γ-ray pulsars in the Fermi LAT era

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on behalf of the
Fermi LAT collaboration,
Pulsar Timing Consortium,
Pulsar Search Consortium

SciNeGHE 2010
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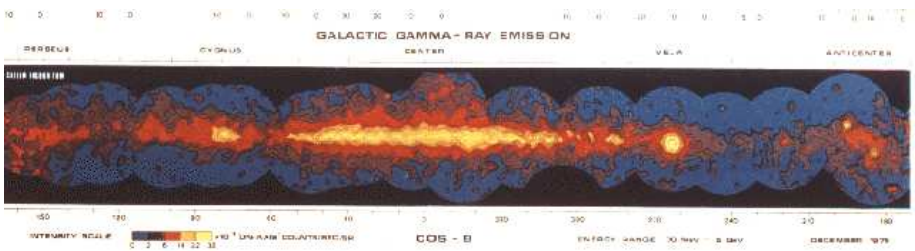
Outline

Prior γ-ray missions



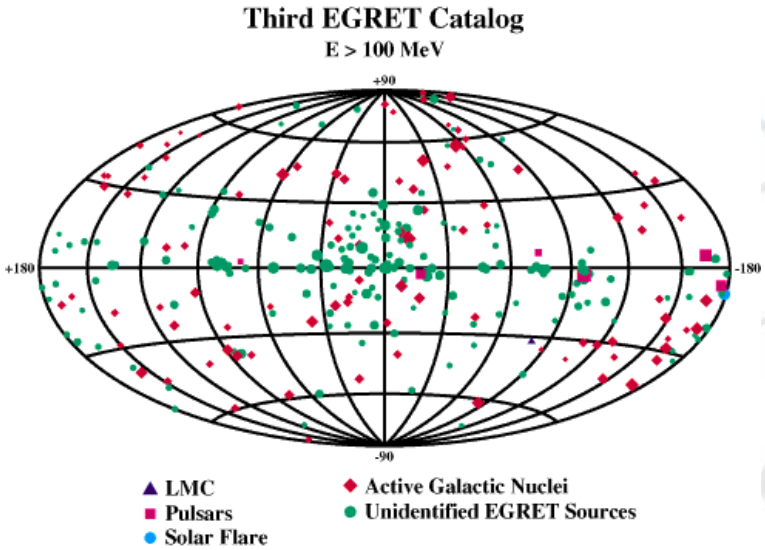
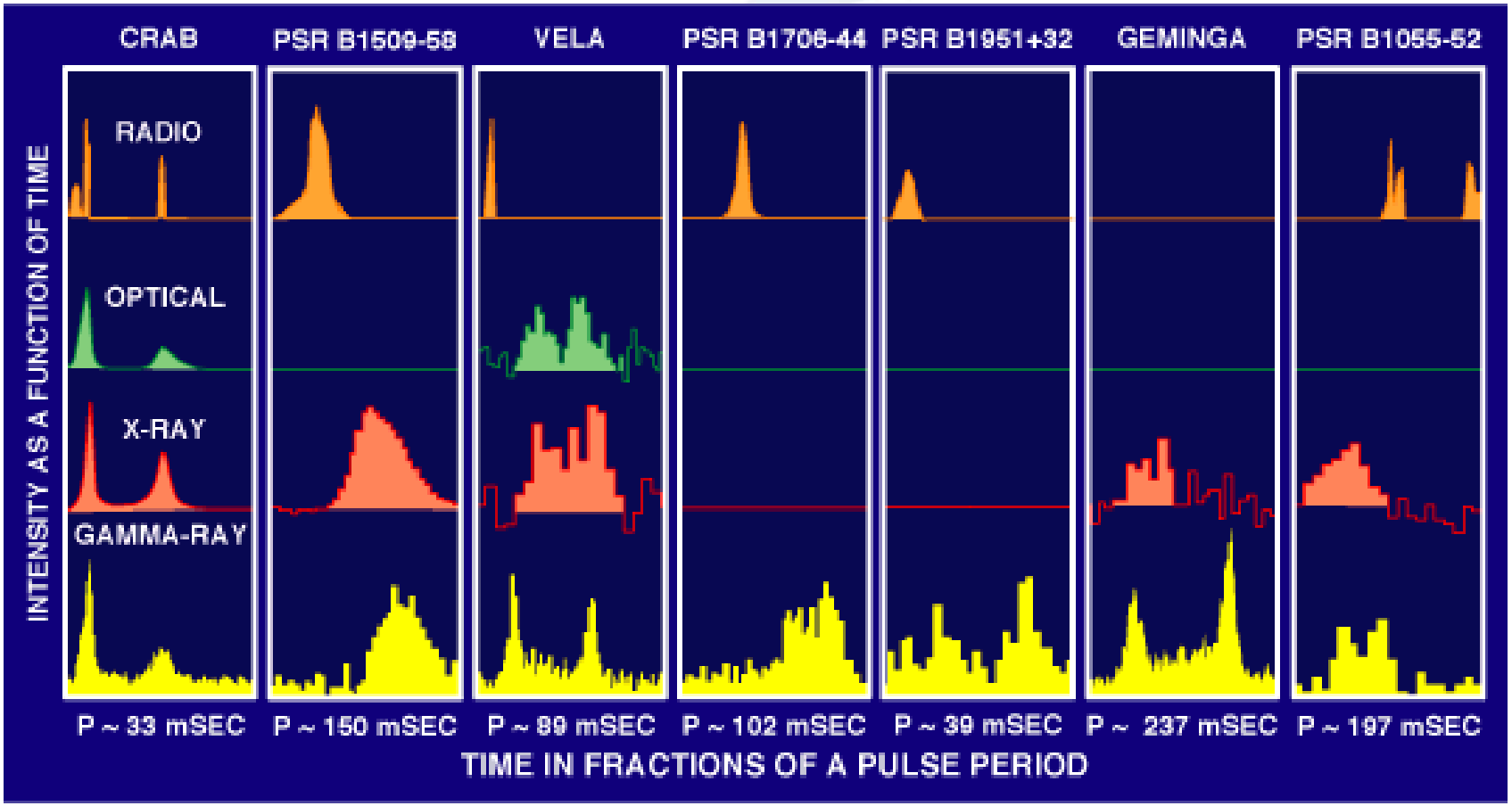


Figure: **Top** – COS-B map of the γ-ray sky. **Bottom** – Third EGRET catalog

1. SAS-2
   - Nov 72 - Jun 73
   - 20 MeV - 1 GeV
   - Detected Geminga
   - $\sim$10k photons
2. COS-B
   - Aug 75 - Apr 82
   - 2 keV - 5 GeV
   - 25 sources (21 unid)
   - $\sim$200k photons
3. EGRET
   - Apr 91 - Jun 00
   - 30 MeV - 10 GeV
   - 6 γ-ray pulsars
   - $\sim$1.5M photons

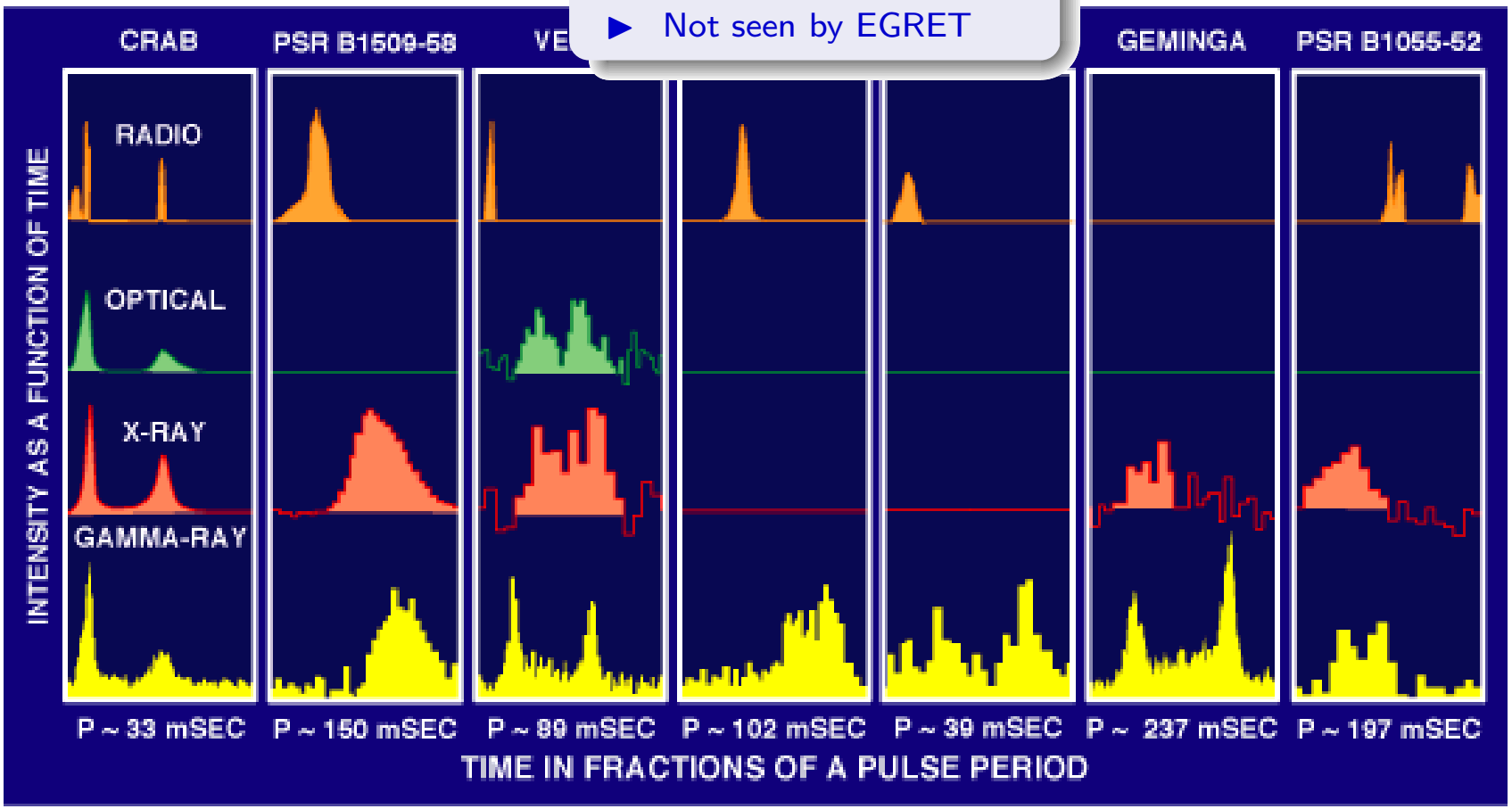
γ-RAY PULSARS IN THE YEAR 2000



γ-RAY PULSARS IN THE YEAR 2000

PSR B1509-58 (J1513-5908)

- Detected by COMPTEL (up to 10 MeV)
- Not seen by EGRET



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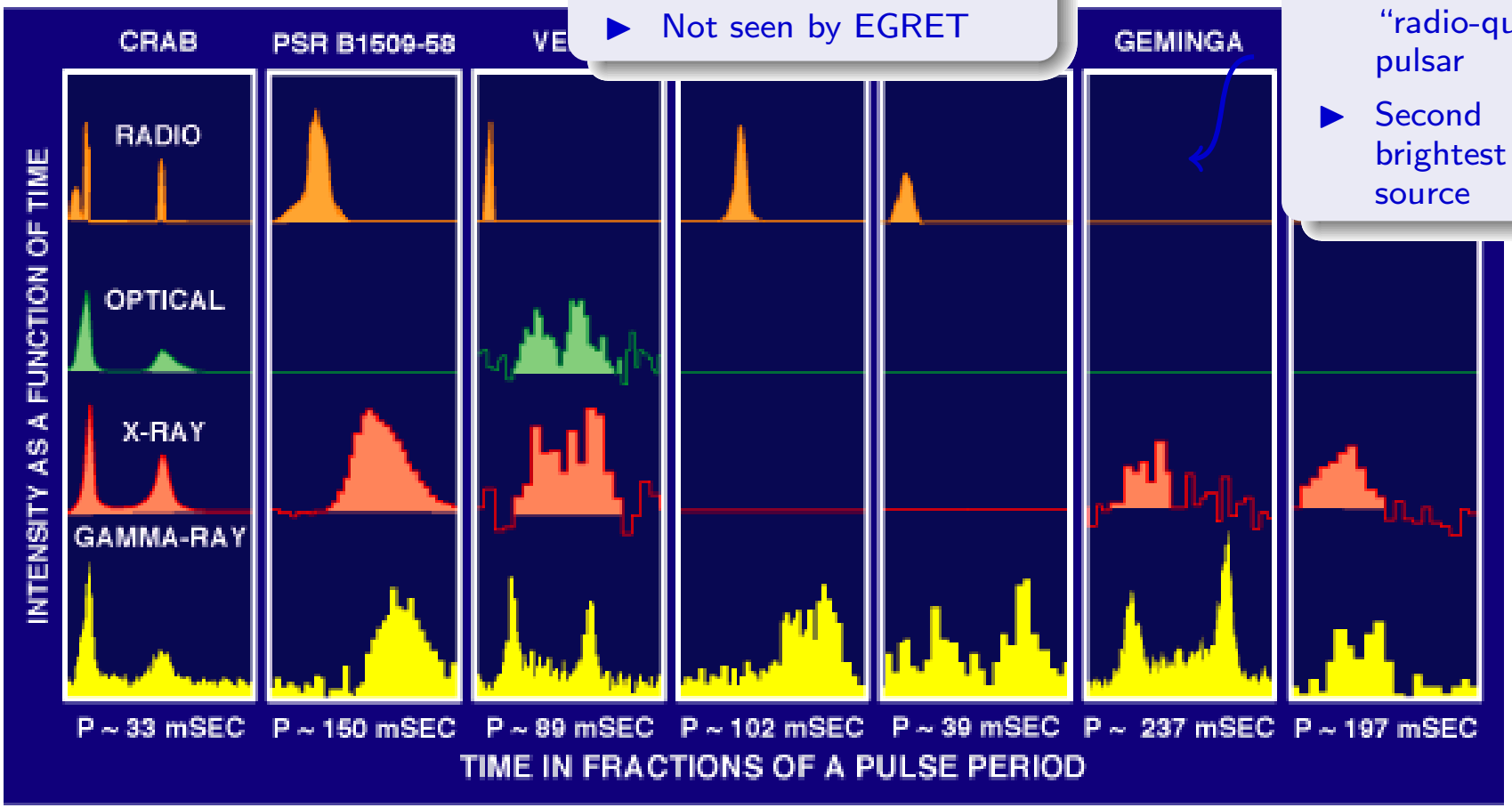
Geminga

- First "radio-quiet" pulsar
- Second brightest GeV source



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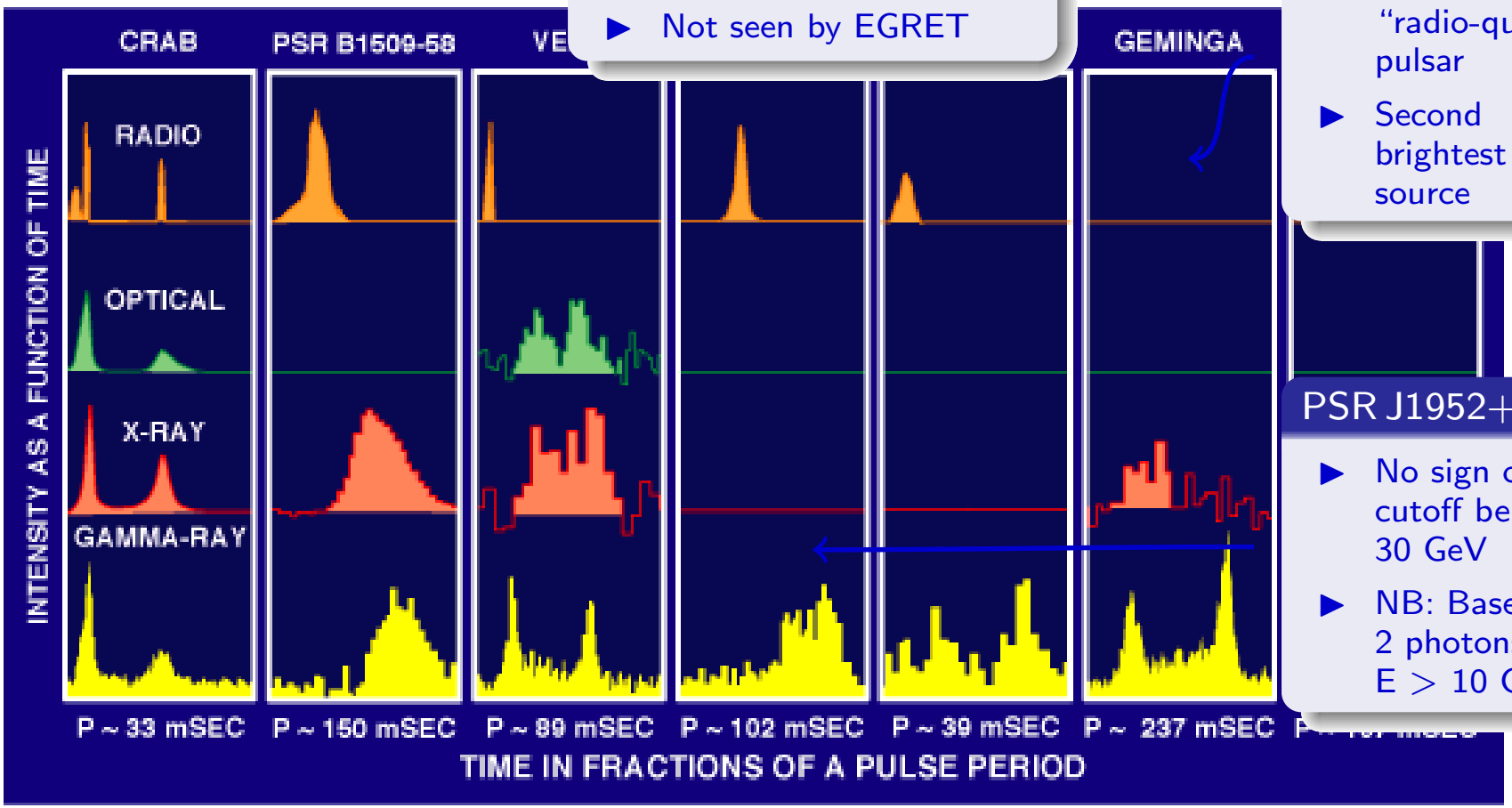


PSR J1952+3252

- No sign of cutoff below 30 GeV
- NB: Based on 2 photons with $E > 10$ GeV

The Fermi Large Area Telescope (LAT)

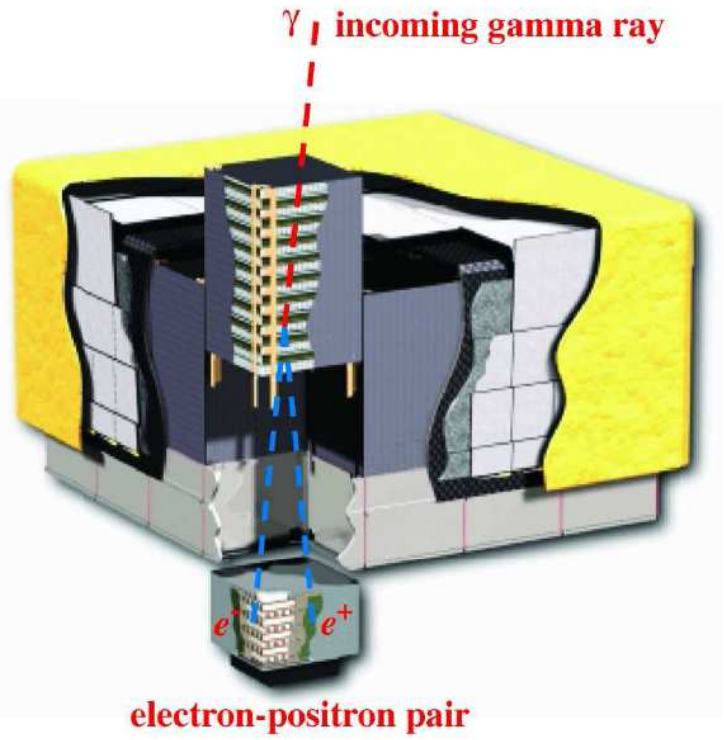


Figure: Schematic diagram of the LAT. The dimensions are 1.8 m $\times$ 1.8 m $\times$ 0.72 m. The LAT weighs $\sim$3000 kg and uses 650 W of power.

- Key improvements
  1. Larger field of view (2.4 sr)
  2. More effective area (9500 cm^2, 1 GeV, normal incidence)
  3. Better PSF (0.6° at 1 GeV)
  4. Much wider energy range (20 MeV – >300 GeV)
  5. Continuous sky survey mode with very uniform coverage
  6. Significantly lower dead-time
- See Atwood et al. 2009 for details

The Pulsar Timing and Search Consortia

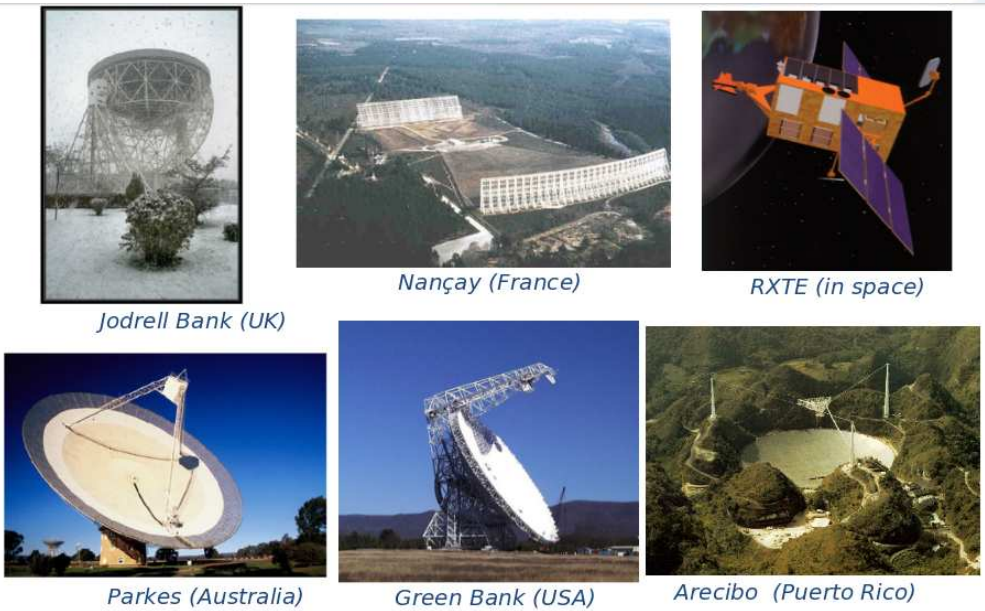


Figure: Telescopes in the LAT Pulsar Timing Consortium (Later added: Effelsberg).

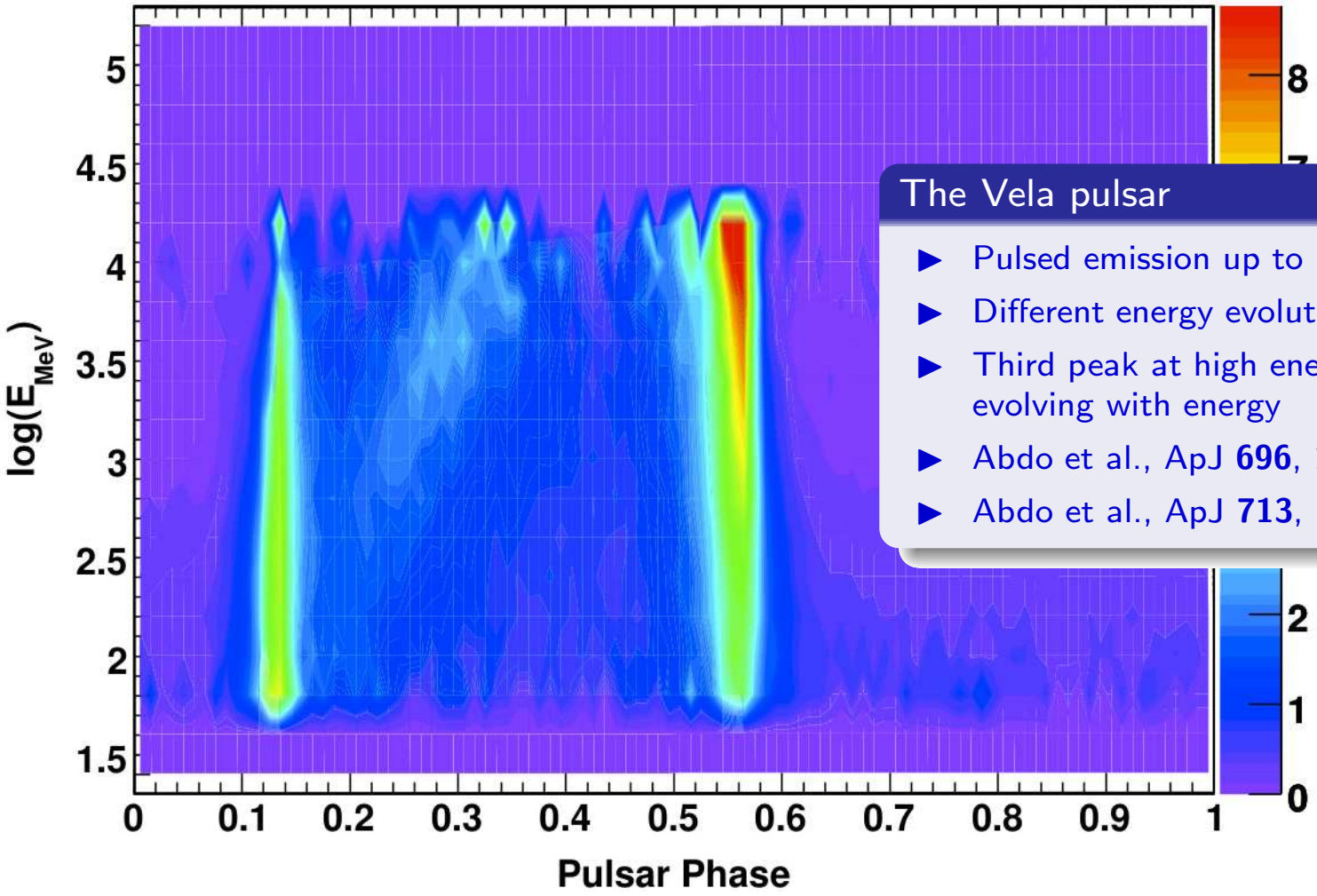
The LAT Pulsar Timing Consortium:

- Set up pre-launch to regularly time pulsars for Fermi
- Top radio telescopes + RXTE
- $>$ 700 pulsars timed
- Smith et al. 2008 A&A, **492**, 923

The LAT Pulsar Search Consortium:

- Set up post-launch
- ~Same people/telescopes
- Goal: Search for radio pulsations from LAT pulsars and sources
- Recently added GMRT (India)

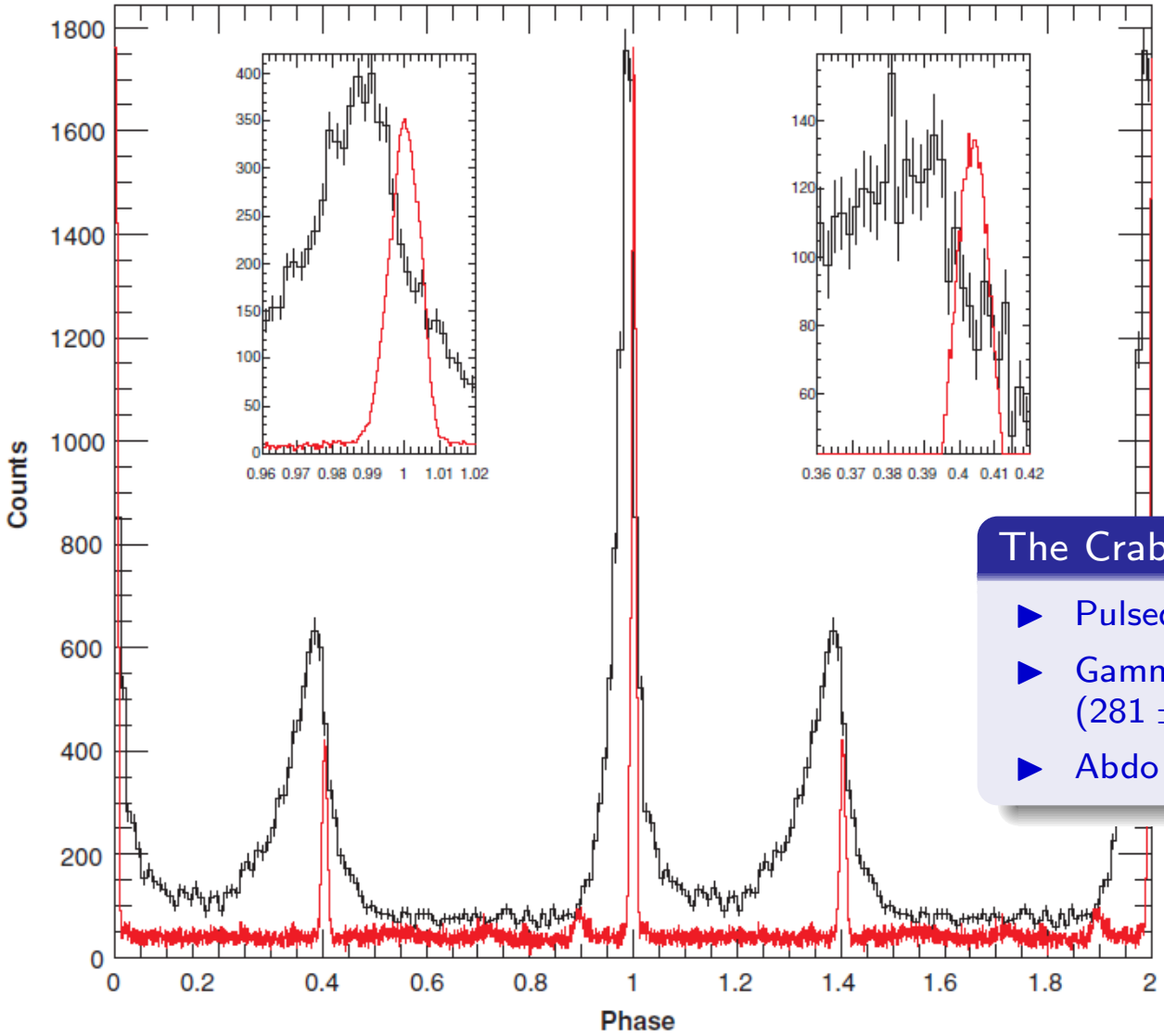
EGRET pulsars as seen by the LAT (I)



The Vela pulsar

- Pulsed emission up to ∼20 GeV
- Different energy evolution of peaks
- Third peak at high energies, evolving with energy
- Abdo et al., ApJ **696**, 1084 (2009)
- Abdo et al., ApJ **713**, 154 (2010)

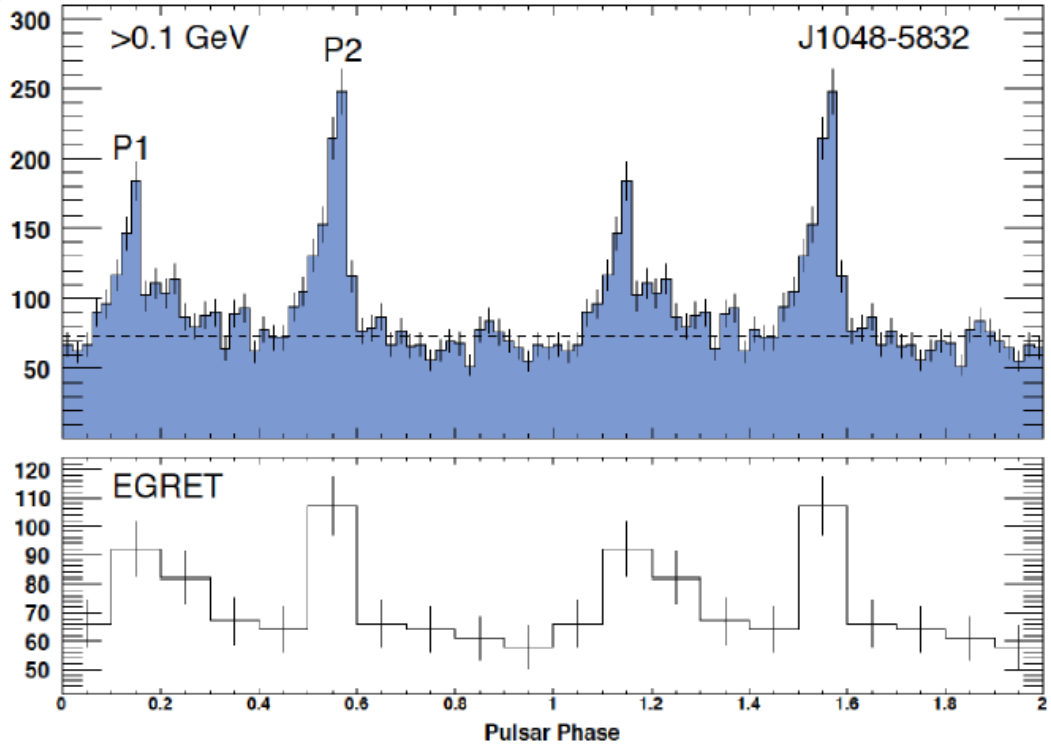
EGRET pulsars as seen by the LAT (II)

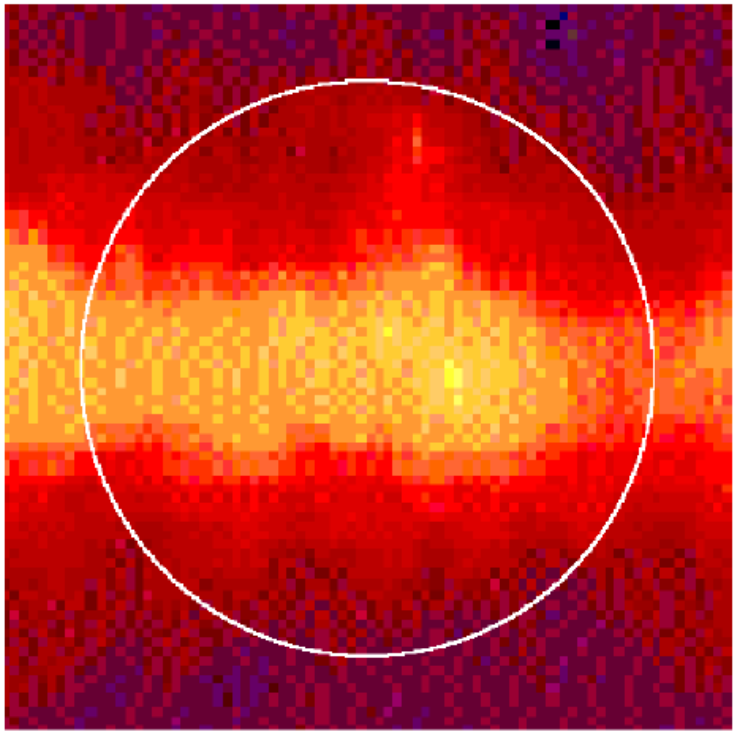


The Crab pulsar

- Pulsed emission up to ~20 GeV
- Gamma peak leads radio by $(281 \pm 12 \pm 21)\ \mu s$
- Abdo et al., ApJ **708**, 1254 (2009)

Young γ-ray pulsars found using ephemerides





Young radio-loud γ-ray pulsars

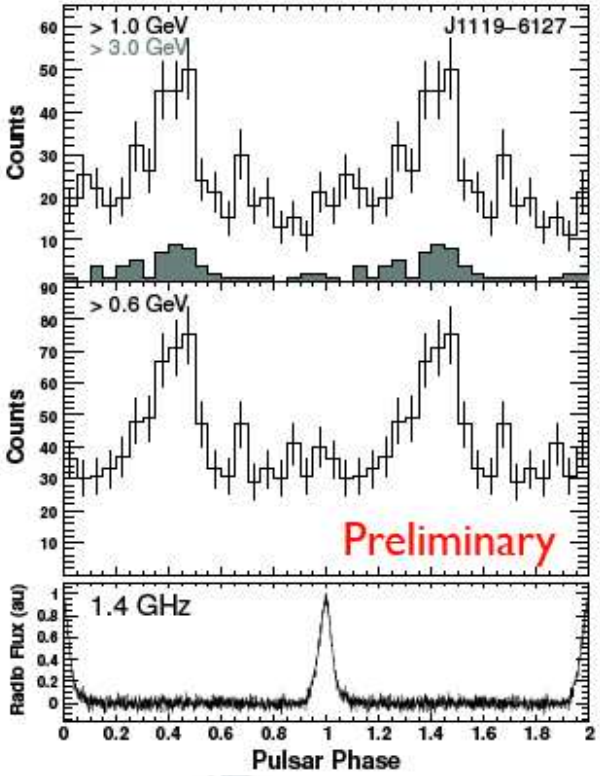
- Early confirmation of *marginal* EGRET pulsars, like PSR J1048-5832 (Kaspi 2000)
- Some bright pulsars (e.g. PSR J2021+3651, PSR J2229+6114) could be found in blind LAT searches, but dimmer ones require precise timing models.

Young γ-ray pulsars found using ephemerides

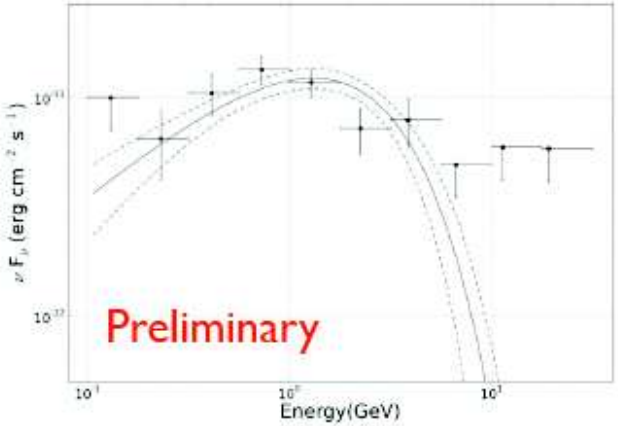
PSR J1119−6127 (= 1FGL J1119.4-6127c)
is the first high B-field PSR detected with Fermi.

After PSR J0007+7303 (CTA1) with $B_{surf} = 1.1 \times 10^{13}$ G and PSR B1509−58 (MSH15−52) with $B_{surf} = 1.5 \times 10^{13}$ G, now PSR J1119−6127 record holder with $B_{surf} = 4.1 \times 10^{13}$ G

Characteristics
(usual dipole assumptions)
$P = 0.408$ s;
$\dot{P} = 4.02 \times 10^{-12}$ s s^{-1}
$B_{surf} = 4.1 \times 10^{13}$ G;
$\tau_{char} = 1700$ years
$\dot{E} = 2.3 \times 10^{36}$ erg s^{-1}



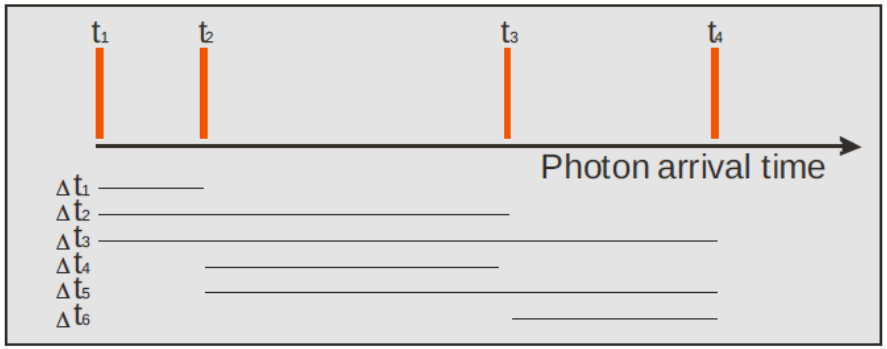
Single-peak pulse profile and power-law with an exponential cutoff spectrum



Parent, Kerr, den Hartog et al., ApJ in prep

γ-SELECTED PULSARS IN BLIND SEARCHES

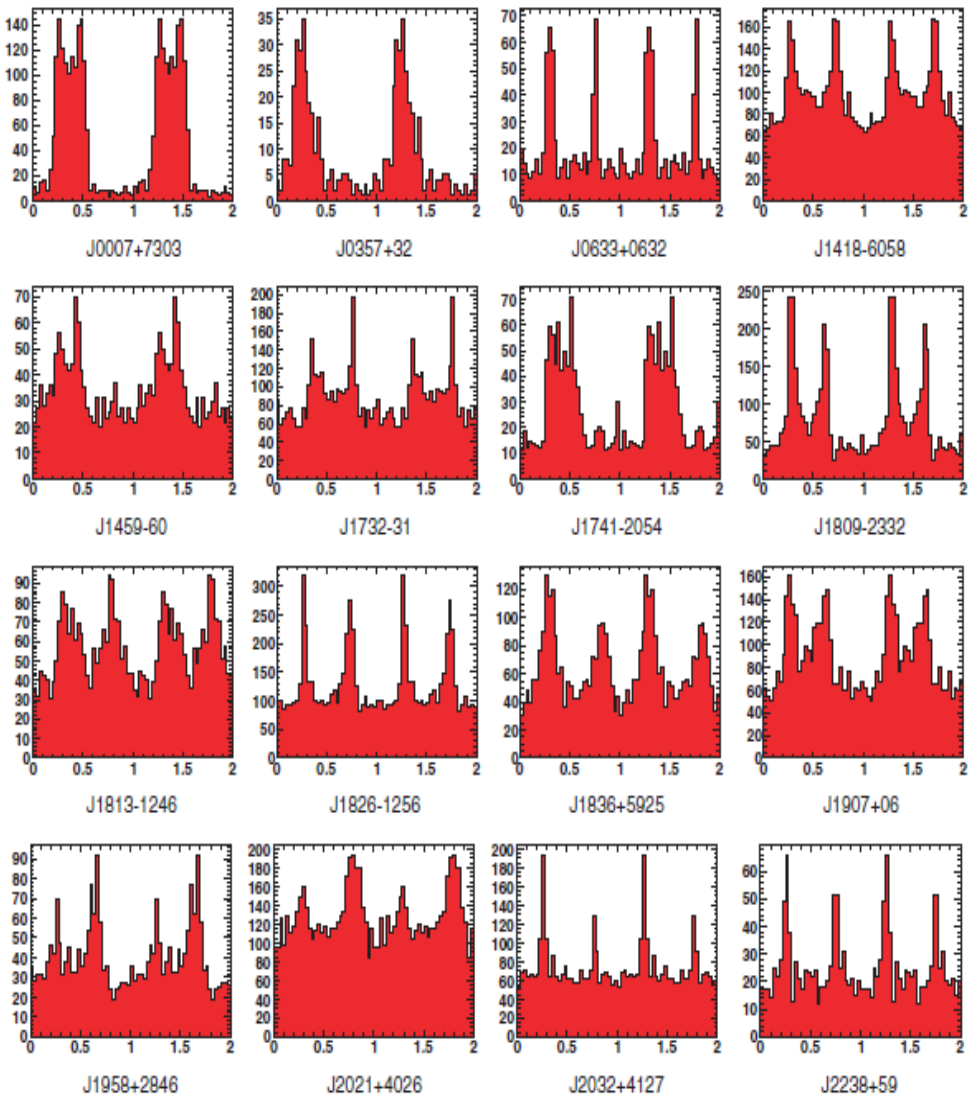
The time-differencing technique



Credit: M. Ziegler

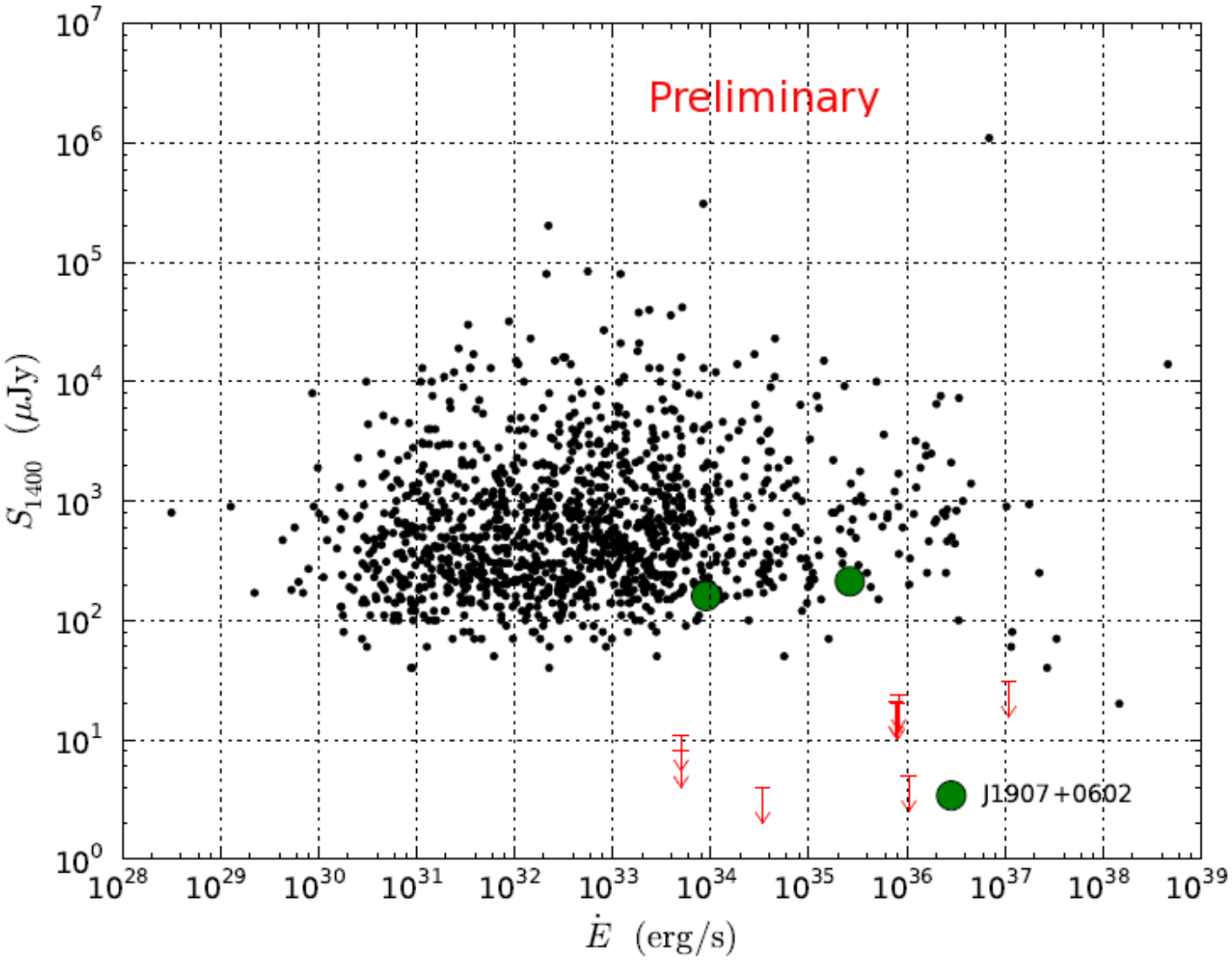
- Sparse gamma-ray data make standard FFT techniques expensive
- Periodic signal shows up in (FFT of) differences of photon times
- Differences computed up to a maximum T_w (days or weeks)
- Interesting candidates investigated with standard techniques
- Atwood et al., ApJL **652**, L49 (2006)
- Ziegler et al., ApJ **680**, 620 (2008)

Blind Search Pulsars

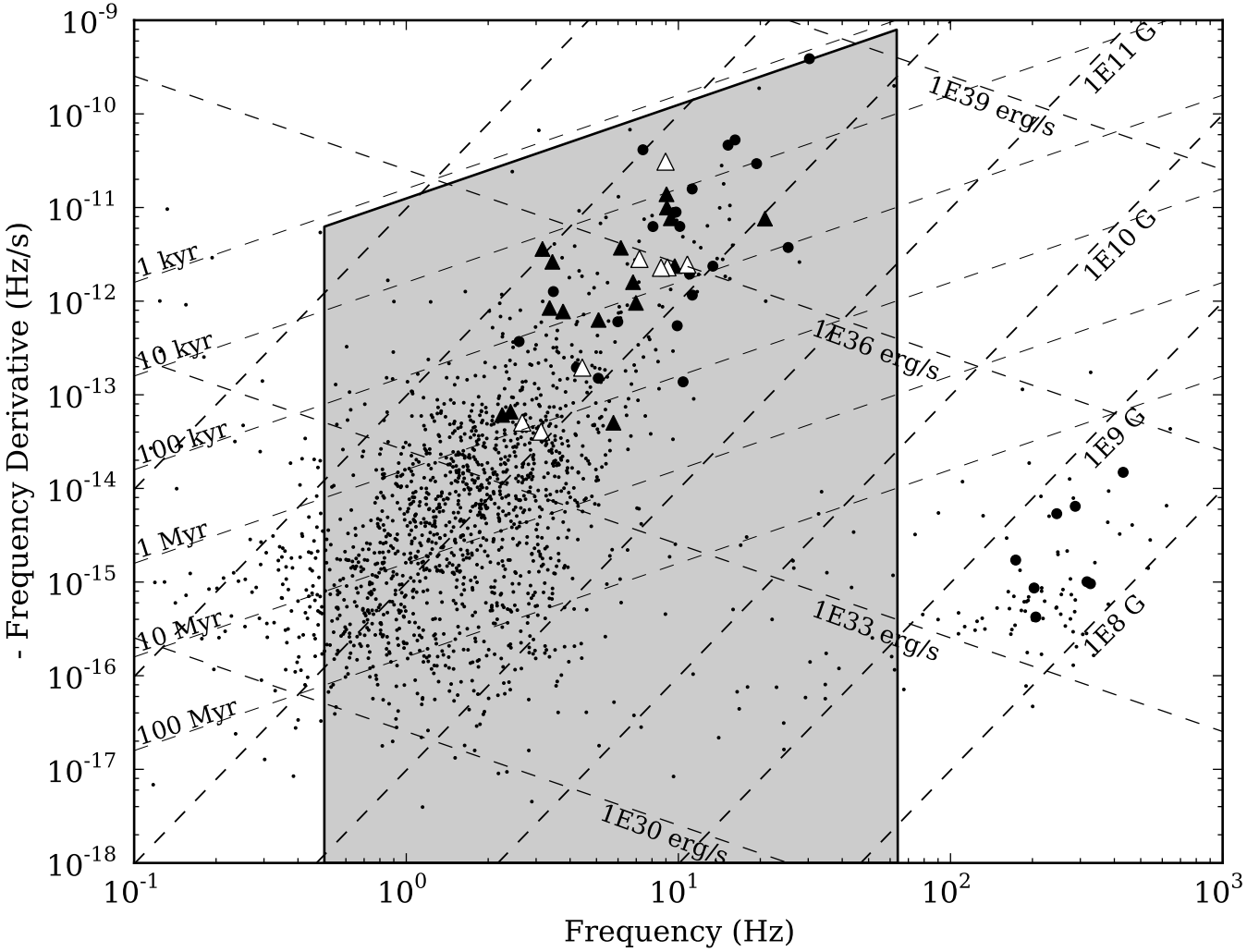


- 24 pulsars (Abdo et al. 2009, Saz Parkinson et al. 2010)
- Many coincident with EGRET UnID sources
- Various within SNR/PWN: Taz, Eel, Rabbit, Gamma Cygni (see M. Razzano's talk)
- Many TeV associations: PSR J2032+4127, PSR J1022–5746, PSR J1907+0602
- Deep radio follow-up searches of all 24 pulsars ⇒ Only 3 detected

What is the meaning of "radio quiet"?



The γ-ray pulsar population



Multiwavelength connections

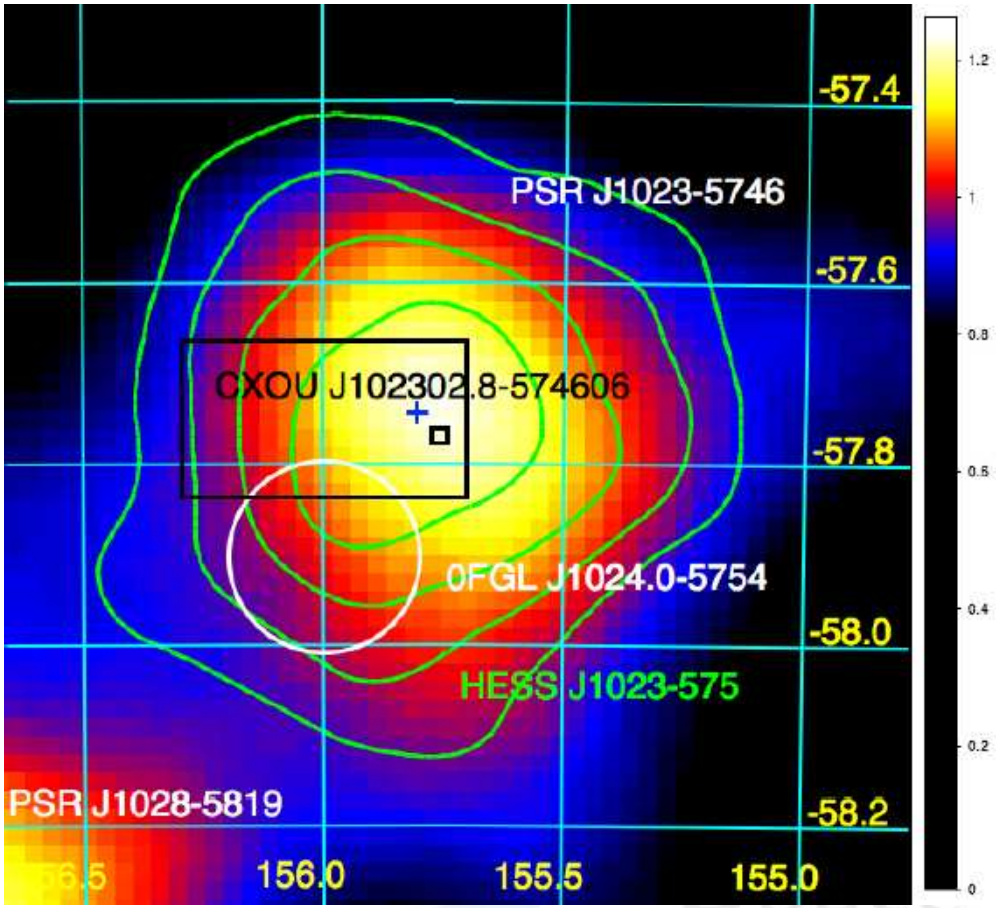
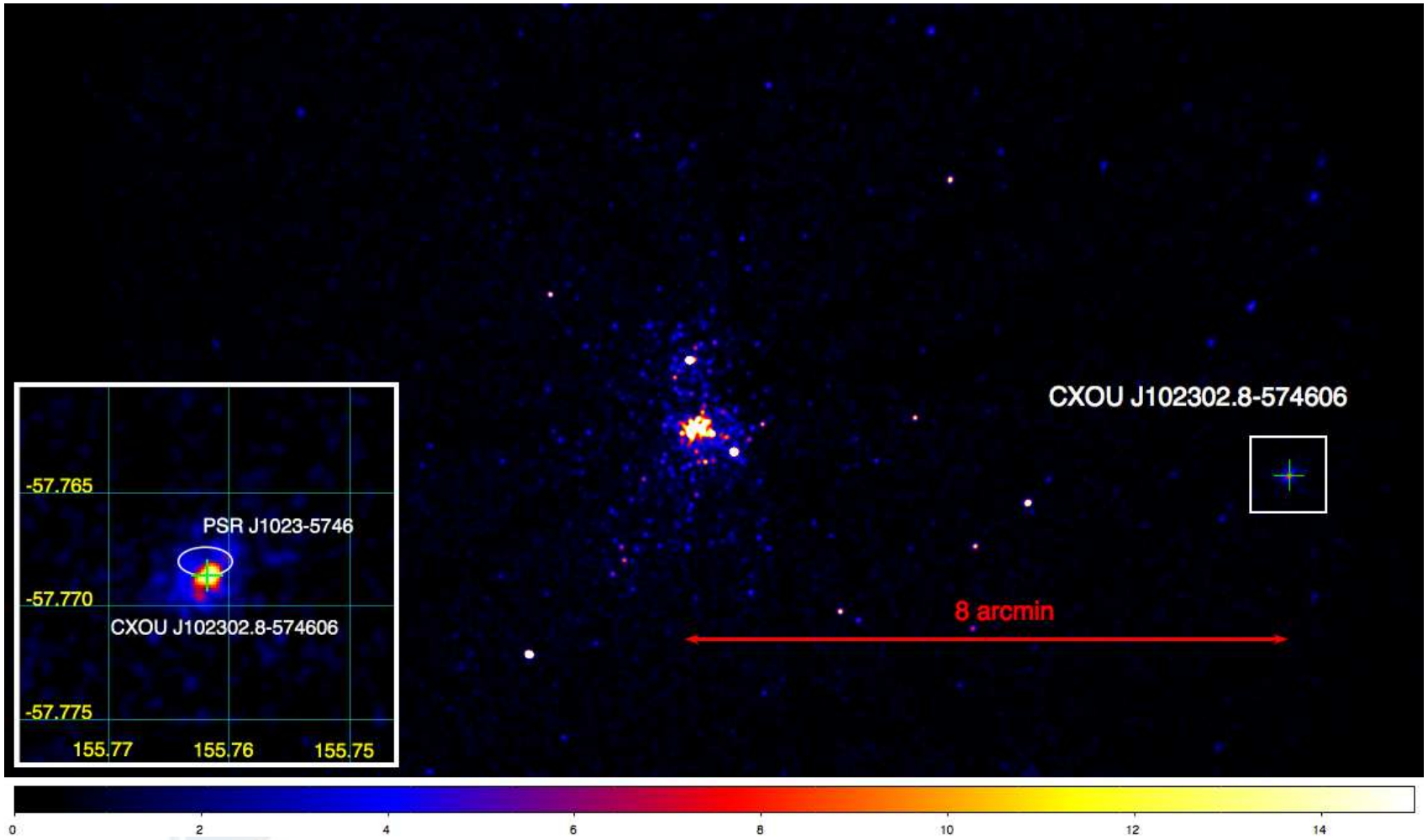


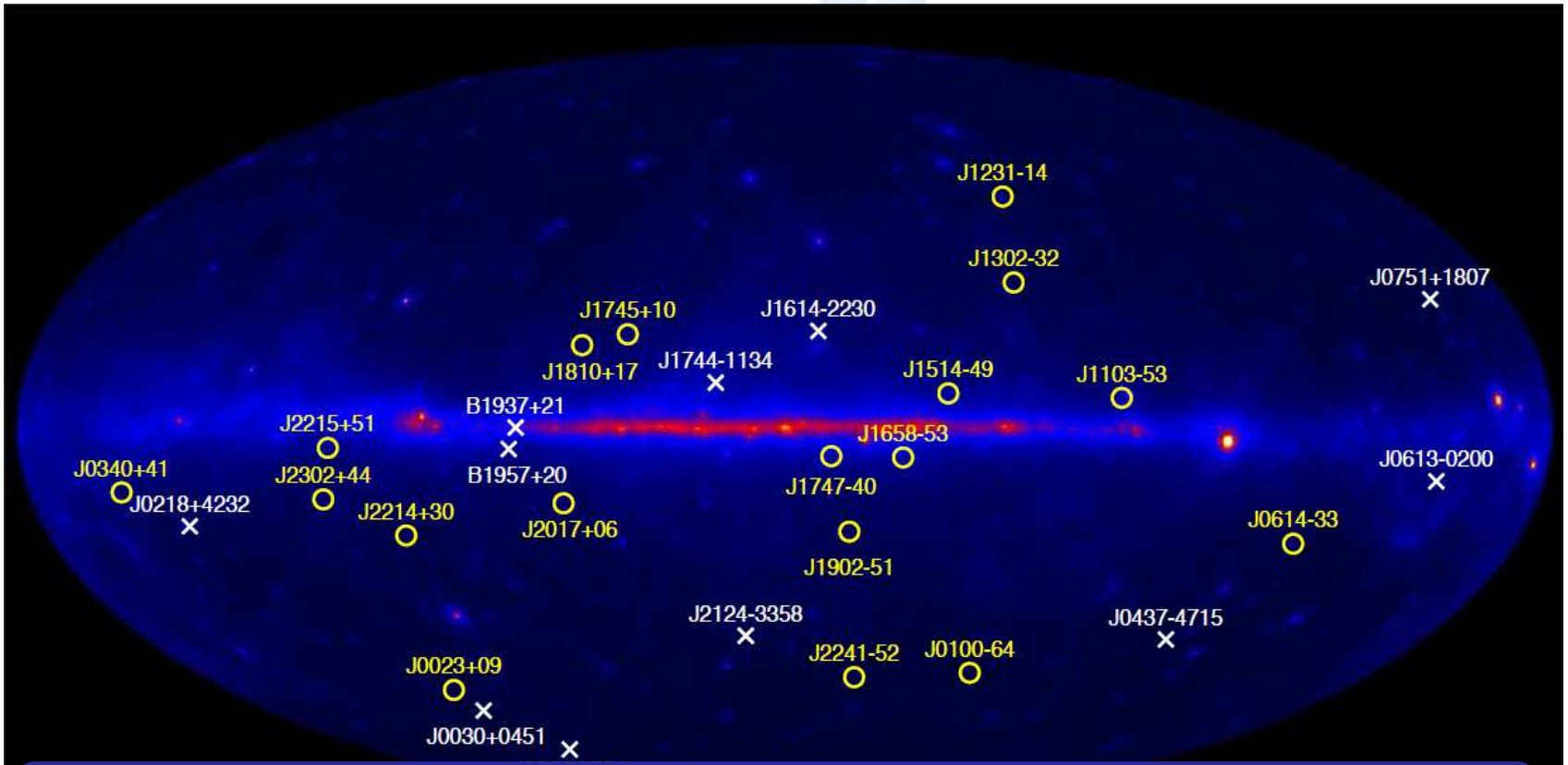
Figure: LAT > 100 MeV image of PSR J1023-5746 [Saz Parkinson et al. 2010].

- Radio timing and searches
- X-ray observations (Swift, XMM, Chandra, Suzaku)
- TeV observations (VERITAS, Milagro, HESS, MAGIC)

Multiwavelength connections (Cont'd)



γ-RAY MILLISECOND PULSARS

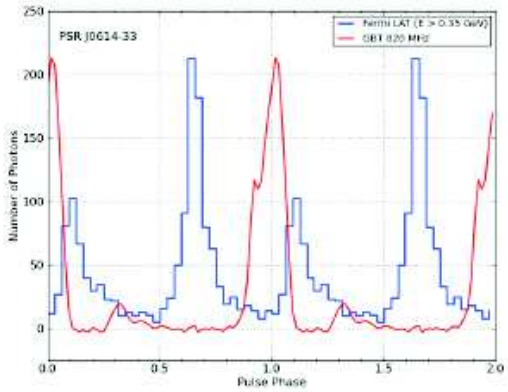


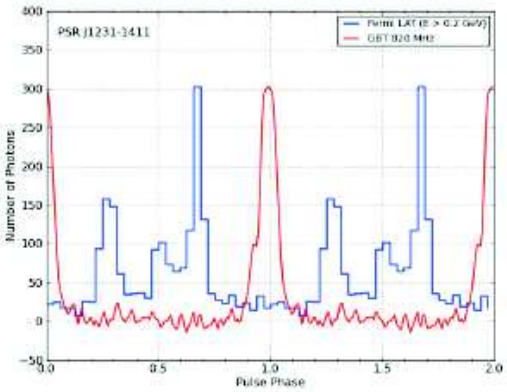
Millisecond pulsars with the LAT

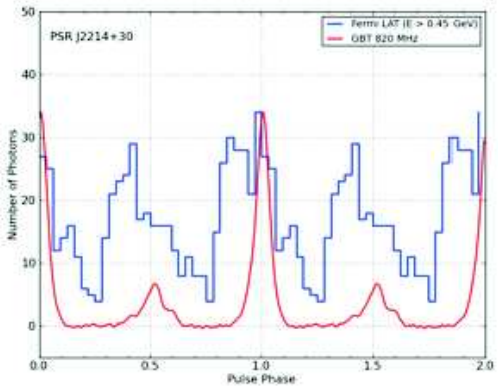
- 11 γ-ray MSPs in previously-known pulsars; e.g. Abdo et al., Science, **325**, 848, (2009)
- 19 MSPs discovered in radio searches of LAT sources
- Most of the 19 will become γ-ray MSPs; e.g. Ransom et al. , ApJ, *submitted*, (2010)

MSPs from searching LAT Unassoc.sources

Three MSPs found at GBT (Ransom et al. 2010, submitted)



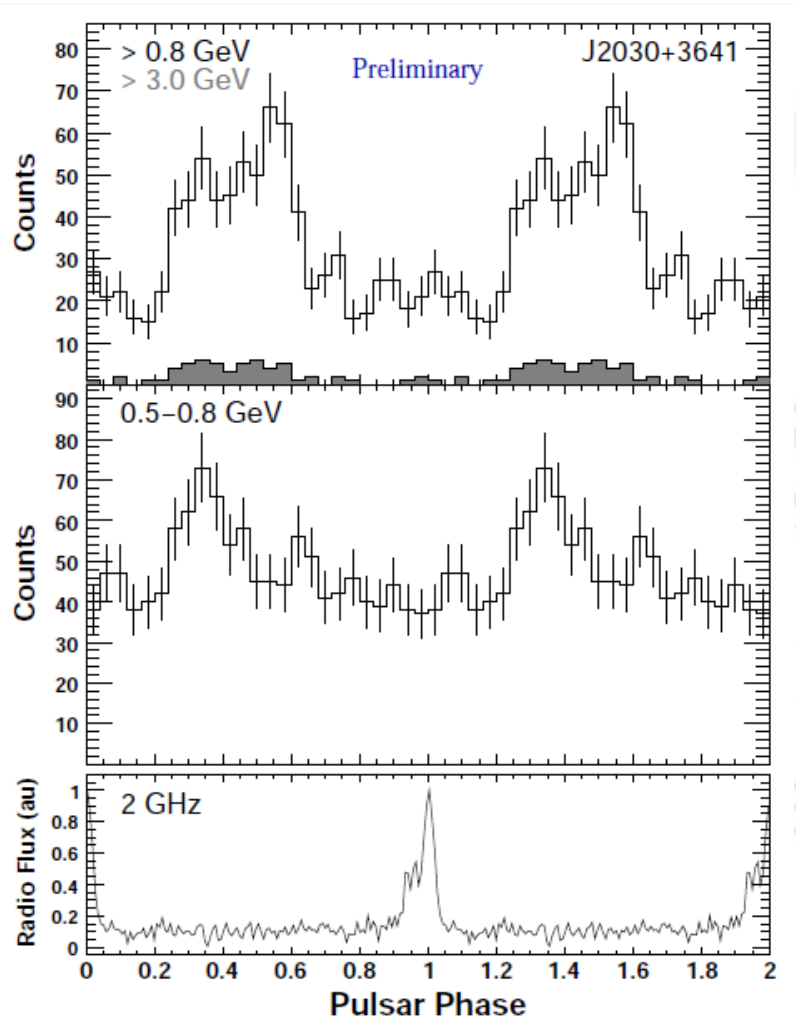




P_{psr} =	3.15 ms	3.68 ms	3.12 ms
P_{orb} =	53.6 days	1.86 days	0.42 days
$M_{c,min}$ =	0.28 $M_\odot$	0.19 $M_\odot$	0.014 $M_\odot$
Dist	1.9 kpc	0.4 kpc	1.5 kpc
Age	2.8 Gyr	3.1 Gyr	3.6 Gyr
B	2.4×10^8 G	2.6×10^8 G	2.1×10^8 G
Edot	2.3×10^{34} erg/s	1.5×10^{34} erg/s	1.8×10^{34} erg/s
F(>100 MeV)	8×10^{-8} ph/cm^2/s	1×10^{-7} ph/cm^2/s	5×10^{-8} ph/cm^2/s
Notes:	Two brightest gamma-ray MSPs		Black Widow

Not just MSPs in LAT Unassoc. sources

PSR J2030+3641: Yet another γ-ray pulsar in the Cygnus region



- Discovered by Fernando Camilo
- P = 200ms
- DM = 246 pc m^{-3} ($\Rightarrow$ 8 kpc?)
- $\dot{E} = 3 \times 10^{34}$ erg s^{-1}
- τ=0.5 Myr
- Coincident with a Milagro candidate (see talk by Gus Sinnis)

Future prospects

Science, December 2009

THE
RUNNERS-UP >>

Opening Up the Gamma Ray Sky

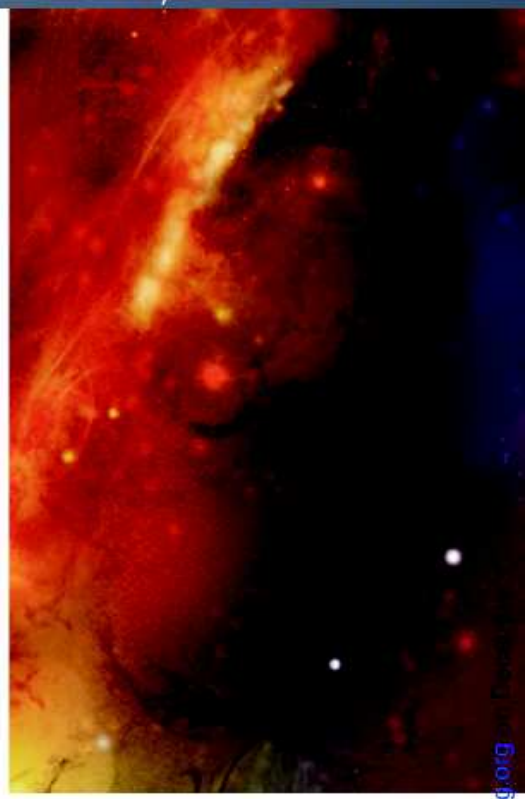
LIKE A LIGHTHOUSE BLINKING IN THE NIGHT, A pulsar appears to flash periodically as it spins in space, sweeping a double cone of electromagnetic radiation across the sky. Since the discovery of the first pulsar 4 decades ago, astronomers have detected hundreds more of these enigmatic objects from the pulsing radio waves they emit. Now, astronomers have opened a new channel of discovery—the highly energetic gamma ray spectrum—to find pulsars that radio observations could not detect. The advance, part of a torrent of recent gamma ray observations, is giving researchers an improved understanding of how pulsars work, along with a rich haul of new pulsars that could help in the quest to detect gravitational waves.

The findings come from the Fermi Gamma-ray Space Telescope, which has been mapping the gamma ray universe since it was launched by NASA in June 2008. Combing through data the telescope collected in its first few months, an international team discovered 16 new pulsars; strong gamma ray pulsations from eight previously known pulsars with spin times of milliseconds, proving that these objects pulse brightly at gamma wavelengths as well as in the radio range; and high-energy gamma rays from the globular cluster 47 Tucanae indicating that the cluster harbors up to 60 millisecond pulsars.

Those Fermi results might be just the beginning. Armed with their new knowledge of pulsar behavior, researchers are checking whether some of the unidentified gamma ray sources Fermi has detected might be pulsars. In November alone, teams of astronomers in the United States and France discovered five new millisecond pulsars by training ground-based radio telescopes on candidate objects Fermi had pointed out—a much more targeted search technique than scanning the sky blindly with ground-based radio telescopes.

Gamma ray beams of pulsars are believed to be wider than their radio beams, so in principle a space-based gamma ray telescope should be more likely to encounter and discern a pulsar's sweep than a radio telescope on Earth is. However, Fermi's forerunner—the Compton Gamma Ray Observatory, which flew from 1991 to 2000—did not have much luck finding these objects. What has made the difference is Fermi's high sensitivity, which enables it to detect pulsations that would have been too faint for Compton.

Already, the discoveries are shedding new light on the physics of pulsars. Researchers



from www.sciencemag.org

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Summary and Prospects

- The LAT has detected $> 60\gamma$-ray pulsars in three categories
  - Young radio-loud pulsars
  - Young radio-quiet pulsars
  - Radio-loud MSPs
- The LAT will continue to find new pulsars, but at a slower rate
- Maybe new categories?
  - High B-field pulsars
  - Radio-quiet MSPs
  - Young binary pulsars
  - Individual MSPs in GCs
- LAT statistics on γ-ray pulsars enabling population studies
- Emission models must explain the wealth of LAT data
- What about non-detections?
- Much more to come ...

Grazie

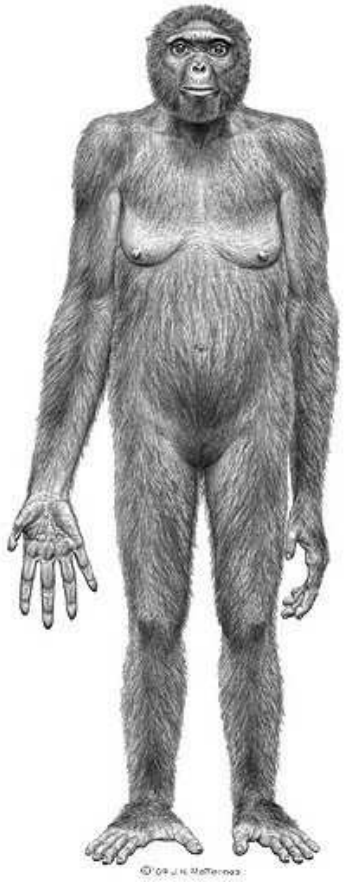

Figure: *Ardi* lived 4.4 milion years ago in what is now Ethiopia, more than a million years before *Lucy*. The last common ancestor shared by humans and chimpanzees lived at least six million years ago.