The search for Very High Energy Pulsars

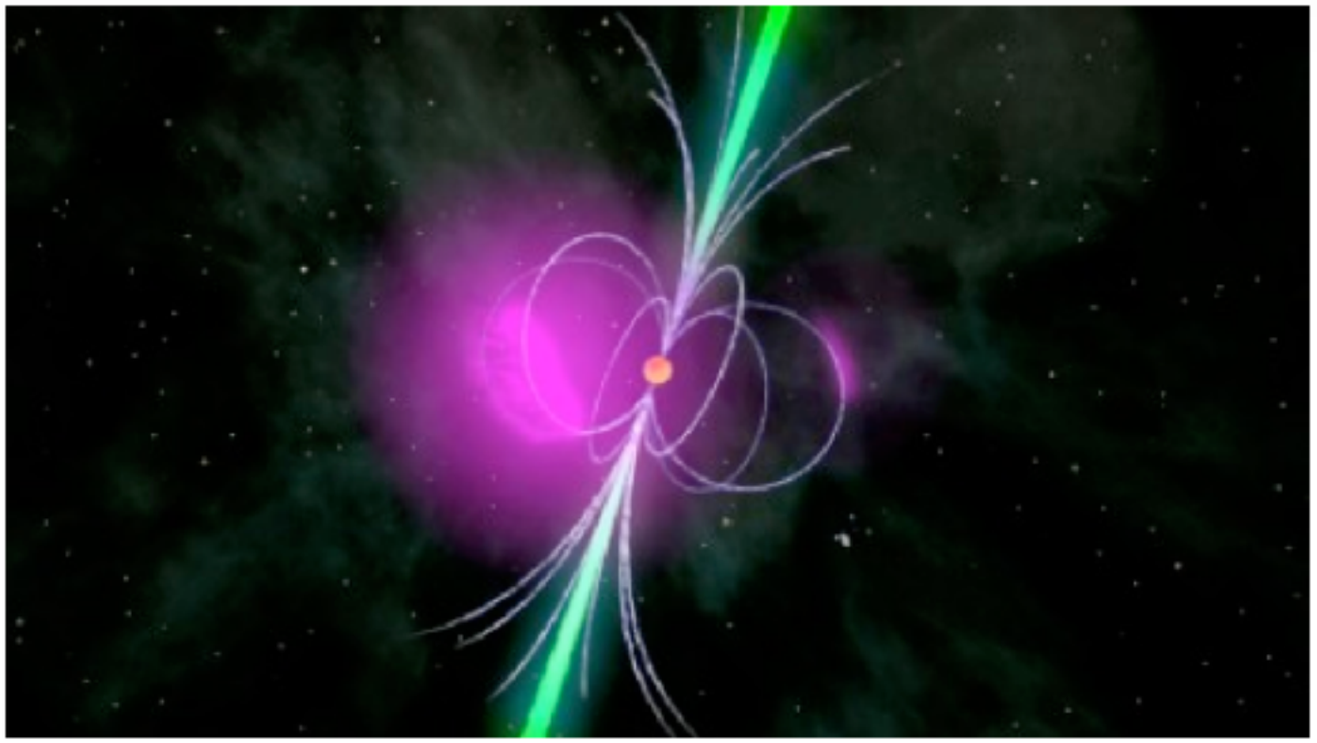
Pablo Saz Parkinson
UCSC/HKU
for the LAT Collaboration

Collaborators: A. Belfiore, D. Carreto-Fidalgo, M. Kerr, S. Ransom, etc.

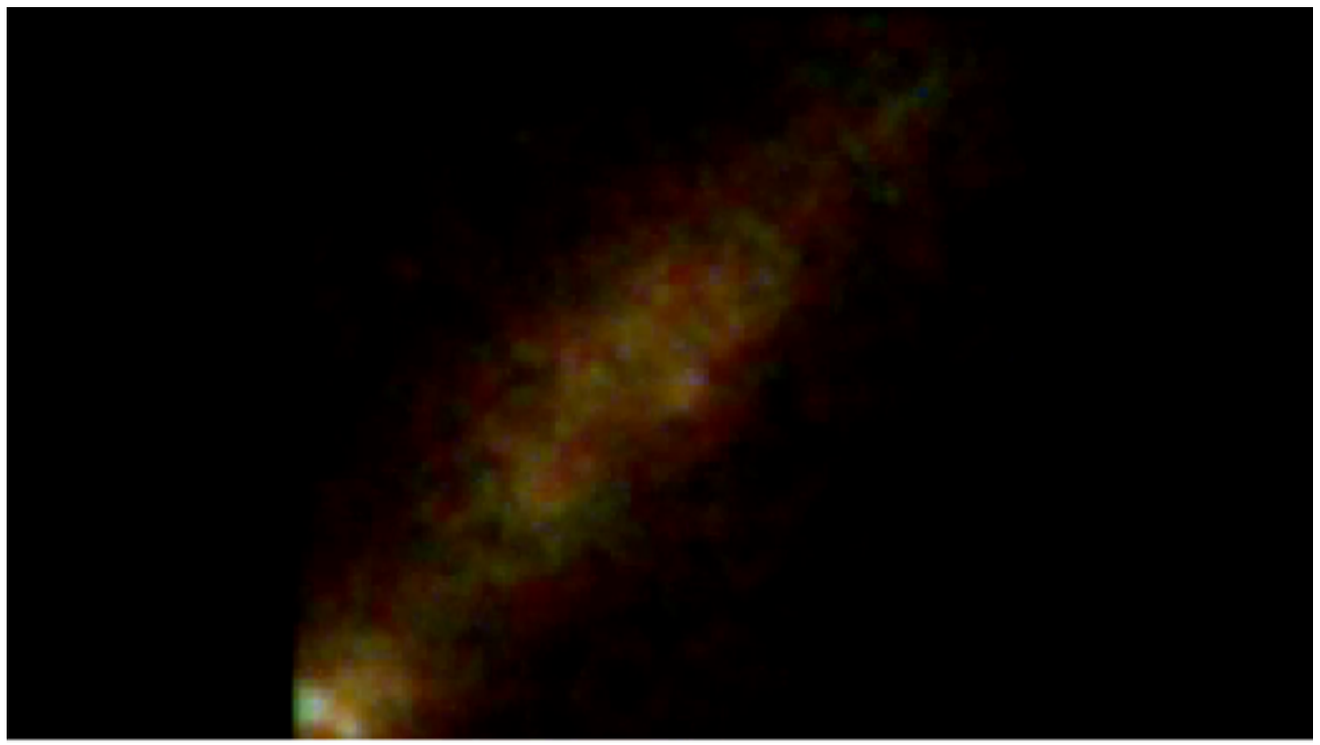
Astro-Siesta
IASF-Milano (INAF)
23 March 2017

What is a pulsar?

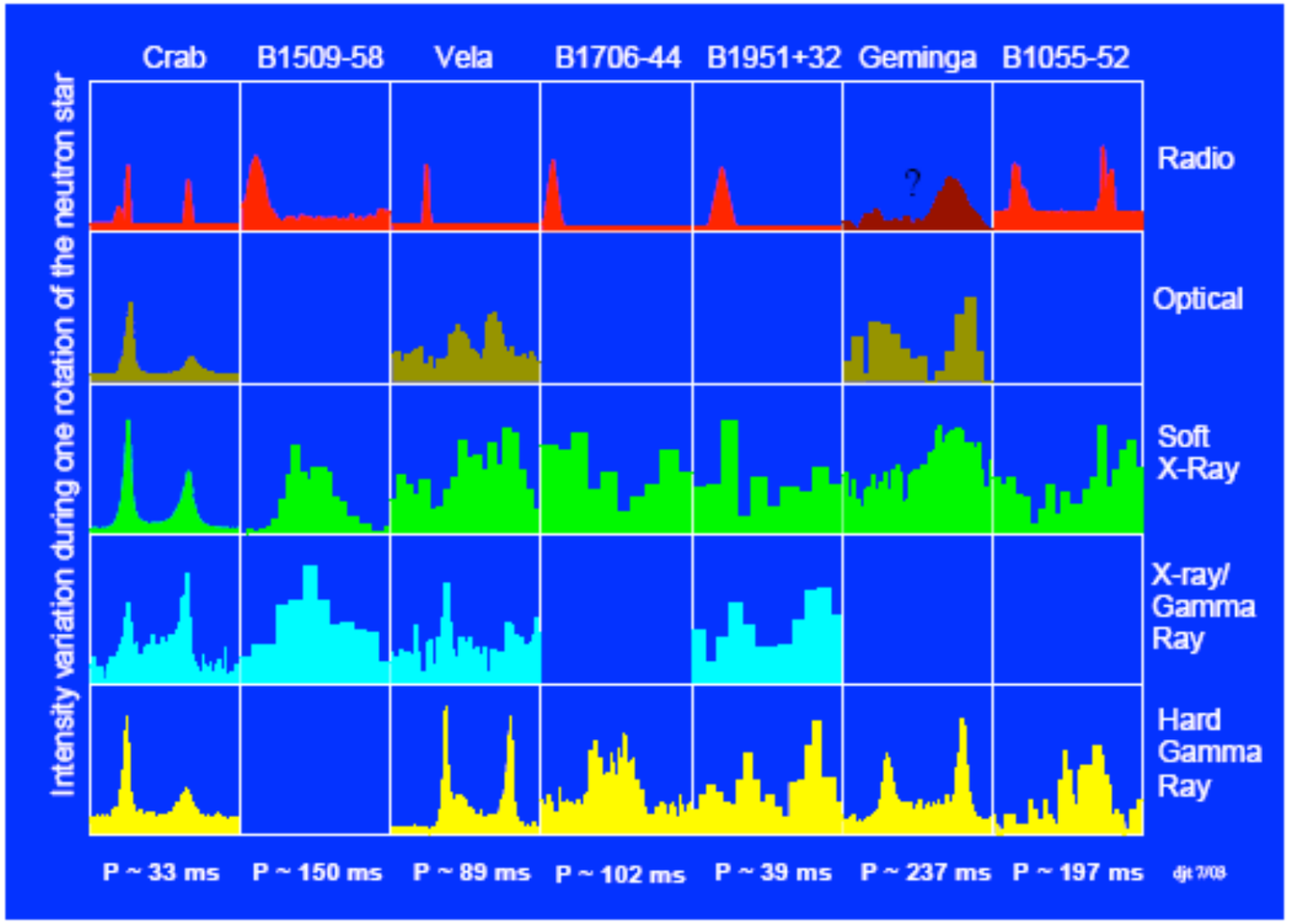
- Highly-magnetized (up to 1E15 Gauss)
- rapidly-spinning (0.1 Hz - 700 Hz)
- neutron star (R~10 km, M~2 Sun)
- created in supernovae
- Discovered in1967
- ~2500 known
- multiwavelength emission



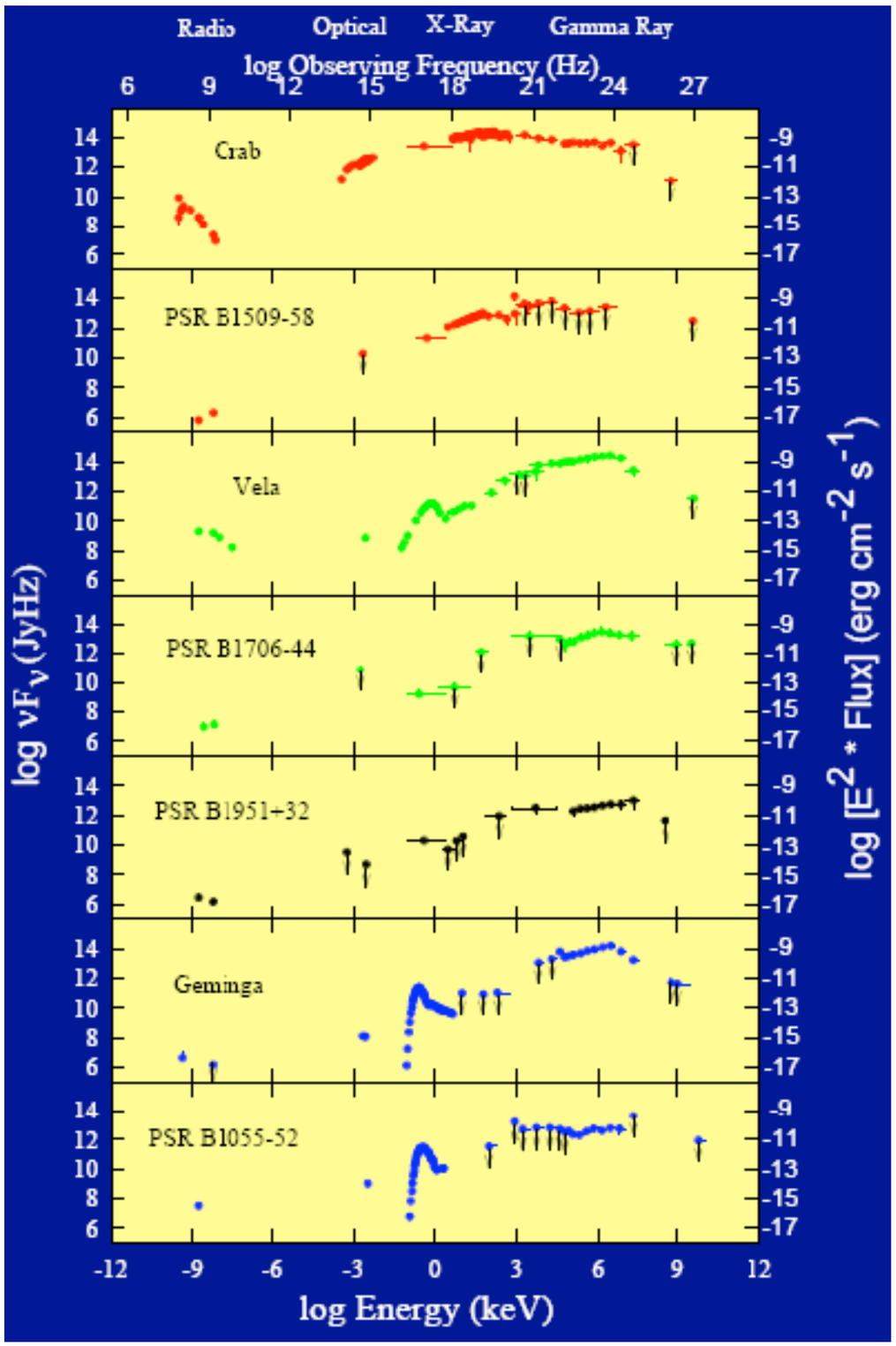
Artist's impression of a gamma-ray pulsar.
Image credits: NASA/Fermi/Cruz de Wilde



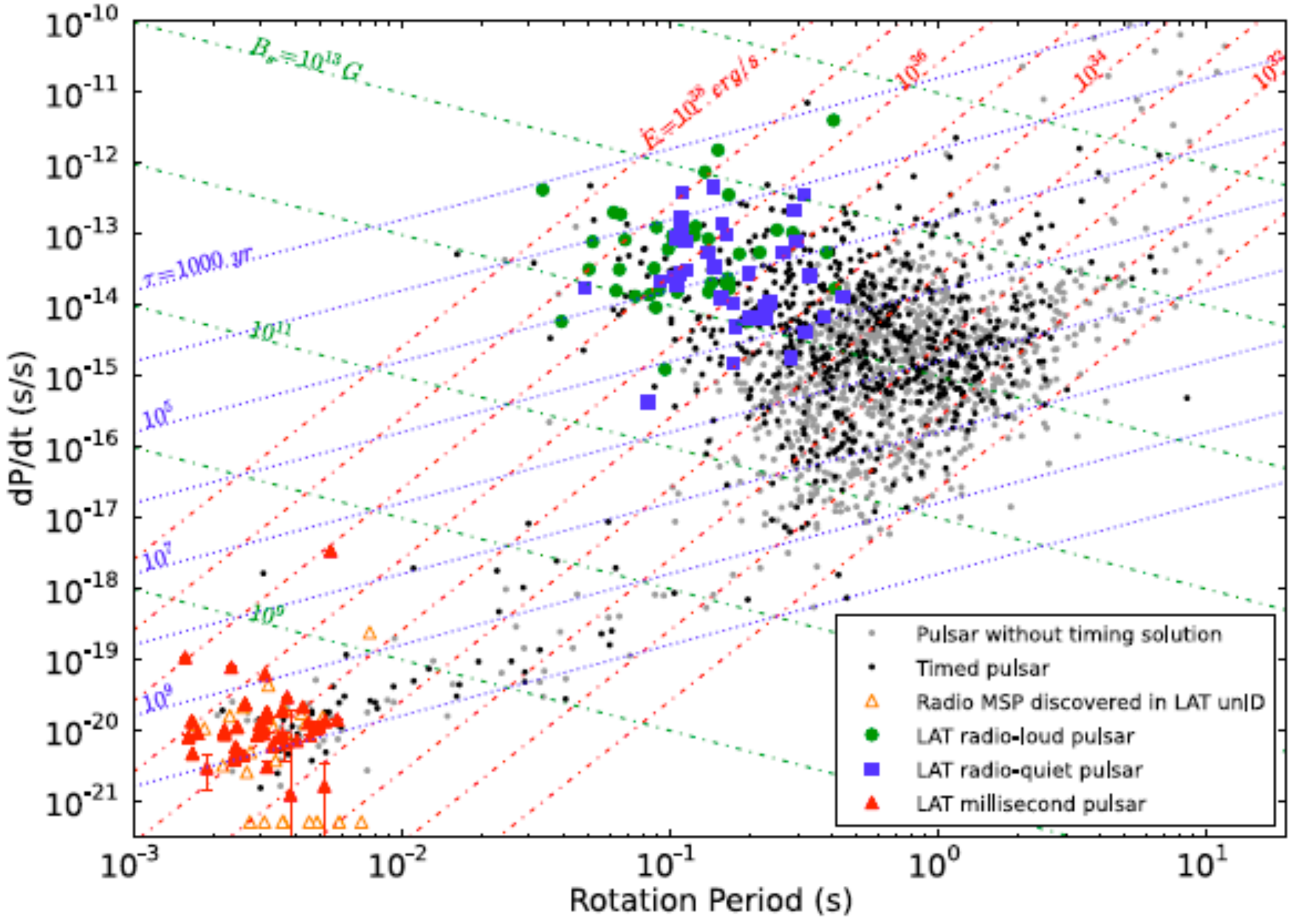
The multi-wavelength nature of pulsars



Credit: Thompson 2004

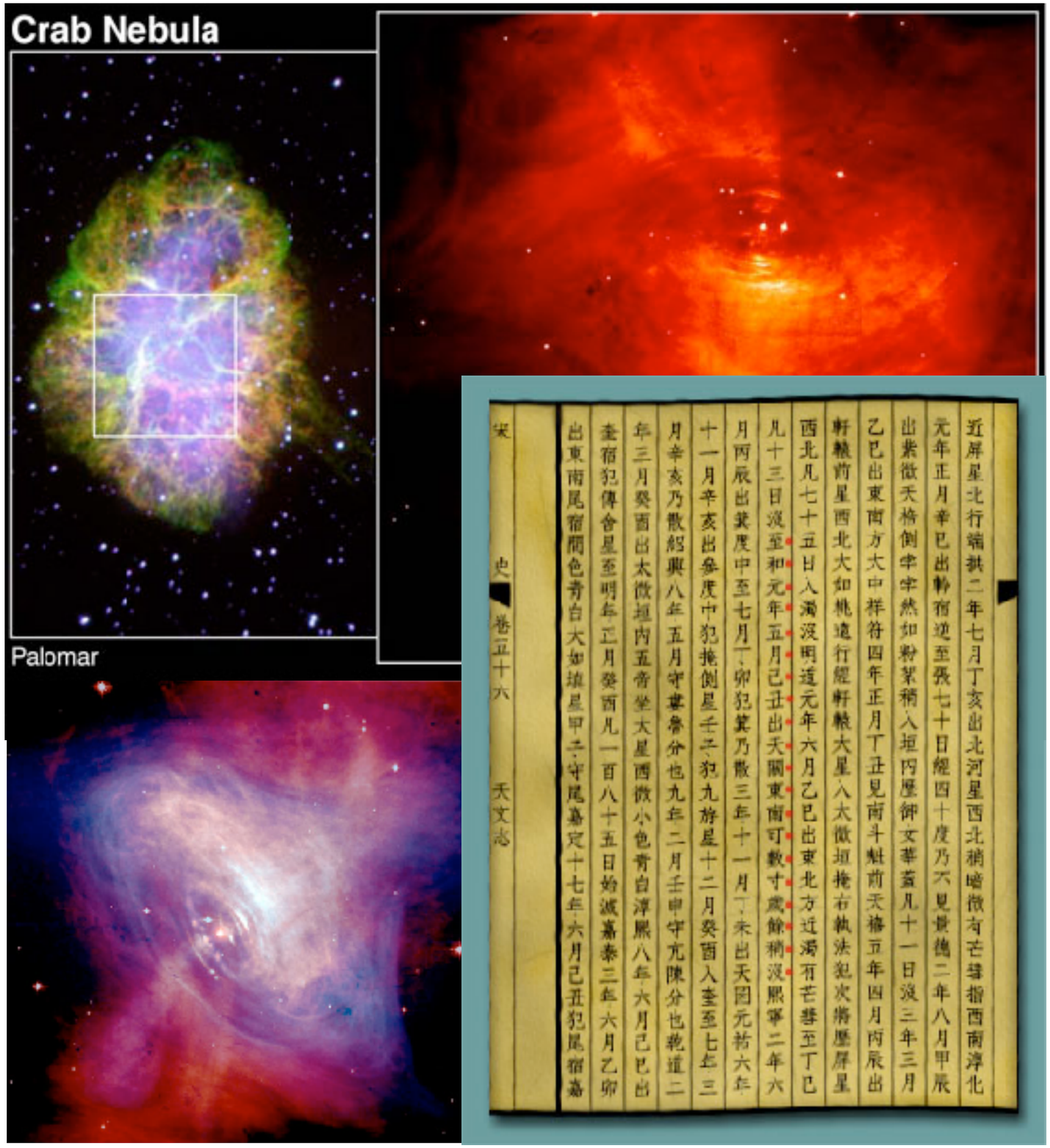


Gamma-ray pulsar population

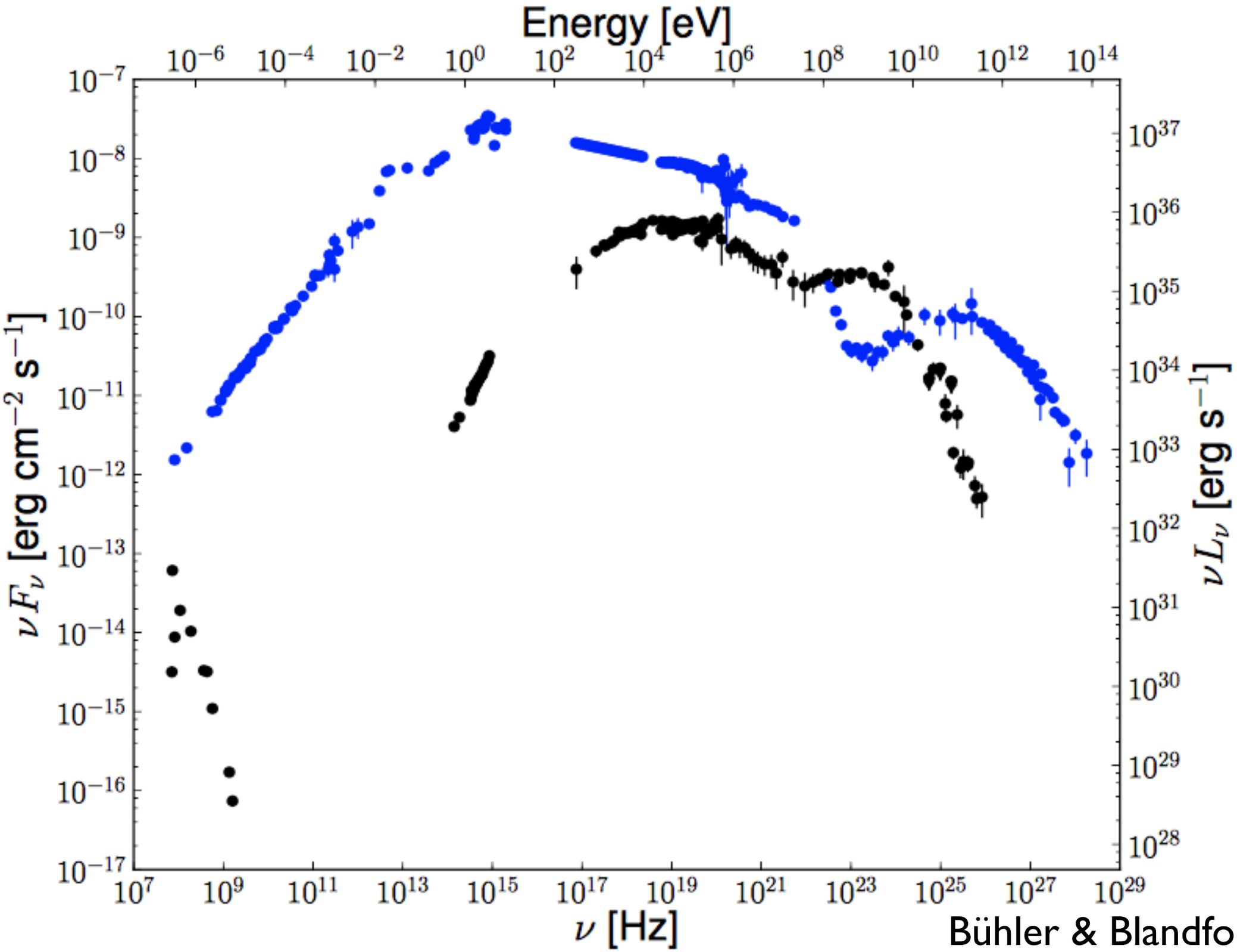


The Crab pulsar

- Remnant of SN 1054 AD (recorded by Chinese astronomers in the Sung Dynasty)
- One of the youngest (and the *most* energetic) known pulsars



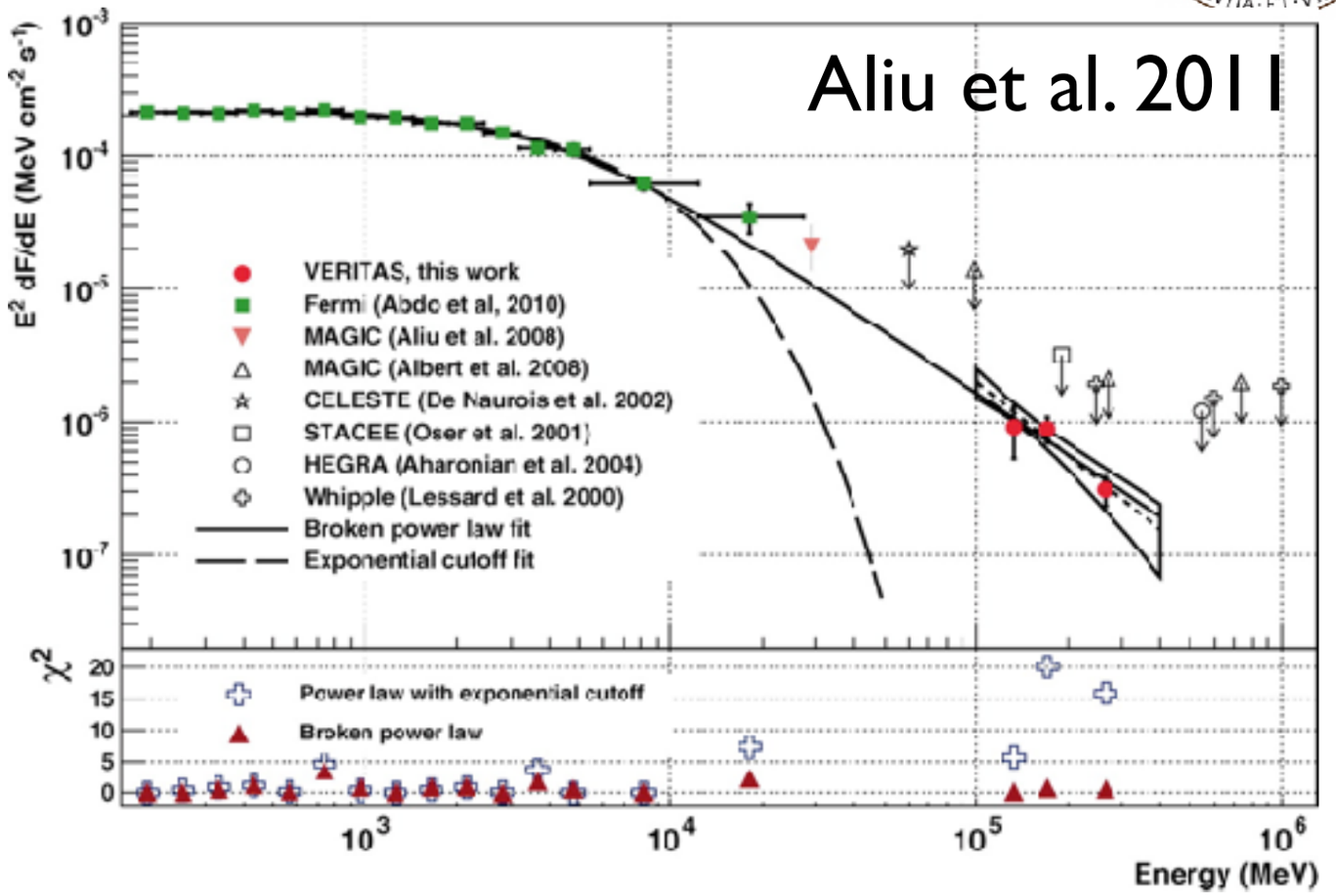
The Crab

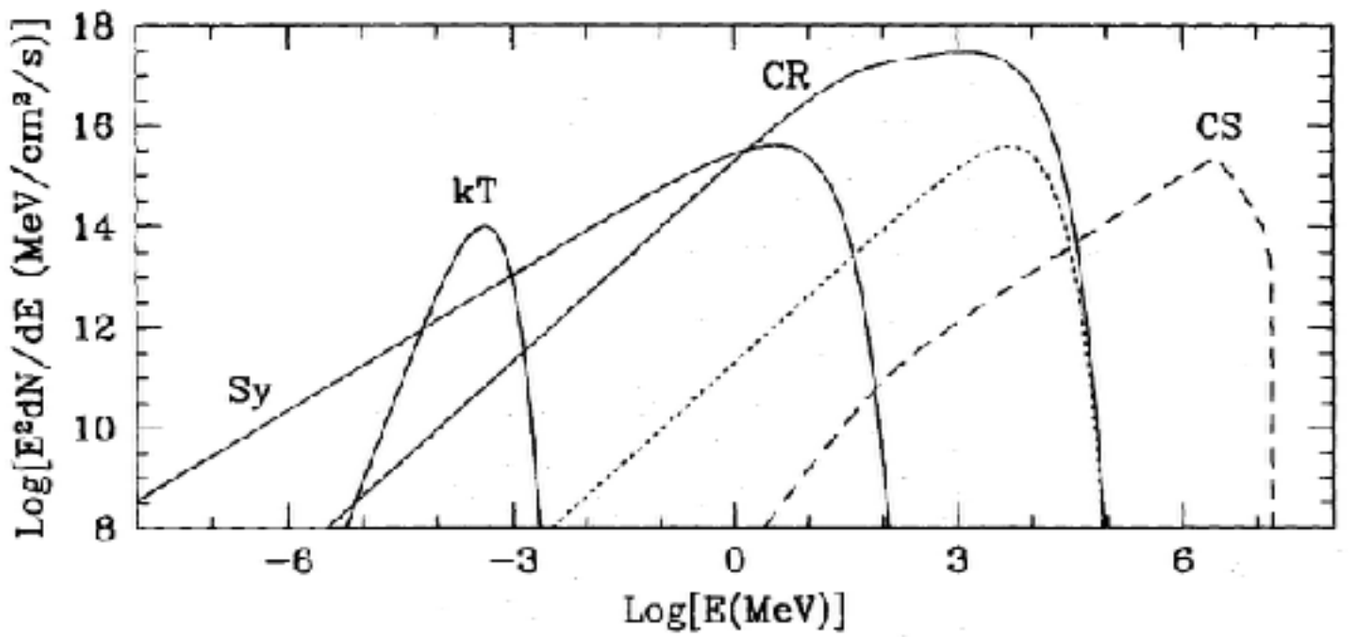


Bühler & Blandford 2014

Pulsars at VHE

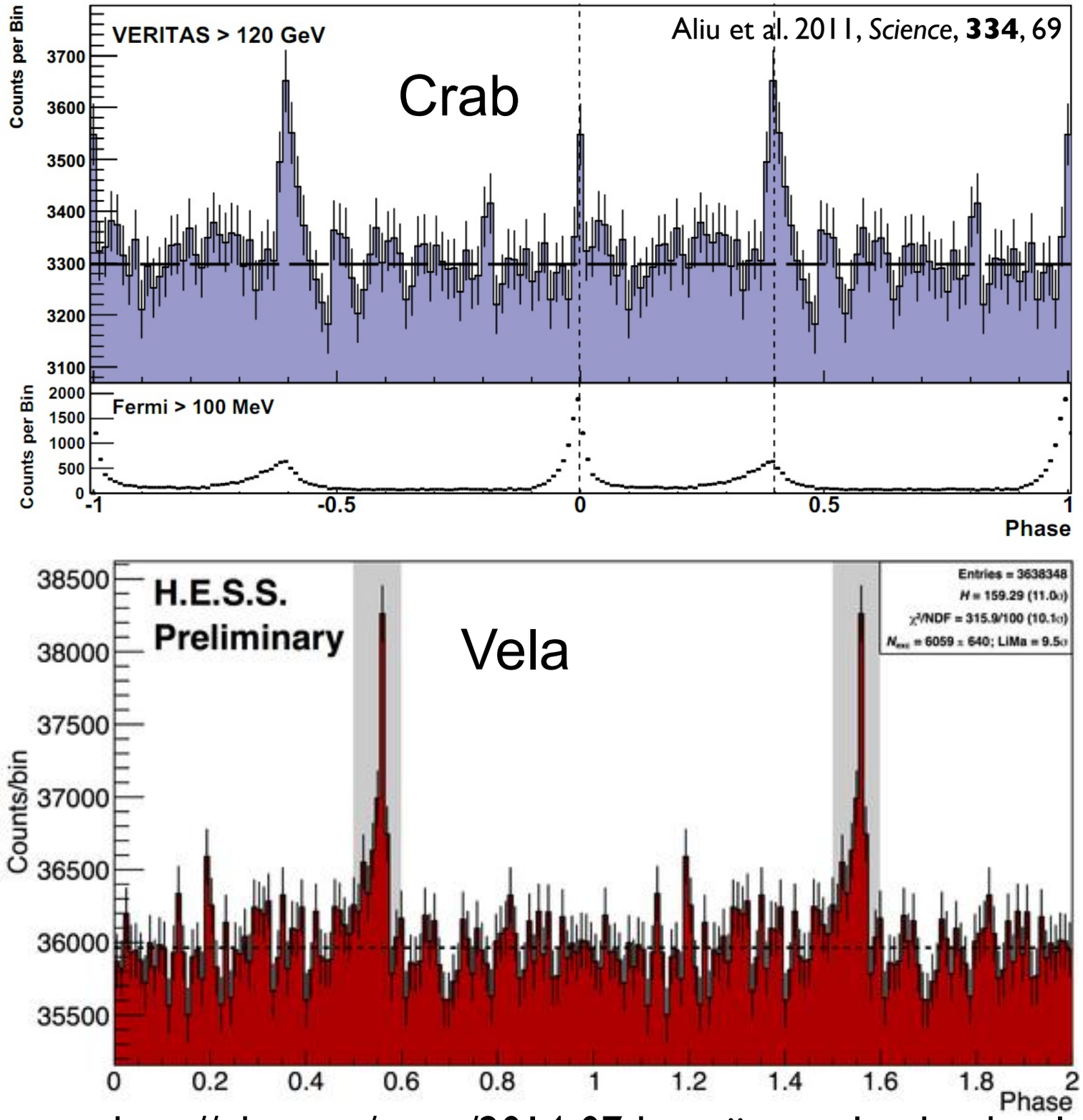
- The Crab was the first pulsar detected at > 100 GeV
- The Vela pulsar has now been detected up to 120 GeV
- Emission mechanism?
- What about other pulsars?





Romani 1996

Pulsars at VHE



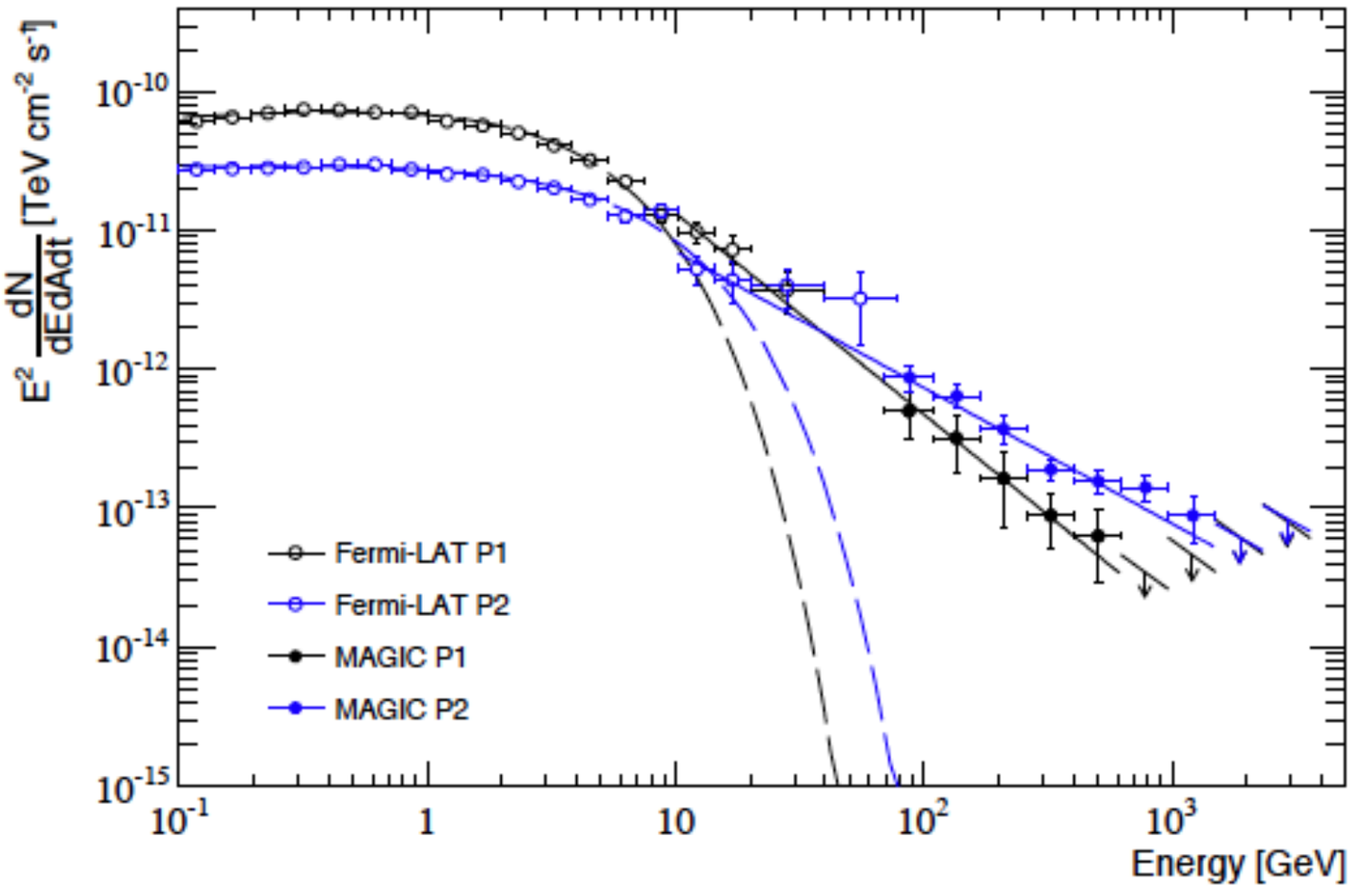
http://phys.org/news/2014-07-hess-ii-reveal-pulsar.html

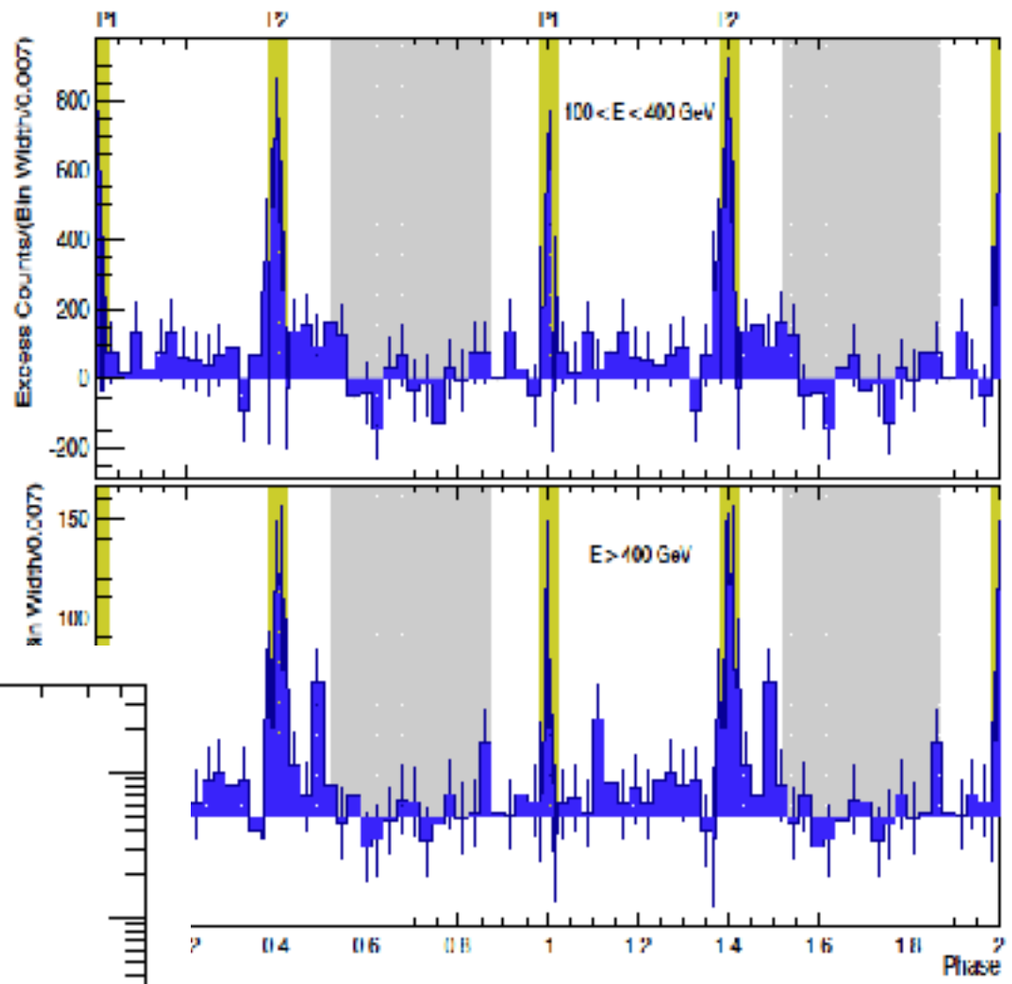
TeV Pulsations from the Crab

Astronomy & Astrophysics manuscript no. crabVHE
October 27, 2015

Teraelectronvolt pulsed emission from the Crab pulsar detected by MAGIC

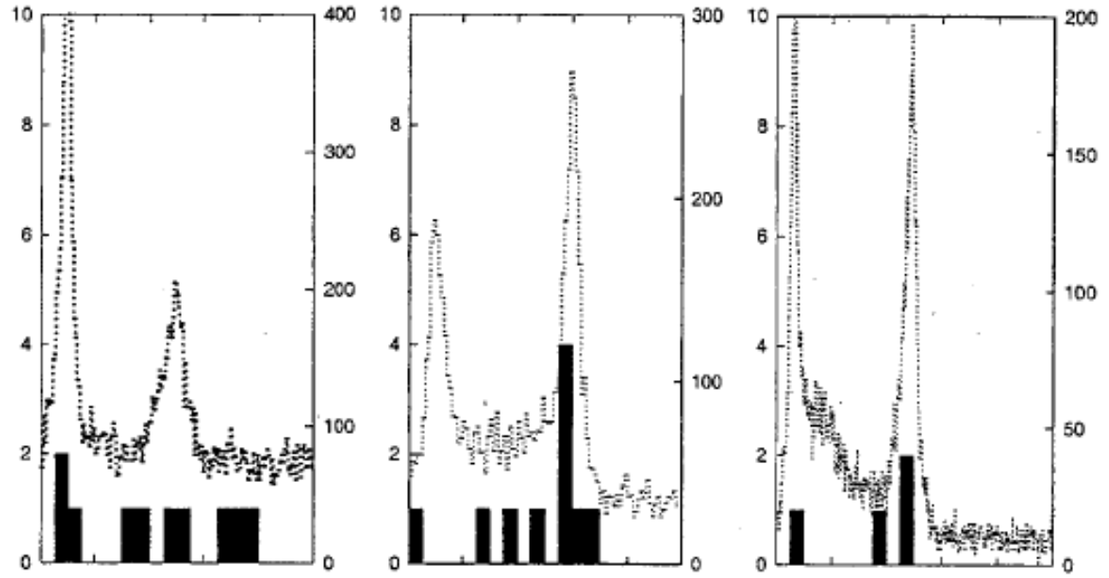
S. Ansoldi[1], L. A. Antonelli[2], P. Antoranz[3], A. Babic[4], P. Bangale[5], U. Barres de Almeida[5,26], J. A. Barrio[6], J. Becerra González[7,27], W. Bednarek[8], E. Bernardini[9], B. Biasuzzi[1], A. Biland[10], O. Blanch[11], S. Bonnefoy[6], G. Bonnoli[2], F. Borracci[5], T. Bretz[12,28], E. Carmona[13], 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. Marcote, P. Mu, K. Nishi, J. M. Pared, R. Rei, V. Scal, D. Sobczy, T. Terzić[4],





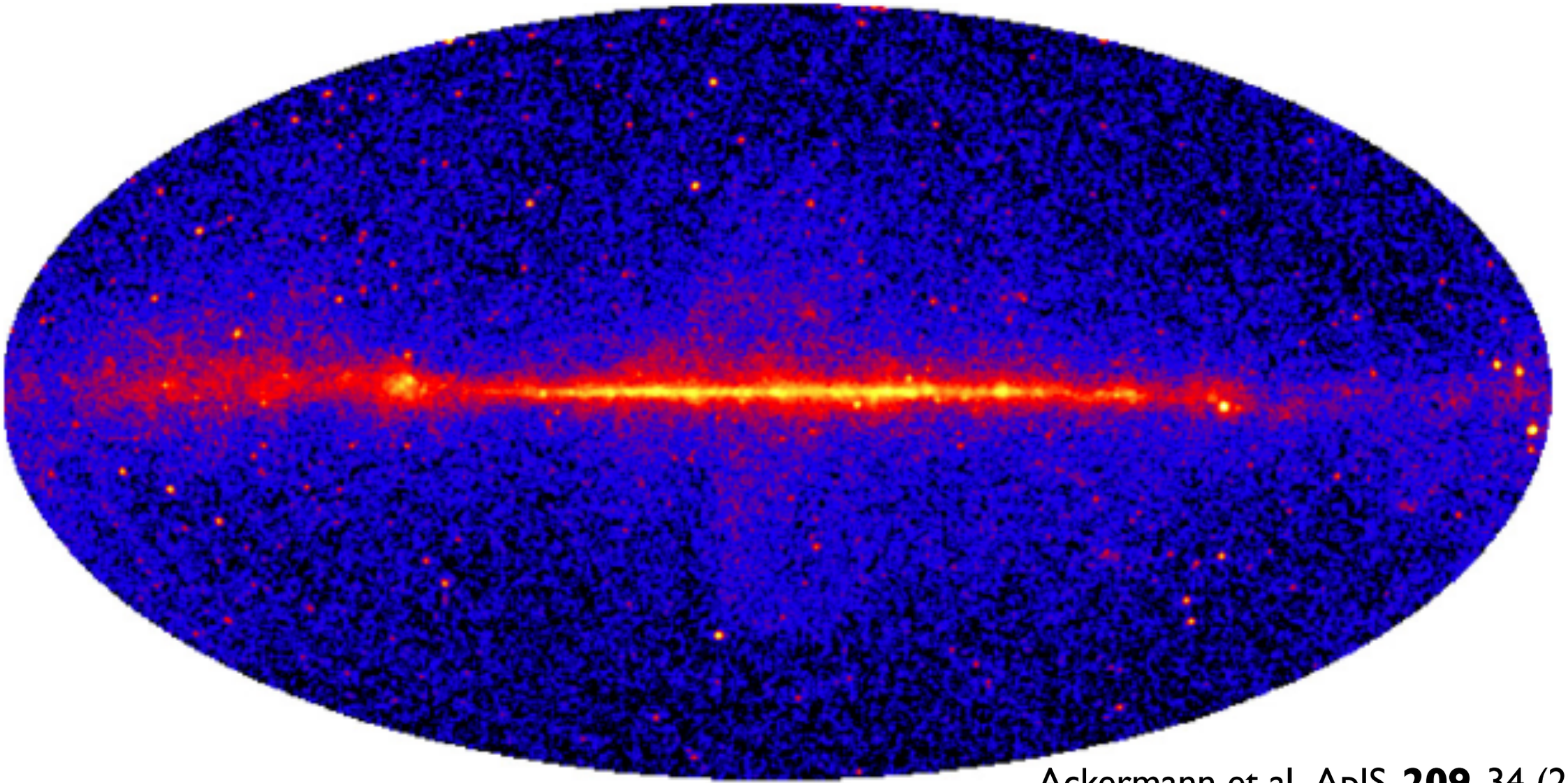
Pulsars above 10 GeV (EGRET)

- 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)

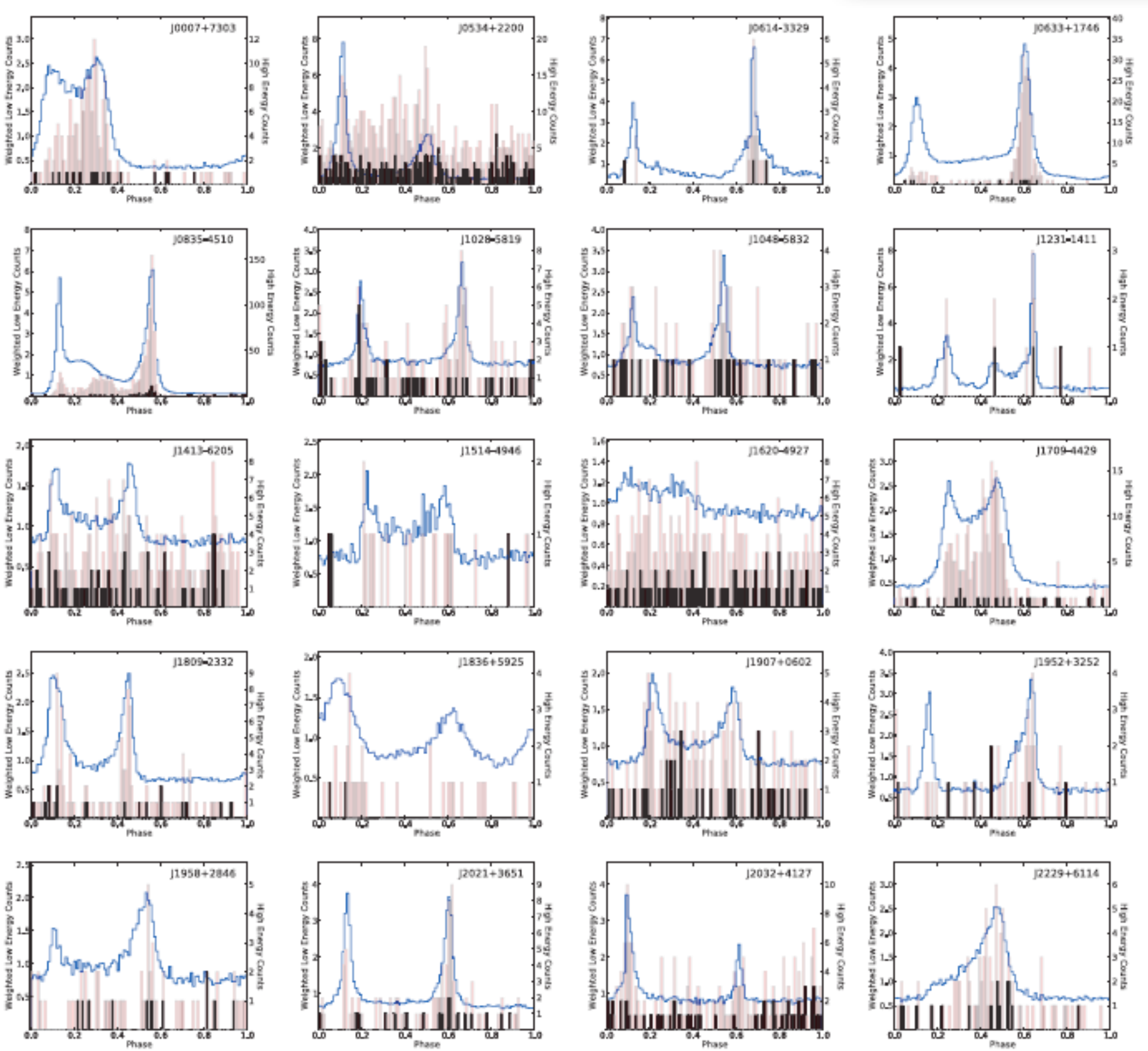
Pulsar associations in 1FHL

- 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

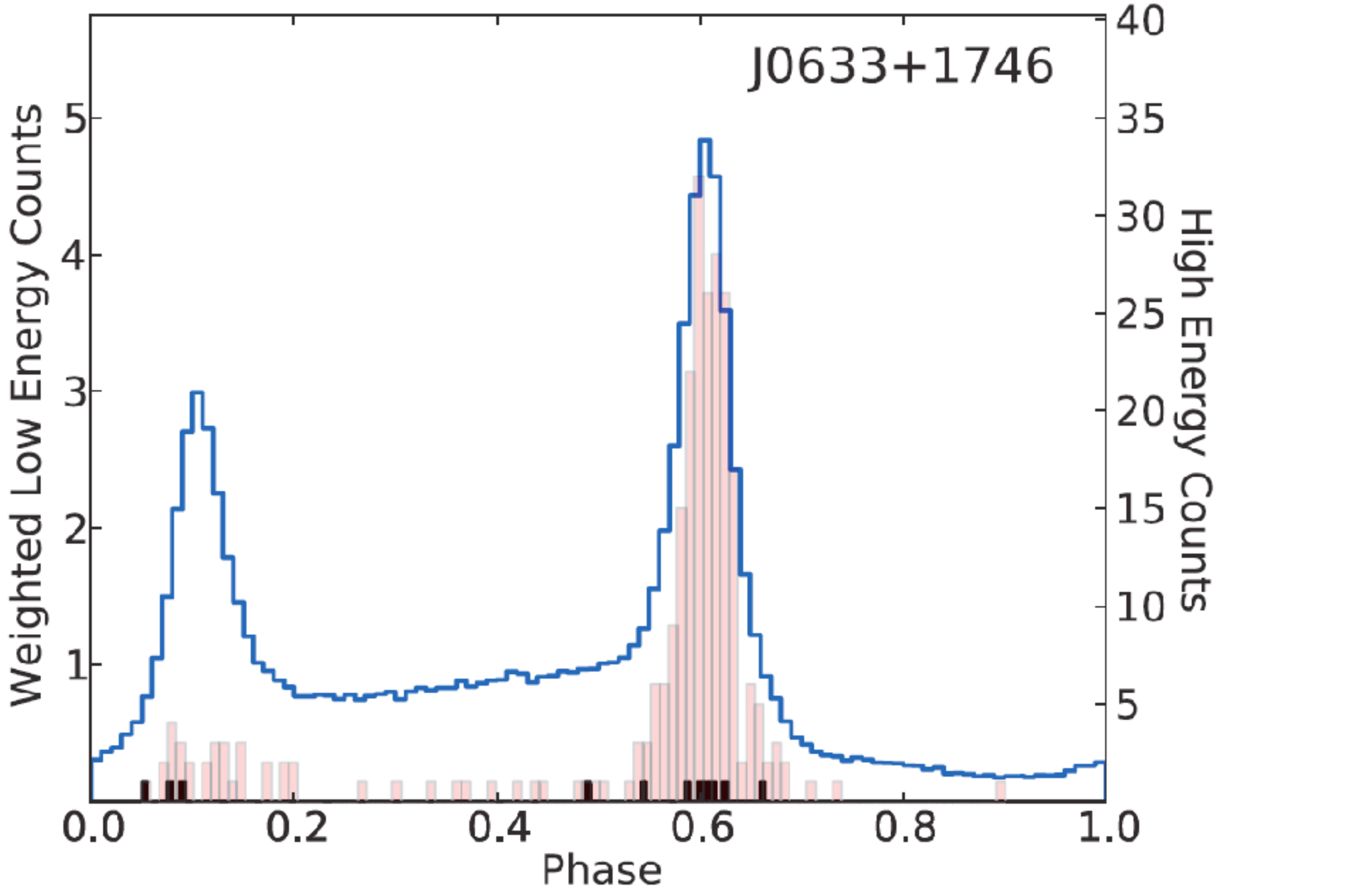
Q: Does the > 10 GeV emission come from the pulsar?

A: Test for pulsations using prior low-energy information

The 1FHL Catalog



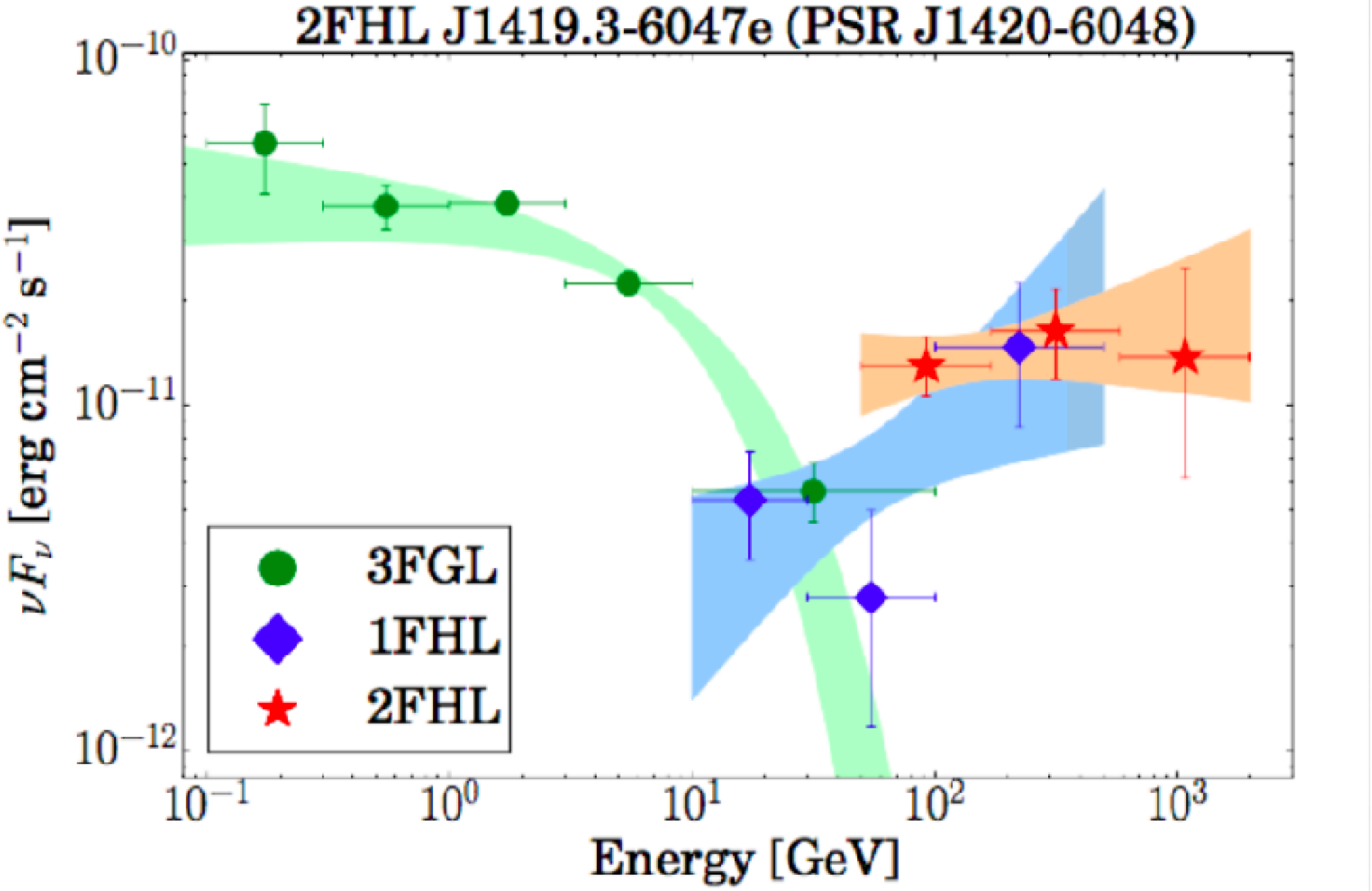
Geminga


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**$^{\dagger\#}$	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**$^{\dagger\#}$	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

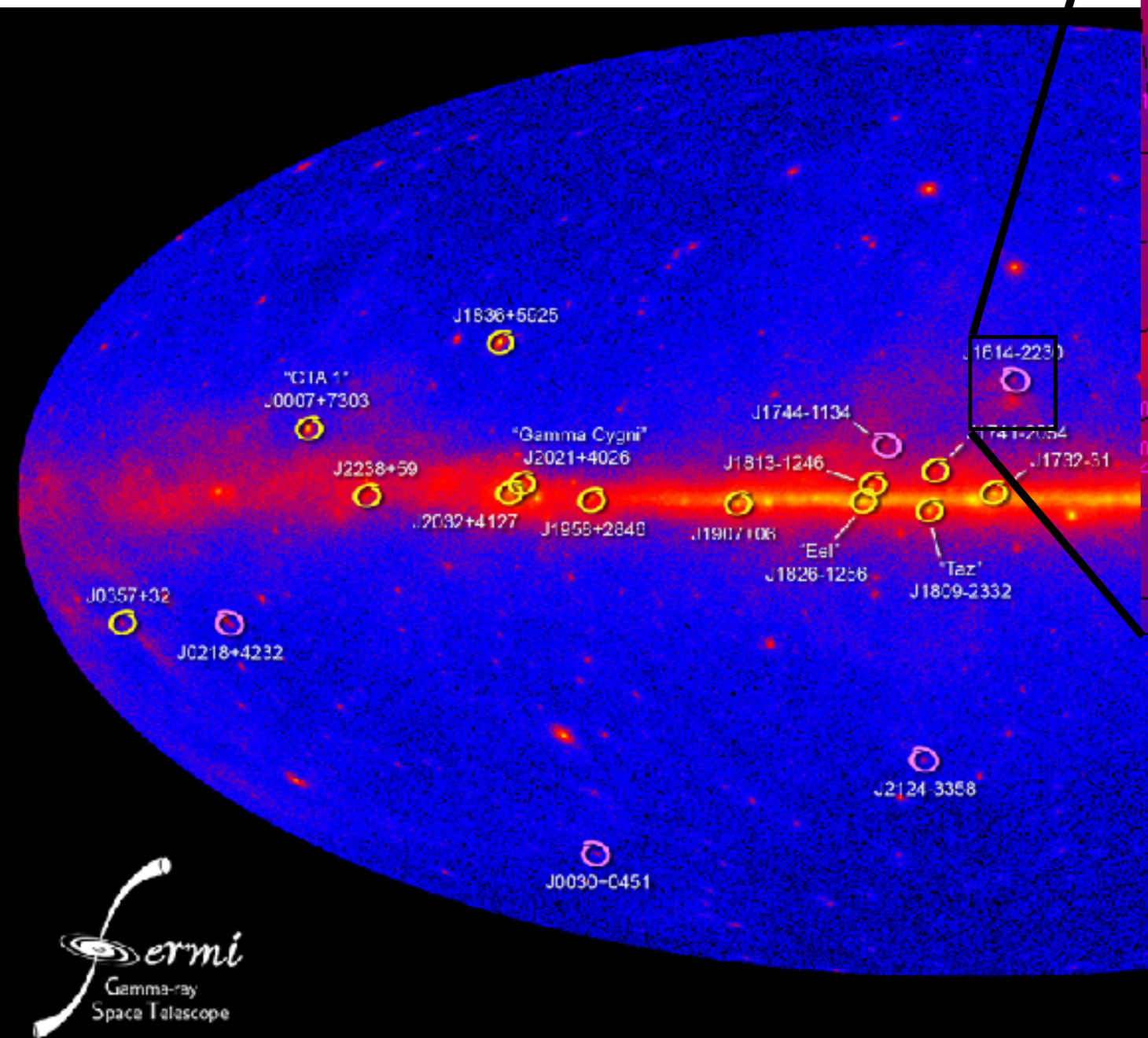
Table 11

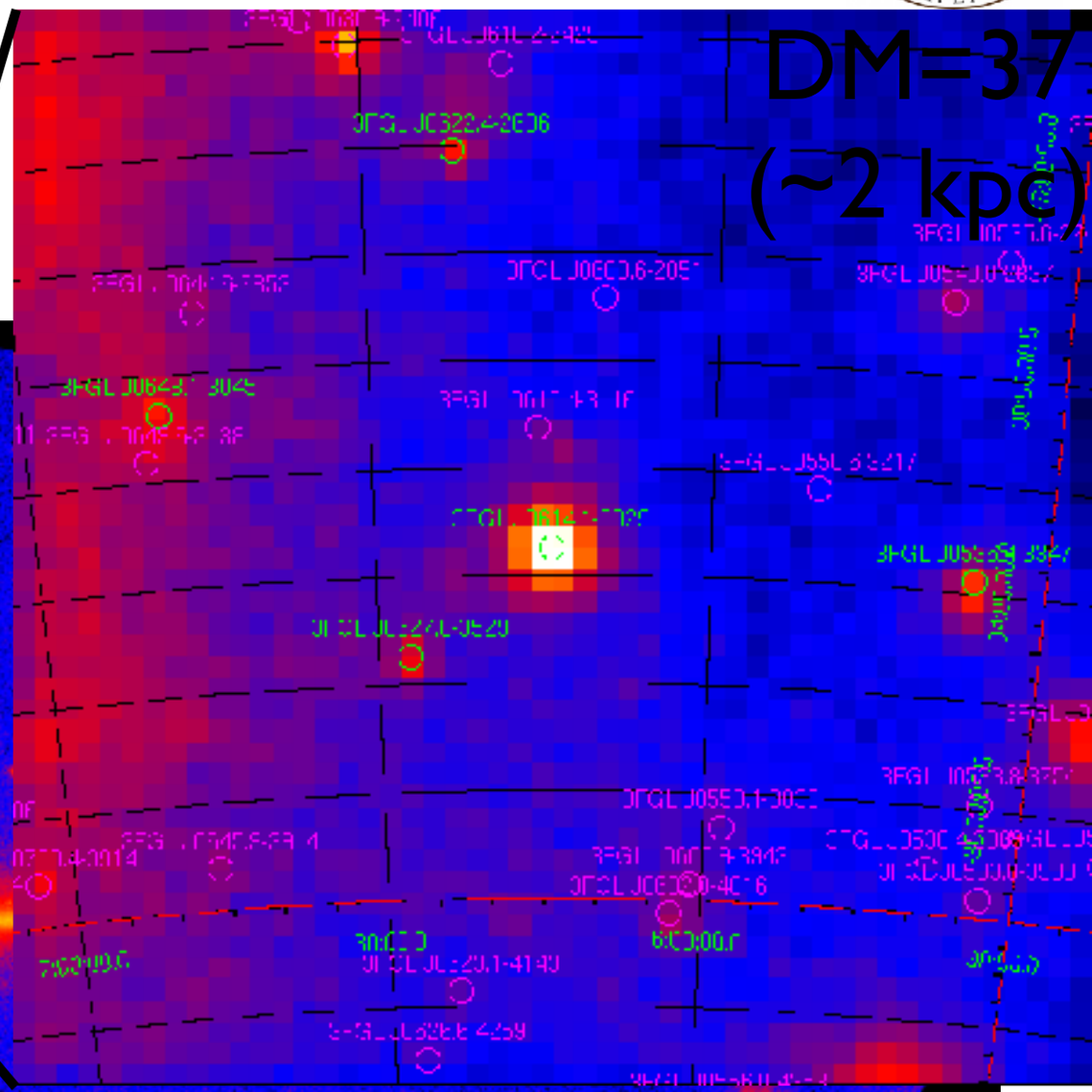
Fermi-LAT γ-Ray Pulsars Detected above 25 GeV

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)



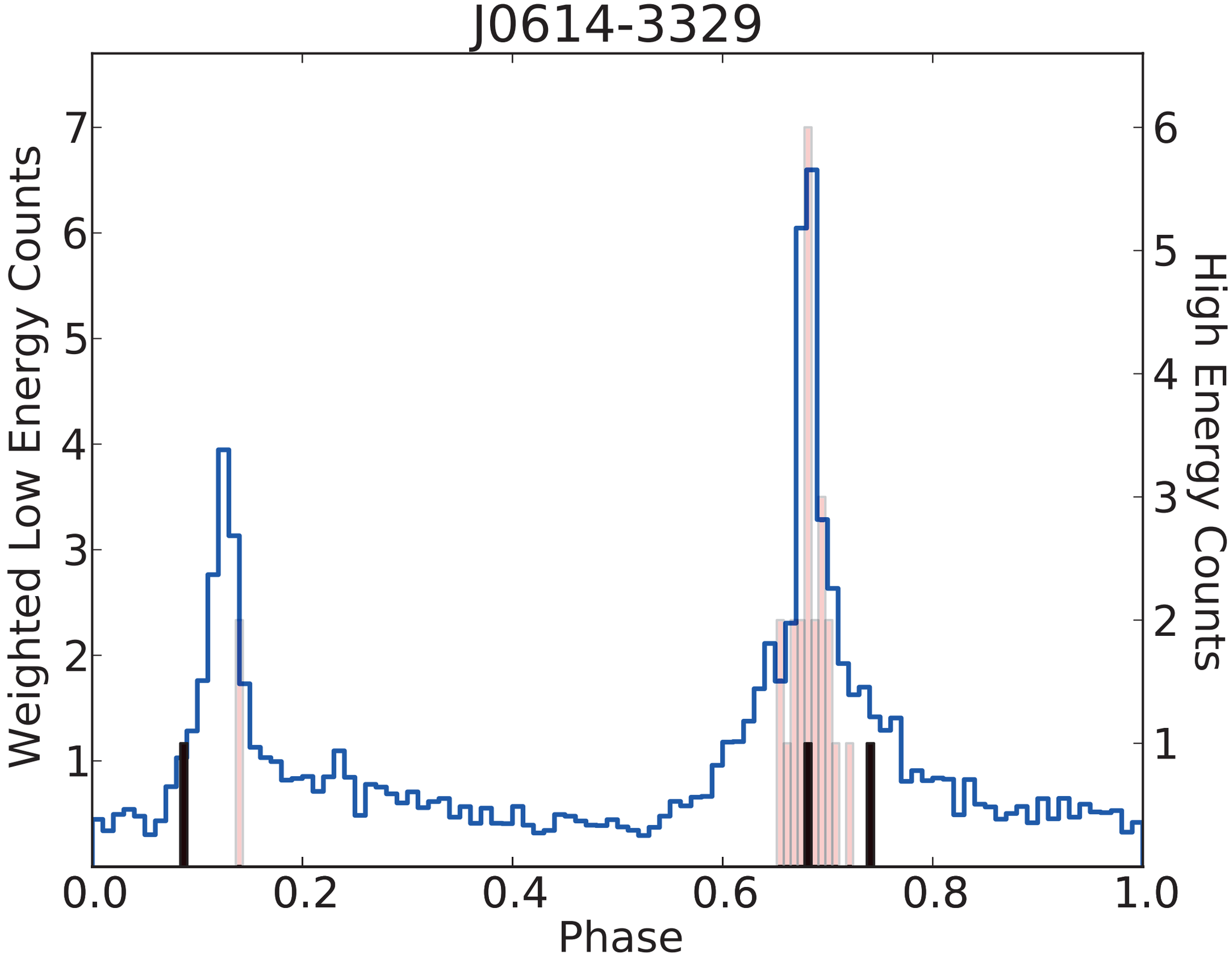


Fermi Gamma-ray Space Telescope

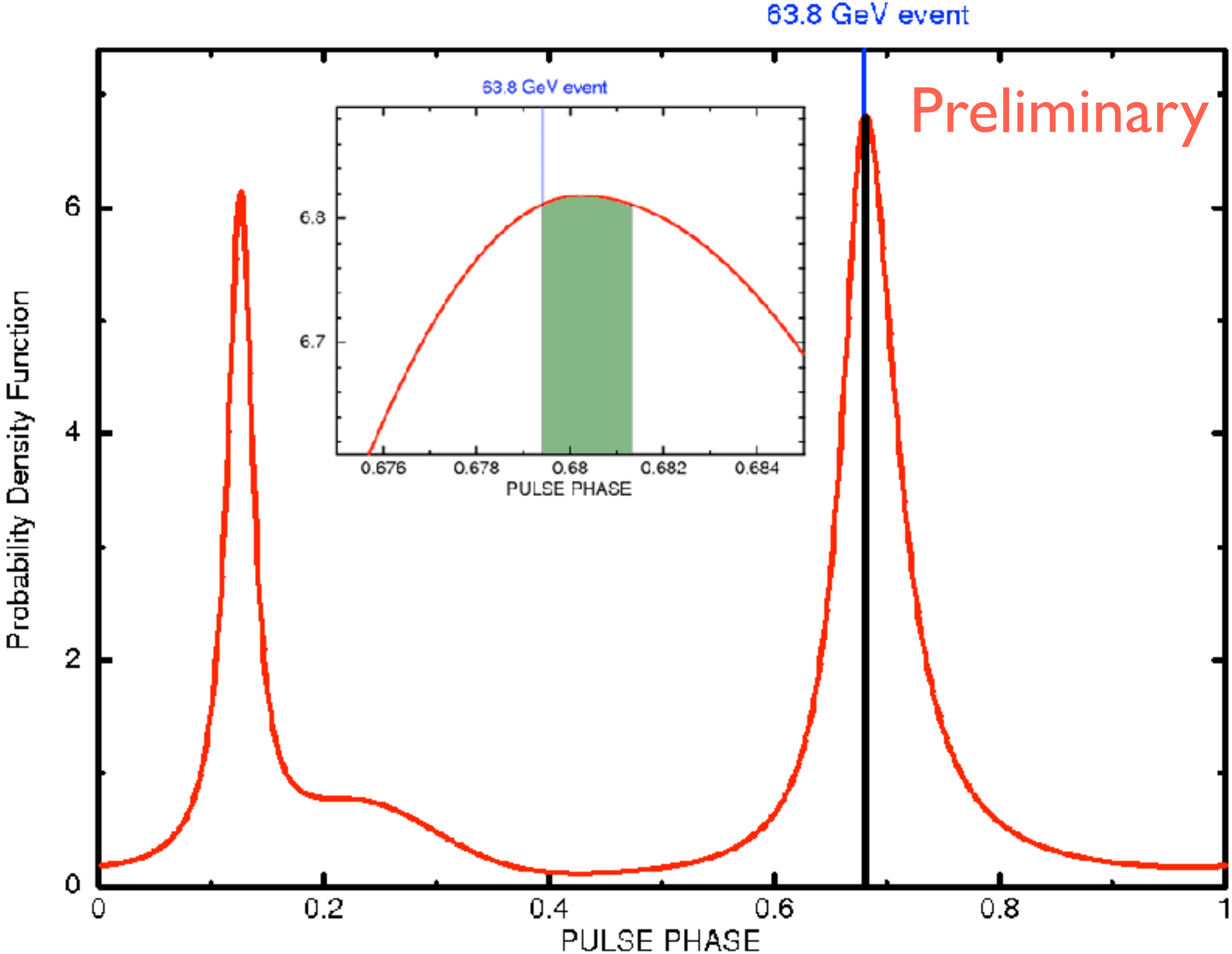
New pulsars found in a blind search

Millisecond radio pulsars

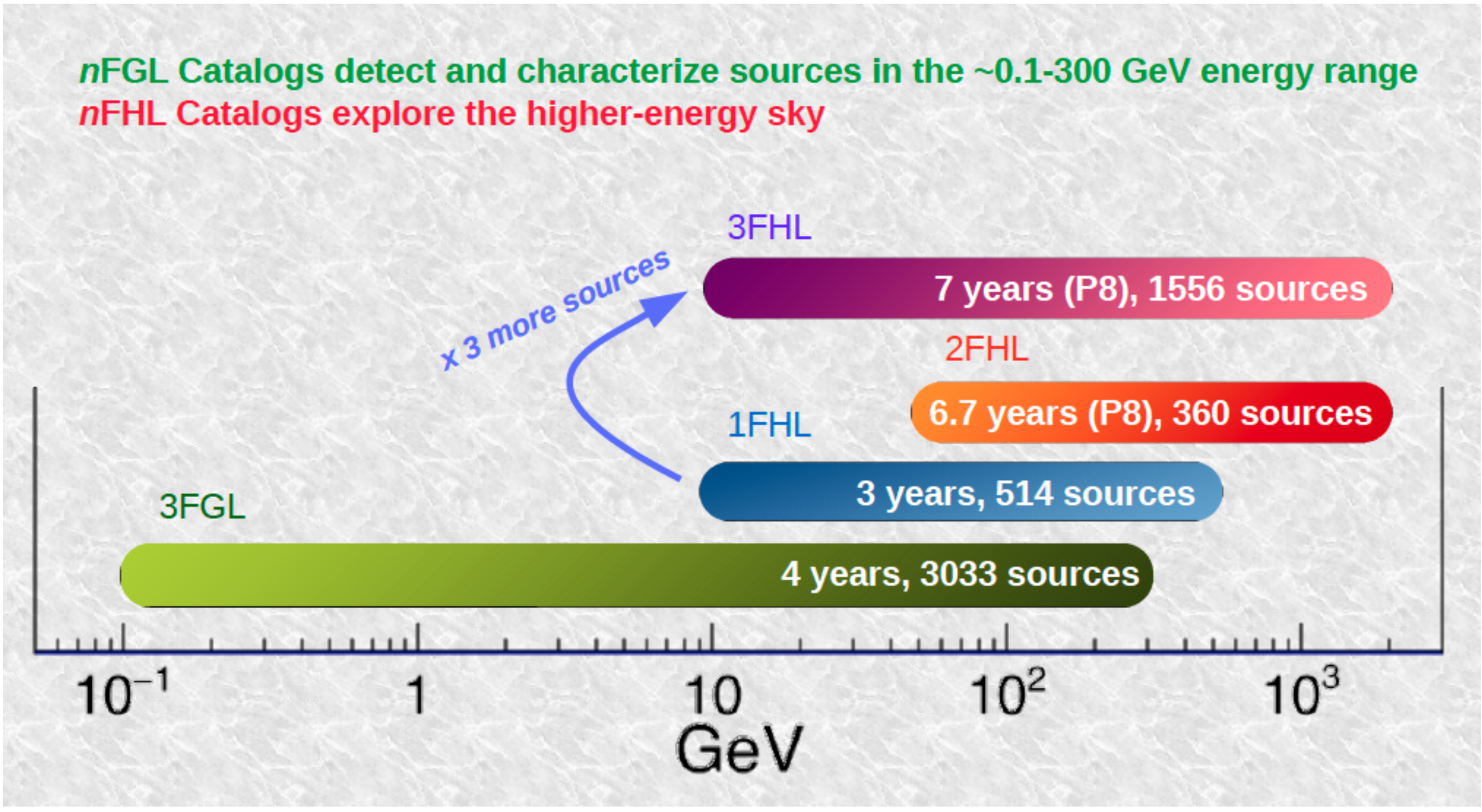
A closer look at J0614-3329



63 GeV pulsations?



3FHL Catalog



Credit: A. Dominguez

3FHL Catalog

Ajello et al. (2017 [arXiv:1702.00664]

Analysis details

- 10 GeV – 2 TeV
- 84 months of data (until August 2015)
- Pass 8 (source)
- PSF types

  Unbinned likelihood

Detections (Preliminary!)

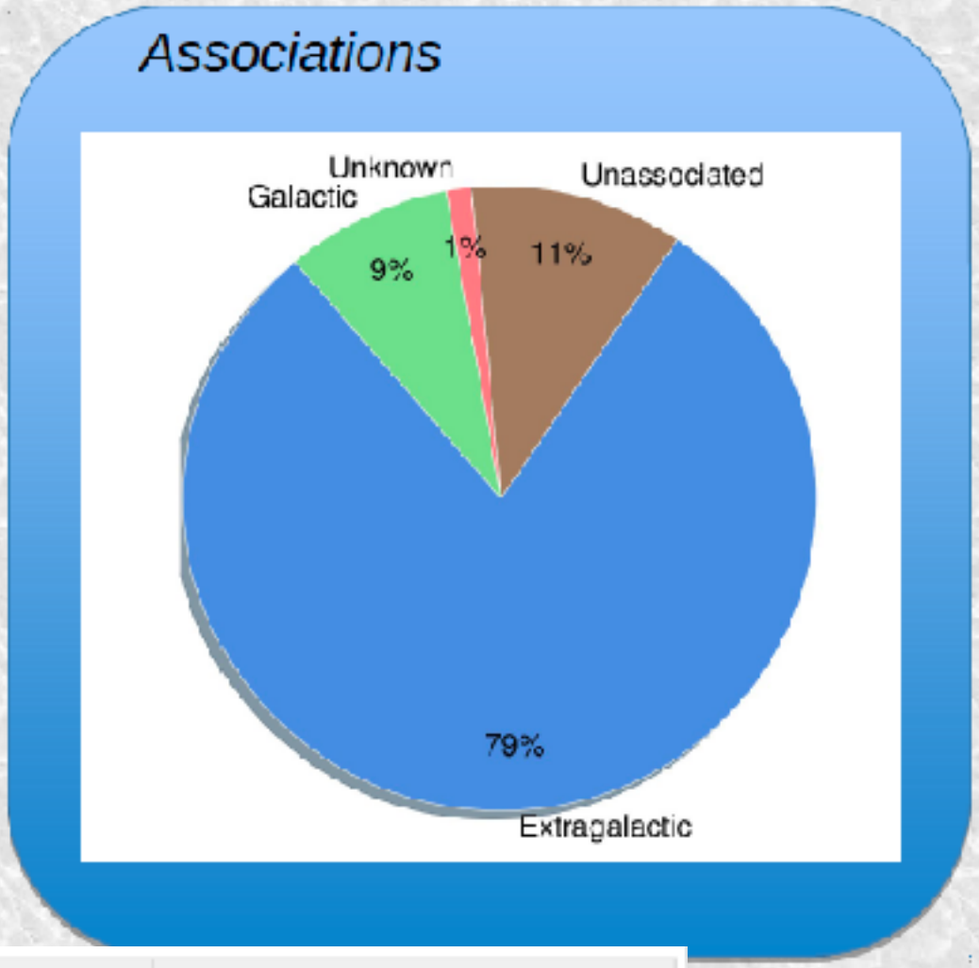
1556 sources (vs. 514 1FHL):

- 79% extragalactic, 9% Galactic, 11% unassociated (in 1FHL 13%), 1% Unknown

48 extended sources (27 from FGES: M. Lemoine-Goumard, J. Cohen, et al.)

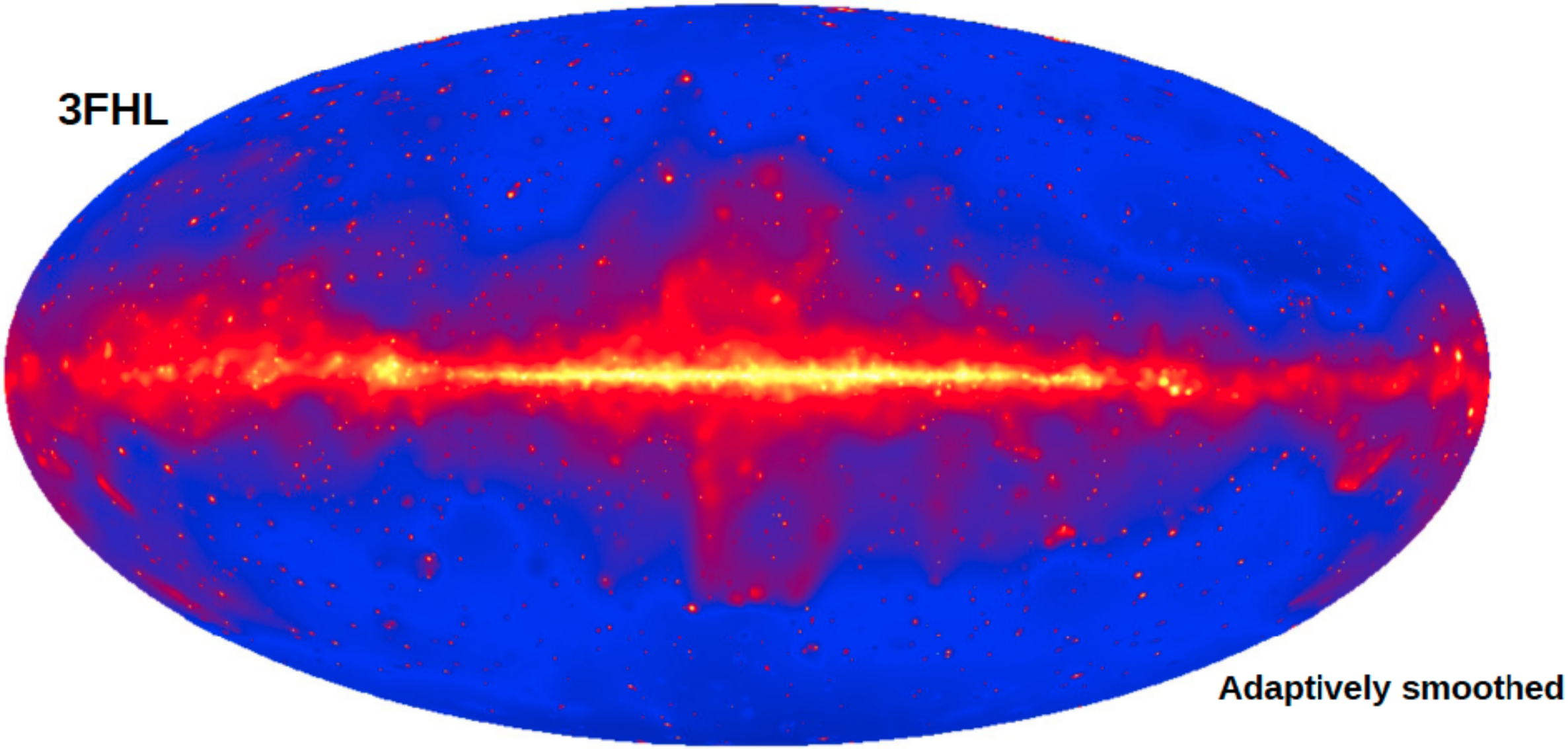
- 1286 detected in 3FGL
- 476 detected in 1FHL

  312 detected in 2FHL
- 132 detected by IACTs (TeVCat)
- 226 brand new sources (not in 1FHL/2FHL/3FGL/TeVCat)

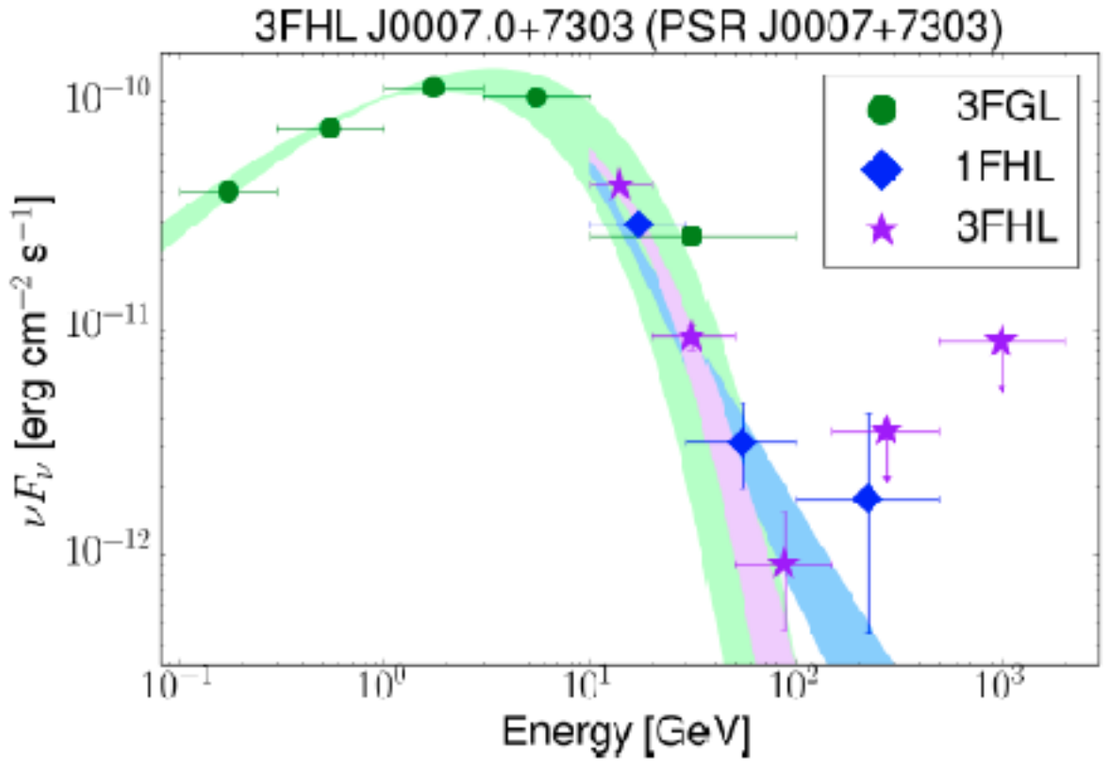


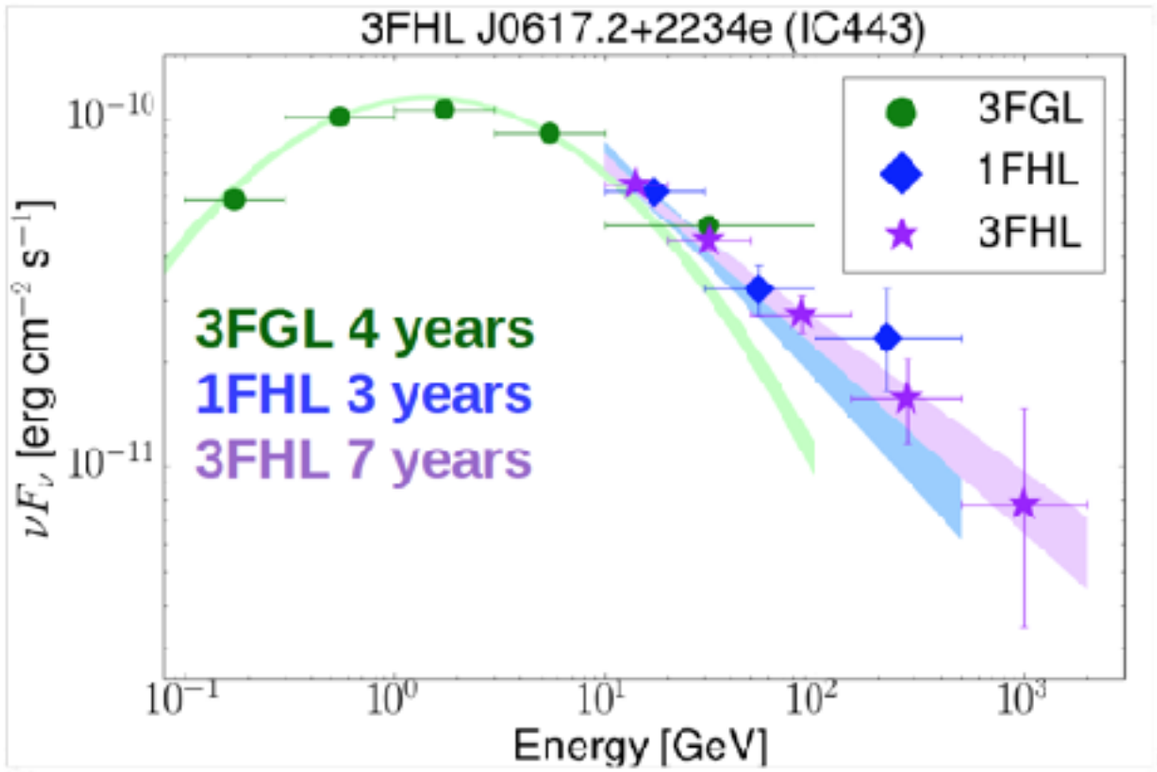
Comparison Summary	1FHL (3 years+Pass7)	3FHL (7 years+Pass8)
Number of sources	514	1556
Number of extended sources	18	48
Flux above 10 GeV (ph/cm2/s)	1.29 (0.87, 2.74) x 10^-10	5.03 (3.22, 10.33) x 10^-11
Spectral Index	2.36 (2.01, 2.90)	2.47 (2.13, 2.93)
Positional Uncertainty (deg)	0.079 (0.054, 0.097)	0.038 (0.028, 0.049)
Significance	6.17 (4.71, 9.37)	7.04 (5.18, 10.88)

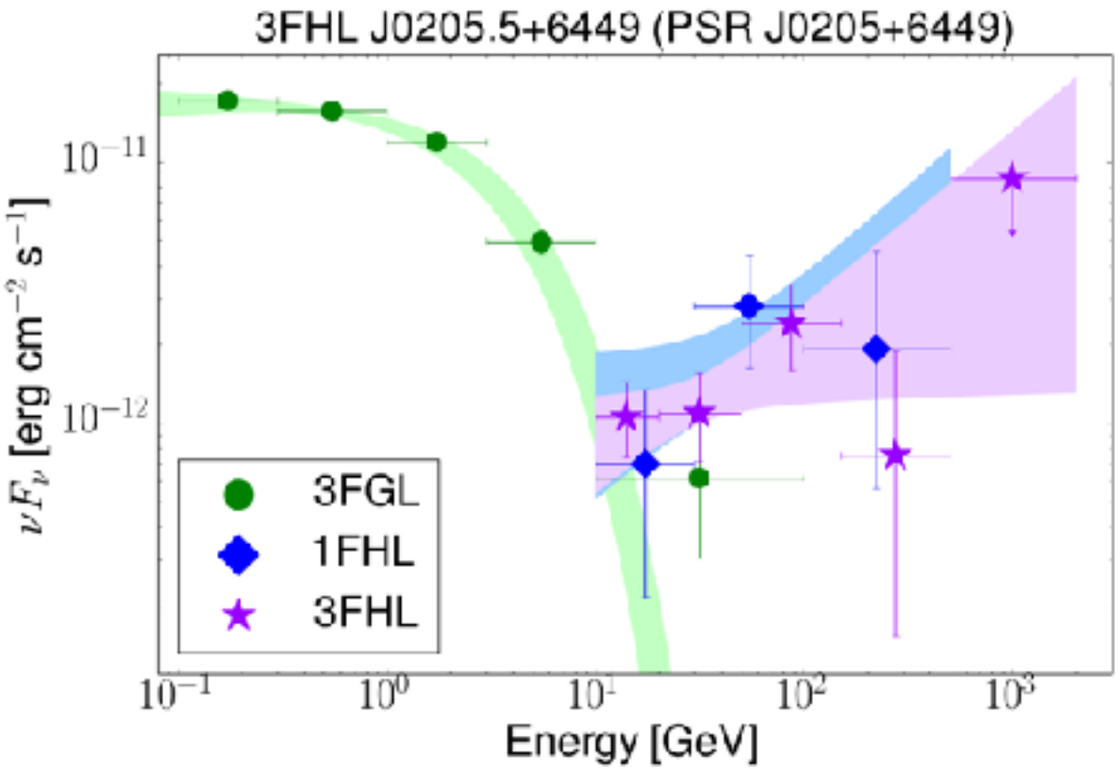
3FHL Sky Map

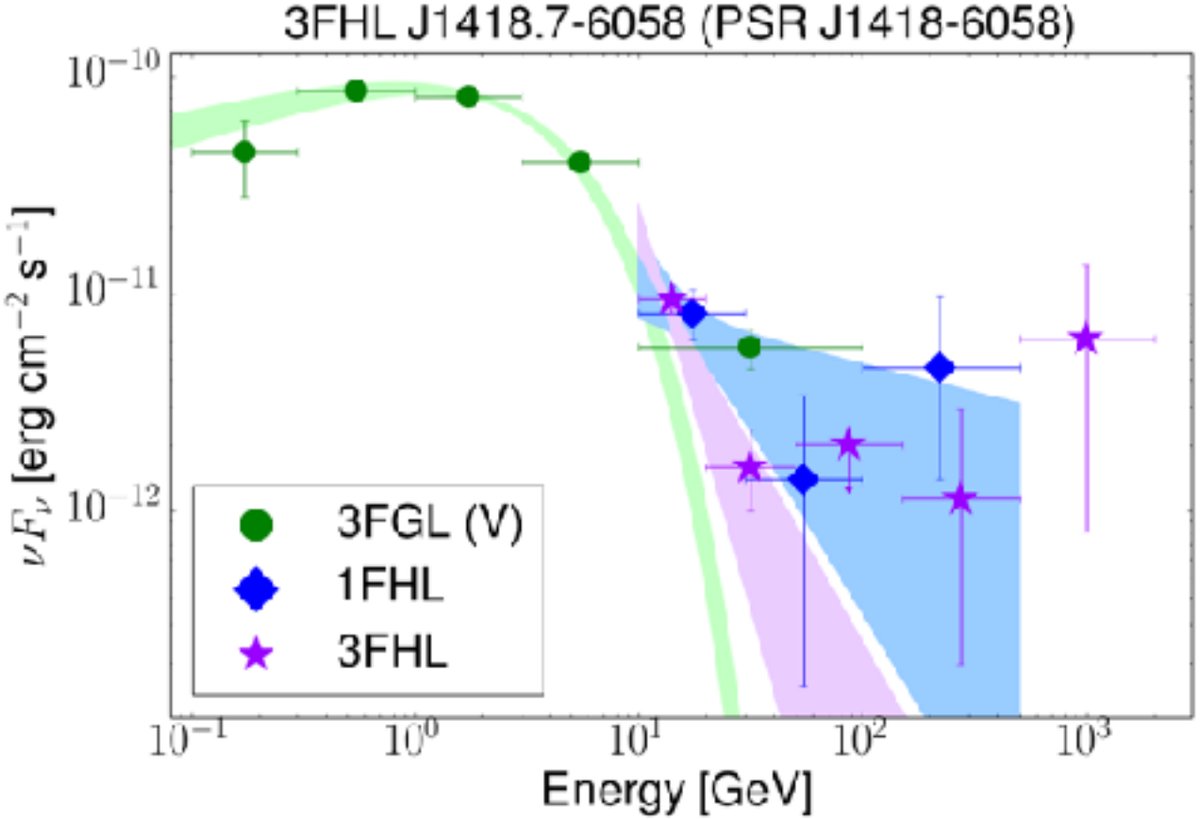

3FHL
Adaptively smoothed
About 1,556 sources at E>10 GeV in 84 months of *Fermi*-LAT data (~700,000 photons)
0
0.0099
0.03
0.069
0.15
0.31
0.62
1.2
2.5
5
10

Spectral Energy Distributions

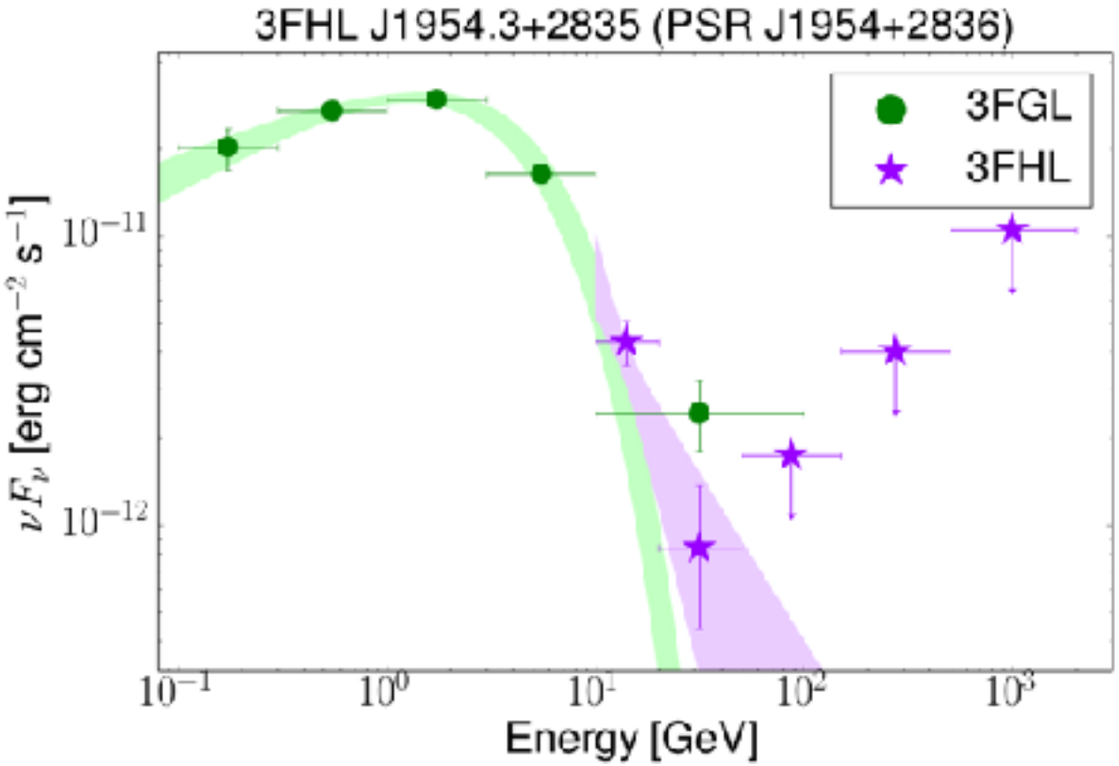


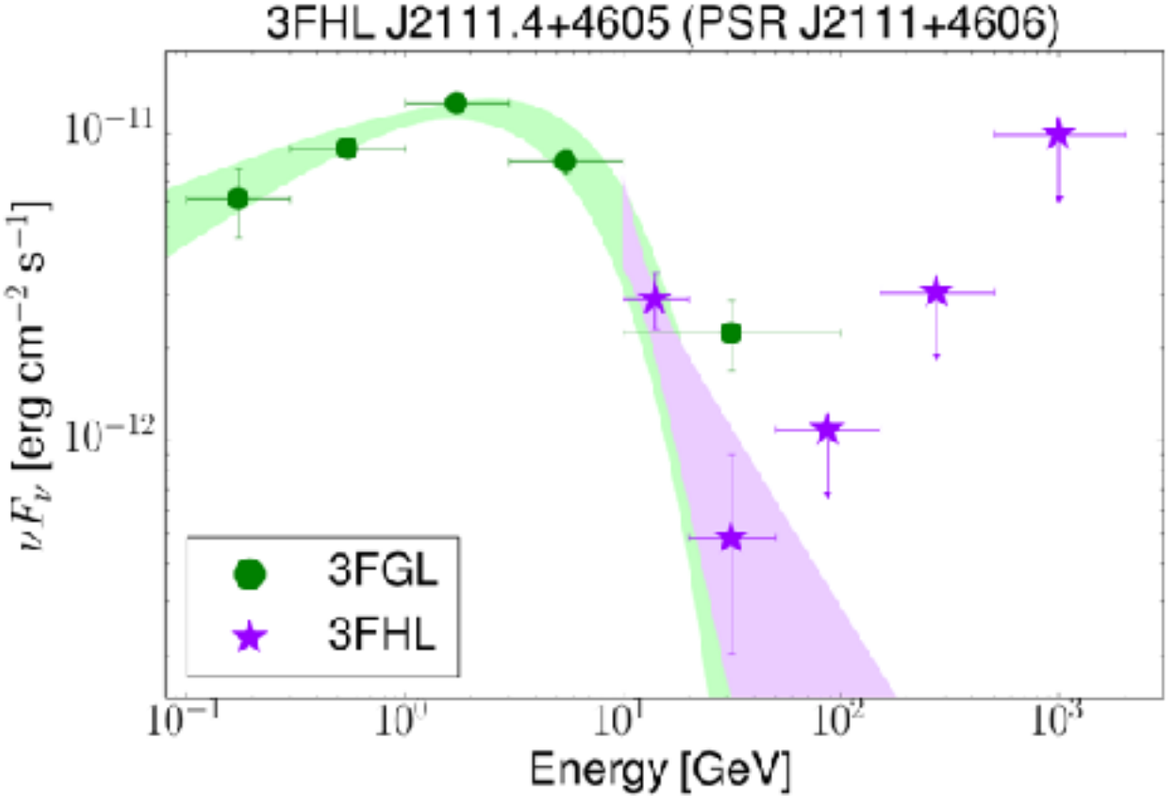


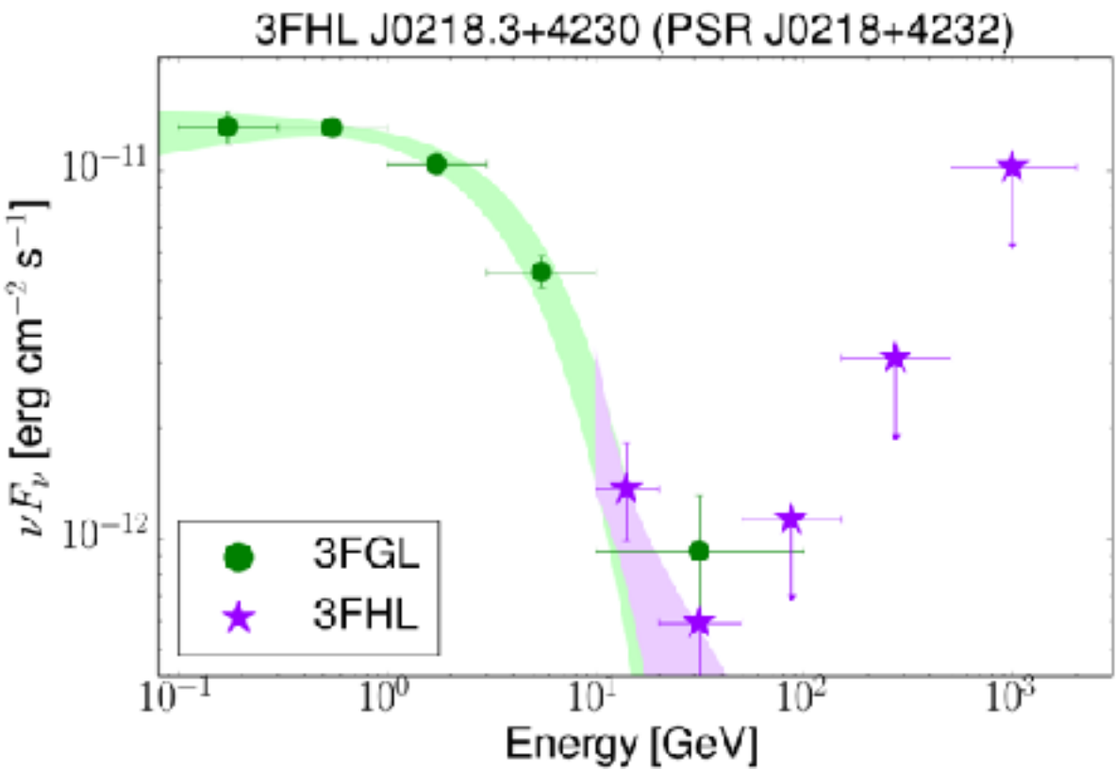


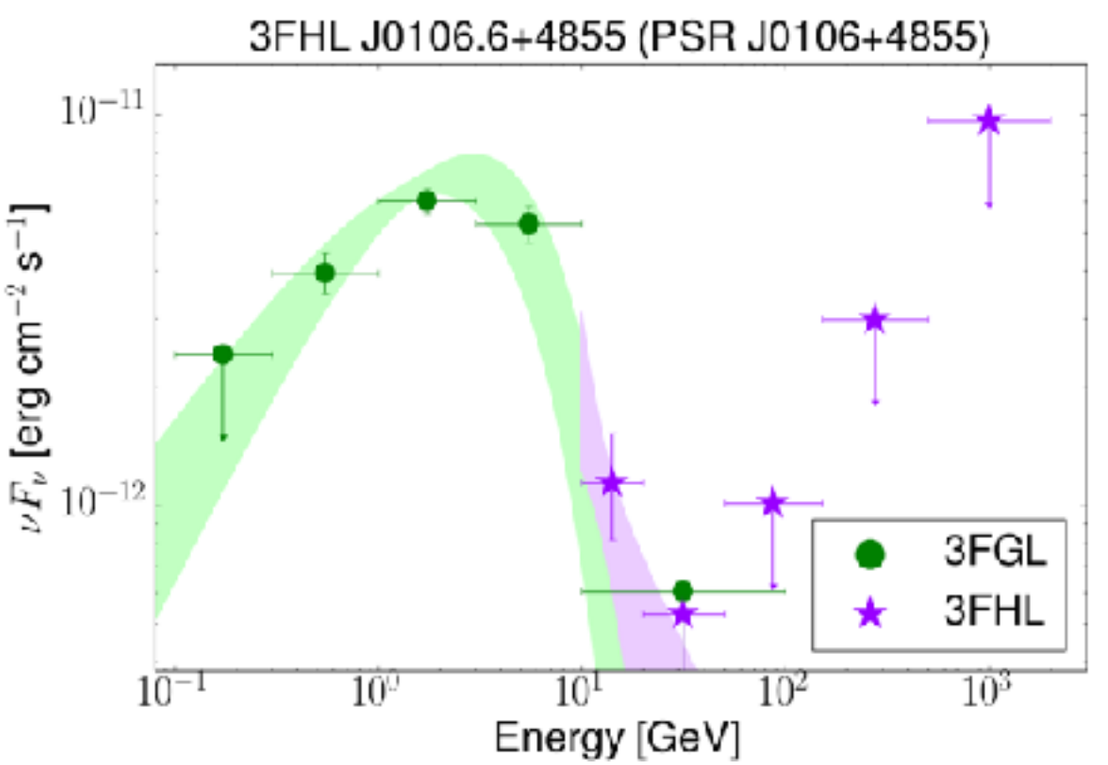


Spectral Energy Distributions





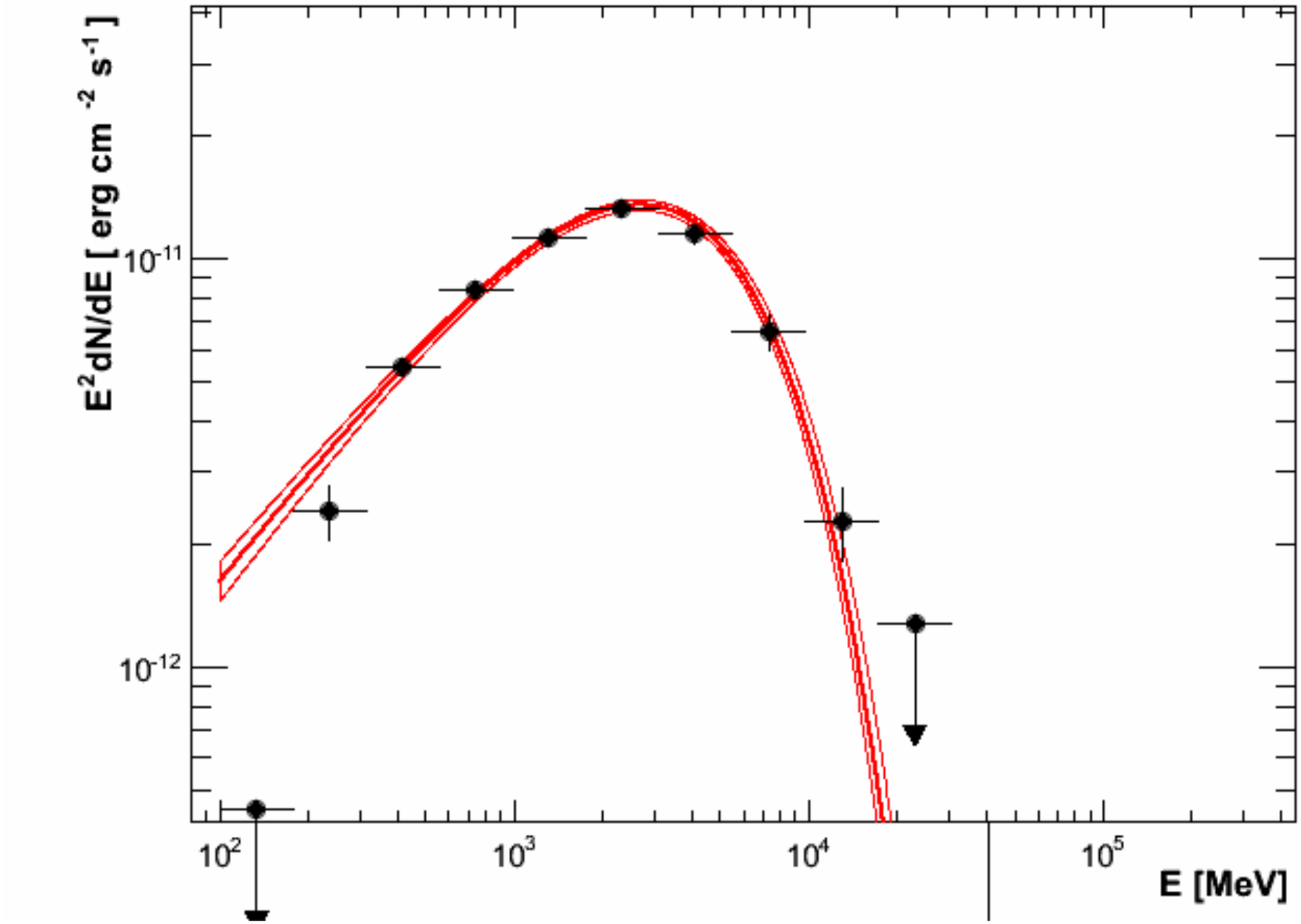




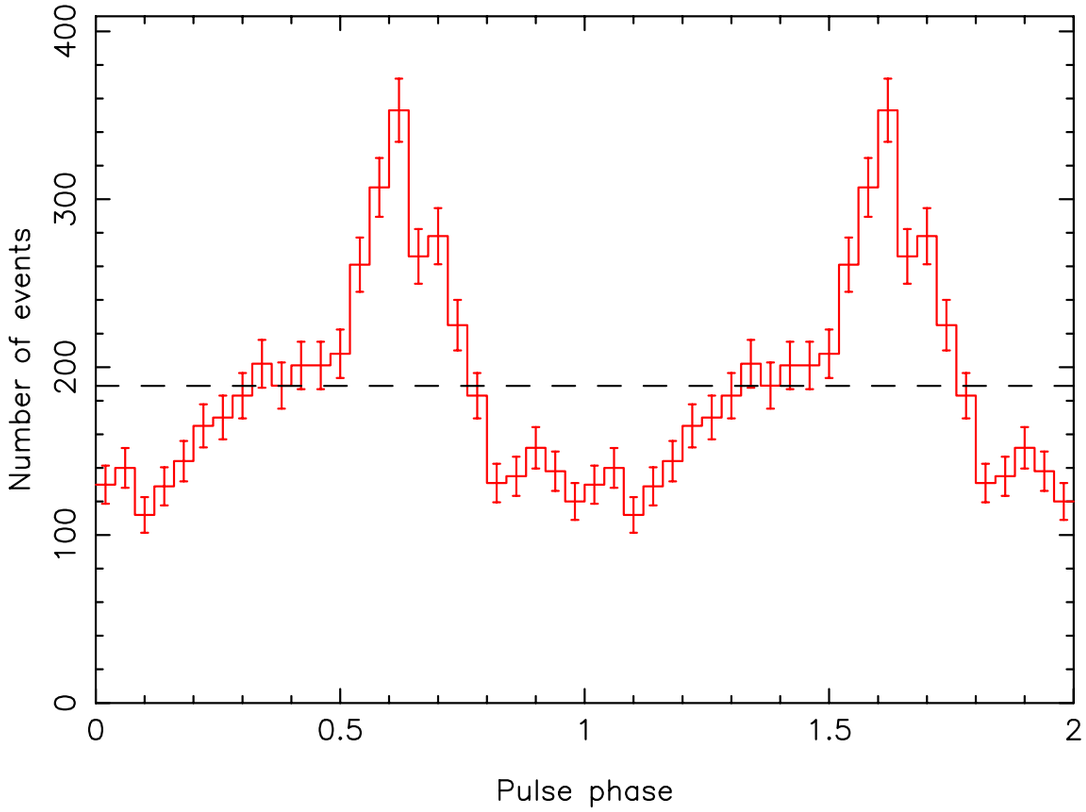
The search for new HPSRs

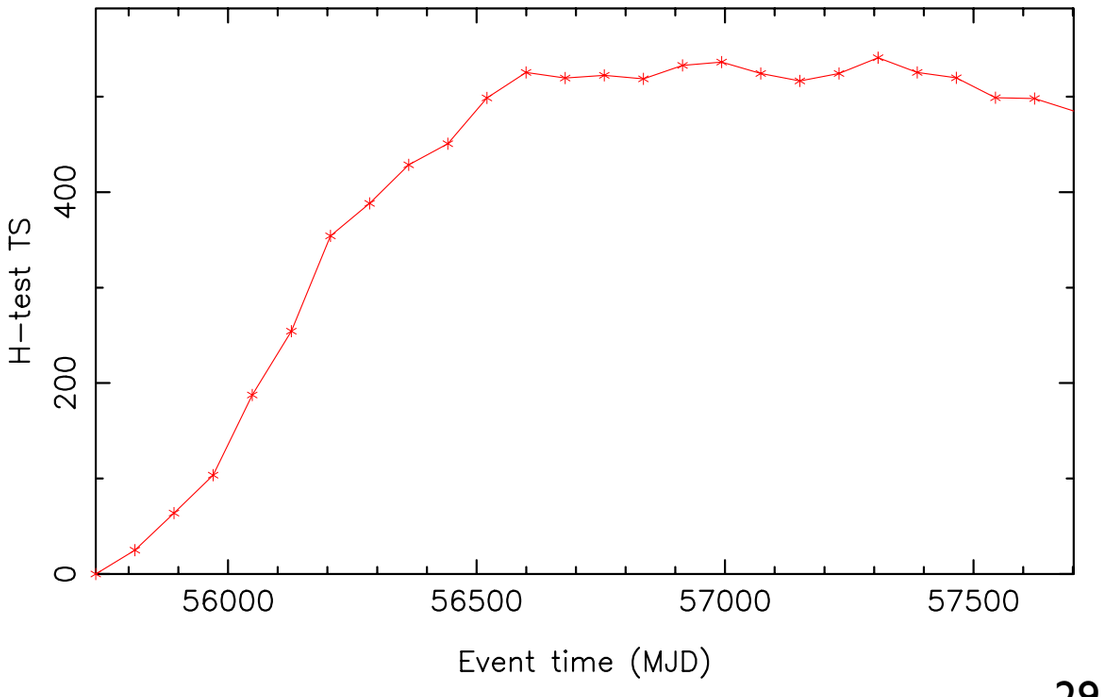
	1FHL	3FHL
Data Span	3 Years	7 Years
LAT IRFs	Pass 7	Pass 8
# Sources	514	1556
# Pulsar Associations	27	62
HPSR (>10 GeV)	20 (+8)	?
HPSR (>25 GeV)	12 (+1)	?

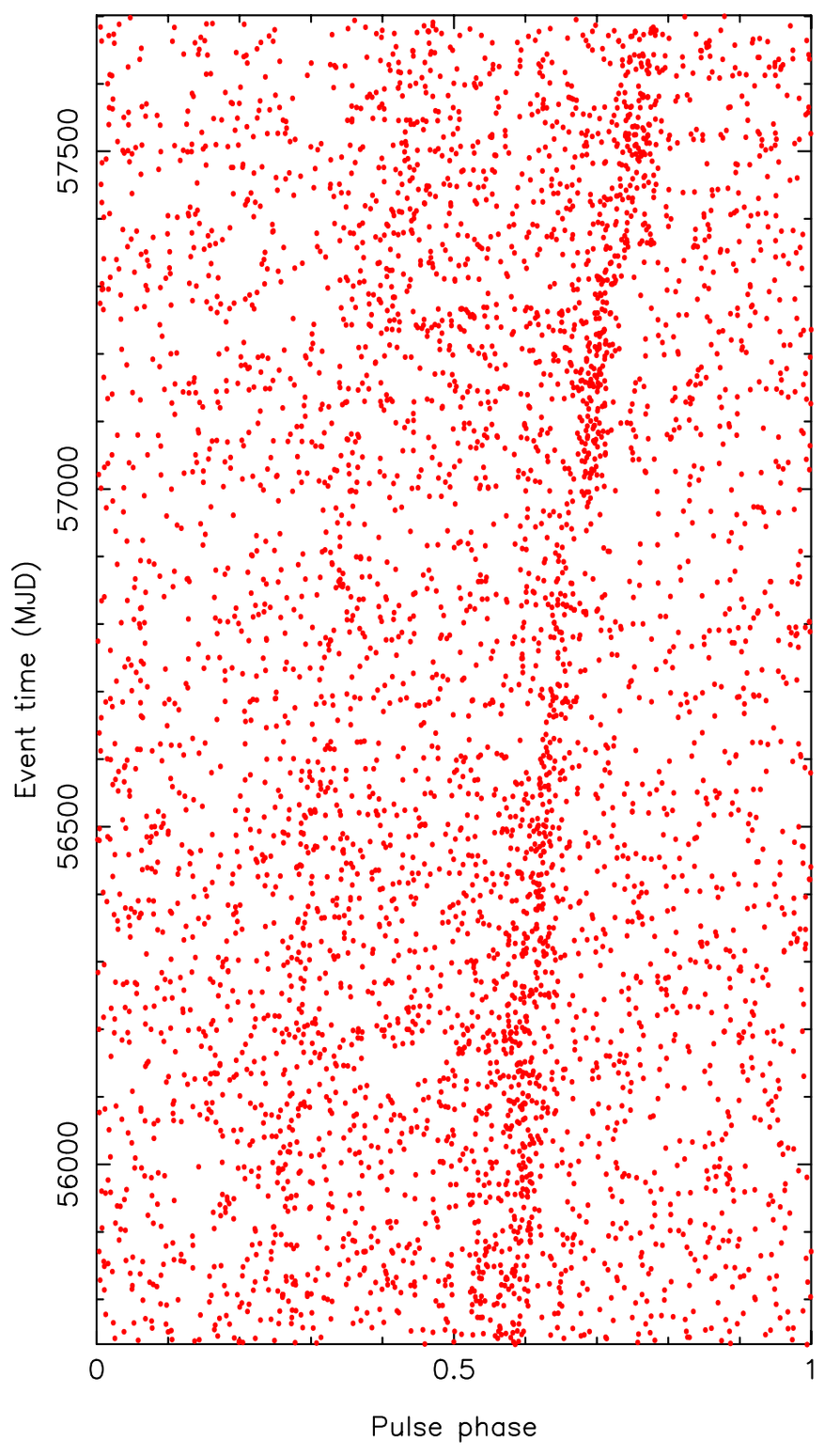
Updating Spectral Models



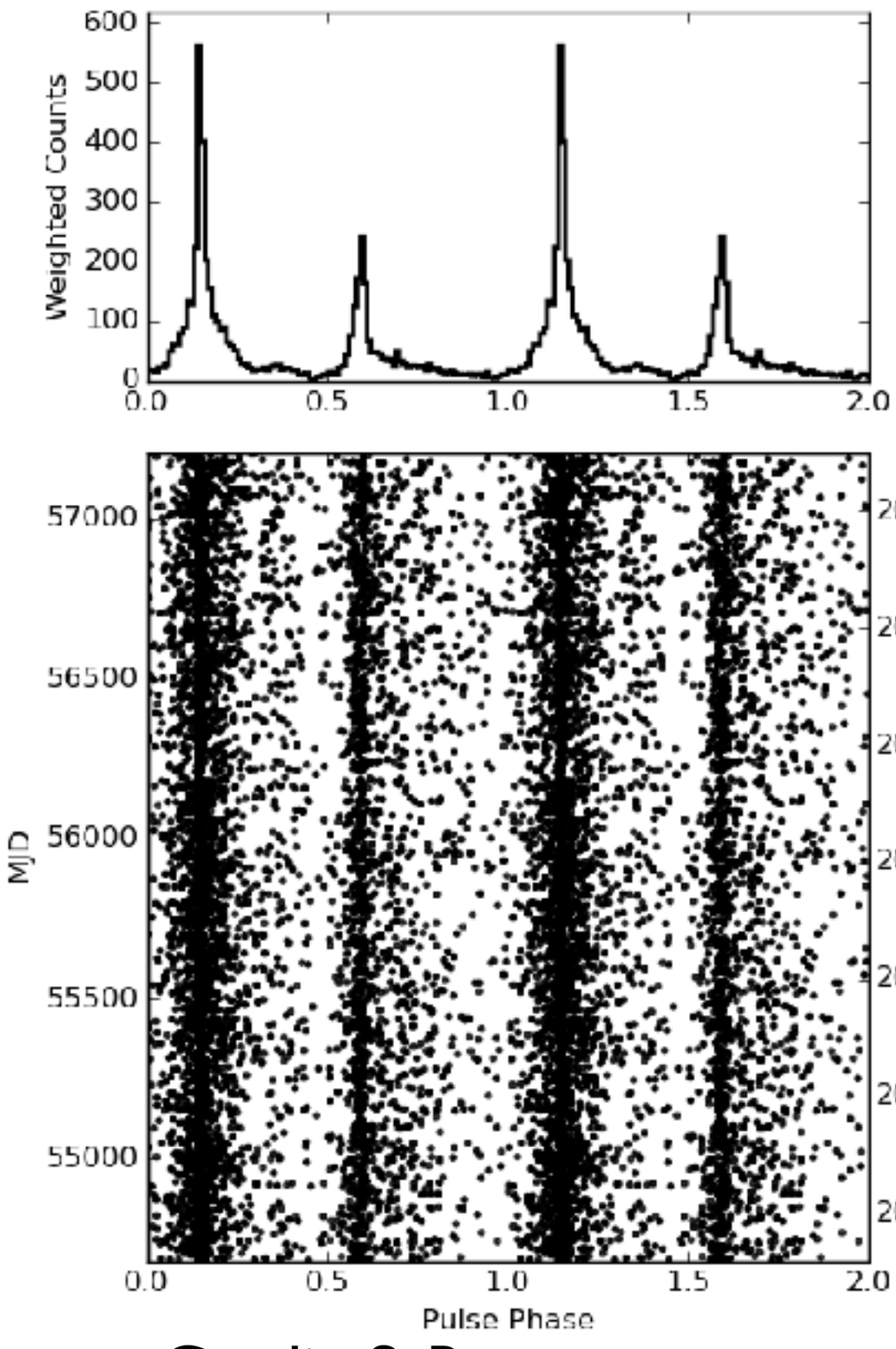
Updating timing models



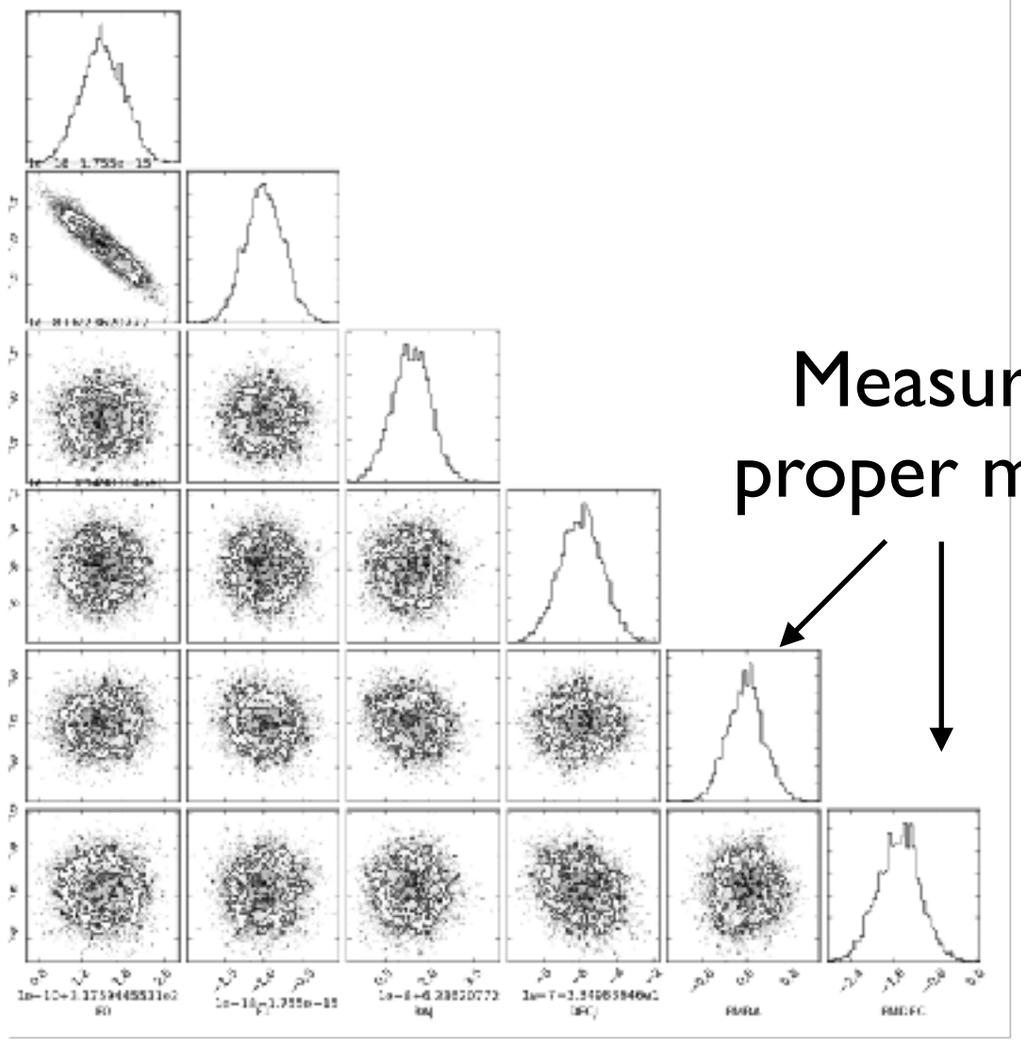




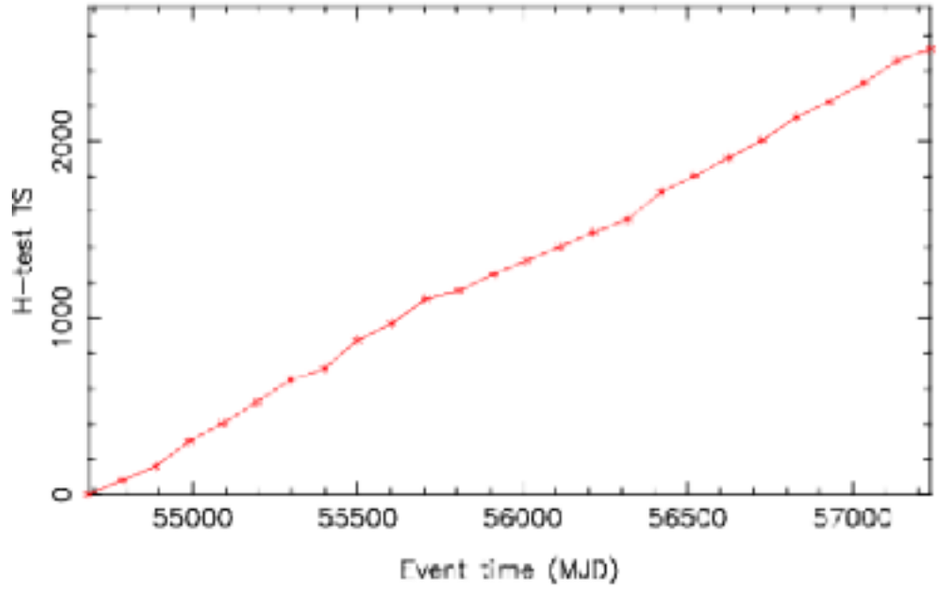
Updated timing model



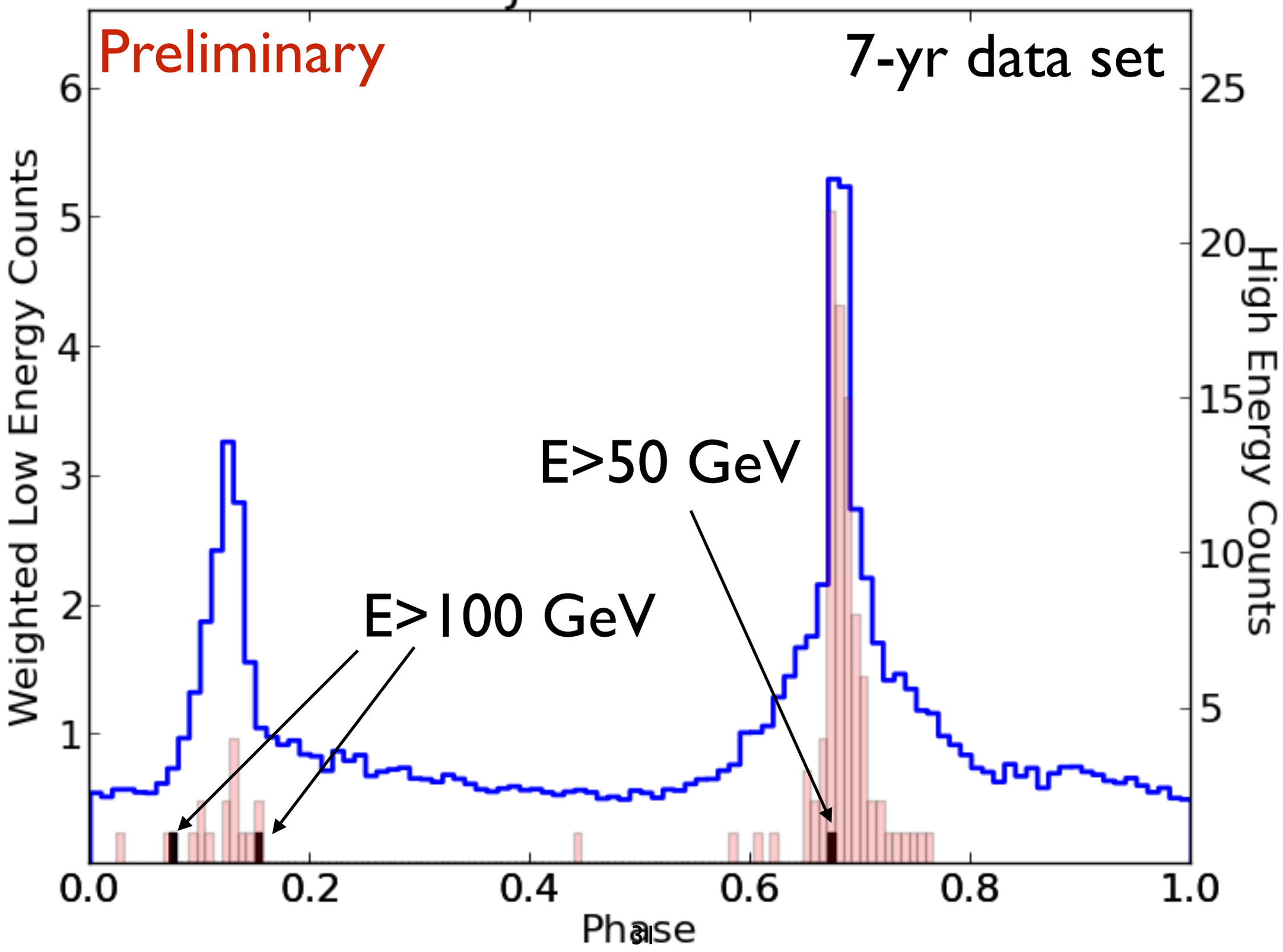
Credit: S. Ransom



Measurable proper motion



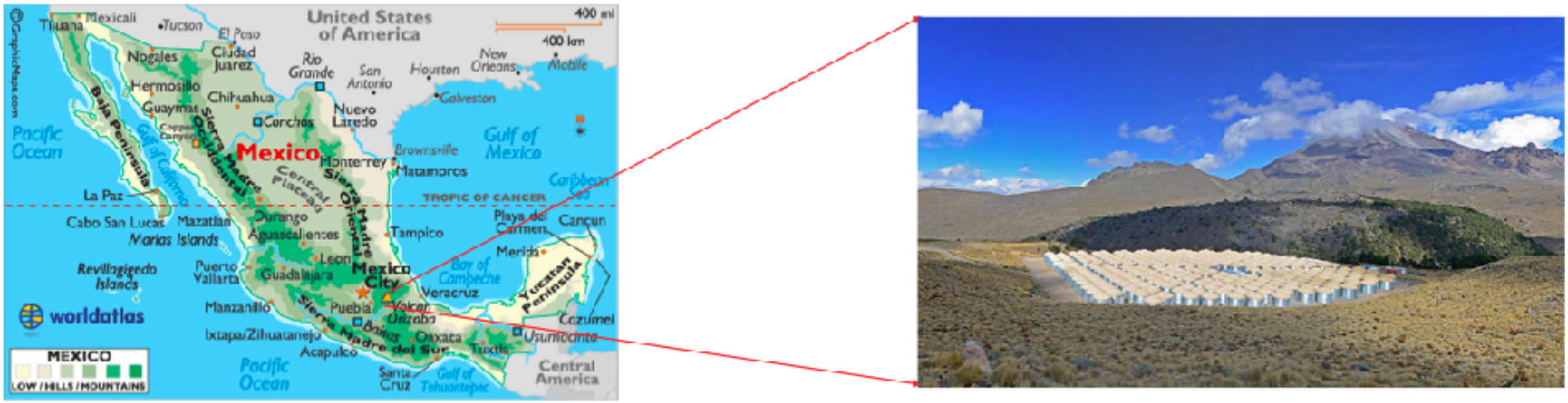
Search for the highest pulsations from J0614-3329



Follow-up TeV observations are key!

HAWC

The HAWC Observatory



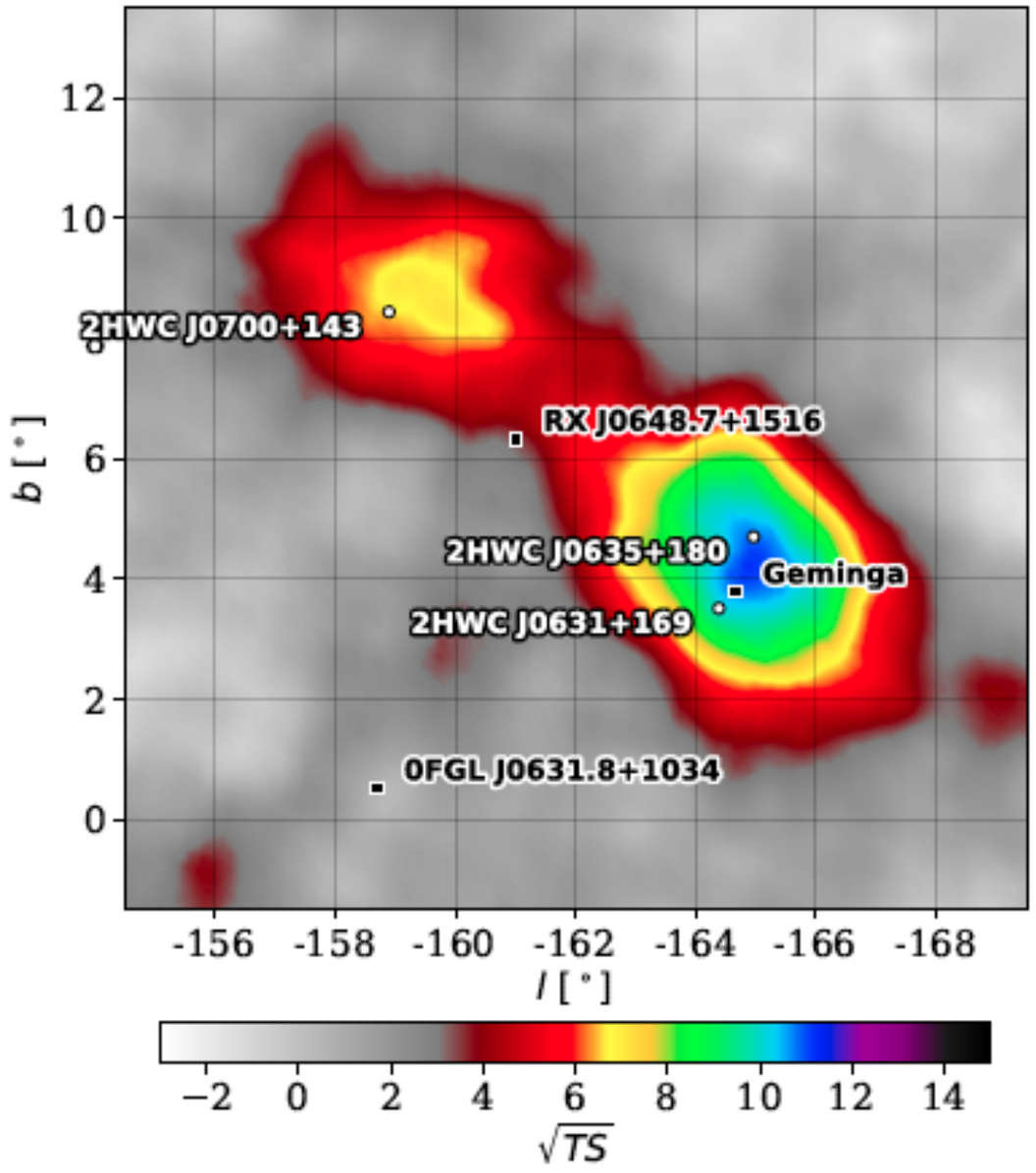
- Located at **4100 m** a.s.l. in Mexico near Pico de Orizaba at 19°N
- Effective Area: **~22,000 m²**
- Instantaneous field of view **2 sr**; daily coverage of **2/3** of the sky.
- 300 Water Cherenkov Detectors (WCDs)
- Declinations from **-26° to 64°** (***Part of Northern Fermi Bubble visible***)
- Inaugurated in **March 2015**, taking science data since **2013**.

6

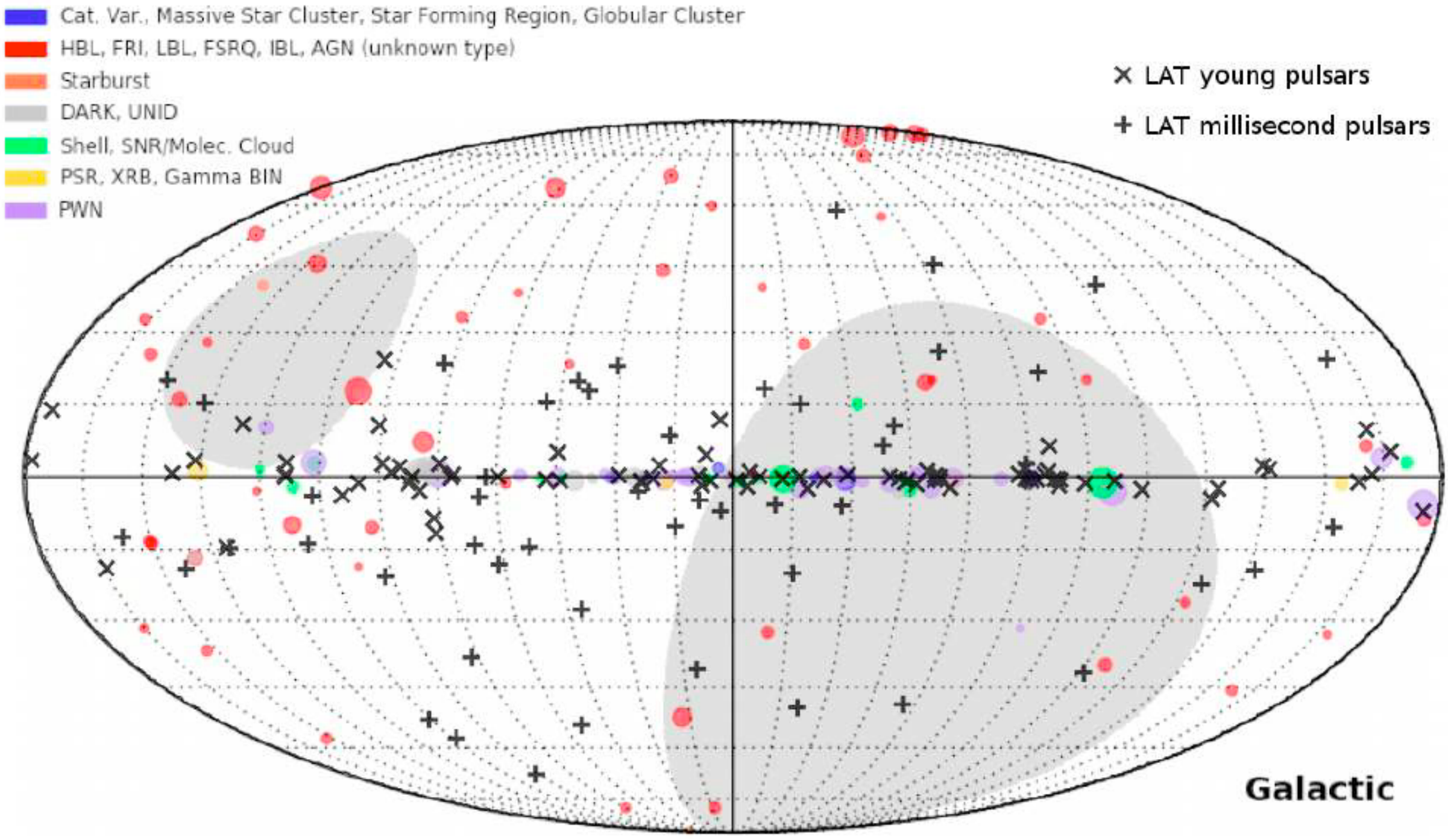
The First HAWC Catalog

Abeysekara et al. (2017) [arXiv:1702.02992]

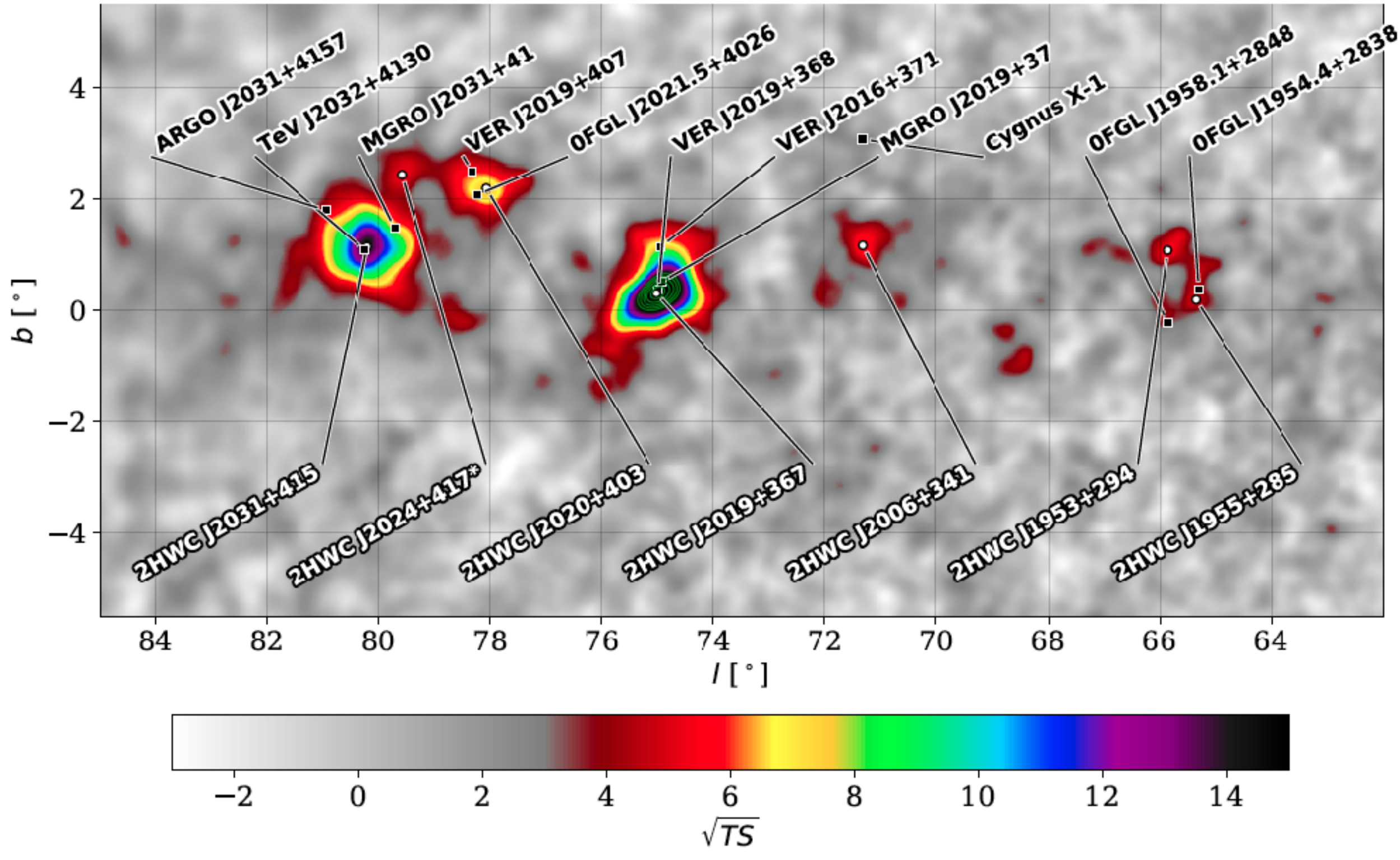
- 507 days of data
- 39 sources
- 23 unidentified
- 10 coincident with PSRs/ PWNe



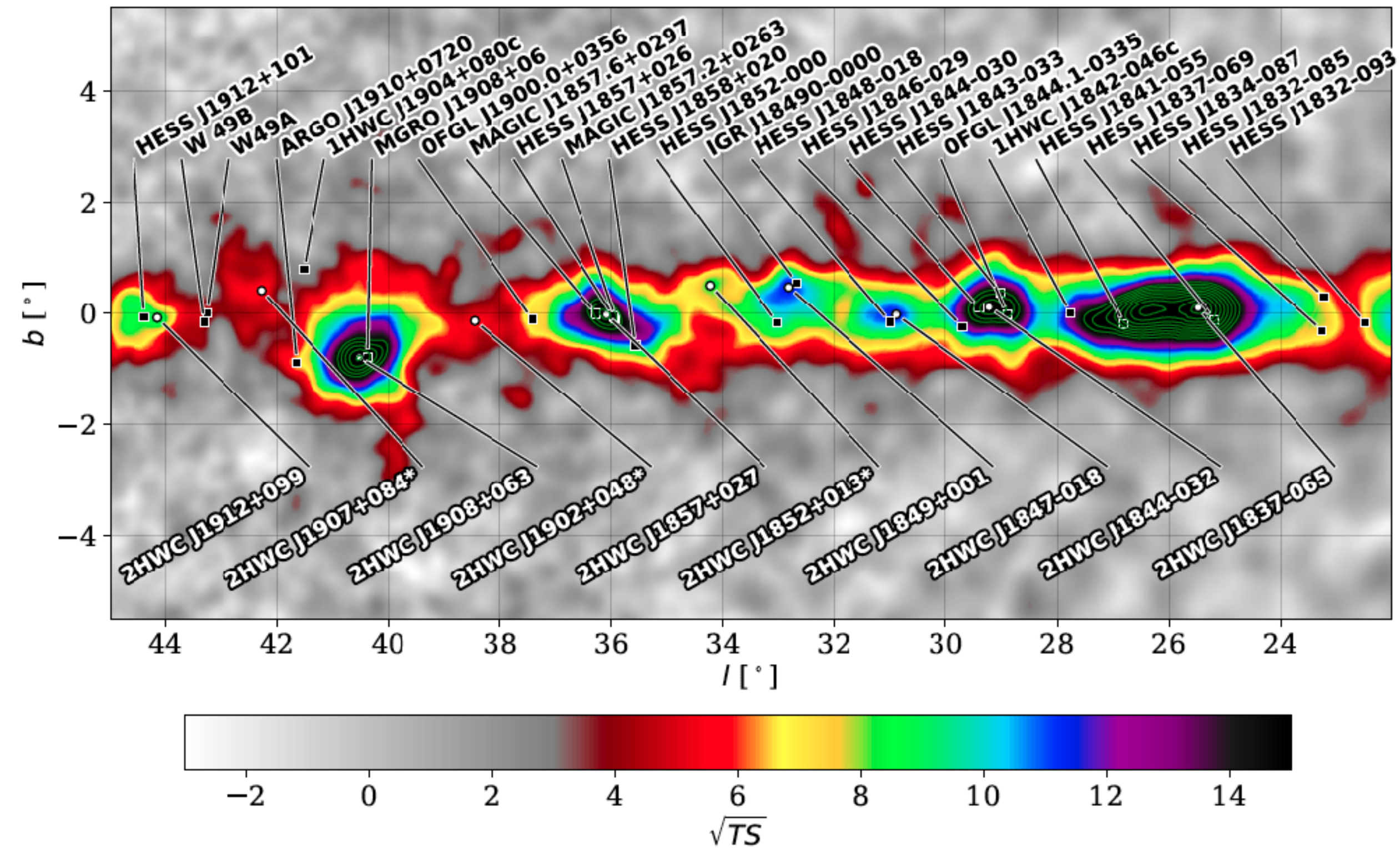
Pulsars in HAWC FOV



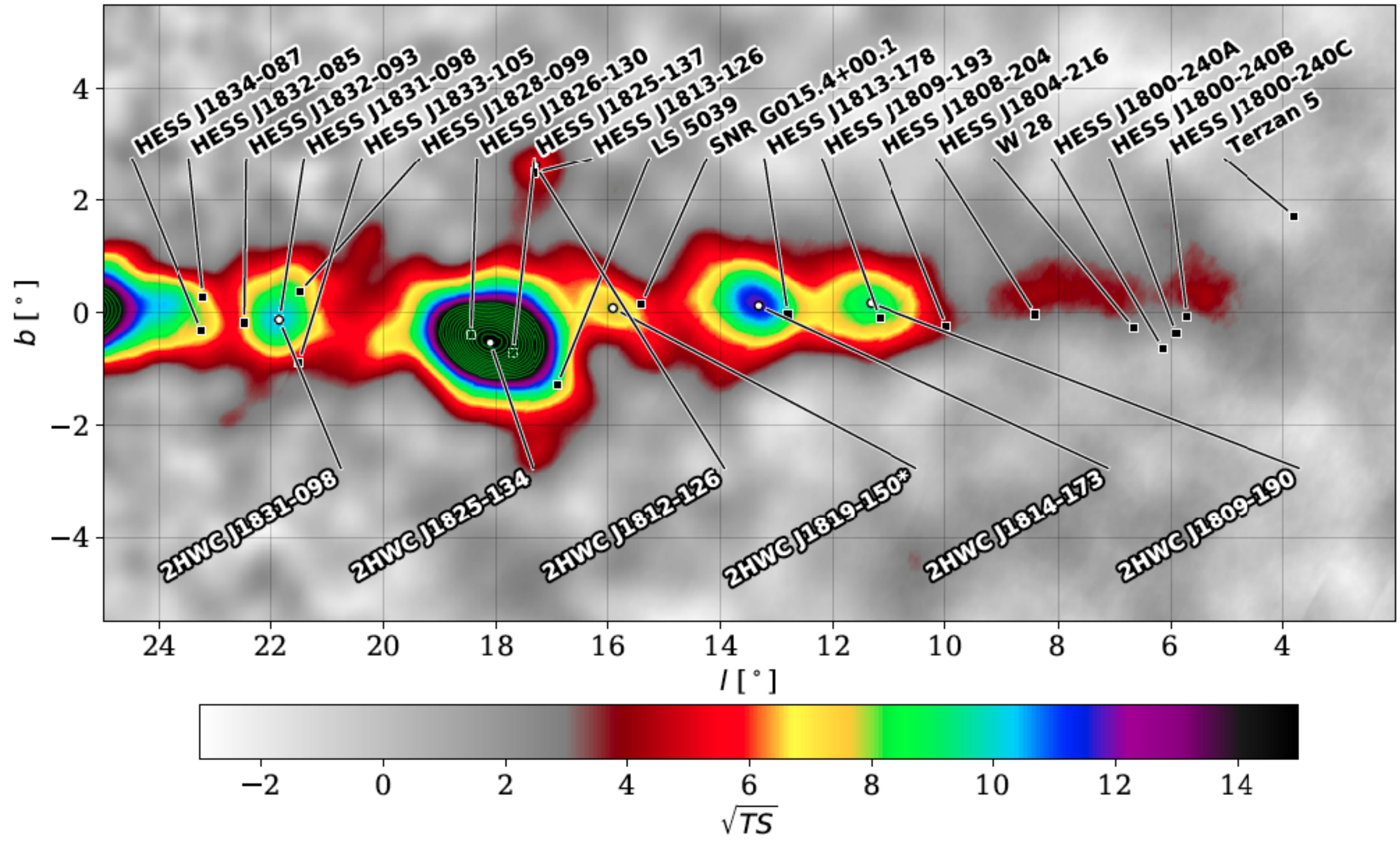
The First HAWC Catalog



The First HAWC Catalog



The First HAWC Catalog



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
- The recent 3FHL Catalog contains ~3 times the number of sources/pulsars as 1FHL. Work is ongoing to determine the number of pulsars at (very) high energies
- Ground-based instruments (HESS, MAGIC, VERITAS, HAWC, CTA) are needed to further investigate pulsar emission above 100 GeV