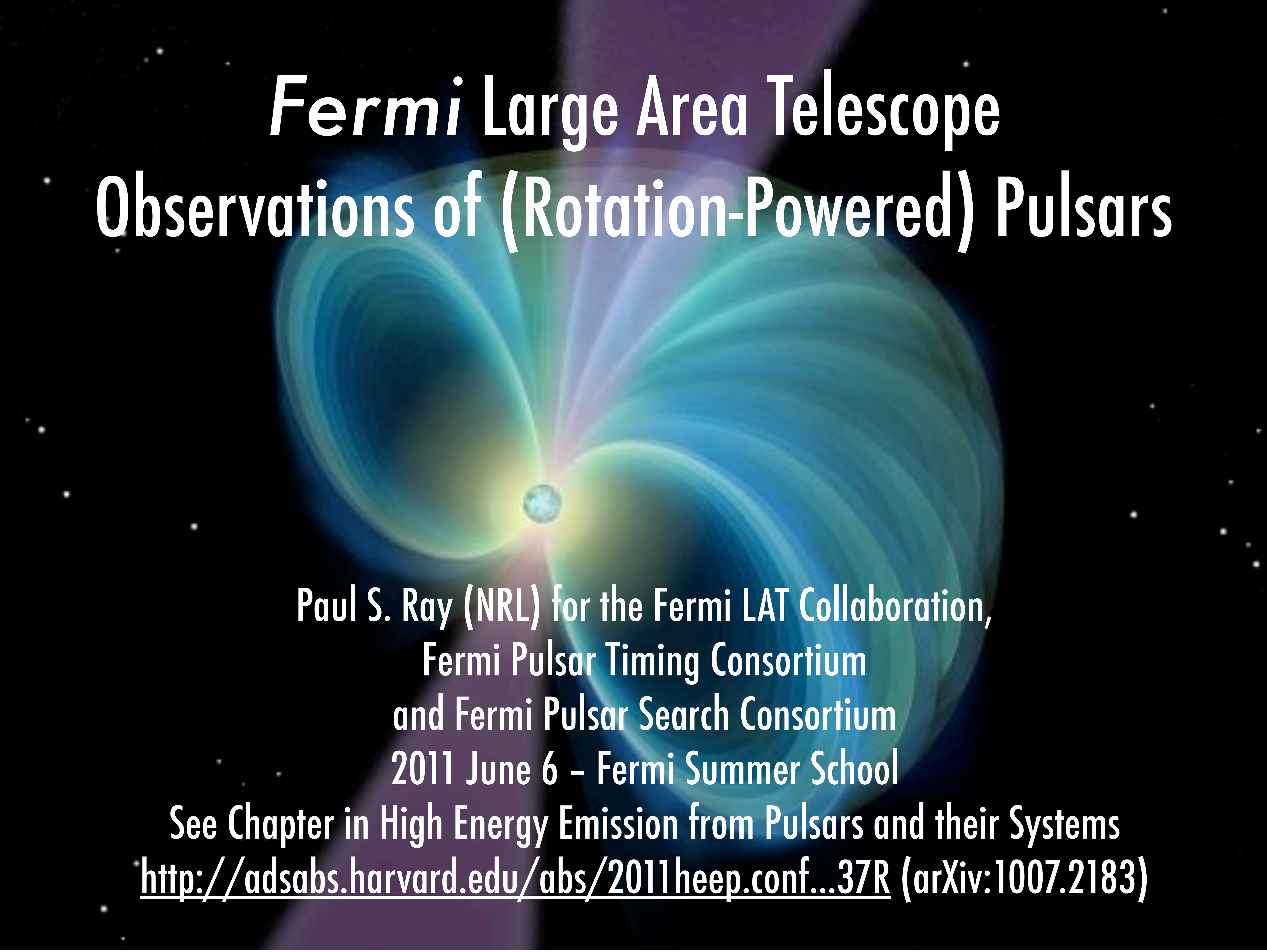


Fermi Large Area Telescope Observations of (Rotation-Powered) Pulsars

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

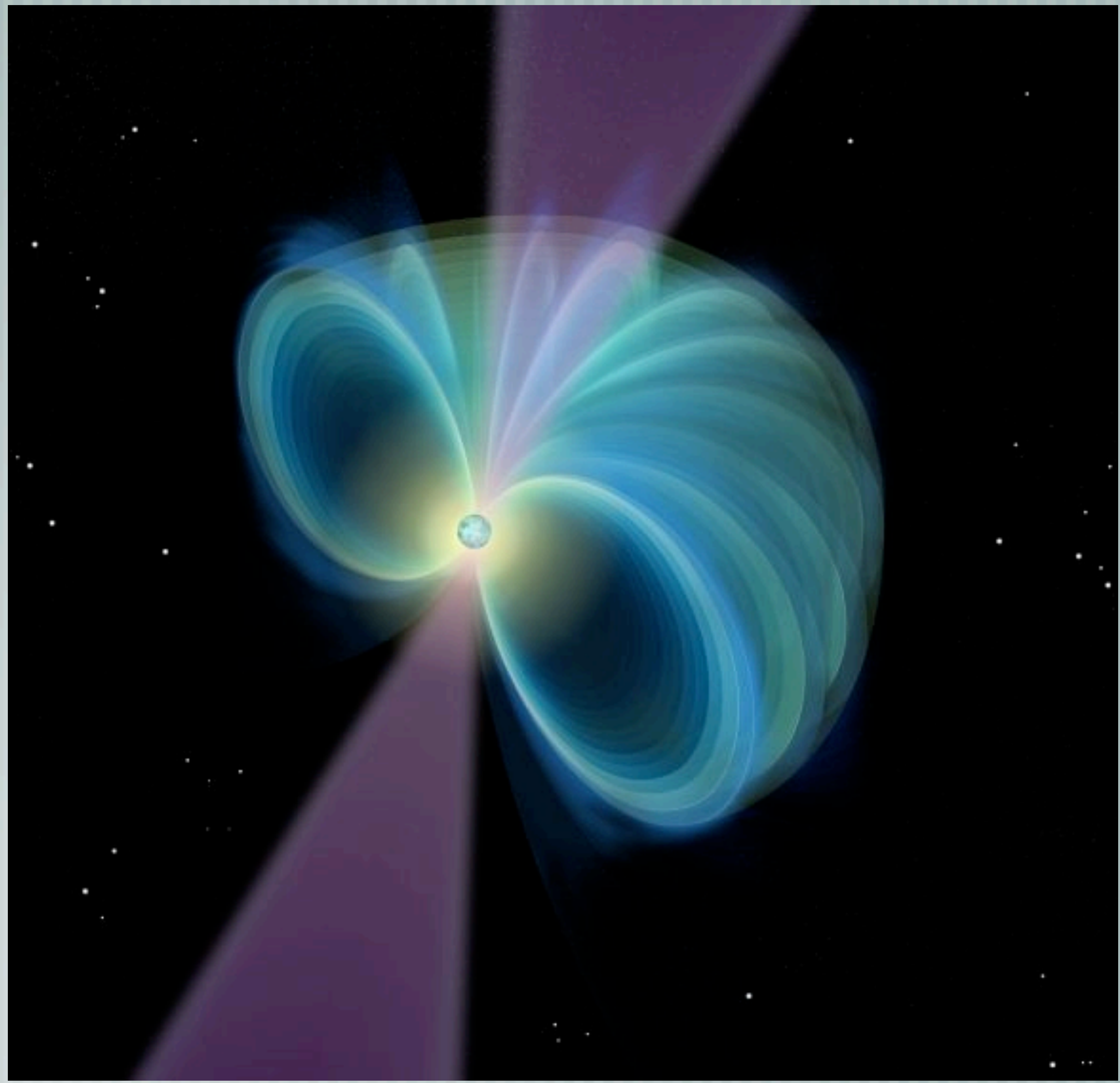
2011 June 6 – Fermi Summer School

See Chapter in High Energy Emission from Pulsars and their Systems
http://adsabs.harvard.edu/abs/2011heep.conf...37R (arXiv:1007.2183)

Pulsar Characteristics

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

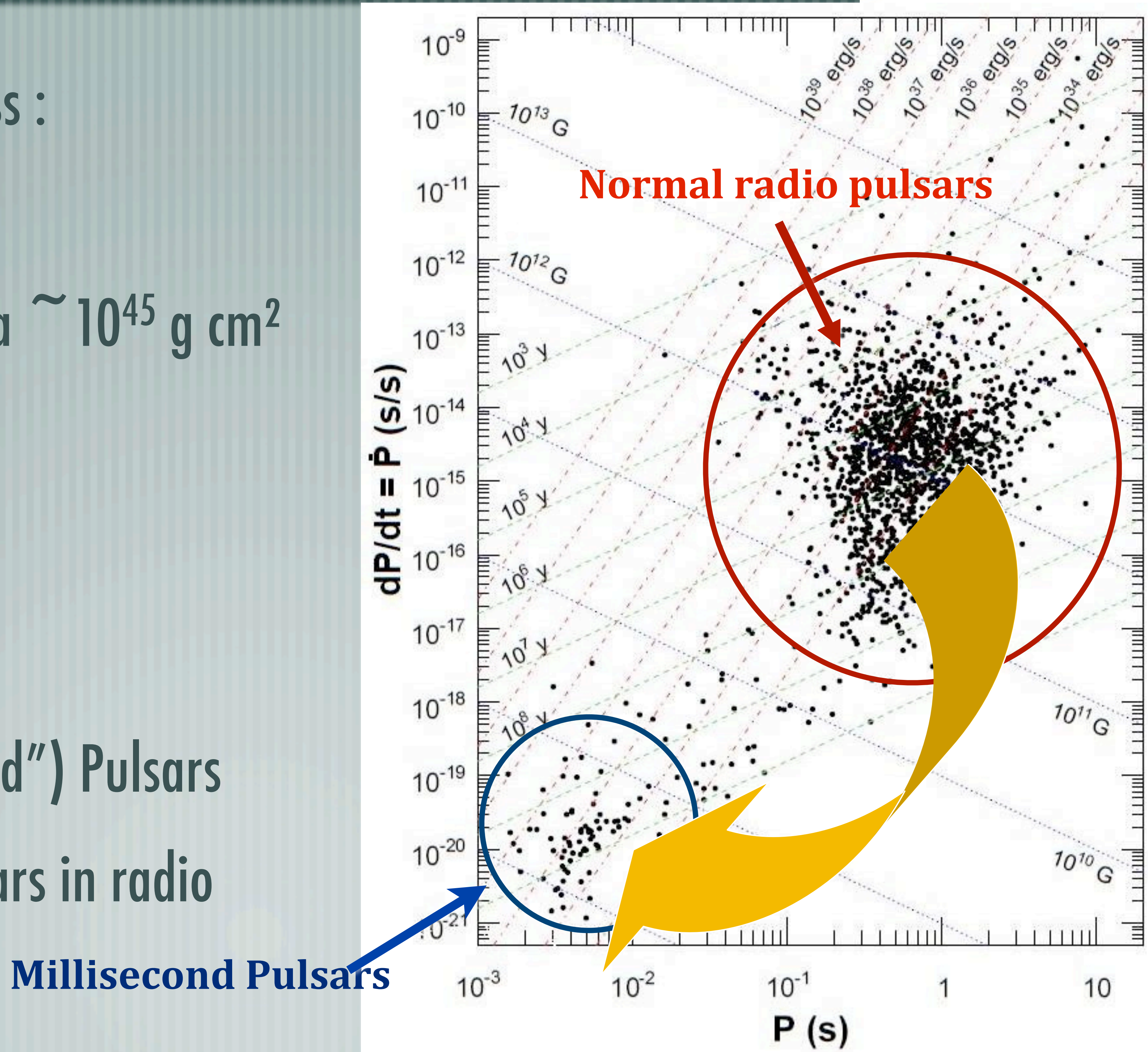


Period and Slowdown

- 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

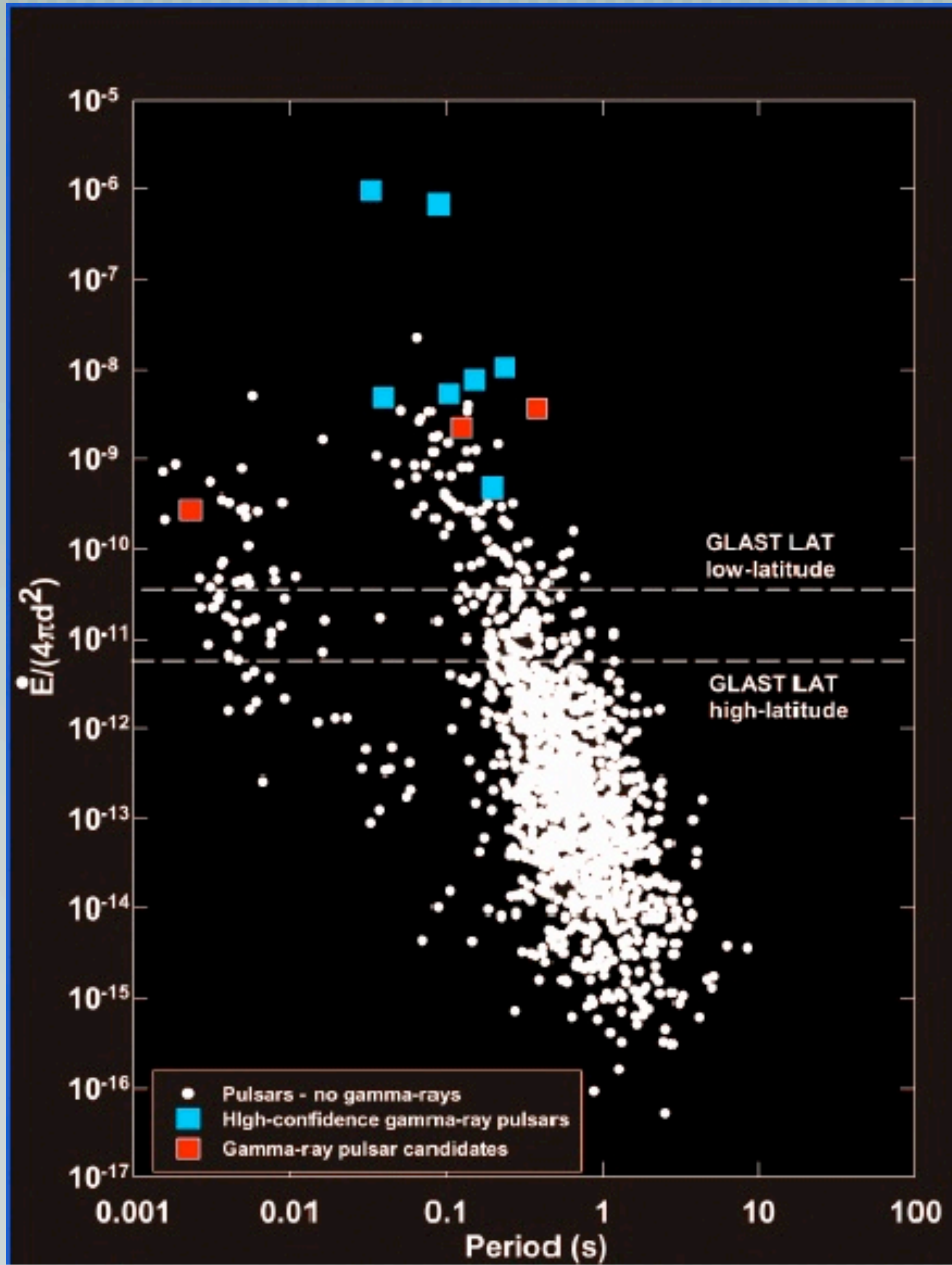
- Extreme Densities
  - The cores of neutron stars reach super-nuclear densities, where the equation of state is unknown
- Extreme Gravitation
  - Binary pulsars probe many predictions of General Relativity to high precision
- Extreme Magnetism
  - Some pulsars have B fields above the quantum critical 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

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)

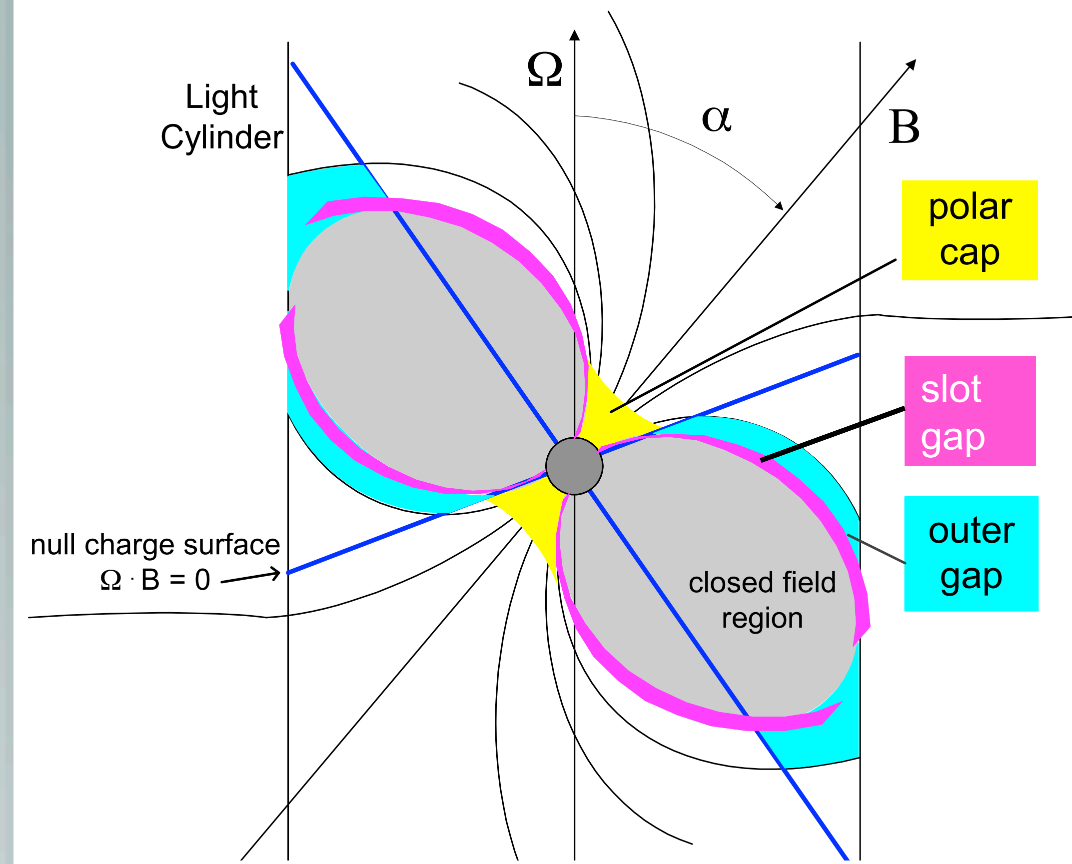
More recently... AGILE (2007 -)

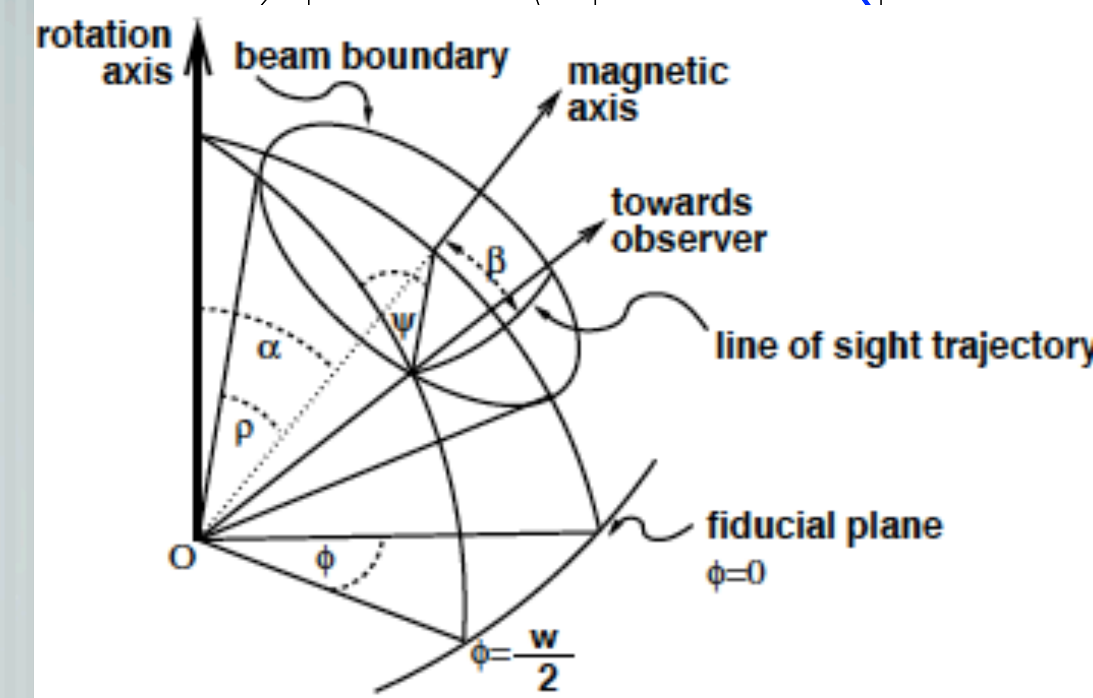


Pulsar Gamma-Ray Emission

- 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**

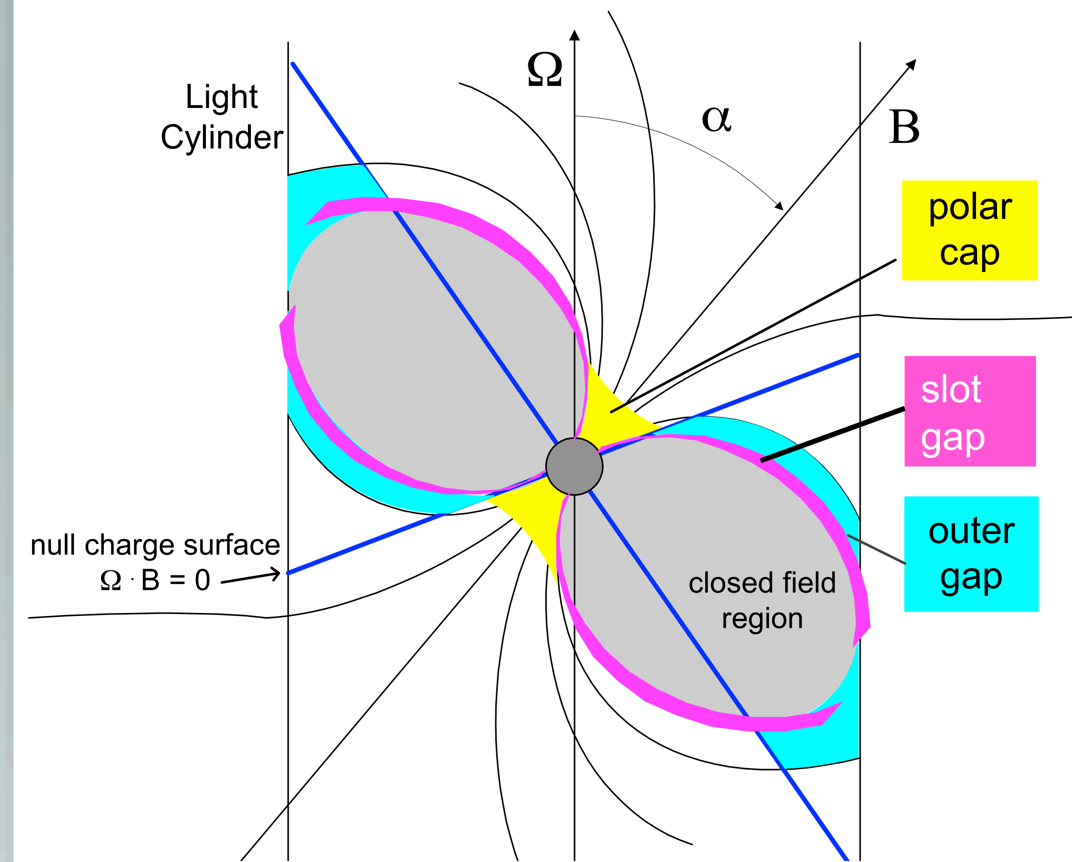
(Also see Watters et al. 2009, ApJ, **695**, 1289)

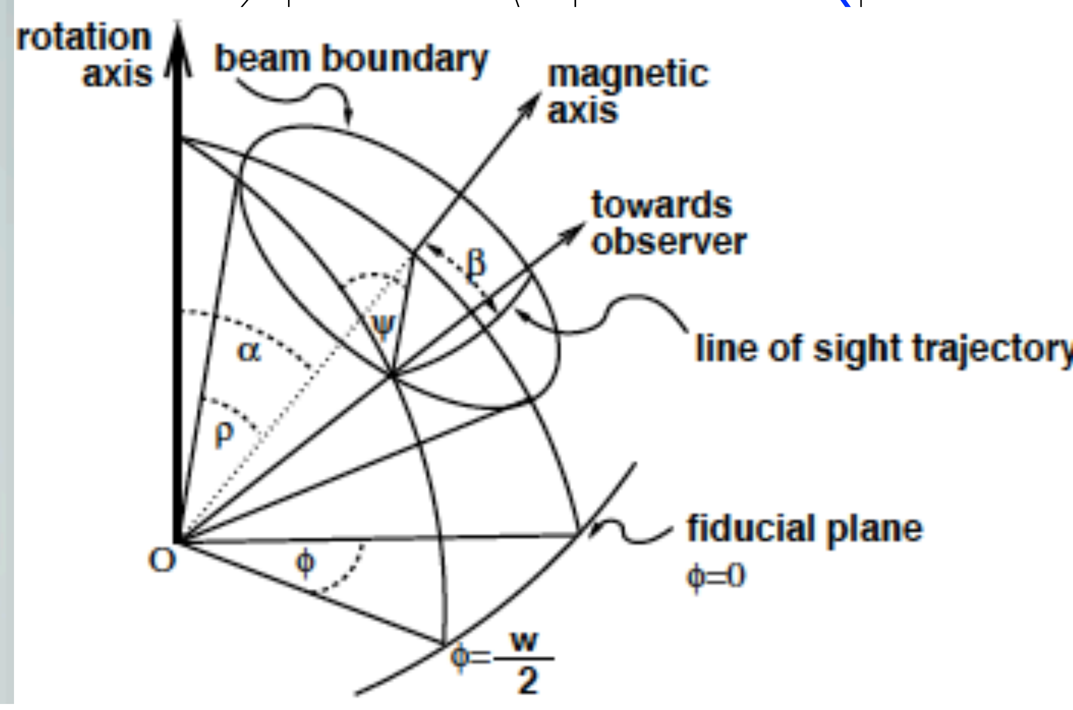




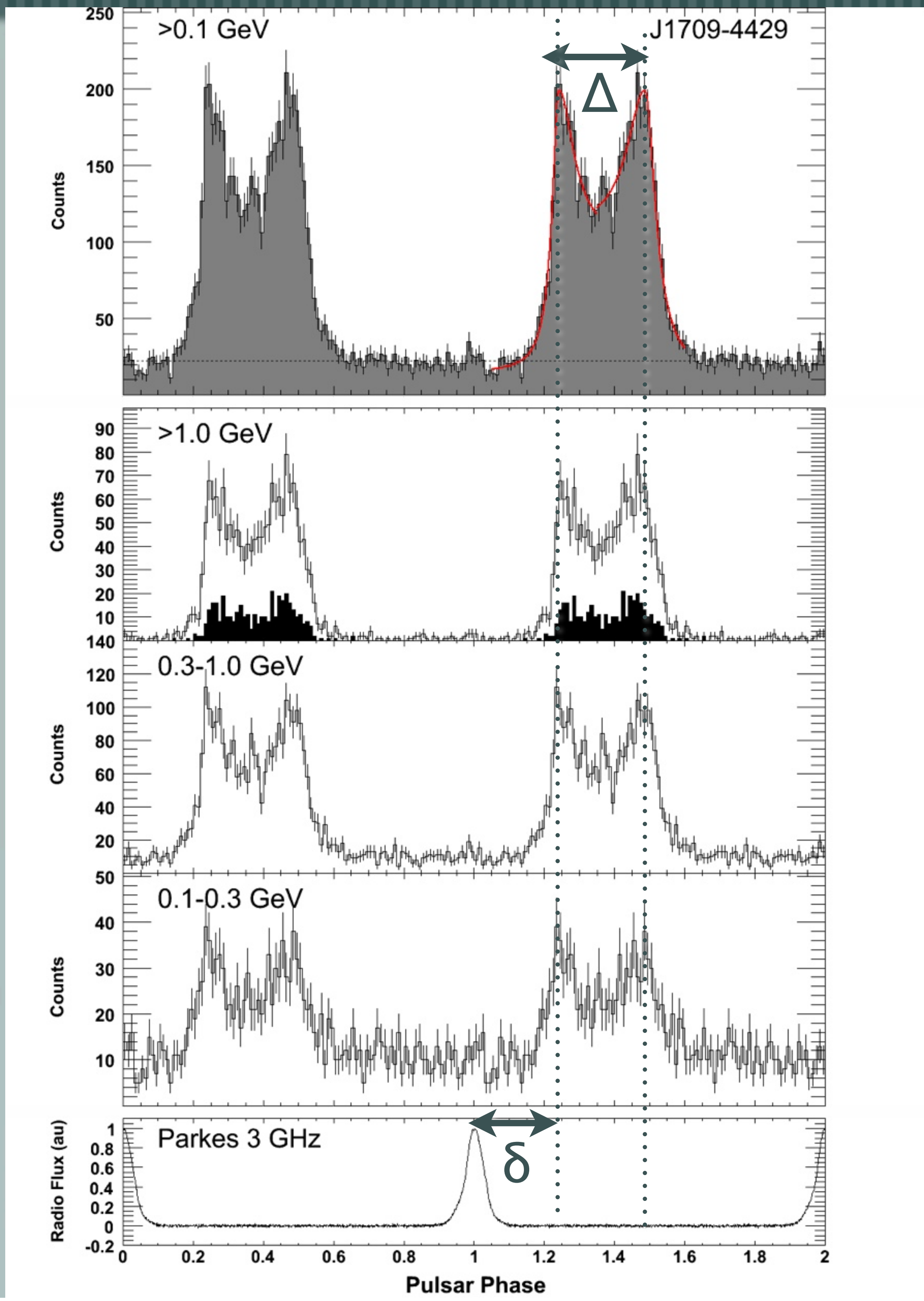
Some (pre-Fermi) open questions:

- 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
  - X-ray images of pulsar wind nebulae
  - Radio Polarization

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)

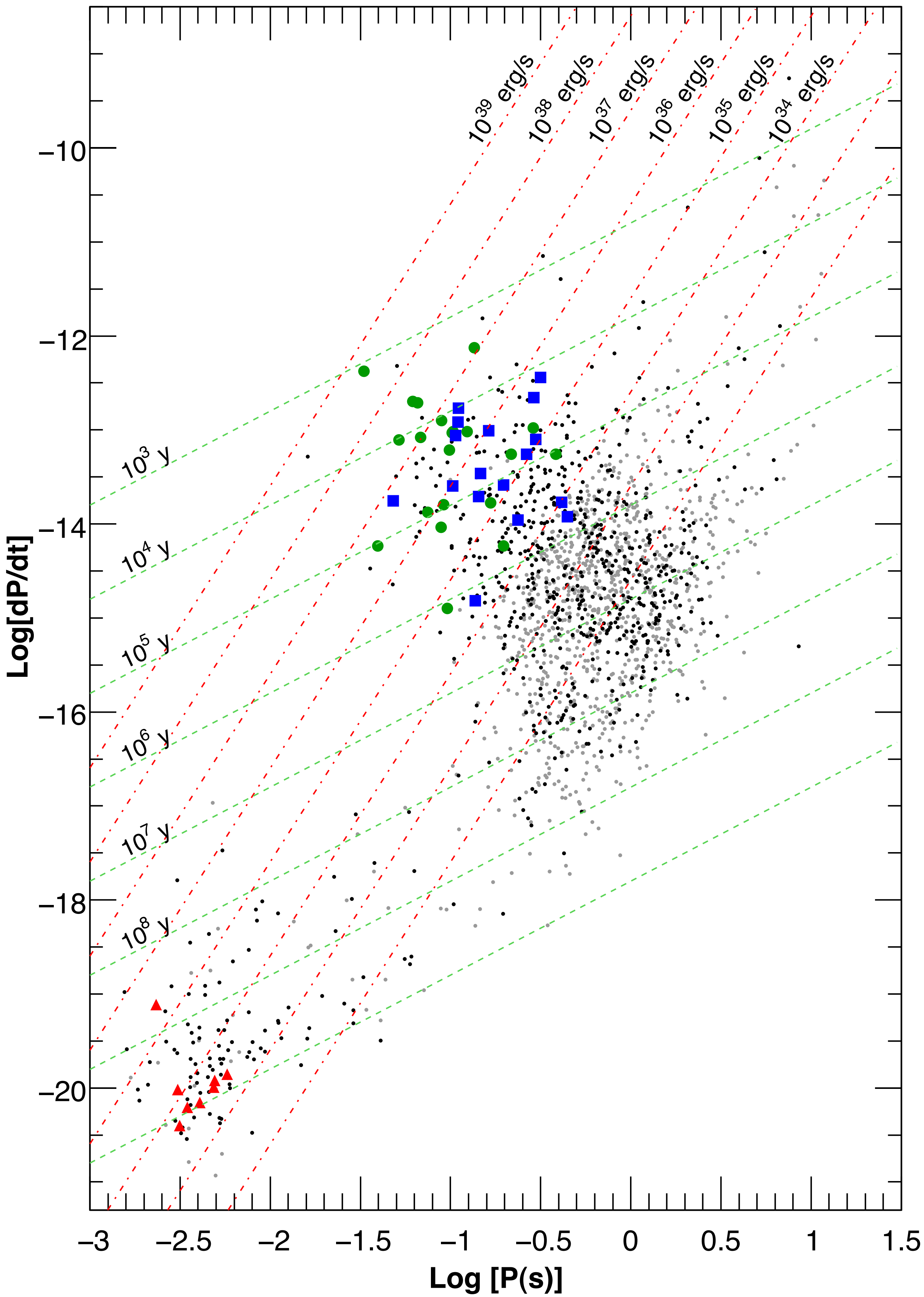
Three Ways to Detect Pulsars with the LAT

- 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
  - Many tried hard with EGRET without success
- Radio pulsar searches of LAT unidentified sources
  - Sensitivity to MSPs, binaries, very noisy pulsars

LAT First Pulsar Catalog

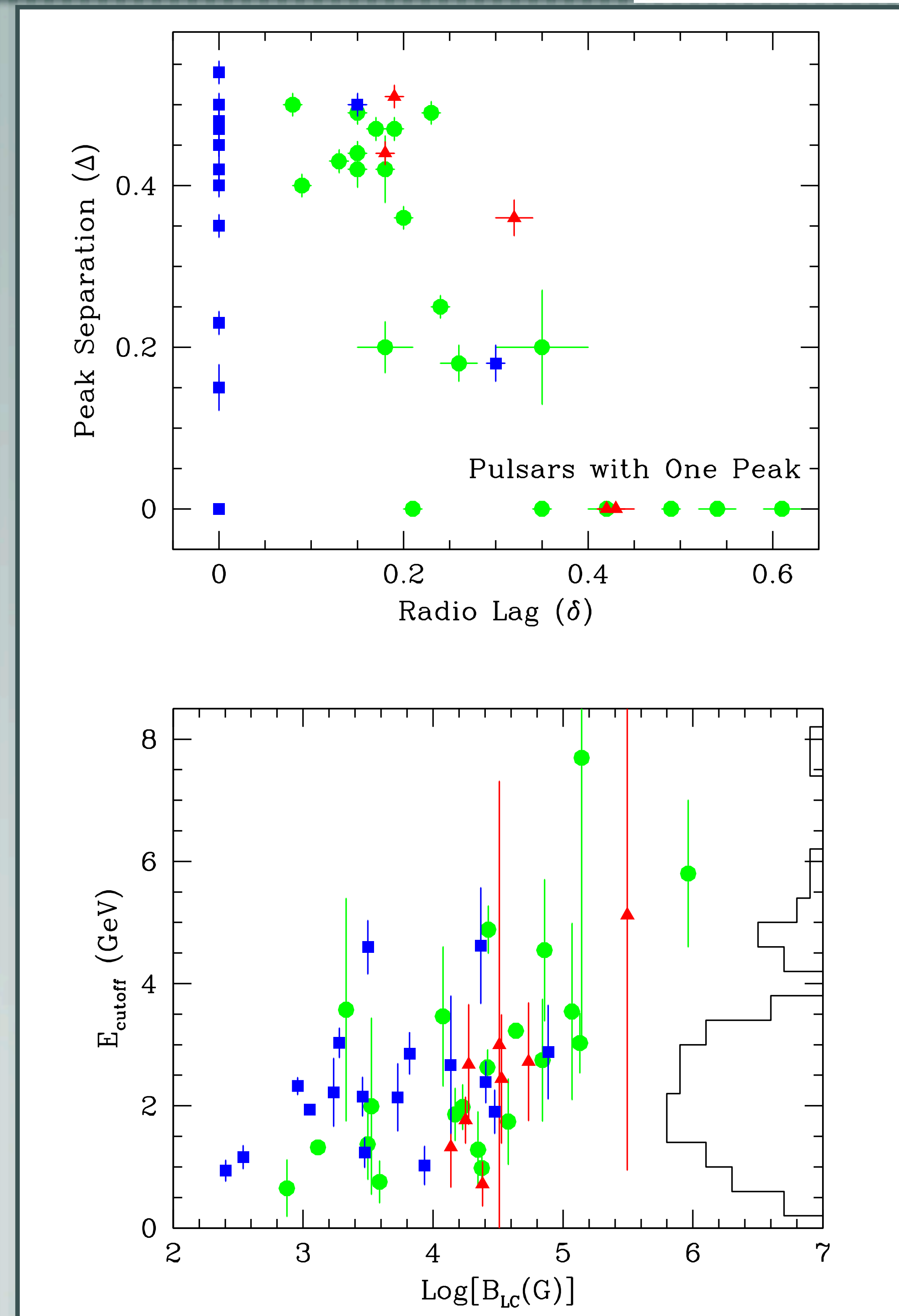
- 46 pulsars included
  - 17 gamma-ray selected (blue squares)
  - 6 EGRET
  - 8 MSPs (red triangles)
  - 16 other radio pulsars
- Multi-band light curves, spectral fits, etc... all done in a uniform way
- First cut at population statistics, correlations

(Abdo et al. 2010, ApJS, **187**, 460)

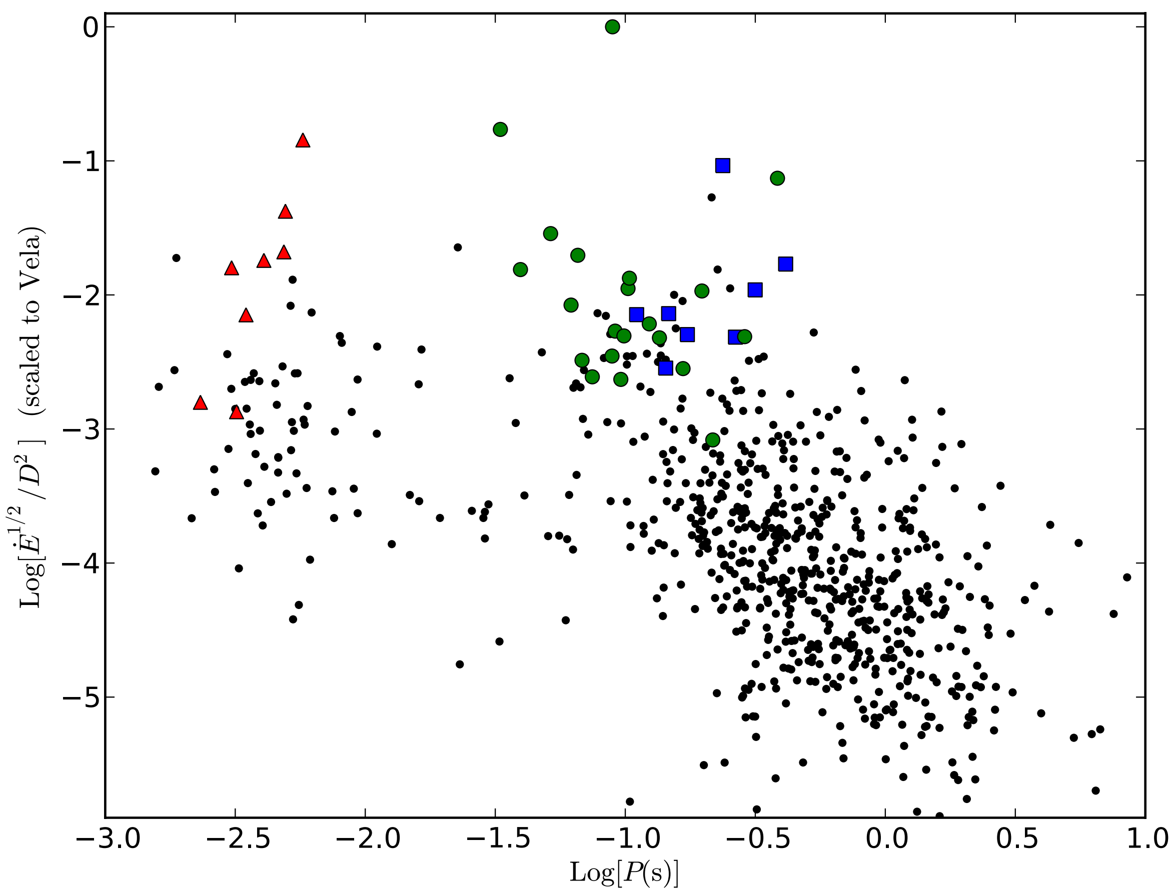


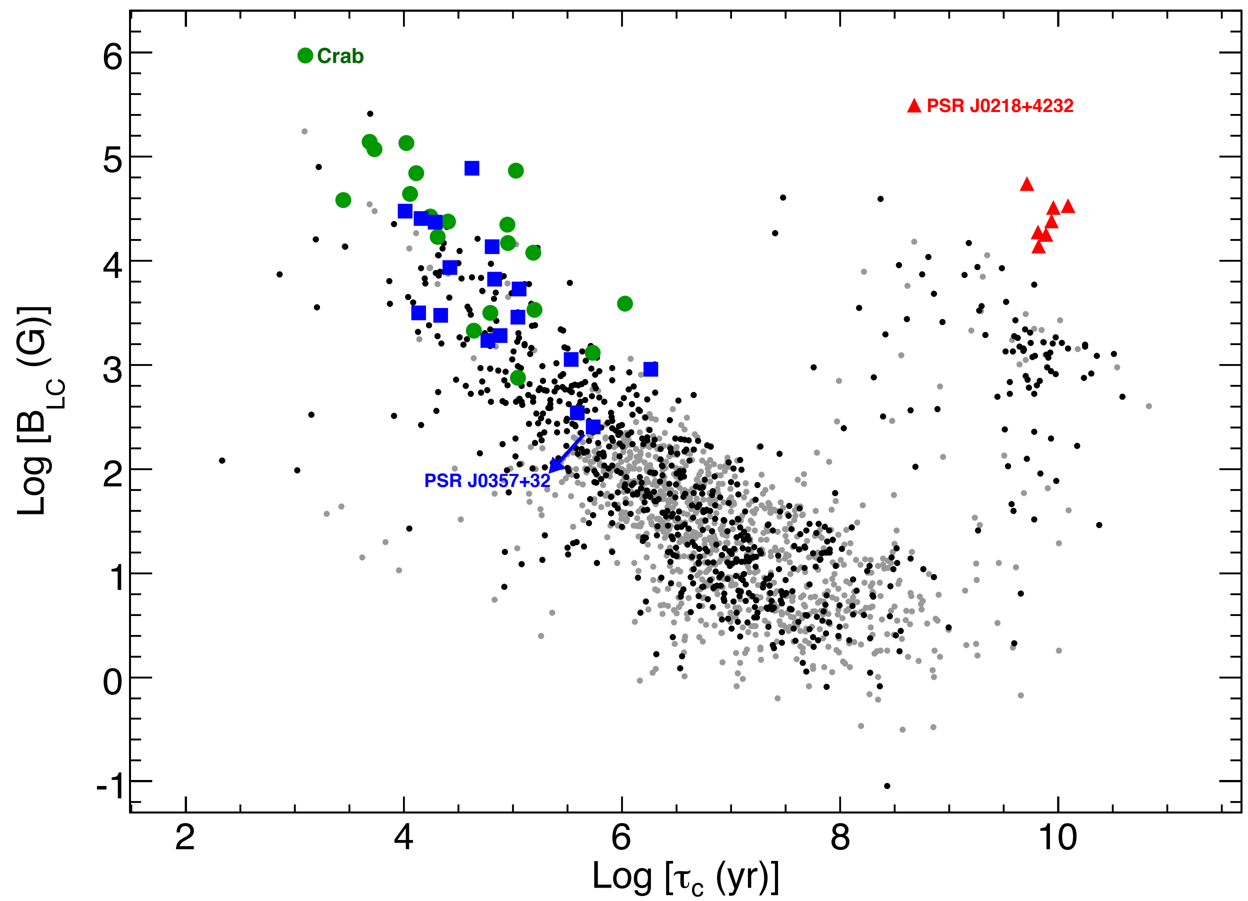
About the LAT-detected Pulsars

- 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?

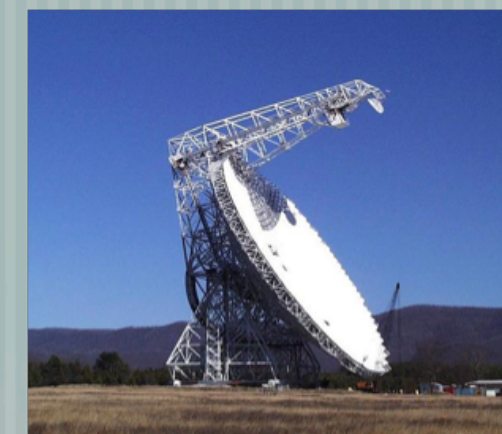




- Mostly seeing high $\dot{E}^{1/2}/D^2$, as expected
- Distance uncertainties dominate, making exceptions a bit tricky to study
- $L\gamma$ relates to $\dot{E}$

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

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

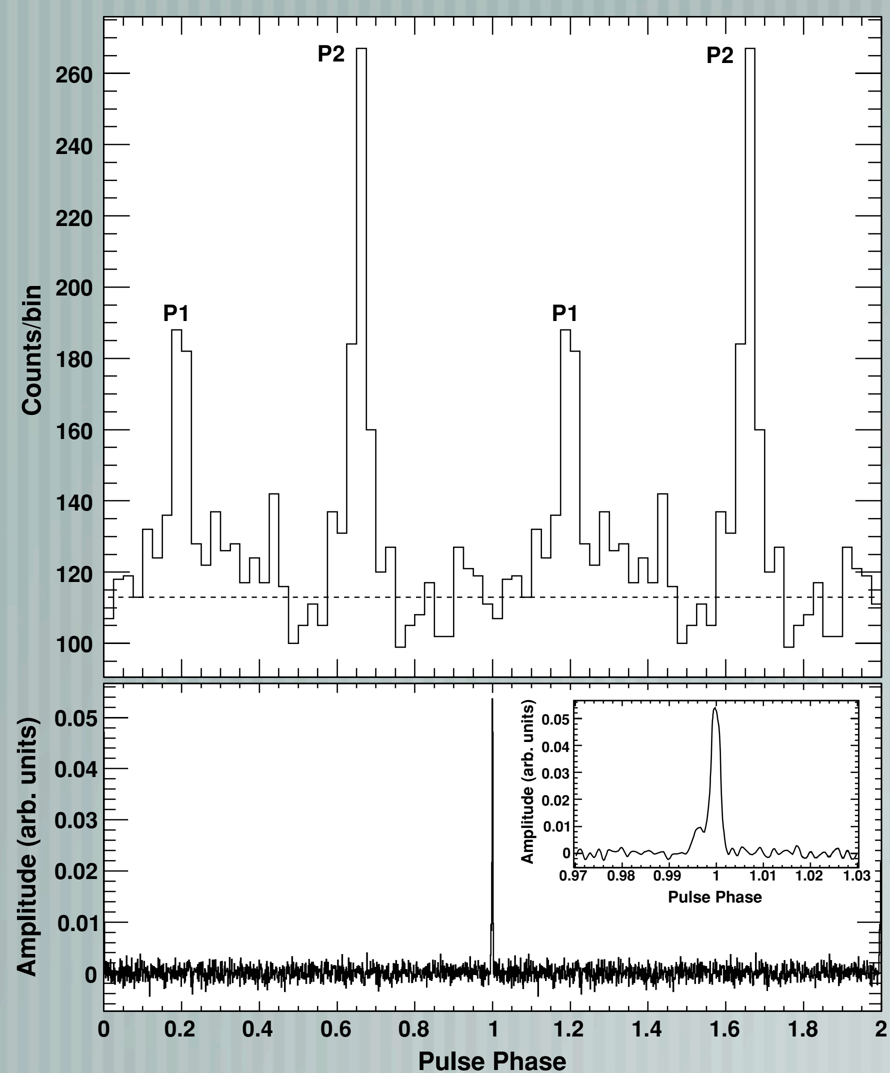
EGRET pulsars with Fermi

- 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.

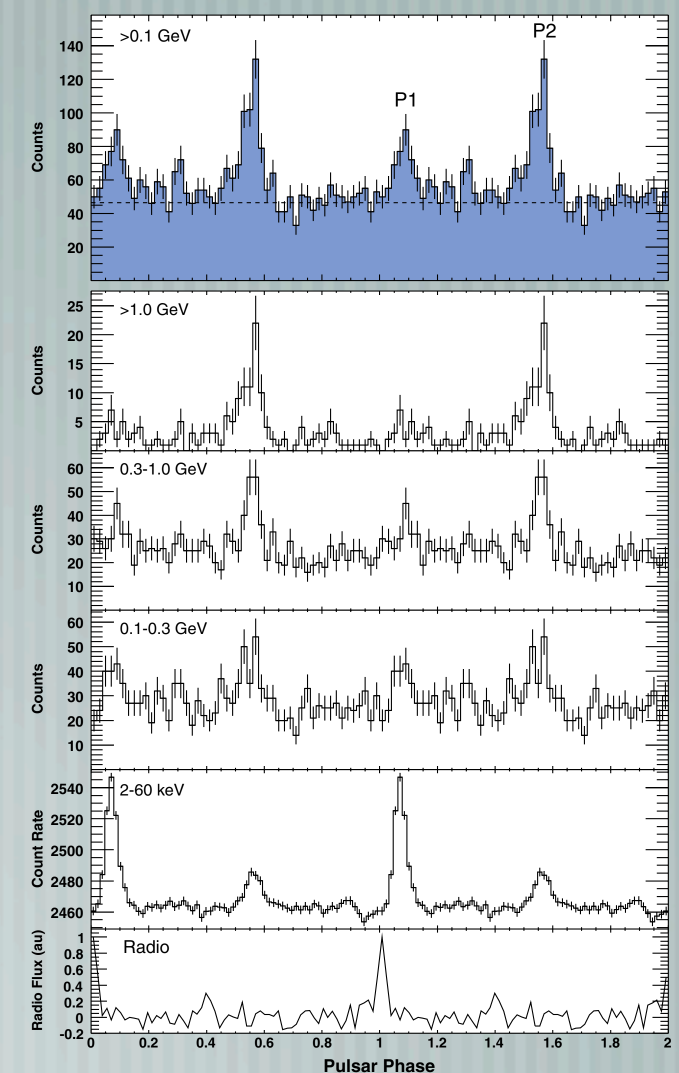
Other Radio/X-ray Pulsars

Fermi Gamma-ray Space Telescope

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



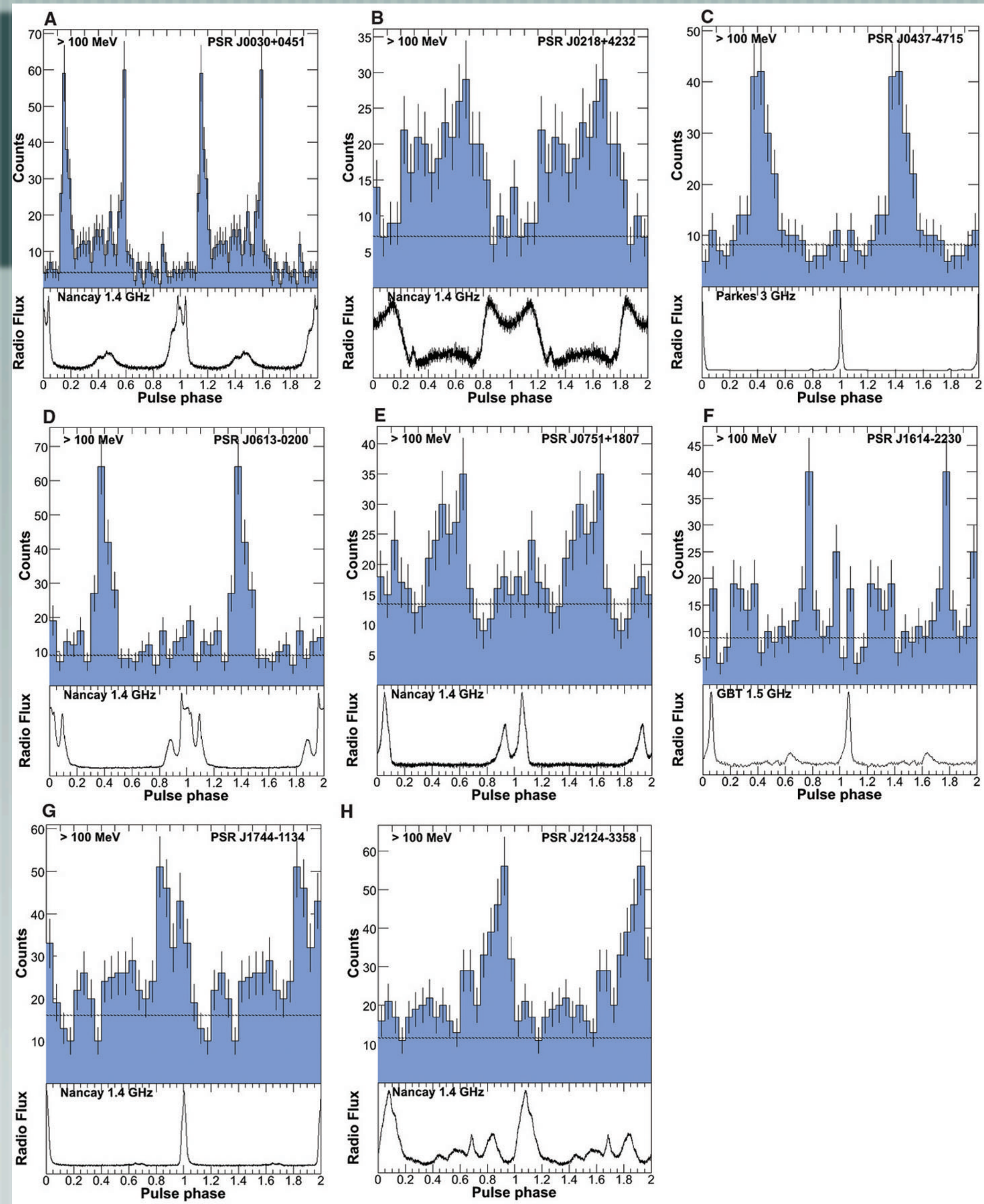
Young (90 kyr) pulsar PSR J1028–5819 discovered in radio search of 3EG J1027-5817
(Abdo et al. 2009 ApJ, 699, L102)



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

Millisecond Pulsars!

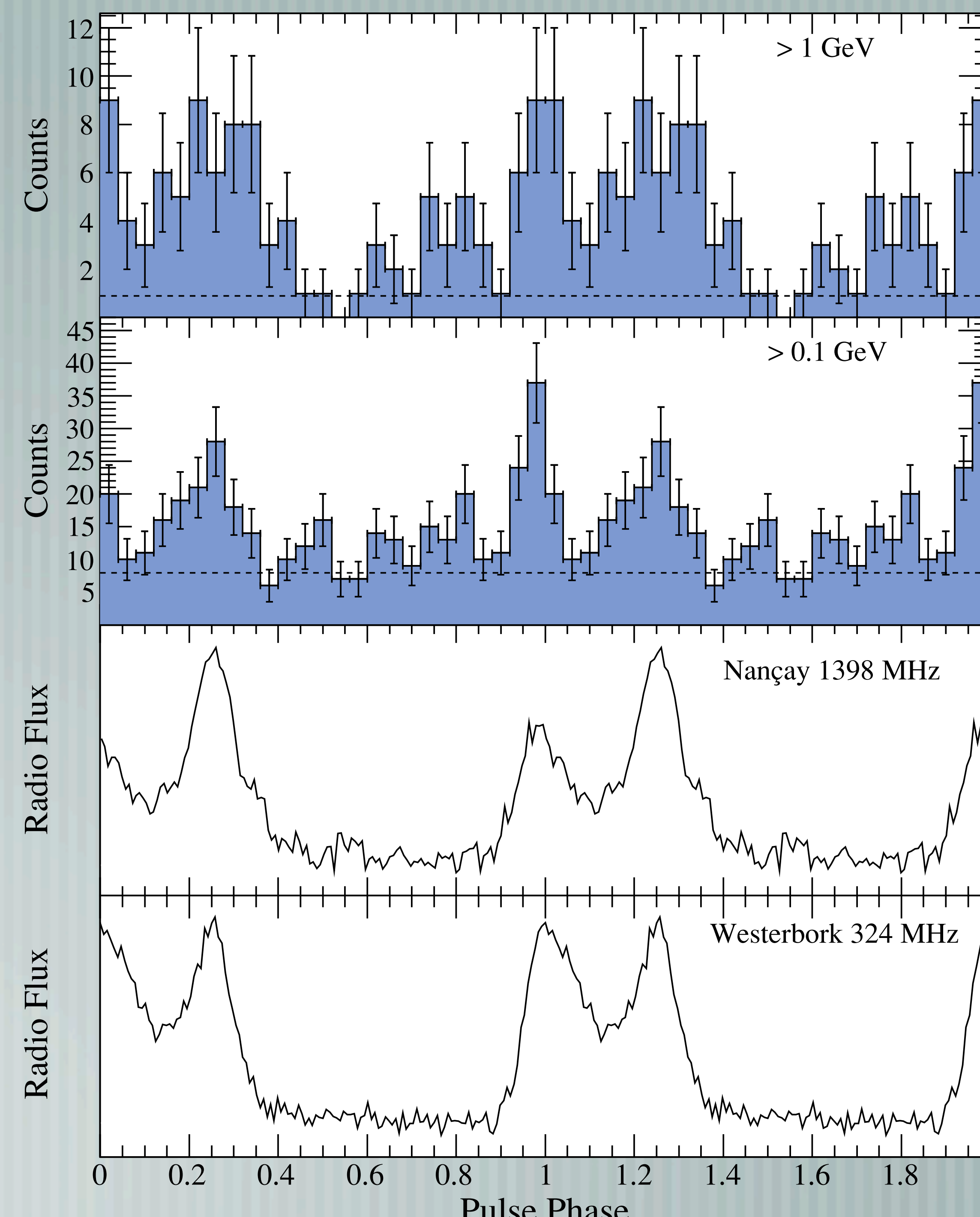
- EGRET had a marginal detection of one MSP (PSR J0218+4232; Kuiper et al. 2000)
- Fermi detected 8 MSPs in first 9 months of data taking
- MSP profiles (peak separation and radio lags) look very much like the young pulsars



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

A 9th MSP: J0034-0534

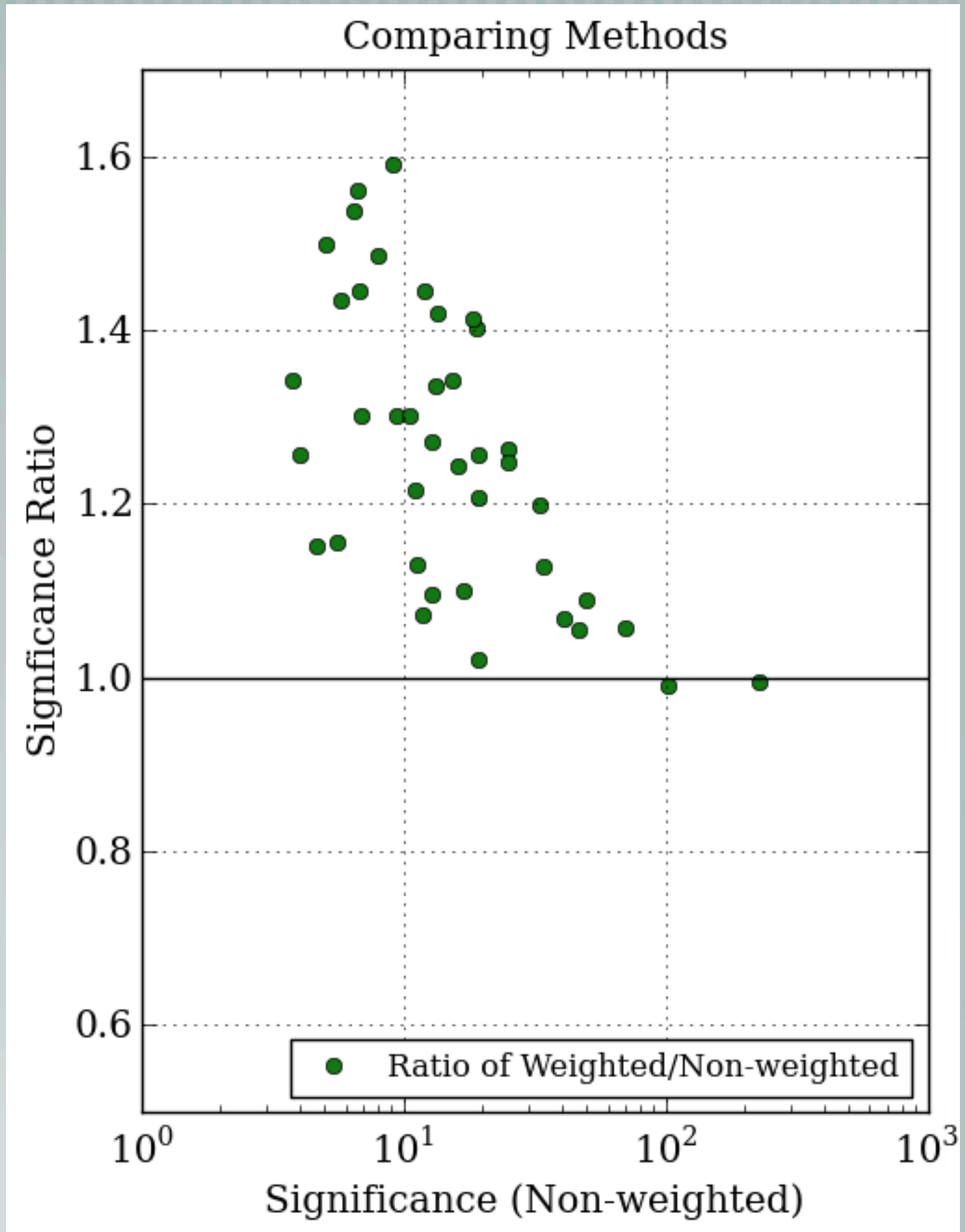
- Two gamma-ray peaks, nearly aligned with the radio profile
  - Resembles the Crab in this way
- Suggests that radio and gamma-ray emission regions may be co-located
- High B_{LC} and seemingly low efficiency



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

New Detections Coming...

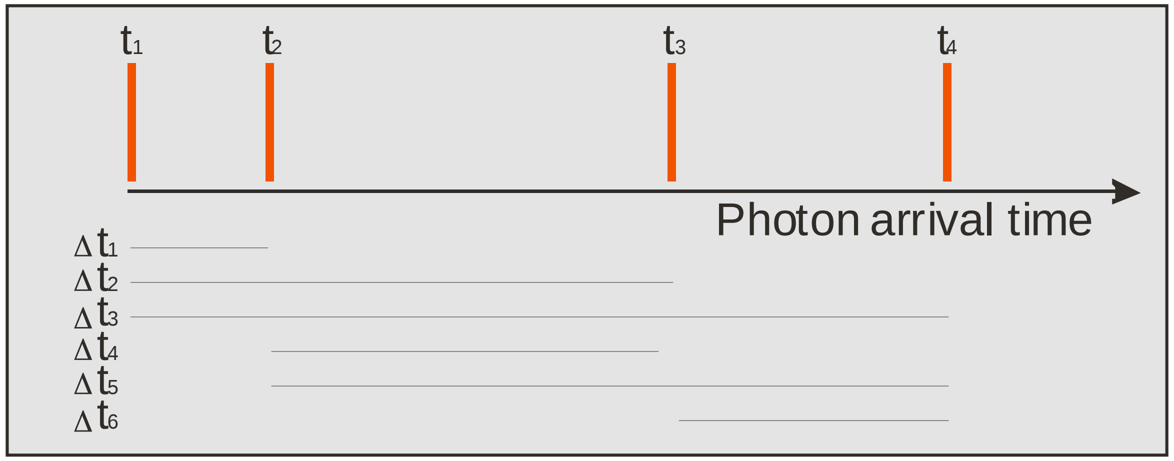
- Most pulsar detections have been done using (unweighted) H-test statistic and trying different ROI and E_{min} cuts
- Improved sensitivity is possible by using photon weighting with weights derived from the maximum likelihood spectral fits of the LAT point sources
- And, LAT data and radio timing models keep coming in...
- 2nd Pulsar Catalog may have 100 pulsars!



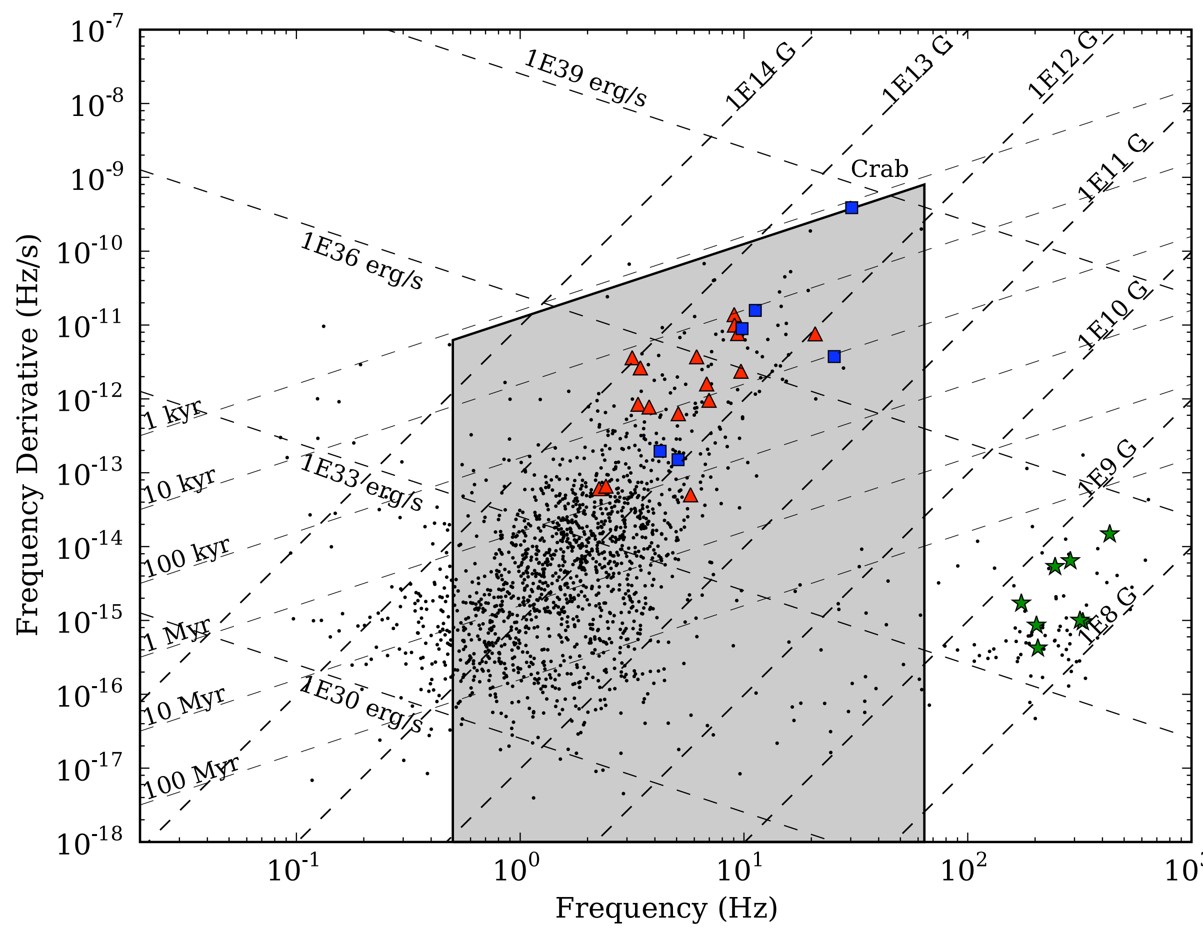
(M. Kerr et al. 2011, ApJ, **732**, 38)

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
- LAT team searched a pre-launch list of ~100 locations of SNR, PWN, or likely NS based on multiwavelength observations
- Then added sources from early versions of the LAT source catalog
- Candidate signals are then verified and optimized using narrow epoch-folding searches

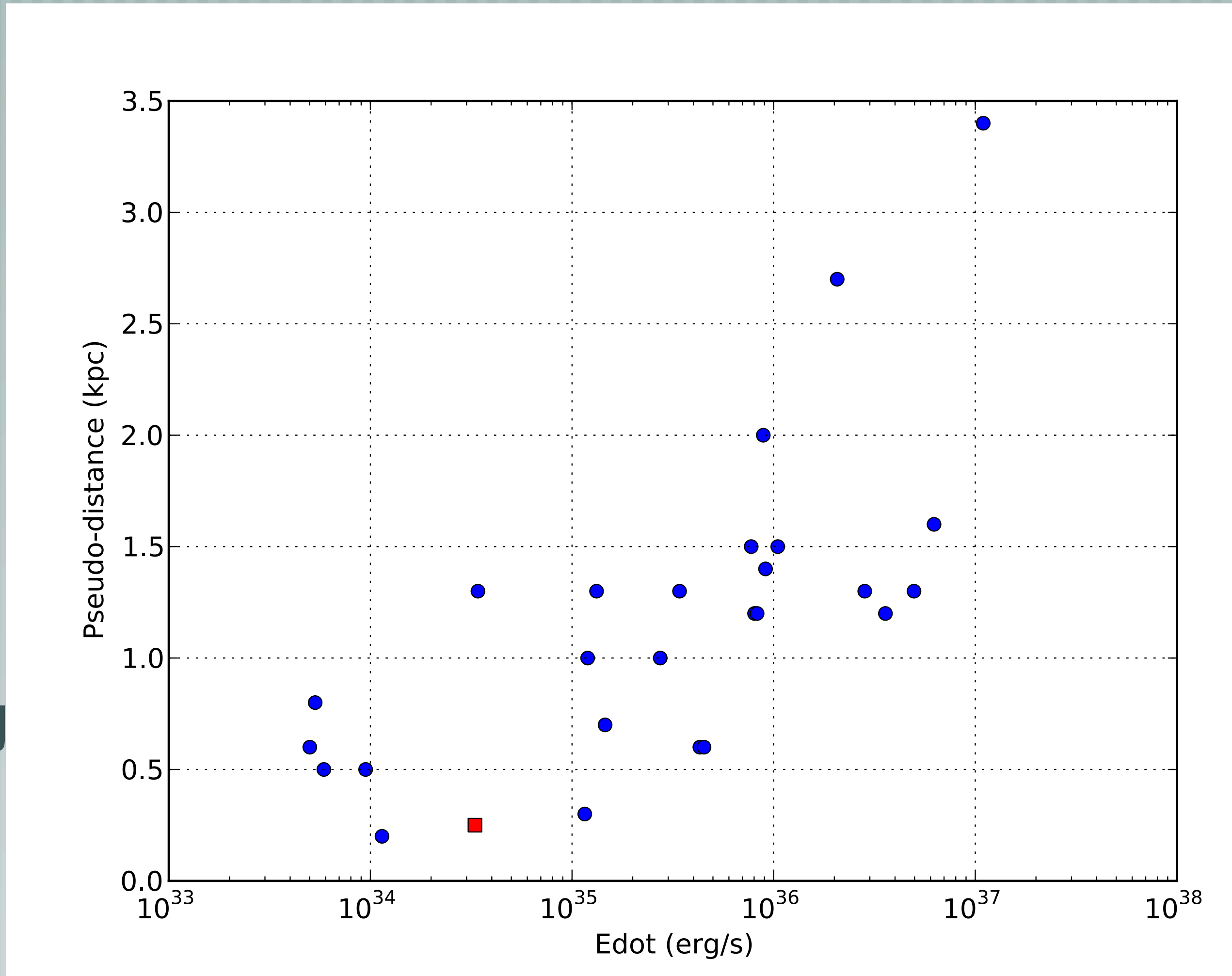


Credit: M. Ziegler



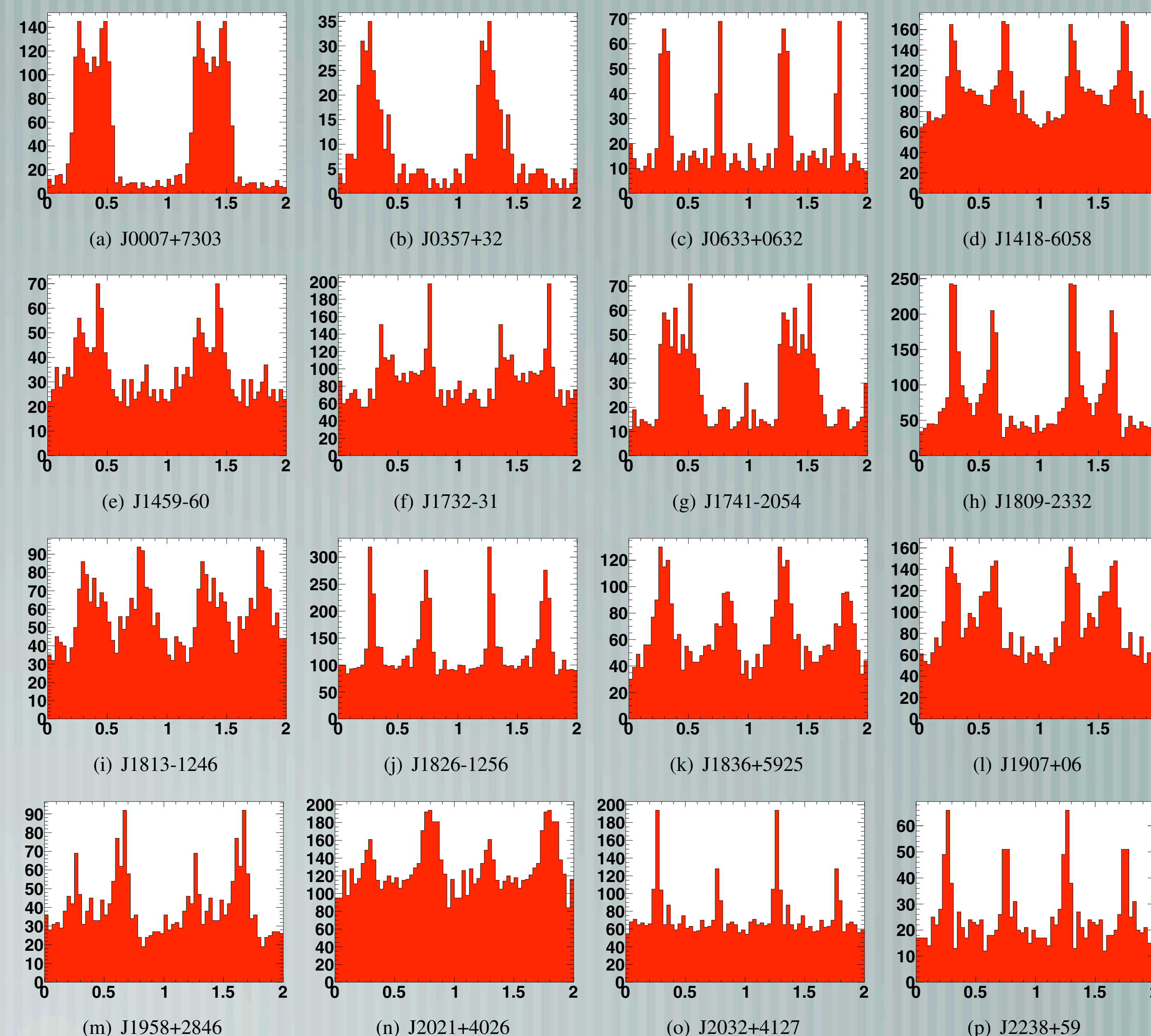
Blind Search Pulsars

- Blind searches of LAT data allow us to find pulsars where the radio beam might not be pointed at us
- 24 discovered in first year of survey data (Abdo et al. 2009, Saz Parkinson et al. 2010)
- 2 new ones in searches of two years of survey data
    - It is getting harder, but more discoveries will be coming
- Science questions: Are they really radio quiet? What is the beaming fraction in gamma-ray vs. radio?
- Pulsar Search Consortium has searched all for radio emission
    - Deep observations at GBT, Parkes, and Arecibo



Sixteen Pulsars Discovered in 6 Months

- 6/16 found using well localized counterparts at other wavelengths including some long suspected of being pulsars (e.g. CTA1, 3EG J1835-5918)
- 13/16 associated with an EGRET unidentified source
- Frequencies from 2.25 – 20.8 Hz
- $\dot{E}$ from 5 x 10^{33} – 6 x 10^{36} erg/s

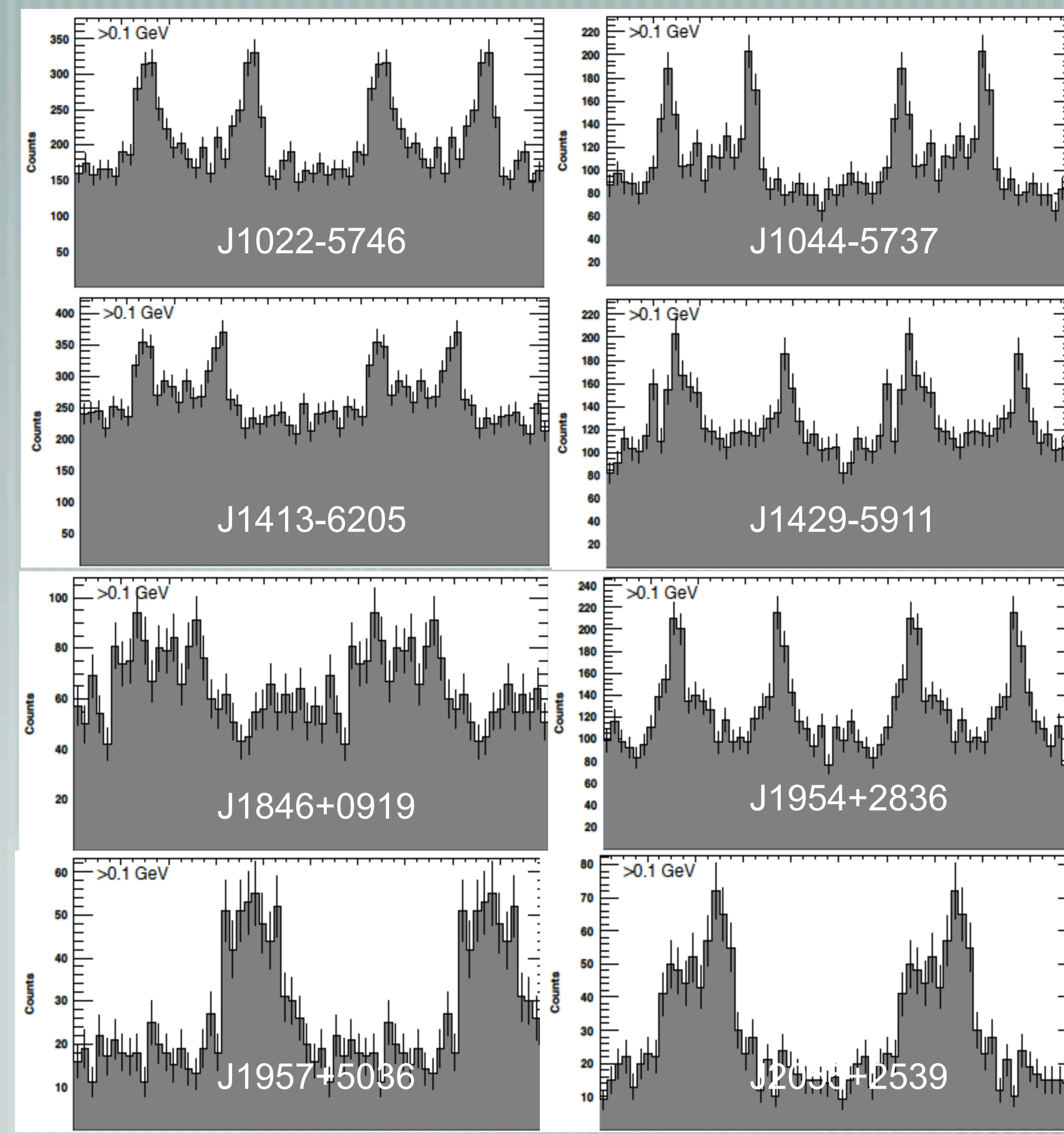


(Abdo et al. 2009, Science, **325**, 840)

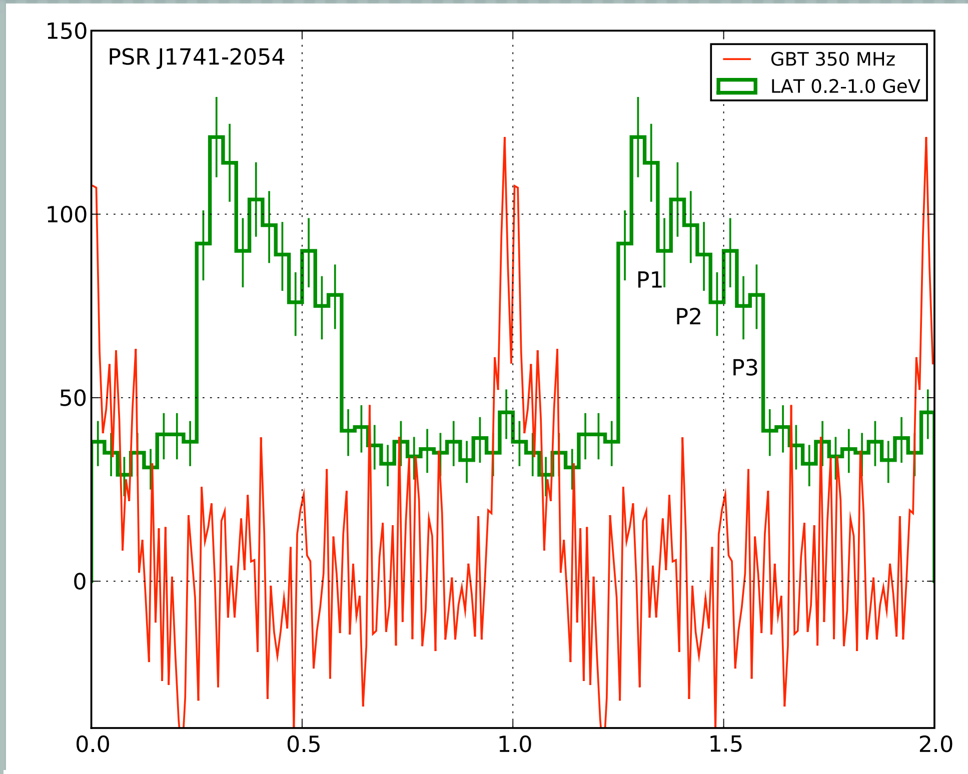
8 new blind search pulsars!

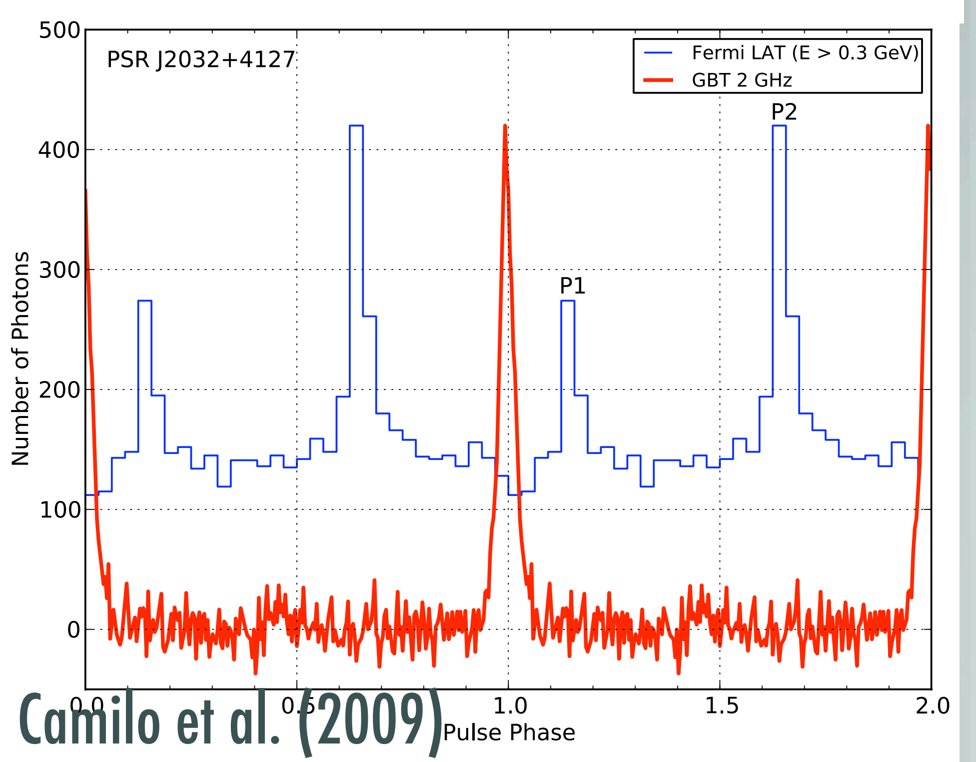
- New pulsars, mostly found in new LAT unidentified sources (only 1 in EGRET source)
- 5 young and energetic
  - 1 very energetic and associated with HESS source
- 2 old (~1 Myr) and off the plane

(Saz Parkinson et al. 2010, ApJ, **725**, 571)

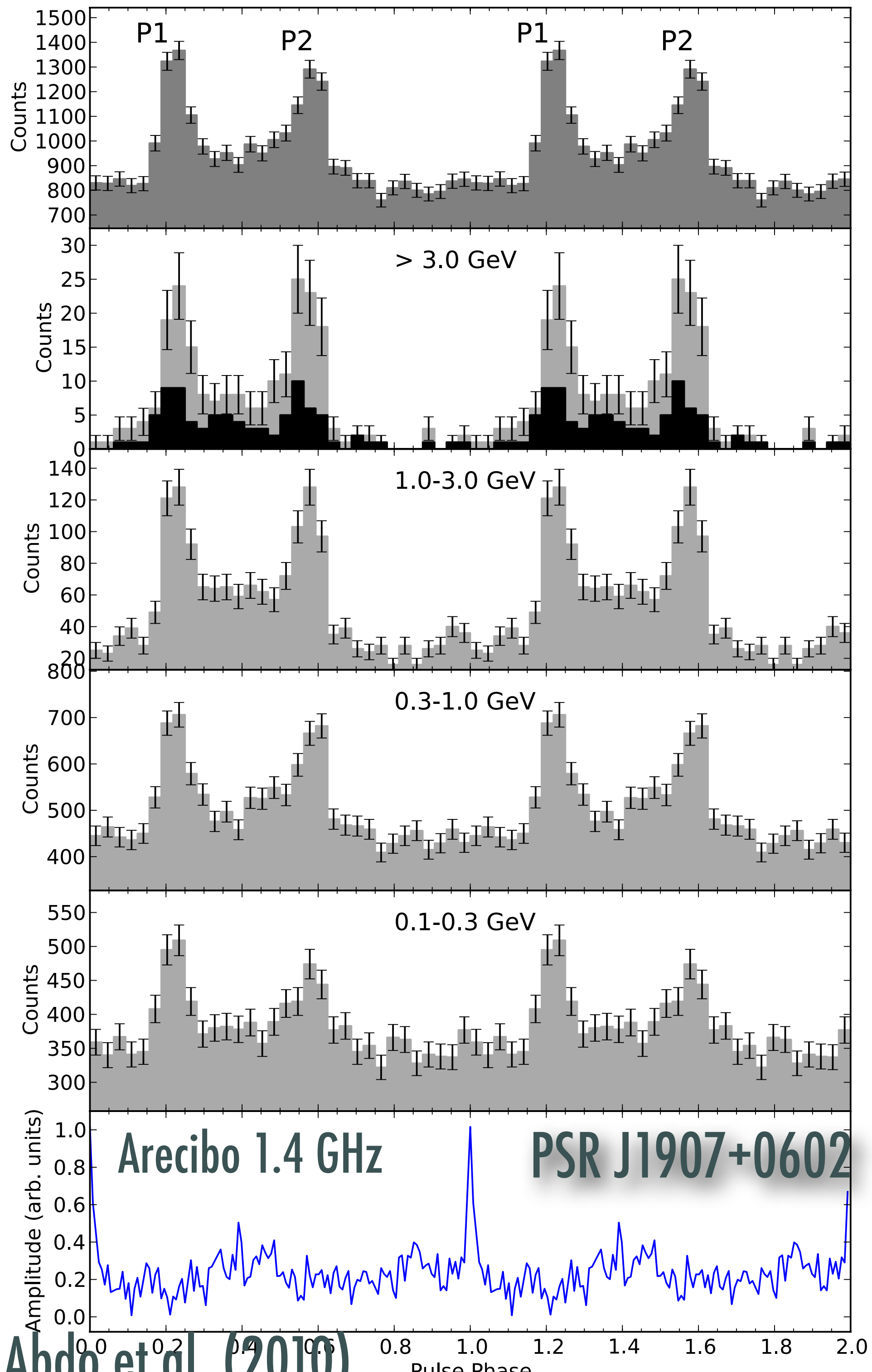


Three Discoveries of Radio Pulsations



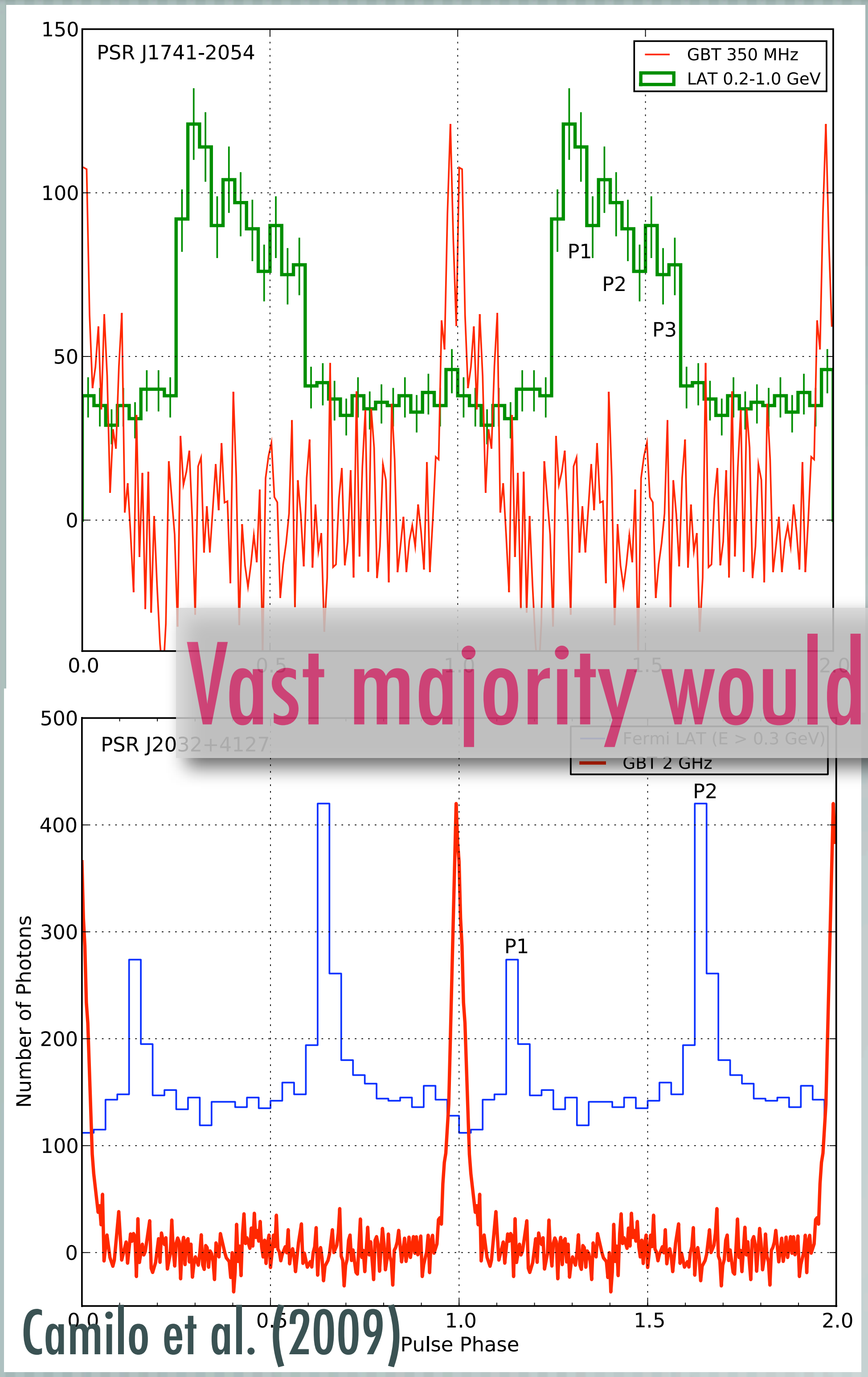


Camilo et al. (2009)

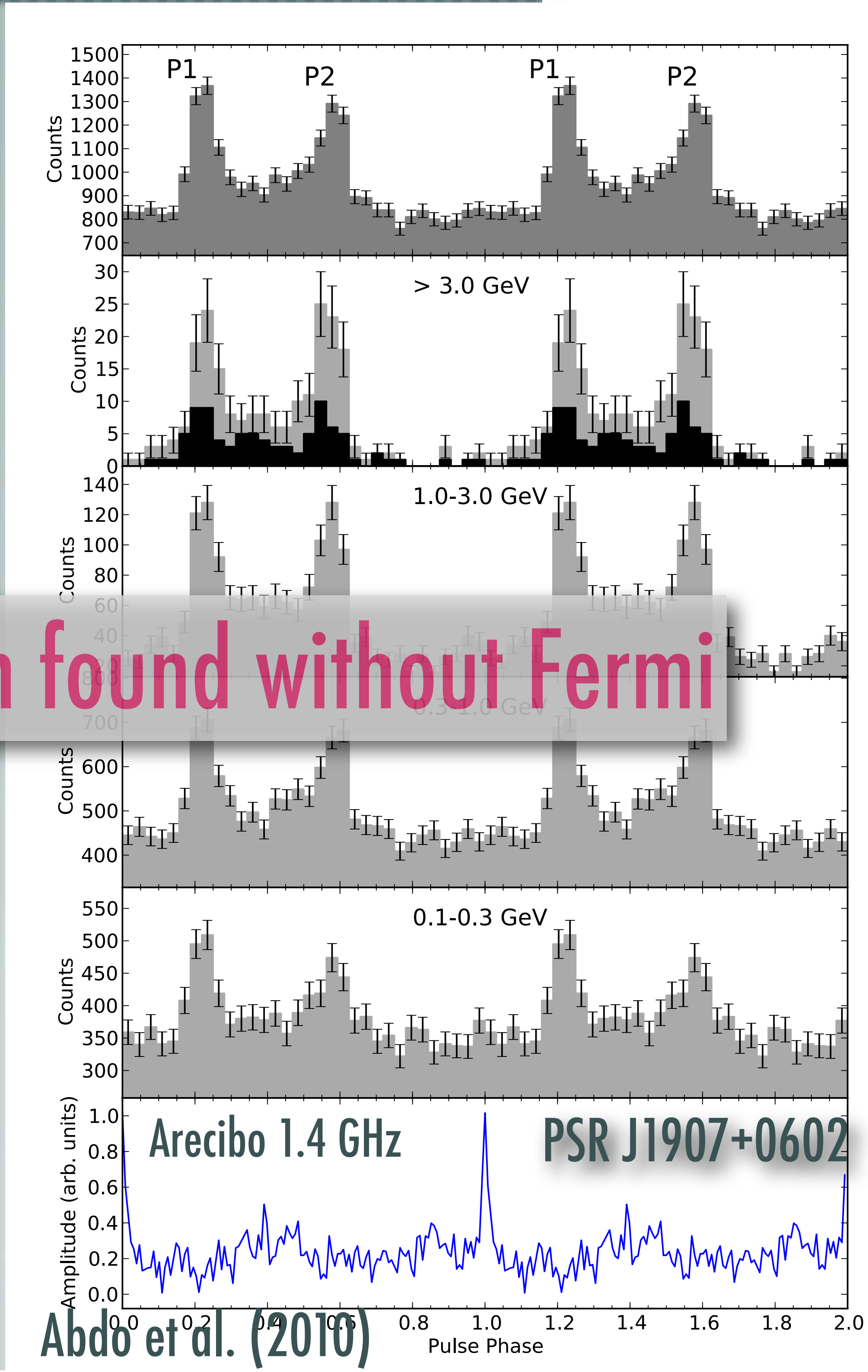


Abdo et al. (2010)

Three Discoveries of Radio Pulsations



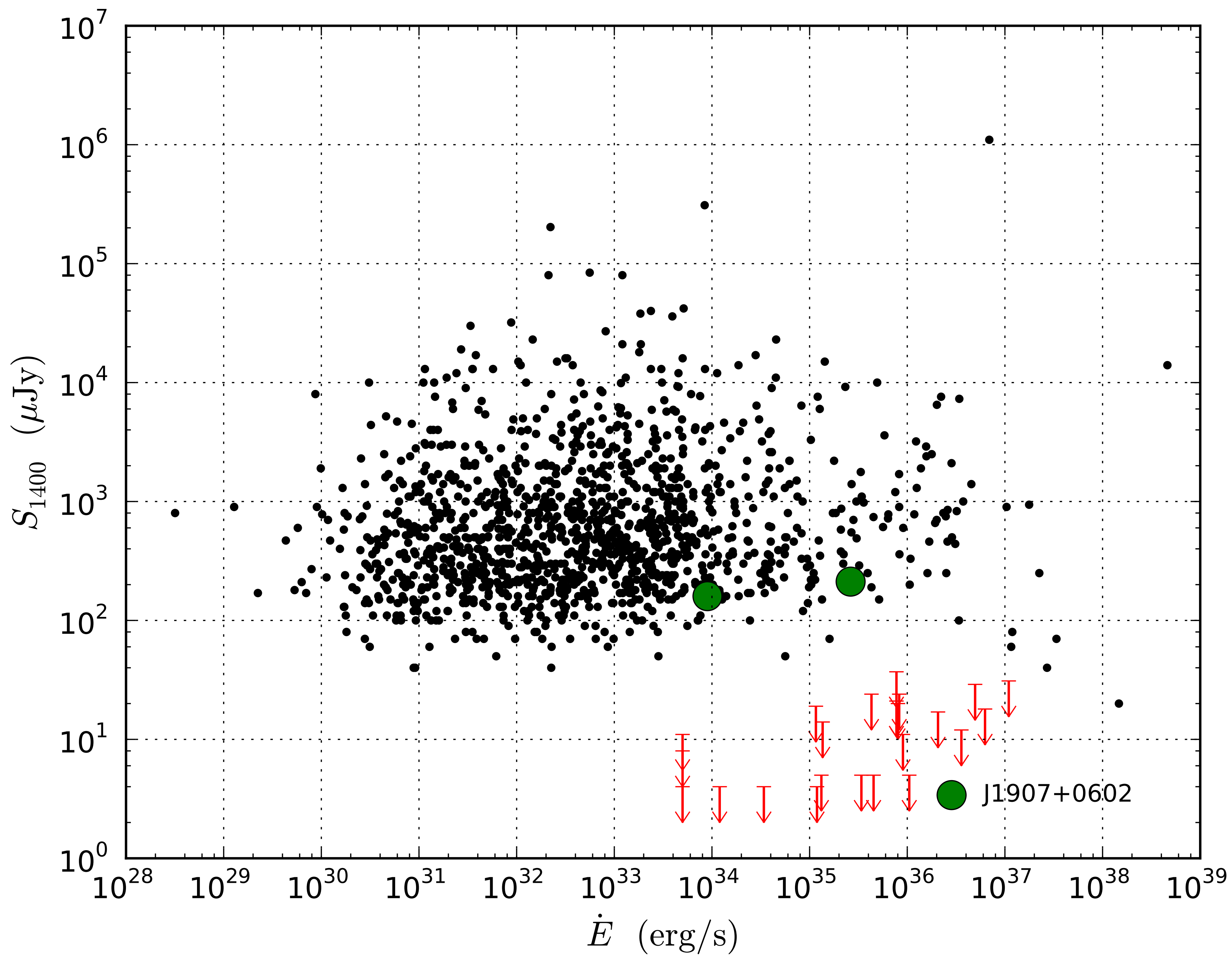
Camilo et al. (2009)



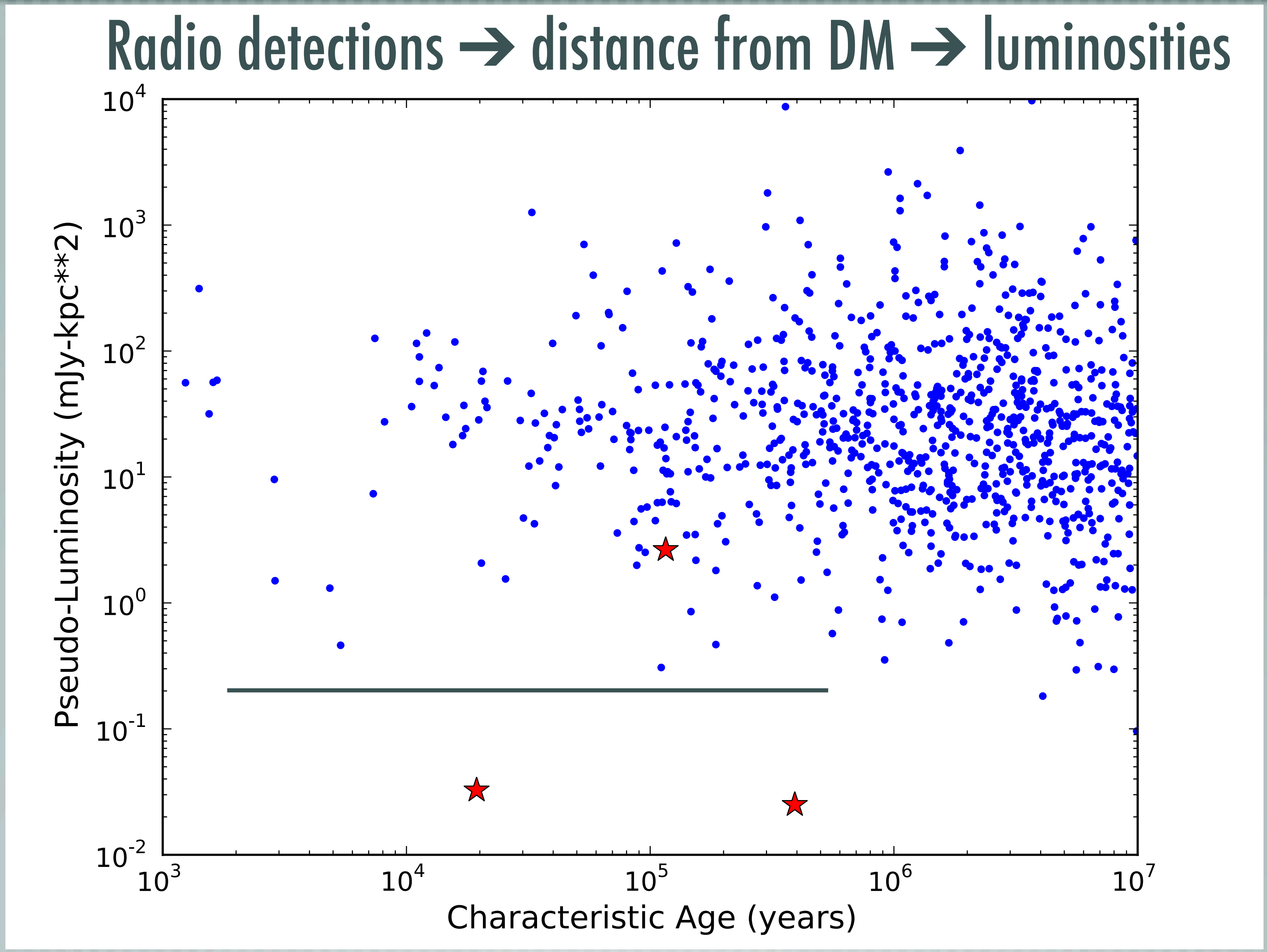
Abdo et al. (2010)

Vast majority would never have been found without Fermi

Radio Fluxes and Upper Limits



Radio Luminosities: How Faint is Faint?

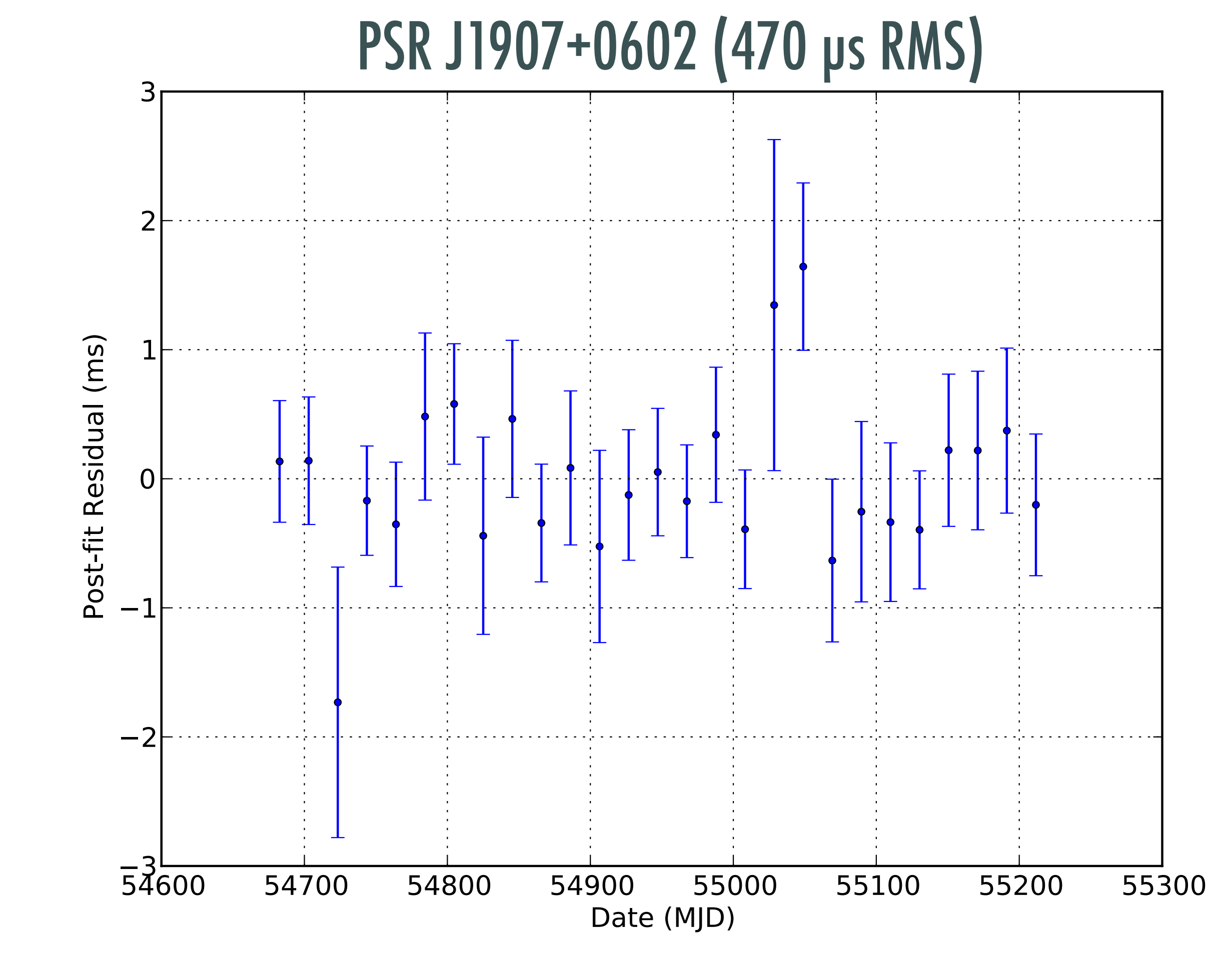


Interesting note: Geminga has a claimed detection at very low frequency (Malofeev & Malov, 1997).
There is a renaissance in low frequency radio astronomy in progress, led by LOFAR, so confirmation and/or other discoveries are possible!

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)

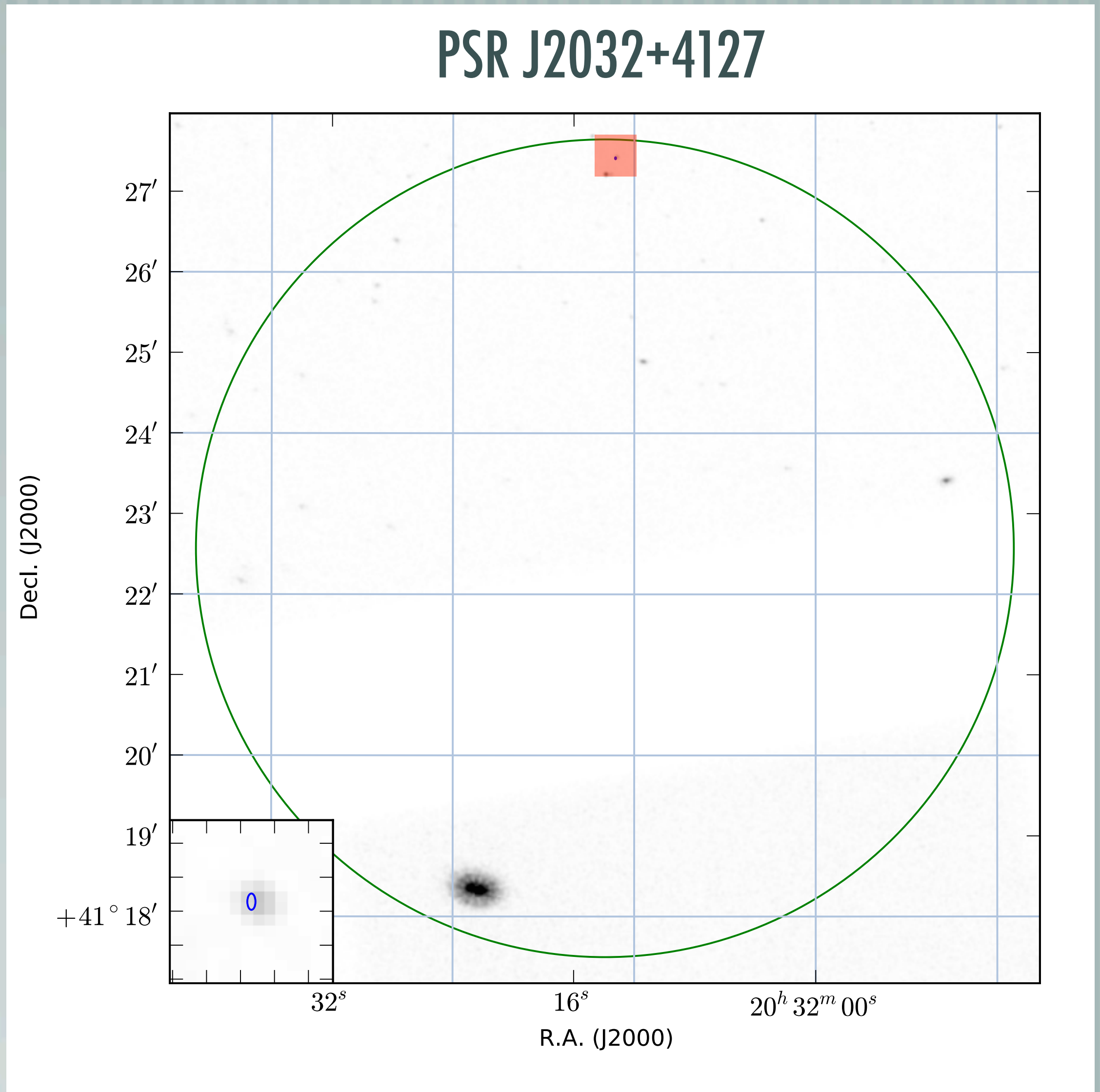


Models posted online:

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

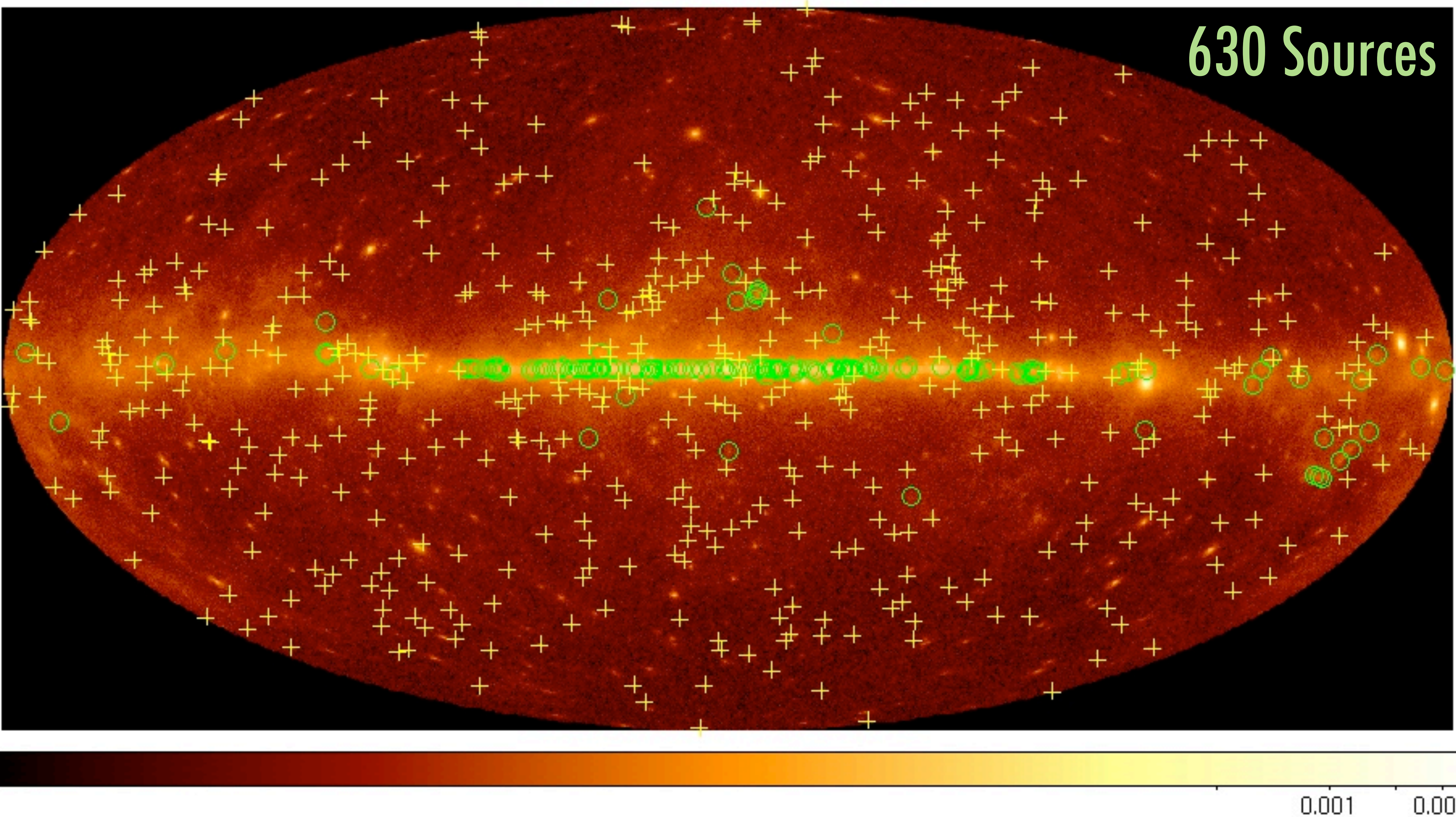
The Power of Timing

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



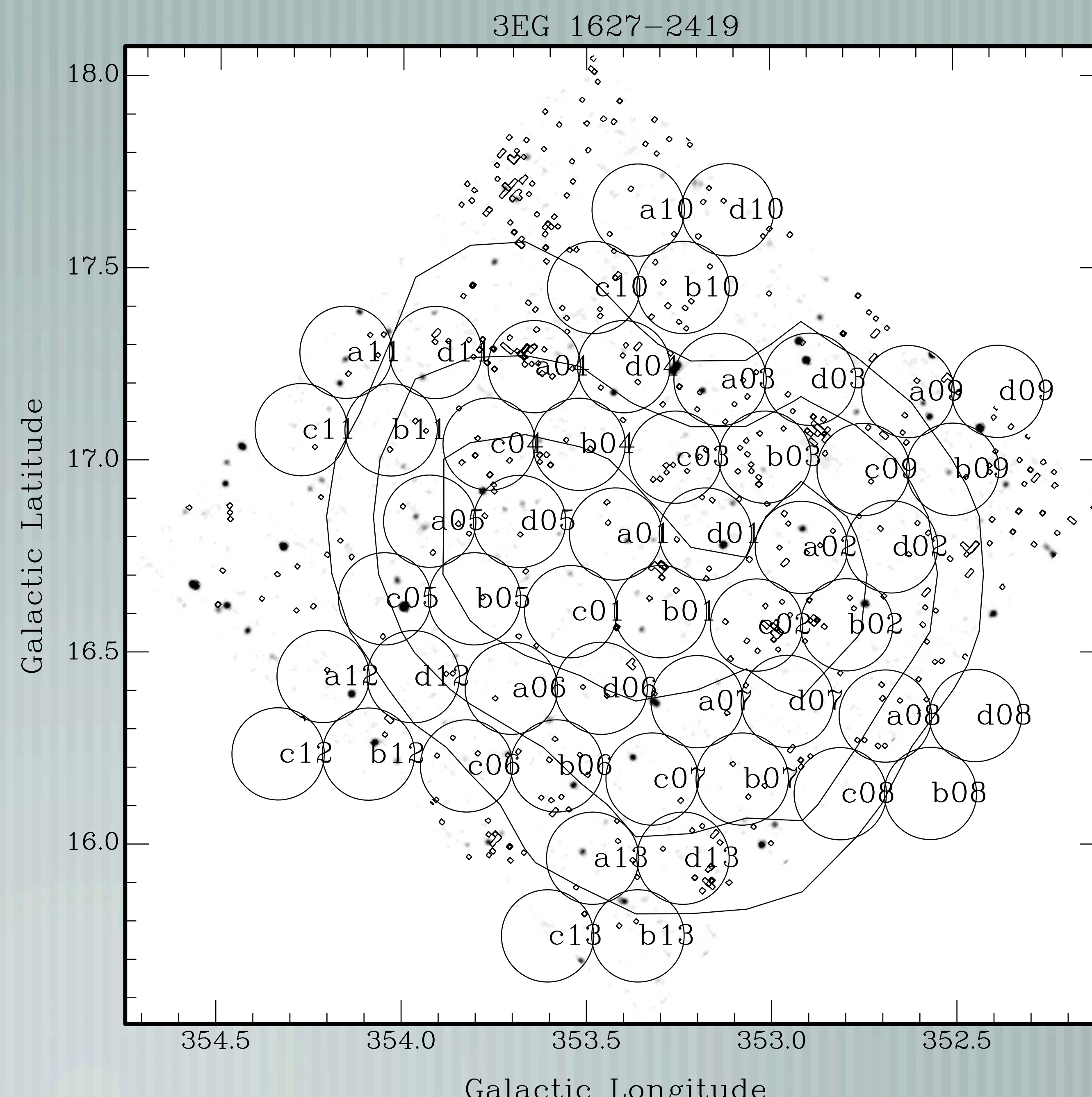
Green circle is LAT Bright Source List position
Blue ellipse in inset is timing position

Unassociated Sources



Gamma-ray Sources as Pulsar Search Targets

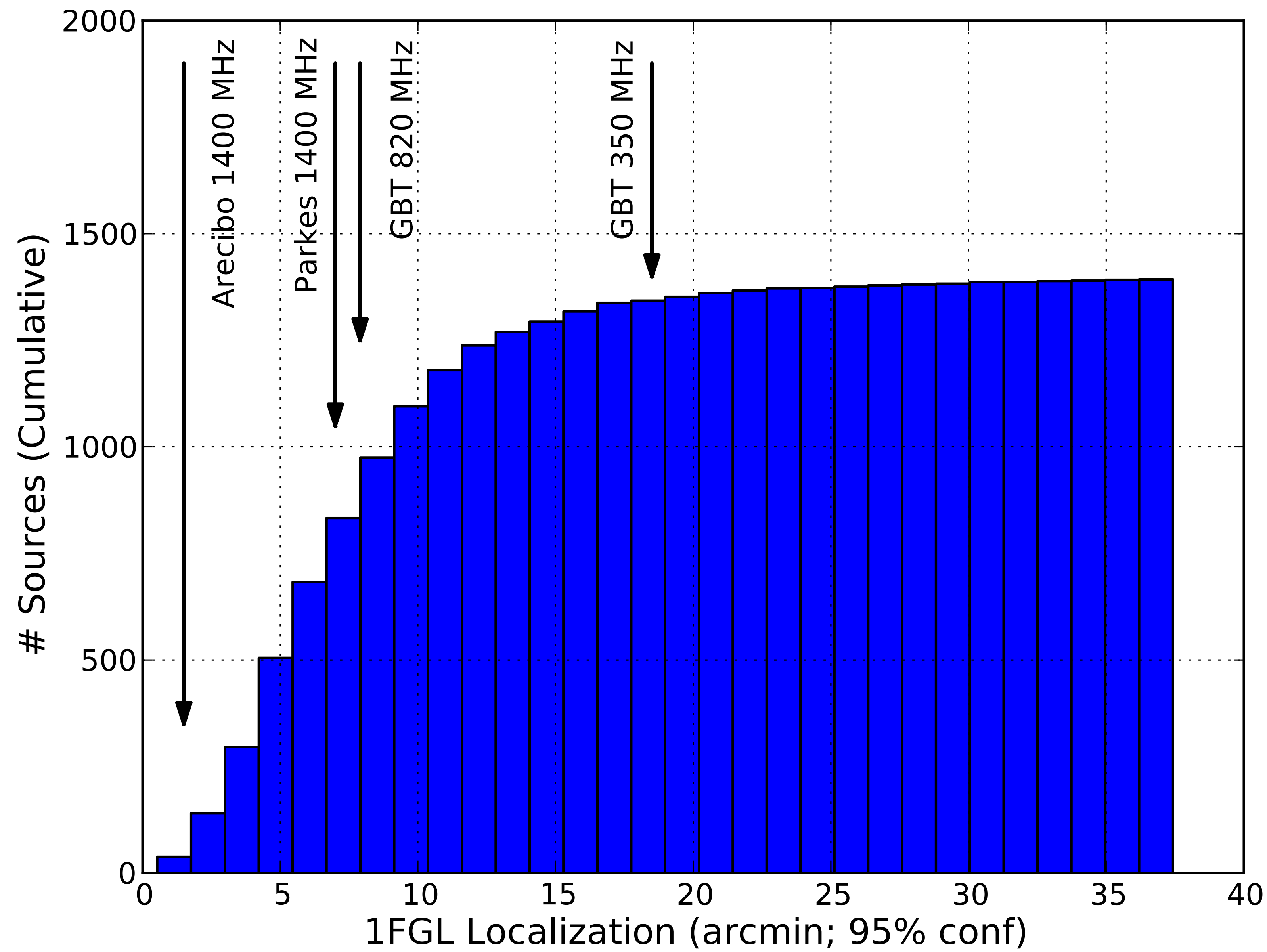
- Many searches were done of EGRET unidentified sources
- Lots of effort with modest success
- Hampered by poor localizations



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

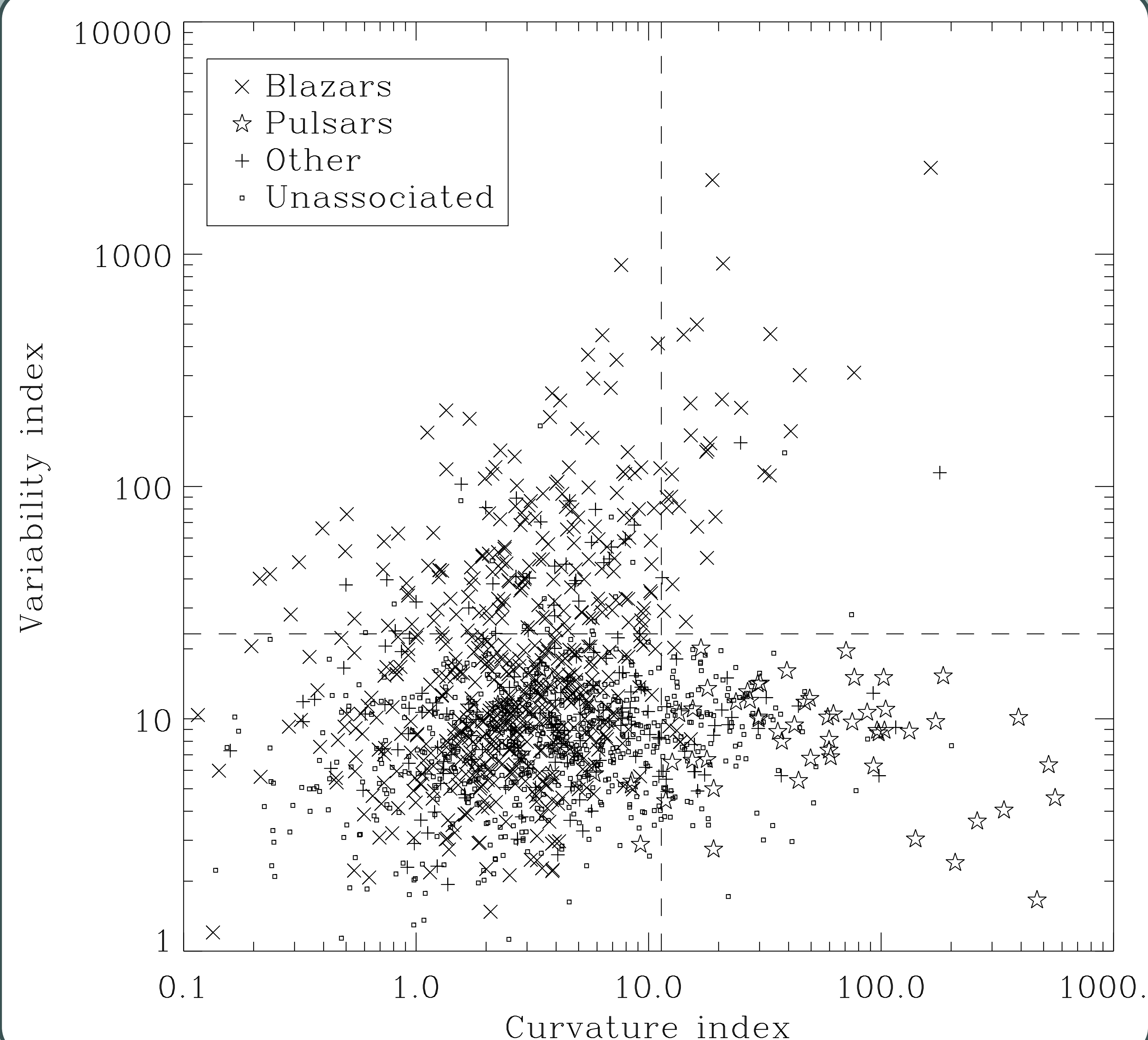
LAT Sources as Pulsar Search Targets

- 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)



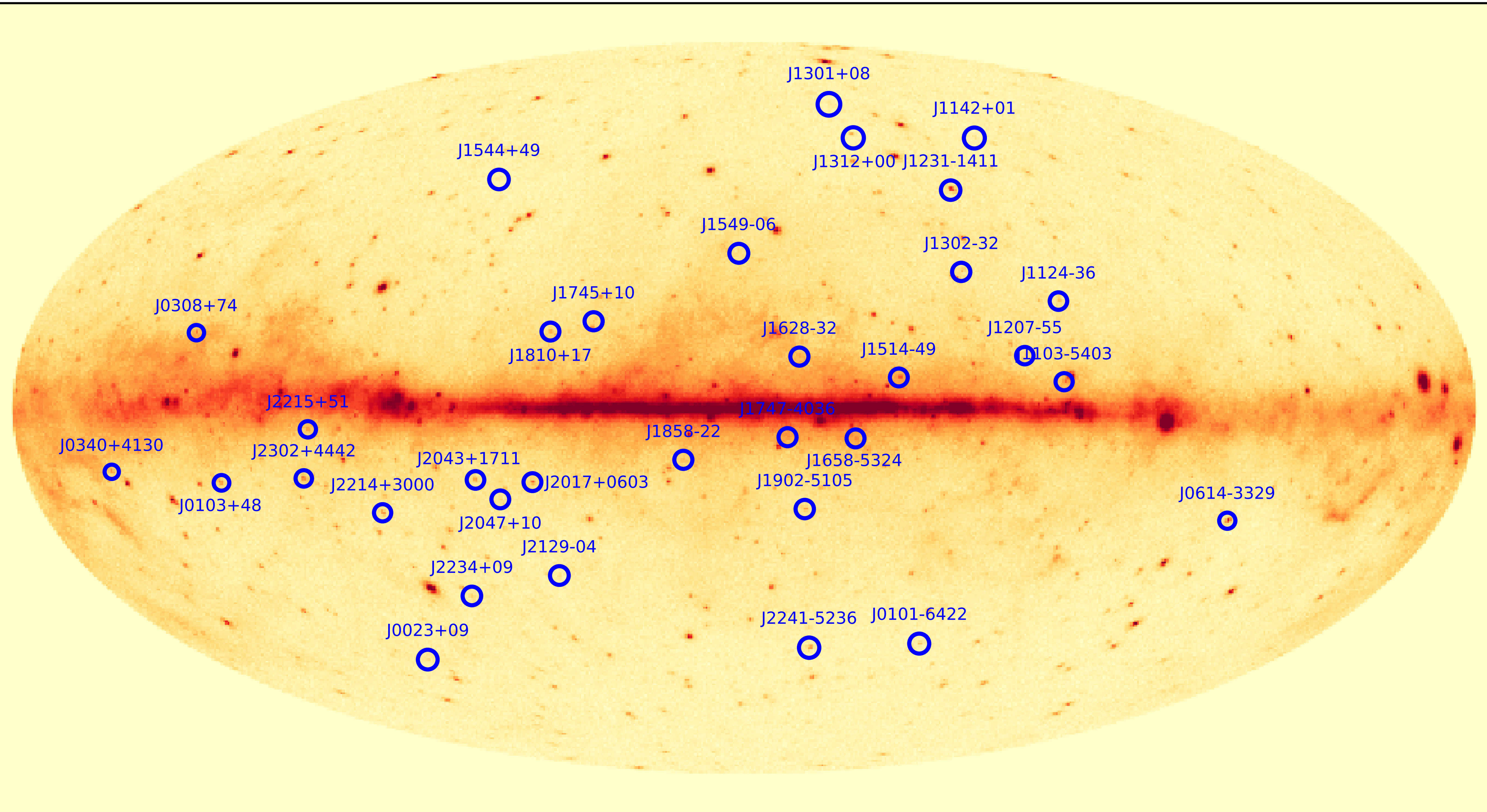
Using LAT to Find Radio Pulsars

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

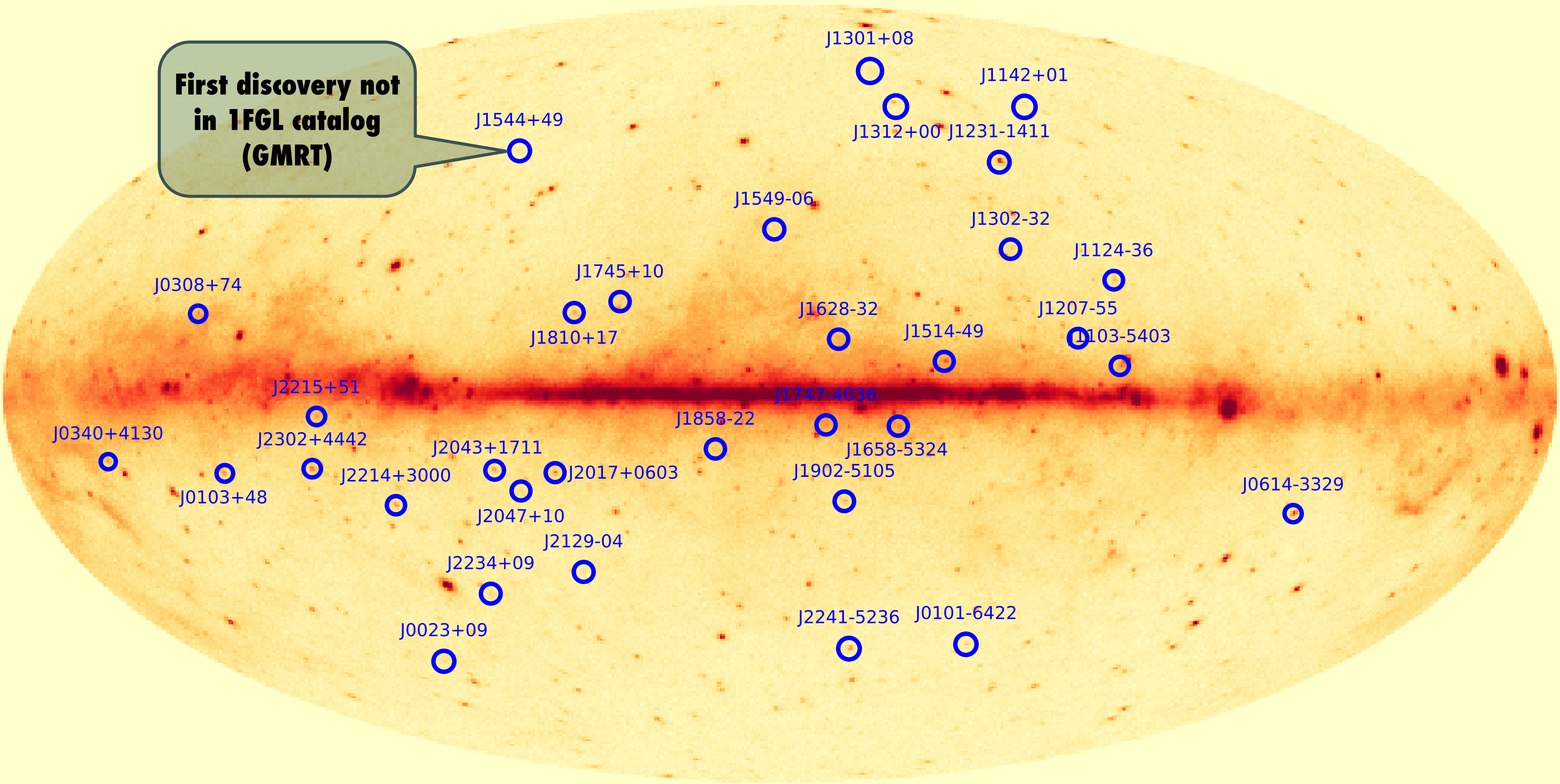


(Abdo et al. 2010, ApJS, **188**, 405)

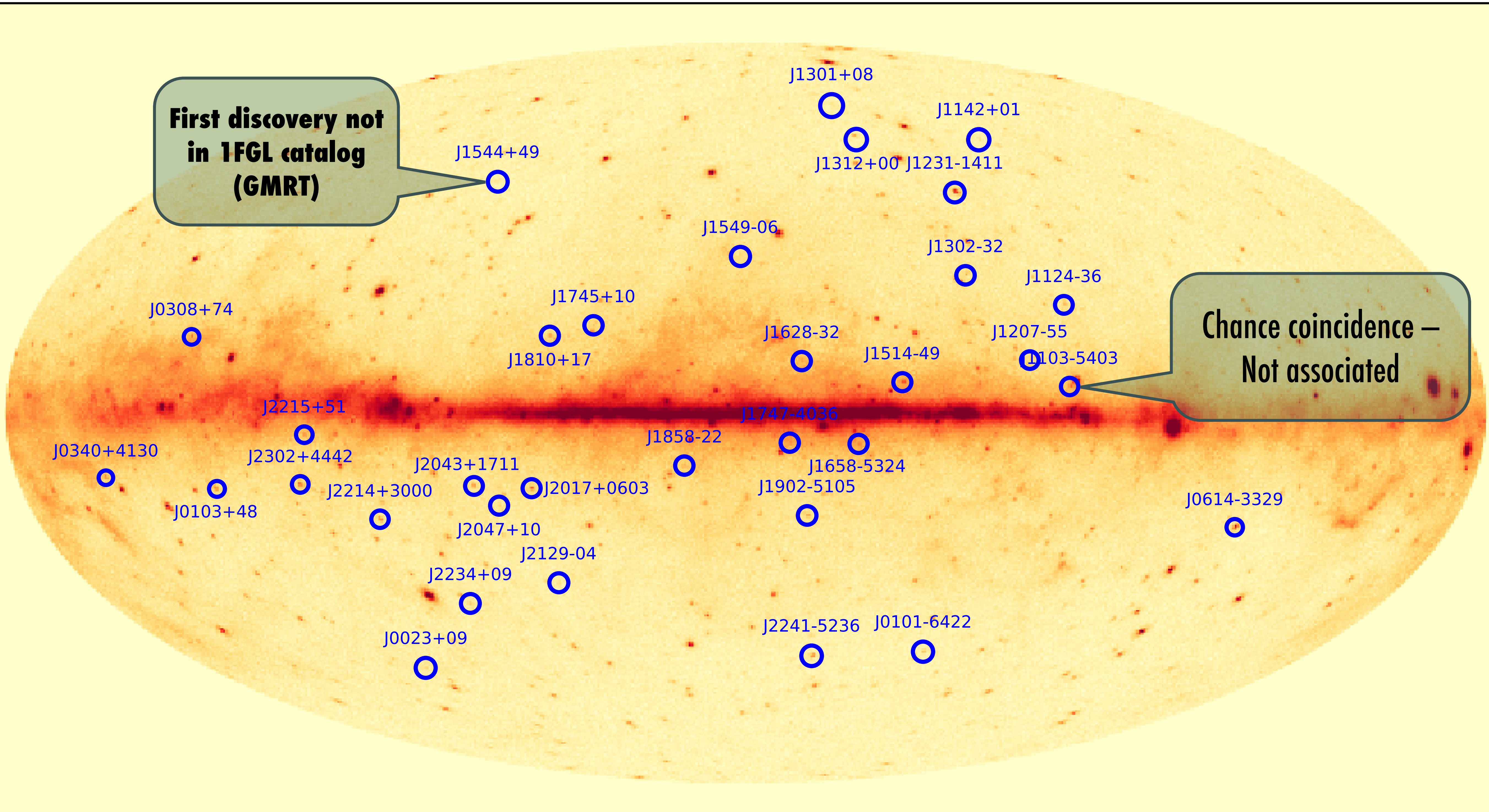
Success! 33 MSPs found!



Success! 33 MSPs found!



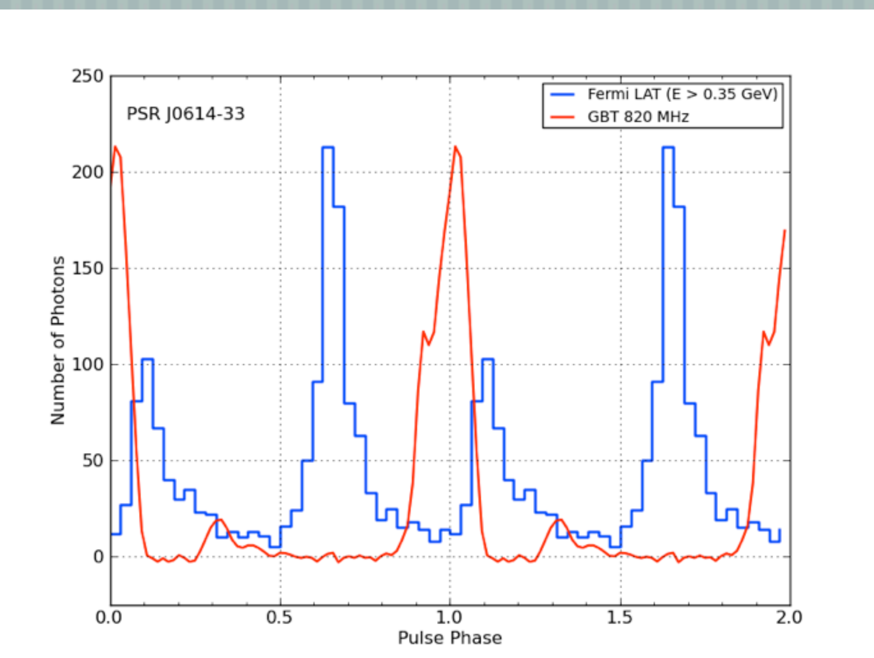
Success! 33 MSPs found!

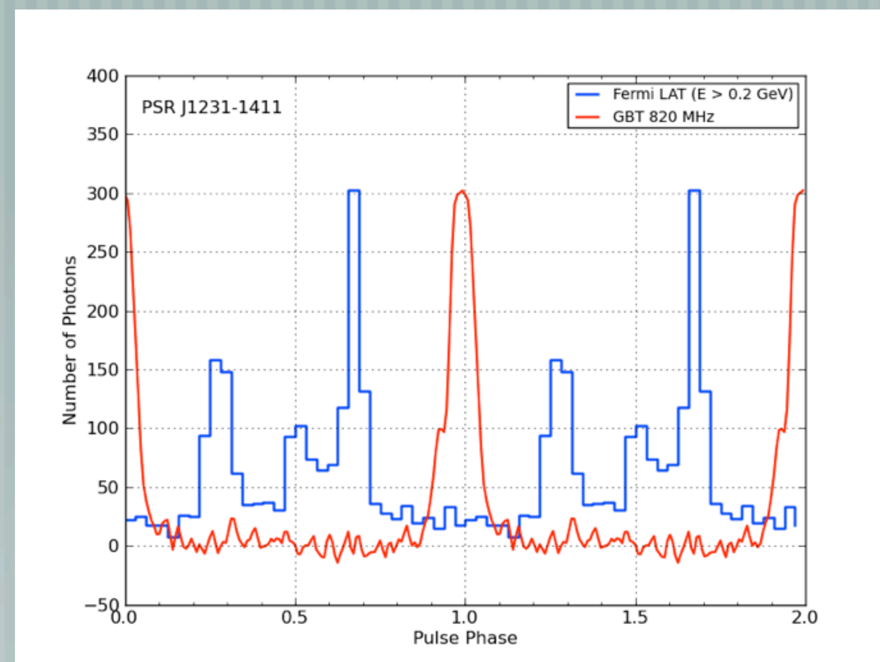


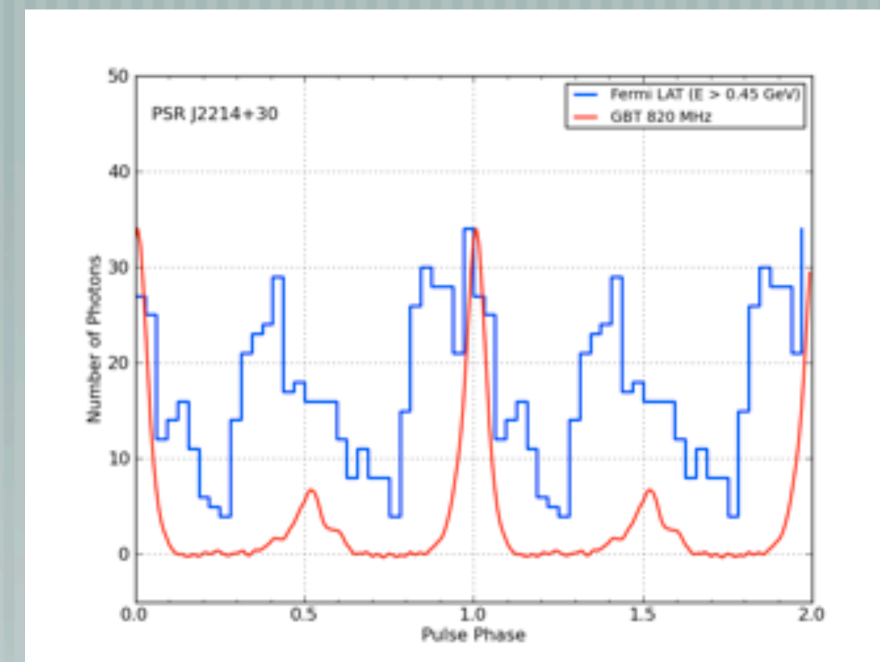
Exciting Discoveries

- **Many** unassociated high-Galactic latitude sources that are non-variable are millisecond pulsars!
- At least **nine** 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 **two** new "Redbacks" that are eclipsing but with a more massive companion (~0.2 Msun). Probably a cousin 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 one chance coincidence)

Twelve 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 longer

Future Expectations

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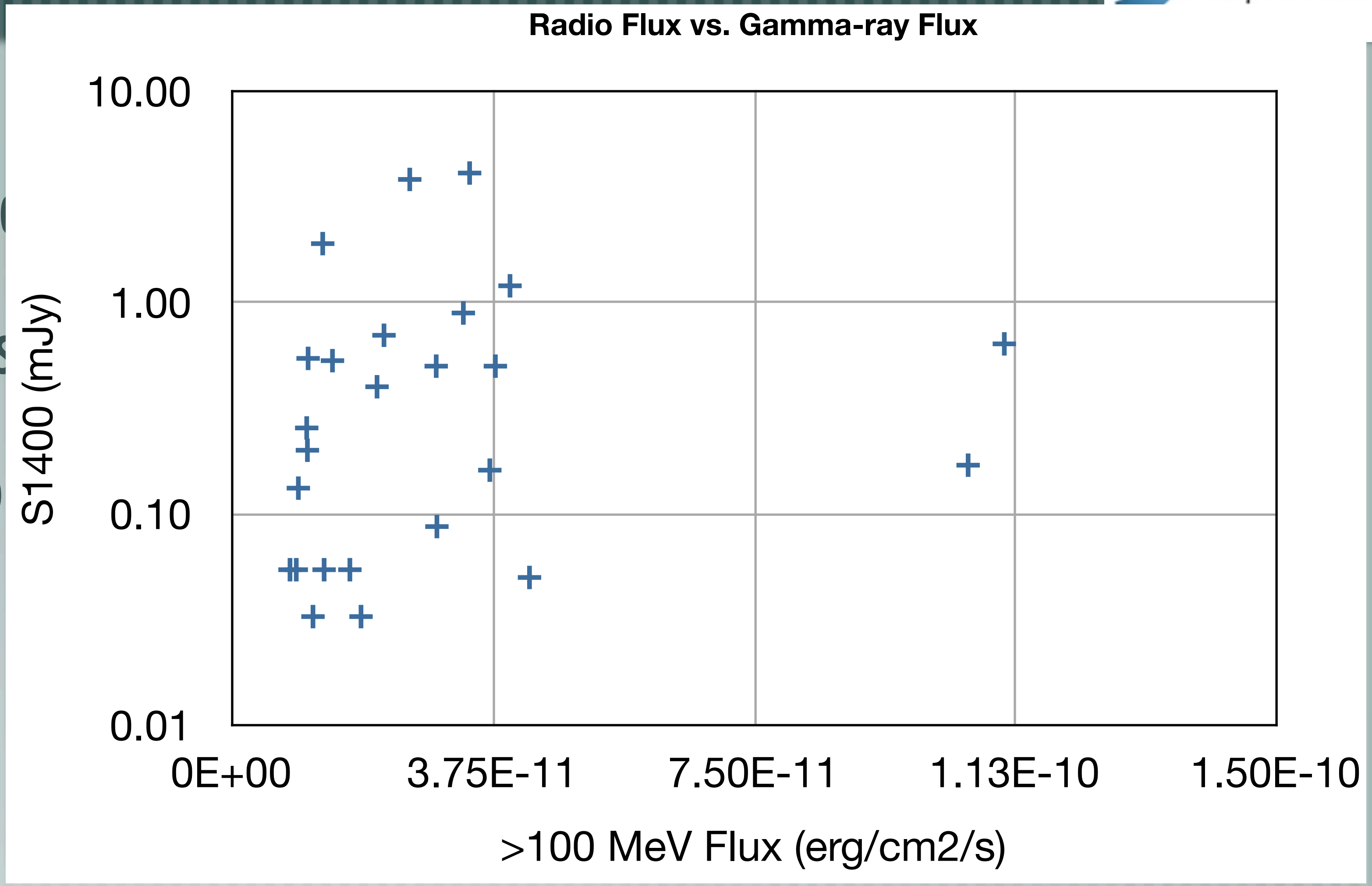

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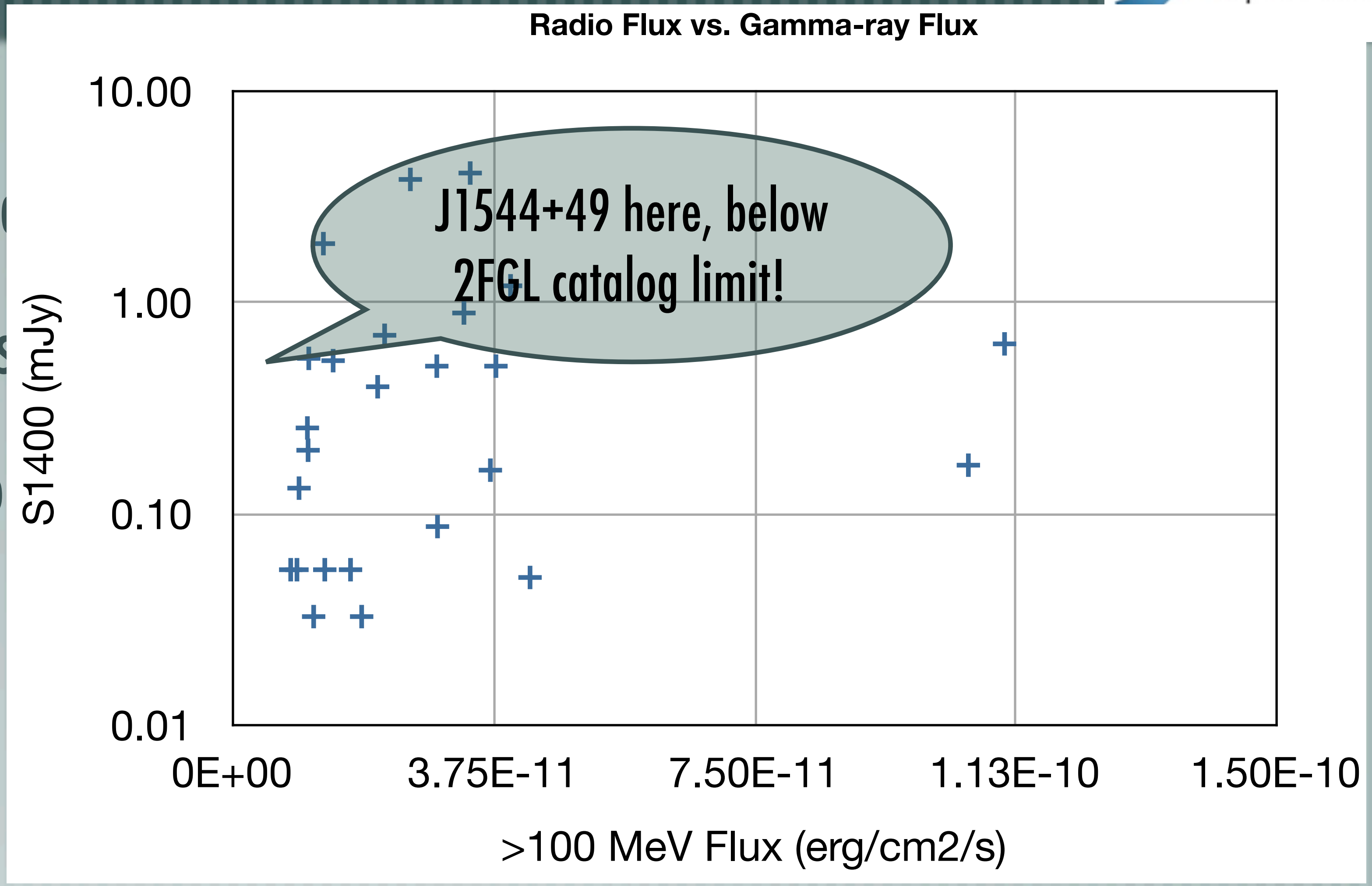

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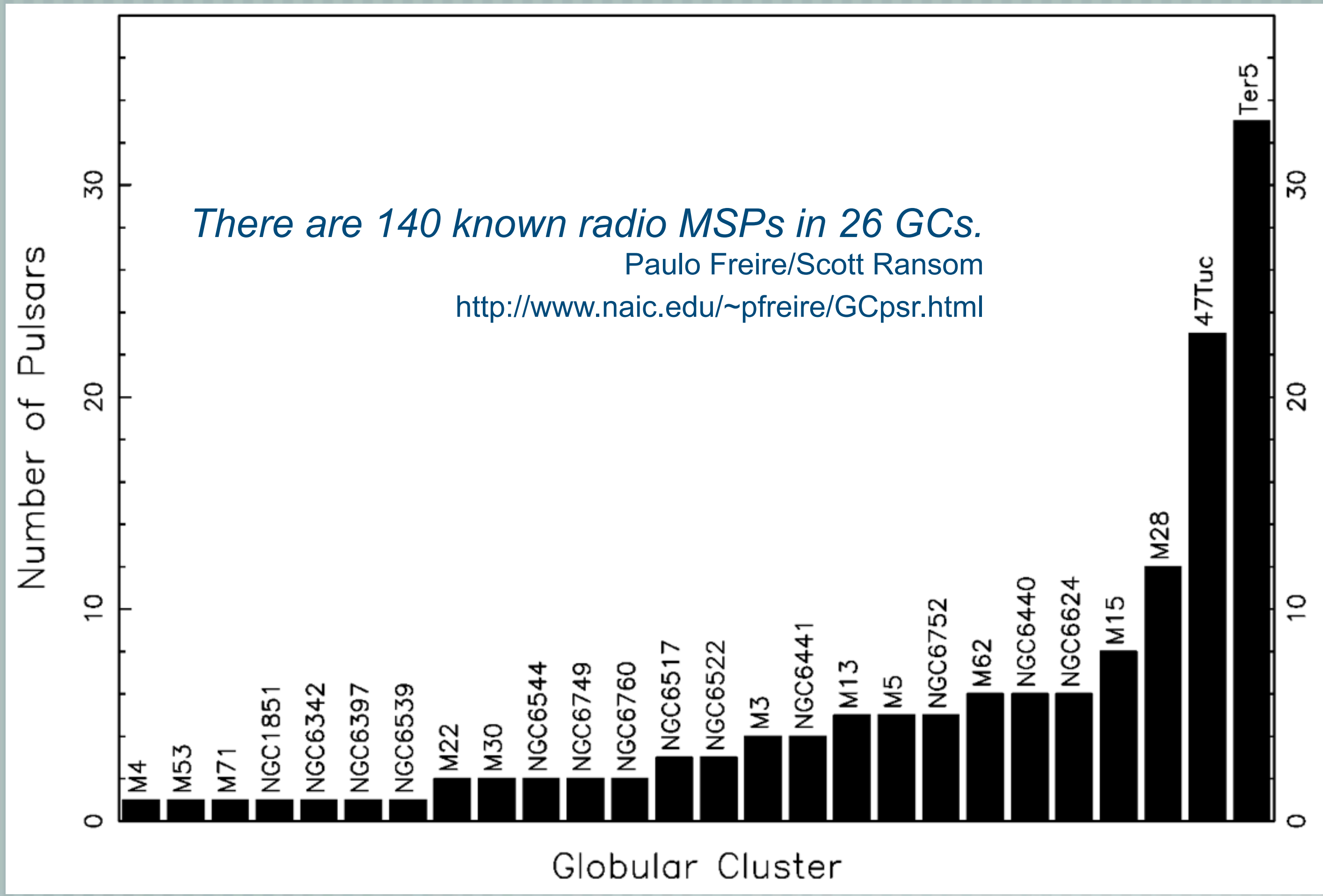
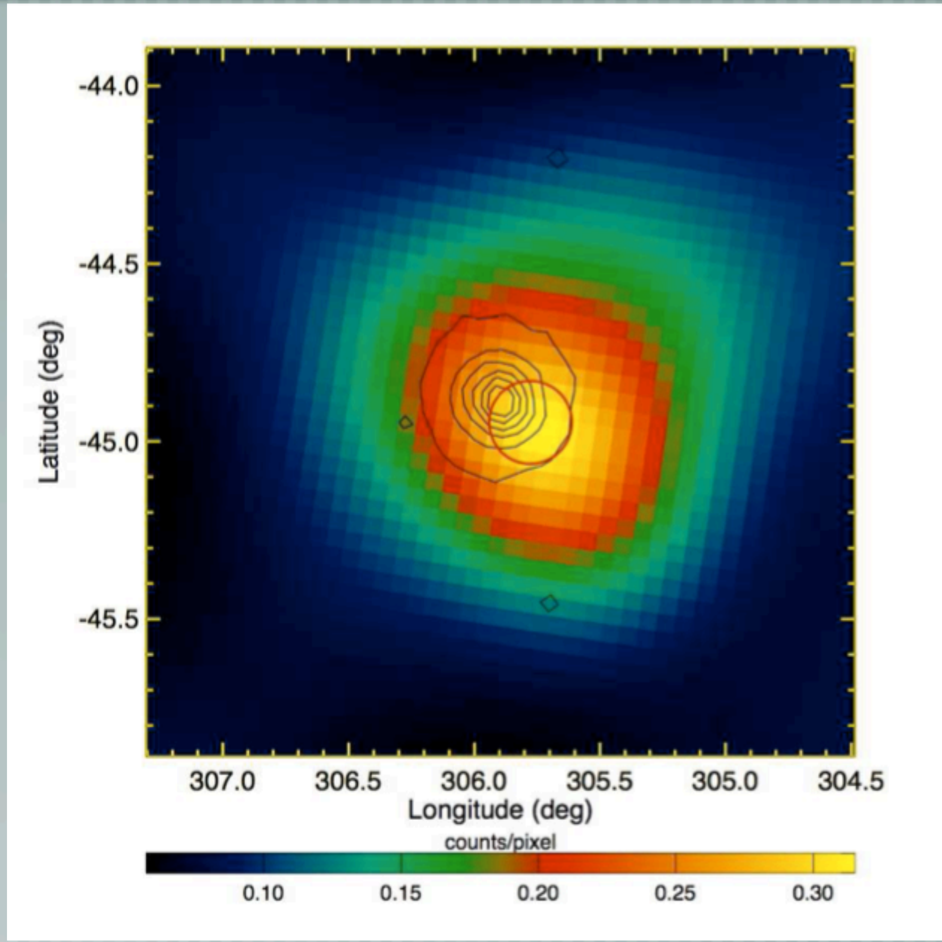
Globular Clusters : MSPs Galore





- 47 Tuc detected as a steady gamma-ray source (Abdo et al. 2009, Science, **325**, 845)
- About 11 other clusters now detected as well
- One recent detection of an MSP in the cluster NGC6624 – This pulsar accounts for all of the observed LAT emission
- DeCesar et al. now searching for MSPs in GCs detected by LAT but that have no known MSPs. One new detection so far!

Summary

- Superb sensitivity has enabled phase-resolved spectroscopy and detailed light curve studies of the EGRET pulsars
- At least 34 new young or middle-aged pulsar detections among known radio pulsars
- At least 27 gamma-ray millisecond pulsars
- 26 pulsars have been discovered in blind searches of LAT data
- LAT unidentified sources have pointed the way to 33 new radio millisecond pulsars!
- 2nd Pulsar Catalog in prep – Should arrive this summer

Lots more to come!

TEMPO2

Pulsar Gating Tutorial

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

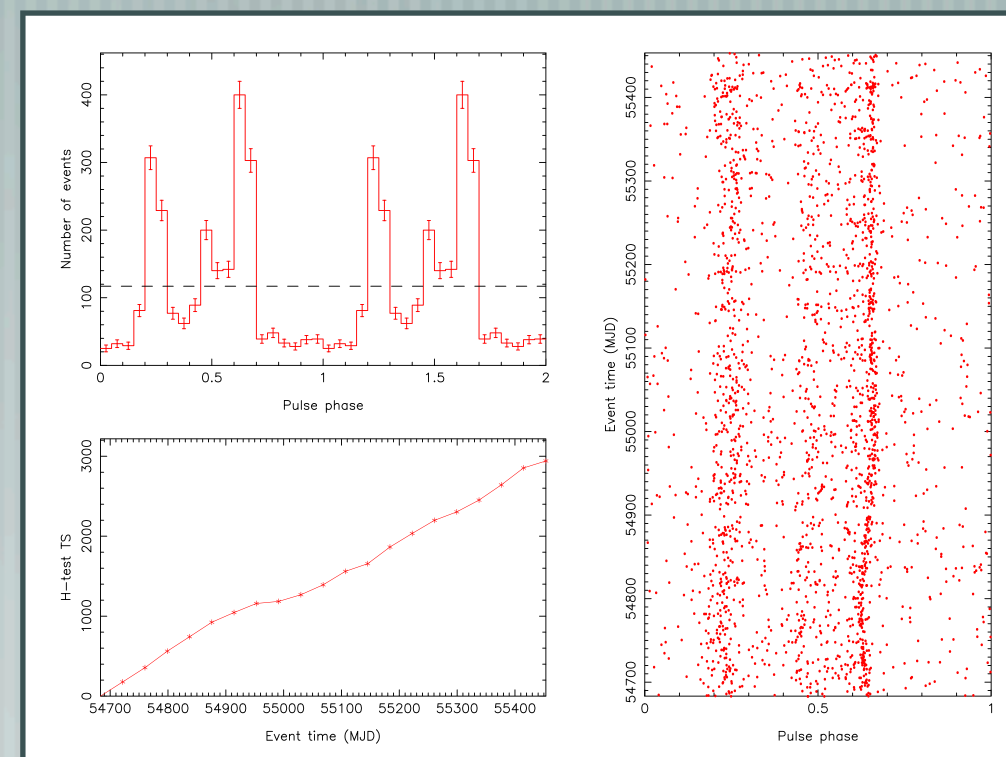
PAR File Example

```
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              -1.6842356436993461129e-15 1  5.9372878389853599515e-18
PEPOCH          55100
POSEPOCH        55100
DMEPOCH         55100
DM              8.089783                    0.00050000000000000000
PMRA            -96.5738814137746663 24   1  7.7289098004797066 5859
PMDEC           -33.566537987050774568   1  18.574103106178091 12536
PX              0
BINARY          BT
PB              1.8601438820982435574    1  0.00000000457056002199
T0              55016.786923229563047    1  0.09236400834581849628
A1              2.0426329197100693447    1  0.00000157528384070272
OM              316.12850131667568751    1  17.875554780854319557 31
ECC             4.4374072274803924573e-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



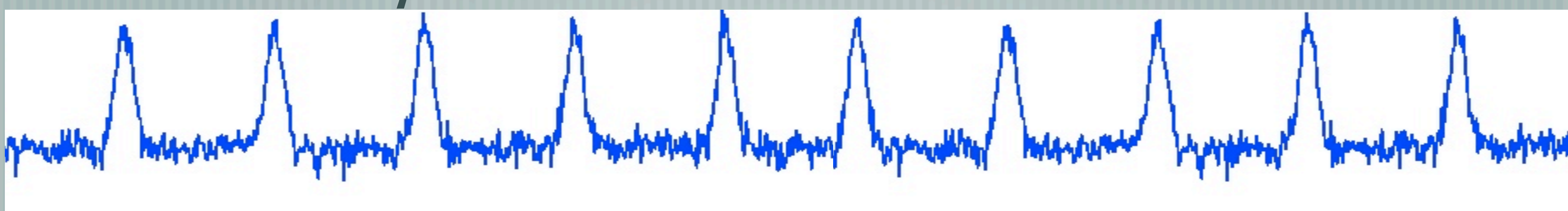
Pulsar Timing

- 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)

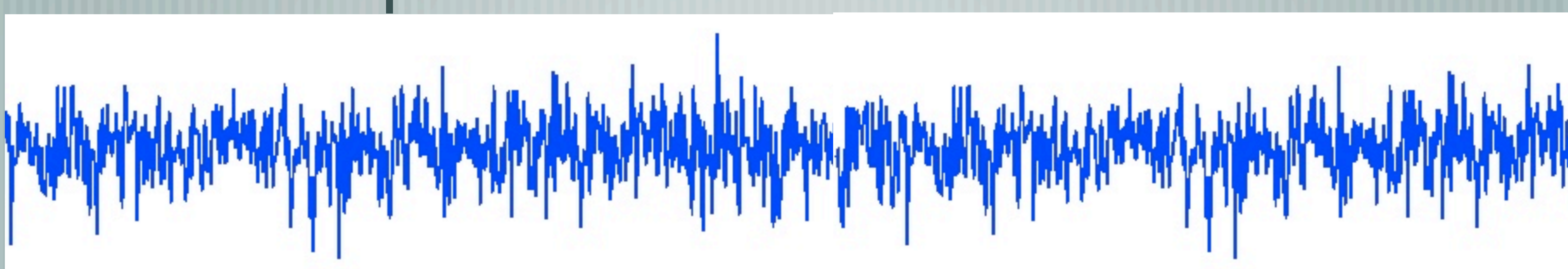
What the Signal Looks Like

Ideally the signal would look like this:

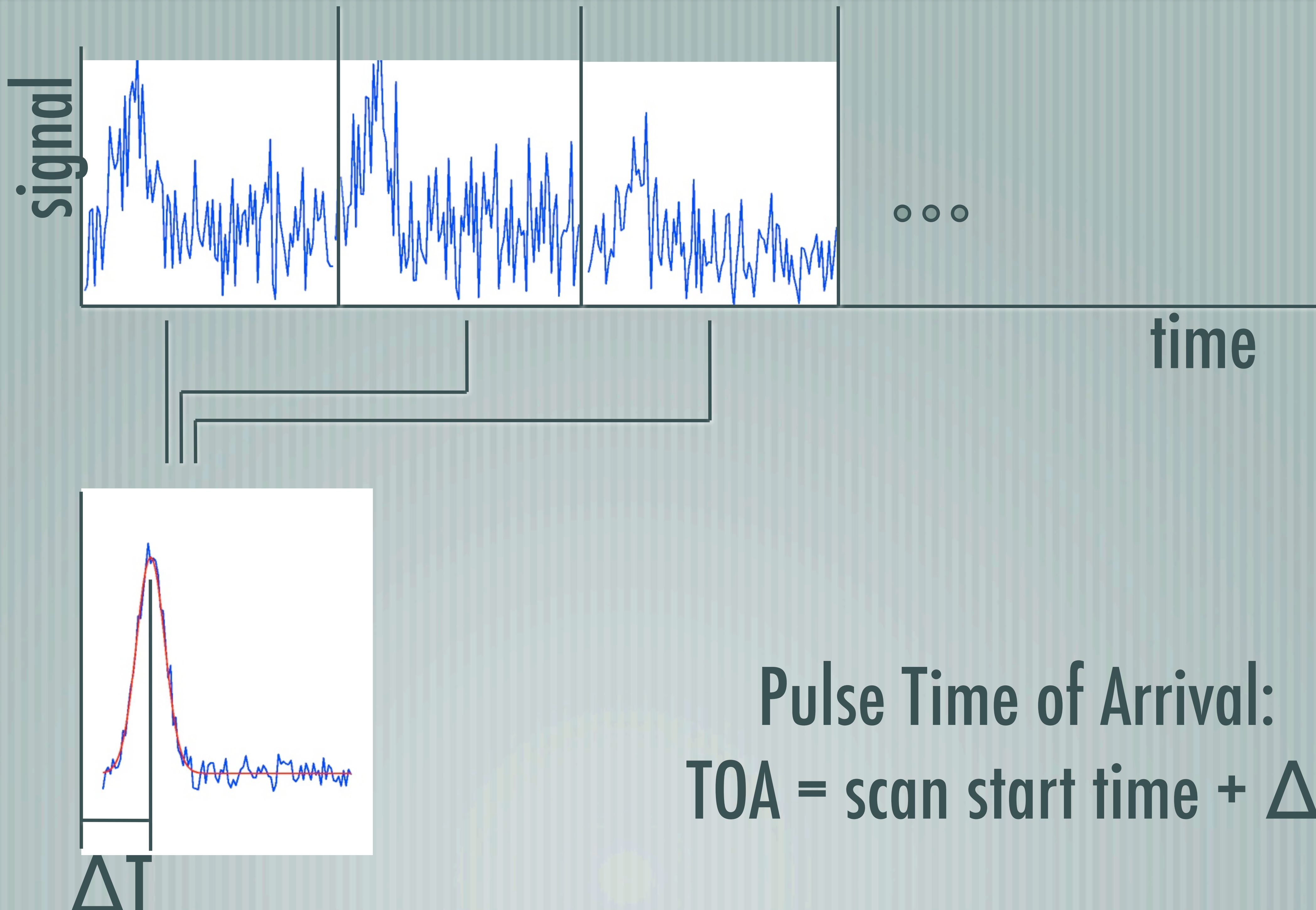
But there is always some noise:



Often individual pulses are not visible at all:



Measuring a Time of Arrival



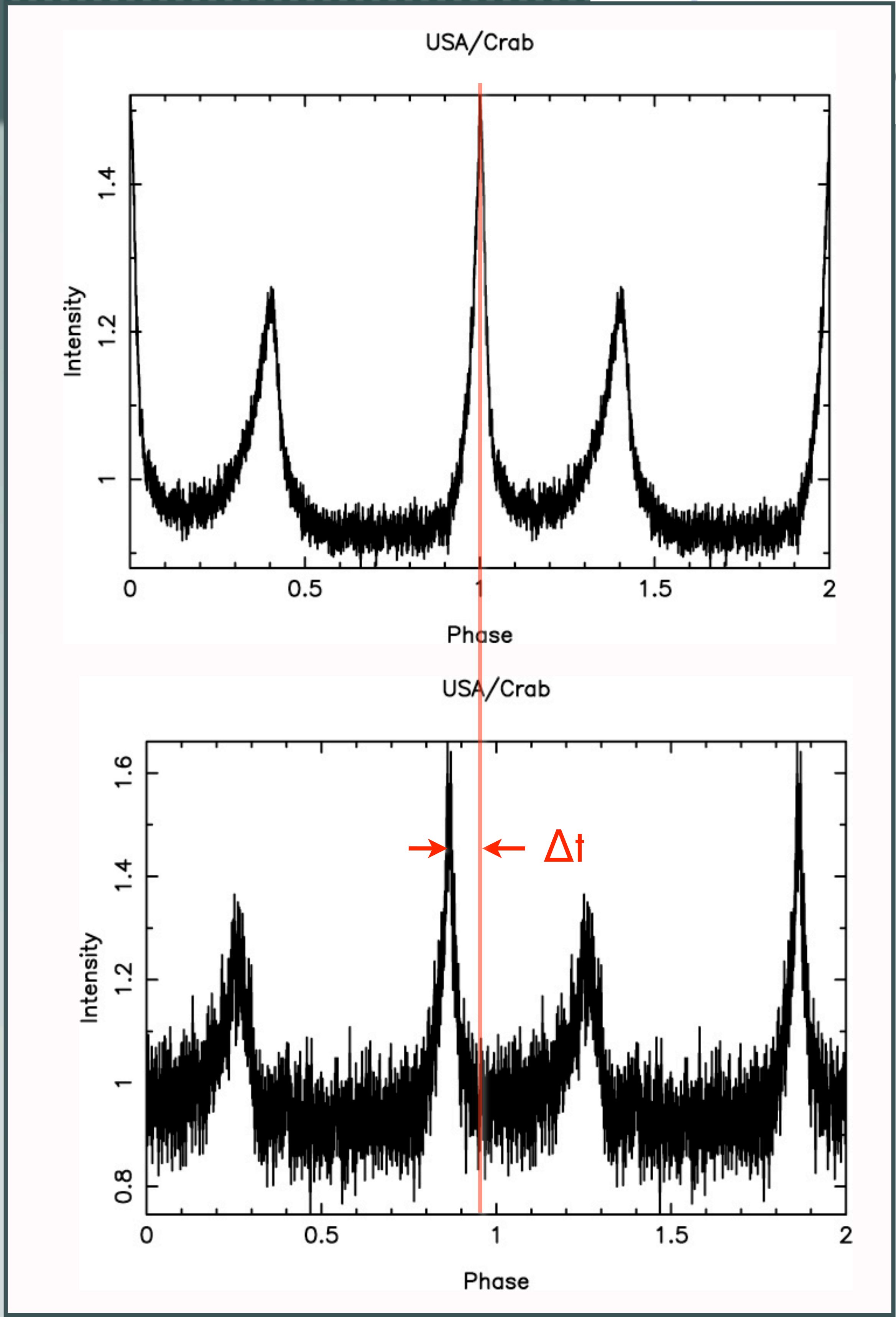
Pulse Time of Arrival:
TOA = scan start time + ΔT

Measuring a TOA

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

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

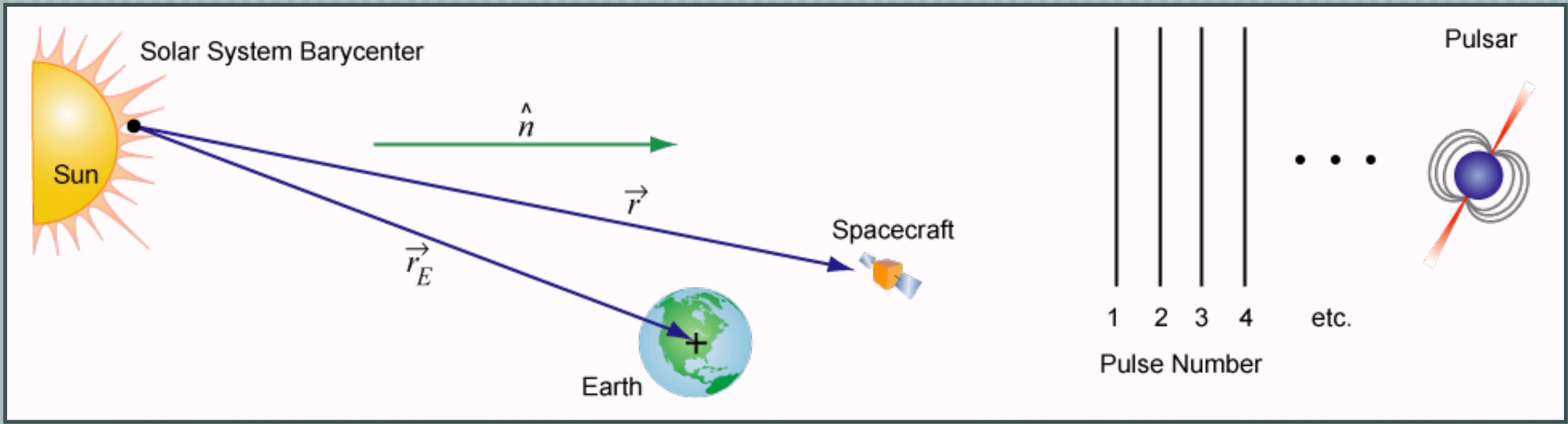
- TOA = $T_{obs} + \Delta t$



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

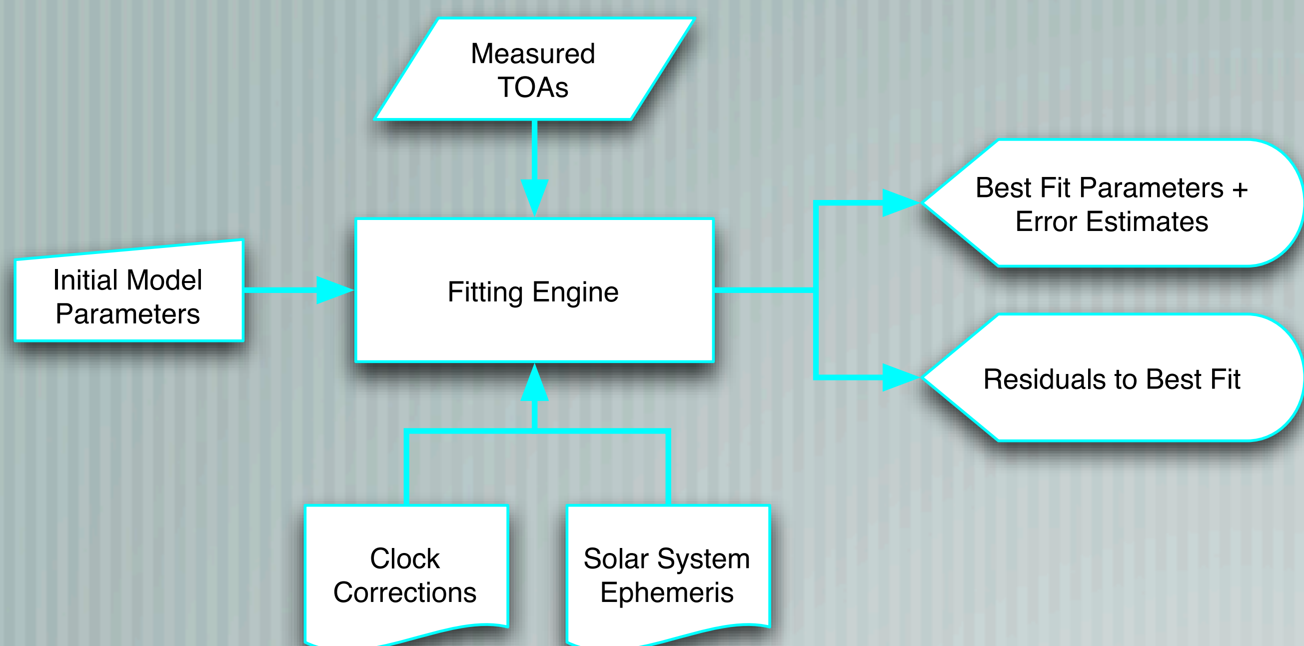


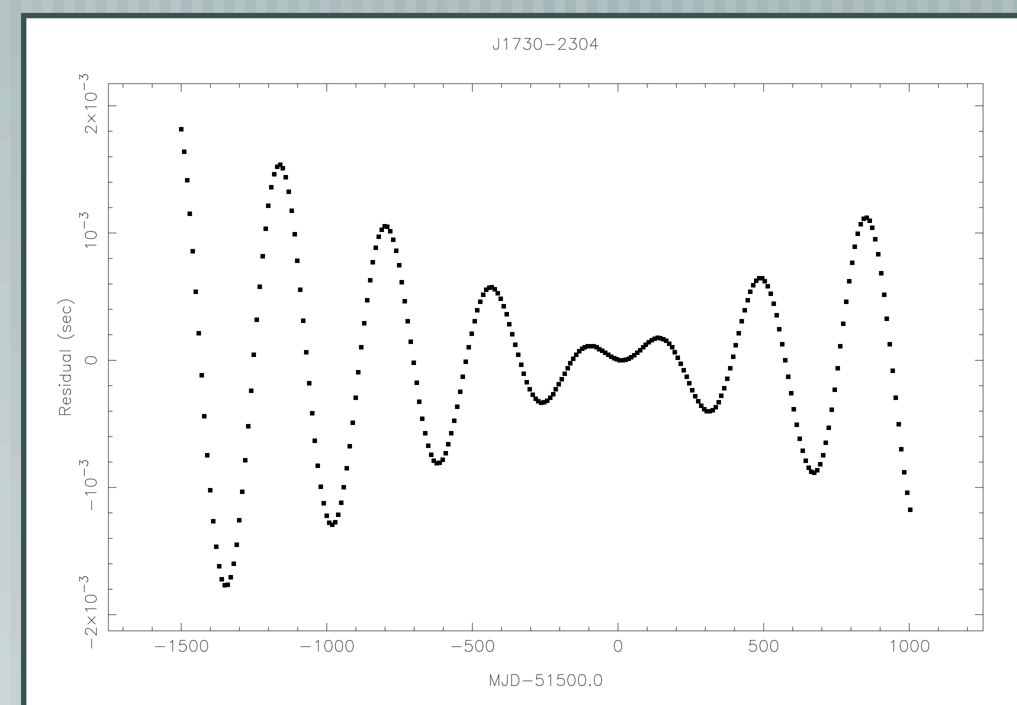
- Arrival times at Earth or spacecraft must be converted to a nearly inertial frame before attempting to fit a simple timing model
- Remove effects of observer velocity and relativistic clock effects
- Convenient frame is the Solar System Barycenter

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

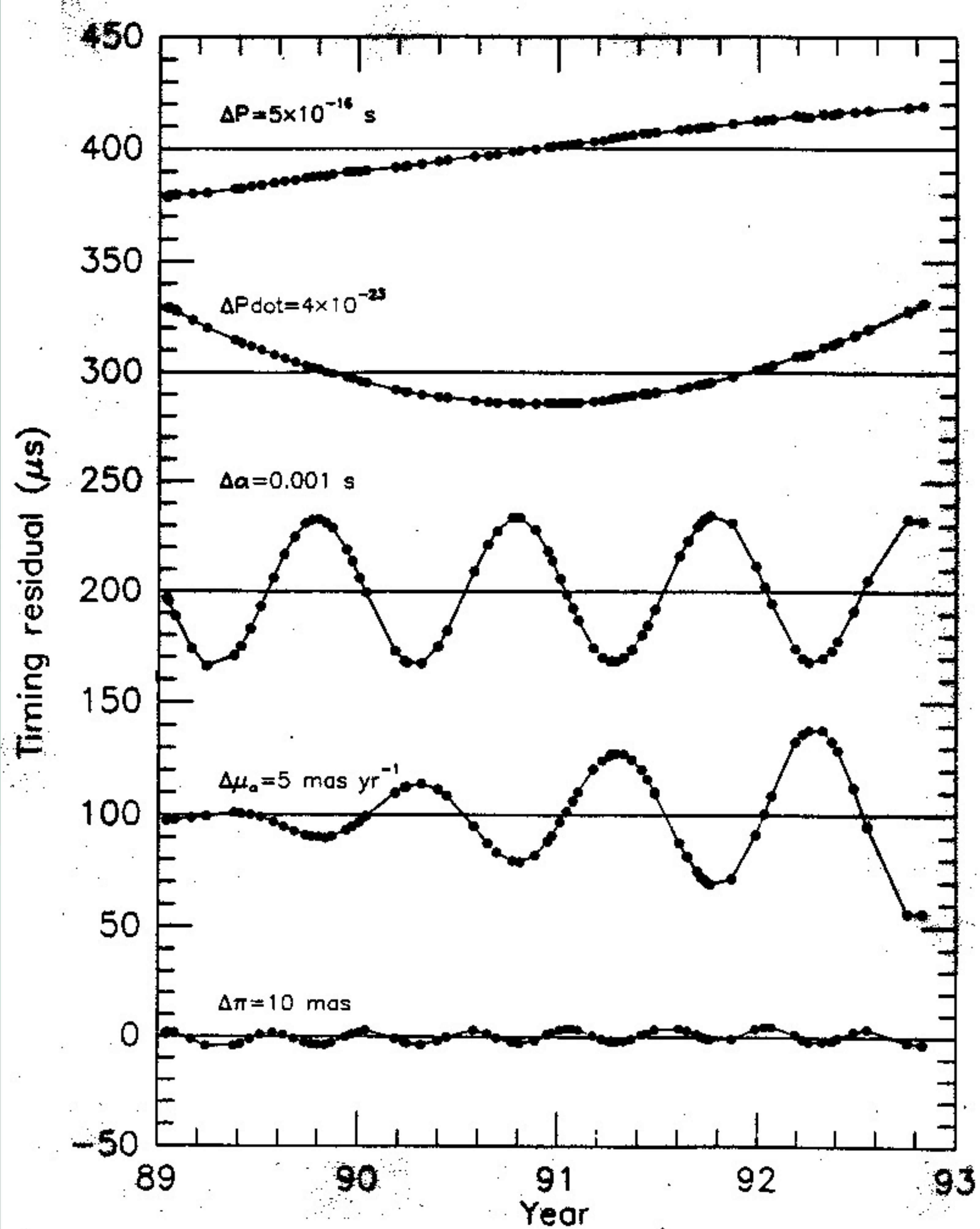
TT = TAI + 32.184 s

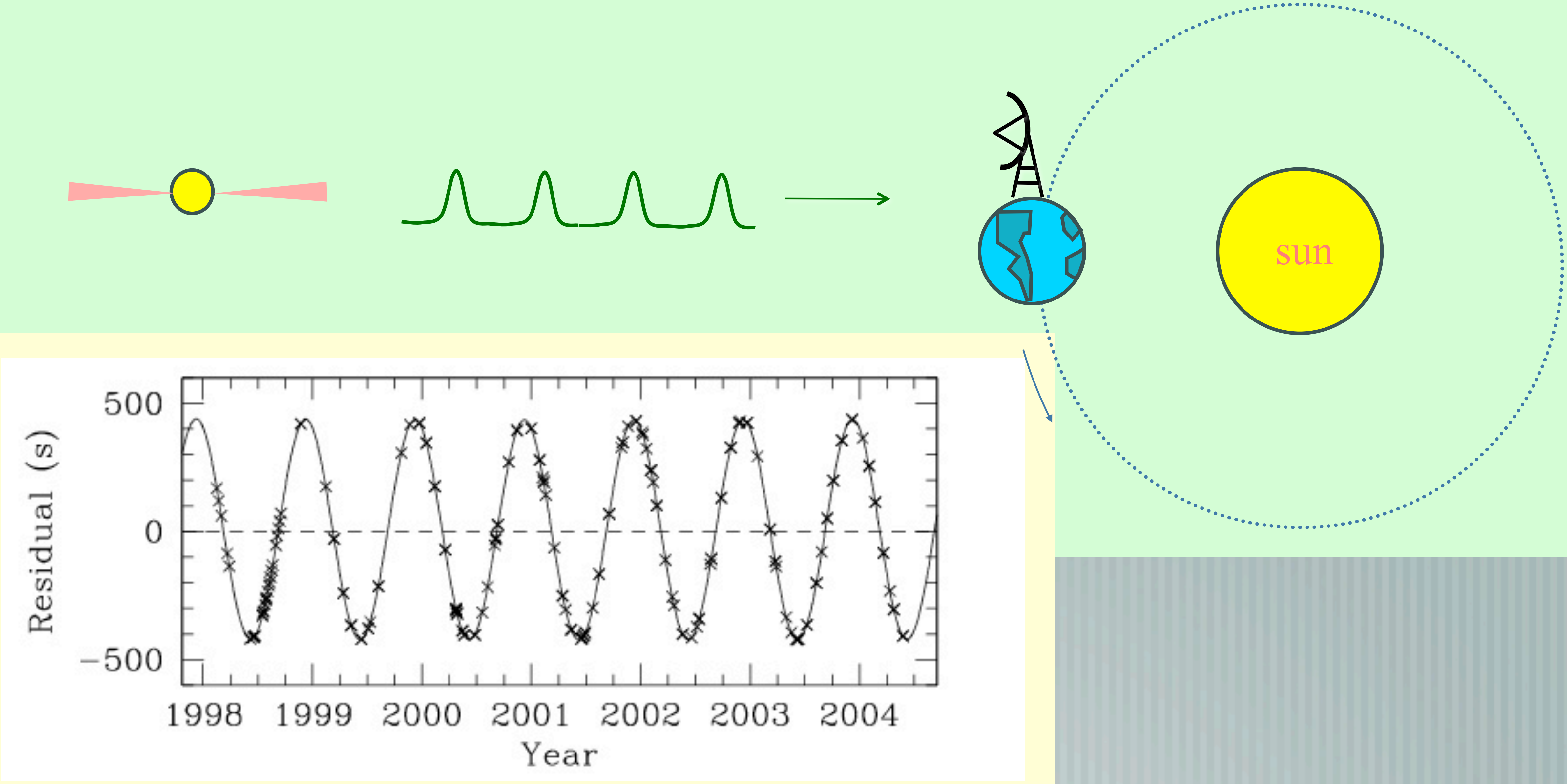
TDB = TT + periodic terms to be uniform at SSB

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

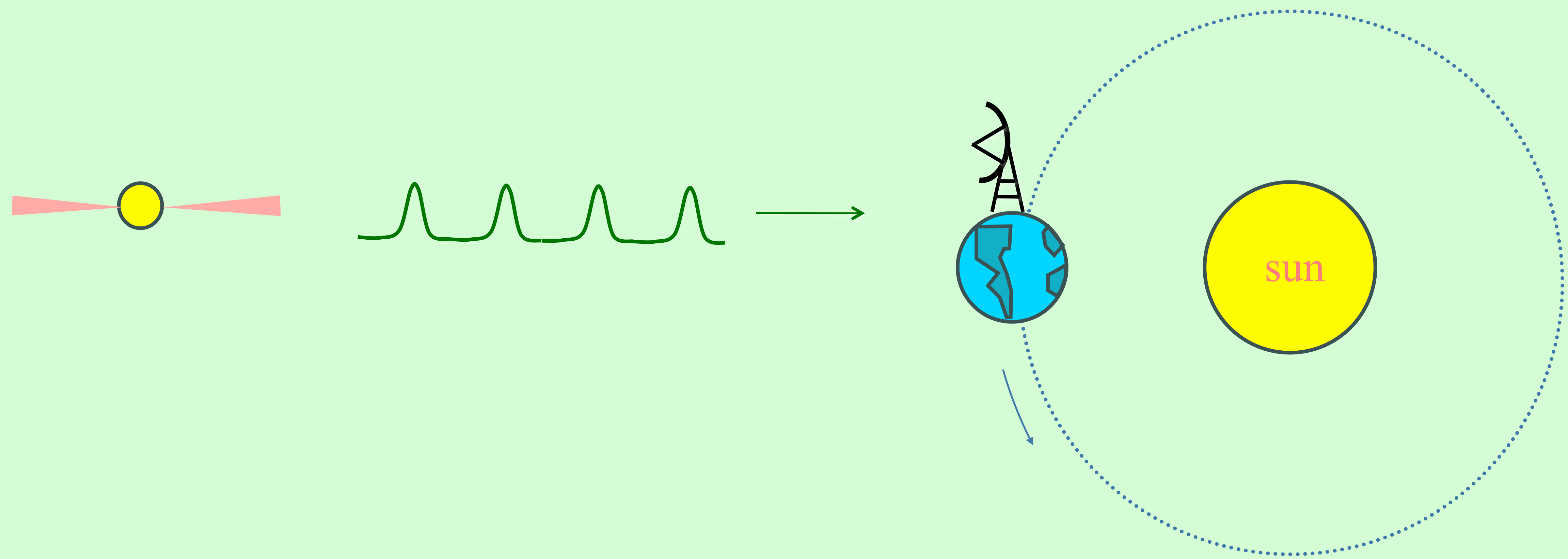


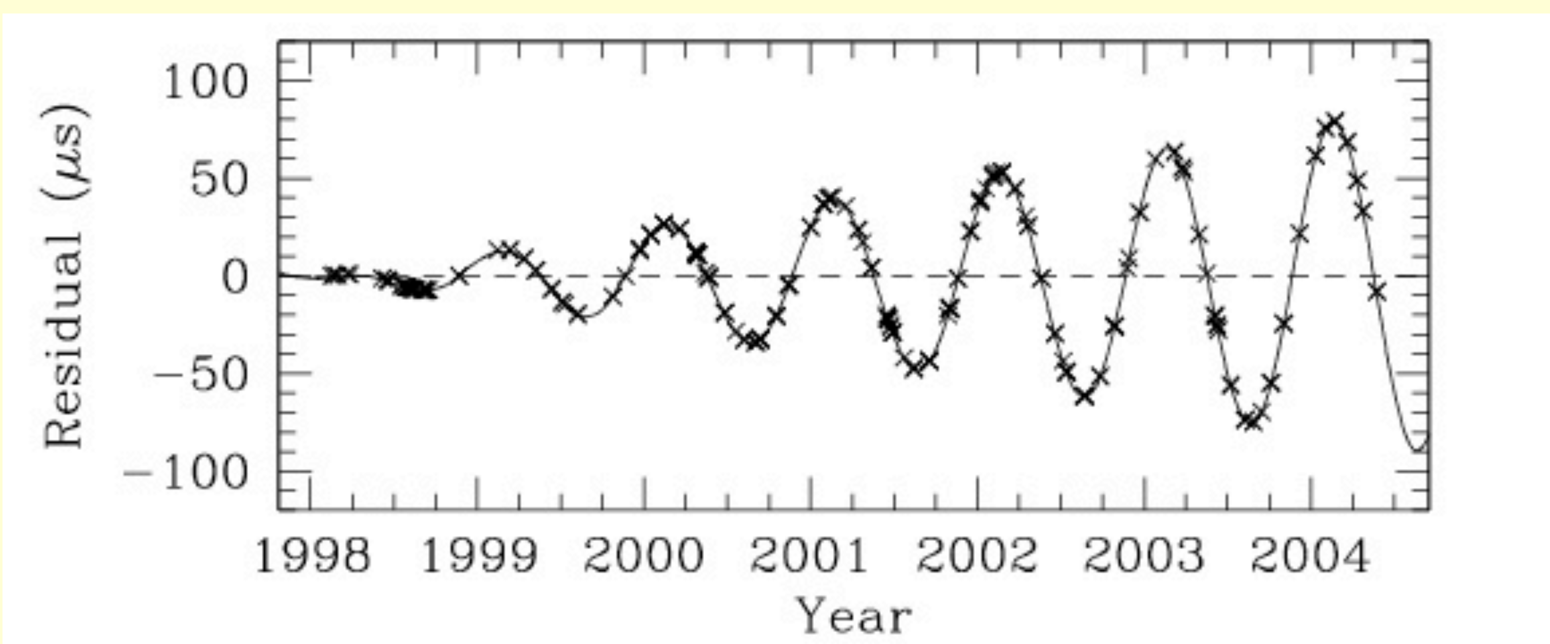


Delays of ~500 s due to time-of-flight across the Earth's orbit.

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

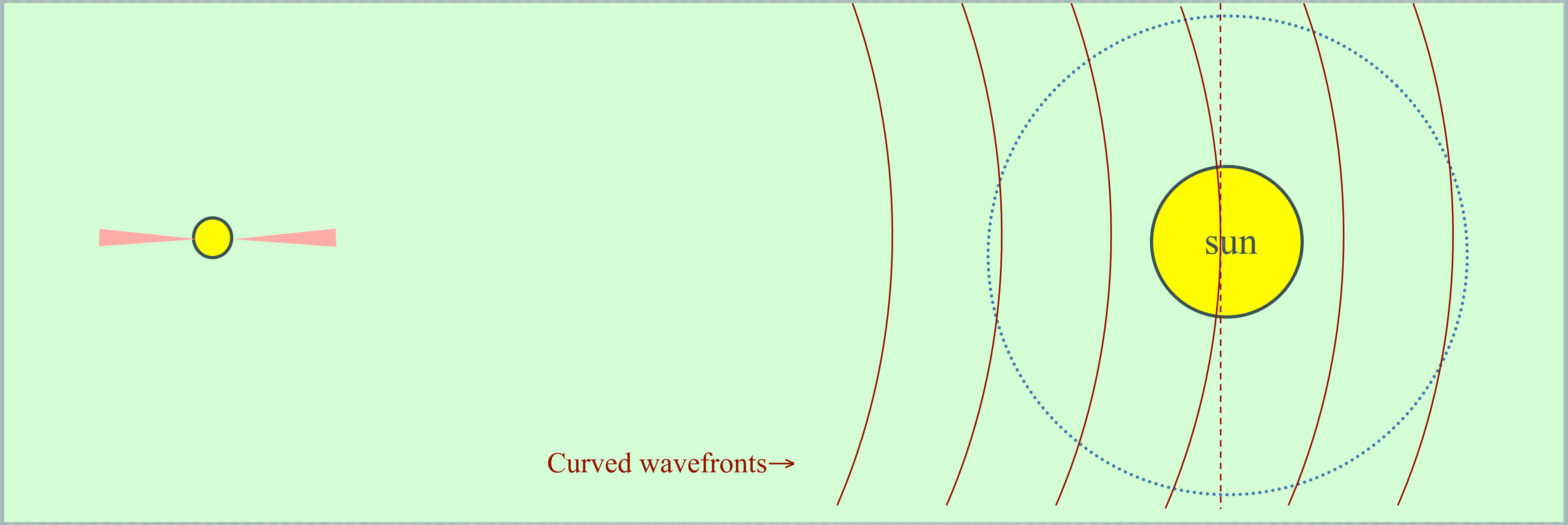
Position known only from timing data
⇒ always need to fit annual terms out of timing solution
⇒ a perturbation due to gravitational waves with ~1 yr period cannot be detected

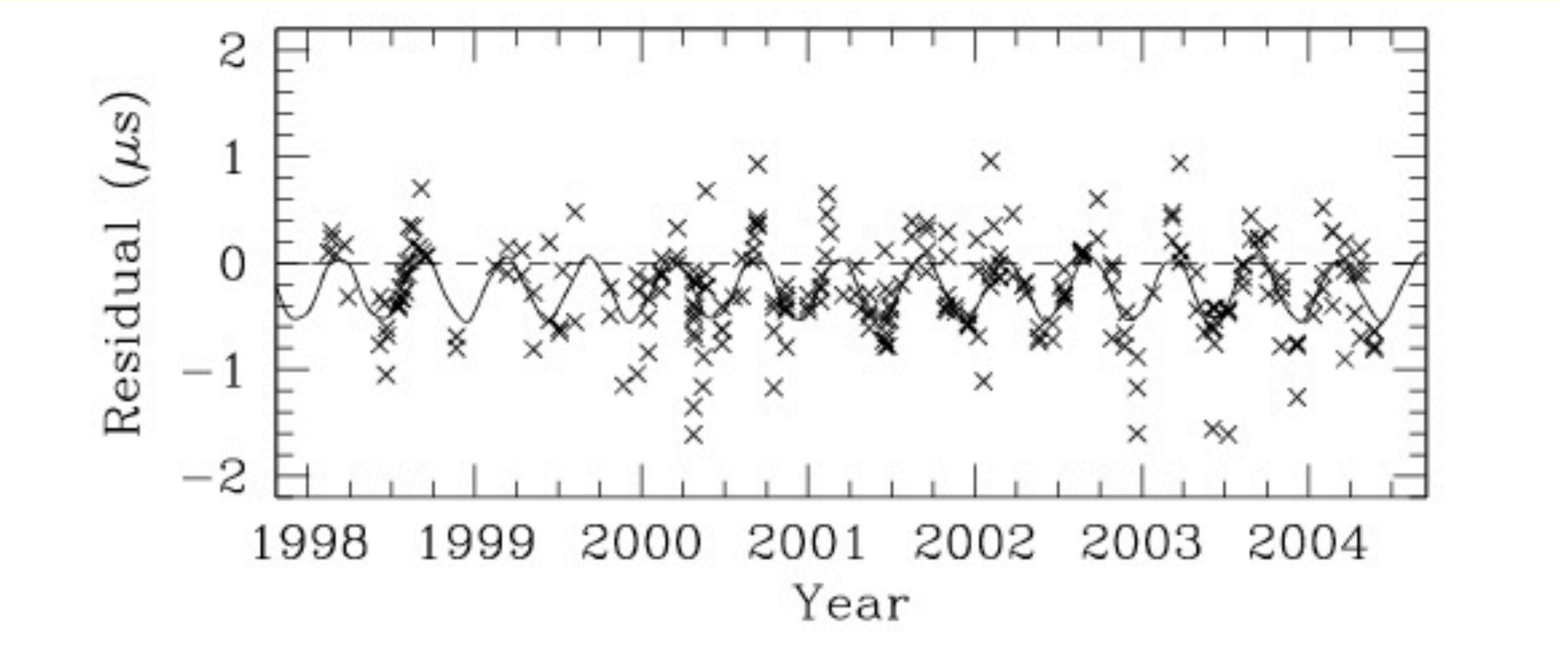




Other astrometric phenomena:

Proper Motion



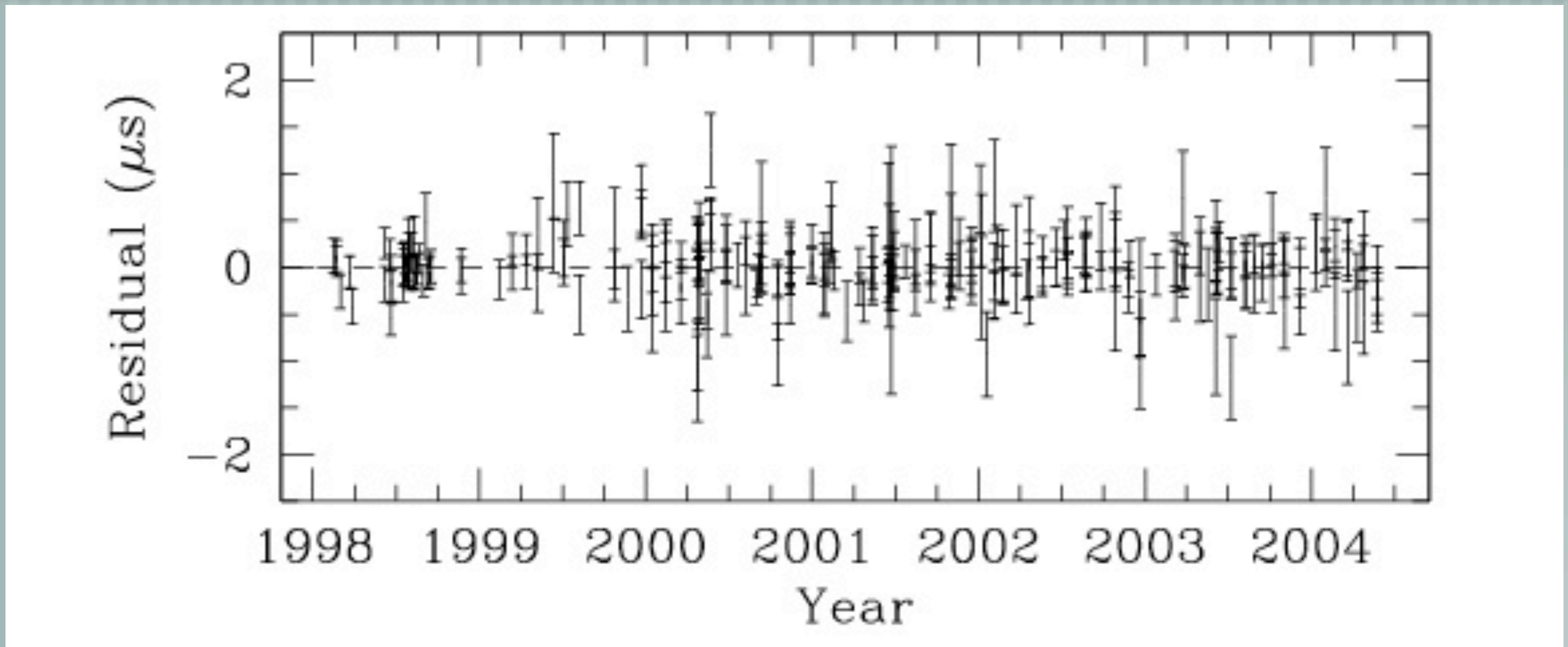


Other astrometric phenomena:

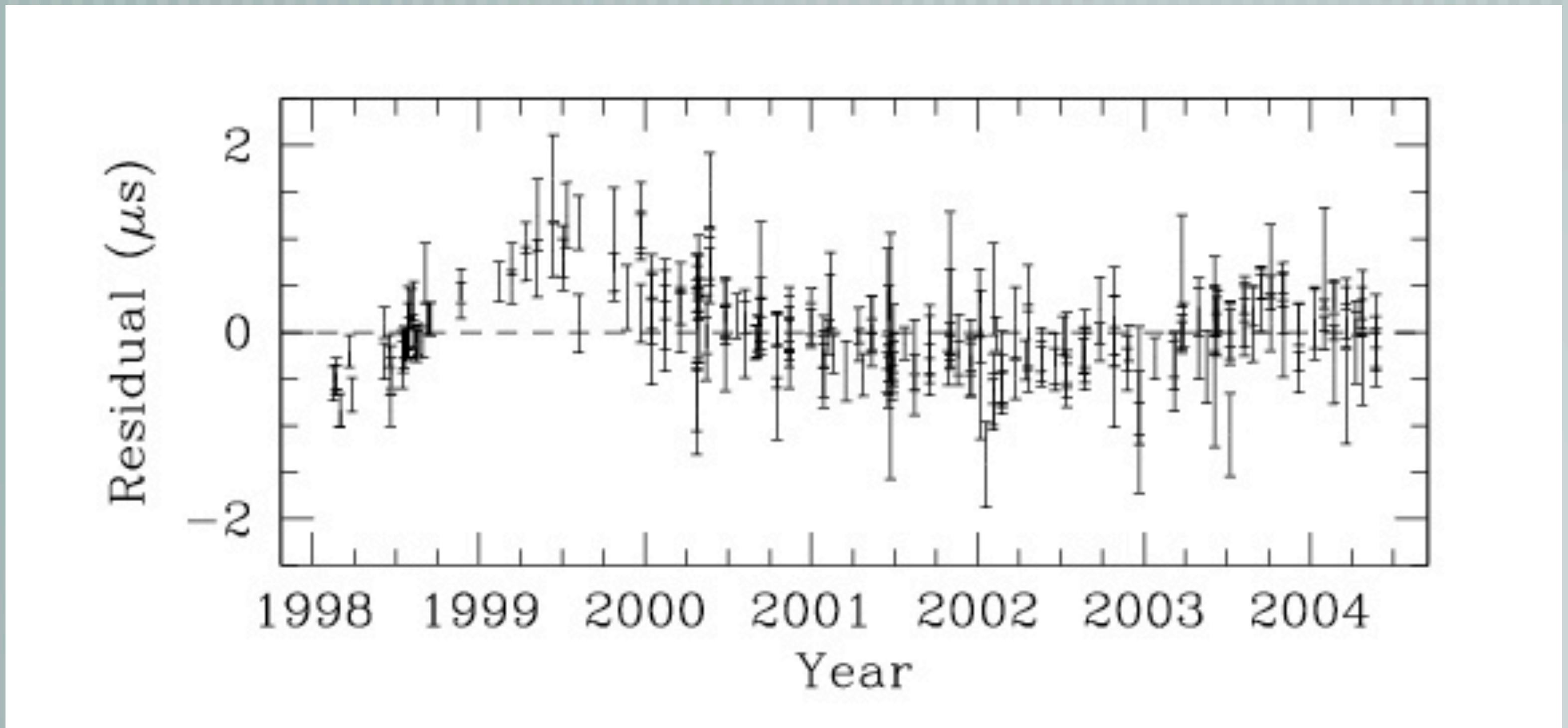
Proper Motion

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