Pulsars seen by *Fermi*

Gamma-ray Space Telescope

9th meeting of the High Energy Astrophysics Association in Japan, March 2009

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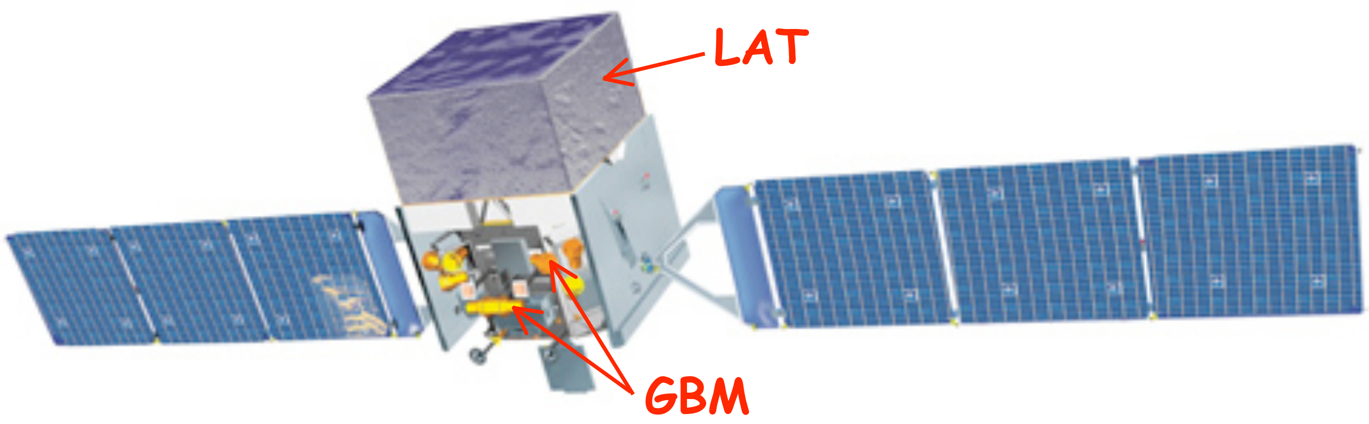
Tokyo Tech
on behalf of the Fermi LAT collaboration

Exploring the High-Energy Universe

- gamma rays provide a direct view into Nature's largest accelerators (neutron stars, black holes)
- gamma rays probe cosmological distances (e.g., $\gamma + \gamma_{EBL} \rightarrow e^+ + e^-$)
- huge leap in key capabilities, including a largely unexplored energy range; great potential for discovery: e.g. dark matter



Two instruments: Large Area Telescope (LAT), 20 MeV - >300 GeV
Gamma-ray Burst Monitor (GBM), 10 keV - 25 MeV

Fermi LAT Collaboration

- **France**
  - IN2P3, CEA/Saclay
- **Italy**
  - INFN, ASI, INAF
- **Japan**
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- **Sweden**
  - Royal Institute of Technology (KTH)
  - Stockholm University
- **United States**
  - Stanford University (SLAC and HEPL/Physics)
  - University of California at Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - Ohio State University
  - University of Washington

~390 Members
(~95 Affiliated Scientists, 68 Postdocs, and 105 Graduate Students)

construction managed by Stanford Linear Accelerator Center (SLAC), Stanford University

Fermi Gamma-ray Space Telescope

Fermi LAT science objectives

20 MeV - > 300 GeV

> 2000 AGNs
blazars and radiogal = f(θ,z)
evolution z < 5
Sag A*

10-50 GRB/year
GeV afterglow
spectra to high energy

γ-ray binaries
Pulsar winds
μ-quasar jets

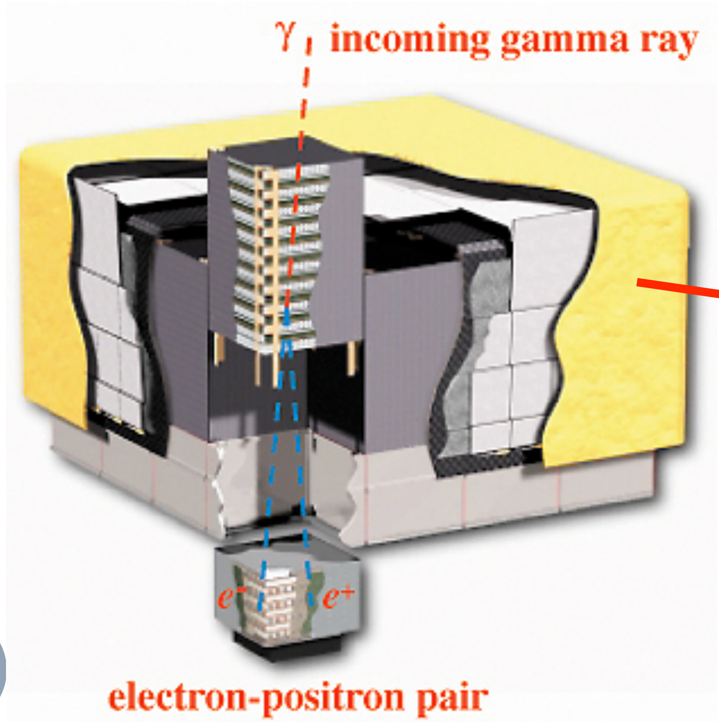
Possibilities
starburst galaxies
galaxy clusters
measure EBL
unIDs

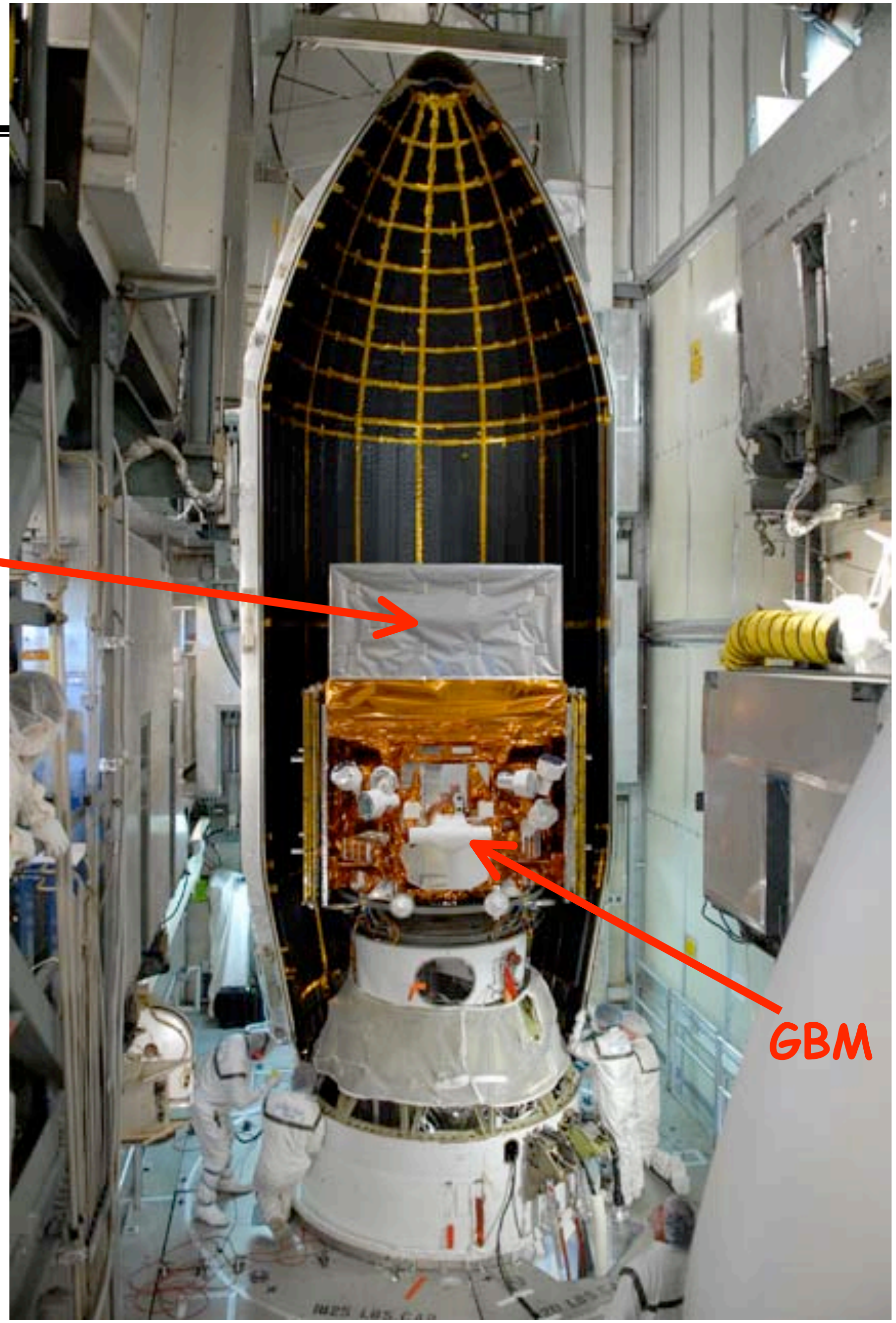
Dark Matter
neutralino lines
sub-halo clumps;
$e^+ + e^-$ spectrum

Cosmic rays and clouds
acceleration in Supernova remnants
OB associations
propagation (Milky Way, M31, LMC, SMC)
Interstellar mass tracers in galaxies

Pulsars
emission from radio and X-ray pulsars
blind searches for new Gemingas
magnetospheric physics
pulsar wind nebulae

The Large Area Telescope (LAT)

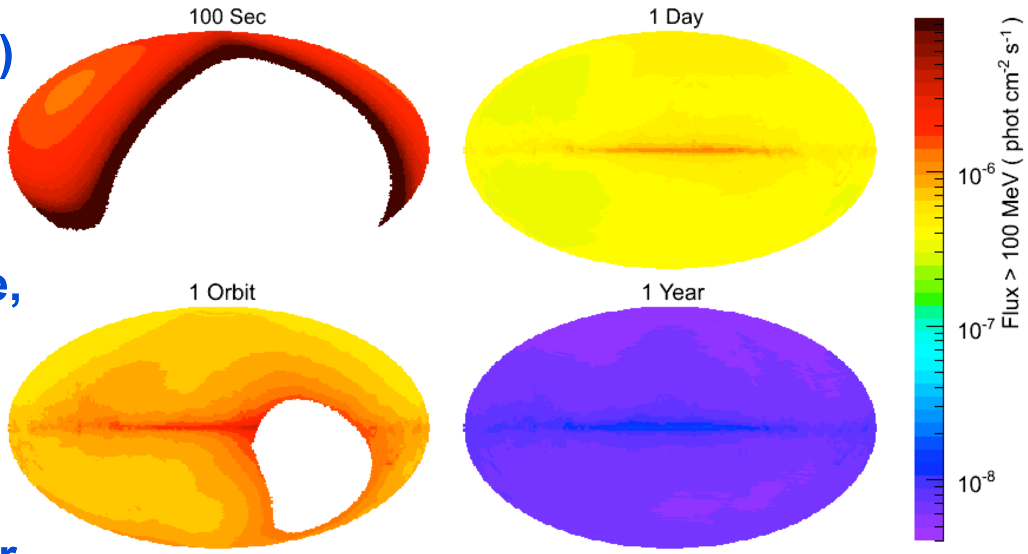




<u>LAT images the sky one photon at a time</u>: γ-ray converts in LAT to an electron and a positron ; direction and energy of these particles tell us the direction and energy of the photon

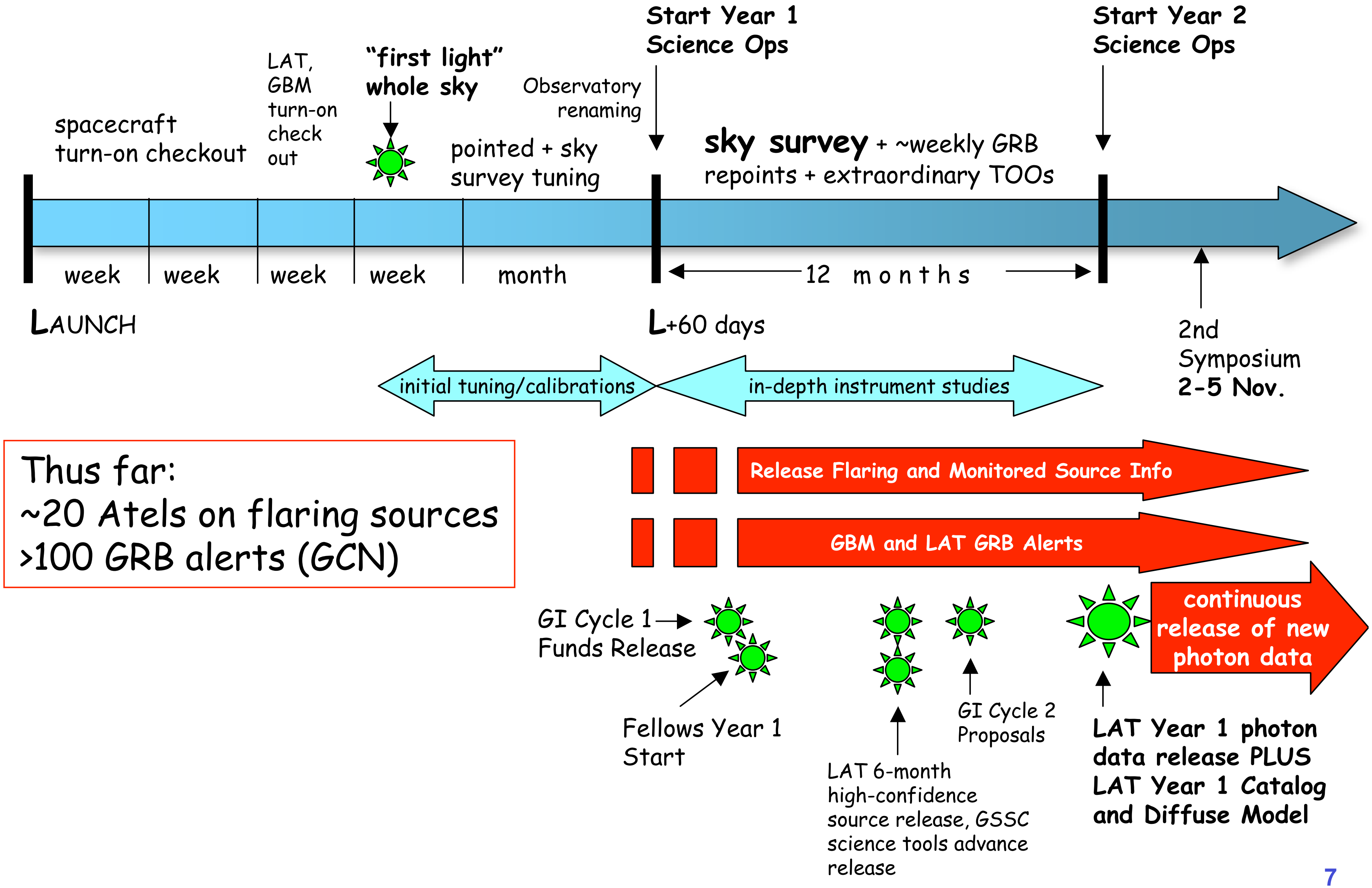
Operating modes

- **Primary observing mode is Sky Survey**
  - **Full sky every 2 orbits (3 hours)**
  - **Uniform exposure, with each region viewed for ~30 minutes every 2 orbits**
  - **Best serves majority of science, facilitates multiwavelength observation planning**
  - **Exposure intervals commensurate with typical instrument integration times for sources**
  - **EGRET sensitivity reached in days**



- **Pointed observations when appropriate (selected by peer review in later years) with automatic earth avoidance selectable. Target of Opportunity pointing.**
- **Autonomous repoints for onboard GRB detections in any mode.**

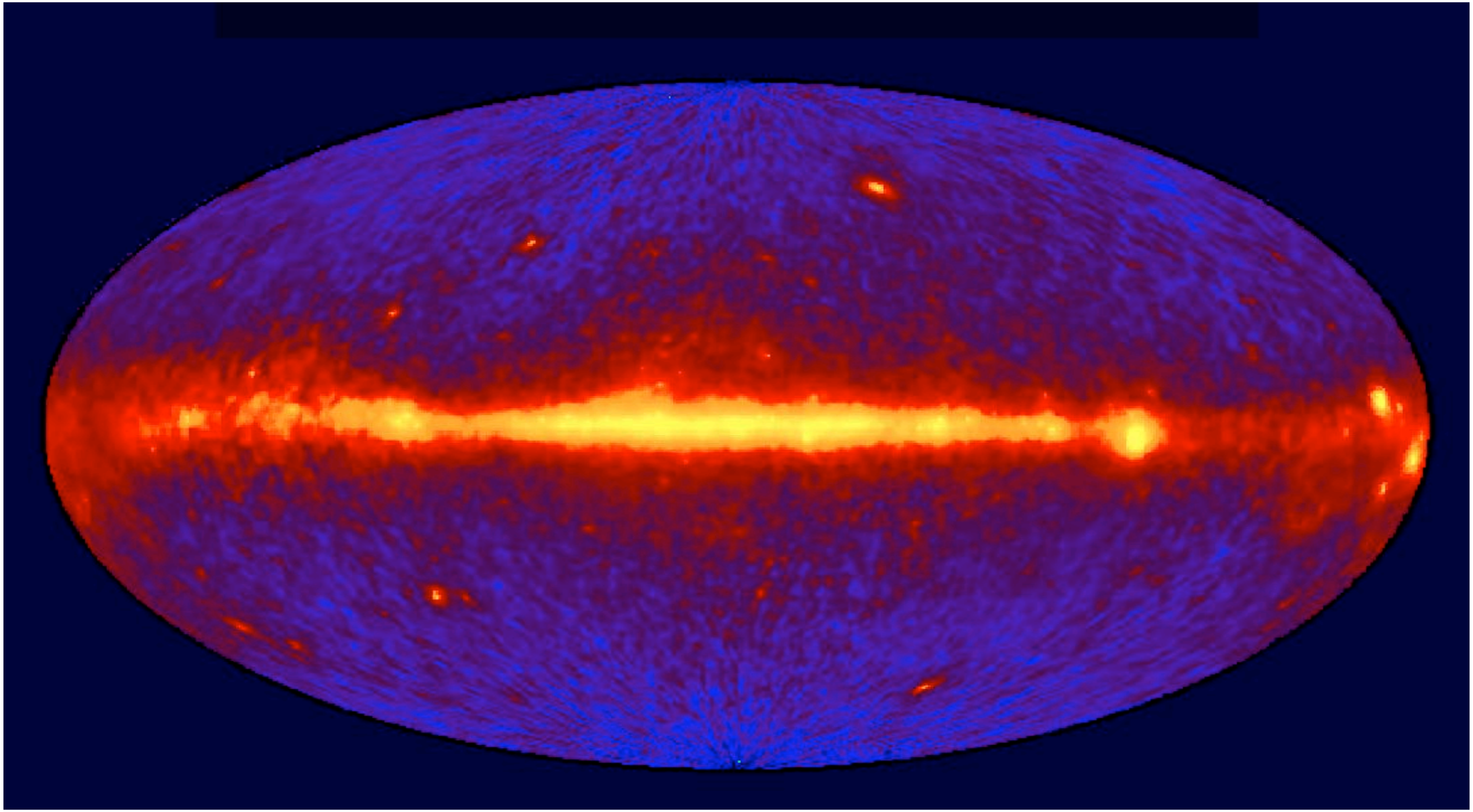
Year 1 Science Operations Timeline Plan

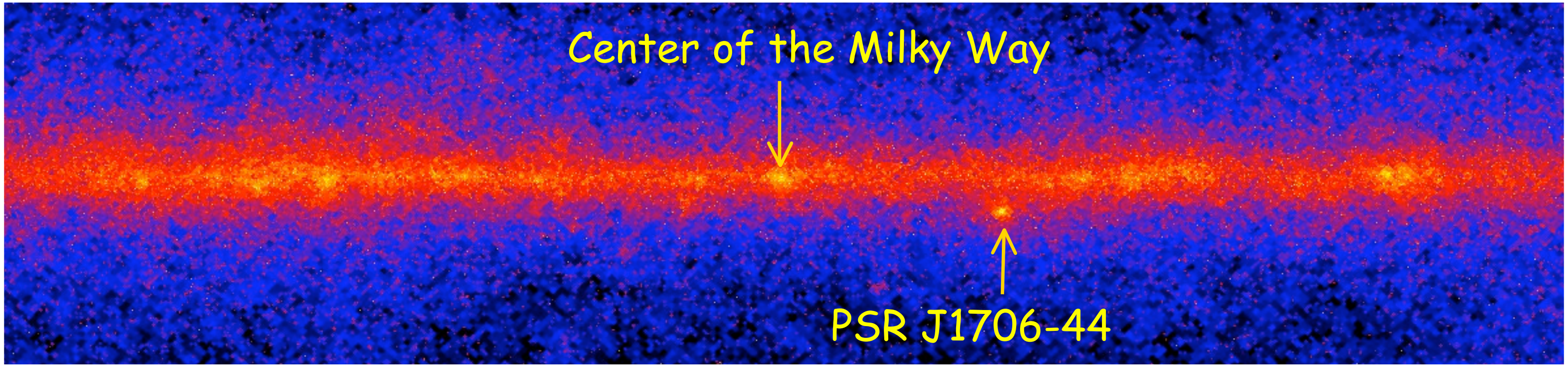


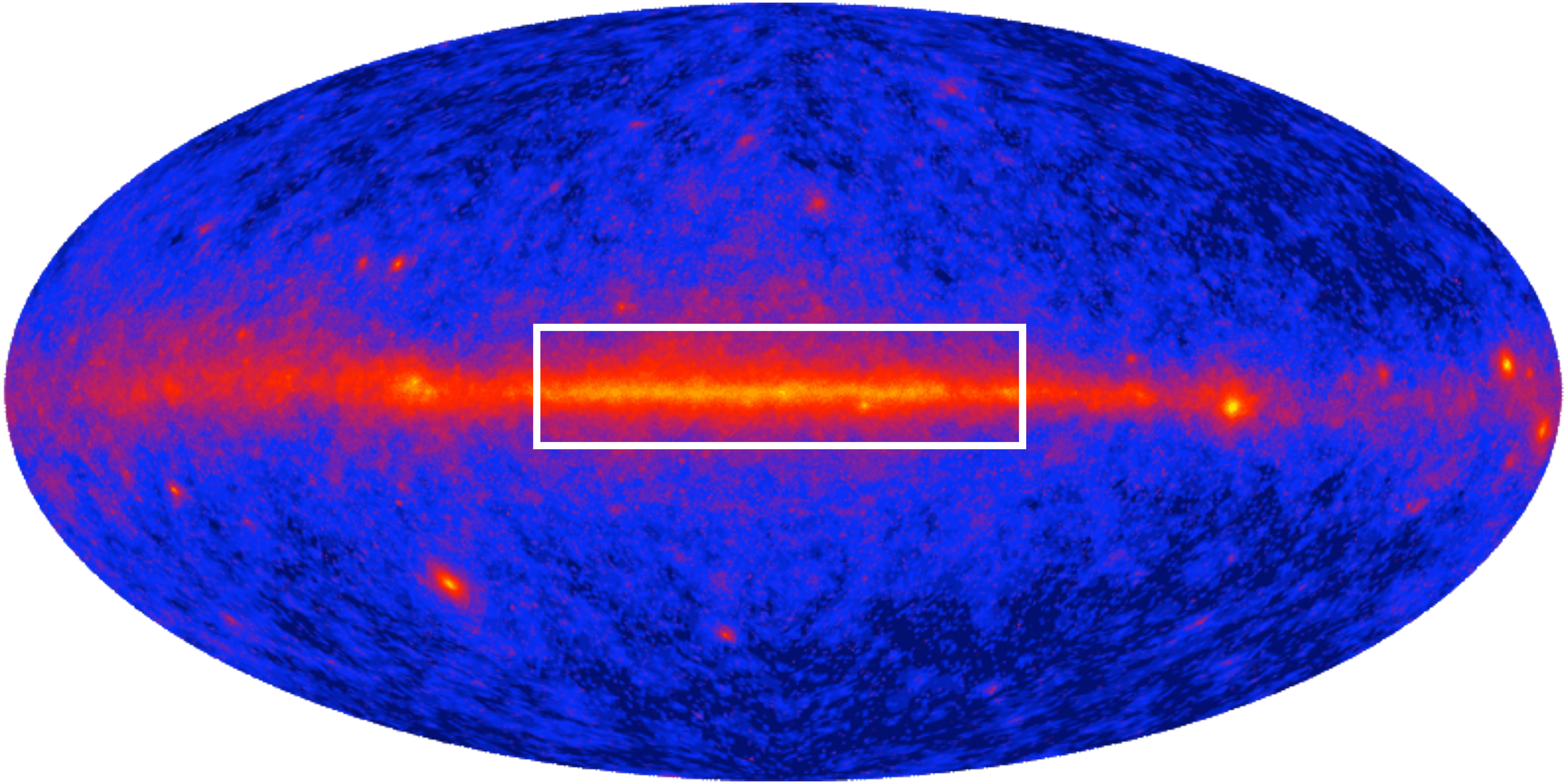
Thus far:
~20 Atels on flaring sources
>100 GRB alerts (GCN)

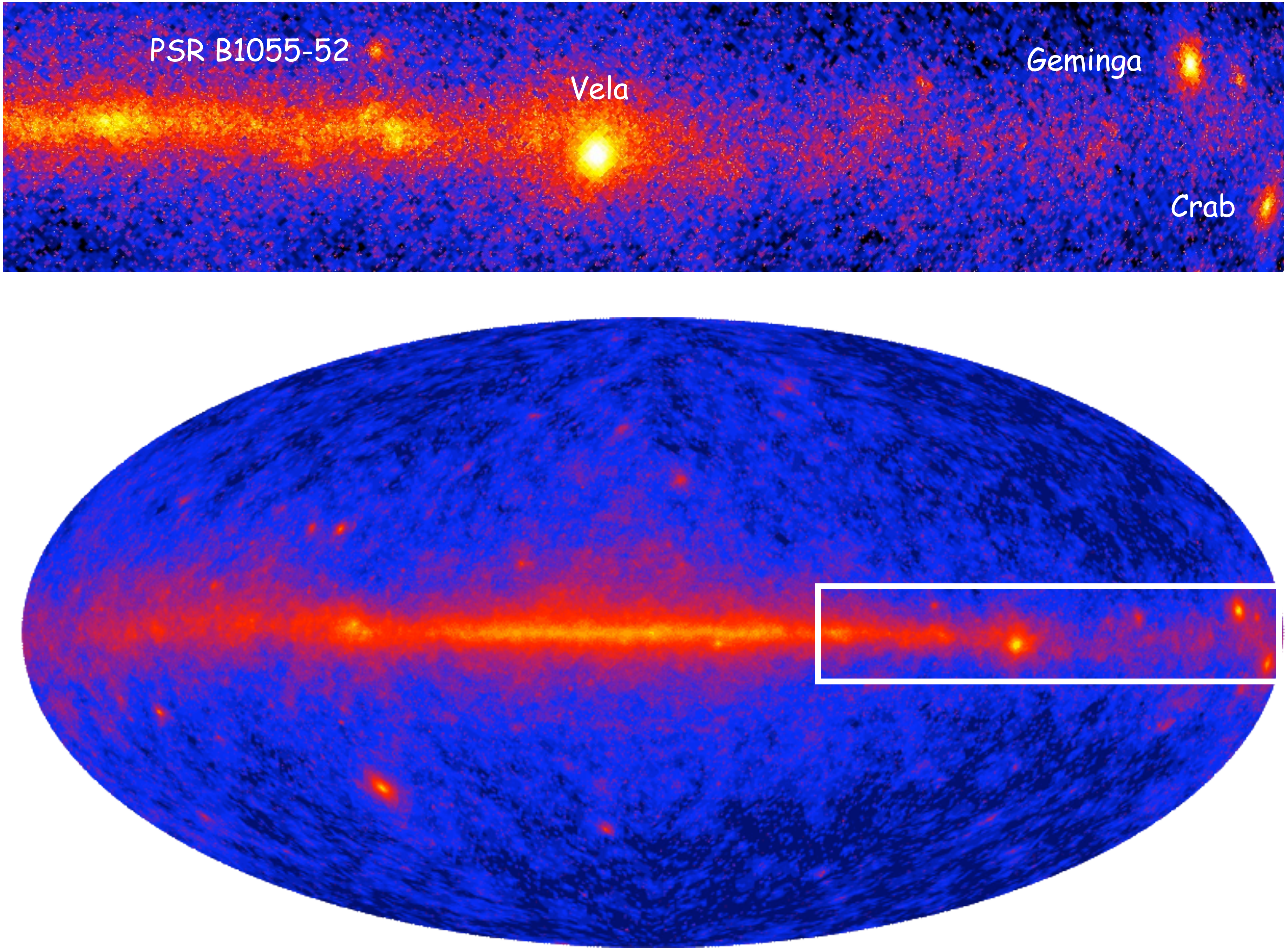
Reminder: Features of the Gamma-Ray Sky seen by EGRET

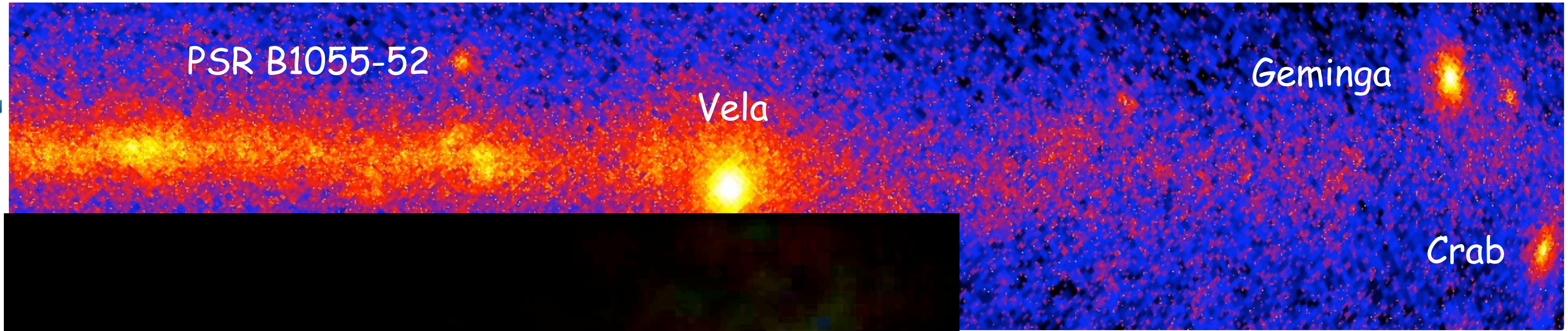
EGRET all-sky survey (galactic coordinates) E>100 MeV




Center of the Milky Way
PSR J1706-44




PSR B1055-52
Vela
Geminga
Crab


PSR B1055-52
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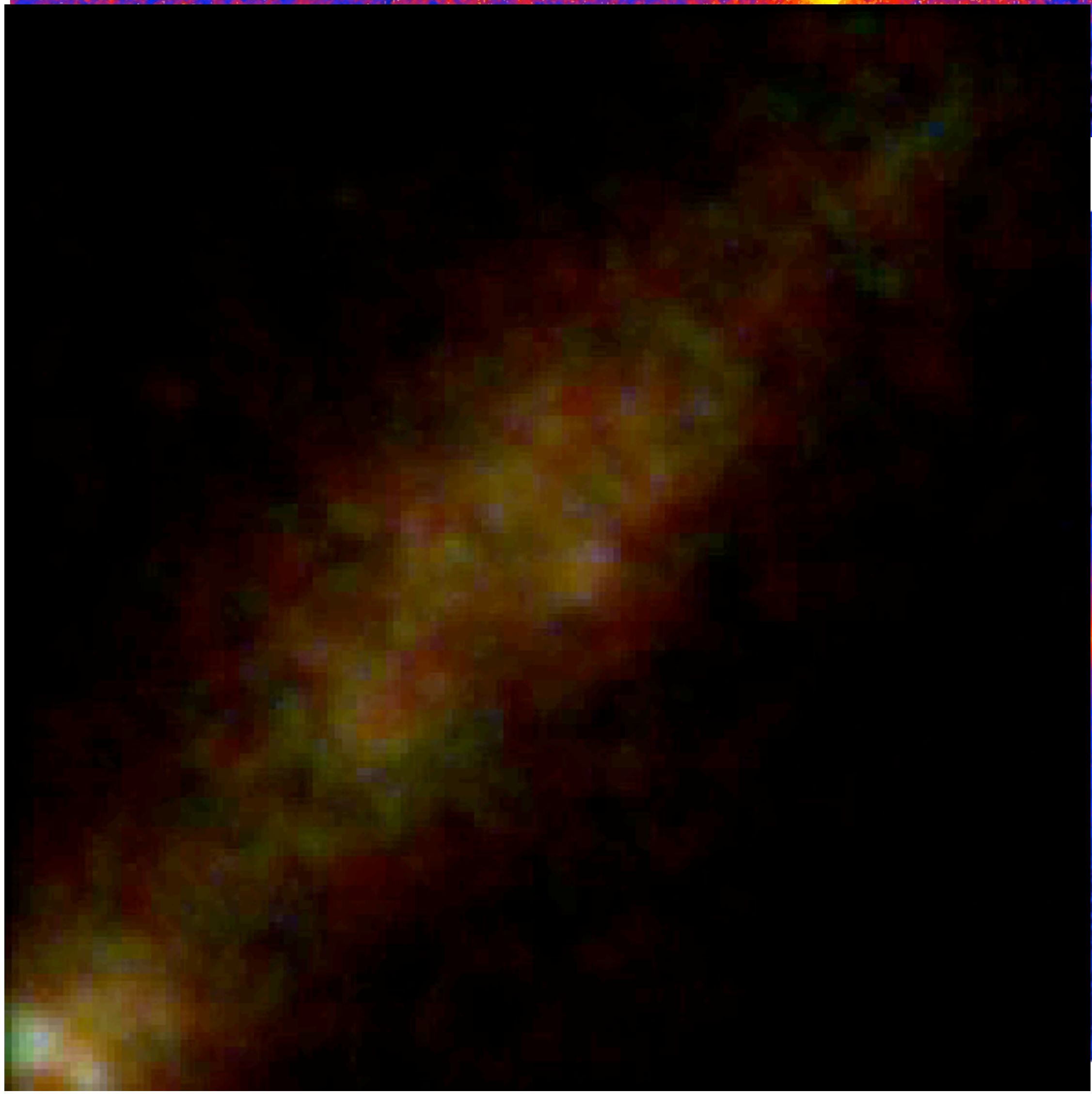
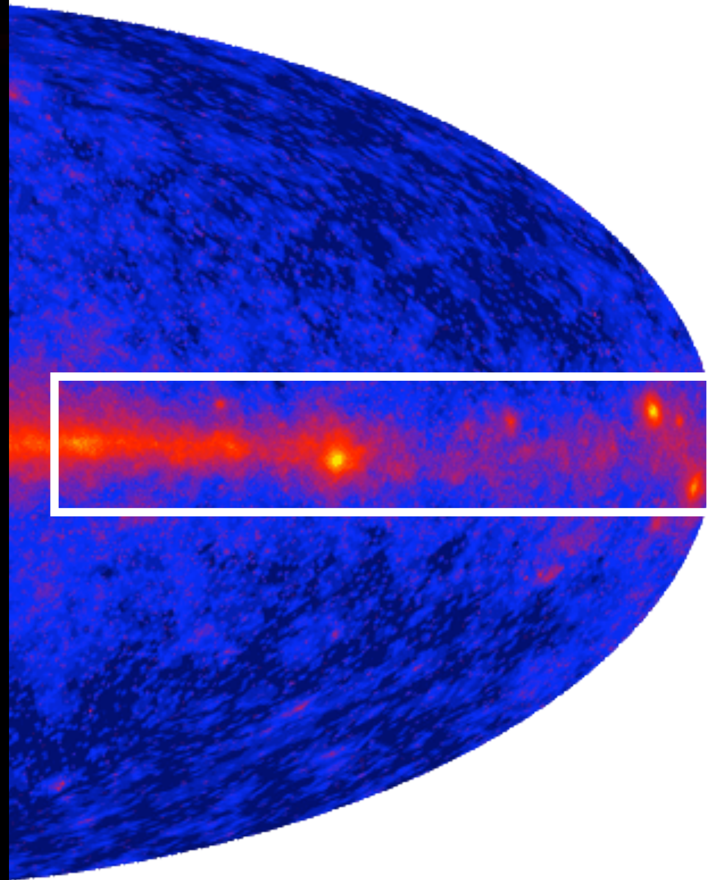




Questions *Fermi* LAT can Pursue Regarding Galactic Sources and Populations

- 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

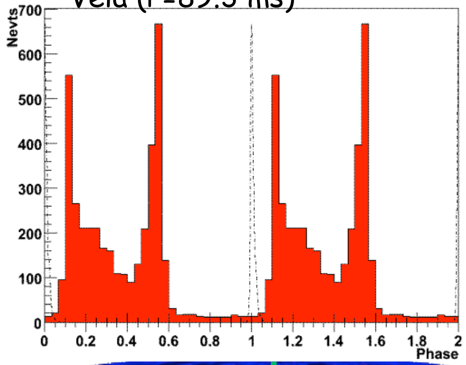
depends on regular timing of radio pulsars by collaborators at Parkes, Jodrell Bank, Nancay, GBT, …

some are found by blind searches

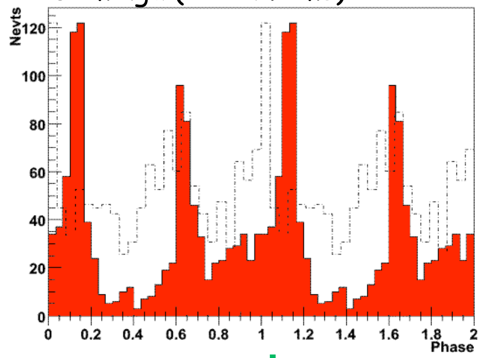
Fermi
Gamma-ray Space Telescope

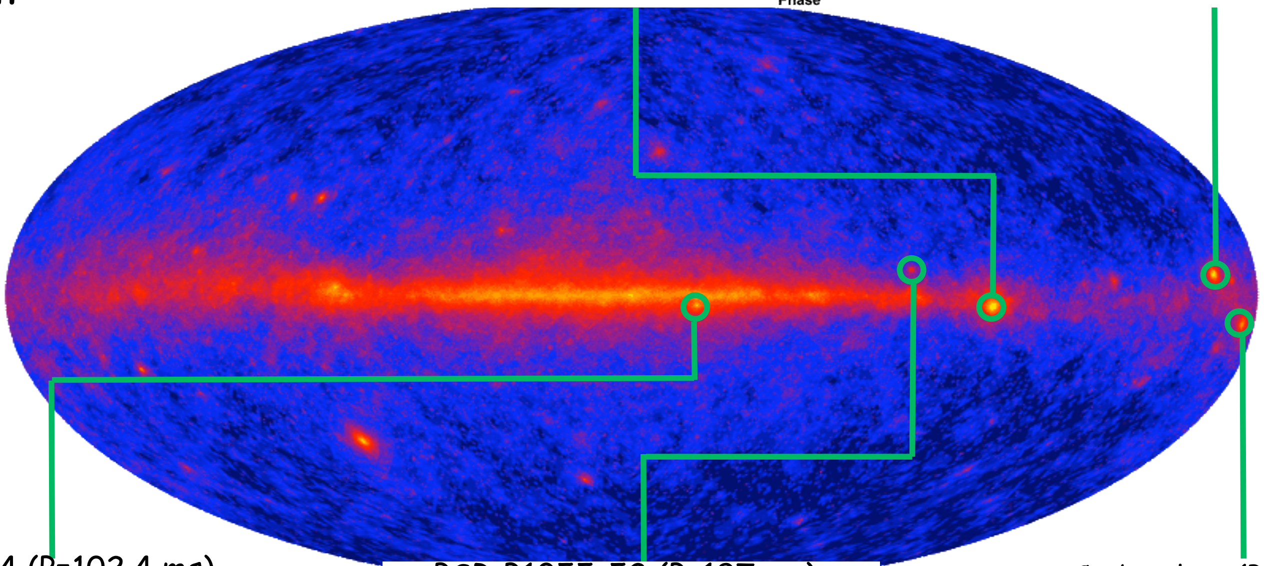
In its first few days, *Fermi* confirmed the EGRET pulsars, and began finding new γ-ray pulsars as well

Vela (P=89.3 ms)

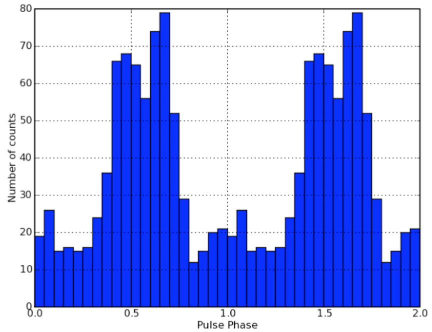


Geminga (P=237.1 ms)

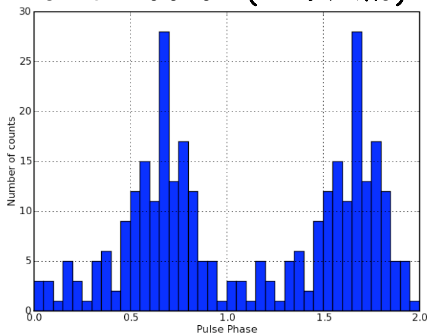




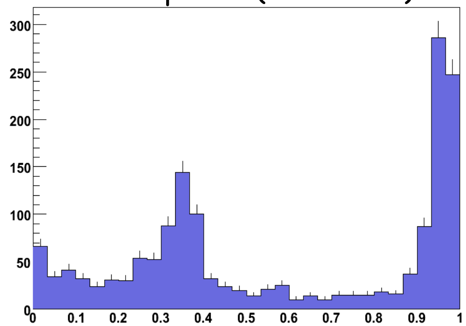
PSR B1706-44 (P=102.4 ms)



PSR B1055-52 (P=197 ms)



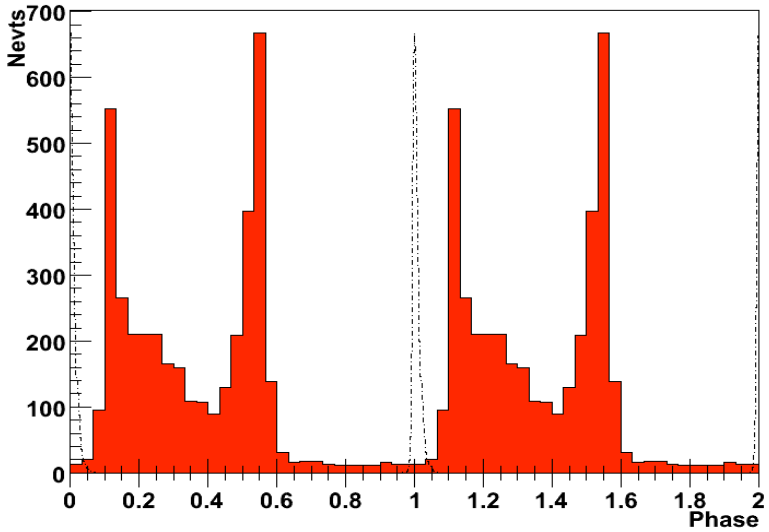
Crab pulsar (P=33.4 ms)

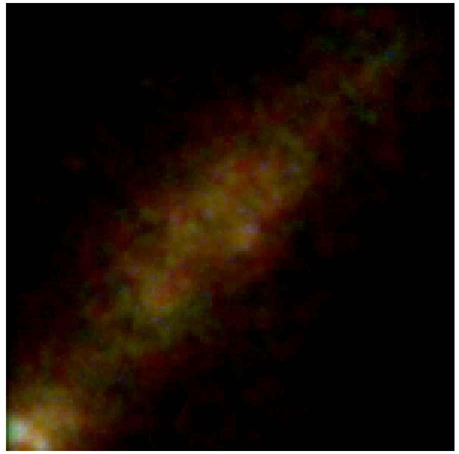


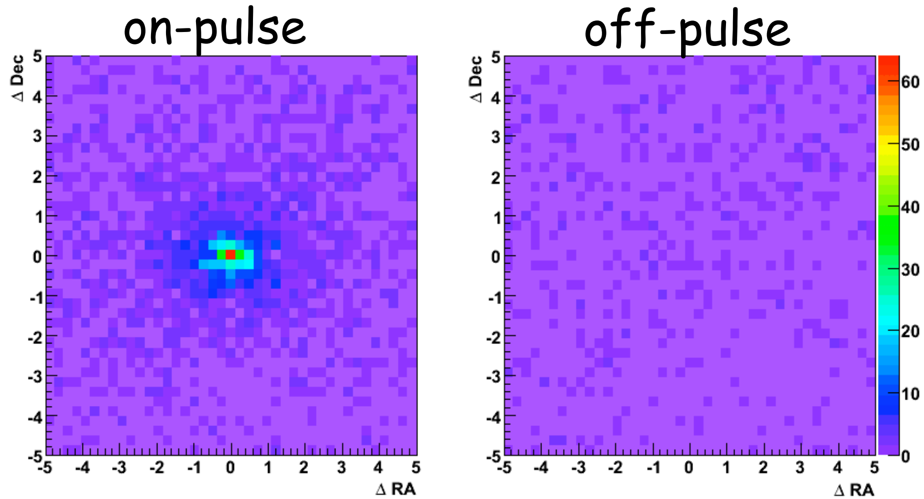
Vela – (very) early returns

Everything works!

- timing
- background rejection
- alignment





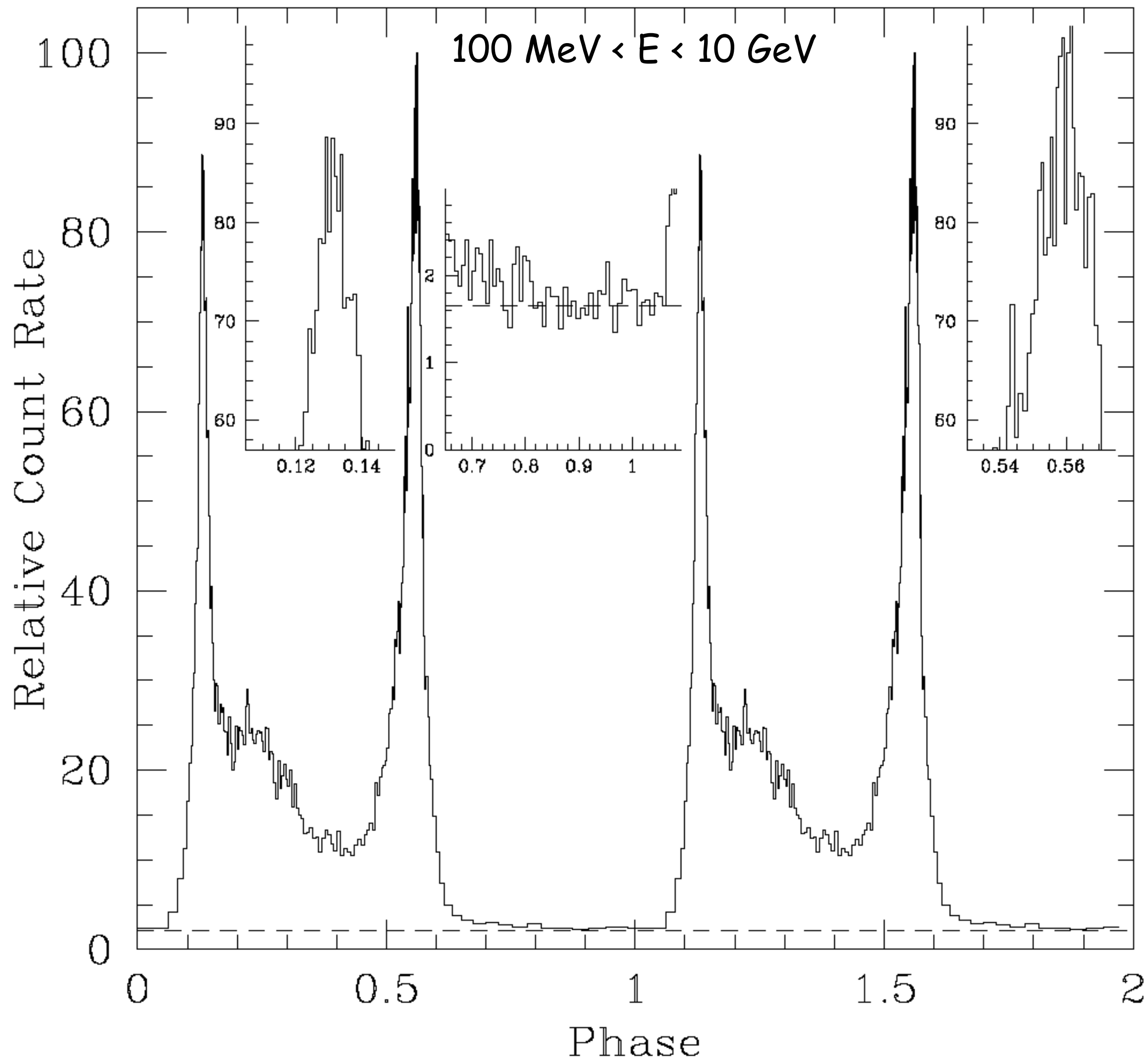


• precise ephemerides of many pulsars provided by Parkes, Jodrell Bank, Green bank, Nançay, Arecibo, Hartbeesthoek, Urumqi, RXTE, XMM...

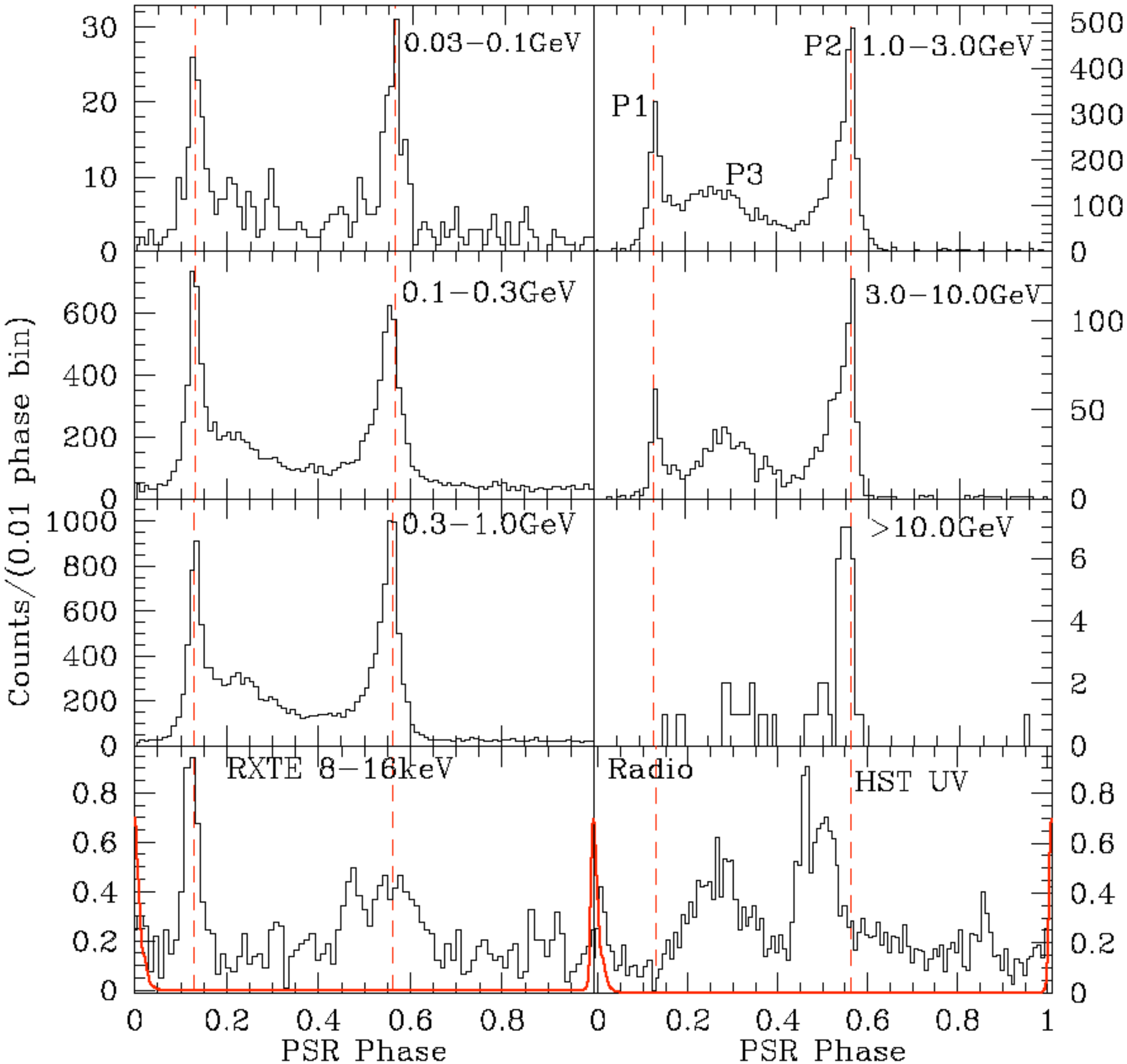
• selecting on-pulse shows point source

- • evaluate PSF
- • alignment of LAT to sky (fit to

First Fermi View of the Vela Pulsar

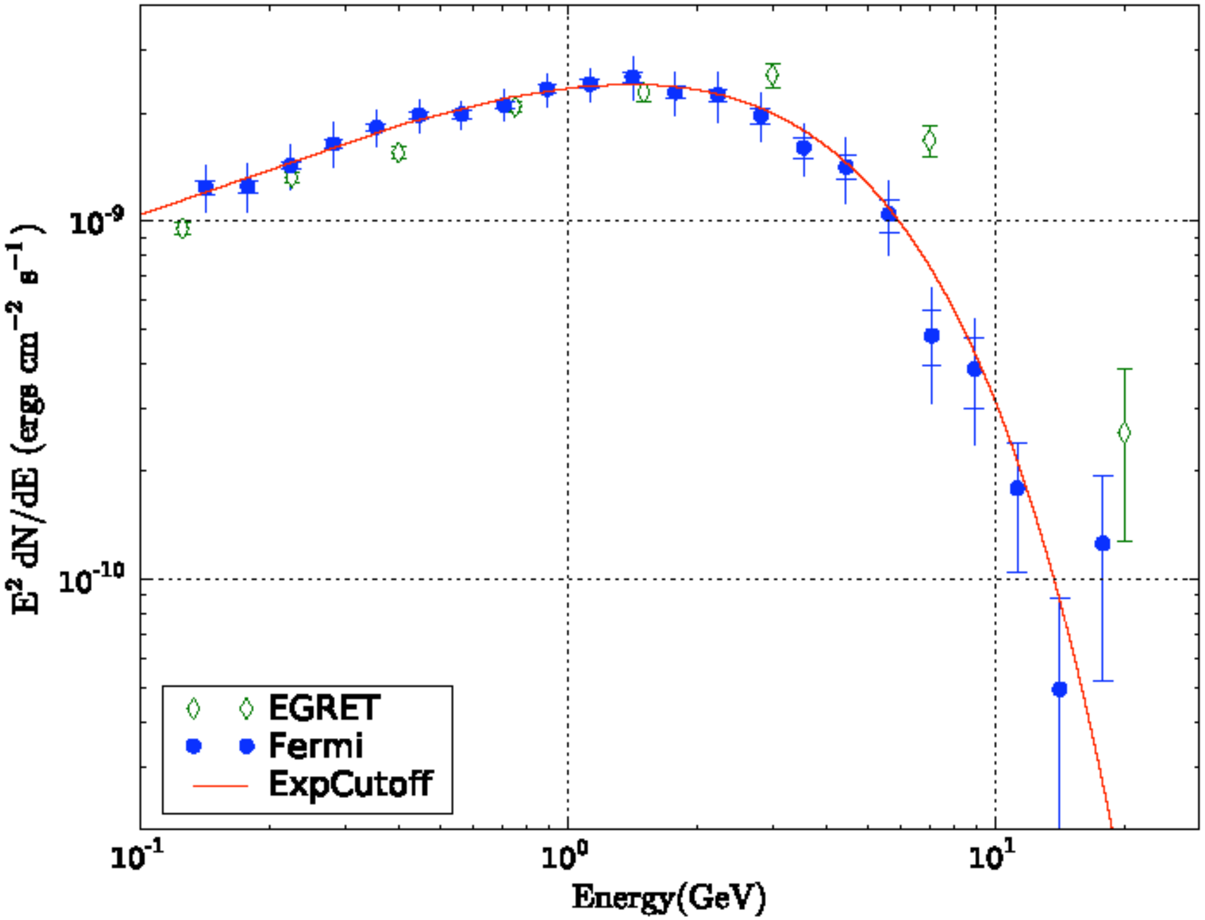


Vela Pulsar – Energy Evolution of Pulse Profile



Vela Pulsar – Phase-averaged SED

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



Consistent with b=1 (simple exponential)

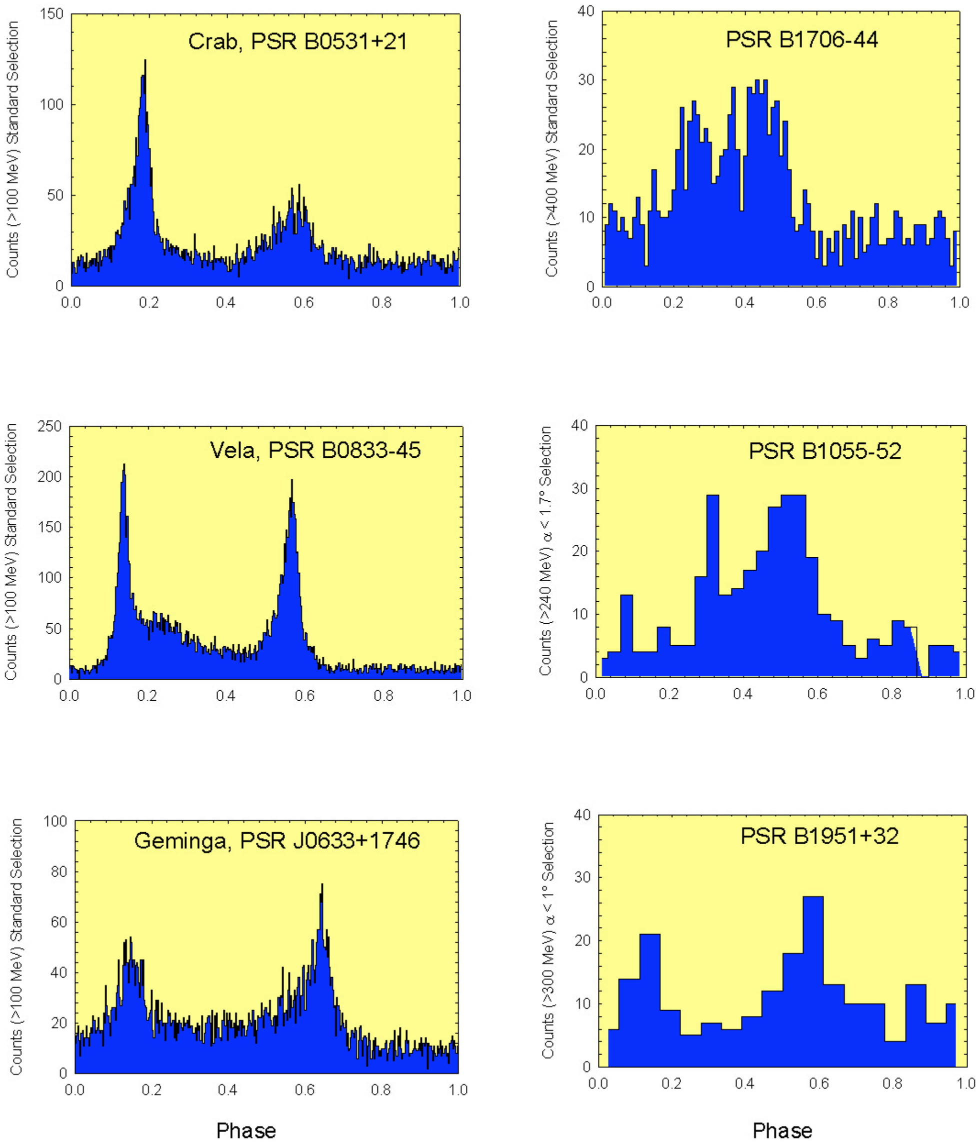
$$\Gamma = -1.51 \begin{matrix} +0.05 \\ -0.04 \end{matrix}$$

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

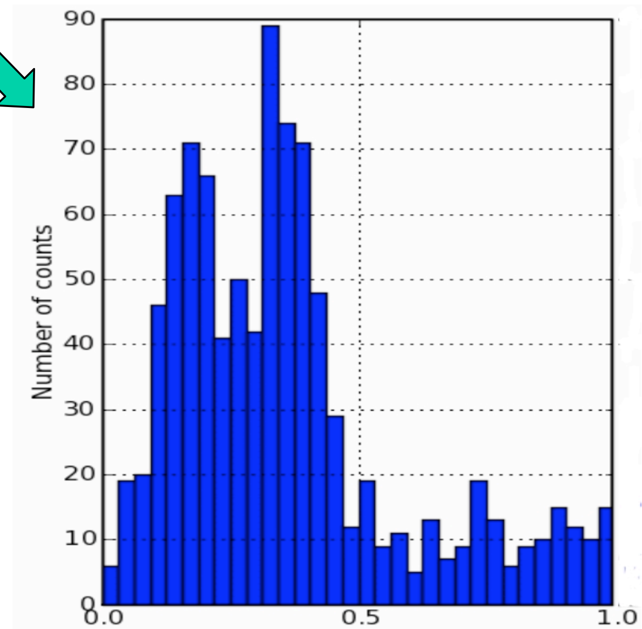
b=2 (super-exponential) rejected at 16.5σ

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

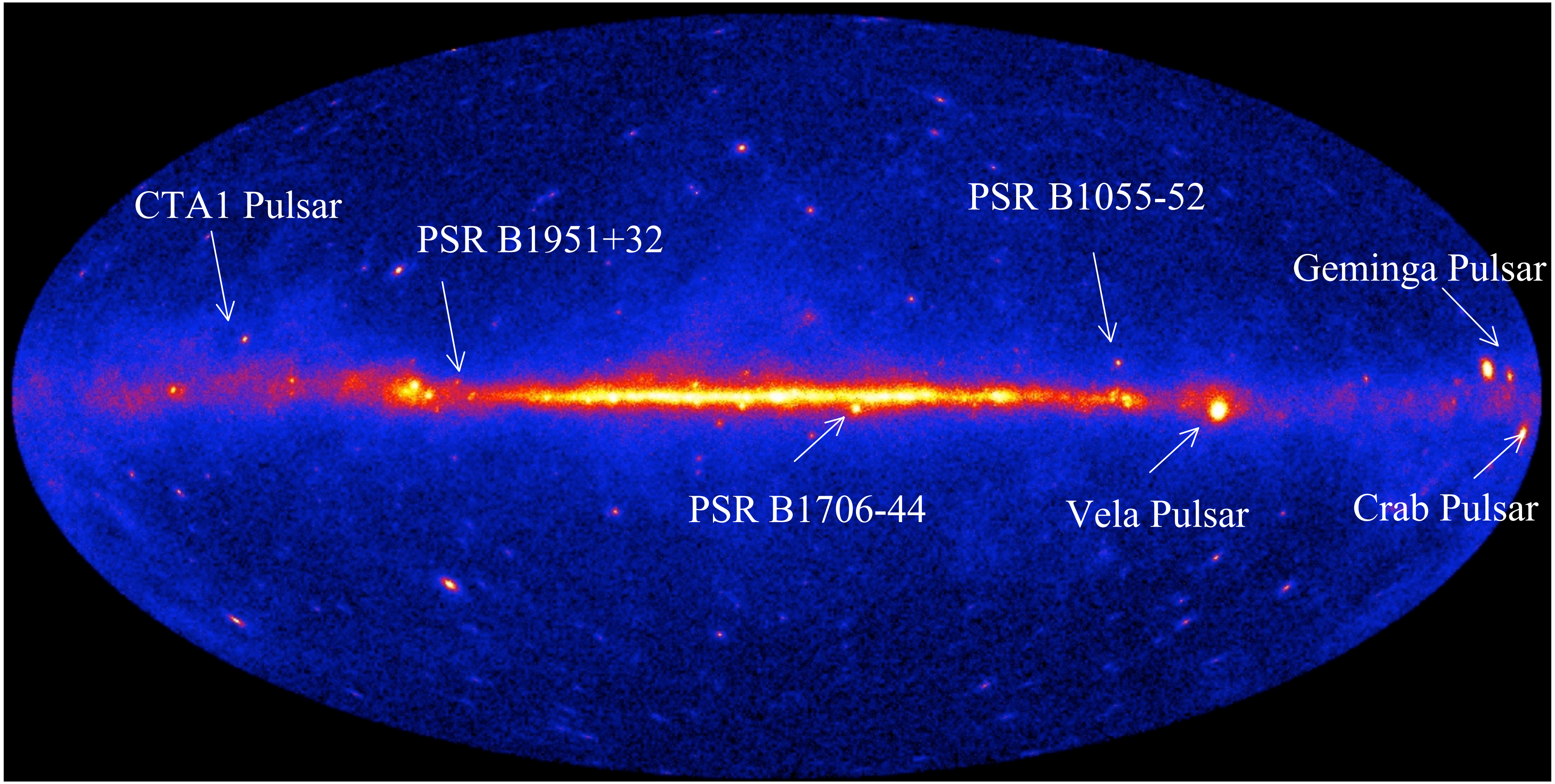
the classic EGRET 6



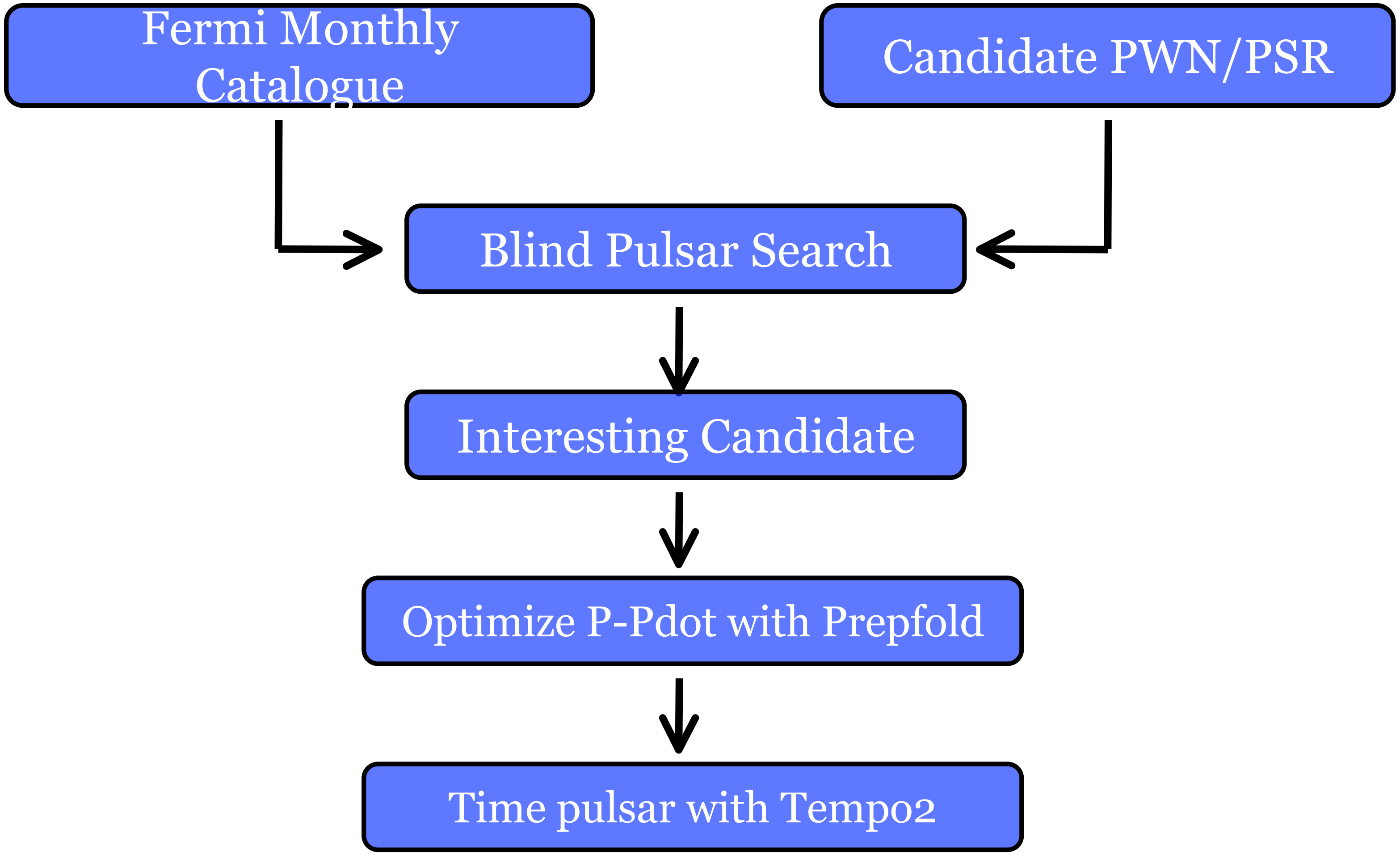
CTA 1



EGRET 6 and CTA1



Blind Pulsar Search



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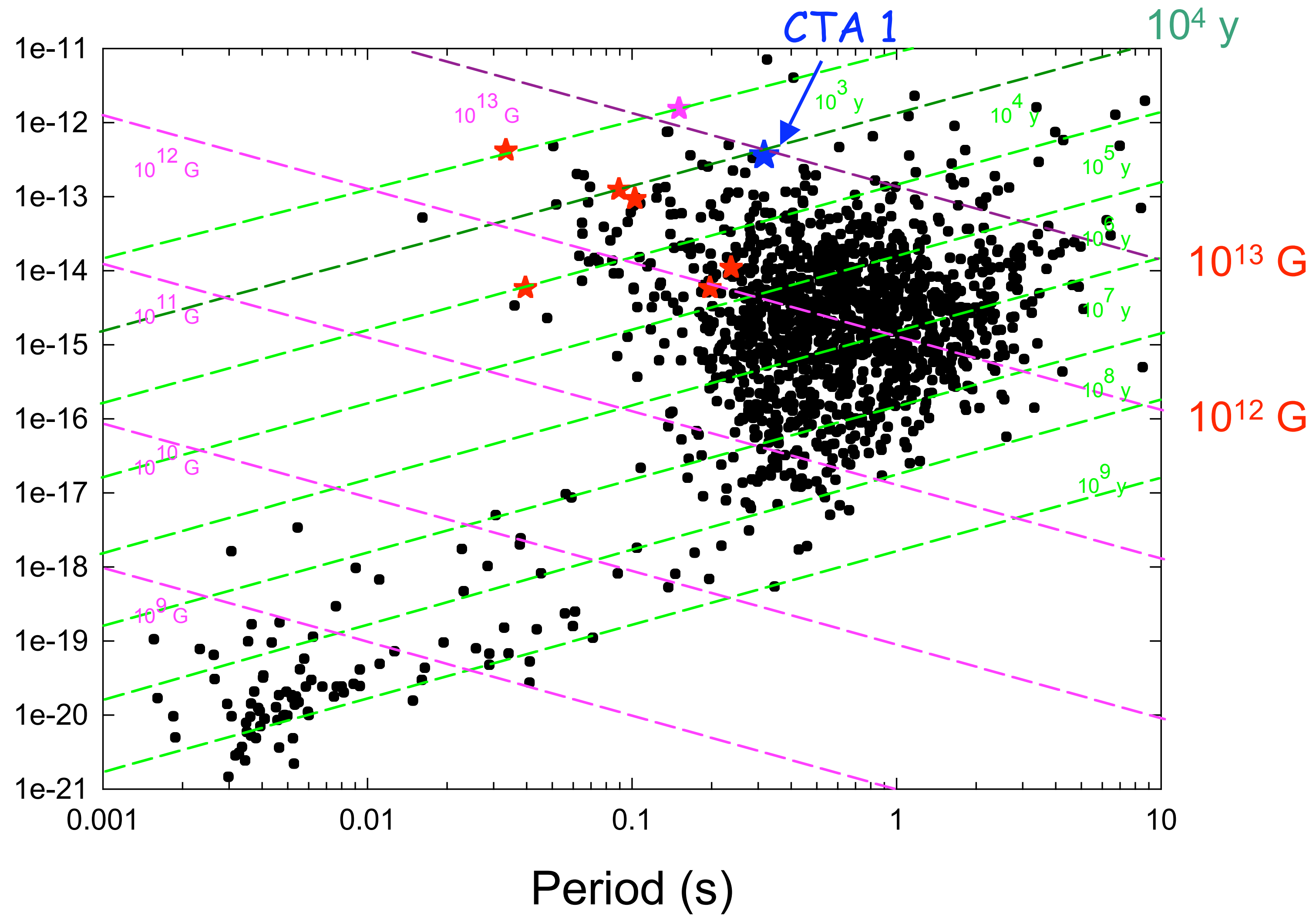
CTA 1 Pulsar Parameters

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



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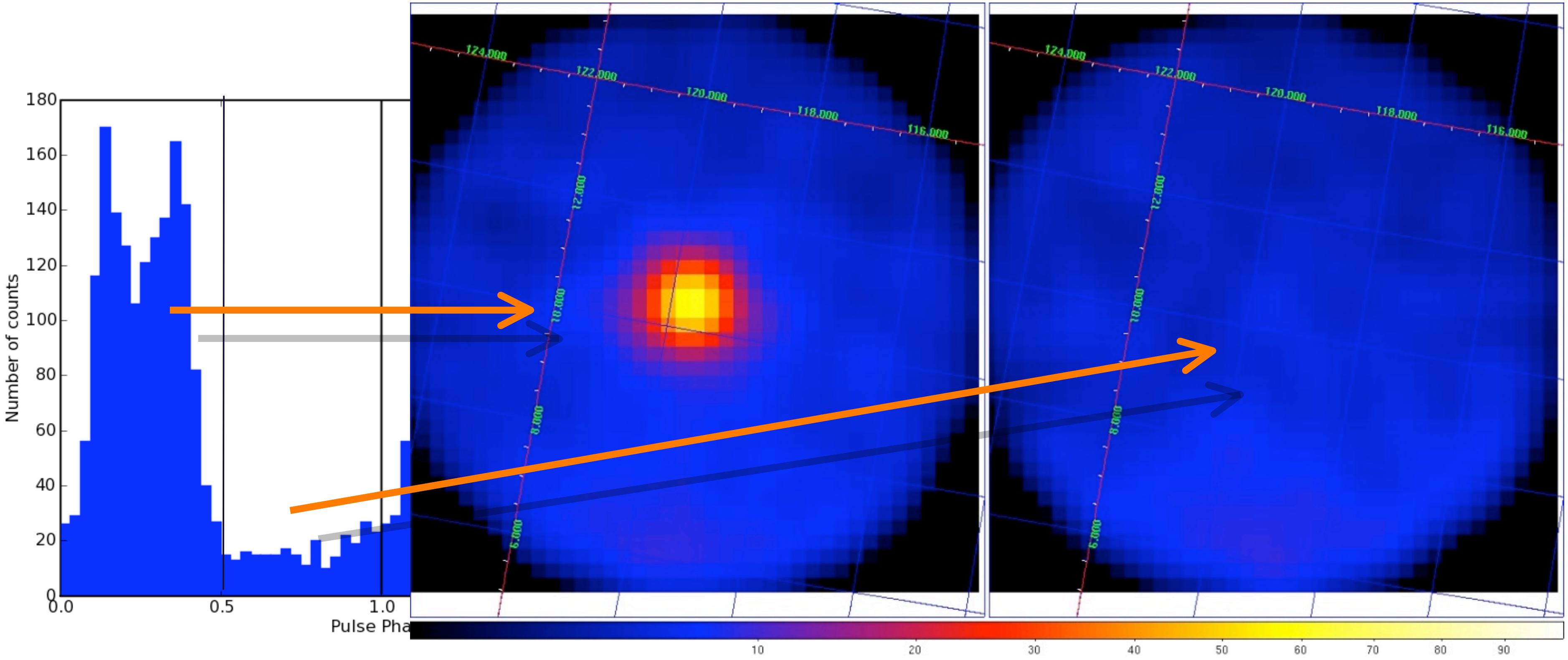
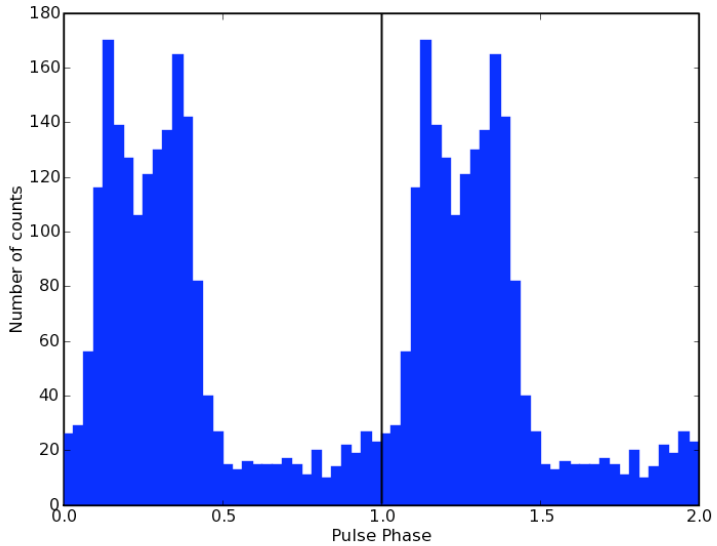
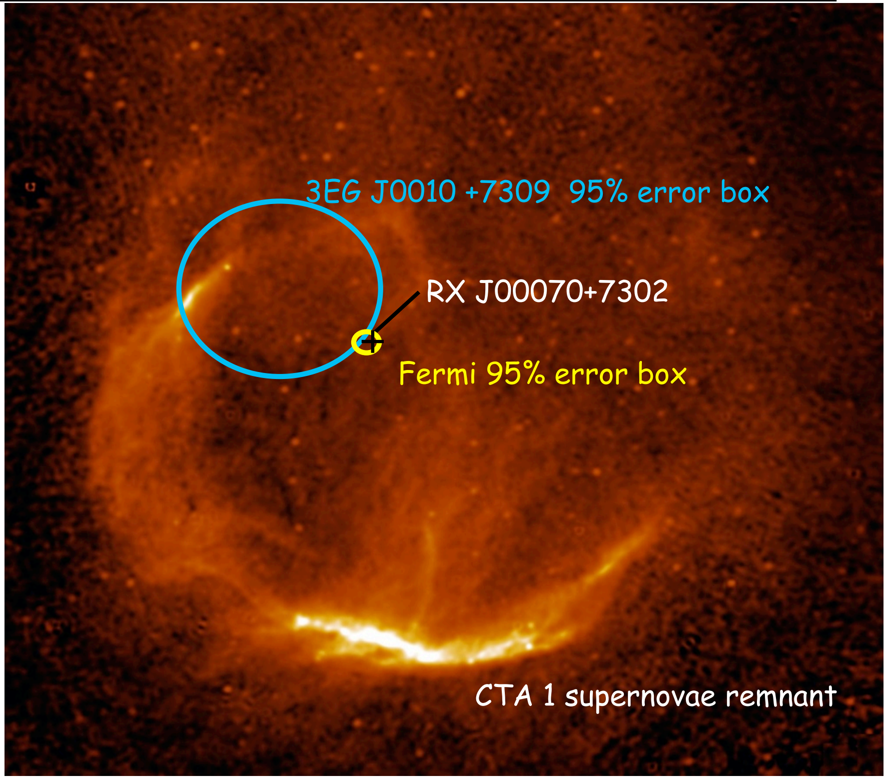
On and off Pulse Images



Pulsar in CTA1





- 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

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First *Fermi* millisecond pulsar

PSR J0030+0451

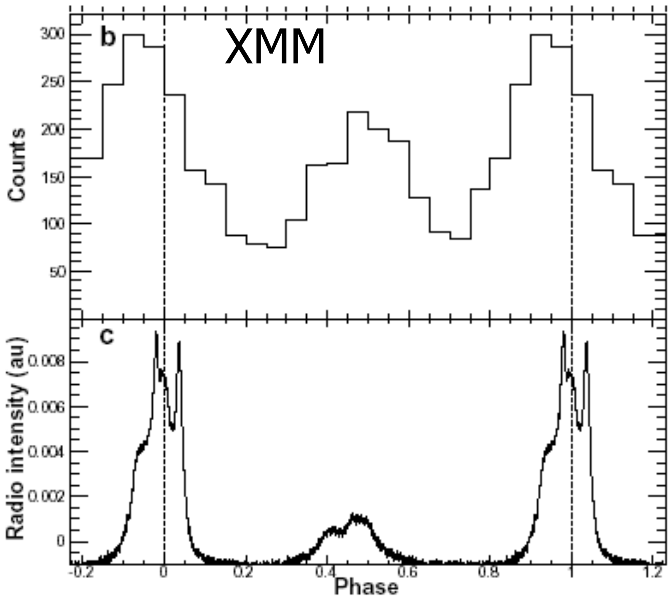
- **P = 4.86 ms**
- **Nearby – d = 317 pc**
- **Low spin-down power**

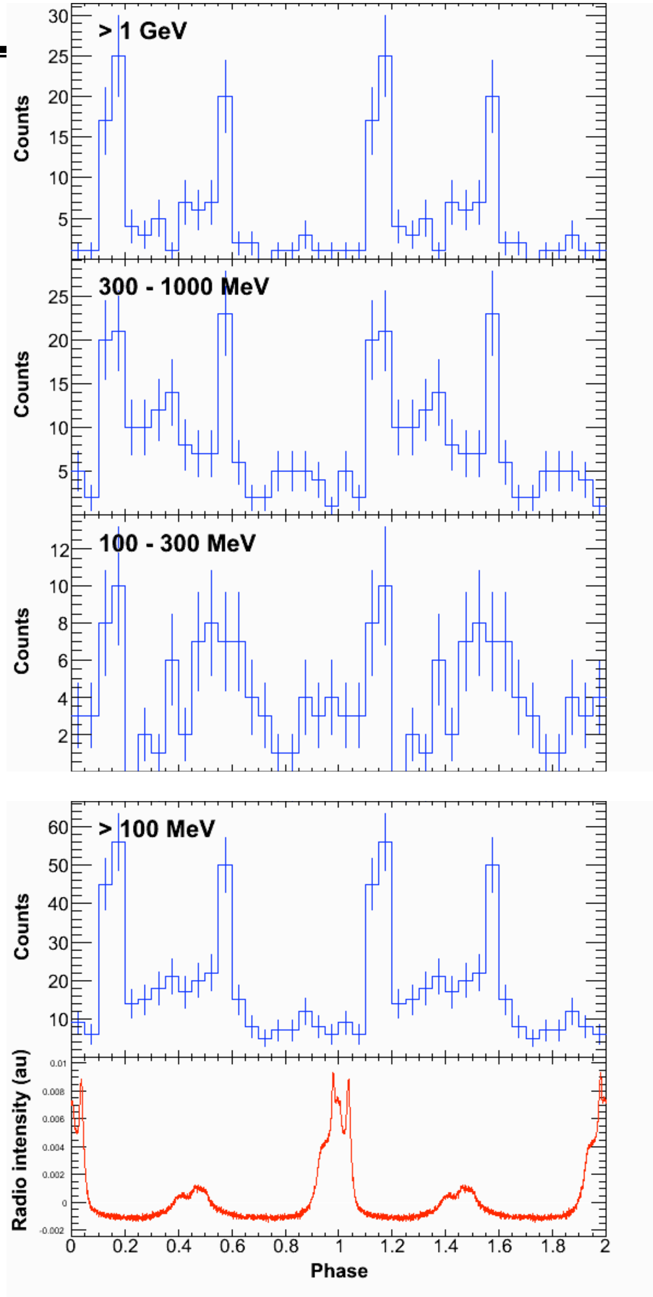
$$\dot{E}_{sd} = 3.3 \times 10^{33}\ \mathrm{erg/s}$$

- **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*

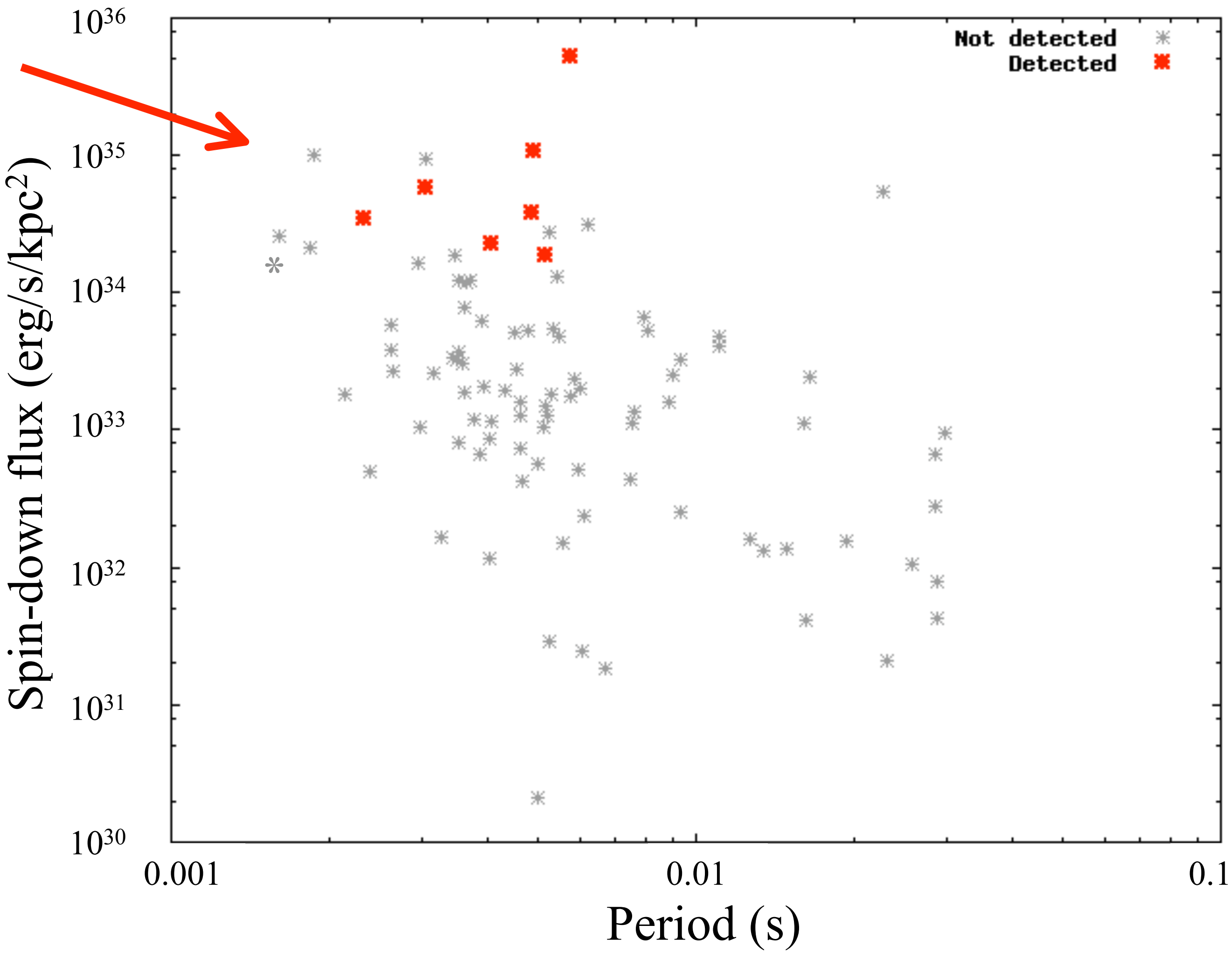
PULSAR	PERIOD	PERIOD DERIV.	D	Edot	# PHOTONS	H-TEST TS	CHANCE PROB
	(ms)	(10^{-20} s/s)	(kpc)	(erg/s)			
J0030+0451	4.86	1	0.317	3.44E+33	361	306.8	< 4e-08
J0218+4232	2.32	7.74	3.2	2.44E+35	455	12	0.0084
J0437-4715	5.76	5.73	0.15	1.18E+34	166	89.1	< 4e-08
J0613-0200	3.06	0.96	0.48	1.32E+34	549	60	< 4e-08
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?

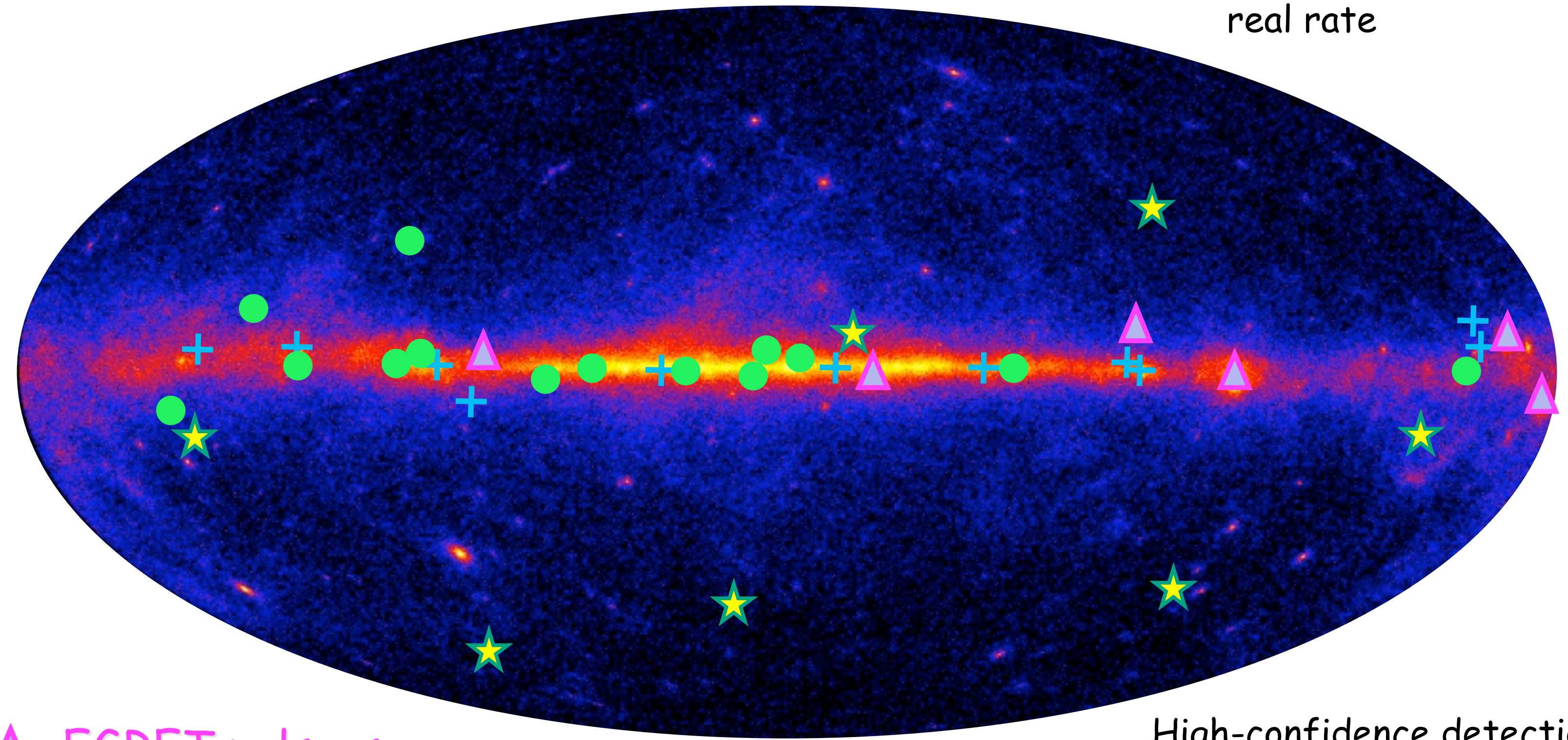
One map can convey all of this graphically, if we represent each pulsar slowed down in frequency (spin period is increased by factor of 10)

Fermi Pulsars

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

13 gamma-ray only pulsars

Pulses at 1/10th real rate



High-confidence detections through 10/31/2008

△ 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

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

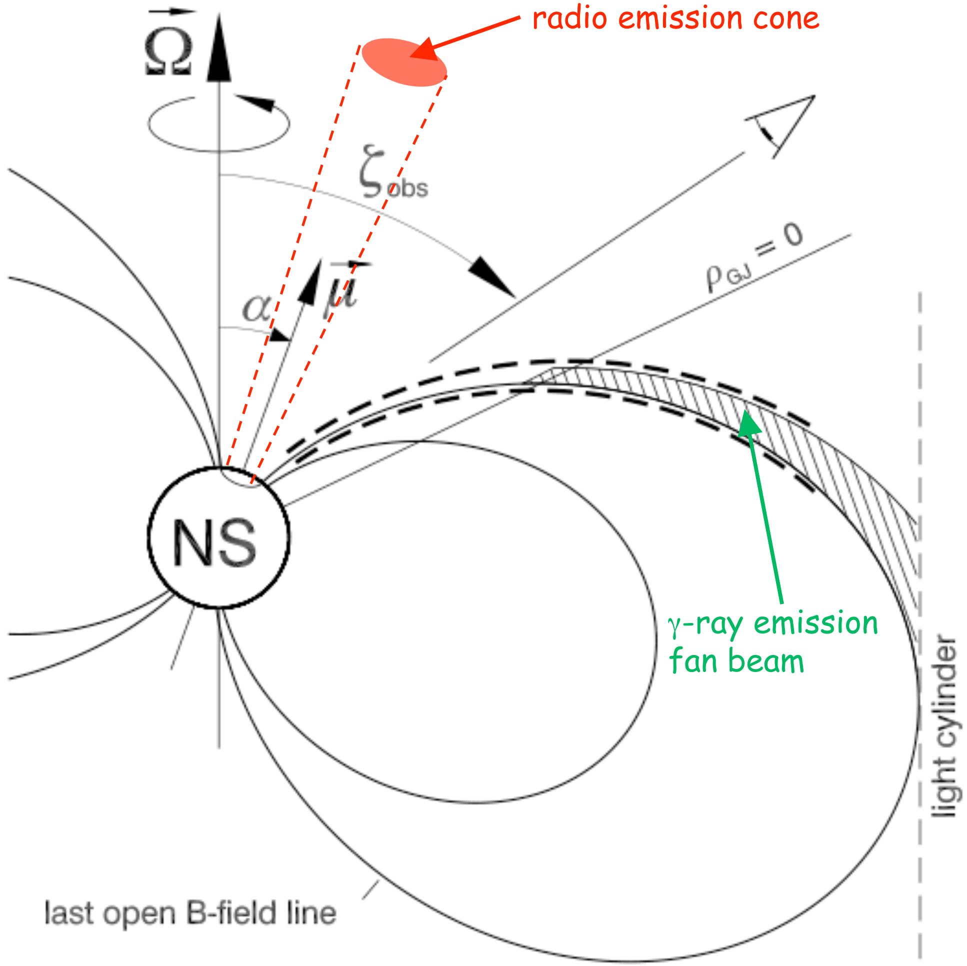
  $\dot{E} = - B^2 R^6 \Omega^4 / c^3$

- derived parameters:

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

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

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



Conclusion

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