Pulsar models

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In the talk:

- Models of pulsars as sources of high energy photons.

- Why the composition of pulsar winds ($e^{\pm}$ content in the context of CR positrons) is connected to the pulsed emission properties?

- Are the results from Fermi LAT challenging to the models?

Pulsars and Cosmic-Ray Positrons

Individual nearby pulsars

Millisecond pulsars - Buesching et al., 2008

Middle-age pulsars - Buesching et al.2008,
Malyshev et al. 2009,

Galactic population

Chi et al. 1996,
Malyshev et al. 2009,
Barger et al. 2009

Reacceleration and evolution of magnetospheric pairs when trapped in PWNe. Semi-empirical treatment used to obtain the input for subsequent propagation.

Pulsars are treated just as time-dependent energy suppliers at the rate of $\sim L_{sd}(t)$.

This list is not complete.

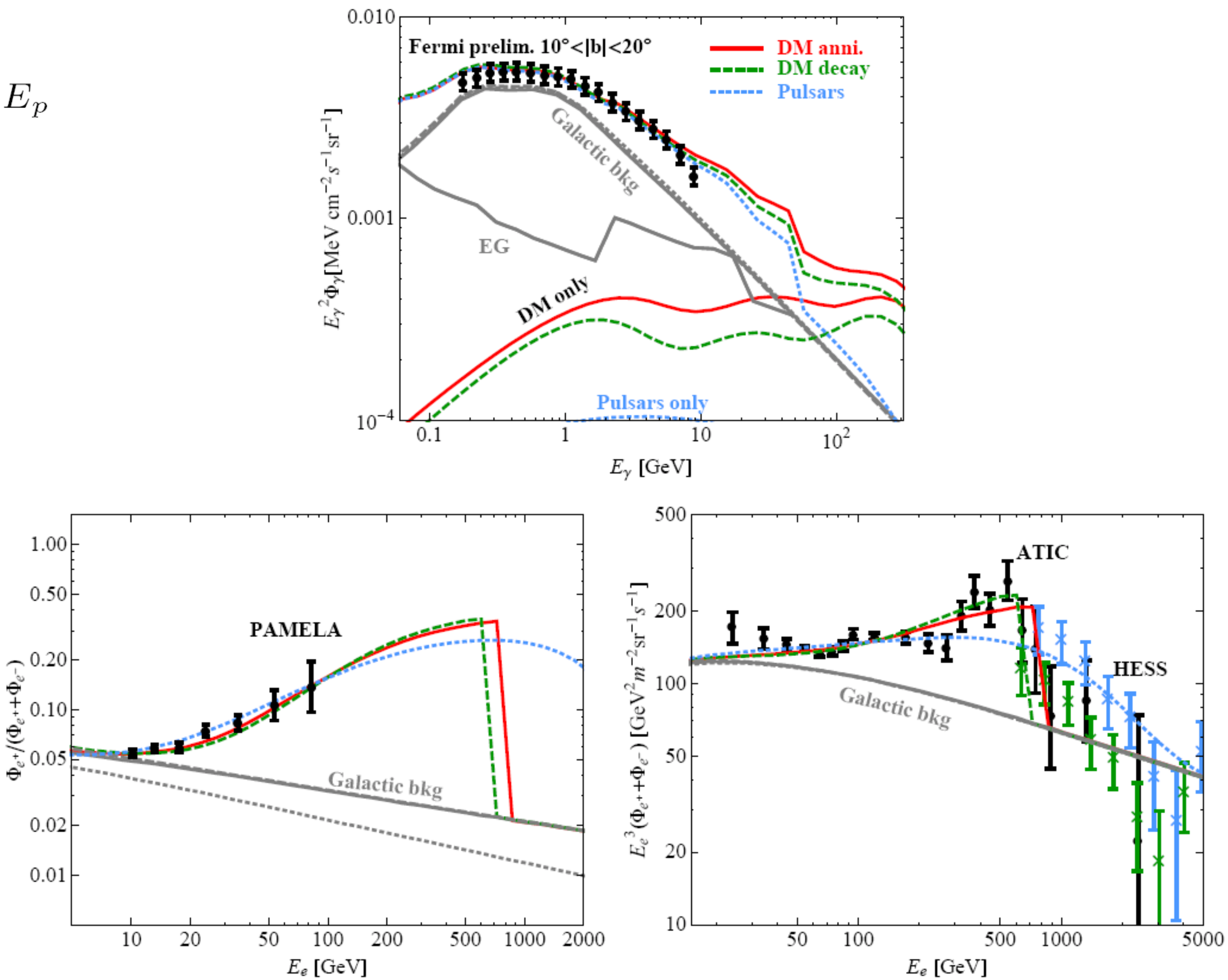
Galactic population of pulsars

Barger et al.2009

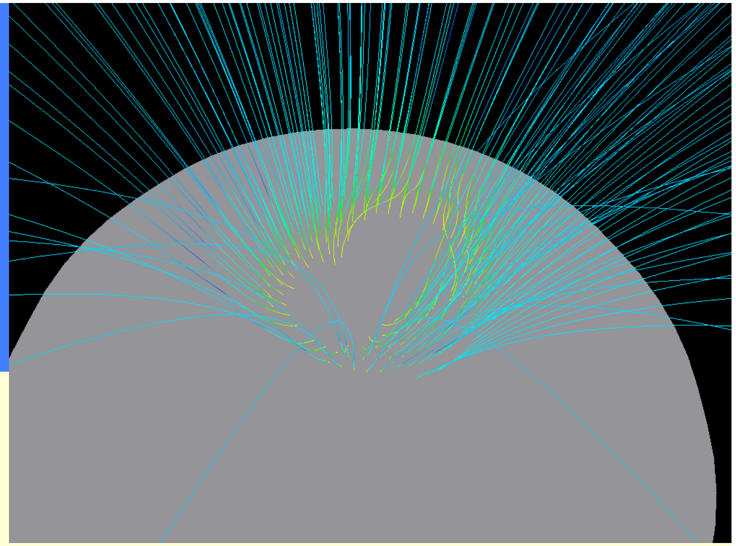
Assumed pair injection spectrum and spatial distribution of pulsars

$$\frac{dN_{e^\pm}}{dE} \propto E^{-\alpha} e^{-E/E_p}$$

+ propagation
using GALPROP



Why do pulsars radiate in high energy domain?



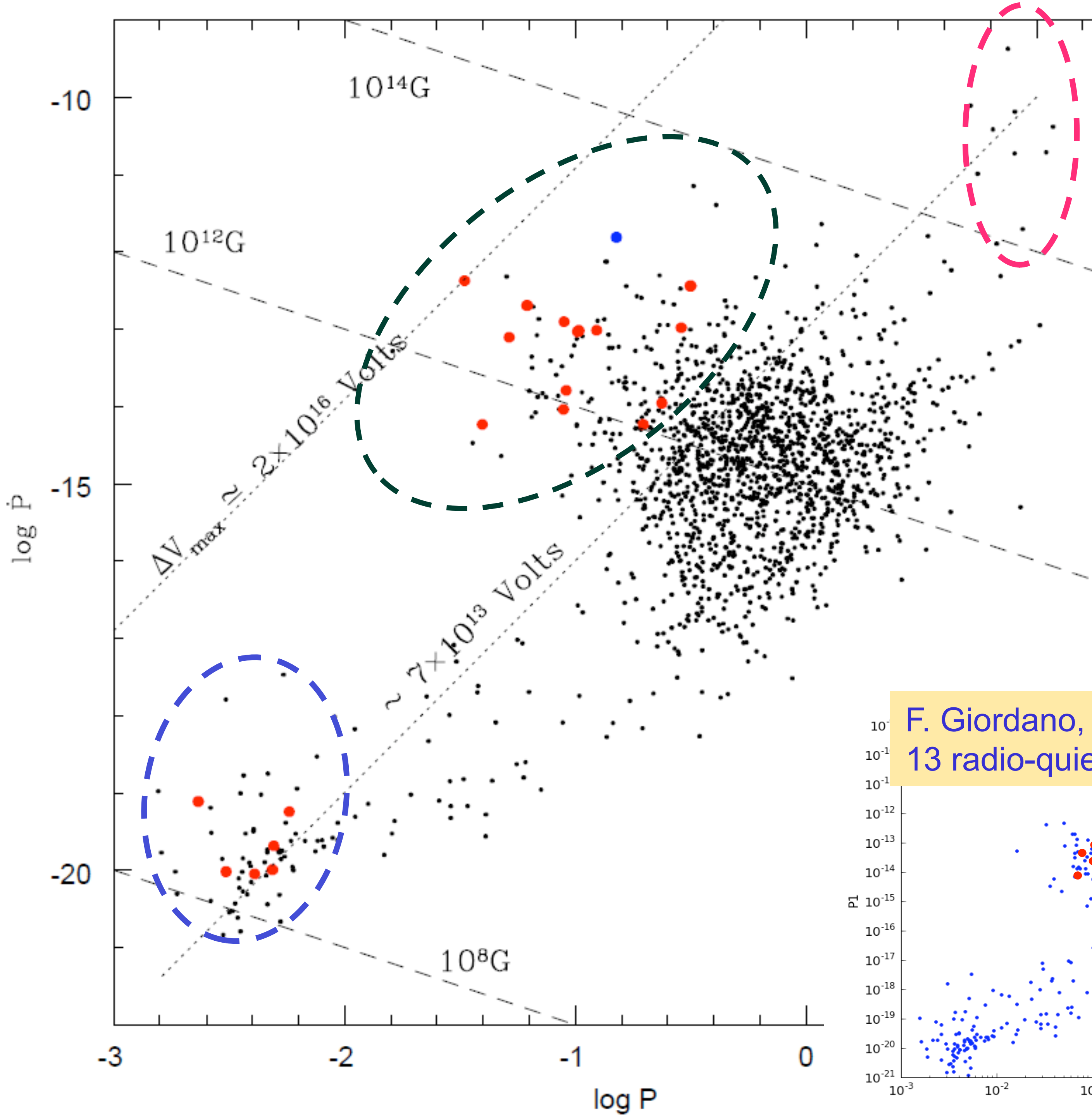
1) Rotating, strongly magnetized neutron stars -> unipolar inductors

2) Maximum potential drop (for vacuum rotator)

$$V_{max} \approx 6 \times 10^{12} B_{12} P^{-2} \text{ Volts,}$$

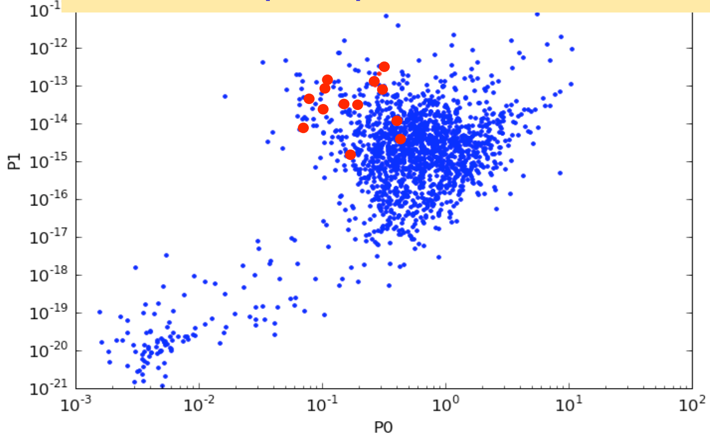
i.e. for young pulsars V_{max} can exceed 10^{16} Volts

Actual potential drops are much smaller, but high enough to accelerate charged particles to ultrarelativistic energies emitting in turn high energy photons.



1667 pulsars
ATNF
Pulsar
Database

F. Giordano, 44th Rec. de Moriond:
13 radio-quiet psrs



Radiative processes in pulsar magnetospheres

1. Curvature radiation

2. Inverse Compton Scattering (resonant + non-resonant)

3. Magnetic pair creation ($1\gamma \rightarrow e^{\pm}$)

4. Photon-photon pair creation ($2\gamma \rightarrow e^{\pm}$)

5. Synchrotron radiation

6. Photon splitting ($1\gamma \rightarrow 2\gamma$)

Daugherty & Harding 1982

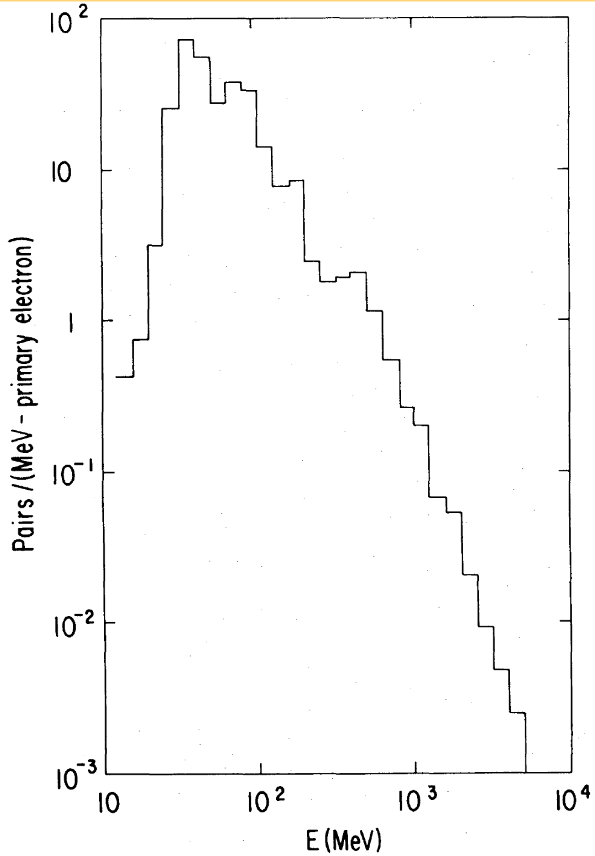
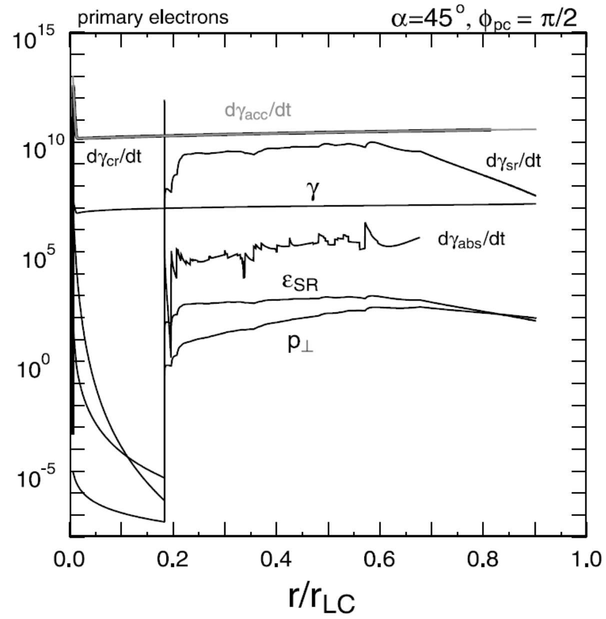
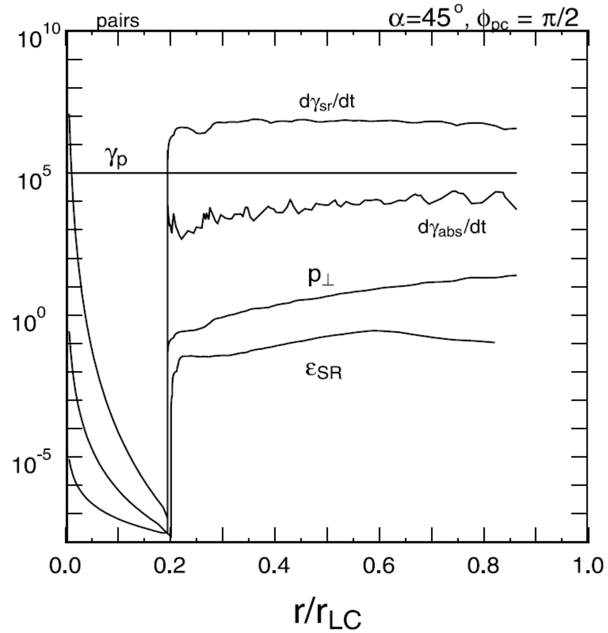


FIG. 7.—Differential e^+e^- spectrum from a cascade with initial electron energy 10^{13} eV, surface field 10^{12} gauss, magnetic colatitude $\theta_0 = 1.0$, and period of the Crab, $P = 0.033$ s.

Harding, Stern, Dyks, Frackowiak 2008





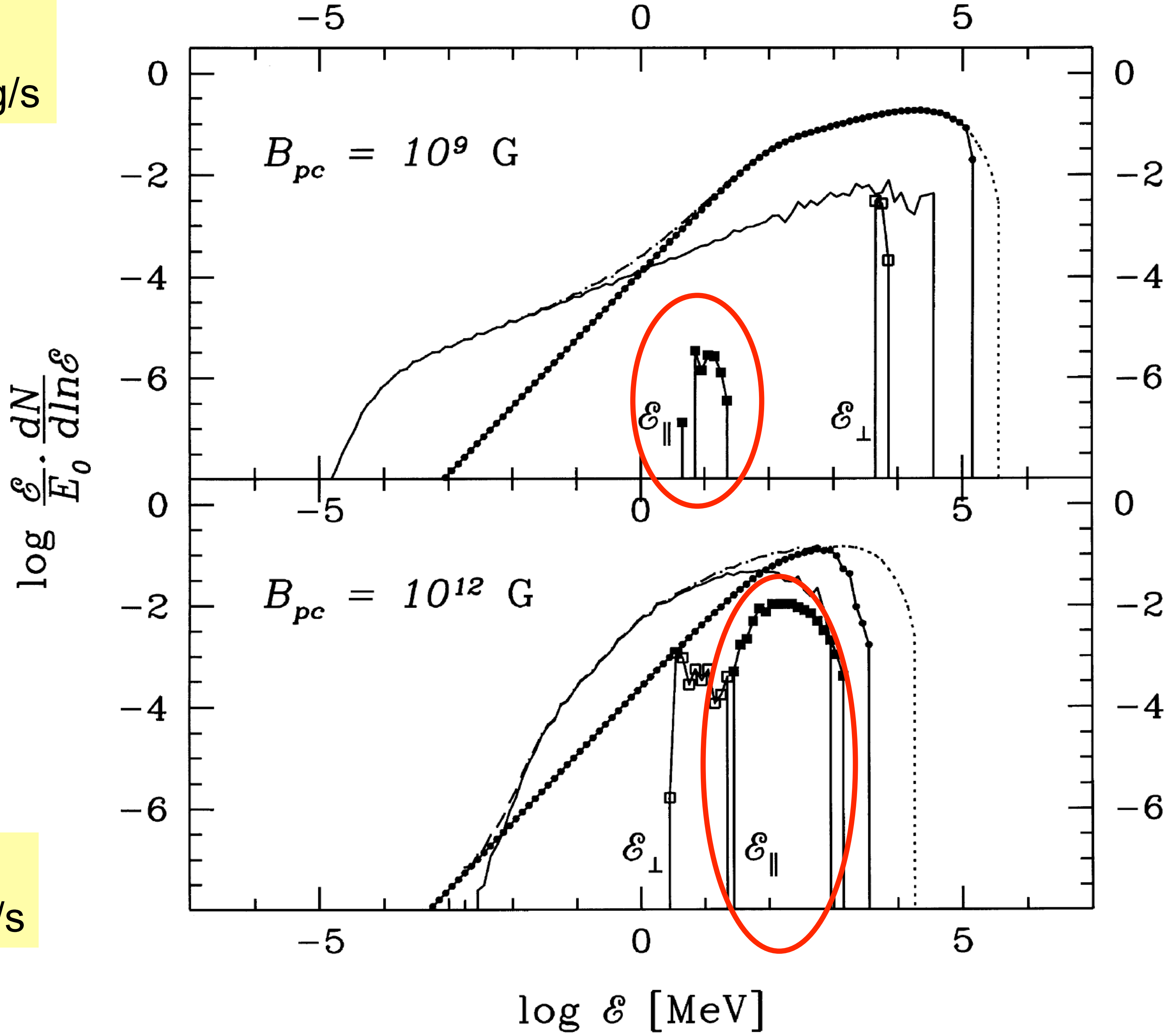
The pairs spectrum: broken power-law

$\gamma_{min} = 10^2$, $\gamma_{break} = 5\times10^3$, $\gamma_{max} = 2\times10^5$

$\delta_1 = 2.0$, $\delta_2 = 2.8$

P = 0.003 s

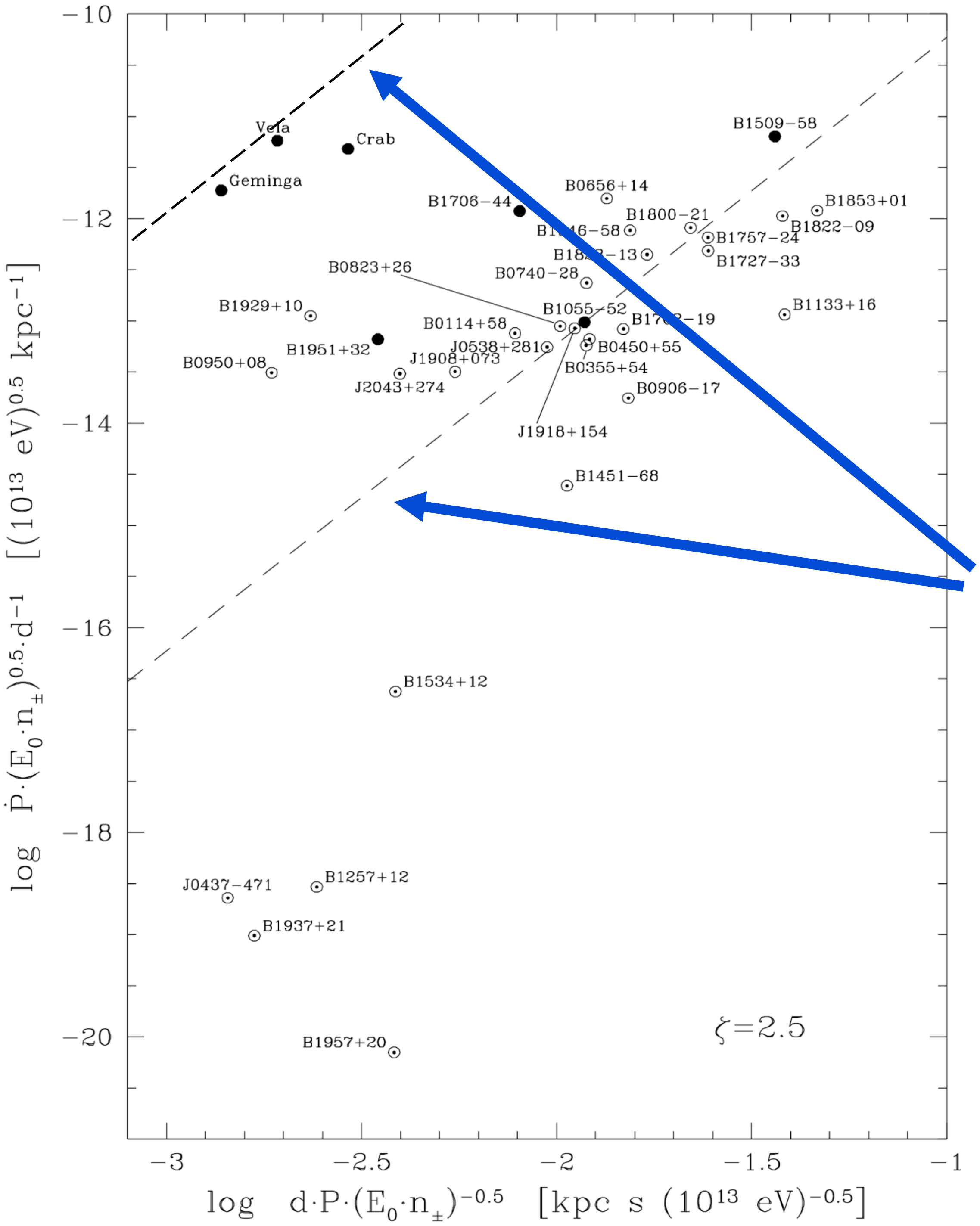
L_{sd} = 10^{35} erg/s



P = 0.056 s

L_{sd} = 10^{36} erg/s

Dyks 1998



Lines of constant values of $\dot{N}(e\pm)/d^2$

Simple criterium to choose promising nearby pulsars

(in addition to the pulsar age)

Spectra and lightcurves

as a result of

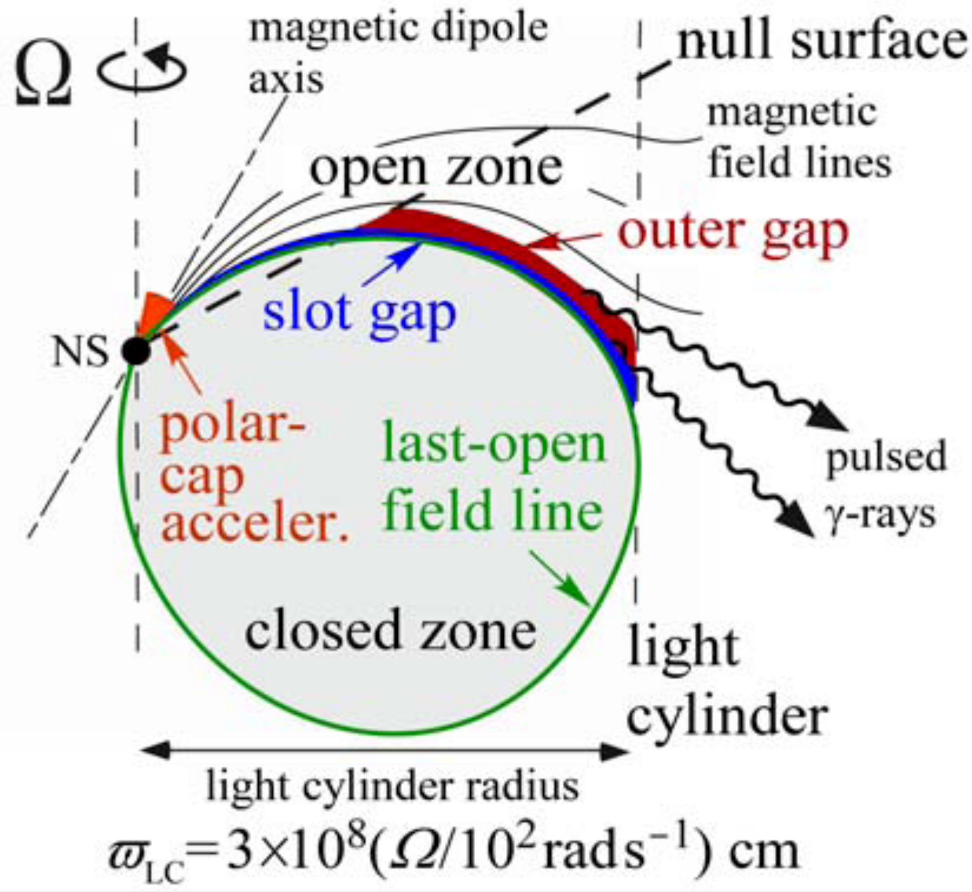
- specific radiative processes,
- location and spatial extent of the emitters,
- geometry (i.e. inclination and viewing angles)

3D models of magnetospheric gaps

Fig. by K. Hirotani

Variety of sizes and shapes of the accelerating gaps lead to a variety of energy spectra and anisotropies of emission.

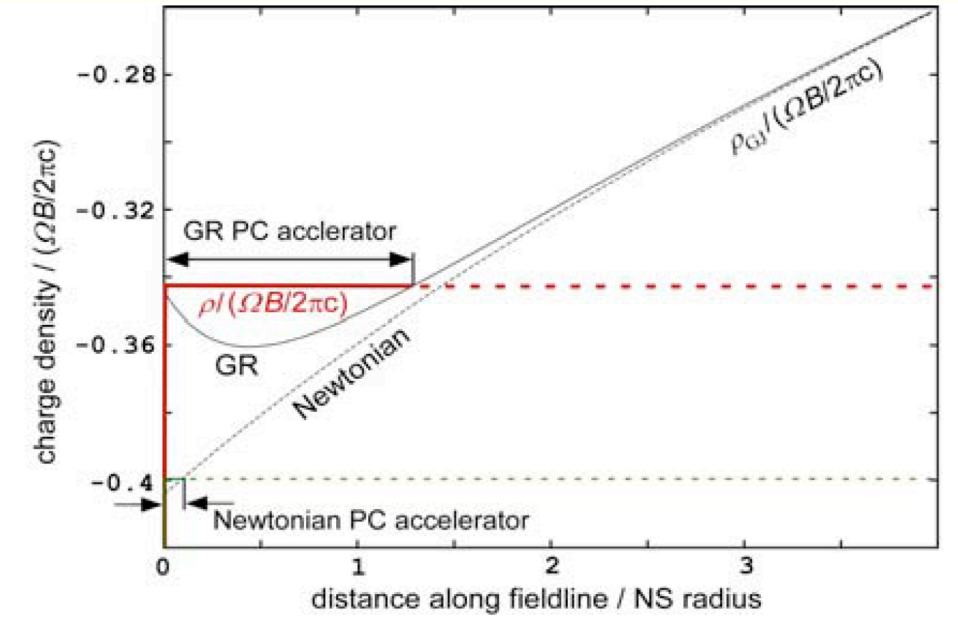
'Observed' characteristics depend strongly on inclination angle and line of sight w.r.t. the spin axis.

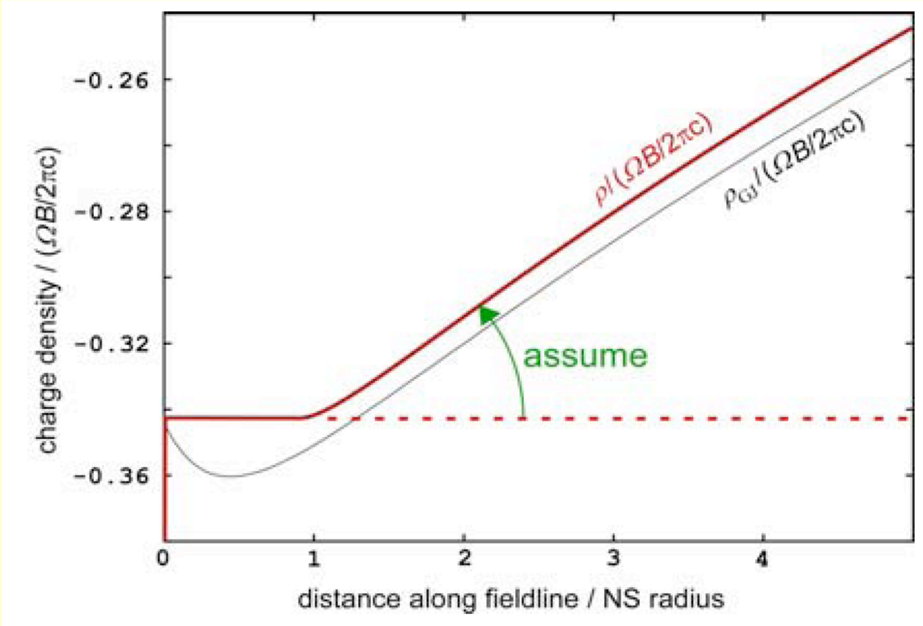


Figs. by K. Hirotani

Extended Polar Gap
Tsygan & Muslimov

Slot Gap
Muslimov & Harding 2004





$$\nabla \cdot \boldsymbol{E} = 4\pi\,(\rho - \rho_{corot})$$

Slot Gap versus Outer Gap

(an example for the Crab parameters)

Full electrostatic potential drop

ΔV (SG) $\sim 10^{13}$ V

ΔV (OG) $\sim 10^{15}$ V

Gap width:

$h_{SG} \cong 0.04$

$h_{OG} \cong 0.14$

Outer Gaps more powerful than Slot Gaps in terms of gamma-ray luminosity

Slot Gap versus Outer Gap

(an example for the Crab parameters)

Similar Multiplicities:

$M_{e\pm} \sim 10^4 - 10^5$

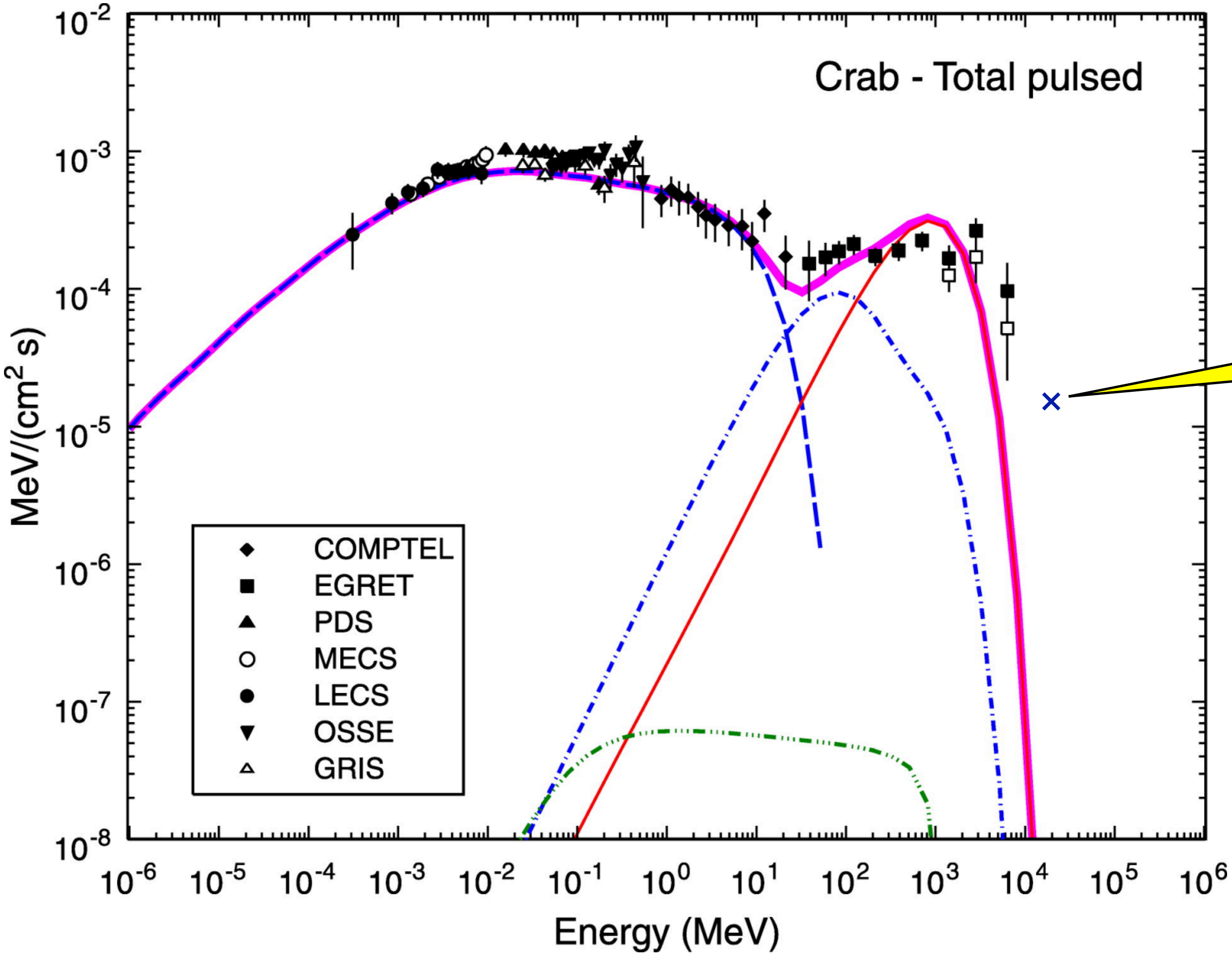
The rate of $e^{\pm}$ -pairs in the wind:

$$M_{e\pm}\, dN_{GJ}/dt \approx 3 \times 10^{38}\ s^{-1}$$

~ 100 times smaller than required for the Crab nebula

3D Slot Gap Model for the Crab Pulsar Harding, Stern, Dyks & Frackowiak 2008

CR + SR (primaries) + SR (pairs) + ICS (primaries with radio)

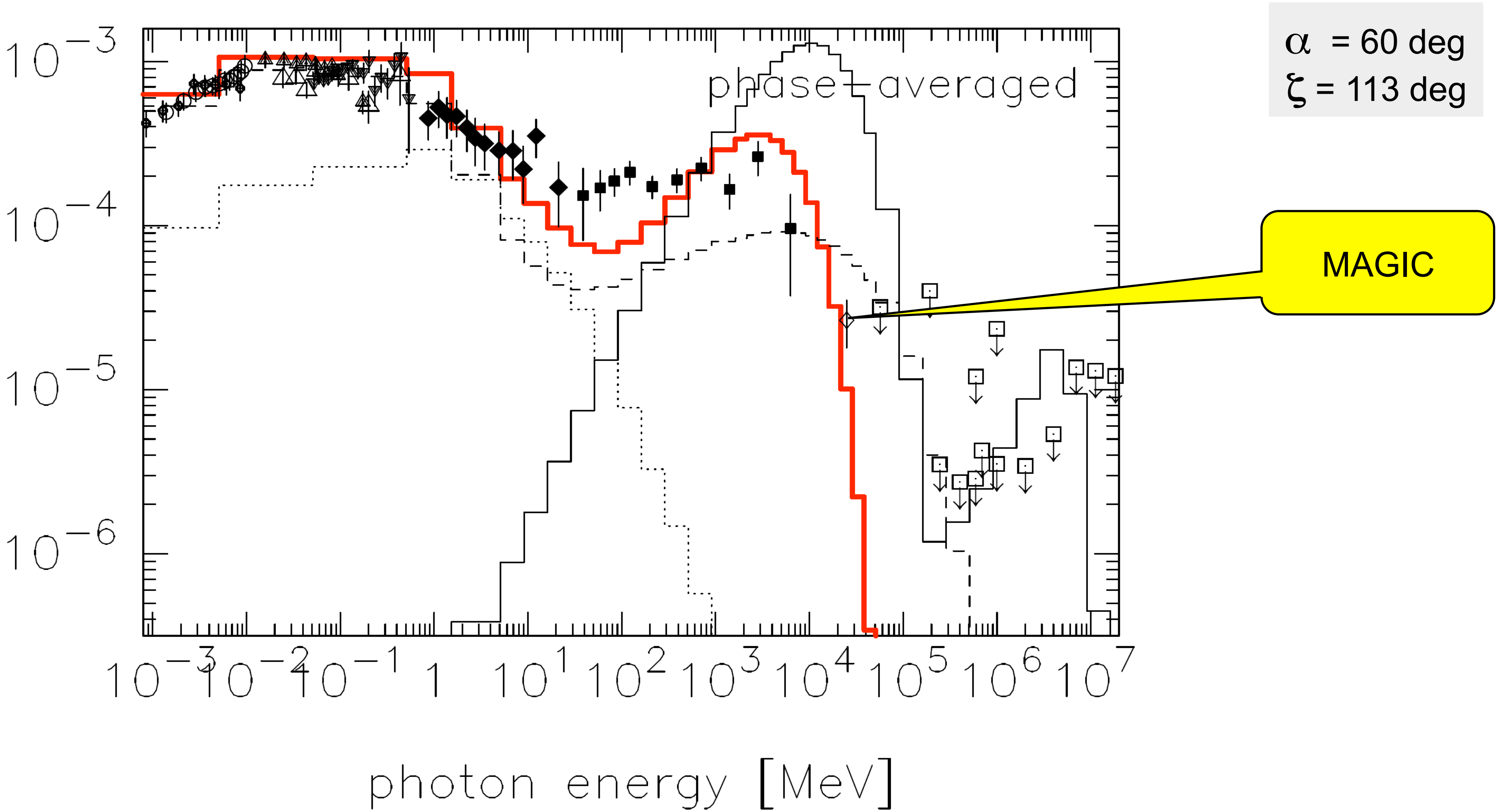


α = 45 deg
ζ = 100 deg

MAGIC

Synchro-curvature + ICS (pairs with IR)

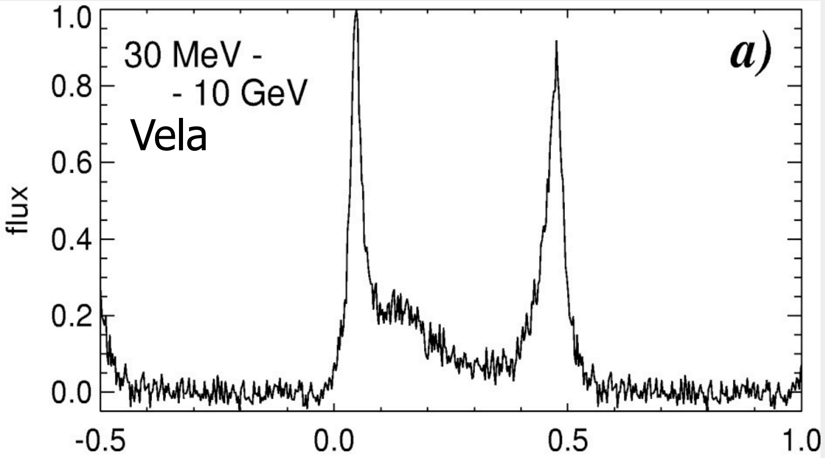
Intrinsic: black line Escaping: red line

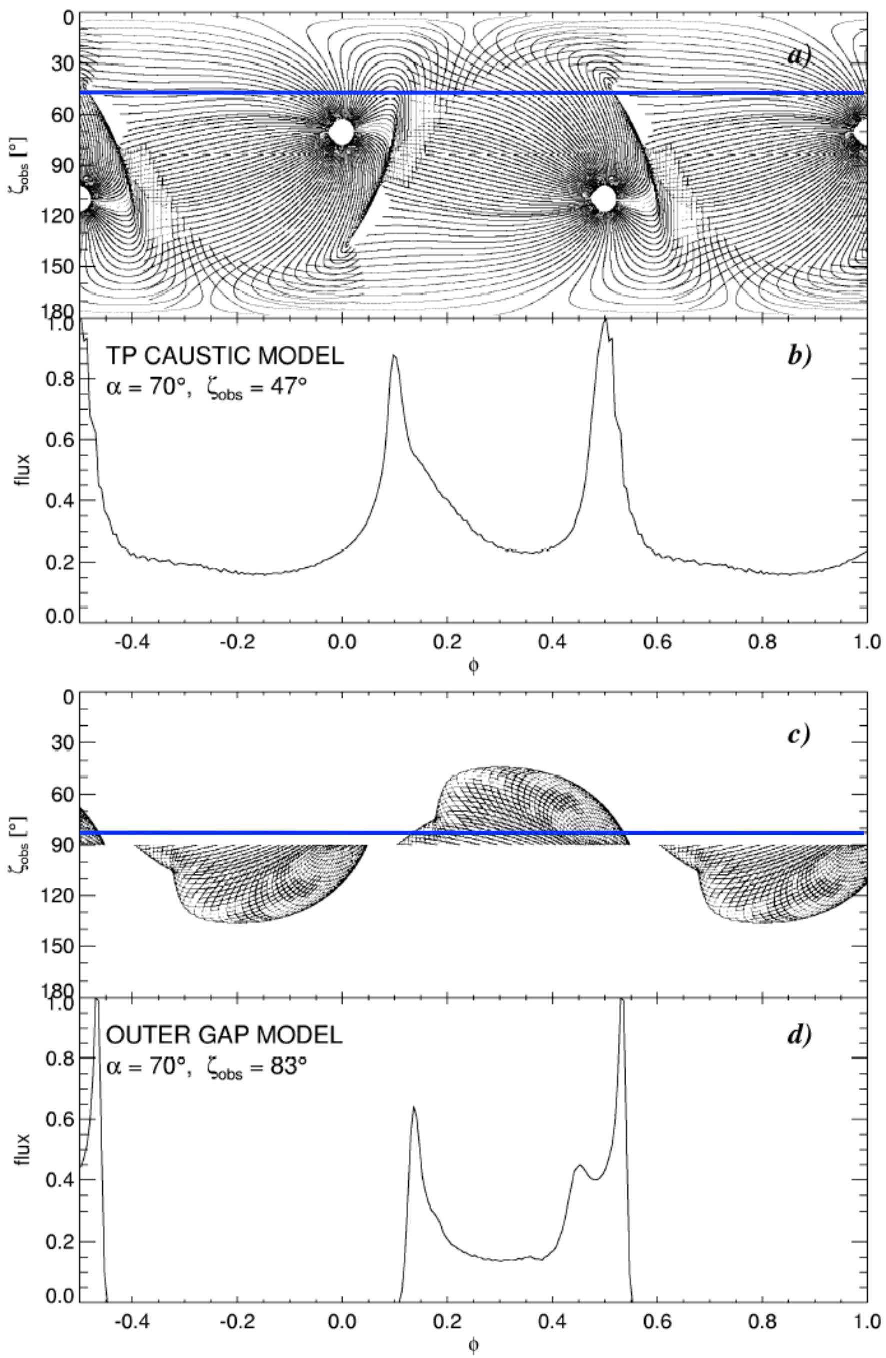


Dyks & Rudak 2003

Two-pole caustic model and outer gap model

The Vela pulsar lightcurve (Kanbach 1998)

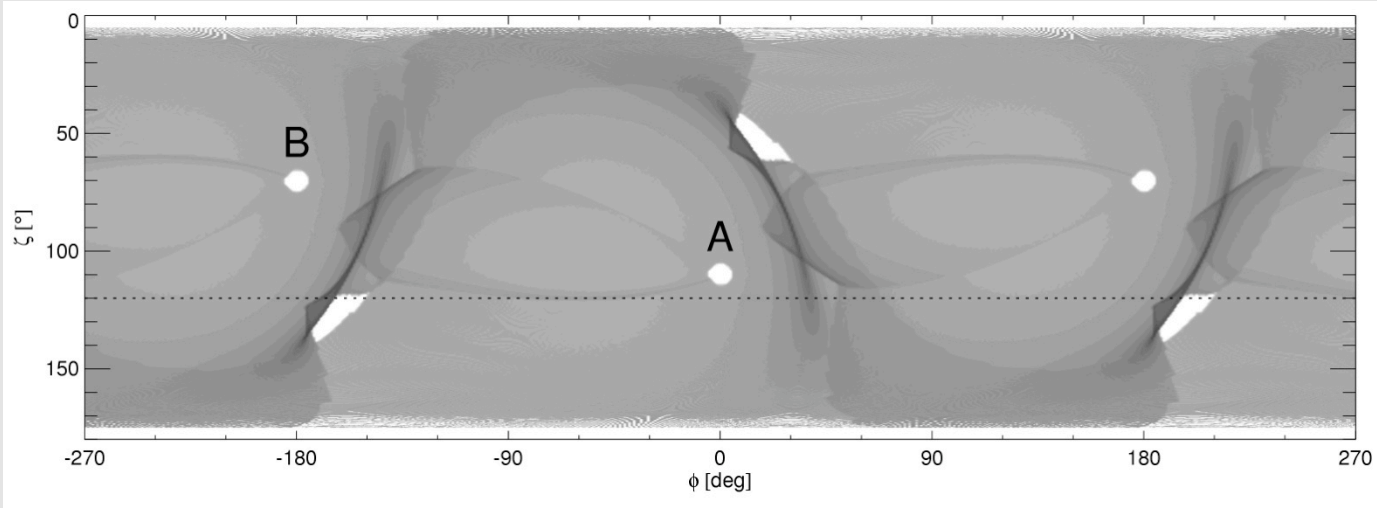


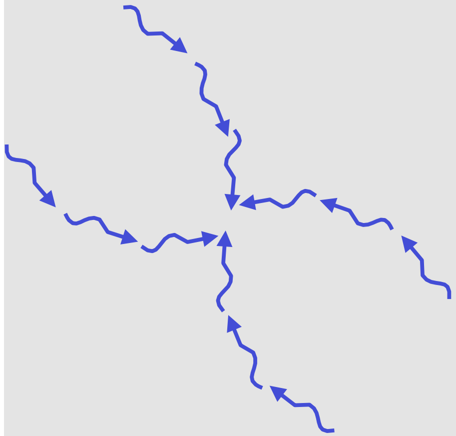


Two-pole caustic slot gap model

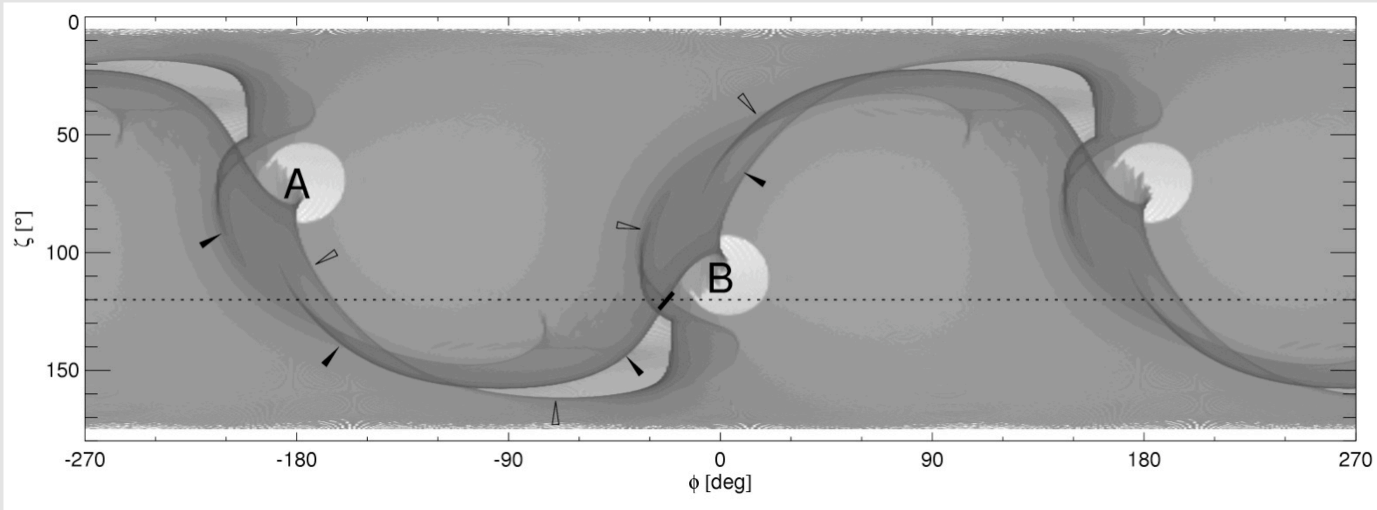
Dyks et al. 2005

Outward emission along last open field lines

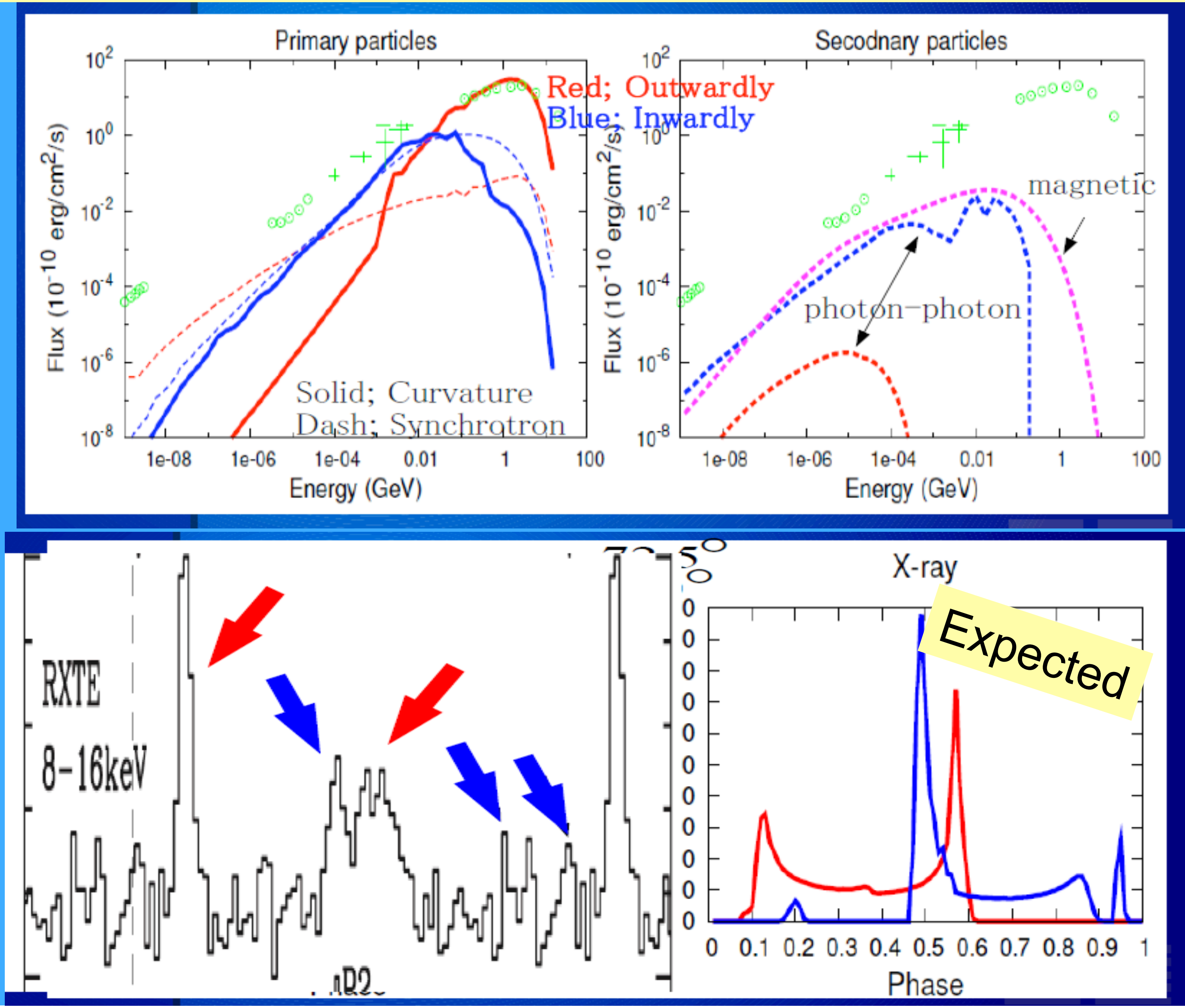




Inward emission along last open field lines



2D Outer gap model of Vela w. significant inward emission   Takata et al. 2008



Millisecond pulsars

Two groups with distinct properties in X-rays:

1) luminosity: relatively low,
   spectrum: mostly thermal-like
   lightcurve: broad single pulse

   best known: J0437-4715

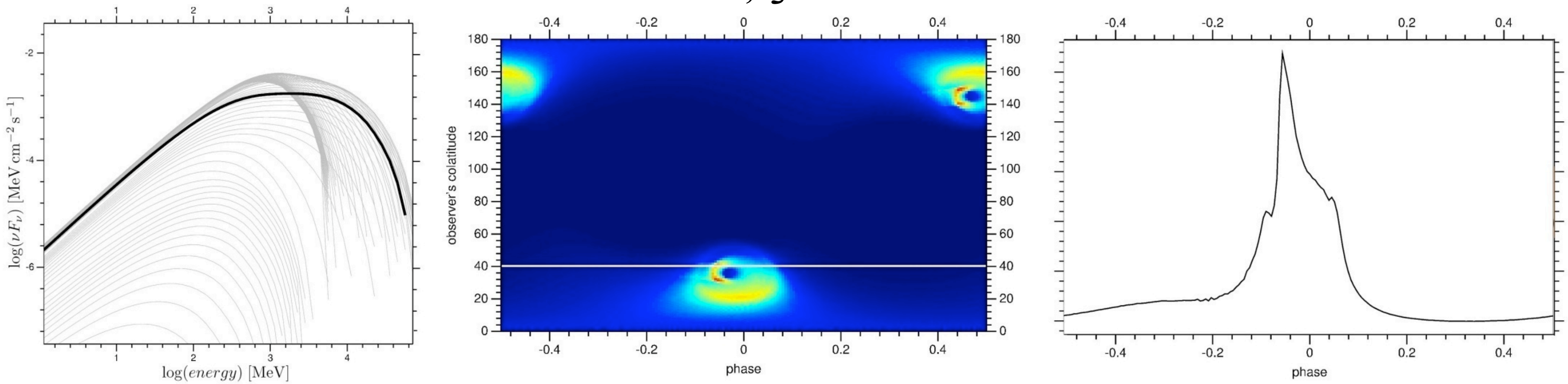
2) luminosity: relatively high,
   spectrum: non-thermal,
   lightcurve: two narrow peaks

   best known: B1821-24, J0218+4232

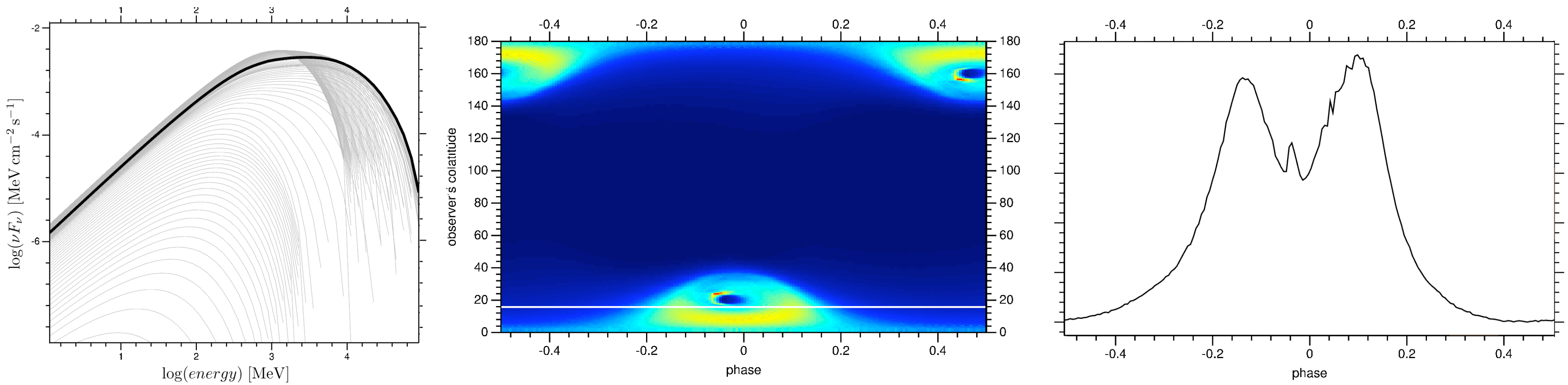
Are these properties reflected in gamma rays?

Photon maps and lightcurves above 100 MeV

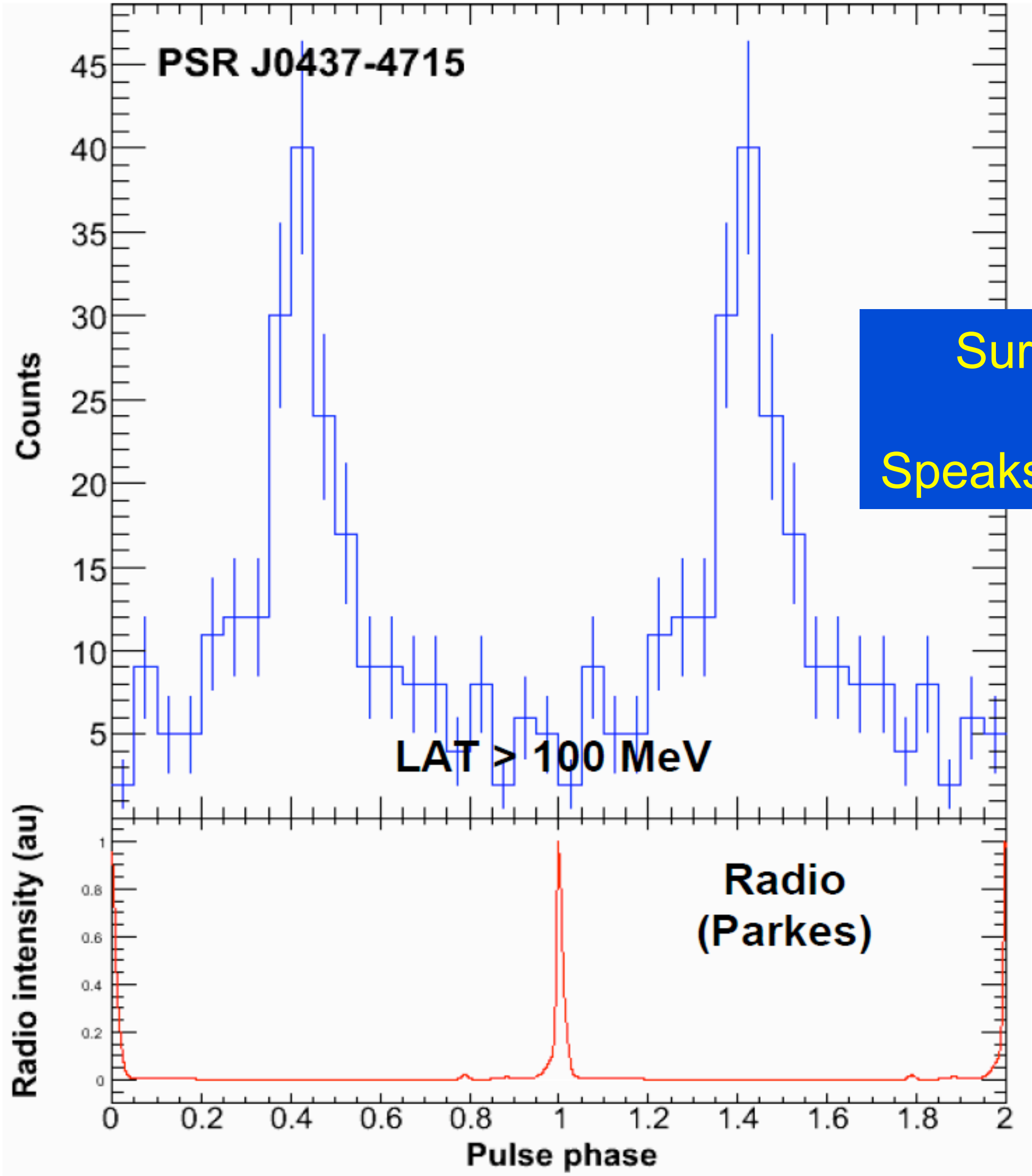
$\alpha = 35°, \zeta = 40°$



$\alpha = 20°, \zeta = 16°$



L. Guillemot, Rencontres de Moriond 2009, 7 February 2009

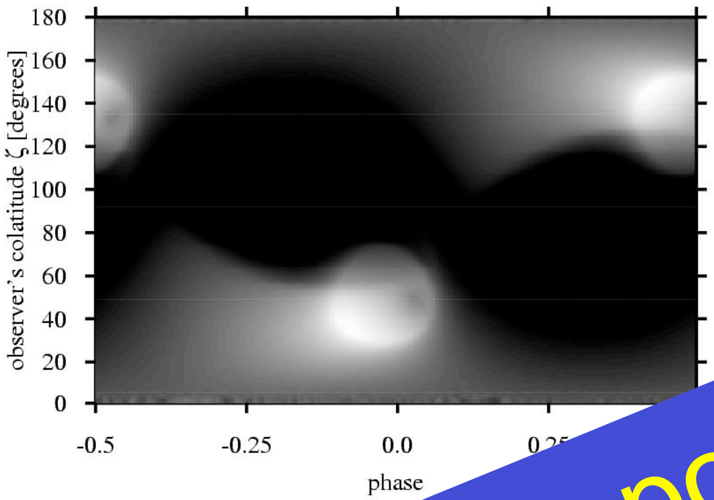


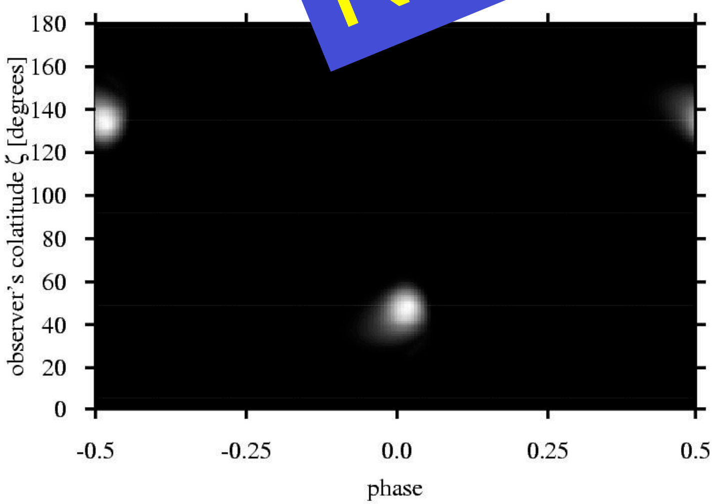
Surprising result !

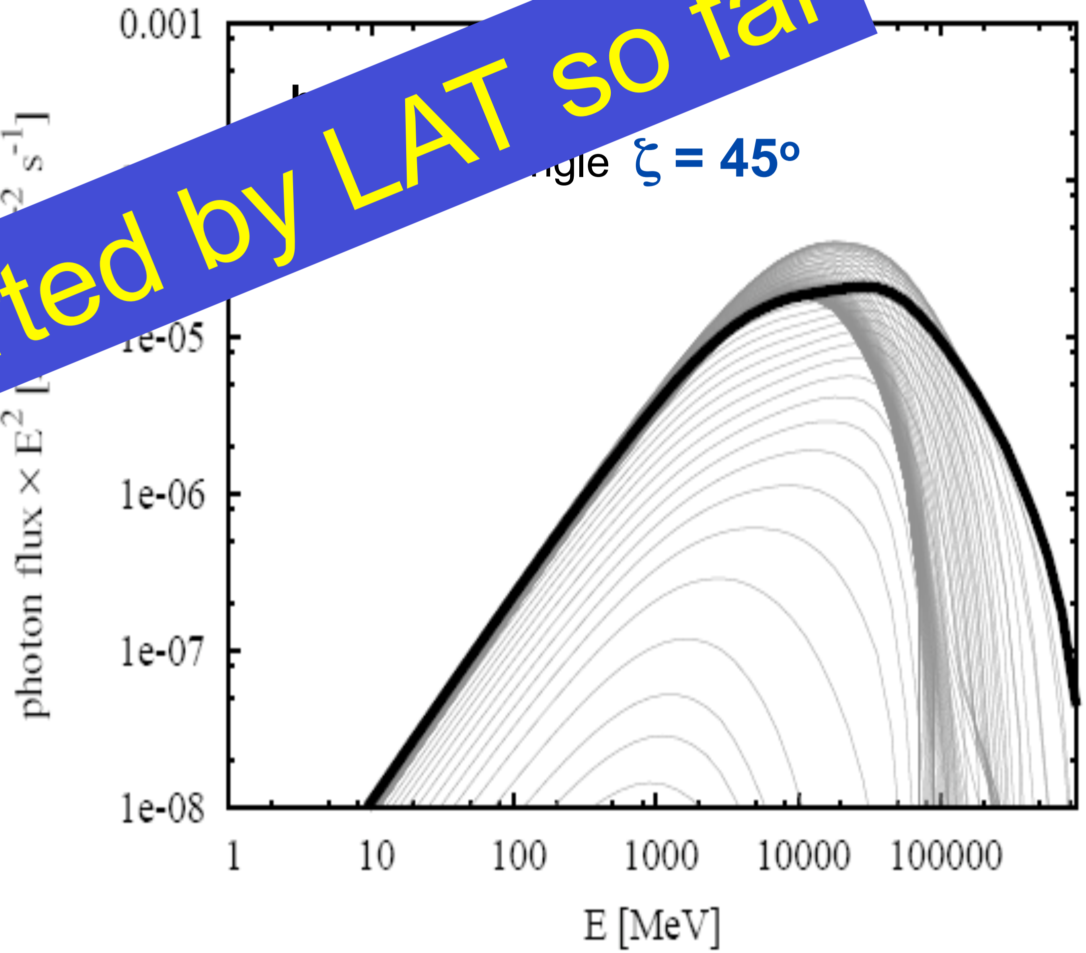
Speaks for Outer Gaps?

3D model of B1821-24: SCLF, unscreened $E_{||}$ Frackowiak & R 2005

P = 3.1 ms, B = 0.002 TG
α = 50°
d = 5.1 kpc







Not reported by LAT so far

Which models are appropriate for MPSRs ?

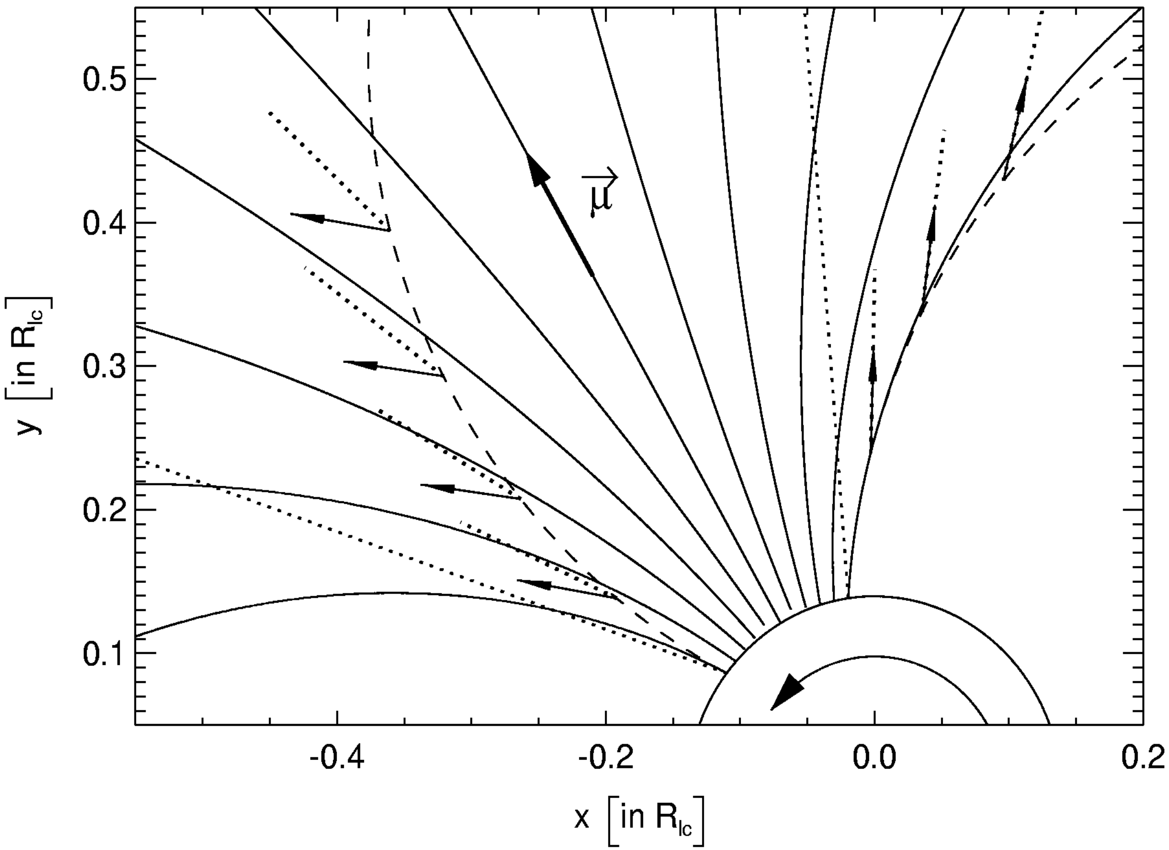
J0218+4232, B1821-24 (but not in gamma-rays so far), J00307+0451:

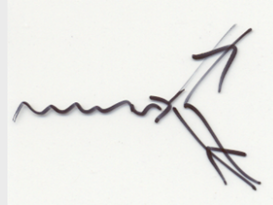
„mini-Crabs" (highly nonthermal MSPs):

- slot gap or outer gap activity

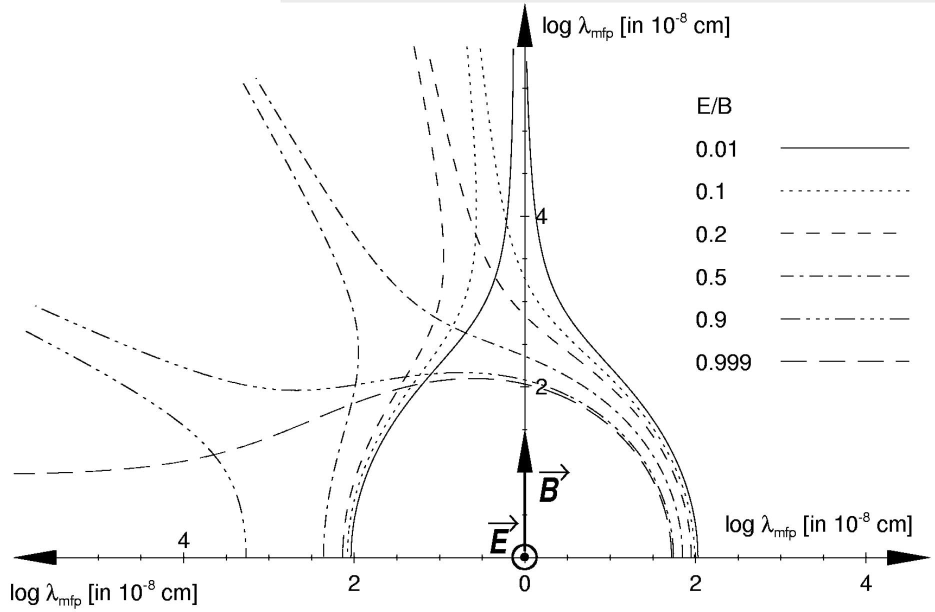
J0437-4715:

- outer gap activity (??), any room for polar caps?





Rotation leads to non-axisymmetric magnetic absorption



Dyks & Rudak02

Expected signatures of one-photon magnetic absorption generated by rotation (can be relevant for slot gaps and polar caps)

Where to look for them?

In gamma-ray lightcurves with double-peak structure.

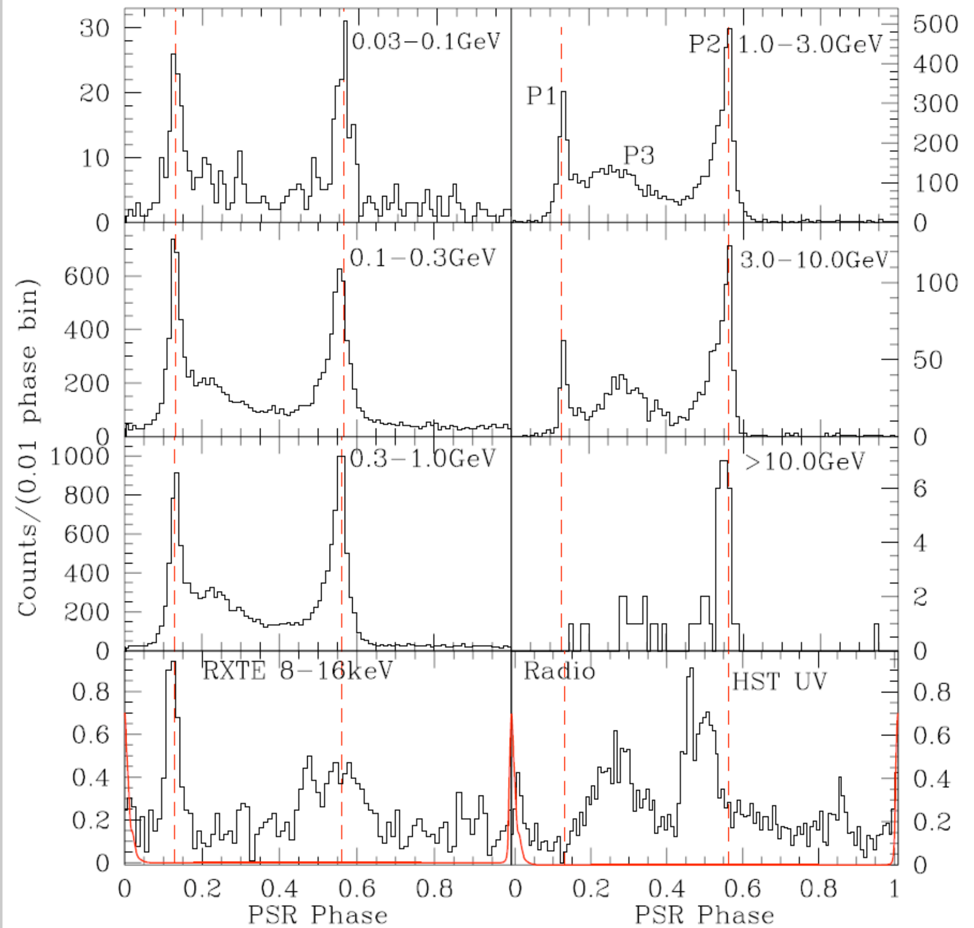
High photon-statistics close to cutoff energy is required.

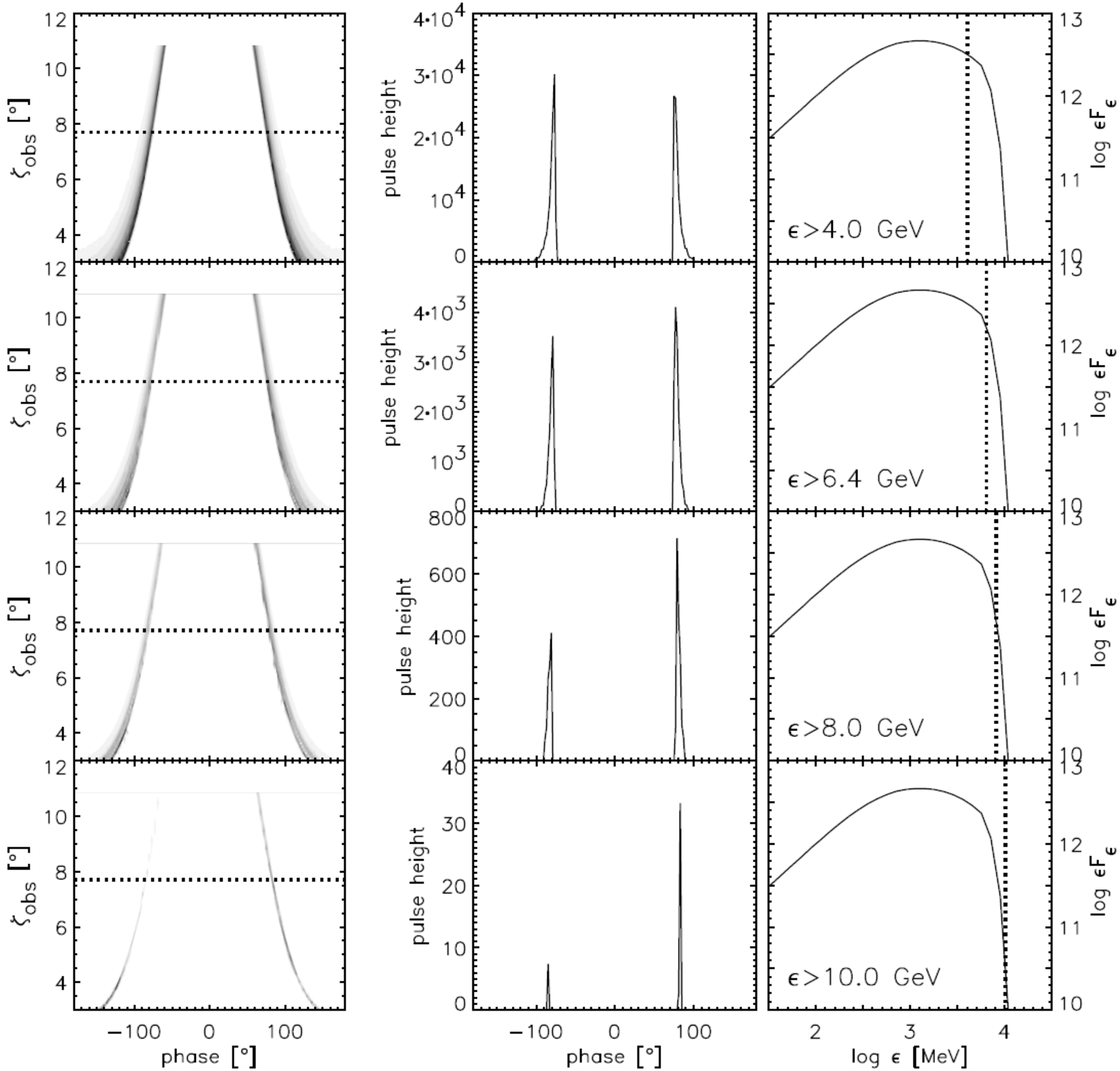
Asymmetric magnetic absorption:

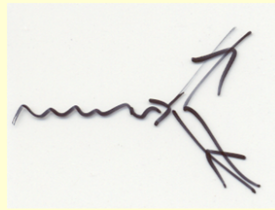
1) Leading Peak becomes weaker than Trailing Peak close to cutoff energy

2) LP-TP separation changes dramatically at cutoff energy

The Vela pulsar, Abdo et al. 2008







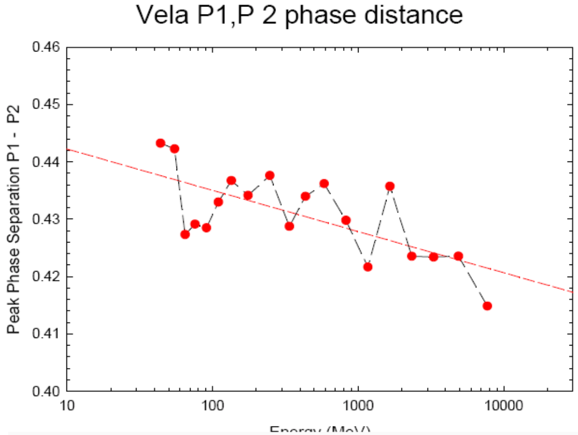
Numerical example:

Vela-like Model

(Dyks & Rudak 02)

Slide by G. Kanbach

Peak separation Vela



Fit (30-10000 MeV):

$\Delta\phi = 0.449 - 7.19\times10^{-3}\log(E_{MeV})$