GAMMA RAY EMISSION FROM PULSARS

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‘Theory’:

local and special solutions for ‘easy’ cases

(eg. steady state, infinite work function or SCLF)

first principle codes not helpful so far

(acceleration not included or dead result [inactive magnetosphere])

Sub-GeV **observations**:

fluxes (<10 GeV)

spectra (power-law, ph. indx ~ 1.7 to 2, nearly flat on nuFnu)

pulse profiles (averaged, often **double-peaked**, **lag radio** MP)

(no variability, no polarization above optical)

$-\nabla^2\Psi = 4\pi(\rho-\rho_{GJ})$ => empty magnetosphere is starved for charges untill it fills up with ρ_{GJ}:

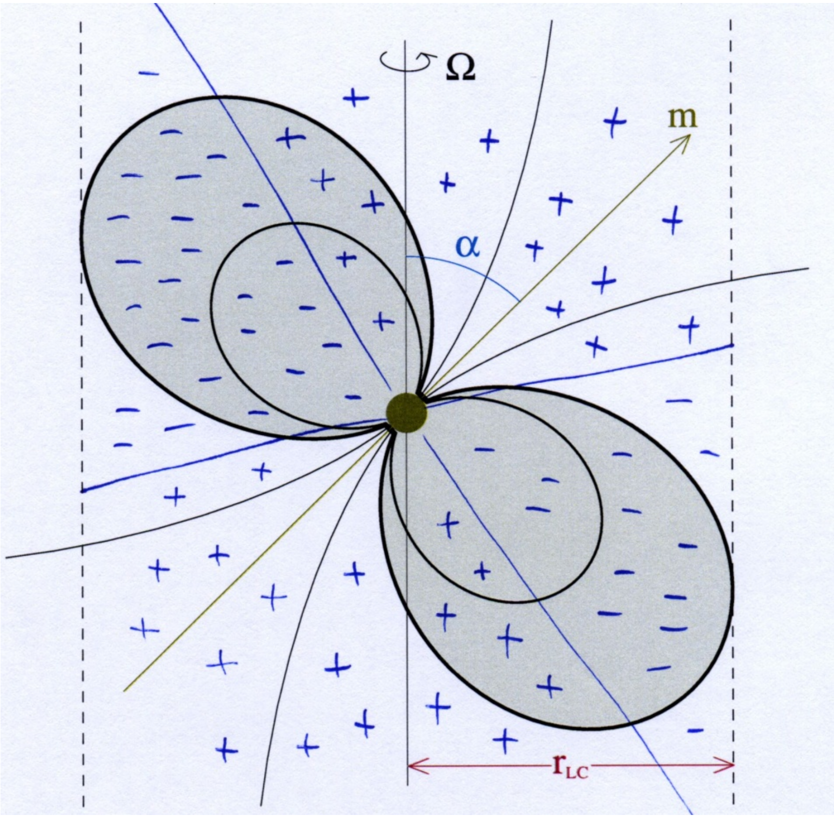
$$\rho_{GJ} = \frac{\nabla\cdot\vec{E}}{4\pi} \simeq -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c} = -\frac{B_z}{P_c} \simeq \rho'_{GJ}$$

'no acceleration' density

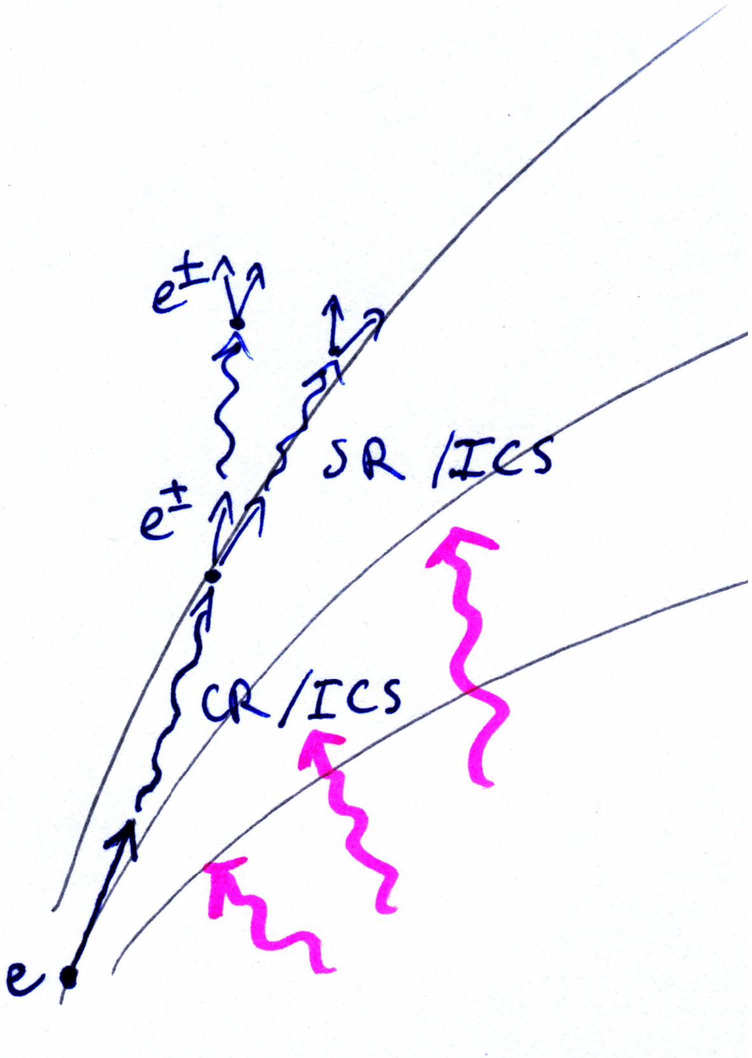
Kramer et al. 2006

=> Charge-filled magnetosphere.
Available ΔV limited to gaps within open field line region:

$$\Delta V_{pc} = 7\cdot 10^{14}\,\mathrm{V}\,\frac{B_{pc,12}\,R_6^3}{P_{0.1}^2}$$



Photon-pair cascade



$\gamma_{CR} + B \Rightarrow e^{\pm}$ polar cap model

$\gamma_{CR} + X_{th} \Rightarrow e^{\pm}$ outer gap model

E-field screening due to polarization of e±

=> $\Delta V \sim 10^{13}\ \mathrm{V}$, $\gamma_e \sim 10^{7}$

Fluxes => ~luminosities (beaming fraction unknown exactly)
Bolometric luminosities understood:

$$L_\gamma \propto L_{\text{particles}} =$$

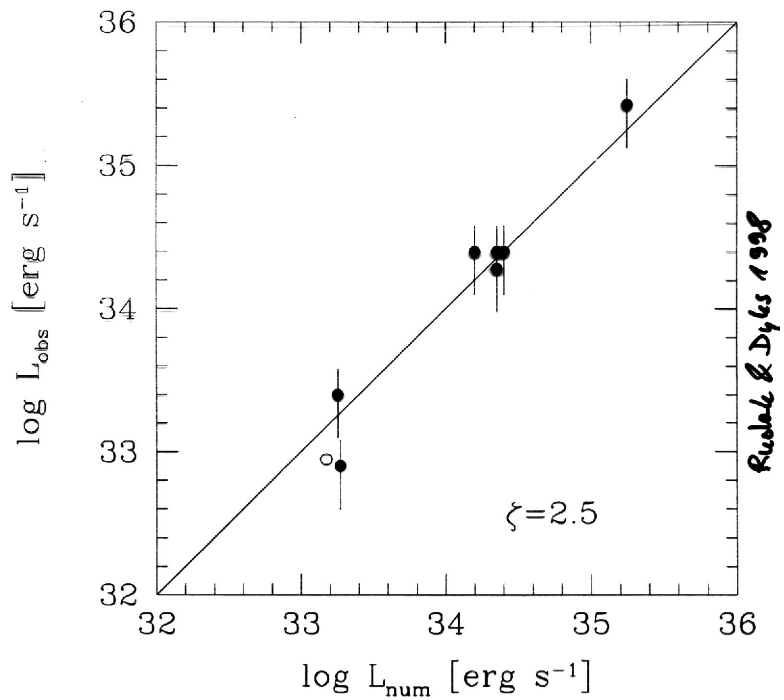
$$\begin{pmatrix}\text{typical energy}\\ \text{of particles}\end{pmatrix} \times (\text{particle flux}) =$$

$$\begin{pmatrix}\text{typical energy}\\ \text{of particles}\end{pmatrix} \times \begin{pmatrix}\text{number density}\\ \text{of particles}\end{pmatrix} \times \begin{pmatrix}\text{polar cap}\\ \text{area}\end{pmatrix} \times \begin{pmatrix}\text{velocity}\\ \text{of particles}\end{pmatrix} =$$

$$E_0 \times \left(\frac{\rho_{GJ}}{e}\right) \times \left(\pi r_{\text{pc}}^2\right) \times c$$

$L_\gamma \propto \dot{E}^{1/2}$

$L_\gamma \propto V_{pc}$



Sub-GeV **spectra**:

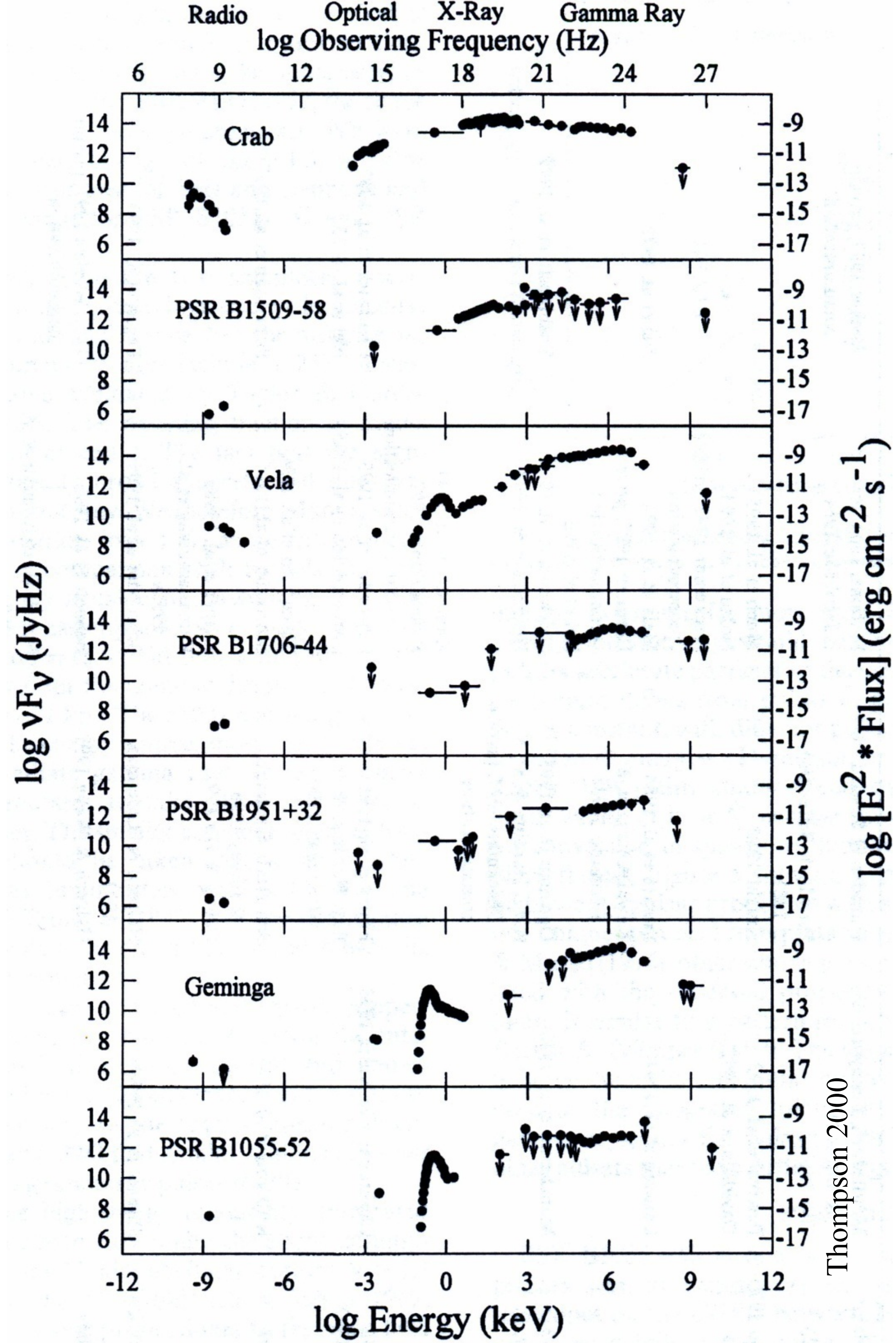
curvature radiation (CR)

CR **high energy cutoff** at:

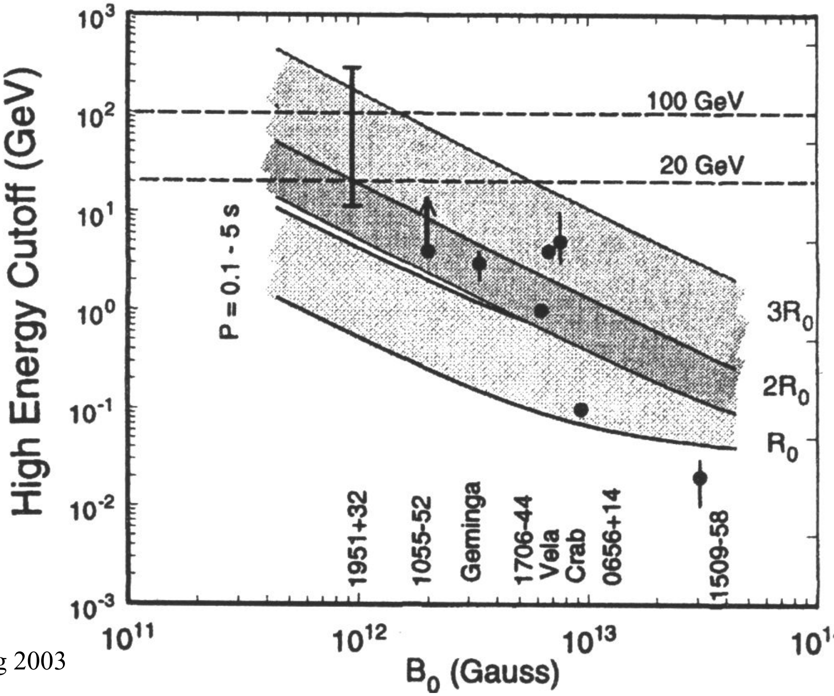
$$\varepsilon_{CR} = \frac{3}{2} c \hbar \frac{\gamma^3}{\rho_{cr}} \sim 5\,\mathrm{GeV}$$

$$(\gamma \sim 10^7, \rho_{cr} \sim 10^7\,\mathrm{cm})$$

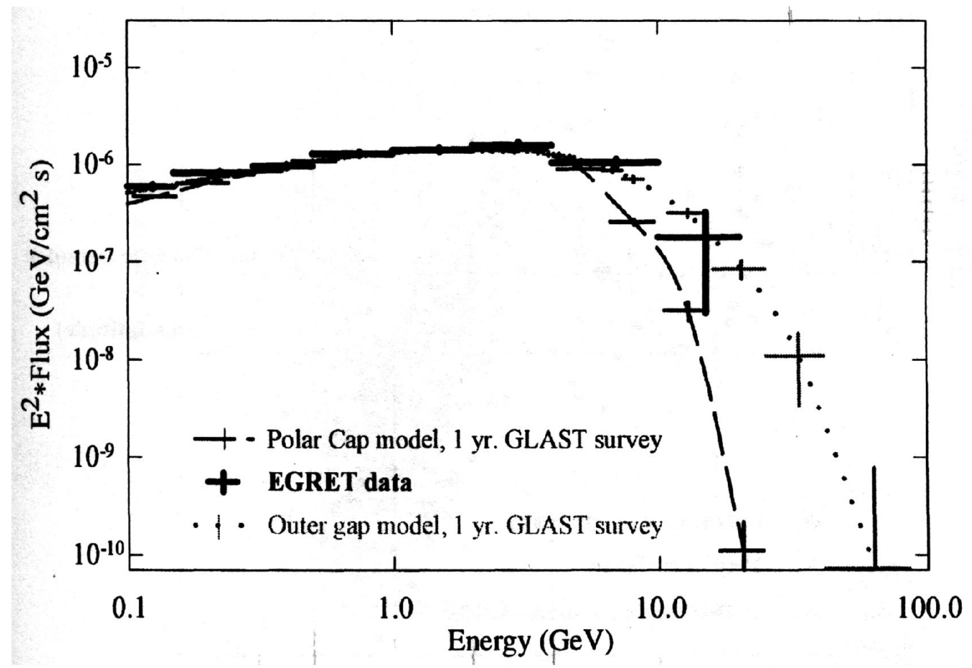
CR **photon index** = 5/3 = 1.67
(for CR-cooled monoenergetic
electron distribution)



Cutoff energy is smaller for larger B_{surf}



Harding 2003



$$\varepsilon_{esc} \cong 760\ \mathrm{MeV}\ R_6^{-1/2}\ B_{pc,12}^{-1}\ P_{0.1}^{1/2} \left(\frac{r_{em}}{R}\right)^{5/2}$$

⇒ one-photon magnetic pair production at work?

⇒ super-exponential cutoff: flux∝exp(exp(ε))

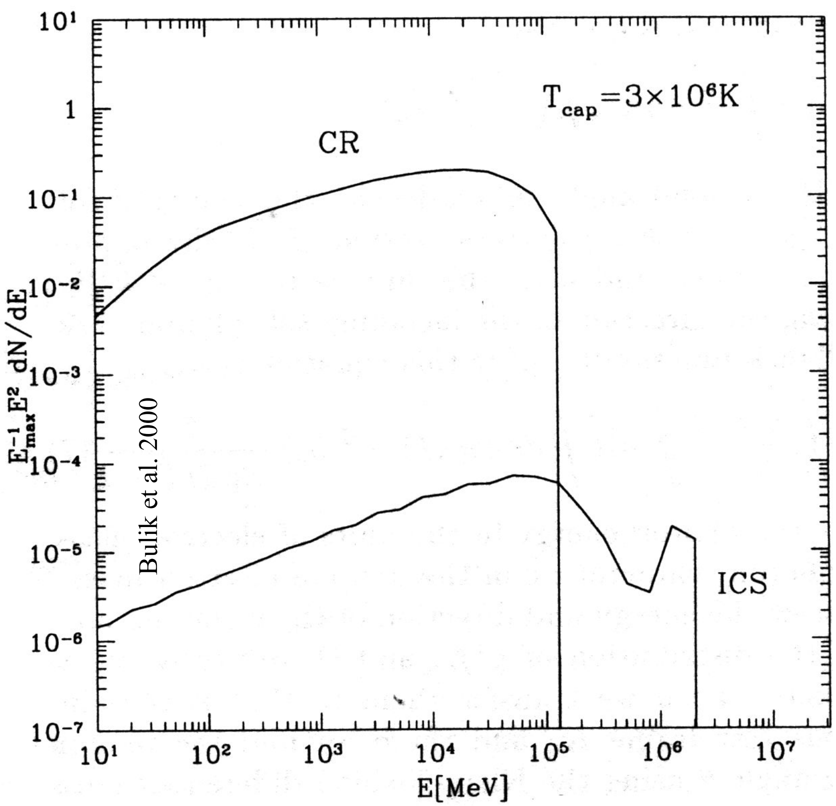
but: several blurring effects neglected,

observed gamma-rays probably not from polar caps

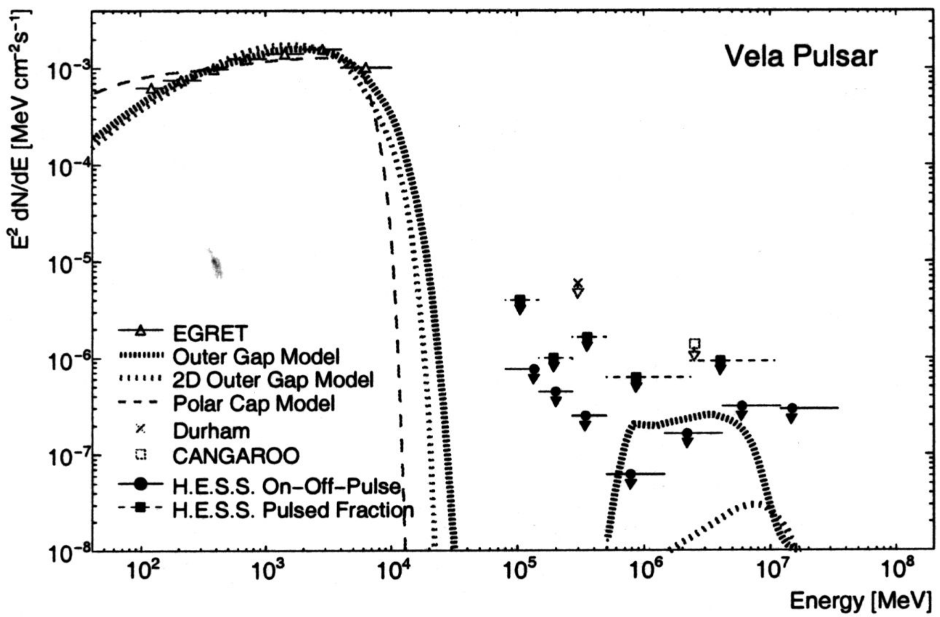
TeV spectra: inverse Compton scattered IR/optical/softX radiation

(SR from cascade e+e- or thermal from surface)

Expected by all models:



Bulik et al. 2000



Hirotani 2001

Level of the ICS component **unpredictable**

Level of ICS sensitive to unknown geometry in several ways:

1. ICS rate: $R_{ICS} = \int d\Omega \int d\varepsilon \, \delta \left(\frac{dn_{ph}}{d\varepsilon \, d\Omega} \right) c \left(1 - \beta \cos \theta_{k\nu}\right)$

2. Absorption of ICS:

$$h\nu \sin\theta_{kB} \geq 2 m_e c^2$$

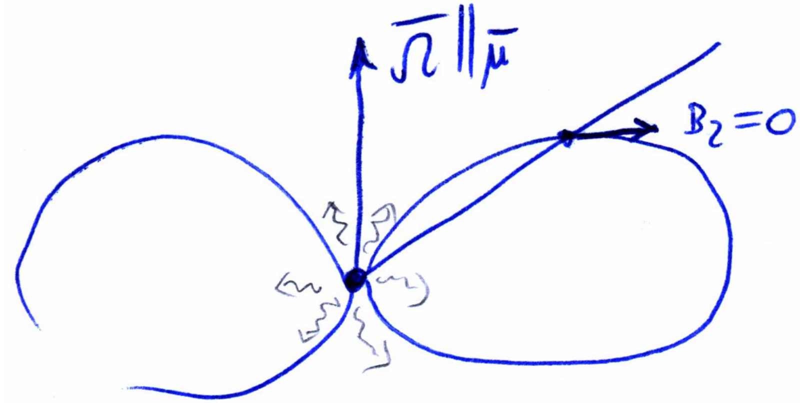
one-photon (magnetic) pair production

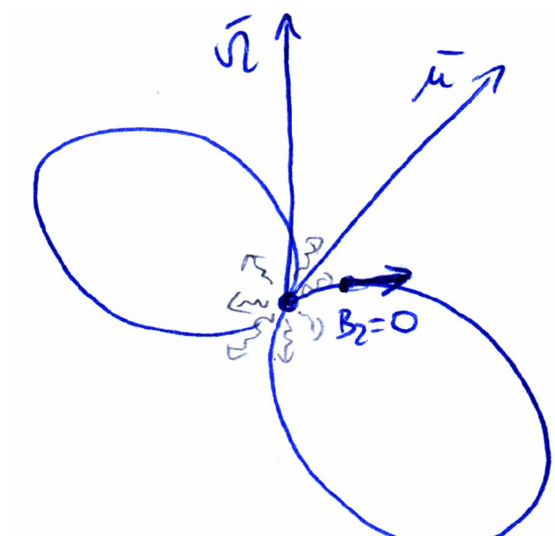
$$E_X E_\gamma (1 - \cos\theta_{X\gamma}) \geq 2(m_e c^2)^2$$

two-photon pair production

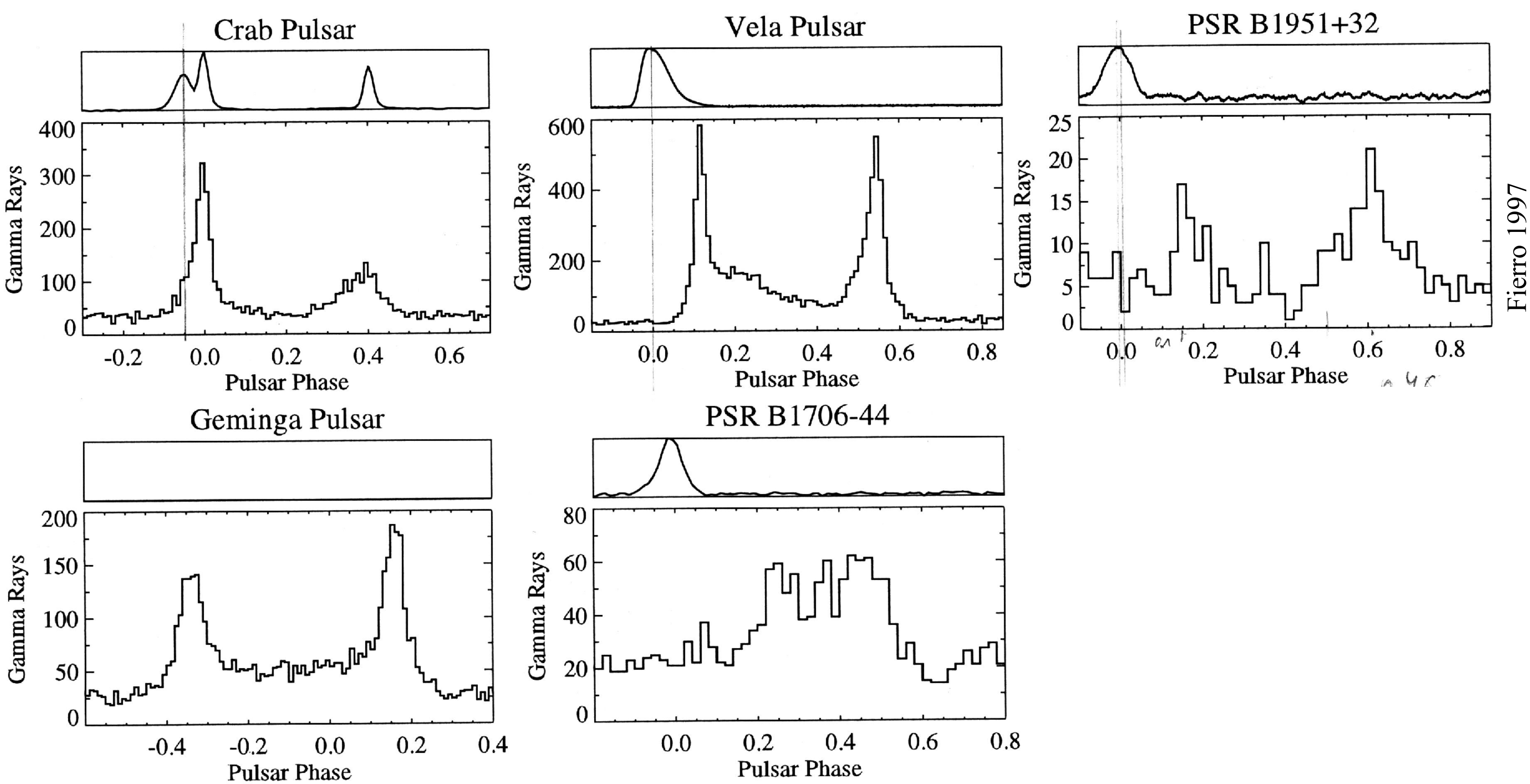
3. Density of photons to be scattered:

Distance of OG from hot surface depends on α:





Pulse profiles (EGRET + radio)



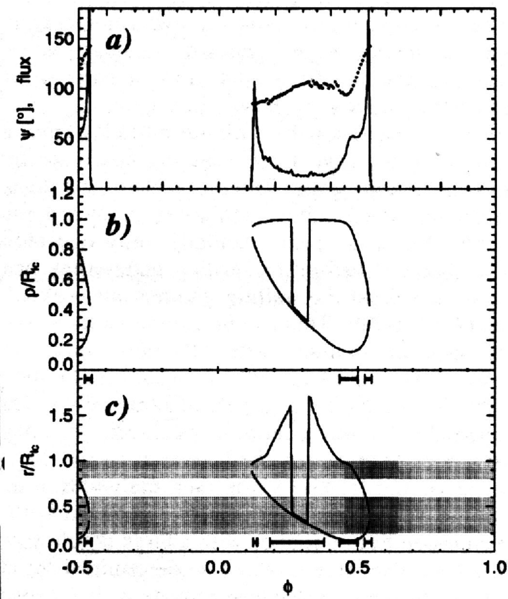
Two peaks separated by ~0.4P + bridge

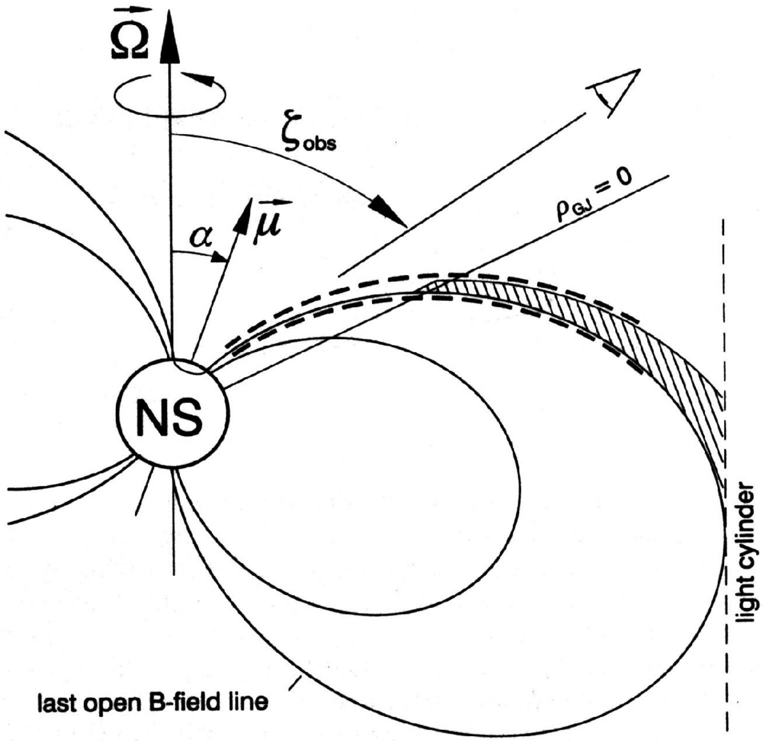
Radio MP (from PC?) precedes gamma => gamma **not from polar cap!**

⇒Extended emitter in outer magnetosphere

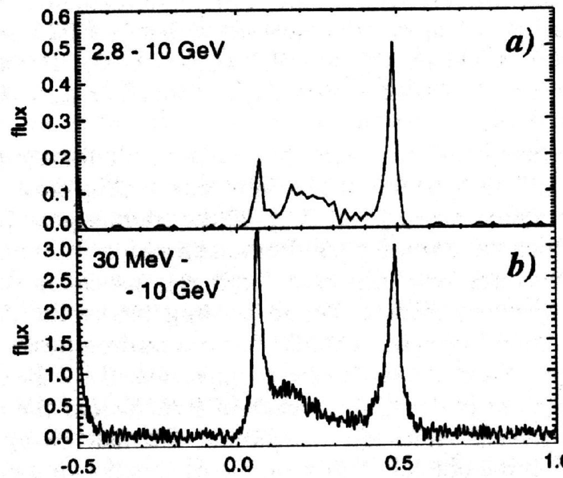
Peaks due to **caustic** effects(?):

Romani & Yadigaroglu 1995

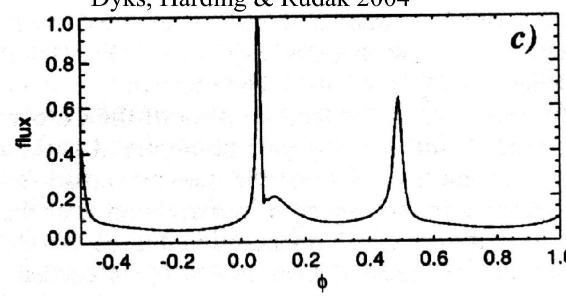




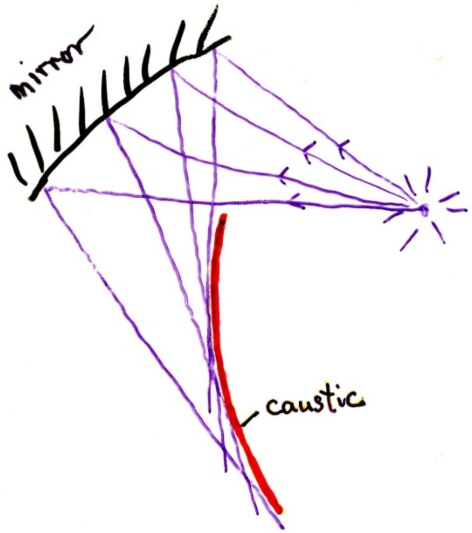
Dyks & Rudak 2003



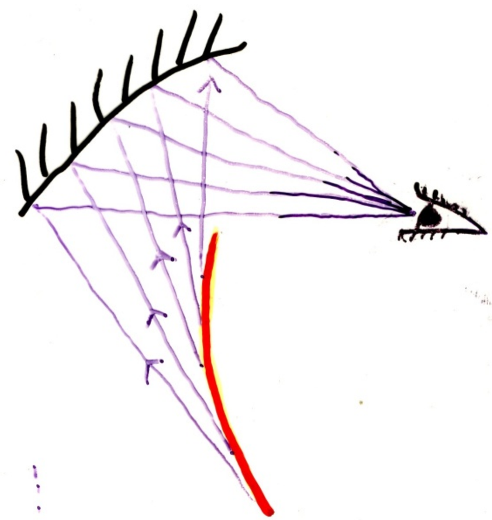
Dyks, Harding & Rudak 2004



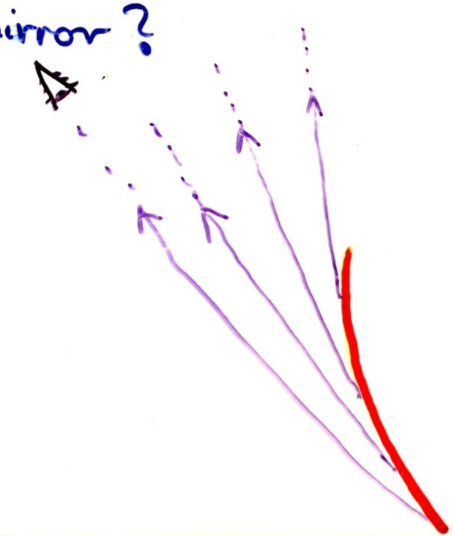
Caustic – (optics) a surface to which rays reflected or refracted by another surface are tangents



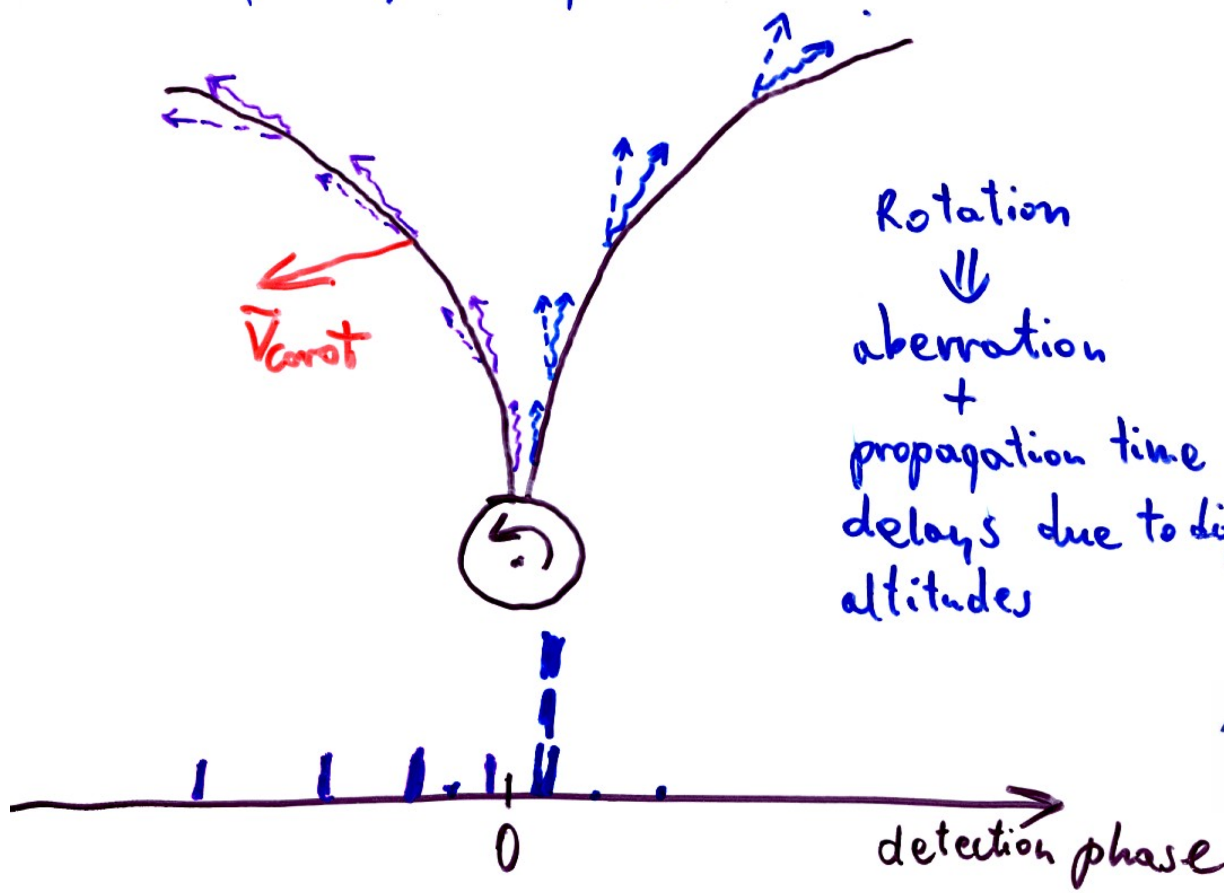
Propagation of rays reversed



Can pulsar do the same trick without the mirror?



Morini (1983): Yes, with ease!



Rotation

$\Downarrow$

aberration

+

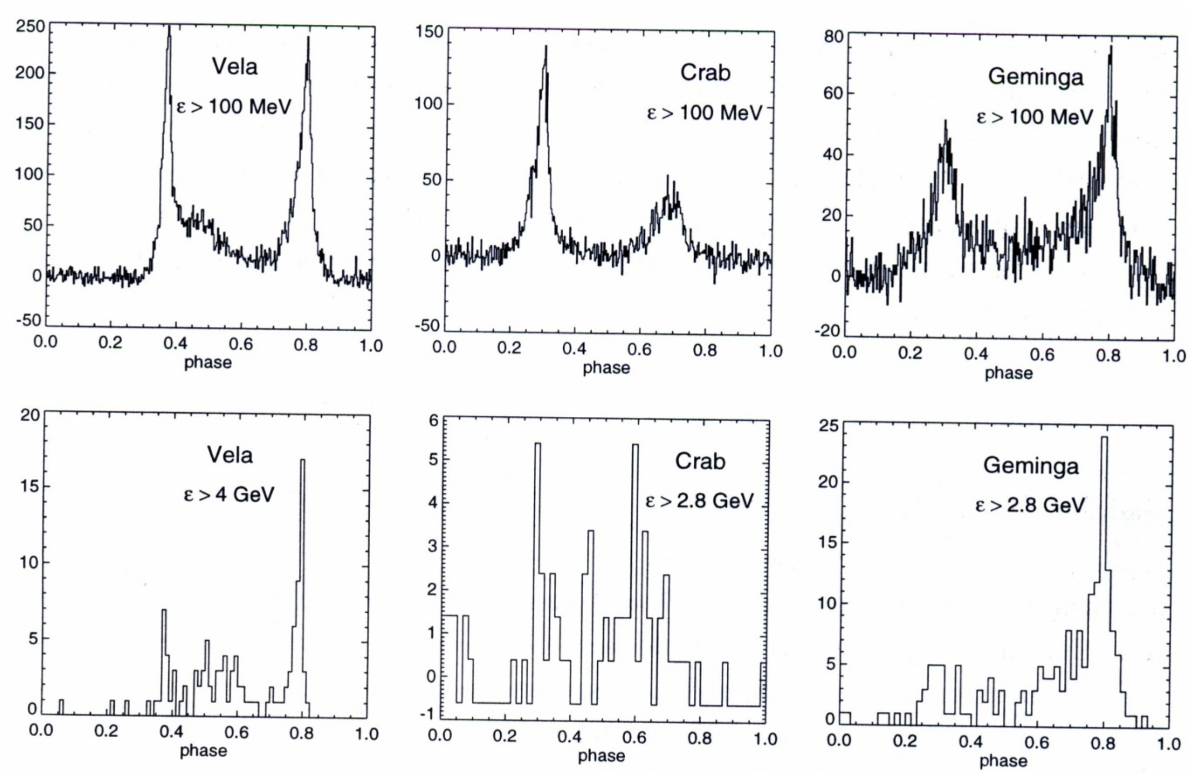
propagation time delays due to different altitudes

$$\Delta\varphi_{ab+ret} \simeq 2\,\frac{r}{R_{LC}}$$

$\Downarrow$

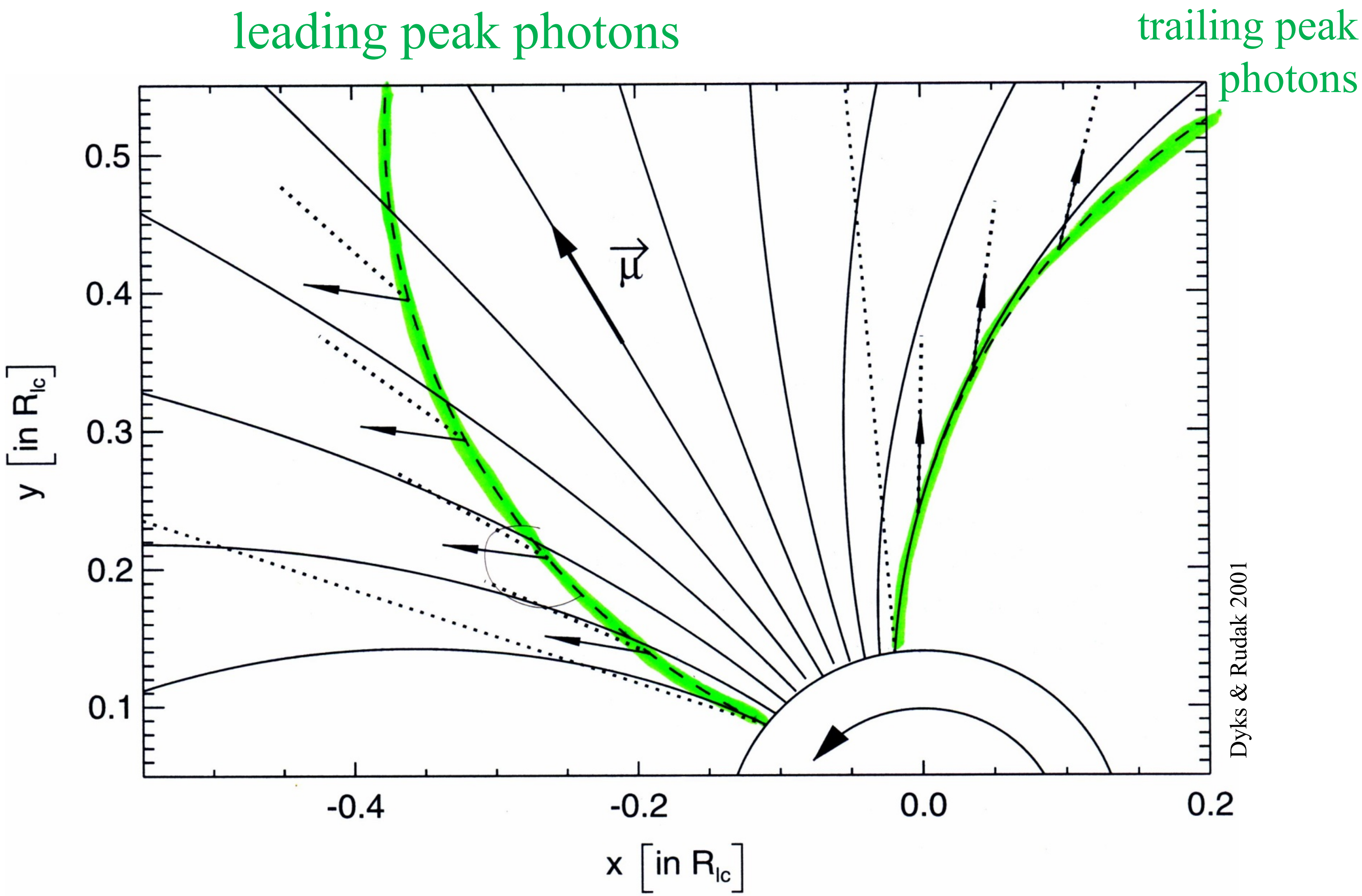
the trailing side of the boundary of the open field line region is the caustic surface

What profiles at TeV?



Possibly quite different than in EGRET band:
the leading peak disappears at the high-energy cutoff (a few GeV)

Photon trajectories in the comowing frame (CM):



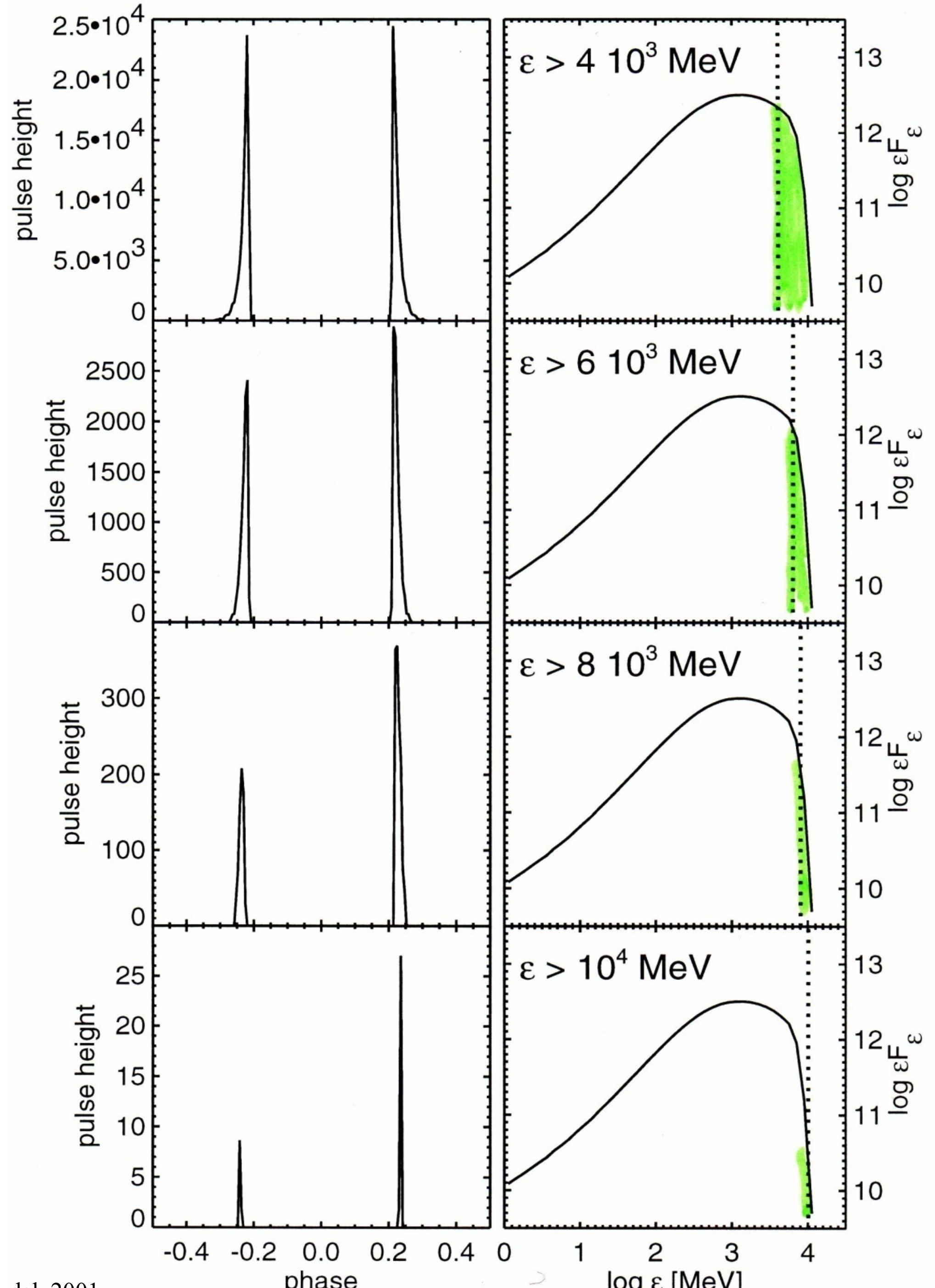
One-photon absorption:

threshold:

$$\varepsilon \sin\theta_{kB} \geq 2mc^2$$

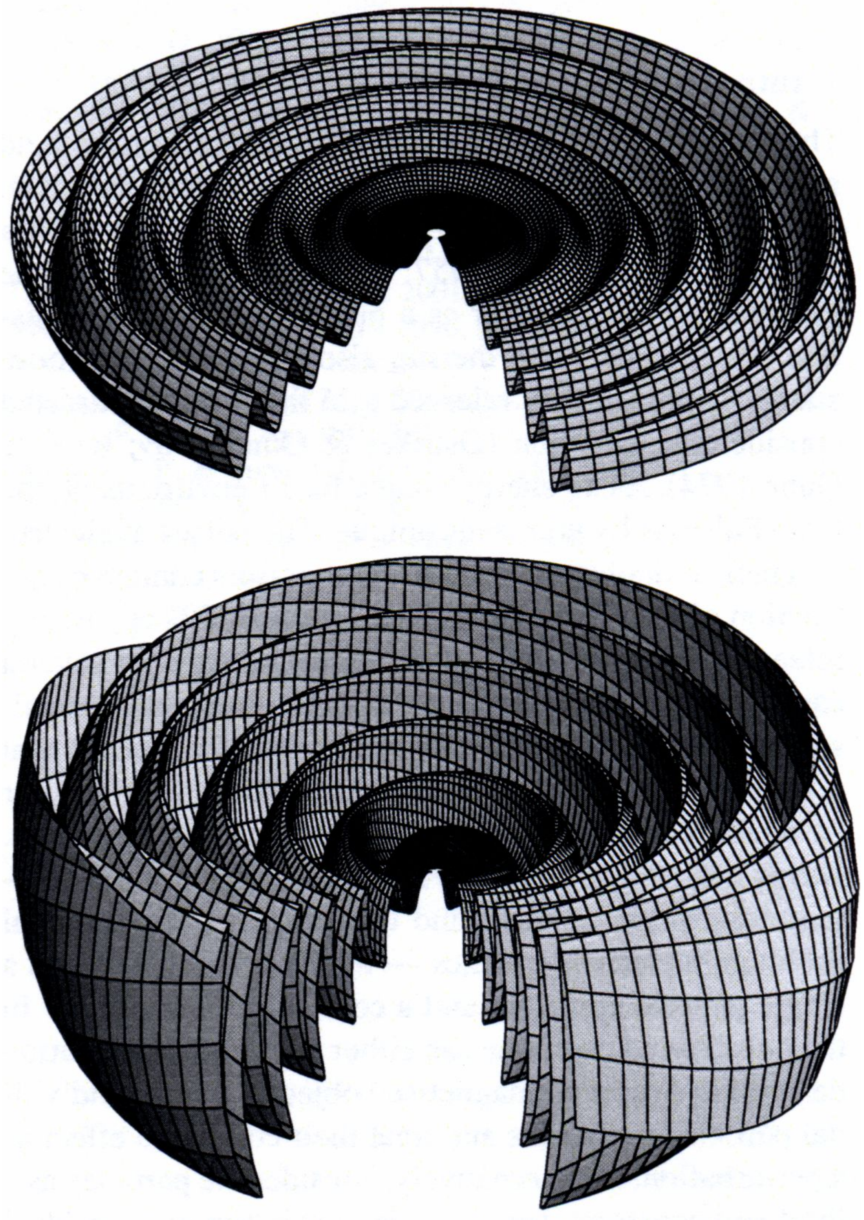
cross-section:

$$\eta \propto \exp(-1/[\varepsilon\, B \sin\theta_{kB}])$$

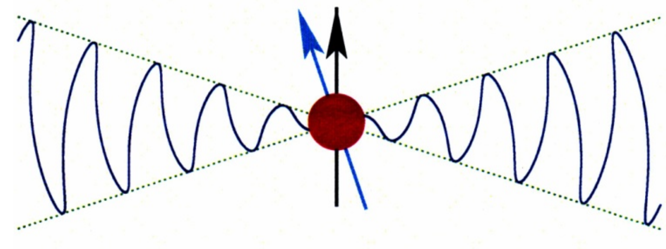


Dyks & Rudak 2001

Another way to reproduce pulses: striped wind

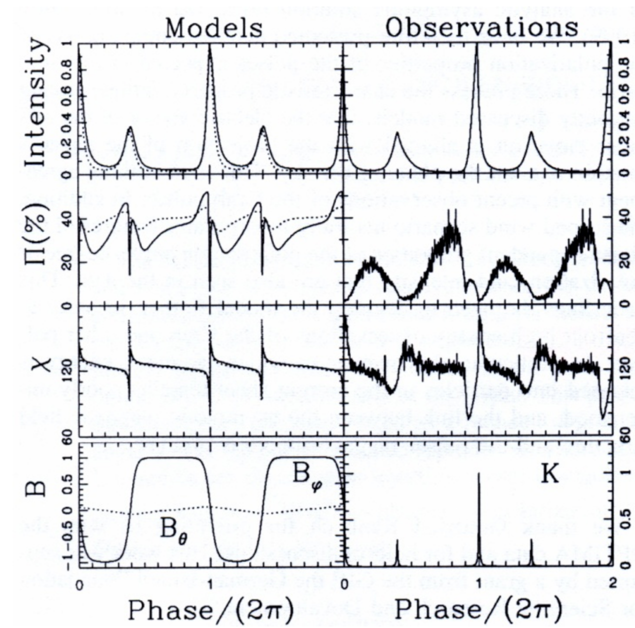


Kirk, Skjaeraasen & Gallant 2001



PULSES FROM WIND?

$$\frac{\Delta T}{\Gamma_w^2} << P$$



Petri & Kirk 2005

Conclusions

1. Detection of TeV ICS component much needed to guide modeling (OG model prediction unreliable due to strong sensitivity to geometry in highly anisotropic environment)

5. Super-exponential he-cutoff is disputable/improbable (we probably do NOT see polar caps, several ‘blurring’ effects possible)

9. TeV pulse profiles can be different from EGRET profiles (possible lack of leading peak, ICS ‘precursor’)

$$\frac{1}{2}\,\frac{\varepsilon}{mc^2}\,\frac{B}{B_Q}\,\sin\psi \simeq \frac{1}{15}$$

$$\varepsilon_{esc} \cong 760\ \mathrm{MeV}\ R_6^{-1/2}\ B_{pc,12}^{-1}\ P_{0.1}^{1/2} \left(\frac{r_{em}}{R}\right)^{5/2}$$

$$\frac{1}{2}\,\frac{\varepsilon}{mc^2}\,\frac{B}{B_Q}\,\sin\psi \simeq \frac{1}{15}$$

$$\varepsilon_{esc} \cong 760\ \mathrm{MeV}\ R_6^{-1/2}\ B_{pc,12}^{-1}\ P_{0.1}^{1/2} \left(\frac{r_{em}}{R}\right)^{5/2}$$

$$\gamma_{\pm} \simeq \frac{\varepsilon_{esc}}{2} \simeq 740\ B_{pc,12}^{-1}\ P_{0.1}^{1/2} \left(\frac{r_{em}}{R}\right)^{5/2}$$

$$\gamma_{\parallel} = \frac{\gamma_{\pm}}{\gamma_{\perp}'} \sim 250 \left(\frac{r_{em}}{R}\right)^{5/2} \left(\frac{r_{\pm}}{R}\right)^{-3} P_{0.1}^{1/2}$$

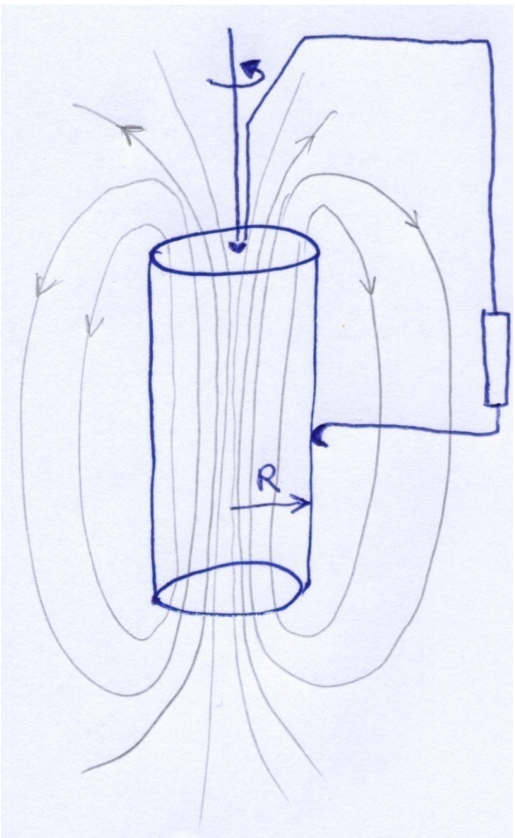
$$n_{GJ} = \frac{\rho_{GJ}}{e} = 7\cdot 10^{10}\ \mathrm{cm}^{-3}\ \frac{B_{pc,12}}{P}$$

Pulsars and PWNs
as sources of high-energy particles

Jarosław Dyks

CAMK, Toruń

Pulsars: unipolar generators of high voltage and strong currents
+ sources of **powerful el-mag wave**



$$\bar{E} = \gamma_{ROT}\left(\bar{E}' - \frac{\bar{v}_{ROT}}{c} \times \bar{B}'\right) =$$

$$\cong -(\bar{\Omega} \times \bar{r}) \times \bar{B}'$$

$$\bar{E}' = 0$$

$$E = \Omega r B$$

$$\Delta V = \int_0^R E\,dr = \frac{\Omega R^2 B}{2c} =$$

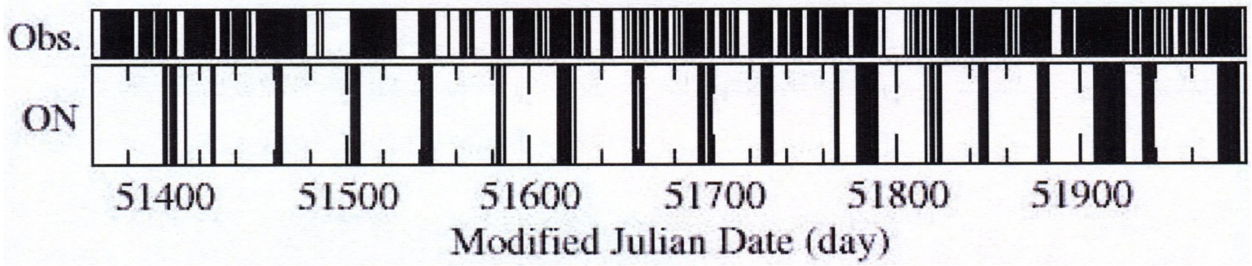
$$= \boxed{3 \cdot 10^{18}\,V} \frac{R_6^2 B_{12}}{P_{01}}$$

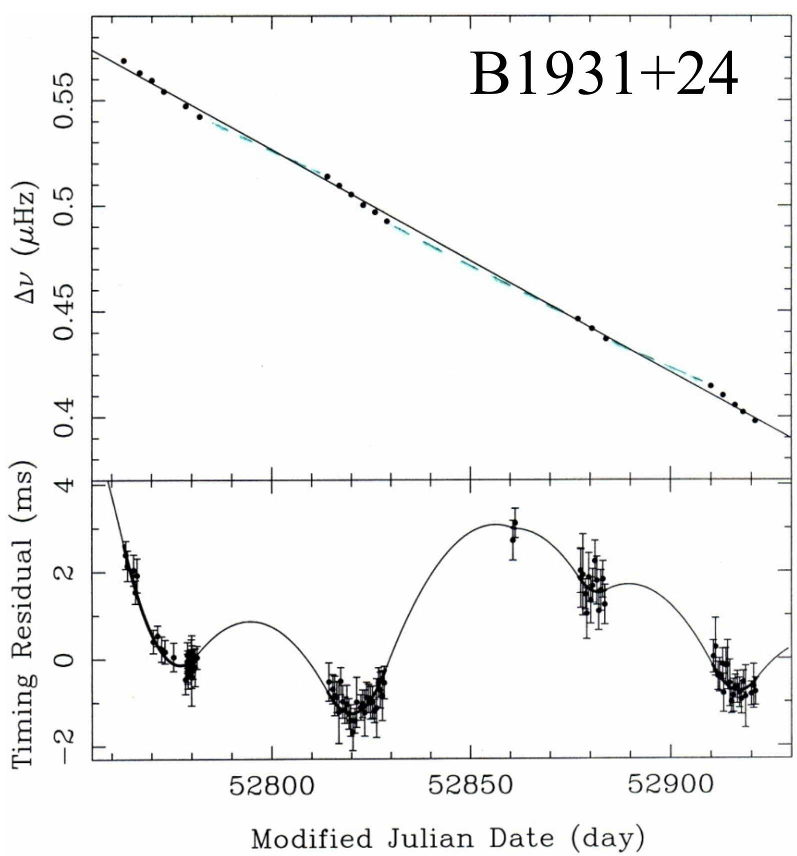
$$\bar{E} = \gamma_{ROT}\left(\bar{E}' - \frac{\bar{v}_{ROT}}{c} \times \bar{B}'\right) =$$

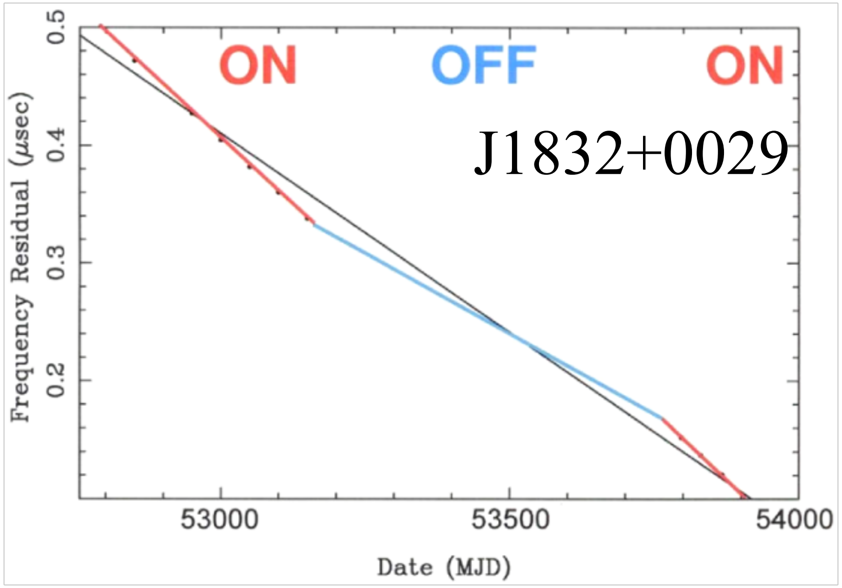
$$\cong -(\bar{\Omega} \times \bar{r}) \times \bar{B}'$$

$$E = \Omega r B$$

Digression: **Intermittent pulsars** (Kramer, Lyne, et al... 2006, 2007)







~2 times faster spin-down when the magnetosphere fills in with charges
=> estimate of ρ possible!

First 'measurement' of ρ_{GJ} (Kramer et al. 2006)

$$\dot{E}_{\substack{ON\\OFF}} = 4\pi^2 I \nu \dot{\nu}_{\substack{ON\\OFF}}$$

$$\dot{E}_{ON} = \dot{E}_{OFF} + \dot{E}_{WIND}$$

$$\dot{E}_{WIND} = \dot{E}_{ON} - \dot{E}_{OFF} = \Omega T$$

$$T = \frac{2}{3c} \, j \, B_{pc} R_{pc}^2$$

$$j = c \pi R_{pc}^2 \rho$$

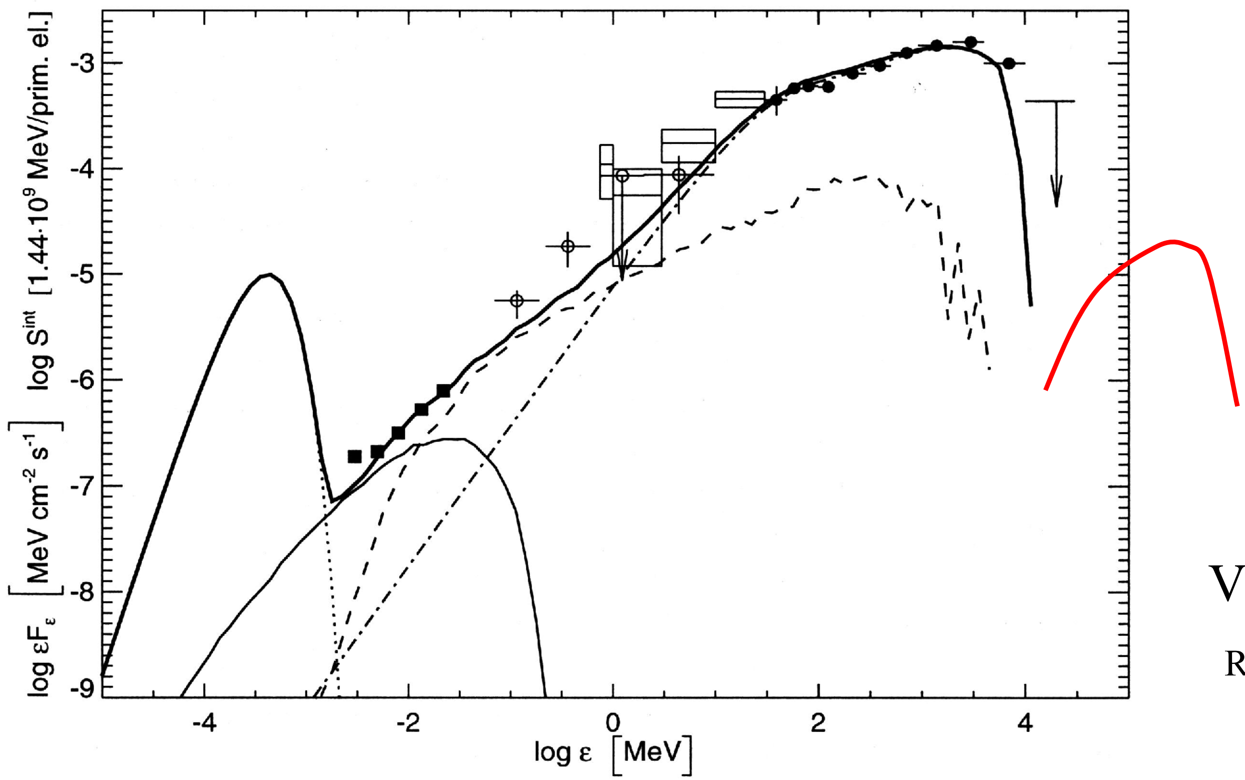
$$\rho = \frac{3I(\dot{\nu}_{ON} - \dot{\nu}_{OFF})}{R_{pc}^4 B_{pc}}$$

$$\rho = 0.034 \frac{C}{m^3}$$ (for B1931+24)

$$\rho_{GJ} = \frac{B_{pc}}{P_c} = 0.033 \frac{C}{m^3}$$

+ order of magnitude agreement for J1832+0029

‘Cascade models’ (PC/OG) roughly reproduce flux and spectra of gamma ray pulsars



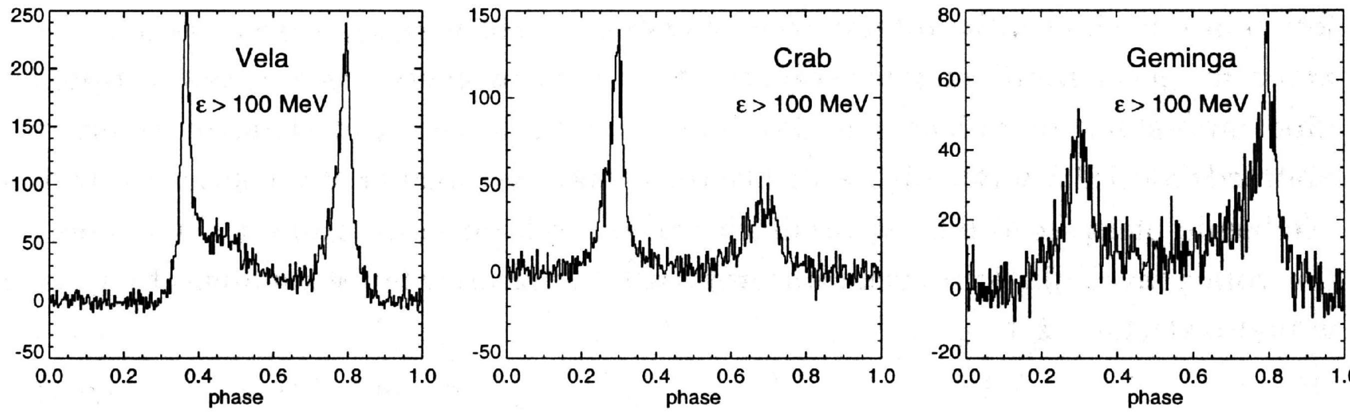
Vela pulsar

Rudak & Dyks 2007

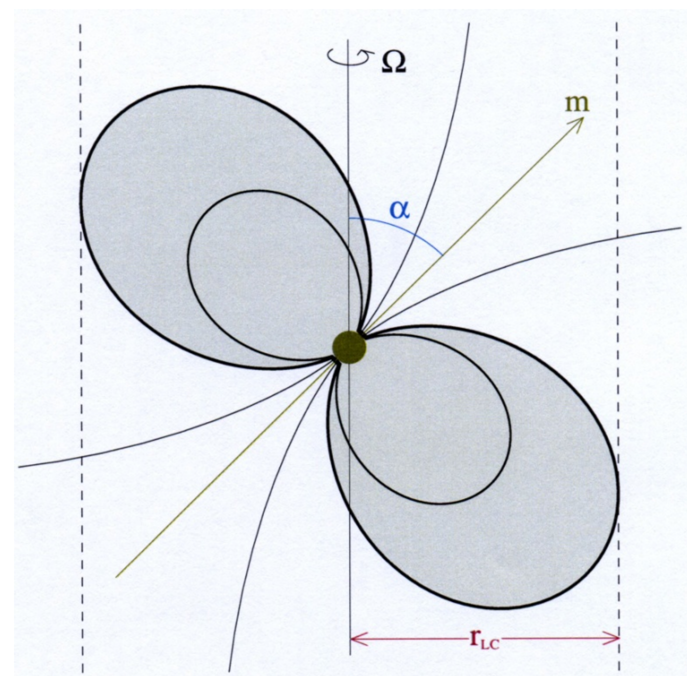
GLAST may detect the super-exponential HE cutoff near 30 GeV

HESS may detect the ICS component in TeV band

EGRET pulse profiles



Difficult to understand (radio ahead of the leading γ-ray peak).
Not from polar cap!
Mostly of caustic origin?
Radially elongated regions required (polar gap => slot gap).



We end up with:

$I_{GJ} \sim 10^{33}$ primary electrons/s with $\gamma \sim 10^6$

$n_\pm I_{GJ} \sim 10^{38}$ secondary $e^\pm$ pairs/s with $\gamma_\pm \sim 10^2$

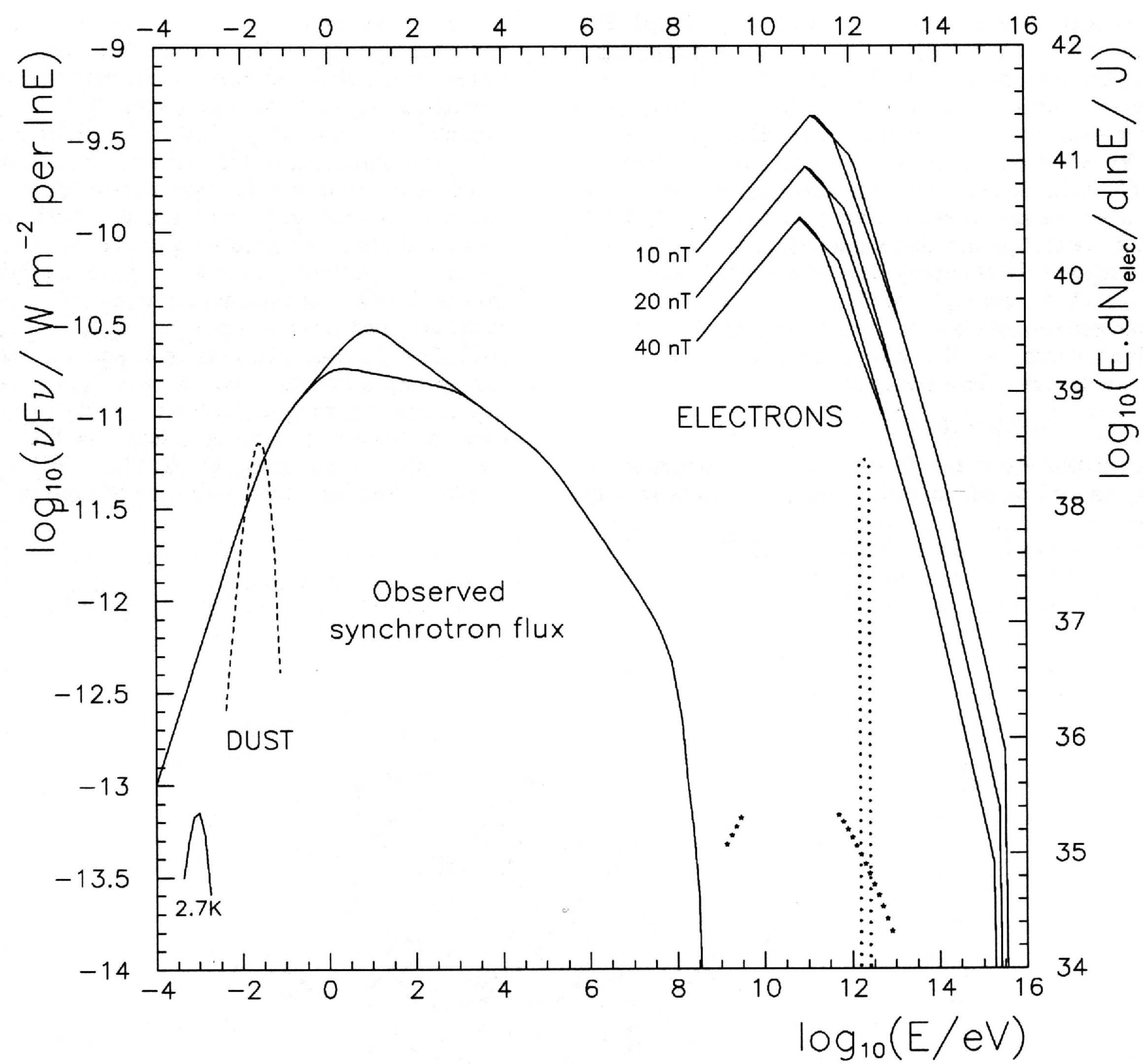
$\sigma \sim 10^4$

$$\sigma = B^2/(4\pi n \gamma m c^2)$$

instead of:

10^{39} electrons/s
$\gamma \sim 10^6$
$\sigma \sim 0.02$

needed to reproduce spectrum and morphology of Crab PWN



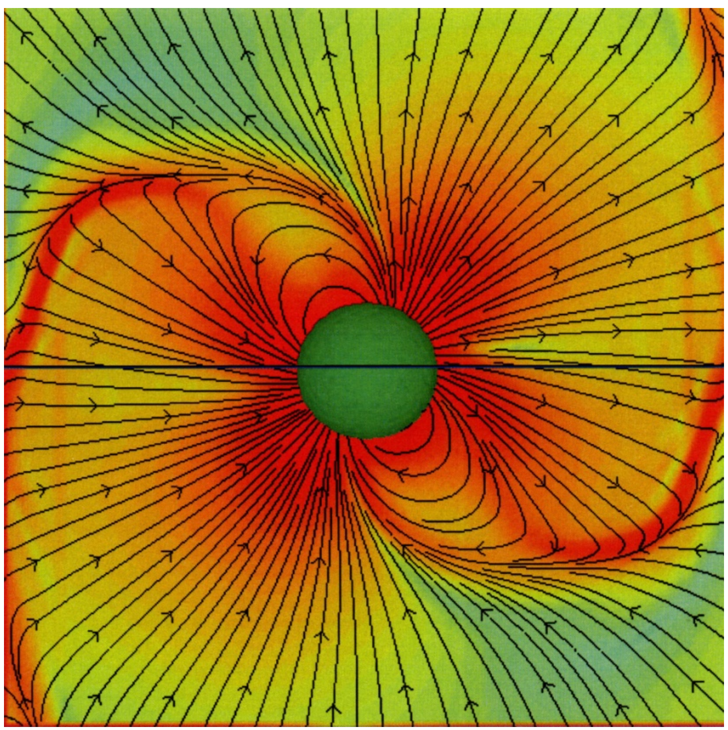
$\log_{10}(\nu F\nu /$ W m^{-2} per lnE$)$
$\log_{10}($E.dN$_{elec}$/dlnE/ J$)$
$\log_{10}(E/eV)$
10 nT
20 nT
40 nT
ELECTRONS
Observed
synchrotron flux
DUST
2.7K

Hillas et al

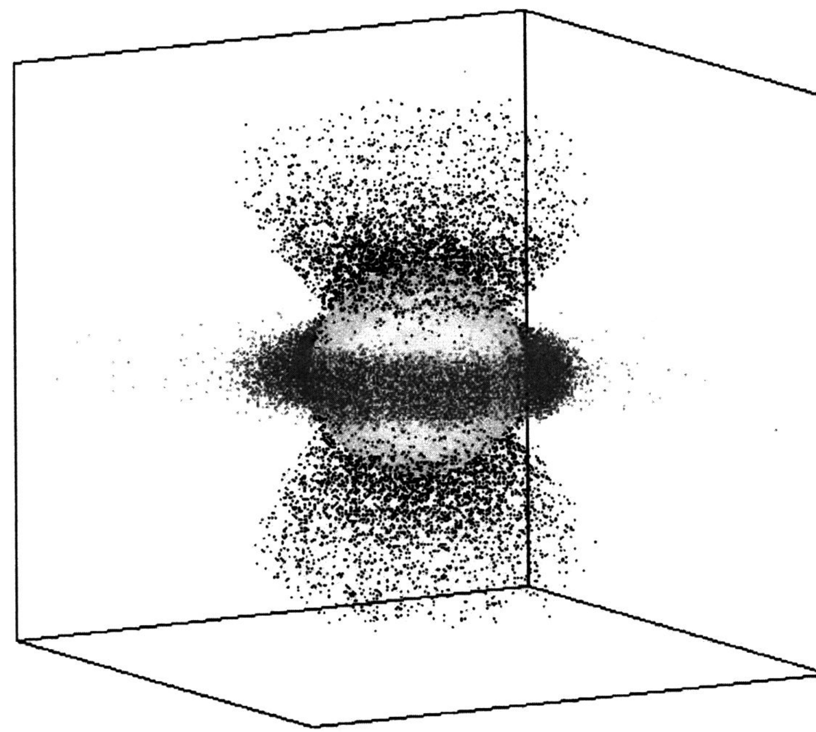
‘Gapology’ may be wrong =>

Force free codes (Spitkovsky 2007)
energy loss for the plasma-filled inclined dipole calculated for the first time

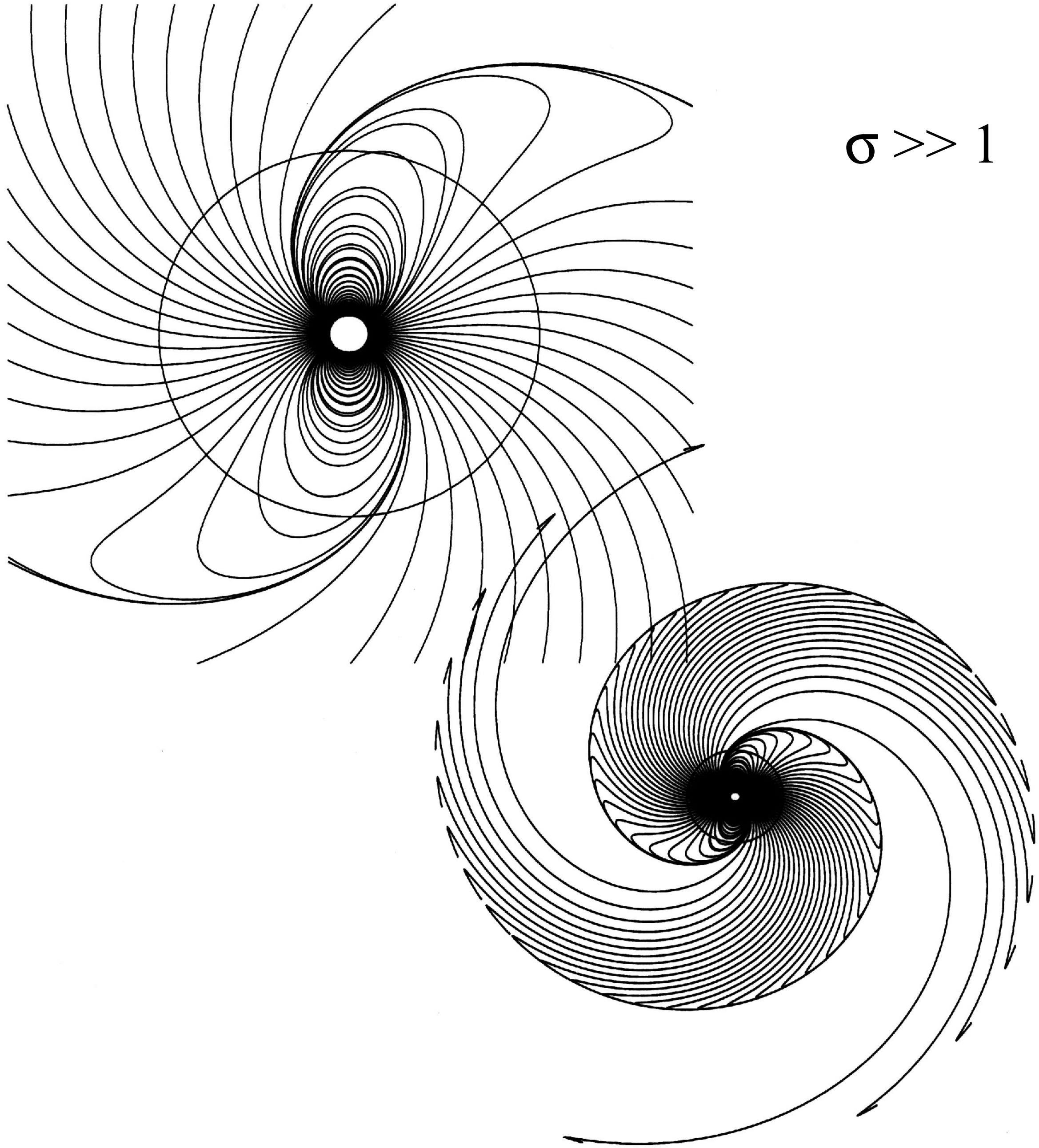
First principle codes (Krause-Polstorff & Michel 1985-200...): **no wind!** mostly empty magnetoshpere



$\rho\mathbf{E} + \mathbf{j}\mathrm{x}\mathbf{B}/c = 0$



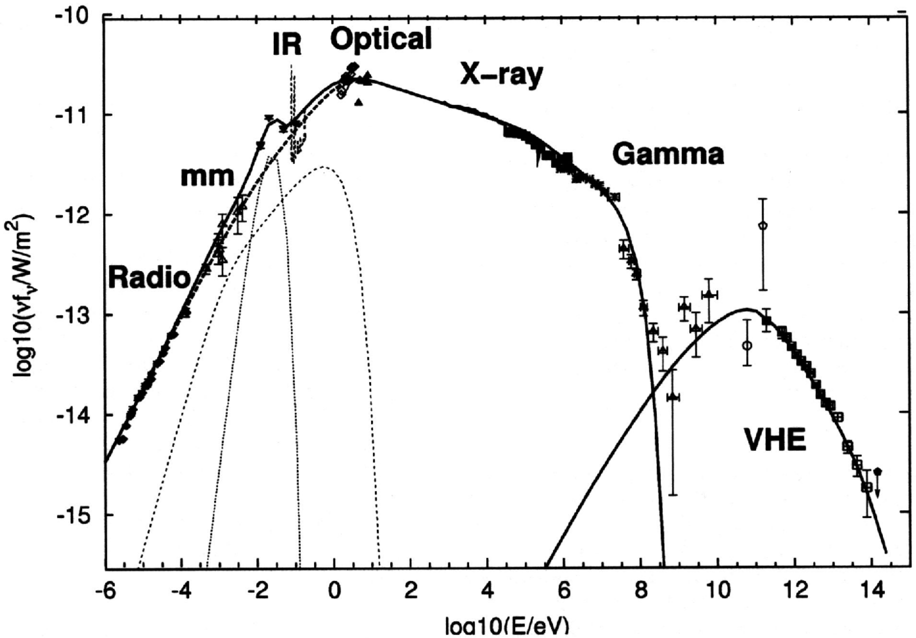
Throwing away toroidal field

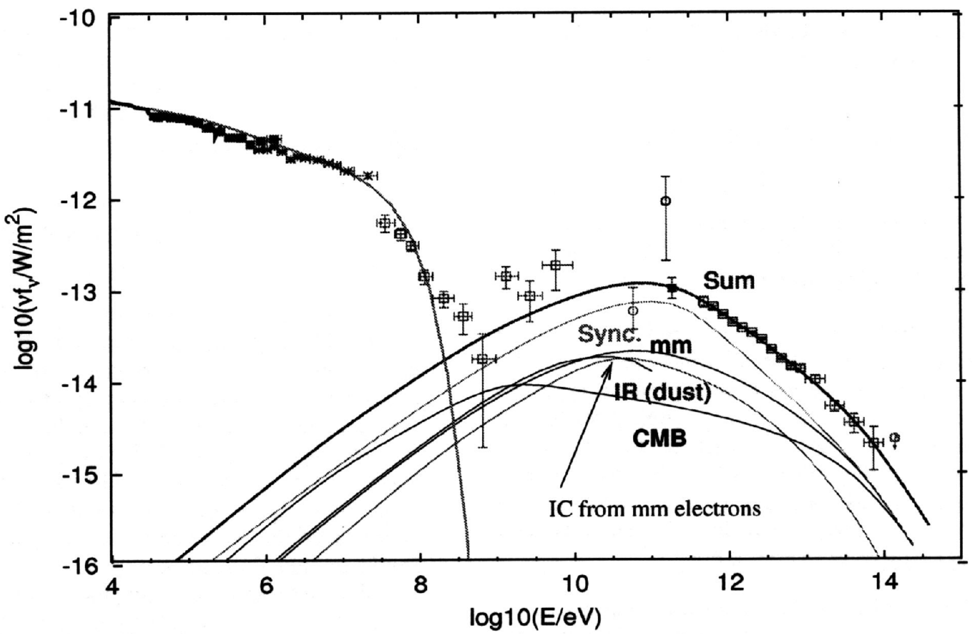


$\sigma >> 1$

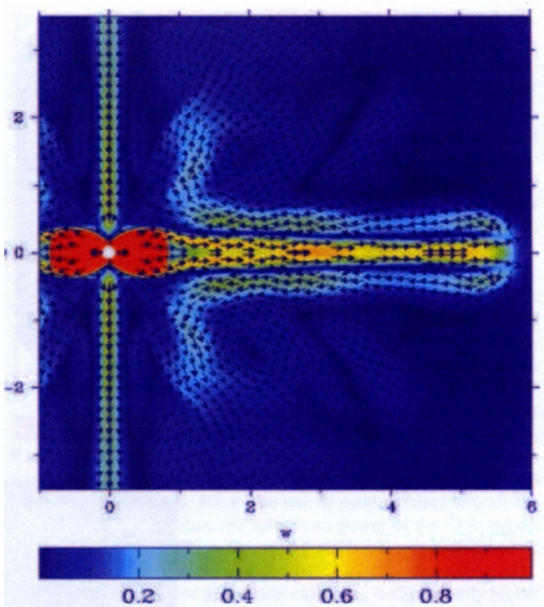
Yadigaroglu 1997

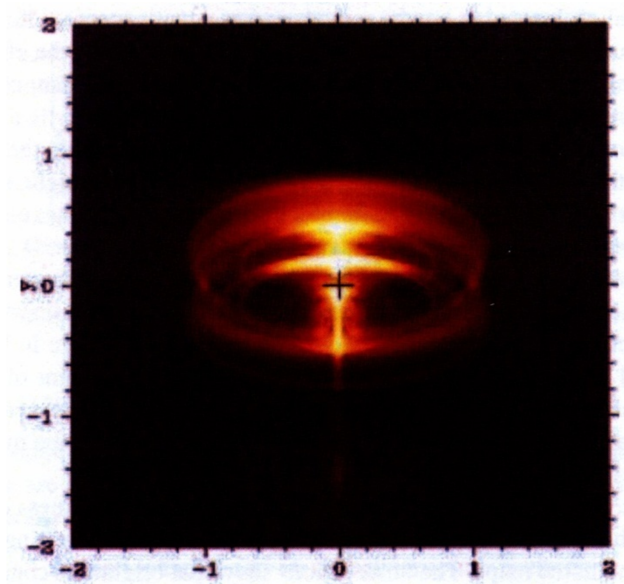
Crab nebula spectrum (SR + ICS)

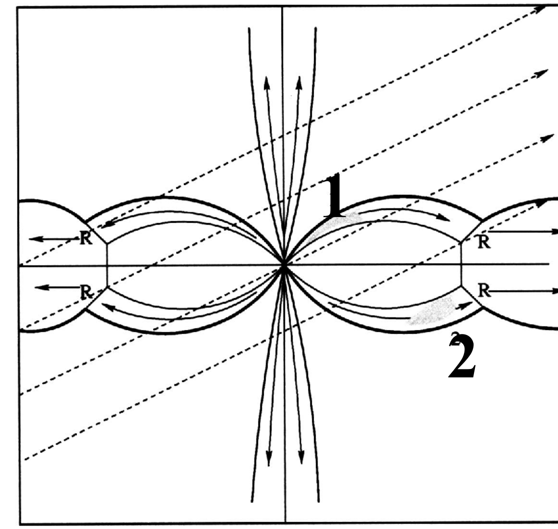




Morphology: jet/torus + knots/wisps



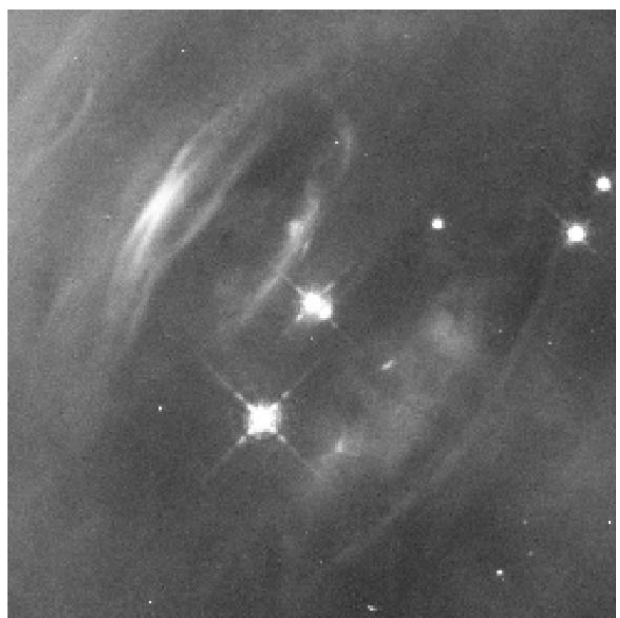




Komissarov
& Lyubarski 2004

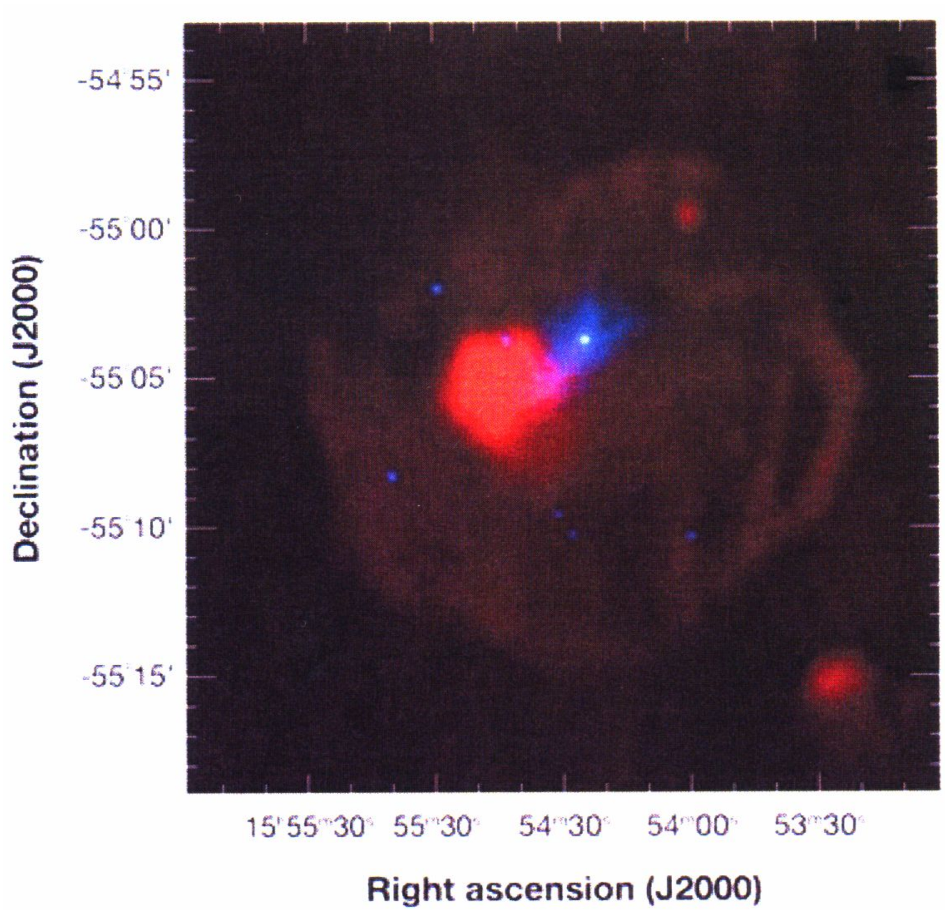
$$B_\varphi \propto \sin\theta$$

Total energy flux
$\propto (\sin\theta)^2 + \text{const}$



Hester et al. 1995

Evolution generally understood (free+Sedov expansion, reverse shock crush, bow shock nebula).
Example: relic PWN.



Conclusions

1. Success in understanding of PWN spectra/morphology/evolution

2. No easy way to connect this to the pulsar (sigma problem)
   Numerical simulations far too ideal to tackle this.

3. Some progress thanks to CGRO and radio observations
   (gamma rays not from polar caps, estimate of GJ density,
   double pulsar: LOS through LC)

4. GLAST will increase the number and quality of HE spectra
   and profiles, HESS keeps constraining the outer gap model