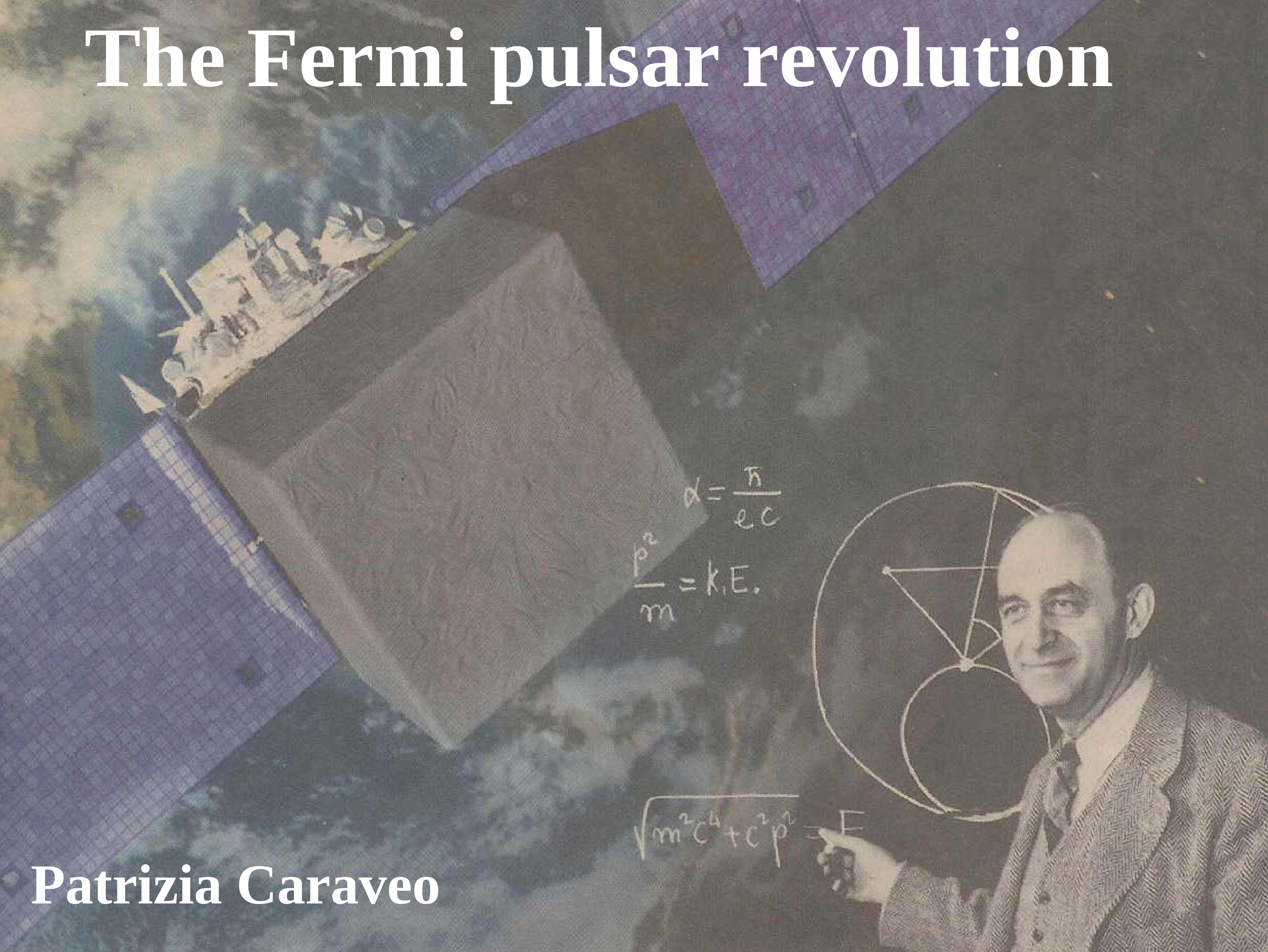
The Fermi pulsar revolution

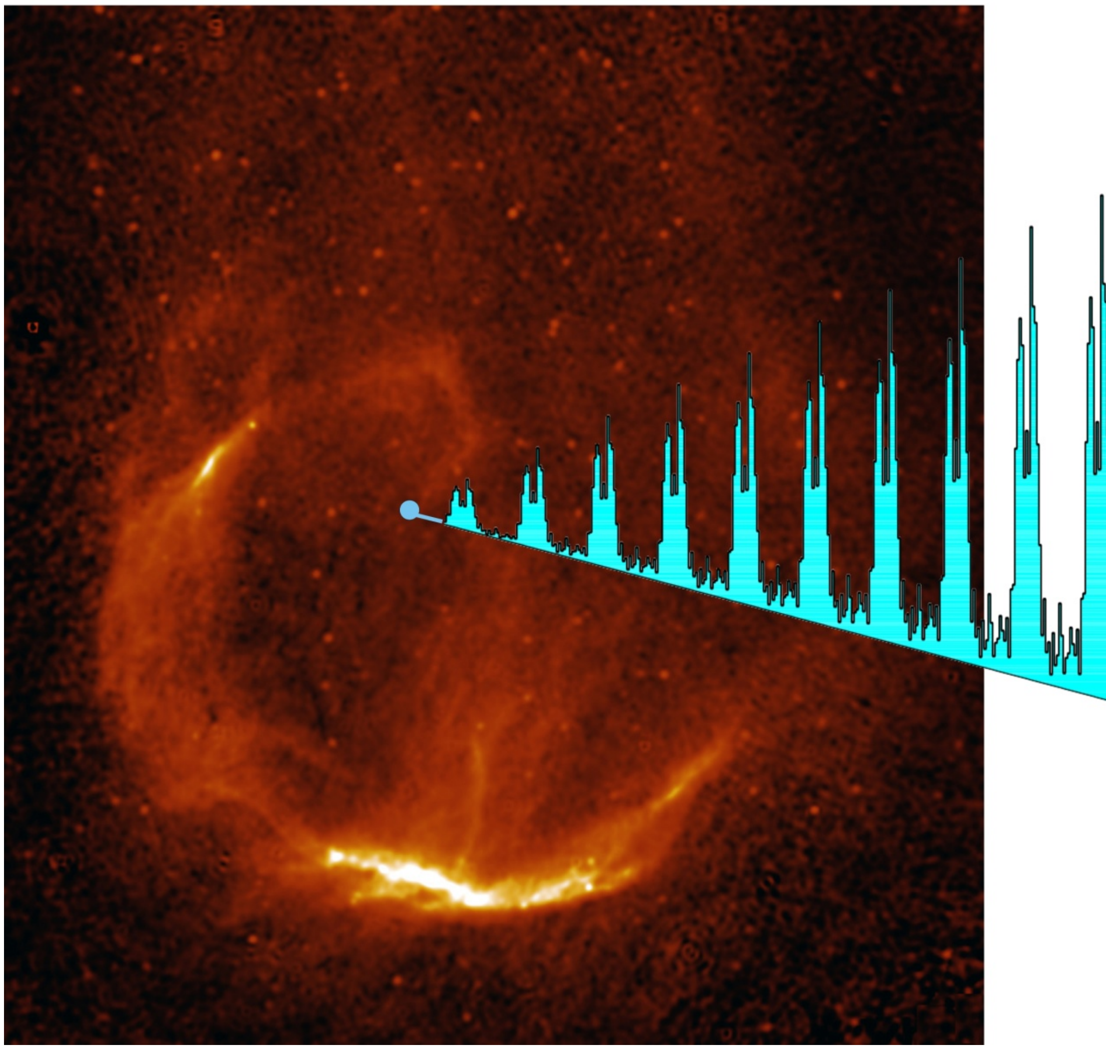


Patrizia Caraveo

Fermi LAT FIRST result

- **2008**

  The Fermi Large Area Telescope discovers the pulsar in the young galactic supernova remnant CTA 1 Abdo, A. A. et al. 2008, Science, 322,



Up to date γ-ray pulsar census

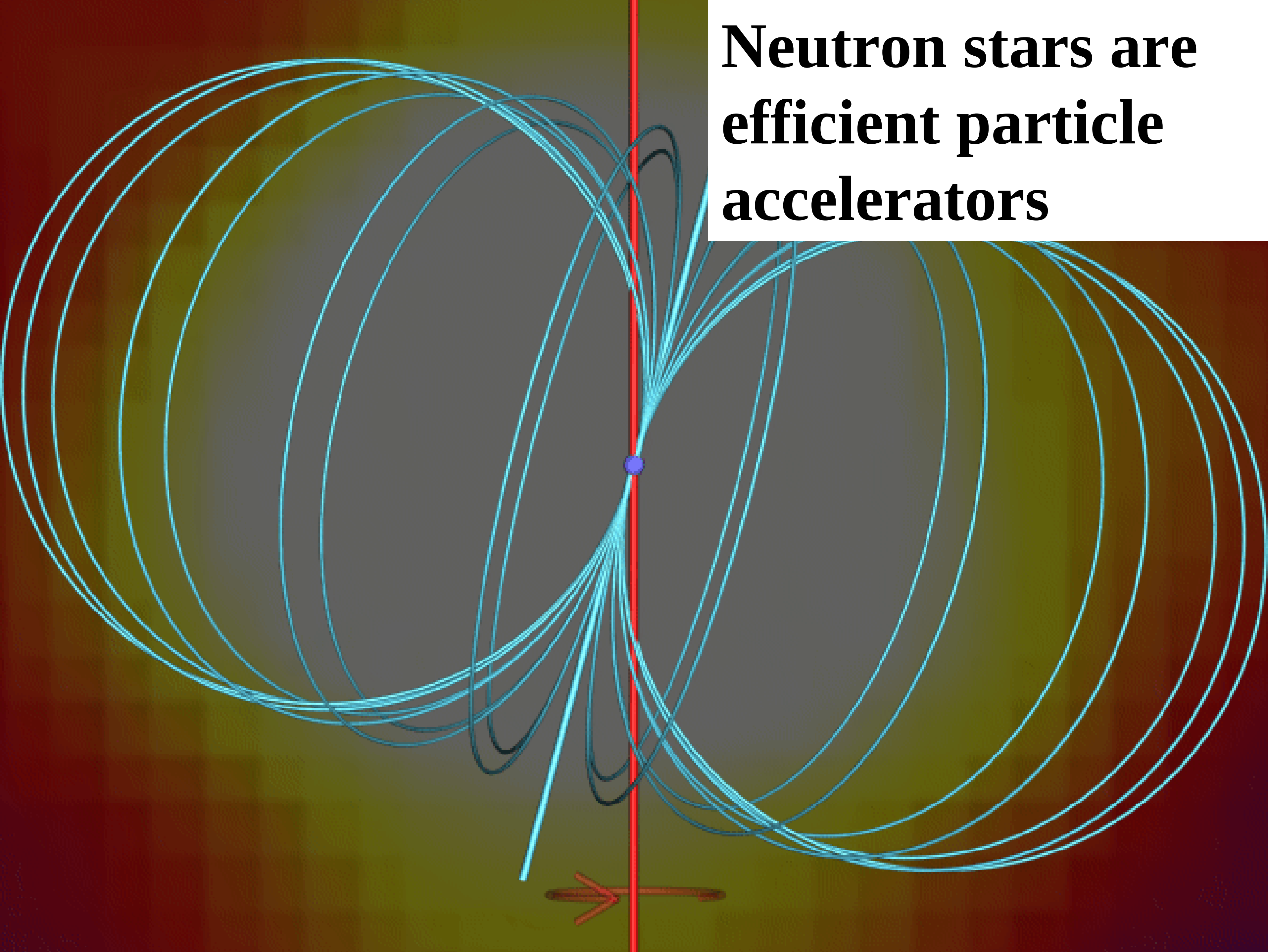
64 gamma-ray emitting neutron stars

25 gamma-selected NSs (24 new + Geminga)

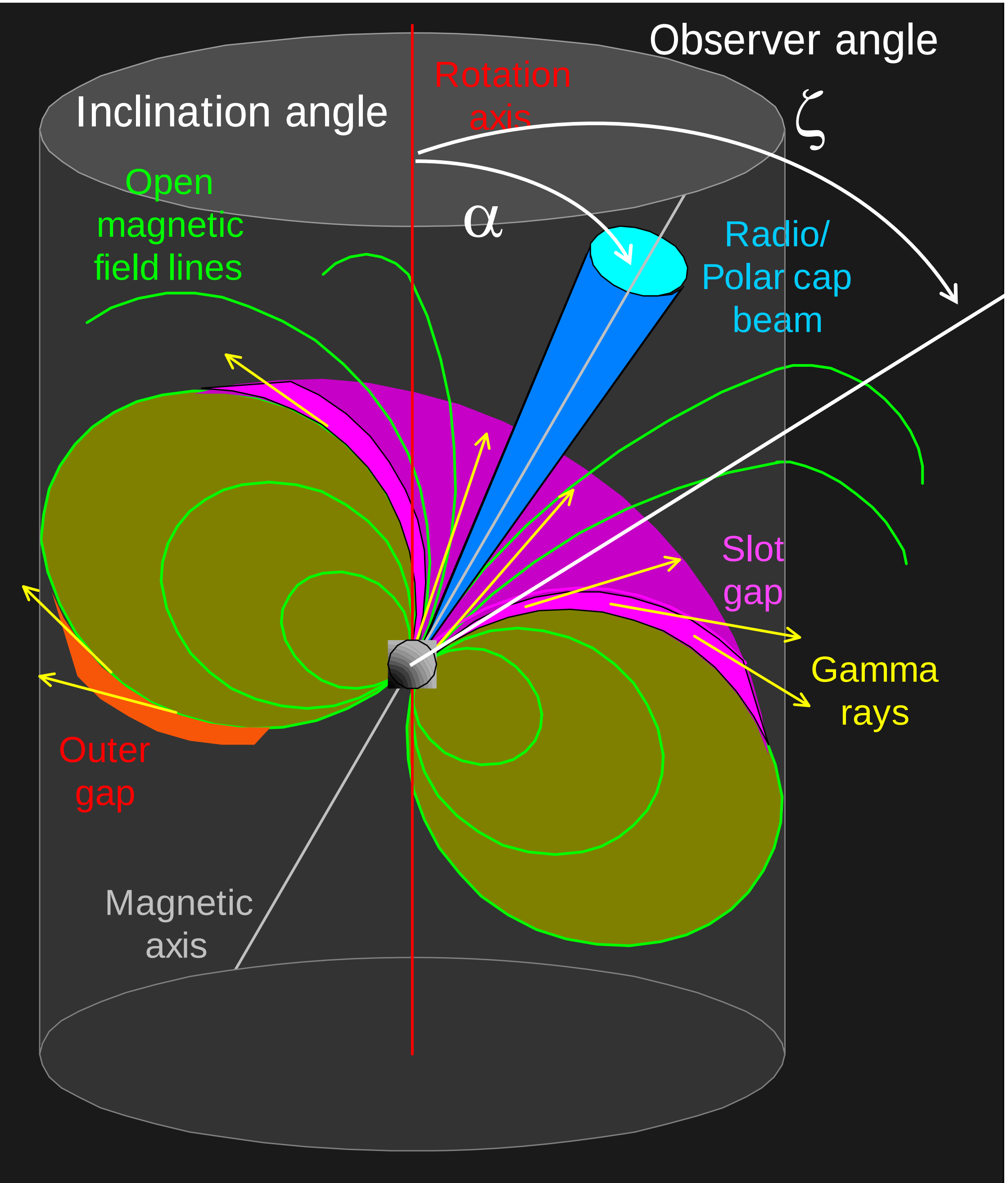
25 radio pulsars

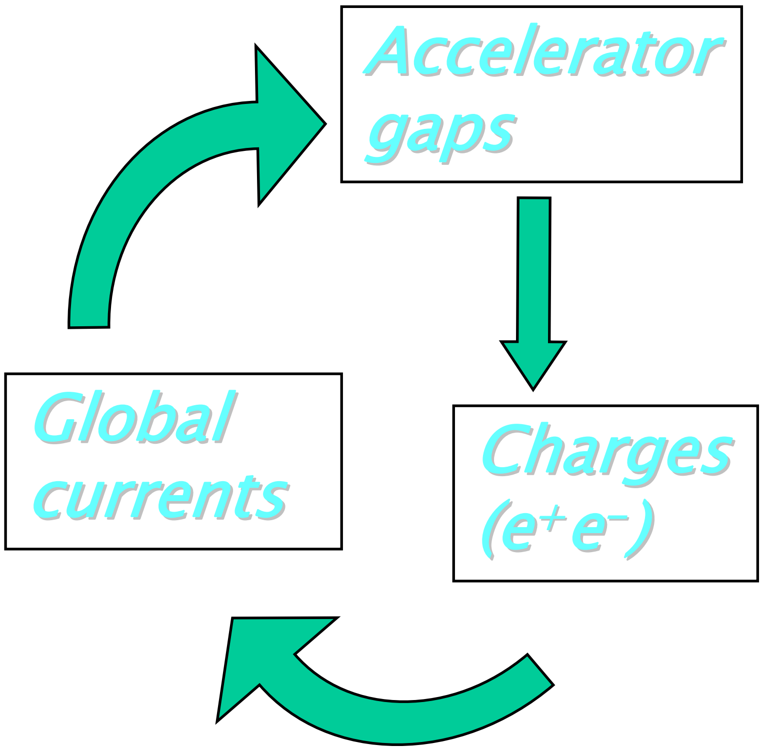
14 msec radio pulsar

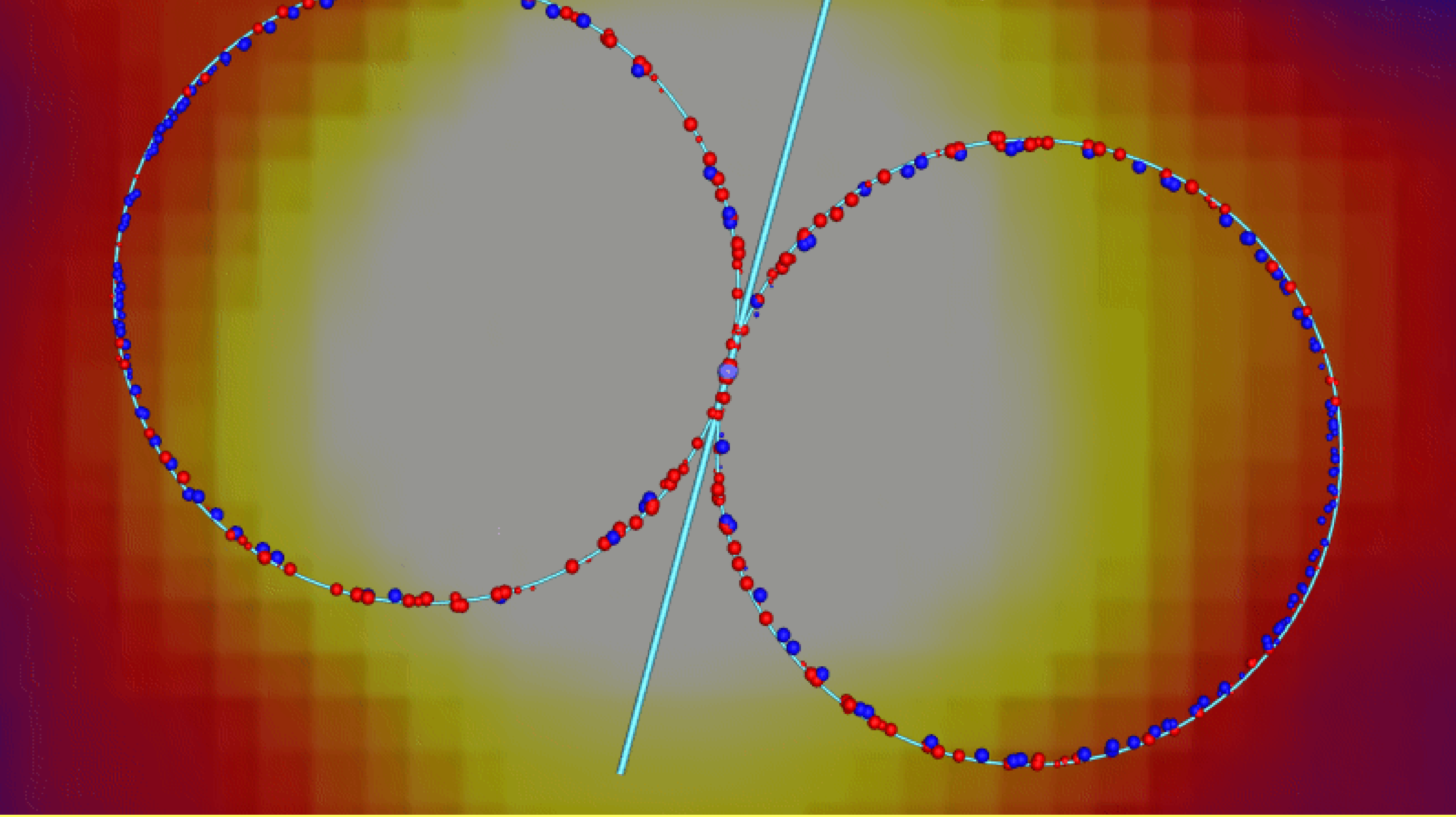
Neutron stars are efficient particle accelerators



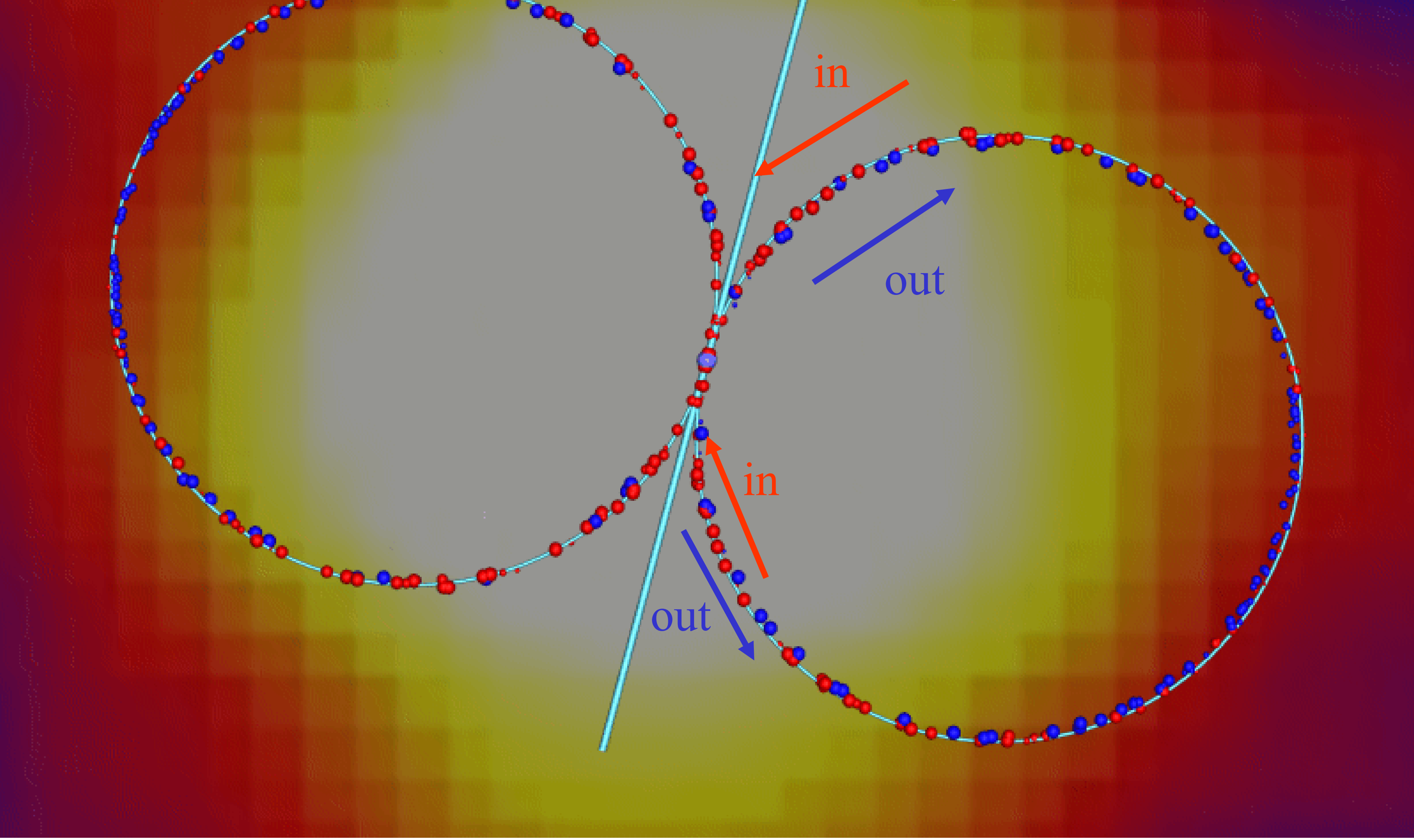
Accelerators and global models







Gamma-ray astronomy tells us that the magnetosphere of a NS (of sufficient Edot) is filled with high energy e+ e-



Magnetic field lines are 2-way streets

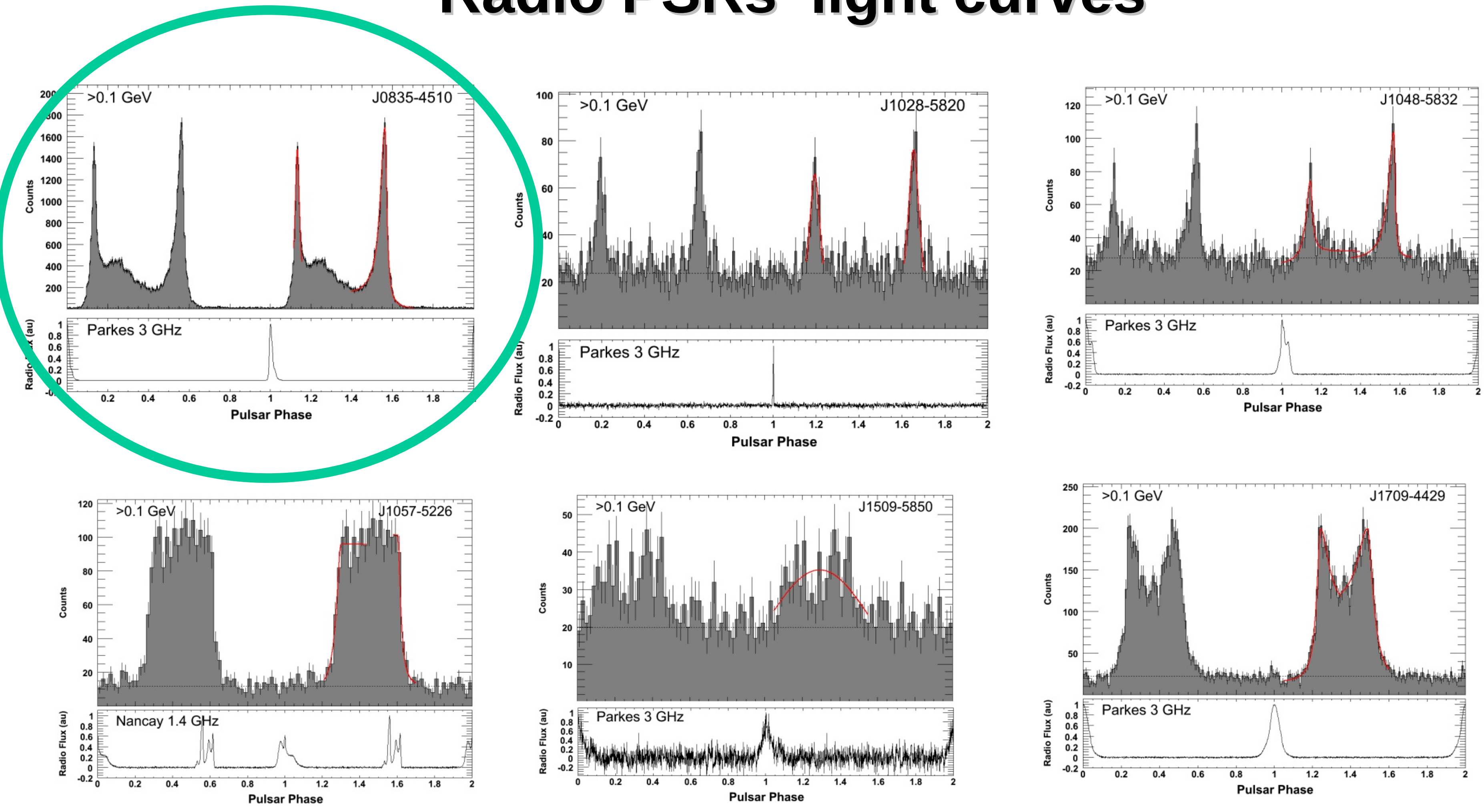
OUT γ–rays, non thermal X-rays-→towards PWNe

IN thermal X-rays

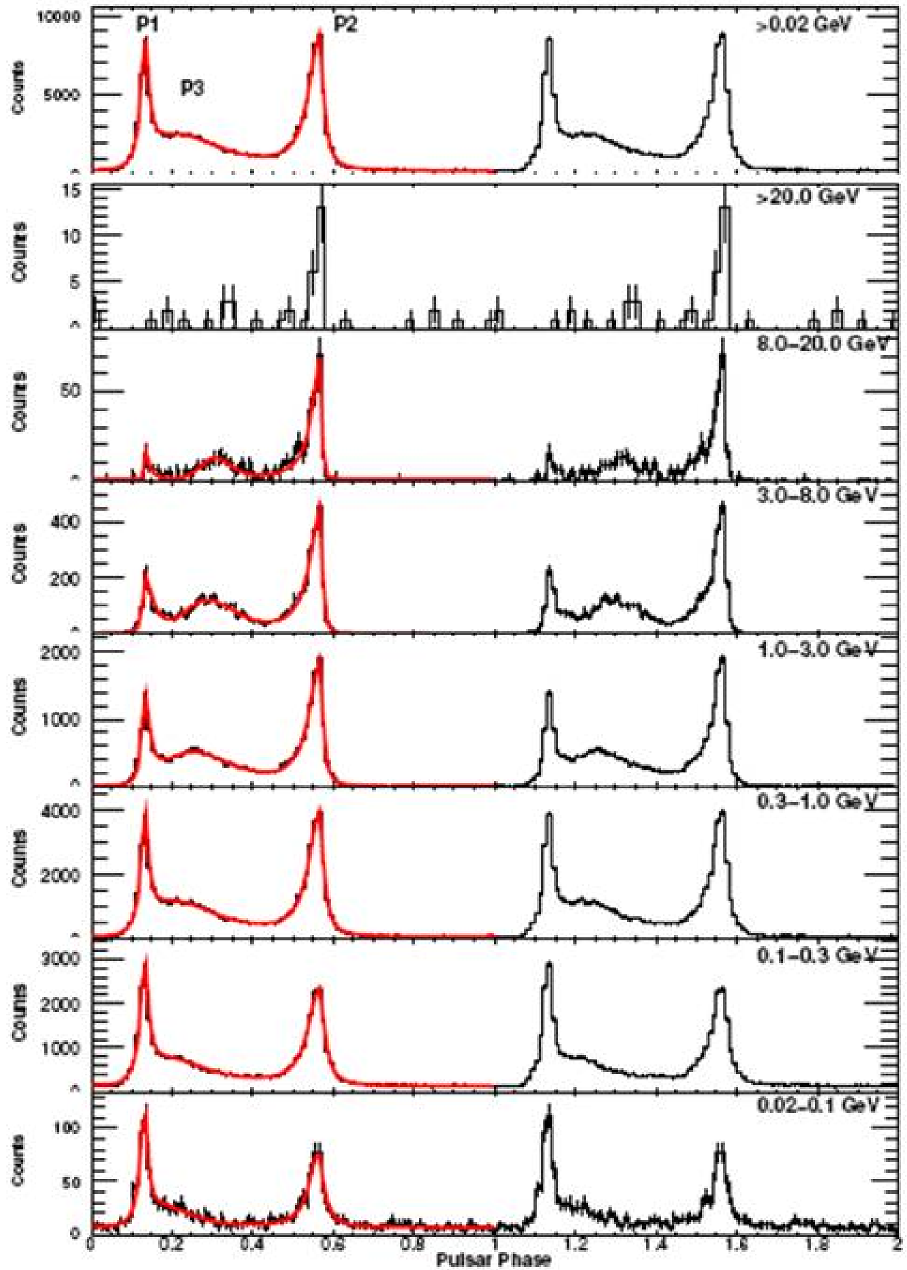
Observational Constraints

- γ-ray light curves
  # of pulses and how they change with energy
- γ-ray spectra (averaged and space resolved)
- comparison with radio light curves
  - -alignment/misalignment
  - - delay
- lack of radio emission
- comparison with X-ray behaviour
- energetics → Lγ vs. Edot

Radio PSRs' light curves

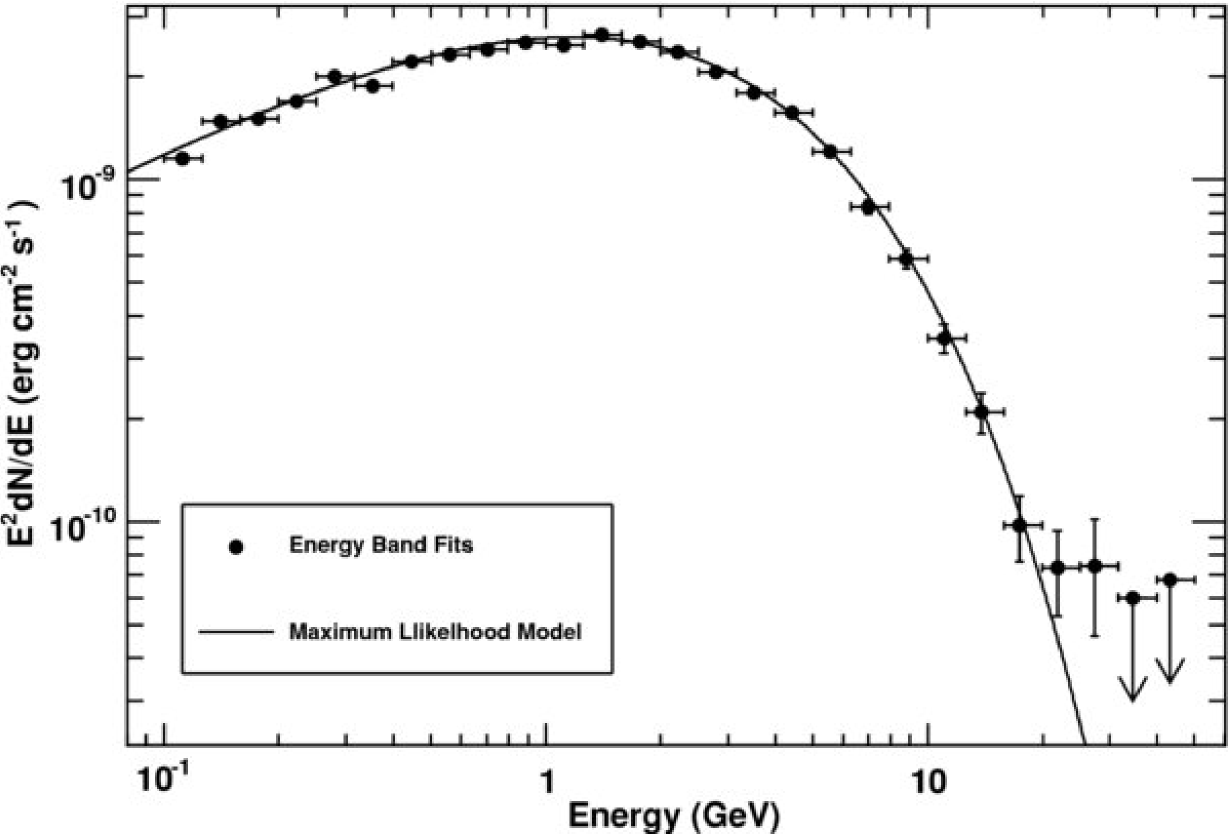


Gamma-ray intensity of Vela pulsar versus energy and phase



Phase-averaged Vela spectrum

$$\frac{dN}{dE} = N_0 E^{-\Gamma} \exp\left(-\frac{E}{E_0}\right)^{b} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$$



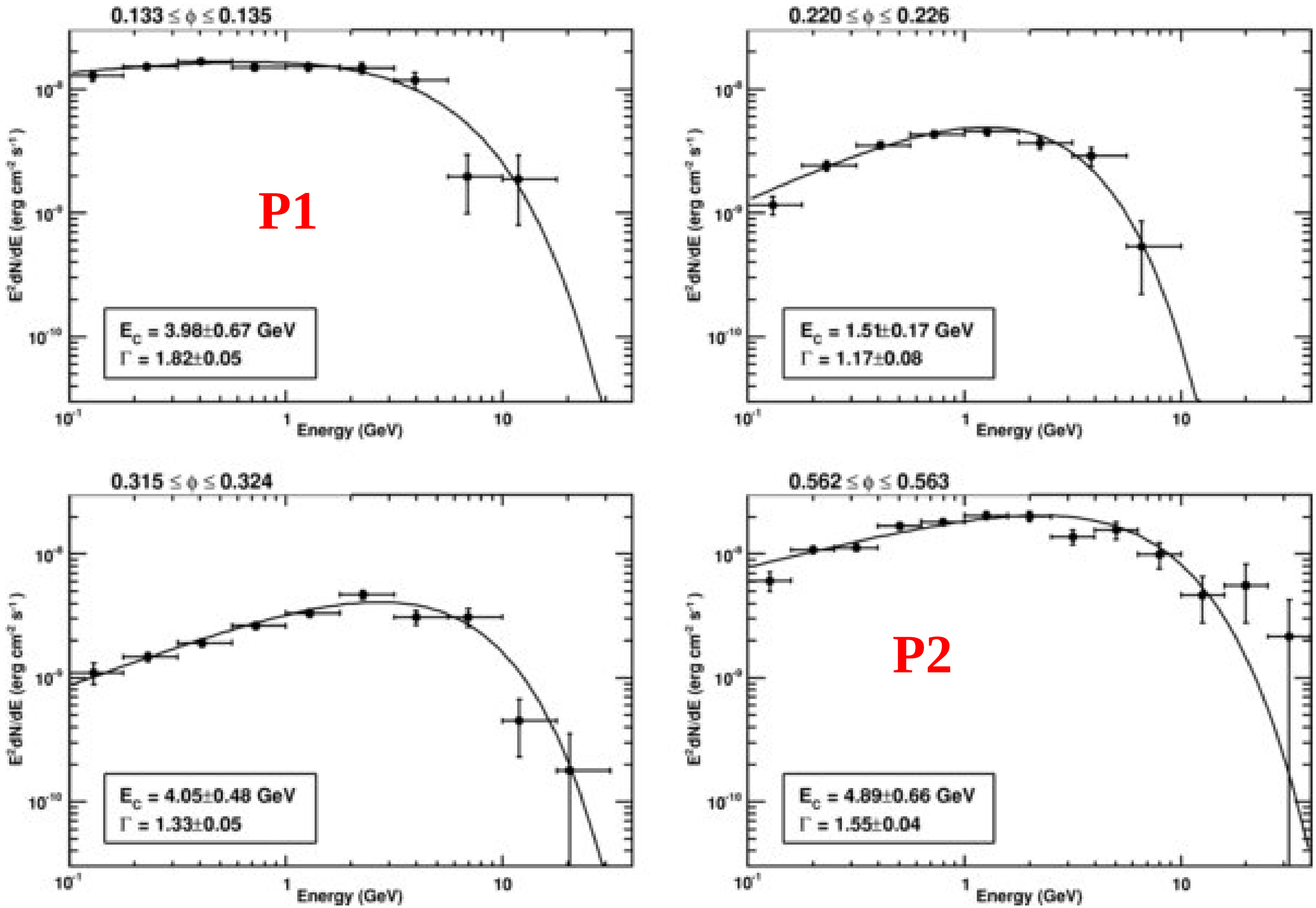
Exponential cutoff

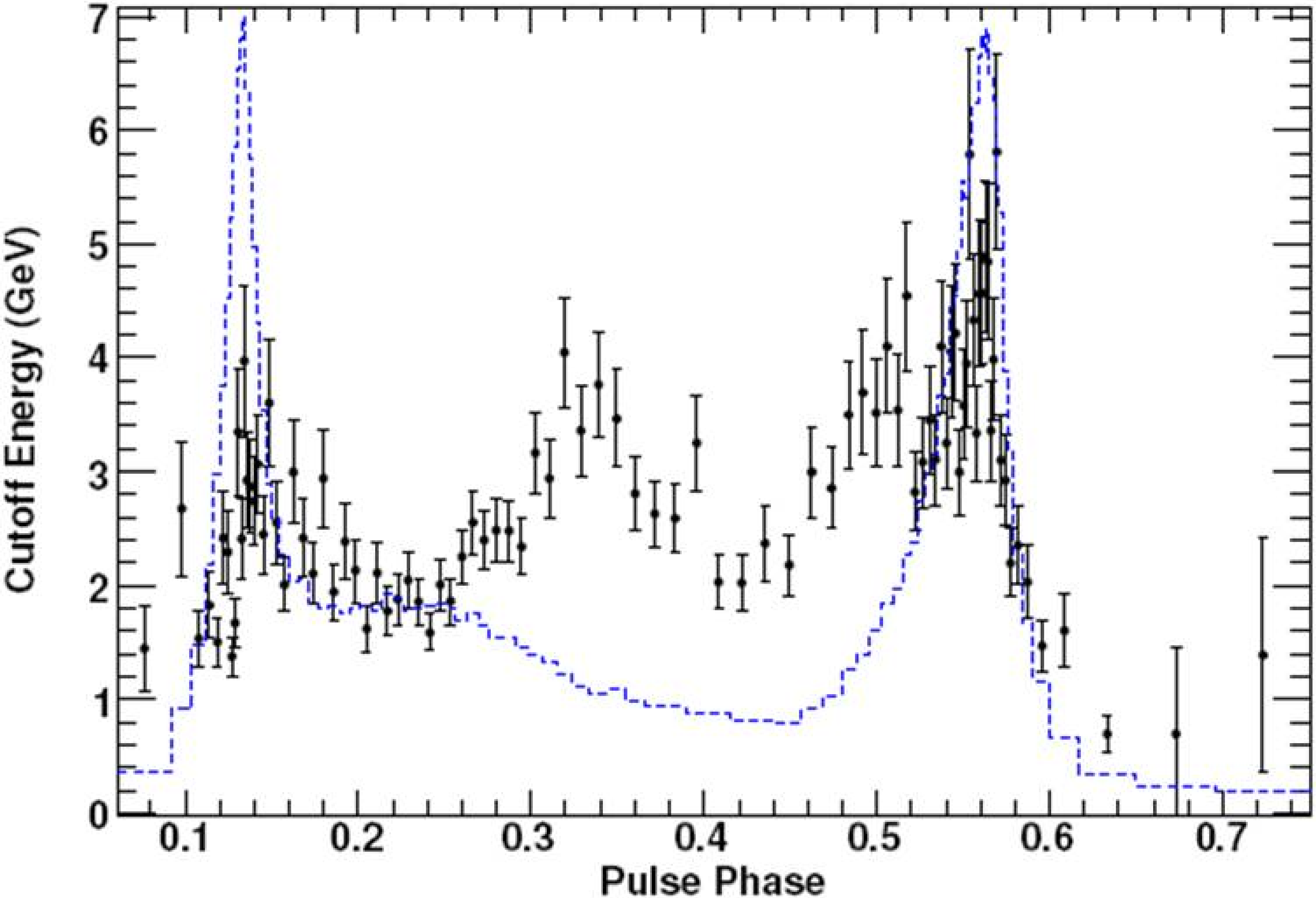
$\Gamma = 1.38 \pm 0.02 \pm 0.07$

$Eo = 1.36 \pm 0.15 \pm 1.0 GeV$

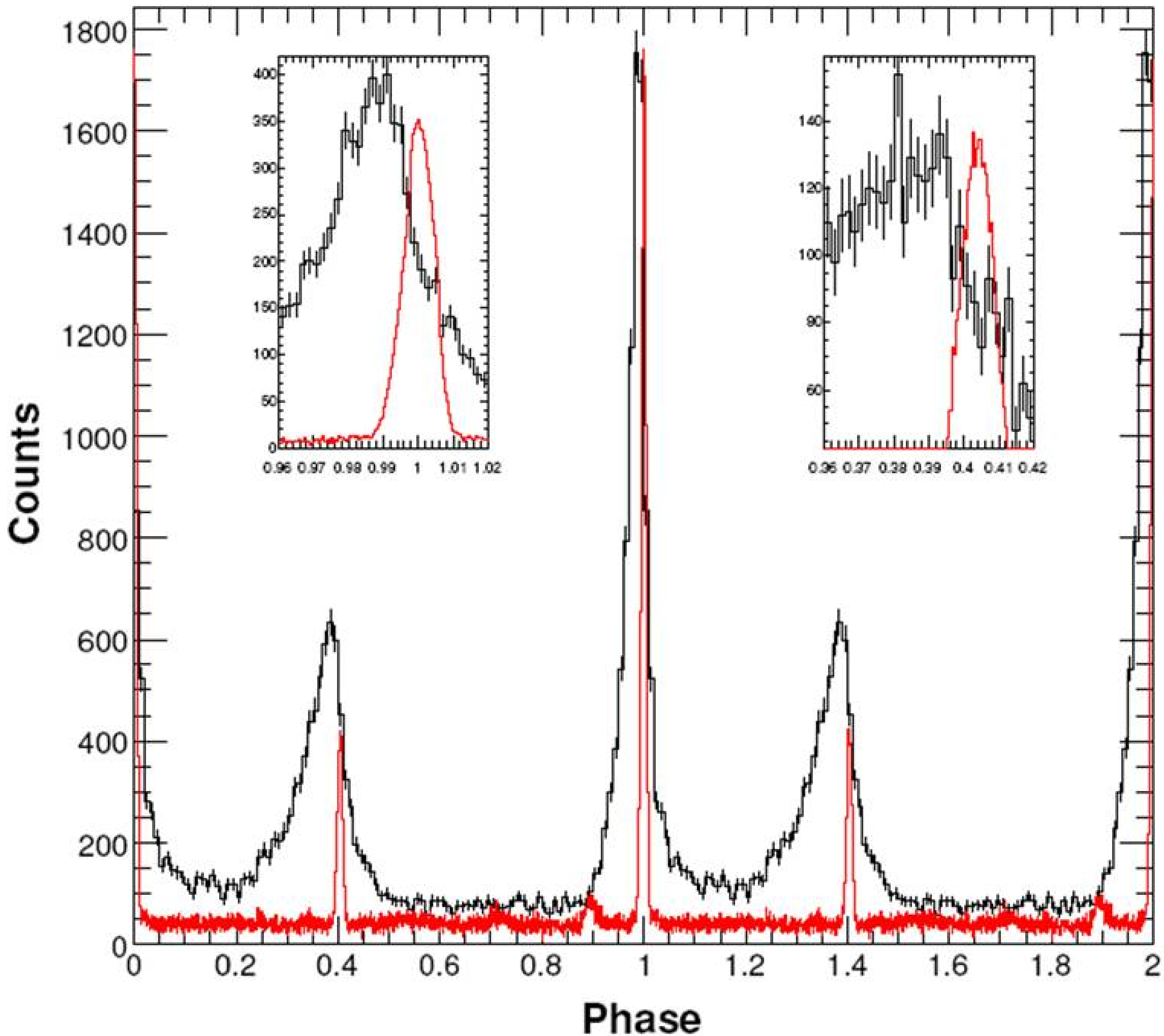
$b = 0.69 \pm 0.02 \pm 0.18$

b<1


0.133 ≤ ϕ ≤ 0.135
P1
E_C = 3.98±0.67 GeV
Γ = 1.82±0.05
0.220 ≤ ϕ ≤ 0.226
E_C = 1.51±0.17 GeV
Γ = 1.17±0.08
0.315 ≤ ϕ ≤ 0.324
E_C = 4.05±0.48 GeV
Γ = 1.33±0.05
0.562 ≤ ϕ ≤ 0.563
P2
E_C = 4.89±0.66 GeV
Γ = 1.55±0.04
E²dN/dE (erg cm⁻² s⁻¹)
Energy (GeV)

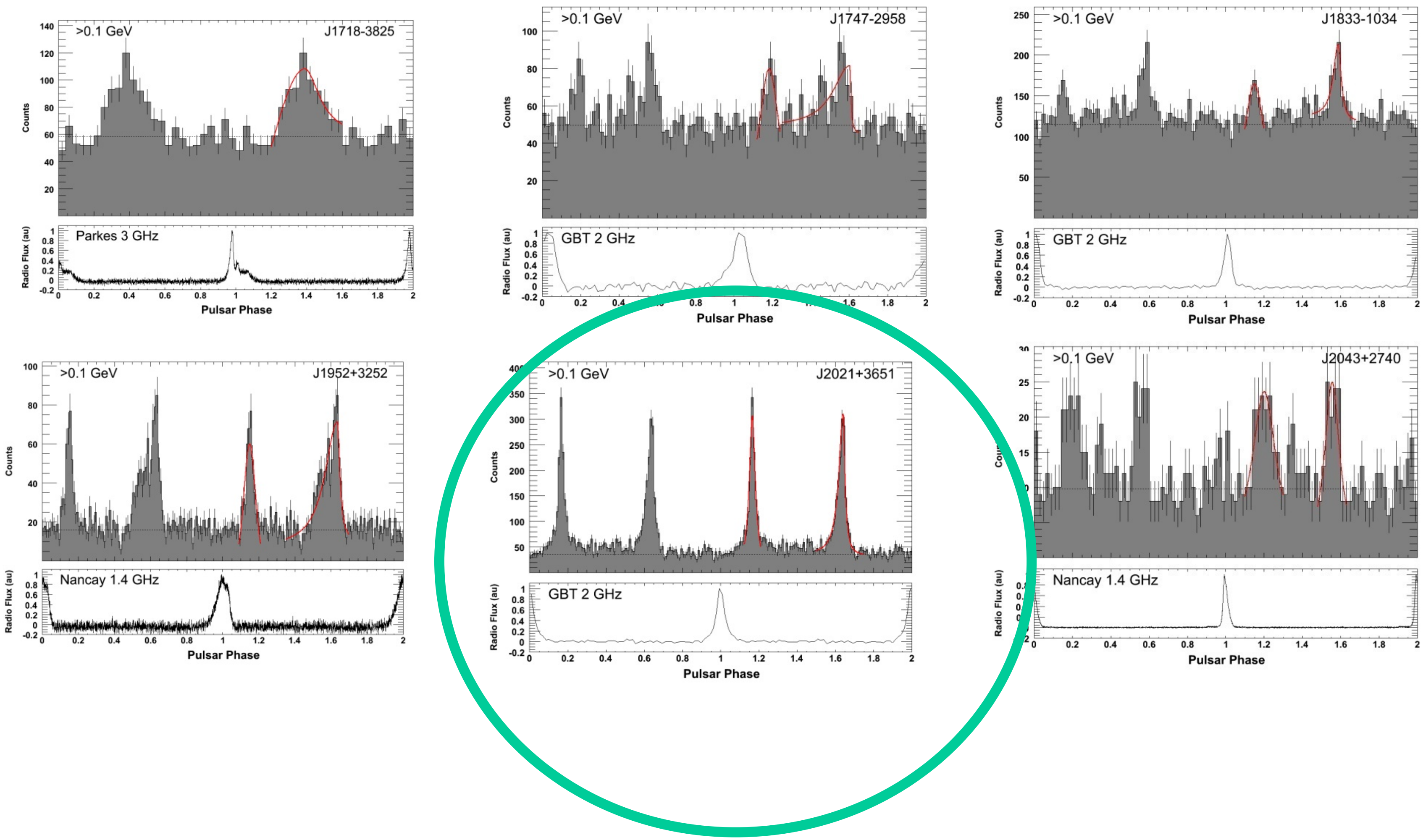


Cutoff Energy (GeV)
Pulse Phase
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7



Counts
Phase
0
200
400
600
800
1000
1200
1400
1600
1800
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

More light curves



Spectral fitting

$$\frac{dN}{dE} = N_0 E^{-\Gamma} \exp\left(-\frac{E}{E_0}\right)^{b} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$$

➔ b=1 ➔ high altitude emission.

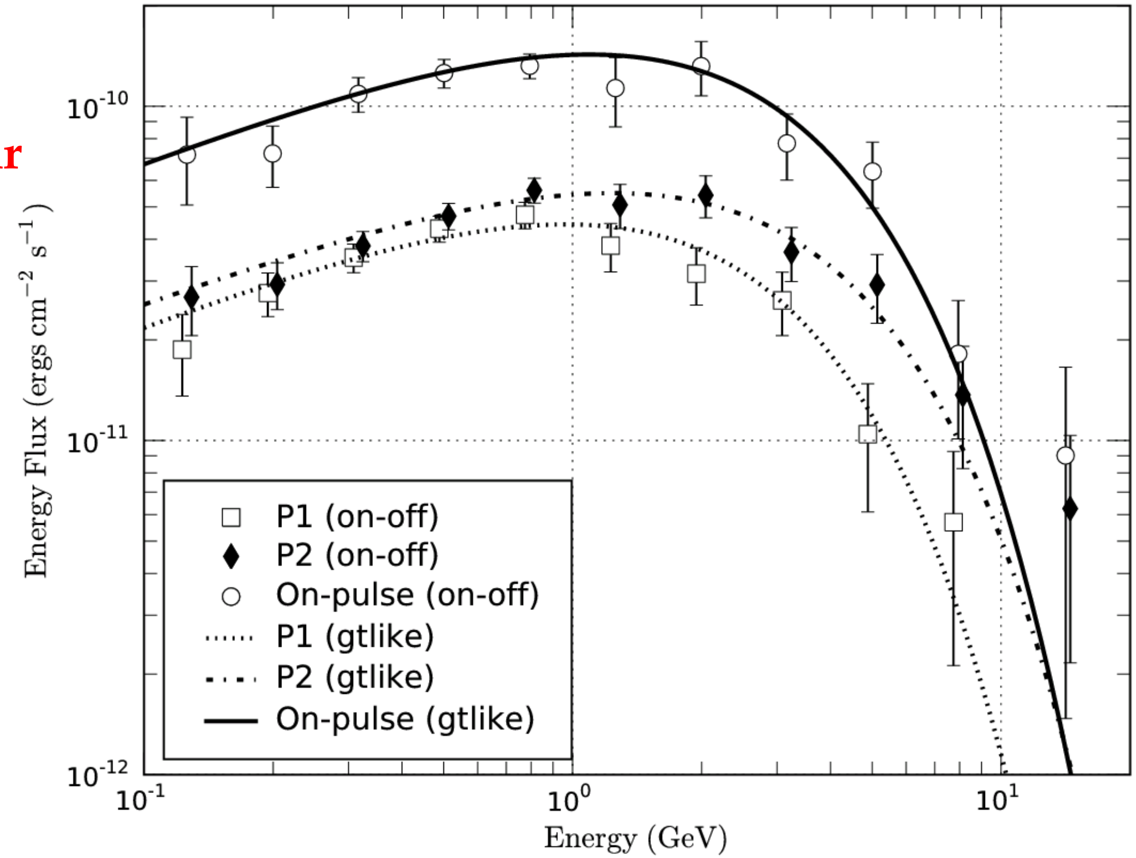
(strong magnetic fields near surface "absorb" gammas.)

Spectral index $\Gamma \sim 1.5$

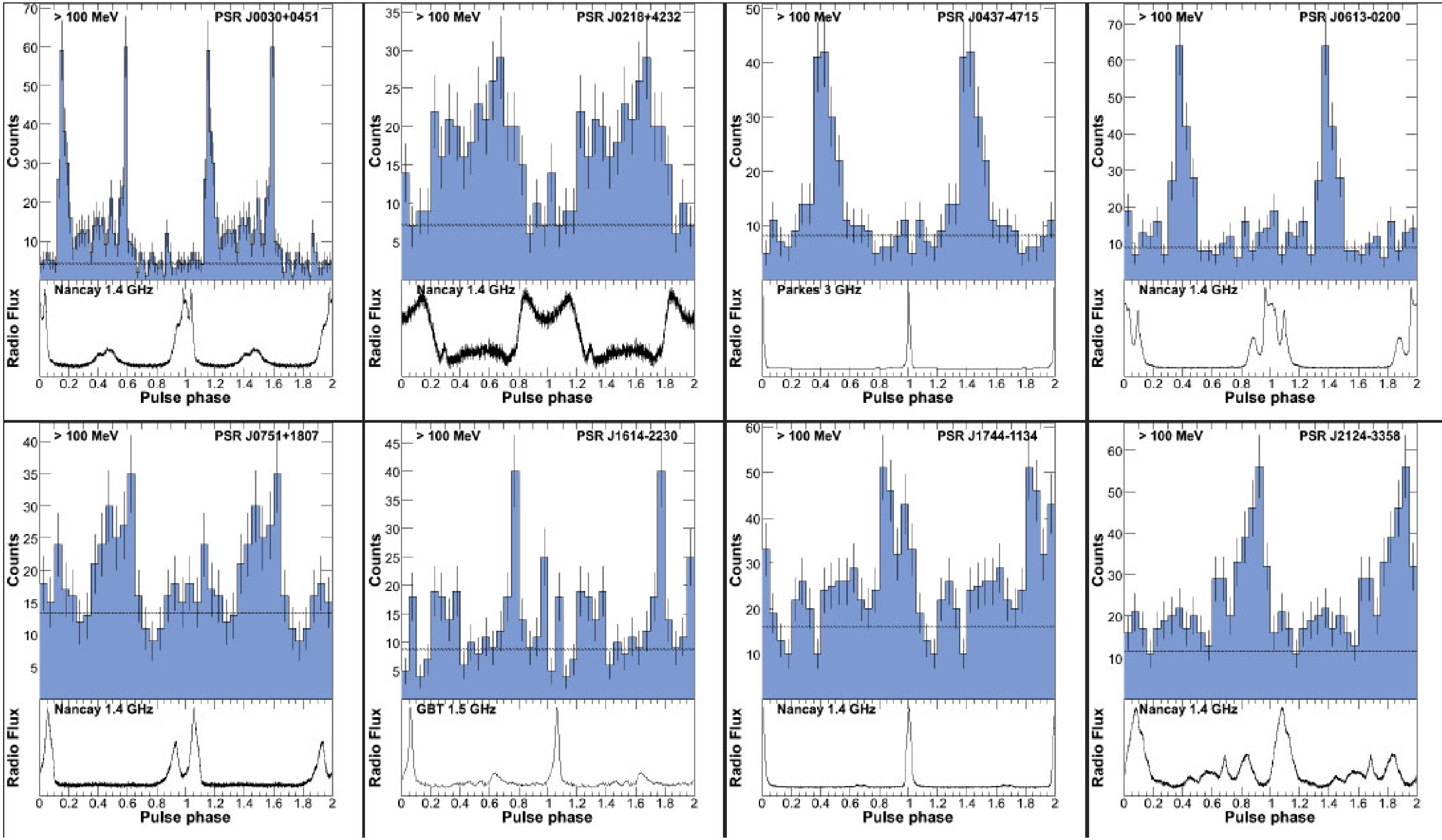
Cutoff $E_0 \sim 2.5$ GeV

Energy flux > 100 MeV

~ 4.3e-10 ergs/cm²/s



A selection of γ-ray pulsar light curves



Millisecond pulsars

Abdo et al 2009 Science 325 848

MSPs resemble young pulsars.

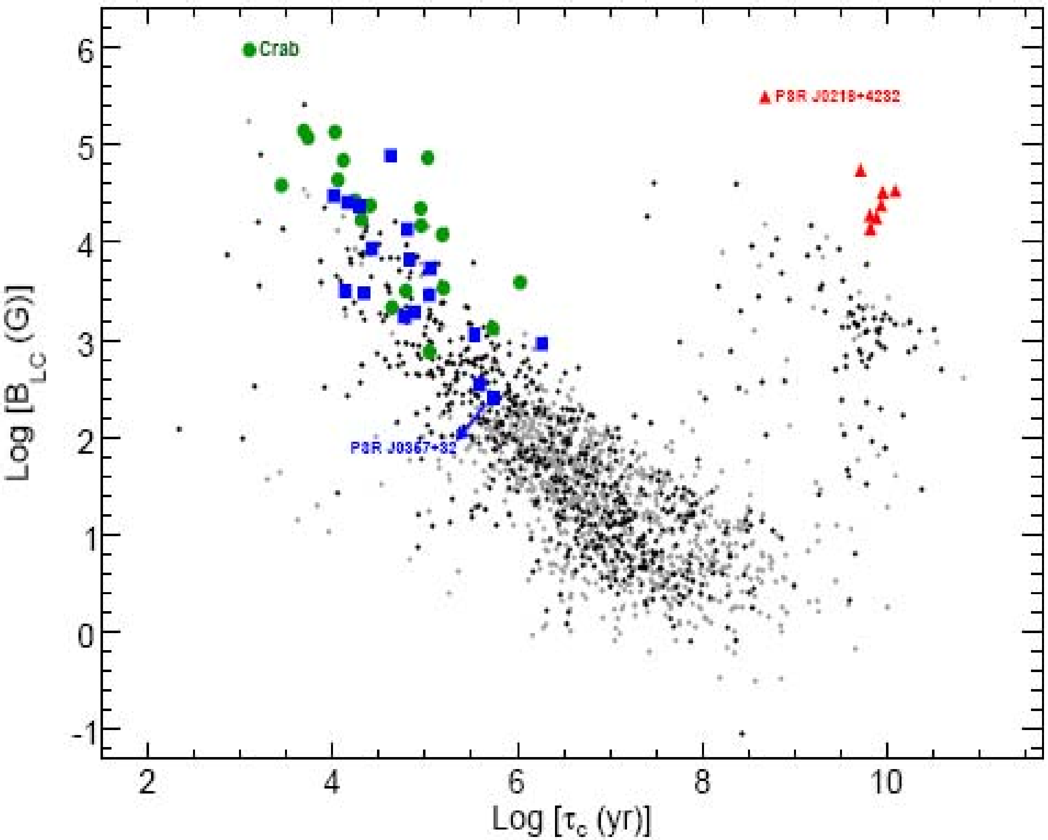
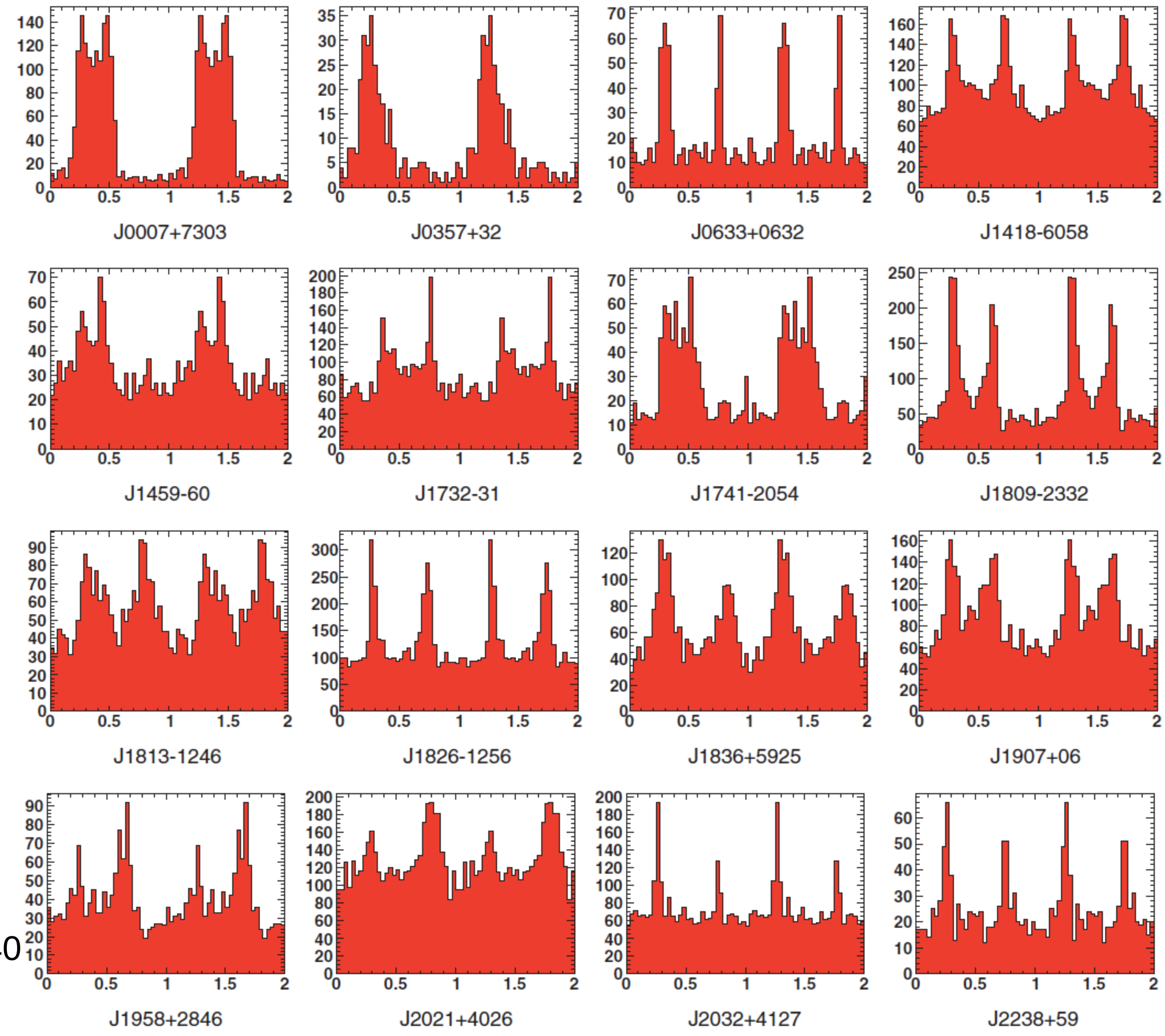


Fig. 5.— Magnetic field strength at the light cylinder $B_{\rm LC}$ versus pulsar characteristic age

A selection of γ-ray pulsar light curves



Blind search pulsars

Abdo et al 2009 Science 325 840

Phase-resolved

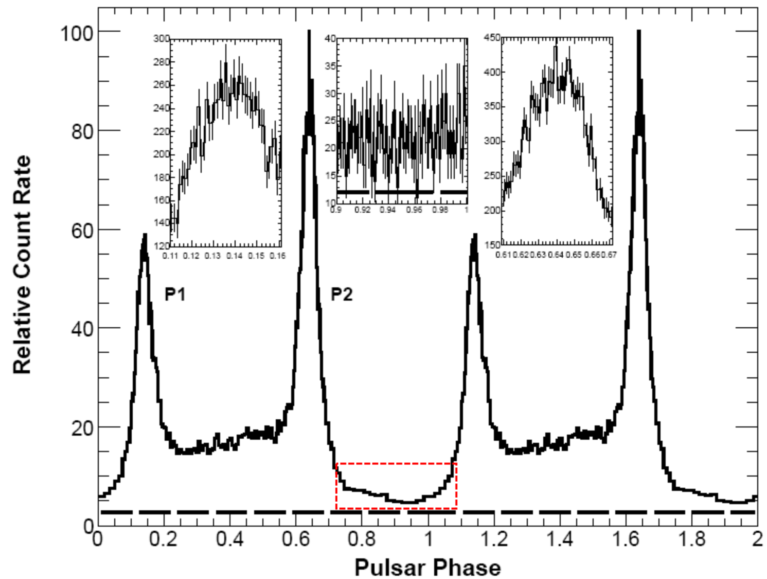


Fig. 2.— Geminga light curve above 0.1 GeV using an energy-dependent ROI, shown over two pulse periods. The count rate is shown in variable-width bins, each one containing 400 counts bin^{-1} and normalized to 100. Insets show the phase intervals centered on the two peaks and on the "off pulse" region (ϕ = 0.9–1.0), binned to 0.00125 in phase. The dashed line represents the contribution of the diffuse background estimated by selecting photons in this "off pulse" interval in an annulus around the source

P0 = 237 ms ➔ 300

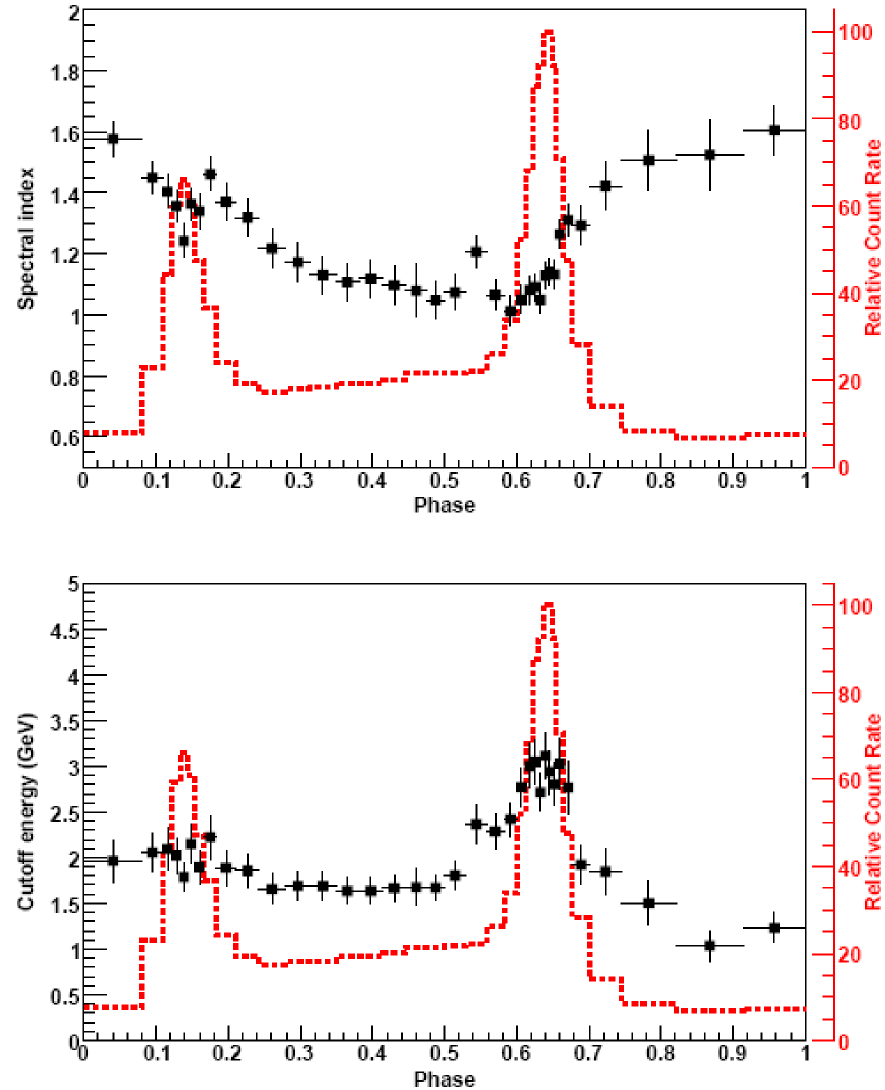
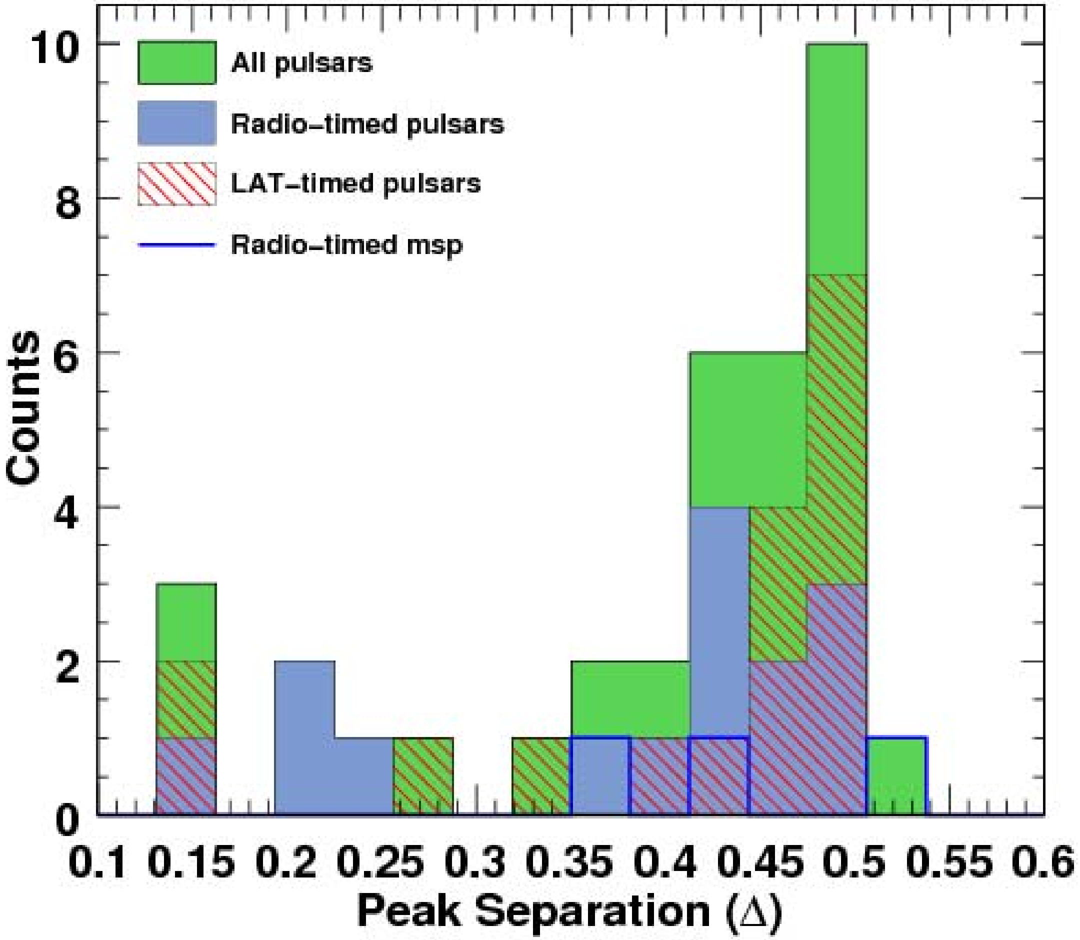


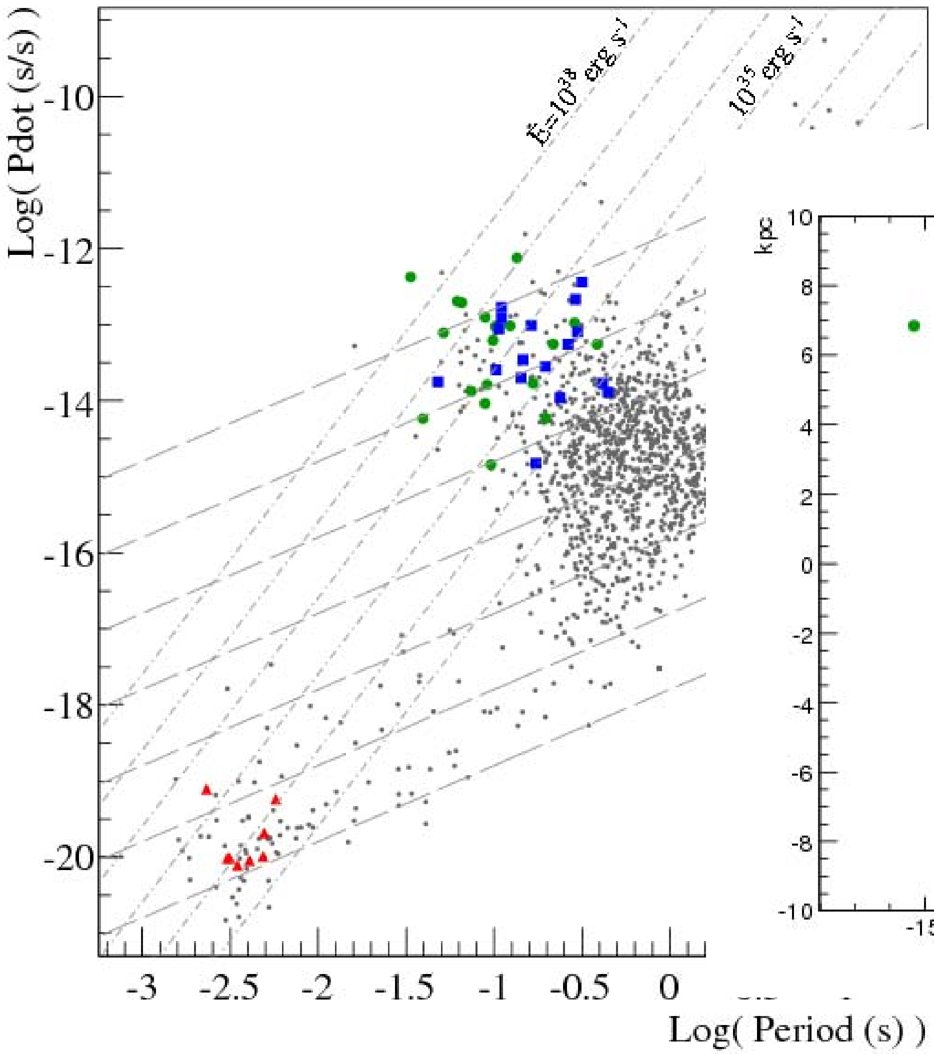
Fig. 6.— Phase evolution of the spectral index (*top*) and energy cutoff (*bottom*) above 0.1 GeV as the function of the pulse phase, divided in phase bins each containing 2000 photons. Vertical bars indicate the combined statistical and systematics uncertainties. For each phase interval (defined in Table 2) a power law with exponential cutoff has been assumed. The shaded histogram represents the *Fermi*-LAT light curve above 0.1 GeV in variable-width phase bin of 2000 photons/bin.

Geminga pulsar with *Fermi* LAT

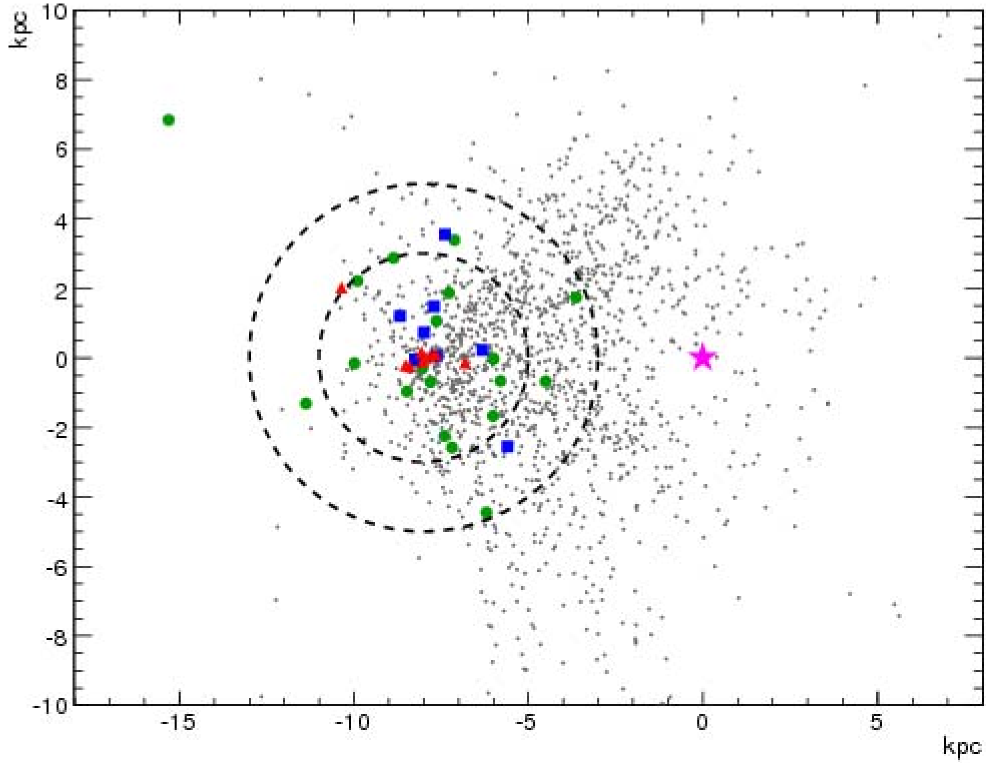
Gamma-Ray pulsars light curves



First Fermi LAT Pulsar Catalogue



A global view



Distances

Energetics

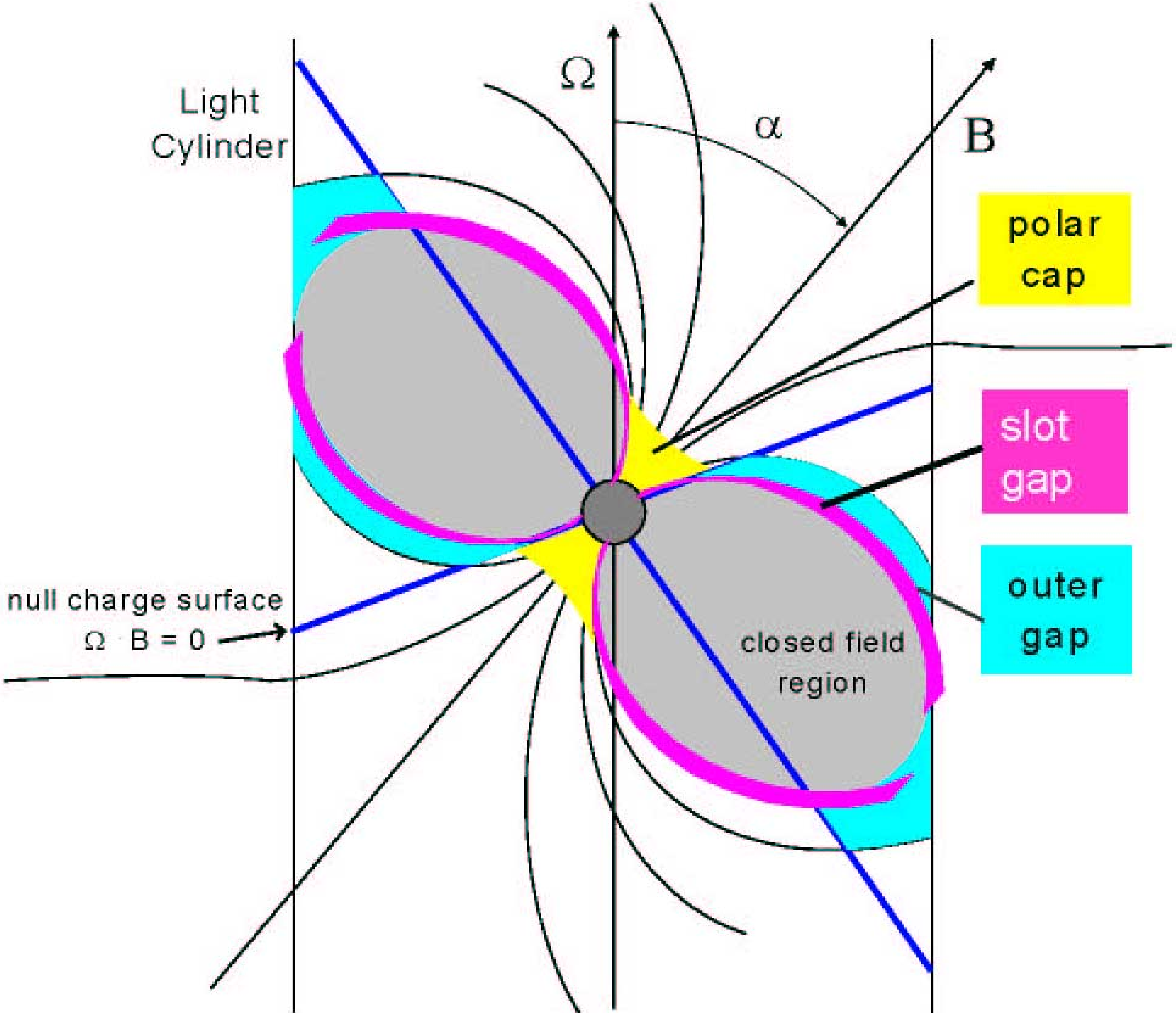
F is the integral energy flux.

$$L_\gamma = 4\pi f_\Omega F_{obs} D^2$$

f_Ω – beam geometry

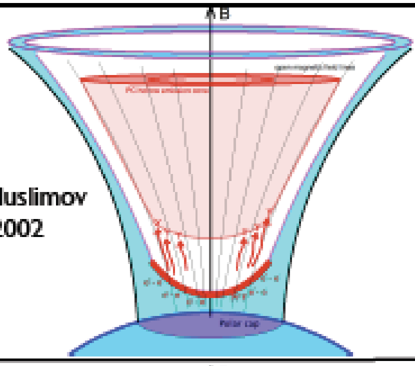
The distance *D* is a big source of uncertainty:

- **For radio pulsars, DM (dispersion measure, the electron column density along the line of sight) gives a distance estimation, via e.g. Cordes & Lazio NE2001 electron model.**
- **Can be off by +/- 50%. Or by a factor of 3.**
- **For nearby pulsars, parallax.**
- **For X-ray sources, absorption, plus a model.**
- **If associated with a known object… *e.g. HII* doppler shift *of the co-located cloud…)***


Light
Cylinder
Ω
α
B
polar
cap
slot
gap
outer
gap
null charge surface
Ω · B = 0
closed field
region

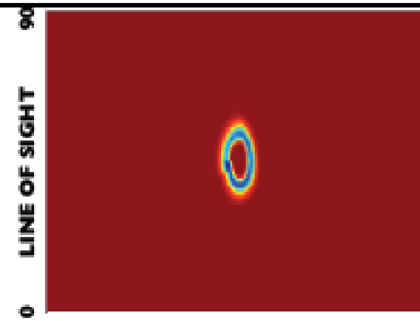
MODELS

PC
Harding, Muslimov
2001/2002



Low altitude emission, PFF formation,
$e^{+/-}{}_{\text{(acc by E)}} + B \rightarrow \gamma\ (+B \rightarrow e^{+/-})$
$e^{+/-}$ increase → E screened

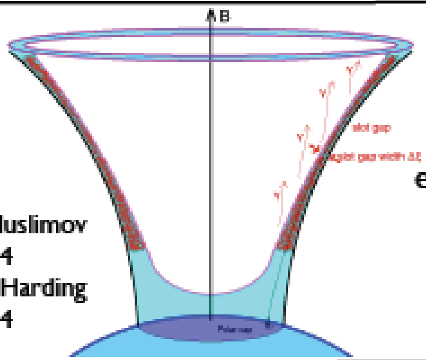
$$L_\gamma \propto \varepsilon_\gamma \dot{E}\, \Delta\xi^3$$



LTC shape and structure

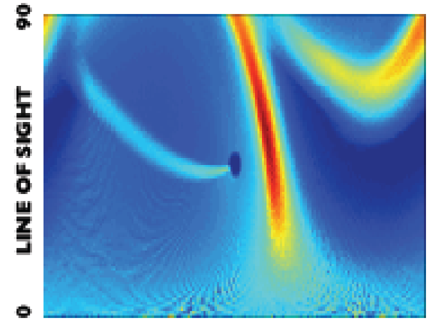
I'll expect smoothed and very peaked curves two peaks per curve low complexity

SG
Harding, Muslimov
2004
Muslimov, Harding
2004



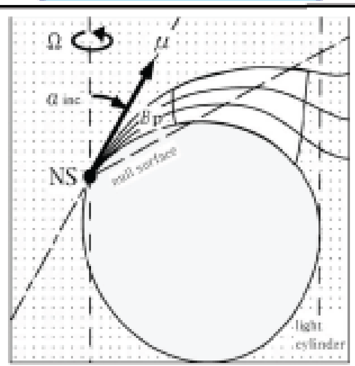
High altitude emission, PFF formation,
$e^{+/-}{}_{\text{(acc by E)}} + B \rightarrow \gamma\ (+B \rightarrow e^{+/-})$
in slot gap regions → no screening
$e^{+/-}$ accelerated until the outer magnetosphere
no upper limit to the γ-ray energy

$$L_\gamma \propto \varepsilon_\gamma \dot{E}\, \Delta\xi^3$$



Pulsar emission everywhere, 2+2 peaks per curve and high complexity

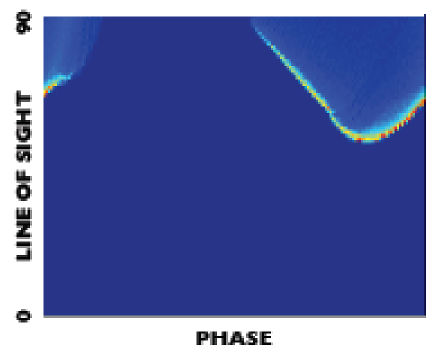
OG/ OPC



Emission from the outer magnetosphere
empty OG gaps form → $\Delta\rho_{GJ}$ → strong E
$e^{+/-}$ accelerated up to very high energy

$$L_{\gamma,OG} \propto \varepsilon_{\gamma,OG} \dot{E}\, \Delta w^3$$

$$L_{\gamma,OPC} \propto \varepsilon_{\gamma,OPC} \dot{E}\, \Delta w$$



Well defined emission regions, often double peak structure with a bridge or three peaks structure

M. Pierbattista, I. Grenier , A.Harding but also Romani, Watters

Gamma-ray luminosity versus spindown power

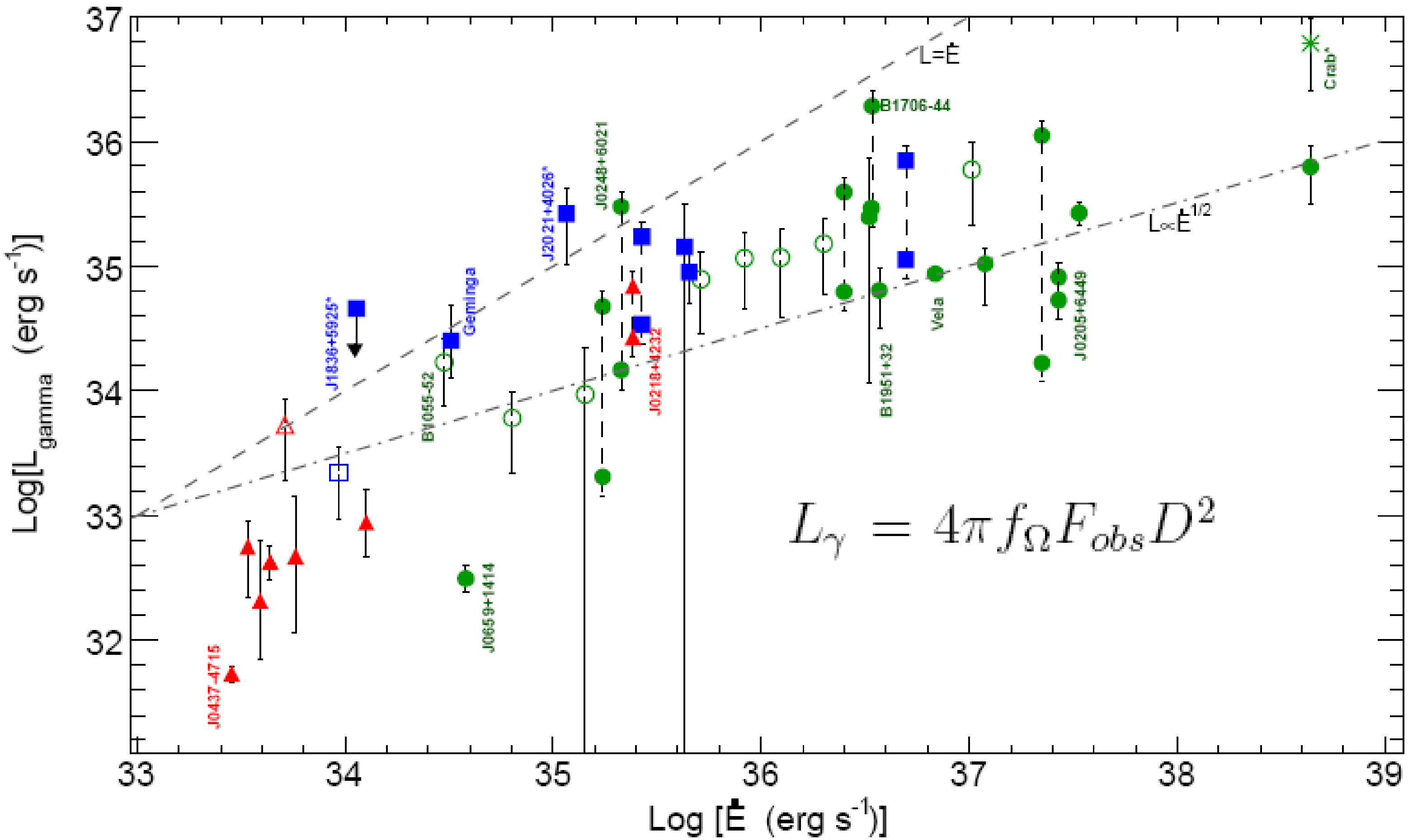


Fig. 6.— Gamma-ray luminosity L_γ versus the rotational energy loss rate $\dot{E}$. Dashed line: L_γ equal to $\dot{E}$. Dot-dashed line: L_γ proportional to the square root of $\dot{E}$. L_γ is calculated using a beam correction factor $f_\Omega = 1$ for all pulsars and the integral energy flux G_{100} from the on-pulse

Pulsars' facts

- **Of the 24 pulsars discovered by Fermi thus far, only 3 have been detected in radio, despite deep searches on all 24.**
- **Including Geminga, about 50% of known <u>young</u> gamma-ray pulsars are radio quiet (despite the significantly reduced flux sensitivity of the blind search compared to folding gamma-ray data with known radio ephemerides)**

About the LAT pulsars

- Generally (but not always), two peaks separated by ½ rotation.
- Generally (but not always), gamma peak offset from radio.
- Exponential cut-offs at ~1 to ~3 GeV. (not *super*-exponential)
- **Favors outer magnetospheric emission.**
- Edot's as low as $3E^{33}$ erg/s