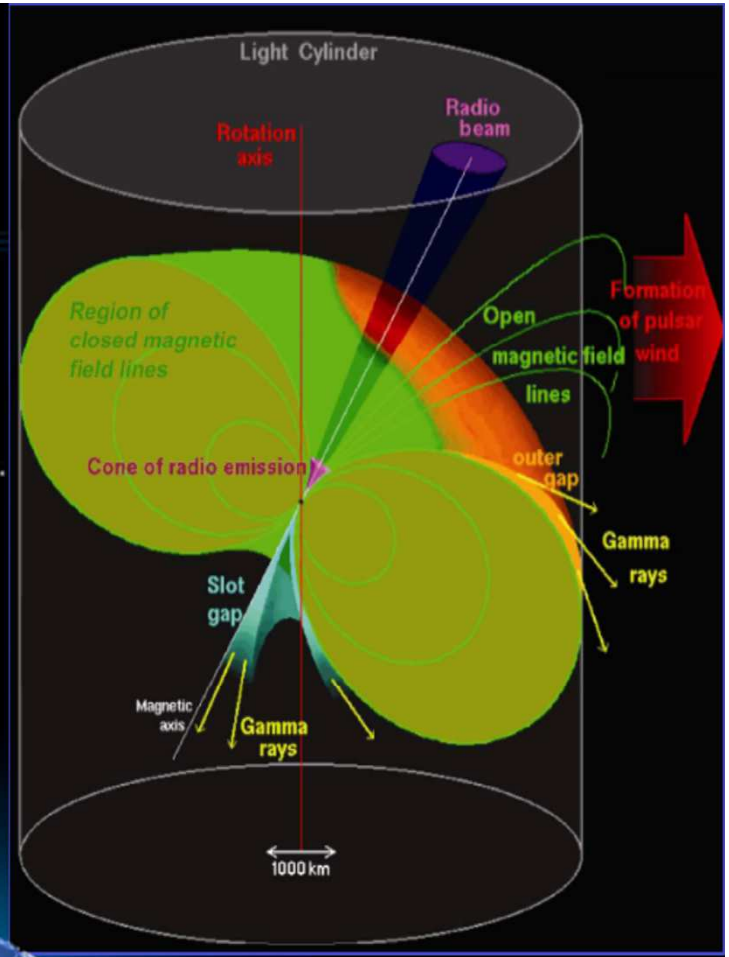
Gamma-ray pulsars with *Fermi* and their radio polarization



David A. Smith, for the *Fermi* LAT collaboration and pulsar consortia
Centre d'Études Nucléaires de Bordeaux-Gradignan (CNRS)
smith@cenbg.in2p3.fr

INTERNATIONAL SPACE SCIENCE INSTITUTE

Bern
9 December 2019

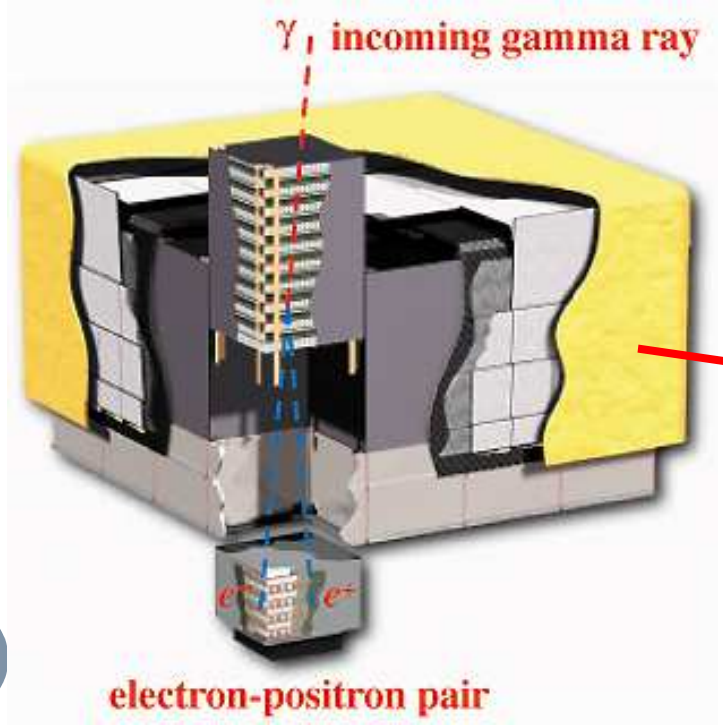
11 June 2008

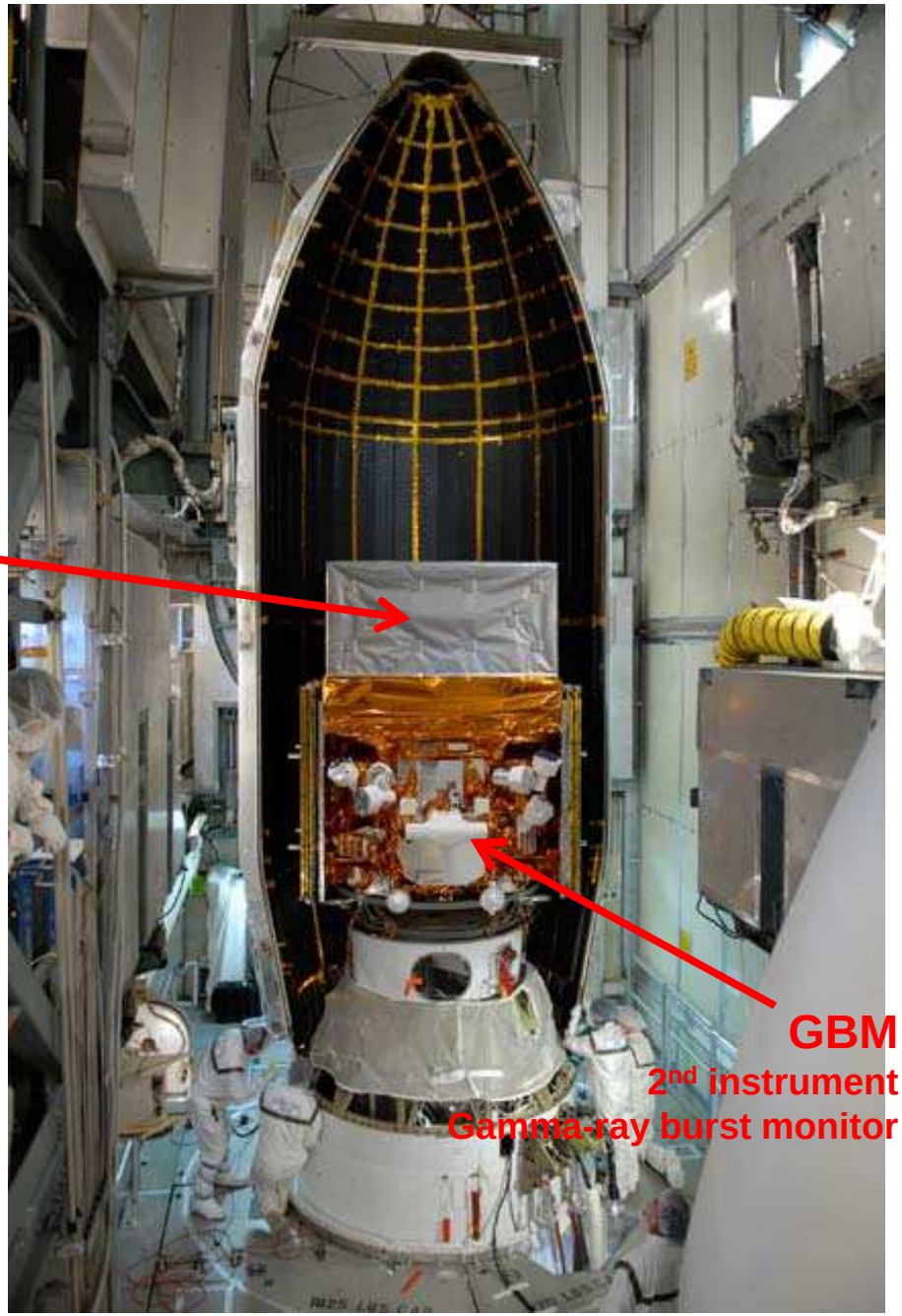
Fermi

Gamma-ray Space Telescope

Formerly "GLAST"

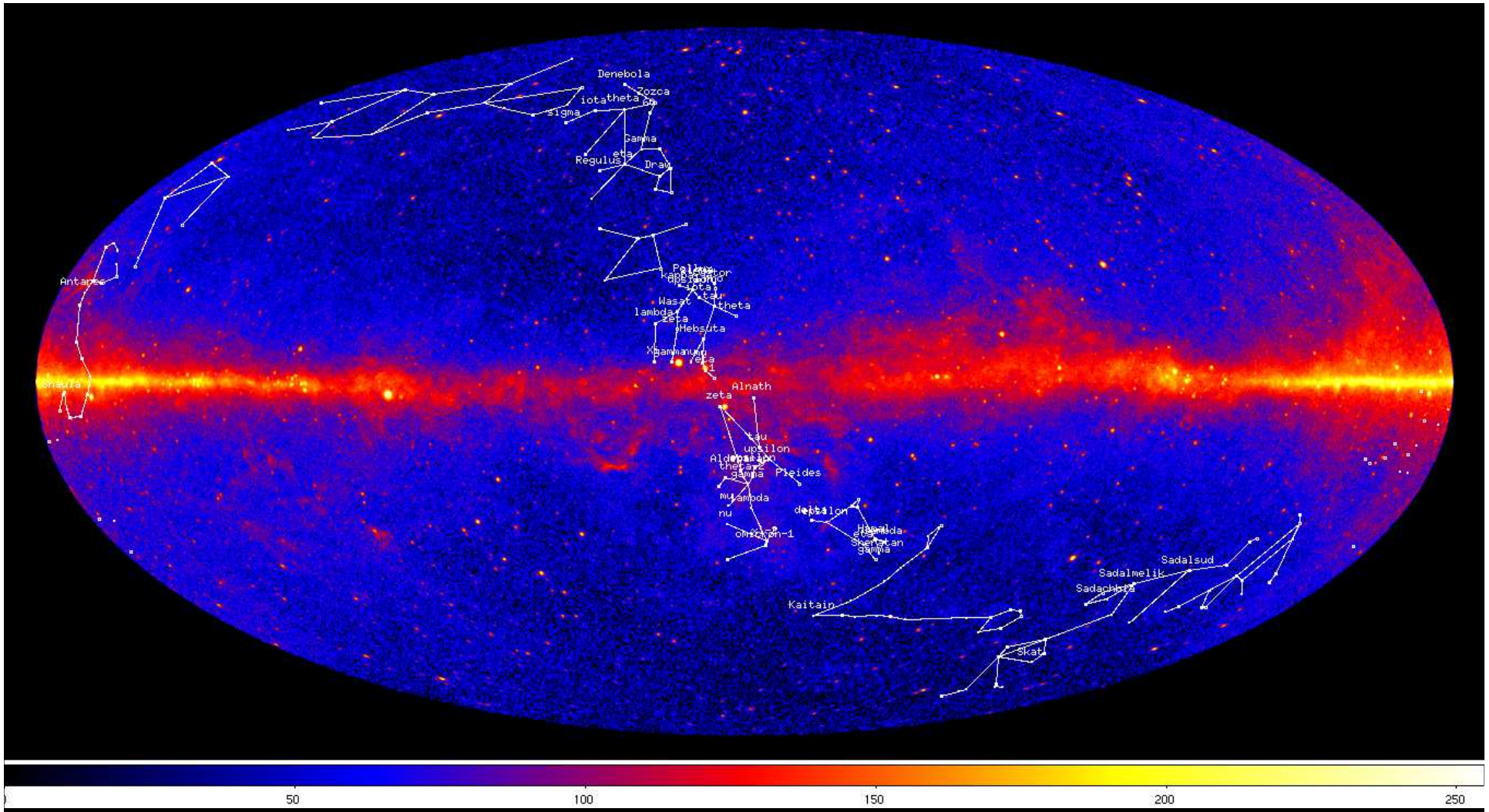
Large Area Telescope
30 MeV to 300 GeV





The whole sky, 8 times per day:

- Known and unknown sources.
- Good localization.



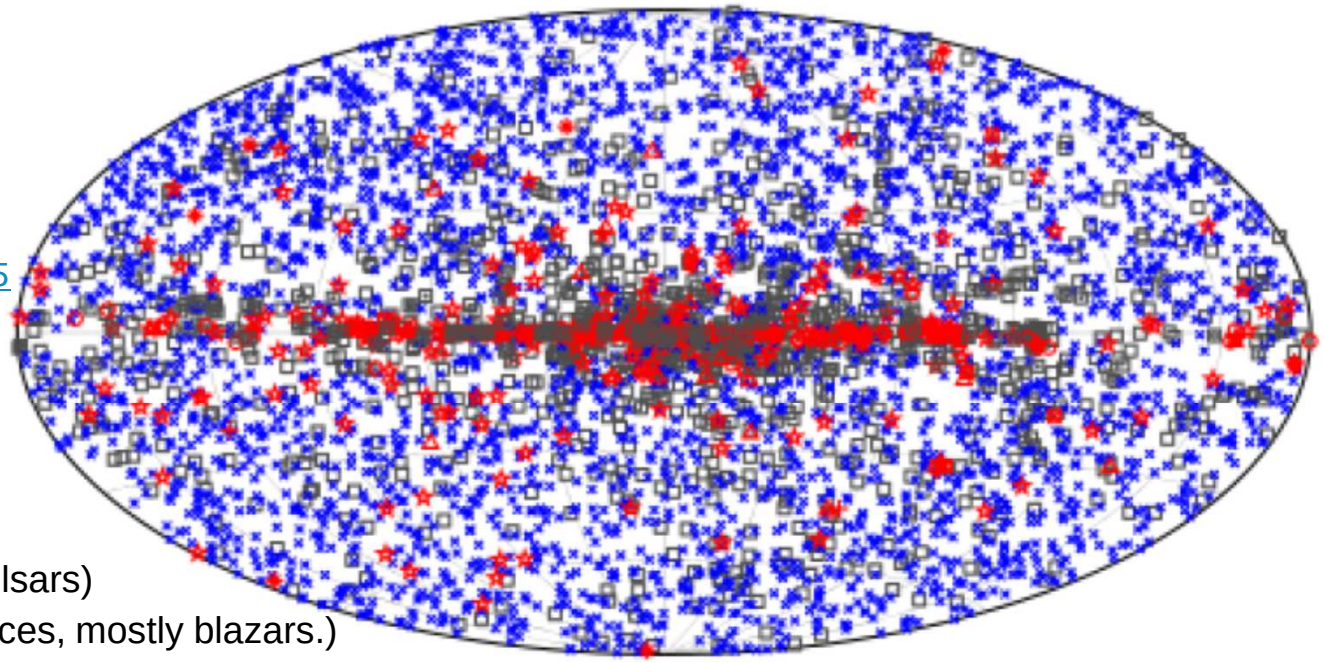
Galactic anti-center in the center.

The constellations of the zodiac lie along the ecliptic (gamma-ray astrology?).

4FGL

4th LAT source catalog

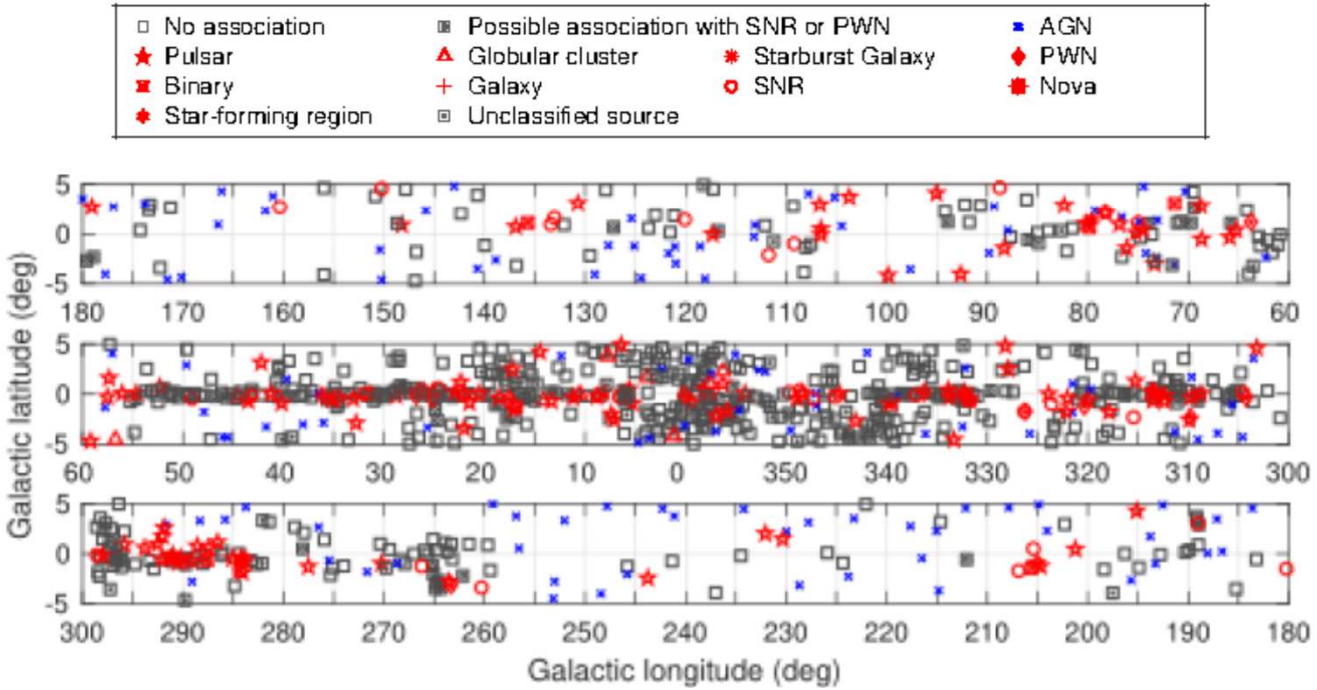
ApJS submitted arXiv:1902.10045



5065 total sources (>4σ)

Red: Firm I.D. (354, 239 are pulsars)
Blue: 'Association' (~¾ of sources, mostly blazars.)
Black: No I.D. (~¼ of sources)

Un Id's == *Gold* mine!

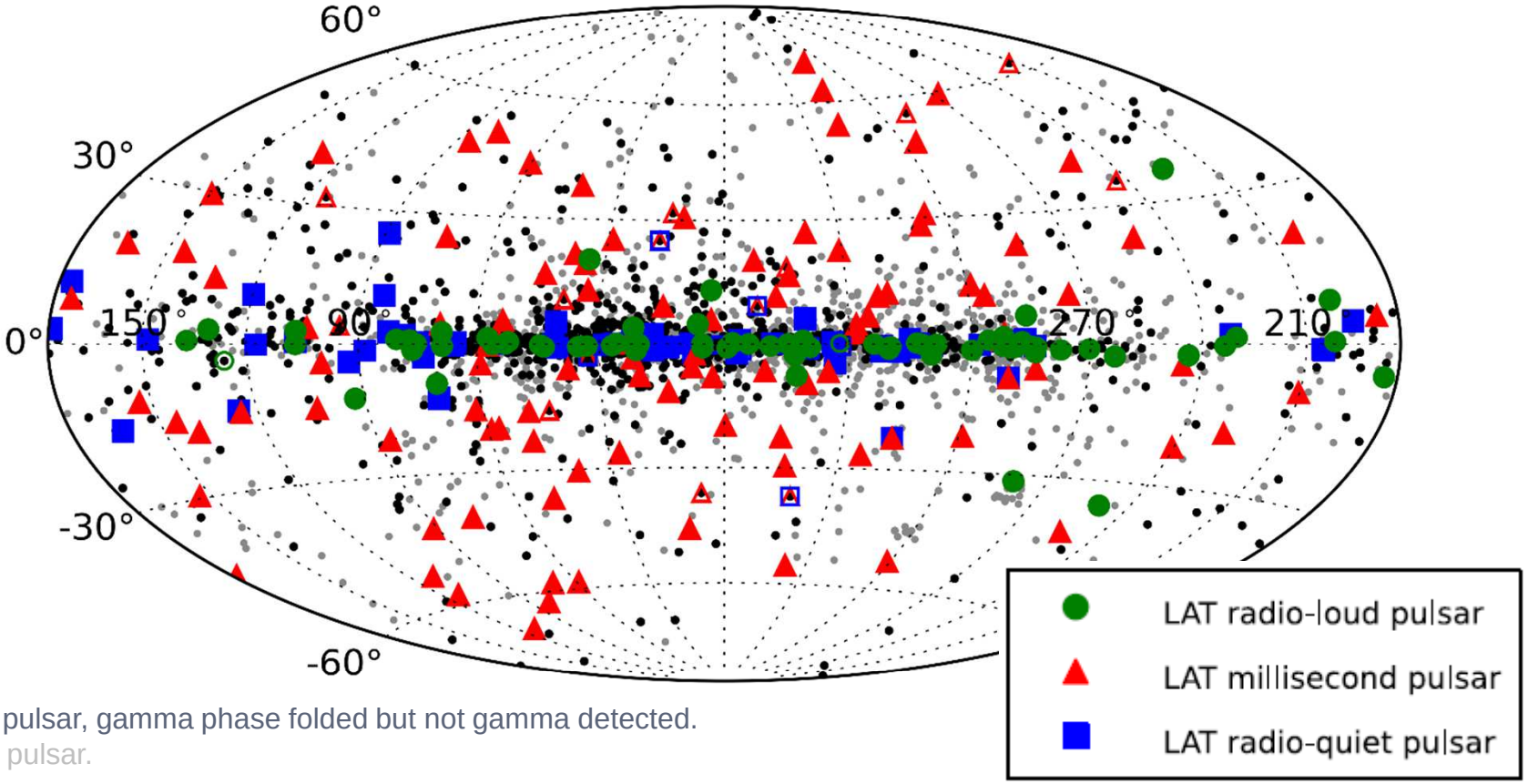


Before *Fermi*: 10 pulsars seen with CGRO (all confirmed), plus PSR J2021+3651 discovered by AGILE.

Now over 257 *Fermi* LAT pulsars.

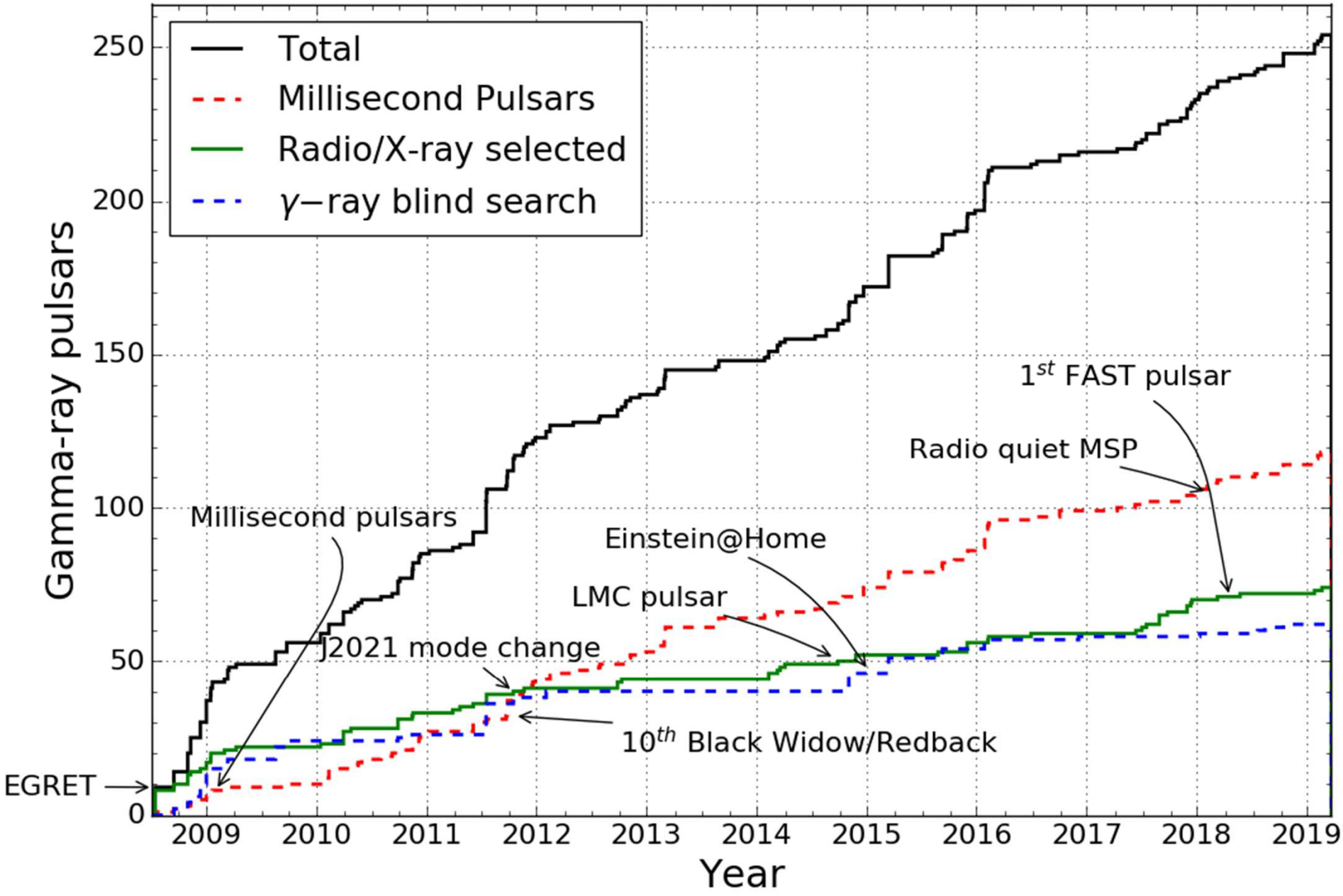
Update of Fig 2 from **2PC** = *2nd Pulsar Catalog* ApJ Suppl. 208 17 (2013)

3PC in preparation for 2020.

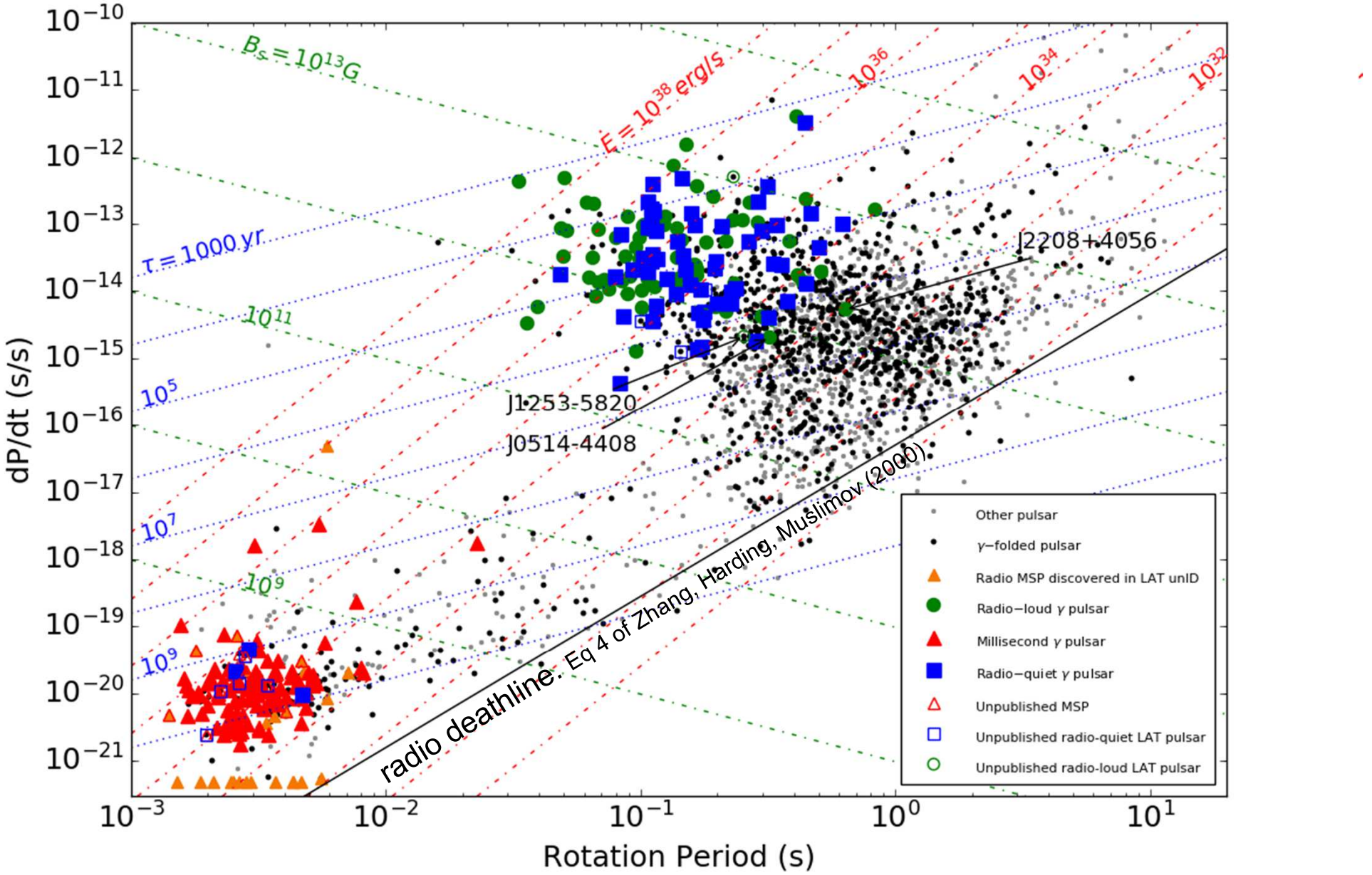


- known pulsar, gamma phase folded but not gamma detected.
- known pulsar.

Fermi LAT still detecting ~25 gamma pulsars per year.

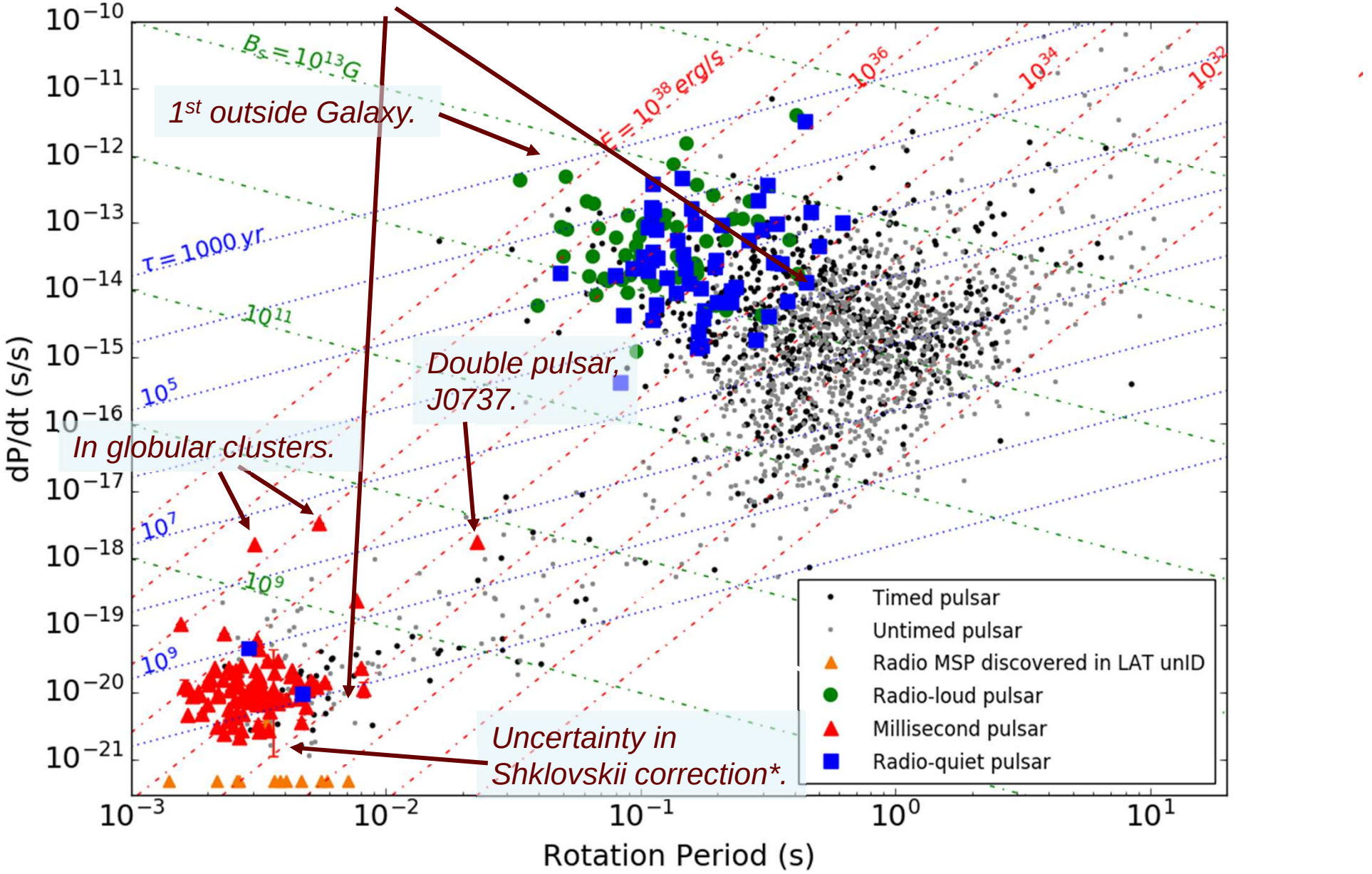


Isolines are variants of $P^{\alpha}\dot{P}^{\beta}$.



Gamma-ray deathline below spin-down power
$\dot{E} = 4I\pi^2 \dot{P} / P^3$ of 1E33 erg/s. (I ≡ 1E45 gm cm² depends on EoS.)

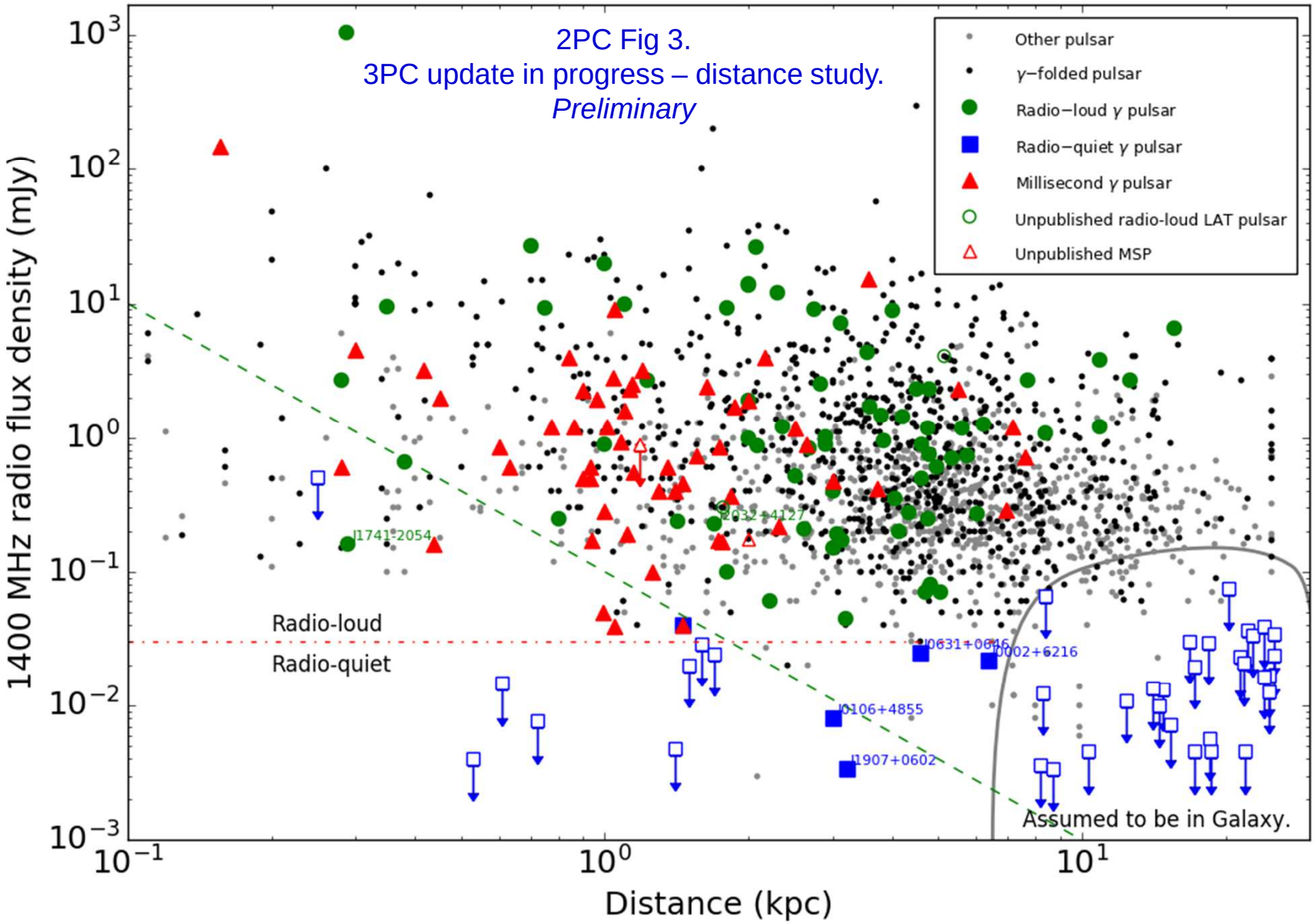
Update of 2PC Fig 1.



*See e.g. *γMSP Deathline, revisited*, Guillemot et al. A&A (2016)

"Radio quiet" ≡ <30 µJy

Diagonal : 100 µJy-kpc² pseudo-luminosity.



Currently, 234 gamma-ray pulsars listed at*

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

½ are young, ½ are MSPs.

Of the young: ½ radio loud, ½ radio quiet

½ already known. ½ found from *Fermi* data (½ radio MSPs, ½ young gamma).

>⅓ of all known field MSPs are gamma MSPs.

For spindown power Ė>5E33 erg/s is >¾.

Most LAT MSPs *faster* and *noisier* than 'traditional' MSPs.
Many 'black widows' & 'redbacks' ➔ laboratories to study recycling.

*257 within the team, + ~20 MSPs waiting.

Today's talk:

Observables that guide emission models

➔ Skip *spiders* (MSP recycling process).

1. Deathlines:
   a) Below some $\dot{E}$ does L_γ die, or just fade away?
   b) If radio polarization dies at same $\dot{E}$, are electrons the same ones?

2. Geometry:
   a) Tallies give relative beam sizes?
   b) From the profiles.
   c) From polarization.
   d) Radio interpulses – orthogonal rotators.

3. Spectral shapes.

Today's talk:

Observables that guide emission models

➔ Skip *spiders* (MSP recycling process).

➔ And in fact not say much about MSPs generally.

1. Deathlines:
   a) Below some $\dot{E}$ does L_γ die, or just fade away?
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2. Geometry:
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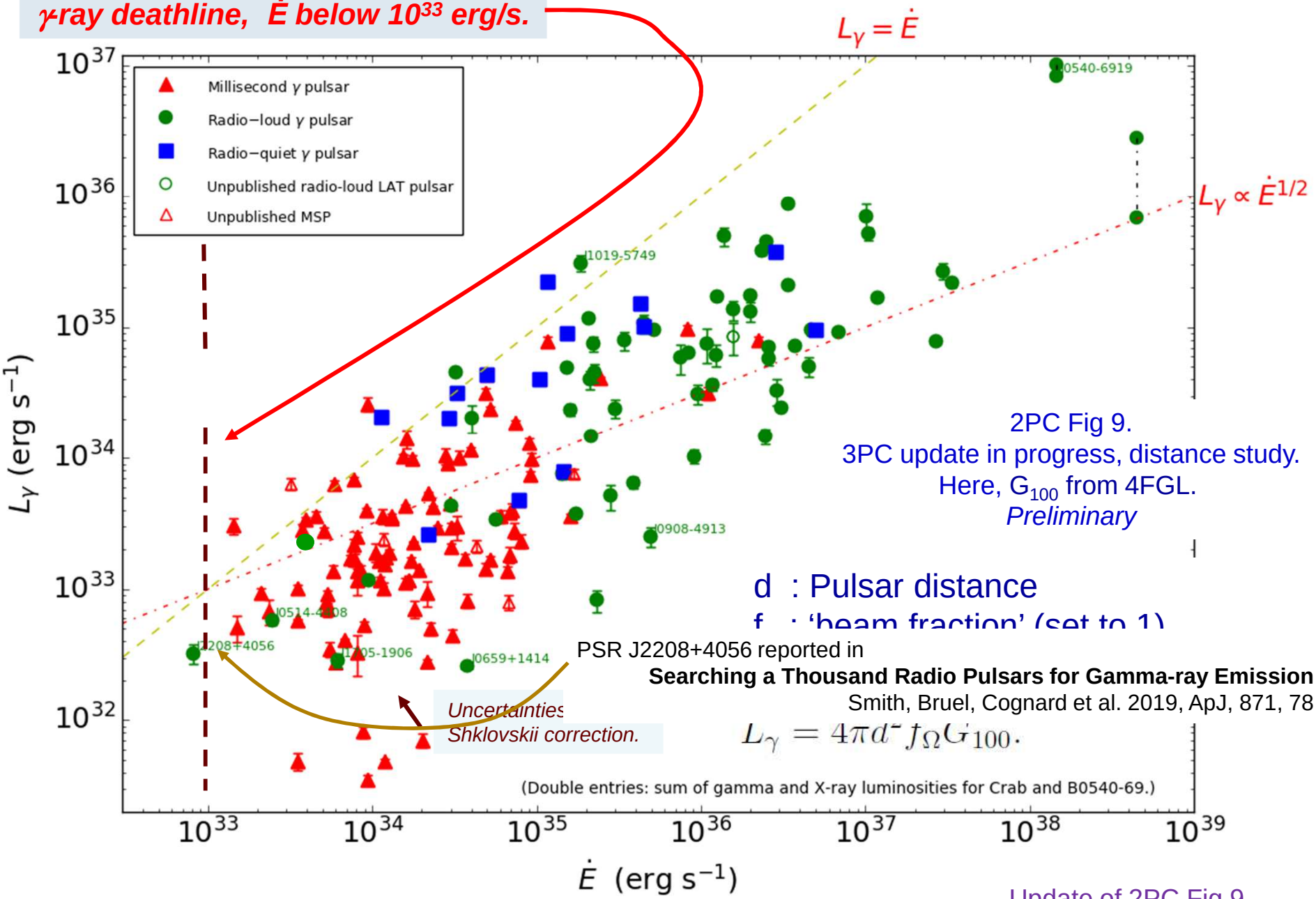
Gamma-ray luminosity versus spindown power



2PC Fig 9.
3PC update in progress, distance study.
Here, G_{100} from 4FGL.
Preliminary

d : Pulsar distance
f : 'beam fraction' (set to 1)

PSR J2208+4056 reported in
Searching a Thousand Radio Pulsars for Gamma-ray Emission
Smith, Bruel, Cognard et al. 2019, ApJ, 871, 78

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

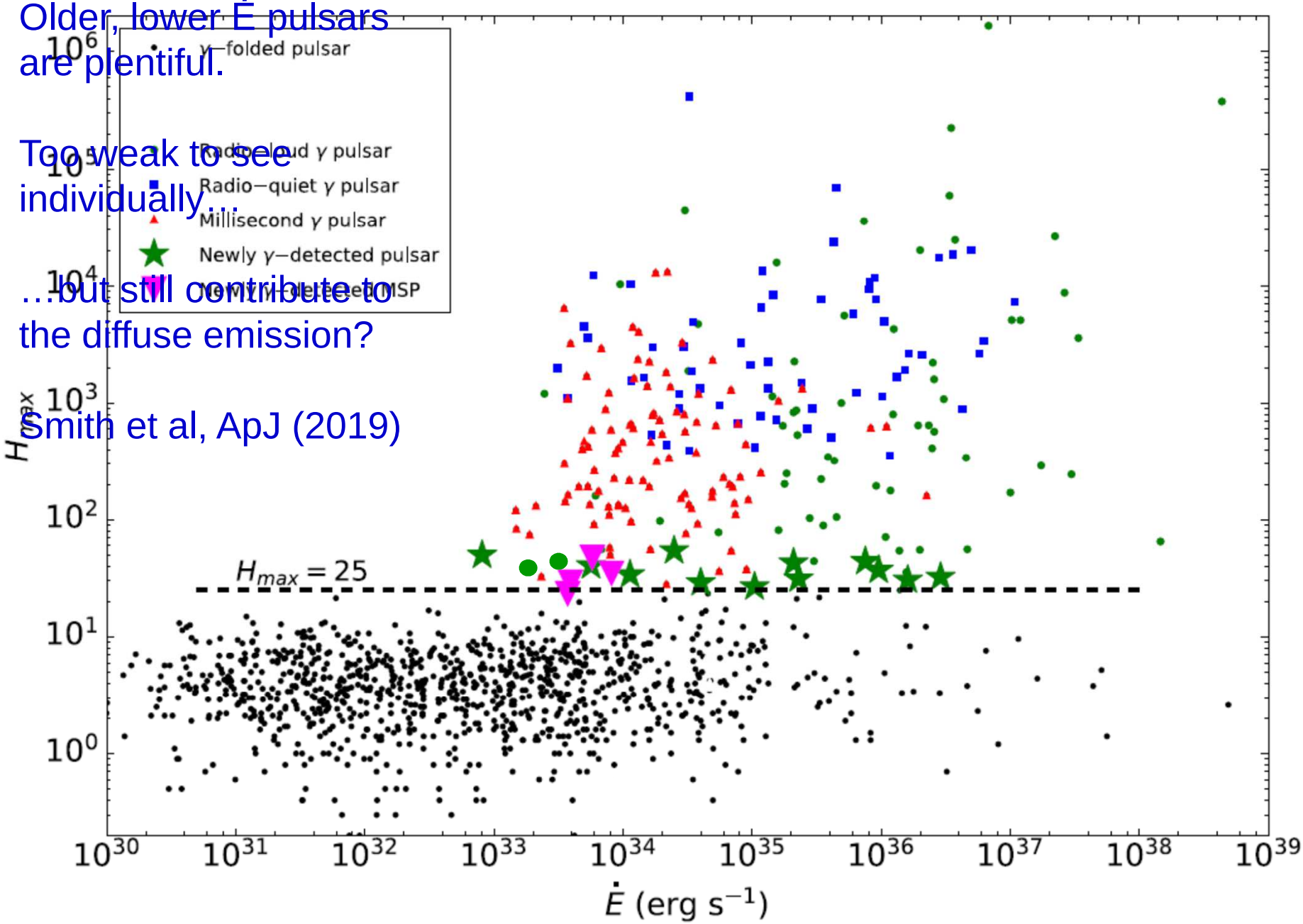
Update of 2PC Fig 9.

Older, lower $\dot{E}$ pulsars are plentiful.

Too weak to see individually…

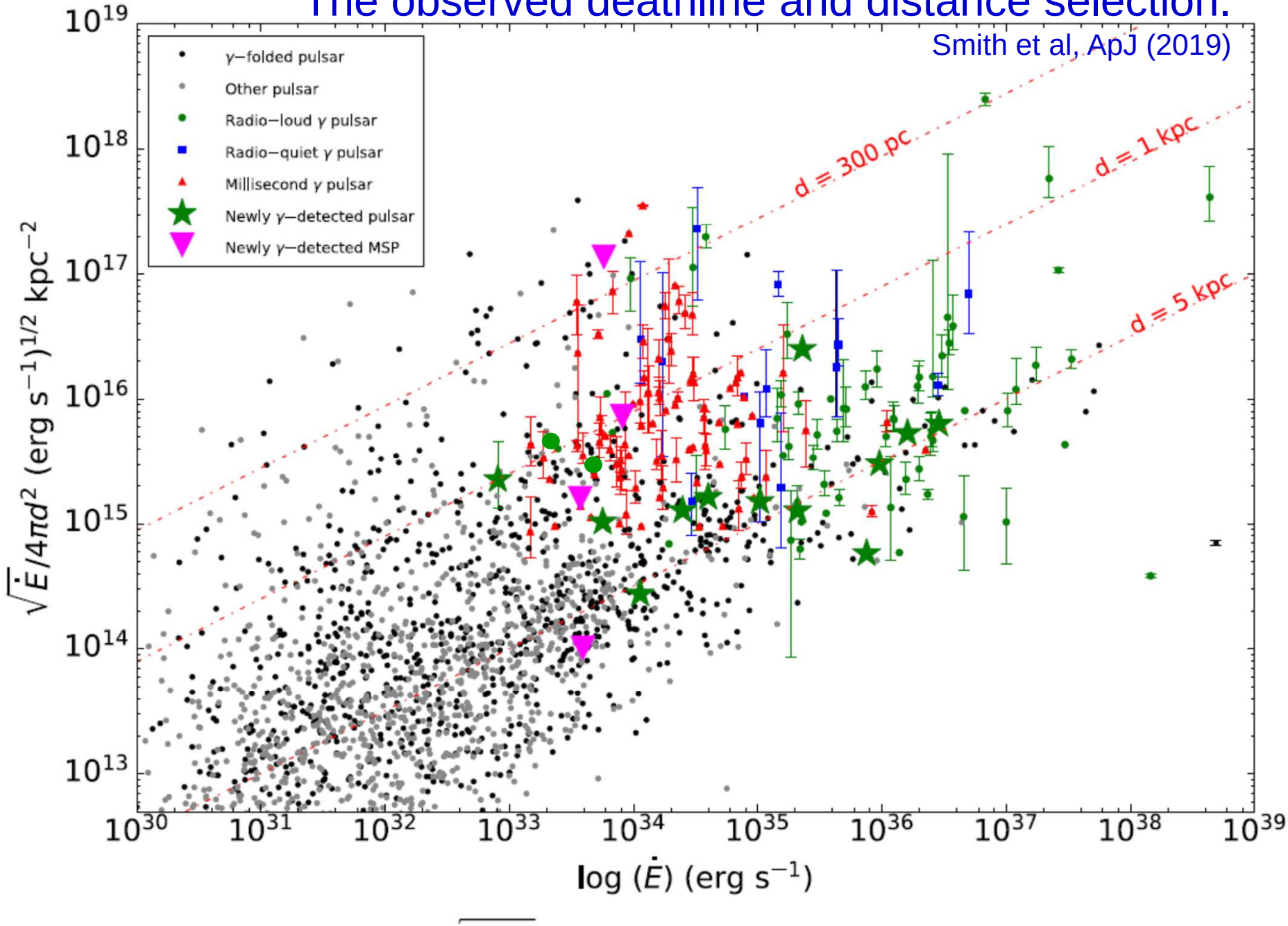
…but still contribute to the diffuse emission?

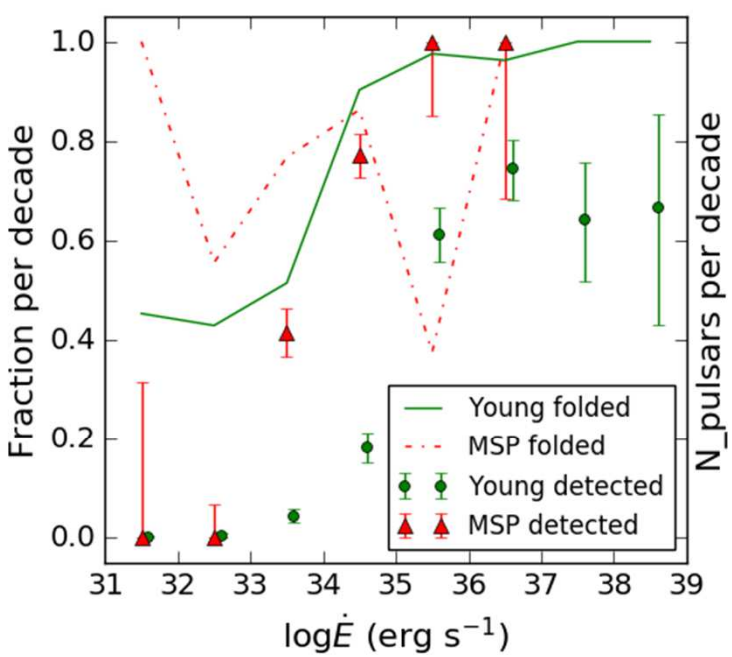
Smith et al, ApJ (2019)

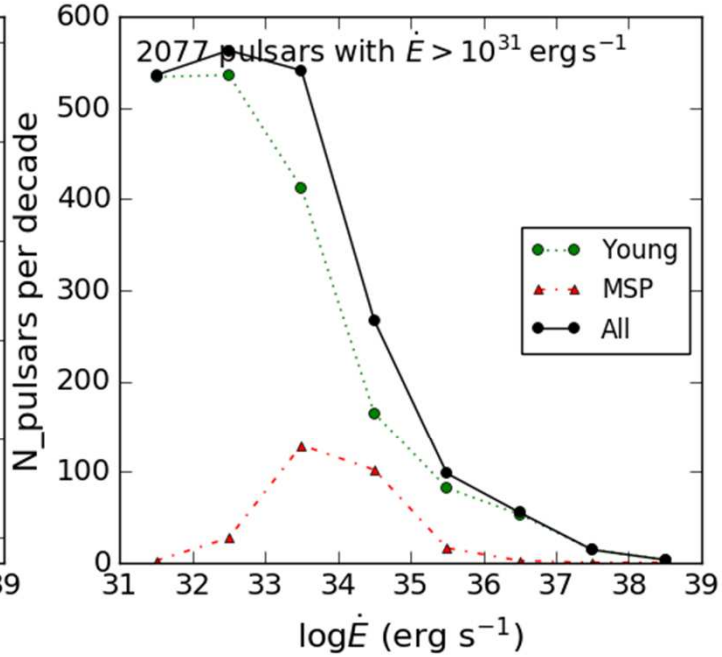


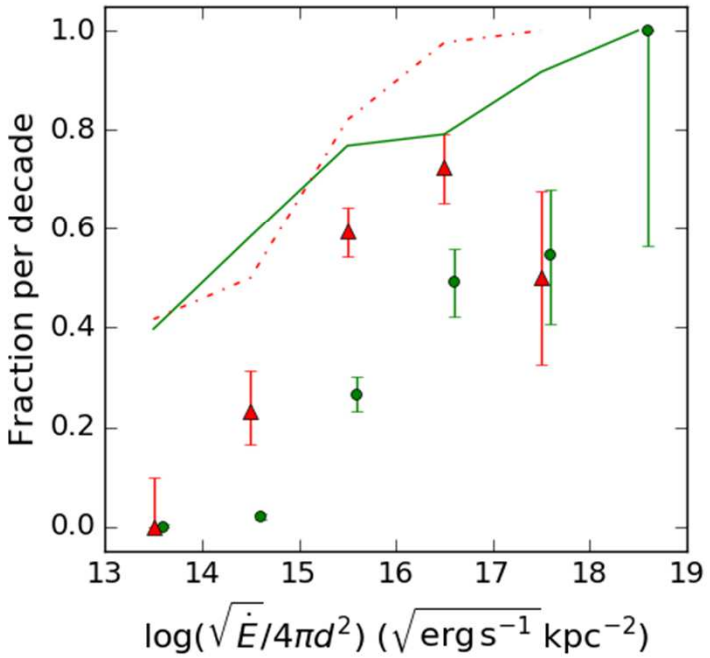
The observed deathline and distance selection.

Smith et al, ApJ (2019)









Pulsar numbers from ATNF database (Manchester et al).

Pulsars folded using ephemerides provided mainly by Parkes (Johnston & Kerr), Jodrell Bank (Stappers, Lyne, Weltevrede, Espinoza) and Nançay (Cognard & Guillemot) radio observatories.

Update of figure in Laffon, Smith, & Guillemot, 5th Fermi Symposium, arXiv:1502.03251

Few pulsar models predict a spindown power* cut-off for gamma emission.

The Astrophysical Journal, 736:127 (8pp), 2011 August 1

DEATH LINE OF GAMMA-RAY PULSARS WITH OUTER GAPS

Ren-Bo Wang[1,3] and Kouichi Hirotani[2,4]

Here: we confirmed a minimum for MSPs near Ė=1.E33 erg/s

A&A 587, A109 (2016)
DOI: 10.1051/0004-6361/201527847

Astronomy & Astrophysics

The gamma-ray millisecond pulsar deathline, revisited

New velocity and distance measurements

L. Guillemot[1,2], D. A. Smith[3], H. Laffon[3], G. H. Janssen[4], I. Cognard[1,2], G. Theureau[1,2], G. Desvignes[5], E. C. Ferrara[6], and P. S. Ray[7]

e.g. Kalapotharakos, Harding, Kazanas, Brambilla ApJ 2017

Emission *shifts* from GeV to MeV range with decreasing Ė ?

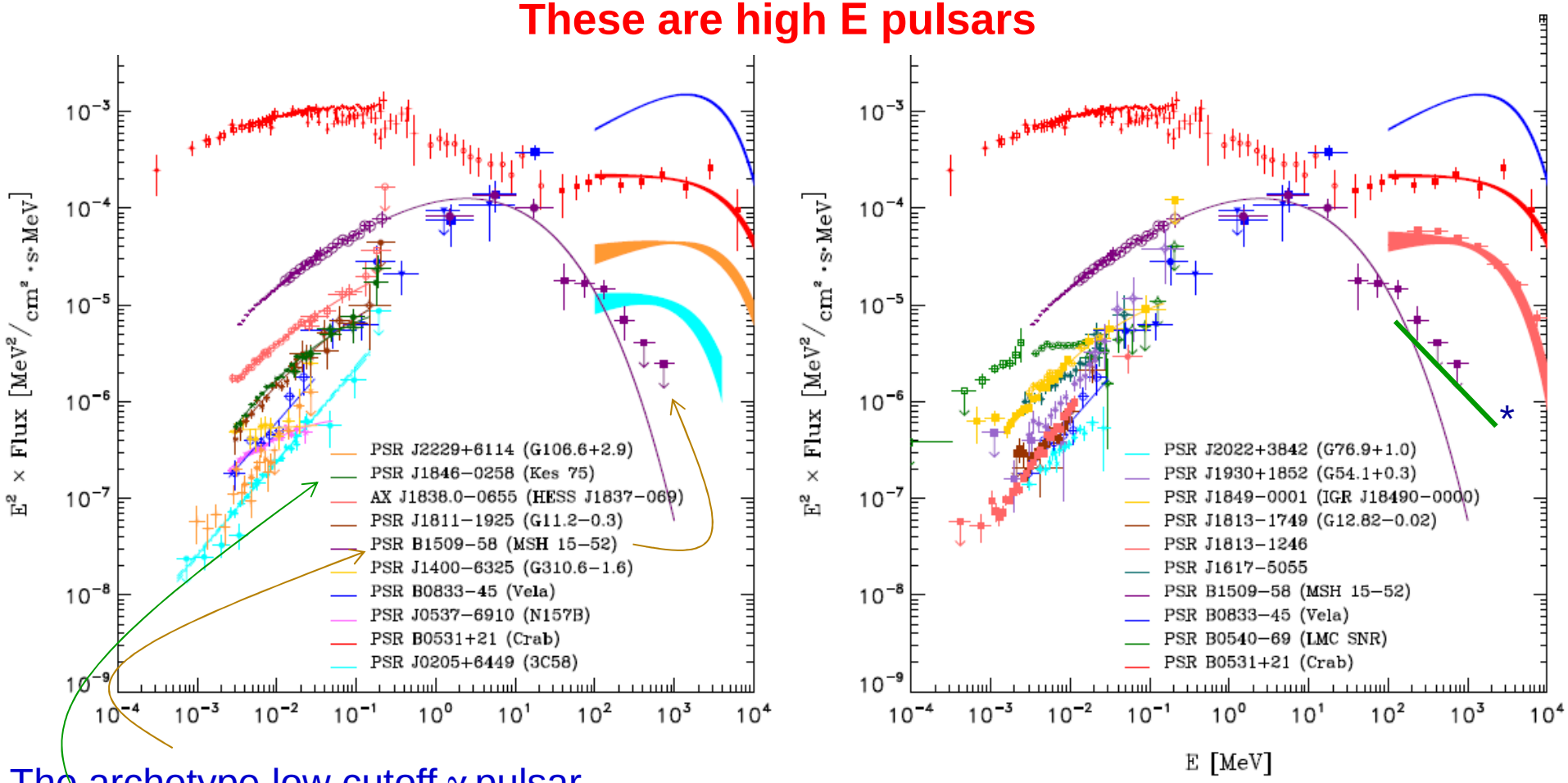
*or other combination of $P^{\alpha}\dot{P}^{\beta}$.

18 pulsars seen at 20 keV < E_γ < 30 MeV

only half are seen in Fermi LAT

due in part to the spectral peak in the MeV range

These are high Ė pulsars



The archetype low cutoff γ pulsar

Kuiper, Hermsen, Dekker: <100 MeV LAT detection, MNRAS (2019)

-ray pulsar population: a high-energy overview

MNRAS 449, 3827–3866 (2015)

and W. Hermsen[1,2]

* B0540-69, Ackermann et al, *Science* 2015

Radio polarization also dies around same Ė?

Mon. Not. R. Astron. Soc. **391,** 1210–1226 (2008) doi:10.11

Profile and polarization characteristics of energetic pulsars

Patrick Weltevrede★ and Simon Johnston

Australia Telescope National Facility, CSIRO, PO Box 76 Epping, NSW 1710, Australia

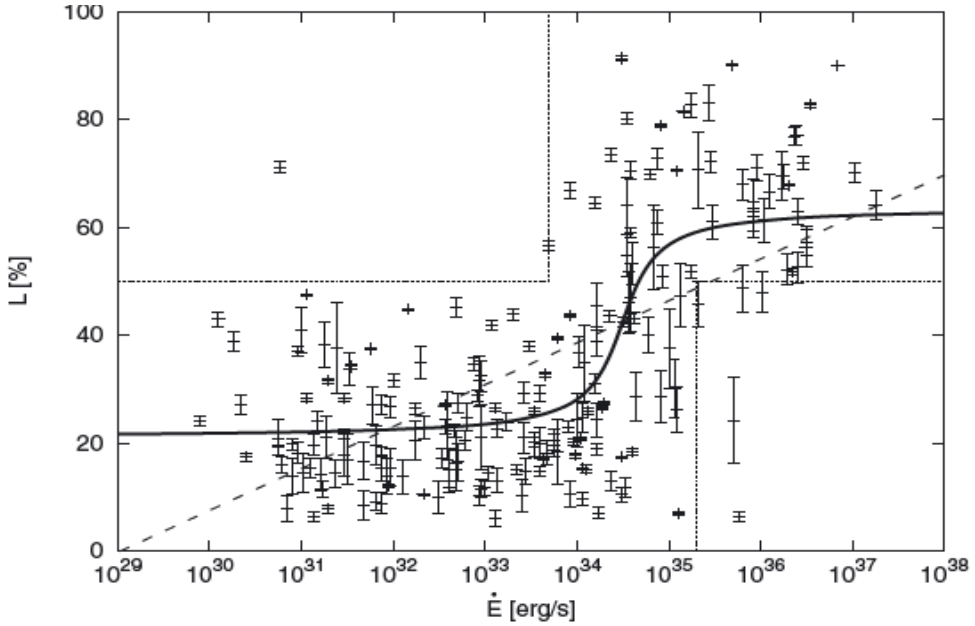
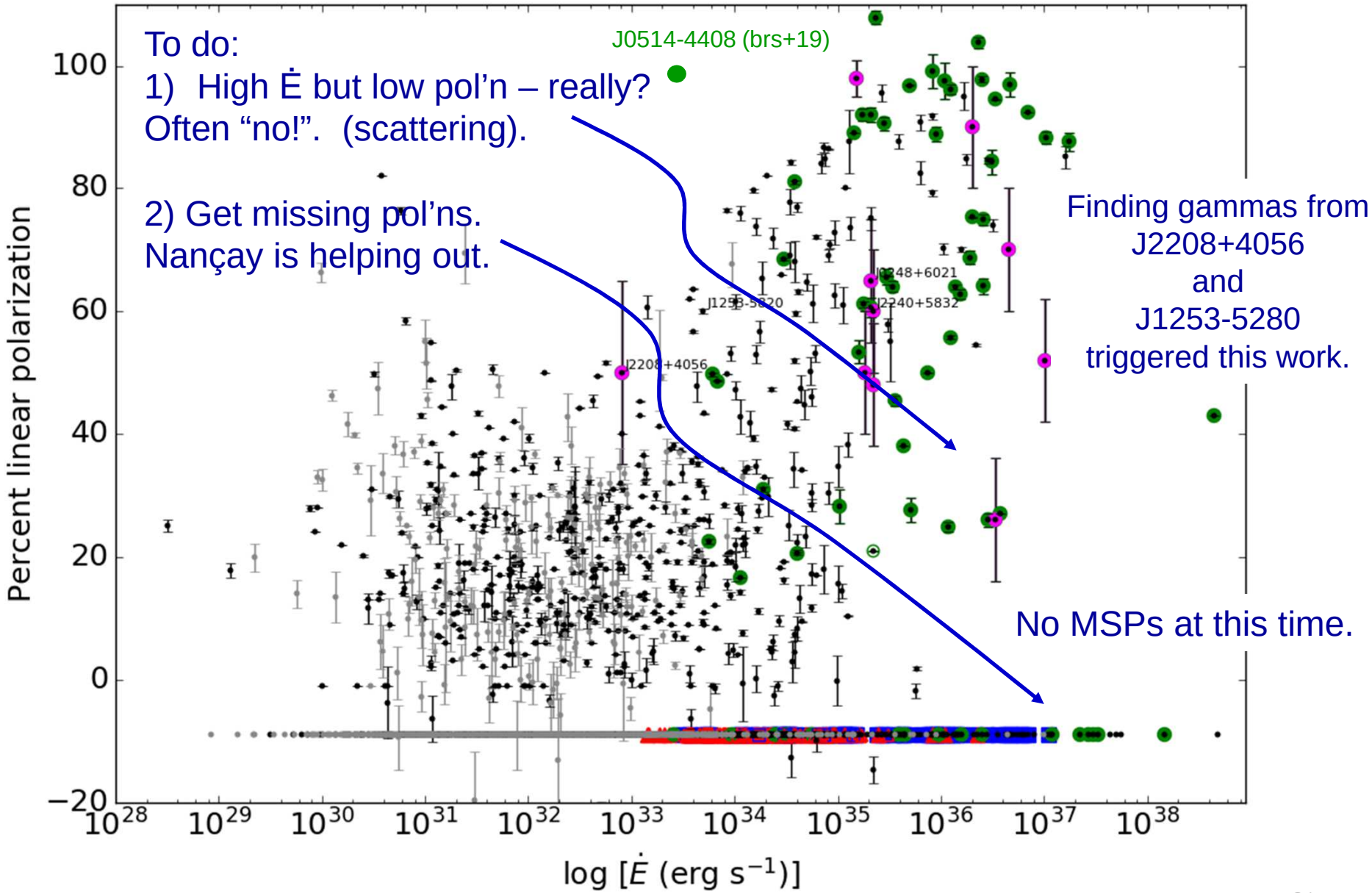


Figure 8. The degree of linear polarization versus $\dot{E}$ of all pulsars observed at 20 cm for which a significant degree of linear polarization was measured. Pulsars which show evidence for scatter broadening were excluded. There are two relatively well-defined regions which are almost empty in this diagram. The dashed line shows the linear fit and the solid curve the fit of an arctan function illustrating the step in the degree of linear polarization.

The Weltevrede & Johnston plot, with gamma rays (work in progress).

600 polarizations from Johnston & Kerr (2018), 300 from Gould & Lyne (1998).



Dave's fantasies:

1) The same electrons make the polarized radio beam (the *core* not the *cone*) and the gammas, having looped from the polar regions to the outer magnetosphere.

Recent cone & core stuff:

Desvignes et al, Science (2019)

Radio emission from a pulsar's magnetic pole revealed by general relativity

Johnston & Kramer, MNRAS (2019)

On the beam properties of radio pulsars with interpulse emission

2) Some $\dot{E} \approx 1e33$ erg/s polarized gamma pulsars are also interpulse. Well-defined geometry, large $f\Omega$.

Eager to see modelers treat radio & gamma together.

Today's talk:

Observables that guide emission models

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   b) From the profiles.
   c) From polarization.
   d) Radio interpulses – orthogonal rotators.

3. Spectral shapes.

Tallies reveal beam sizes

in the absence of selection biases.

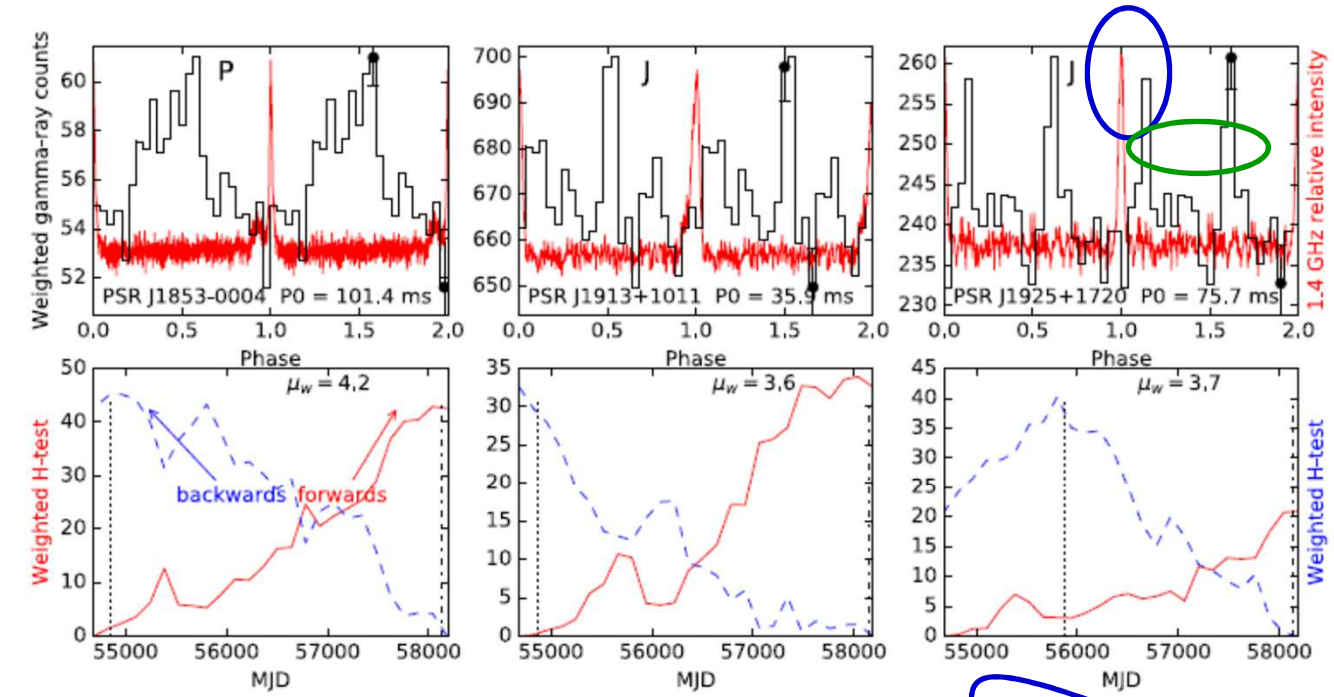
. Pulsar varieties

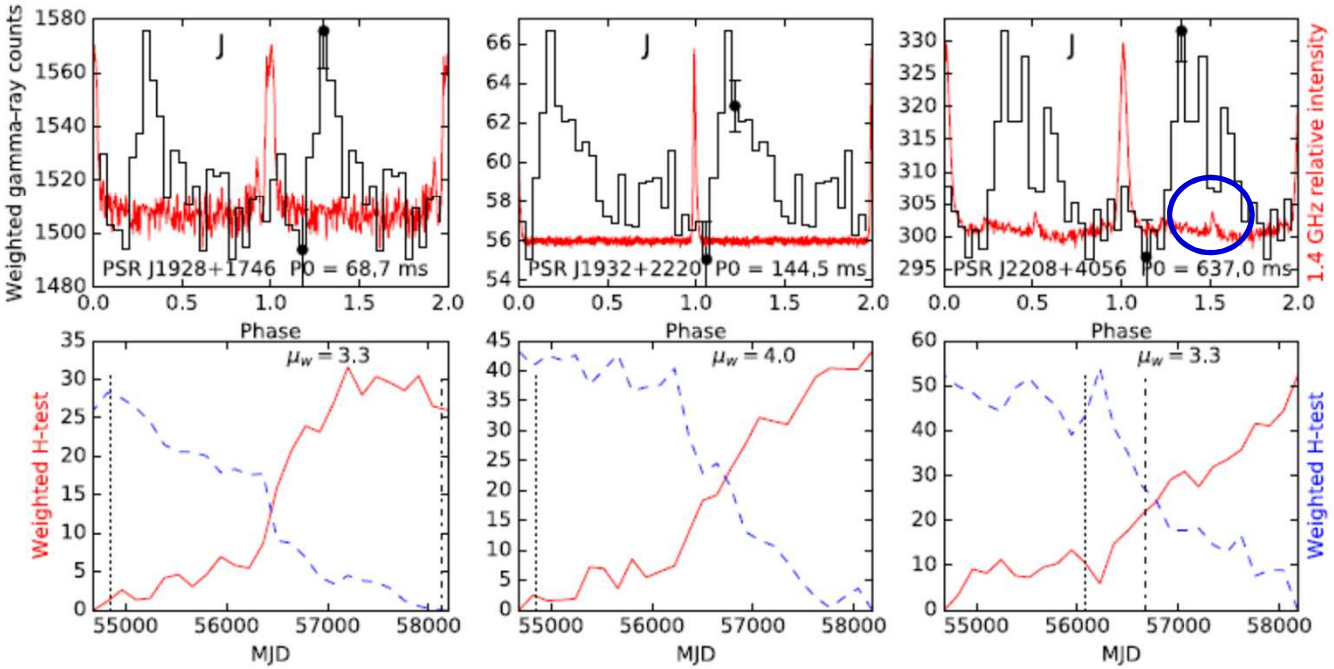
Category	Count	Sub-count	Fraction
Known rotation-powered pulsars (RPPs)[a]	2960		
RPPs with measured $\dot{E} > 3 \times 10^{33}$ erg s^{-1}		712	
Millisecond pulsars (MSPs, $P < 30$ ms)	459		
Field MSPs		304	
MSPs in globular clusters		134	
Field MSPs with measured $\dot{E} > 3 \times 10^{33}$ erg s^{-1}		214	
Globular cluster MSPs with measured $\dot{E} > 3 \times 10^{33}$ erg s^{-1}		25	
Gamma-ray pulsars in this catalog	255		
Young or middle-aged		136	
Radio-loud gamma-ray[b]		73	29%
Radio-quiet gamma-ray		63	25%
Gamma-ray MSPs (isolated + binary)		(25+94) = 119	47%
Black Widows + Redbacks:		27 + 9 = 36	
Radio MSPs discovered in LAT sources	86		
Gamma-ray MSPs discovered in LAT sources	8	7 (?) are radio-quiet	
with gamma-ray pulsations		73	

3PC preliminary

[a]Includes the 2796 pulsars, which are all RPPs, in the ATNF Pulsar Catalog (v1.61, Manchester et al. 2005), see `http://www.atnf.csiro.au/research/pulsar/psrcat`, as well as more recent discoveries. D. Lorimer maintains a list of known field MSPs at `http://astro.phys.wvu.edu/GalacticMSPs/`.

[b]$S_{1400} > 30\,\mu$Jy, where S_{1400} is the radio flux density at 1400 MHz.





δ: γ-radio separation.
Δ: γ-peak separation.

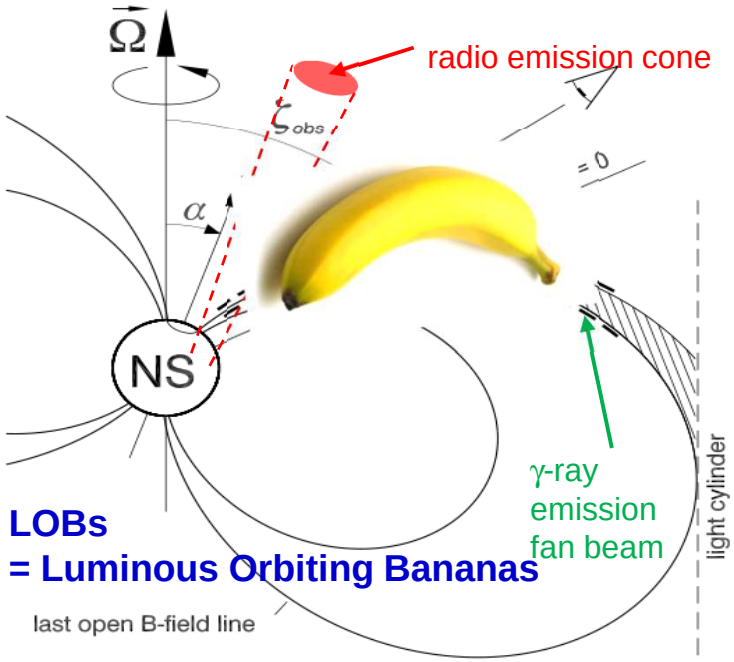
J2208+4056
Ė=8e32 erg/s, ~50% polarized.

%5 of radio pulsars have an “interpulse”.

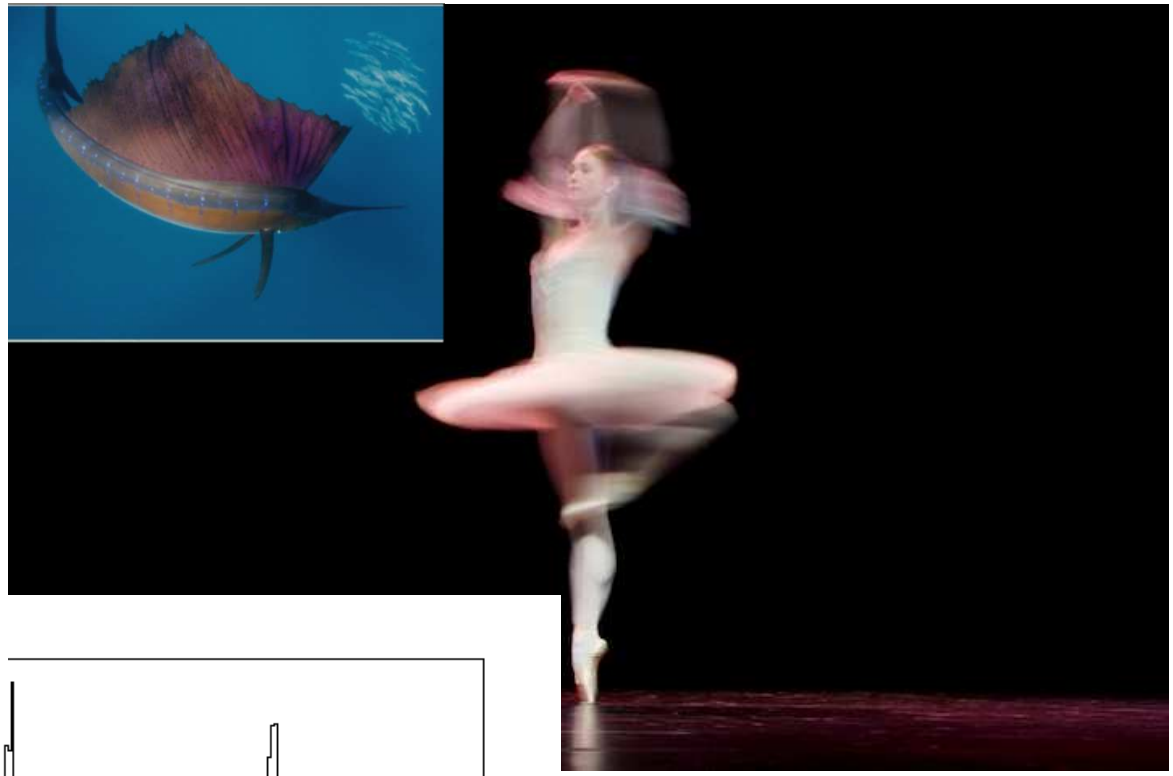
Smith et al, ApJ (2019)

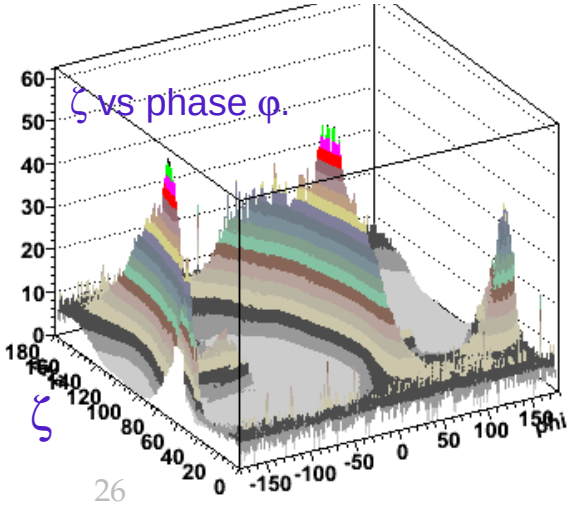
Gamma-ray beam:Long in latitude, thin in longitude (*caustics*).

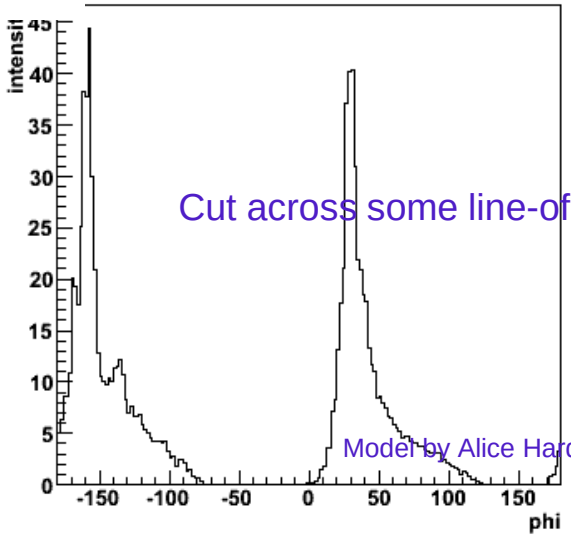
Curvature radiation in '*gaps*'.



LOBs
= Luminous Orbiting Bananas







Cut across some line-of-sight ζ.

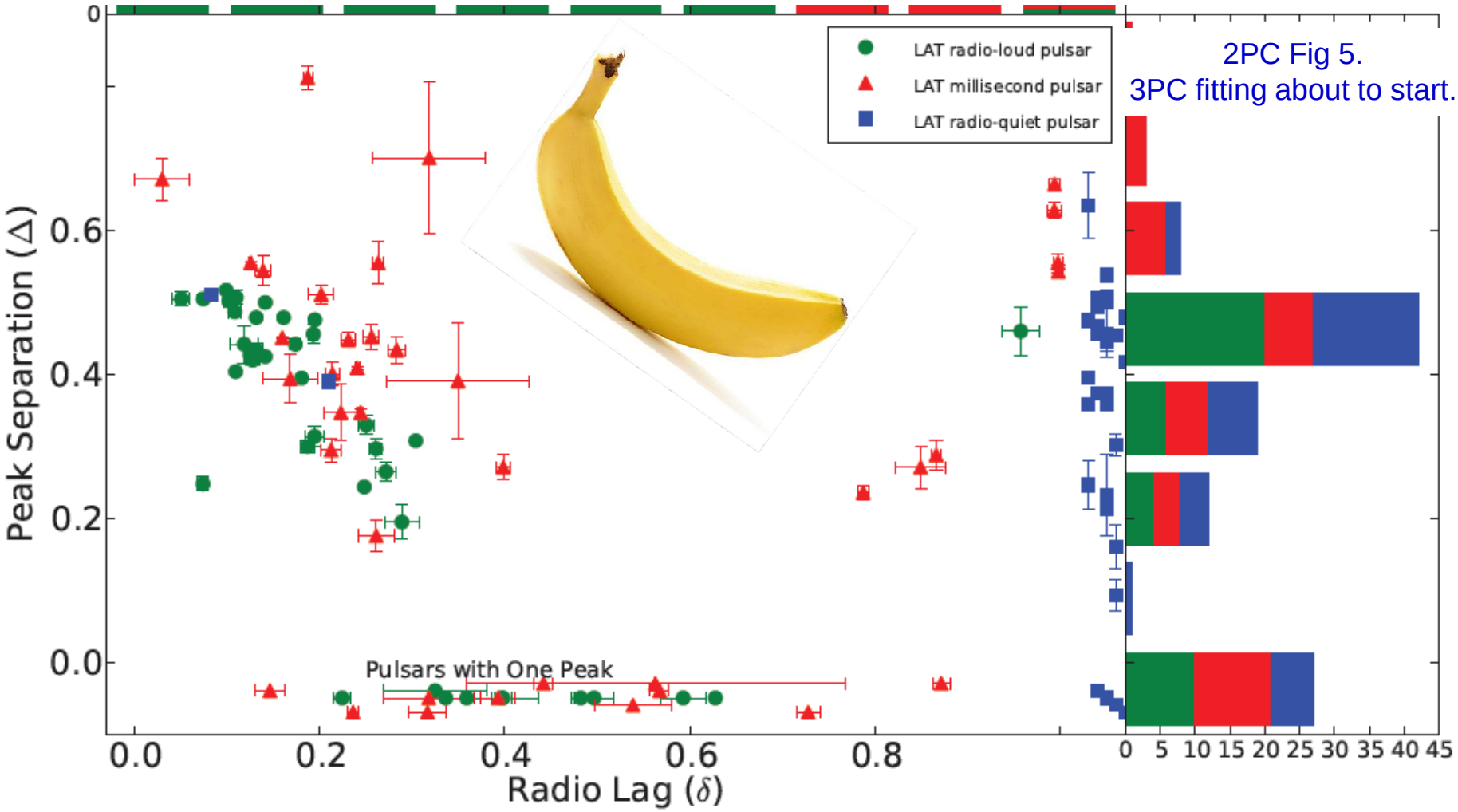
Model by Alice Harding

Radio-loud γ pulsars: closer peaks ➔ bigger offset from radio.

Insight into banana *shape & location*.

Current trend in pulsar models:

Gamma-ray emission may come from beyond the light cylinder.

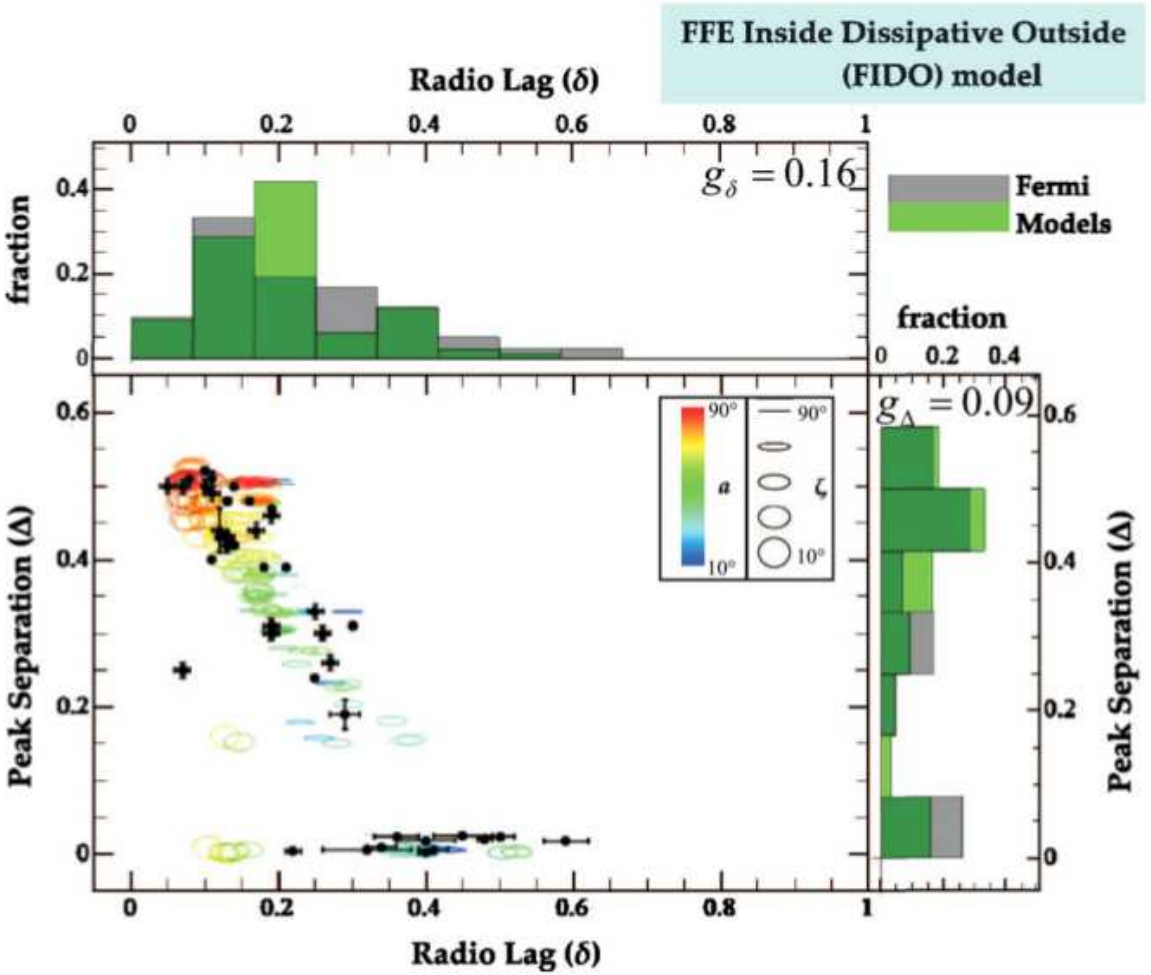


2PC Fig 5.
3PC fitting about to start.

Li et al. (2012) and Kalapotharakos et al. (2014) use a resistive MHD simulation with a quasi-consistent prescription for the gamma-ray emissivity.

Choose various portions of the magnetosphere to make resistive, including the model at right: FIDO.

The resulting gamma-ray light curves are a near-perfect match for Fermi data, including both radio-loud and radio-quiet pulsars!



Kalapotharakos et al. (2014)

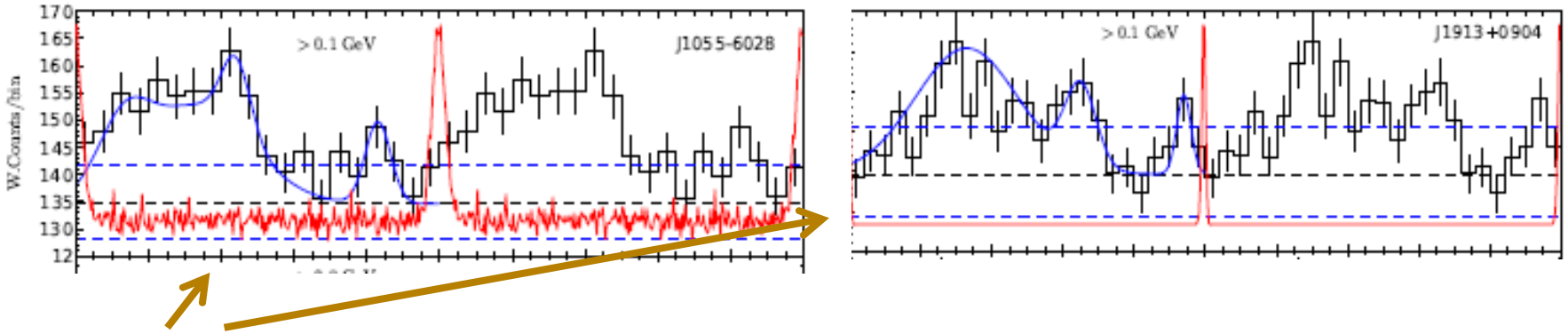
Words from Matthew Kerr, HEAD March 2019.

Six faint gamma-ray pulsars seen with the *Fermi* Large Area Telescope

A&A 570, A44 (2014)

Towards a sample blending into the background

X. Hou (侯賢)[1], D. A. Smith[1], L. Guillemot[2,10], C. C. Cheung[3], I. Cognard[2,10], H. A. Craig[4], C. M. Espinoza[5], S. Johnston[6], M. Kramer[7,8], O. Reimer[9,4], T. Reposeur[1], R. Shannon[6], B. W. Stappers[7], and P. Weltevrede[7]



60% duty cycles! Needs sensitive pulse searches.

"Faint": Far. Background. Small fΩ. Large duty cycle.

Low Lγ because: a) inefficient b) near deathline.

The dark corners of parameter space.

Most deep in plane
➔High b'kgrd

Slowest.
From 1968!

1 lo, 1 hi Ė.

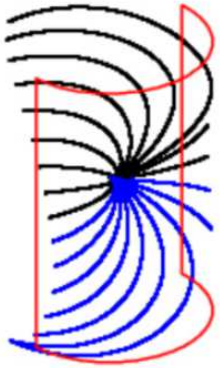
Some very narrow peaks.
But not all.

PSR	Ref.	l (°)	b (°)	P (ms)	Distance (kpc)	$\dot{E}/10^{34}$ (erg s^{-1})	S_{1400} (mJy)	H-test signif.	Timing
J0729-1836	mlt+78	233.76	-0.34	510.2	2.4 / 2.9	0.56	1.4	43.6	P (J)
J1731-4744†	lvw68	342.56	-7.67	829.8	4.1 / 4.6	1.13	12.0	41.6	P
J1740+1000†	mca00	34.01	20.27	154.1	1.2 / 1.2	23.16	9.2	26.3	J (N)
J1757-2421	kom74	5.28	0.05	234.1	3.1 / 4.4	4.00	3.9	26.2	P (J, N)
J1816-0755	lfl+06	21.87	4.09	217.6	3.1 / 2.8	2.48	0.17	51.2	J
J1841-0524	hfs+04	27.02	-0.33	445.7	4.1 / 5.3	10.42	0.2	28.7	J (P)
J1853-0004†	hfs+04	33.09	-0.47	101.4	5.3 / 7.2	21.09	0.87	42.0	P (J, N)
J1913+1011	mhl+02	44.48	-0.17	35.9	4.6 / 4.8	287.14	0.5	34.7	J
J1925+1720	lbh+15	52.18	0.59	75.7	5.1 / 6.9	95.42	0.07	36.9	J
J1928+1746	cfl+06	52.93	0.11	68.7	4.3 / 5.8	160.39	0.279	22.0	J (N)
J1932+2220†	ht75b	57.36	1.55	144.5	10.9 / 7.5	75.38	1.2	33.1	J
J0636+5129	slr+14	163.91	18.64	2.86	0.2 / 0.5	0.57	*	50.1	
J1125-6014†	fsk+04	292.50	0.89	2.63	1.0 / 1.5	0.58	0.05	32.9	
J1327-0755	blr+13	318.38	53.85	2.68	25.0 / 1.7	0.36	*	25.1	N (G)
J1946+3417	bck+13	69.29	4.71	3.17	7.0 / 5.2	0.12	0.29	23.4	J

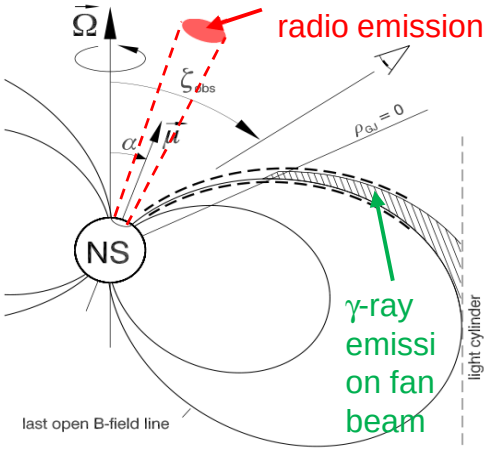
Top: 11 young pulsars (one with a radio interpulse. Another with predicted low luminosity).
Bottom: 4 MSPs (one has 1.8 $M_\odot$).
P=Parkes, J=Jodrell Bank, N=Nançay, G=Green Bank.
† = in 8-year source list.

Smith et al, ApJ (2019)

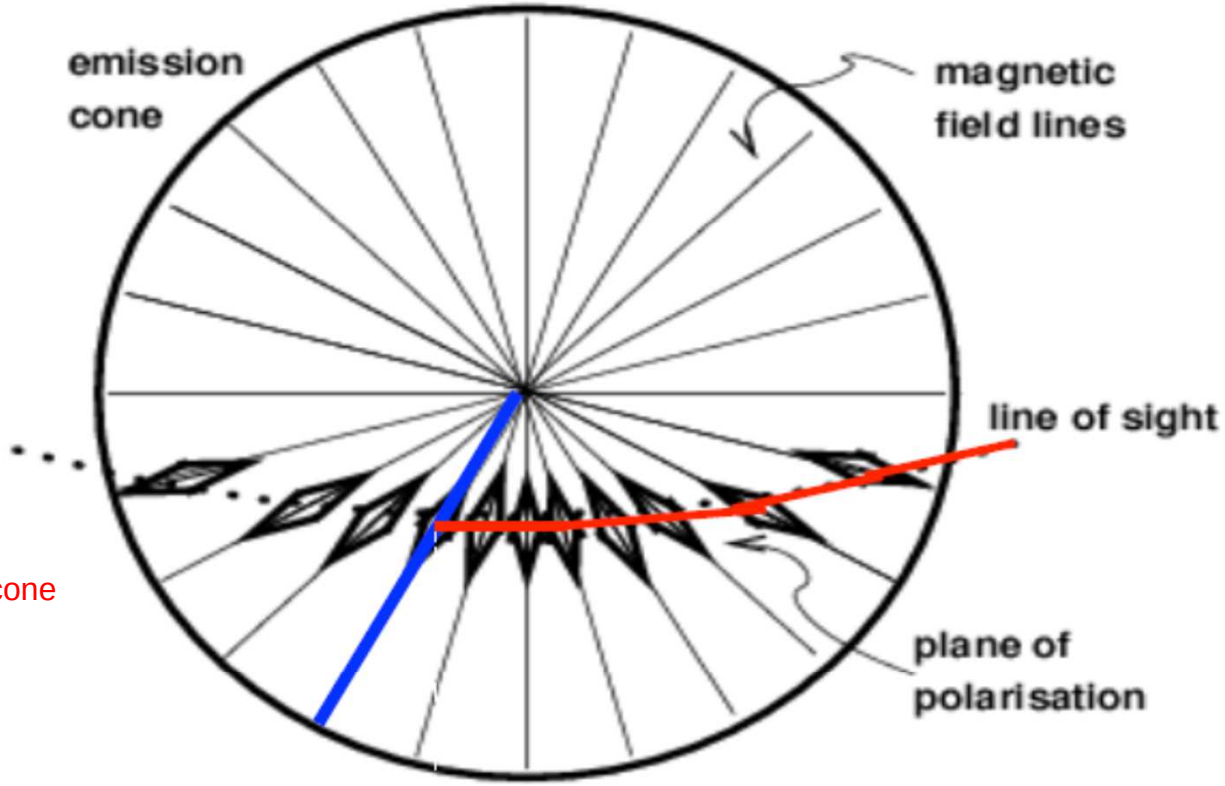
The Rotating Vector Model (RVM) for polarization



Looking into the radio beam is like looking down a 3-D dipole "trumpet horn".



Radhakrishnan & Cooke. 1969



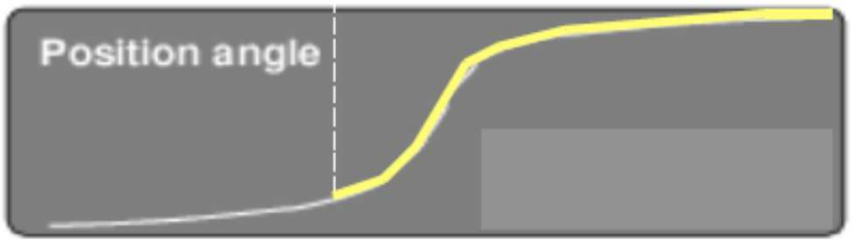
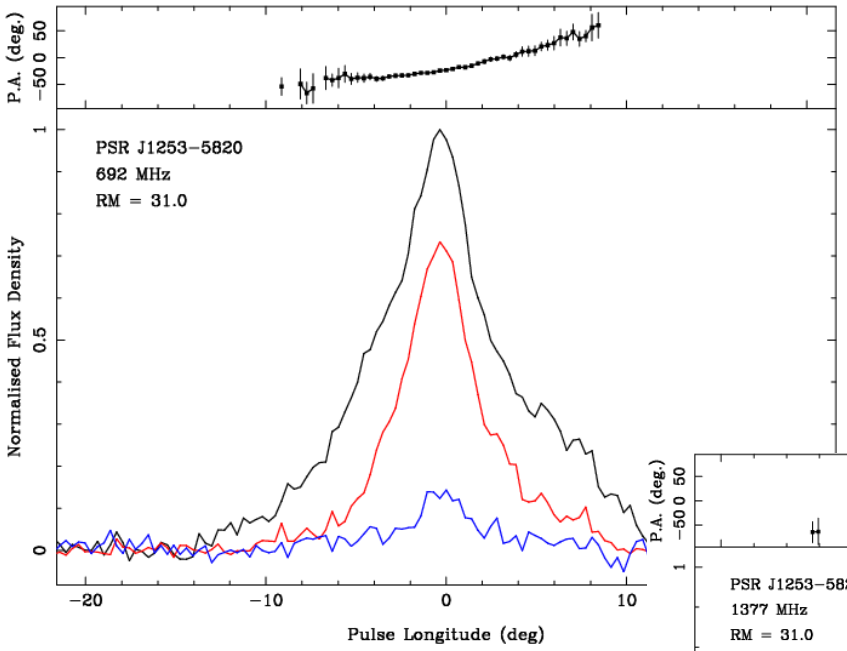
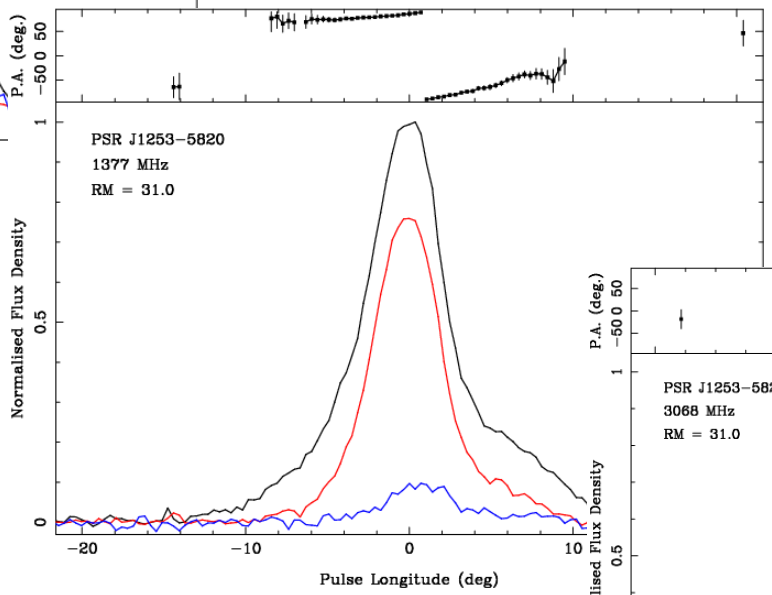


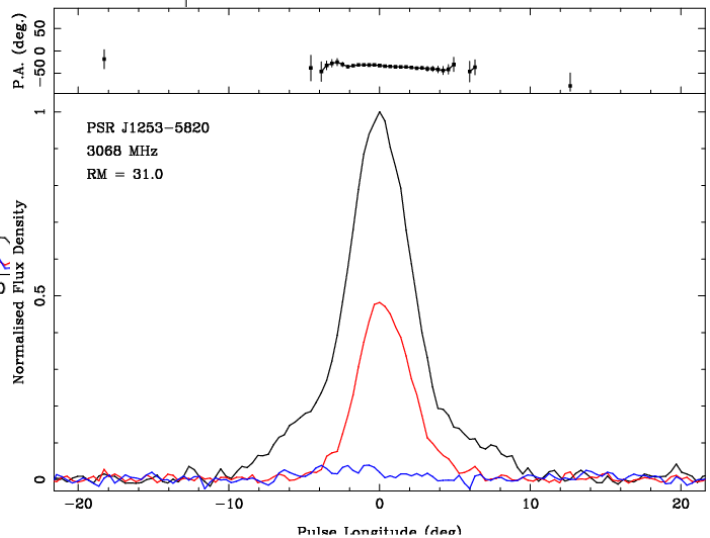
Illustration by A. Karastergiou via S. Johnston

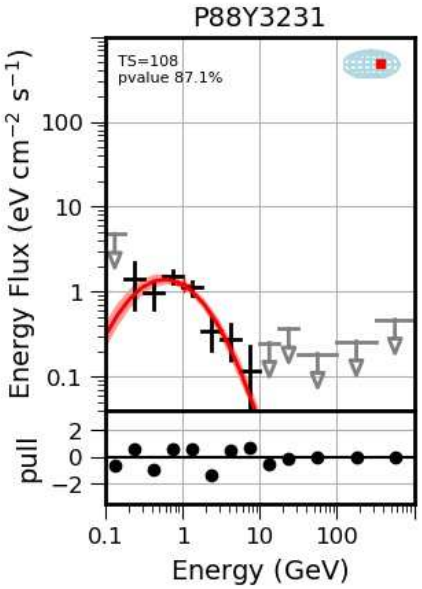
Example: PSR J1253-5820

Ė= 5e33 erg/s P0 = 255 ms. 4σ γ pulsations last week. 4FGL J1253.3-5816





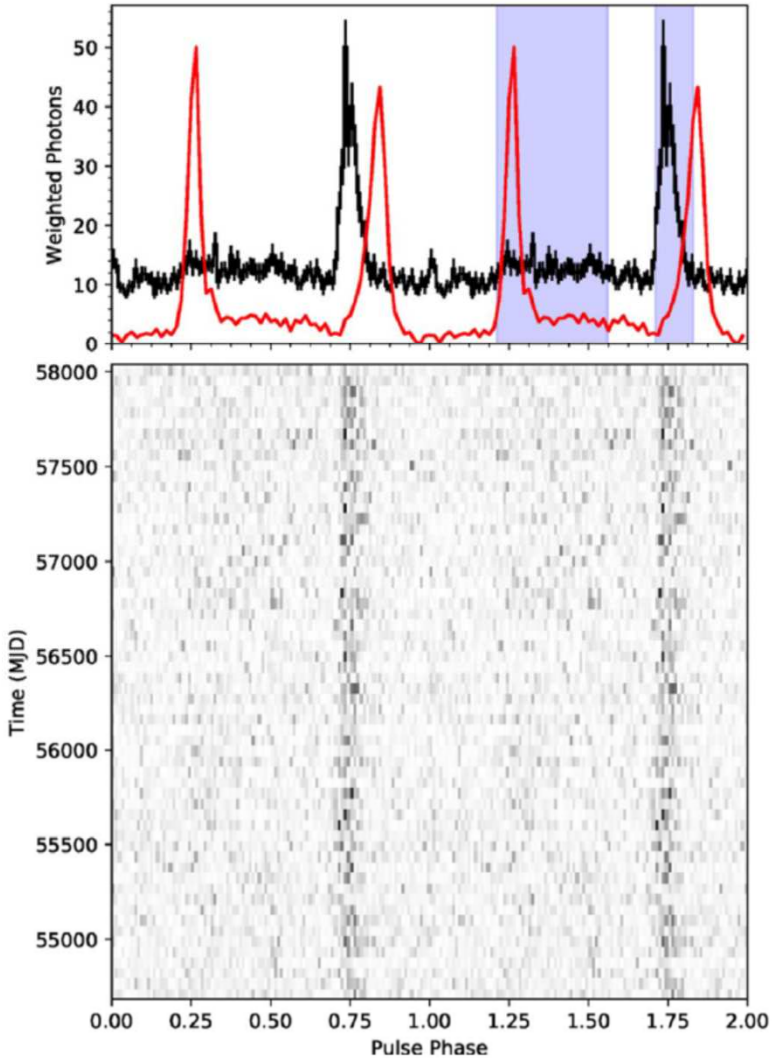


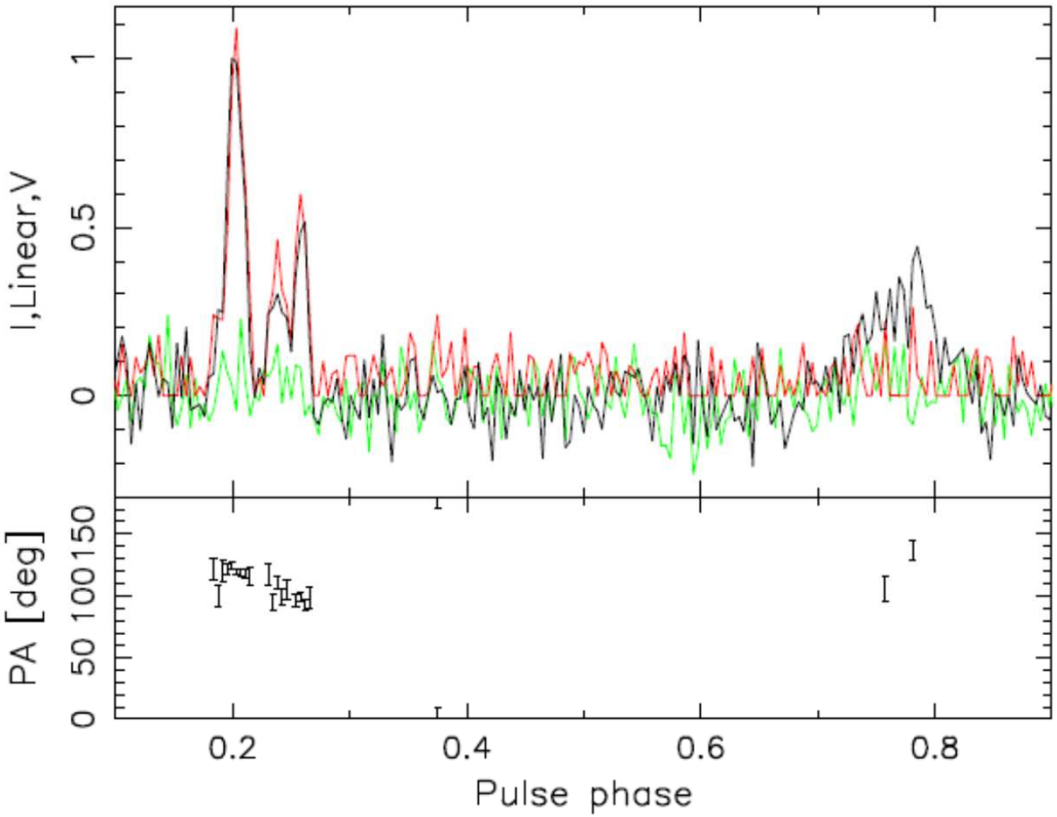


Example: PSR J0514-4408

Ė= 2.5e33 erg/s P0 = 320 ms. 3FGL J0514.6-4406

Figures from Bhattacharya et al, ApJ (2019)





Main (gamma) pulse ~100% linear polarization.
Interpulse *not* polarized.

GAMMA-RAY AND RADIO PROPERTIES OF SIX PULSARS DETECTED BY THE *FERMI* LARGE AREA TELESCOPE

Weltevrede, Abdo et al, ApJ (2010).

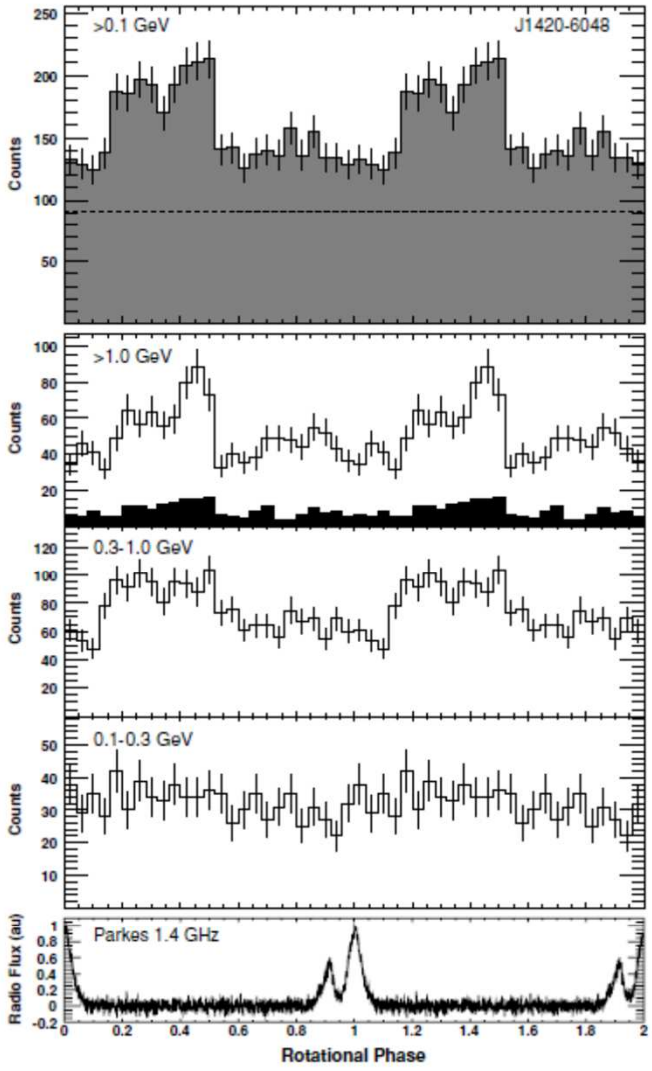
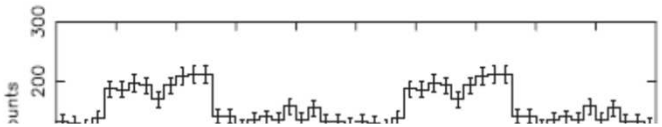


Figure 11. As in Figure 1, but for PSR J1420–6048.



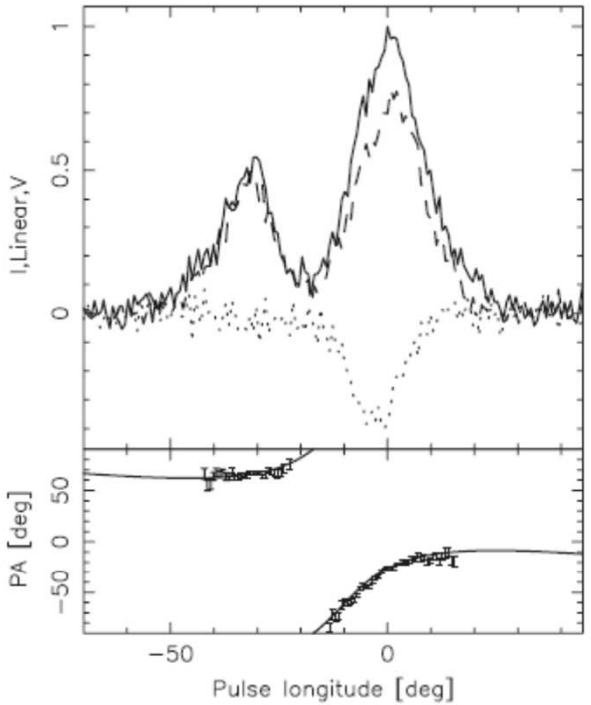


Figure 13. As in Figure 2, but for Parkes data of PSR J1420–6048 at 1369 MHz.

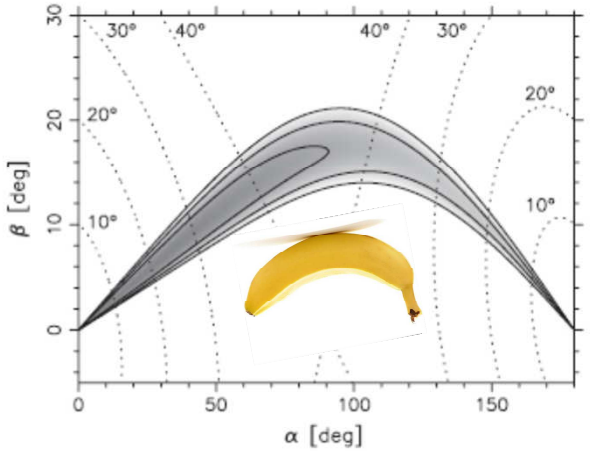


Figure 14. As in Figure 3, but for PSR J1420–6048. The lowest reduced χ^2 is 1.3.

Careful RVM analysis.

Narrow radio peak
➔ Short lever arm, large degeneracy.

Compare gamma data to model for RVM α,ζ.

Conclusions a tad disappointing.

2019: better gamma profiles, and large sample of radio+gamma pulsars.

Today's talk:

Observables that guide emission models

➔ Skip *spiders* (MSP recycling process).

1. Deathlines:
   a) Below some $\dot{E}$ does L_γ die, or just fade away?
   b) If radio polarization dies at same $\dot{E}$, are electrons the same ones?

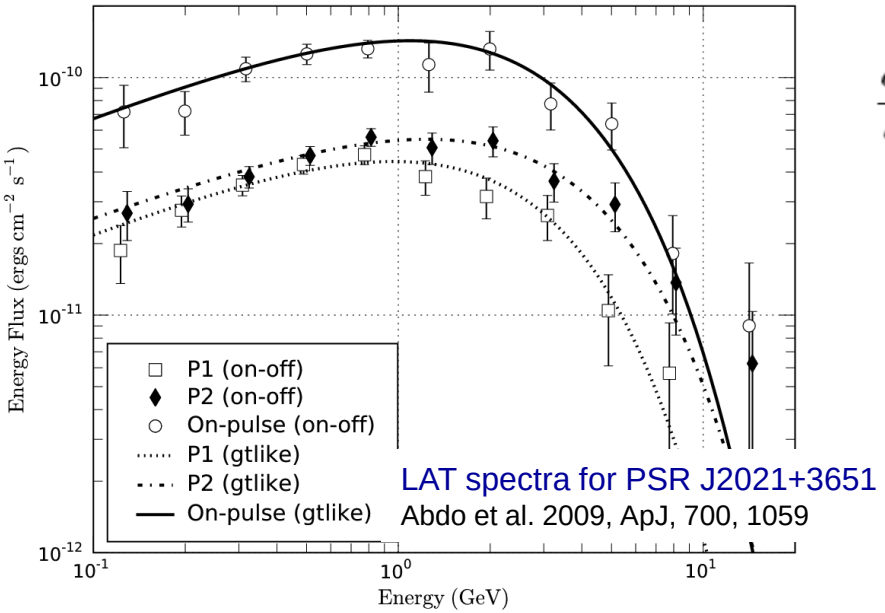
2. Geometry:
   a) Tallies give relative beam sizes?
   b) From the profiles.
   c) From polarization.
   d) Radio interpulses – orthogonal rotators.

3. Spectral shapes.

Of the ~5700 sources in a current pre-4FGL list, pick

stable, cut-off unidentified targets.

e.g. *Ranking LAT sources with Machine Learning*, Saz Parkinson et al, ApJ 820:8 (2016)



LAT spectra for PSR J2021+3651
Abdo et al. 2009, ApJ, 700, 1059

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

➔ b=1 ➔ high altitude curvature radiation.

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

Pulsar spectral 'signature'

Most gamma spectra (=blazars) extend to high energy. And blazars flare, pulsars mostly don't.

New – Match Unld gamma sources to Unld steep spectrum radio sources.

Pulsar candidates towards *Fermi* unassociated sources

MNRAS 461, 1062 (2016)

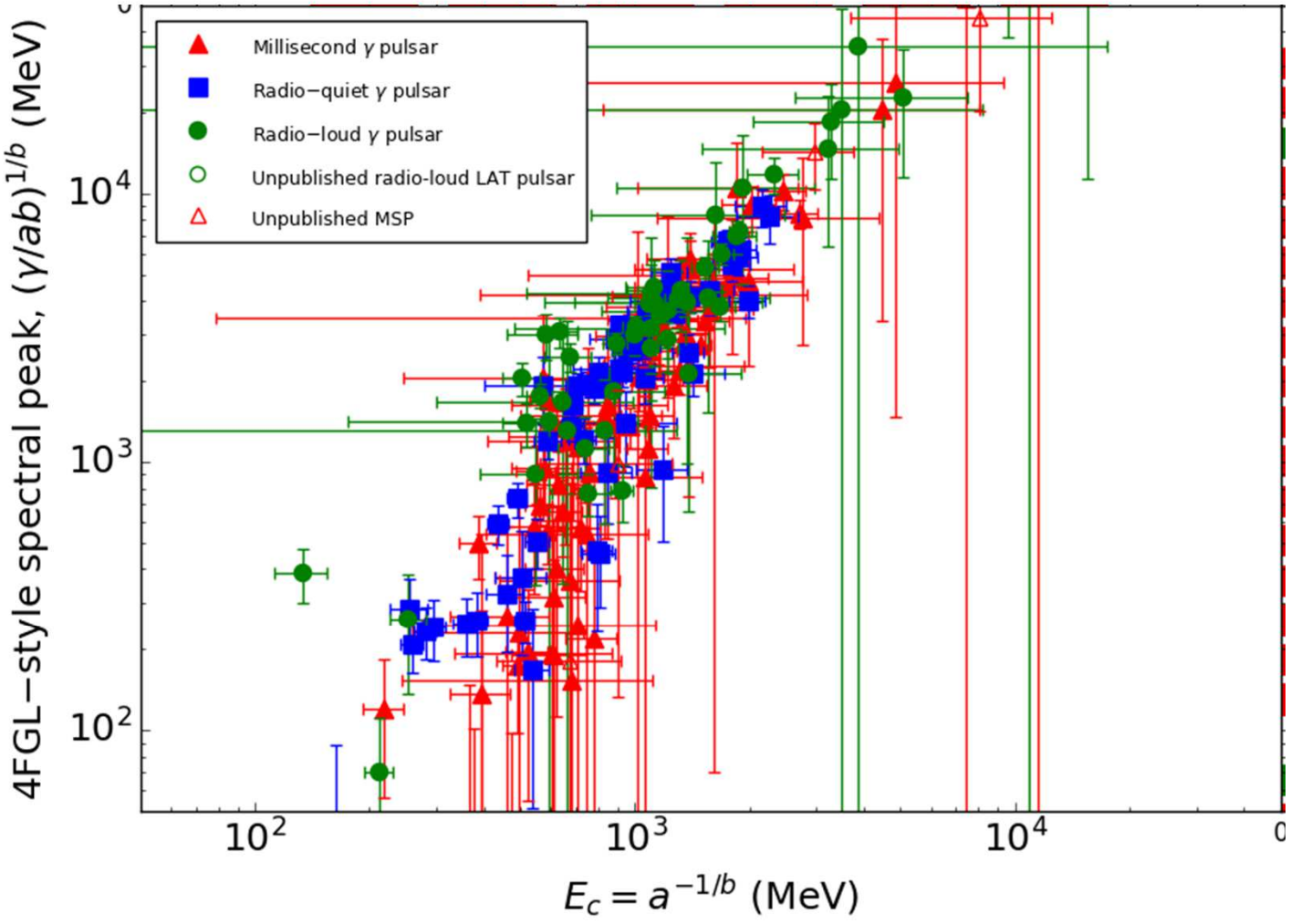
KNOWN PULSARS IDENTIFIED IN THE GMRT 150 MHz ALL-SKY SURVEY

ApJ 829:119 (2016)

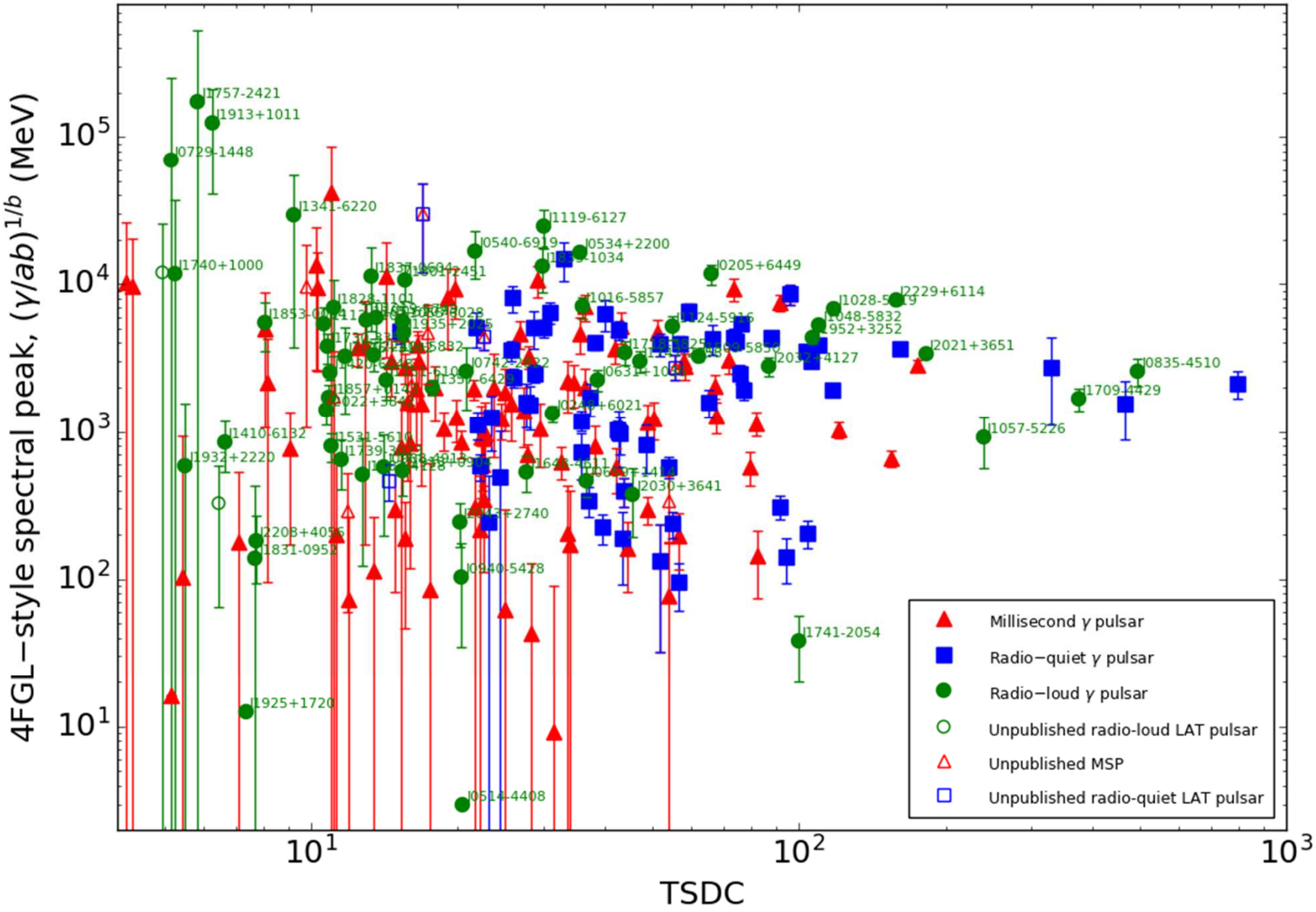
D. A. Frail[1], P. Jagannathan[1,2], K. P. Mooley[3,5], and H. T. Intema[1,4]

New spectral shape in 4FGL (and so, in 3PC too).

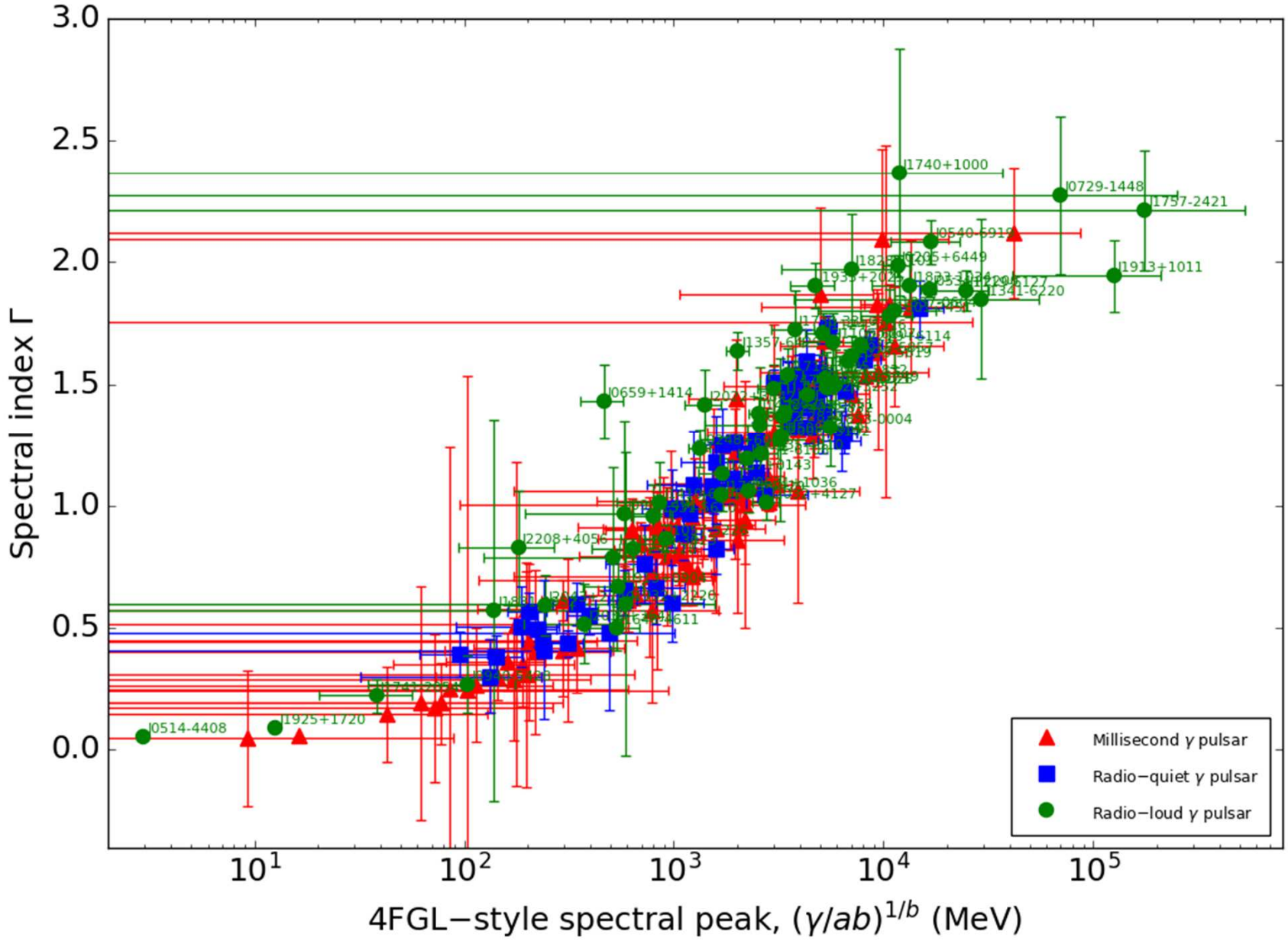
$$\frac{\mathrm{d}N}{\mathrm{d}E} = K\left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left(a\left(E_0^b - E^b\right)\right)$$



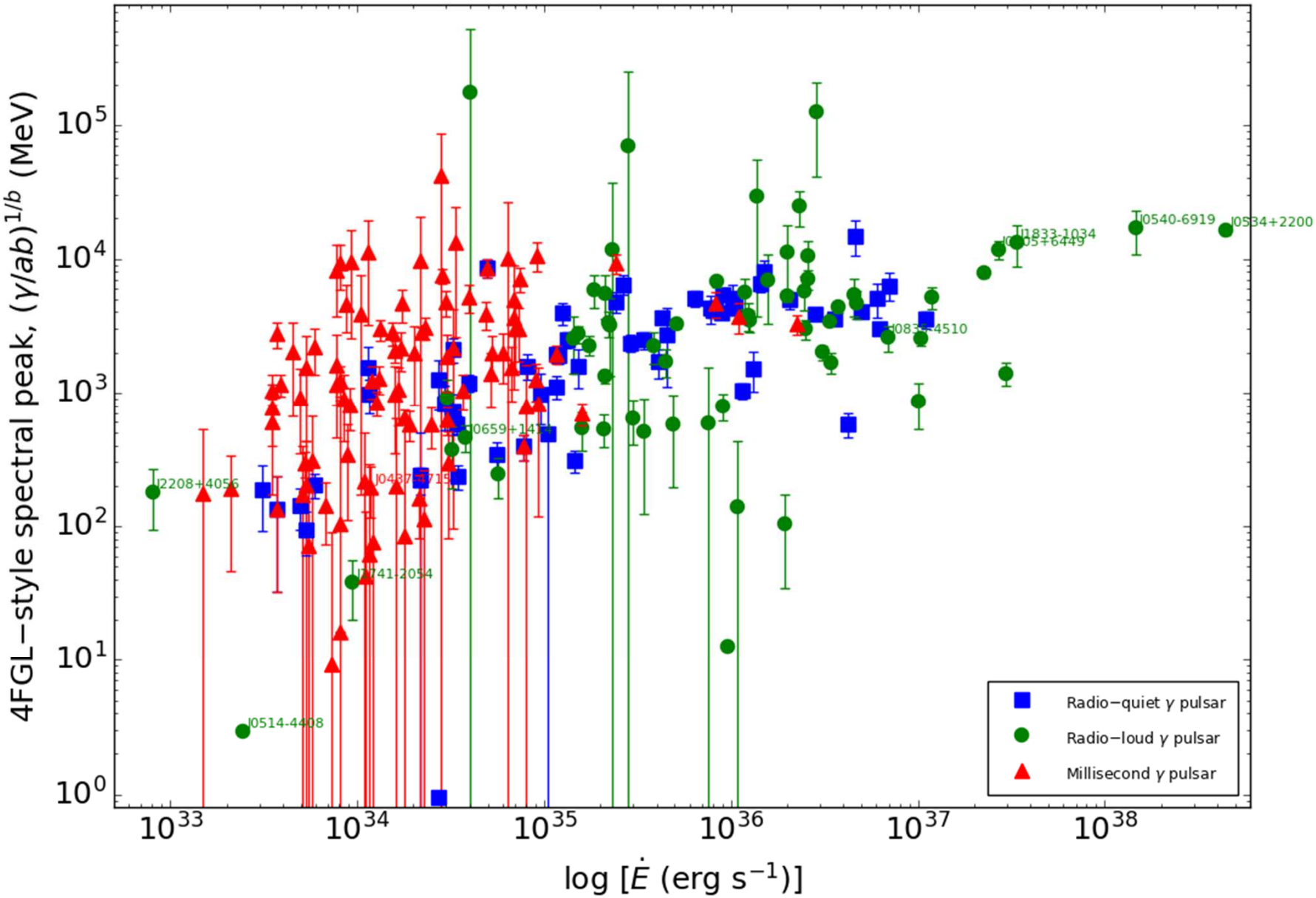
4FGL spectra of 3PC pulsars.



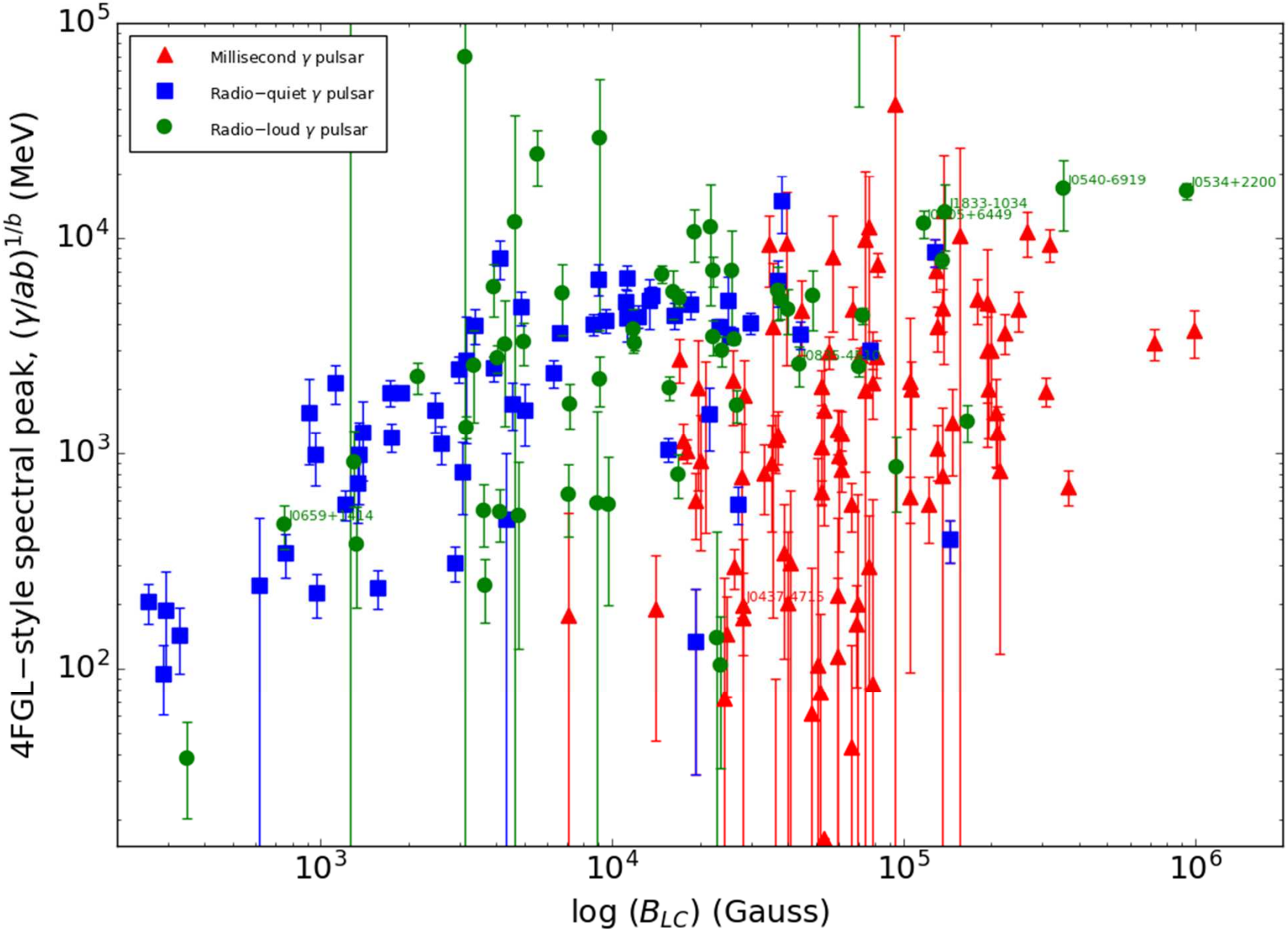
4FGL spectra of 3PC pulsars.



4FGL spectra of 3PC pulsars.



4FGL spectra of 3PC pulsars.



Two last things:

- *Braking indices*

Torque $\tau = I\,\Omega dot = k\Omega^n$ ➔ $n = nudotdot*nu/nudot^2$

PSR B0540-69 (Crab's twin in the LMC) had Ė jump by 36% (!) and n➔ ~0, with no apparent change in gamma flux or profile.

- *Mode changes*

PSR J1048-5832 changes mode every 17 periods, pol'n to no pol'n, strong to weak, and is a gamma pulsar. Model *that*!

Yan, Manchester, Wang et al https://arxiv.org/abs/1912.01165

Jérôme Pétri's request for 3PC:
"gamma pulse widths versus energy bands, please."

We're doing it!

Tell us your dream parameters, we'll include if we can.

(Phase-resolved spectra: a 3PC companion paper.)

(Also not in 3PC: optical & X-ray compilations ; SNR associations.)

Conclusions:

- Still collecting ~25 γ-pulsars/year, in 12th year.
- A wealth of observables – a challenge for modelers.
- Faint, low Ė pulsars – a useful special case.

Some excellent reviews:

γ-ray Pulsar Revolution, P. Caraveo, Annual Review of Astronomy and Astrophysics 52, 2014.
γ-ray Pulsars: a Gold Mine, I. Grenier & A.K. Harding, Compte rendus Physique 16, 2015
The Soft γ-ray Pulsar Population: a High-Energy Overview, L. Kuiper & W. Hermsen, MNRAS 449, 2015
γ-ray Pulsars with *Fermi*, D.A. Smith et al., arXiv:1706.03592