Finding the next VHE pulsar with the Fermi Large Area Telescope

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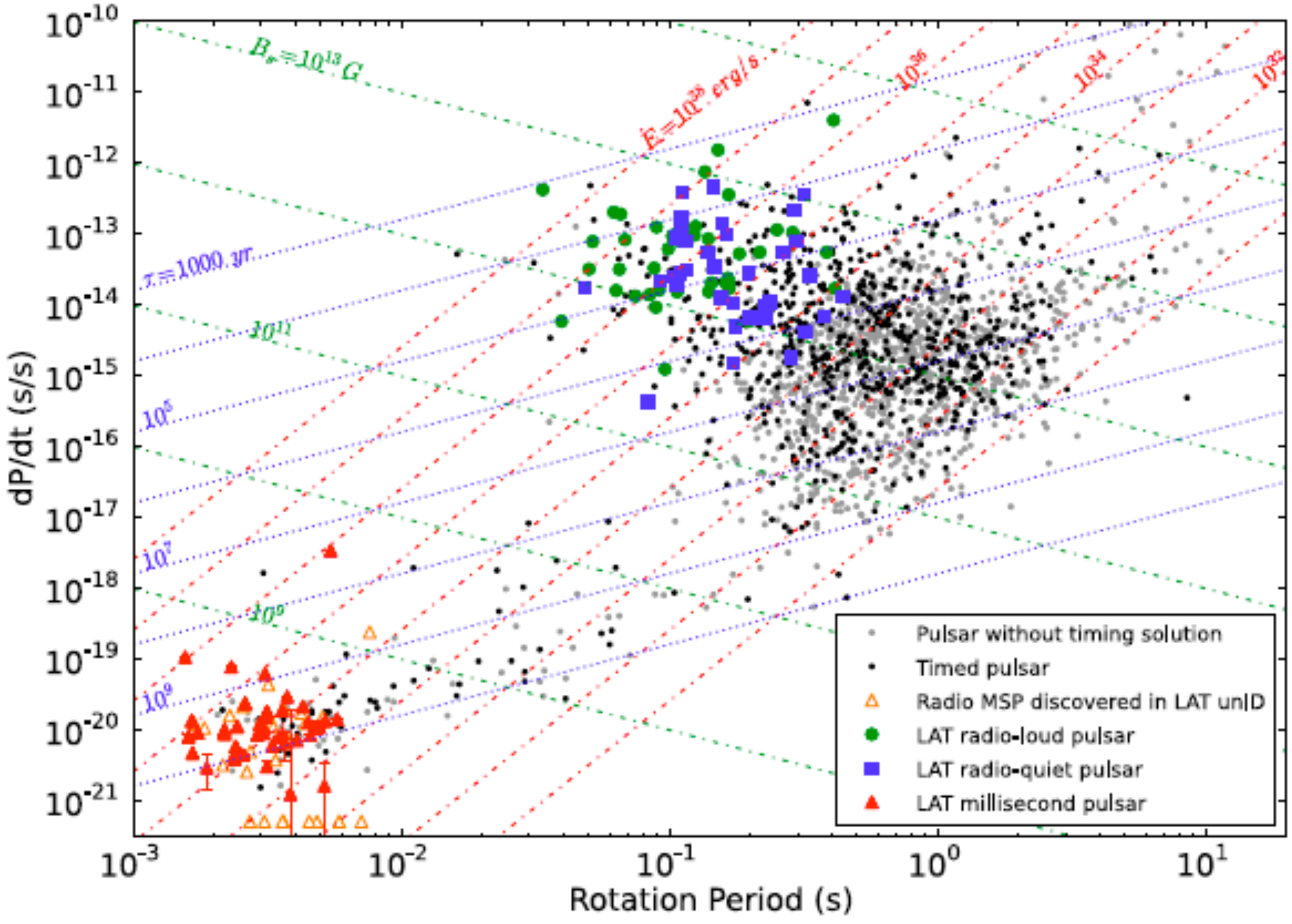
on behalf of the Fermi LAT Collaboration

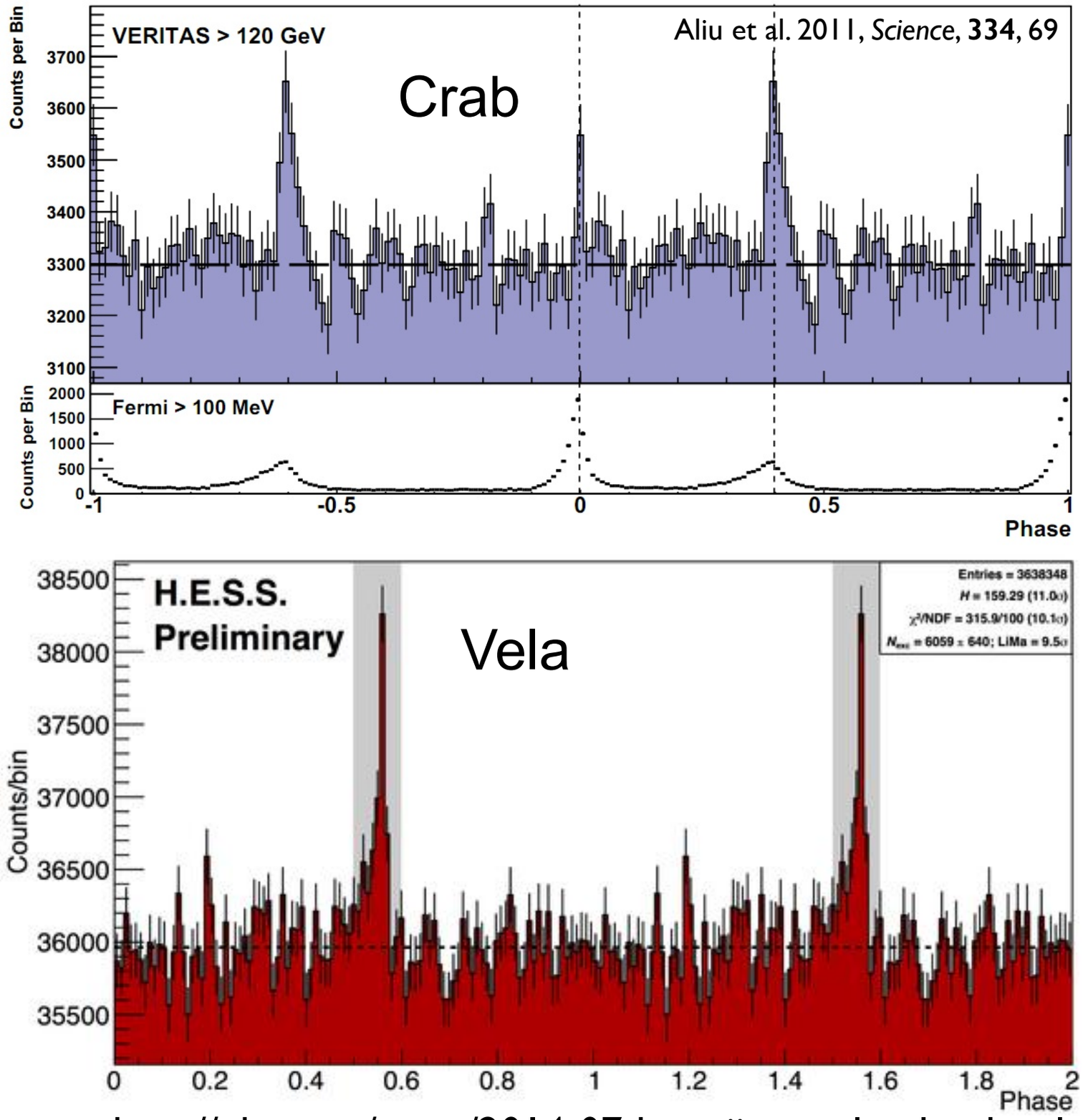
Collaborators: A. Belfiore, M. Kerr, S. Ransom, etc.

Sixth International Fermi Symposium
Arlington, VA, 11 November 2015

Gamma-ray pulsar population



Pulsars at VHE



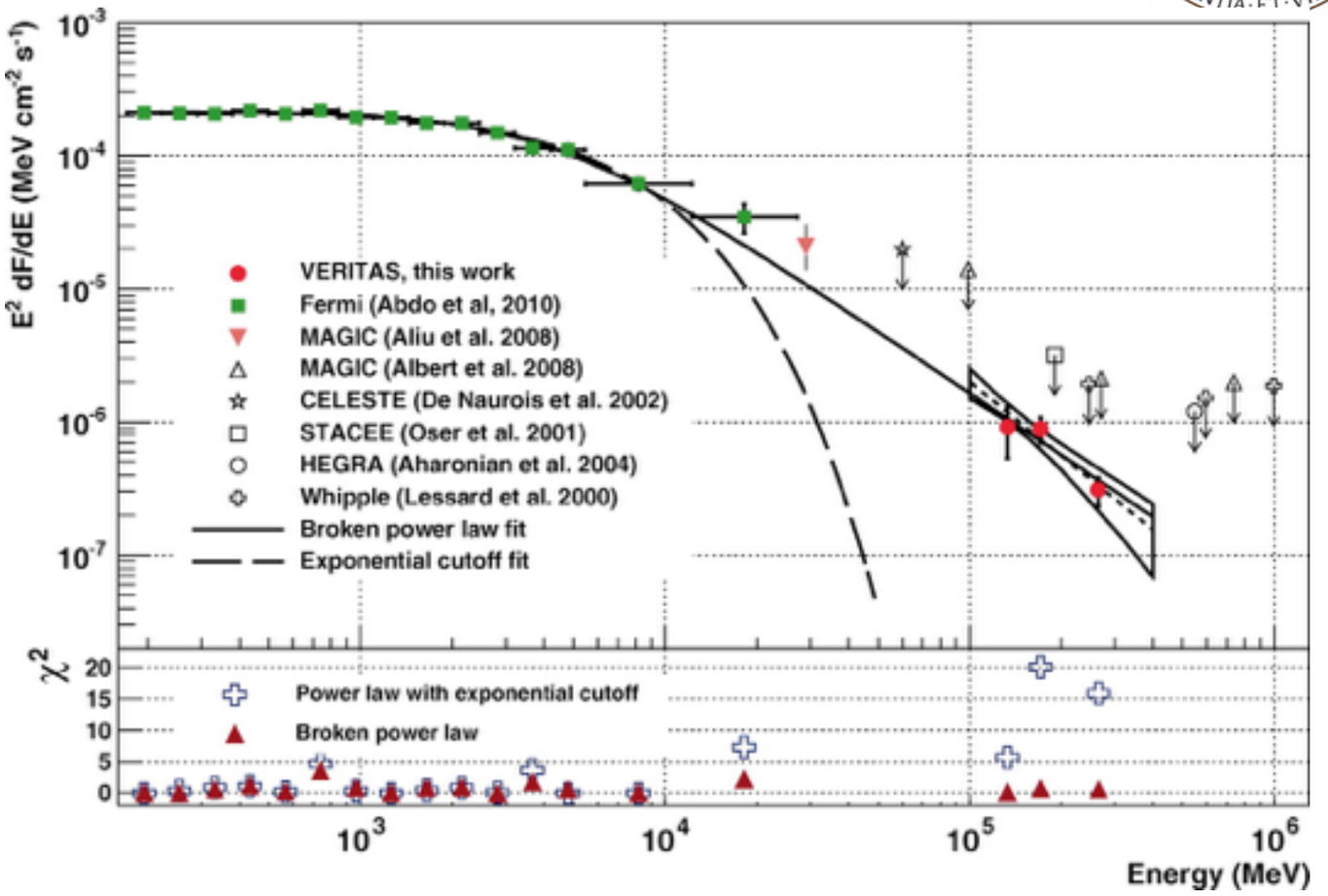
cf. Talk by B. Rudak

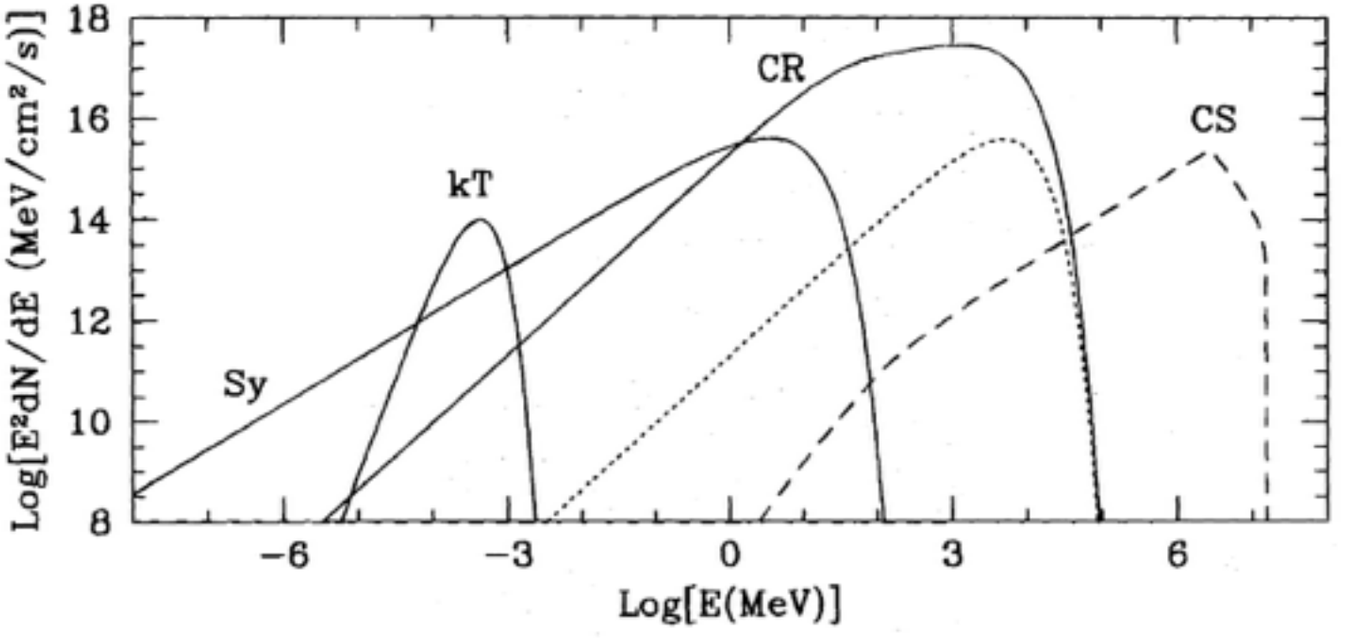
http://phys.org/news/2014-07-hess-ii-reveal-pulsar.html

Pulsars at VHE

- The Crab was the first pulsar detected at > 100 GeV
- The Vela pulsar has now been detected up to 120 GeV
- Emission mechanism? (cf. A. Harding talk)
- What about other pulsars?

cf. Poster by S. Bonnefoy on Geminga





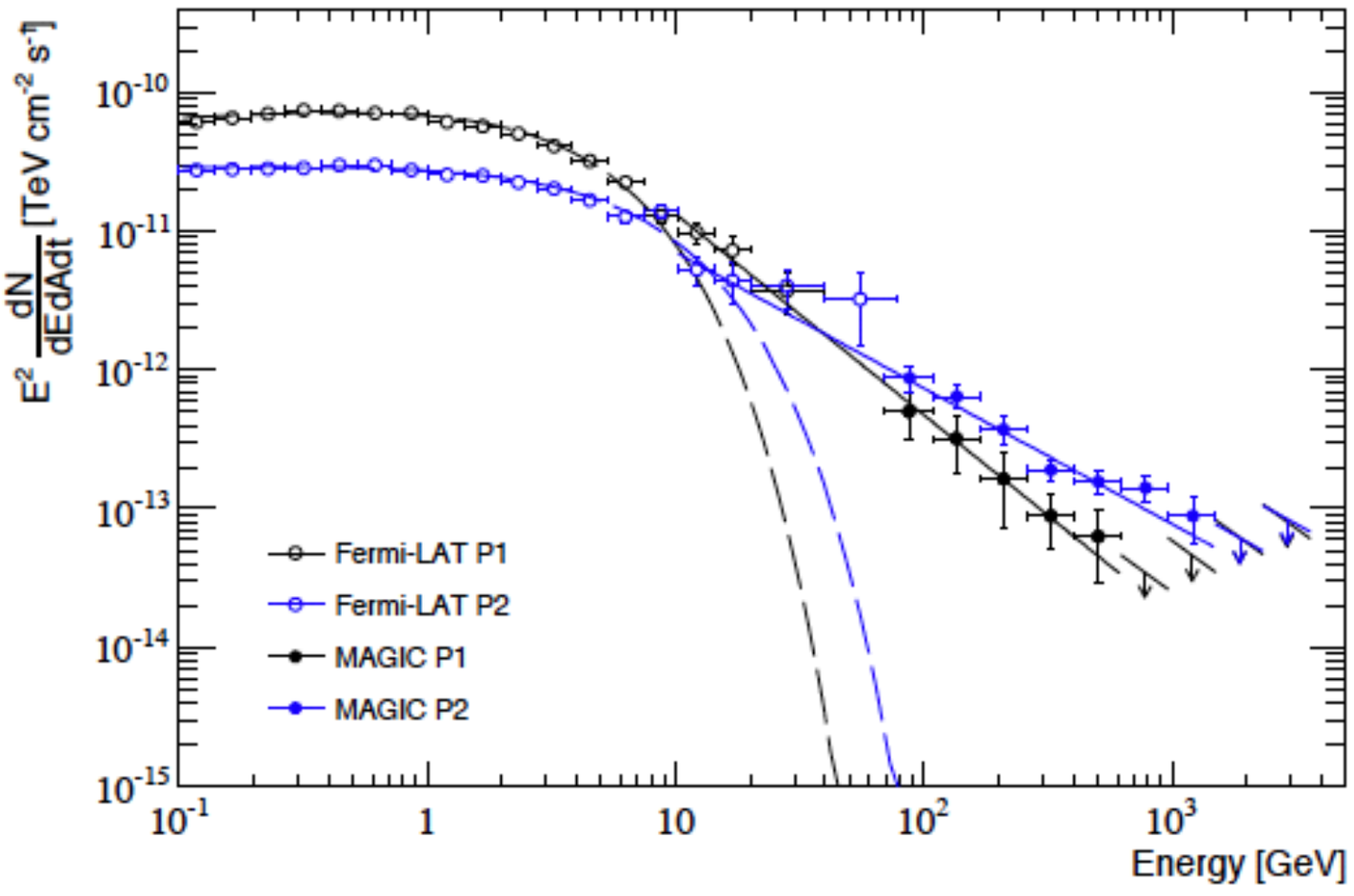
Romani 1996

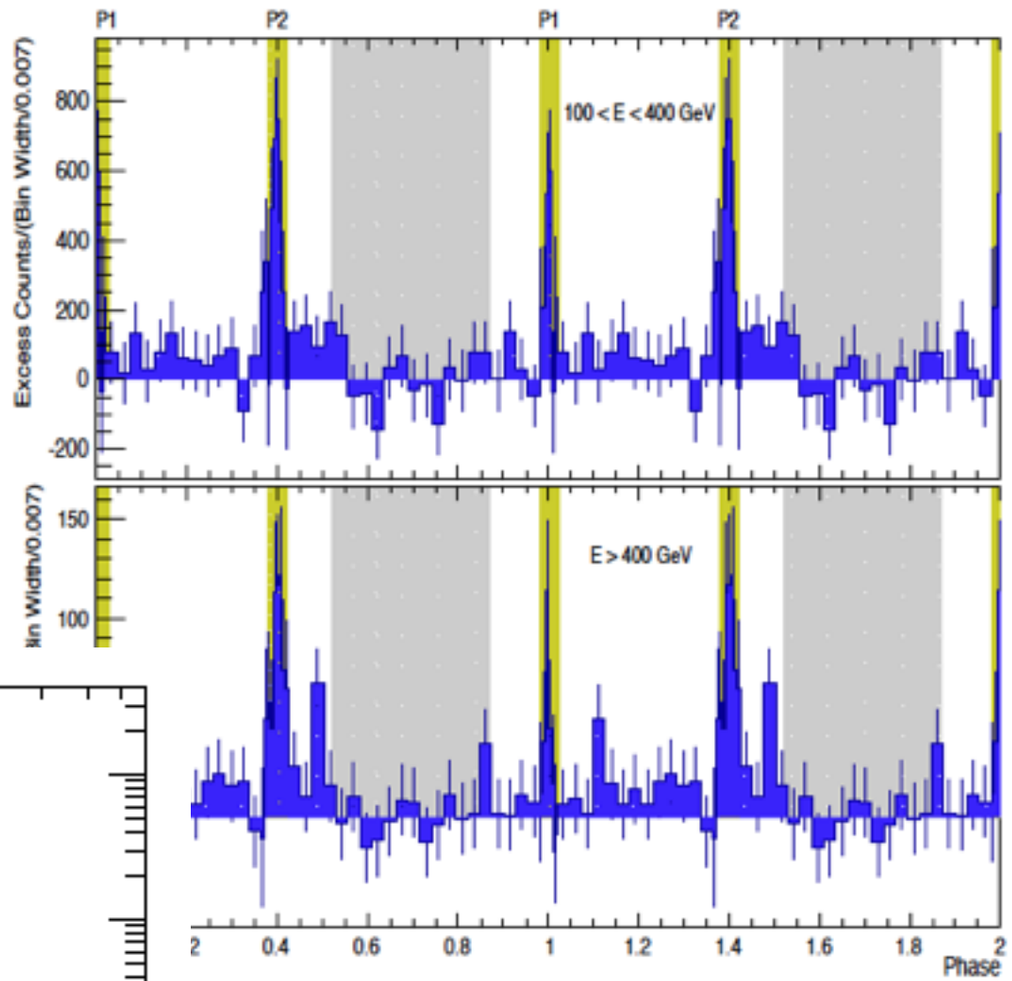
TeV Pulsations from the Crab

Astronomy & Astrophysics manuscript no. crabVHE
October 27, 2015

Teraelectronvolt pulsed emission from the Crab pulsar detected by MAGIC

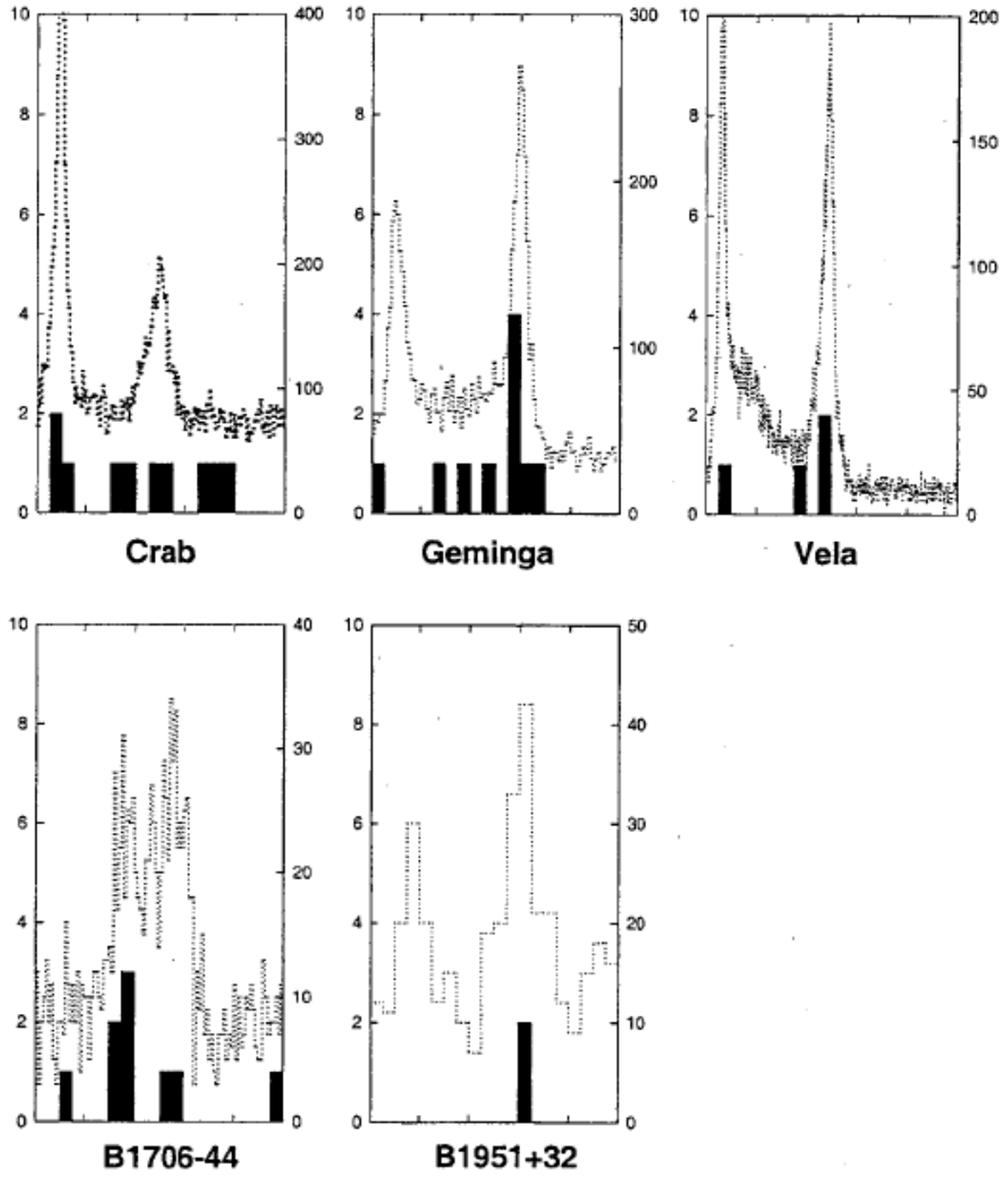
S. Ansoldi[1], L. A. Antonelli[2], P. Antoranz[3], A. Babic[4], P. Bangale[5], U. Barres de Almeida[5,26], J. A. Barrio[6], J. Becerra González[7,27], W. Bednarek[8], E. Bernardini[9], B. Biasuzzi[1], A. Biland[10], O. Blanch[11], S. Bonnefoy[6], G. Bonnoli[2], F. Borracci[5], T. Bretz[12,28], E. Carmona[13], A. Carosi[2], P. Colin[5], E. Colombo[7], J. L. Contreras[6], J. Cortina[11], S. Covino[2], P. Da Vela[3], F. Dazzi[5], A. De Angelis[1], G. De Caneva[9], B. De Lotto[1], E. de Oña Wilhelmi[14], C. Delgado Mendez[13], F. Di Pierro[2], D. Dominis Prester[4], D. Dorner[12], M. Doro[15], S. Einecke[16], D. Eisenacher Glawion[12], D. Elsaesser[12], A. Fernández-Barral[11], D. Fidalgo[6], M. V. Fonseca[6], L. Font[17], K. Frantzen[16], C. Fruck[5], D. Galindo[18], R. J. García López[7], M. Garczarczyk[9], D. Garrido Terrats[17], M. Gaug[17], N. Godinović[4], A. González Muñoz[11], S. R. Gozzini[9], Y. Hanabata[19], M. Hayashida[19], J. Herrera[7], K. Hirotani[20], J. Hose[5], D. Hrupec[4], G. Hughes[10], W. Idec[8], H. Kellermann[5], M. L. Knoetig[10], K. Kodani[19], Y. Konno[19], J. Krause[5], H. Kubo[19], J. Kushida[19], A. La Barbera[2], D. Lelas[4], N. Lewandowska[12], E. Lindfors[21,29], S. Lombardi[2], F. Longo[1], M. López[6], R. López-Coto[11], A. López-Oramas[11], E. Lorenz[5], M. Makariev[22], K. Mallot[9], G. Maneva[22], K. Mannheim[12], L. Maraschi[2], B. Marcot
P. Mu
K. Nishi
J. M. Pared
R. Rei
V. Scal
D. Sobczy
T. Terzić[4]





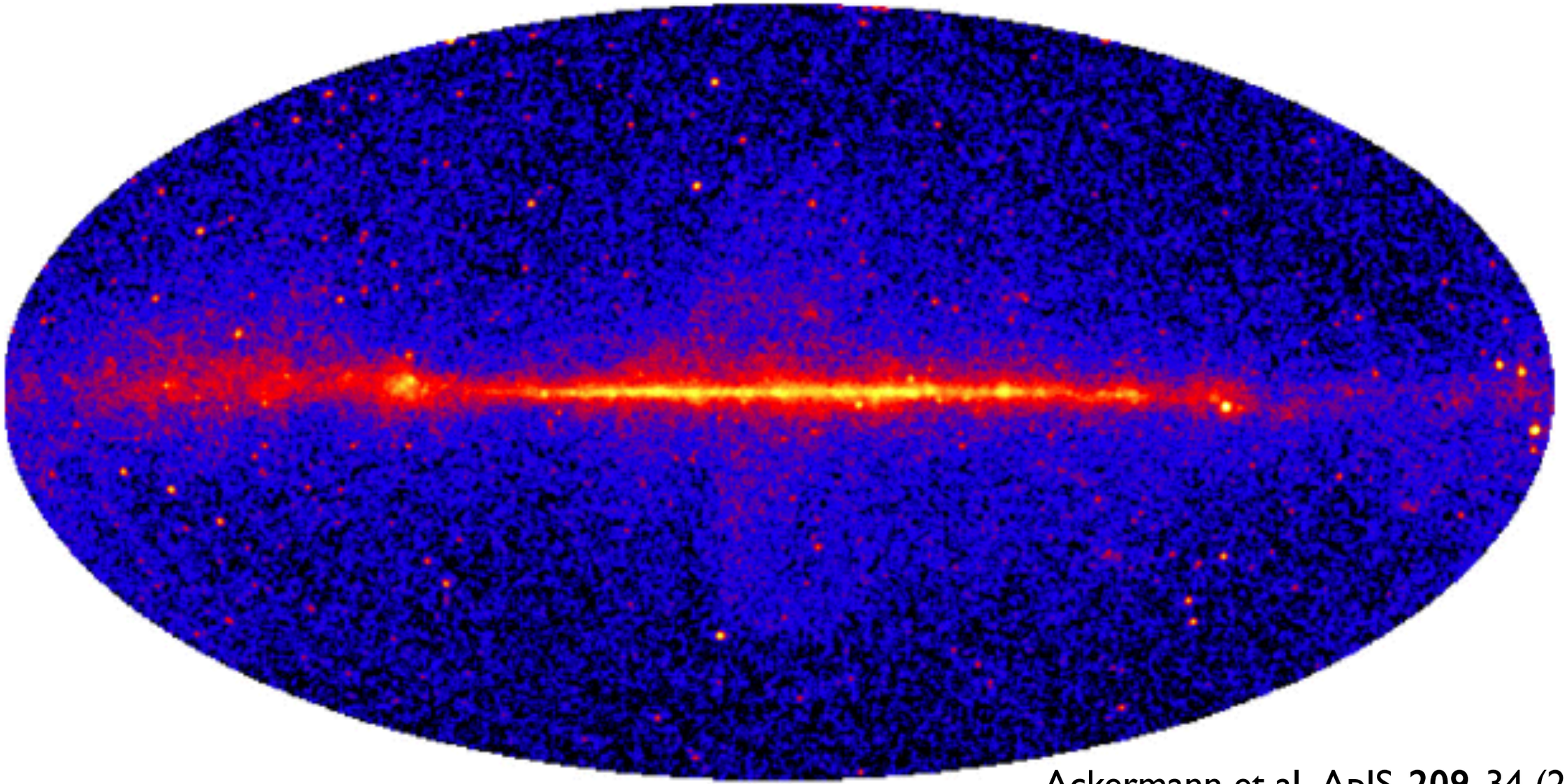
Pulsars above 10 GeV (EGRET)

- 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)



Note: Equivalent numbers for LAT,
(7 Yr, P8, 1deg): ~100,000 ph within 1 deg. of a pulsar:
2677, 4299, and 1118 respectively from Crab, Vela, Geminga

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)

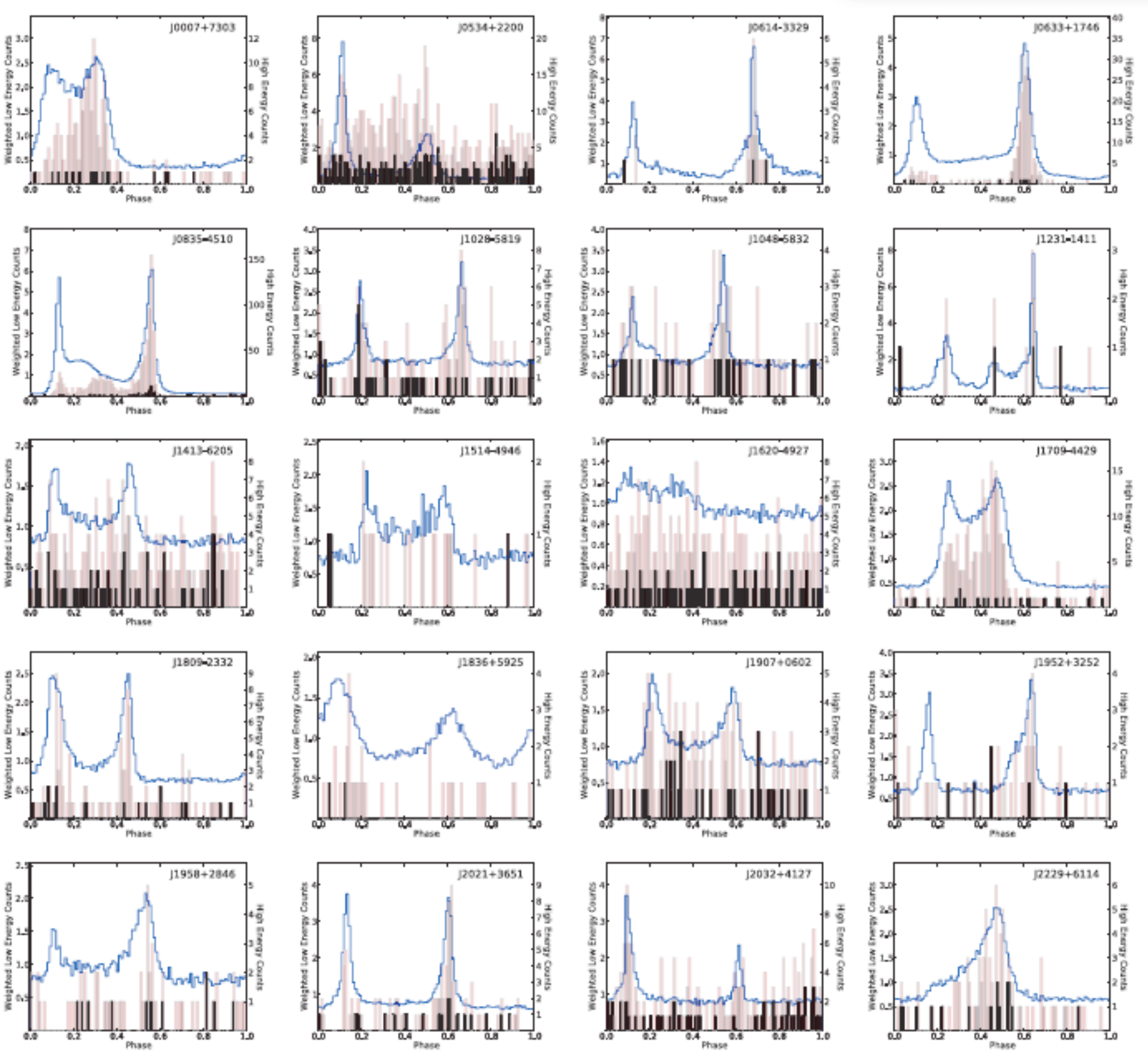
Pulsar associations in 1FHL

- 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

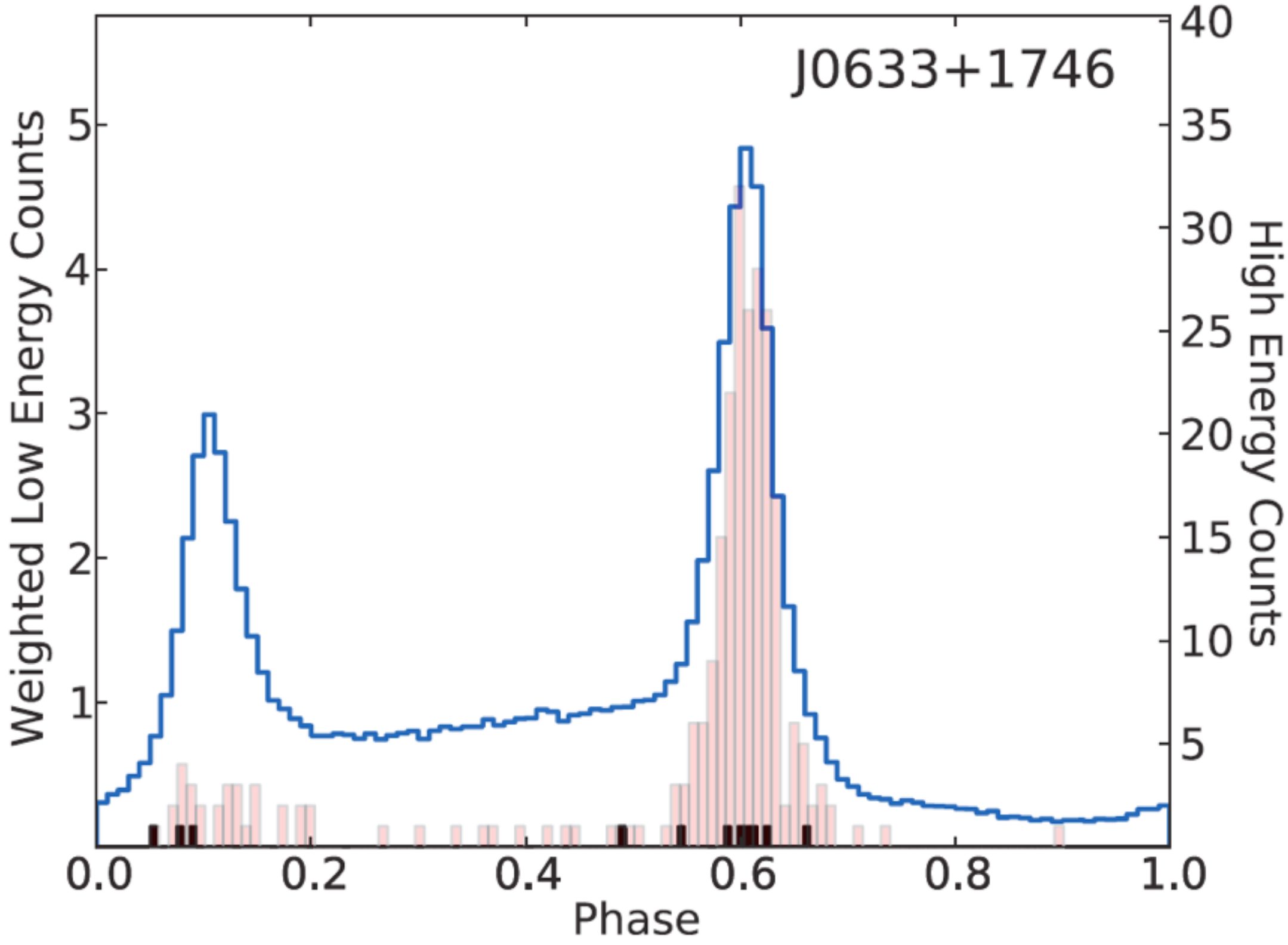
Q: Does the > 10 GeV emission come from the pulsar?

A: Test for pulsations using prior low-energy information

The 1FHL Catalog



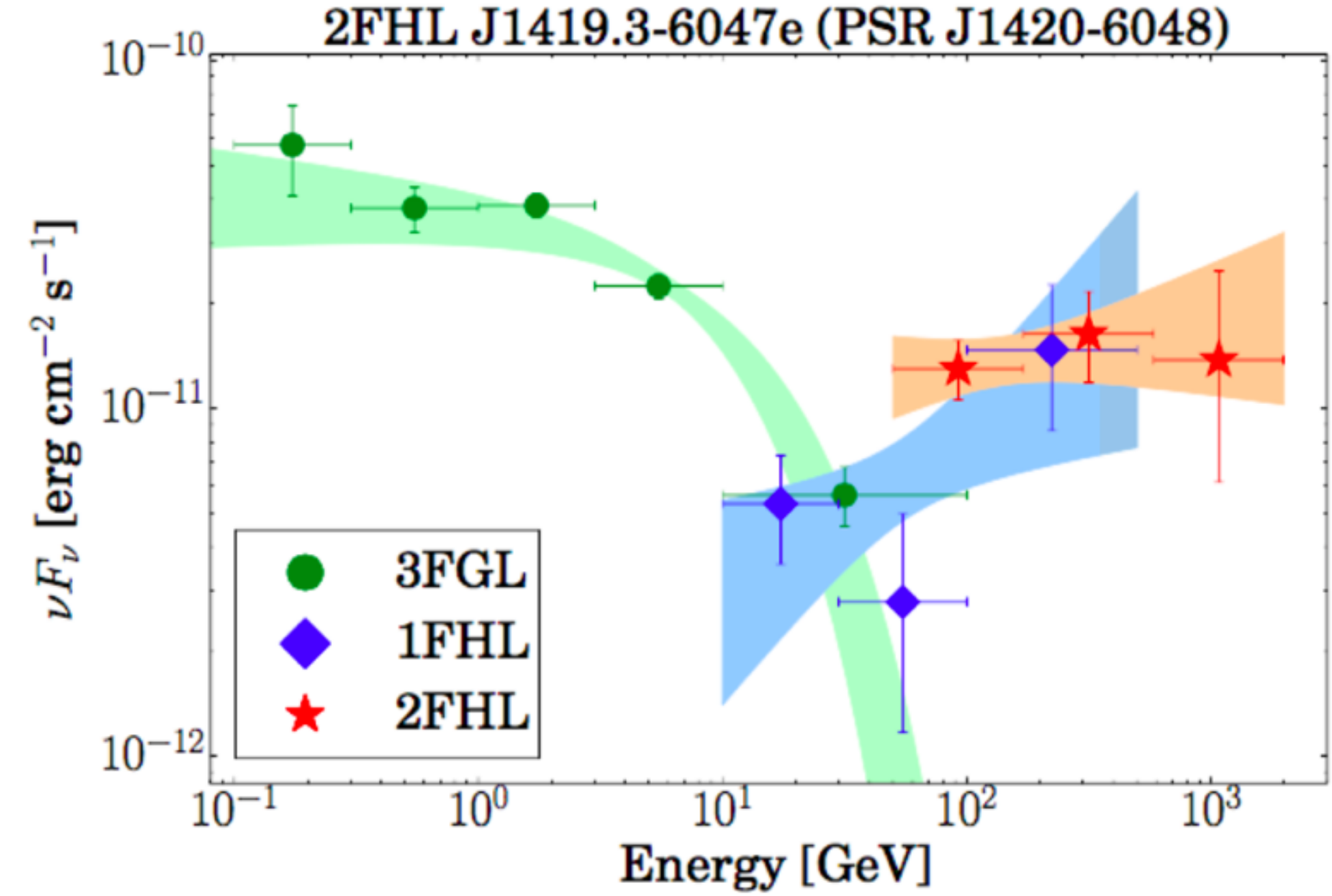
Geminga


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

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	$1.0\times10^{-2*}$	[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

Non-pulsing pulsar in 1FHL



Fermi-LAT Collaboration 2015

cf. Jeremy Perkins talk

Pulsars above 25 GeV

Table 11

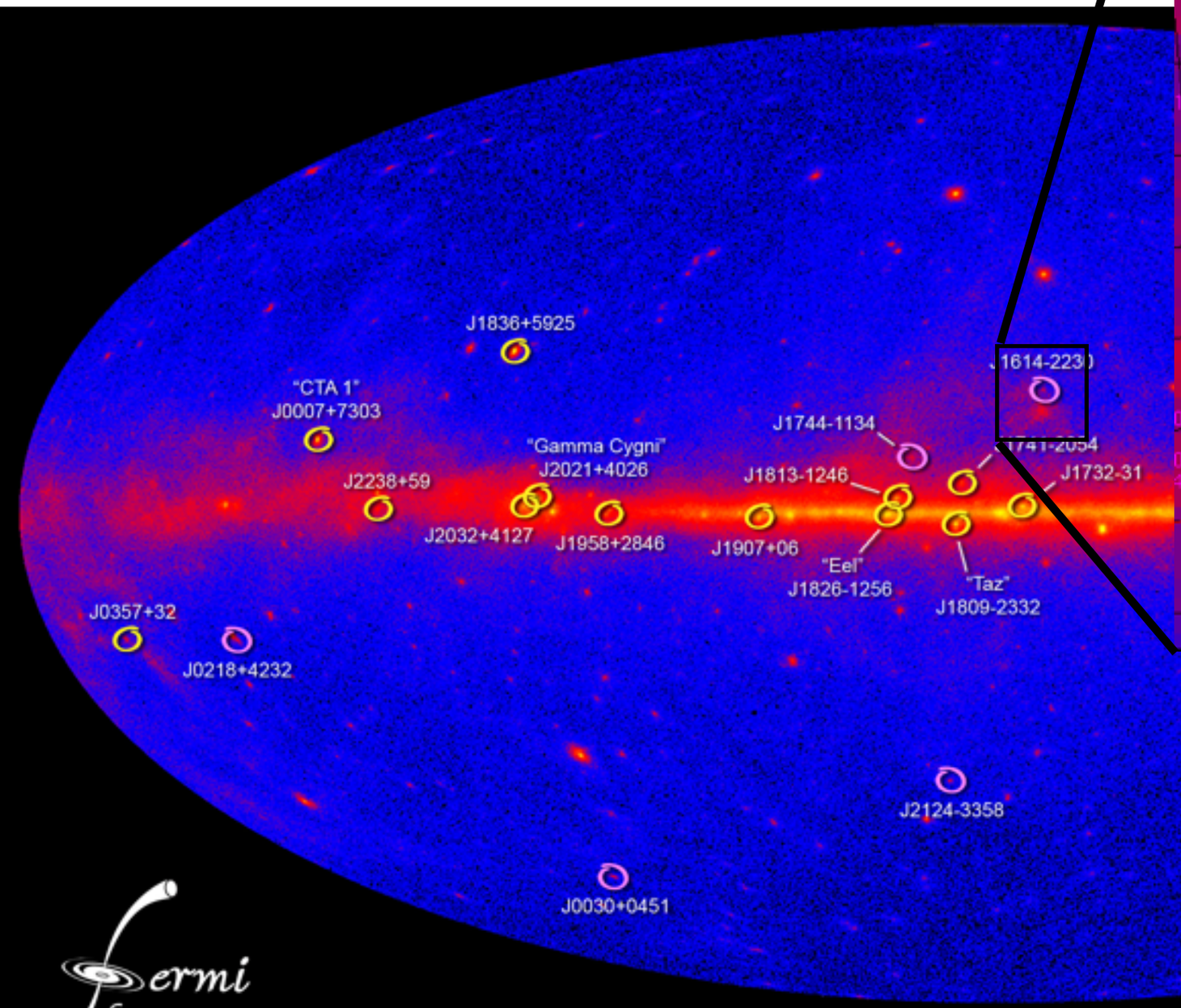
Fermi-LAT γ-Ray Pulsars Detected above 25 GeV

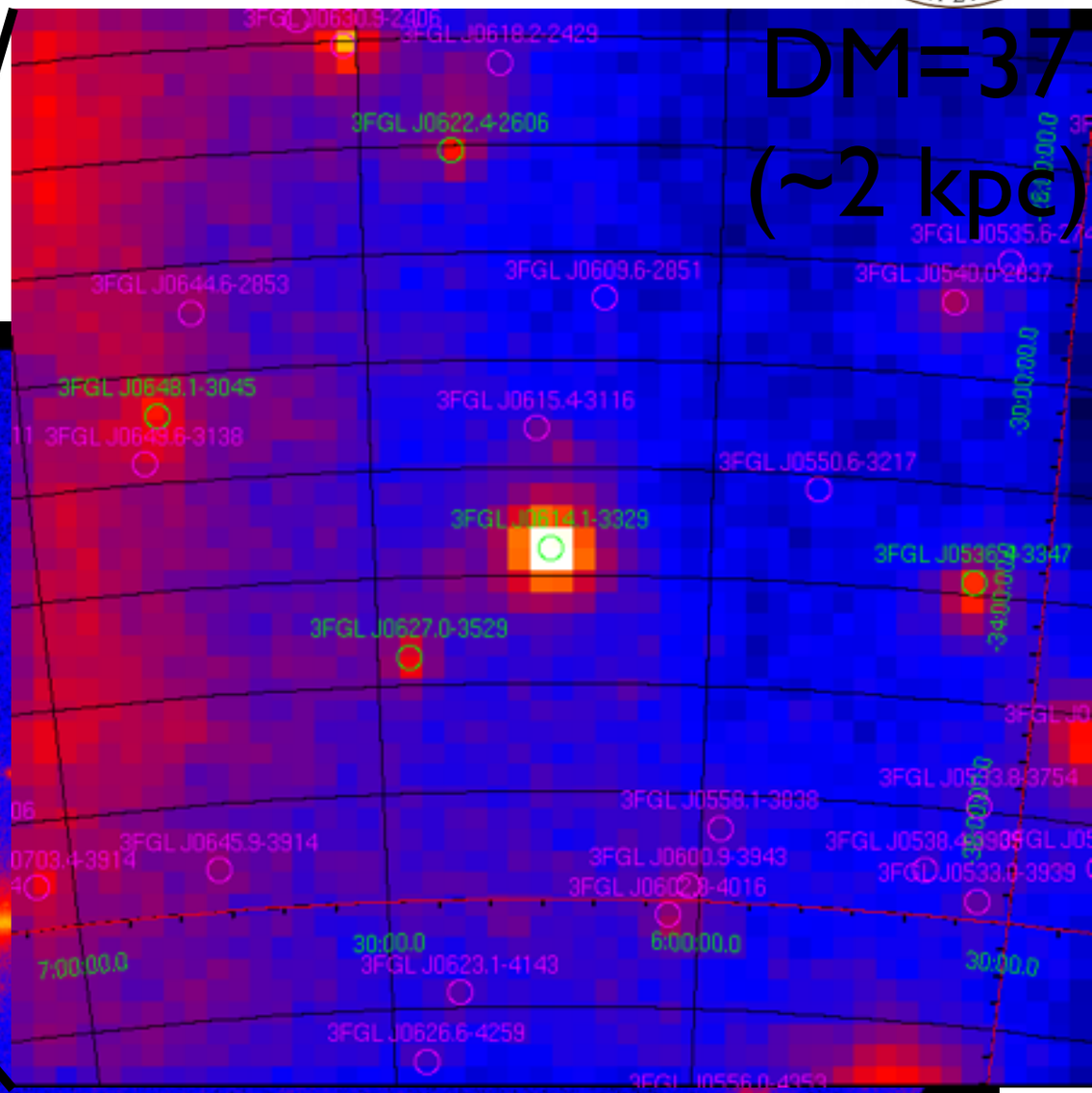
PSR	$E_{\rm max}$	$E_{\rm max}^{\rm detected}$	$\Phi_{\gamma{\rm max}}$	Notes
J0007+7303[#]	28	788	0.64	
J0534+2200[†#]	26	784	0.33	Crab
J0614–3329	63	63.6	0.68	
J0633+1746[#]	33	52.7	0.05	Geminga
J0835–4510[†#]	37	752	0.28	Vela
J1028–5819	27	386	0.49	
J1048–5832	35	201	0.28	
J1413–6205	29	331	0.28	
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	

PSR J0614-3329

Early PSC discovery
(Ransom et al. 2011)
Very bright (EGRET source)

DM=37
(~2 kpc)

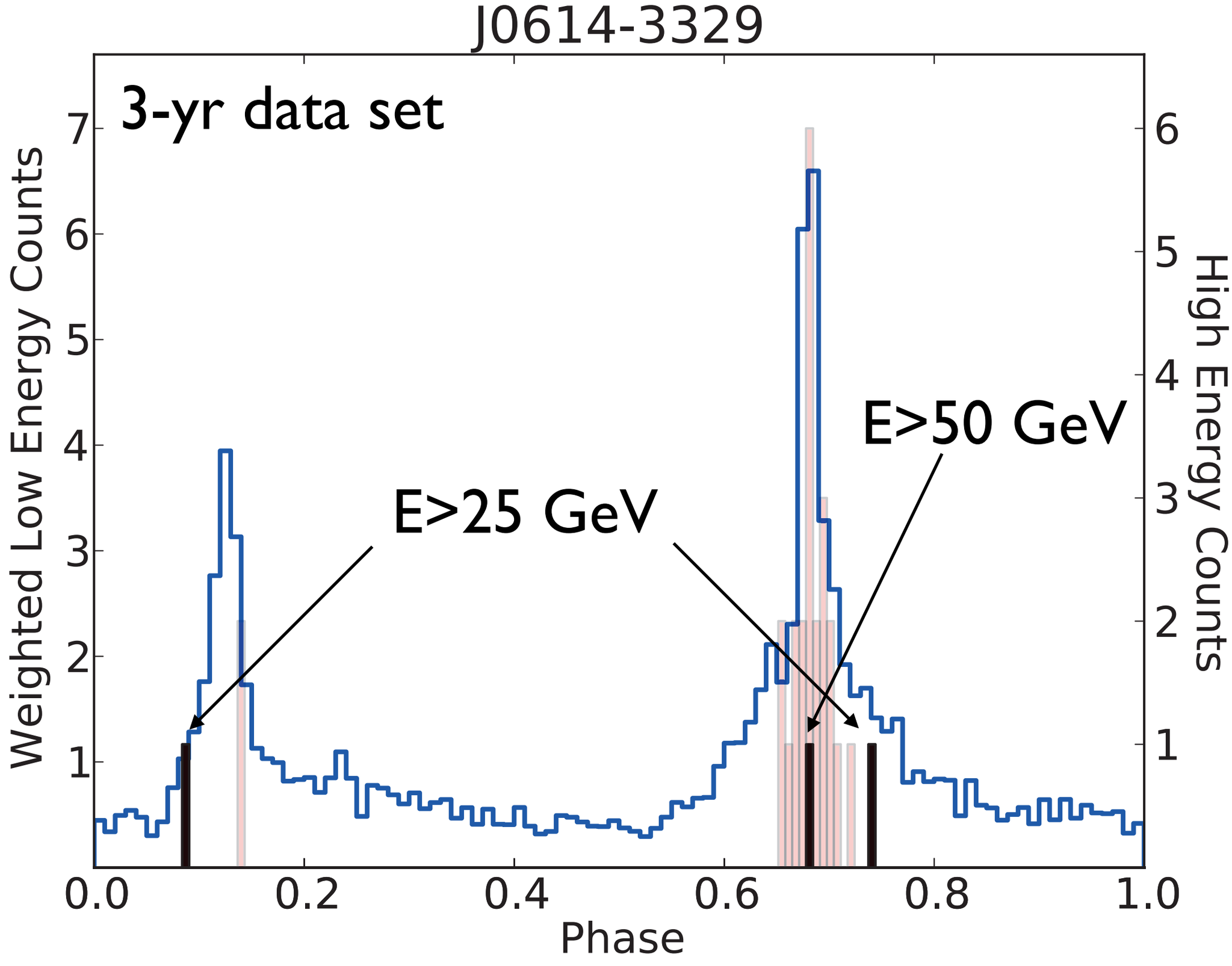




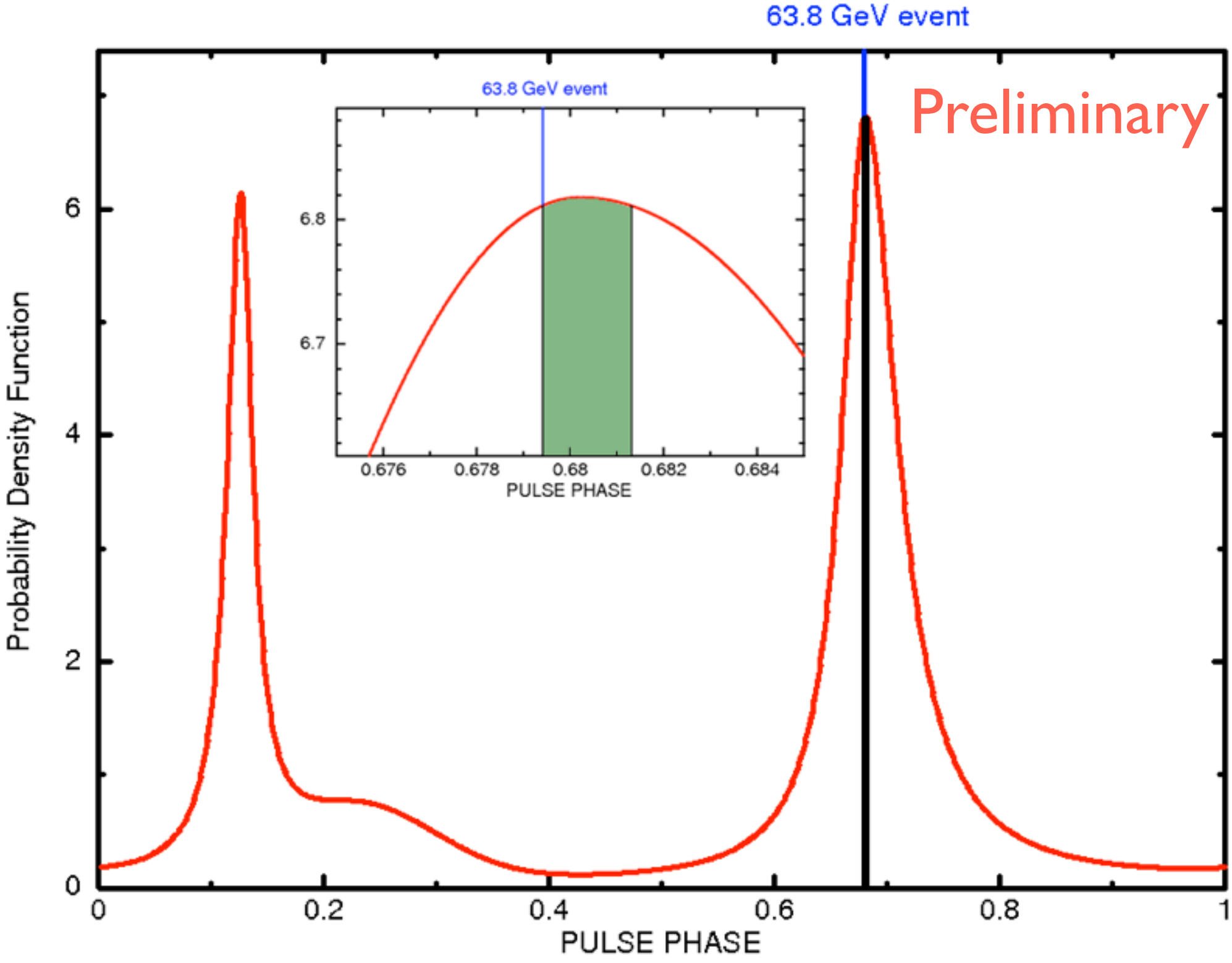
Fermi Gamma-ray Space Telescope

New pulsars found in a blind search
Millisecond radio pulsars

A closer look at J0614-3329



63 GeV pulsations?

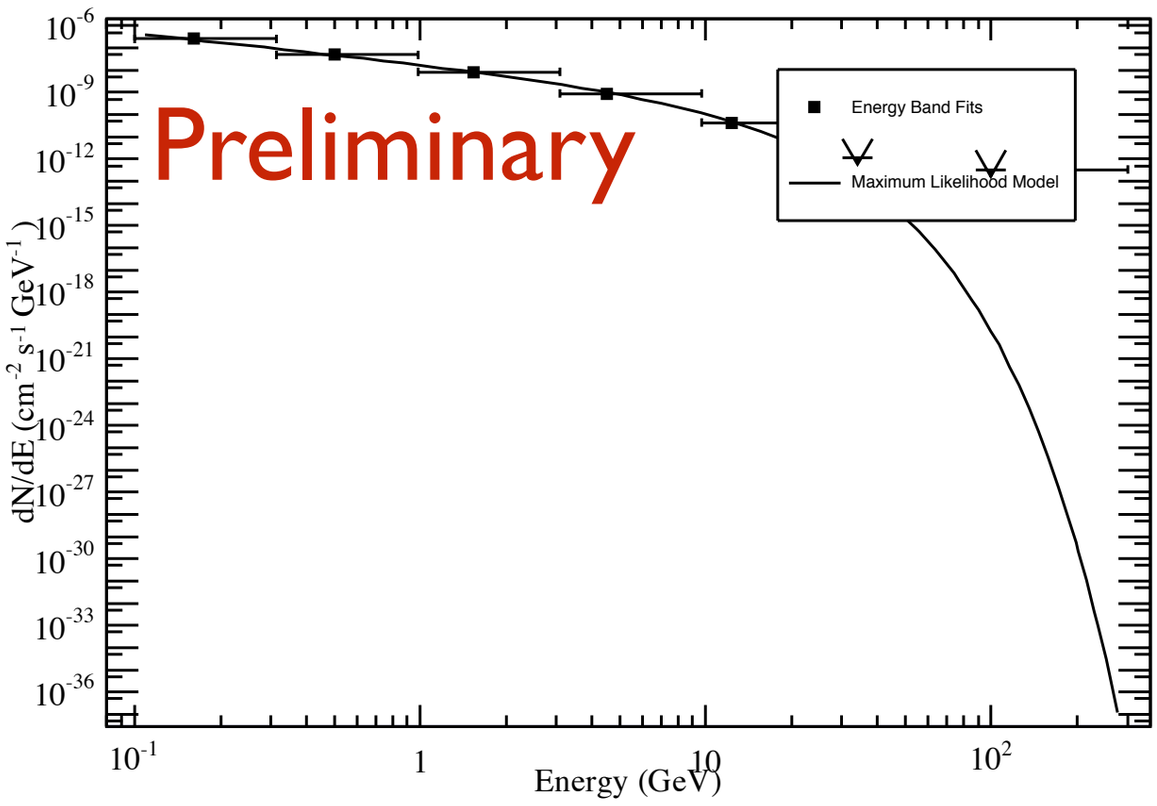


What next with the LAT?

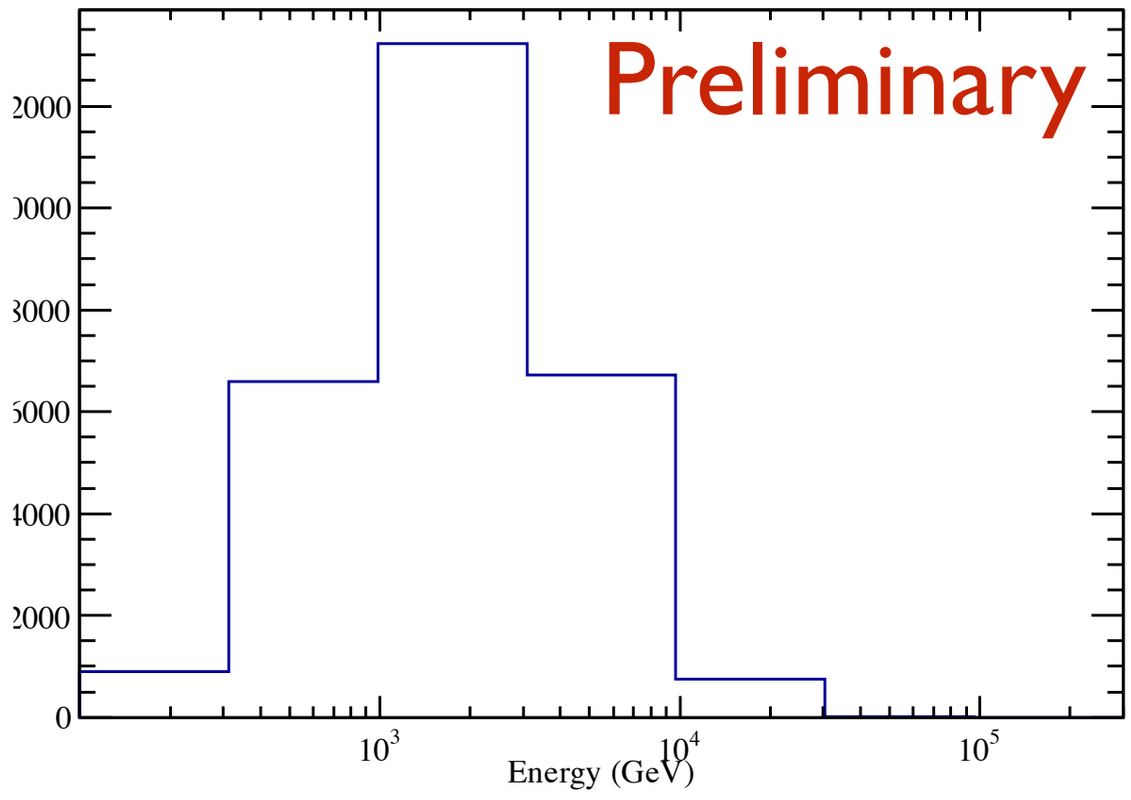
	1FHL	Now
Data span	3 years	7 years
LAT IRFs	Pass 7	Pass 8
# Pulsars investigated	39	~160
Dedicated PWN treatment	No	Yes
Lower Energy Template	>100 MeV	>100 MeV, >1 GeV, Other (TBD)

Updated spectral model

dN/dE



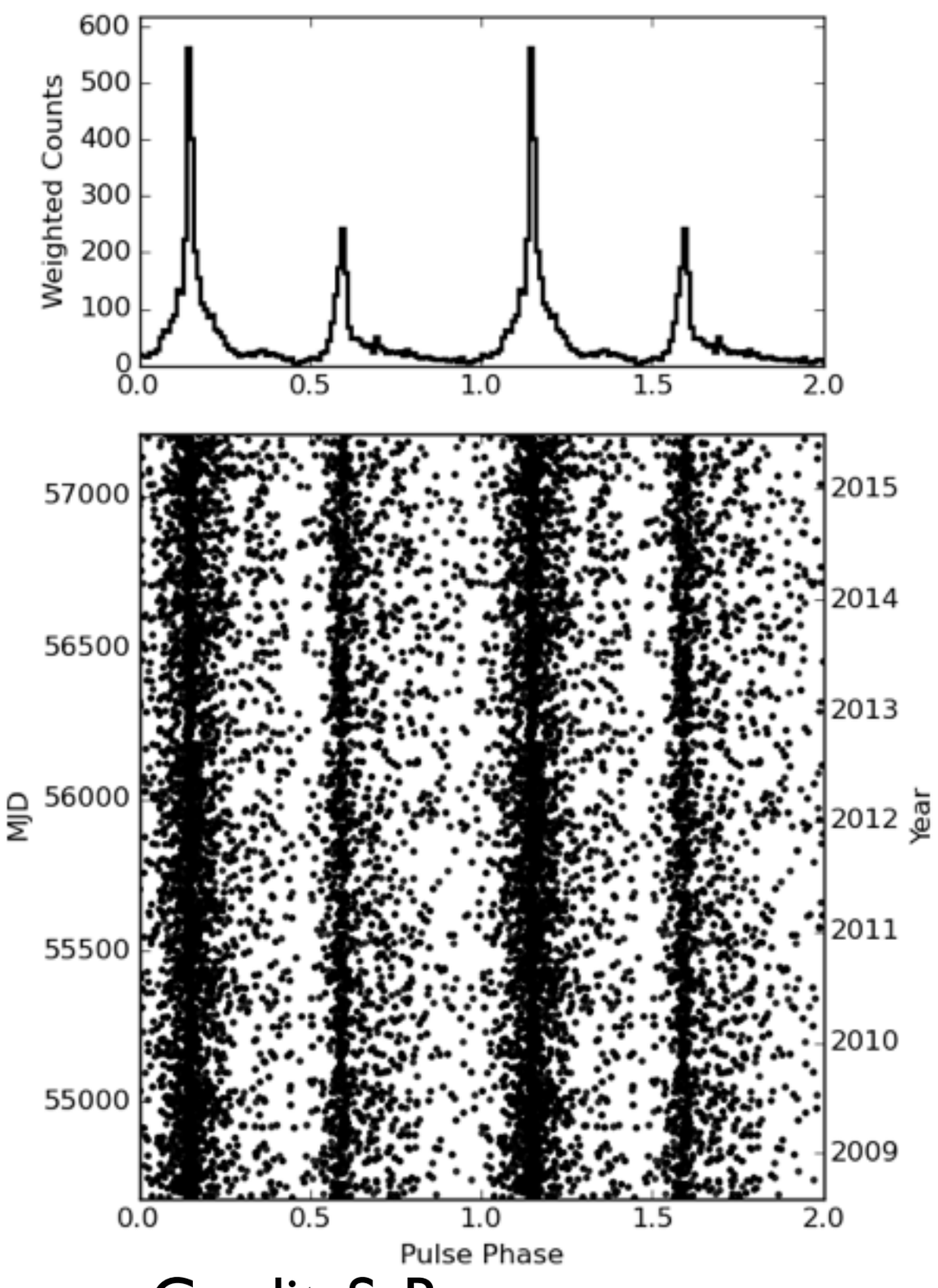
TS vs Energy



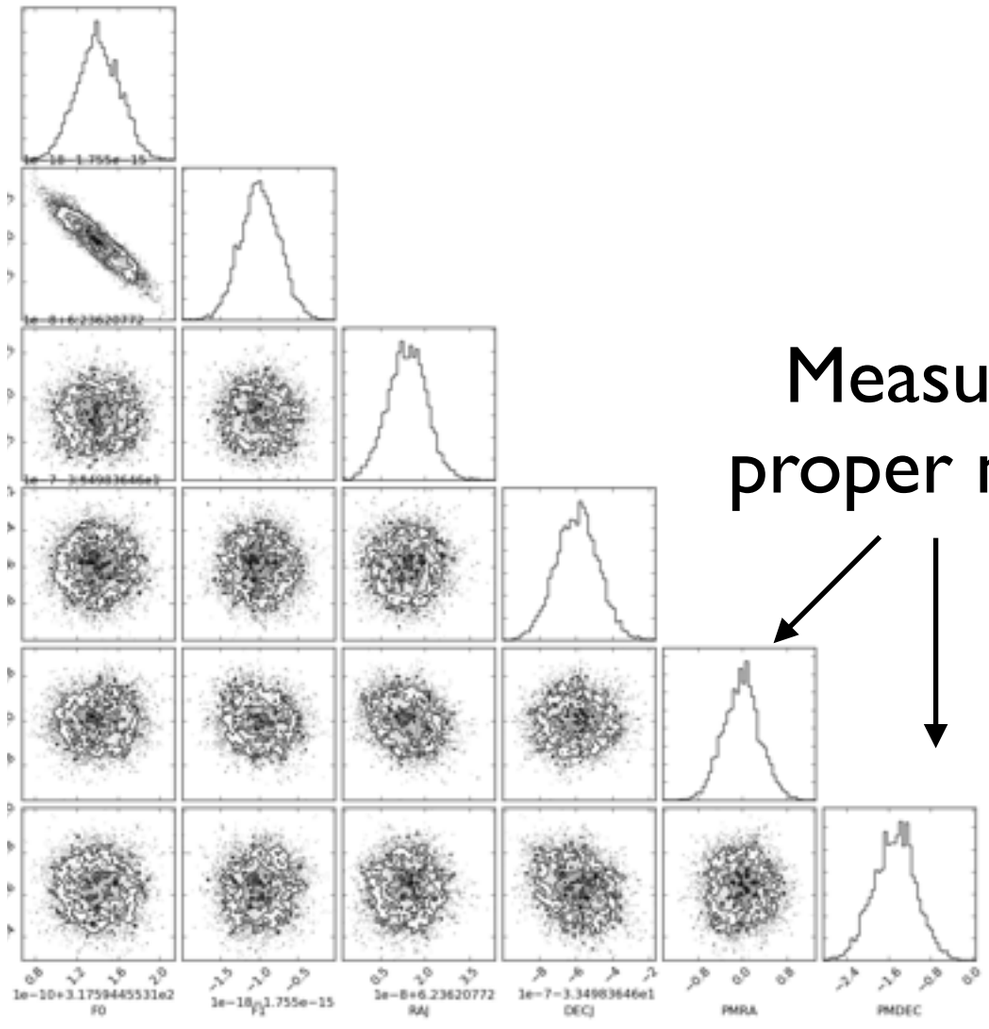
100 MeV - 10 GeV
Flux: 8.0 E-8 ph/cm^2/s

10-100 GeV
Flux: 3.8 E-10 ph/cm^2/s

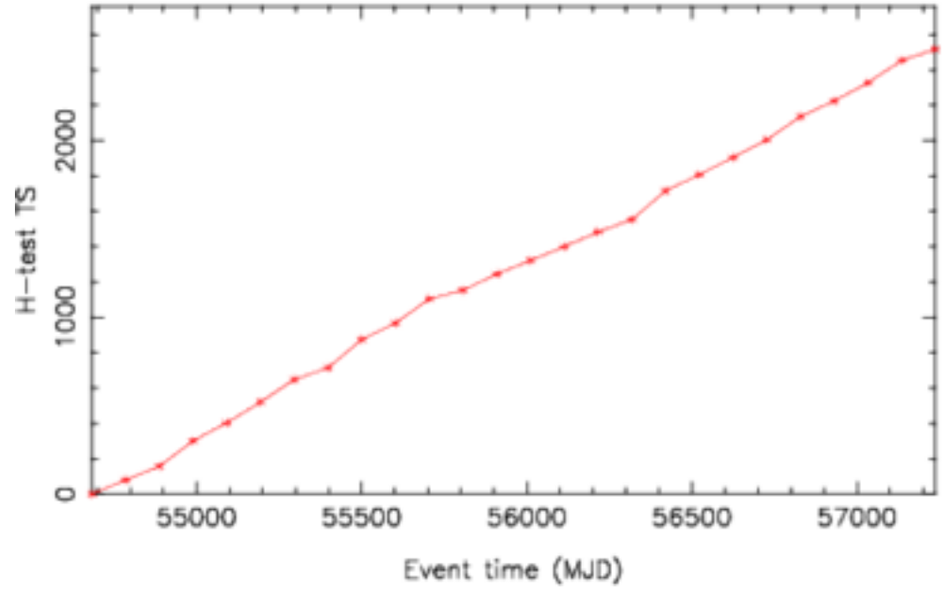
Updated timing model



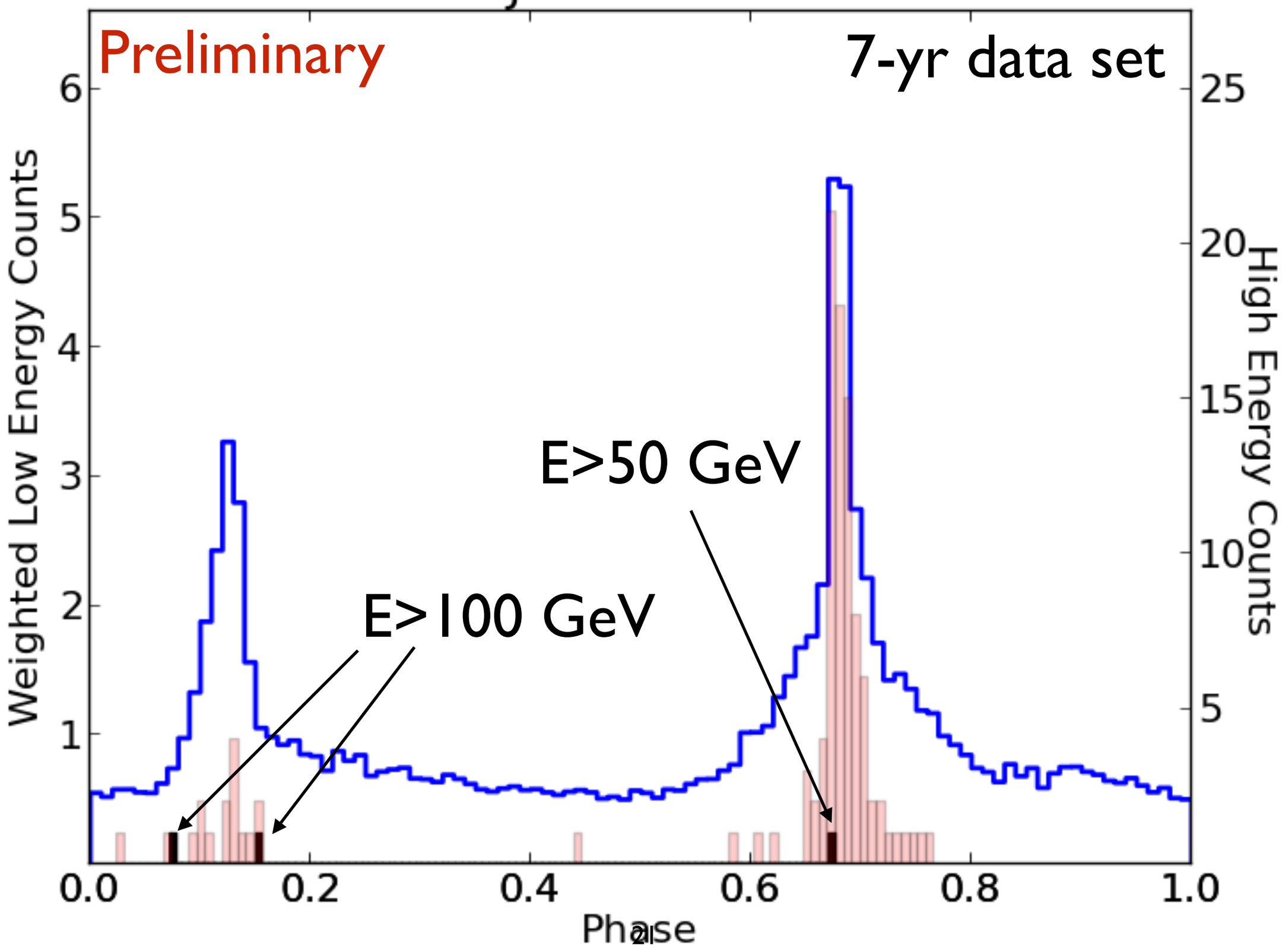
Credit: S. Ransom



Measurable proper motion



Search for the highest pulsations from J0614-3329



Follow-up TeV observations are key!

Summary

- Fermi has greatly improved our knowledge of gamma-rays sources in the 100 MeV-100 GeV energy range
- 28 (12) LAT pulsars were shown to emit pulsations at >10 (25) GeV, based on 3 years of data
- Recent improvements in LAT reconstruction (Pass 8) and the addition of more than twice the amount of data are improving these results significantly
- PSR J0614-3329 is a promising VHE pulsar candidate
- Ground-based instruments (HESS, MAGIC, VERITAS, HAWC, CTA) are needed to further investigate pulsar emission above 100 GeV