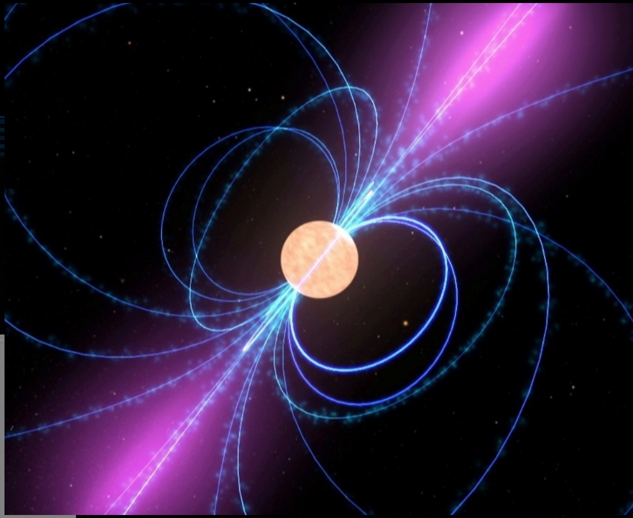
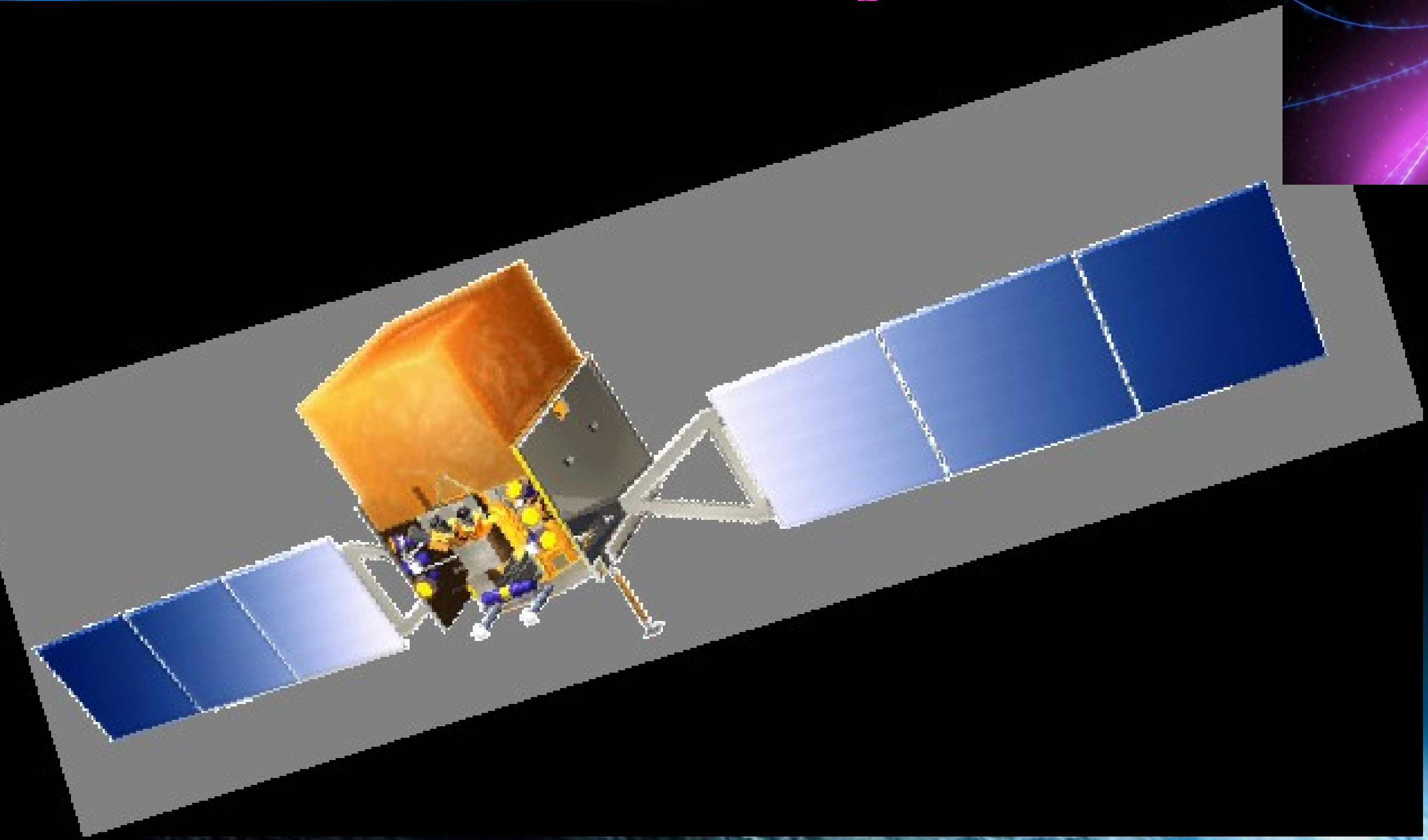
Gamma-Ray Pulsars in the Fermi Era

Alice Harding

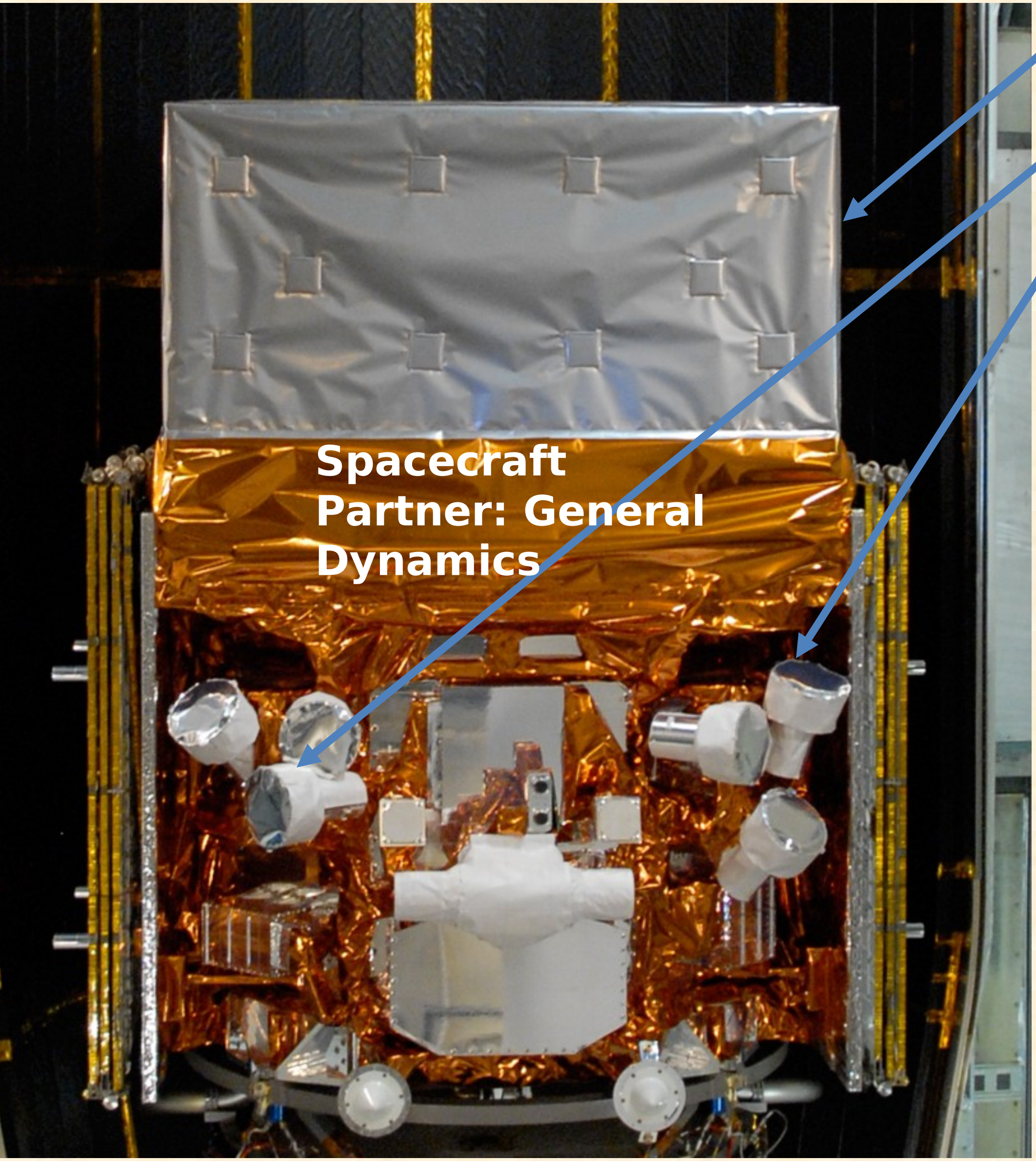




Consortium & Pulsar Search Consortium

- Launch June 2008 from Cape Canaveral
- Circular orbit, 565 km altitude (96 min period) 25.6 deg inclination.

The Fermi Observatory



Large AreaTelescope (LAT)
20 MeV - >300 GeV

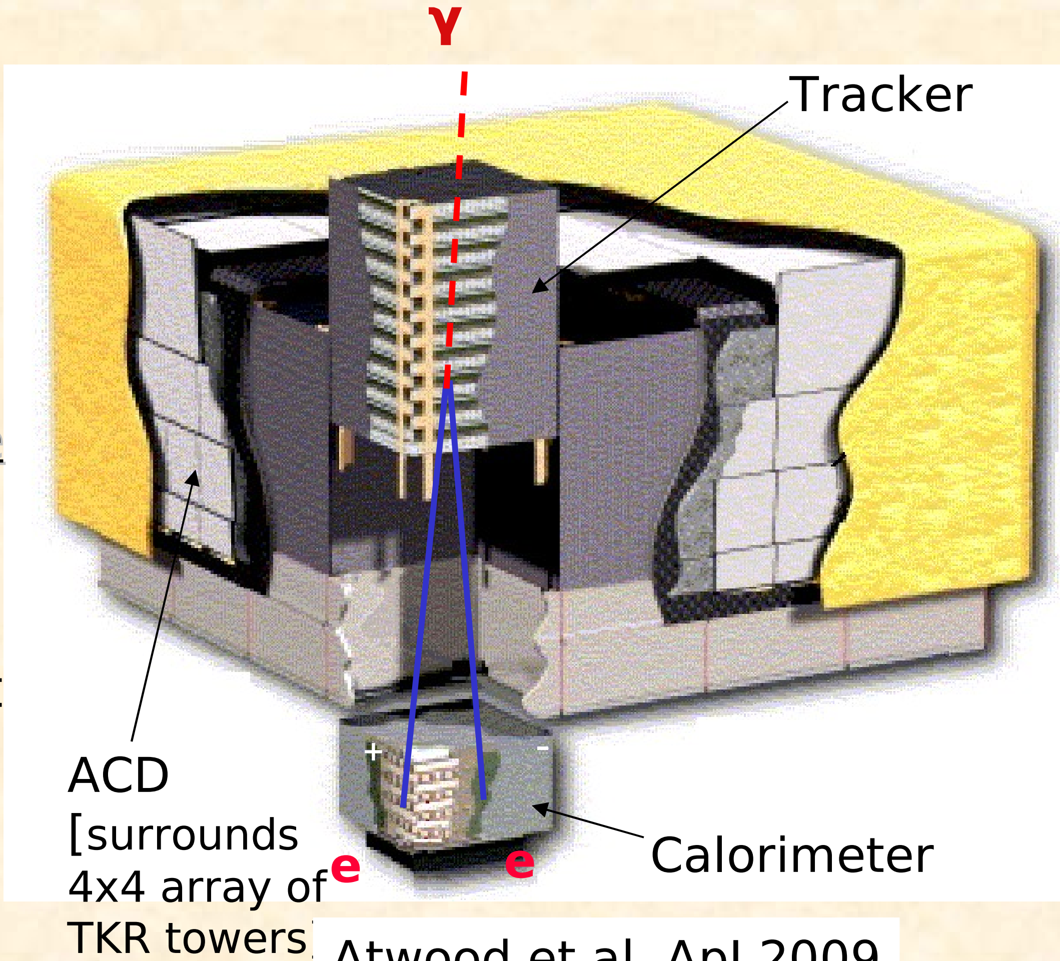
Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 30 MeV

KEY FEATURES

- **Huge field of view**
  - **–LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.**
- **Huge energy range, including largely unexplored band 10 GeV - 100 GeV. Total of >7 energy decades!**
- **Large leap in all key capabilities. Great**

Overview of LAT: How it works

- Precision Si-strip Tracker (TKR) Measure the photon direction; gamma ID.
- Hodoscopic CsI Calorimeter (CAL) Measure the photon energy; image the shower.
- Segmented Anticoincidence Detector (ACD) Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.
- Electronics System Includes flexible, robust hardware trigger and software filters.



Atwood et al, ApJ 2009

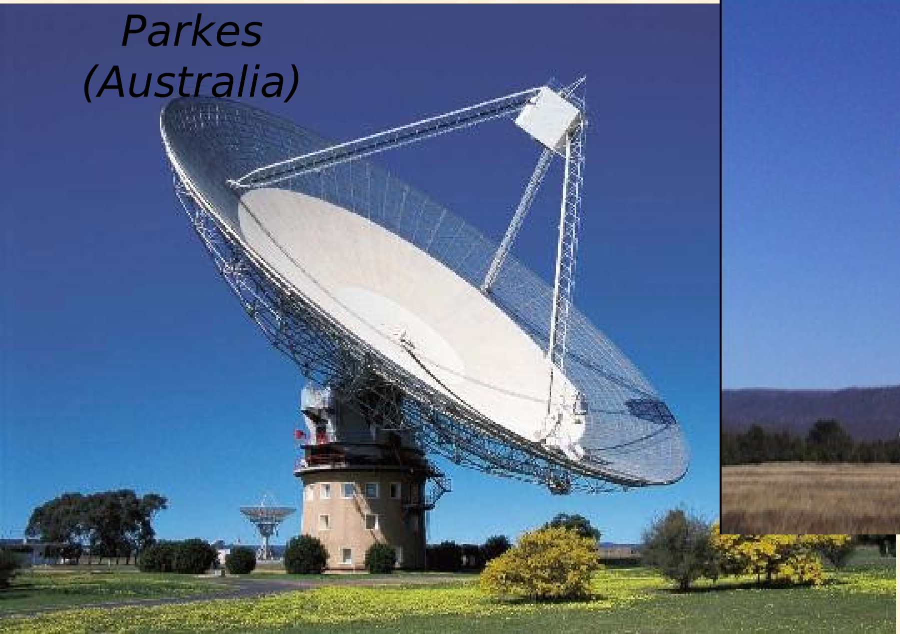
Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

Pulsar Timing Campaign

Jodrell Bank (UK)

Nançay

RXTE (in space)



Parkes (Australia)

Green Bank (USA)

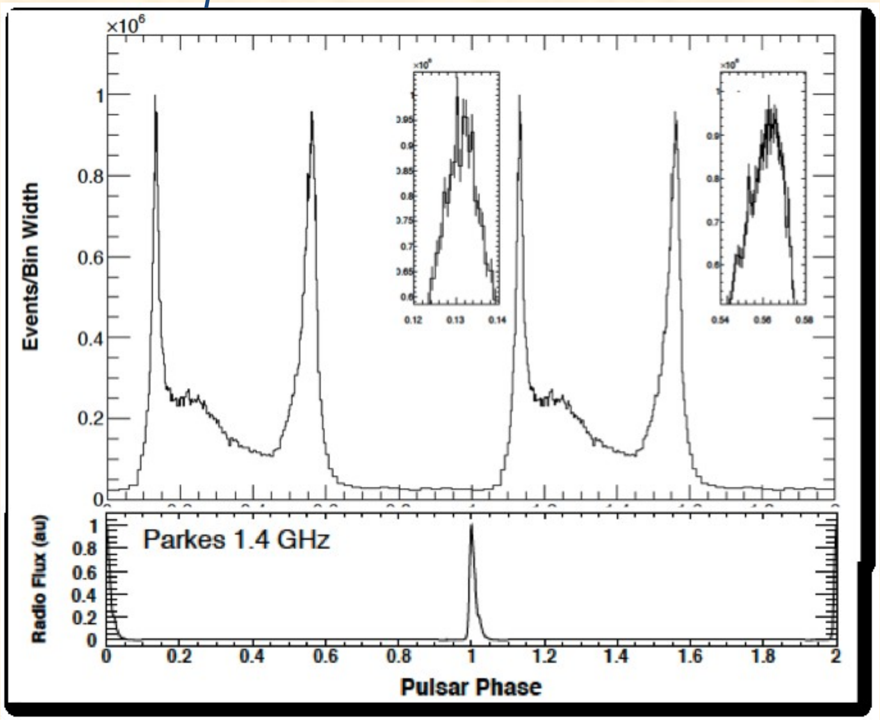
+ other contributions: Arecibo, Hartebeesthoek, etc.

⇒ Timing for ~ 230 energetic pulsars, of interest for Fermi.

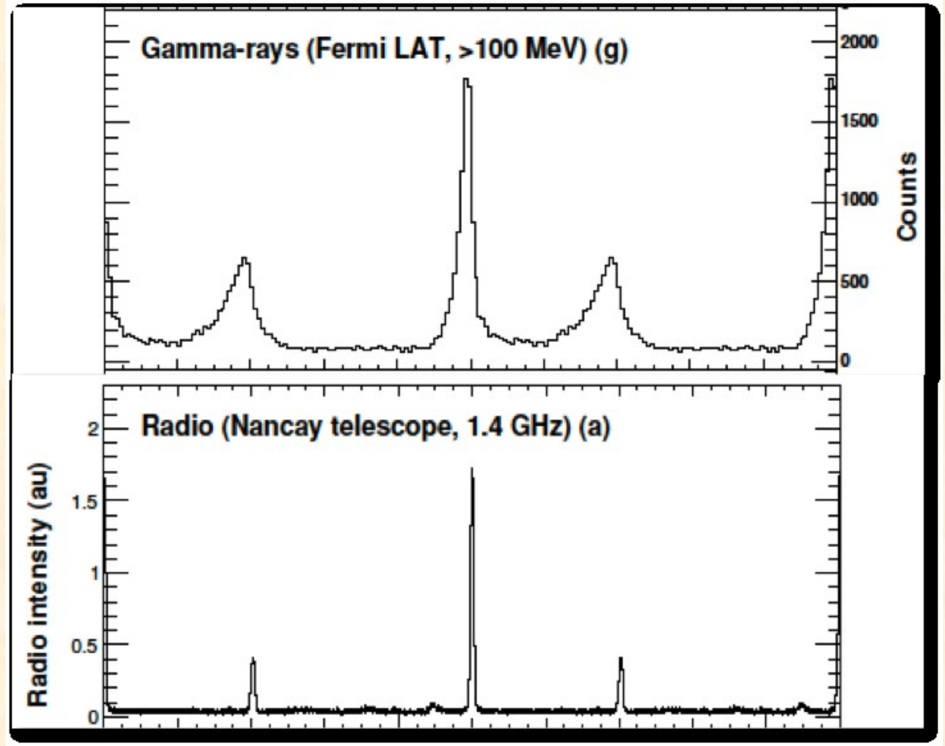
⇒ (Smith, Guillemot, Camilo et al., A&A 492, 923, 2008)

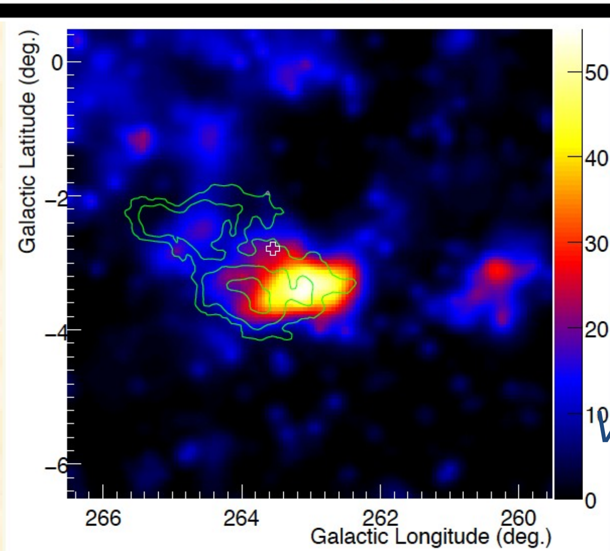
Known γ-ray pulsars

Vela pulsar



Crab pulsar



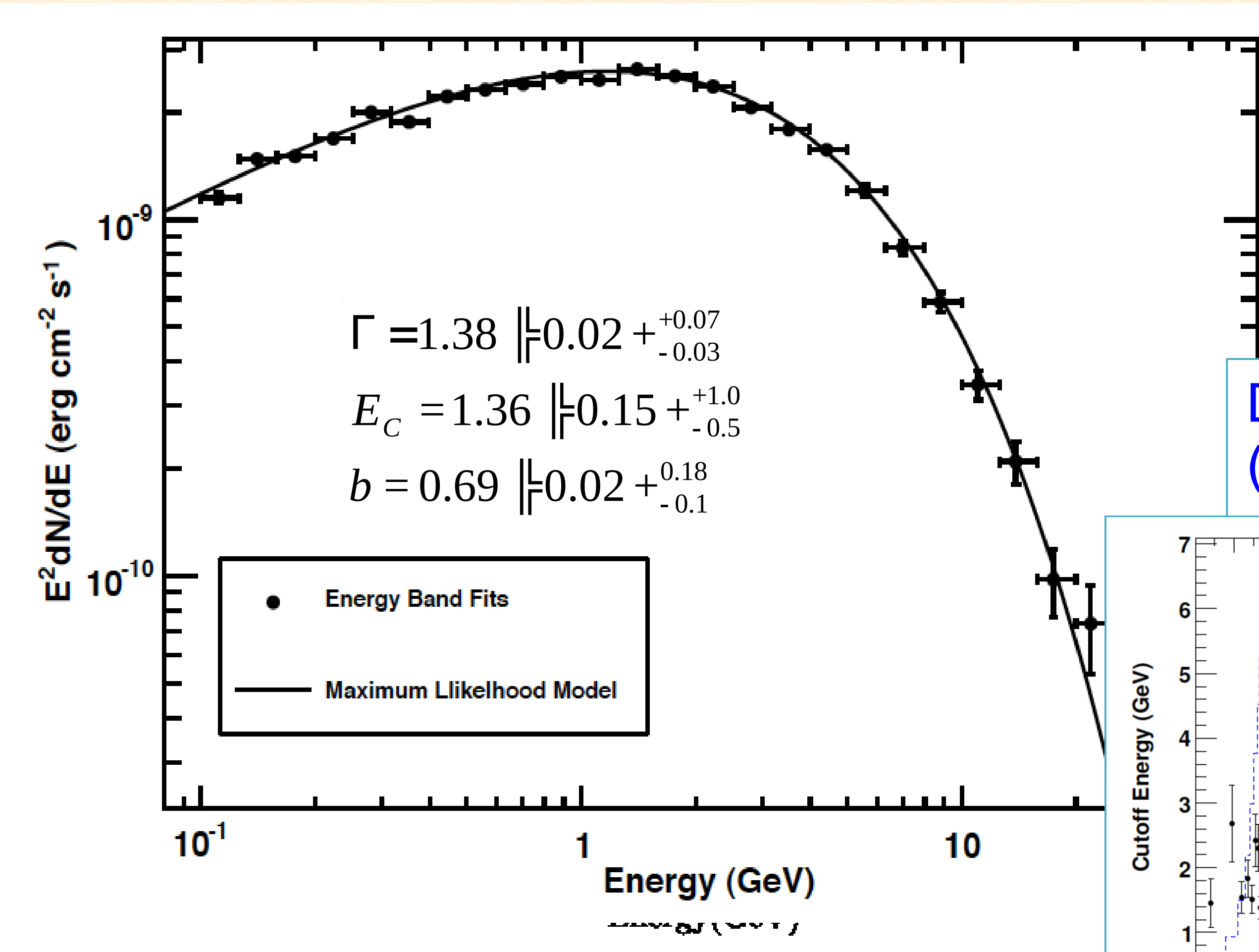


Vela pulsar wind nebula

Abdo et al. 2010

Vela Pulsar spectrum

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

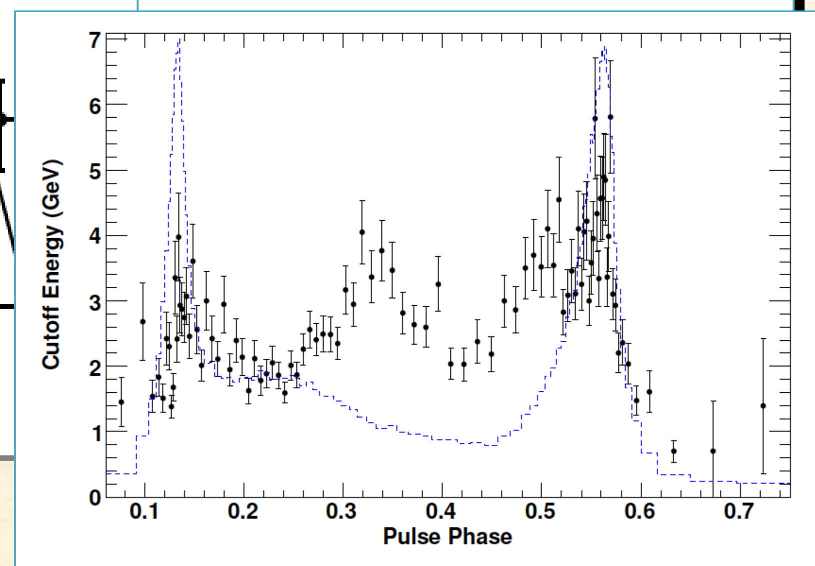


Spectrum falls off *slower* than exponential

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

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

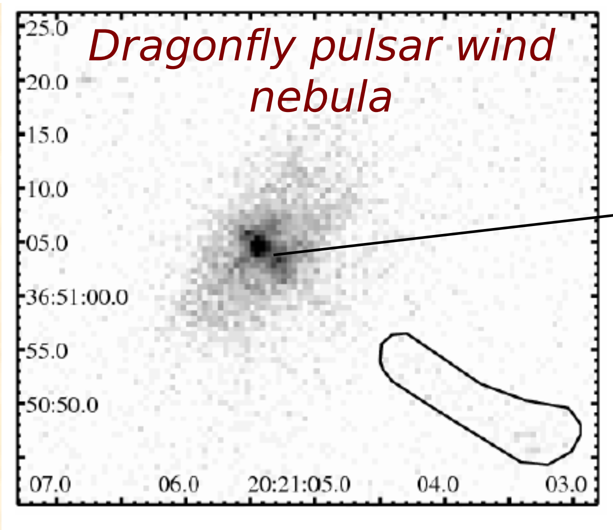
Due to variation of Ec (b=1) with phase

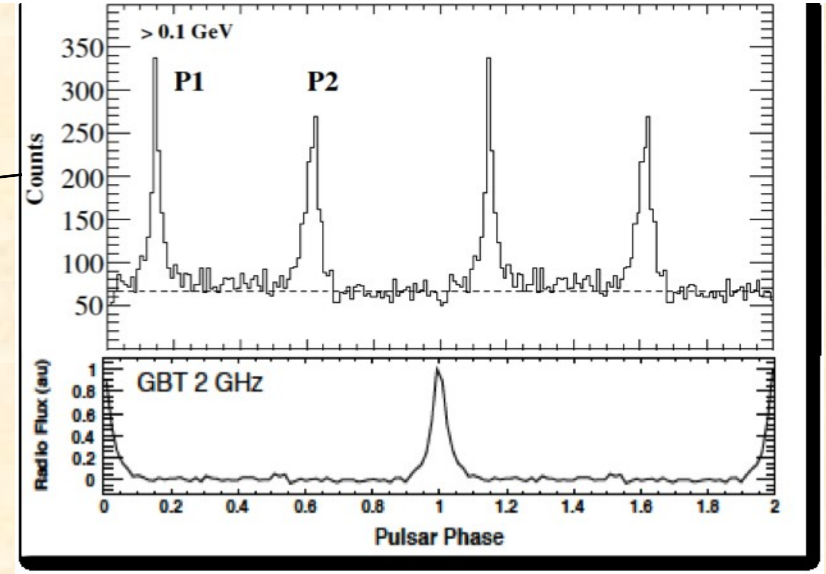


Abdo et al. 2010

New young radio-loud pulsars

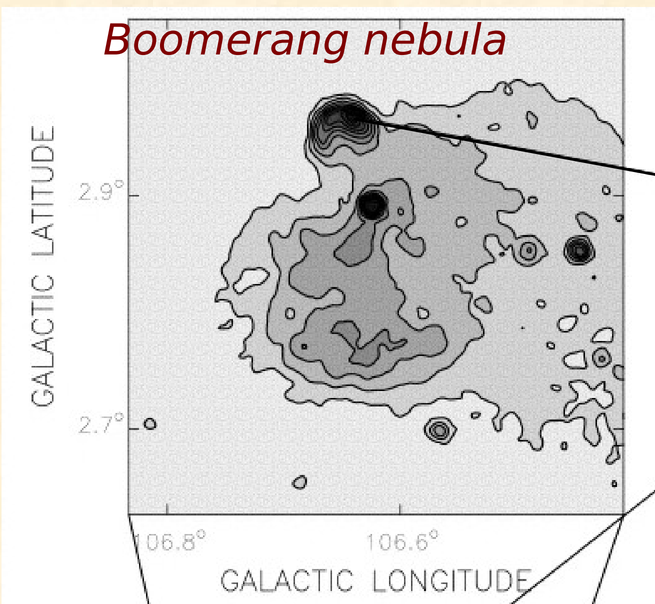
Dragonfly pulsar wind nebula

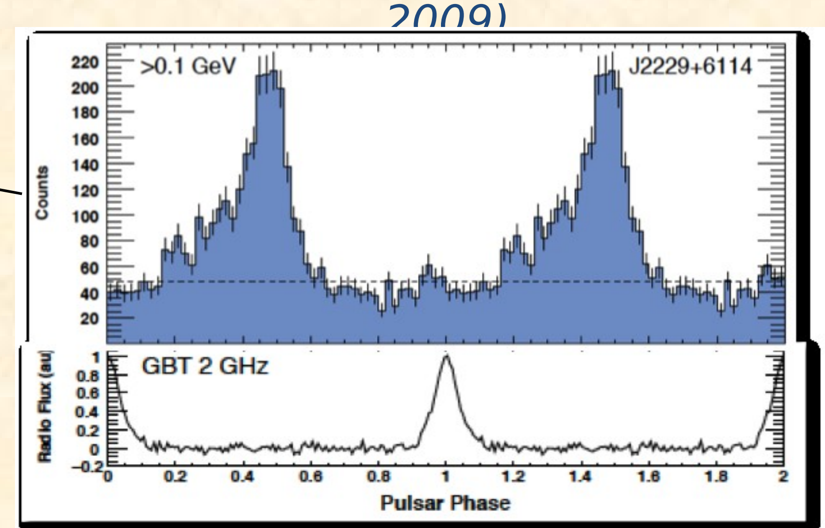




PSR J2021+3651, (Abdo et al. 2009)

Boomerang nebula

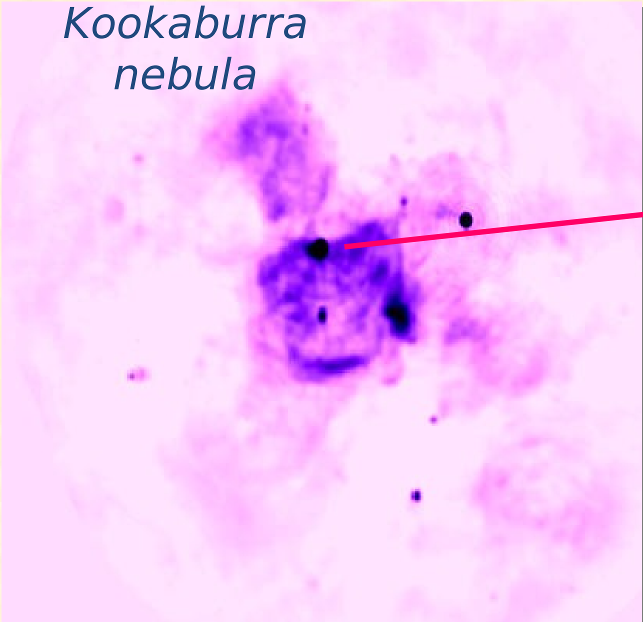


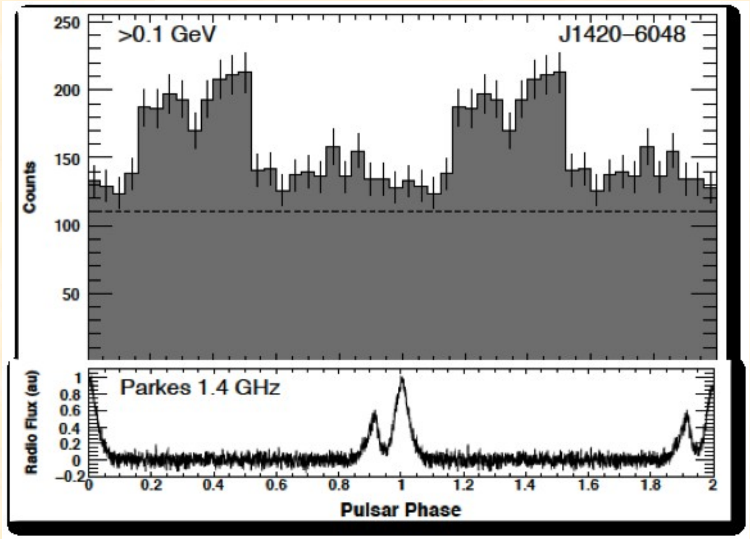


PSR J2229+6114, Abdo et al. 2009

Young radio-loud pulsars

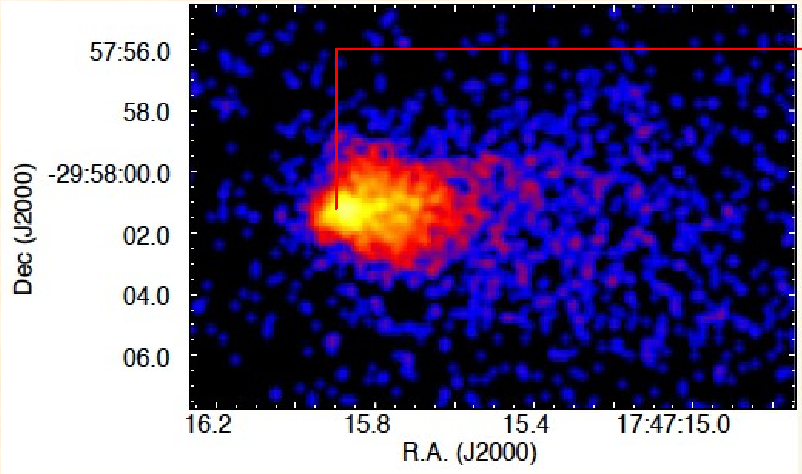
Kookaburra nebula

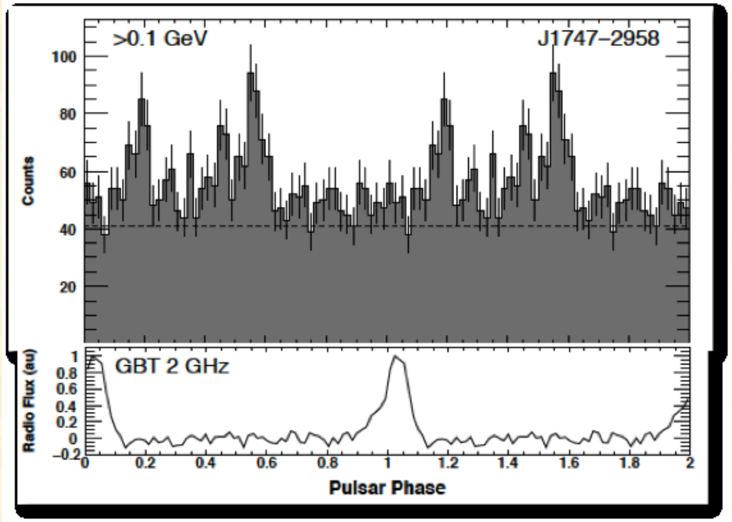




PSR J1420-6048, Abdo et al. 2010

Mouse nebula





PSR J1747-2958, Abdo et al. 2010

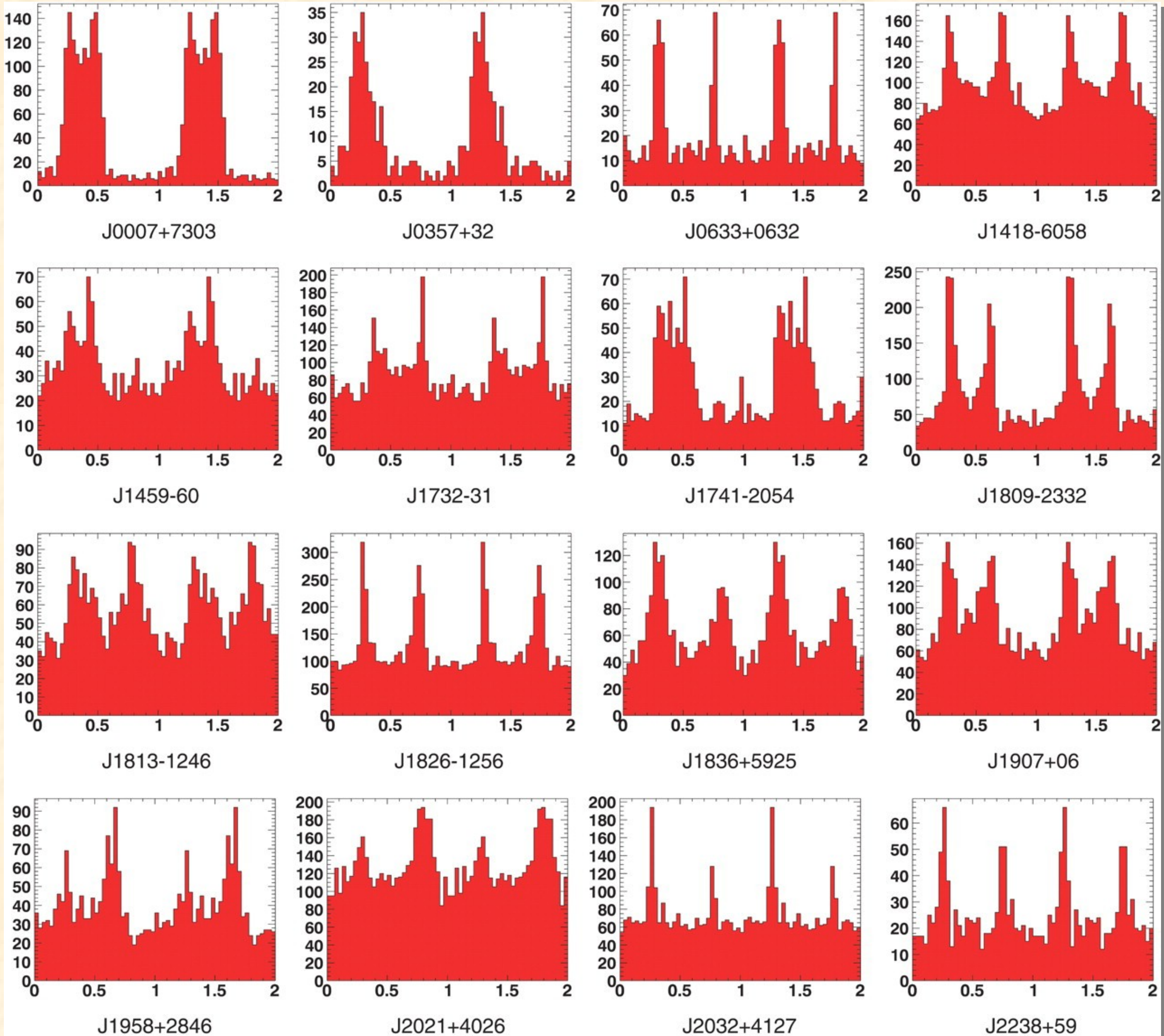
Pulsars Found in Blind Searches

After 4 months of data taking, 16 pulsars found with blind search technique!

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

13 were unidentified sources for EGRET

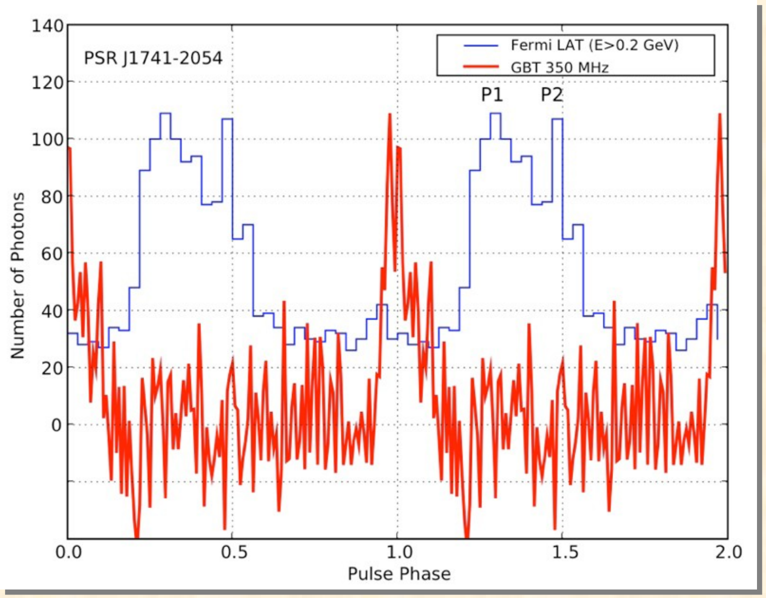
At present, 26



Radio Follow-up of New LAT Pulsars

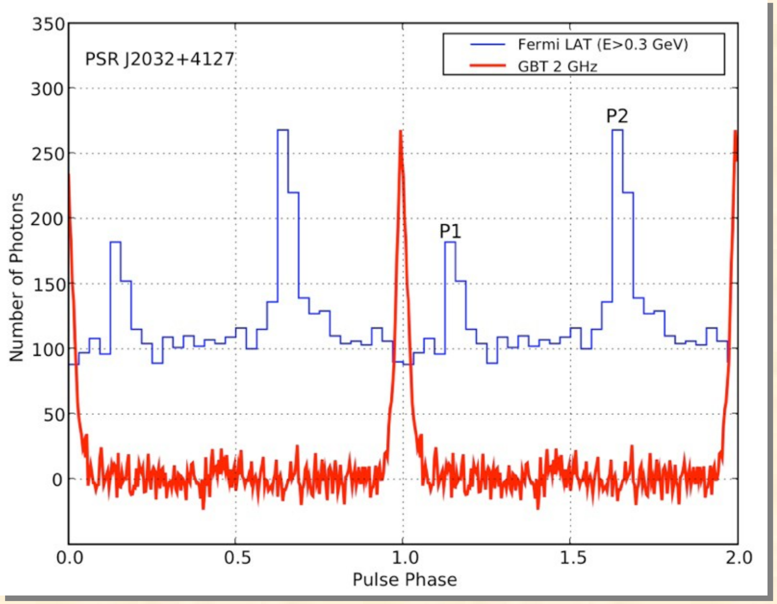
PSR J1741-2054

- 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)



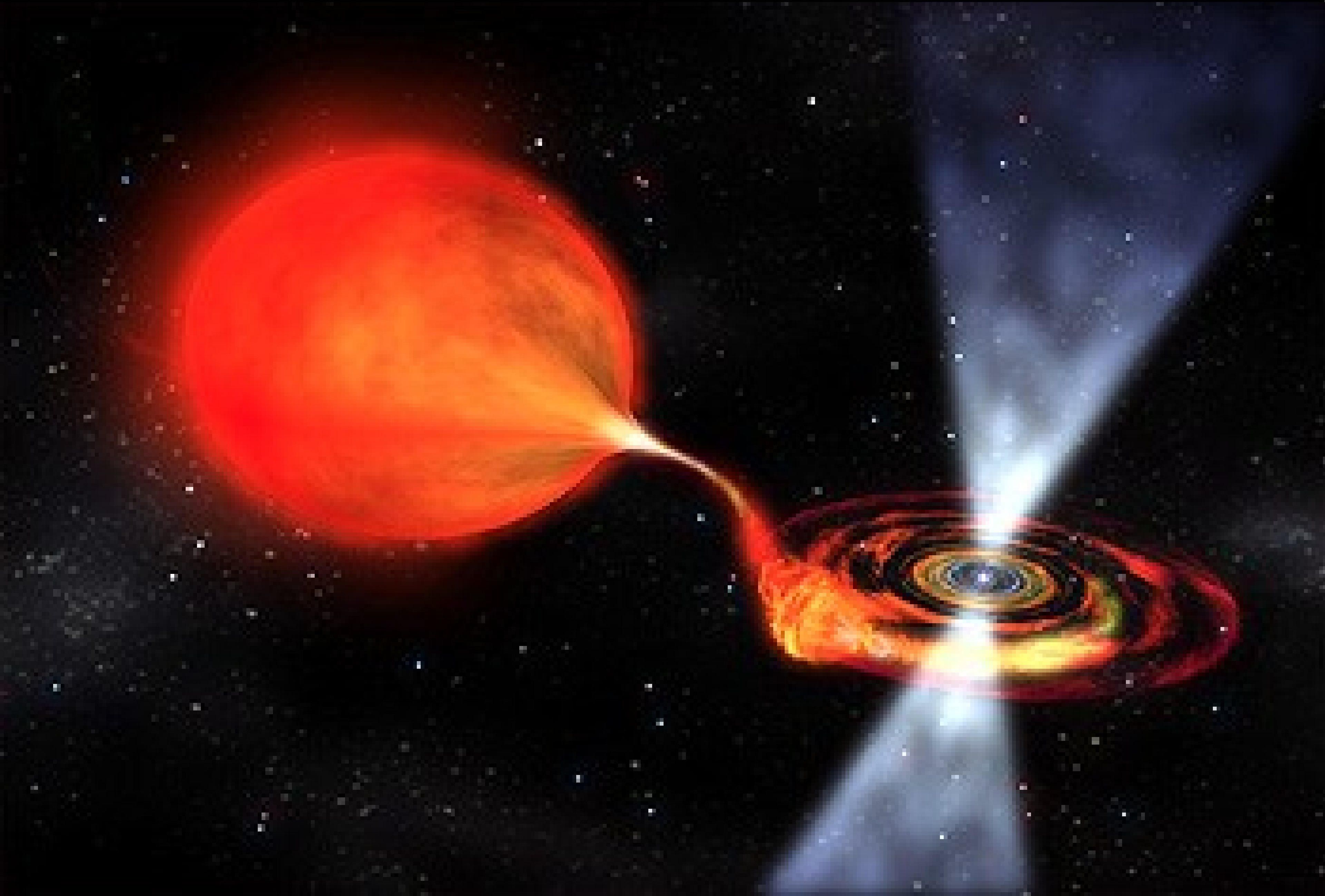
PSR J2032+4127

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



Camilo et al. 2009

Millisecond Pulsars

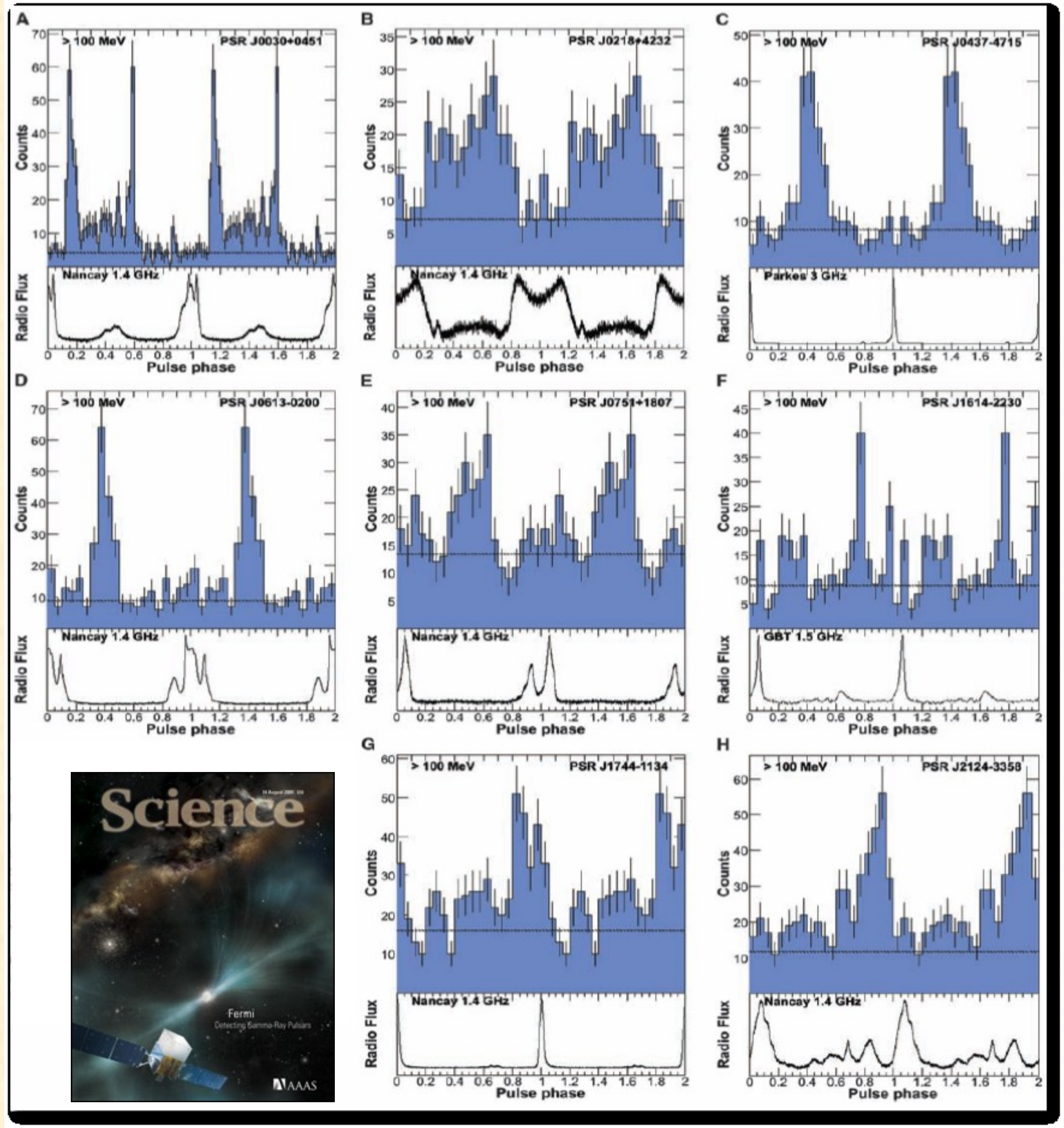


Gamma-ray MSPs – the Fermi original 8

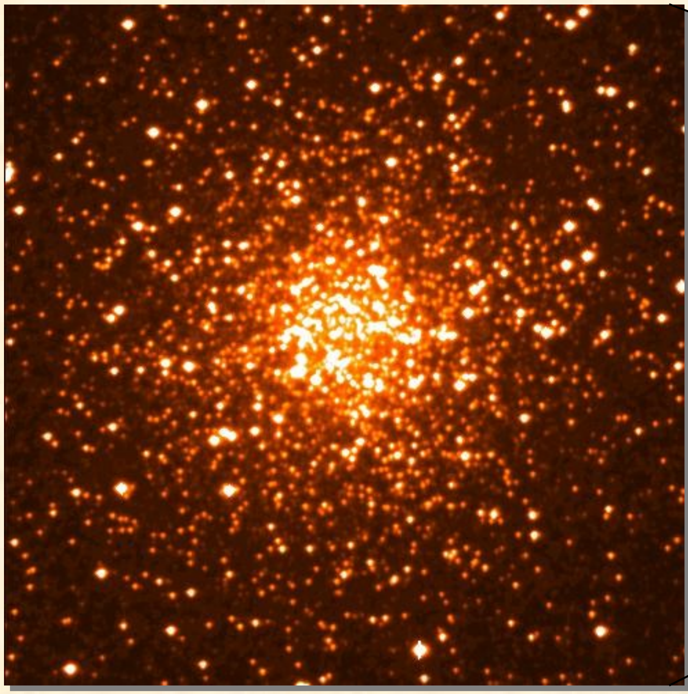
- With 9 months of data, the LAT had detected 8 gamma-ray MSPs (Abdo et al. Science 325, 848, 2009).

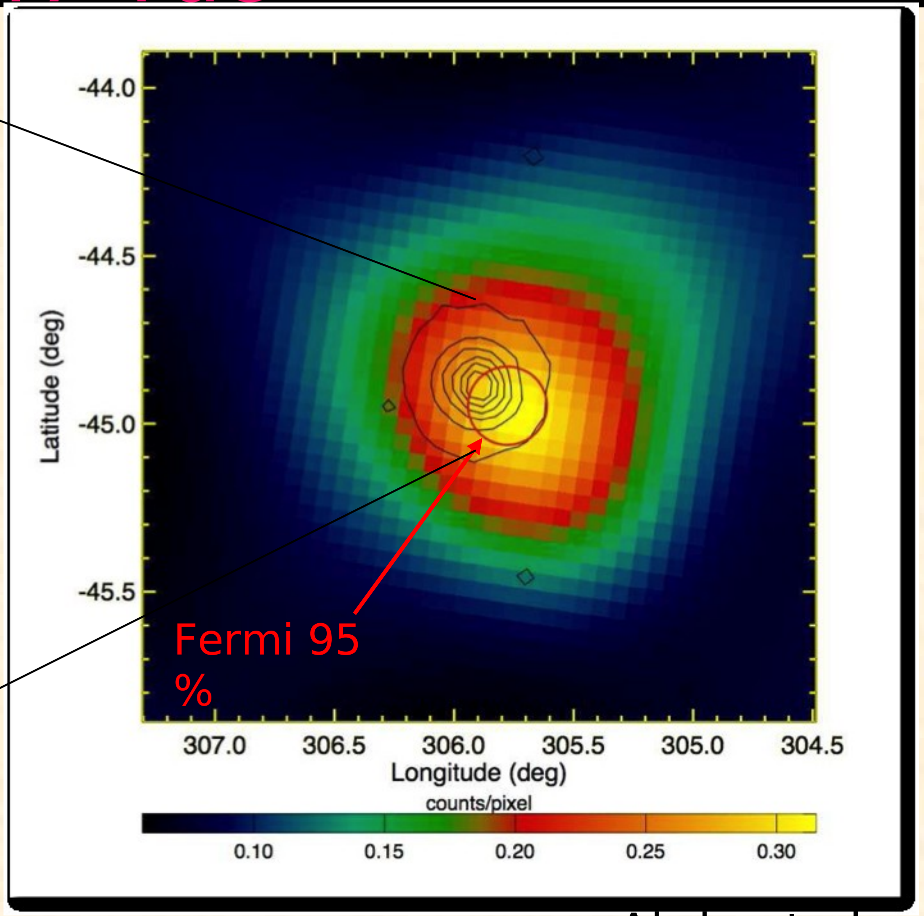
- Gamma-ray peaks not aligned with radio pulses

- Similar γ-ray characteristics to young pulsars



Fermi detection of globular cluster 47 Tuc



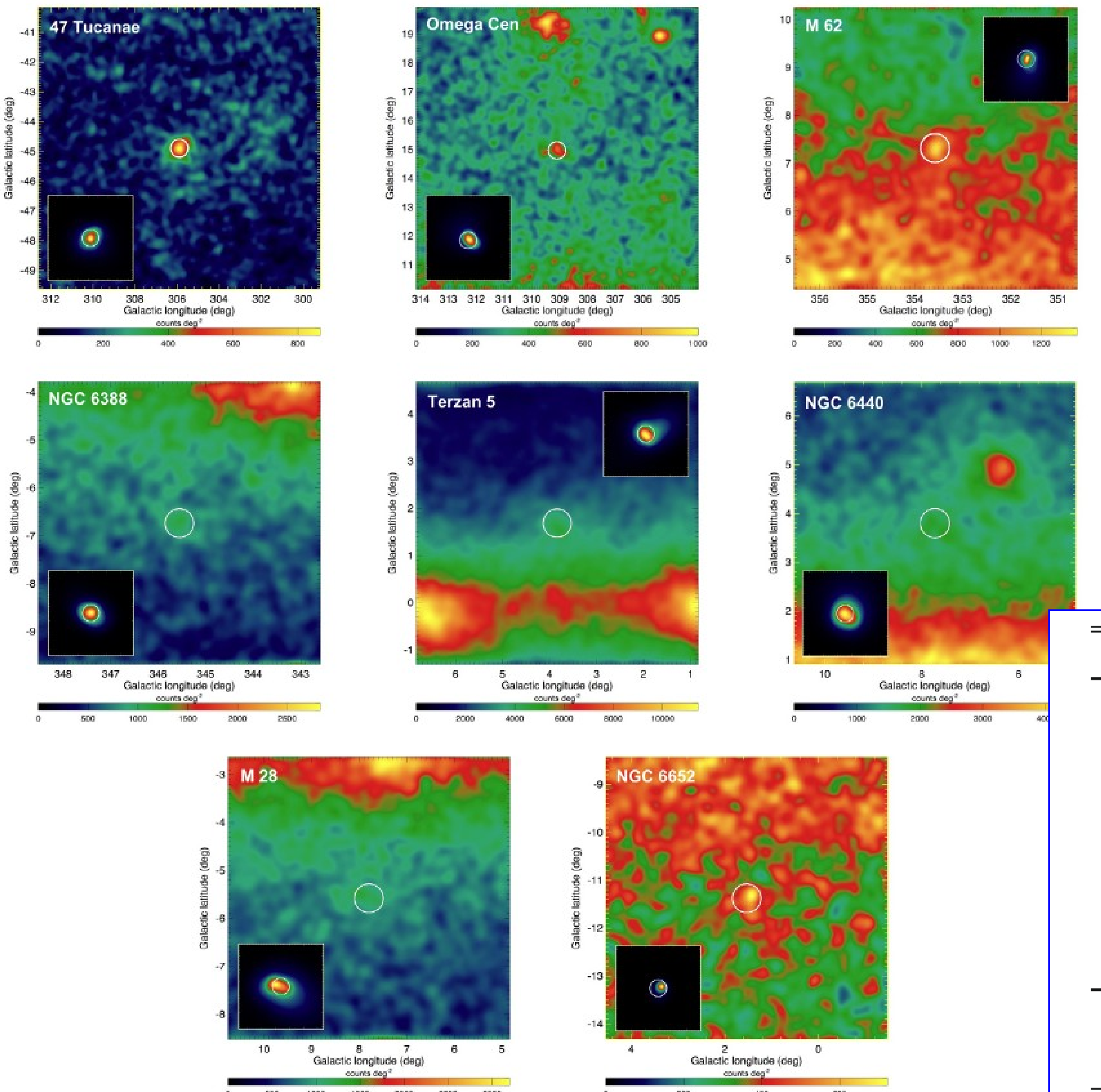


Abdo et al. 2009

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.

A population of γ-ray globular clusters



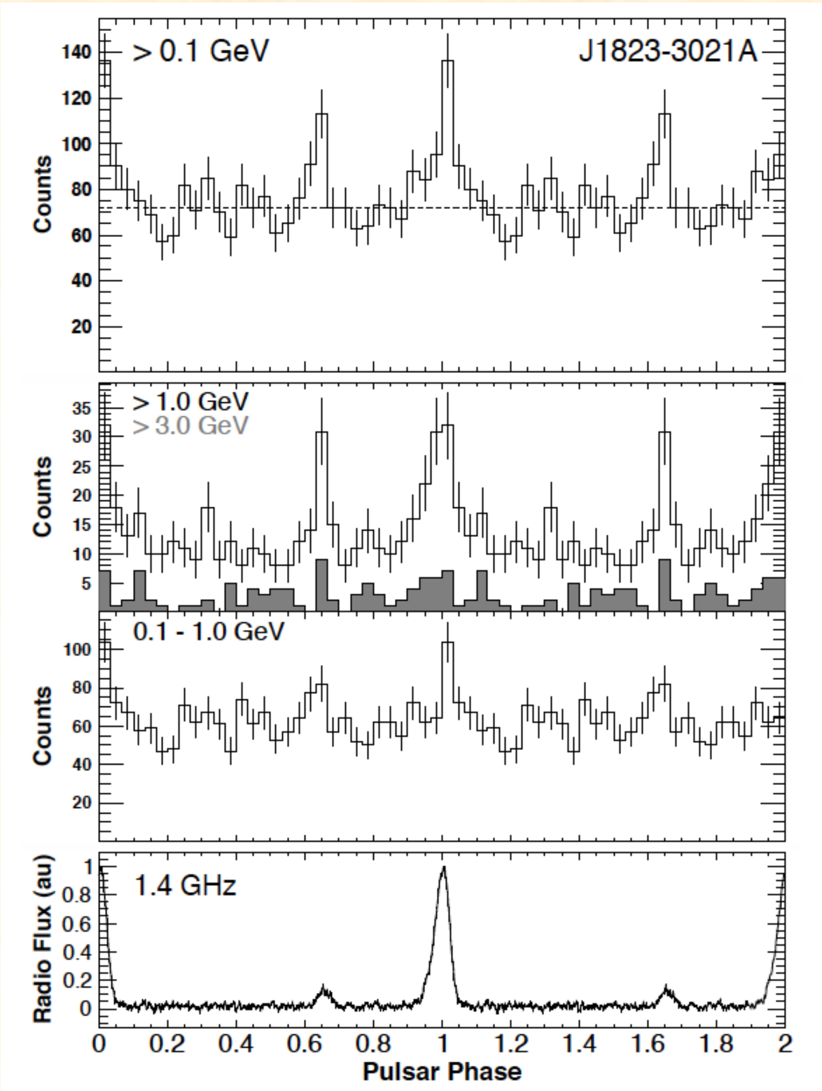
Abdo et al. 2010, A&A, 524, A75

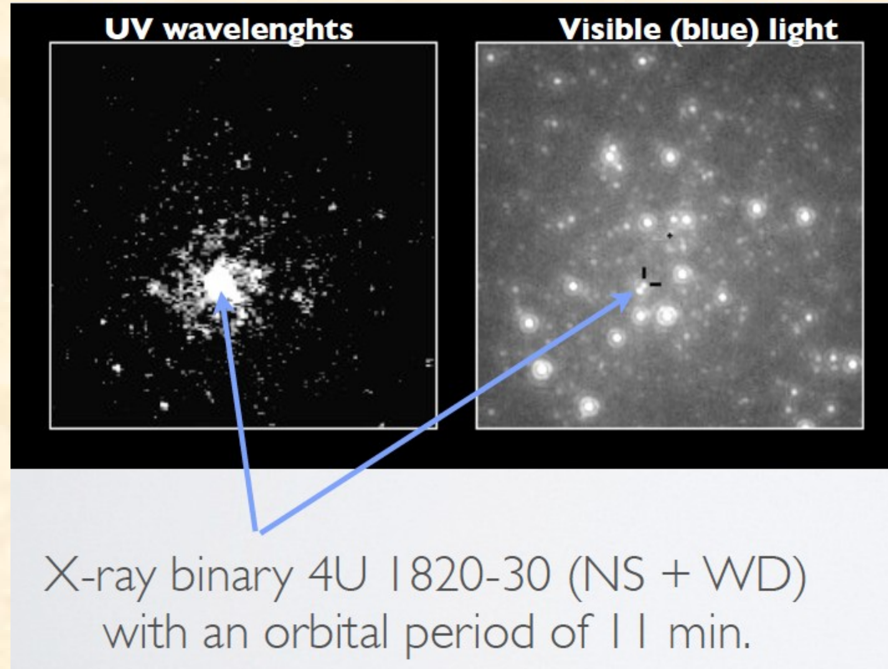
Also Liller 1, NGC 6624, and NGC 6752 (Tam et al. 2011)

Name	d (kpc)	L_γ (10^{34} erg s^{-1})	N_{MSP}
47 Tucanae	4.0 ± 0.4 [1]	$4.8^{+1.1}_{-1.1}$	33^{+15}_{-15}
Omega Cen	4.8 ± 0.3 [2]	$2.8^{+0.7}_{-0.7}$	19^{+9}_{-9}
M 62	6.6 ± 0.5 [3]	$10.9^{+3.5}_{-2.3}$	76^{+38}_{-34}
NGC 6388	11.6 ± 2.0 [4]	$25.8^{+14.0}_{-10.6}$	180^{+120}_{-100}
Terzan 5	5.5 ± 0.9 [5]	$25.7^{+9.4}_{-8.8}$	180^{+100}_{-90}
NGC 6440	8.5 ± 0.4 [6]	$19.0^{+13.1}_{-5.0}$	130^{+100}_{-60}
M 28	5.1 ± 0.5 [7]	$6.2^{+2.6}_{-1.8}$	43^{+24}_{-21}
NGC 6652	9.0 ± 0.9 [8]	$7.8^{+2.5}_{-2.1}$	54^{+27}_{-25}
NGC 6541	6.9 ± 0.7 [9]	<4.7	<47
NGC 6752	4.4 ± 0.1 [10]	<1.1	<11
M 15	10.3 ± 0.4 [11]	<5.8	<56

First γ-ray MSP in a globular cluster

In NGC 6624 preliminary

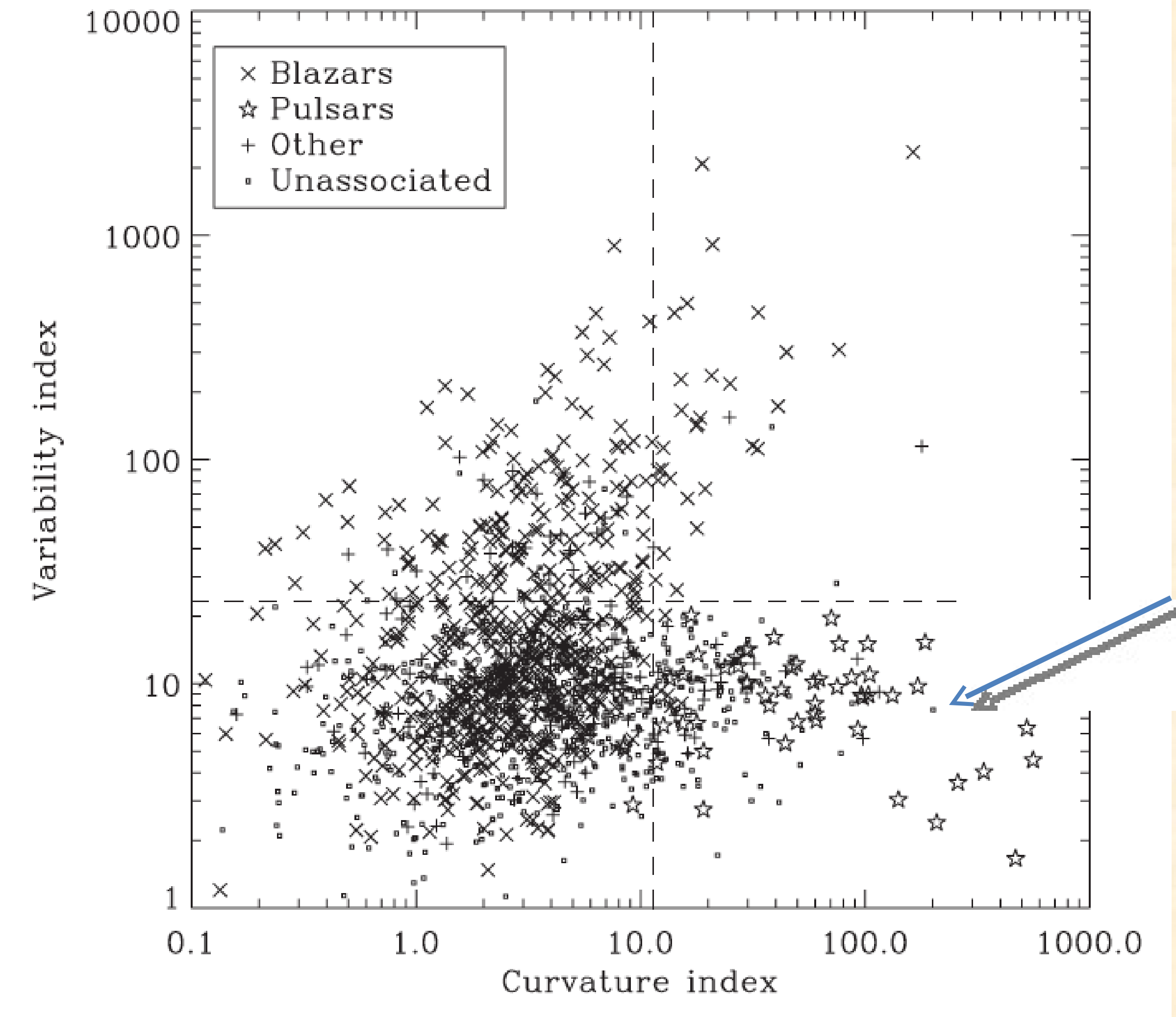




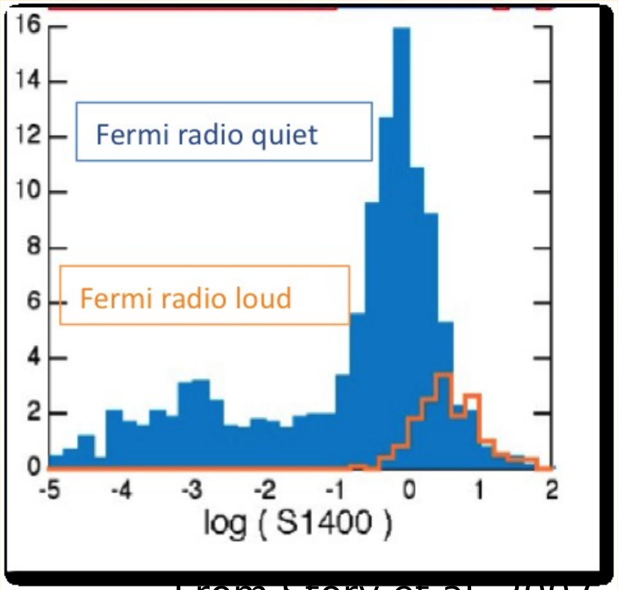
High spin-down luminosity
E = 8.3 x 10^{35} erg/s
and gamma-ray luminosity
L_γ = 8.4 x 10^{34} erg/s

Freire et al. 2011

Radio observations of unidentified Fermi sources



From Abdo et al. 2010



From Story et al. 2007

Pulsars have low variability and high spectral curvature

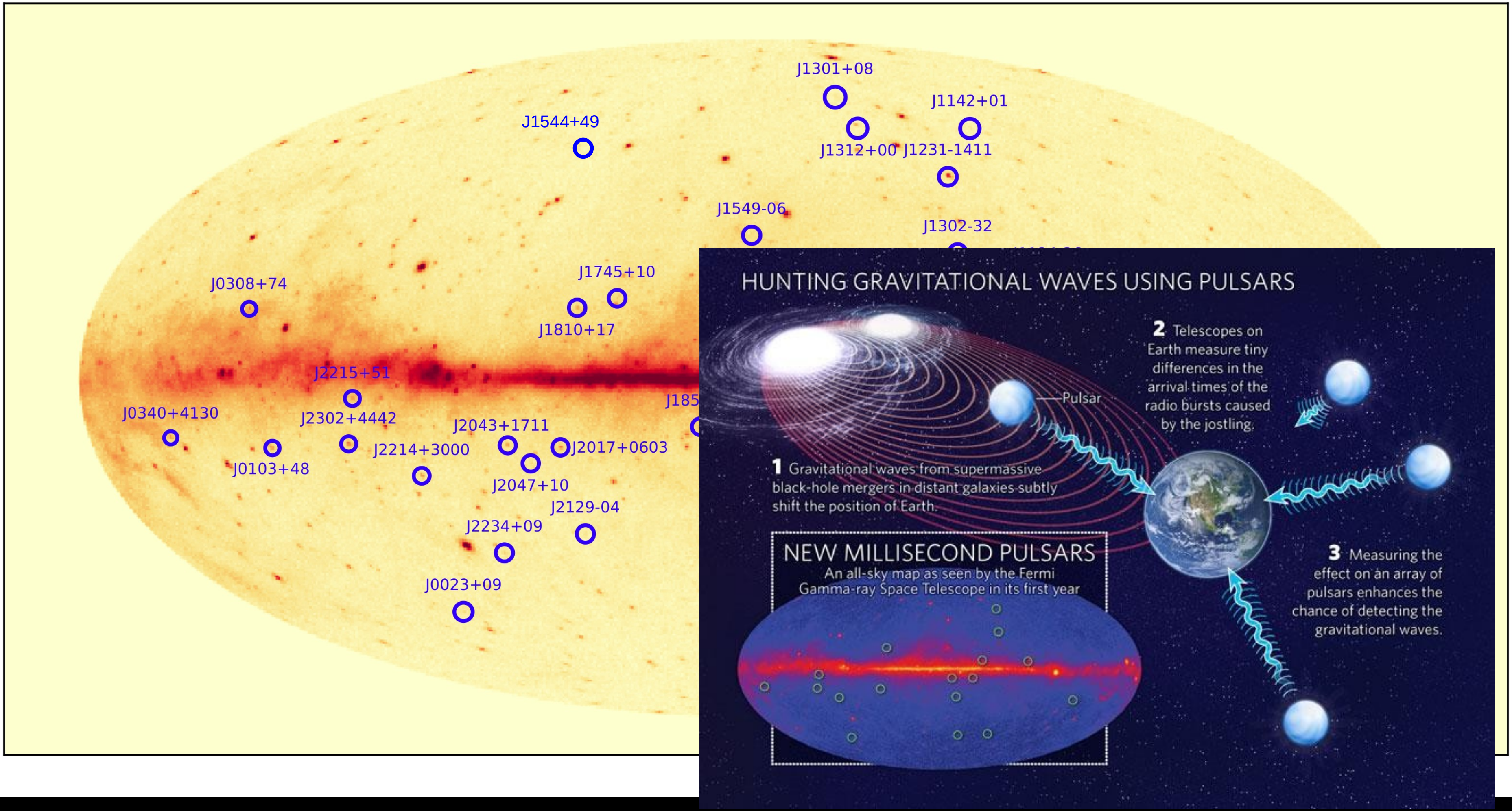
Who is searching?

Fermi Pulsar Search Consortium

- radio astronomers
- members of Fermi Coll.

MSPs discovered in Fermi unID sources

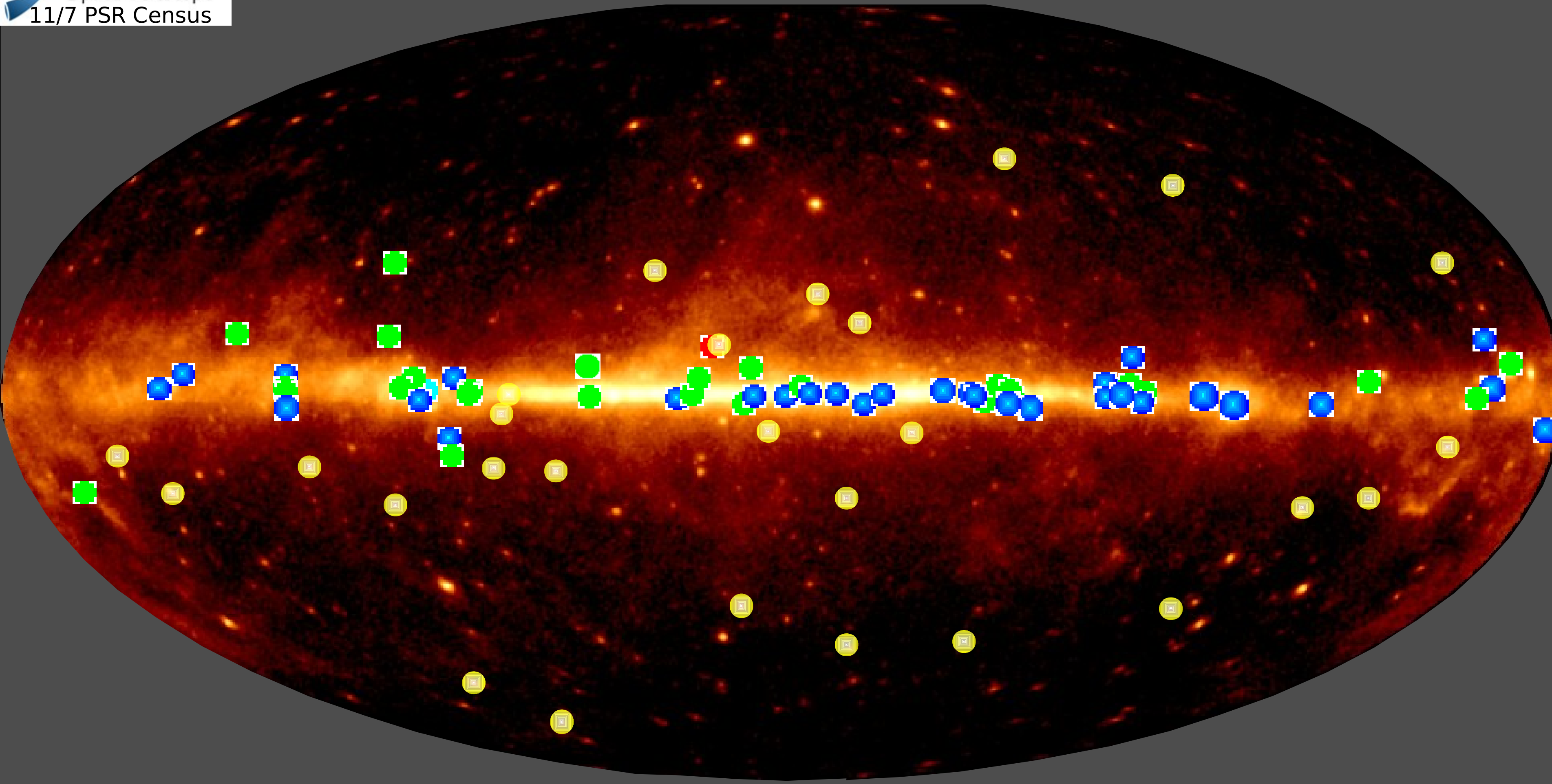
34 new radio MSPs discovered in Fermi unidentified sources! – so far



Credit: Paul Ray

Fermi
Gamma-ray Space Telescope
11/7 PSR Census

The LAT Pulsar Sky



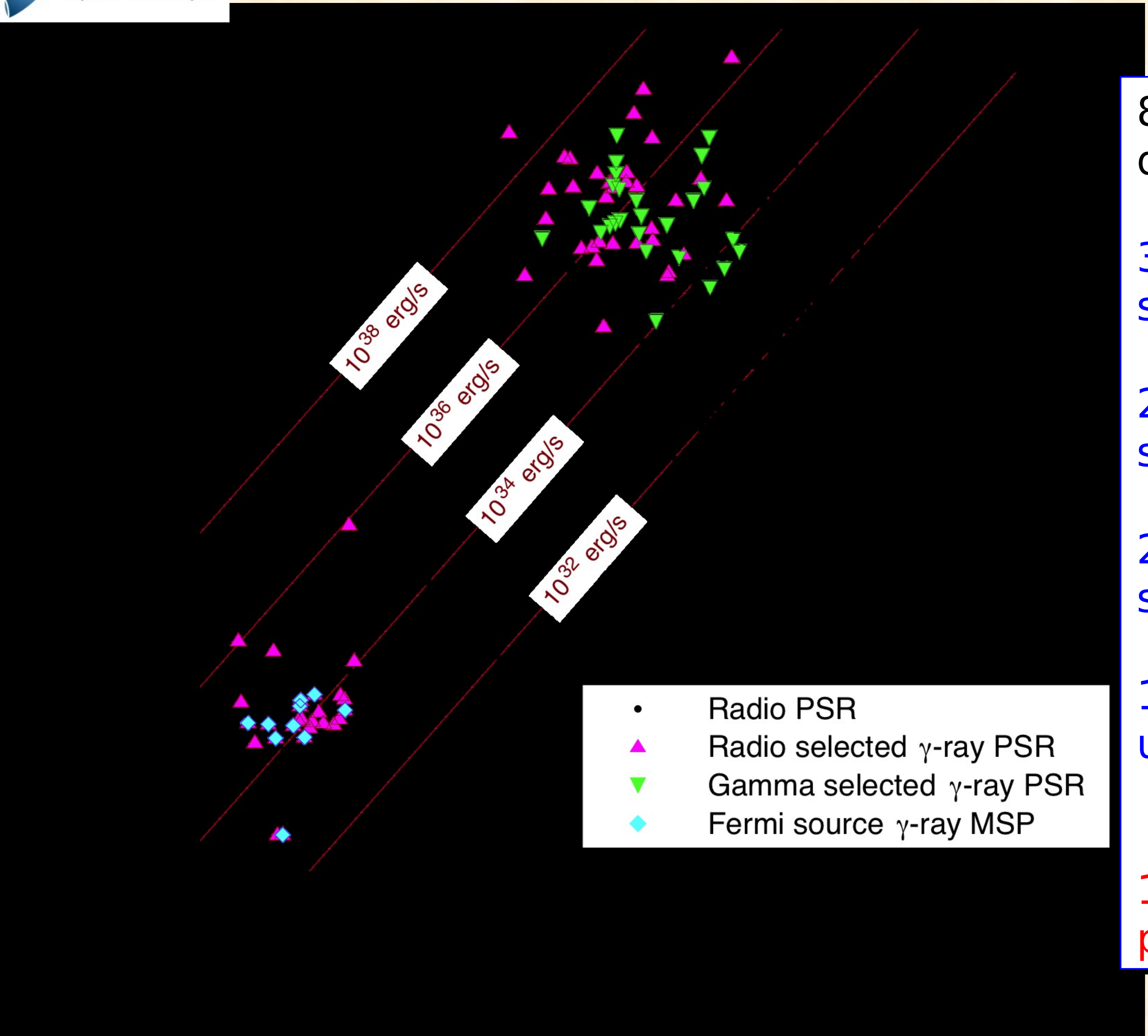
34 Young Radio-selected

27 Young γ-selected

27 MSP Radio-selected

Credit: LAT Coll. and R.

Fermi gamma-ray pulsars



88 γ-ray pulsars detected

34 young radio selected

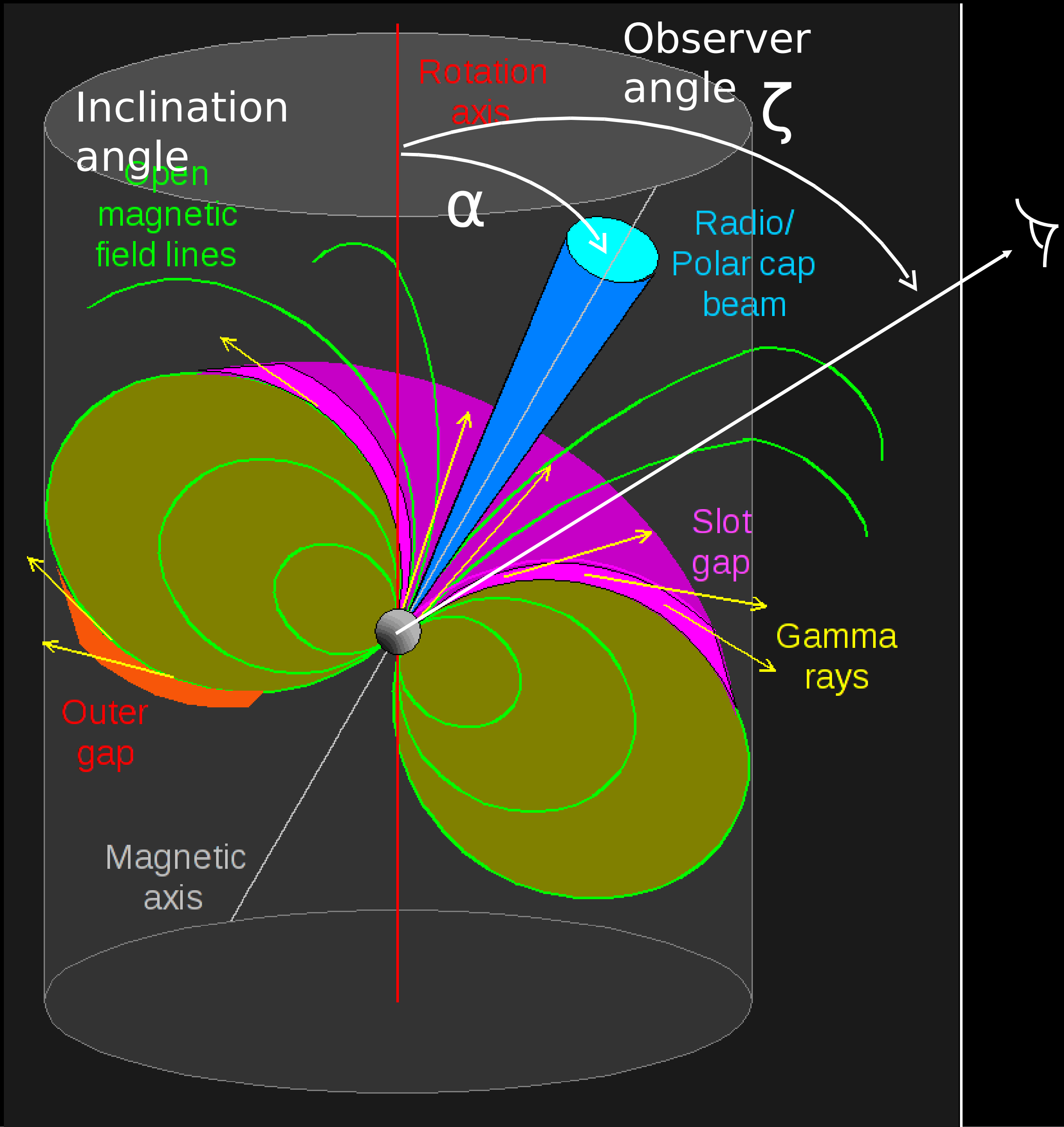
27 young γ-ray selected

27 MSPs radio selected

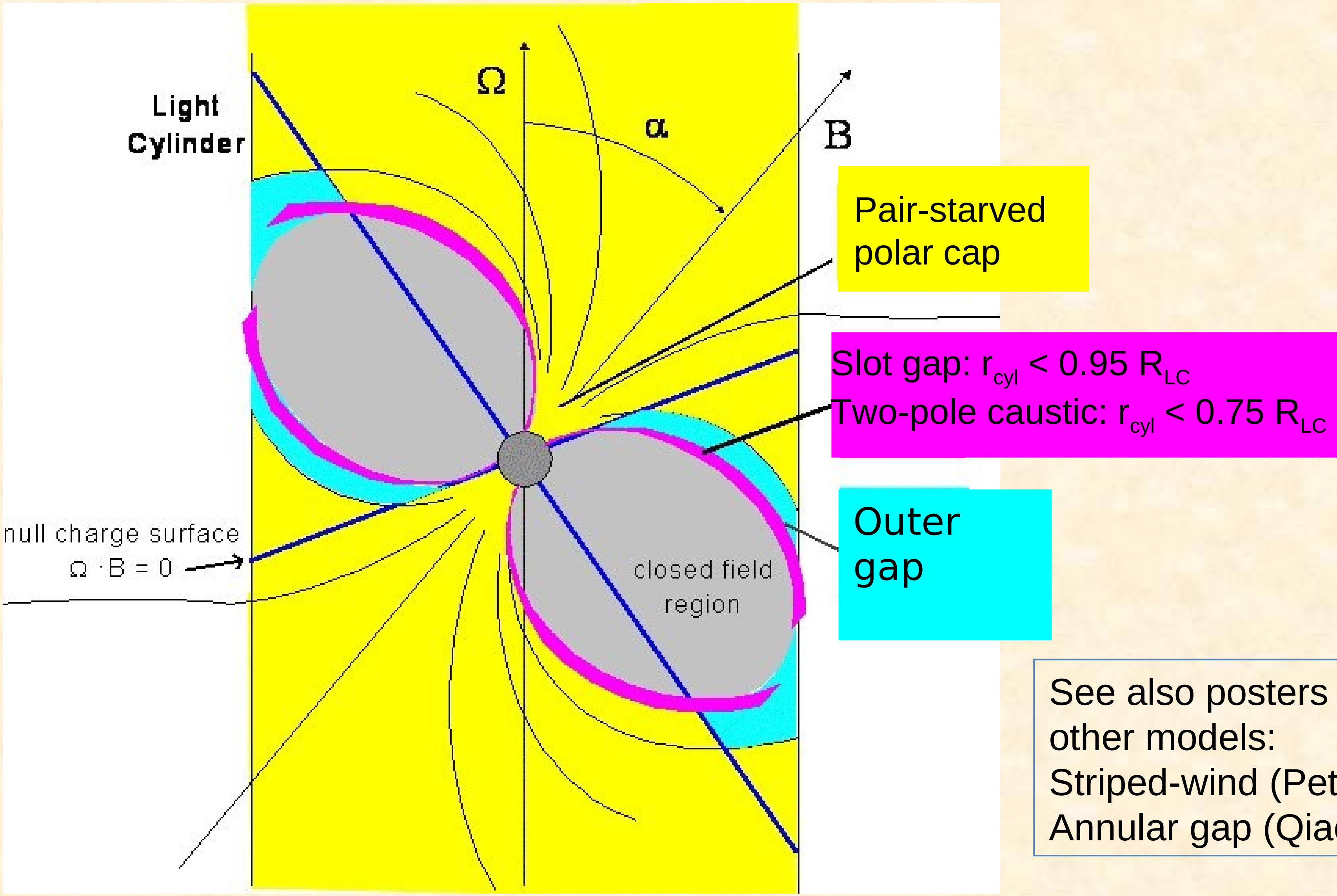
10 new MSPs in Fermi unID

10% of MSP are γ-ray pulsars!

Where do the pulsations come from?

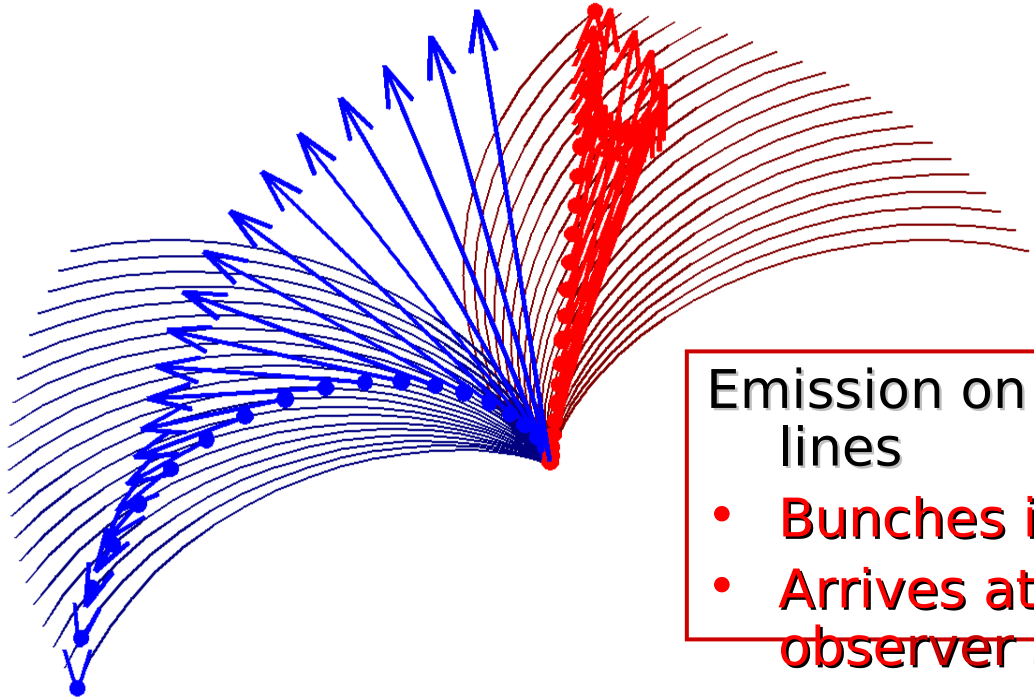


Pulsar particle accelerators



See also posters on other models:
Striped-wind (Petri)
Annular gap (Qiao)

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

- In narrow gaps along edge of open volume
- Phase delays from aberration, light travel time and field line curvature cancel

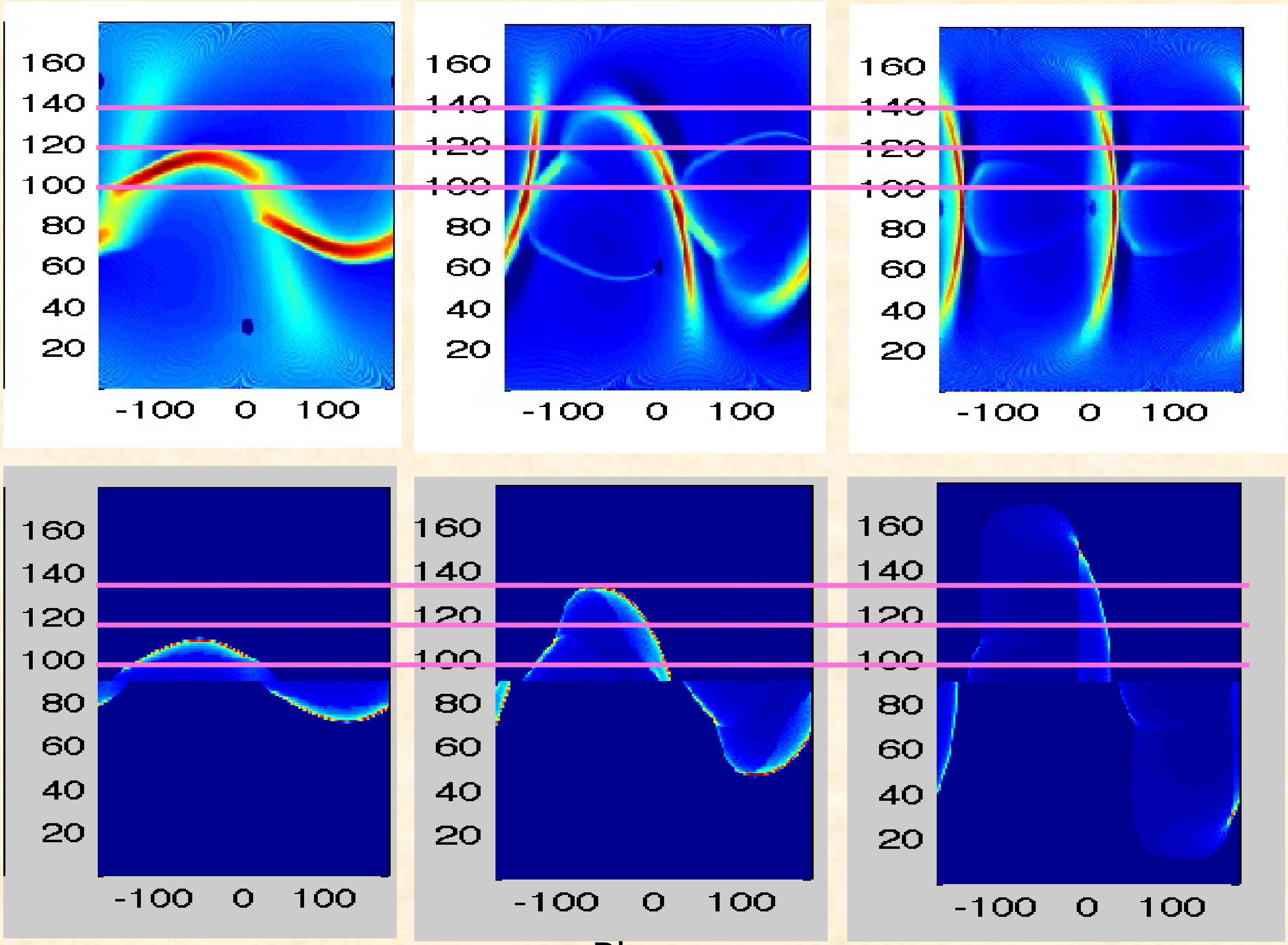
Sky distribution of intensity

Pulsar inclination α = 30⁰ α = 60⁰ α = 90⁰

Slot gap

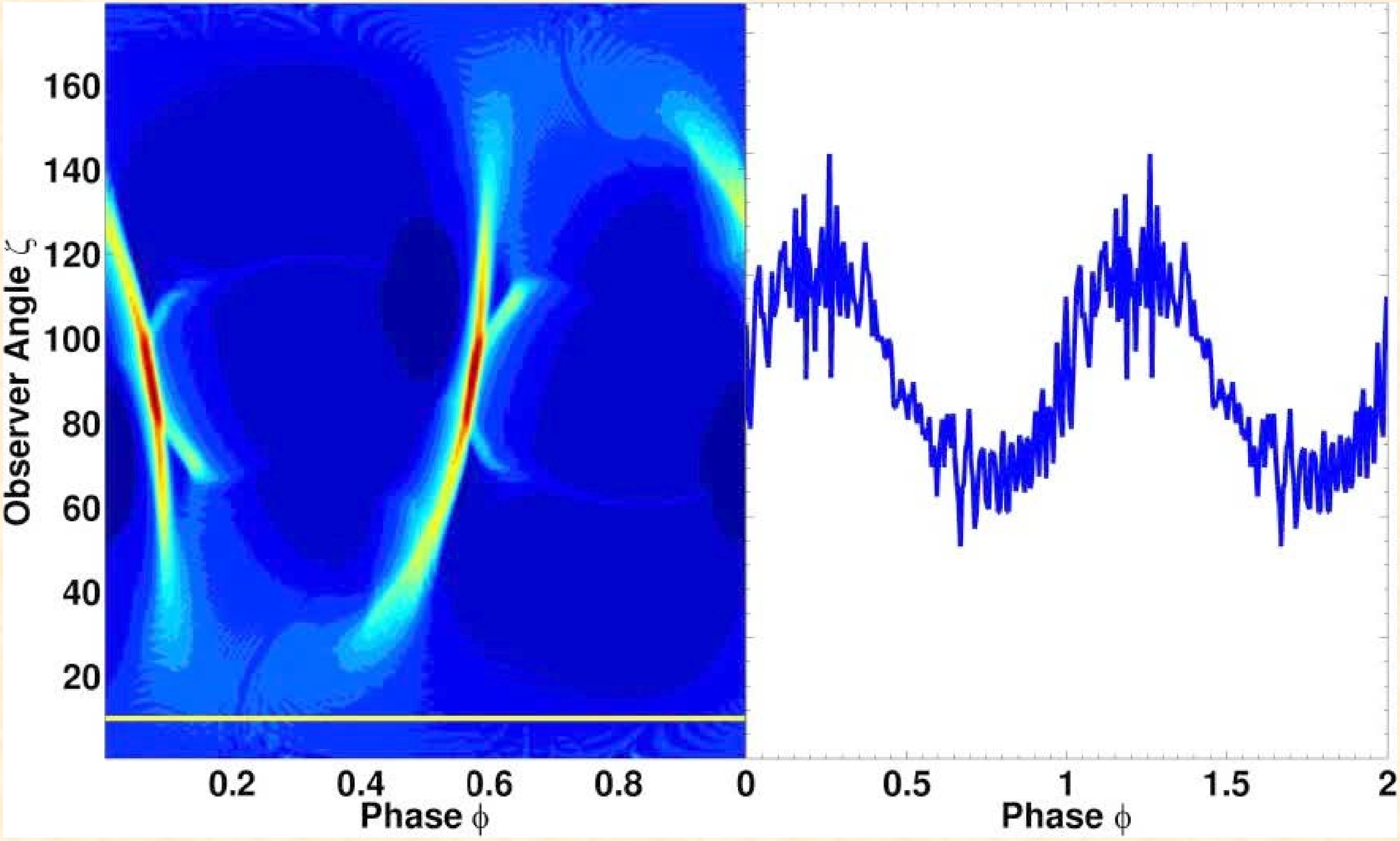
Observer angle

Outer gap



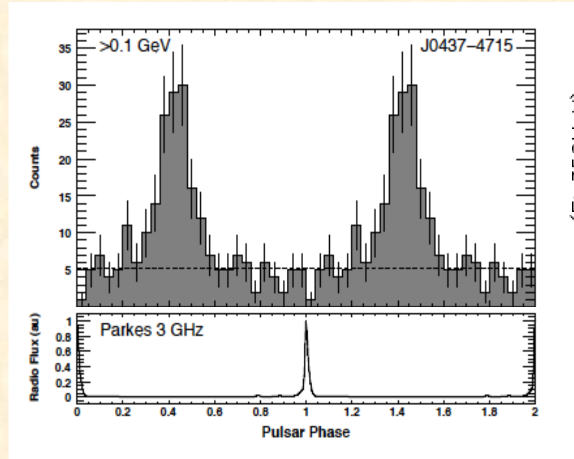
Phase

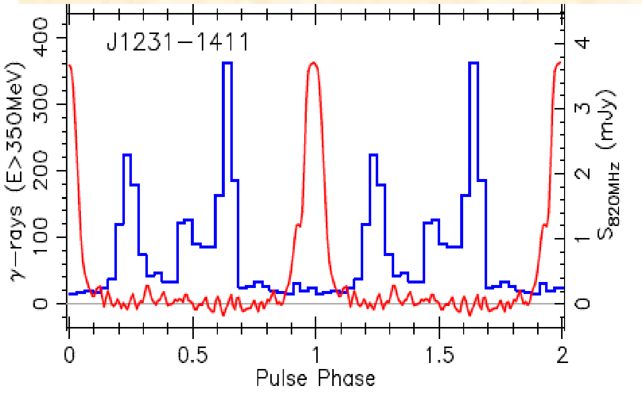
Light Curve vs. Viewing Angle



MSPs light curve types

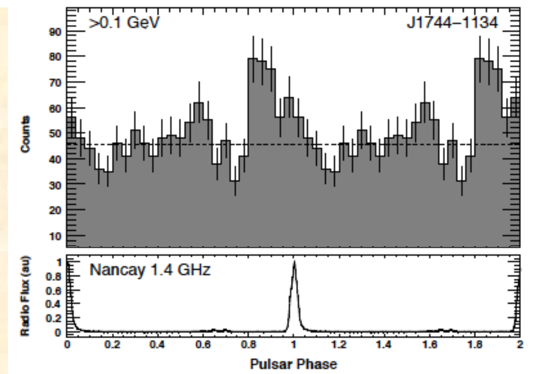
1. γ-ray peak(s) lag main radio peak
   – similar to young pulsars





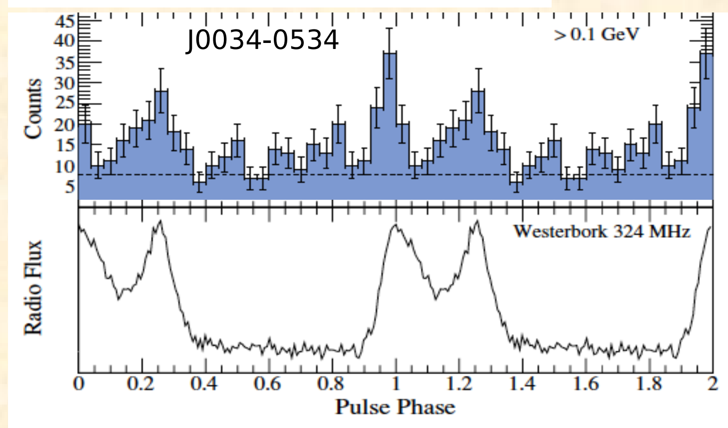
Ransom et al. 2011

1. γ-ray peak(s) lead main radio peak
   – Exclusive to MSPs



Abdo et al. 2010

1. γ-ray peaks aligned with radio peaks
   – *Nearly* exclusive to MSPs



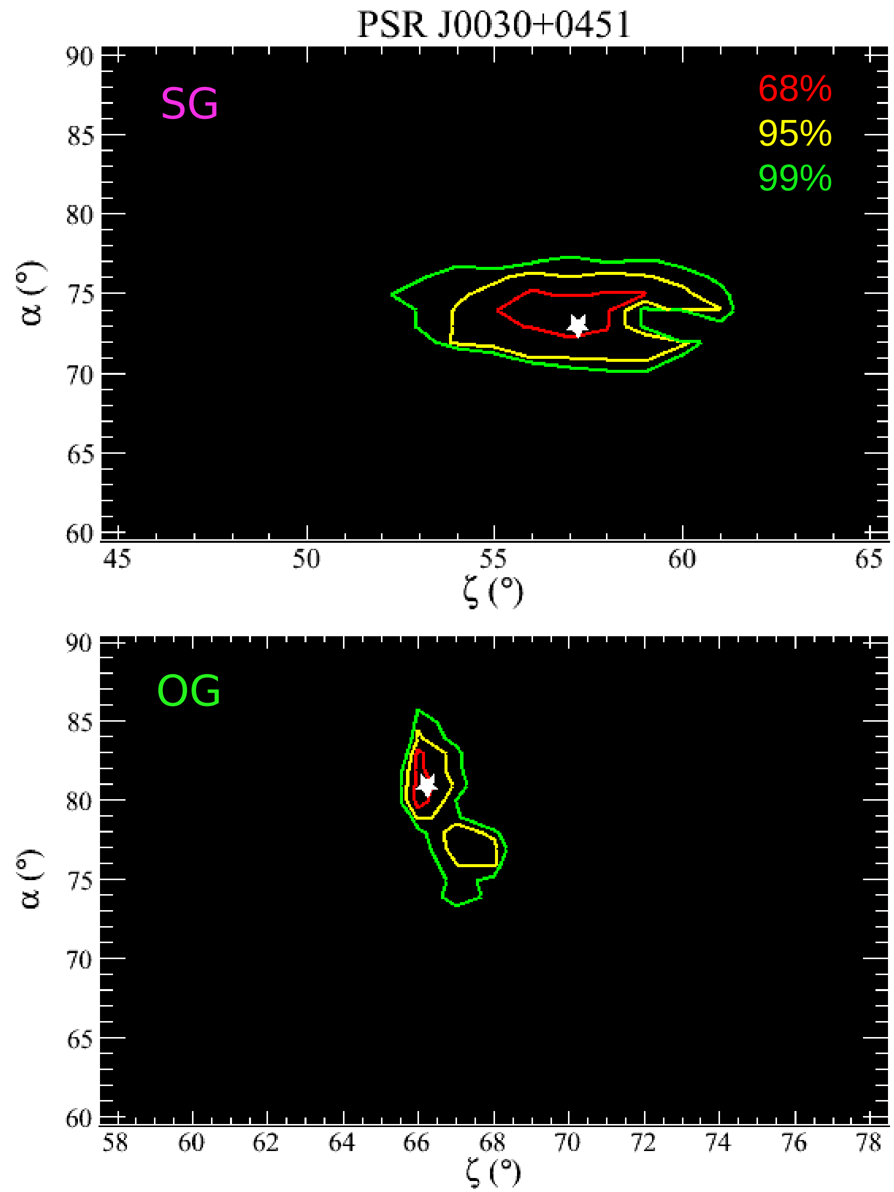
Abdo et al. 2010

PSR J0030+0451

Tyrel Johnson PhD thesis (University of Maryland 2011)

OG, α = 81 , ζ = 66 , -log(L)=321,

preliminary



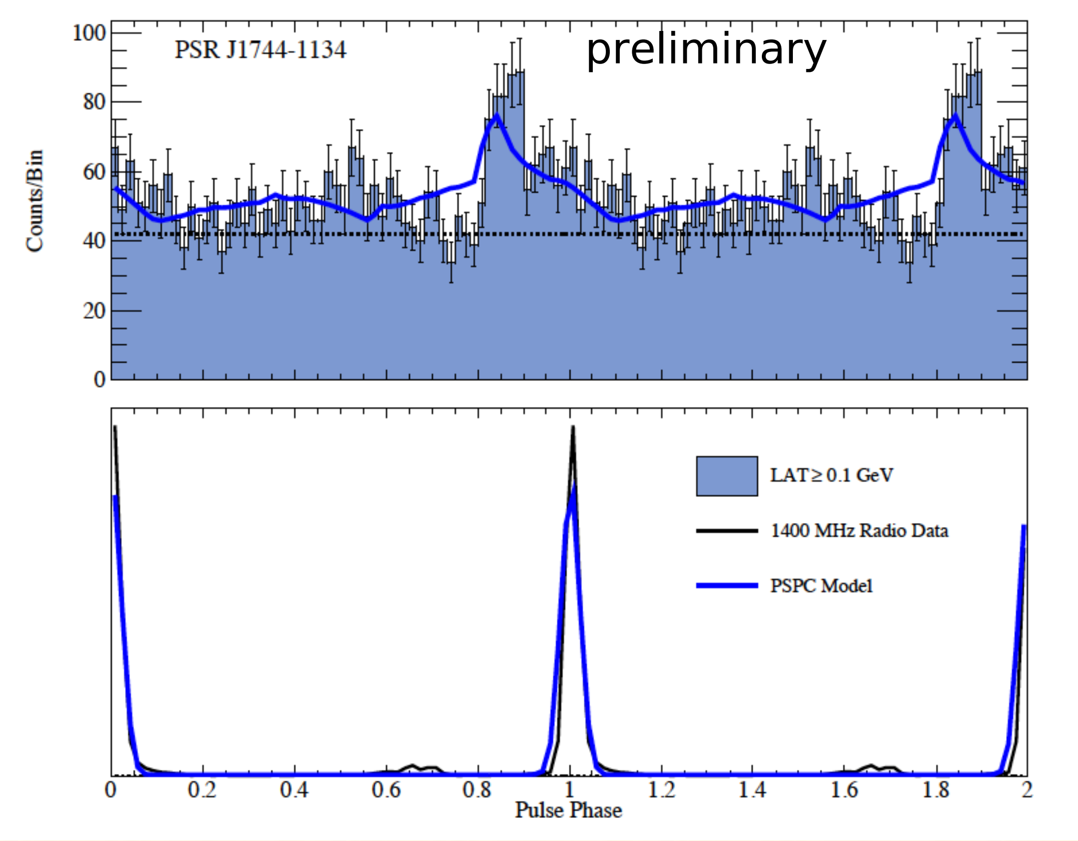
w=0

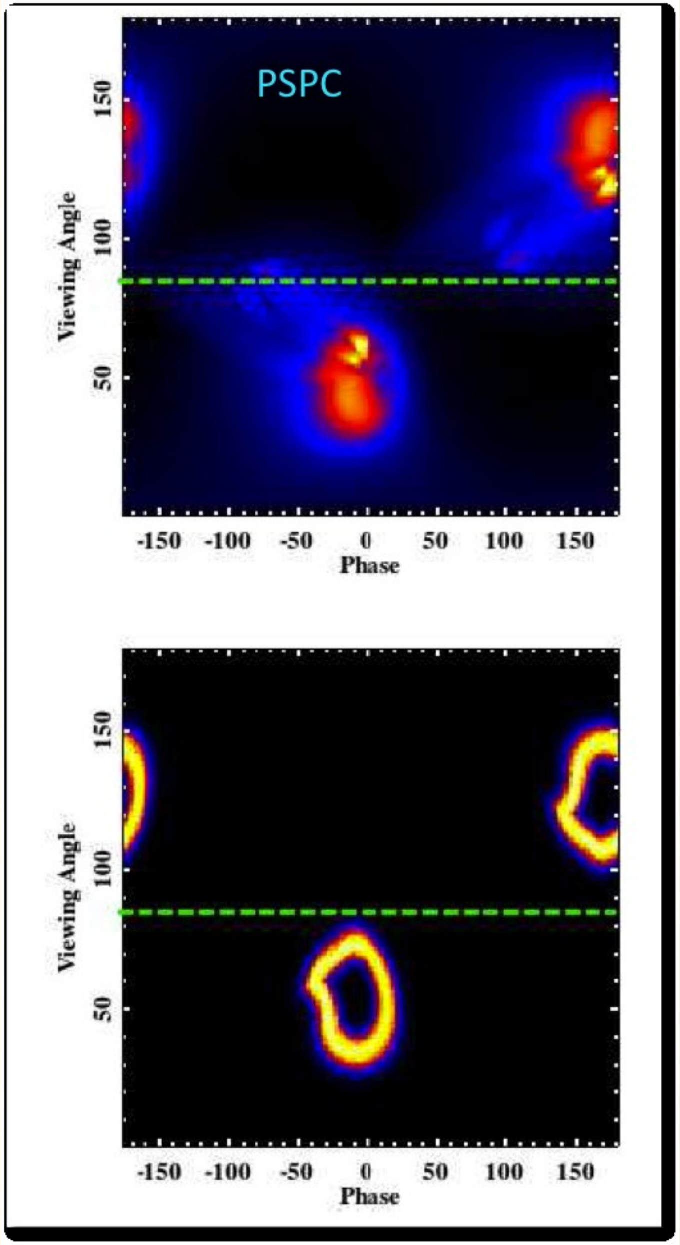
Markov Chain Monte Carlo maximum likehood fits

PSR J1744-1134

Pair-starved polar cap

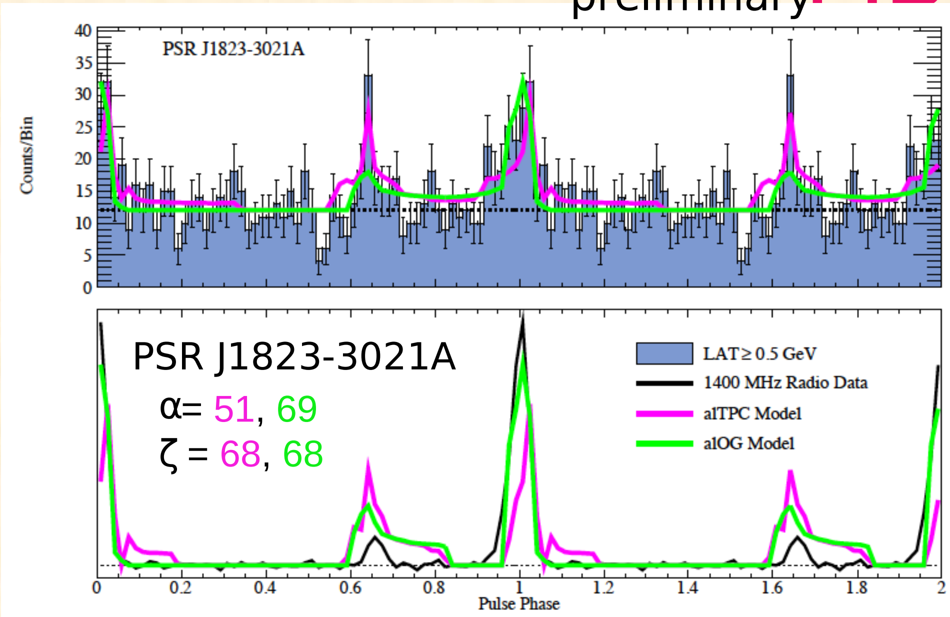
PSPC, α = 51 0, ζ = 85 0,
-log(L)=227

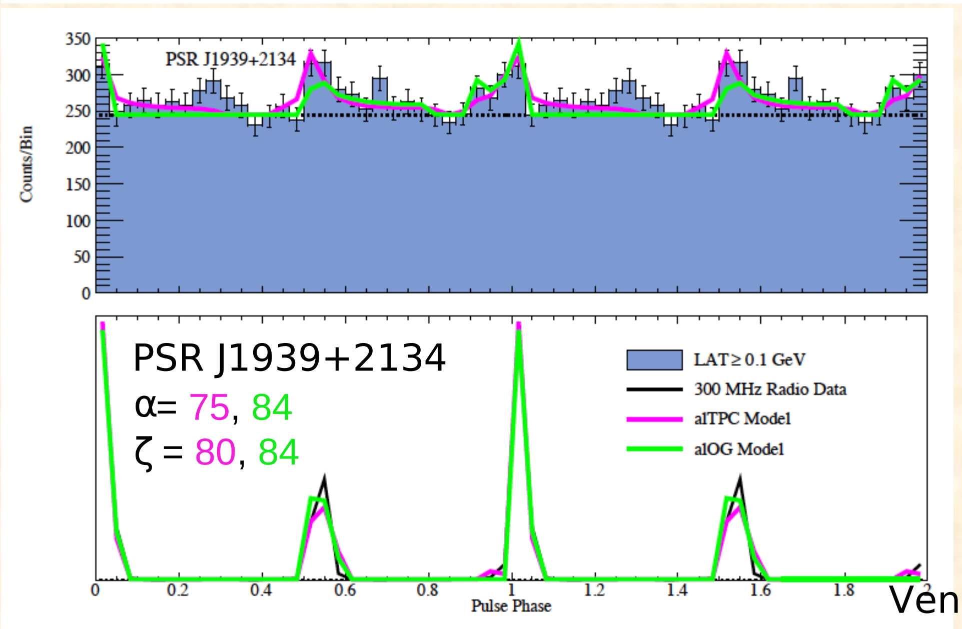


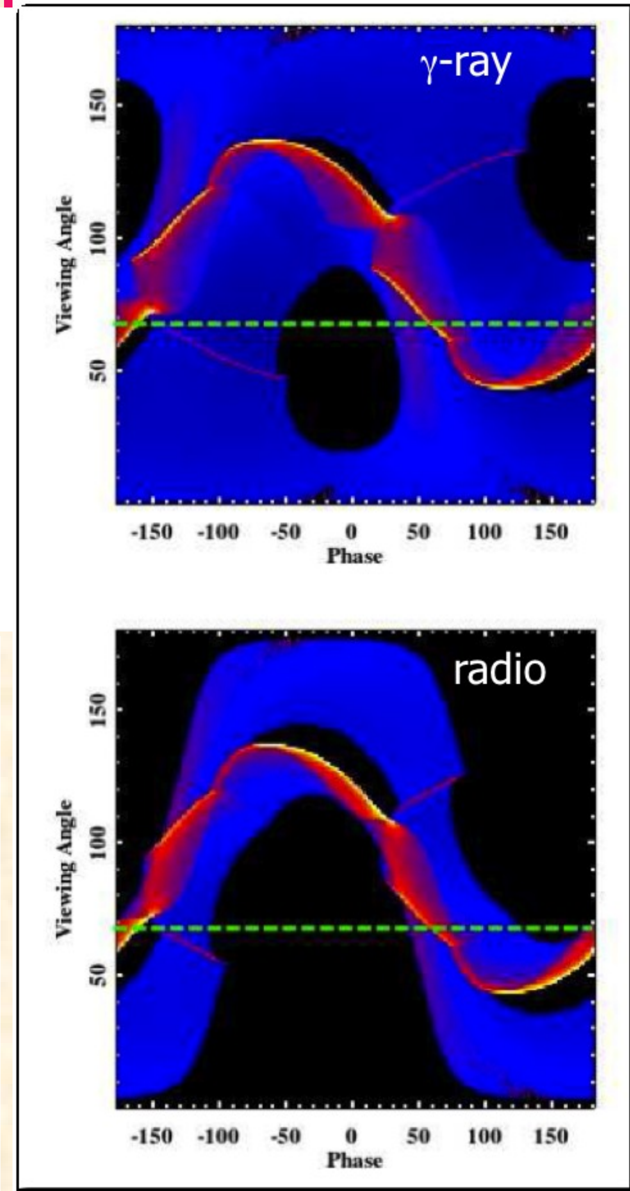


Maximum likelihood fits of aligned MSPs

preliminary







γ- ray and radio emission both caustic but with different altitude ranges:

R^{γ}_{max} = 1.0 R_{LC}

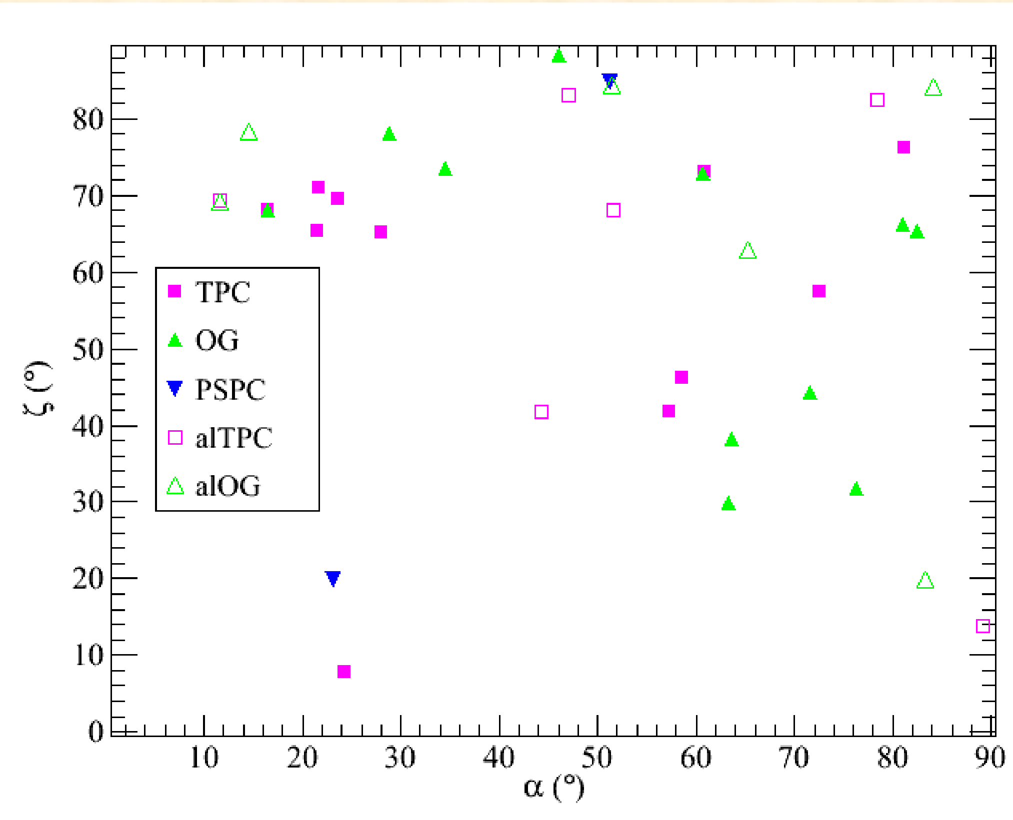
J1823-3021A

R^{r}_{min} = 0.2, 0.2 R_{LC}

R^{r}_{max} = 0.9,0.8 R_{LC}

Venter et al. 2011, Parent et al. 2011, Johnson et al, 2

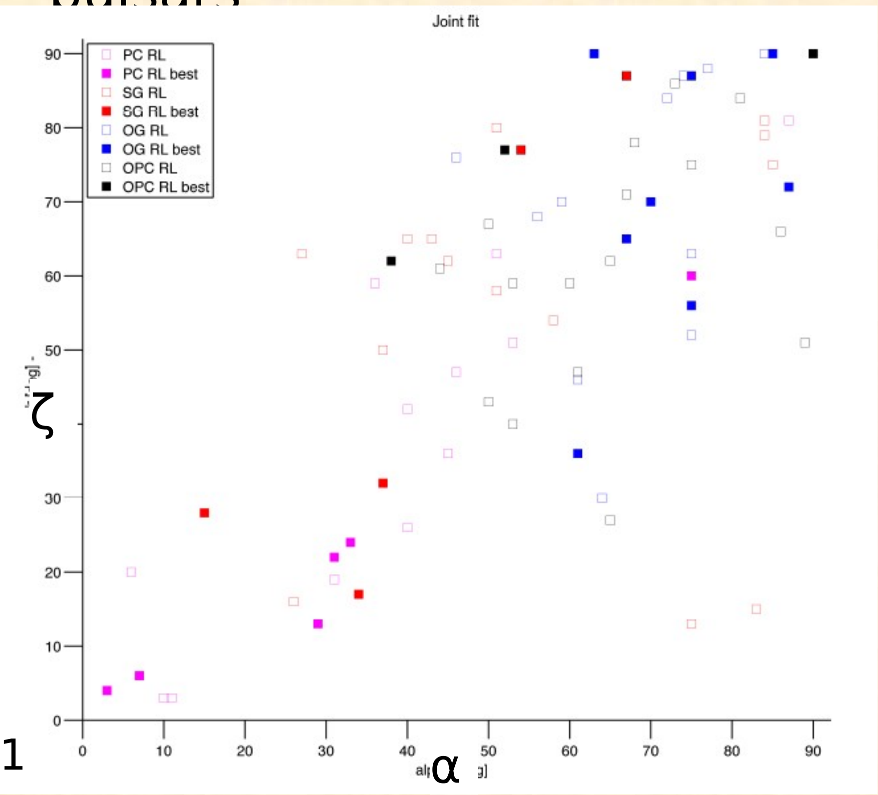
Fit results for 19 MSPs



Johnson et al, 2011

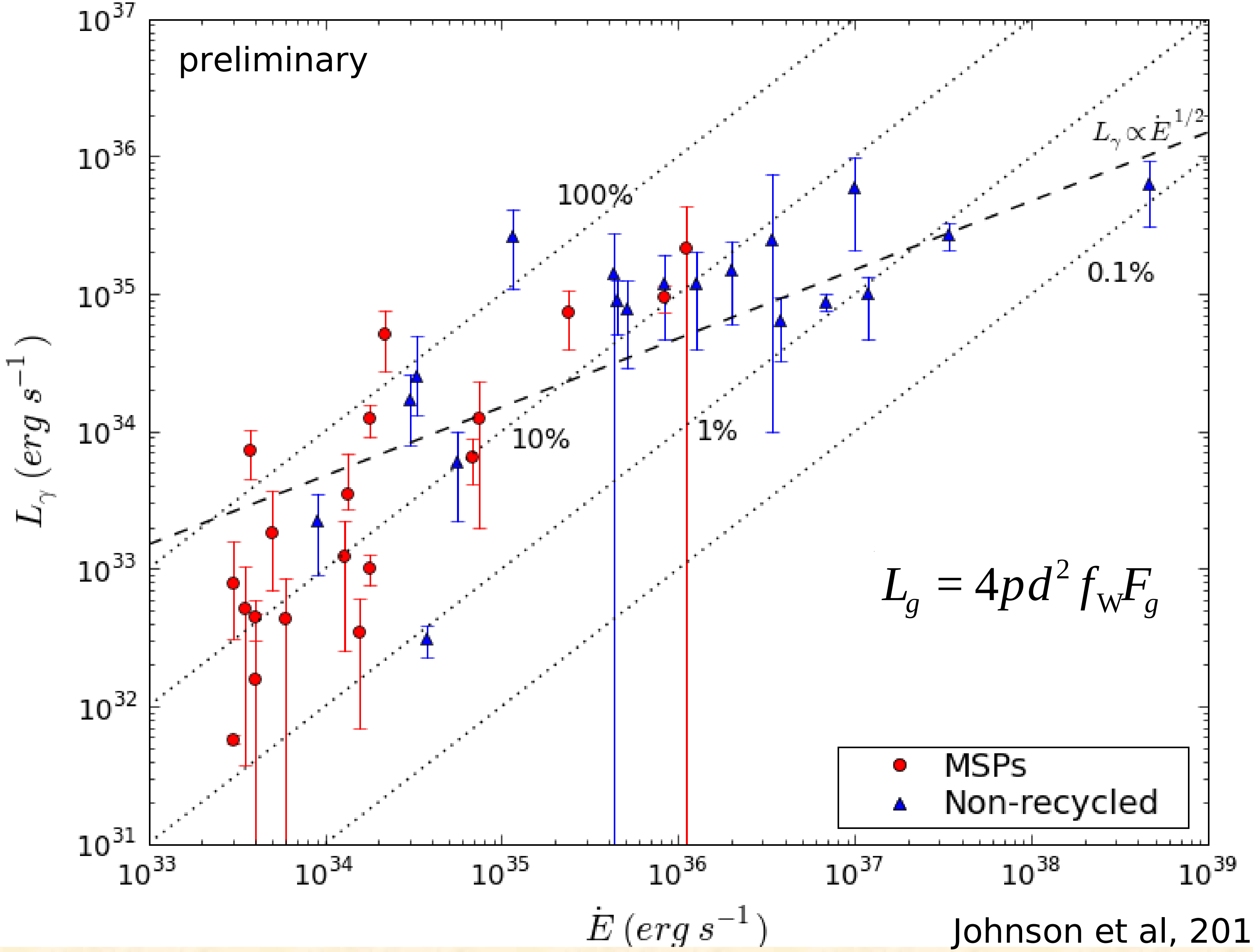
Large viewing angles with the rotation axis favored
expected for outer magnetosphere model emission

Uniform MSP inclination angle distribution, unlike young pulsars



Pierbattista et al, 2011

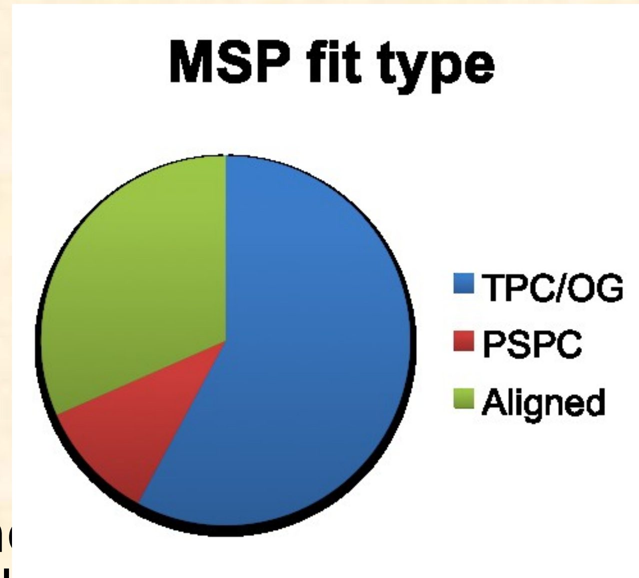
Gamma-ray vs. spin-down luminosity



Johnson et al, 2011

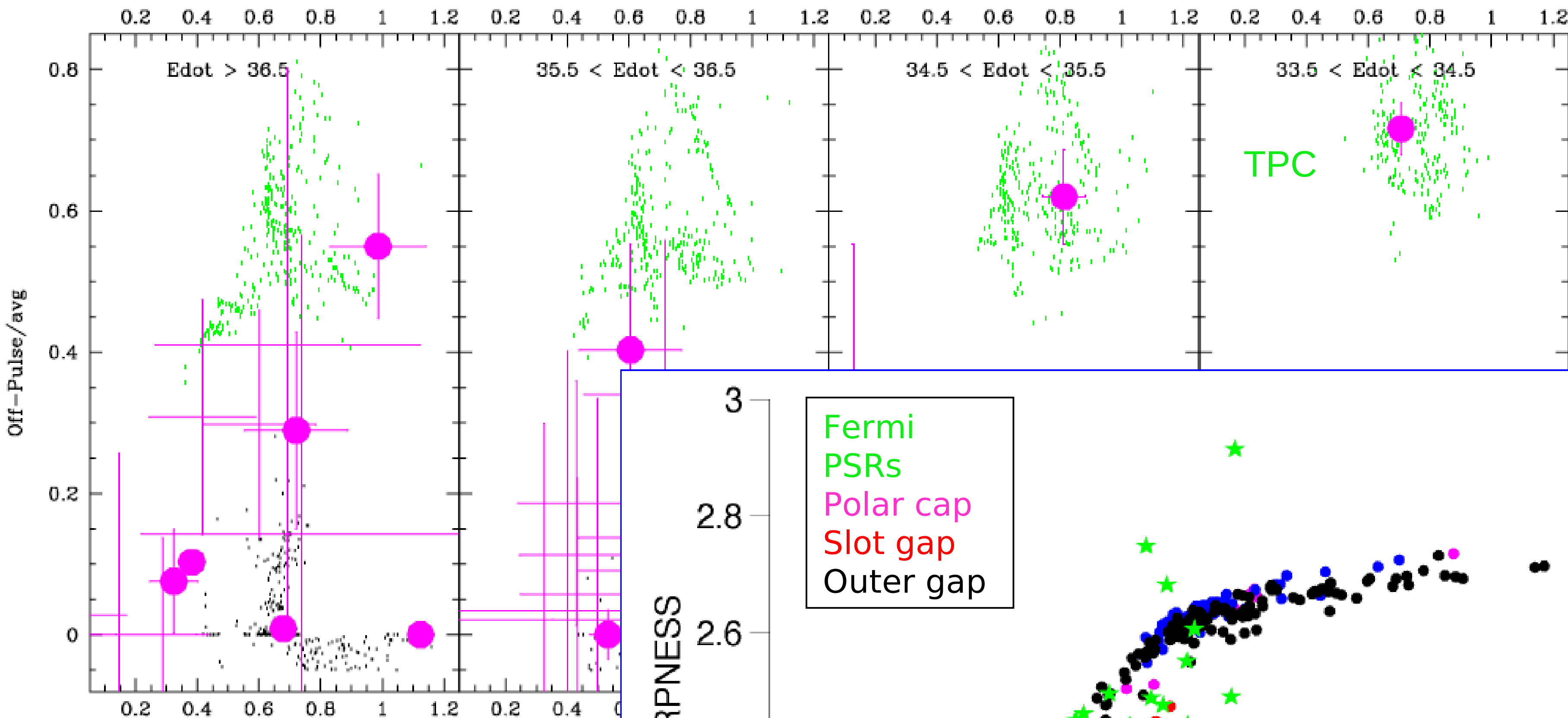
Conclusions from MSP fits

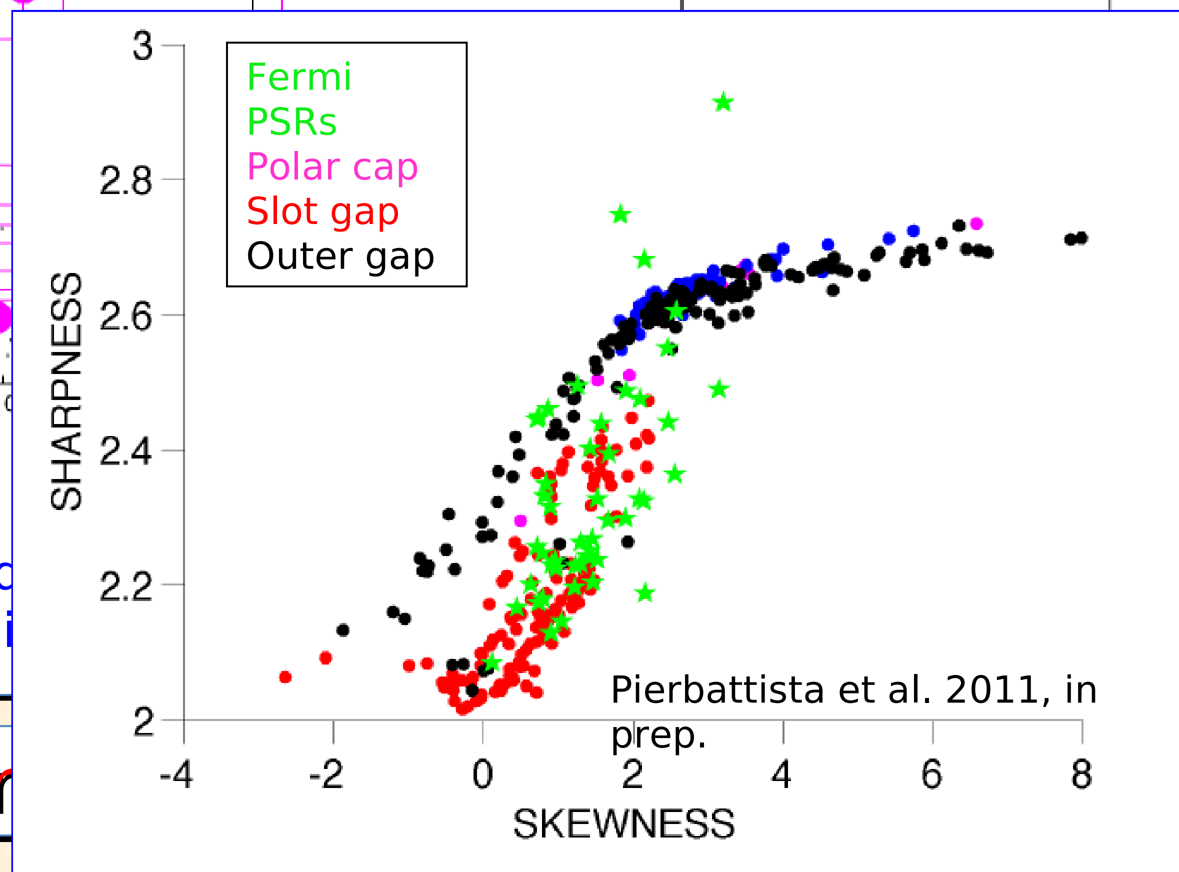
- Gamma-ray emission comes from the outer magnetosphere
  - Outer gap, slot gap (TPC) or pair starved models provide good fits



- Aligned radio an… cate radio caustic emission – mostly short period MSPs
- Most MSPs are NOT pair starved (narrow gaps) - how are they producing pair cascades?
- Few radio-quiet MSPs expected: larger radio beam widths than for canonical pulsars

Light Curve Trends





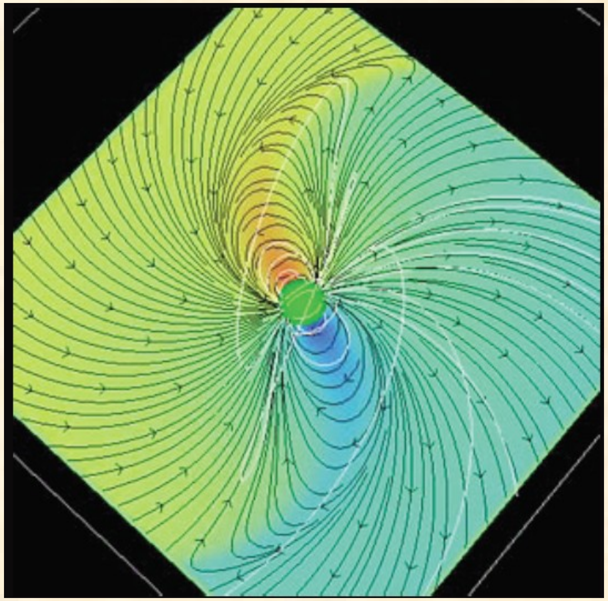
Small ratio of off-peak to bric
R) and requires hi

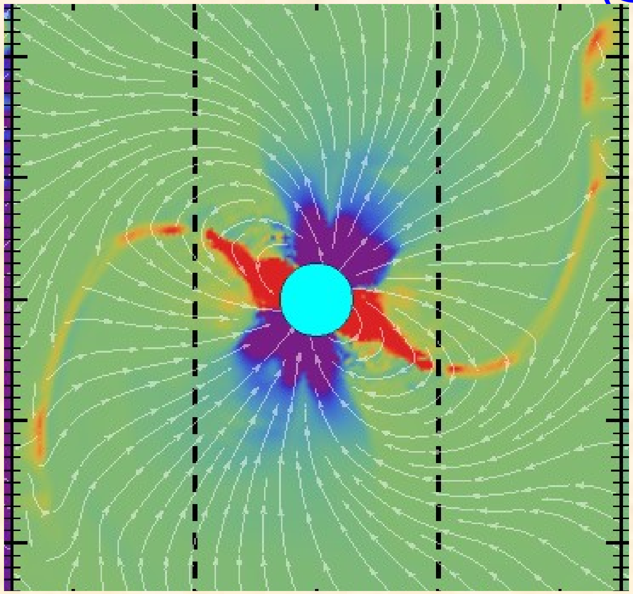
Good model discrir

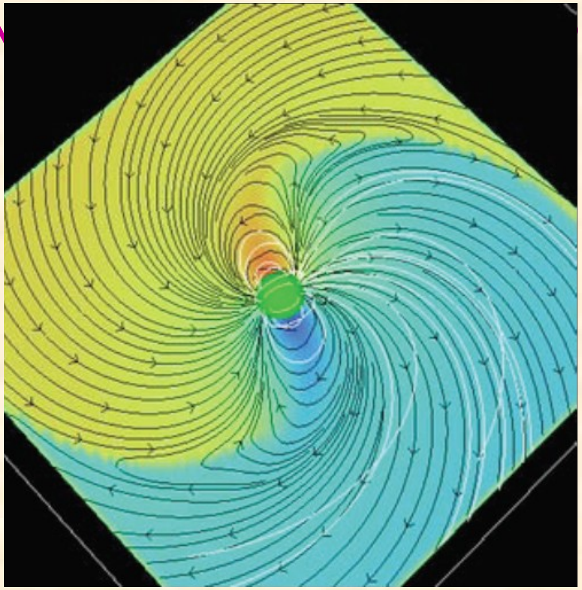
Magnetic field geometry

Retarded vacuum dipole
(Deutsch 1954)
- No charges, no currents

Force-free
magnetosphere
(Spitkovsky 2008)
N n







Non-ideal MHD magnetosphere
Kalapotharokos et al. 2011

$E \cdot B \neq 0$

currents +
on!
ontopoulos)

γ-ray light curves and phase-resolved spectroscopy will help constrain

Force-free electrodynamics:

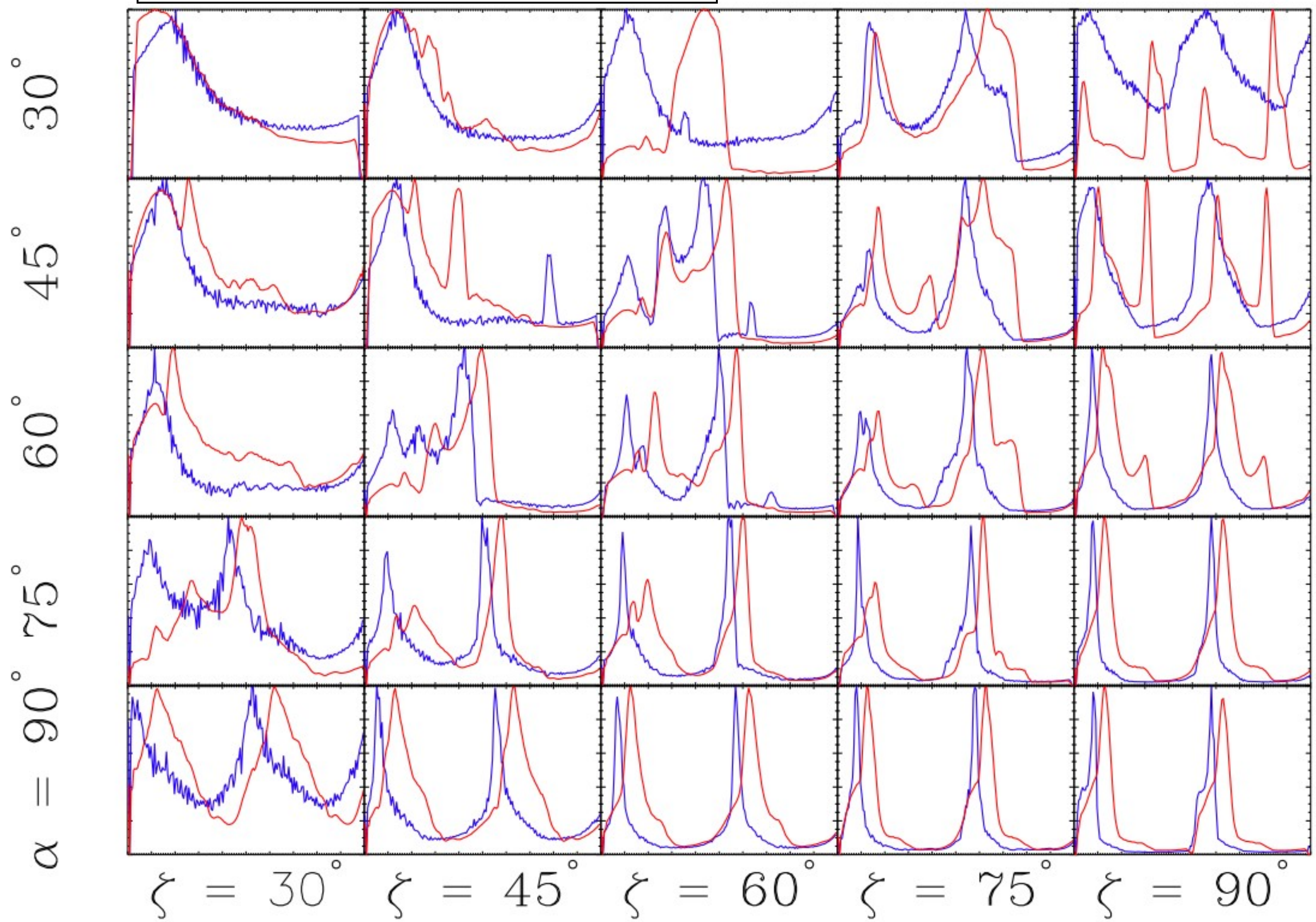
$E \cdot B = 0$ <u>everywhere</u>

No accelerator gaps!

Slot gap light curves: vacuum vs. force-free

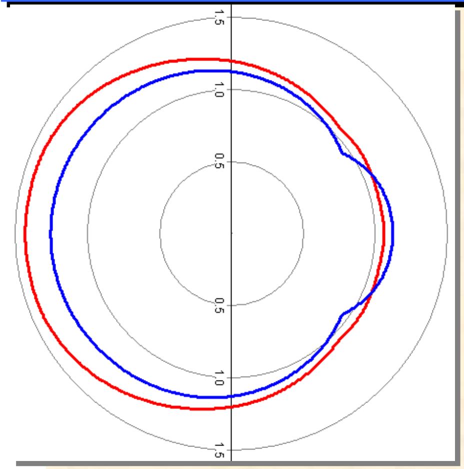
Vacuum dipole

Force-free

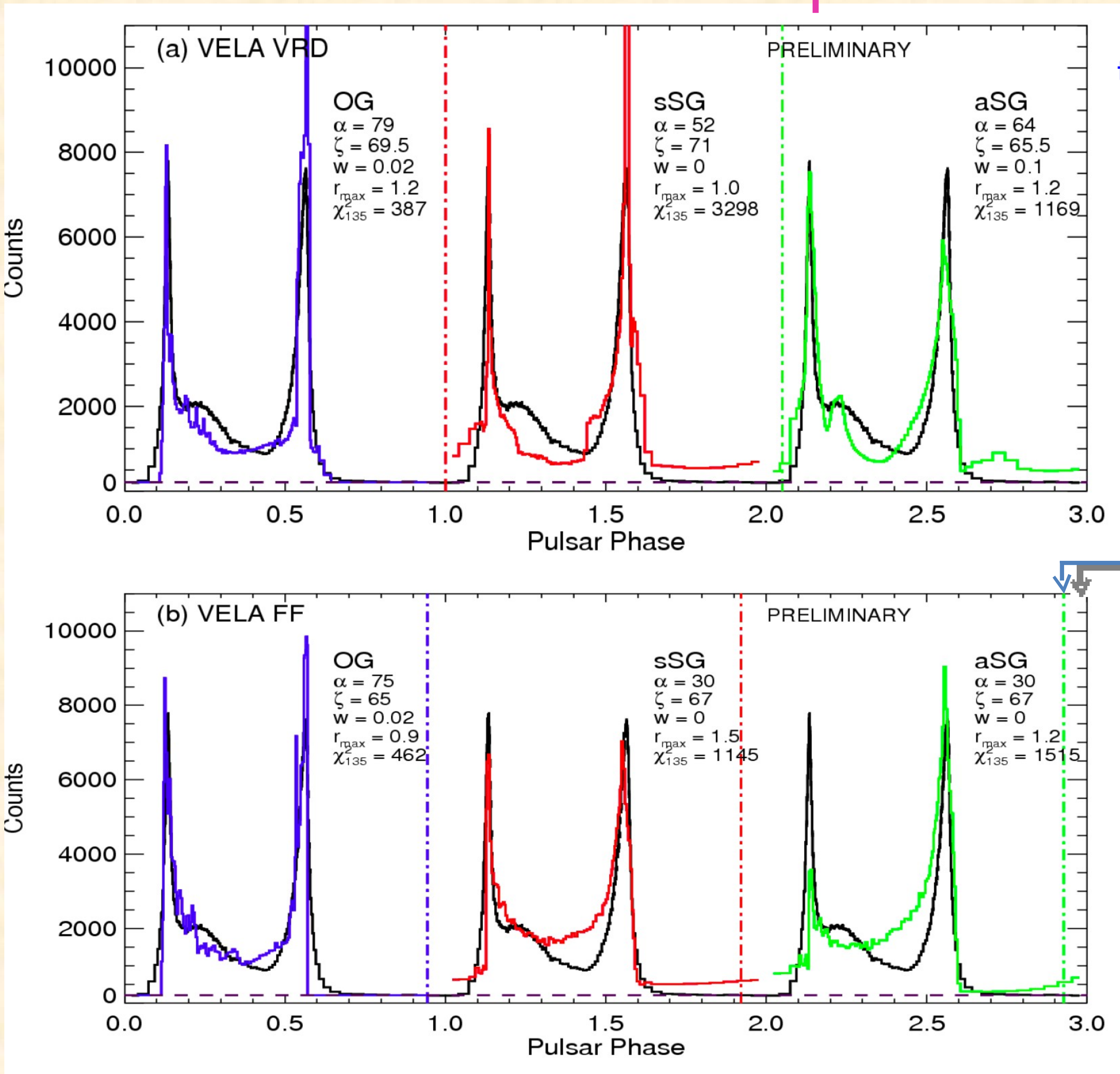


Force-free LC peaks occur at later phase by .05 – .15 due to:

- Larger polar cap
- Later phase of trailing field lines



Fits to Vela pulsar



Megan DeCesar thesis

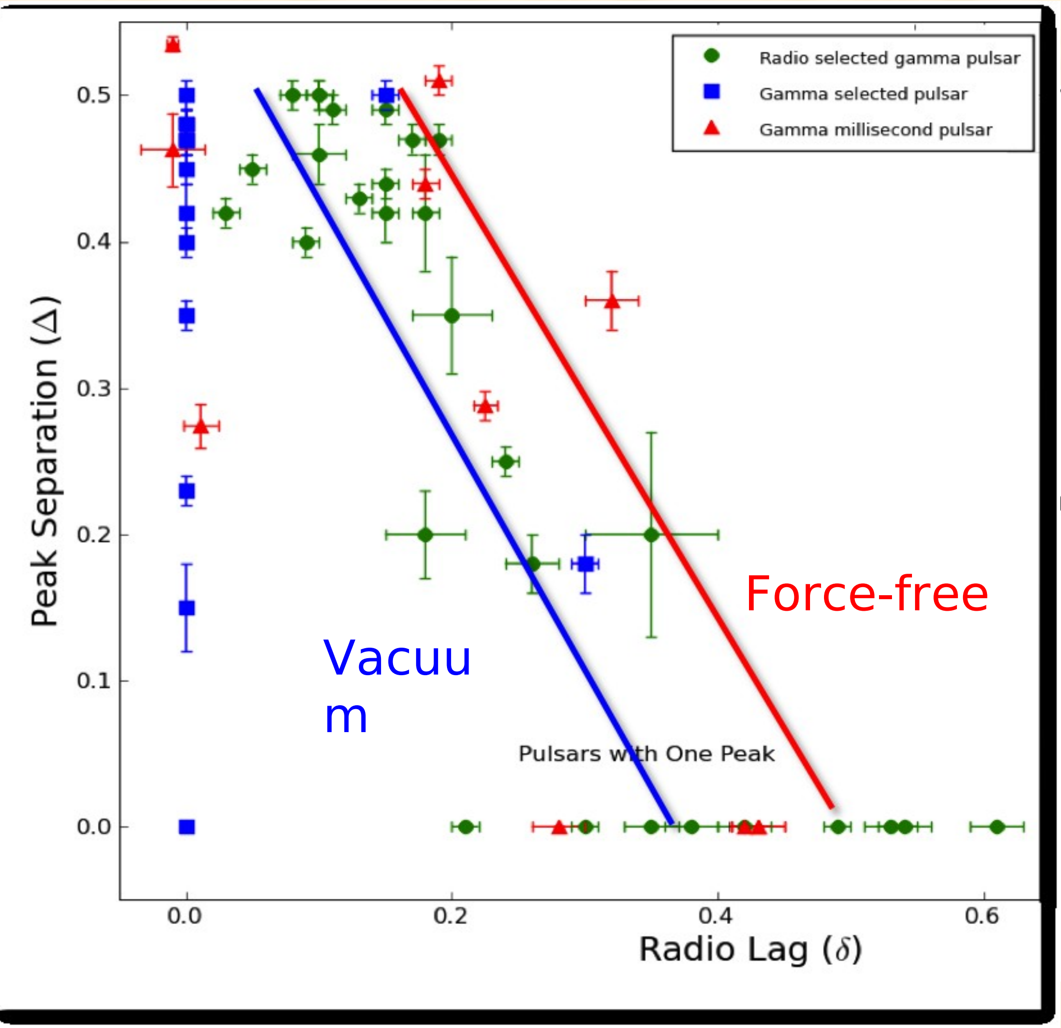
30 month survey data
4000 counts/bin

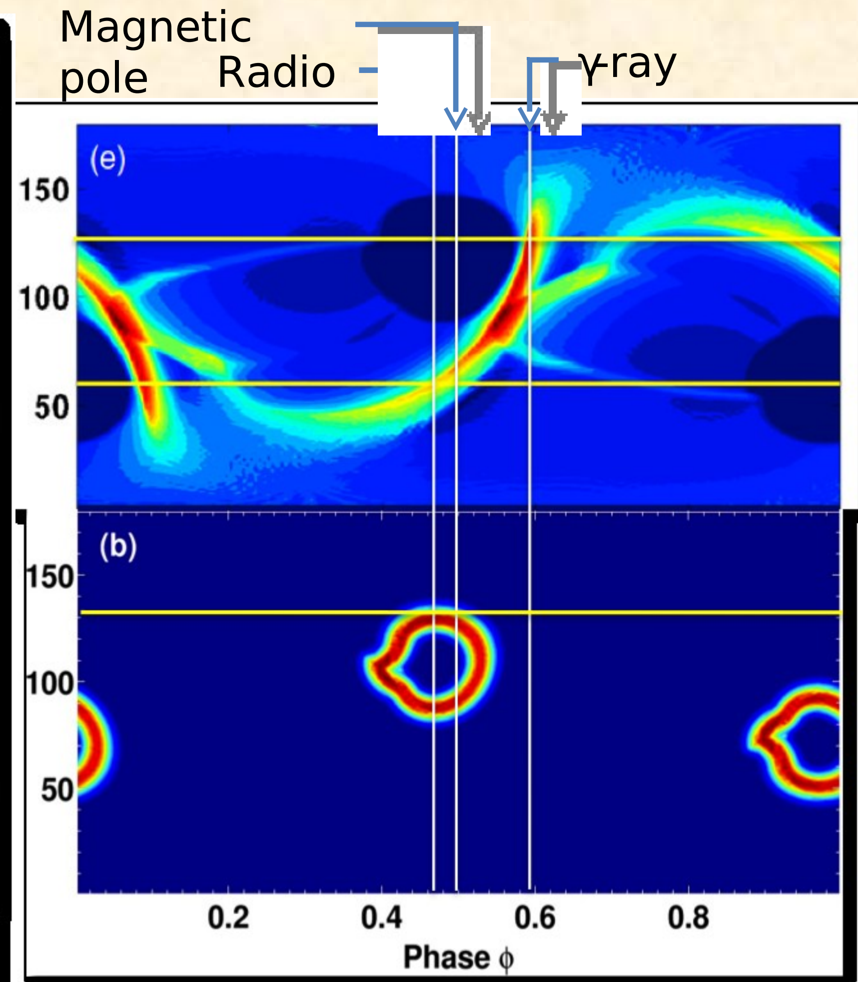
Markov Chain Monte Carlo method used to find maximum likelihood in α,ζ,ω, r_{max}

Magnetic pole

Gamma-ray/radio phase lag

Data from Smith et al. preliminary





What can we learn from phase-resolved spectra?

- Balance CR losses with acceleration gain

$$eE_{\parallel} = P_{CR} = \frac{2e^2\gamma^4}{3r_c^2}$$

- Steady-state Lorentz factor

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

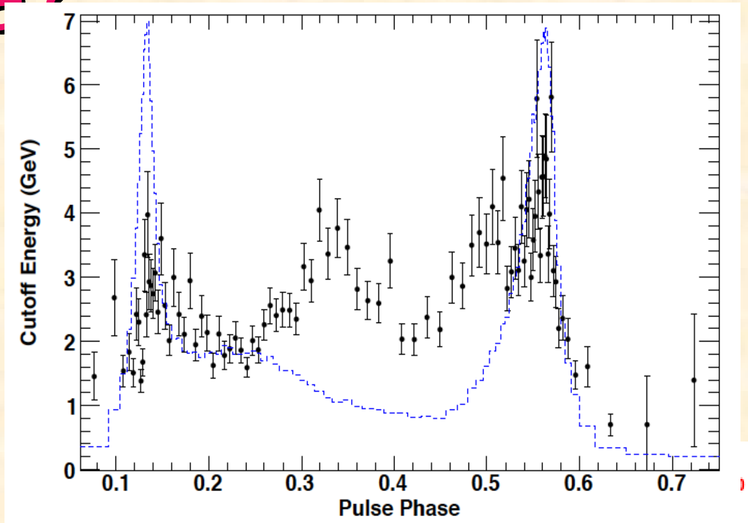
- Curvature radiation peak energy:

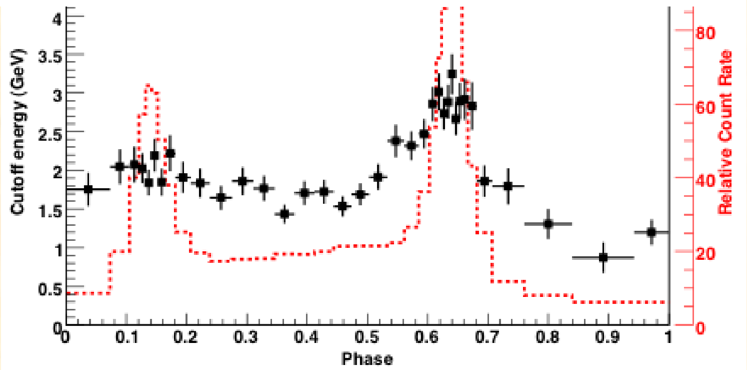
$$\varepsilon_{CR} = \frac{2}{3}\frac{\hbar c\gamma_{CRR}^3}{r_c} = \left(\frac{3}{2}\right)^{7/4}\left(\frac{E_{\parallel}}{e}\right)^{3/4}\hbar c r_c^{1/2} \approx 3\ GeV$$

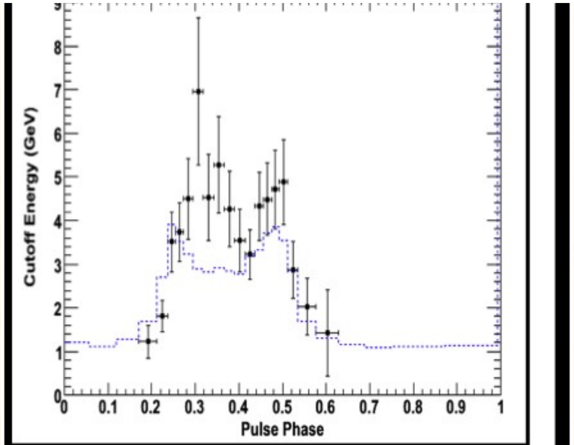
c CR

Is E = ε ?
c

Does E variation map magnetic field curvature vs. phase?

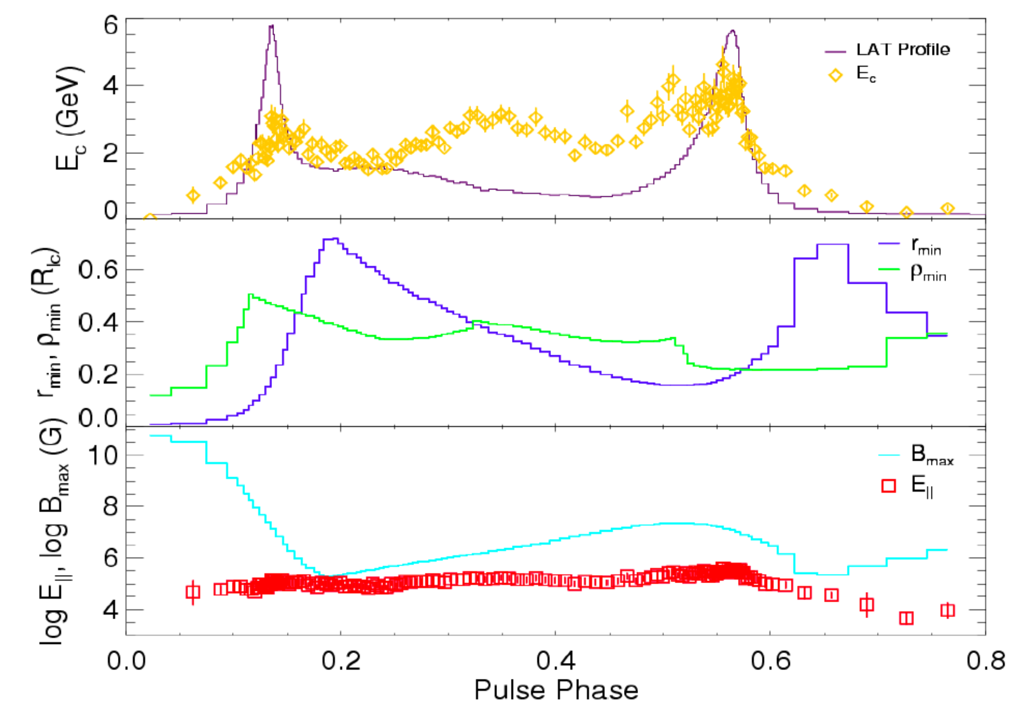






Abdo et al. 2010

Electric field in accelerator gap - Vela



Megan DeCesar thesis

LAT data

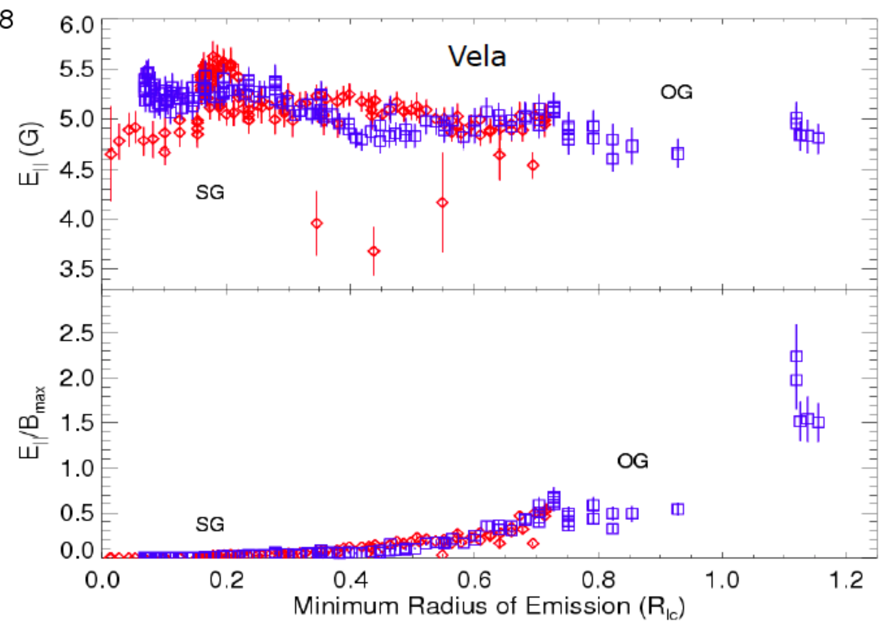
Slot gap model emission radius and magnetic field radius of curvature

Derived $E_{\|} \propto E_c^{4/3} r_c^{2/3}$

And B(r_{min}) in retarded dipole field

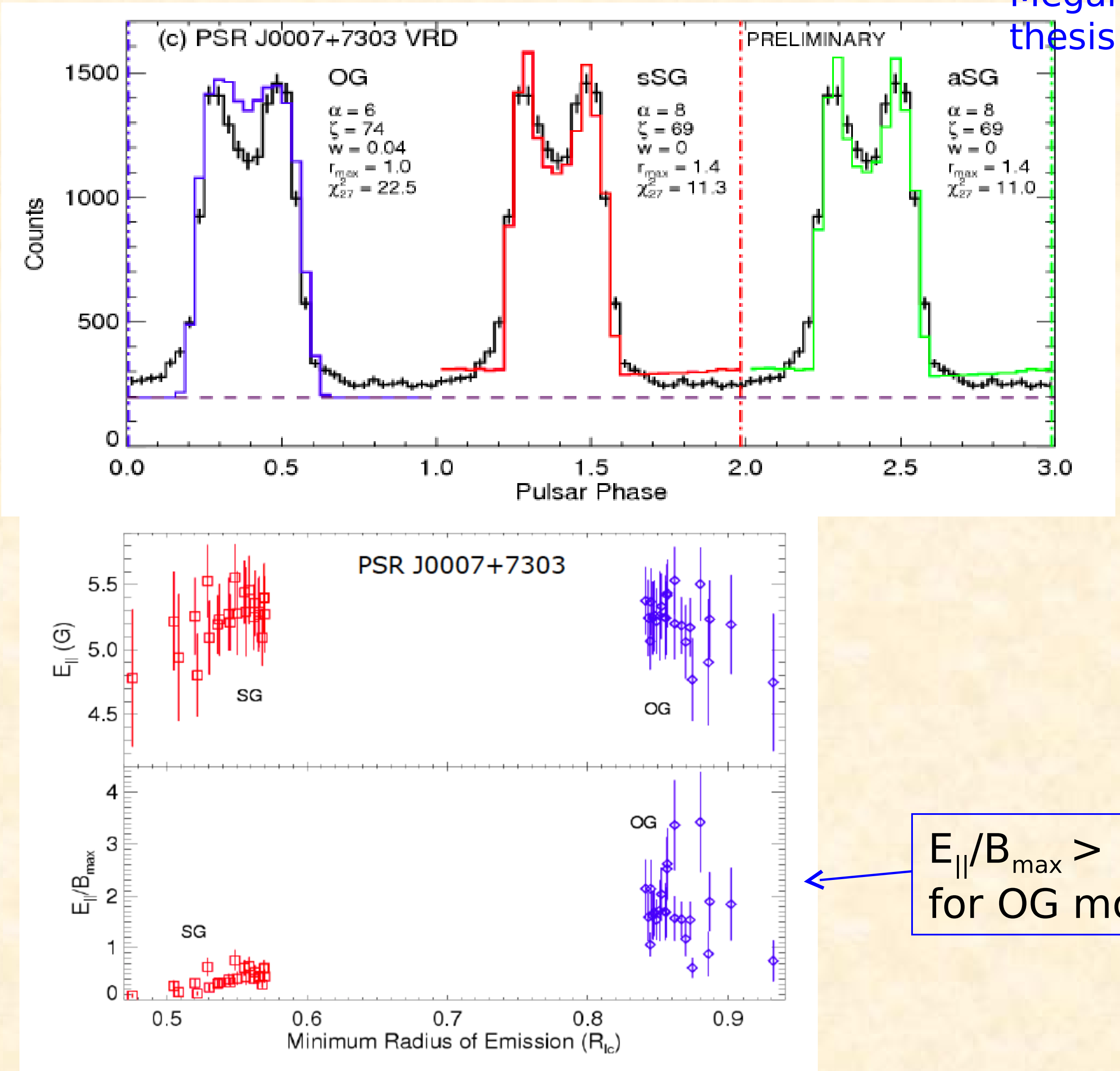
$E_{\|}$(r) can be compared with models

$E_{\|}/B_{max}$ > 1 not physical



Electric field in accelerator gap – CTA1

Megan DeCesar thesis



$E_{||}/B_{max} > 1$ a problem for OG model

Summary

- We are finally answering fundamental questions of γ-ray pulsar astrophysics – but raising new ones
  - High-energy emission comes from outer magnetosphere
  - Likely curvature radiation from continuously accelerated particles
- The mystery of unidentified Galactic gamma-ray sources from the EGRET era has largely been solved – they're pulsars - many radio-quiet
- 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 88 γ-ray pulsars - including ms pulsars –– 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!