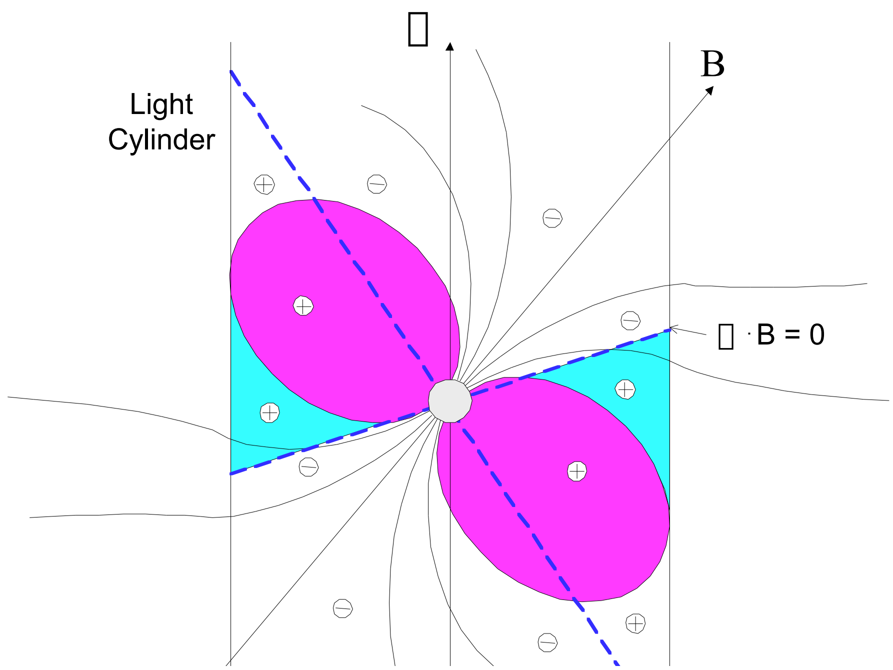
Polar Cap Emission: Modeling Acceleration and Beam Geometry

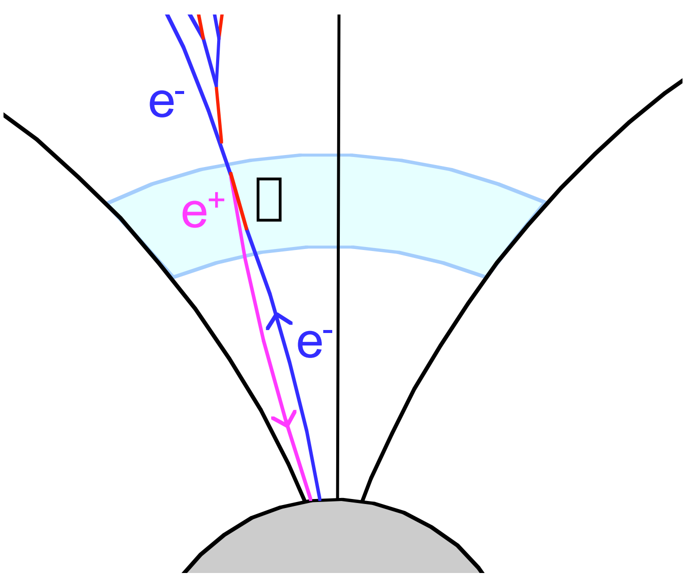
A.K. Harding
NASA Goddard Space Flight Center

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

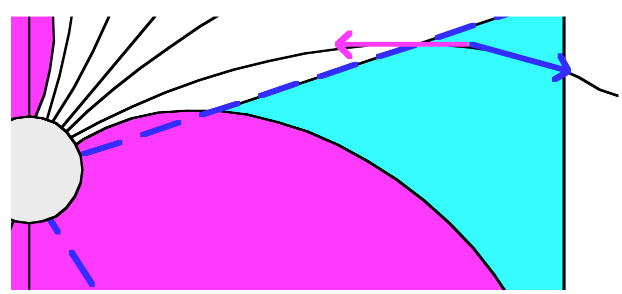
- Polar cap acceleration & Pairs
- Electric field screening – Limits on acceleration
- High-energy luminosity
- Geometry of γ-ray and radio beams

Pulsar Acceleration and Pairs





Polar cap



Outer gap

Polar Cap Acceleration

- What's new?
  - GR inertial frame dragging
    Muslimov & Tsygan 1992

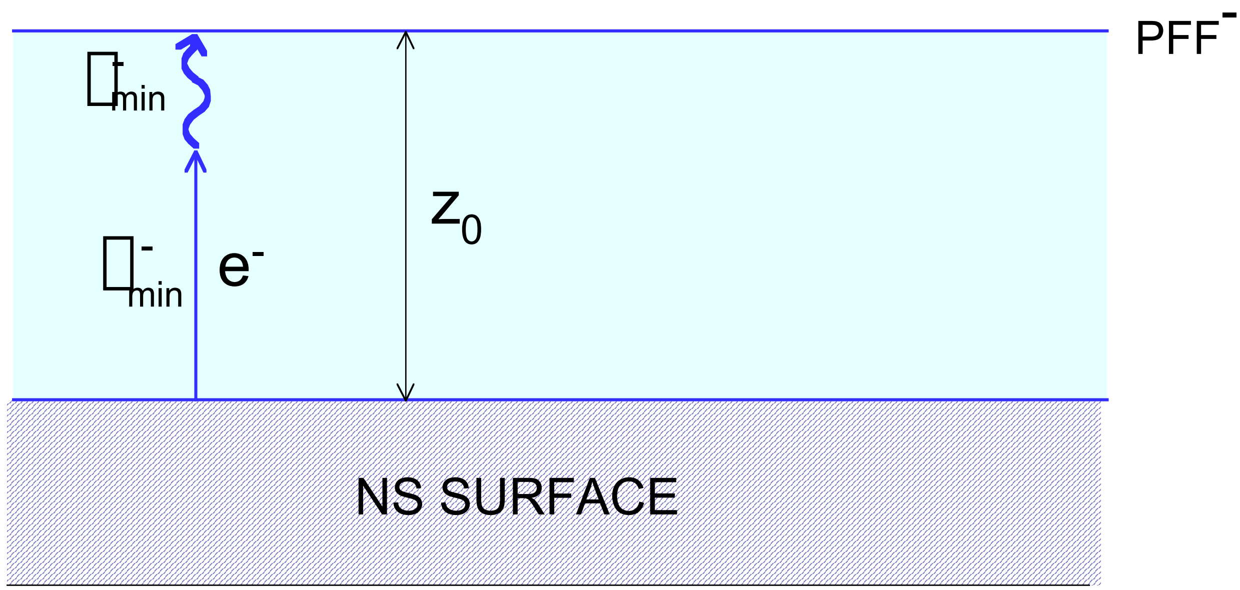
$$E_{\parallel} = 10^{6}\,\mathrm{esu}\,\frac{B_{12}}{P}\,\kappa_{0.15}\begin{cases} 3\ z\ P^{-1/2}, & \textit{unsaturated} \\ 5\times 10^{-3}\,P^{-1}, & \textit{saturated} \end{cases}$$

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

  - Inverse Compton pairs
    Zhang et al 1997, Harding & Muslimov 1998

    Acceleration limit?

The Pair Formation Front



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

- Curvature Radiation $\Box_{CR} = \left(\frac{3}{2}\frac{\hbar}{mc}\right)\frac{\Box^3}{\Box_c}$

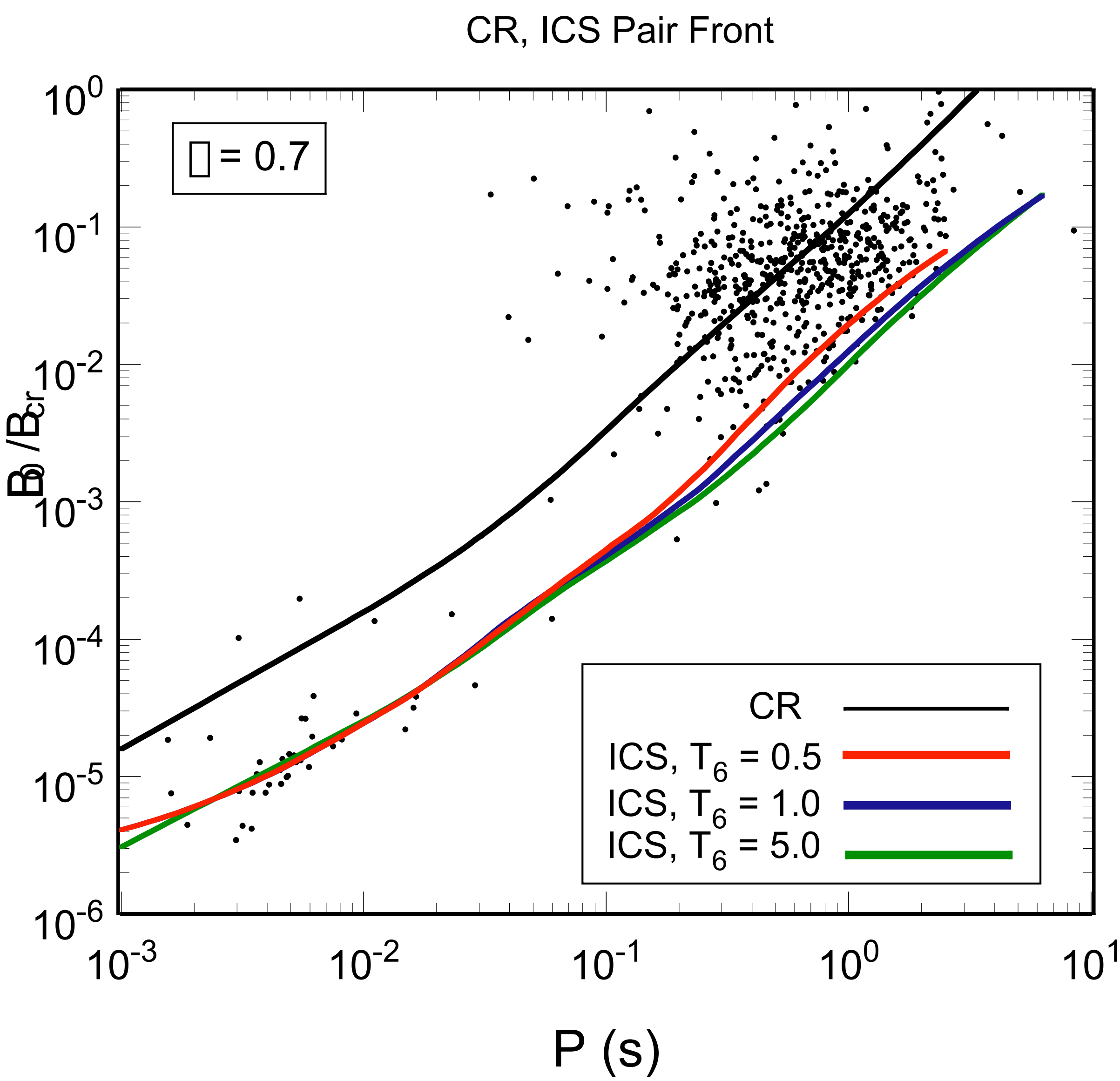
$$z_0 \Box 0.3 \begin{cases} 1.2\, P^{11/14} B_{12}^{\Box 4/7} \\ 16.8\, P^{7/4} B_{12}^{\Box 1} \end{cases}$$

- Resonant ICS $\Box_{RICS} = 2\Box\left(B / B_{cr}\right)$

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

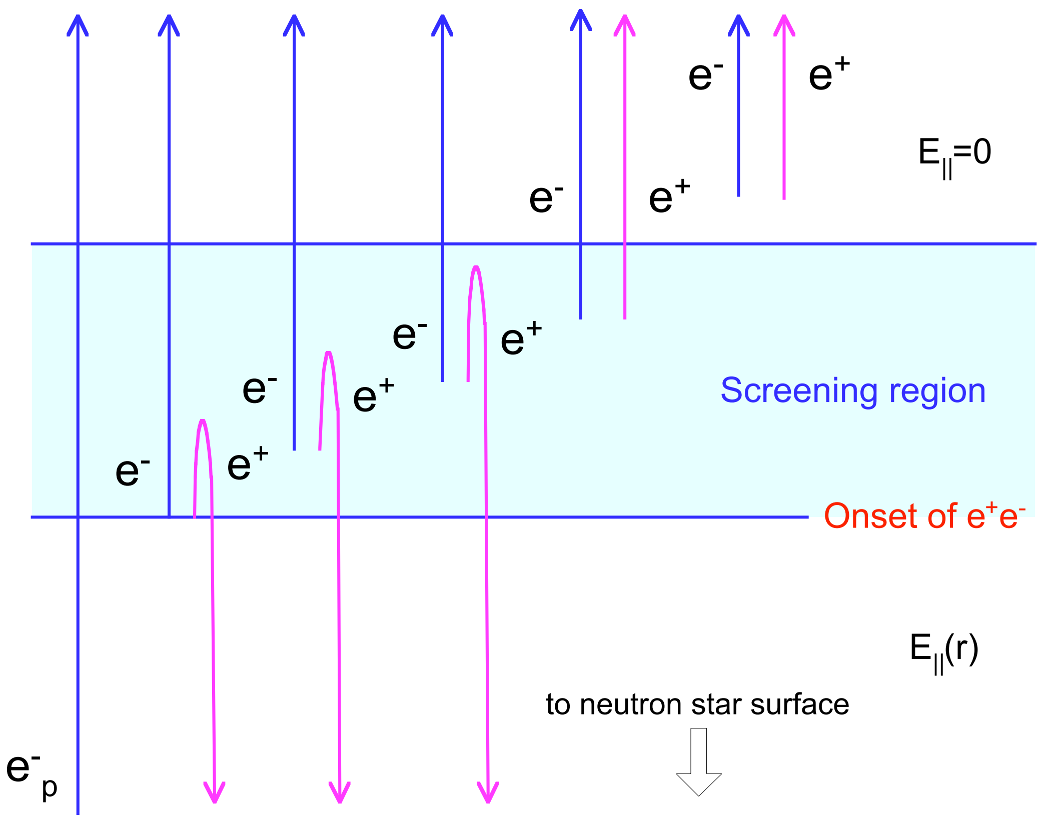
- Non-resonant ICS $\Box_{NRICS} = \Box$

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



CR, ICS Pair Front
= 0.7
B_0/B_{cr}
P (s)
CR
ICS, T_6 = 0.5
ICS, T_6 = 1.0
ICS, T_6 = 5.0
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



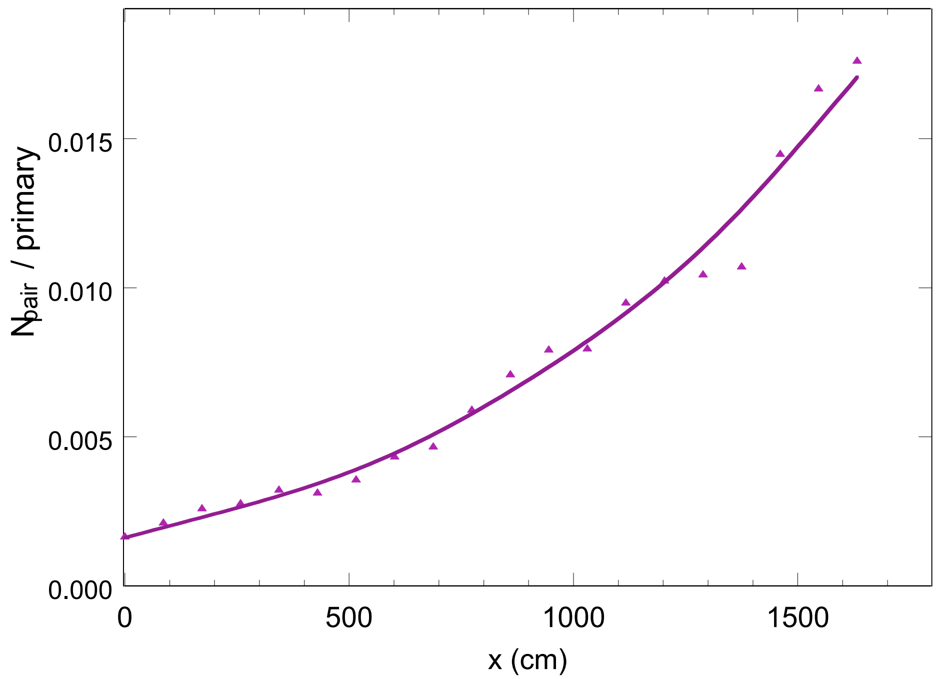
Maximum fraction of returning positrons:

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

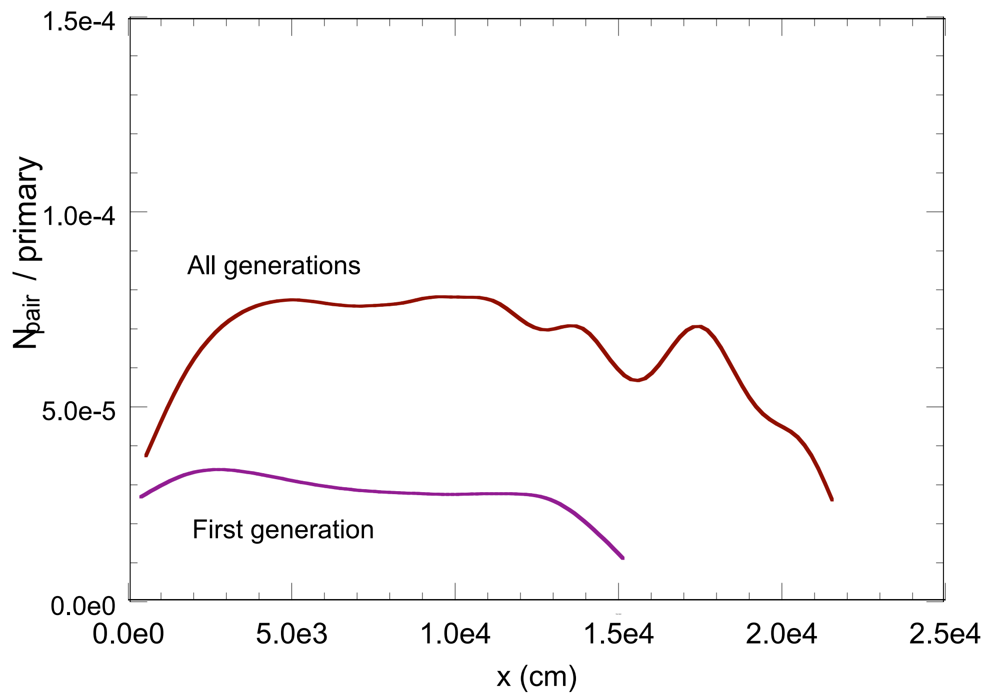
$$L_+^{\max} = f_+ \square(z_0)\,\dot{n}_{prim}$$

Pair Source Function

Curvature radiation

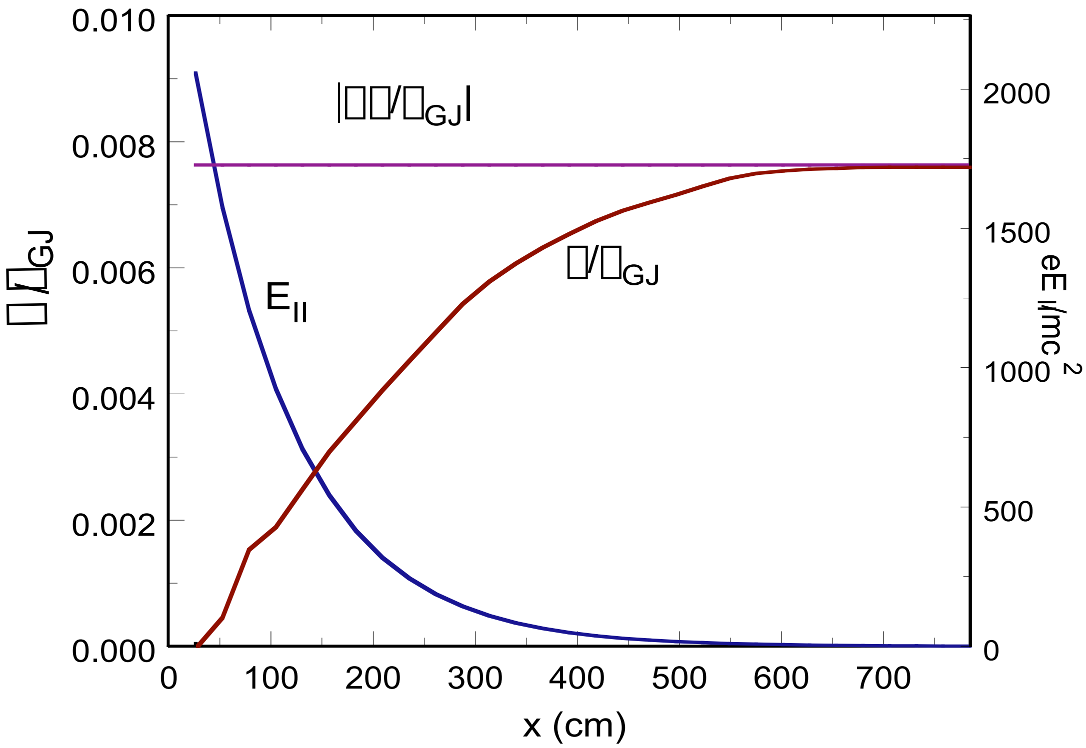


Inverse Compton radiation

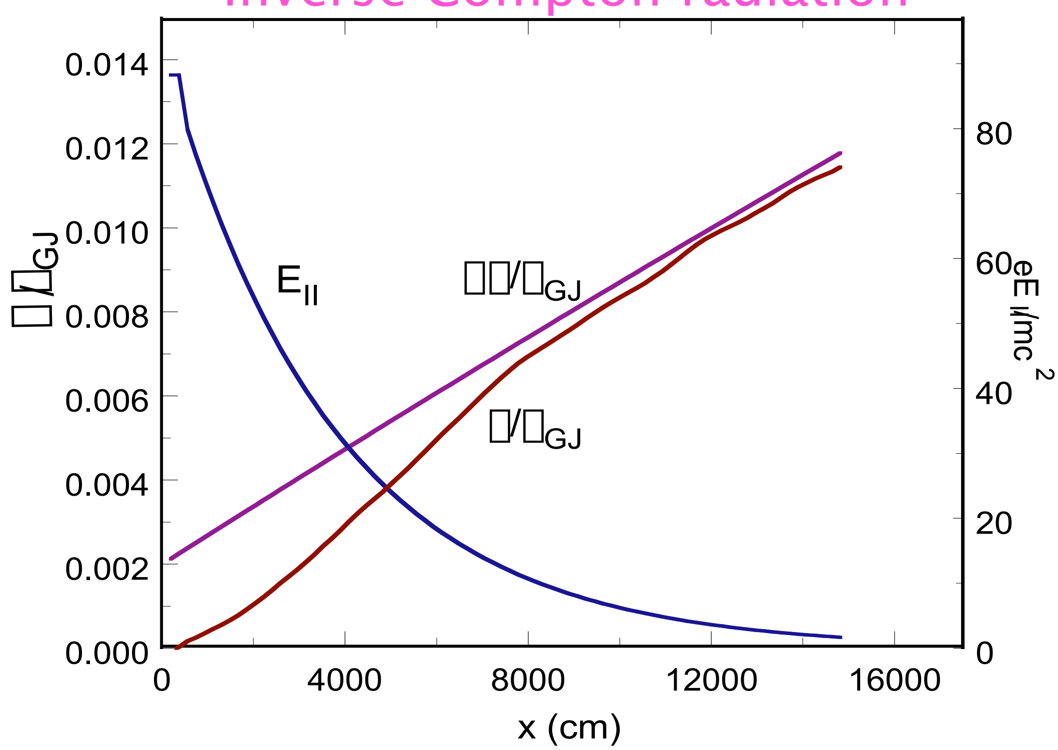


Screening $E_{||}$

Curvature radiation



Inverse Compton radiation



Voltage at the Pair Formation Front and γ-ray Luminosity

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

- Curvature Radiation

$$\Phi(z_o) = 10^{13} V \begin{cases} 2(\tau_6 / P)^{1/14} \\ P^{-1/4} \end{cases}$$ Nearly constant!!

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

- Resonant ICS

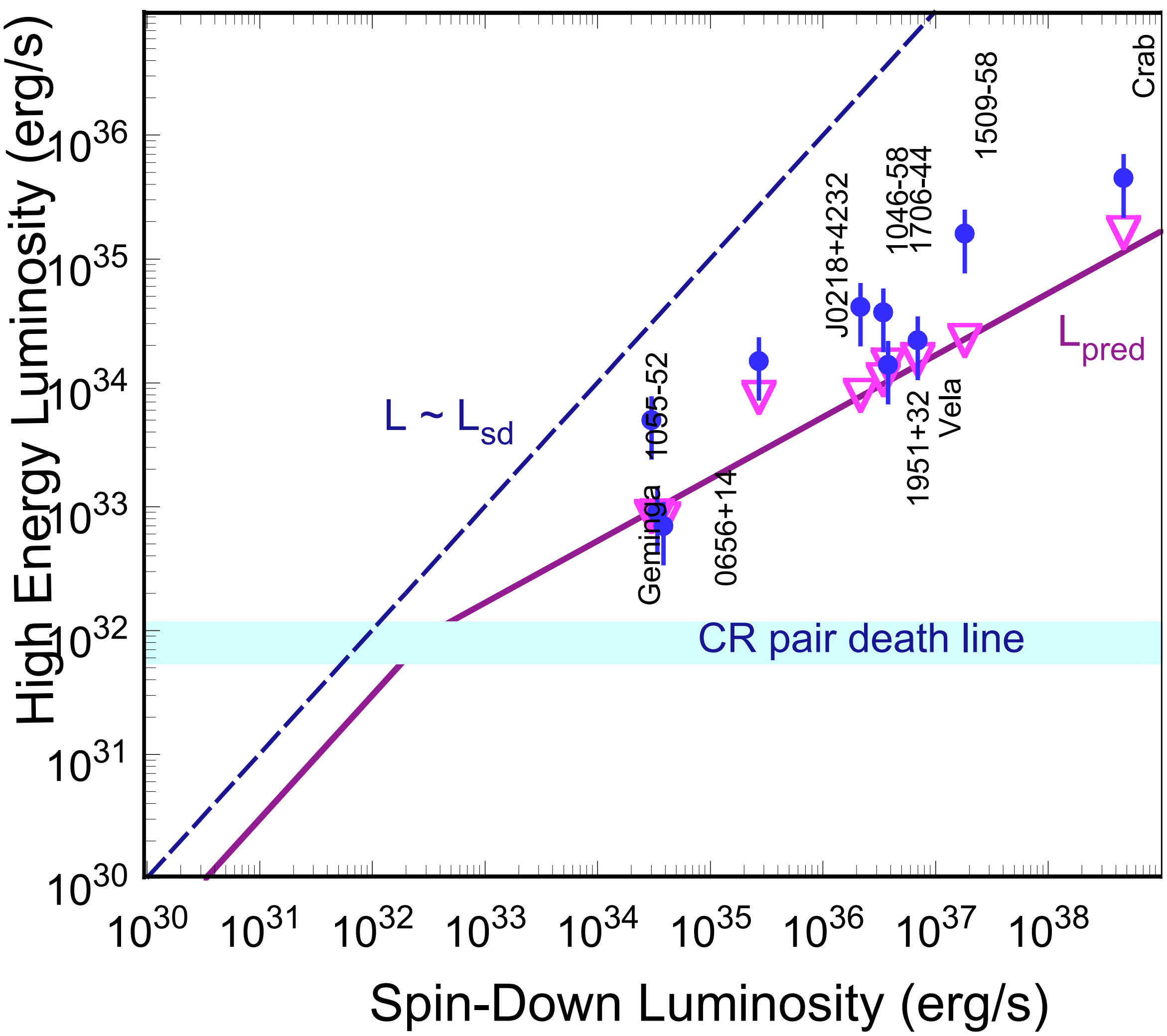
$$\Phi(z_o) = 10^{11} V \begin{cases} 3 P^{-7/6} \tau_6^{1/2} \\ 2 P^{-5/4} \tau_6^{1/4} \end{cases}$$

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

- Non-resonant ICS

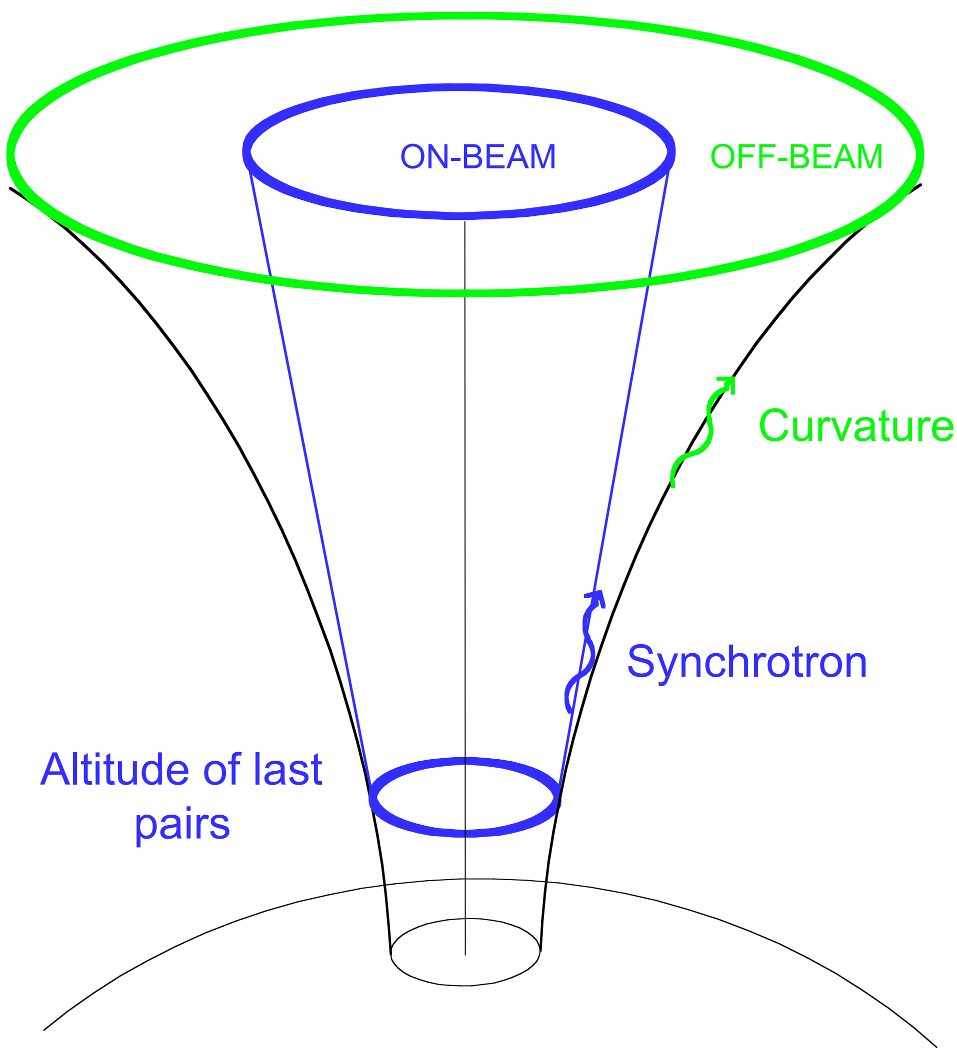
$$\Phi(z_o) = 10^{11} V \begin{cases} 2 P^{-1/2} \tau_6^{1/6} \\ P^{-3/4} \end{cases}$$

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

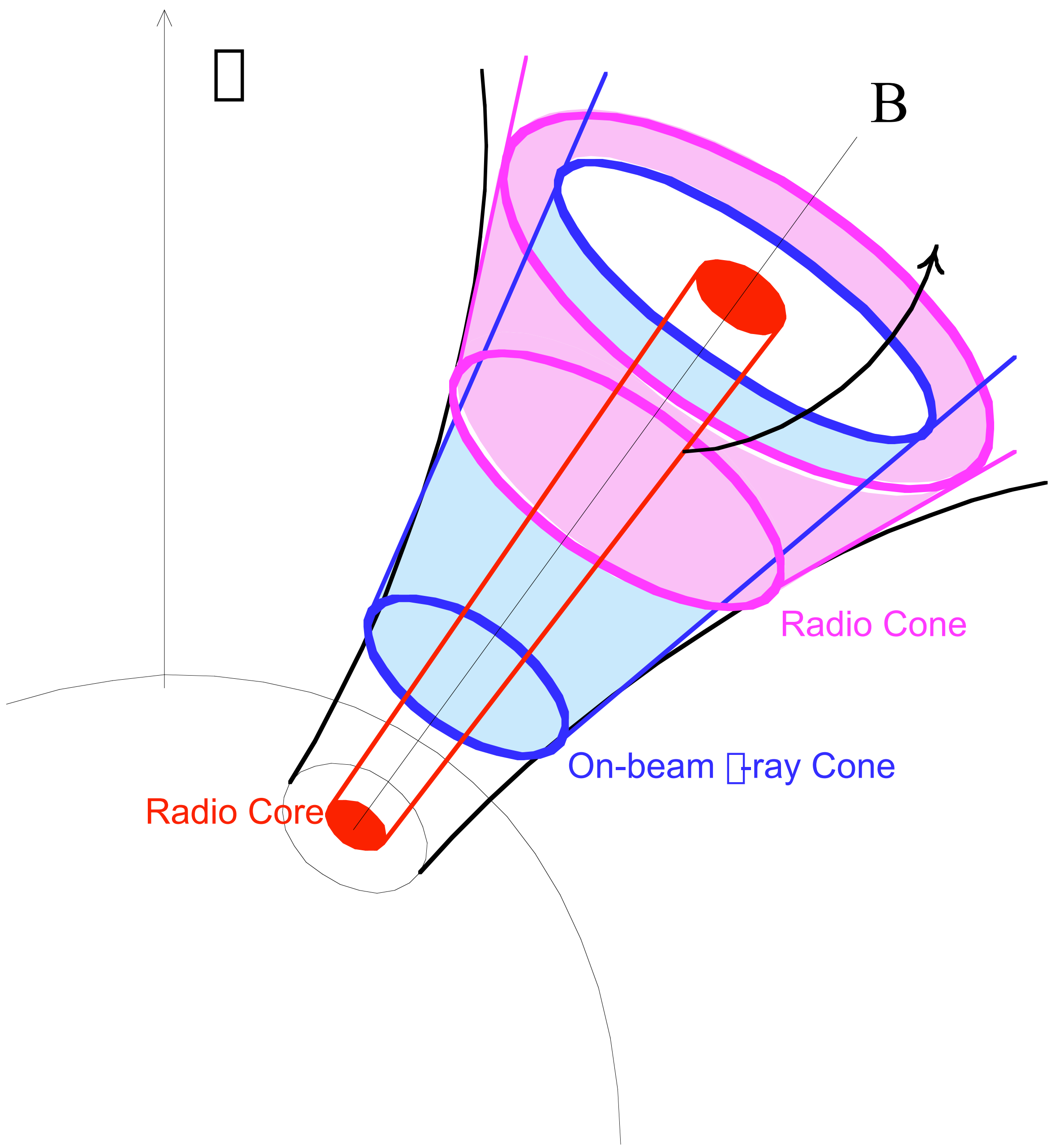


High Energy Luminosity (erg/s)
Spin-Down Luminosity (erg/s)
10^{30}
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
10^{37}
10^{38}
$L \sim L_{sd}$
L_{pred}
CR pair death line
Crab
1509-58
1046-58
1706-44
J0218+4232
1055-52
Geminga
0656+14
1951+32
Vela

Geometry of PC □-ray beams

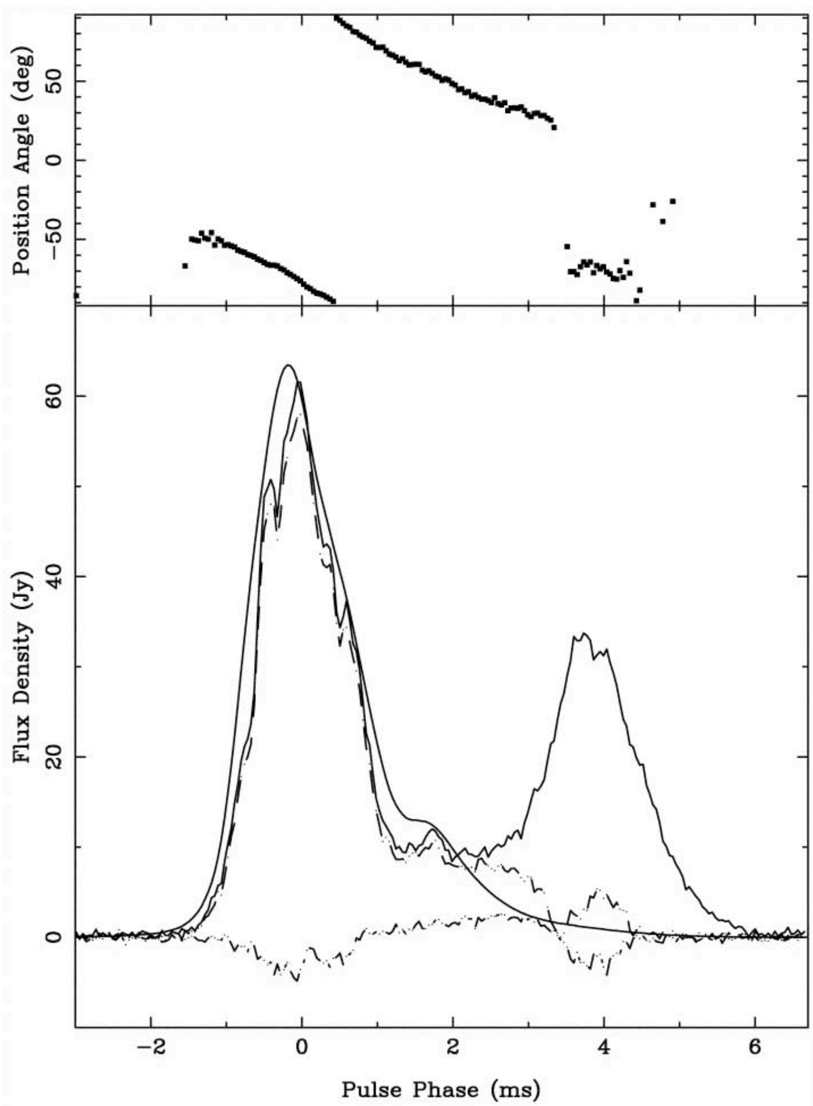


Geometry radio and -ray beams

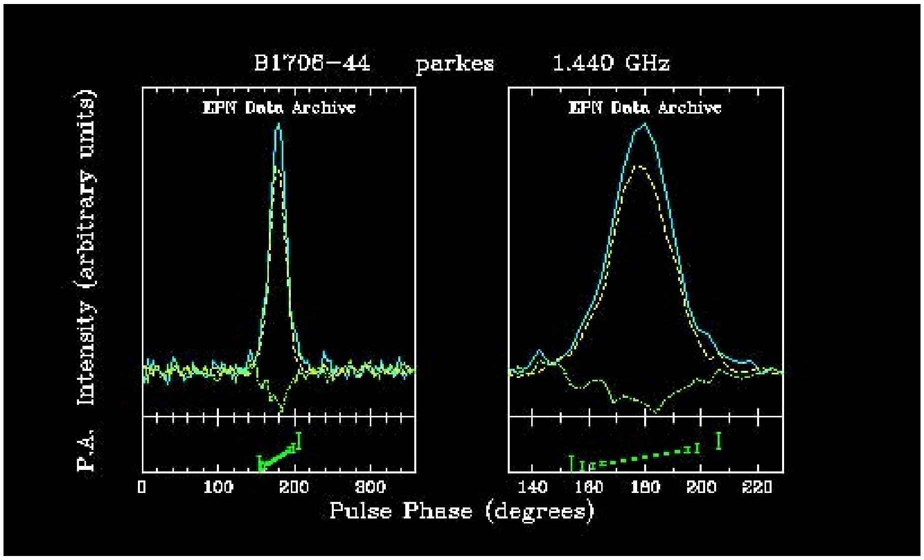


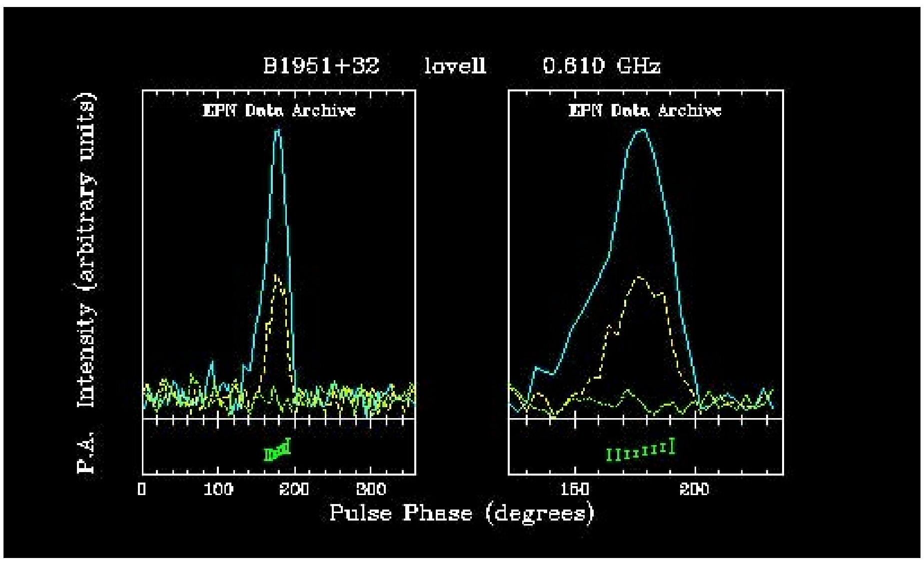
Vela pulsar radio profile

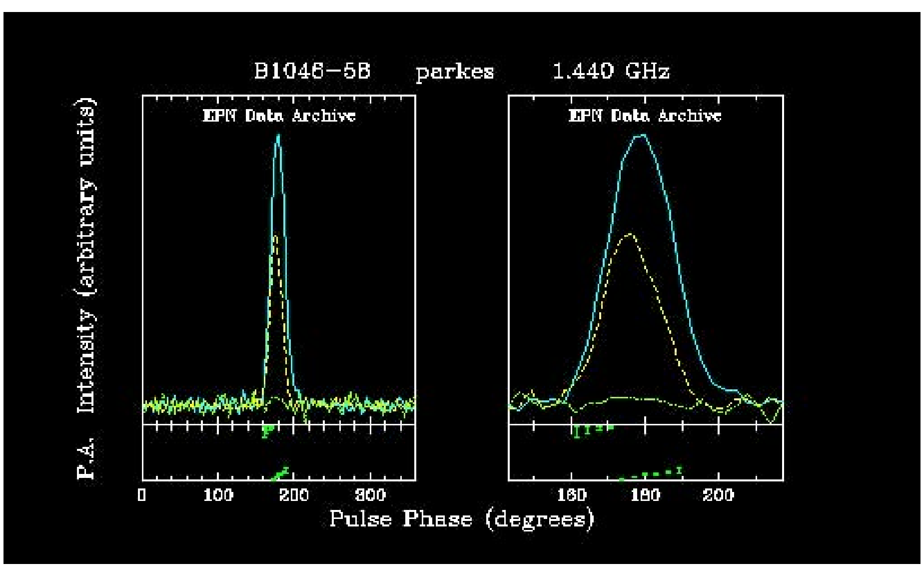
(Johnston et al. 2001)



Radio profiles of EGRET pulsars







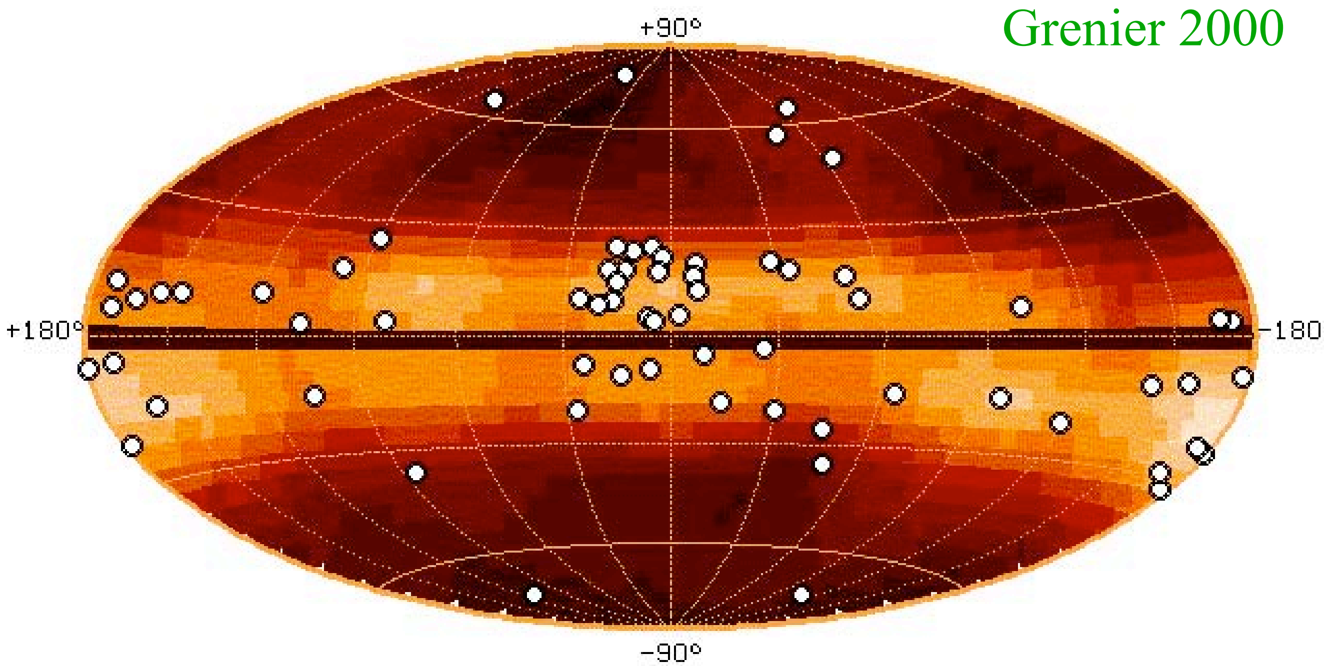
Unidentified EGRET sources in the Gould Belt

- 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

iso + Gould Belt model, α = -2.20

0.002 0.265 source/bin

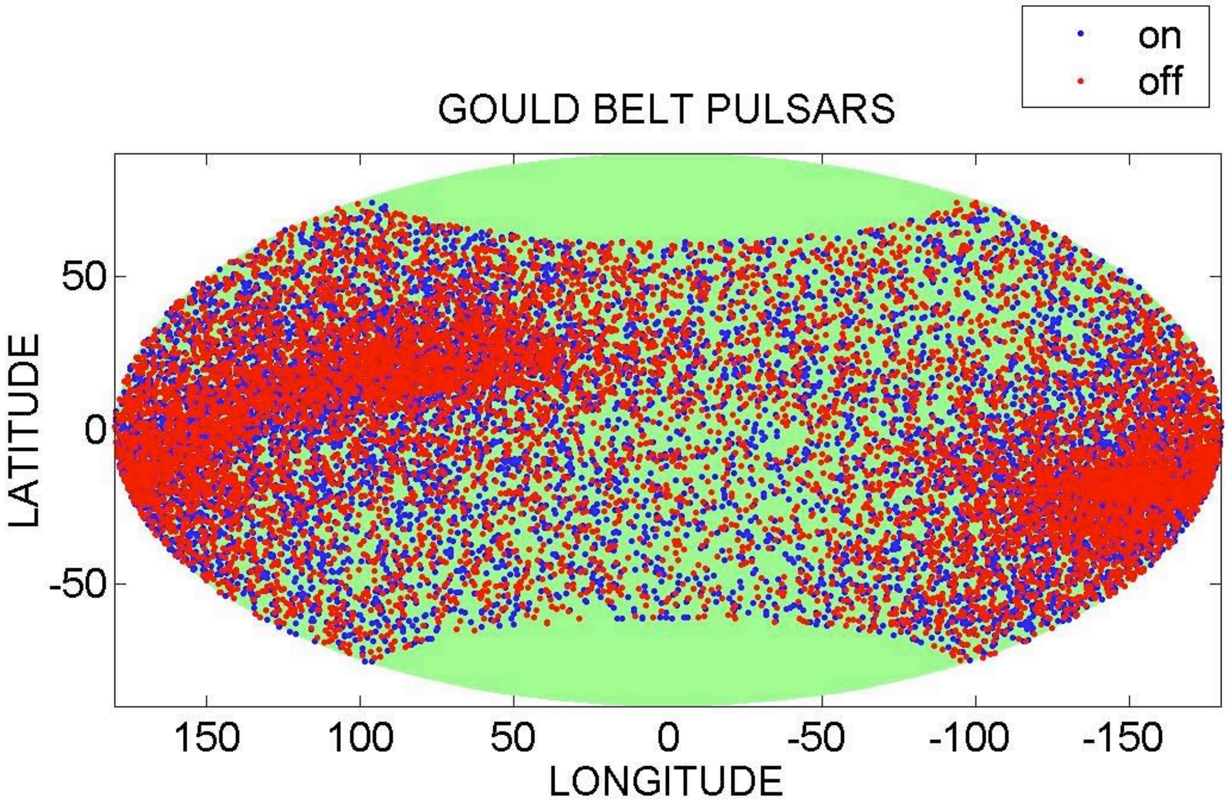
Grenier 2000

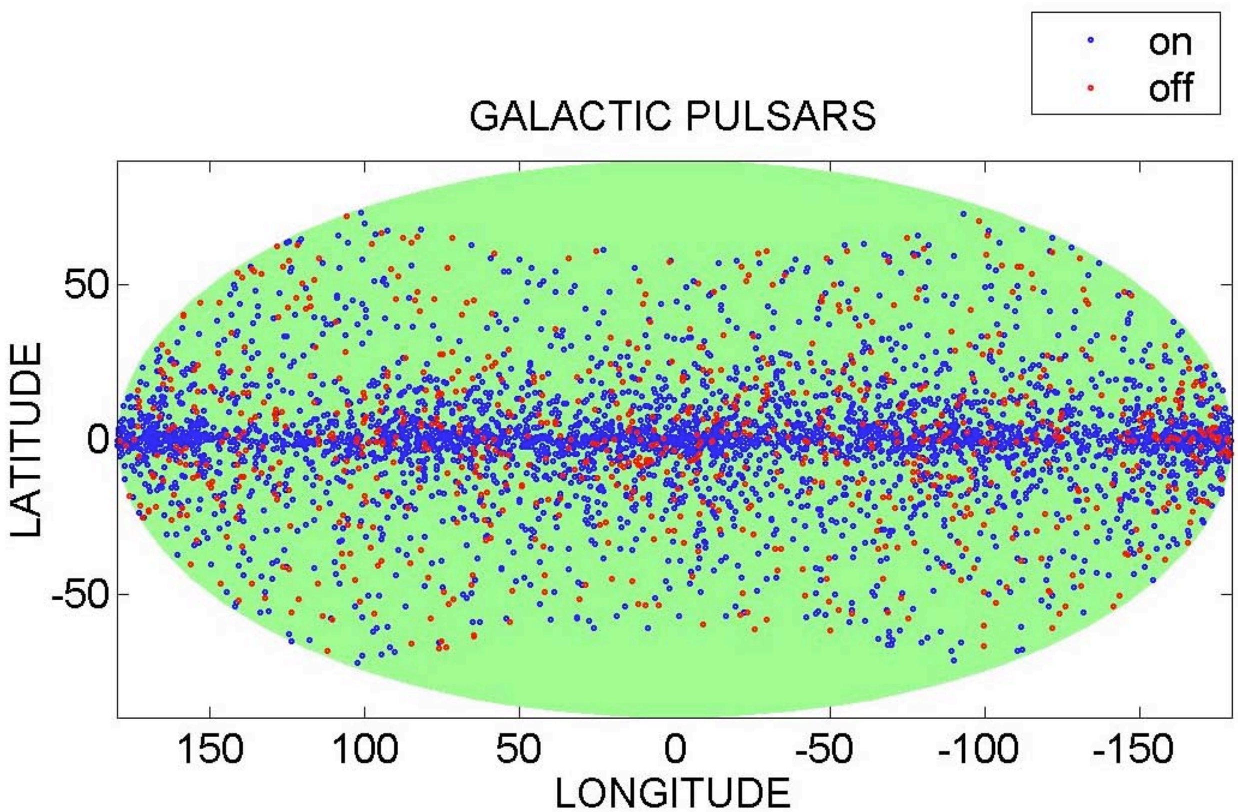


67 persistent unid. EGRET sources |b| > 2.5°

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

(Perrot, Grenier & Harding 2002)





Summary

Polar cap models

What works ….

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

Problems …

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