Gamma-Ray and Multiwavelength Studies of Rotation-Powered Pulsars

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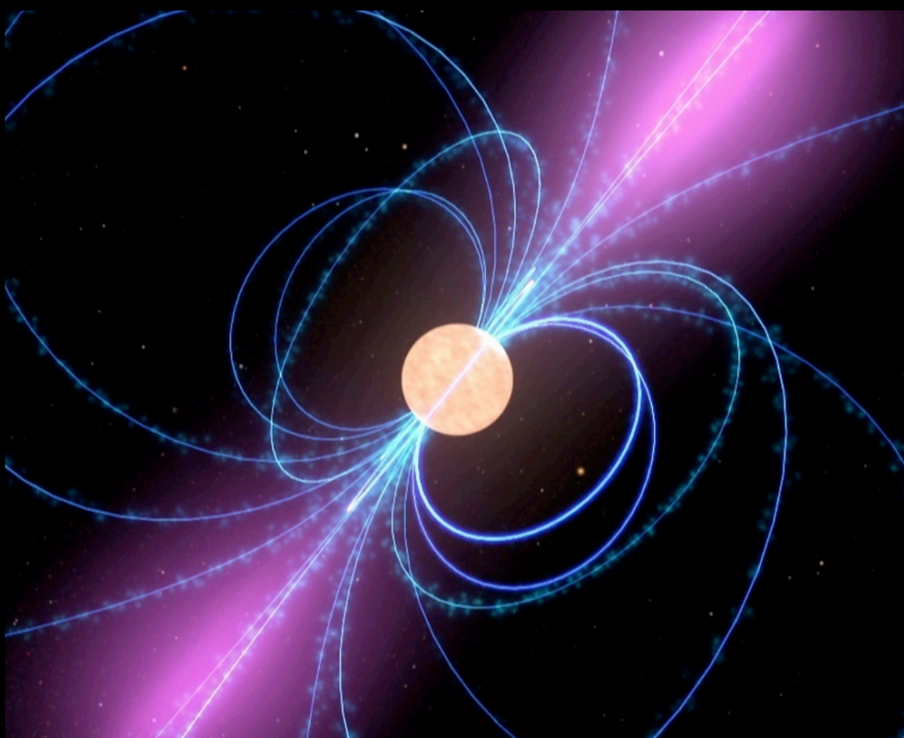
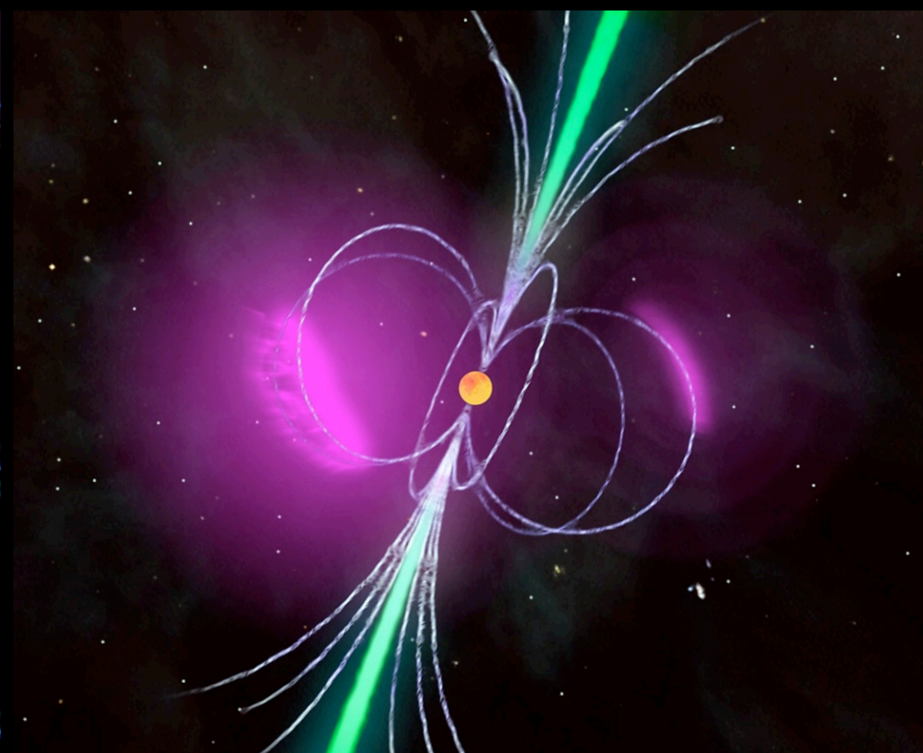
With special thanks to

Alice Harding





Outline

- Pulsar Basics
- Gamma-ray and multiwavelength pulsars
- Pulsar observations with Fermi
  - Known pulsars
  - New classes of pulsars
  - Related observations
- Multiwavelength observations
- Modeling gamma-ray pulsars

Neutron Stars and Pulsars – Early History

Walter Baade & Fritz Zwicky 1934

Existence of neutron stars

Franco Pacini 1967

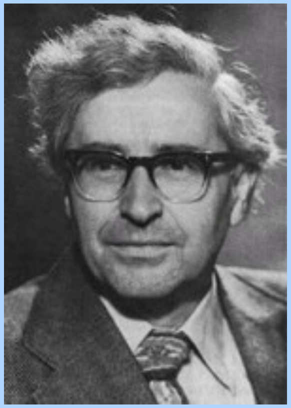
Energy from a rotating neutron star

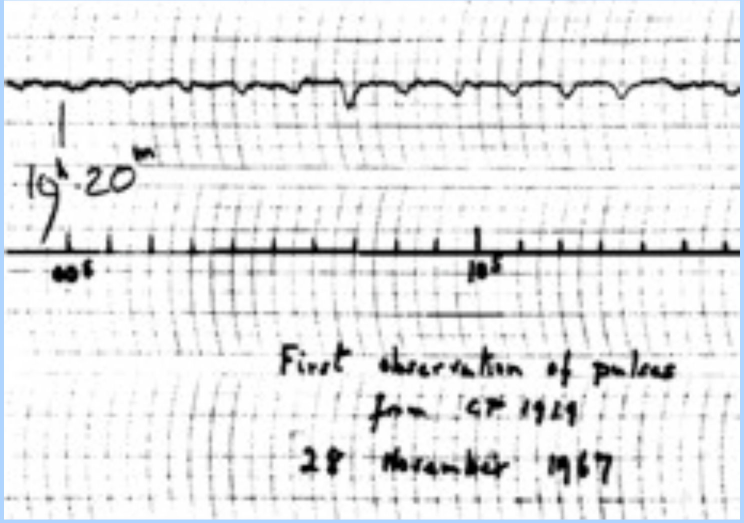
$$\dot{E}_{rot} = \frac{B_0^2 \Omega^4 R^6}{6c^3}$$

Neutron Stars and Pulsars – Early History

Jocelyn Bell (graduate student), Antony Hewish et al. 1968

Discovery of radio pulsars

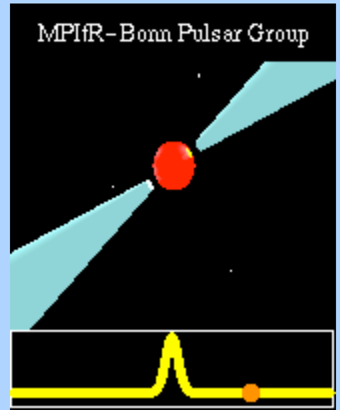




Neutron Stars and Pulsars – Early History

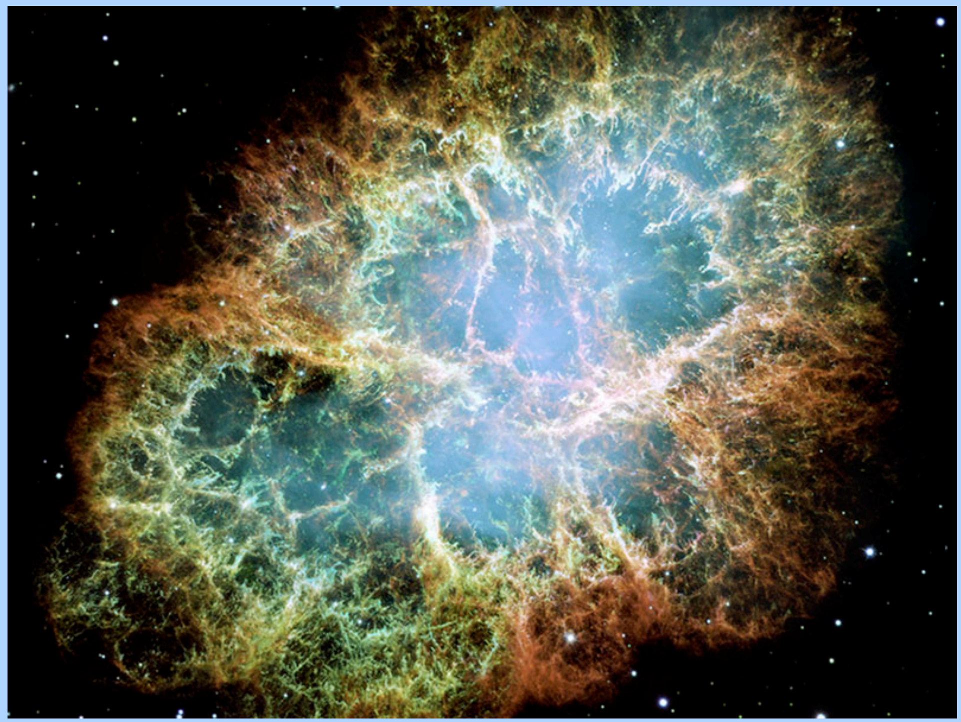
Tommy Gold 1968

Lighthouse model of pulsations

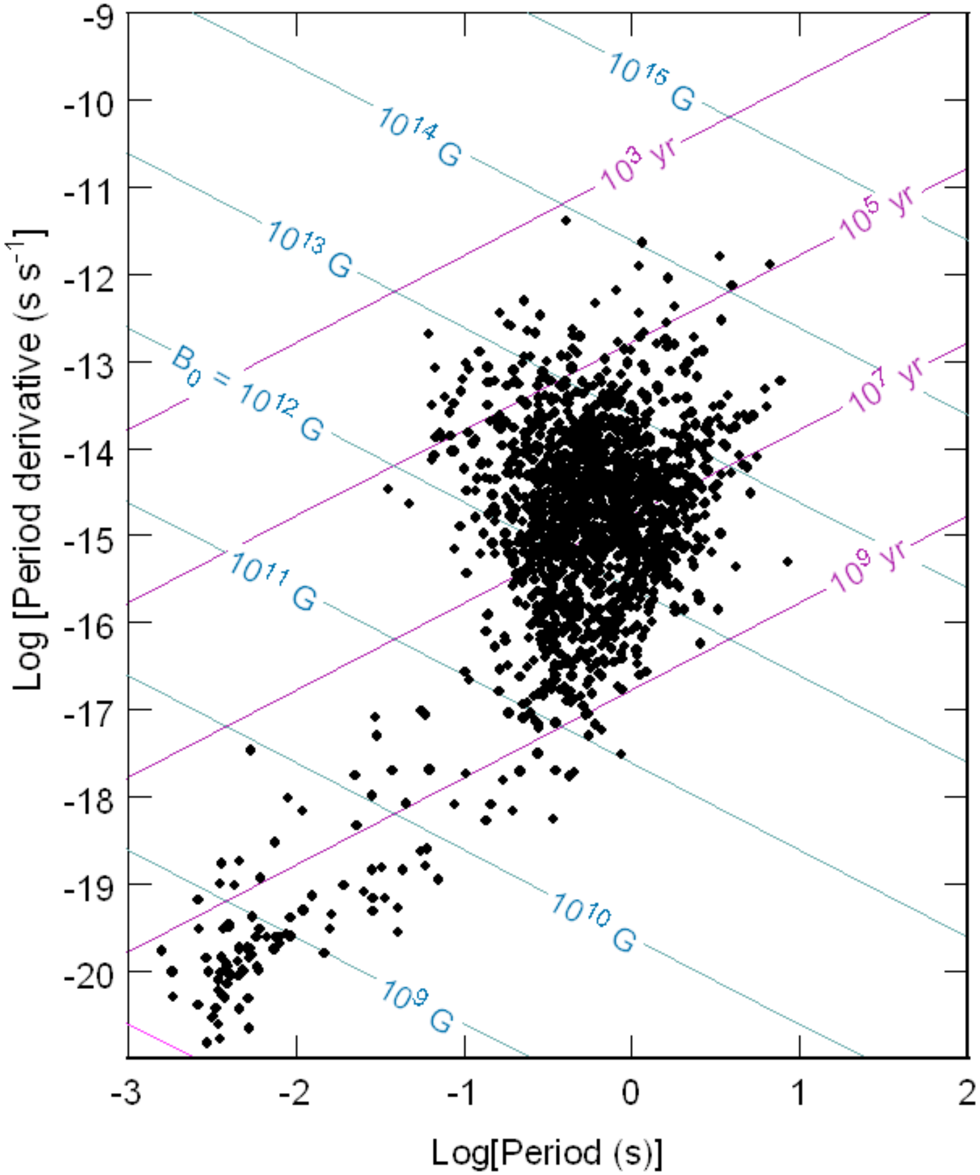


Franco Pacini 1968

Spin-down energy from Crab pulsar powers the Crab nebula!



Radio Pulsars



>1800 currently known
Characterized by
rotation Period P and
Period derivative dP/dt = $\dot{P}$

Under reasonable assumptions, these timing parameters can be used to estimate physical conditions.

Surface dipole field

$$B_0 = 6.4 \times 10^{19}\,\mathrm{G}\ (P\dot{P})^{1/2}$$

Characteristic age $\tau = \dfrac{P}{2\dot{P}}$

Pulsars - Conceptual Picture

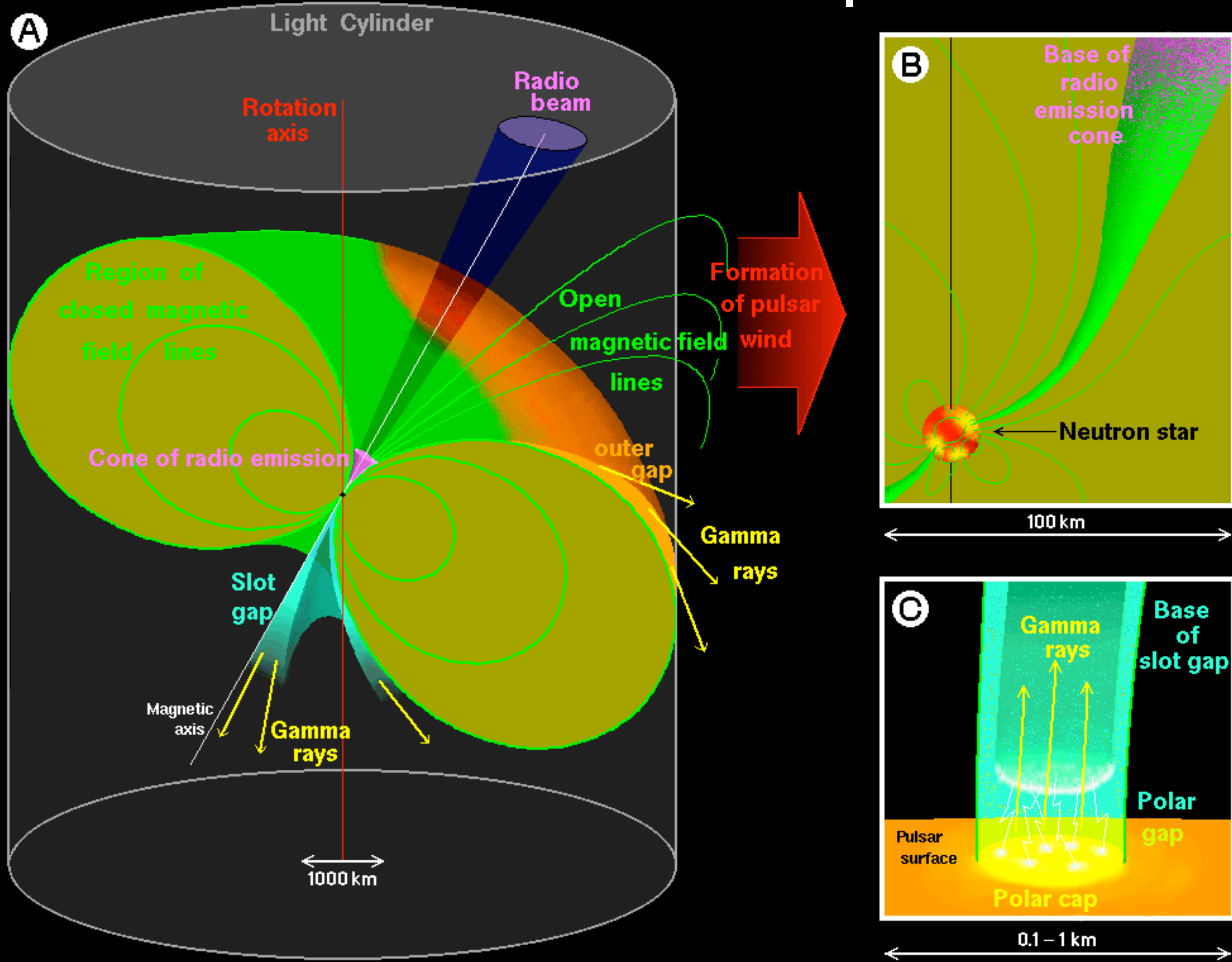


Figure by Dany Page

Detecting Gamma-Ray Pulsars

PROBLEMS

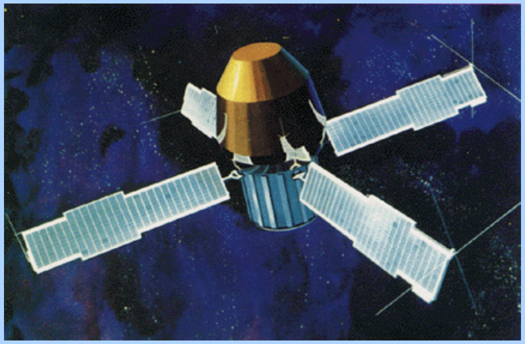
- Very low rate of gamma-ray photons (4 ph/min for Vela!)
  - Collecting enough photons can require MONTHS to YEARS
- Young pulsars spin down rapidly and have glitches in rotation and spin-down rate

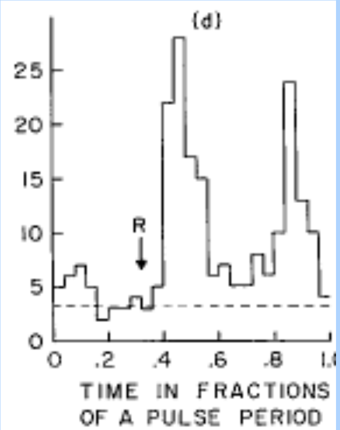
SOLUTIONS

- Use known pulsation (ephemeris) from other wavelength
  - Need supporting observations from other telescopes
- Search for pulsations in gamma-rays
  - Need good search algorithm
  - And lots of computer time

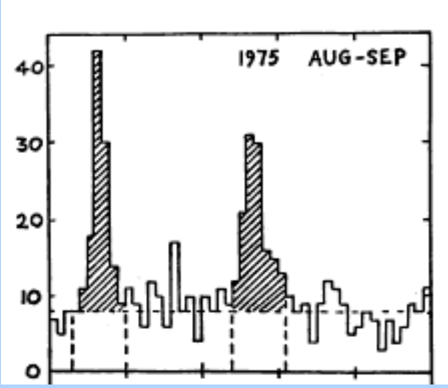
First Gamma-Ray Pulsars

SAS-2 1973





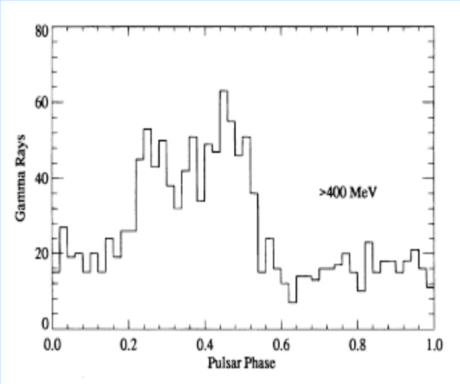
Vela



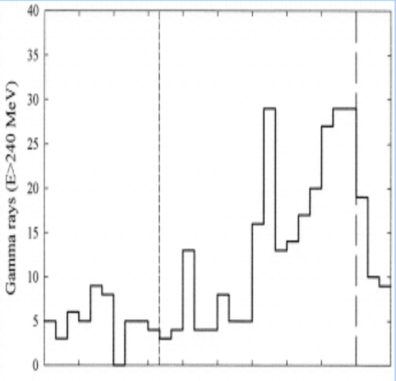
Crab

COS-B 1980

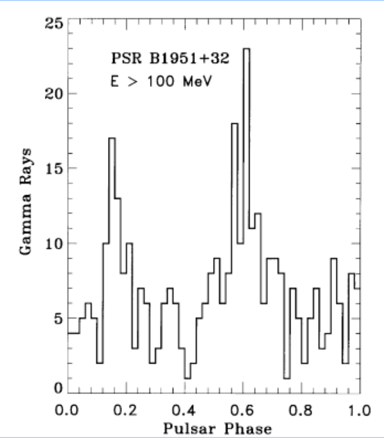
COMPTON 1991



B1706-44

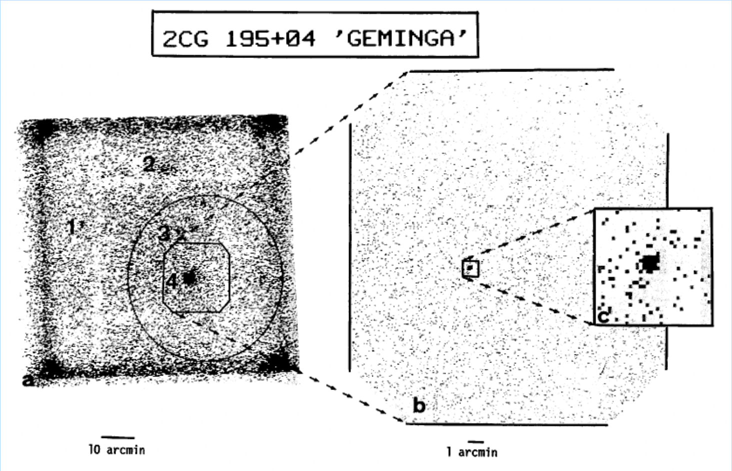


B1055-52

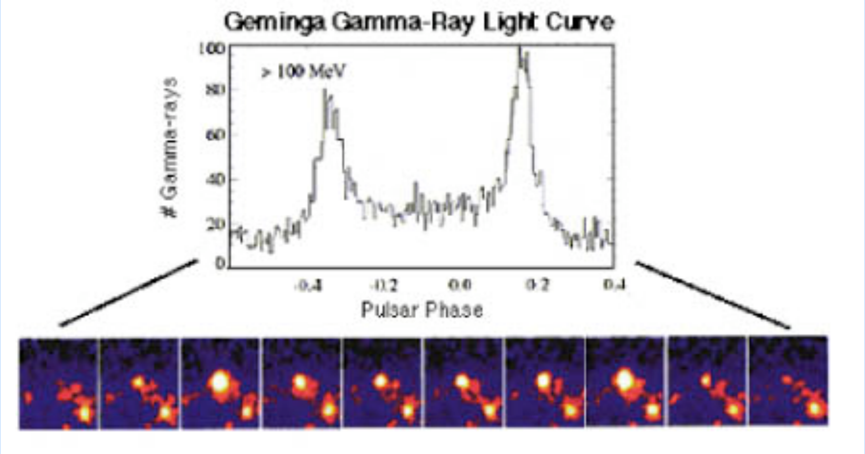


B1952+32

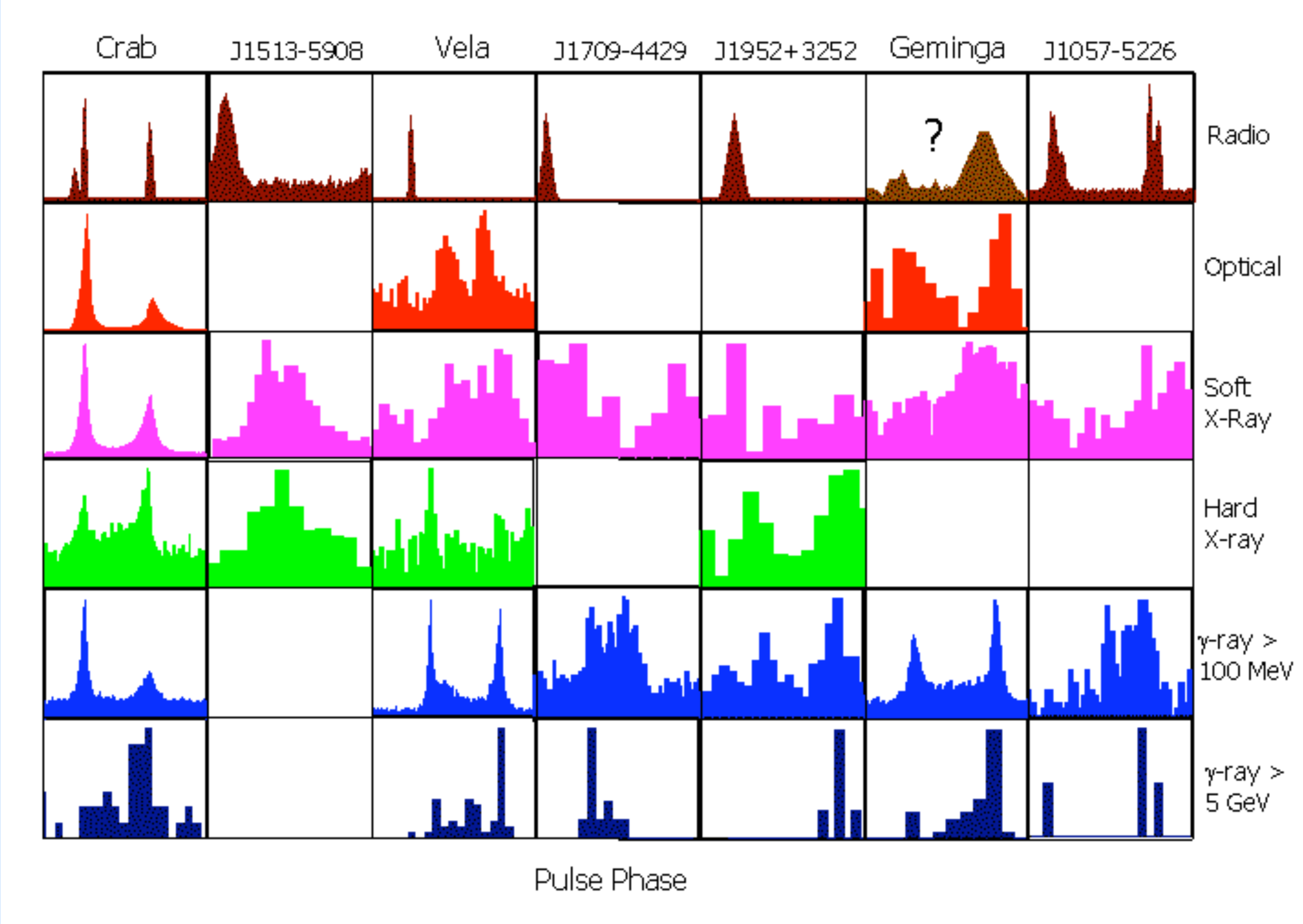
First Radio-Quiet Pulsar - Geminga



- Point source discovered by SAS-2 1975
- X-ray counterpart (Bignami et al. 1983)
- Optical counterpart (Bignami et al. 1987)
- Discovery of X-ray pulsations (Halpern & Holt 1992) measured P
- Discovery of gamma-ray pulsations (Bertsch et al. 1992) - measured $\dot{P}$
- Parallax distance – in local superbubble!

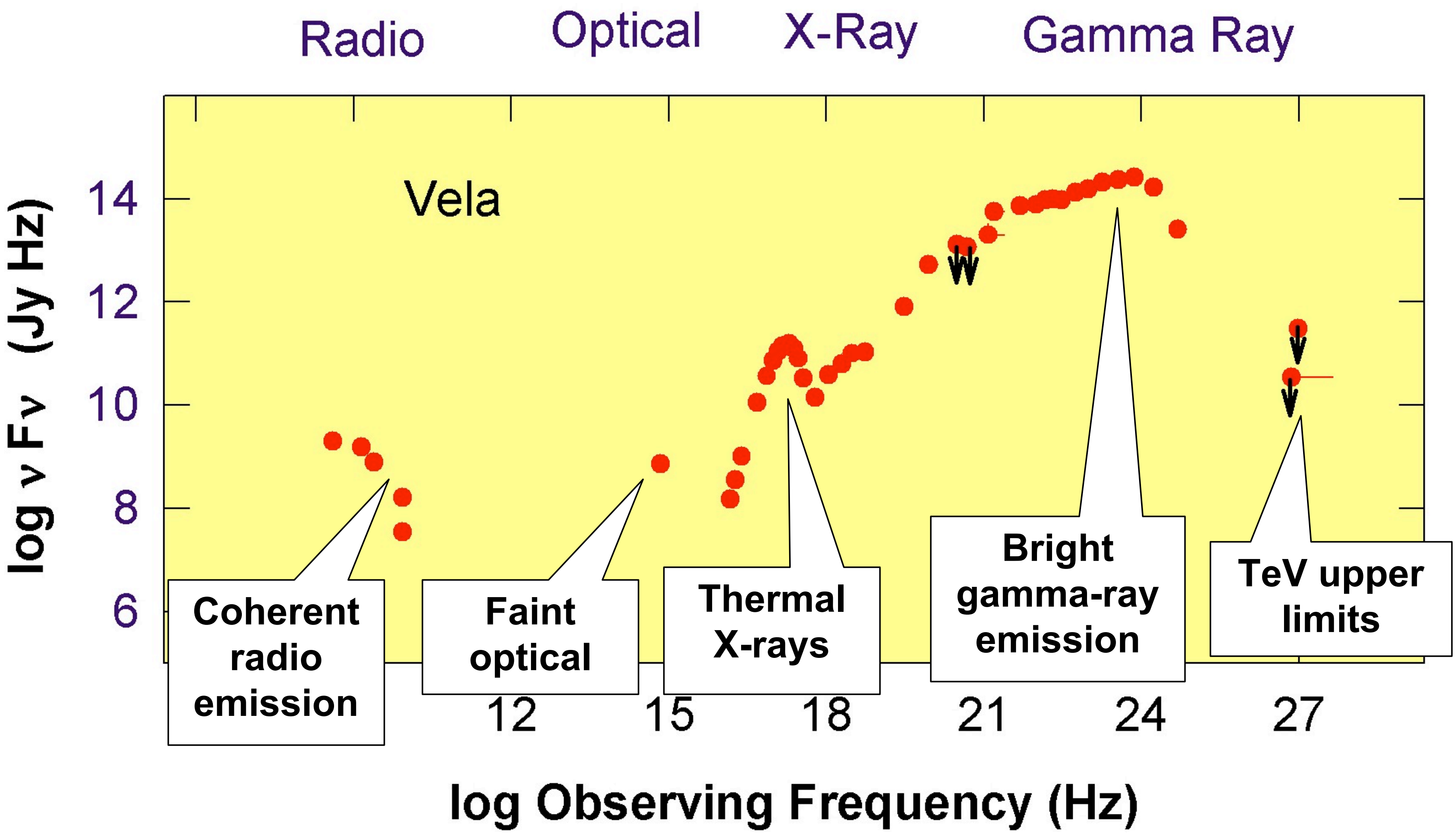


Compton Gamma-Ray Observatory Pulsars

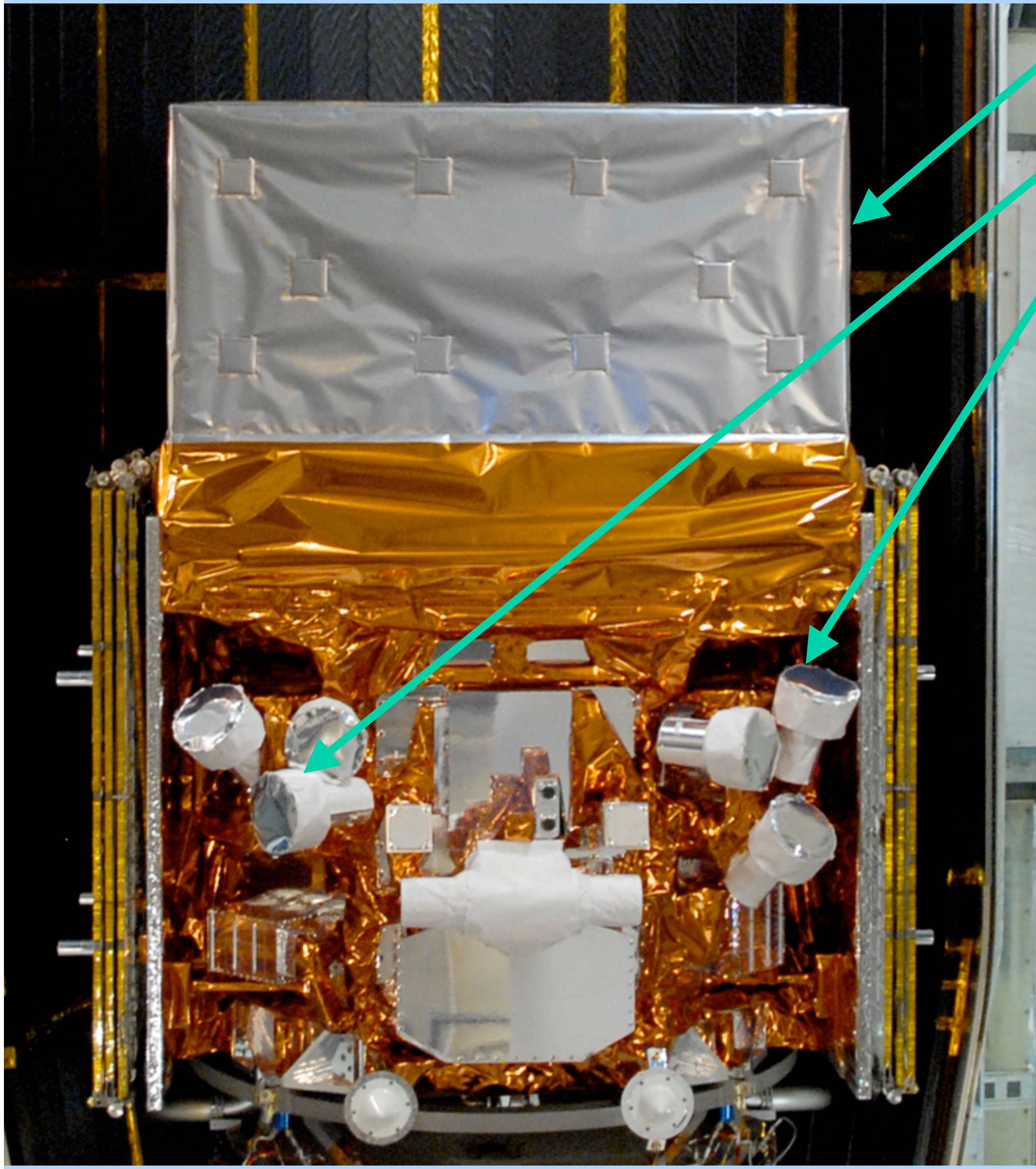


- 7 gamma-ray pulsars detected

An Example – The Vela Pulsar



Fermi Pulsar Capabilities



Large AreaTelescope (LAT)
20 MeV - >300 GeV

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 30 MeV

KEY FEATURES

- **Huge field of view**
  - **LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for every 3 hours. GBM: whole unocculted sky at any time.**
- **Broad energy range.**
- **Large effective area.**
- **Excellent time resolution (microseconds UTC).**

Pulsar Goals with Fermi

1. Better measurements of known gamma-ray pulsars.
2. Discovery of new gamma-ray pulsars and new classes of gamma-ray pulsars.
3. Improved understanding of how pulsars work and what they can tell us about our Galaxy.

Pulsar Timing Campaign

Jodrell Bank (UK)

Nançay (France)

RXTE (in space)

Parkes (Australia)

Green Bank (USA)

+ other contributions: Arecibo, Hartebeesthoek, etc.

=> Timing for ~ 230 energetic pulsars, of interest for Fermi.

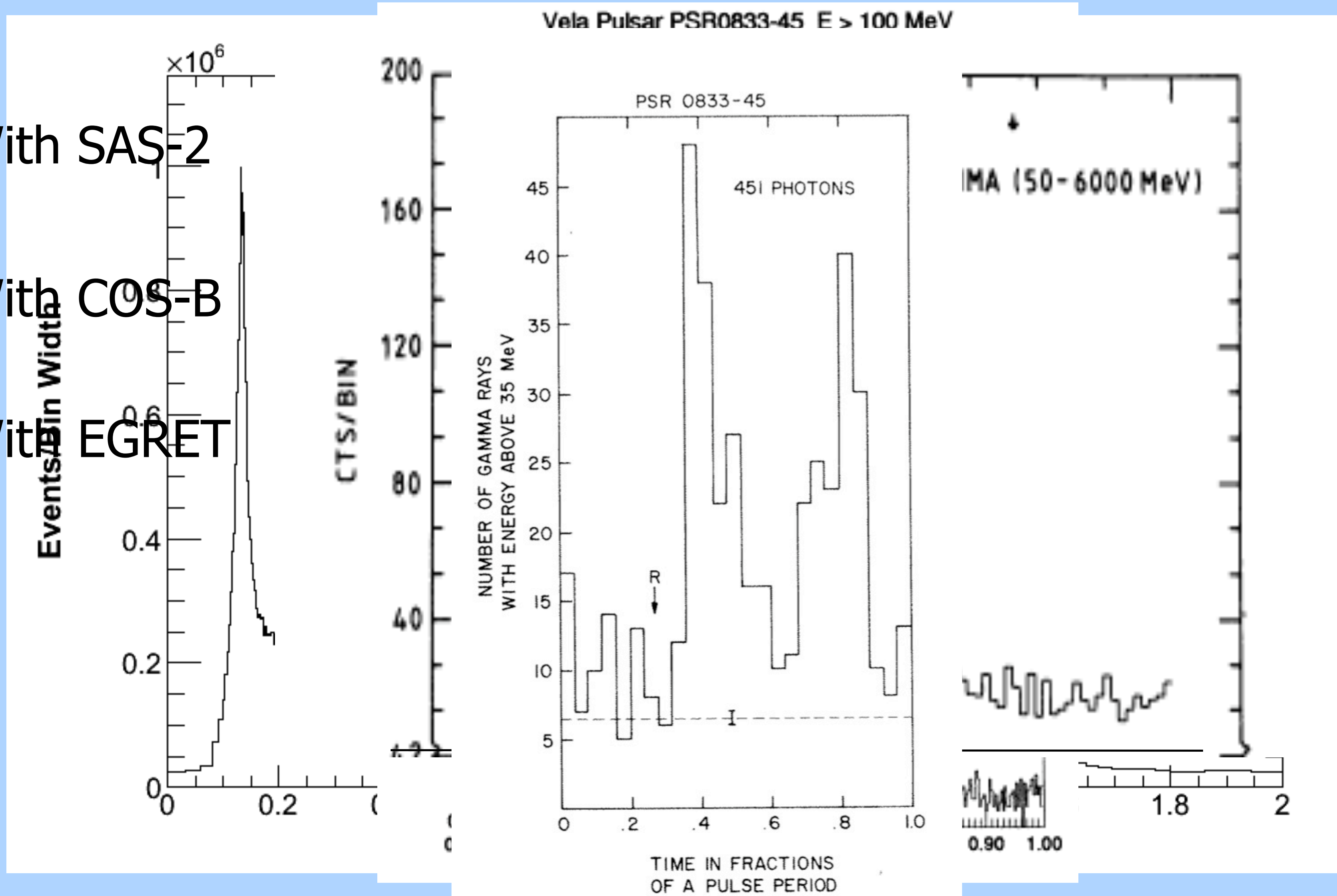
(Smith, Guillemot, Camilo et al., A&A 492, 923, 2008)

Vela Pulsar

With SAS-2

With COS-B

With EGRET

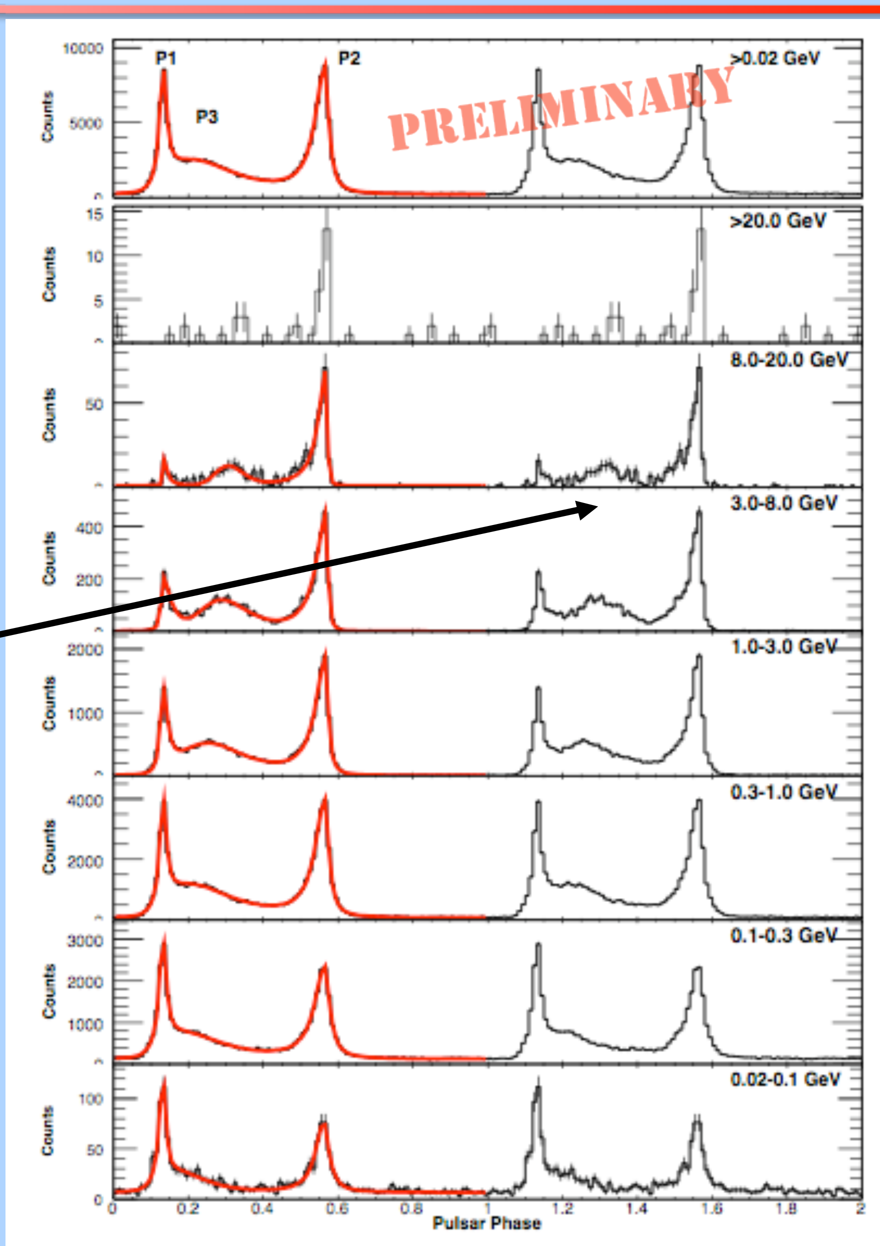


With Fermi LAT

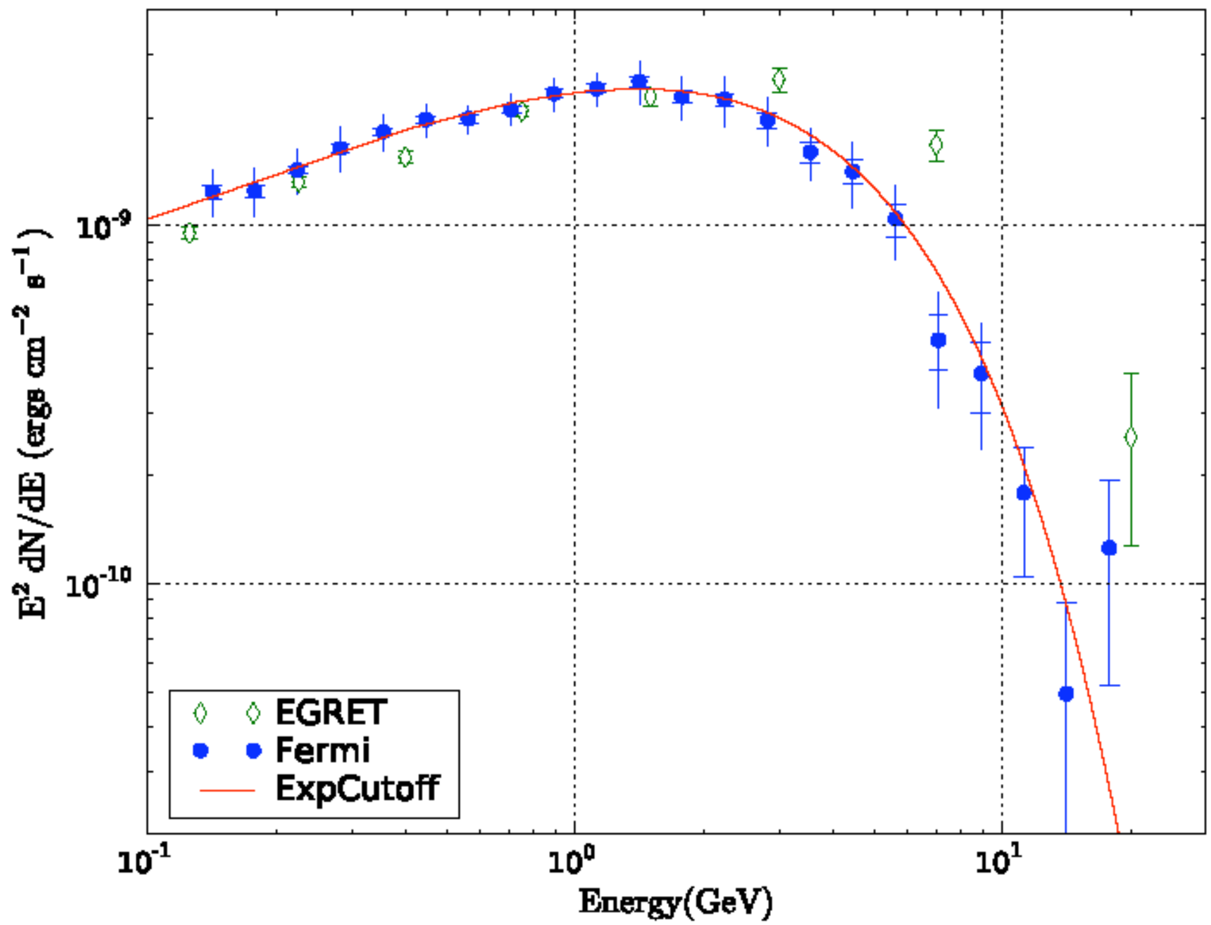
The Vela Pulsar with Fermi

EGRET pulsars generally are prime targets for spectral analyses with unprecedented details, because of their brightness.

Vela: complex P1 and P2 behaviors. A shift of P3 with energy has been observed (Abdo et al., ApJ 696, 1084, 2009, Abdo et al. 2010, ApJ, submitted.)!



Vela Phase-averaged spectrum



Consistent with simple exponential

Not consistent with sharp pair production cutoff

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

Abdo et al. 2009

EGRET pulsars with Fermi

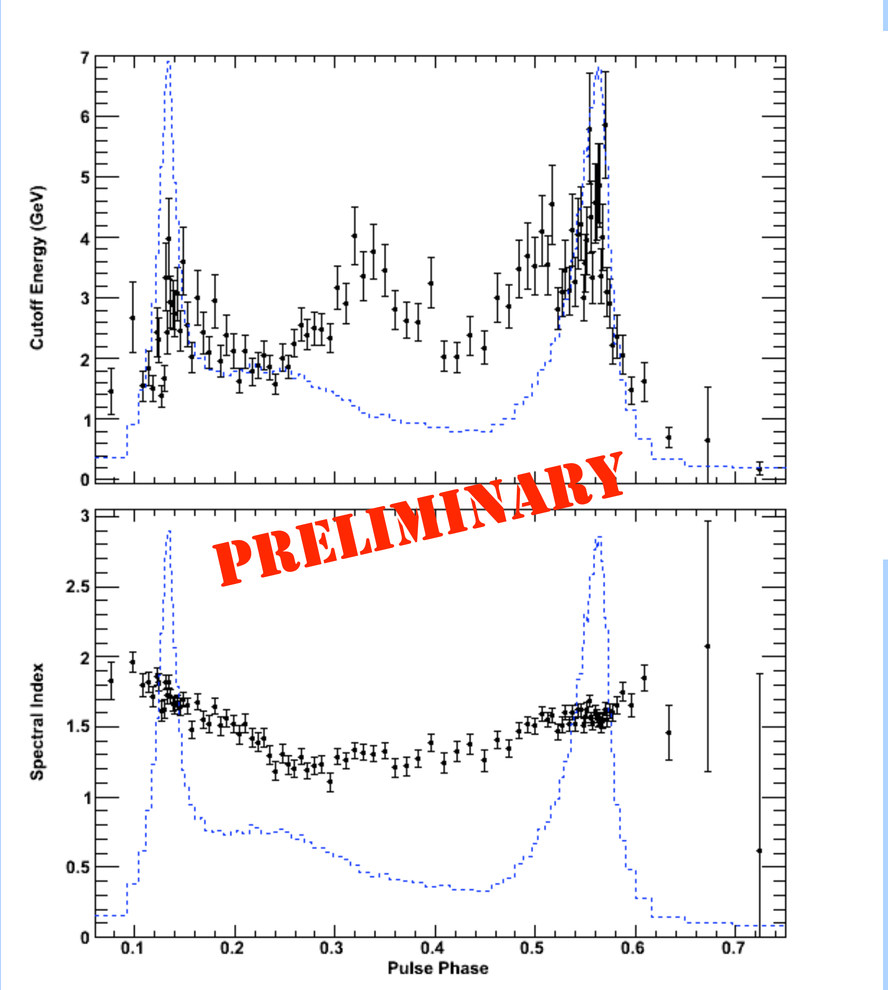
EGRET pulsars generally are prime targets for spectral analyses with unprecedented details, because of their brightness.

Important variation is seen in spectral properties across the rotation.

Vela: complex P1 and P2 behaviors. A shift of P3 with energy has been observed (Abdo et al., ApJ 696, 1084, 2009)!

Spectral index and cutoff energy variations are thought to be due to emission altitude changes with energy (see e.g. Geminga).

In general, pulsar spectra are consistent with simple-exponential cutoffs, indicative of absence of magnetic pair attenuation.



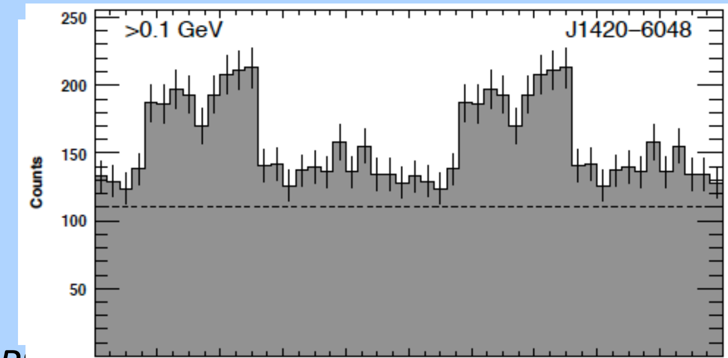
Cutoff energy and spectral index vs. pulse phase, for the Vela pulsar

Cutoff energy vs. pulse phase, for the Geminga pulsar

Young Radio-loud Pulsars

Fermi LAT has detected a number of young radio-loud gamma-ray pulsars, all highly energetic ($\dot{E} > 3\ 10^{33}$ erg/s).

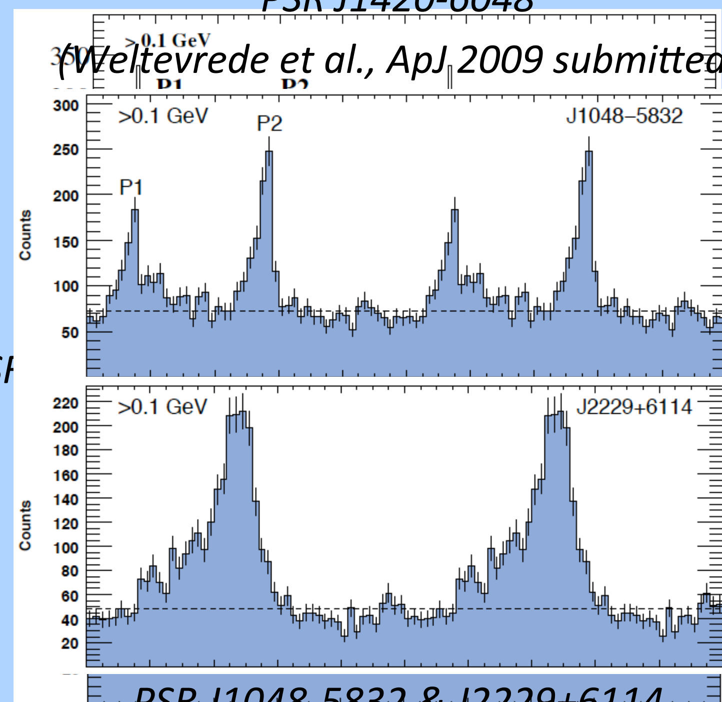
Many are seen in unidentified EGRET sources error boxes: 3EG J1027-5817, 3EG J2021+3716, 3EG J1048-5840, 3EG J2227+6122, …



PSR J1028-5819 (Abdo et al., ApJL 695, 72, 2009)

PSR J1420-6048

(Weltevrede et al., ApJ 2009 submitted)



PSF … 2009)

PSR J1048-5832 & J2229+6114

PSR J0205+6449 (Abdo et al., ApJL 699, 102, 2009)

(Abdo et al., ApJ 2009 accepted)

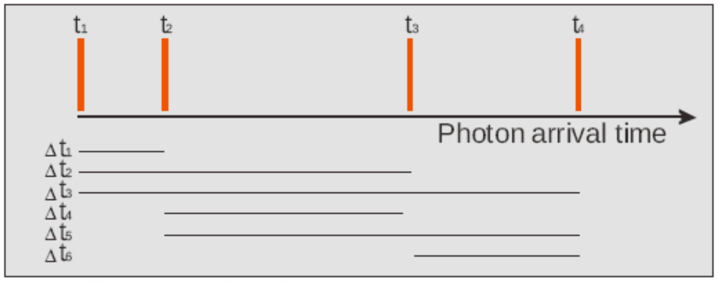
A Fermi first: Discovering Pulsars Through Blind Search

The "Time-Differencing" Technique

- Datasets are large and direct FFTs are time-consuming and computer-intensive.
- The periodicity can also be seen in differences of arrival times!
- Where to look?

  UnID EGRET sources, SNRs, Geminga candidates, unID Fermi sources

Atwood et. al., **ApJ Lett., 652, 49 (2006)**
Ziegler et. al., **ApJ 680, 620 (2008)**

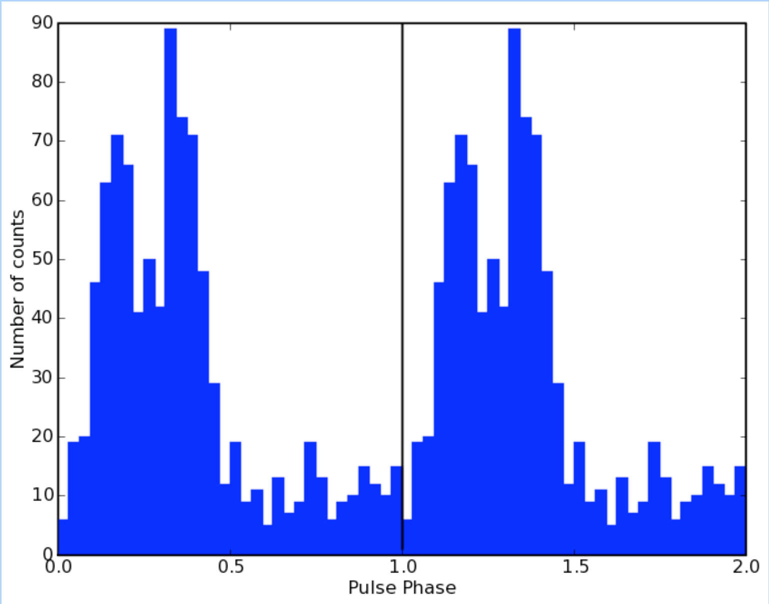


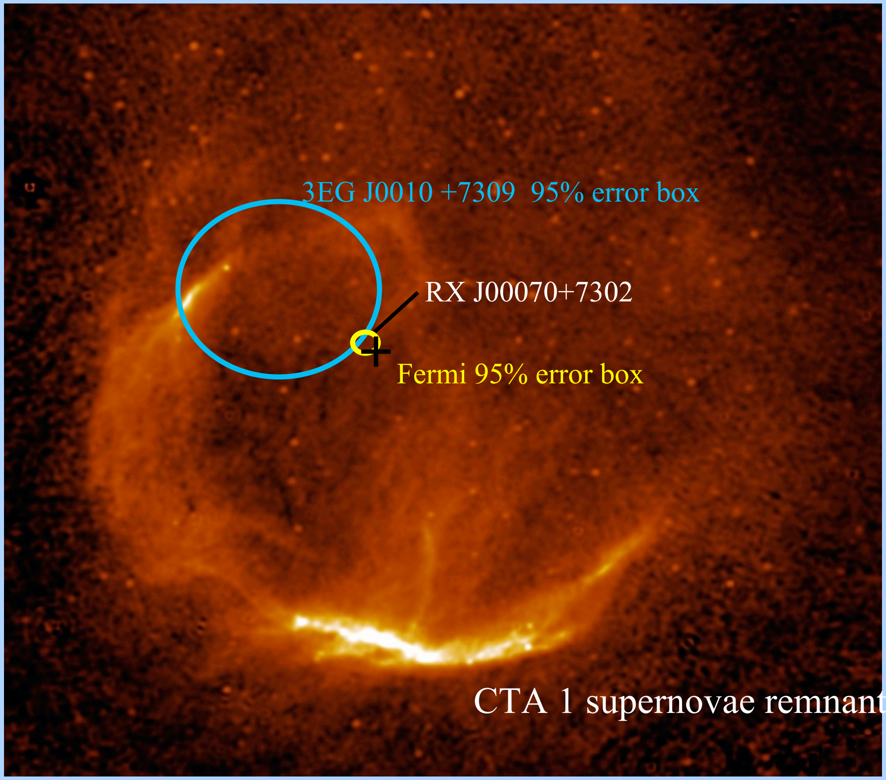
Credit: M. Ziegler

# of FFT bins = $f * t_{max\_diff} * 2$

PC with 2GB can handle 33×10^6 bin FFT

Pulsar in Supernova Remnant CTA 1





- Exhibits all characteristics of a young high-energy pulsar (P = 316 ms, 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)

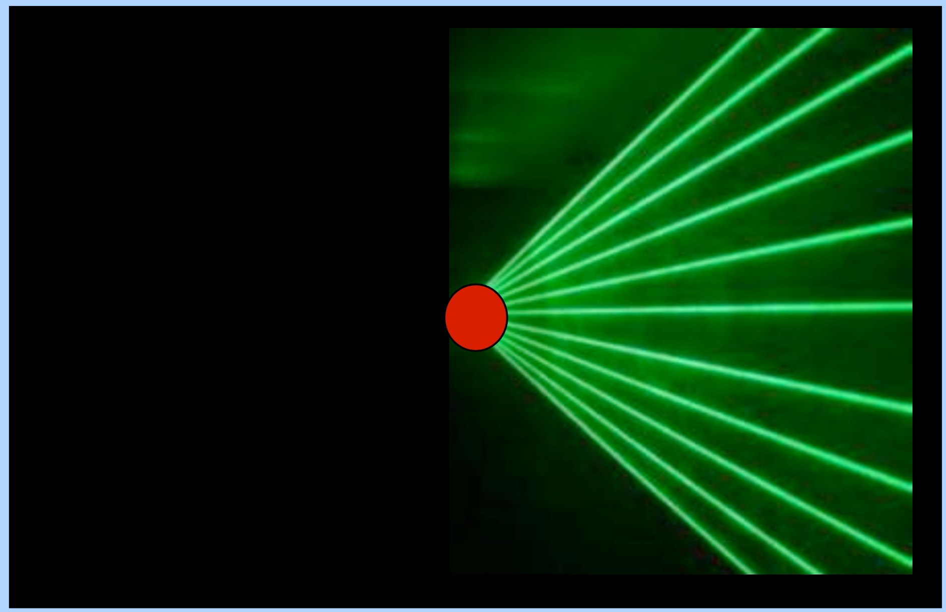
- γ-ray source at *l,b* = 119.652, 10.468; 95% error circle radius =0.038° contains the X-ray source RX J00070+7302, central to the PWN superimposed on the radio map at 1420 MHz.

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

Gamma-only Pulsars: Beamshape

Traditional 'Lighthouse' Beam

Wide 'Fan beam'



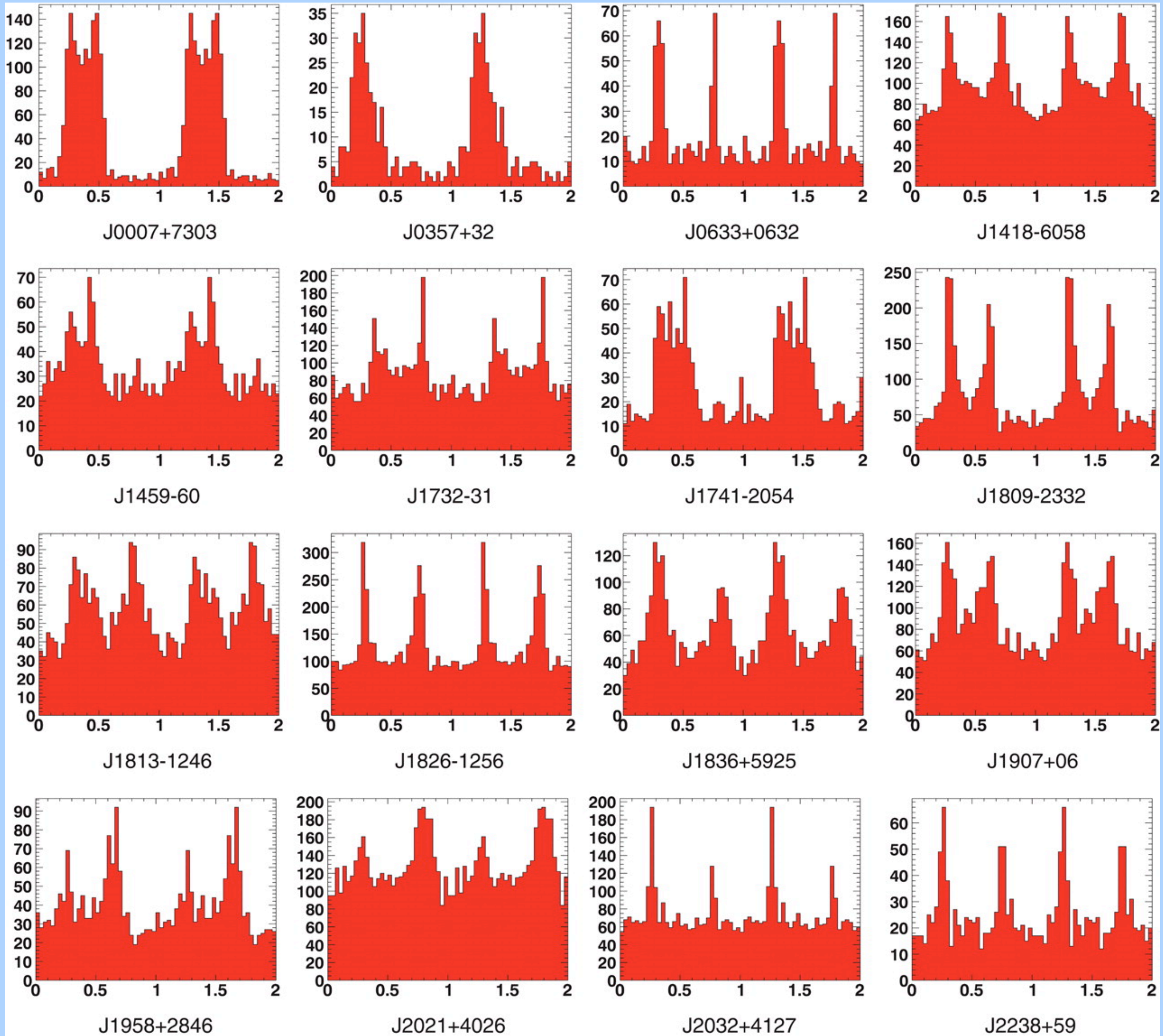
Gamma-ray-only pulsars open a new window on these exotic and powerful objects, helping us learn how they work and how they influence our Galaxy.

16 Pulsars Found in Blind Searches

After 4 months of data taking, 16 pulsars have been found with the same technique!

(Abdo et al., Science 325, 840, 2009).

13 were unidentified sources for EGRET

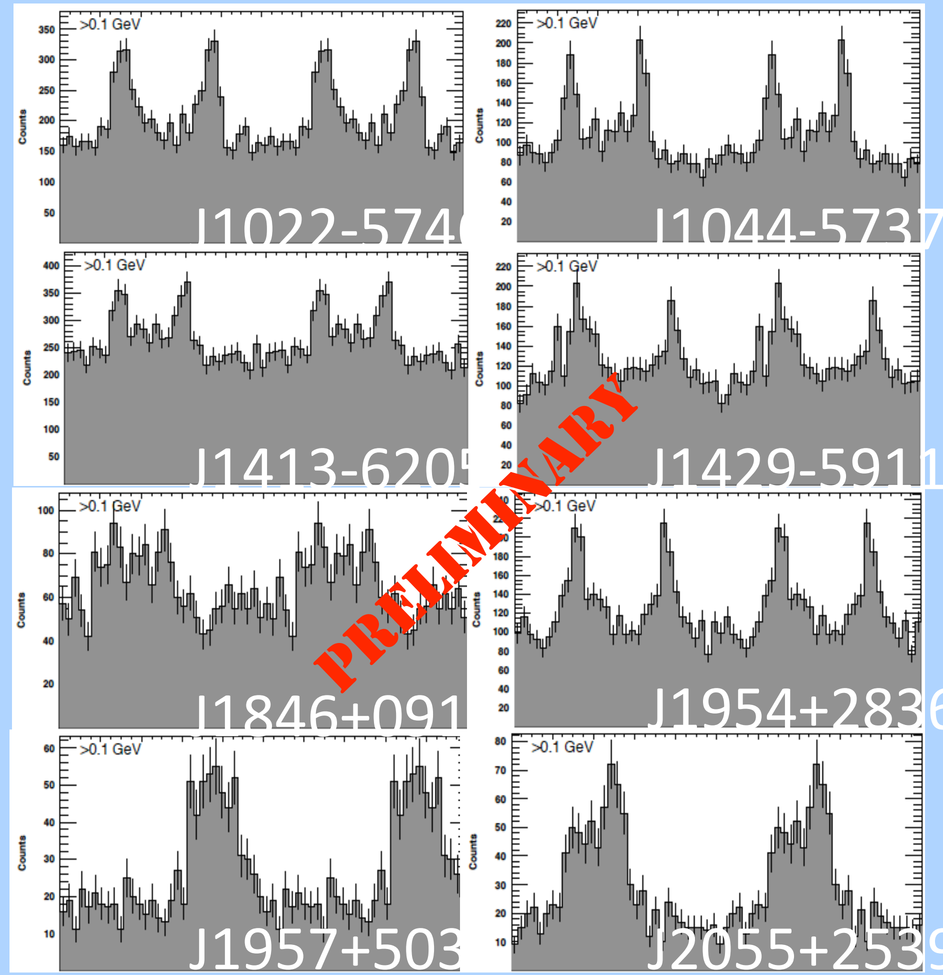


8 More Pulsars Found in Blind Search

After 1 year of data taking, 8 more pulsars have been found

Locations can be refined to as precise as several arcsec by timing

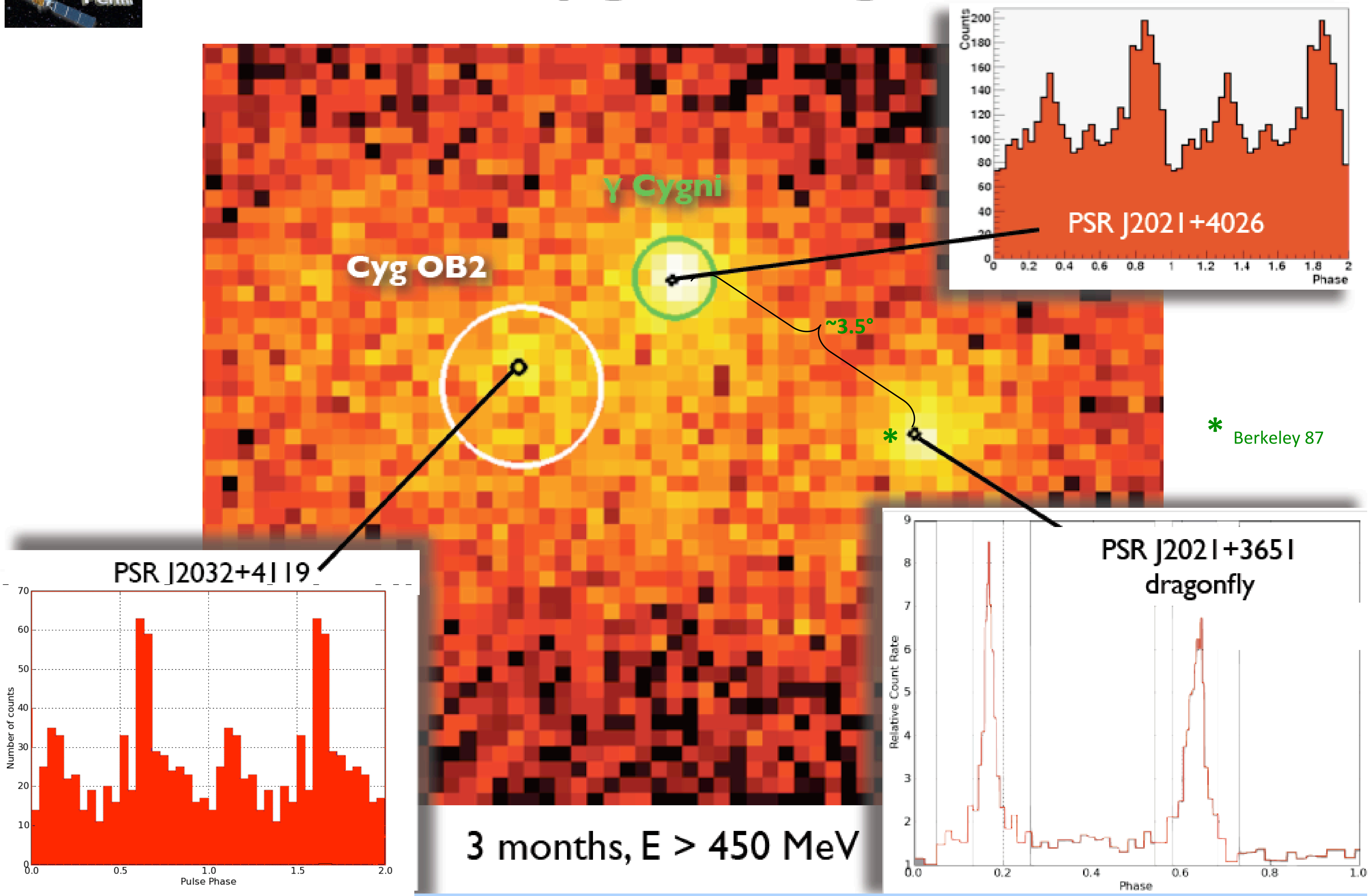
Ray et al. 2009,



8 new detections in blind search!

(Abdo et al., in prep)

Cygnus region

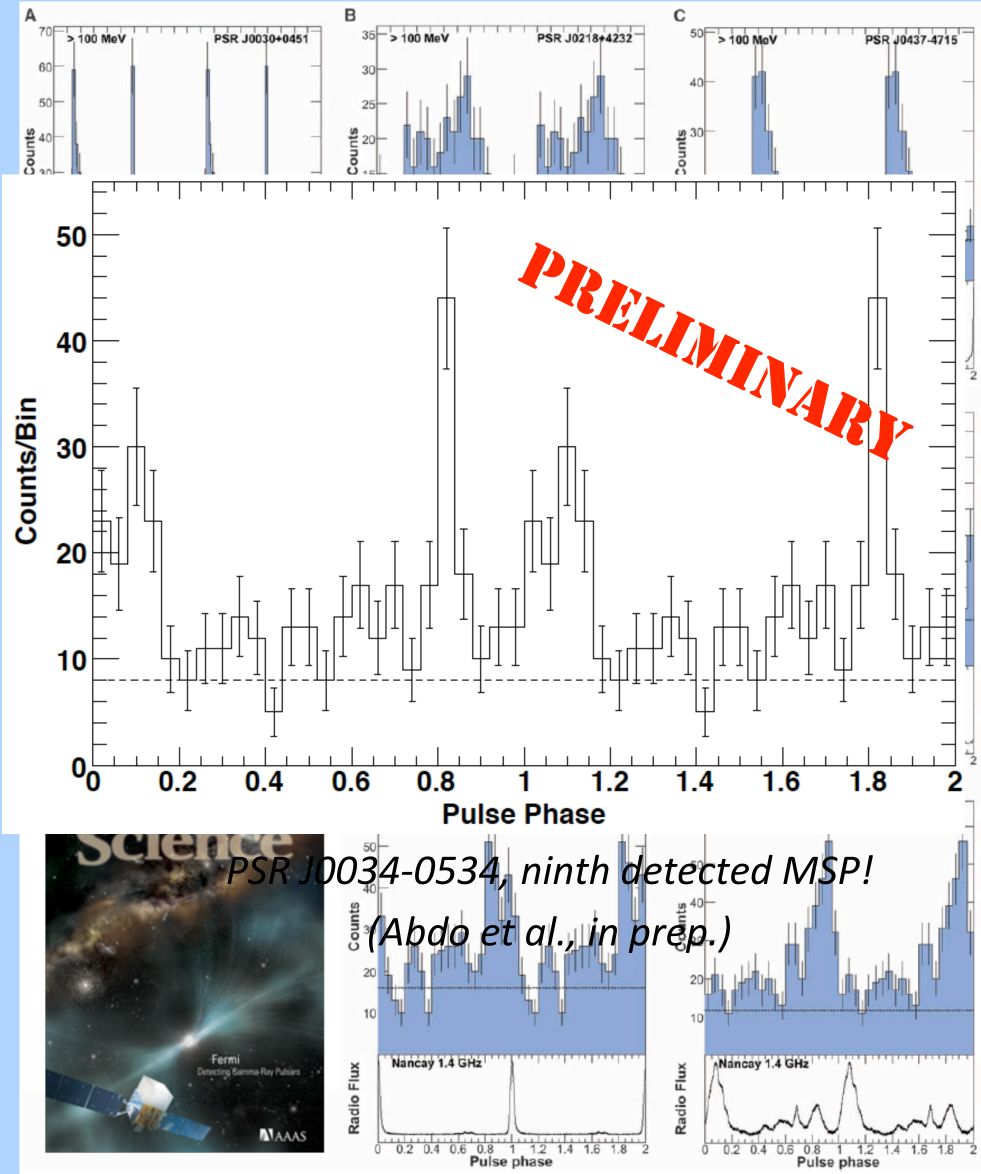


Radio-loud millisecond pulsars

The LAT detected pulsed gamma-ray emission from J0030+0451, making it the first firm detection of an MSP in gamma rays (Abdo et al., ApJ 699, 1171, 2009).

After 9 months of data taking, the LAT had detected 8 gamma-ray MSPs (Abdo et al. Science 325, 848, 2009).

For the first time, a population of gamma-ray MSPs has been observed.

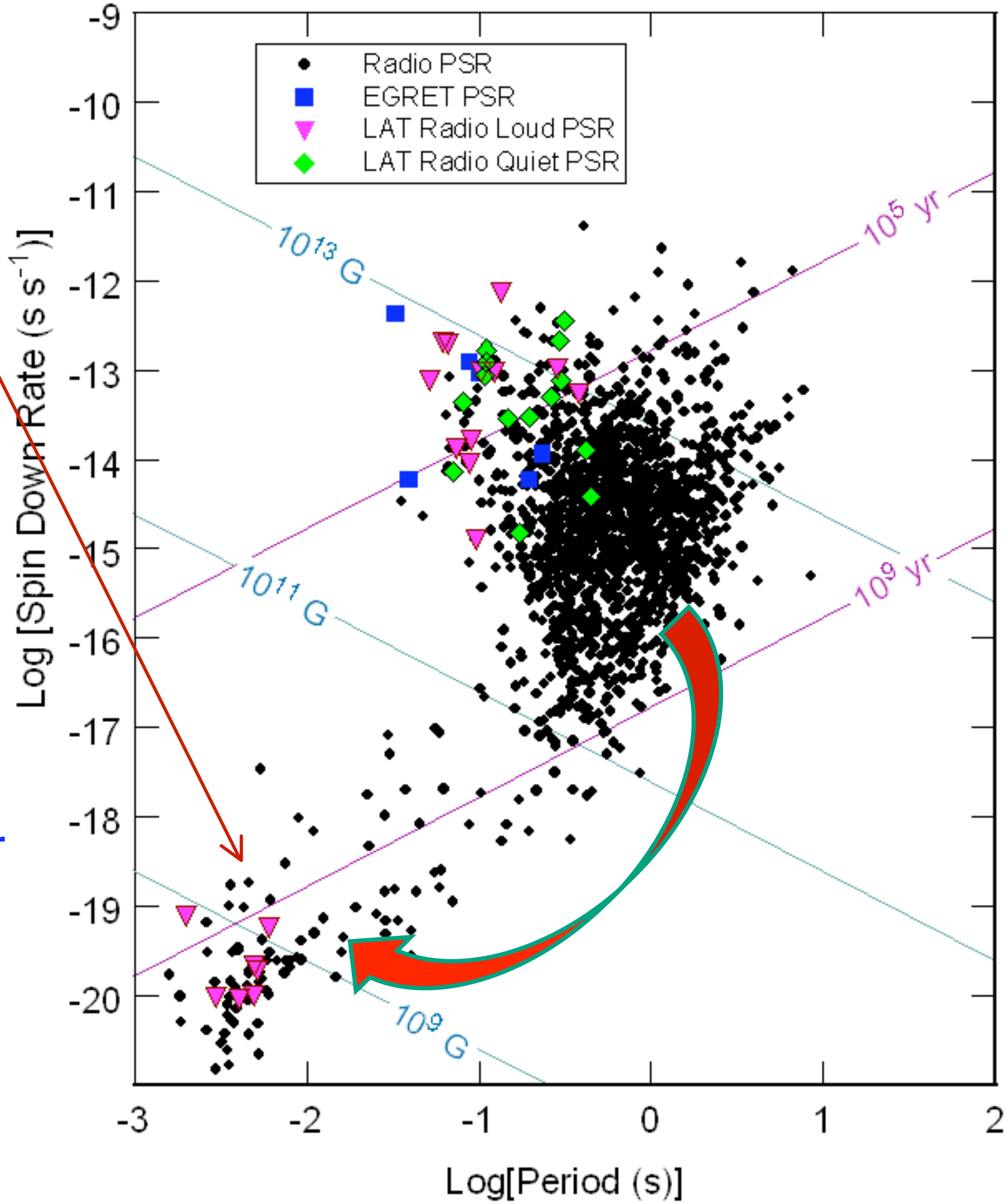


PSR J0034-0534, ninth detected MSP!

(Abdo et al., in prep.)

ms γ-ray pulsars

- Very different characteristics from the normal γ-ray pulsars:
  - Spinning 100 times faster
  - Magnetic fields ~10,000 times lower
  - ~10,000 times older
- "Recycled" pulsars spun-up by binary companion stars



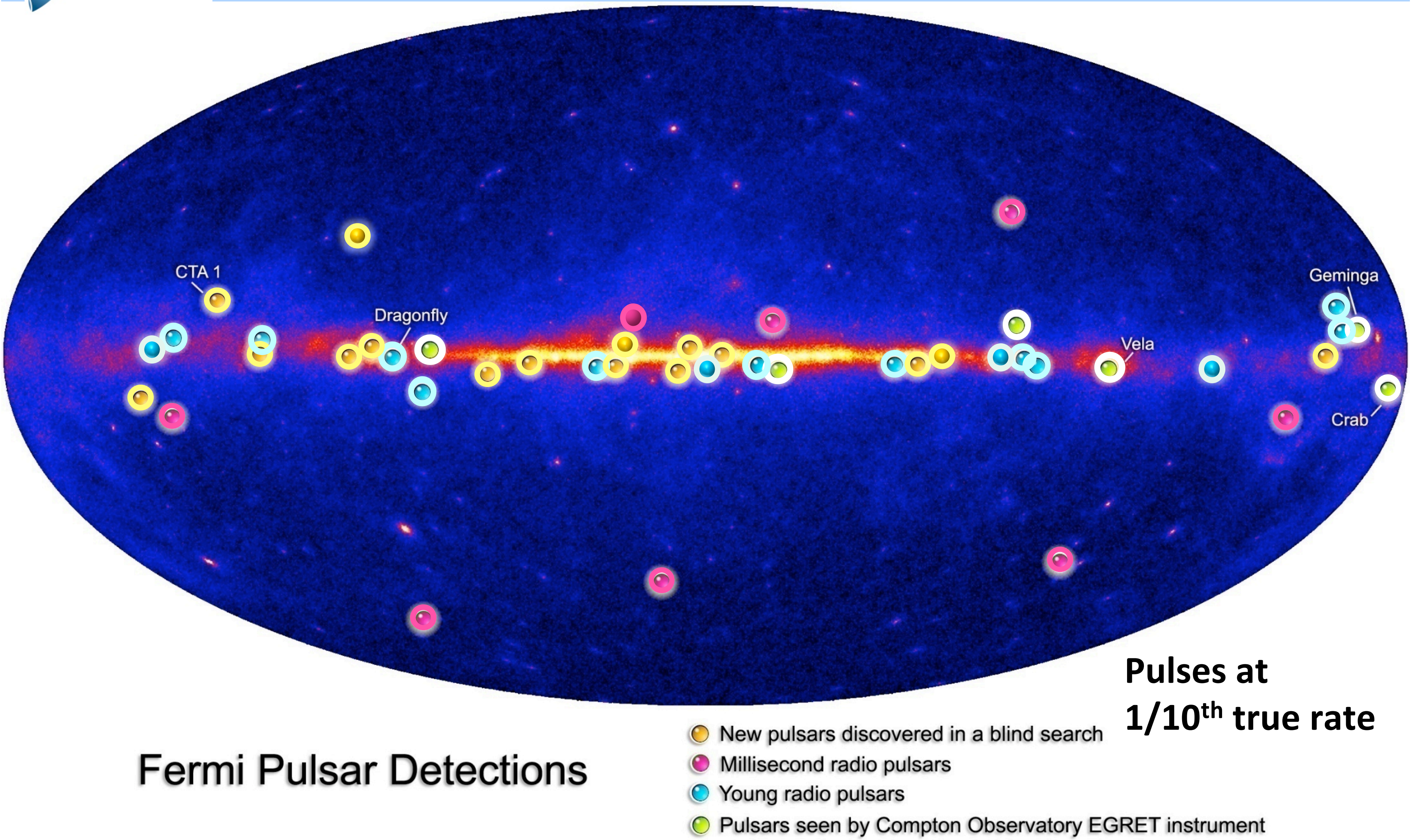
Pulsars,

Pulsars,

and

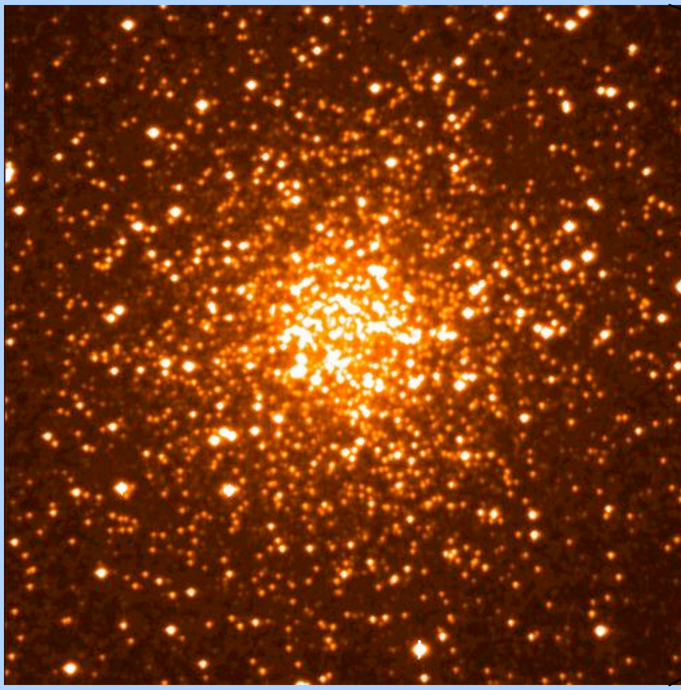
Pulsars!

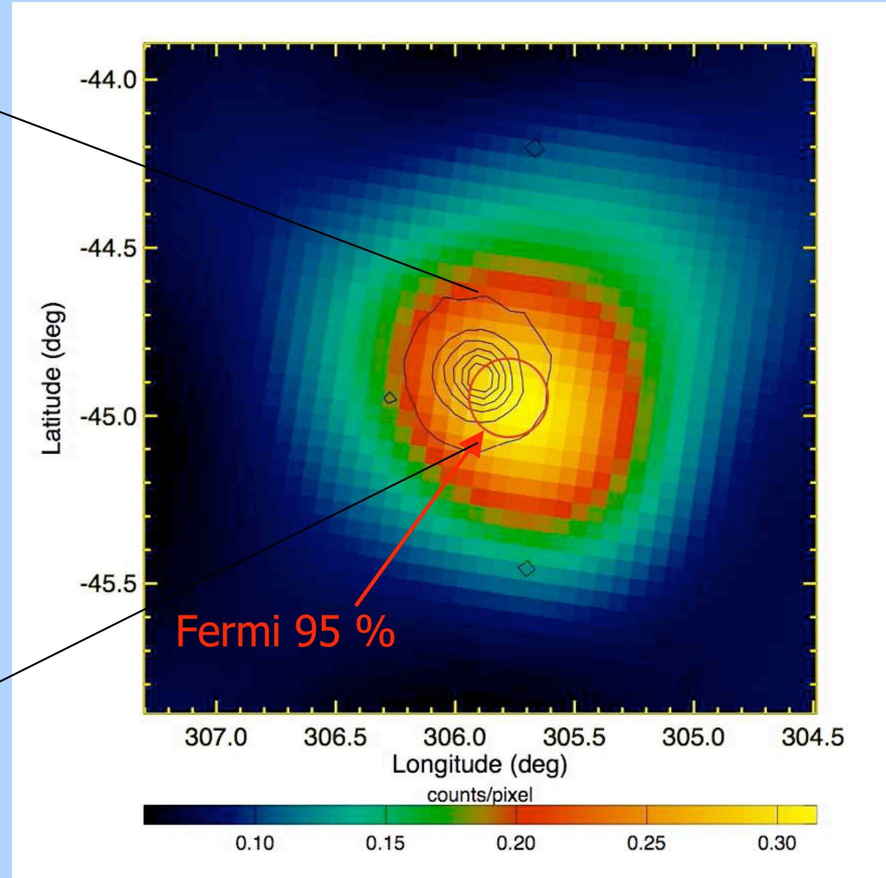
The Pulsing γ-ray Sky



Pulses at 1/10th true rate

Fermi detection of 47 Tuc



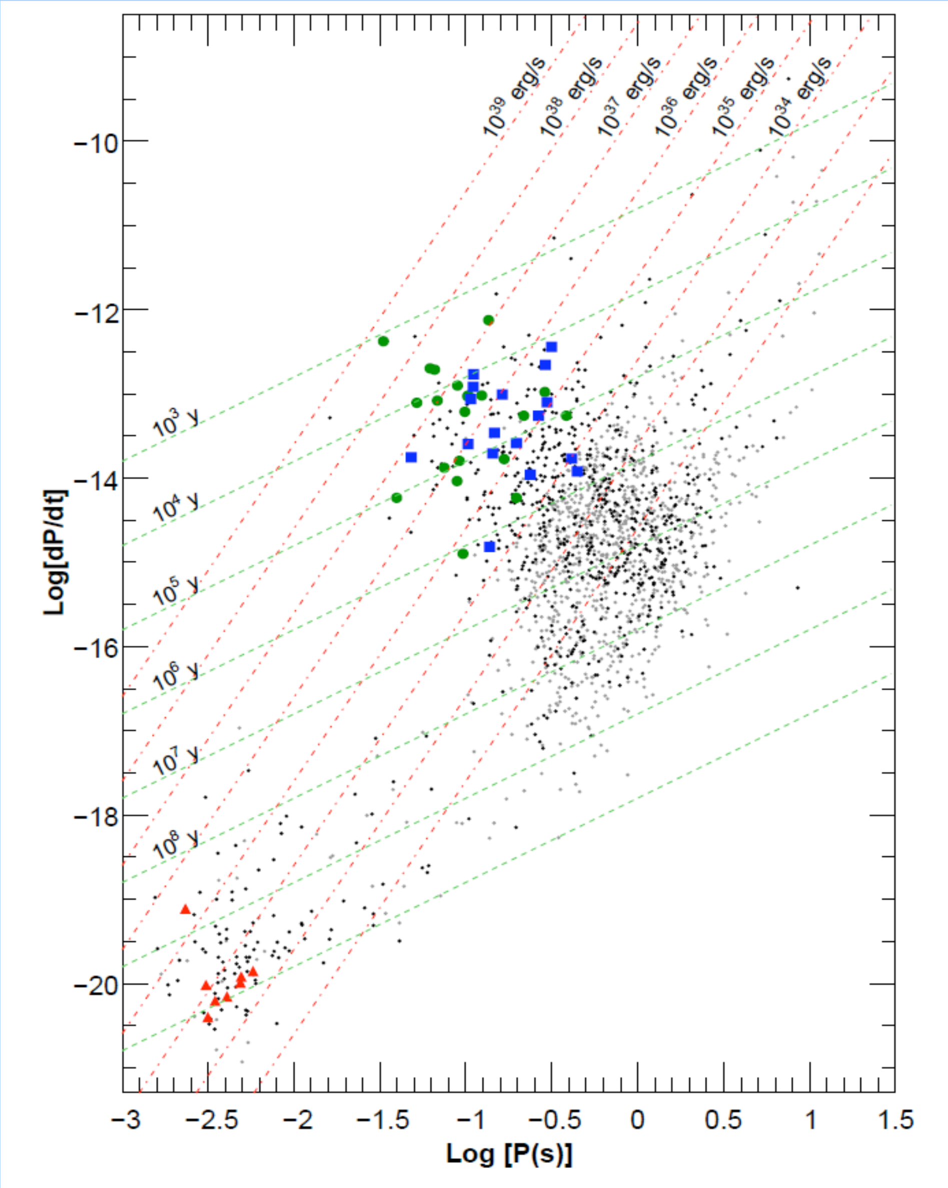


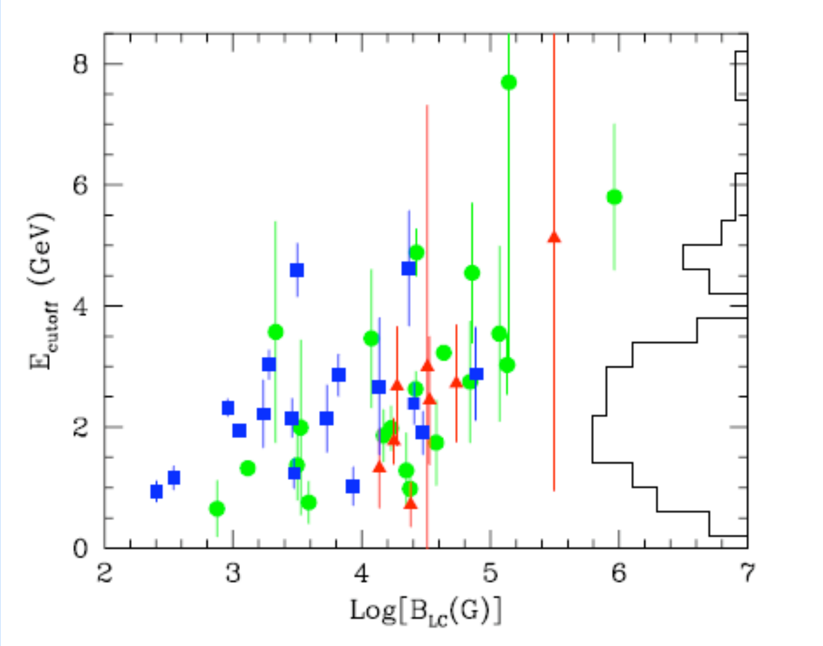
47 Tuc is a globular cluster (GC) in which 23 MSPs are known.

The Fermi LAT detects 47 Tuc as a point source.

We might be seeing the collective emission from MSPs in 47 Tuc.
Individual detections ? We'll see. 47 Tuc is 4.9 kpc away: comparable to J0218+4232 (~ 3 kpc)

The Population of Fermi Pulsars





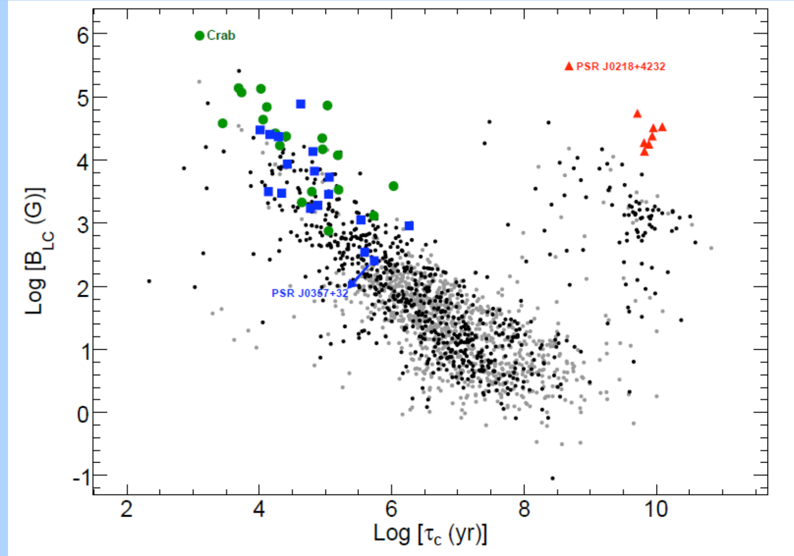
What do we learn ?

As for EGRET, the detected pulsars are relatively close and highly energetic.

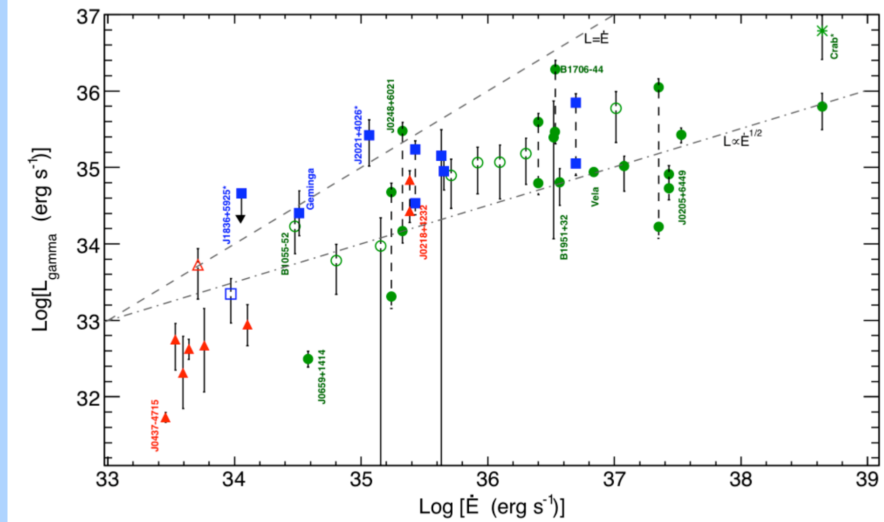
The detected pulsars also have the highest values of magnetic field at the light cylinder, B_{LC}.

Both detected normal PSRs and MSPs have comparable B_{LC} values. Similar emission mechanisms operating?

Luminosities are affected by distance uncertainties. However, the luminosity seems to grow with spin-down energy; with a $L \propto \dot{E}$ at low $\dot{E}$, $L \propto \sqrt{\dot{E}}$ at high $\dot{E}$.



B_{LC} vs. characteristic age for the catalog PSRs

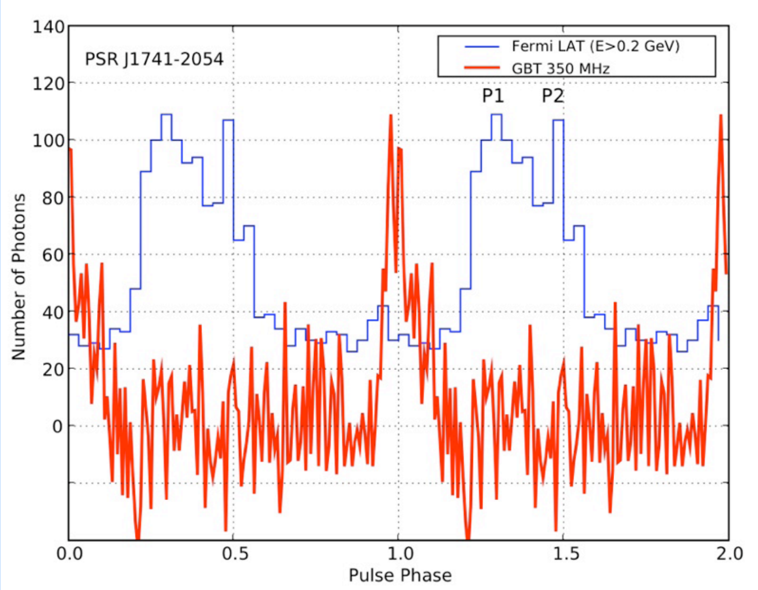


Gamma-ray luminosity vs. spin-down energy for the catalog PSRs

Radio Follow-up of New LAT Pulsars

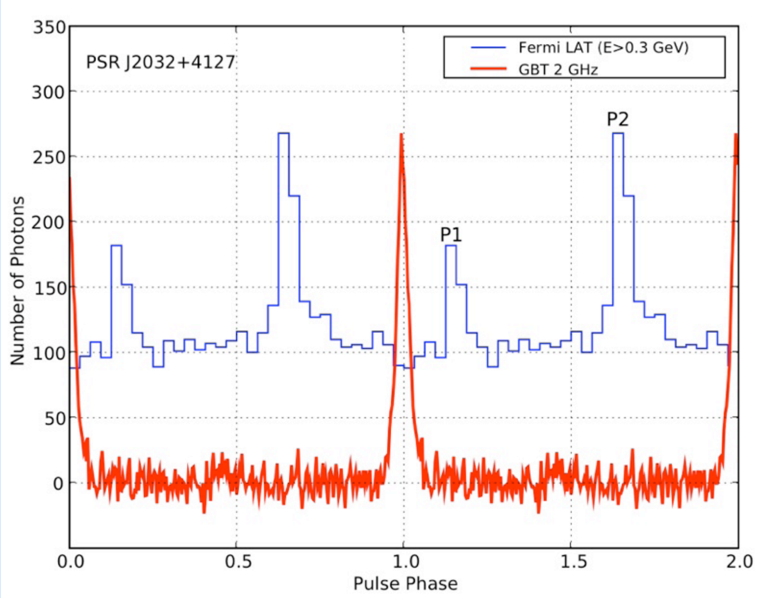
PSR J1741-2054

- Radio pulsar found in archival Parkes multibeam data
- Extremely low DM (4.7 pc cm-3), implies D=400pc
- May be lowest luminosity of any radio pulsar (L ~0.025 mJy kpc2)



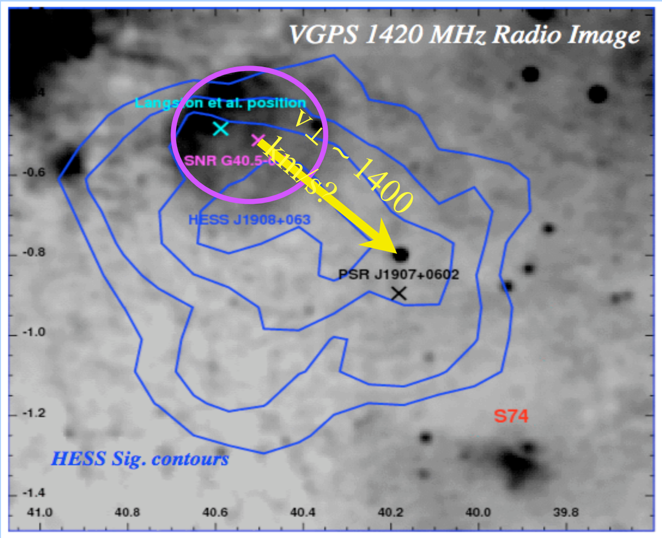
PSR J2032+4127

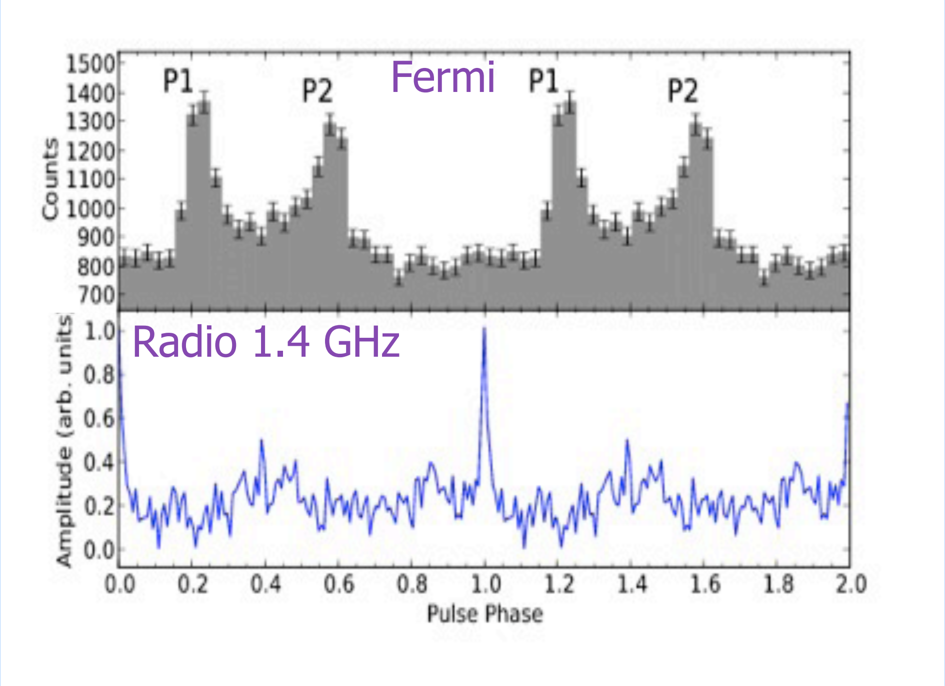
- Pulsations discovered at GBT
- DM=115 implies D=3.6 kpc, but may be at half that distance (possibly associated with Cyg OB2)



Radio Follow-up of New LAT Pulsars

PSR J1907+0602



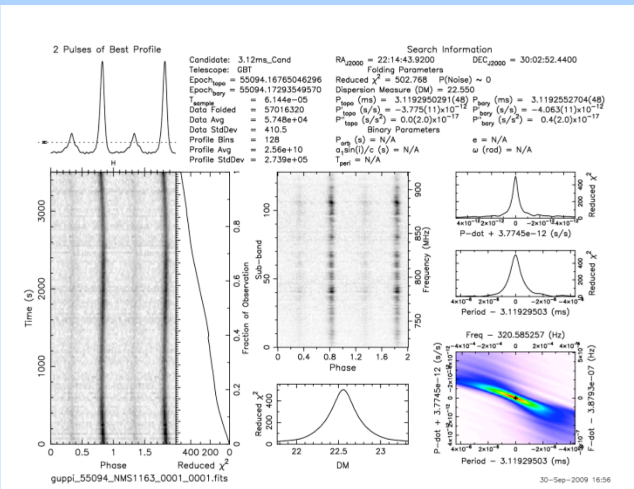


- Extended source seen by ground-based TeV gamma-ray telescopes
- Possibly a pulsar wind nebula powered by the pulsar

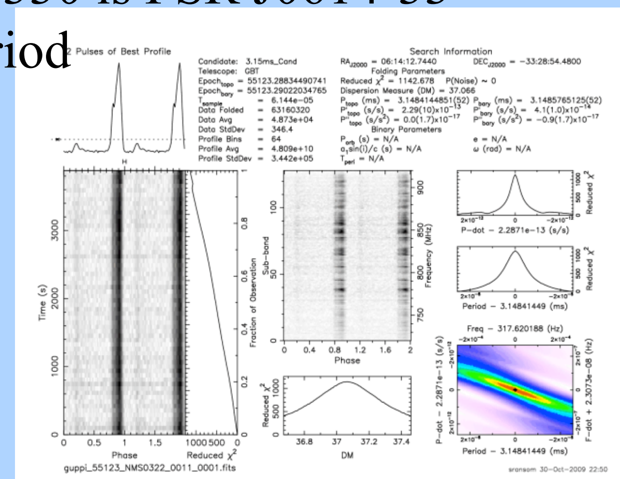
Search for Radio Pulsars in LAT UnID Sources

- 17 new millisecond pulsars found!

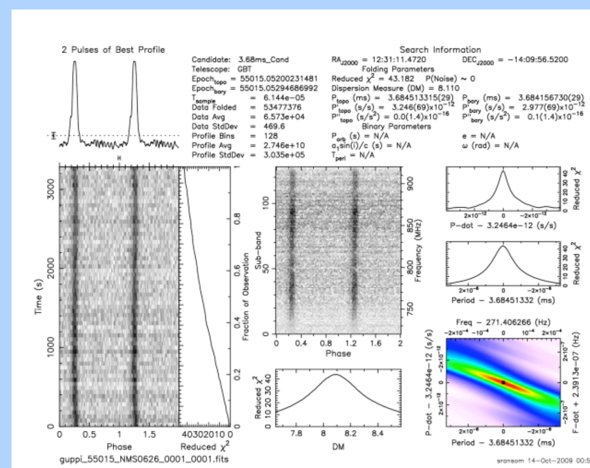
0FGL J2214.8+3002 is PSR J2214+30
‘Black Widow’ pulsar
3.12 ms spin period
10 hour orbit



0FGL J0614.3-3330 is PSR J0614-33
3.15 ms spin period
Unknown orbit



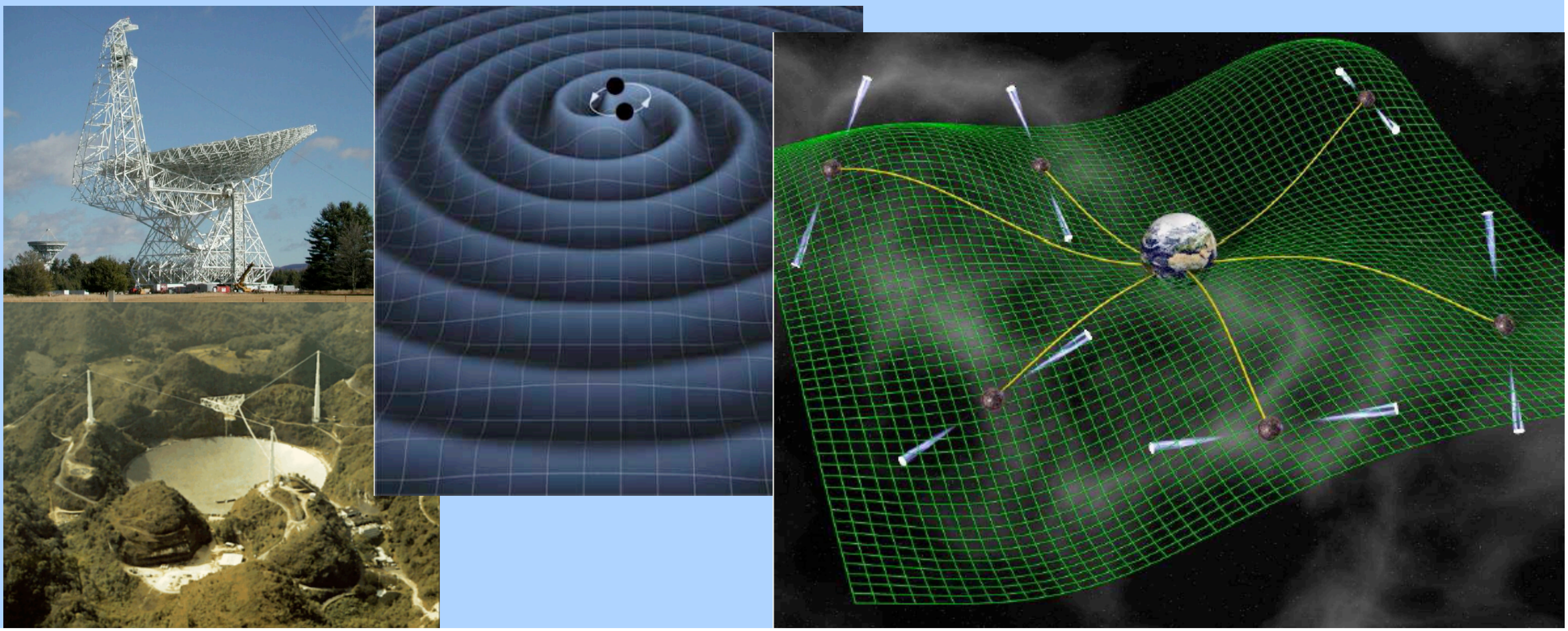
0FGL J1231.5-1410 is PSR J1231
3.68 ms spin
1.86 day orbit



Bright and stable millisecond pulsars are in high demand to complete timing arrays searching for gravitational radiation

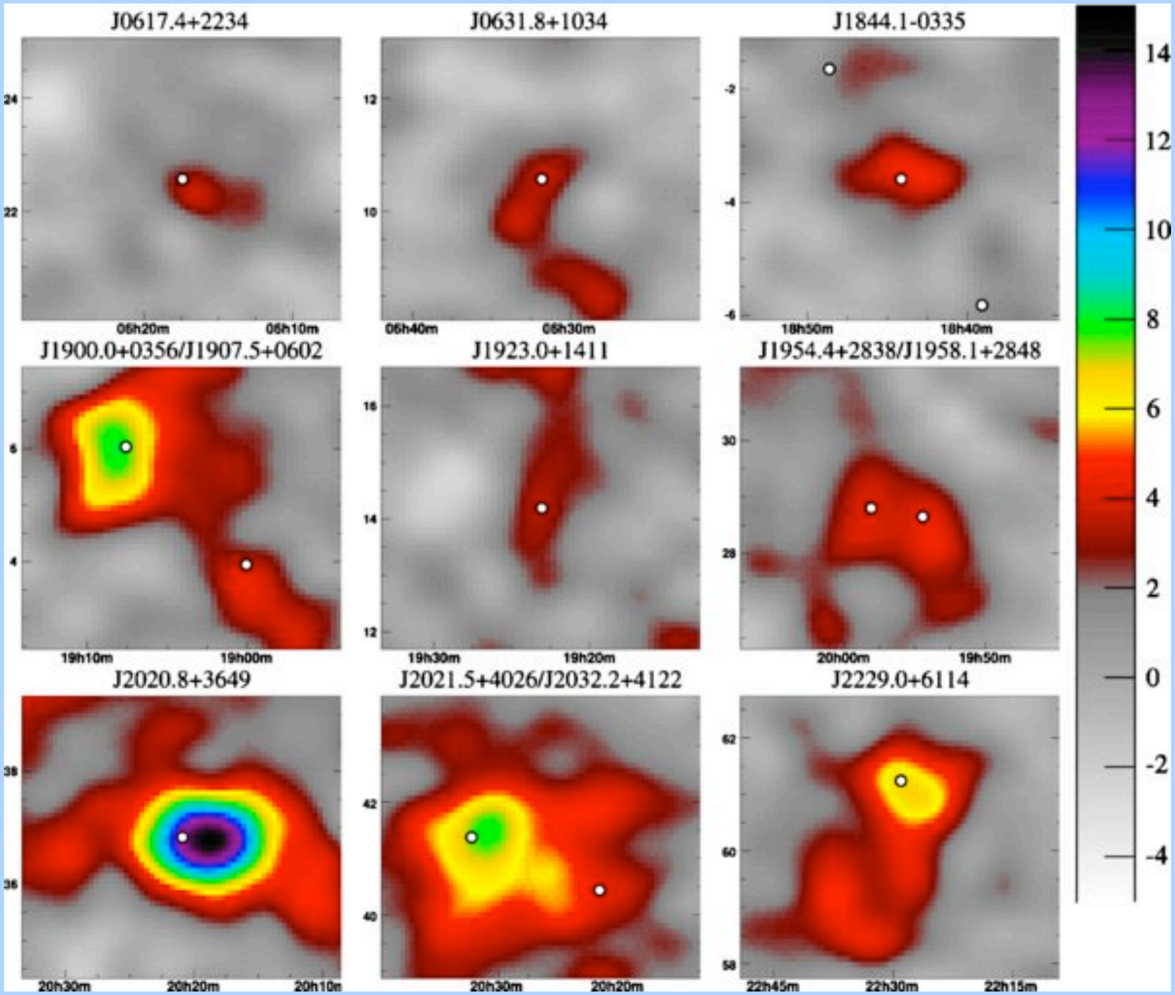
Pulsar Timing Arrays as Gravitational Wave Detectors

- Time millisecond pulsars to 100 nanoseconds
- Arrays of MSPs can be sensitive to nHz gravitational waves – need 20-40 MSPs for detection in 5 years
- Search for stochastic gravitational wave background from black hole/galaxy mergers

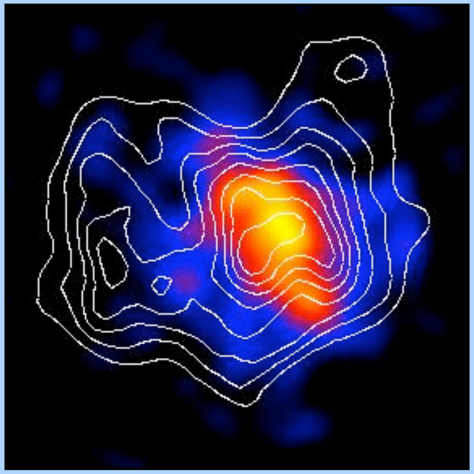


LAT pulsar - TeV nebula connection

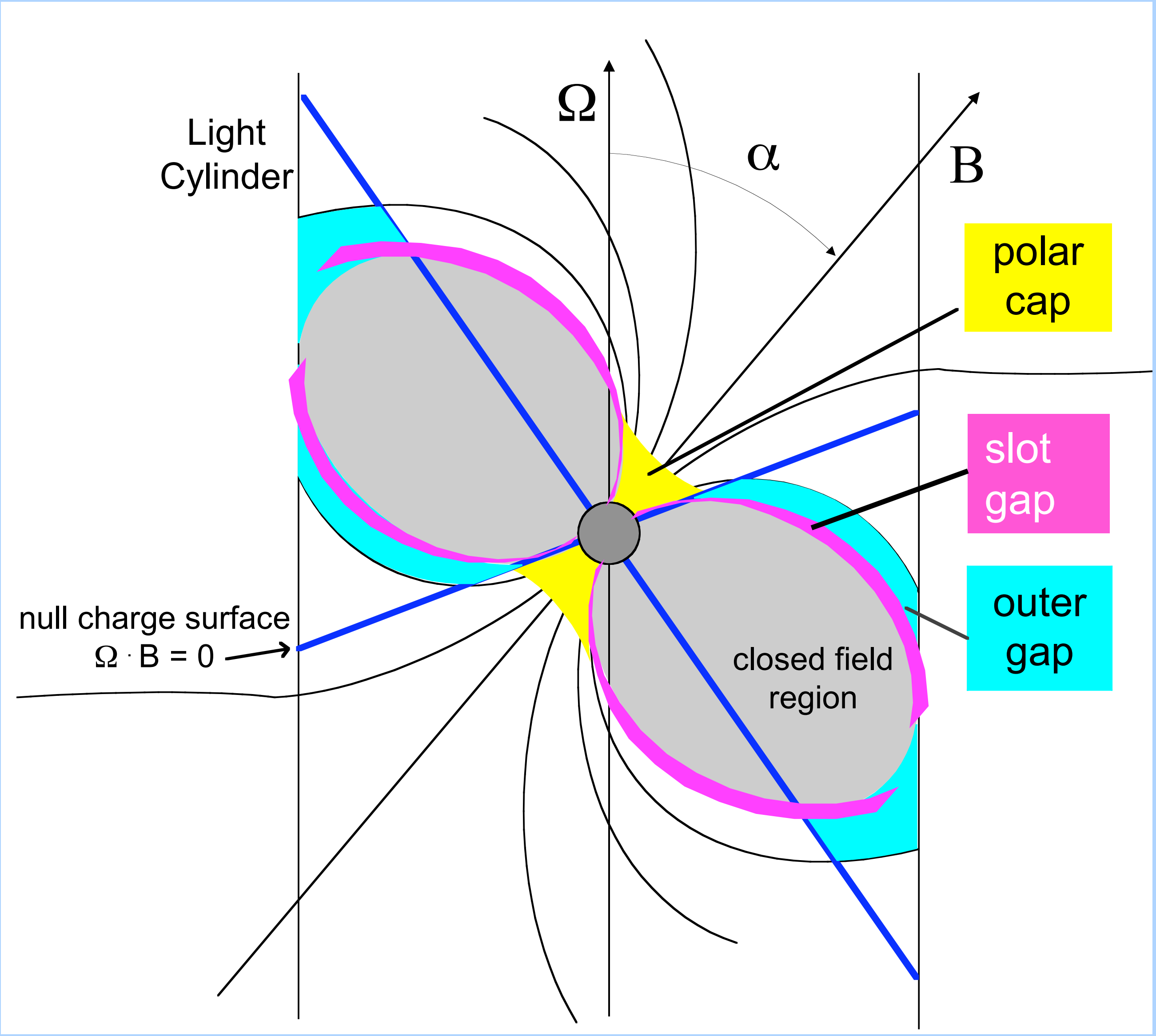
Large percentages of LAT pulsars have associated TeV sources – pulsar wind nebulae?



Vela Pulsar – Vela X

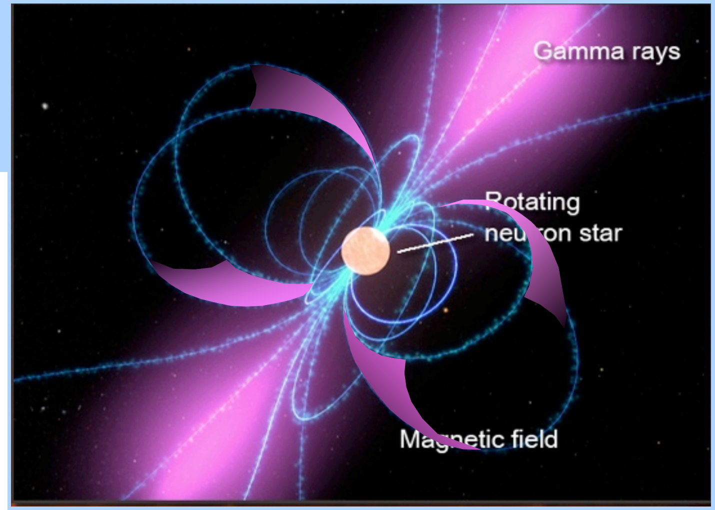


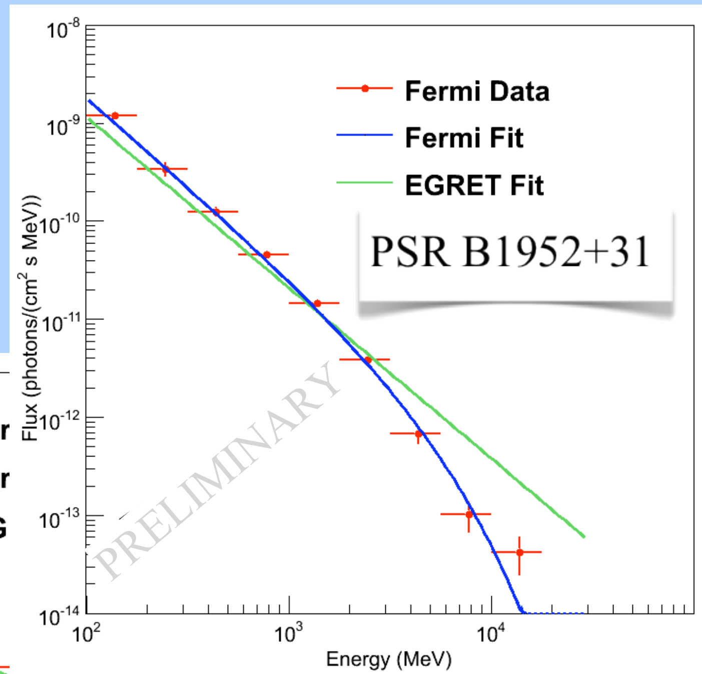
Possible sites of particle acceleration

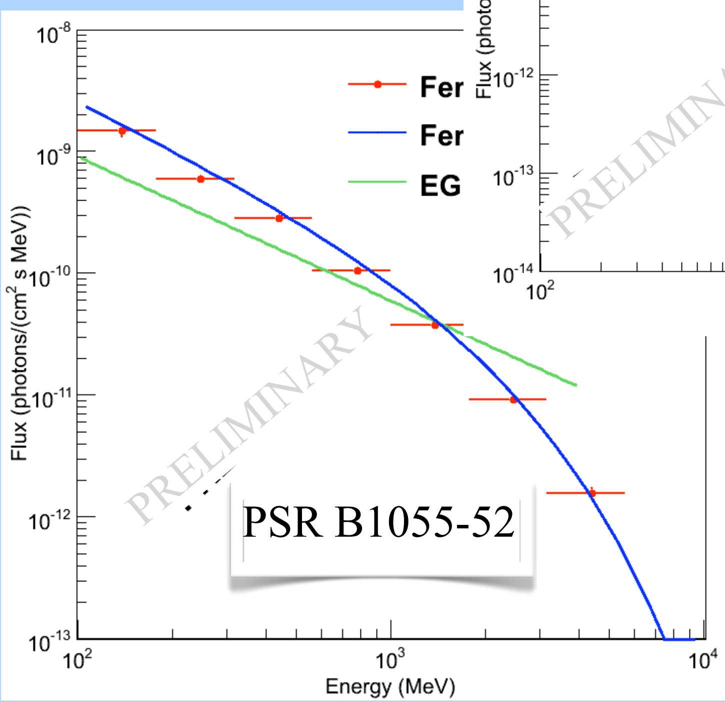


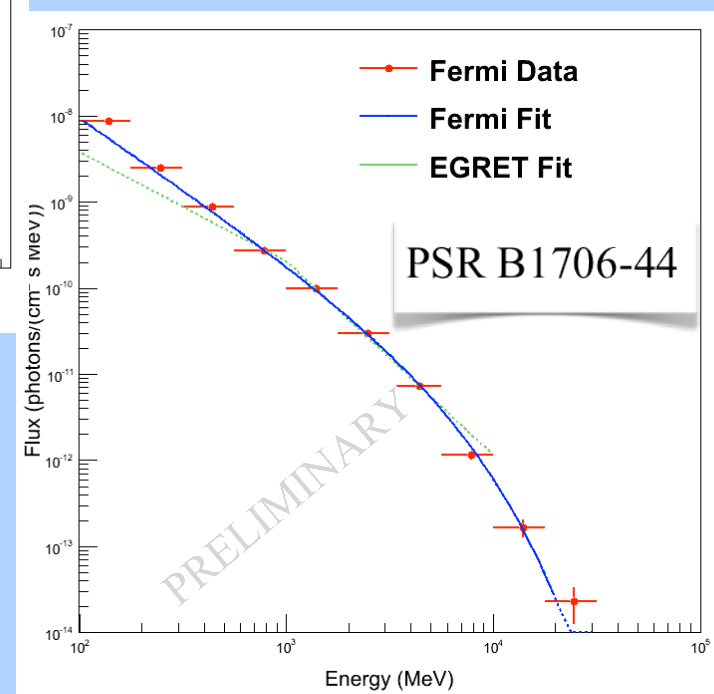
Outer Magnetospheric Accelerators

- exponential cut-off at a few GeV
  - no $\gamma + B \rightarrow e^{\pm}$ absorption $\Rightarrow$
  - outer accelerators

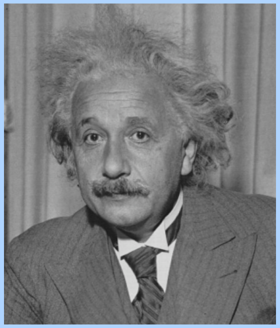




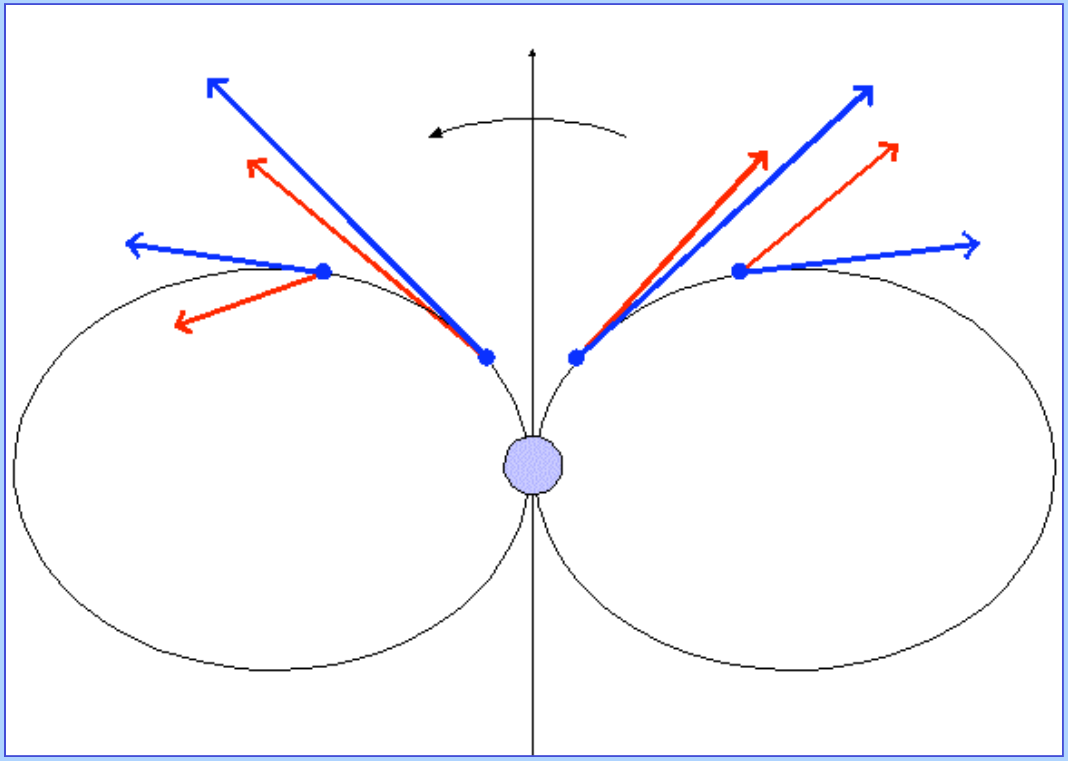




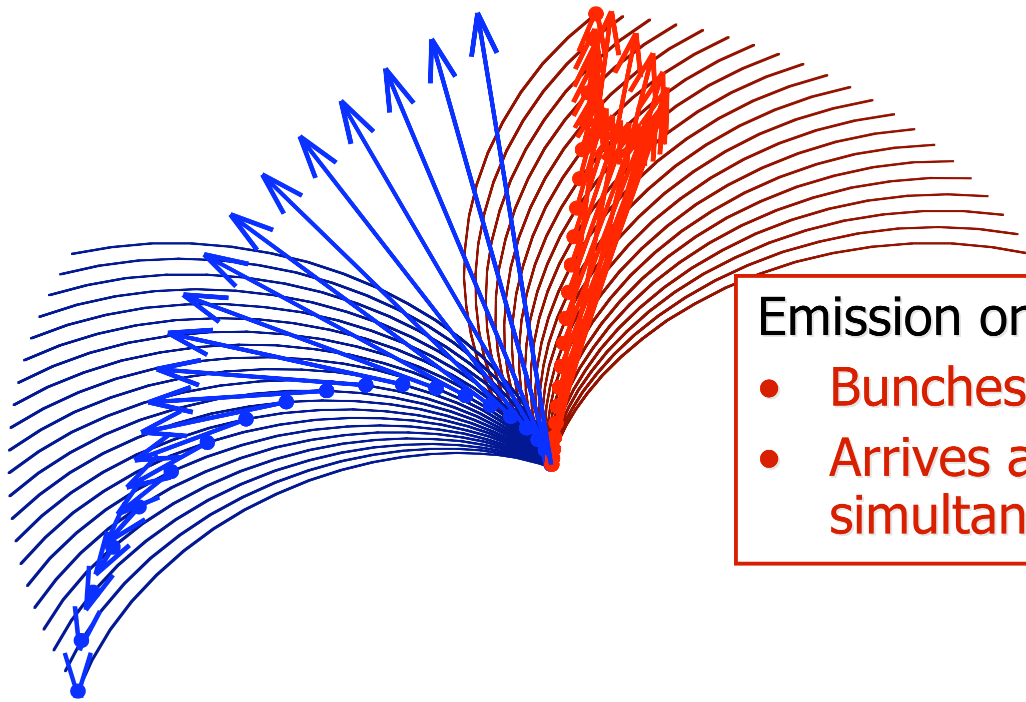
Distortions of Radiation in Pulsar Magnetosphere - Is It All Relative?



- Aberration
- Time-of-flight delays
- Sweep-back of magnetic field



Formation of caustics



Emission on trailing field lines

- Bunches in phase
- Arrives at inertial observer simultaneously

Emission on leading field lines

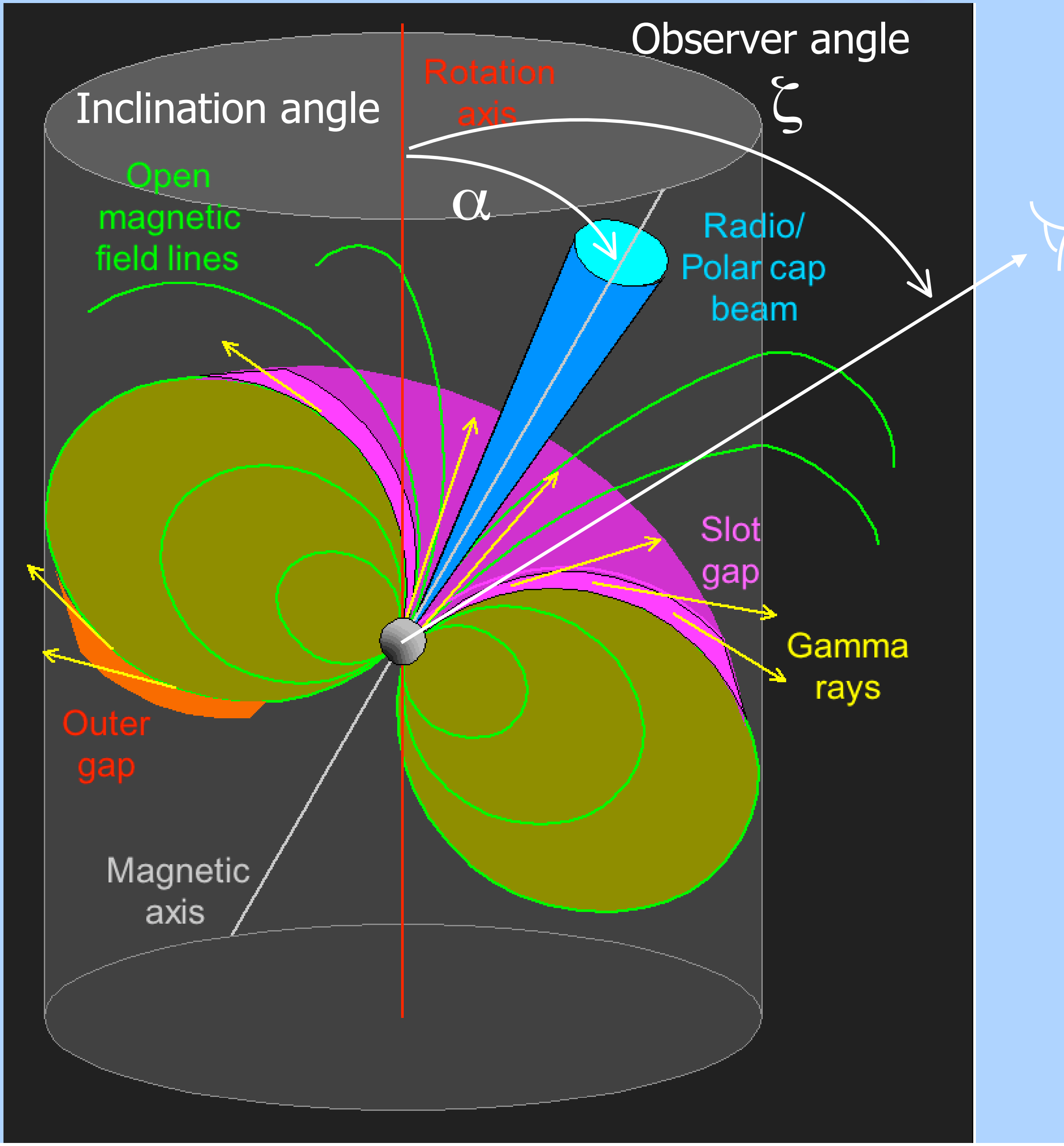
- Spreads out in phase
- Arrives at inertial observer at different times

Caustic emission

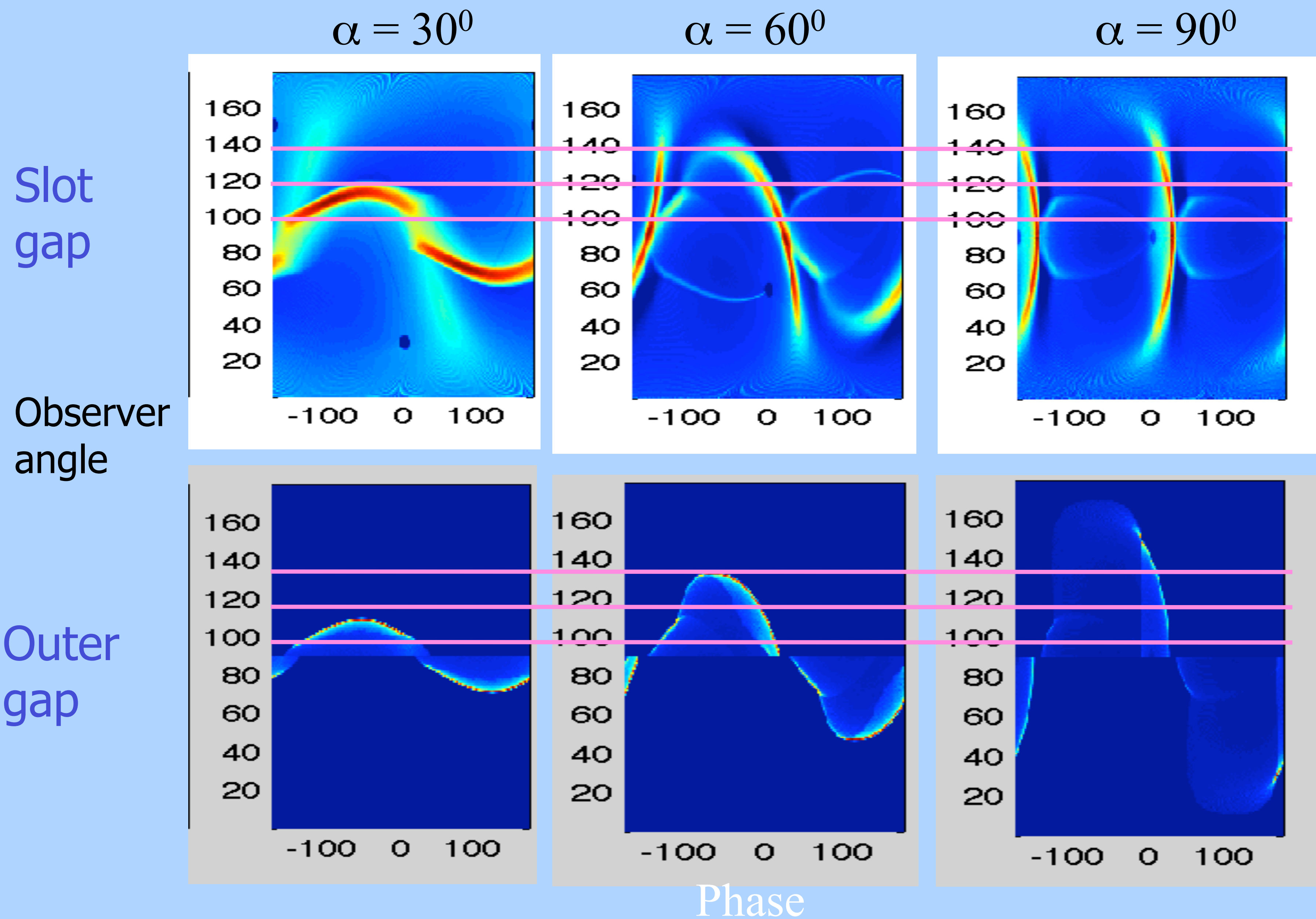
- Dipole magnetic field
- Outer edge of open volume

Caustics in water

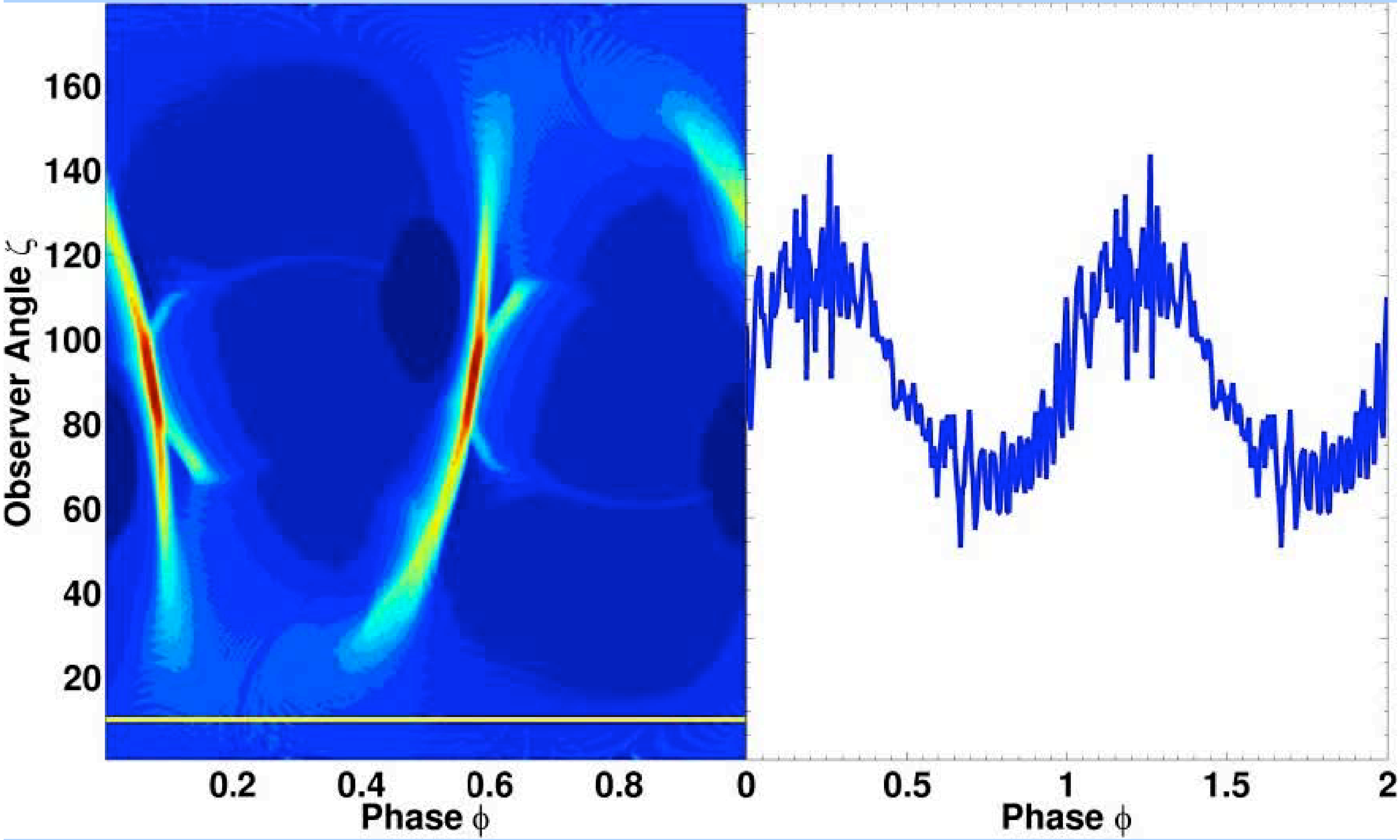
Pulsar Emission Geometry



Sky distribution of intensity

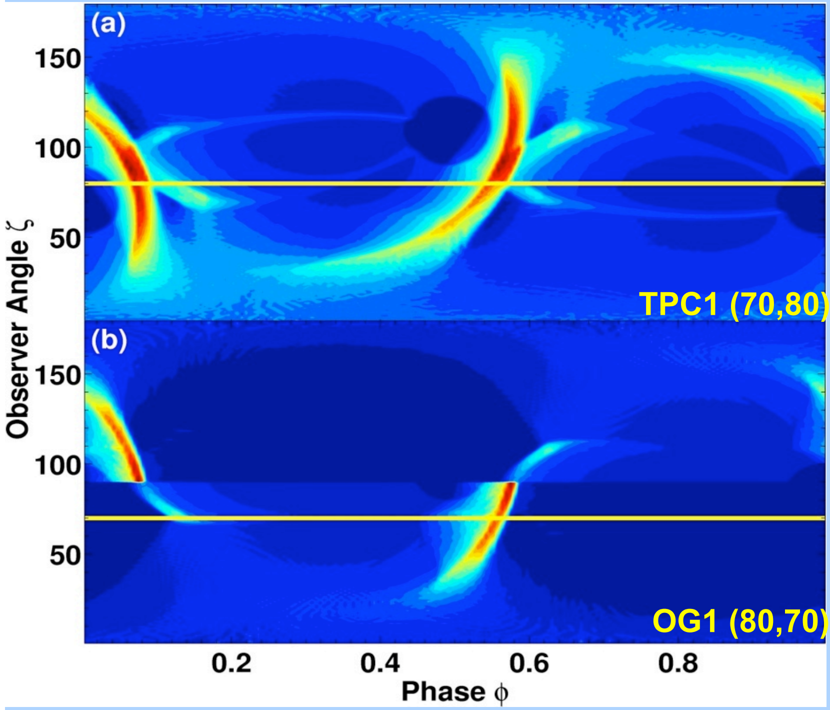


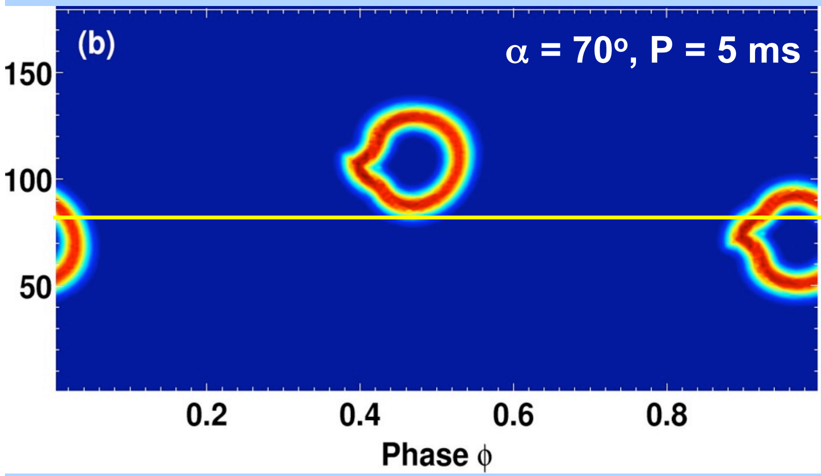
Light Curve vs. Viewing Angle



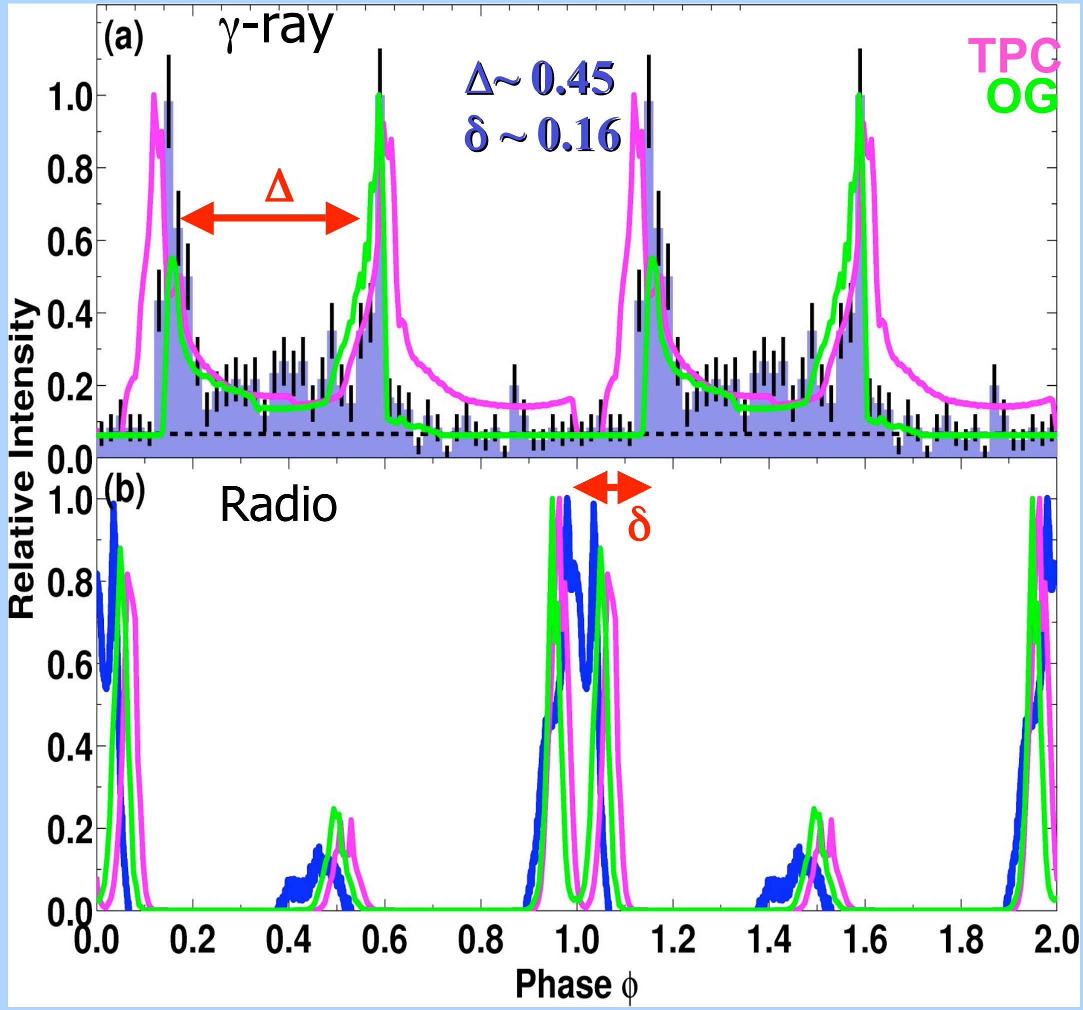
Modeling MSP Light Curves

Venter, Harding & Guillemot 2009

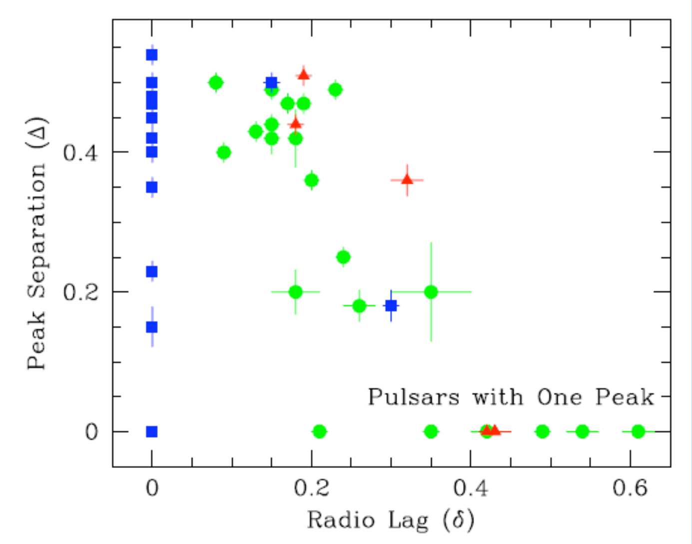




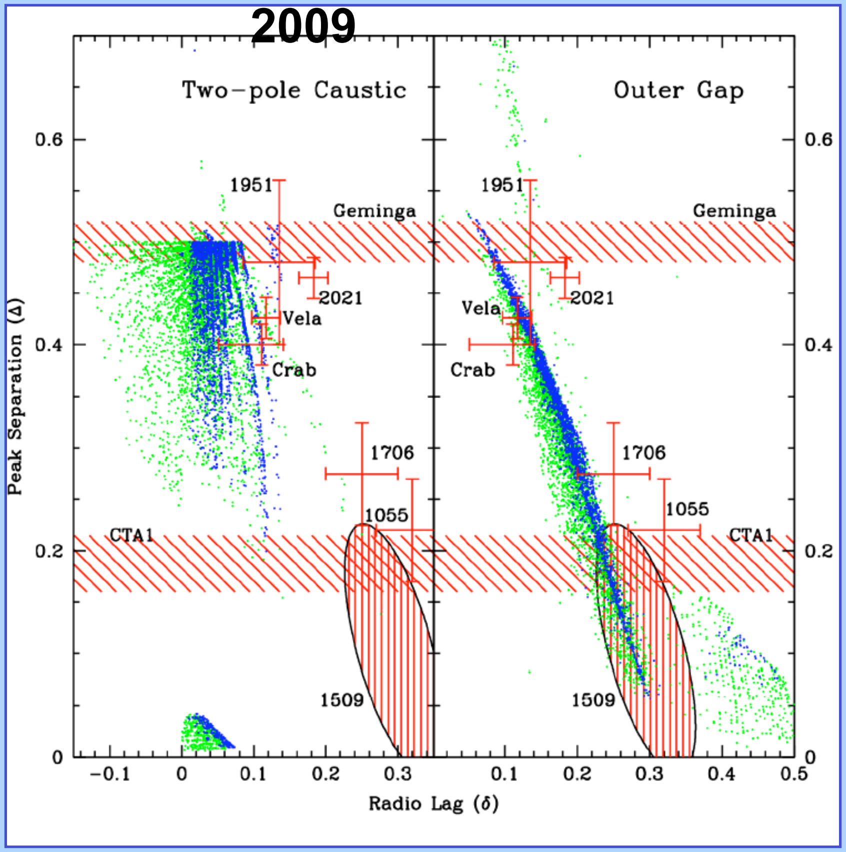
PSR J0030+0451

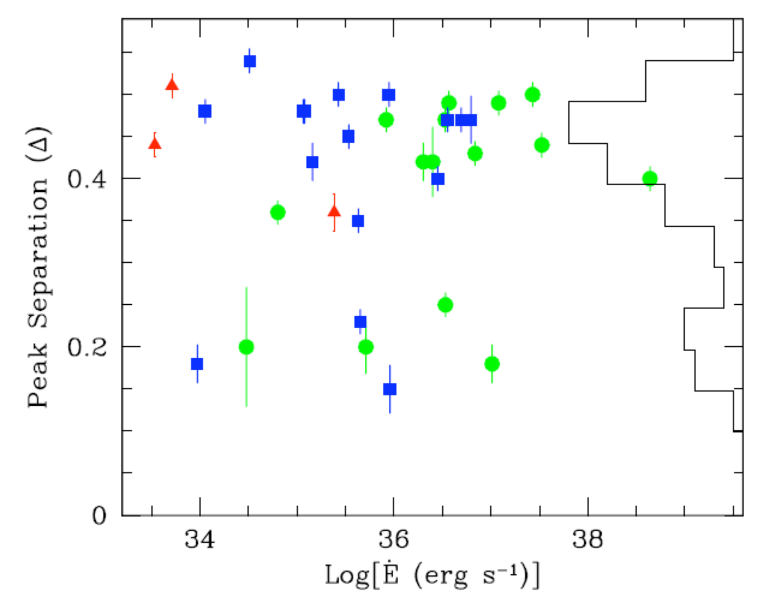


Light Curve Trends



Watters et al. 2009





Good model discriminator

What can we learn from phase-resolved spectra?

- Balance CR losses with acceleration gain

$$eE_{\parallel} = \dot{\gamma}_{CR} = \frac{2e^2\gamma^4}{3\rho_c^2}$$

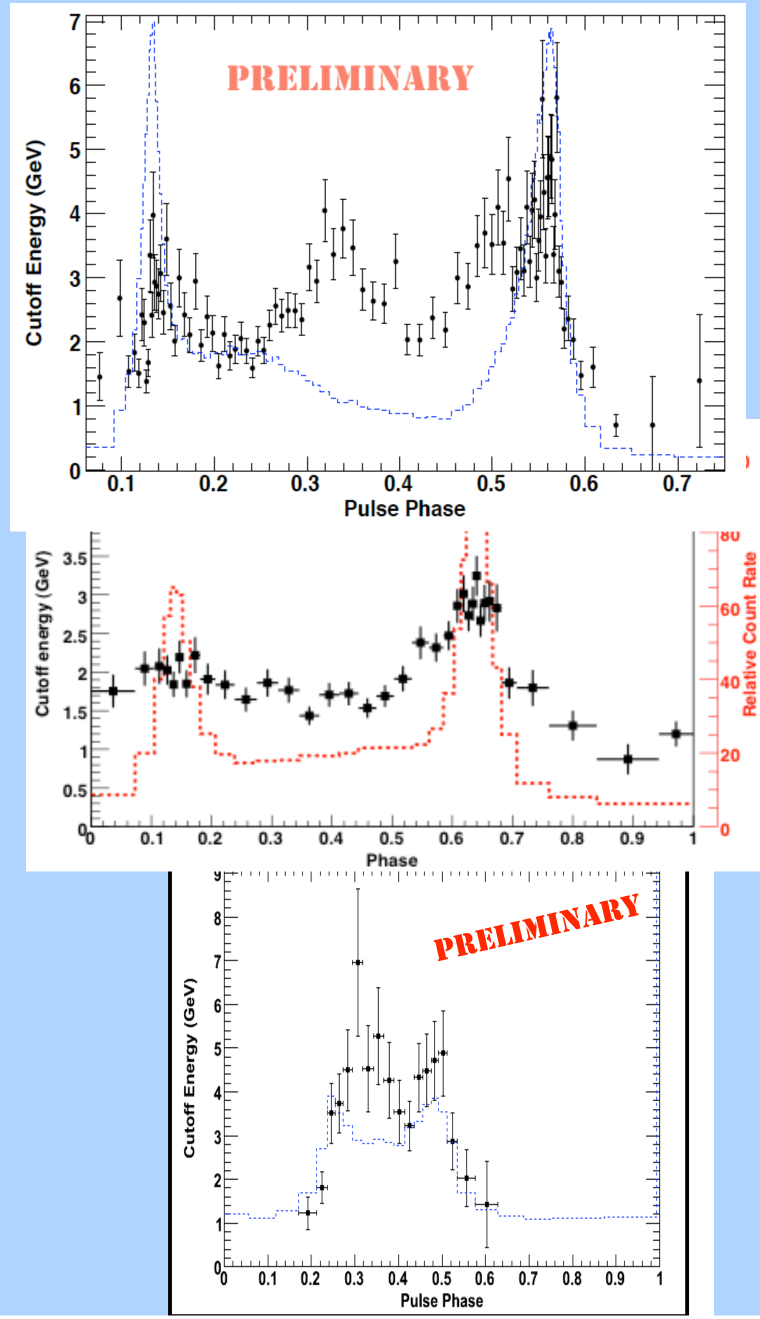
- Steady-state Lorentz factor

$$\gamma_{CRR} = \left(\frac{3}{2}\frac{E_{\parallel}\rho_c^2}{e}\right)^{1/4} \approx 2\times10^7$$

- Curvature radiation peak energy:

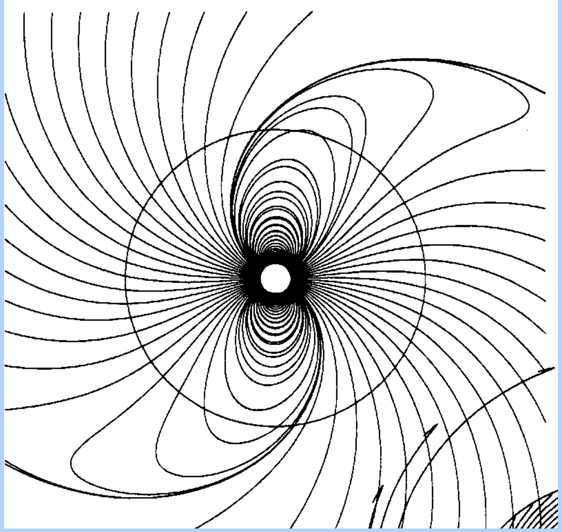
$$\varepsilon_{CR} = \frac{2}{3}\frac{\lambda\!\!\!^{-}_c\gamma_{CRR}^3}{\rho_c} = \left(\frac{3}{2}\right)^{7/4}\left(\frac{E_{\parallel}}{e}\right)^{3/4}\lambda\!\!\!^{-}_c\rho_c^{1/2} \approx 3\ GeV$$

Is $E_c = \varepsilon_{CR}$?
Does E_c variation map magnetic field curvature to phase?

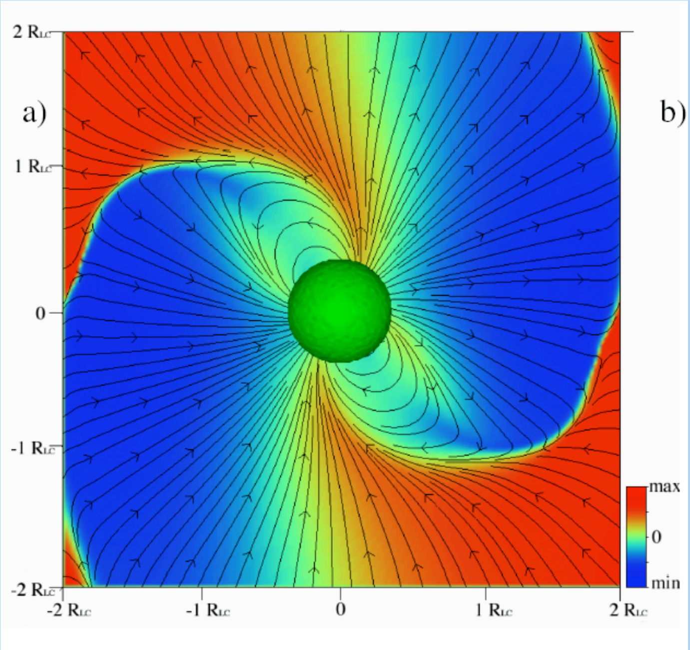


Magnetic field geometry

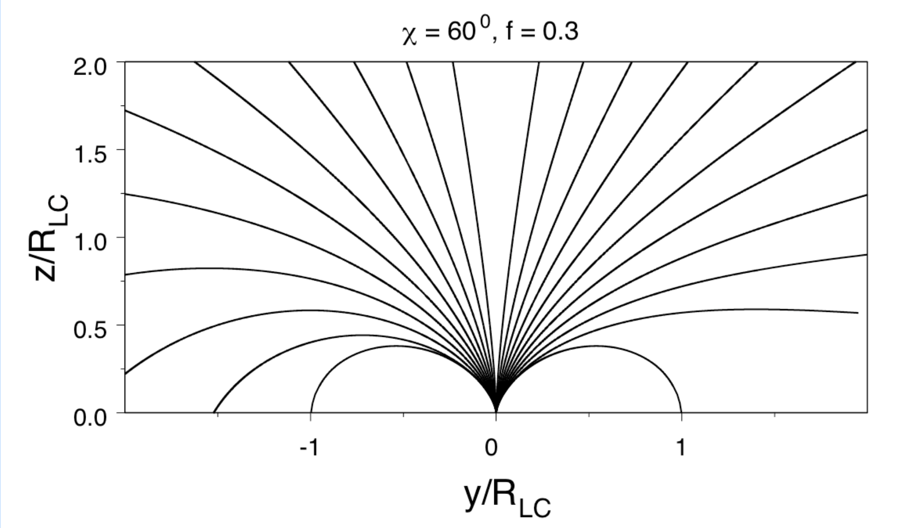
Retarded vacuum dipole
Deutsch 1954



Force-free magnetosphere
Spitkovsky 2008



Pair-starved magnetosphere
Muslimov & Harding 2009



Phase-resolved spectroscopy will help constrain these

Fermi pulsars – what have we learned?

- Majority have double γ-ray peaks with phase separation 0.2 – 0.5
- γ-ray peaks are not aligned with radio peak(s)
- γ-ray beams are must be larger that radio beams
- Spectra are power-laws with simple exponential cutoffs at 1-6 GeV

⇨ High-energy emission comes from the outer magetosphere

⇨ Emission mechanism is likely curvature radiation from continuously accelerated particles

Summary

- We are finally answering fundamental questions of γ-ray pulsar astrophysics – but raising new ones
  - High-energy emission comes from outer magnetosphere
- The mystery of unidentified Galactic gamma-ray sources from the EGRET era has largely been solved – they're pulsars
- Radio-loud, radio-quiet and millisecond pulsars have similar gamma-ray light curves and spectra
  - Similar emission mechanisms and geometry
- Fermi has so far detected about 55 γ-ray pulsars - including ms pulsars – many radio-quiet – more to come!
- Fermi is aiding discovery of new millisecond pulsars perfect for nanosecond timing arrays – first direct detection of gravitational radiation may be sooner that we thought!