Fermi-LAT Detection of gamma-ray pulsars above 10 GeV

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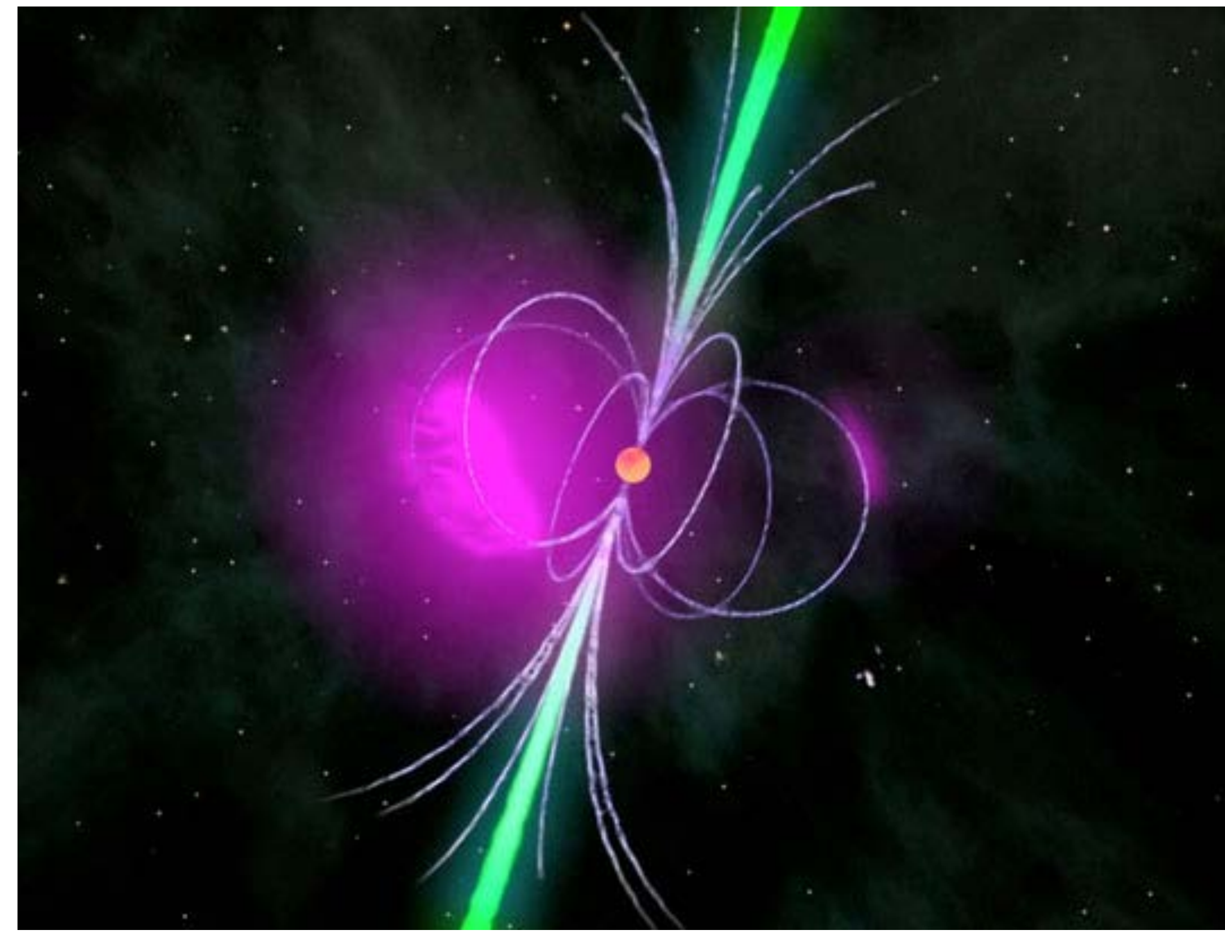
on behalf of the Fermi LAT Collaboration

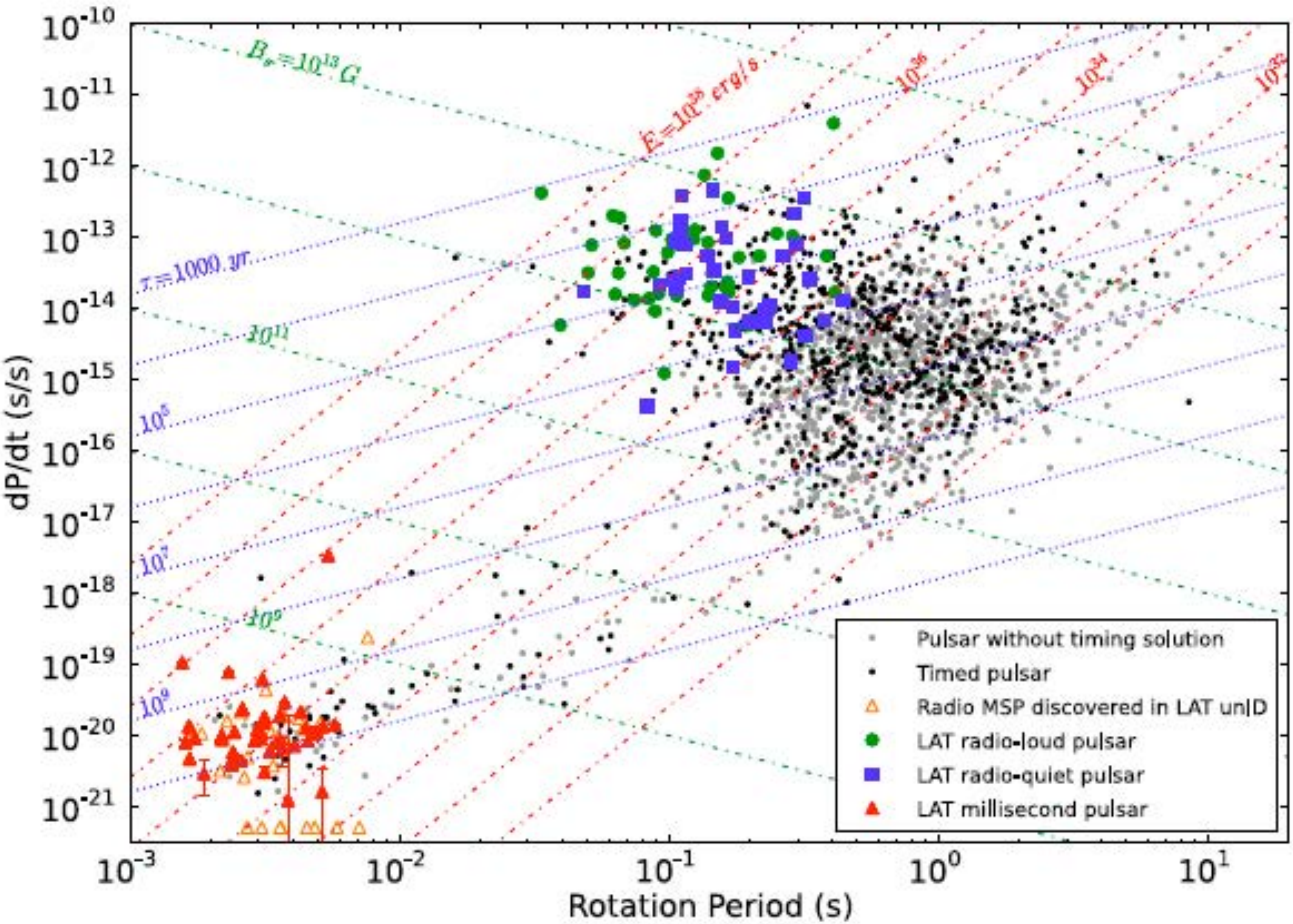
The Future of Research on Cosmic Gamma Rays
La Palma, Canary Islands, 27 August 2015

What is a pulsar?

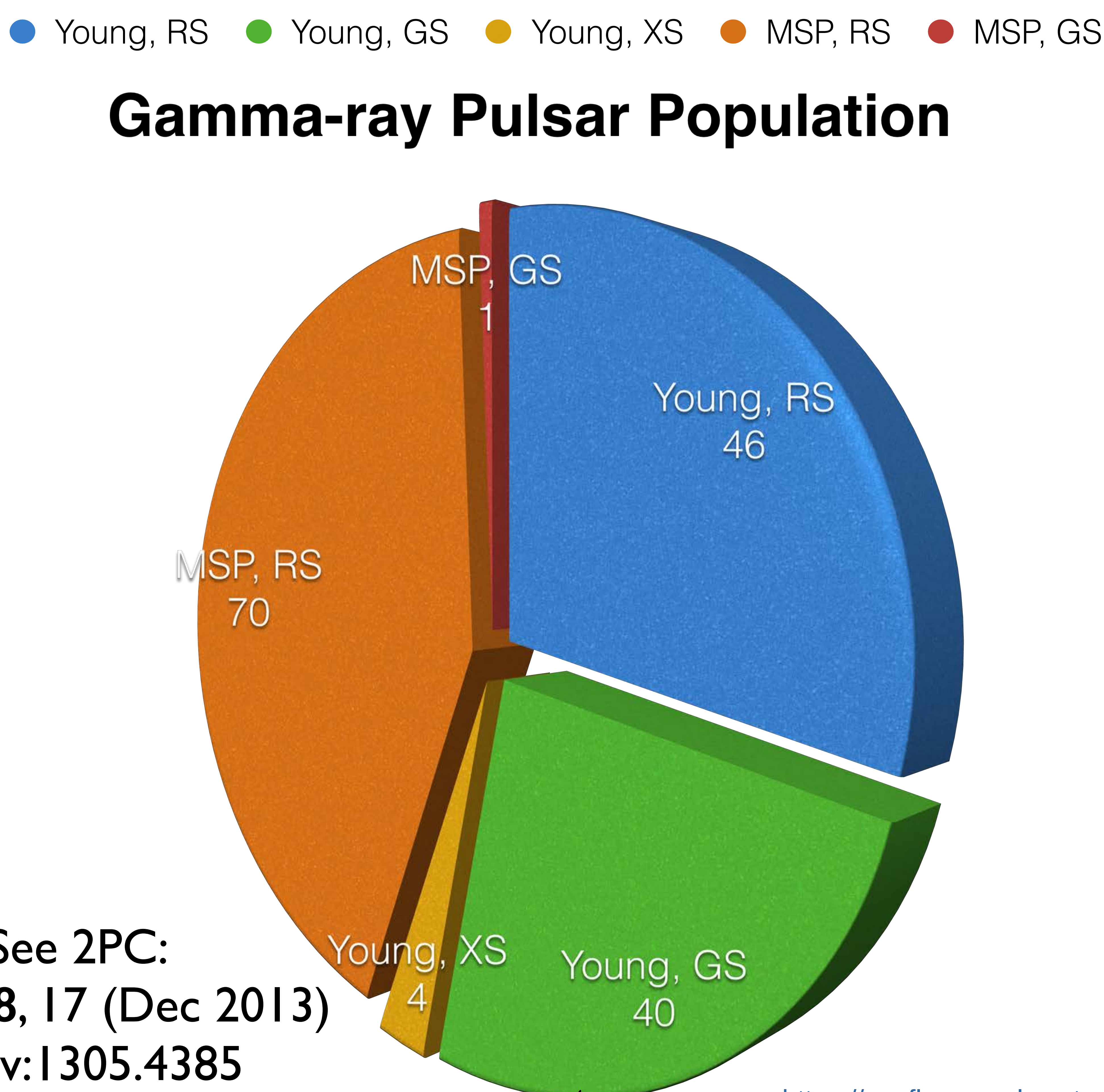
- Rapidly-spinning (0.1 Hz - 700 Hz),
- highly-magnetised (up to 1E15 G),
- neutron star (R ~ 10 km, M ~ Sun)
- Discovered almost 50 years ago but still not completely understood
- > 2000 known pulsars
- Two “varieties”: young and millisecond pulsars



Gamma-ray pulsar population



Gamma-ray Pulsar Population



See 2PC:
ApJS, **208**, 17 (Dec 2013)
arXiv:1305.4385

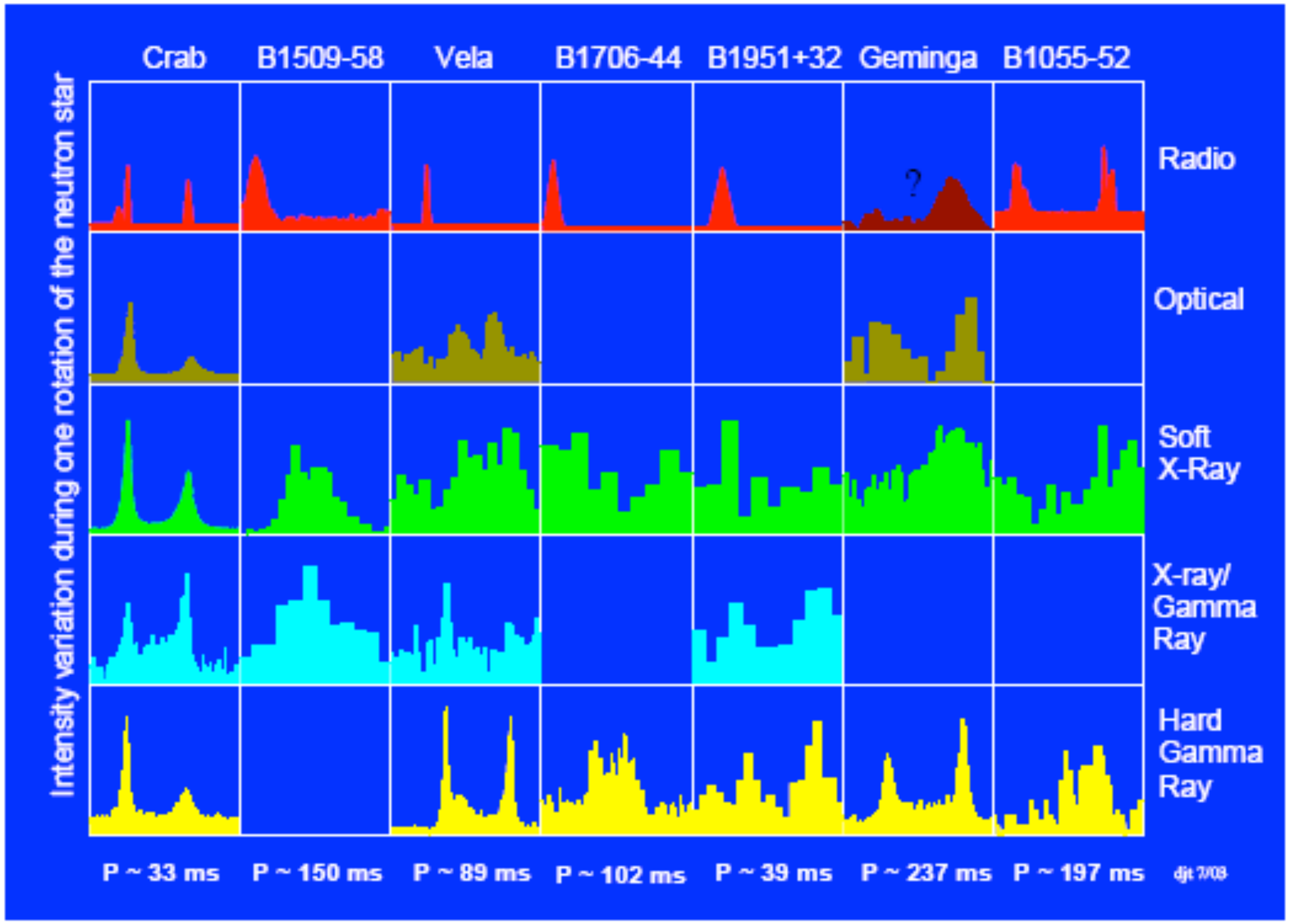
https://confluence.slac.stanford.edu/x/5Jl6Bg

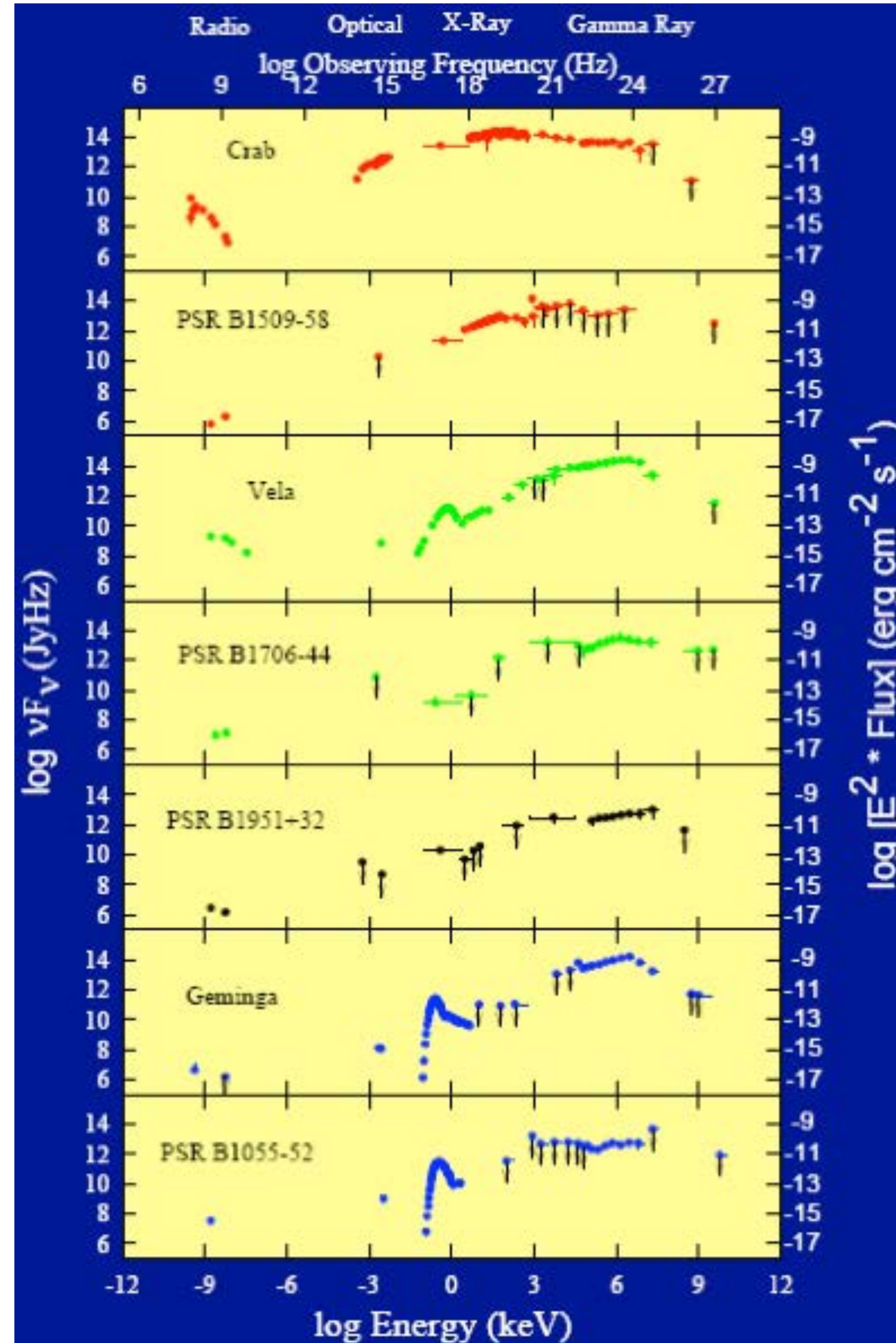
Why are pulsars interesting?

- Extreme physical properties (e.g. density, B-field)
- Extreme 'timing' properties

e.g. The period of MSP J0437-4715 at 8:40 AM CST on 23 Aug 2012 was 5.7574518556687(1) ms and the first six digits will remain constant for the ~1000 years (Ransom 2013)

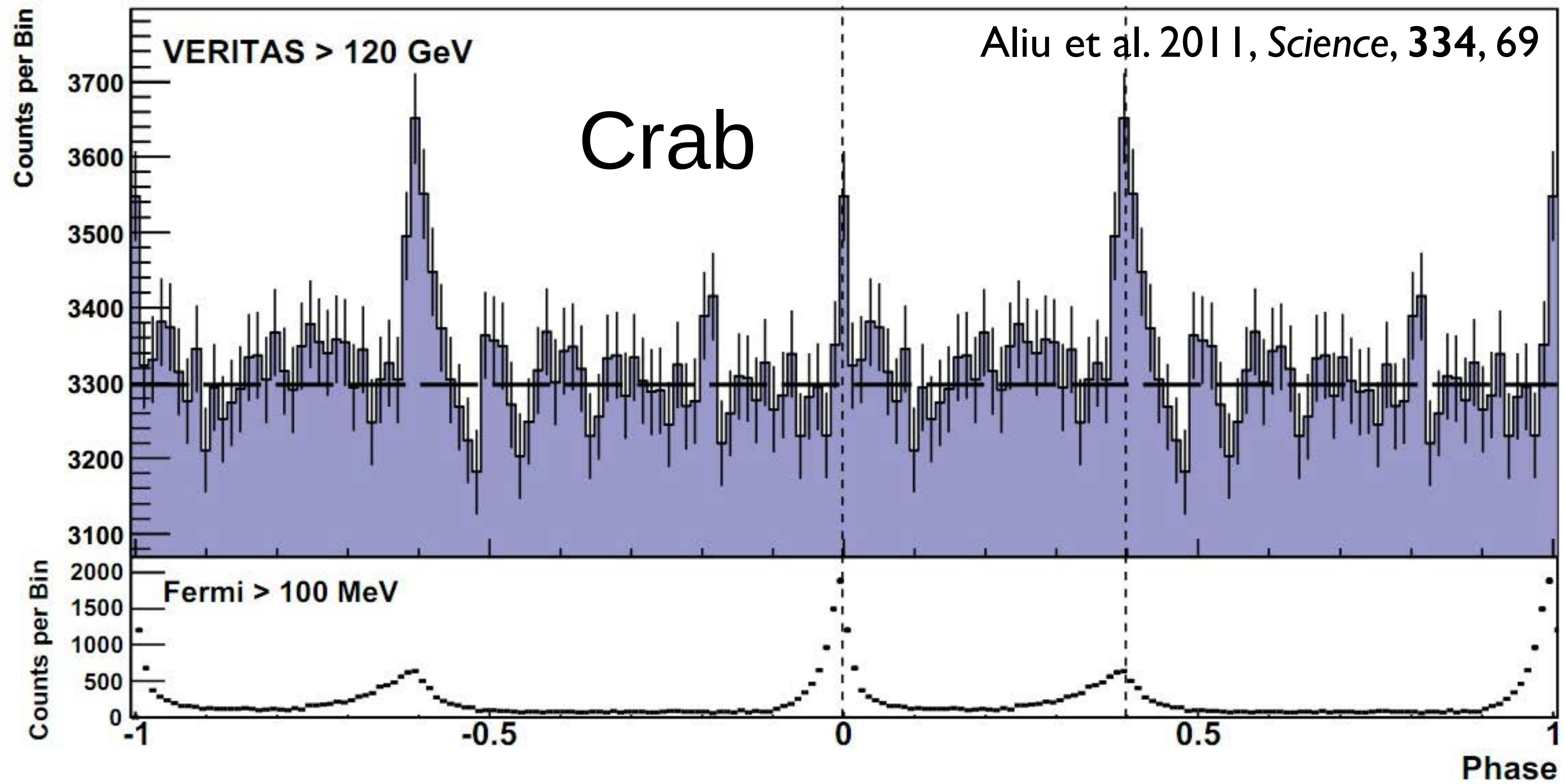
The multi-wavelength nature of pulsars

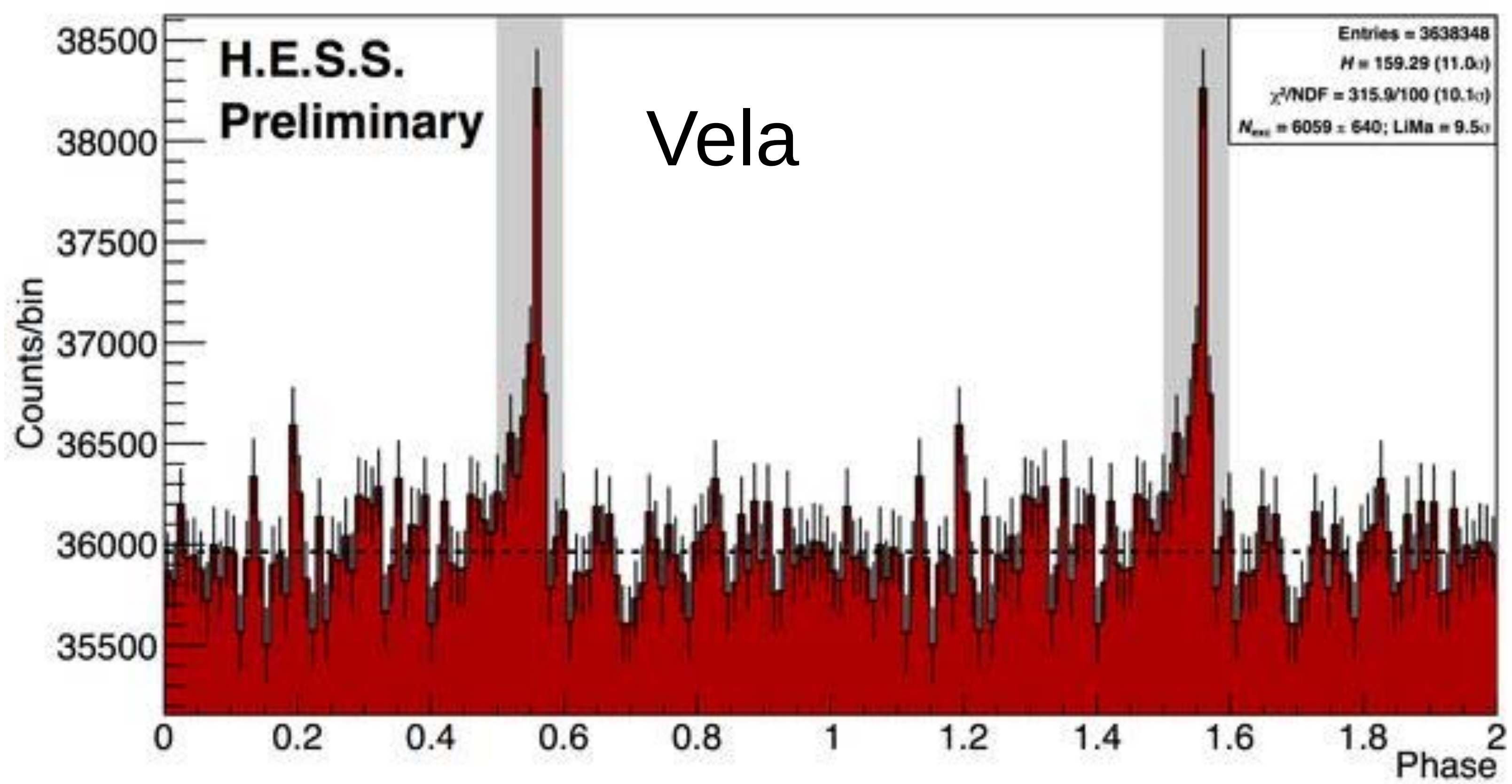




Credit: Thompson 2004

Pulsars at VHE

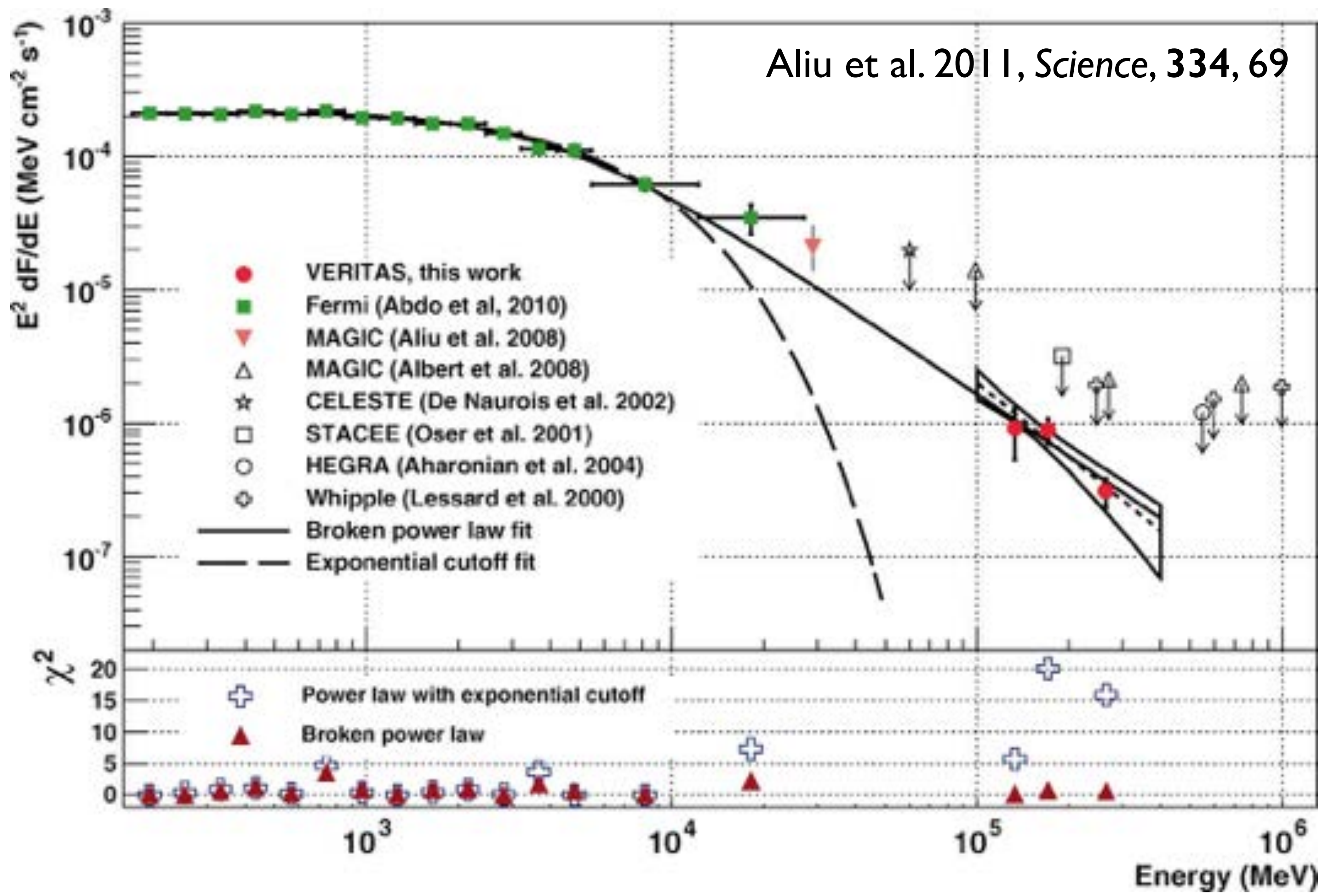


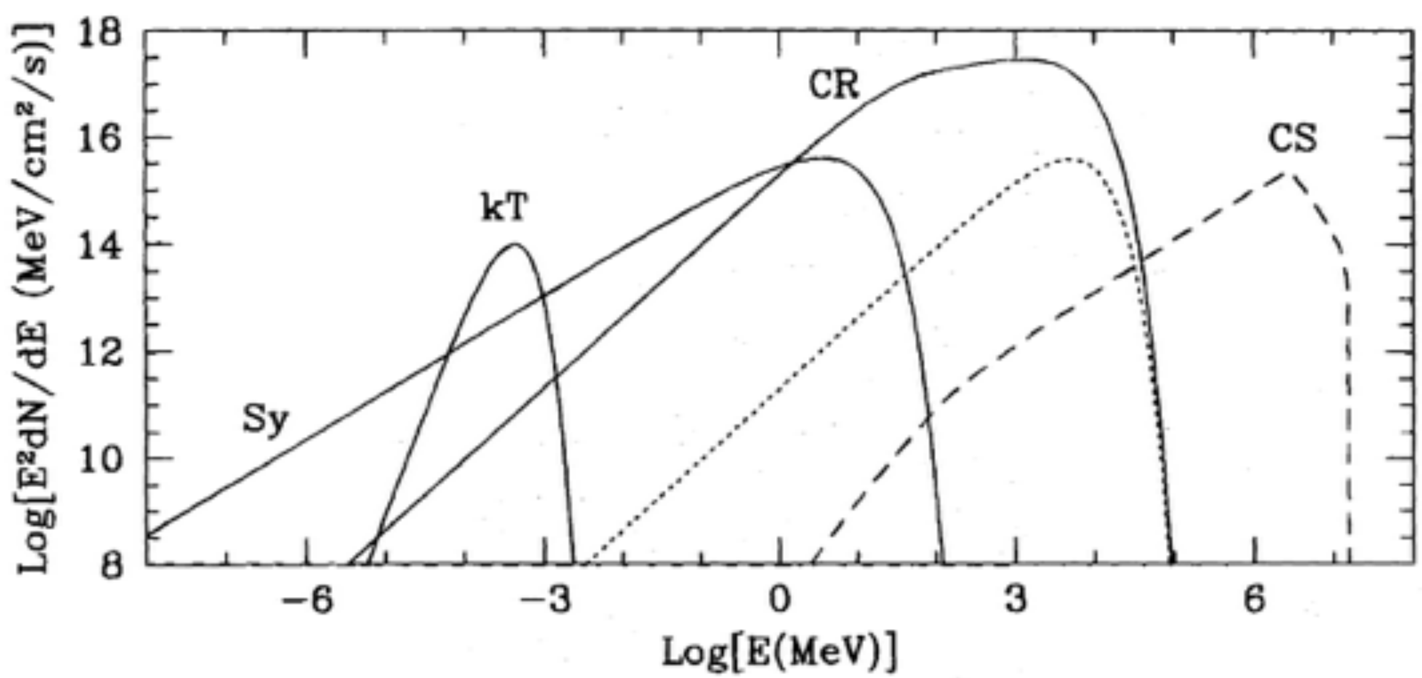


http://phys.org/news/2014-07-hess-ii-reveal-pulsar.html

Pulsars at VHE

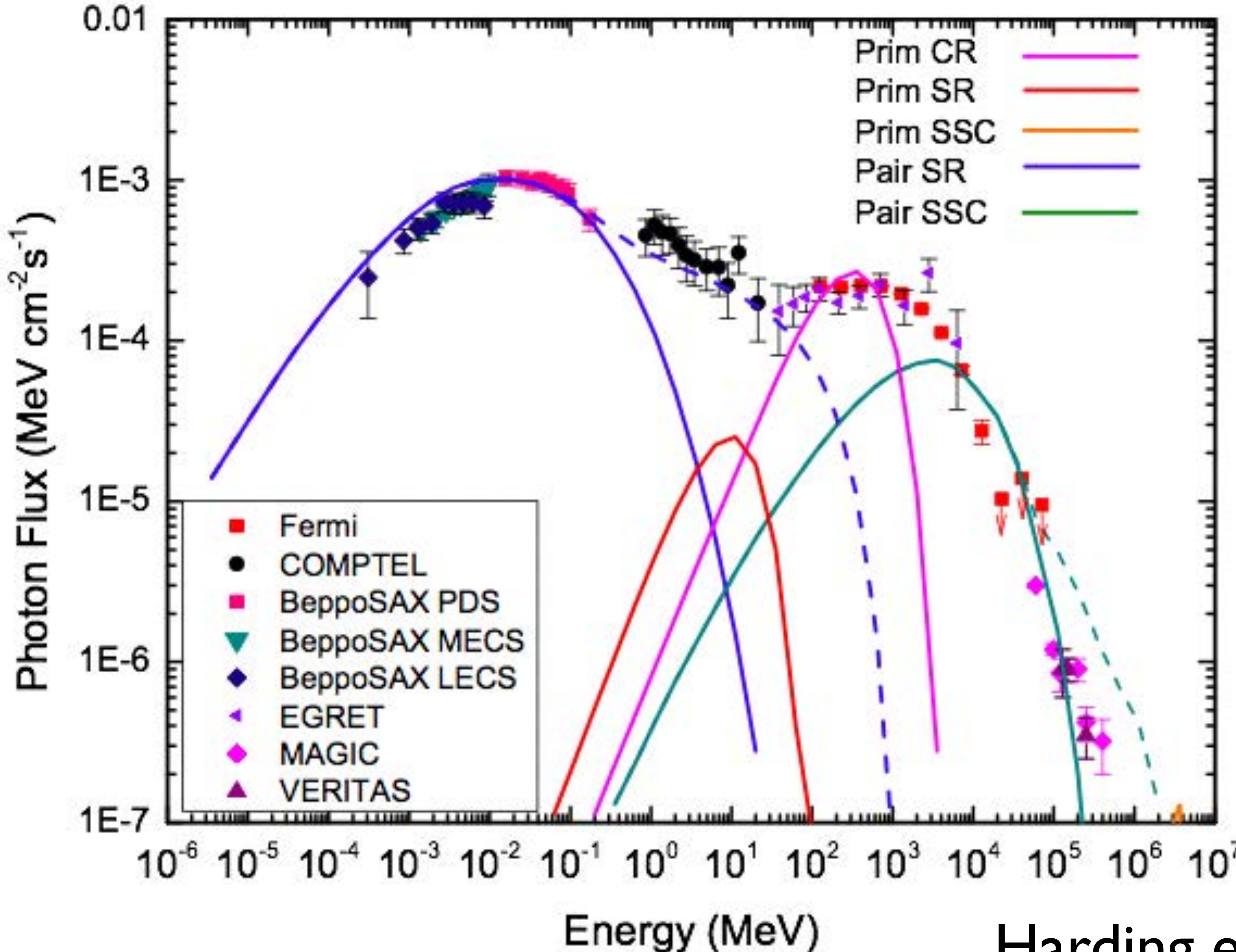
- The Crab pulsar has been detected at > 100 GeV (possibly up to TeV energies)
- The Vela pulsar has been detected by H.E.S.S. up to 70 GeV
- Emission mechanism?
- What about other pulsars?





Romani 1996

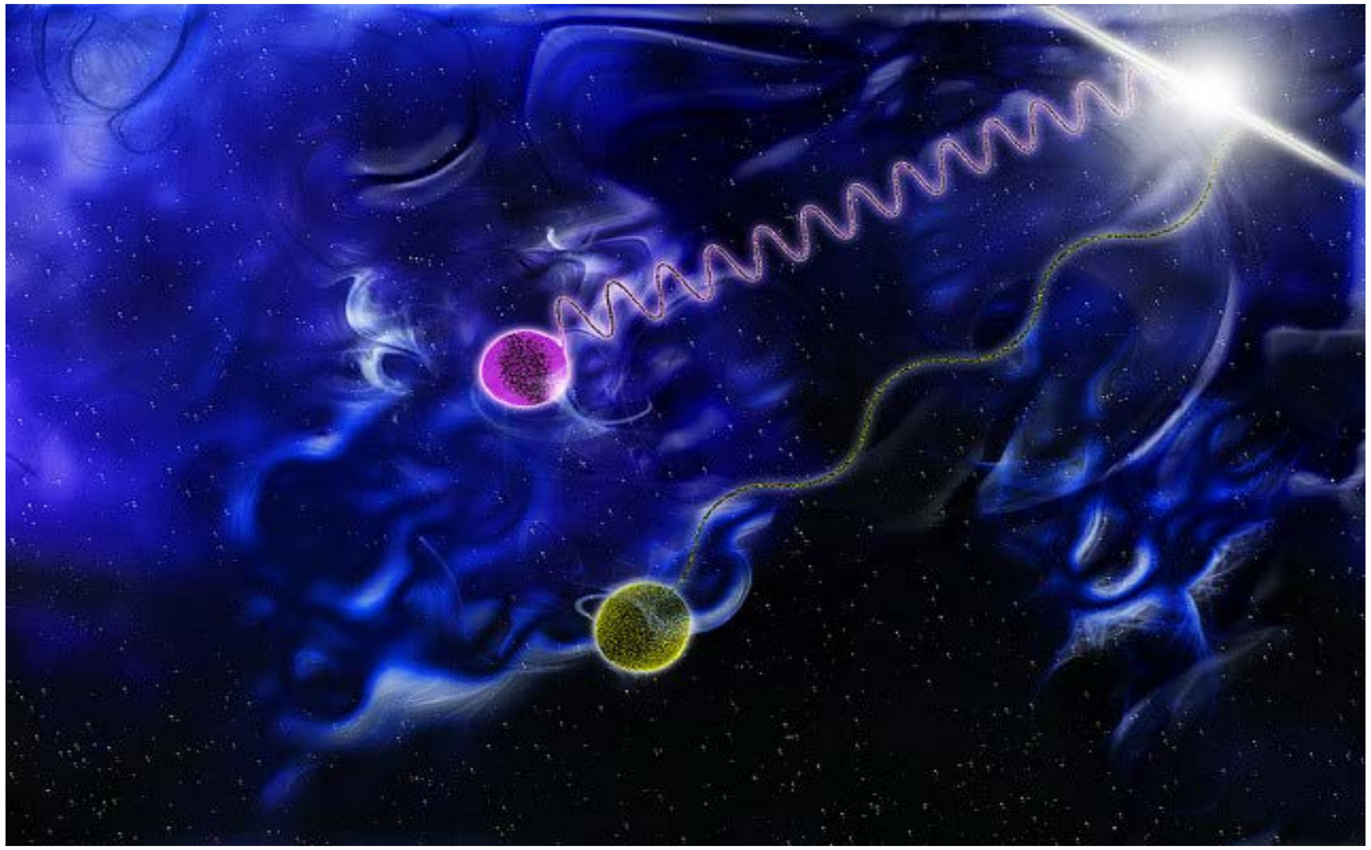
Modeling the Crab with SSC



Harding et al. 2015

Fig. 5.— Model spectra of phase-averaged pulsed emission components from primary electrons and pairs (as labeled) from the Crab pulsar, for magnetic inclination angle $\alpha = 45°$ and observer angle $\zeta = 60°$ and pair multiplicity $M_+ = 3 \times 10^5$. The dashed lines are the SR and SSC spectra resulting from a power law extension to the cascade pair spectrum.

Testing GR with pulsars



Credit: Aurore Simonnet

Search for a possible dispersion of electromagnetic radiation, as might be expected from quantum gravity:

$$c^2p^2 = E^2[1 + f(E/E_{QG})]$$

Kaaret 1999

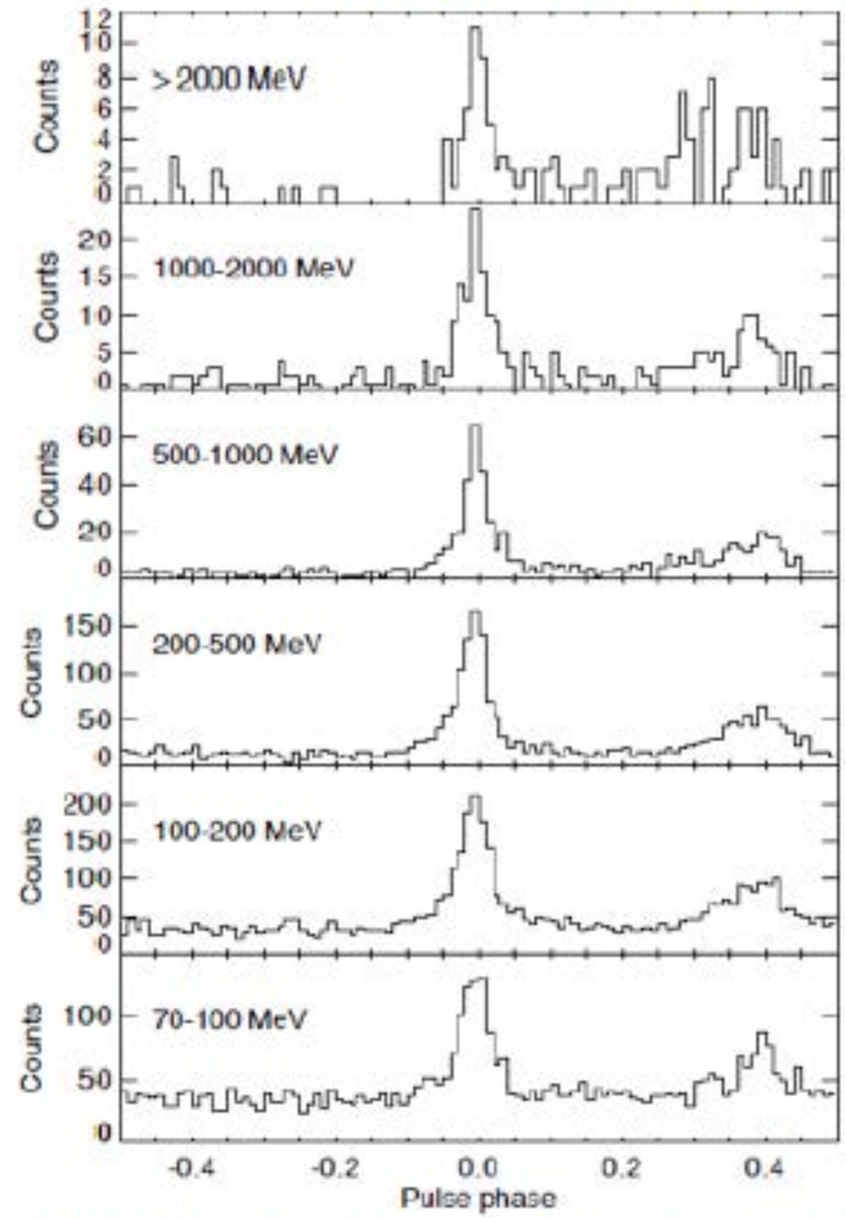


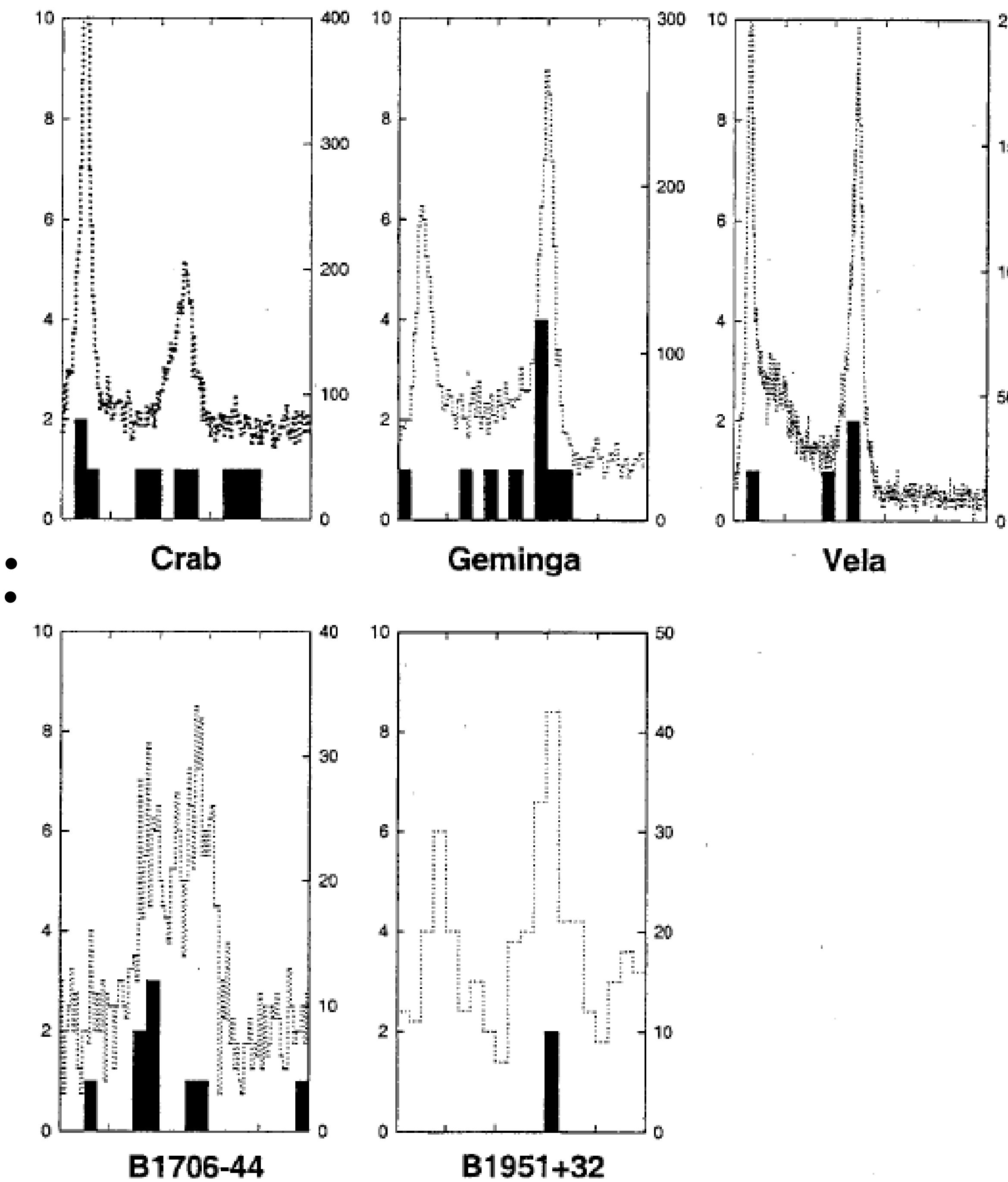
Fig. 1. Crab pulsar phase histograms for various γ-ray energy bands. Zero phase is set by the radio ephemeris.

EGRET (70 MeV - > 2 GeV)

See also Otte 2011

Pulsars above 10 GeV (EGRET)

- Thompson et al. 2004
- ~1500 photons > 10 GeV
- 187 within 1 deg. of a source
- 37 from 5 gamma-ray pulsars:
  - Crab: 10 (7 in peaks)
  - Vela: 4 (all in peaks)
  - Geminga: 10 (5 in peaks)



LAT specifications

LAT Specifications & Performance

Quantity	LAT (Minimim Spec.)	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area [1]	> 8000 cm^2	1500 cm^2
Field of View	> 2 sr	0.5 sr
Angular Resolution [2]	< 3.5° (100 MeV) < 0.15° (>10 GeV)	5.8° (100 MeV)
Energy Resolution [3]	< 10%	10%
Deadtime per Event	< 100 μs	100 ms
Source Location Determination [4]	< 0.5'	15'
Point Source Sensitivity [5]	$< 6 \times 10^{-9}$ cm^{-2} s^{-1}	$\sim 10^{-7}$ cm^{-2} s^{-1}

[1] After background rejection

[2] Single photon, 68% containment, on-axis

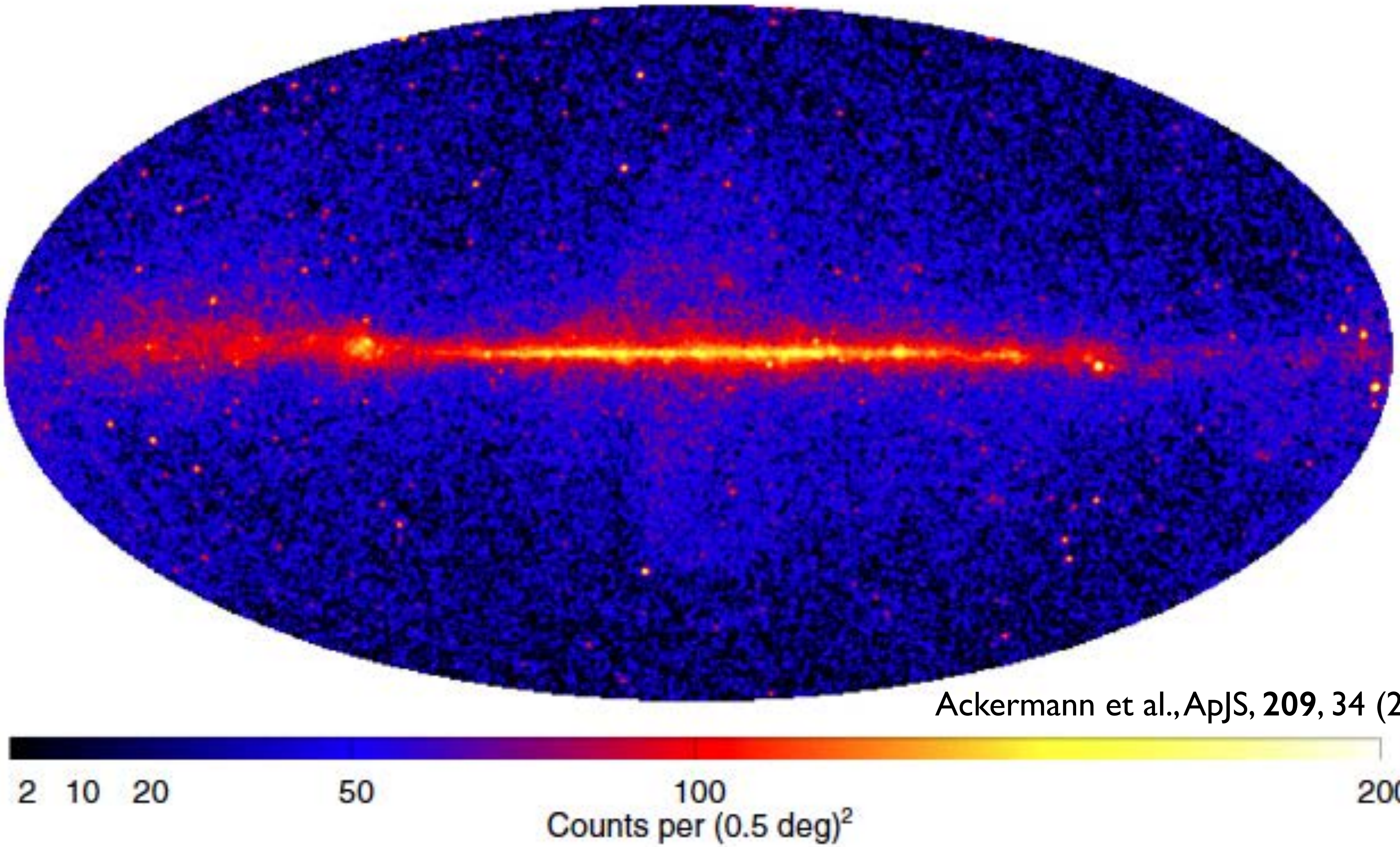
[3] 1-σ, on-axis

[4] 1-σ radius, flux 10^{-7} cm^{-2} s^{-1} (>100 MeV), high |*b*|

[5] > 100 MeV, at high |*b*|, for exposure of one-year all sky survey, photon spectral index -2

http://fermi.gsfc.nasa.gov/ssc/

Fermi LAT Catalog of Sources Above 10 GeV (1FHL)



Ackermann et al., ApJS, **209**, 34 (2013)

The 1FHL Catalog

- 36 Months, P7V6 Clean, E>10 GeV
- Locations, spectra, variability, associations
- 514 sources
  - 393 (76%) associated with AGN
  - 65 (13%) unassociated
  - *27 (5%) associated with pulsars -> how many identified (HPSR)?*
- Ackerman et al., ApJS **209**, 34 (Dec 2013)

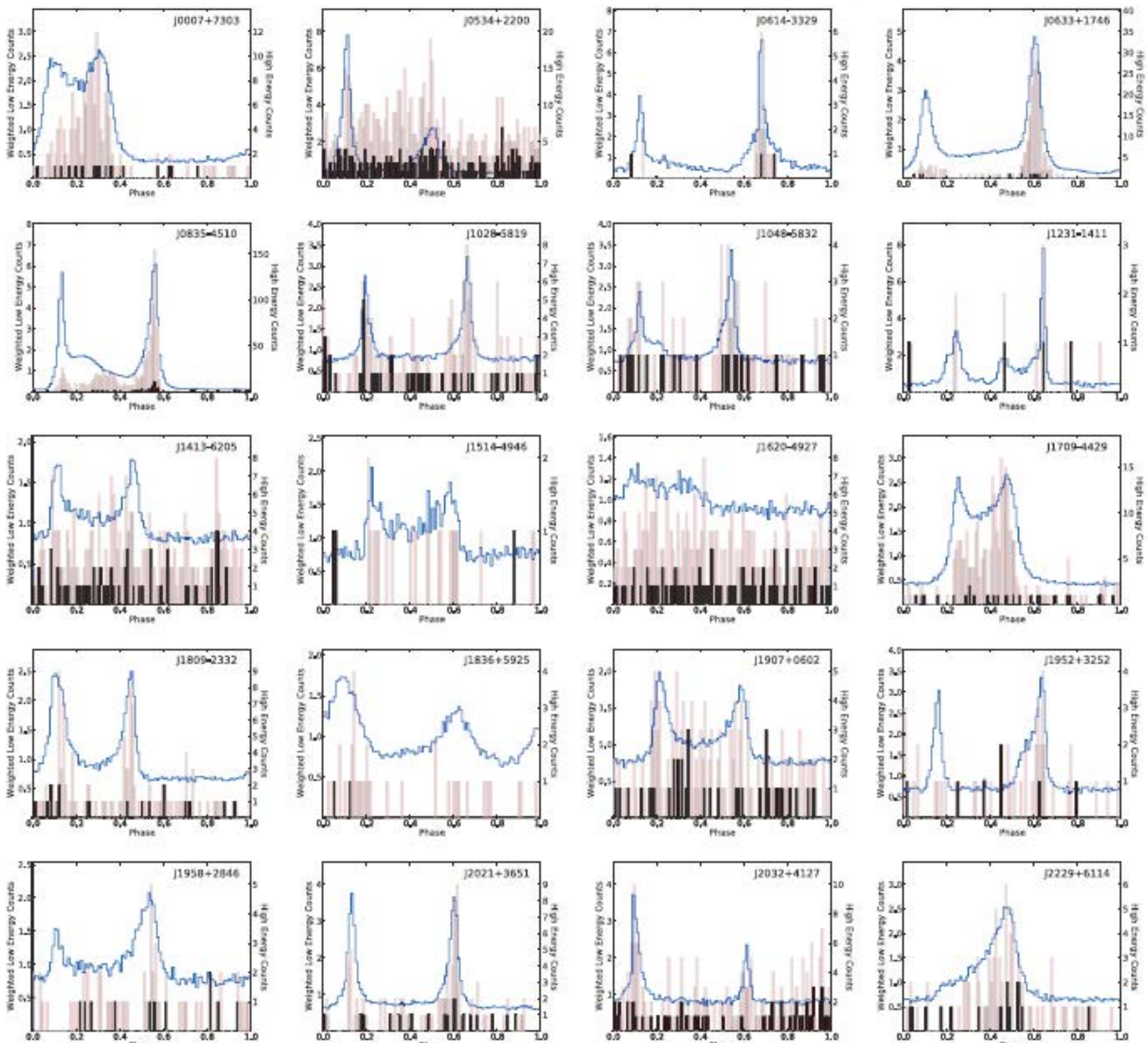
Pulsar associations in 1FHL

- 27 1FHL sources associated with pulsars
- 25 associated with 2PC pulsars (all except J2339-0533 and J1536-4948)
  - 5 EGRET pulsars
  - 7 young (non-recycled) radio-selected
  - 10 young gamma-selected
  - 3 gamma-ray MSPs

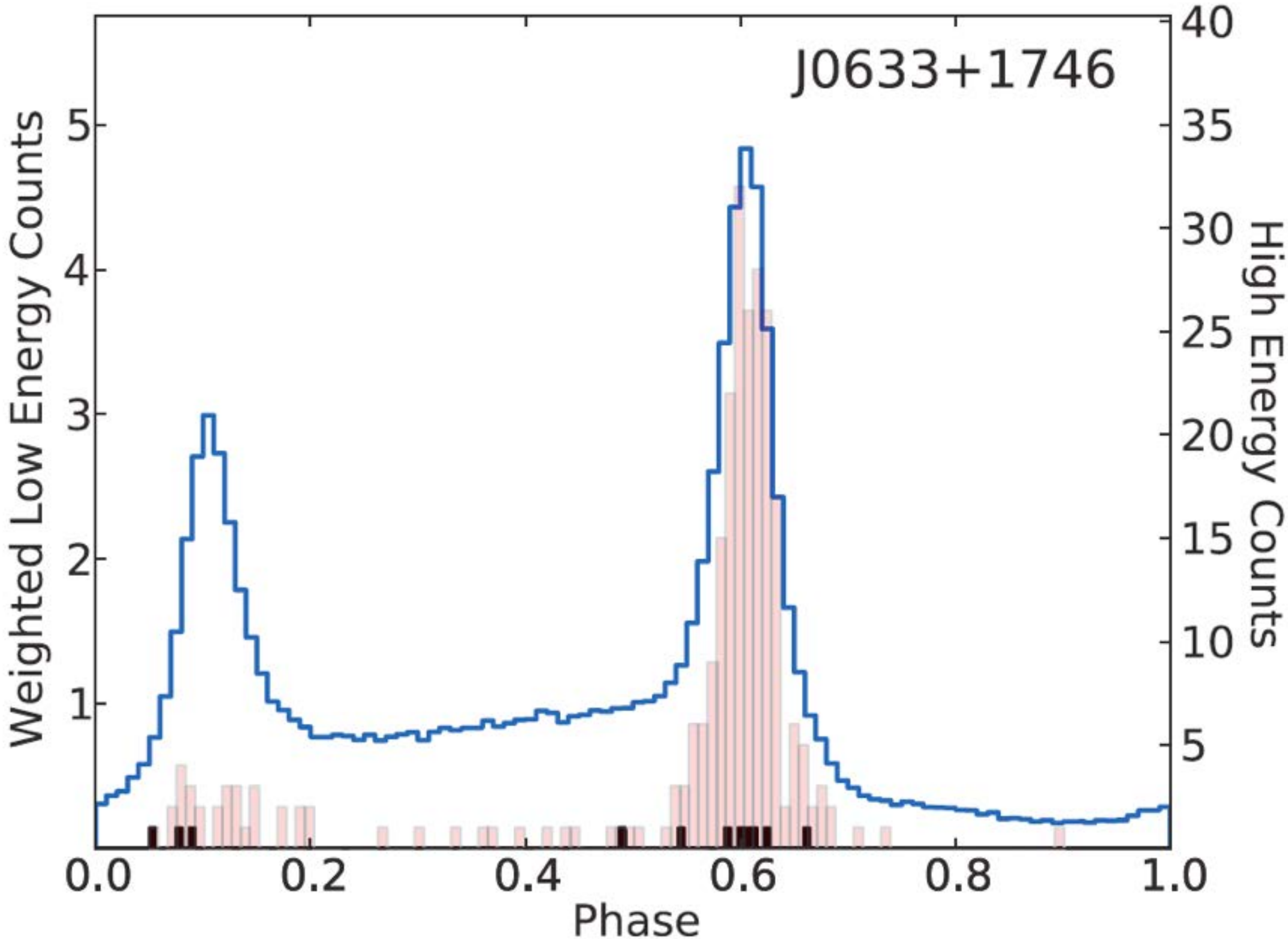
Q: Does the > 10 GeV emission come from the pulsar?

A: Test for pulsations using prior low-energy information

The 1FHL Catalog

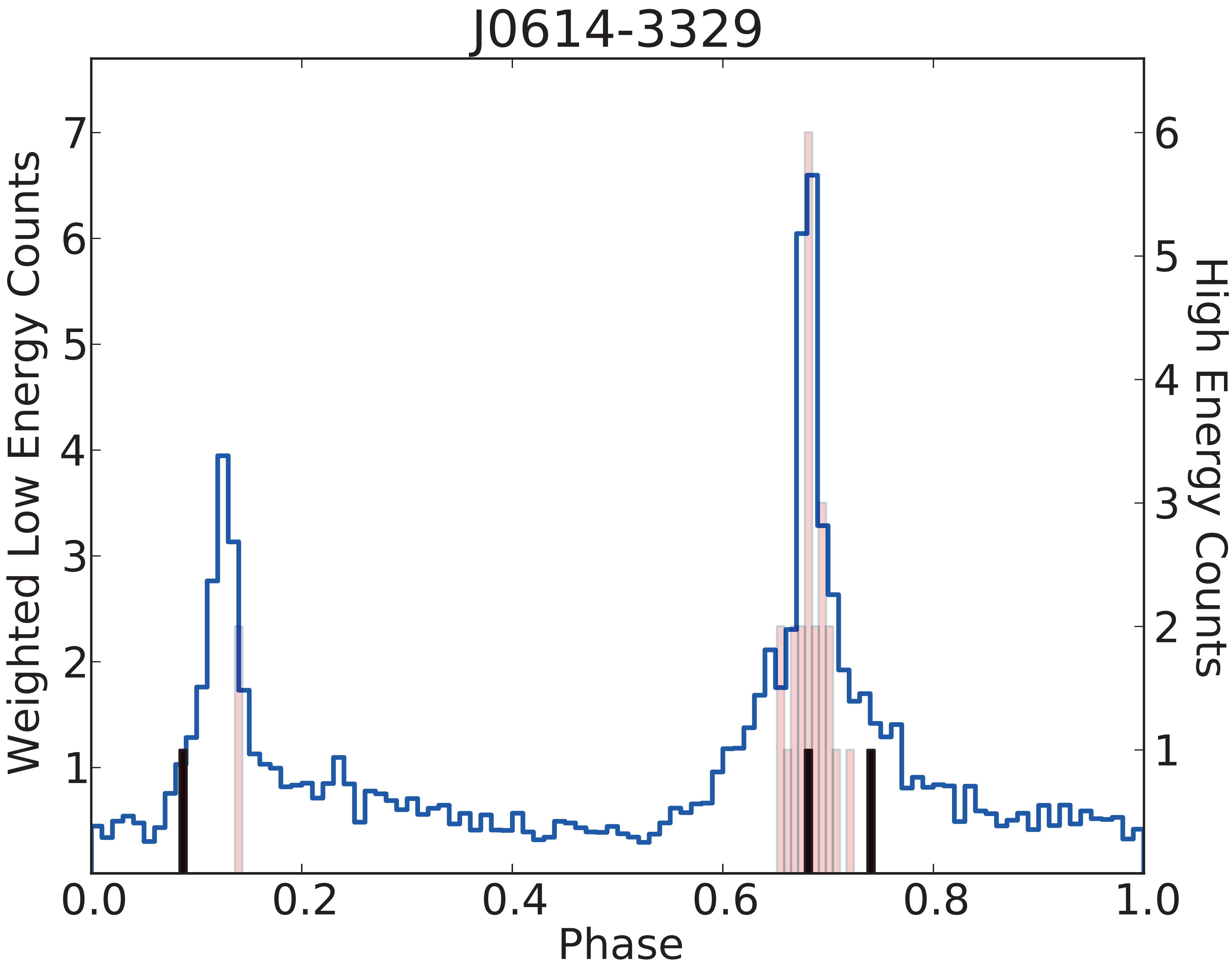


Geminga



J0633+1746
Weighted Low Energy Counts
High Energy Counts
Phase
0.0
0.2
0.4
0.6
0.8
1.0
1
2
3
4
5
5
10
15
20
25
30
35
40

Not all look that nice …



1FHL gamma-ray pulsars (HPSR)

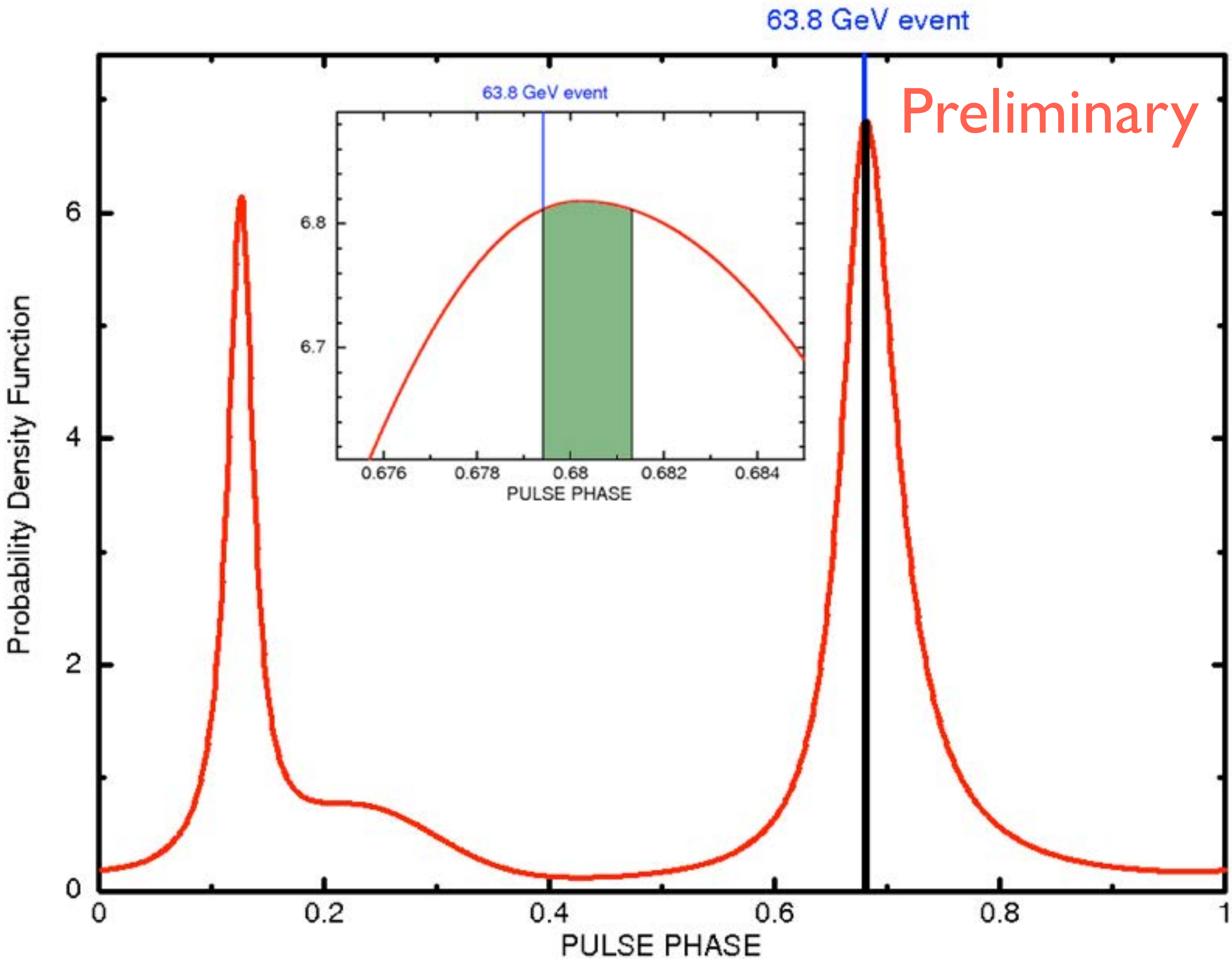
1FHL	PSR	P [ms]	l [deg]	b [deg]	n_{10}	P_{10}	n_{25}	P_{25}	Ref.
J0007.3+7303	**J0007+7303**#	316	119.7	+10.5	179	$< 2 \times 10^{-9}$	20	1.7×10^{-3}	[1, 2, 3]
J0205.7+6448	J0205+6449	65.7	130.7	+3.1	38	> 0.05	12	> 0.05	[4]
J0534.5+2201	**J0534+2200**†#	33.6	184.6	–5.8	674	6.3×10^{-8}	191	2.4×10^{-2}	Crab [5, 6, 7]
J0614.0–3325	**J0614–3329**	3.15	240.5	–21.8	26	$< 2 \times 10^{-9}$	3	2.0×10^{-2}	[8]
J0633.9+1746	**J0633+1746**#	237	195.1	+4.3	260	$< 2 \times 10^{-9}$	11	1.4×10^{-5}	Geminga [9]
J0835.3–4510	**J0835–4510**†#	89.4	263.6	–2.8	1005	$< 2 \times 10^{-9}$	56	$< 2 \times 10^{-9}$	Vela [10, 11]
J1022.6–5745	J1023–5746	112	284.2	–0.4	152	> 0.05	46	> 0.05	[12]
J1028.4–5819	**J1028–5819**#	91.4	285.1	–0.5	164	$< 2 \times 10^{-9}$	41	4.0×10^{-2}	[13]
J1048.4–5832	**J1048–5832**	124	287.4	+0.6	85	9.7×10^{-6}	22	2.1×10^{-2}	[14]
J1112.5–6105	J1112–6103	65.0	291.2	–0.5	112	> 0.05	28	> 0.05	
J1231.2–1414	J1231–1411	3.68	295.5	+48.4	15	5.3×10^{-7}	4	> 0.05	[8]
J1413.4–6205	**J1413–6205**	110	312.4	–0.7	278	4.4×10^{-3}	64	1.5×10^{-2}	[12]
J1418.6–6059	J1418–6058	111	313.3	+0.1	324	> 0.05	72	> 0.05	[2]
J1420.1–6047	J1420–6048	68.2	313.5	+0.2	278	> 0.05	65	> 0.05	[15]
J1514.3–4945	J1514–4946	3.58	325.2	+6.8	24	1.7×10^{-4}	3	> 0.05	[16]
J1536.4–4951	J1536–4948	3.08	328.2	+4.8	...	...	...	...	Not in 2PC
J1620.7–4928	J1620–4927	172	333.9	+0.4	297	9.4×10^{-3}	77	> 0.05	[17]
J1709.7–4429	J1709–4429#	103	343.1	–2.7	272	$< 2 \times 10^{-9}$	25	> 0.05	[18]
J1809.8–2329	**J1809–2332**	147	7.4	–2.0	119	$< 2 \times 10^{-9}$	18	4.3×10^{-2}	[2]
J1836.4+5925	**J1836+5925**	173	88.9	+25.0	36	1.0×10^{-4}	2	1.0×10^{-2}*	[2, 19]
J1907.7+0600	J1907+0602#	107	40.2	–0.9	158	2.3×10^{-4}	36	> 0.05	[2, 20, 21]
J1953.3+3251	J1952+3252	39.5	68.8	+2.8	48	1.2×10^{-5}	7	> 0.05	[18]
J1958.6+2845	J1958+2846	290	65.9	–0.4	64	1.0×10^{-2}	11	> 0.05	[2]
J2021.0+3651	**J2021+3651**#	104	75.2	+0.1	107	$< 2 \times 10^{-9}$	20	7.6×10^{-3}	[21, 22, 23]
J2032.1+4125	J2032+4127#	143	80.2	+1.0	210	5.6×10^{-8}	54	> 0.05	[2, 24]
J2229.0+6114	**J2229+6114**#	51.6	106.7	+3.0	86	$< 2 \times 10^{-9}$	14	6.1×10^{-3}	[14, 25]
J2339.8–0530	J2339–0533	2.88	81.1	–62.4	...	...	...	...	Not in 2PC

Pulsars above 25 GeV

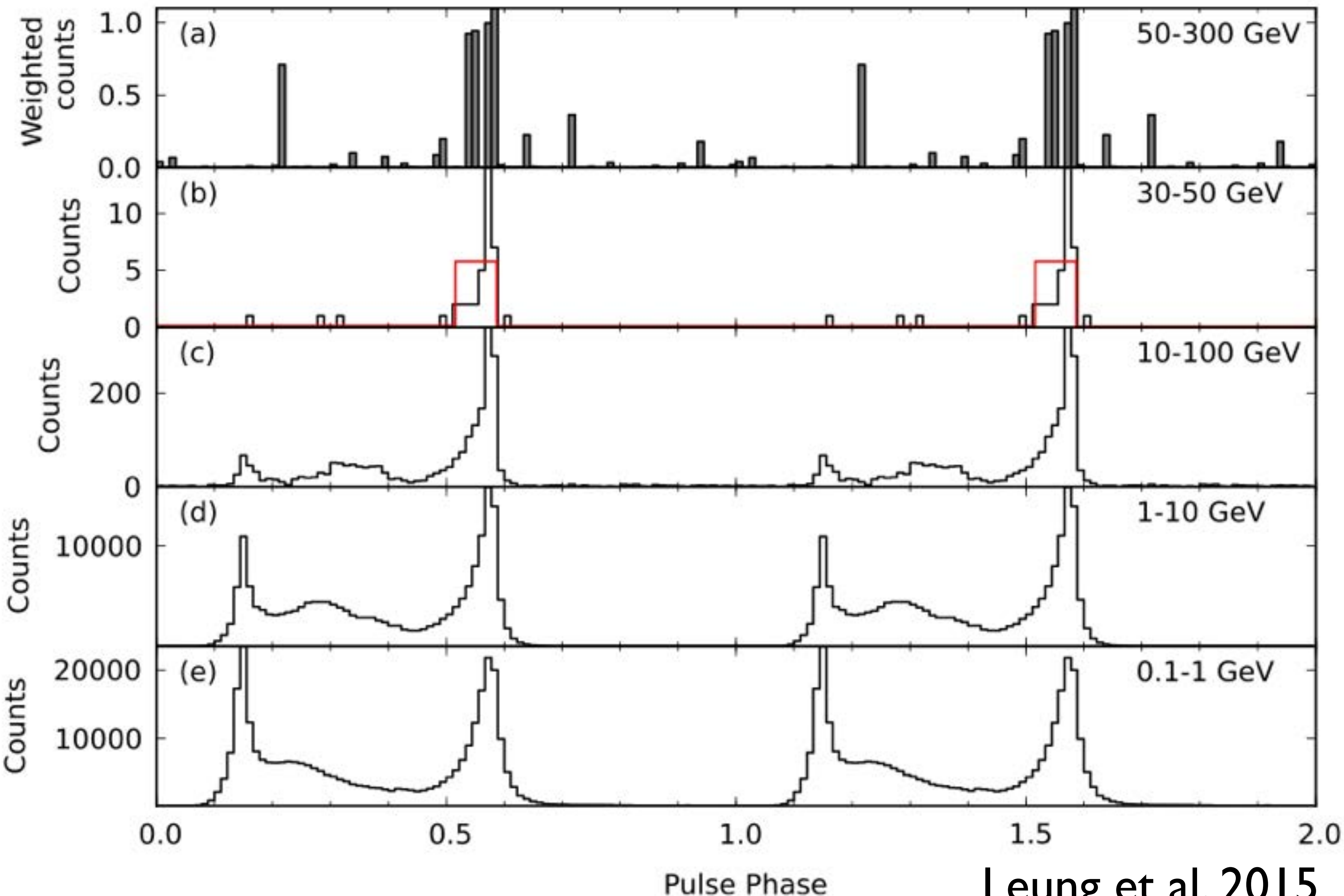
Table 11
Fermi-LAT γ-Ray Pulsars Detected above 25 GeV

PSR	E_{max}	$E_{max}^{detected}$	$\Phi_{\gamma max}$	Notes
J0007+7303[#]	28	788	0.64	
J0534+2200[†#]	26	784	0.33	Crab
J0614–3329	63	63.6	0.68	
J0633+1746[#]	33	52.7	0.05	Geminga
J0835–4510[†#]	37	752	0.28	Vela
J1028–5819	27	386	0.49	
J1048–5832	35	201	0.28	
J1413–6205	29	331	0.28	
J1809–2332	26	159	0.07	
J1836+5925	26	97.9	0.05	
J1954+2836	62	95.7	0.57	
J2021+3651[#]	26	113	0.64	
J2229+6114[#]	31	169	0.17	

63 GeV pulsations?



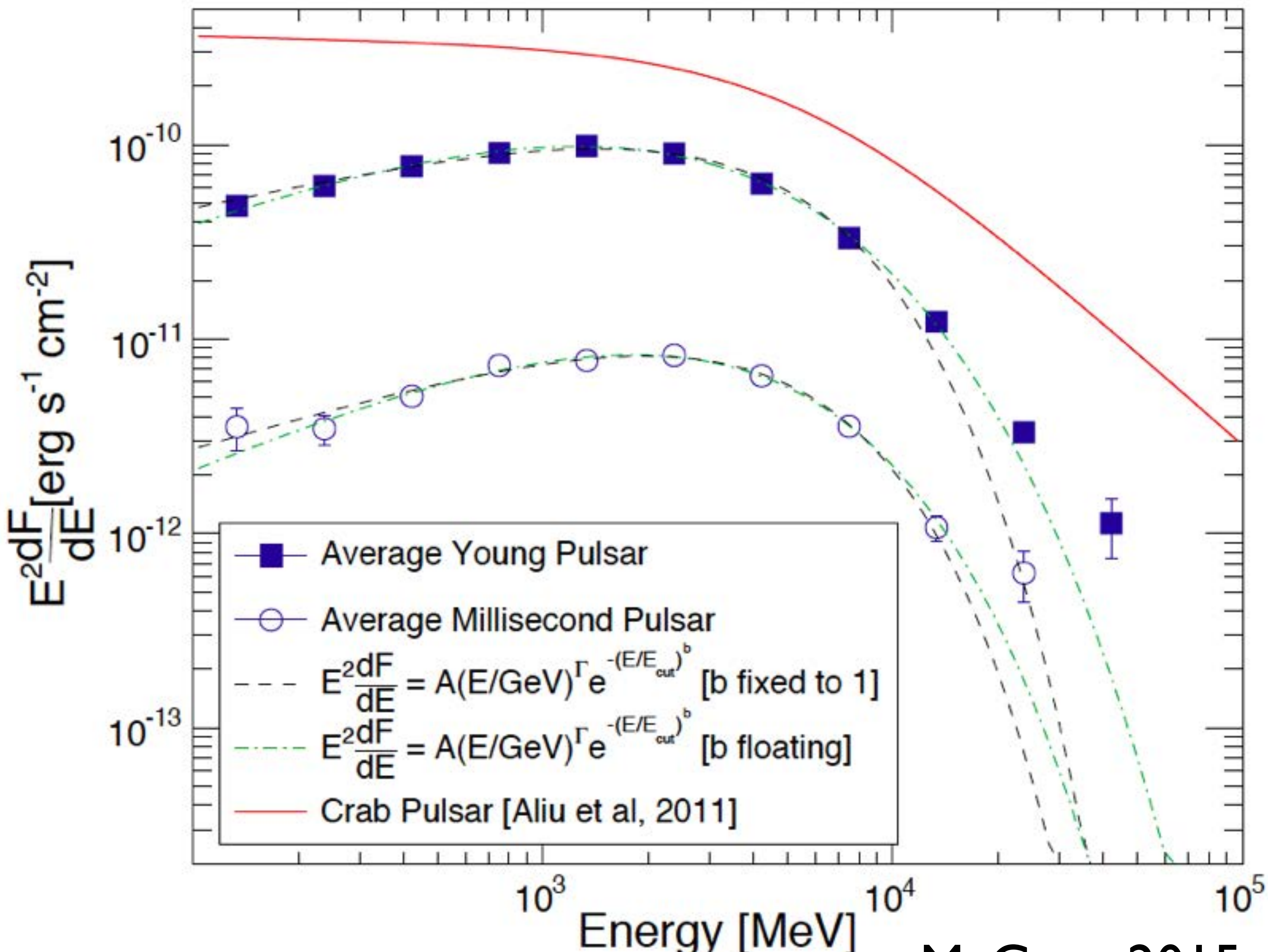
Vela above 50 GeV



Leung et al. 2015

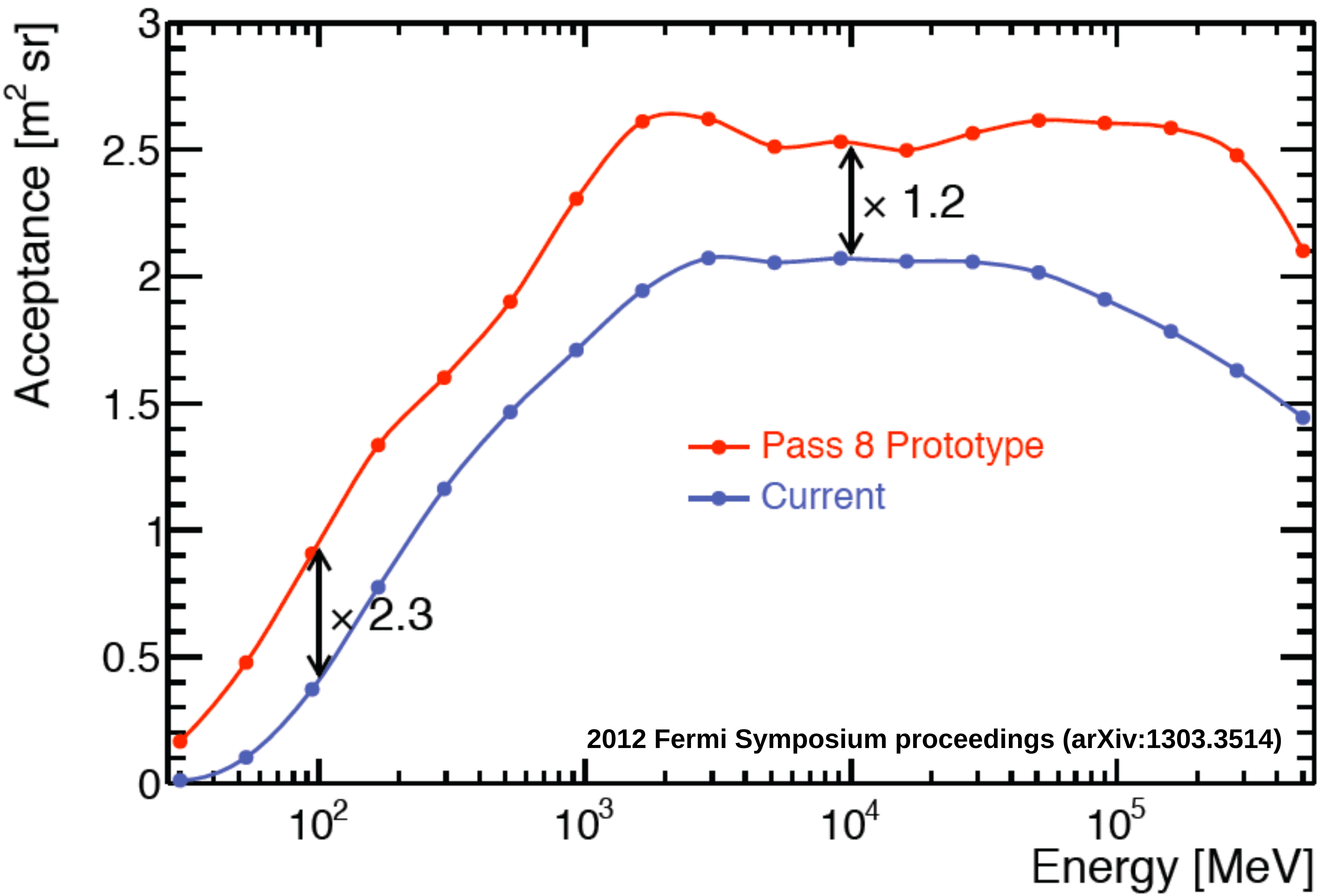
Figure 3. (a) Weighted light curve in 50–300 GeV. (b) Folded light curve in 30–50 GeV with a 0°.4 radius aperture. The black histogram represents the observed counts, the red line represents the Bayesian block decomposition. Folded light curves in (c) 10–100 GeV, (d) 1–10 GeV and (e) 0.1–1 GeV with a 1° radius aperture.

Stacked spectra of pulsars



McCann 2015

Fermi upgrade: Pass 8



2FHL

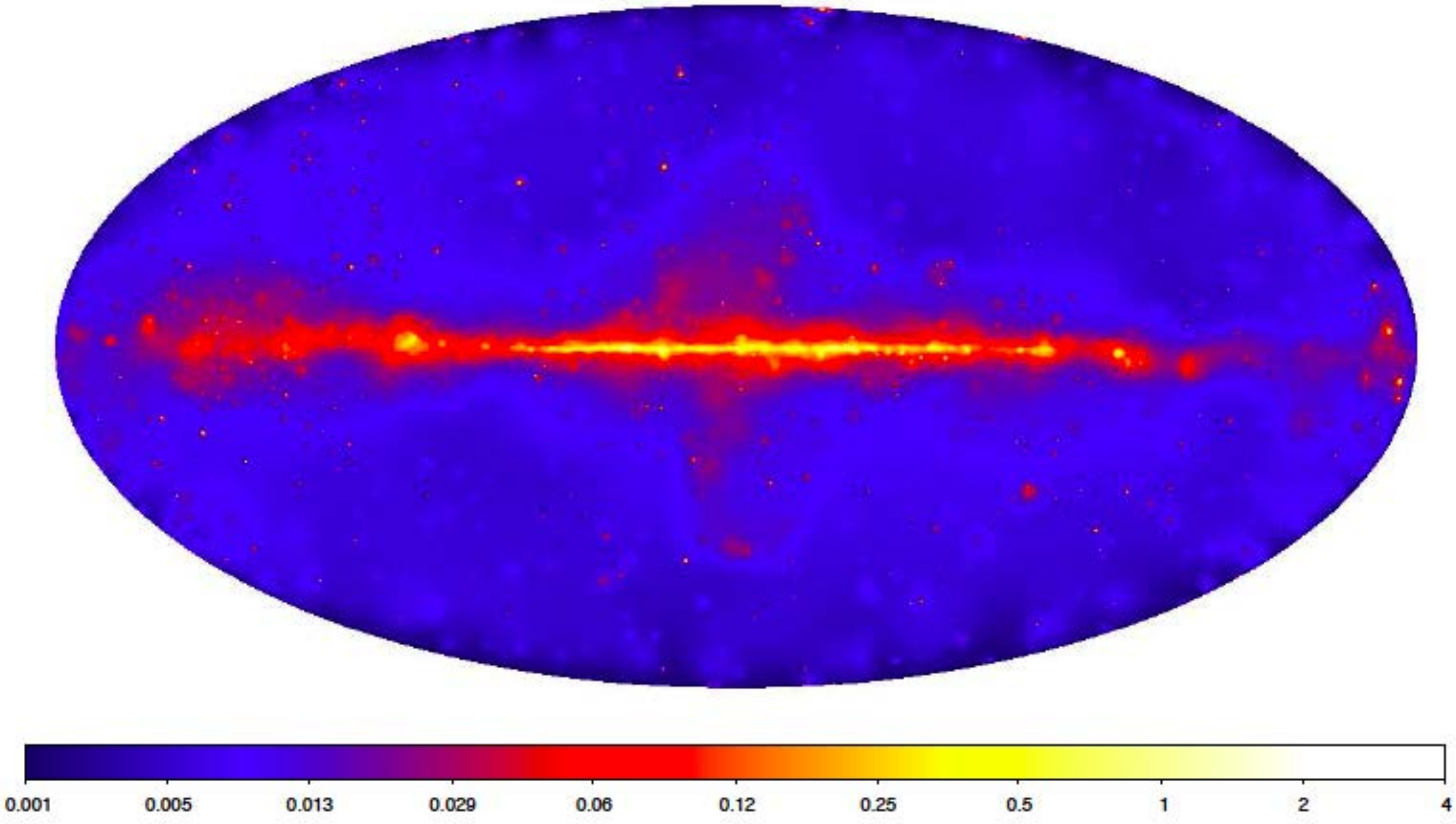


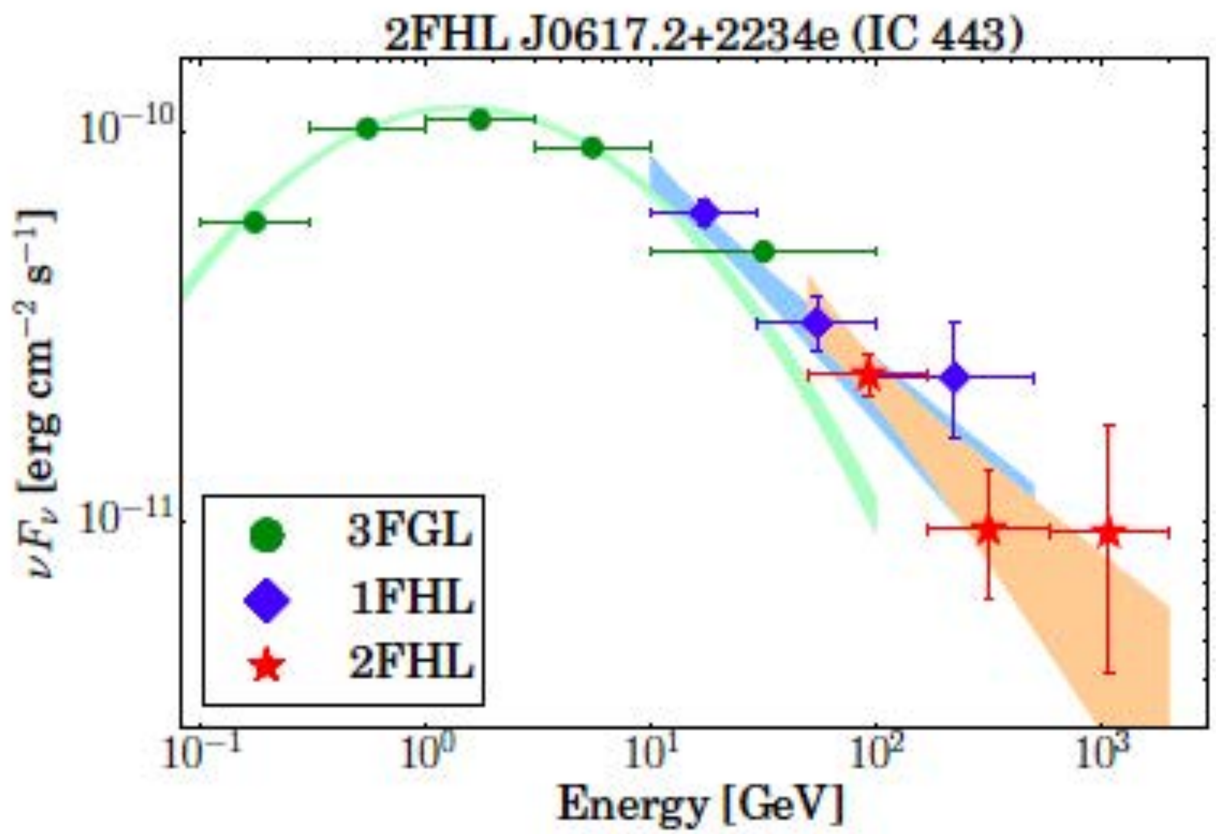
Fig. 1.— Adaptively smoothed count map in the 50 GeV–2 TeV band represented in Galactic coordinates and Hammer-Aitoff projection. The image has been smoothed with a Gaussian kernel whose size was varied to achieve a minimum signal-to-noise ratio under the kernel of 2. The color scale is logarithmic and the units are counts per $(0.1\,\mathrm{deg})^2$.

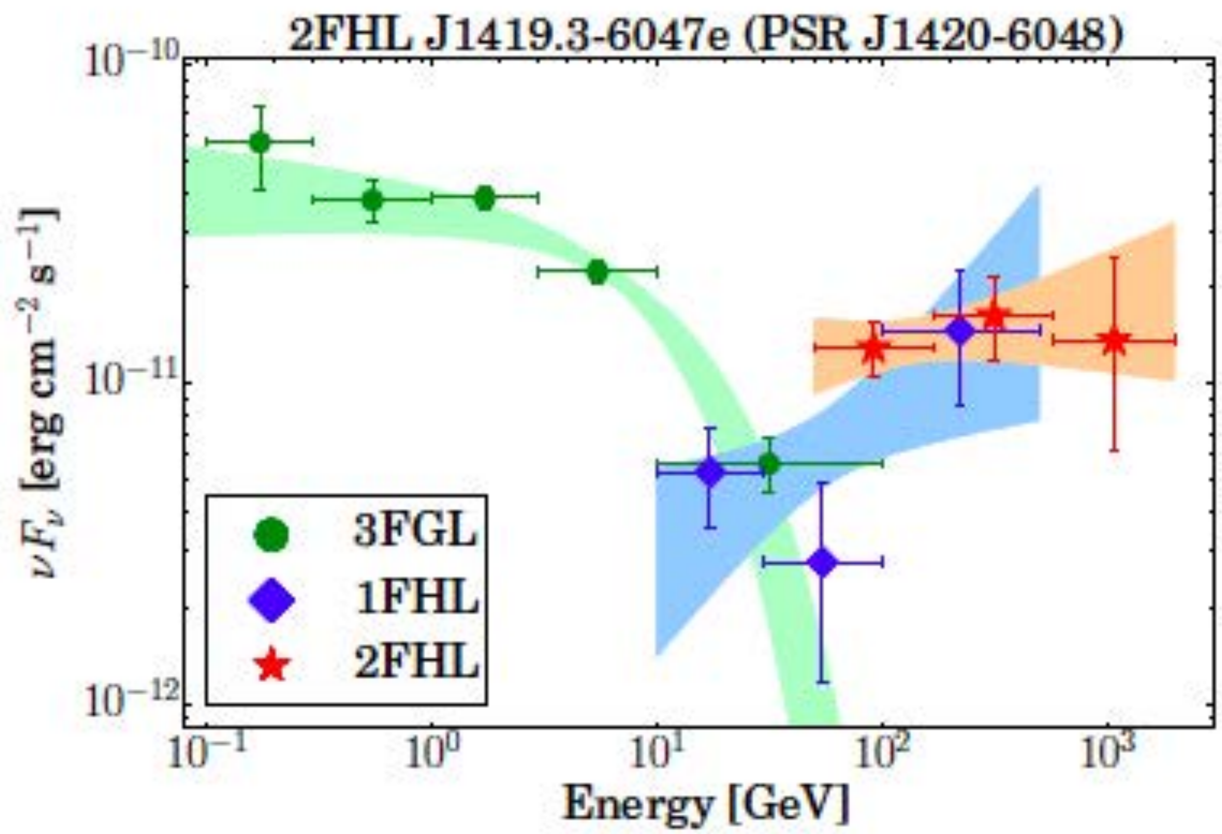
2FHL Source Classes

2FHL Source Classes

Description	Associated Designator	Number
Pulsar	psr	1
Pulsar wind nebula	pwn	14
Supernova remnant	snr	16
Supernova remnant / Pulsar wind nebula	spp	4
High-mass binary	hmb	2
Binary	bin	1
Star-forming region	sfr	1
BL Lac type of blazar	bll	180
BL Lac type of blazar with prominent galaxy emission	bll-g	13
FSRQ type of blazar	fsrq	10
Non-blazar active galaxy	agn	2
Radio galaxy	rdg	4
Radio galaxy / BL Lac	rdg/bll	2
Blazar candidate of uncertain type I	bcu I	7
Blazar candidate of uncertain type II	bcu II	34
Blazar candidate of uncertain type III	bcu III	19
Normal galaxy (or part)	gal	1
Galaxy cluster	galclu	1
Total associated	...	312
Unassociated	...	48
Total in 2FHL	...	360

SNR/PWN in 2FHL





What next with the LAT?

	1FHL	Now
Data span	3 years	~ 7 years
LAT IRFs	Pass 7	Pass 8
# Pulsars investigated	39	~160
Dedicated PWN treatment	No	Yes
Lower Energy Template	>100 MeV	>100 MeV, >1 GeV, Other (TBD)

Summary

- Fermi has greatly improved our knowledge of gamma-rays sources in the 100 MeV-100 GeV energy range
- 28 (12) LAT pulsars have been shown to emit pulsations at >10 (25) GeV
- Recent improvements in Fermi (Pass 8) with the addition of more than twice the amount of data will improve these results significantly
- Ground-based instruments (HESS, MAGIC, VERITAS, HAWC, CTA) are needed to further investigate pulsar emission above 100 GeV

Extra Slides

LIV with pulsars

At small energies $E << E_{QG}$ a series expansion of the dispersion relation should be applicable (Amelino-Camelia et al. 1998)

$$c^2p^2 = E^2[1 + \xi E/E_{QG} + \vartheta(E^2/E_{QG}^2)]$$

- Search for a difference in travel time between photons of different energies:

$$\Delta t = L\Delta E/E_{QG}$$

- We can turn this around, to determine the energy scale which we probe:

$$E_{QG} = \frac{L}{c}\frac{E_h - E_l}{\Delta t}$$

- Note that for the quadratic term of the expansion, we obtain the following:

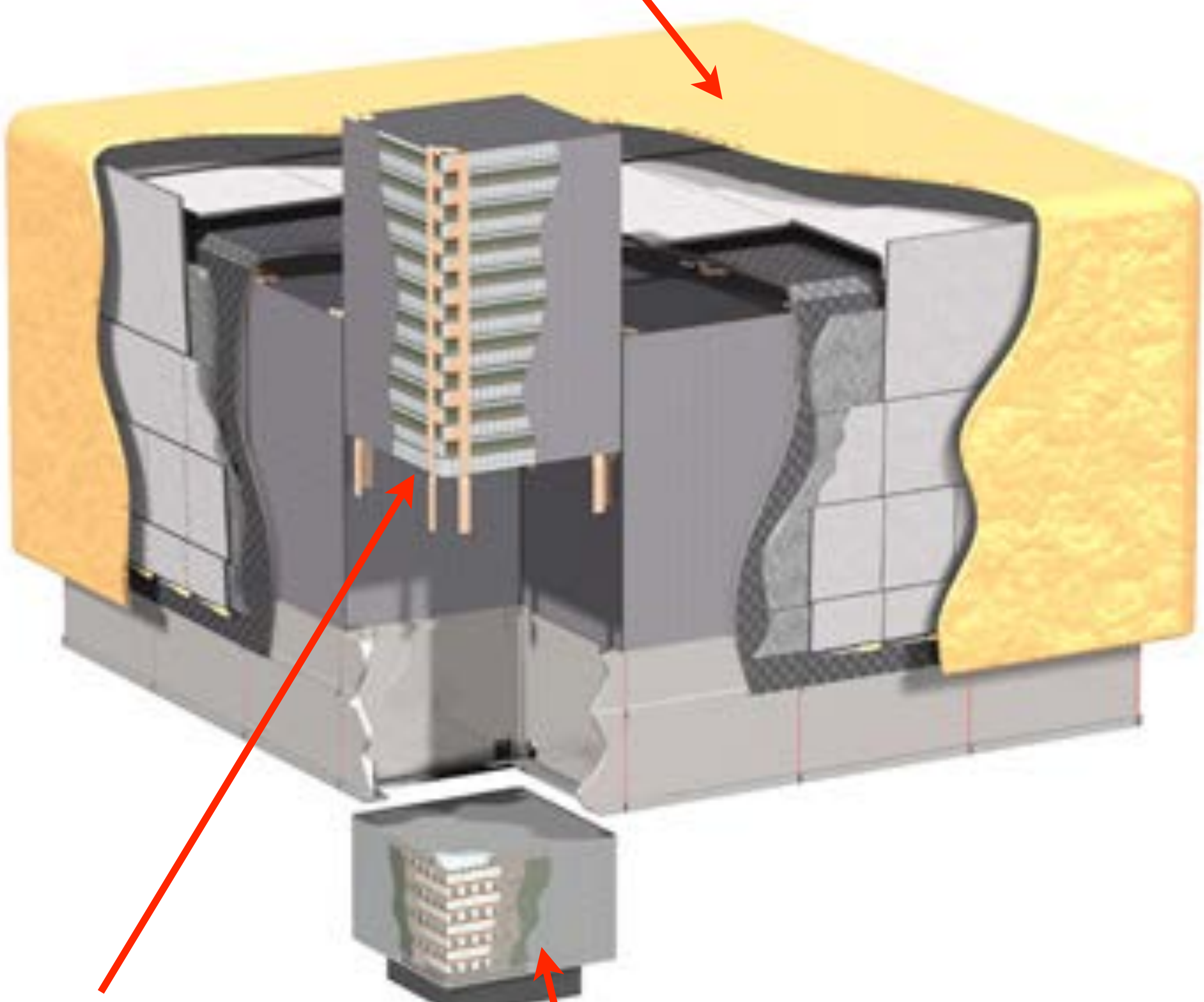
$$E_{QG} = \sqrt{\frac{3L}{2c}\frac{E_h^2 - E_l^2}{\Delta t}}$$

8

$$E_P = \sqrt{\frac{\hbar c^5}{G}} \simeq 1.22 \times 10^{19}\text{GeV}$$

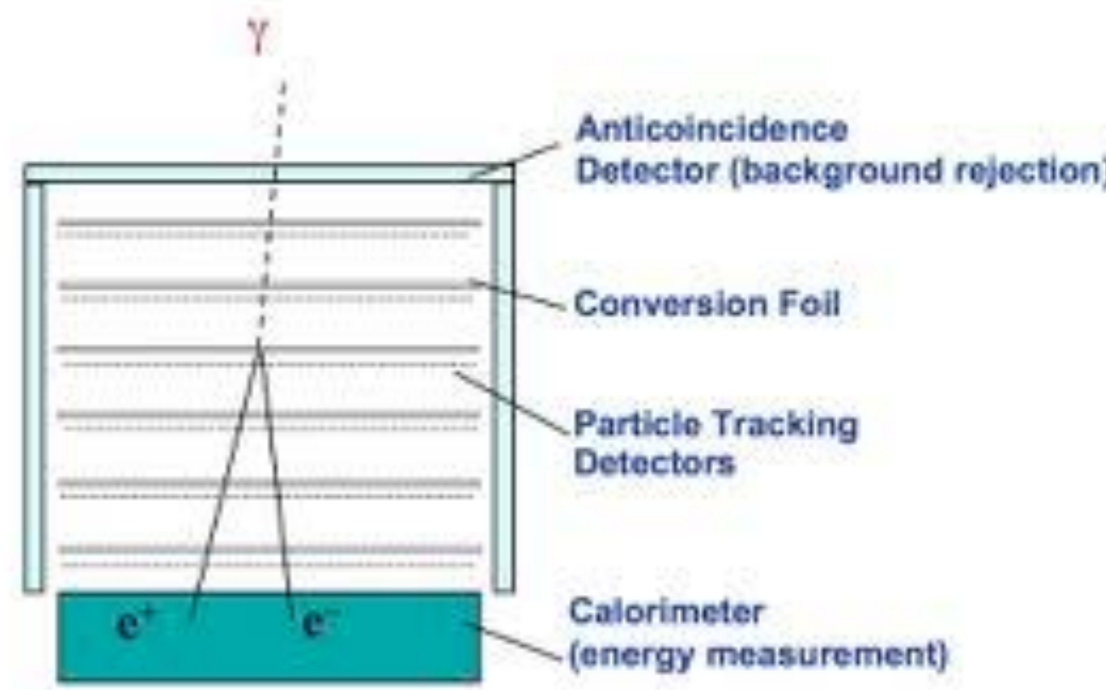
The Large Area Telescope (LAT)

Anti-coincidence Detector



Tracker

Calorimeter



Atwood et al., ApJ, 697, 1071 (2009)