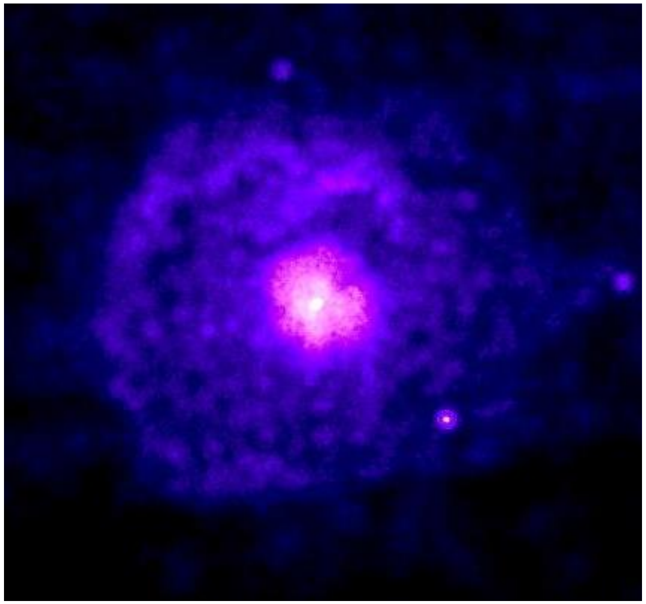
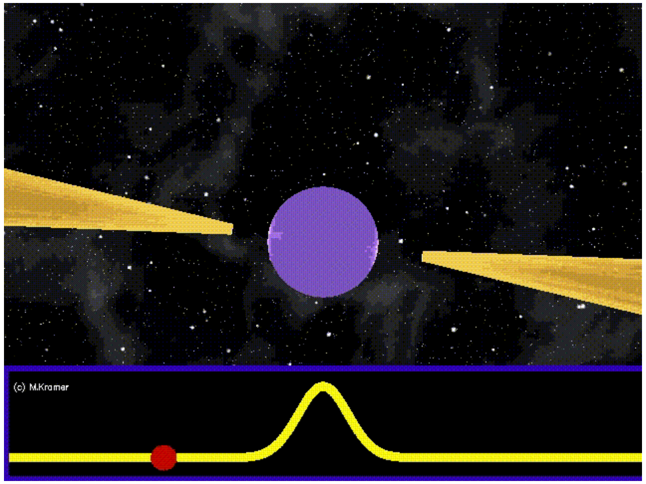
# Broadband spectrum and surface brightness of pulsar wind nebulae with 1D steady modeling




Wataru Ishizaki

Yukawa Institute for Theoretical Physics (YITP)

# Introduction –Rotation Powered Pulsar-

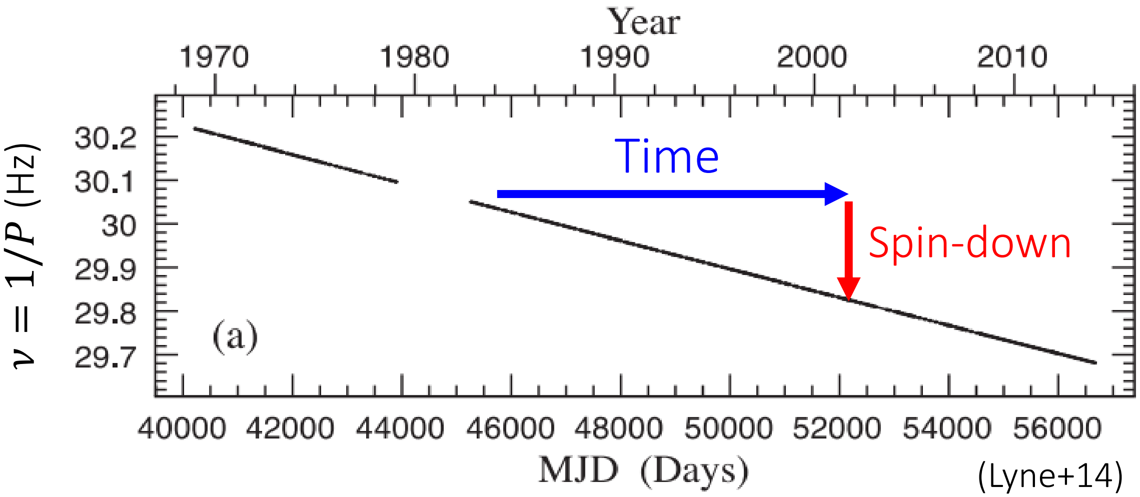



(Credit: Michael Kramer)

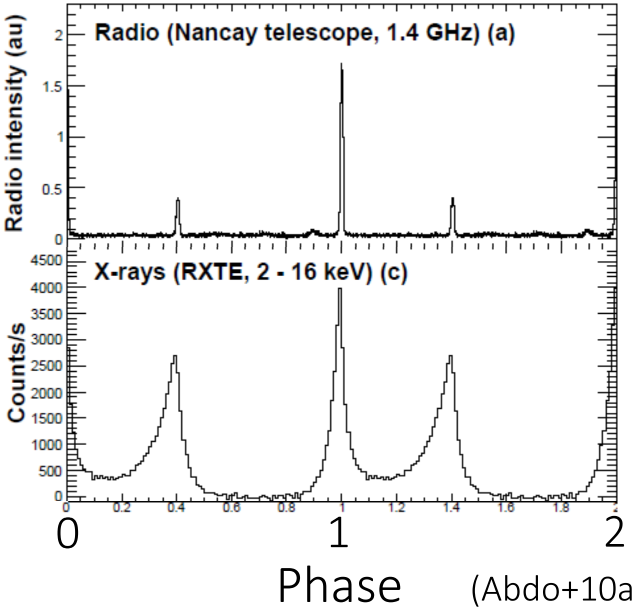
- Rotation-powered pulsar
  - Energy source : rotation energy
  - Spin period : $P \sim 10^{-3} - 10\ s$
  - Spin-down with time : $\dot{P} \sim 10^{-(12-13)} s s^{-1}$
  - Magnetic braking by strong $B \sim 10^{12}$G
  - Energy loss rate (Spin-down luminosity)

$\rightarrow$ $L_{\rm sd} \sim 5 \times 10^{38}$ erg s$^{-1}$ $\left(\frac{P}{33\ \rm ms}\right)^{-3} \left(\frac{\dot{P}}{4.21\times10^{-13}}\right)$ (Crab pulsar)

- eg. Crab pulsar



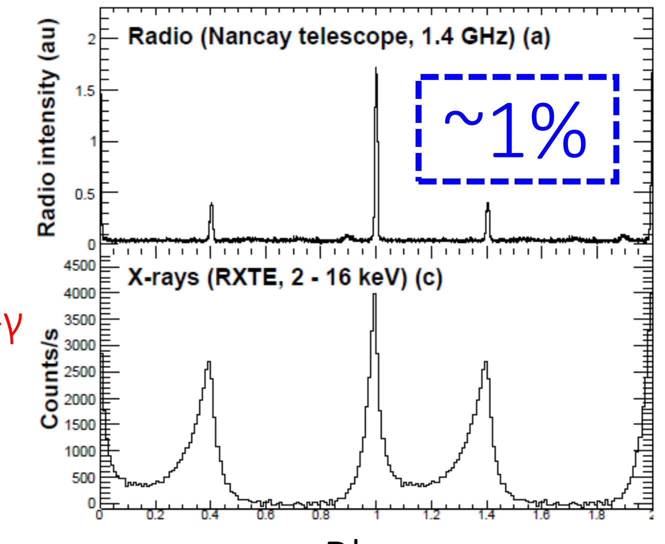

(Lyne+14)

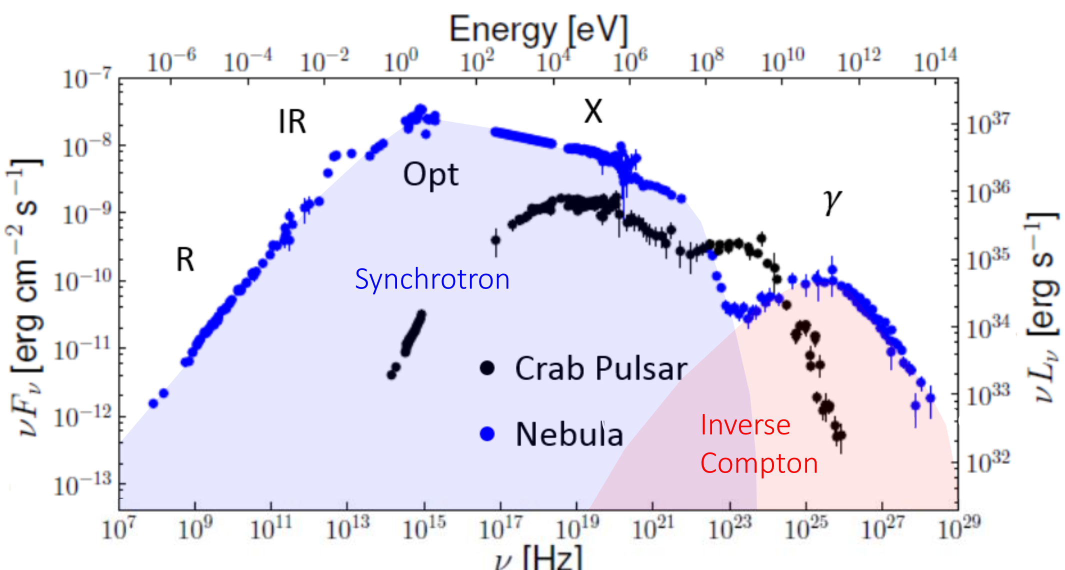



(Abdo+10a)

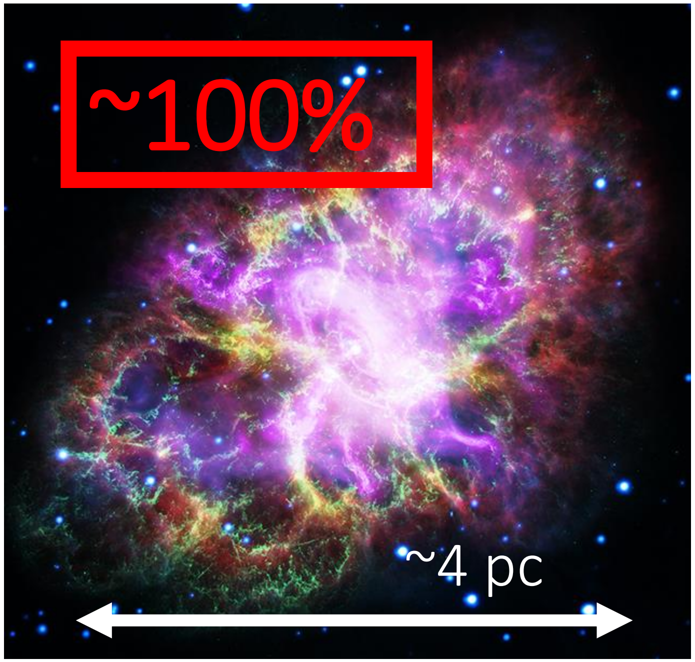
# Introduction –Pulsar Wind Nebulae-

- Pulsar Wind Nebulae (PWNe)
  - Extended source around a rotation powered pulsar
  - Broadband non-thermal spectrum from radio to TeV-γ
- Spin-down Luminosity
  - Pulse emission : $\sim 1\% \times L_{sd} \ll L_{sd}$
  - PWNe (emission+expansion) : $\sim\ L_{sd}$
  - Most of $L_{sd}$ is injected to PWN



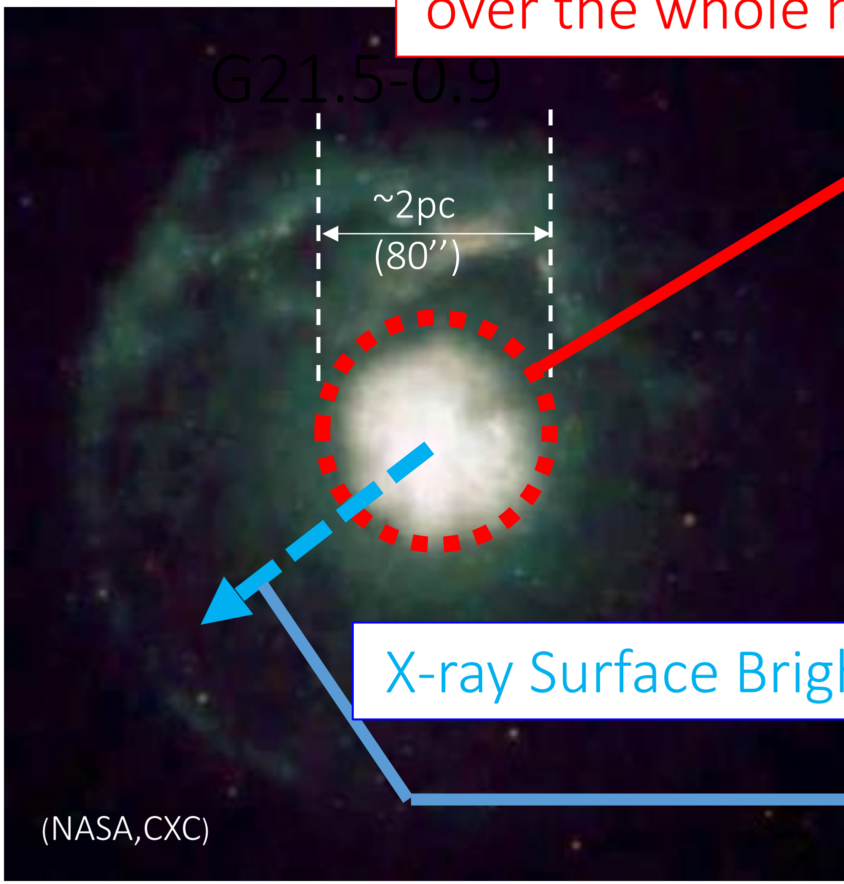




(Buhler & Blandford , 2014)

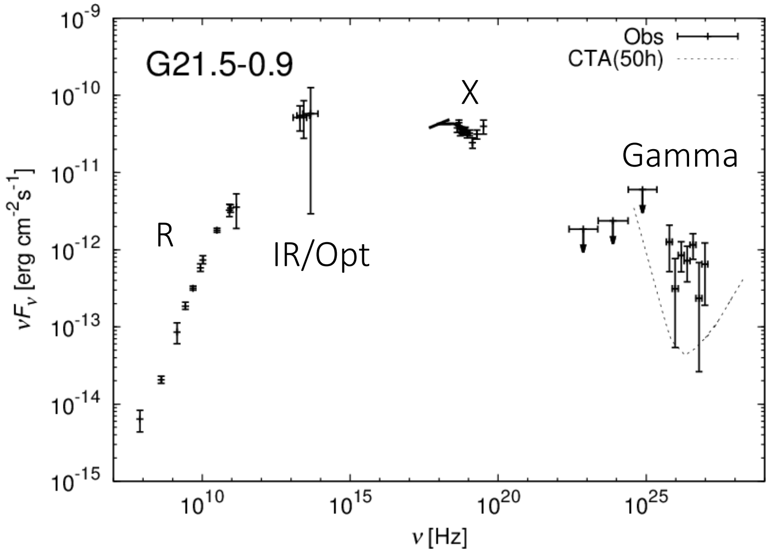


# Observed Quantities

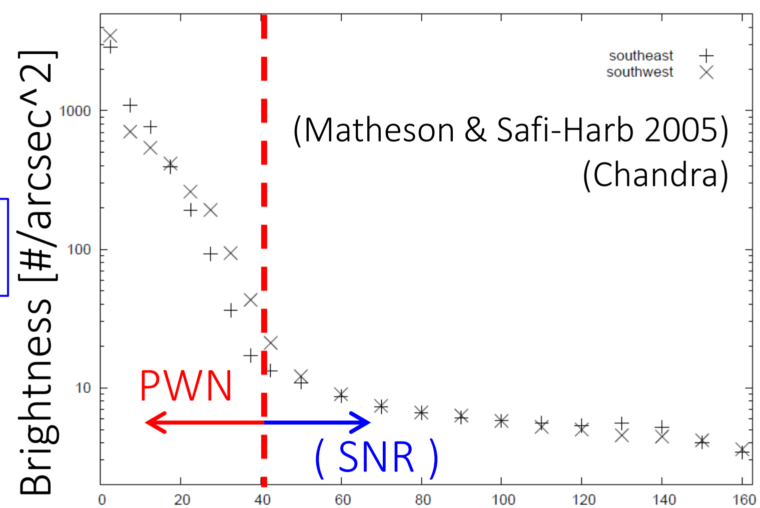
- eg. G21.5-0.9




Spectrum integrated over the whole nebula



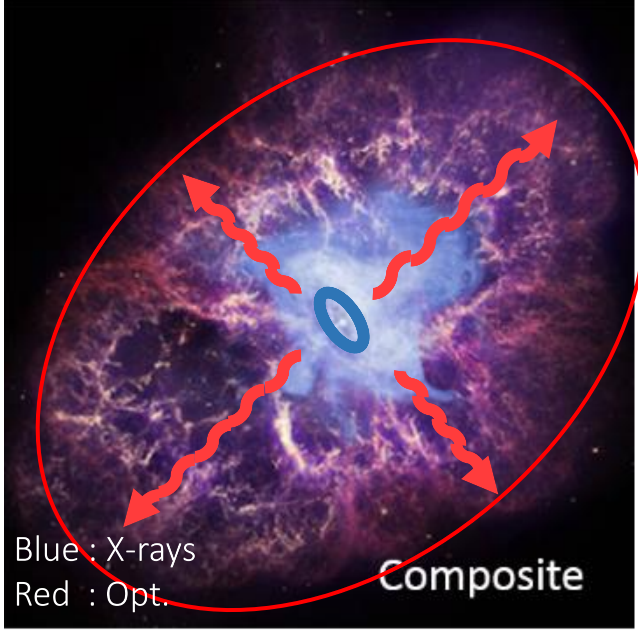

X-ray Surface Brightness



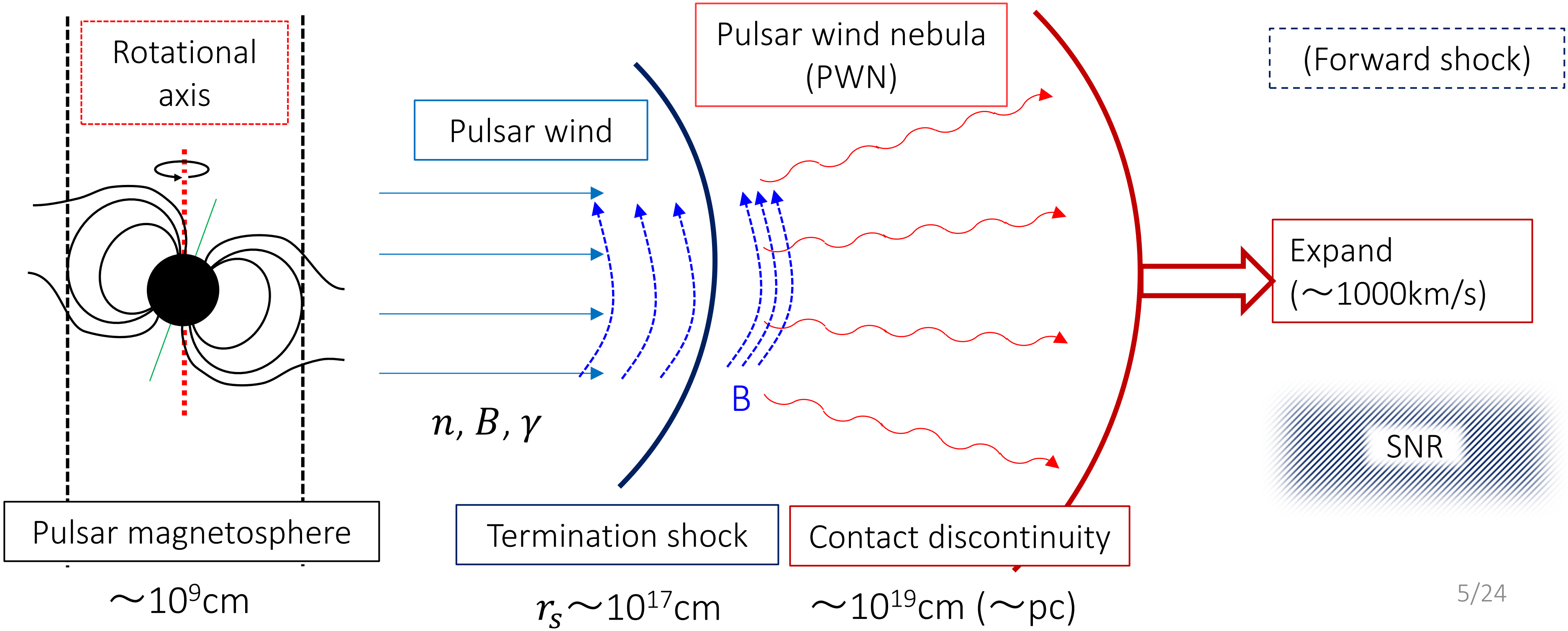

Most simplified spatial model → 1D model!

# "Standard model" of PWNe

- 1D-steady model ; Rees & Gunn (1974), Kennel & Coroniti (1984)
  - Assuming a radial flow and a troidal field.
  - Non-thermal $e^{\pm}$ produced at termination shock $r_s$
  - Propagating in PWN with radiative cooling
  - Non-thermal $e^{\pm}$ only advect with flow

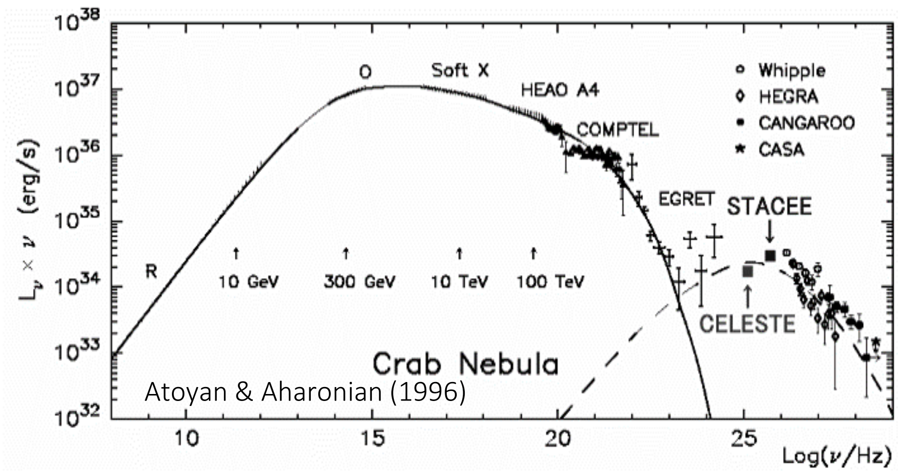



Well explains observed property of the Crab Nebula

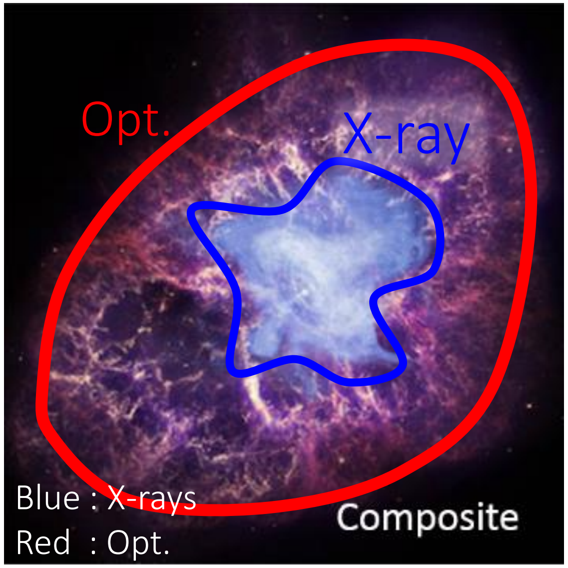


# What KC model explains

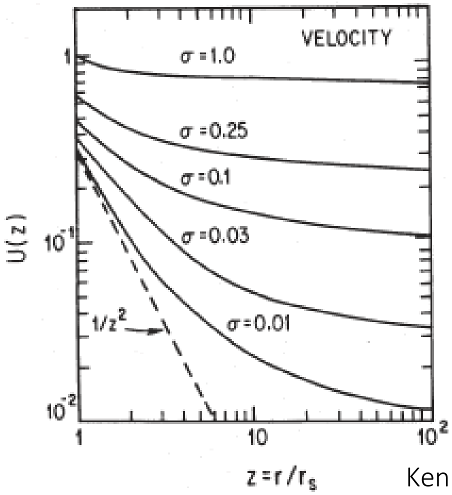
- SED (Spectrum of the whole nebula)




- Energy dependent morphology




- Deceleration of the flow




Kennel & Coroniti (1984)

@shock : ~c/3

@edge : ~1000 km/s

Q. How decelerates ?

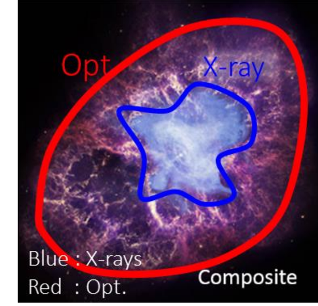
A. Low sigma flow

KC model can explain these properties

→ KC model was accepted as a standard model

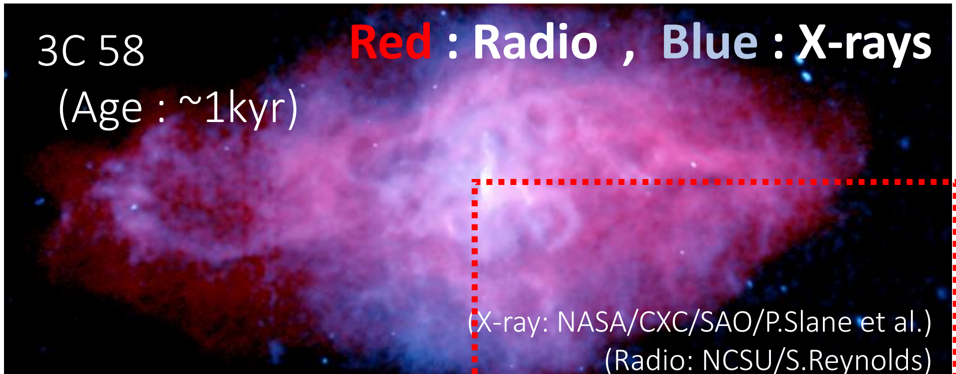
**However,** such a test has performed for the Crab Nebula **ONLY**.

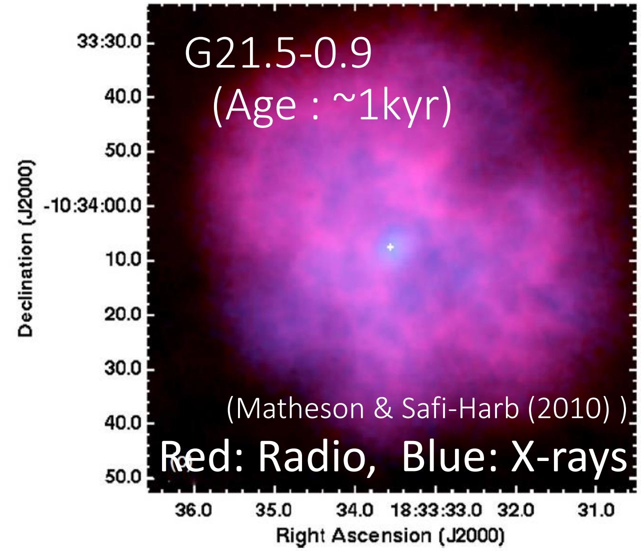
cf. the Crab Nebula

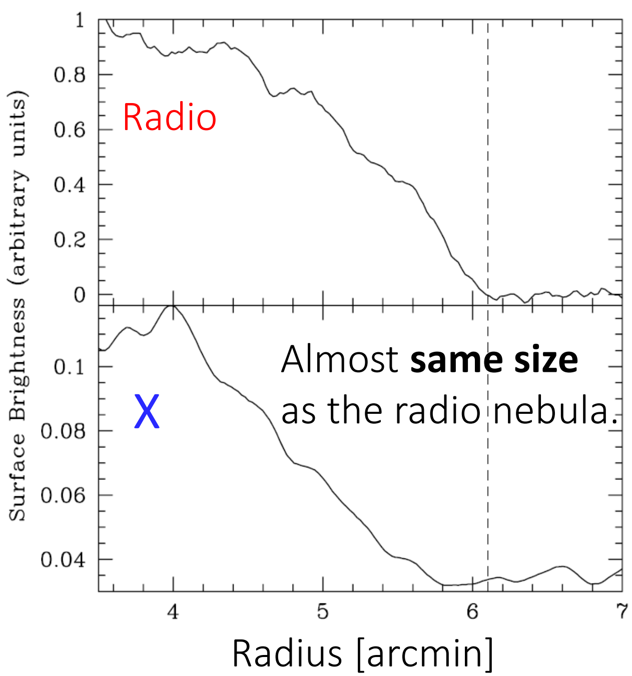



# 3C 58, G21.5-0.9

PWNe which show large extent of X-ray emission (**unlike** the Crab Nebula).




Q : Can these observation explain by KC model?

A : Lack of information.

It is necessary to calculate the SED and constraint the parameters.

Can KC model reproduce
SED & X-ray profile **simultaneously**?

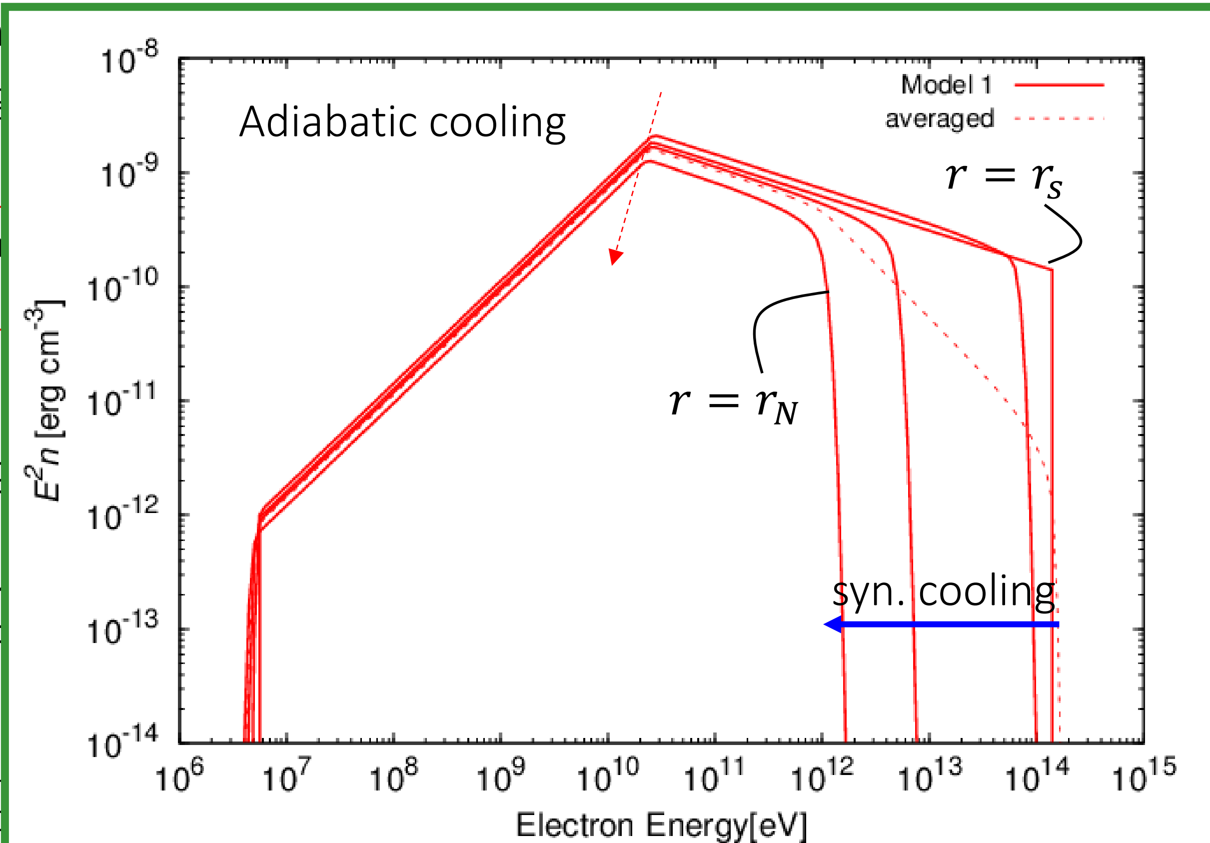
M

Flow solution given by MHD model

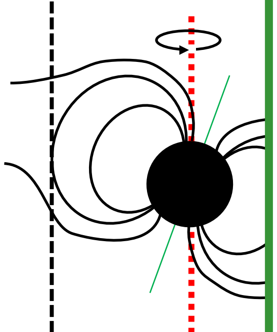
$$\frac{\partial n}{\partial t}^{\,0} + u\frac{\partial n}{\partial r} = \frac{\partial}{\partial E}\left(Q_{\rm syn}E^2 n\right) + \frac{\partial}{\partial E}\left(Q_{\rm IC}E^2 n\right) + \frac{\partial}{\partial E}\left(\frac{c}{3r^2}\frac{d}{dr}(ur^2)En\right) - \frac{c}{r^2}\frac{d}{dr}(ur^2)n$$

Time evolution | Syn. cooling | ICS cooling | Adiabatic cooling | Dilution

- S
  - Pulsar wind forms the shock structure ⇒Rankine-Hugoniot condition
  - Downstream flow is free streaming ⇒Steady MHD equation
  - Assum
  - Propag spectrum of $e^{\pm}$




Rotationa axis



(Forward shock)

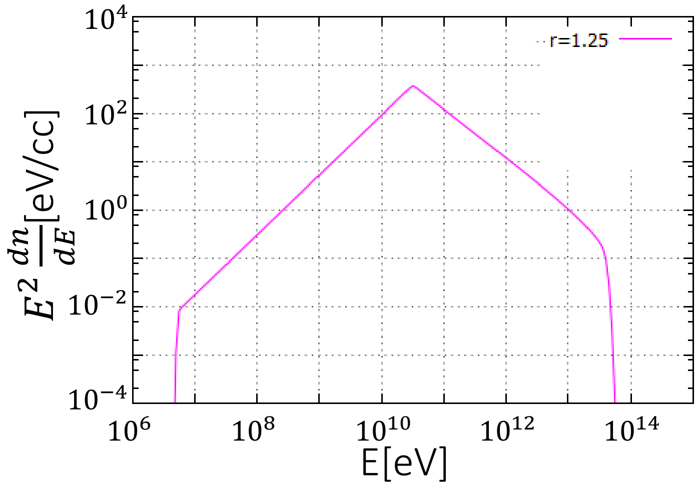
Expand (～1000km/s)


Pulsar magneto

～$10^9$cm $r_s$～$10^{17}$cm ～$10^{19}$cm (～pc)

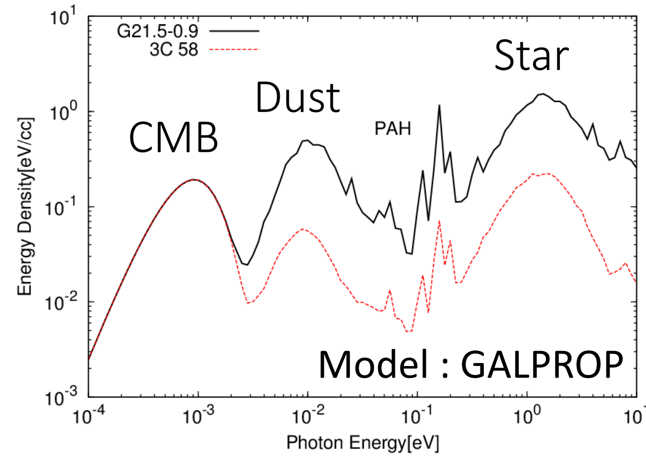
# Model –Emission-

- Particle spectrum at each radius

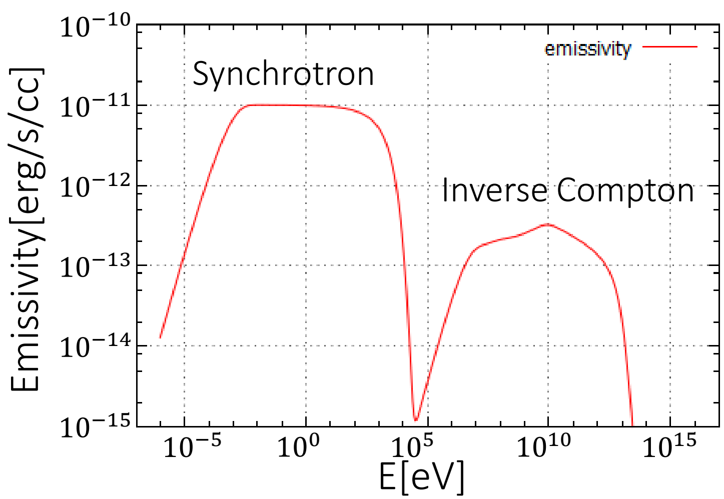


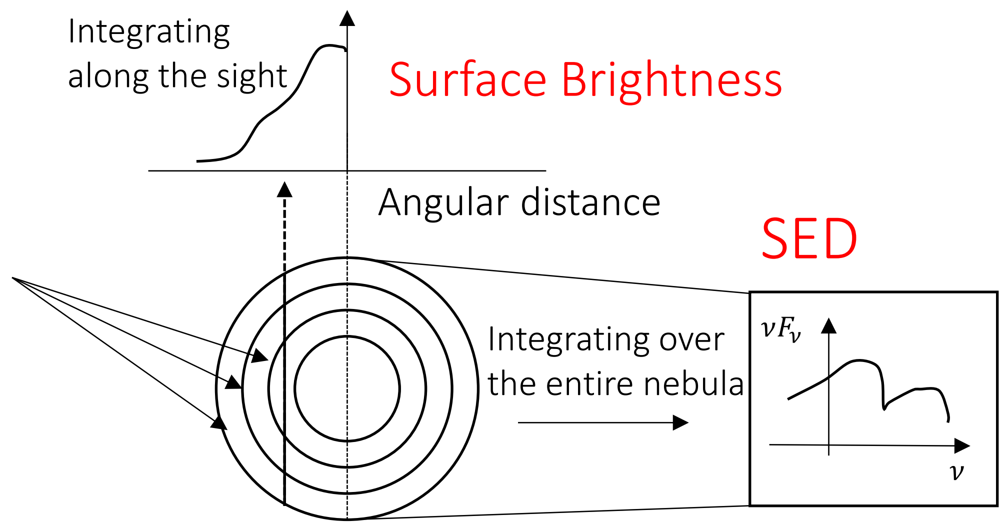

B(r) from MHD eqs. → Syn. emission

Target photon of ICS → IC emission




- Emissivity



# Test of KC model

See Ishizaki+17 (ApJ, arXiv: 1703.05763) for detail

- SED
- X-ray surface brightness
- X-ray photon index

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- SED : almost reproduced w/ KC model
  - Obtained the parameters almost uniquely
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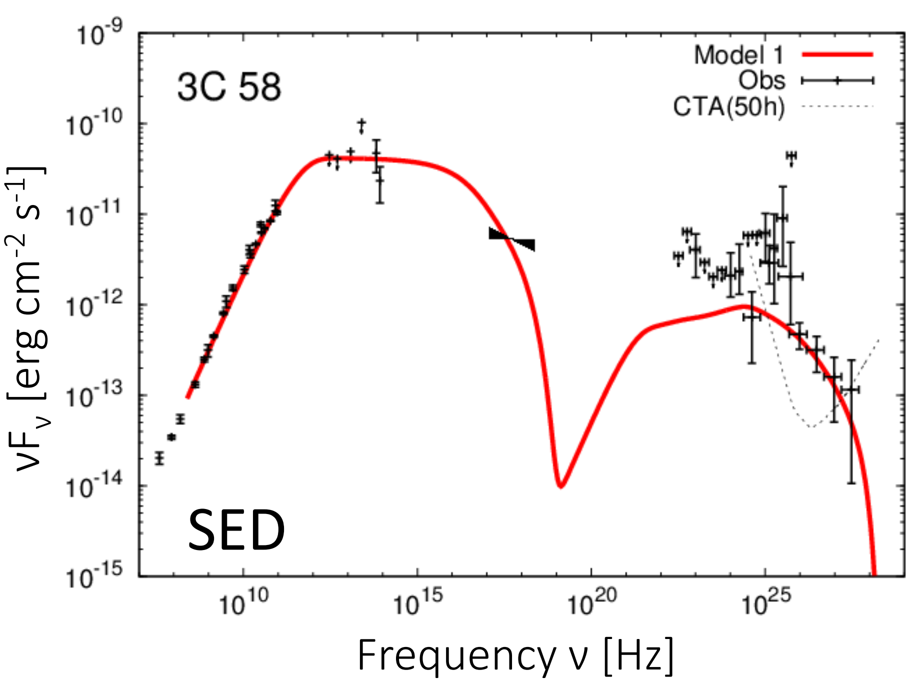


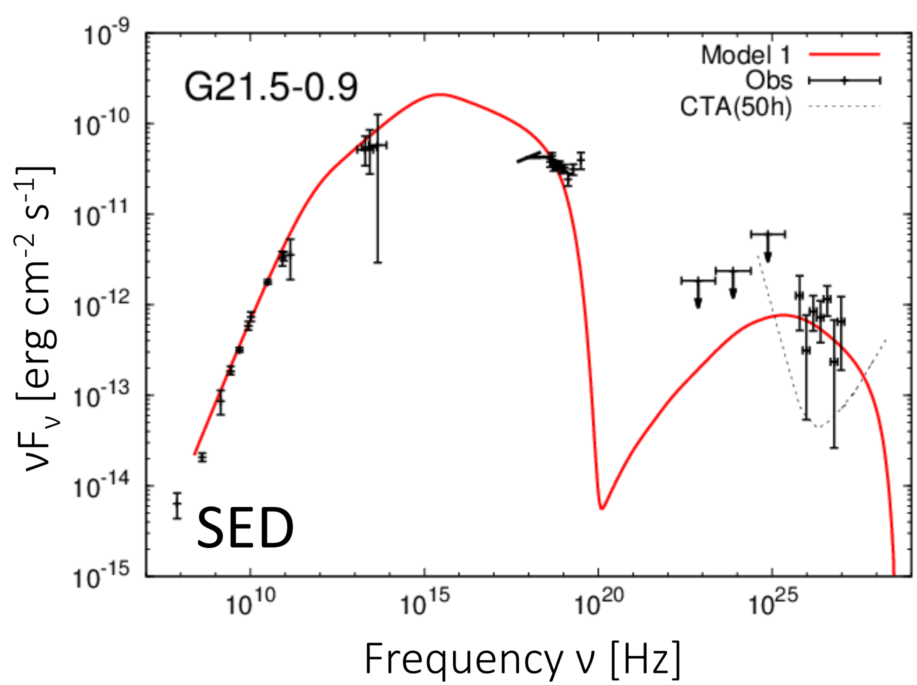

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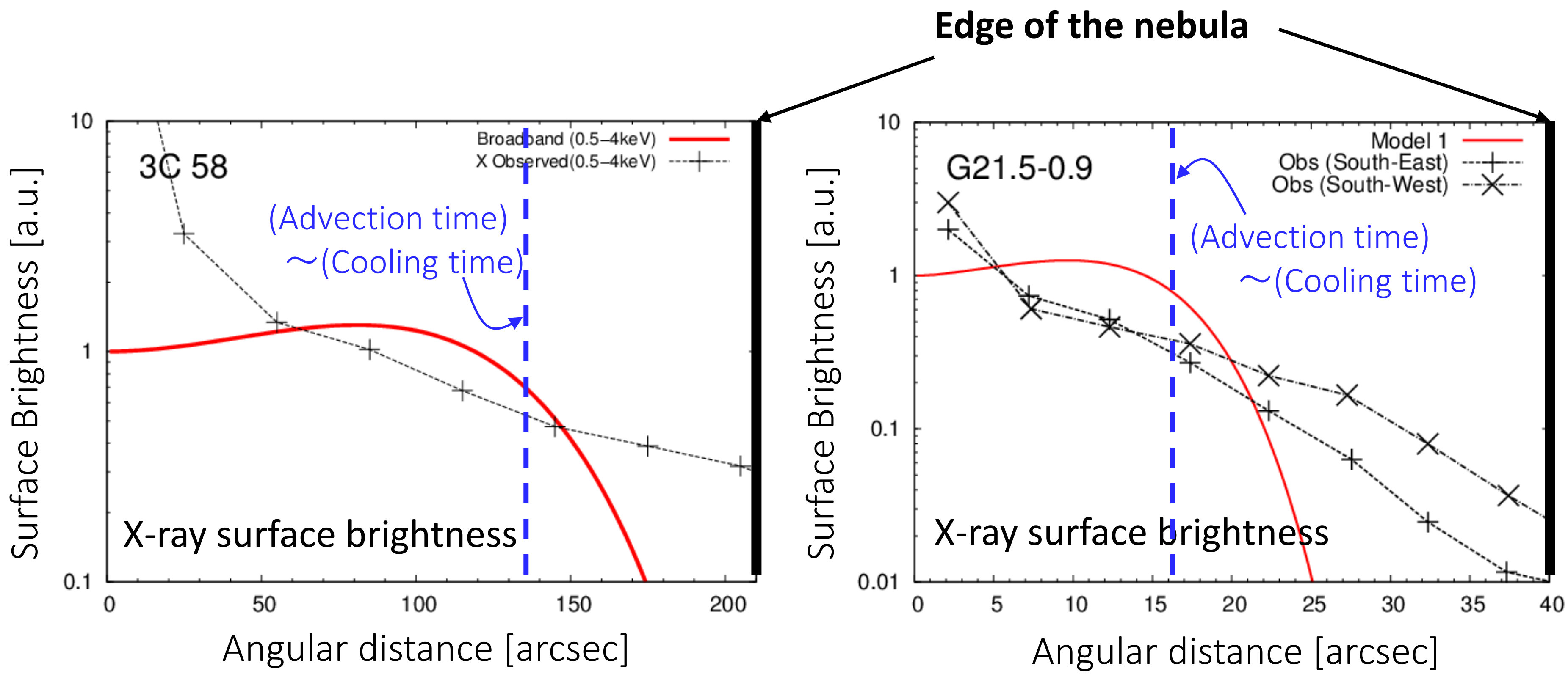
- X-ray surface brightness : NOT reach the edge
  - High energy $e^{\pm}$ exhaust their energy by emission.
- X-ray photon index



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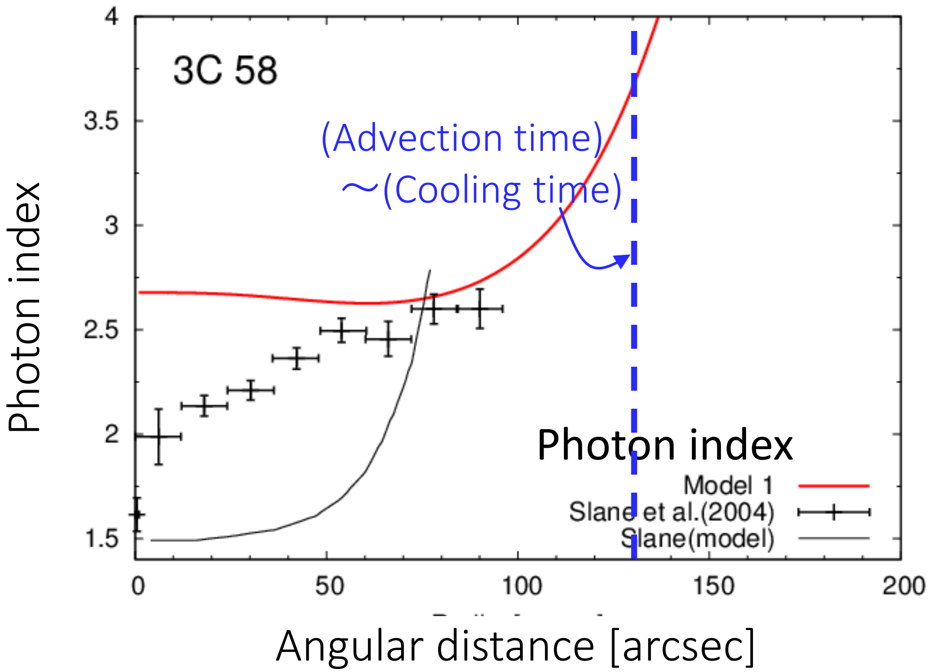


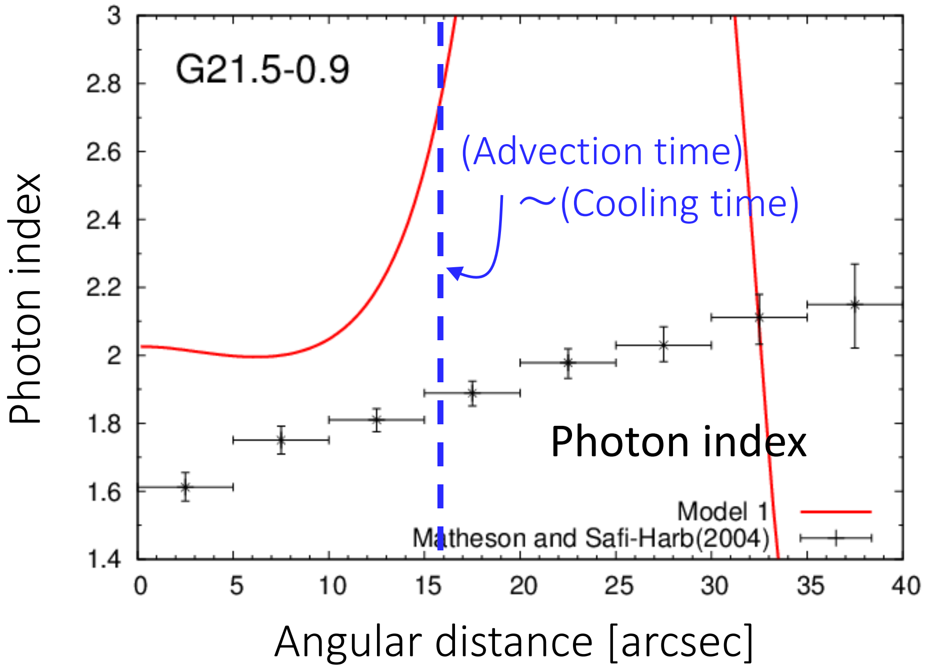

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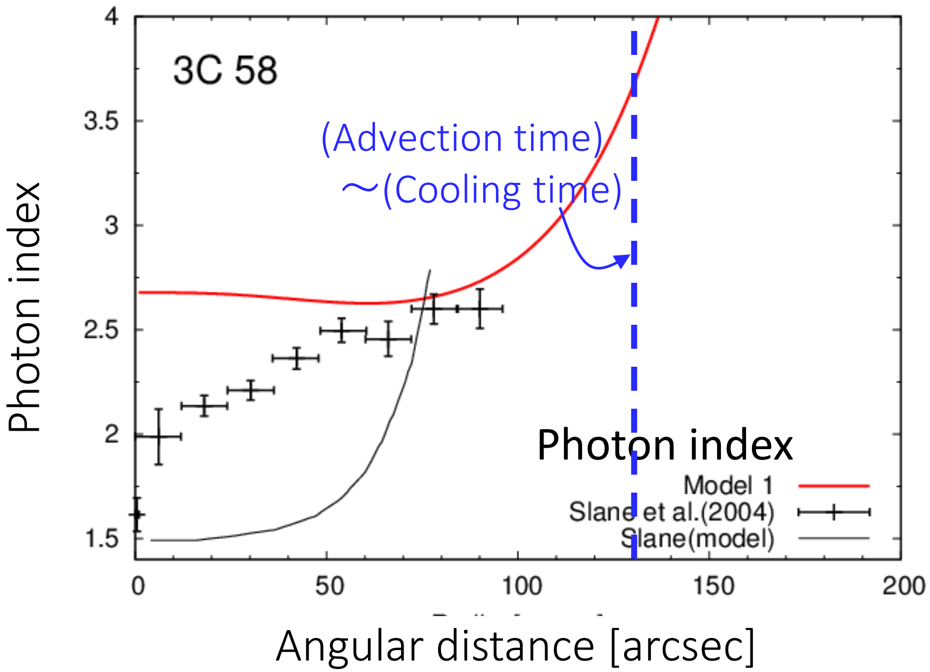


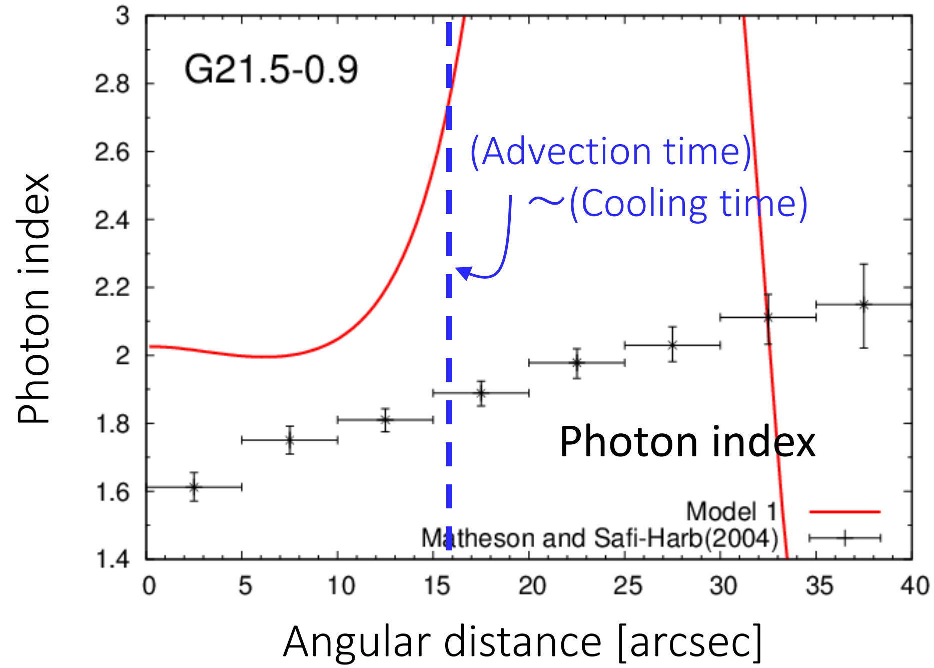

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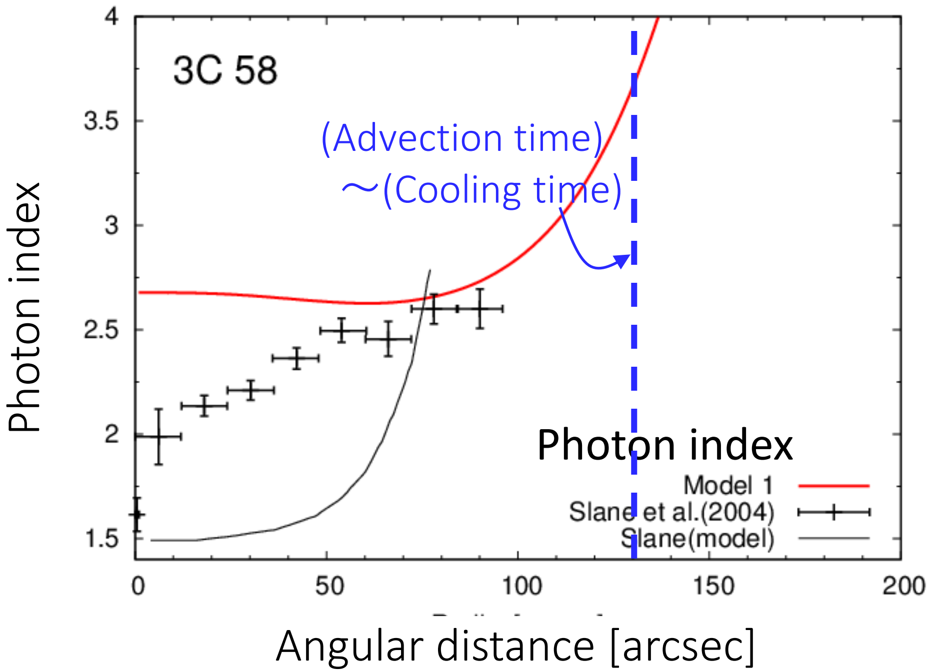
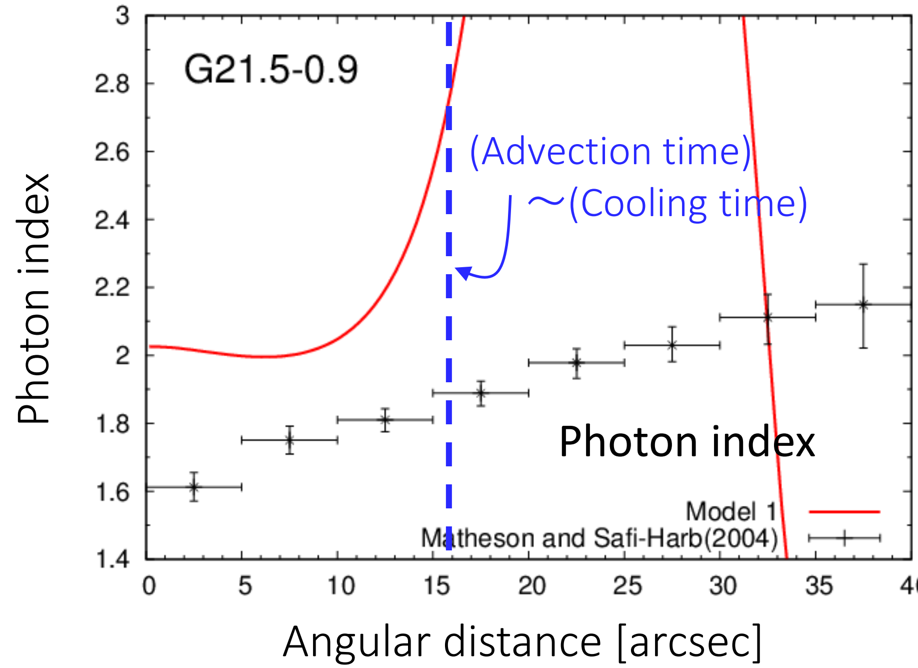
NG

KC model **CANNOT** reproduce SED and X-ray profile **simultaneously**!



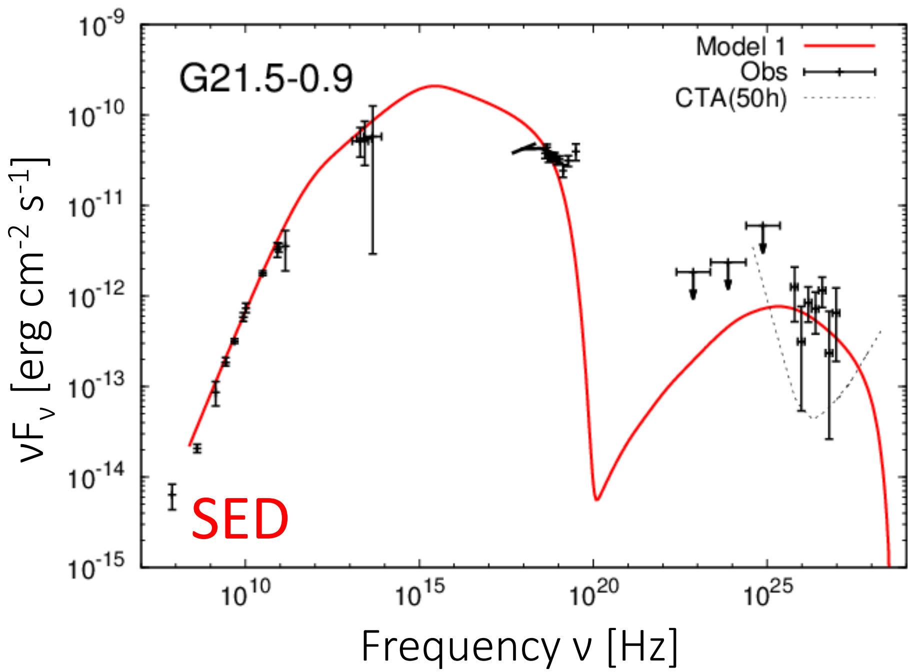
# Why cannot?

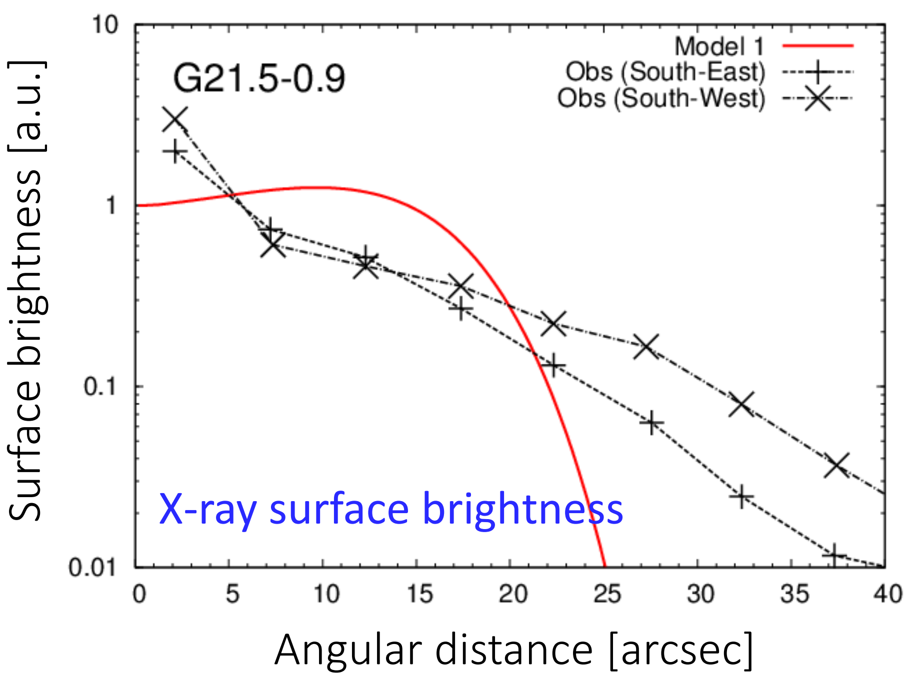
Why cannot?

“Magnetic Field to reproduce the SED” > “Magnetic field to reproduce the X-ray extent”

How do we do?

B-field to reproduce SED : determined from the flux ratio of synchrotron and ICS.



# Why cannot?

Determined by the balance of cooling and advection time

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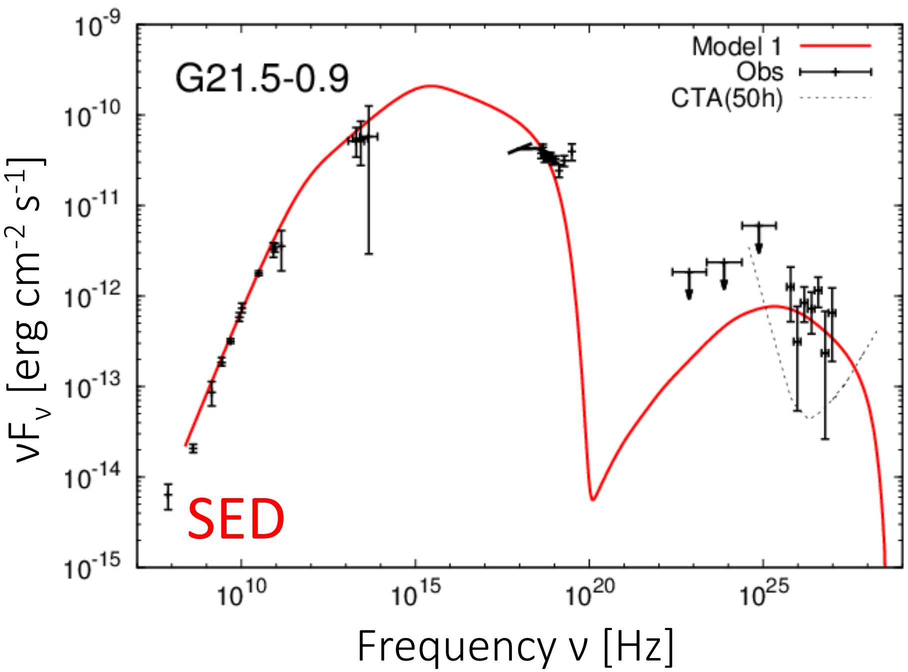


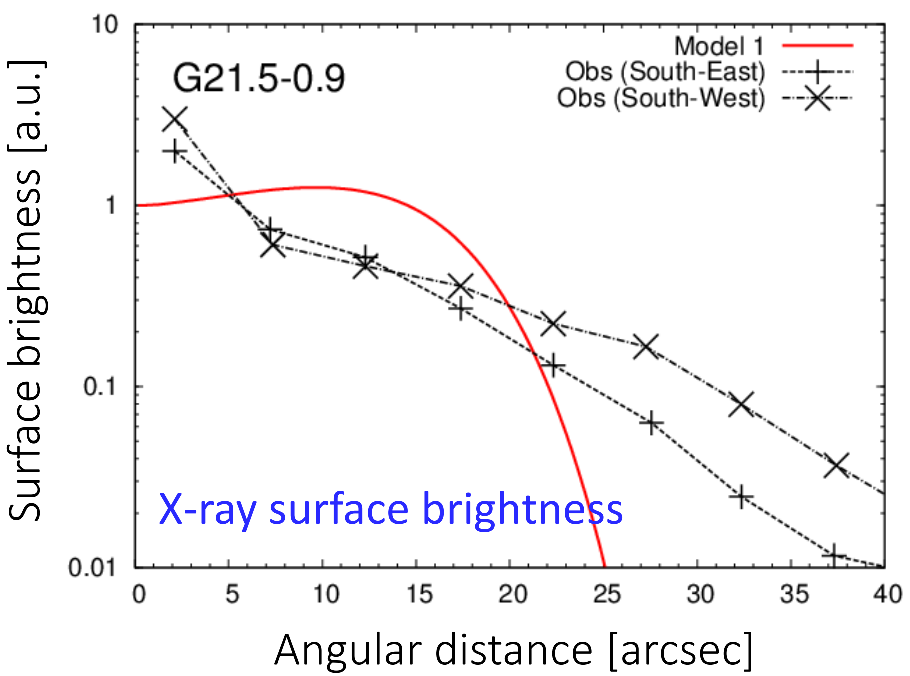

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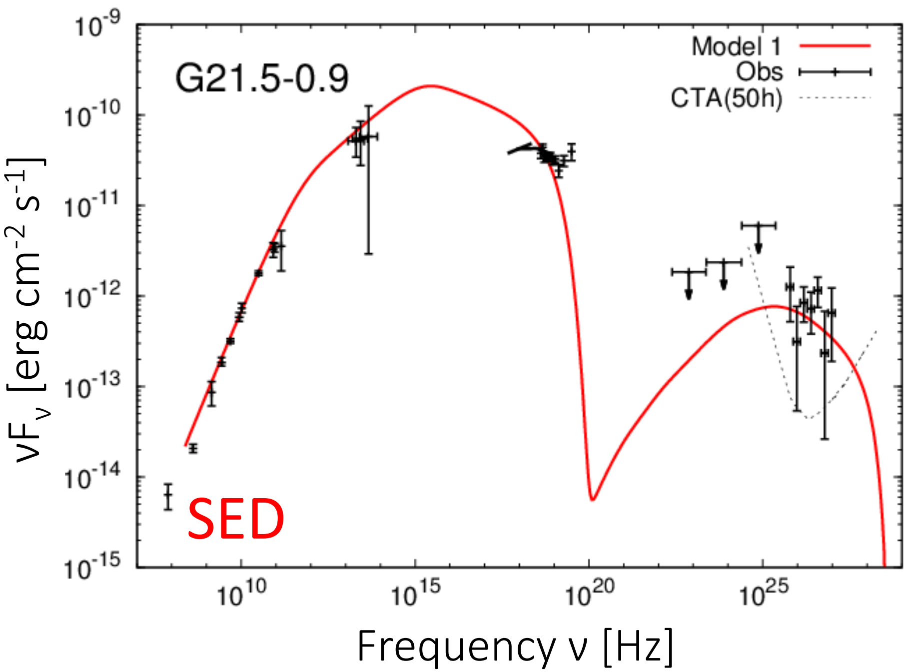


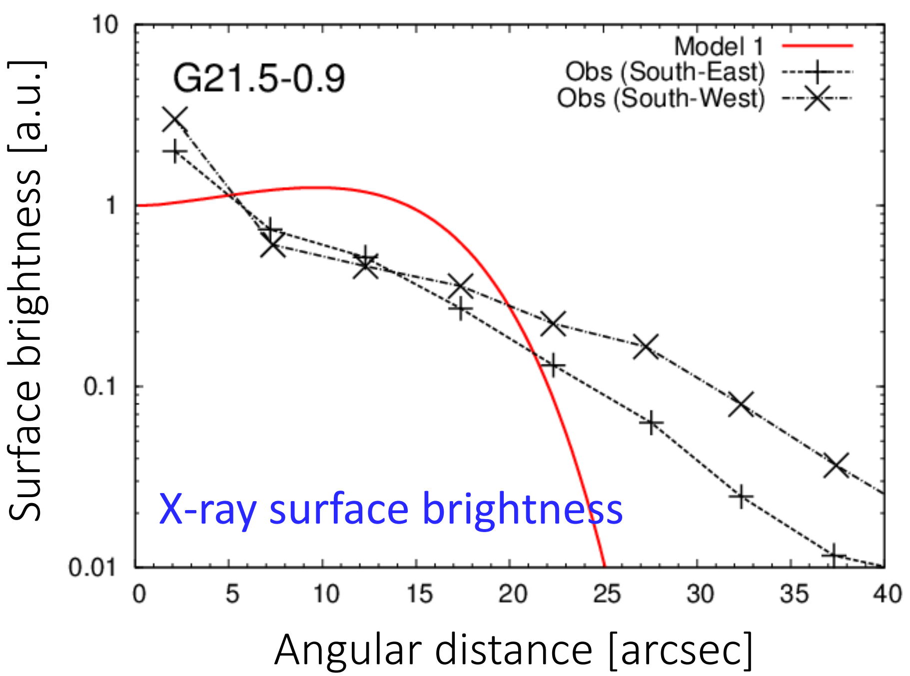

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"Magnetic Field to reproduce the SED" > "Magnetic field to reproduce the X-ray extent"

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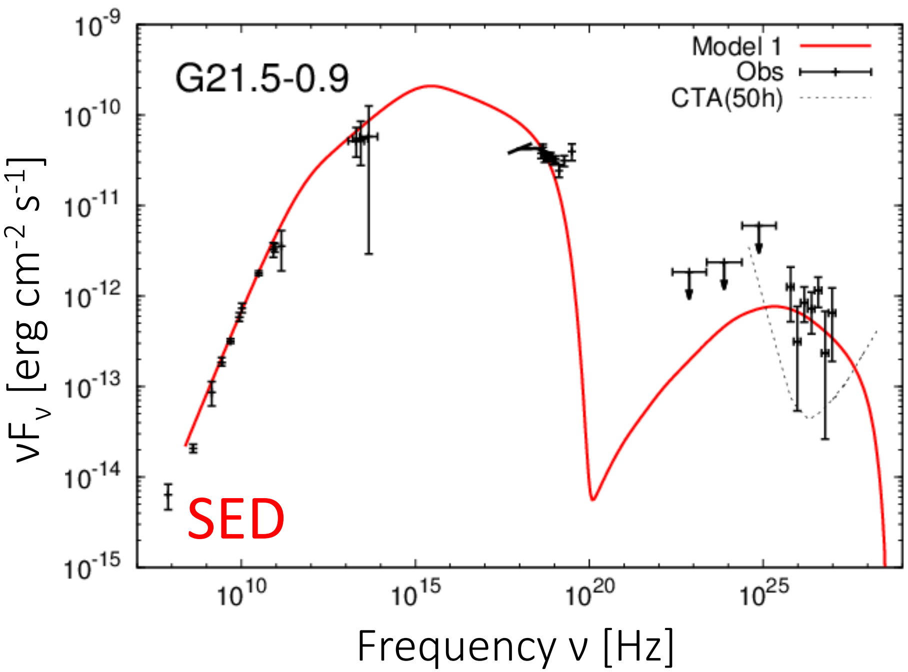
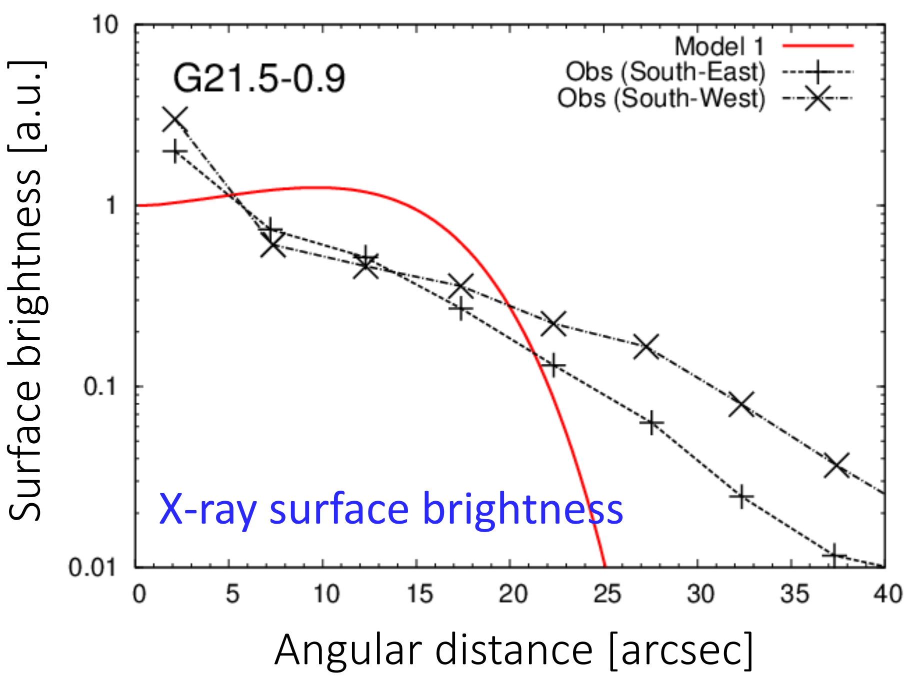
B-field to reproduce SED : determined from the flux ratio of synchrotron and ICS.

⇒ It is necessary to propagate outward more efficiently. (rather than to suppress cooling)



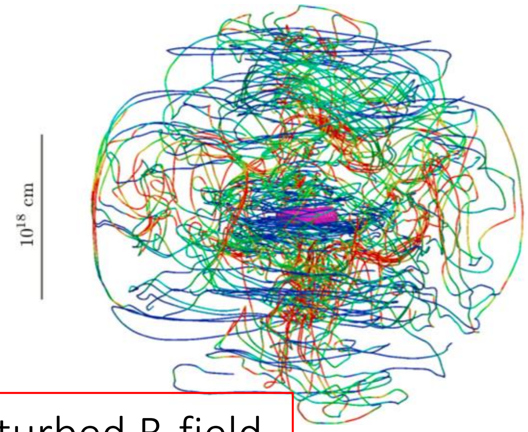



# Efficient transport?

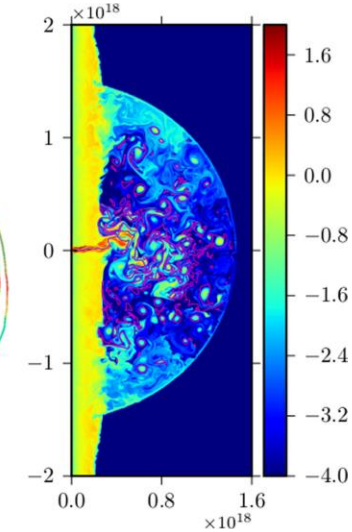
- To solve the problem of X-ray extent...
  - A) Suppress the radiative cooling
  - B) Transport efficiently

⇒ Spatial diffusion by interacting with disturbed B-field

2-D, 3-D simulation




(Tang & Chevalier 2012, Porth+ 2016)

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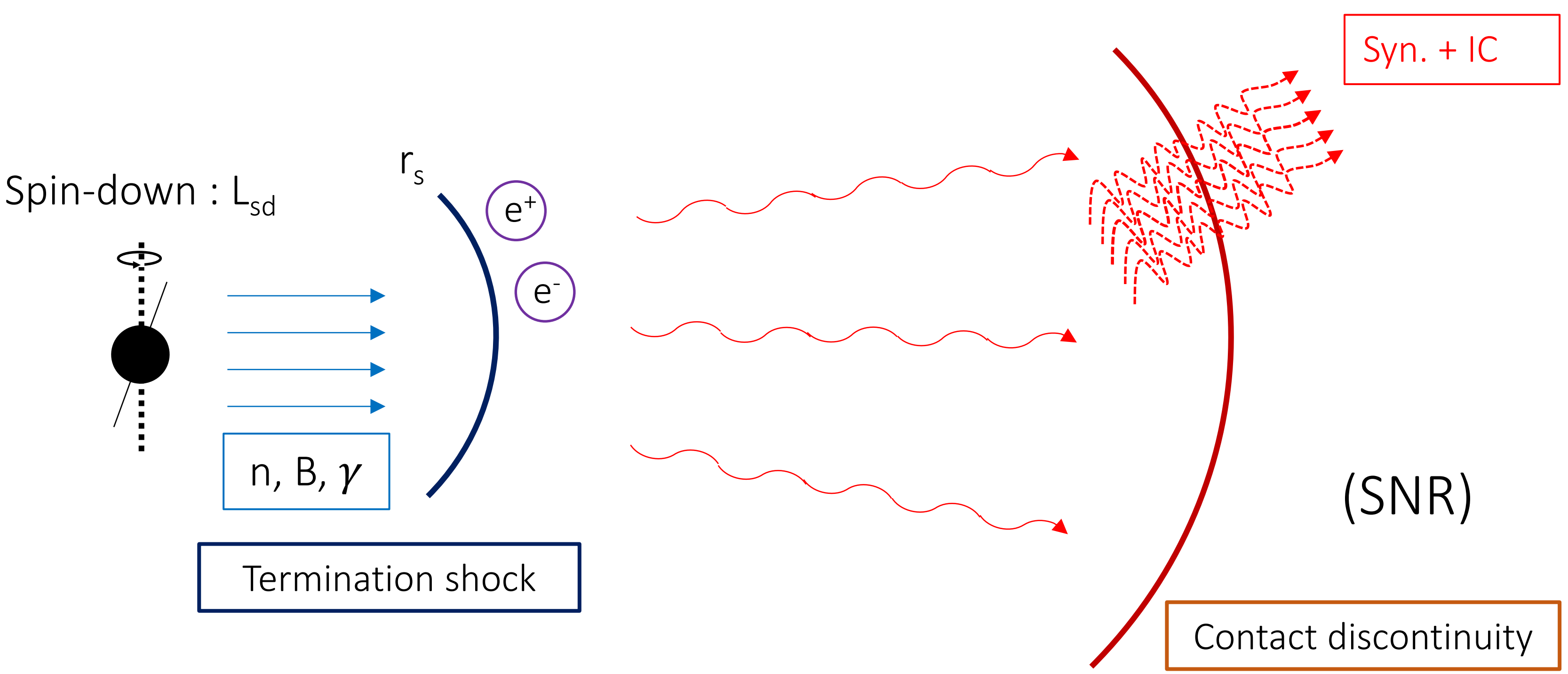

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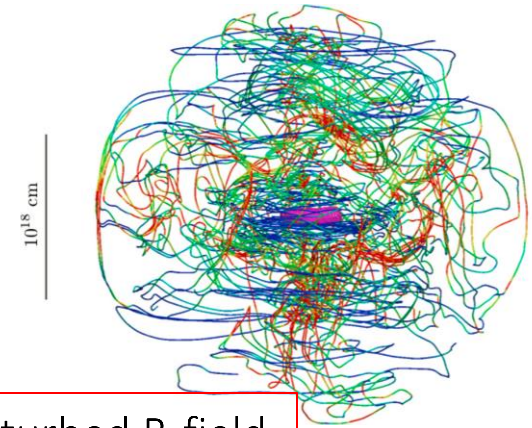


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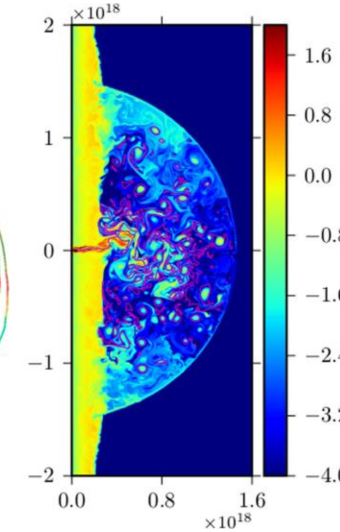
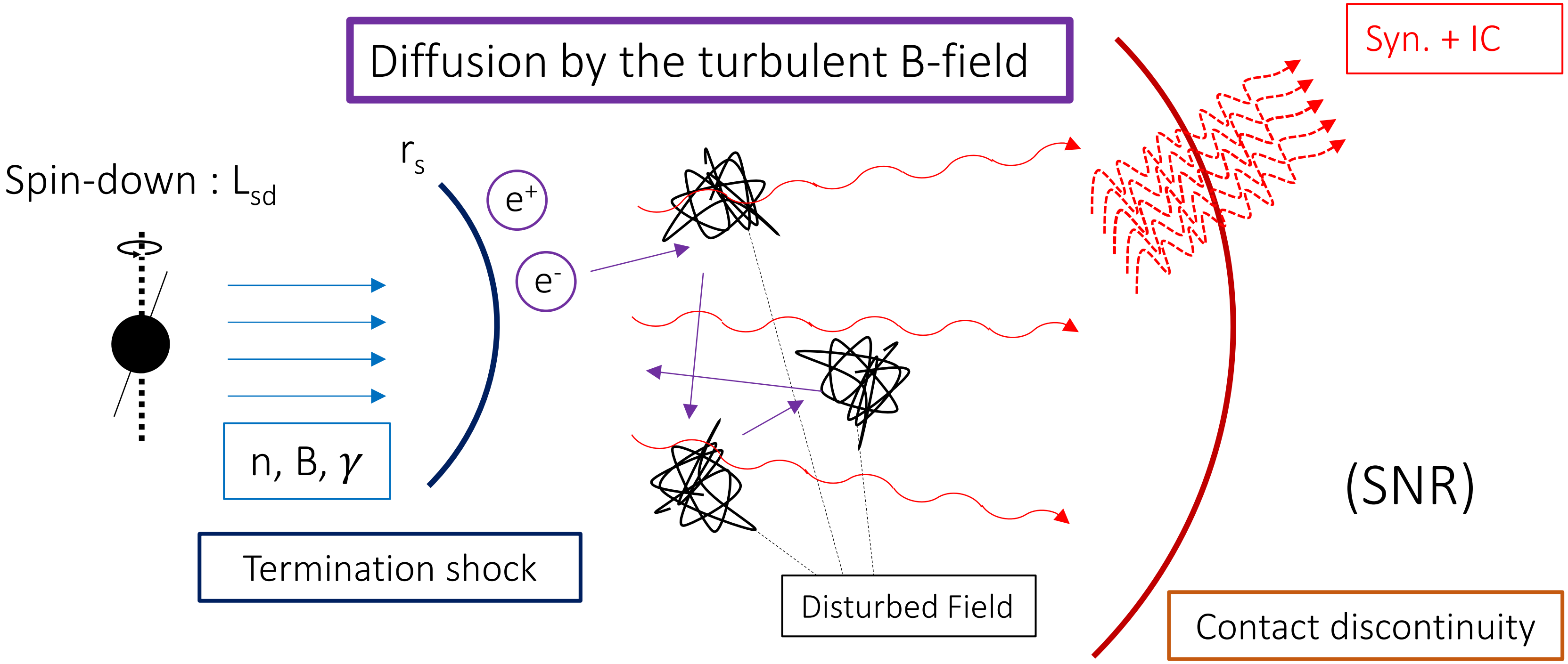



(Porth+ 2014b)

Let us consider the situation

"While advecting with the fluid, deviating from the fluid by diffusion little by little."



# Model –Calculation procedure-

Flow solution given by MHD model

$$\frac{\partial n}{\partial t} + u\frac{\partial n}{\partial r} = \frac{\partial}{\partial E}\left(Q_{\rm syn}E^2 n\right) + \frac{\partial}{\partial E}\left(Q_{\rm IC}E^2 n\right) + \frac{\partial}{\partial E}\left(\frac{c}{3r^2}\frac{d}{dr}(ur^2)En\right) - \frac{c}{r^2}\frac{d}{dr}(ur^2)n$$

Time evolution (→ 0) | Syn. cooling | ICS cooling | Adiabatic cooling | Dilution

- S
  - Assuming that the energy d
  - Propagating in the PWN wit

volution of energy spectrum of $e^{\pm}$

Rotational axis

(Forward shock)

WN)

**Transeportation process→ Advection + Diffusion**

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Time evolution (→ 0) | Syn. cooling | ICS cooling | Adiabatic cooling | Dilution

$$+\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa\frac{\partial n}{\partial r}\right)$$

**Diffusion term**

Puls

$\sim 10^9$cm $\quad r_s \sim 10^{17}$cm $\quad \sim 10^{19}$cm ($\sim$pc)

# Result -G21.5-0.9-

$$\tilde{\kappa} = \kappa_0 \left( \frac{E}{E_b} \right)^{1/3}$$

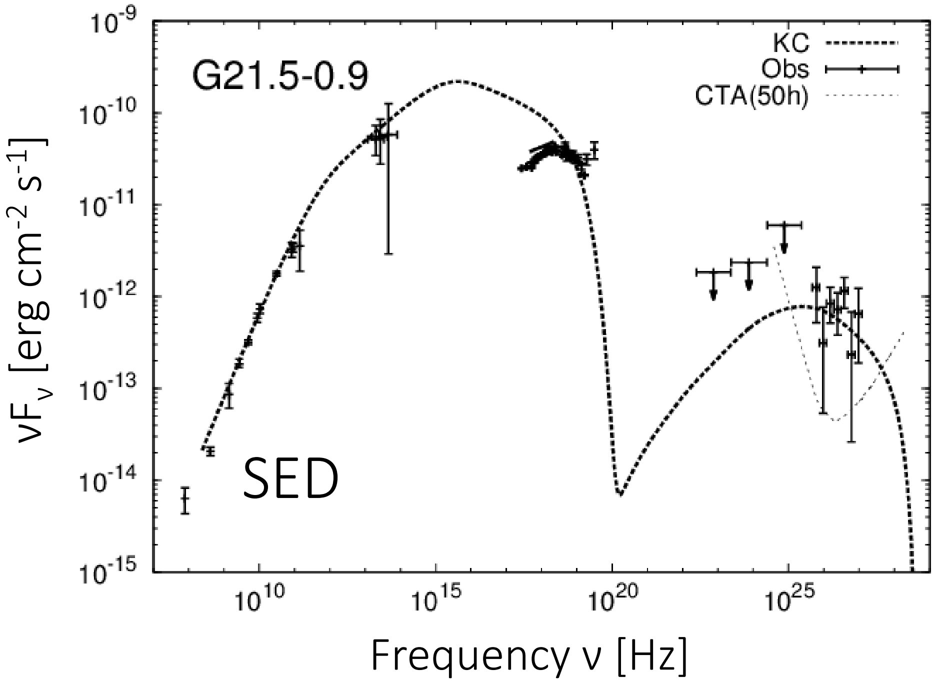
- Result for G21.5-0.9 (Omitted 3C 58)

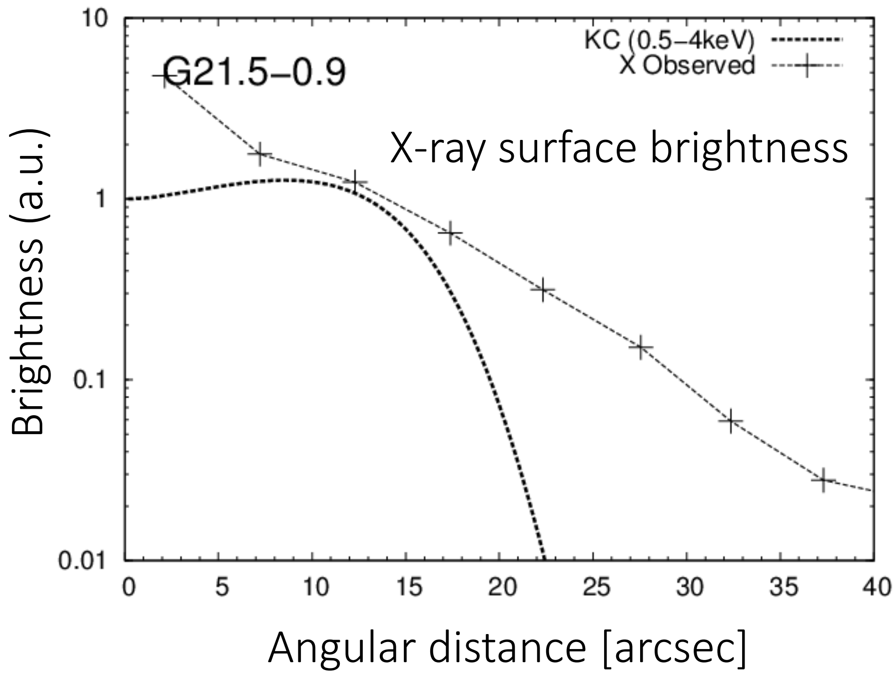
diffusion coefficient of X-ray emitting particles : $\kappa \sim 10^{27}\ \mathrm{cm^2\ s^{-1}}$

Consistent with previous models

SED : The hard spectrum of X-rays is reproduced better (than KC).

See Ishizaki+18 (ApJ, arXiv: 1809.09054) for detail



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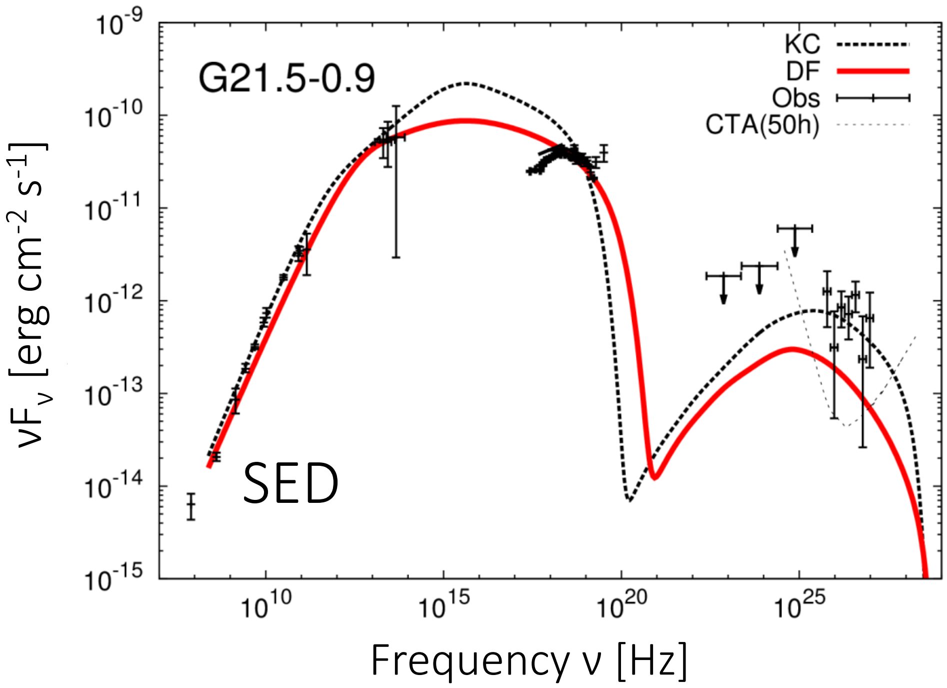
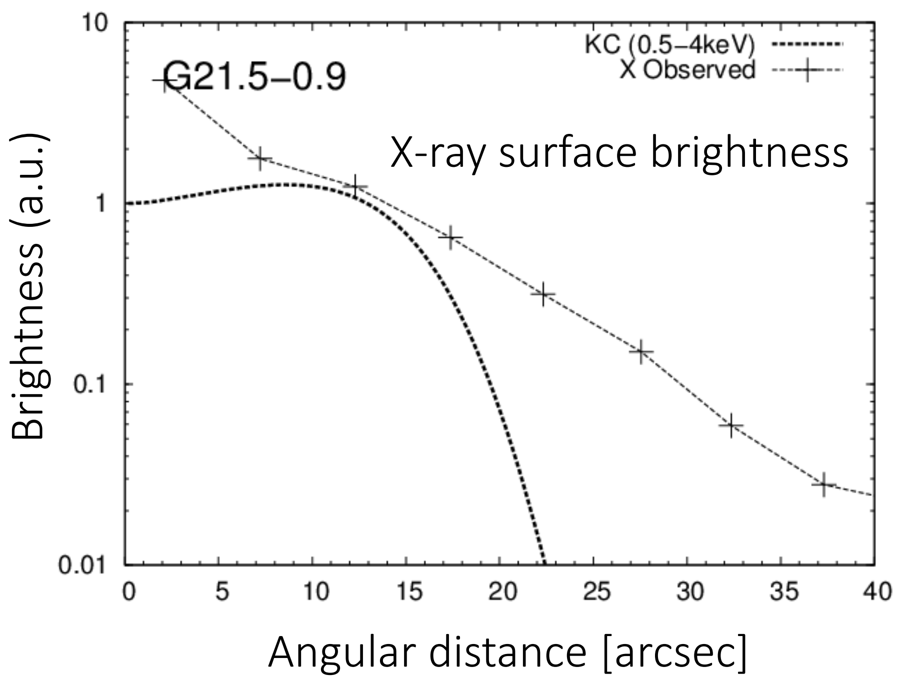


# Result -G21.5-0.9-

$$\tilde{\kappa} = \kappa_0 \left( \frac{E}{E_b} \right)^{1/3}$$

- Result for G21.5-0.9 (Omitted 3C 58)

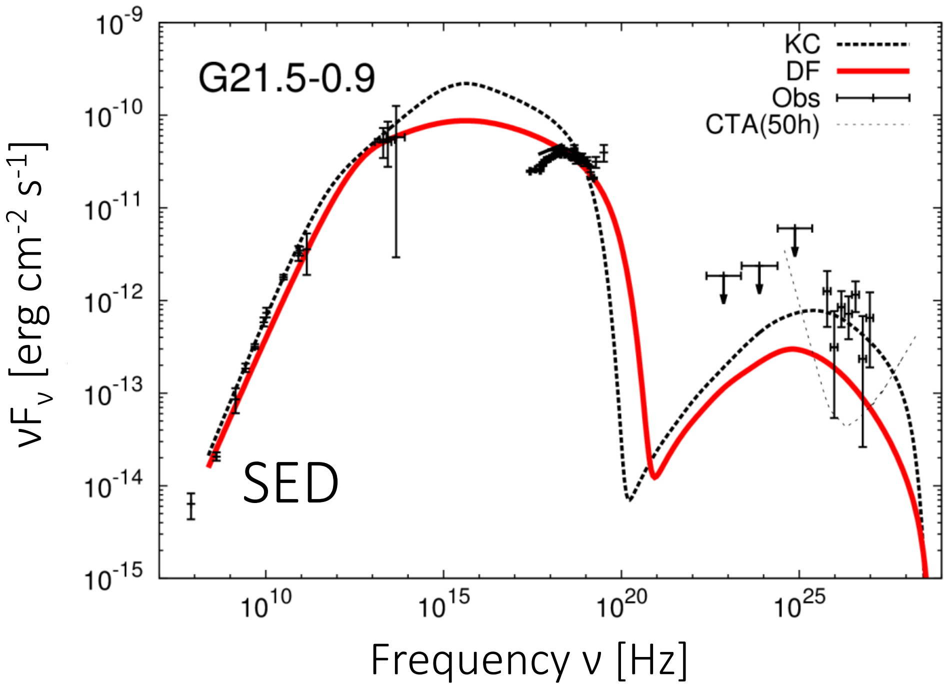
diffusion coefficient of X-ray emitting particles : $\kappa \sim 10^{27}$ cm$^2$ s$^{-1}$

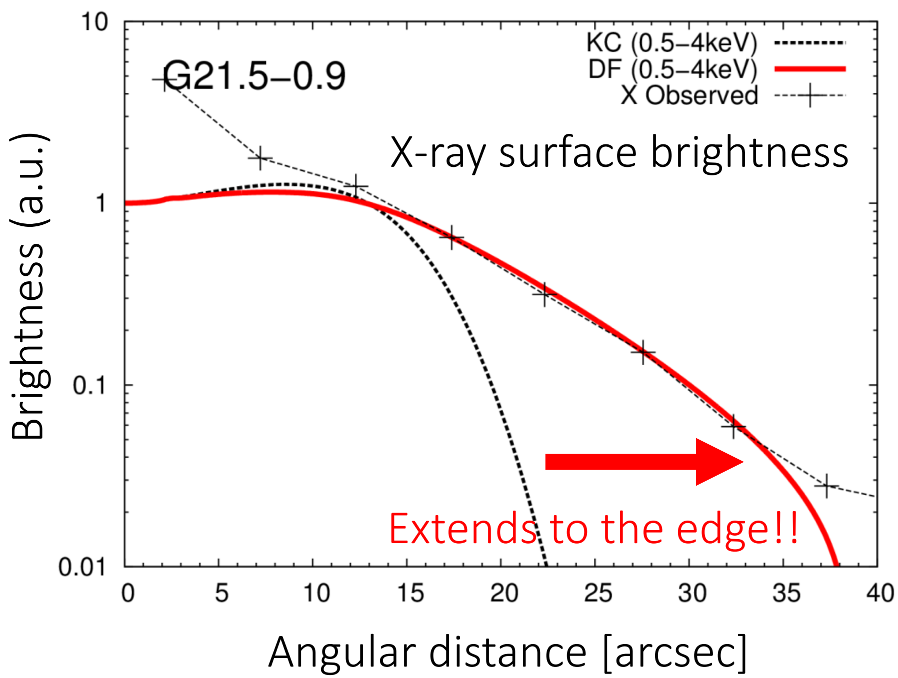
Consistent with previous models

SED : The hard spectrum of X-rays is reproduced better (than KC).

X-ray surface brightness : **Extends to the edge!**

See Ishizaki+18 (ApJ, arXiv: 1809.09054) for detail



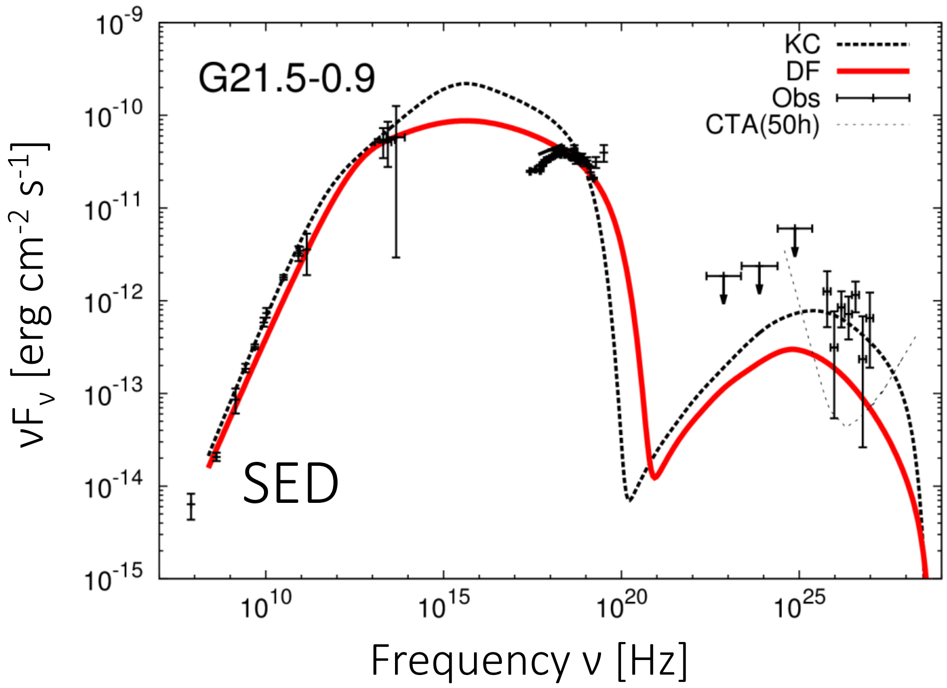
# Result -G21.5-0.9-

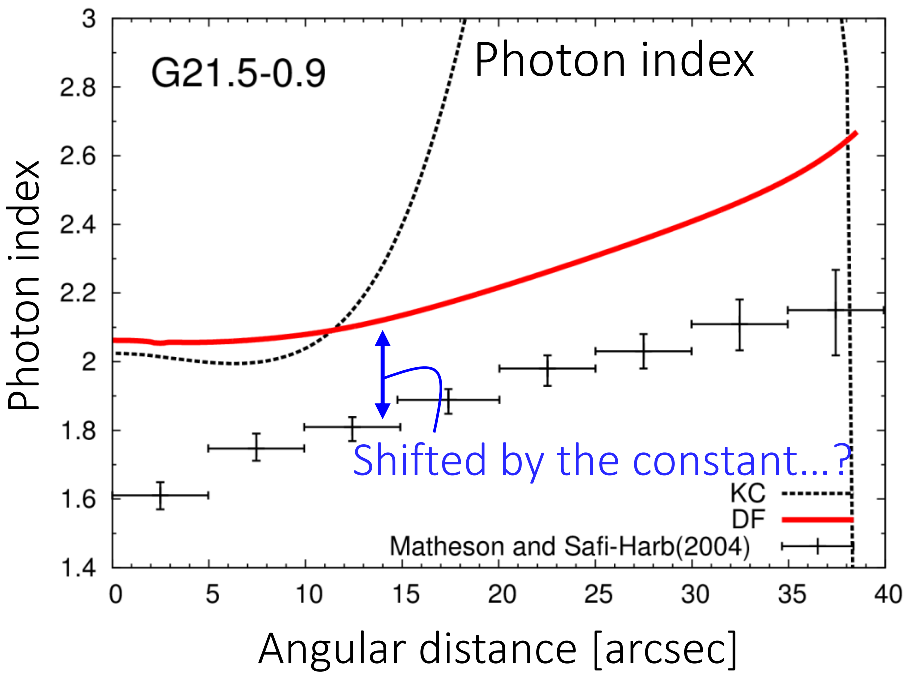
$$\tilde{\kappa} = \kappa_0 \left( \frac{E}{E_b} \right)^{1/3}$$

- Result for G21.5-0.9 (continues)

Photon index : The problematic softening is solved.
The radial dependence is in good agreement.
However it is shifted by the constant systematically.

SED: flux around 1 TeV is about 2 times ($10^{-13}$ erg cm$^{-2}$ s$^{-1}$) insufficient as observed value.



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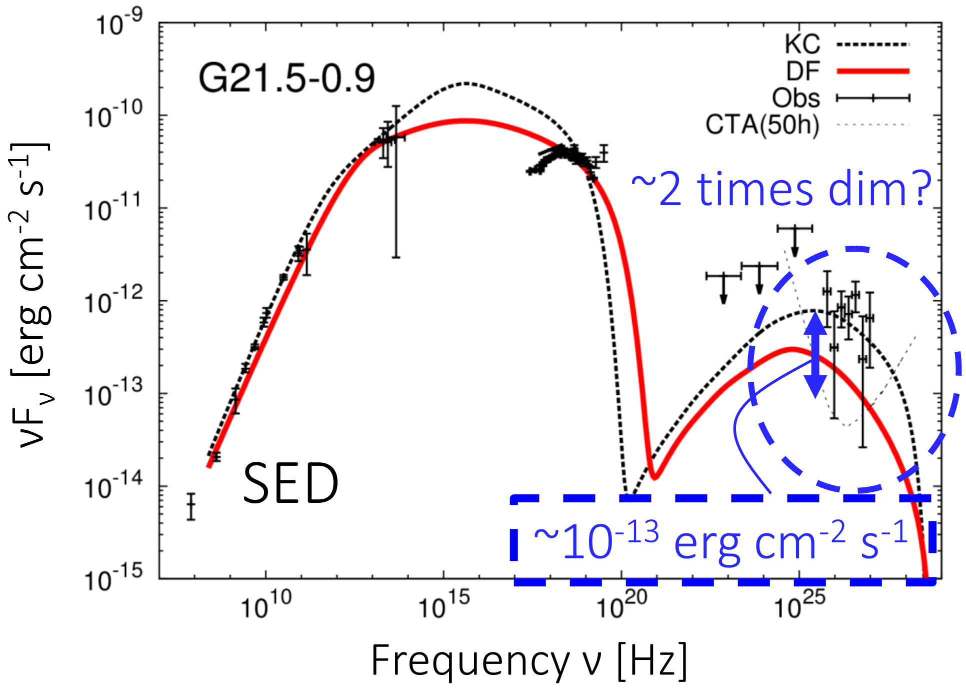
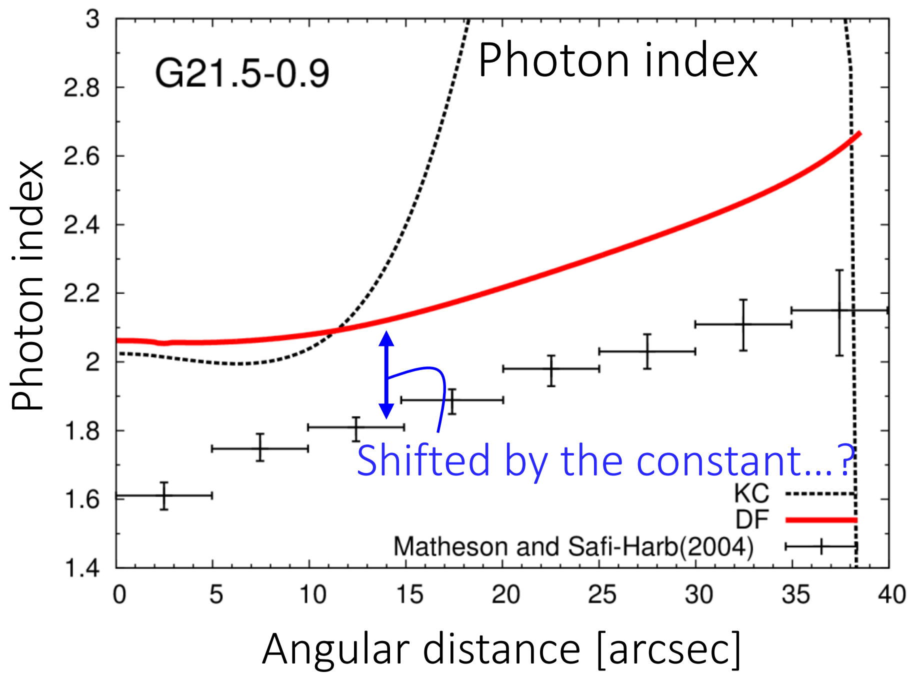


# Escaped particles…?

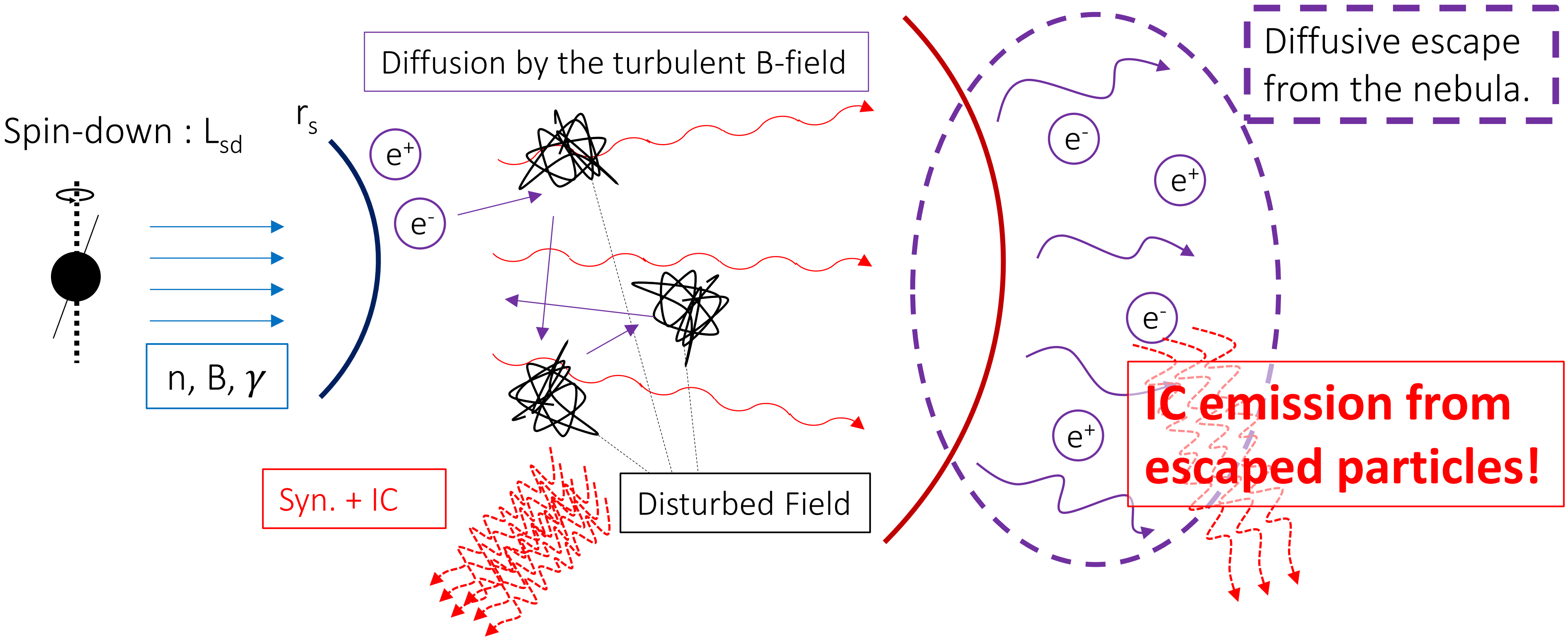
- The γ-ray emission from the particles which escaped out of the nebula.

  → predict a “**young TeV-halo**” which extends larger than the radio or X-ray nebula.

  Contribution from the escaped particels : $\sim 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ → CAN cover the shortfall.

  Assuming that the diffusion coefficient outside the nebula is same as inside one,

  the extent of the γ-ray halo is $\sim 2$ pc ( corresponding to $90''$ )



# Conclusion & Summary

- Summary :
  - ✗ The standard 1D steady model (KC model) CANNOT explain observation facts of PWNe where X-rays extends to the same as radio nebula.
  - ❀ We have shown that the SED and the extent of X-ray can be reproduces simultaneously by the 1-D steady diffusion model.
  - Assuming that the diffusion coefficient outside the nebula is the same as in the nebula, we have suggest that the "young TeV-halo" extends larger than the radio or X-ray nebula.
- Future prospects and issues :
  - A physical interpretation of the obtained diffusion coefficient $\kappa(E = 10^{14}\ \mathrm{eV}) \sim 10^{27}\ cm^2 s^{-1}$, which is much larger than the predicted value by the standard cosmic-ray diffusion model.
  - More quantitative modeling of the process of particle escaping from PWNe.
  - More objects.