Fermi pulsar results and their implications

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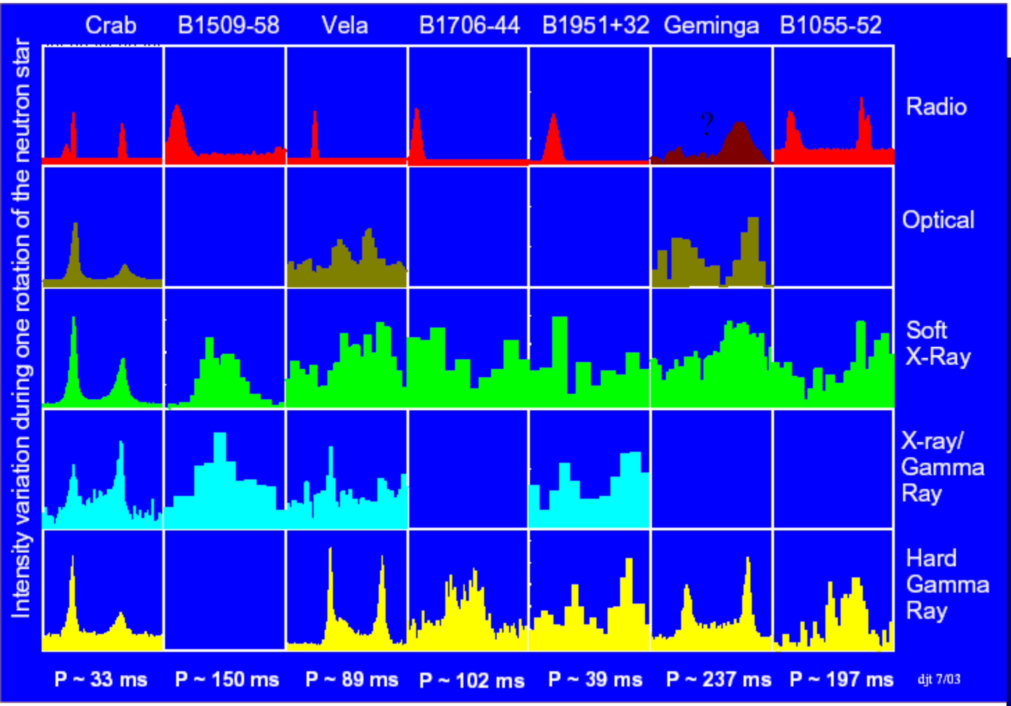
(INFN-Pisa)

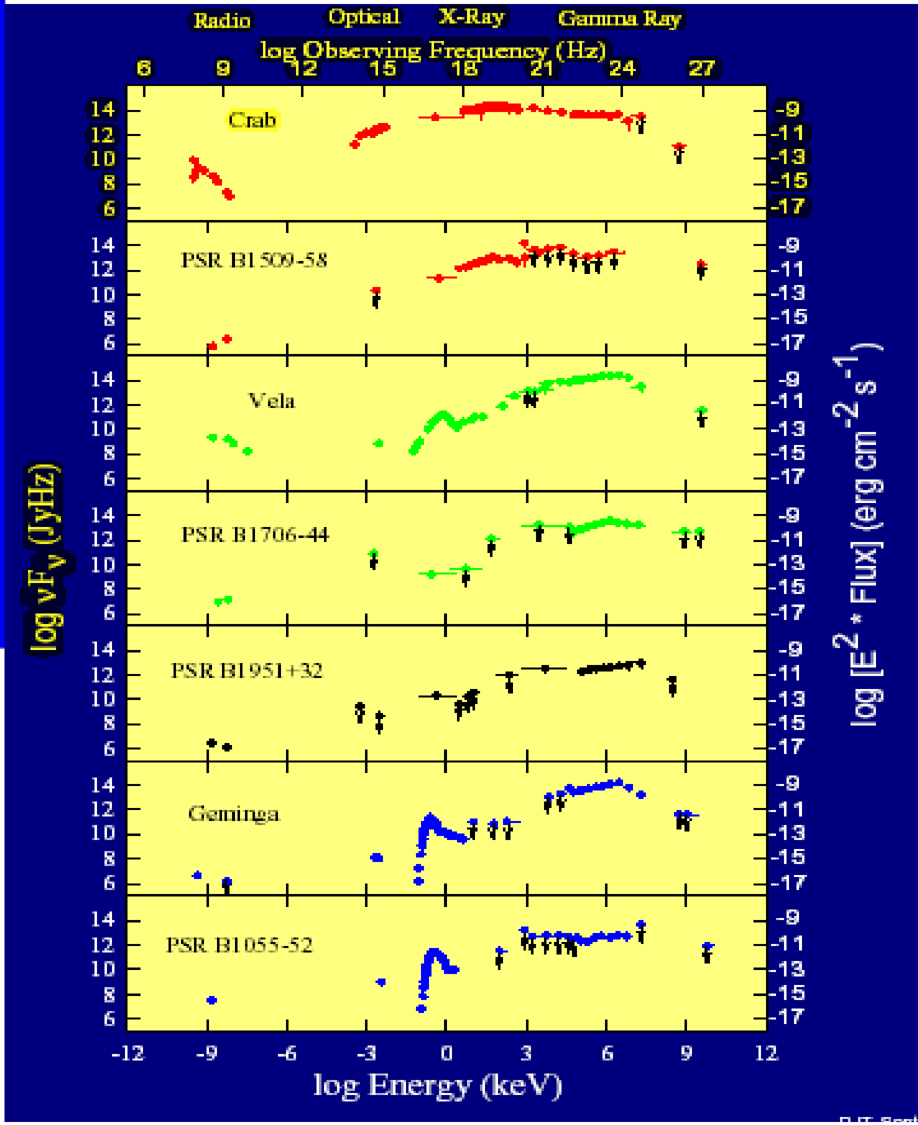
On behalf of the Fermi-LAT Collaboration and the Pulsar timing consortium

Cosmic ray backgrounds in dark matter searches
Albanova, January 26th 2010

Before Fermi…



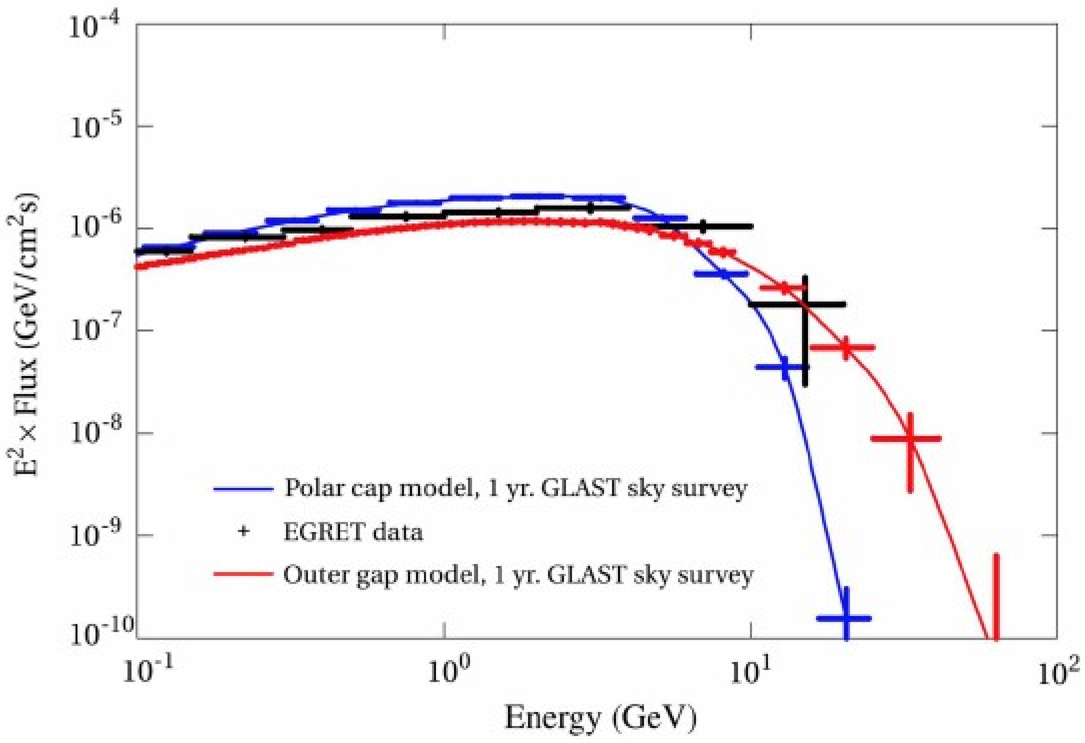
(From D.J.Thompson, 2003)



EGRET pulsars

LAT and pulsars: what we expected

- Large collection area - High sensitivity
- High-resolution timing
- Discovery of many new pulsars
- Detailed spectral studies



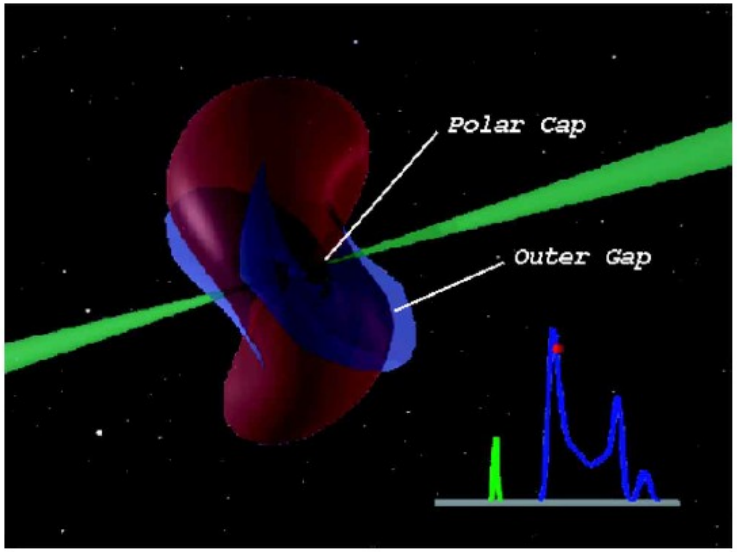


Figure 7-2 Three-dimensional simulation of the Vela pulsar. The spin axis is vertical. The red surface is the closed zone, the polar cap is at the base of the green (radio) beam, and the outer gap surface is in blue. The light curve, calculated for the Outer Gap model, has the same color coding.

- ***Plots from GLAST Science document***

LAT for pulsar studies

Many improvements over EGRET!

- Observations
  - Observing in scanning mode (uniform coverage every ~3 hr)
  - Large set of known radio pulsars+contemporaneous ephemerids
  - Many deep searches and multi-λ campaigns on brighter 3EG sources
  - New time differencing technique – UCSC team *(Atwood et al 2008)*

- LAT performances
  - Large Field of View (~2.4 sr)
  - Excellent absolute timing (<1 μs)
  - Sharp PSF (0.6 68% cont. angle at 1 GeV on axis)
  - Large effective area (~8000 cm^2 on-axis)

Pulsar timing for *Fermi*

- Campaign to time 224 high Edot "Egret-like" pulsars
- *Excellent* working relation with the radio and X-ray pulsar experts.
- In addition 544 pulsars with observations shared with the LAT team

Pulsar Timing for the *Fermi* Gamma-ray Space Telescope

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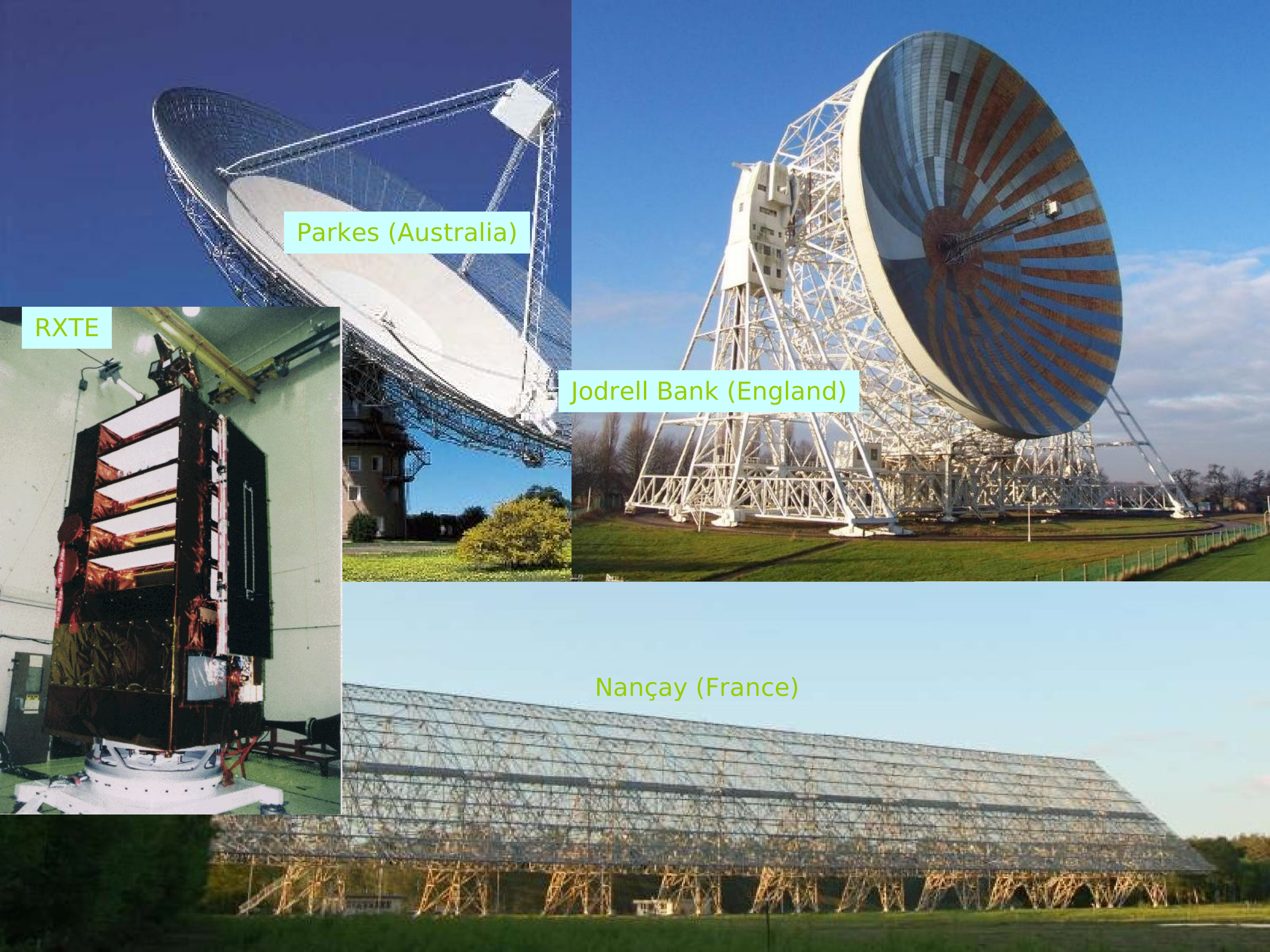
Preprint online version: September 4, 2008

ABSTRACT

We describe a comprehensive pulsar monitoring campaign for the Large Area Telescope (LAT) on the *Fermi Gamma-ray Space Telescope* (formerly GLAST). The detection and study of pulsars in gamma rays give insights into the populations of neutron stars and supernova rates in the Galaxy, into particle acceleration mechanisms in neutron star magnetospheres, and into the "engines" driving pulsar wind nebulae. LAT's unprecedented sensitivity between 20 MeV and 300 GeV together with its 2.4 sr field-of-view makes detection of many gamma-ray pulsars likely, justifying the monitoring of over two hundred pulsars with large spin-down powers. To search for gamma-ray pulsations from most of these pulsars requires a set of phase-connected timing solutions spanning a year or more to properly align the sparse photon arrival times. We describe the choice of pulsars and the instruments involved in the campaign. Attention is paid to verifications of the LAT pulsar software, using for example giant radio pulses from the Crab and from PSR B1937+21 recorded at Nançay, and using X-ray data on PSR J0218+4232 from XMM-Newton. We demonstrate accuracy of the pulsar phase calculations at the microsecond level.

Key words. pulsars:general – Gamma-rays:observations – Ephemerides

A&A 492, 293 (2008)

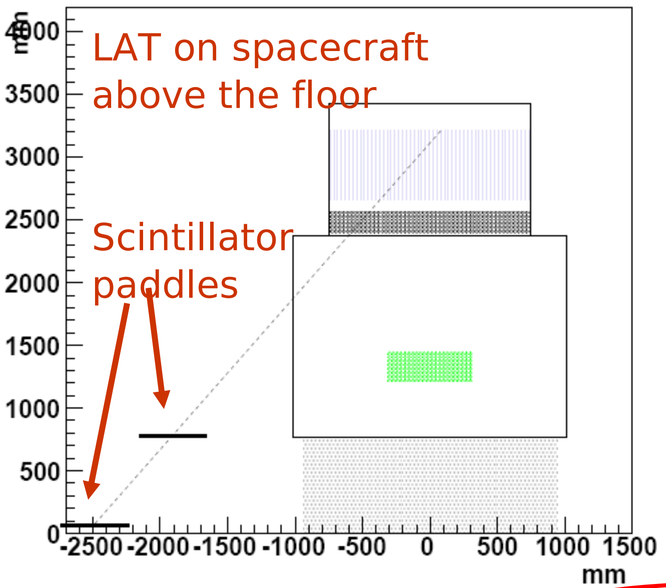

Parkes (Australia)
RXTE
Jodrell Bank (England)
Nançay (France)

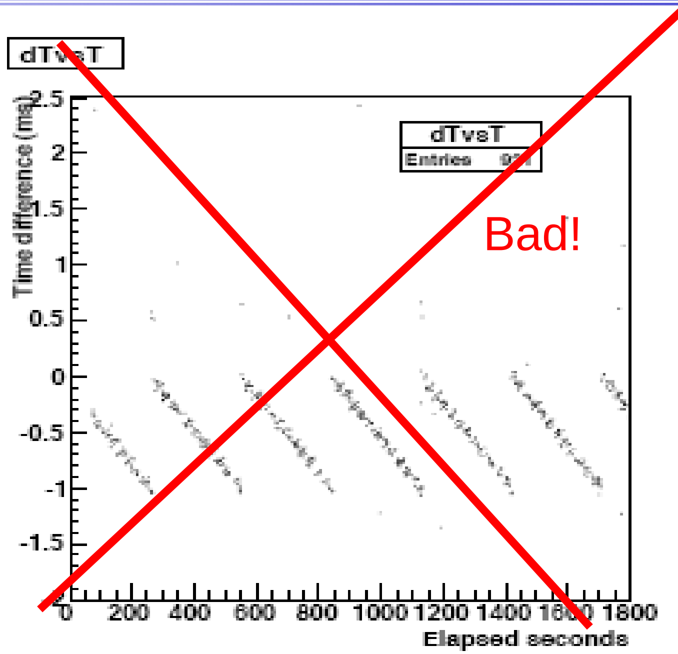

GBT (US)


Westerbork WSRT
(Netherland)


Arecibo (Puerto rico)

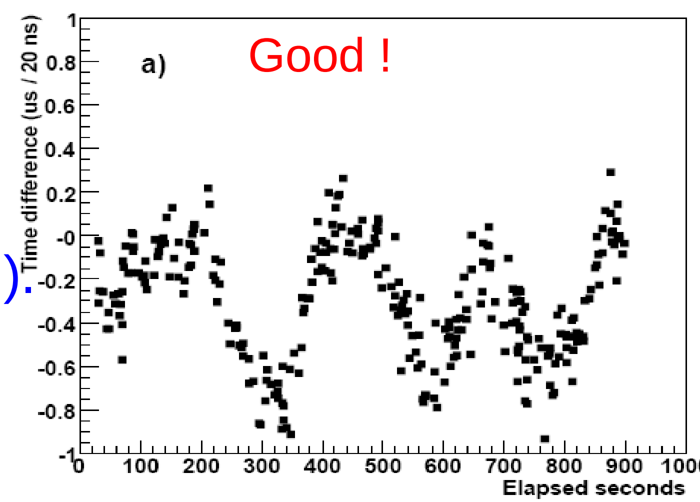
Ground tests of Fermi clocks:
Cosmic ray muons through LAT and standalone detector





GPS of Fermi LAT compared
to a standalone GPS.

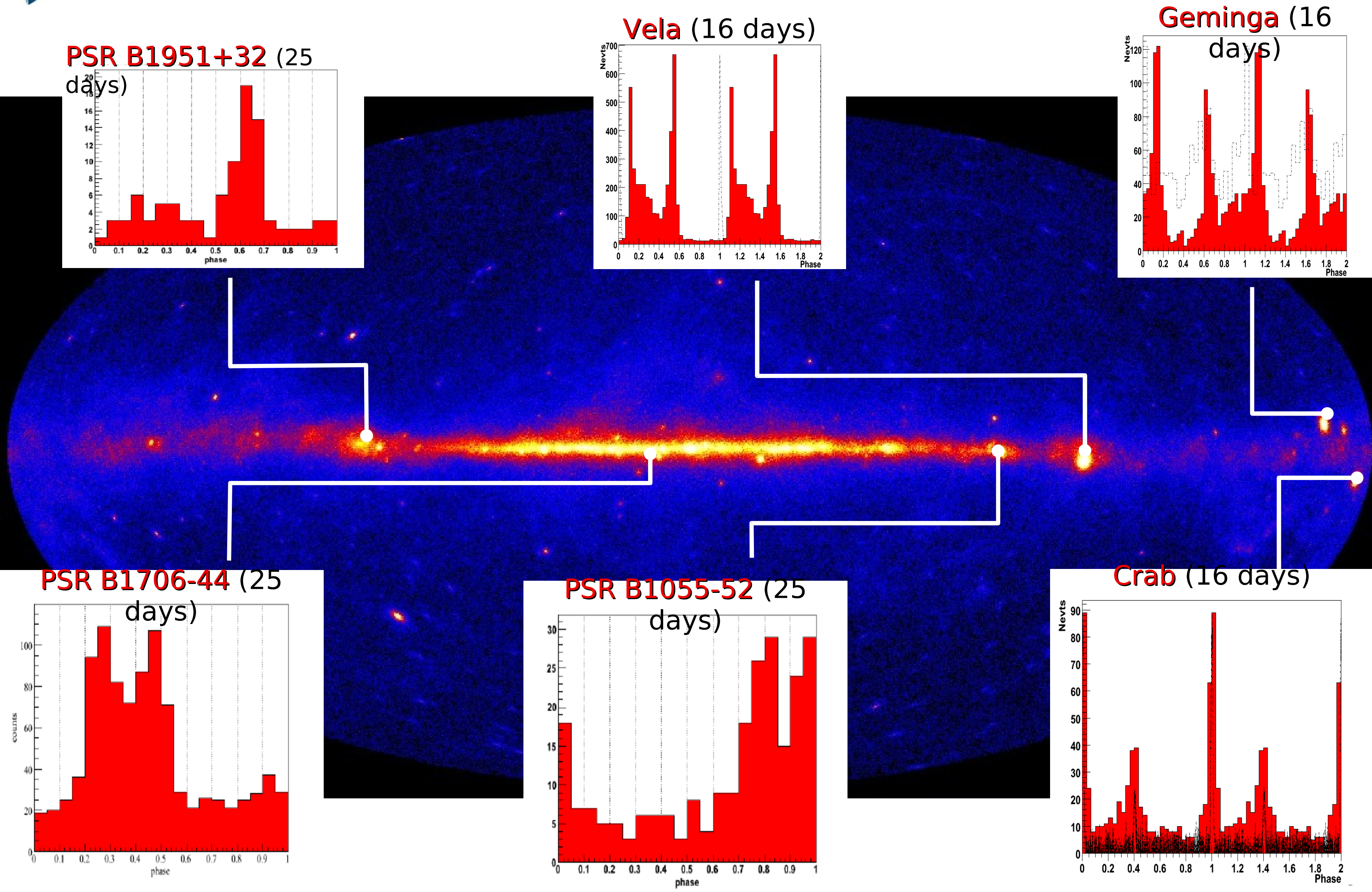
Big bug found and fixed (millisecond sawtooth).
Would have compromised γ-MSP discovery



Sub µs accuracy relative to UTC

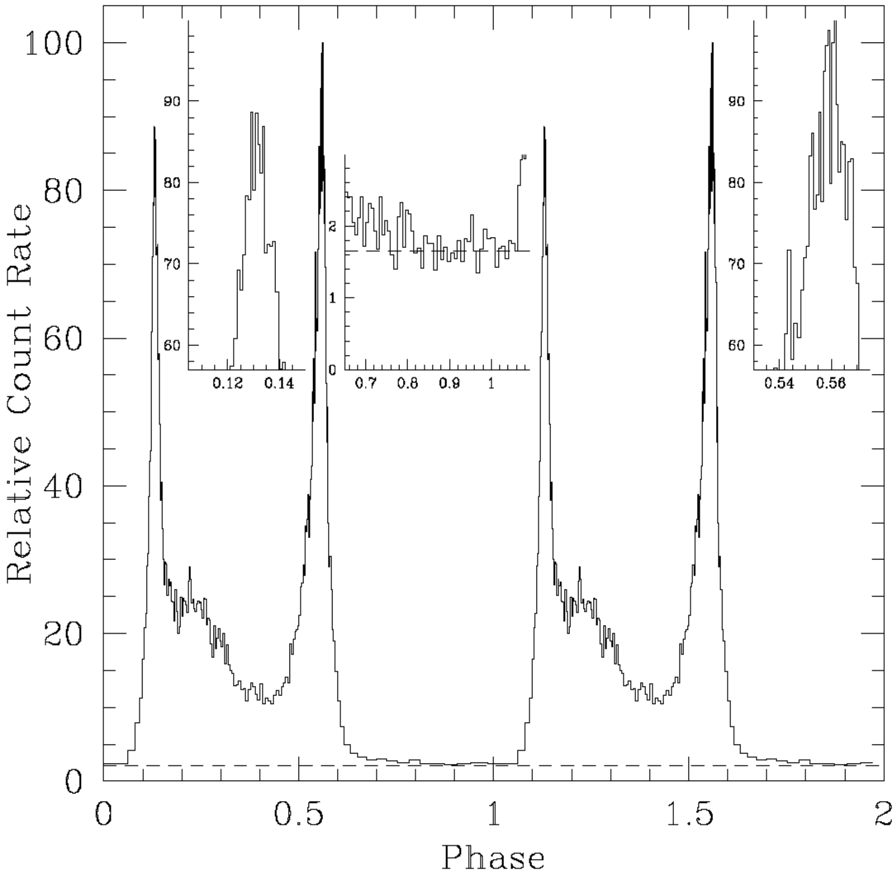
The On-orbit Calibrations for the Fermi Large Area Telescope
Abdo, A. A. et al. 2009, Astropart. Phys., 32, 193

After launch: the usual suspects



First Fermi view of Vela

Abdo et al. 2008, ApJ 696, 1084

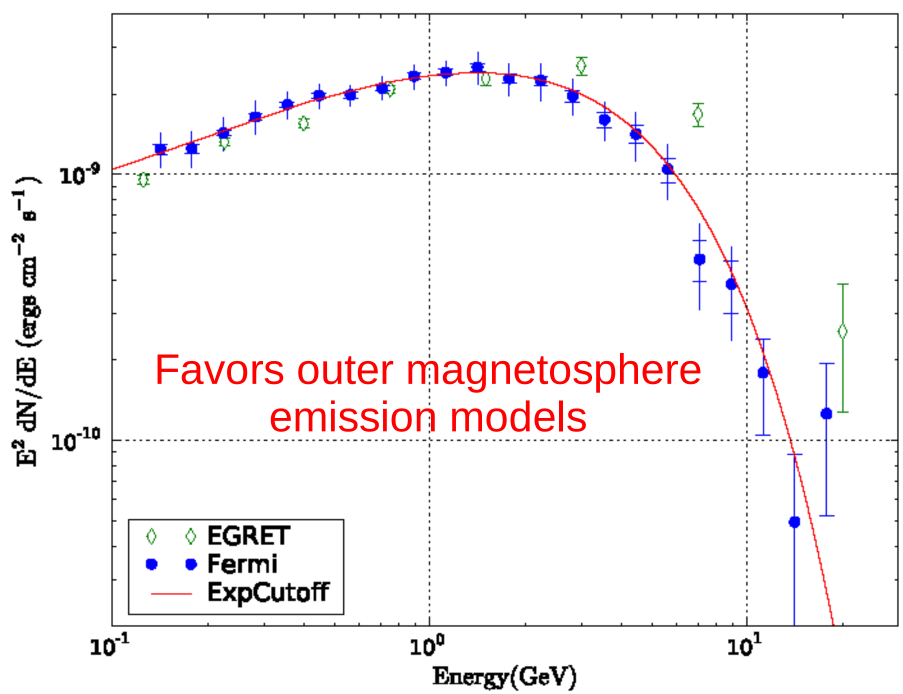


- Remarkably sharp peaks (features to ~0.3 ms)
- High statistics (~50k photons)

Exponential cutoff

$$\Gamma = 1.51^{+0.04}_{-0.05}$$

$$E_c = 2.9 \pm 0.1\,\mathrm{GeV}$$

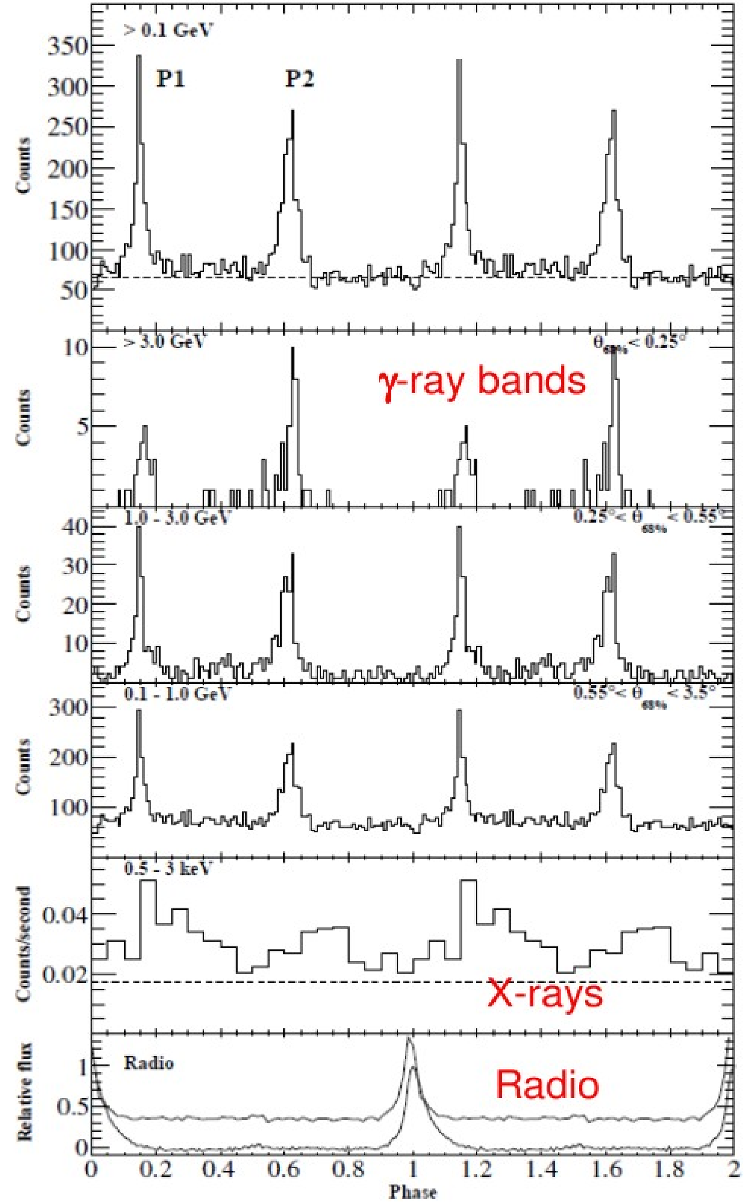


PSR J2021+3651

First new pulsar seen with the LAT
Multi-wavelength Pulsations

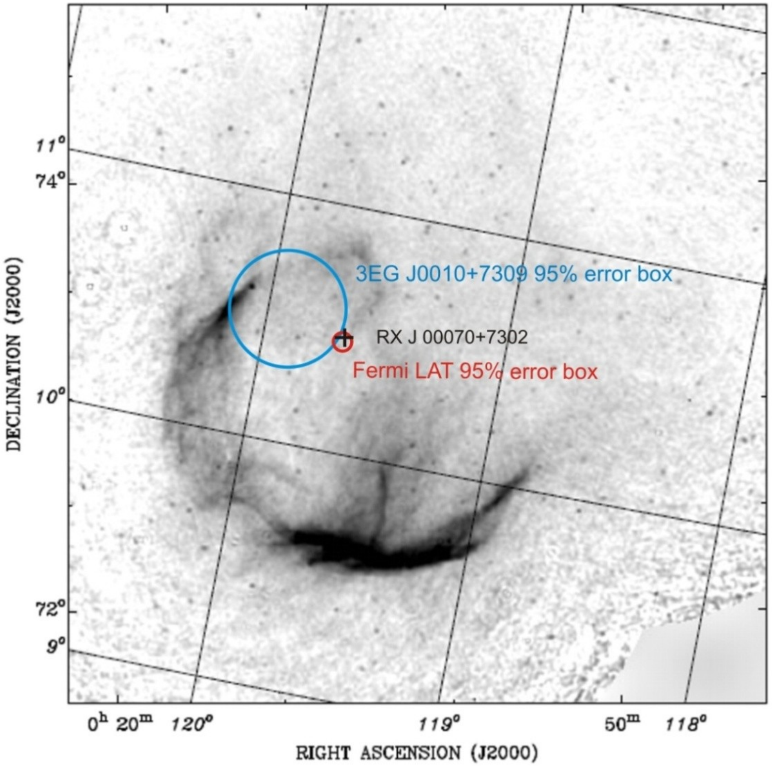
- P2/P1 ratio grows with energy
- No significant change in ϒpeak location or shape with energy
- Chandra X-ray light curve (Hessels et al 2004, re-analyzed by Andrea De Luca):
    - pulsed at the 4-sigma level
    - appears roughly aligned with ϒpeaks (interpretation in OM model)
- Radio polarization data provides "tilt" of the magnetic dipole axis
    - "RVM" = Rotating Vector Model

Very high
quality radio/gamma synergy



LAT "blind" search for pulsars

- Search is "blind" in terms of timing parameters
  - Spinning period: P
  - Period derivative: Pdot
- Where do we look?
  - ~100 "interesting" locations in the sky
  - ~200 LAT unidentified sources
- How do we search?
  - Time-differencing technique (Atwood et al. 2006, Ziegler et al. 2008)
  - Once a good candidate is found, standard pulsar tools are used: e.g. PRESTO, Tempo2

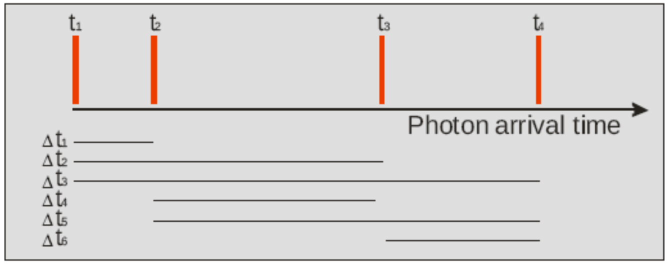


The region of CTA1 SNR

The “Time-Differencing” Technique

- Periodicity in photon arrival times will also show up in differences of photon arrival times.
- Time differences cancel out long term phase slips and glitches because differencing starts the "clock" over and over, and over...
- Despite the reduced frequency resolution (and therefore number of bins), the sensitivity is not much reduced because of a compensating reduction in the number of fdot trials.

Atwood et. al., **ApJ Lett., 652, 49 (2006)**
Ziegler et. al., **ApJ 680, 620 (2008)**

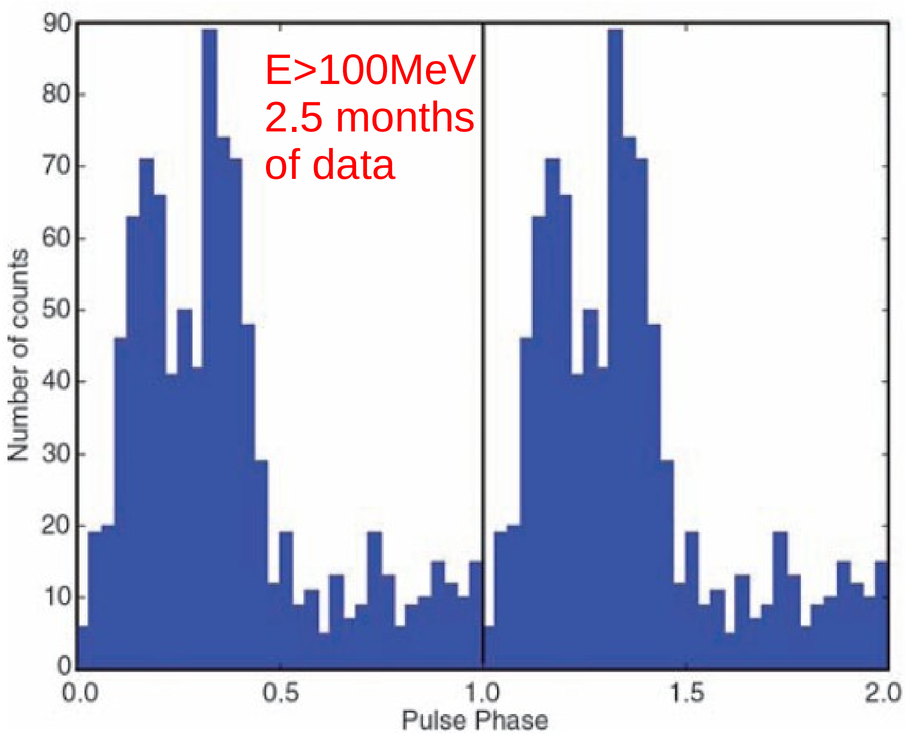


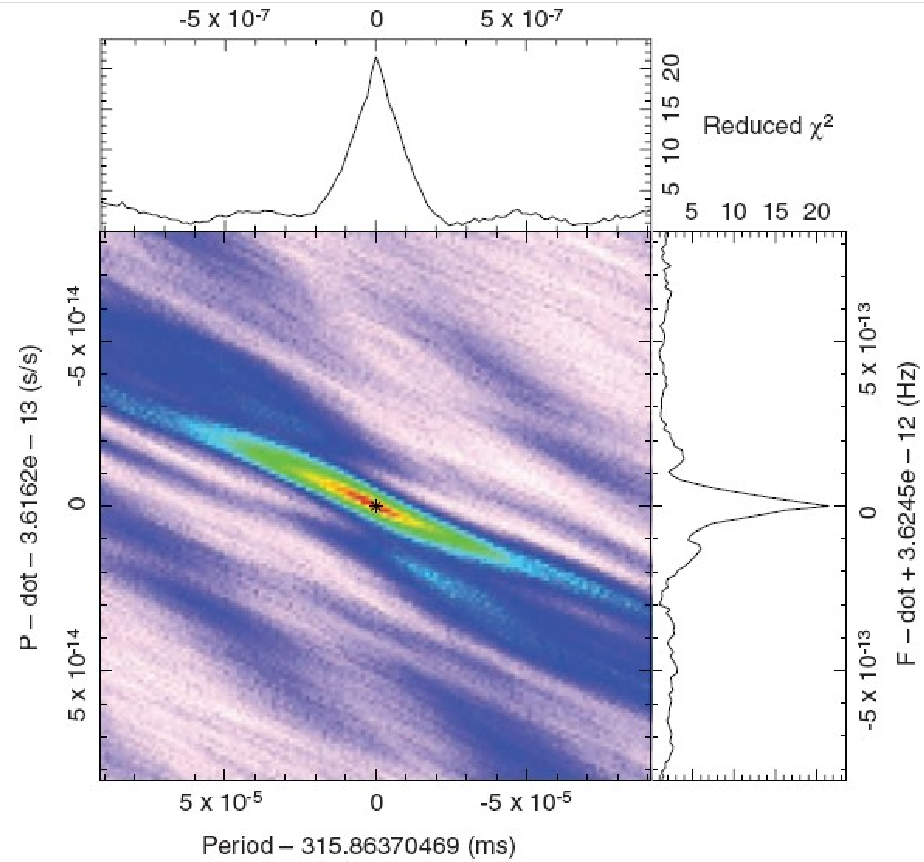
Credit: M. Ziegler

# of FFT bins = f * t_{max_diff} * 2
PC with 2GB can handle 33 x 10^6 bin FFT

The pulsar in CTA 1

- First *discovery* of the LAT
  - PSR J0007+7309
  - ~14000 years old
  - Embedded in CTA1 SNR
- *Science 322 (21 nov 08)*





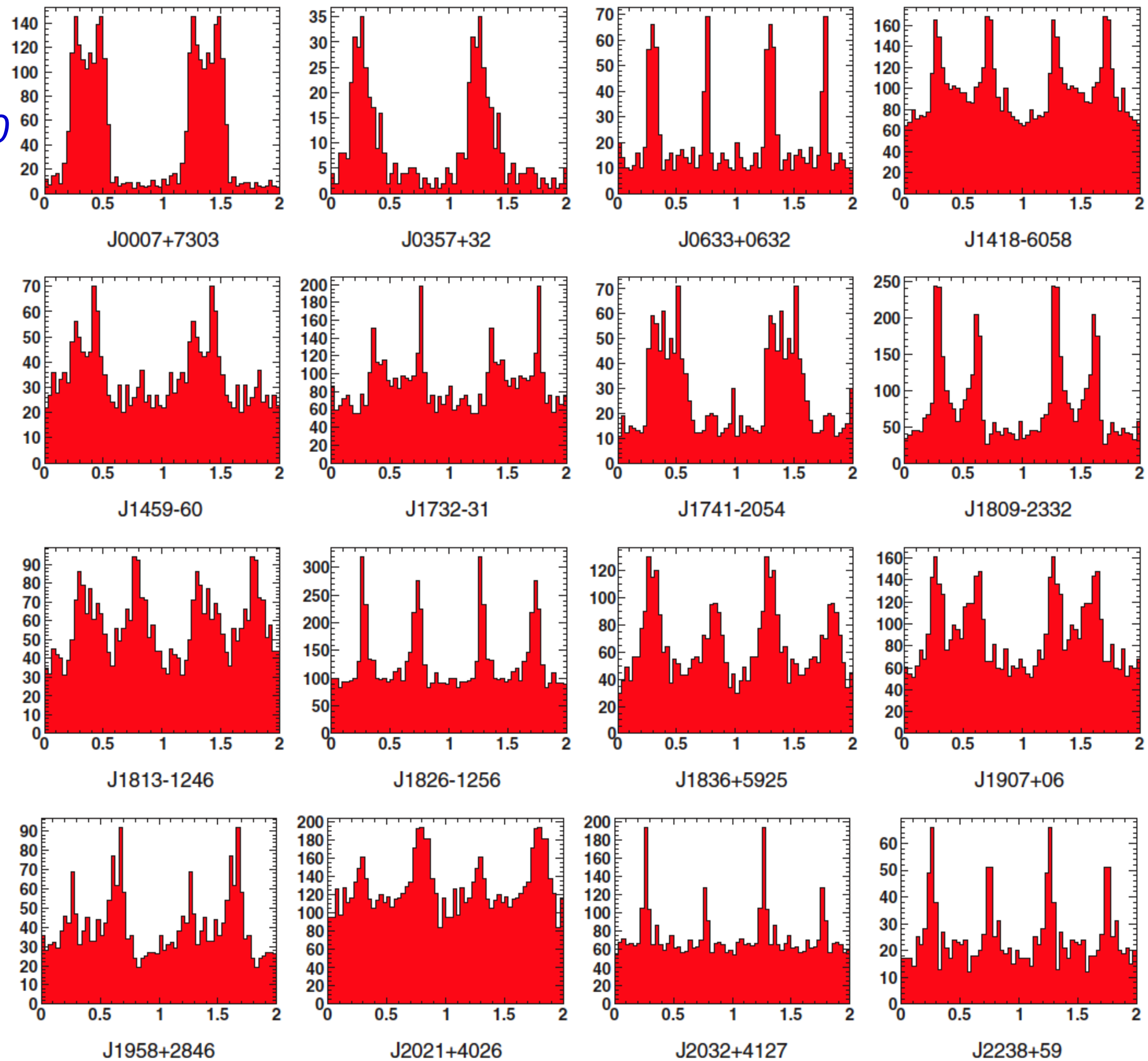
- P = 316.86 milliseconds
- Pdot = 3.614 x 10-13 s/s

More γ-ray "selected" pulsars

Blind search pulsars

Abdo et al 2009 Science 325 840

- 16 pulsars initially published
- 8 more recently discovered



- Favor broad gamma-ray emission but narrow radio cone

- 3 out of the 24 gamma-ray selected pulsars were found in radio !

- Detected at Parkes & GBT

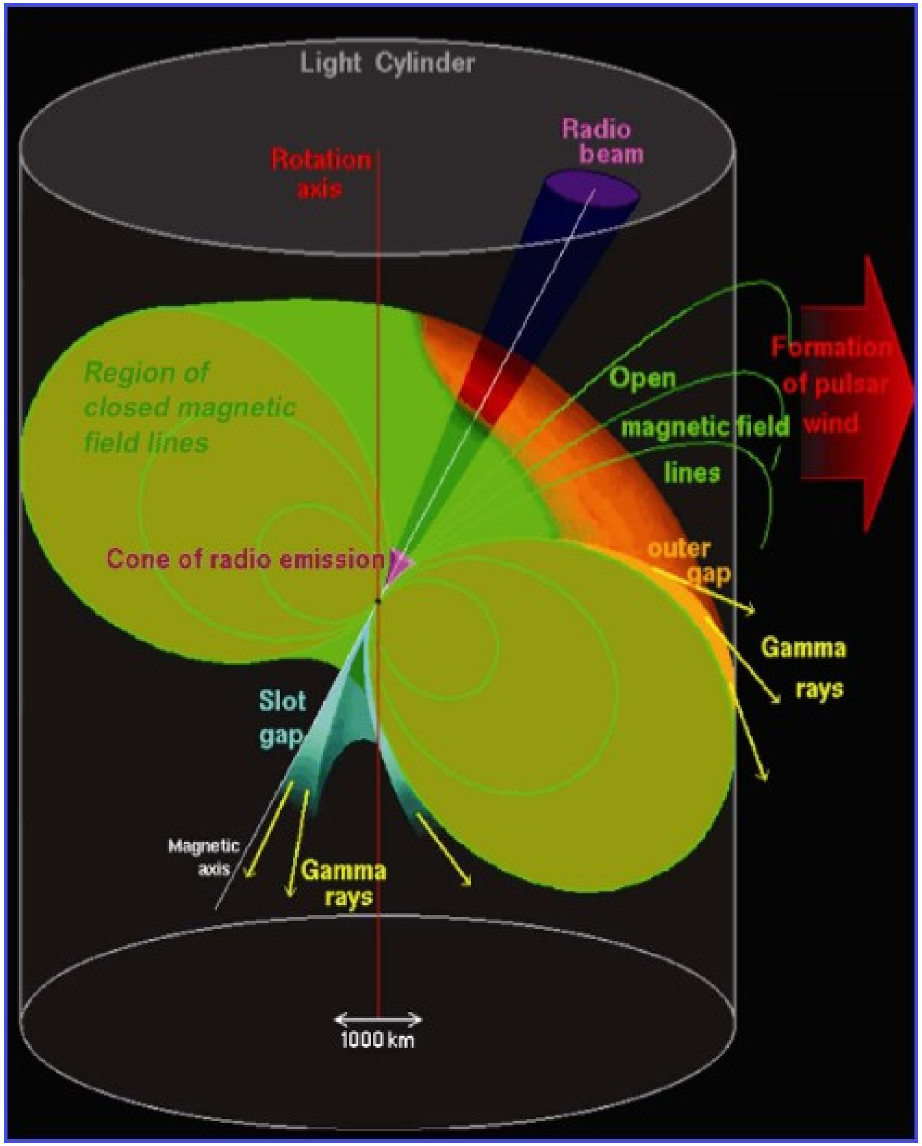
γ -ray or radio "selected" pulsars ?

- Fan-like gamma beam
    - From "outer" or "slot" gap ?

- Radio vs gamma pulse profiles
    - Powerful model discriminant

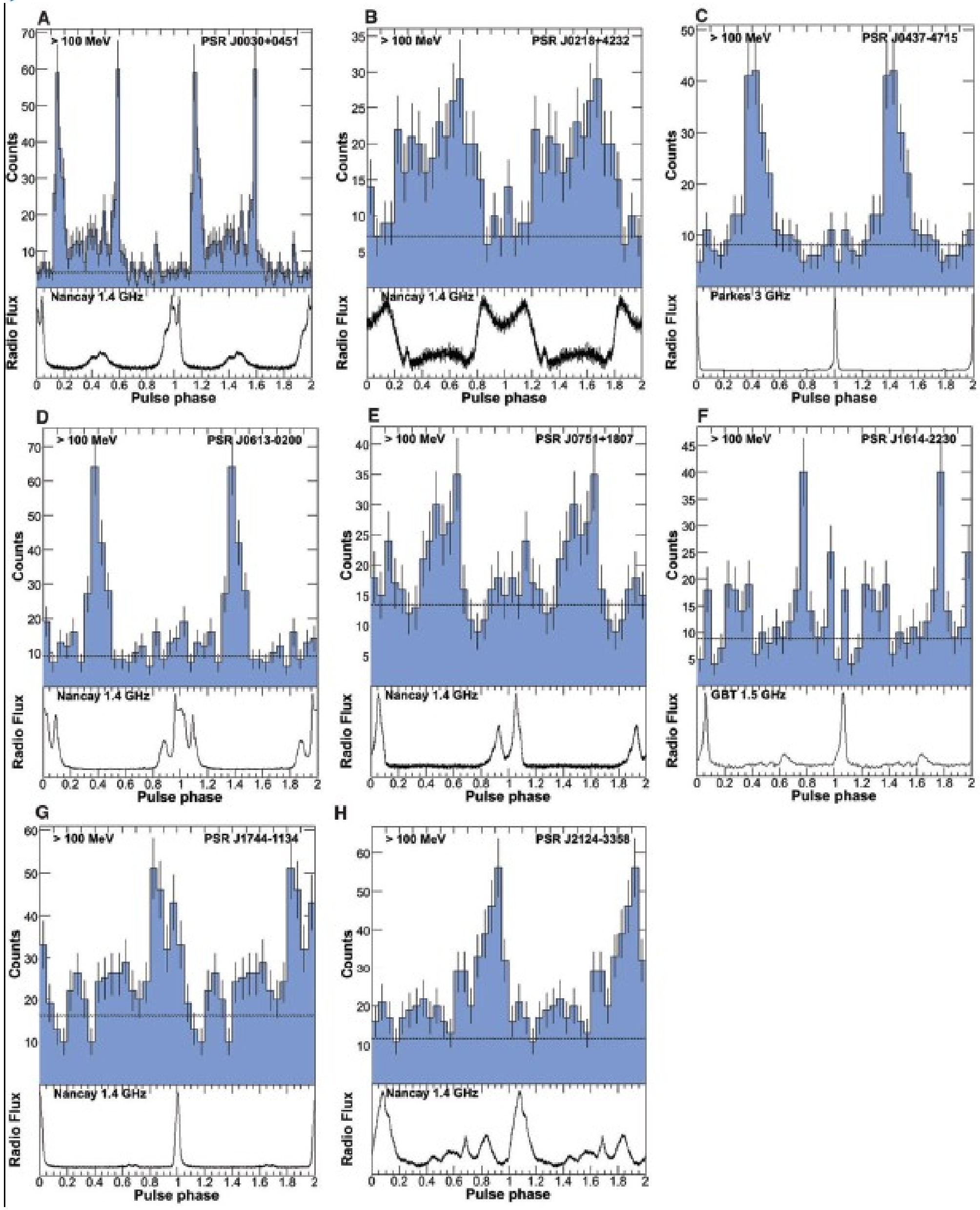
- Many parameters to take into account
    - Line of sight
    - Emission regions
    - Emission spectrum
    - Distances

With more than 20 gamma-ray selected pulsars, we have a new population to study...



Fermi Gamma-ray Space Telescope

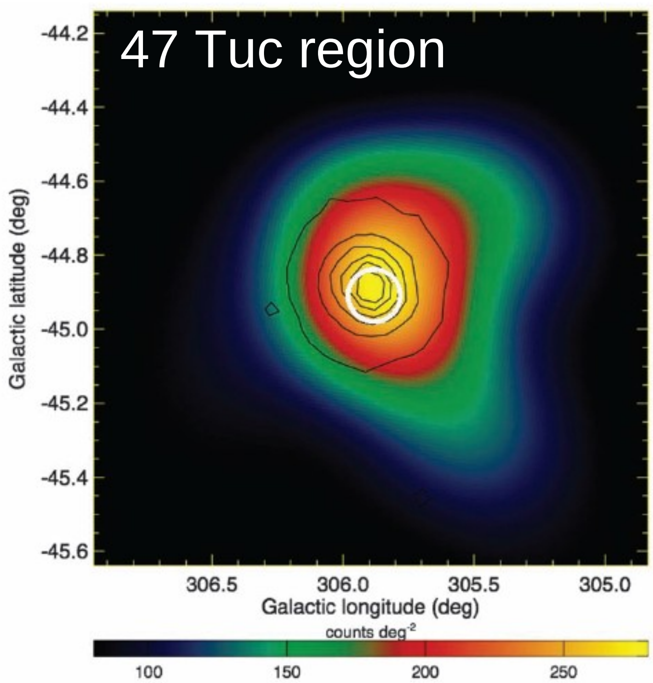
Gamma-ray millisecond pulsars

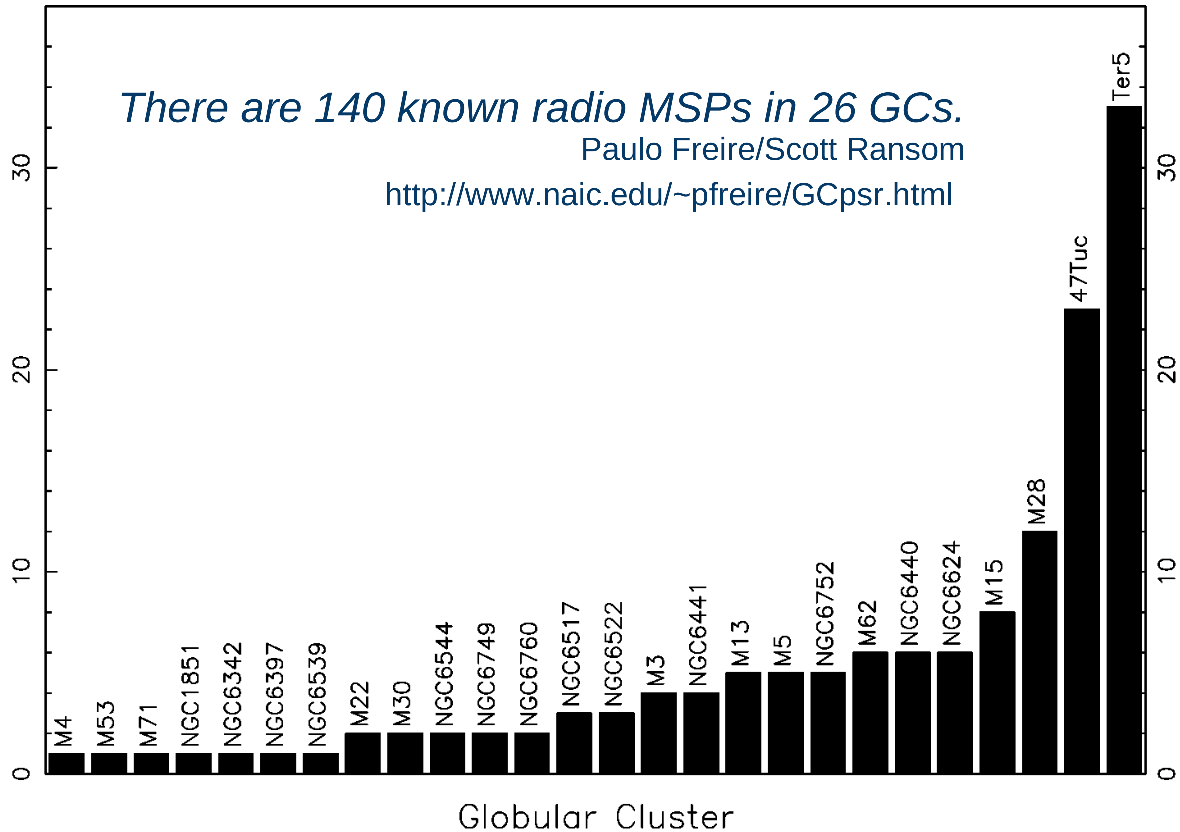


- 8 Millisecond pulsars
  - Abdo et al 2009 Science 325 848
  - 5 are in binary orbits
- A ninth near submission
  - PSR J0034-0534
  - radio and peaks *aligned*
- ...and more to come.

MSPs, the old recycle pulsars, have similar light curves and spectra as the young pulsars, suggesting the same emission mechanism.

MSPs in globular clusters?

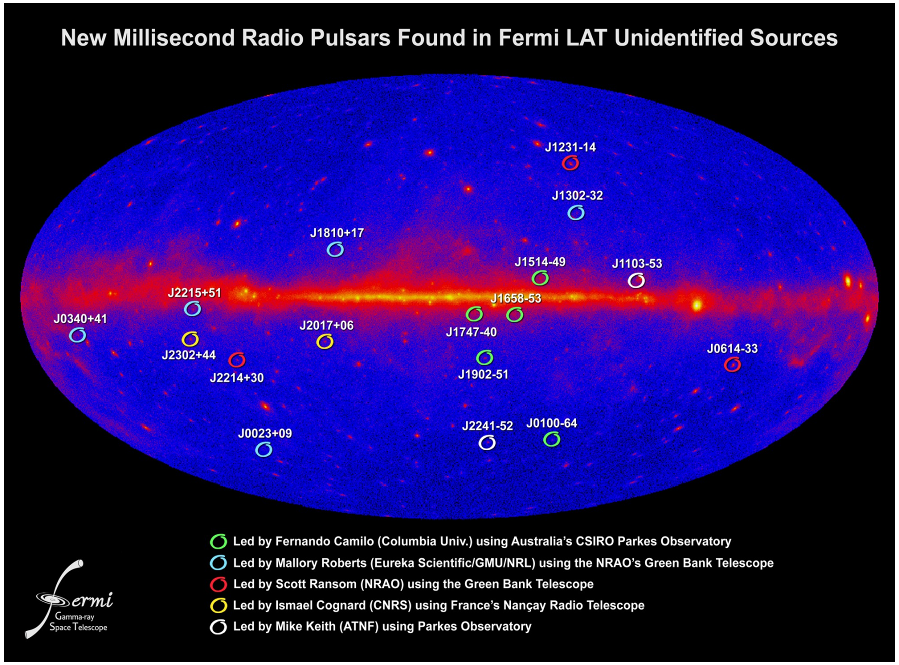




- Detection of 47 Tuc as a steady γ-ray source *(Science325,845)*
  - Number of gamma-ray pulsar lies between 7 and 62 at a 95% level
  - Very likely that MSPs are the primary population of gamma-ray sources
  - ➡ Pulsed searches on-going

Many UFOs are radio MSPs

- UFO: Unidentified Fermi-LAT Object
  - The *Pulsar Search Consortium* was setup to look for pulsation in other wave length.
  - 17 millisecond Radio pulsars found in Fermi-LAT unidentified sources !
- Closing the loop
  - Now studying these MSPs to understand whether they pulse in gamma-ray too...
  - Steady UFO → search for pulsation in radio → find pulsation in radio → use radio ephemerids to search for pulsation in gamma-rays



NASA Press release January 5th 2010

Nature's Most Precise Clocks May Make "Galactic GPS" Possible

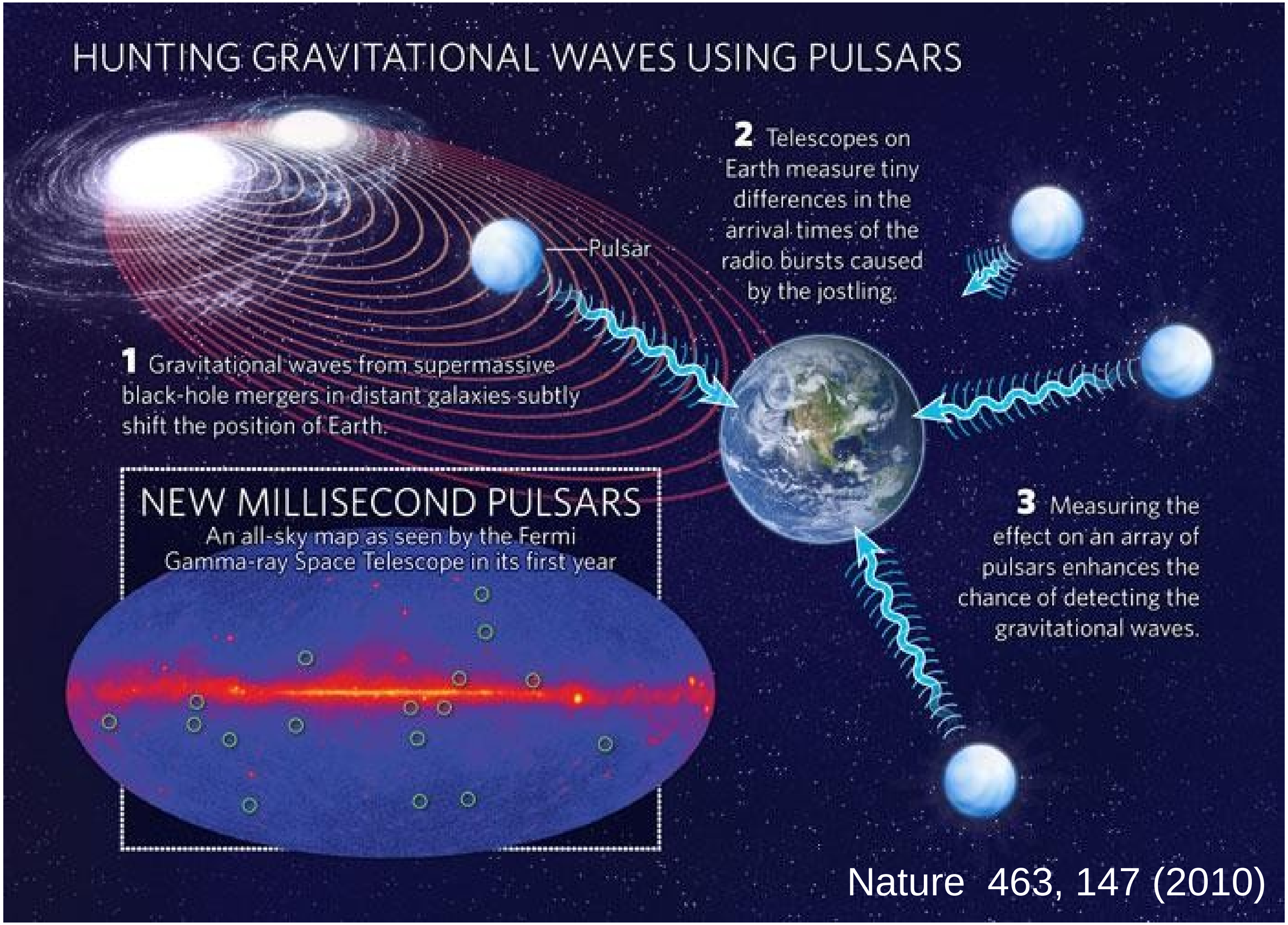
http://www.nasa.gov/mission_pages/GLAST/news/galactic-gps.html

Nature news January 13th 2010

Pulsar watchers race for gravity waves

http://www.nature.com/news/2010/100113/full/463147a.html

MSPs and gravitational waves



Many Galactic EGRET unidentified sources are pulsars

- 3EG J2033+4118 coincides with the TeV source near Cyg OB2.
  - Shocks between the winds of massive stars?
    - T. Montmerle, ApJ 231, 95-110 (1979)
    - M. Cassé & J. Paul, ApJ 237, 236-243 (1980)
    - R. Mukherjee et al, ApJ 589, 487-494 (2003)
  - No! LAT PSR J2032+4127
- 3EG J2021+3716 coincides with the open cluster Berkeley 87.
  - A hadron accelerator driven by shocks from winds from WR star ?
    - W. Bednarek MNRAS 382, 367 (2007) and references therein
  - No! radio PSR J2021+3651 in the "Dragonfly" PWN.
- 3EG J2020+4017 associated with SNR γ Cygni.
  - Shock acceleration?
  - No! LAT PSR J2021+4044

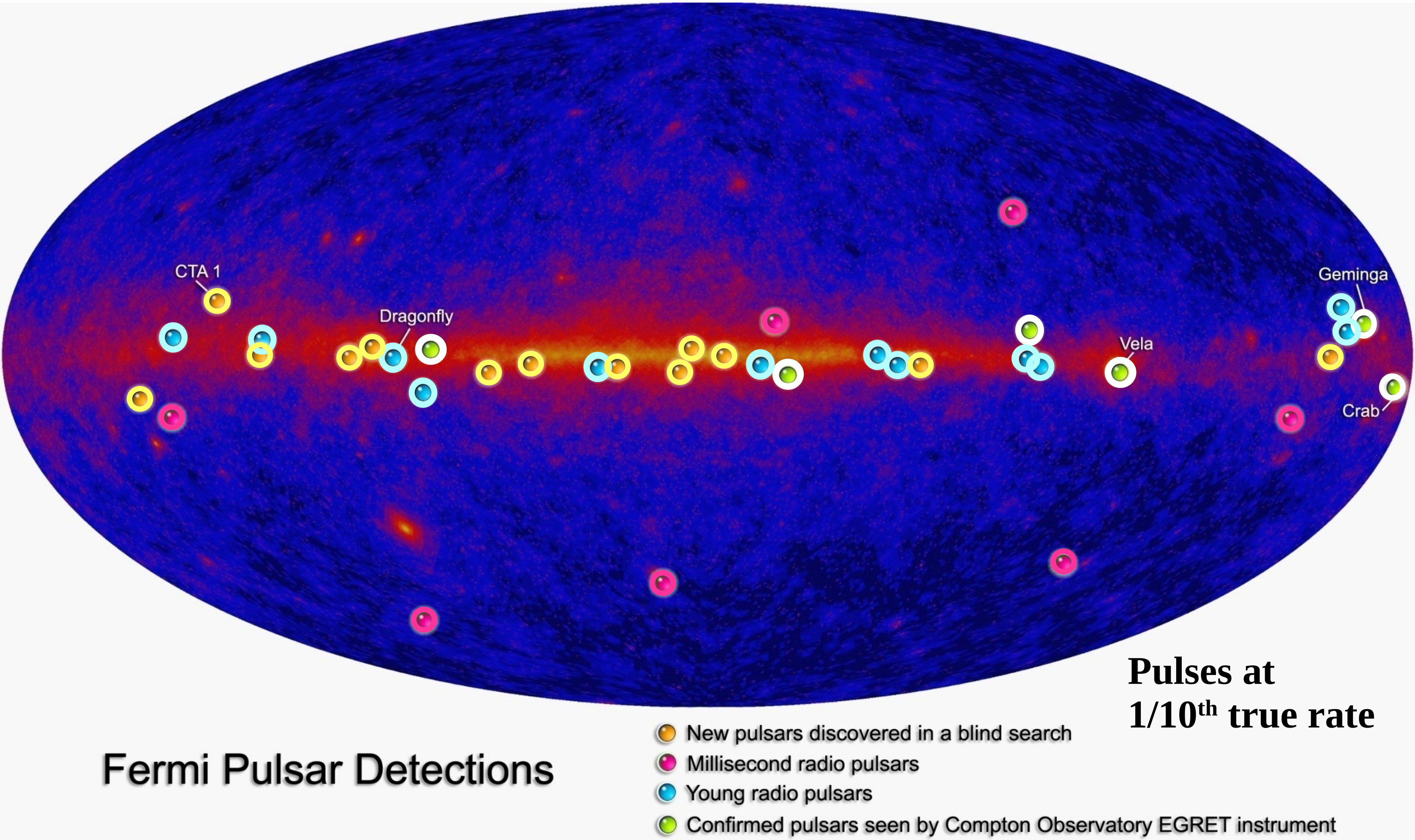
The point is: of the large variety of proposed accelerators, the correct answer is "*pulsar*" in a majority of cases so far.

A Population of Gamma-Ray Millisecond Pulsars Seen with the Fermi LAT
Abdo, A. A. et al. 2009, Science, 325, 848

Detection of 16 Gamma-Ray Pulsars Through Blind Frequency Searches Using the Fermi LAT
Abdo, A. A. et al. 2009, Science, 325, 840

Discovery of high-energy gamma-ray emission from the globular cluster 47 Tucanae with Fermi
Abdo, A. A. et al. 2009, Science, 325, 845

46 (and counting) gamma-ray pulsars
(6 before Fermi)

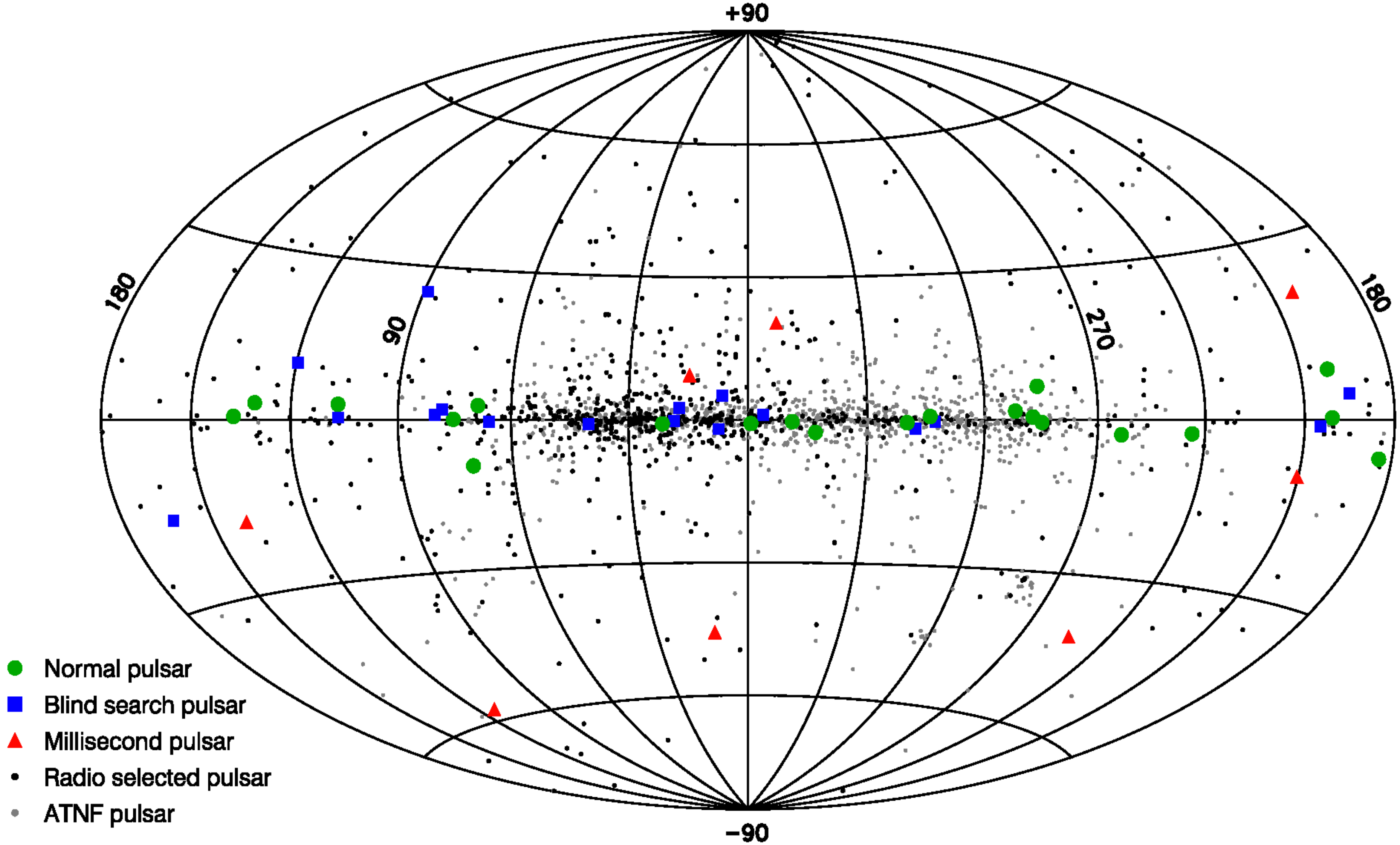


Pulses at $1/10^{th}$ true rate

Fermi pulsar catalog

First Fermi LAT Catalog of gamma-ray pulsars

Abdo et al., ApJS submitted, arXiv:0910.1608



Period vs Period derivative

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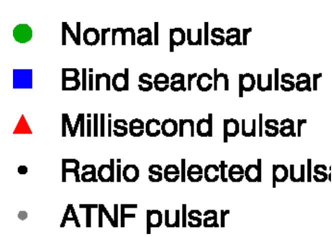
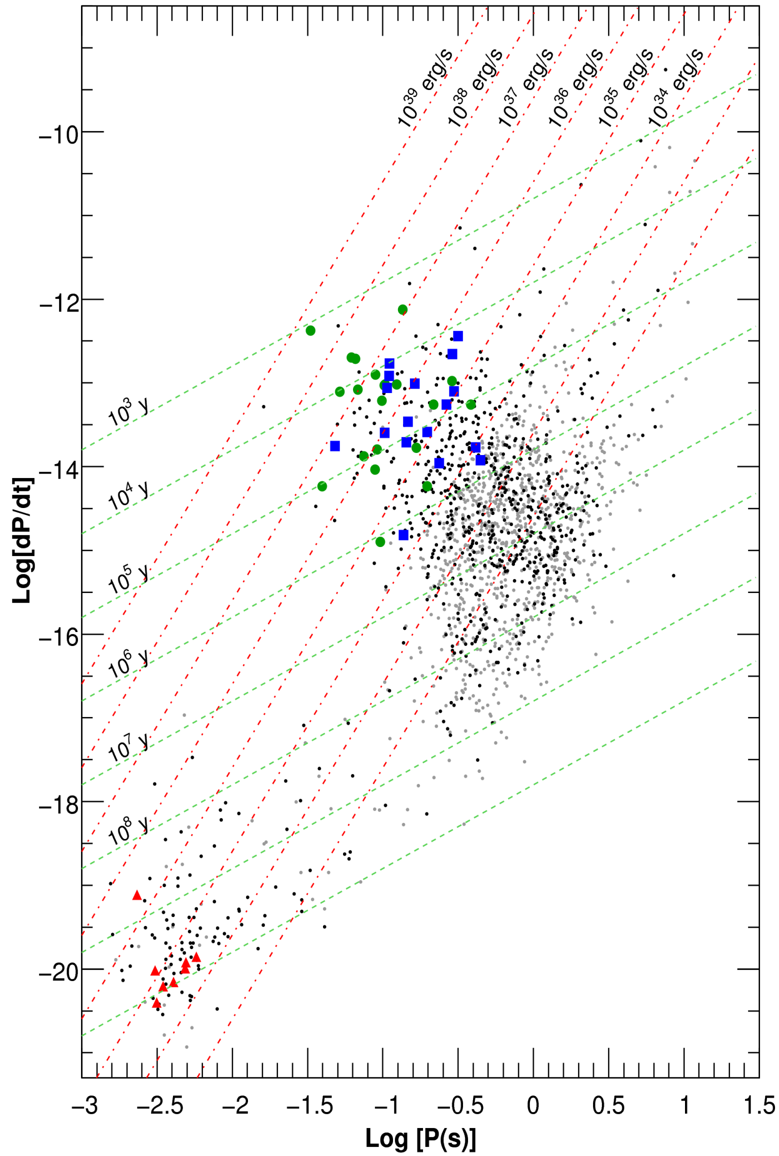
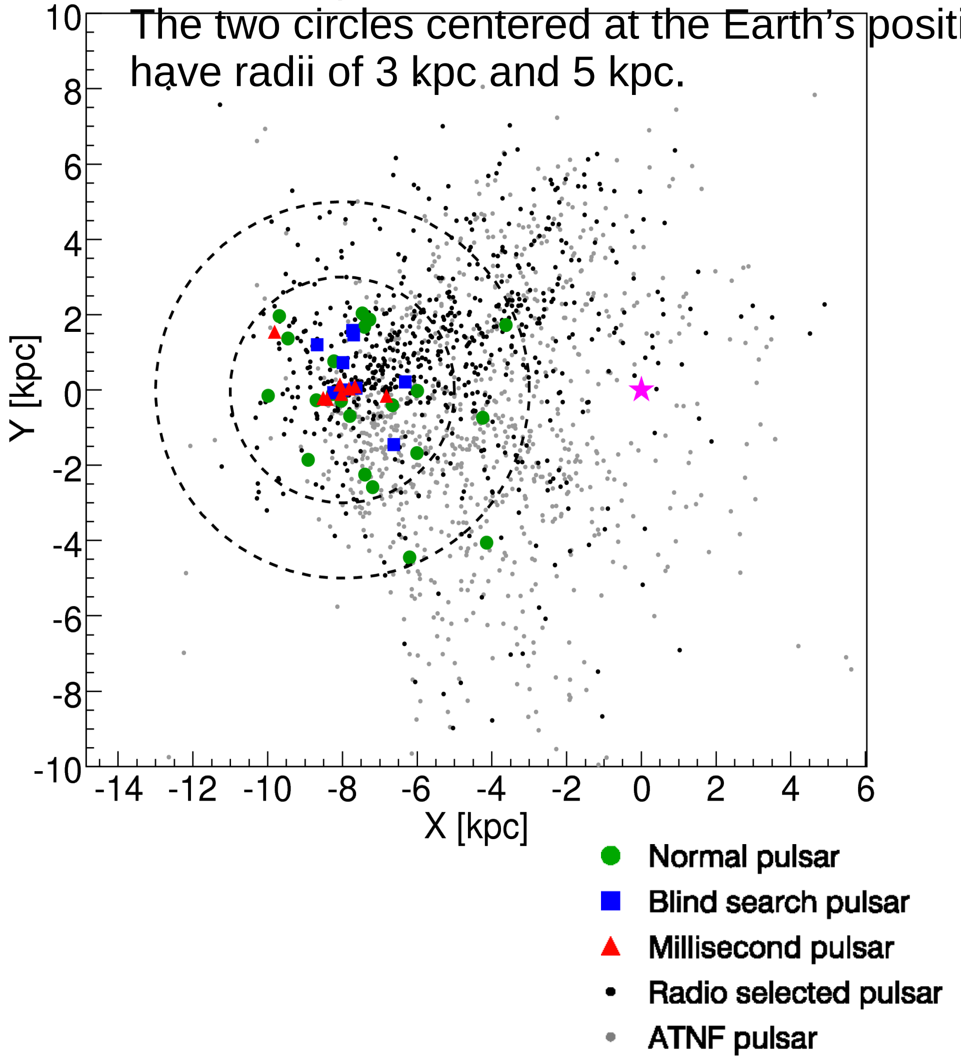
- P−Pdot diagram
  - Dashed lines: characteristic age τc .
  - Dot-dashed lines: rotational energy loss rate E.
  - Blue squares: gamma-ray-selected pulsars.
  - Red triangles: millisecond gamma-ray pulsars.
  - Green circles: all other radio loud gamma-ray pulsars.
  - Black dots: Pulsars for which gamma-ray pulsation searches were conducted using rotational ephemerides.
  - Gray dots: Known pulsars which were not searched for pulsations.





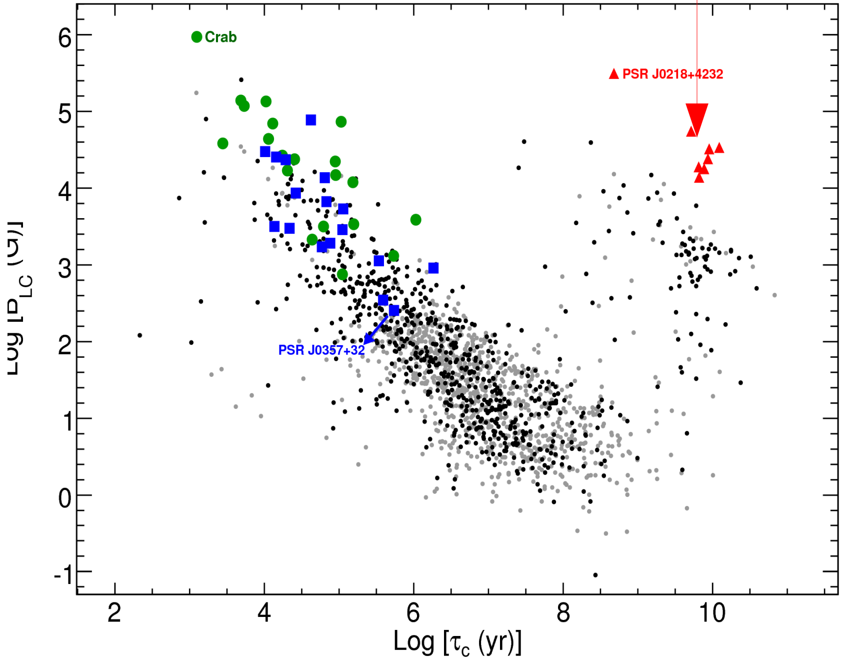
Distance, age and magnetic field

Galactic plane pulsar distribution (polar view).
The star represents the Galactic center.
The two circles centered at the Earth's position have radii of 3 kpc and 5 kpc.

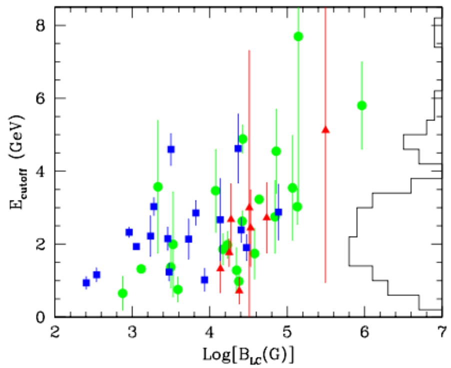


Magnetic field strength vs log of the pulsar age.

MSPs are old but with strong B



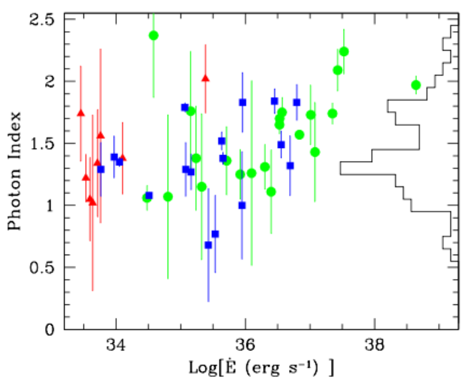
Spectral properties



Exponential cutoff
vs Magnetic field

Fig. 7.— Value of the exponential cutoff $E_{\rm cutoff}$ versus the magnetic field at the light cylinder, $B_{\rm LC}$. The statistical uncertainties on $E_{\rm cutoff}$ are shown. An additional systematic bias of (+20%, −10%) may affect $E_{\rm cutoff}$ (see text). The histogram of $E_{\rm cutoff}$ values is projected along the right-hand axis. Blue squares: gamma-ray-selected pulsars. Red triangles: millisecond gamma-ray pulsars. Green circles: all other radio loud gamma-ray pulsars.

- Normal pulsar
- Blind search pulsar
- Millisecond pulsar
- Radio selected pulsar
- ATNF pulsar



Photon index vs
Edot

Fig. 8.— Photon index Γ versus the rotational energy loss rate, $\dot{E}$. For Γ, the statistical uncertainties combined with the systematic uncertainties due to the diffuse emission model are shown. An additional systematic bias of (+0.3, −0.1) affects Γ (see text). The histogram of the photon indices is projected along the right-hand axis. Blue squares: gamma-ray-selected pulsars. Red triangles: millisecond gamma-ray pulsars. Green circles: all other radio loud gamma-ray pulsars.

Conclusions

LAT great capabilities have driven new advances in pulsar physics

- ~24 young pulsars, "radio-selected"
- 24 young pulsars, "gamma-selected"   (= blind period search)
- > 9 millisecond pulsars (radio-selected)
- 3 radio pulsars found from "gamma-selected" pulsars
- 17 Radio millisecond pulsars found at the location of Unidentified Fermi-LAT Objects

Two new populations were highlighted by the Fermi-LAT observations

- “Gamma-selected” pulsars found in blind period search
  - Not less than half the Fermi sample !
- Gamma-ray Millisecond pulsars : old recycled pulsars but...
  - High magnetic field
  - Similar characteristics of young pulsars
  - There are a lot of them, and they've been sitting here for a long time

Fermi observes a lot of pulsars, and expects to find more and more !
Gamma-ray millisecond pulsars are a peculiar new population,
they're certainly old but not dead...

Special credits: most of the slides were stolen from D.Smith and M.Razzano