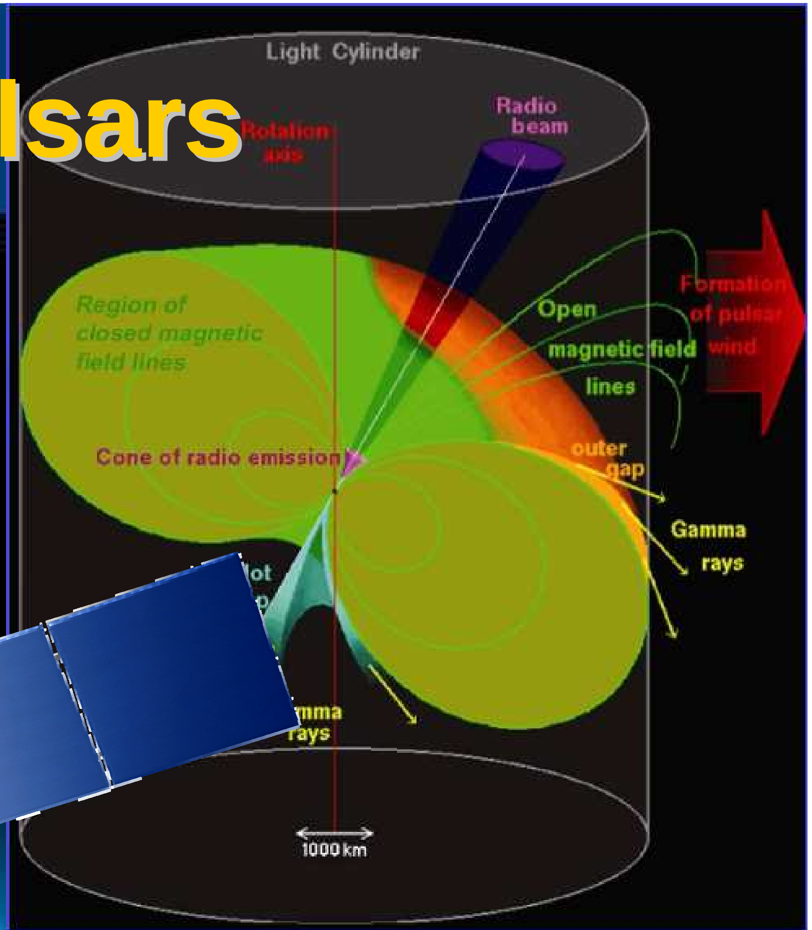
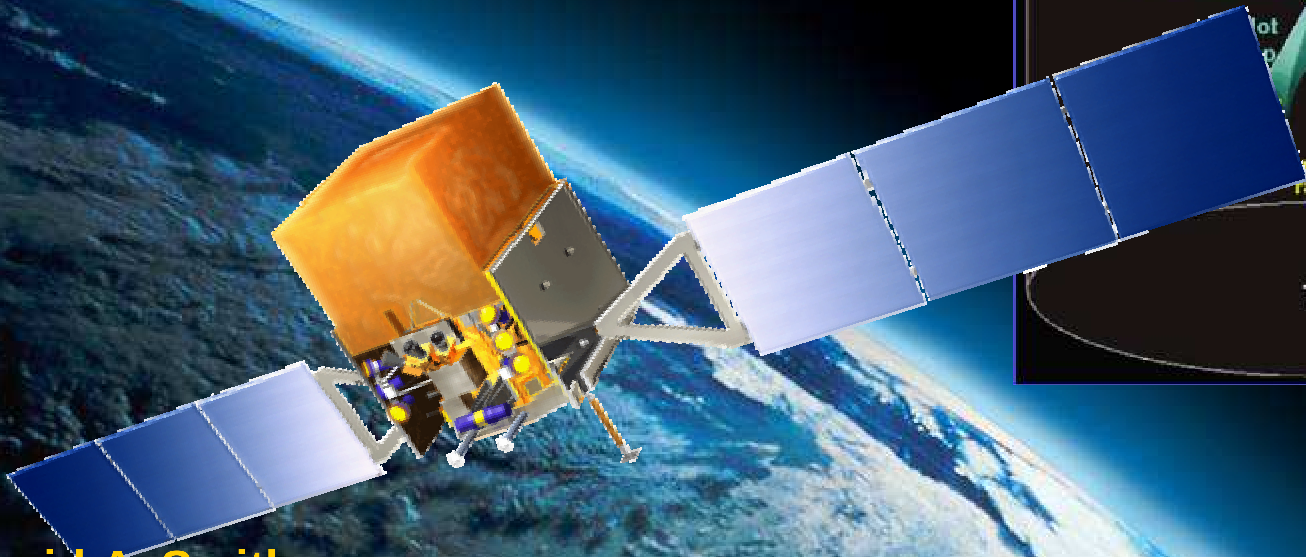
# Gamma Ray Pulsars

with the

# *Fermi* LAT



**David A. Smith,** for the

*Fermi* LAT collaboration ☸ Pulsar Timing and ☸ Search Consortia (PTC / PSC )

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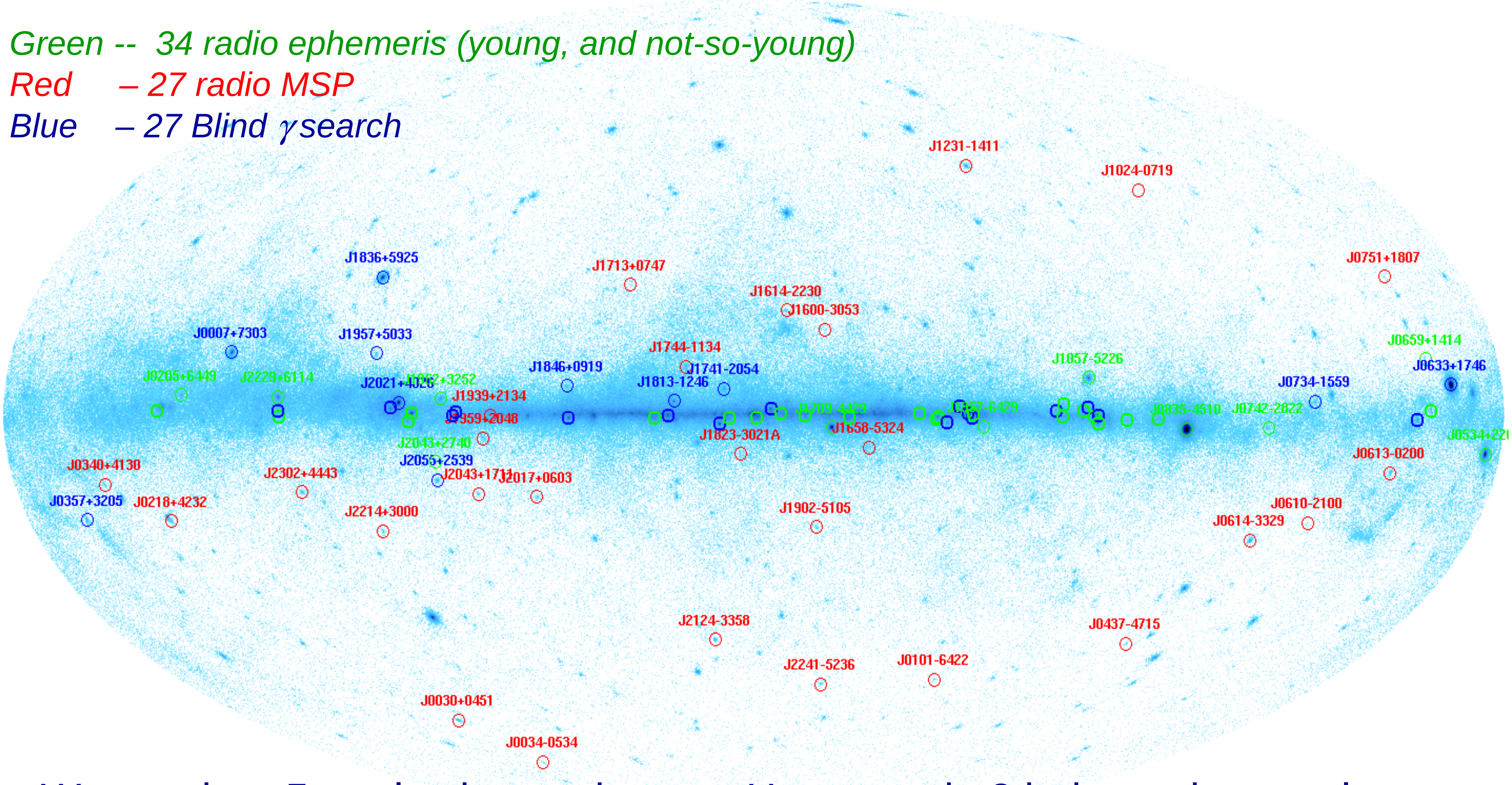
**3rd *Fermi* Symposium**
**Rome, 12 May 2011**

# 88 Gamma-ray pulsars

*One for every musical note on a piano. One for every constellation.*

*Green -- 34 radio ephemeris (young, and not-so-young)*
*Red – 27 radio MSP*
*Blue – 27 Blind $\gamma$ search*




We require >5σ pulsations using e.g. H-test, and ≥2 independent analyses.

*~10 more with >4σ. Also awaiting ephemerides for ~20 MSPs found in UnId sources.*

*There were 46 in the "1st Fermi Pulsar Catalog",* Abdo et al. ApJS 187, 460 (2010)

# 88 γ pulsars, *seen from above*

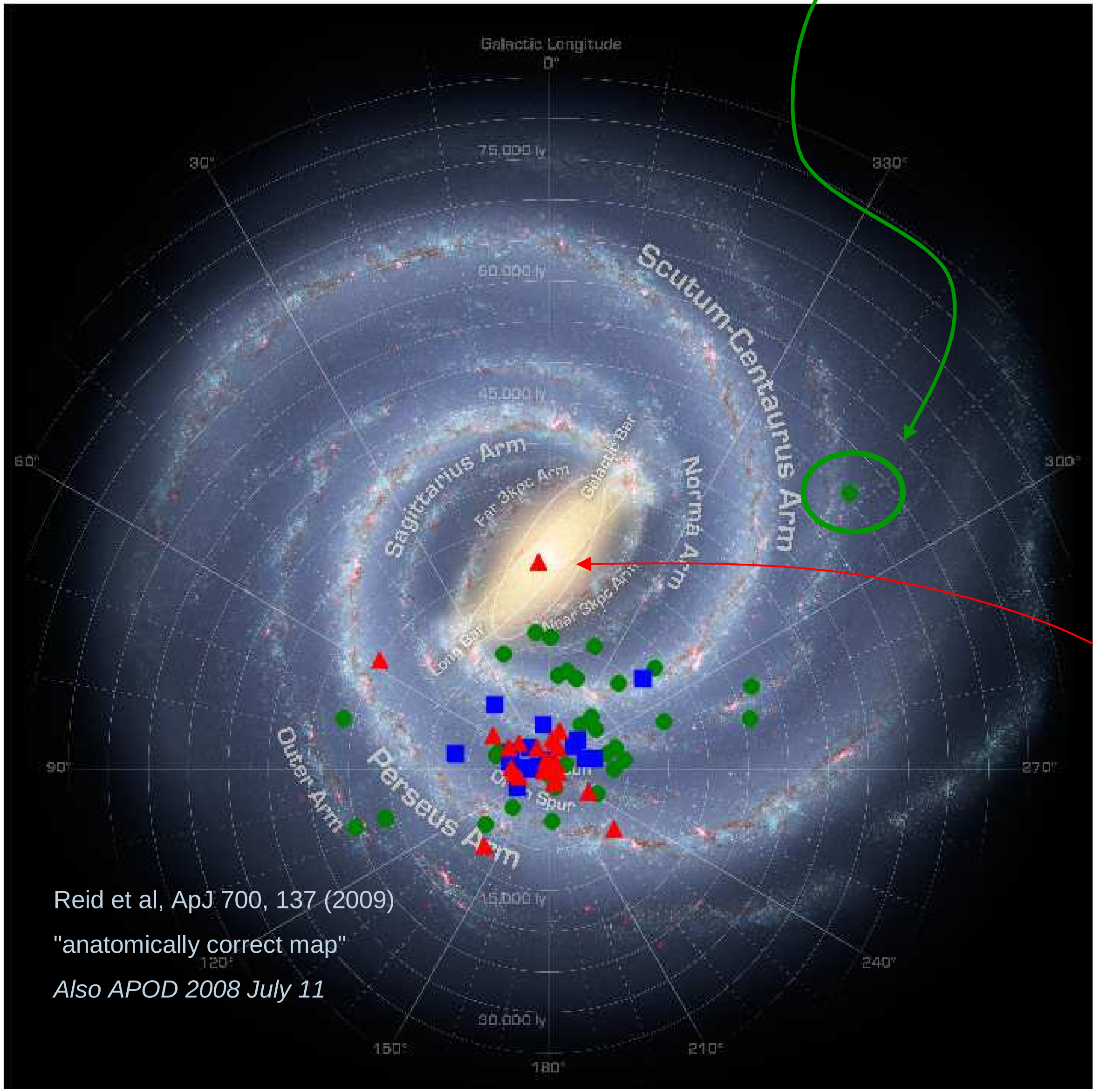
Example: PSR J1410-6132

Parkes radio rotation ephemeris

Period = 50 ms
$\dot{E}$ = 1E37 erg/s

HESS TeV PWN overlaps.

*The NE2001 DM distance of 15.6 kpc needs cross-checks.*



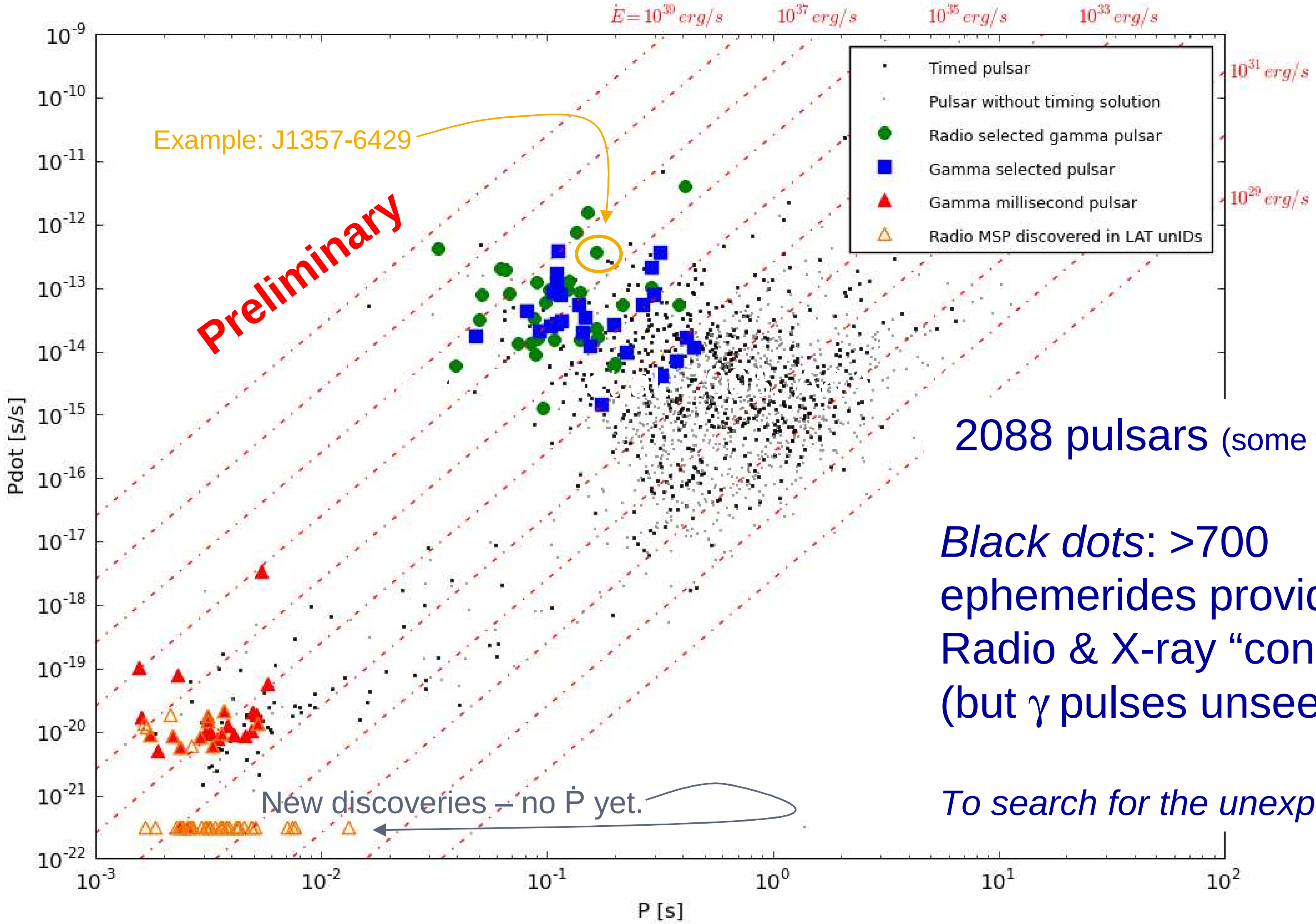

Reid et al, ApJ 700, 137 (2009)
"anatomically correct map"
*Also APOD 2008 July 11*

*The MSP-in-globular cluster is far above the galactic plane.*

D. Parent et al, poster PSR S2.N23.

# P-Ṗ diagram

Pre-launch timing campaign*: Ė > 1E34 erg/s. We see pulsars down to Ė ~ 3E33 erg/s



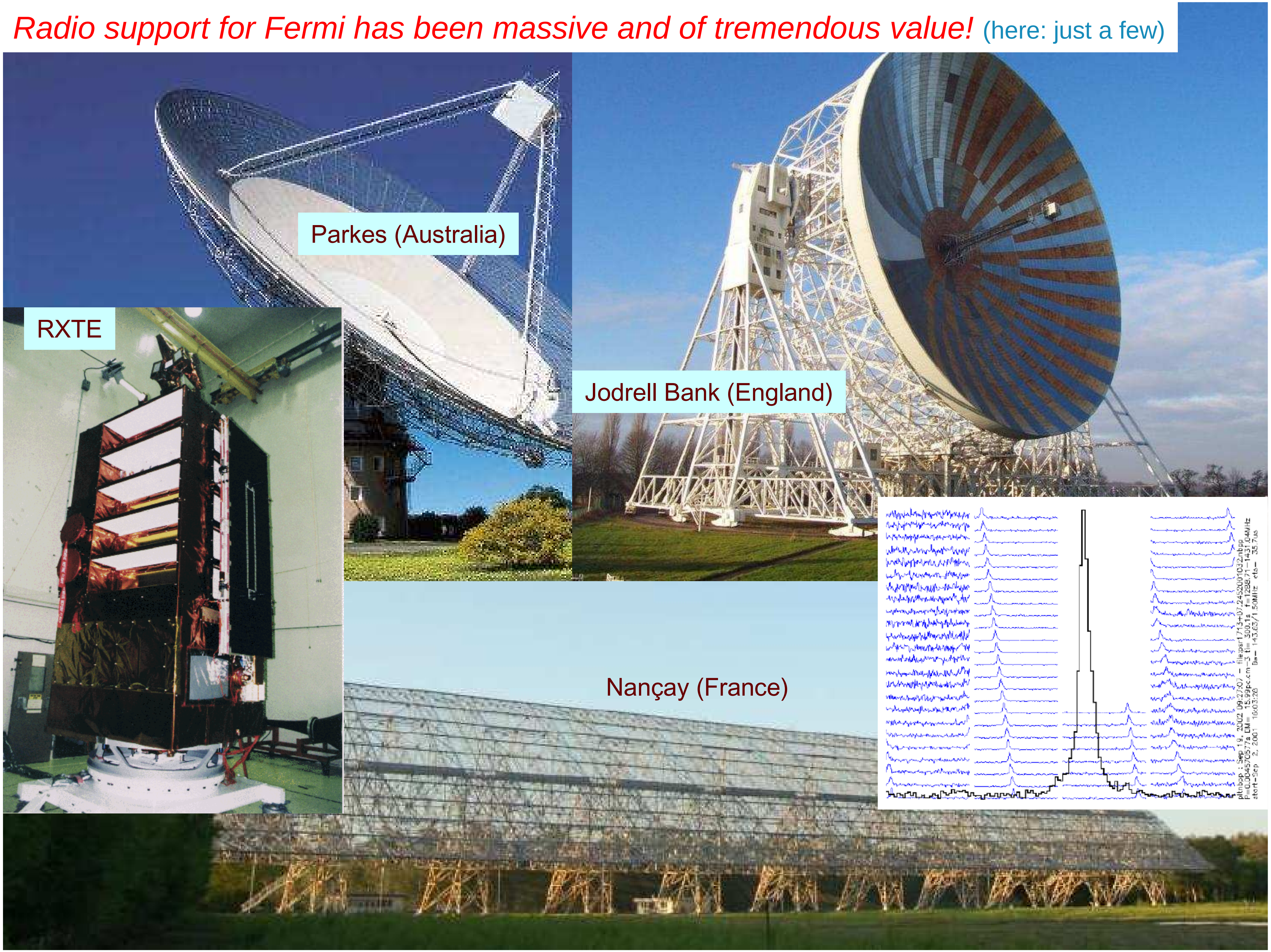

2088 pulsars (some without Ṗ).

*Black dots*: >700 ephemerides provided by Radio & X-ray "consortium" (but γ pulses unseen).

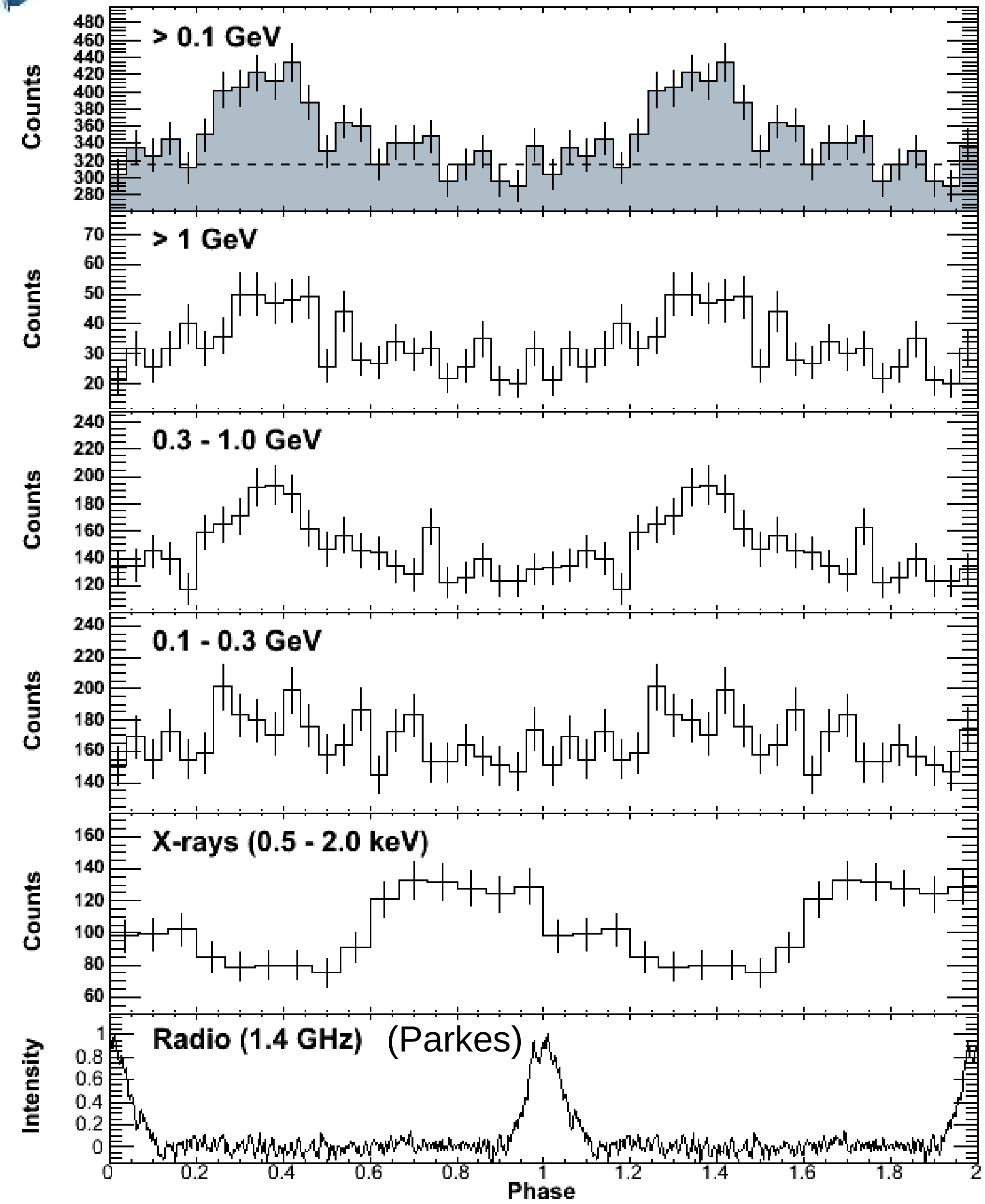
*To search for the unexpected…*

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

*Radio support for Fermi has been massive and of tremendous value!* (here: just a few)



# Example: PSR J1357-6429 (1 of 3)

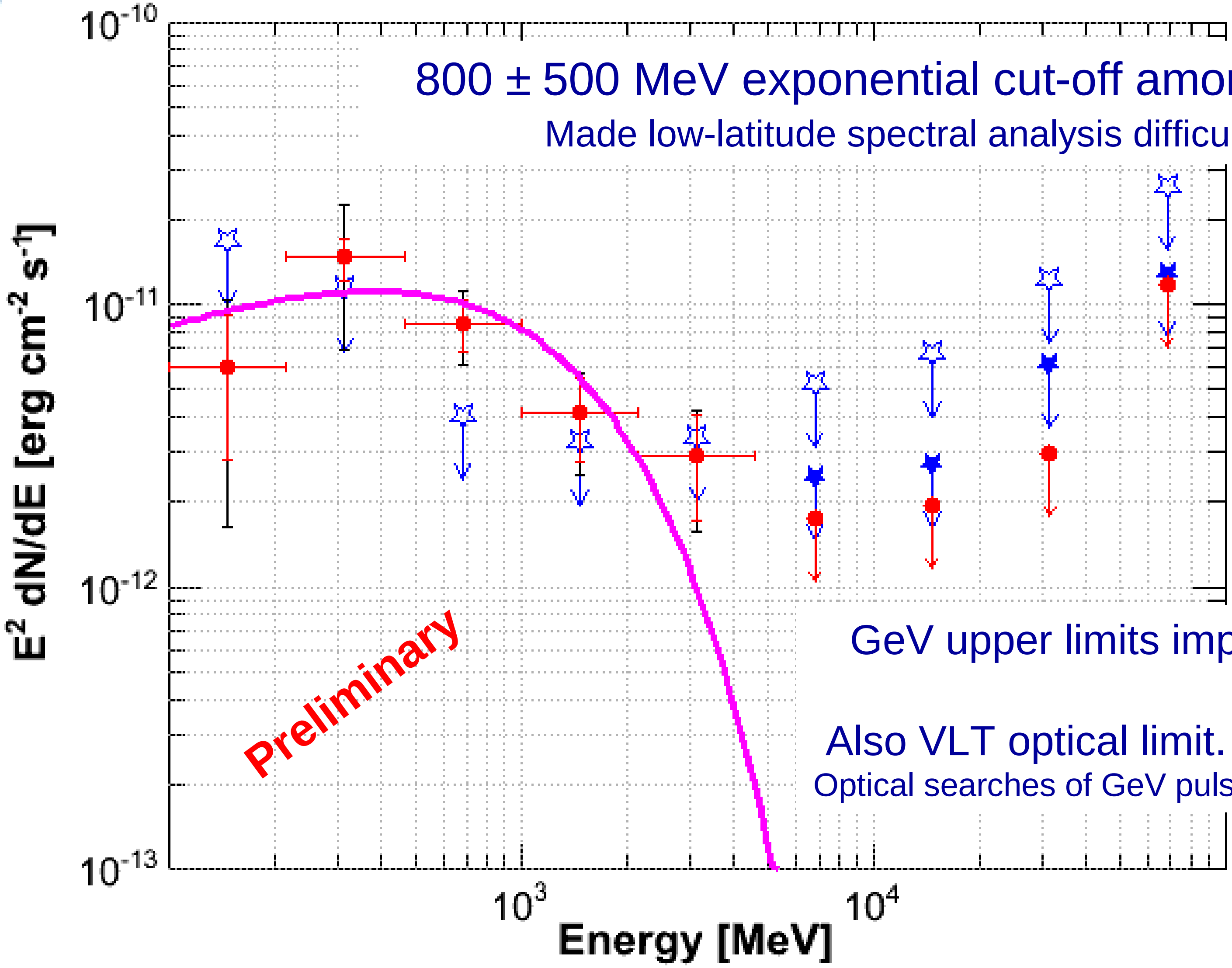



- HESS was concluding their analysis of the associated TeV pulsar wind nebula (PWN).
  Abramowski et al, A&A to be submitted.
- They thought "LAT sees no pulses? Perhaps GeV PWN!"
- *Wrong* – a glitch in 2009 and timing noise ➔ no ephemeris.
- Got ephemeris. Got $\gamma$ pulsations.
  Lemoine-Goumard et al, A&A to be submitted.
- Applied ephemeris to public 2009 XMM data, and confirmed Zavlin (2007)'s weak *Chandra* pulsations.

# Example: PSR J1357-6429 (2 of 3)

800 ± 500 MeV exponential cut-off amongst LAT's lowest.

Made low-latitude spectral analysis difficult… (typical $\Gamma$=1.5±0.3)



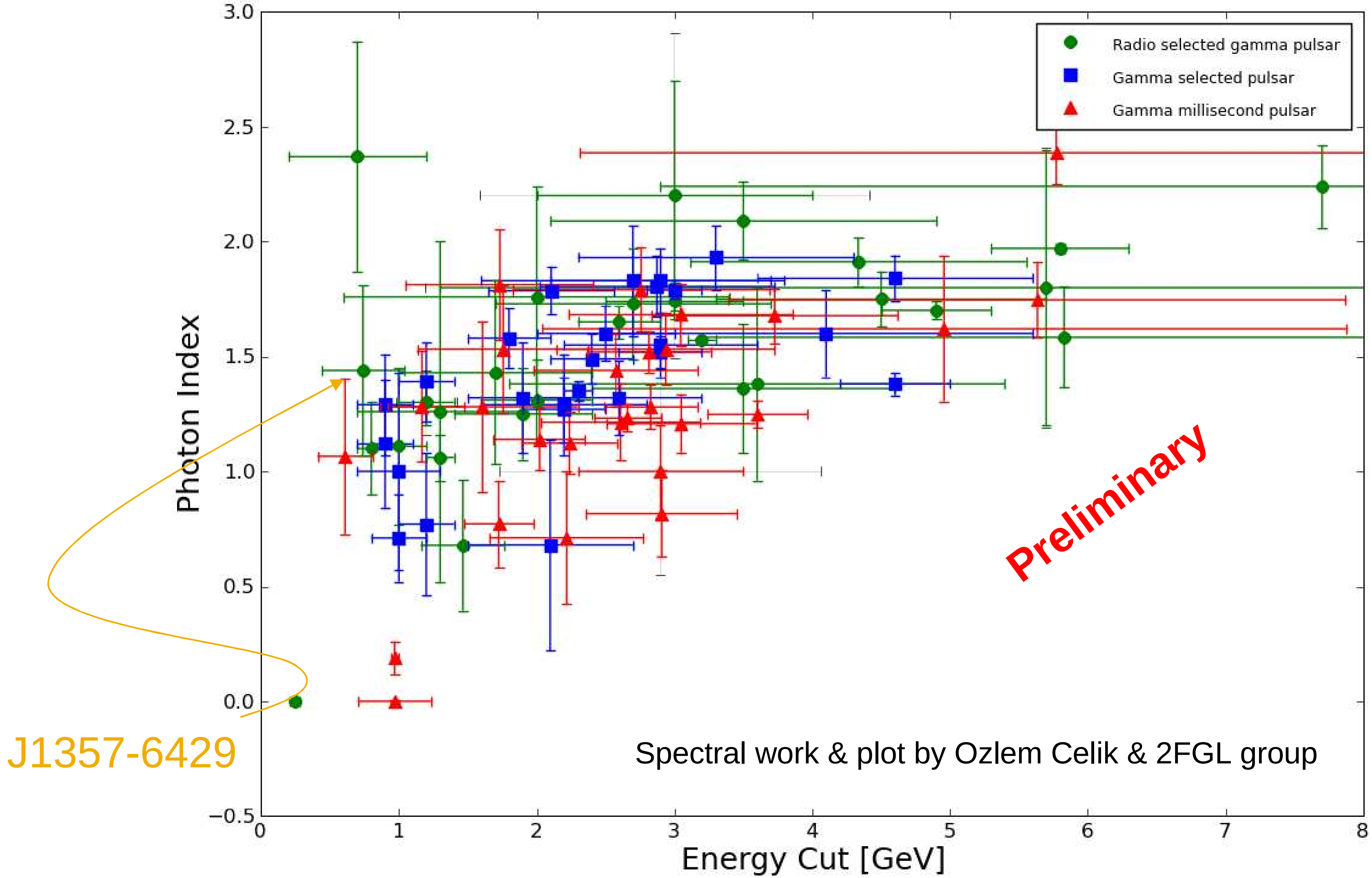

GeV upper limits improve PWN modeling.

Also VLT optical limit. Mignani et al, A&A in prep.

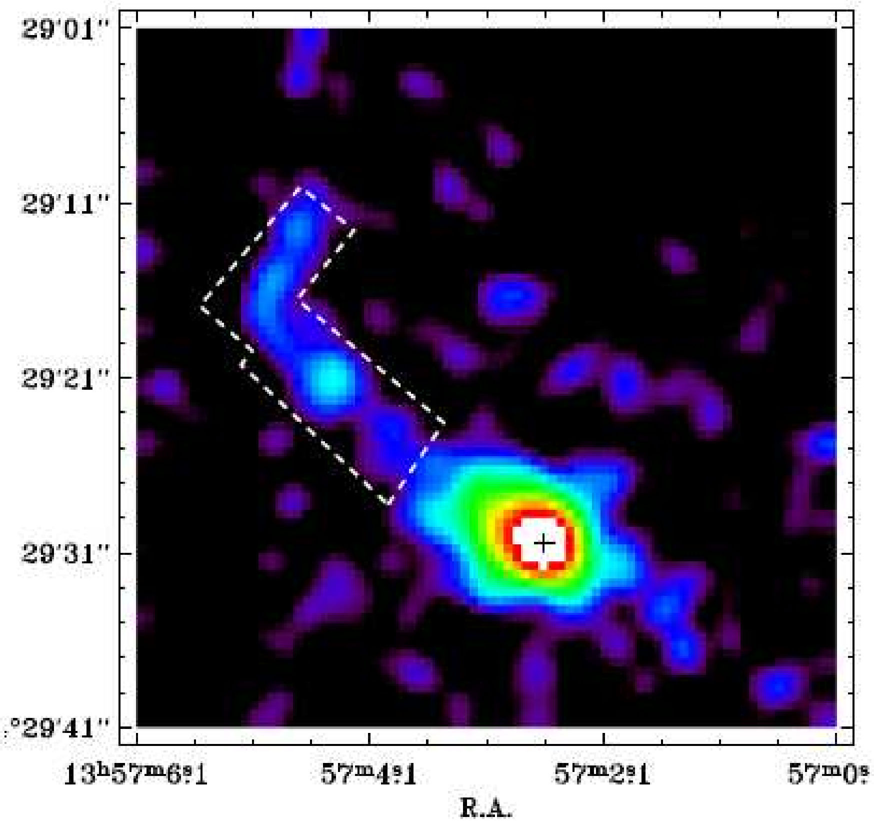
Optical searches of GeV pulsars: see A. Shearer poster.

# Cutoff energy vs Spectral Index

Exponential cut-offs?
Stick around for Nepomuk Otte's talk on the Crab with VERITAS.



# Example: PSR J1357-6429 (3 of 3)




*Chandra* image. Lemoine-Goumard et al, A&A to be submitted.

- Chandra 2009 data confirms the hint of an X-ray PWN in the 2005 XMM data.

Esposito et al, A&A (2007).

- Pulsar's X-ray spectrum seems mainly thermal, with non-thermal nebula.
- All about Fermi PWN's by Marie-Hélène Grondin this morning.
- More on X-ray pulsars by Andrea De Luca – *next talk!*

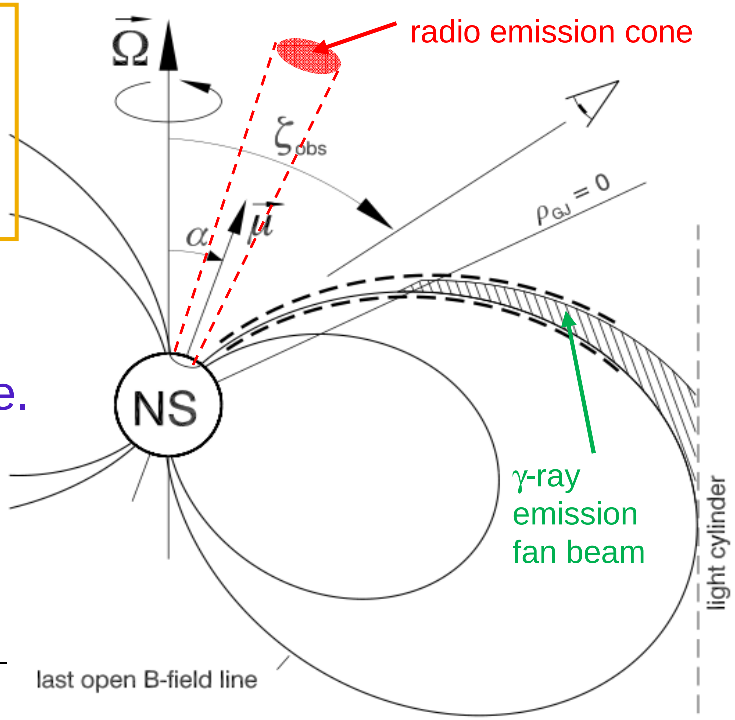
# "Geminga-like" pulsars

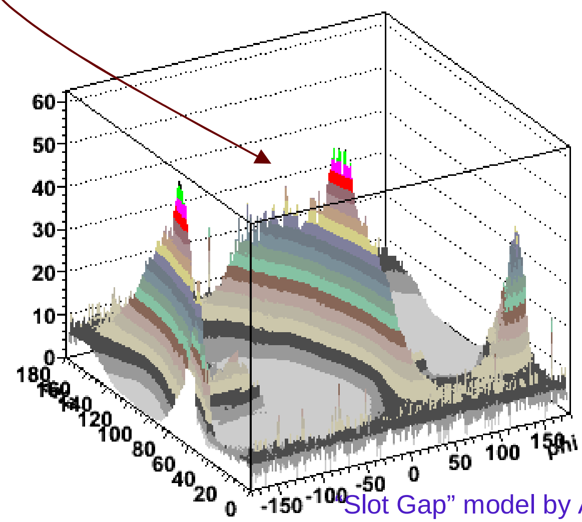
*Radio-quiet (or faint) pulsars if the radio cone misses (grazes) the Earth.*

*Or is simply weak…*

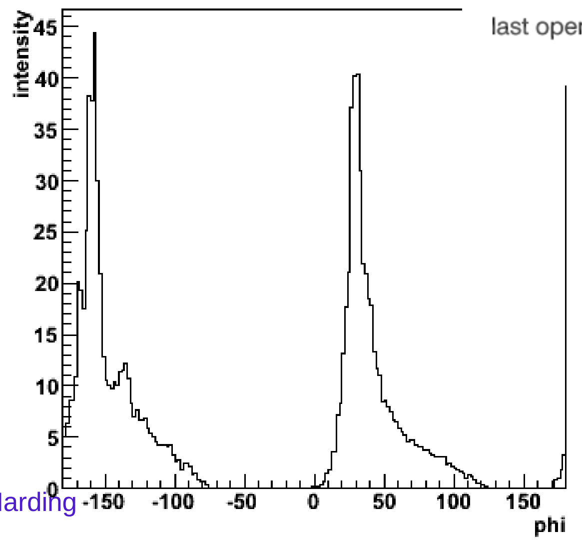
Fan-like gamma beam from outer magnetosphere.

- Below left: ζ vs phase φ.
- Below right: Cut across some line-of-sight ζ.

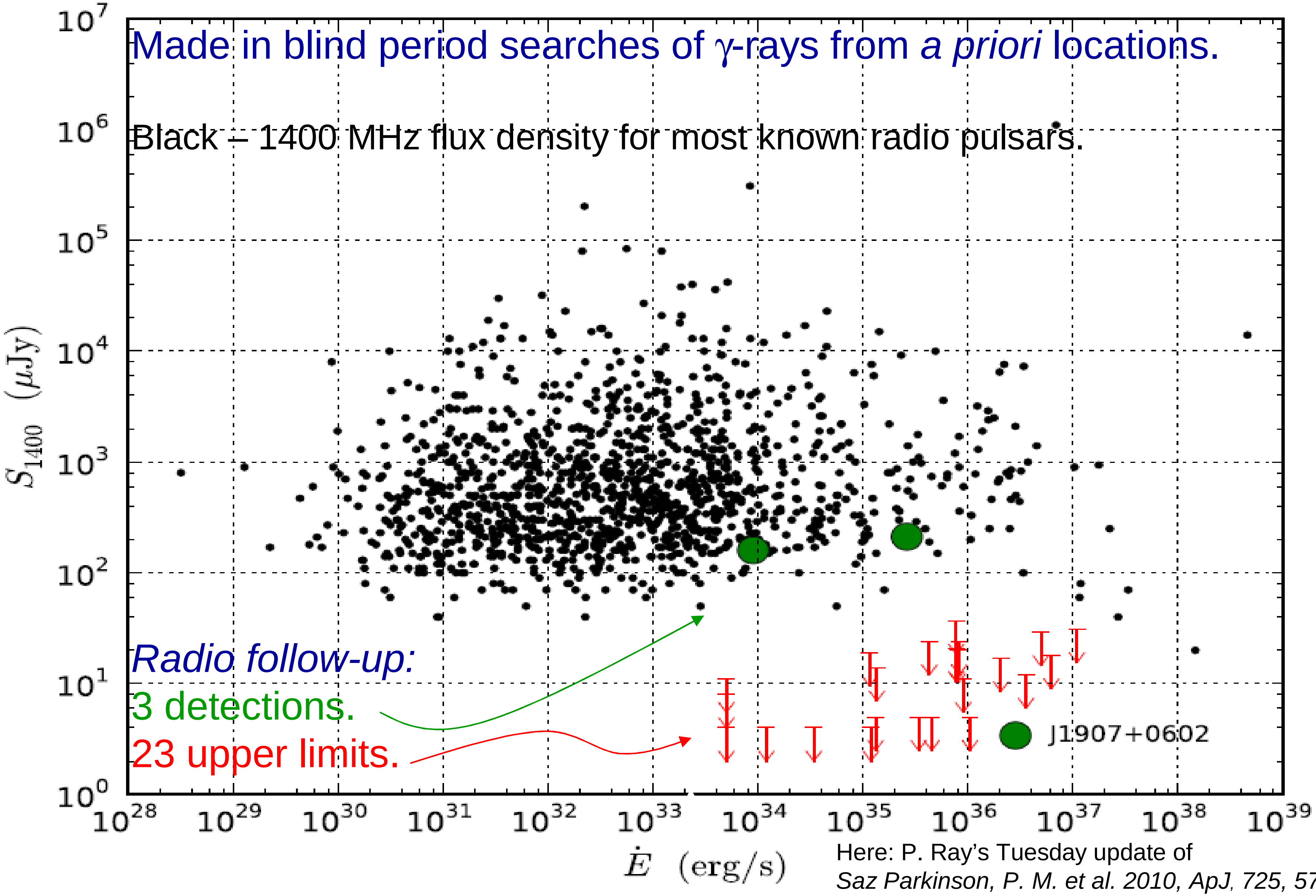



"Slot Gap" model by Alice Harding

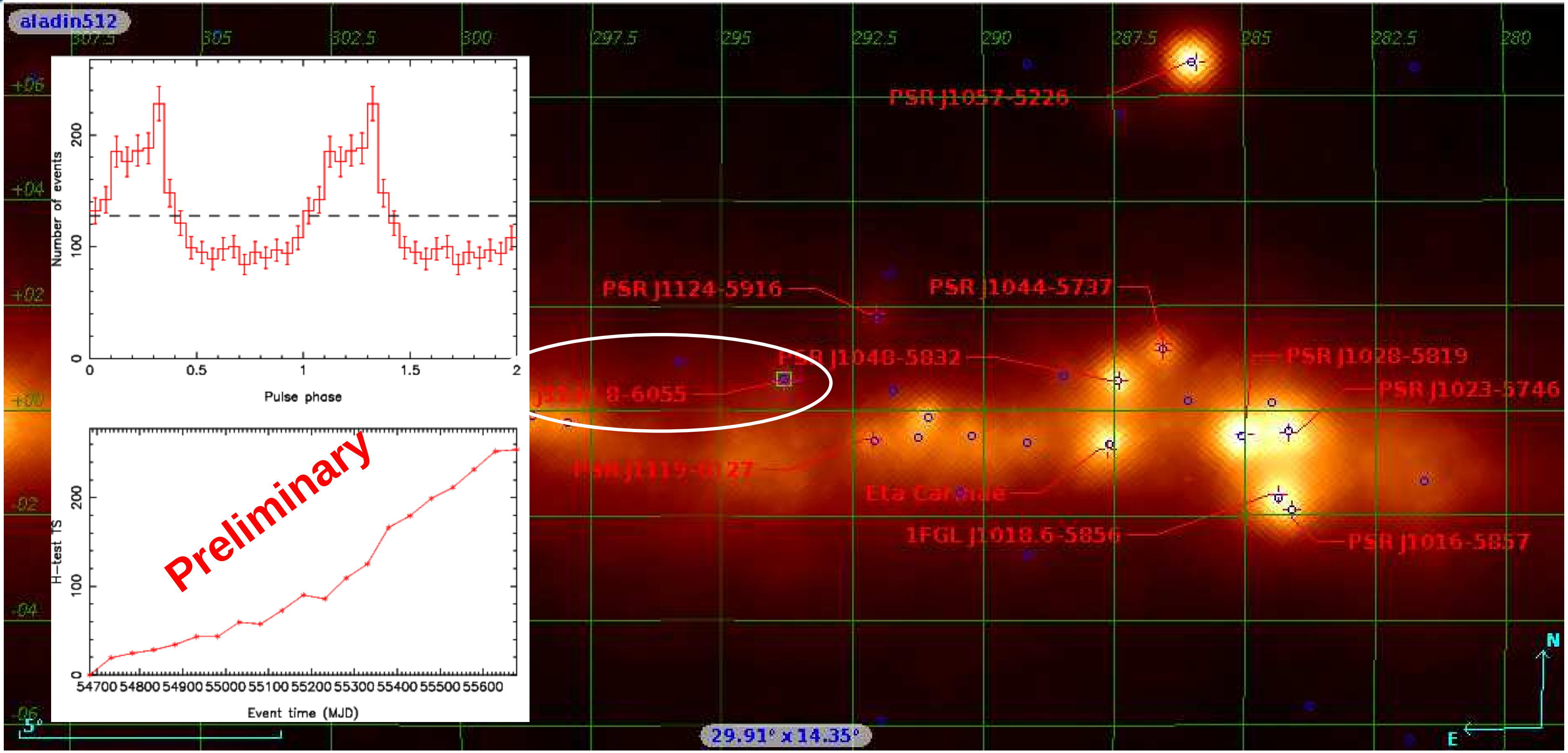


# 27 pulsar discoveries



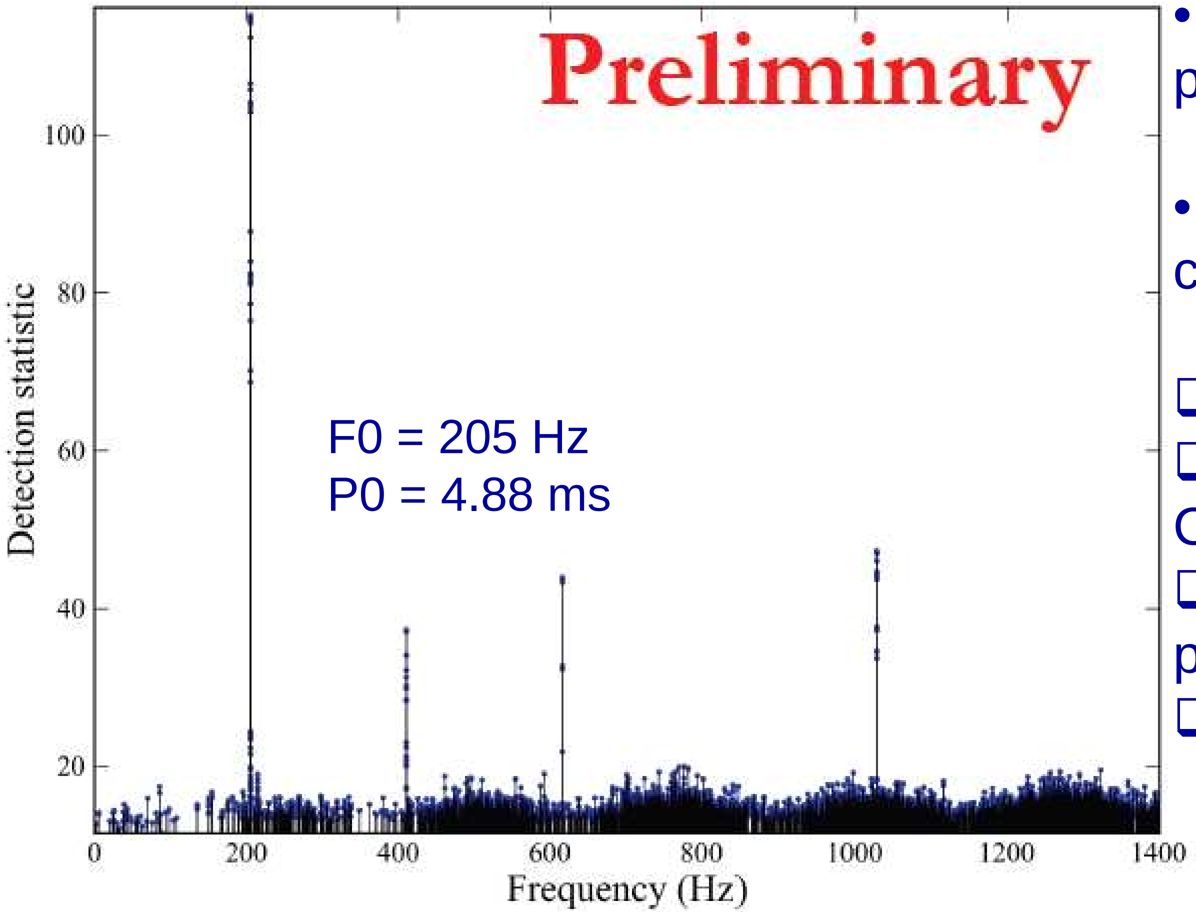

Here: P. Ray's Tuesday update of
*Saz Parkinson, P. M. et al. 2010, ApJ, 725, 571*

# New Blind Search PSR J1135-6055




From poster by P. Saz Parkinson et al.

# Gamma MSP blind search




- So far, no millisecond pulsars found in γ-rays.

- Big computer load: need clever strategies.

❑ Poster by Kong et al.
❑ a focus at UC Santa Cruz.
❑ e.g. Ransom G.I. proposal.
❑ **Here**: Guillemot poster.

**Figure 2 (left):** Example spectrum for PSR J0030+0451.

(30 months data) (a previously known radio/gamma MSP)

# LAT-only pulsar timing

**Precise Gamma-Ray Timing and Radio Observations of 17 Fermi γ-Ray Pulsars**

Ray, P. S. et al. 2011, ApJS, 194, 4

- Timing residuals on millisecond scale.
- Sub-ms timing gives sub-arcsecond positions.
- Arcsecond localization critical for multi-wavelength follow-ups.

- Thanks to LAT timing, no longer using Green Bank radio Telescope time for 5 of 6 very high $\dot{E}$ pulsars targetted before launch ;
- nor Parkes radio telescope for e.g. J1124-5916
- These few pulsars consumed a disproportionate amount of available radio resources.

Timing noise figure-of-merit:

$$\Delta(t) = \log\left(\frac{1}{6\nu}|\ddot{\nu}|t^3\right)$$

*Fermi* pulsars noisier than average.

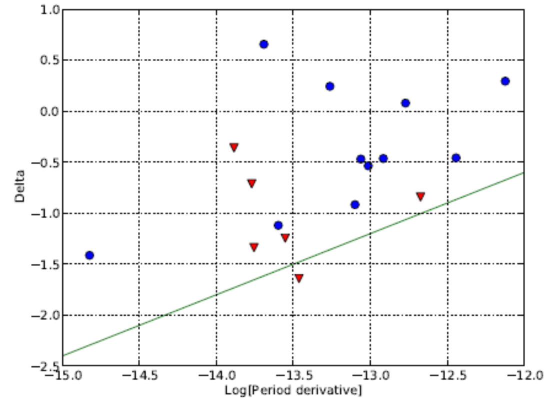
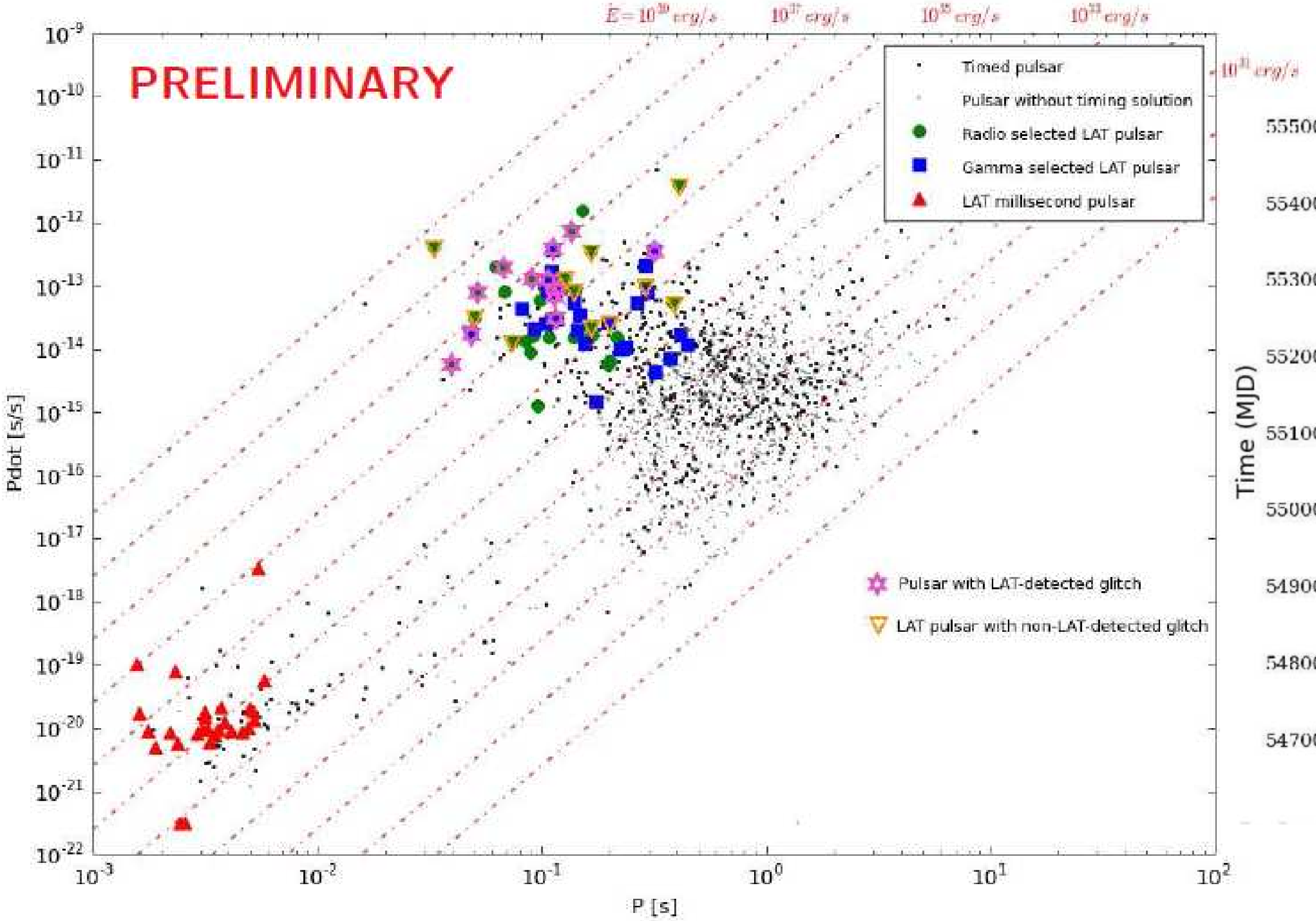


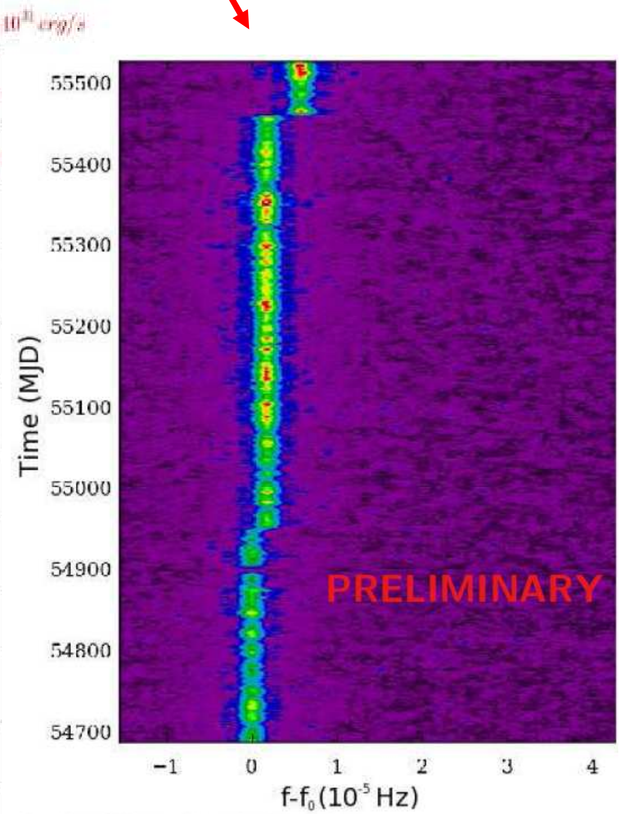

Fig. 72.— Δ parameter characterizing timing noise vs. $\dot{\nu}$ for these pulsars. The red triangles represent upper limits. The green line is the relation found by Arzoumanian et al. (1994b)

# Glitch monitoring!

- From Belfiore et al's talk on Tuesday.
- 3E-8 < $\delta F_0/F_0$ < 5E-6

*Example*:
radio-quiet PSR J0007+7303 (CTA1)



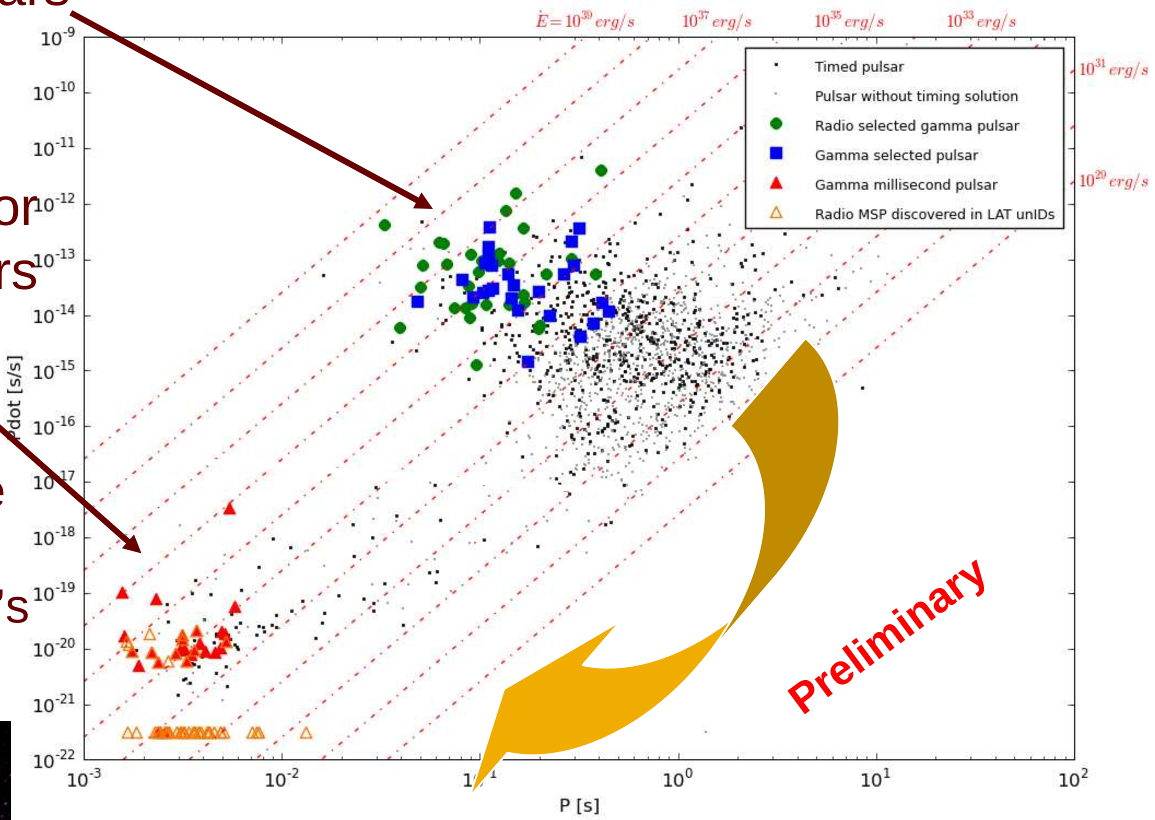



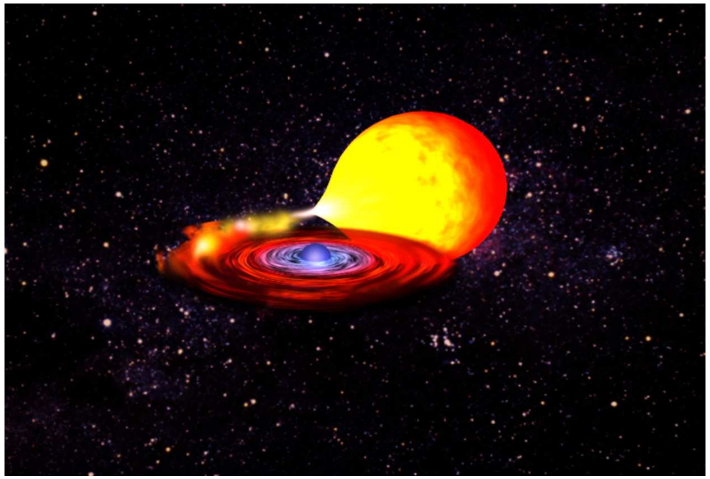
# Recycled pulsars

Newborn ("young") pulsars

“Recycled”, or *millisecond* pulsars

Pulsars age, slow, and become invisible ("*past the Death Line*"). They can accrete a companion’s spin and "reincarnate".



*Are millisecond pulsars gamma-bright?*

Before *Fermi*, L. Kuiper claimed EGRET pulsations of PSR J0218+4232.

*One of the 1st Fermi MSPs!*

# Famous MSPs

## Pulsed Gamma Rays from the Original Millisecond and Black Widow Pulsars: a case for Caustic Radio Emission?

L. Guillemot[5,1], T. J. Johnson[8,10,1], C. Venter[20,1], M. Kerr[12,1], B. Pancrazi[14,15], M. Livingstone[13], and others, ApJ *submitted*.

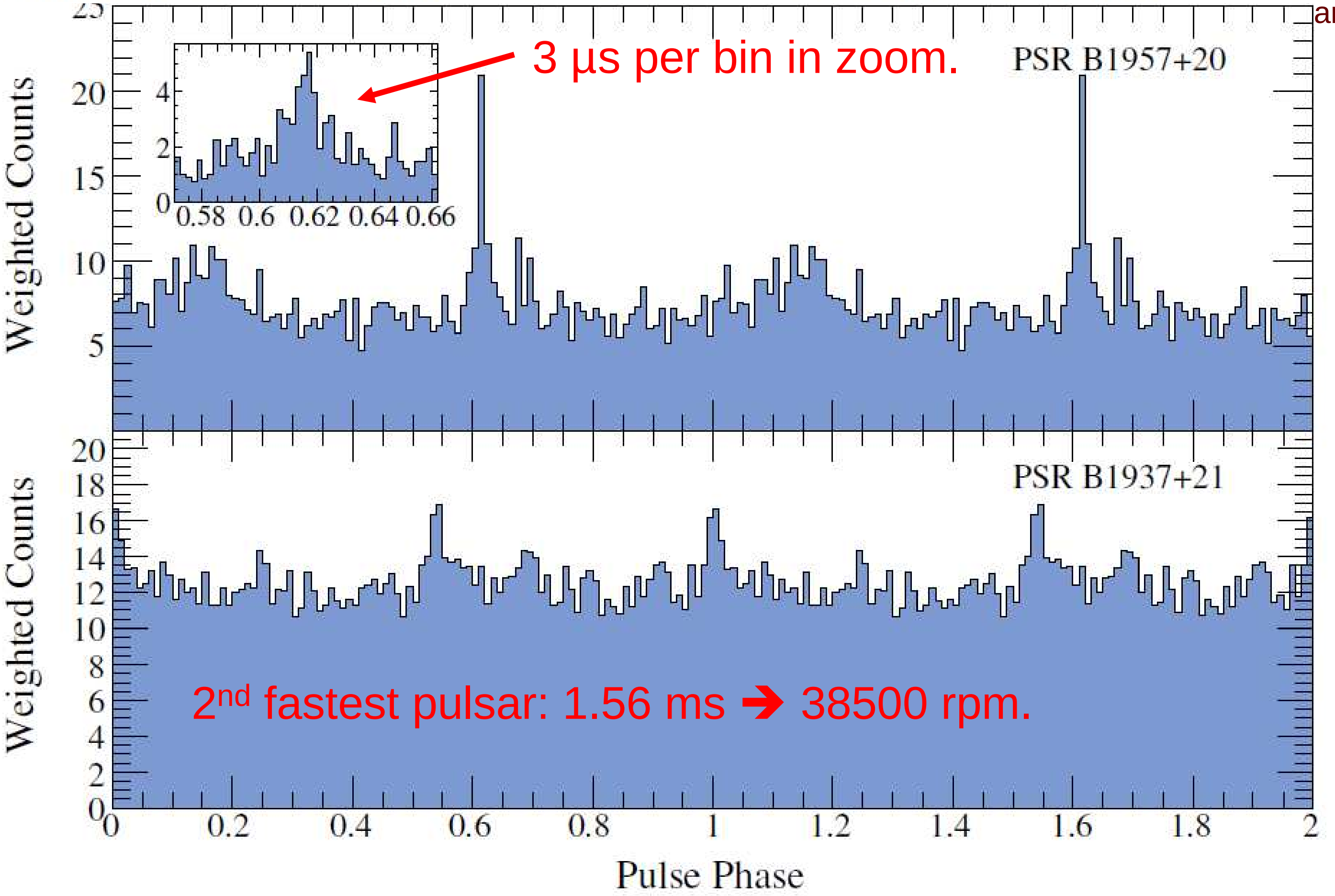



Fig. 3.— Gamma-ray light curves of PSRs B1937+21 (bottom panel) and B1957+20 (top panel)

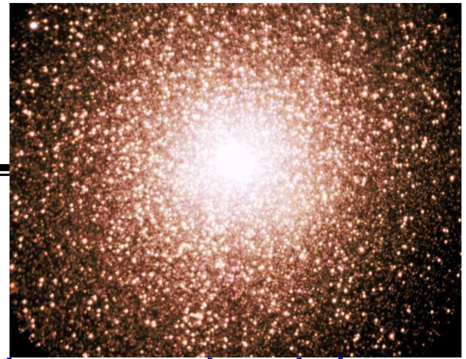
# Millisecond Pulsars

• After Fermi's first $\gamma$-MSP discoveries we said "they look like the young pulsars" (in their spectra and pulse profiles).

• Having tripled the sample, we now see sub-categories:

- For the "slower" ones ($P_o$ ~5 ms), it's true.
- But the *fast* MSPs tend to have gamma peaks phase-aligned with the radio peaks (like the Crab).
- See Christo Venter's, Alice Harding's talks.

# Globular Clusters

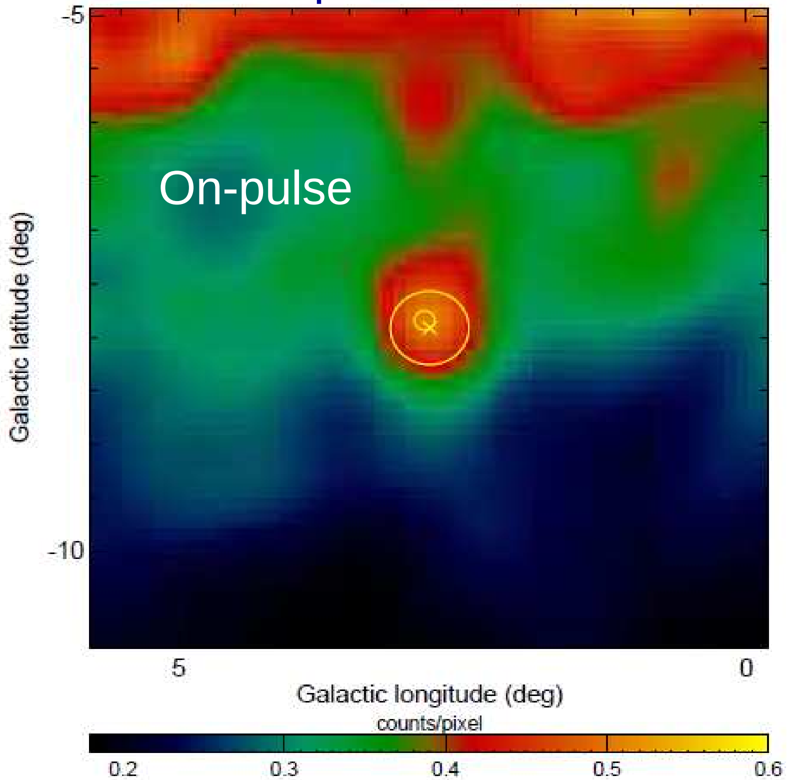


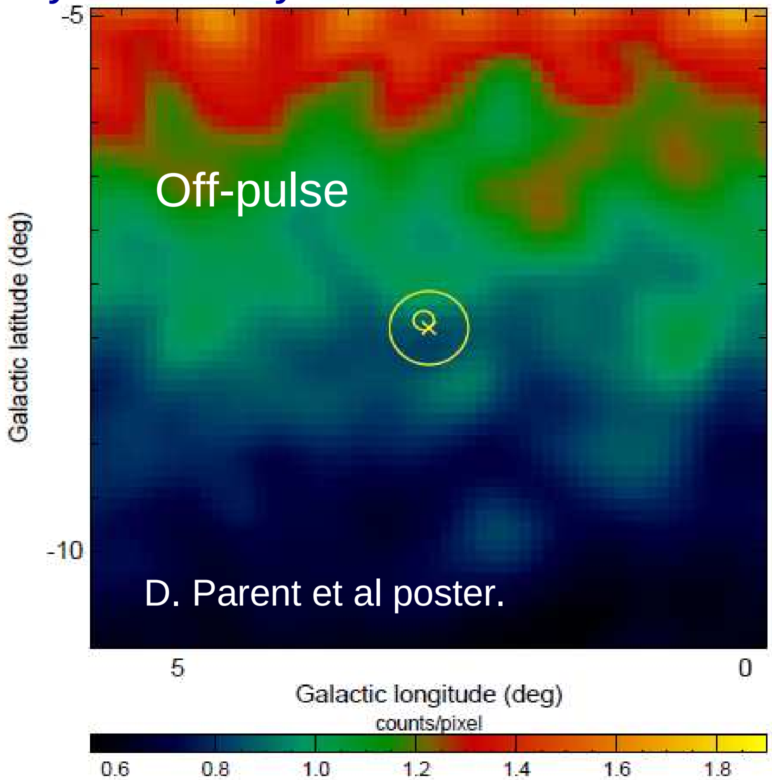

- Half of known MSPs are in Globular clusters.
- We showed pulsar-like gamma-ray spectra for 8 GC's, and constrained the number of MSPs therein, in Abdo, A. A. et al. 2010, A&A, 524, A75

**NEW** *We see pulsations from PSR J1823-3021A in NGC6624 !*

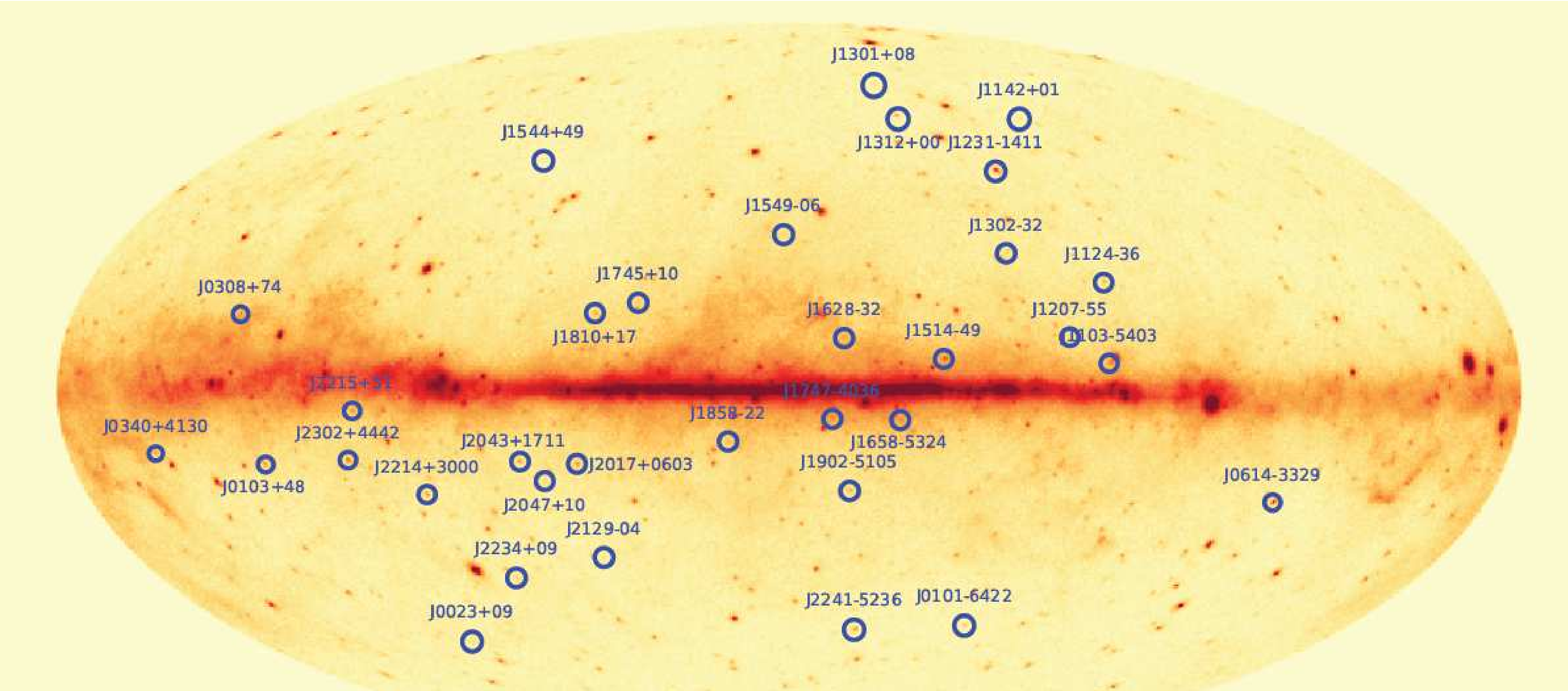
*P. Freire et al, Science submitted*

*Curious*… no off-pulse GeV emission. All γ-ray luminosity of the GC from one MSP.



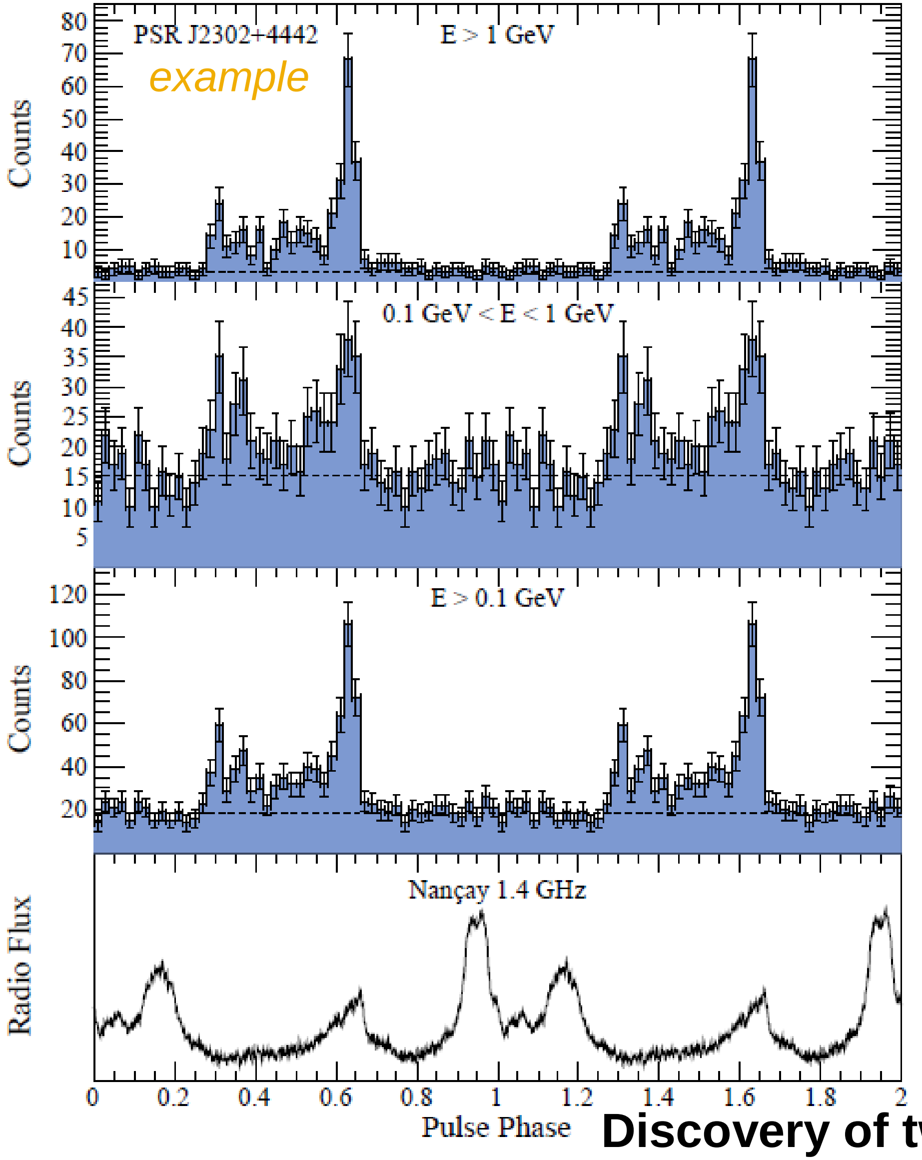
# Radio MSPs found in Fermi UnId's




• Some *Fermi* unidentified sources have pulsar-like spectra, i.e., an exponential cutoff below 5 GeV. (Monday talks by Burnett & Thompson.)

• This "treasure map" has lead radio telescopes to 33 MSP discoveries (~70 had been found outside of globular clusters since 1982). (Tuesday talk by Ray.)

# γ-Pulsations from new radio MSPs




*Take away message*:

Radio and gamma-ray fluxes uncorrelated.

As *Fermi* mission continues, new *Fermi* sources are weaker and weaker.

But they can still point to undiscovered radio-bright pulsars!

Therefore, *Fermi*-directed radio searches can/will continue.

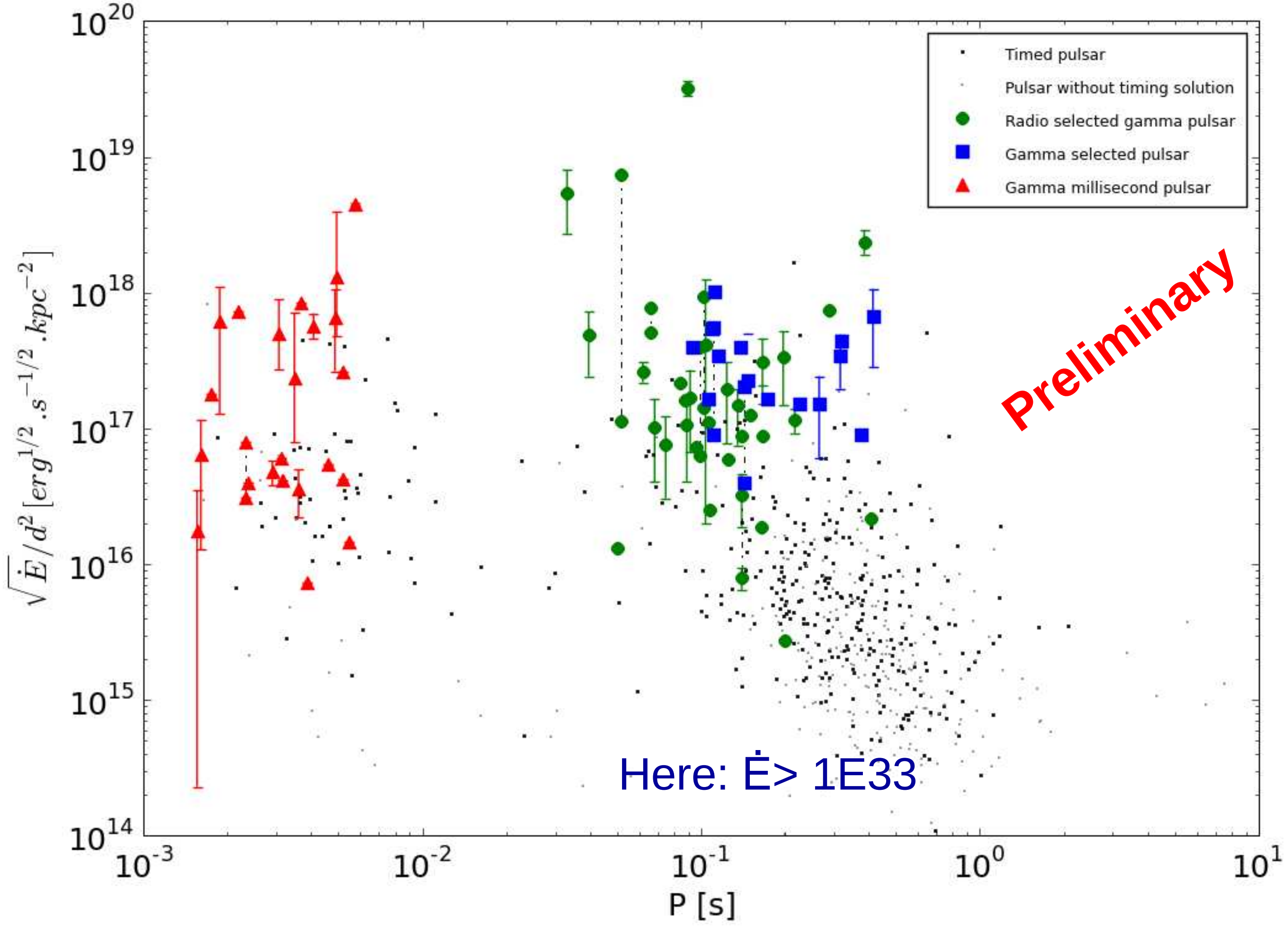
SPIN-OFF: new very stable MSPs for gravity wave searches.
(need ~20 MSPs with ~100 ns timing accuracy, spread over sky .)

**Discovery of two MSPs with the Nançay radio telescope**
Cognard, I. et al. 2011, ApJ, 732, 47

# Gamma quiet pulsars?

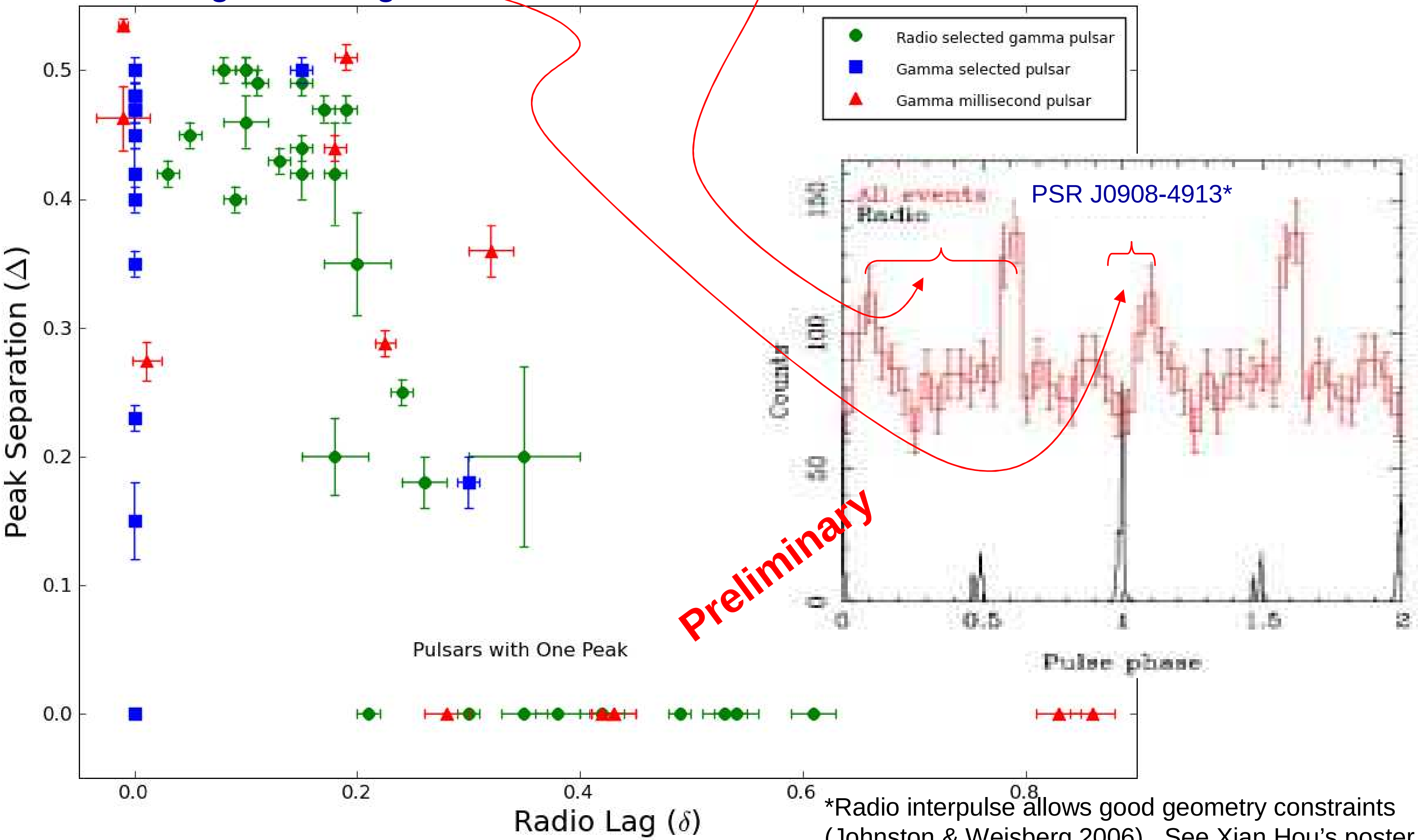
Why do we see some high $\sqrt{\dot{E}}/d^2$ pulsars but not others?

- Emission physics? Beam geometry? See R. Romani's talk.
- Wrong distance? (VLBA parallax campaign in progress, S. Chatterjee P.I.)
- Ephemerides issues? Continued vigilance…



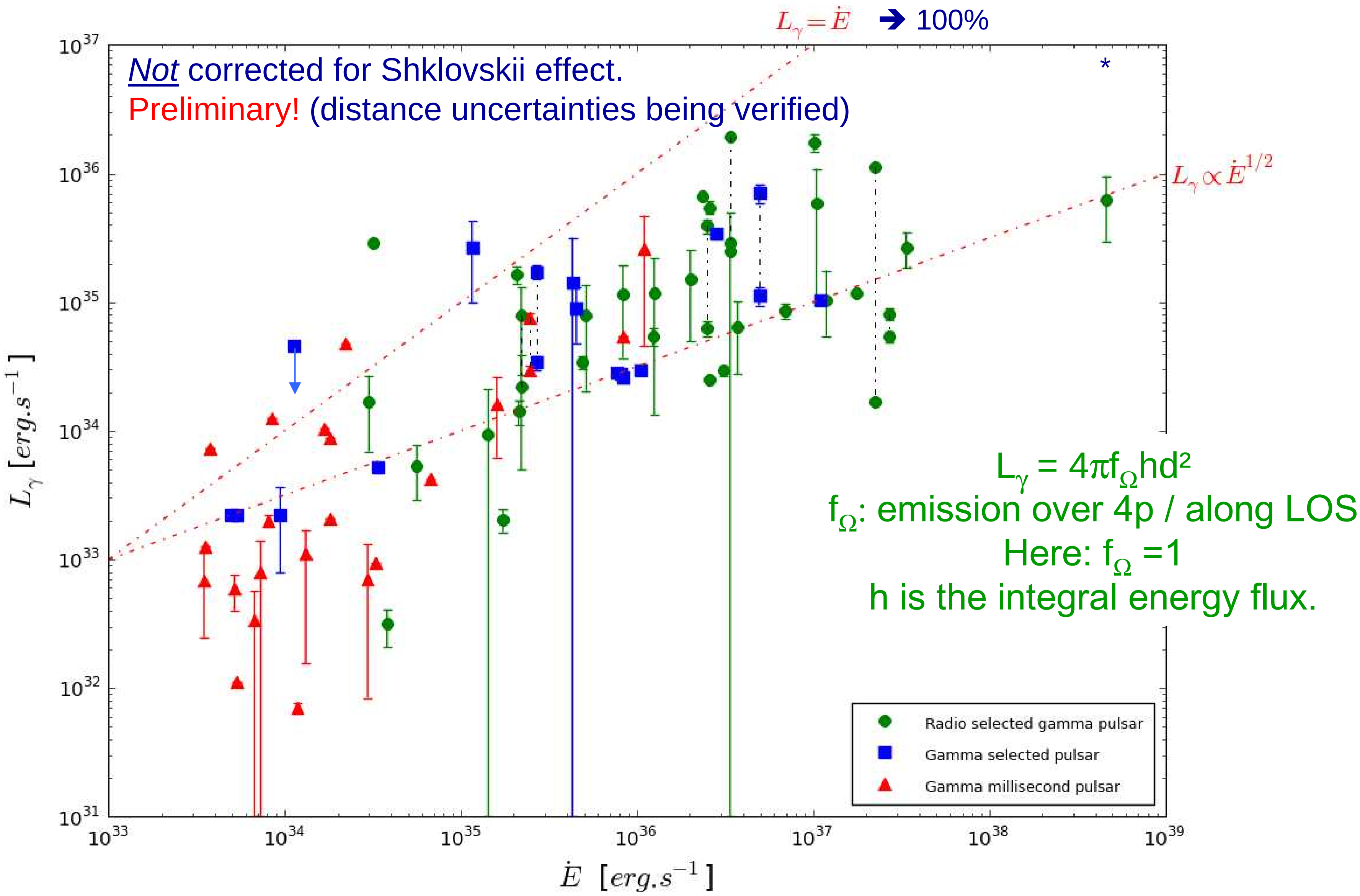
# Peak separations

Δ: Separation of two gamma peaks.
δ: Radio-to-gamma lag.




*Radio interpulse allows good geometry constraints (Johnston & Weisberg 2006). See Xian Hou's poster.

# Luminosity



$L_\gamma = \dot{E}$ → 100%
Not corrected for Shklovskii effect.
Preliminary! (distance uncertainties being verified)
*
$L_\gamma \propto \dot{E}^{1/2}$
$L_\gamma$ [$erg.s^{-1}$]
$\dot{E}$ [$erg.s^{-1}$]
$L_\gamma = 4\pi f_\Omega h d^2$
$f_\Omega$: emission over 4p / along LOS
Here: $f_\Omega$ =1
h is the integral energy flux.
Radio selected gamma pulsar
Gamma selected pulsar
Gamma millisecond pulsar

# Things learned, and learning

• Soon after launch, it was clear that outer magnetospheric gamma emission dominates for most pulsars ("outergap versus polar cap") .

• As the mission continues, we're discovering interesting exceptions that confirm/refine the "rule".

The dramatic increase in the sample of known high-energy pulsars, and improved knowledge of their beaming and intensity is input for:

- High latitude unidentified source identification
- Contributions to the diffuse gamma-ray and electron/positron backgrounds…
- … which is important for the Dark Matter searches.

# **Prospects** *Towards our first NASA Science Review*

• Has all the low-hanging fruit been picked?
Not completely:

- ➢ J1357-6429 was just waiting for a good radio ephemeris…
- ➢ J1135-6055 was just waiting for a good blind search seed location.
- ➢ The 2FGL MSP "treasure hunt" continues: no gamma/radio correlation.

• Nota bene: $2\sigma * \sqrt{[(10 \text{ years})/(2.5 \text{ years})]} = 4\sigma < 5\sigma$

- ➢ However high-performance pulsar analyses being applied (e.g. Kerr ; Bruel)

• Studying individual objects is necessary to "get them right", but…

• … Population studies will also teach us about the massive star progenitors, supernova rates, and more. *Towards a statistically complete sample…*

• The $\gamma$-pulsar sample has re-newed interest in improved pulsar distances…
…which will feed back to the Galactic models of electrons, gas, etc.

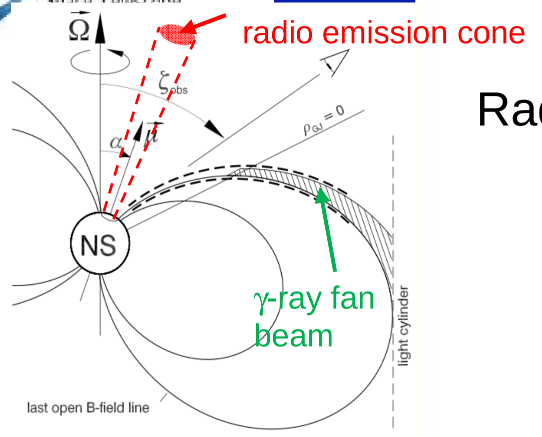
• Some years from now, LOFAR will double the radio pulsar sample.

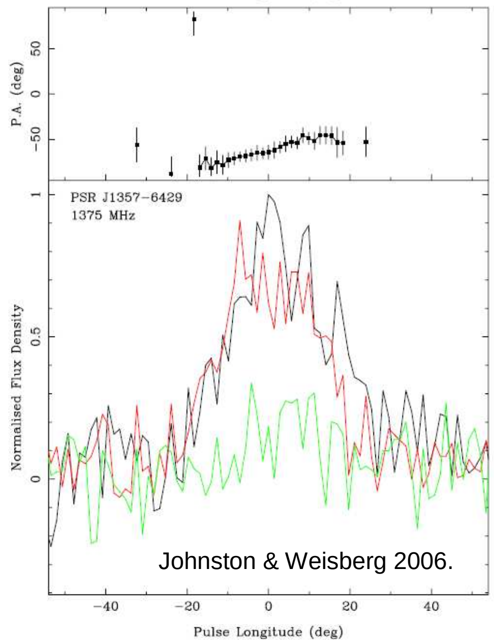
# Conclusions

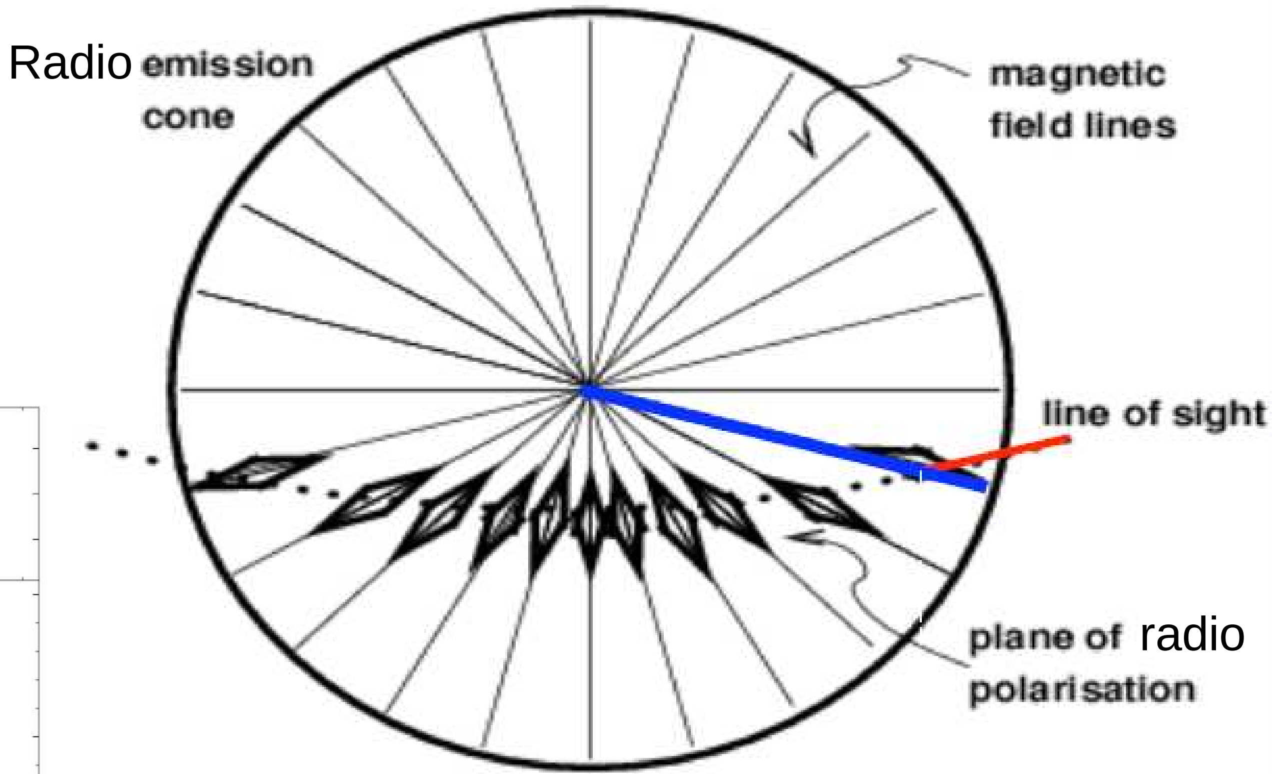
- $2^{nd}$ catalog in progress: >88 pulsars, with enhanced ancillary information.

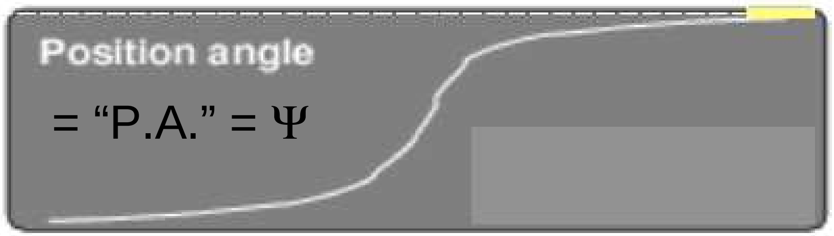
***THANK YOU!***

# The Rotating Vector Model (RVM) for polarization




This slide: Karastergiou via Johnston.
RVM: Radhakrishnan & Cooke 1969.

$$\tan(\psi - \psi_0) = \frac{\sin\alpha \sin(\phi - \phi_0)}{\sin\zeta \cos\alpha - \cos\zeta \sin\alpha \cos(\phi - \phi_0)}$$

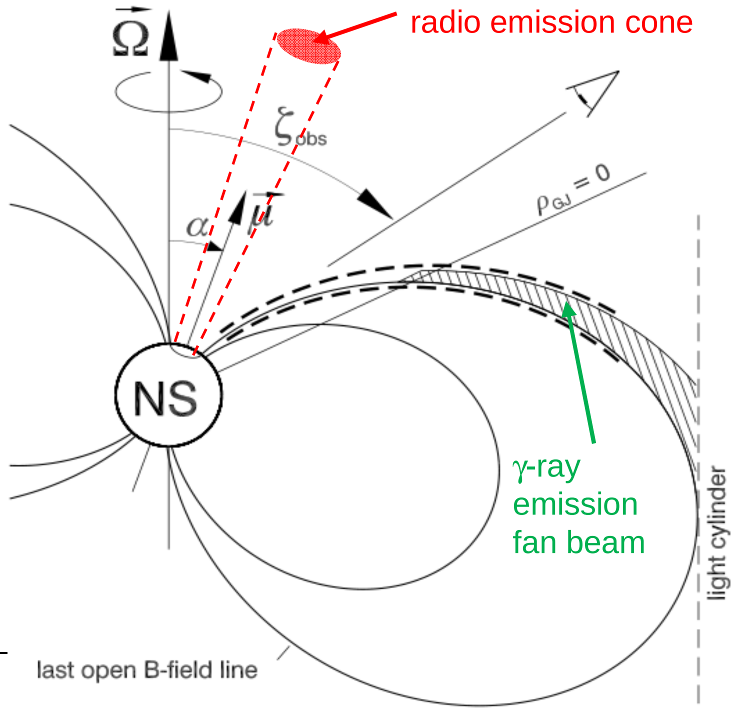
$L_\gamma = 4\pi f_\Omega h d^2$

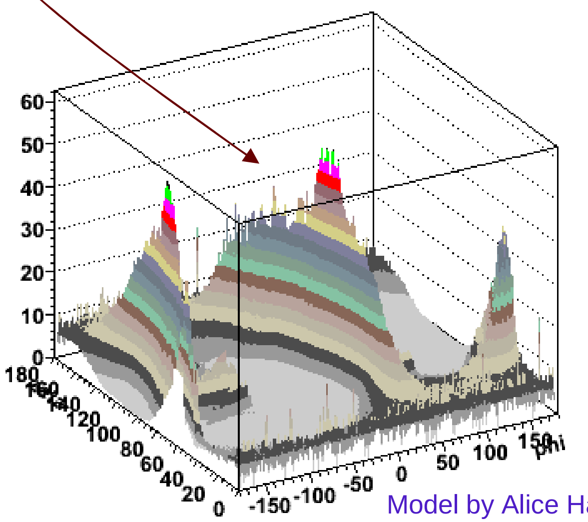
$$f_\Omega(\alpha, \zeta_E) = \frac{\int F_\gamma(\alpha; \zeta, \phi)\sin(\zeta)d\zeta d\phi}{2\int F_\gamma(\alpha; \zeta_E, \phi)d\phi}$$

$f_\Omega$ : total flux / flux beamed along one line of sight

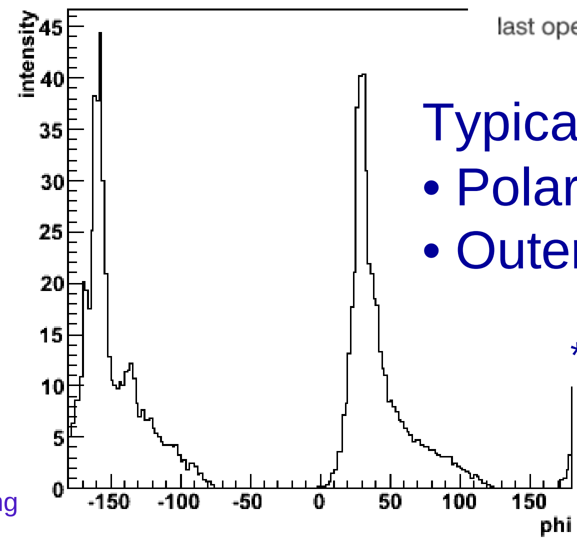
- Fan-like gamma beam from "outer" or "slot" gap?
- Radio vs gamma pulse profiles
  - ➔ Powerful model discriminant

- Below left: $\zeta$ vs phase $\varphi$ for a "slot gap" model.
- Below right: Cut across some line-of-sight $\zeta$.




Model by Alice Harding




Typical values for $f_\Omega$ :
- Polar cap, $f_\Omega = 1/4\pi \sim 0.1$*
- Outer, slot gap, $f_\Omega \sim 1$

* The famous pre-*Fermi* "1 steradian".