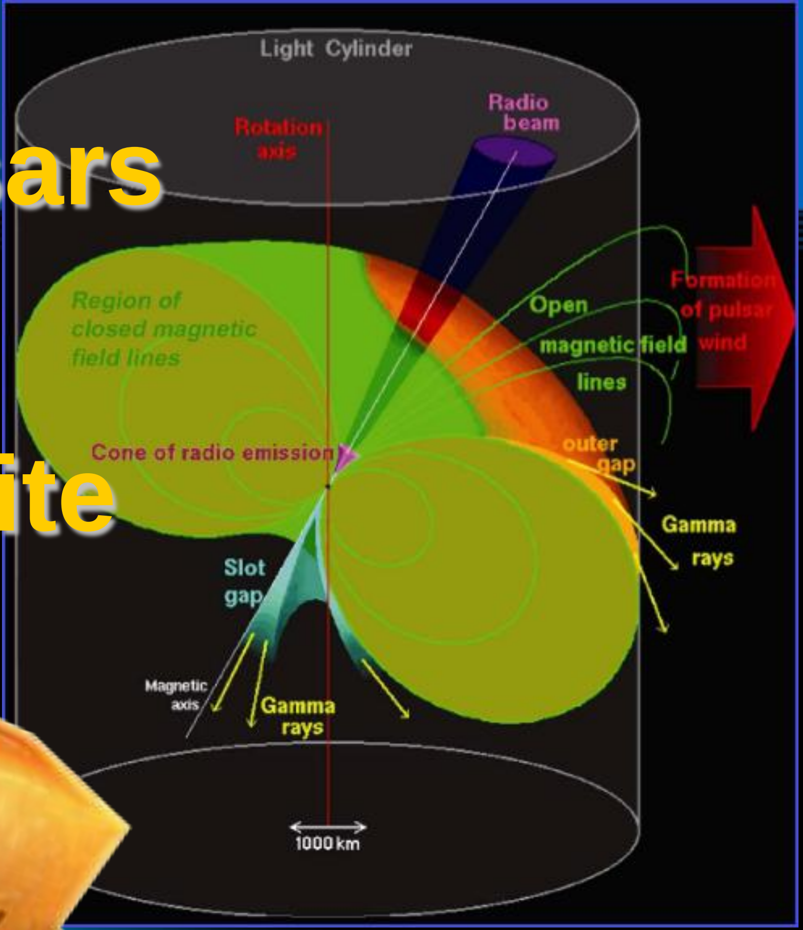
Gamma-ray Pulsars

with

the *Fermi* satellite



David A. Smith, for the *Fermi* LAT collaboration and the radio consortia
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smith@cenbg.in2p3.fr

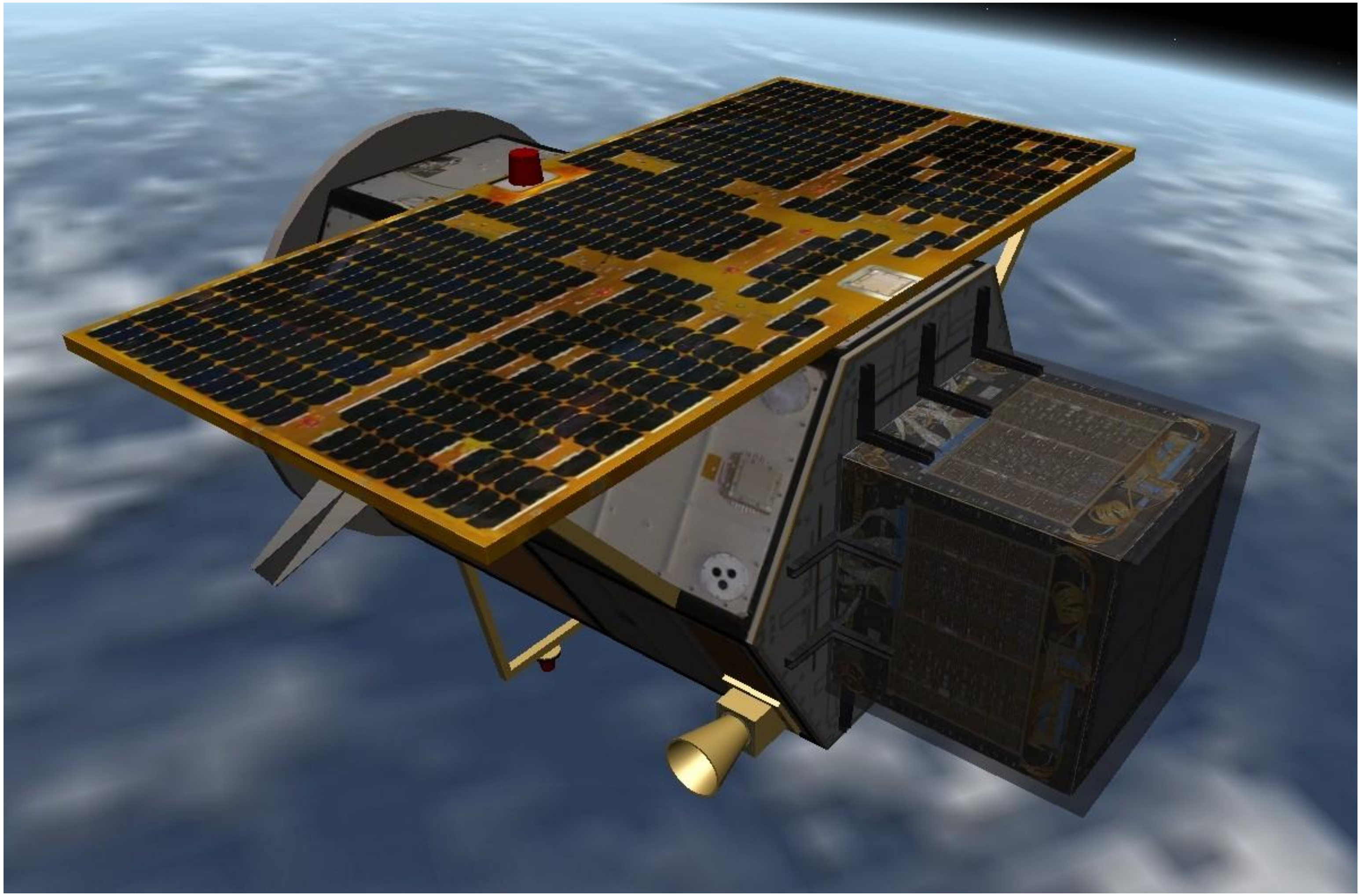
***Fast n' Furious*, ESAC, Madrid**
22 May 2013


June 11, 2008
5ième !
APPELLATION PREMIÈRES CÔTES DE BORDEAUX CONTRÔLÉE
1ER ANNIVERSAIRE
fermi
GLAST
PSR J2021+3651
Abdo et al. 2009,
ApJ, 700, 1059
BORDEAUX
11 juin 2009
CENBG
75 cl
12,5% vol
LR07-1 CONTAINS SULFITES
CHATEAU ROZIER-MORILLONS 2007
MIS EN BOUTEILLE AU CHATEAU - PRODUCT OF FRANCE
PAR SCEA VIGNOBLES CRACHEREAU & FILS À DONZAC F.33410
CONCOURS DE BORDEAUX
VINS D'AQUITAINE
fermi
Gamma-ray
Space Telescope
Formerly "GLAST"

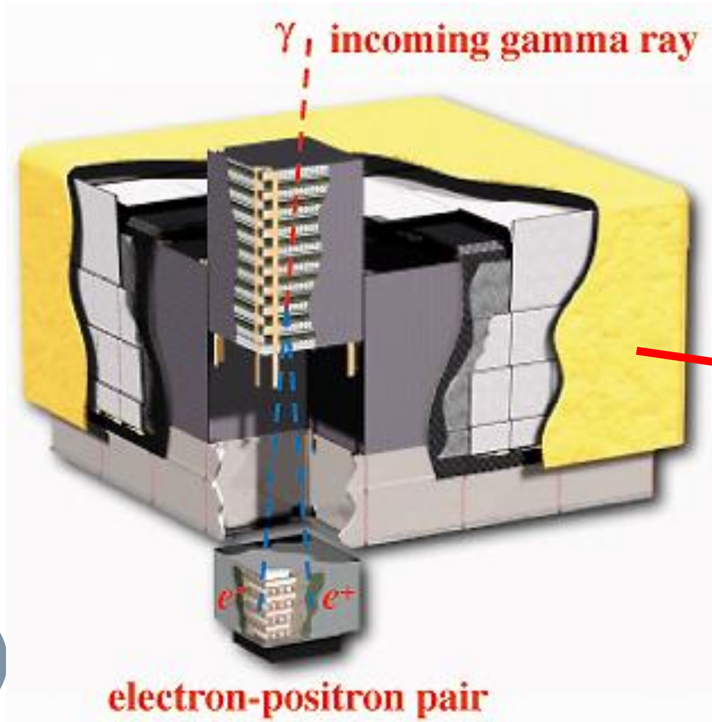
Actually, *AGILE* scooped *Fermi* for this first post-EGRET pulsar:

Discovery of high-energy gamma-ray pulsations from PSR J2021+3651 with AGILE,
Astrophys. J., 688, L33-L36 (2008)

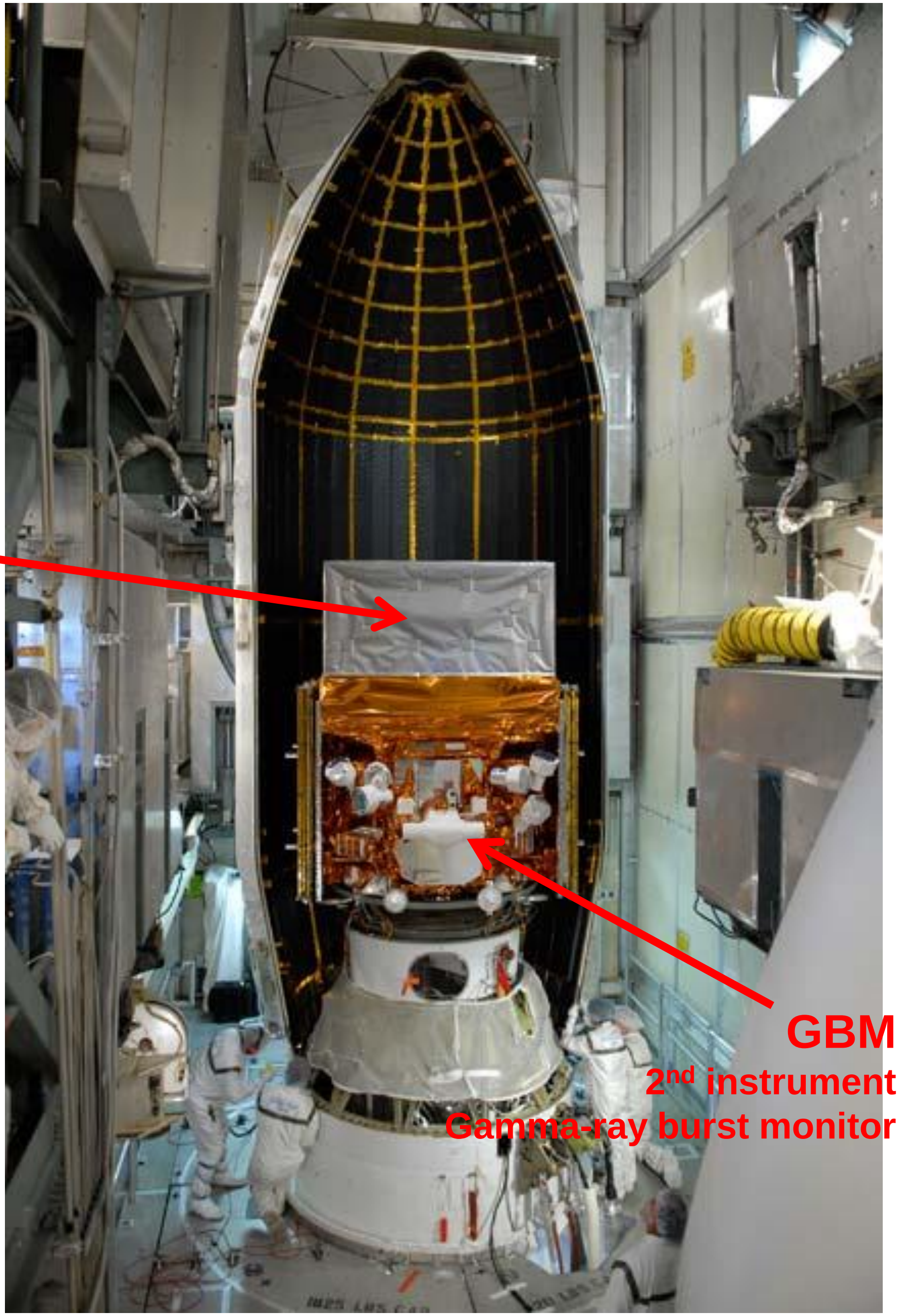
For more AGILE results, see Marco Tavani's talk, Friday.

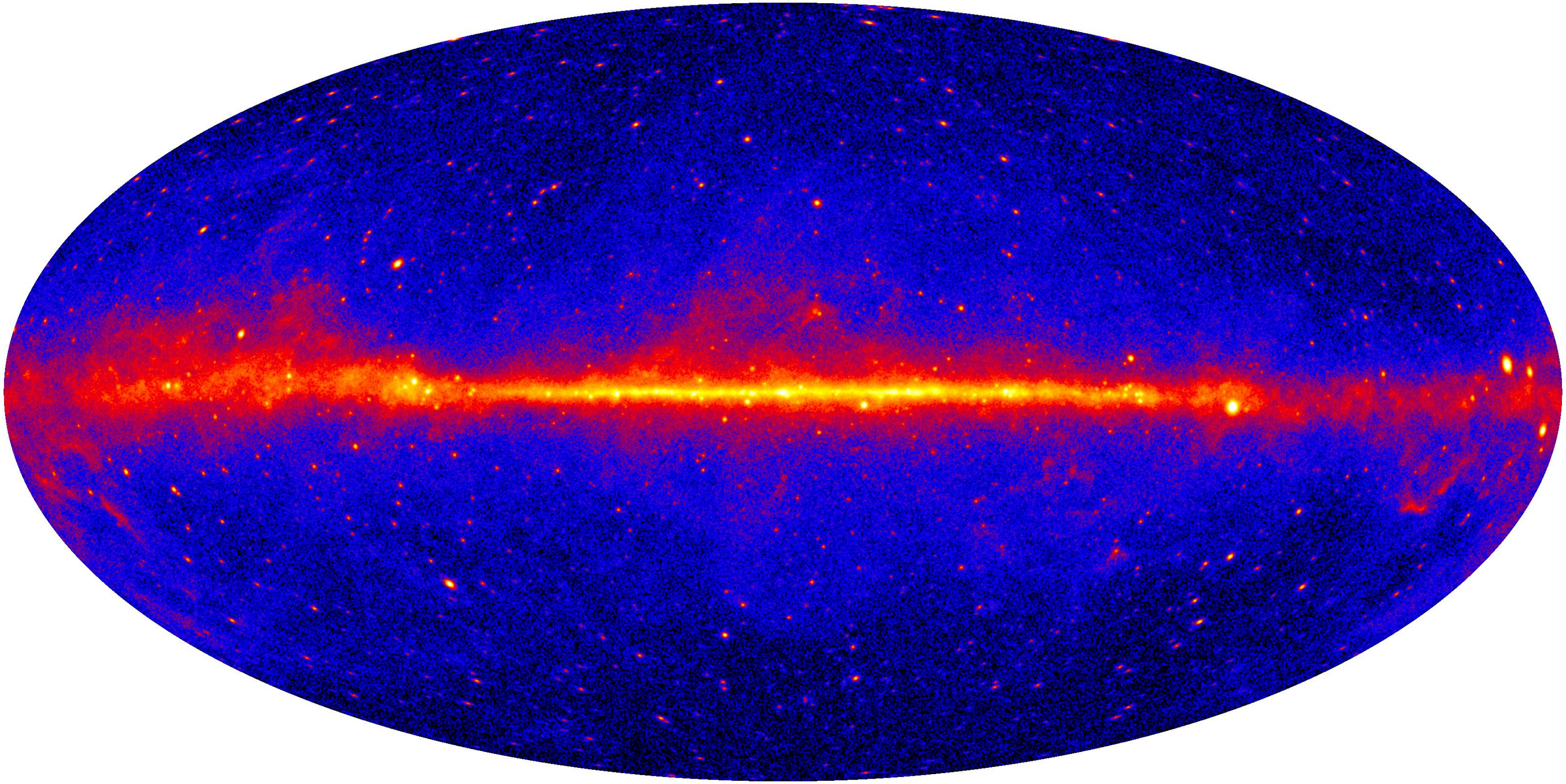


Large Area Telescope
30 MeV to 300 GeV



The whole sky, 8 times per day





48 months of data

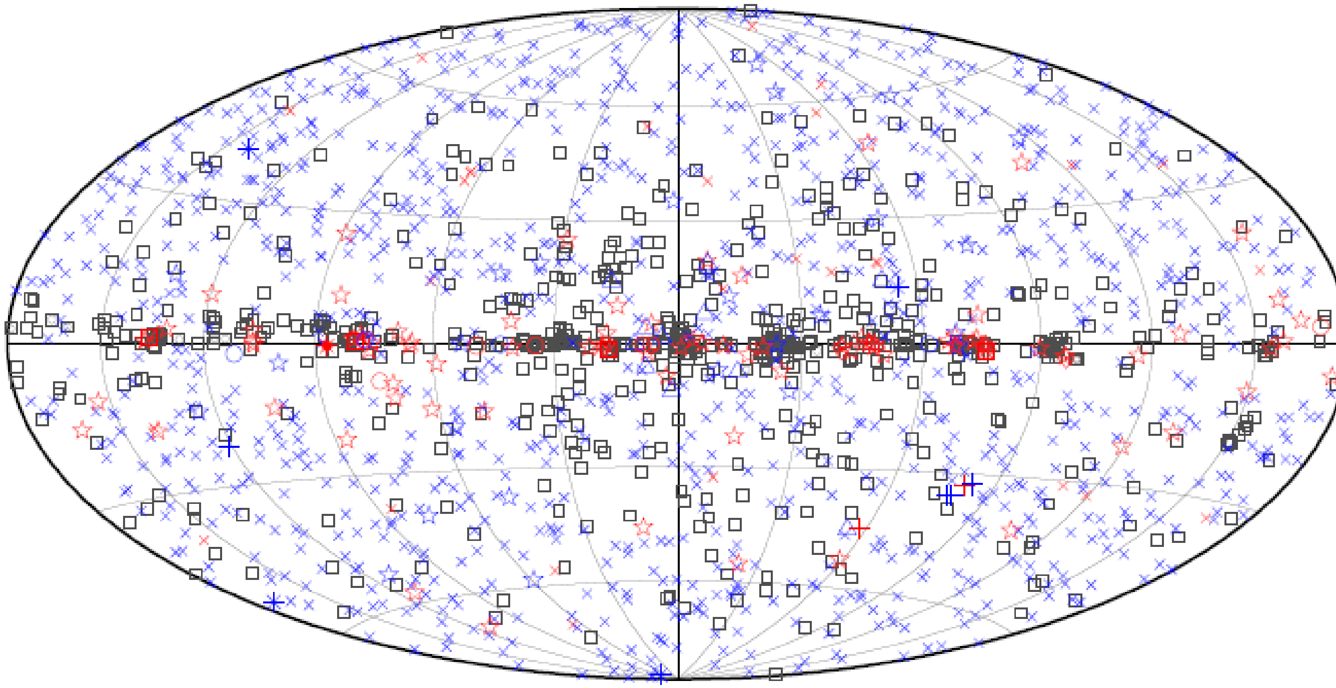
>1 GeV. 4.52M events. Pass 7v6 Source class events from August 4, 2008 through August 4, 2012.
LAT rocking angle <52° and zenith angle <100°.

Point sources in the plane are mostly pulsars.
(Off the plane, mostly blazars. Also MSPs, and globular clusters w. MSPs.)

2FGL

LAT 2nd Source Catalog

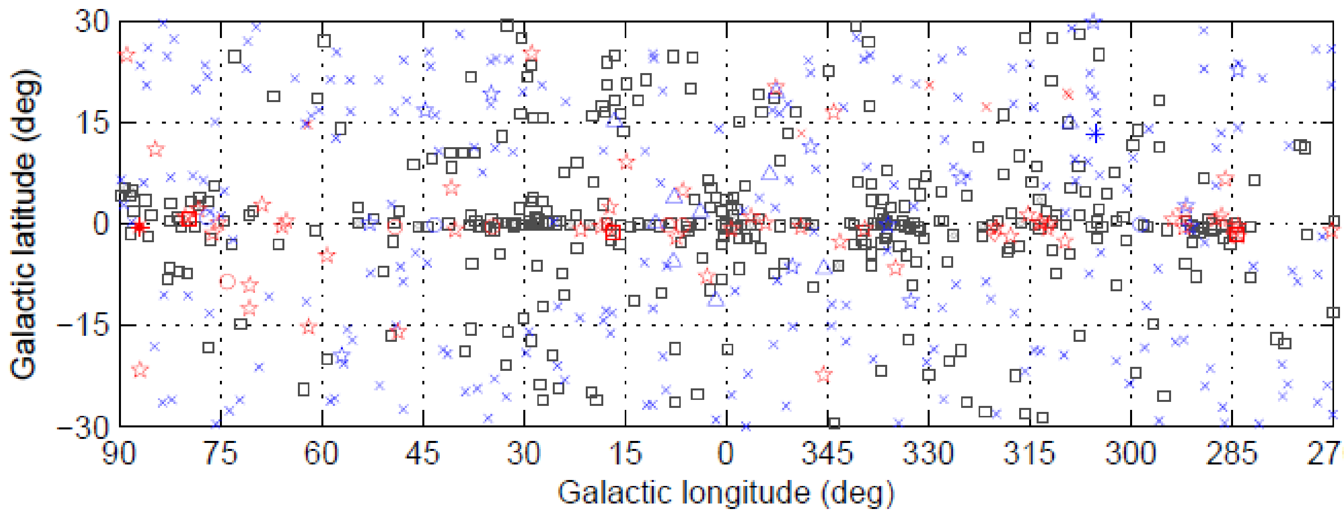
Nolan et al. 2012, ApJS, 199, 31



Red: id'd.
Blue: Assc'd.
Black: UnId. == ***Gold*** mine!

□ No association	⊡ Possible association with SNR or PWN	
× AGN	☆ Pulsar 83+25=108	△ Globular cluster 11
✳ Starburst Gal	◇ PWN 3	⊠ HMB 4
+ Galaxy	○ SNR 6+4+58	✦ Nova 1

4-year version, within the LAT team.



Breaking news: "2PC" posted to arXiv:1305.4385 yesterday.

(submitted to ApJ Suppl 2 weeks ago.)

The catalog contents are online at

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2nd_PSR_catalog/

Described in loving detail in Appendix B.

46 pulsars in *"1PC"* (6 months data),
Abdo et al., ApJS 187 460-494 (2010)

National Aeronautics and Space Administration
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Data

- Data Policy
- **Data Access**
  - + LAT Data
  - + LAT Catalog
  - + LAT Data Queries
  - + LAT Query Results
  - + LAT Weekly Files
  - + GBM Data
- Data Analysis
- Caveats
- Newsletters
- FAQ

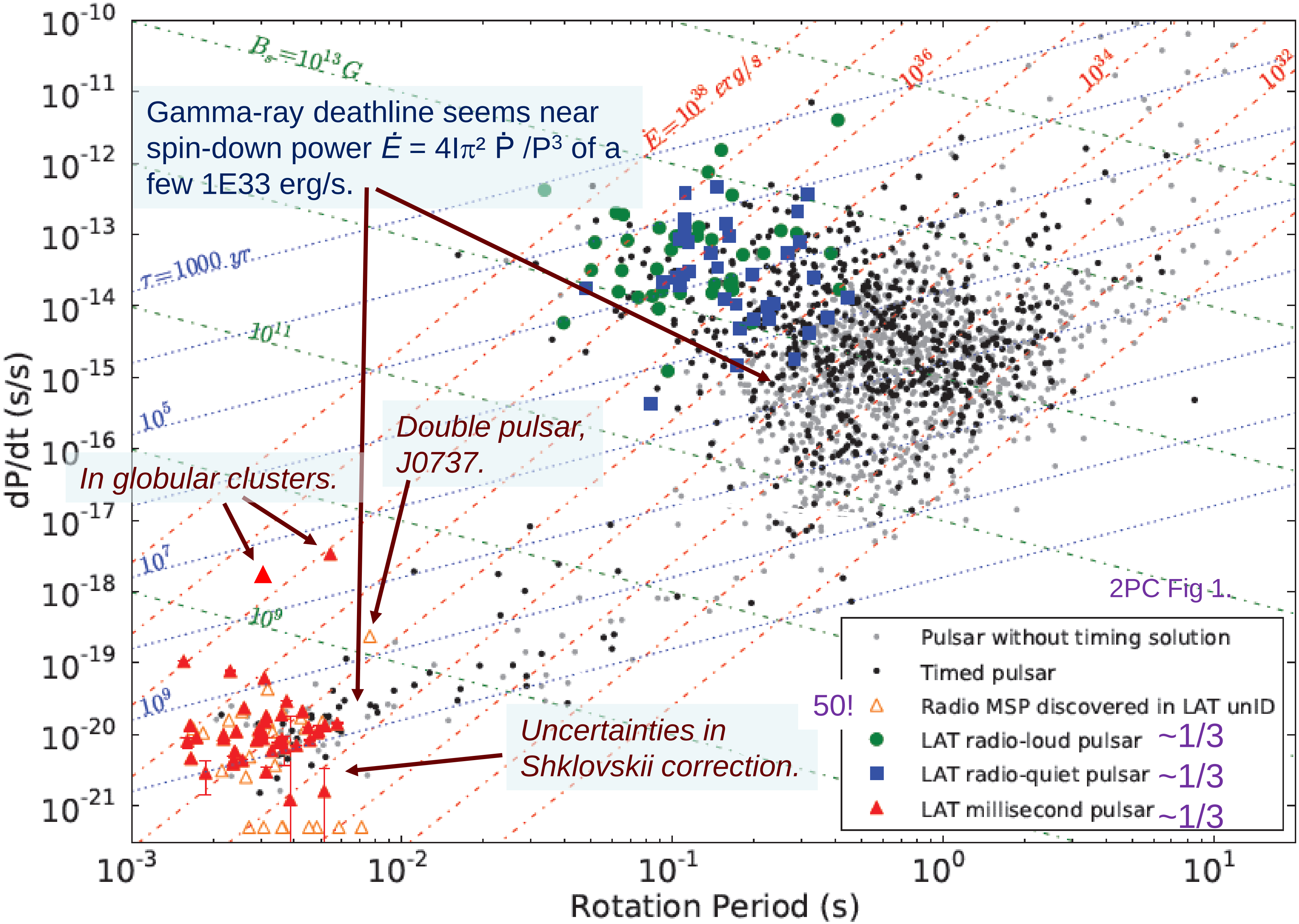
LAT Second Catalog of Gamma-ray Pulsars

The Fermi Gamma-ray Space Telescope (Fermi) Large Area Telescope (LAT) has discovered dozens of radio-quiet gamma-ray pulsars and dozens of millisecond pulsars (MSPs), establishing pulsars as the dominant GeV gamma-ray source class in the Milky Way. Here they present 117 gamma-ray pulsars unveiled in three years of on-orbit observations. They characterize the known gamma-ray pulsars as uniformly as feasible, and provide additional information from other wavebands where available. For a full explanation about the catalog and its construction see the LAT Second Pulsar Catalog Paper draft on arxiv.

LAT Catalog Data Products

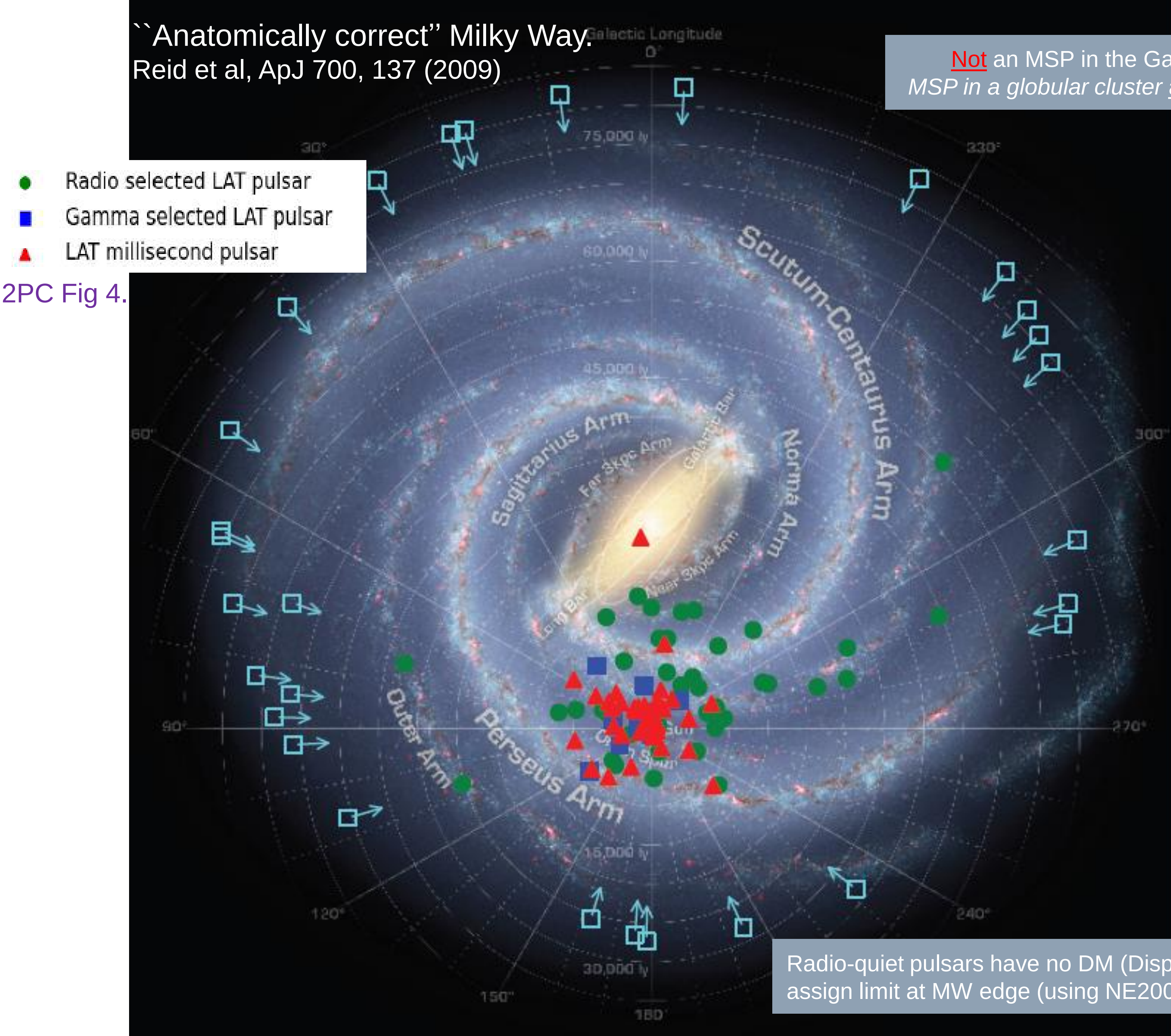
The LAT Second Pulsar Catalog is currently available as a .tgz (tarred and zipped) archive file. The archive includes a main catalog FITS file with the data from the paper tables, images of the light curve and spectral energy distributions (SEDs) for each pulsar, FITS files containing the data points used in those images, and the timing parameters used in the analysis. A full description of the online archive is given in Appendix B of the preprint. Upon final publication, this catalog will also be generated as a BROWSE table that will be linked to this page.

The LAT Second Pulsar Catalog archive of electronic files is linked below. To extract the content of the file, save the file to the target destination on your system. Navigate that directory and use the following command on the command line:



117(+8) gamma-ray pulsars in 2PC. *20 more to be published ➔ 145 total.*

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



2PC Fig 4.

Not an MSP in the Galactic center.
MSP in a globular cluster above the center.

Radio-quiet pulsars have no DM (Dispersion Measure): assign limit at MW edge (using NE2001).

Three ways to discover gamma-ray pulsars

1. "PSUE" = "*Pulsar Search Using Ephemerides*":
   - Phase-fold gamma-rays using rotation parameters of a known pulsar.
   - Weights from spectrum⊗point-spread-function eliminate ~few trials over ROI & energy cuts. But… spectra tricky for faint pulsars.
   - Except Geminga, all *Fermi* PSUE's from radio, not X-rays.

2. Blind period search in gamma-rays at target** positions :
   - 41 young PSRs. One MSP, J1311-3430.
   - Only 4 radio detections.

3. Deep radio search at UnId gamma positions :
   - 46 MSPs, off the plane. ~Few young, and/or accidental coincidences.
   - Can take a year before PSUE allows pulsed gamma detection.

** *Targets*: *early in mission, e.g. X-ray CCO's. Later, UnId gamma sources. Now also deep X-ray and optical companion searches.*

See Pablo Saz Parkinson's talk.

Campaign to time 224 high Edot pulsars.
(best gamma-ray candidates, but *unstable spin-down rate*.)

We obtained another 700 ephemerides.

Pulsar Timing for the *Fermi* Gamma-ray Space Telescope

D. A. Smith[1,2], L. Guillemot[1,2], F. Camilo[3], I. Cognard[4,5], D. Dumora[1,2], C. Espinoza[6], P. C. C. Freire[7], E. V. Gotthelf[3],
A. K. Harding[8], G. I
Manchester[9], F. E. Ma
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1 Université de Bord
2 CNRS/IN2P3, Ce
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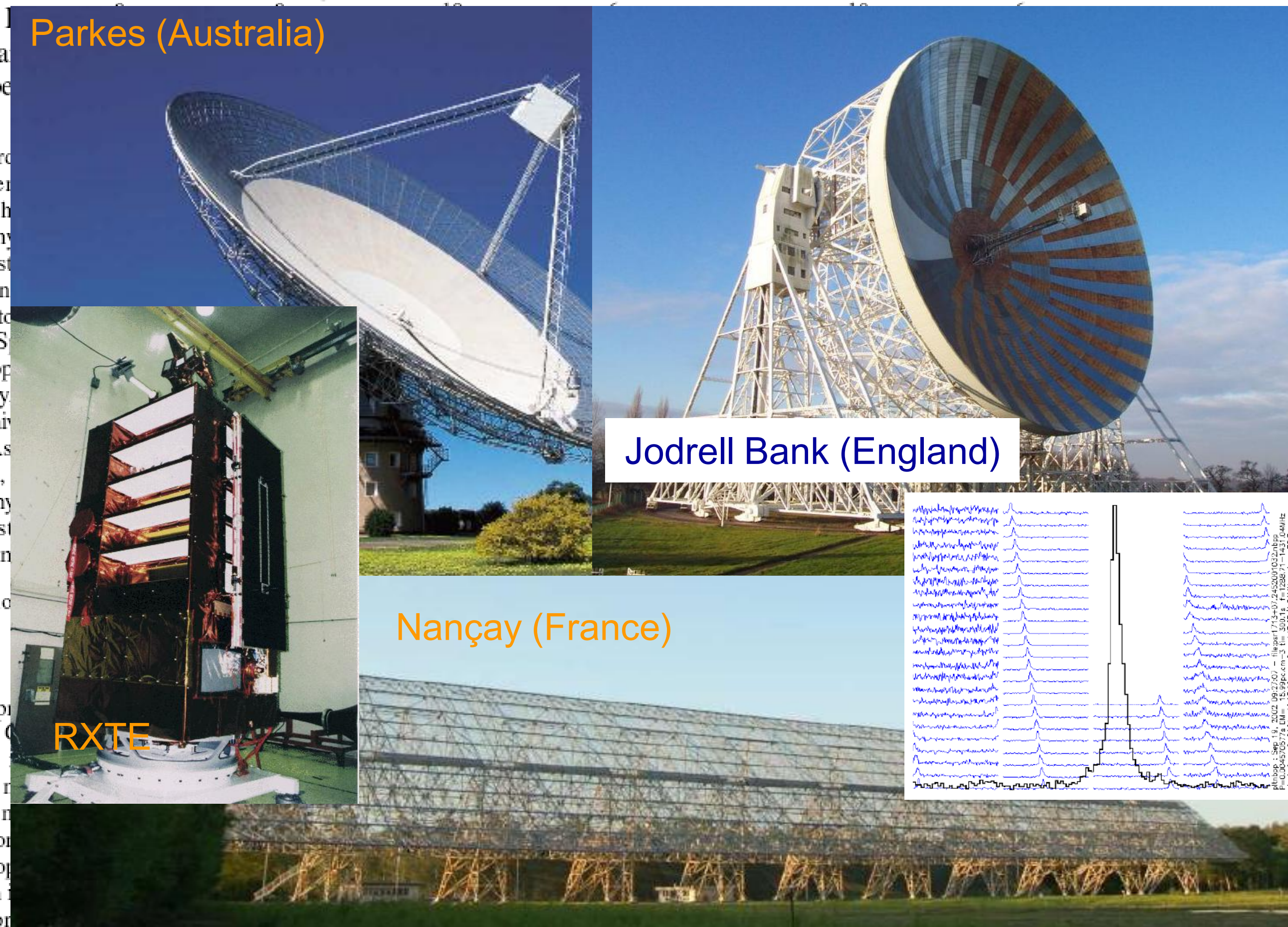
5 Station de radioast
6 University of Man
7 Arecibo Observat
8 NASA Goddard S
9 Australia Telescop
10 McGill University
11 West Virginia Uni
12 National Radio As
13 Eureka Scientific,
14 Department of Phy
15 Department of Ast
16 National Astronon

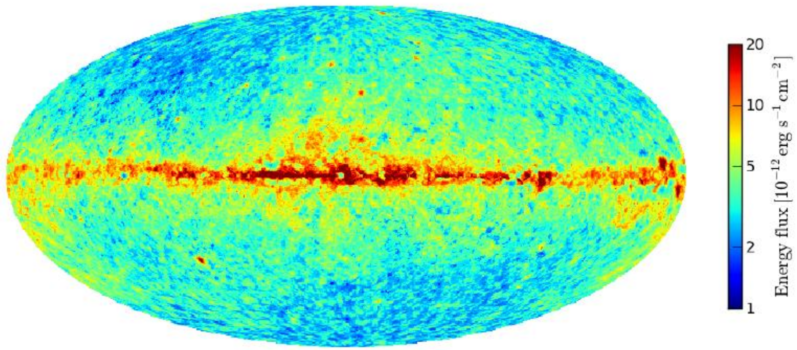
Preprint online versio



We describe a comp
Telescope (formerly
and supernova rates
driving pulsar wind
makes detection of
powers. To search fo
a year or more to pro
campaign. Attention
PSR B1937+21 reco
pulsar phase calculations at the microsecond level.

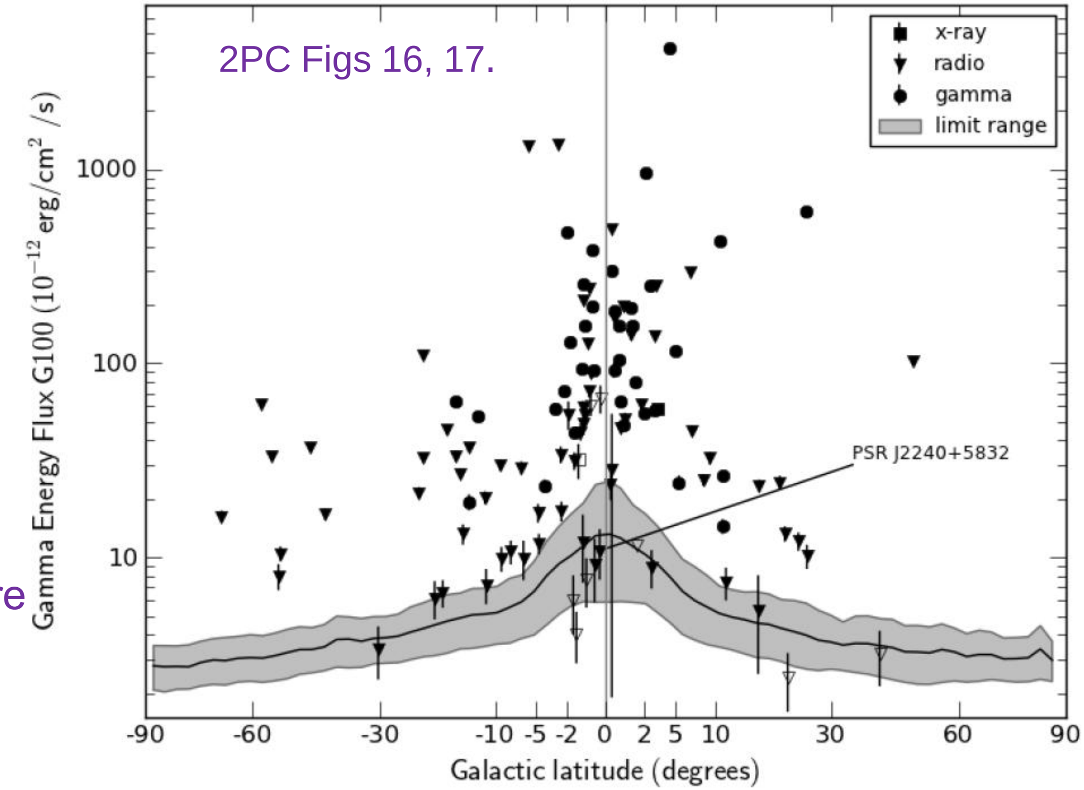
Key words. pulsars:general – Gamma-rays:observations – Ephemerides

A&A 492, 293 (2008)



Above: 3-year point-source sensitivity, assuming pulsar-like spectra.

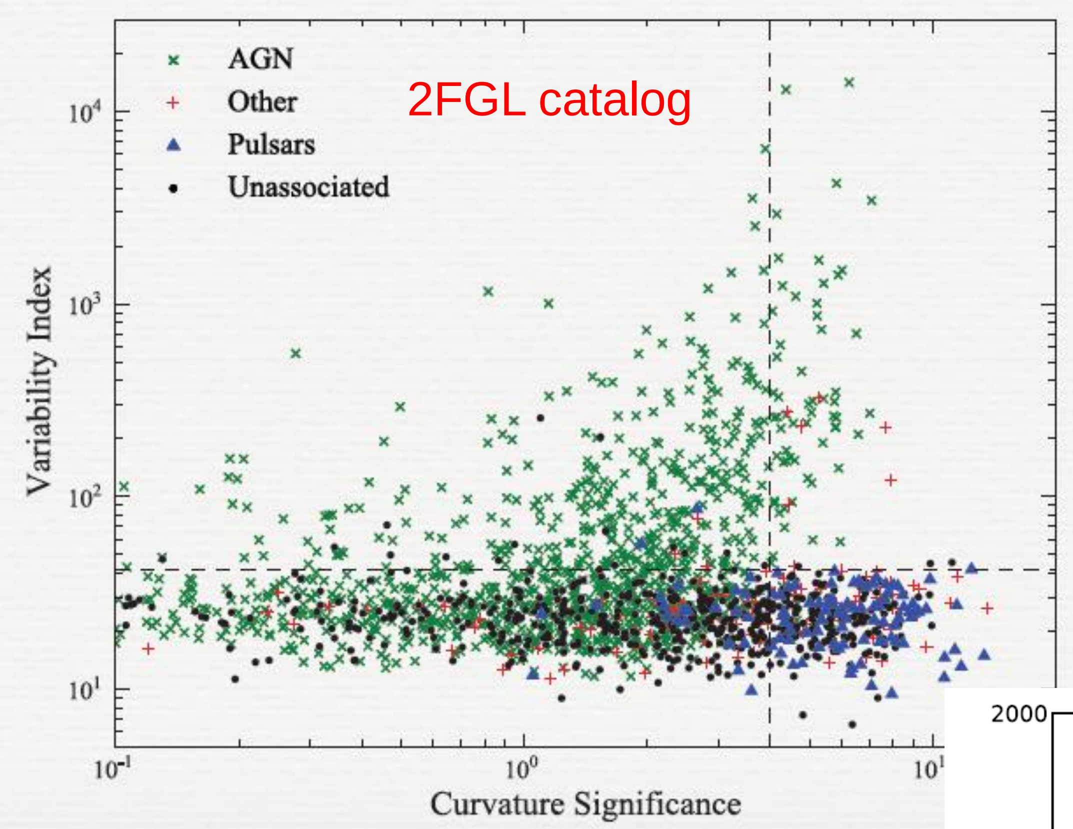
Right: Ditto, averaged over longitude, showing 10%, 90% percentiles. “PSUE” are the radio, X-ray point. Else, γ blind search.



2PC Figs 16, 17.

- PSUE is easiest*, and picks up fainter pulsars than the catalog point source search.
- BUT suffers the same selection biases as ‘historical’ radio surveys.
- Gamma-triggered pulsar detections unveil complementary neutron star populations.

* *Because your radio and Xray friends did the hard part!*



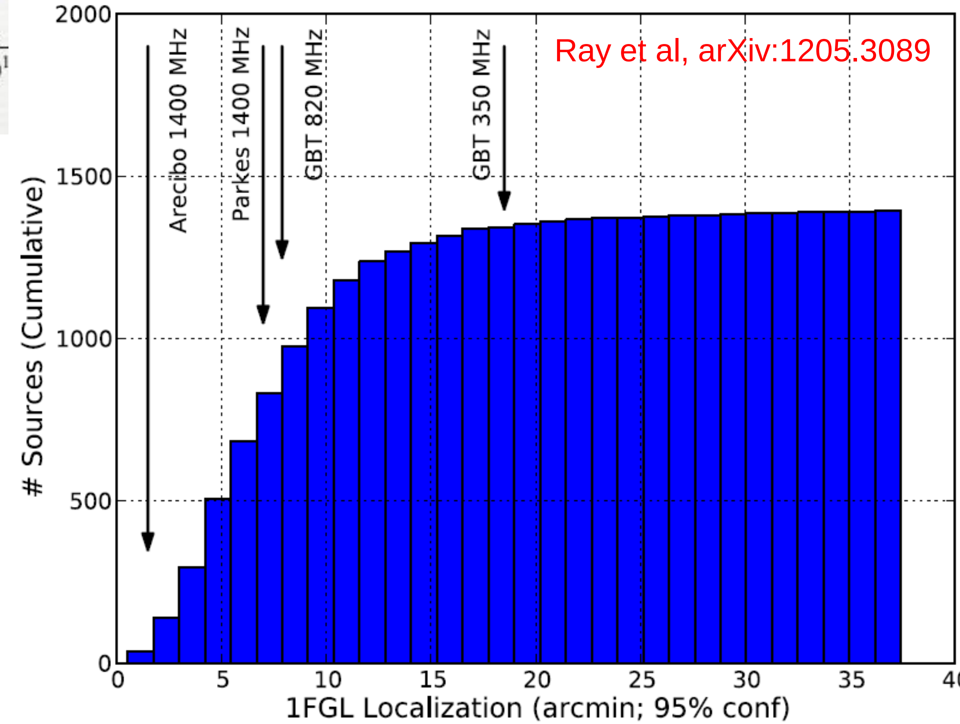
Blazars (AGNs) are variable, with power-law spectra.

Pulsars are steady, with cut-off spectra.

(*New – learning to ignore cut-offs.*)

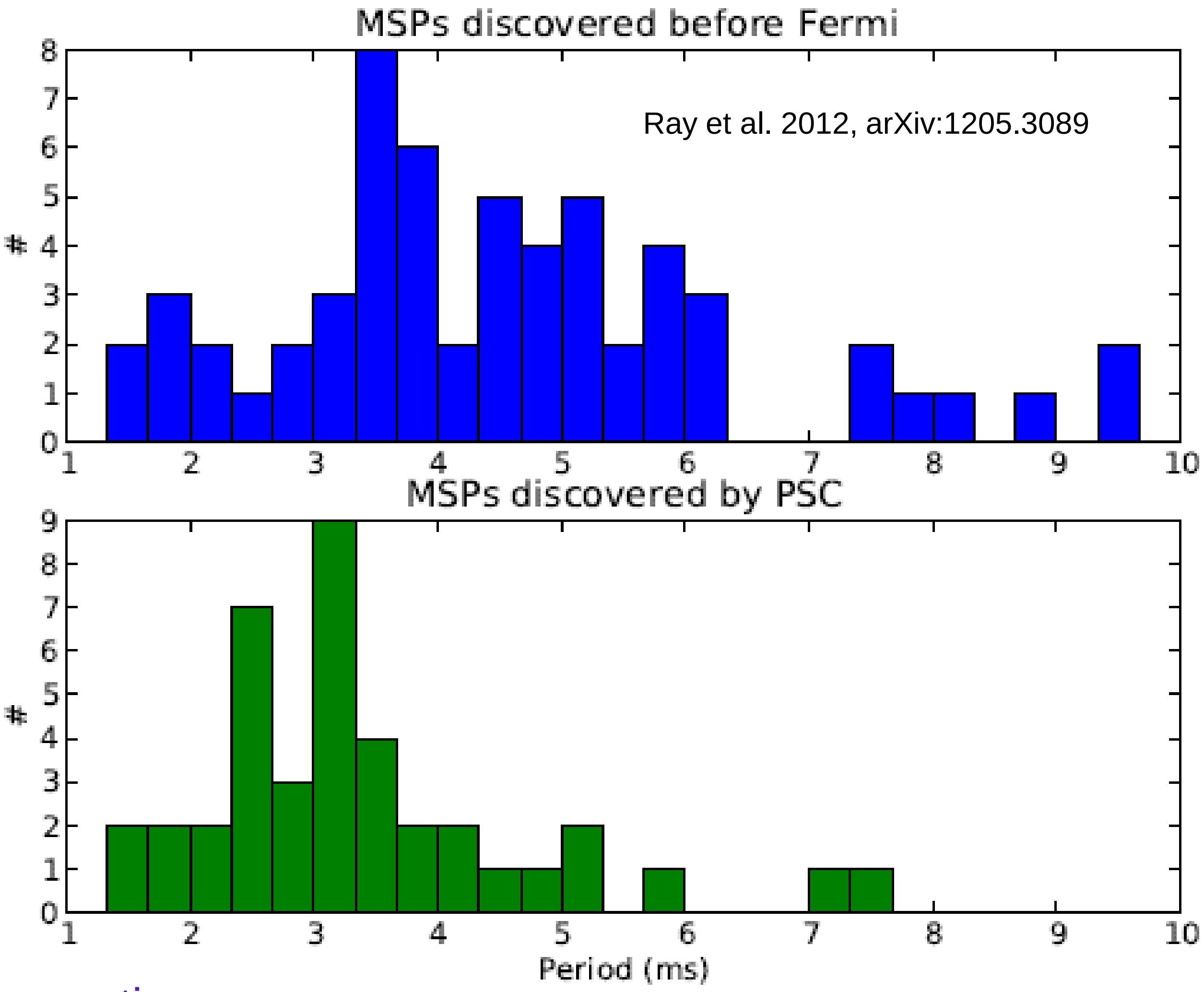
LAT sources are well-localized.

Nançay



Pablo's talk:
target selection, and gamma blind searches.

MSPs from pre-*Fermi* radio surveys are slower than the *Fermi*-induced discoveries.



'PSC' =
Fermi Pulsar Search Consortium =
radio astronomers coordinating deep searches of *Fermi* unidentified sources.

Table 1. Black Widows and Redbacks in the Galactic Field

Paul Ray 2013 *Fermi* Guest Observer application.

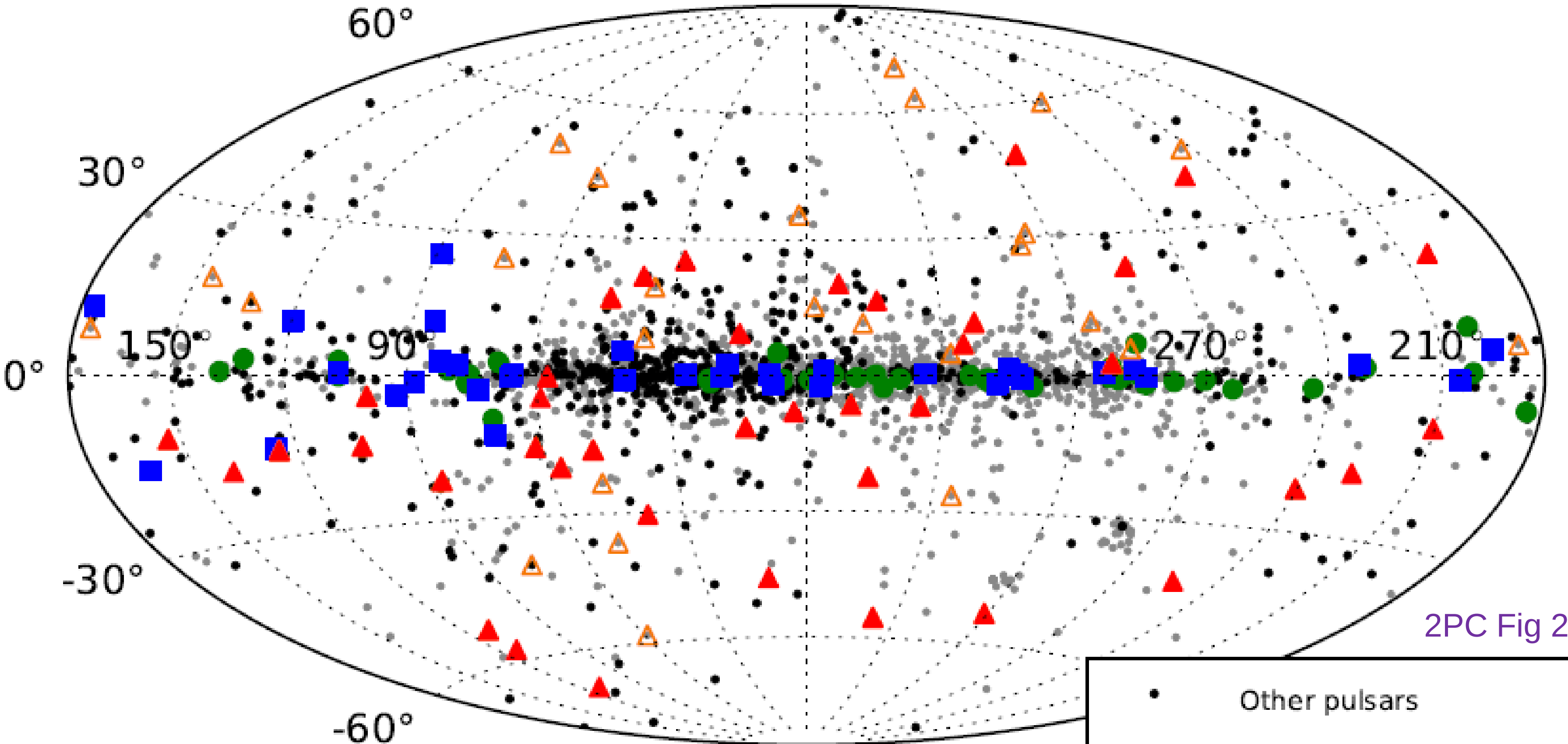
PSR	P (ms)	$\dot{E}/10^{34}$ (erg/s)	D (kpc)	$P_{\rm orb}$ (hr)	$M_{\rm c,min}$ ($M_\odot$)	Fermi	Timing
Old Black Widows							
B1957+20	1.61	11.0	2.5	9.2	0.021	P	Eff, NRT, WSRT
J0610−2100	3.86	0.23	3.5	6.9	0.025	P	NRT
J2051−0827	4.51	0.53	1.0	2.4	0.027	P	Eff, NRT, WSRT
New Black Widows							
J1311−3430	2.56	4.92	1.4	1.3	0.008	P, B	(Other proposal)
J2241−5236	2.19	3.27	0.5	3.4	0.012	P, U	Parkes
J1745+1017	2.65	0.54	1.3	17.5	0.014	P, U	Eff, WSRT, Jodrell, NRT
J2214+3000	3.12	1.95	1.5	10.1	0.014	P, U	NANOGrav, Eff, WSRT, Jodrell, NRT
J2234+0944	[illegible]	[illegible]	[illegible]	[illegible]	0.015	P, U	Eff, Jodrell, NRT, Parkes
J0023+0923	3.05	1.51	0.7	3.4	0.017	P, U	Eff, NANOGrav, WSRT, Jodrell, NRT
J1544+4937	2.16	1.22	1.2	2.8	0.018	A, U	GMRT
J1301+0833	1.84	6.66	0.7	6.5	0.024	A, U	GBT(Camilo)
J1124−3653	2.41	1.62	1.7	5.5	0.027	P, U	**(This proposal)**
J2256−1024	2.29	[illegible]	0.6	5.1	0.034	P	GBT(Stairs)
J1731−1847	2.35	7.63	2.5	7.5	0.040		WSRT, Jodrell, NRT
J2047+1053	4.29	1.05	2.0	2.9	0.036	P, U	Eff, Jodrell
J1810+1744	1.66	4.00	2.0	3.6	0.045	P, U	Eff, WSRT, Jodrell
New Redbacks							
J1023+0038	1.69	9.85	0.9	4.8	0.13	A	Eff, WSRT, Jodrell, NRT
J2215+5135	2.61	5.2	3.0	4.1	0.21	P, U	WSRT
J1723−2837	1.86	5.3	0.8	14.8	0.24		Jodrell
J1628−3205	3.21	1.35	1.2	5.0	0.16	A, U	GBT(Camilo)
J1816+4510*	3.19	5.03	2.4	8.7	0.16	P, U	GBT(GBNCC)
J2129−0429	7.61	3.88	0.9	15.2	0.38	A, U	WSRT
J2339−0533	2.88	2.30	0.5	4.6	0.26	P, U	WSRT

Many *Fermi* MSPs are Black Widows and Redbacks. **Rare before *Fermi*.**

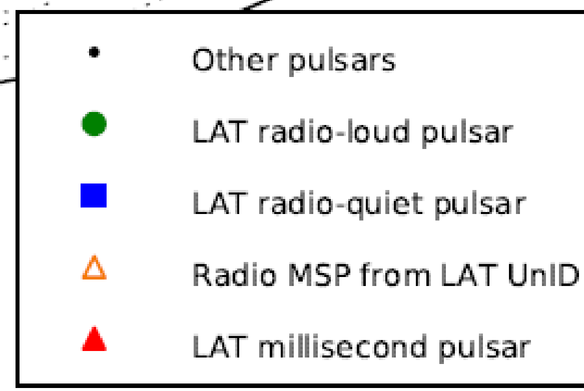
Explore the recycling process.

See Mallory Roberts talk, today.

Note. — (*) Companion may be somewhat degenerate (Kaplan et al. 2013, ApJ, accepted). Fermi column codes: (P) LAT pulsations detected, (A) associated with a LAT source but without pulsations so far, (U) discovered in a radio search targeting LAT unassociated sources, (B) found it a LAT blind search of an unassociated source.



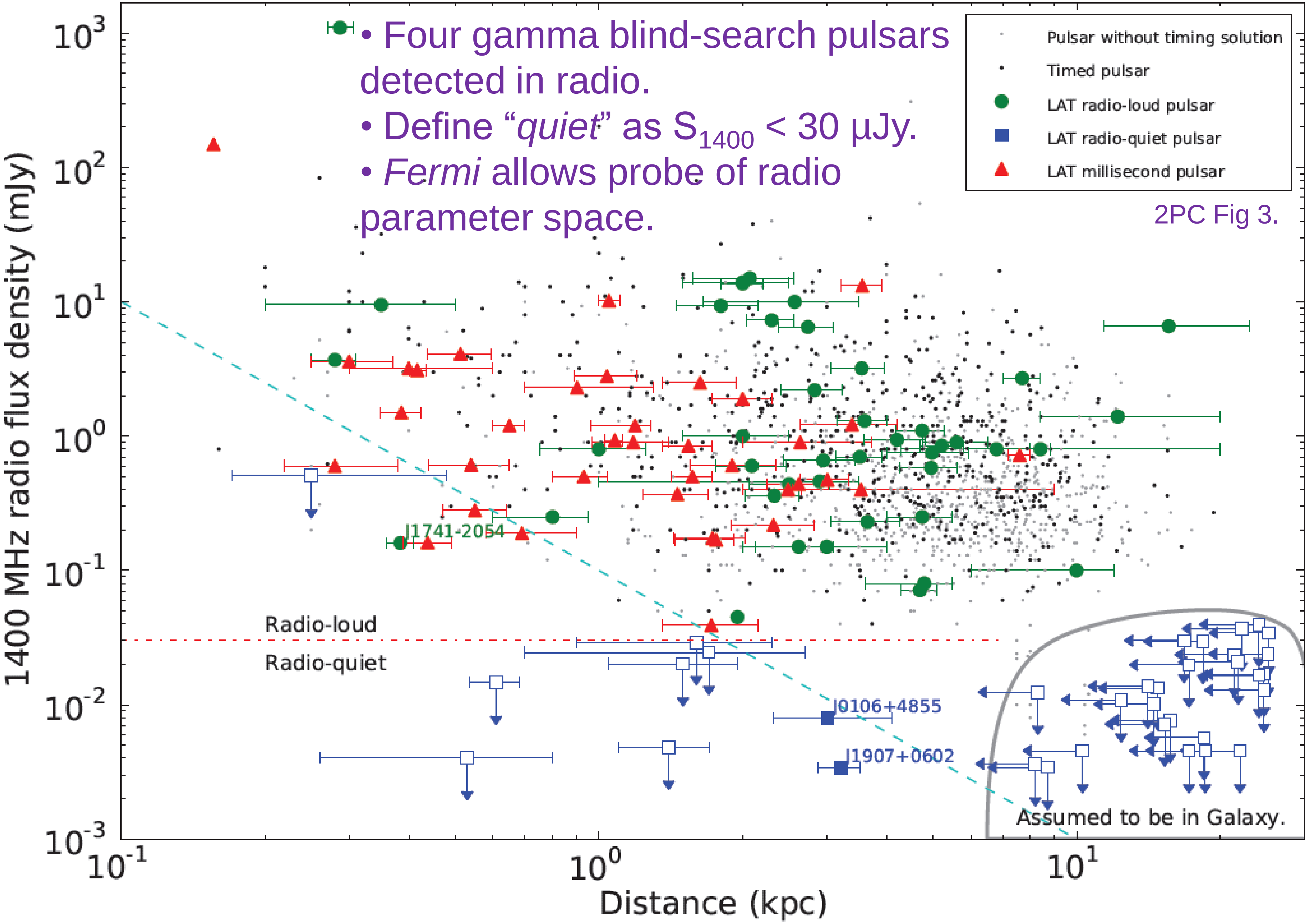
2PC Fig 2.



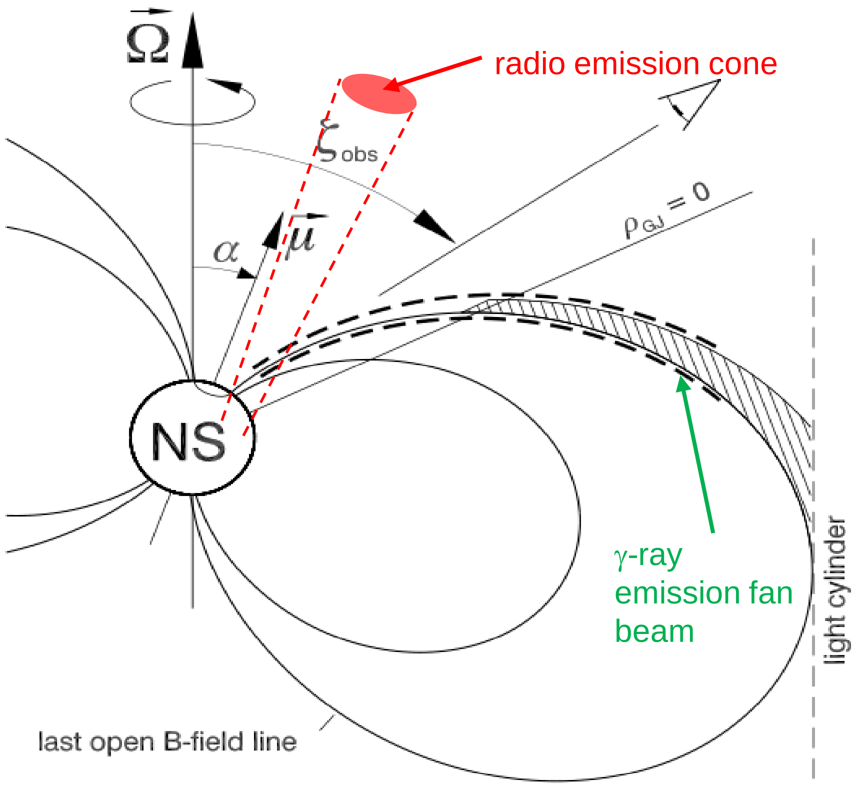
- The MSPs are faint:
  low $\dot{E}$ → low L_γ → nearby → big latitude spread.

- The *Fermi* "treasure map" has allowed deeper, repeated (scintillation! eclipsing!) radio searches than radio surveys.
- Some new radio MSPs 'good timers' suitable for gravity wave searches.

- Four gamma blind-search pulsars detected in radio.
- Define "*quiet*" as S_{1400} < 30 μJy.
- *Fermi* allows probe of radio parameter space.



Diagonal : 100 μJy-kpc² pseudo-luminosity.



Radio pulsars have a limited range of magnetic (α) and overall (ζ) inclinations: the radio beam must sweep the Earth.

LAT shows, γ-ray beams are mostly *wide*: large number of young, radio-quiet pulsars.

MSPs have a smaller light-cylinder.
The magnetic field lines are cut close in, making broader radio beams.

No radio-quiet MSPs yet. Expect few or none.

Not in 2PC –
compilation of (α,ζ) estimates, from radio polarization (e.g. RVM), or pulsar wind nebulae inclinations (e.g. X-ray images).

(S. Johnston; ,M. Kerr, R. Shannon working on it…)

Many individual gamma pulsar papers provide those analyses.
Useful for modeling (we hope).

2PC: characterizing gamma-ray pulsars

- Gamma pulse profiles in different energy bands. Profile fit for >0.1 GeV. Radio when available ; background levels ; off-pulse.

- Spectral fits for all but the very faintest. Power law with pure exponential cutoff works well, generally. Provide alternatives when called for.

- "*The pulsars not seen*" – tabulate undetected good candidates.

- X-ray and optical compilations for the 117 γ-pulsars.

- All of the above in the online FITS, image, and ascii files.

Profile example: PSR J2240+5832

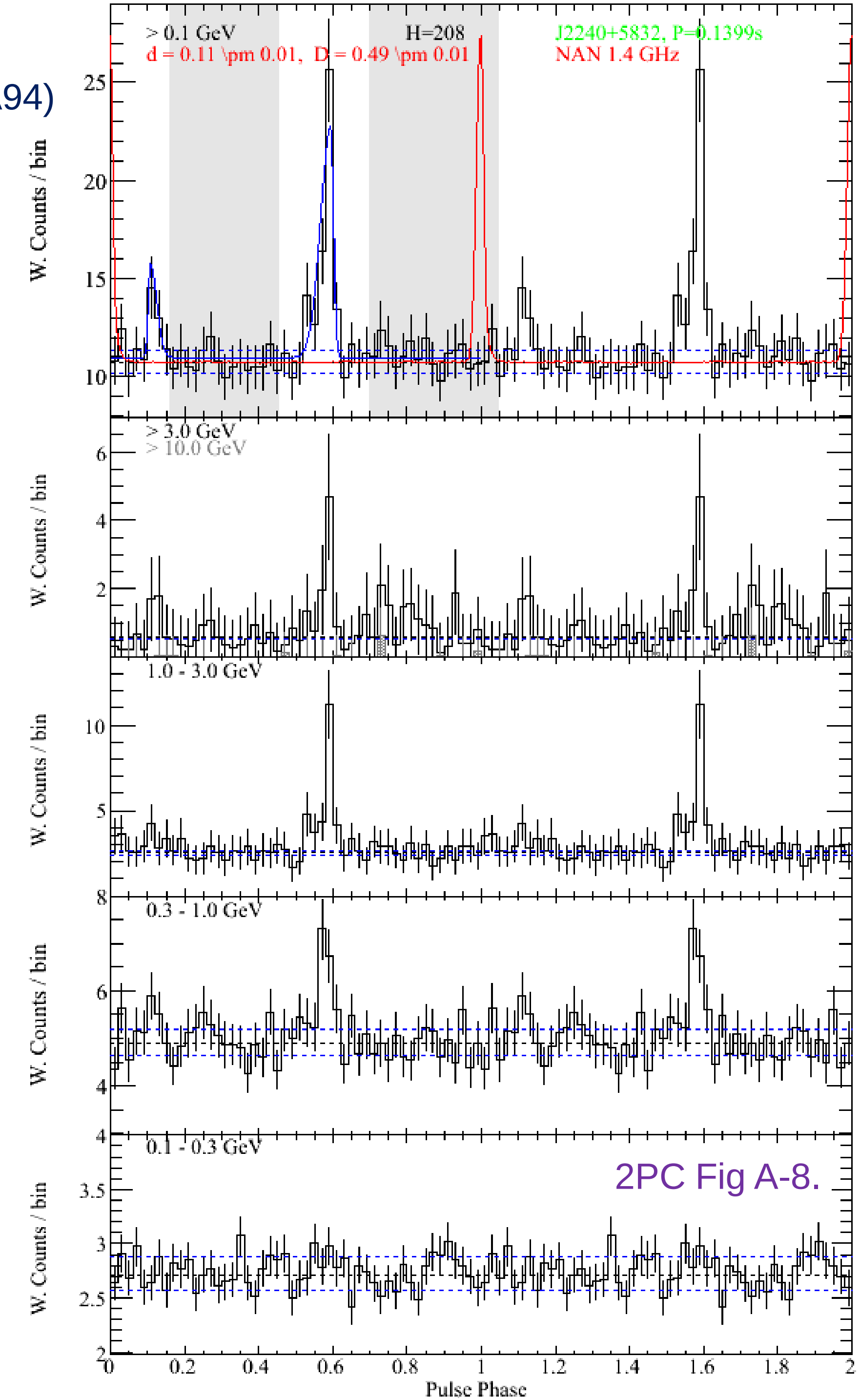
(see also Theureau et al. 2011, A&A, 525, A94)

- Black – weighted gamma-ray profiles.
- Blue – fit
- Red – phase-aligned radio profile.
- Gray – ‘off-peak’ phase range
- Horizontal dash – local gamma-ray b’grd

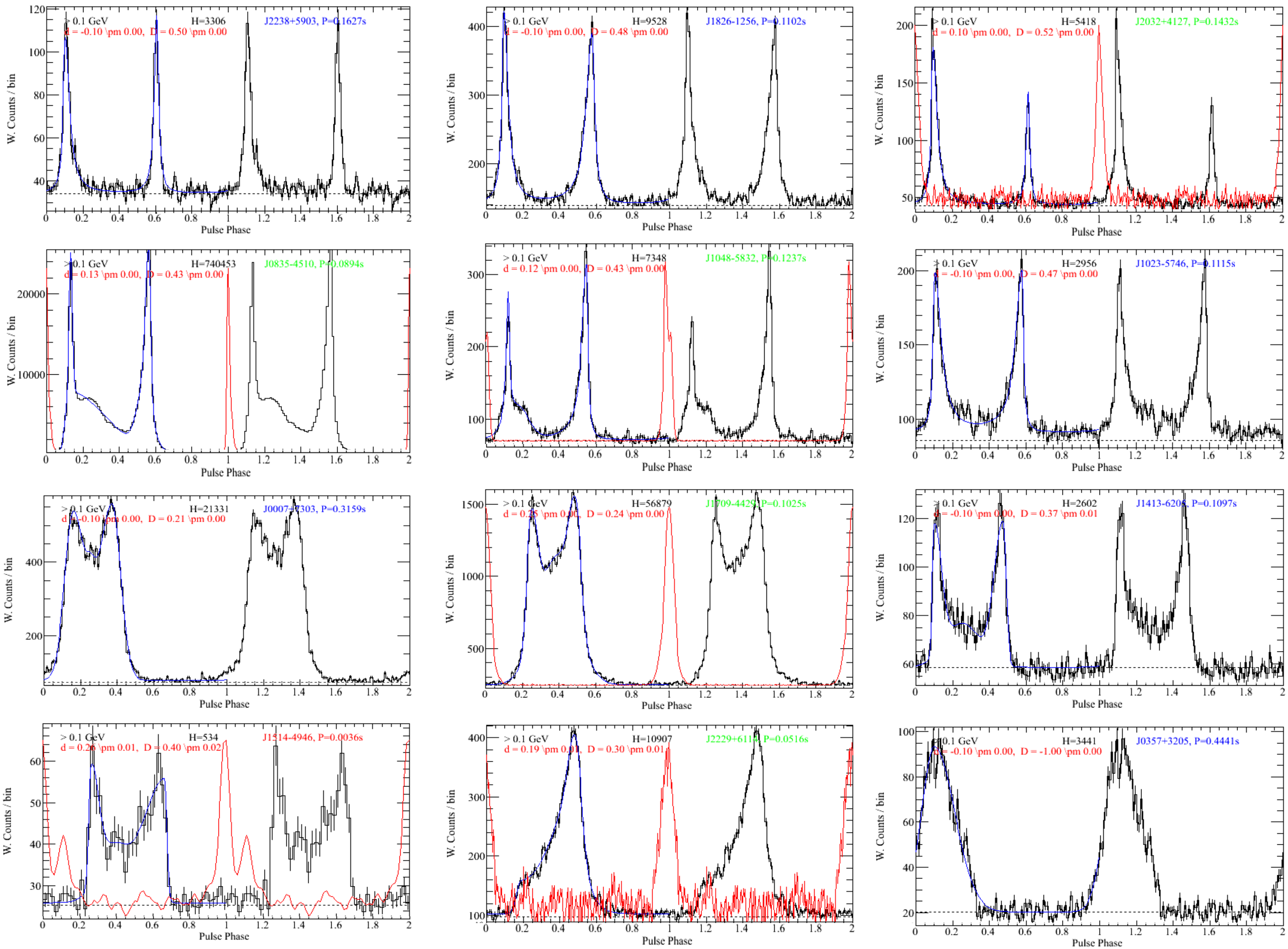
- d = δ = ‘radio lag’
- D = Δ = ‘peak separation’
- H-test pulse significance

Online files have these in .png, .pdf, .FITS, and ascii.

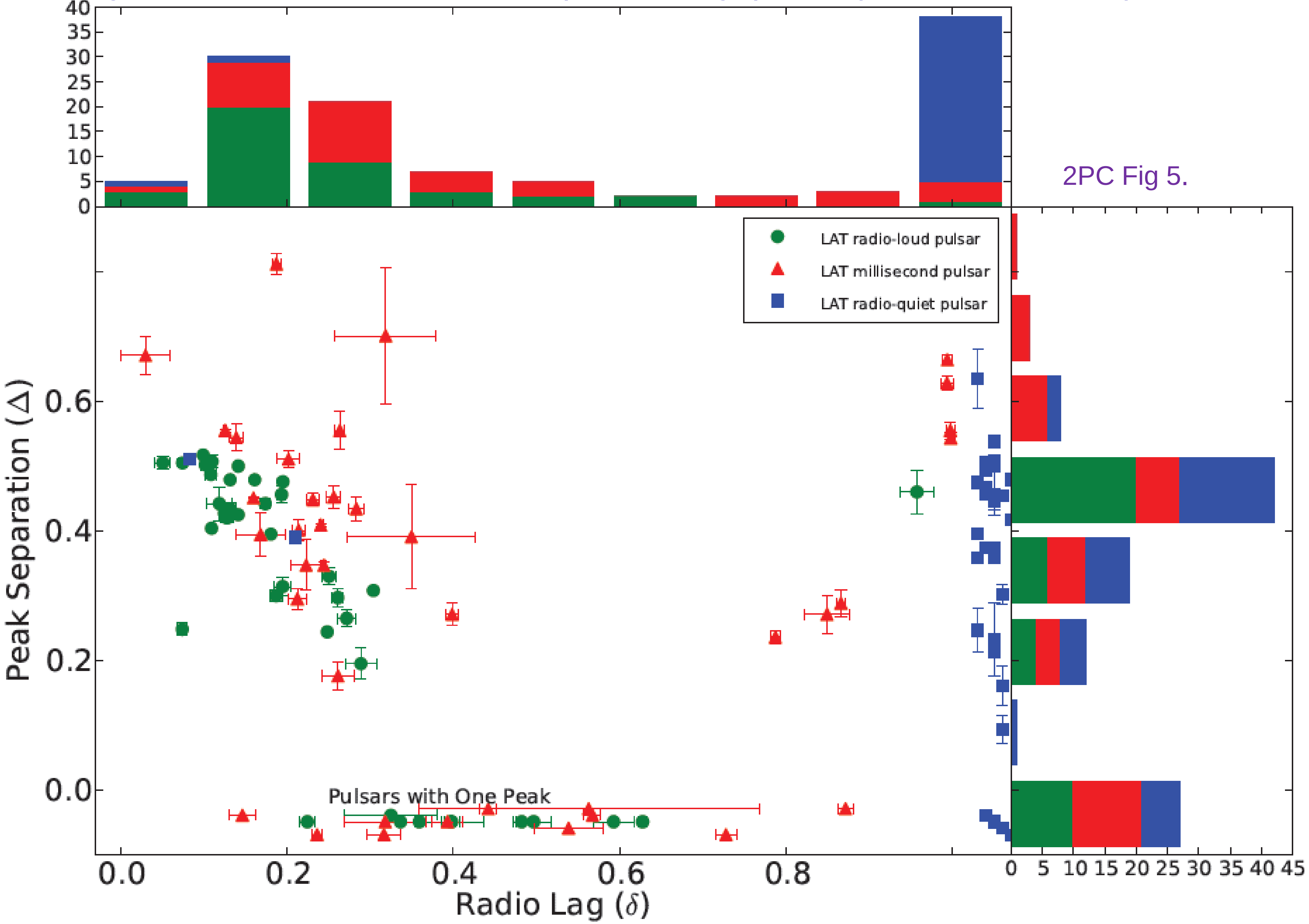
Online files also contain the leading and trailing half-widths of the gamma peak(s).



Gamma-ray pulse profile shapes

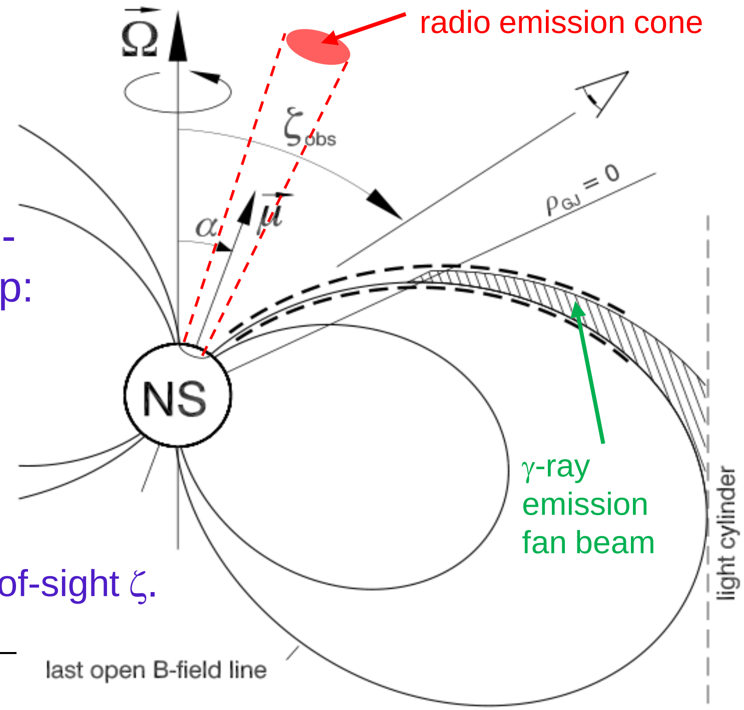


For radio-loud gamma pulsars: closer peaks means bigger offset from radio pulse.
A geometrical effect, but also depends on gap size (*see Christo's talk*)



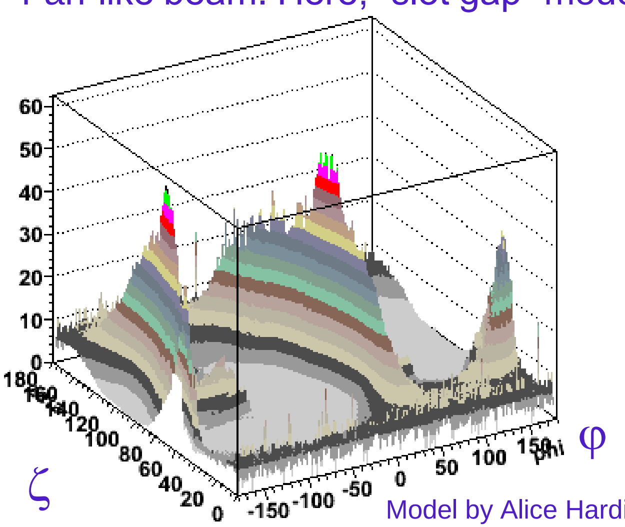
2PC Fig 5.

Large gamma-ray sample: test models for a broad range of magnetic (α) and overall (ζ) inclinations.



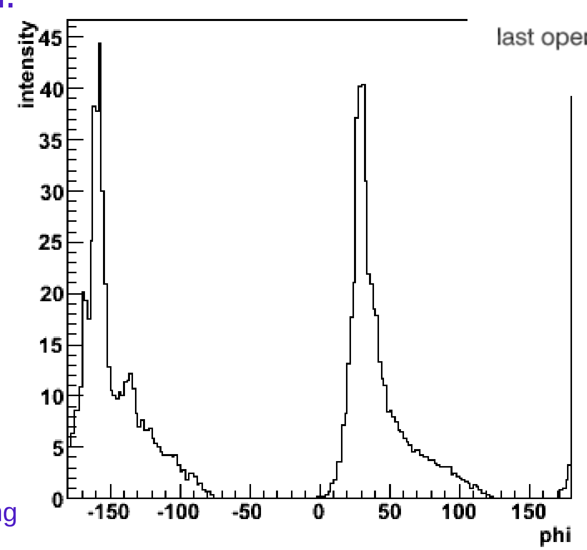
(this is an XMM conference – the caricature of a thermal X-ray pulse profile is the aberrated sinusoïd of a hot polar cap: *strikingly different*.)

ζ vs phase φ.
Fan-like beam. Here, "slot gap" model.



Model by Alice Harding

Cut across some line-of-sight ζ.



Compare data with simulated “atlases” of predicted gamma-ray pulse profiles, for different models, magnetic inclinations α, and inclinations ζ to the line-of-sight.

Here: ApJ 714, 810 (2010).

Gap size scales $\propto 1/\sqrt{\dot{E}}$.

Match observed to predicted profiles.

See also e.g.
Venter et al (2012)
and
Pétri MNRAS (2011)
and
Pierbattista, Grenier, Harding, Gonthier, arXiv:1103.2682
and
Bai & Spitkovsky 2009

ROMANI & WATTERS

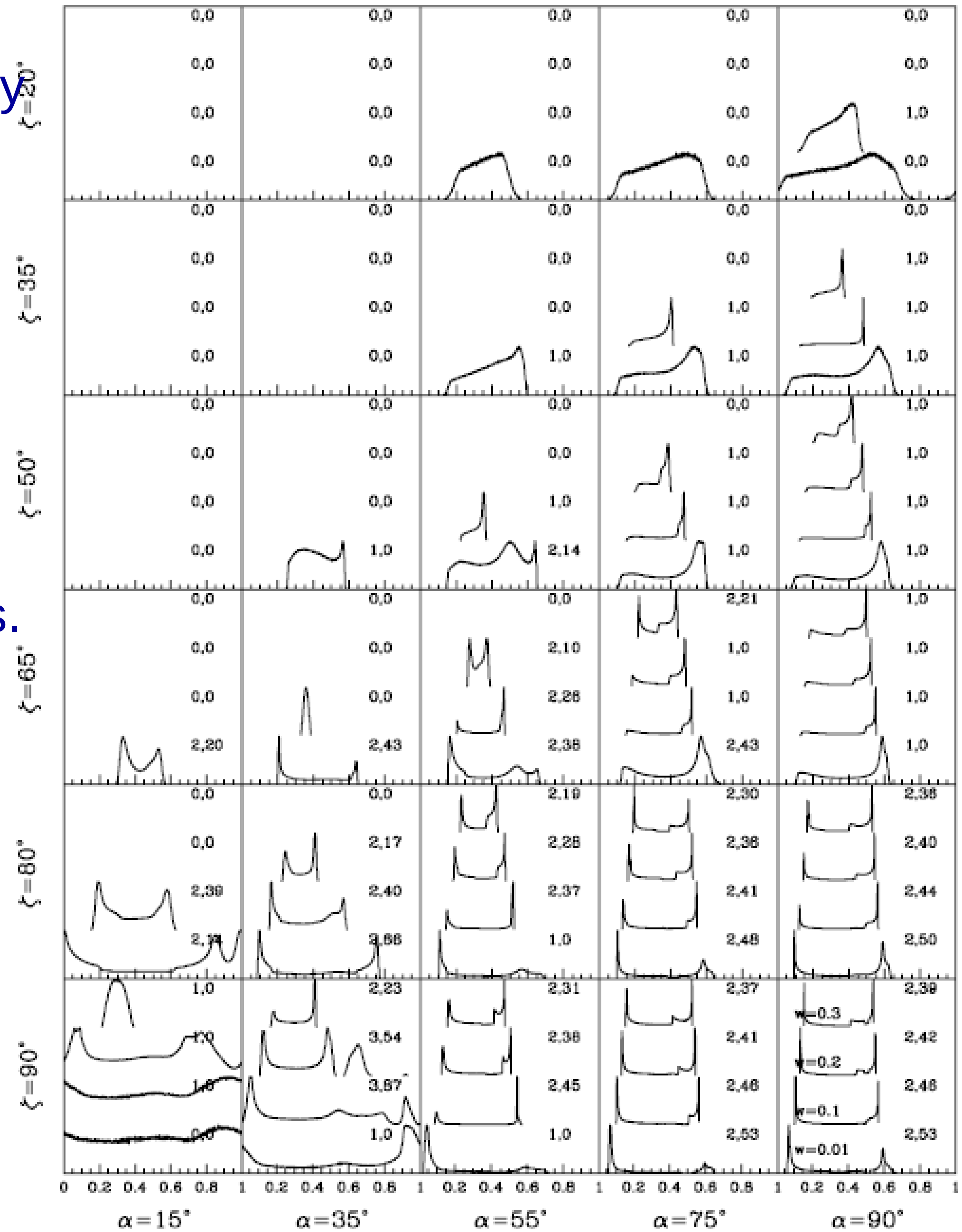
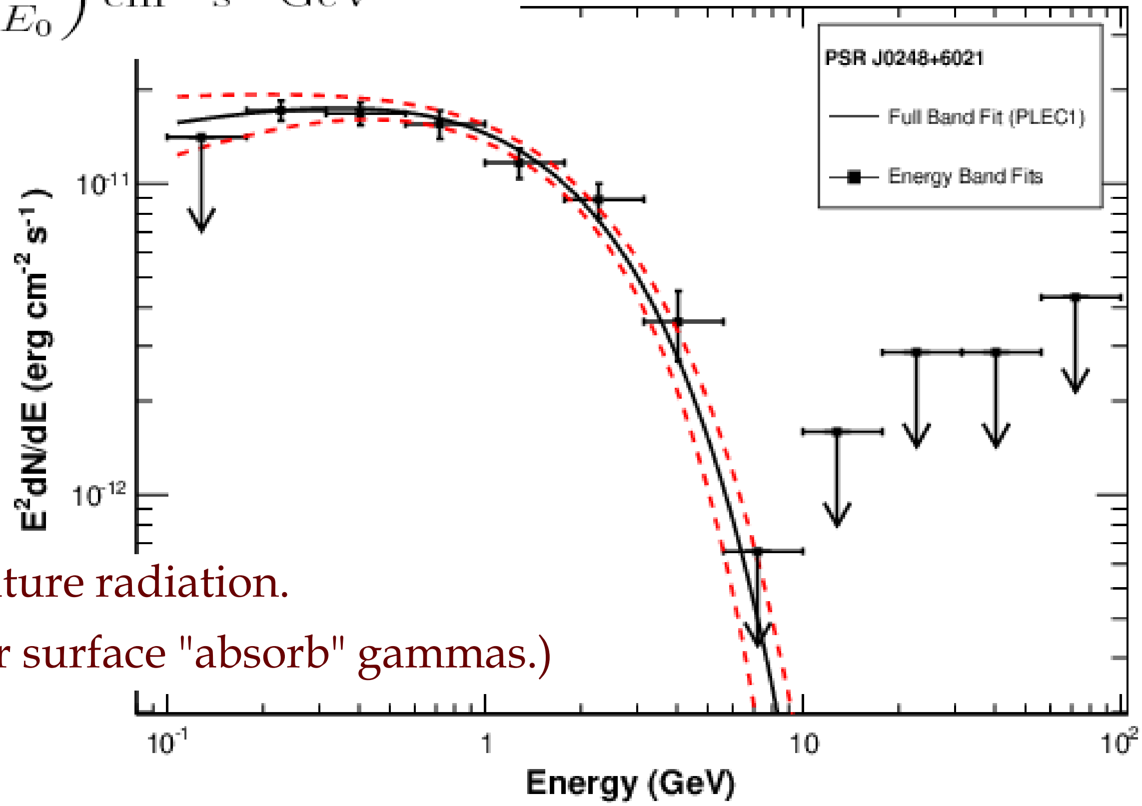


Figure 15. OG lightcurves. Labels as for Figure 14.

$$\frac{dN}{dE} = N_0 E^{-\Gamma} \exp\left(-\frac{E}{E_0}\right)^b \mathrm{cm^{-2}s^{-1}GeV^{-1}}$$

2PC online.



b=1 ➔ high altitude curvature radiation.

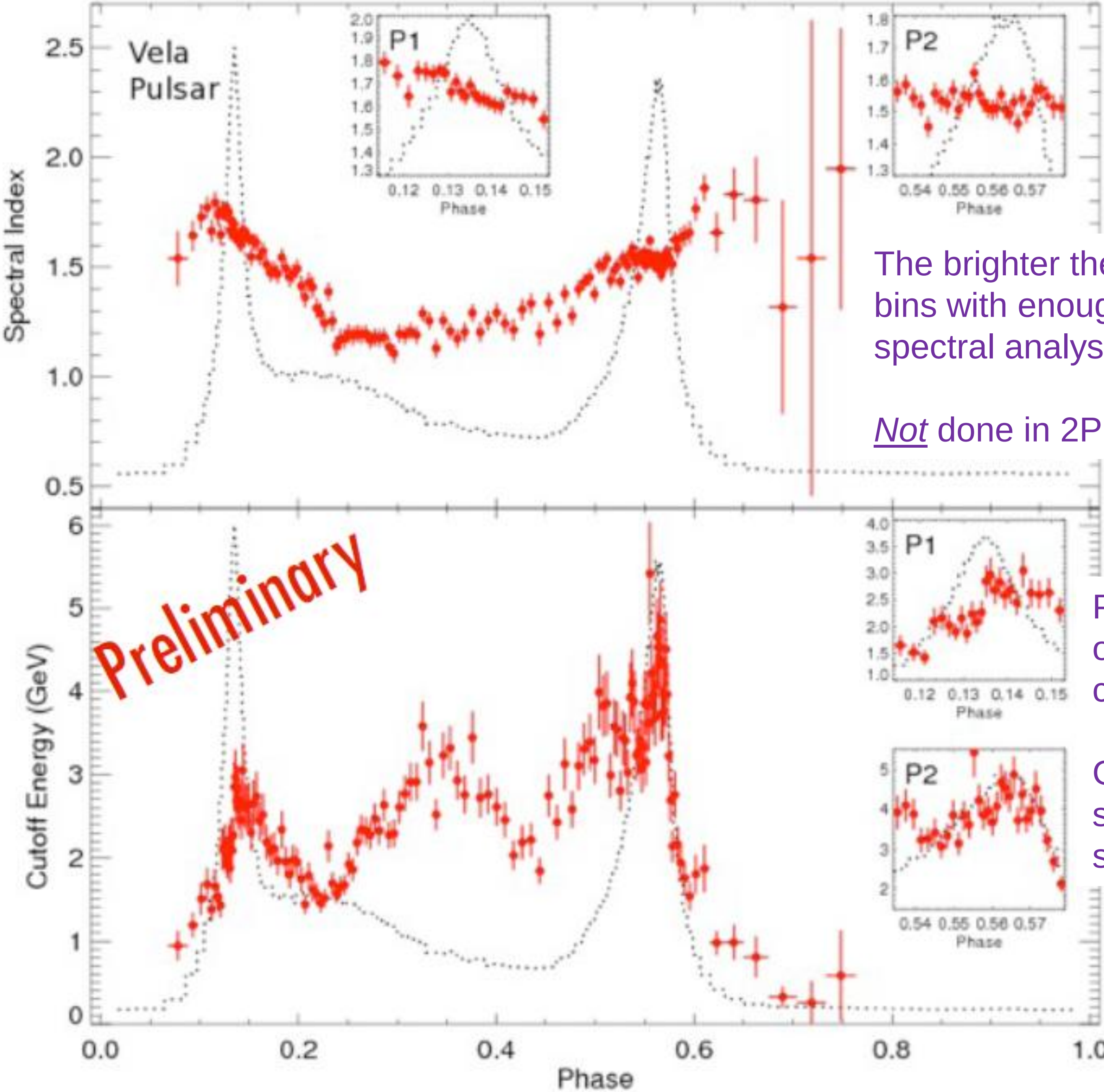
(strong magnetic fields near surface "absorb" gammas.)

G_{100} : integral energy flux >100 MeV

Pulsar spectral '<u>signature</u>'.

(Most sources, e.g. blazars, have power law spectra with little or no curvature.)

This said – as the mission progresses, we study fainter & fainter sources, and spectral details become less discriminating. *<u>Future</u>*: a) subtler candidate selections b) search 'em all!



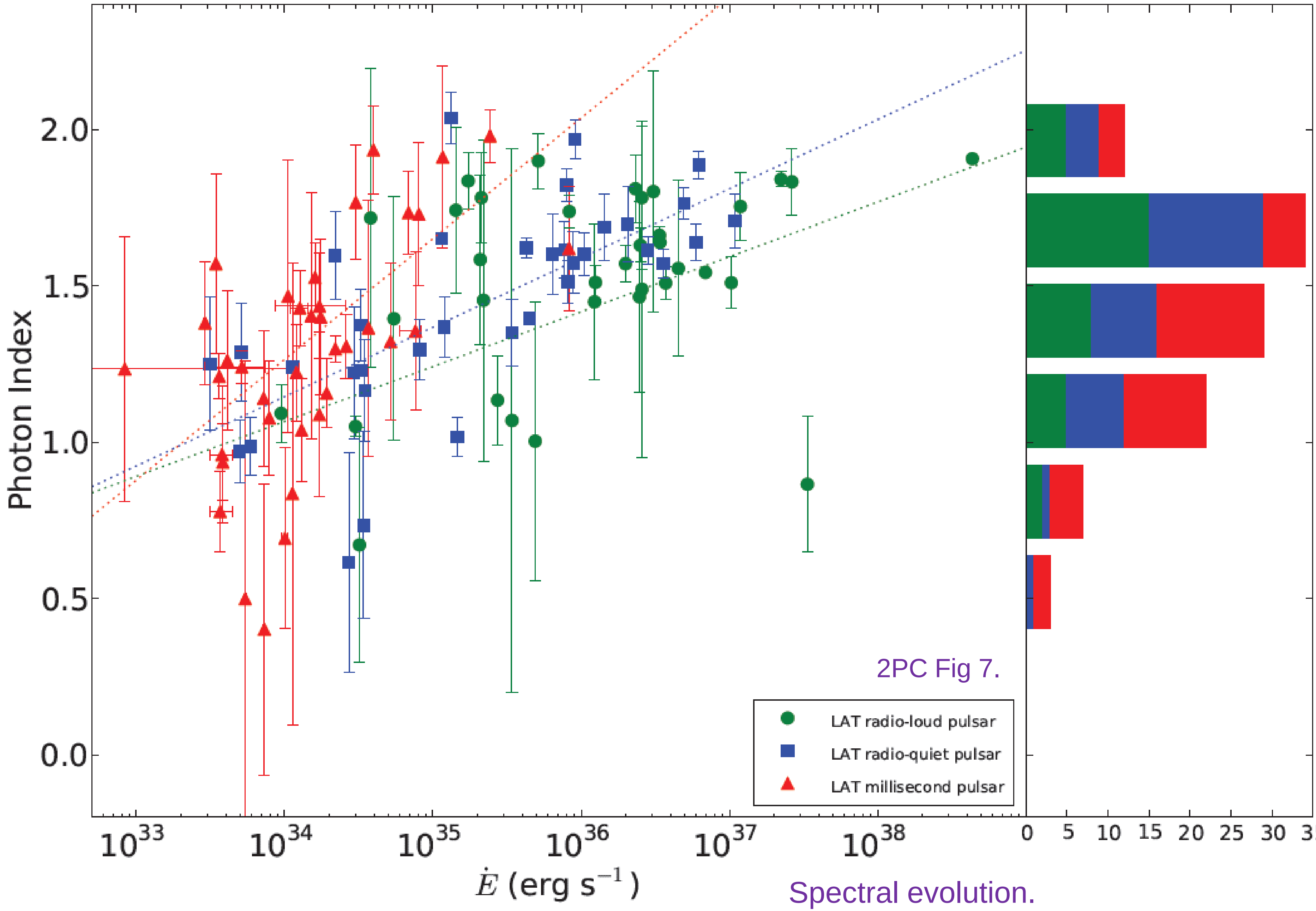
The brighter the pulsar, the more phase bins with enough statistics for a full spectral analysis.

Not done in 2PC. See individual papers*.

Phase-averaged spectra often show sub-exponential cutoffs (b<1).

Generally an *artifact* of the sum of varying spectral shapes.

*e.g. Megan DeCesar (this) and Nicolas Renault doctoral theses.



2PC Fig 7.

Spectral evolution.

See Jérôme Pétri, C. Venter talks for emission modeling.

Gamma luminosity:
a key observable, but with difficulties:

$$L_\gamma = 4\pi d^2 f_\Omega G_{100}.$$

• Distance *d* dominates luminosity L_γ uncertainties.

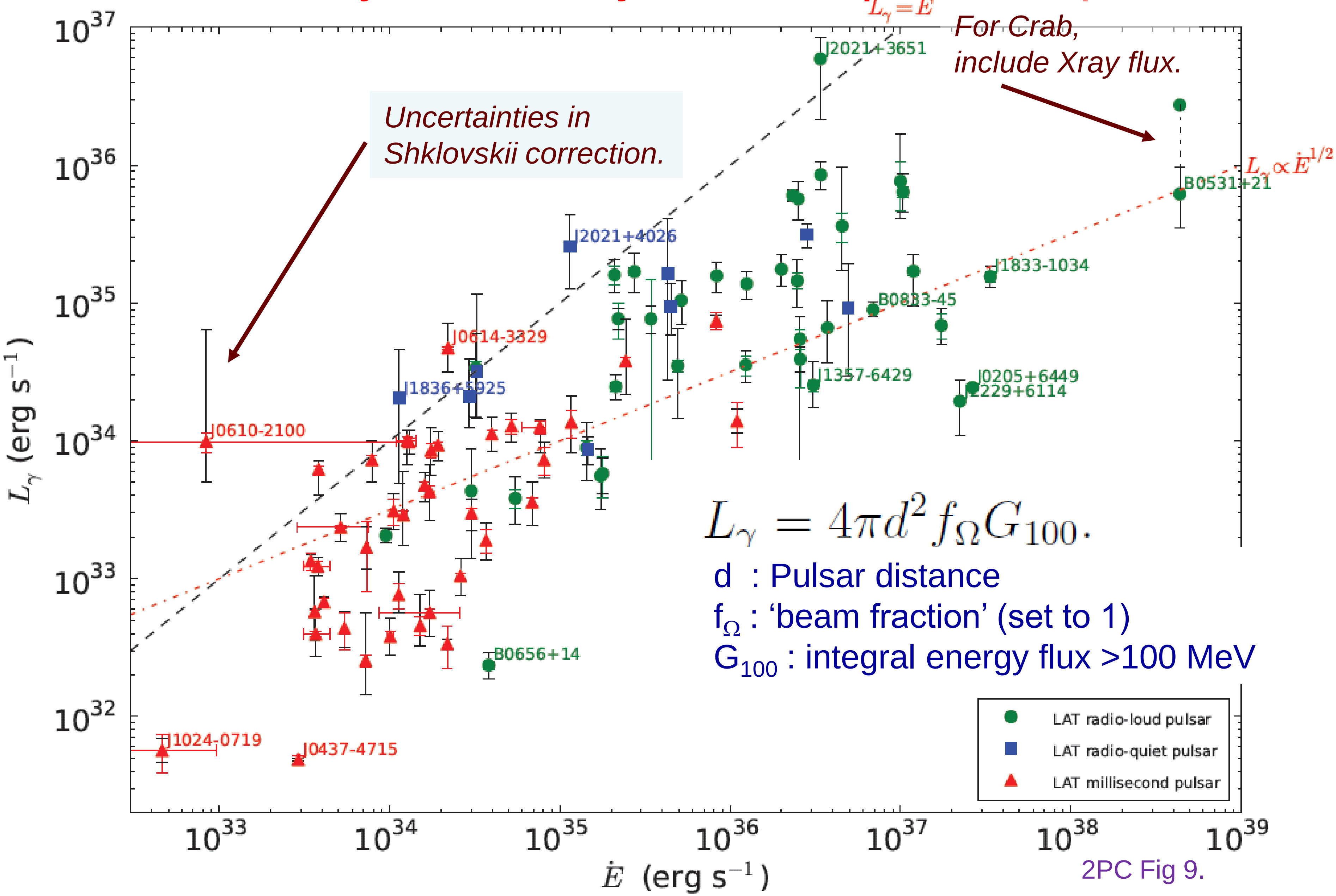
• The model "beam factor" f_Ω depends on the inclinations α, ζ of the magnetic and rotation axes.

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

Radio polarization and X-ray nebula images help constrain α, ζ …

G_{100} : integral energy flux >100 MeV

Gamma-ray luminosity versus spindown power



$$L_\gamma = 4\pi d^2 f_\Omega G_{100}.$$

d : Pulsar distance

f_Ω : 'beam fraction' (set to 1)

G_{100} : integral energy flux >100 MeV

2PC Fig 9.

X-ray spectral compilation

and the explosive power of positive feedback

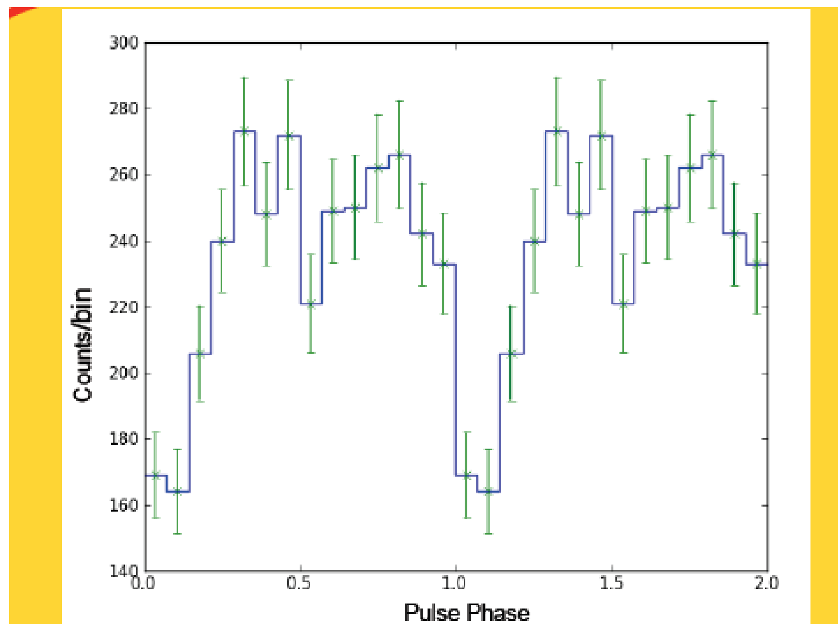
from 2PC Table 16. X-ray spectral parameters of LAT-detected MSPs

(an extension of M. Marelli et al's work.) (young ones, too!)

PSR[a]	Inst[b]	N_H 10^{20} cm^{-2}	F_X^{nt} 10^{-13} erg cm^{-2}s^{-1}	Sp.Type, pulsed[d]	G_{100}/F_X^{nt}	F_X^{pwn} 10^{-13} erg cm^{-2}s^{-1}
J0023+0923[1]	C	5[c]	$0.21^{+0.20}_{-0.17}$	Pow	381^{+374}_{-321}	...
J0030+0451[2]	X	$6.4^{+3.4}_{-2.4}$	2.55±0.29	BB+Pow, P	241±29	N
J0034−0534[0]	X	<56.3	<0.06	BB	>2800	N
J0101−6422[0]	S	1[c]	<2.31	...	>45.3	...
J2214+3000[2]	C	<21.3	0.74±0.03	Pow	441±34	...

XMM pulsations for a new LAT MSP,
Mike Wolff et al (NRL), in 2012 *Fermi* Symposium.

Gamma⇔radio⇔X-ray⇔theory feeding frenzy.



The X-ray pulse profile applying the Nancay radio ephemeris in the 0.32 – 1.51 keV energy range. The detection significance with the H-

The future: ***MORE*** gamma-ray pulsars

"*The dark corners of parameter space*" – dream of seeing not just the ***bright*** ones (nearby; hi $\dot{E}$, perhaps due to strong B_S; favorable α,ζ ; low background regions) but also a sampling that allows model tests for atypical parameters.

Multiple approaches in progress:

• Search for gamma-quiet pulsars: F. Acero talk, Friday.

Beyond the 'sub-luminous' pulsars? (Romani et al. 2011, ApJ, 738, 114)

• Point-source search seeding with pulsar-like spectra (Toby Burnett).

• 'Pass 8' – better acceptance at low energies good for pulsars.

'P7REP' (= 'reprocessed Pass 7') already giving performance gains.

arXiv.org > astro-ph > arXiv:1303.3514

Search or

Astrophysics > Instrumentation and Methods for Astrophysics

Pass 8: Toward the Full Realization of the Fermi-LAT Scientific Potential

W.Atwood, A. Albert, L. Baldini, M. Tinivella, J. Bregeon, M. Pesce-Rollins, C. Sgrò, P. Bruel, E. Charles, A. Drlica-Wagner, A. Franckowiak, T. Jogler, L. Rochester, T. Usher, M. Wood, J. Cohen-Tanugi, S. Zimmer for the Fermi-LAT Collaboration

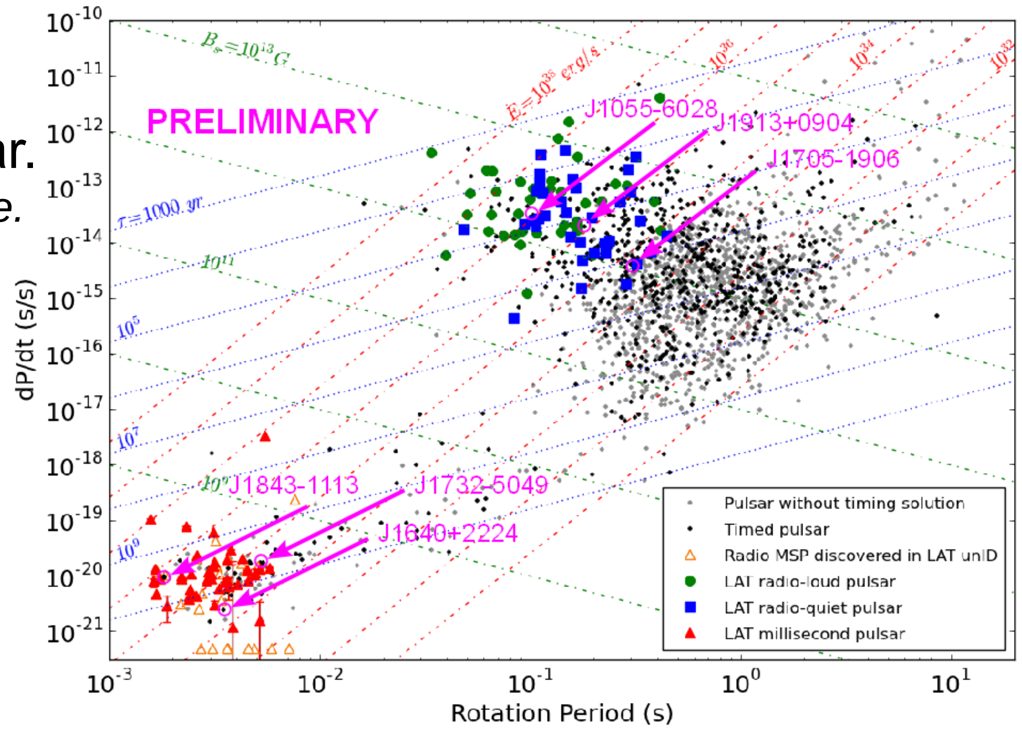
The future: *fainter* gamma-ray pulsars

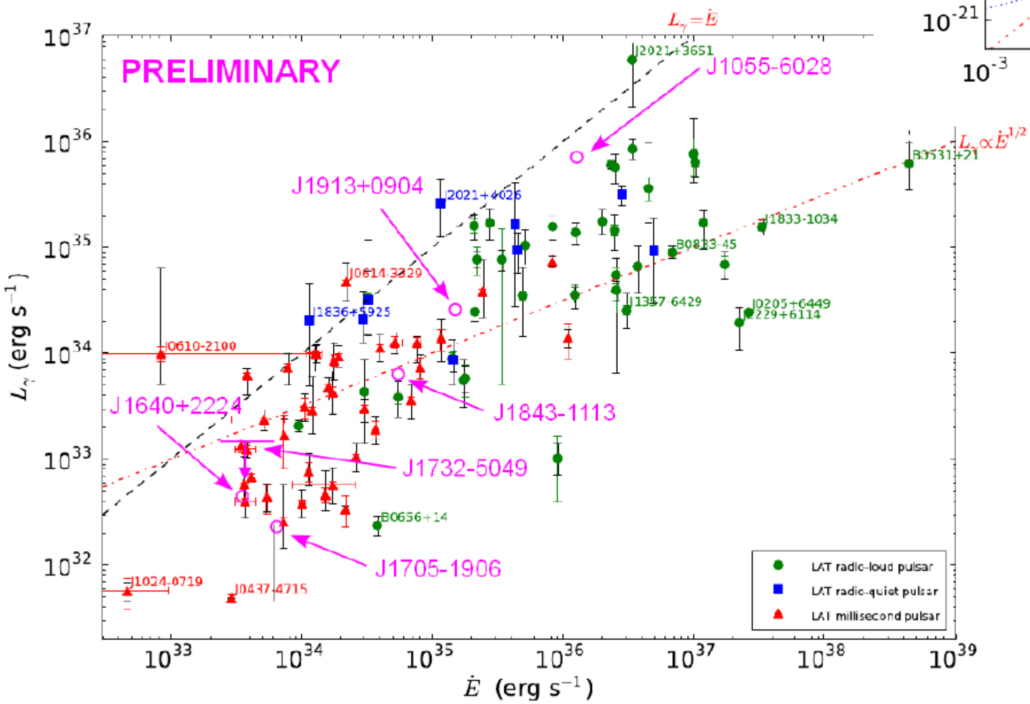
From Xian Hou's poster –

- J1705, lowest Ė young radio pulsar.

One of 3 young γ pulsars with radio interpulse.

- J1640, J1732, low Ė MSPs
- J1055, far, in plane.
- J1913, hi b'grd





Thank you!

All LAT team publications at

https://www-glast.stanford.edu/cgi-bin/pubpub

David A. Smith,

para muchas personas.

Curvature Radiation

Matches most of what we see

(as does b=1)

even if inverse compton scattering, other, may also occur in some cases (e.g. pulsed Crab TeV)

$$\gamma_{\rm lim} = \left(\frac{eE_{\parallel}}{5.6 \times 10^{-3} mc}\right)^{1/4} \rho^{1/2}$$

$$\approx 5.1 \times 10^{7} \left(\frac{X_e B_{12}}{P_{-1}}\right)^{1/4} \rho^{1/2}$$

Radiation losses limit acceleration by $E_{||}$.
(electric field component parallel to the B-lines.)

Radius of curvature $\rho \approx R_{LC}$

X_e is the fraction of the open-field line region where acceleration works ('gap size').

Romani ApJ 1996 : **$X_e \propto \sqrt{\dot{E}}$**

Paradox:
High luminosity means wide gaps. Narrow peaks means narrow gaps.

~2200 known radio pulsars (millions must exist)

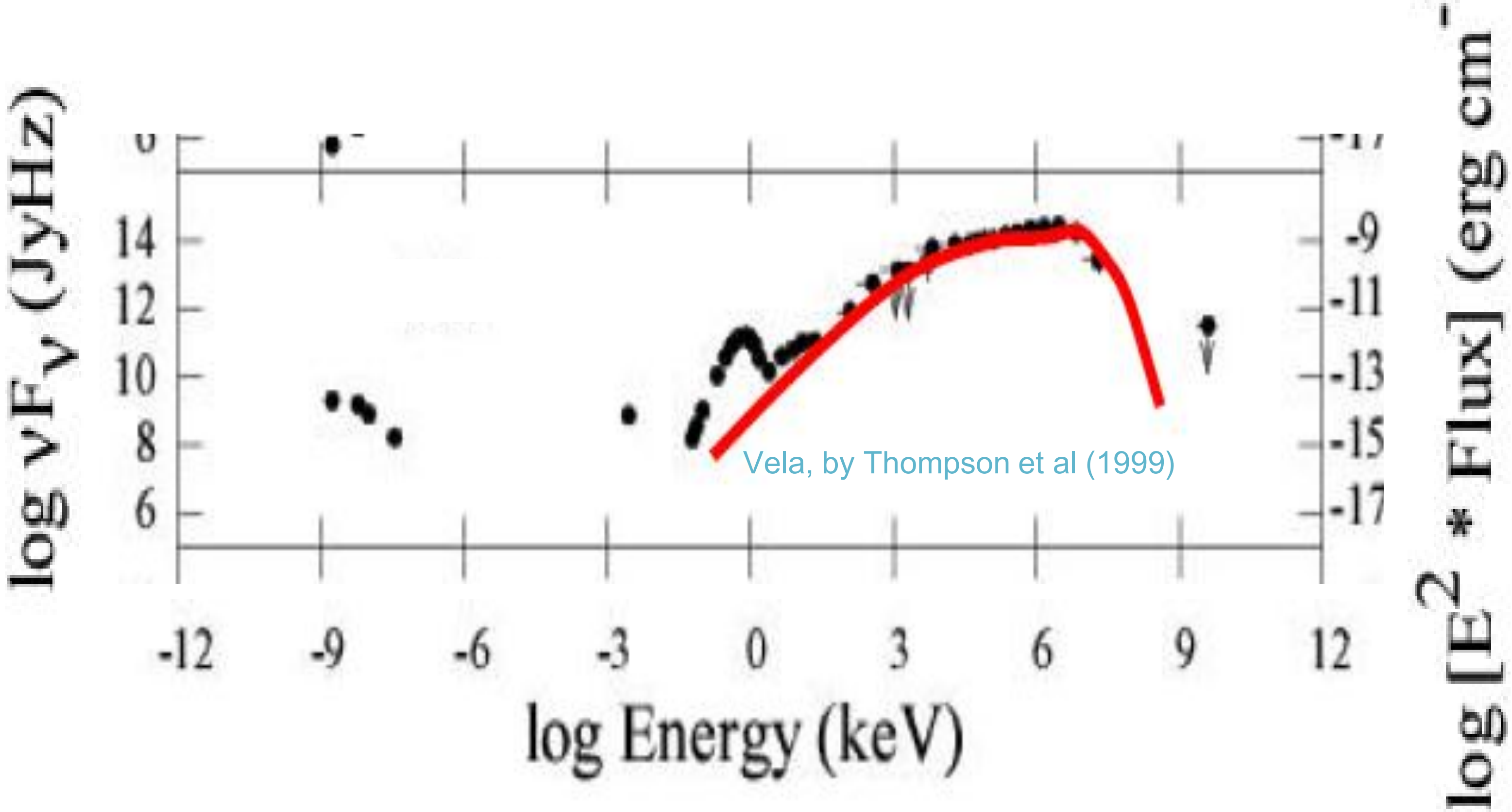
("millions": ~1 supernova/century x ~10 Gyr = 10^8. They live mega-years.)

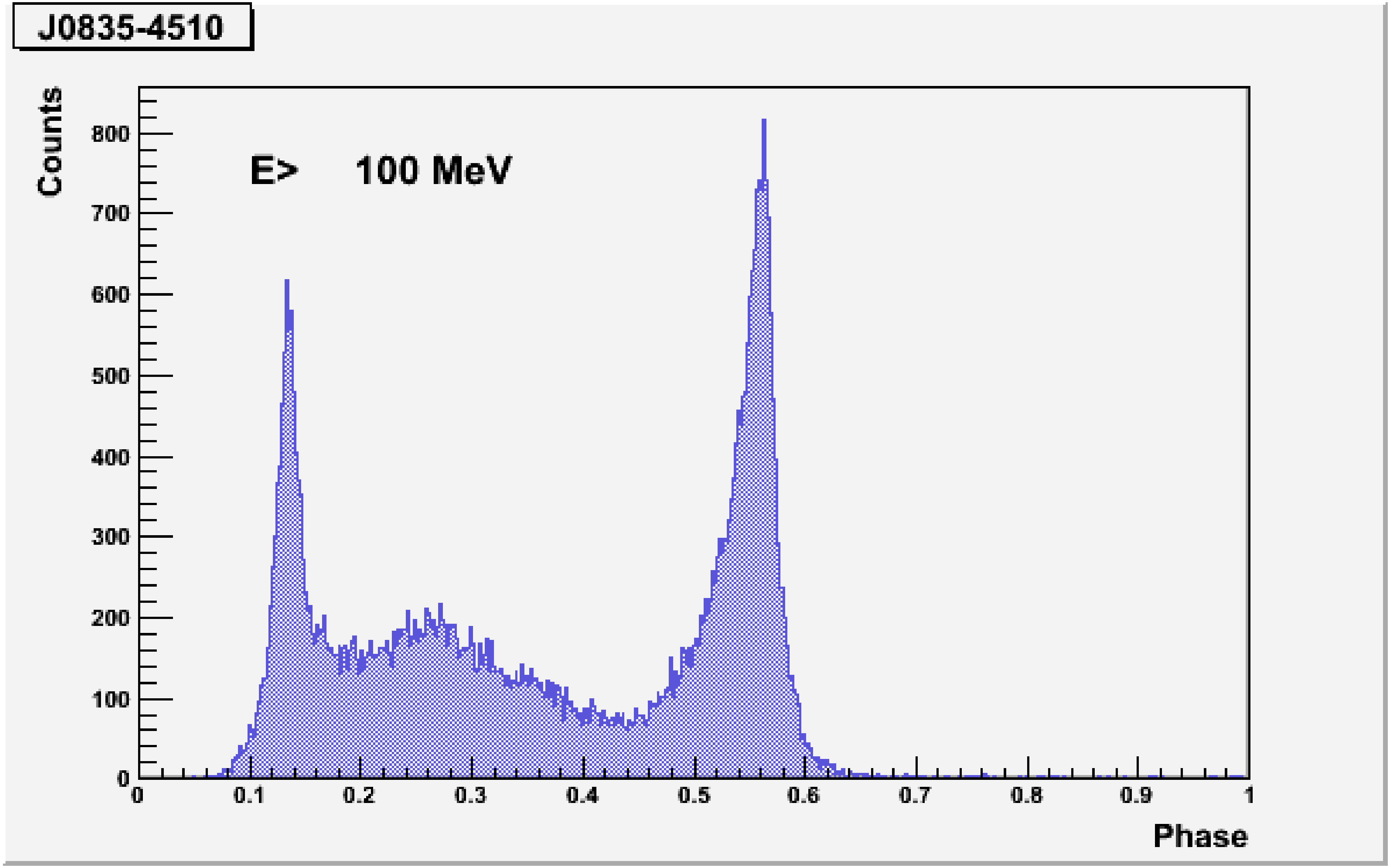
~ 50 in X-rays, 6 in optical, and, before *Fermi*, ≤10 in γ-rays.

Few percent of Ė in gammas. >80% in the wind!

Most power in gammas (for known γ psr's) (i.e. high Edot pulsars) .

Power





Vela pulsar. Abdo, A. A. et al. 2009, ApJ, 696, 1084

Atypical 3rd peak ("shoulder") drifts with phase. Two main peaks are typical.
(here, 3 years of data.)

By Thierry Reposeur, Bordeaux.

How pulsars are interesting and/or useful:

Interesting in their own right. But also:

• Unresolved (distant) pulsars contribute to diffuse gamma emission. ~10%, increasing at higher energies.

- ➢ Diffuse model tests [(cosmic rays) ⊗ (dust, gas)] throughout Milky Way.
- ➢ Diffuse model allows deep, uniform (``complete'') population samples.
- ➢ Especially for faint things like, perhaps, Dark Matter signatures.

• On the origin of cosmic rays

- ➢ Pulsar Wind Nebulae (PWN) can be confused with supernova remnants (SNRs), probable proton etc accelerators. Identifying PSRs helps.
- ➢ Towards complete PWN models: pulsar wind and B field as inputs.
- ➢ PWNe dominate TeV sky. But there are UnId'd TeV sources too.
- ➢ Nearby pulsars contribute to the local e+ e- flux,
  - ➢ a foreground to *other* Dark Matter signatures.

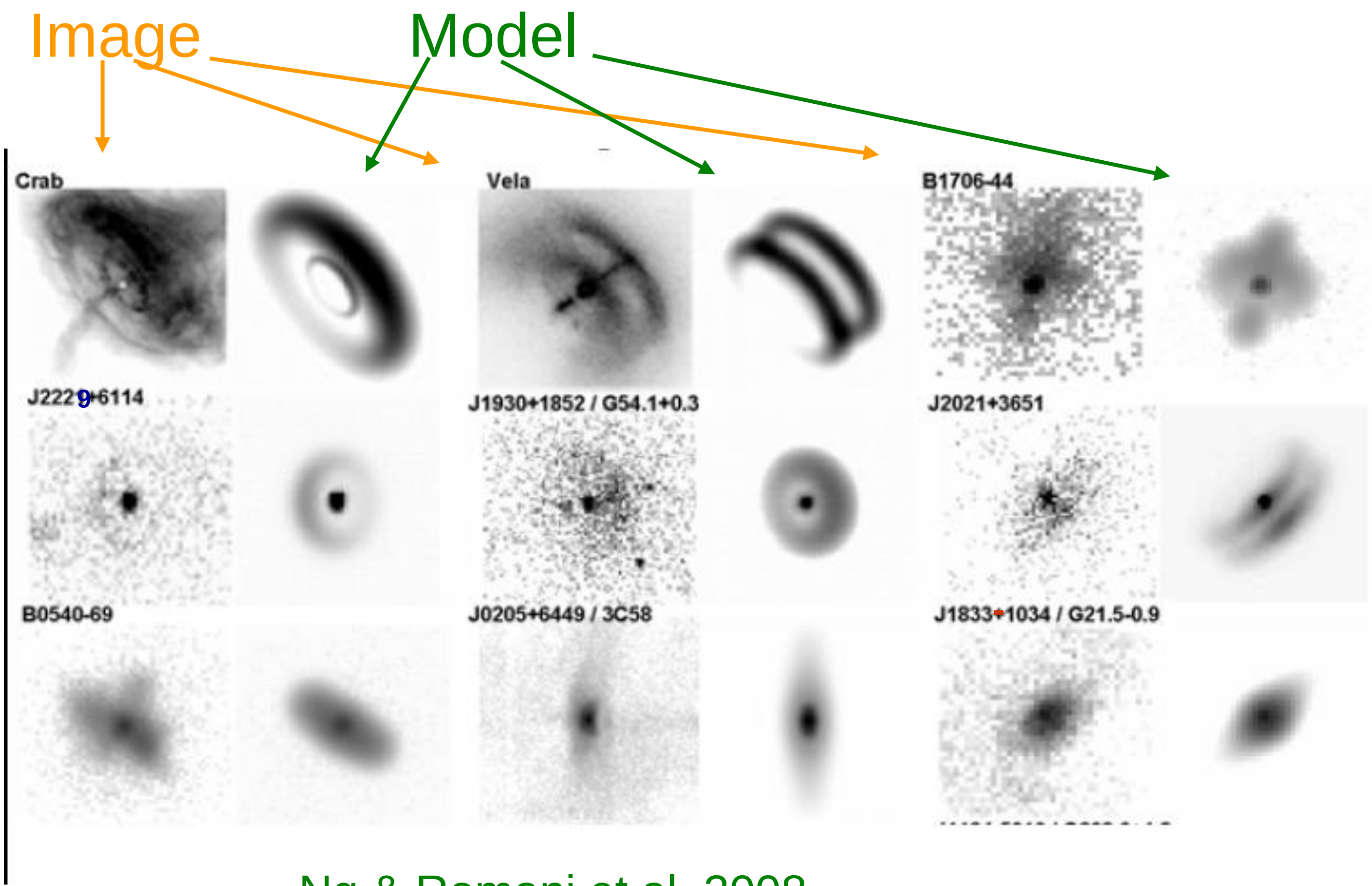
• "Endpoint of stellar evolution" – pulsar census to cross-check massive star tallies & supernova rates.

•To get MSP population right, need to understand the young pulsars. GWs!

- Chandra X-ray images of the PWN can give the angle ζ of the pulsar rotation axis relative to the Earth line-of-sight.

- *Fermi* LAT sees pulsations for 7 of these 9.

  Great X-ray PWN review: Kargaltsev & Pavlov, arXiv:0801.2602. *Fermi* sees PSRs in >20 of 40 PWNs.



Ng & Romani et al. 2008