Fermi-LAT: An Amazing Pulsar Finding Machine

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Fermi Pulsar Timing Consortium
and Fermi Pulsar Search Consortium

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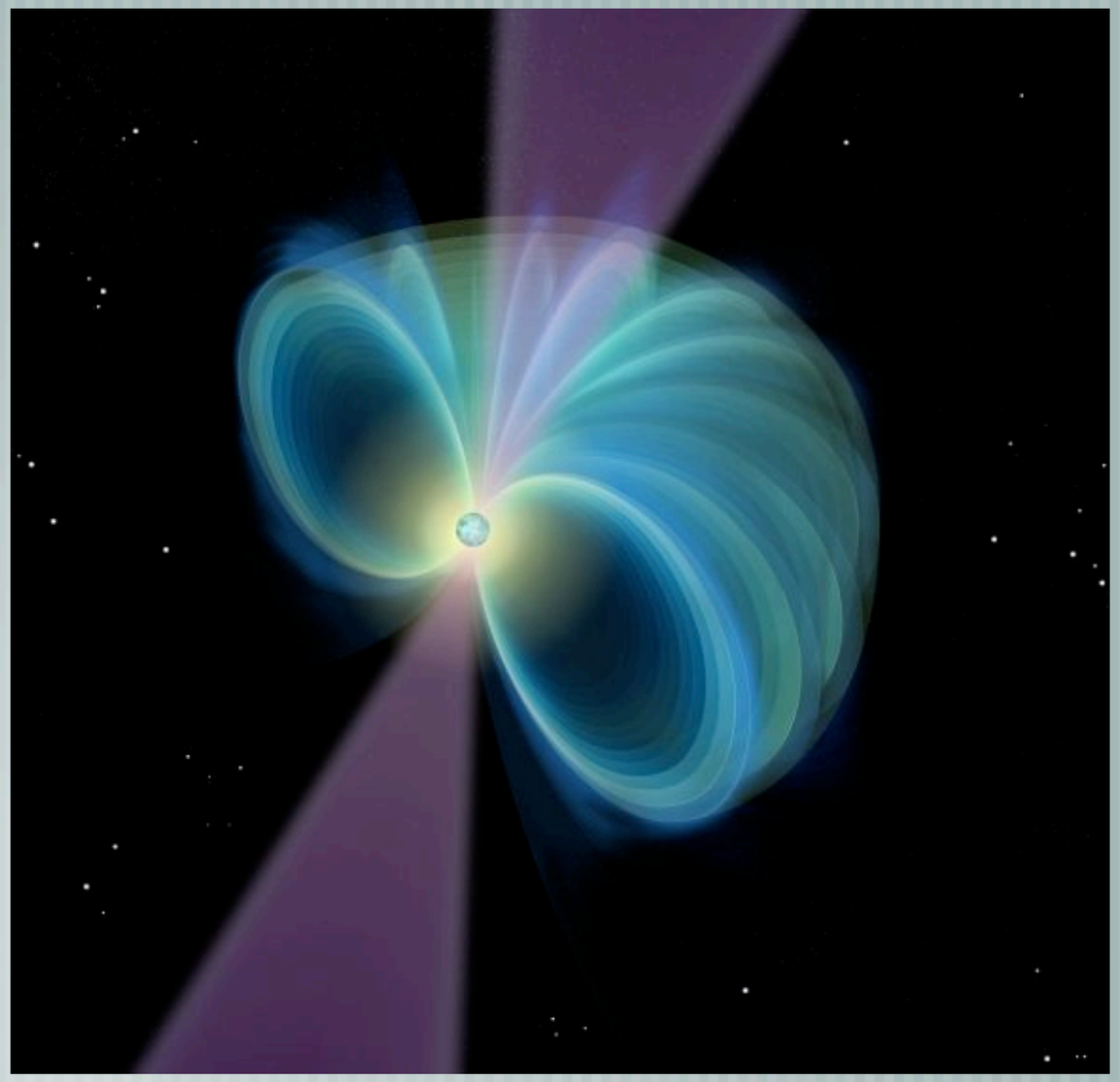
(Rotation-Powered) Pulsars

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

- Mass ~ 1.4 $M_\odot$ & R ~ 10 km
  - ➡ Density ~ nuclear matter.
- Rotating magnetic dipole field
  - ➡ Electromagnetic radiation
  - ➡ Particle acceleration in the magnetosphere
  - ➡ Slowdown due to energy loss

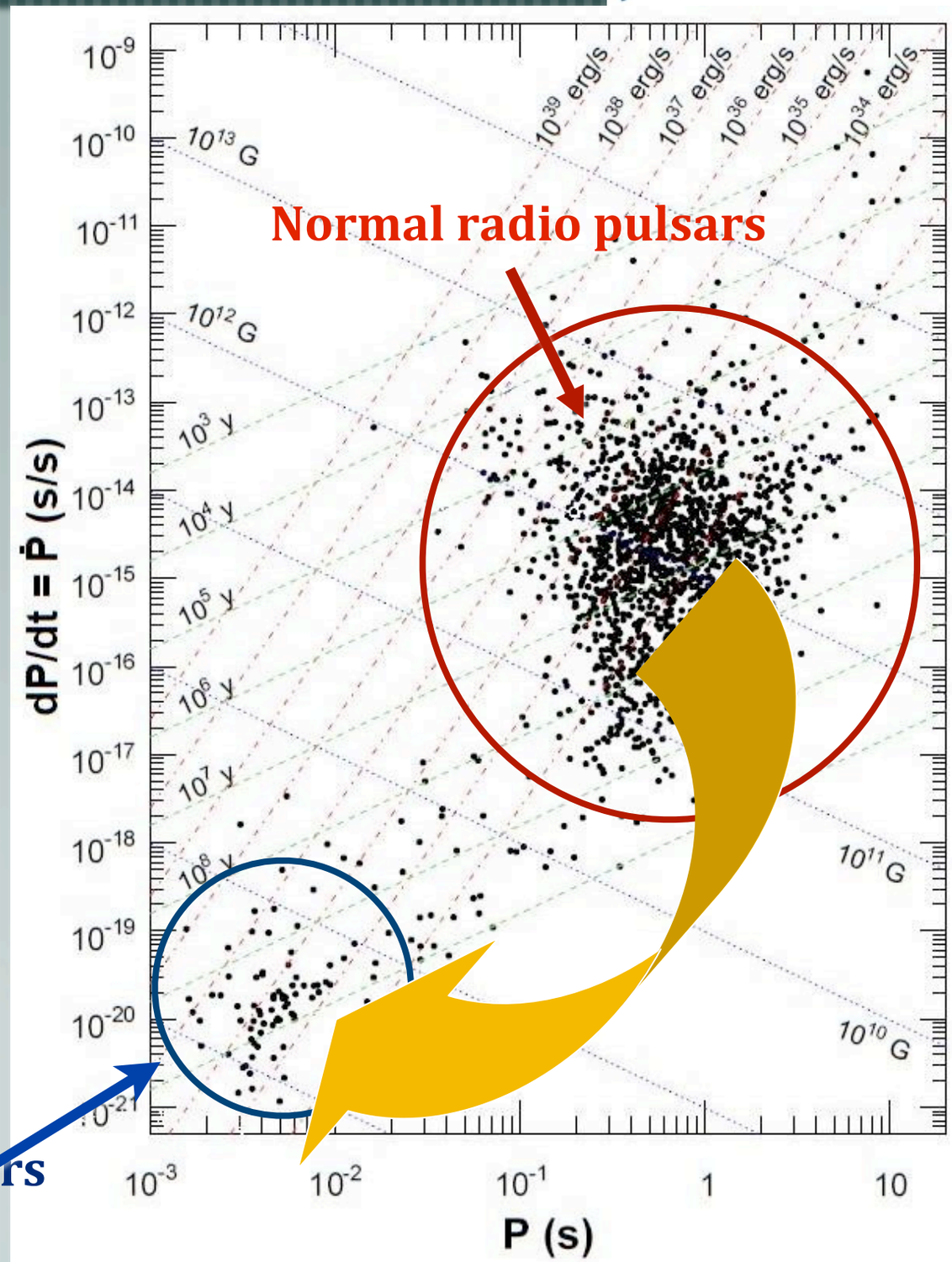


Period and Slowdown

- 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
- ~ 2000 known pulsars in radio



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

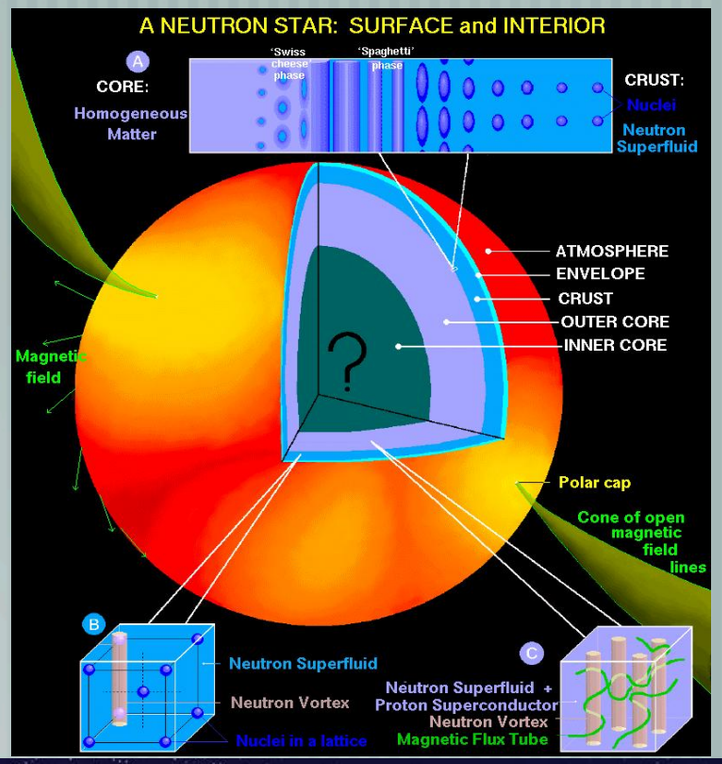
- Binary pulsars probe many predictions of General Relativity to high precision
- Pulsar timing arrays should be able to directly detect nHz gravitational waves

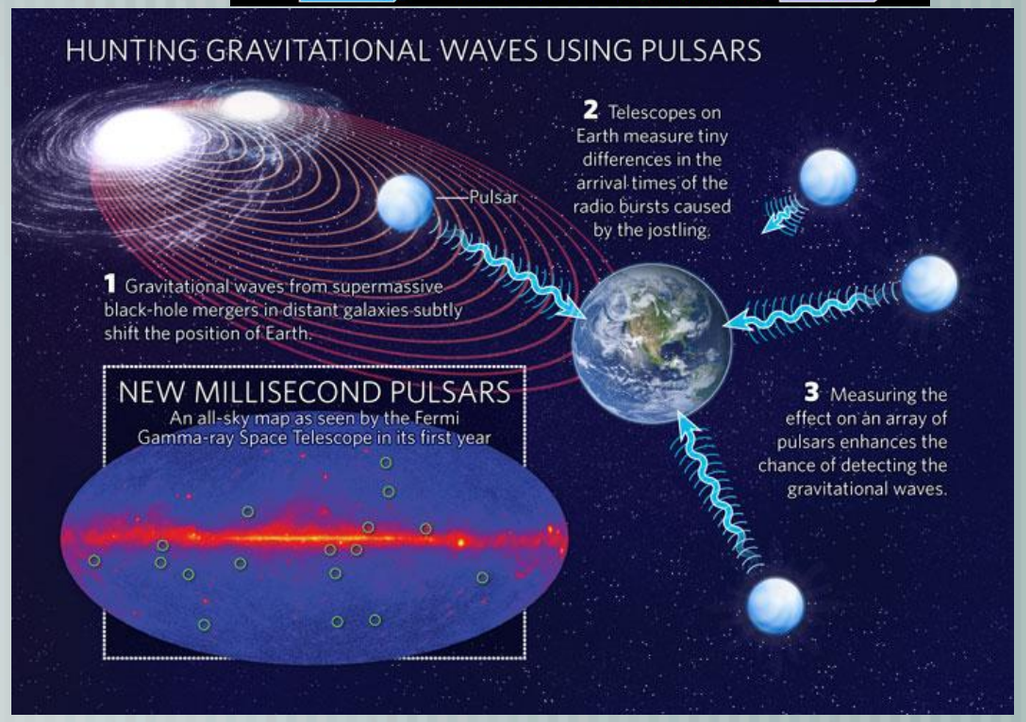
Extreme Magnetism

- Some pulsars have B fields above the quantum critical field ($B \sim 10^{14}$ Gauss in "magnetars")

Extreme acceleration

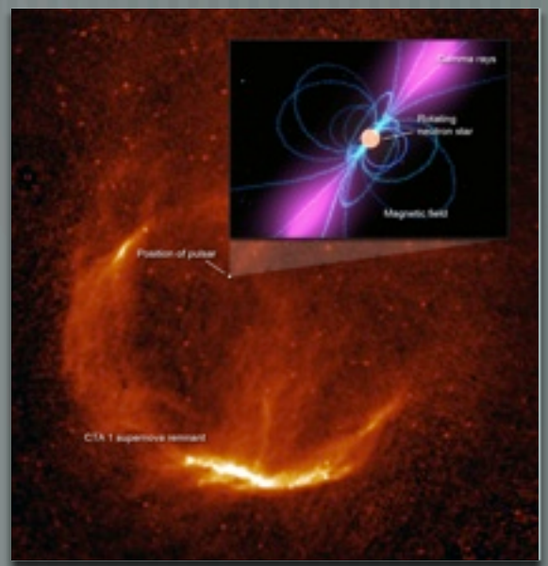
- Shocks in pulsar winds accelerate particles to >TeV energies
- Potential sources of cosmic-ray electrons





Motivations for Gamma-ray Astrophysics

- Gamma-ray astrophysics opens a new window on the non-thermal, relativistic Universe
- Crucial for our understanding of some fundamental problems in modern physics:
  - Origin of cosmic rays
  - Quantum gravity
  - Dark matter
- Probes the physics of extreme objects that are poorly understood:
  - Pulsars
  - Supernova remnants
  - Active Galactic Nuclei
  - Gamma-ray bursts



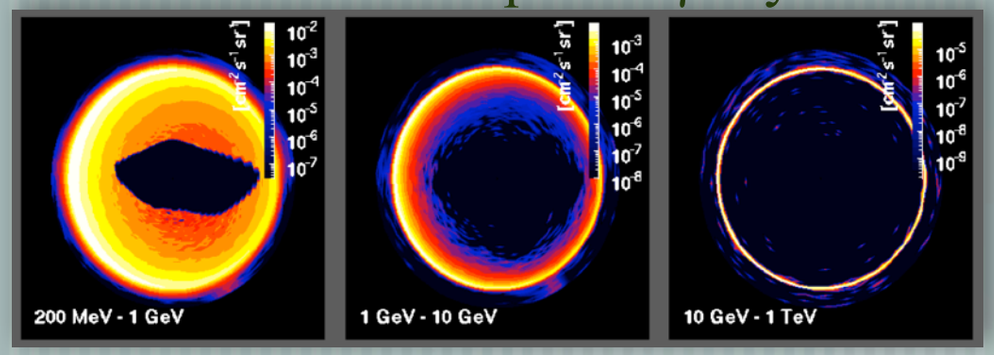
The Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope

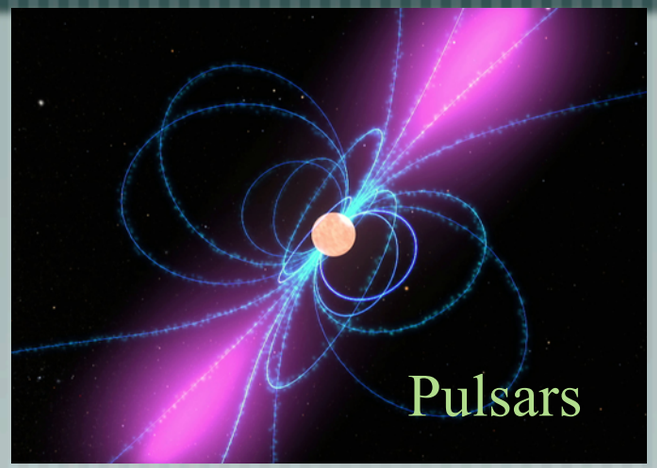
- Pair production telescope with silicon tracker, CsI calorimeter, and segmented anti-coincidence detector
  - 20 MeV to >300 GeV
  - 8000 cm^2 area (at 1 GeV)
  - 0.6–0.8 deg radius PSF (1 GeV)
- Continuous sky survey mode of operation
- Big improvement in area, FOV, and reduction in background compared to EGRET
- Sky survey started August 4, 2008

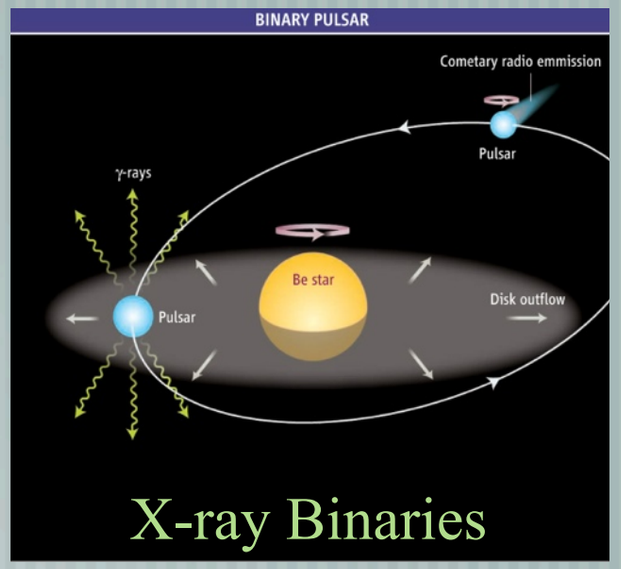
(Atwood et al. 2009, ApJ, 697, 1071)

Fermi Science Highlights

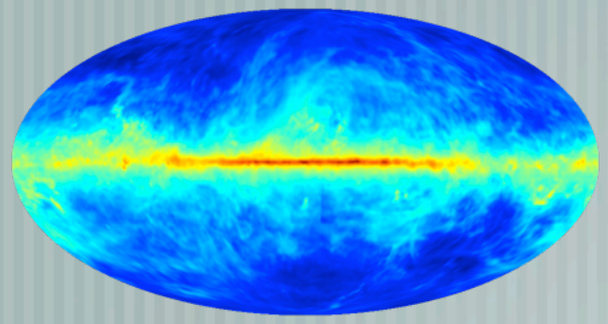
Earth's atmospheric γ-rays





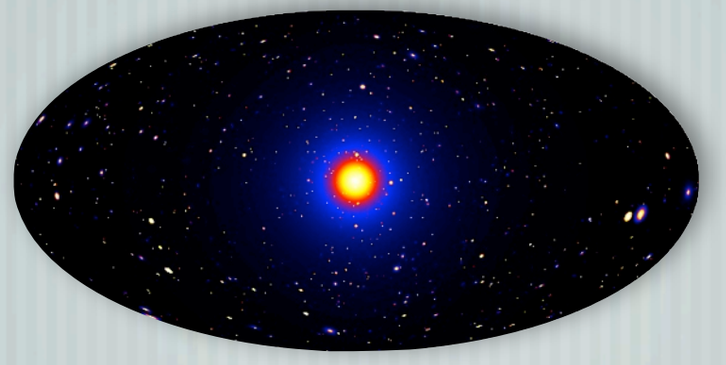


Diffuse Galactic γ-rays



Active Galactic Nuclei

Dark Matter?

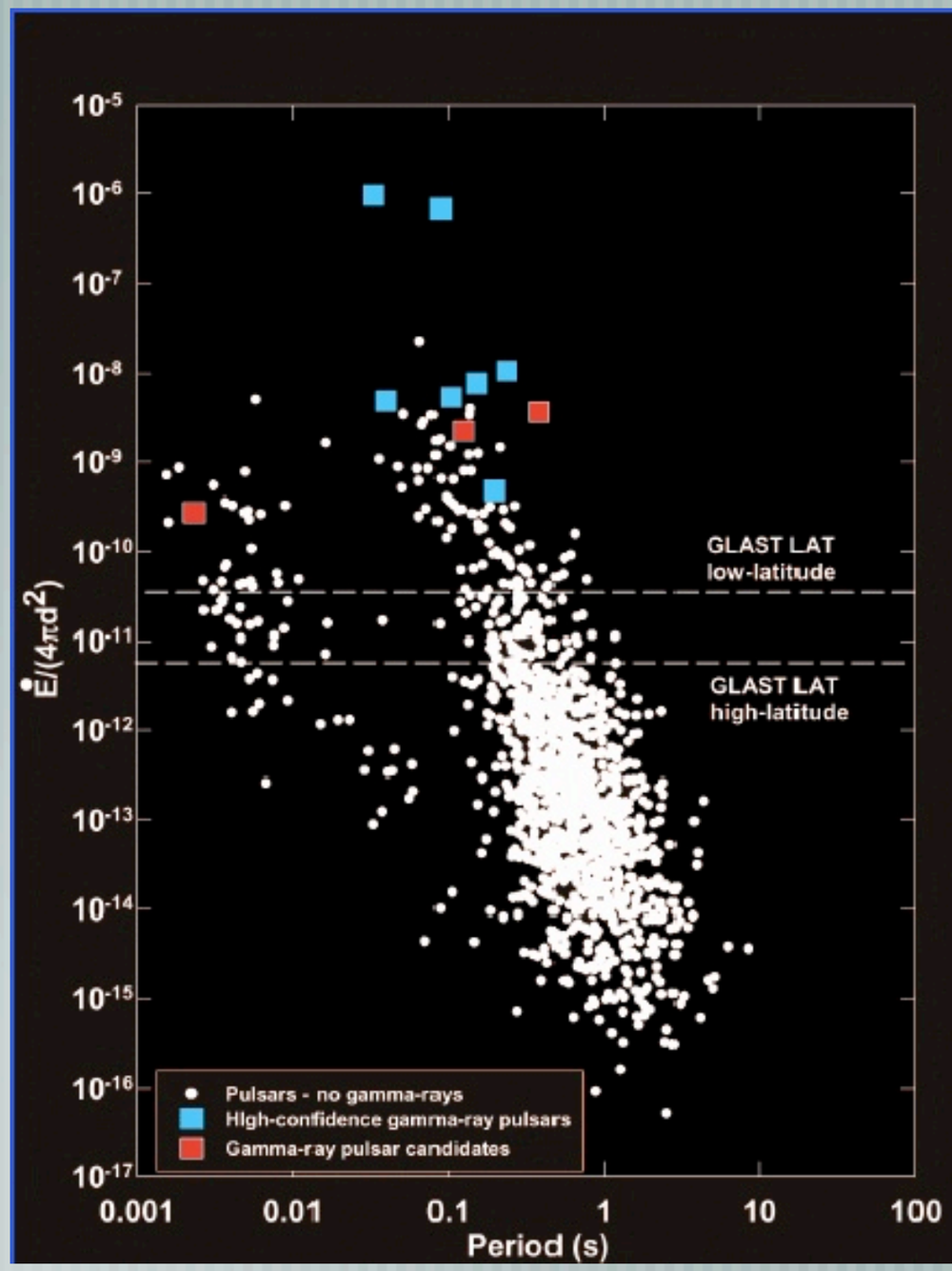


Previous Observations of Gamma-ray Pulsars

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

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

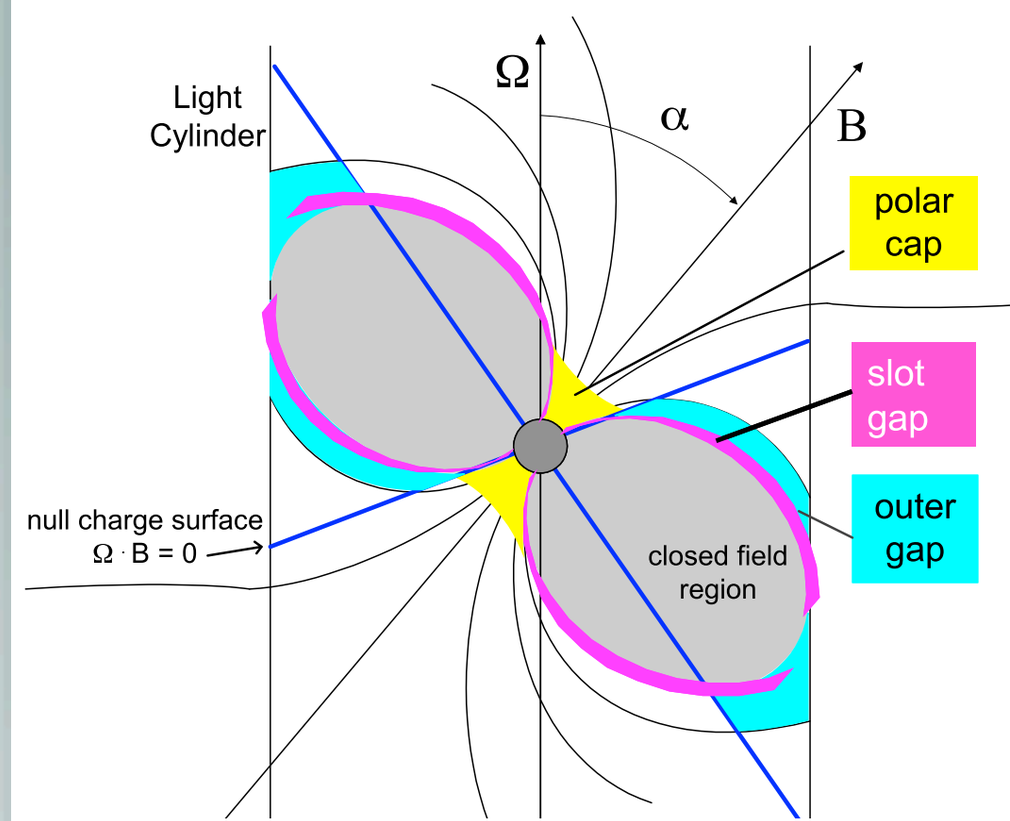
More recently... AGILE (2007 -)

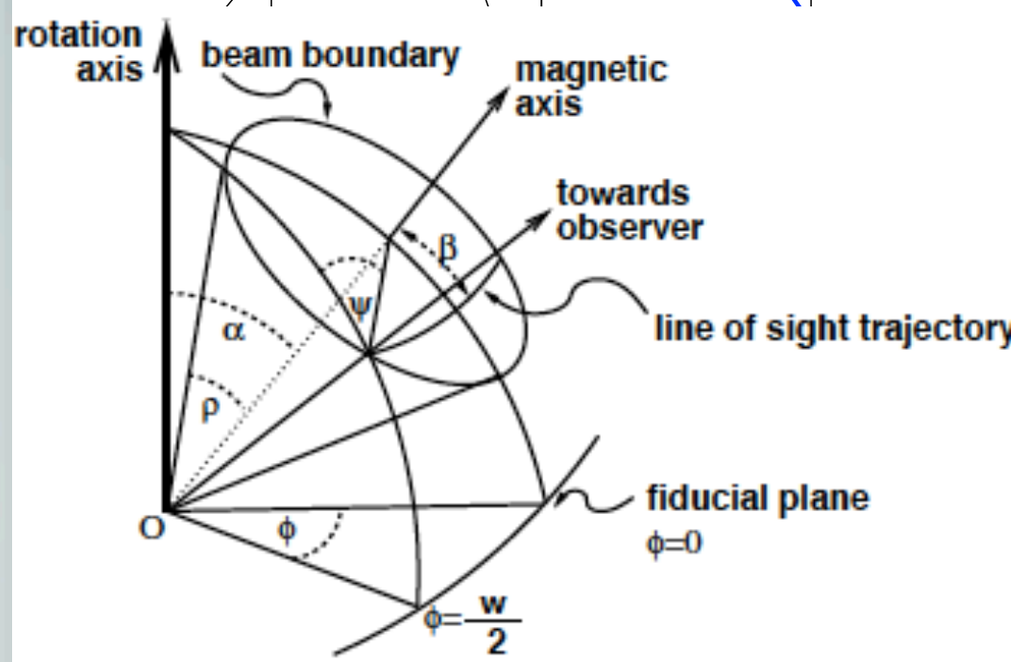


Pulsar Gamma-Ray Emission

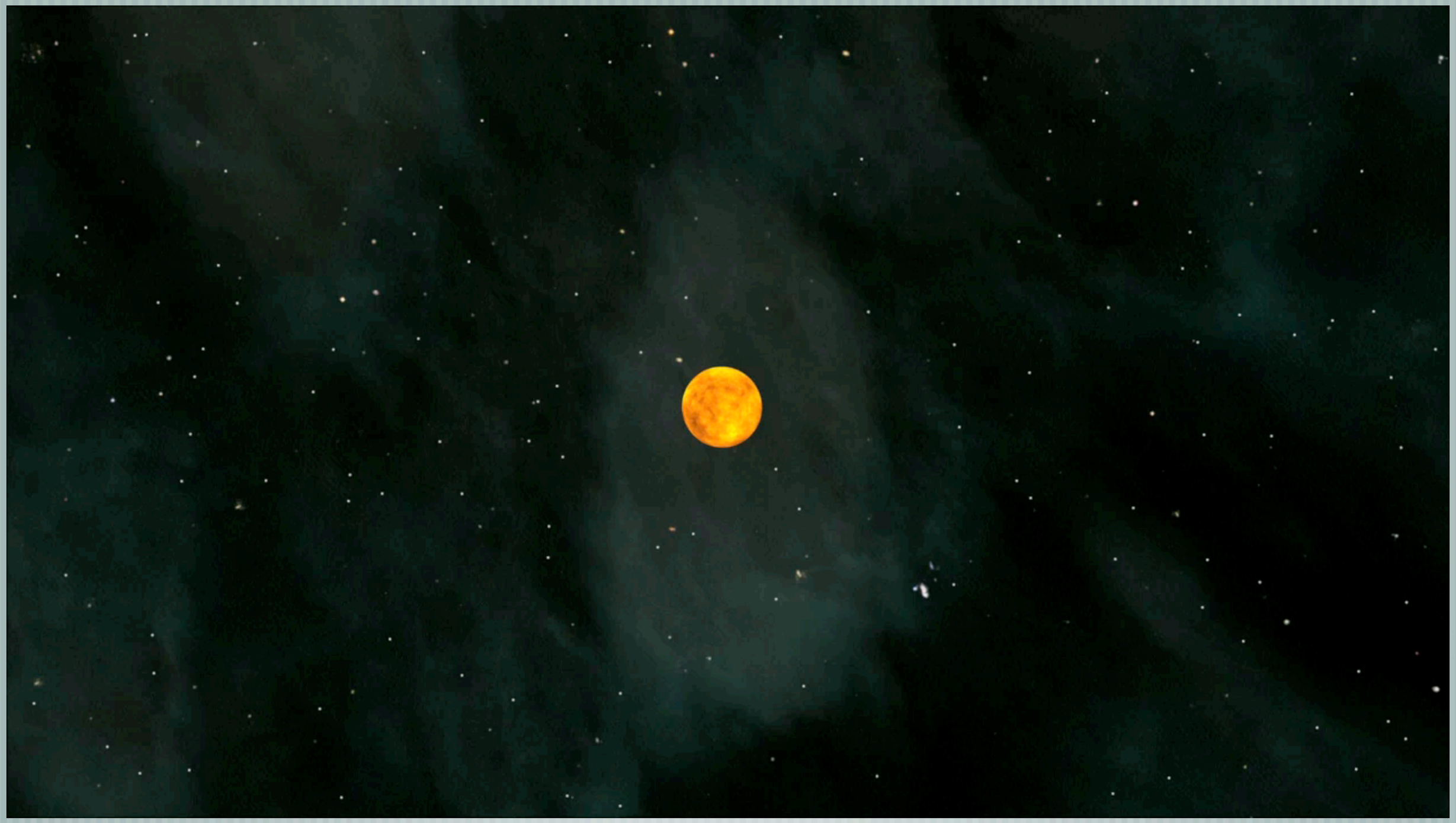
- Very significant portion of the energy budget (~10% or more)
- Theoretical models try to explain the observed gamma-ray emission as coming from different regions of the magnetosphere and with different magnetosphere configurations
- Different emission patterns are expected (number of peaks, separation, radio/gamma lag, ratio of radio-loud/radio-quiet) for each model as a function of:
  - α: angle between magnetic and rotation axis
  - β: angle between line-of-sight and magnetic axis (or , ζ the angle between line-of-sight and spin axis)
- **Gamma-ray observations can help disentangle the geometry of pulsars**

(Also see Watters et al. 2009, ApJ, **695**, 1289)



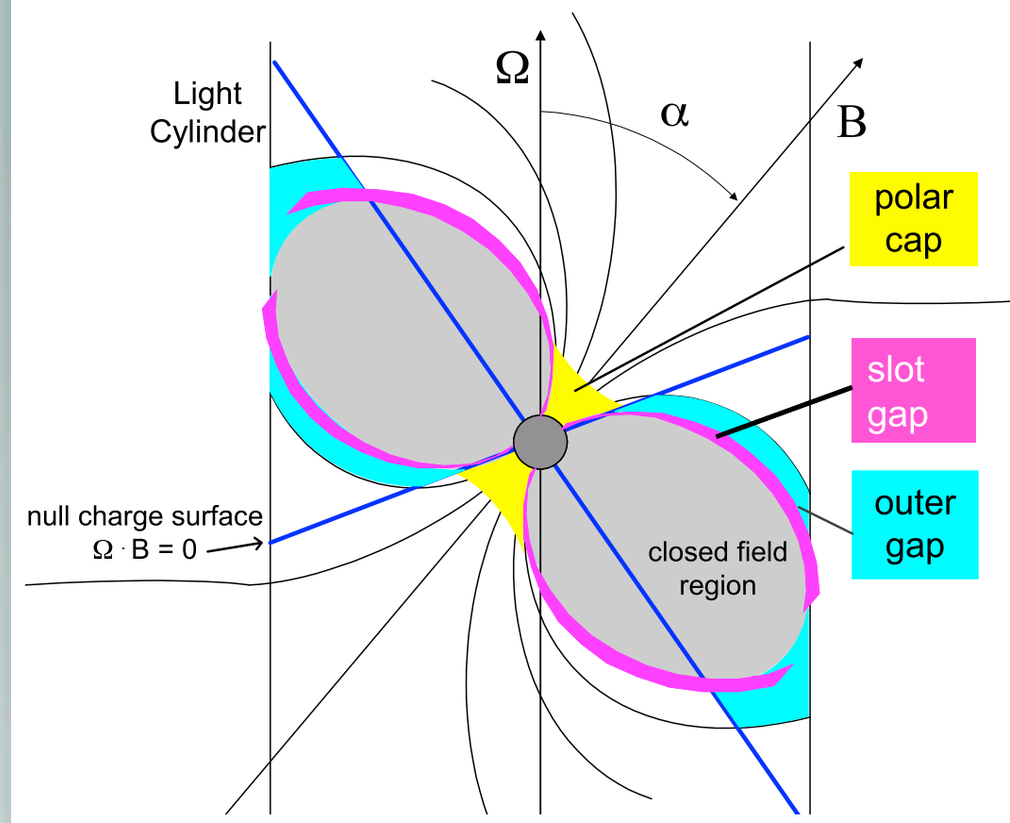


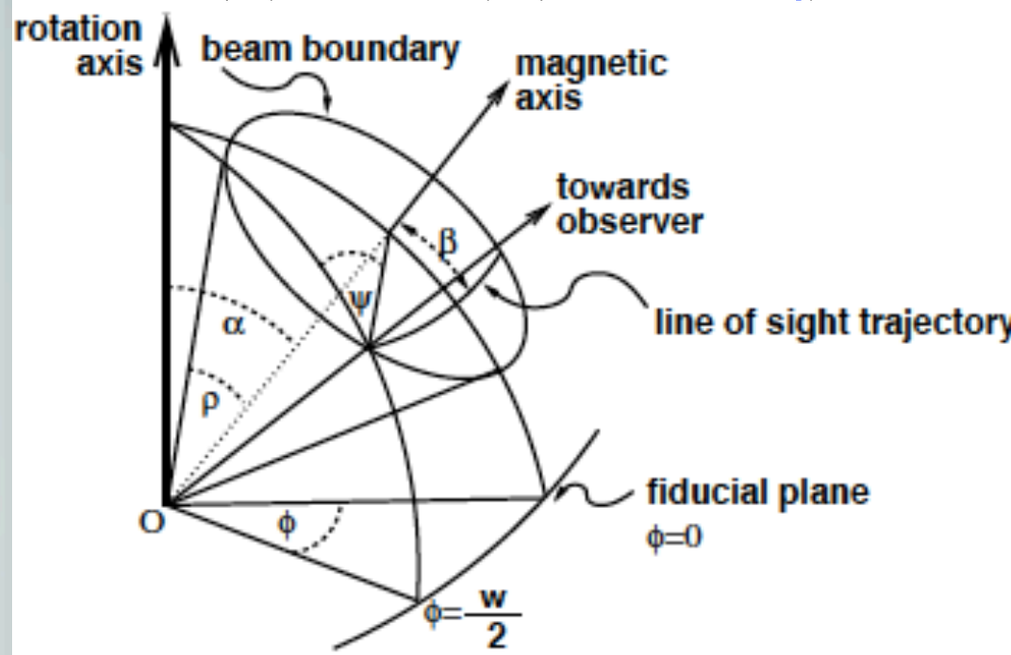
Radio-Quiet Pulsar Animation



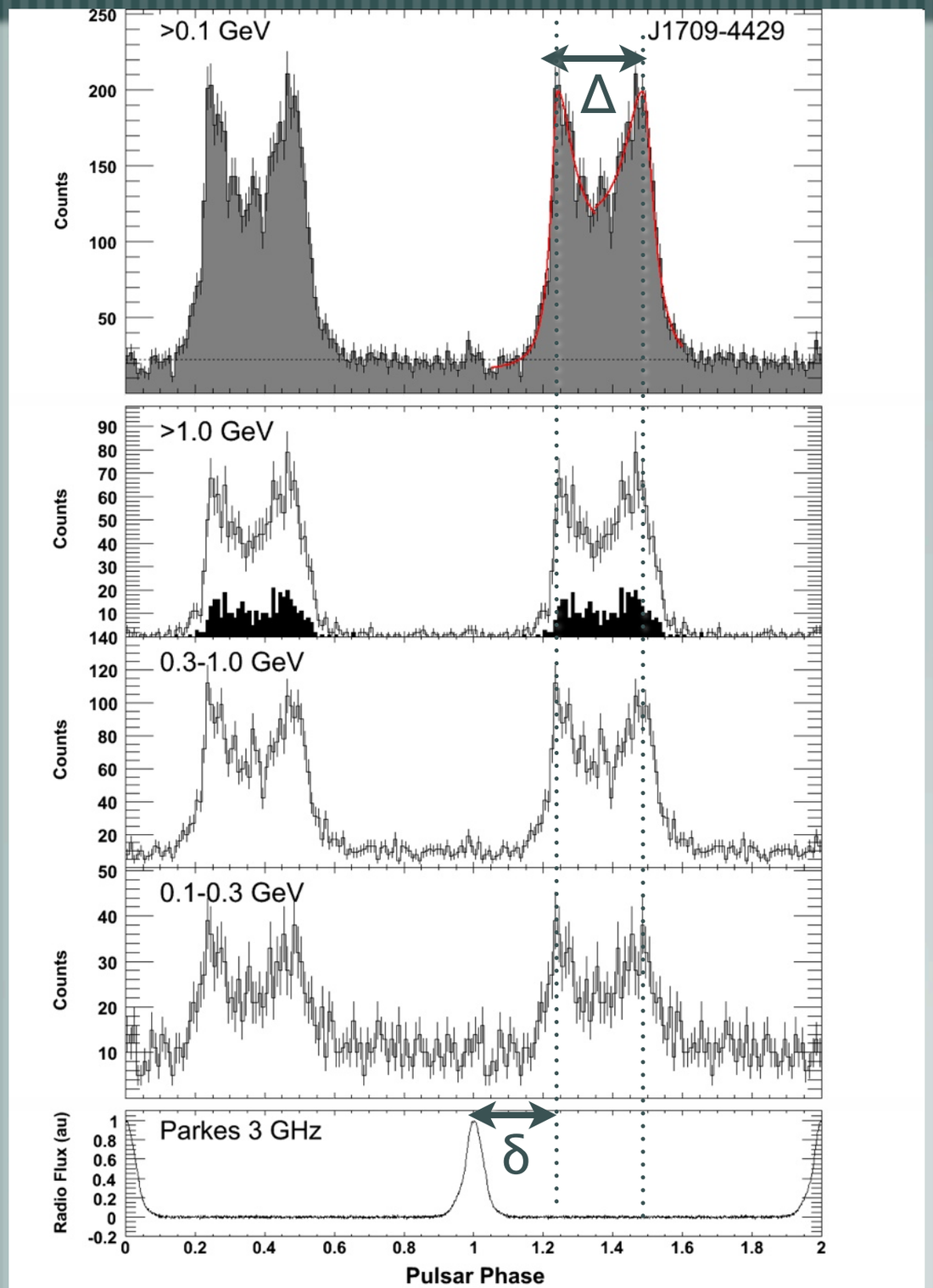
Some (pre-Fermi) open questions:

- What mechanisms produce the emission of pulsars, from radio to gamma rays ?
- Where do these phenomena take place ?
- Are there gamma-ray millisecond pulsars ?
- What is the fraction of radio-loud and radio-quiet pulsars ?
- What is the contribution of gamma-ray pulsars to the diffuse galactic emission and the unidentified gamma-ray sources?





Key Observables: Light Curve



- Light curve parameters
  - Peak multiplicity
  - Radio lag (δ)
  - γ-ray peak separation (Δ)
  - (Evolution with E, but theories don't predict this at all, yet)
- Geometry can be constrained in other ways as well, multiwavelength info important
  - X-ray pulse profile and images of pulsar wind nebulae
  - Radio Polarization (RVM fits)

Key Observables: Energy spectrum

The energy spectrum can be described by a power law with an (hyper) exponential cutoff :

Spectral Index

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

Cutoff Energy

β : cutoff index

~ 1 : Slot Gap and Outer Gap models (high altitude emission)

~ 2 : Polar Cap model (low altitude emission)

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)
- Blind searches for pulsations directly in the gamma-ray data
  - Spectacularly successful for young pulsars
  - **Really** hard for MSPs! None so far...
- Radio pulsar searches of LAT unidentified sources
  - Sensitivity to MSPs, binaries, very noisy pulsars

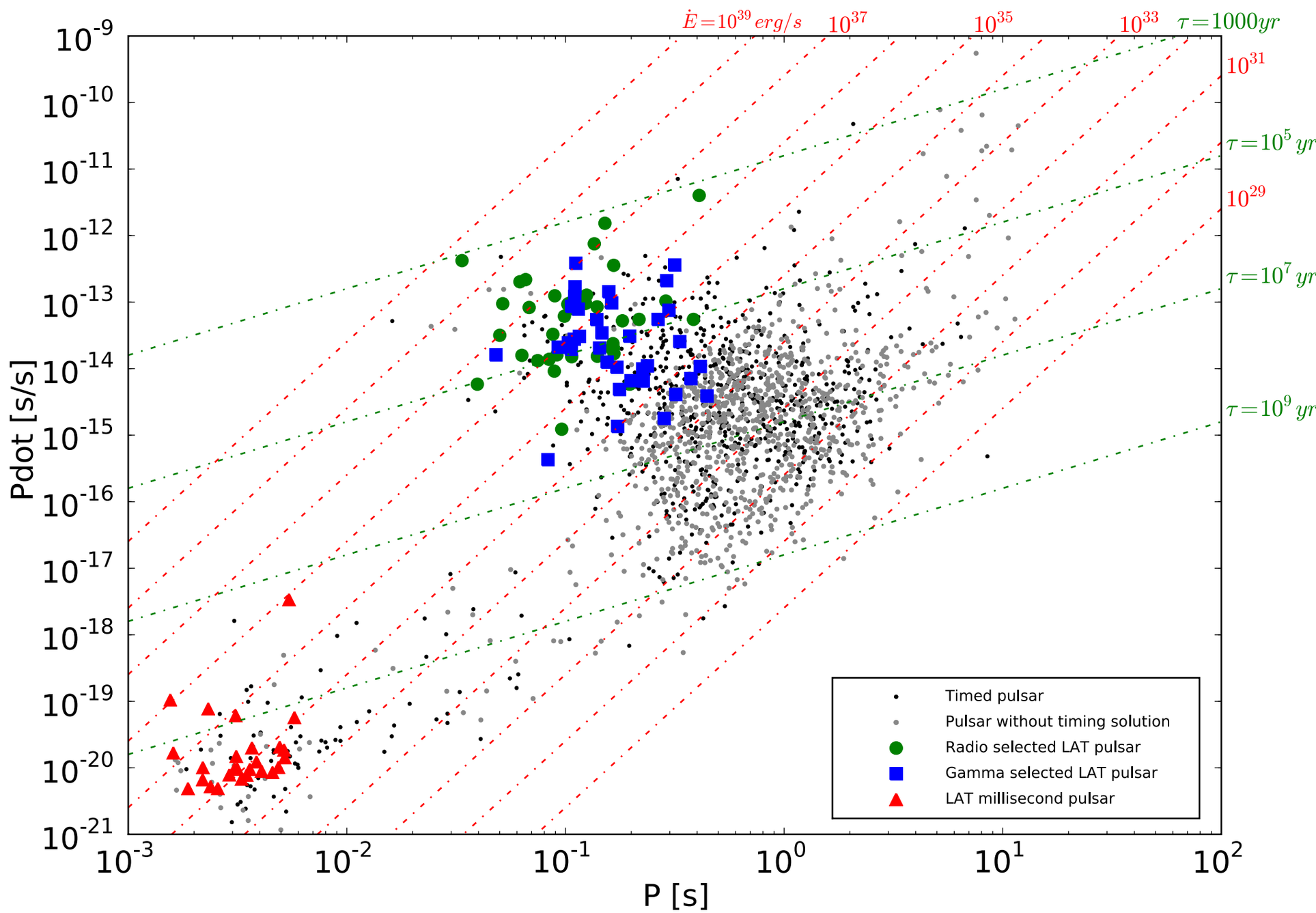
117 LAT-Detected Pulsars!

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

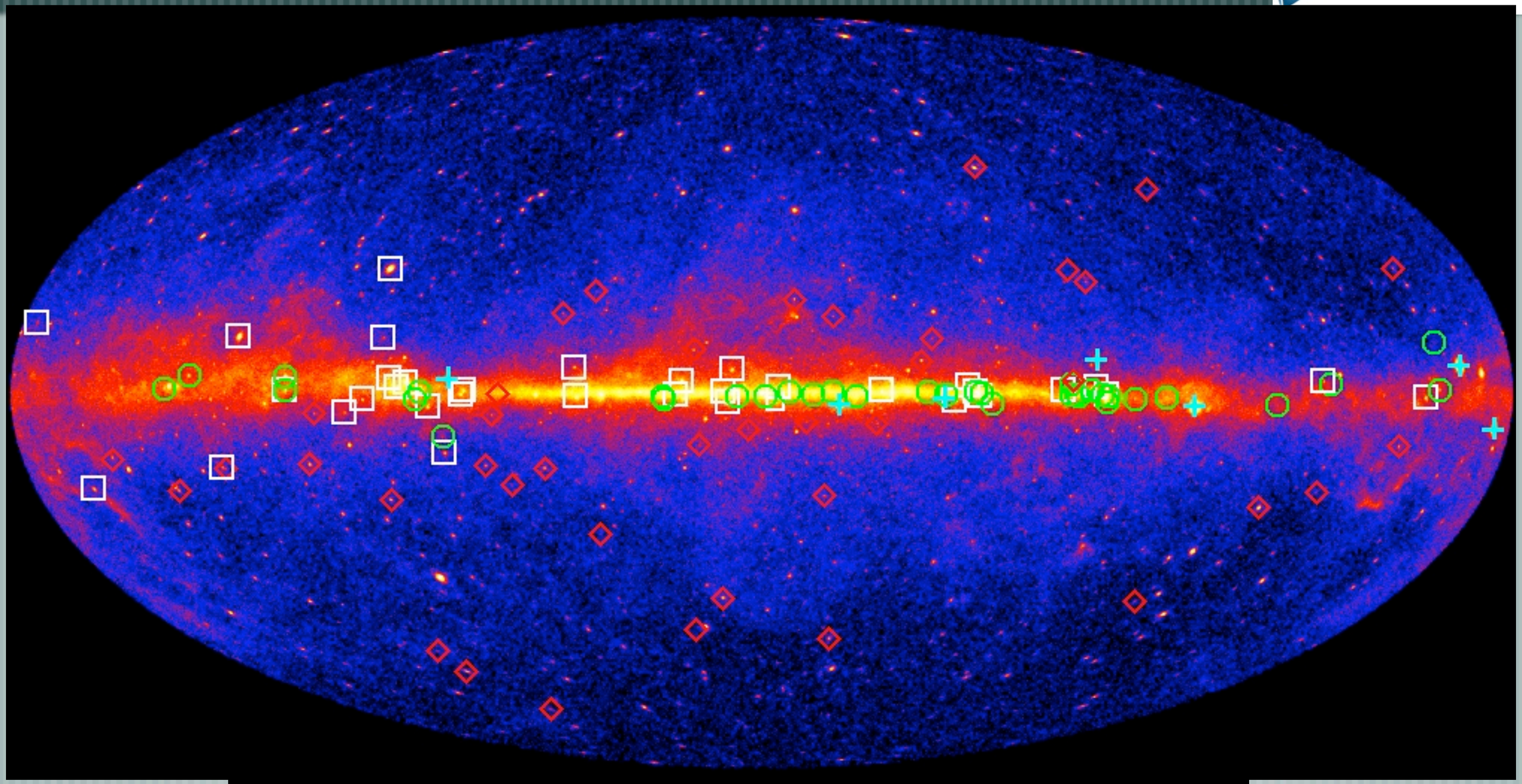
LAT team has stringent criteria before claiming detection, typically >5σ

Current Statistics

Young, radio selected: 38
Young, gamma selected: 36
Young, X-ray selected: 3
MSP, radio selected: 40
MSP, gamma selected: 0

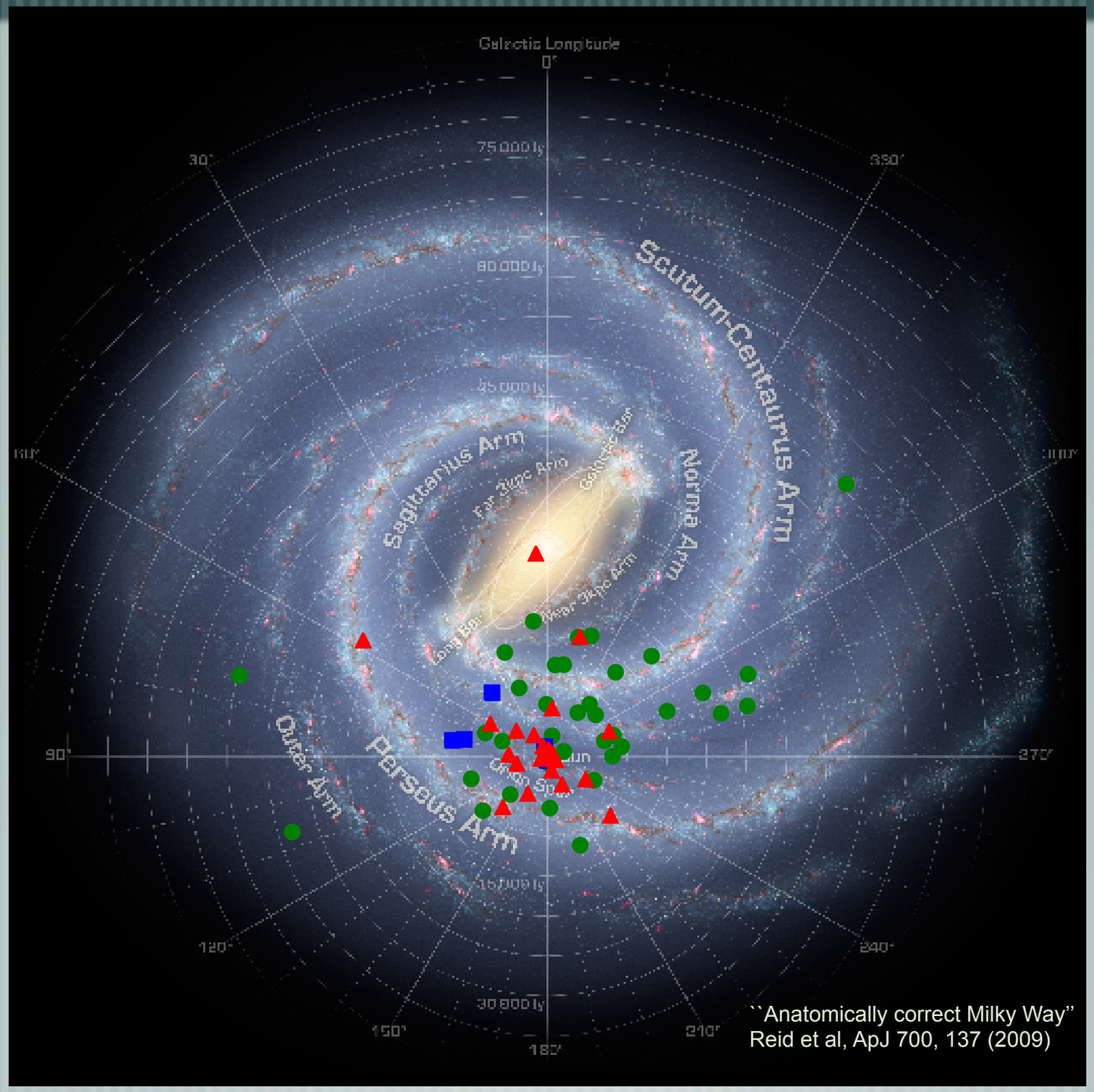


117 Gamma-Ray Pulsars



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(◇).

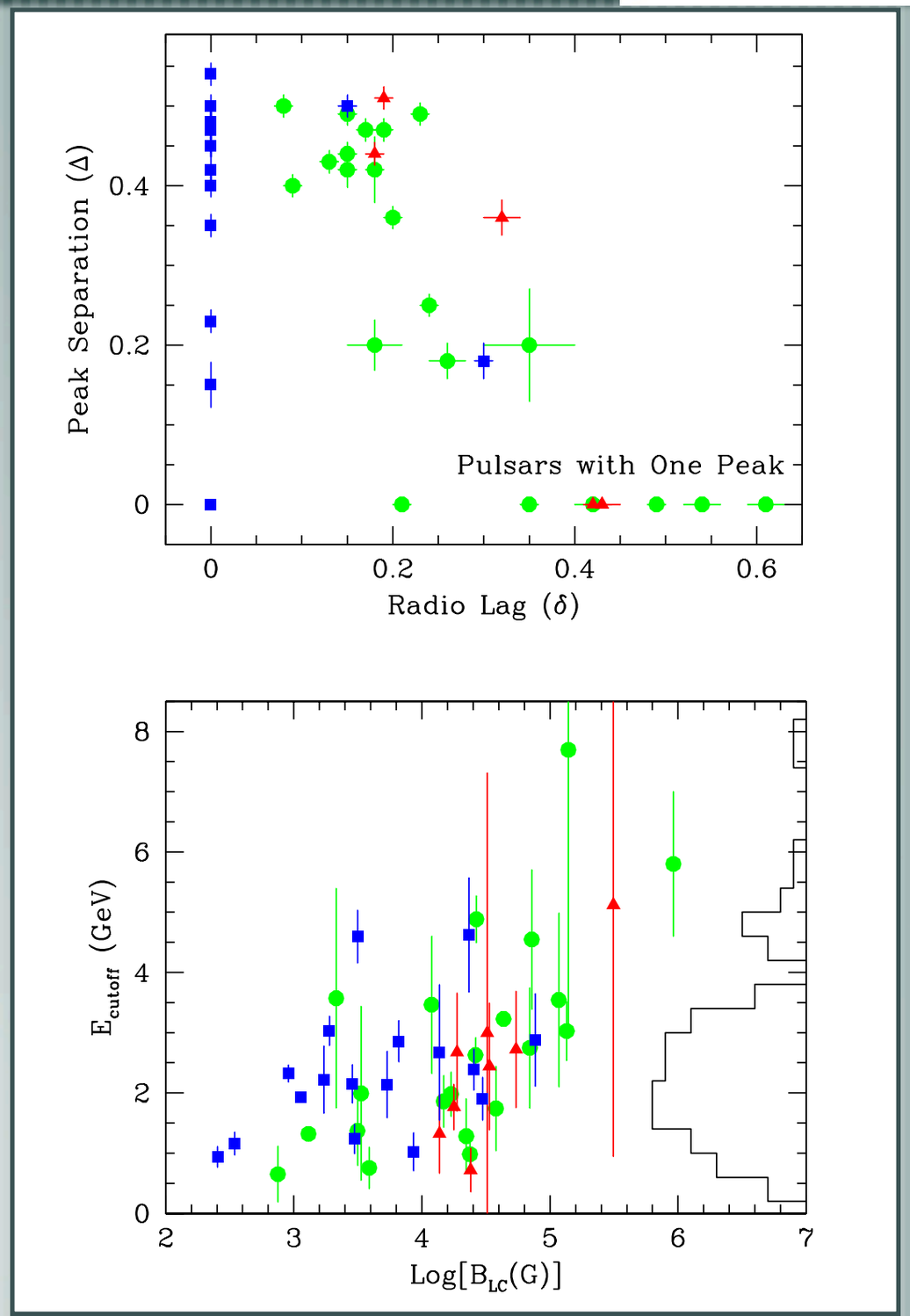
Where in the Galaxy Are They?



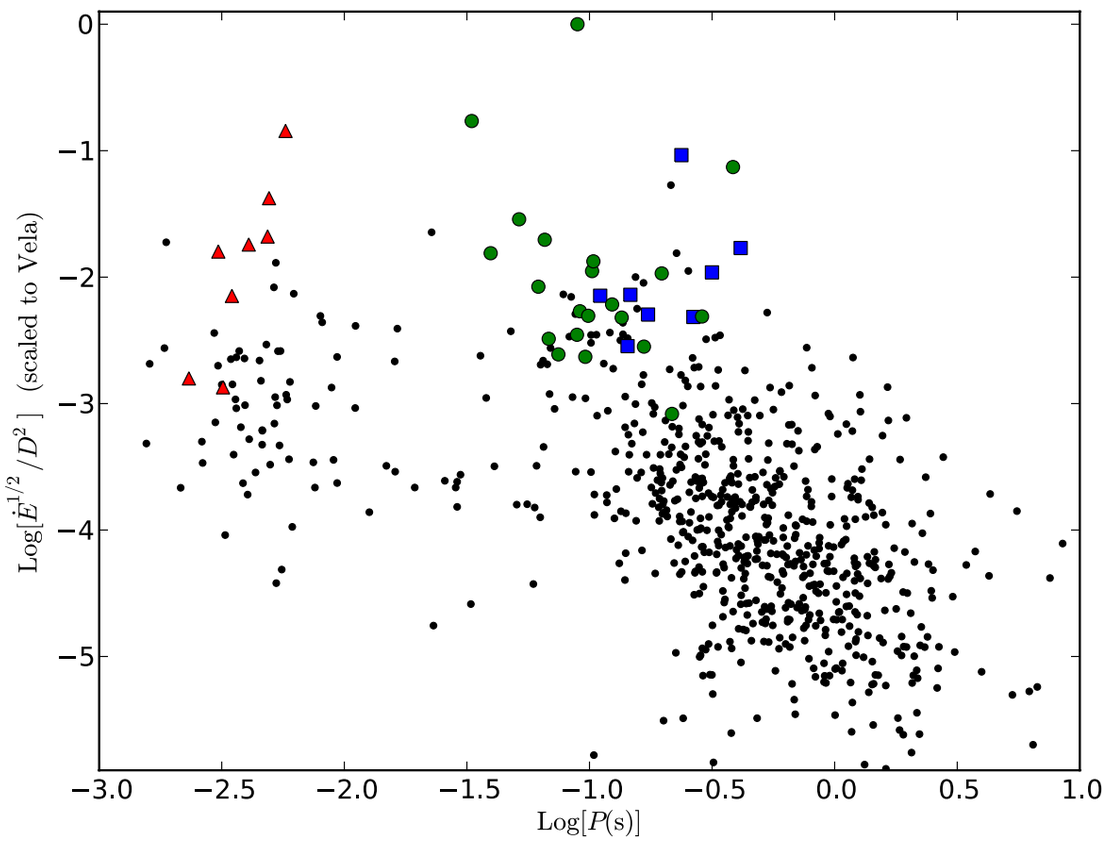
``Anatomically correct Milky Way''
Reid et al, ApJ 700, 137 (2009)

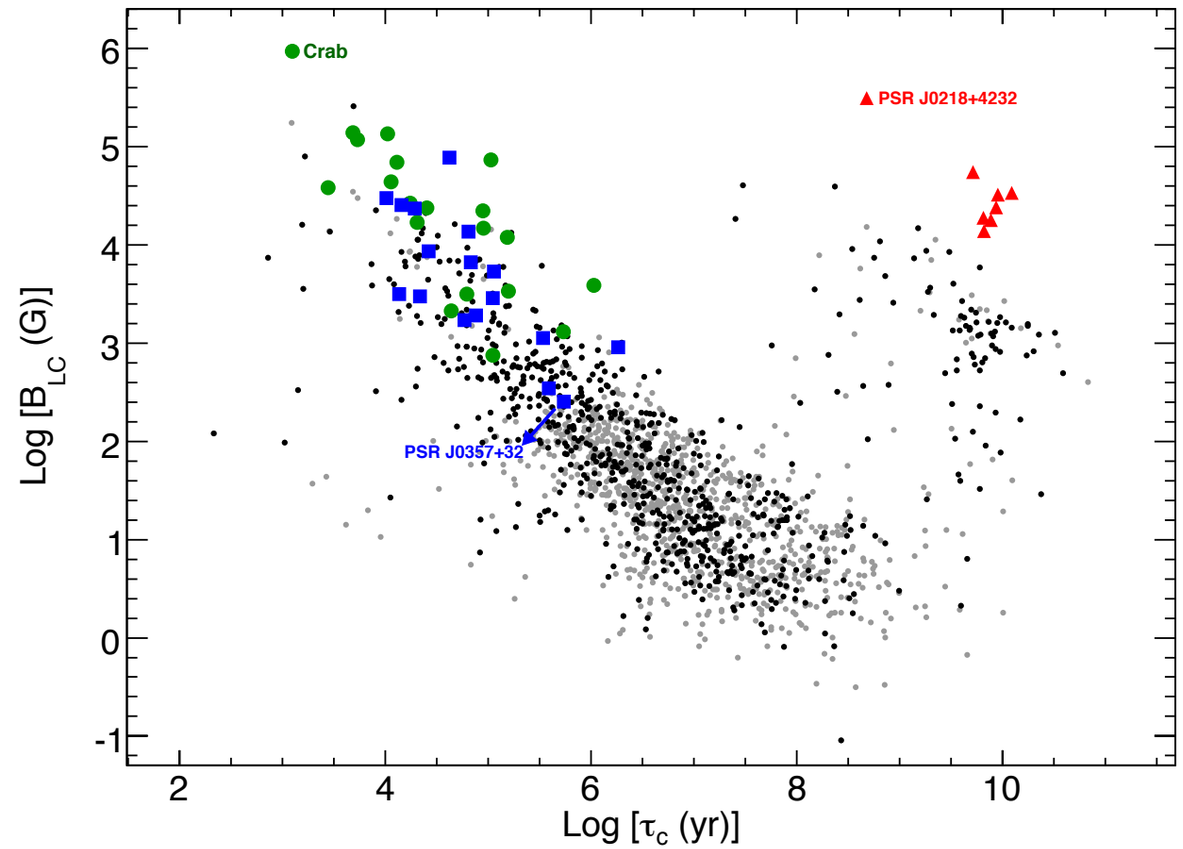
About the LAT-detected Pulsars

- Generally (but not always) two peaks separated by about ½ rotation
- Generally (but not always) gamma-ray peak offset from radio
- (Simple) Exponential cutoffs in the 1–3 GeV range
- MSPs resemble young pulsars
  - Both have similar values of B_{LC}
  - But more likely to have aligned and/or complex gamma-ray profiles
- Outer magnetosphere models favored



What Pulsars Are We Seeing?





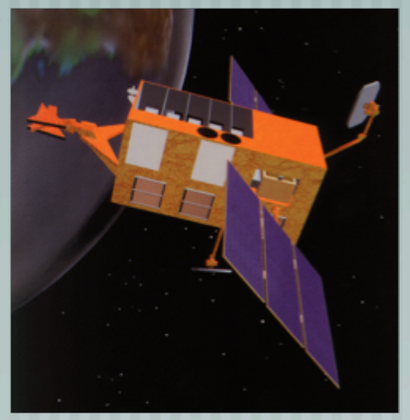
- Mostly seeing high $\dot{E}^{1/2}/D^2$, as expected
- Distance uncertainties dominate, making exceptions a bit tricky to study
- $L\gamma$ relates to $\dot{E}$

- High B_{LC} also preferred, both for normal PSRs and MSPs
- Similar outer magnetosphere mechanisms in both classes?

All of this to be revisited in 2nd Pulsar Catalog

Folding With Known Ephemerides

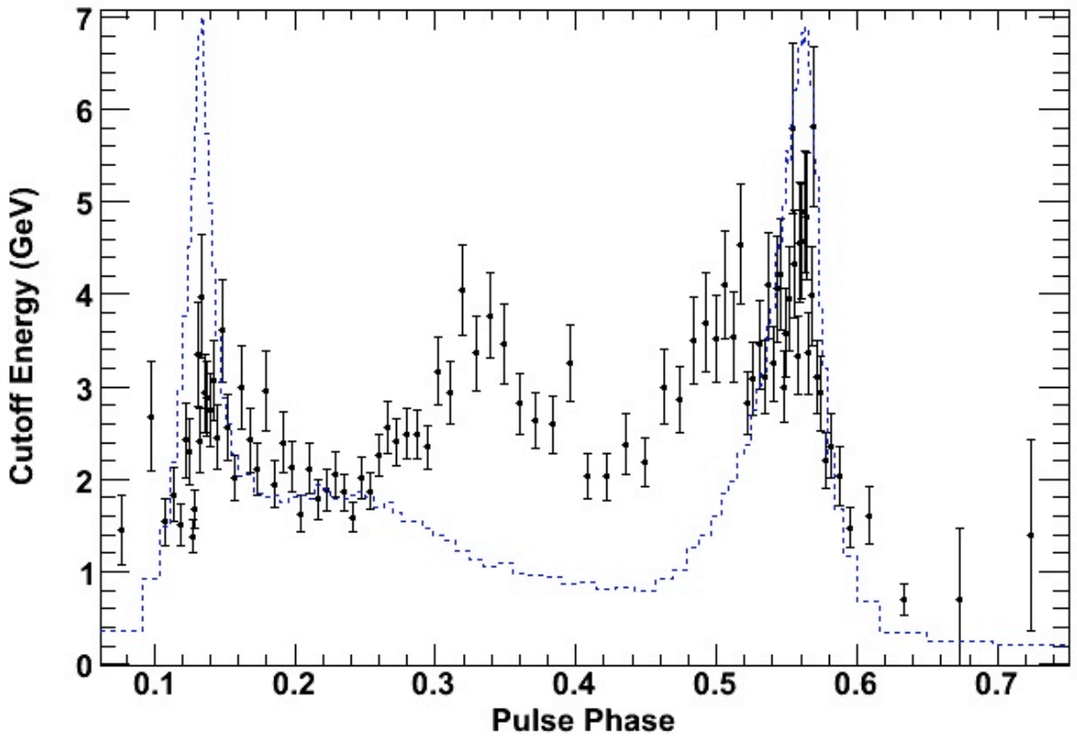




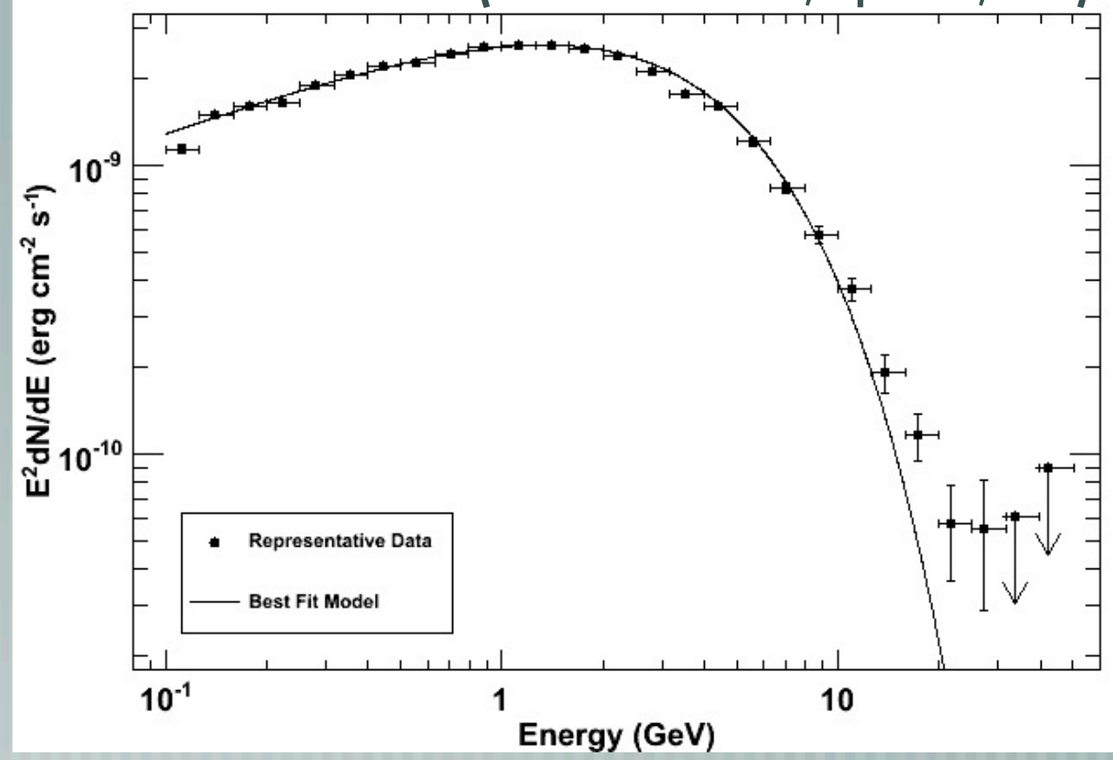
- Large campaign organized to provide radio (and X-ray) timing models for all (~200) pulsars with $\dot{E} > 1 \times 10^{34}$ erg/s (Smith et al. 2008 A&A, 492, 923)
  - Thanks to all members of the Pulsar Timing Consortium!
- Folded LAT photons for 762 pulsars

EGRET pulsars with Fermi

Vela Pulsar



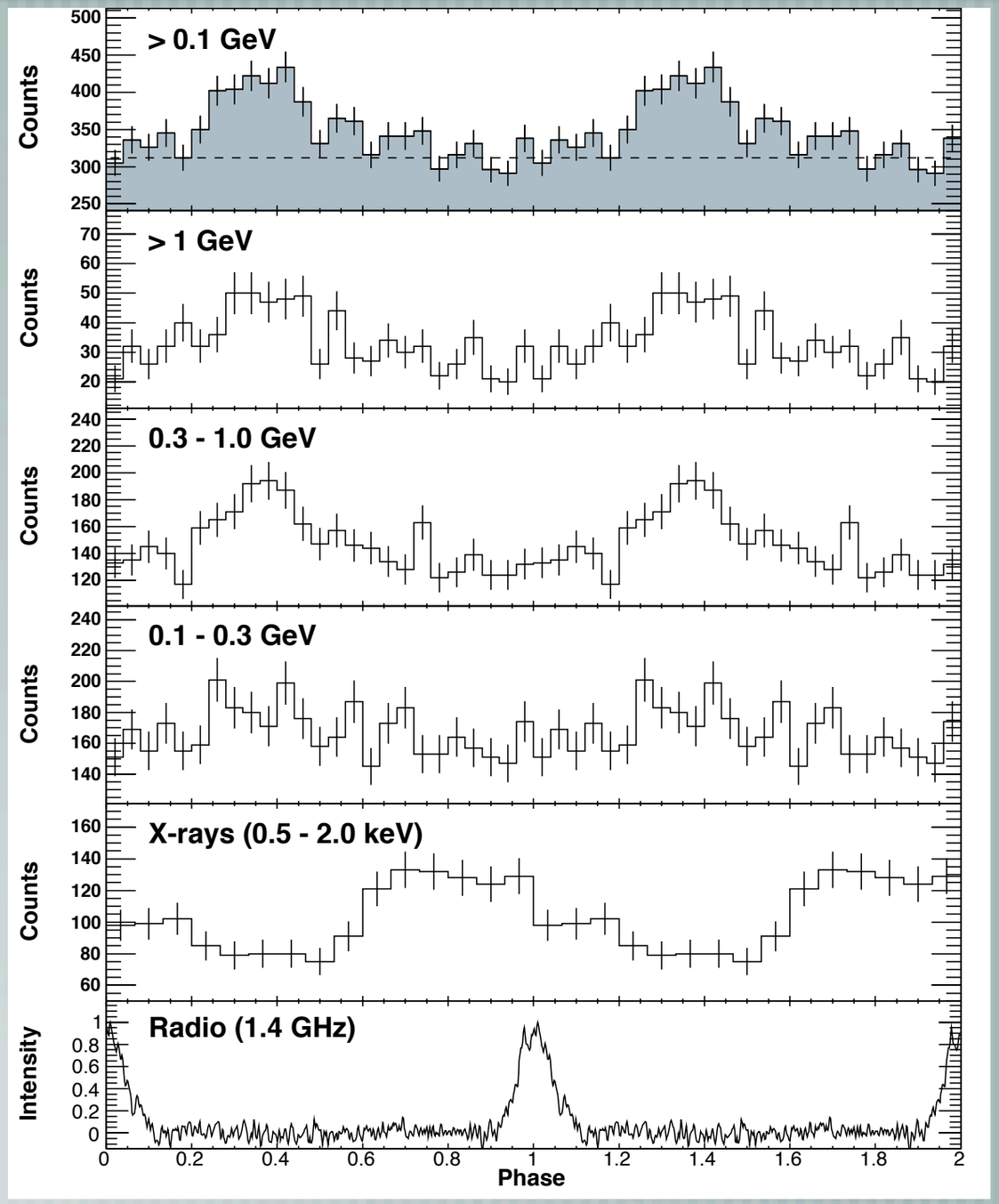
(Abdo et al. 2010, ApJ 713, 154)



- The 6 EGRET pulsars are prime targets for spectral analyses with unprecedented details, because of their brightness.
- 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, perhaps due to variation in emission altitude
- In general, pulsar spectra are consistent with simple exponential cutoffs, indicative of absence of magnetic pair attenuation.

Example: PSR J1357–6429

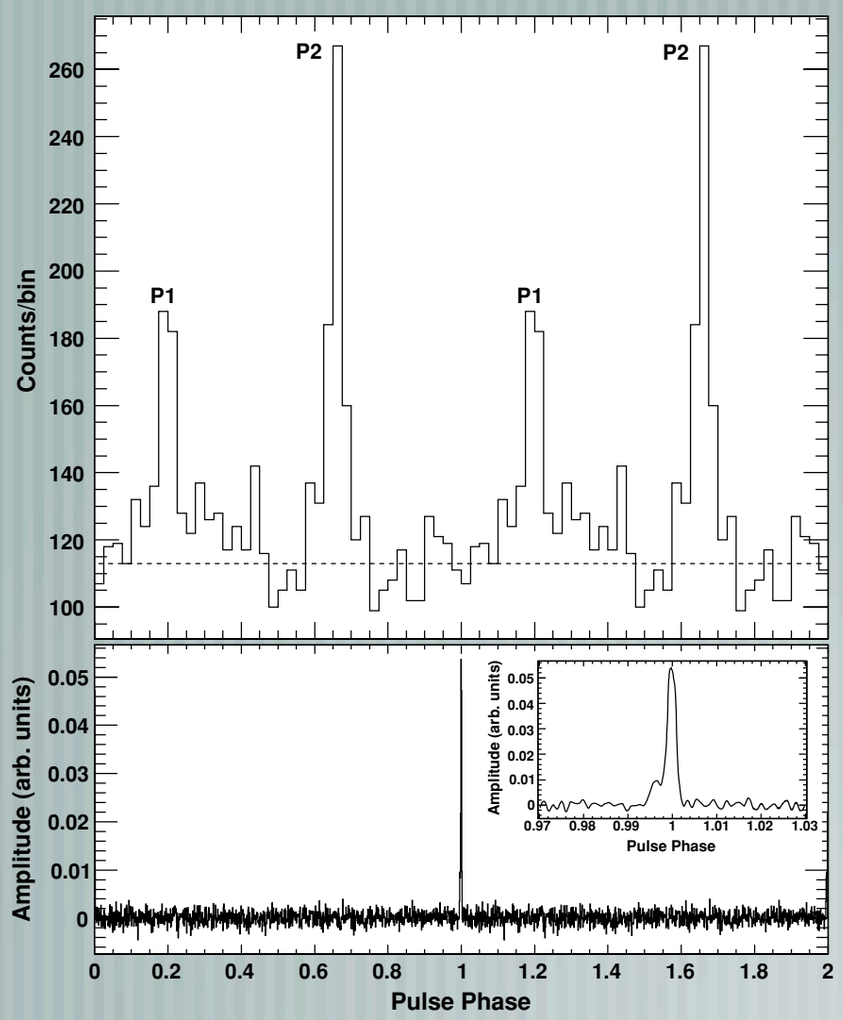
- High $\dot{E}$ (3.1×10^{36} erg/s) radio pulsar
- HESS was concluding their analysis of the associated TeV PWN
- They thought "LAT sees no pulses? Perhaps GeV PWN!"
- Nope – a glitch in 2009 and timing noise meant LAT searches weren't done
- Got new ephemeris → Got gamma-ray pulsations!



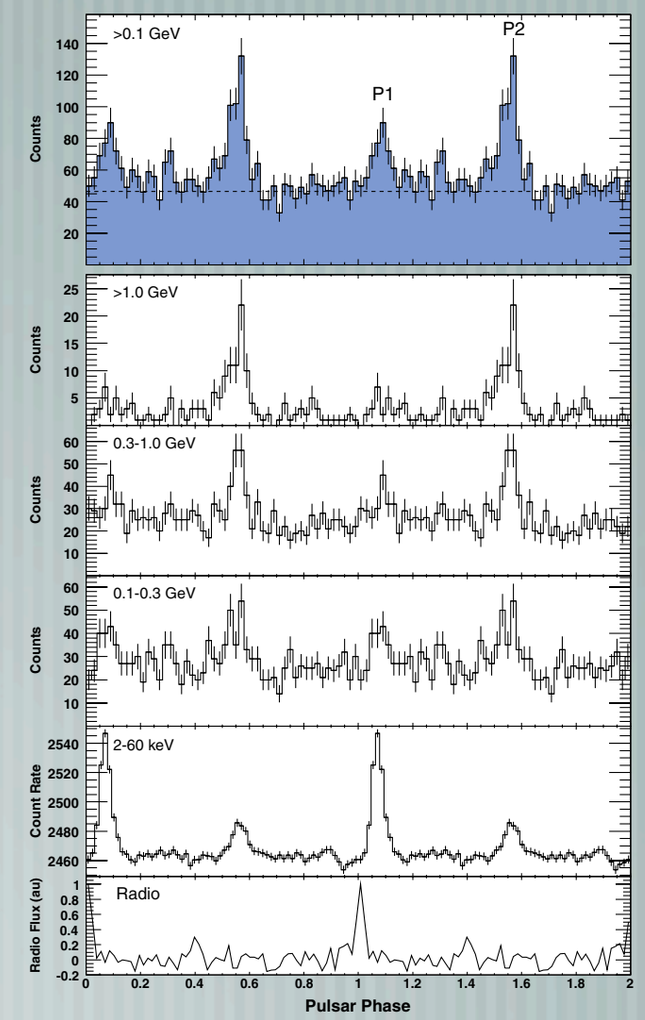
(Lemoine-Goumard et al. 2011, A&A, 533, A102)

Other Radio/X-ray Pulsars

About two dozen new LAT detections of young, energetic, radio pulsars
Too many to discuss individually here...



Young (90 kyr) pulsar PSR J1028–5819 discovered in radio search of 3EG J1027-5817
(Abdo et al. 2009 ApJ, 699, L102)

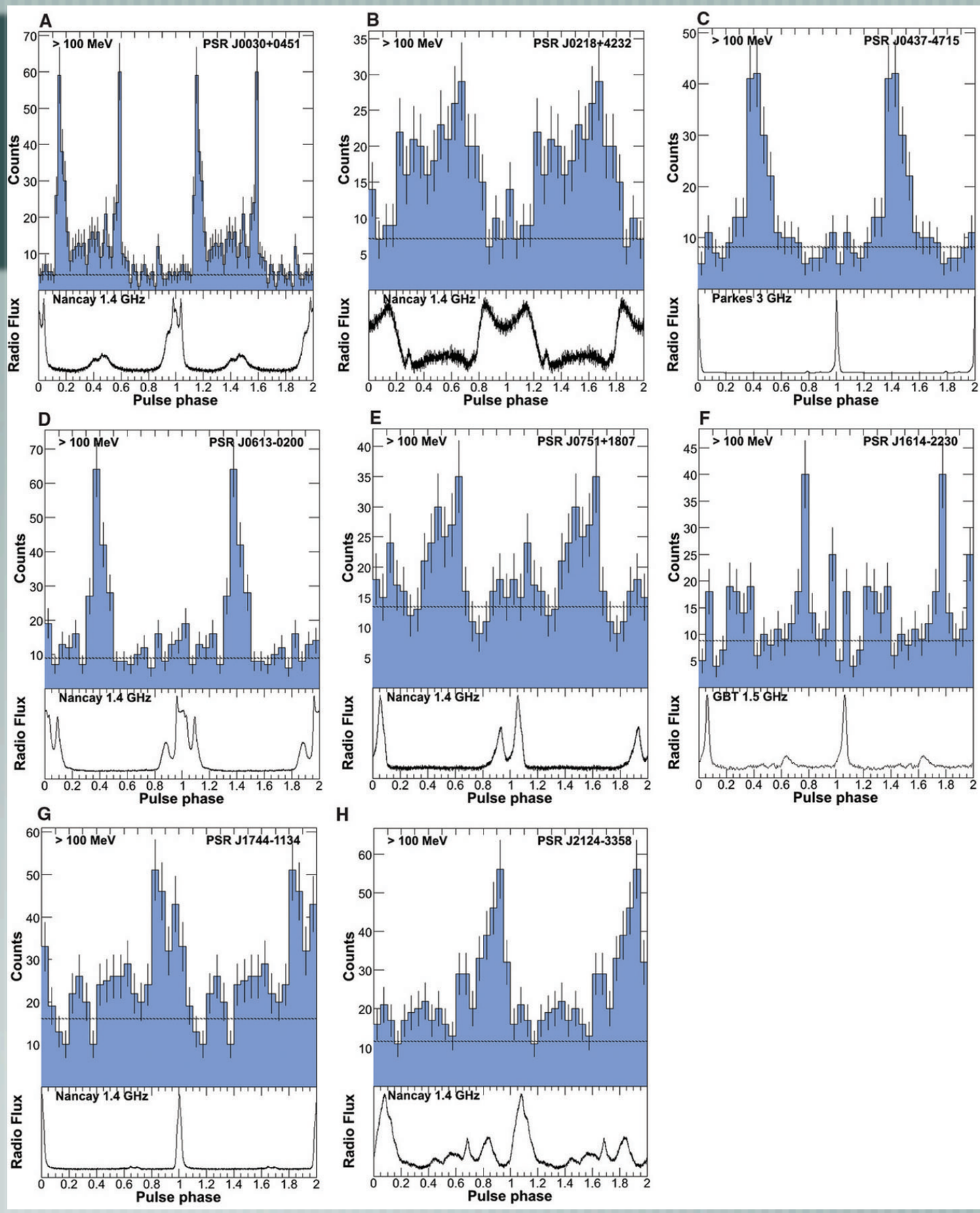


Very young (5.4 kyr), **very** faint radio pulsar in SNR/PWN 3C58
(Abdo et al. 2009, ApJ, 695, L72)

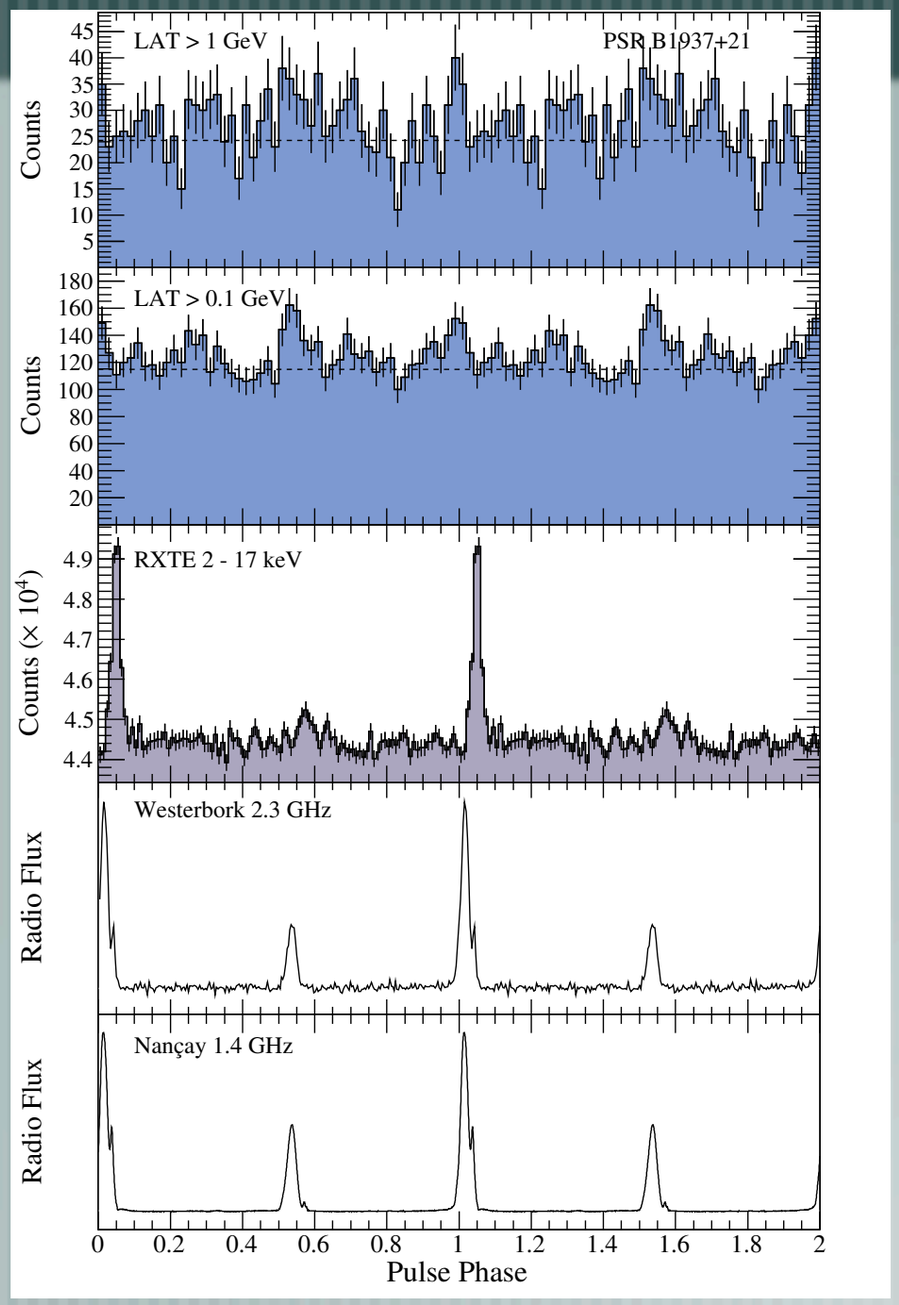
Millisecond Pulsars!

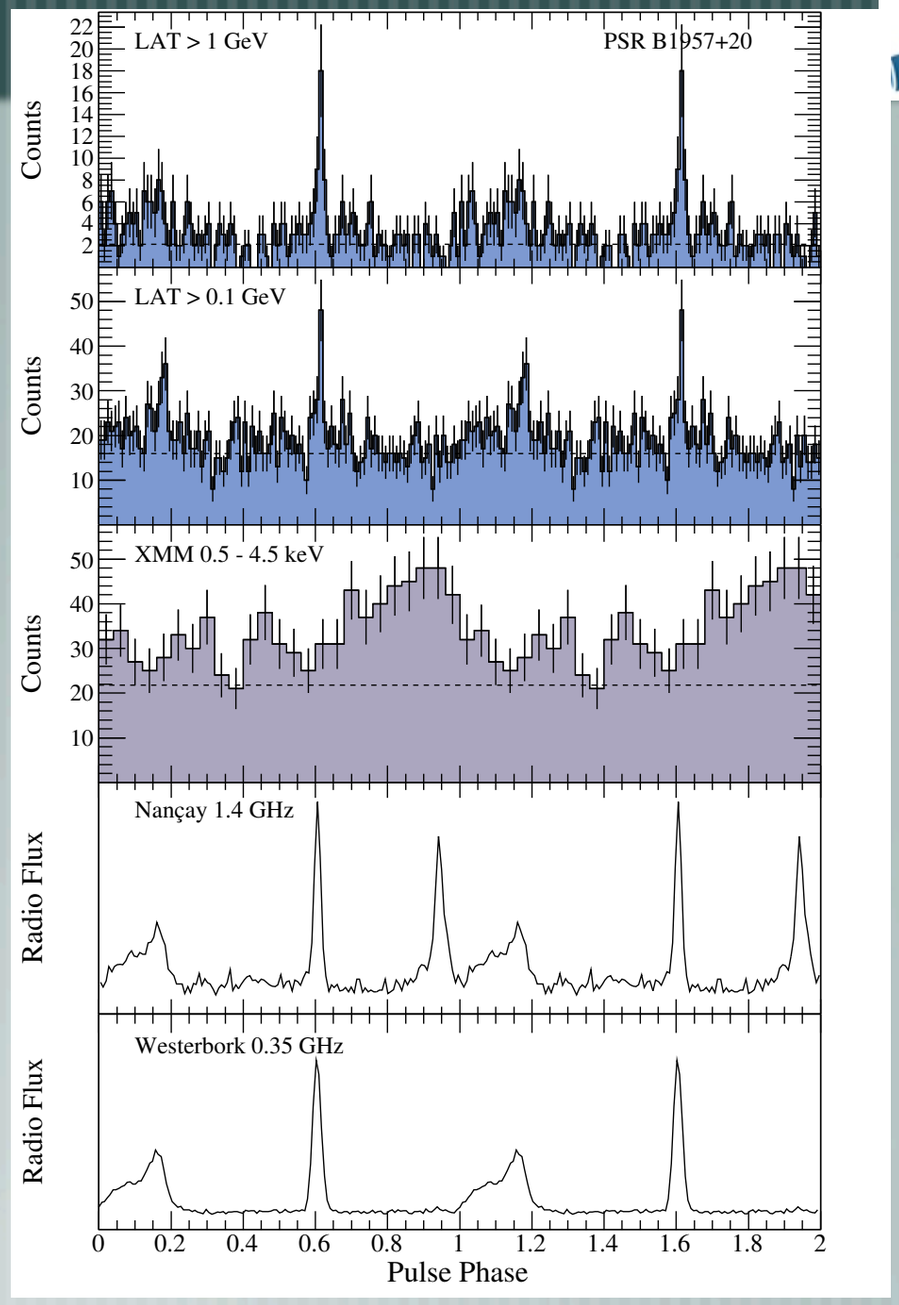
- EGRET had a marginal detection of one MSP (PSR J0218+4232; Kuiper et al. 2000)
- Fermi detected 8 MSPs in first 9 months of data taking
  - Now up to 40!
- Most MSP profiles (peak separation and radio lags) look very much like the young pulsars

(Abdo et al. 2009, Science, **325**, 848)



B1937+21 and B1957+20



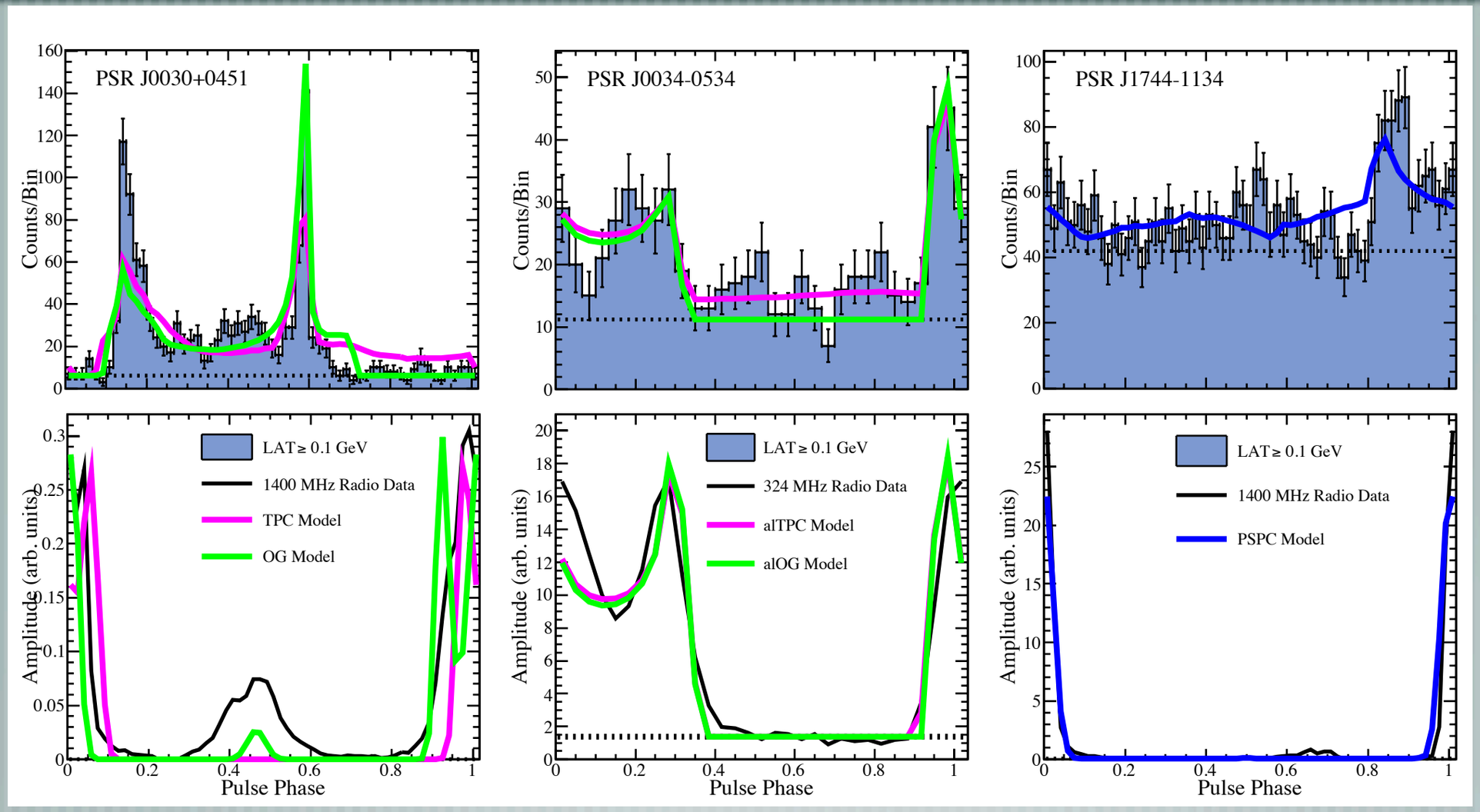


Both are examples of aligned radio/gamma profiles

Most MSPs seem to be gamma-ray emitters

Guillemot et al. (arXiv:1110.1271)

MSPs: A Variety of Pulse Profiles

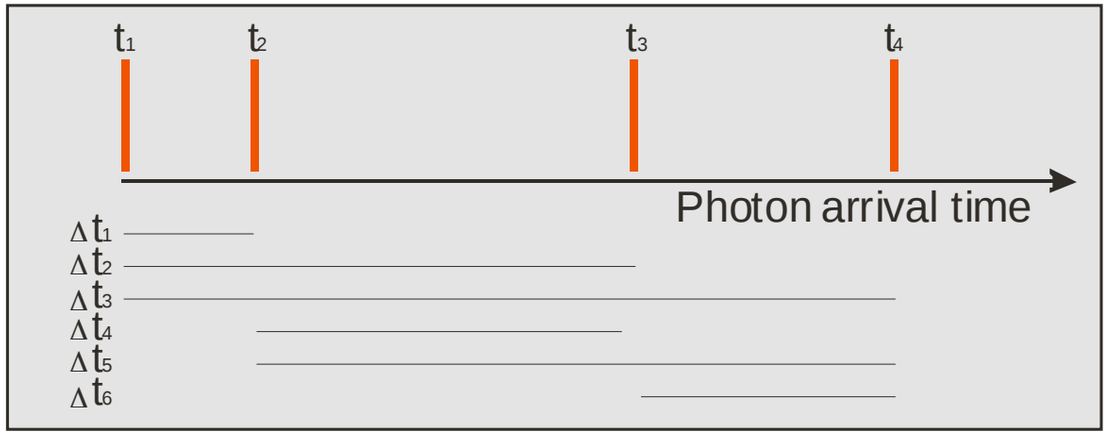


- Wider variety of behaviors than normal pulsars
  - 3 apparent categories: (A) Aligned radio/g-ray profile, (N) Normal radio/g-ray alignment, (W) Wide radio profiles
- More degrees of freedom required in light curve fits (PSPC and altitude limited models)

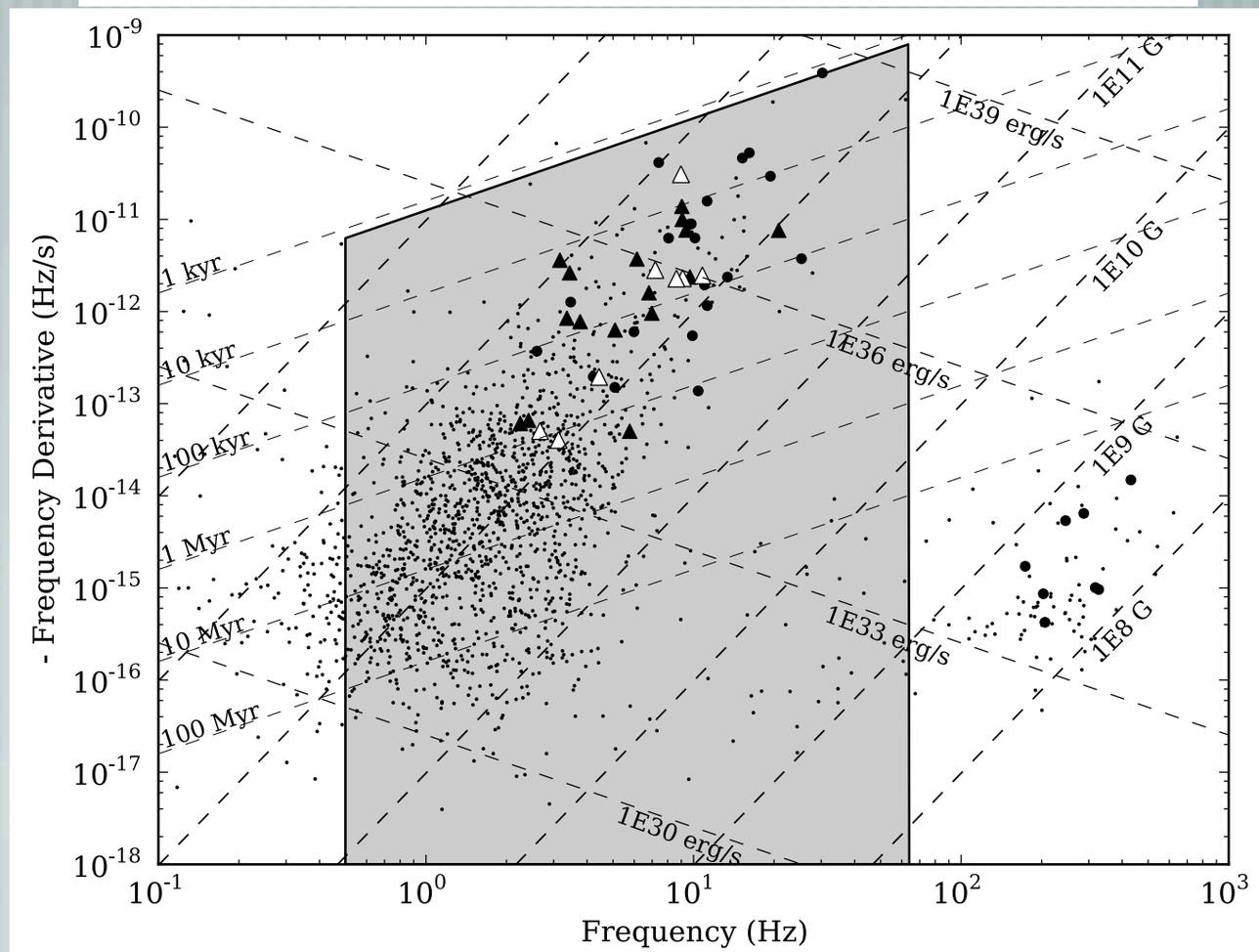
T. Johnson et al. 2011, Fermi Symposium Proceedings (arXiv:1110.5476)
see also Espinoza et al. 2012, in prep

Blind Searches

- Long, very sparse data sets make traditional epoch folding or FFT searches extremely computationally intensive
- Atwood et al. (2006, ApJ, 652, L49) developed a time differencing search method that maintains good sensitivity with greatly reduced computational requirements
- Resulted in 26 discoveries in first 2 years of data (Abdo et al. 2009, Saz Parkinson et al. 2010, 2011)
- 14 associated with EGRET sources
- Young to middle age pulsars, $\dot{E} \sim 10^{33.5} - 10^{37}$

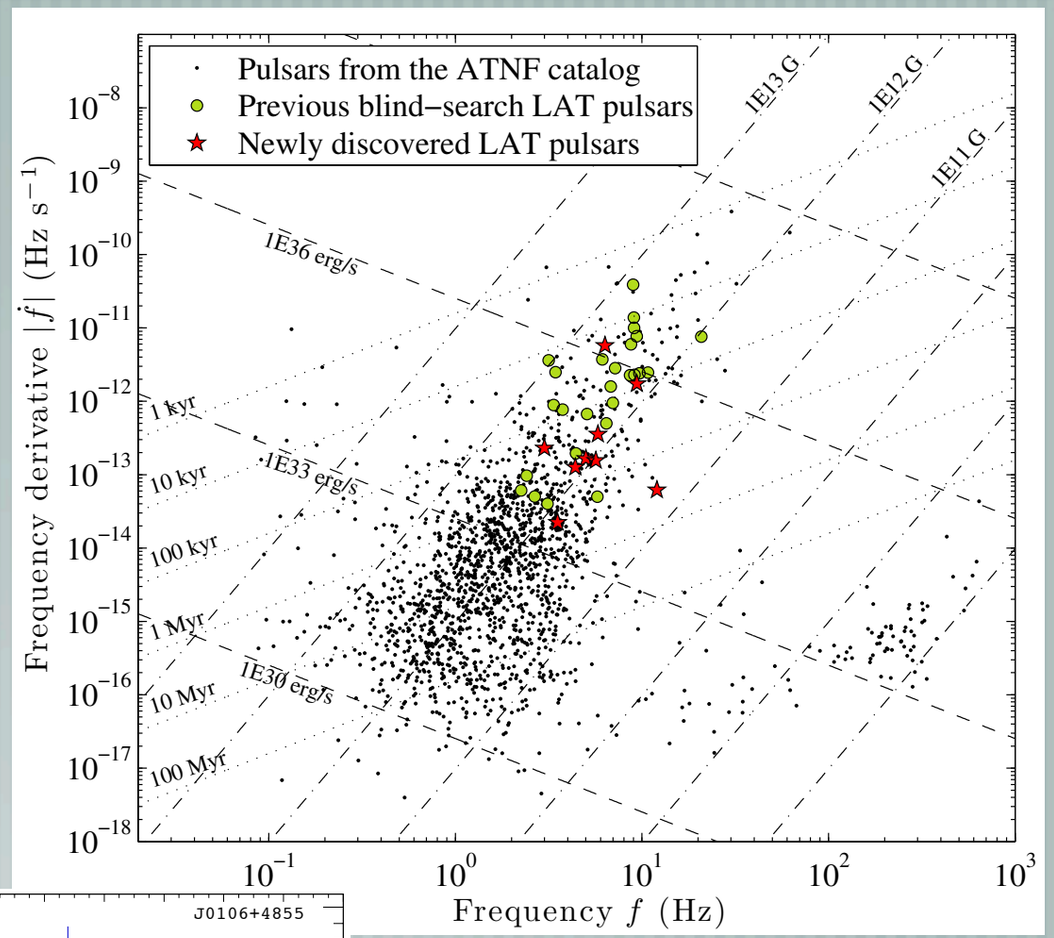


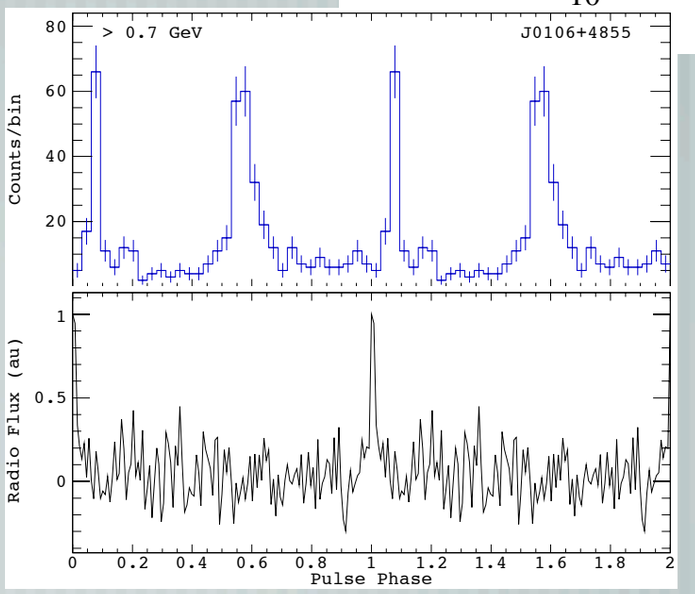
Credit: M. Ziegler



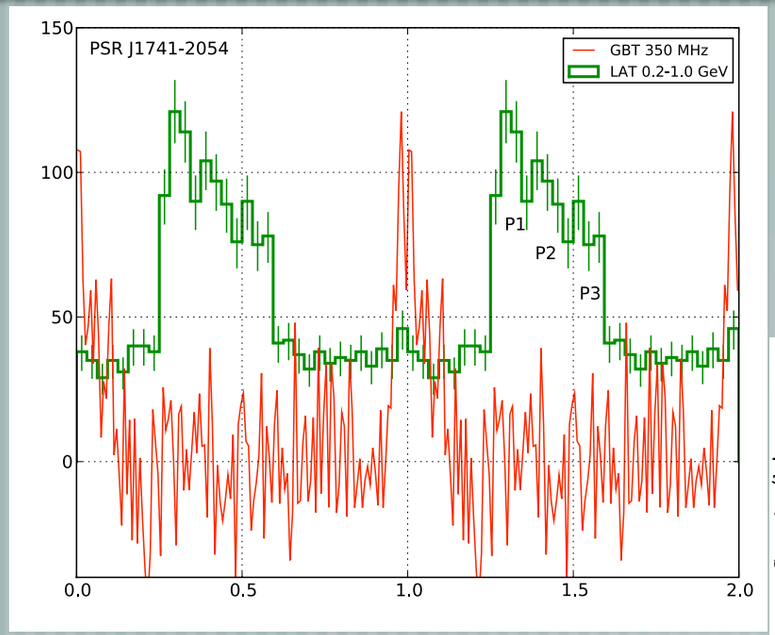
Hannover Joins the Blind Search Party

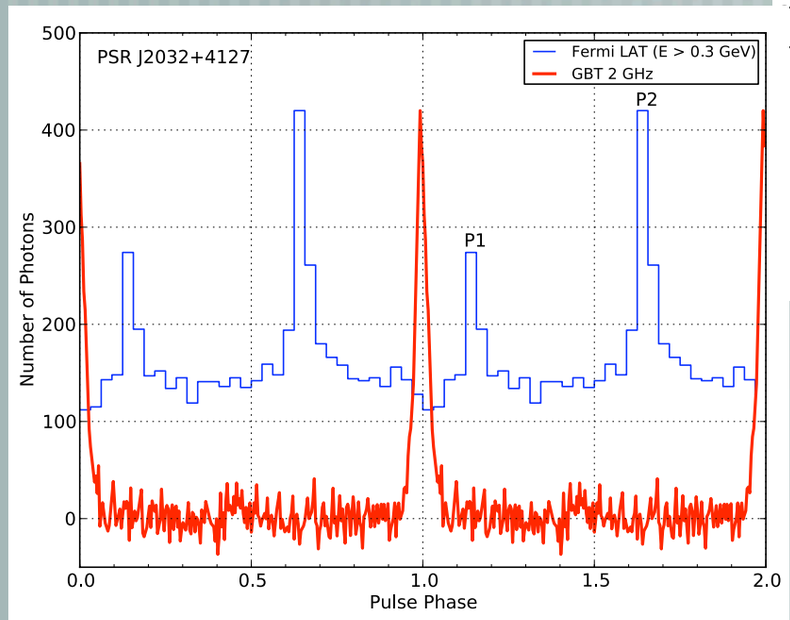
- Holger Pletsch, Bruce Allen and others at AEI in Hannover, working with Lucas Guillemot and the LAT team
- Adapted search techniques from LIGO gravitational wave searches
  - Basic technique is semicoherent search with 6 day coherence time, similar to UCSC method
  - Used weighted photons (so no ` cuts' trials)
  - Searched grid of positions
  - Optimal parameter gridding including covariances
- 6000 node ATLAS cluster searched 100 LAT sources for pulsations up to 384 Hz
- Ten pulsars discovered so far!



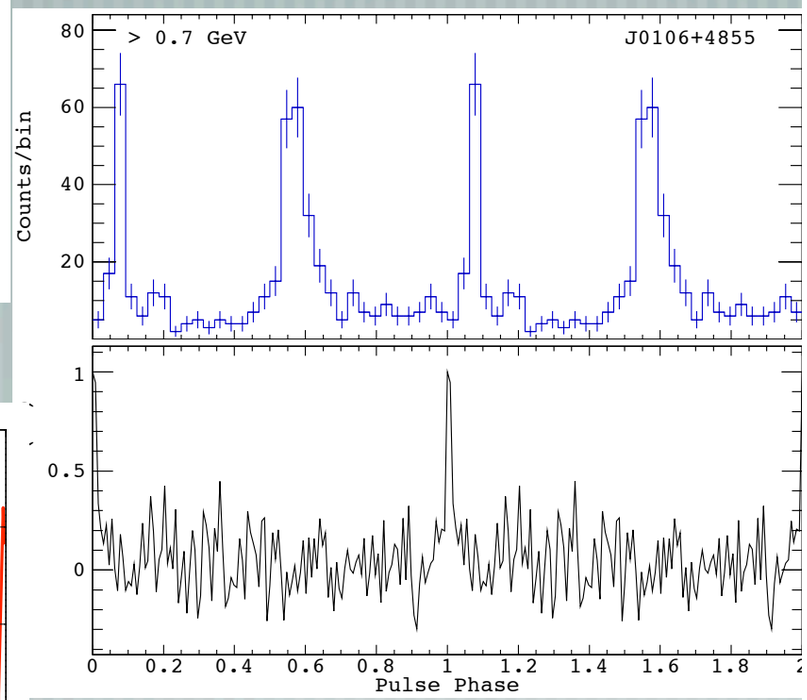


Four Discoveries of Radio Pulsations

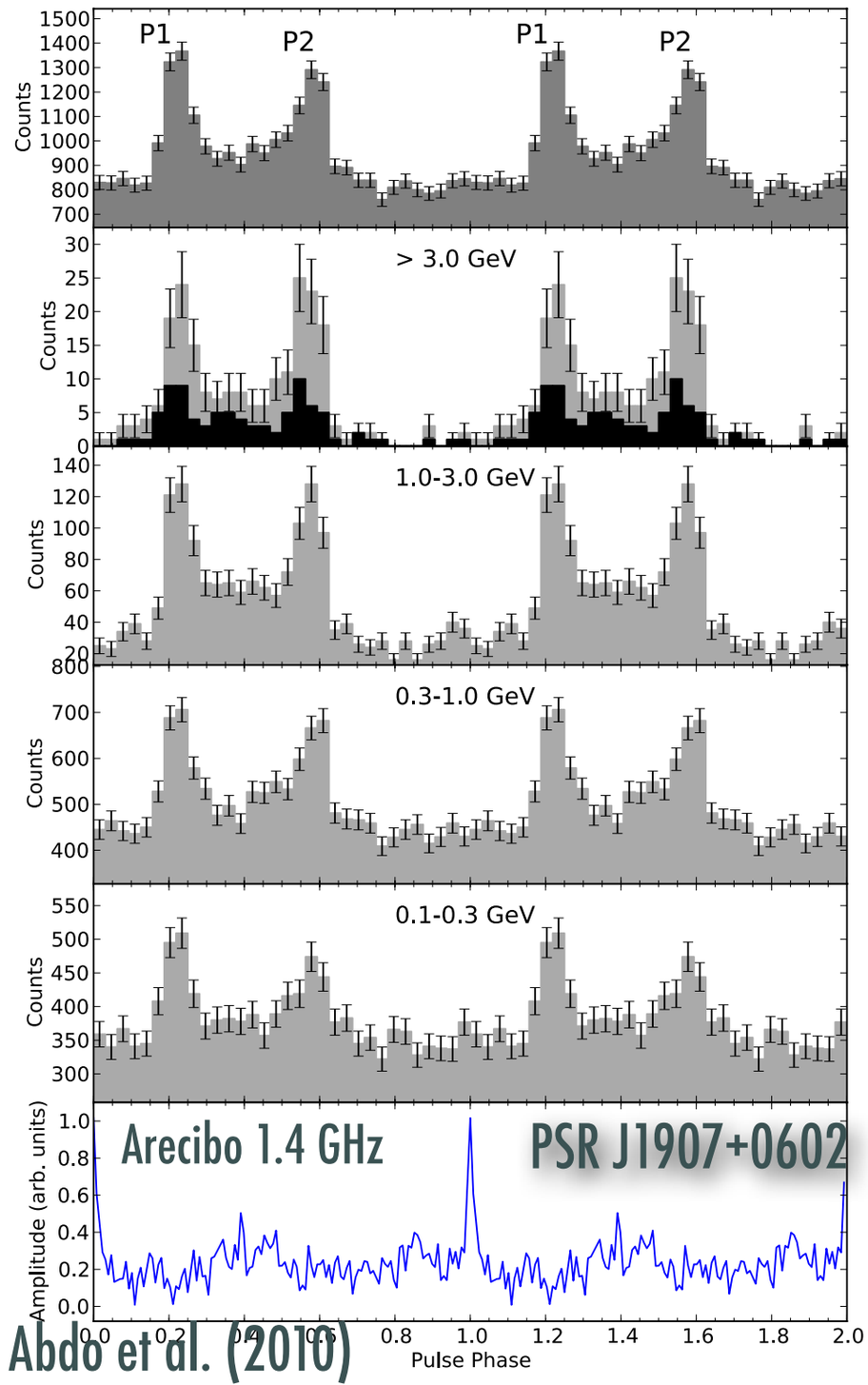




Camilo et al. (2009)

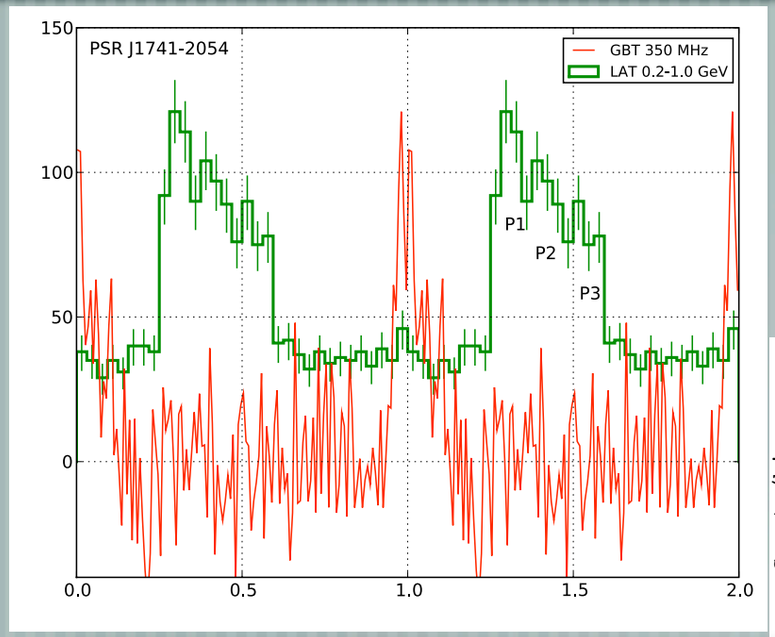


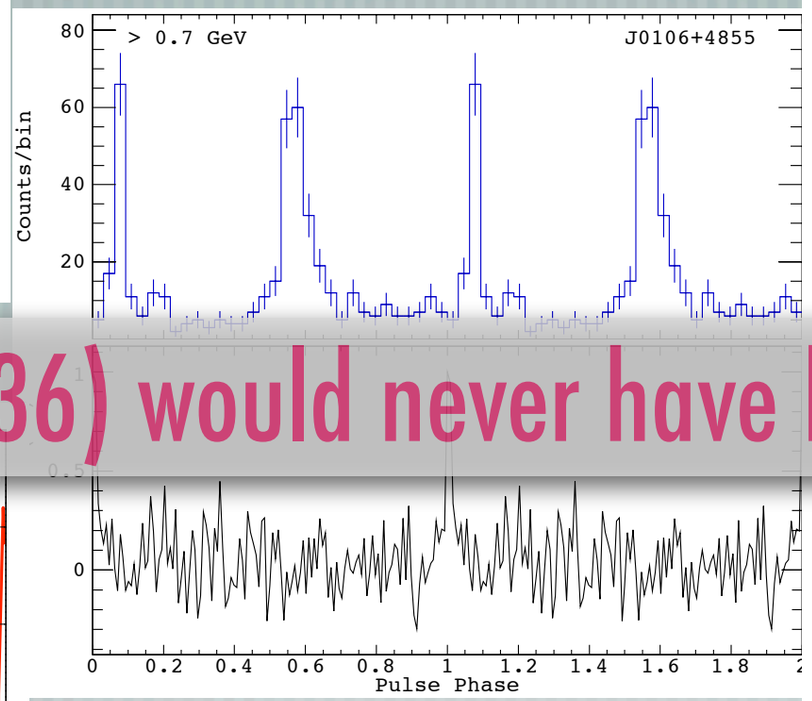
Pletsch et al. (2011)

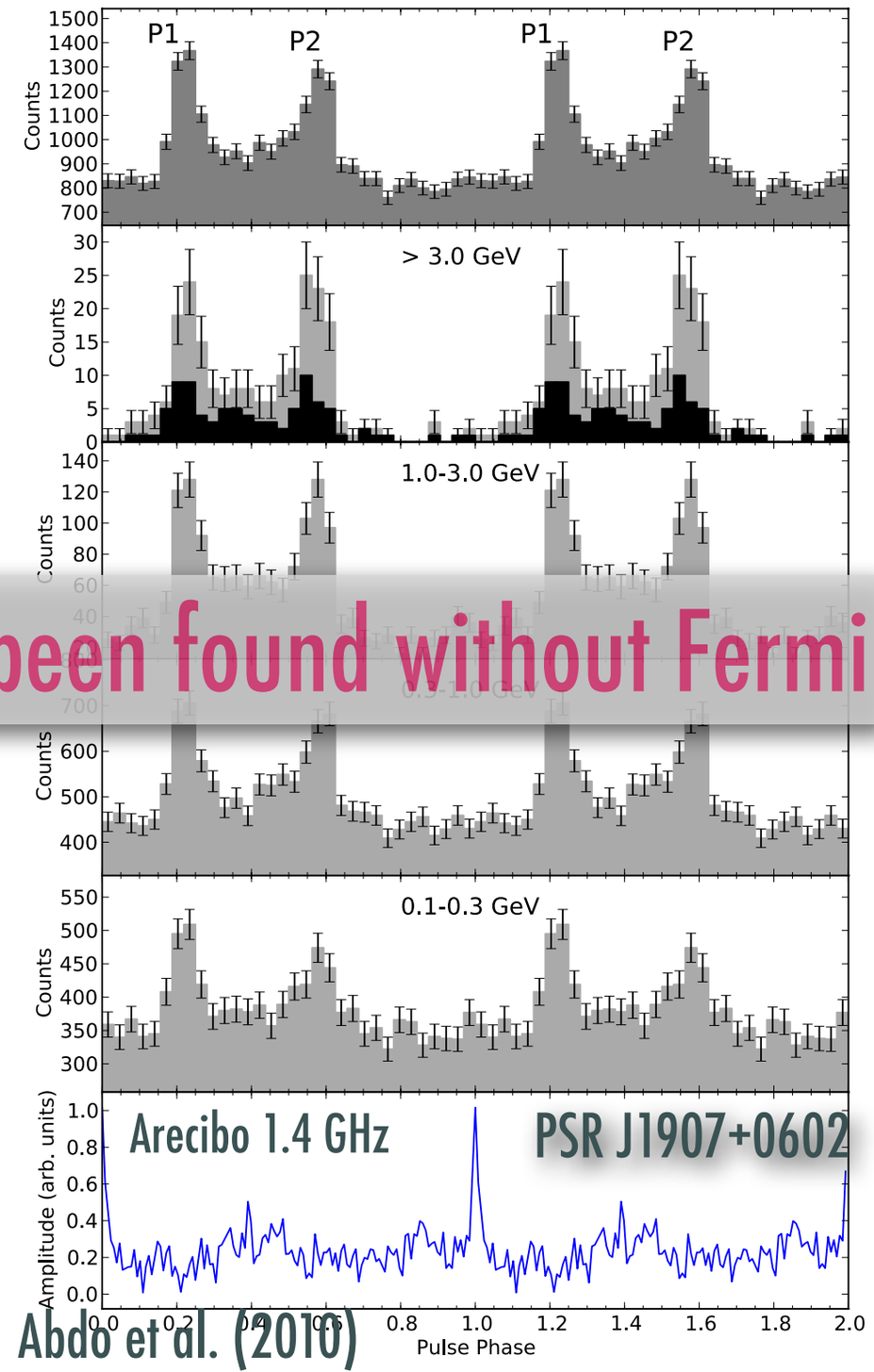


Abdo et al. (2010)

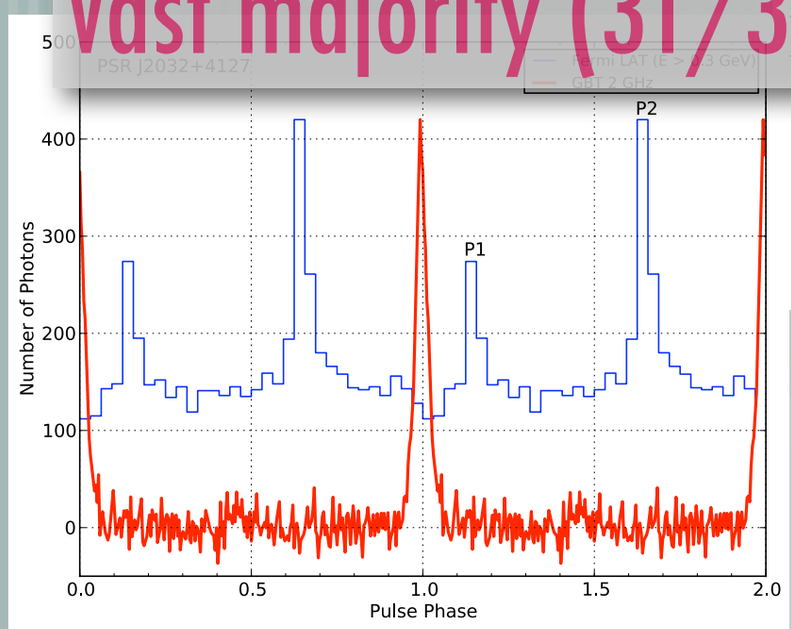
Four Discoveries of Radio Pulsations







Vast majority (31/36) would never have been found without Fermi

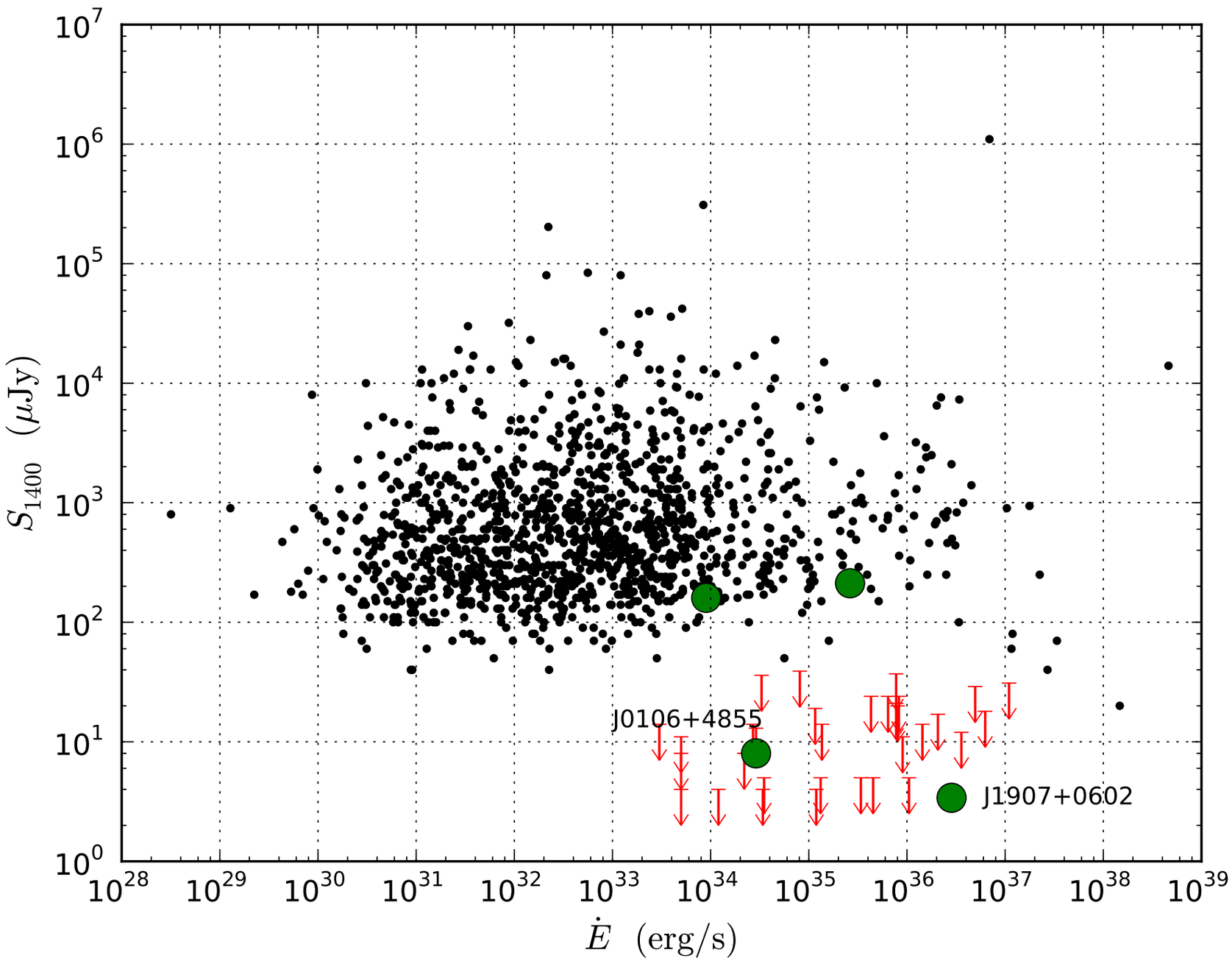


Pletsch et al. (2011)

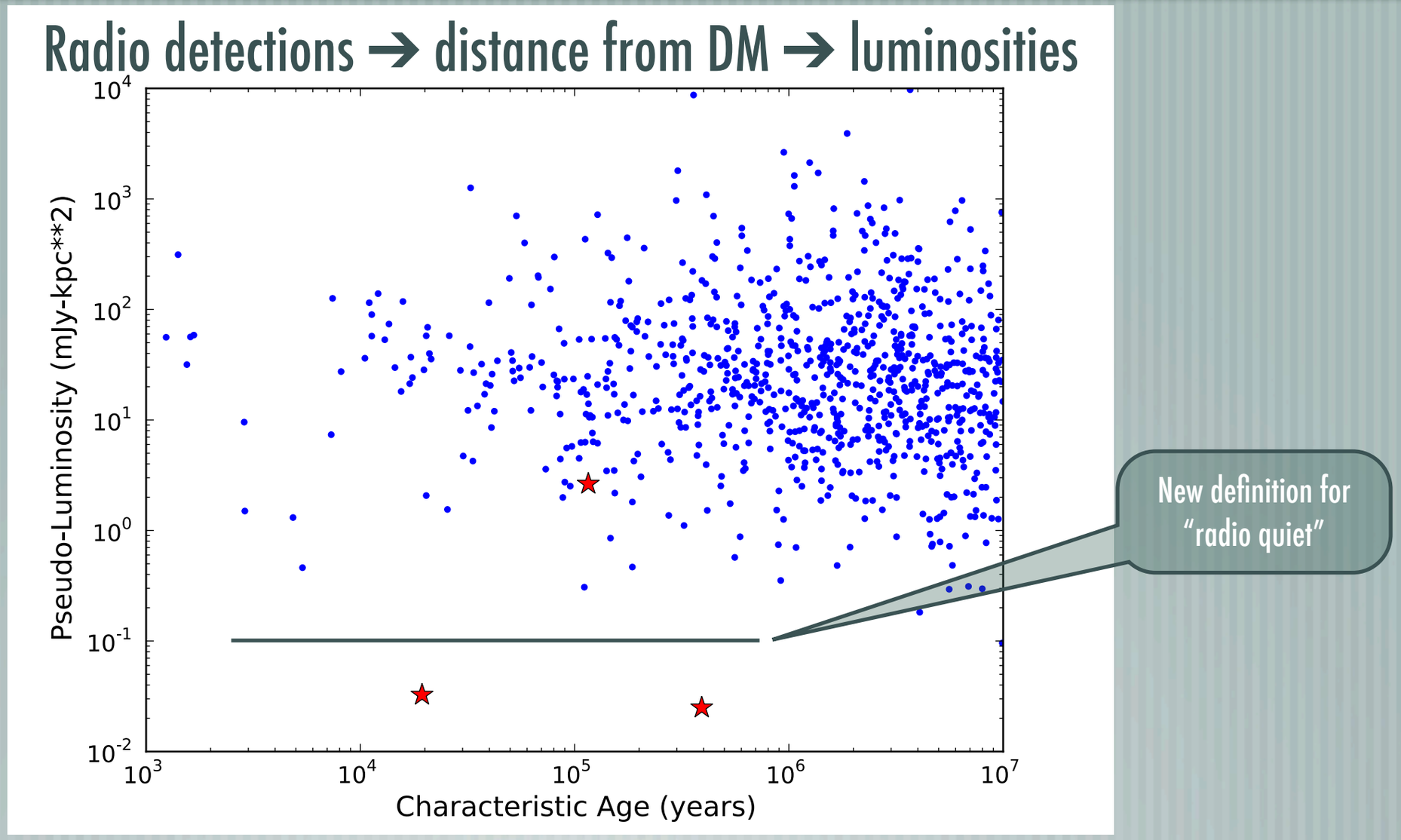
Camilo et al. (2009)

Abdo et al. (2010)

Radio Fluxes and Upper Limits



Radio Luminosities: How Faint is Faint?



Interesting notes:

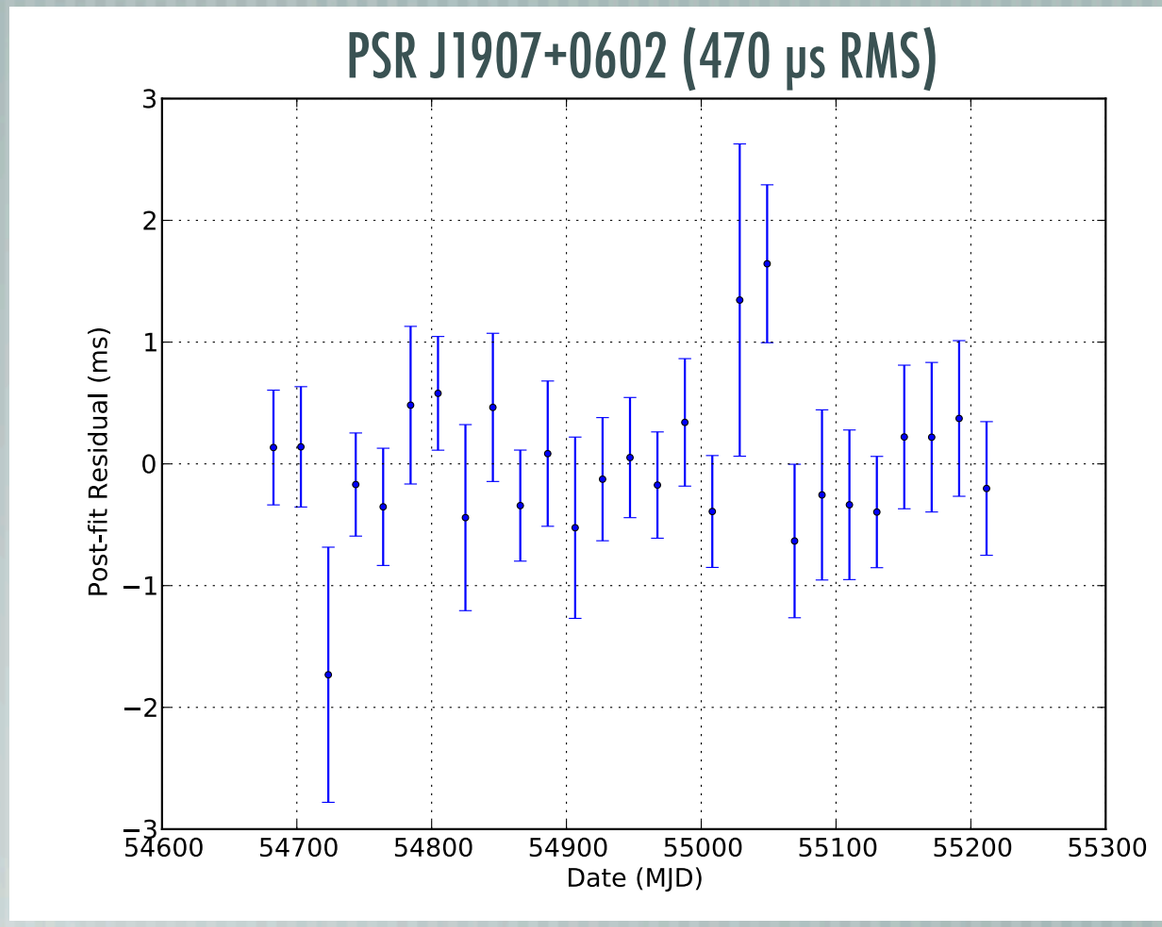
* Geminga has a claimed detection at very low frequency (Malofeev & Malov, 1997)
* New claimed detection of J1732-3131 at 34.5 MHz by Gauribidanur (arXiv:1109.6032)

There is a renaissance in low frequency radio astronomy in progress, led by LOFAR, so confirmation and/or other discoveries are possible!

LAT Pulsar Timing

- Survey mode observing and large FOV and area make for excellent long term timing of pulsars discovered
- Developed Maximum Likelihood method for measuring TOAs from small numbers of photons (typically ~100 photons per 2-week TOA). Achieves sub-ms residuals on most pulsars
- All 26 blind search pulsars timed, plus several others where the LAT is better than any alternative (e.g. Geminga, PSR J1124–5916)

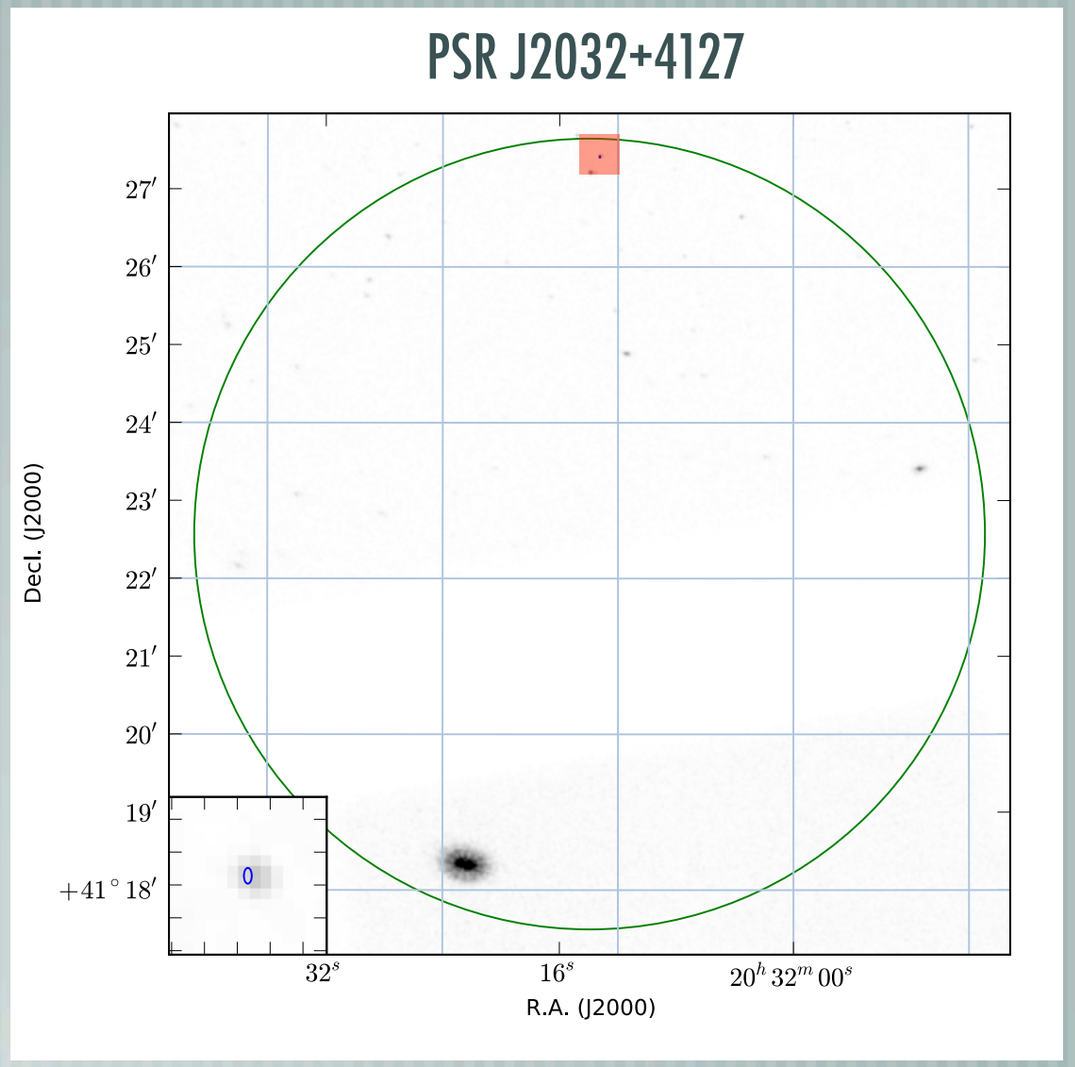
(Ray et al. 2011, ApJS, **194**, 17)



Models posted online:
https://confluence.slac.stanford.edu/display/GLAMCOG/LAT+Gamma-ray+Pulsar+Timing+Models

The Power of LAT Timing

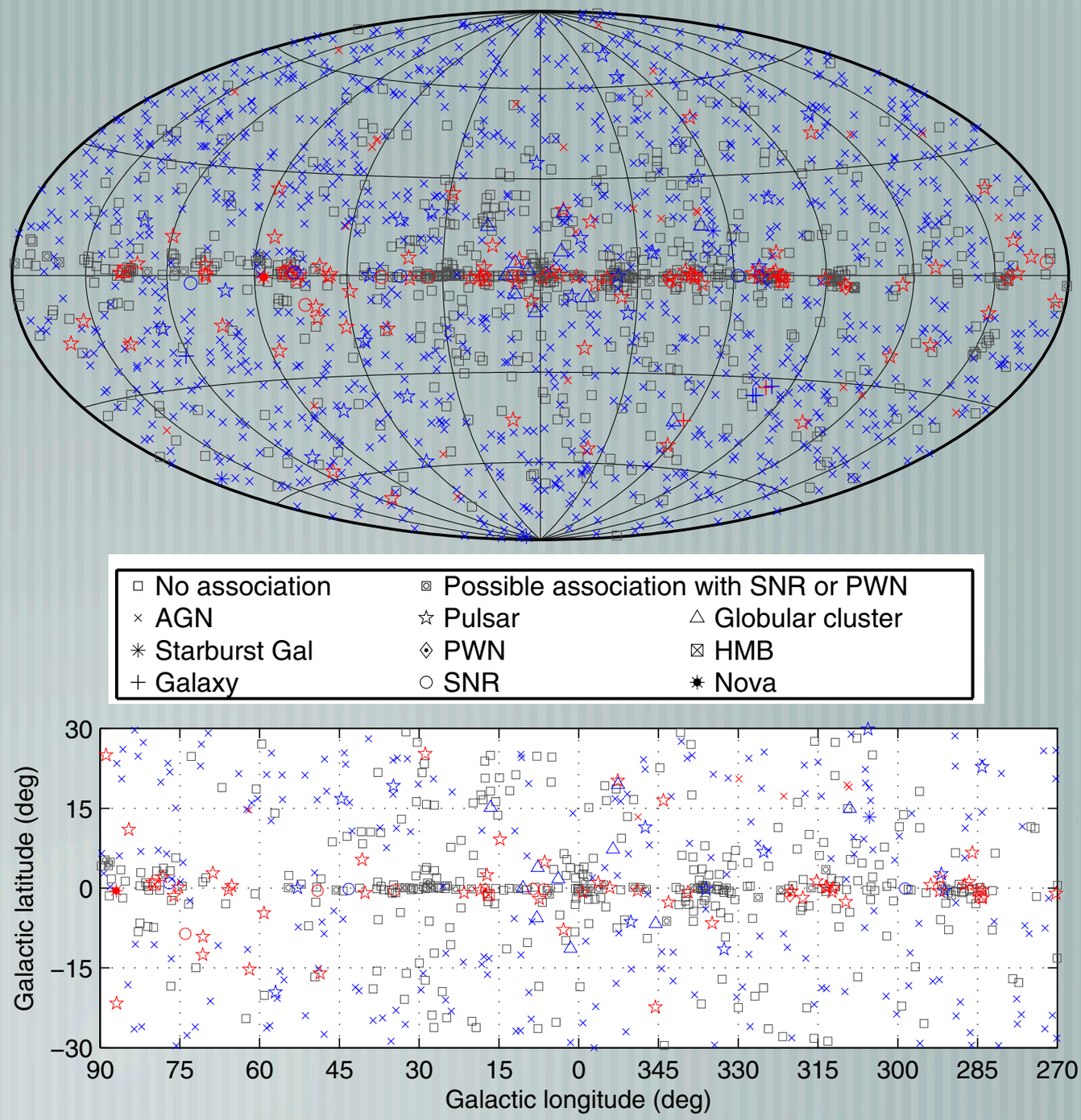
- Improved rotational parameters
- Study timing noise and glitches (free from any radio propagation effects)
- Relieve load on radio telescopes
- **Precise positions**, which enable multiwavelength follow up!
  - Sub-ms residuals lead to arcsec position accuracy



Green circle is LAT Bright Source List position
Blue ellipse in inset is timing position

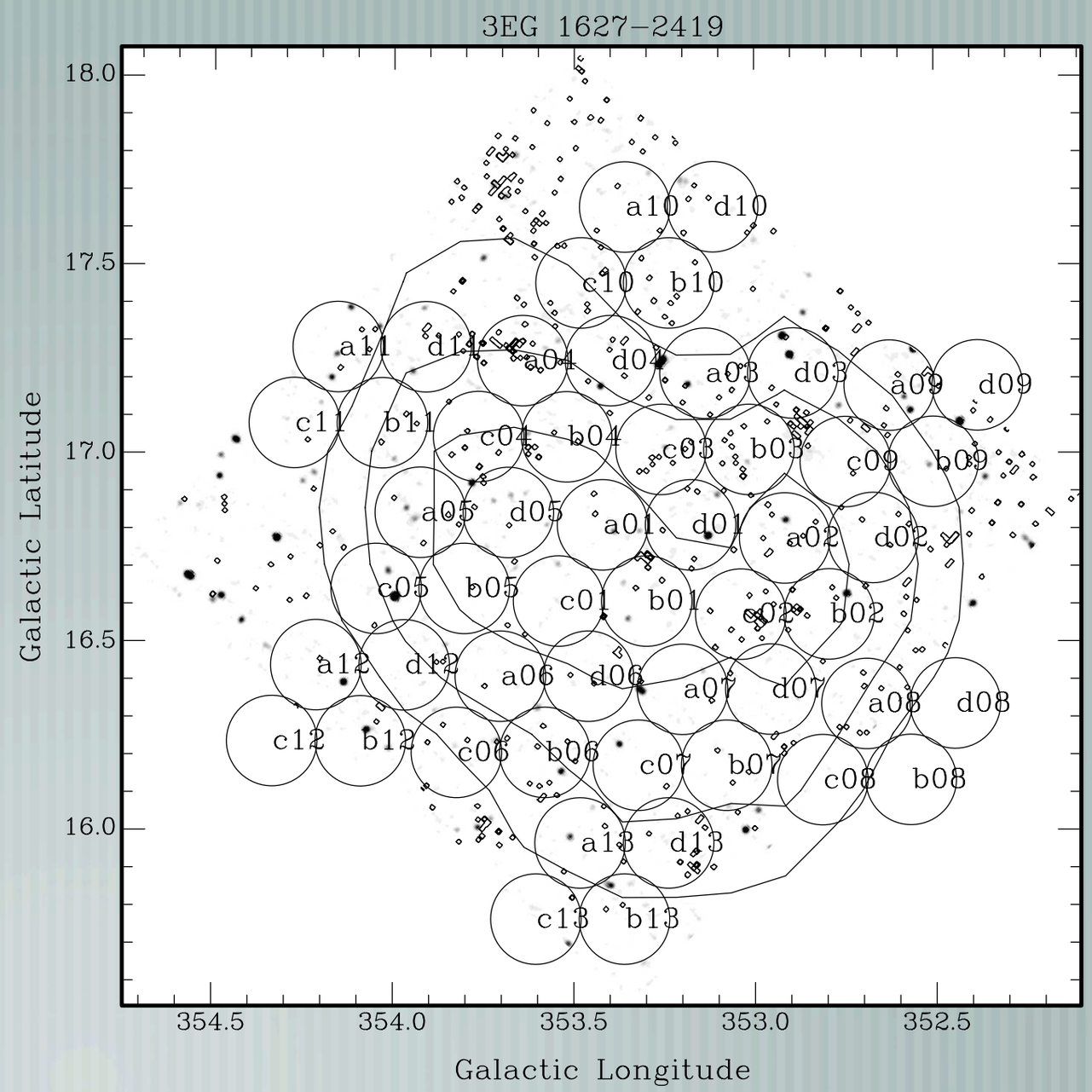
Unassociated Sources

- 2FGL Catalog (Nolan et al. 2012)
  - 1873 sources
  - 575 (31%) remain unassociated with plausible counterparts



Gamma-ray Sources as Pulsar Search Targets

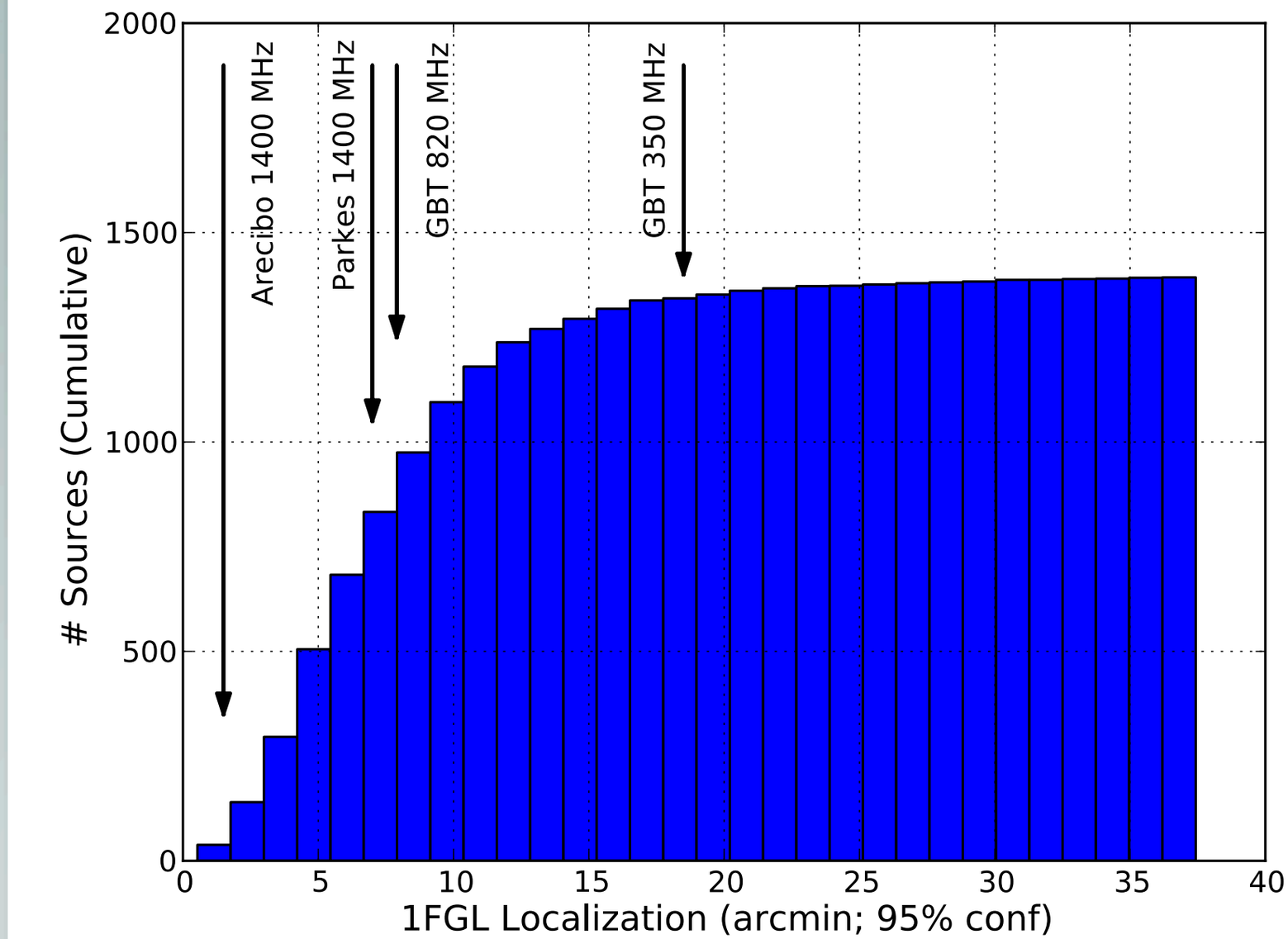
- Many searches were done of EGRET unidentified sources
- Lots of effort with modest success
- Hampered by poor localizations



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

LAT Sources as Pulsar Search Targets

- LAT localizations make the job MUCH easier!
- Vast majority of 1FGL sources can have full 95% confidence region covered in a **single** pointing (with the right frequency choice)

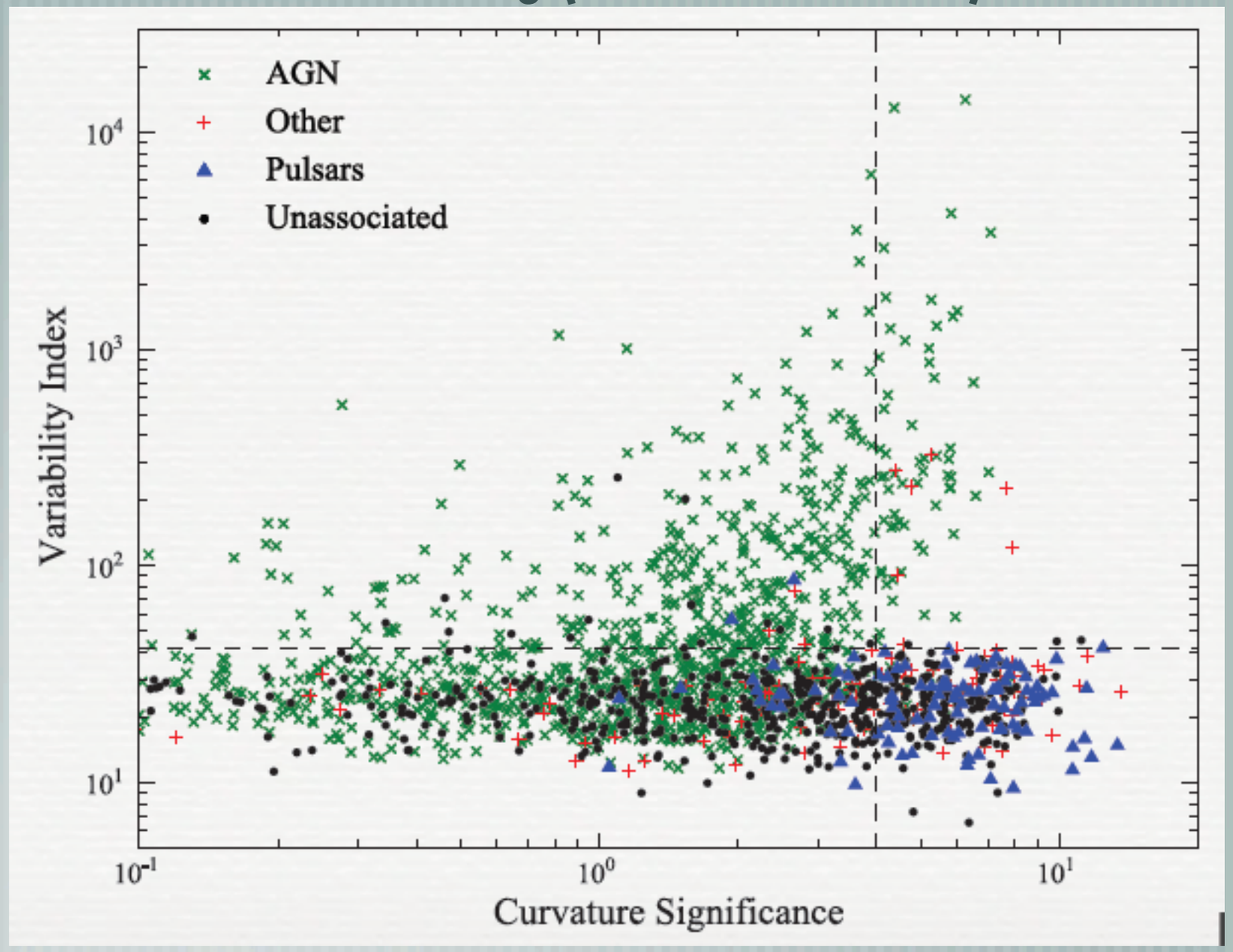


Using LAT to Find Radio Pulsars

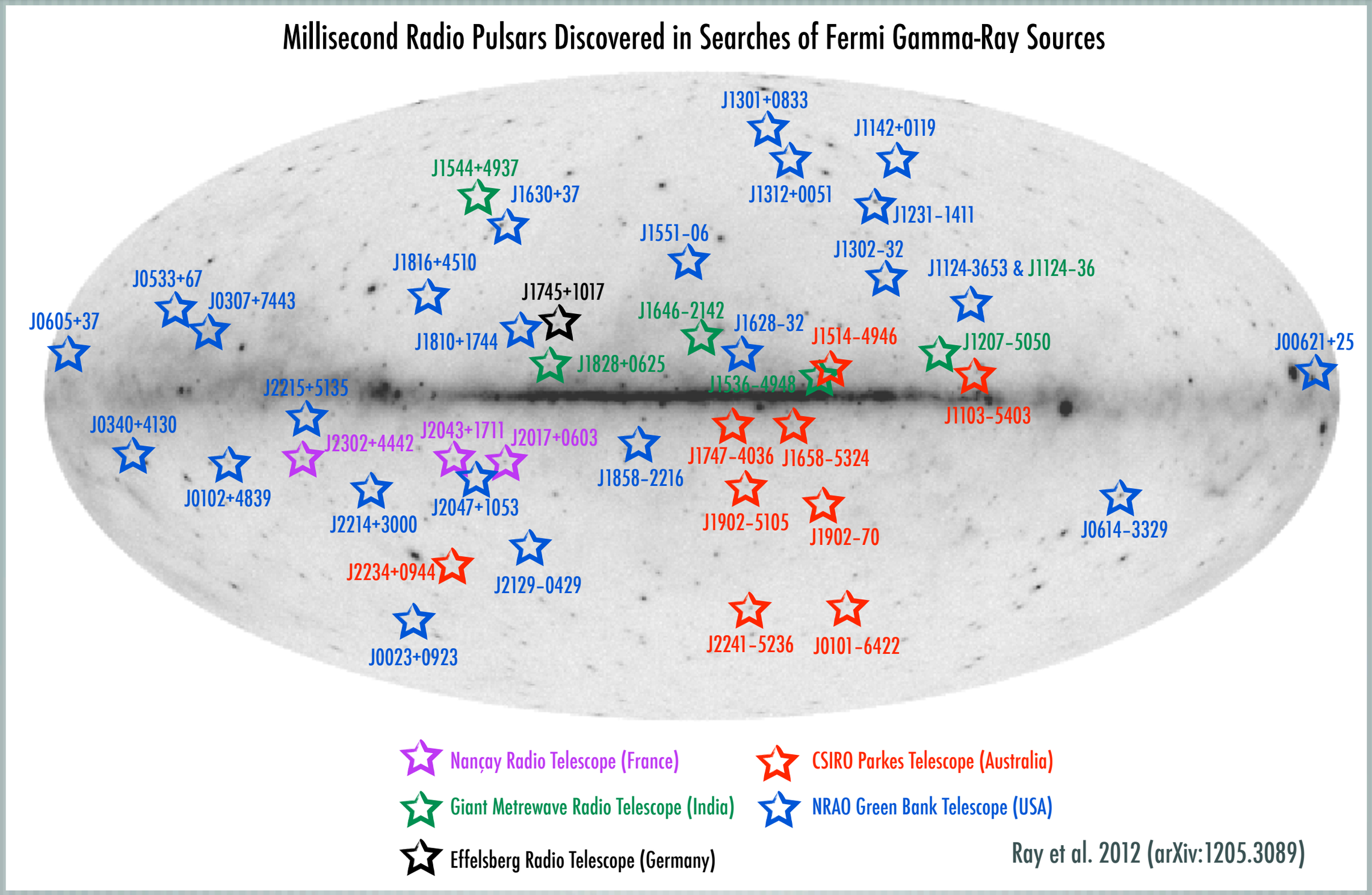
- Best targets are sources with low variability and "pulsar-like" spectra
- Used multiple techniques for ranking sources
  - Visual inspection has been best technique

More details on ranking of "pulsar-likeness":
Abdo et al. 2012, ApJ, in press (arXiv:1108.1202)
Lee et al. 2012, MNRAS, in press (arXiv:1205.6221)

2FGL Catalog (Nolan et al. 2012)



Success! 43 MSPs found!



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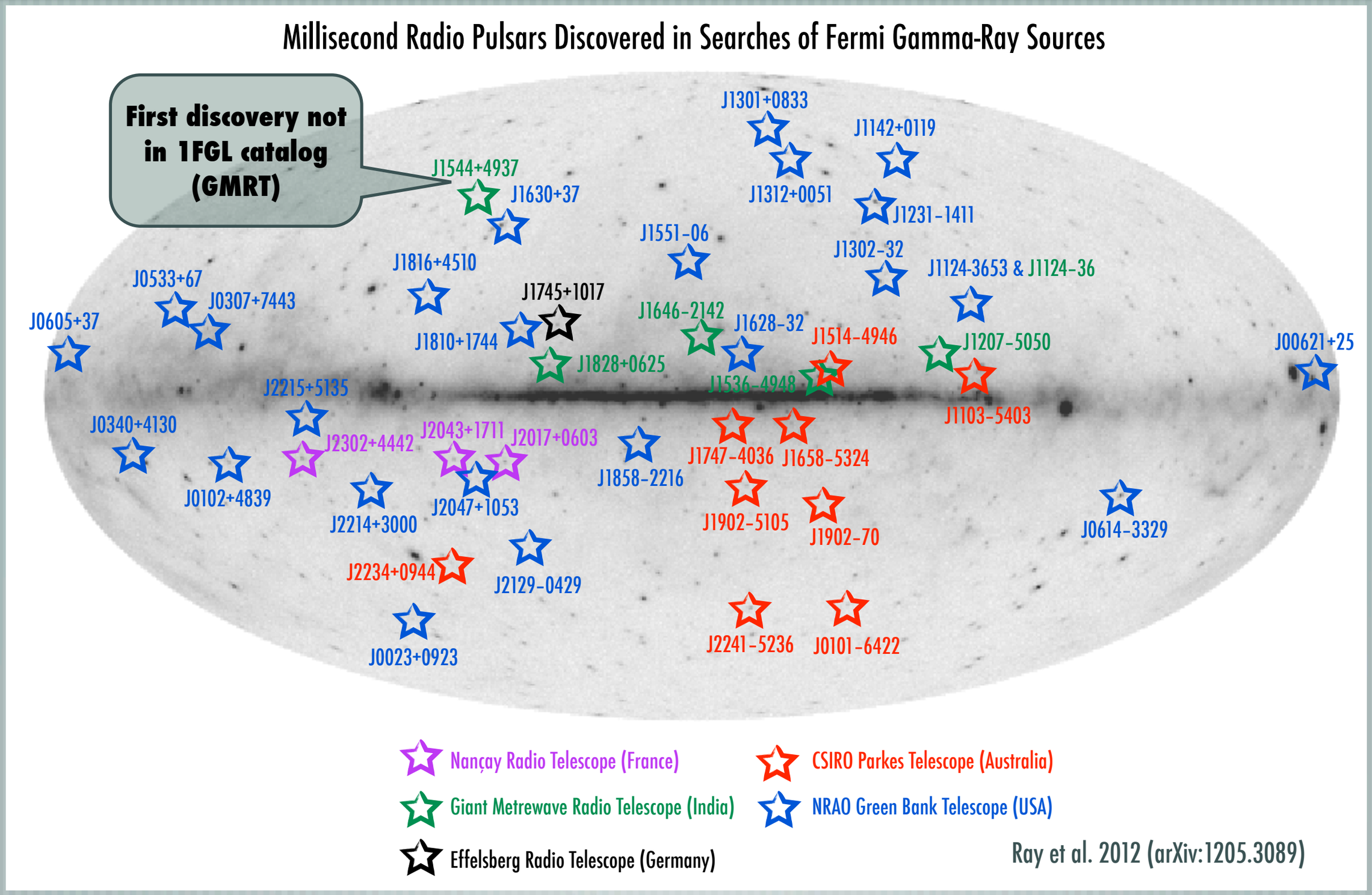
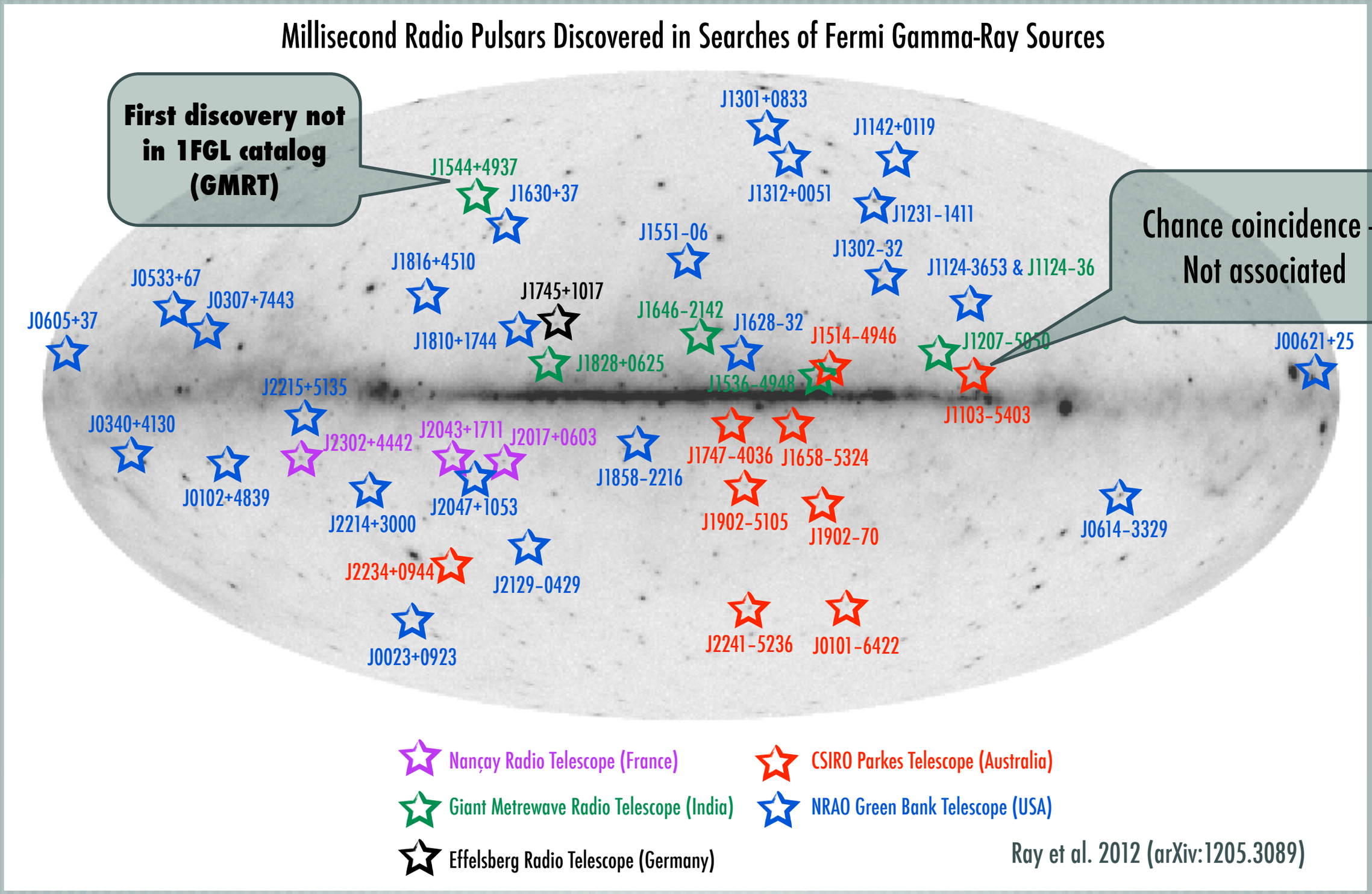


Ray et al. 2012 (arXiv:1205.3089)

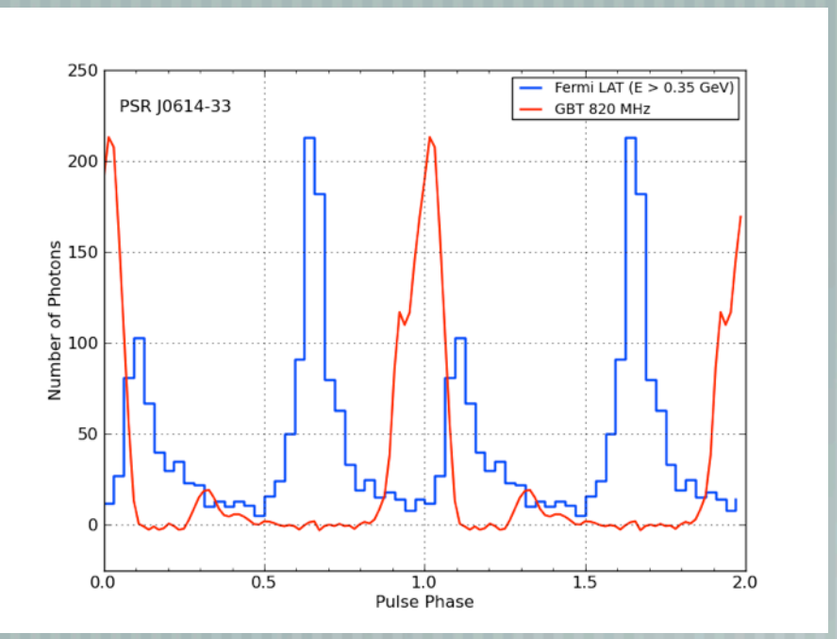
Success! 43 MSPs found!

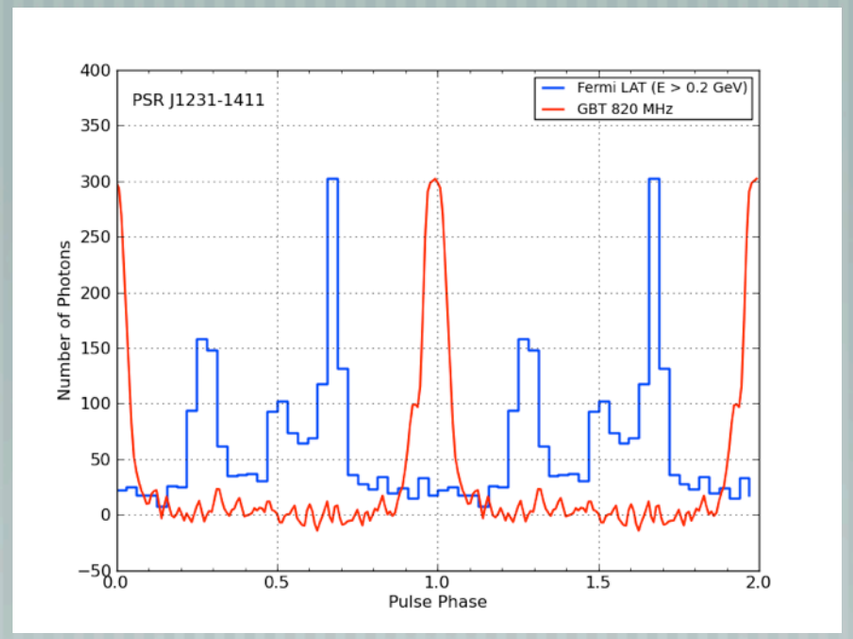


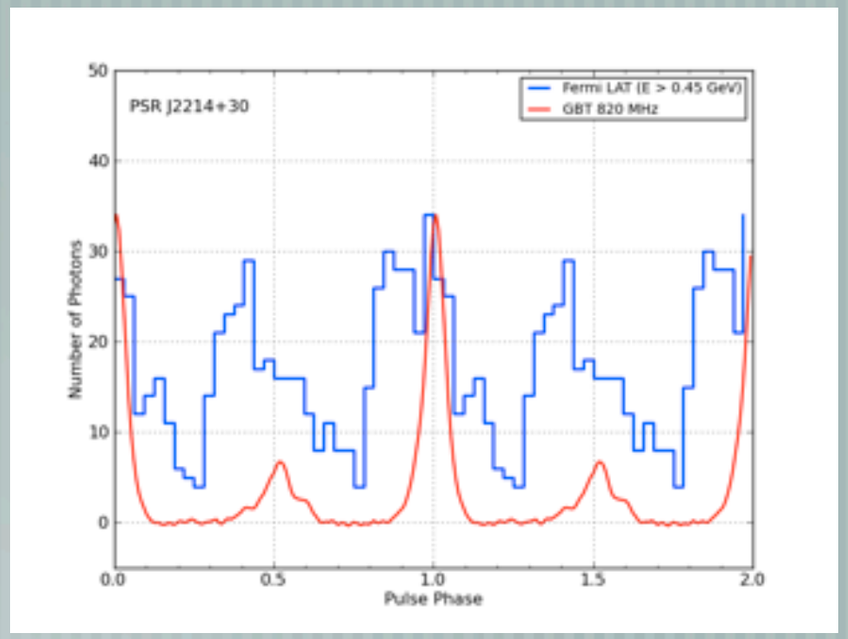
Exciting Discoveries

- Pre-Fermi, only about 60 field MSPs known from 25+ years of searching!
- **Many** unassociated high-Galactic latitude sources that are non-variable are millisecond pulsars!
- At least **ten** new "Black Widow" systems (only 3–4 previously known outside of globular clusters) found in these searches
  - Much larger fraction than in typical surveys. Why?
  - Plus, at least **four** new "Redbacks" that are eclipsing but with a more massive companion (~0.2 Msun). Cousins of the ` missing link' pulsar J1023+0038
- Several are very bright and may be great additions to pulsar timing arrays
- Since they are all coincident with LAT pulsar-like point sources, we expect to find GeV pulsations from them (except a small number chance coincidences)

25 Now Have LAT Detections!







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**

(Ransom et al. 2011, ApJL, 727, L16)

Future Expectations

- Searches of LAT unidentified sources ongoing
  - 2FGL catalog analysis has given us a bunch of new targets
  - Re-observations are important due to eclipses, scintillation, unknown pulsar spectra, RFI, etc...
  - Radio flux not correlated with gamma-ray so plenty more to find
- Timing results take time
  - 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

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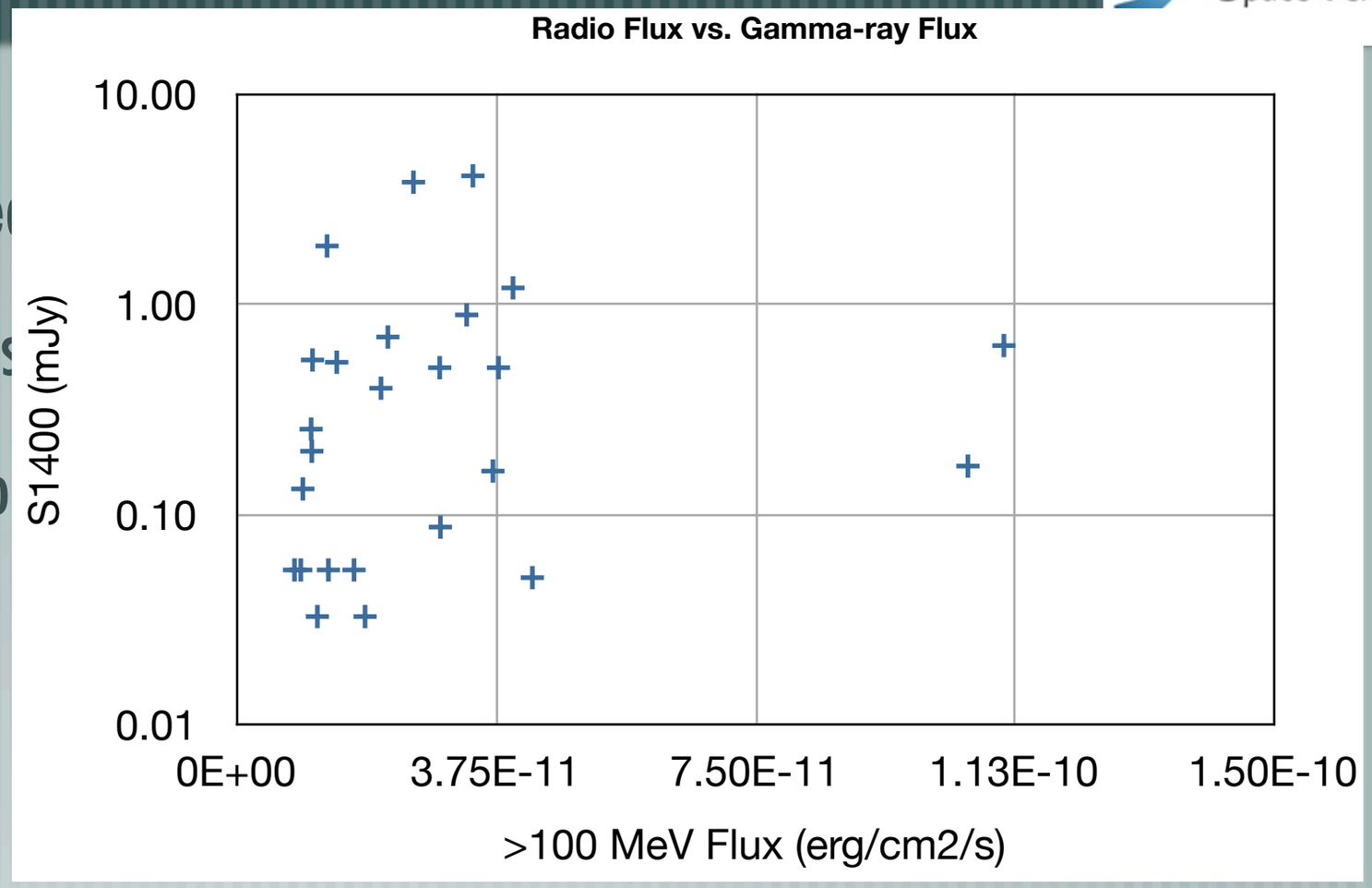

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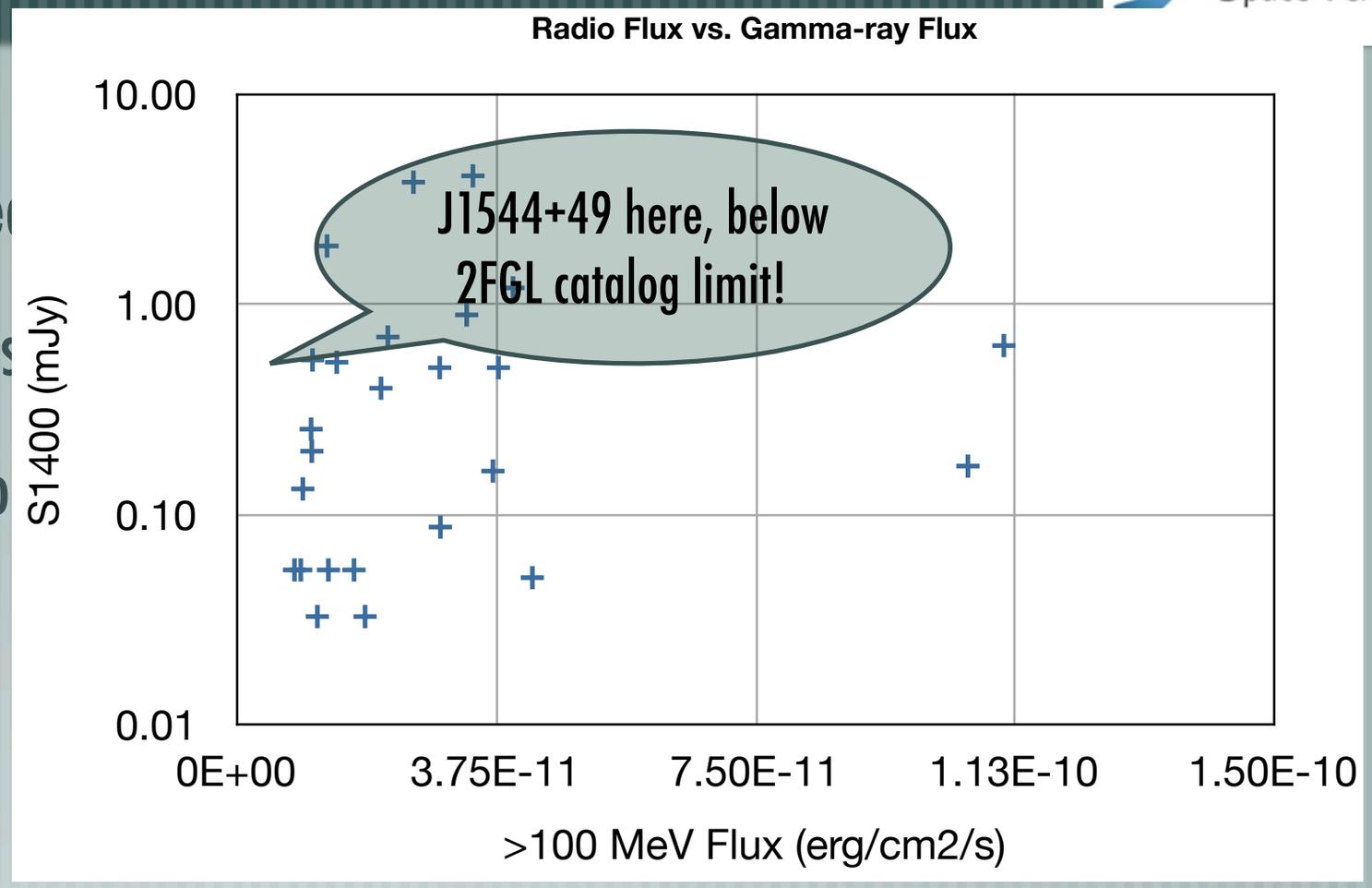

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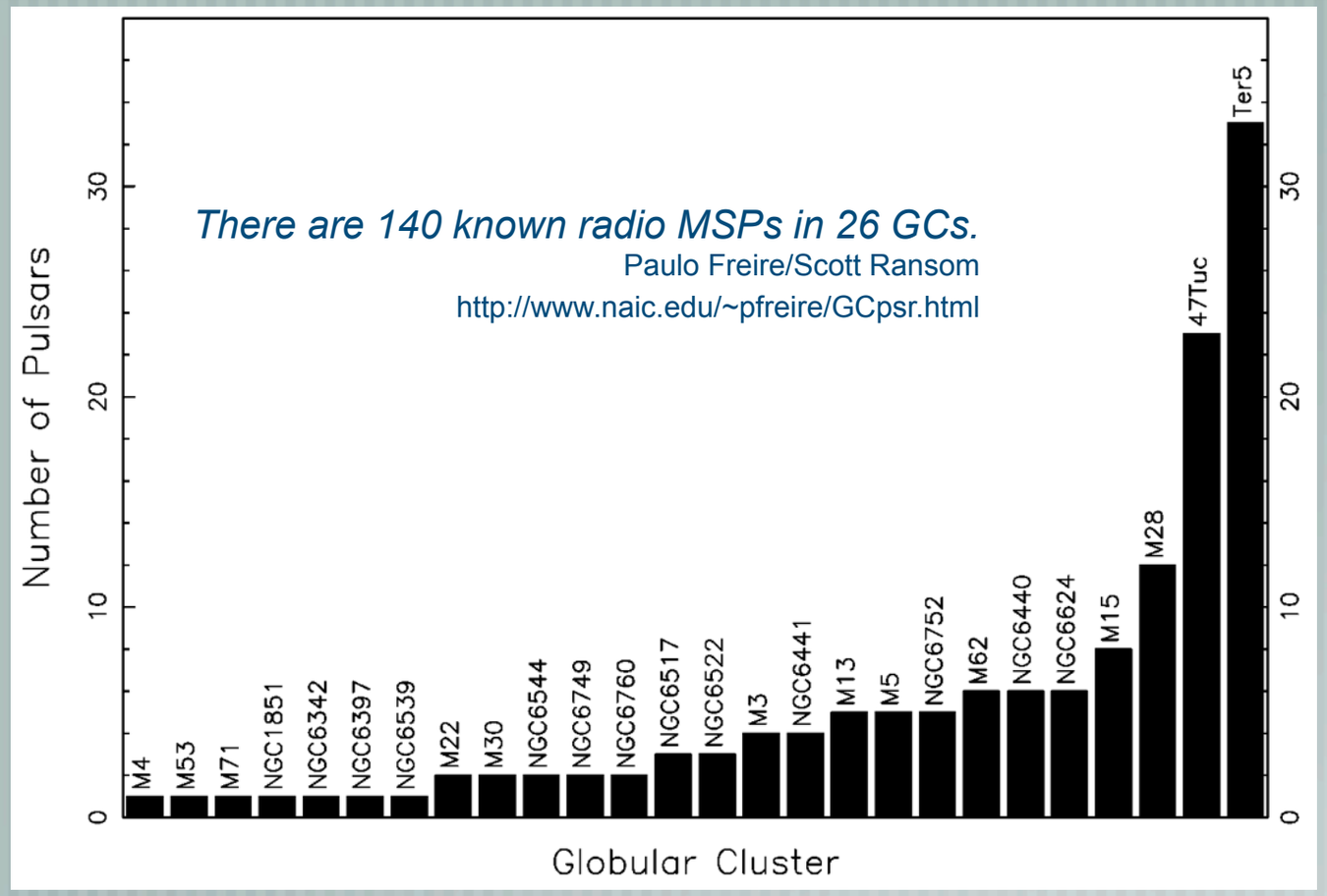
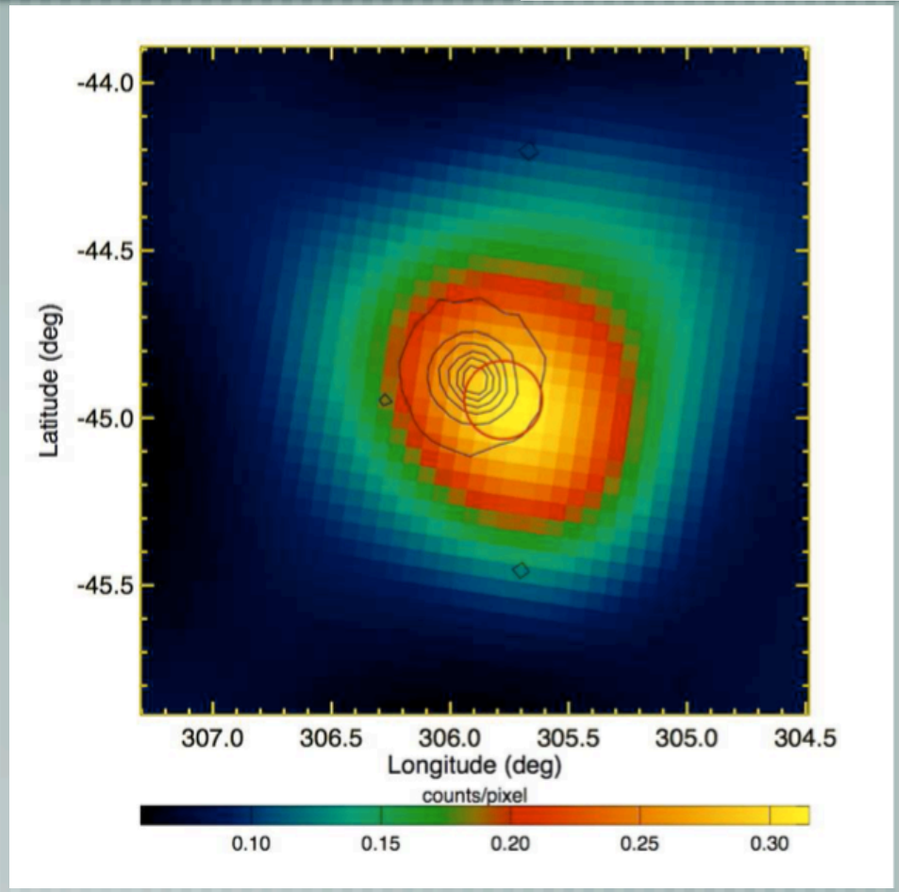
Globular Clusters : MSPs Galore





- 47 Tuc first GC to be detected as a steady gamma-ray source (Abdo et al. 2009, Science, **325**, 845)
- About 14 other clusters now detected as well (Abdo et al. 2010, 2011, Kong et al. 2010, Tam et al. 2011)
- Presumably gamma-rays are the integrated emission of dozens of MSPs
- Provides a way to estimate N_{MSP} independent of radio beaming fraction

NGC6624A

- LAT pulsations detected from PSR J1823-3021A in NGC6624
  - First LAT detection of pulses from a GC MSP
- Highest luminosity (8.4×10^{34} erg/s) and most distant (8.4 kpc) MSP detected by LAT so far
- Gamma-ray luminosity proves that large observed spindown is intrinsic, not just from acceleration in the cluster
- This single pulsar is responsible for all of the observed LAT emssion from the cluster
  - Revised N_{MSP} from 101 to <32

NGC6624A

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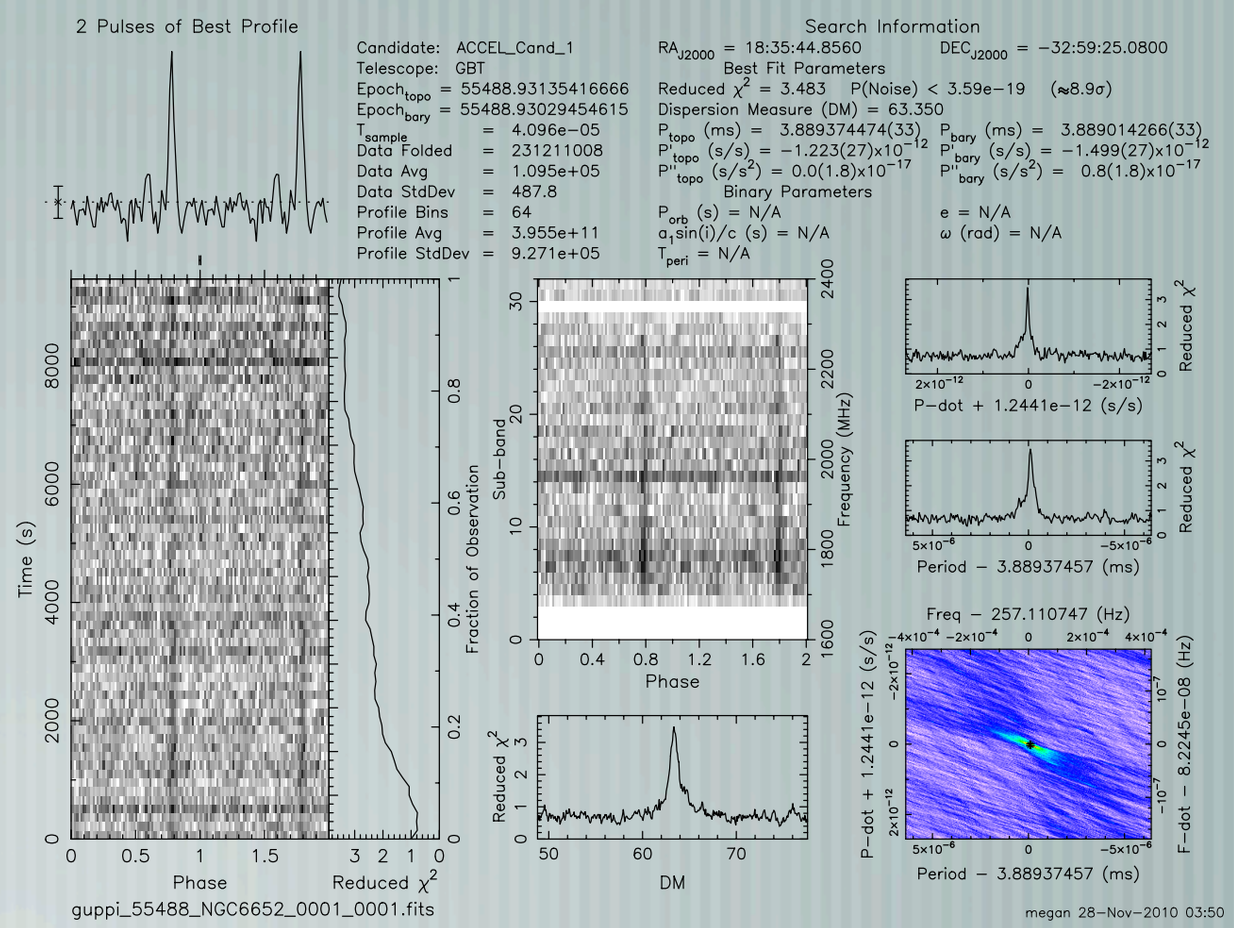
Radio Searches of LAT-Detected GCs

- DeCesar et al. (arXiv:1111.0365) now searching for MSPs in GCs detected by LAT but that have no known MSPs
  - First Targets: NGC 6388 and NGC 6652
  - Long S-band GBT observations, using coherent dedispersion mode of GUPPI
- PSR J1839-3259 discovered in direction of NGC 6652
  - DM 63.35 pc cm^{-3}, which is much less than expected from NE2001
  - Timing required to get precise position and confirm cluster association

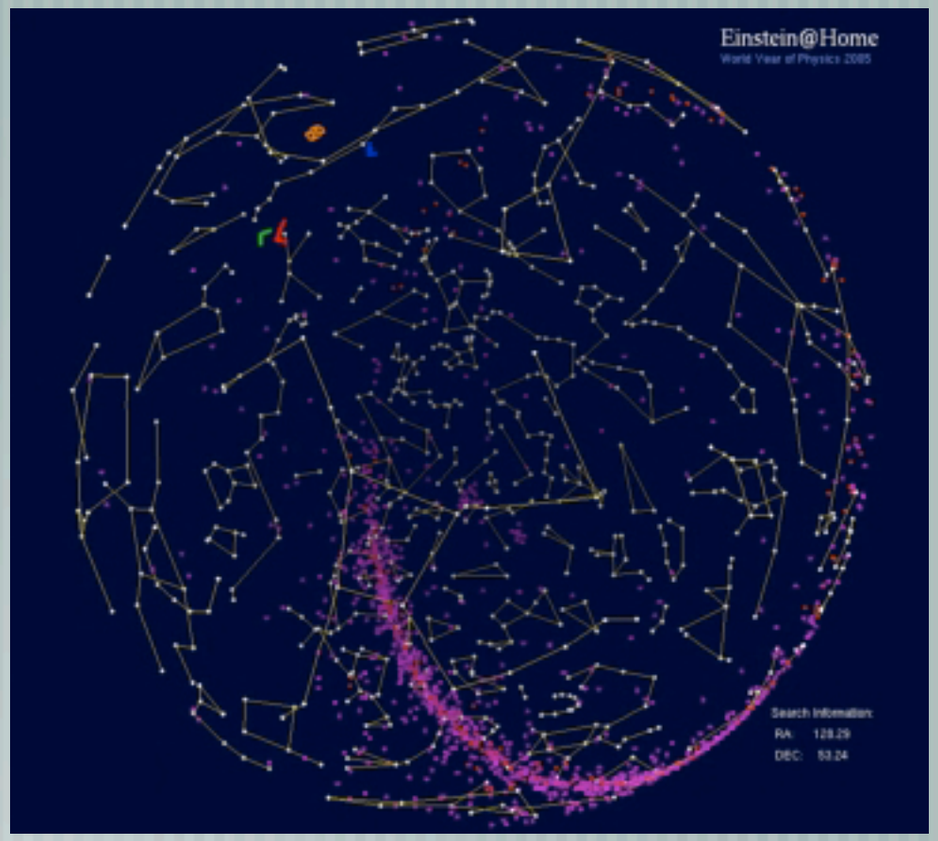


Radio Quiet MSPs?

- Both blind searches and radio searches have been very successful in identifying LAT unassociated sources, but many pulsar-like sources remain
  - Are they radio quiet MSPs?
- Two strategies being pursued...

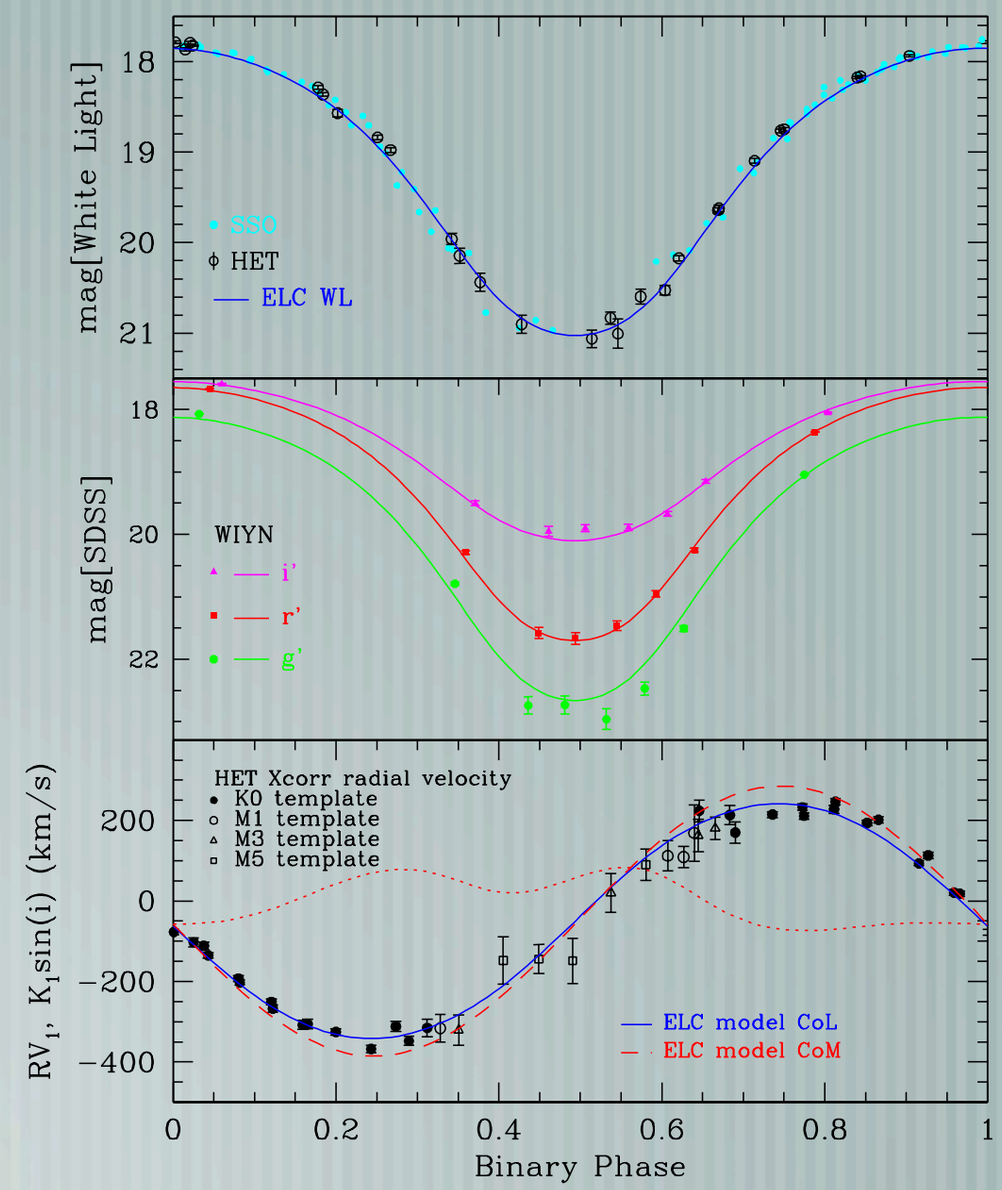
E@H Searches for MSPs

- Einstein@Home is a distributed computing project to search for gravitational waves from pulsars
  - 300,000 people have contributed
- Infrastructure is perfect fit for LAT MSP searches
  - Lots of compute cycles needed, but data volumes are tiny
- Currently using E@H to search 100 best LAT candidates up to 1200 Hz
  - Only sensitive to isolated MSP (1/4 of the total population)



Multiwavelength Obs of LAT Sources

- Only two high-latitude sources from the Bright Source List remain unidentified (J2339-0533 and J1311-2439)
- X-ray source found with Chandra (Kong et al.), optical counterpart shows variability
- Romani et al. got optical photometry and spectroscopy and solved the orbit!
  - Porb = 4.6 hours, modeling constrains A1*sin(i)
  - Companion ~0.04-0.09 $M_\odot$
- Deep radio searches found nothing
- Now using orbit params for restricted blind search of LAT data
- First radio-quiet MSP?



Romani et al. 2011, ApJL, in press (arXiv:1111.3074)

Summary

- Superb sensitivity has enabled phase-resolved spectroscopy and detailed light curve studies of many pulsars
- At least 35 new young or middle-aged pulsar detections among known radio pulsars
- At least 40 gamma-ray millisecond pulsars
- 36 pulsars have been discovered in blind searches of LAT data
- LAT unidentified sources have pointed the way to 43 new radio millisecond pulsars!
- **2nd Pulsar Catalog in prep with complete details on 117 gamma-ray pulsars**

Lots more to come!

BACKUPS

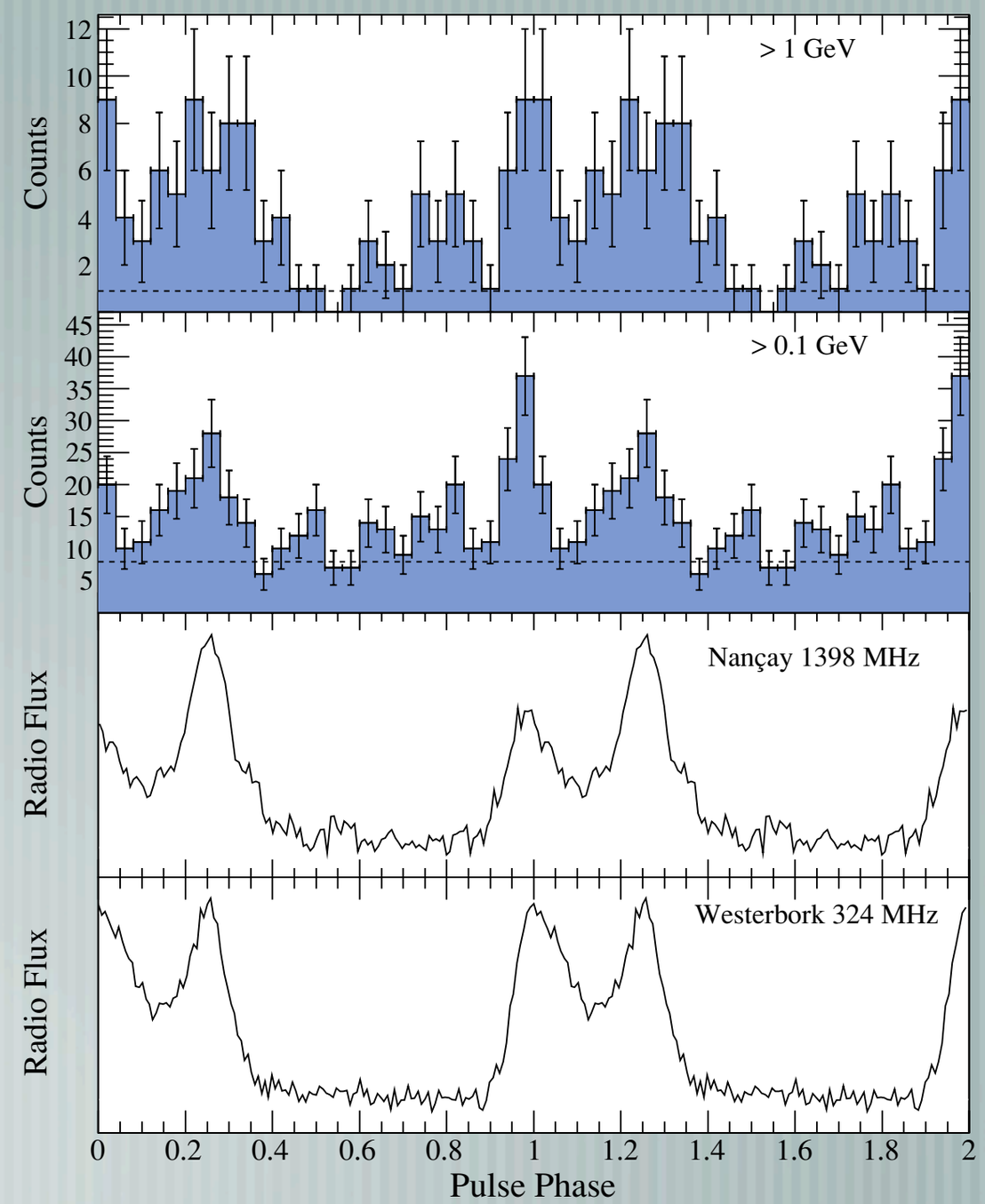
Acknowledgements

The Fermi LAT Collaboration acknowledges generous ongoing support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as scientific data analysis. These include the National Aeronautics and Space Administration and the Department of Energy in the United States, the Commissariat à l'Energie Atomique and the Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules in France, the Agenzia Spaziale Italiana and the Istituto Nazionale di Fisica Nucleare in Italy, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), High Energy Accelerator Research Organization (KEK) and Japan Aerospace Exploration Agency (JAXA) in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the Swedish National Space Board in Sweden.

Fermi work at NRL is supported by NASA

A 9th MSP: J0034-0534

- Two gamma-ray peaks, nearly aligned with the radio profile
  - Resembles the Crab in this way
- Suggests that radio and gamma-ray emission regions may be co-located



(Abdo et al. 2010, ApJ, **712**, 957)

TEMPO2

Pulsar Gating Tutorial

http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/pulsar_gating_tutorial.html

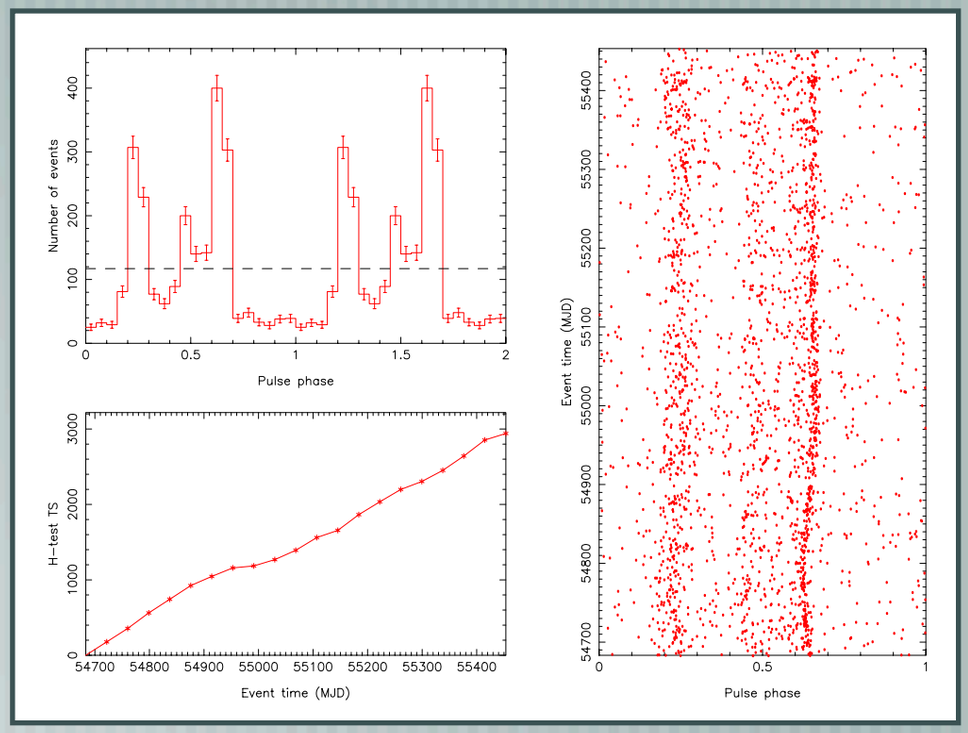
PAR File Example

```
PSRJ           J1231-1411
RAJ             12:31:11.3131569         1  0.00036267481701809421
DECJ           -14:11:43.62692           1  0.01172184923971937825
F0             271.4530196103020655      1  0.00000000010345854759
F1             -1.684235643699346112 9e-15 1  5.93728783898535995 15e-18
PEPOCH         55100
POSEPOCH       55100
DMEPOCH        55100
DM             8.089783                     0.00050000000000000000
PMRA           -96.57388141377466632 4    1  7.72890980047970665859
PMDEC          -33.56653798705077456 8    1  18.57410310617809112536
PX             0
BINARY         BT
PB             1.860143882098243557 4     1  0.00000000457056002199
T0             55016.786923229563047     1  0.09236400834581849628
A1             2.042632919710069344 7     1  0.00000157528384070272
OM             316.12850131667568751     1  17.87555478085431955731
ECC            4.437407227480392457 3e-06 1  0.00000152889659809816
START          54682.655440881677553     1
FINISH         55429.787001841814142     1
TZRMJD         55044.170744582670324
TZRFRQ         0
TZRSITE        coe
TRES           9.782
EPHVER         5
CLK            TT(TAI)
MODE 1
UNITS          TDB
EPHEM          DE405
NTOA           168
```

Practical Aside: Assigning Phases to LAT Photons

Add PULSE_PHASE column to LAT FT1 (gamma-ray events) file

- Science Tool: `gtpphase`
  - Limited model complexity
- TEMPO2 `fermi` plugin (by Lucas Guillemot)
  - Distributed with Tempo2
  - Works on raw FT1 events file, so suitable for phase-selection
- Polyco evaluation on geocentered data
  - Works on geocentered FT1 file

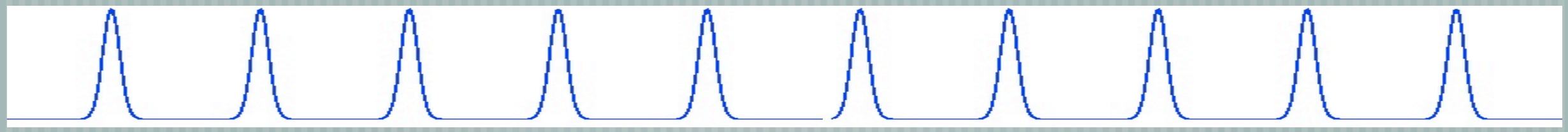


Pulsar Timing

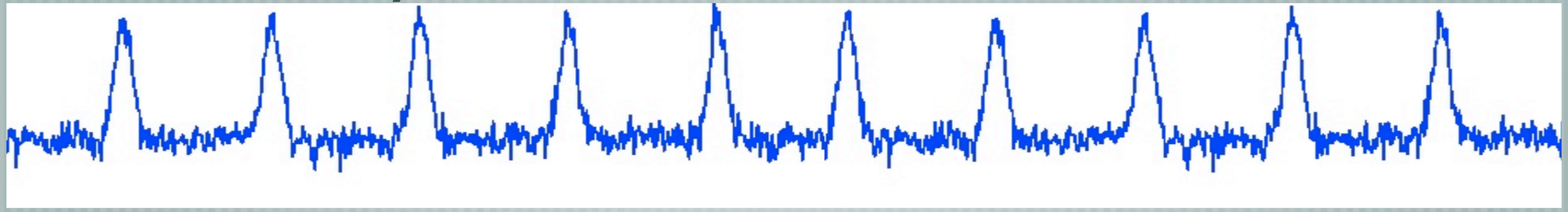
- Coherent timing over long time baselines is very powerful and precise since *every* cycle is accounted for
- Goal: To determine a *timing model* that accounts for all of the observed pulse arrival times (TOAs)
- Parameters that can be determined:
  - Spin (ν, ν', ... $\Rightarrow$ torques, magnetic fields, ages)
  - Orbital (P_{orb}, T_0, e, ω, $a_x \sin i$, GR terms)
  - Positional (α, δ, π, proper motion)

What the Signal Looks Like

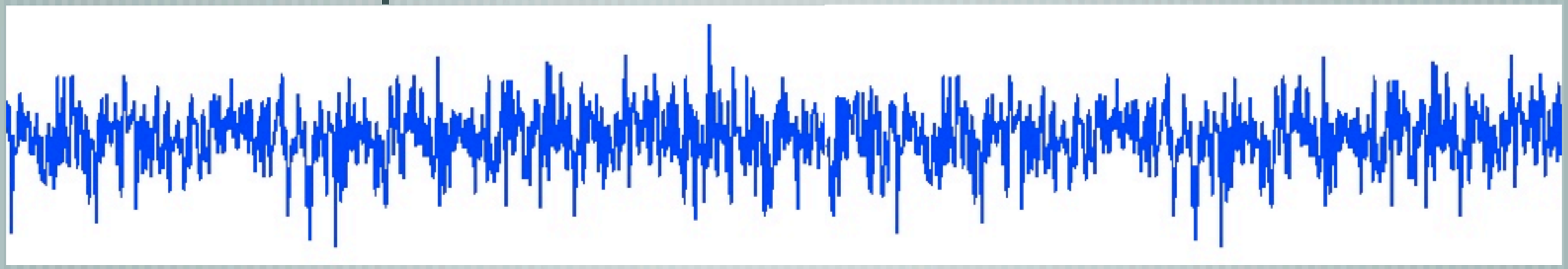
Ideally the signal would look like this:



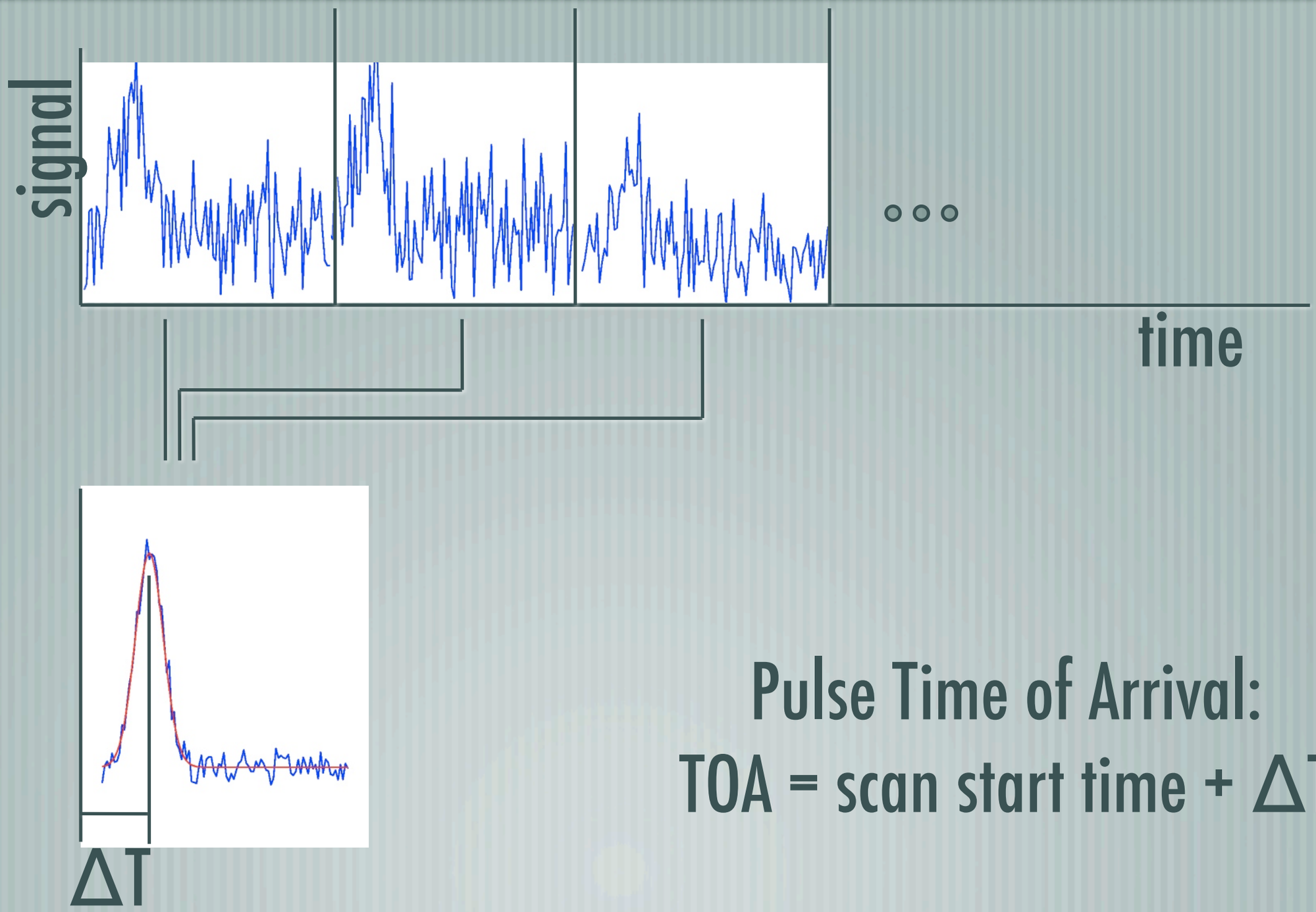
But there is always some noise:



Often individual pulses are not visible at all:



Measuring a Time of Arrival



Pulse Time of Arrival:

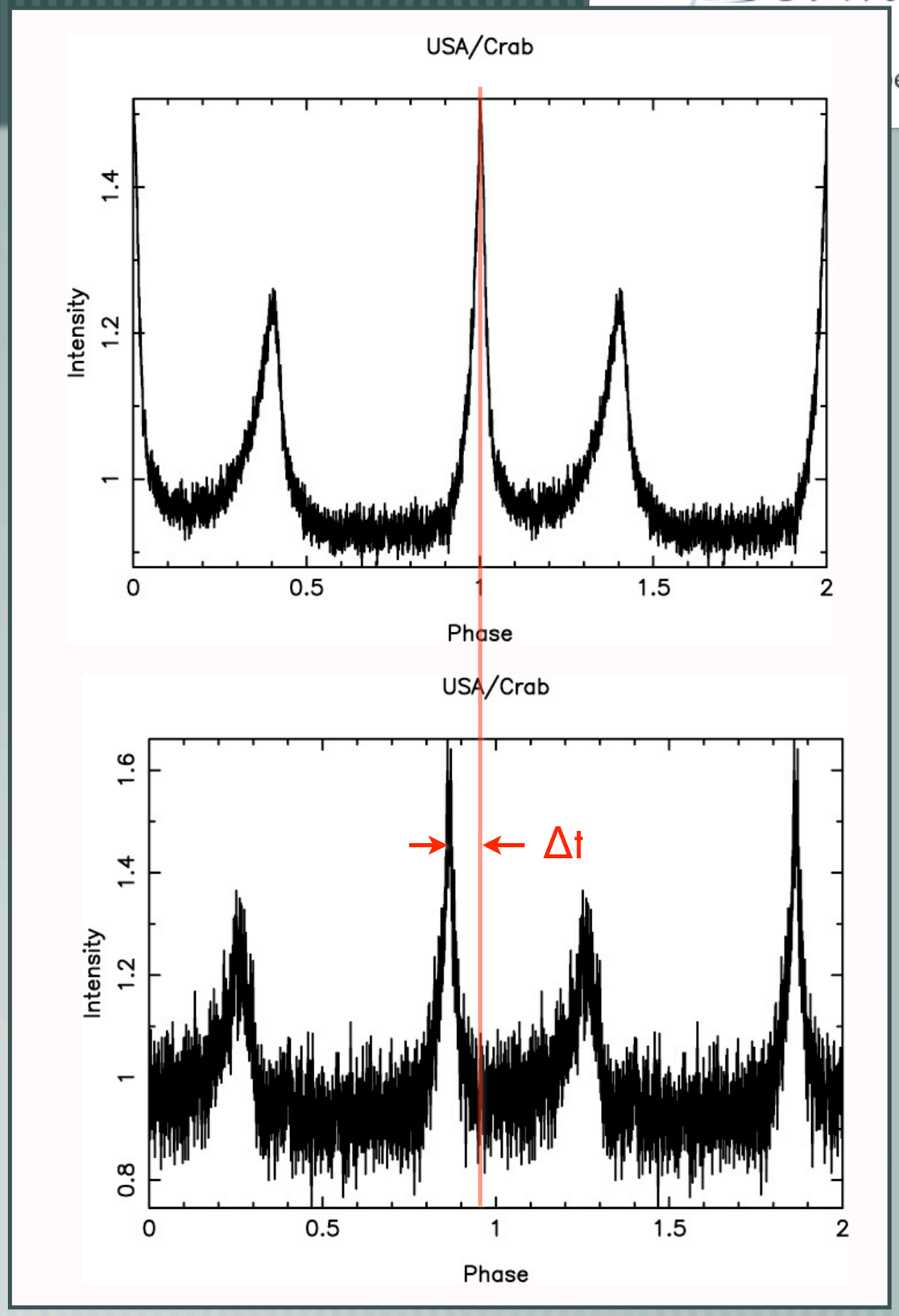
TOA = scan start time + ΔT

Measuring a TOA

- Measure phase shift between measured TOA and a template profile
  - Application of the FFT shift theorem (and linearity)

$$x(t - t_0) \Leftrightarrow X(f)e^{2\pi i f t_0}$$

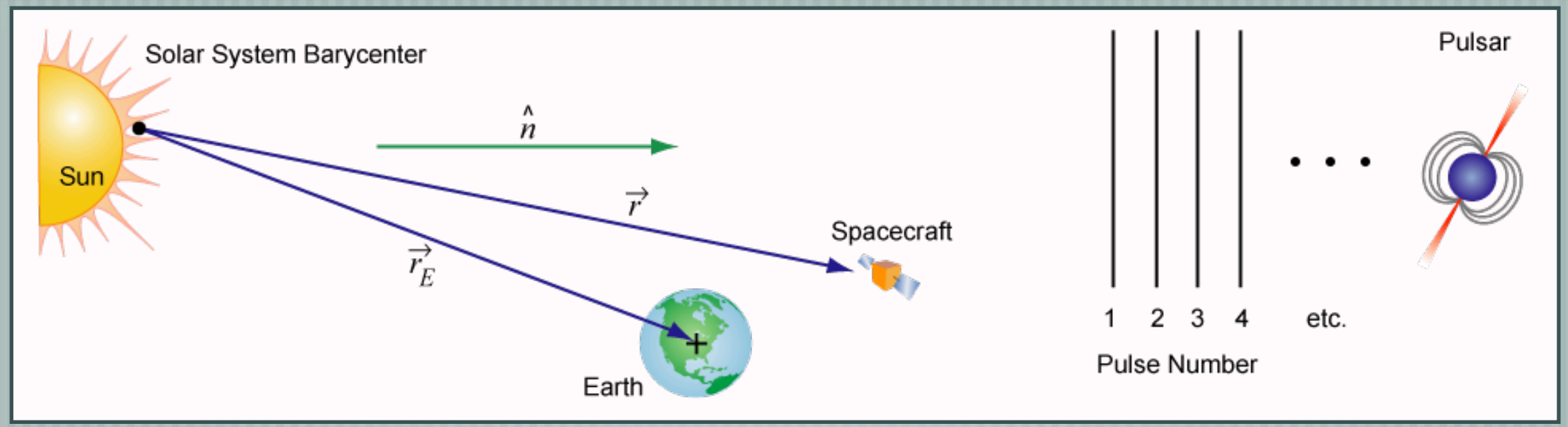
- TOA = T_{obs} + Δt



Pulse Times of Arrival

Observatory			Radio Frequency	Pulse Time of Arrival	Measurement Uncertainty		
a	3751	1518+49	370.000	50942.02369981804596	69.1	9-May-98	460.2
a	3751	1518+49	370.000	50942.02508871578912	74.9	9-May-98	460.8
a	3752	1518+49	370.000	50942.02710263928441	107.8	9-May-98	460.1
a	3752	1518+49	370.000	50942.02849153928888	68.4	9-May-98	463.7
a	3753	1518+49	370.000	50942.03050309034722	63.0	9-May-98	459.7
a	3753	1518+49	370.000	50942.03189199466585	71.4	9-May-98	468.7
a	3754	1518+49	370.000	50942.03389643284537	64.2	9-May-98	461.5
a	3754	1518+49	370.000	50942.03528532340819	57.4	9-May-98	456.3
a	3755	1518+49	370.000	50942.03728740139970	74.4	9-May-98	459.7
a	3755	1518+49	370.000	50942.03867629785610	65.1	9-May-98	461.5
a	3756	1518+49	370.000	50942.04067884384616	54.2	9-May-98	458.8
a	3756	1518+49	370.000	50942.04206774860490	87.3	9-May-98	470.2
a	3757	1518+49	370.000	50942.04406981298474	88.9	9-May-98	461.2
a	3757	1518+49	370.000	50942.04545870833792	71.8	9-May-98	463.1
a	3758	1518+49	370.000	50942.04748447411745	110.3	9-May-98	463.0
a	3758	1518+49	370.000	50942.04887336536594	78.6	9-May-98	461.1
a	3759	1518+49	370.000	50942.05089865820880	60.2	9-May-98	463.4
a	3759	1518+49	370.000	50942.05228755033977	131.1	9-May-98	463.1
a	3760	1518+49	370.000	50942.05428961858992	63.4	9-May-98	460.9
a	3760	1518+49	370.000	50942.05567851214494	93.2	9-May-98	462.8
a	3761	1518+49	370.000	50942.05768105475176	116.2	9-May-98	461.0
a	3761	1518+49	370.000	50942.05906994776154	75.0	9-May-98	463.0
a	3762	1518+49	370.000	50942.06108244410689	72.2	9-May-98	465.9
a	3762	1518+49	370.000	50942.06247133259781	76.9	9-May-98	463.6
a	3763	1518+49	370.000	50942.06450988581265	86.1	9-May-98	461.4
a	3763	1518+49	370.000	50942.06589877480622	61.9	9-May-98	460.4
a	3764	1518+49	370.000	50942.06790794988299	90.1	9-May-98	460.5
a	3764	1518+49	370.000	50942.06929683956486	67.2	9-May-98	460.8
a	3765	1518+49	370.000	50942.07129227137214	63.5	9-May-98	460.6
a	3765	1518+49	370.000	50942.07268116130441	139.5	9-May-98	461.8

Barycentering TOAs

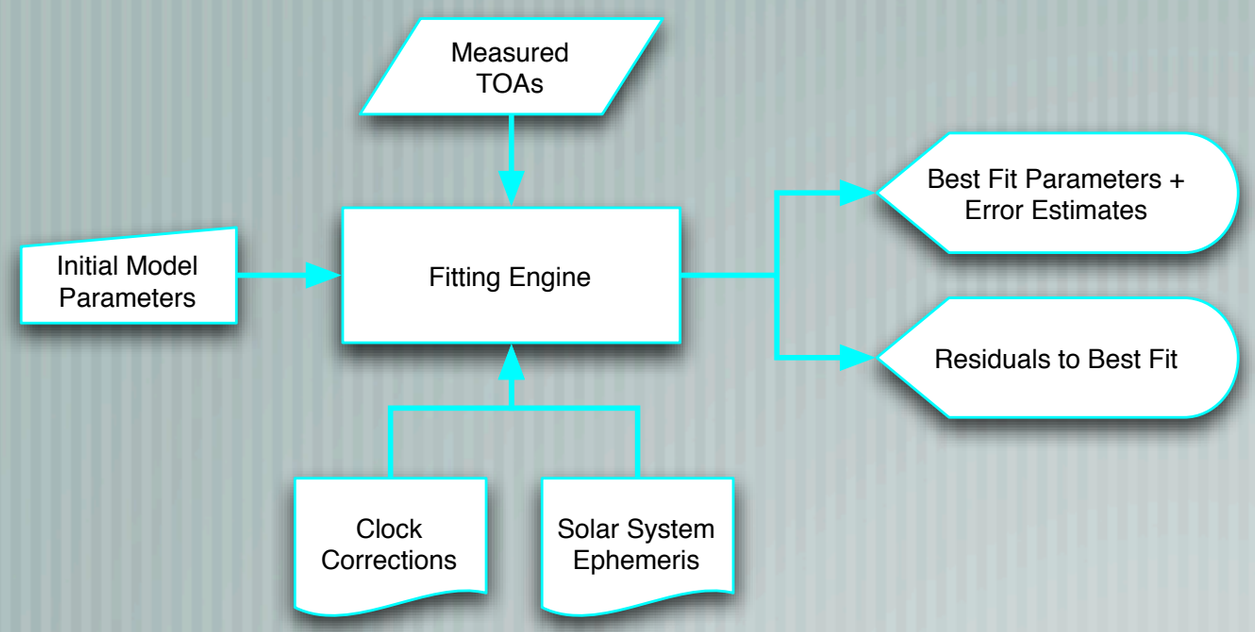


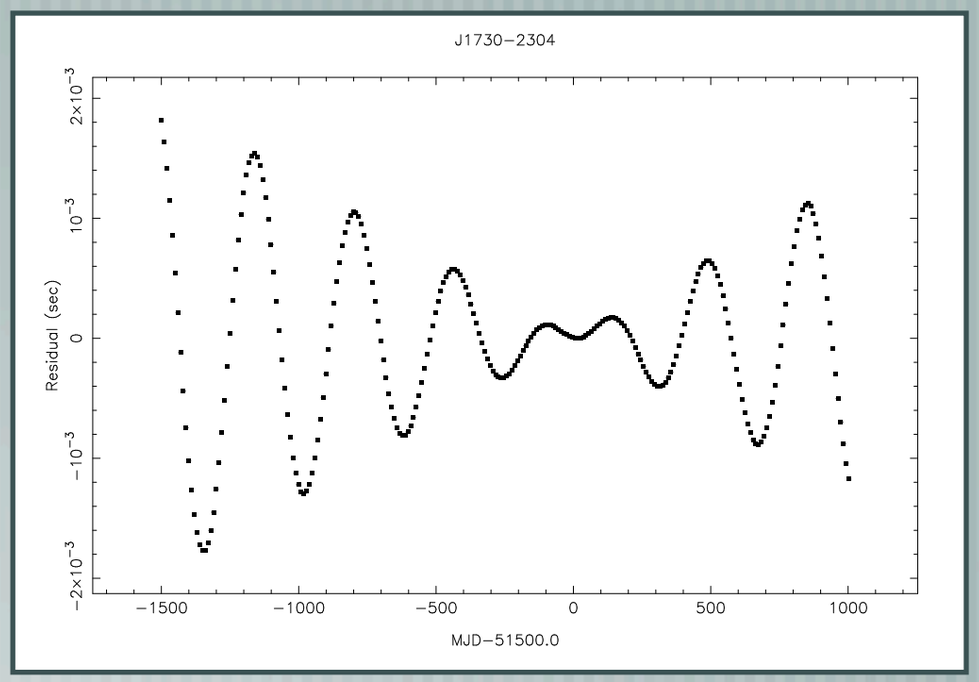
- Arrival times at Earth or spacecraft must be converted to a nearly inertial frame before attempting to fit a simple timing model
- Remove effects of observer velocity and relativistic clock effects
- Convenient frame is the Solar System Barycenter

Fitting TOAs to a Timing Model

$$\phi(t) = \phi(0) + \nu t + \frac{1}{2}\dot{\nu} t^2 + \frac{1}{6}\ddot{\nu} t^3 + \ldots$$

Full model can include spin, astrometric, binary, and other parameters.





Goal: Find parameter values that minimize the residuals between the data and the model

Tools for Fitting Timing Models

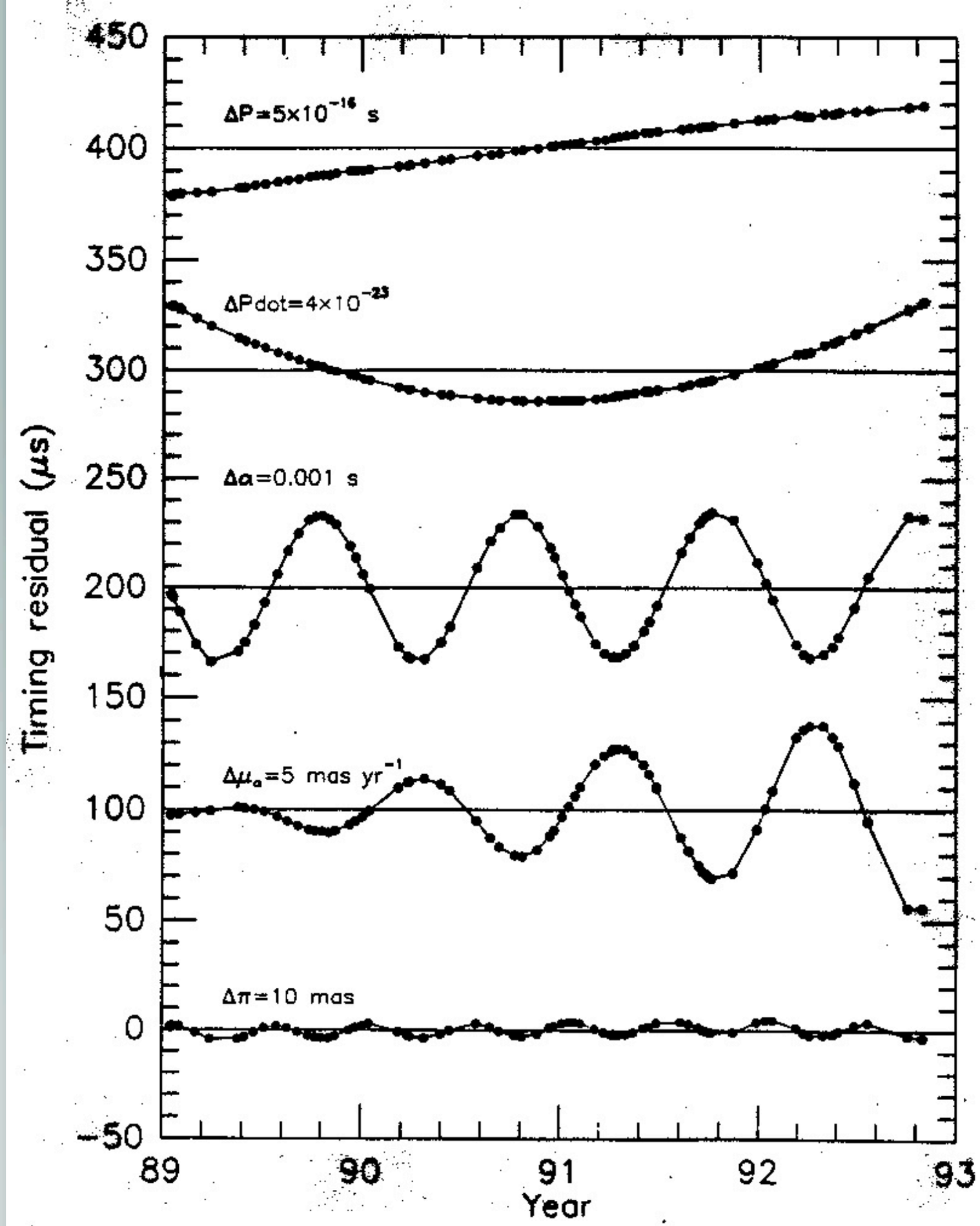
- Tempo < http://pulsar.princeton.edu/tempo/ >
  - Developed by Princeton and ATNF over 30+ years
  - Well tested and heavily used
  - Based on TDB time system
  - But, nearly undocumented, archaic FORTRAN code
- Tempo2 < http://www.atnf.csiro.au/research/pulsar/tempo2/ >
  - Developed at ATNF recently
  - Based on TCB time system (coordinate time based on SI second)
  - Well documented, modern C code, uses `long double` (128 bit) throughout
  - Easy plug-in architecture to extend capabilities

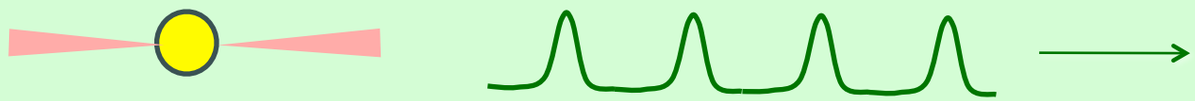
Time Systems

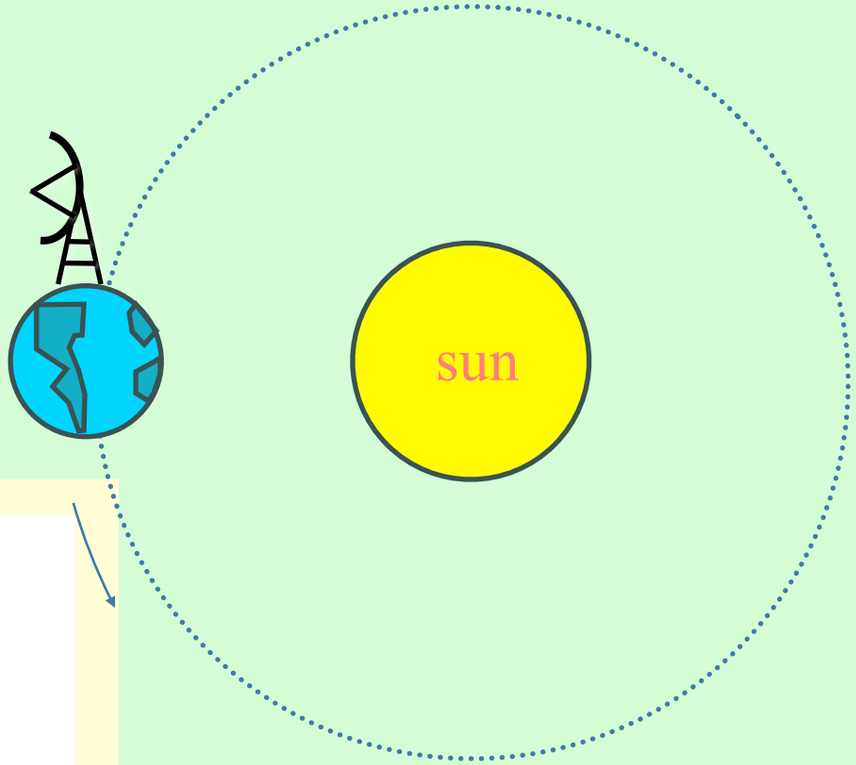
TAI = Atomic time based on the SI second
UT1 = Time based on rotation of the Earth
UTC = TAI + "leap seconds" to stay close to UT1
TT = TAI + 32.184 s
TDB = TT + periodic terms to be uniform at SSB
TCB = Coordinate time at SSB, based on SI second

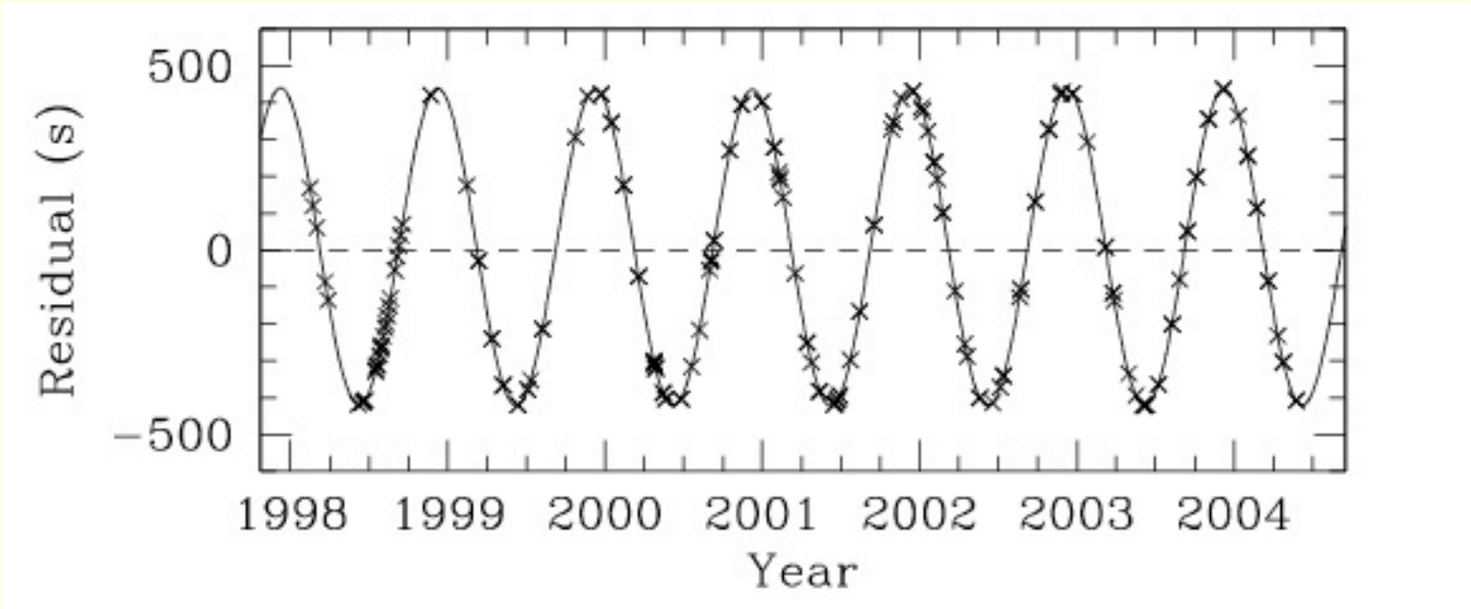
Model timing residuals

- Period: $\Delta P = 5 \times 10^{-16}$ s
- Pdot: $\Delta Pdot = 4 \times 10^{-23}$
- Position: $\Delta\alpha = 1$ mas
- Proper motion: $\Delta\mu = 5$ mas/yr
- Parallax: $\Delta\pi = 10$ mas









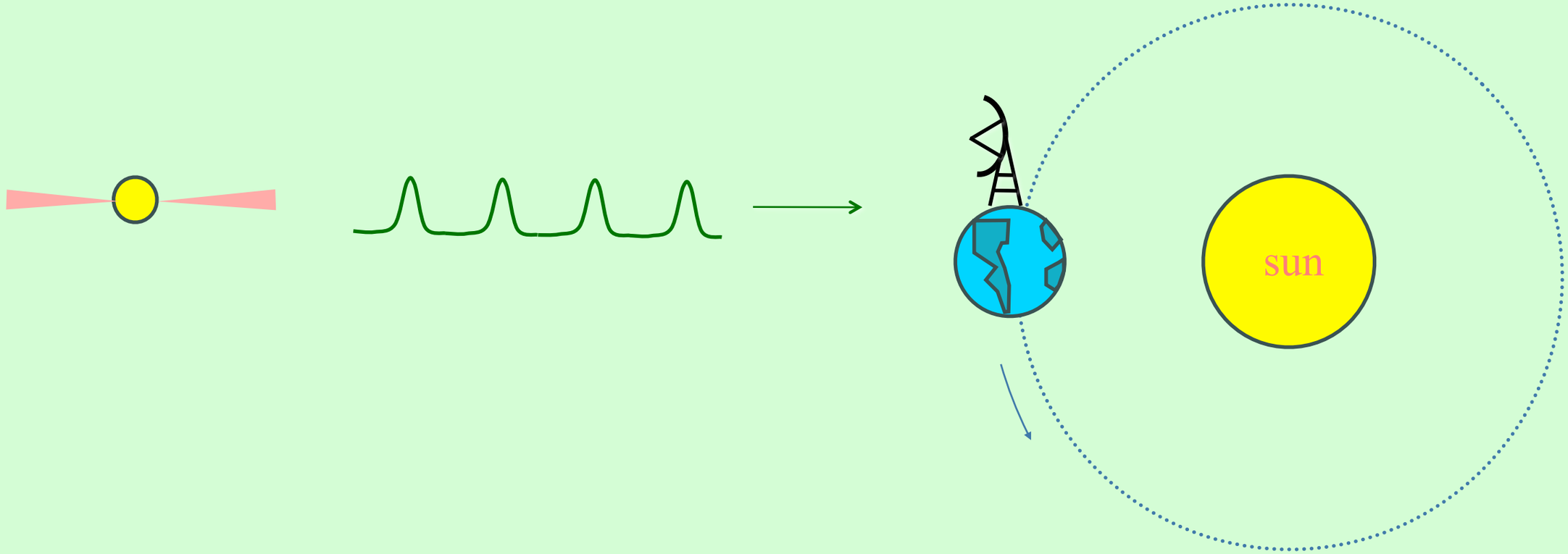
Delays of ~500 s due to time-of-flight across the Earth's orbit.

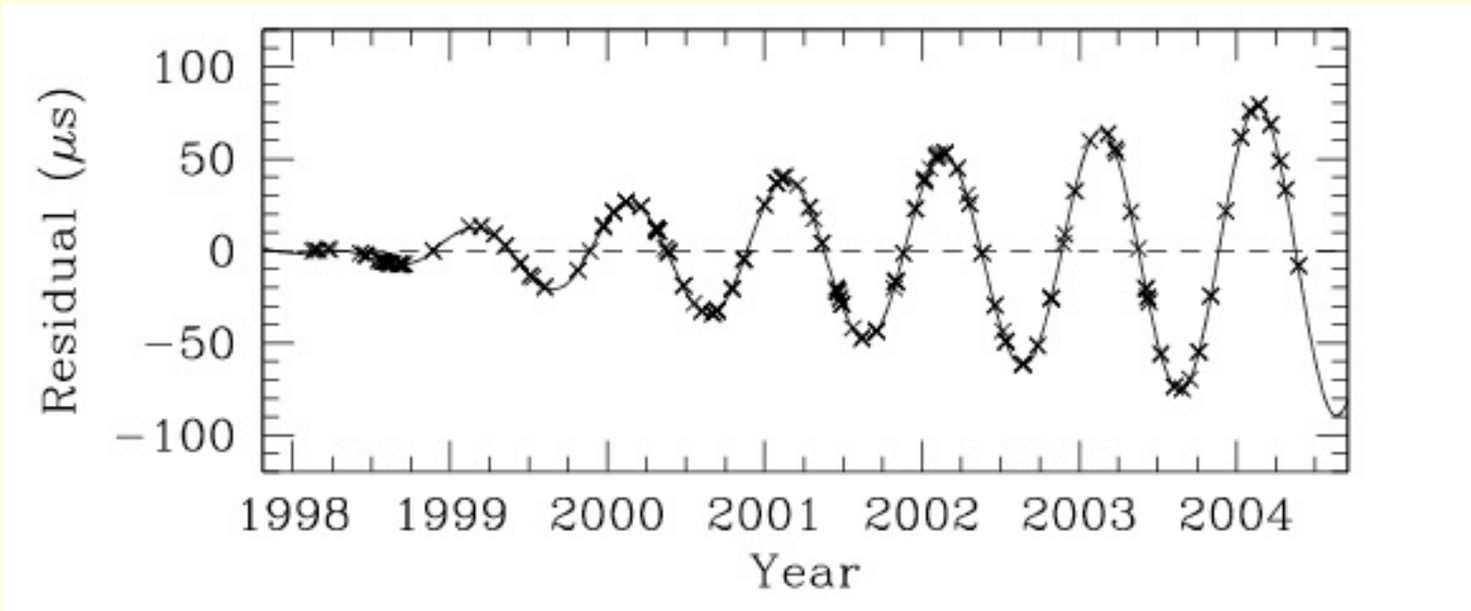
The amplitude and phase of this delay depend on the pulsar position.

Position known only from timing data

⇒ always need to fit annual terms out of timing solution

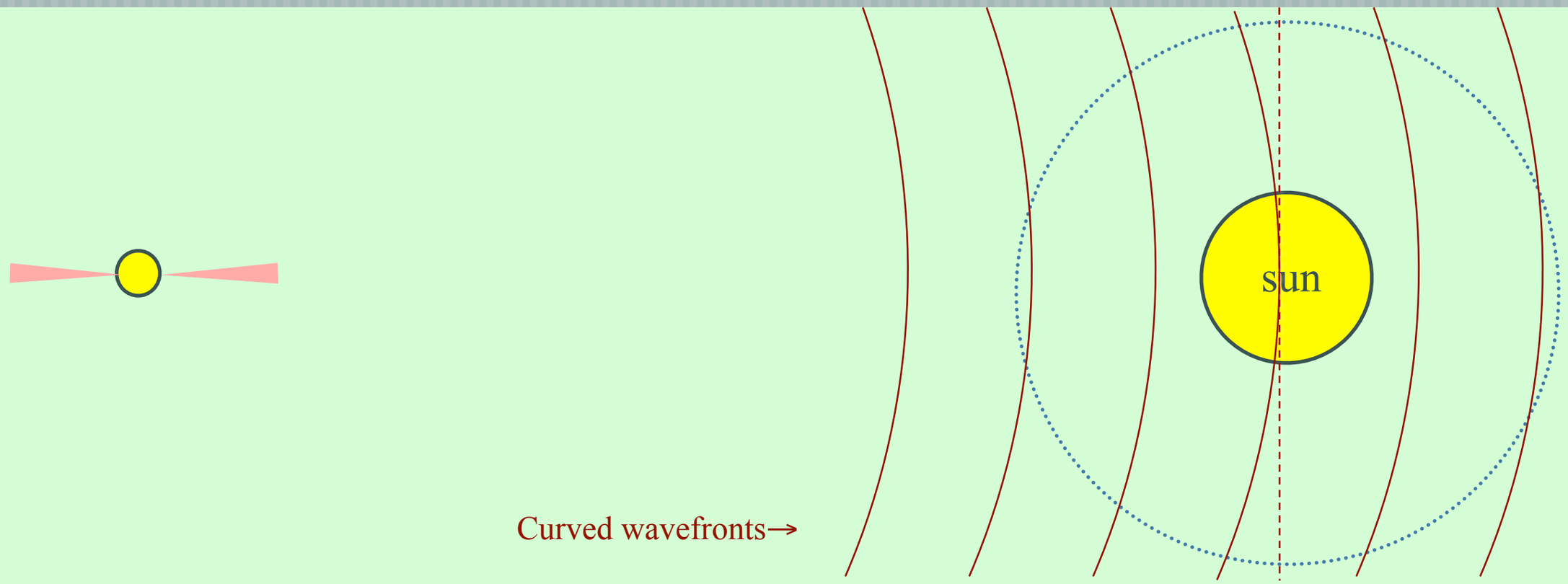
⇒ a perturbation due to gravitational waves with ~1 yr period cannot be detected

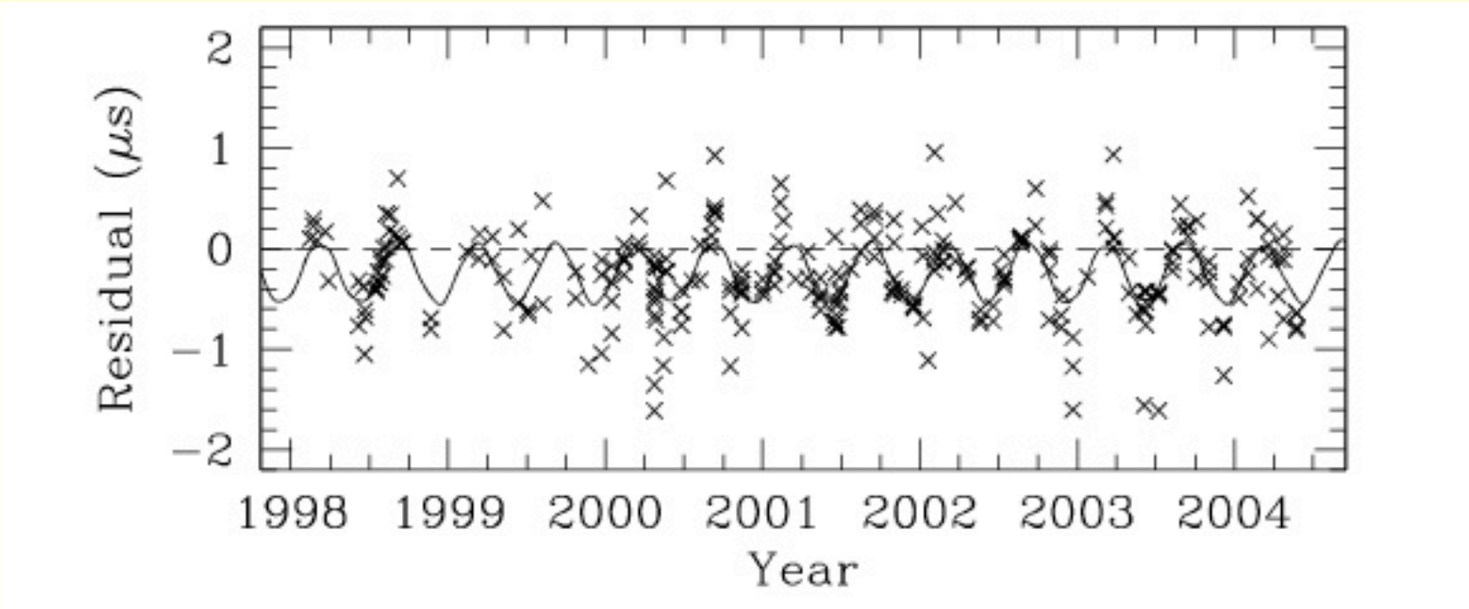




Other astrometric phenomena:

Proper Motion



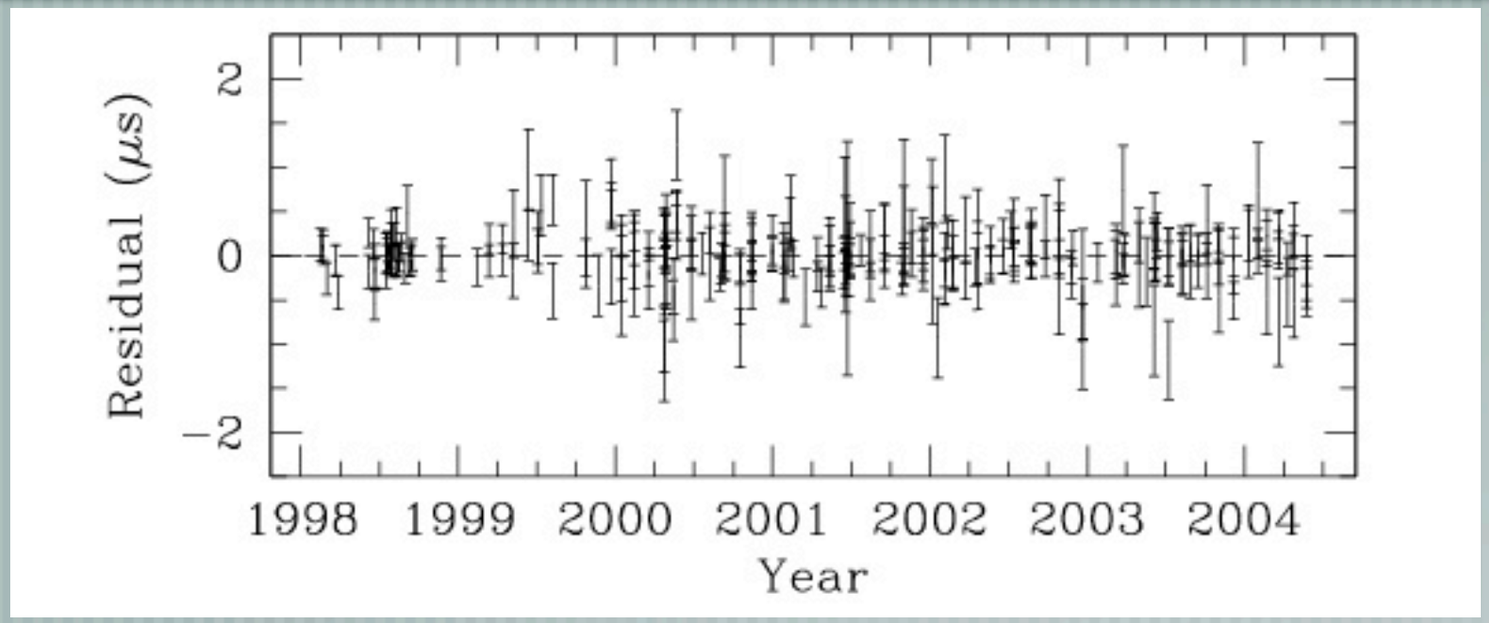


Other astrometric phenomena:

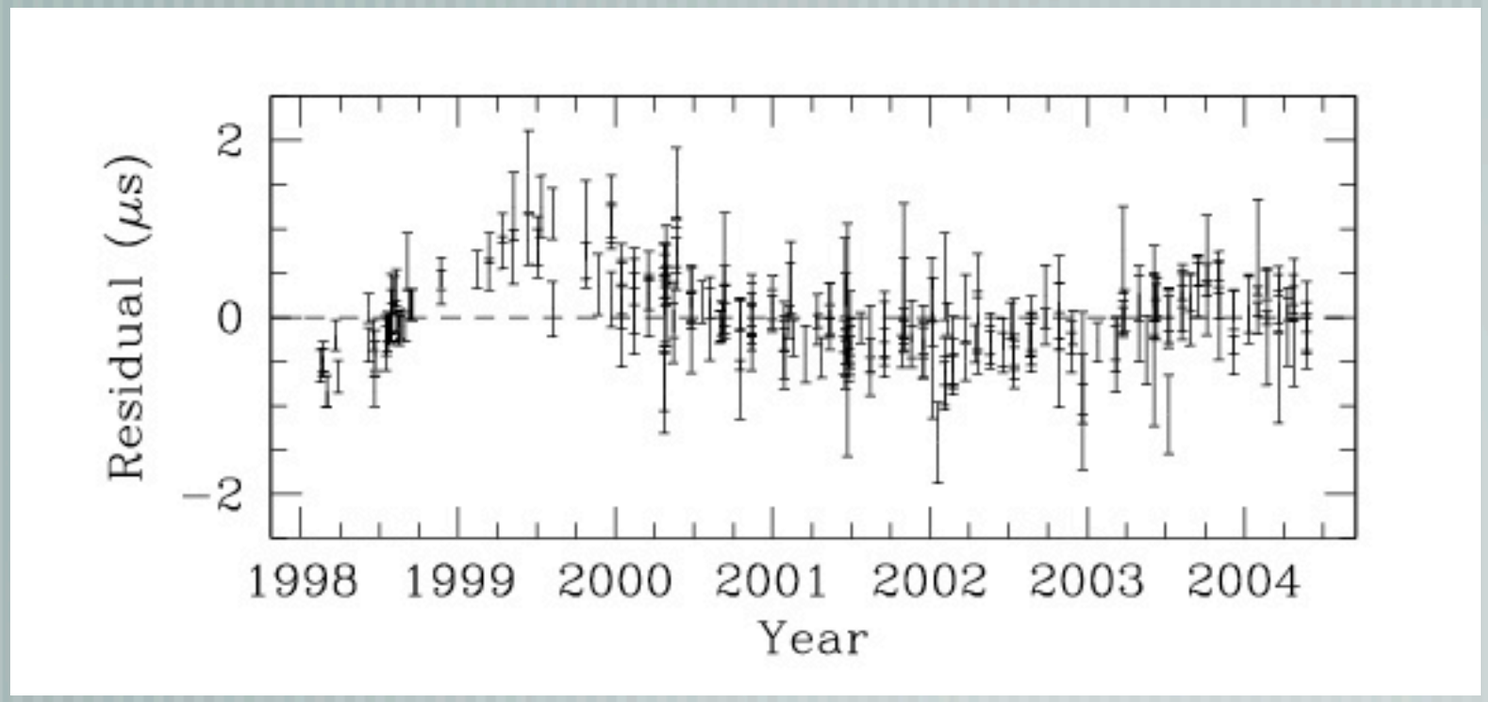
Proper Motion

Parallax

Effects of Planetary Ephemeris



PSR J1713+0747 analyzed using DE 405 solar system ephemeris



PSR J1713+0747 analyzed using previous-generation DE 200 solar system ephemeris.

~1μs timing errors
⇔ 300 m errors in Earth position.

Timing Noise in Young Pulsars