Multiwavelength analysis of four* gamma-ray millisecond pulsars

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on behalf of the Fermi LAT Collaboration

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Pulsar Conference 2010

** now five...*

Outline

- Searches for gamma-ray pulsations from the two fast millisecond pulsars J1939+2134 and J1959+2048
- Discovery of millisecond pulsars with the Nançay radio telescope and subsequent radio and gamma-ray observations
- Summary

Millisecond pulsars in gamma rays

(See T.J. Johnson's presentation)

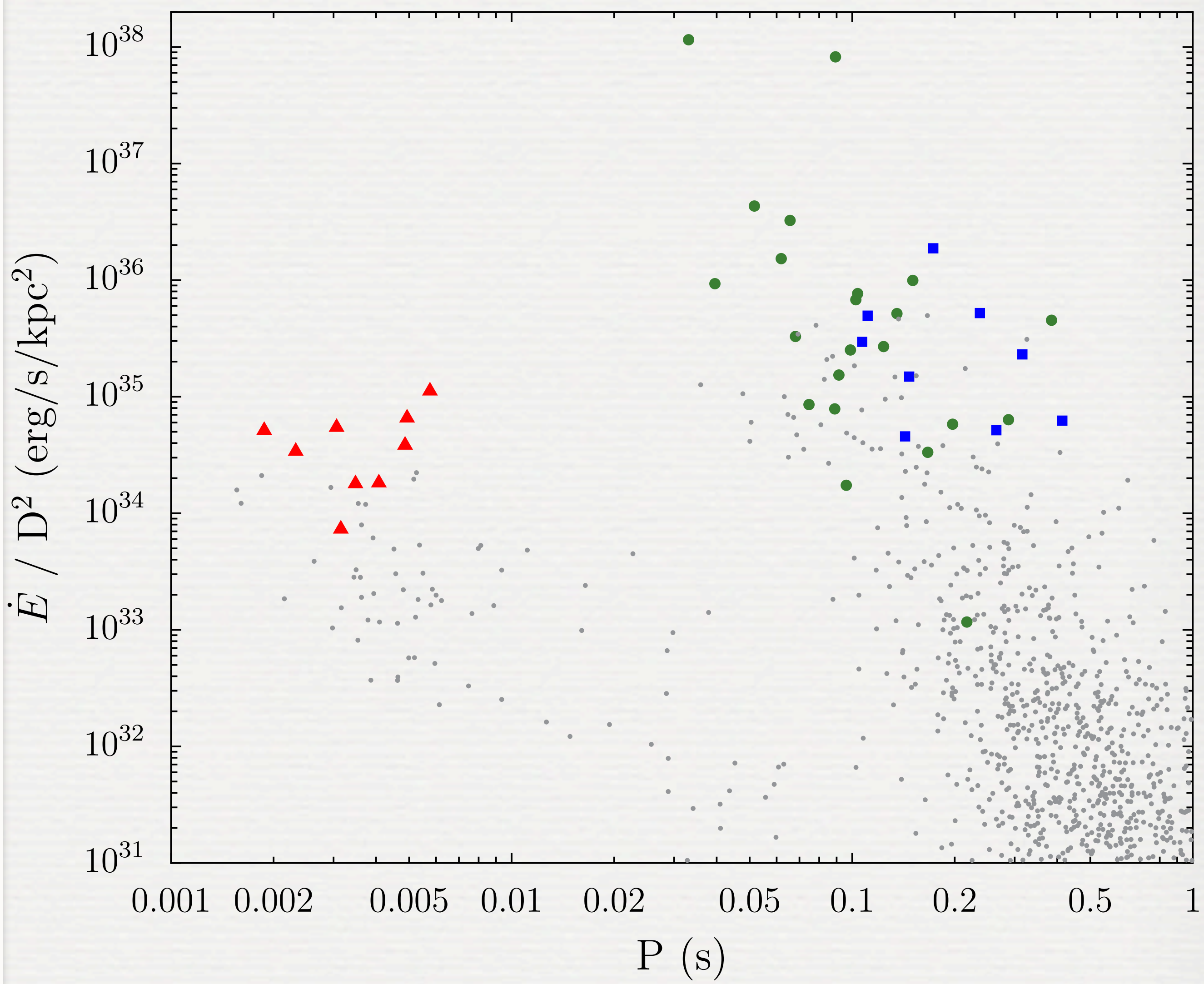
Nine MSPs have been detected in gamma rays in 13 months of survey with the LAT.

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

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

Most MSPs above $\dot{E} / d^2 \sim 10^{34}$ erg/s/kpc^2 are seen in gamma rays.

As the survey continues, the LAT detects pulsars with lower $\dot{E} / d^2$ values.



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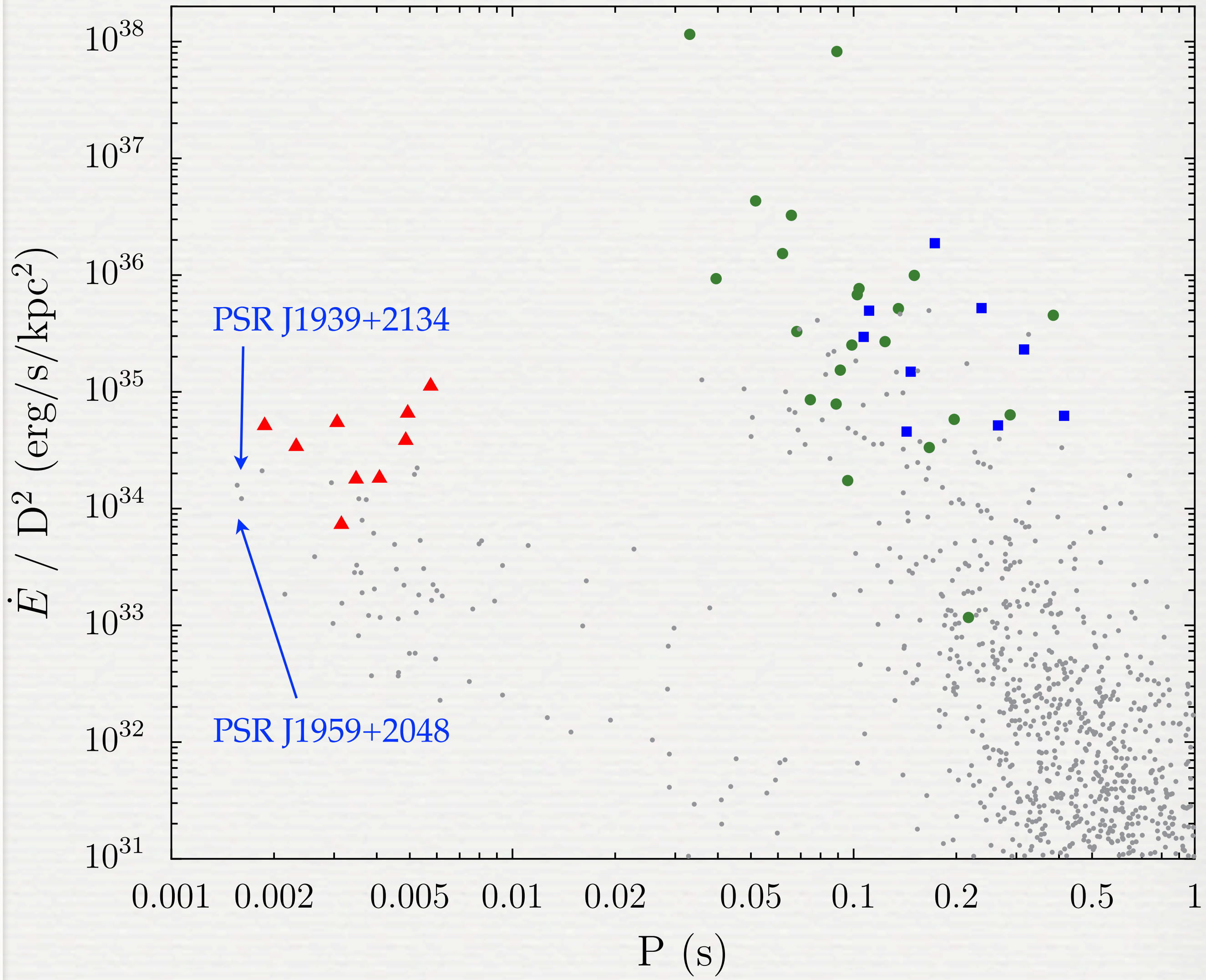
Most MSPs above $\dot{E}$ / d^2 ~ 10^{34} erg/s/kpc^2 are seen in gamma rays.

As the survey continues, the LAT detects pulsars with lower $\dot{E}$ / d^2 values.

With their large $\dot{E}$ but also relatively large distances, PSRs J1939+2134 and J1959+2048 are good candidates for gamma-ray emission!



PSR J1939+2134 (a.k.a. B1937+21):
$\dot{E}$ = 1.1 10^{36} erg/s, d = (7.7 +/- 3.8) kpc

PSR J1959+2048 (B1957+20):
$\dot{E}$ = 7.5 10^{34} erg/s, d = (2.5 +/- 1.0) kpc

The need for pulsar timing

MSPs have short periods and 80% are in binary systems. Direct searches for pulsations in the gamma-ray data are too computer and time intensive.

For MSPs, <u>we have to do pulsar timing</u> in radio and/or X-rays and monitor the apparent period as a function of time.

➡ Pulsar timing campaign for Fermi: multi-wavelength monitoring of pulsars on a regular basis.

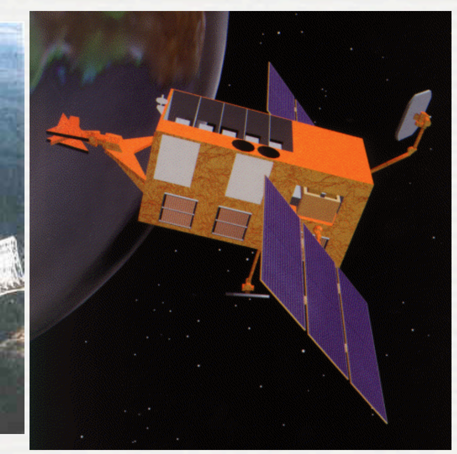
Smith, Guillemot, Camilo et al., A&A 492, 923 (2008)

Parkes (Australia)

Jodrell Bank (England)

Green Bank (US)

Nançay (France)



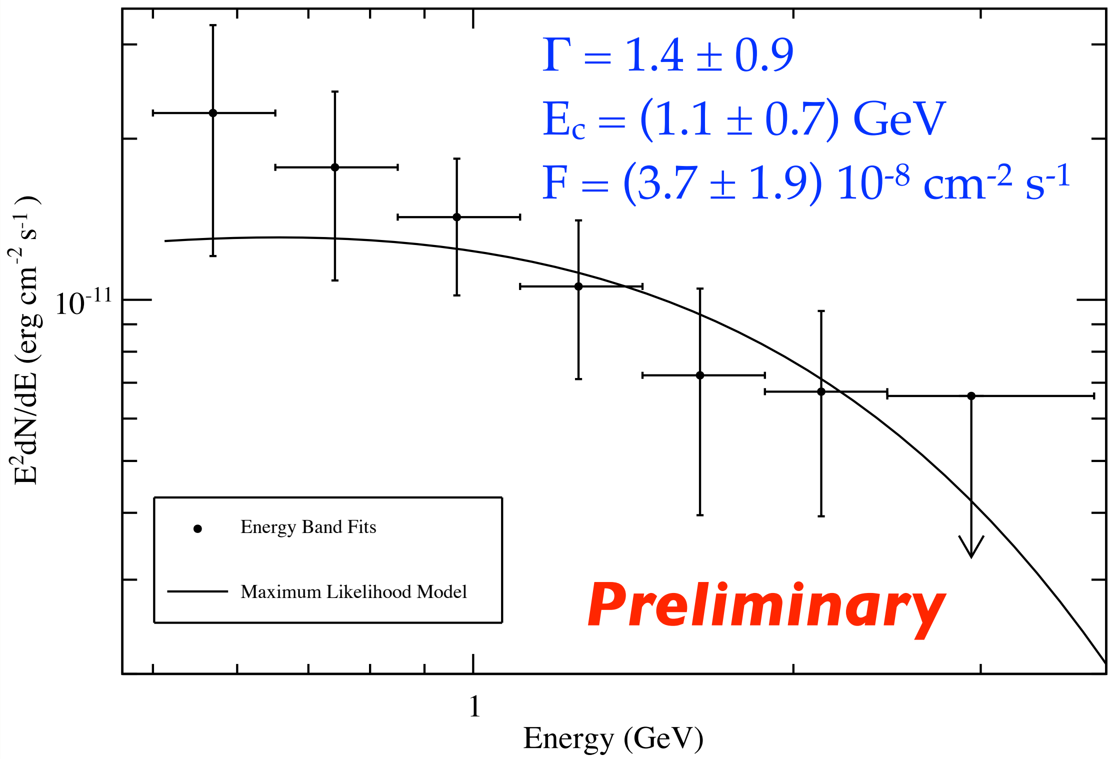
RXTE

(and other contributions)

Accurate ephemerides obtained for most known Galactic disk MSPs, including PSRs J1939+2134 and J1959+2048.

Gamma-ray pulsations from J1939+2134*

** First MSP ever discovered, D. Backer et al. (1982)*



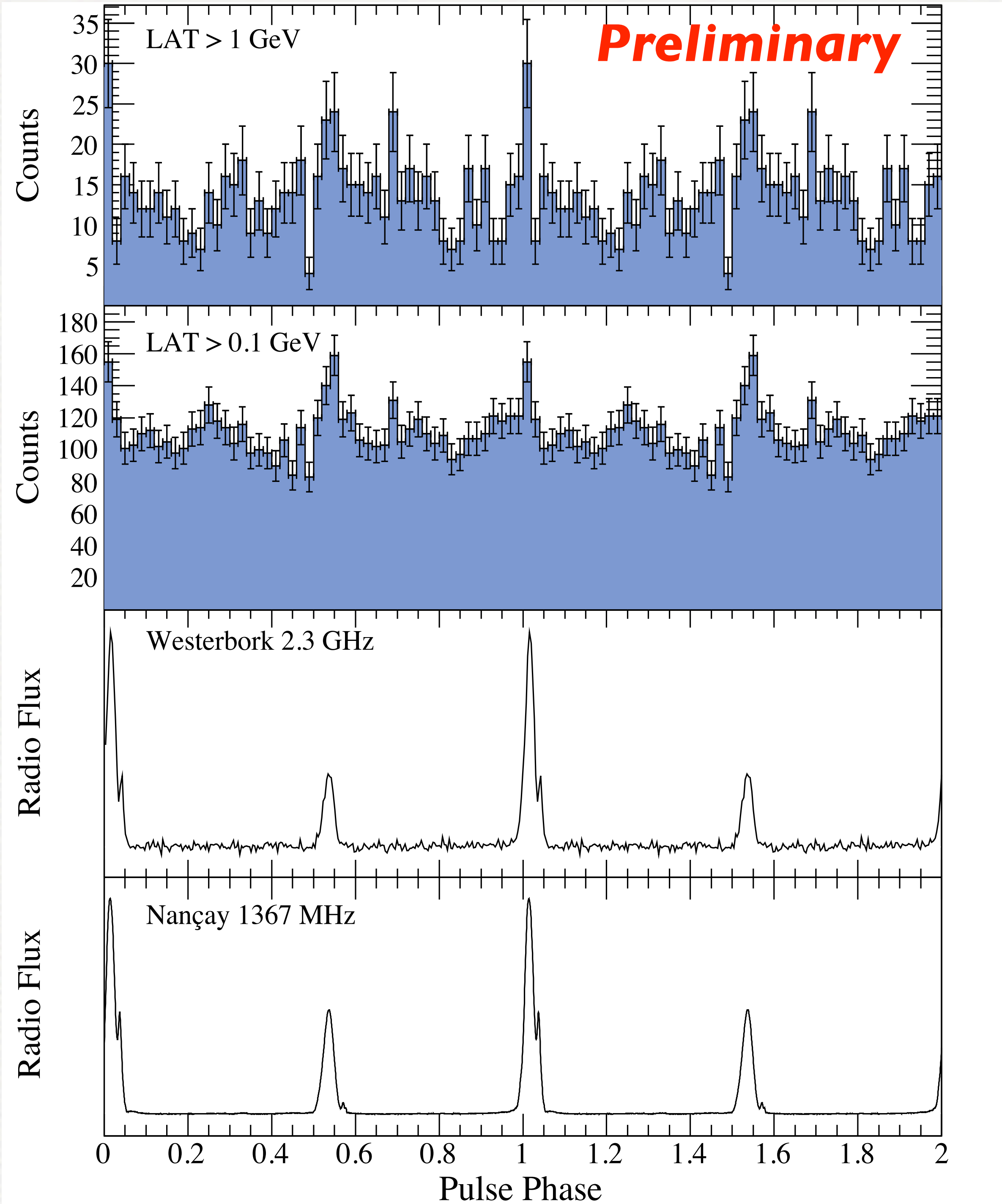
Gamma-ray pulsations observed for J1939+2134 with 18 months of LAT data. Radio and gamma-ray emission in close alignment!

A fit of the spectrum using an exponentially cut off PL yields the above spectrum:

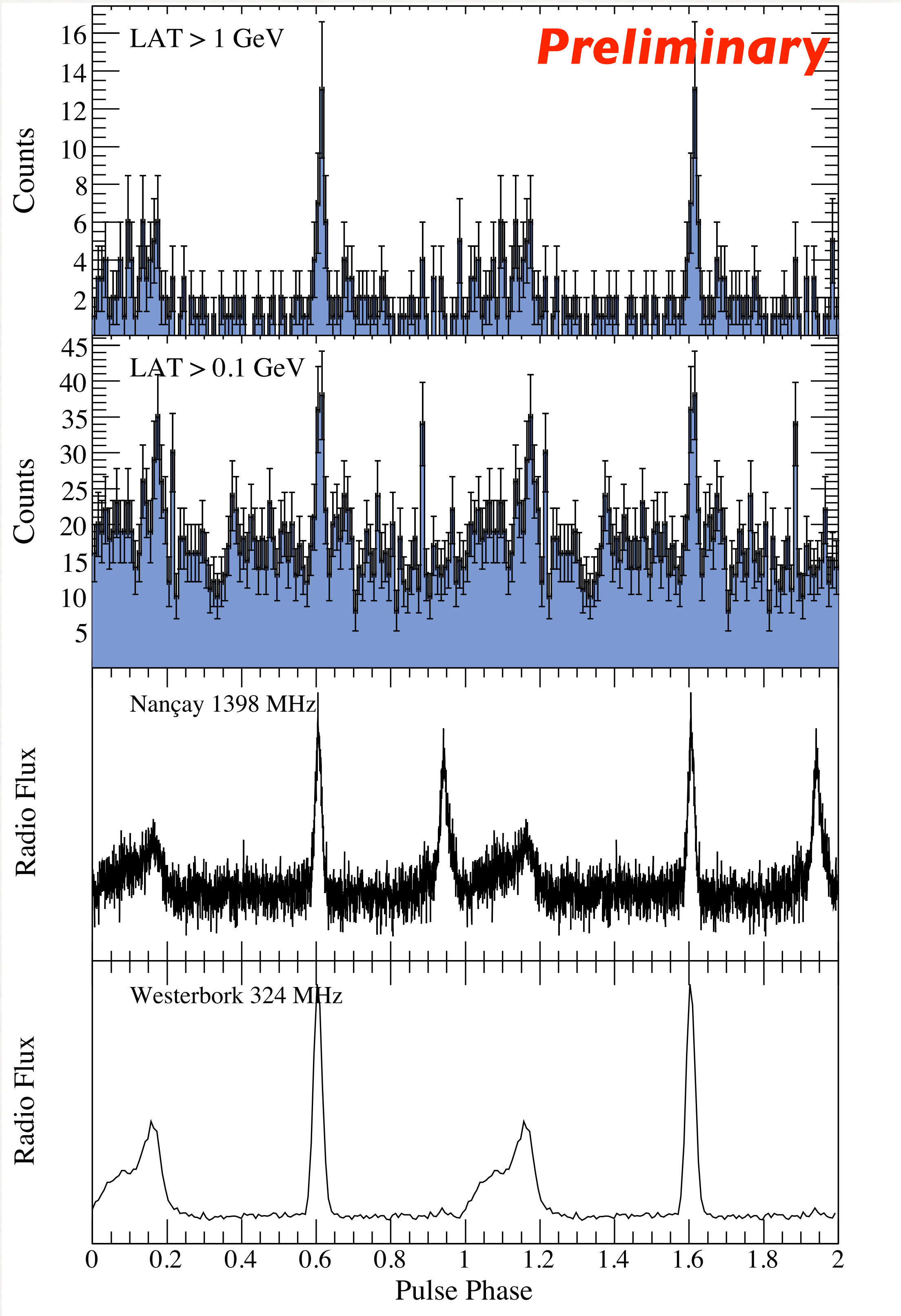
$$\frac{dN}{dE} = N_0 E^{-\Gamma} \exp\left(-\frac{E}{E_c}\right)$$

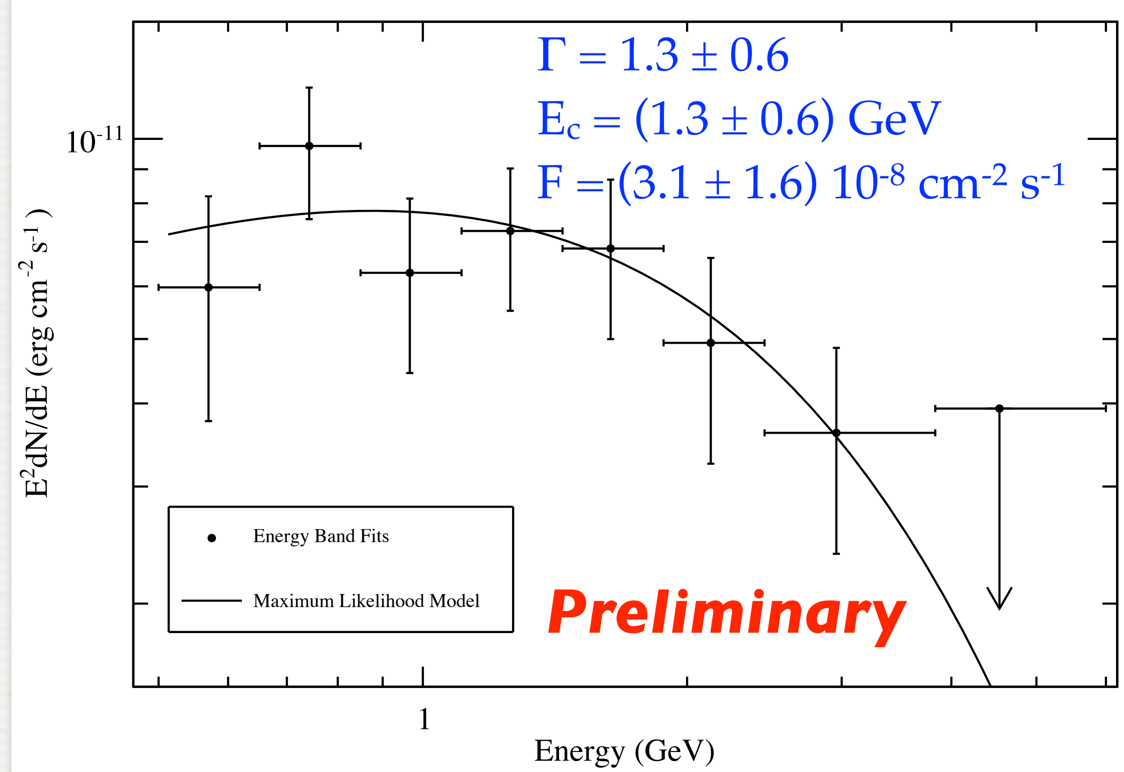
Large error bars, because of intense background.

However, the cutoff is statistically preferred over a simple power-law. Spectral properties similar to other MSPs.



PSR J1959+2048



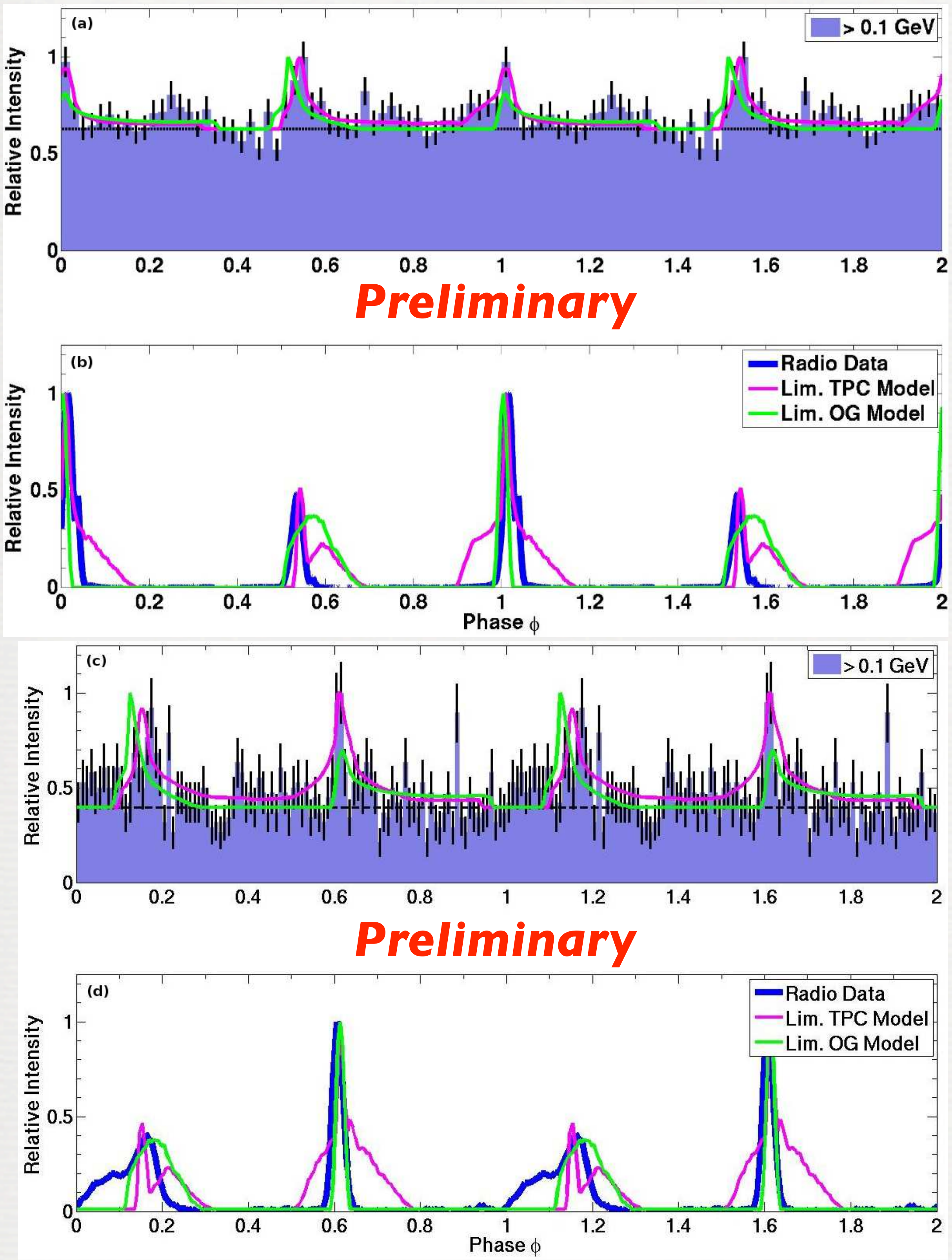


Similarly, pulsations for J1959+2048 were observed using 18 months of data.

Again, close radio/gamma-ray alignment!

The spectral modeling again shows a clear cutoff in the spectrum, and properties that resemble those of other gamma-ray MSPs.

Light curve modeling



PSR J0034-0534 *(Abdo et al., ApJ 712, 957, 2010)* was the first example of an MSP with aligned radio and gamma-ray emission.

We now have a subset of gamma-ray MSPs with aligned low and high-energy emission. The alignment suggests co-located emission regions.

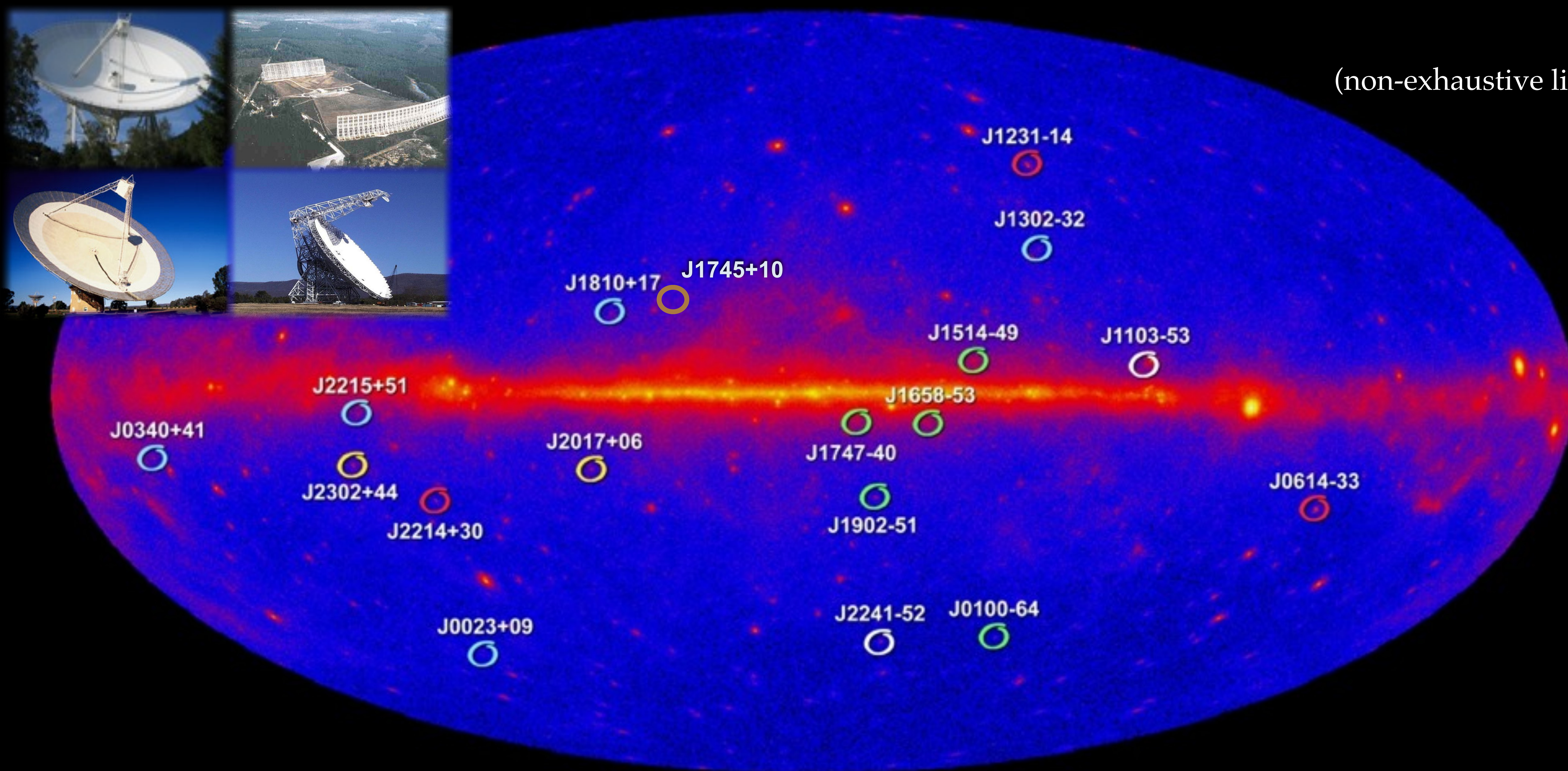
Radio and gamma-ray light curves well reproduced by «altitude-limited» Two-Pole Caustic (TPC) and Outer Gap (OG) models (ie, both radio and gamma-ray peaks are produced by caustics).

- <u>Outer Gap (OG):</u> two « caustics » originating from one magnetic pole.
- <u>Two-Pole Caustic (TPC):</u> « caustics » from both magnetic poles.

TPC and OG model fits yield large (α,ζ) angles, suggesting orthogonal rotators. Consistent with the observation of radio interpulses.

(Guillemot, Johnson, Venter et al., in preparation)

New MSPs in Fermi unidentified sources!



- Led by Fernando Camilo (Columbia Univ.) using Australia's CSIRO Parkes Observatory
- Led by Mallory Roberts (Eureka Scientific/GMU/NRL) using the NRAO's Green Bank Telescope
- Led by Scott Ransom (NRAO) using the Green Bank Telescope
- Led by Ismael Cognard (CNRS) using France's Nançay Radiotelescope
- Led by Mike Keith (ATNF) also using Parkes Observatory

Fermi Gamma-ray Space Telescope

>20 MSPs found in radio searches for pulsars in Fermi sources
(Previously: 70 Galactic disk MSPs found in 30 years!)

Two new MSPs found at Nançay

Distinctive indicators of emission from a gamma-ray pulsar are:

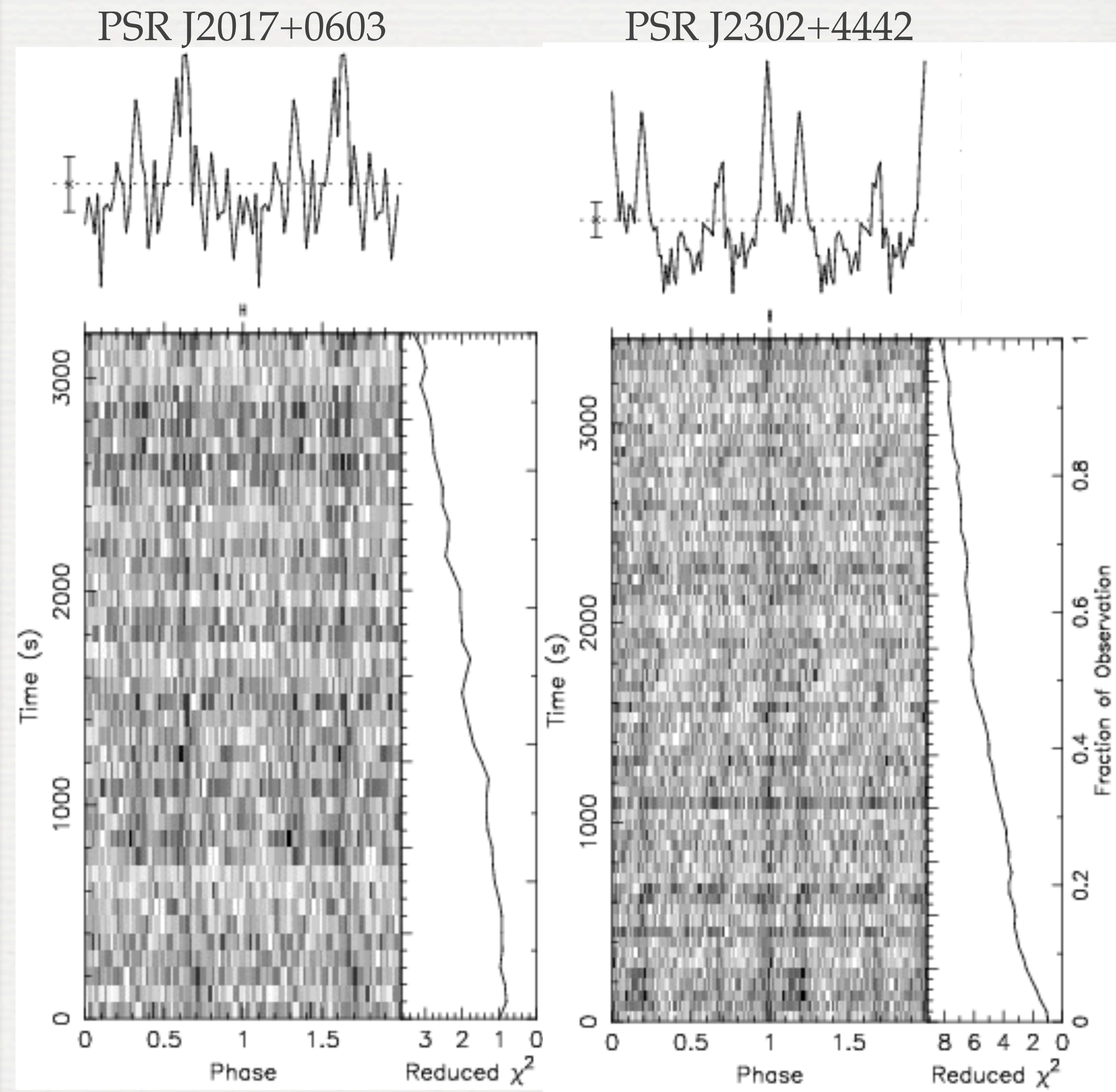
- Emission cutting off at a few GeV
- Lack of flux variability

Fermi sources exhibiting curvature in their spectra were searched with the Nançay radio telescope.

Two MSPs discovered in November 2009!

- PSR J2017+0603: P = 2.896 ms, d = 1.56 kpc (NE2001), P_b = 2.19 d
- PSR J2302+4442: P = 5.192 ms, d = 1.18 kpc (NE2001), P_b = 125.9 d

Cognard, Guillemot, Johnson et al., in prep (2010)



~1 hour observations of PSR J2017+0603 (left) in 1FGL J2017.3+0603 and PSR J2302+4442 (right) in 1FGL J2302.8+4443 at Nançay

Radio & gamma-ray pulsar timing

Timing observations were undertaken at different telescopes, after the discoveries.

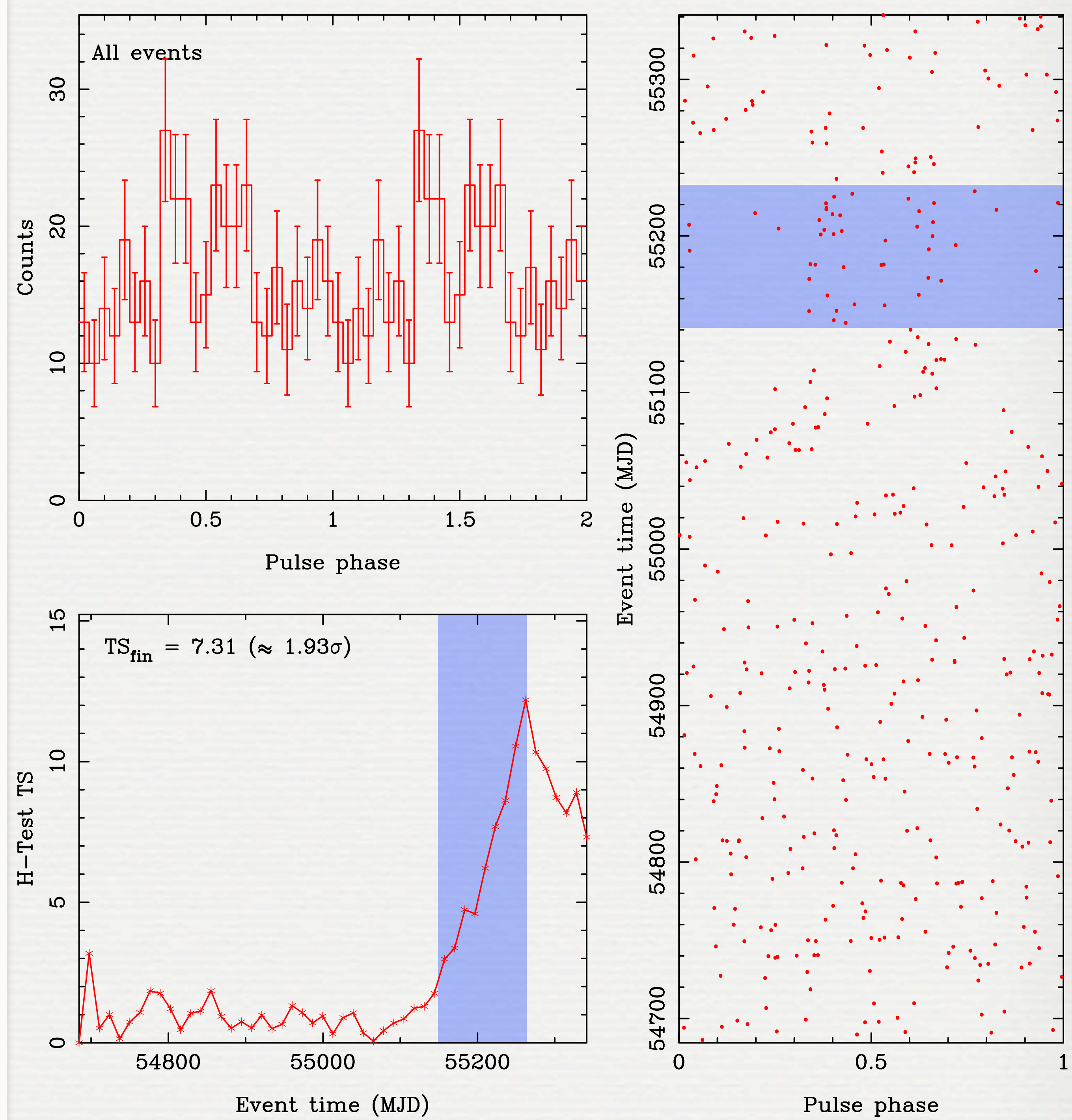
➡ PSR J2017+0603: Nançay, Lovell telescope at JBO.

➡ PSR J2302+4442: Nançay, JBO, Green Bank.

The initial timing solutions were used to fold the gamma-ray data. Clear hints of pulsations observed!

However: quick loss of phase-coherence outside the ephemeris validity interval (mainly due to uncertain position and dP/dt).

➡ Need to use the gamma-ray data to nail down pulsar parameters.



Gamma-ray light curves for PSR J2017+0603 (initial timing solution)

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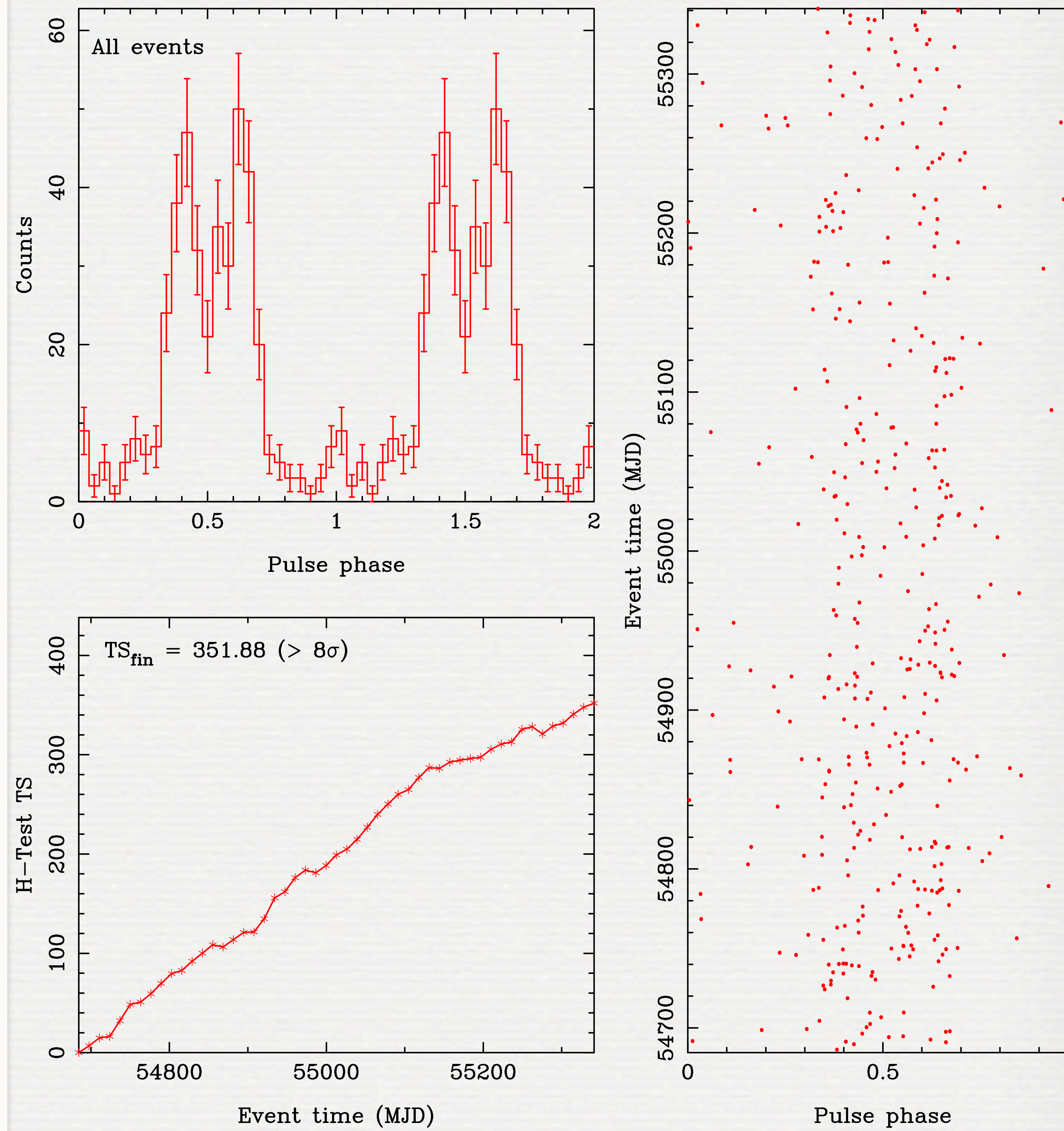
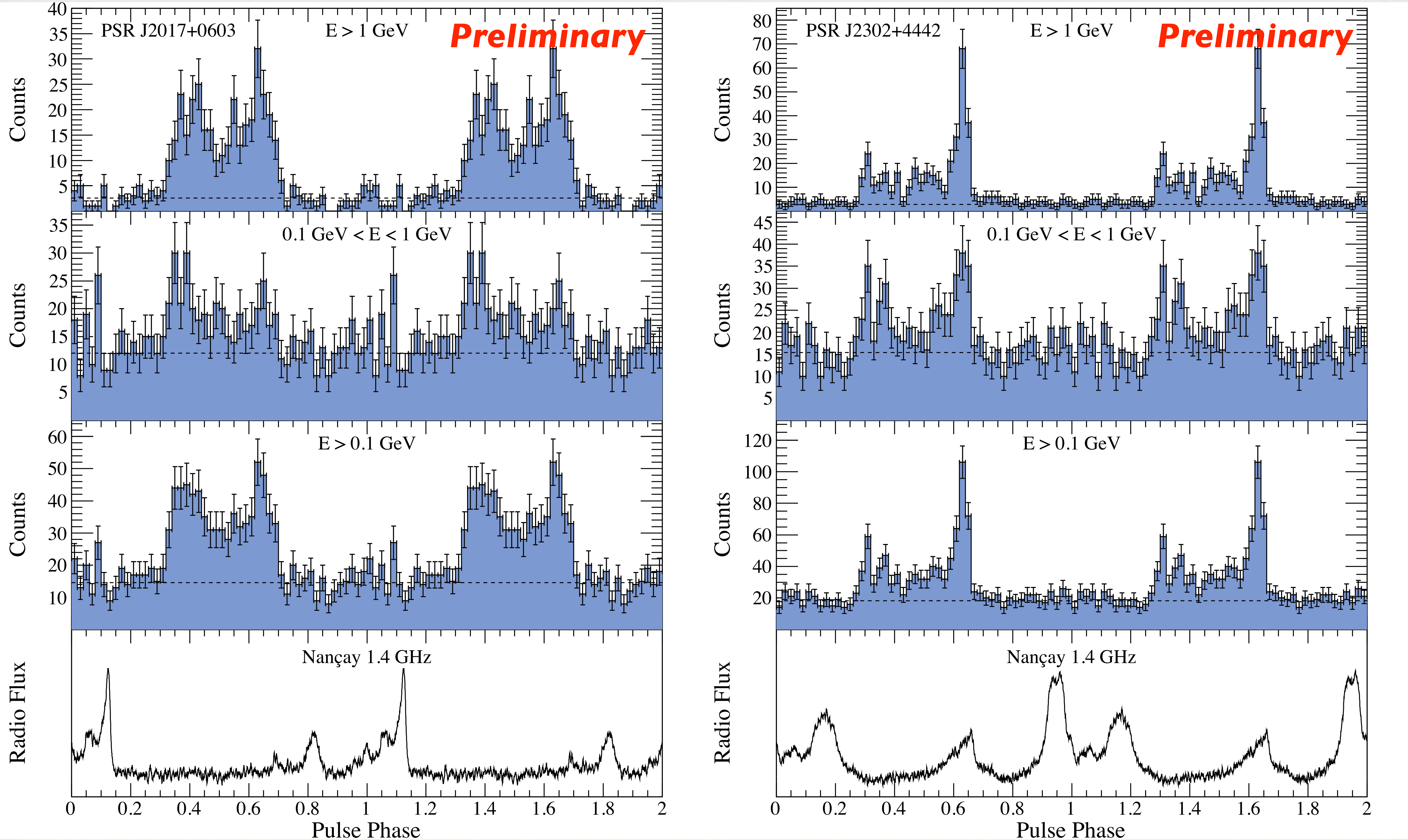
Gamma-ray TOAs were extracted using the prescriptions in *Ray, et al., in prep. (2010)*.

Phase-coherence ensured over > 2 yr!



Gamma-ray light curves for PSR J2017+0603 (final timing solution)



Above: light curves in different energy bands for PSRs J2017+0603 and J2302+4442.

Reminiscent of other radio and gamma-ray light curves of millisecond pulsars: radio profiles exhibiting complexity, two-peak gamma-ray profiles with mid-points separated by ~0.5 from the radio emission.

Spectral analysis

Gamma-ray spectra are well reproduced by exponentially cutoff power law models.

(the current data do not allow to discriminate between β=1 and $\beta \neq 1$ fits)

Measured spectral properties are also very similar to those of other gamma-ray MSPs.

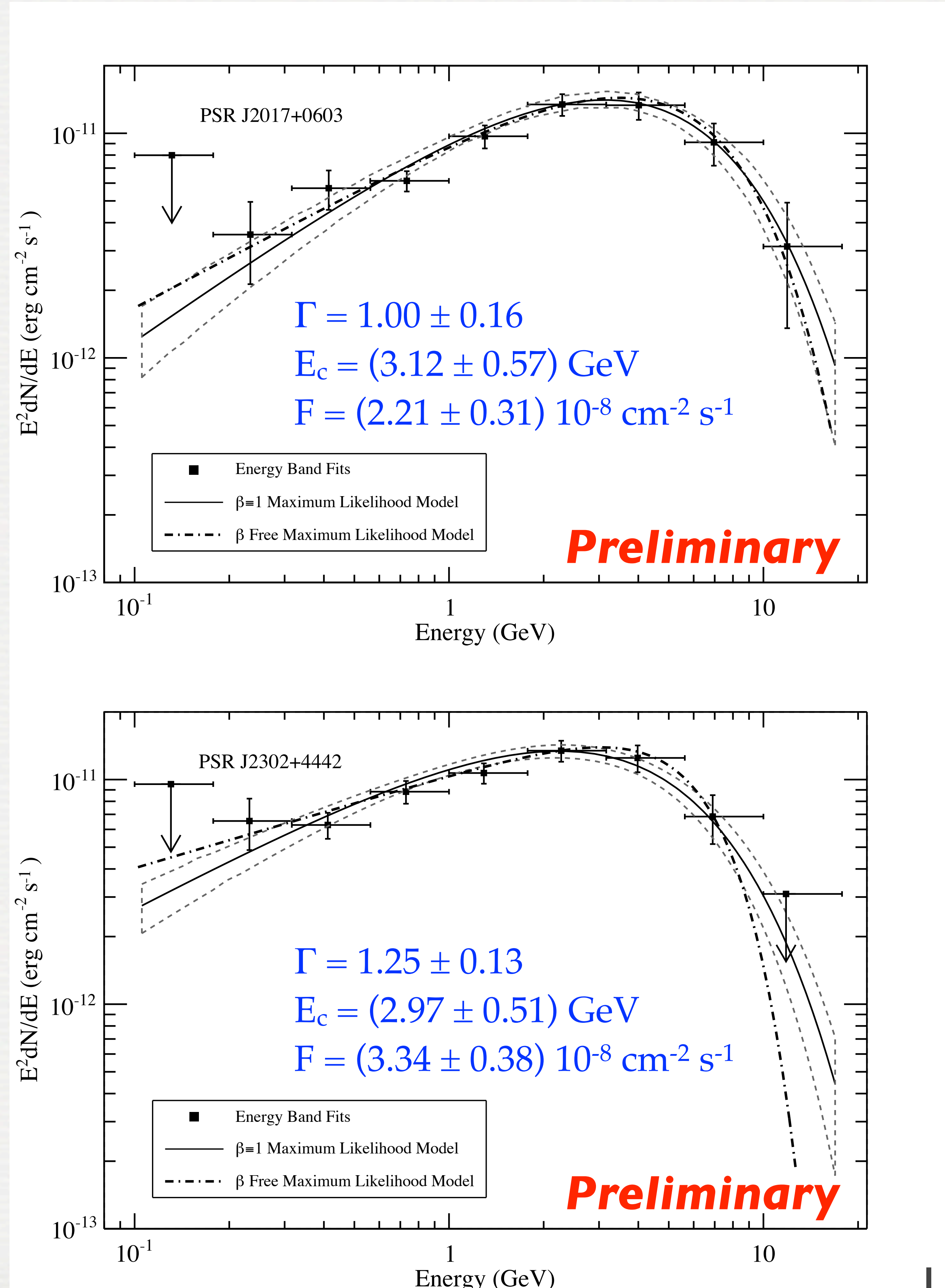
Energy fluxes:

➡ J2017+0603: G = (3.71 ± 0.24) 10^{-11} erg cm^{-2} s^{-1}

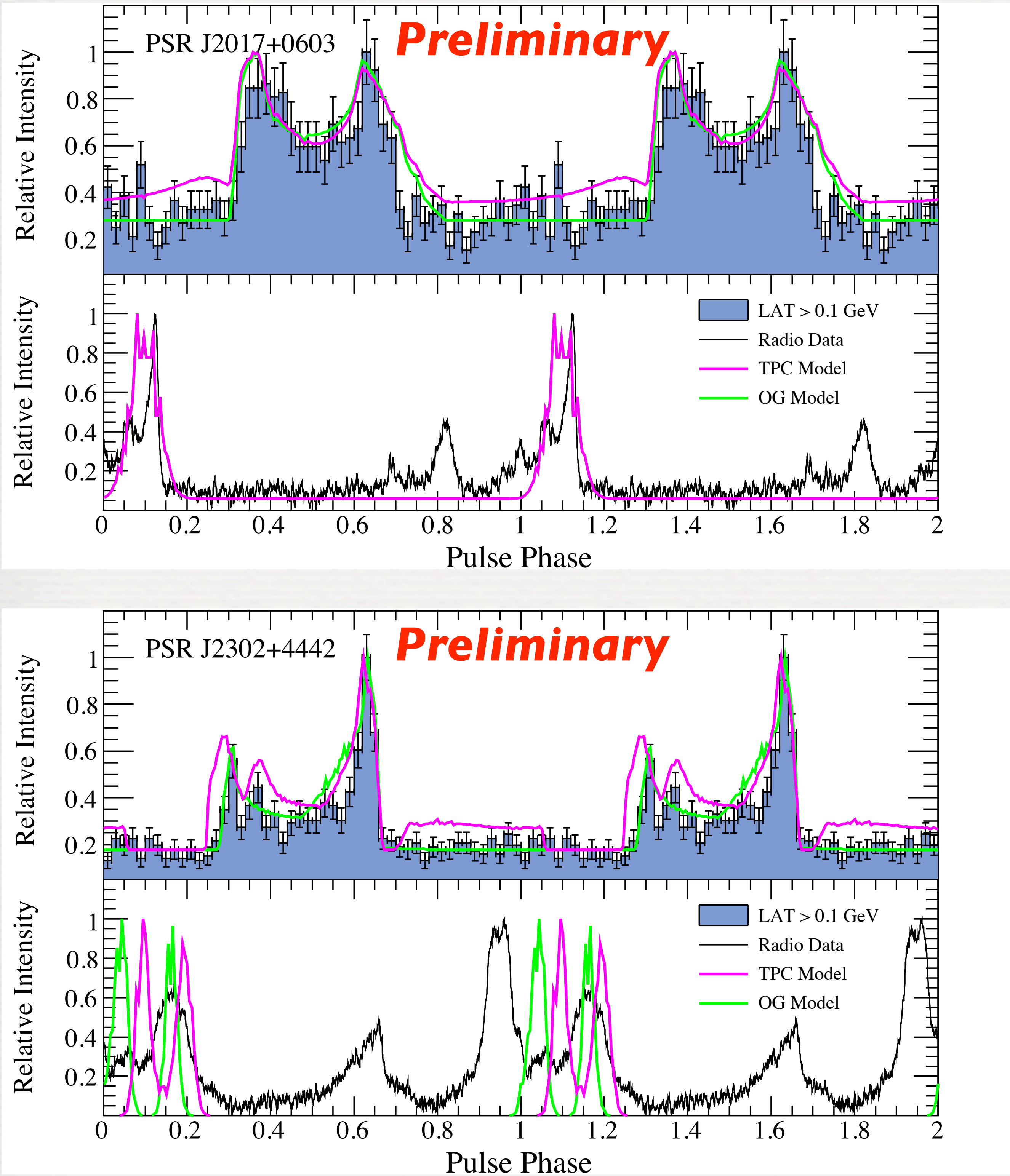
➡ J2302+4442: G = (3.94 ± 0.22) 10^{-11} erg cm^{-2} s^{-1}

= consistent with fluxes of 1FGL sources.

The two pulsars thus are the natural associations for the 1FGL sources.



Light curve modeling



Gamma-ray light curves were modeled using standard magnetospheric models.

Radio emission modeled using a cone beam centered on the magnetic axis, at a single altitude *(Story et al., 2007).*

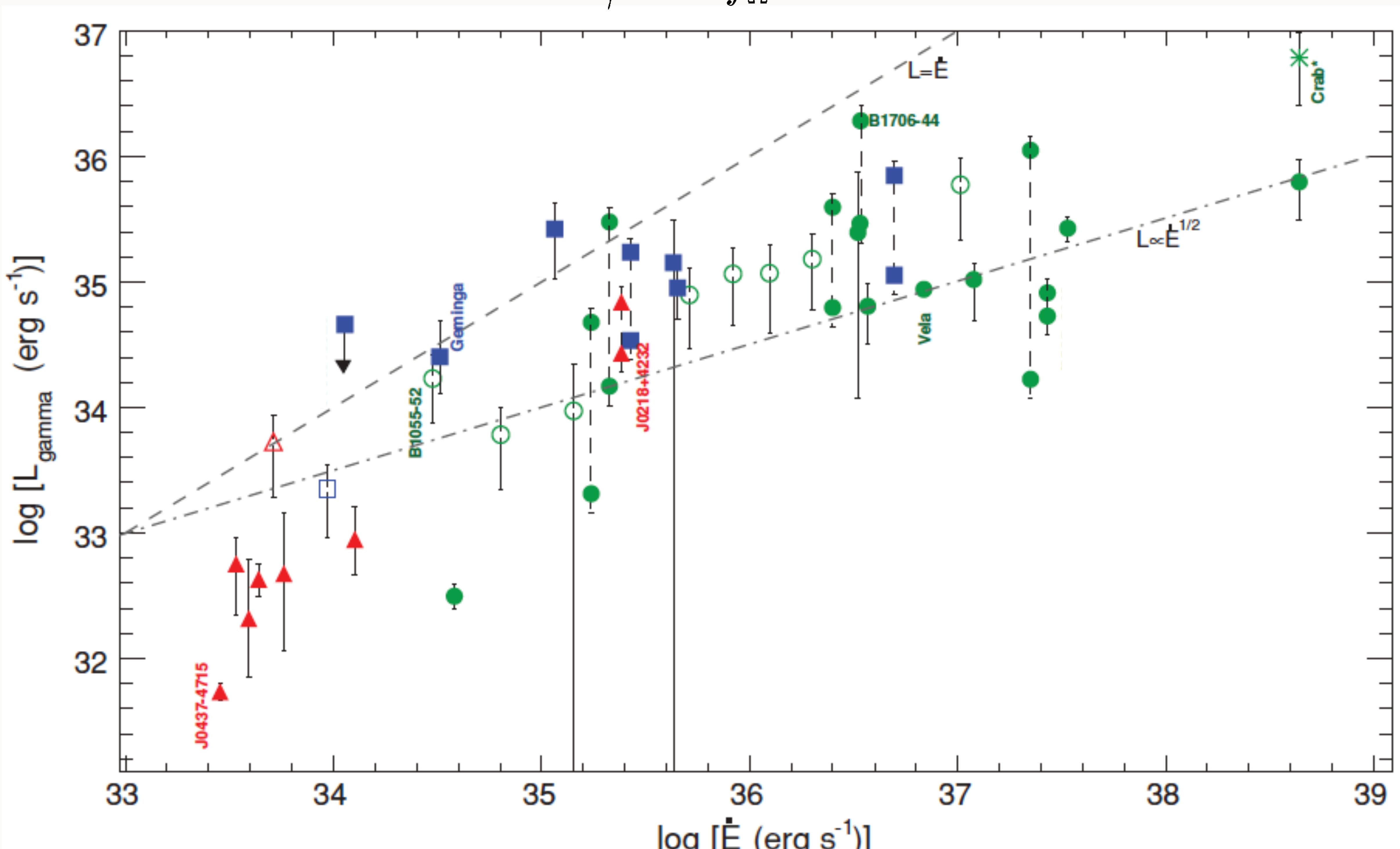
High-energy profiles are reproduced well by both models.

The radio model is however not successful at reproducing the observed light curves.

Radio emission coming from both poles? Multiple altitudes? Still much to be learned about radio emission geometry...

Gamma-ray luminosities

$$L_\gamma = 4\pi f_\Omega G d^2$$



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

Gamma-ray luminosities

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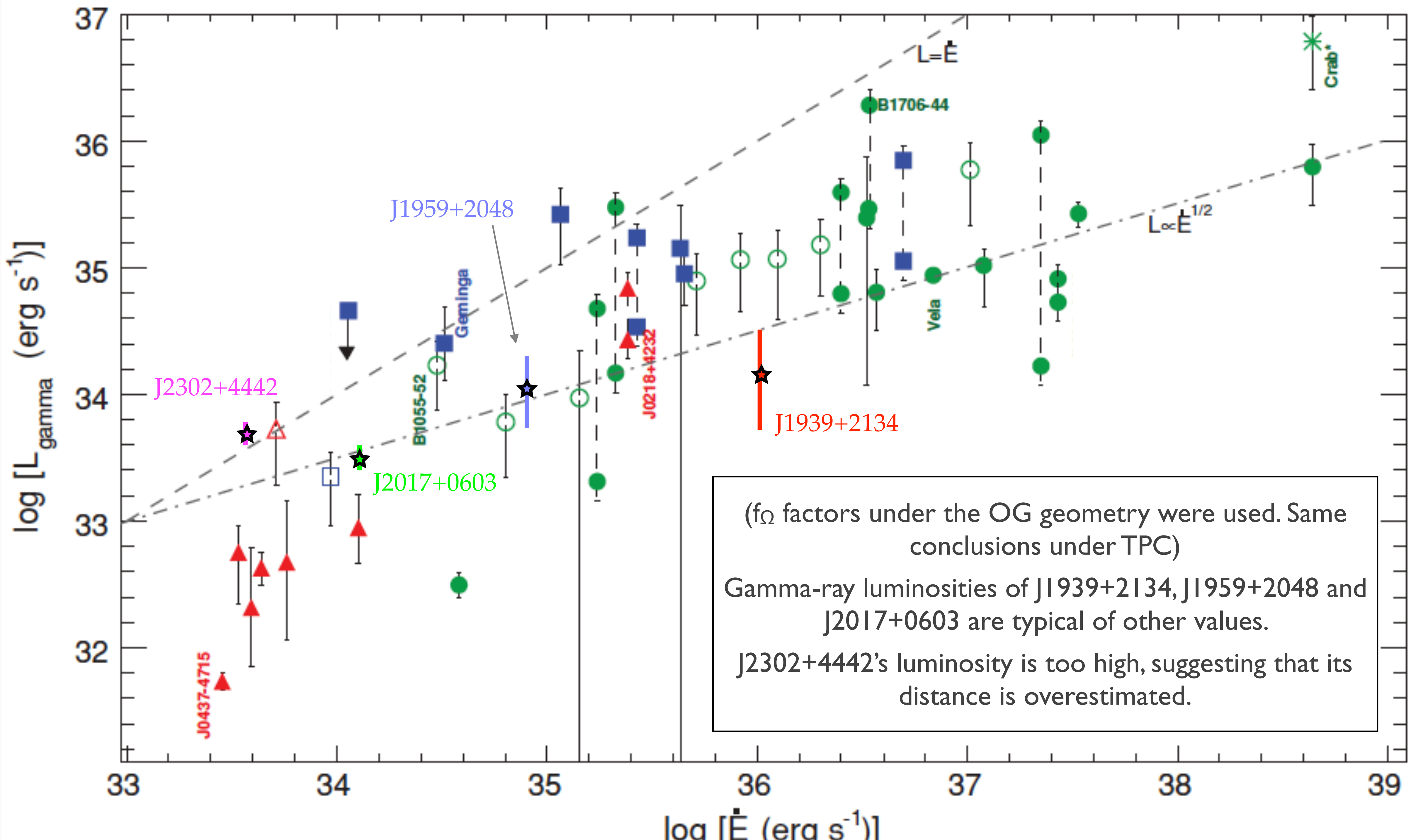


(f$_\Omega$ factors under the OG geometry were used. Same conclusions under TPC)

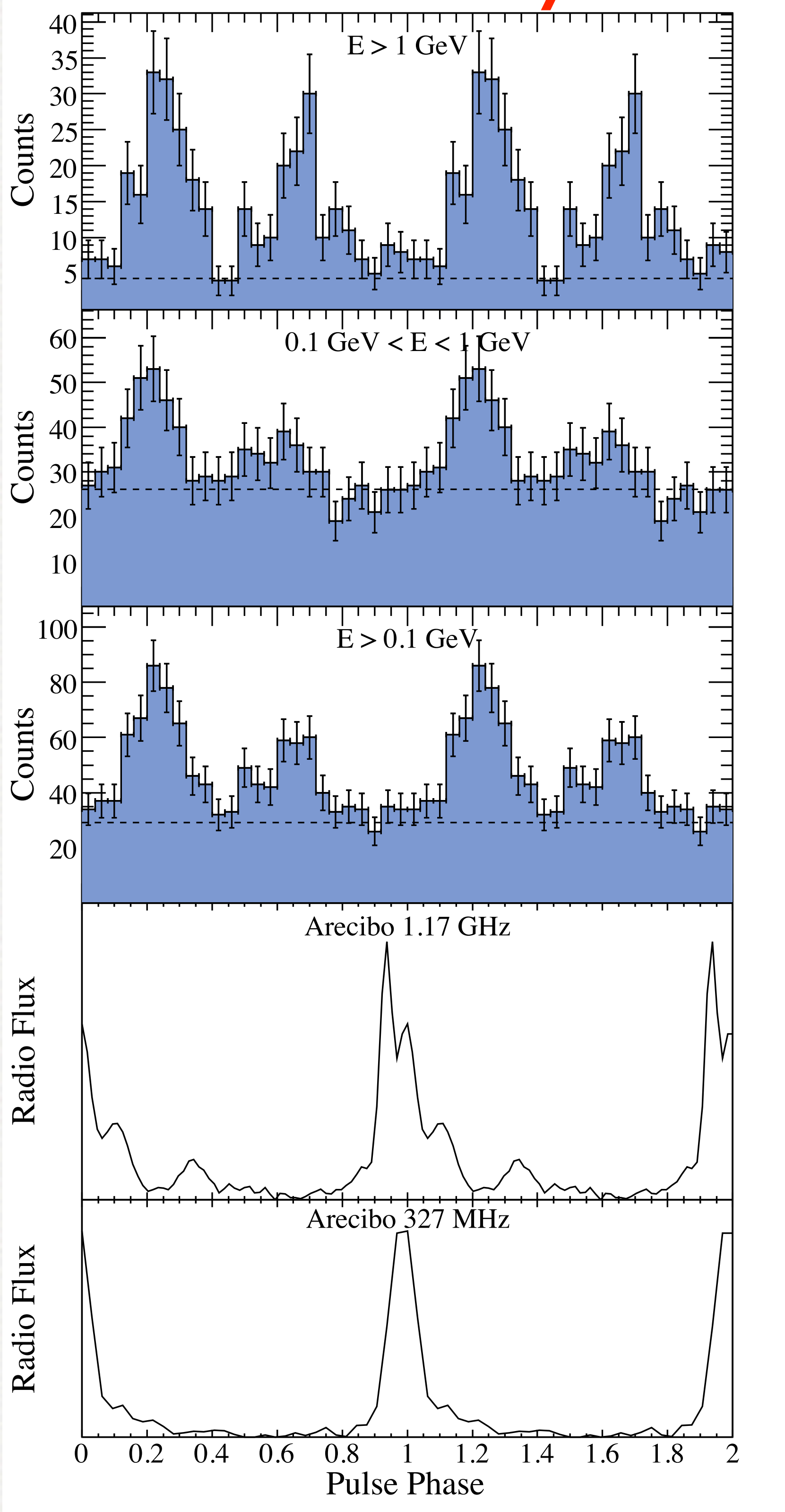
Gamma-ray luminosities of J1939+2134, J1959+2048 and J2017+0603 are typical of other values.

J2302+4442's luminosity is too high, suggesting that its distance is overestimated.

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

A third MSP found at Nançay!

Preliminary



Recently (June 2010), a 3rd MSP, PSR J2043+1710, has been discovered with the Nançay radio telescope!

Discovery confirmed with GBT (thanks Scott Ransom and Paul Ray!)

(P = 2.379 ms, $\dot{E}$ = 1.8 10^{34} erg/s, d = 1.8 kpc,

P_b = 1.48 d)

In ~10 observations, the pulsar was only seen once at Nançay. However, observations conducted by Paulo Freire showed that the pulsar can be monitored well at Arecibo.

A sharp peak, yet unresolved, is observed at 1.17 GHz, making it a potentially good addition for PTAs.

Using a timing solution based on Arecibo timing observations made after the discovery, gamma-ray pulsations were detected!

Analysis in progress (*Guillemot, Freire, Cognard,et al., in preparation*).

Summary

As data accumulate, the Fermi LAT continues to detect radio MSPs. We detected PSRs J1939+2134 and J1959+2048 in gamma rays, using 18 months of data.

They exhibit aligned radio and gamma-ray profiles. There is now a subclass of MSPs with aligned radio and gamma-ray profiles. Light curve modeling suggests co-located radio and gamma-ray emission, at high altitude.

The last year has seen a burst of discoveries of MSPs in Fermi unassociated sources. Three of the >20 MSPs have been discovered at Nançay, and all three are gamma-ray pulsars.

Light curves and spectra of these MSPs are similar to those of other gamma-ray MSPs. However, PSR J2302+4442 appears too efficient, indicating an overestimated distance.

If most newly discovered MSPs are also gamma-ray emitters, then 1/3 of the gamma-ray pulsar population will be MSPs!

Fermi
Gamma-ray
Space Telescope

Thank you for your attention!

Two nearby energetic MSPs

<u>PSR J2017+0603:</u>

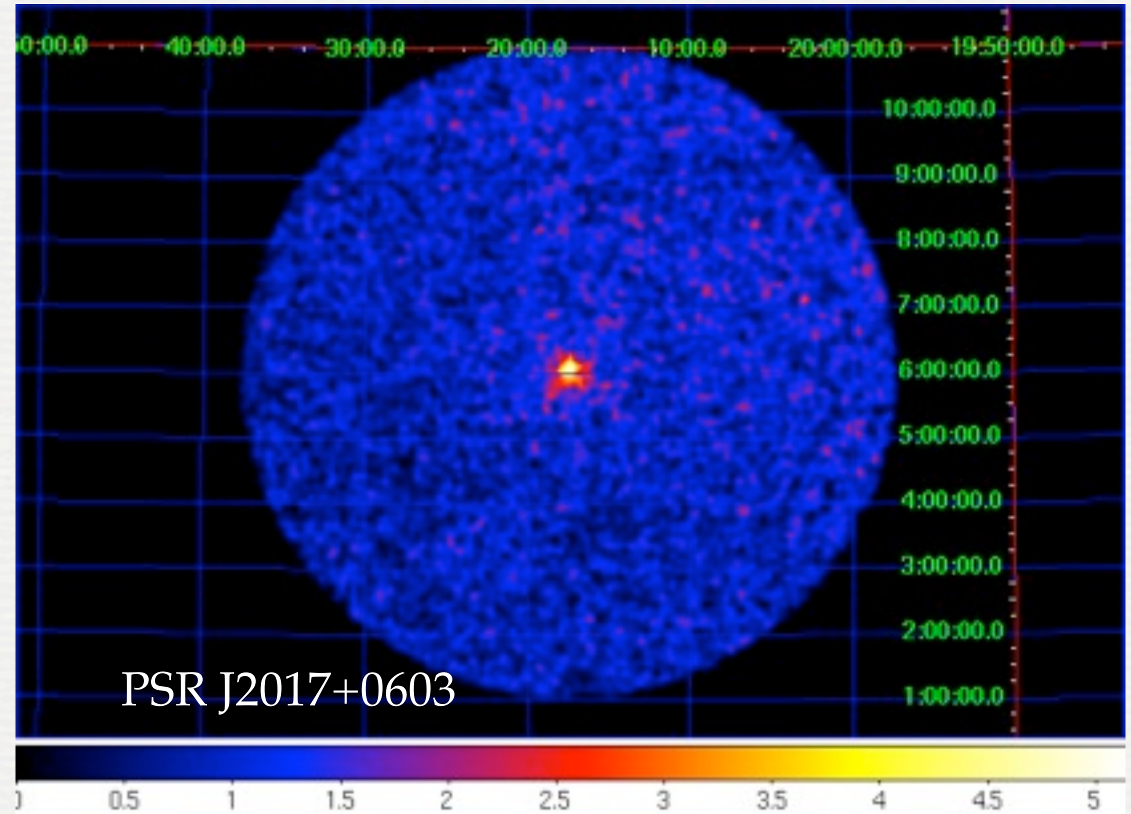
- (l,b) = (48.6, -16.0)
- DM = 23.9 cm^{-3} pc ⇒ d = 1.56 kpc (NE2001)
- P = 2.896 ms, dP/dt = 8.3 10^{-21} s/s
- dE/dt = 1.34 10^{34} erg/s
- 2.19 day orbital period.

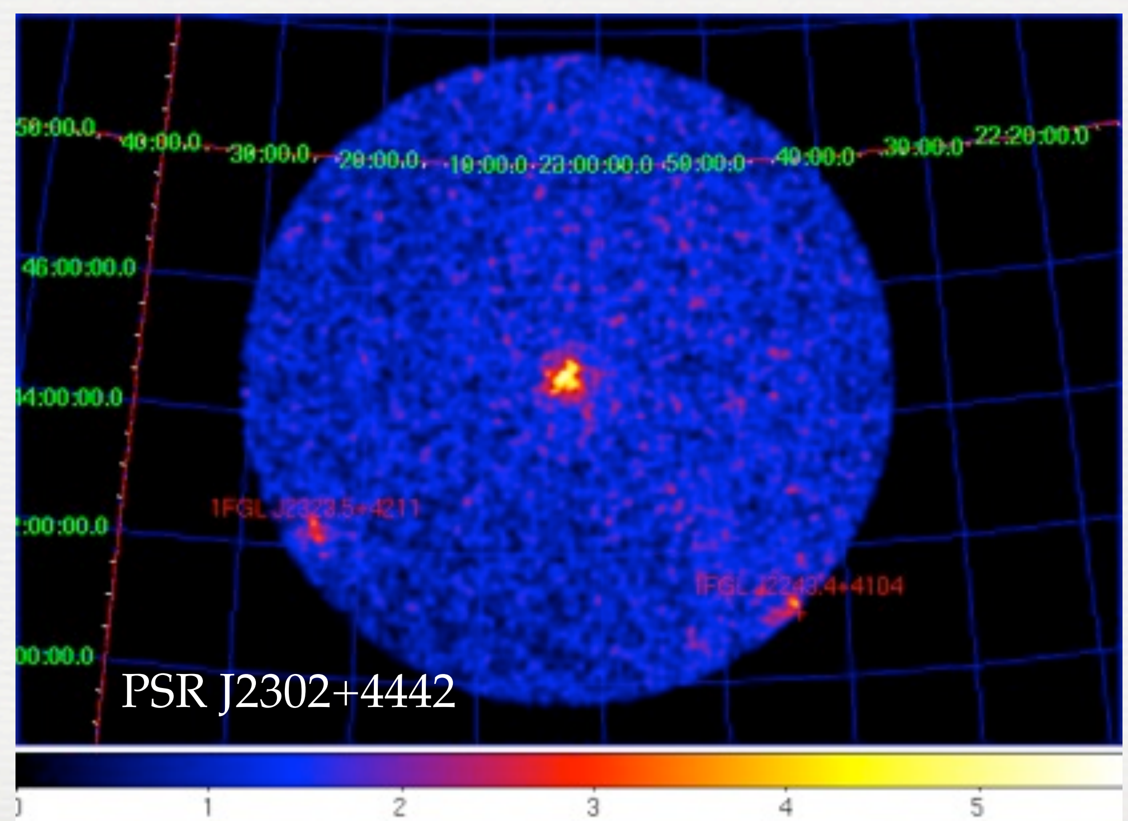
<u>PSR J2302+4442:</u>

- (l,b) = (103.4,-14.0)
- DM = 13.8 cm^{-3} pc ⇒ d = 1.18 kpc (NE2001)
- P = 5.192 ms, dP/dt = 13.3 10^{-21} s/s
- dE/dt = 3.75 10^{33} erg/s
- 125.9 day orbital period.

Are the two MSPs powering the gamma-ray sources in which they were found?

Right: 5° radius maps of the gamma-ray sky around PSR J2017+0603 (top) and J2302+4442 (bottom)





Optical, UV & X-ray observations

Swift UVOT (optical & UV) data were searched for counterparts, to no avail.

No X-ray counterpart for J2017+0603 was found in Swift XRT data (0.5 to 8 keV).

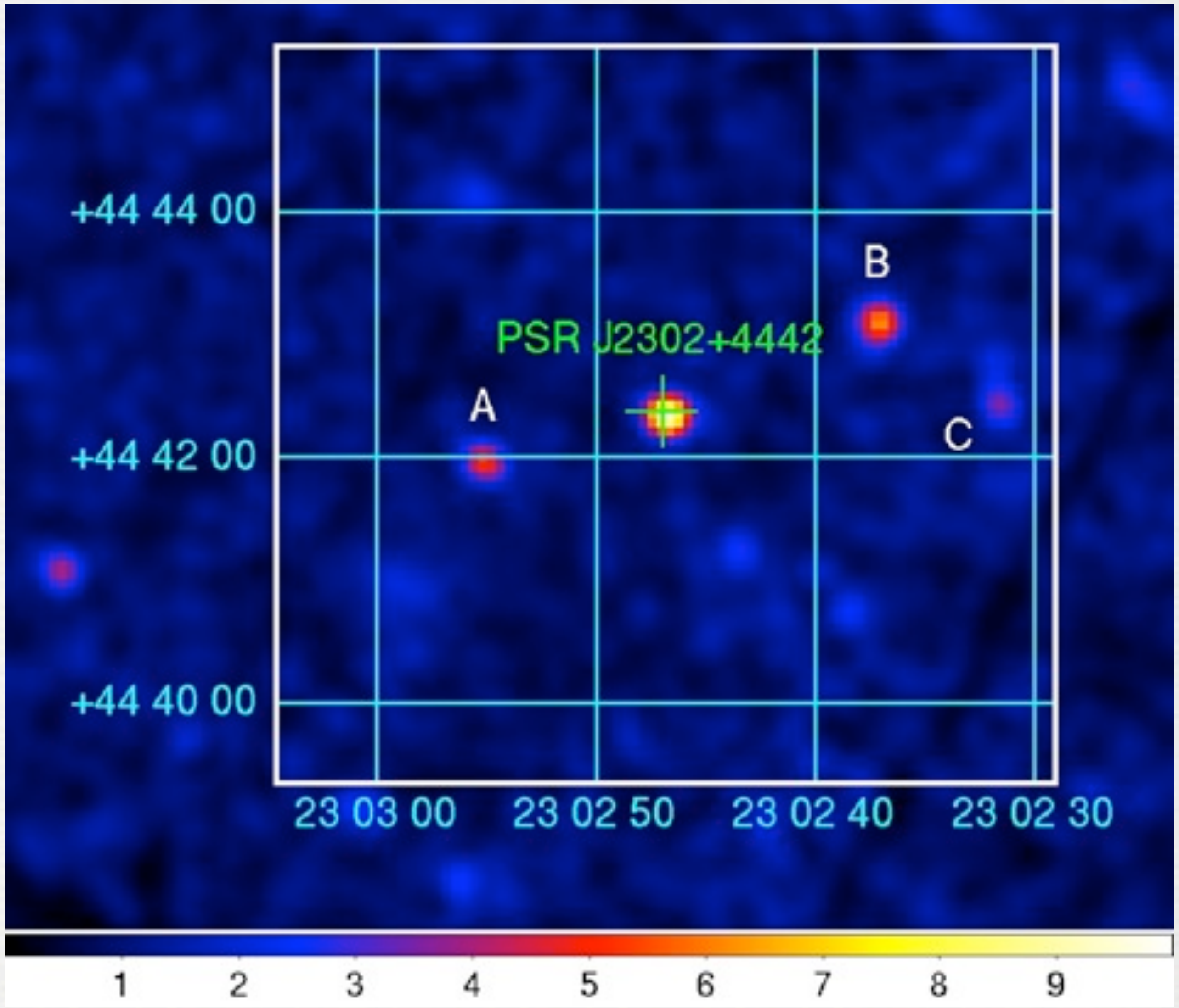
However, a faint X-ray source is observed at the position of J2302+4442, confirmed with XMM observations.

Derived X-ray flux and neutron star temperature (blackbody model):

- $G = (1.8^{+1.9}_{-1.3})\ 10^{-14}$ erg cm^{-2} s^{-1}.
- $T_{eff} = (7.5^{+1.3}_{-1.1})\ 10^{5}$ K, comparable to old neutron star temperatures *(Lattimer & Prakash 2004)*.

X-ray signal likely to be produced by the pulsar!

A long observation in timing mode is thus likely to yield X-ray pulsations.



XMM image of the field of PSR J2302+4442 (25 ks exposure). Color scale: counts/pixel.