Pulsar Acceleration and High-Energy Emission from the Polar Cap and Slot Gap

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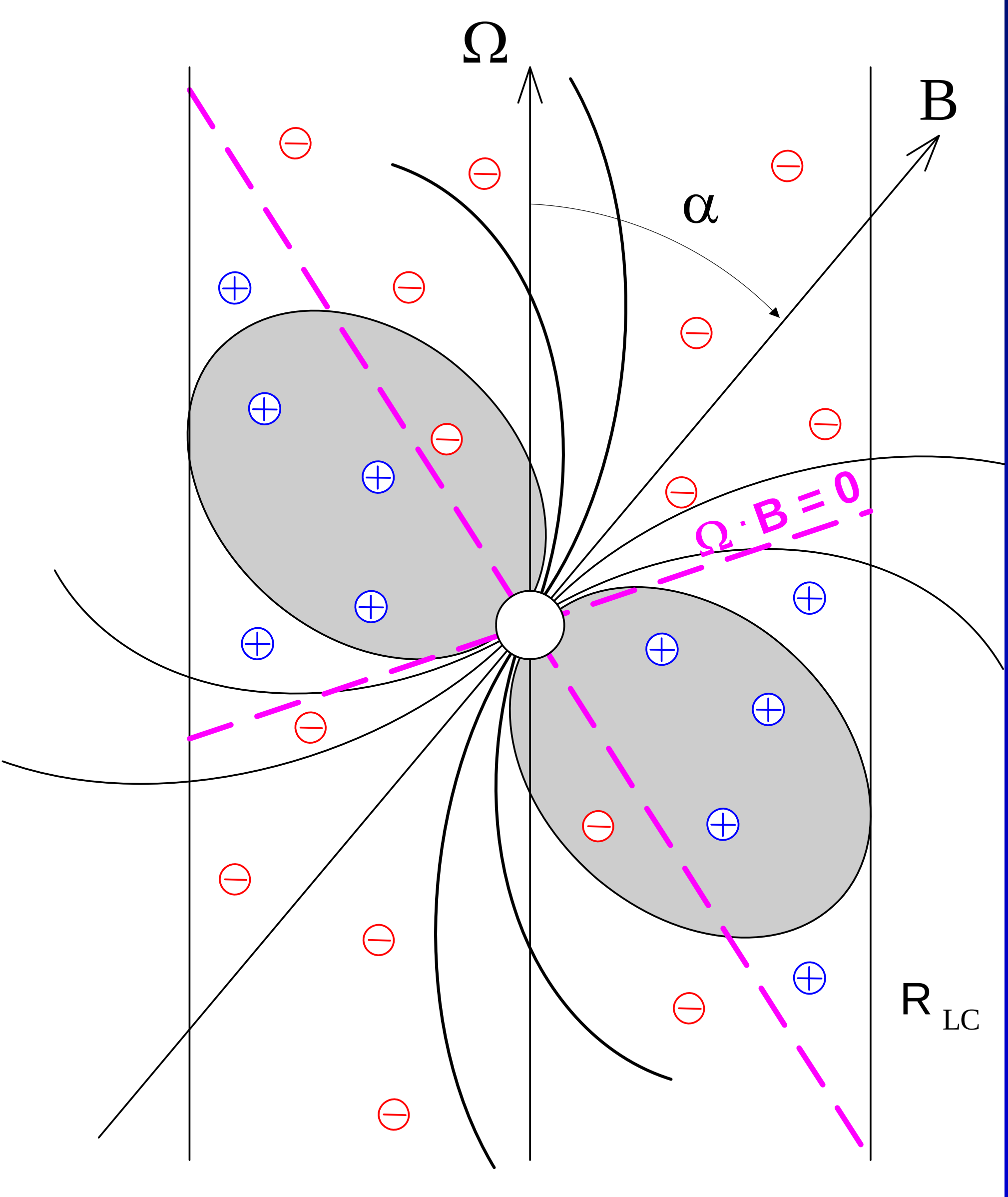
with help from Alex Muslimov, Jarek Dyks, Michal Frackowiak, Isabelle Grenier, Julie Stern

- Acceleration near the polar cap and beyond
- High energy emission in 3D
- Open questions

Force-free magnetosphere

Goldreich & Julian 1969



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

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

- Goldreich-Julian charge density

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

- Corotating dipole field
- NO particle acceleration

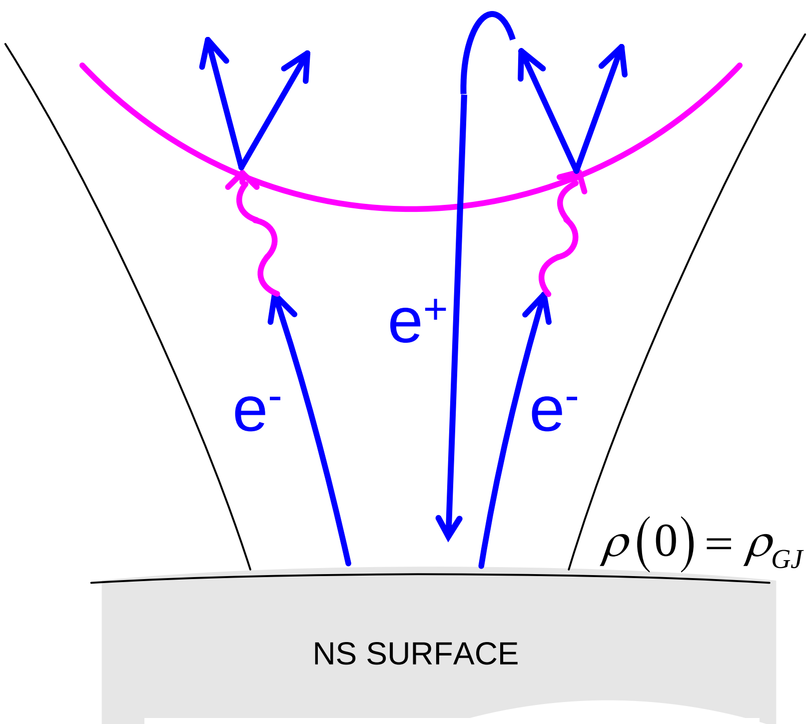
Polar cap accelerators

SPACE CHARGE "GAP"

$$T_s > T_{e,i}$$

Arons & Sharlemann 1979

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



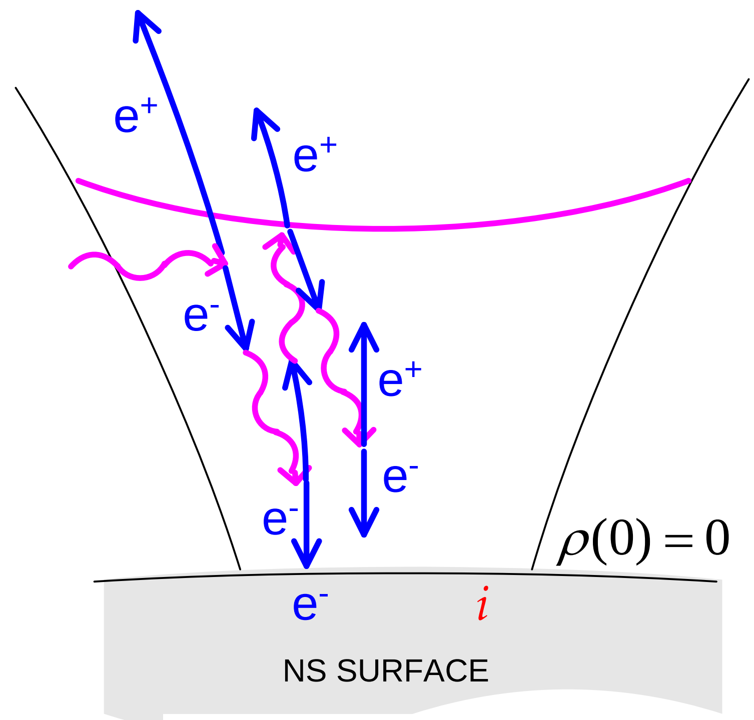
$$T_e \cong 3.6\times10^5 K \left(\frac{Z}{26}\right)^{0.8}\left(\frac{B_o}{10^{12}G}\right)^{0.4}$$

VACUUM GAP

$$T_s < T_{e,i}$$

Ruderman & Sutherland 1975

$$\nabla \bullet E_{\|} = 4\pi\rho_{GJ}$$



$$T_i \cong 3.5\times10^5 K \left(\frac{B_o}{10^{12}G}\right)^{0.73}$$

Accelerating electric field

- **Space charge limited flow (SCLF)**

$$\rho_{GJ} \approx -\frac{1}{4\pi c}\nabla\bullet\left[\frac{1}{\alpha}(\mathrm{w}\text{-}\mathrm{v})\times B\right]$$

$$-\nabla^2\Phi = \nabla\bullet E_{\parallel} = 4\pi(\rho - \rho_{GJ})$$

$$E_{\parallel} \approx E_0\theta_{\mathrm{PC}}^2\left[\frac{\theta_{\mathrm{PC}}}{2}\left(\frac{r}{R}\right)^{-1/2}\sin\alpha\cos\phi \quad + \kappa\left(\frac{r}{R}\right)^{-4}\cos\alpha\right]$$

Arons & Scharlemann 1979

Muslimov & Tsygan 1992

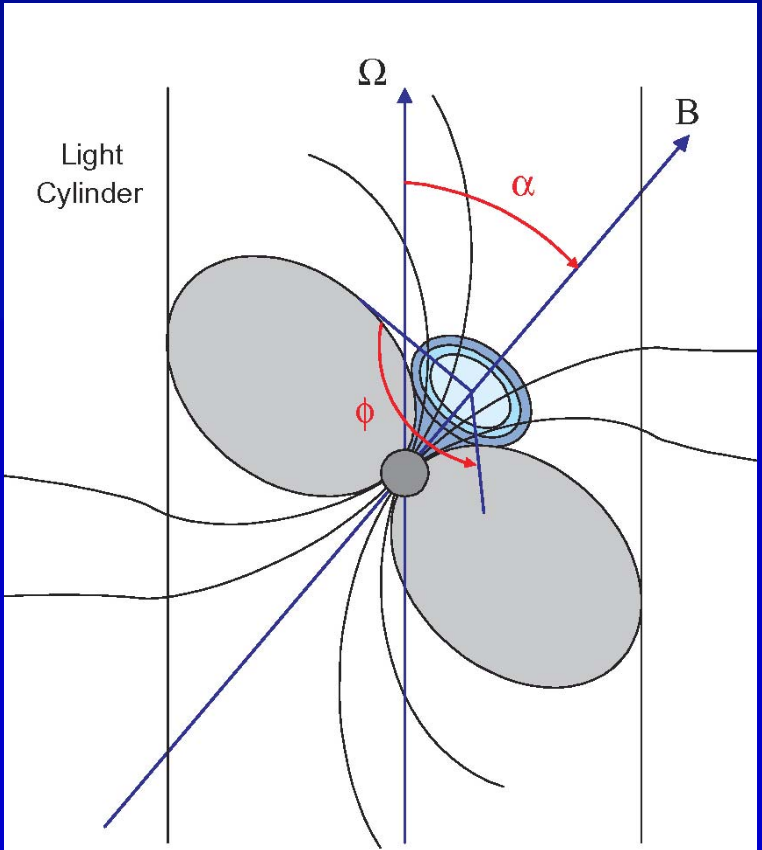
$$\kappa \propto \frac{I}{R^3} \sim 0.15$$

Frame-dragging dominates!

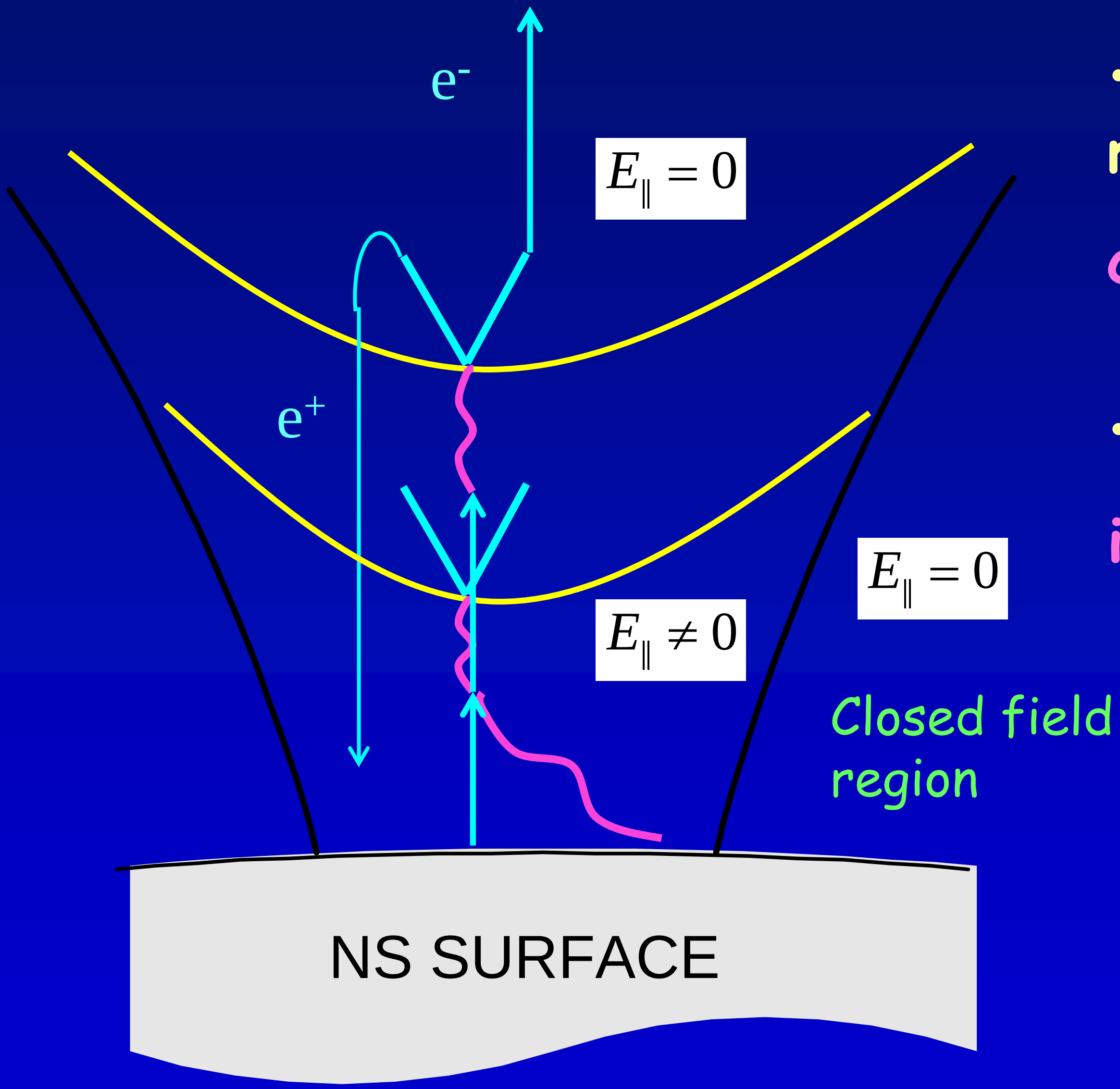
$$\frac{E_{\parallel}^{GR}}{E_{\parallel}^{Cl}} \approx 42\ P$$

- **Vacuum gap**

$$E_{\parallel} = E_0 = \frac{\Omega R B}{c}$$



SCLF Pair Formation Front



- Curvature radiation pair front

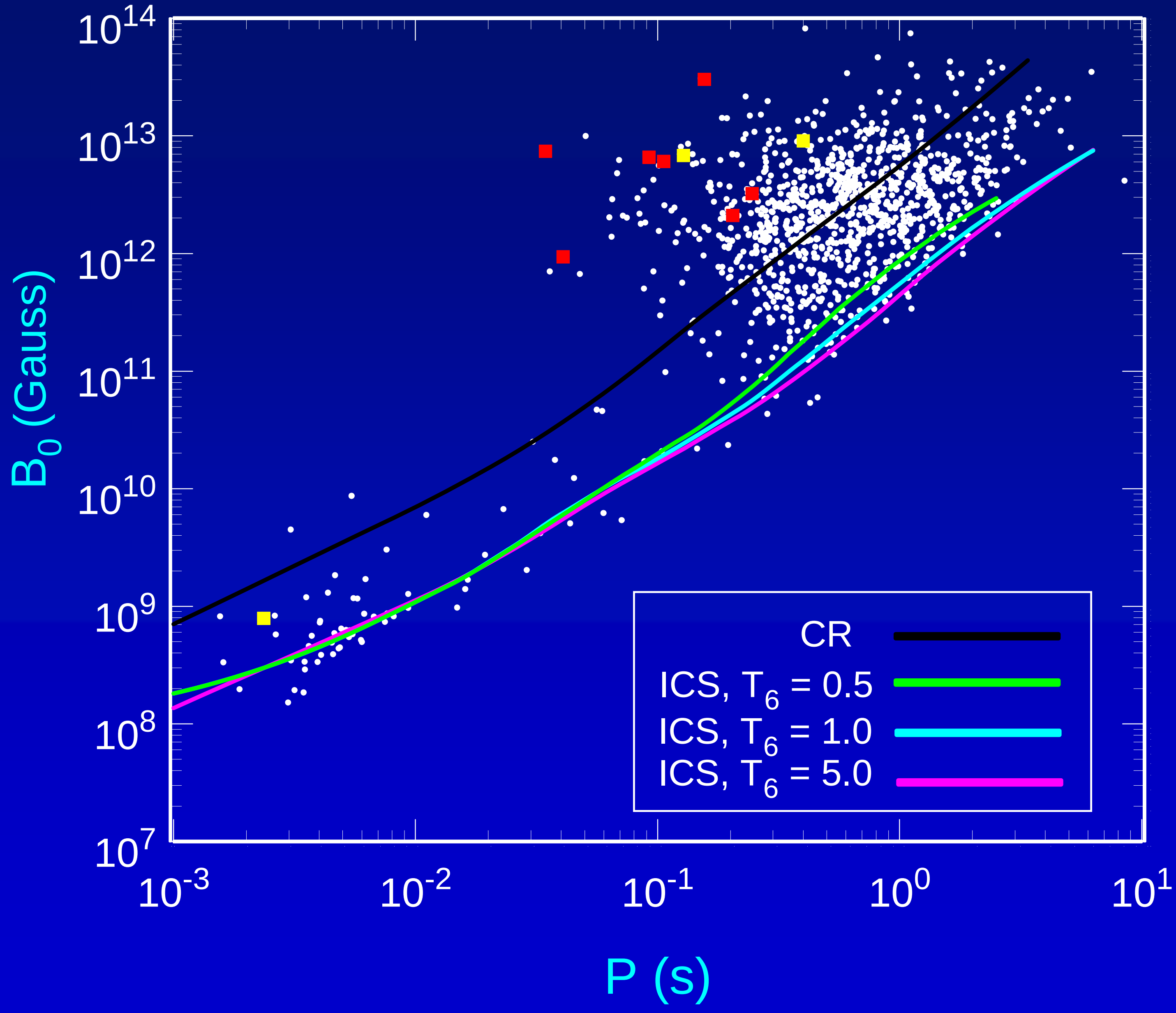
  complete screening

- ICS pair front

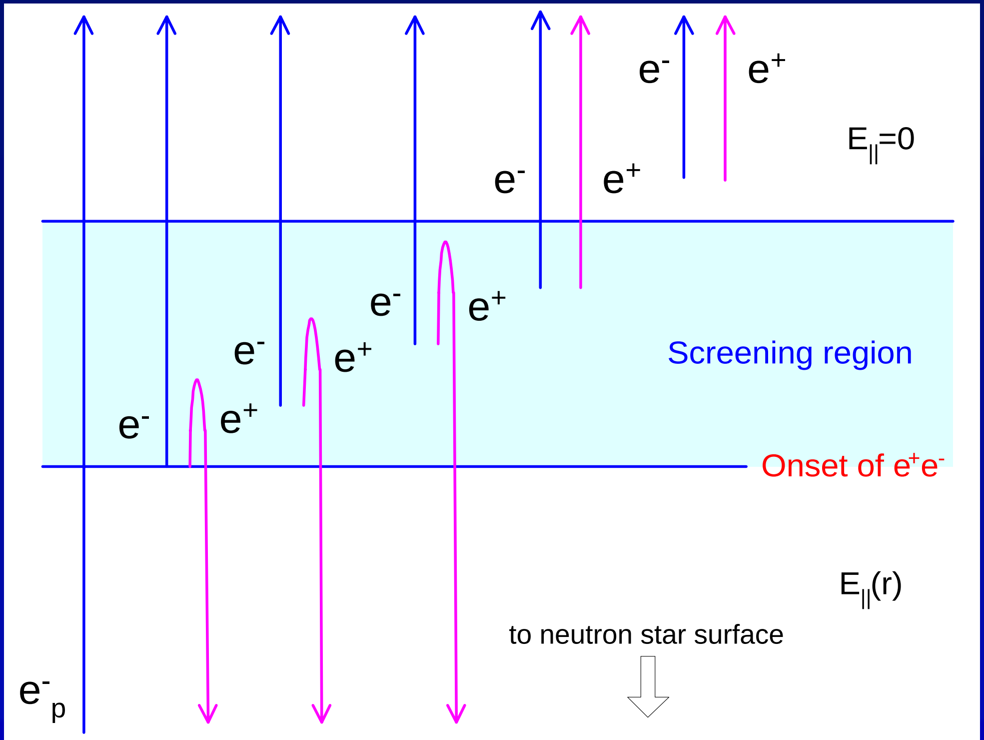
  incomplete screening

Polar Cap Pair Death lines

Harding & Muslimov 2002



Electric field screening & Polar cap heating

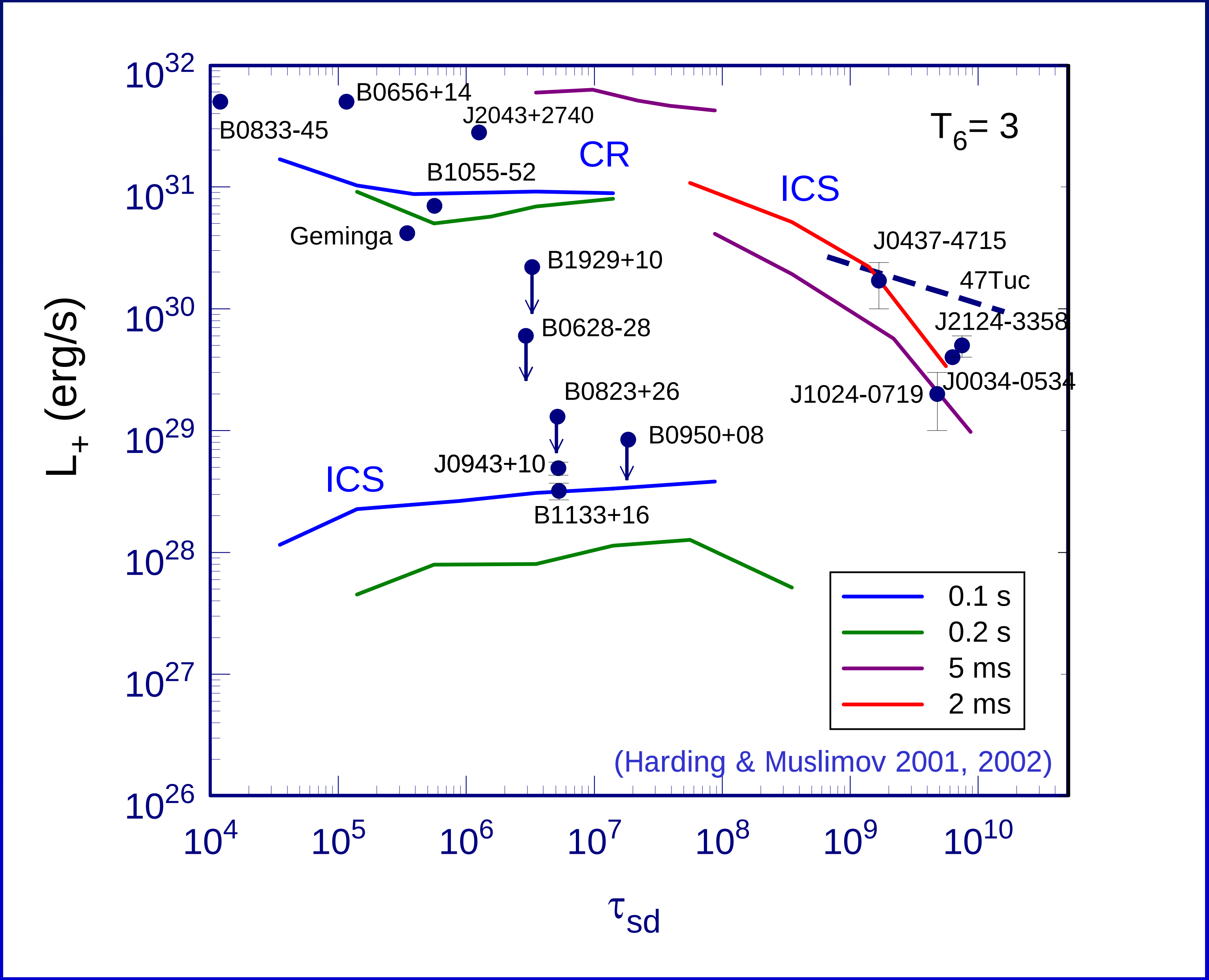


Maximum fraction of returning positrons:

$$f_+ = \frac{\rho_+}{\rho_{GJ}} = \frac{\rho_{GJ} - \rho}{2\rho_{GJ}}\bigg|_{z_0} \approx \frac{3}{2}\frac{\kappa}{(1-\kappa)} z_0$$

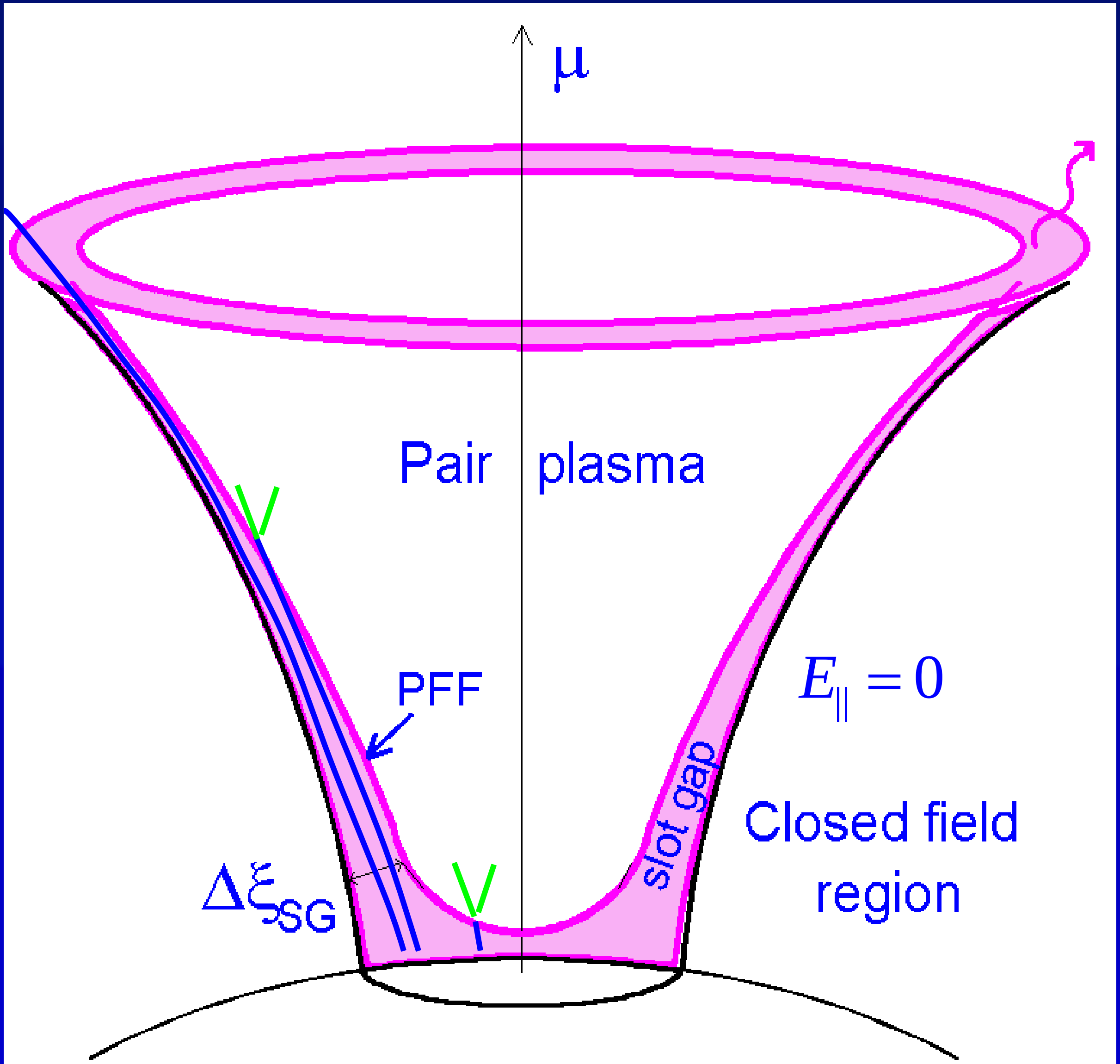
$$L_+^{max} = f_+ \Phi(z_0)\, \dot{n}_{prim}$$

Polar cap heating

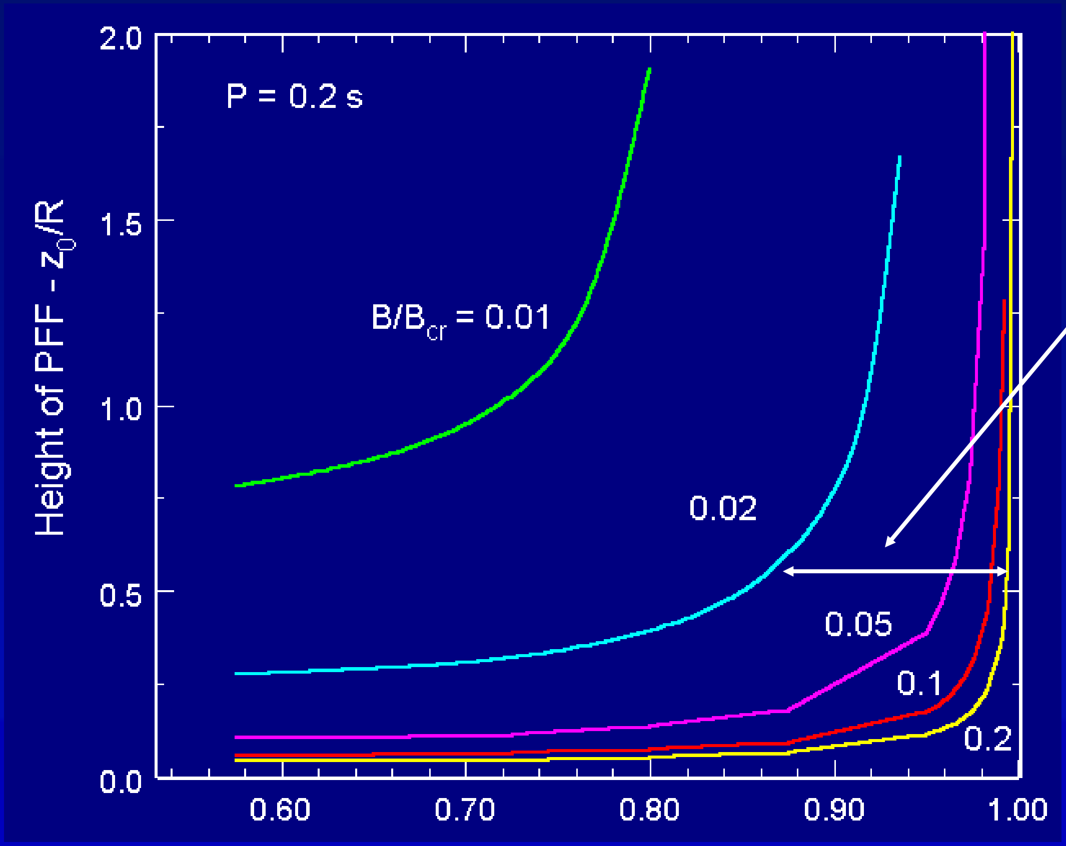


Slot gap model

- **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**



Slot gap energetics (Muslimov & Harding 2003)



$$\xi = \theta / \theta_{PC}$$

Slot gap width:

$$\Delta\xi_{SG} \approx 0.15 P_{0.1} B_{12}^{-4/7}$$

Solid angle:

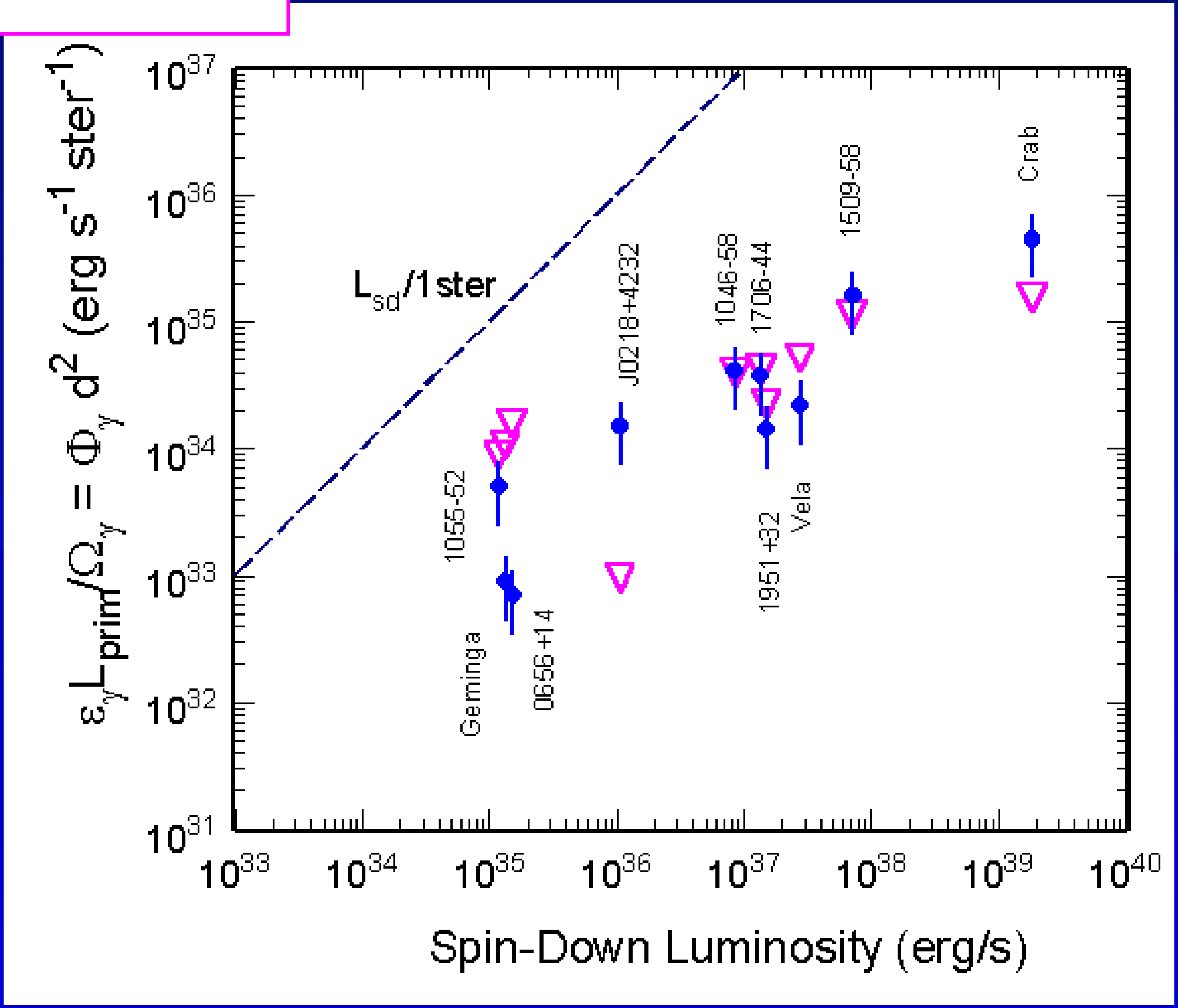
$$\Omega_{SG} \propto \theta_o^2 r \ \Delta\xi_{SG}$$

$$A_{SG} \approx \pi R_{SG}^2 \Delta\xi_{SG}$$

$$L_{prim} = \Phi_{SG} \ n_{GJ} \ A_{SG} c$$

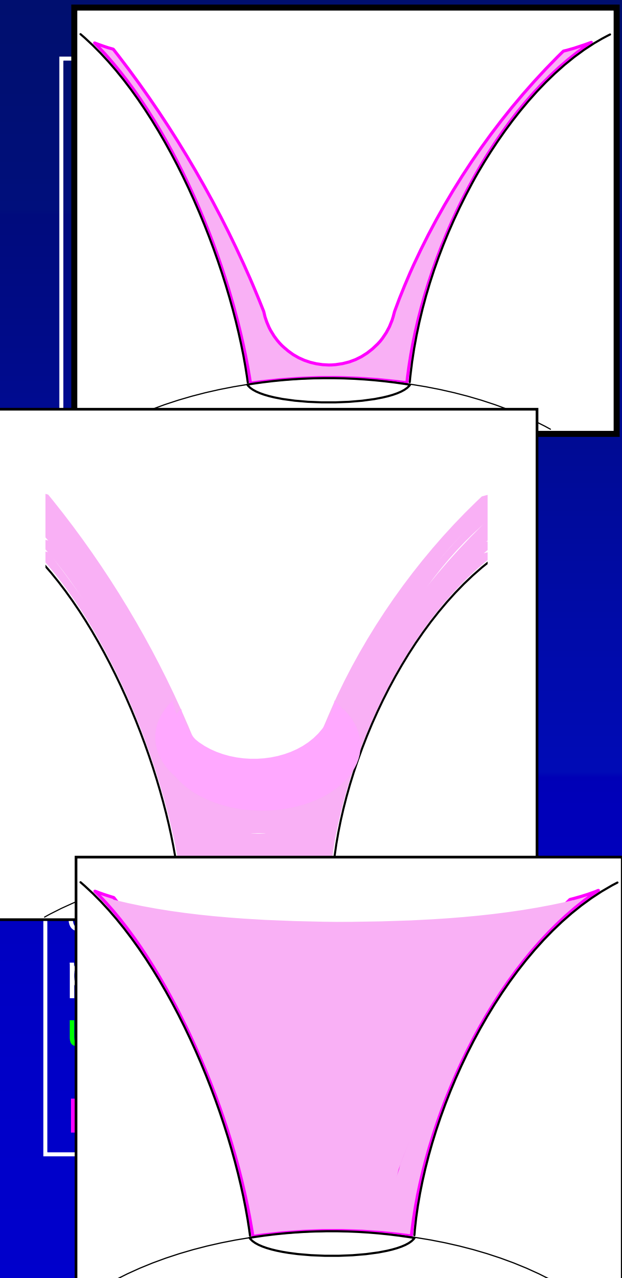
High energy "luminosity" from slot gaps

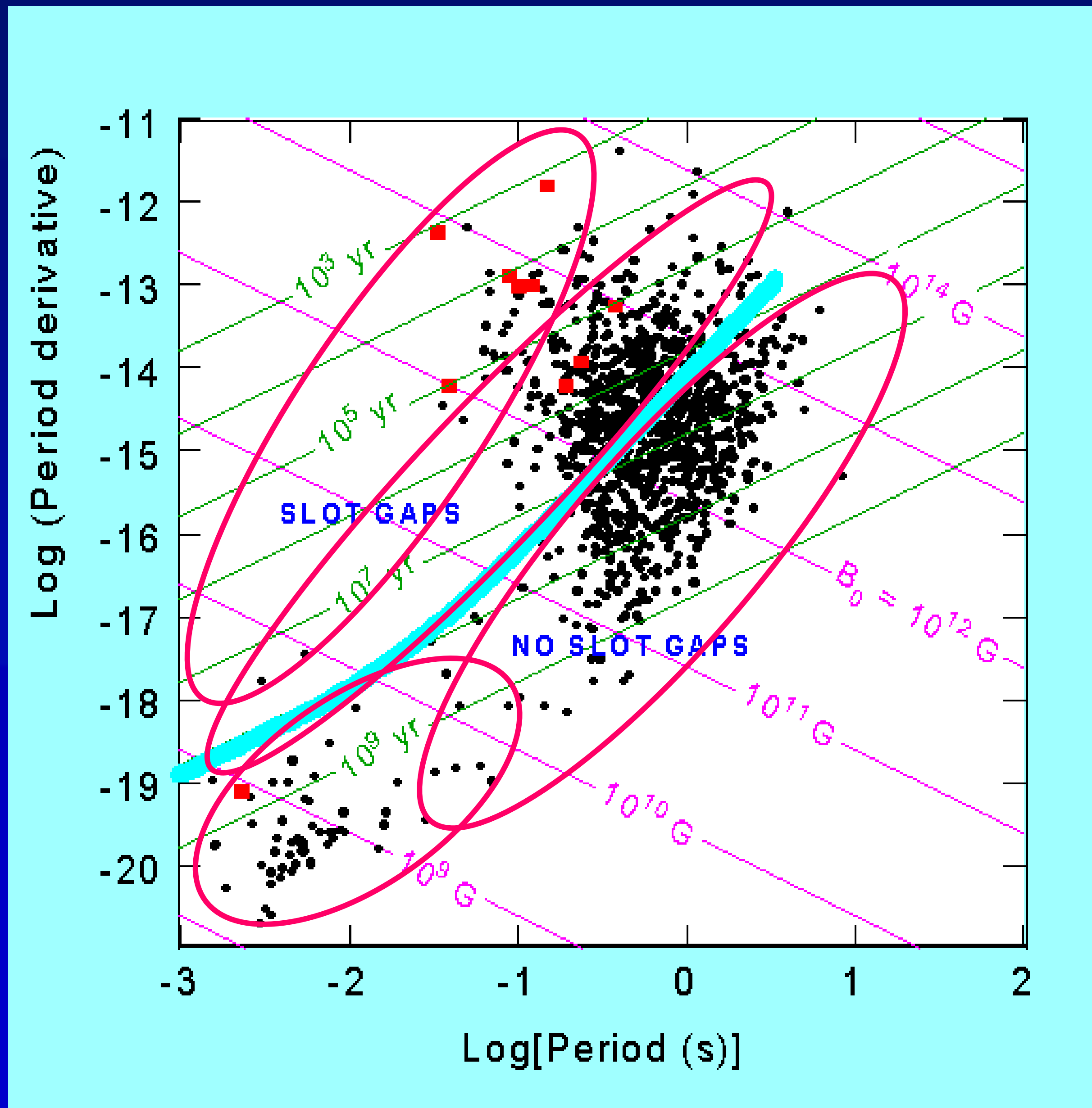
$$\frac{L_{prim}}{\Omega_{SG}} \approx 2\times10^{34}\, erg\ \ s^{-1} ster^{-1} L_{SD,35}^{3/7} P_{0.1}^{5/7}$$



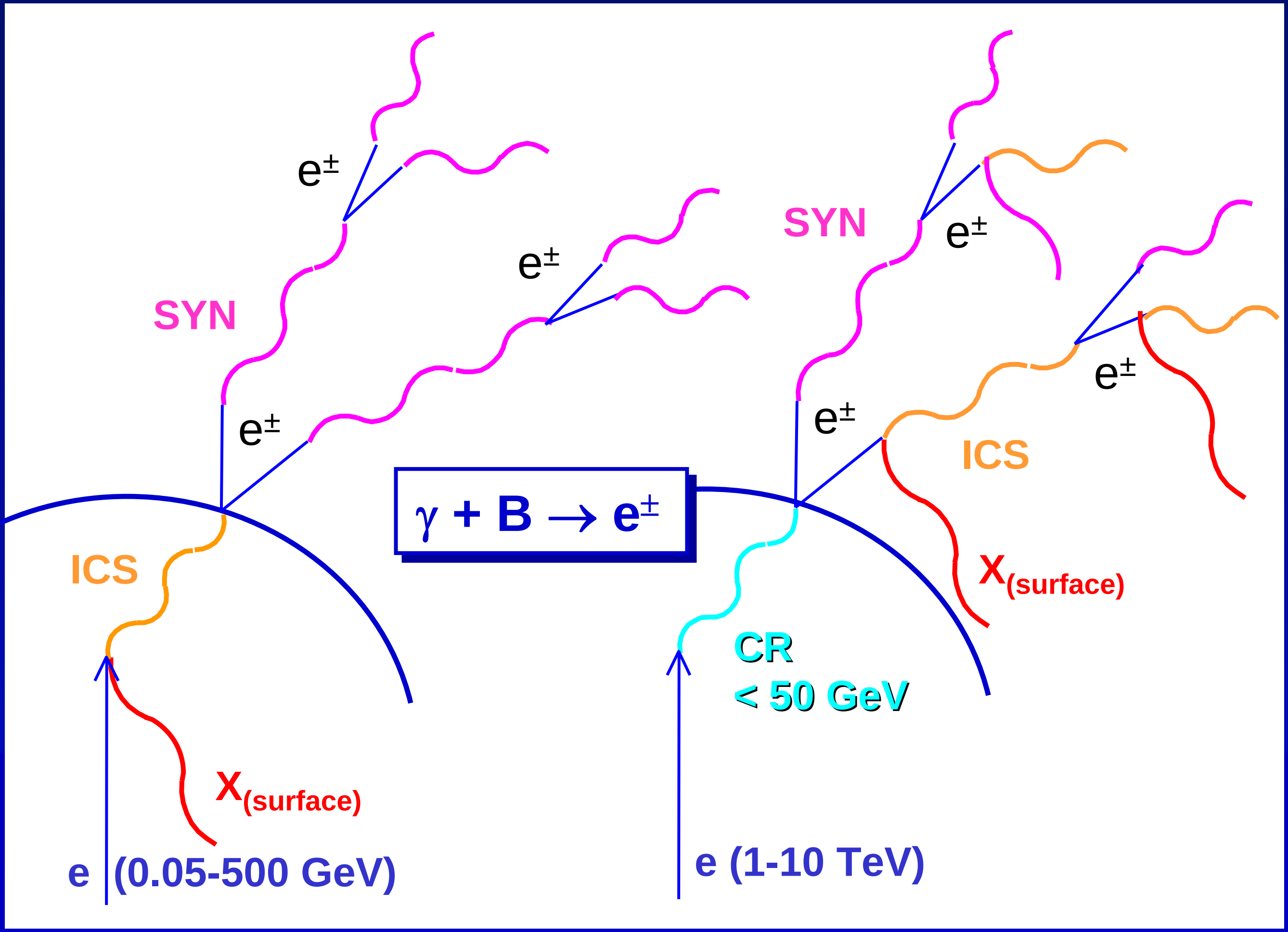
Which pulsars have slot gaps?

Harding, Muslimov & Zhang 2002





Polar cap cascades



near the surface
not efficient screening
$N_{e2}/N_{e1} = 10^{-3}\text{-}10^{2}$

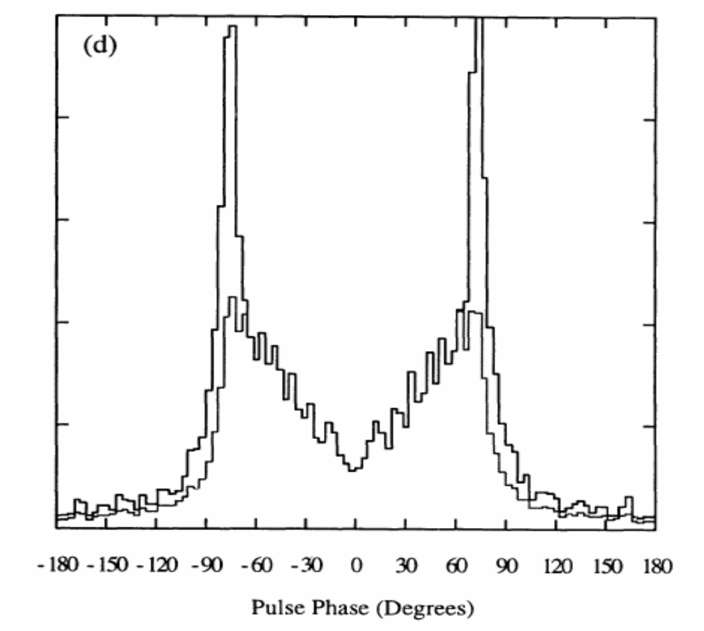
Sturner & Dermer '94
Hibschmann & Arons '01

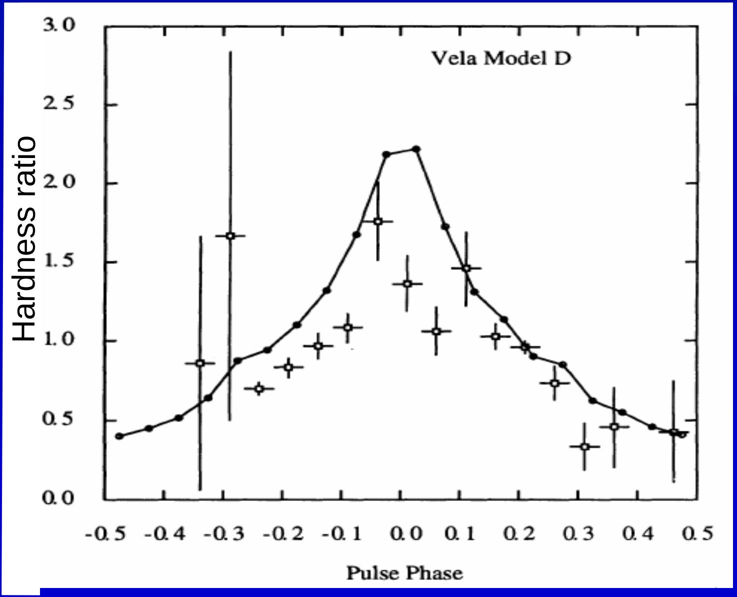
higher above the surface
$E_{//}$ screening
$N_{e2}/N_{e1} = 10\text{-}10^{4}$

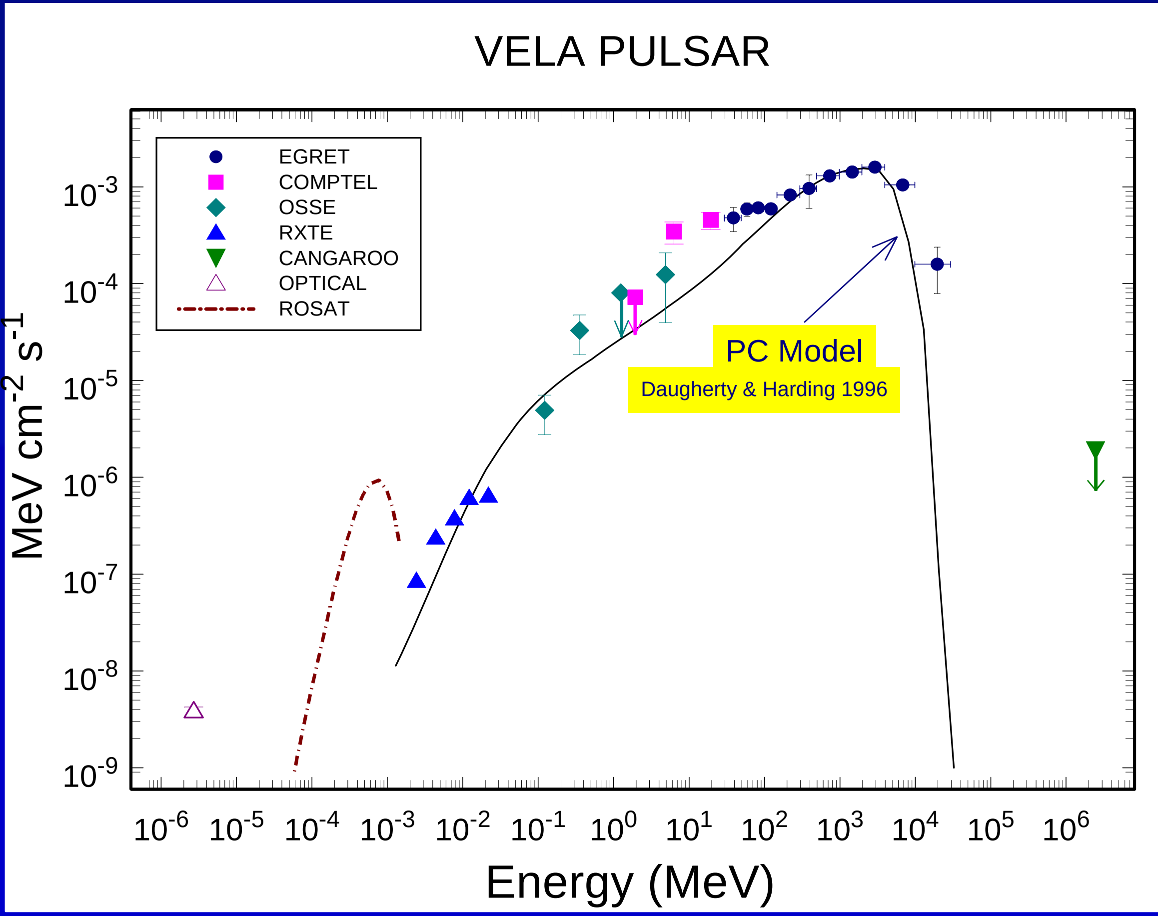
Daugherty & Harding '82
Zhang & Harding '00

Traditional PC Model (Daugherty & Harding 1996)

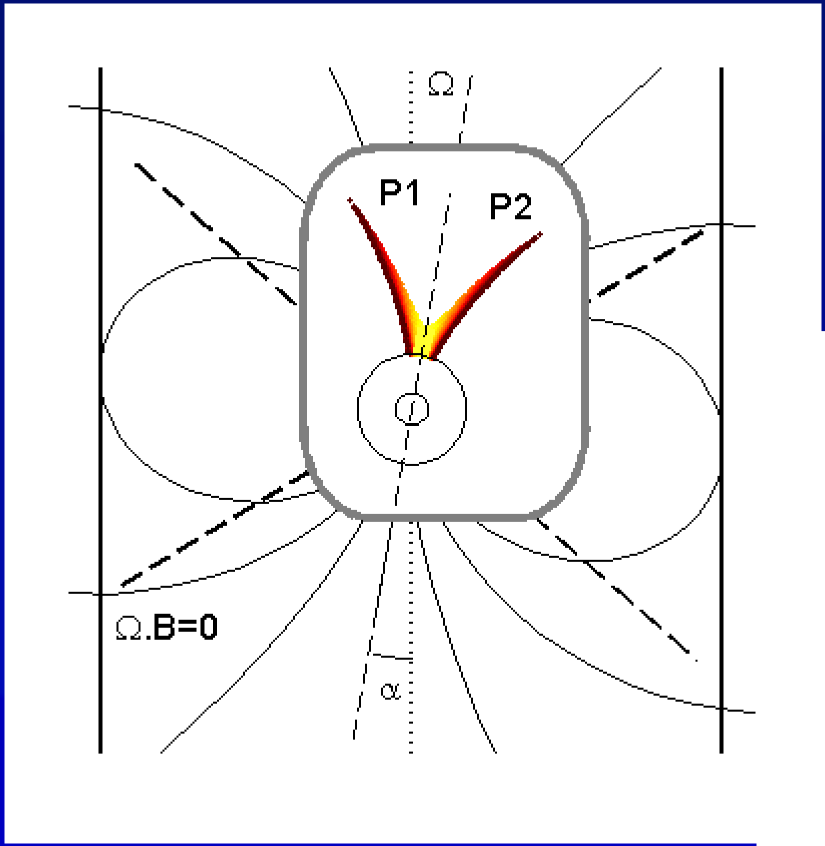
- Acceleration artificially placed at r = 3 R
- Assumed PC rim enhancement
- α = 10^0 to generate broad pulse profile

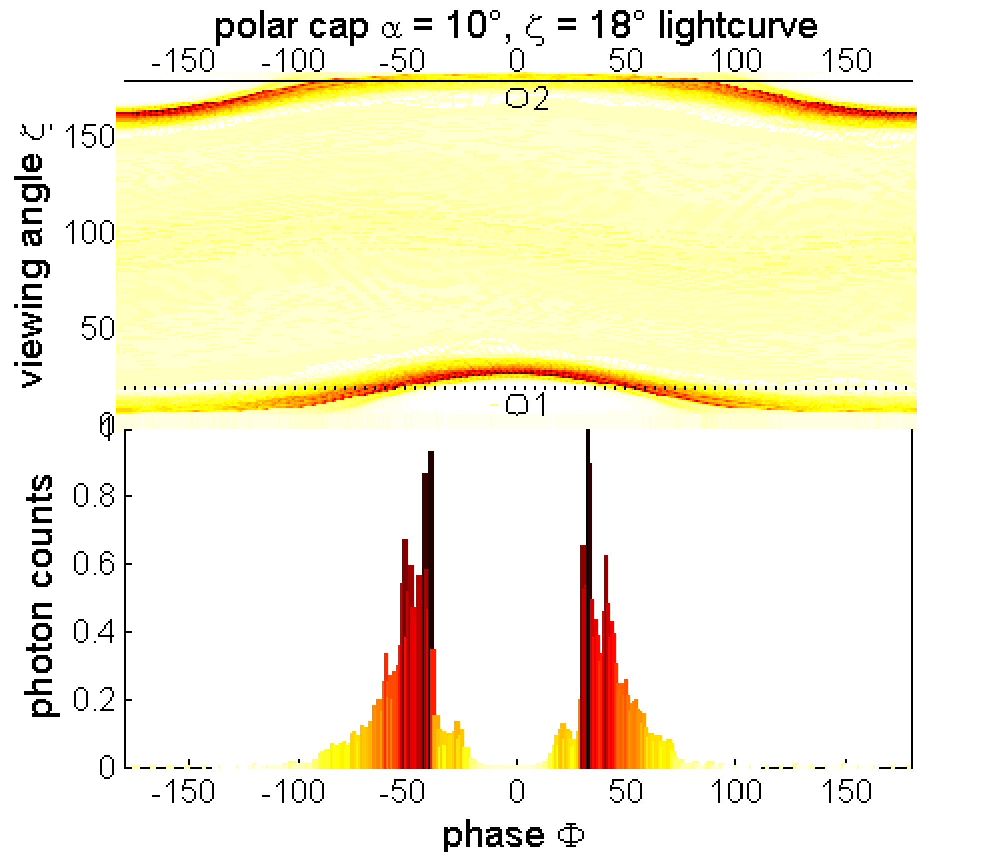






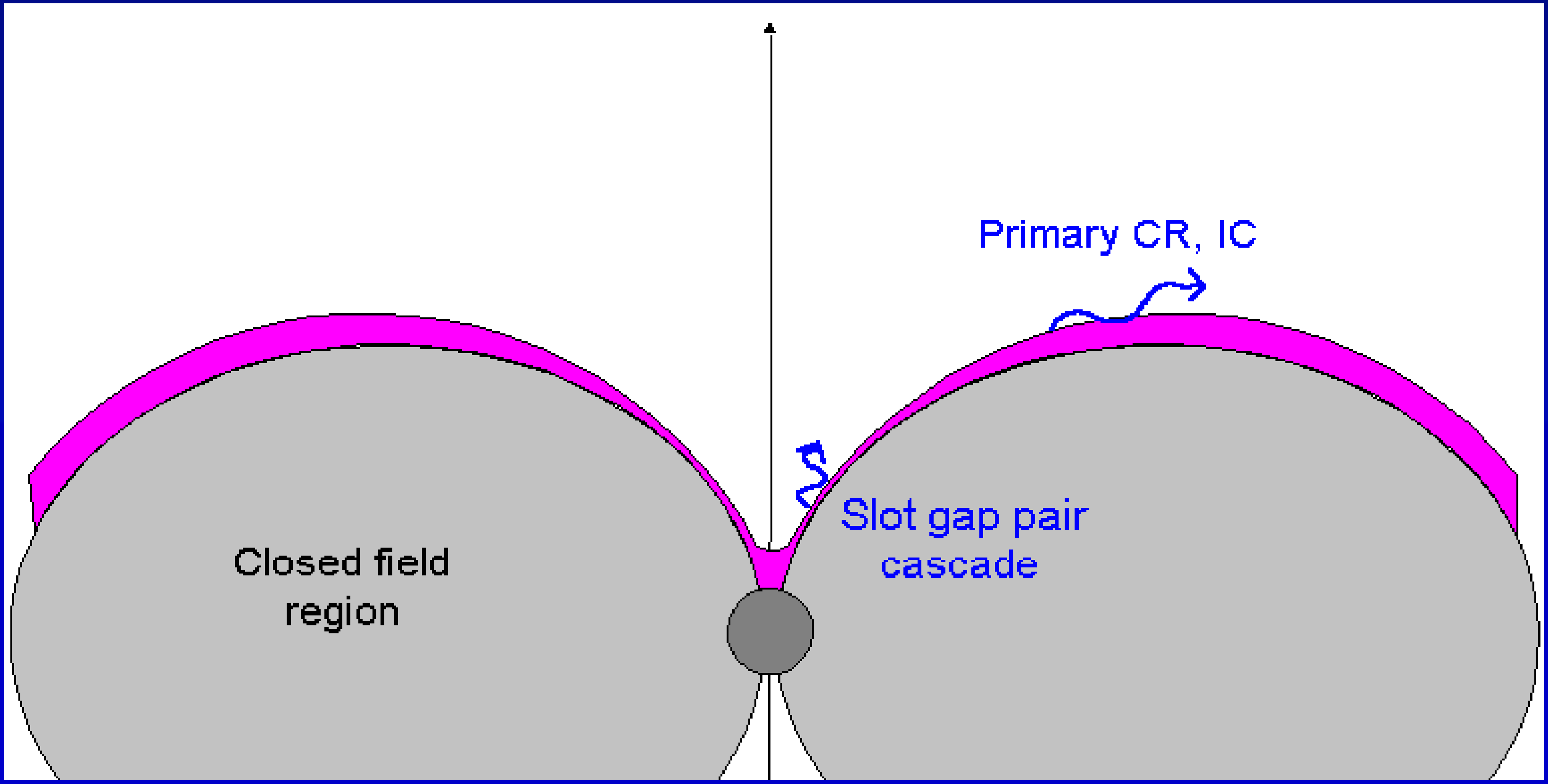
Polar cap/low altitude slot gap





High altitude slot gap

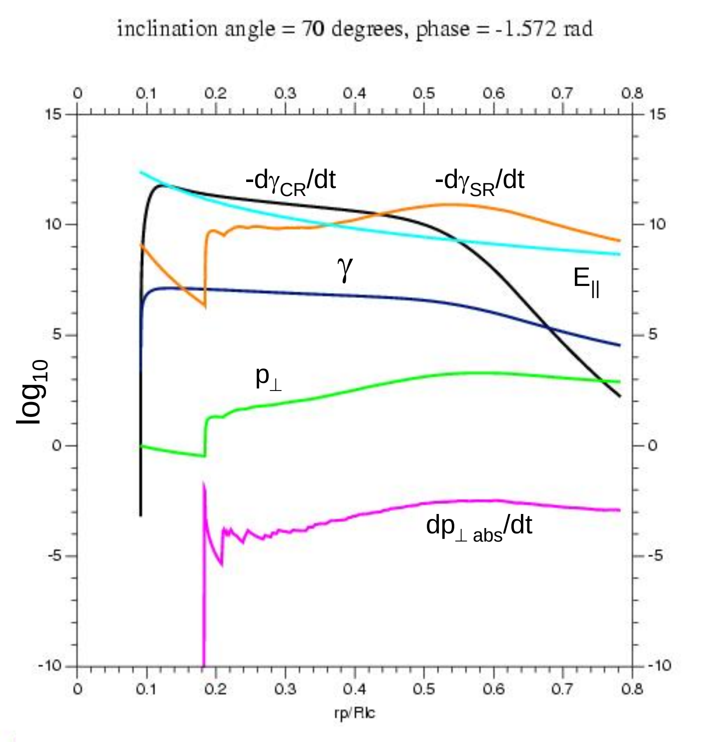
(Muslimov & Harding 2004)



High altitude slot gap - radiation

Continuous acceleration in gap -> particles reach radiation reaction limit

- Curvature
  - Balance CR losses with acceleration gain $$eE_{\|} = \dot{\gamma}_{CR} = \frac{2e^2\gamma^4}{3\rho_c^2}$$
  - Steady-state Lorentz factor $$\gamma_{CRR} = \left(\frac{3}{2}\frac{E_{\|}\rho_c^2}{e}\right)^{1/4} \sim 3\times10^7$$
  - Curvature radiation peak energy: $$\varepsilon_{peak}^{CR} = 2\frac{\lambda_C\gamma_{CRR}^3}{\rho_c} \approx 30\ \mathrm{GeV}$$
- Synchrotron
  - Cyclotron resonant absorption of radio photons (Lyubarsky & Petrova 1998) $$\gamma_R = 3\times10^5 \frac{B_8}{\varepsilon_{0,GHz}(1-\beta\mu_0)}$$
  - Steady-state: SR losses balance acceleration and resonant absorption (Harding et al. 2005) $$p_{\perp}^{SRR} \simeq 302\ \ B_8^{-1}E_{\|,5}^{1/2}$$
- Inverse Compton
  - Scattering of radio photons $$\varepsilon_{\max} \sim \gamma_{CRR}^2\varepsilon_R \sim \mathrm{few}\ GeV$$



Tracing the path of an electron along a magnetic field line

Special Relativistic Effects

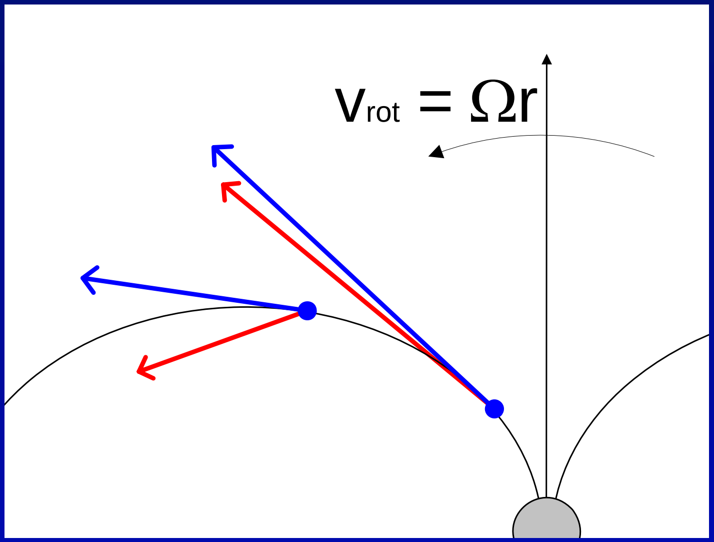
- Aberration

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

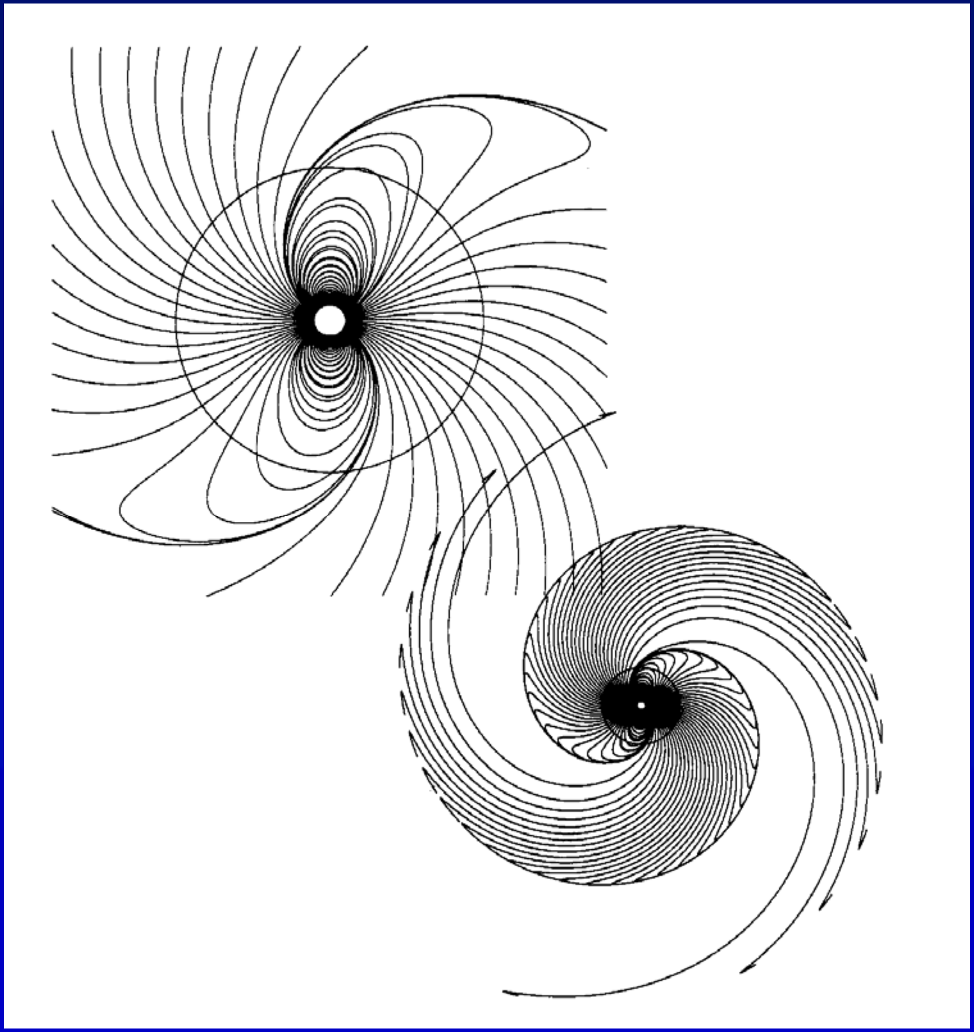
- Time-of-flight delays

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

- Retardation of magnetic field



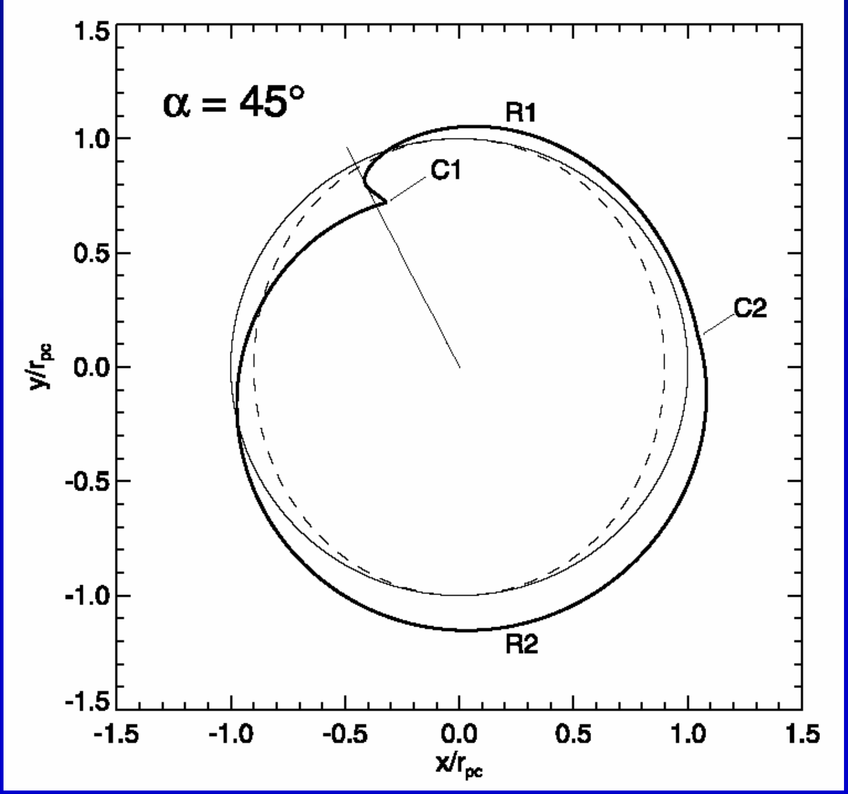
Magnetic field retardation: distortion of polar cap



$$t_r = t - r / c$$

Arendt & Eilek 1998

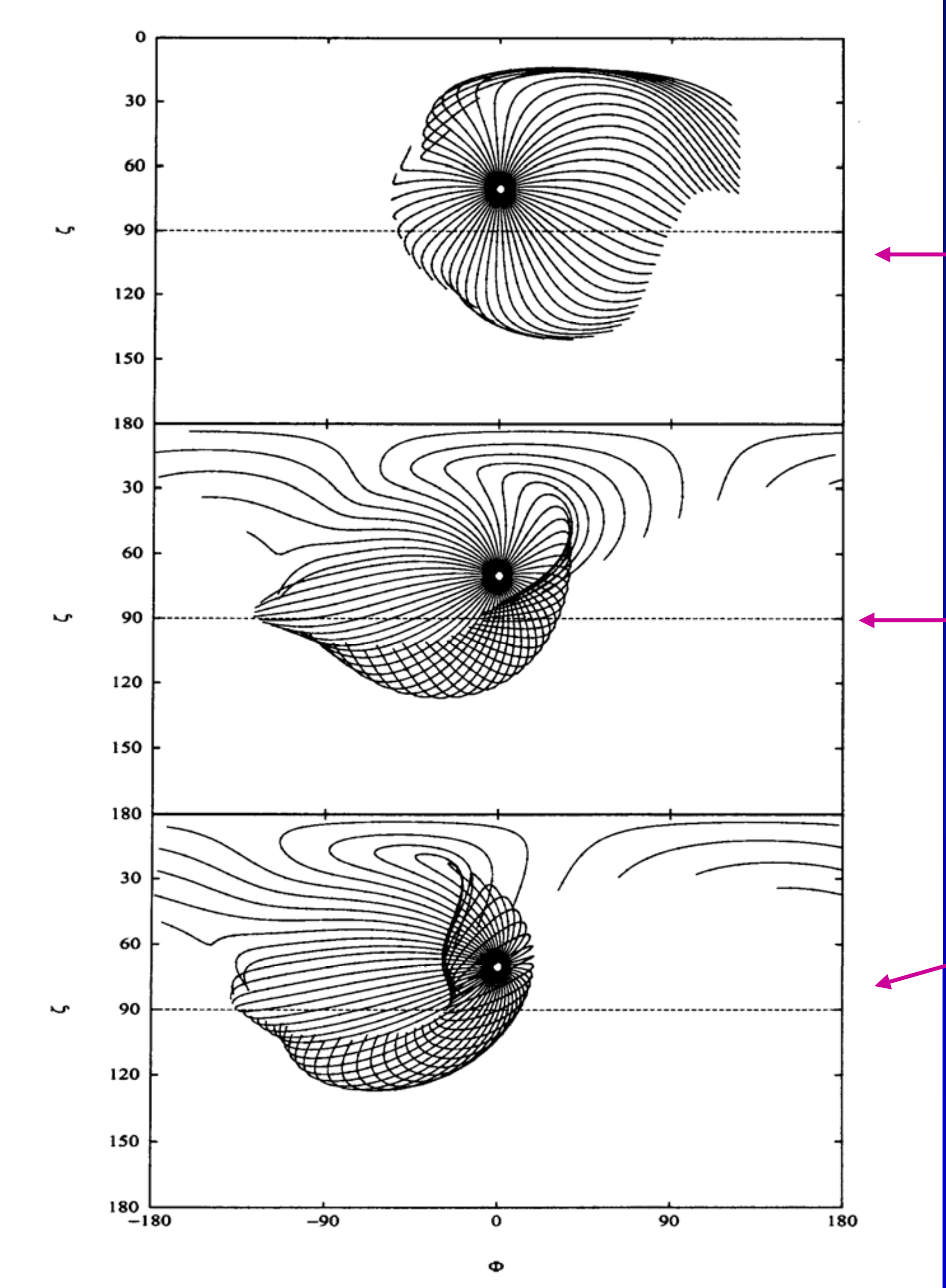
Dyks & Harding 2004



Deutsch 1955

Yadigaroglu 1997

Projected field lines from single pole



Sweepback only ...

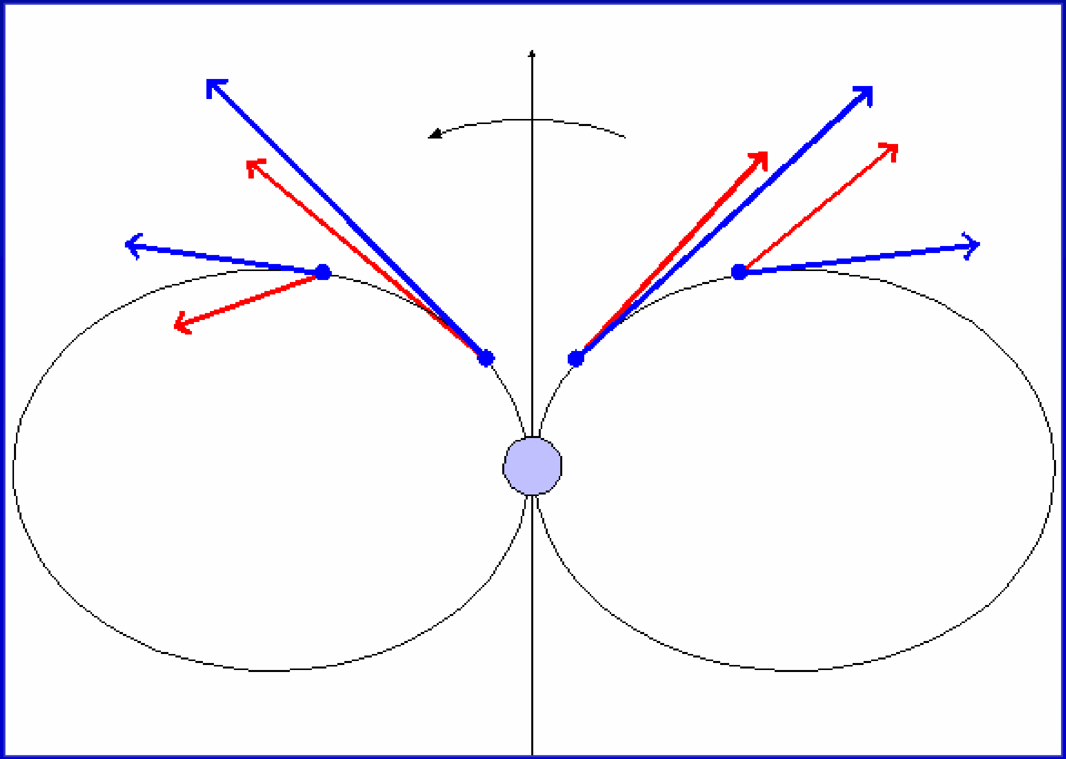
plus aberration ...

... and travel time delay

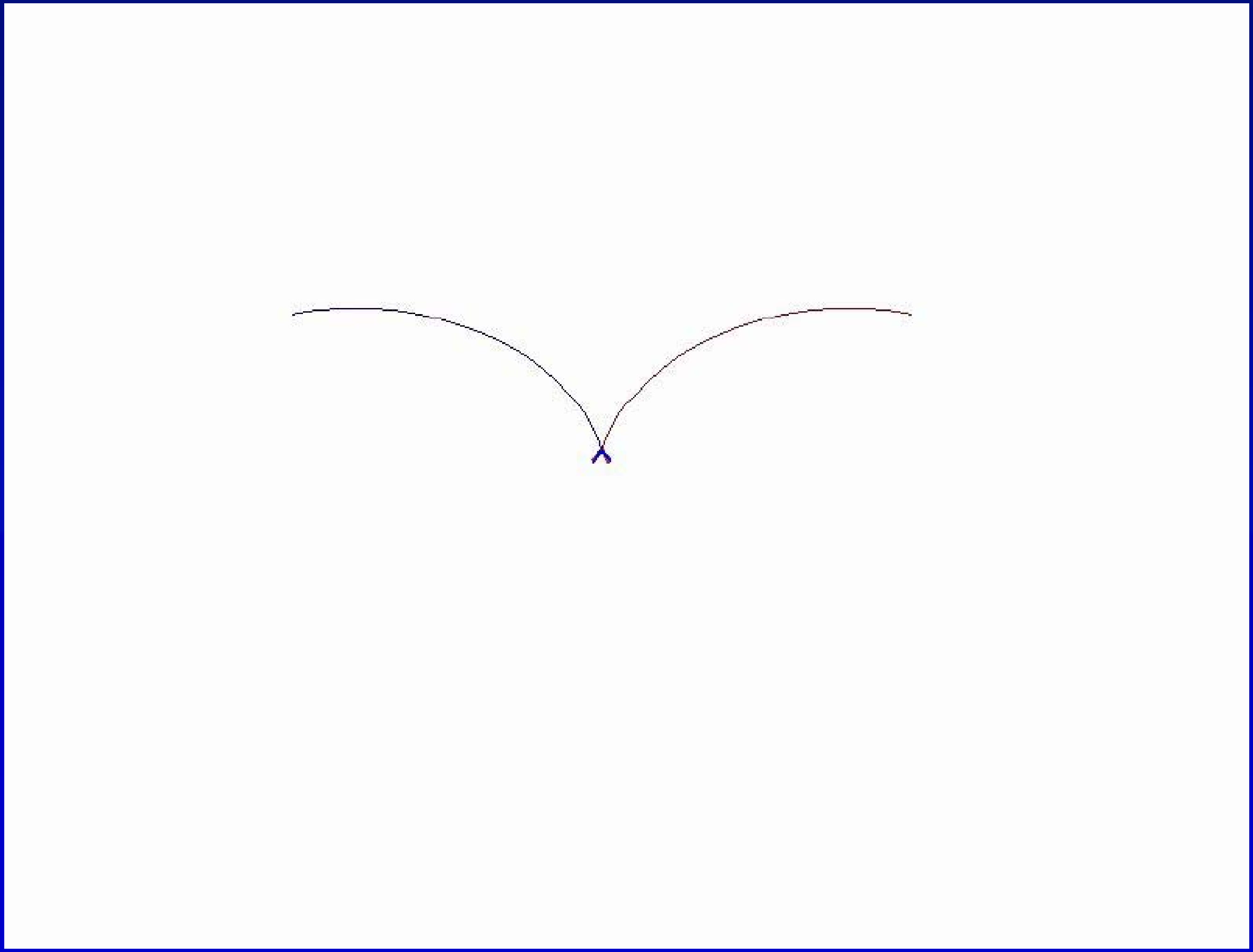
Yadigaroglu 1997

Caustic emission *Morini 1983*

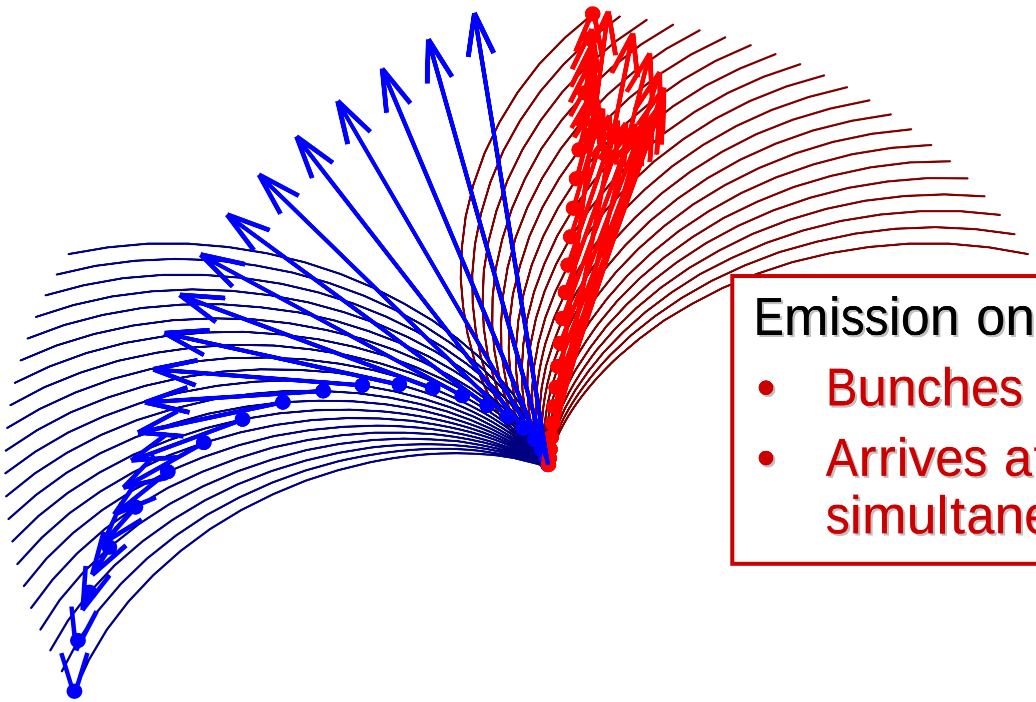
- Particles radiate along last open field line from polar cap to light cylinder
- Time-of-flight, aberration and phase delay cancel on trailing edge → emission from many altitudes arrive in phase → caustic peaks in light curve



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

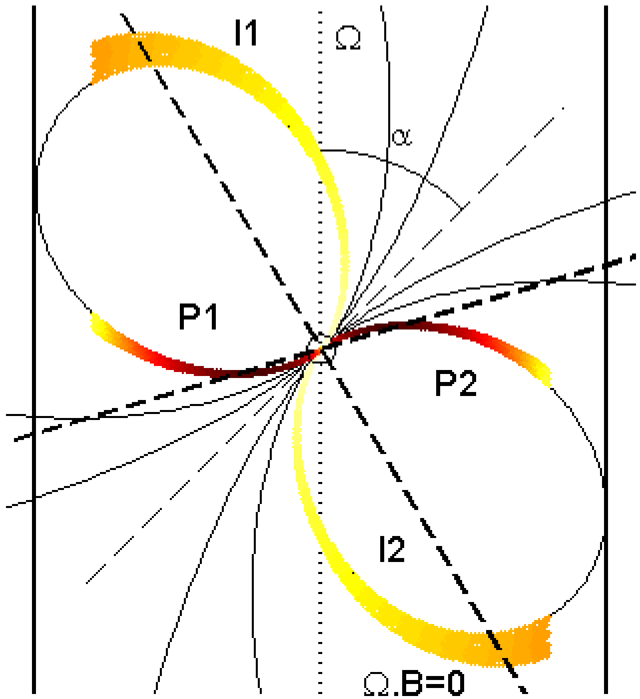
- Dipole magnetic field
- Outer edge of open volume

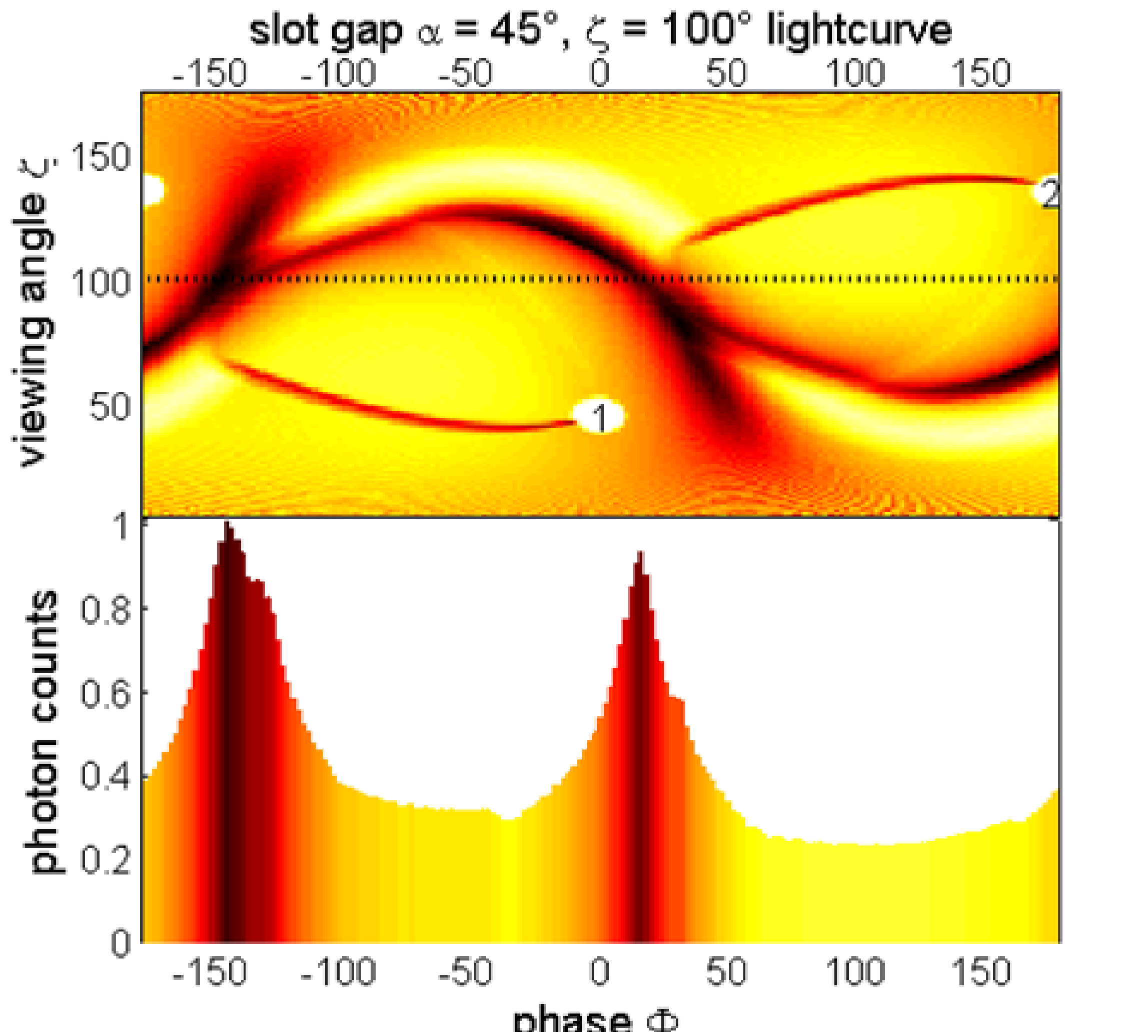
High-altitude slot gap - geometry

Two-pole caustic geometry

(Dyks & Rudak 2003, Dyks et al. 2004)

-> good pulse profiles for large α and ζ





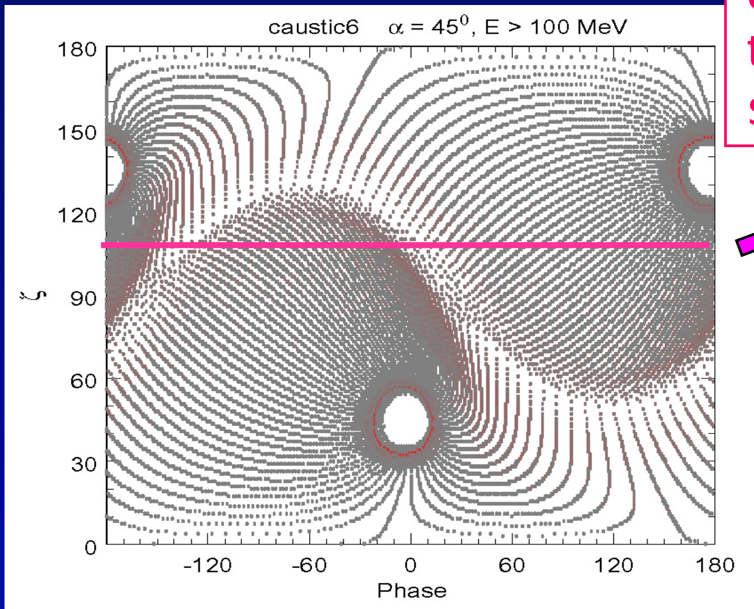
Problem:

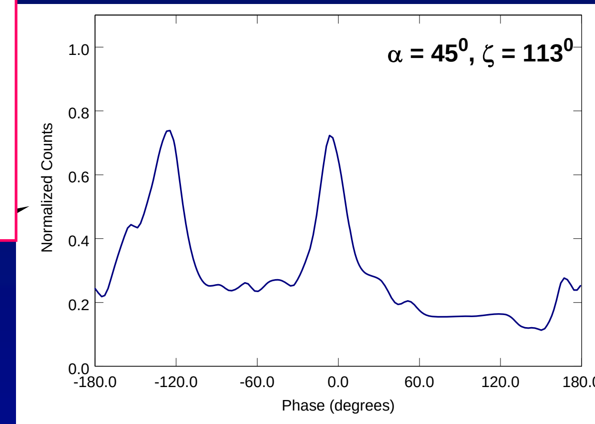
Reversals of $E_{||}$ on some field lines

Slot gap radiation

(Muslimov

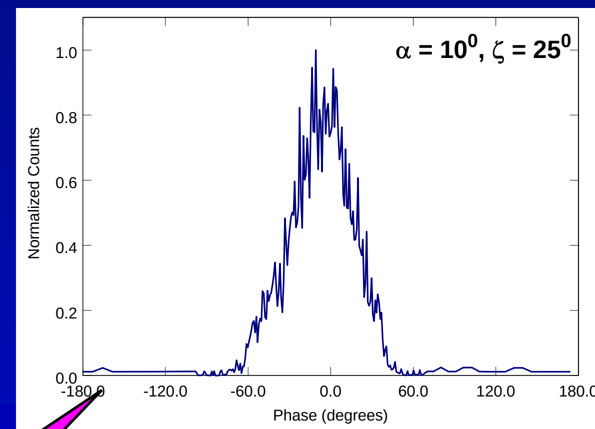
But CR alone does not give the right spectrum

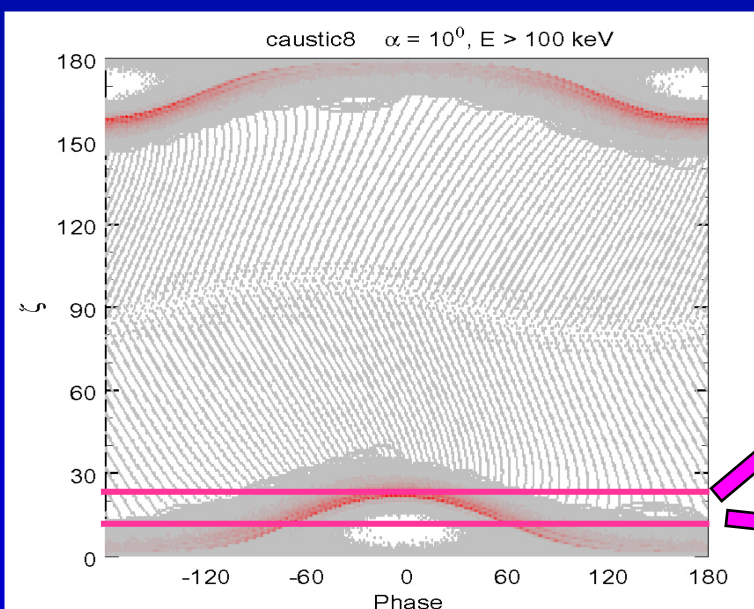


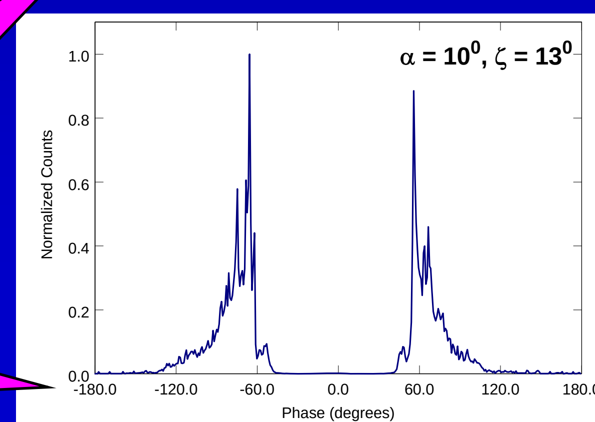


Two-pole caustic pattern at high altitude

Hollow cone from low-altitude pair cascades

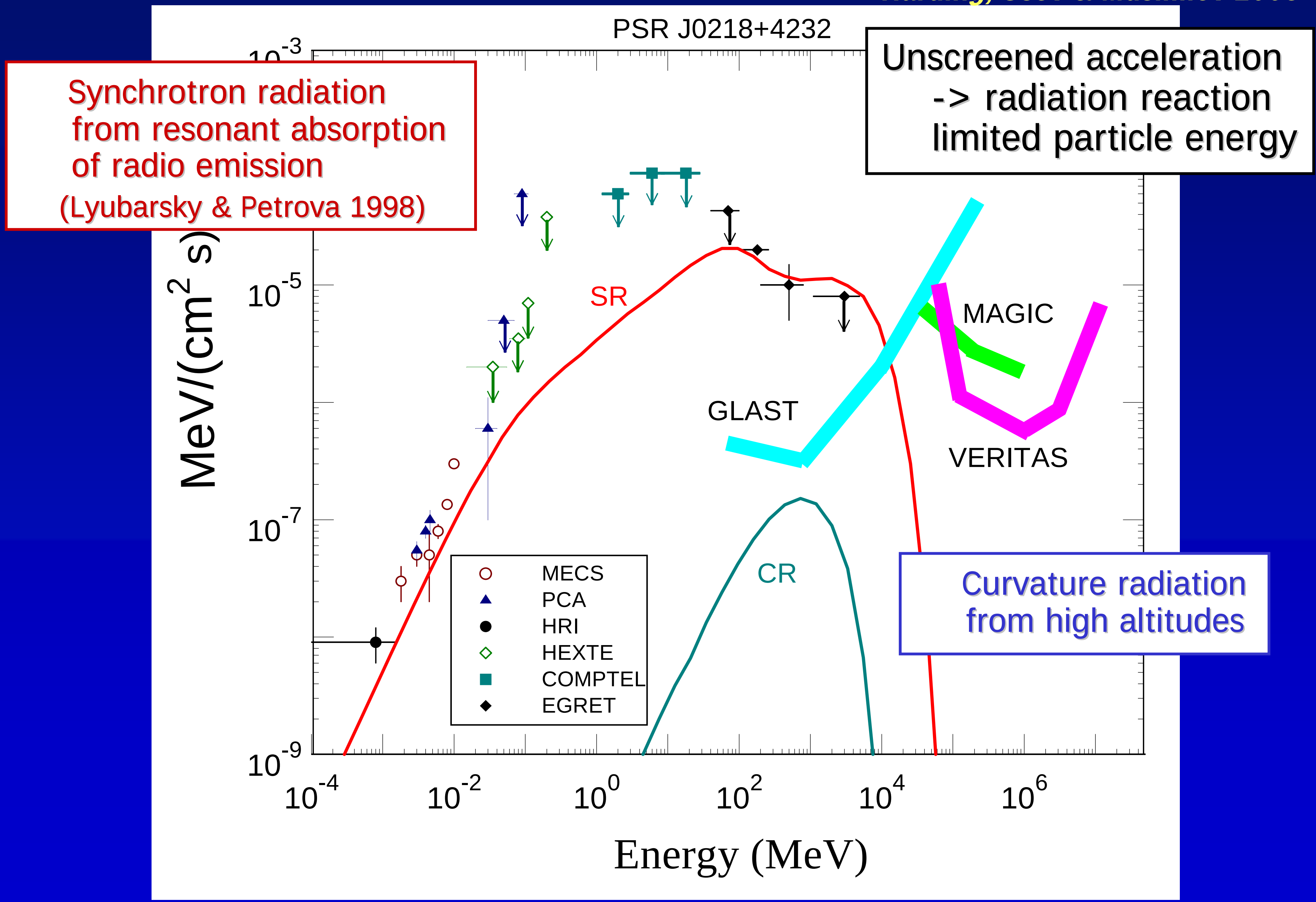






High energy spectrum of J0218+4232 in 2D

Harding, Usov & Muslimov 2005

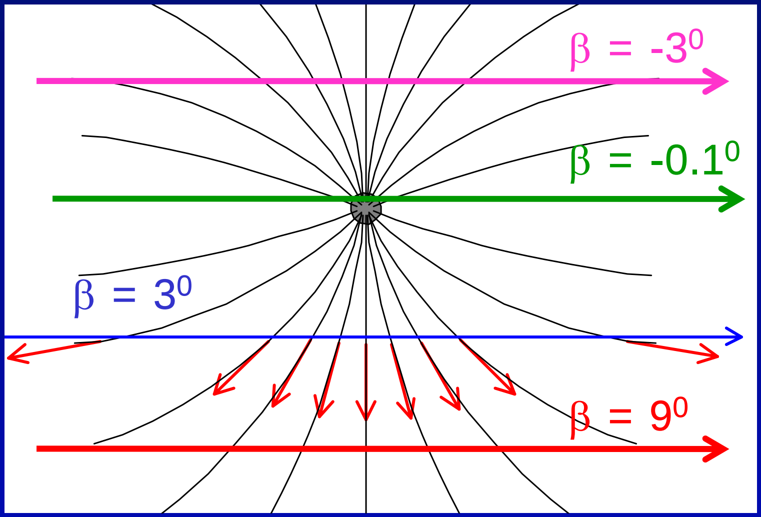


Radio beams of fast pulsars

- High altitude (Kijak & Gil 2003)

$$r_{radio} \approx .01\ r_{LC}\ \dot{P}_{-15}^{0.07} P^{-0.7} \nu_{GHz}^{-0.26}$$

- Flat polarization swings (RVM) (Johnston & Weisberg 2006, Crawford et al. 2003)



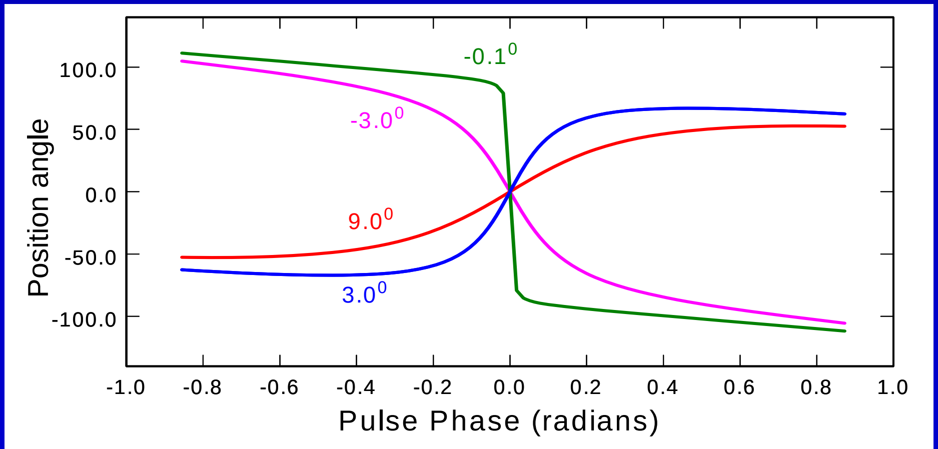
Line of sight

- Wide cone beams (Manchester 1996)

With distortion by relativistic effects

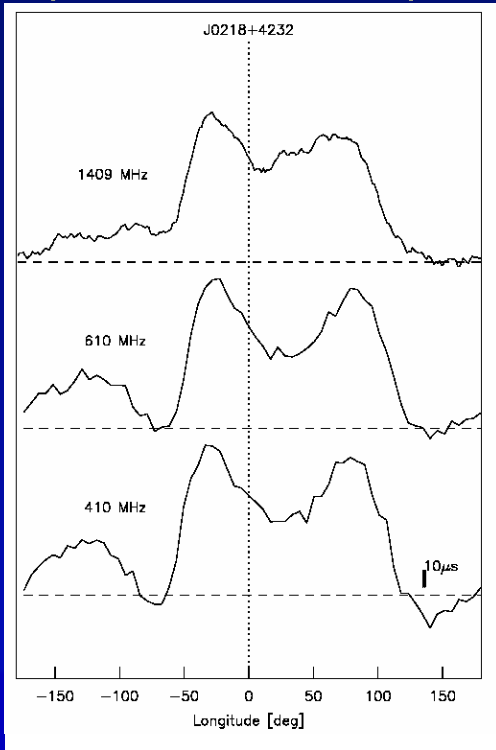
$$R_{core-to-cone} = \begin{cases} 16 P^{1.3} \nu_{GHz}^{-1} & \text{for}\quad P < 0.7s \\ 6.3 P^{-1.8} \nu_{GHz}^{-1} & \text{for}\quad P > 0.7s \end{cases}$$

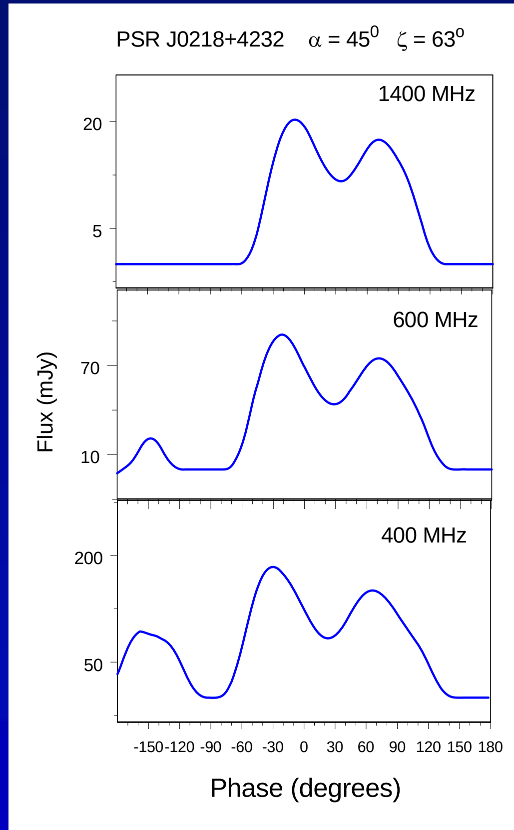
(Gonthier et al. 2006)



Radio profile of J0218+4232

(Kramer et al. 1999)





$$r_{radio} \approx 0.3\ r_{LC} \nu_{GHz}^{-0.26}$$

Use core and cone beams (Arzoumanian et al. 2002) with radius-to-frequency mapping (Kijak & Gil 2003)

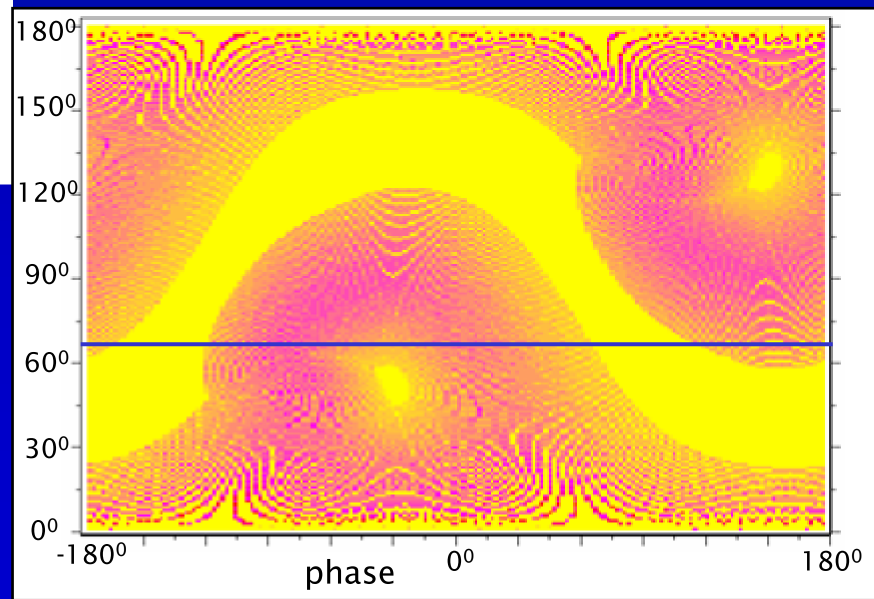
$$S_{cone}(\theta,\nu) = A(\nu)\ e^{(\theta-\bar{\theta})^2/w_e^2},$$

$$w_e = 0.8^0 \left(\frac{r_{radio}}{R}\right)^{1/2} p^{-1/2}$$

Cone beam

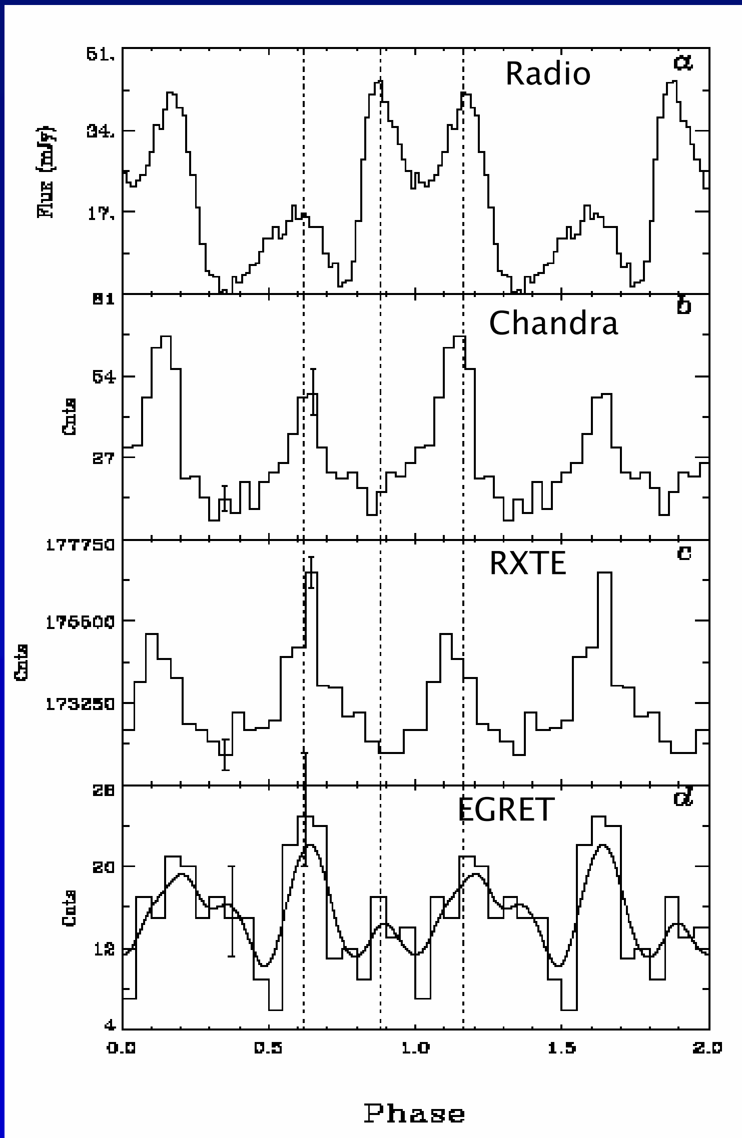
$\alpha = 45^0$

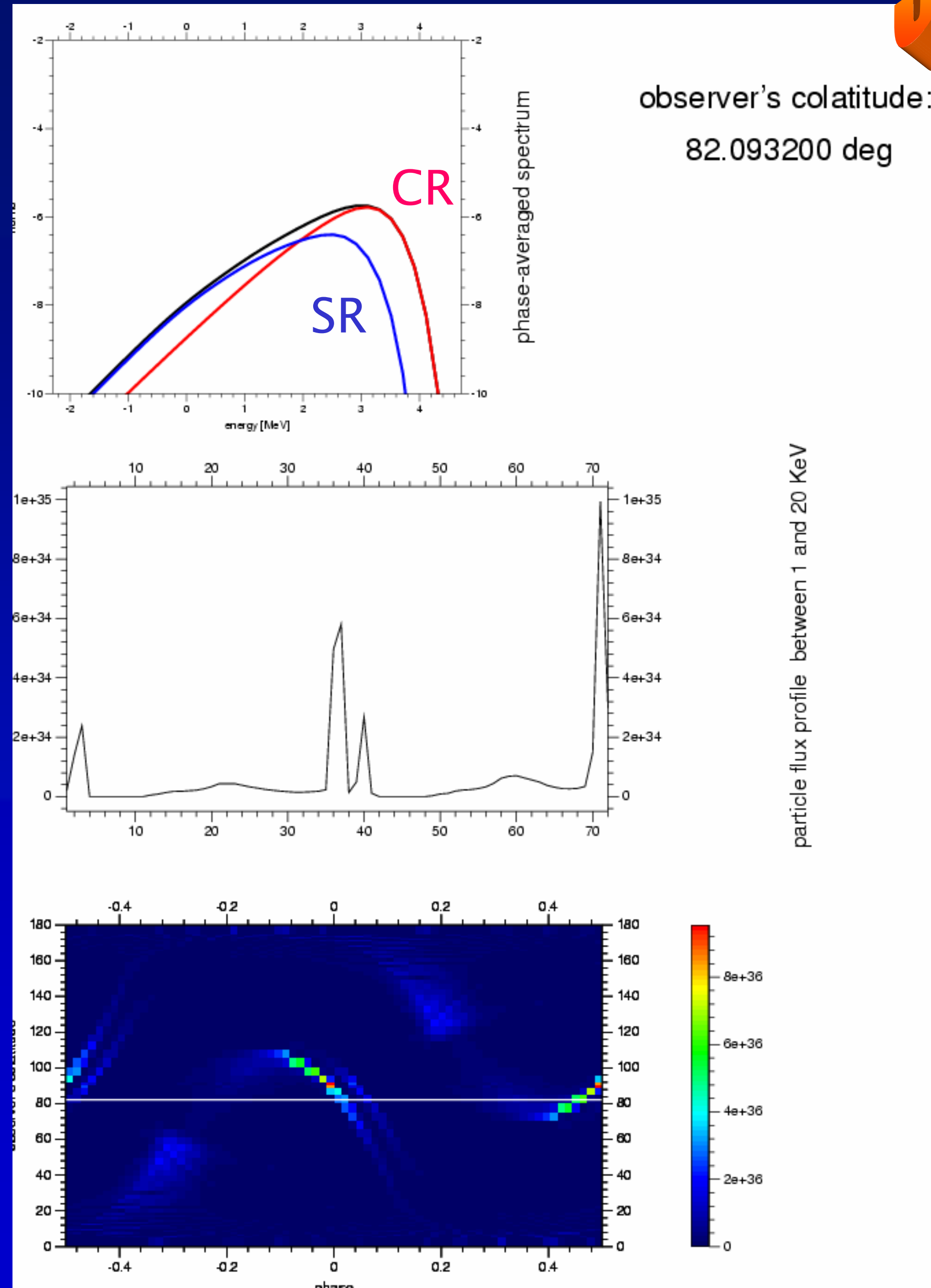
$\zeta = 63^0$



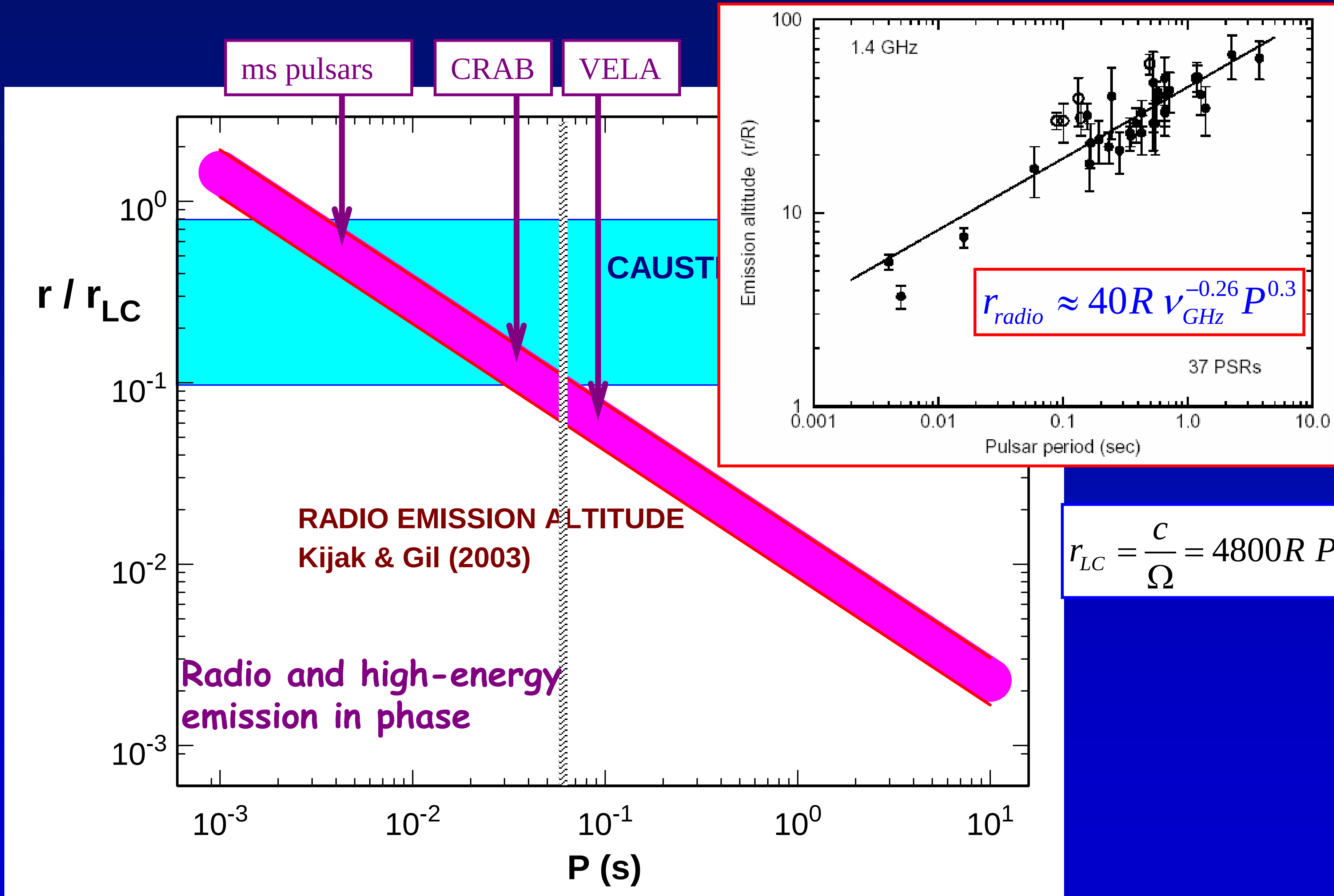
High energy emission of J0218+4232 in 3D

Stern, Dyks, Frackowiak,Harding, in prep



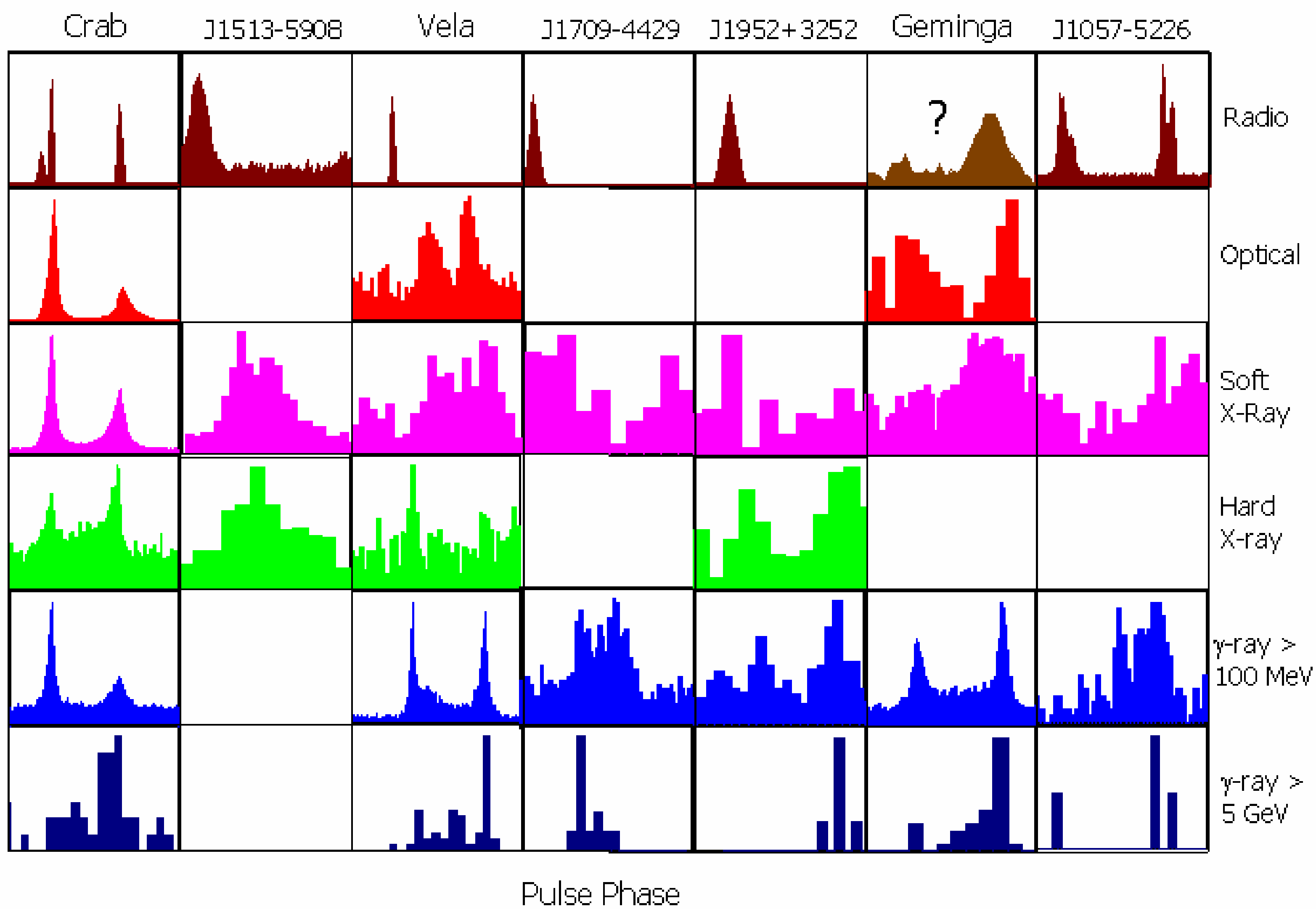


Radio caustic emission?

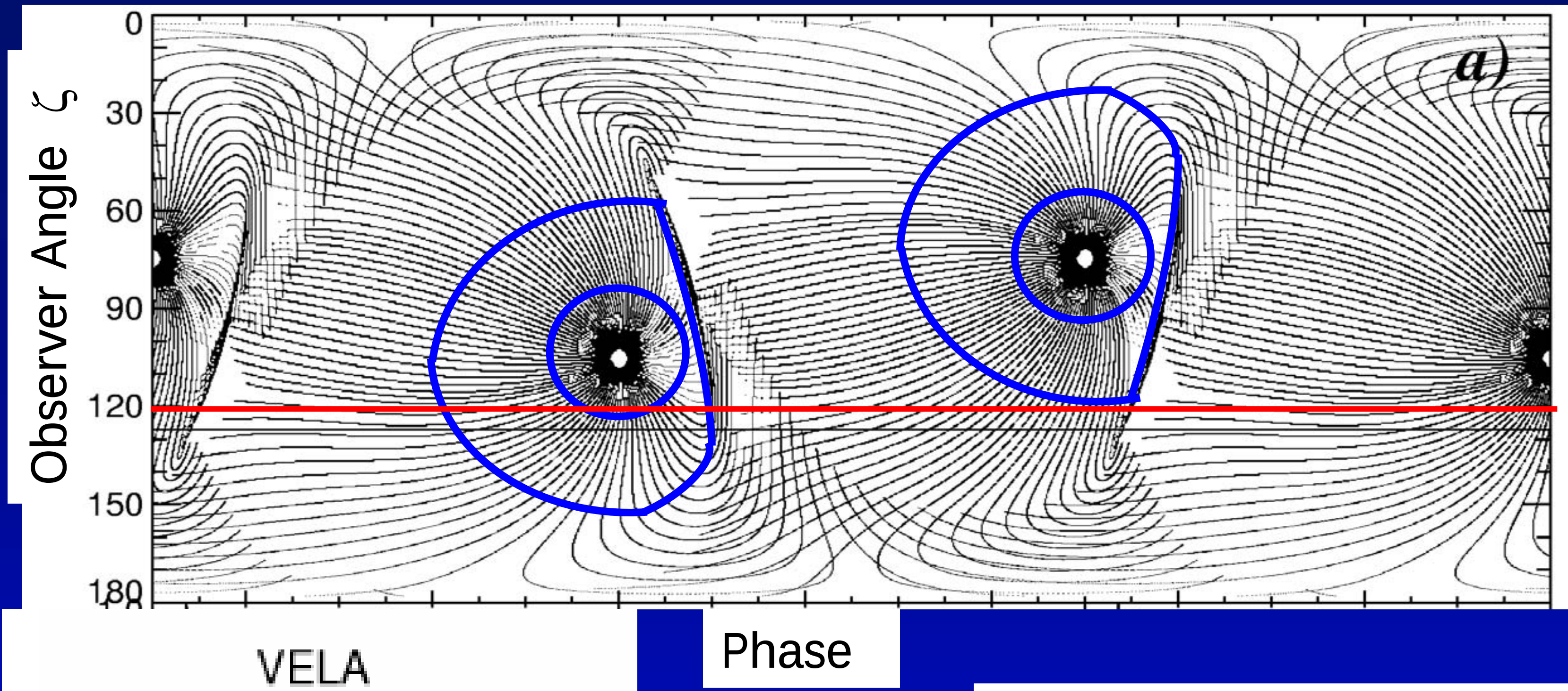


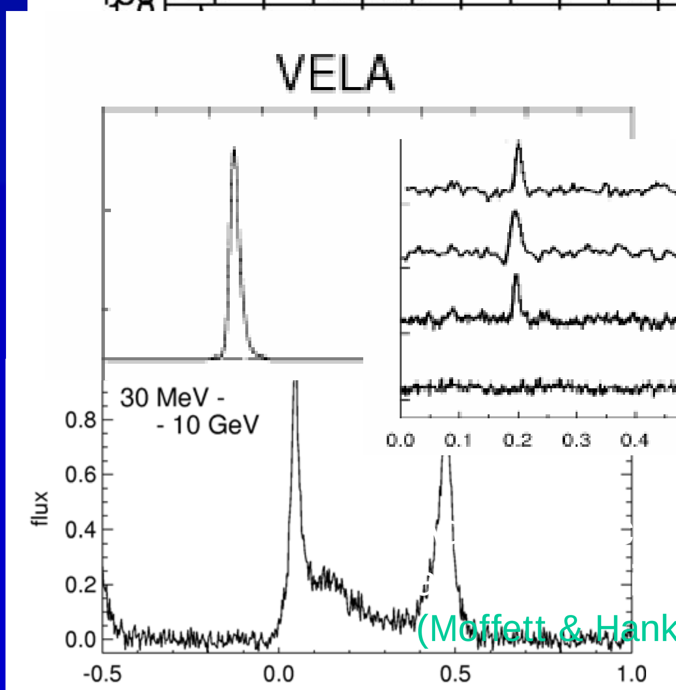
$$r_{LC} = \frac{c}{\Omega} = 4800 R\, P$$

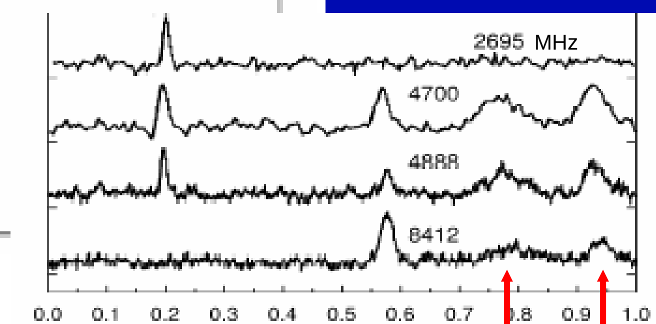
Multi-wavelength profiles of γ-ray pulsars



Gamma-ray and radio caustic peaks



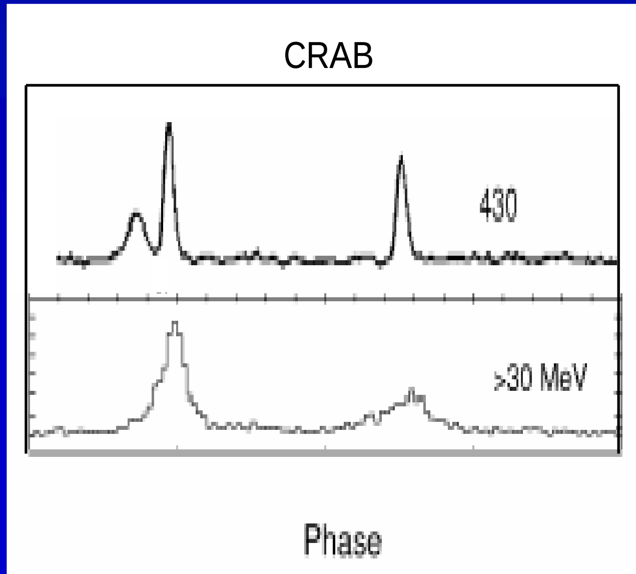




mponents appear

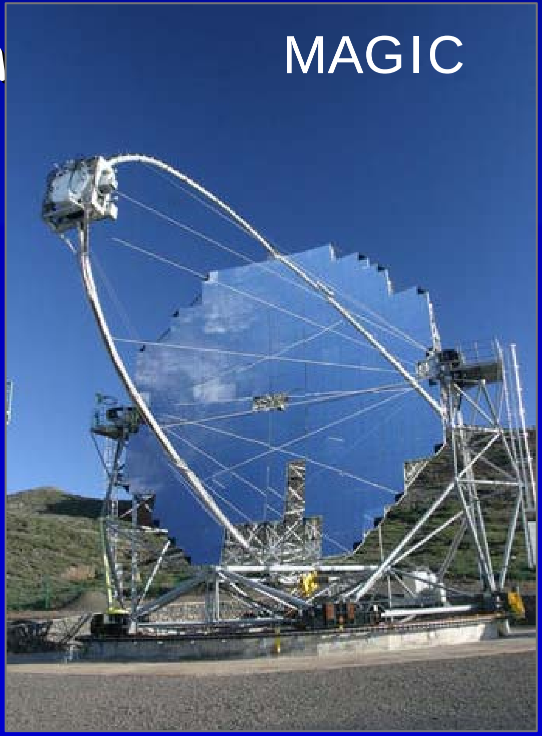
above 2 GHz

(Moffett & Hankins 1996)



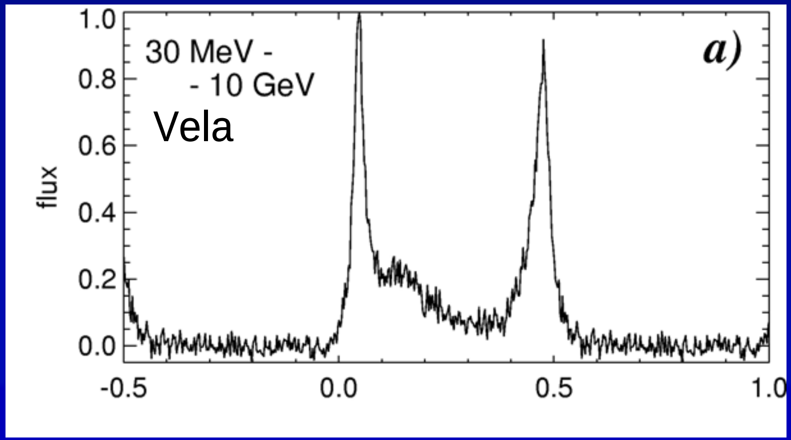
Open questions

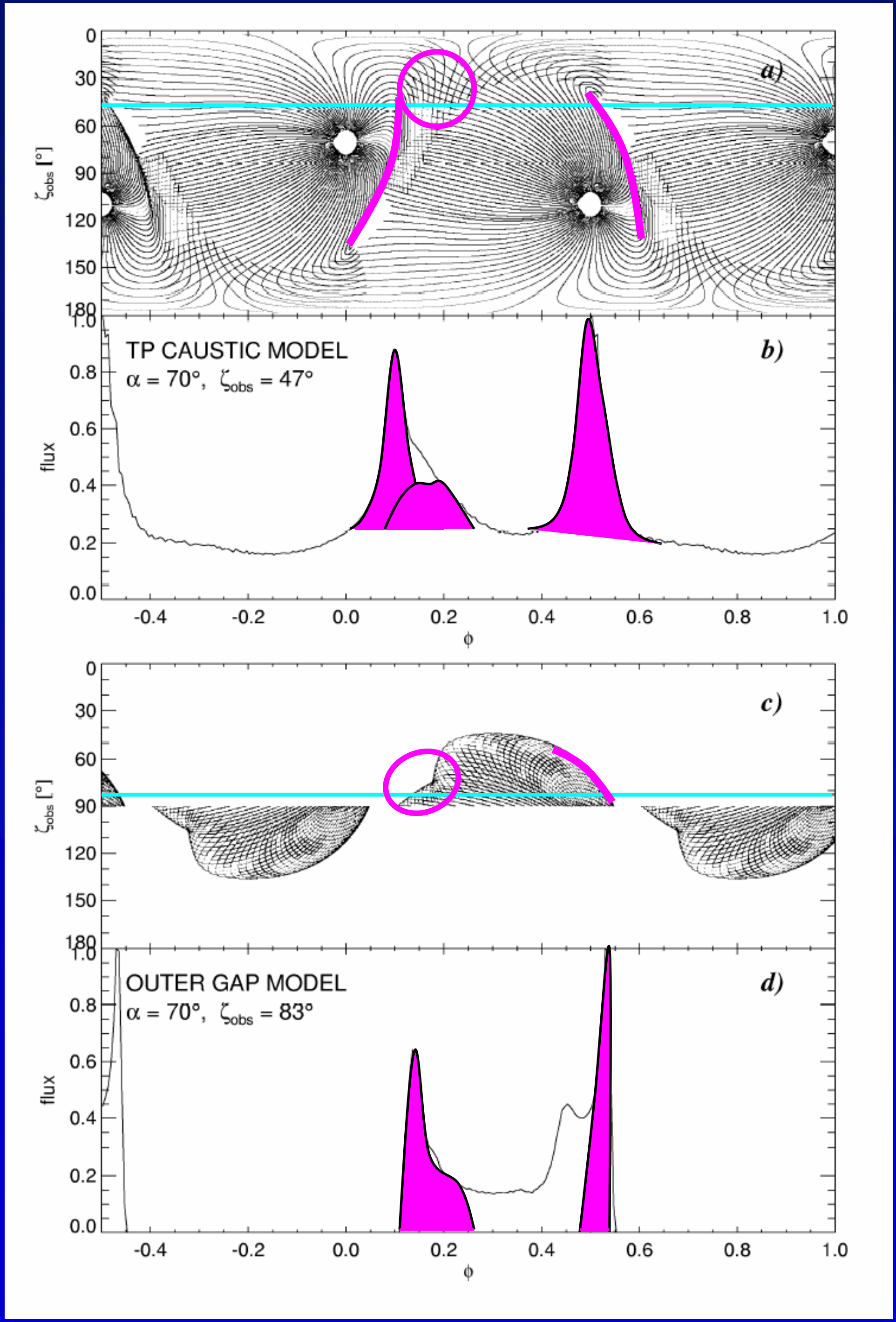
- What are the boundary conditions on charge flow?
  - SCLF or vacuum?
  - $\Omega \bullet B > or < 0$
- What is $E_{||}$ in high altitude slot gap?
  - Will distorted field lines avoid sign reversals?
  - Simulation of cross field particle m
- Connection of pair cascades to
  - Radio emission
  - Wind flow/solutions
- Slot gaps or outer gaps?



Two-pole caustic and outer gap models

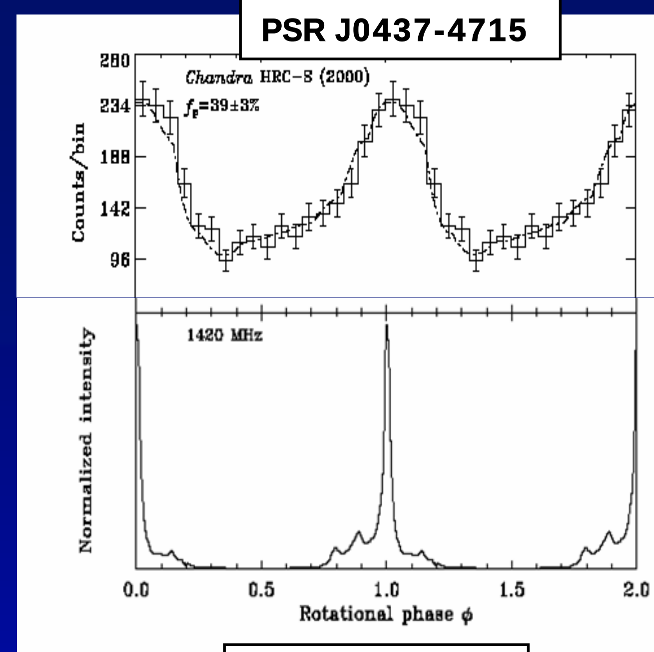
Dyks & Rudak 2003
Dyks, Harding & Rudak 2004

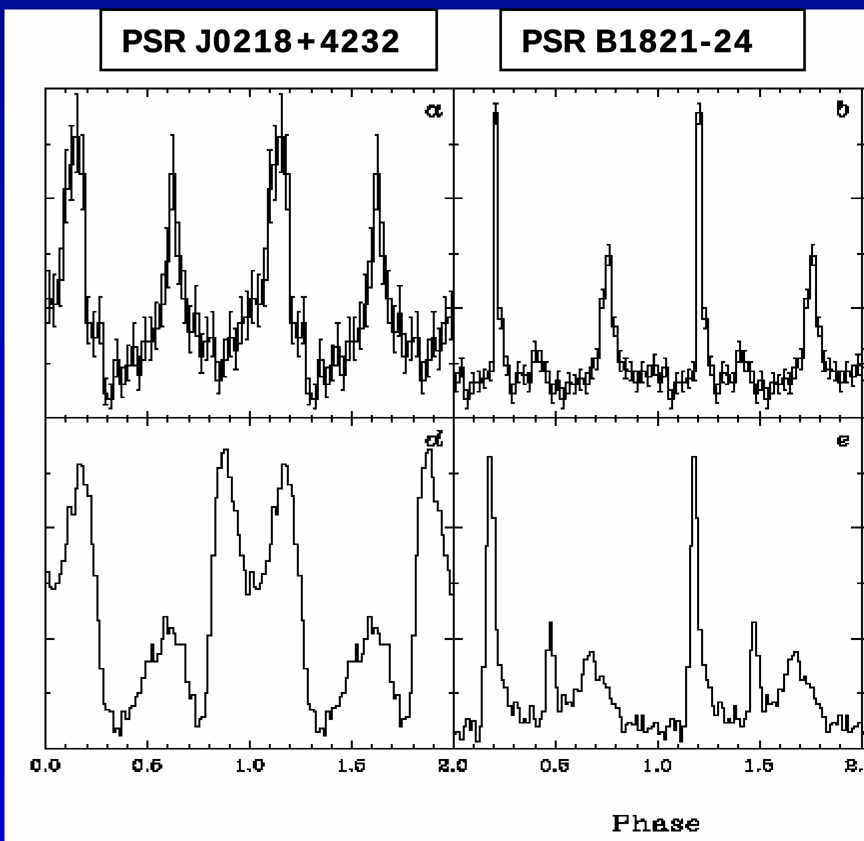




Profiles of millisecond pulsars

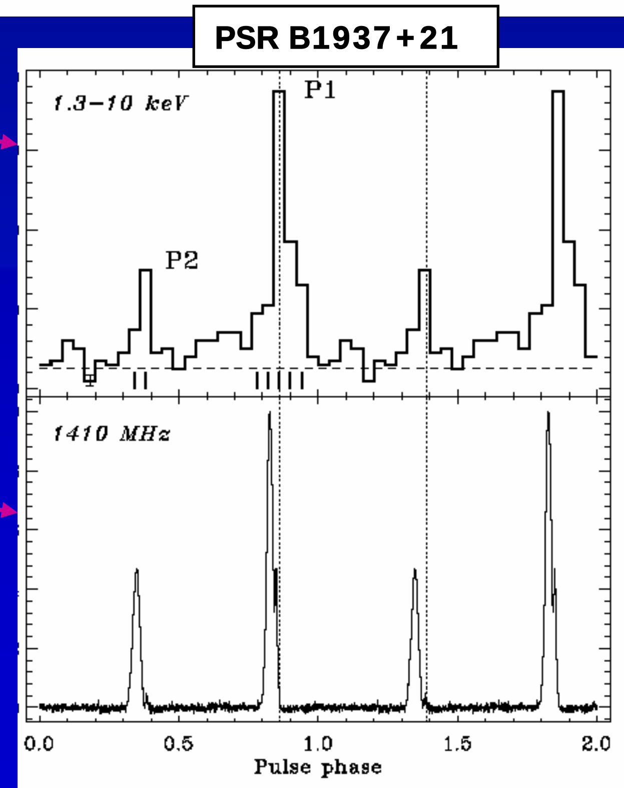
X-ray peaks (mostly) in phase with radio peaks





X-Ray

Radio



Pulsar high-energy emission models