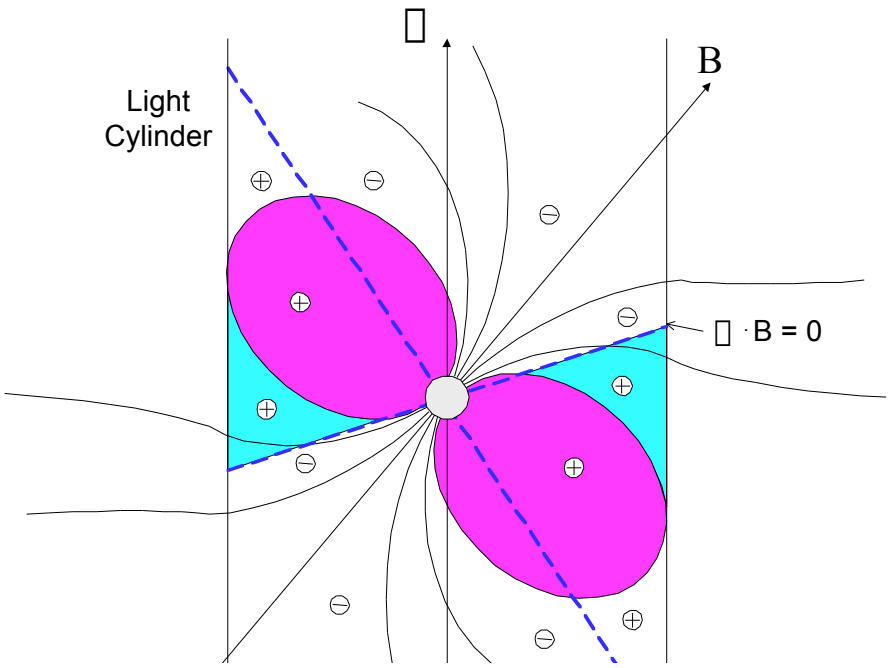
Polar Cap Emission: Modeling Acceleration and Beam Geometry

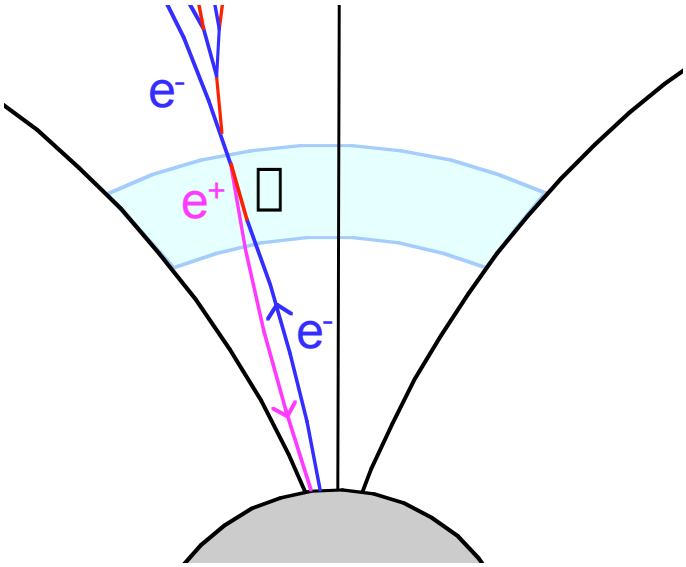
A.K. Harding
NASA Goddard Space Flight Center

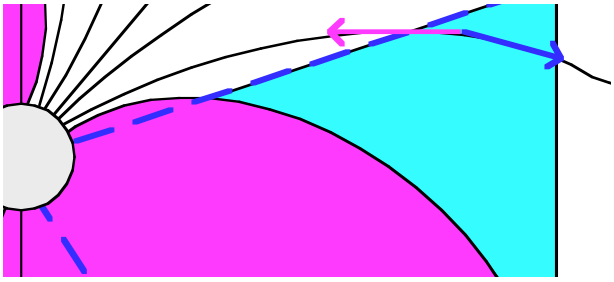
Collaborators: M. Baring, I. Grenier, P. Gonthier, A. Muslimov, B. Zhang

- Polar cap acceleration & Pairs
- Electric field screening – Limits on acceleration
- High-energy luminosity
- Geometry of γ-ray and radio beams

Pulsar Acceleration and Pairs







Polar cap

Outer gap

Polar Cap Acceleration

- What's new?
  - GR inertial frame dragging

    Muslimov & Tsygan 1992

$$E_{\parallel} = 10^{6}\,\mathrm{esu}\,\frac{B_{12}}{P}\,\square_{0.15}\,\begin{cases} 1.3\ z\ P^{\square 1/2}, & \textit{unsaturated} \\ 5\,\square\,10^{\square 3}\,P^{\square 1}, & \textit{saturated} \end{cases}$$

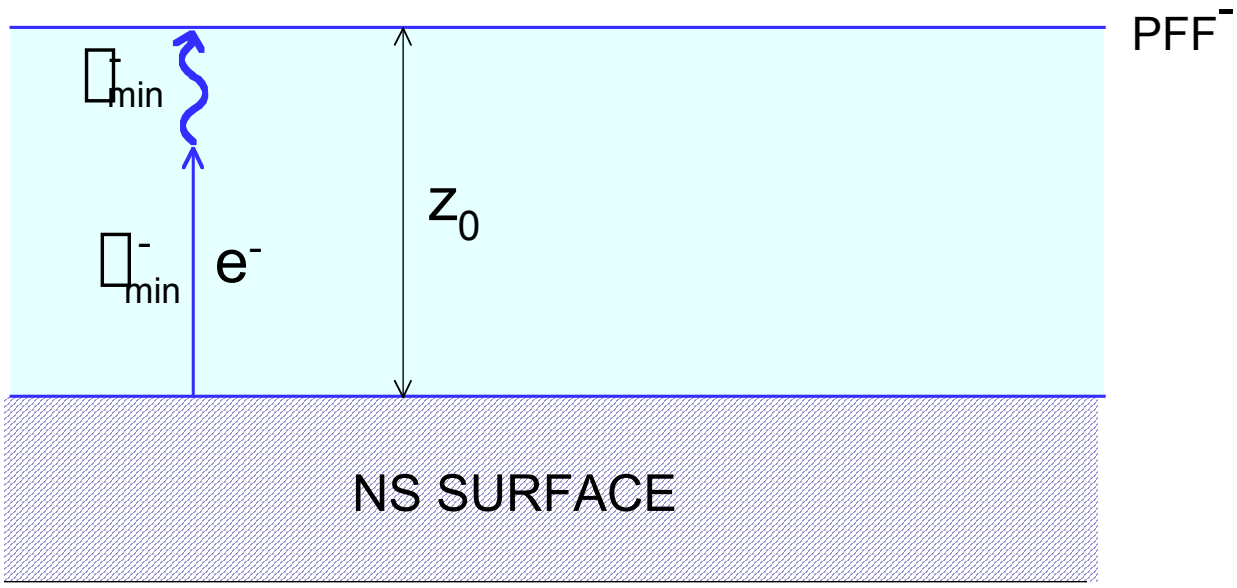
$$\square = \frac{r_g I}{MR^3}$$

  - Inverse Compton pairs

    Zhang et al 1997, Harding & Muslimov 1998

    Acceleration limit?

The Pair Formation Front



$$S_0 = z_0 R = \min[S_a(\gamma_{\min}) + S_p(\gamma_{\min})]$$

- Curvature Radiation $\gamma_{CR} = \frac{3}{2}\frac{\hbar}{mc}\frac{\gamma^3}{\rho_c}$

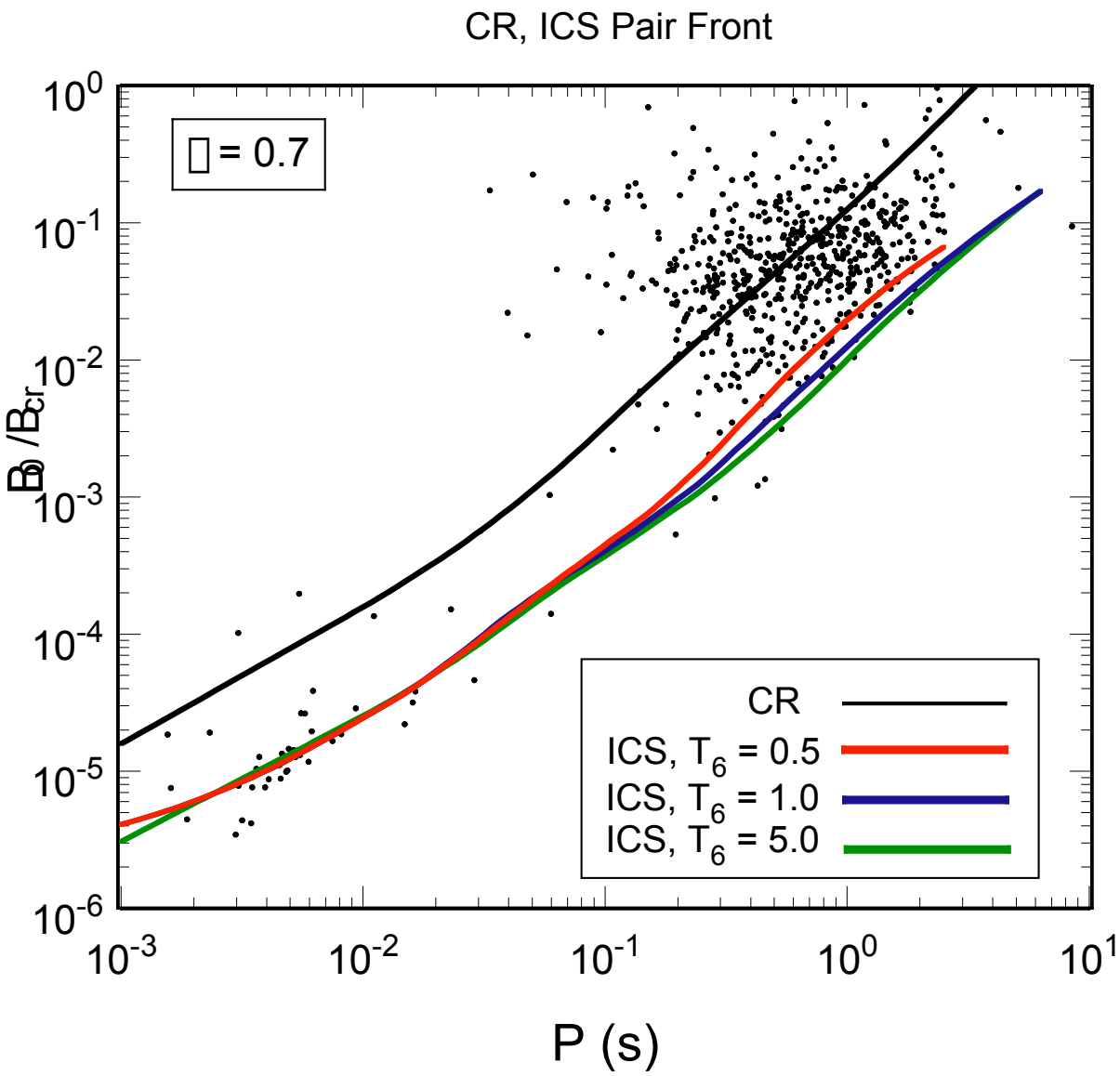
$$z_0 \propto 0.3 \begin{cases} 2 P^{11/14} B_{12}^{-4/7} \\ 16.8 P^{7/4} B_{12}^{-1} \end{cases}$$

- Resonant ICS $\gamma_{RICS} = 2\gamma B/B_{cr}$

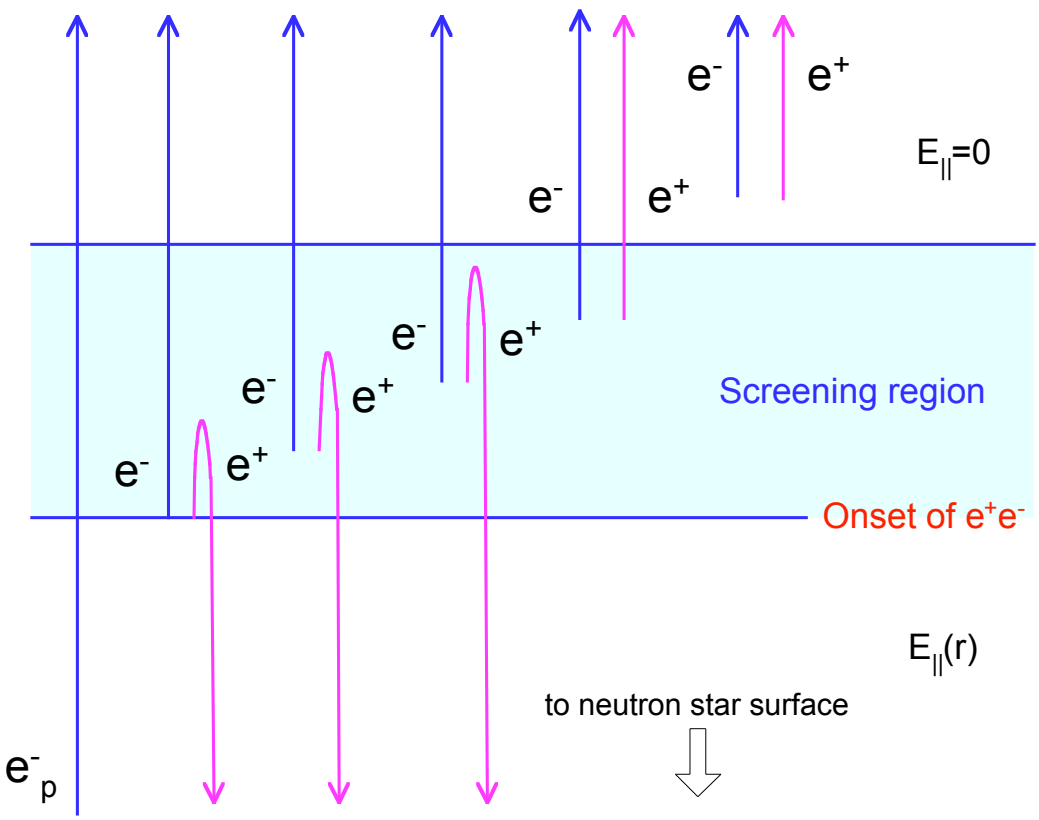
$$z_0 \propto 0.01 \begin{cases} 7 P^{2/3} B_{12}^{-1} \\ 7 P^{5/4} B_{12}^{-3/2} \end{cases}$$

- Non-resonant ICS $\gamma_{NRICS} = \gamma$

$$z_0 \propto 0.01 \begin{cases} 3 P^{2/3} B_{12}^{-2/3} \\ 4 P^{5/4} B_{12}^{-1} \end{cases}$$


CR, ICS Pair Front
= 0.7
CR
ICS, T6 = 0.5
ICS, T6 = 1.0
ICS, T6 = 5.0
B0 /Bcr
P (s)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-3
10^-2
10^-1
10^0
10^1

Polar cap model:
Electric field screening & Polar cap heating



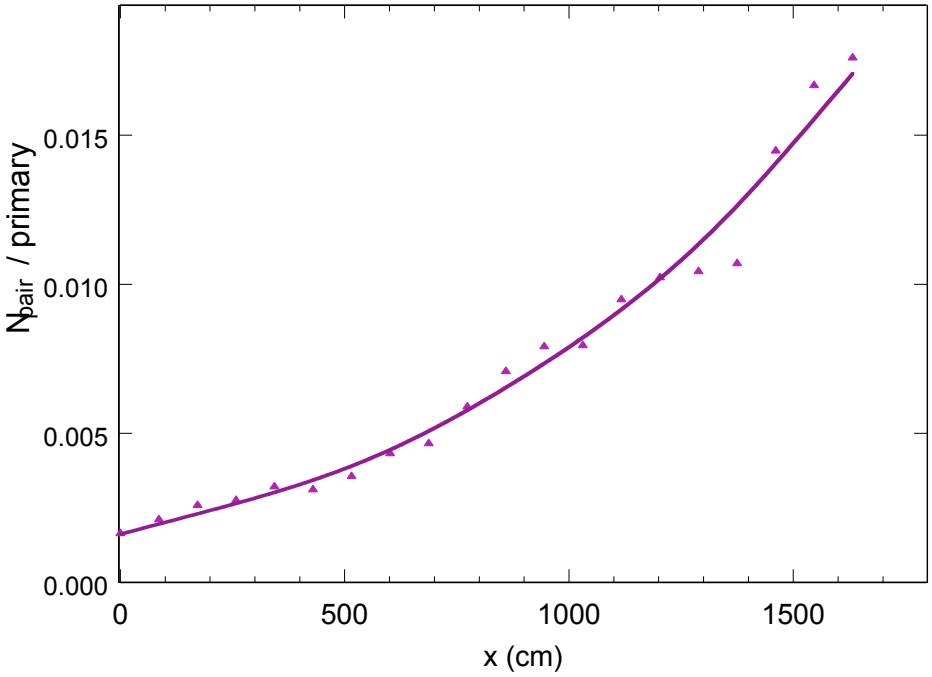
Maximum fraction of returning positrons:

$$f_+ = \frac{\square_+}{\square_{GJ}} = \left.\frac{\square_{GJ}\,\square\,\square}{2\square_{GJ}}\right|_{z_0} \square\, \frac{3}{2}\frac{\square}{(1\square\square)} z_0$$

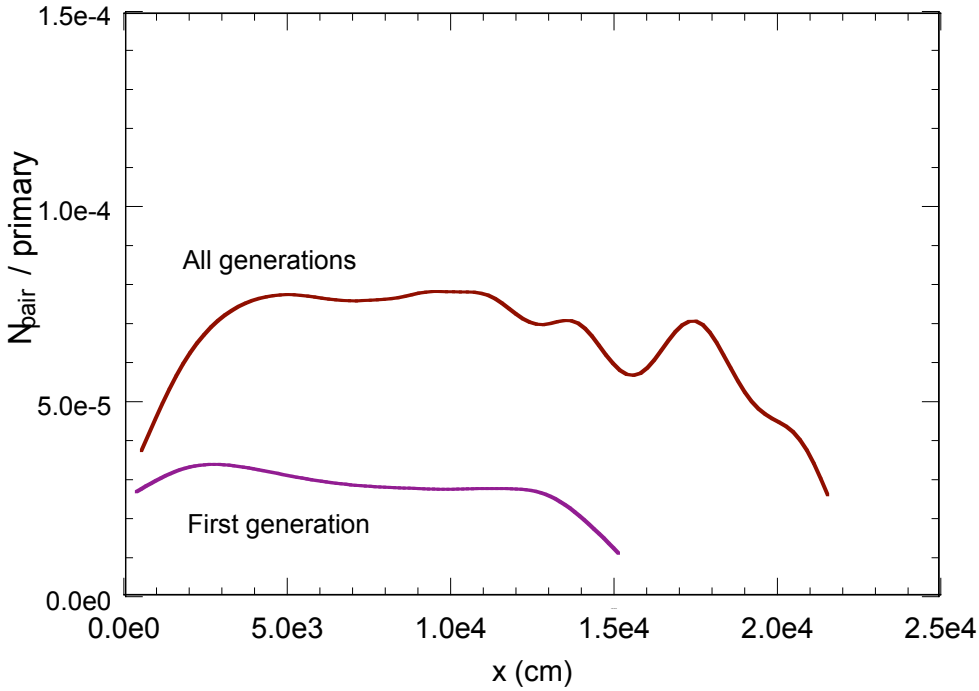
$$L_+^{\max} = f_+ \square\,(z_0)\,\dot{n}_{prim}$$

Pair Source Function

Curvature radiation

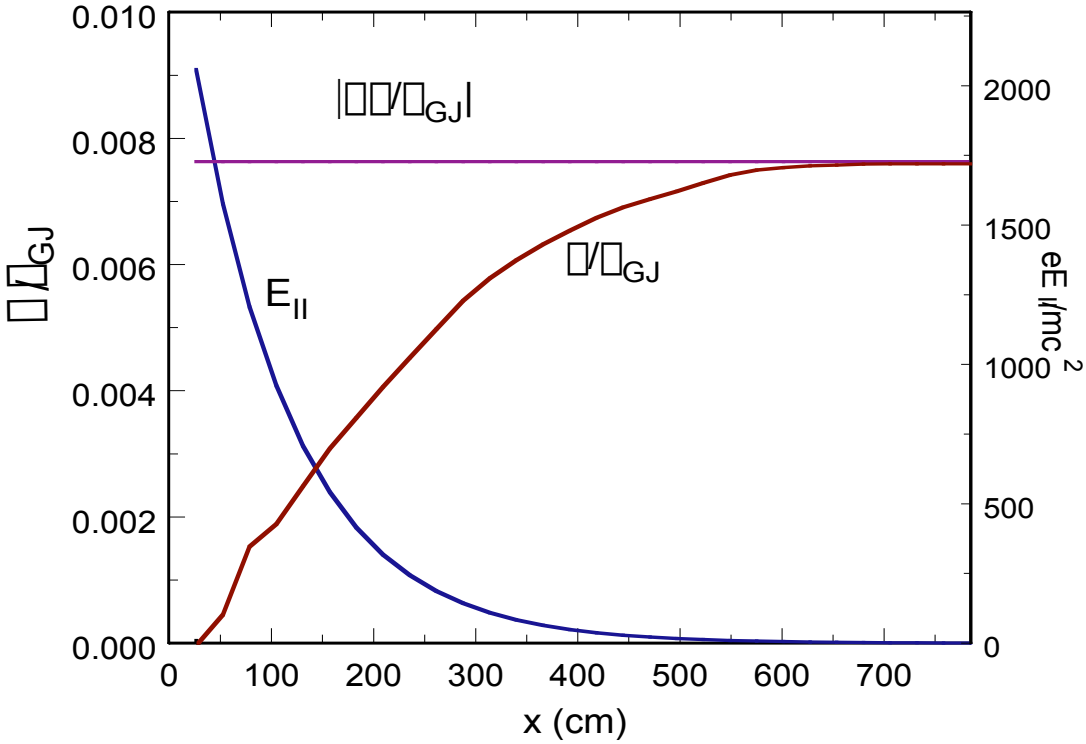


Inverse Compton radiation

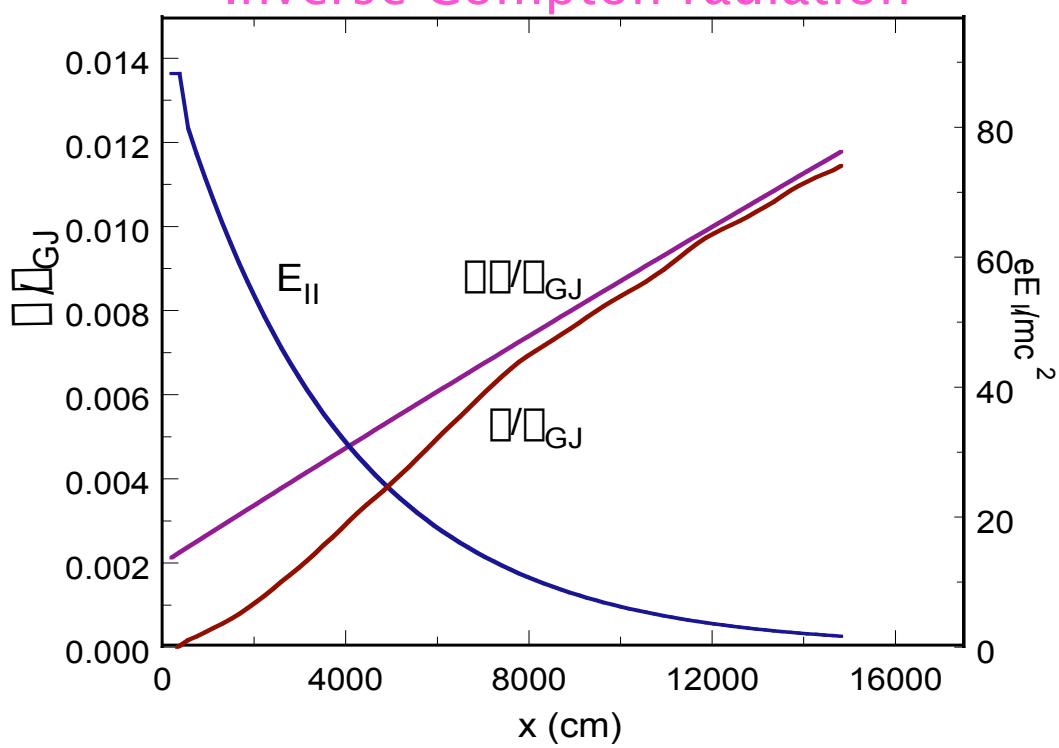


Screening $E_{||}$

Curvature radiation



Inverse Compton radiation



Voltage at the Pair Formation Front and γ-ray Luminosity

$$L_\gamma \approx \Phi(z_0)\dot{n}_{prim} = \Phi(z_0) n_{GJ} \pi R_{PC}^2 c$$

- Curvature Radiation

$$\Phi(z_o) = 10^{13} V \begin{cases} \kappa(\rho_6 / P)^{1/14} \\ P^{-1/4} \end{cases}$$

Nearly constant!!

$$L_\gamma = 10^{32}\,\mathrm{erg/s} \begin{cases} 0.3 P^{-27/14} B_{12}^{6/7} \\ 0.1 P^{-9/4} B_{12} \end{cases} \begin{cases} \dot{E}_{rot} \\ \dot{E}_{rot}^{1/2} \end{cases}$$

- Resonant ICS

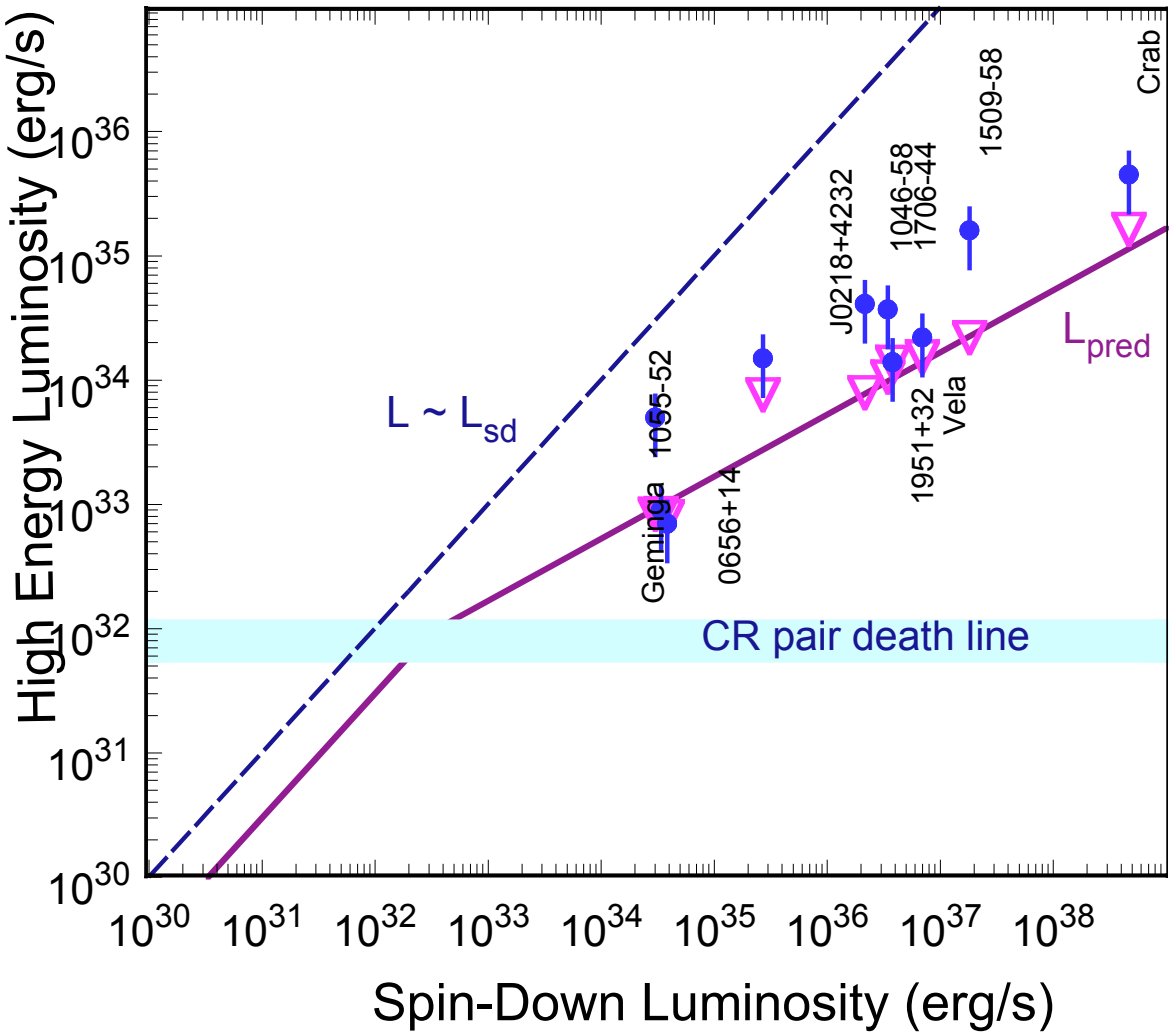
$$\Phi(z_o) = 10^{11} V \begin{cases} \kappa P^{-7/6} \rho_6^{1/2} \\ P^{-5/4} \rho_6^{1/4} \end{cases}$$

$$L_\gamma = 10^{31}\,\mathrm{erg/s} \begin{cases} 0.3 P^{-13/6} \\ 0.05 P^{-11/4} B_{12}^{1/2} \end{cases} \begin{cases} \dot{E}_{rot} \\ \dot{E}_{rot}^{1/2} \end{cases}$$

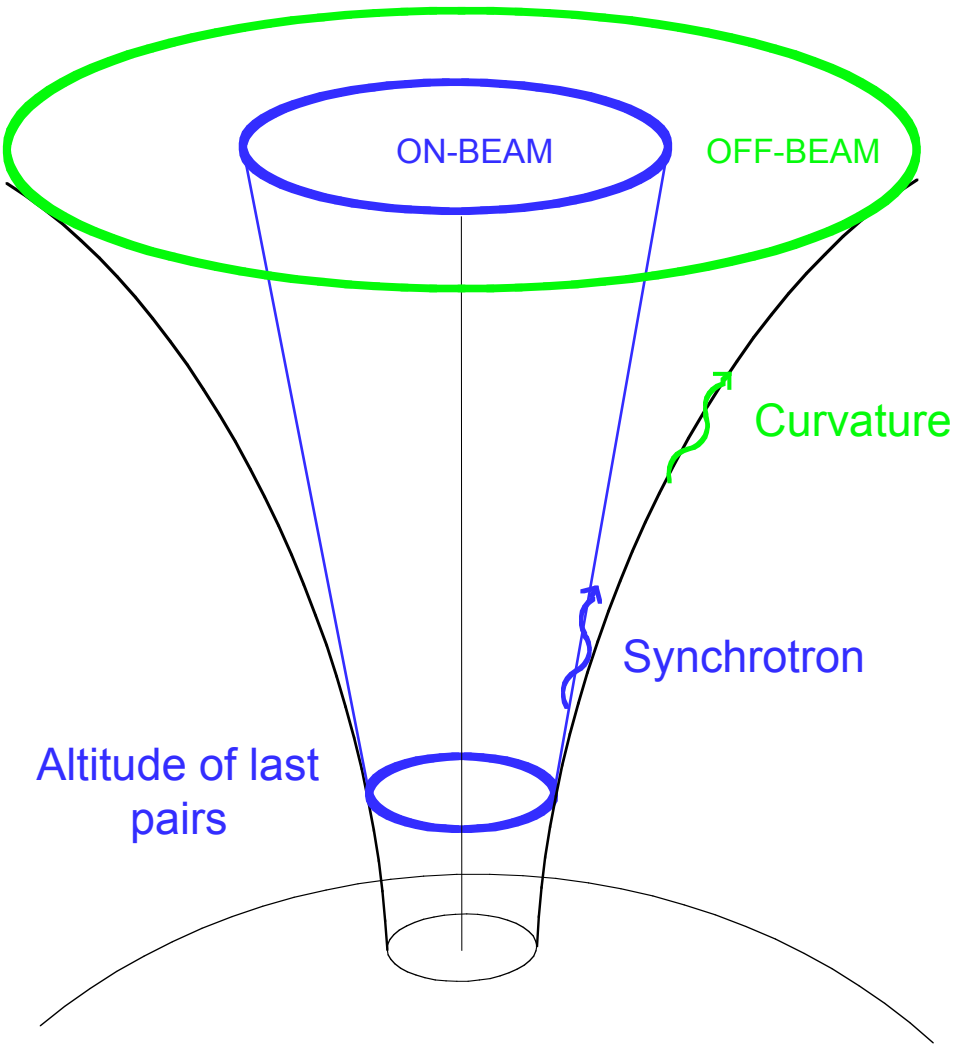
- Non-resonant ICS

$$\Phi(z_o) = 10^{11} V \begin{cases} \kappa P^{-1/2} \rho_6^{1/6} \\ P^{-3/4} \end{cases}$$

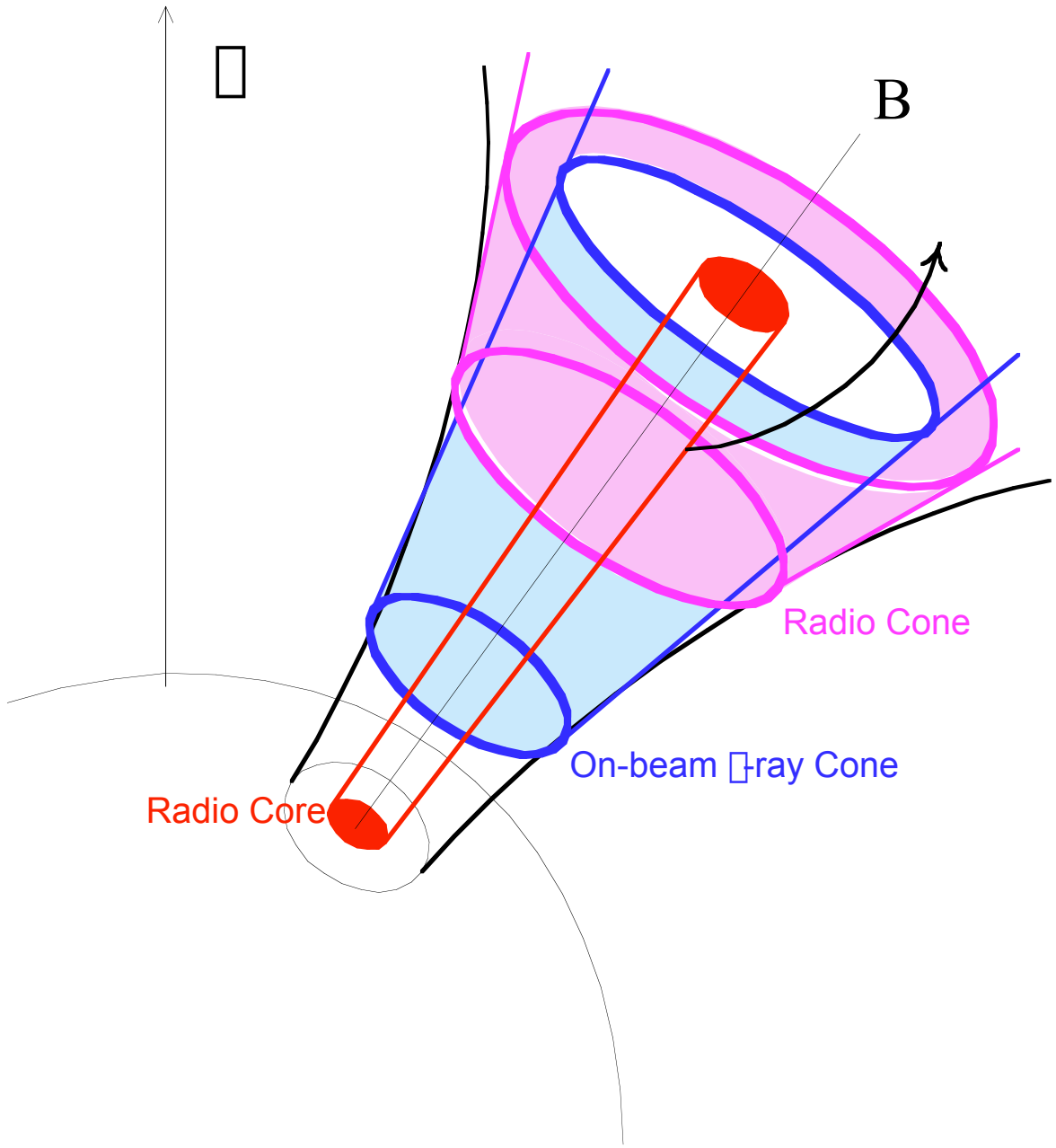
$$L_\gamma = 10^{30}\,\mathrm{erg/s} \begin{cases} 0.3 P^{-13/6} B_{12}^{2/3} \\ 0.1 P^{-11/4} B_{12} \end{cases} \begin{cases} \dot{E}_{rot} \\ \dot{E}_{rot}^{1/2} \end{cases}$$


High Energy Luminosity (erg/s)
Spin-Down Luminosity (erg/s)
10^{30}
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
10^{37}
10^{38}
L ~ L_{sd}
L_{pred}
CR pair death line
Geminga
1055-52
0656+14
J0218+4232
1046-58
1706-44
1951+32
Vela
1509-58
Crab

Geometry of PC γ-ray beams

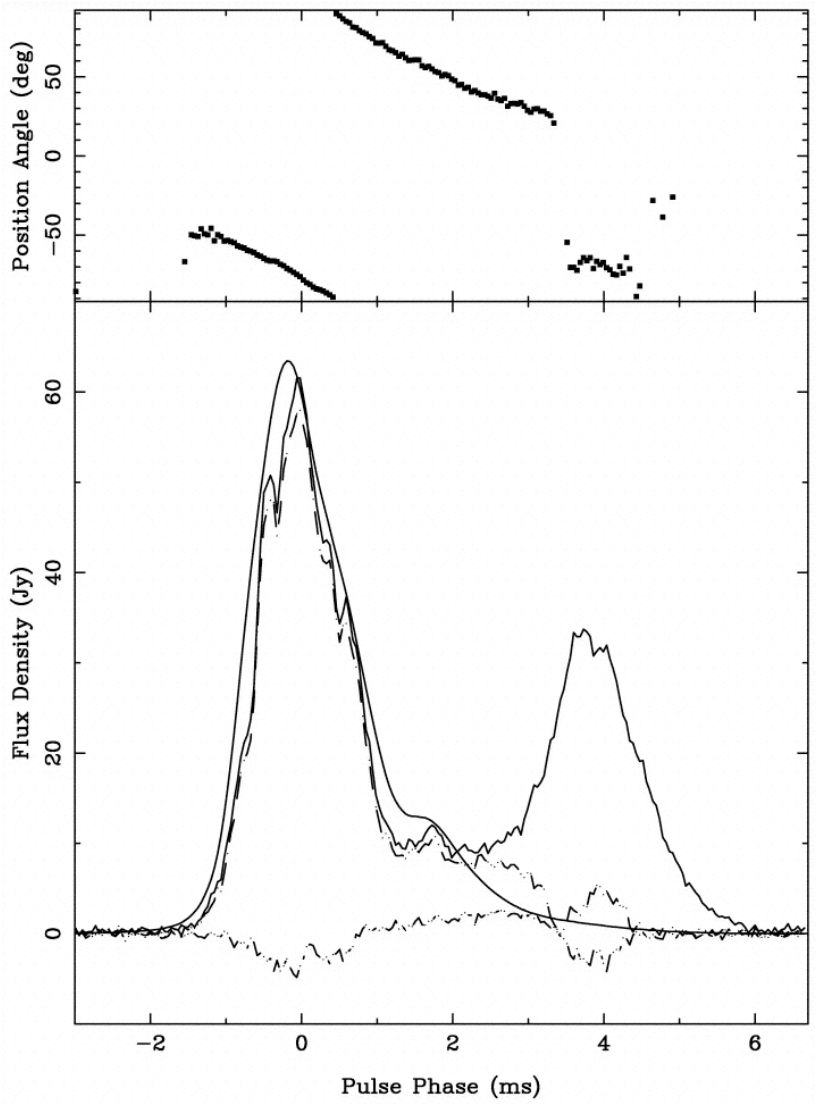


Geometry radio and γ-ray beams

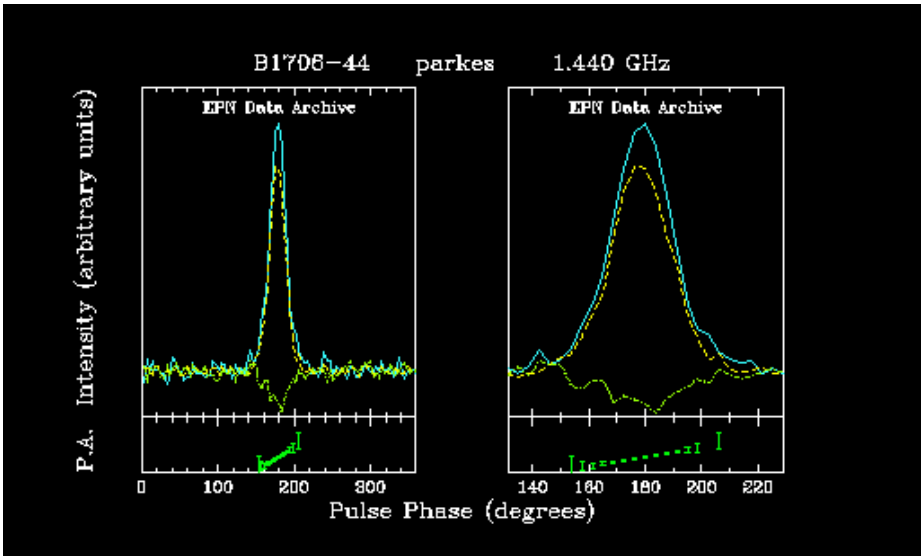


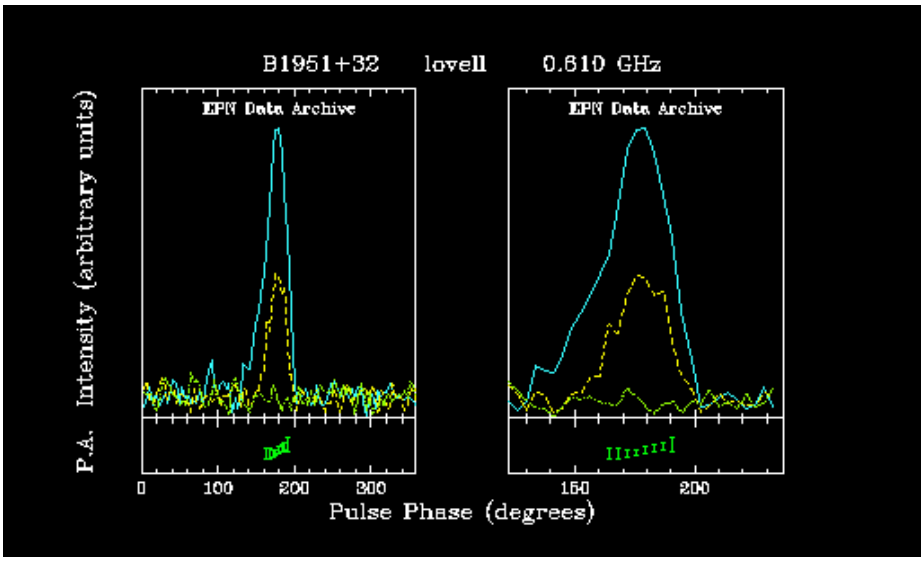
Vela pulsar radio profile

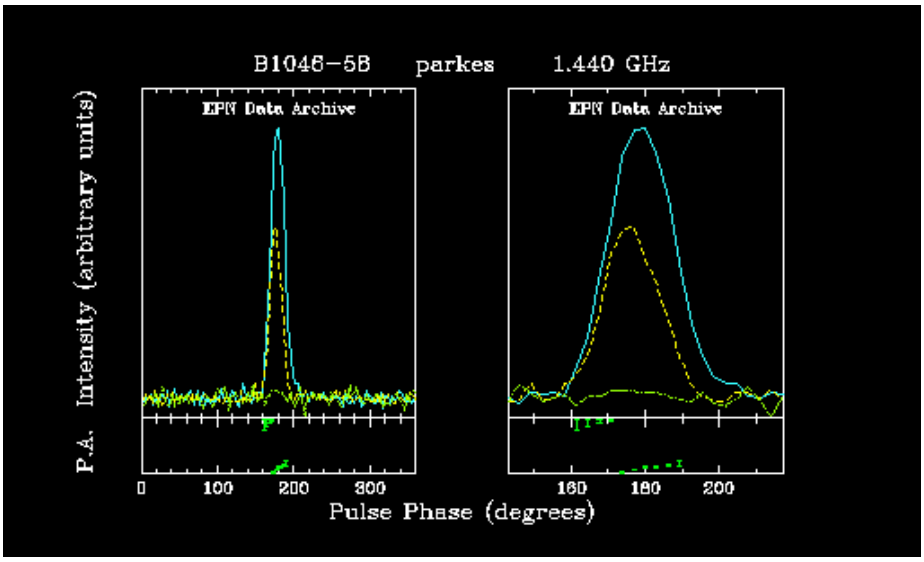
(Johnston et al. 2001)



Radio profiles of EGRET pulsars



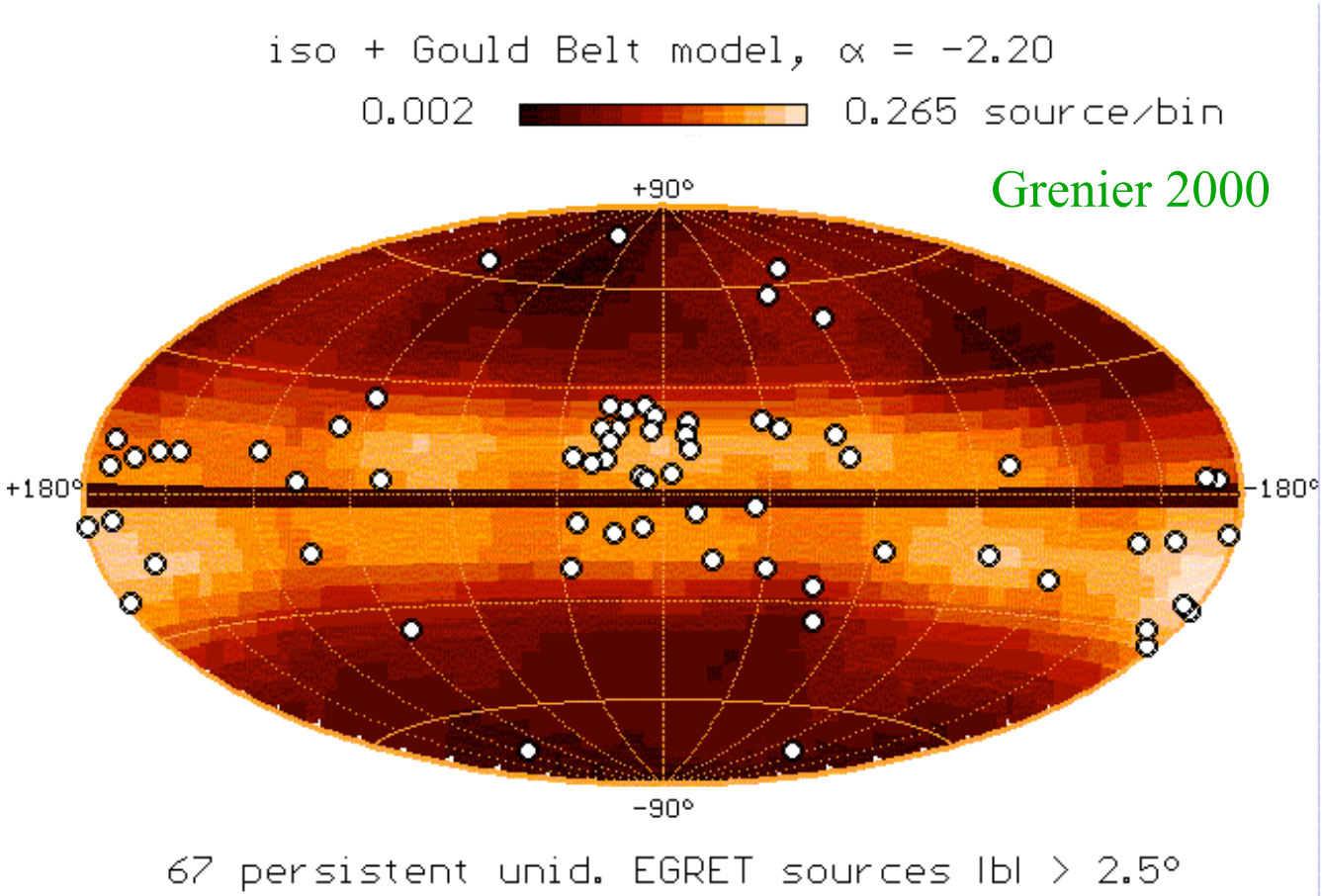




Unidentified EGRET sources in the Gould Belt

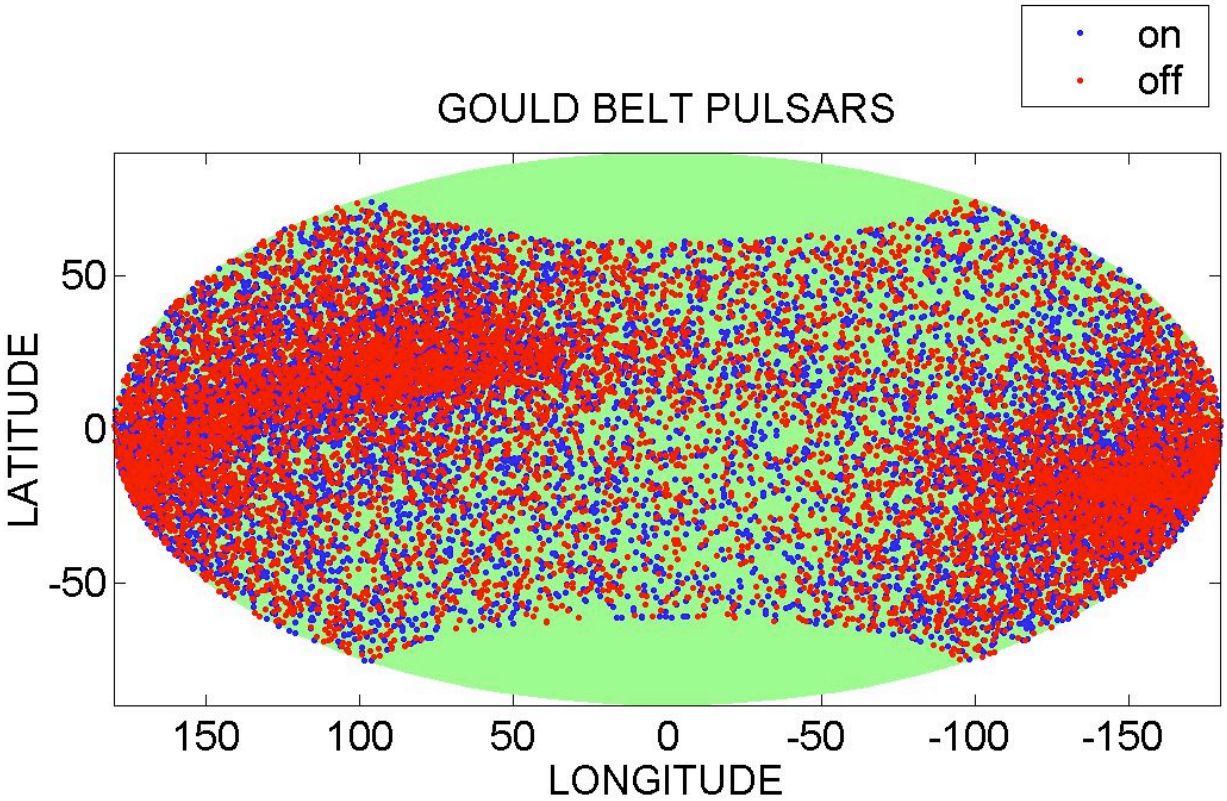
- Distances 100-300 pc
- Luminosities: $L(>100\text{MeV}) \sim 6 \times 10^{30}\ \text{erg s}^{-1}$
- Possible origin: Accreting BHs? X
  Accreting NSs? X
  O or WR stars? X
  Radio-quiet pulsars?

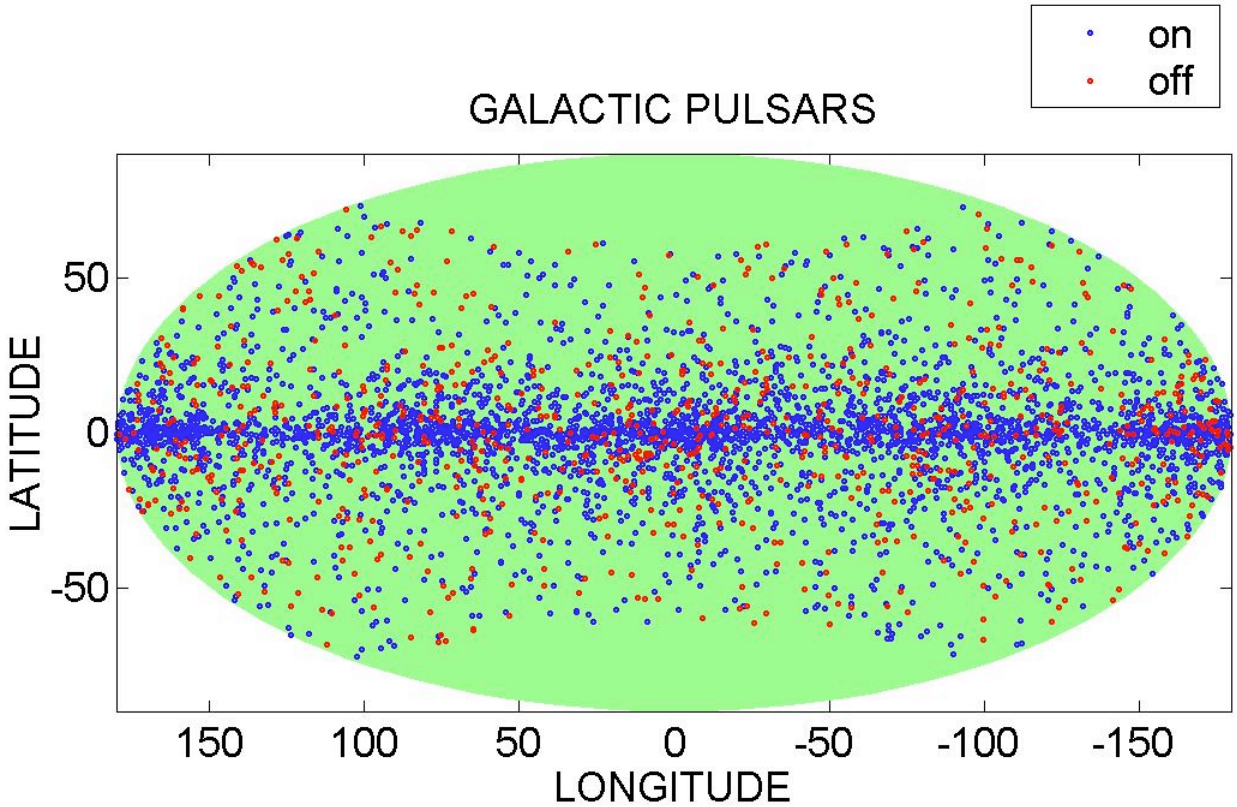
Maybe



Simulation of off-beam and on-beam γ-ray pulsars

(Perrot, Grenier & Harding 2002)





Summary

Polar cap models

What works ….

- Predicted luminosity $L_{\gamma} \quad \dot{E}_{rot}^{1/2}$
- High-energy spectral turnovers
- Off-pulse (off-beam) emission

Problems …

- Predicted (standard) size of γ-ray beam
- Geometry of radio and γ-ray beams