Theory of High Energy Emission from Pulsars

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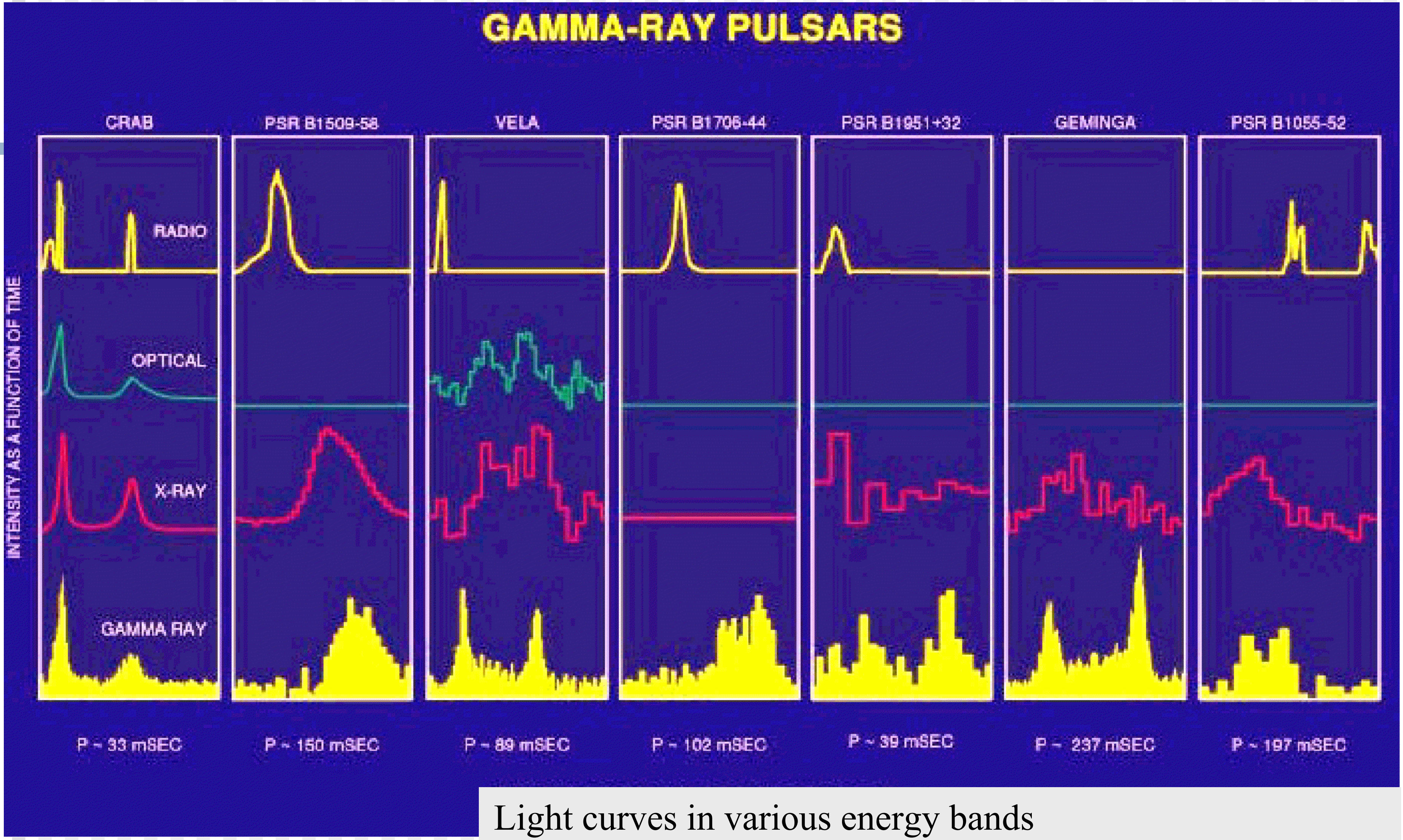
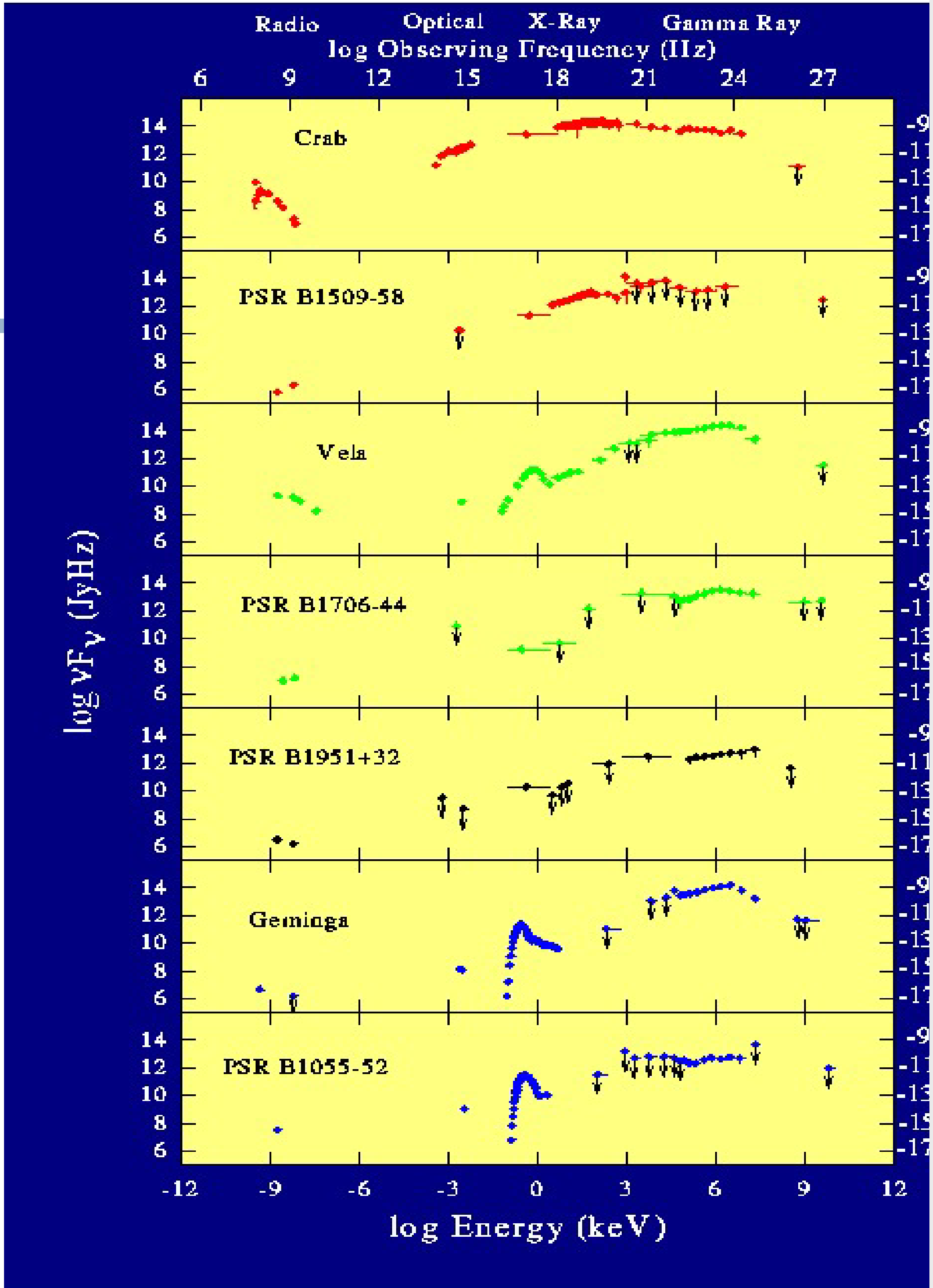
Outline

- Introduction :Accelerators – polar gap, slot gap and outer gap
- Relevant observed data
- 3D outer gap model
- Discussion

X-rays and gamma-rays from Pulsars (7 hc + 3 lc)



Light curves in various energy bands
http://antwrp.gsfc.nasa.gov/gamma/bro/bro10.thml

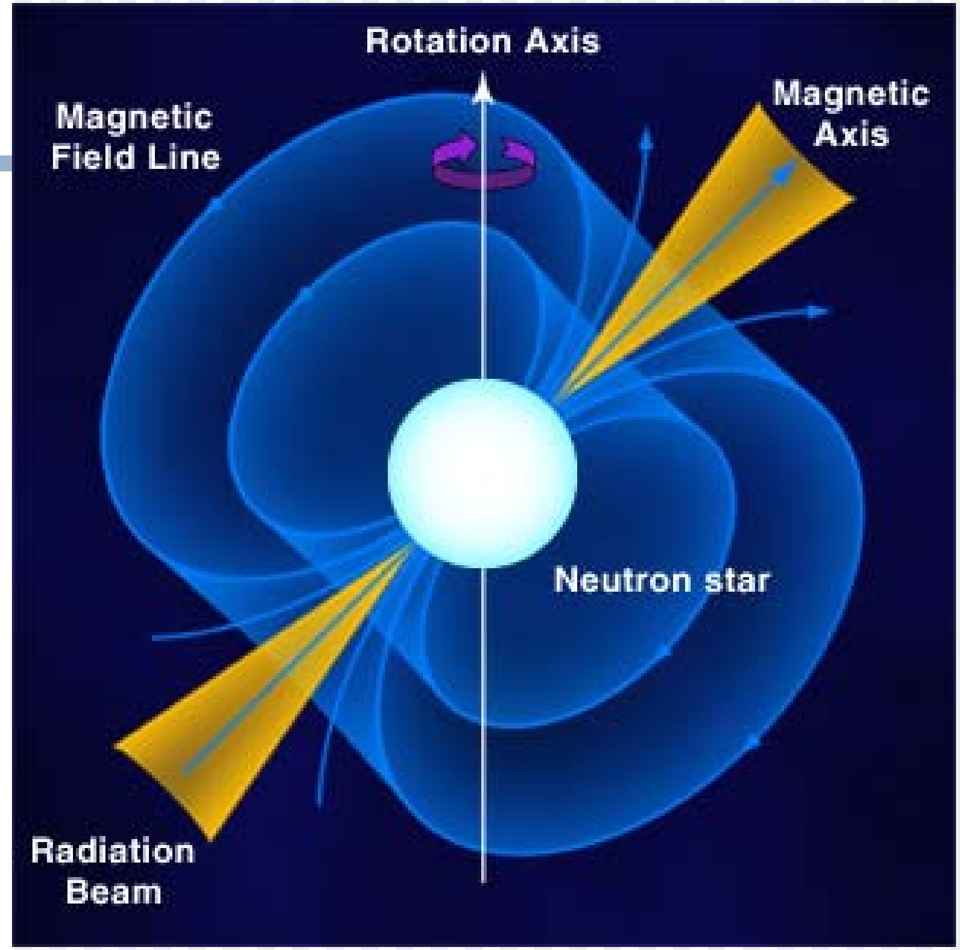


Broad-band spectra

- Non-thermal spectrum
- Most radiation power in γ-rays
- Turnover > 10 GeV
- Thermal component appears in older pulsars

Why are pulsars powerful radiation sources?

- Pulsars are rotating and strongly magnetized objects, so they can act like unipolar inductor
- The maximum potential drop can be as large as
  $$V_{max} \approx 6.6\times10^{12} B_{12}\, P^{-2} volts$$
- For young pulsars, the maximum potential can be much higher than 10^{15} volts
- This potential drop can accelerate charged particles and radiate high energy photons from various accelerators in the magnetosphere



Accelerators

- There are three possible accelerators existing in the pulsar magnetosphere, i.e.
- (1) Polar cap (inner gap) (Arons, Scharlemann 1979 ApJ 231, 854;Daugherty & Harding 1982 ApJ 252, 337;1996 ApJ 458, 278),
- (2) slot gap (Arons 1983, ApJ 302, 301; Muslimov, Harding 2004, ApJ 606, 1143)
- (3) outer gap (Cheng, Ho, Ruderman 1986, ApJ 300, 500; 300, 522)

Polar cap accelerators

SPACE CHARGE "GAP"

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

Arons & Sharlemann 1979

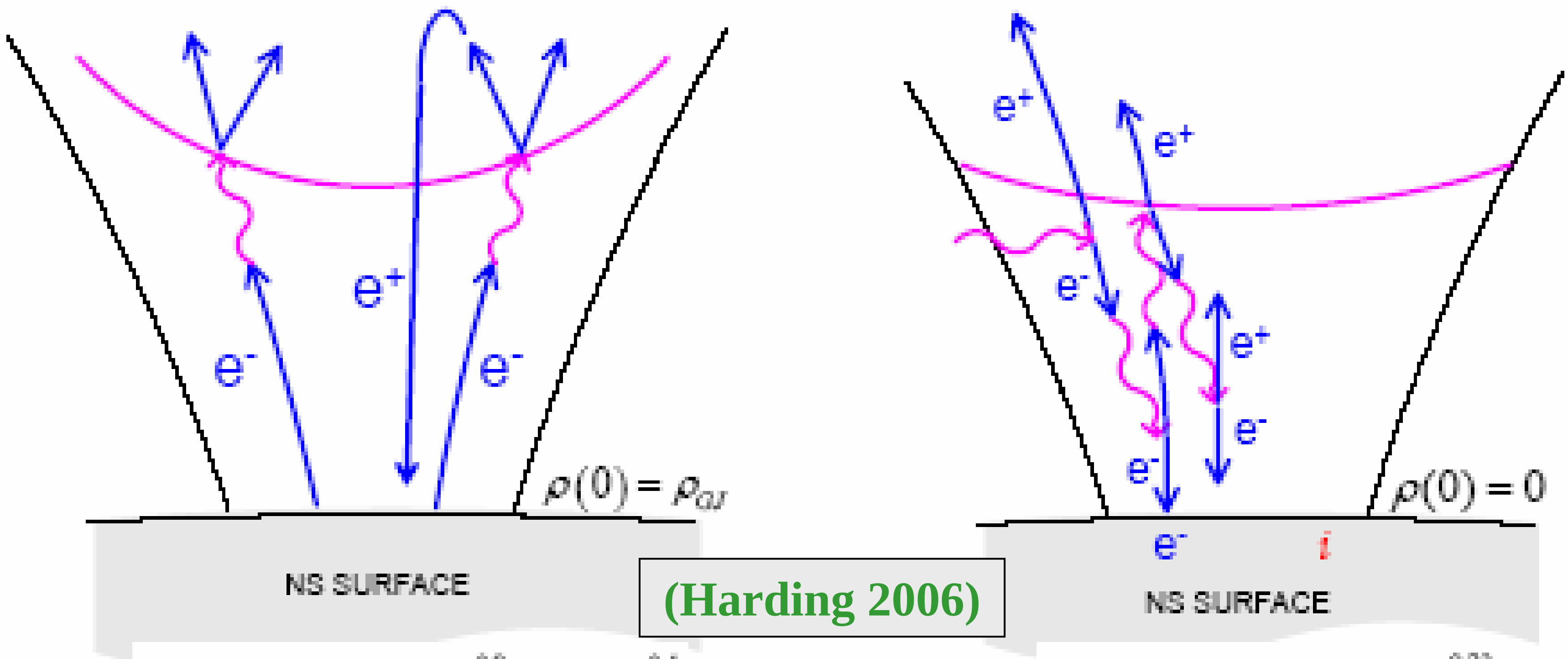
$$\nabla \cdot E_{\parallel} = -4\pi(\rho - \rho_{GJ})$$

VACUUM GAP

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

Ruderman & Sutherland 1975

$$\nabla \cdot E_{\parallel} = 4\pi\rho_{GJ}$$

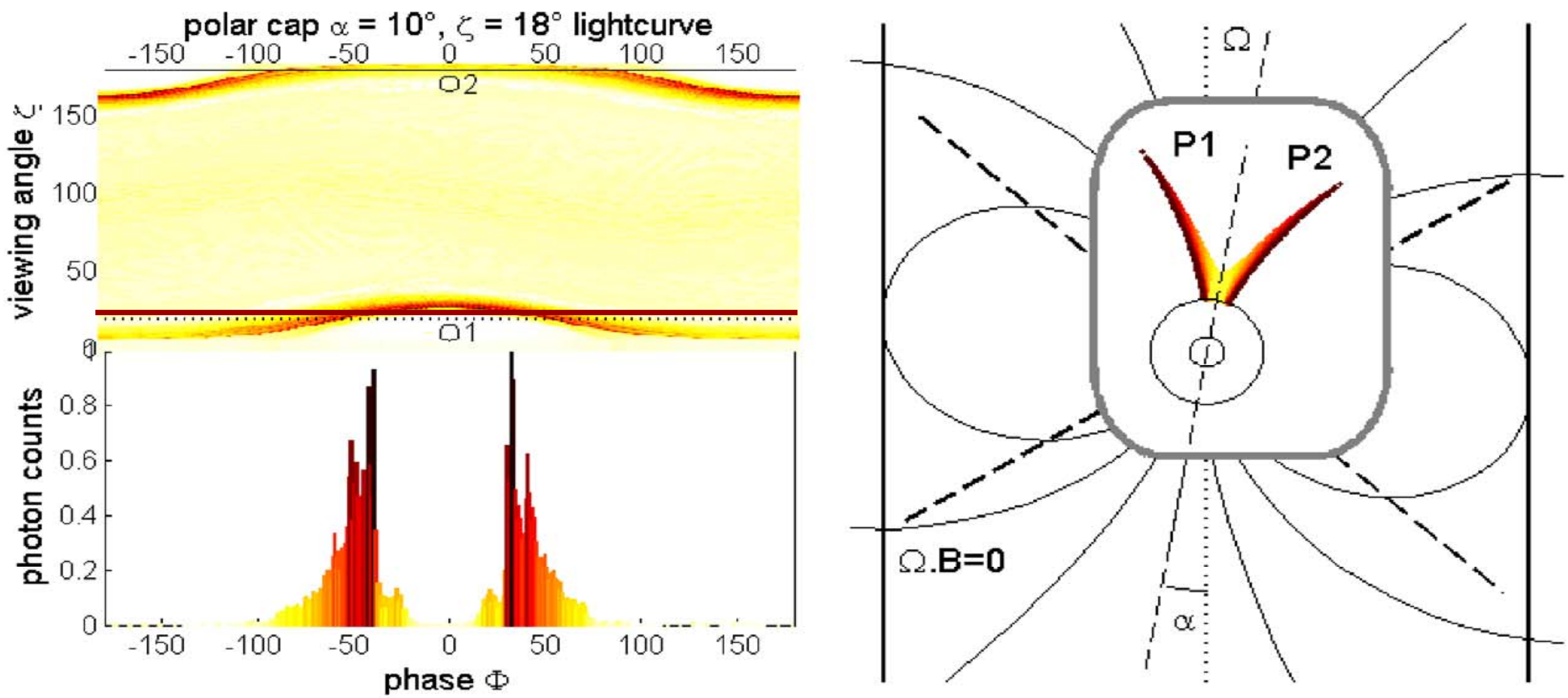


$$T_e \cong 3.6\times10^5 K \left(\frac{Z}{26}\right)^{0.8}\left(\frac{B_o}{10^{12} G}\right)^{0.4}$$

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

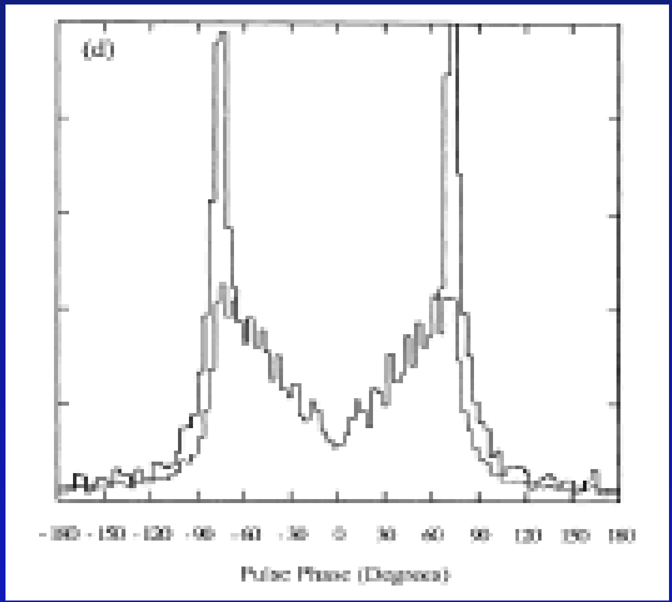
(Harding 2006)

A single inner-gap beam produces various pulse profiles with any peak separation between 0^o and 180^o. However, one has to assume a small inclination and a lucky viewing angle (α~ξ< 30^o).

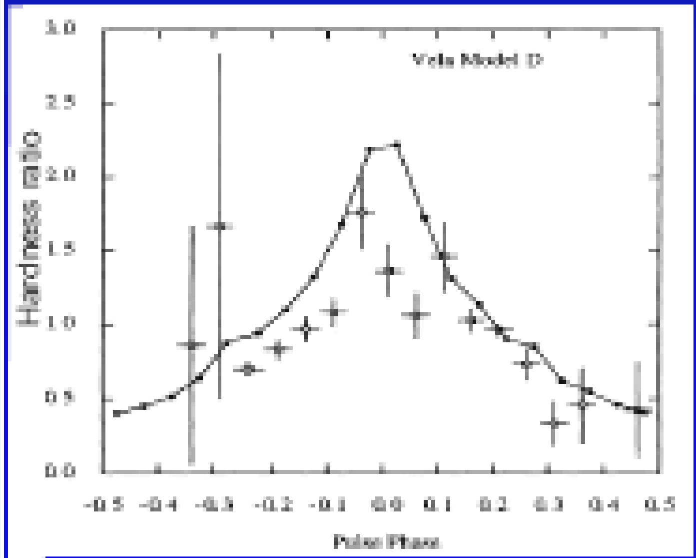


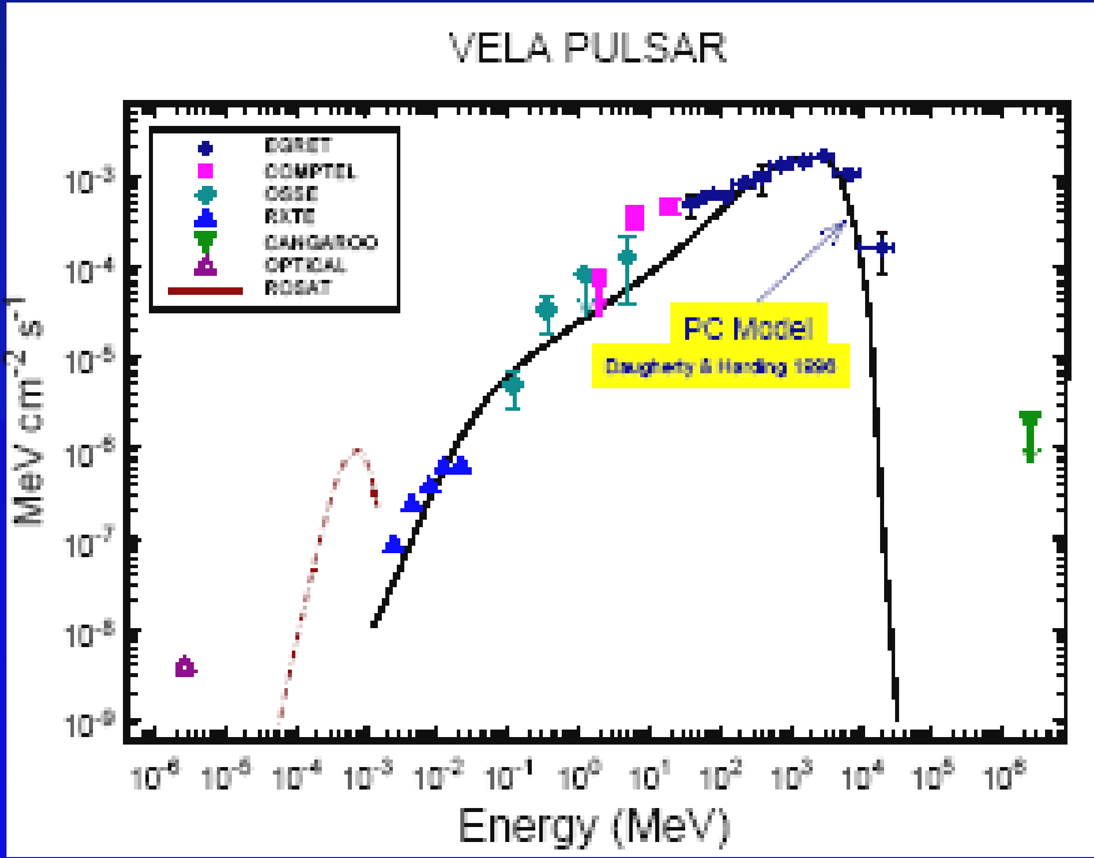
Grenier & Harding (2006)

Traditional PC Model (Daugherty & Harding 1996)



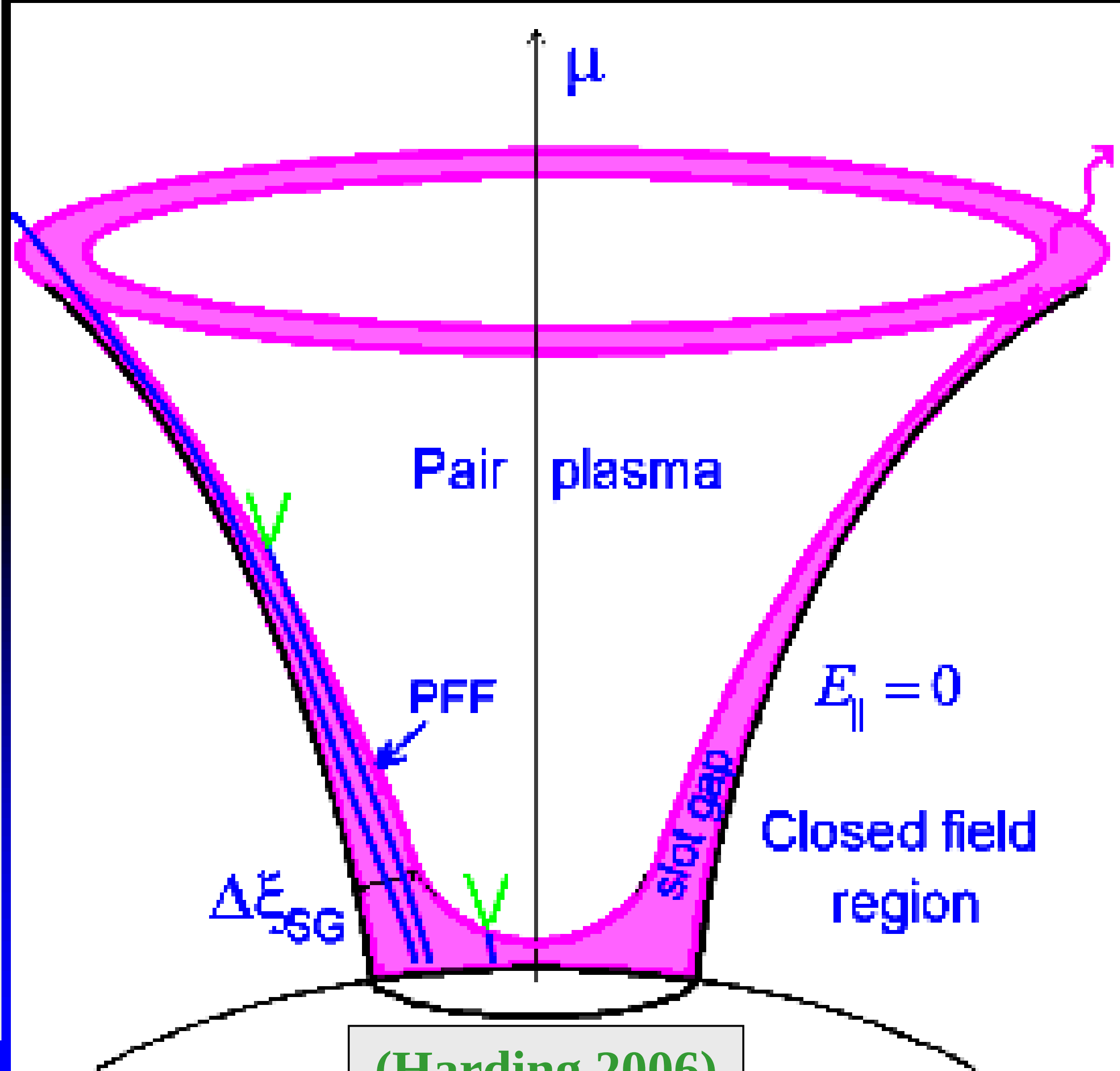
- Acceleration artificially placed at r = 3 R
- Assumed PC rim enhancement
- $\alpha = 10^0$ to generate broad pulse profile





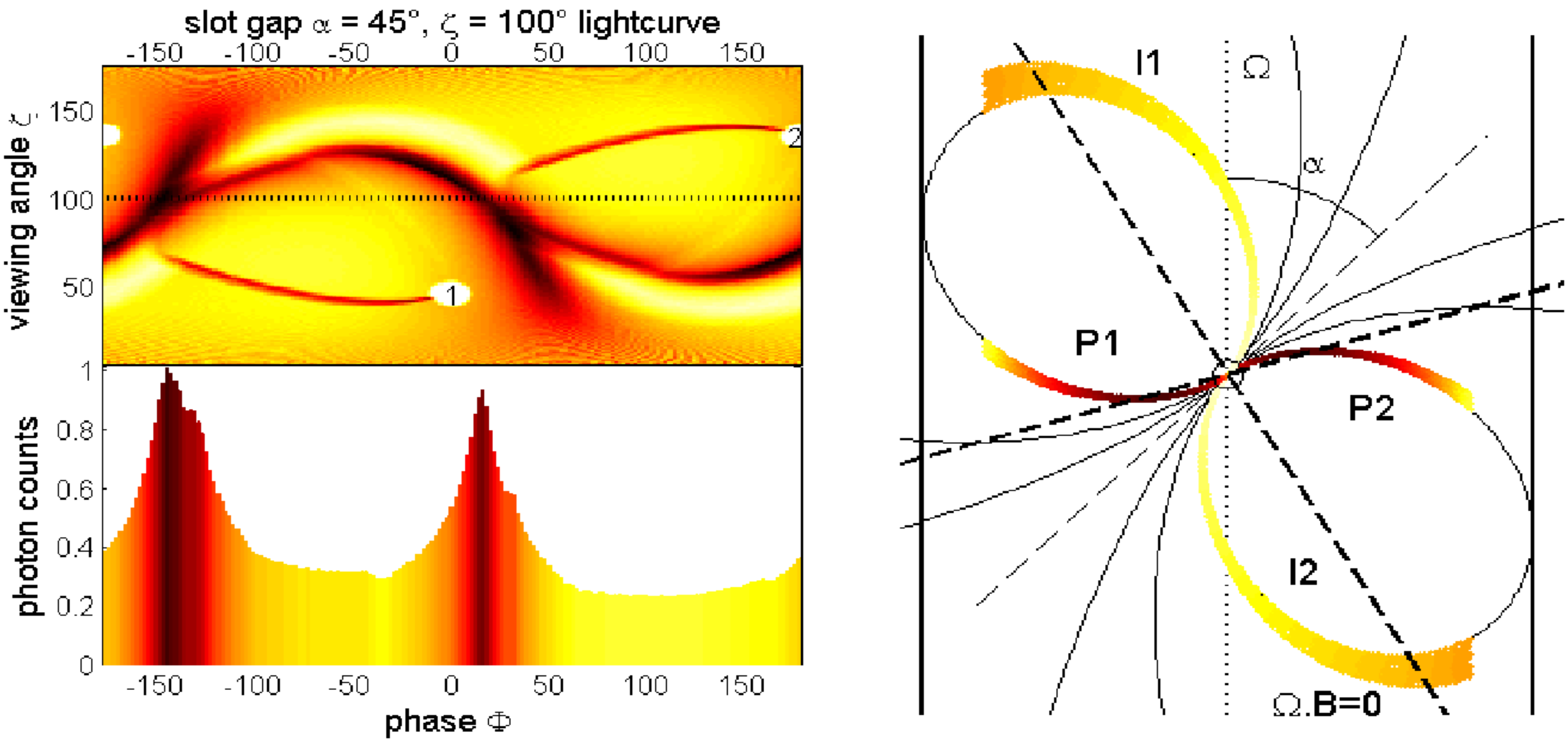
Slot gap model

Seeking the possibility of a wide hollow cone emission due to flaring ***B*** field lines, Arons (1983) first examined a gap formation in higher altitudes along last-closed field line. This type of gap - a slot gap – is formed because the screening of E|| occurs at increasing altitudes near the last-open field line.



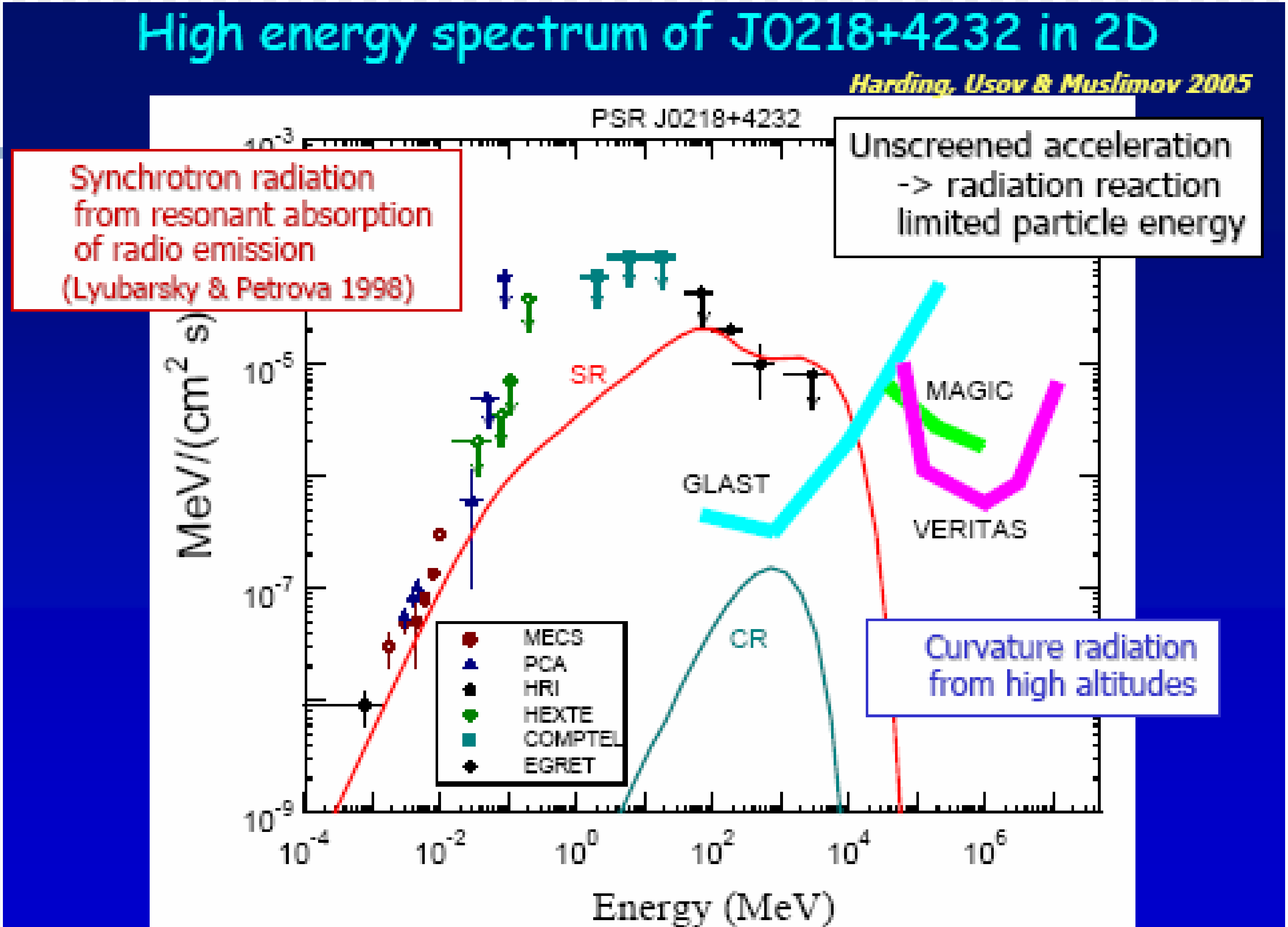
(Harding 2006)

Slot-gap model (Dyks & Rudak 2003; Dyks, Harding, Rudak 2004) - Two-pole caustic model predicts that double peaks arise from the crossing of caustics associated with both poles. They have also explained some polarization features of the Crab pulsar.

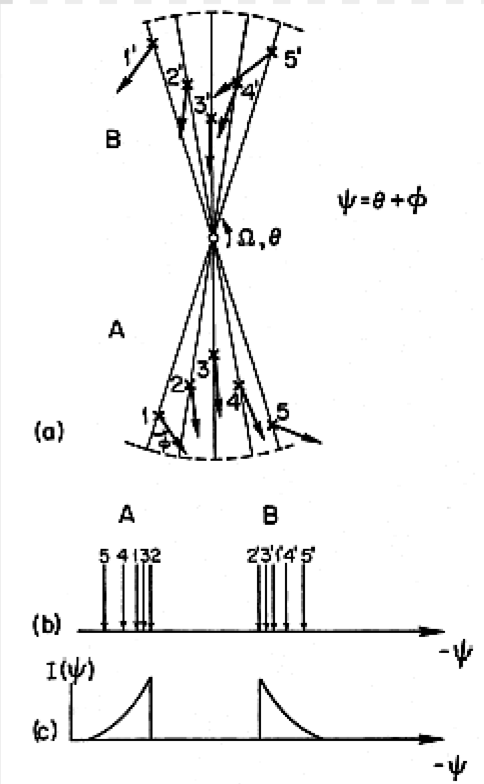


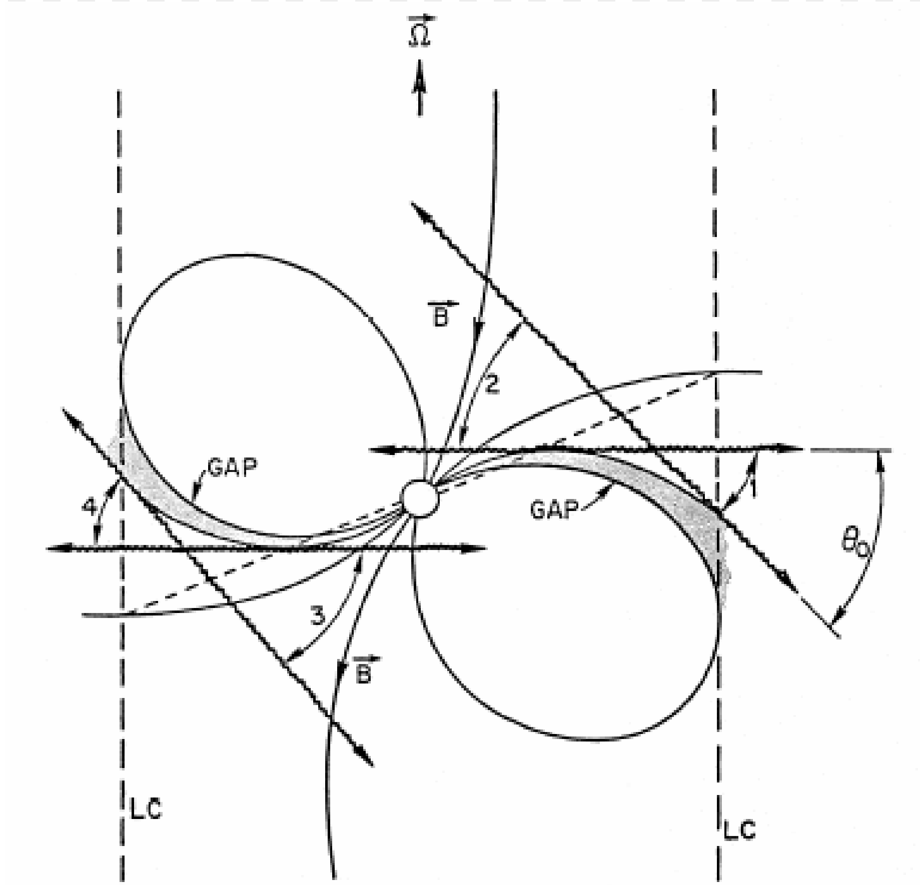
Grenier & Harding (2006)

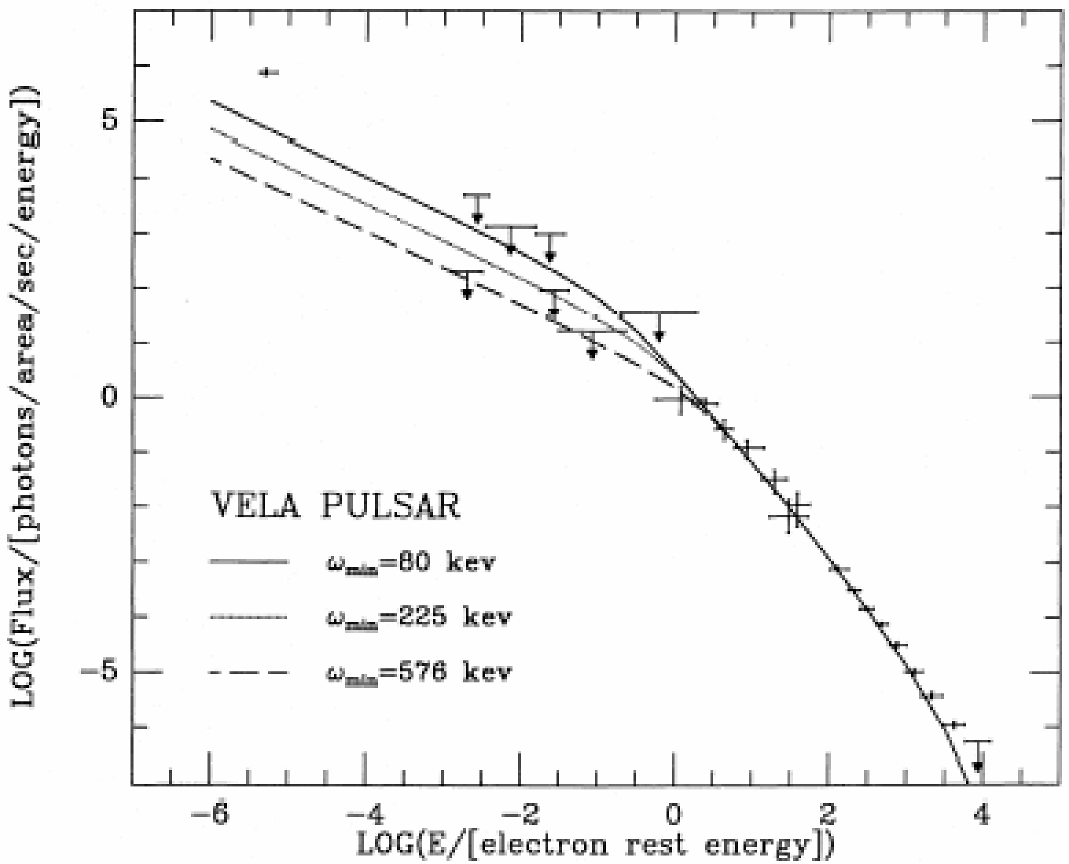
Accelerator in MSP



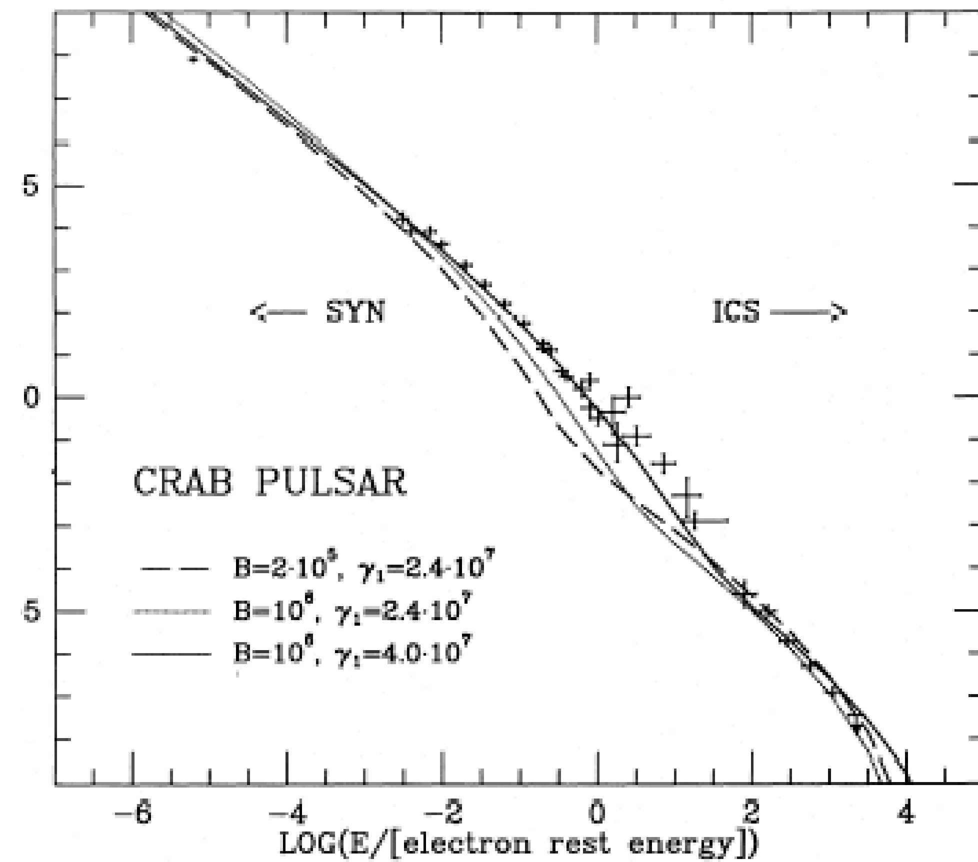
2D outer gap model (cheng, Ho and Ruderman 86)







VELA PULSAR
ω_{min}=80 kev
ω_{min}=225 kev
ω_{min}=576 kev
LOG(Flux/[photons/area/sec/energy])
LOG(E/[electron rest energy])



<-- SYN
ICS -->
CRAB PULSAR
B=2·10^5, γ_1=2.4·10^7
B=10^6, γ_1=2.4·10^7
B=10^6, γ_1=4.0·10^7
LOG(E/[electron rest energy])

New outer-gap model (Hirotani & Shibata 2001; Hirotani, Harding & Shibata 2003)

Hirotani and his co-workers have pointed out that the large current in the outer gap can change the boundary of the outer gap. They solve the set of Maxwell & Boltzmann equations in pulsar magnetospheres

demonstrate the existence of outer-gap accelerators, as stationary solutions,

quantitatively solve

(1) gap position & extent,

(2) $E_{||}$ distribution, voltage drop,

(3) particle energy distribution,

(4) γ-ray spectra

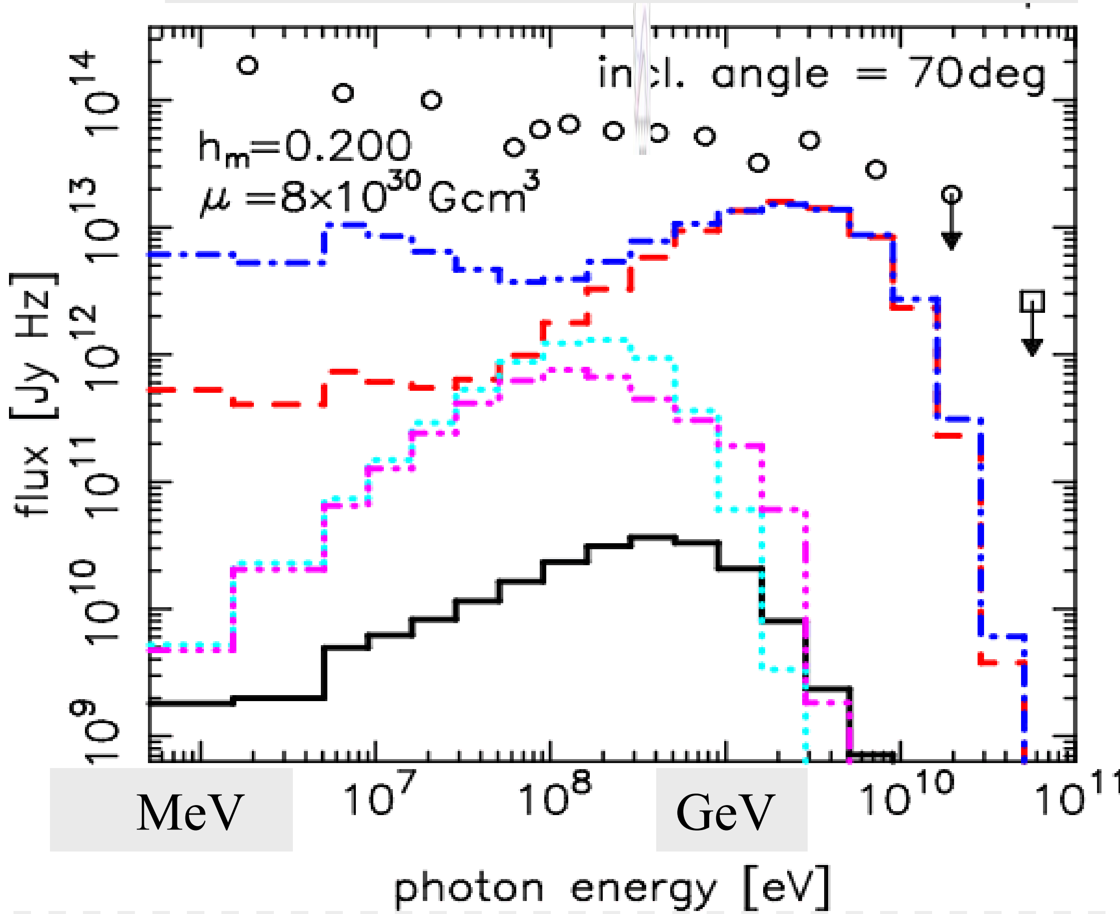
Hirotani (2006) calculates the spectrum of the Crab pulsar for various viewing angles

Flux appears still insufficient.

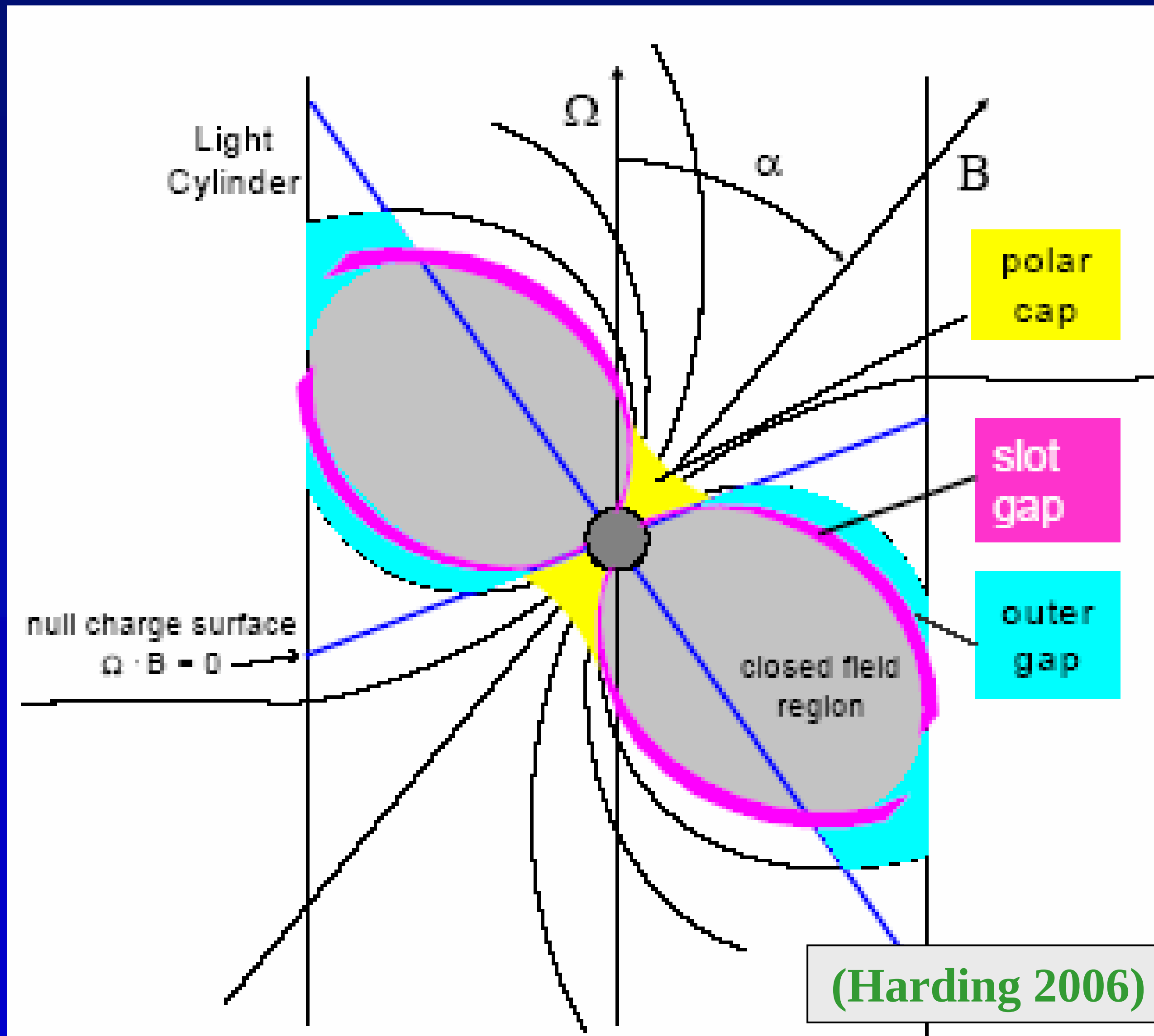
Nevertheless, in future 3-D analysis, emission solid angle will be found to be much smaller on the trailing side (by aberration).

→ stronger γ-ray flux

Crab pulsar spectrum



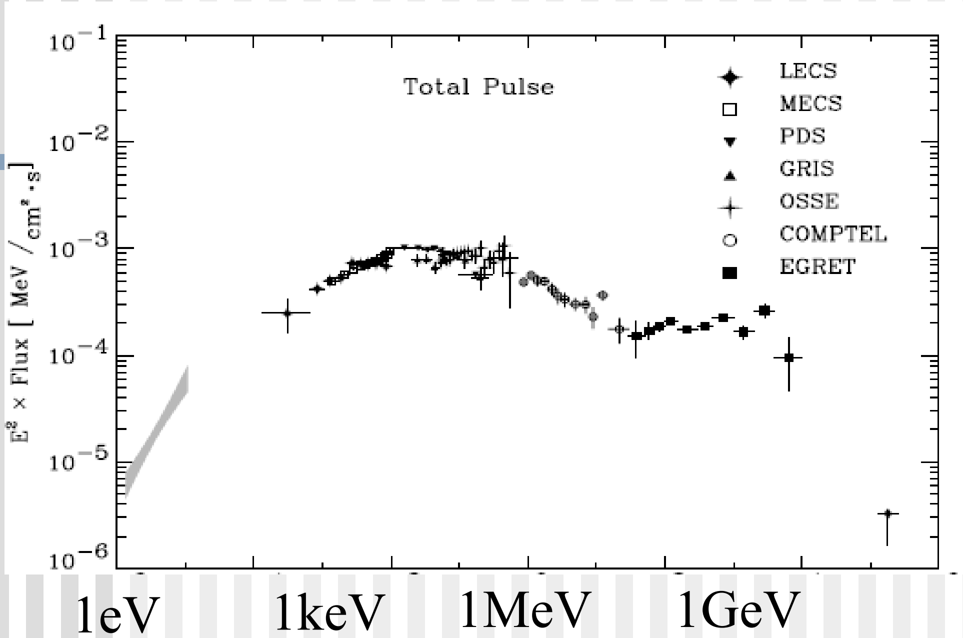
Pulsar high-energy emission models

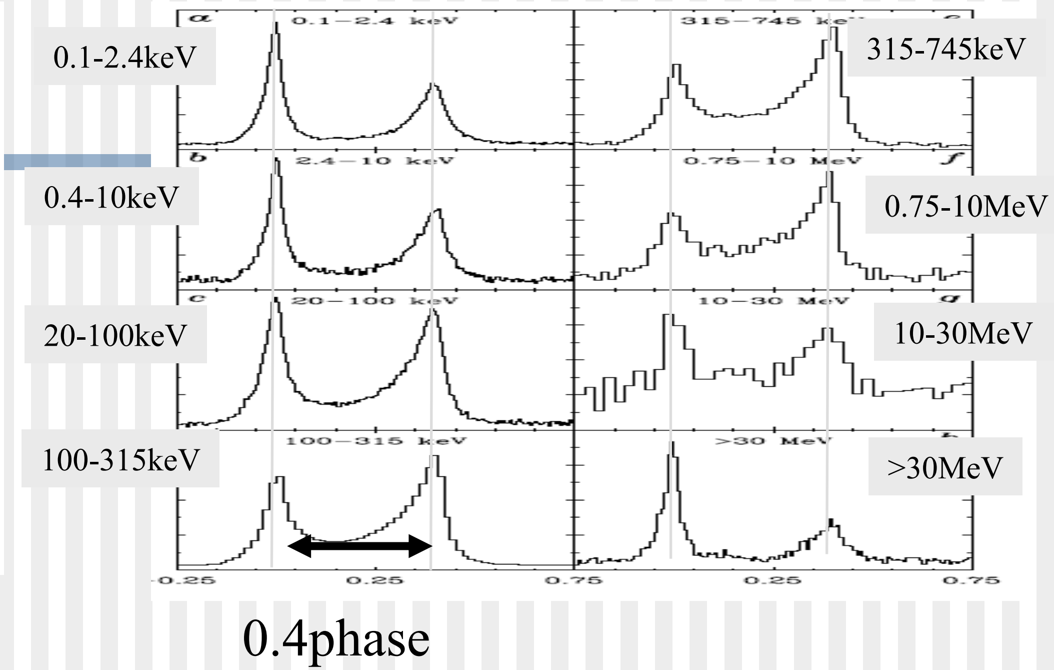


(Harding 2006)

The Crab pulsar

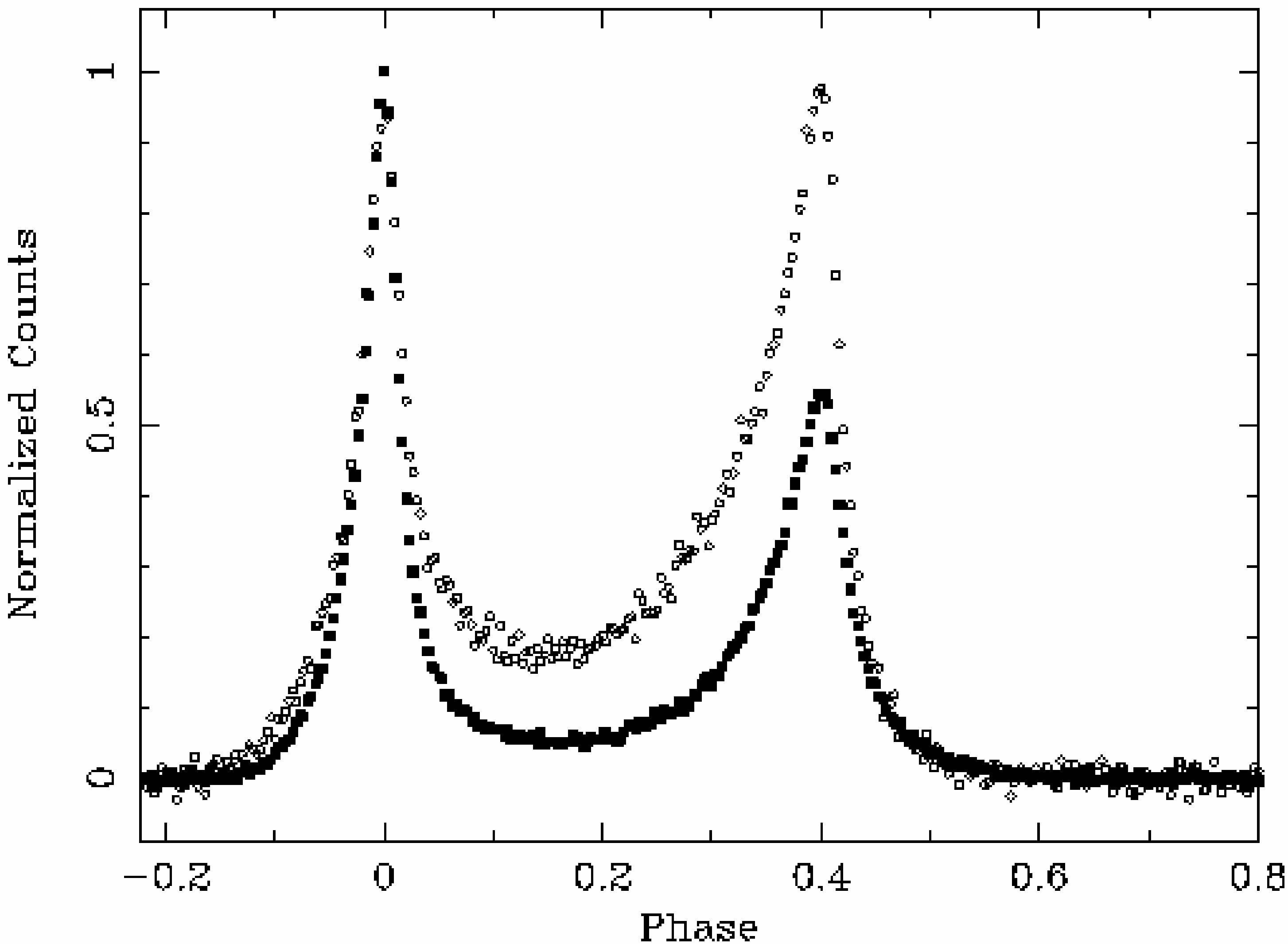
(Kuiper, et al. 2001)

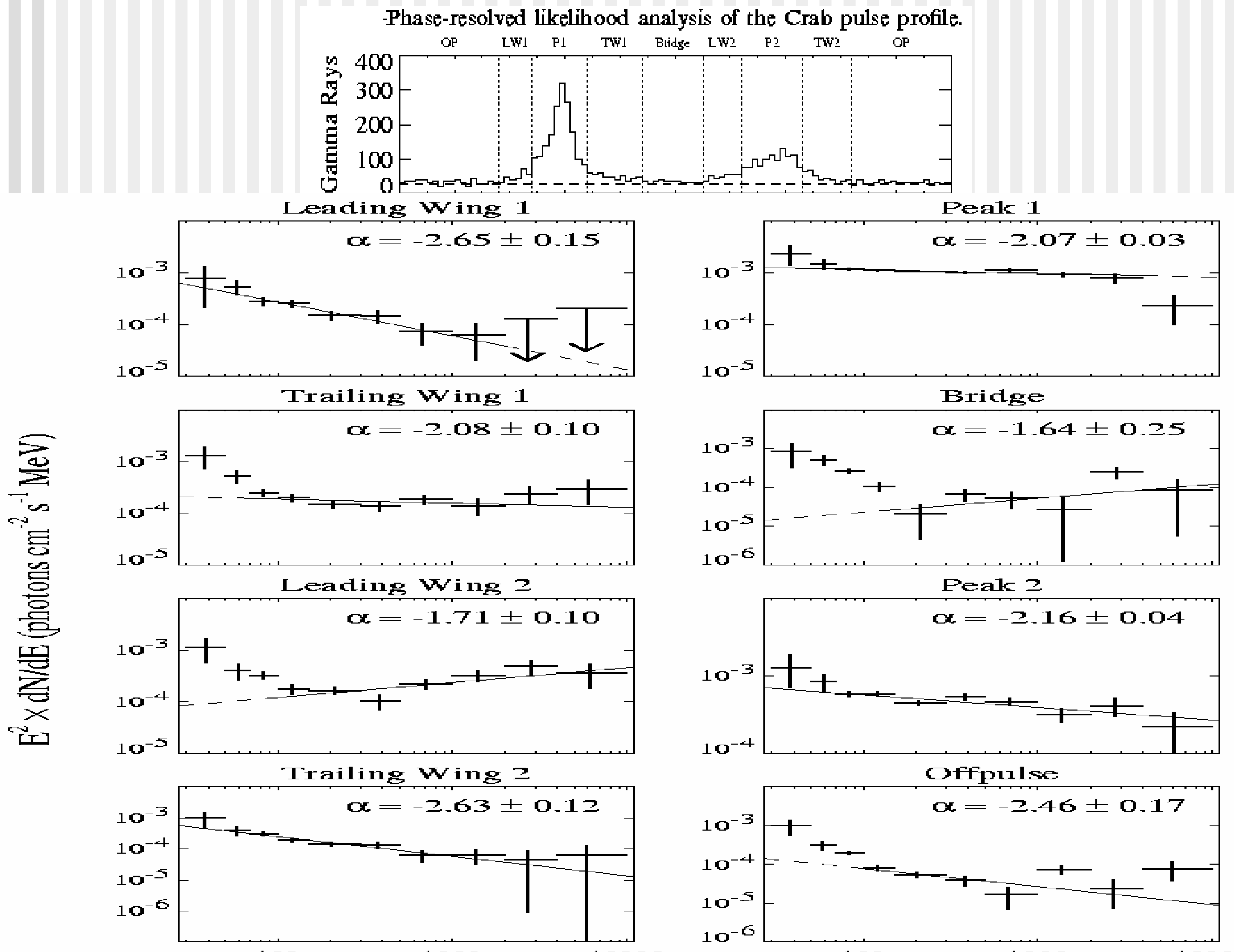




- The spectrum extends continuously from the optical to GeV bands
- The light curves have two peaks in one rotational period, and the pulses in wide energy bands are all **in phase.**

X-ray light curves of the Crab pulsars: Filled squares(1.5-5keV) and open circles(100-300keV)

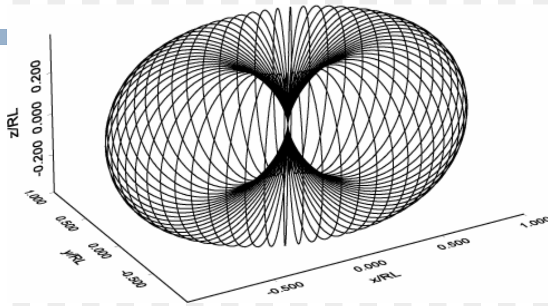



Phase-resolved likelihood analysis of the Crab pulse profile.
OP
LW1
P1
TW1
Bridge
LW2
P2
TW2
OP
Gamma Rays
Leading Wing 1
α = -2.65 ± 0.15
Peak 1
α = -2.07 ± 0.03
Trailing Wing 1
α = -2.08 ± 0.10
Bridge
α = -1.64 ± 0.25
Leading Wing 2
α = -1.71 ± 0.10
Peak 2
α = -2.16 ± 0.04
Trailing Wing 2
α = -2.63 ± 0.12
Offpulse
α = -2.46 ± 0.17
E² × dN/dE (photons cm⁻² s⁻¹ MeV)

A self-consistent 3D pulsar model (Cheng, Ruderman & Zhang 2000)

Static dipole field

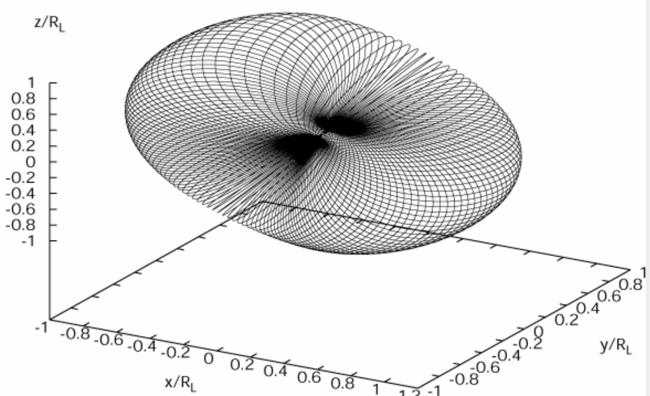
- non-rotating pure dipole



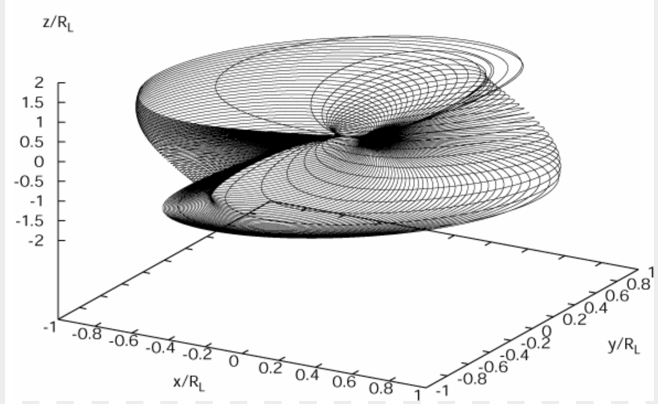
$\alpha = 0$

Retarded magnetic field lines of the rotating and inclined dipole field

- Relativistic effects are taken into account

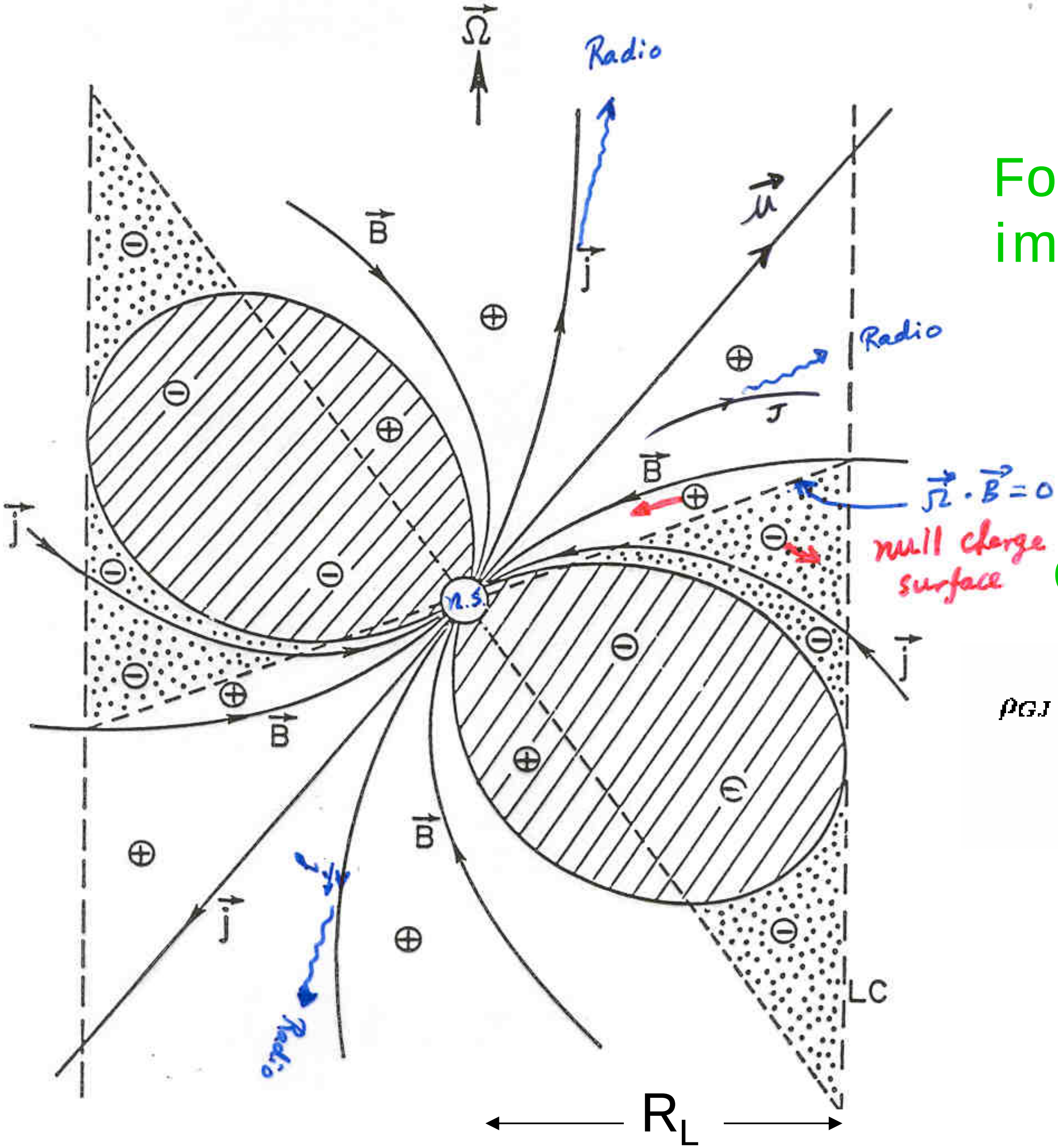


$\alpha = 30^o$



$\alpha = 60^o$

α: magnetic inclination angle



Force free condition implies:

$$\mathbf{E} + \frac{1}{c}(\mathbf{\Omega} \times \mathbf{r}) \times \mathbf{B} = 0$$

Charge distribution:

$$\rho_{GJ} = \frac{1}{4\pi}\nabla \cdot \mathbf{E} \approx -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c}\frac{1}{1-|\,\mathbf{\Omega} \times \mathbf{r}/c\,|^2} \approx -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c}$$

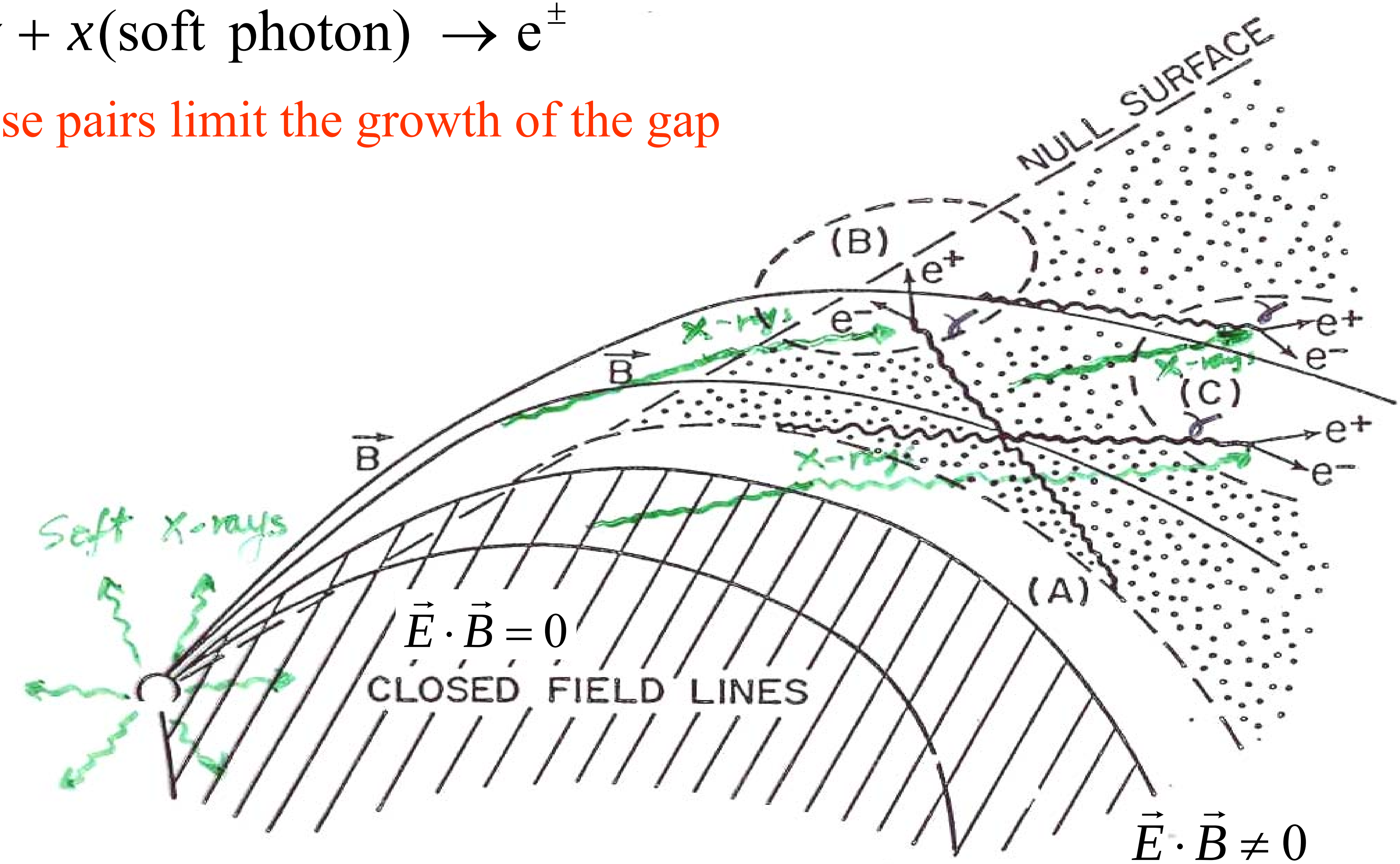
Goldreich-Julian charge density

Pair creation in Outergap where $(\vec{E} \bullet \hat{B}) \neq 0$

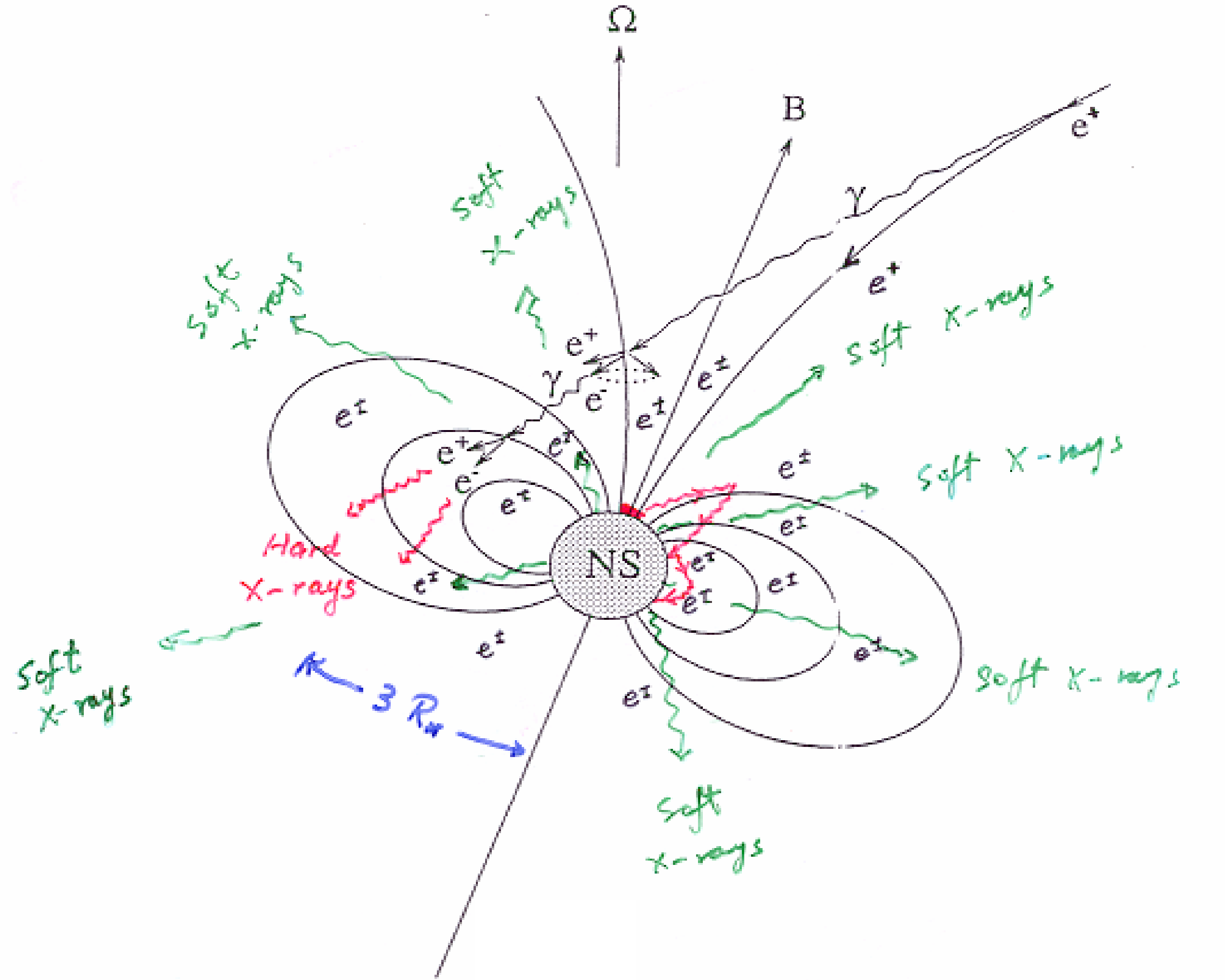
The high energy photons emitted by the charged particles in the gap can become pairs by

$$\gamma + x(\text{soft photon}) \rightarrow e^{\pm}$$

These pairs limit the growth of the gap



Self-sustained Mechanism - Pair Production and (Thermal and Non-thermal) X-ray emission from near and on NS surface



Geometry of the 3D Outer Magnetospheric Gap

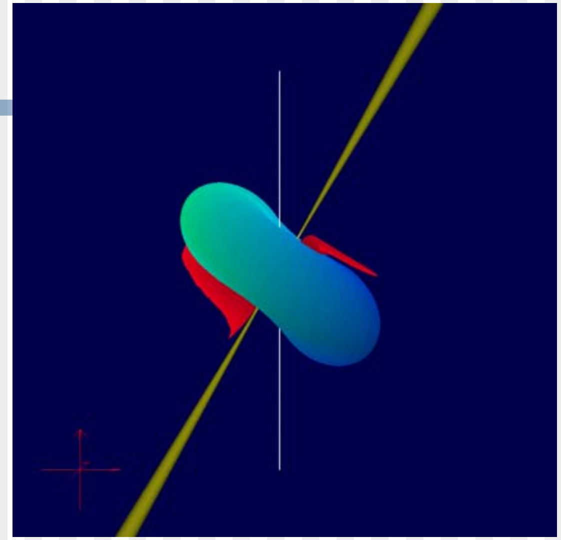
- Fractional vertical size *f*

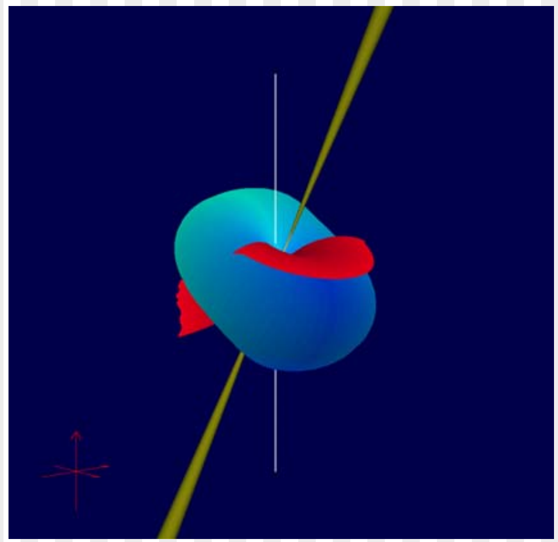
  $f = h / R_{L,}$ *h: vertical height*

  - control by the photon-photon pair production

- Fractional azimuthal size ξ

  $\xi = \Delta\Phi / 2\pi$, $\Delta\Phi$: *azimuthal extension- boundary define by where the pair production rate drop to ½ of the maximum. In case of the Crab pulsar this value is ~160 degrees*





- In this model, the typical energies of the soft X-rays and the γ-rays are completely determined by pulsar parameters and the geometric parameters of the outer gap
- Soft X-ray photon:

$$E_X \approx 9.8\times 10^1 f^{1/4}\xi^{1/4}B_{12}^{1/4}P^{-5/12}$$

- Curvature gamma-ray photon:

$$E_\gamma \approx 1.4\times 10^8 f^{3/2}B_{12}^{3/4}P^{-7/4}$$

- Using pair production condition $E_X E_\gamma \sim (m_e c^2)^2$ we obtain:

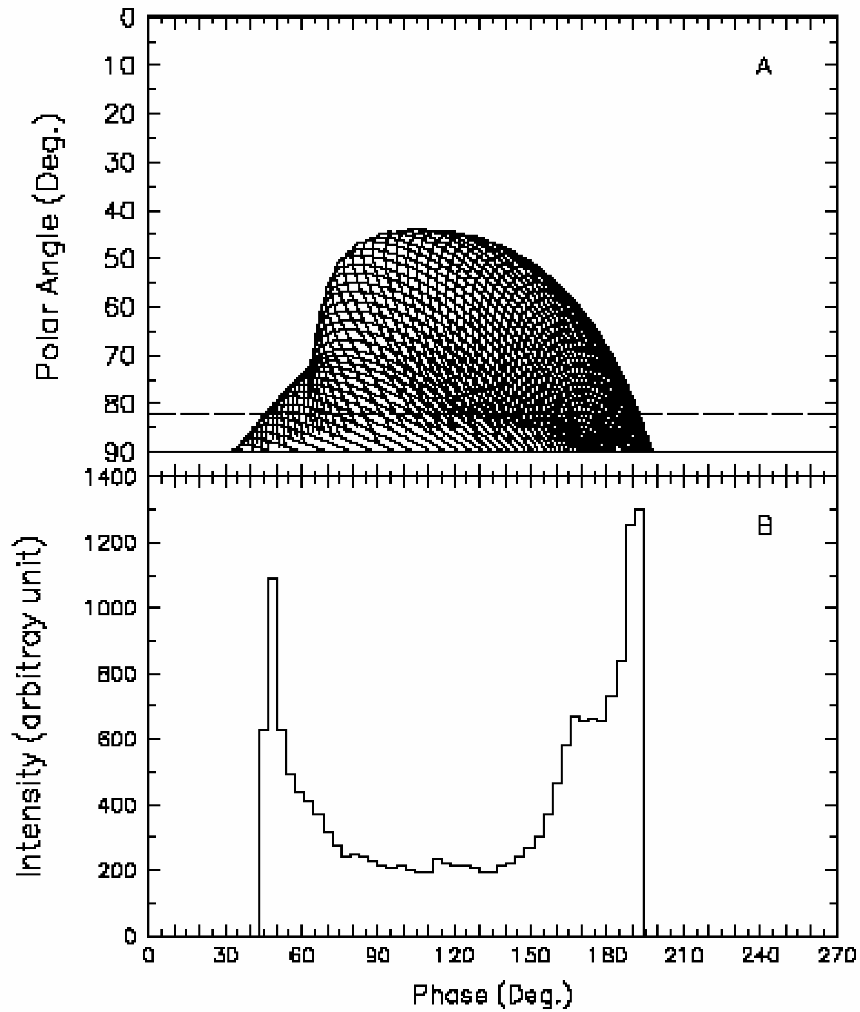
$$\boxed{f \approx 5.3 B_{12}^{-4/7}P^{26/21}\xi^{-1/7}}$$

where $f \approx h/r_L$ is the fractional size of the gap.

- **In this model we assume that if the gap current is weak the gap begins at the null charge surface, where the electric field is zero.**

Light curves

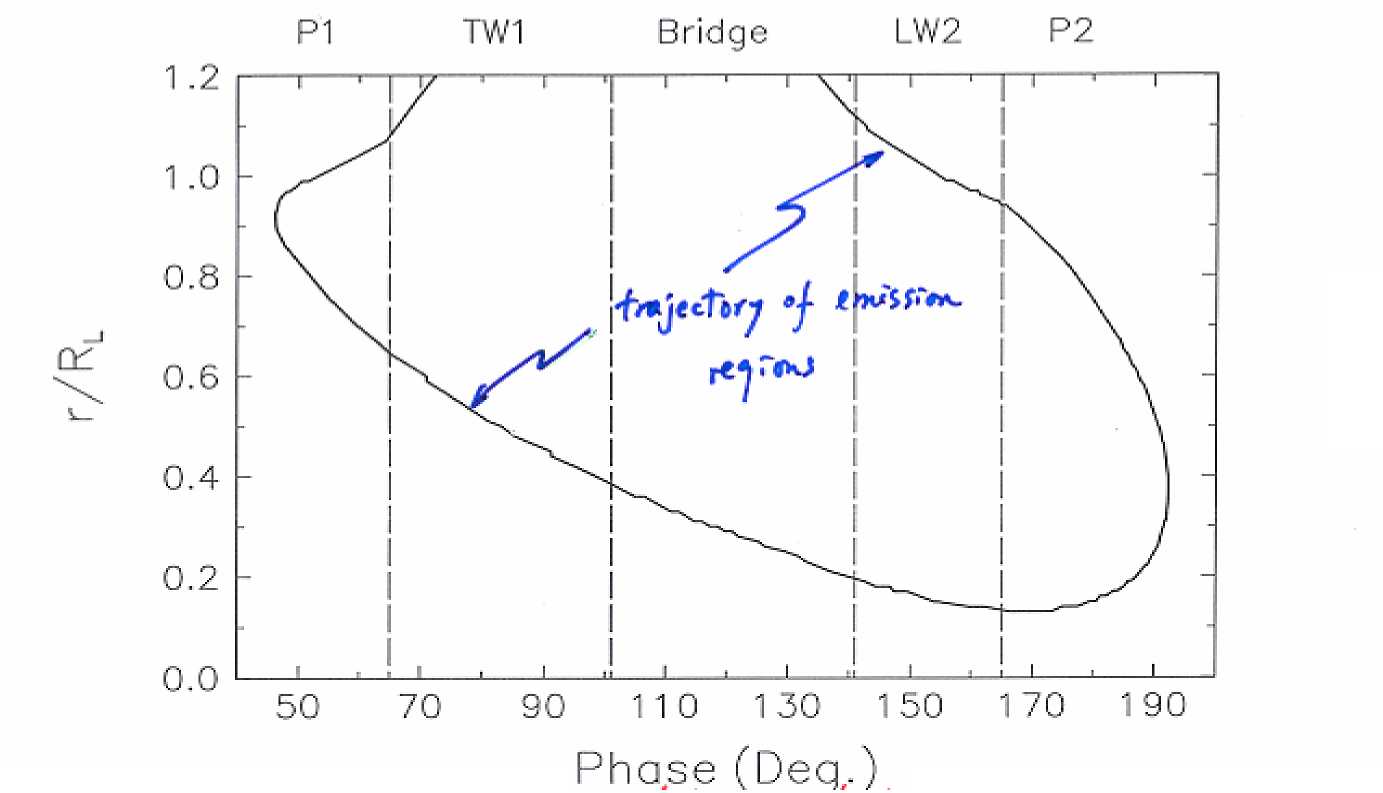
- The figure shows the photon emission direction. Once the observed angle is given, we can determine the light curve
- N.B. The emission direction is affected by the relativistic effects:
  - Aberration effect
  - Time of flight effect
- Consequently photon emission directions are squeezed into the boundary of the open field lines, a double peak structure is formed



$\alpha = 65^\circ \quad \zeta = 81^\circ$

Calculation of Radiation Spectra -Trajectory of observed emission regions

Radial distance



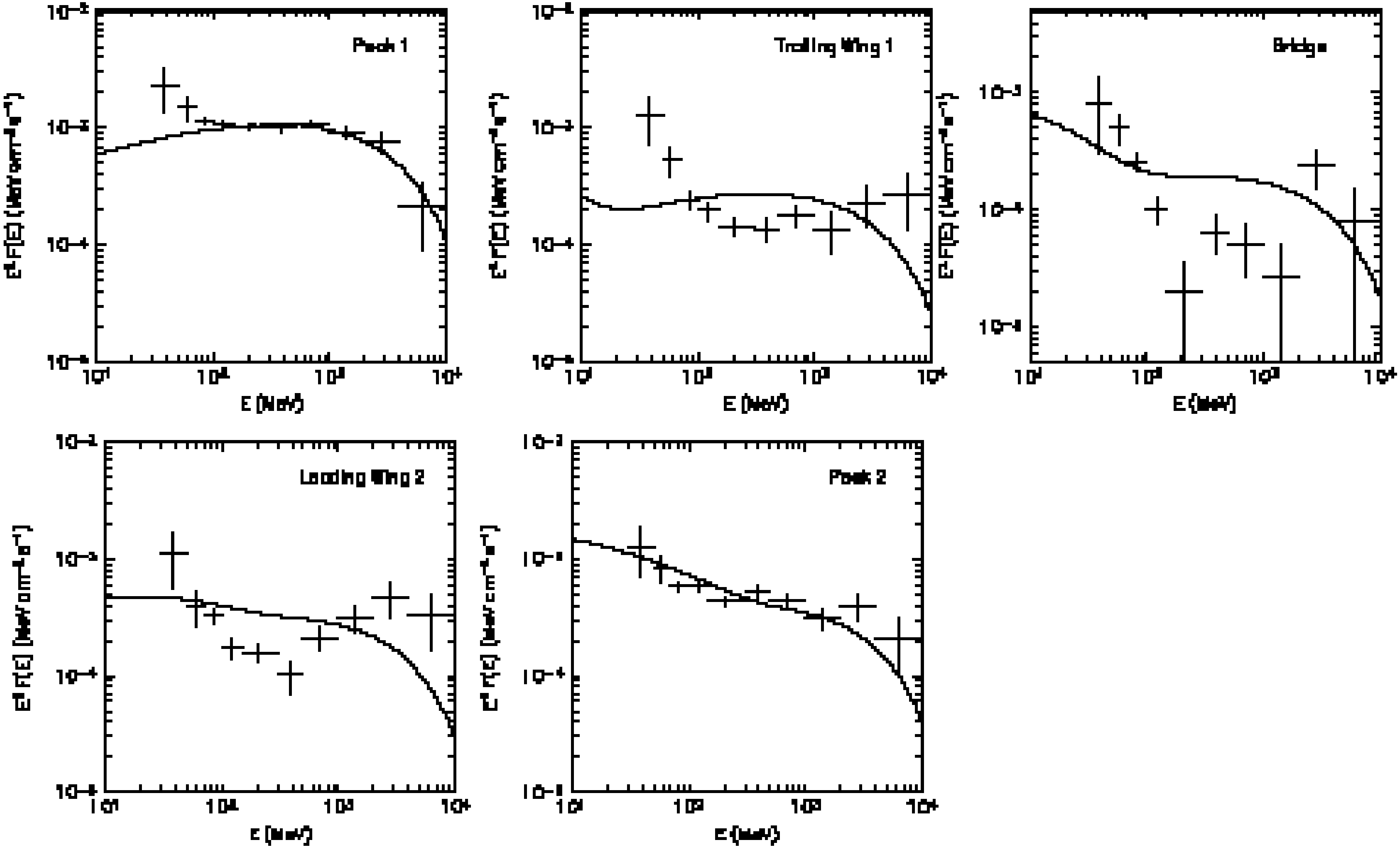
Calculate the local γ-ray emissivity including

curvature radiation,

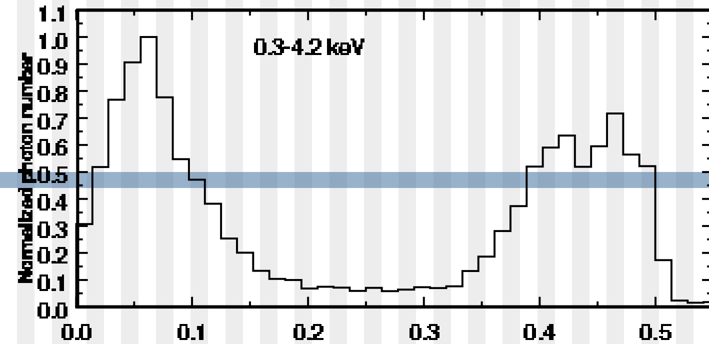
synchrotron radiation and

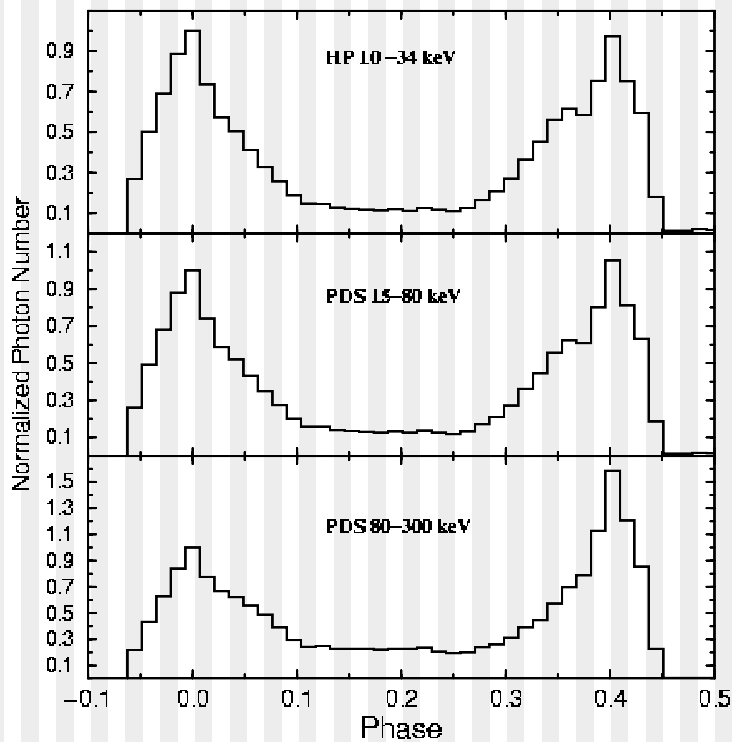
inverse Compton scattering

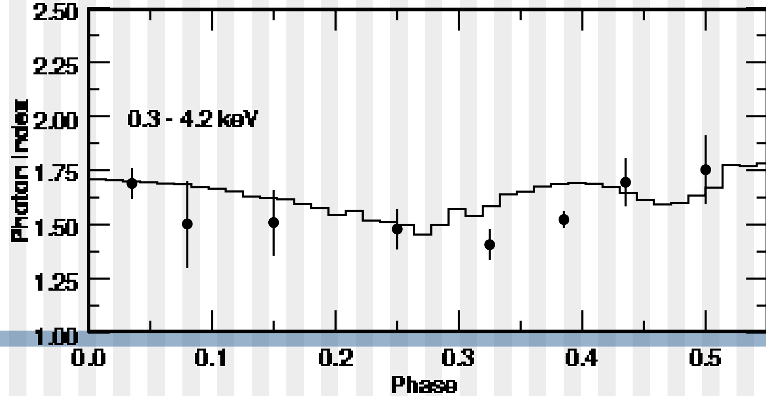
30MeV-10GeV Phase-resolved Spectrum of Crab Pulsar



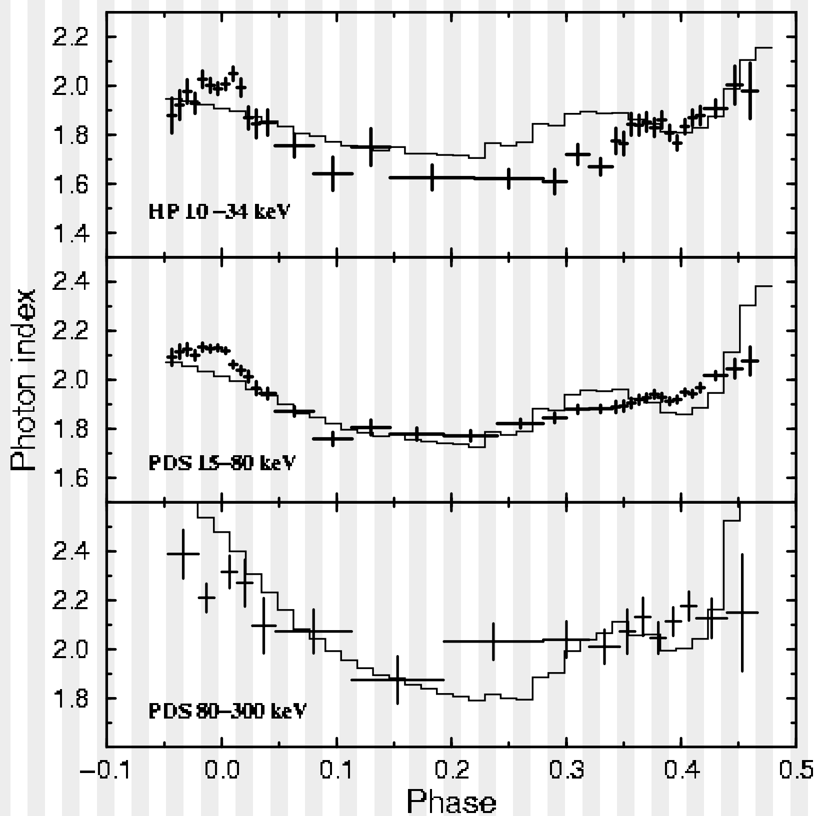
Expected X-ray light curves for different energy bands (Zhang & Cheng 2002)







Expected X-ray phase dependent energy spectrum for different energy bands (Zhang & Cheng 2002)



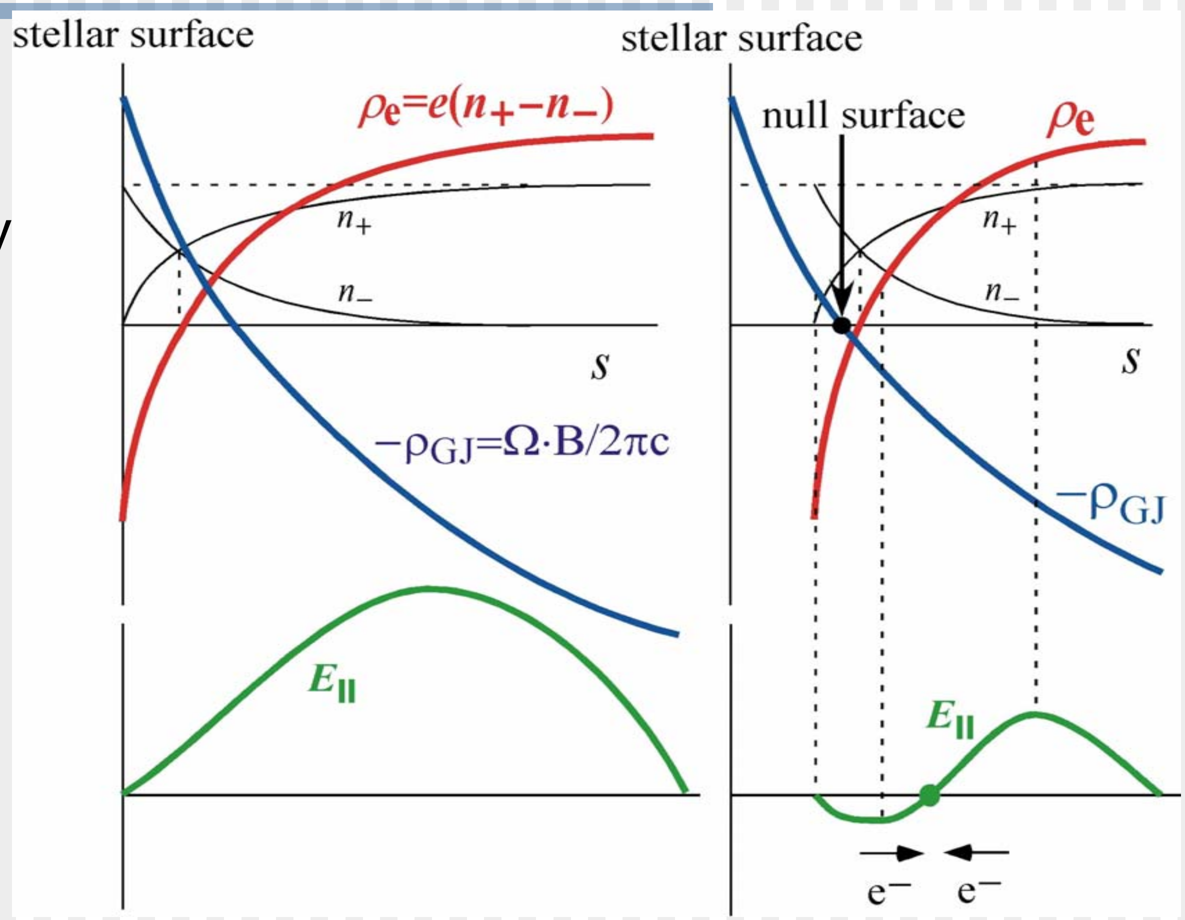
Limitations of our 3D model

- Because we have assumed the outer gap accelerator only exists from the null charge surface to the light cylinder
- Consequently the radiation is restricted between two pulses. Data outside this region cannot be explained.

Problems of Geometry of CHR model

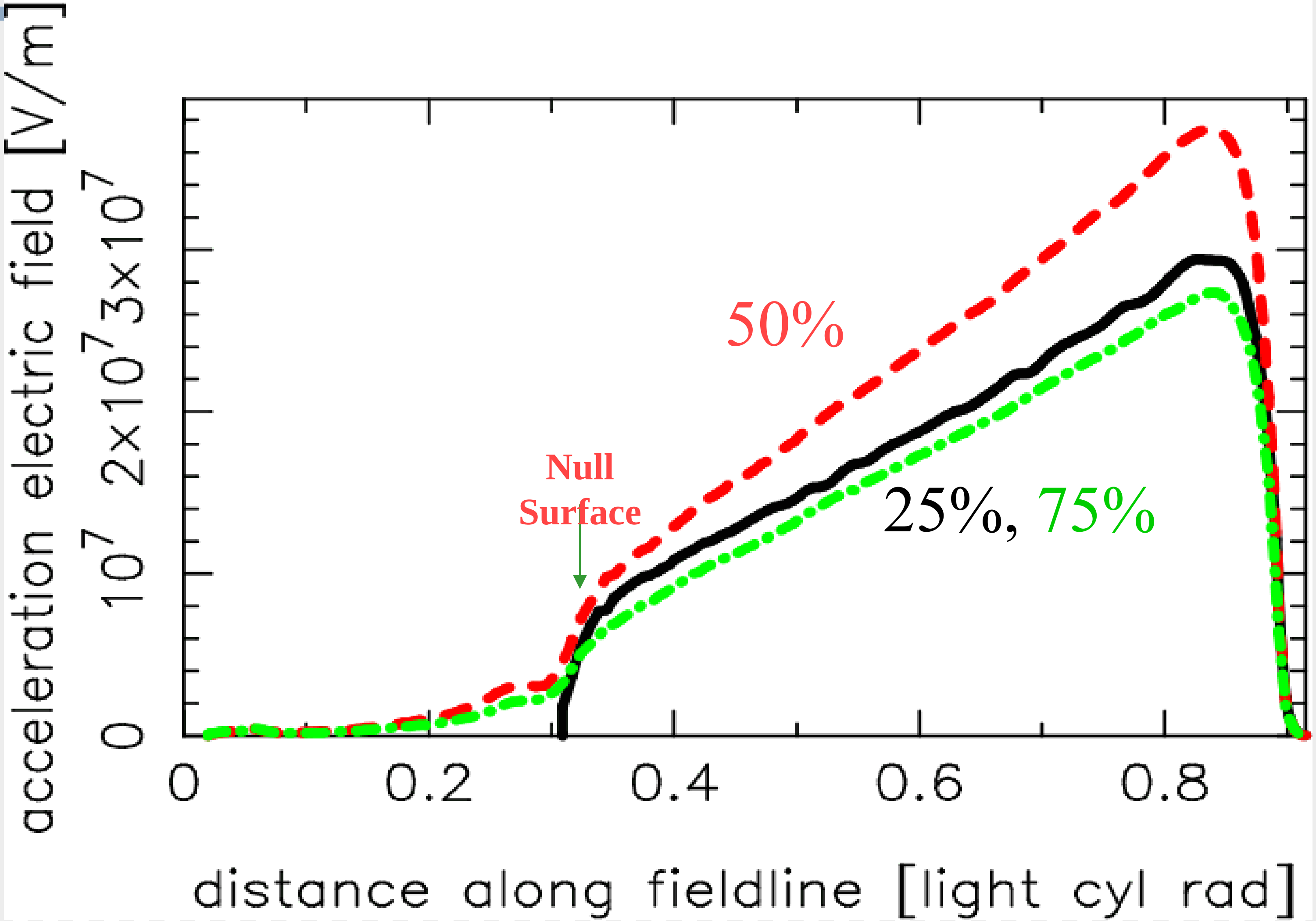
$$\text{Maxwell eq: } \nabla \cdot E_{\parallel} = 4\pi(\rho_e - \rho_{GJ})$$

- Shibata, Hirotani, Takata et. al. (2003, 2004, 2005) they have pointed out that the assumed outer gap geometry will not be stable one when the electrodynamics is taken into account. The inner boundary of the outer gap will be no longer located at the null surface. The inner boundary will move toward the star when current flow is very large and near the Goldreich-Julian current density.



Hirotani 2005

Electric along B-field depends on the fraction of GJ current density (Hirotani 2005)



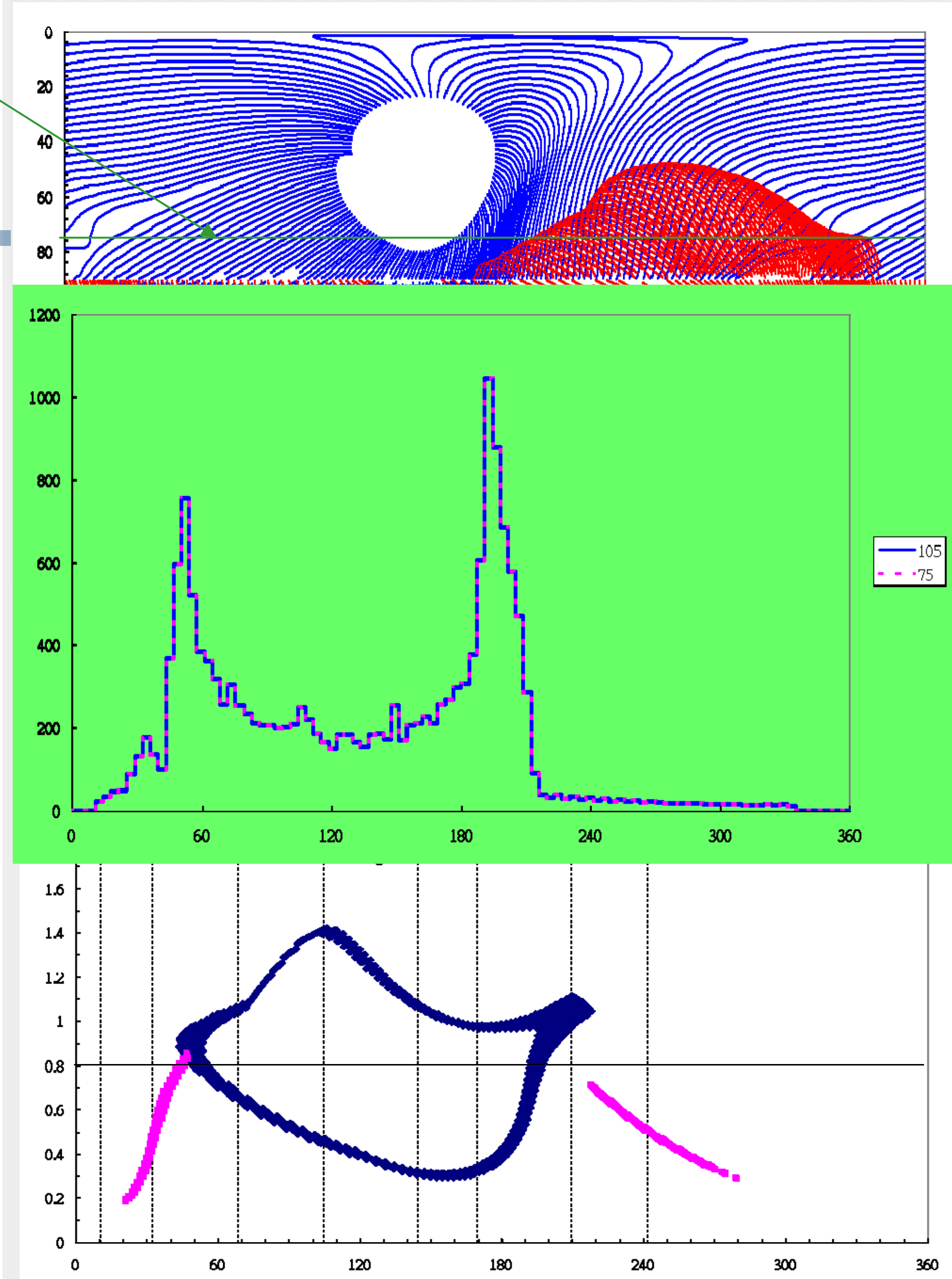
Emission Trajectories of New Geometry and Light Curve

Line of sight

➢**Although the inner boundary is located at ~10R, the pair creation can only start ~0.5r_{null} ~0.2 r_L because the electric field decreases rapidly toward the inner boundary.**

➢**The light curve is weighted according to the local radiation intensity.**

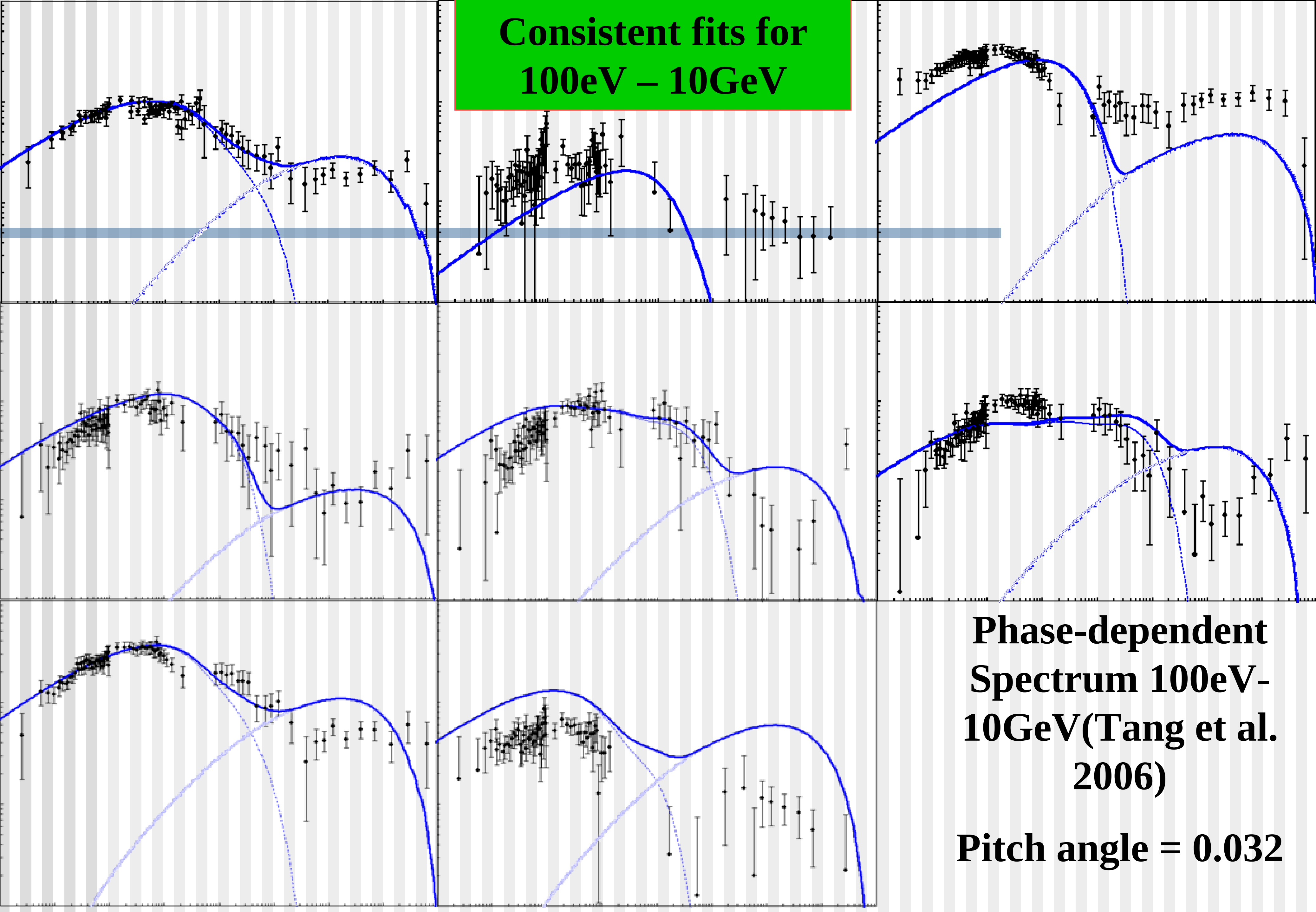
➢**The pink curves are outgoing radiation of gap 1 from the null surface to the inner boundary near the star and the blue curve is the outgoing radiation of gap 2 from the null surface to the light cylinder.**



Fitting parameters

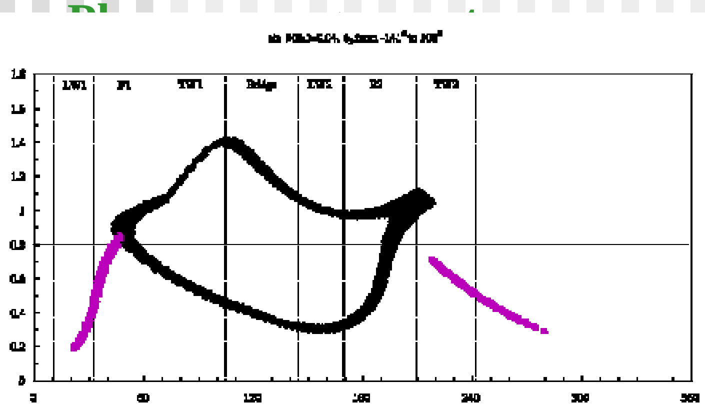
- Inclination angle and viewing (50^o and 79^o respectively)- determine the light curve
- Solid angle (~1 sterian) - determine the nomralization
- Pitch angle (~o.o3) – the peak of the hard X-rays

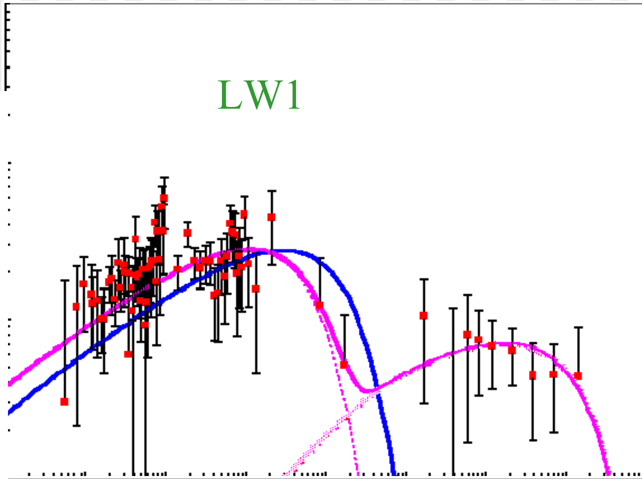
Consistent fits for 100eV – 10GeV

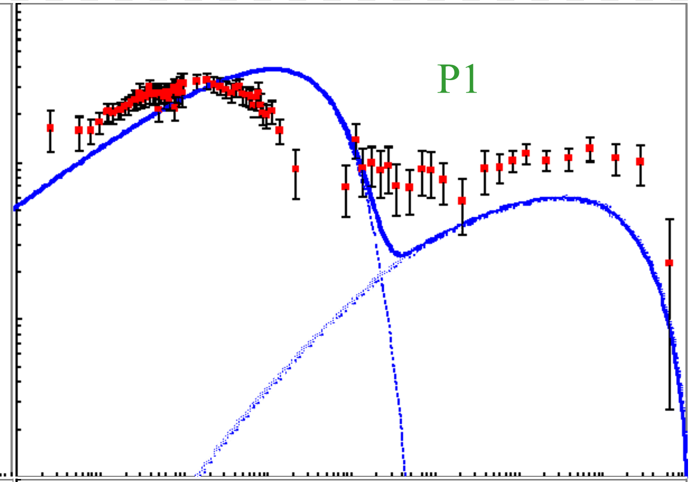


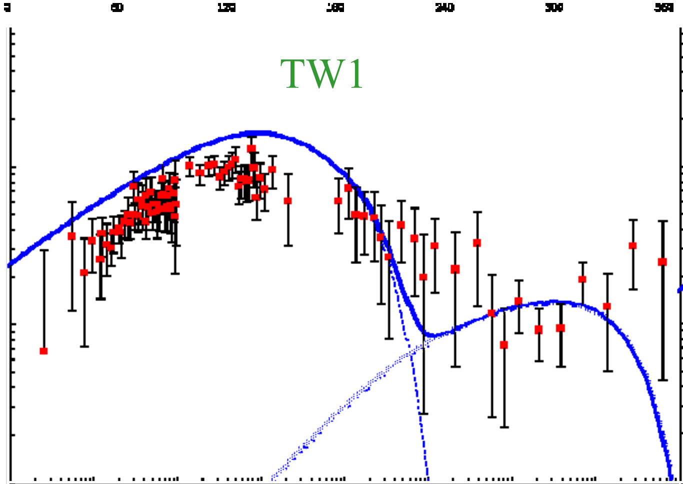
Phase-dependent Spectrum 100eV-10GeV(Tang et al. 2006)

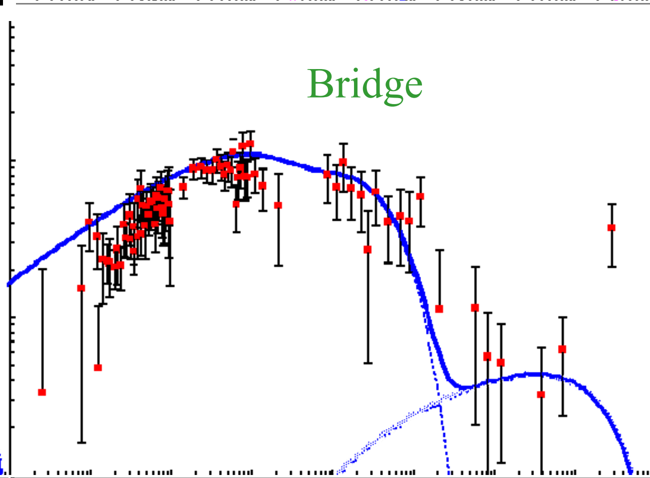
Pitch angle = 0.032

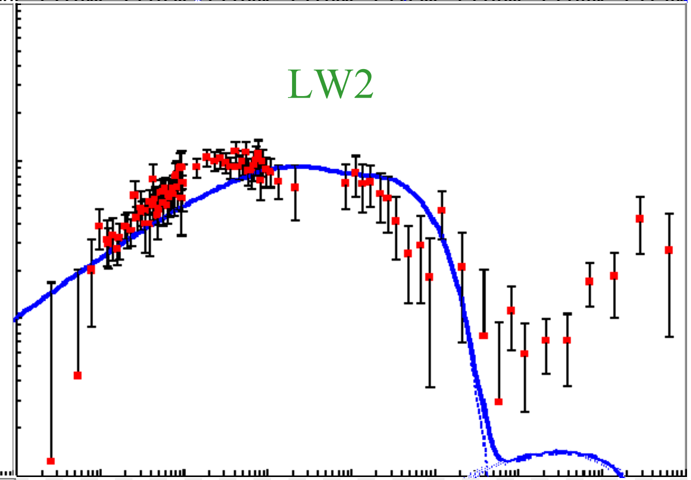


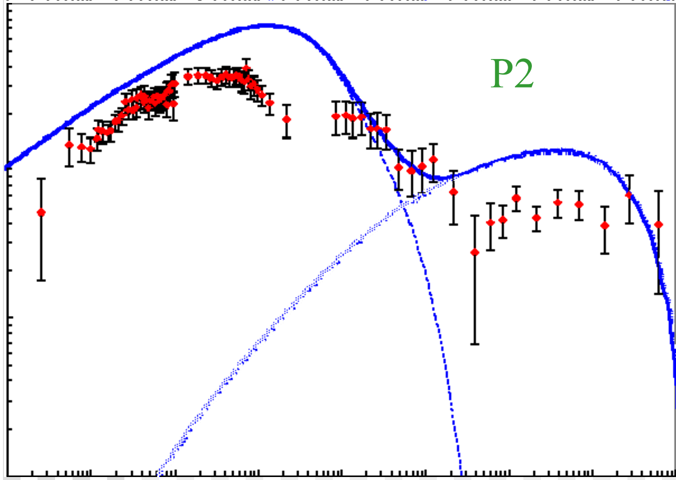


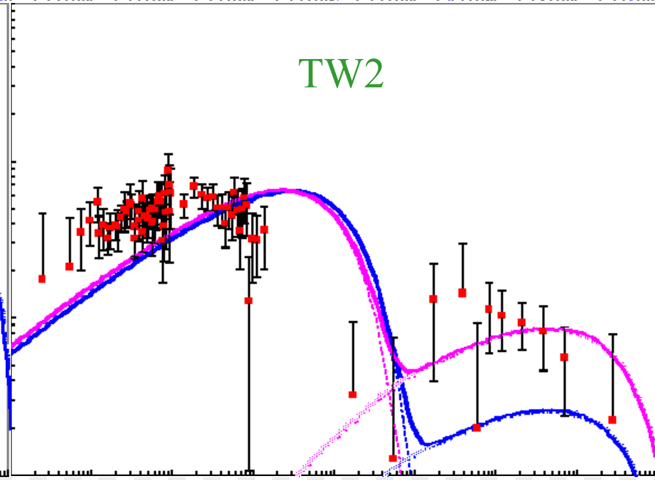












Phase-dependent Spectrum 100eV- 10GeV(Tang et al. 2006)

Two parameters : pitch angles for gap 1 and gap 2

Pink curves come from the outgoing radiation of the gap 2

Polarization of the Crab pulsar

- The optical data for the Crab pulsar has been available

1,K. Chen et al (1996)

-Polarization at two peaks with synchrotron emission

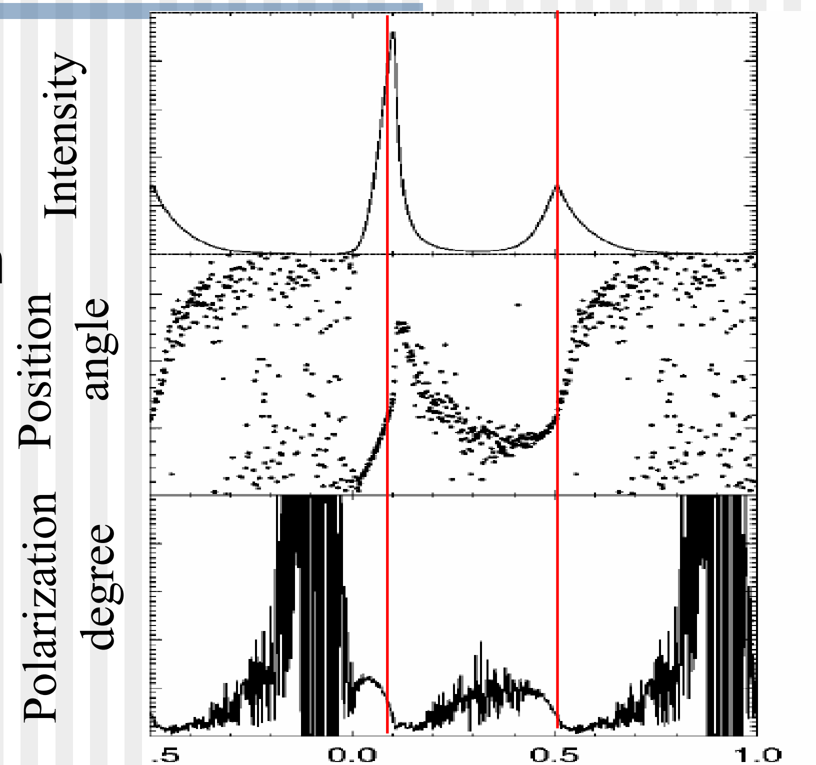
2, J.Dyks et al. (2004)

-Curvature emission model, which predicted too high degree of polarization

3, J.Petri & J.Kirk (2005)

-Pulsar strip wind model

Crab optical data

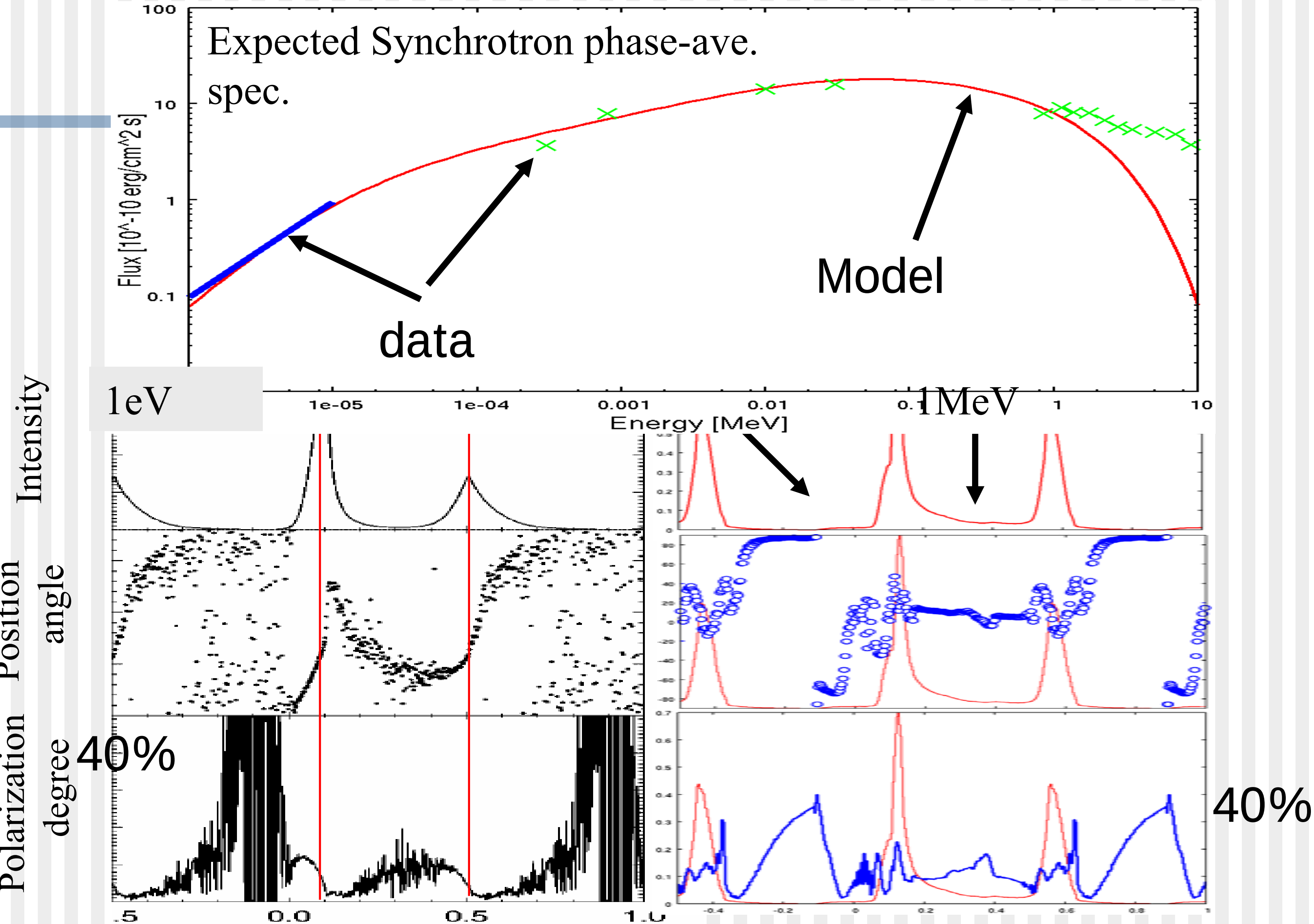


Kanbach et al 2004

They did not explain the Crab optical polarization data, optical spectrum and light curve together

Modified outer gap model

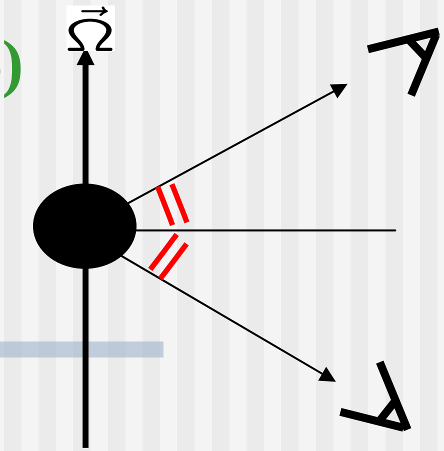
J. Takata et al. (2006)

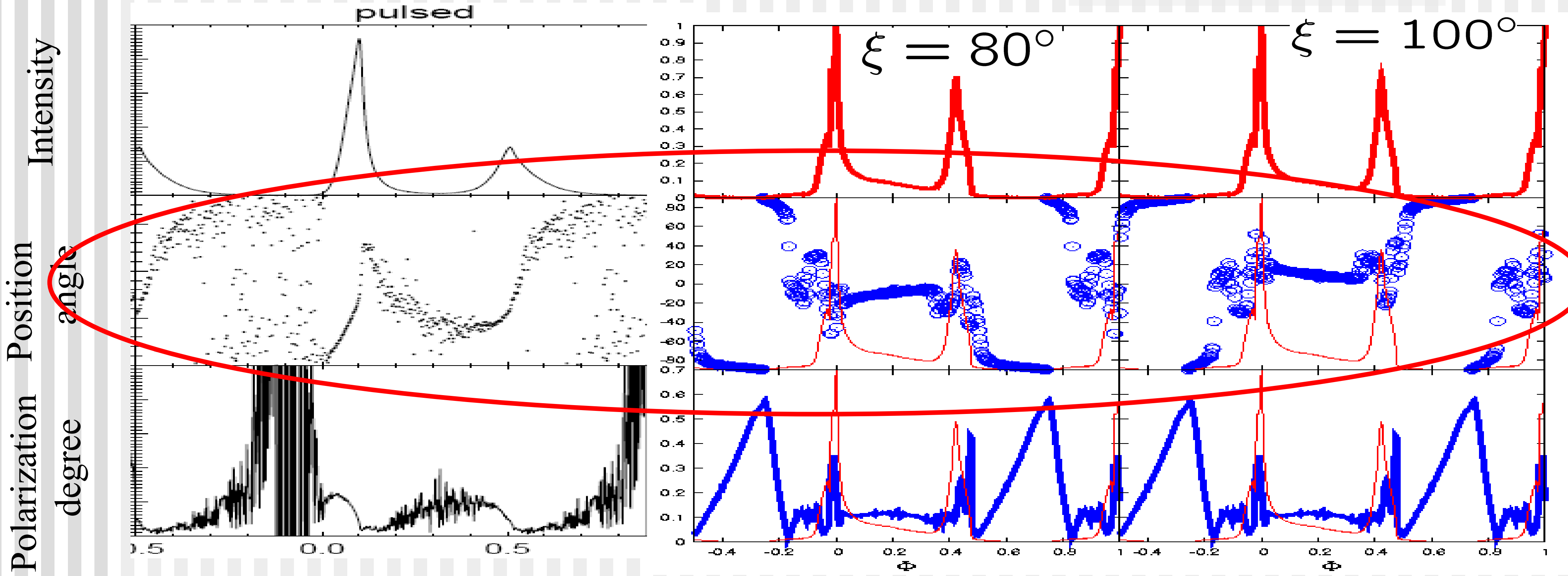


Viewing angle

J. Takata et al. (2006)

- The light curve and spectrum are degenerate for ξ and 180- ξ . However, the projection of the magnetic field for these angles are different. This causes the position angle swing different.





For the Crab pulsar, the viewing angle is lager than 90deg !

Summary and discussion

- Gaps (accelerators) must exist in the pulsar magnetosphere
- It is not known if the existing data can discriminate different accelerator models because the model predictions from polar cap and slot gap models are non-trivial and they are not available yet
- However, the high energy emission must come from the outer magnetosphere in order to avoid magnetic pair creation and the optical emission of the Crab pulsar cannot be emitted near the star
- Polarization, light curves and phase-resolved spectra of pulsars must be explained by 3D pulsar model and they are best data to discriminate different models
- The break in ultra-violet results from small pitch angle in synchrotron radiation and most important the swing of polarization angle suggests that the viewing angle must be larger than 90 degree.