パルサー星雲における
高エネルギー粒子の空間分布

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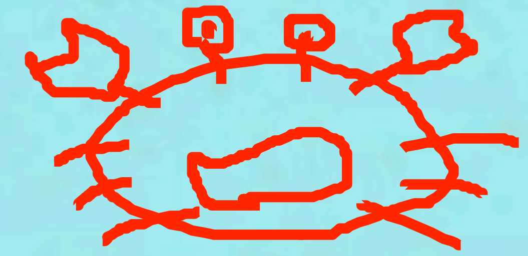
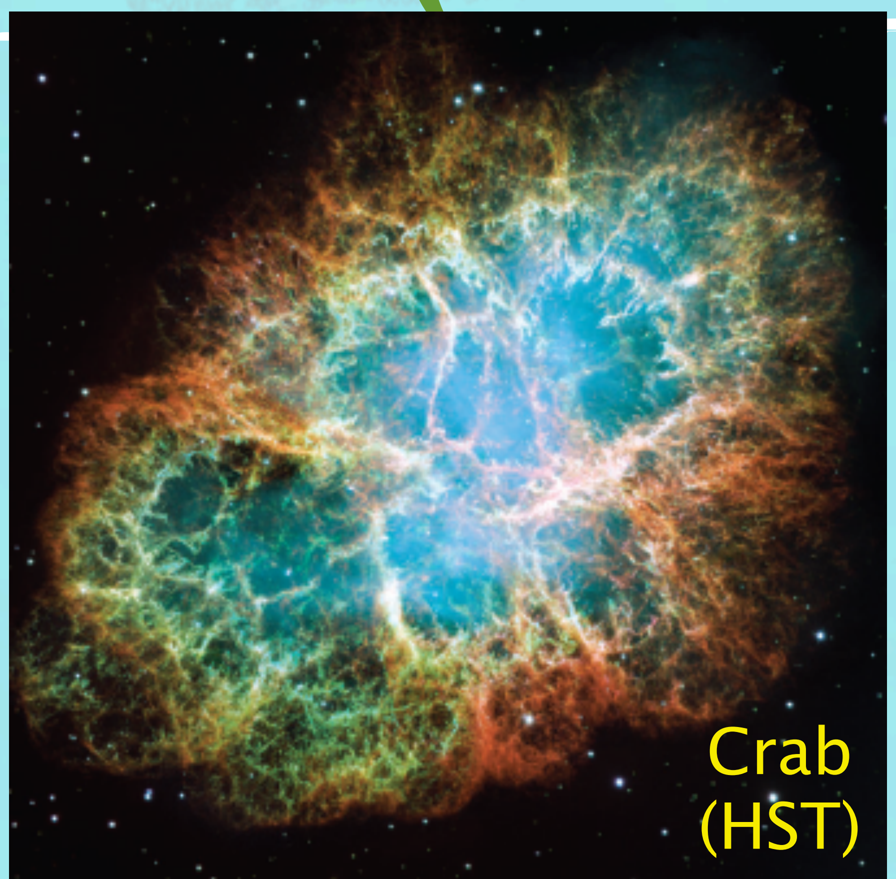
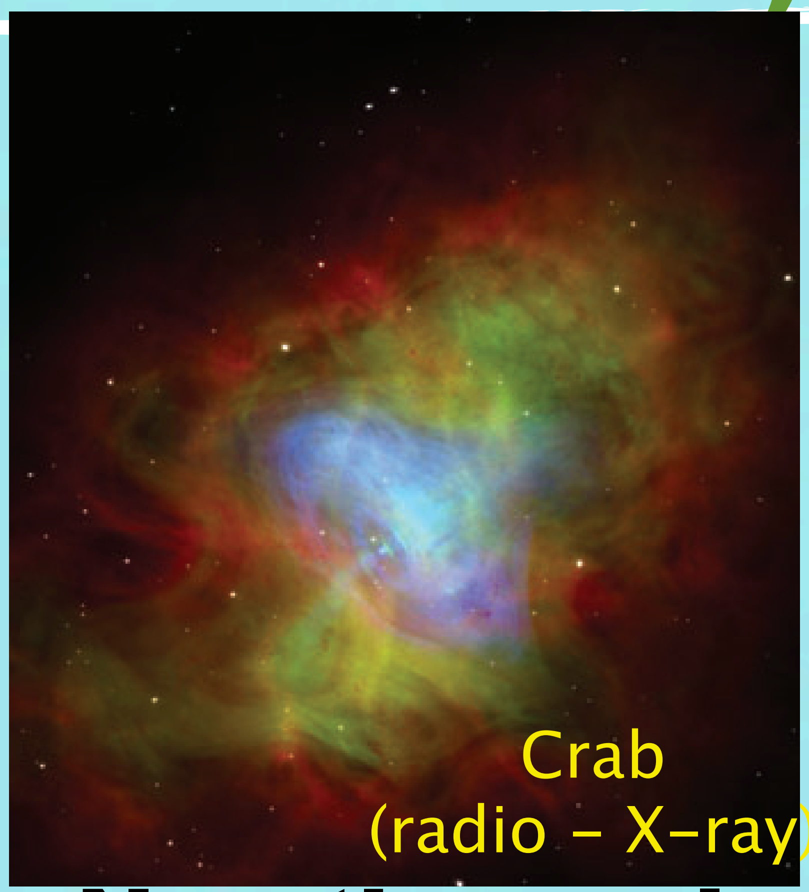
3, Sep., 2013, 高エネルギーガンマ線でみる極限宇宙@宇宙線研

Introduction to 

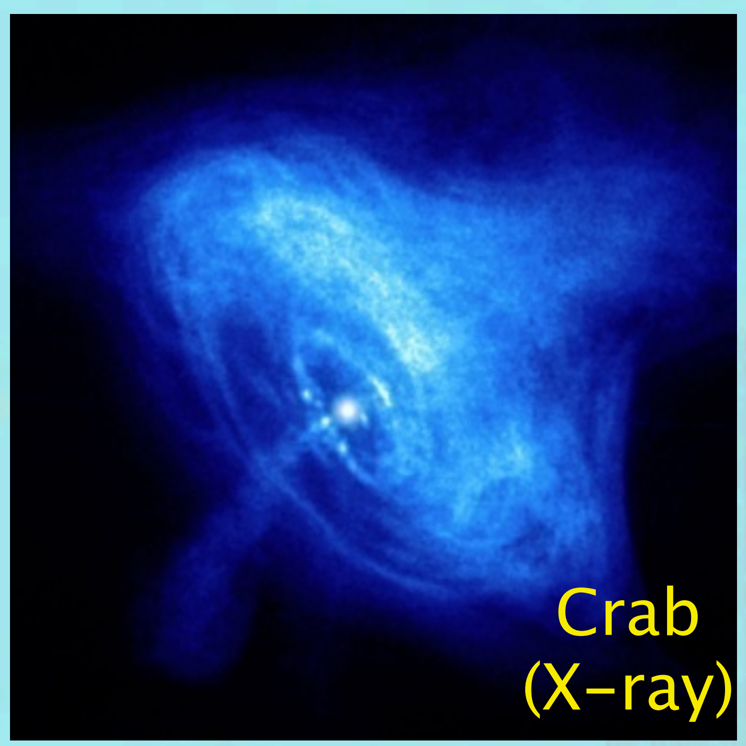
PWN (Pulsar wind nebula)





Line emission (SN ejecta)

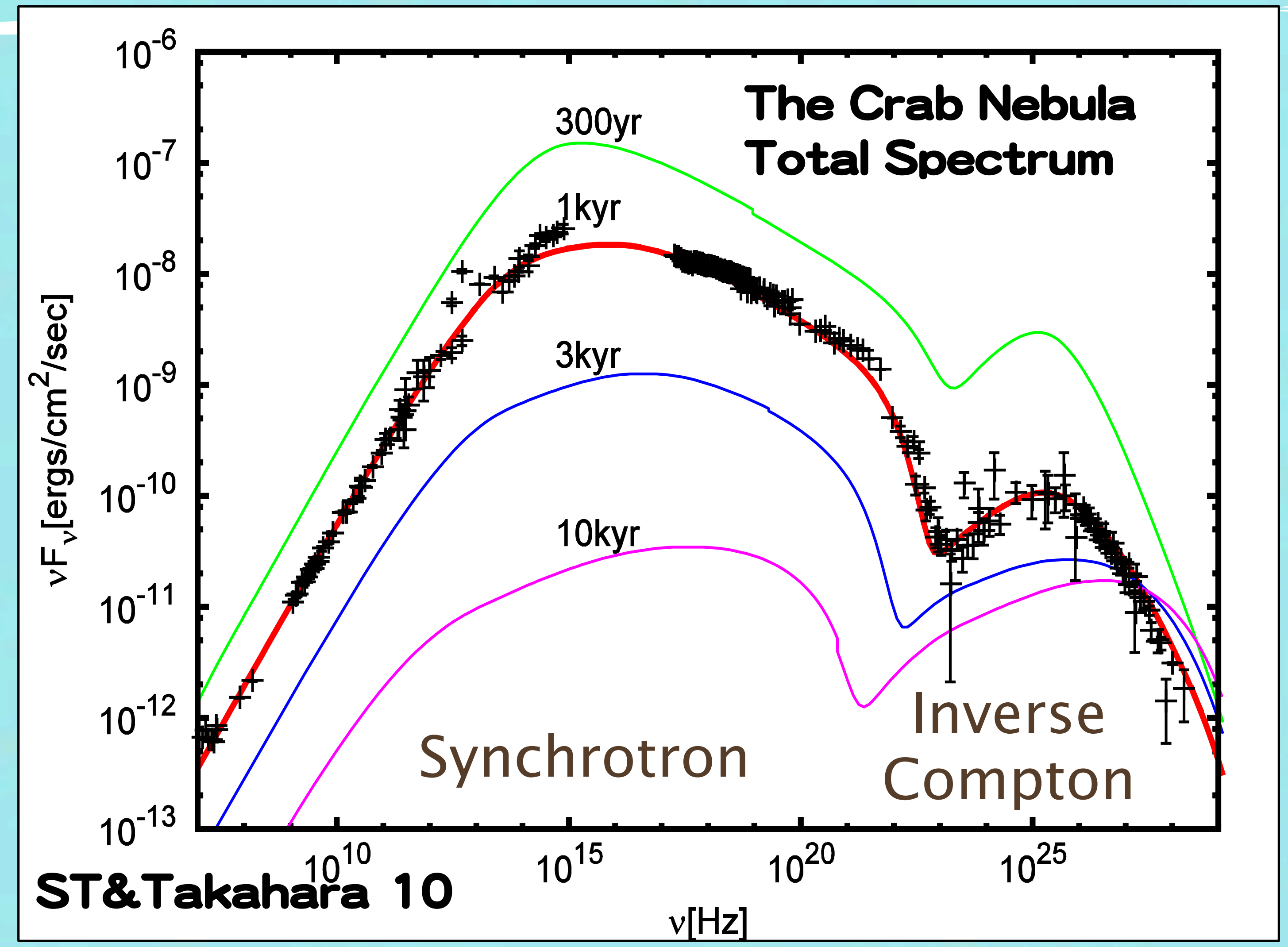
Non-thermal (Pulsar wind)



Confined by SNR

Powered by PSR

Total spectrum

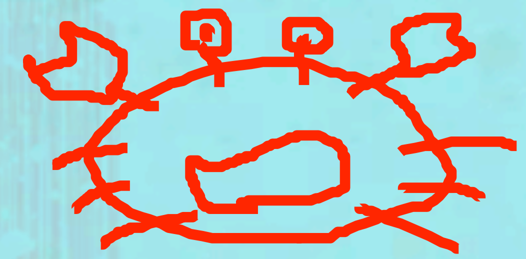


We reproduced

- **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.**

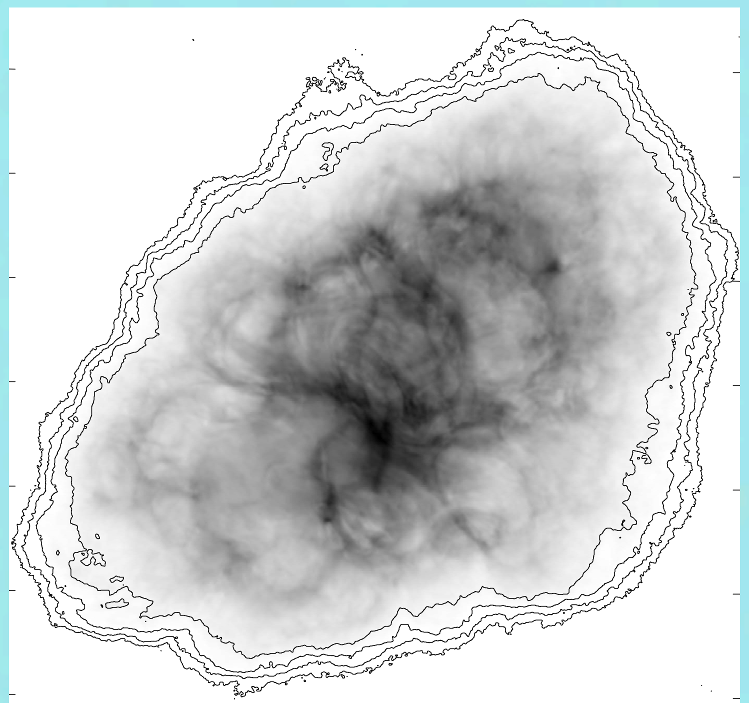
Virtue of 

Bright and extended object

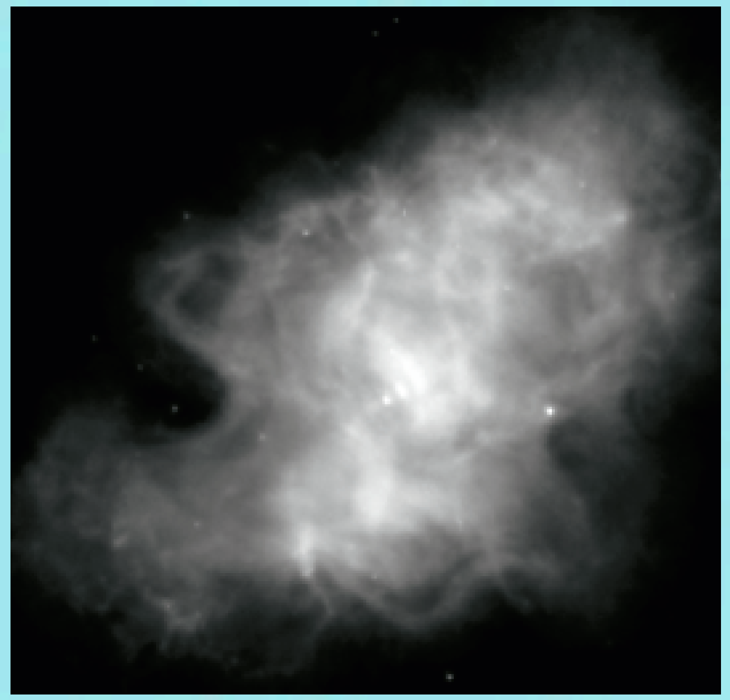
Crab は 点源なので

- Brightness map in different frequencies of the Crab.

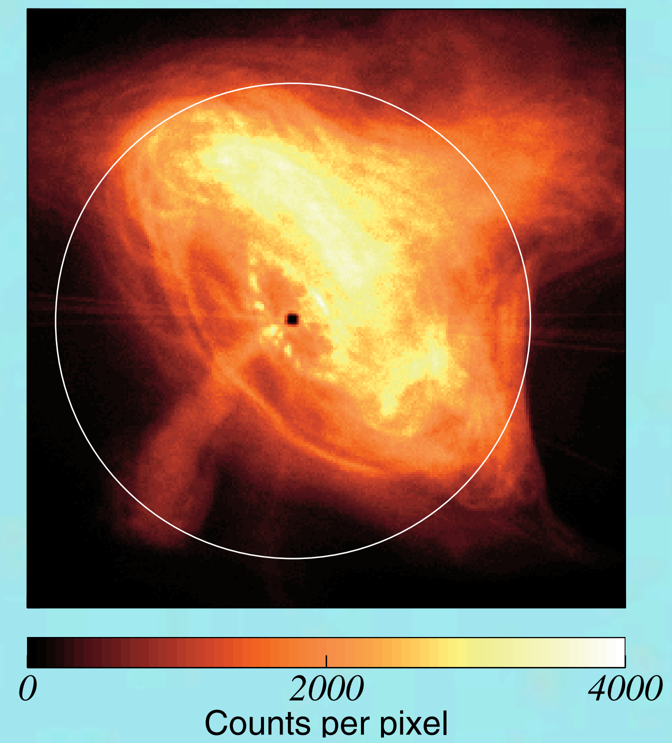
Bietenholz+04ApJ (radio)



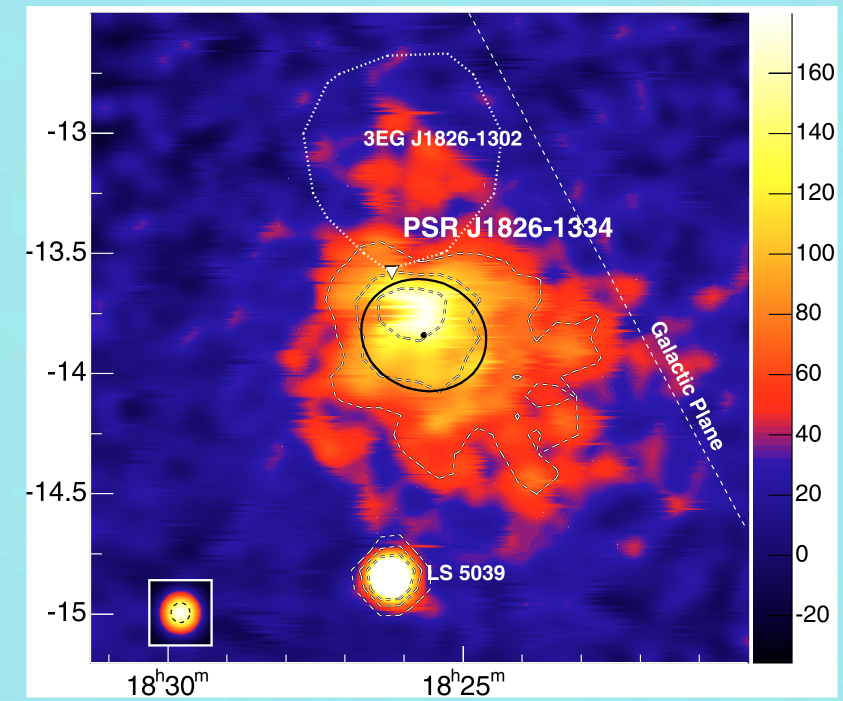
Temim+06ApJ (IR)



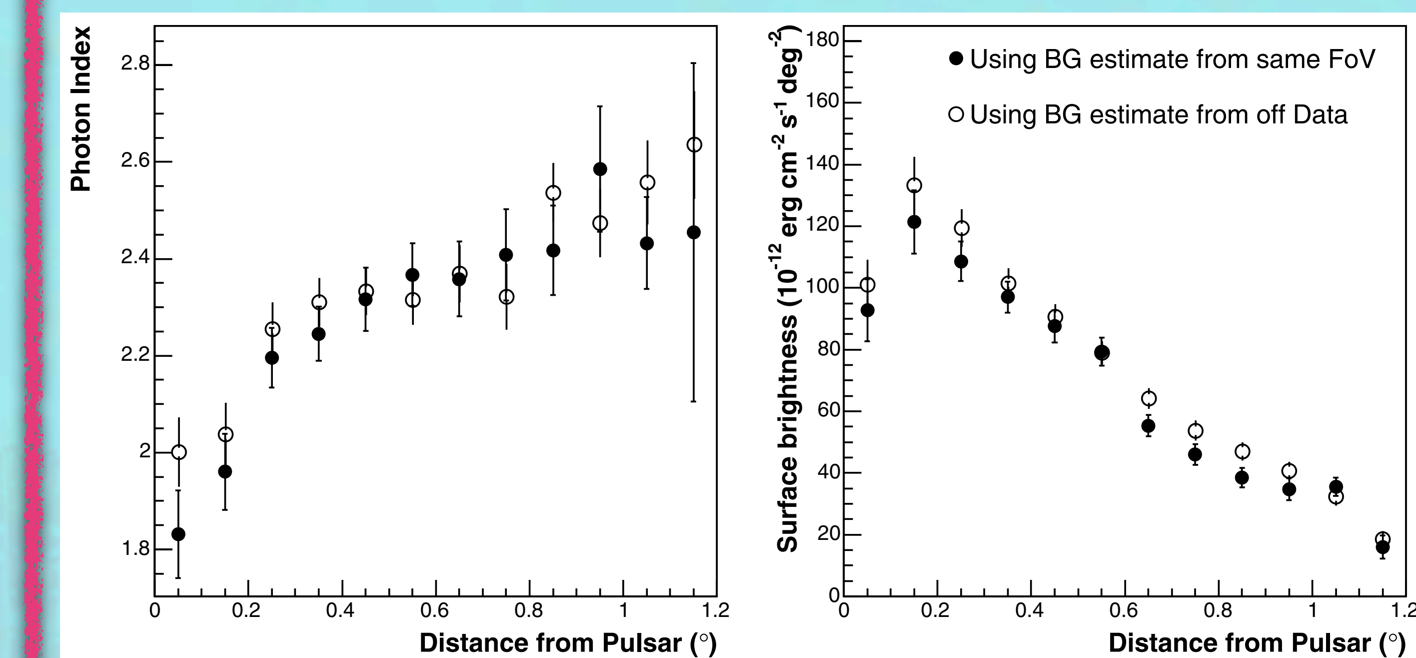
Mori+04ApJ (X-ray)



HESS J1825-137

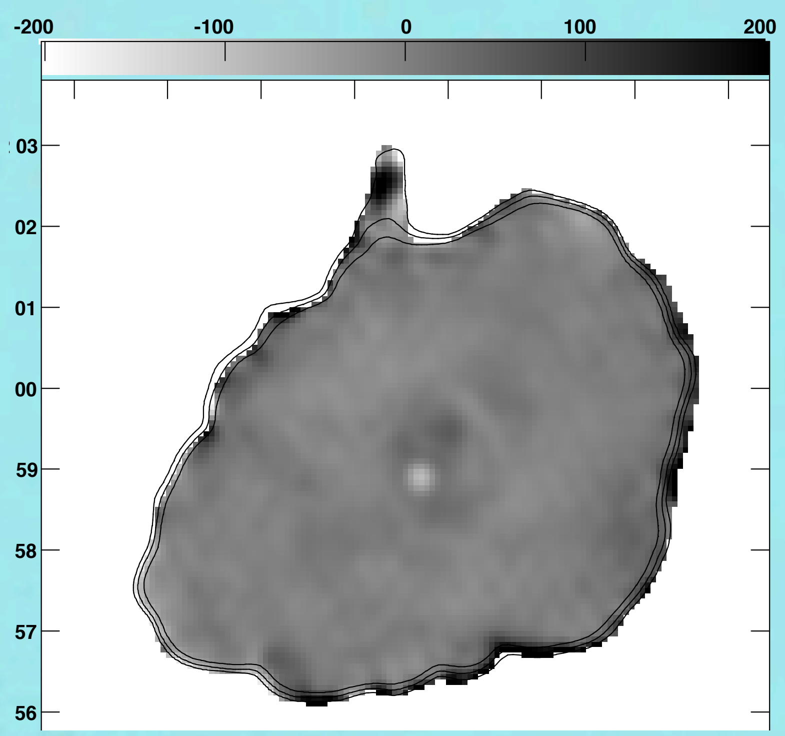


Aharonian+06A&A (γ-ray)

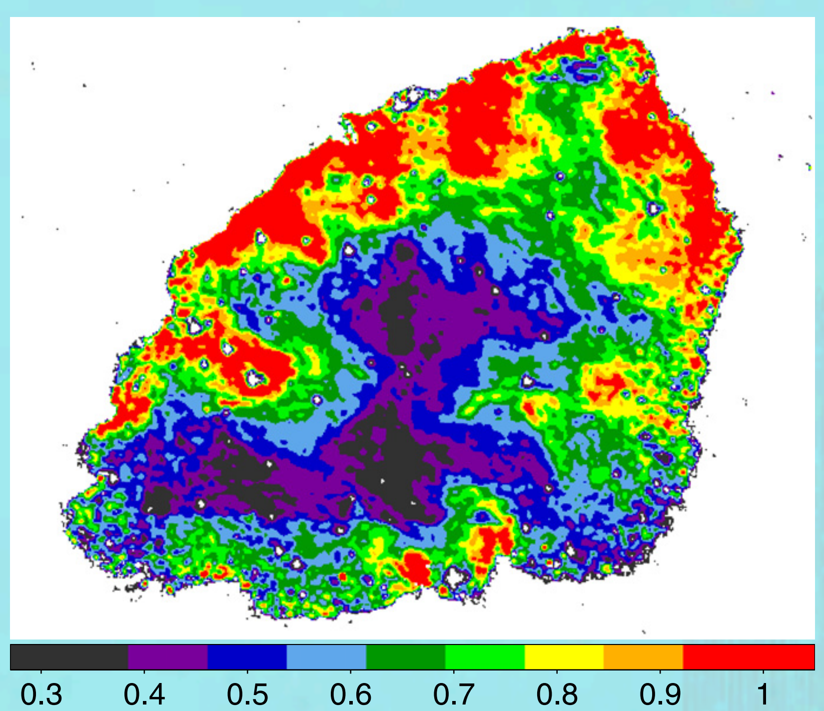


- Spectral index map in different frequencies of the Crab.

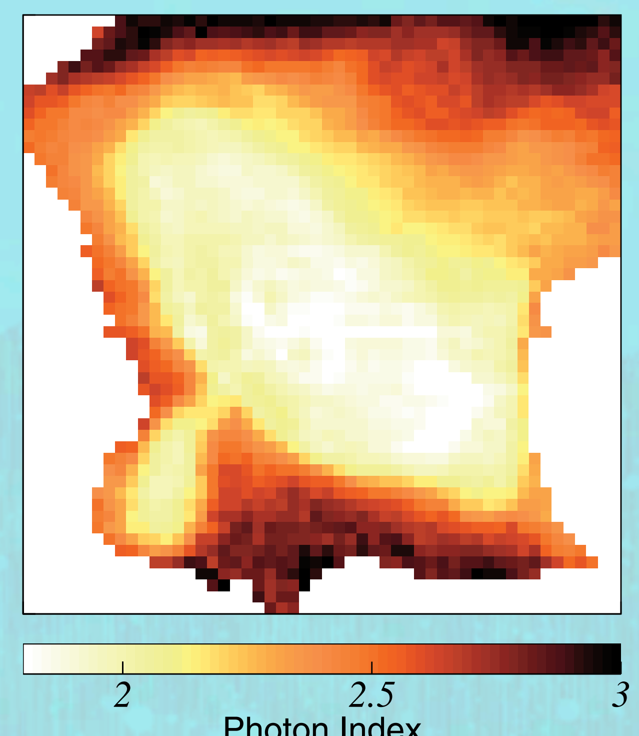
Bietenholz+97ApJ (radio)



Temim+12ApJ (IR)



Mori+04ApJ (X-ray)



PWN emission reflects B-field & particle distribution of PWN

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Motivation

What do we learn from observations of the Crab Nebula?

PSR & PWN properties

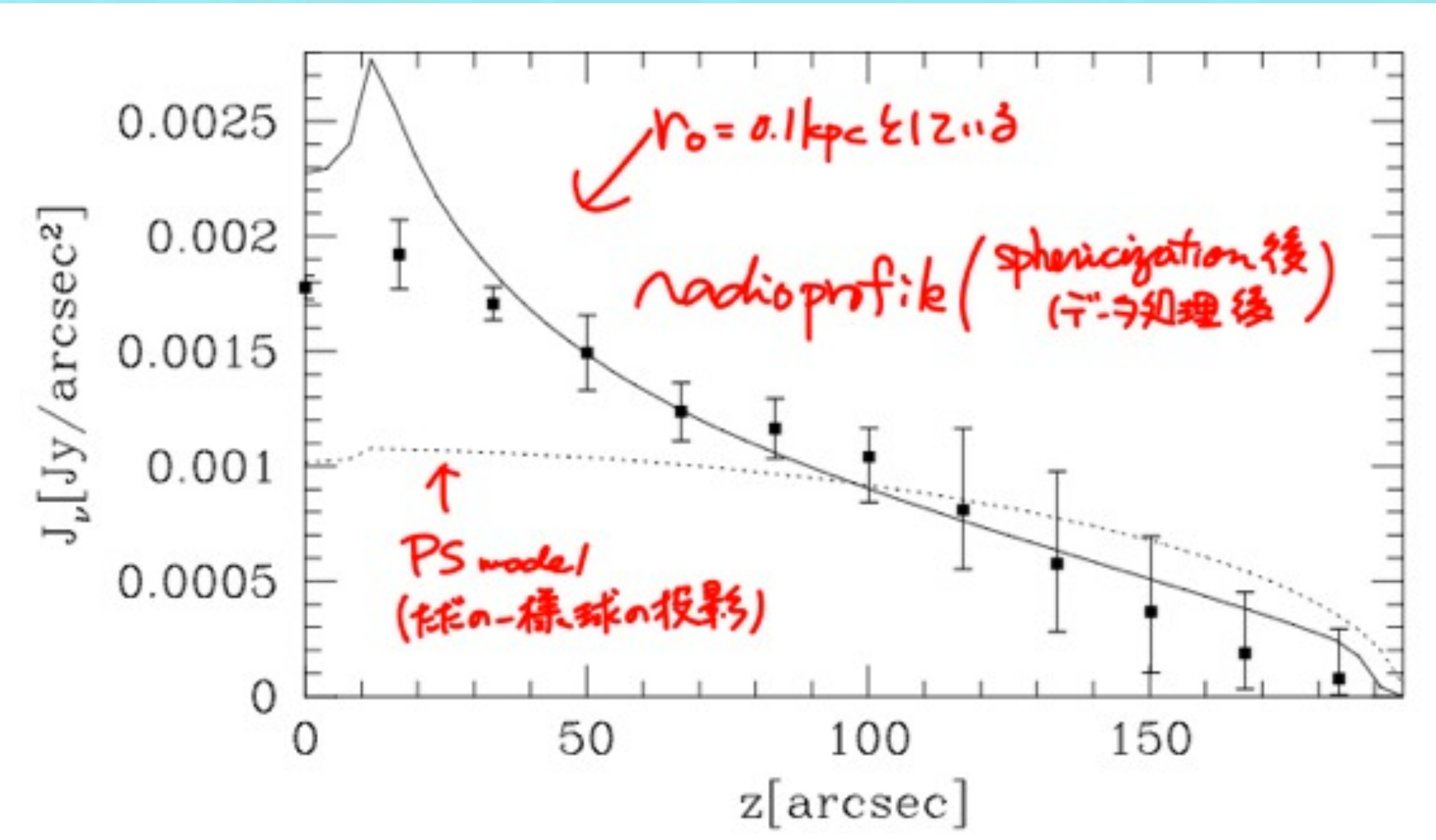
- Magnetization of pulsar wind. → σ-problem
- Injection spectrum of particles. → κ-problem & particle acceleration
- $e^{\pm}$ escaping process from PWN. → PAMELA anomaly

Physics

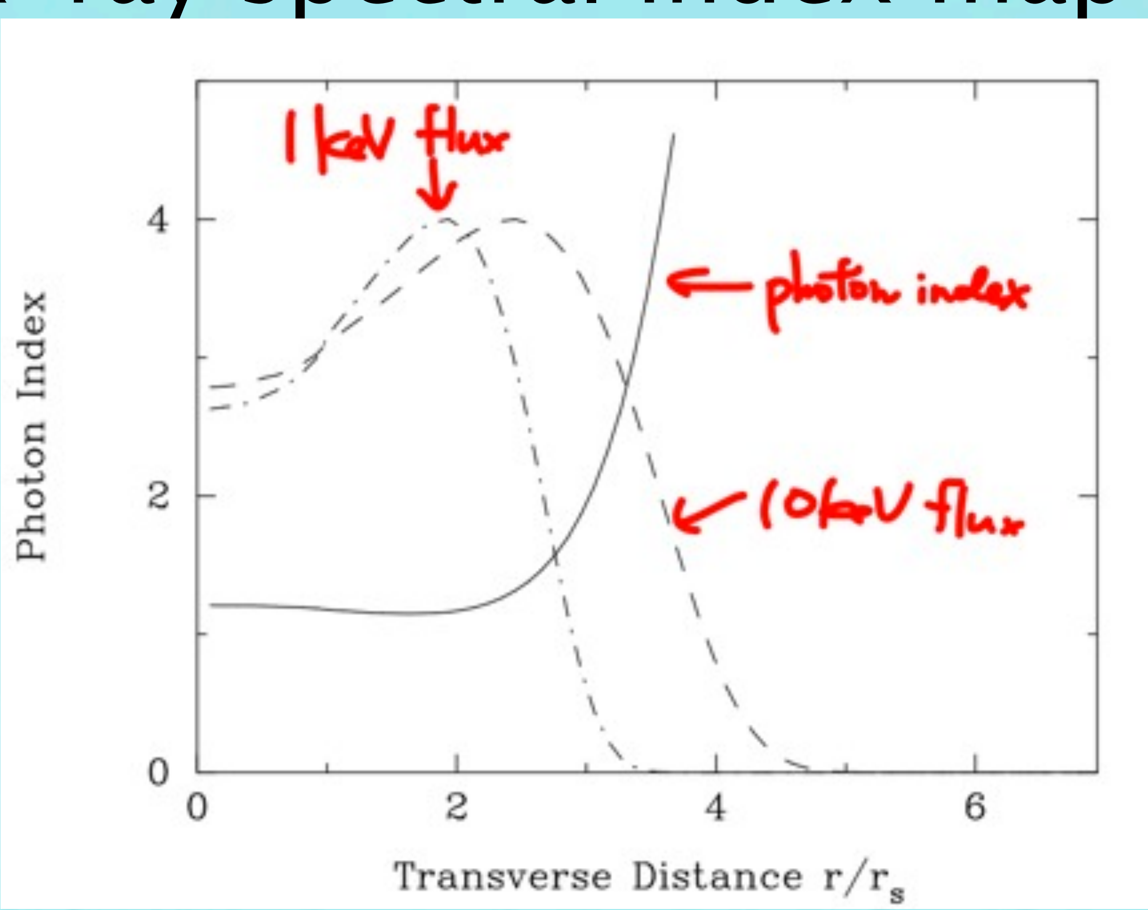
- Particle transport mechanism inside PWN. → advection? diffusion?
- Particle acceleration process inside PWN. → second-order acceleration?
- Expansion of PWN. → Interaction between PWN & SNR at outer boundary.

Past Studies

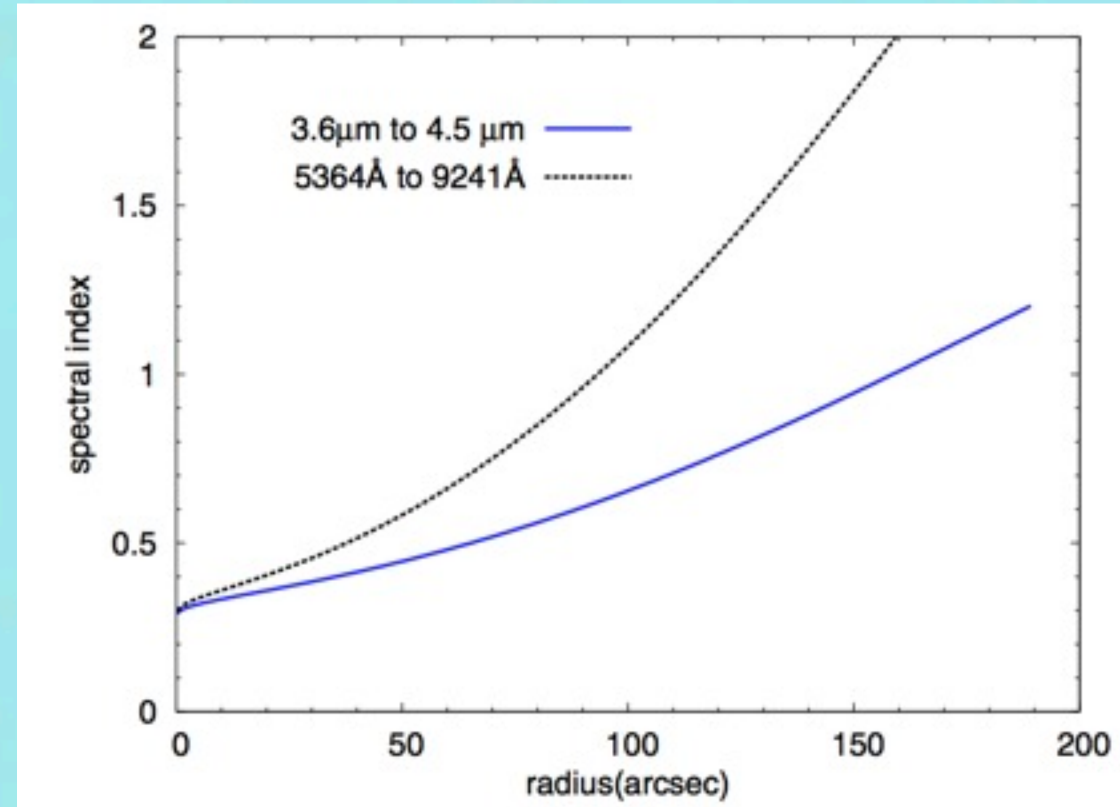
Amato+00, advection only
Radio brightness map



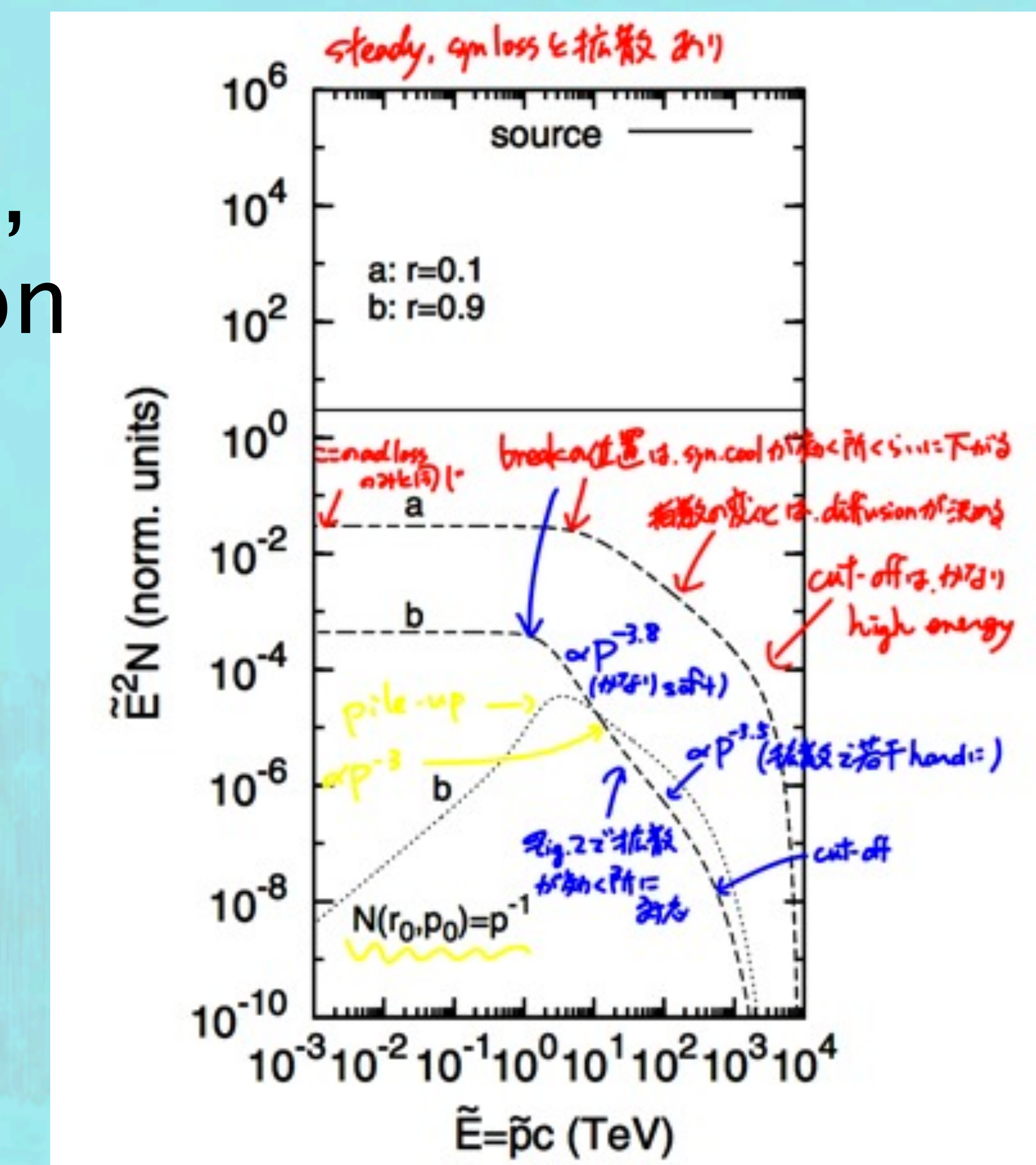
Reynolds03, advection only
X-ray spectral index map



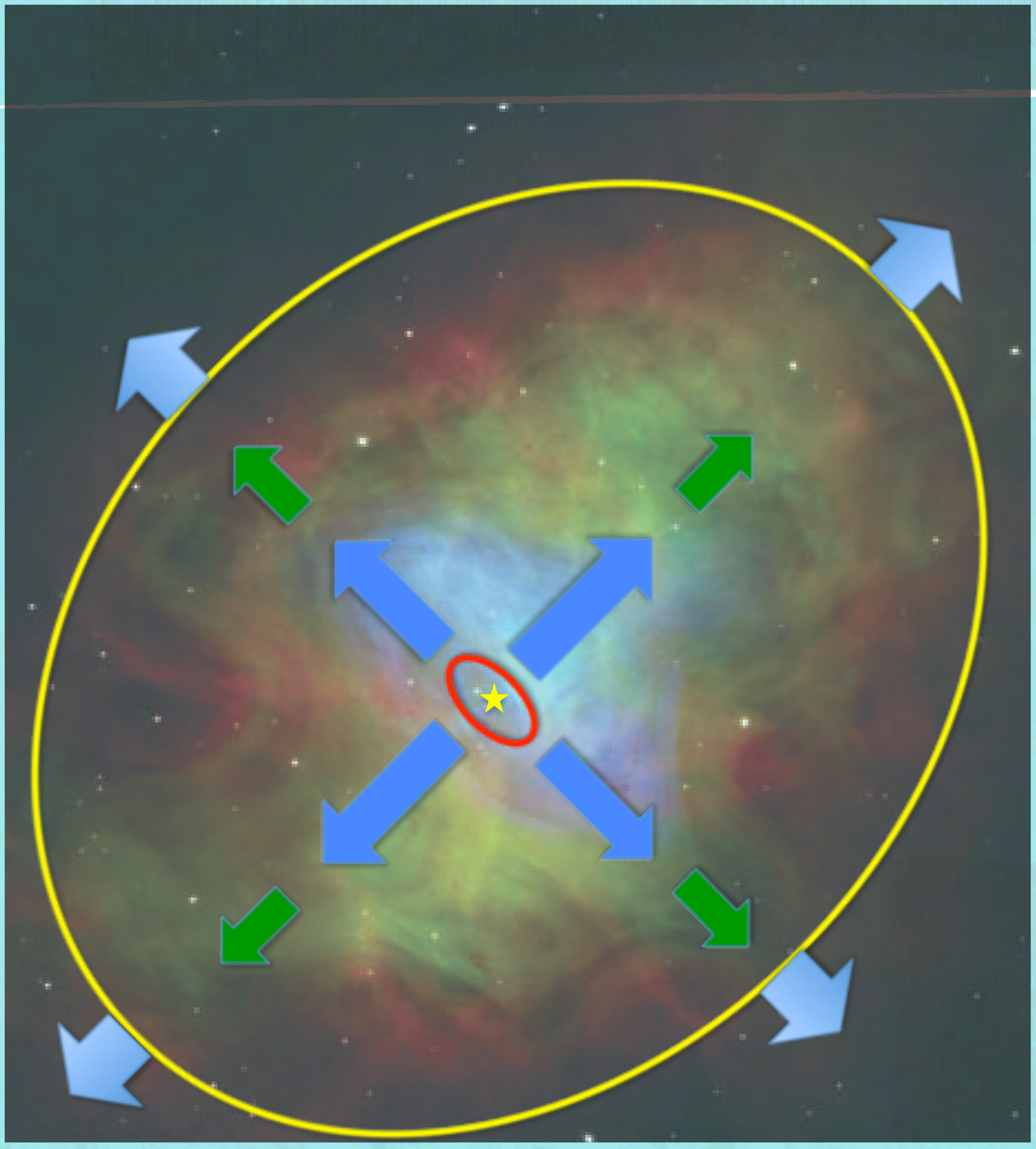
Tang & Chevalier12, diffusion
optical spectral index map



Vorstar & Moraal13,
diffusion & advection
particle spectrum



1D - Model



Dynamics

- **radial expansion**

$$\boldsymbol{v}(r) = v_0 \left(\frac{r}{r_0}\right)^{-\alpha_v} \boldsymbol{e}_r$$

- **toroidal B-field**

$$\boldsymbol{B}(r, t_{\mathrm{inj}}) = B(t_{\mathrm{inj}}) \left(\frac{r}{r_0}\right)^{-\alpha_B} \boldsymbol{e}_\varphi$$

- **induction equation (MHD condition)**

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

- **parameters**

inner radius: r0
inner velocity: v0
vel. profile index: αv
injection B-field: Binj

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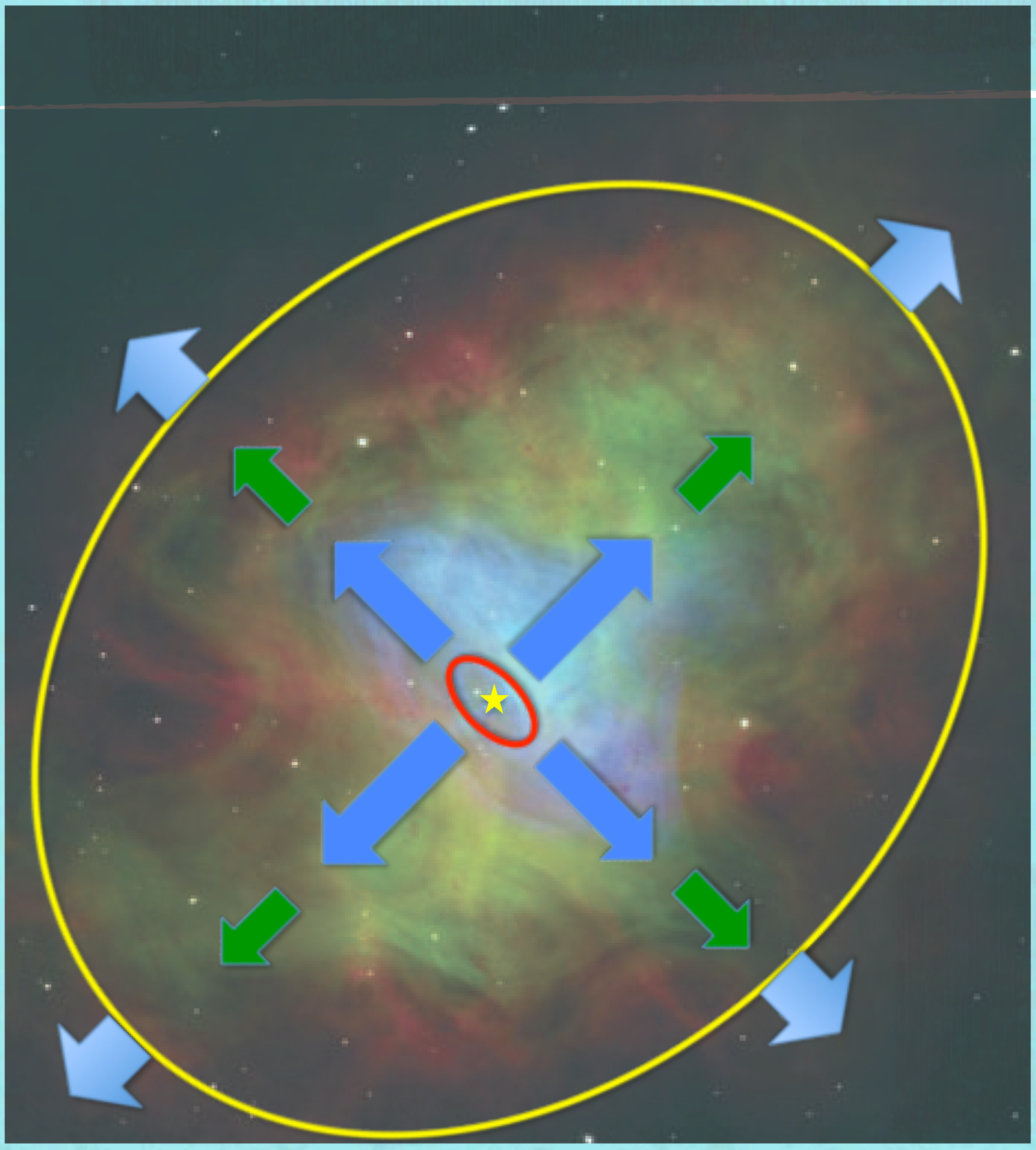
1D - Model



Particle Spectrum

- **diffusion & convection transport**

  + adiabatic & radiative cooling

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

- **diffusion coefficient**

$$K = \frac{1}{3}\xi c r_{\rm gyro}$$

- **injection spectrum**

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

- **parameters**

  diffusion coefficient: ξ

  injection paramters: p1, p2, γmin, γmax, γb

Mimicking 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,
   $R_{PWN} = 2.0$pc, $V_{PWN} = 1.500$km/s @ $t_{age} = 1$kyr
   ($r0 = 0.1$pc & $v0 = c/3$ are too much.)

3. injected B-field or magnetization σ
   $B0 = 300\mu G$

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

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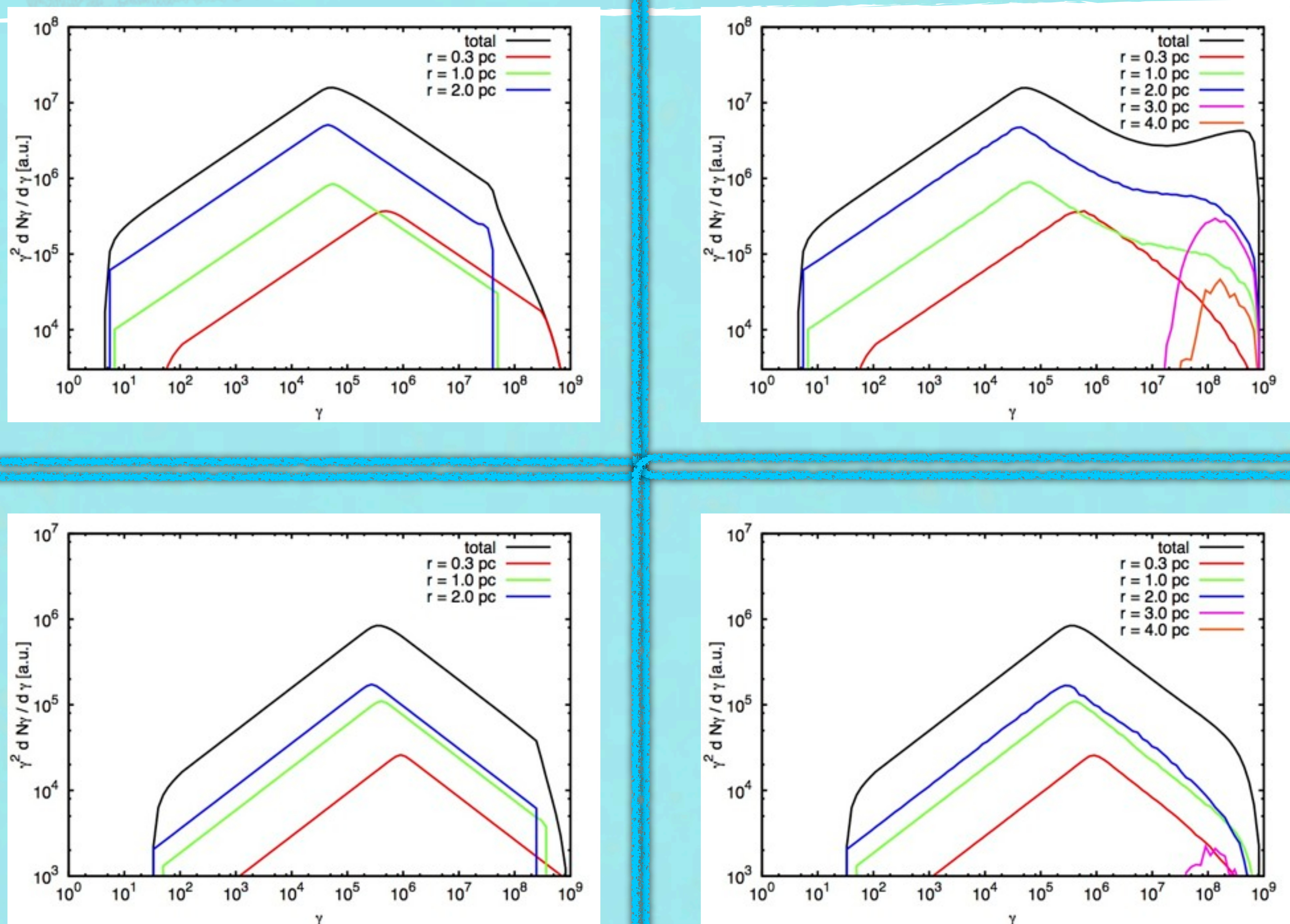


1. strong adiabatic cooling for r_0 = 0.007pc.

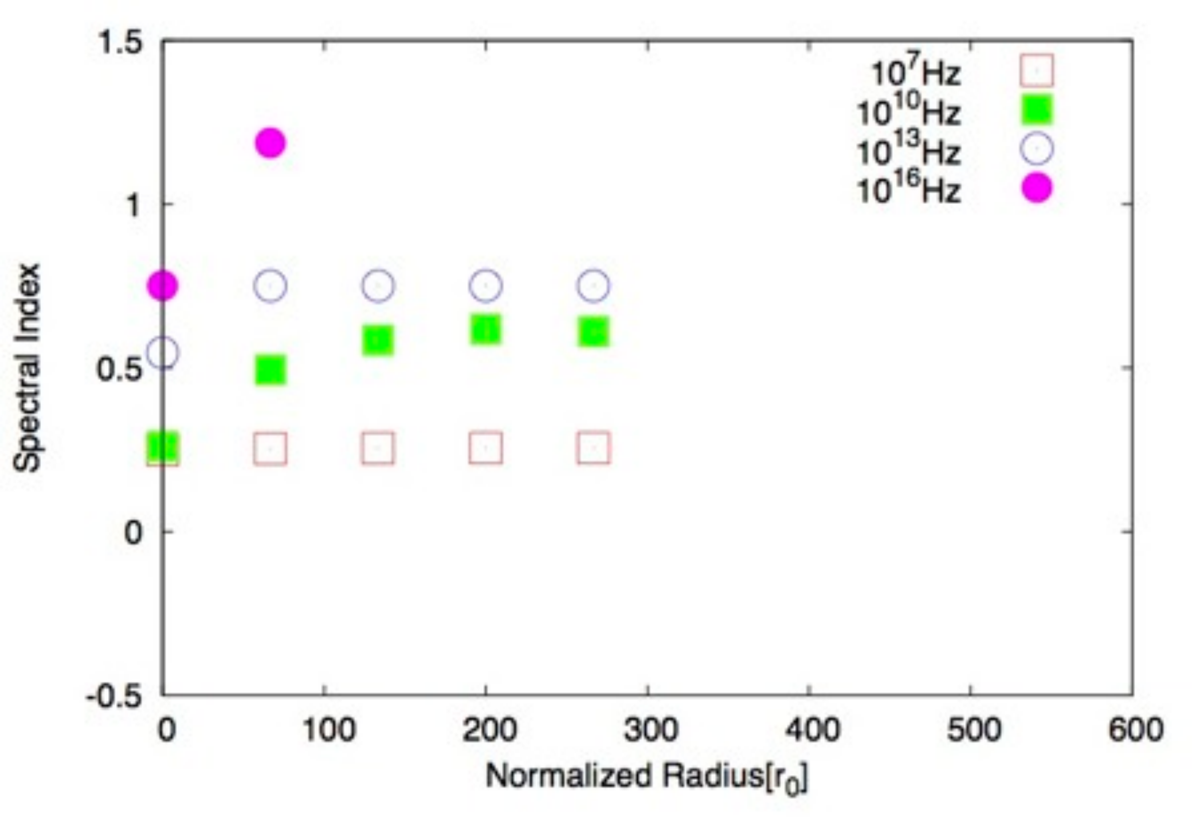
2. When ξ is non-zero, $e^{\pm}$ can escape from PWN (r >> R_{PWN}).

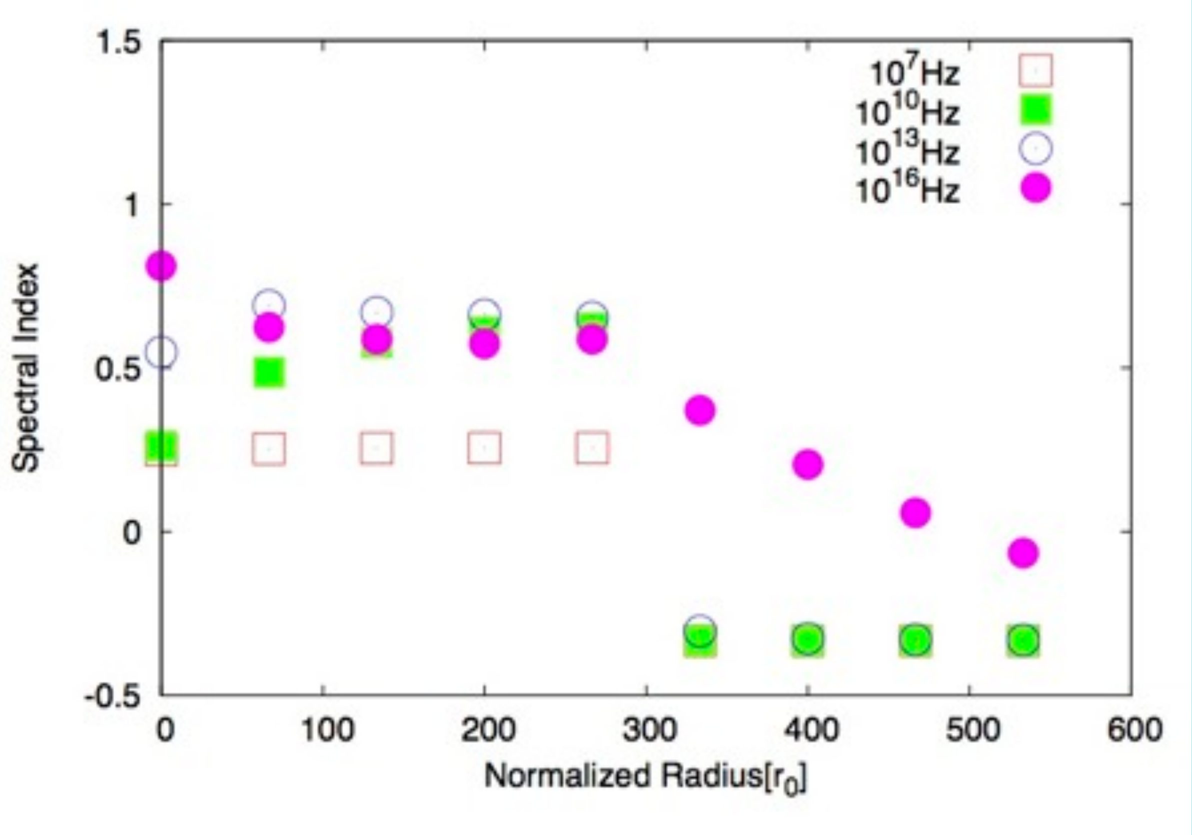
3. Escaped high energy $e^{\pm}$ are cooled slowly.

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

[r_0 = 0.007pc, i.e., R_{PWN} ~ 300r_0]





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 at10^{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.

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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 ($\alpha > 2$).