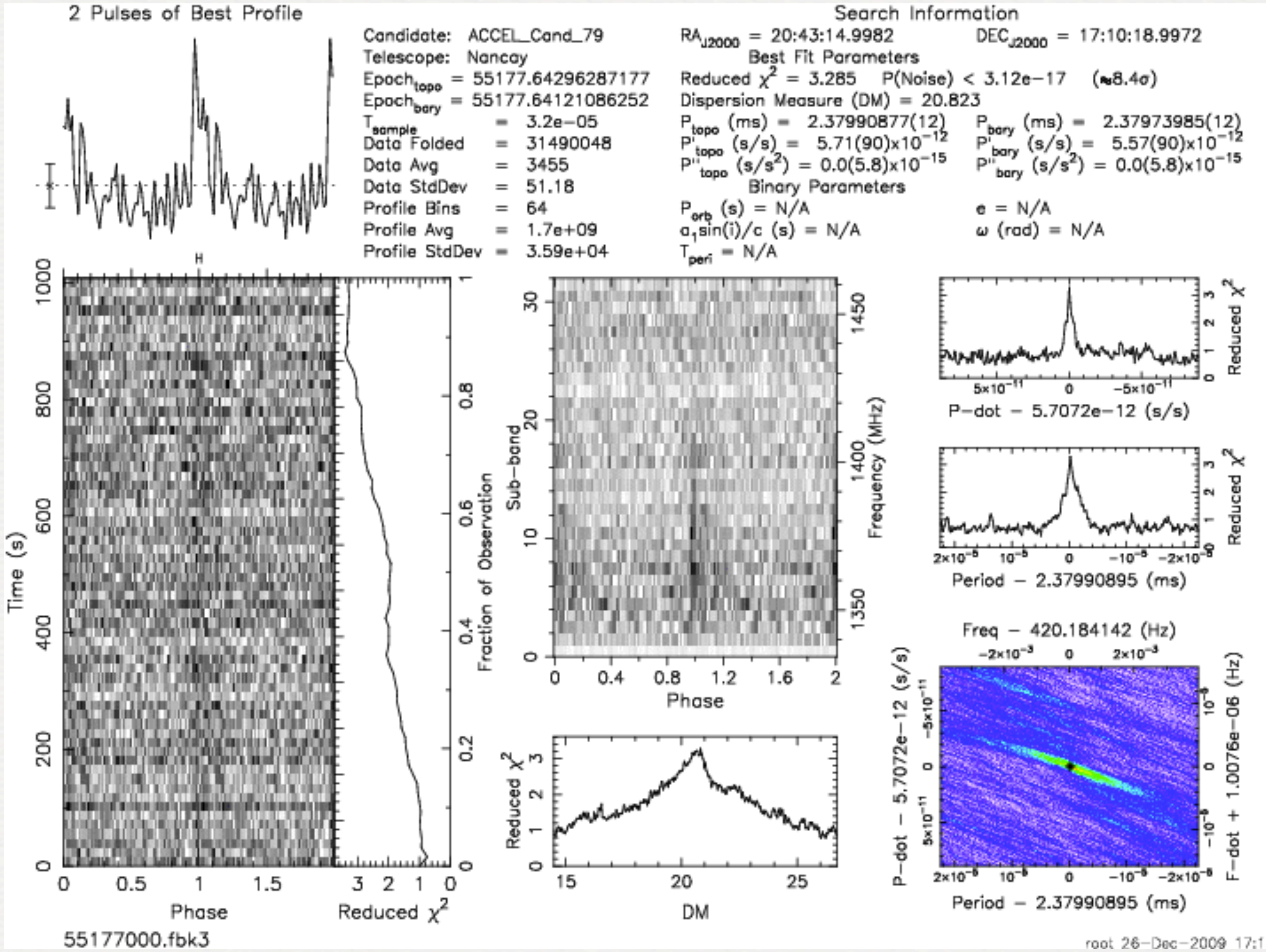
(from Crawford et al., ApJ 652, 1499, 2006)

Bottom: distribution of 2FGL source localization accuracies.



# Success!

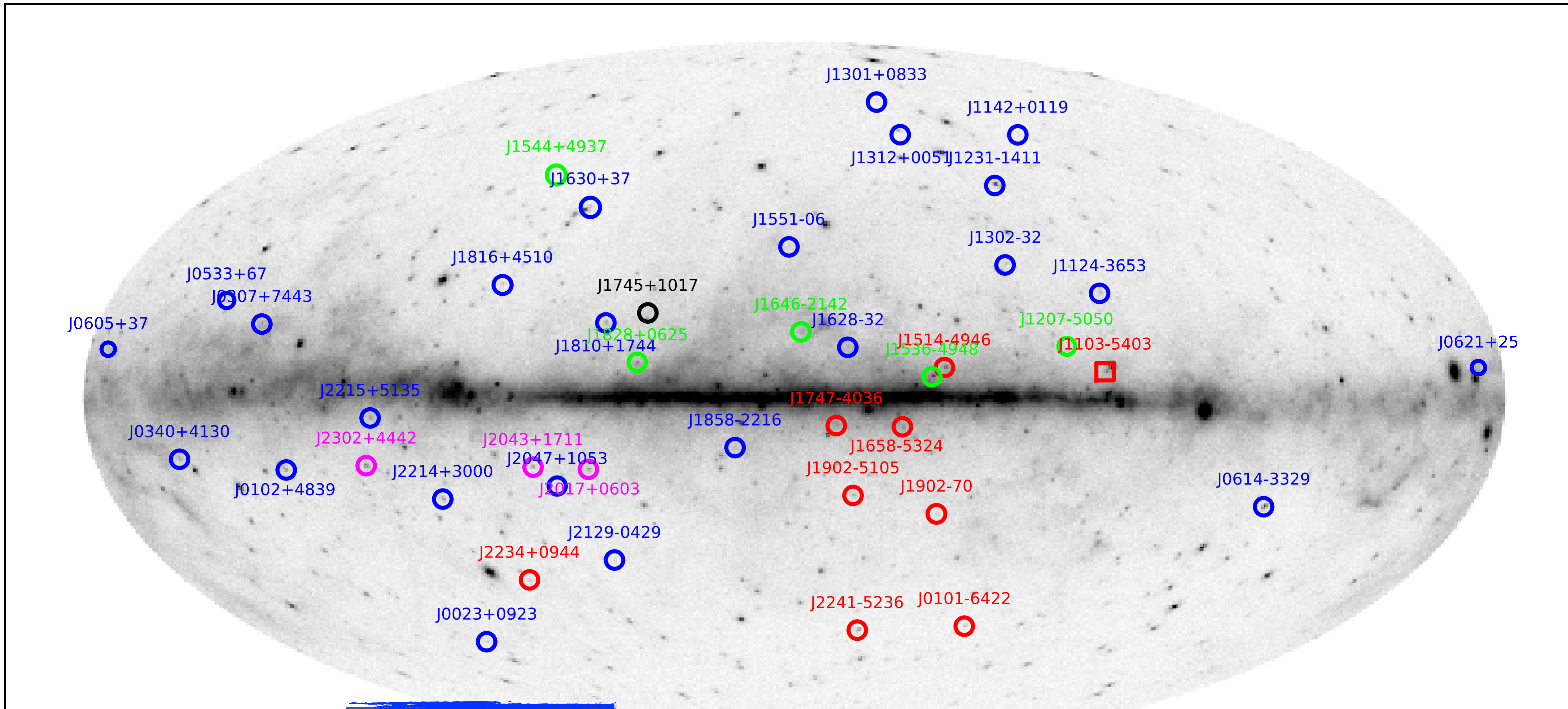


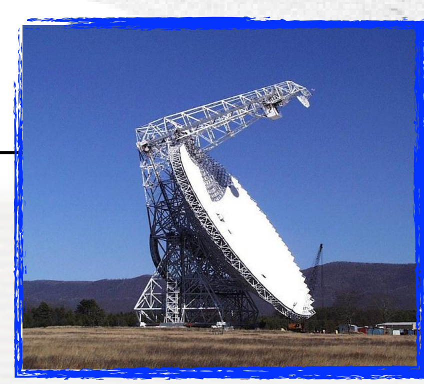

PSR J2043+1711: a 2.38-ms pulsar in a 1.48-d orbit, discovered in a LAT source with the Nançay radio telescope, later confirmed at the Green Bank and Arecibo telescopes.

(Guillemot et al., MNRAS 422, 1294, 2012)

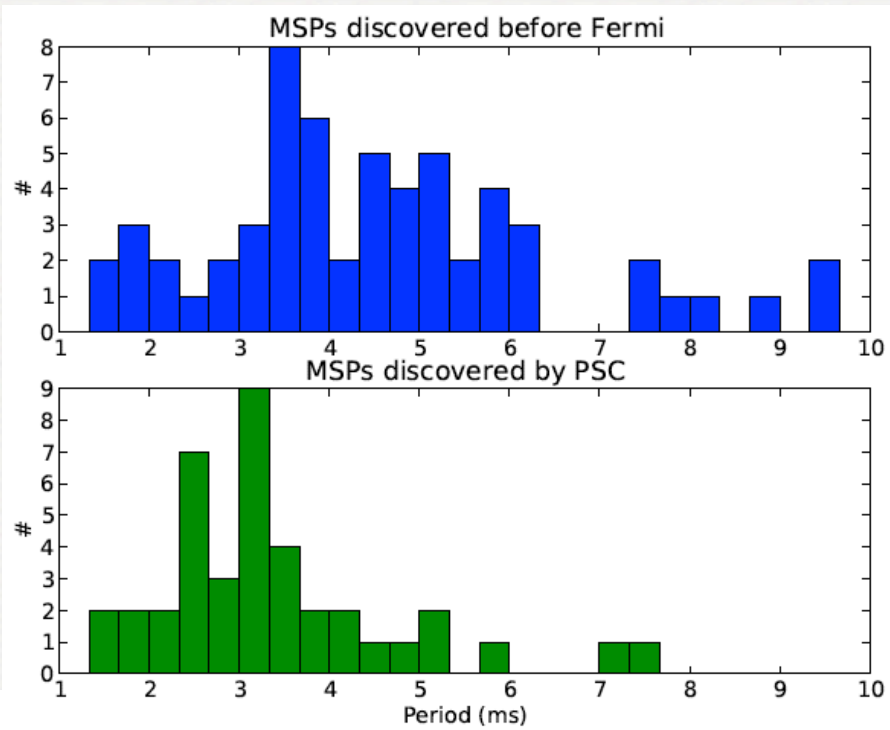
# 43 radio MSPs discovered!

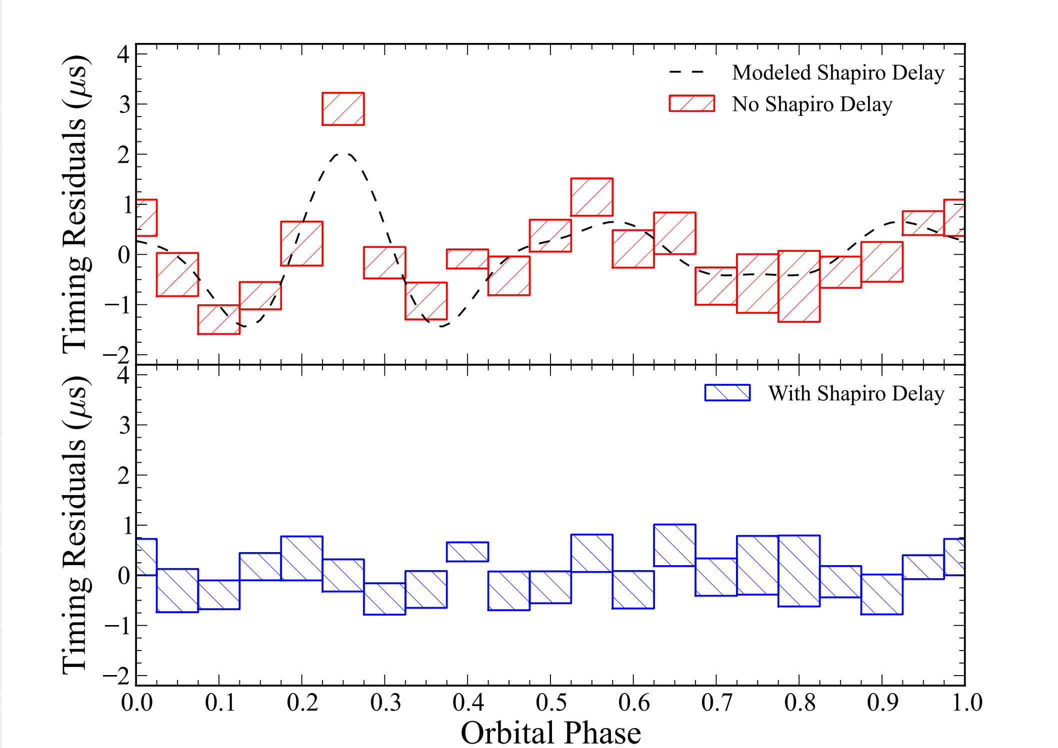
+ 4 other young pulsars. See Ray et al. (2012), arXiv: 1205.3089



# Results & prospects




Shapiro delay measurement for PSR J2043+1711, Guillemot et al., MNRAS 422, 1294 (2012)

Before *Fermi*, only ~70 Galactic field MSPs in 30 years of searching!

At least 10 "Black Widow" systems (only ~4 previously outside of globular clusters)

+ at least 4 "Red Backs": eclipsing pulsars with ~0.2 $M_\odot$ companions.

Several may be useful for pulsar timing arrays.

- Future *Fermi* LAT catalogs will provide new targets.
- Re-observations are important: eclipses, scintillation, RFI, etc.
- γ-ray and radio fluxes uncorrelated.

# Optical and X-ray studies of *Fermi* sources

Deep optical and X-ray observations conducted for bright unassociated sources.

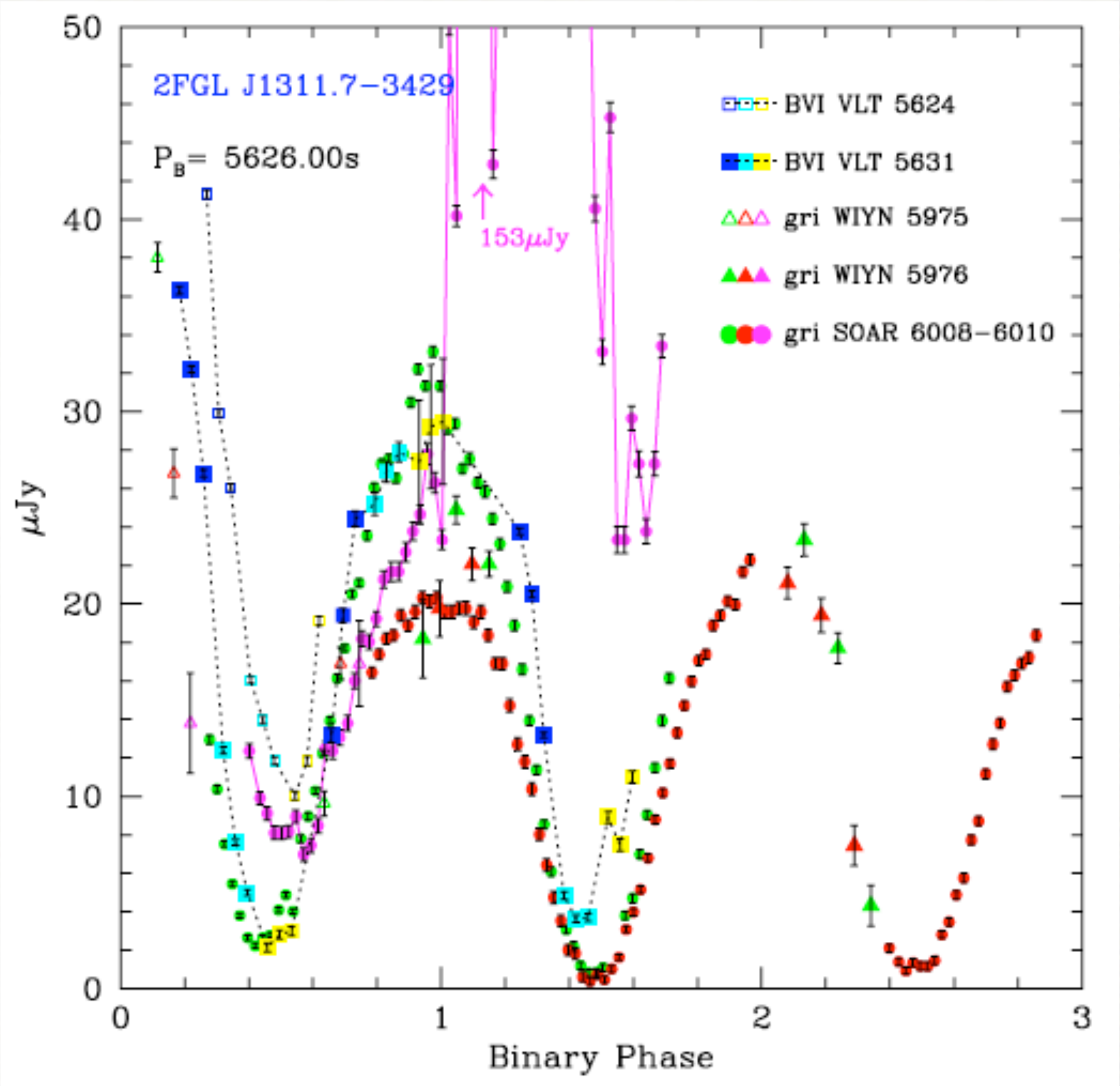
Two of them (0FGL J1311.9-3419 & J2339.8-0530) were found to exhibit hr-scale variability, indicative of orbital modulations:

- J1311-3430: $P_b$ ~ 1.6 hours
- J2339-0533: $P_b$ ~ 4.6 hours

(See Kong et al. 2012, Romani et al. 2011, Romani 2012).

Orbital parameters indicate light companions. Likely black-widow MSPs!

First radio-quiet MSPs?




From Romani ApJL 754, 25 (2012)

# PSR J1311-3430

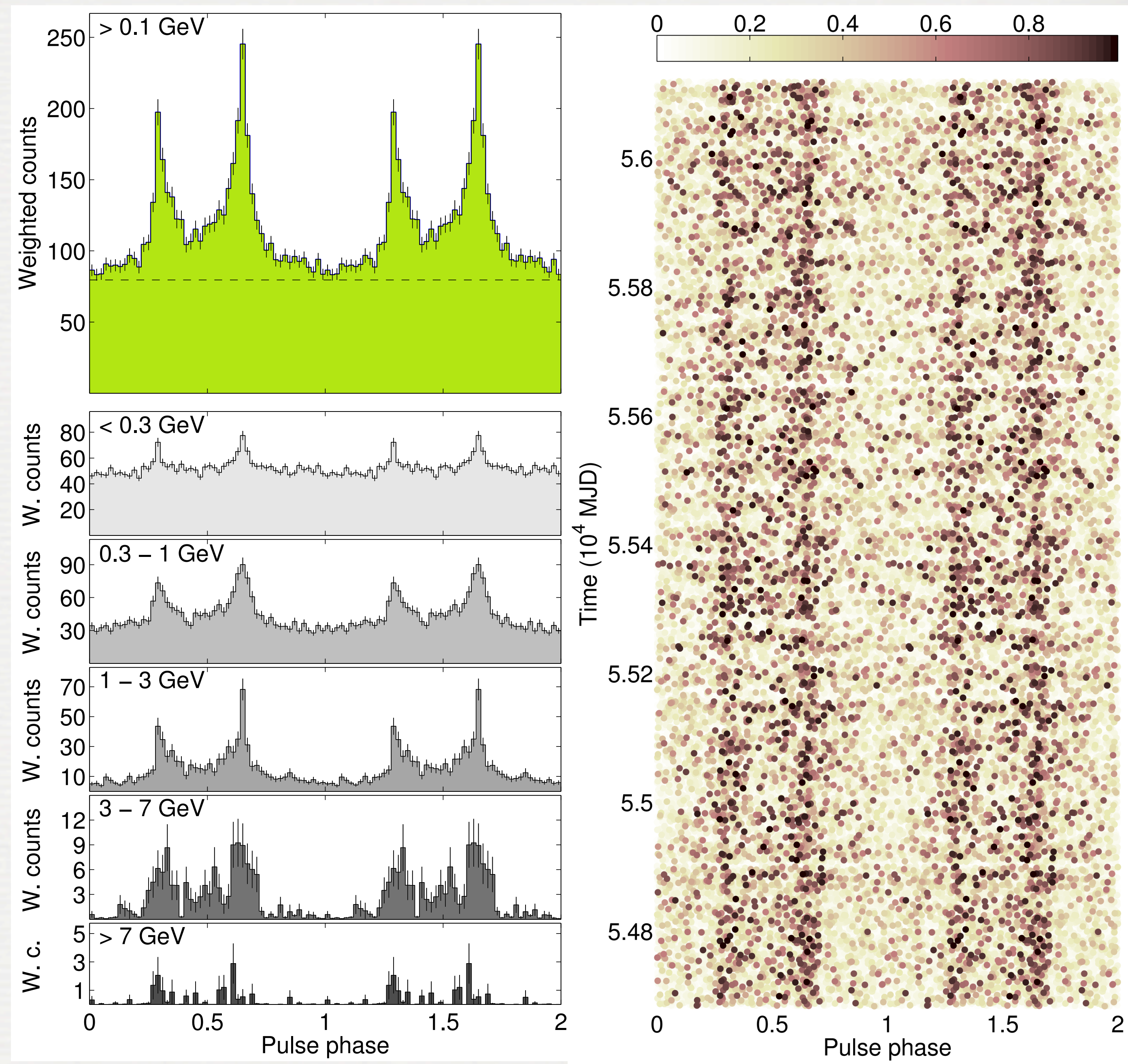
Pletsch et al., Science 338, 1314 (2012)

Black widow pulsar interpretation: nearly circular orbit. Sky location confined with good precision. Blind search feasible!

Still a challenge: uncertainties on orbital parameters large, and $f_0 + f_1$ unknown. 5-dimensional parameter space:

- spin frequency: $0 < f < 1400$ Hz
- its rate of change: $-5 \times 10^{-13}$ Hz/s $< f < 0$
- orbital period: $P_{orb} = 5626.0 \pm 0.1$ s
- time of ascending node: $T_{asc} = 56009.131 \pm 0.012$ MJD
- projected semi-major axis: $0<x<0.1$ lt-s

Computing done on the ATLAS cluster (6780 CPU-cores) in Hannover.




**First blind discovery of an MSP in γ rays!**

Shortest orbital period known for a rotation-powered pulsar, extremely compact system (separation ~0.75 $R_{sun}$).

Radio pulsations found later, also for 0FGL J2339.8-0530.

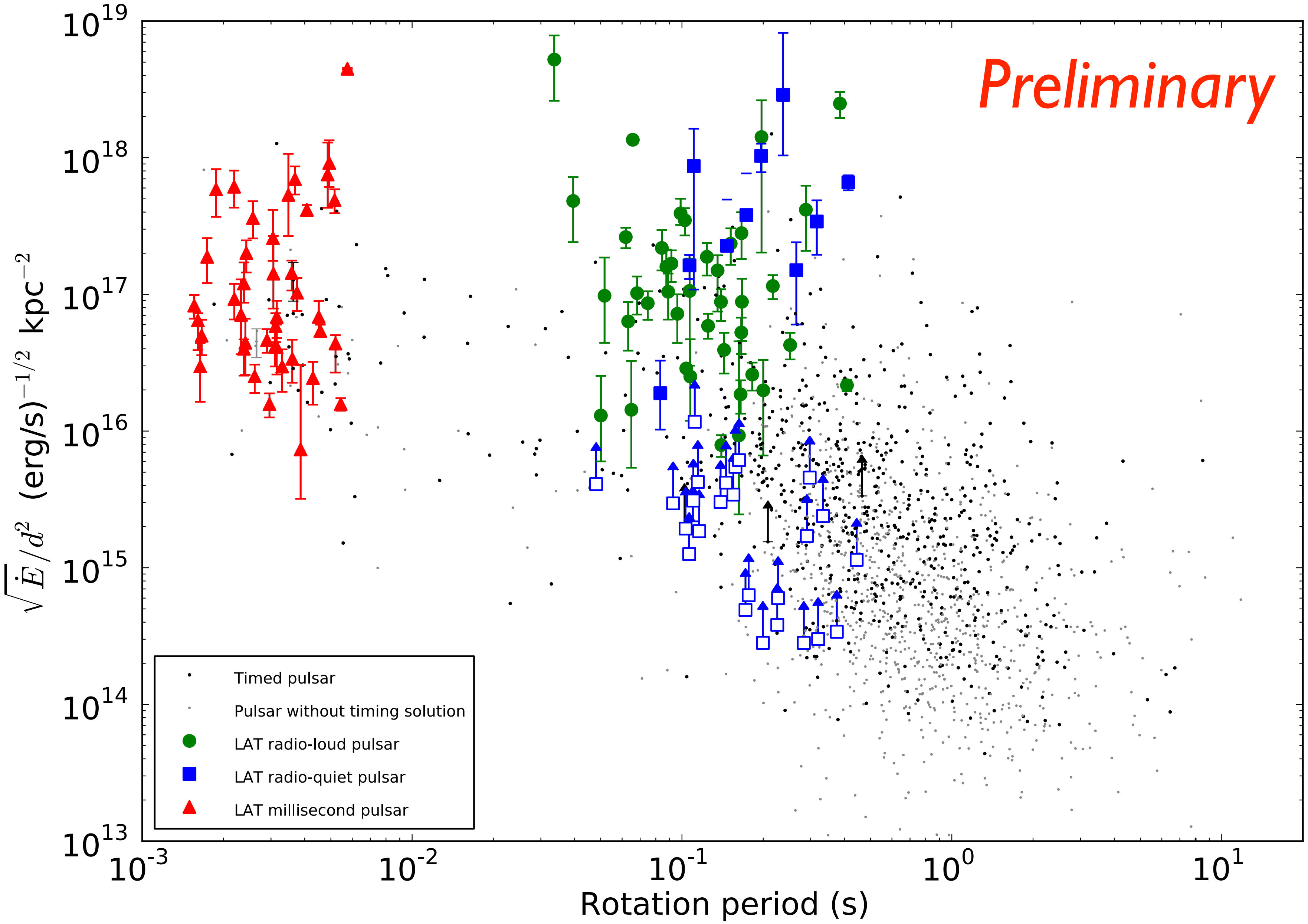
(Ray et al. ApJL 763, 13, 2013)


Sciencexpress

Binary Millisecond Pulsar Discovery via Gamma-Ray Pulsations

H. J. Pletsch,[1,2]* L. Guillemot,[3] H. Fehrmann,[1,2] B. Allen,[1,2,4] M. Kramer,[3,5] C. Aulbert,[1,2] M.

# Which pulsars are we seeing?




$L_\gamma$ depends on $\dot{E}$, as expected: γ-ray pulsars are nearby energetic objects.

Distance uncertainties very large, interpretation of non-detections not always trivial.

# Radio and γ-ray beaming

Selecting the 249 sources from the 2FGL catalog with >20 σ significance and average energy flux > 3 x $10^{-11}$ erg $cm^{-2}$ $s^{-1}$:

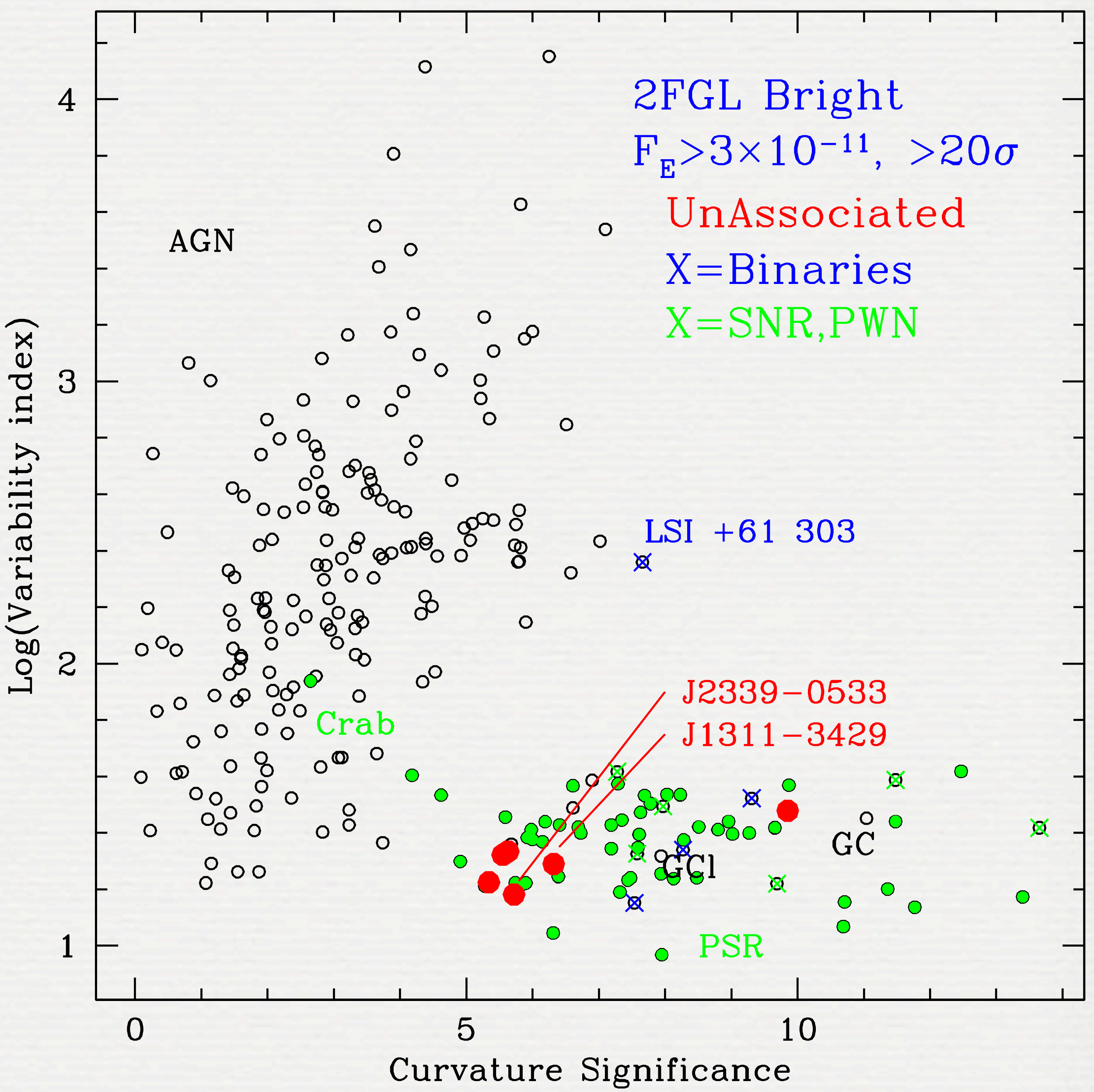
- 4 are still unidentified.
- 41 are young pulsars, incl. 17 radio selected.
- 14 are MSPs, all radio emitters.

(See Romani ApJL 754, 25, 2012)

If all 4 unidentified sources are radio-quiet MSPs, then >75% of MSPs are radio-loud.

2x γ-ray-selected young PSRs as radio-selected: γ-ray beams are likely larger.

However, the most energetic γ-ray pulsars are all detected in radio (Ravi et al. ApJL 716, 85, 2010). High altitude radio emission from high $\dot{E}$ pulsars, producing wider radio beams?




From Romani ApJL 754, 25 (2012)

# Summary

Pulsars are the dominant class of Galactic γ-ray sources. Pulsar emission from globular clusters also detected!

Light curves and spectra indicate that γ rays are emitted from the outer magnetosphere.

*Fermi* points radio telescopes to unknown MSPs. 50% population increase!

2nd Pulsar Catalog paper in preparation. Will be a great resource for population, light curve and spectral studies of γ-ray pulsars.

**Thank you for your attention!**