パルサー星雲からの高エネルギー放射の一次元モデル

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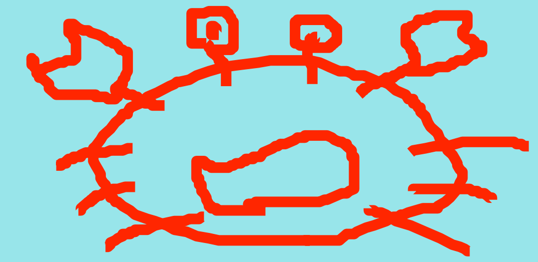
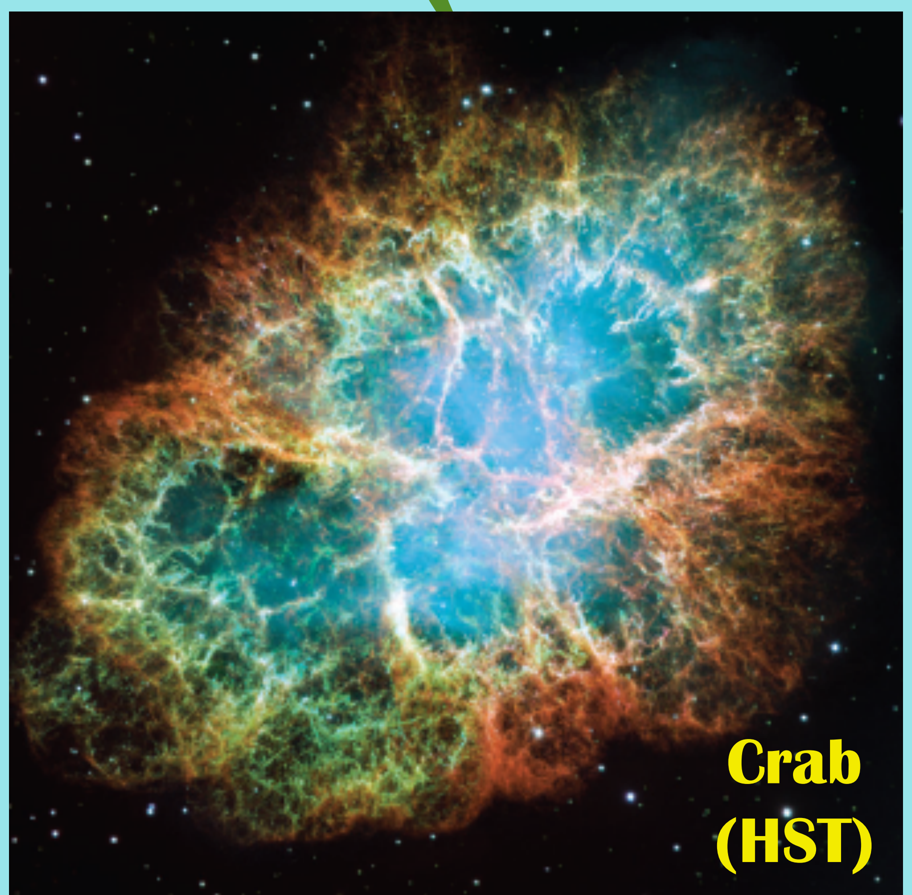
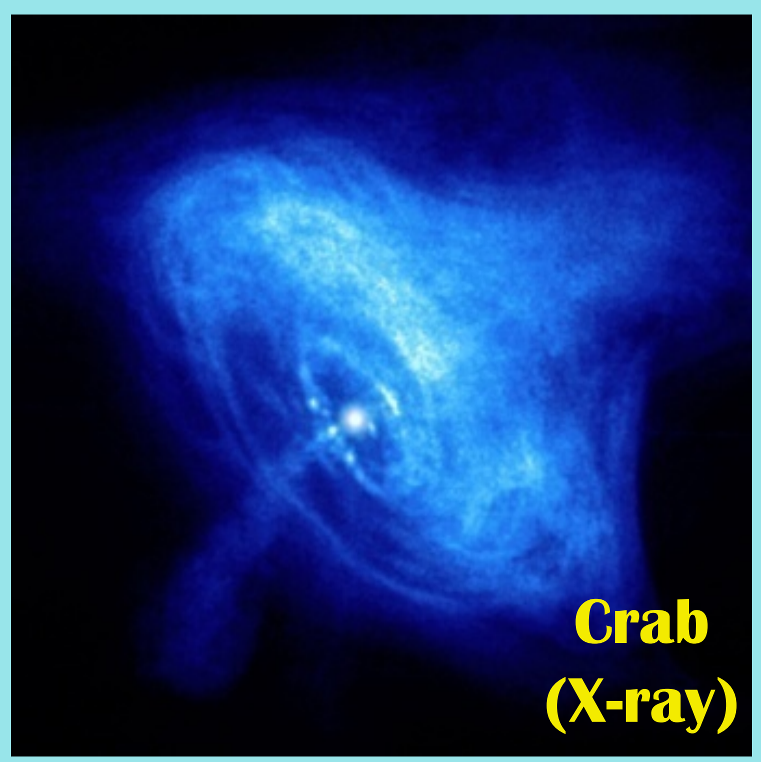
Introduction to 

PWN (Pulsar wind nebula)



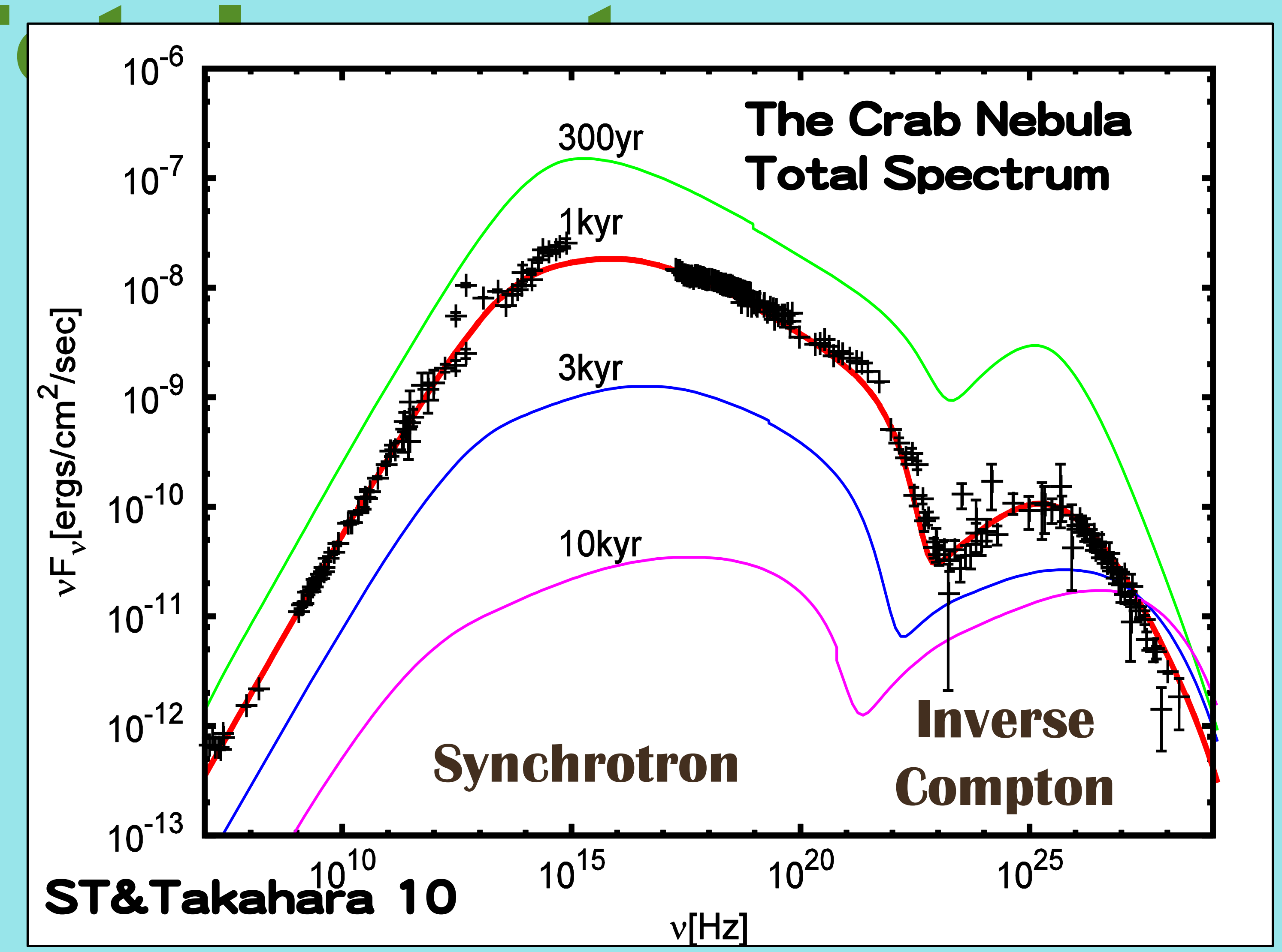
Line emission (SN ejecta)

Non-thermal (Pulsar wind)



Confined by SNR

Powered by PSR

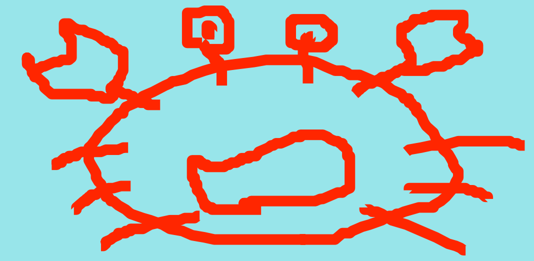


We reproduced

- **Total spectrum @ 1kyr**
- **Flux decrease rate ~0.2%/year @ radio**

We obtain

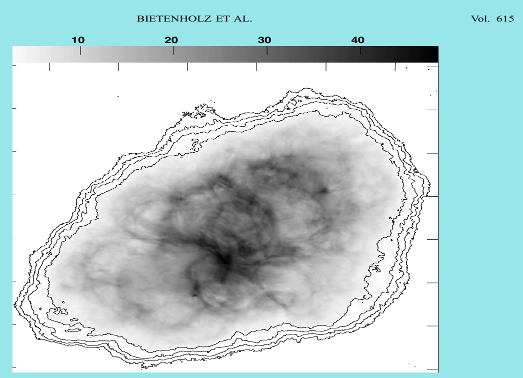
- **mean B-field inside PWN.**
- **particle energy & number inside PWN.**
- **magnetization at injection.**
- **particle injection spectrum (broken PL).**
- **spin evolution of the central PSR.**

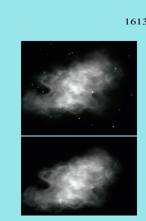
Virtue of 

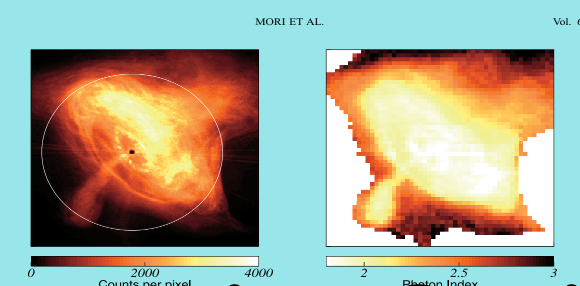
Bright and extended object

- **Brightness map in different frequencies of the Crab.**

Bietenholz+04ApJ (radio) | Temim+06ApJ (IR) | Mori+04ApJ (X-ray)

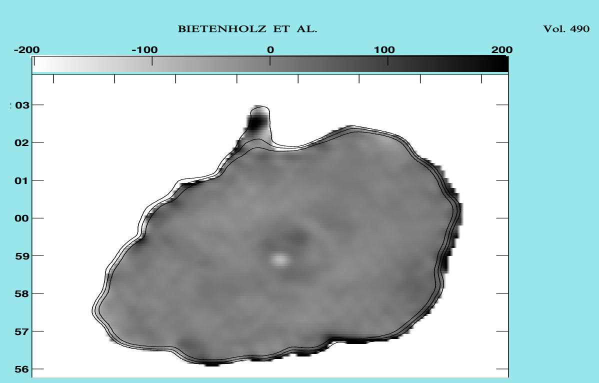


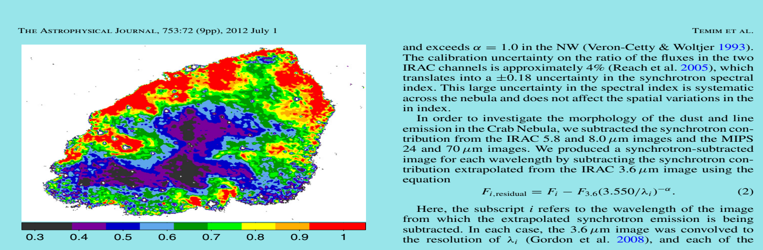


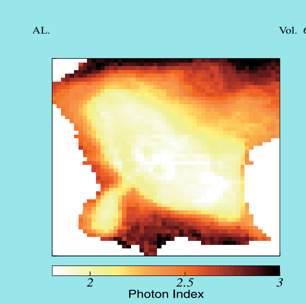


- **Spectral index map in different frequencies of the Crab.**

Bietenholz+97ApJ (radio) | Temim+12ApJ (IR) | Mori+04ApJ (X-ray)



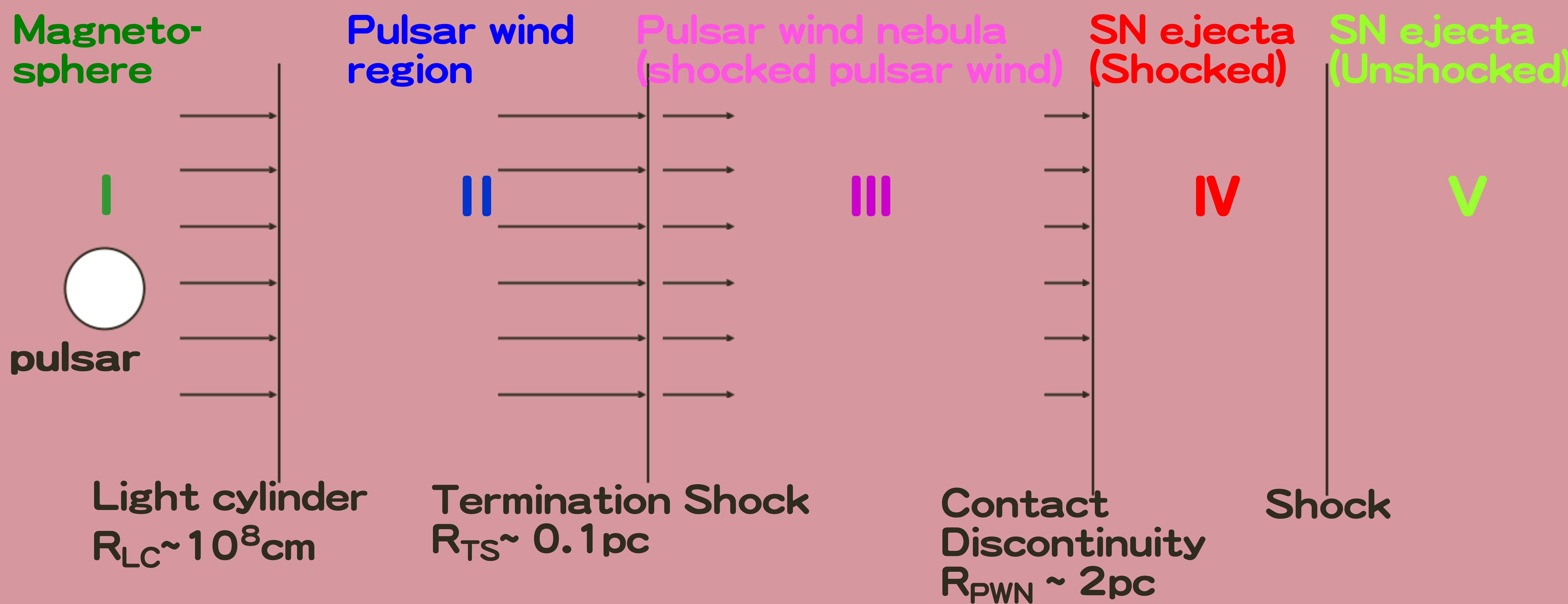




PWN emission reflects B-field & particle distribution of PWN

2-1: Qualitative Description

PWN is powered by central pulsar



Young PWNe are almost spherical.
(Whole particles are confined within SNR)

Motivation

What do we learn from observations of the Crab Nebula?

PSR & PWN properties

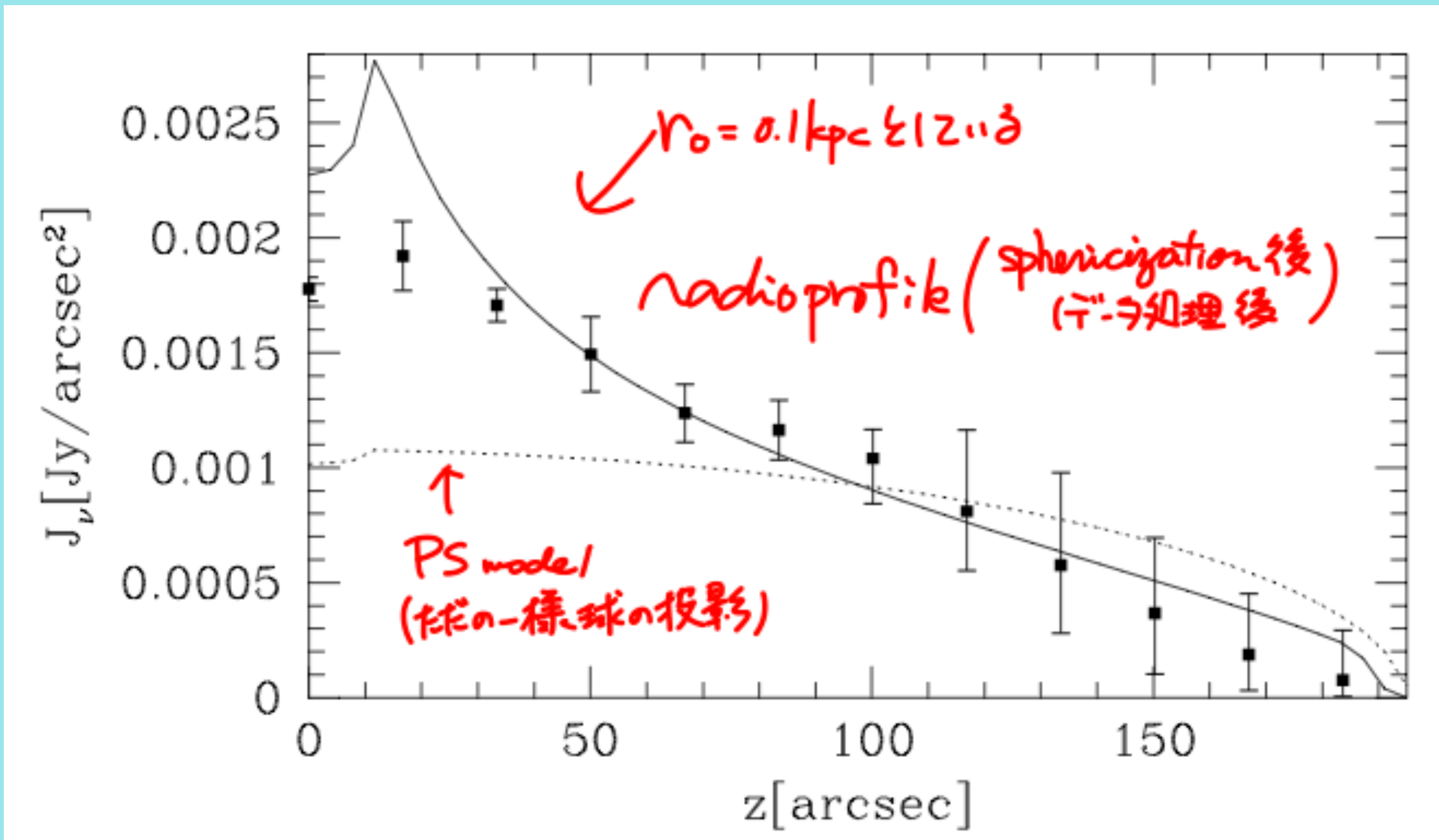
- Magnetization of pulsar wind. → σ-problem
- Injection spectrum of particles. → κ-problem & particle acceleration
- $e^{\pm}$ escaping process from PWN. → PAMELA anomaly

Physics

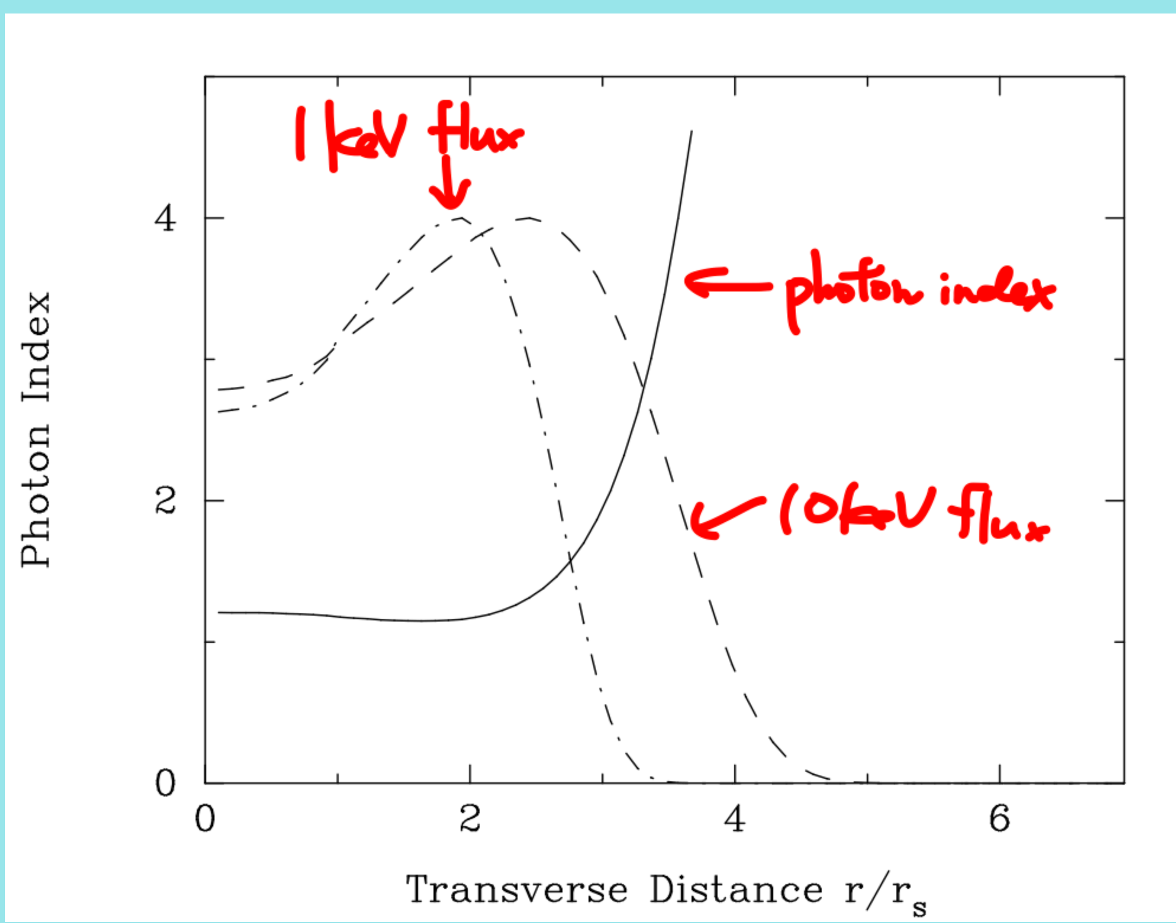
- Particle transport mechanism inside PWN. → advection? diffusion?
- Particle acceleration process inside PWN. → second-order acceleration?
- Expansion of PWN. → Interaction between PWN & SNR at outer boundary.

Past Studies

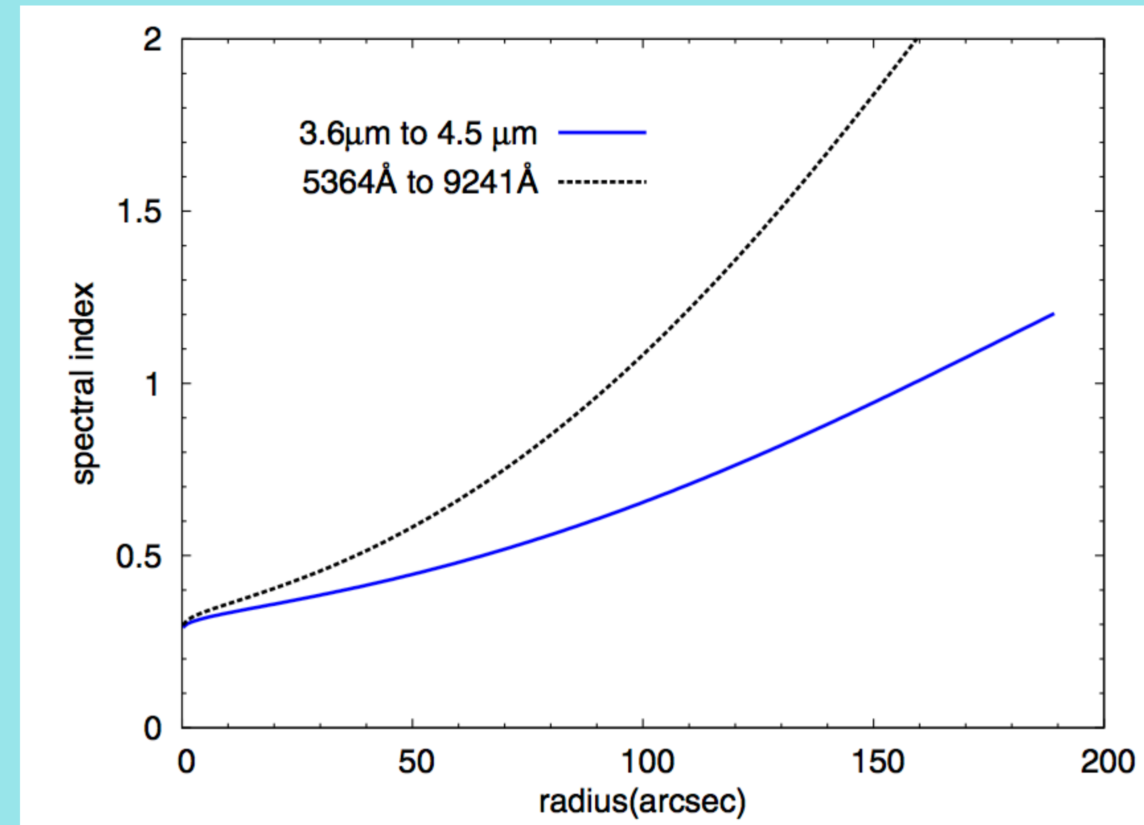
Amato+00, advection only
Radio brightness map



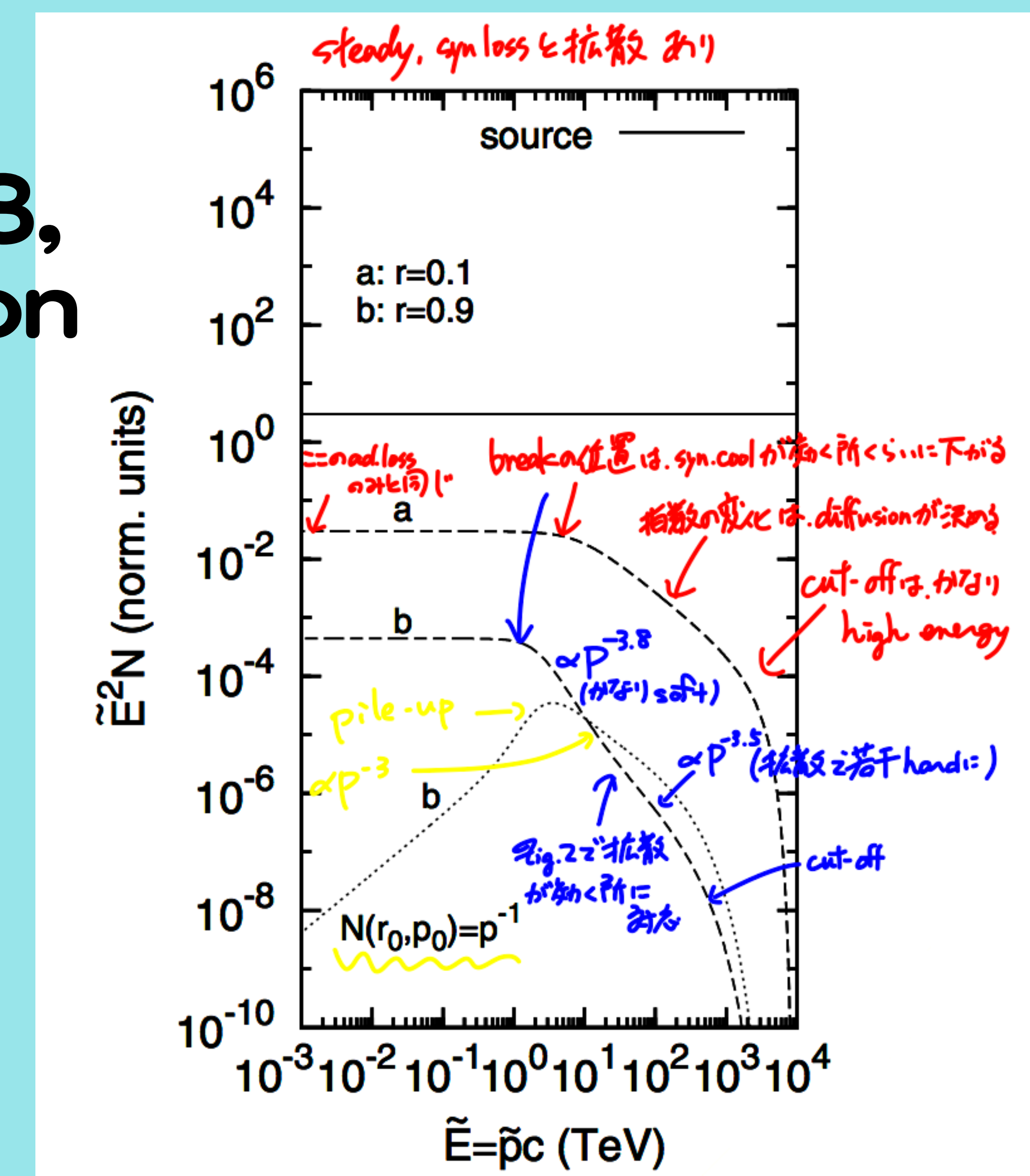
Reynolds03, advection only
X-ray spectral index map



Tang & Chevalier 12, diffusion
optical spectral index map



Vorstar & Moraal 13, diffusion & advection particle spectrum



Model

Transport Equation

$$\frac{\partial f}{\partial t} = -\boldsymbol{\nabla}\cdot[(\boldsymbol{v} - K\boldsymbol{\nabla})f] + \frac{1}{p^2}\frac{\partial}{\partial p}\left[\left(\frac{1}{3}\boldsymbol{\nabla}\cdot\boldsymbol{v} + (\beta_{\rm syn} + \beta_{\rm IC}\right)p^3 f\right] + Q_{\rm inj}$$

Radial flow & toroidal B-field + induction equation

$$\boldsymbol{v}(r) = v_0\left(\frac{r}{r_0}\right)^{-\alpha_v}\boldsymbol{e}_r,\ \ \boldsymbol{B}(r, t_{\rm inj}) = B(t_{\rm inj})\left(\frac{r}{r_0}\right)^{-\alpha_B}\boldsymbol{e}_\varphi,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B})$$

Bohm-type diffusion & particle injection

$$K = \frac{1}{3}\xi c r_{\rm gyro} \qquad Q_{\rm inj}(r,t,p) = q(t)\frac{\delta(r-r_0)}{4\pi r_0^2}\times\begin{cases}(p/p_{\rm b})^{2-{\rm p}_1} & \text{for } p_{\rm min}\le p\le p_{\rm b}\ ,\\ (p/p_{\rm b})^{2-{\rm p}_2} & \text{for } p_{\rm b}\le p\le p_{\rm max}\ ,\end{cases}$$

We take into account the evolution of the spin-down luminosity (injection) & the R_{PWN} (expansion).

Application to the Crab Nebula

We consider that the particles and the magnetic field are injected at the inner radius $r = r_0$ at a time $t = t_{inj}$.

Main parameters are

1. gyro-factor ξ,

2. inner radius r_0 or velocity profile index α_v,

   R_{PWN} = 2.0pc, V_{PWN} = 1.500km/s @ t_{age} = 1kyr

   (r0 = 0.1pc & v0 = c/3 are too much.)

3. injected B-field or magnetization σ

   B0 = 300μG

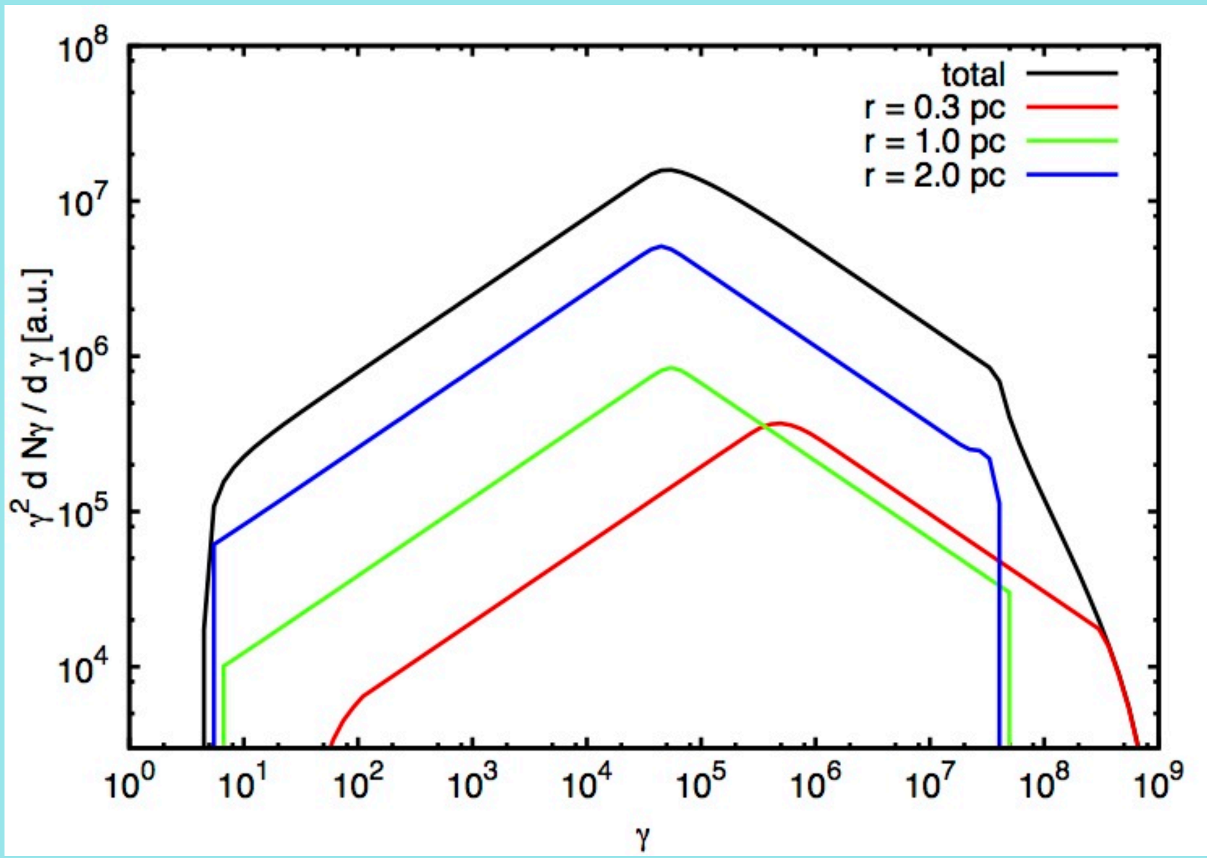
4. broken power-law injection with

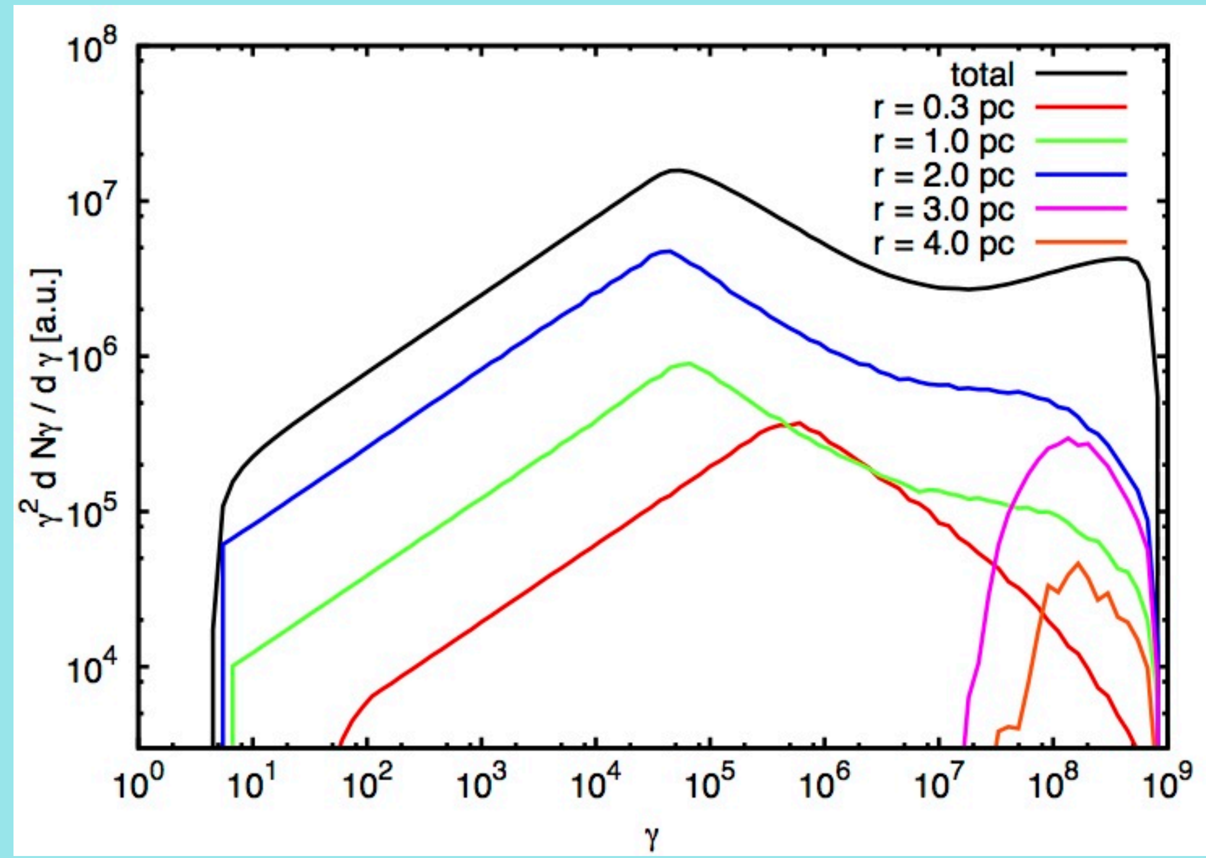
   p_1 = 1.5, p_2 = 2.5, $\gamma_{min} = 10^2$, $\gamma = 10^6$, $\gamma_{max} = 10^9$

Results: Particle

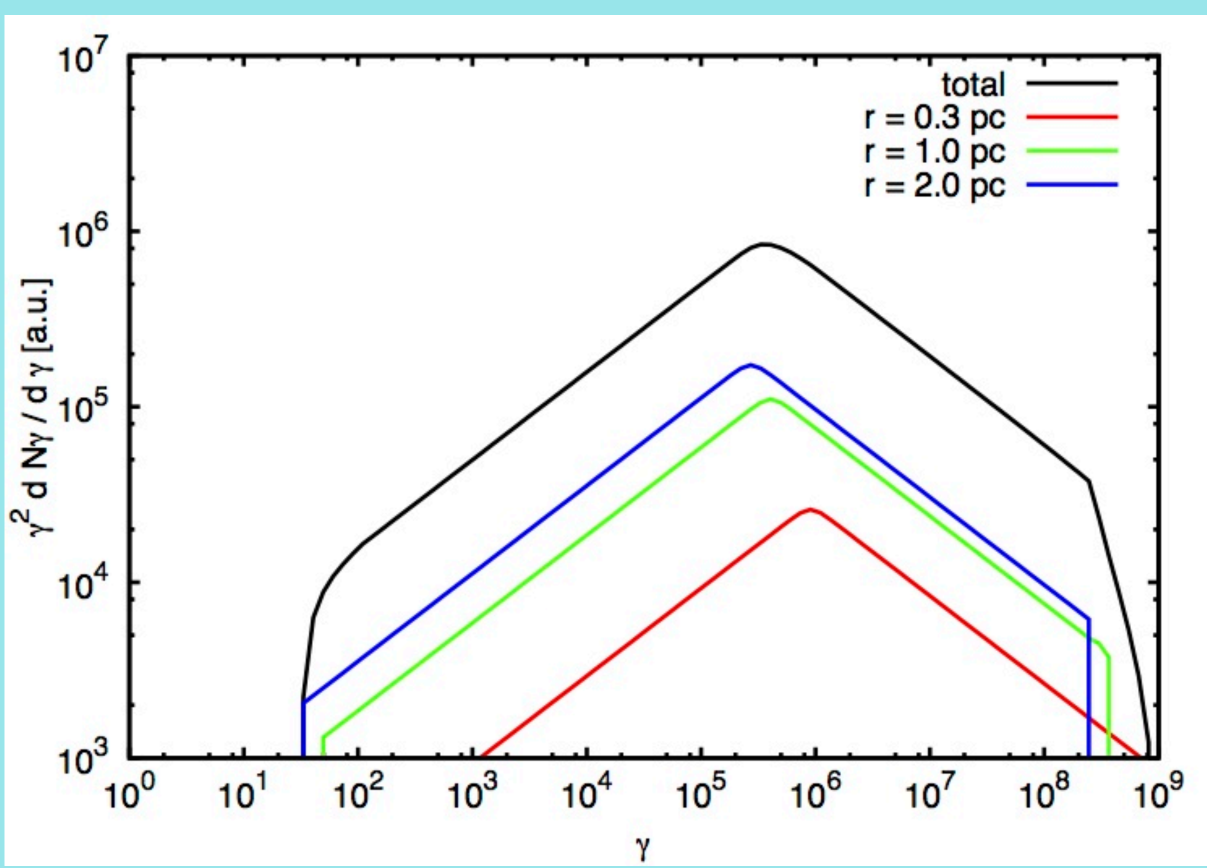
without diffusion | with diffusion(ξ=1)

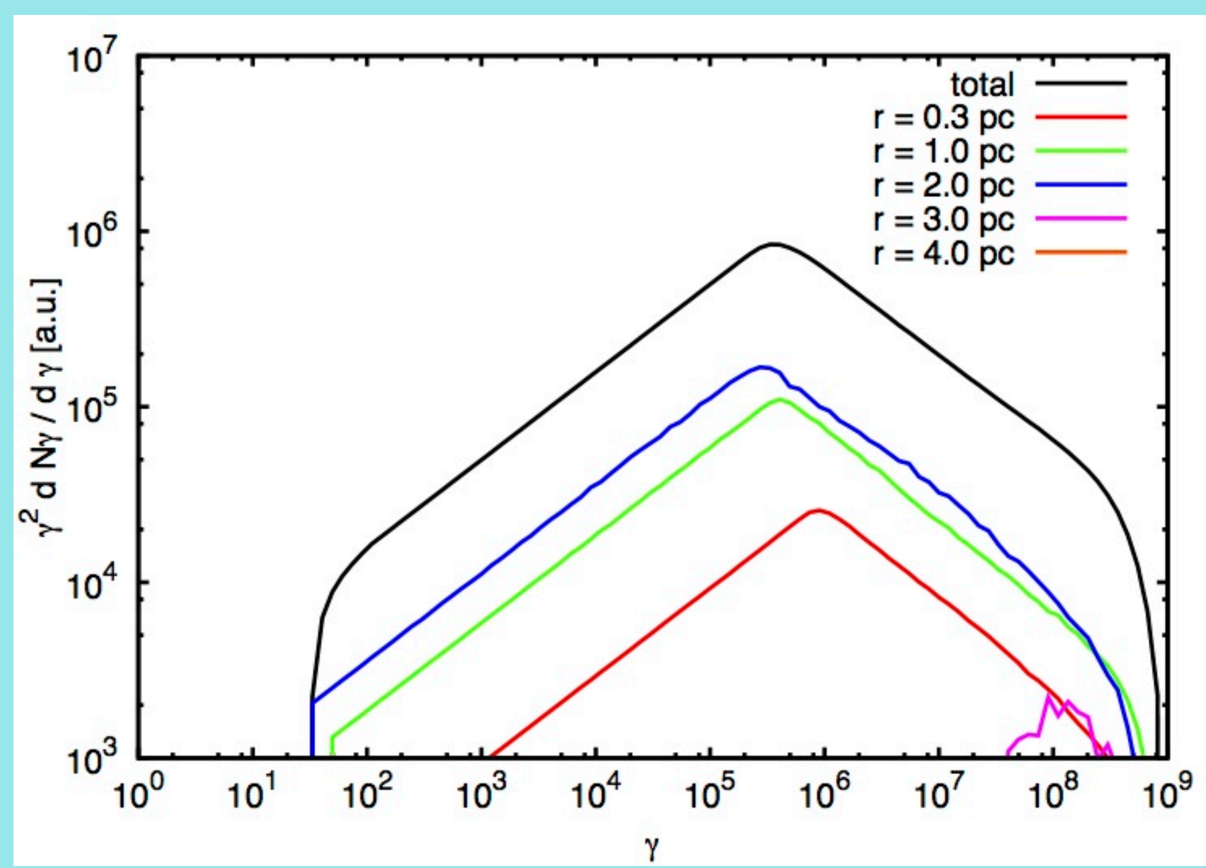
r_0 = 0.007pc





?





1. strong adiabatic cooling for r_0 = 0.007pc.

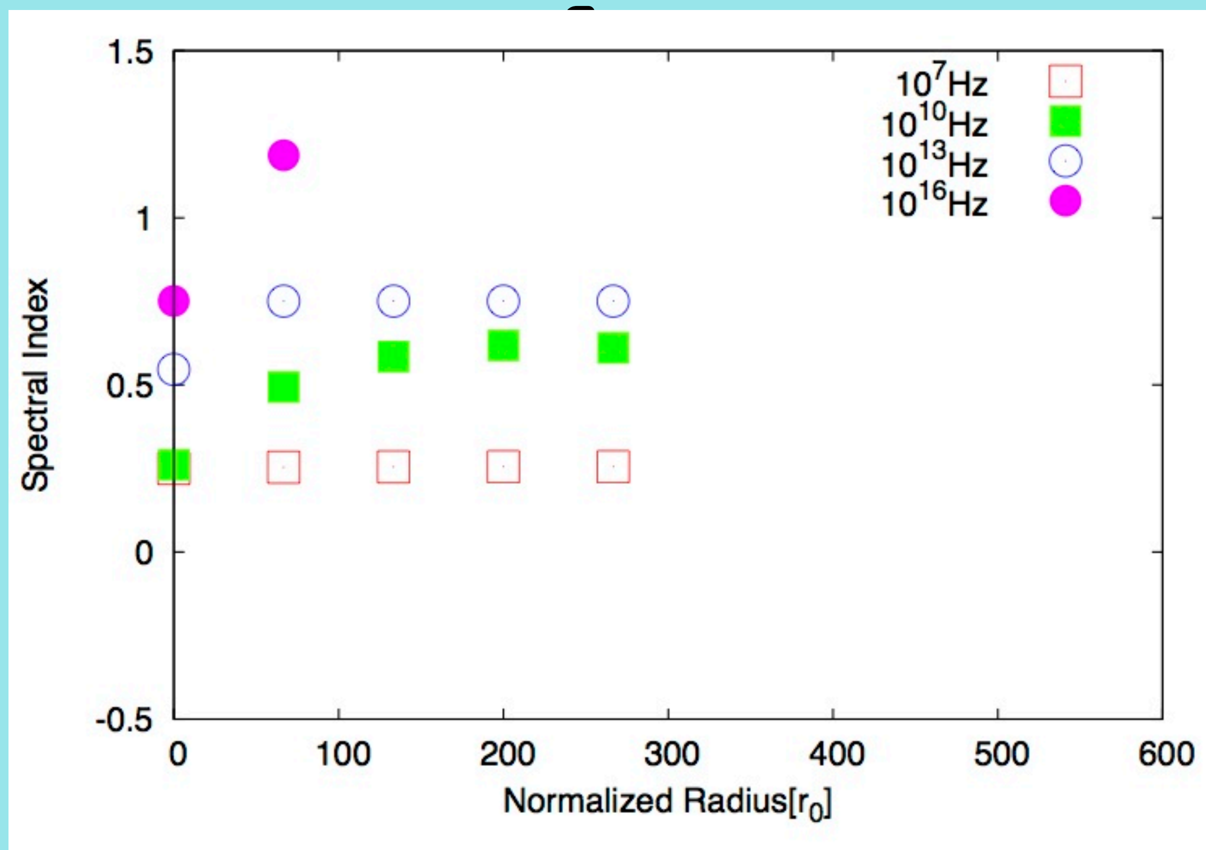
2. When ξ is non-zero, $e^{\pm}$ can escape from PWN ($r \gg R_{PWN}$).

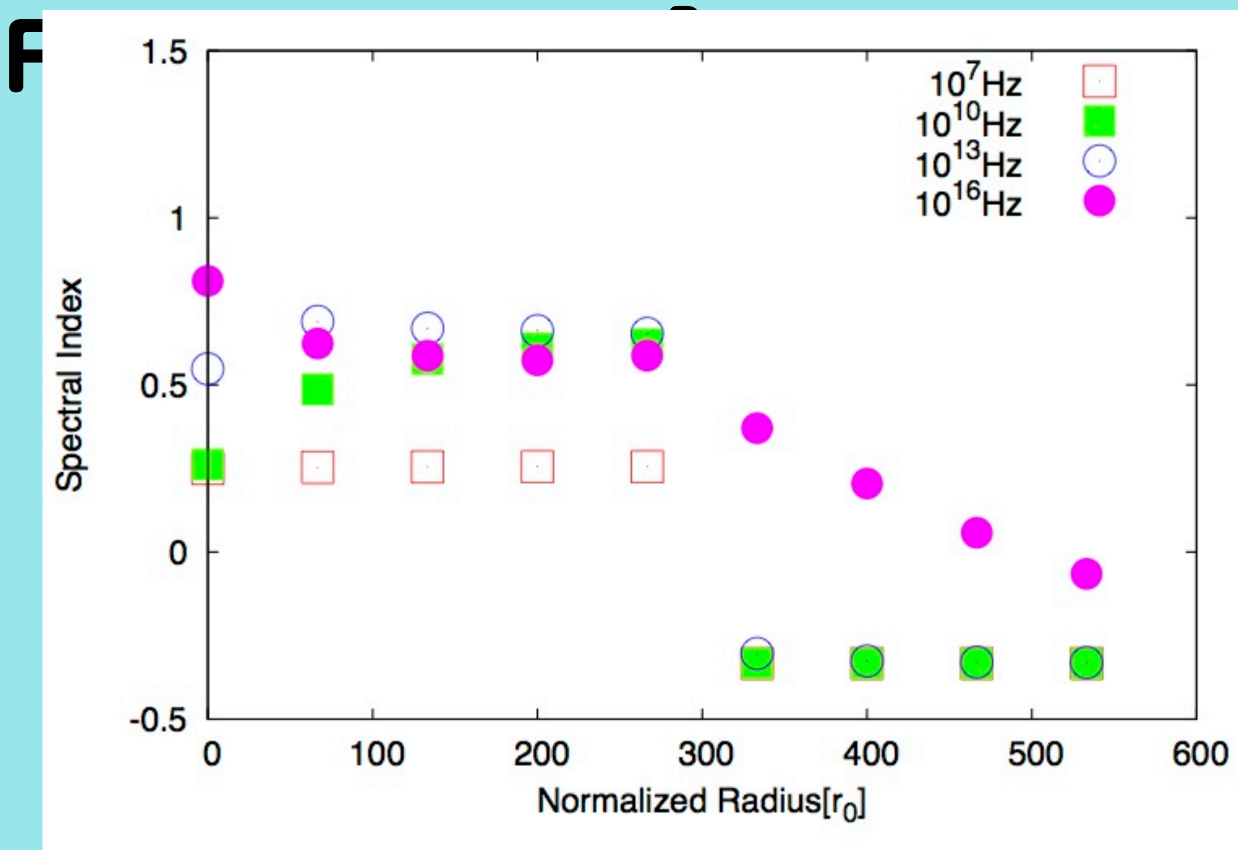
3. Escaped high energy $e^{\pm}$ are cooled slowly.

4. For r_0 = 0.007pc, because r_0 is smaller than diffusion length for high energy $e^{\pm}$, more particles can escape than for r_0 = 0.2pc, mostly in an early phase of evolution.

Results: Spectral Index Profile

c, i.e., F





without diffusion **with diffusion (ξ=1)**

p_1 = 1.5 & p_2 = 2.5 corresponds α = 0.25 & 0.75

1. Without diffusion, we find synchrotron cooling effect increases spectral index at 10^{16}Hz > 10 at $100r_0$ ~ 0.7pc.

2. Diffusion effect smooths spectral index profile and we do not find synchrotron cooling hardening of the spectrum for B_0 = 100μG. We need to select appropriate parameter set of (ξ, B_0) to fit the spectral index distribution.

3. α=-1/3 corresponds to low freq. side of synchrotron spectra and is appeared at r > R_{PWN} @ < 10^{16}Hz.

Conclusion

- Convection-Diffusion transport equation is considered to study the broadband emission structure of PWNe.

- For the escaping of $e^{\pm}$ from PWNe, we should compare diffusion length & r0.

- γ-ray distribution almost traces the particle distribution for inverse Compton scattering off CMB.

- Synchrotron Self-Compton process is considered to be dominated in the Crab Nebula in γ-rays and should be considered the future work.

- We need larger value of B-field at injection point, to obtain softer spectra observed for many PWNe in X-rays ($\alpha > 2$).