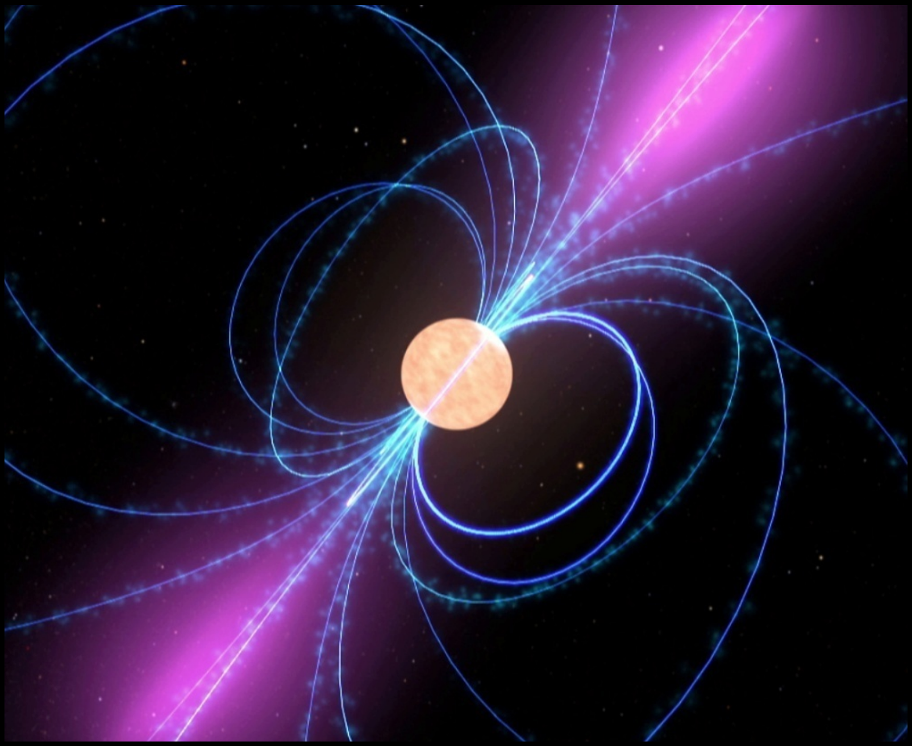
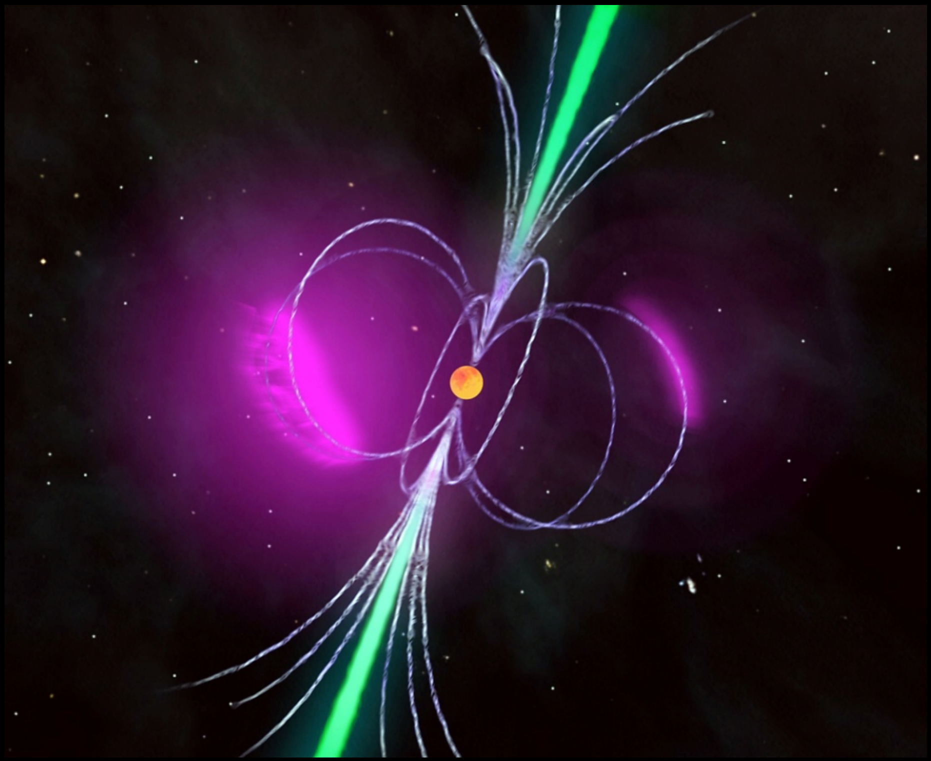
Gamma-Ray Pulsars – Theory and Modeling

Alice Harding
NASA Goddard Space Flight Center





Pulsar spin down

- All pulsars spin down

$$\dot{\Omega} = -K\Omega^n$$

- Magnetic dipole spin-down (n = 3)

$$\dot{E}_d = \left(\frac{B_0^2\Omega^4}{3R^6c^3}\right) = \frac{1}{2}I\Omega\dot{\Omega}$$

- Surface magnetic field (at poles)

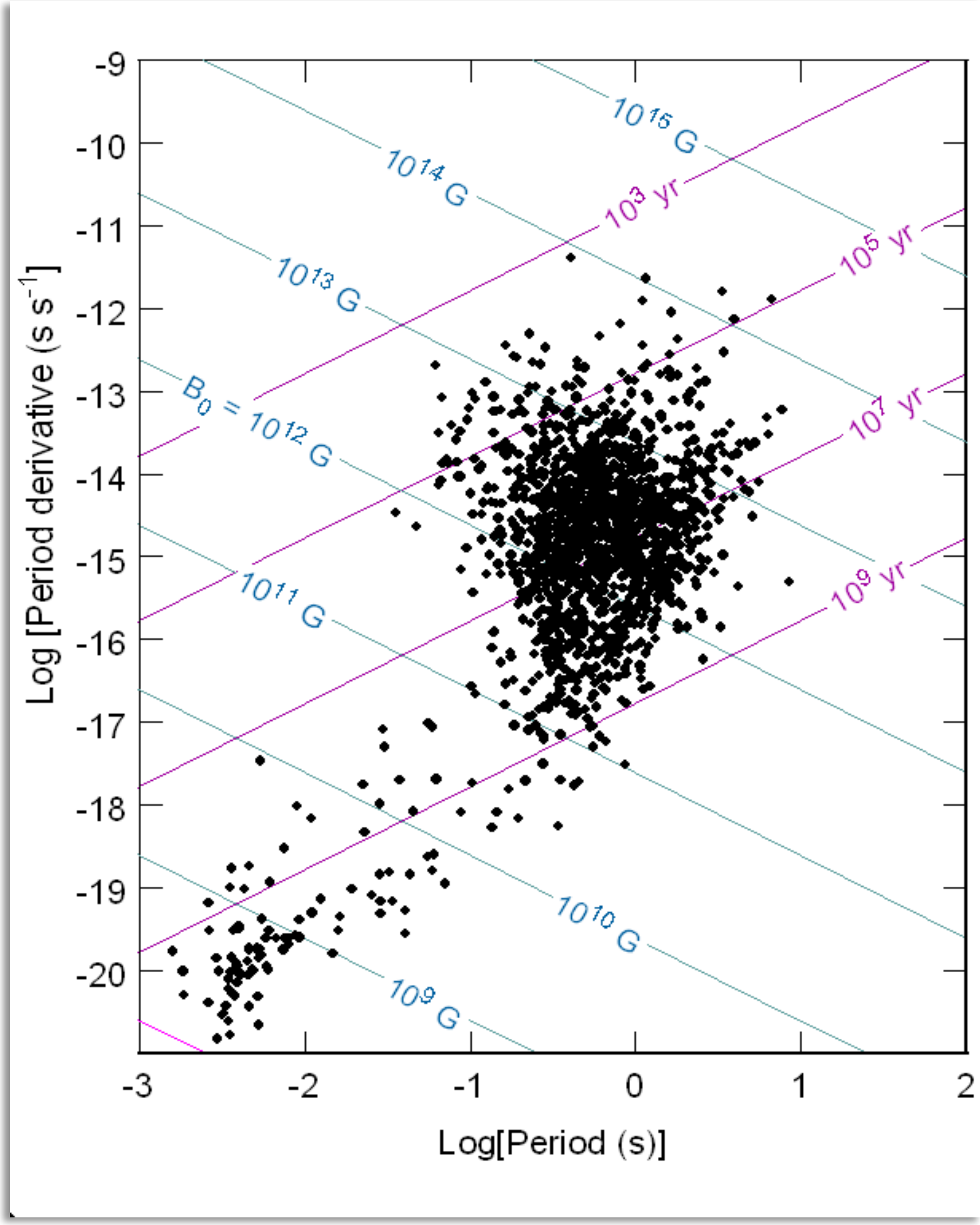
$$B_0 = \left(\frac{3Ic^3P\dot{P}}{4\pi^2R^6}\right)^{1/2} = 6.4\times10^{19}\ G\ (P\dot{P})^{1/2}$$

- Characteristic age

$$\tau = \frac{P}{(n-1)\dot{P}}$$

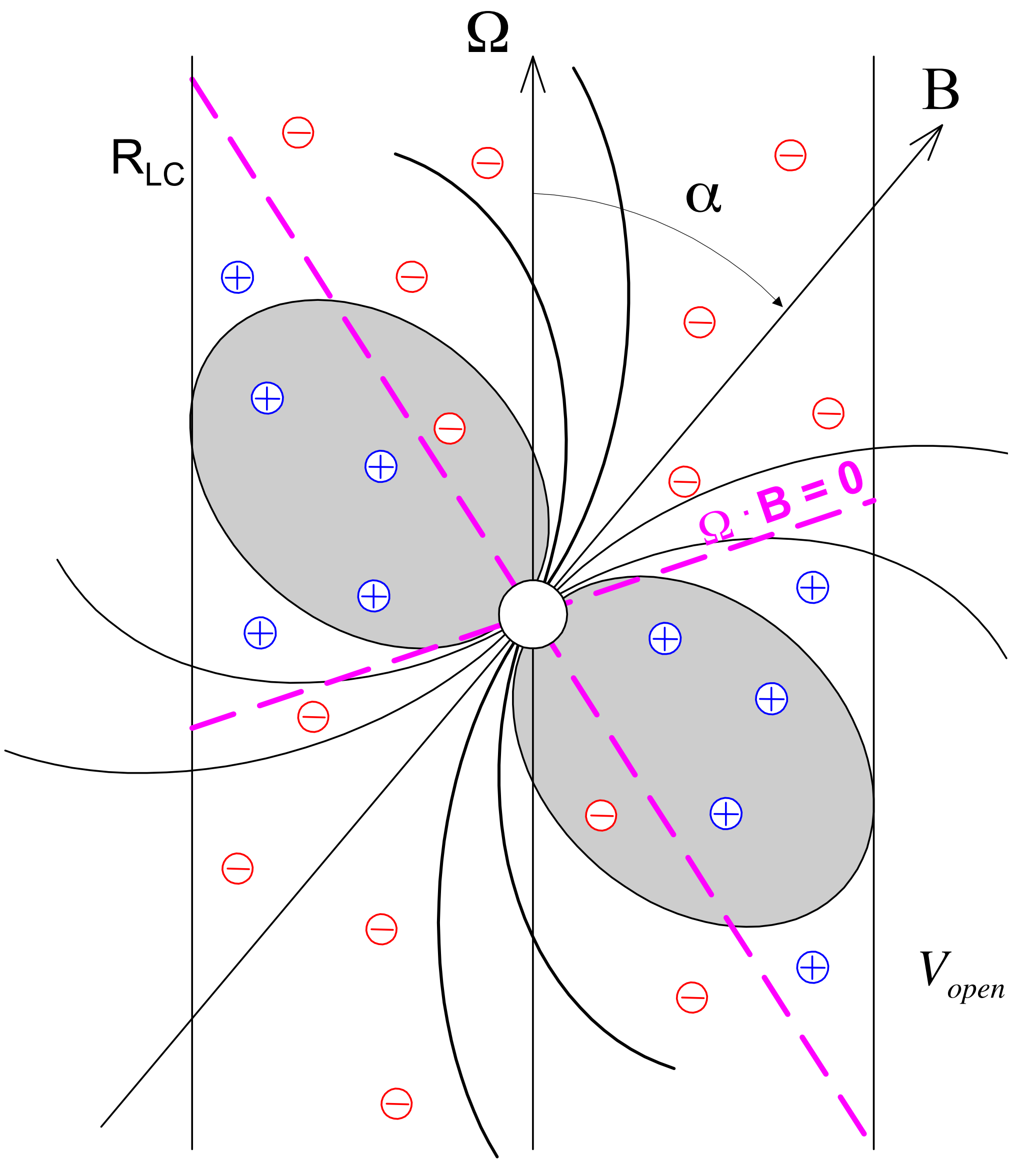
- Breaking index

$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2}$$



Pulsar Electrodynamics

Goldreich & Julian 1969



- In vacuum $E_{||} >> F_{grav}$ at NS surface
- Vacuum conditions (Deutsch 1955) cannot exist!
- If charge supply creates force-free conditions,

$$E = -\frac{\mathbf{v} \times \mathbf{B}}{c}$$

- Goldreich-Julian charge density

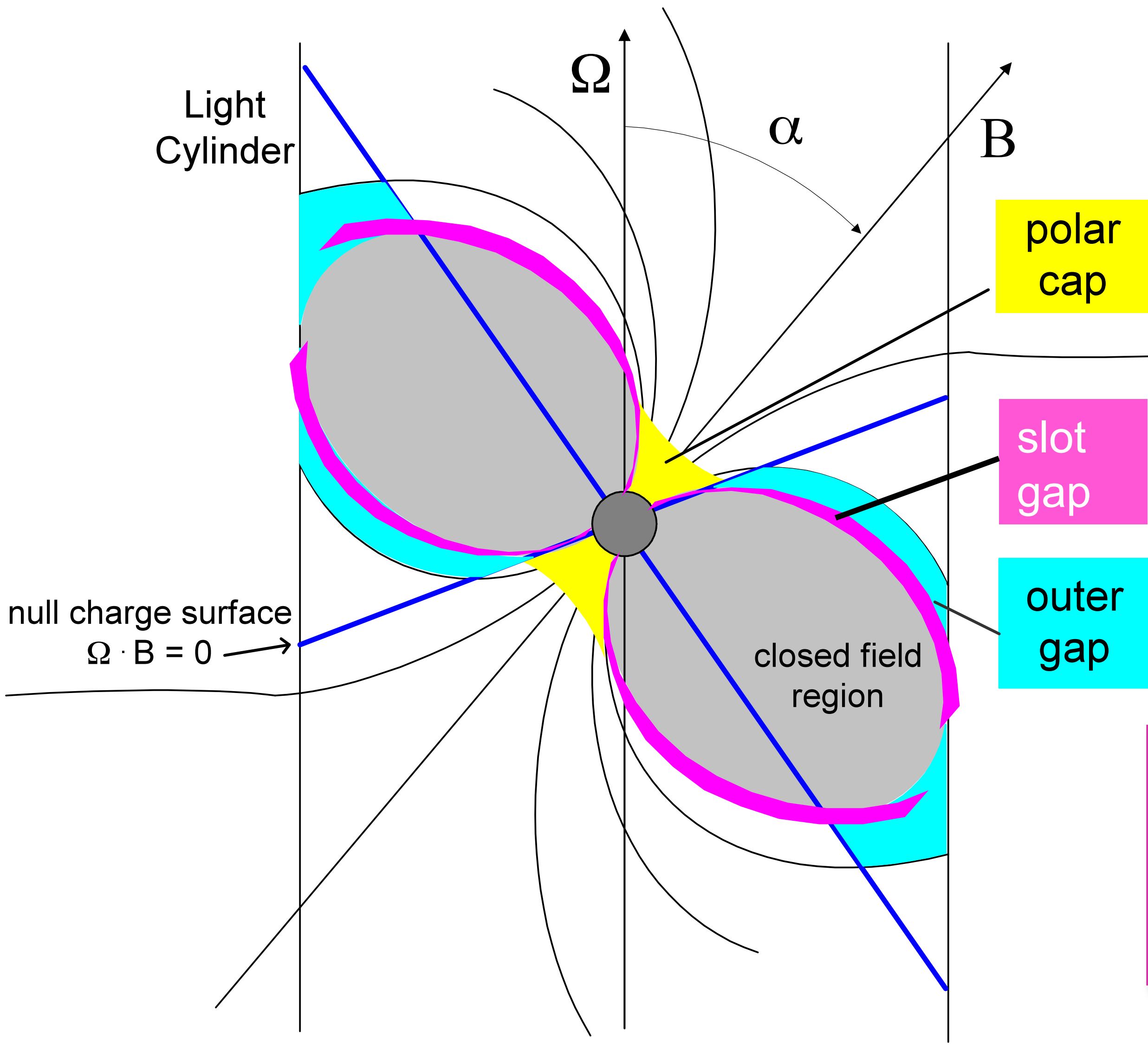
$$\rho_{GJ} = \frac{\nabla \cdot E}{4\pi} \approx -\frac{\Omega \cdot B}{2\pi c}$$

- Corotating dipole field
- Vacuum potential drop across open field (i.e. Polar cap)

$$V_{open} = \int_0^{R_{PC}} \frac{\Omega r}{c} B_0 \, dr = \frac{2\pi^2 B_0 R^3}{c^2 P^2} = 6 \times 10^{12} V \; B_{12} P^{-2}$$

- NO particle acceleration

Possible sites of particle acceleration



In most of magnetosphere

$$E \bullet B = 0$$

Deficient charge supply

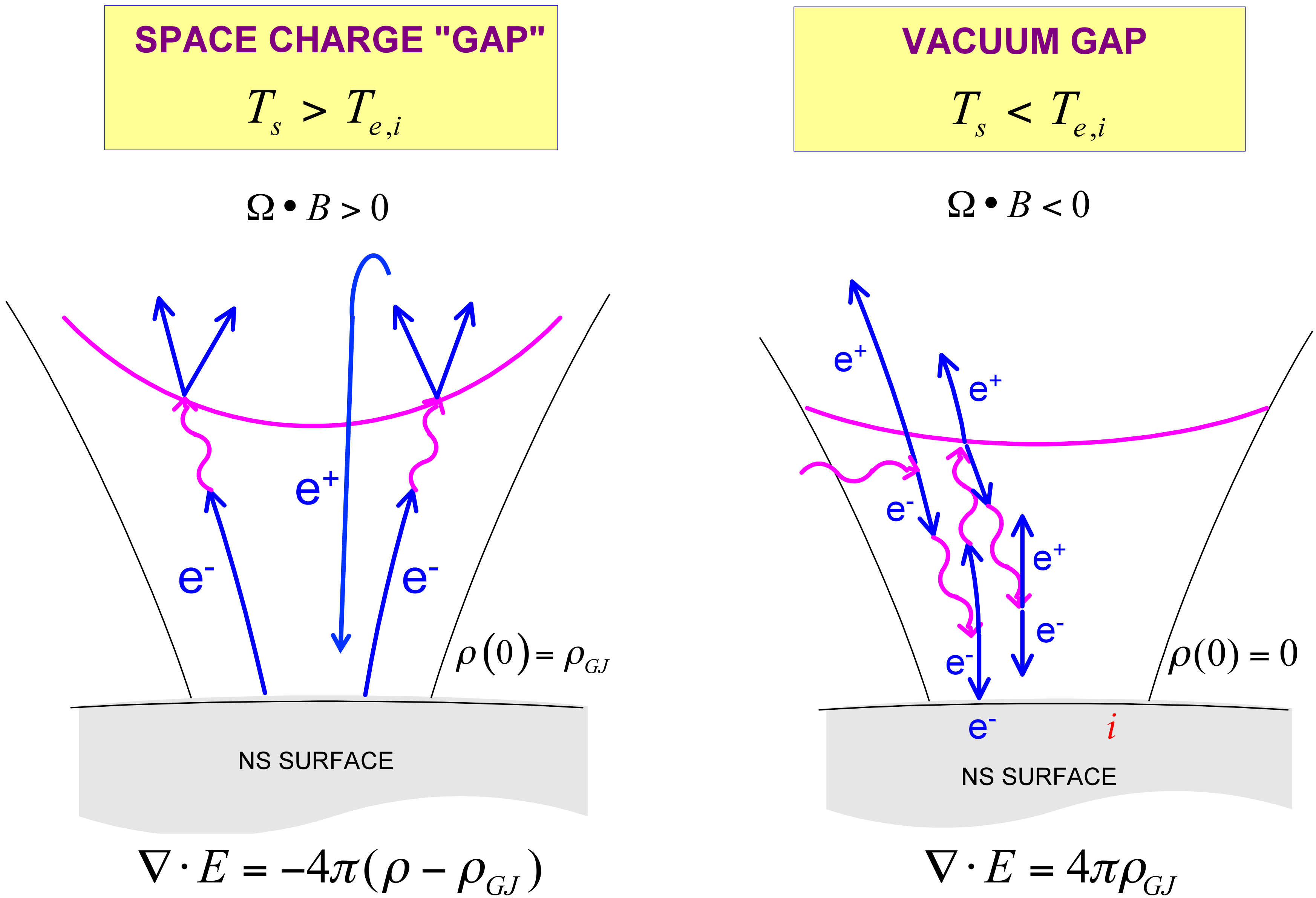
$$E \bullet B \neq 0$$

→ acceleration

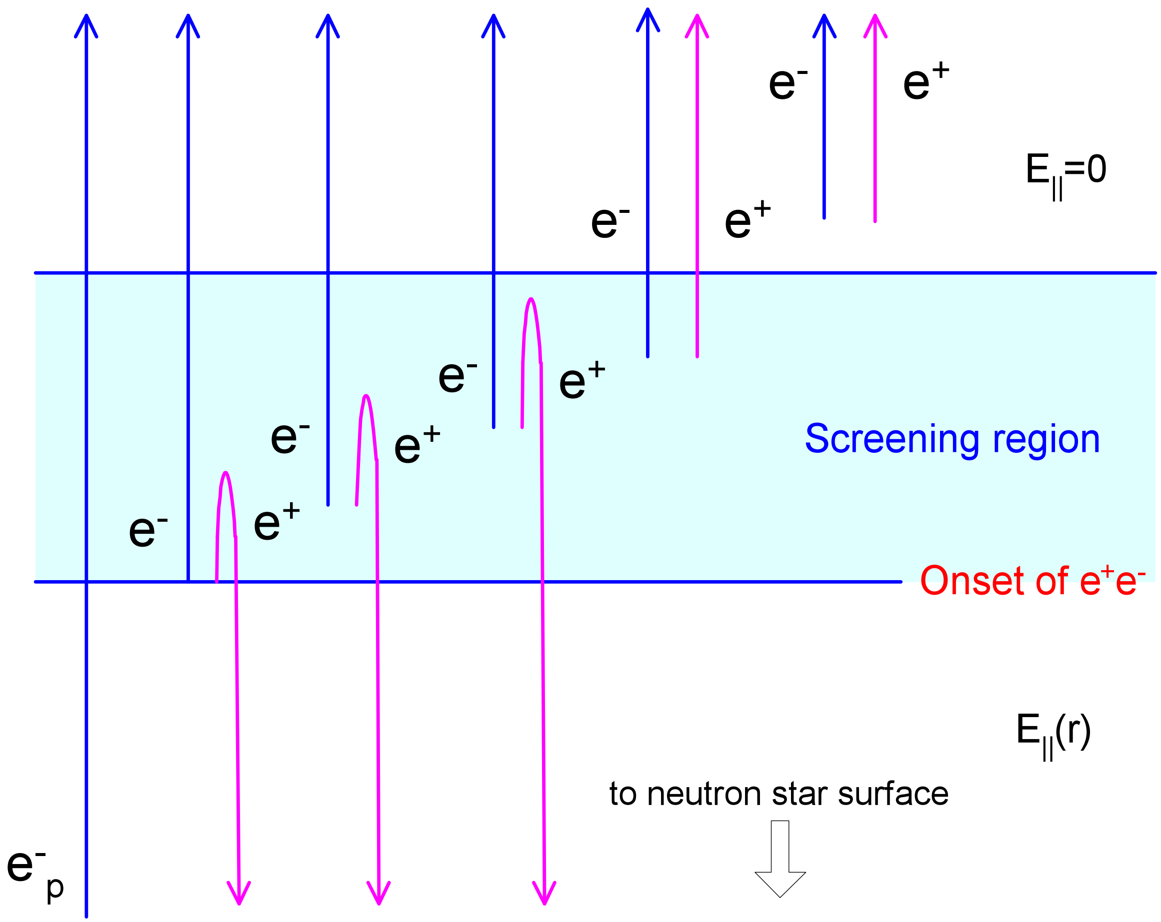
Solve Poisson's Eqn

$$\nabla \bullet E_{\parallel} = 4\pi(\rho - \rho_{GJ})$$

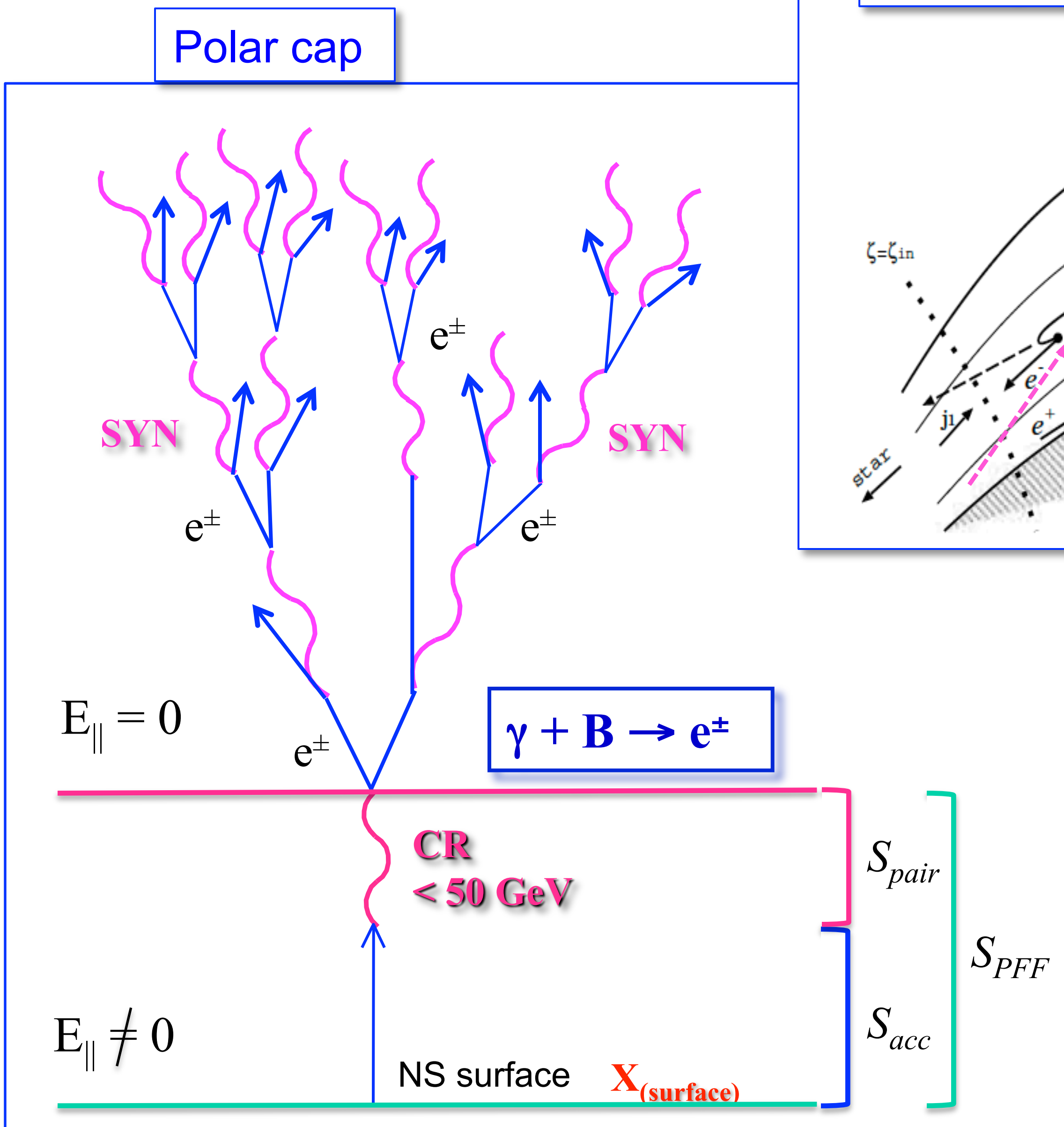
Polar cap accelerators

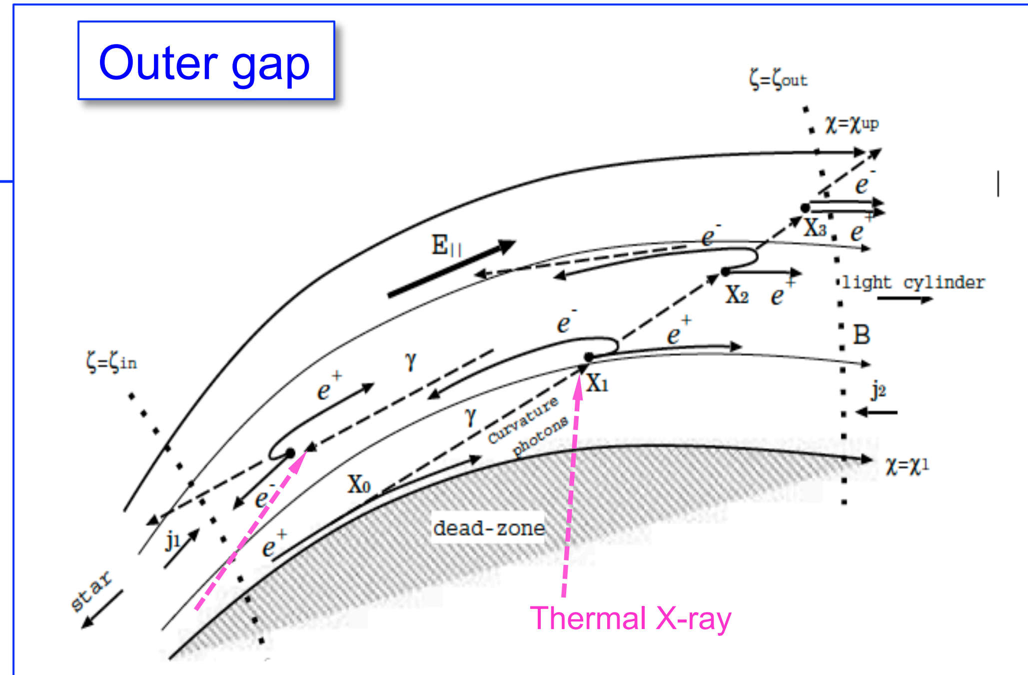


Electric field screening & Polar cap heating

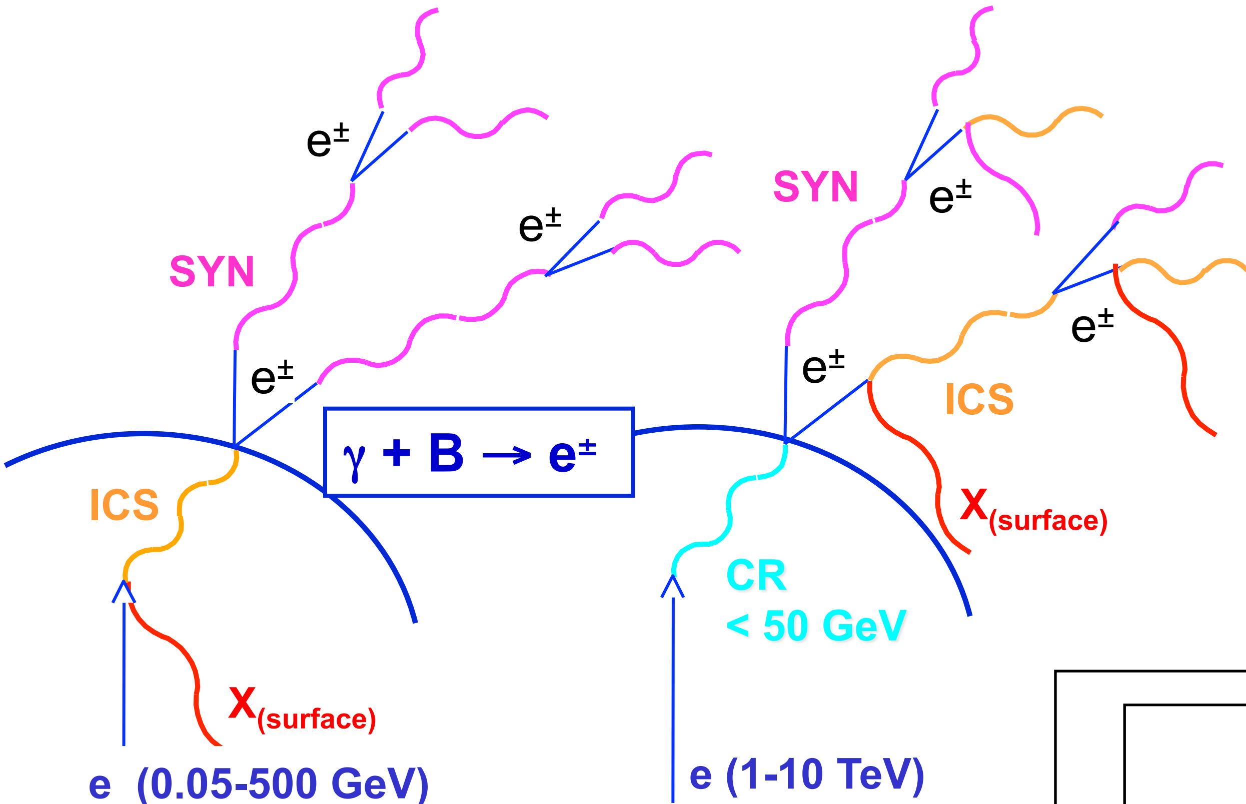


Pulsar pair cascades





Polar cap pair cascades



$M_p < 10$ $M_p \sim 10^2 - 10^5$

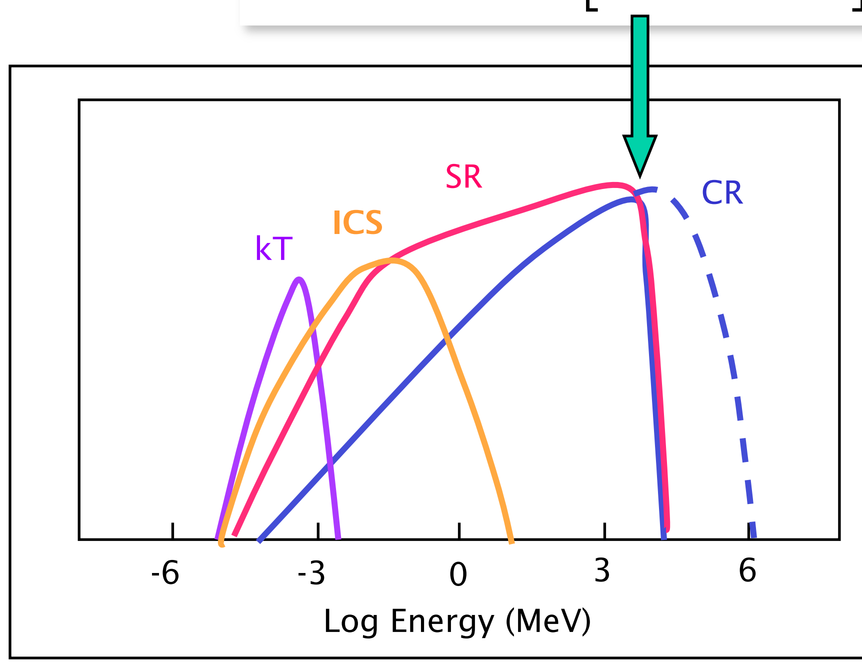
Magnetic pair production

Threshold $\varepsilon_{th} = mc^2/\sin\theta$

Spectral attenuation is "super-exponential"

$$f(\varepsilon) = A\varepsilon^{-a}\exp(-\tau_{1\gamma})$$

$$\tau_{1\gamma} \approx C(B)\exp\left[-\frac{8}{3\varepsilon B'\sin\theta}\right]$$



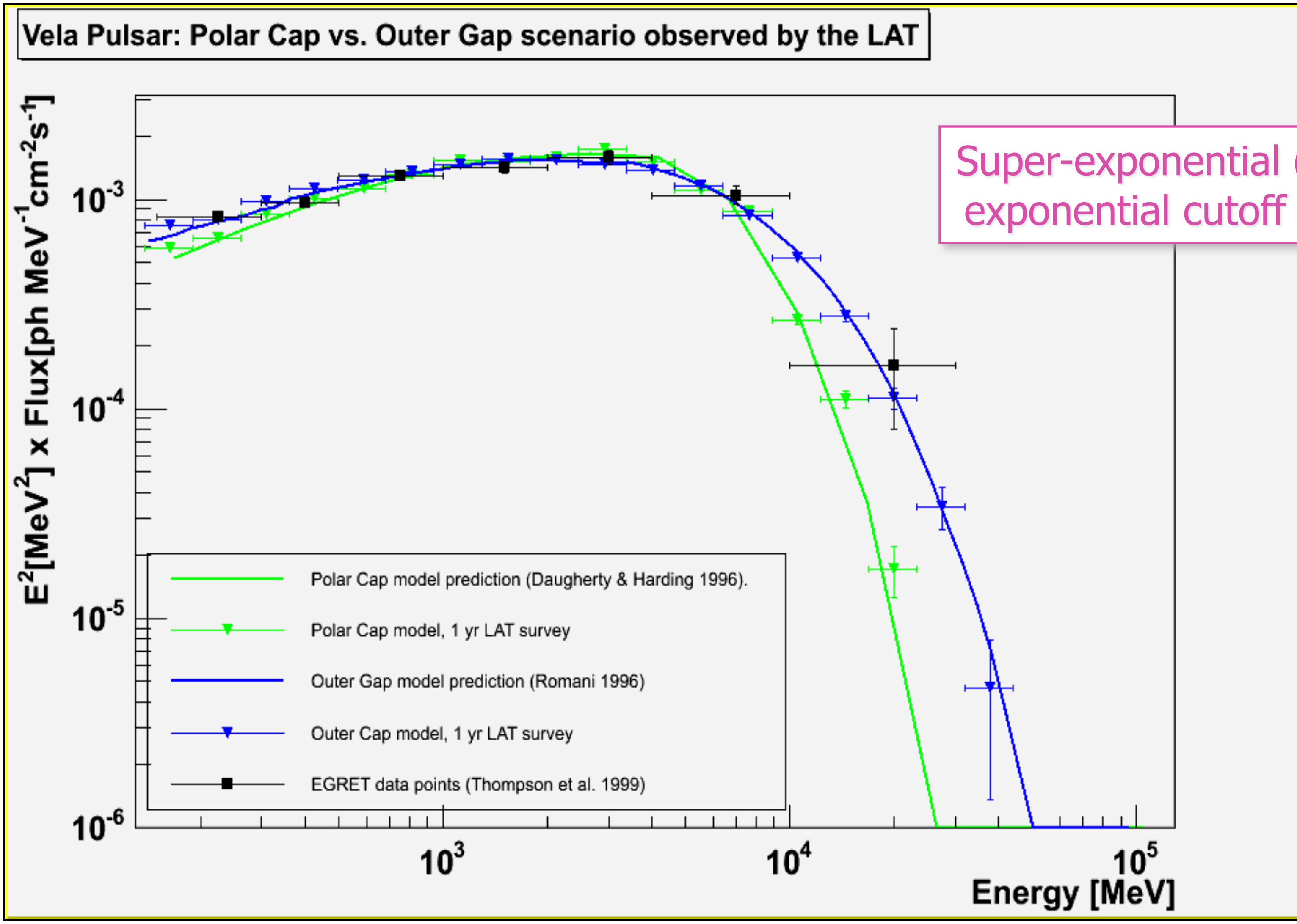
Daugherty & Harding 1982

Zhang & Harding 2000

Sturner & Dermer 1994

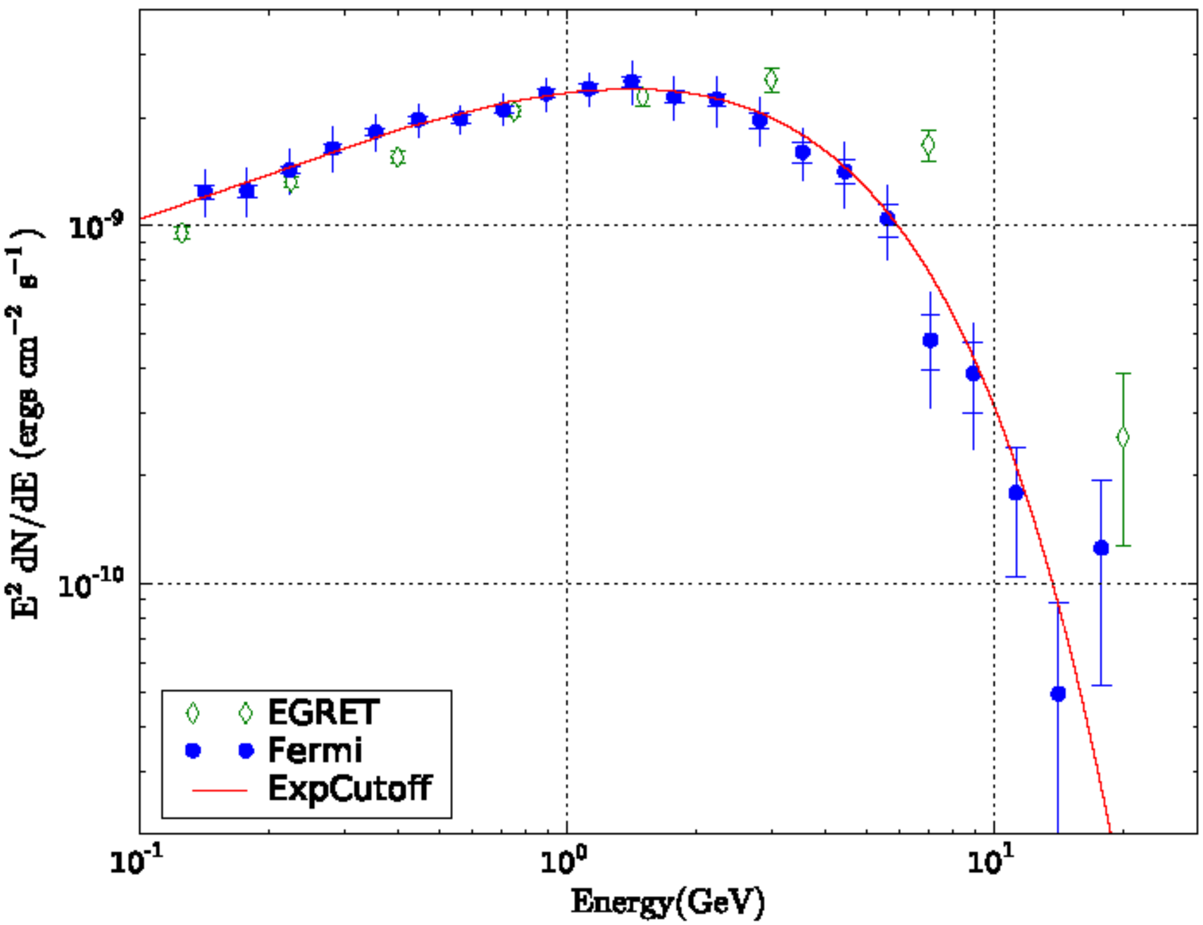
Hibschmann & Arons 2001

Measuring spectral cutoffs with Fermi



Super-exponential (PC) or exponential cutoff (OG) ?

Vela Phase-averaged spectrum



Abdo et al. 2009

Consistent with simple exponential

Not consistent with sharp pair production cutoff

No evidence for magnetic pair attenuation:
Near-surface emission ruled out

Slot gap

- Pair-free zone near last open field-line

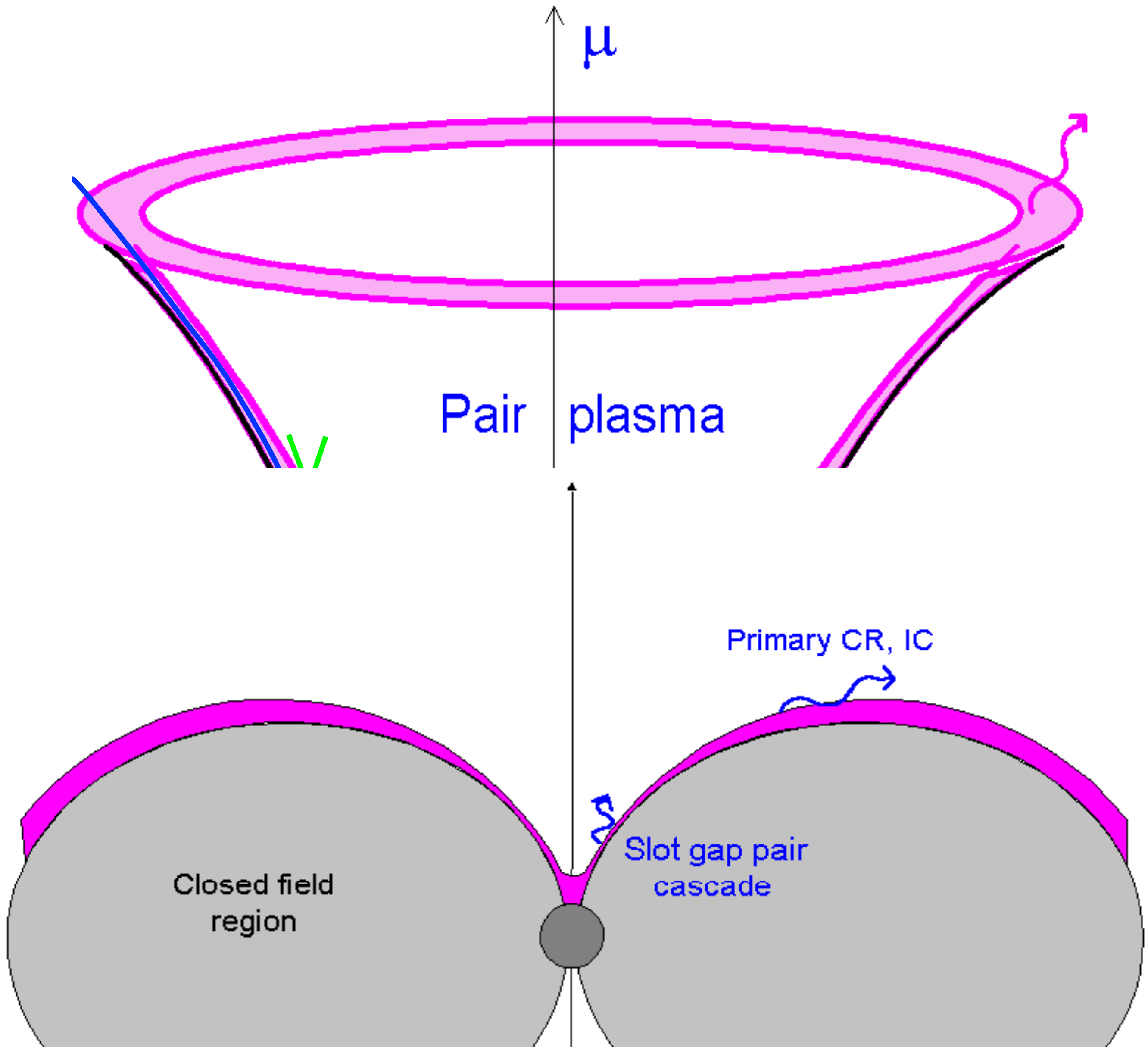
  (Arons 1983, Muslimov & Harding 2003, 2004)

  ⇨ Slower acceleration

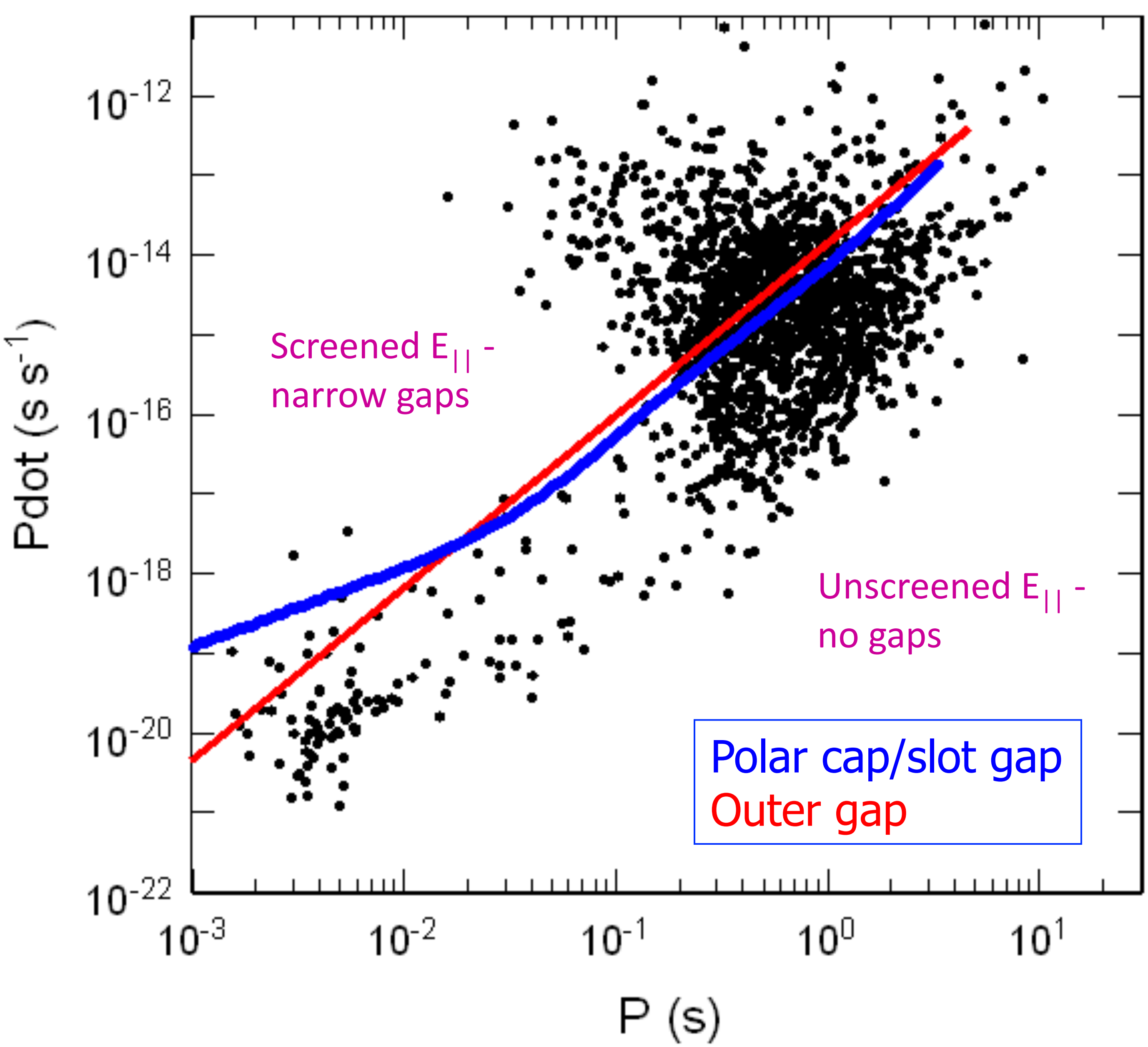
  ⇨ Pair formation front at higher altitude

  ⇨ Slot gap forms between conducting walls

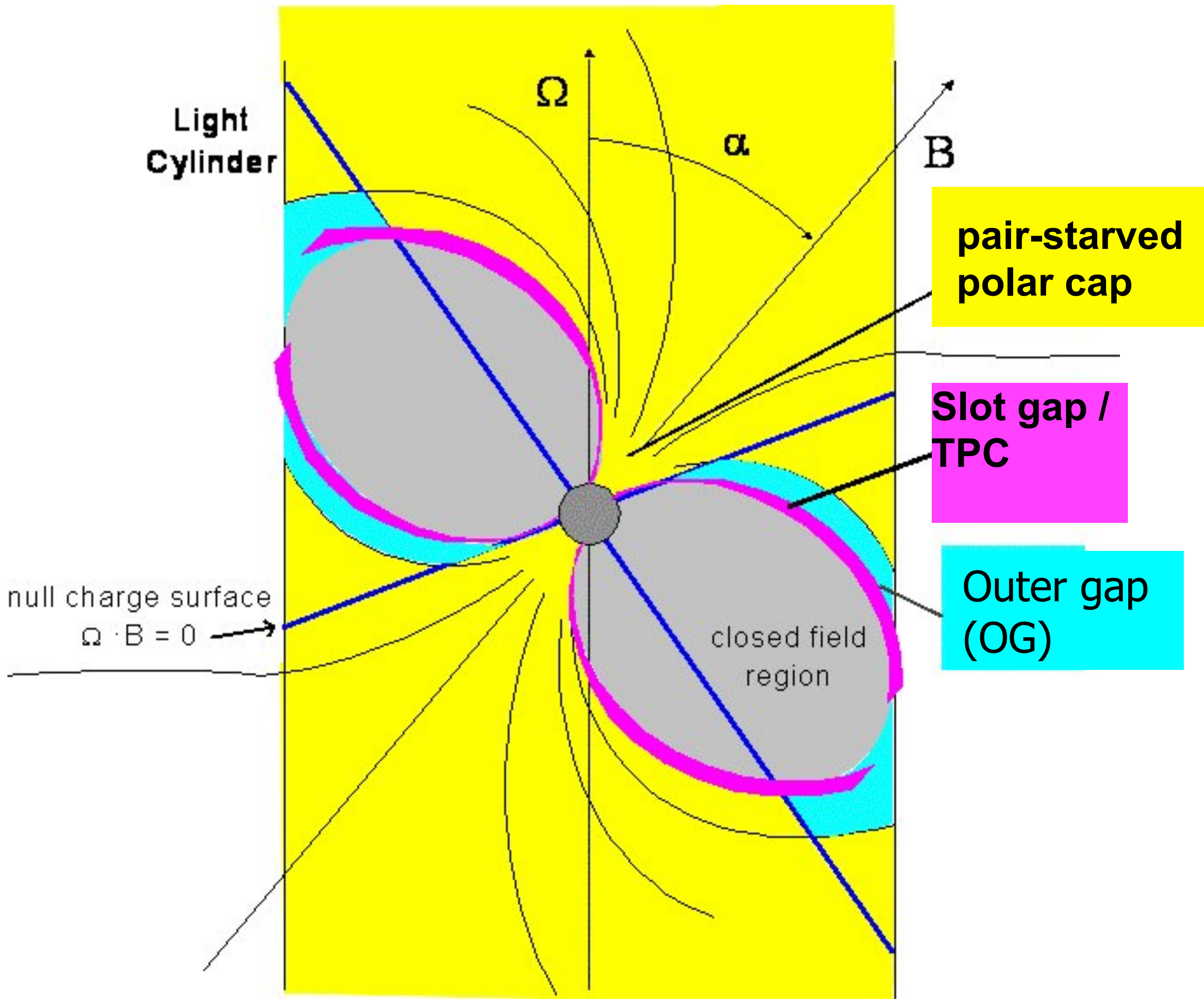
- $E_{||}$ acceleration is not screened



Accelerator gap pair death lines



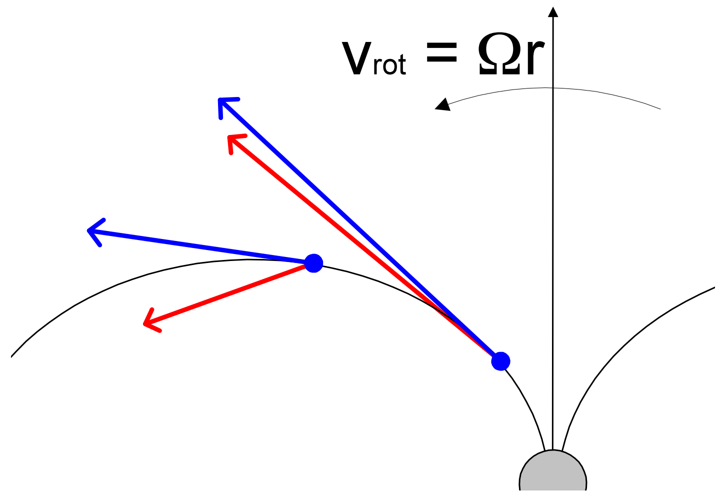
Screened and unscreened accelerators



Special relativistic effects

- Aberration

$$\Delta\phi_{ab} \approx -\frac{r_{em}}{R_{LC}}$$



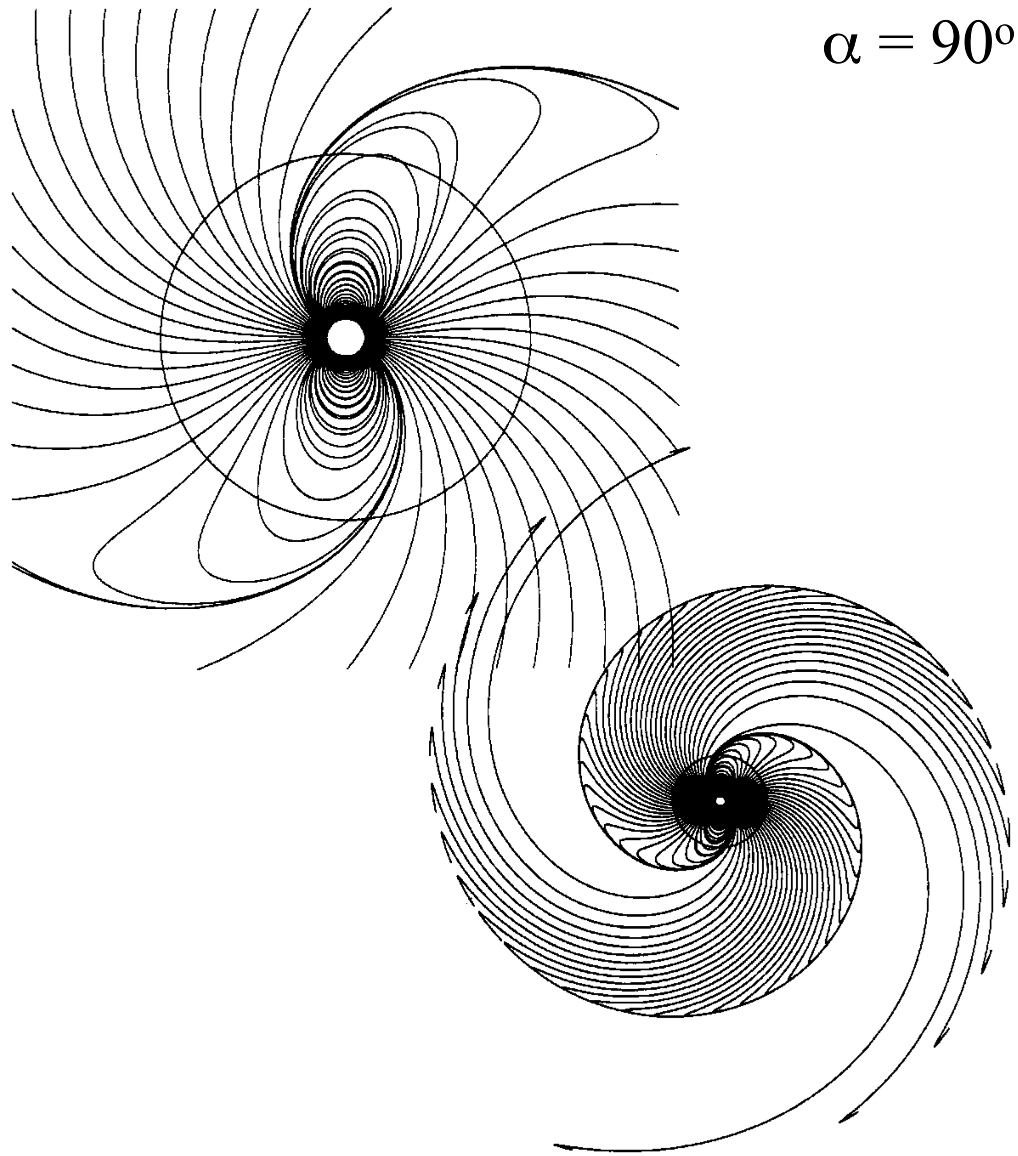
- Time-of-flight delays

$$\Delta\phi_{ret} \approx -\frac{r_{em}}{R_{LC}}$$

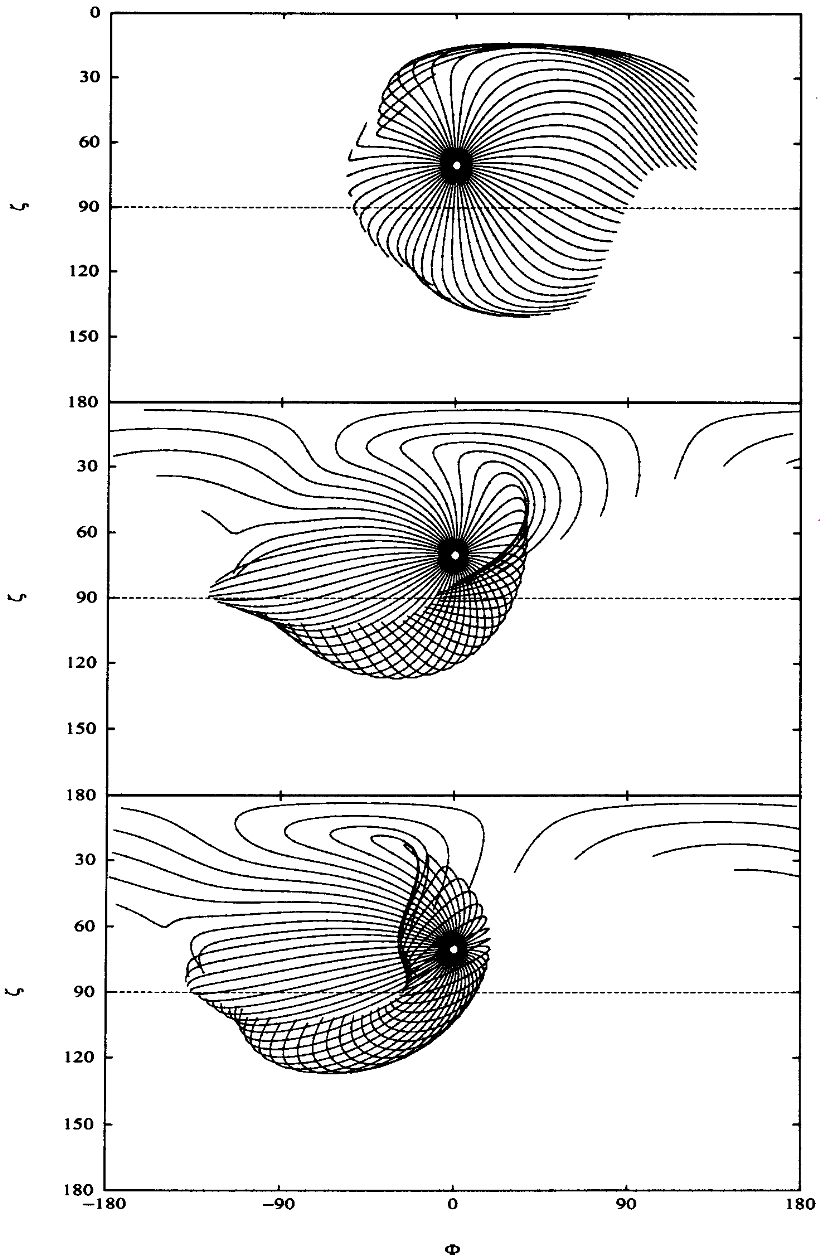
- Retardation of magnetic field

Magnetic field sweepback

$\alpha = 90^o$



Projected field lines from single magnetic pole



Sweepback only …

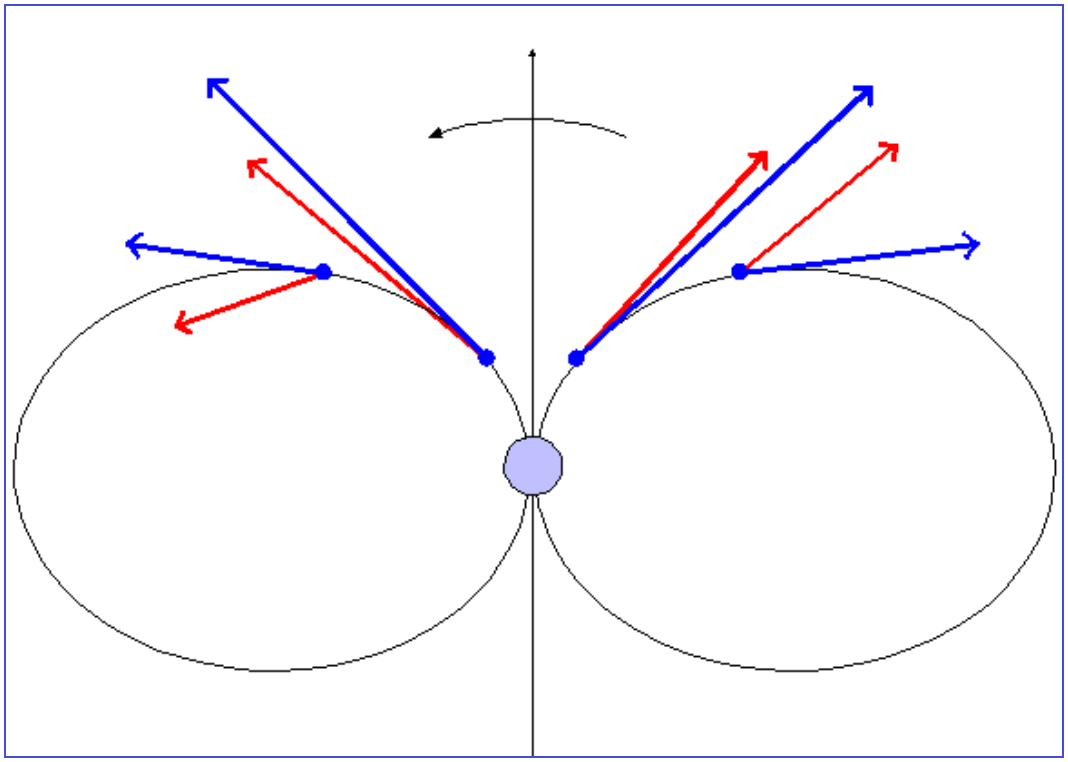
plus aberration …

… and travel time delay

Distortions of Radiation in Pulsar Magnetosphere

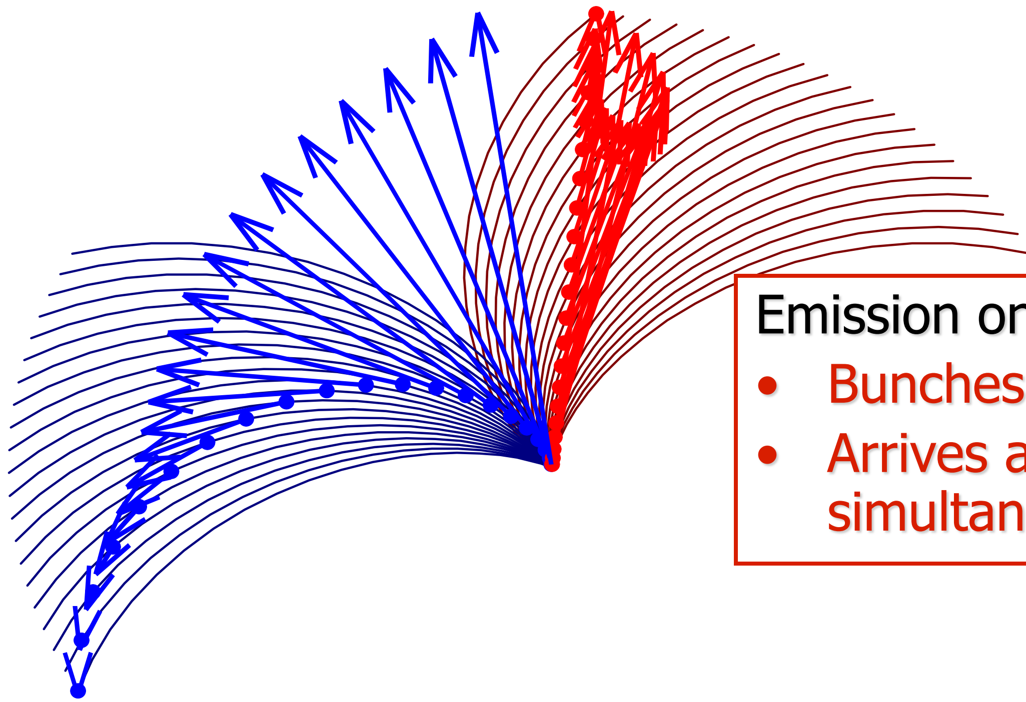
Phase shifts from

- Aberration
- Time-of-flight delays
- Curved magnetic field lines



Formation of caustics

Formation of caustics



Emission on trailing field lines

- Bunches in phase
- Arrives at inertial observer simultaneously

Emission on leading field lines

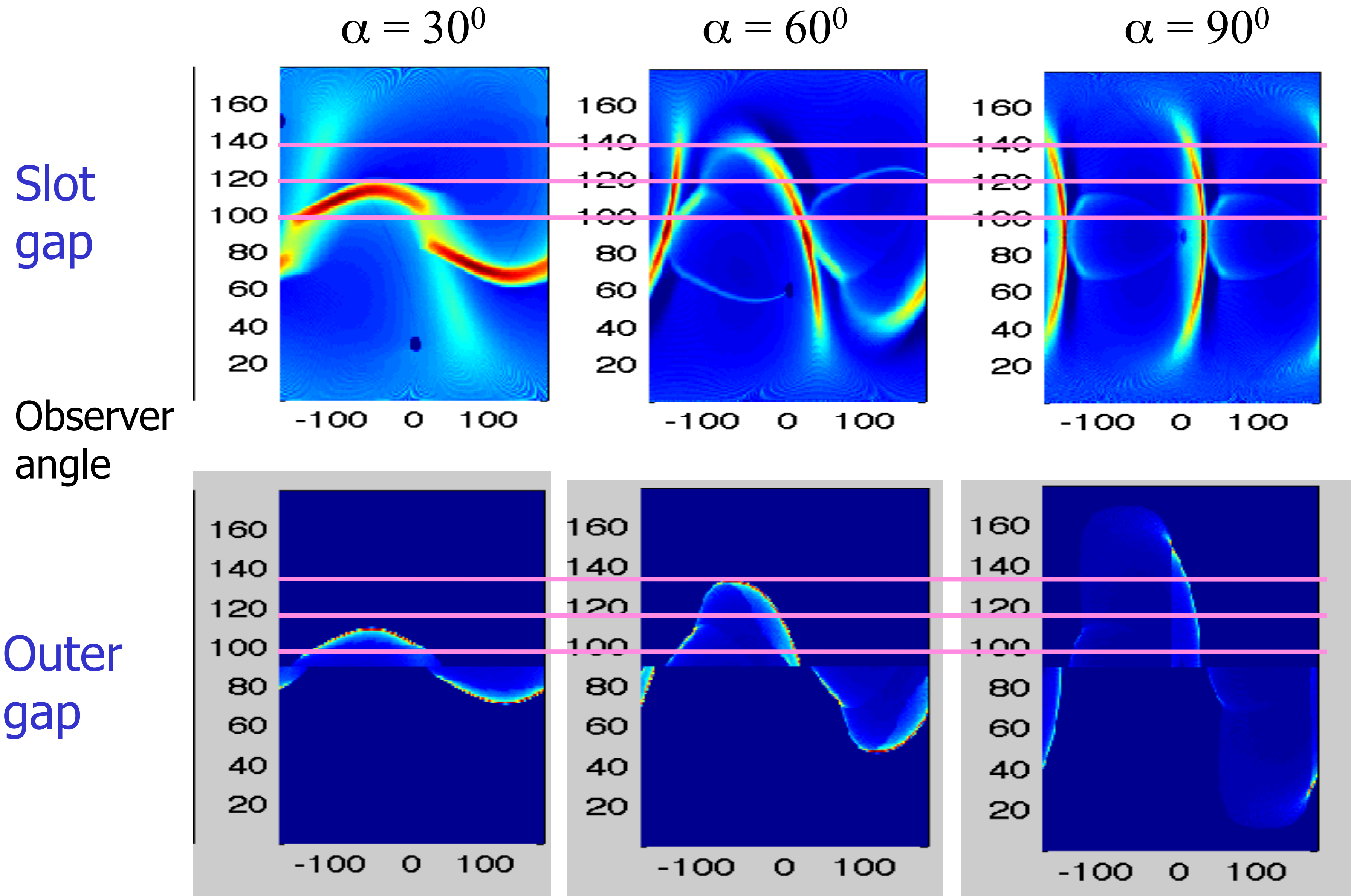
- Spreads out in phase
- Arrives at inertial observer at different times

Caustic emission

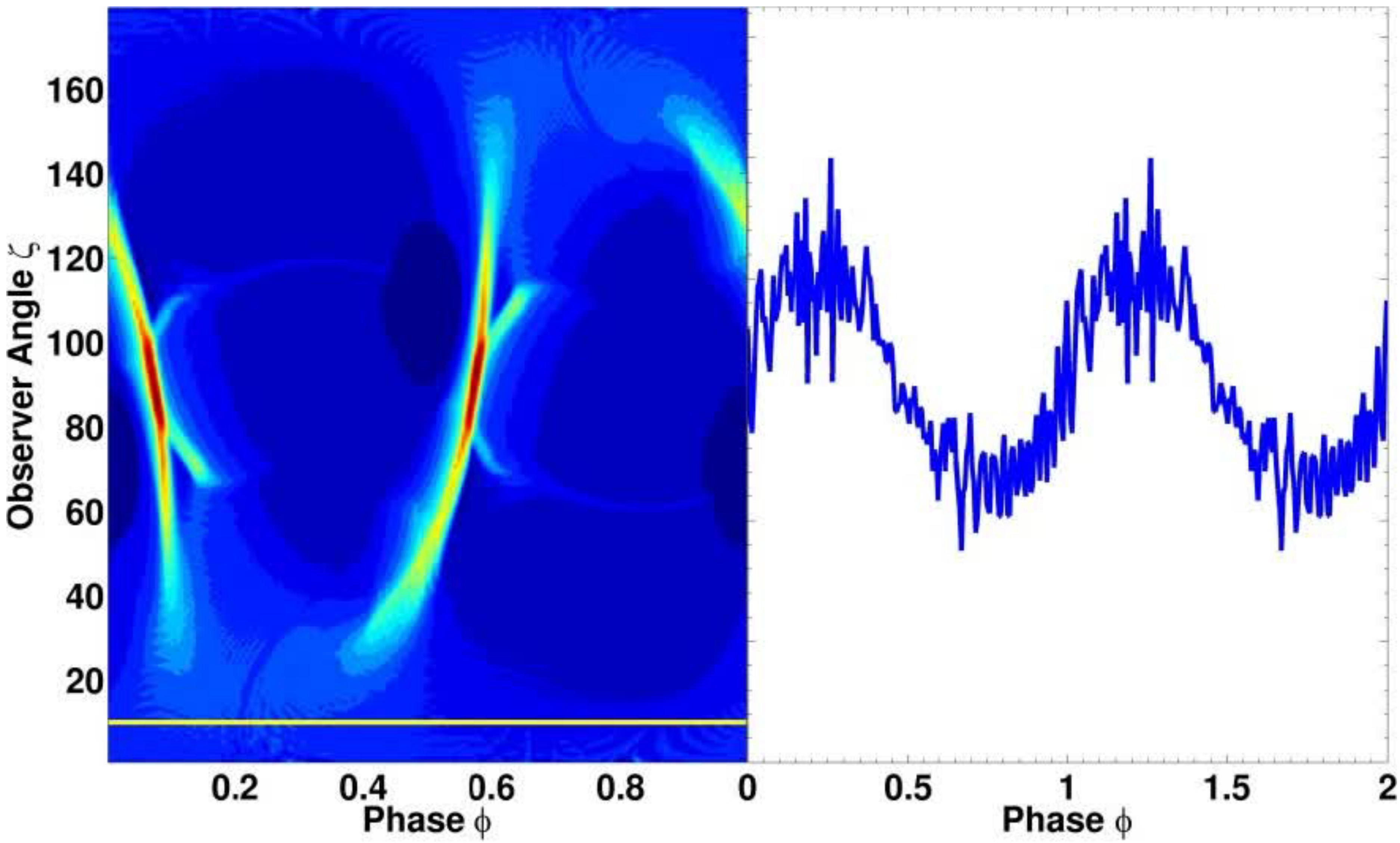
- Dipole magnetic field
- Outer edge of open volume

Caustics in water

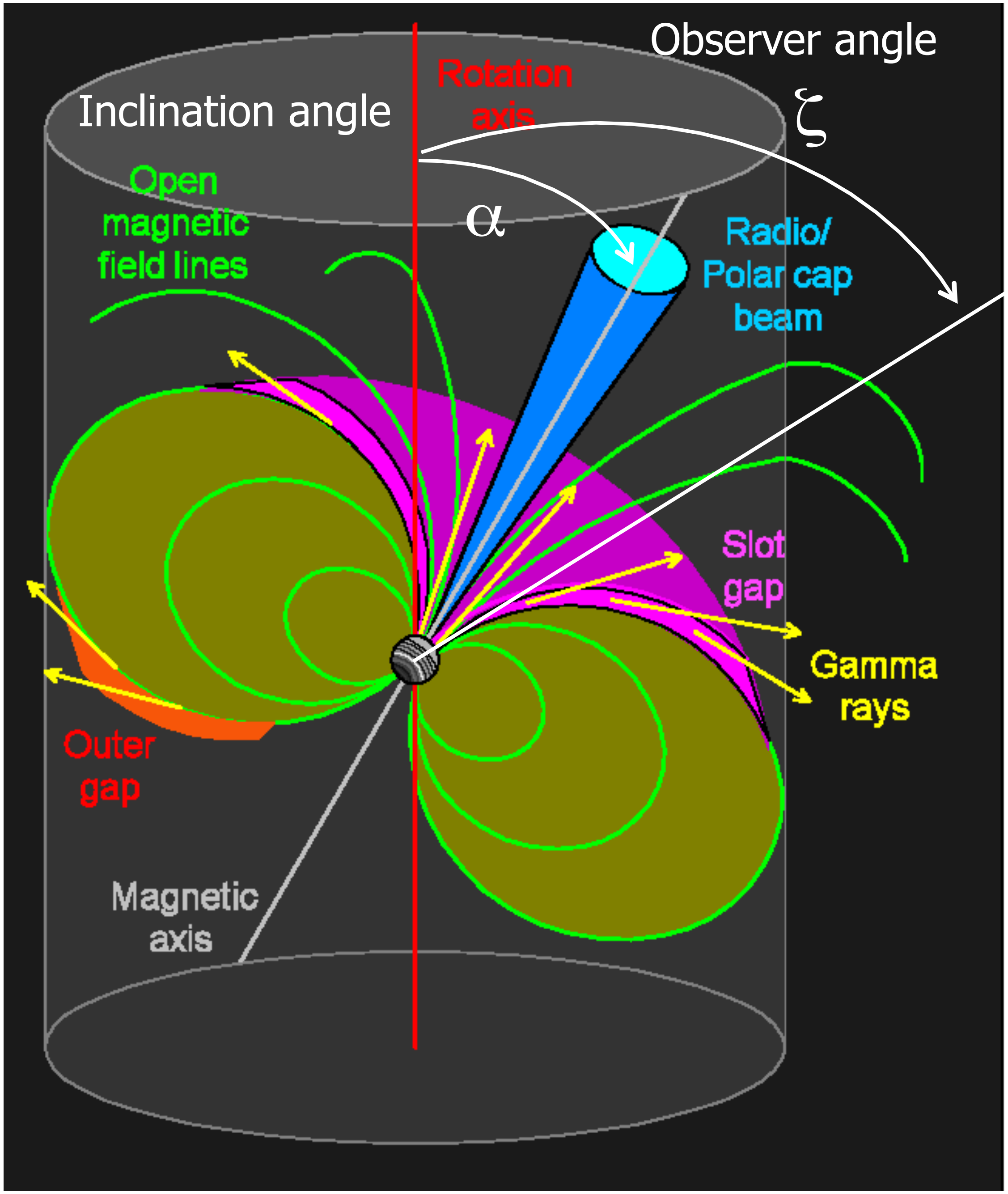
Sky distribution of intensity



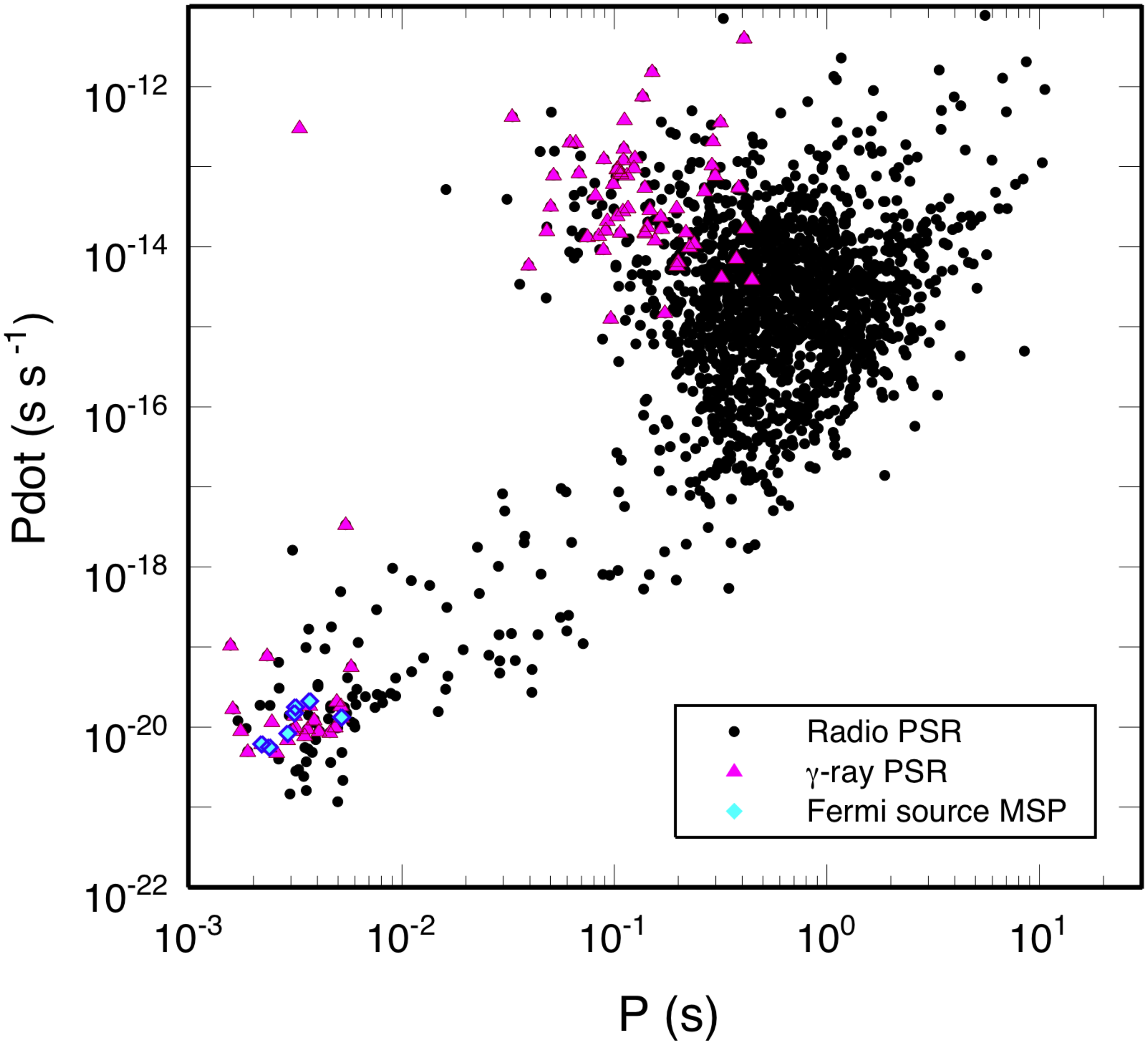
Light Curve vs. Viewing Angle



Pulsar emission geometry



Fermi gamma-ray pulsars



88 γ-ray pulsars

34 normal radio selected

27 normal γ-ray selected

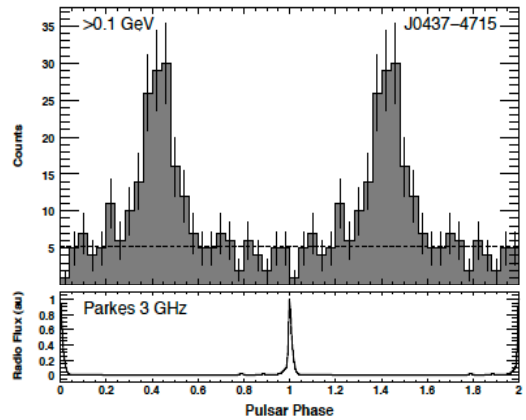
27 MSPs radio selected

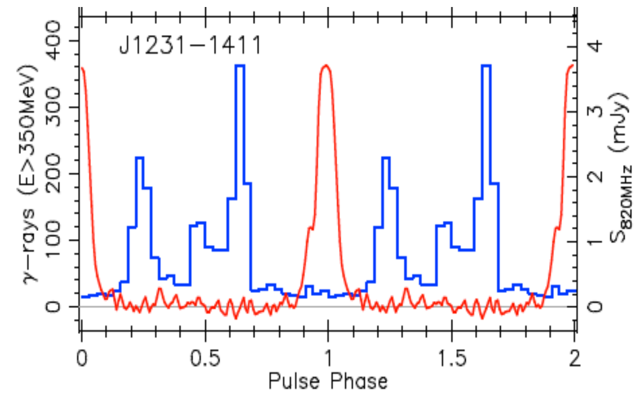
7 new MSPs in Fermi unID

10% of MSP are γ-ray pulsars!

MSPs light curve types

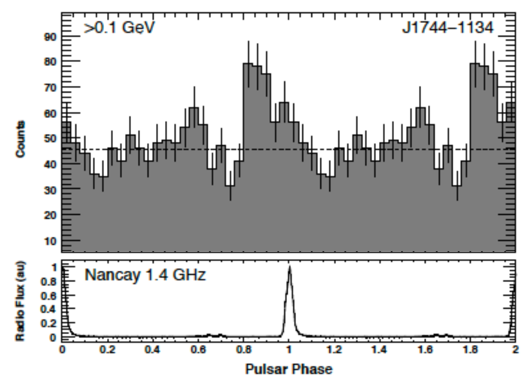
1. γ-ray peak(s) lags main radio peak
   – similar to young pulsars





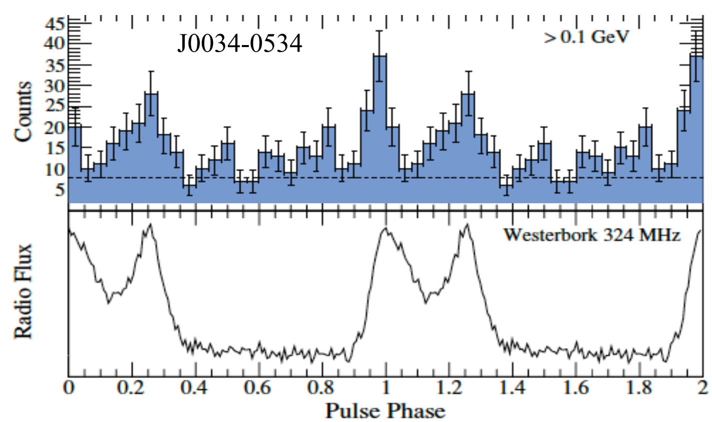
Ransom et al. 2011

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



Abdo et al. 2010

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



Abdo et al. 2010

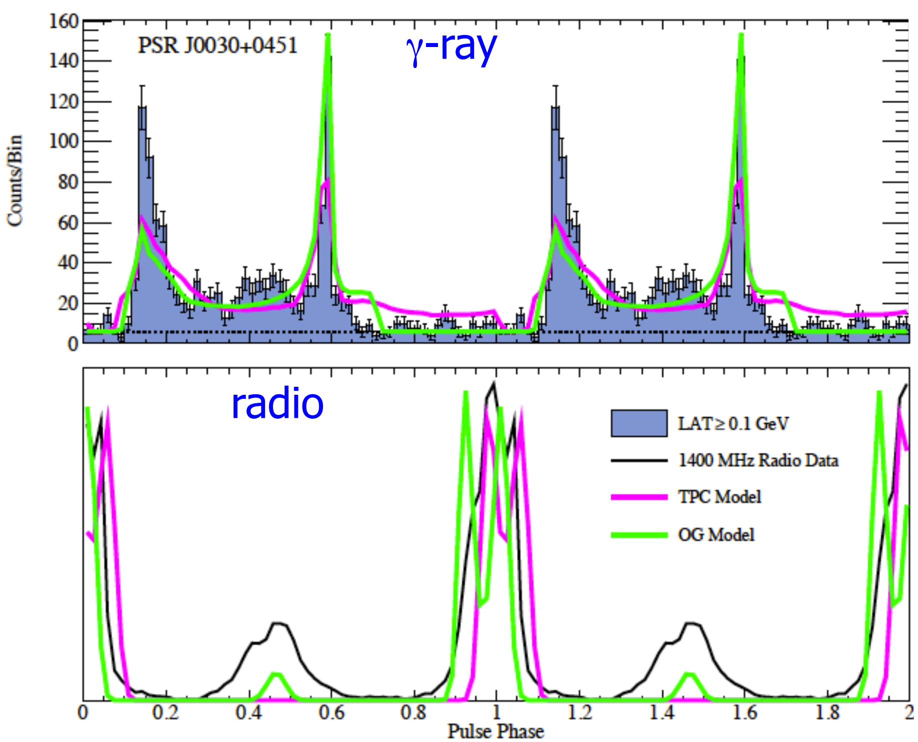
PSR J0030+0451

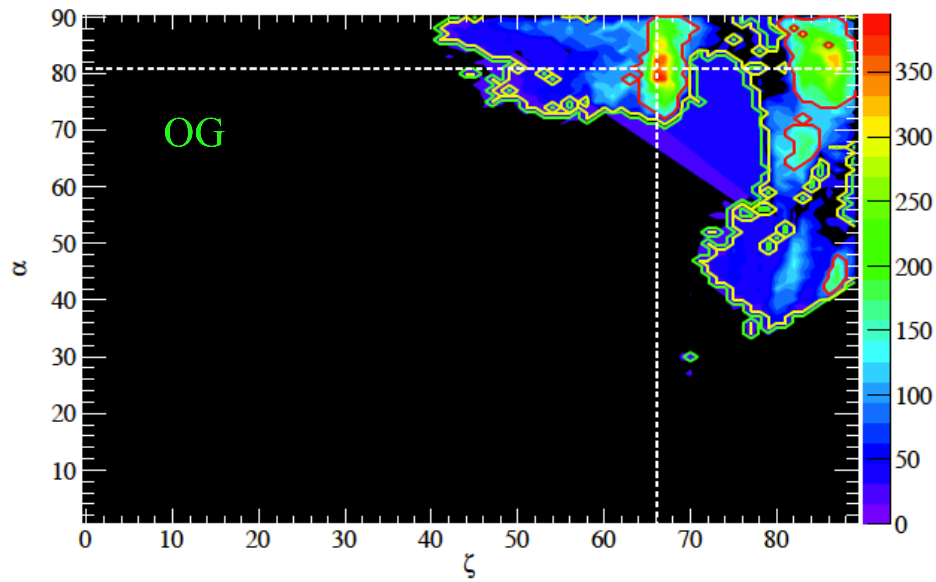
Tyrel Johnson thesis

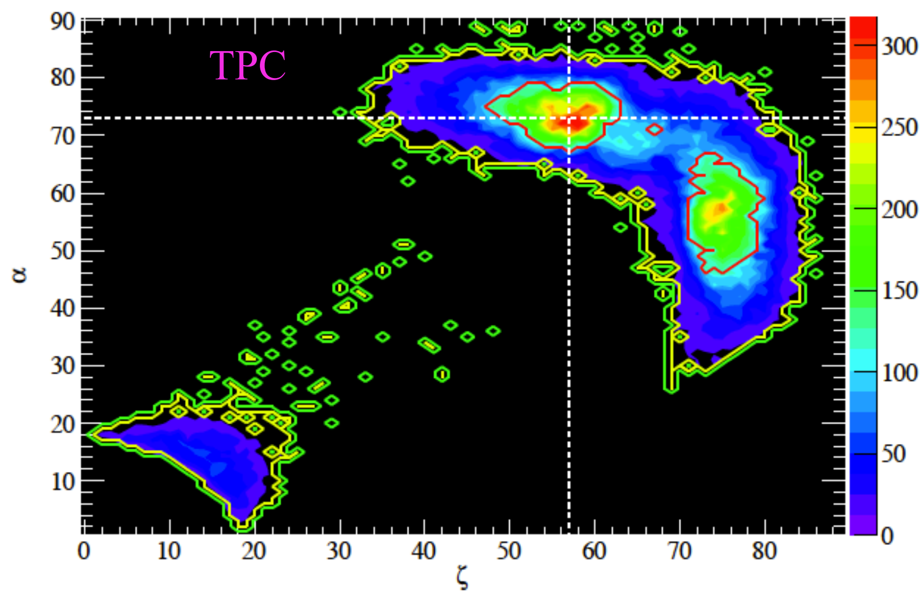
Outer Gap favored

OG, α = 81^0, ζ = 66^0, -log(L)=321, w=0

TPC, α = 73^0, ζ = 57^0, -log(L)=357, w=.05





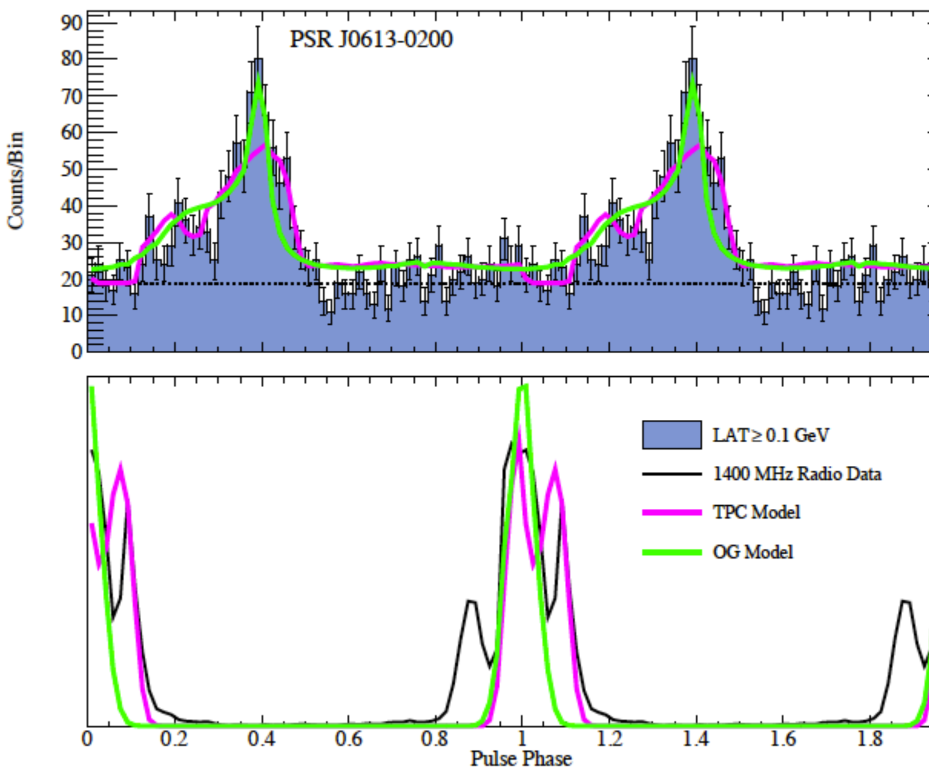


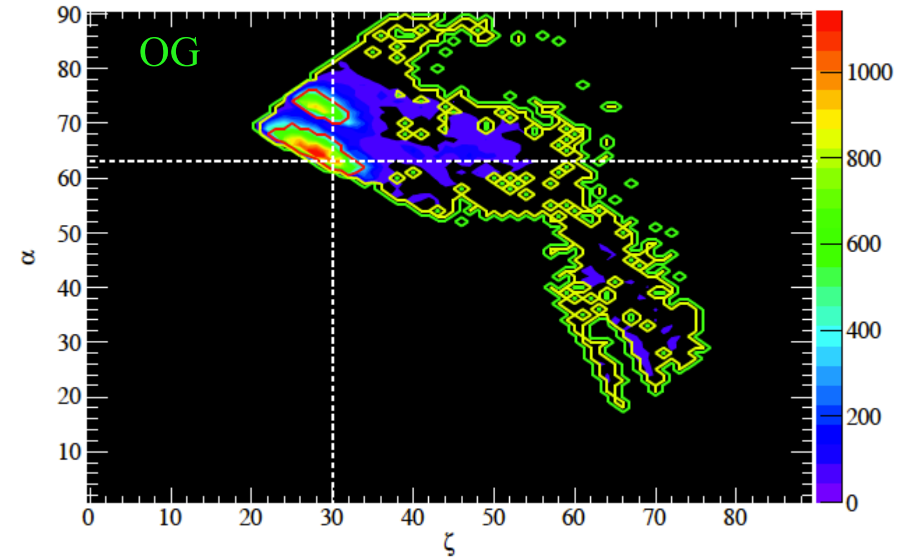
PSR J0613-0200

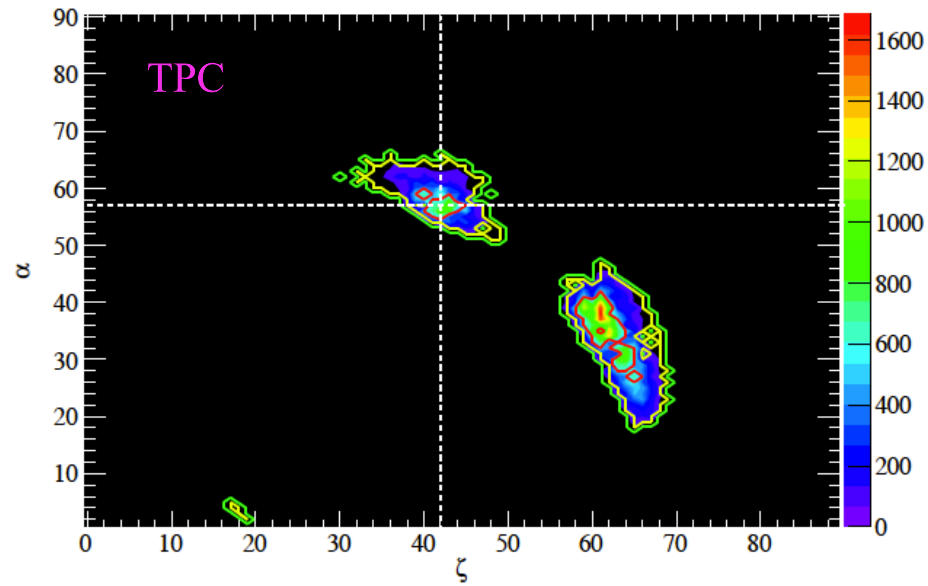
Two-pole caustic favored

OG, α = 63^0, ζ = 30^0, -log(L)=248, w=0

TPC, α = 57^0, ζ = 42^0, -log(L)=232, w=.05



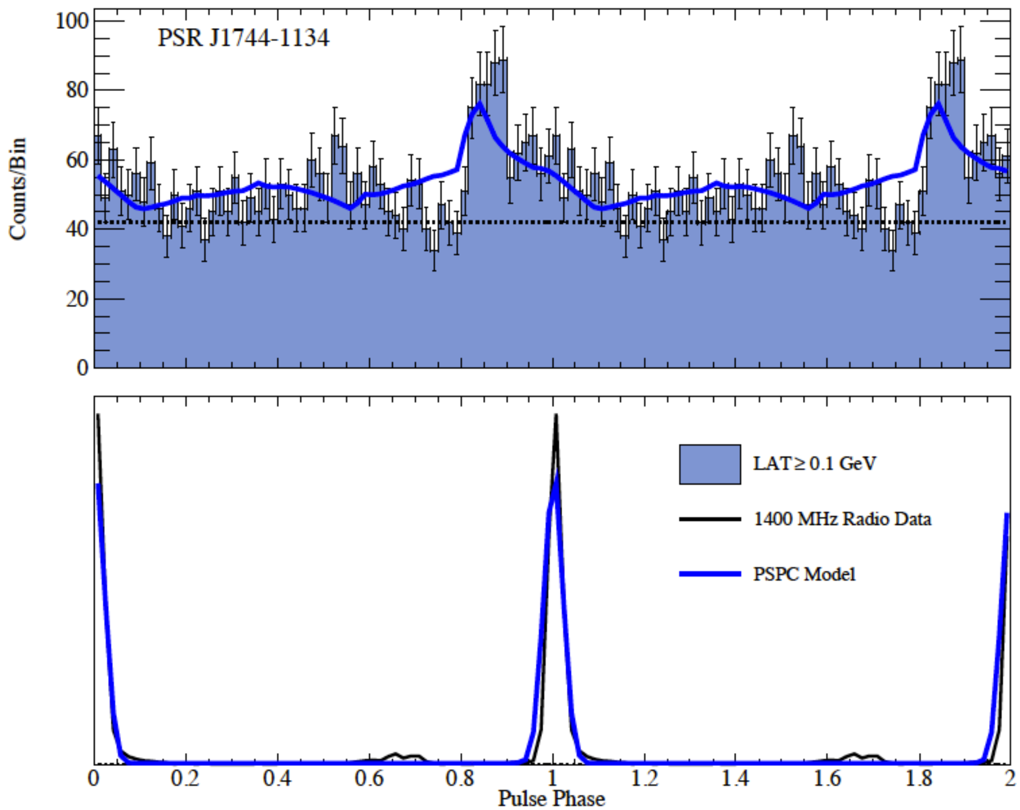


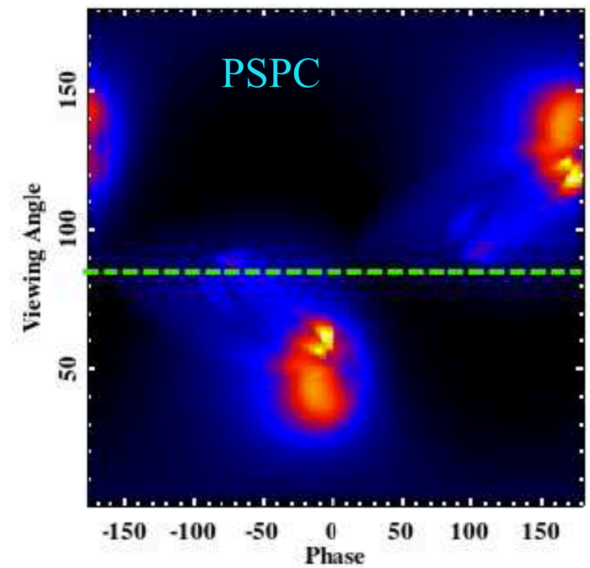


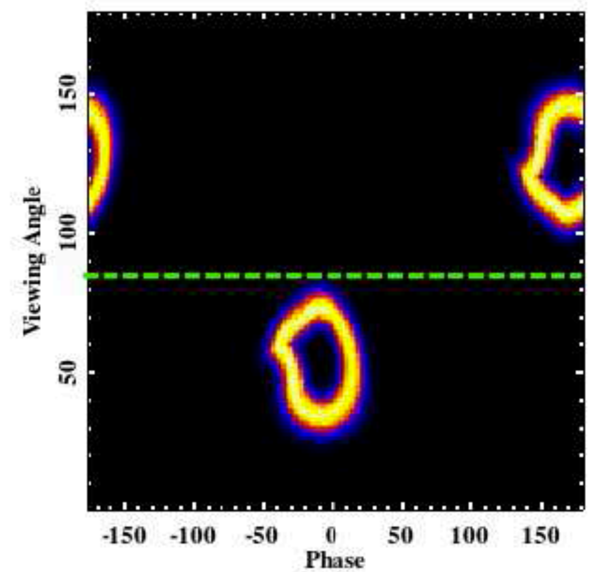
PSR J1744-1134

Pair-starved polar cap

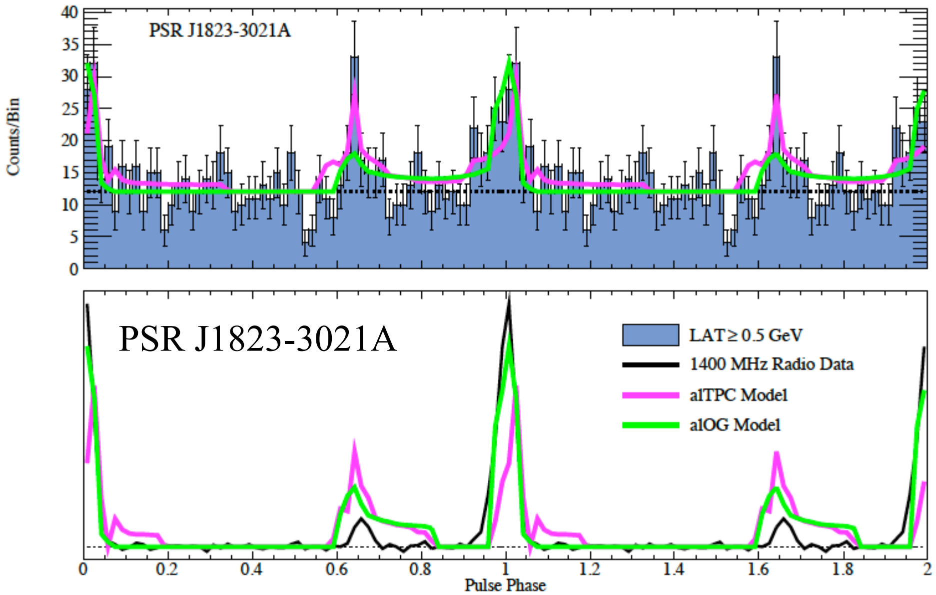
PSPC, $\alpha = 51^0$, $\zeta = 85^0$, -log(L)=227

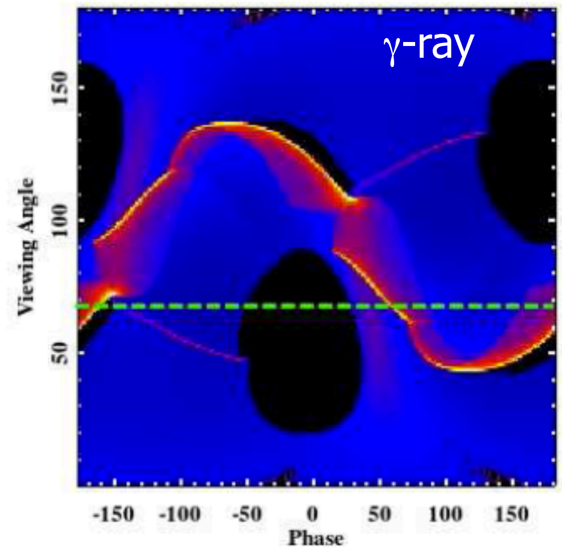


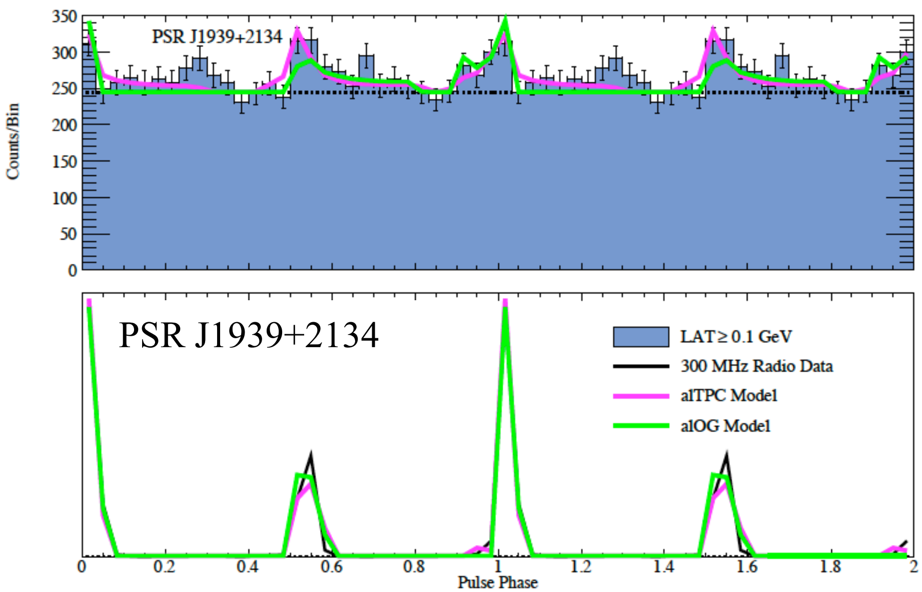


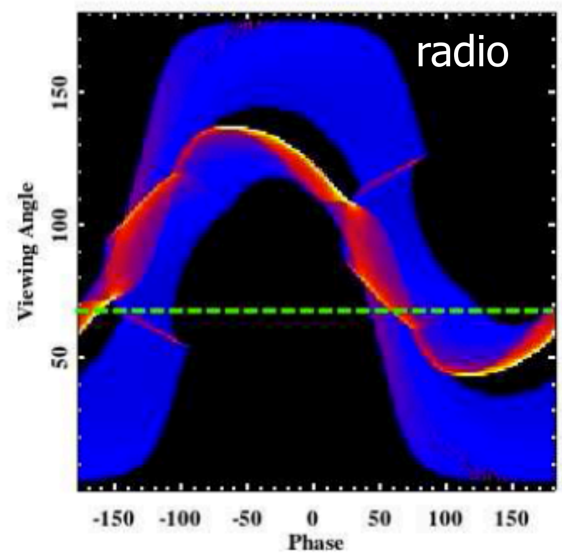


Maximum likelihood fits of aligned MSPs





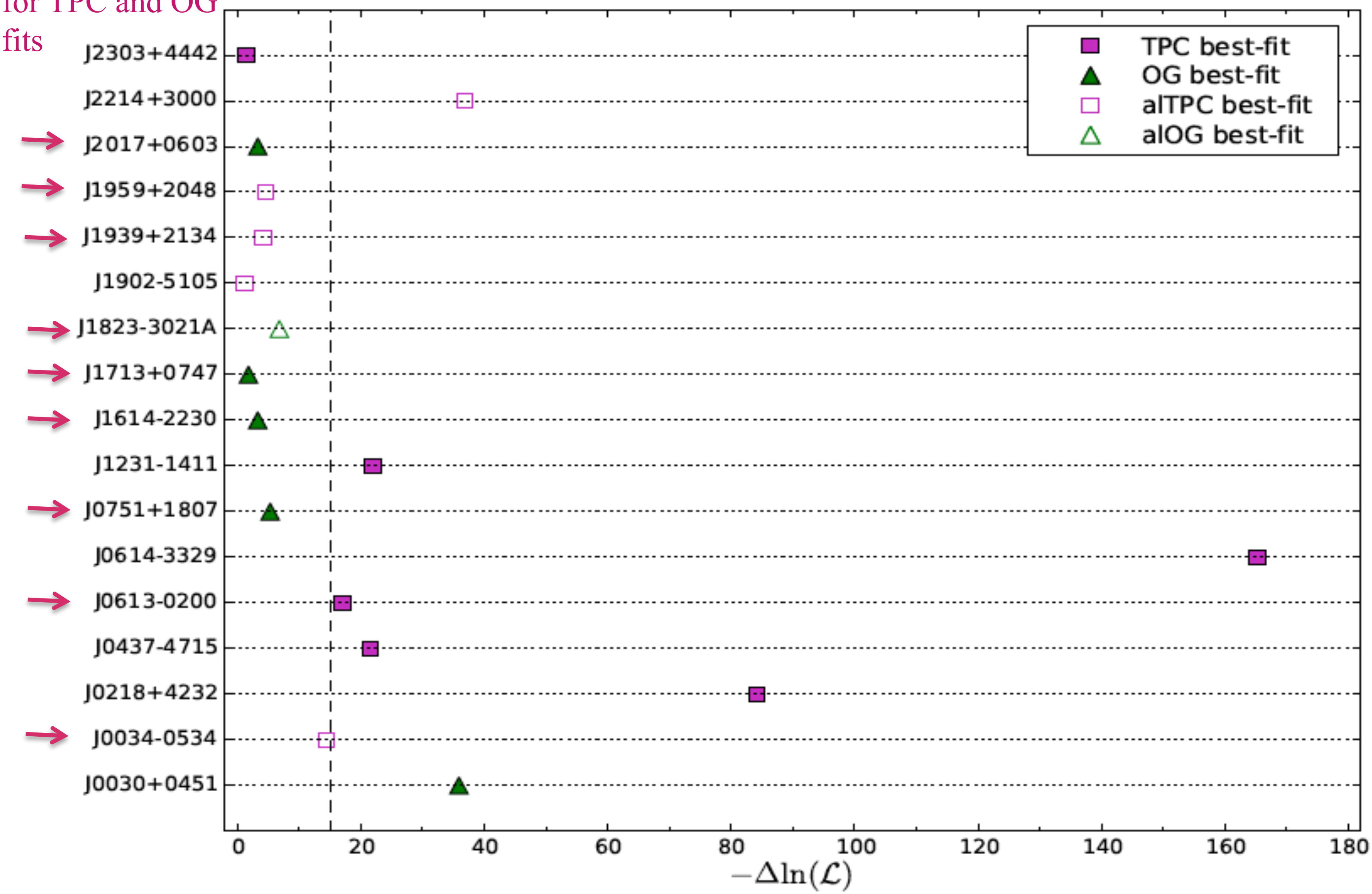




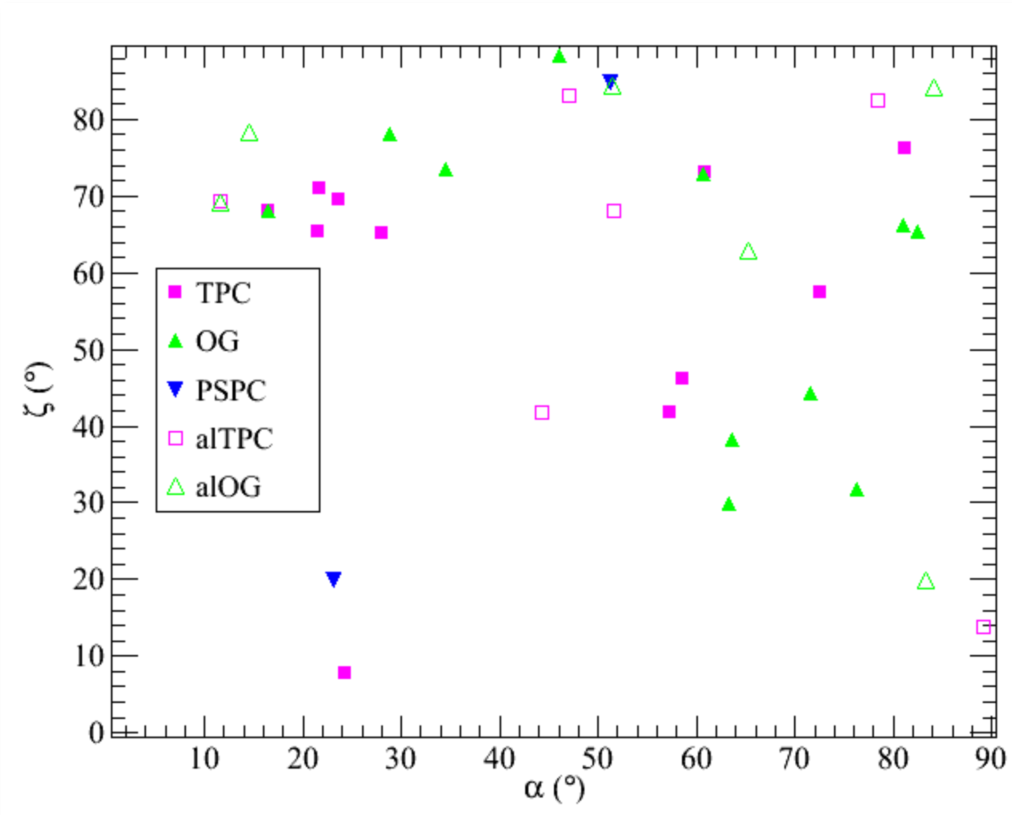
Johnson et al, 2011

Summary of fits

Similar geometry for TPC and OG fits



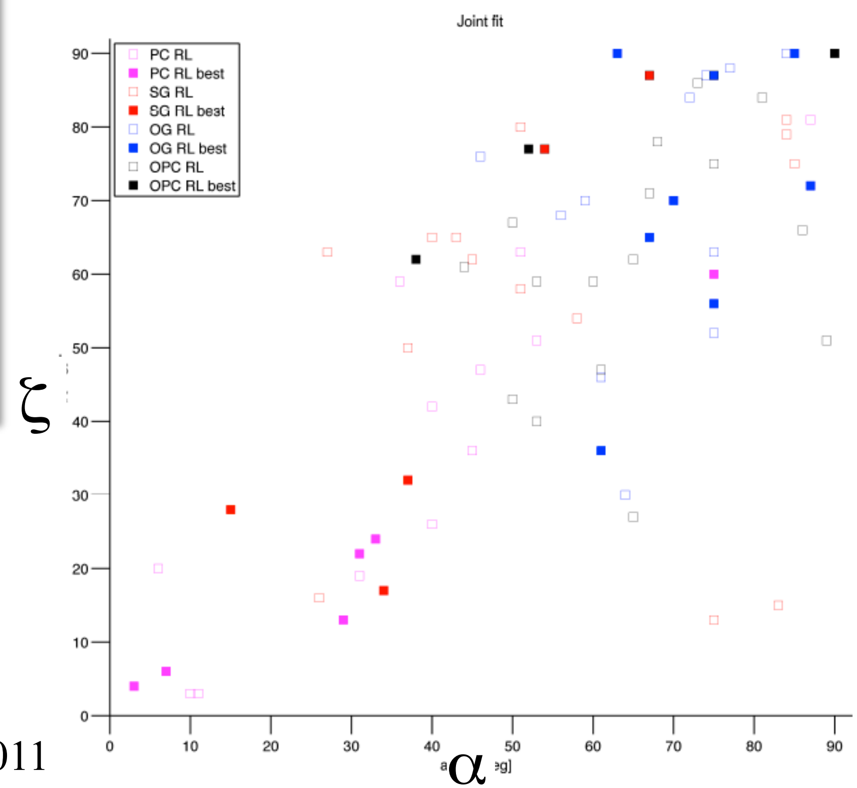
Fit results for 19 MSPs



Johnson et al, 2011

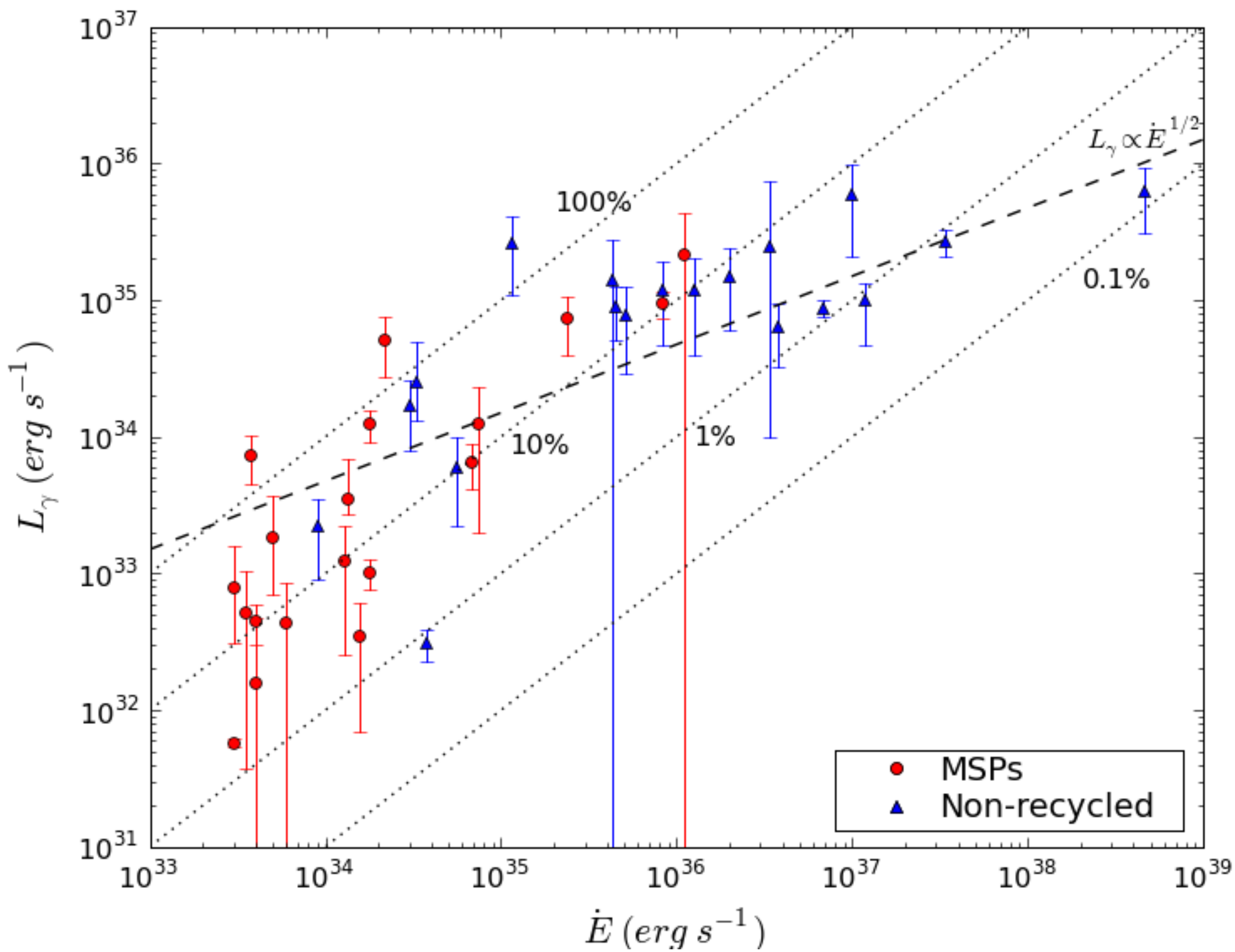
- Large viewing angles with the rotation axis favored
  - expected for outer magnetosphere model emission

- Uniform MSP inclination angle distribution, unlike young pulsars



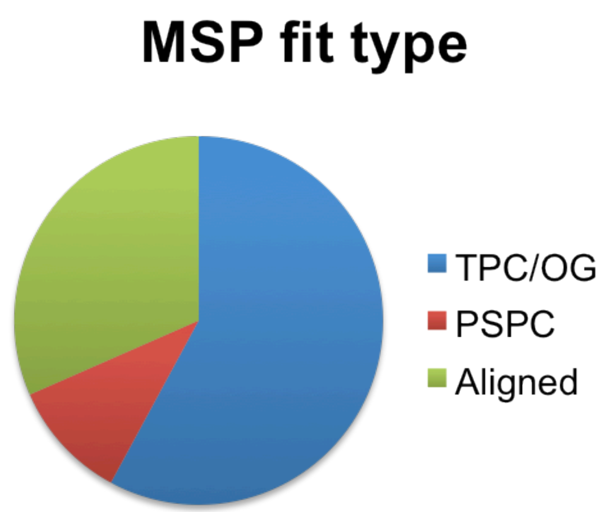
Pierbattista et al, 2011

Gamma-ray vs. spin-down luminosity



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 and gamma-ray peaks indicate radio caustic emission – mostly short period MSPs
- Most MSPs are NOT pair starved - how are they producing pair cascades?

Millisecond pulsars gamma rays

- **Originate in outer magnetosphere (OG/TPC or PSPC)**

- **How do MSPs have narrow accelerator gaps??**

  - Small E and surface (dipole) B
  - Don't expect strong screening of E|| high pair multiplicity
  - Higher B/smaller ρ_c near surface – off-center dipole, multipoles?

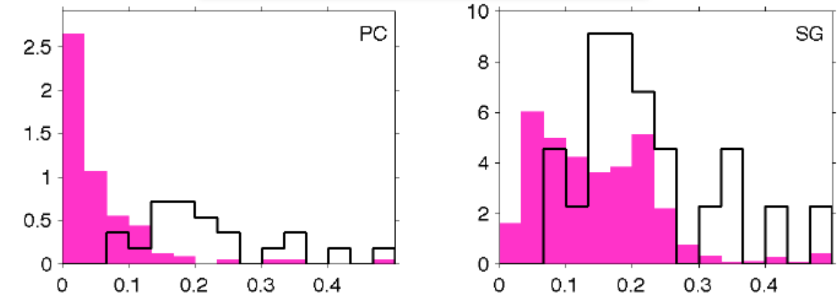
  - **Few radio-quiet MSPs expected: larger radio beam widths than for canonical pulsars**

- **Gamma-ray MSPs have a wider distribution of inclination angles than young gamma-ray pulsars**

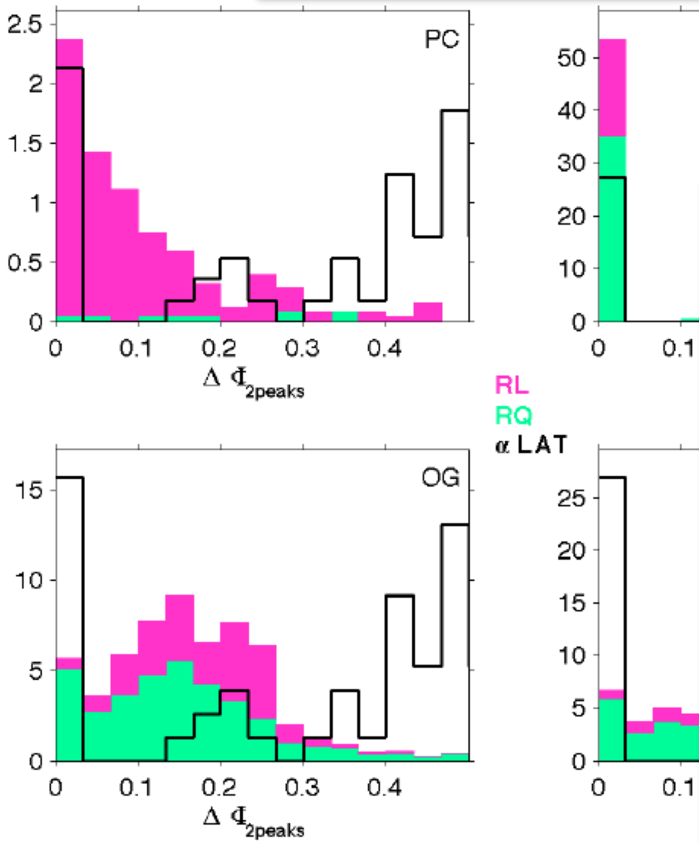
Light Curve Trends

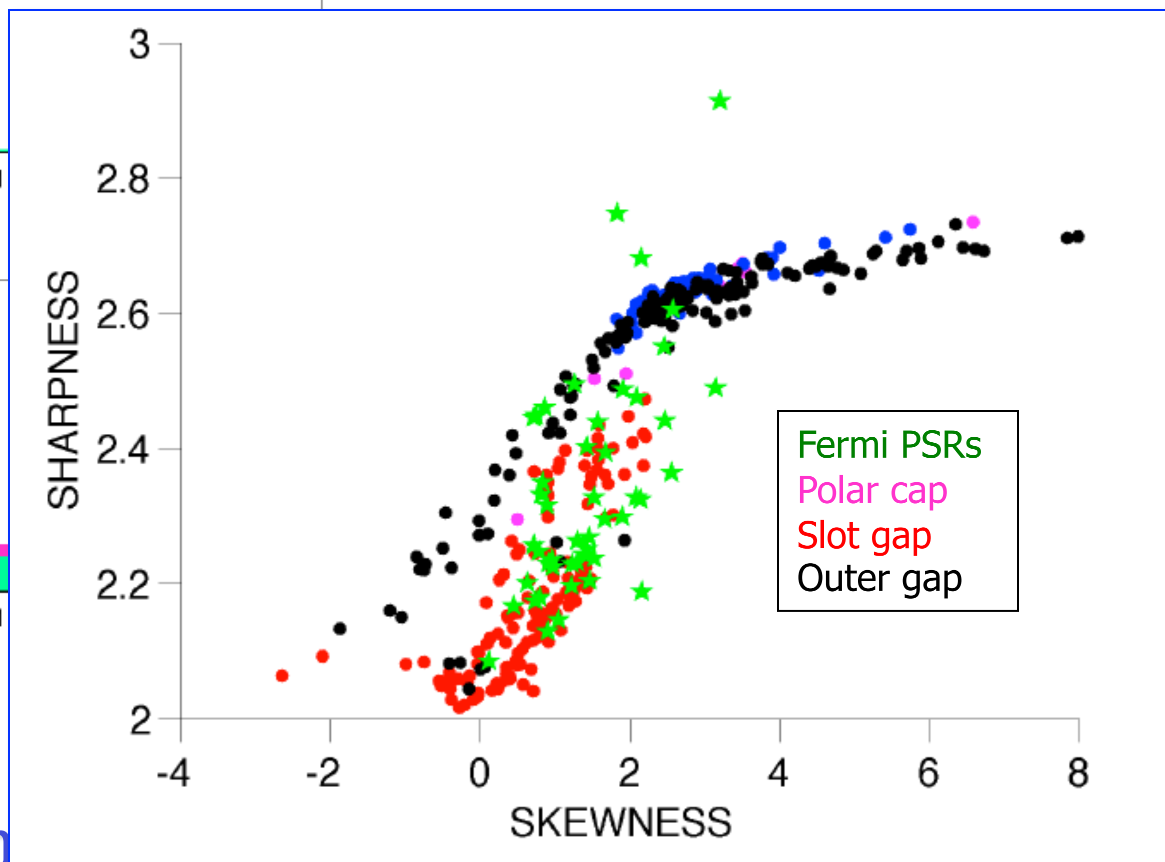
Pierbattista et al. 2011, in prep.

γ-ray – radio lag



γ-ray peak separation

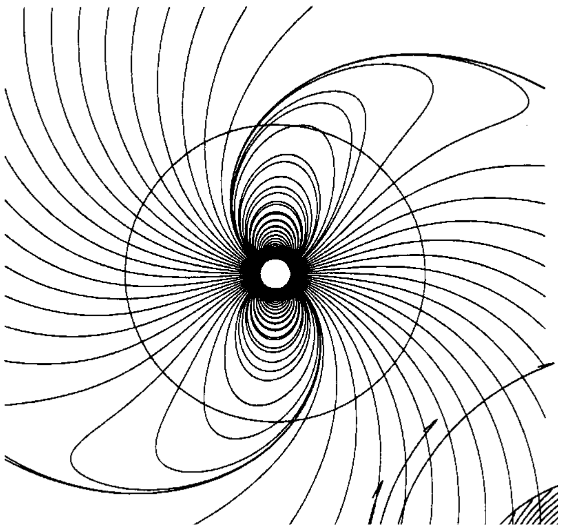


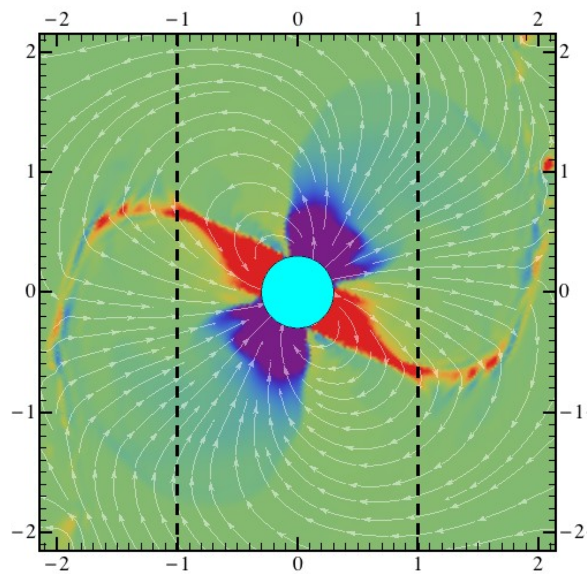


Good model discrin

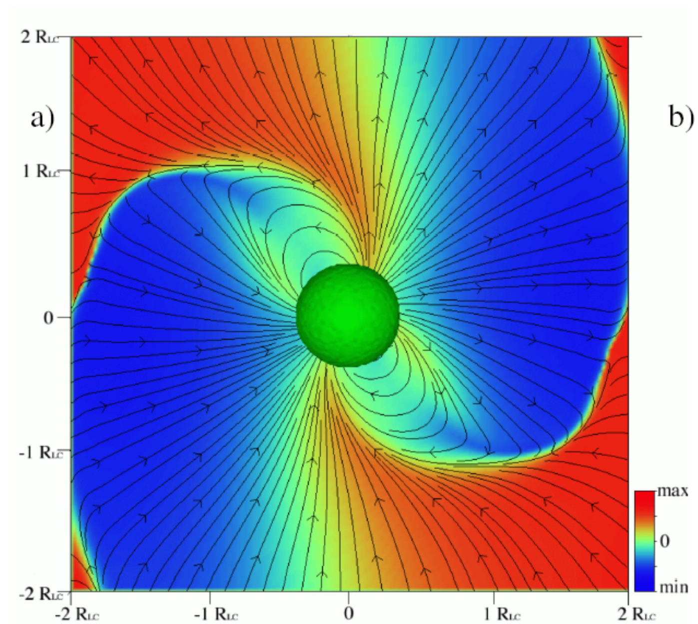
Magnetic field geometry

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





Force-free magnetosphere
(Spitkovsky 2008)
- No particle acceleration



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

HD magnetosphere
os et al. 2011
$B \neq 0$
urrents + acceleration!

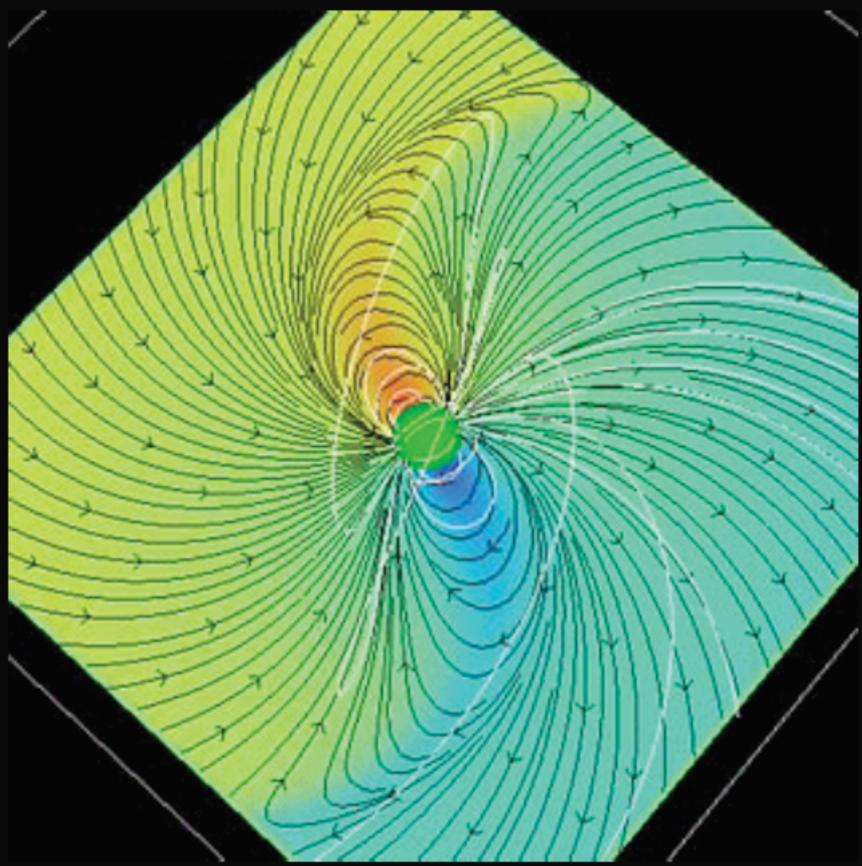
Force-free electrodynamics:

$E \bullet B = 0$ everywhere

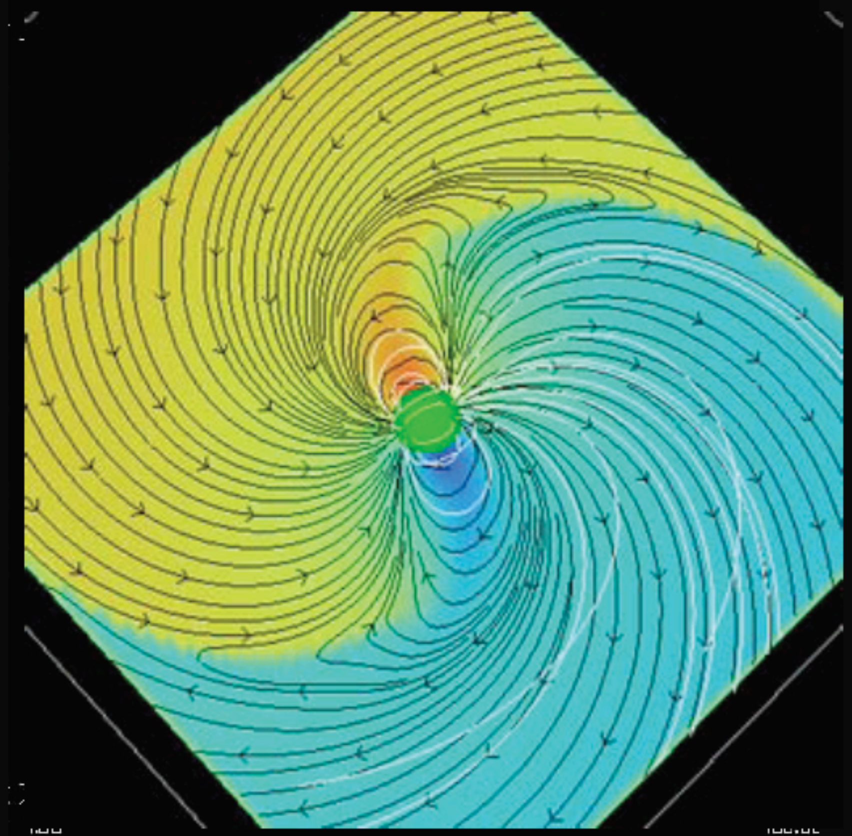
No accelerator gaps!

Vacuum vs. force-free magnetospheres

Vacuum
Deustch 1955



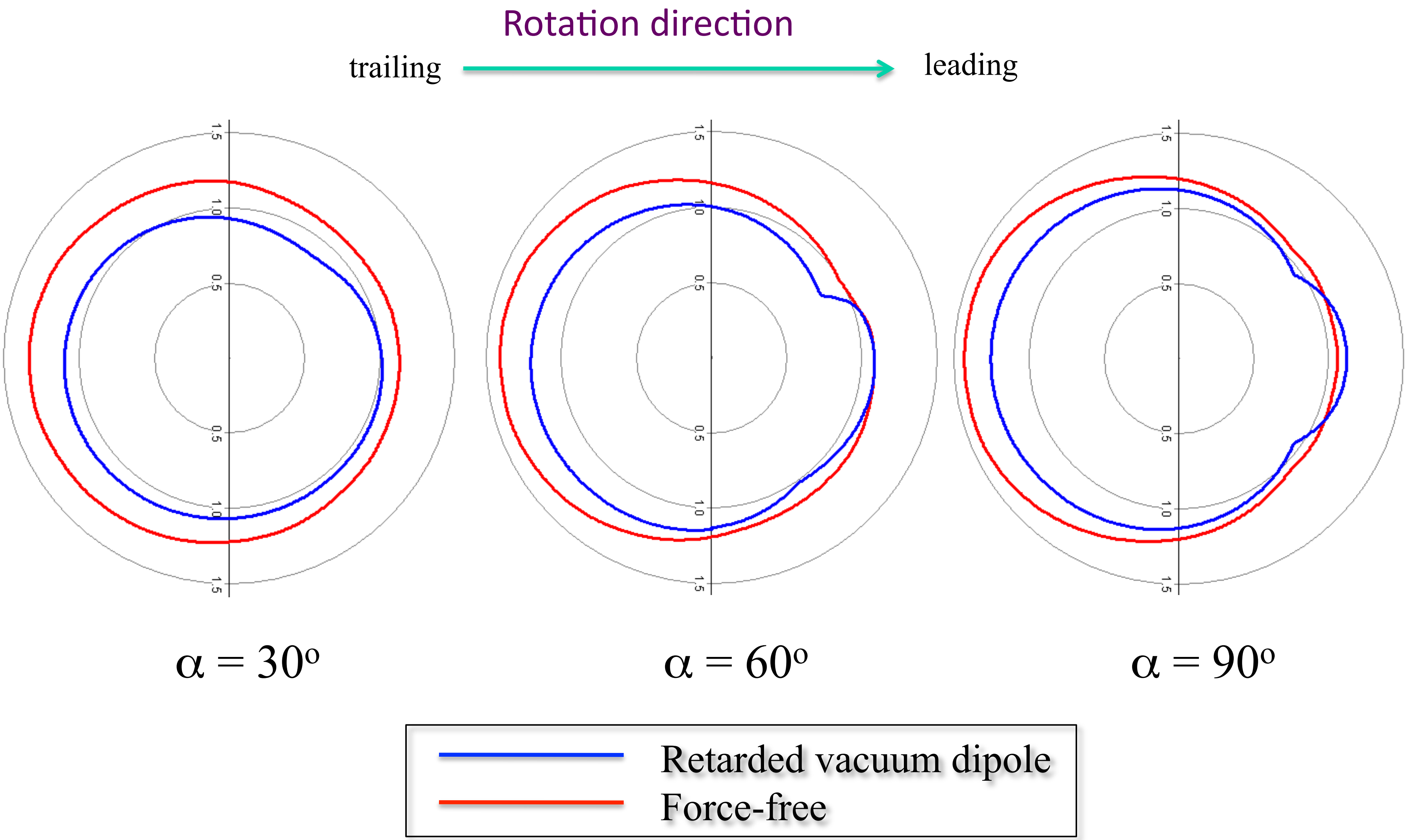
Force-free
Spitkovsky



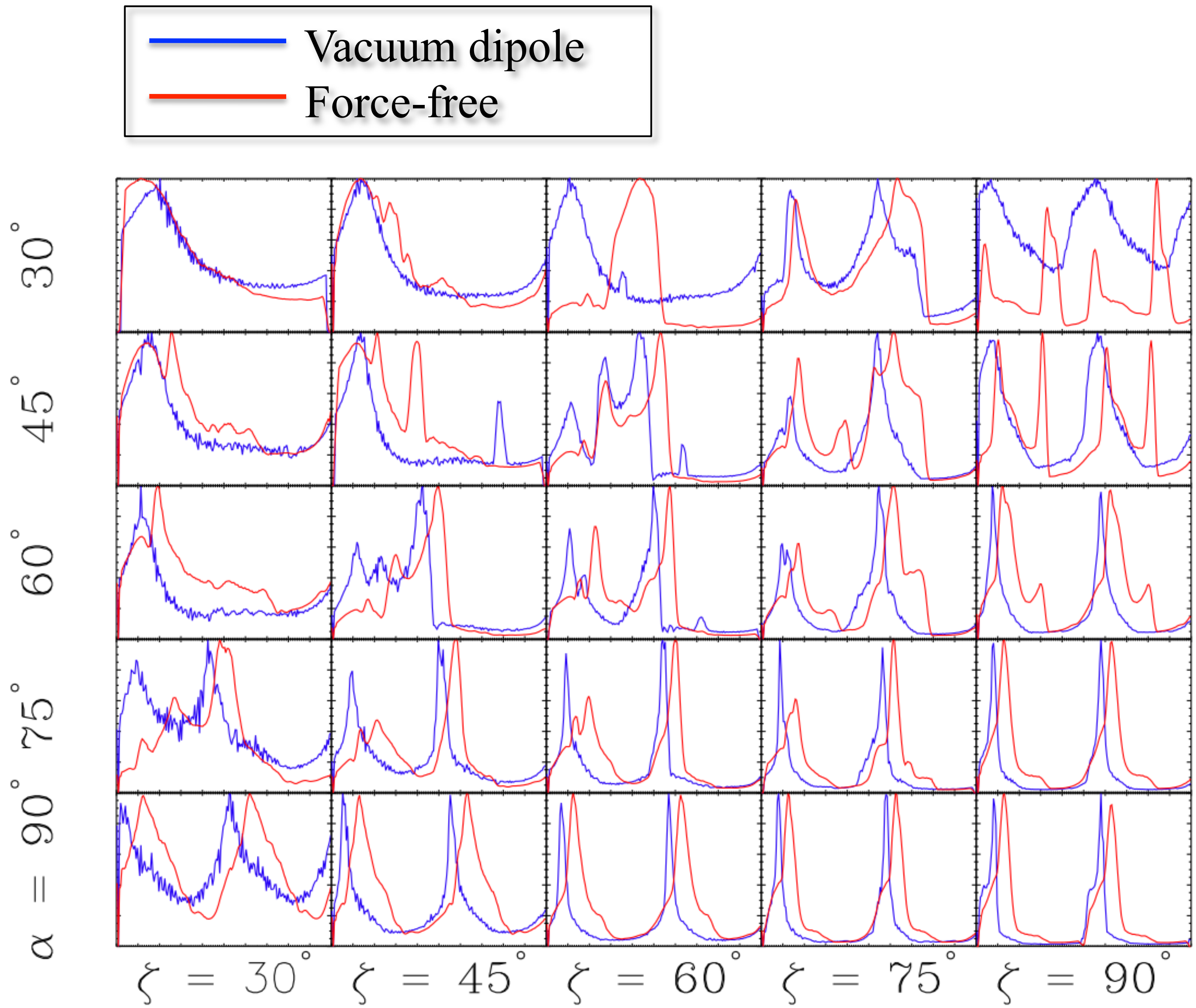
90^0 inclination

A.

Polar caps in retarded magnetic fields

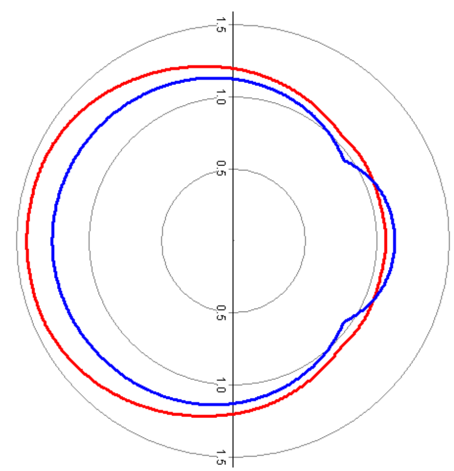


Slot gap light curves: vacuum vs. force-free



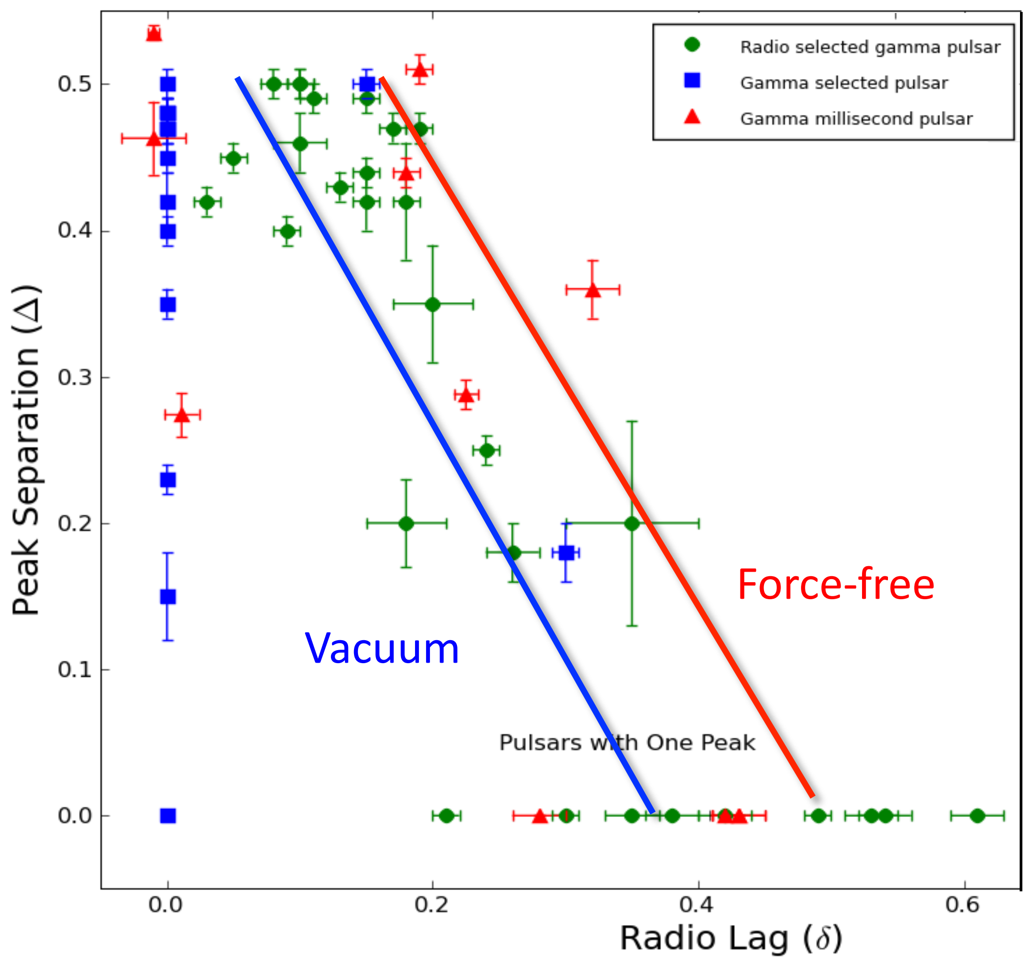
Force-free LC peaks occur at later phase by .05 – .15 due to:

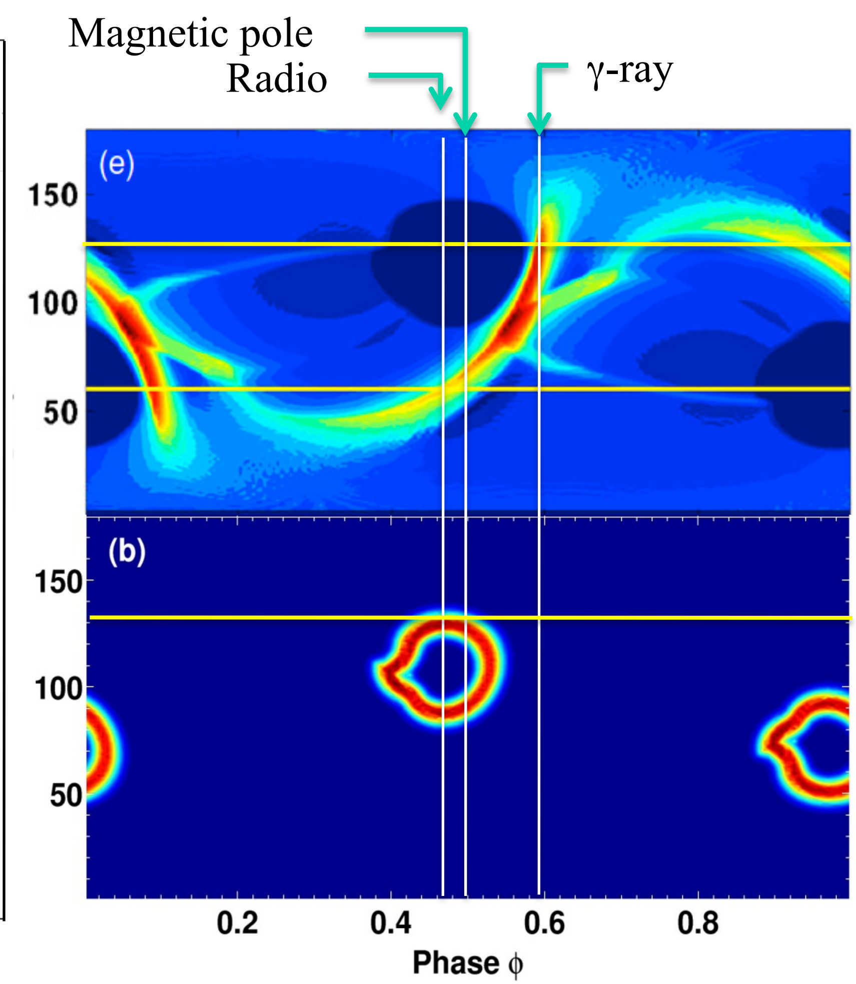
- Larger PC
- Later phase of trailing field lines



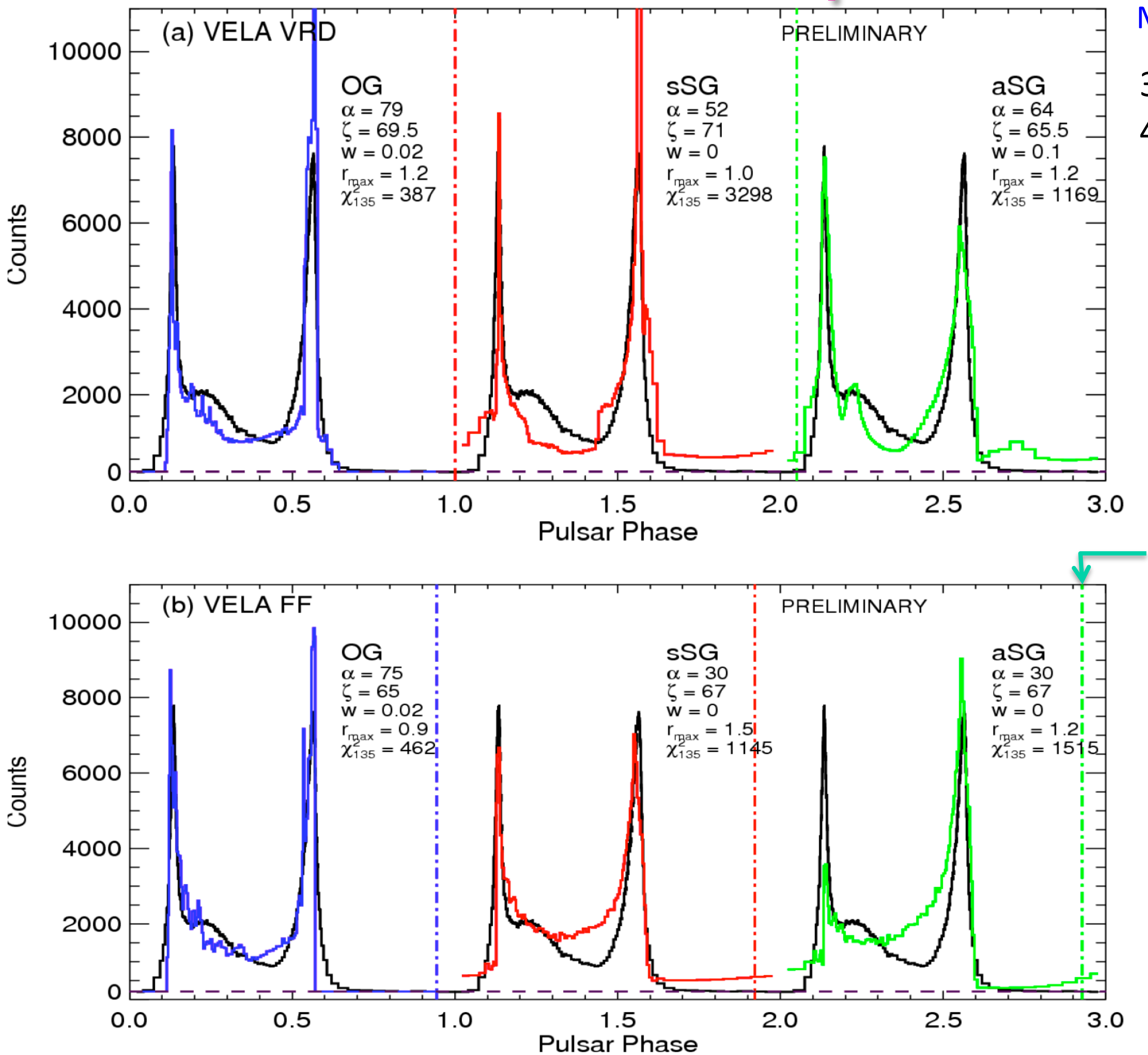
Gamma-ray/radio phase lag

Data from Smith et al. (2011)





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 $\alpha,\zeta,\omega, r_{max}$

What can we learn from phase-resolved spectra?

- Balance CR losses with acceleration gain

$$eE_{\parallel} = \dot{\gamma}_{CR} = \frac{2e^2\gamma^4}{3\rho_c^2}$$

- Steady-state Lorentz factor

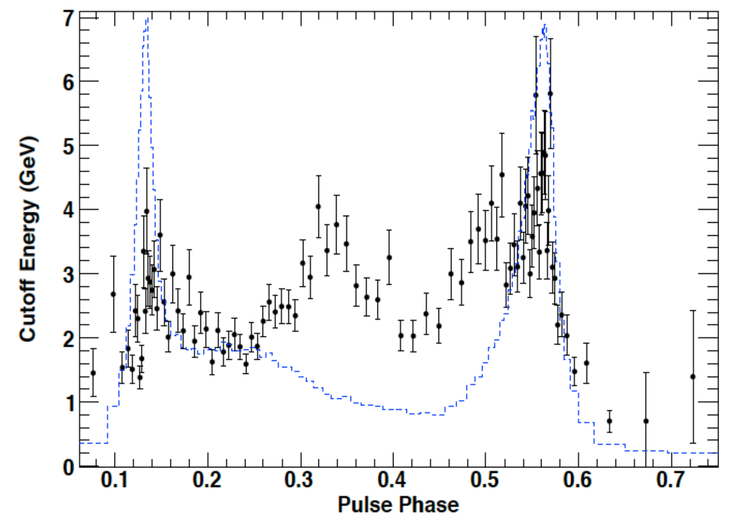
$$\gamma_{CRR} = \left(\frac{3}{2}\frac{E_{\parallel}\rho_c^2}{e}\right)^{1/4} \approx 2\times10^7$$

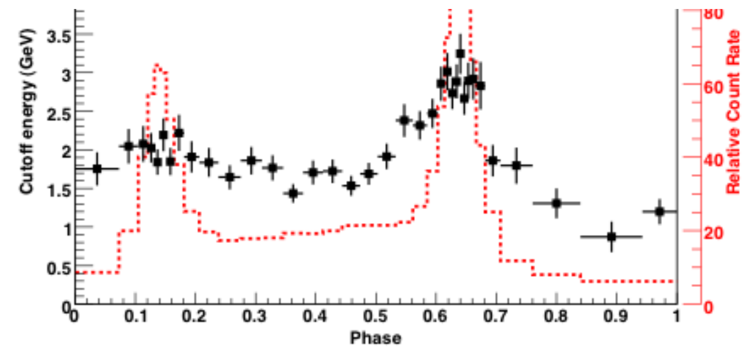
- Curvature radiation peak energy:

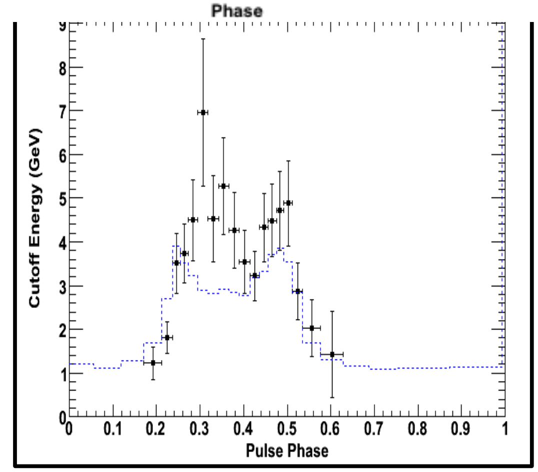
$$\varepsilon_{CR} = \frac{2}{3}\frac{\lambda\!\!\!^{-}_c\gamma_{CRR}^3}{\rho_c} = \left(\frac{3}{2}\right)^{7/4}\left(\frac{E_{\parallel}}{e}\right)^{3/4}\lambda\!\!\!^{-}_c\rho_c^{1/2} \approx 3\ GeV$$

- If $E_c = \varepsilon_{CR}$,

$$E_{\parallel} \propto E_c^{4/3}\rho_c^{2/3}$$

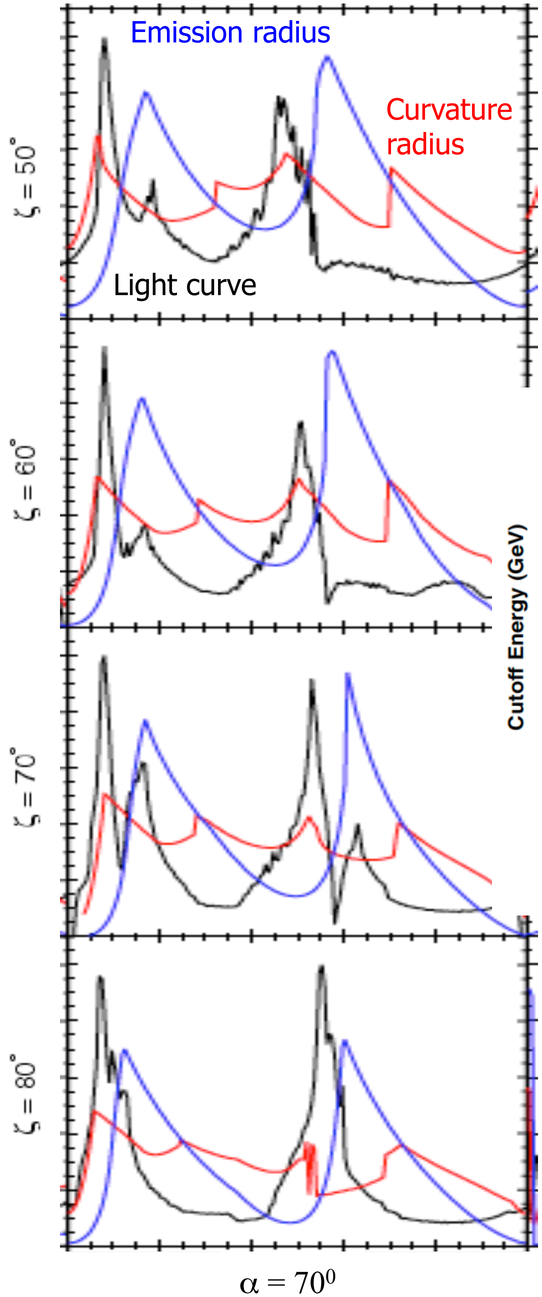






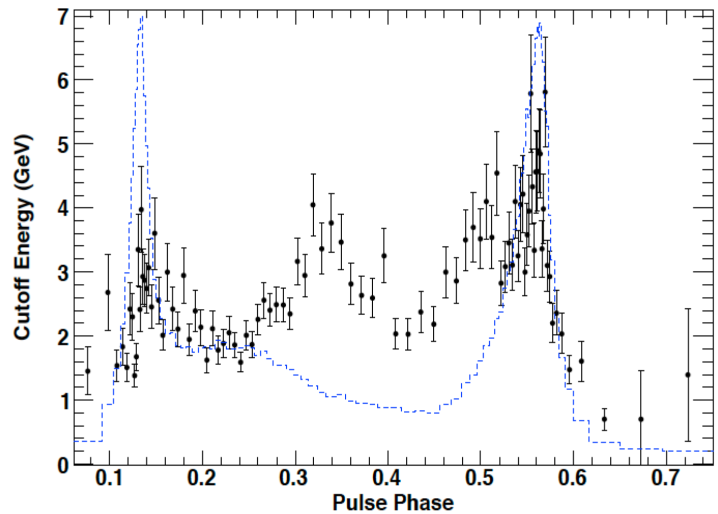
Model variation of emission, curvature radius

DeCesar & Harding, in prep.

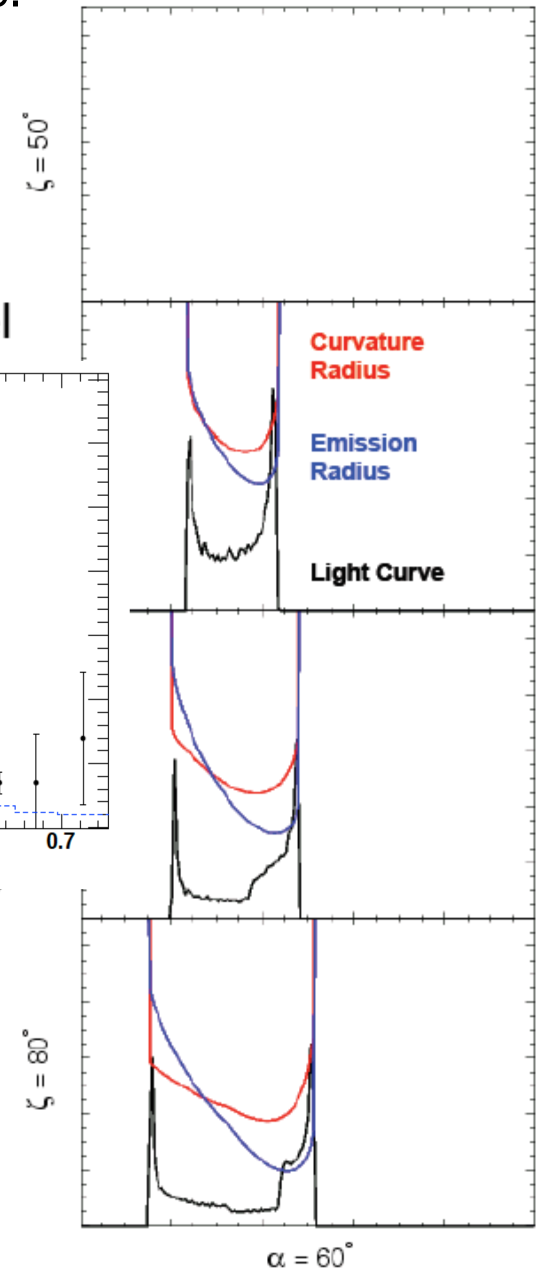


Examples

- Two-pole caustic model

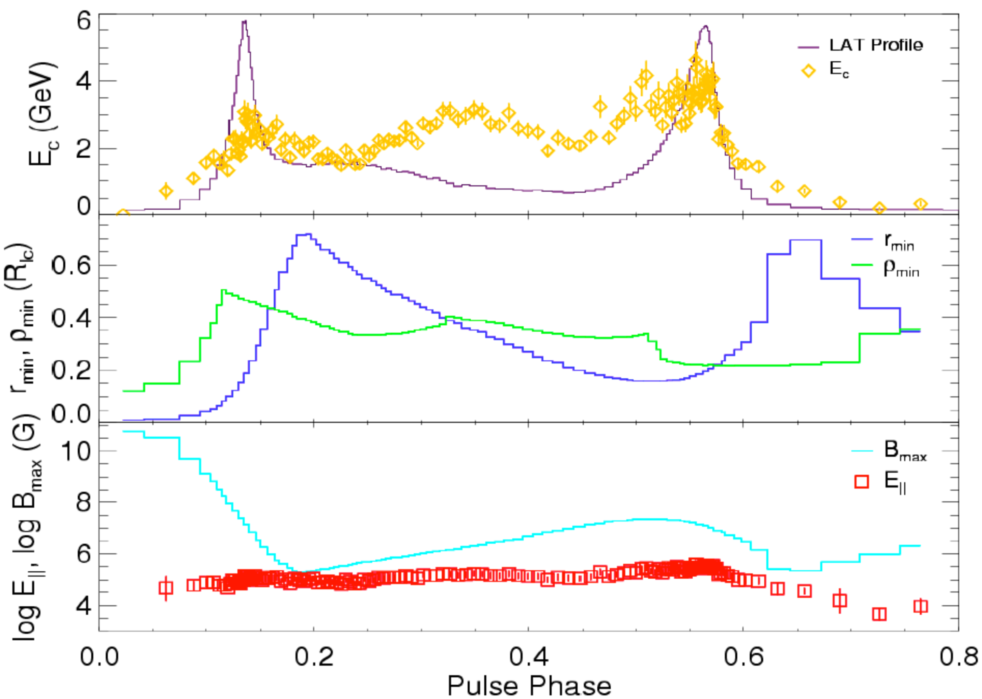


(Romani & Yadigaroglu 1995) with vacuum retarded dipole field



Electric field in accelerator gap - Vela

Megan DeCesar thesis



LAT data

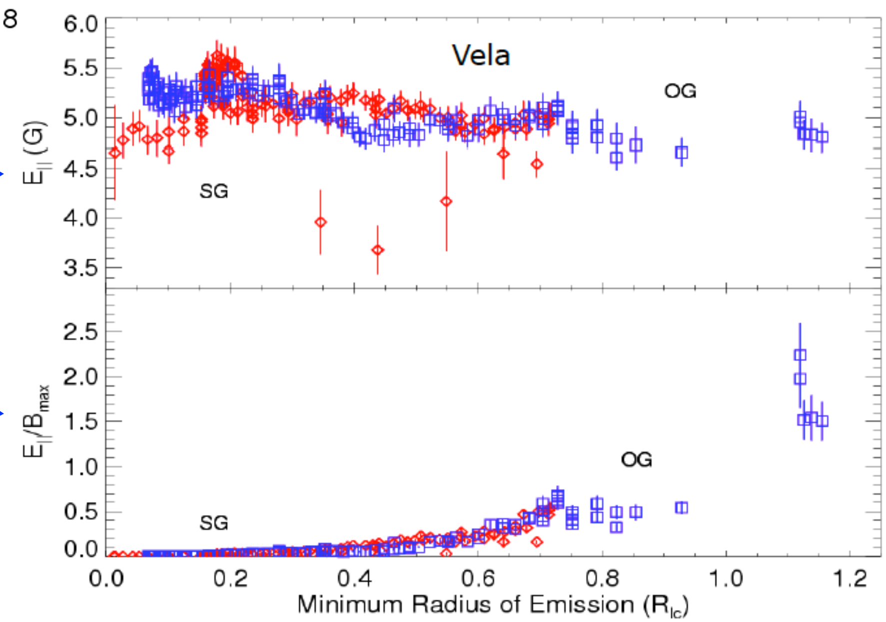
Slot gap model emission radius and magnetic field radius of curvature

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

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

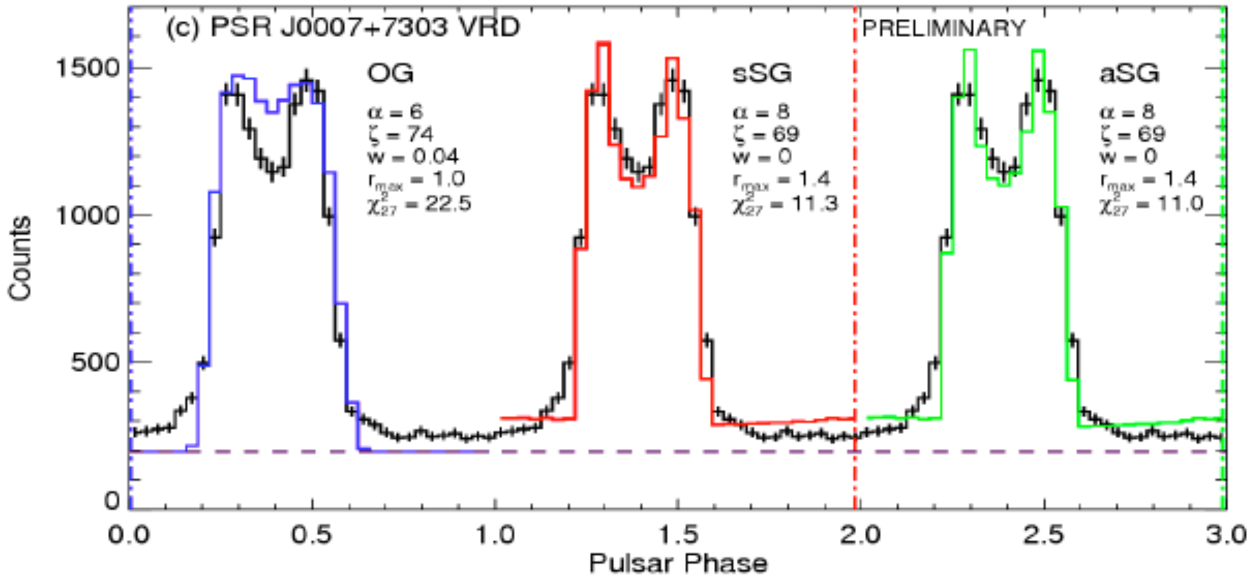
$E_{||}(r)$ can be compared with models

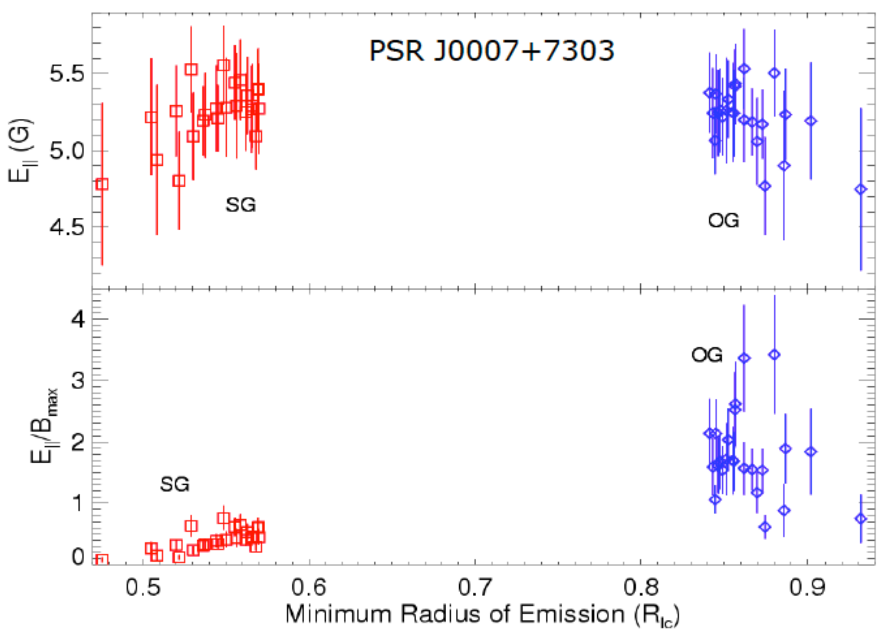
$E_{||}/B_{max} > 1$ not physical



Electric field in accelerator gap – CTA1

Megan DeCesar thesis





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

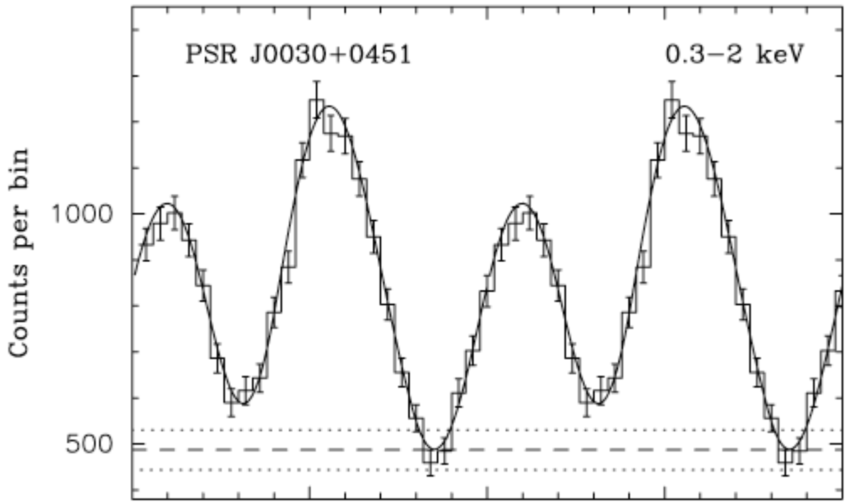
Summary

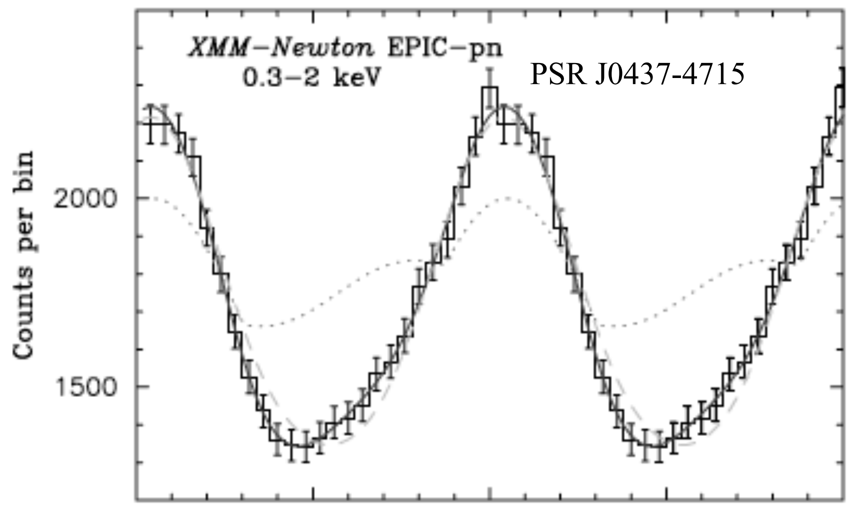
- We are finally answering fundamental questions of γ-ray pulsar astrophysics – but raising new ones
  - High-energy emission comes from outer magnetosphere
- Radio-loud, radio-quiet and millisecond pulsars have similar gamma-ray light curves and spectra
  - Similar emission mechanisms and geometry
- We can begin constraining emission and magnetic field geometry with light curve fitting
- We can derive the (model dependent) accelerator electric field from phase resolved spectral cutoff energies
- We can do pulsar physics with Fermi!

Offset polar caps in pulsars?

- Idea has been in literature for some
  - Smaller field curvature radius invoked to increase pair yields, but required large offsets of 0.7R – 0.8R (Arons 1983, 1997, Hibschman & Arons 2001) or even 0.95R Medin & Lai (2010) for high pair yields in all pulsars

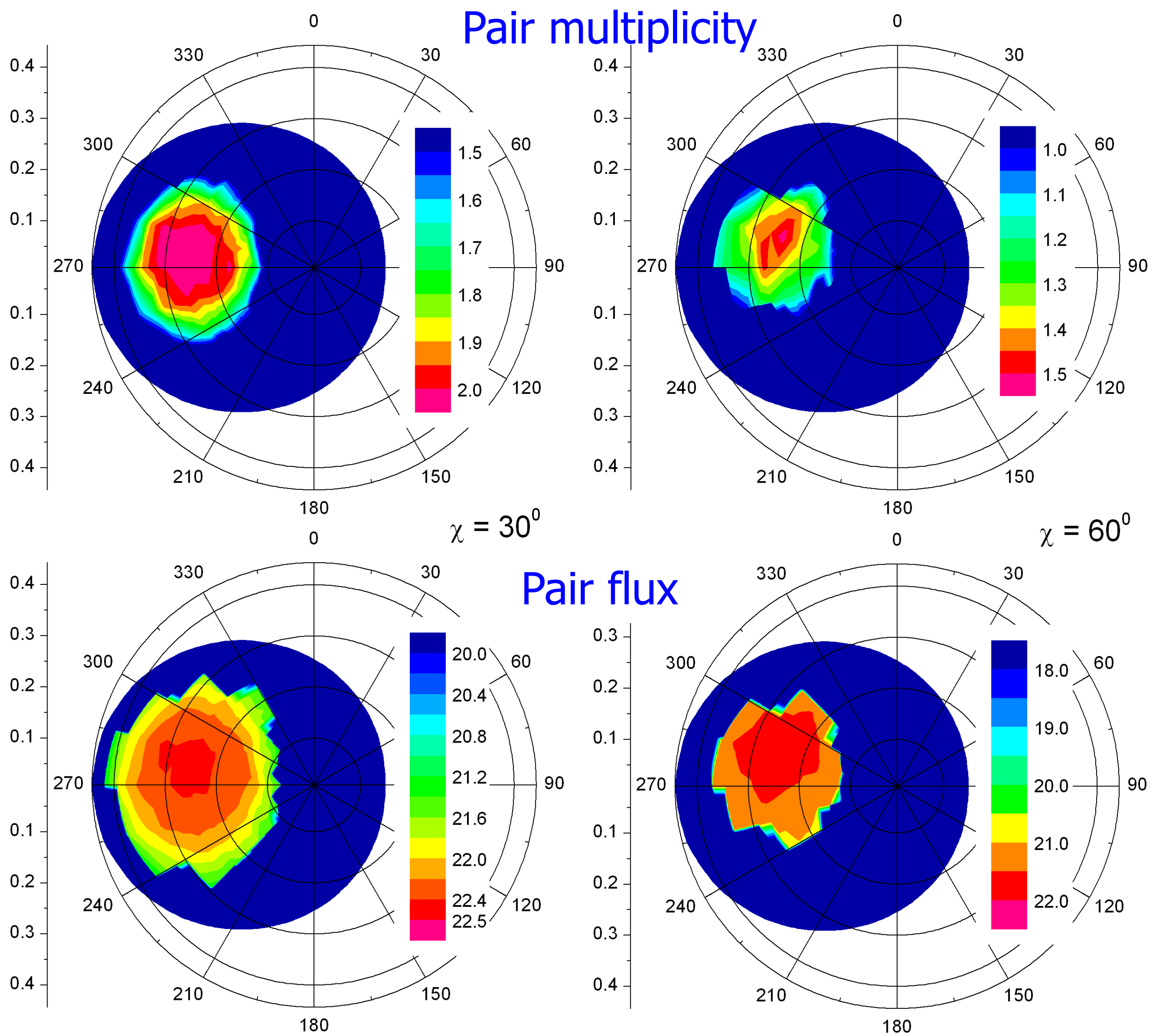
- Evidence for offset polar caps in MSPs
  - Models of X-ray light curves from J0437-4715 (Bognanov et al. 2007)and J0030+0451 (Bogdanov & Grindlay 2009) require offsets ~ 0.1 R





Pairs in MSPs with offset PCs

Harding & Muslimov, in prep.



- Offset PCs produce asymmetry in PC angle and electric field
- Increase in $E_{||}$ and acceleration toward offset
- Pair cascades become possible over part of polar cap
- Accelerator gap can form along offset rim

Pair death lines for centered and offset PCs

Harding & Muslimov 2011