Fermi Large Area Telescope:

Early Results on Pulsars

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for the
***Fermi* LAT Collaboration**

Tokyo Institute of Technology
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Fermi LAT Collaboration

United States
- California State University at Sonoma
- University of California at Santa Cruz - Santa Cruz Institute of Particle Physics
- Goddard Space Flight Center – Laboratory for High Energy Astrophysics
- Naval Research Laboratory
- Ohio State University
- Stanford University (SLAC and HEPL/Physics)
- University of Washington
- Washington University, St. Louis

France
- IN2P3, CEA/Saclay

Italy
- INFN, ASI

Japanese GLAST Collaboration
- Hiroshima University
- ISAS, RIKEN
- Tokyo Inst of Technology

Swedish GLAST Collaboration
- Royal Institute of Technology (KTH)
- Stockholm University

PI: Peter Michelson (Stanford & SLAC)

~270 Members (including ~90 Affiliated Scientists, plus 37 Postdocs, and 48 Graduate Students)

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Managed at Stanford Linear Accelerator Center (SLAC).

Fermi LAT View of the Galaxy

Prospects for Fermi observations of Galactic point sources, as suggested by results released to date

Outline:

I. *CGRO* EGRET to *Fermi* LAT

II. Results on pulsars from *Fermi*
- **Vela Pulsar**
- **CTA1 and blind searches**
- **Millisecond pulsars**

III. Pulsar categories, totals, and distribution

Conclusion

I. *EGRET* to *Fermi*

Fermi LAT gives a magnificent new view of the Galaxy and Galactic sources

Performance improvements:

Angular resolution helps overcome confusion

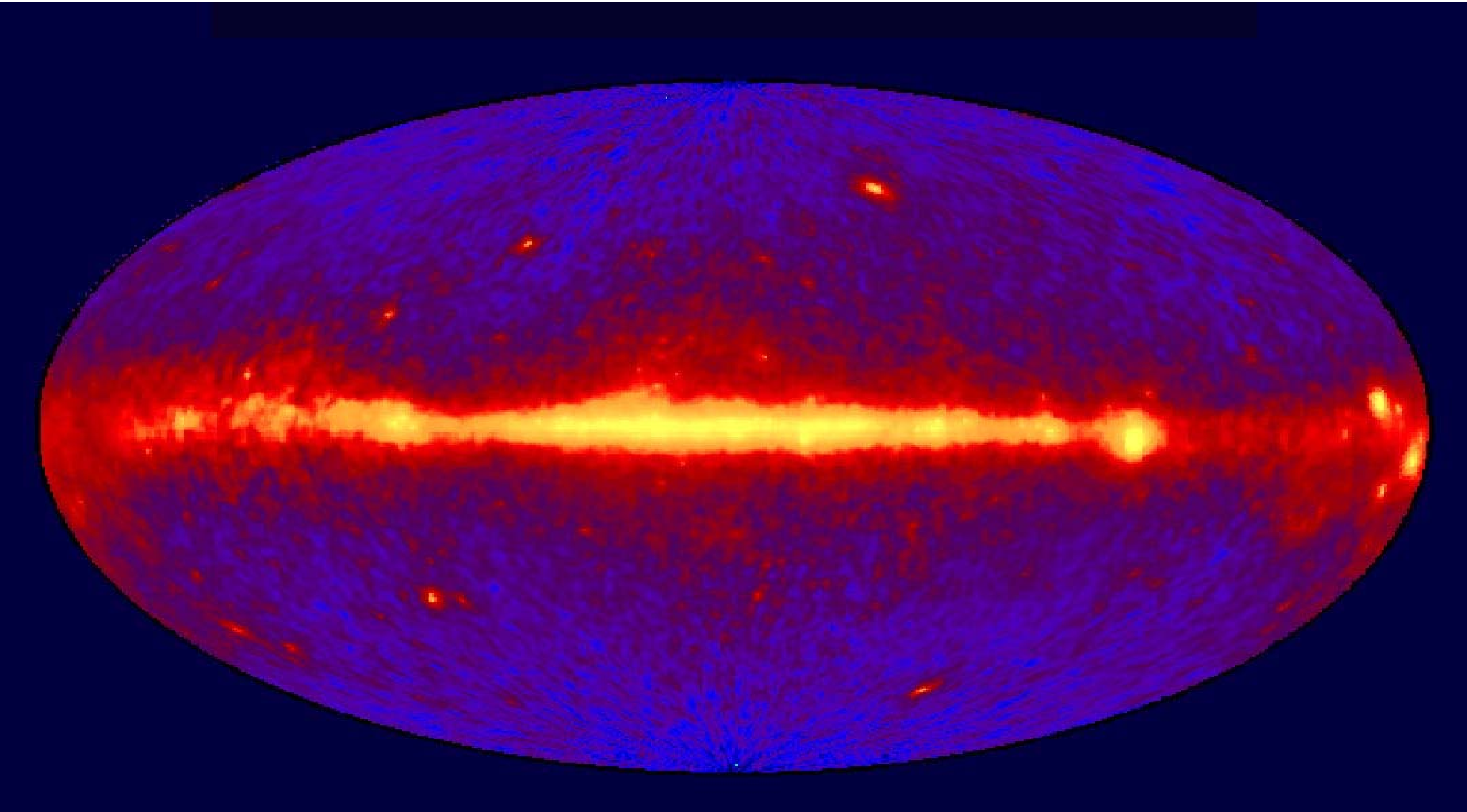
- **PSF helps select photons for pulsar work**

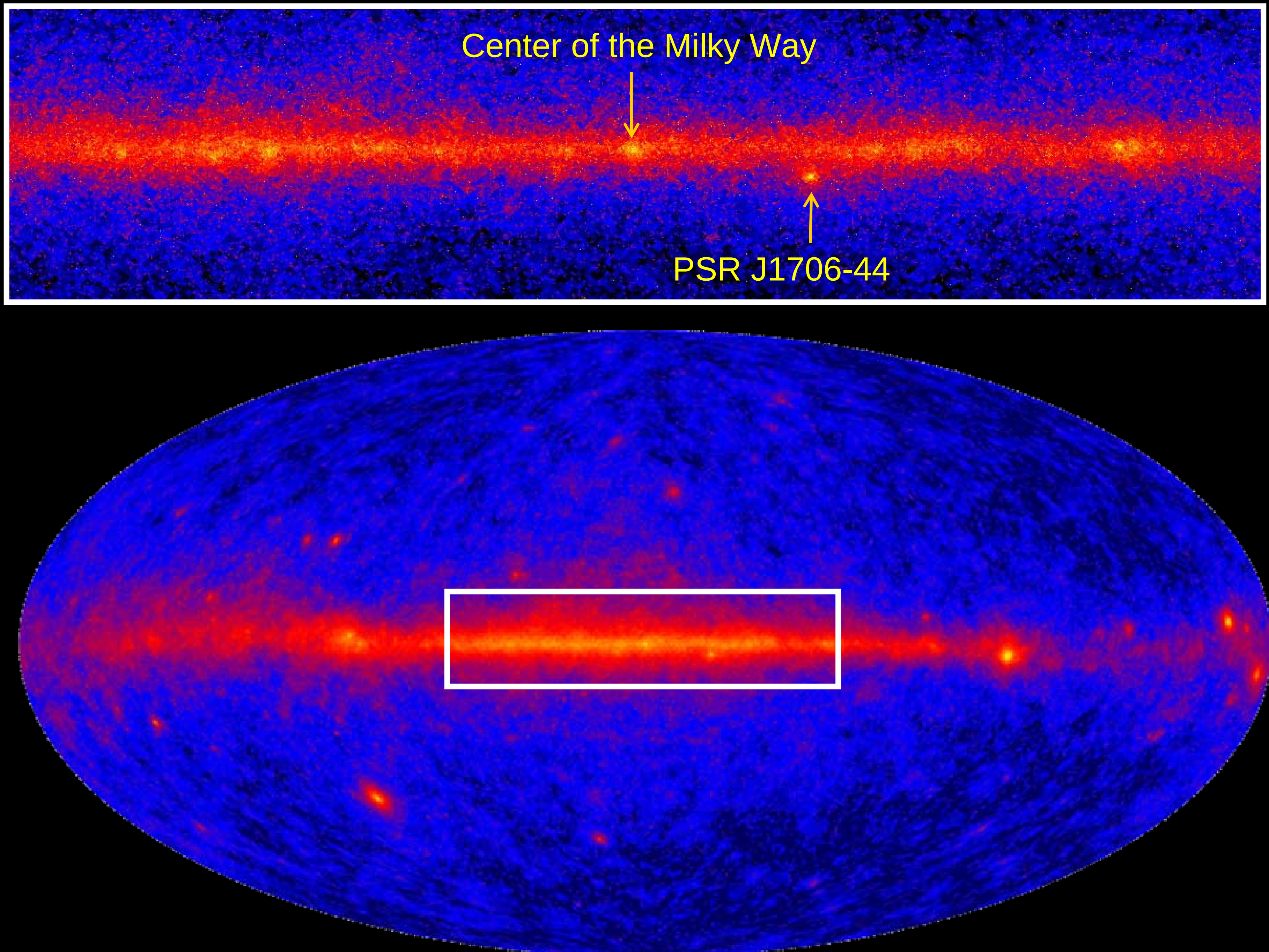
Sensitivity advantage supports pulsar detection

- **large area * large solid angle**
- **efficient use of live time on orbit**

Reminder: Features of the Gamma-Ray Sky seen by EGRET

EGRET all-sky survey (galactic coordinates) E>100 MeV




Center of the Milky Way
PSR J1706-44

Questions *Fermi* LAT can Pursue Regarding Galactic Sources and Populations

- **New pulsar detections**
- **Light curve features, using high-statistics profiles**
- **Pulsar spectra and emission models**
- **Relation of pulsars to supernovae (SNe) and pulsar wind nebulae (PWNe)**
- **Relation to TeV sources**
- **New classes of pulsars**
- **Refining magnetosphere and emission mechanism models**

II. *Fermi* LAT results on Pulsars and PWNe

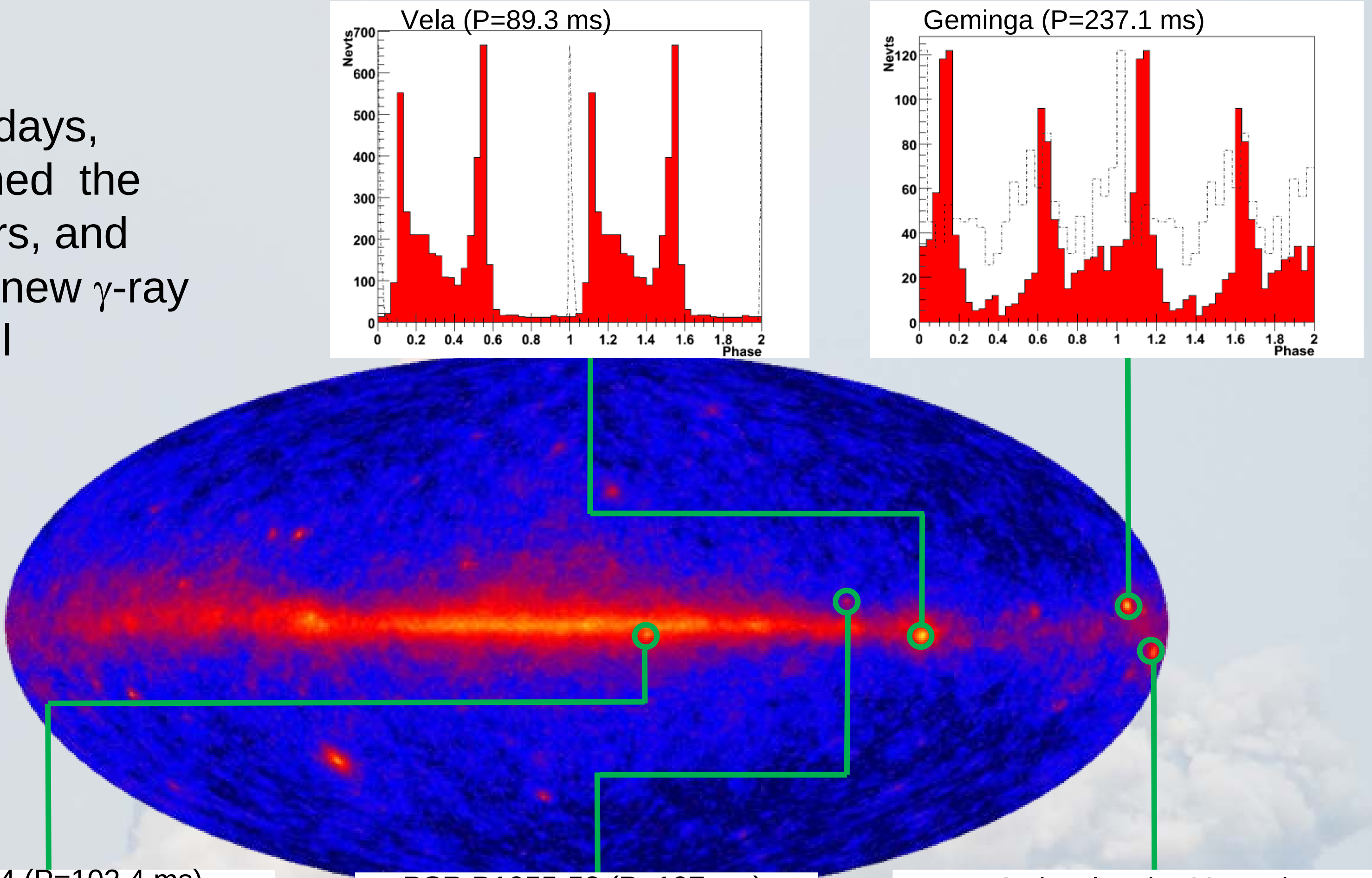
EGRET on *CGRO* clearly detected 6 pulsars

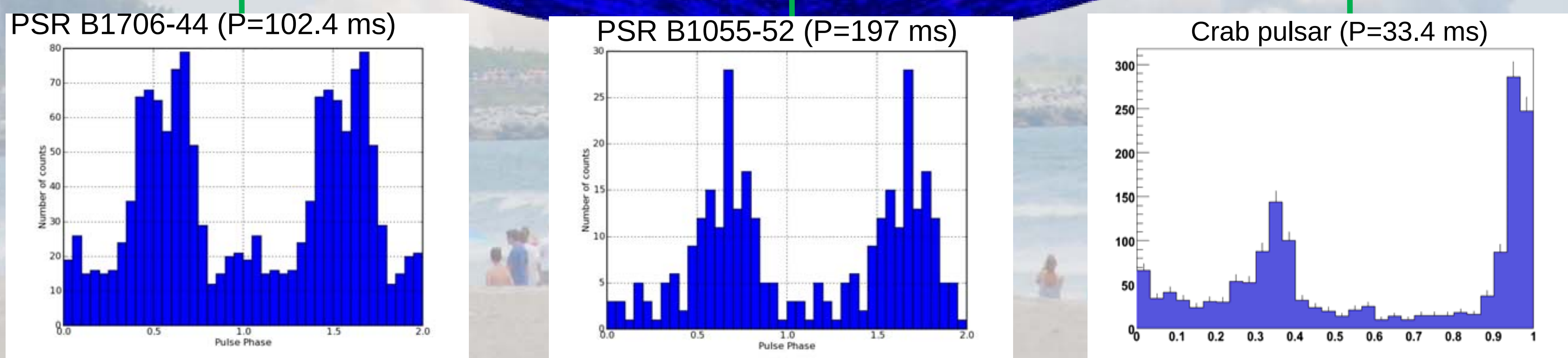
***Fermi* LAT is seeing the 6 EGRET pulsars and finding many more**

These are rotation-powered pulsars

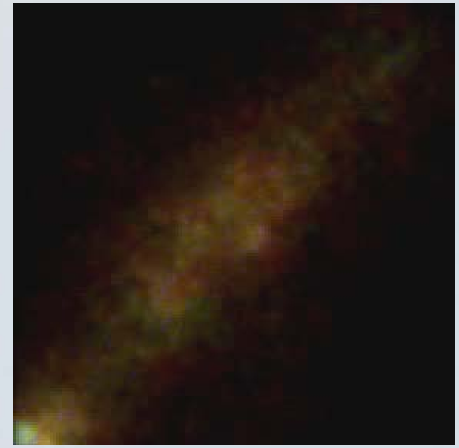
- **some are found using radio ephemerides**
  - **depends on regular timing of radio pulsars by collaborators at Parkes, Jodrell Bank, Nancay, GBT, …**
- **some are found by blind searches**

In its first few days, *Fermi* confirmed the EGRET pulsars, and began finding new γ-ray pulsars as well

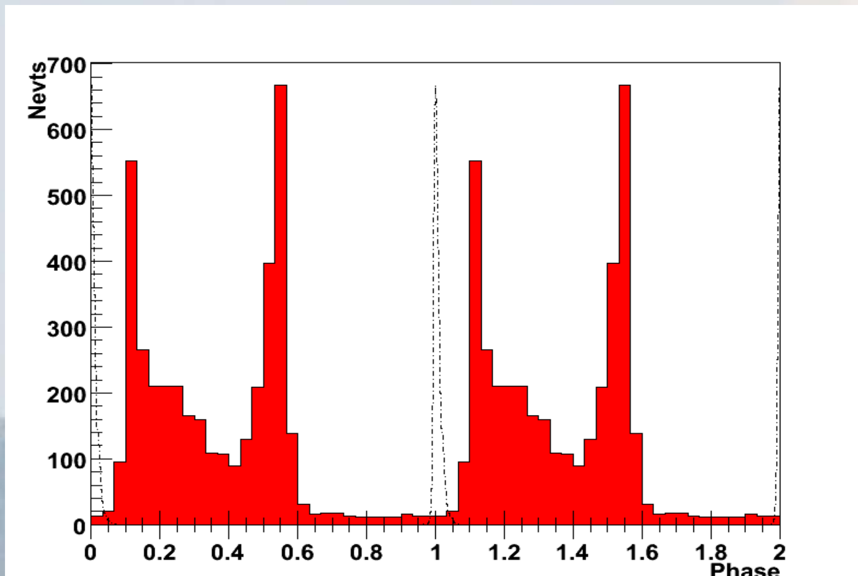




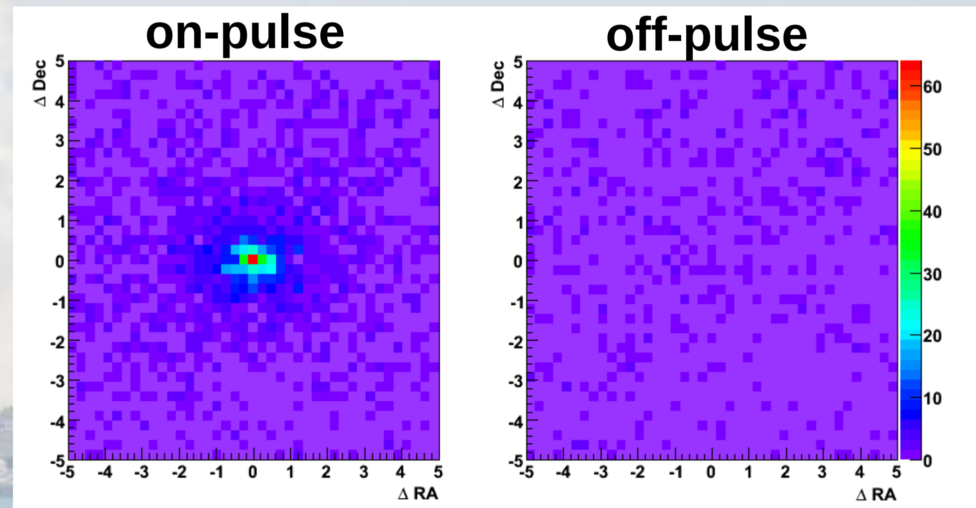
Vela – (very) early returns



Everything works!
- timing
- background rejection
- alignment

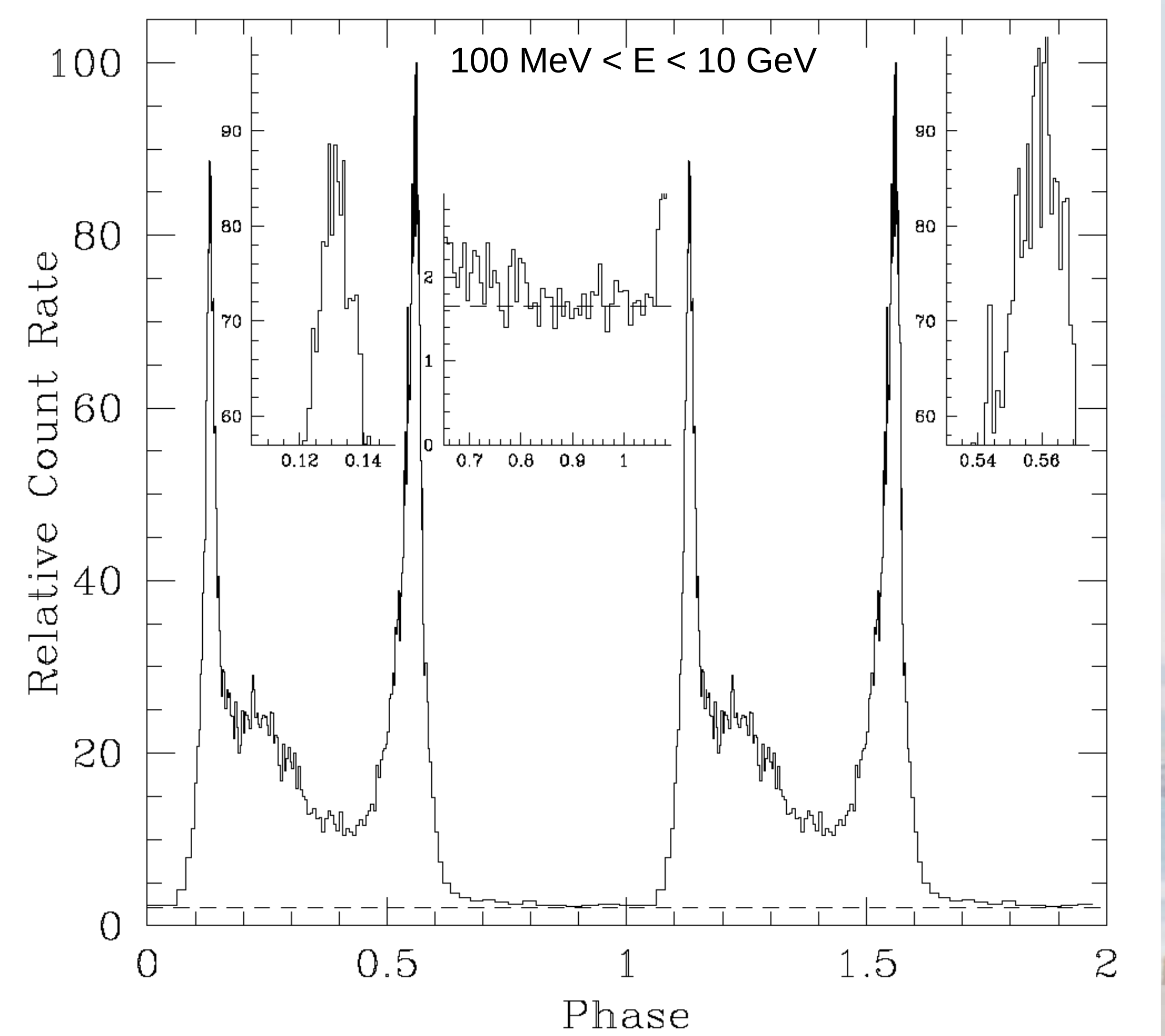


- precise ephemerides of many pulsars provided by Parkes, Jodrell Bank, Green bank, Nançay, Arecibo, Hartbeesthoek, Urumqi, RXTE, XMM...

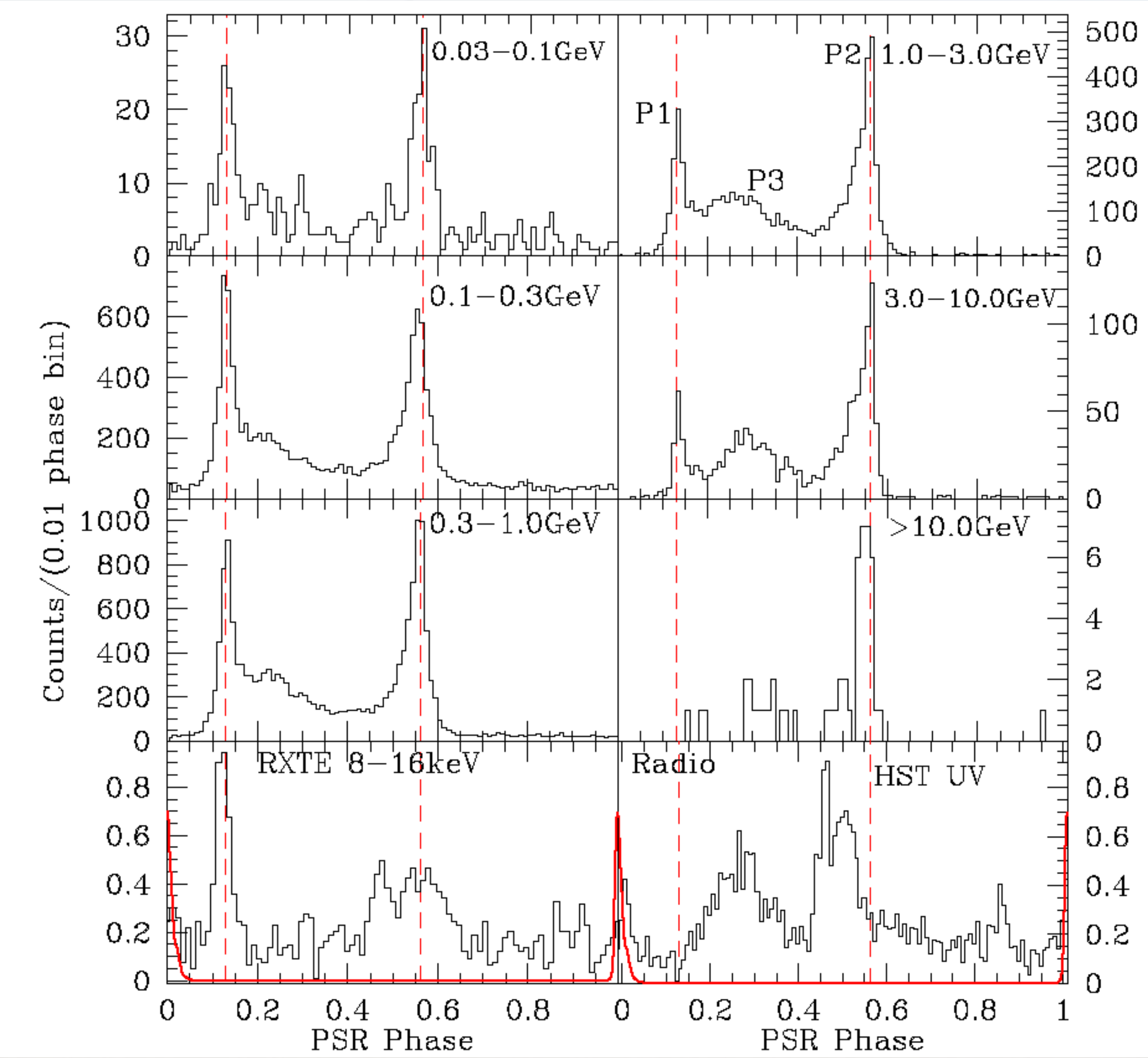


- selecting on-pulse shows point source
  - evaluate PSF
  - alignment of LAT to sky (fit to several point sources)

First Fermi View of the Vela Pulsar

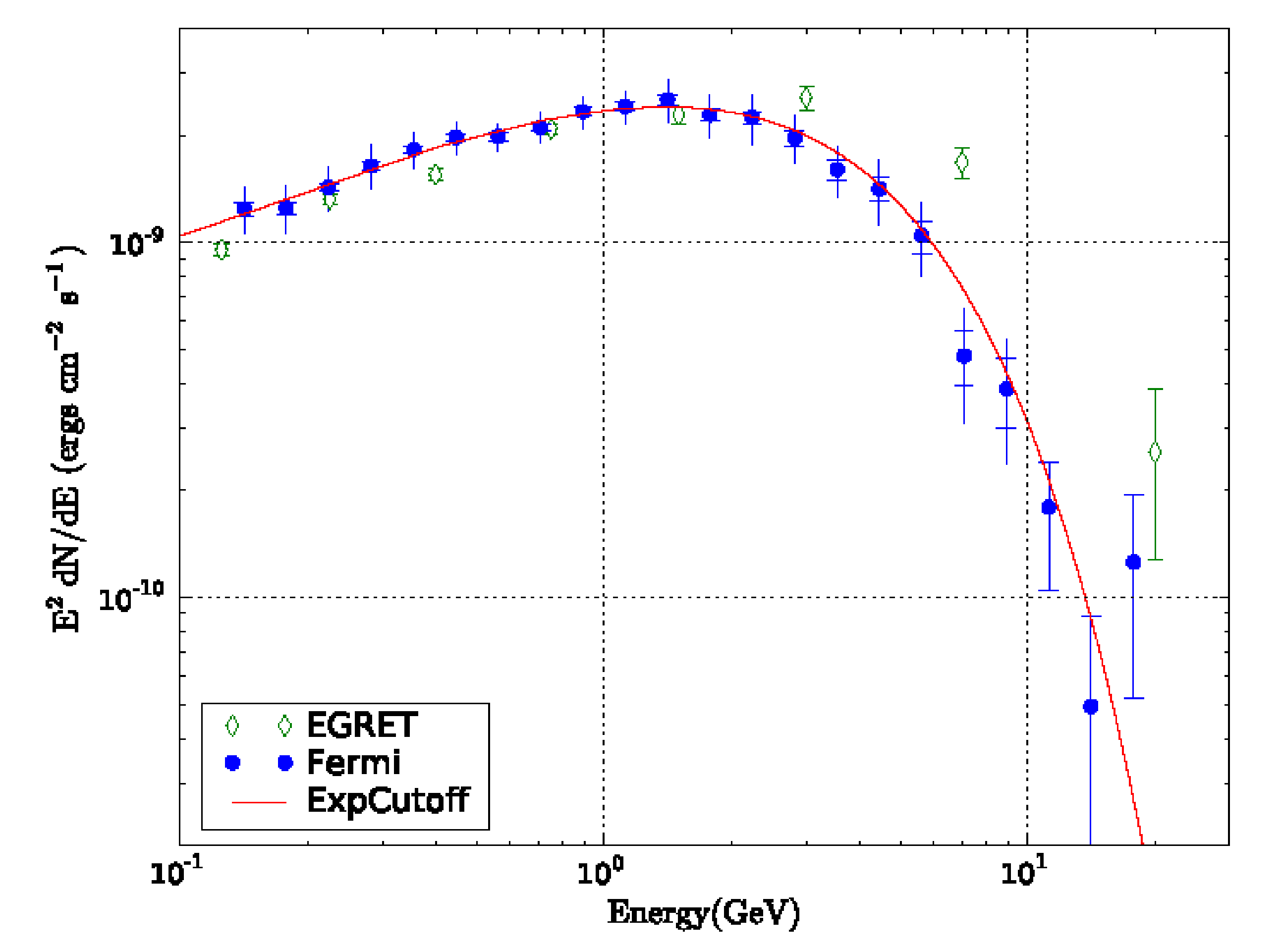


Vela Pulsar – Energy Evolution of Pulse Profile



Vela Pulsar – Phase-averaged SED

$$N(E) = N_0 E^{\Gamma} e^{-(E/E_c)^b}$$



Consistent with b=1 (simple exponential)

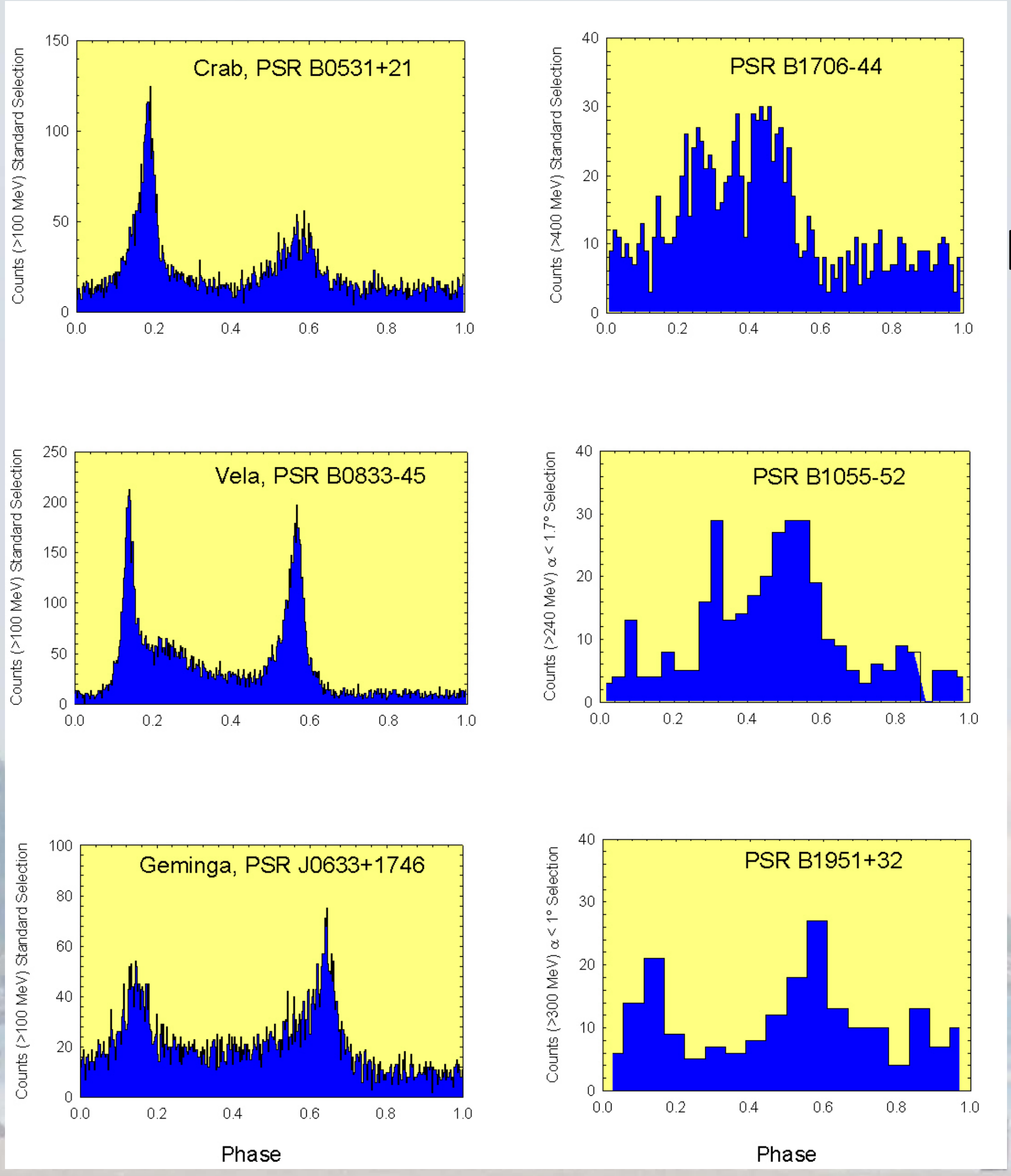
$$\Gamma = -1.51^{+0.05}_{-0.04}$$

$$E_c = 2.9 \pm 0.1 \text{ GeV}$$

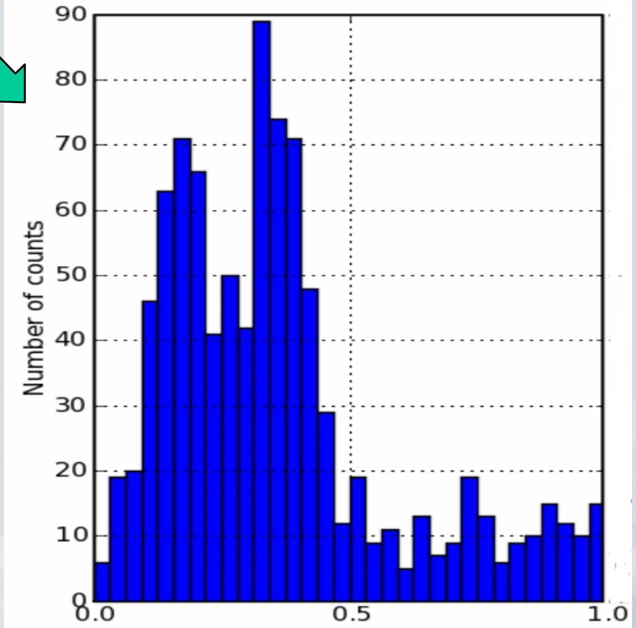
b=2 (super-exponential) rejected at 16.5σ

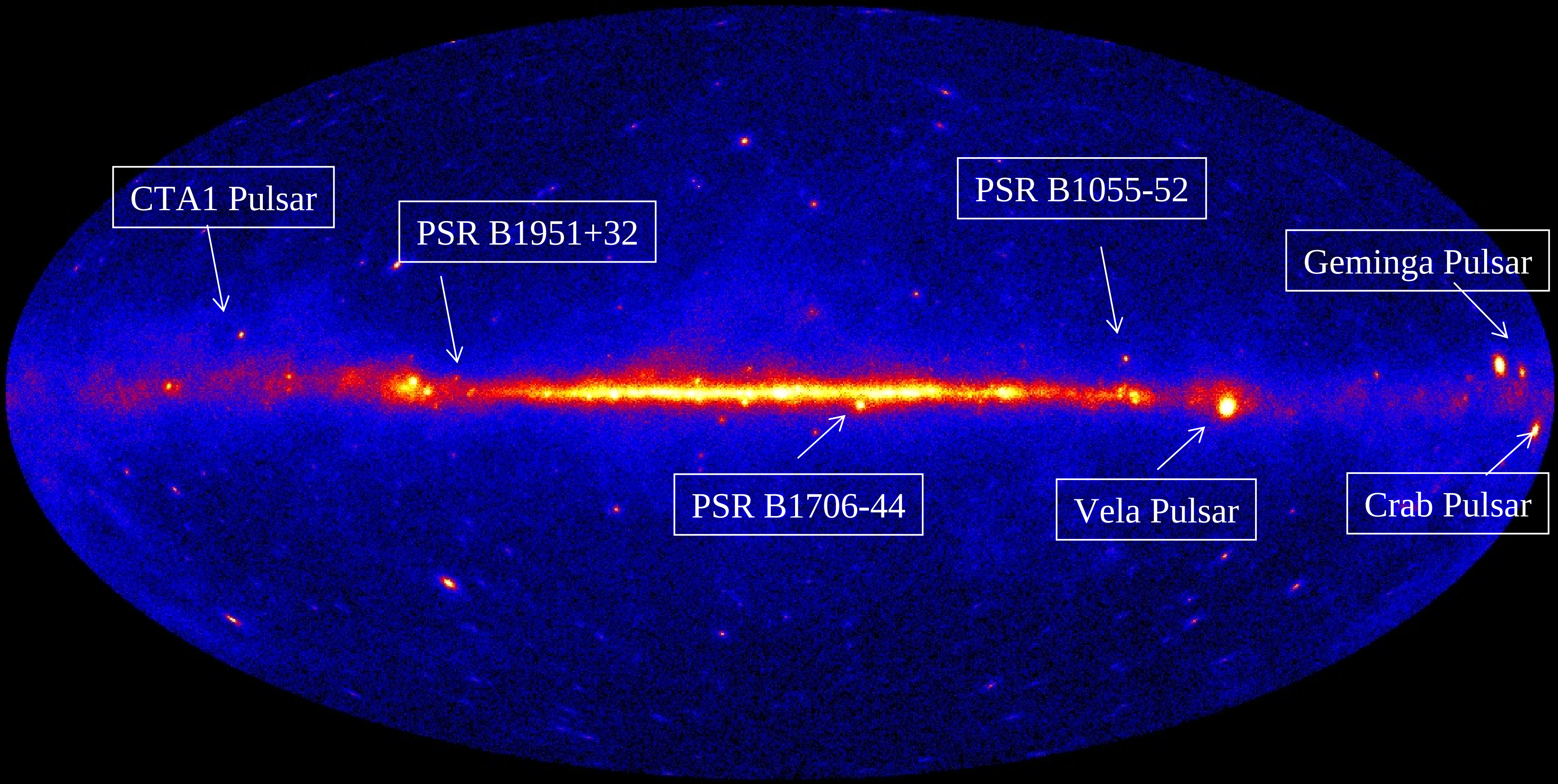
No evidence for magnetic pair attenuation – Near-surface emission ruled out

the classic EGRET 6



CTA 1




CTA1 Pulsar
PSR B1951+32
PSR B1055-52
Geminga Pulsar
PSR B1706-44
Vela Pulsar
Crab Pulsar

Blind Pulsar Search

Fermi Monthly Catalogue

Candidate PWN/PSR

Blind Pulsar Search

Interesting Candidate

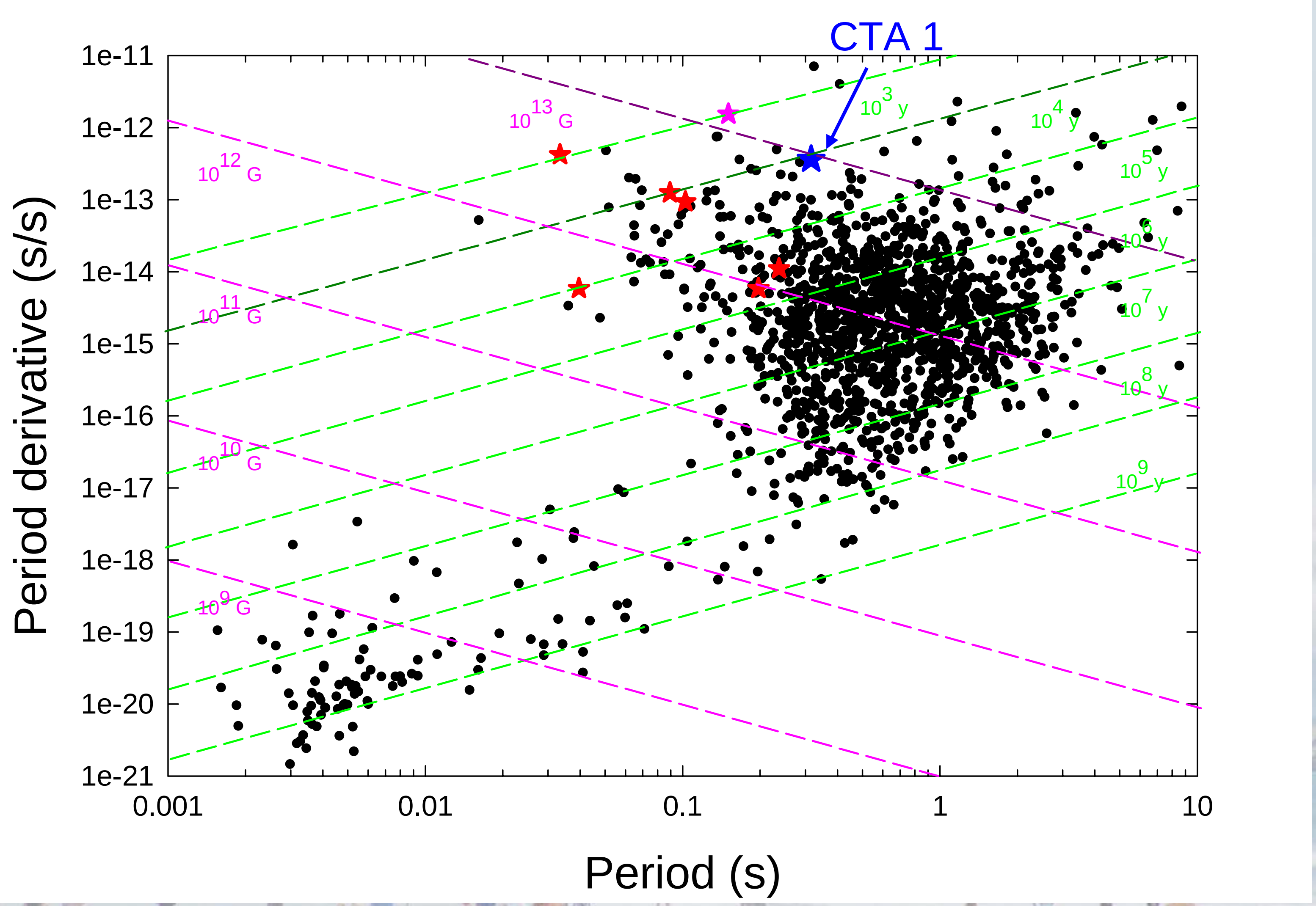
Optimize P-Pdot with Prepfold

Time pulsar with Tempo2

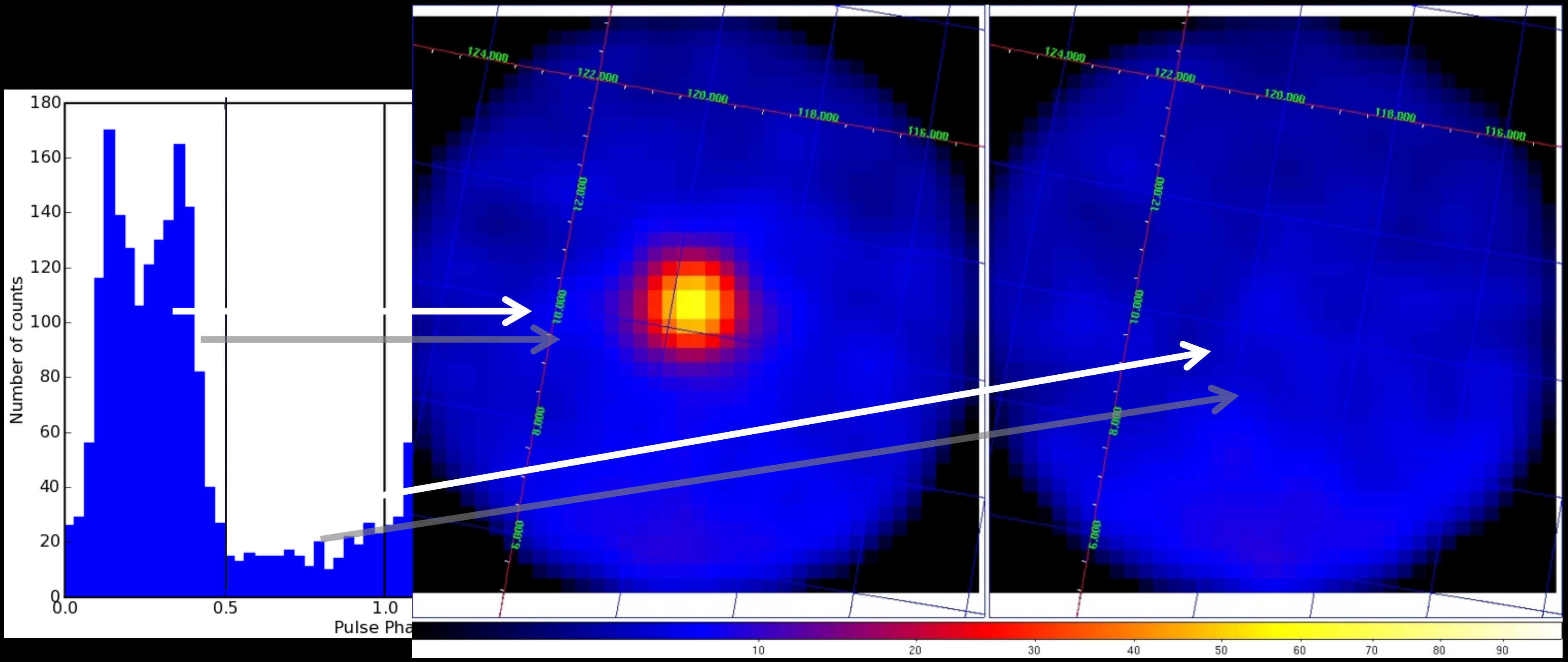
CTA 1 Pulsar Parameters

Parameter	Value
Frequency (Hz)	3.165922467(9)
Frequency Derivative (s^{-2})	$-3.623(4) \times 10^{-12}$
Period (ms)	315.8637050(9)
Period Derivative ($s\ s^{-1}$)	$3.615(4) \times 10^{-13}$
Epoch (MJD (TDB))	54647.440 938
R.A. (J2000.0)	$00^h\ 07^m\ 01^s.56$
DEC. (J2000.0)	+73° 03´ 08´´.1
Galactic Longitude	119° .65947(3)
Galactic Latitude	+10° .463348(3)
Derived Parameters	
E_{rot}	4.5×10^{35} erg s^{-1}
B_{surf}	1.1×10^{13} G
τ_{rot}	1.4×10^{4} years

Location in P-Pdot Diagram

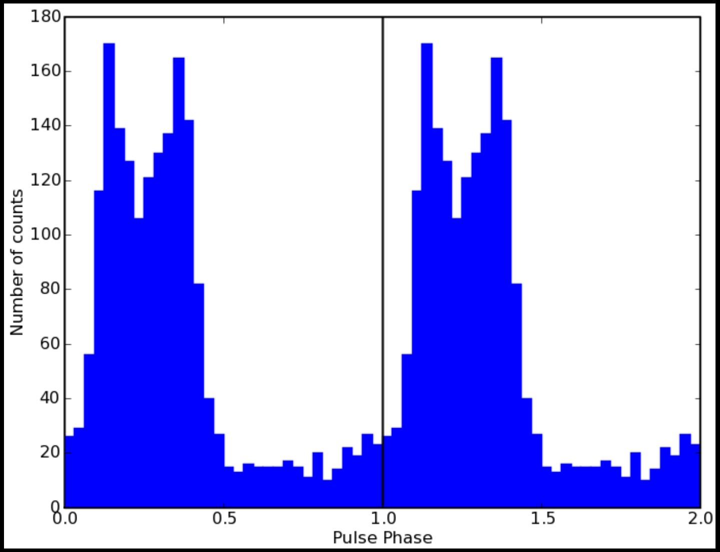


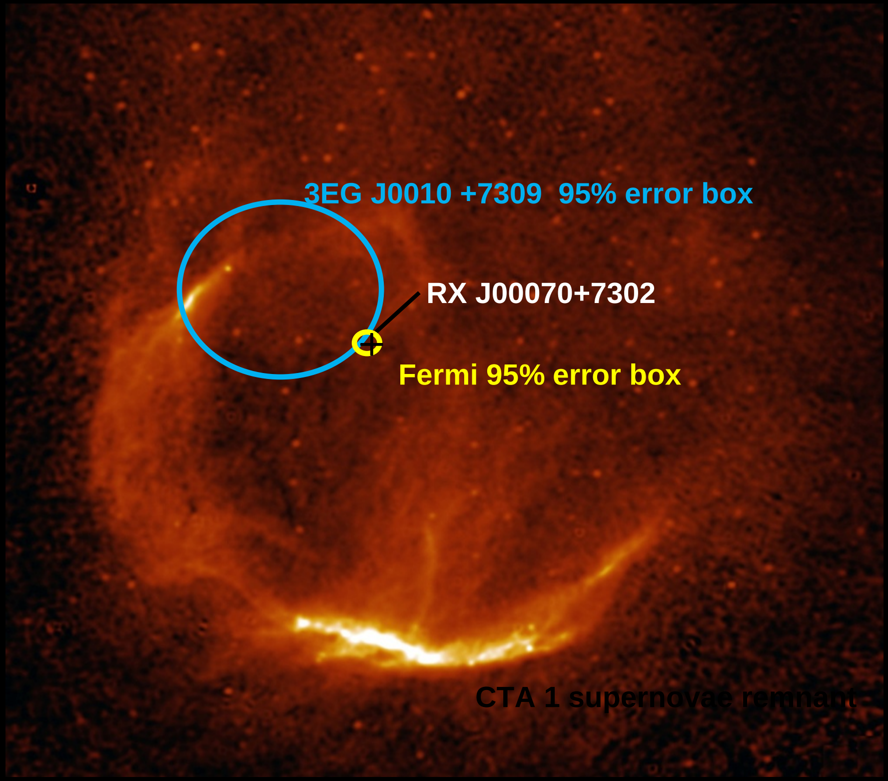
On and off Pulse Images



Pulsar in CTA1

CTA 1 pulsar (2 cycles, P=315.86 ms)





- Exhibits all characteristics of a young high-energy pulsar (characteristic age ~1.4 x 10^4 yr), which powers a synchrotron pulsar wind nebula embedded in a larger SNR.

- Spin-down luminosity ~10^{36} erg s^{-1}, sufficient to supply the PWN with magnetic fields and energetic electrons.

- The γ-ray flux from the CTA 1 pulsar corresponds to about 1-10% of E_{rot} (depending on beam geometry)

- γ-ray source at *l*,*b* = 119.652, 10.468; 95% error circle radius =0.038° contains the X-ray source RX J00070+7302, central to the PWN superimposed on the radio map at 1420 MHz.

- Pulsar off-set from center of radio SNR; rough estimate of the lateral speed of the pulsar is ~450 km/s

CTA1 Summary

- CTA1 is the first pulsar whose pulsations were initially found in gamma-rays
  - Dramatically confirms prior hints that the X-ray point source in the CTA1 SNR is a neutron star
  - Pulsations from γ-rays give characteristic age and energetics that match expectations from models of the remnant
  - Inferred magnetic field is strong, ~ 10^{13} G
- Bright enough to time with few ms residuals in 1-week integrations
- Blind discovery in a few days; improved statistics with months of data
- No source detected yet at pulsar position in off-pulse phases

- CTA1 is just a start: Fermi-LAT is discovering many γ-ray pulsars
- Studying this population will shed light on issues such as beaming, emission models, and population statistics

First *Fermi* millisecond pulsar

PSR J0030+0451

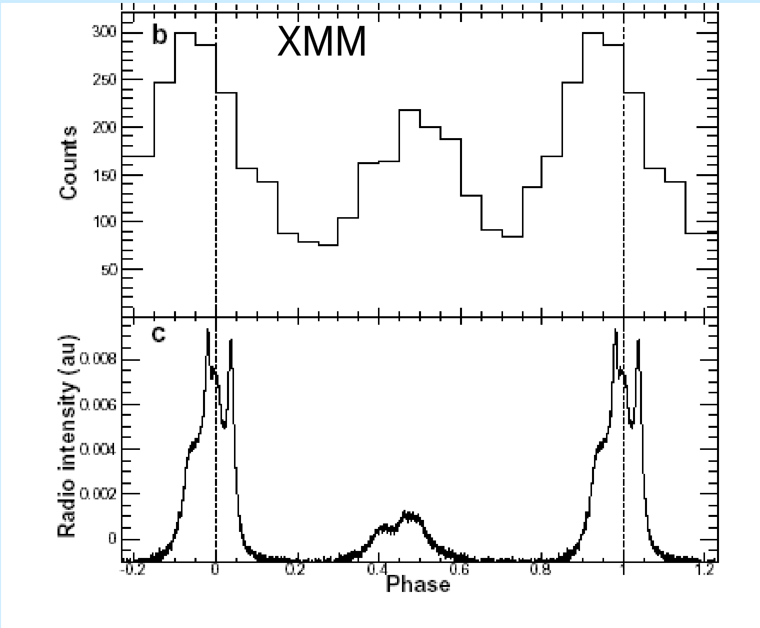
- **P = 4.86 ms**
- **Nearby – d = 317 pc**
- **Low spin-down power**

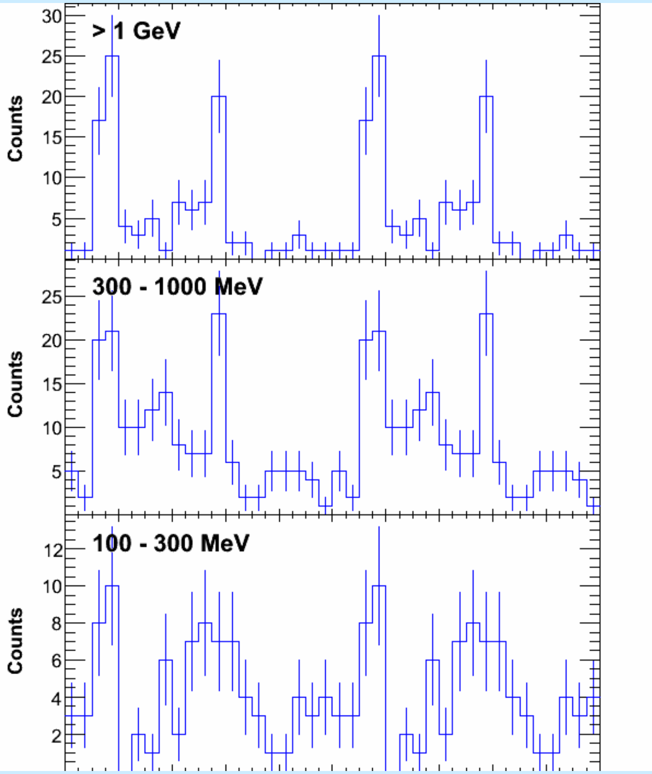
$$\dot{E}_{sd} = 3.3\times10^{33}\,\mathrm{erg/s}$$

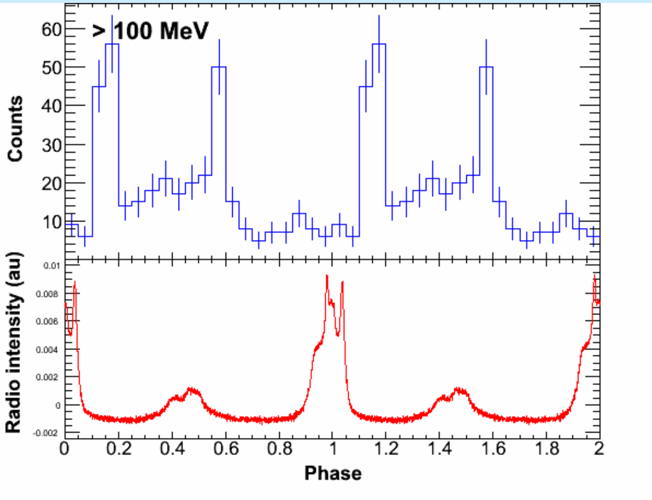
- **γ-ray and radio are not aligned**
- **X-ray and radio pulses nearly aligned**

Peak separation: 0.4 ± 0.02

Radio lag: 0.14 ± 0.01







Millisecond pulsars detected by *Fermi*

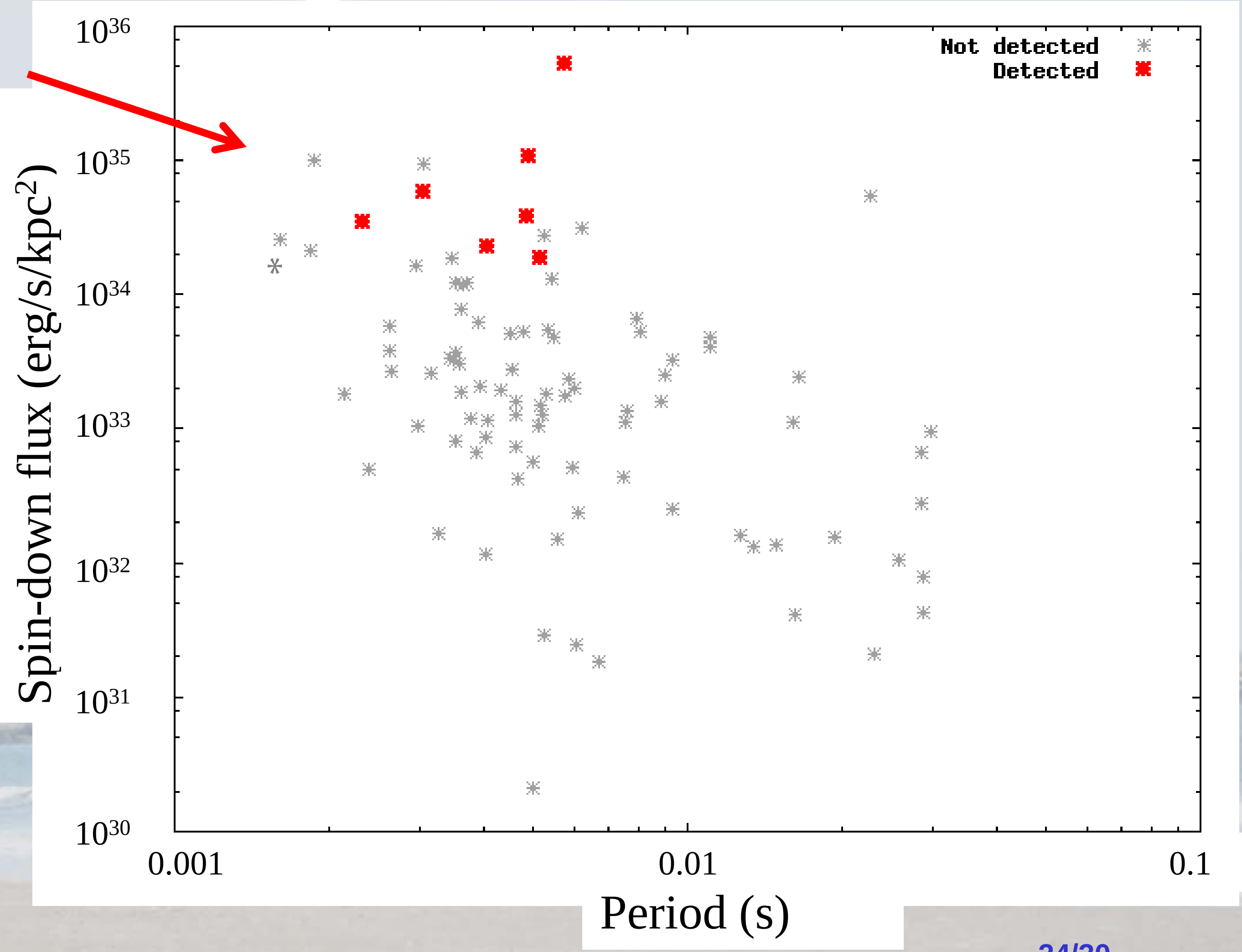
PULSAR	PERIOD	PERIOD DERIV.	D	Edot	# PHOTONS	H-TEST TS	CHANCE PROB
	(ms)	(10^{-20} s/s)	(kpc)	(erg/s)			
J0030+0451	4.86	1	0.317	3.44E+33	361	306.8	< 4e-08
J0218+4232	2.32	7.74	3.2	2.44E+35	455	12	0.0084
J0437-4715	5.76	5.73	0.15	1.18E+34	166	89.1	< 4e-08
J0613-0200	3.06	0.96	0.48	1.32E+34	549	60	< 4e-08
J1024-0719	5.16	1.85	0.53	5.31E+33	135	14	0.0038
J1744-1134	4.07	0.89	0.48	5.21E+33	1014	25.1	5.04E-05
J2124-3358	4.93	2.1	0.25	6.91E+33	277	57.7	< 4e-08

Which ones is *Fermi* detecting?

Those with high 'spin-down flux'

$$\dot{E}_{sd} / d^2$$

- The nearby population



III. *Fermi* Pulsars :
Types, Numbers Detected, Distributions

How many pulsars of different types are being seen by Fermi?

How are they distributed on the sky?

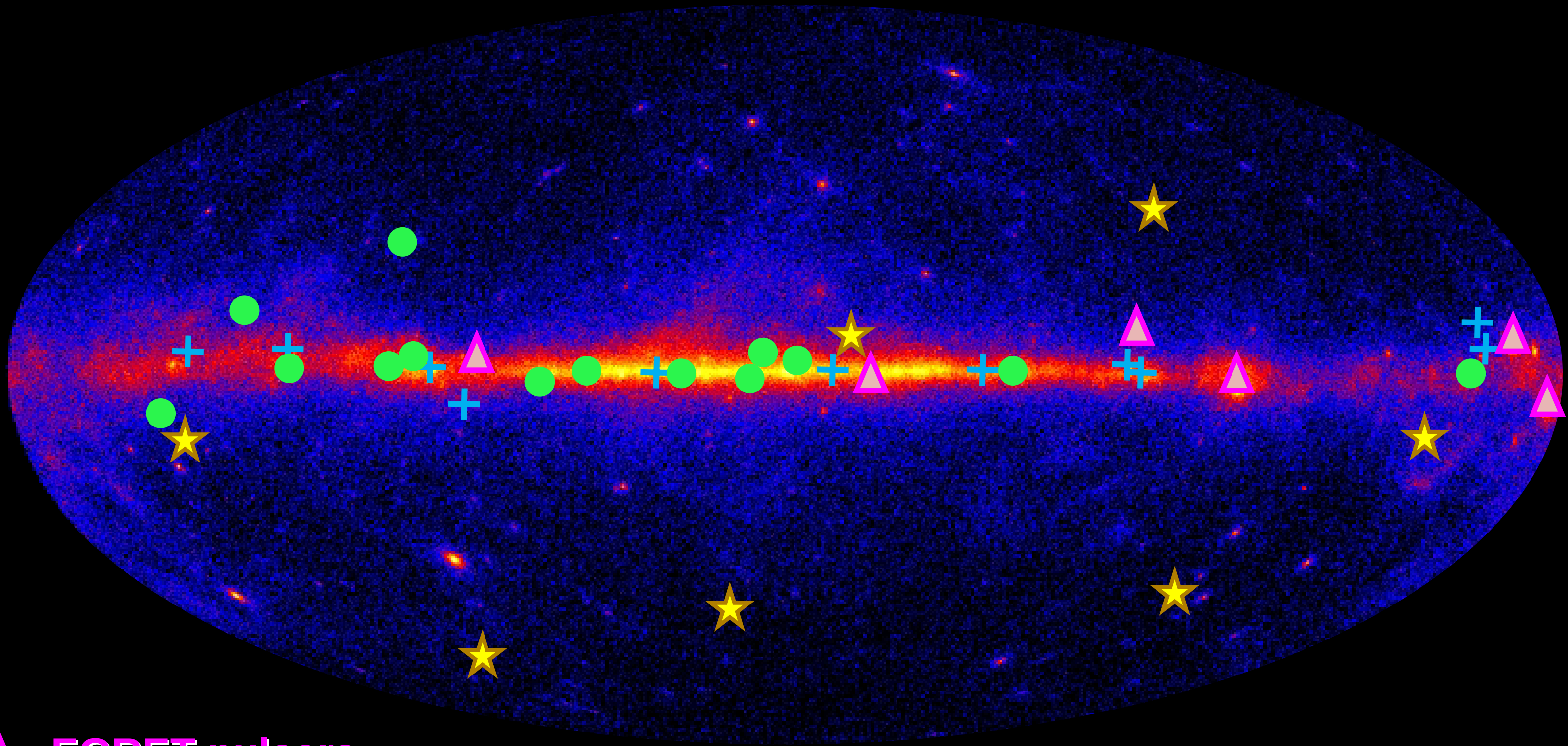
How are they distributed in period?

One map can convey all of this graphically, if we represent each pulsar slowed down in frequency (spin period is increased by factor of 10)

Fermi Pulsars

25 gamma-ray and radio pulsars (including 7 ms psrs)

13 gamma-ray only pulsars



- EGRET pulsars
- young pulsars discovered using radio ephemeris
- pulsars discovered in blind search
- millisecond pulsars discovered using radio ephemeris

Pulsar emission

In the simplest model, the emission should depend on 4 parameters: spin period, magnetic field, magnetic dipole inclination, and viewing angle

- luminosity derived from rotational energy

$$E_{rot} = \frac{1}{2} I \Omega^2$$

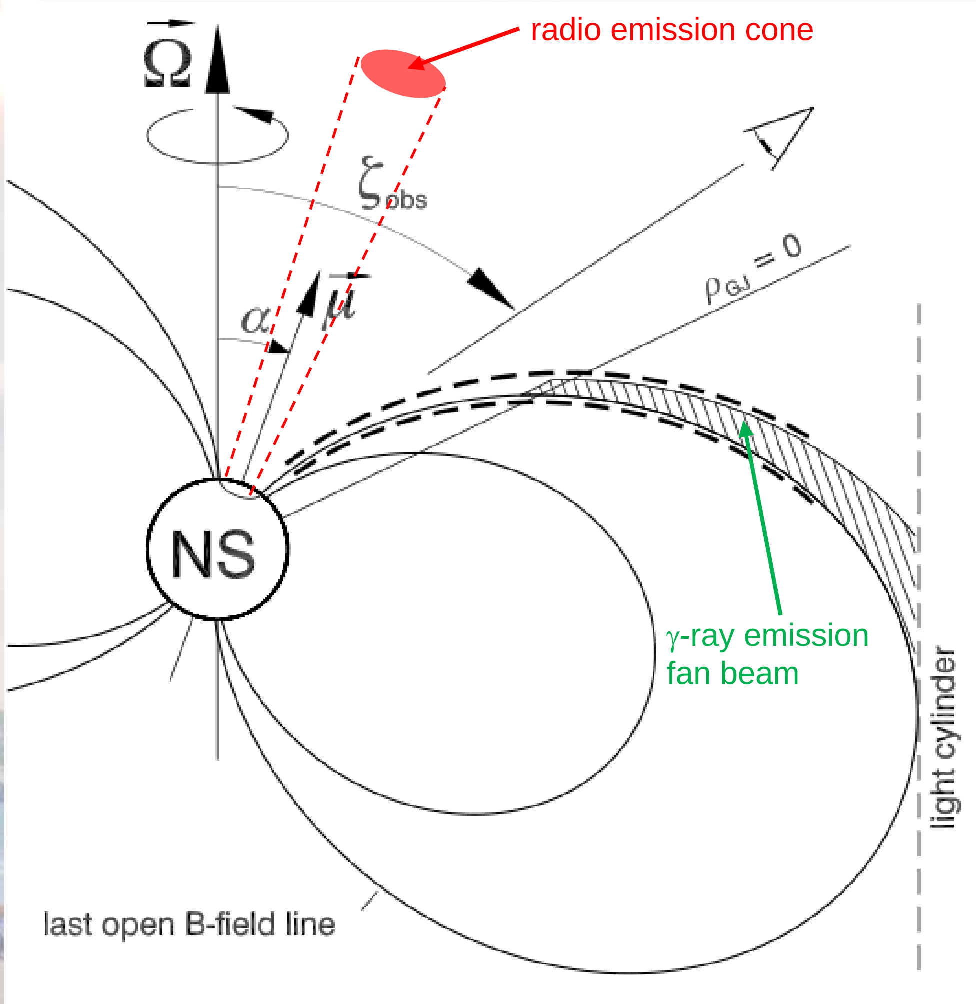
$$\dot{E} = - B^2 R^6 \Omega^4 / c^3$$

- derived parameters:

rotational age : $\tau = \Omega / 2\dot{\Omega}$

B field: $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G

spin-down power: $L = I\Omega\dot{\Omega}$



Conclusion

We are just beginning to grasp the new picture of pulsars in the Galaxy in GeV energies emerging from *Fermi* LAT