Fermi Gamma-ray Space Telescope

Gamma-ray Pulsars

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and Pulsar Search and Timing Consortia

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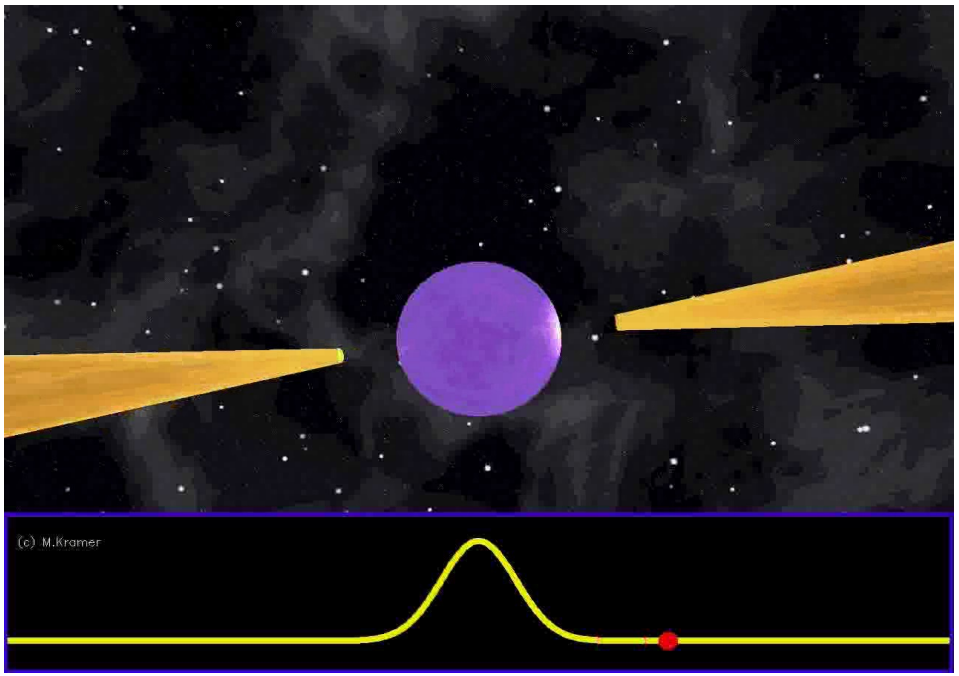
Pulsars

Rapidly-rotating, highly-magnetized neutron stars.

$R_{NS} \sim 10$ km , $M_{NS} \sim 1 - 2\ M_{\odot}$, $B_{surf} \sim 10^{8}$-10^{15} G

Spin periods (P) very stable, slowly increasing dP/dt > 0.

(Focus on rotation-powered pulsars)



Animation Credit: M. Kramer

Why?

Magnetic fields and density we can't reproduce on Earth

- Extreme systems
- Allows observations of processes (one-photon pair production) can't see in laboratories

Born in supernova explosions, one endpoint of stellar evolution

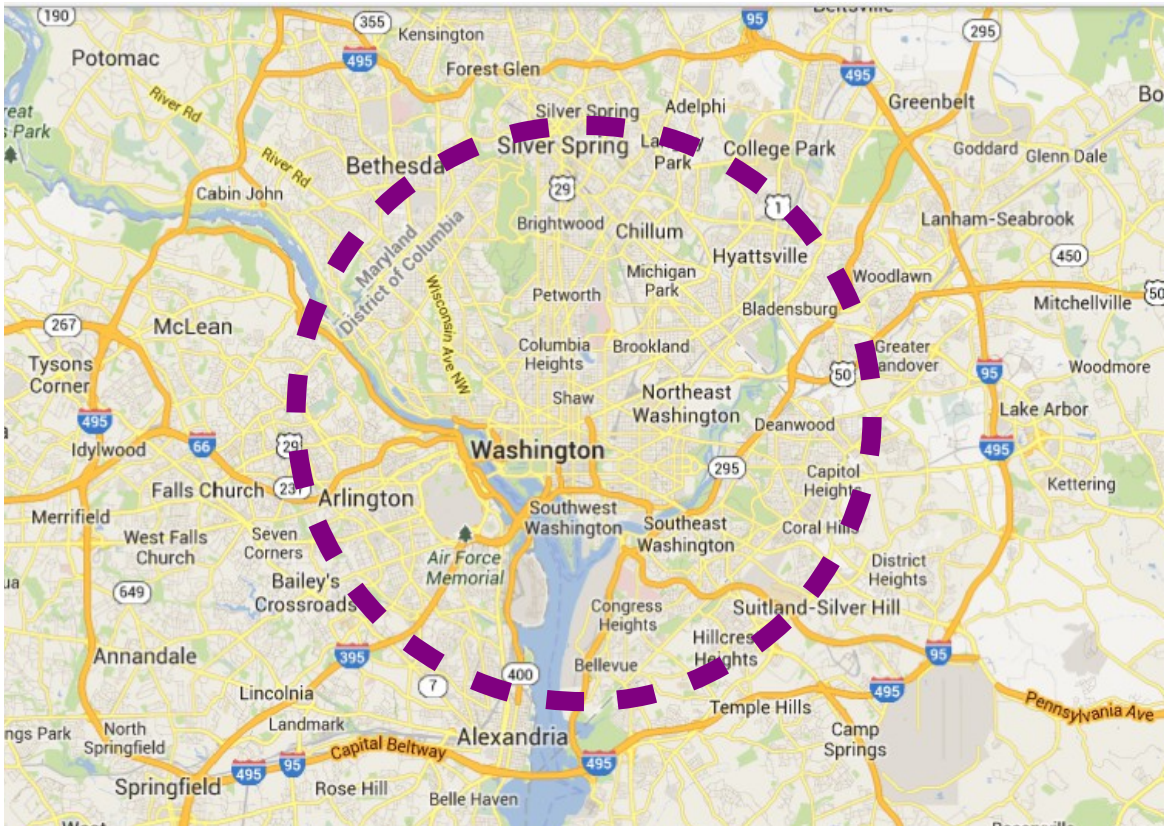
Most stringent test of general relativity to date

- Pulsar timing arrays may detect gravitational waves before LIGO

Pulsar navigation

- Use known X-ray millisecond pulsars (MSPs) as reference points

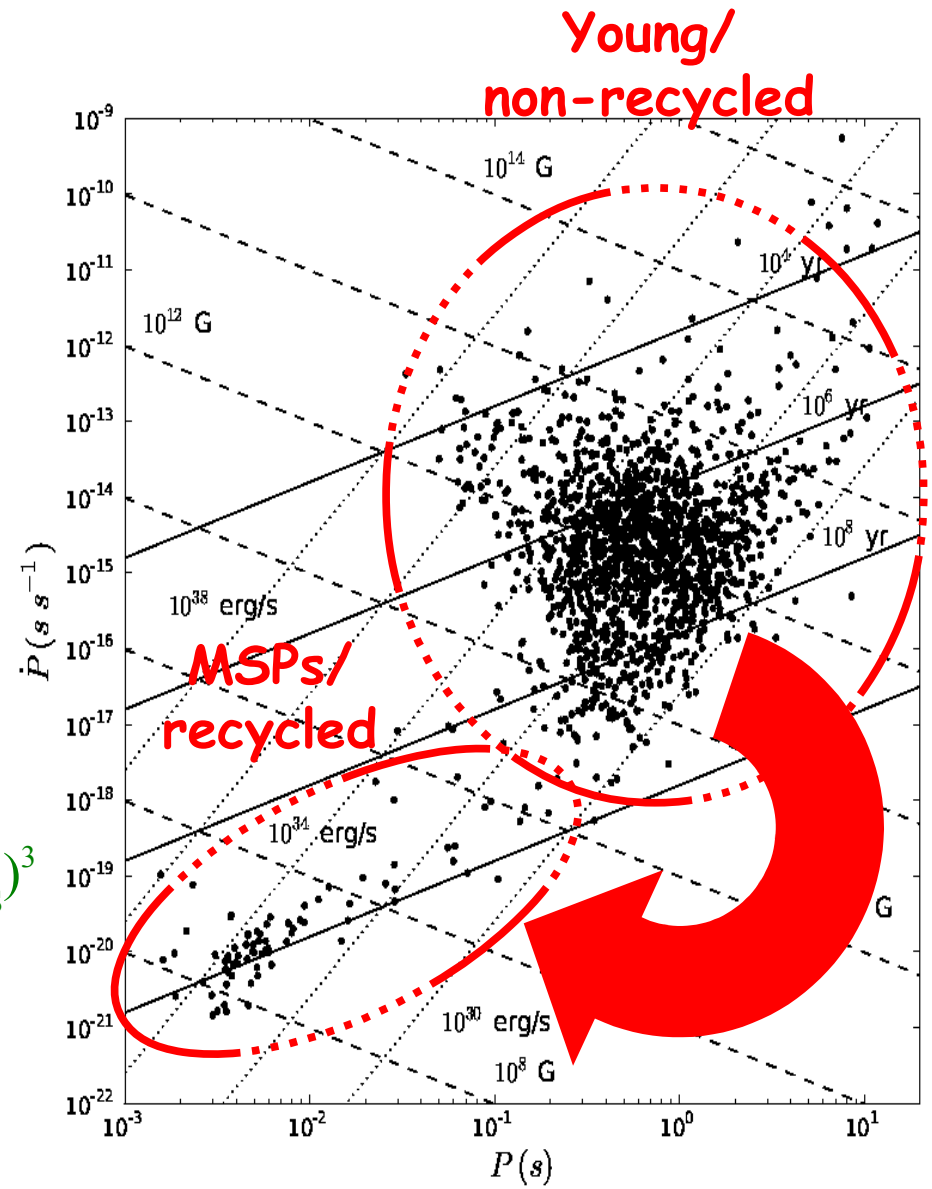
Why?


Potomac
Kensington
Forest Glen
Silver Spring
Adelphi
Greenbelt
Bethesda
College Park
Goddard
Glenn Dale
Cabin John
Brightwood
Chillum
Lanham-Seabrook
Hyattsville
Woodlawn
Michigan Park
Petworth
Bladensburg
Mitchellville
McLean
Columbia Heights
Brookland
Tysons Corner
Shaw
Northeast Washington
Deanwood
Woodmore
Lake Arbor
Idylwood
Washington
Capitol Heights
Kettering
Falls Church
Arlington
Merrifield
Southwest Washington
Southeast Washington
Coral Hills
West Falls Church
Seven Corners
Air Force Memorial
District Heights
Bailey's Crossroads
Congress Heights
Suitland-Silver Hill
Annandale
Hillcrest Heights
Bellevue
Lincolnia
Temple Hills
Landmark
Alexandria
Camp Springs
North Springfield
Springfield
Rose Hill
Belle Haven
Capital Beltway
Pennsylvania Ave
Maryland
District of Columbia
Wisconsin Ave NW
River Rd

The Pulsar Population

~2200 rotation-powered pulsars known
-radio, X-rays, gamma rays
ATNF pulsar databse v1.46
http://www.atnf.csiro.au/people/pulsar/psrcat/

Timing Parameters and Derived quantities:
– spin period P and derivative $\dot{P}$
– spin-down power $\dot{E} = 4\pi^2 I\dot{P}/P^3$ (dotted lines)
– surface magnetic field $B_s = (1.5Ic^3\dot{P}P)^{1/2}/2\pi(R_{NS})^3$ (dashed lines)
– characteristic age $\tau_c = P/2\dot{P}$ (solid lines)



Gamma-ray Pulsars (pre-*Fermi*)

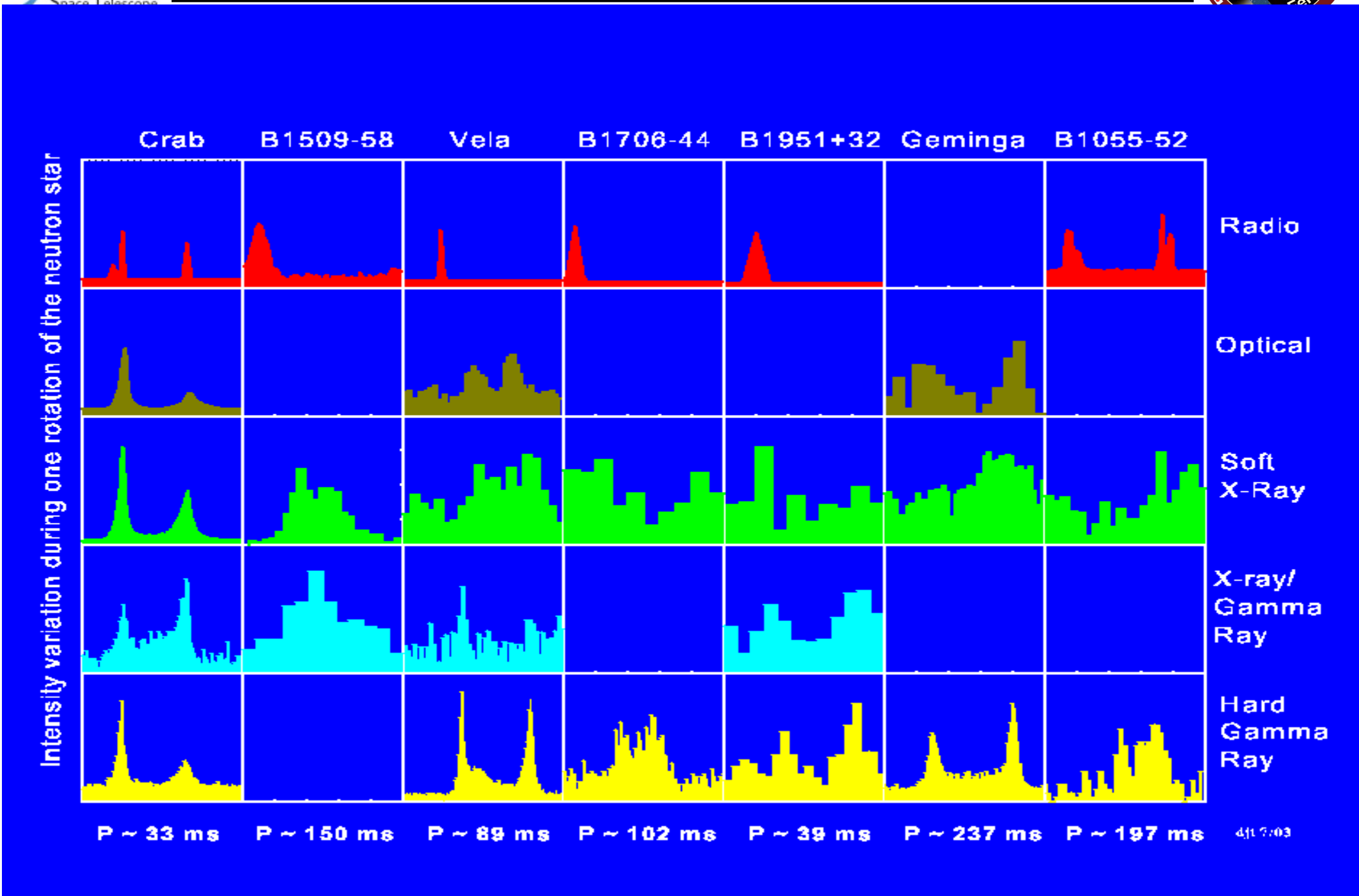
Pulsations ≥50 MeV from the Crab pulsar detected by Browning+ (1971), balloon experiment.

SAS-2 satellite detects pulsed gamma rays from the Vela pulsar (Thompson+ 1975).

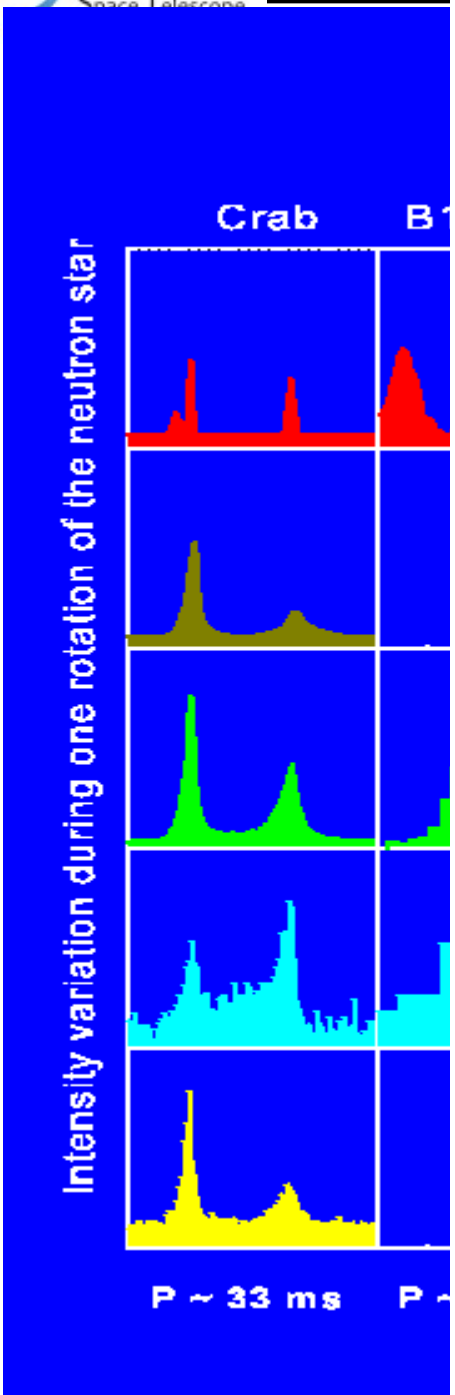
EGRET on the *Compton Gamma-Ray Observatory* detects 6 pulsars ≥100 MeV, +1 seen only at lower energies by *OSSE* and *COMPTEL*.

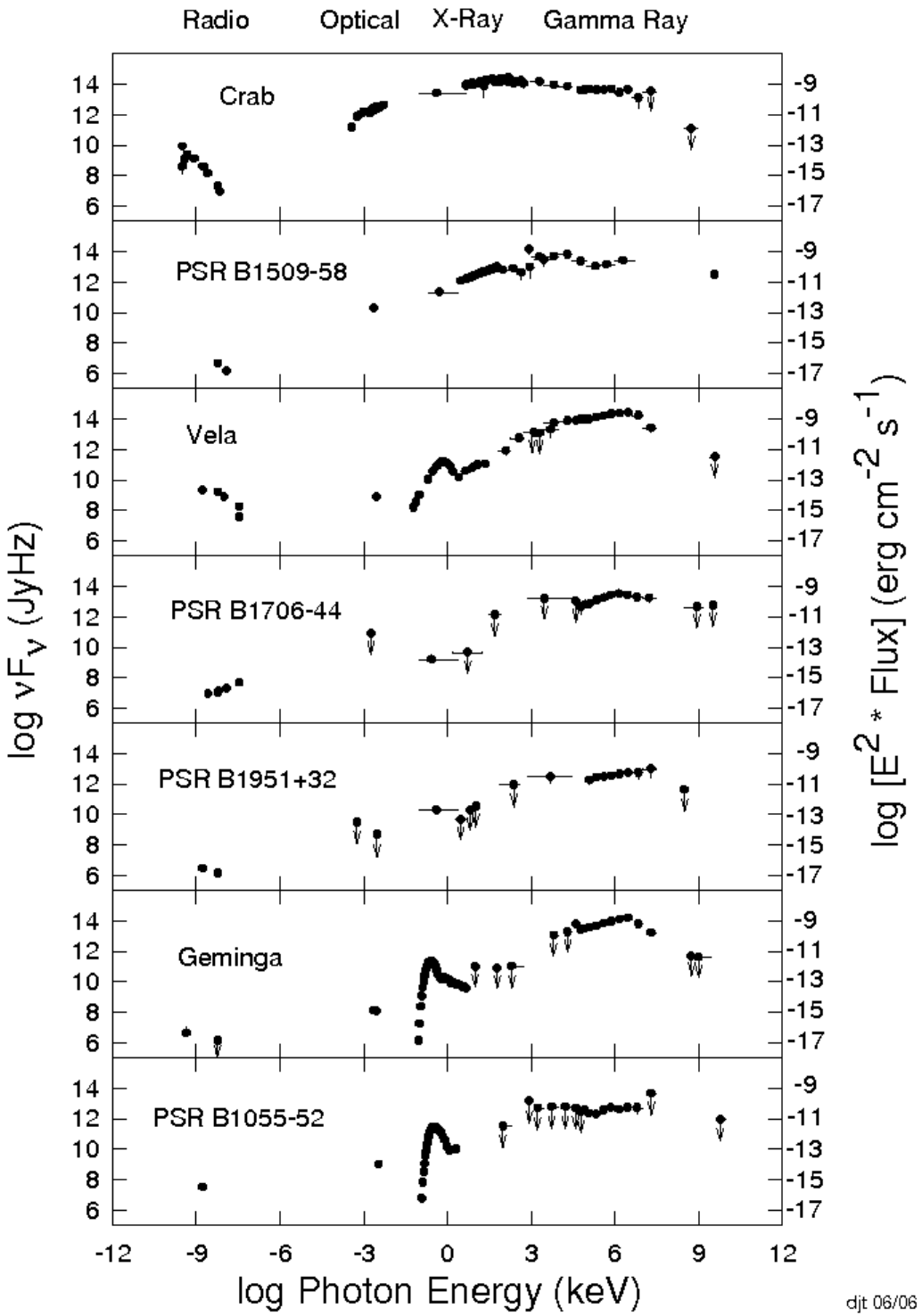
- Emission cutoff ~few GeV, couldn't characterize cutoff
- Gamma-rays lag radio by ≥0 phase shift (if seen)

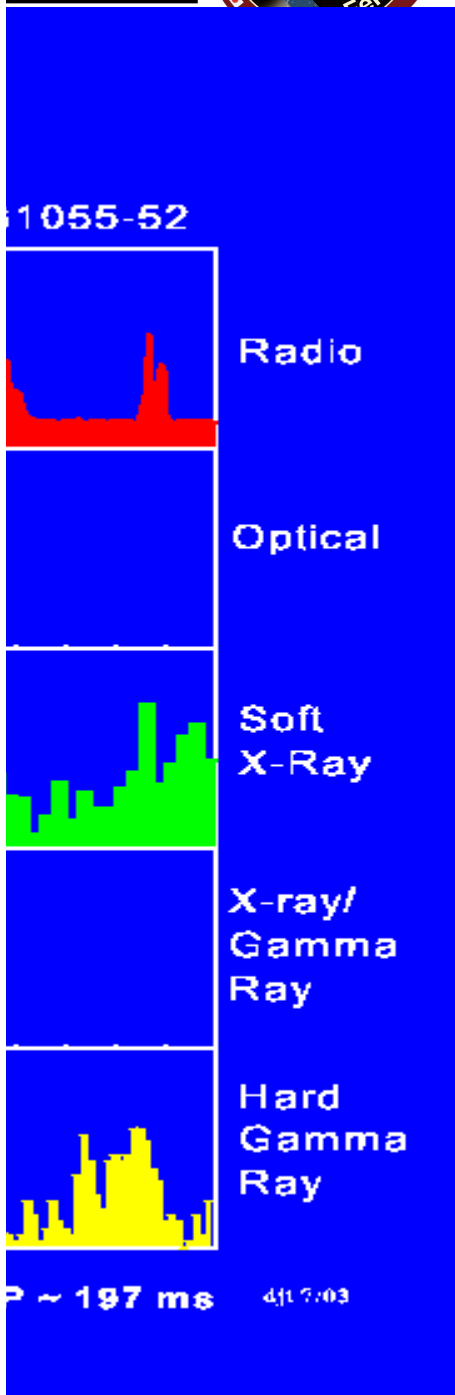
Gamma-ray Pulsars (pre-*Fermi*)



Ga mi)







Figures courtesy D. J. Thompson

PULSAR EMISSION

Gamma rays

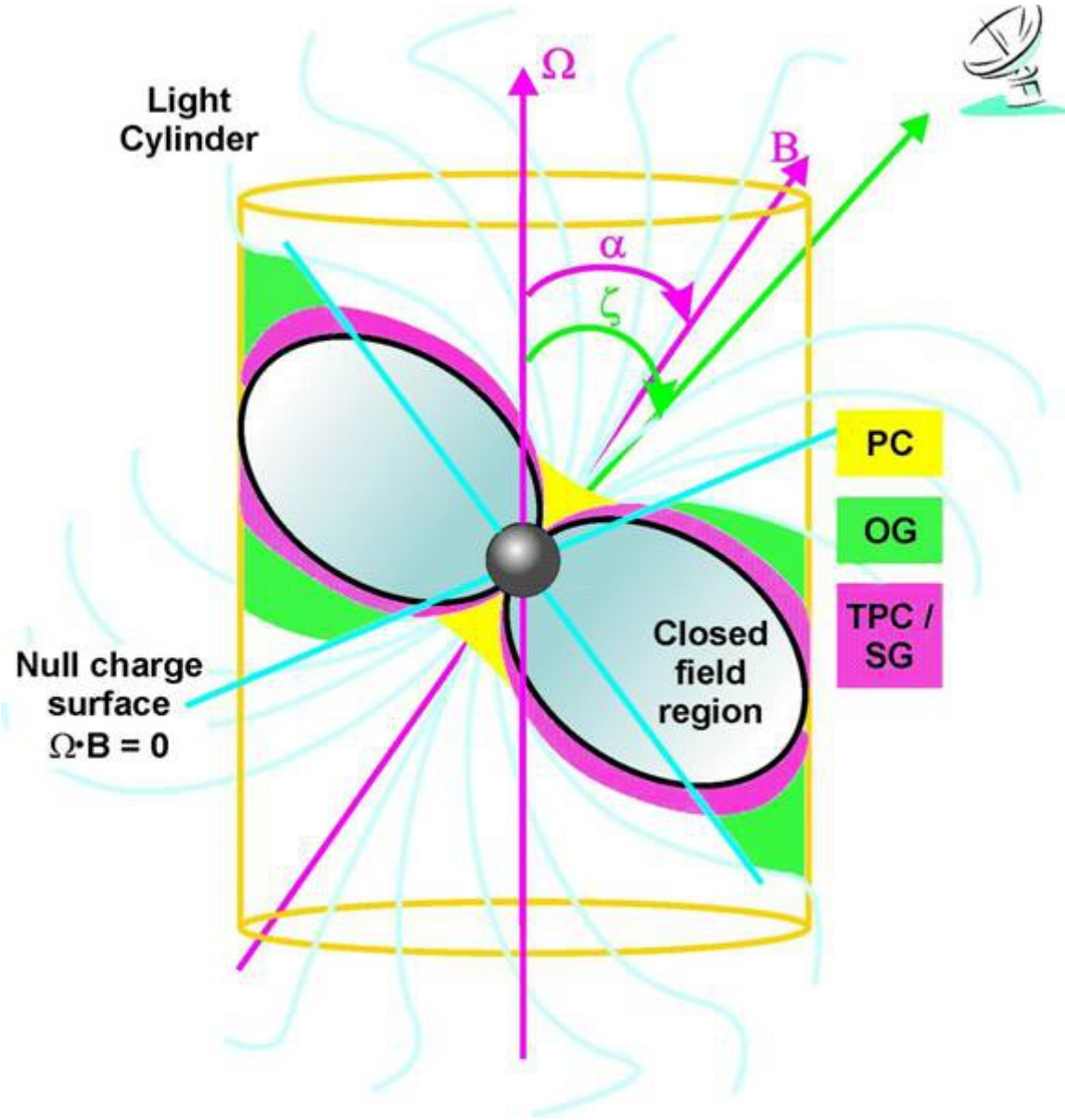
Curvature radiation, exponentially-cutoff power-law spectrum

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left\{-\left(\frac{E}{E_C}\right)^{b}\right\}$$

Polar cap – emission from just above the surface, strong B-field, one-photon pair production, b>1 (e.g., Daugherty & Harding 1996)

Slot gap/two-pole caustic – emission from surface to light cylinder in narrow vacuum gap, b=1 (e.g., Dyks & Rudak 2003;Muslimov & Harding 2004)

Outer gap – emission above NCS only, b=1 (e.g., Cheng+ 1986; Romani 1996)



Screening, not just for the TSA

How do you get vacuum gaps?

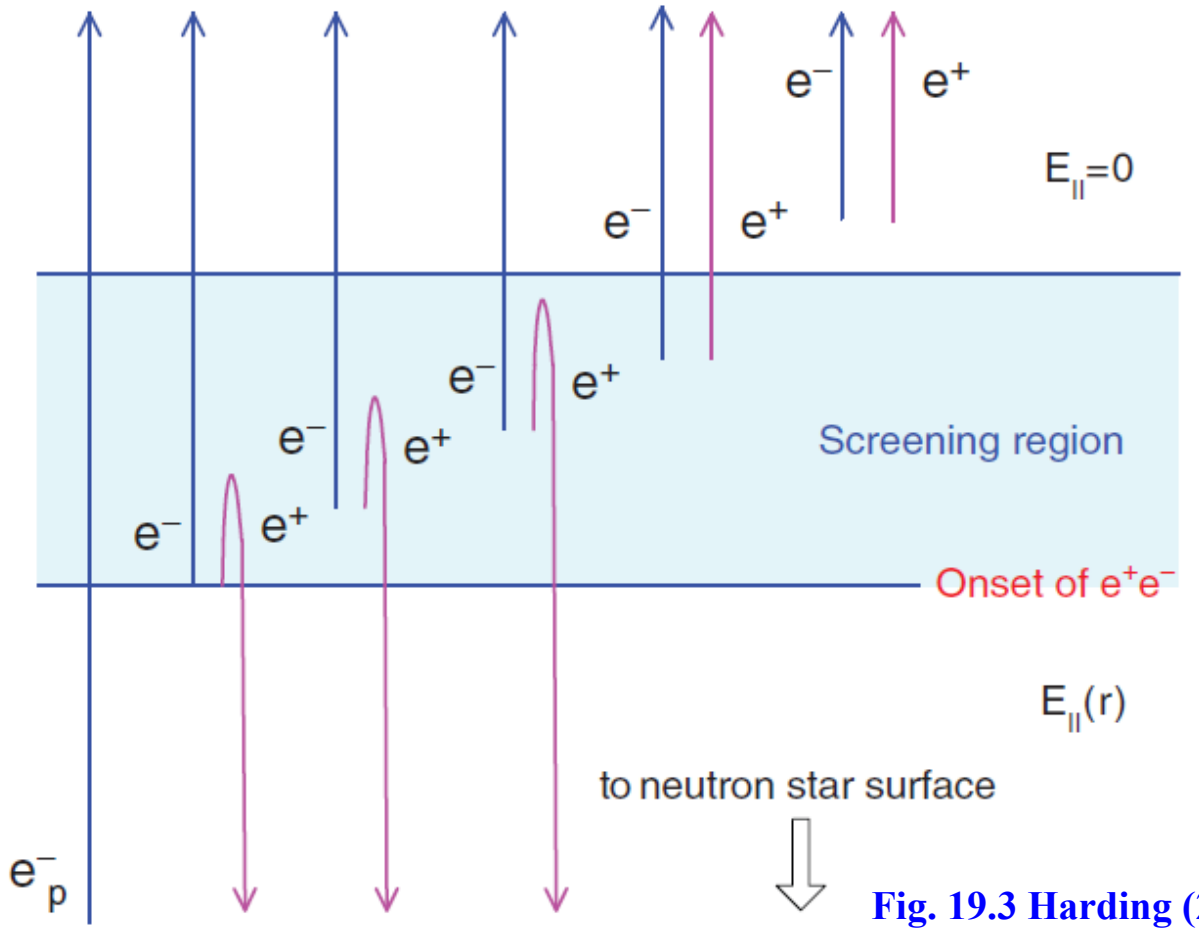


Fig. 19.3 Harding (2009)

Screening, not just for the TSA

Depends on accelerating field strength.

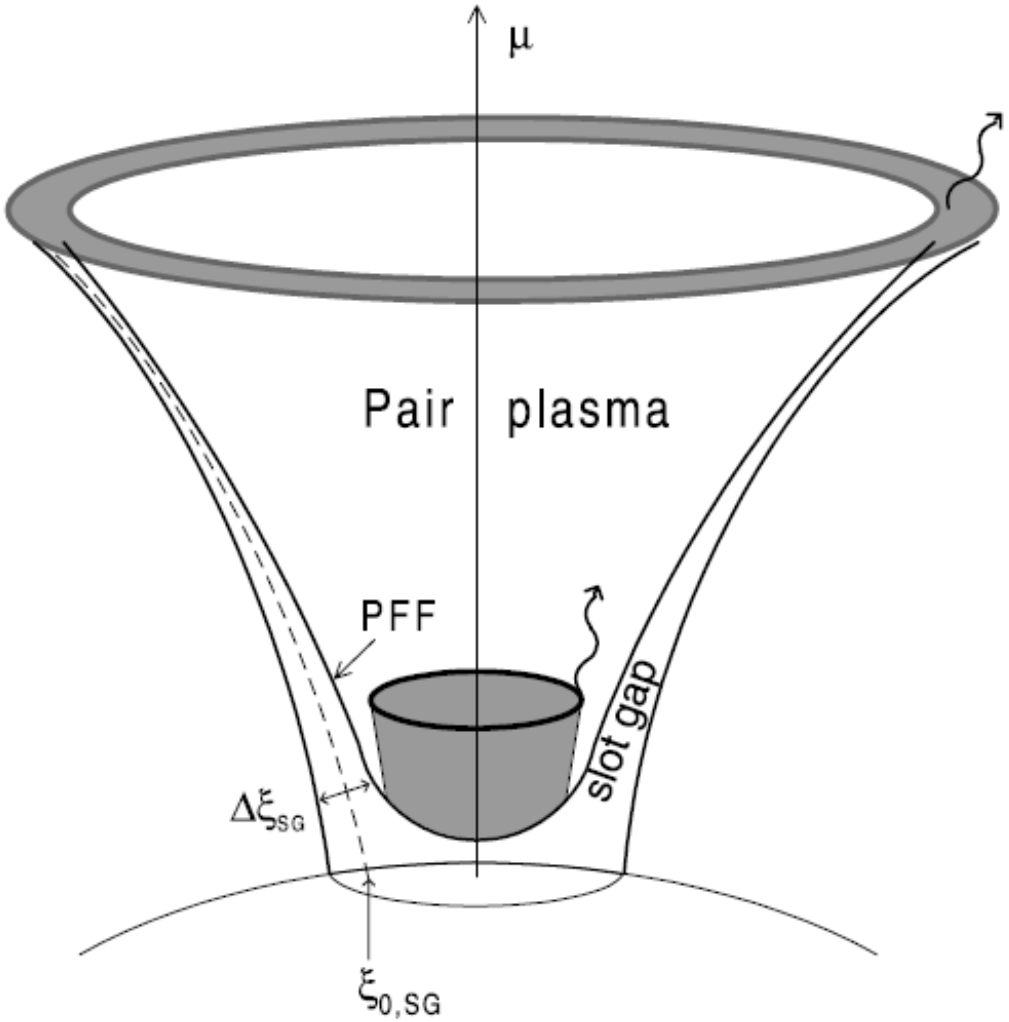


Fig. 1 Harding & Muslimov (2003)

Screening, not just for the TSA

Depends on accelerating field strength.

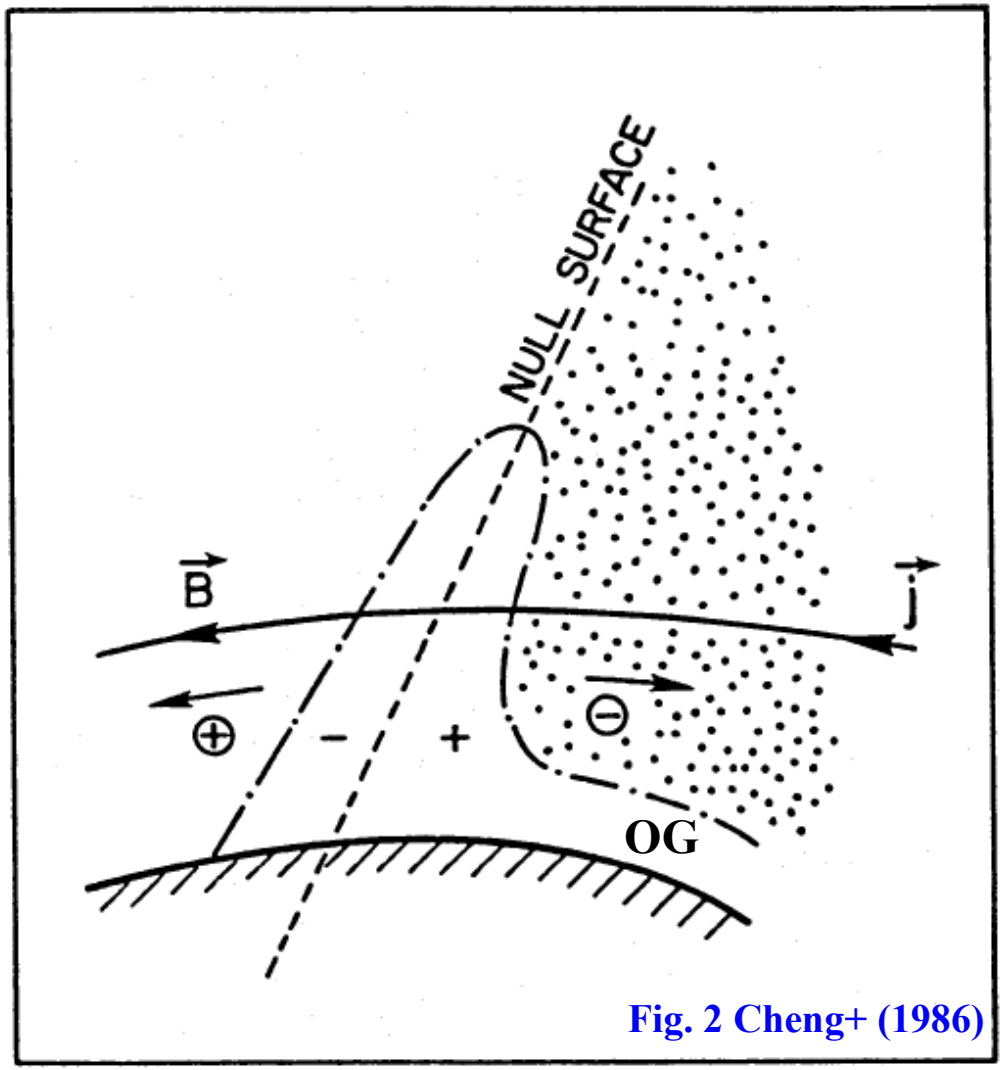


Fig. 2 Cheng+ (1986)

Screening, not just for the TSA

Depends on accelerating field strength.

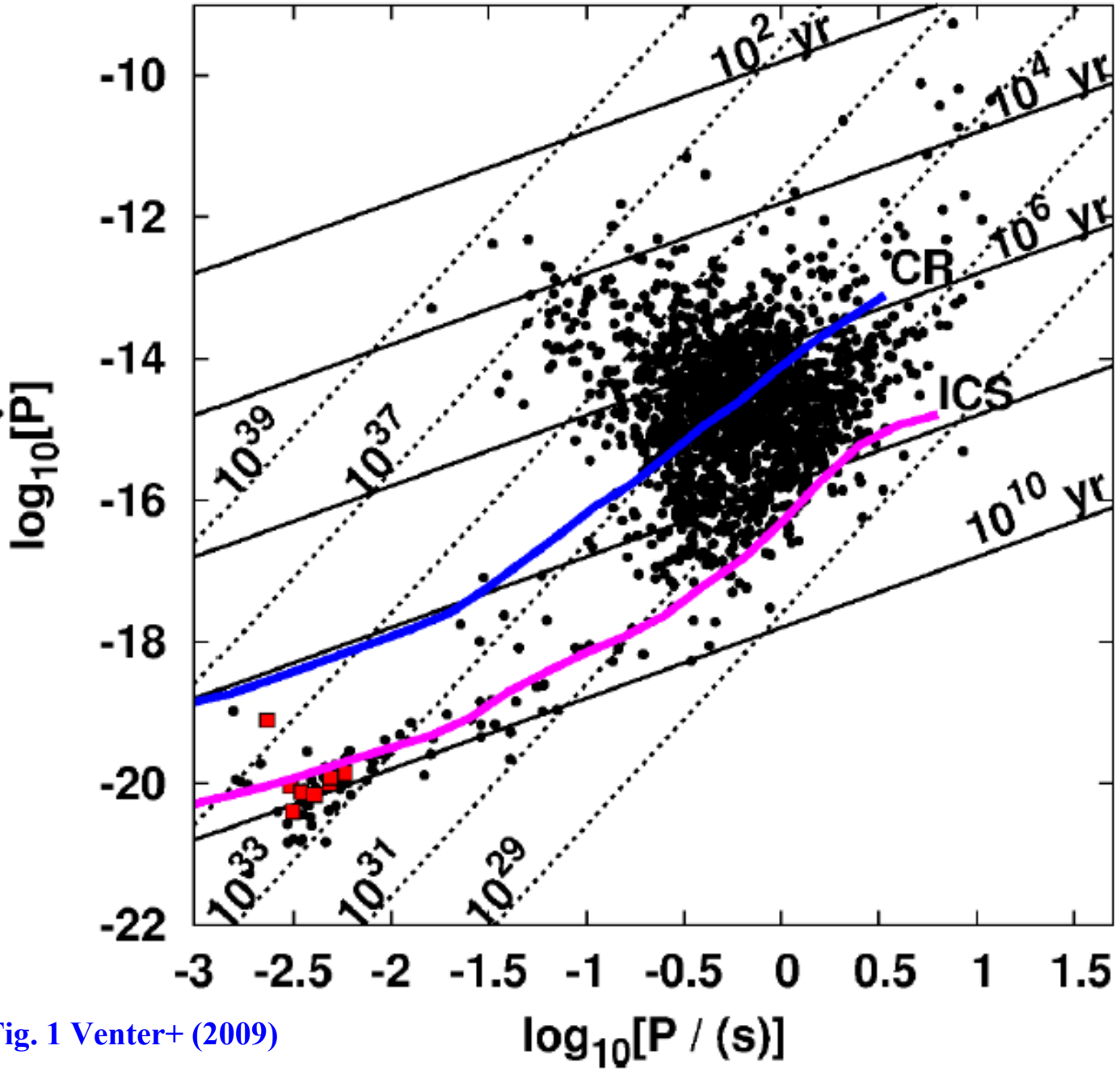
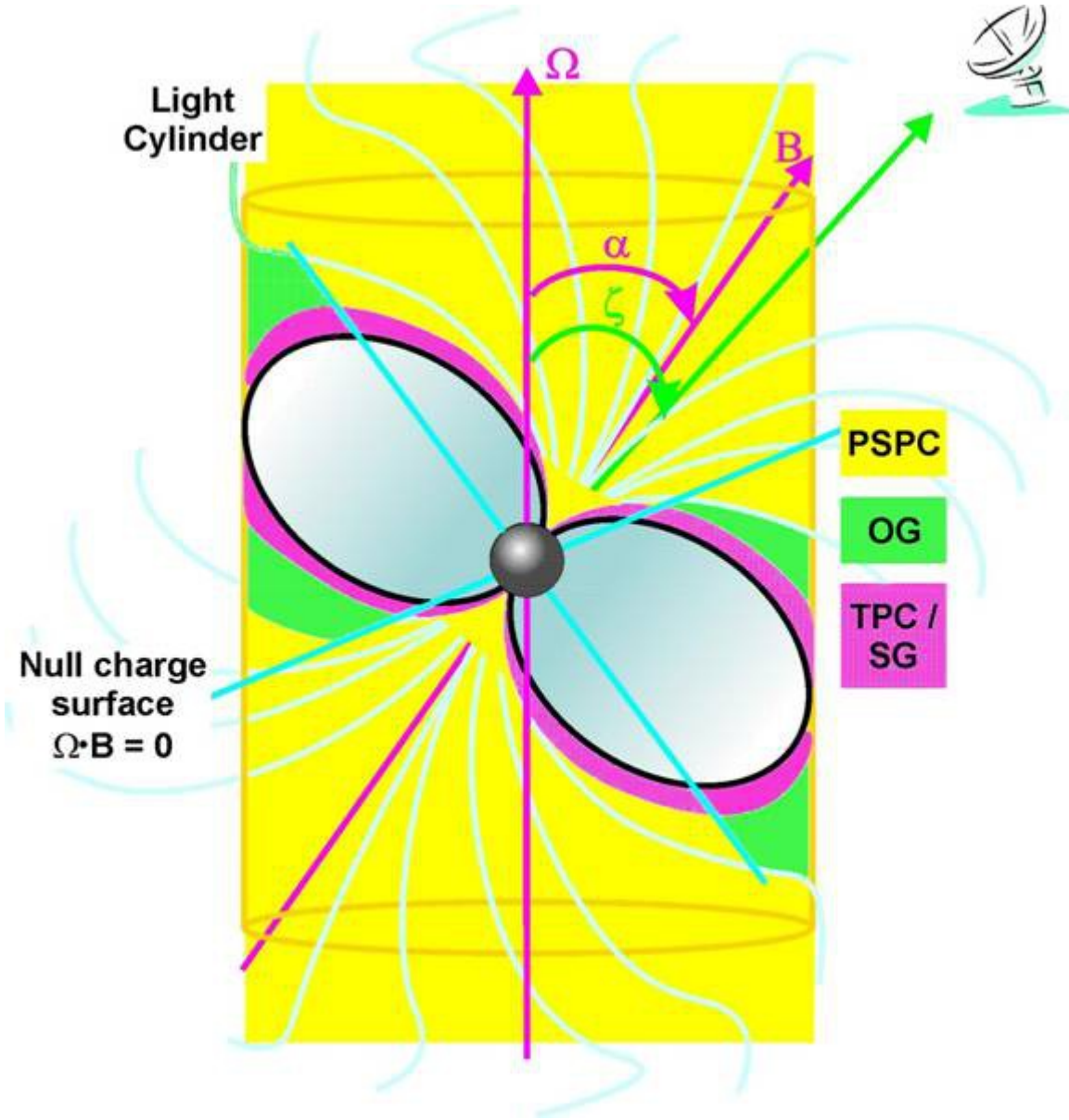


Fig. 1 Venter+ (2009)

Emission Without Screening

Pair-starved polar cap – accelerating field unscreened over open volume, particle acceleration and gamma-ray production possible over larger region (e.g., Harding+ 2005)

Suggests broad peaks, slightly leading radio pulse in phase.



Pulsar Luminosity

Outer-magnetospheric models,
$L_\gamma \star w_{gap} \star \Delta V \star \dot{E}^{1/2}$

distance

luminosity:

$$L_\gamma = 4\pi f_\Omega G d^2$$

beaming factor

efficiency: gamma-ray energy flux

$$\eta_\gamma = \frac{L_\gamma}{\dot{E}}$$

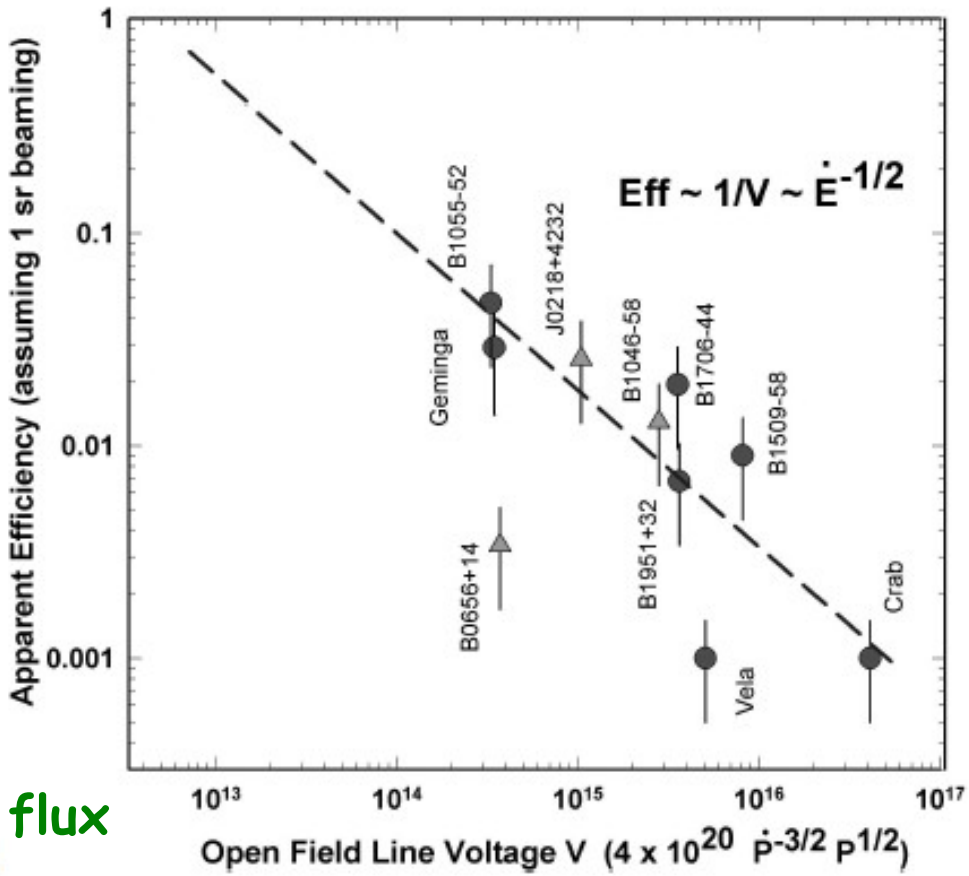


Figure 10. Calculated pulsed high-energy (X-ray and gamma ray) efficiencies of the known and candidate gamma-ray pulsars, as a function of the open field line voltage. Circles: high-confidence gamma-ray pulsars. Triangles: lower-confidence gamma-ray pulsars.

Thompson (2008)

Pulsar Questions for *Fermi*

Are there more radio-quiet pulsars?

- And can we find them?

How many unassociated *EGRET* sources are pulsars?

- Several radio pulsars discovered in *EGRET* error circles
- could not extrapolate timing back and confirm associations

Does the emission come from near the surface or the light cylinder?

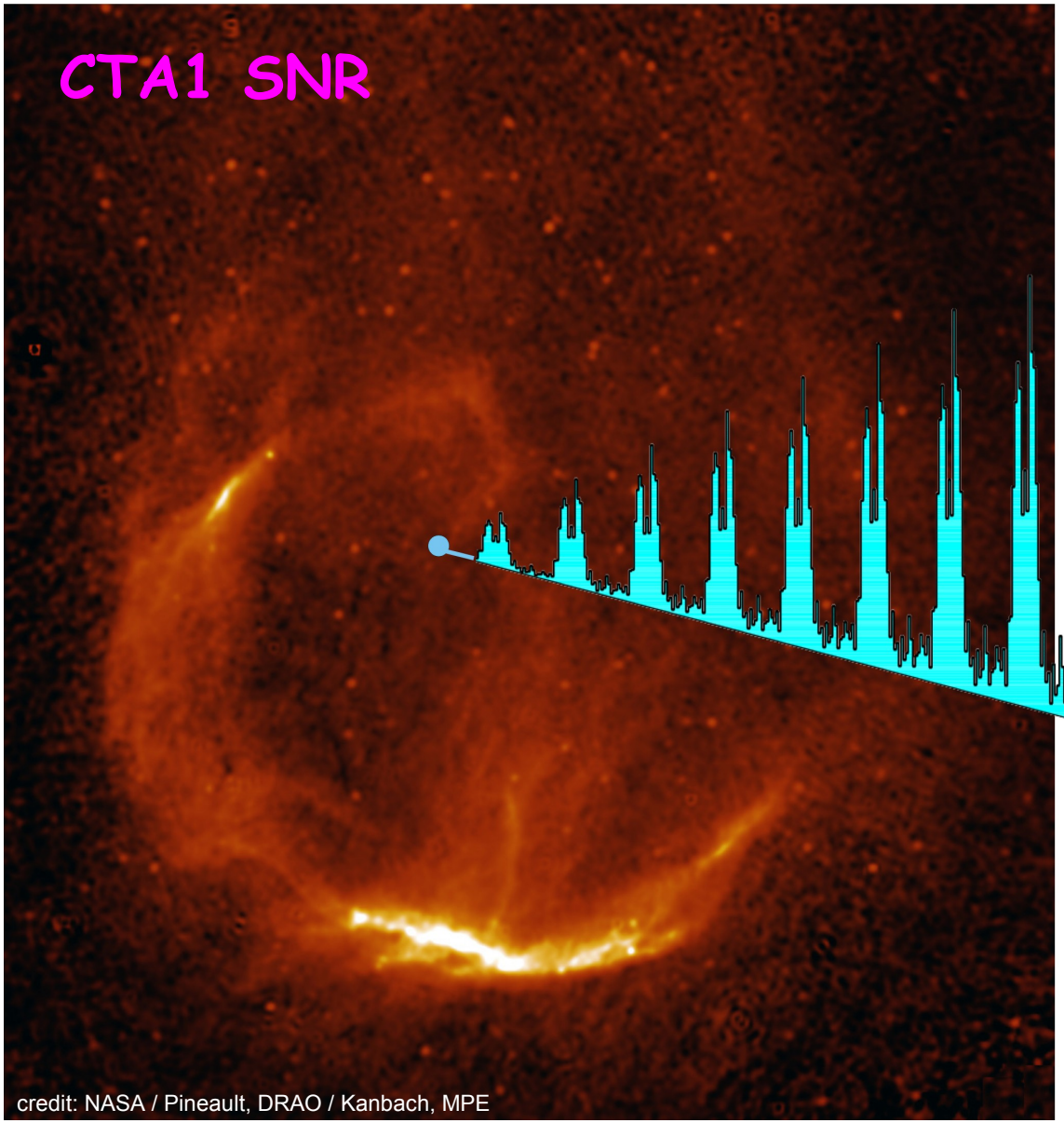
Are there gamma-ray MSPs?

- Possible detection of MSP J0218+4232 with *EGRET*

How does the gamma-ray luminosity behave at lower Ė?

EARLY LAT PULSAR SCIENCE

We Have a Pulse



~12 days into early calibrations, detection of pulse period in gamma rays.
Associated with 3EG J0010+7309.

P = 316.86 ms
P = 3.614 10^{-13} s s^{-1}

PSR J0007+7303

1420 MHz Radio Map:
Pineault et al., A&A **324**, 1152 (1997)

Gamma-ray pulsar:
Abdo et al., Science Express, 16 Oct. 2008

It's Out There Man

Vela Pulsar:
Calibration pointing-mode and early sky-survey data

$E_C = 2.86 \pm 0.09$ GeV

$\Gamma = 1.51 \pm 0.01$

b = 2 excluded at 16.5σ

More pulsars detected, similar result...near-surface emission ruled out as dominant gamma-ray emission site.

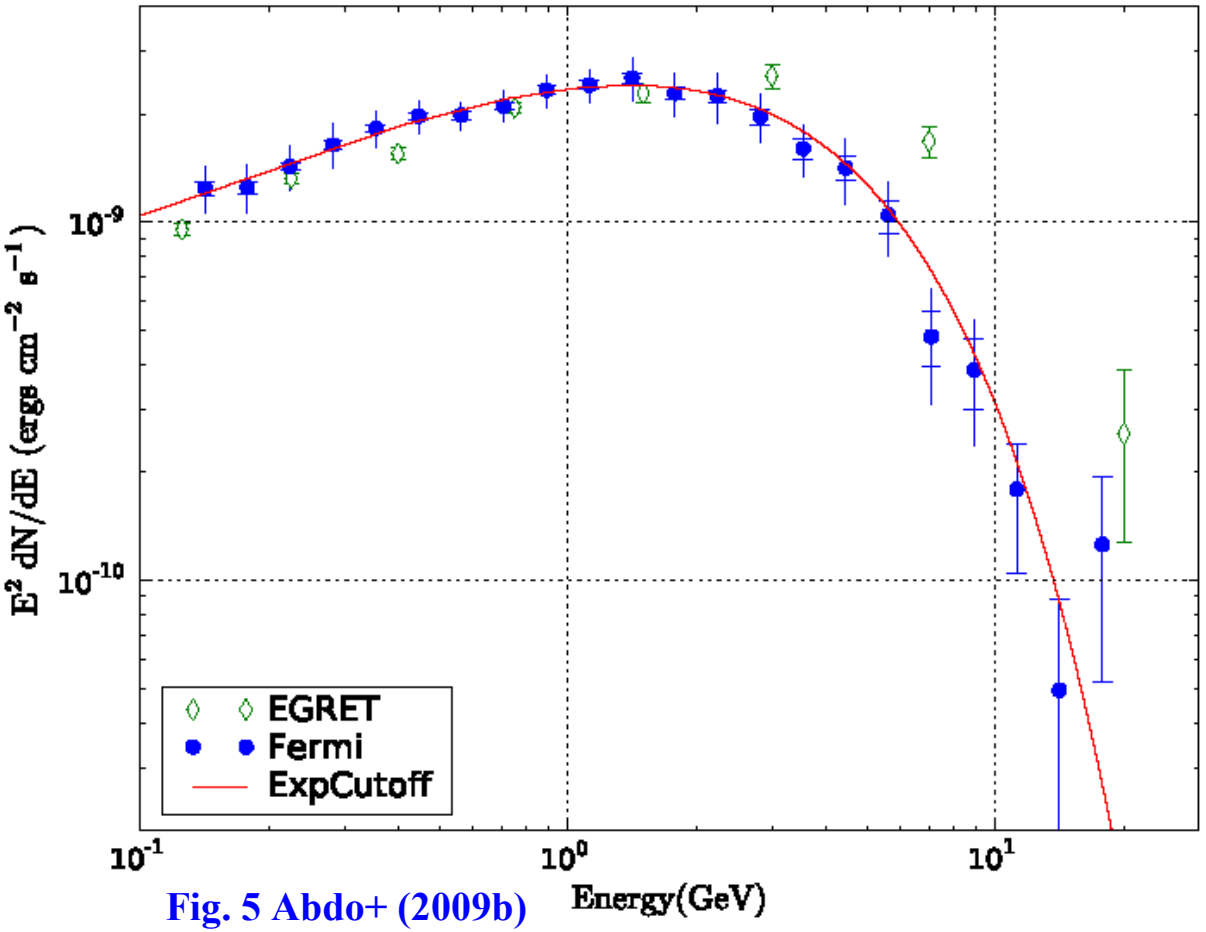
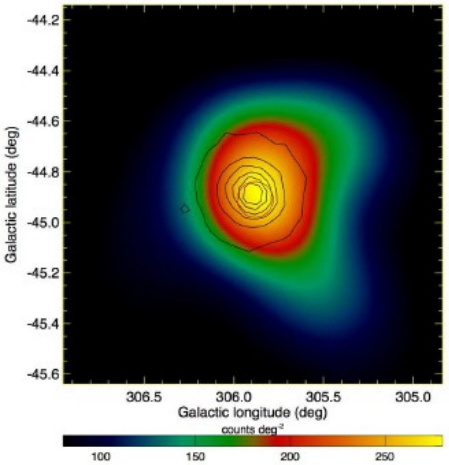
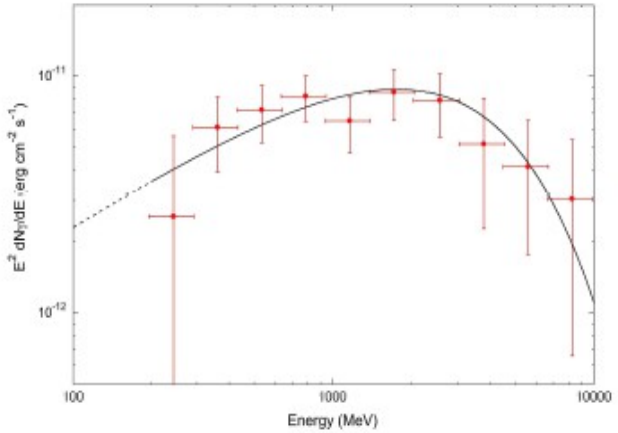


Fig. 5 Abdo+ (2009b)

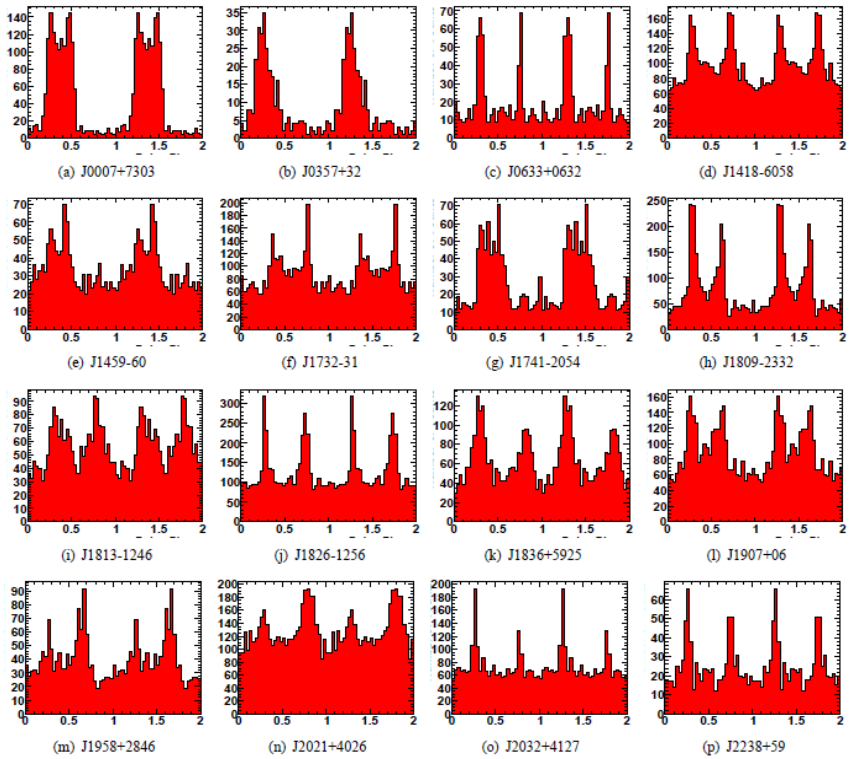
They're Everywhere



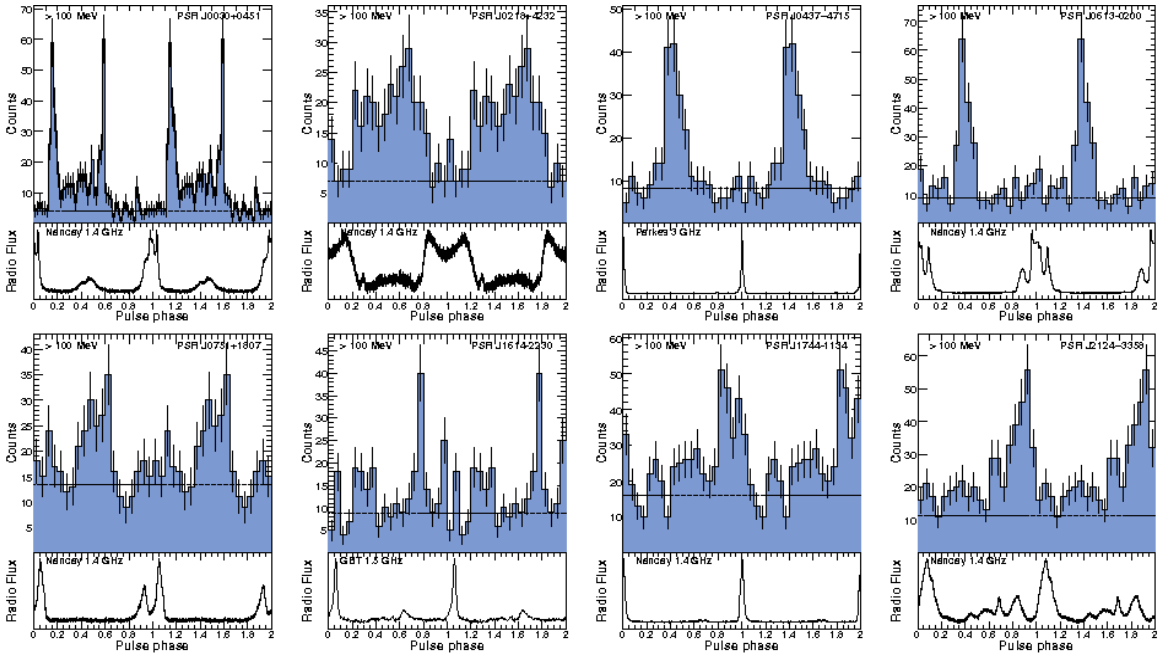
Globular cluster 47 Tucanae,
23 known MSPs
pulsar-like gamma-ray spectrum



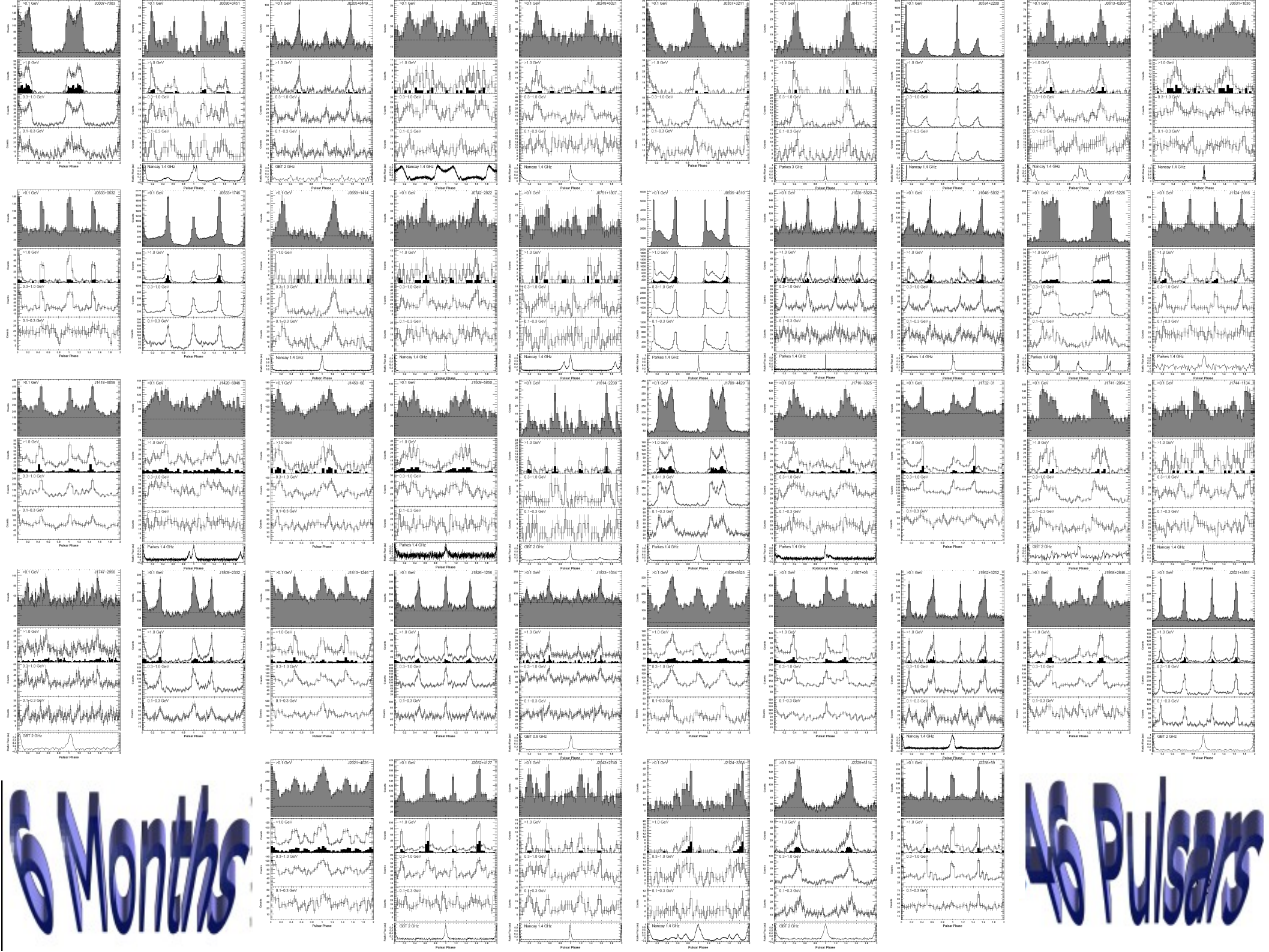
16 blind search pulsars, all young



8 MSPs



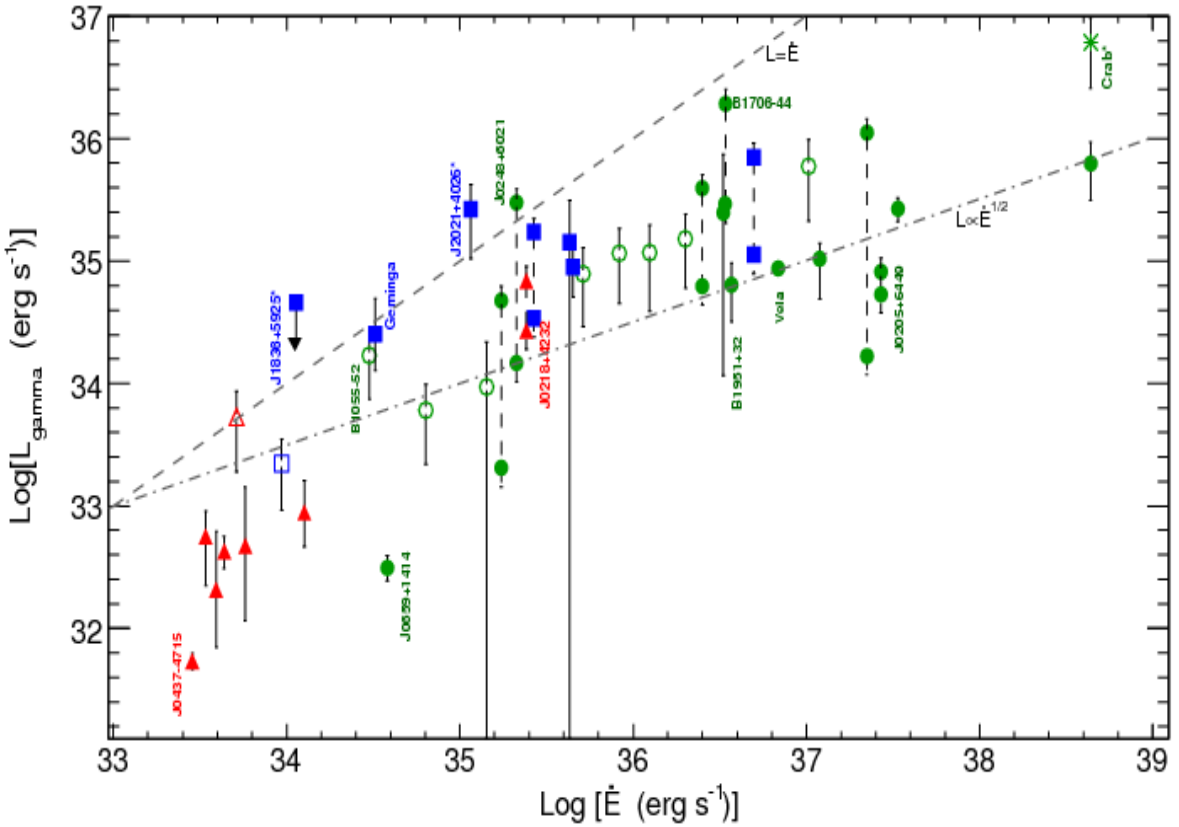
Abdo+ (2009d,e,f)

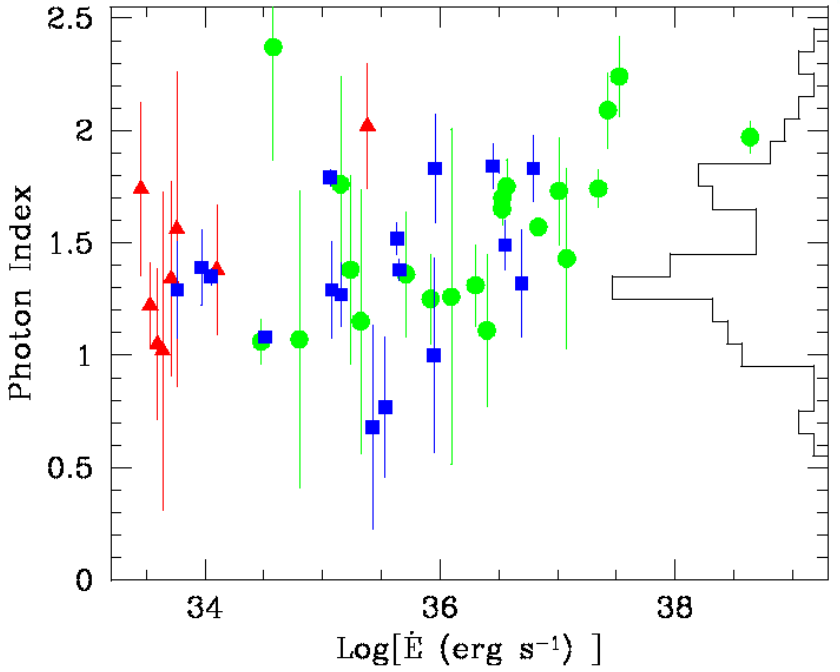

6 Months
46 Pulsars

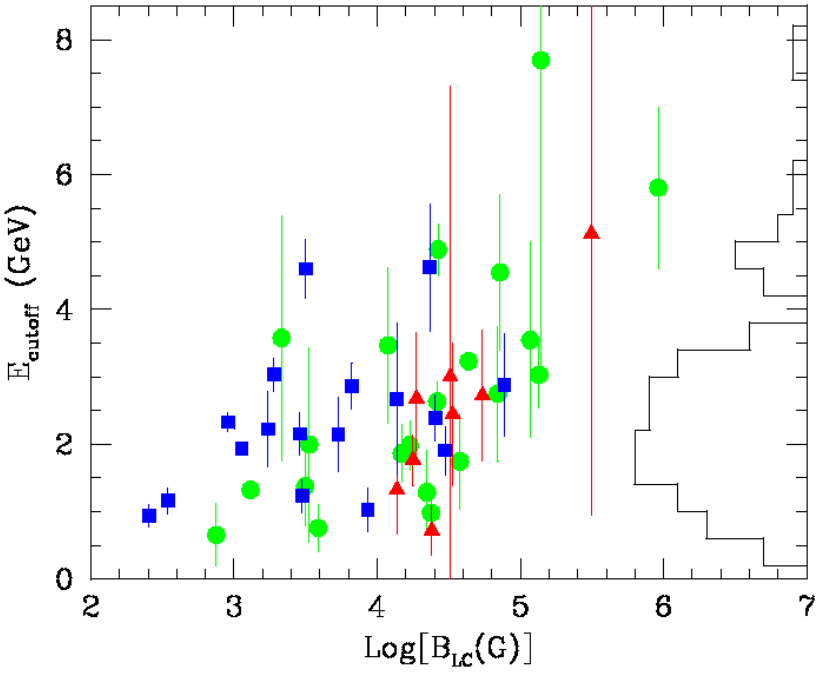
The First LAT PSR Catalog

1PC – Abdo+ 2010b

All pulsars with pulsed detections ≥5σ in first 6 months of sky survey







If it looks like a pulsar...

...it might be a pulsar!

Successful discovery of non-recycled pulsars in *EGRET* error circles, find more with LAT?

PSR J1028-5819

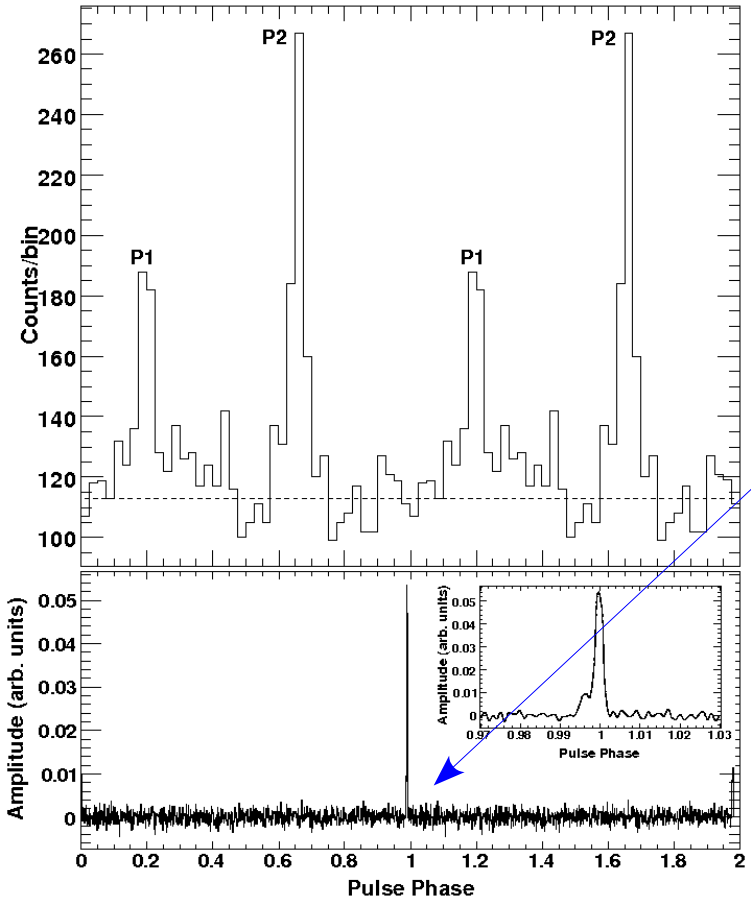


Fig. 1 Abdo+ (2009a)

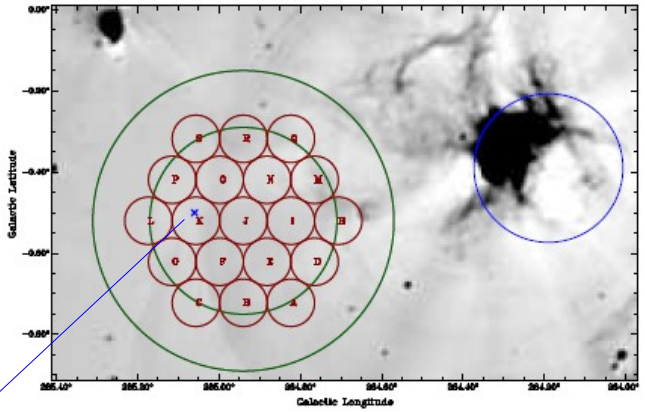


Fig. 1 Keith+ (2008)

PSR J2021+3651

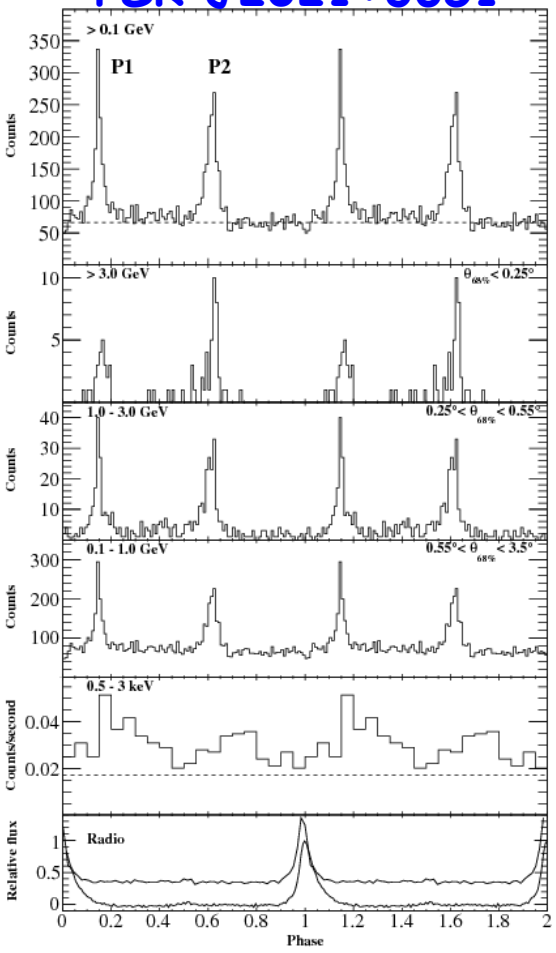
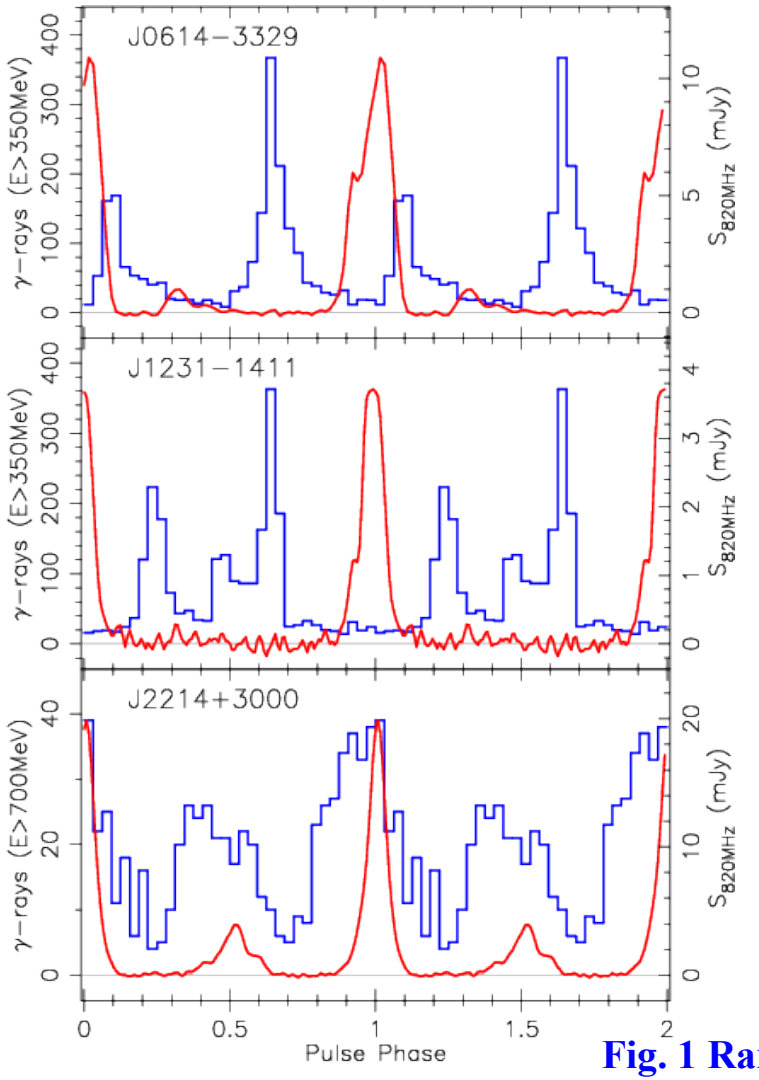


Fig. 1 Abdo+ (2009g), pulsar discovered by Roberts+ (2002) associated with dragonfly nebula

If it looks like a pulsar...



Big surprise, found a few non-recycled pulsars but quickly found several, bright MSPs

Fig. 1 Ransom+ (2011)

NEW QUESTIONS

MSP #9

PSR J0034-0534

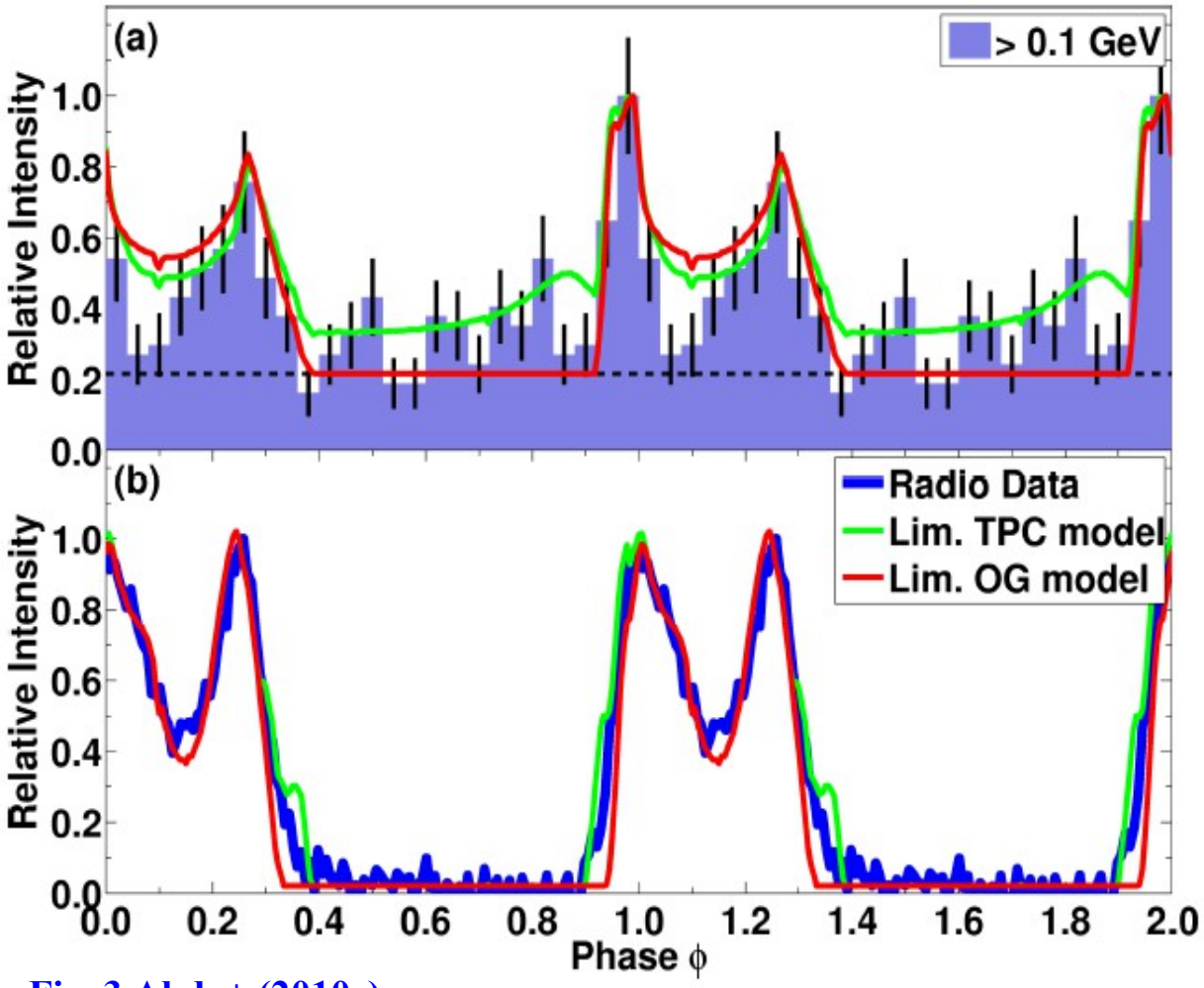


Fig. 3 Abdo+ (2010c)

1.9 ms spin period

$B_{LC} = 9.9 \times 10^4$ G

(higher than most pulsars in 1PC)

Gamma-ray and radio peaks aligned in phase

only seen in the Crab previously

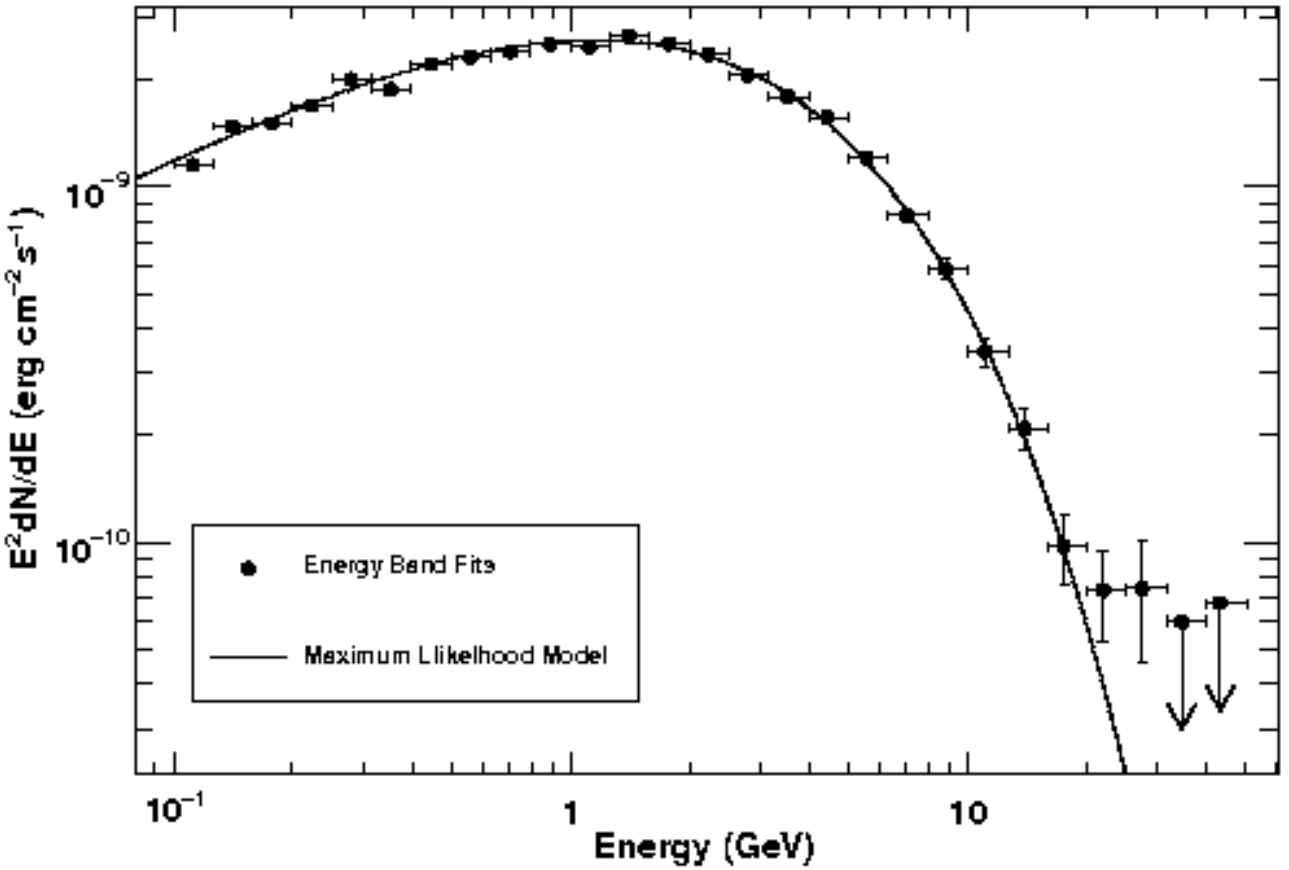
co-located emission regions

radio emission region extended in altitude

Now have 6 such MSPs

Changing Viewpoints

The Vela pulsar after 11 months, Abdo+ (2010d)



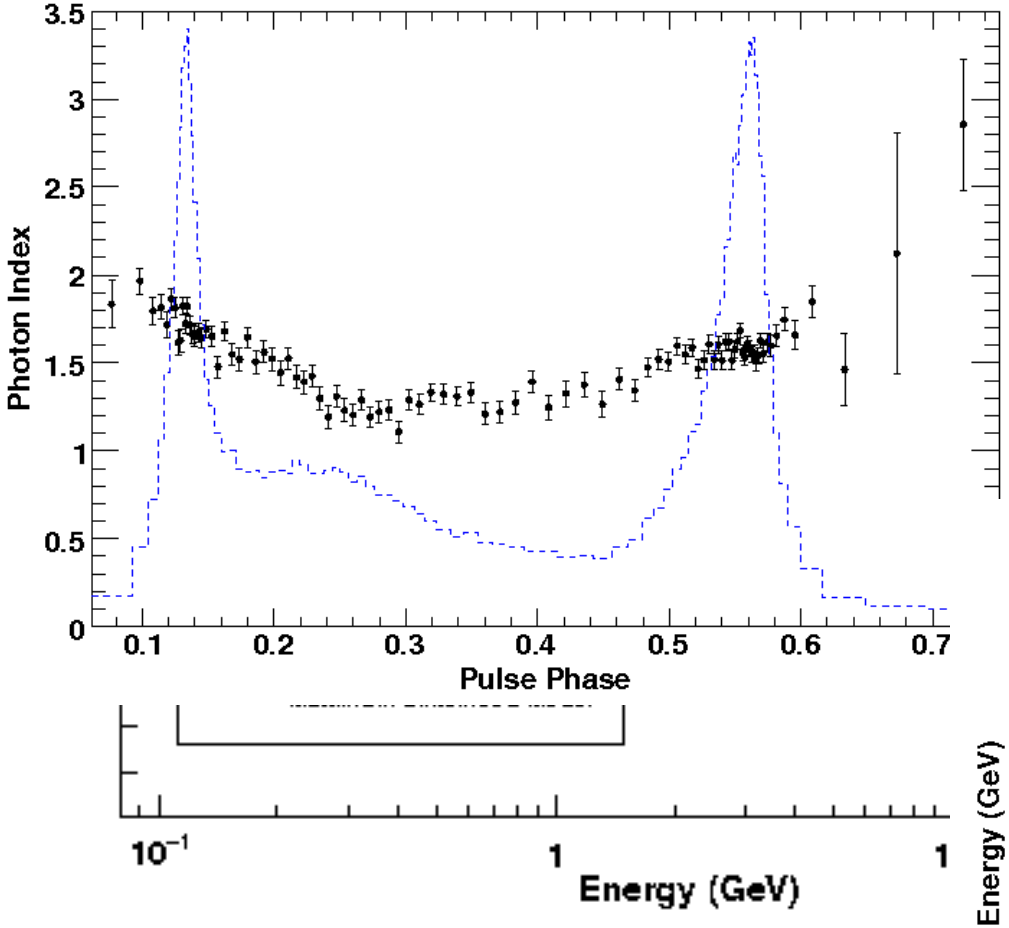
Best-fit spectrum has b<1 not physical

superposition of spectra with varying E_C and Γ.

Could also mean emission isn't curvature radiation...

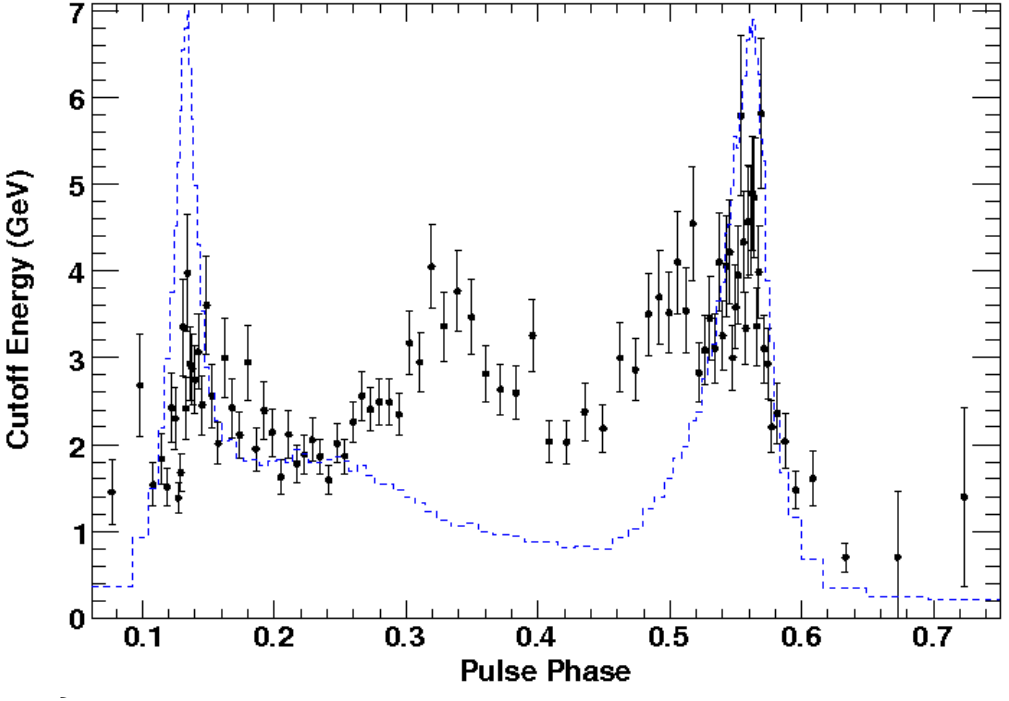
Changing Viewpoints

The Vela pulsar after 11 months, Abdo+ (2010d)



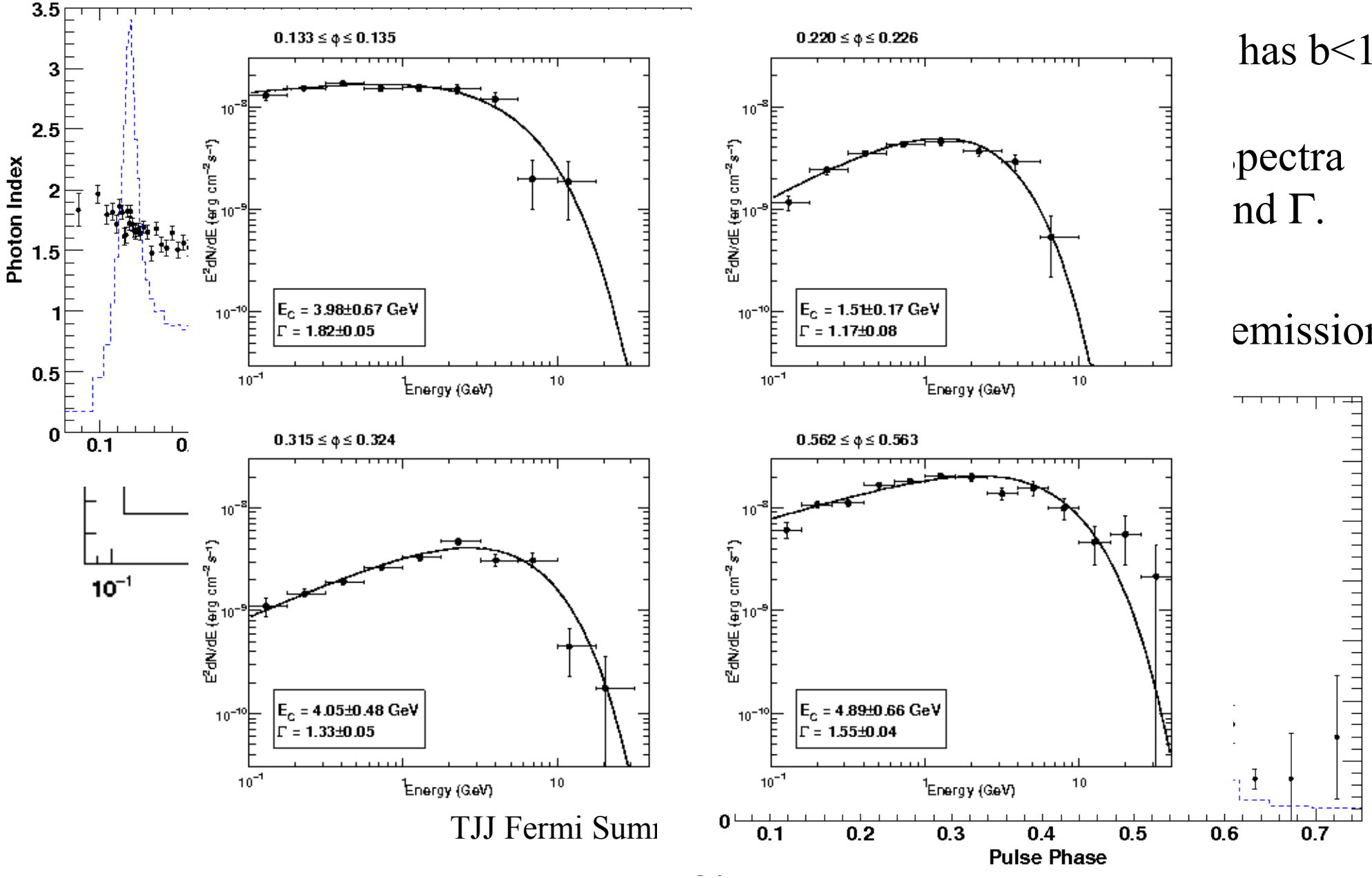
Best-fit spectrum has b<1
not physical
superposition of spectra
with varying E_C and Γ.

Could also mean emission



Changing Viewpoints

The Vela pulsar after 11 months, Abdo+ (2010d)



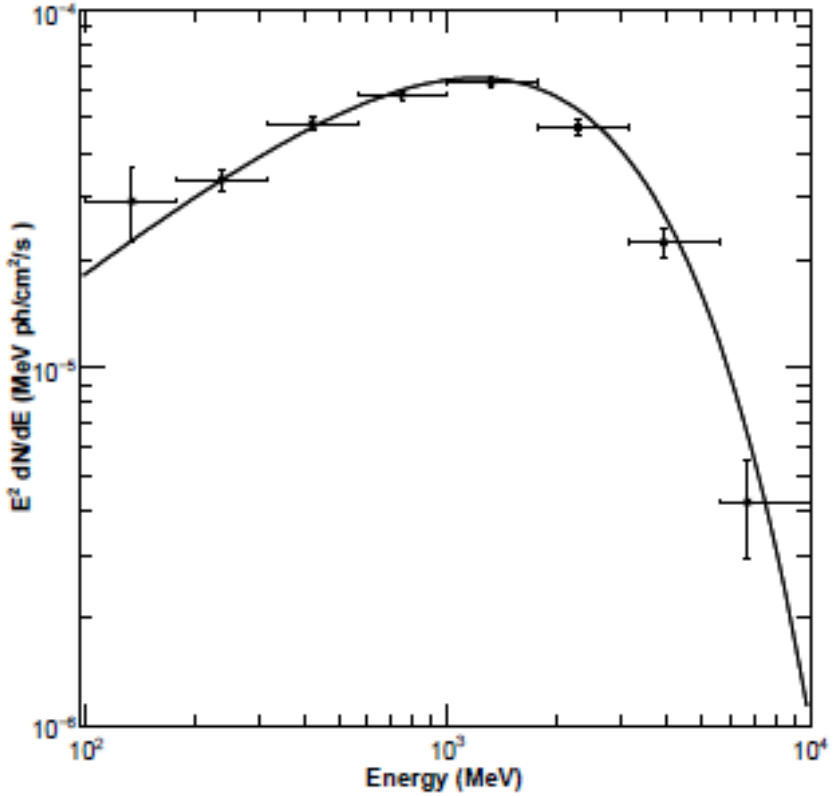
has b<1

pectra
nd Γ.

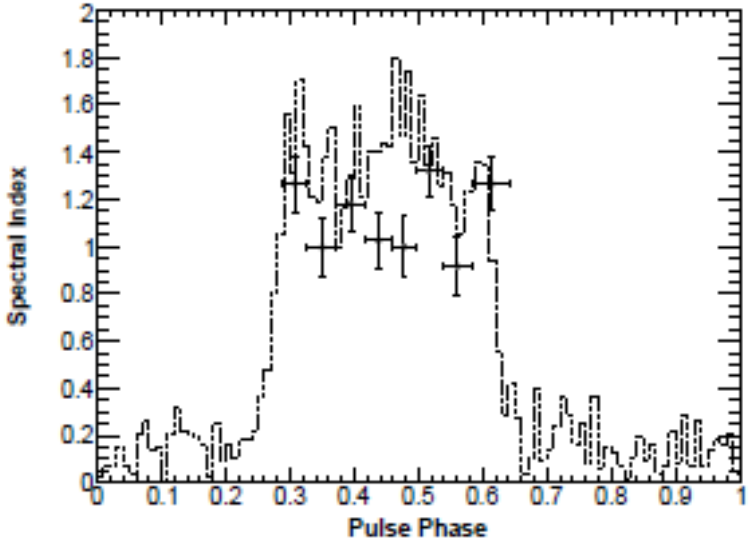
emission

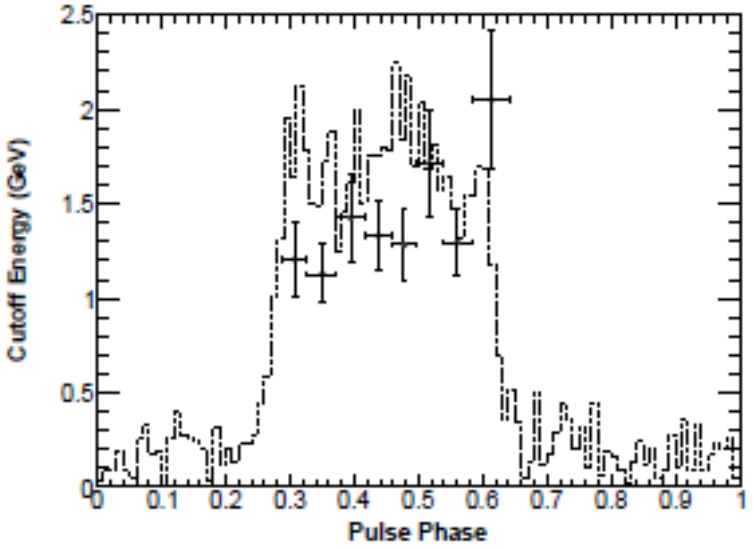
A Boring Viewpoint

PSR J1057-5226



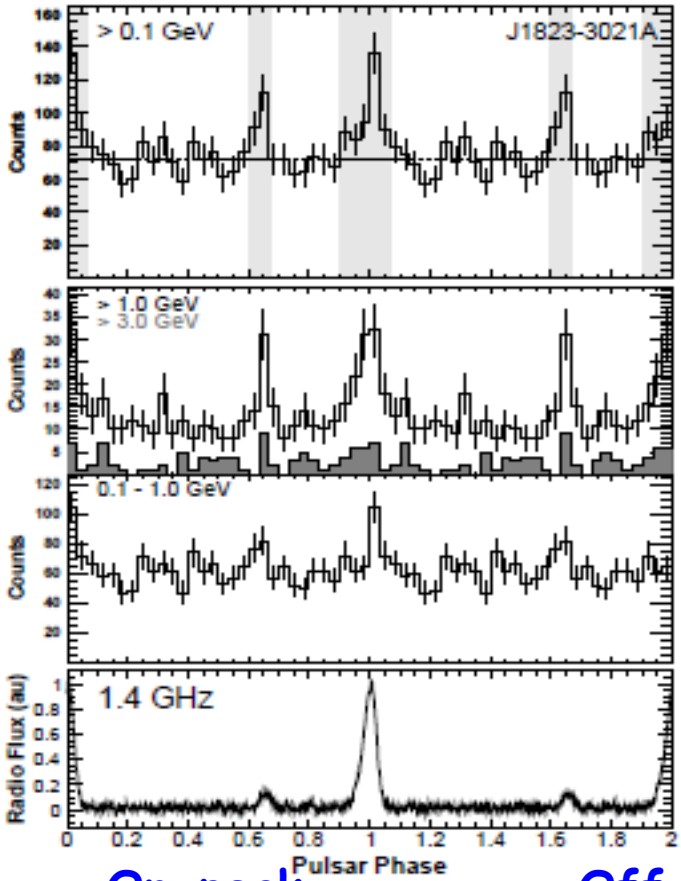
Abdo+ (2010e), phase-resolved spectroscopy of 3 bright pulsars.





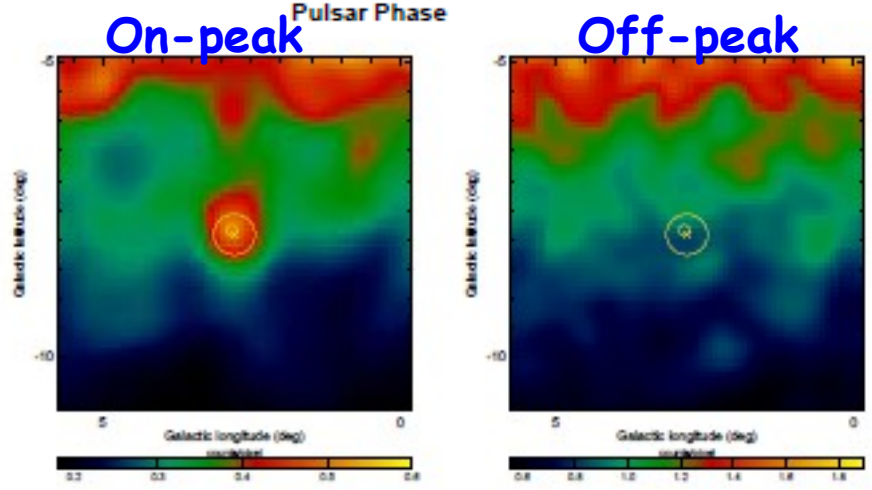
Viewing geometry such that similar regions of magnetosphere viewed across pulse?

Cluster Divas

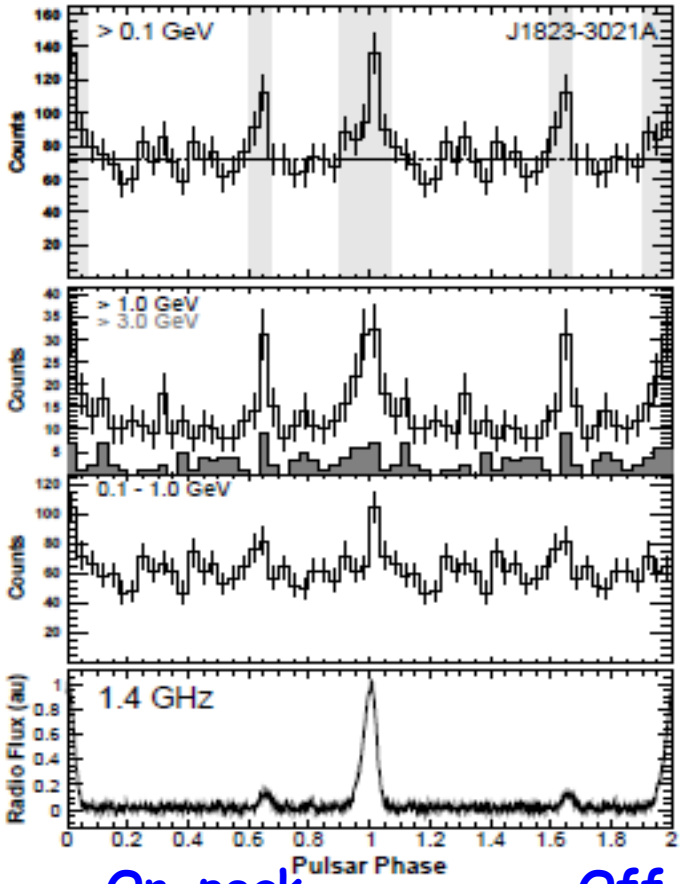


Freire+ (2011), luminous MSP in globular cluster NGC 6624, d = 8.4 kpc

Accounts for all LAT emission.



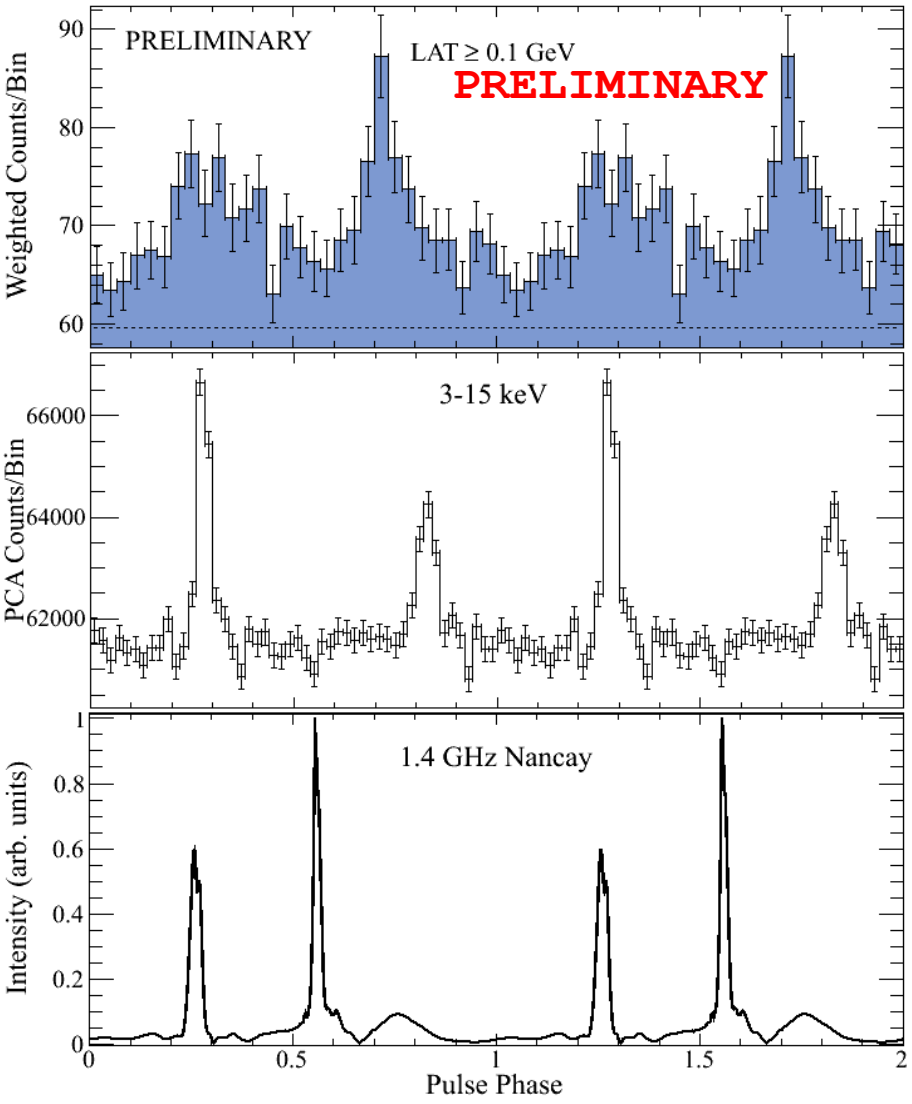
Cluster Divas

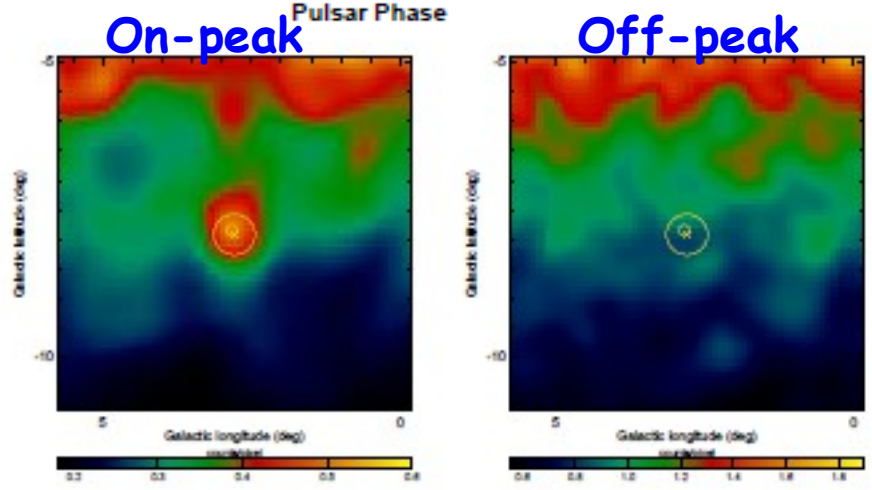


Freire-

globul

Accou





Johnson+ (*in prep*) PSR B1821-24 in M28.
Doesn't account for all LAT emission.

Trouble with...MSPs

>43 radio MSPs discovered in unassociated LAT sources
gamma-ray pulsations from >20
~15 are “black widow” or “redback” systems

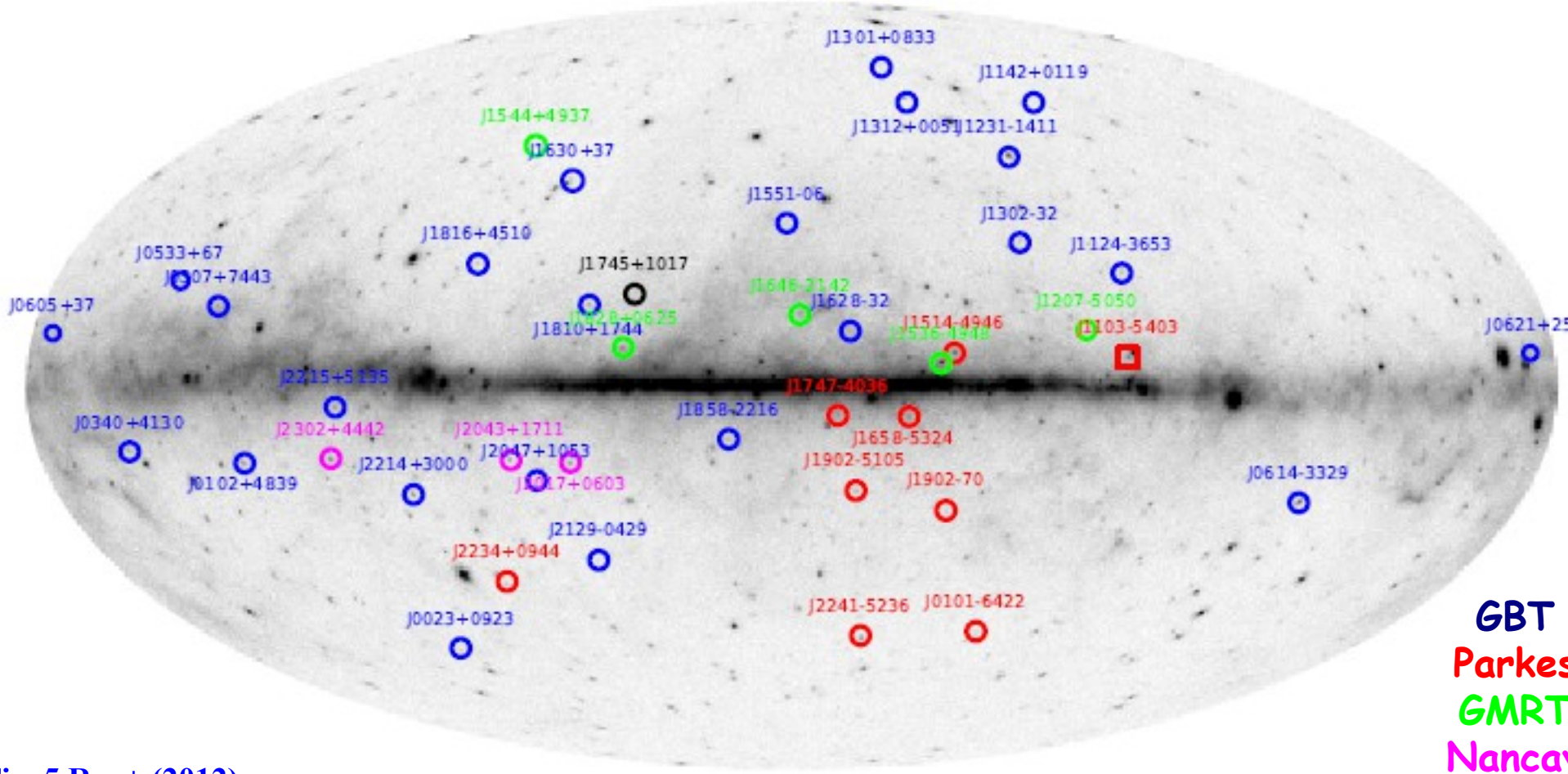
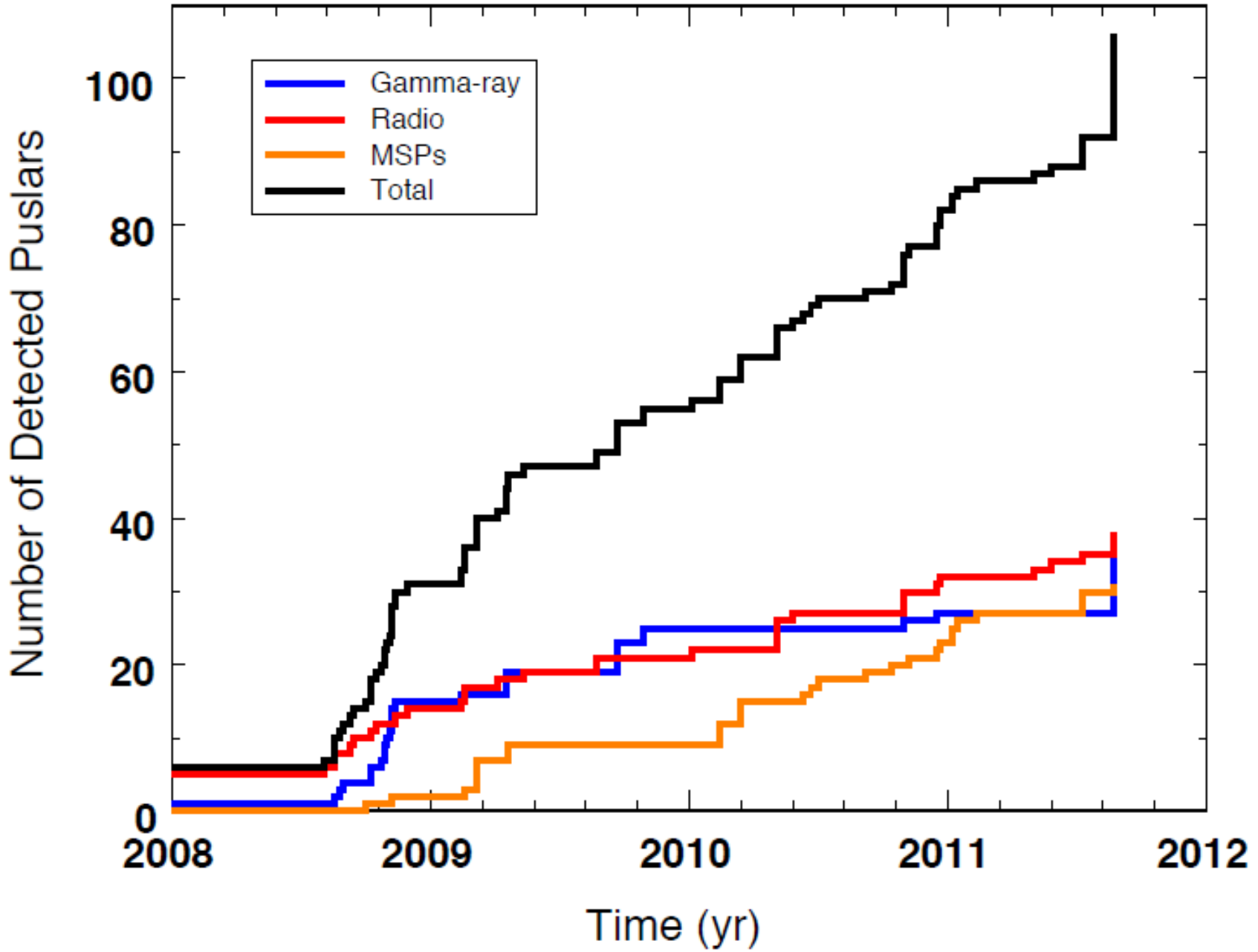


Fig. 5 Ray+ (2012)

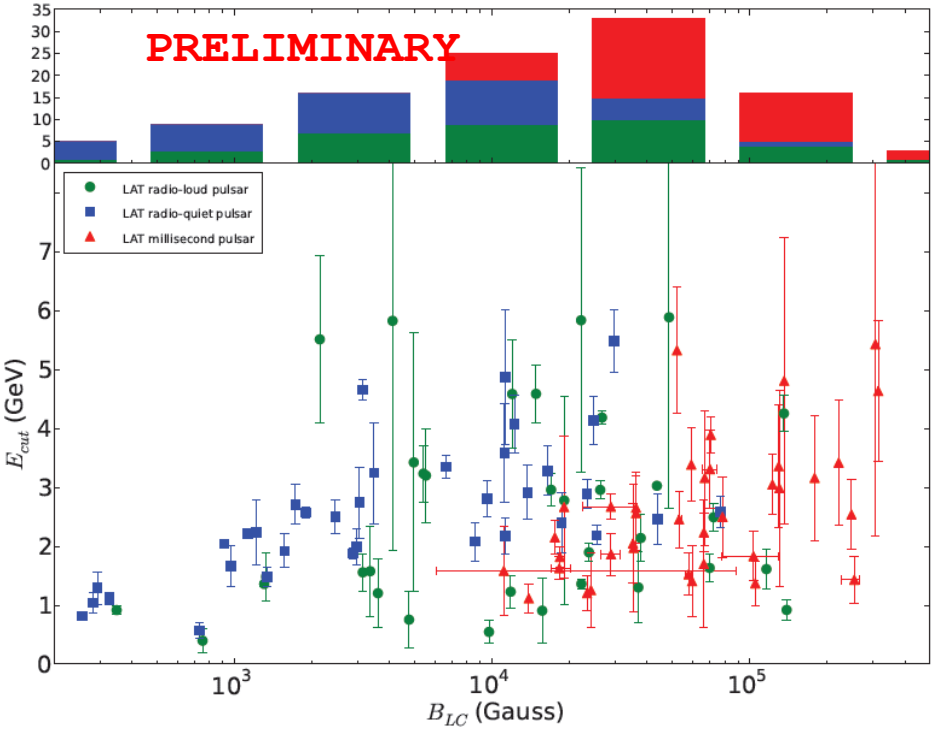
They Keep on Comin'

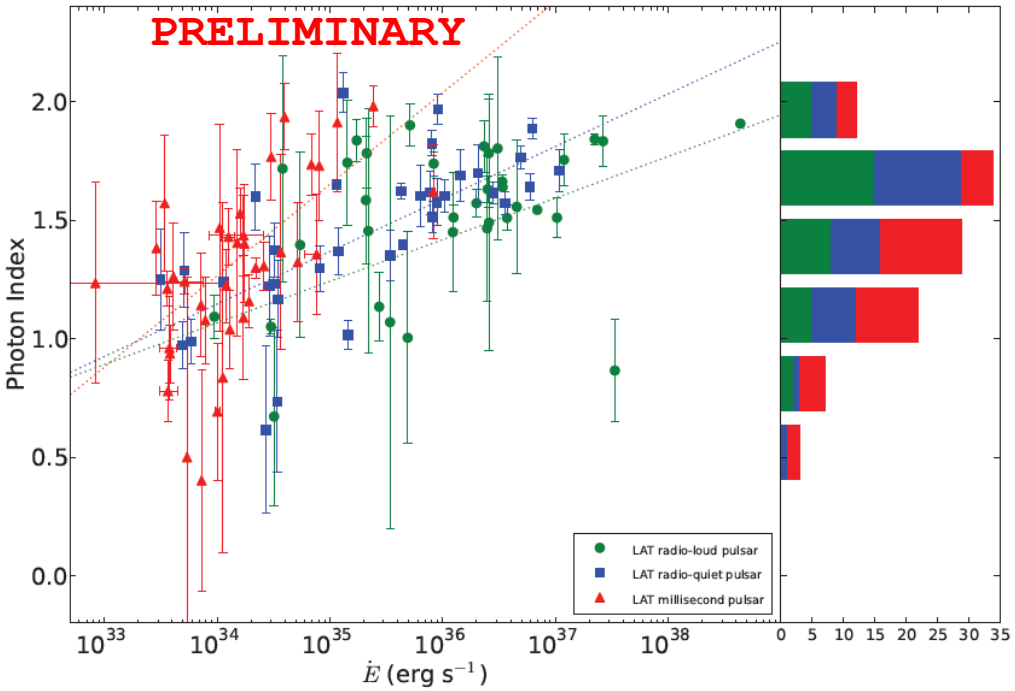


The Second LAT PSR Catalog

Abdo+ (*submitted*), arXiv:1305.4385; auxiliary files at
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2nd_PSR_catalog/

117 pulsars
- 77 young
  - 42 radio-loud
  - 35 radio-quiet
- 40 millisecond
  - 20 known before *Fermi*

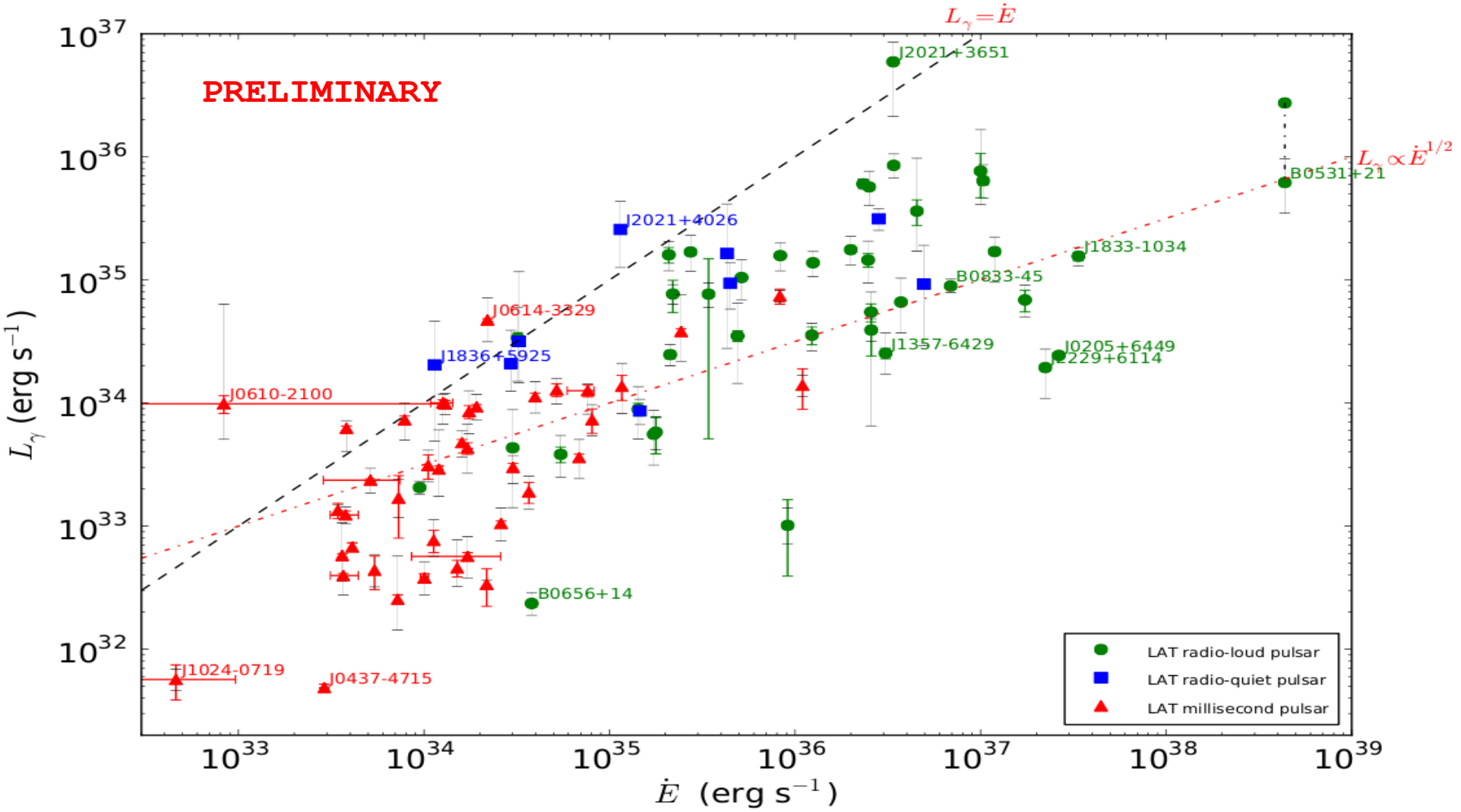




chool 3 June 2013

The Second LAT PSR Catalog

Abdo+ (*submitted*), arXiv:1305.4385; auxiliary files at
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2nd_PSR_catalog/



Blind Search MSPs?

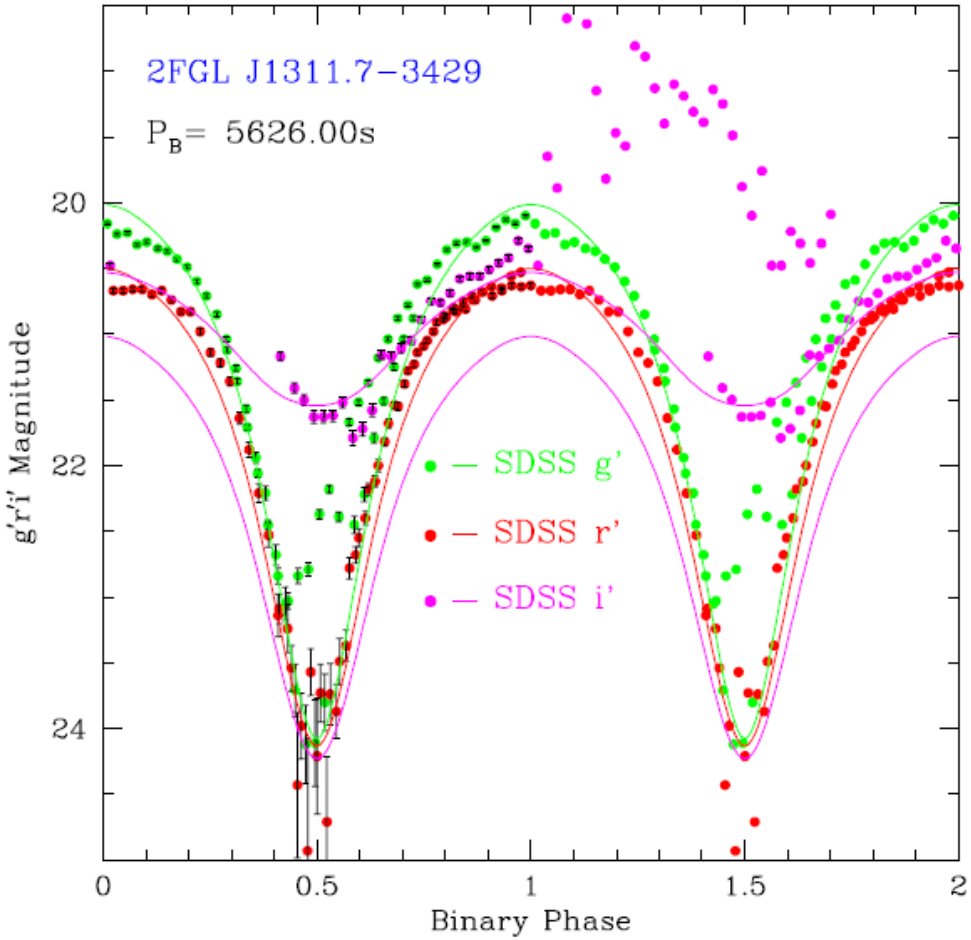


Fig. 3 Romani (2012)

Bright unassociated source
pulsar-like characteristics
Radio searches for pulsations come empty

93 minute orbital period identified with X-ray and optical observations
Black widow MSP?

Blind Search MSPs?

Use supercomputers and slick detection optimization algorithm
Detect 2.5ms pulsations in LAT data!

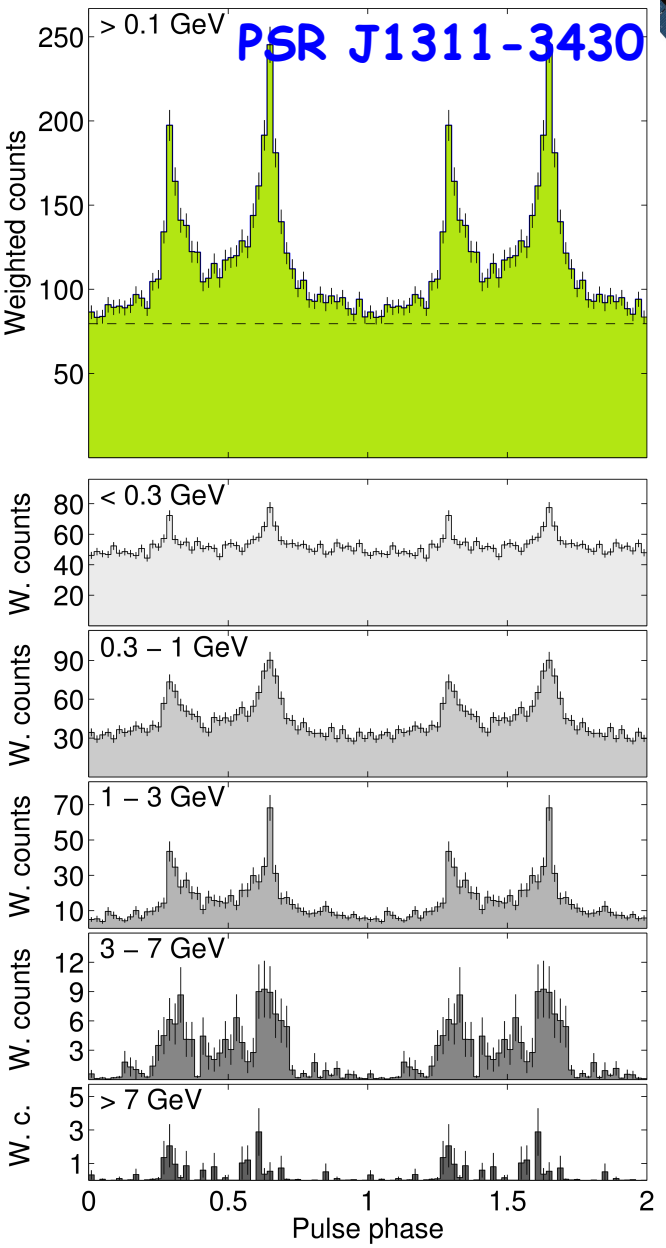


Fig. 1b Pletsch+ (2012)

ch MSPs?

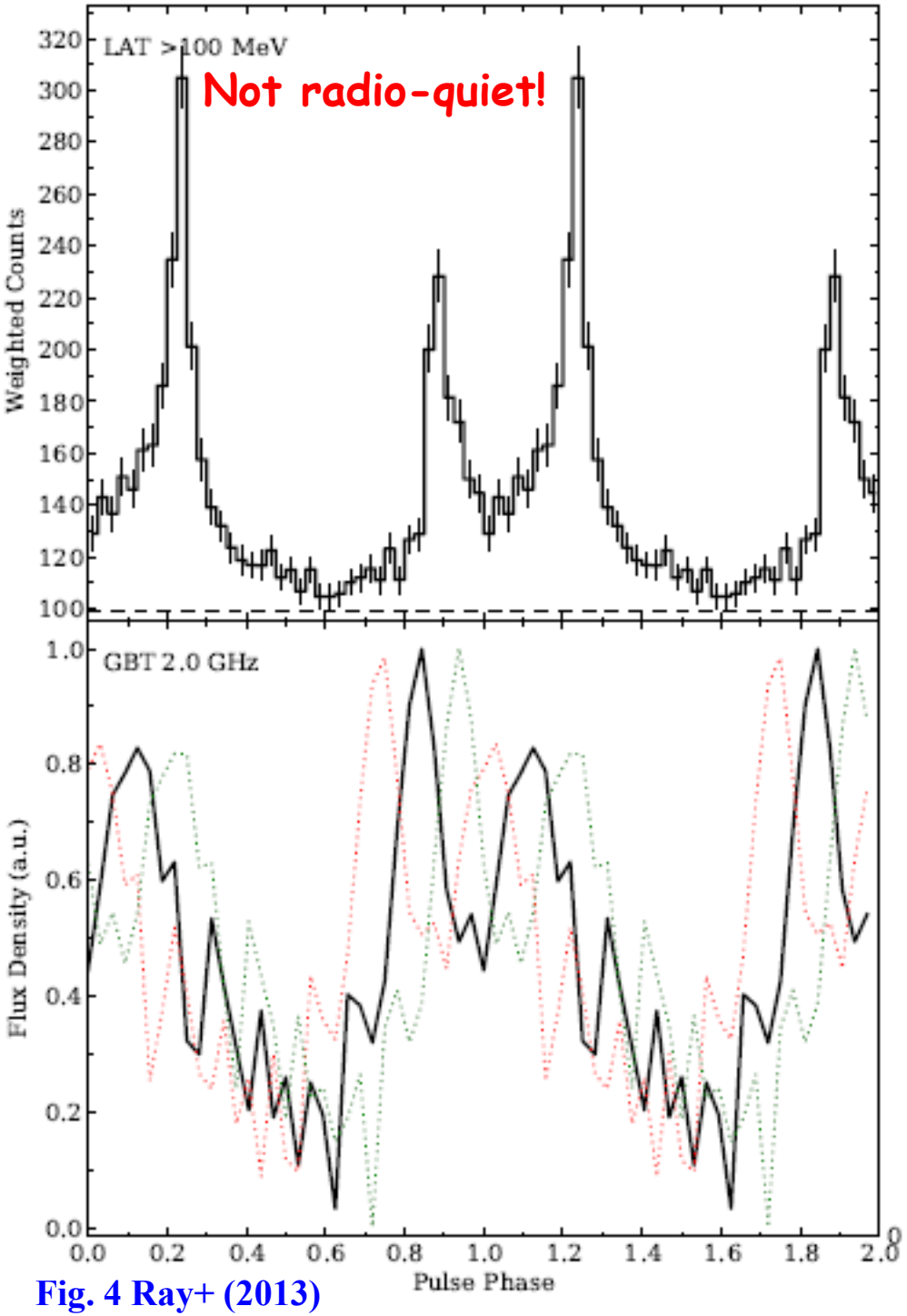


Fig. 4 Ray+ (2013)

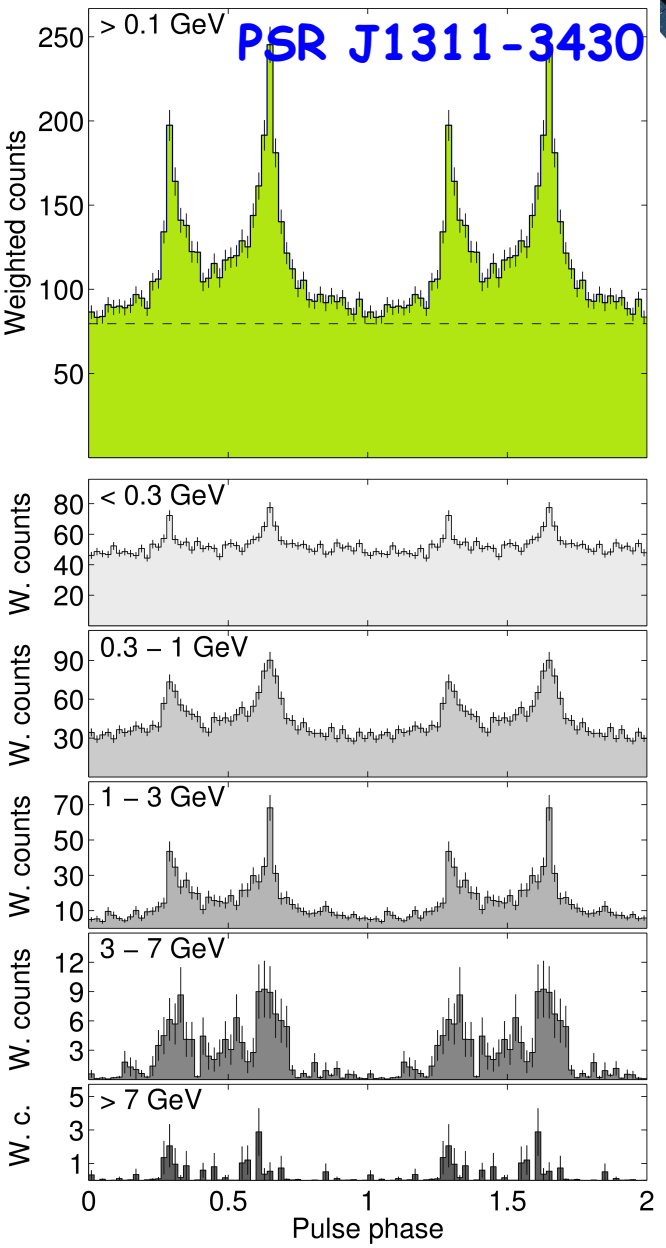


Fig. 1b Pletsch+ (2012)

Double Pulsar System

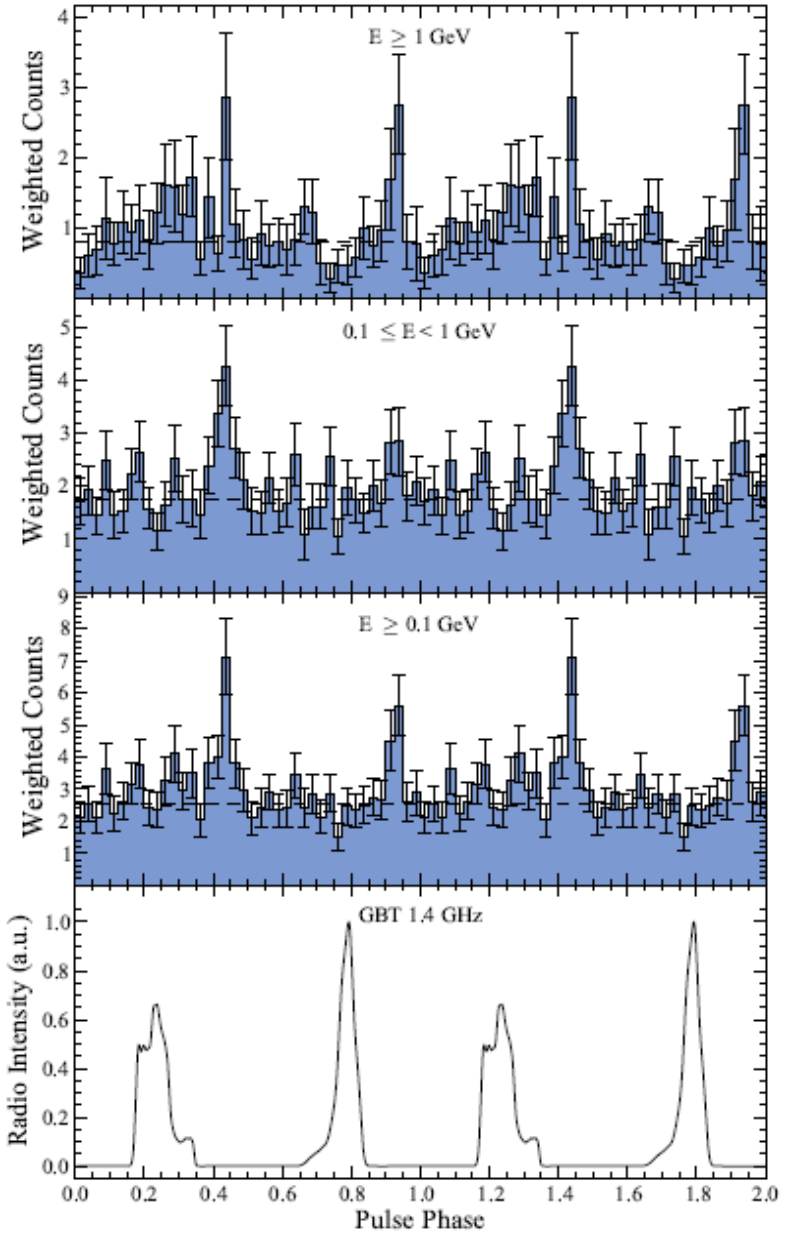


Fig. 1 Guillemot+ (2013)

PSR J0737-3039A/B:

- double neutron star binary (2.4 hr orbital period)
- radio pulsations have been detected from both A & B
- used to show general relativity correct to within 0.05% (McLaughlin, Aspen 2013)

PSR A is 22 ms:

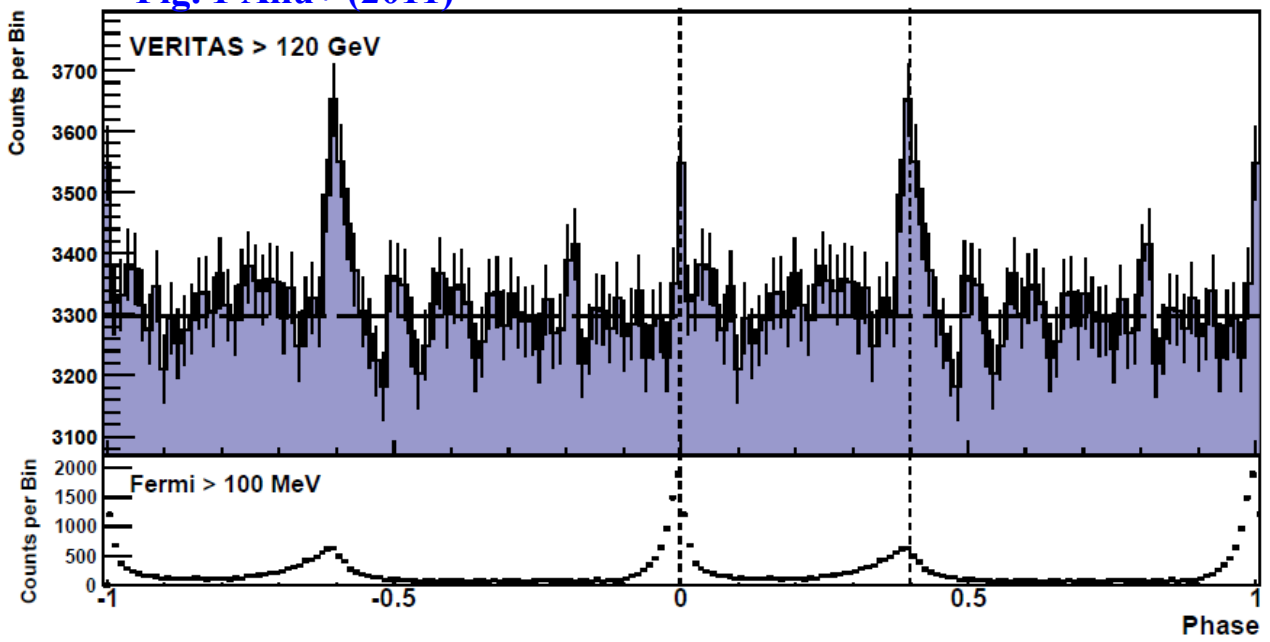
- partially recycled
- Ė makes it a gamma-ray pulsar candidate

Gamma-ray detection:

- light curve modeling and radio polarization fitting argue for orthogonal rotator viewed edge on
- Supports electron-capture supernova formation for PSR B

VHE Pulsations from the Crab

Fig. 1 Aliu+ (2011)

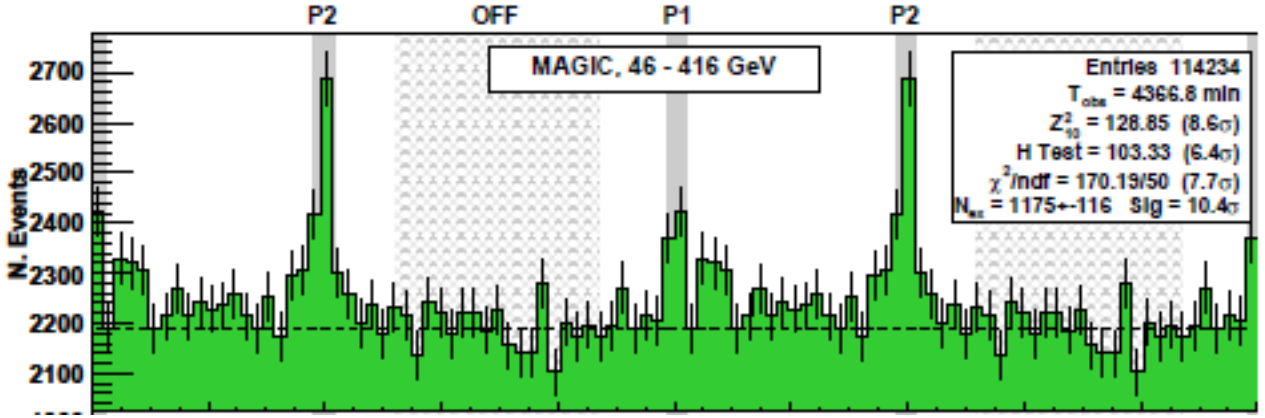


Pulsations detected out to ~400 GeV

Curvature radiation ruled out at these energies

Second component or not curvature?

Fig. 1 Aleksic+ (2012)



VHE Pulsations from the Crab

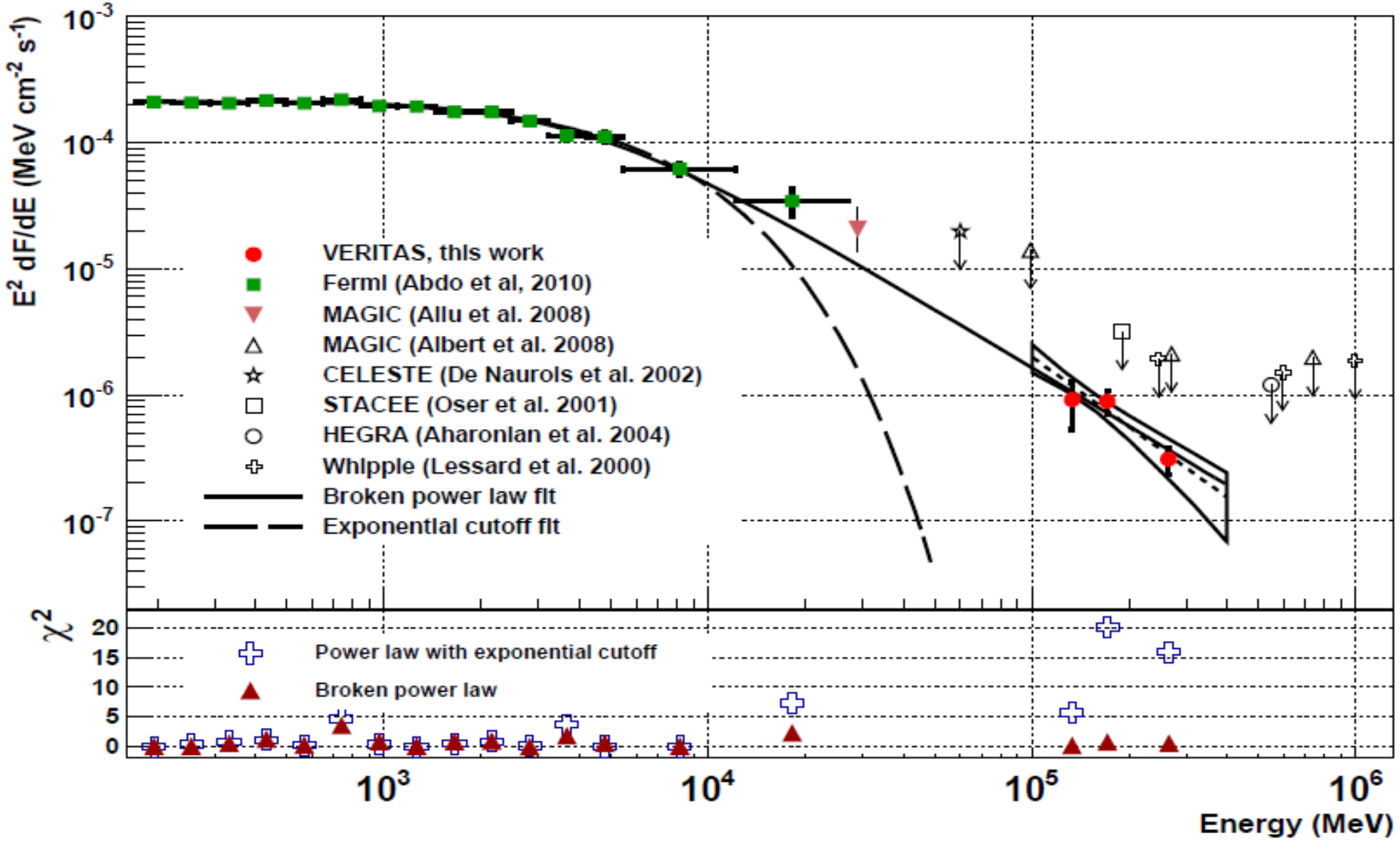


Fig. 2 Aliu+ (2011)

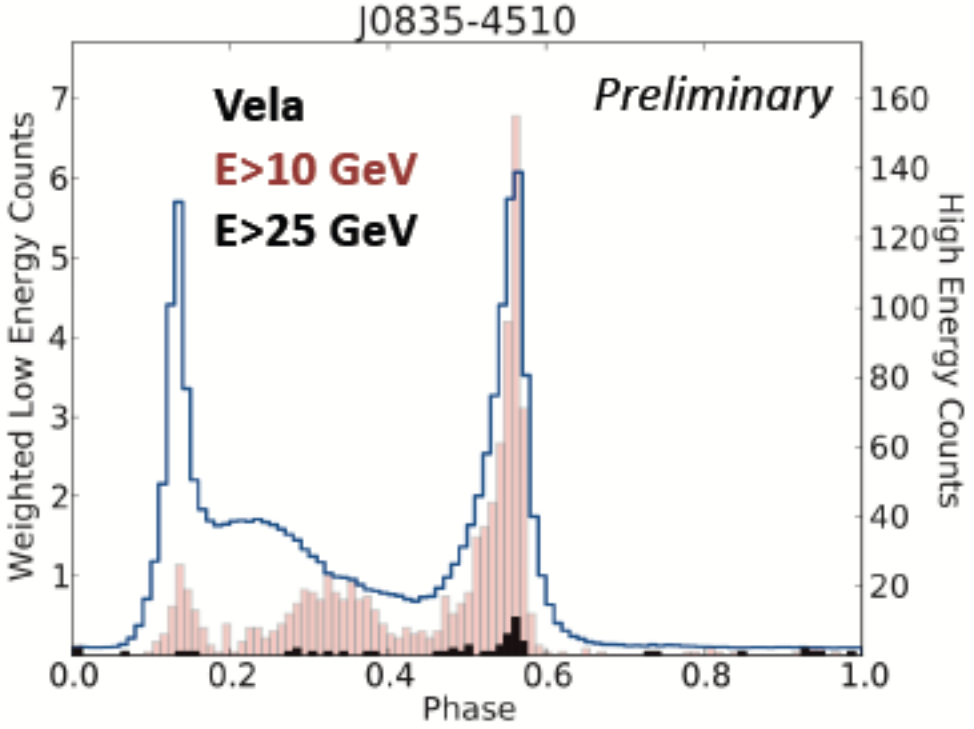
Hard Pulsars

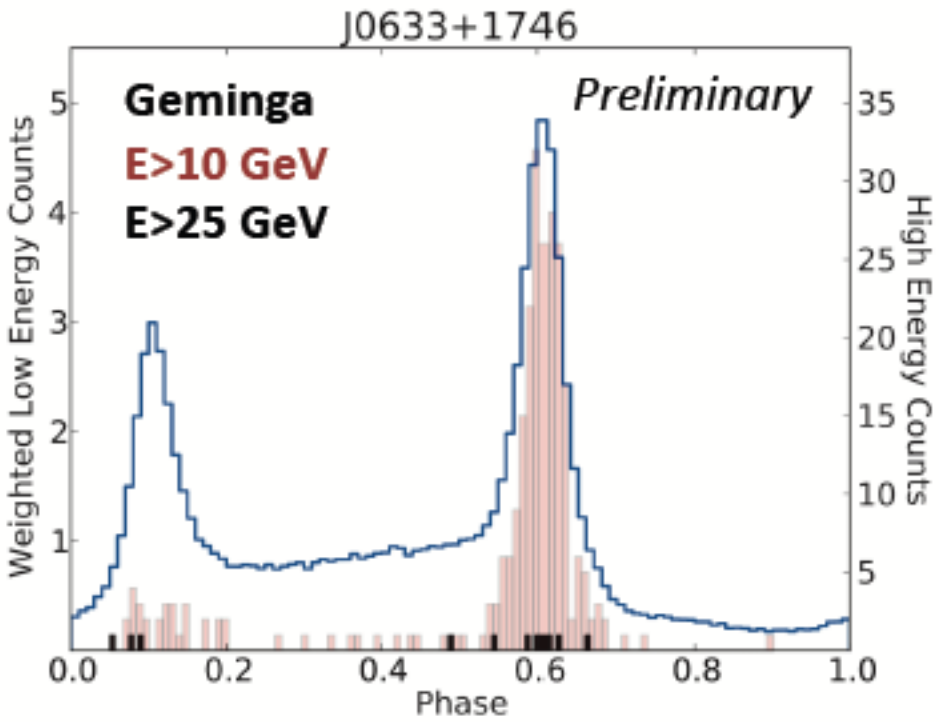
Difficult to predict what TeV telescopes will see from LAT data

1FHL catalog (*in prep*), 3 years, ≥10 GeV

Associations with 27 gamma-ray pulsars

≥10 GeV pulsations from >20





*Normalized weighted light curve (100 bins) in the 0.1-10 GeV range (blue) and un-weighted light curve above 10 GeV (pink) and above 25 GeV (**black**) (0.6 and 1.2 deg RoI were for used for Front and Back evts respectively)*

MSPs and Cosmic Rays

PAMELA, *Fermi*, AMS – rise in positron fraction

Local source

Dark Matter or Pulsars (Yuksel+ 2009; Profumo 2012)?

Most MSPs have narrow peaks

more screening (i.e., more pairs) than previously thought

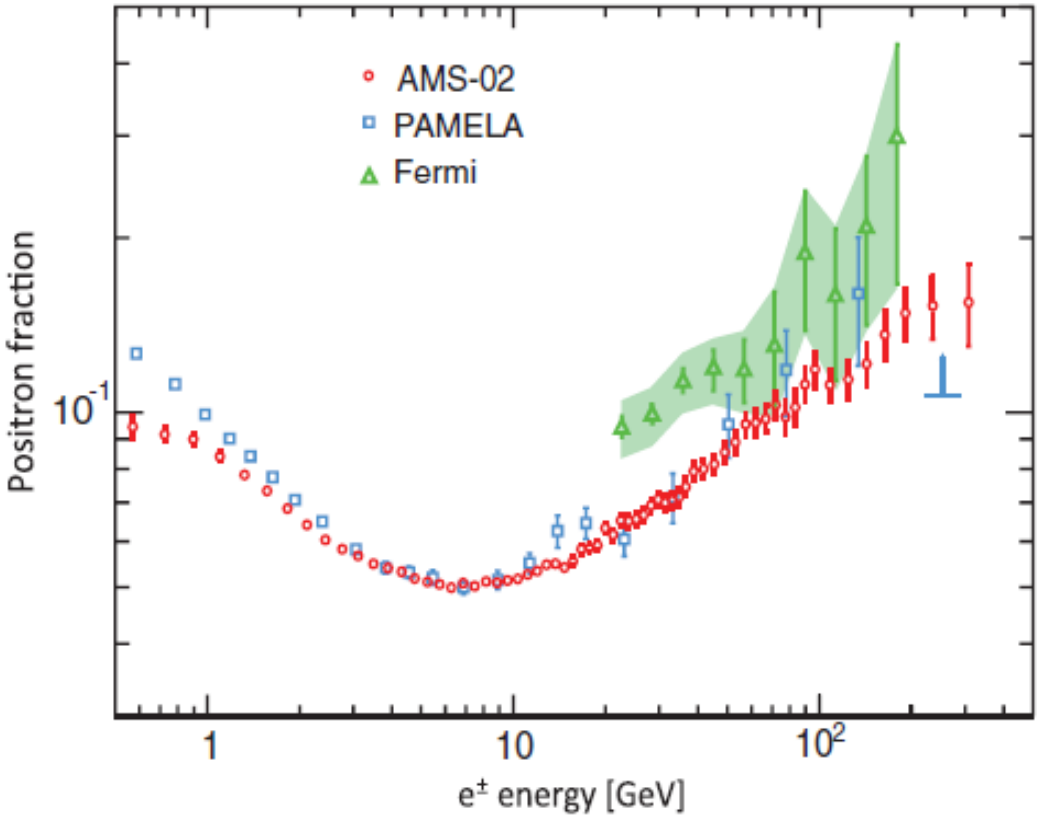
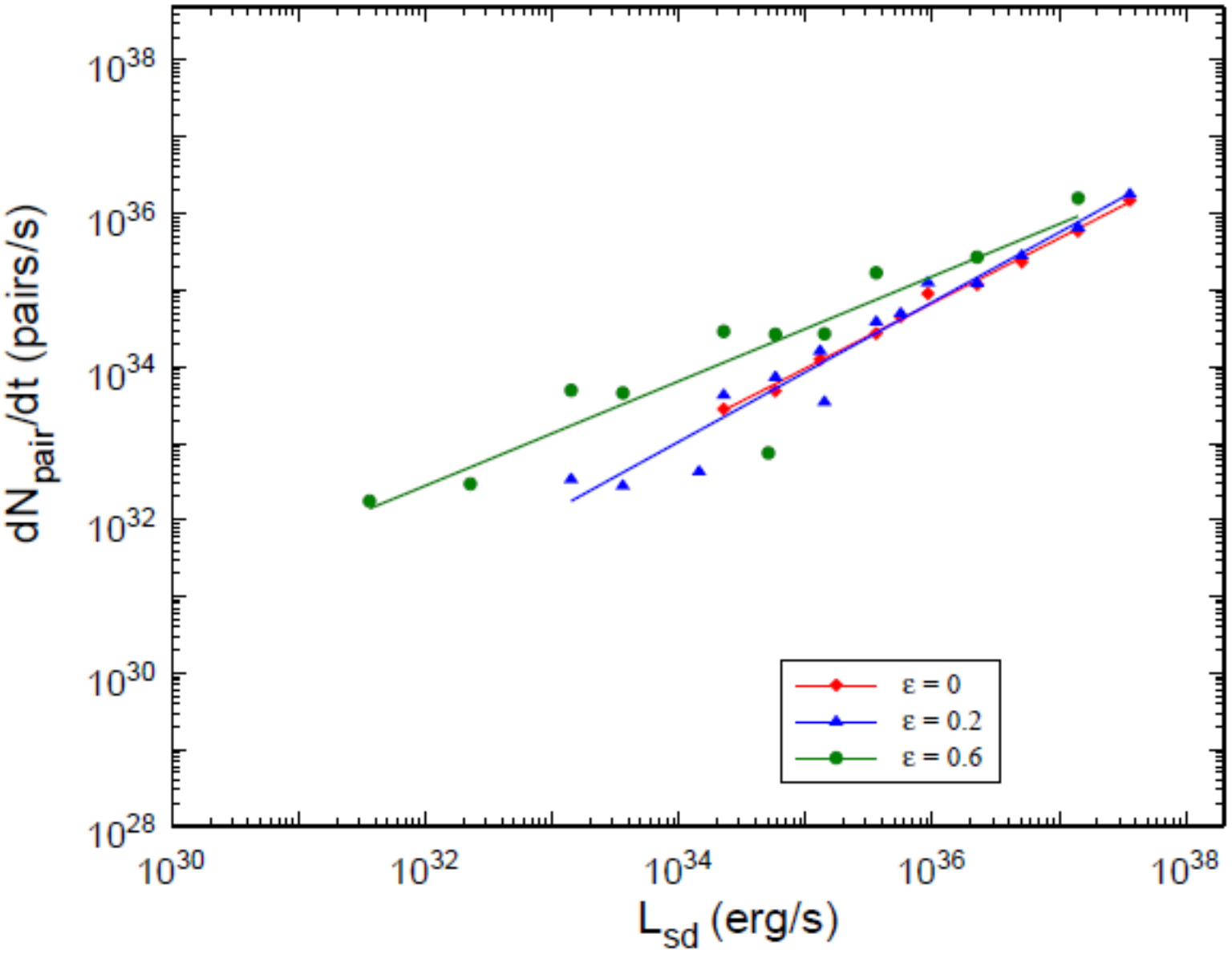


Fig. 5 Aguilar+ (2013)

MSPs and Cosmic Ravs



Introduce offset dipole, higher flux to lower Ė MSP population has also increased.

But may not be enough alone.

Harding & Muslimov (2011)

Fig. 12.— Total pair flux (in units of pairs s^{-1}) from each polar cap as a function of spin down luminosity L_{sd} for millisecond pulsars, for different values of offset parameter ε.

Conclusions

Pulsars are extreme systems from which we can learn about...

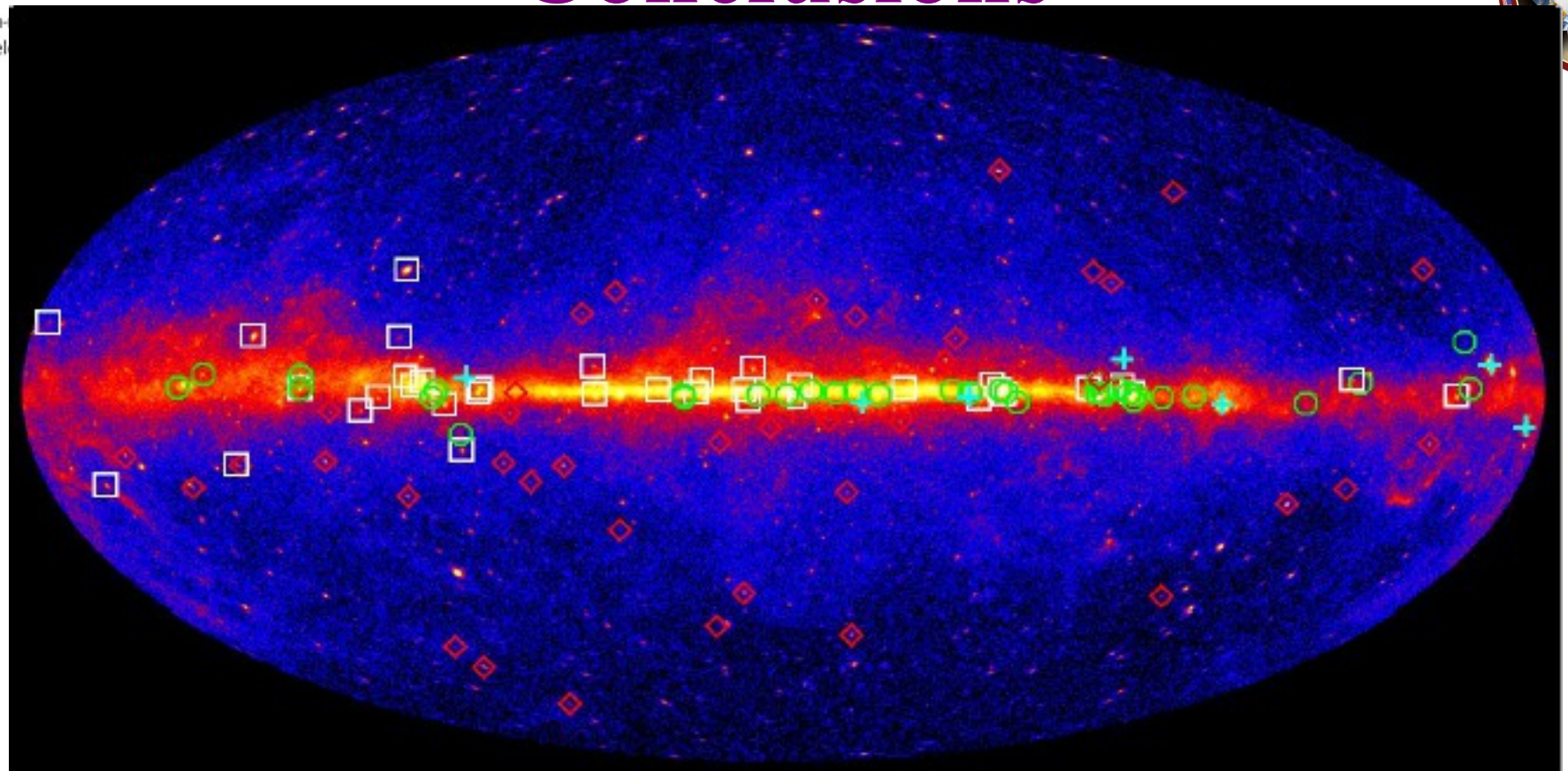
- particle acceleration
- strong magnetic fields and strong gravity
- energetic plasmas
- matter at nuclear densities

The LAT is a pulsar machine

- increased the known gamma-ray pulsar by a factor of ~20
- increased the Galactic field MSP population by ~50%

Great pulsar science is still being done

Conclusions



117 Gamma-ray Pulsars

Shown above are the gamma-ray pulsars detected with the LAT superimposed on the 3 year, front-converting, ≥ 1 GeV sky map: CGRO PSRs(✚), young radio-selected (○), young gamma-selected(□), and MSPs(◇).

For an up-to-date list see:
https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

Auxiliary files for the second LAT pulsar catalog can be found at:
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2nd_PSR_catalog/

Timing Models

Where to find pulsar timing models:

from published papers

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ephems/

LAT timed pulsars

https://confluence.slac.stanford.edu/display/GLAMCOG/LAT+Gamma-ray+Pulsar+Timing+Models

or just ask...

Paul Ray (paul.ray@nrl.navy.mil)

David Thompson (David.J.Thompson@nasa.gov) multi-wavelength coordinator

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BACKUP SLIDES

Millisecond Pulsars – Being Green

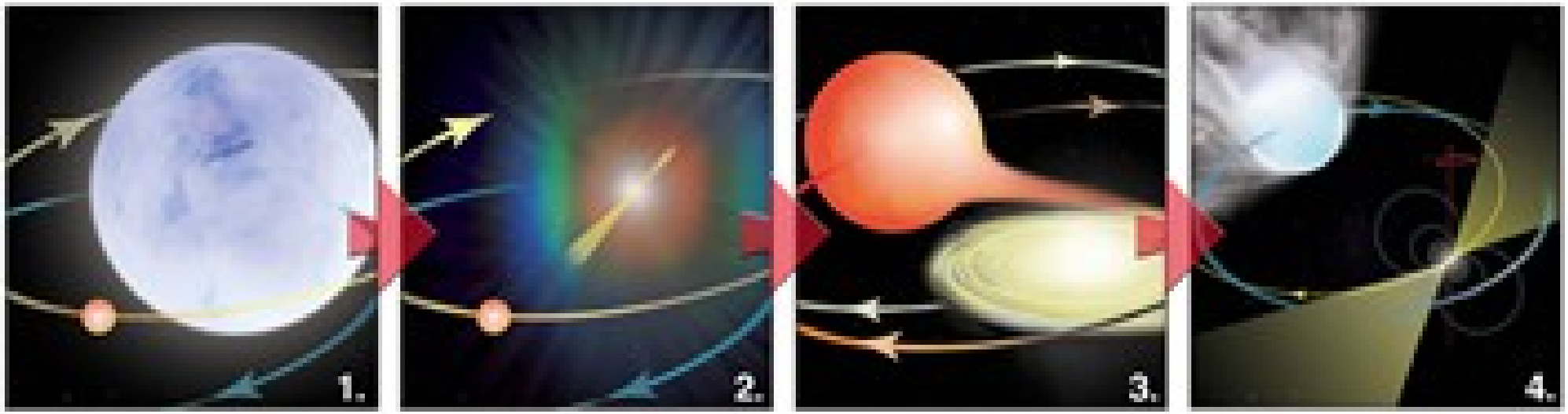
1st MSP discovered by Backer+ (1982). Recycled pulsars (e.g., Alpar+ 1982).

Observational evidence:

Millisecond X-ray pulsations from low-mass X-ray binaries (e.g., Wijnands & van der Klis 1998)

A missing link radio MSP (Archibald+ 2009)

M28I, radio pulsar to accreting X-ray source and back (Papitto+ 2013; ATEL #5069)

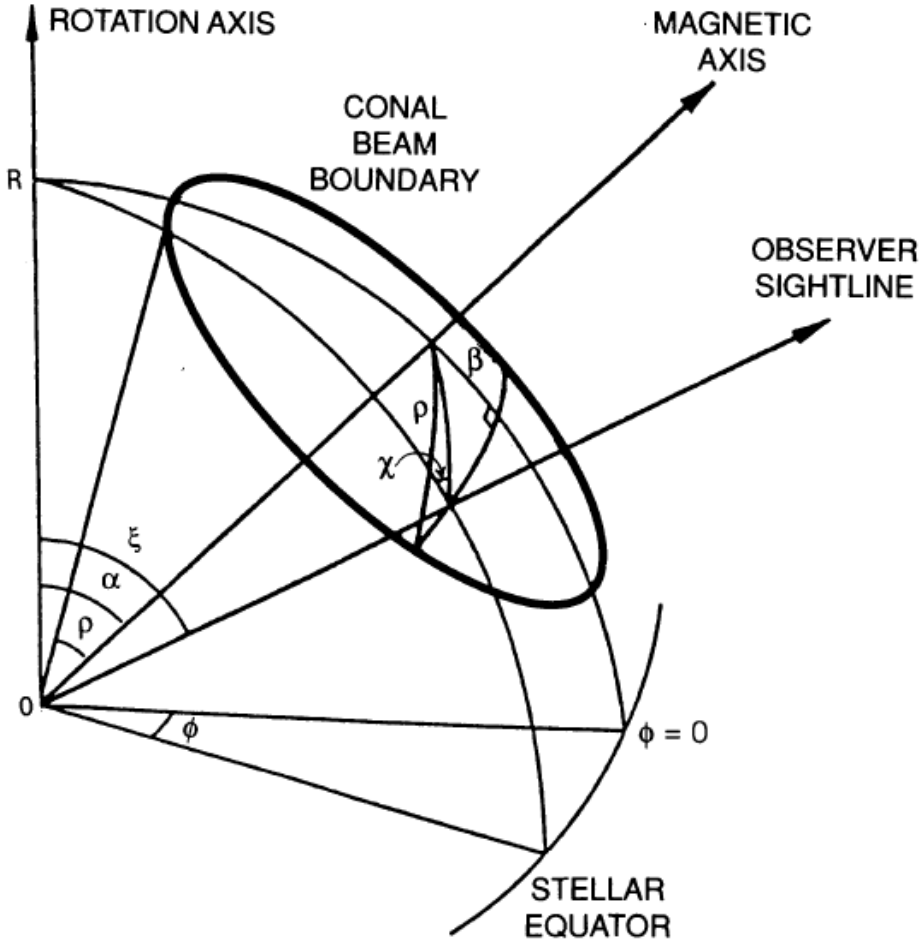


Radio Beam

Pulsar radio emission is:

coherent, non-thermal (brightness temp $>10^{20}$ K), & often highly polarized

single-altitude (frequency-dependent)



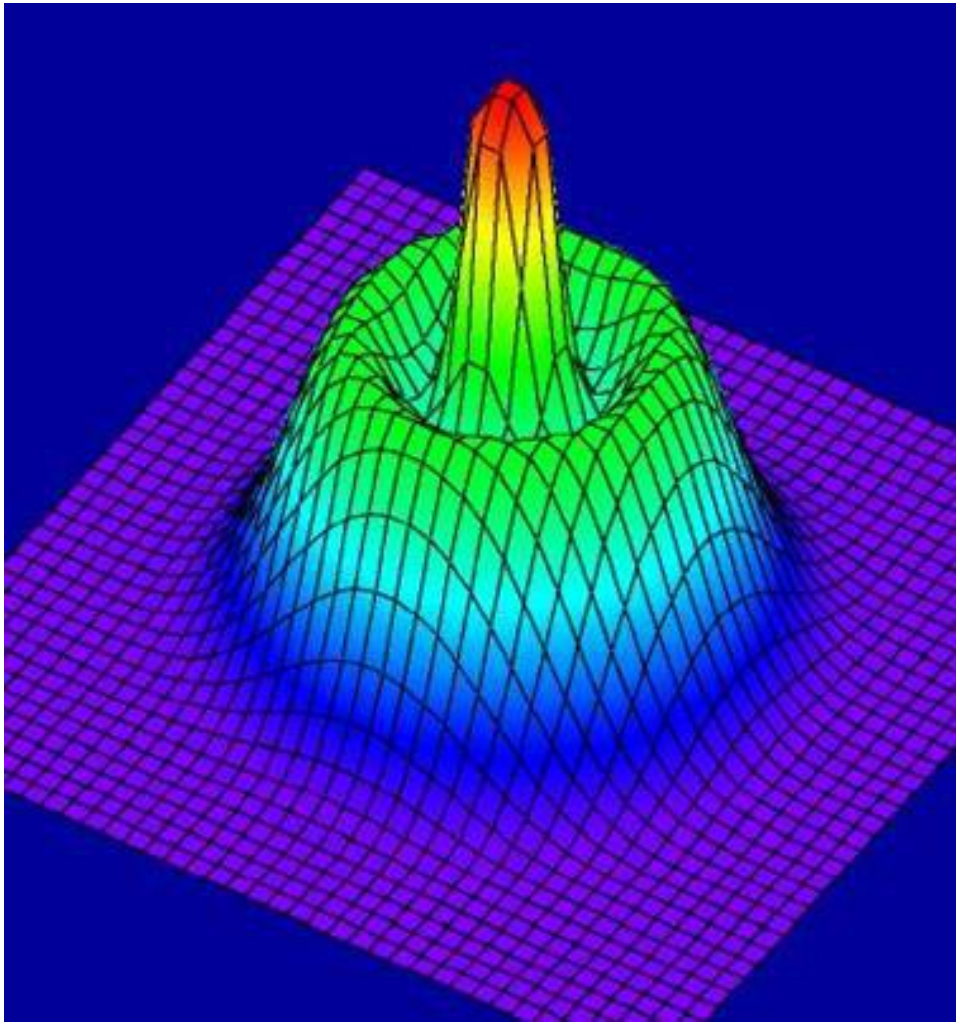


Fig. 2 Rankin (1993)

The Pulsar Magnetosphere

Pacini (1968
dipole radiat

Goldreich &

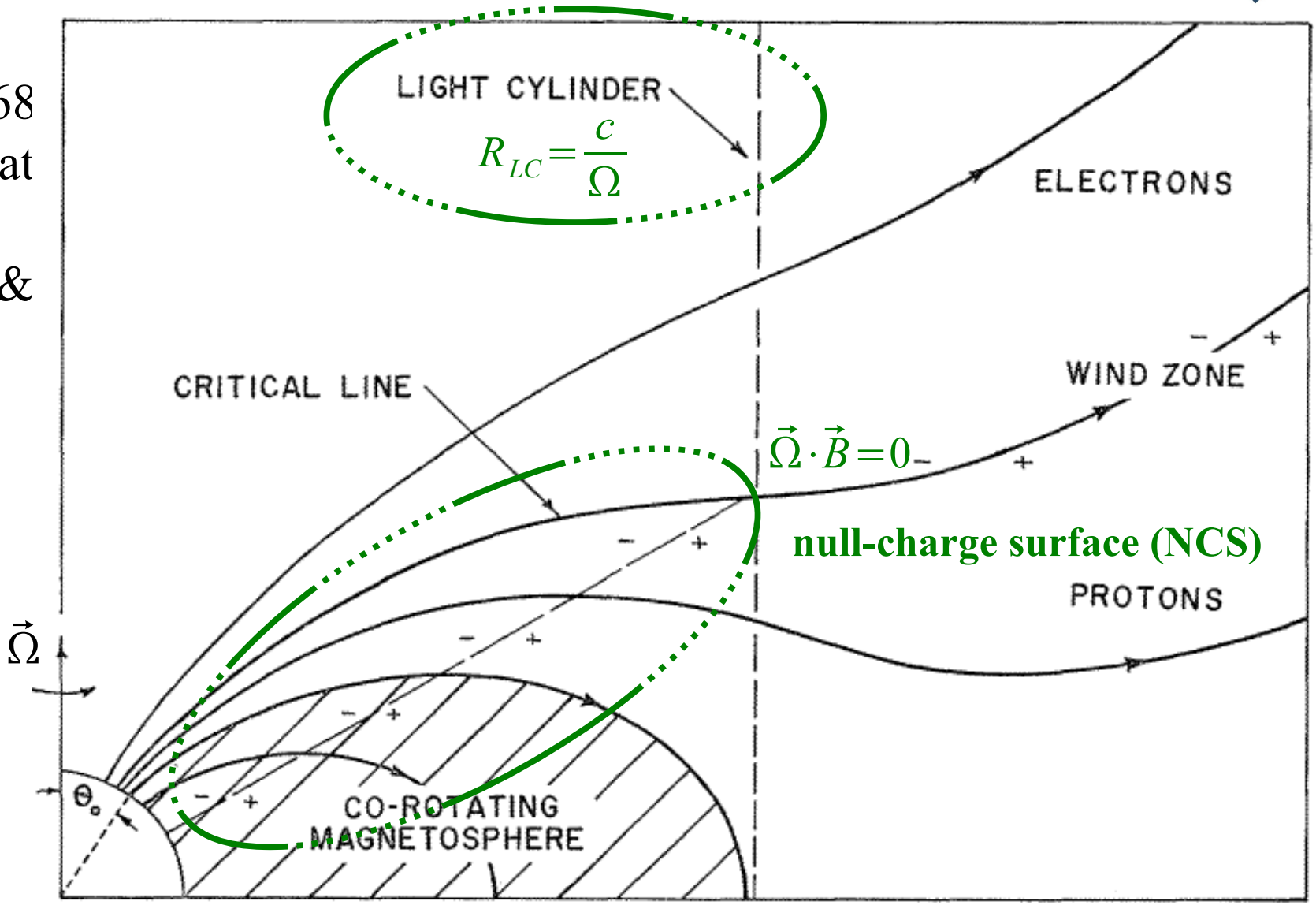
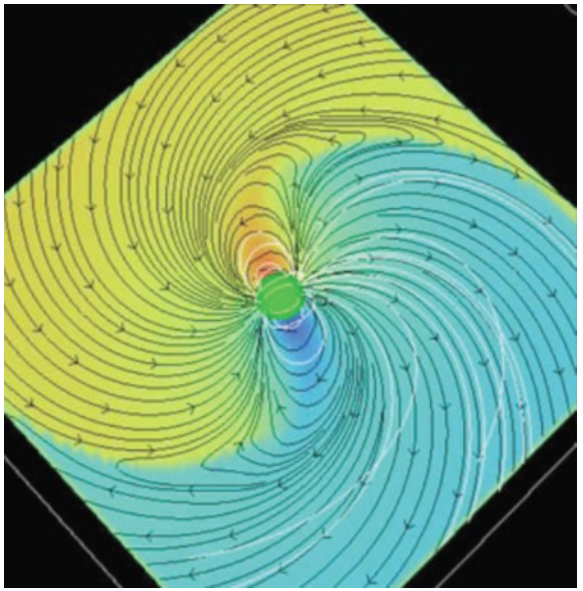


Fig. 1 of Goldreich & Julian (1969)

MHD Solutions

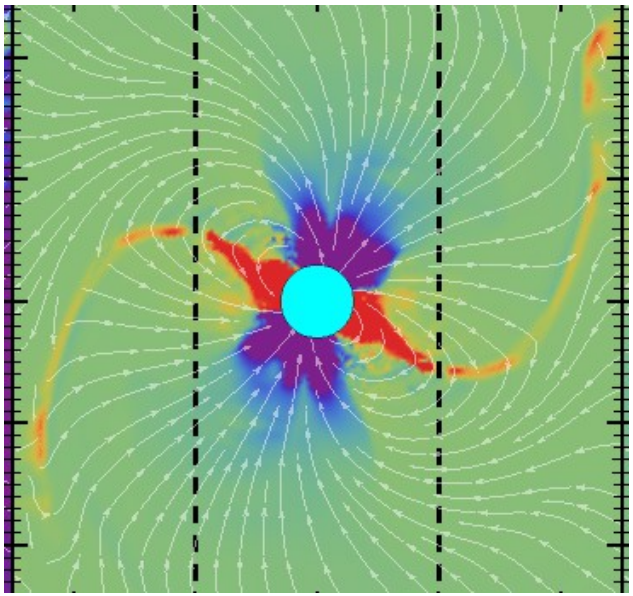
Force-free magnetosphere
(Spitkovsky 2006)
No particle acceleration



$$\vec{E} \cdot \vec{B} = 0$$

Filled with plasma

$$E_{||} = 0$$



Non-ideal MHD magnetosphere
(Kalapotharakos et al. 2012, Li & Zhang 2011)
Charges, currents + acceleration!

$$\vec{E} \cdot \vec{B} \neq 0$$

Curvature Radiation

Charged particle accelerated along a curved path

radius of curvature ρ & Lorentz factor γ

$$P_{CR} = -\sqrt{3}\,\alpha_f \frac{\gamma\, c}{2\pi\,\rho} F\left(\frac{\epsilon}{\epsilon_{CR}}\right),\ \epsilon_{CR} = \frac{3}{2}\frac{\hbar\,\gamma^3}{\rho}$$

$$\gamma_{RR} = \left(\frac{1.5\,E_{\parallel}}{e}\right)^{1/4}\sqrt{\rho} \qquad \epsilon_{CR}^{RR} \sim 4\,E_{\parallel}^{3/4}\sqrt{\rho}$$

$$\epsilon \ll \epsilon_{CR},\ F\left(\frac{\epsilon}{\epsilon_{CR}}\right) \sim \epsilon^{1/3} \qquad \epsilon \gg \epsilon_{CR},\ F\left(\frac{\epsilon}{\epsilon_{CR}}\right) \sim \epsilon^{0.5}\exp\left\{-\frac{\epsilon}{\epsilon_{CR}}\right\}$$

For population of electrons, power law index depends on distribution of γ's

A Gamma-ray MSP

PSR J0030+0451

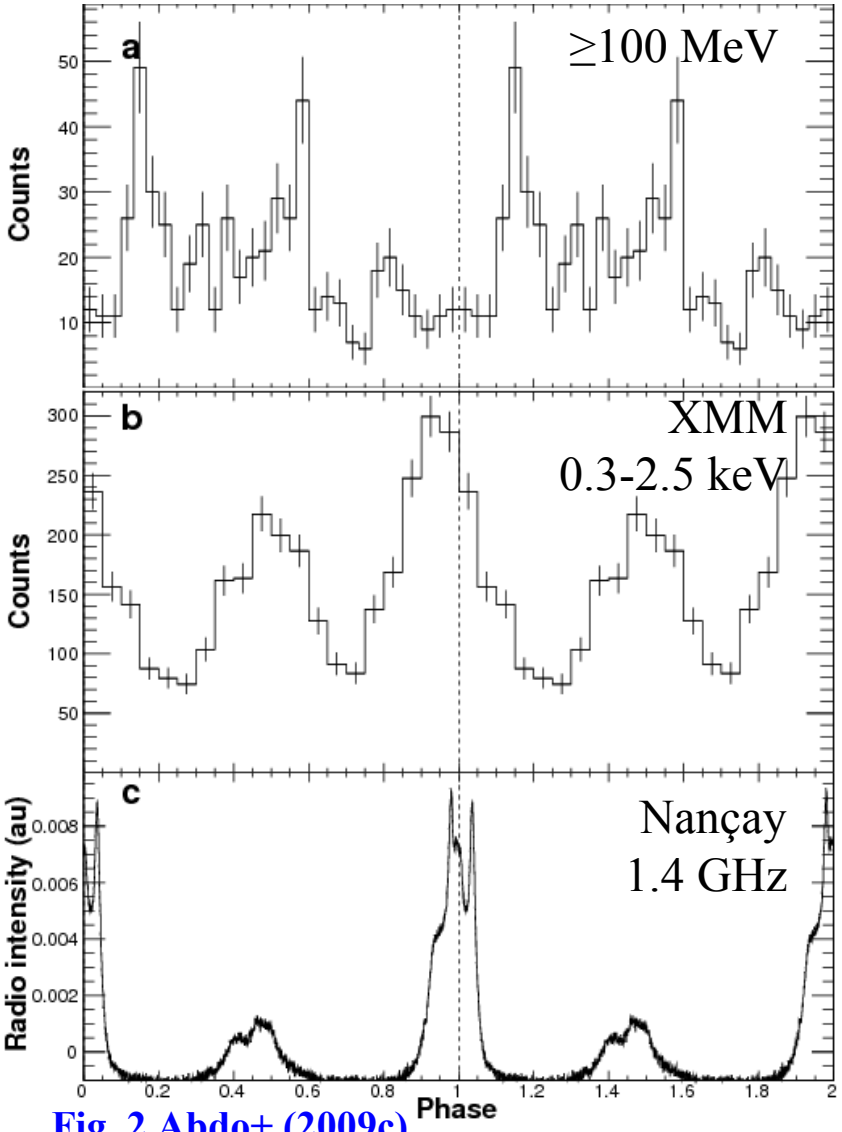


Fig. 2 Abdo+ (2009c)

2nd gamma-ray MSP after PSR J0218+4232 (4.9σ detection with *EGRET*)

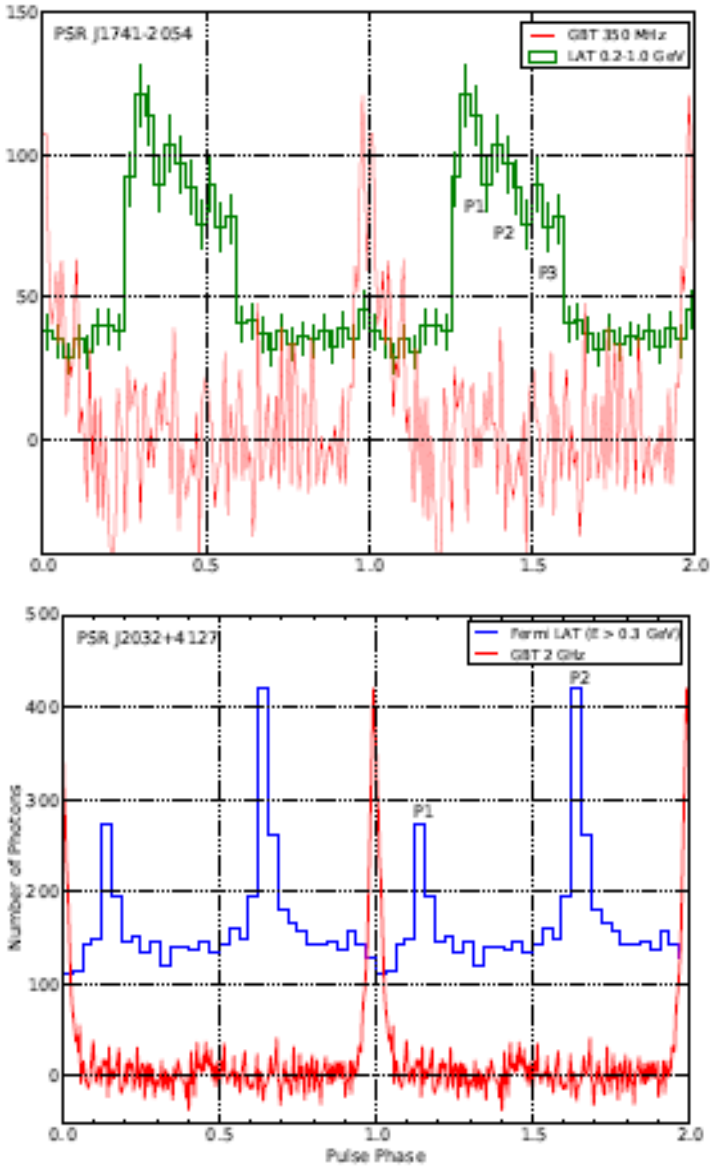
$P = 4.87$ ms, $\dot{P} = 1.0\times10^{-20}$ s s^{-1}

below CR and ICS pair-creation death lines

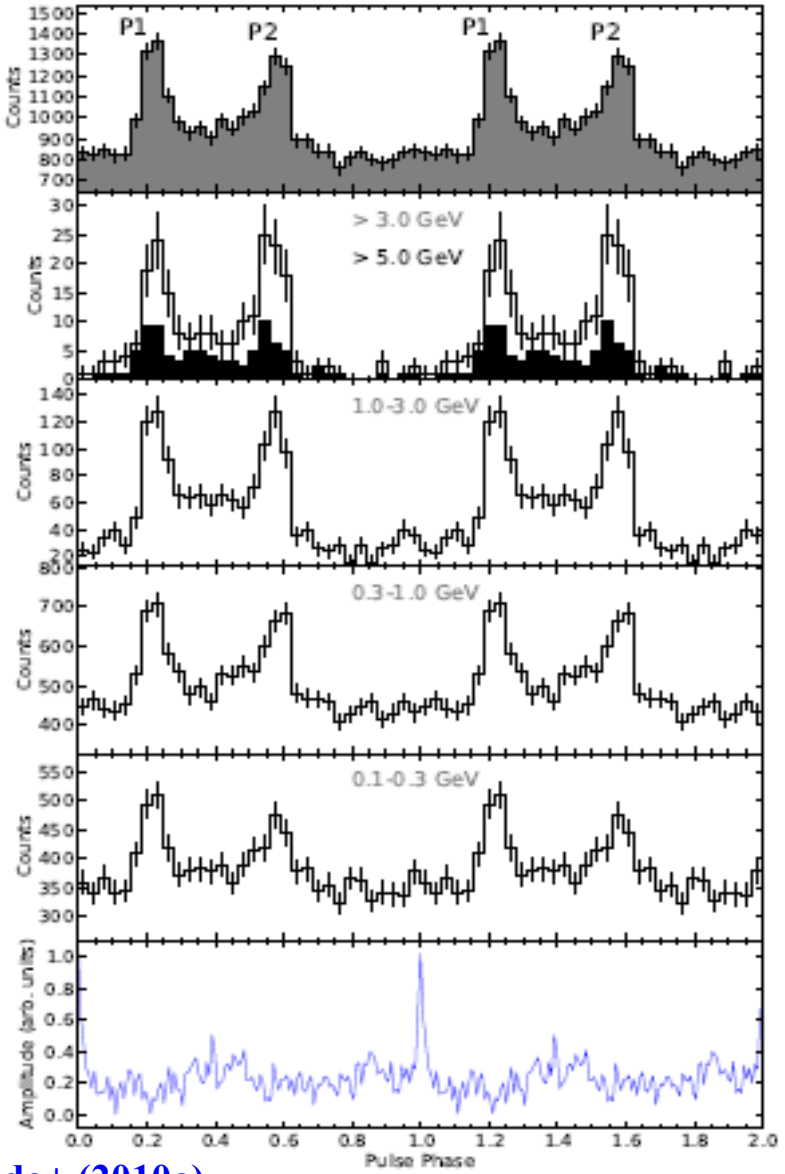
$E_C = 1.7\pm0.4$ GeV

$\Gamma = 1.4\pm0.2$ GeV

All's Not Quiet on the Radio Front

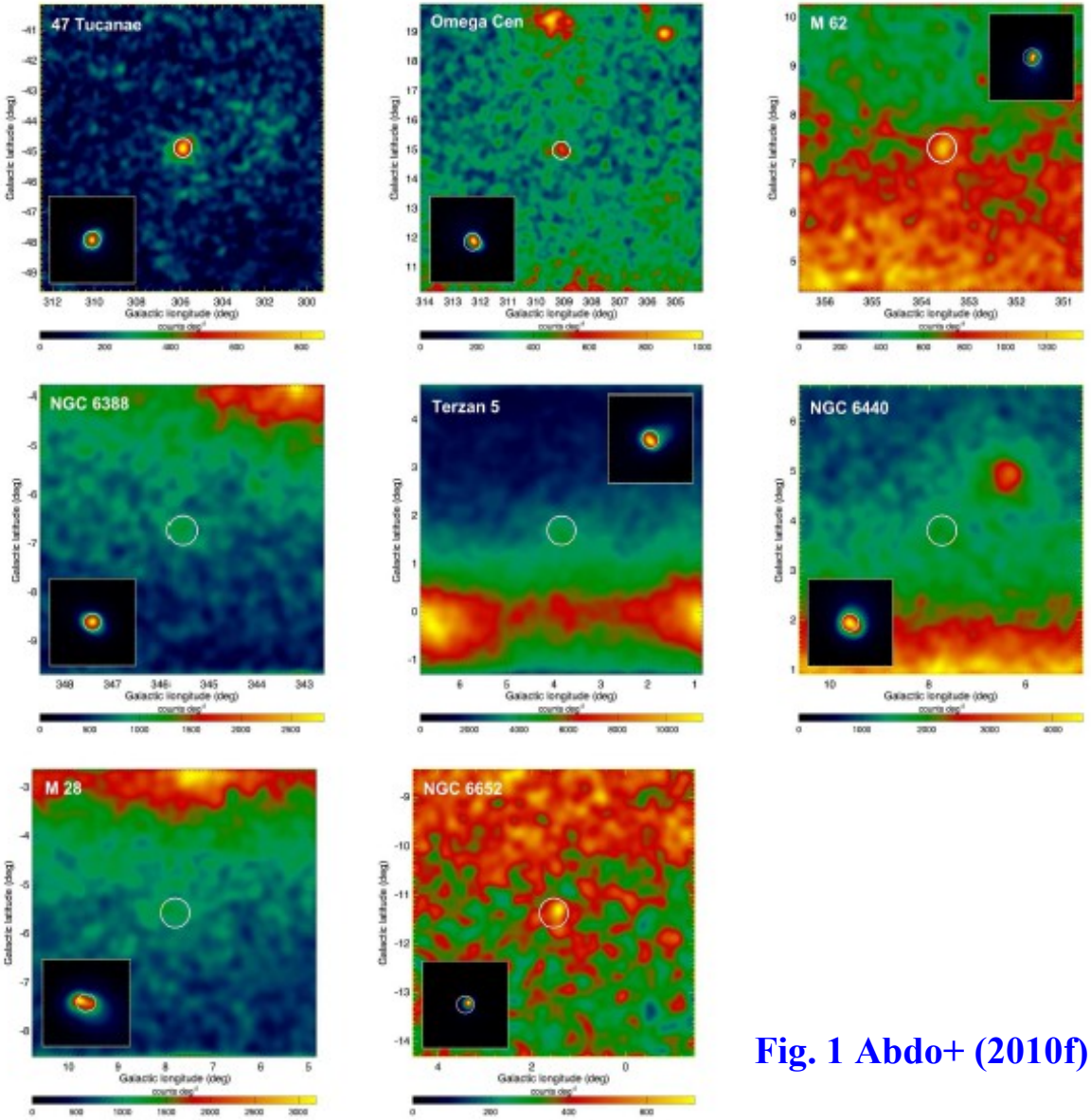


Camilo+ (2009)



Abdo+ (2010a)

More Globular Clusters

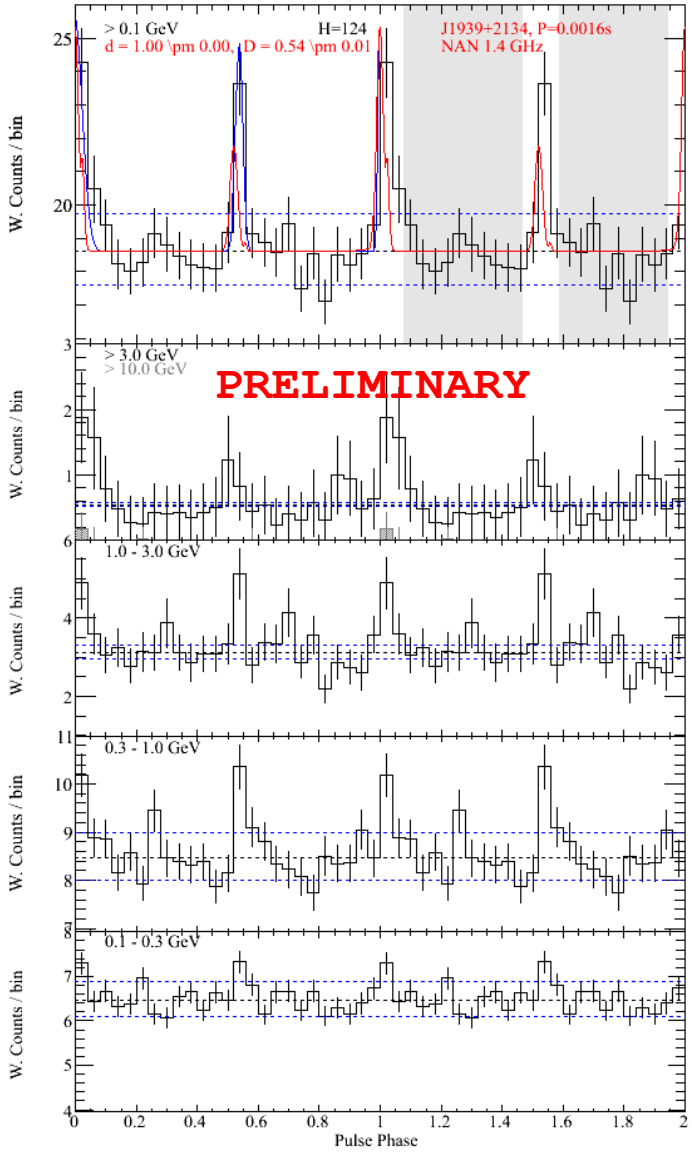


Detection of emission associated with more globular clusters.

More than a dozen detected to date (see also Kong+ 2010; Tam+ 2011; Nolan+ 2012)

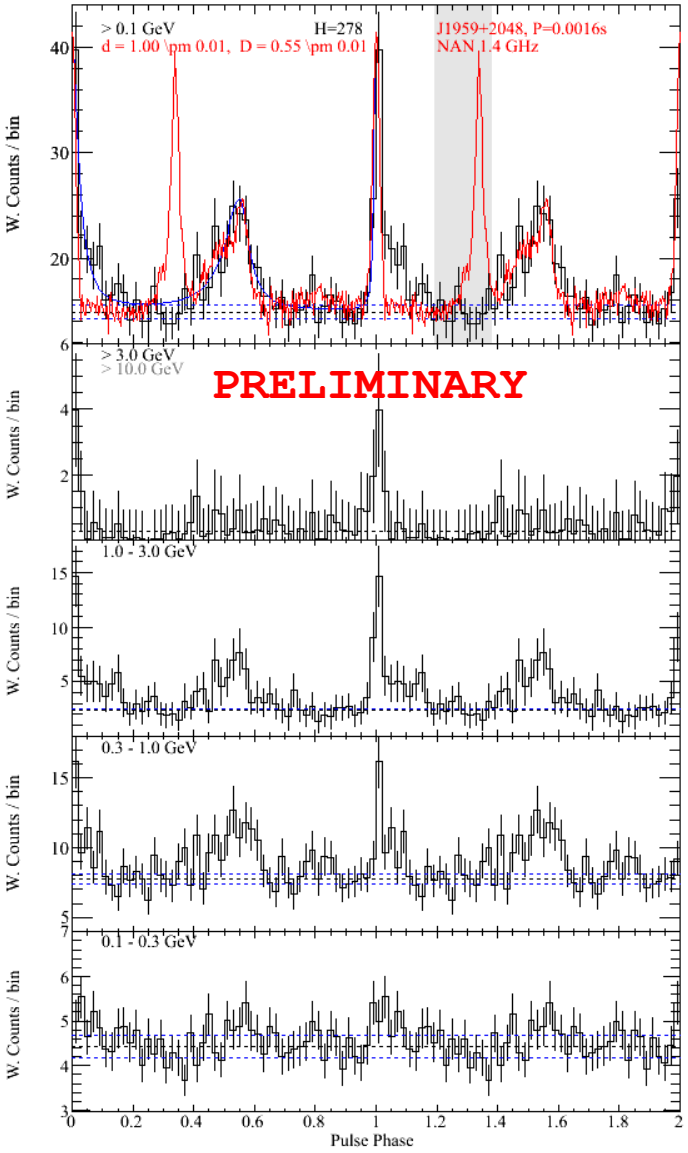
Fig. 1 Abdo+ (2010f)

More Aligned MSPs



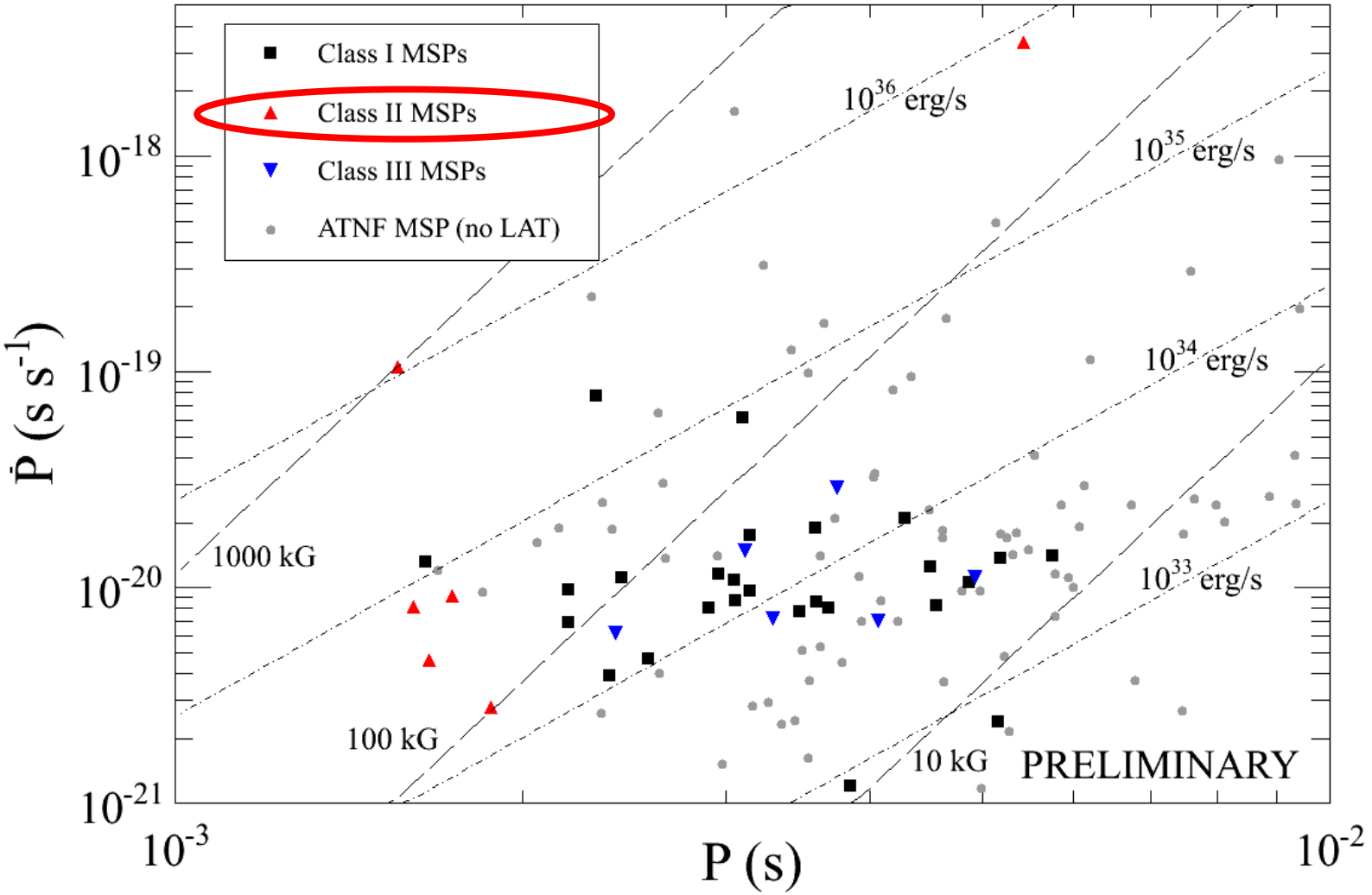
PSRs B1937+21 and B1957+20 (Guillemot+ 2012)

Both very energetic, and fast, P < 2ms



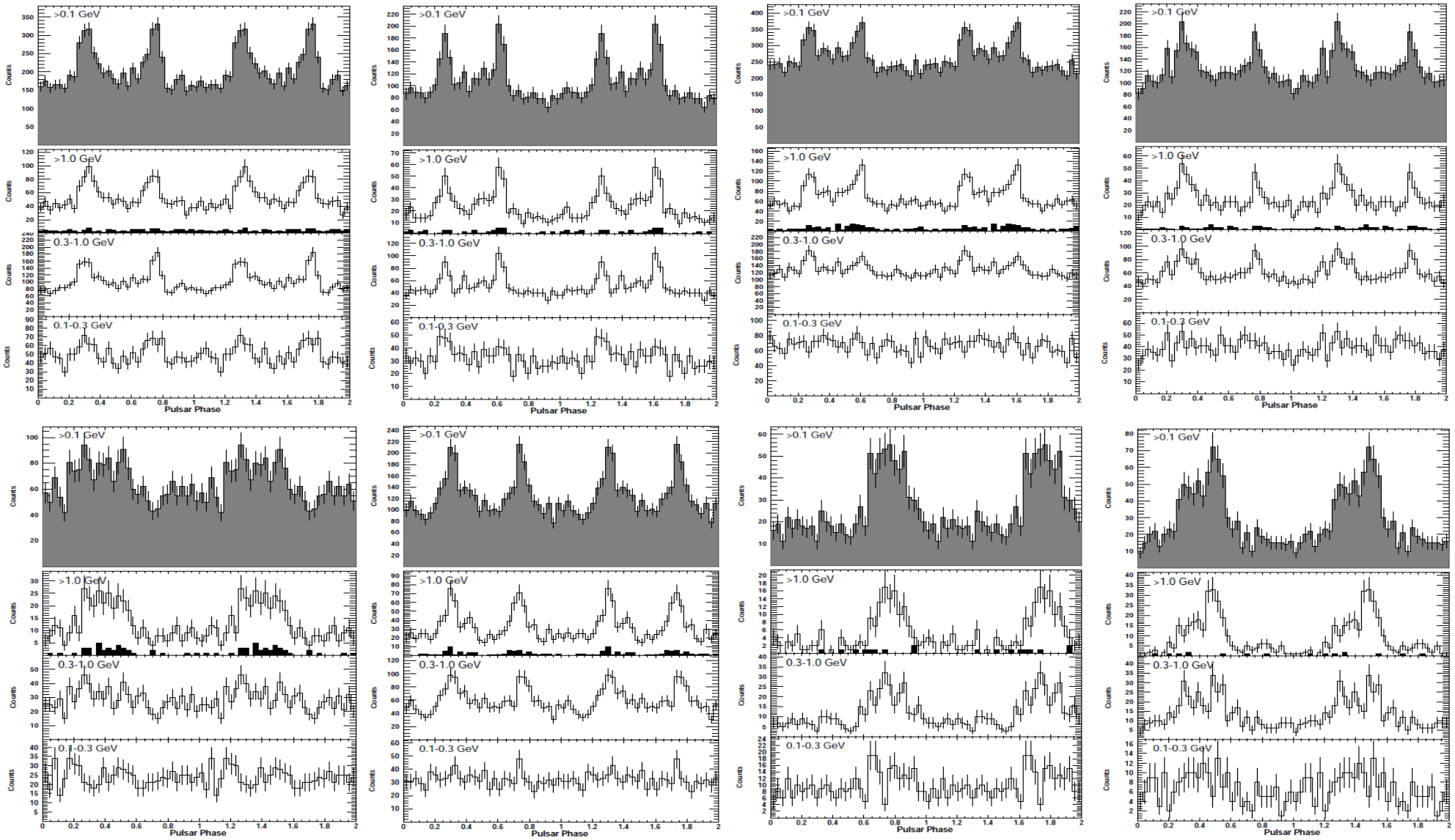
Light curves from Abdo+ (*submitted*) arXiv:1305.4385

Nature of the Aligned MSPs



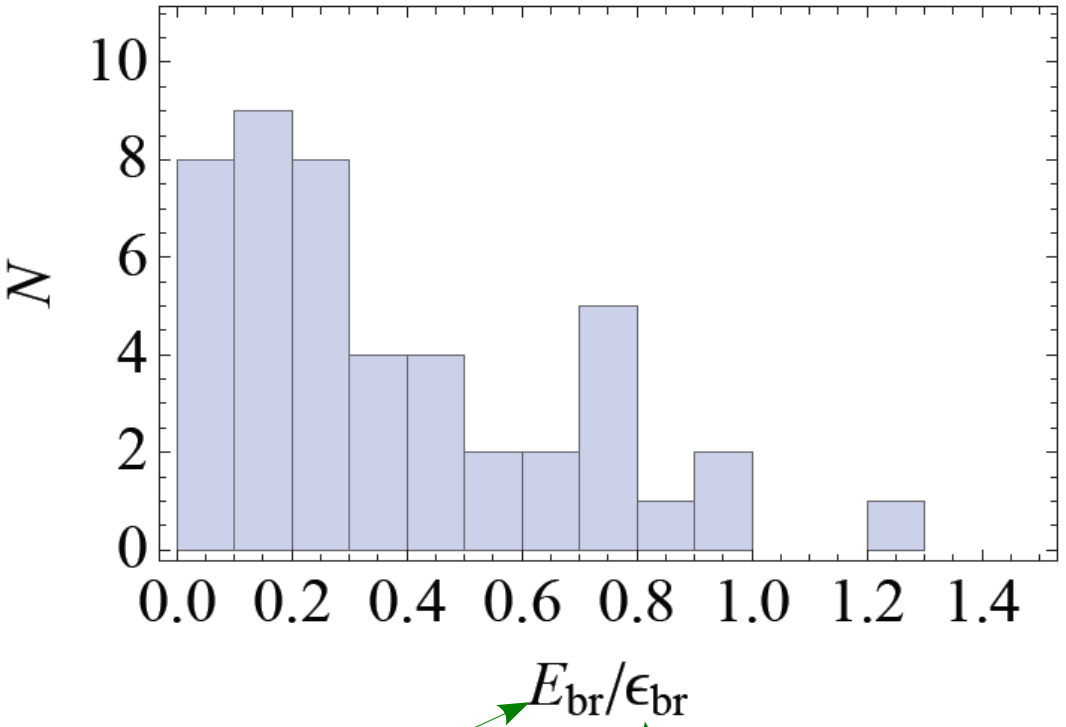
Johnson+ (*in prep*)

More Blind Search Pulsars



Eight more detections in 11 months, Saz Parkinson+ (2010)

Inverse Compton Emission?

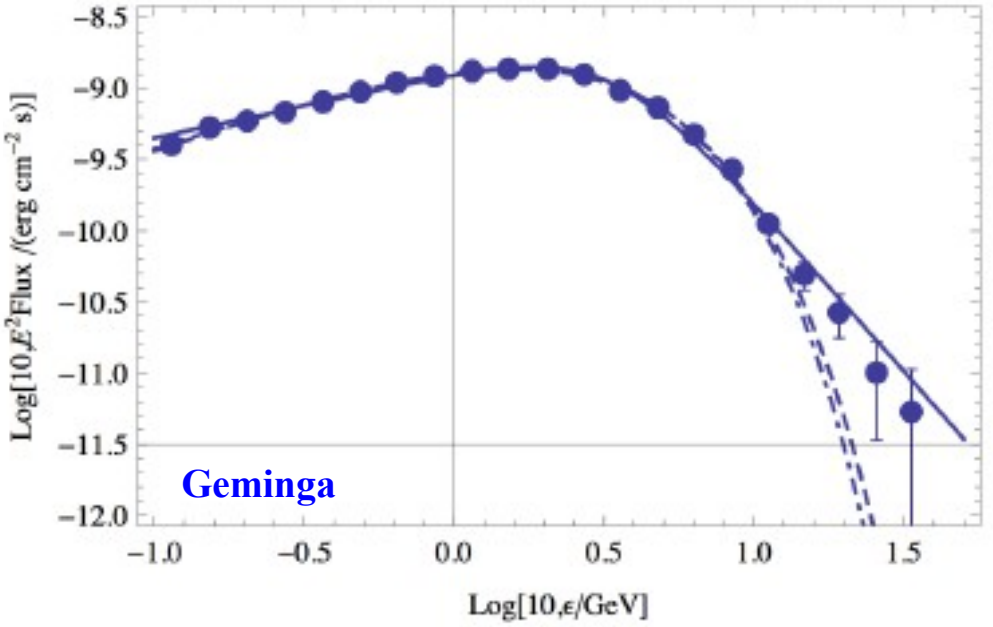


Lyutikov (2012)

1PC cutoff energy

maximumal cutoff energy assuming E=B

Broken power law fits phase-averaged (and some phase-resolved) spectra as well as sub-exponential



Offset Dipoles

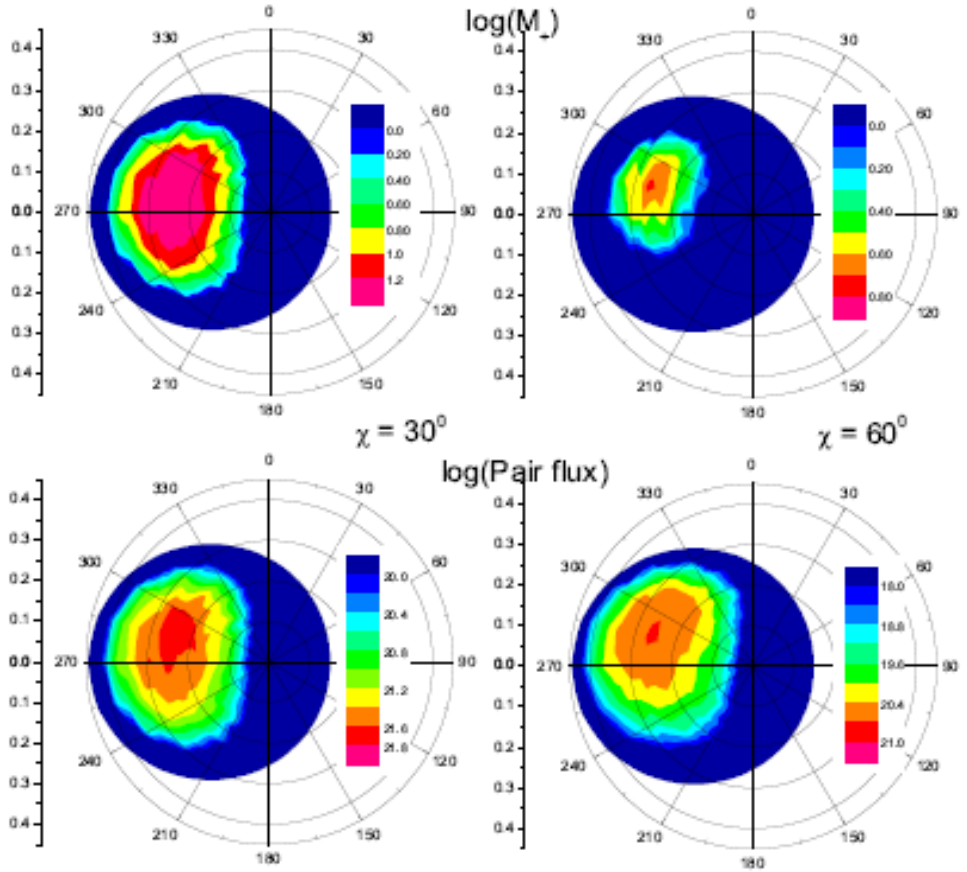
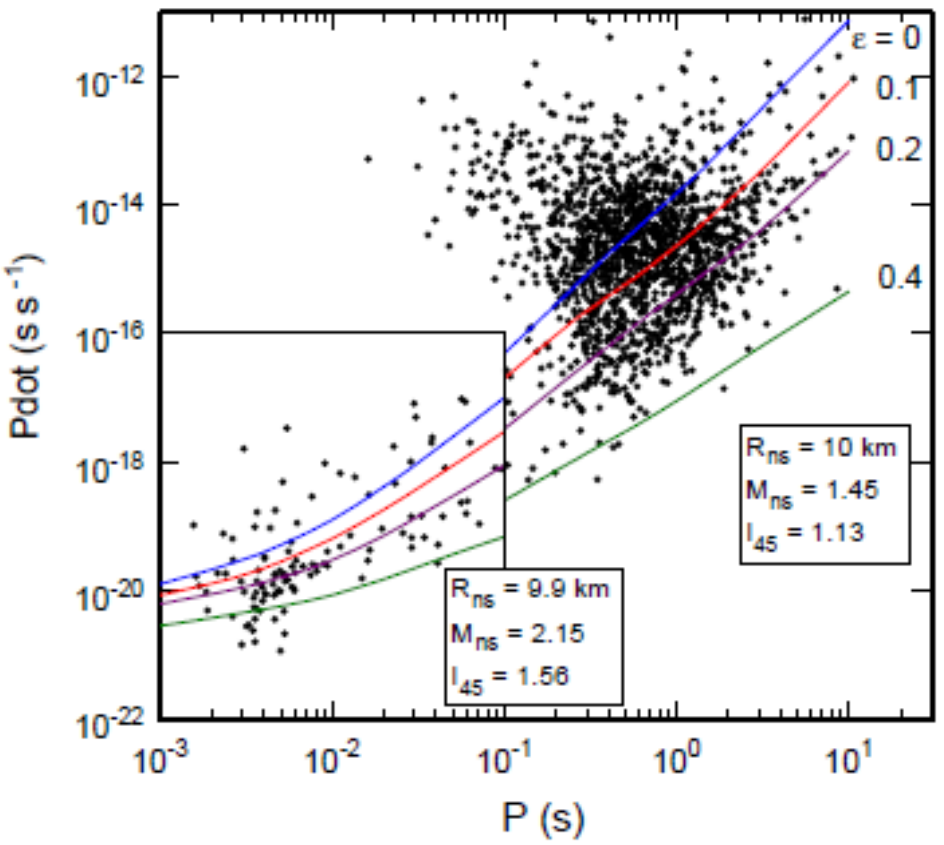


Fig. 5.— Contours of log of pair multiplicity (top) and pair flux (bottom in units of s^{-1} cm^{-2}) as a function of radial distance from the magnetic axis (in units of neutron star radius) and magnetic azimuth for $P = 3$ ms, $B_0 = 4 \times 10^8$ G and $\chi = 45°$, for $\varepsilon = 0.4$ and different values of inclination angle χ.



Harding & Muslimov (2011a,b)

MSPs and Diffuse Backgrounds

Dark matter decay signature in extragalactic gamma-ray background? (e.g, Abazajian+ 2012)

MSPs can appear extragalactic, unresolved sources contribute to background?

- Likely less than ~1% (Ackerman+ 2012; Gregoire & Knodlseder 2013)

Dark matter annihilation in the Galactic center (e.g., Abazajian & Kaplinghat 2012)

- spectrum also consistent with MSP population
- MSP contribution likely ~few % of diffuse towards the Galactic center (Gregoire & Knodlseder 2013)