Gamma-ray Emission from Pulsars – an Outer Magnetospheric Gap Prospective

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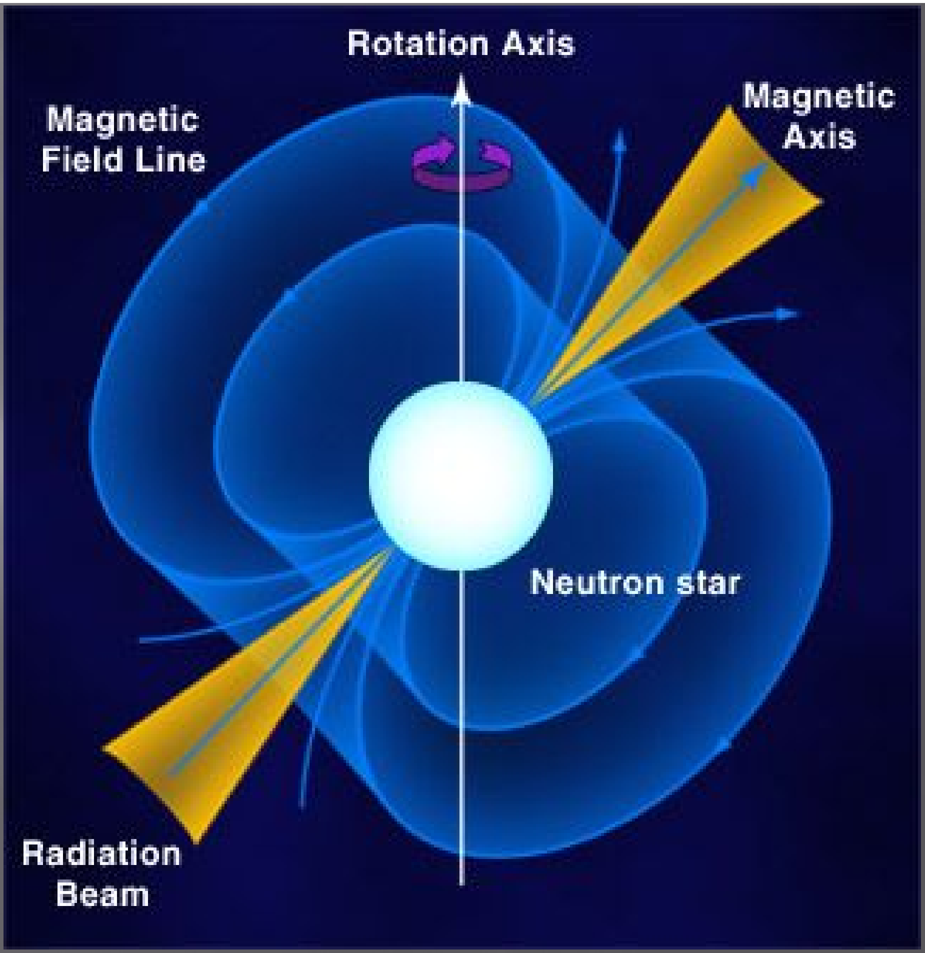
Why are pulsars powerful radiation sources?

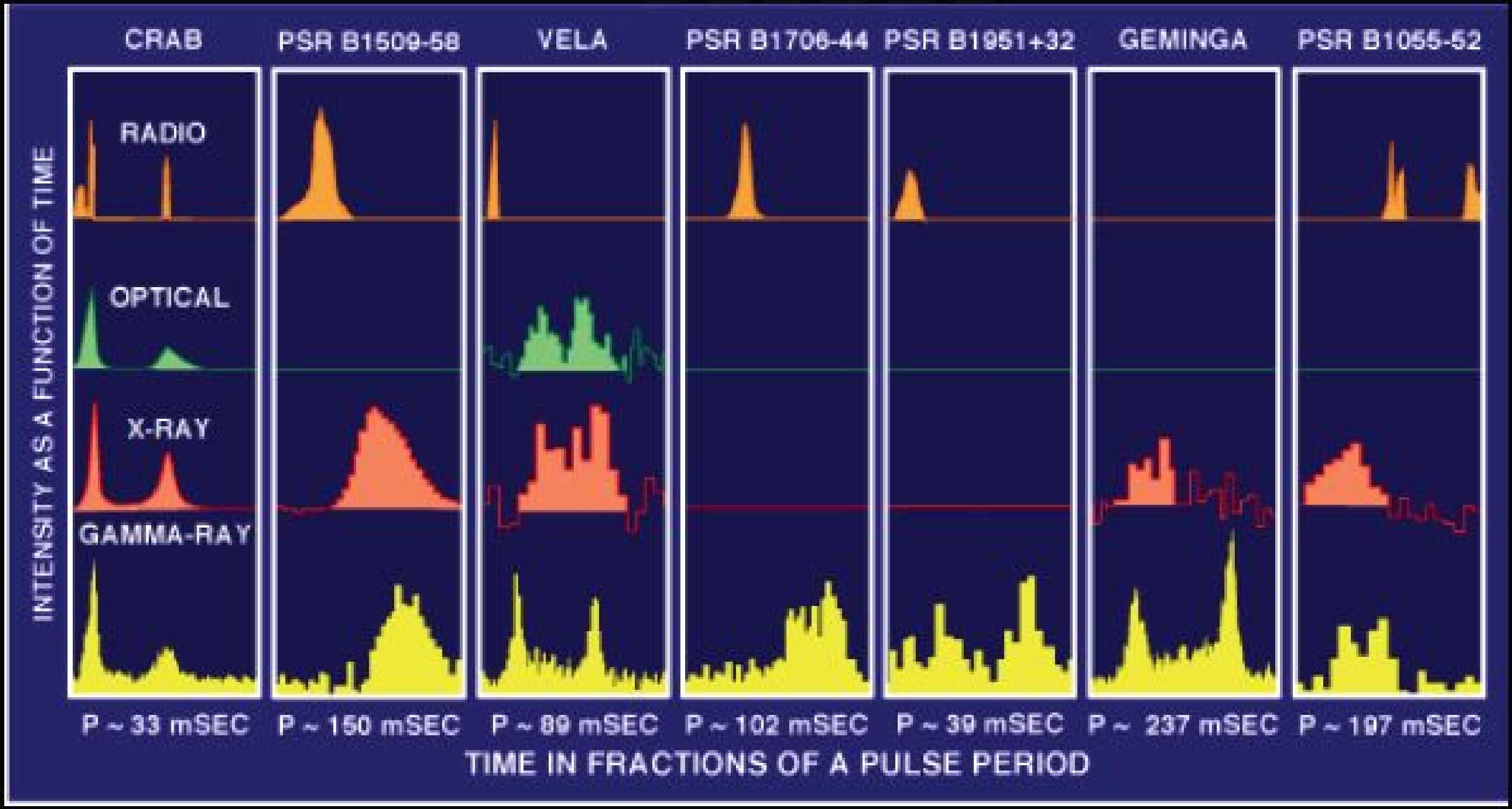
- Pulsars are rotating and strongly magnetized objects, so they can act like unipolar inductor
- The maximum potential drop can be as large as

$$V_{max} \approx 6.6 \times 10^{12} B_{12} P^{-2} volts$$

- For young pulsars, the maximun potential can be much higher than 10^{15} volts
- This potential drop can accelerate charged particles and radiate high energy photons from various accelerators in the magnetosphere



Gamma-ray pulsars detected before 2009



- Only 7 γ-ray pulsars known in EGRET era
- Only 1 radio-quiet pulsar was known.
- No MSPs was found.

Fermi Satellite –The Gamma-ray Large Space Telescope (launch 11/6/2008)

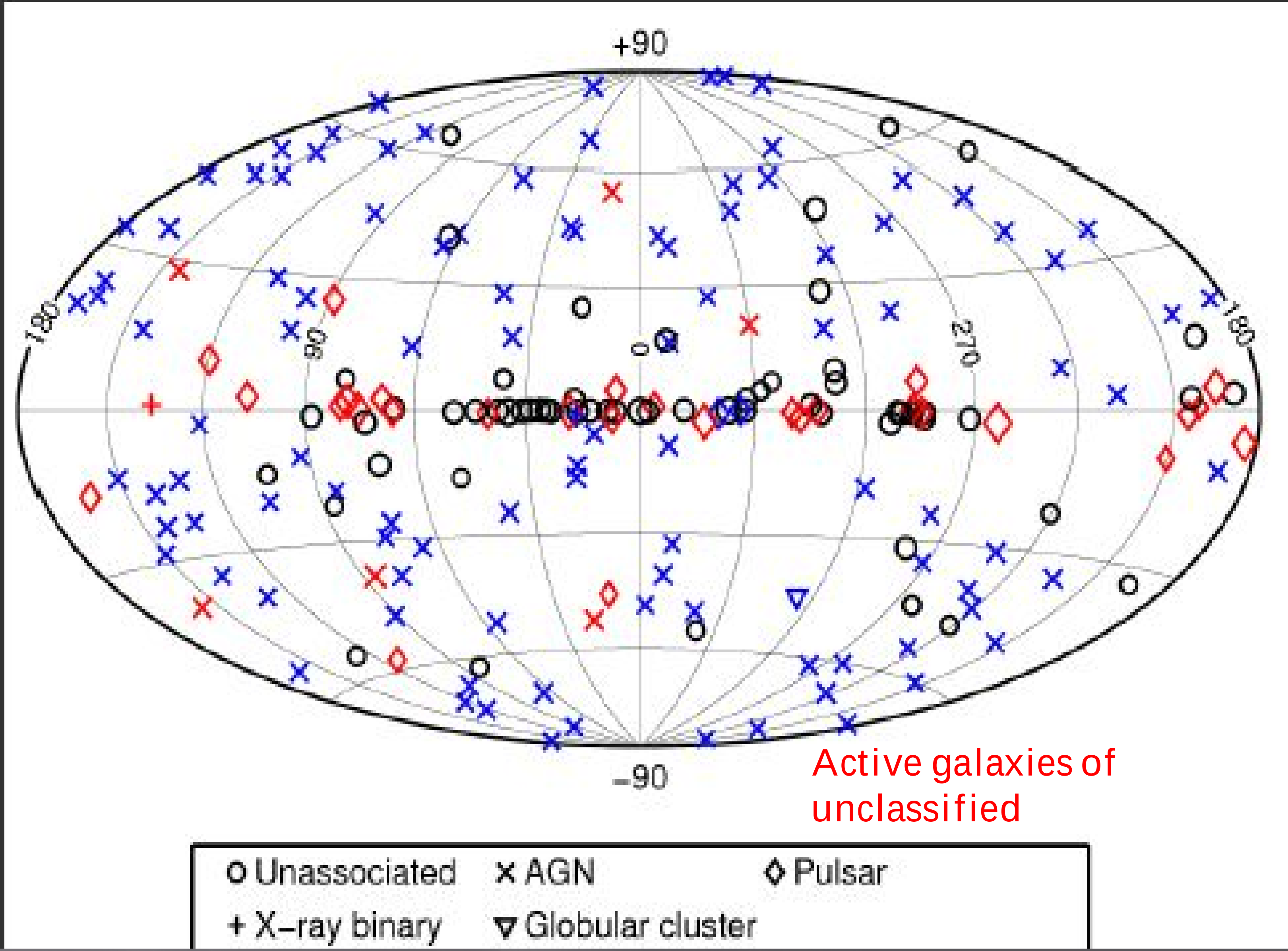
The Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope

Fermi Gamma-ray Space Telescope

- Pair production telescope with silicon tracker, CsI calorimeter, and segmented anti-coincidence detector
  - 20 MeV to >300 GeV
  - 8000 cm^2 area (at 1 GeV)
  - 0.6–0.8 deg radius PSF (1 GeV)
- Continuous sky survey mode of operation
- Big improvement in area, FOV, and reduction in background compared to EGRET

(Ray 2010)

Abdo et al, 2009, ApJS, 183, 46

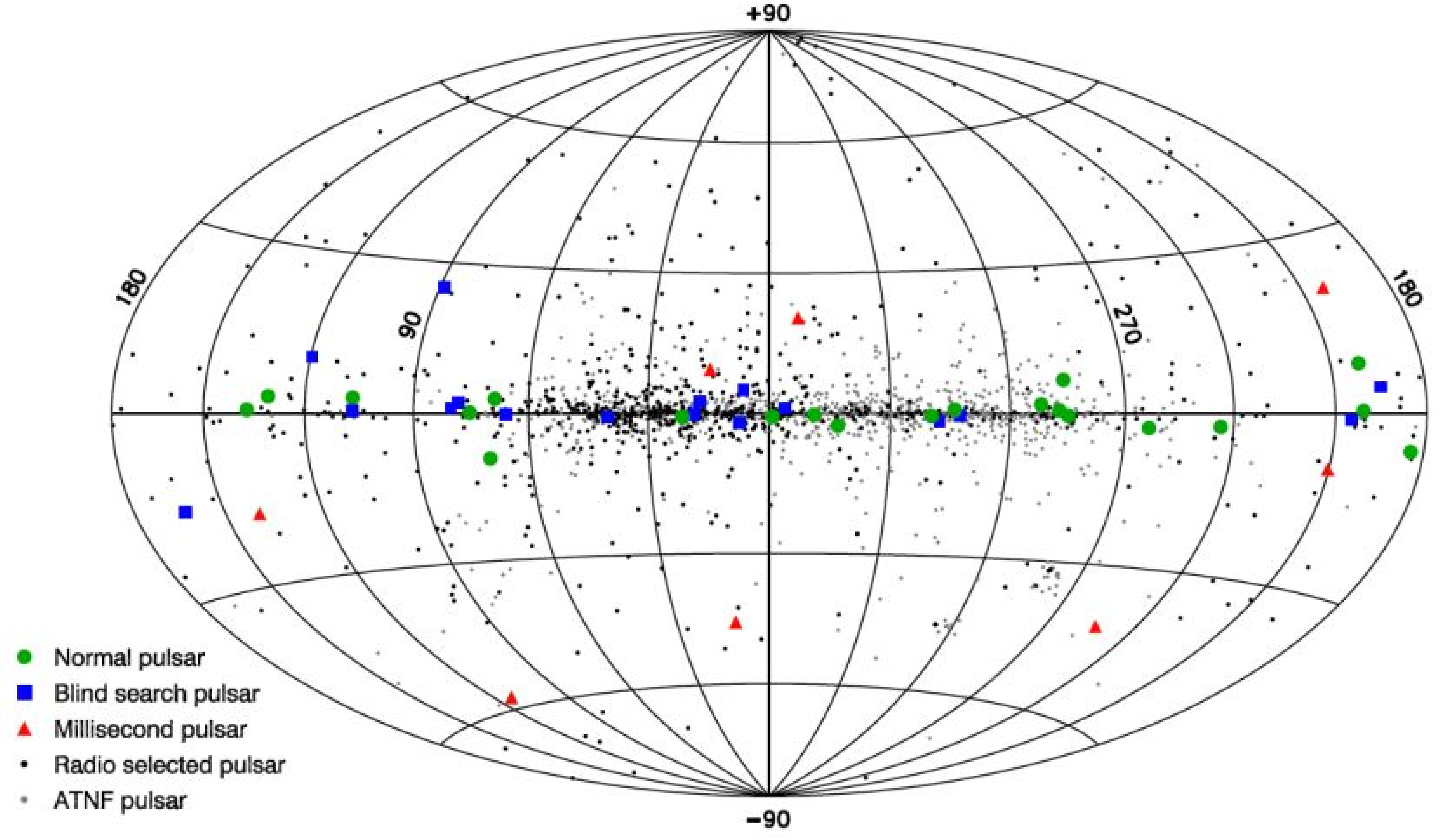


Active galaxies of unclassified

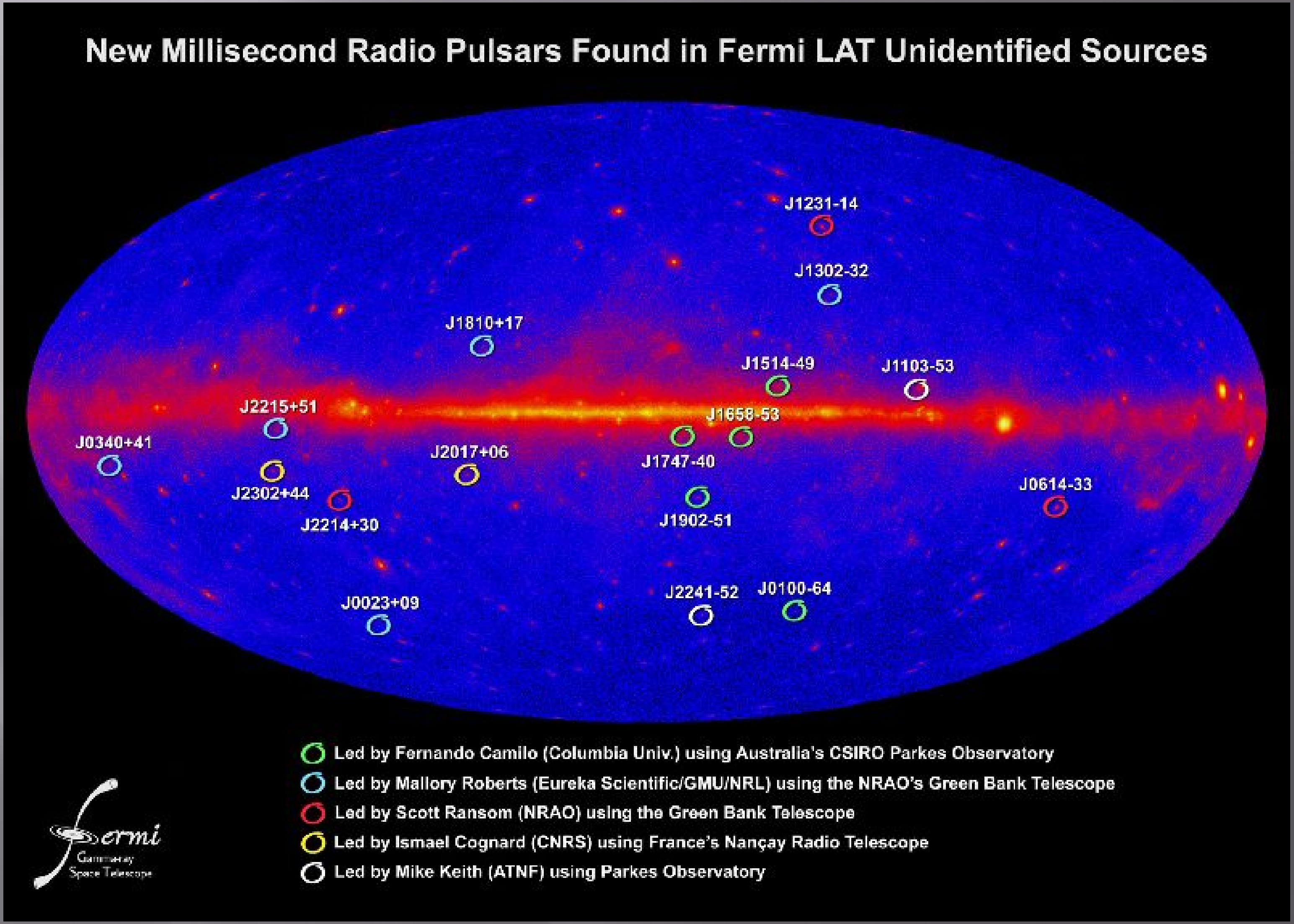
THE 1ST FERMI PULSAR CATALOG

In addition to the search for new pulsars, 762 known pulsars with ephemerides were searched for pulsations in nine months of data.

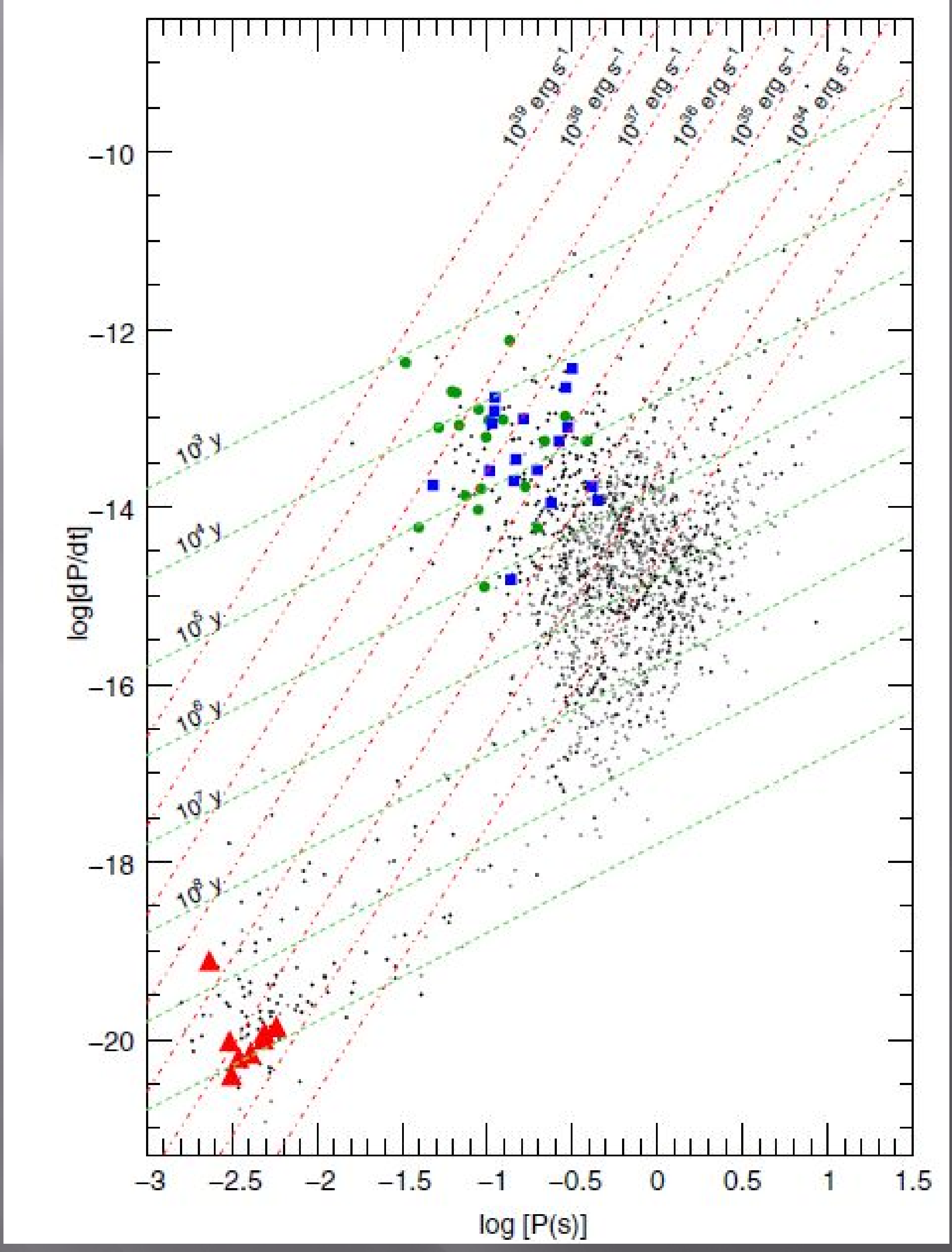
=> 46 pulsars were detected: 22 radio-loud normal PSRs, 8 radio-loud MSPs, 16 radio-quiet PSRs (blind search). (den Hartog 2010)



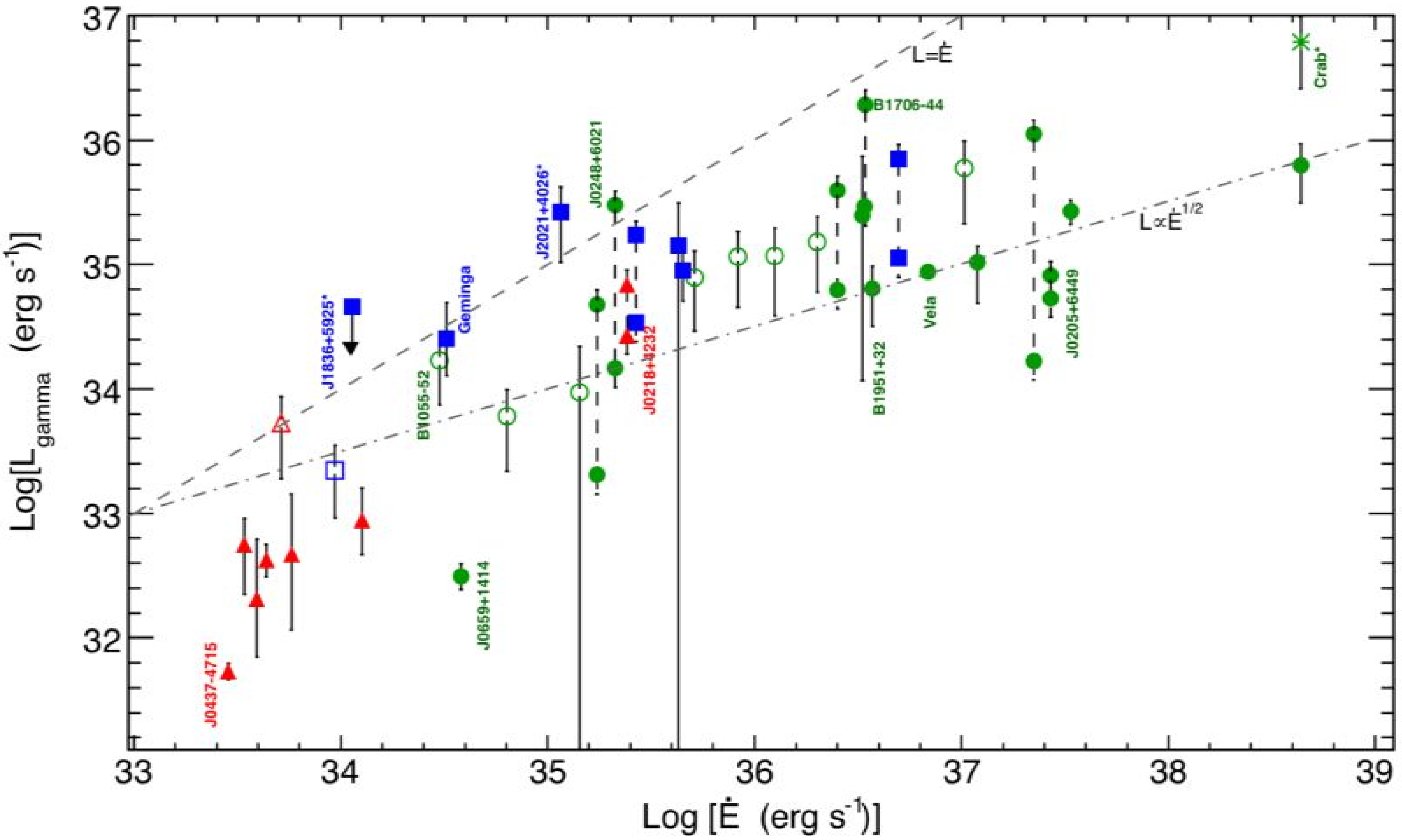
- New radio MSPs discovered at Fermi unassociated sources (Ray 2010)- currently 33 MSPs



MSPs are a major contributor to the Galactic γ-ray sources



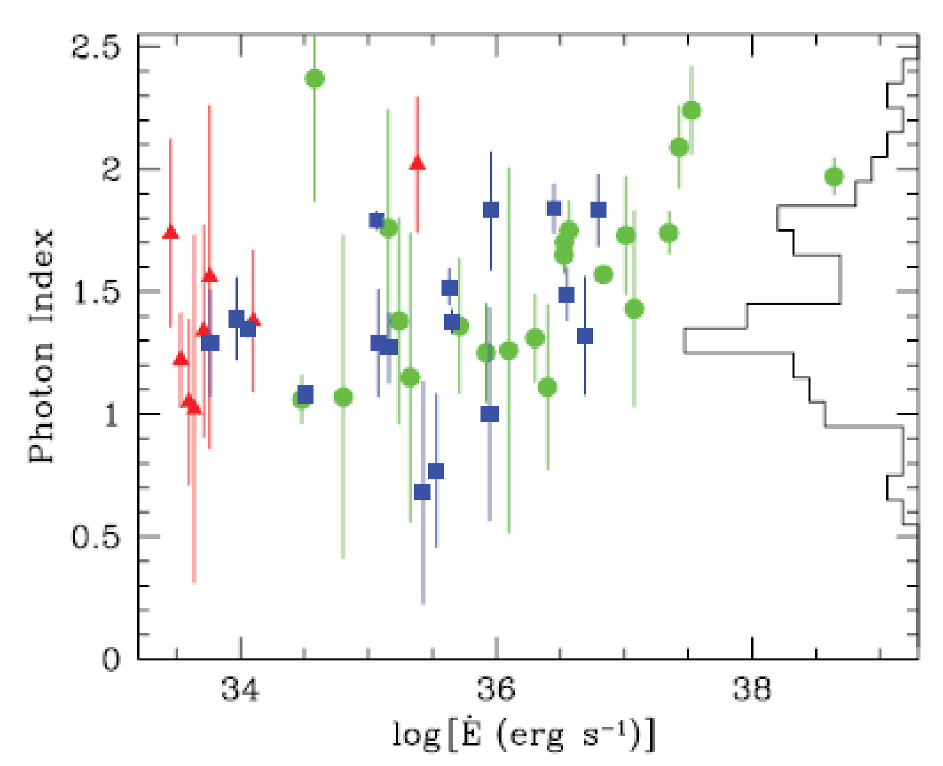
10^39 erg s^-1
10^38 erg s^-1
10^37 erg s^-1
10^36 erg s^-1
10^35 erg s^-1
10^34 erg s^-1
10^3 y
10^4 y
10^5 y
10^6 y
10^7 y
10^8 y
log[dP/dt]
−10
−12
−14
−16
−18
−20
−3
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
log [P(s)]

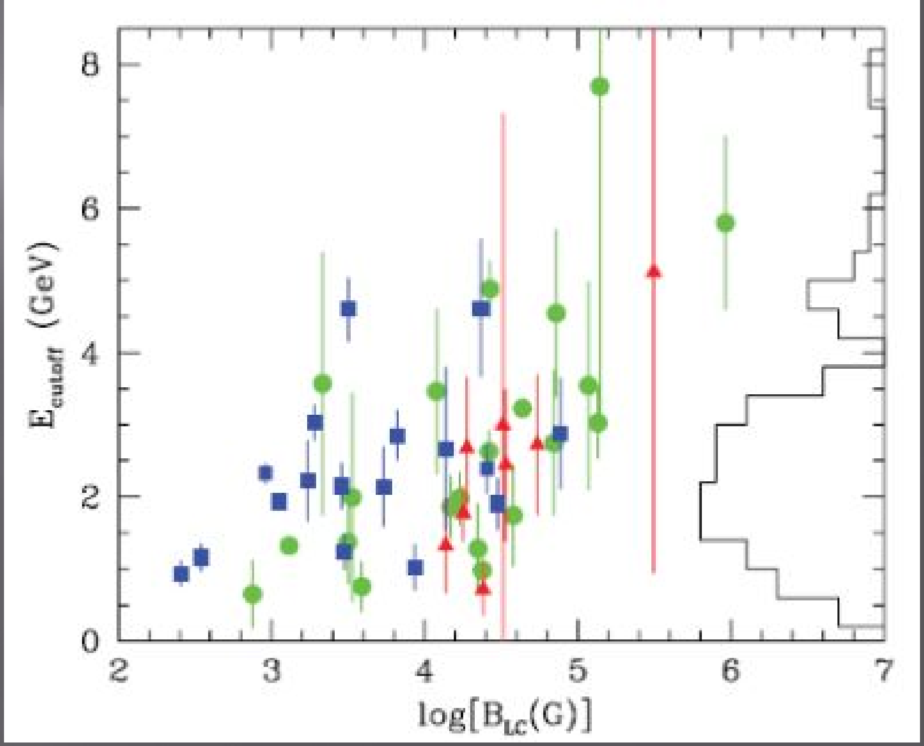


(Abdo et. Al. 2009) The gamma-ray luminosity roughly increases with spin-down power of pulsars, rougly speaking $L \propto \sqrt{\dot{E}}$ (N.B. the gamma-ray power depends sensitively on the real distance to the pulsar.)

Observed spectral properties

- F(E) ~ E^-Γ exp(-E / E_c) where Γ ~ 0.6 -2.4 and E_c ~ 1-8 GeV

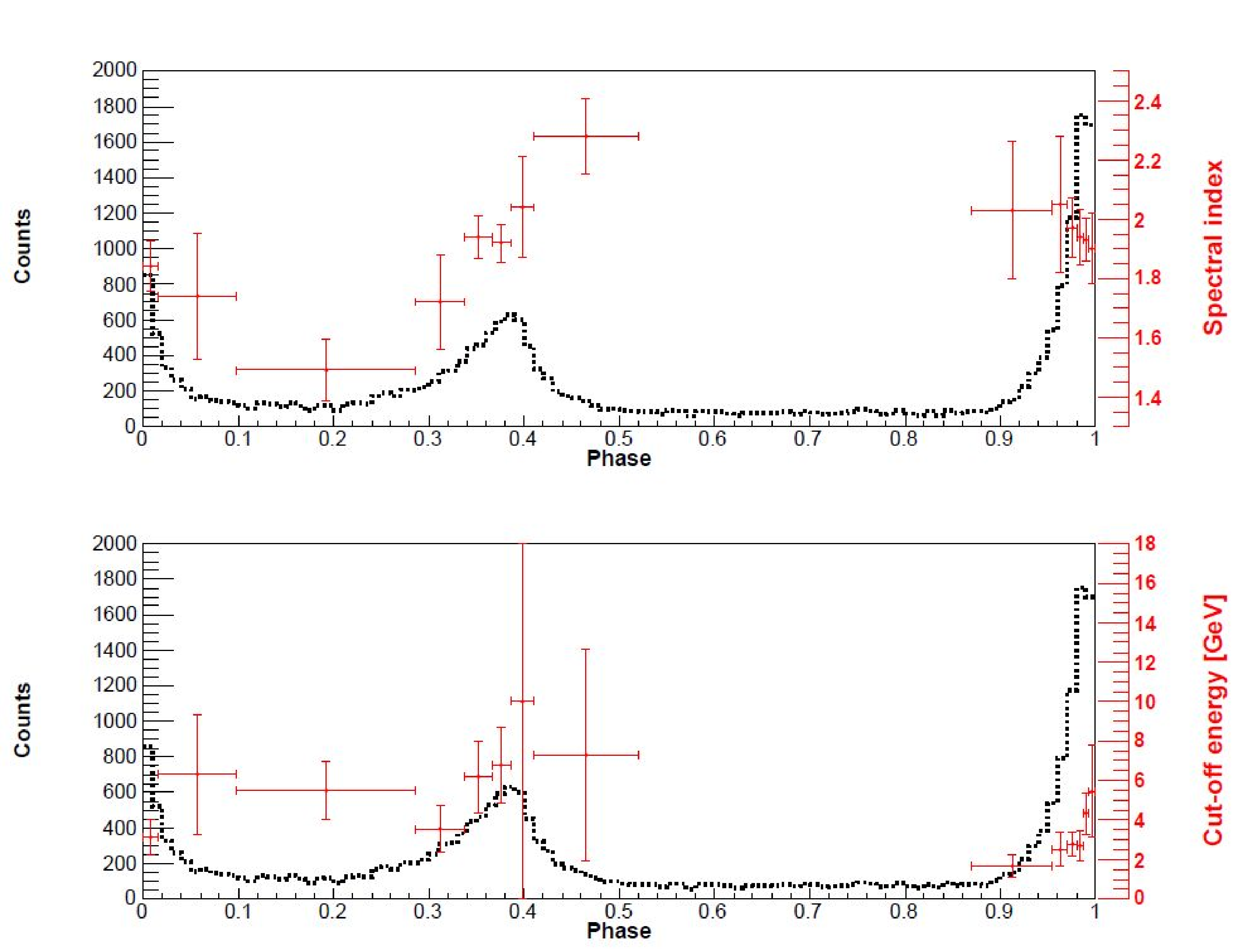




Abdo et al. 2009

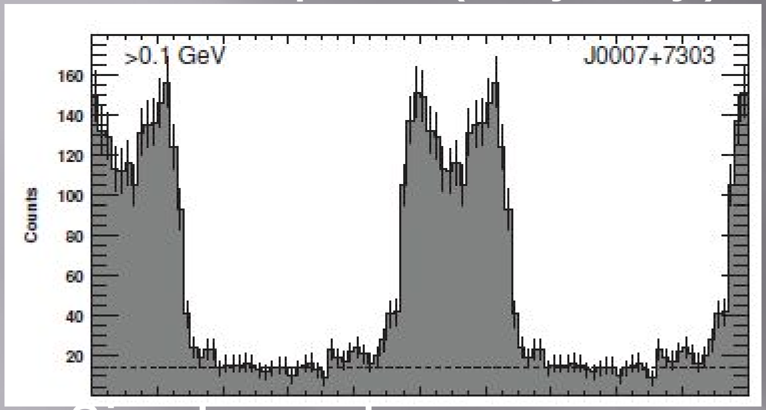
Spectral properties of individual pulsars

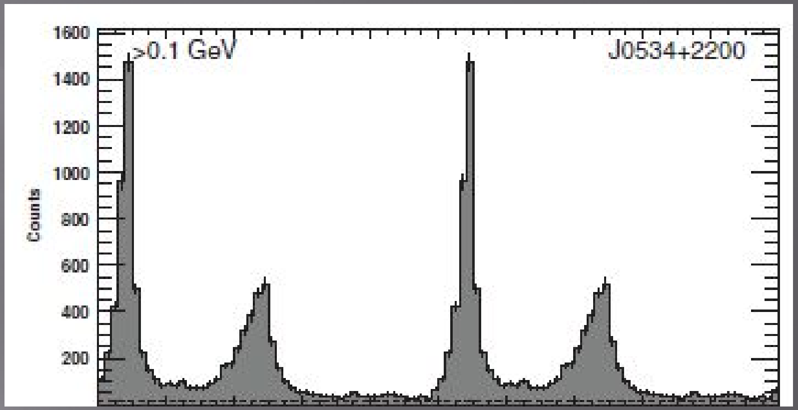
- Phase-dependent spectra – e.g. Crab pulsar



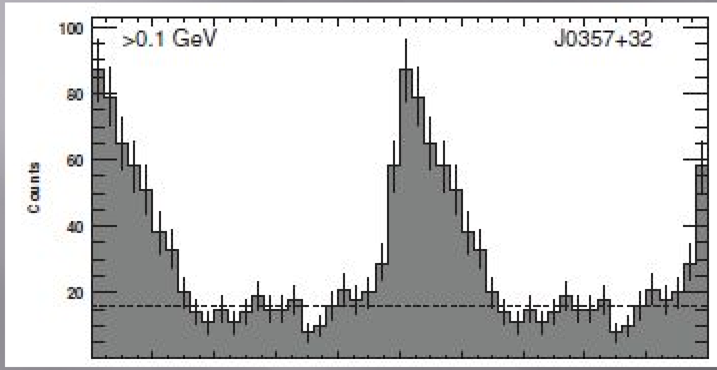
Emission morphologies

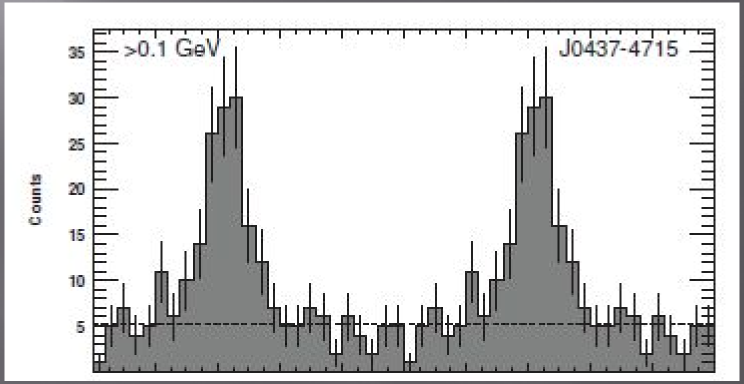
- Double peak (majority)



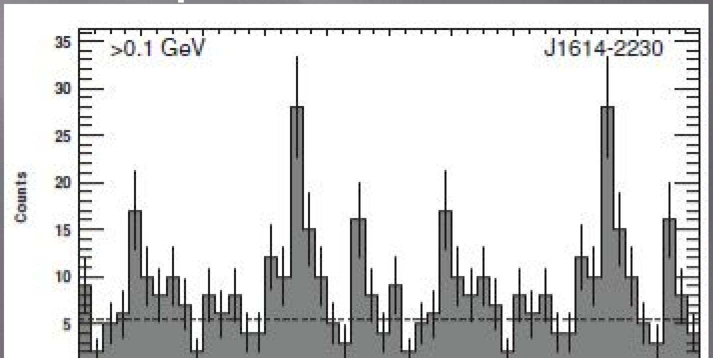


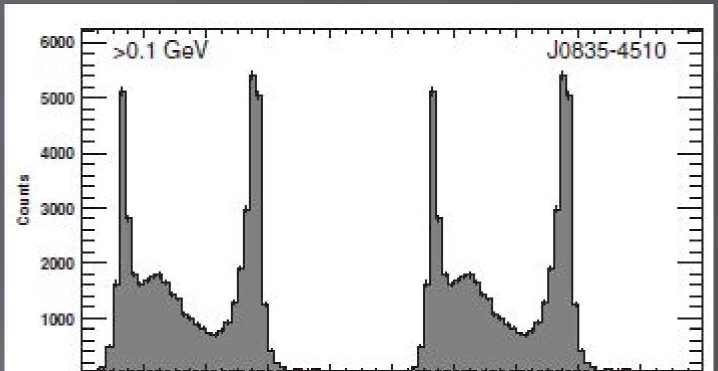
- Single peak



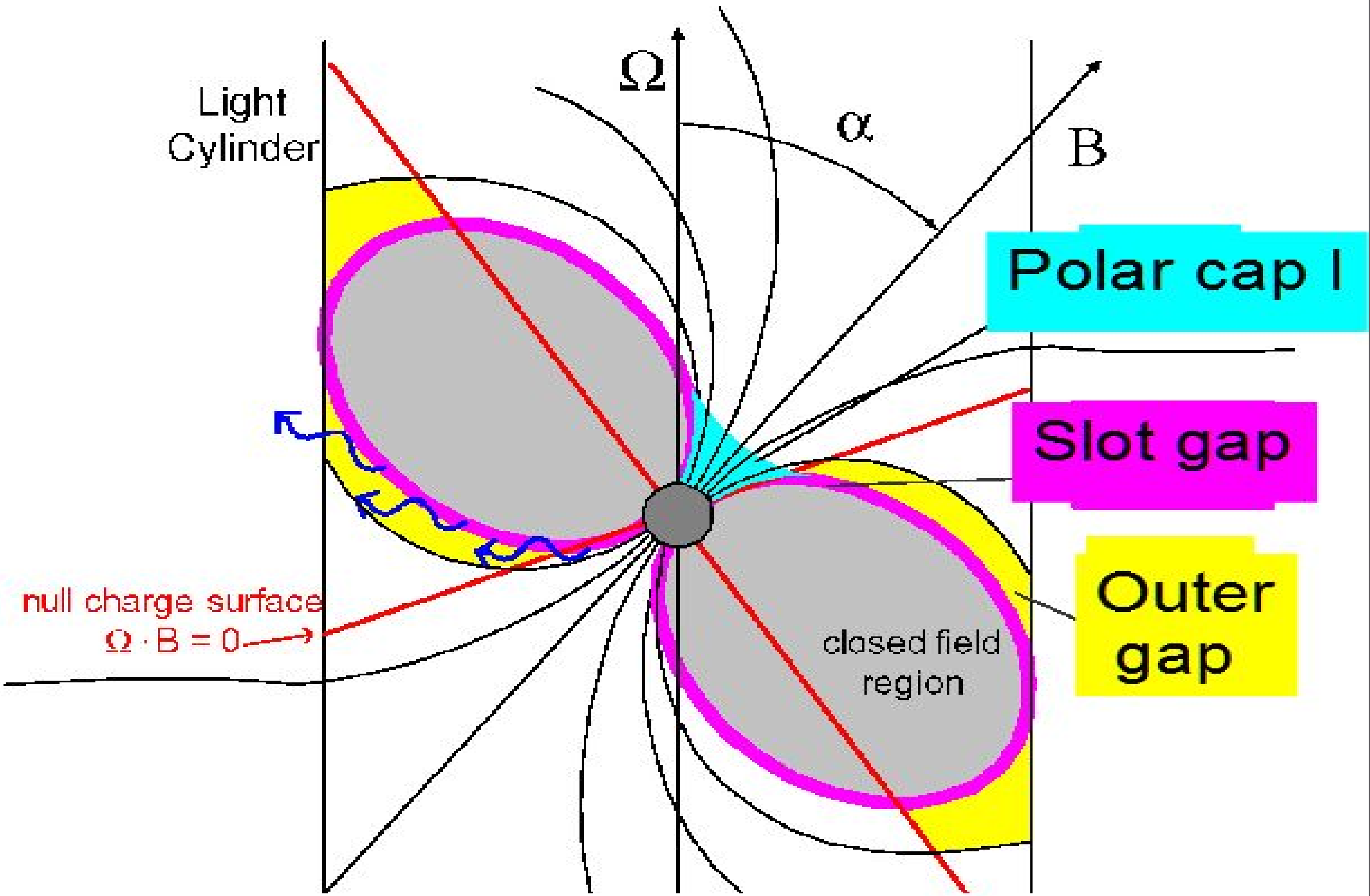


- Multiple ?



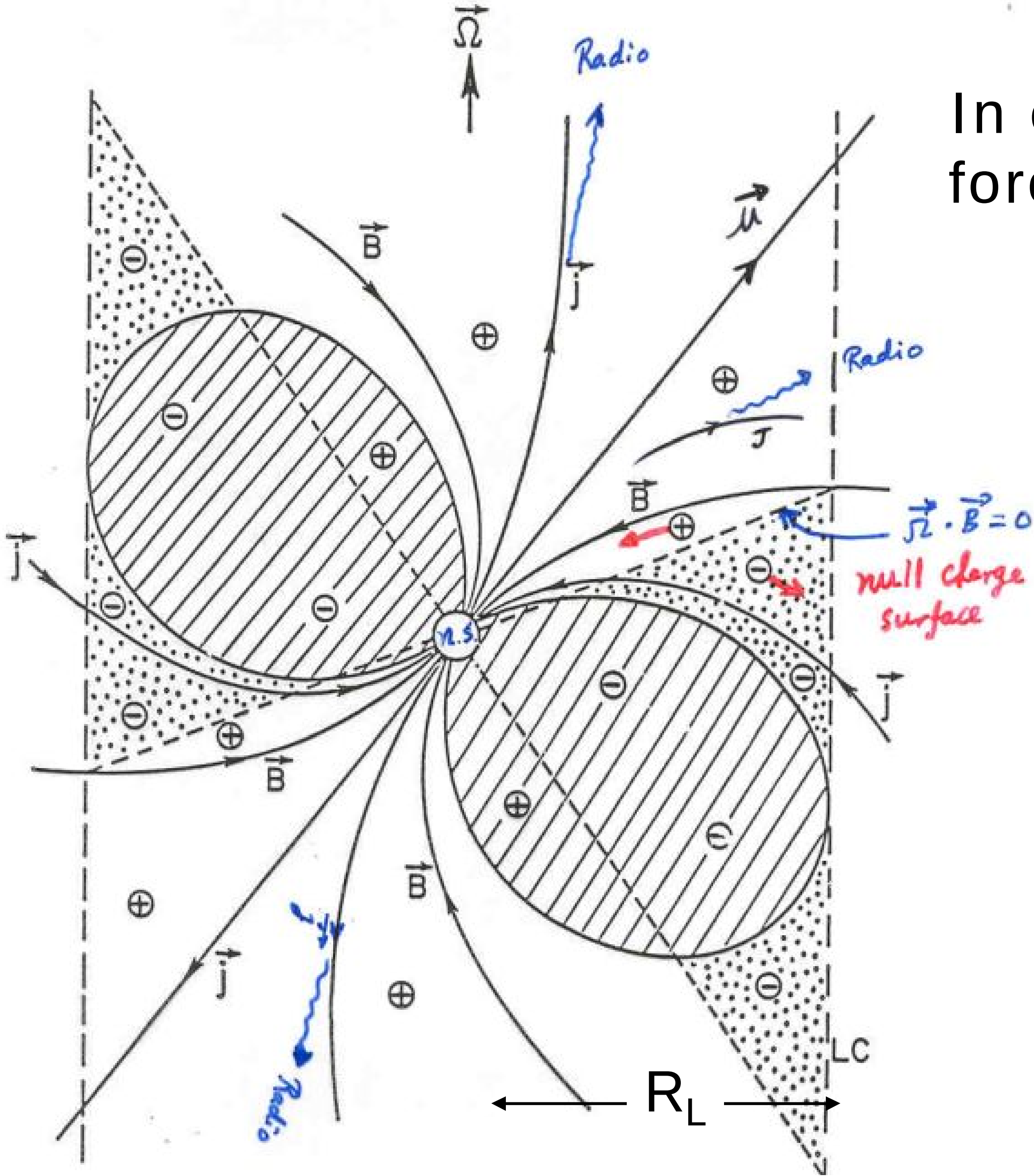


Various Accelerator Models



Harding 2006

Pulsar magnetosphere



In equilibrium the Lorentz force is assumed to be

$$\mathbf{E} + \frac{1}{c}(\boldsymbol{\Omega} \times \mathbf{r}) \times \mathbf{B} = 0$$

Charge distribution:

$$\rho_{GJ} = \frac{1}{4\pi}\nabla \cdot \mathbf{E}$$
$$\approx -\frac{\boldsymbol{\Omega} \cdot \mathbf{B}}{2\pi c}\frac{1}{1-|\boldsymbol{\Omega} \times \mathbf{r}/c|^2} \approx -\frac{\boldsymbol{\Omega} \cdot \mathbf{B}}{2\pi c}$$

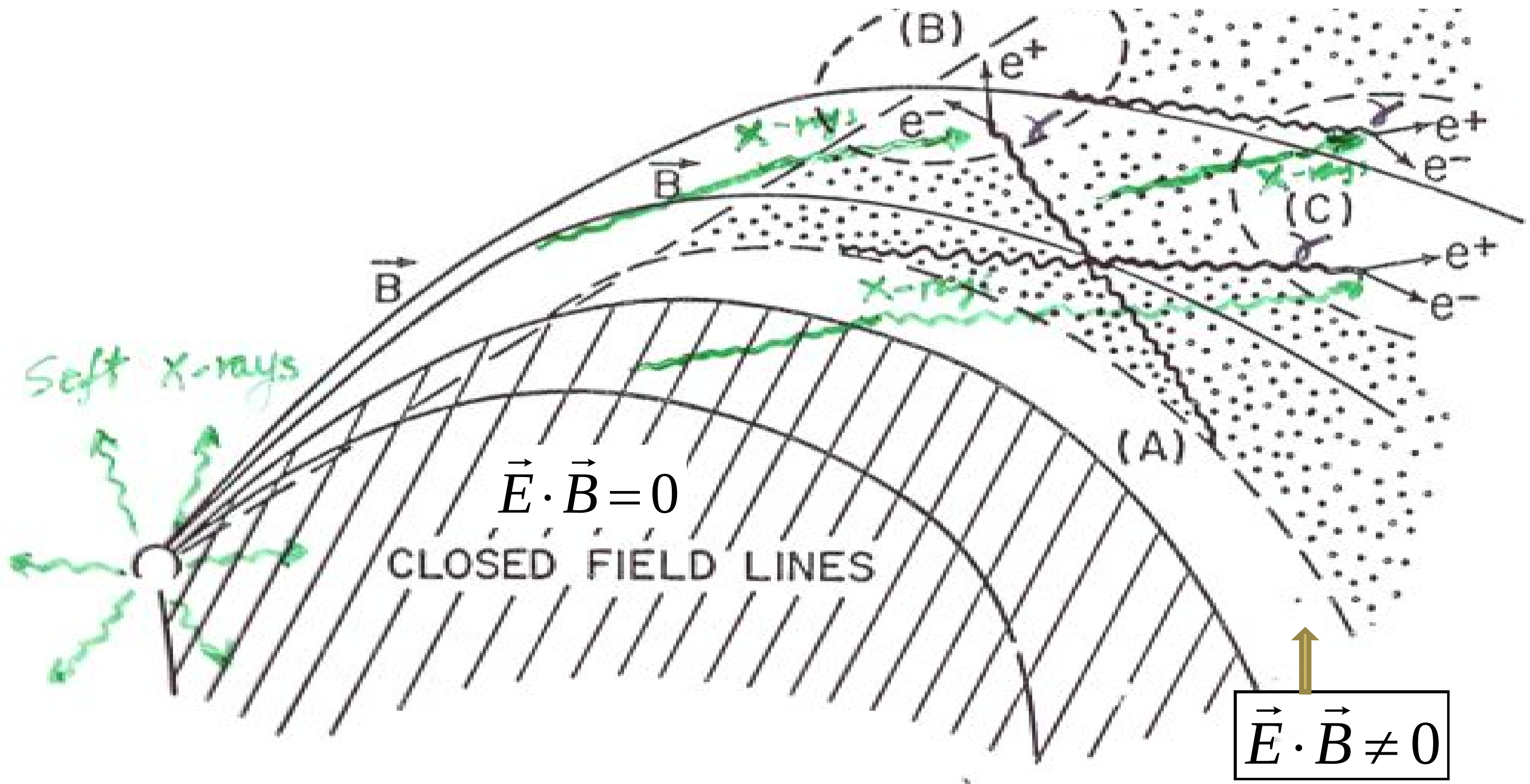
Goldreich-Julian charge density

Pair creation in Outergap where $(\vec{E} \bullet \hat{B}) \neq 0$

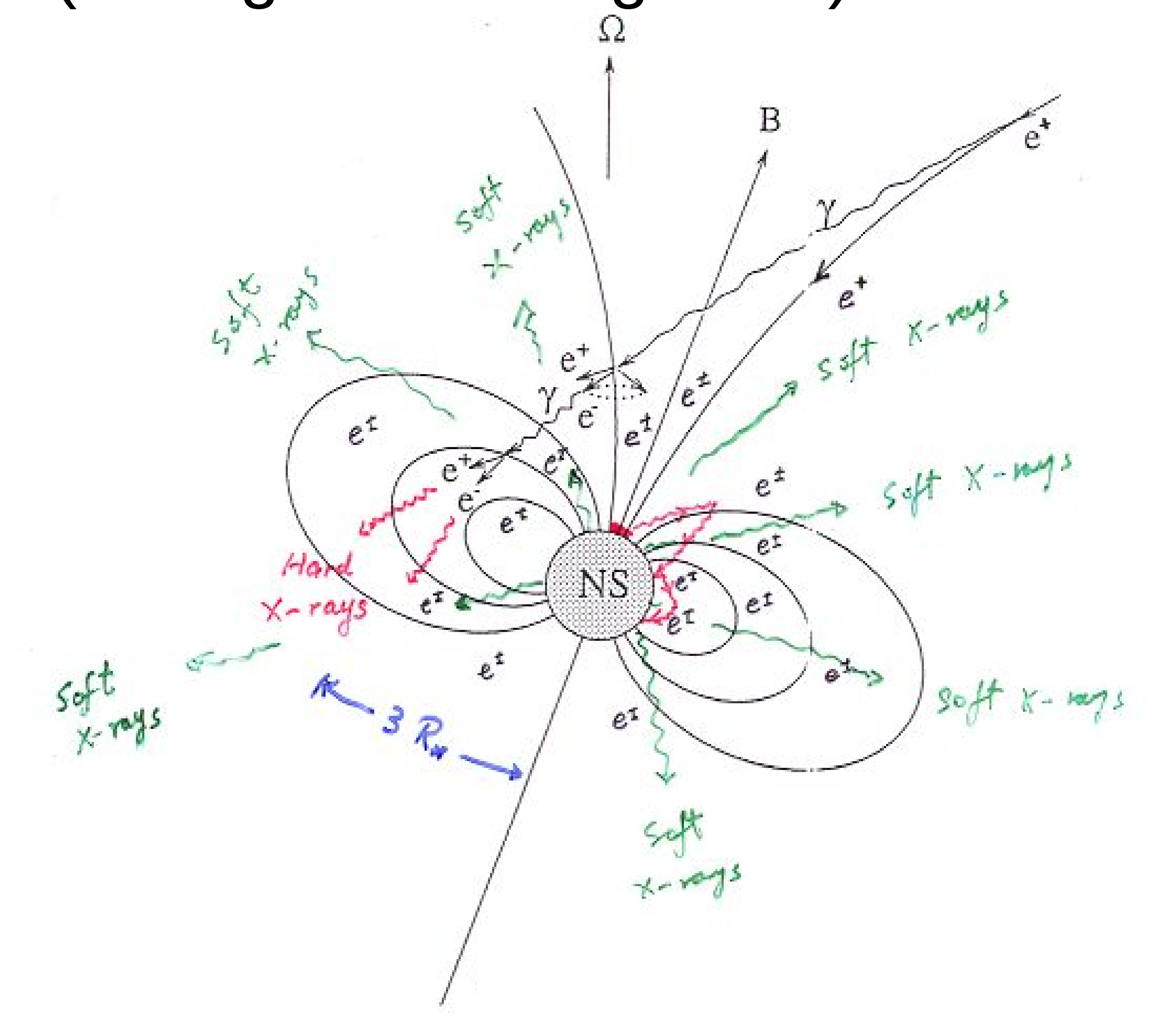
The high energy photons emitted by the charged particles in the gap can become pairs by

$$\gamma + x(\text{soft photon}) \rightarrow e^{\pm}$$

These pairs limit the growth of the outer gap, where Gamma-rays can be emitted steadily.



Pair creation processes I: photon-photon pair creation (Zhang and Cheng 1997)



- In this model, the typical energies of the soft X-rays and the γ-rays are completely determined by pulsar parameters and the gap size f
- Soft X-ray photon:

$$E_X \approx 9.8\times 10^1 f^{1/4} B_{12}^{1/4} P^{-5/12} eV$$

- Curvature gamma-ray photon:

$$E_c = E_\gamma \approx 1.4\times 10^8 f^{3/2} B_{12}^{3/4} P^{-7/4} eV$$

- Using pair production condition $E_X E_\gamma \sim (m_e c^2)^2$ outergap size (Zhang & Cheng 1997) :

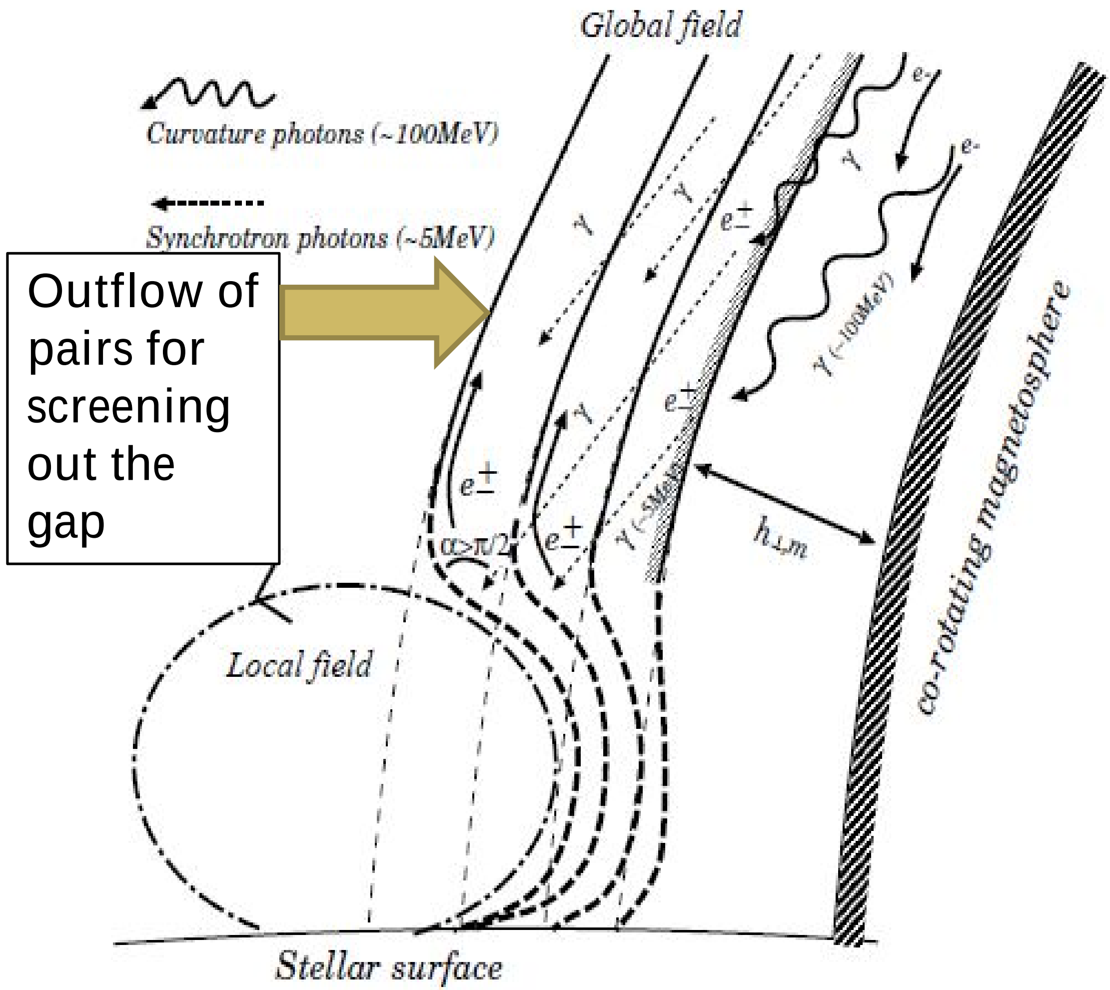
$$f \approx 5.5 B_{12}^{-4/7} P^{26/21}$$

This model predicts $L_\gamma \approx f^3 L_{sd} \sim (L_{sd})^{1/14} B^{1/7}$ and $E_c \sim (L_{sd})^{3/112} B^{-3/56}$

Insensitive to pulsar parameters

Pair creation processes II: magnetic pair creation and strong surface magnetic field (Takata etal. 2010)

The incoming e+ can continue to radiate high energy curvature photons, in which part of them can be converted into pairs. If the surface multiple field is sufficiently strong to bend the dipolar field sideward, these pairs can flow back to the outermagnetosphere to restrict the size of the outer gap. The fractional size of the outer gap restricted by this mechanism is given by



$f_m = 0.25K(B_m, s)P_{-1}^{1/2}$, where K depends on the local magnetic field (B_m) and the local curvature radius (s).

Model predictions I

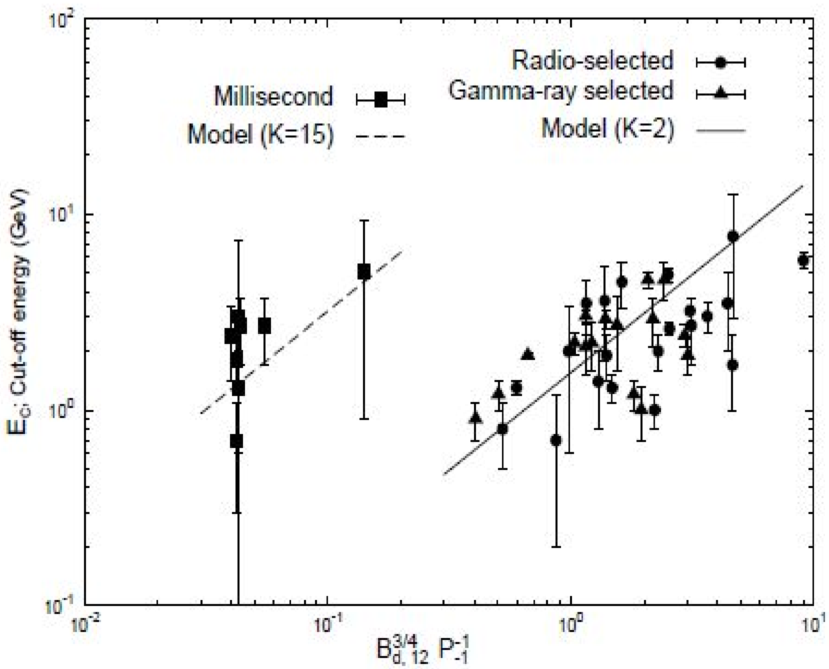
Once the outergap size f_m is known, we can estimate the gamma-ray power

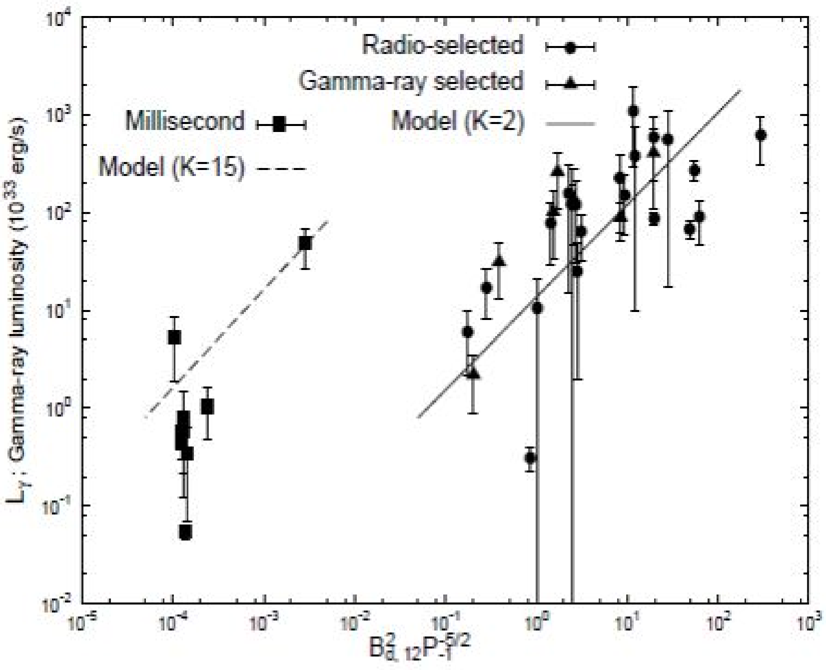
$$L_\gamma(K, B_d, P) \sim I_{gap}V_{gap} \sim (f_m I_{GJ})(f_m^2 V_{tot}) \sim 2\times 10^{33} K^3 B_{d,12}^2 P_{-1}^{-5/2}\ \mathrm{erg/s}.$$

And the characteristic energy in the outergap is

$$E_c(K, B_d, P) = \frac{3}{4\pi}\frac{hc\gamma^3}{s} \sim 0.55 K^{3/2} B_{d,12}^{3/4} P_{-1}^{-1}\ \mathrm{GeV}.$$

Here *K is an unknown const. depending on surface magnetic field properties.*
We can estimate K~1 (B_m ~10^{13}G , m=2)for canonical pulsars and K~10 (B_m ~10^{11}G, which is the minimum field to convert 100MeV photons) for MSPs.

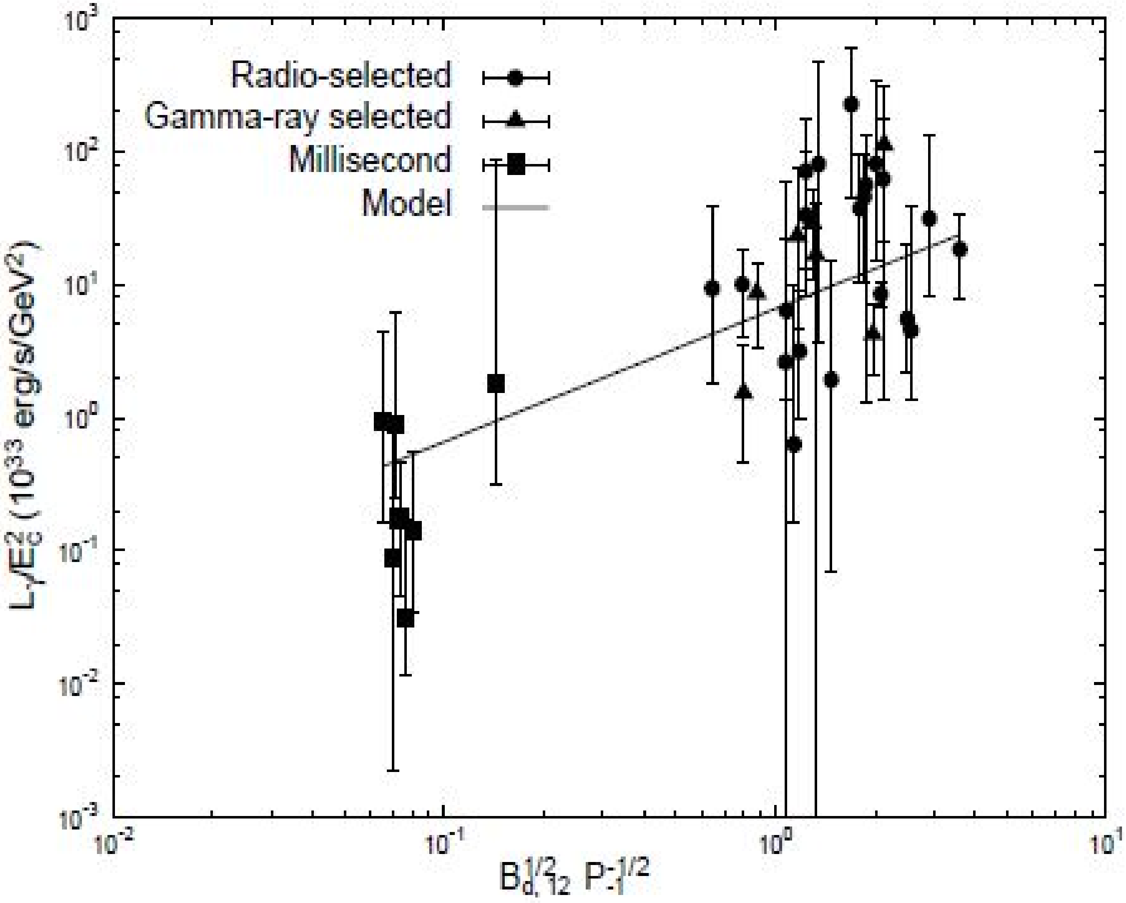




Model predictions II

It is interesting to note that we can eliminate K from and L_γ as E_c

$$\frac{L_\gamma}{E_c^2} \sim 6.6 \times 10^{34} B_{d,12}^{1/2} P_{-1}^{-1} \text{ erg/s GeV}^2$$



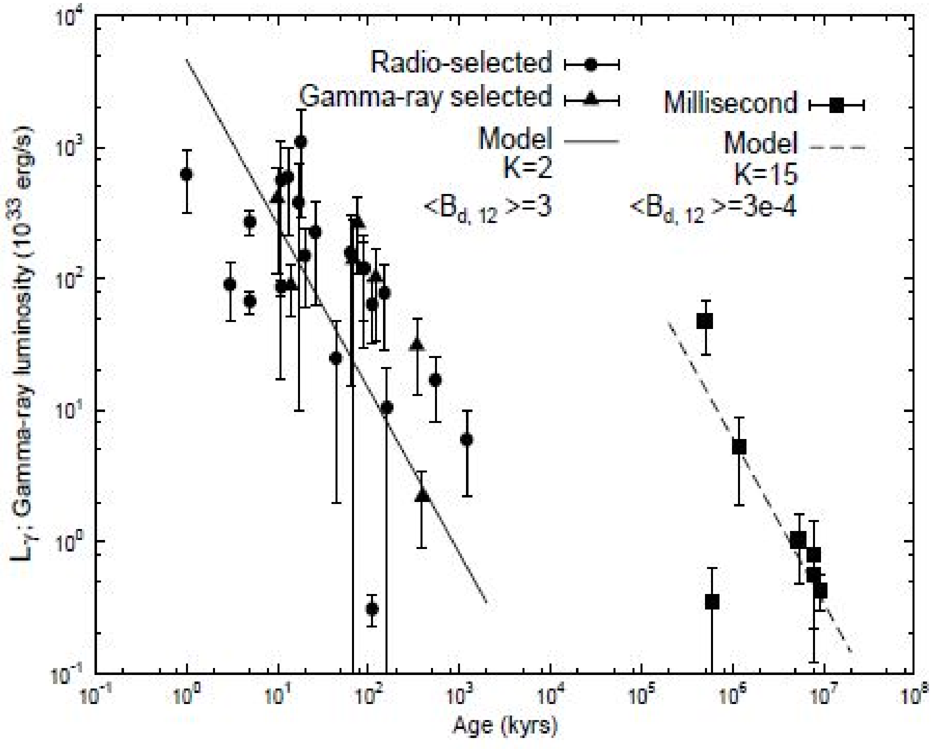
Model predictions III

We can also express L_γ ıd E_c terms of spin-down age as τ

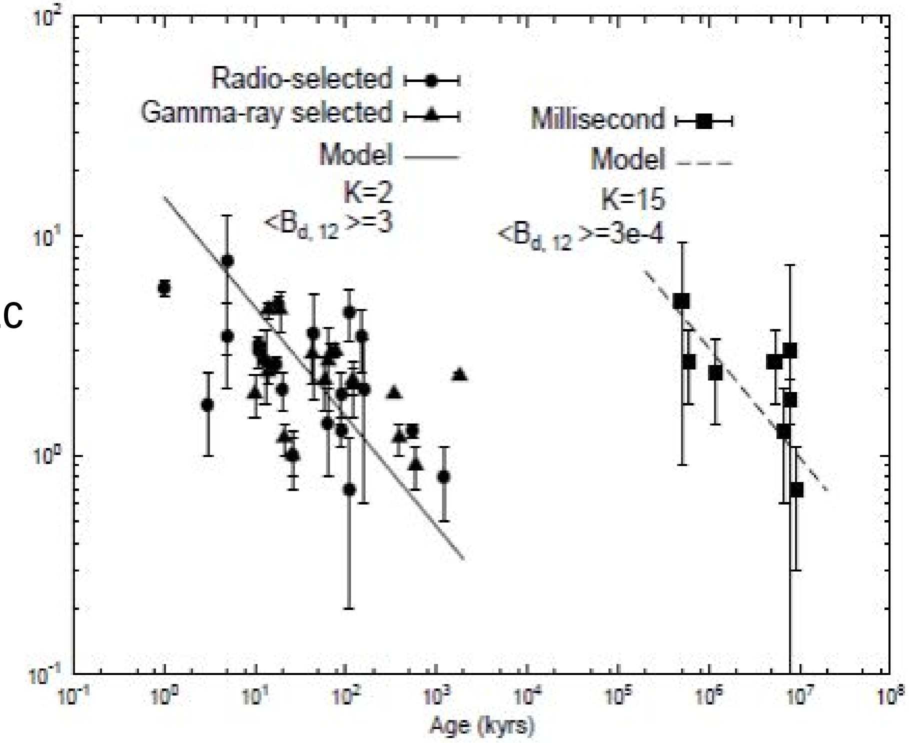
$$L_\gamma \sim 10^{36} K^3 B_{d,12}^{-1/2} \tau_3^{-5/4} \text{ erg/s.} \qquad E_c \sim 7 K^{3/2} B_{d,12}^{-1/4} \tau_3^{-1/2} \text{ GeV}$$

for $K = 2$ and the typical magnetic field of $< B_{d,12} >= 3$ for the canonical pulsars

for $K = 15$ and $< B_{d,12} >= 3 \times 10^{-4}$ for the millisecond pulsars



Ec



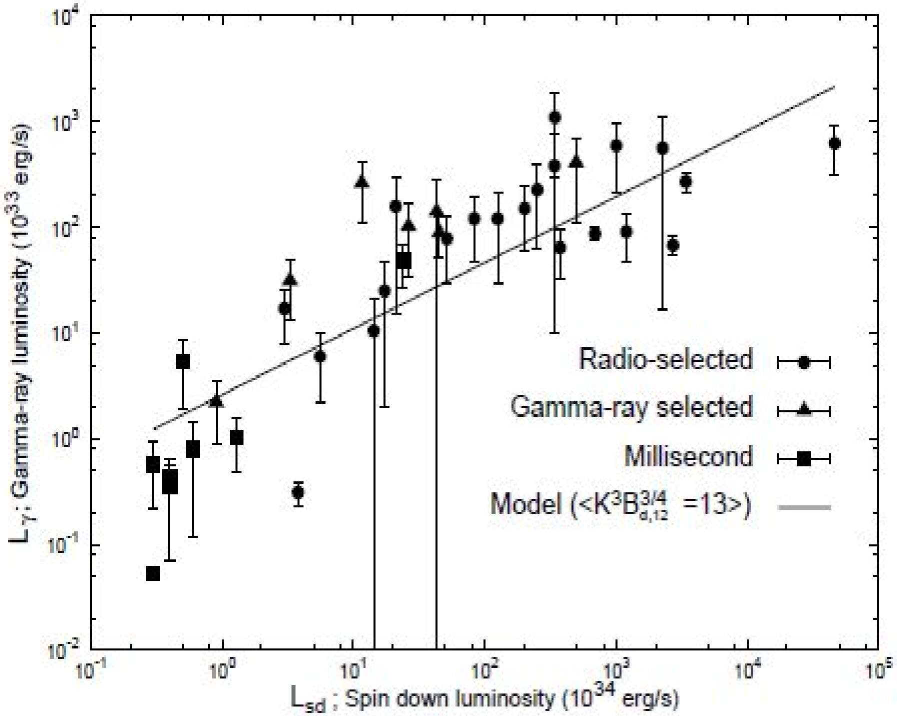
Model predictions IV

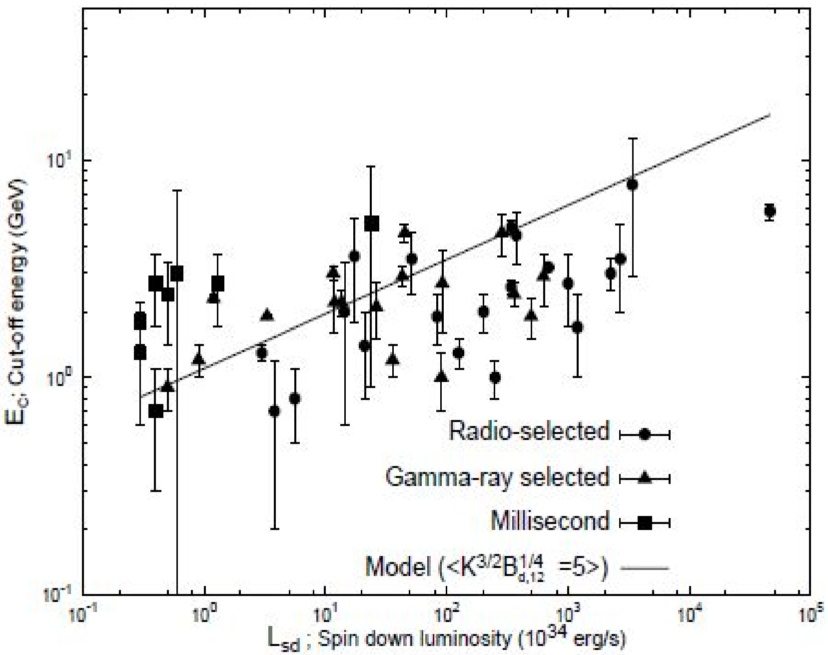
We can also express L_γ nd E_c terms of spin-down power as L_{sd}

$$L_\gamma \sim 2\times10^{32}K^3B_{d,12}^{3/4}L_{sd,34}^{5/8},\ \mathrm{erg/s} \qquad E_c \sim 0.22K^{3/2}B_{d,12}^{1/4}L_{sd,34}^{1/4}\ \mathrm{GeV}$$

for $K = 2$ and the typical magnetic field of $< B_{d,12} >= 3$ for the canonical pulsars
for $K = 15$ and $< B_{d,12} >= 3\times10^{-4}$ for the millisecond pulsars

It turns out that the numerical values of $K^{3/2}B_{d,12}^{1/4}$ $K^3B_{d,12}^{3/4}$ onical pulsars and MSPs are only differs by a factor of 2.

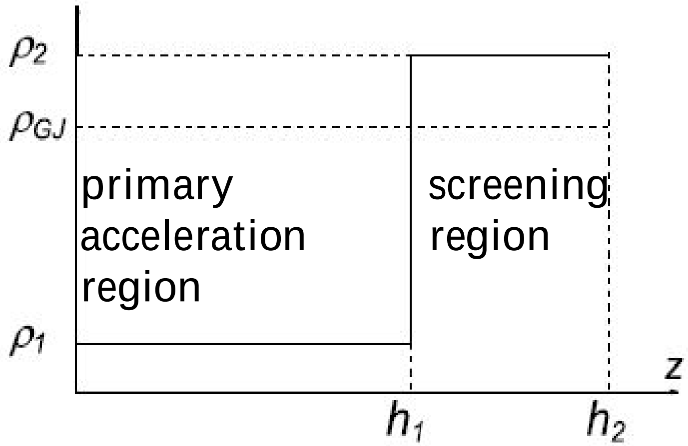




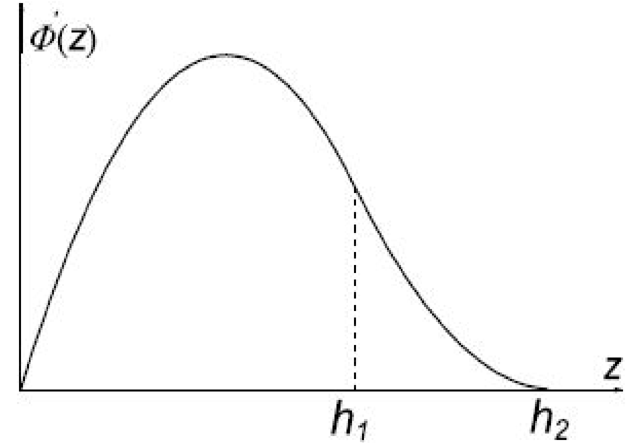
Model fitting of the observed spectra – simple two-layer model (Wang et al. 2010)

The charge distribution is approximated by two regions and there are two parameters in this model, i.e. the ratio of charges and the ratio of the thickness between these regions.

(N.B. the total thickness and charges are restricted by pair creation conditions and Goldreich-Julian charge respectively.)



(b)



(d)

Gamma-ray emission from outergap

We assume that electrons radiate γ-rays via curvature radiation in the gap

$$F_{cur}(E_\gamma)^{single} = \frac{\sqrt{3}e^2\gamma_e}{2\pi\hbar s E_\gamma}F(x) \quad (1$$

where γ_e, is determined by $eE_{\|}(z)c = l_{cur} = 2e^2c\gamma_e^4(z)/3s^2$

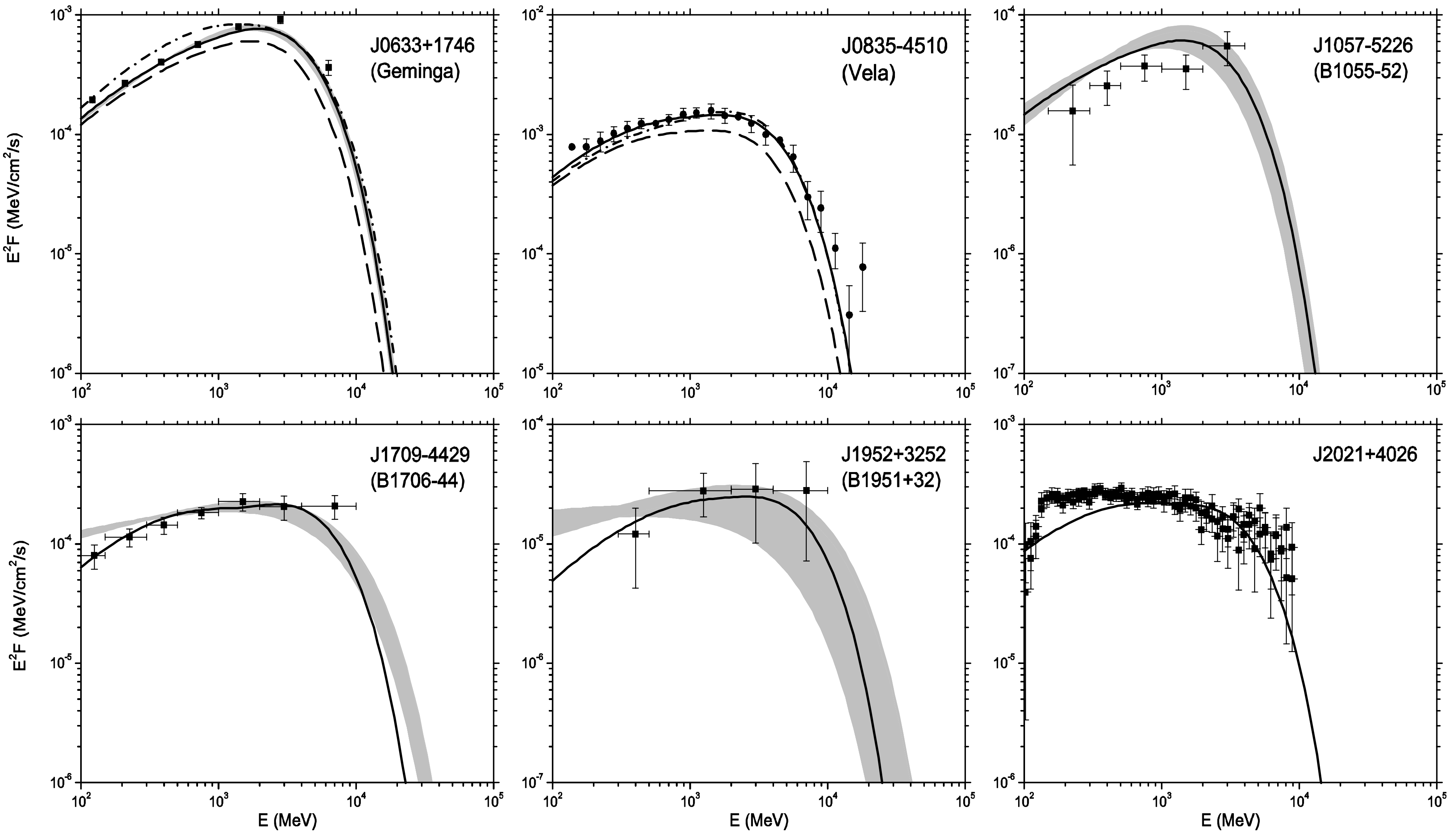
The total curvature radiation spectrum from the outer gap is given by

$$F_{cur} = \int \frac{dN}{dz} F_{cur}^{single}(z)dz. \quad (1$$

In this model once the gap size h_2, the current in the main gap region g_1 and the current in the screening region g_2. The total gamma-ray power is completed fixed. Of course in comparing with the observed flux we need to assume $\Delta\Omega d^2$.

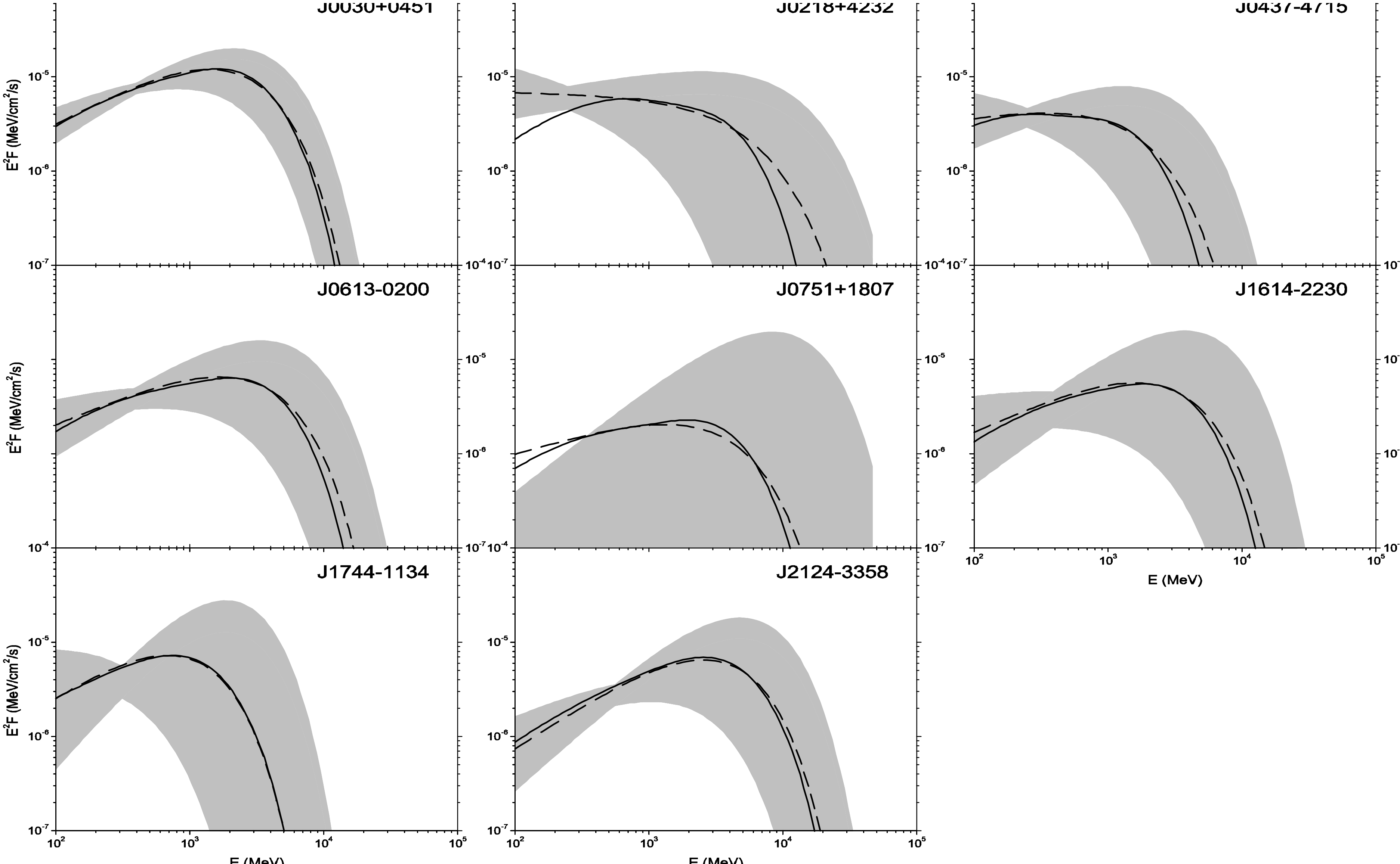
Spectral fits I – EGRET/Fermi pulsars

Solid line is the model predicted curve

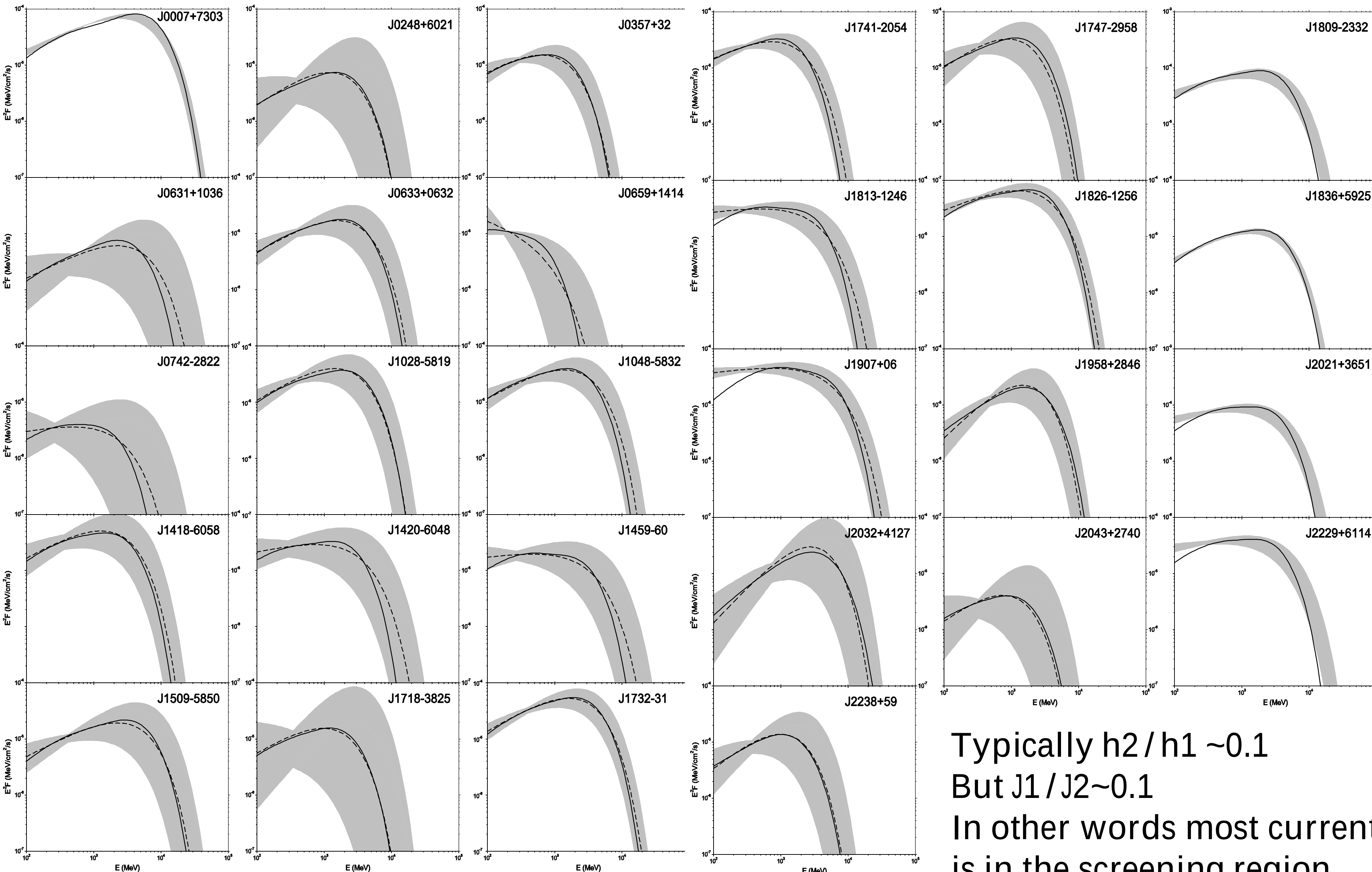


Spectral fits II-MSPs

The dashed line is the best fit curve of data and the solid line is the model curve.



Spectral fits III-other Fermi pulsars



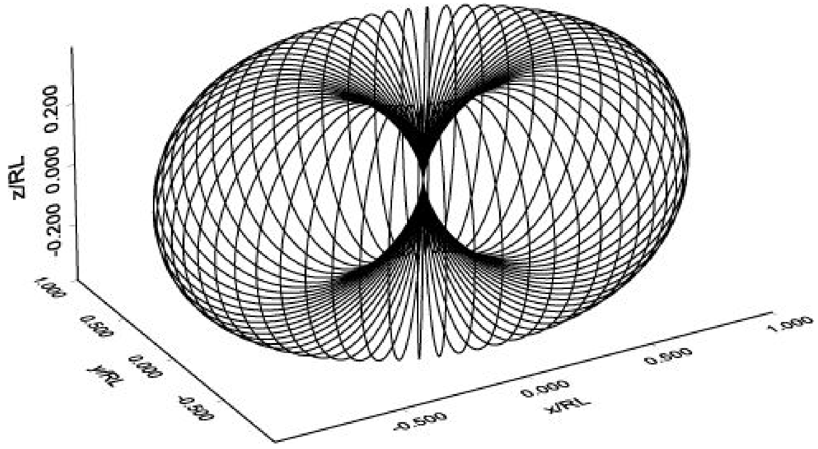
Typically h2 / h1 ~0.1
But J1 / J2~0.1
In other words most current
is in the screening region

Model fitting of the pulse morphologies

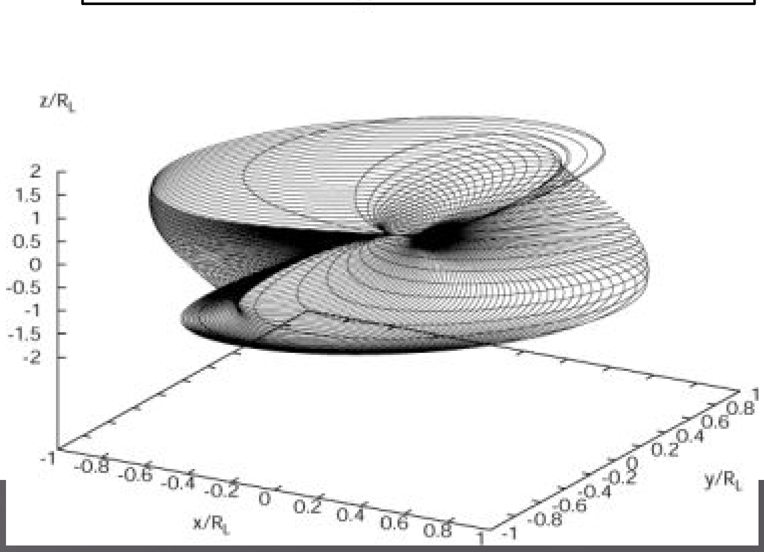
In order to explain the pulse morphologies and phase-dependent spectra of pulsars, a 3D model is necessary

- We adopt a Retarded magnetic field lines of the rotating and inclined dipole field- Relativistic effects are taken into account

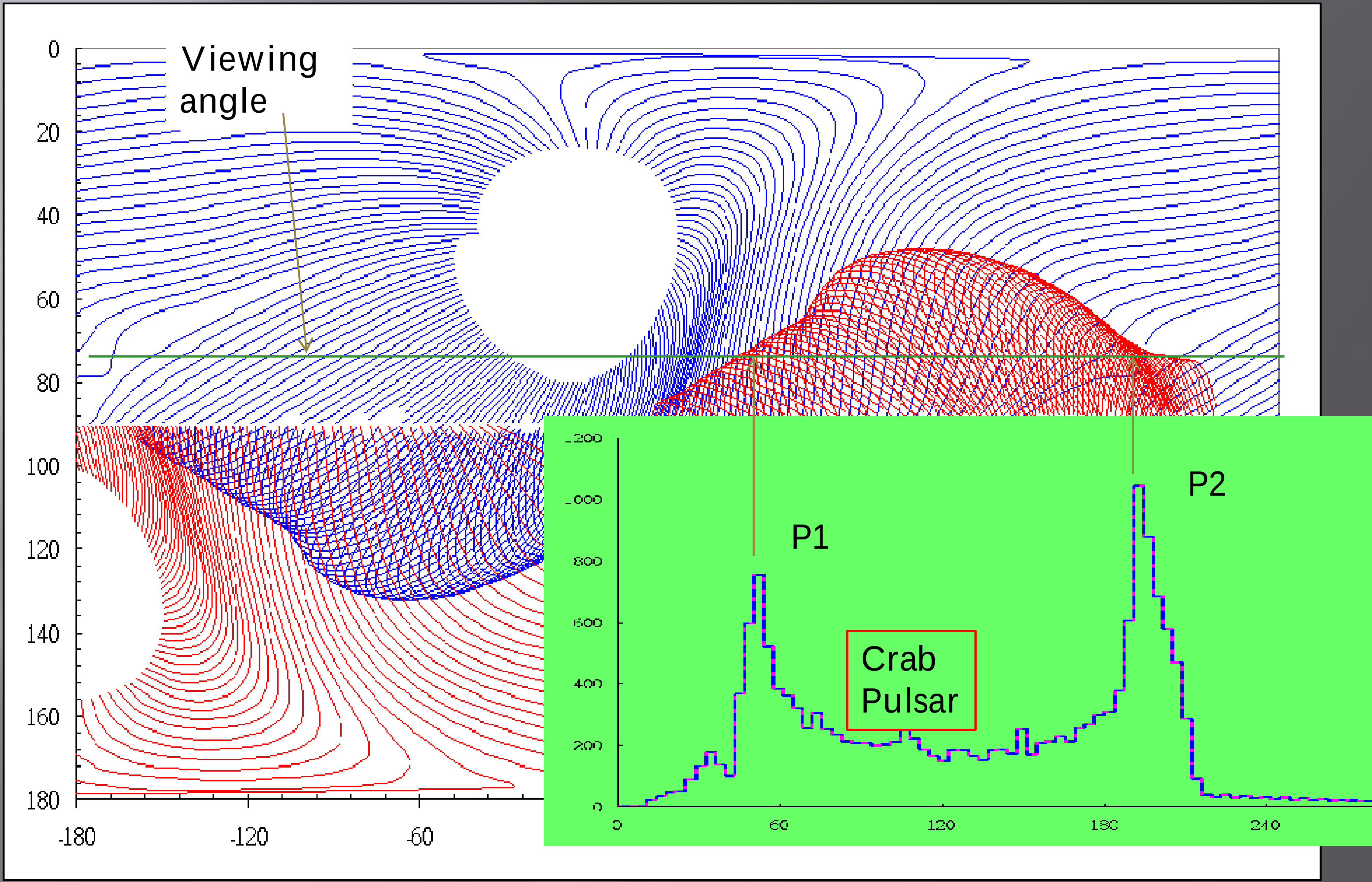
Rotating dipole field



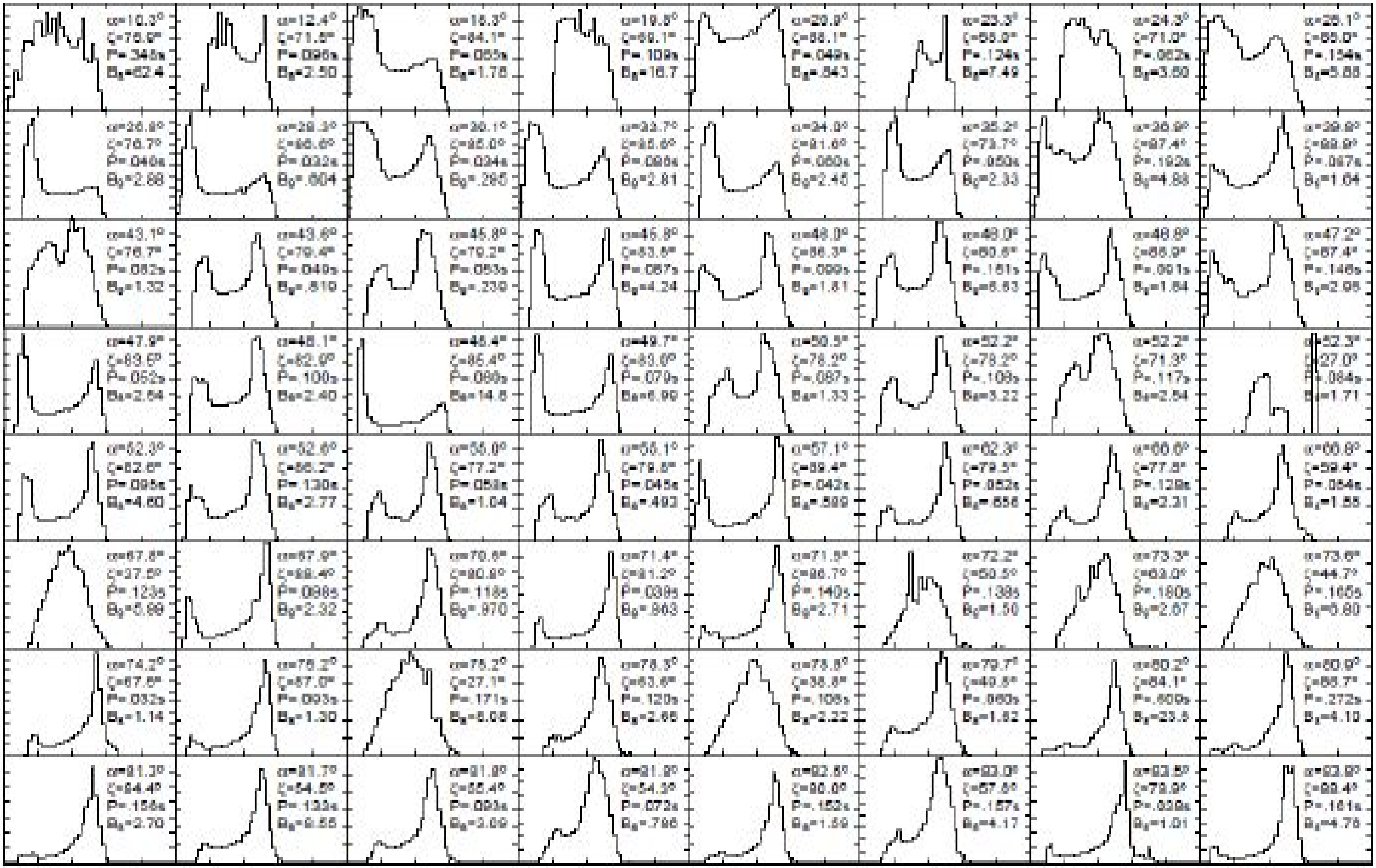
Static dipole field



Emission Morphology in (θ, φ)



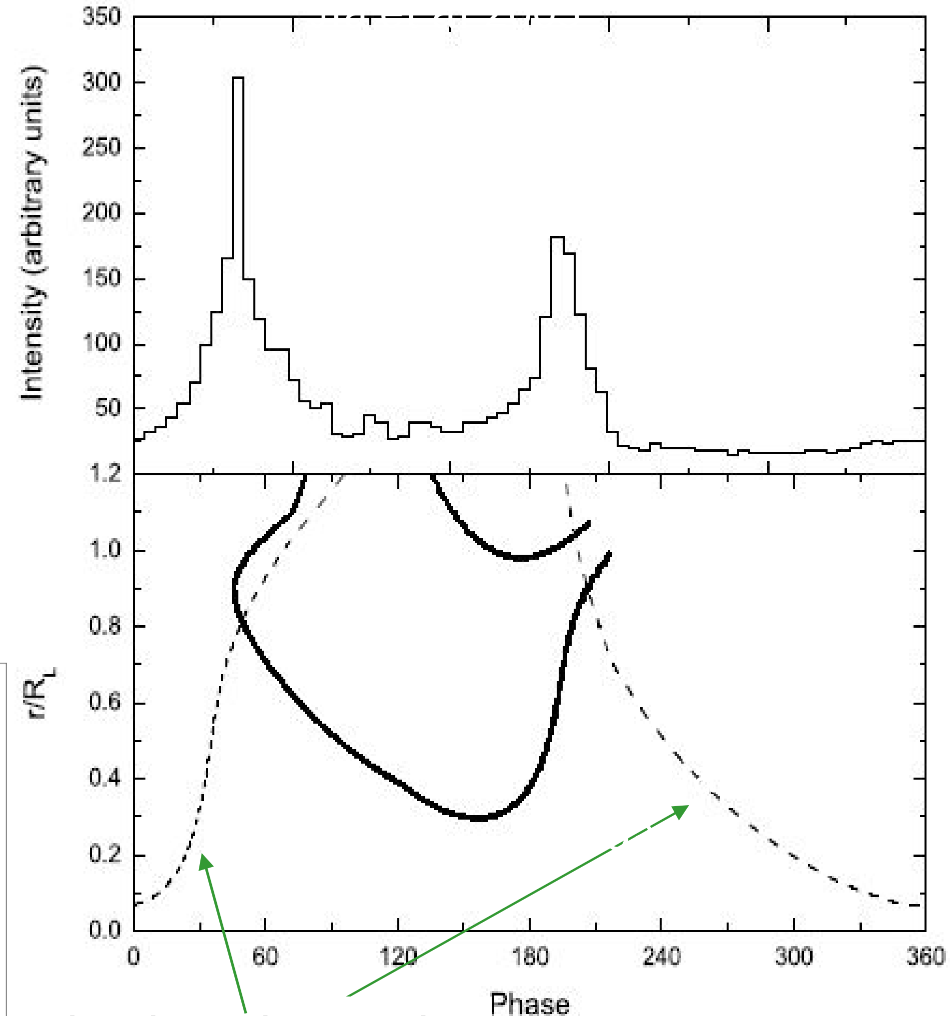
Various pulsed morphologies (Takata et al. 2011)



Light Curves and Emission Trajectories in the magnetosphere (Tang et al. 2008)

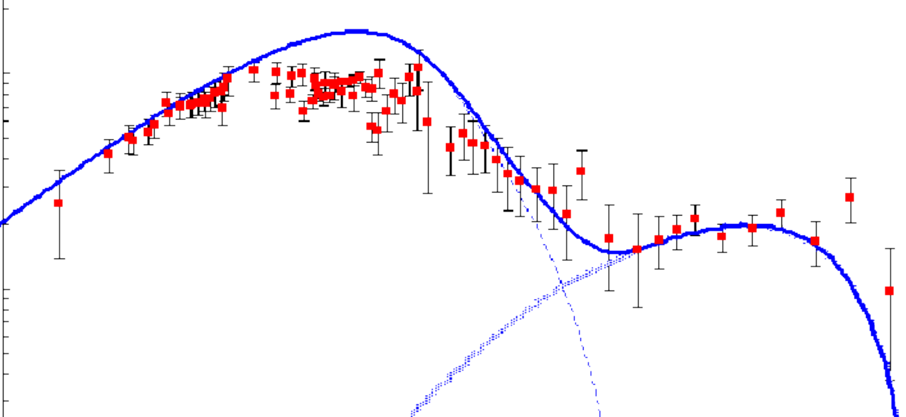
- The light curve is affected by the relativistic effects:
  - Aberration effect
  - Time of flight effect

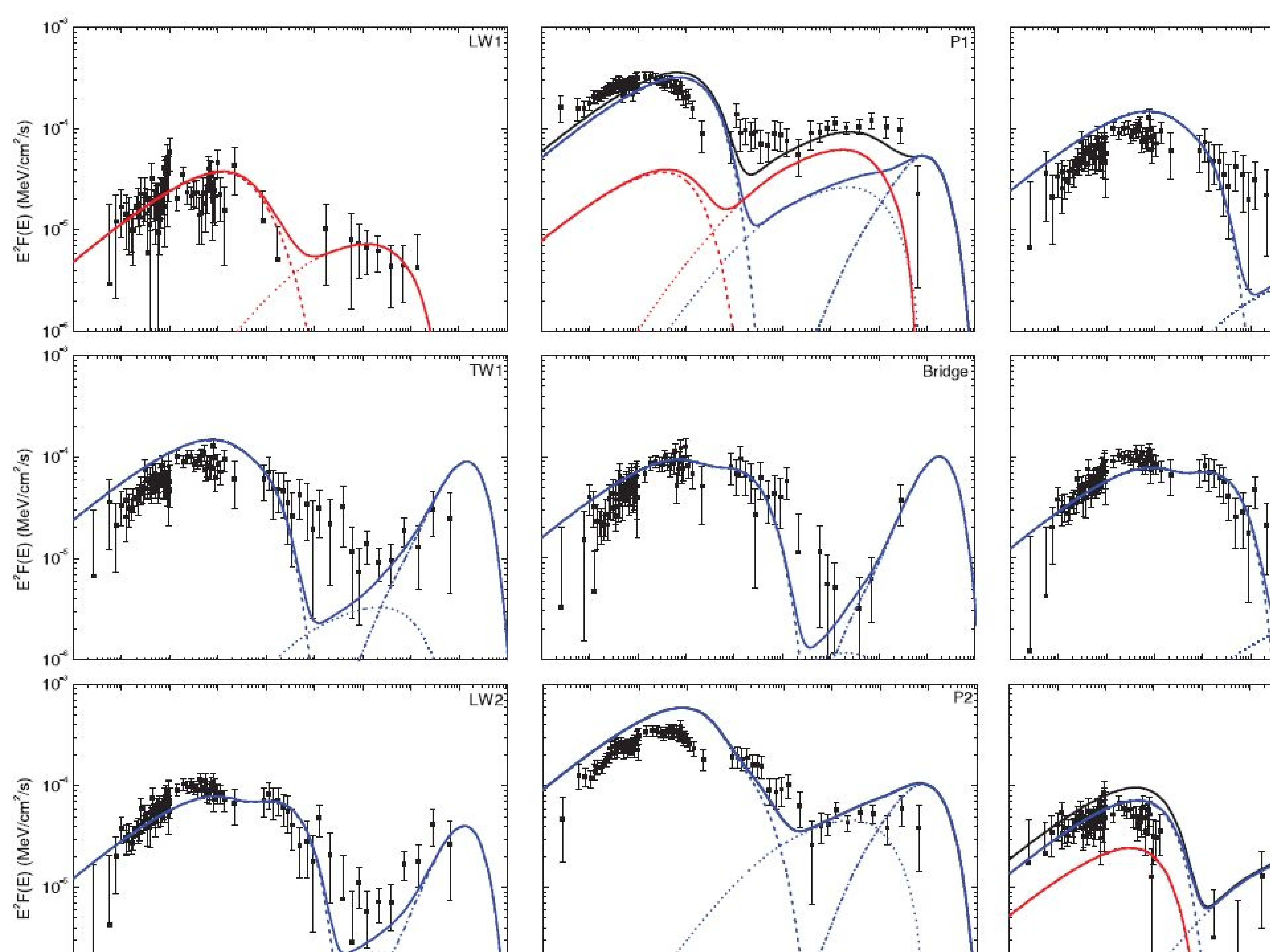
Calculate the local radiation emissivity including Curvature radiation, Synchrotron radiation and inverse Compton scattering



the dotted curve is the outgoing radiation of gap 2

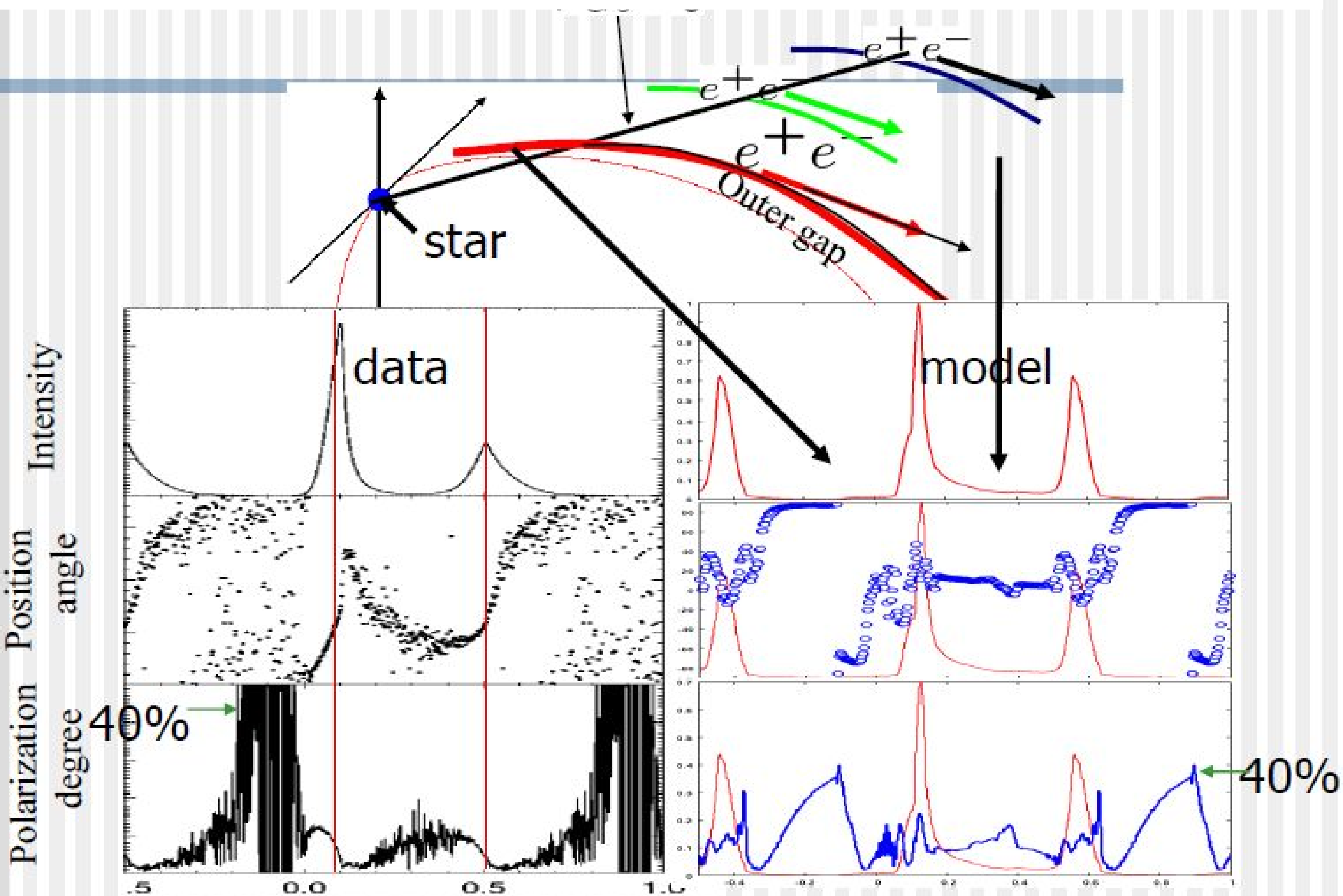
Phase-average spectrum of the Crab Pulsar





LW1
P1
TW1
Bridge
LW2
P2
$E^2F(E)$ (MeV/cm^2/s)
10^{-3}
10^{-4}
10^{-5}
10^{-6}

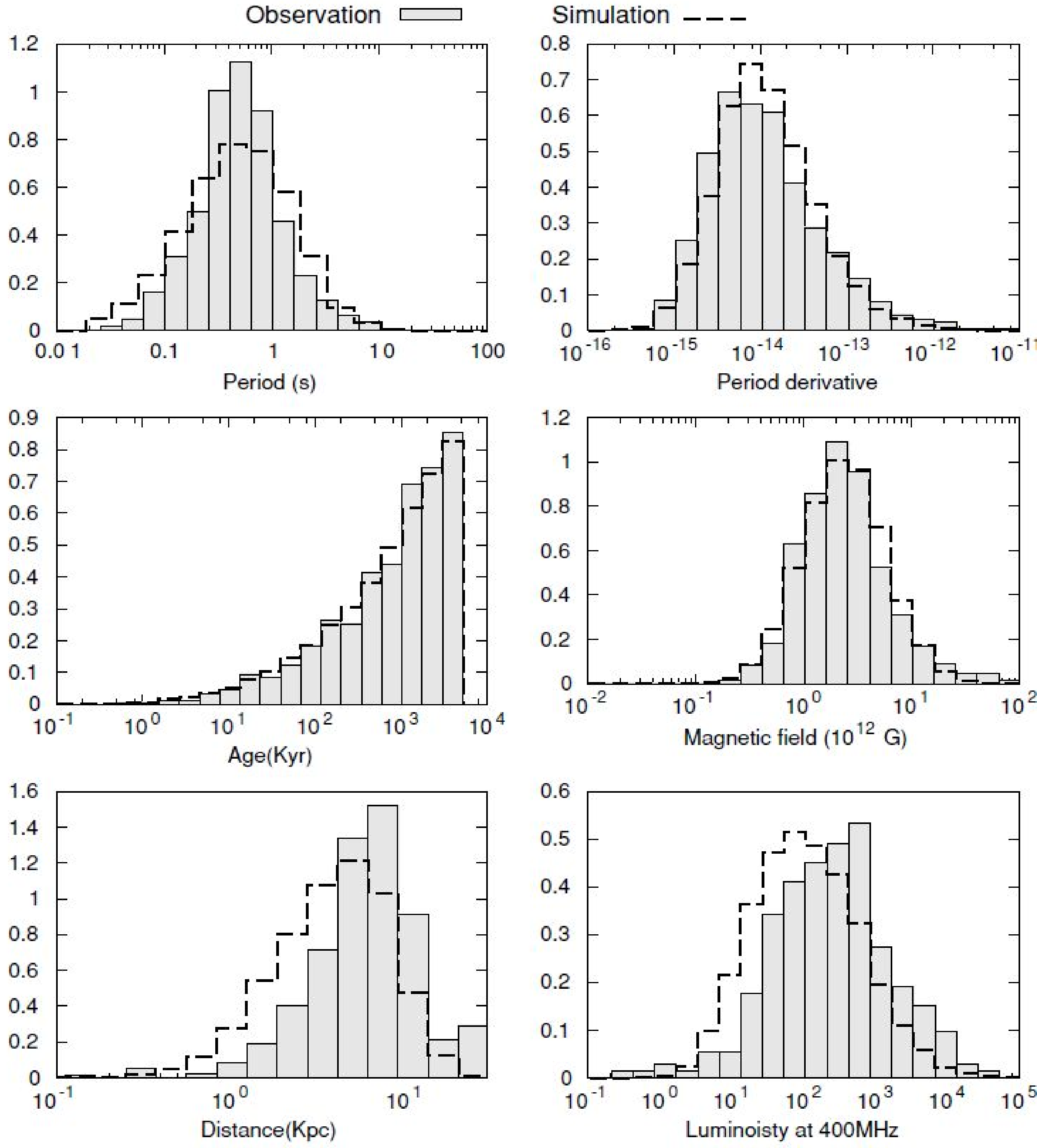
Phase-dependent optical polarization properties (Takata et al. 2007)



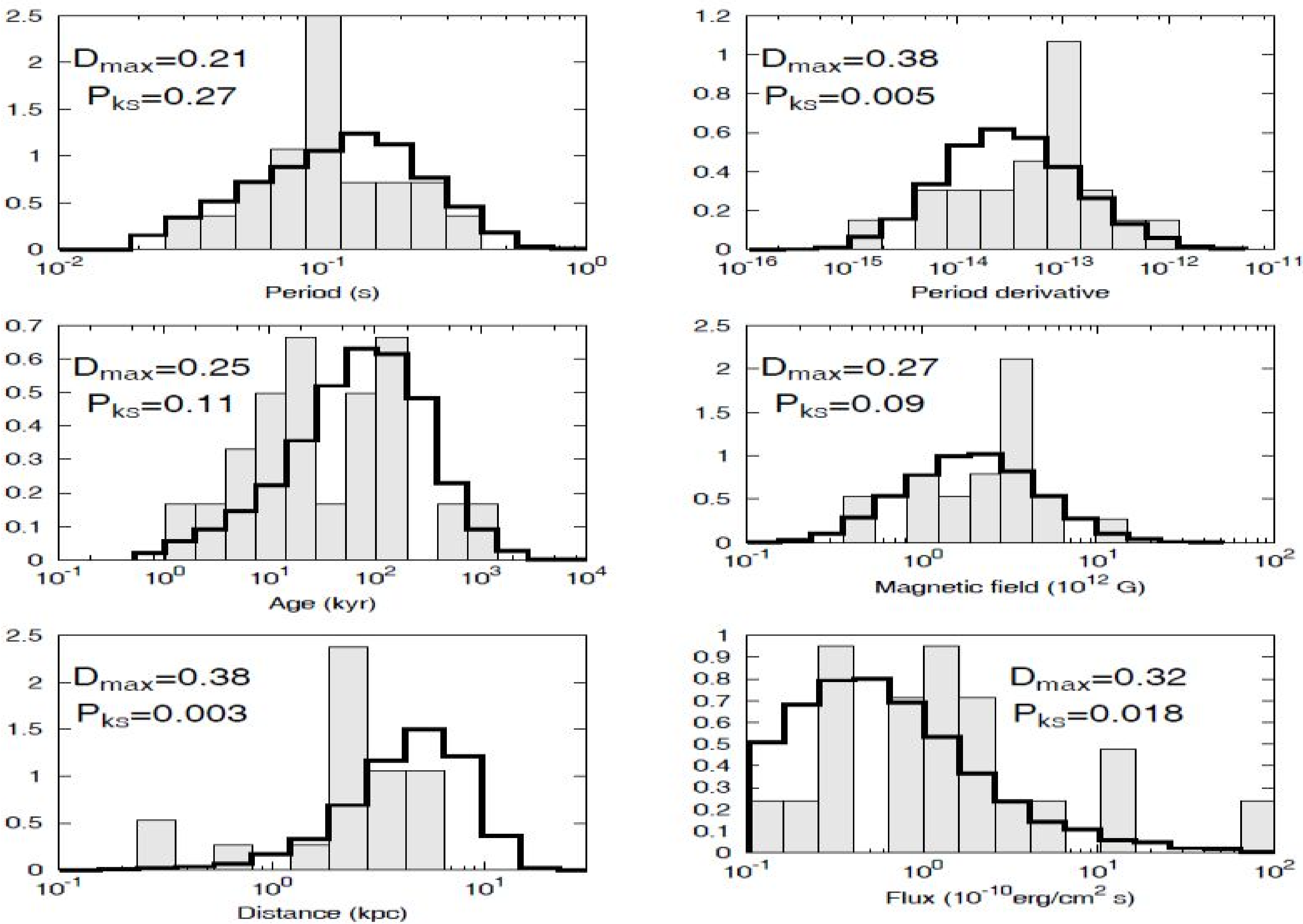
Testing gamma-ray pulsar models by Population Synthesis (Takata et al. 2011, 2012)

- #Birth rate ~1 per century
- #Randomly born in the galaxy with initial kick velocity
- #Effect of rotation of galaxy and gravitational potential is included
- #Gaussian distribution of logB
- #Initial period with dipole spin-down
- #Using best known radio emission models for calculating the radio emission properties
- #Using the outergap model for calculating the gamma-ray emission properties

Radio Pulsars

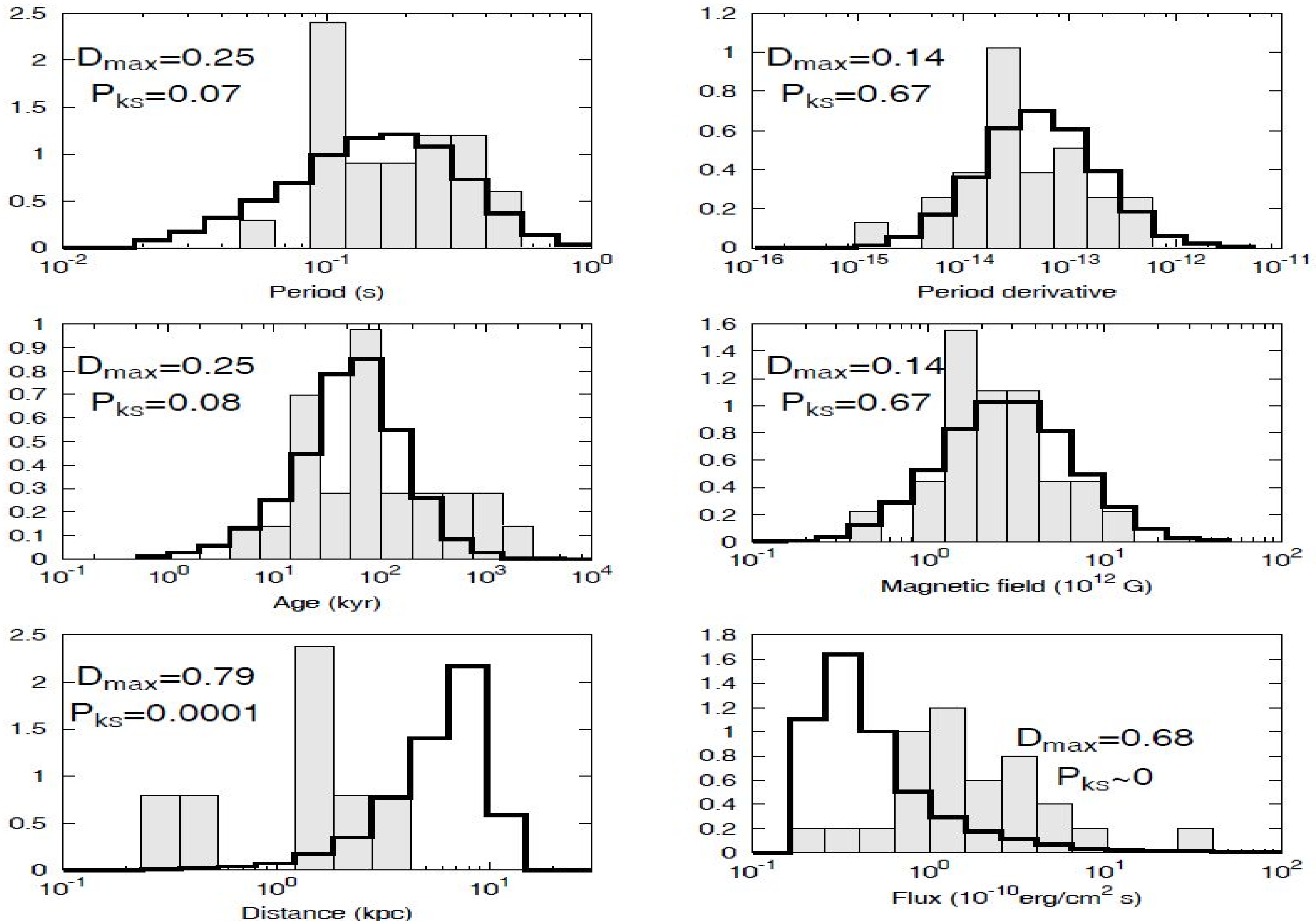


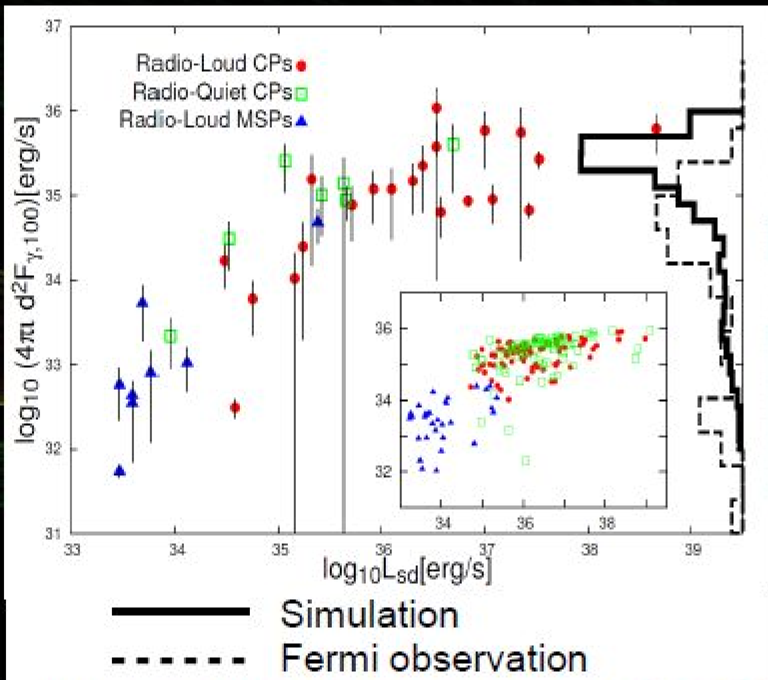
Radio-loud gamma-ray pulsars with $F_\gamma \geq 10^{-11}$ erg/cm^{2}s

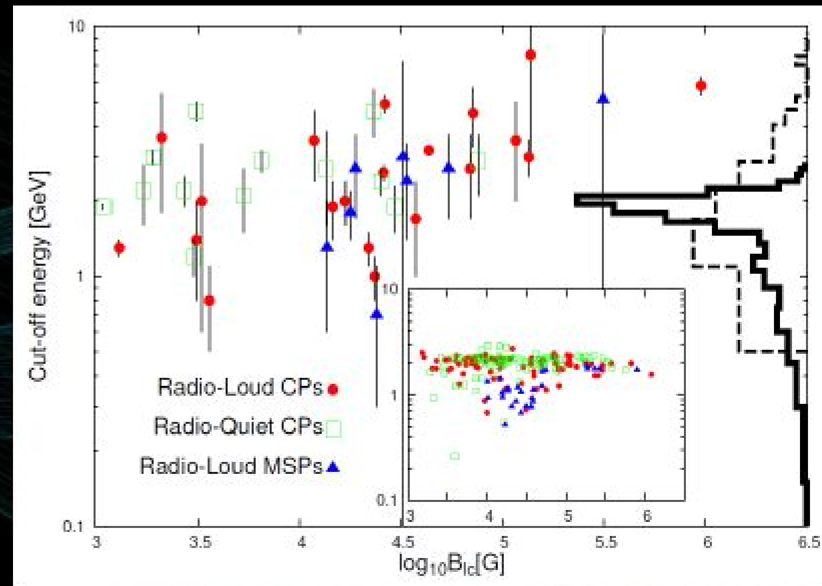


Radio-quiet gamma-ray pulsars

$F_\gamma \geq 2 \times 10^{-11}$ erg/



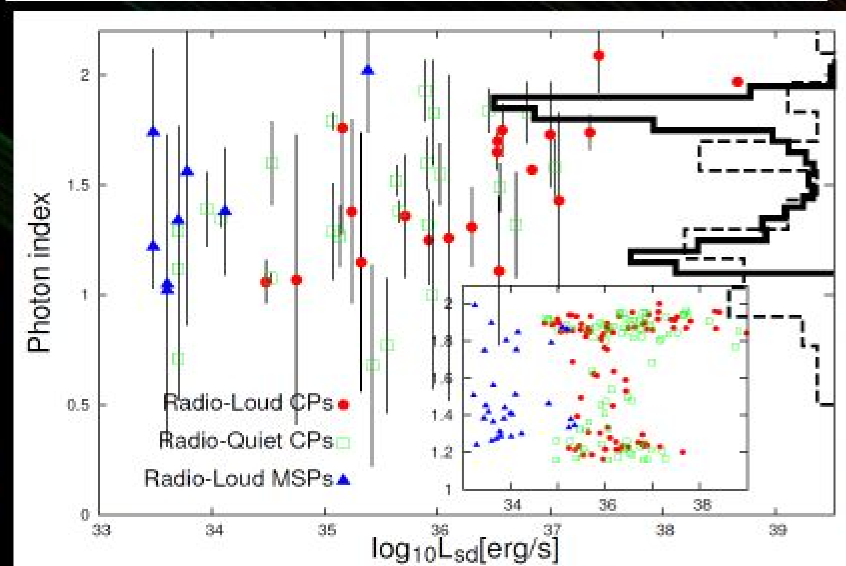




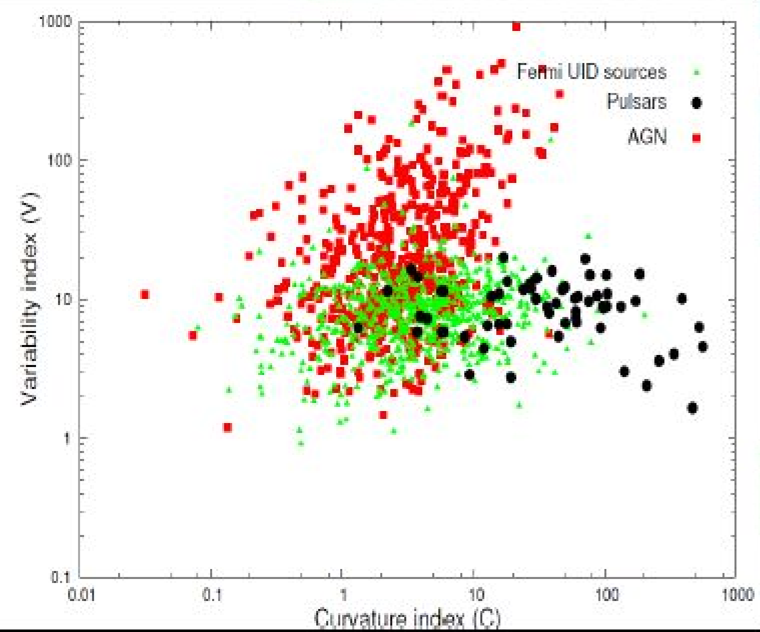
- Two peaks in distribution of photon index

  -1.8~2; we observe emissions from main region + screening region with viewing angle ~90deg.

  - 1.2~1.4; emission from only main region with a smaller viewing angle



Fermi unidentified source and Pulsars



- Curvature index and Variability index (Abdo, et al. 2010)

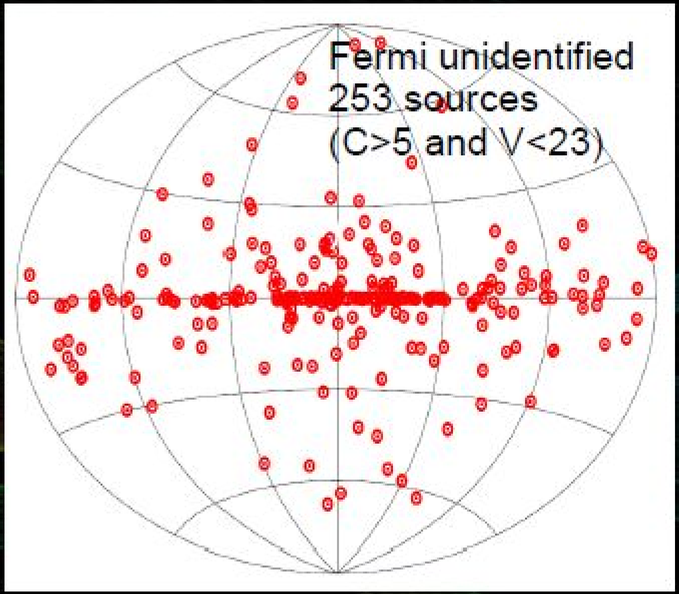
C-index>11 -->Spectral shape can not be fitted by single power low

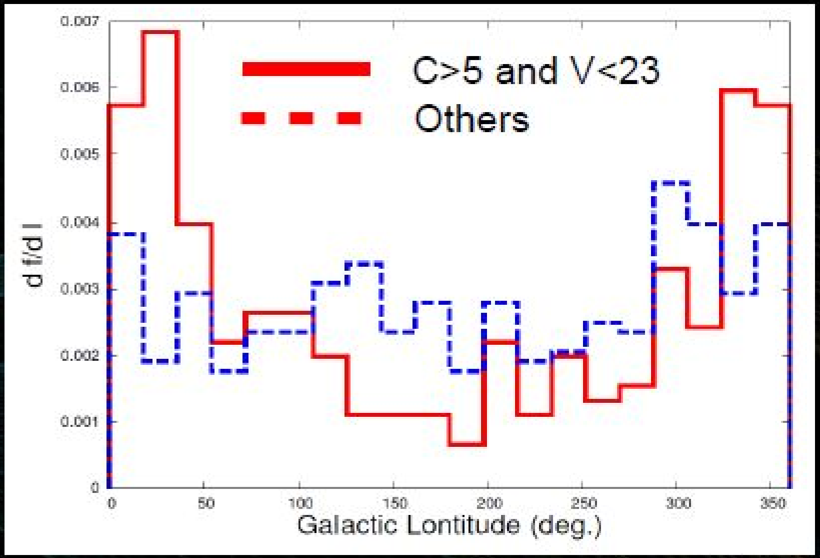
V<23.1 -->Steady sources

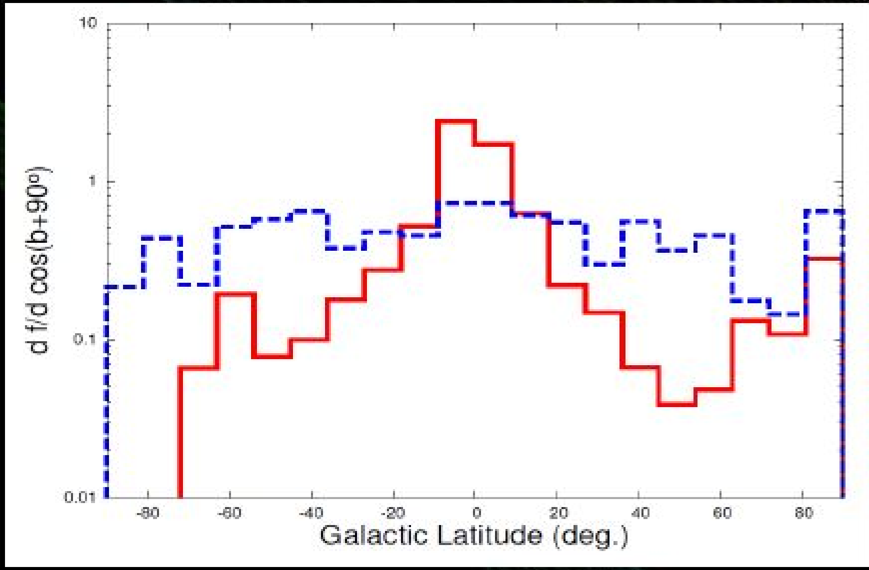
- *Fermi* Pulsars

  -C>5

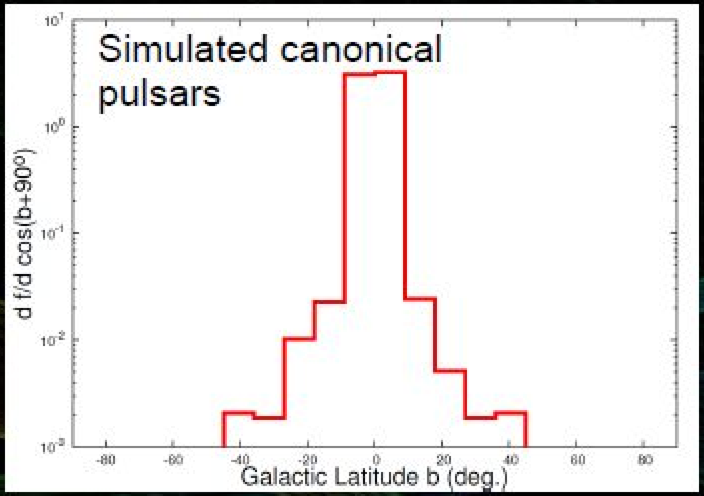
  -V<23

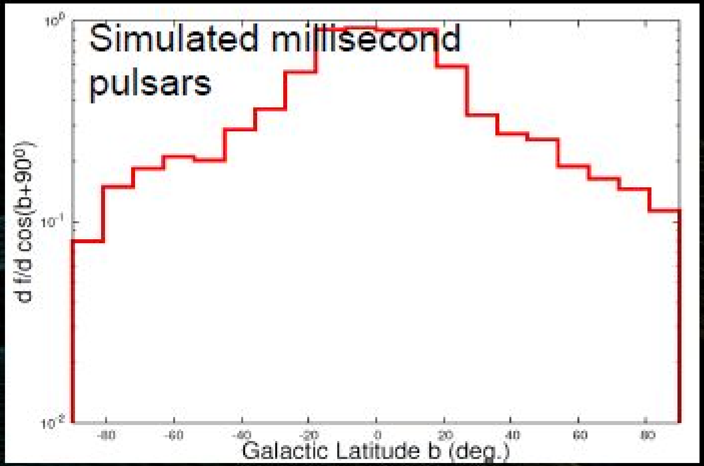


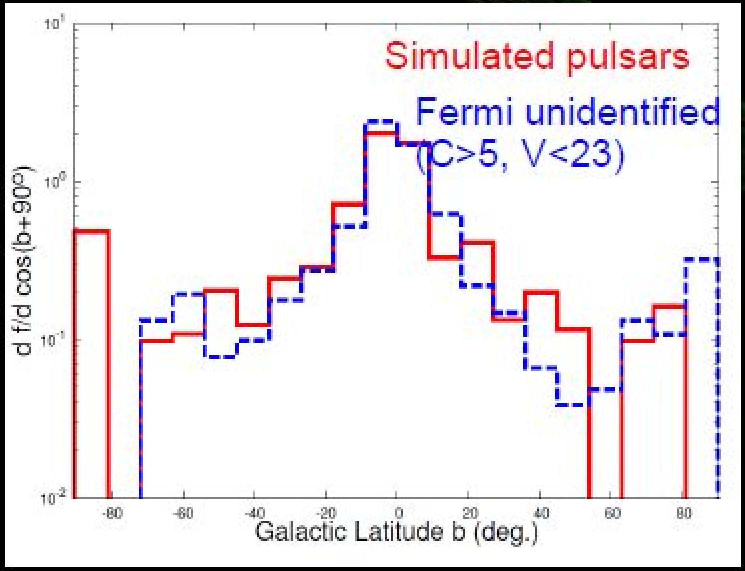




- Fermi unidentified sources with C>5 and V<23 must be dominated by the Galactic sources.
- Others will be dominated by Extra Galactic sources







Fermi unidentified sources with C>5 and V<23 will be canonical pulsars (low latitude) and the millisecond pulsars (high latitude).

Summary and Discussion

#The outer gap model provide possible explanation for some of the observed gamma-ray pulsar data detected by Fermi Satellite

#Currently Only radio-loud MSPs were found, it is interesting to find the existence of radio-quiet gamma-ray MPSs – it is virtually impossible to find the period in gamma-rays but X-rays is an alternative

#There are many other observed properties, which require explanation. For example only 1 normal pulsar, i.e. the Crab pulsar, whose radio pulse and gamma-ray pulse are completely aligned but there are 4 MSPs with this feature, why?

#Realistically the magnetic field is not pure dipolar, for example a completely force free field is different from that of dipolar field. How does the realistic field structure, i.e. a partial force free plus a partial vacuum magnetosphere, affect the model predictions?