Particle Acceleration and Emission Regions of Gamma-Ray Pulsars

Shota Kisaka (ICRR, Univ. of Tokyo)

with Norita Kawanaka (Hebrew Univ. of Jerusalem)
Toshio Terasawa (ICRR, Univ. of Tokyo)
Takayuki Saito (MPI)

Outline

1. Introduction

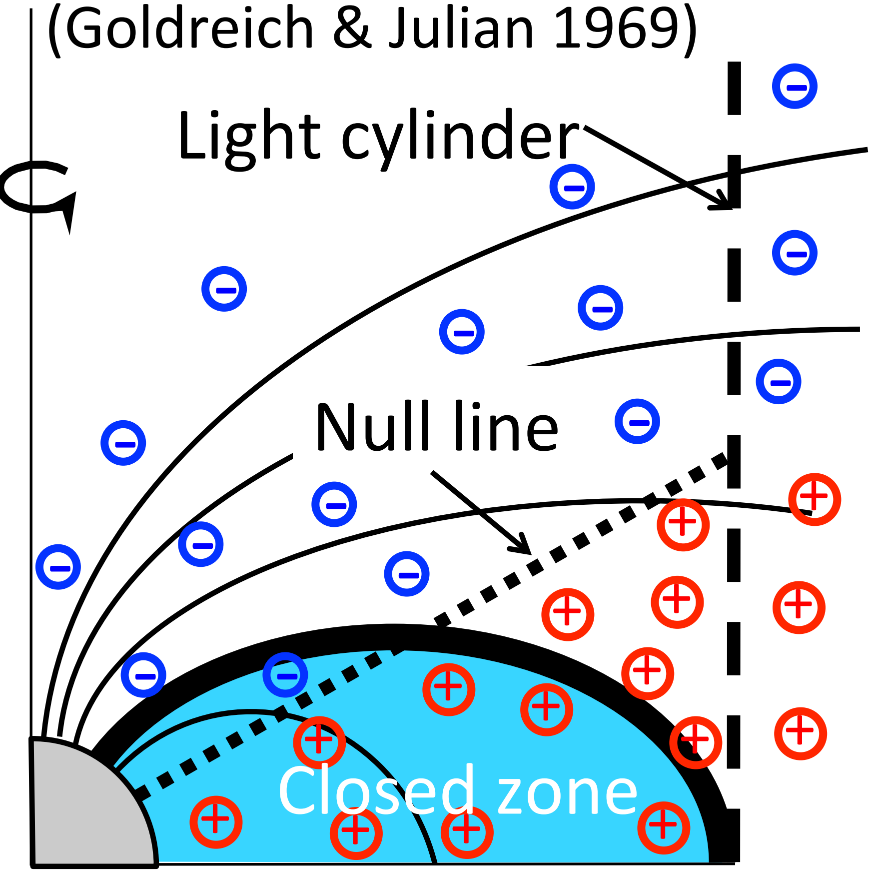
2. Acceleration region : Pair-starved MSPs

3. Emission region : sub-TeV emission region

Structure of pulsar magnetosphere

Rotating magnet → Unipolar induction
→ $E_{||}$ screening → Magnetosphere

Basic concept
(Goldreich & Julian 1969)



To maintain the force-free condition, following processes work in some regions.

- Particle acceleration
- Particle supply (particle creation)
- $E_{||}$ screening (ρ & J adjustment)

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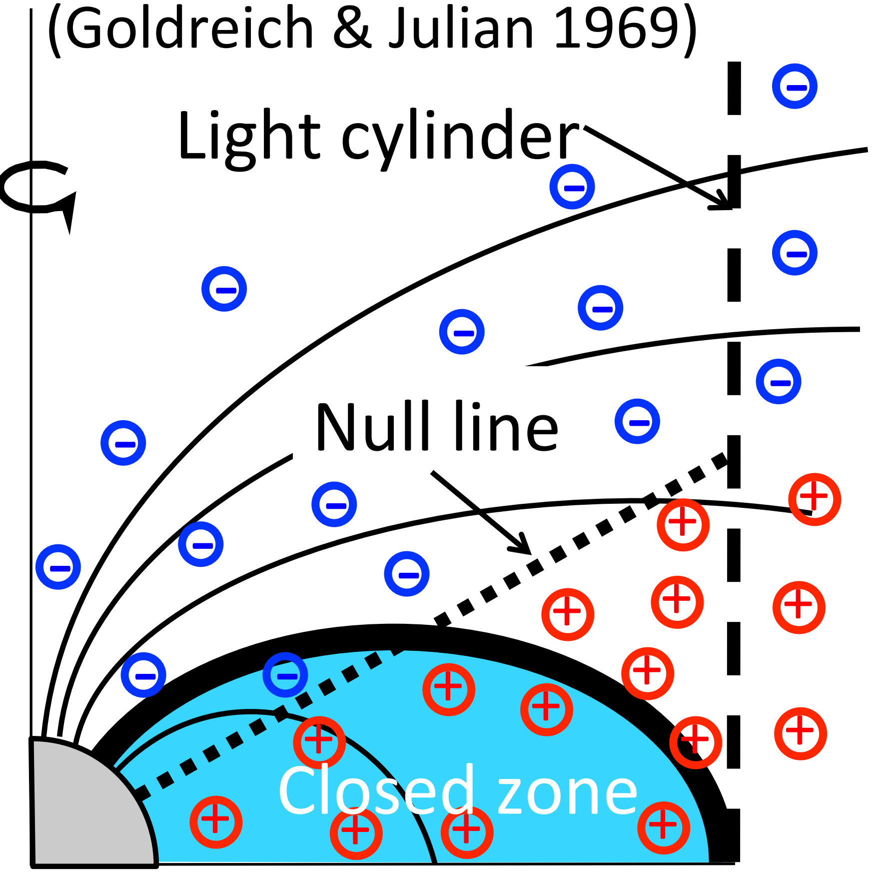

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  → GeV γ-ray
- Particle supply (particle creation)
  → IR ~ X-ray
- $E_{||}$ screening (ρ & J adjustment)
  → Radio ?

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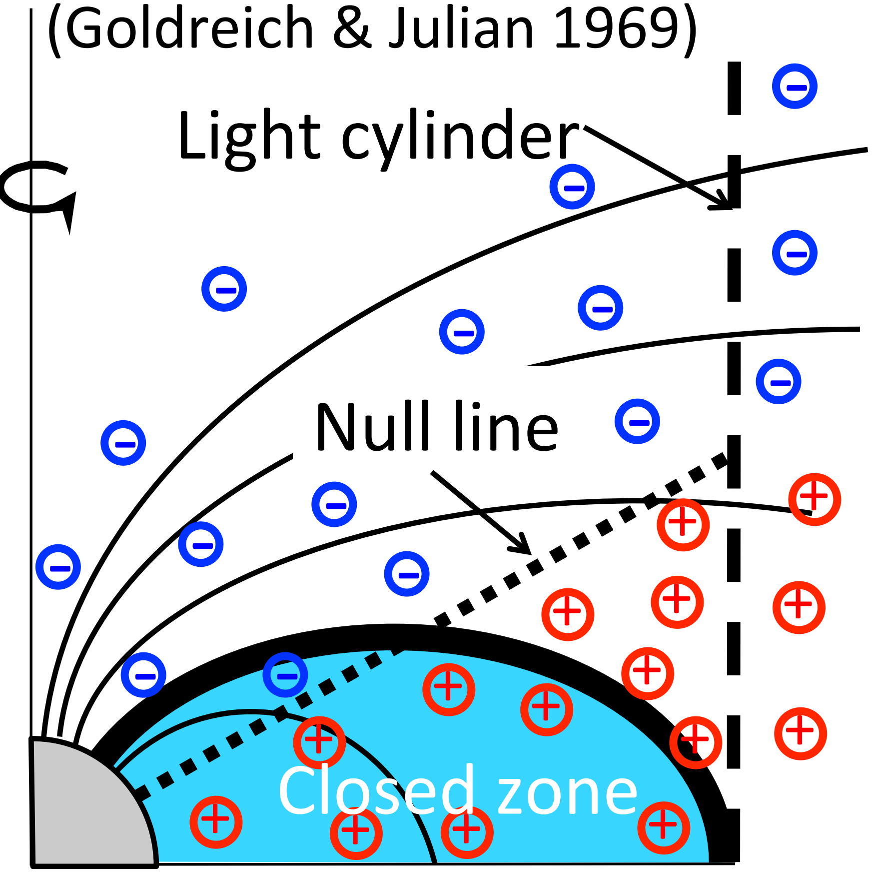


To maintain the force-free condition, following processes work in some regions.

- Particle acceleration
  → GeV γ-ray (e$^{\pm}$ CR ?)
- Particle supply (particle creation)
  → IR ~ X-ray (& TeV γ-ray ?)
- $E_{||}$ screening (ρ & J adjustment)
  → Radio ?

Problems

- Outer gap model cannot reproduce observed γ-ray light curves in some millisecond pulsars (MSPs).

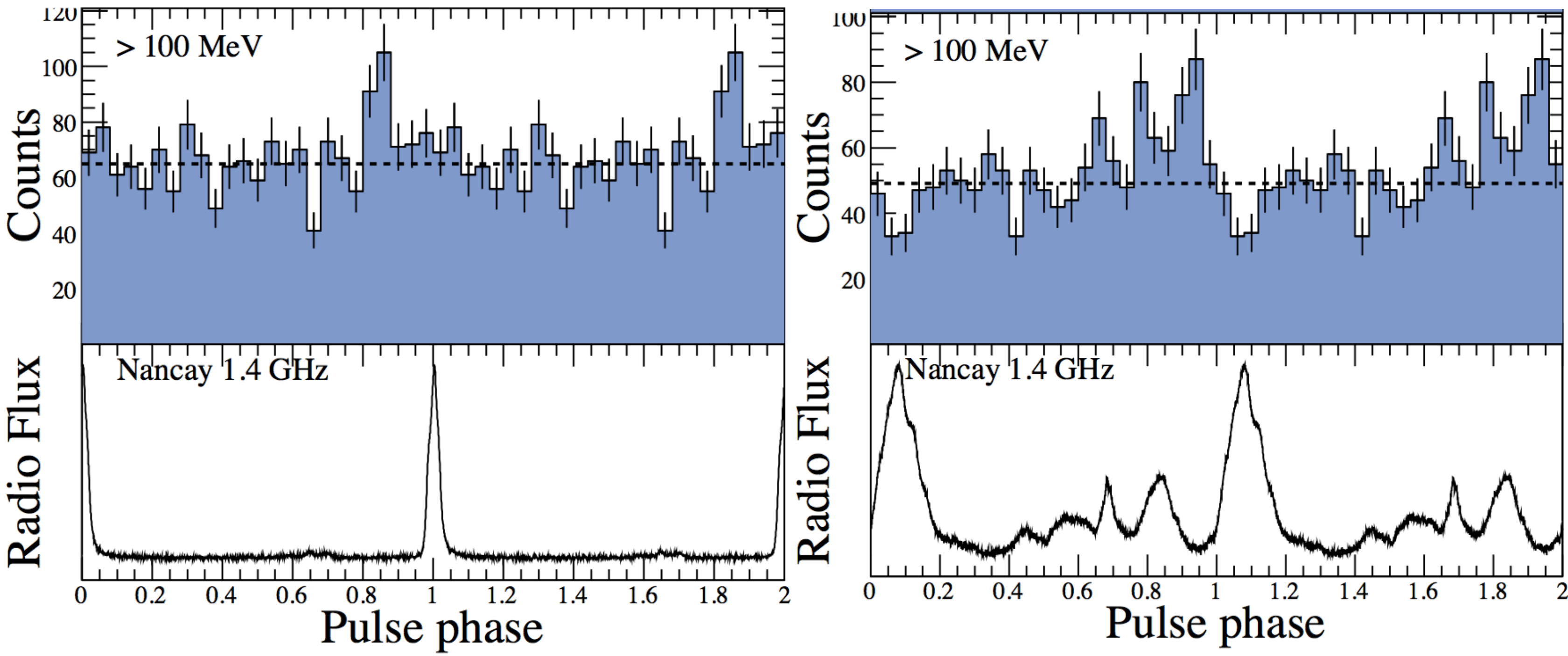
- VERITAS and MAGIC detected sub-TeV pulsed emission from Crab pulsar.

Unusual γ-ray light curve

Two MSPs show unusual light curves that the γ-ray peak lead the radio peak. Young γ-ray pulsars do not show such light curves.

γ-ray

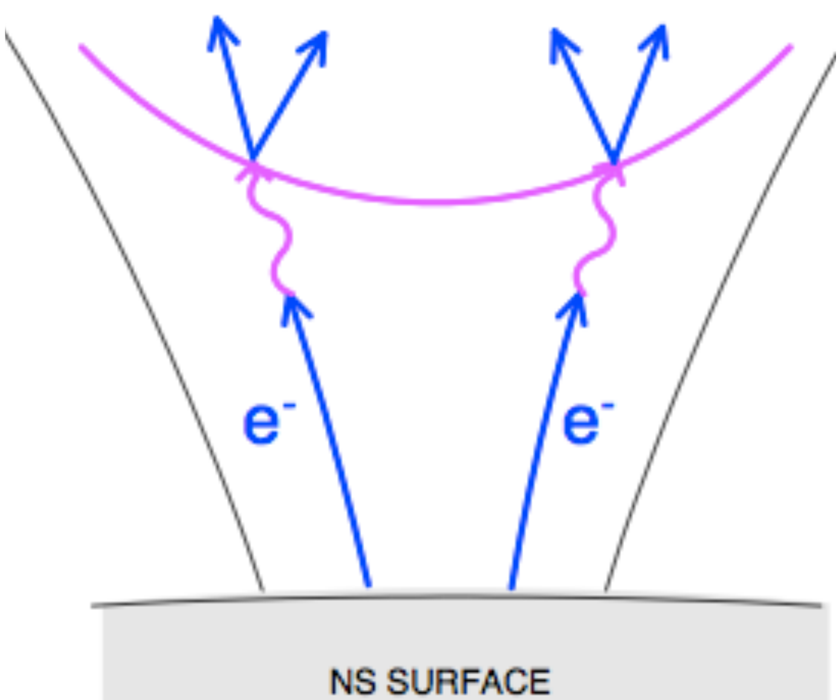
Radio

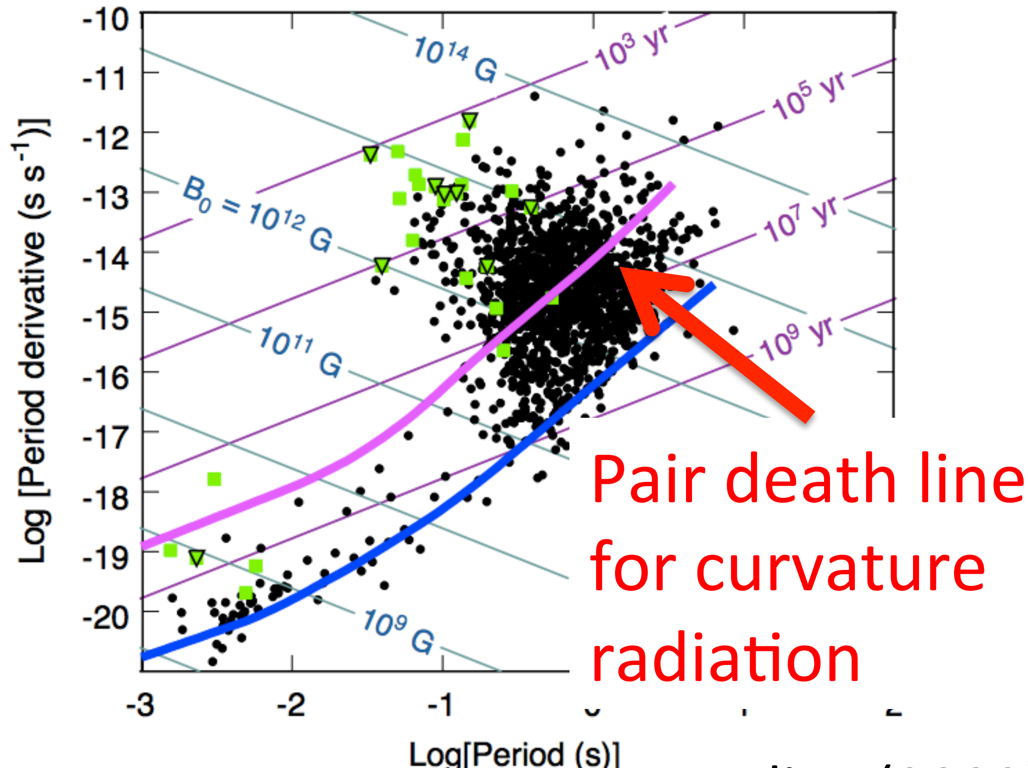


Guillemot (2009)

Pair-Starved Polar Cap (1/2)

Muslimov & Harding (2004) suggest that most MSPs can not produce pairs through curvature radiation.
In this case, particle acceleration can occur in almost open field volume (Pair-Starved Polar Cap model).

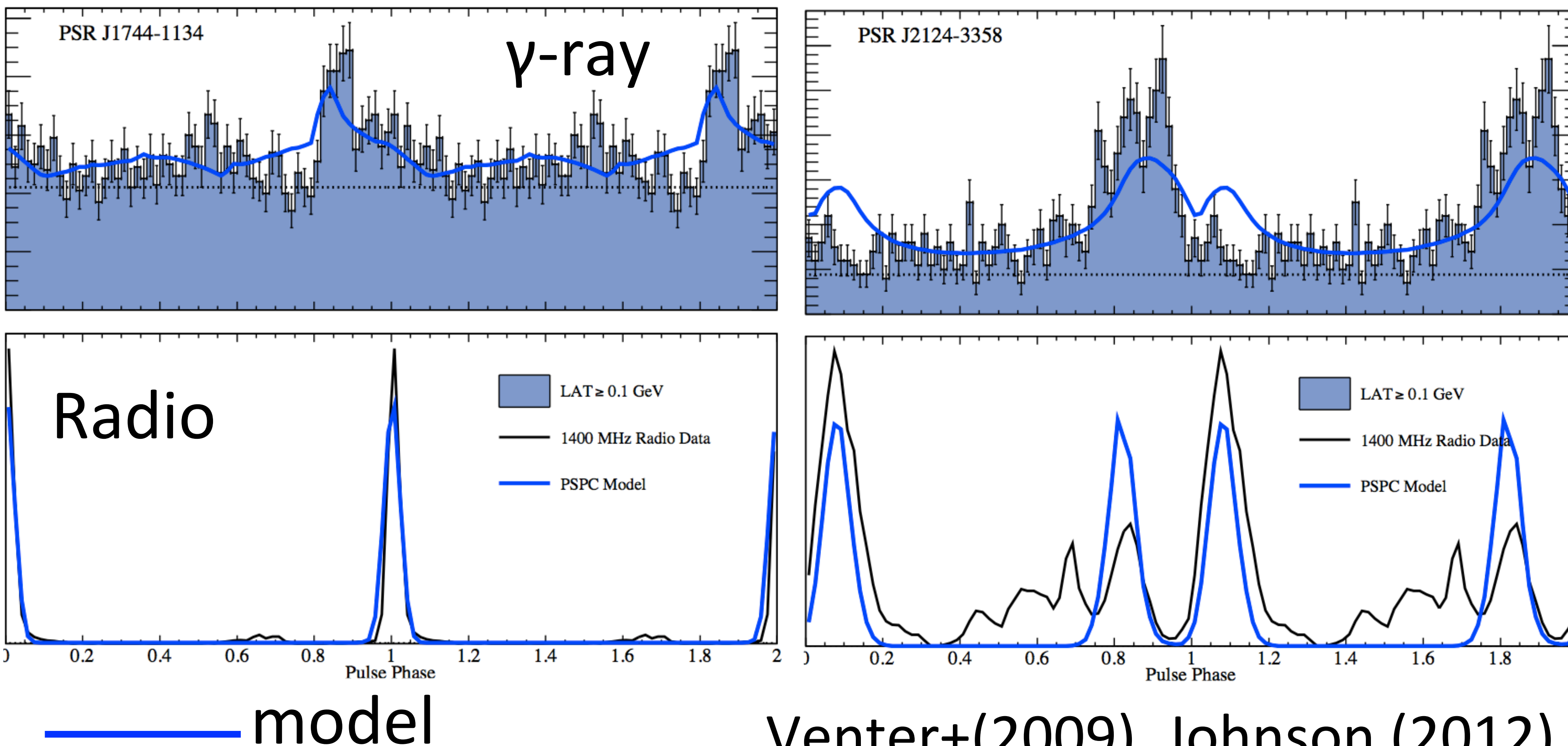




Harding (2009)

Pair-Starved Polar Cap (2/2)

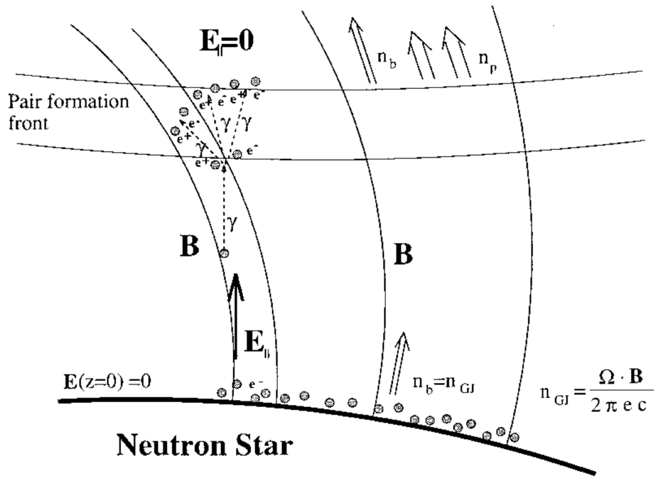
The model that have extended particle acceleration region can explain observed light curves.

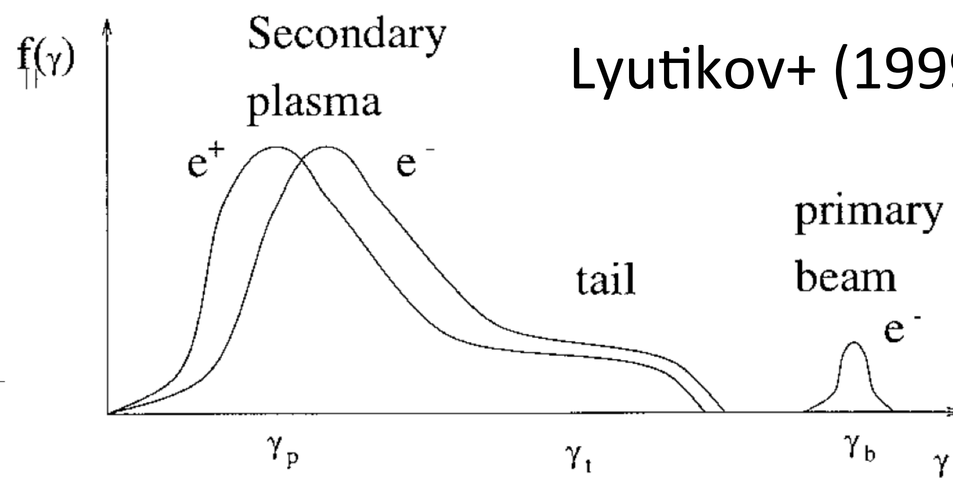


Venter+(2009), Johnson (2012)

Conditions for radio-emitting region

In general, people have believed the conditions of a primary beam with γ_b~10^7 and n_b~n_{GJ}, and a secondary $e^{\pm}$ with γ_p~10-10^3 and n_p~10^3-$10^5 n_{GJ}$ in the radio-emitting region.





Lyutikov+ (1999)

However, the existence of pair-starved MSPs suggest that radio emission mechanisms should be insensitive to the particle number density down to sub-GJ one.

Therefore, further verification is important.

Acceleration

Assumptions

In the wind region,

- the energy equipartition between B and $e^{\pm}$.
- the flux conservation of B and $e^{\pm}$.

Typical energy is related to the number of particles.

$$\varepsilon_e = e\Delta V_{\max}\kappa^{-1} \sim 50\boxed{\kappa^{-1}}\mathrm{TeV}$$

κ : multiplicity

Ω : angular velocity

Propagation of $e^{\pm}$ cosmic ray

$$\frac{\partial}{\partial t} f(t, r, \epsilon_e) = D(\epsilon_e) \nabla^2 f + \frac{\partial}{\partial \epsilon_e}(P(\epsilon_e) f) + Q(t, r, \epsilon_e)$$

Diffusion coefficient $D(\varepsilon_e) = D_0 (1 + \varepsilon_e / 3\mathrm{GeV})^{\delta}$

Cooling function $P(\varepsilon_e) = \frac{4\sigma_T \varepsilon_e^2}{3 m_e^2 c^3} \left[\frac{B^2}{8\pi} + \int d\varepsilon_\gamma u_{\mathrm{tot}}(\varepsilon_\gamma) f_{\mathrm{KN}} \left(\frac{4\varepsilon_e \varepsilon_\gamma}{m_e^2 c^4} \right) \right]$

Source function $Q_0(\varepsilon_e, \tilde{t}) \propto \varepsilon_e^{-\alpha} \exp\left(-\frac{\varepsilon_e}{\varepsilon_{\mathrm{cut}}} \right) \left(1 + \frac{\tilde{t} - t_i}{\tau} \right)^{-2}$

Assumptions

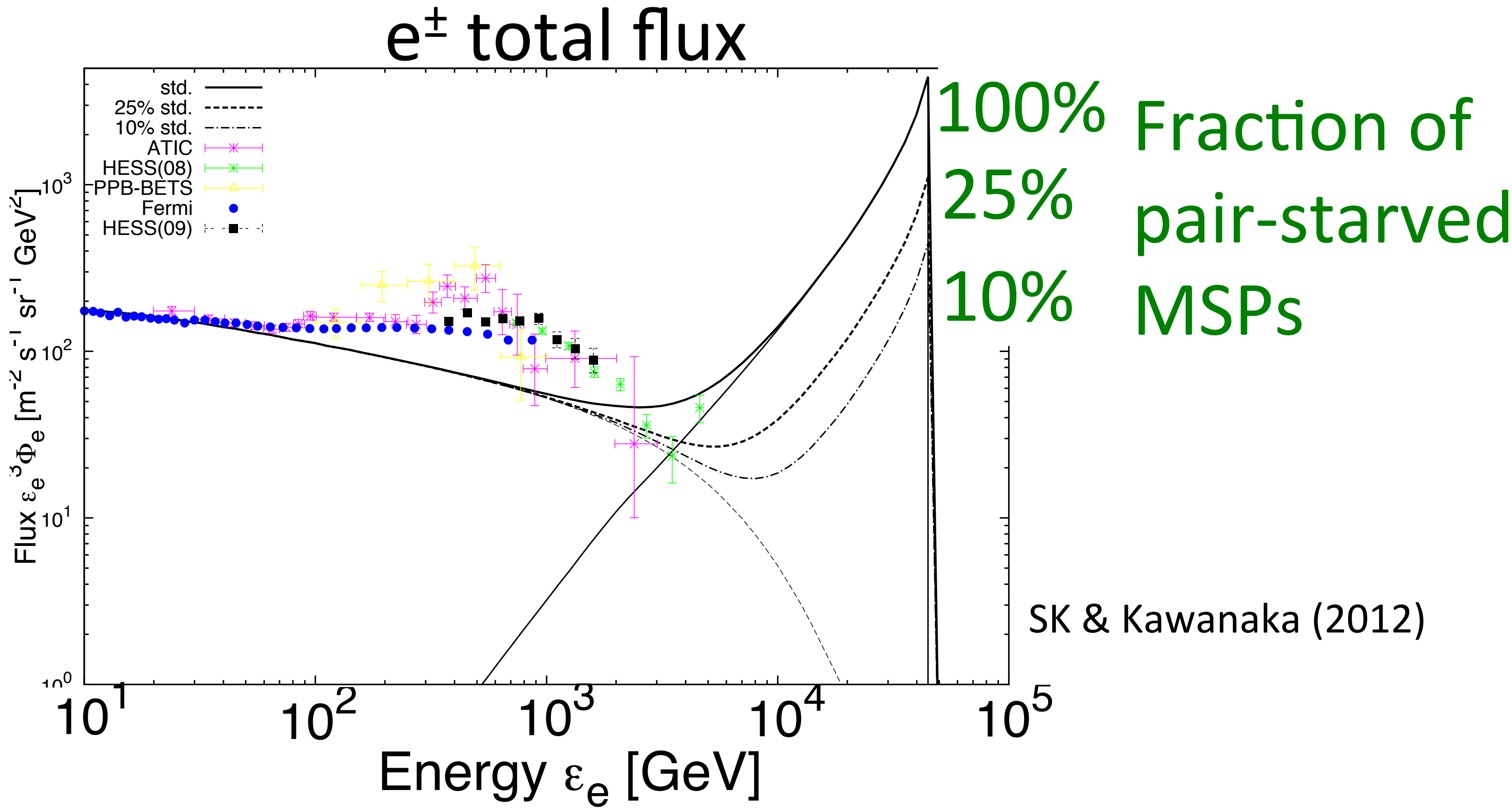
- MSPs are single population.
- Source function is mono-energetic distribution.

Spectrum

$$f_{\mathrm{ave}}(\varepsilon_e) = \int_0^{t_0} dt_i \int_0^{d_{\mathrm{diff}}(\varepsilon_e, \varepsilon_{e,i})} 2\pi r dr f(t_0, r, \varepsilon_e; t_i) R$$

$R \sim 3\times10^{-9}\ \mathrm{kpc^{-2} yr^{-1}}$: local birth rate

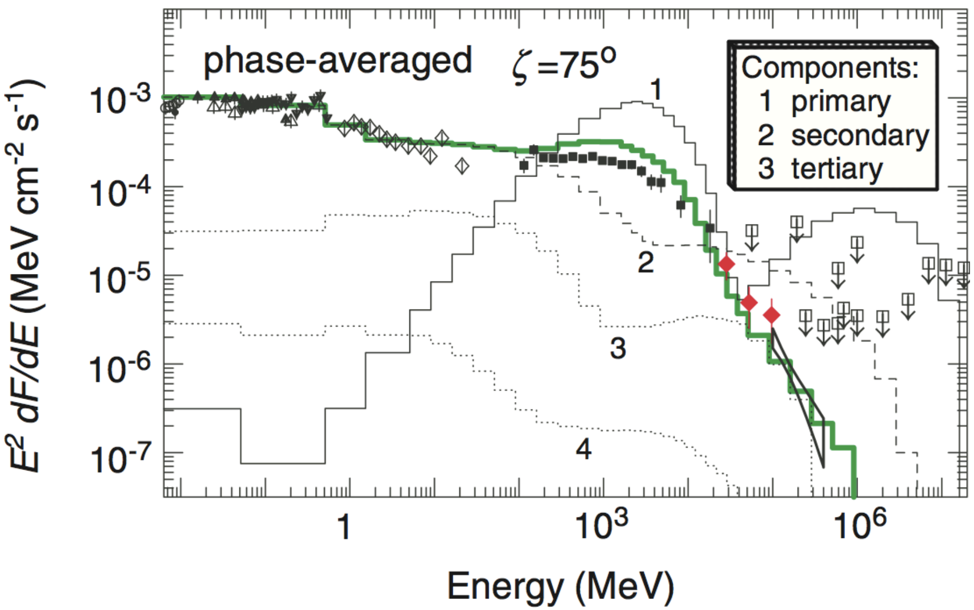
Result for κ=1 (ε_e=50TeV)



Large peak form in 10-50 TeV range and may be detectable by CALET and CTA.

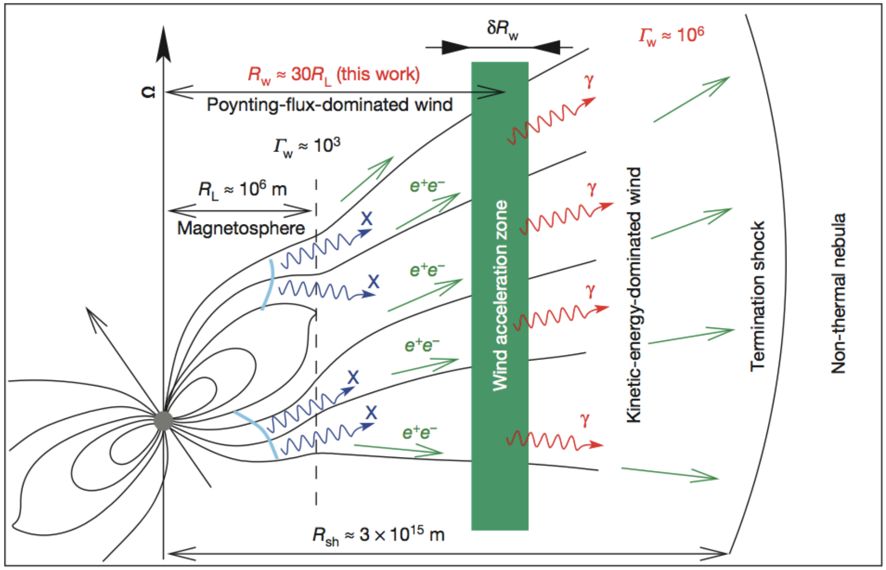
Sub-TeV pulse model

▪Outer gap



Aleksic et al. (2011)

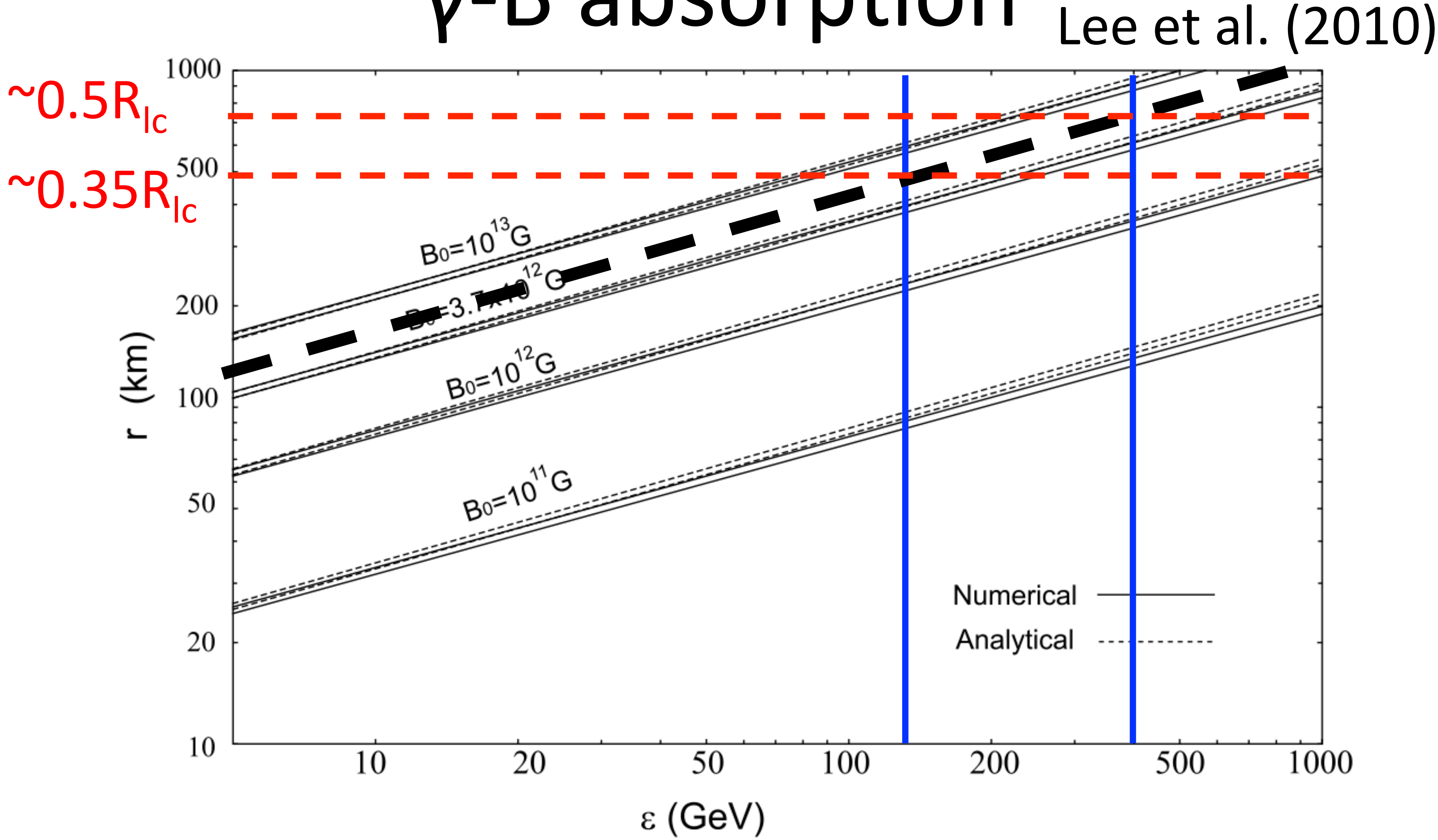
▪Cold wind



Aharonian et al. (2012)

Do Sub-TeV emission regions locate inside the light cylinder ? or outside ?

γ-B absorption



The value of the last escaping radius for a 400(120) GeV photon is 0.5(0.35) R_{lc}.

Geometrical modeling

Assumptions

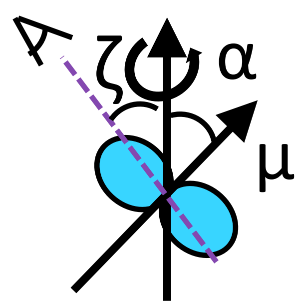
- Magnetic field : Rotating dipole
- Emission direction : Along the particle trajectory
- Emission region : $r_{null} < r < R_{lc}$ (Outward)
- Emissivity : Constant

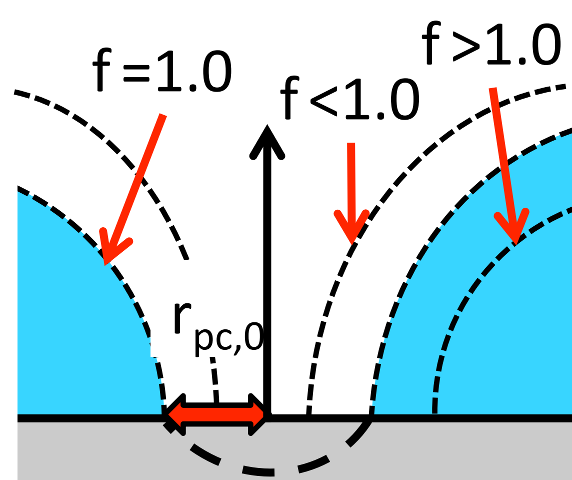
r_{null}: Distance to null surface
R_{lc} : Light cylinder radius

We focus on the peak phases of the light curve.

Parameters

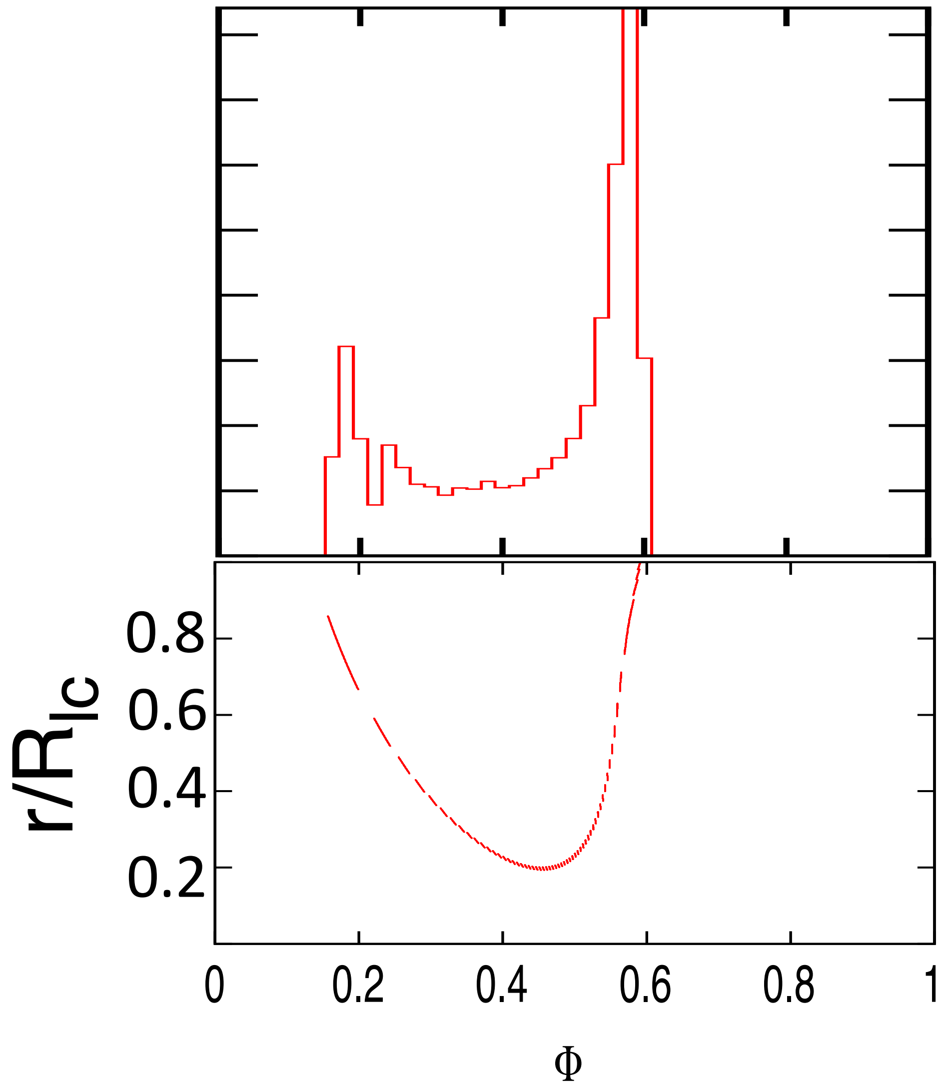
- Magnetic colatitude : $f \equiv r_{pc}/r_{pc,0}$
- Inclination angle : α
- Viewing angle : ζ





Emission region in outer gap

The distance distribution from NS to emission regions



Peaks include photons emitted from relatively far region.

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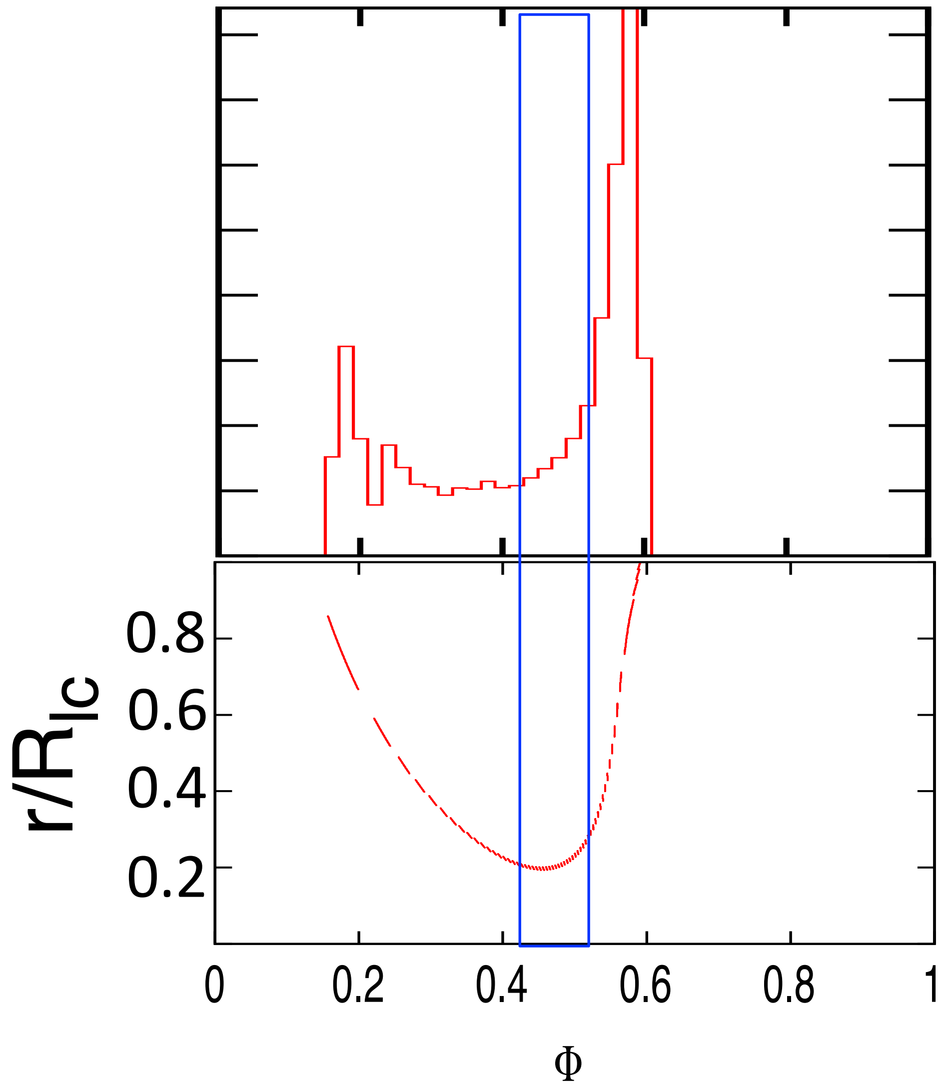
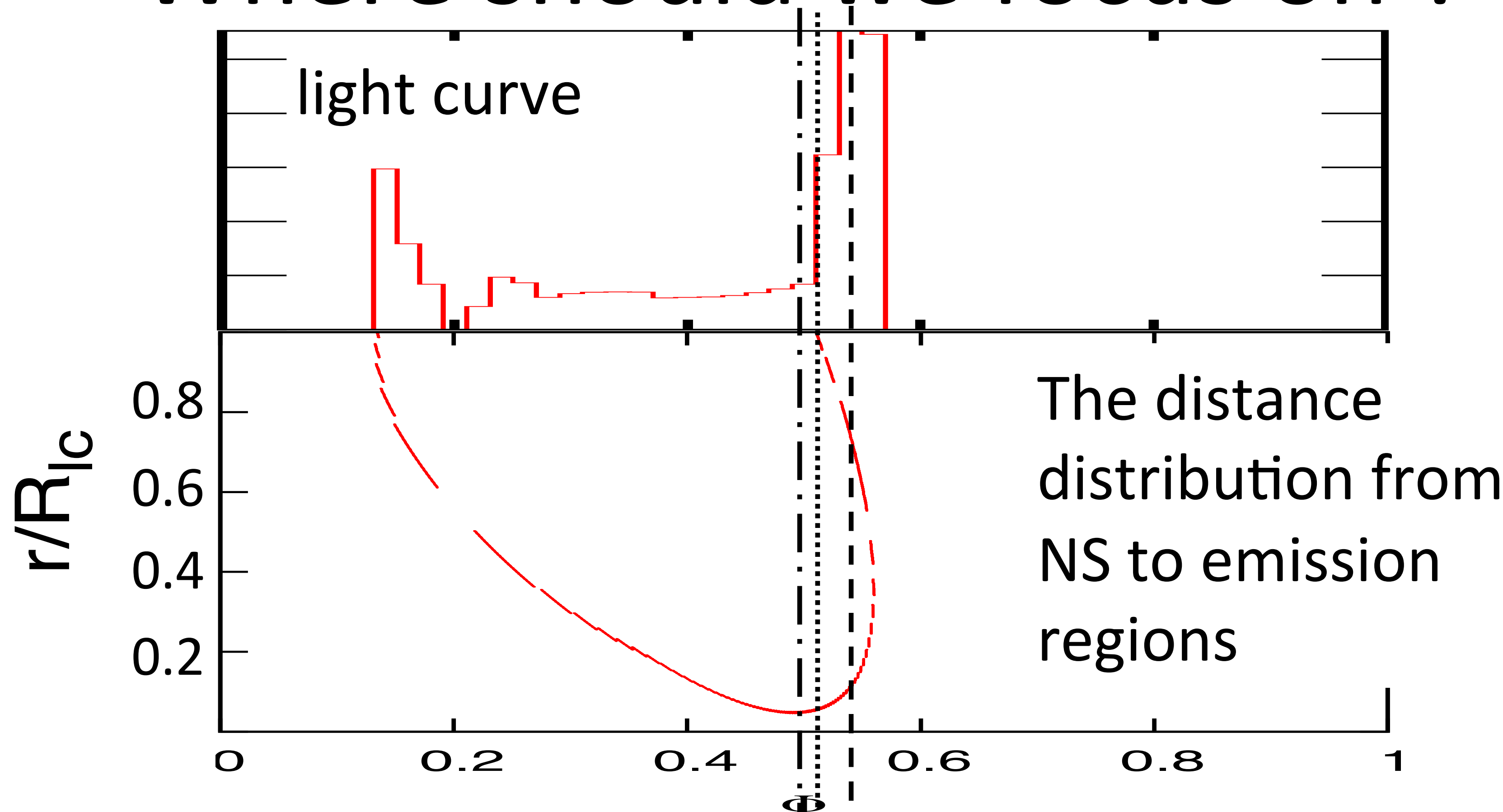


Peaks include photons emitted from relatively far region.

All photons at leading side of second peak come from the closest region in the magnetosphere.

Where should we focus on ?



Phase of second peak : ϕ_peak

Phase where photons from outer region are included : ϕ_out

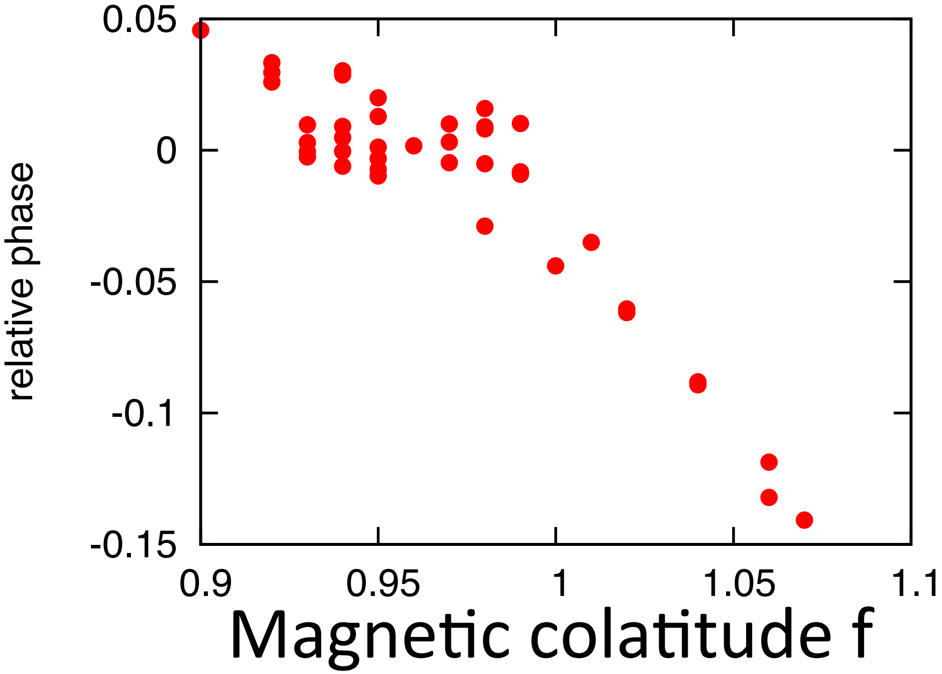
Phase where photons from the closest region are included : ϕ_in

① : ϕ_peak – ϕ_out

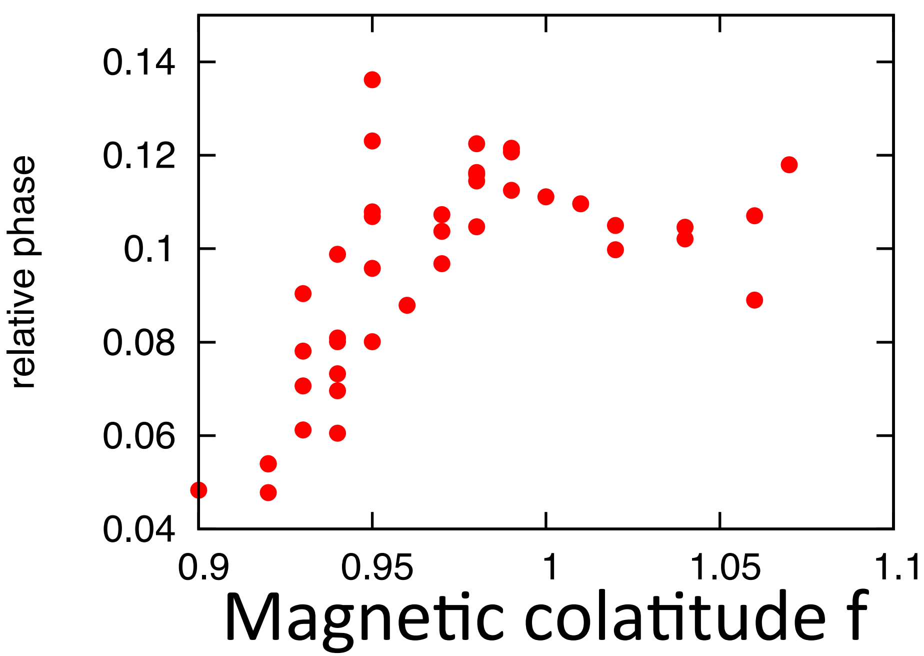
② : ϕ_peak – ϕ_in

Where should we focus on ?

① : ϕ_peak – ϕ_out



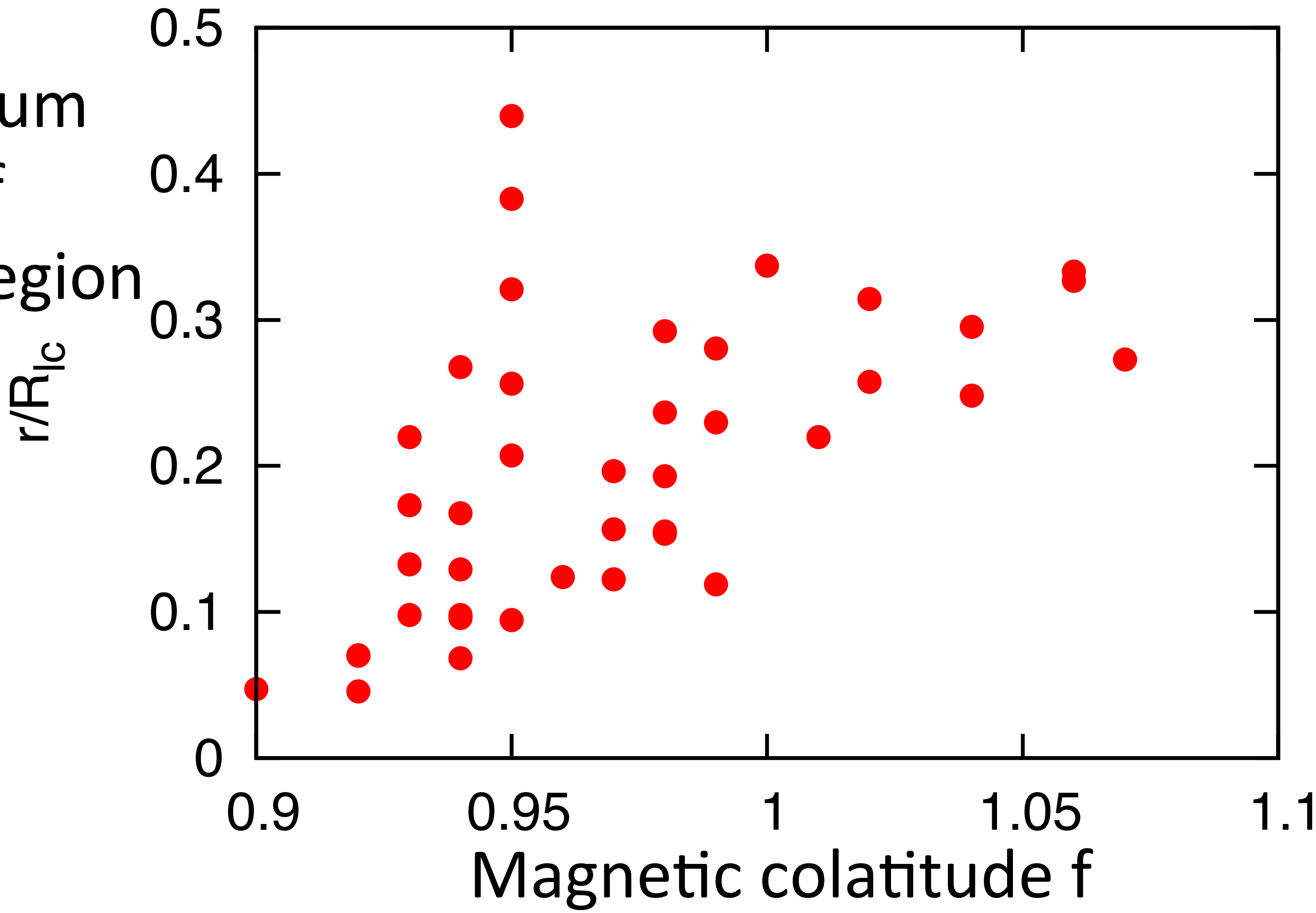
② : ϕ_peak – ϕ_in



- We can exclude the photons from outer region when we use photons in phase < ϕ_peak – 0.05.
- Photons from the closest region from NS are included in phase ϕ_peak – (0.05 - 0.15).

Constraint for outer gap model

The minimum distance of emission region



- ~400GeV : $r >$ ~$0.5R_{lc}$ → Outer gap can not explain this energy of photons.
- ~120GeV : $r >$ ~$0.35R_{lc}$ → $35 < \alpha < 45$, ζ~80, f~0.95.

Prospects

1. If the spectrum have the power-law component…
   outer gap → Constraint for geometrical parameters.

2. If the spectrum show the strong cut-off…
   outer gap → Constraint for the altitude of emission region.
   cold wind → Constraint for the anisotropy of
   the particle distribution in pulsar wind.

3. If the spectrum do not have the power-law component…
   outer gap → Constraint for the condition of IC.
   cold wind → Constraint for the anisotropy of
   the particle distribution in pulsar wind.

Summary

- Outer gap model cannot reproduce observed γ-ray light curve in some MSPs.

→ CTA can detect the evidence of the existence of pair-starved MSPs in the $e^{\pm}$ cosmic ray spectrum.

- VERITAS and MAGIC detected sub-TeV emission from Crab pulsar.

→ CTA can restrict the emission region using the spectrum at the phase of the bridge.