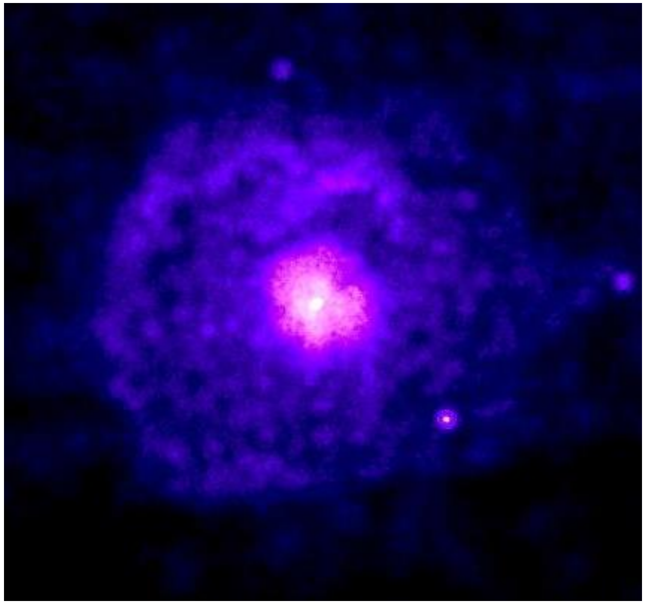
Modeling of Broadband Spectra and Radial Profiles of Emission of Pulsar Wind Nebulae



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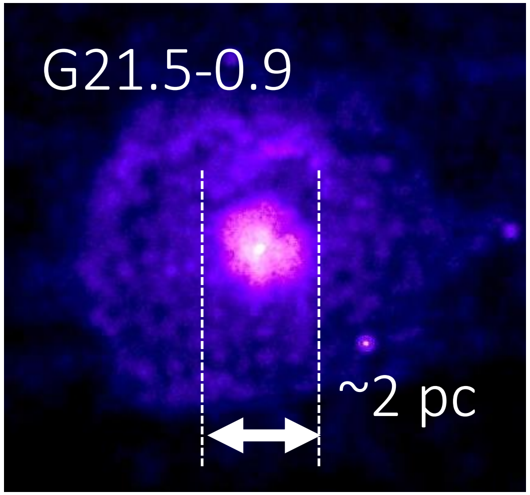
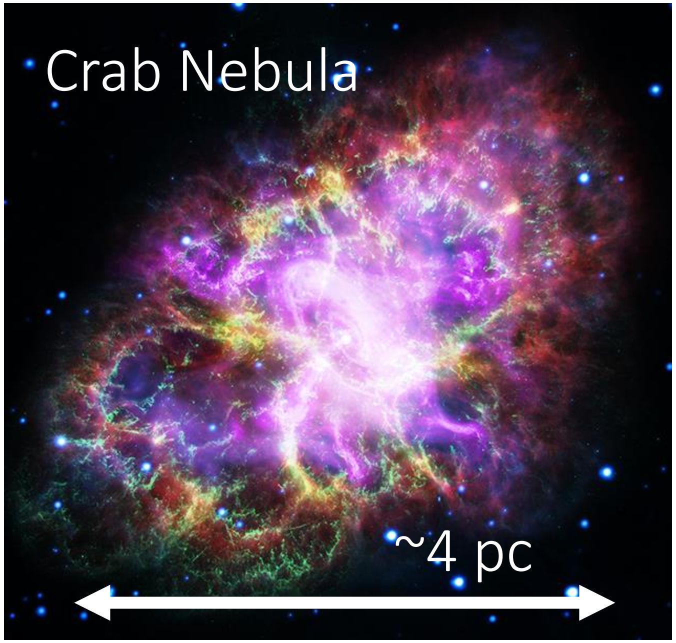
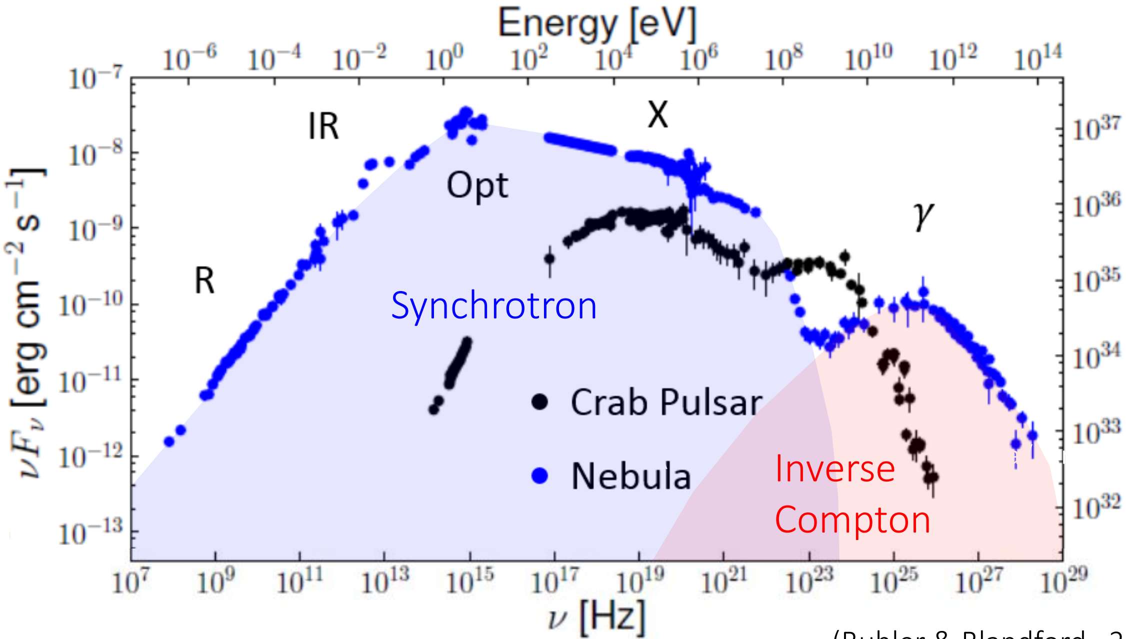
Introduction –Pulsar Wind Nebulae-



- Pulsar Wind Nebulae (PWNe)
  - Extended source around a rotation powered pulsar
  - Broadband non-thermal spectrum from radio to TeV-γ
- Non-thermal emission
  - Radio – X : Synchrotron
  - γ-rays : Inverse Compton (external or SSC)
  - X-ray photons are emitted by $e^{\pm}$ with highest energy

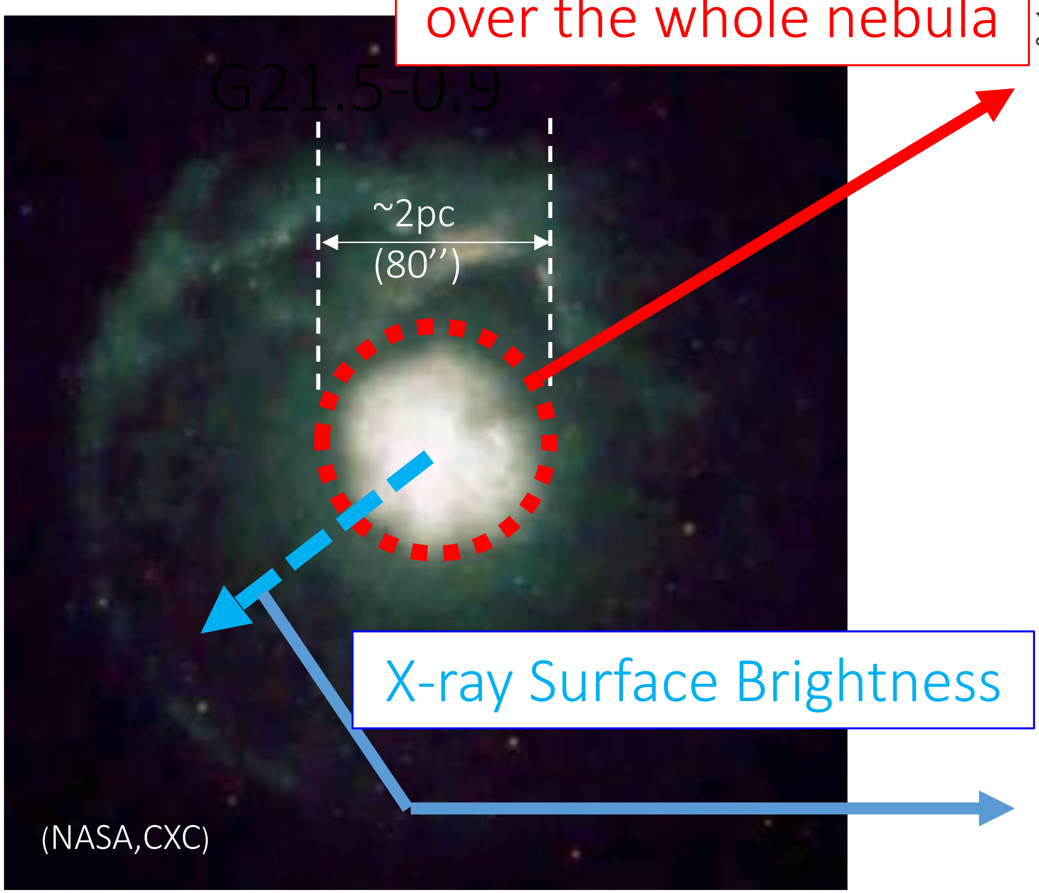


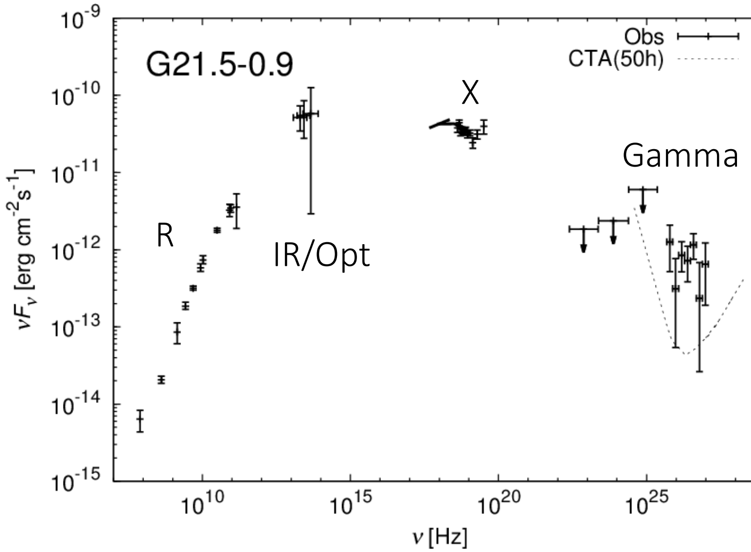


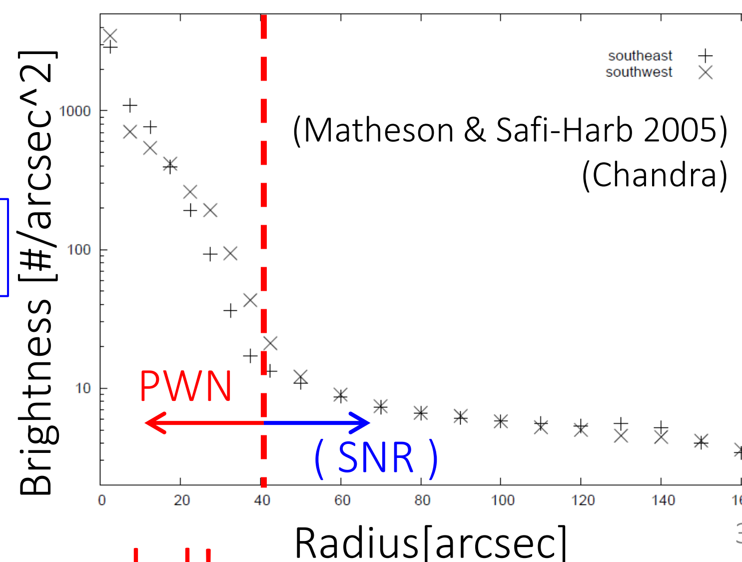
(Buhler & Blandford , 2014)

Observed Quantities

- eg. G21.5-0.9



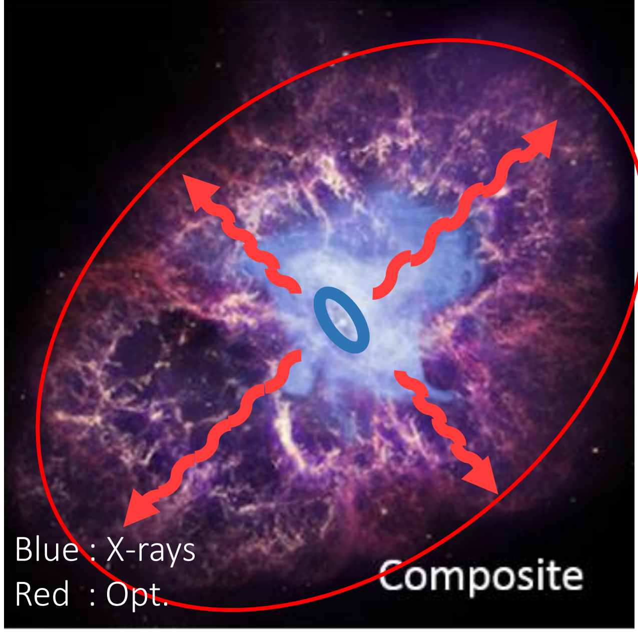




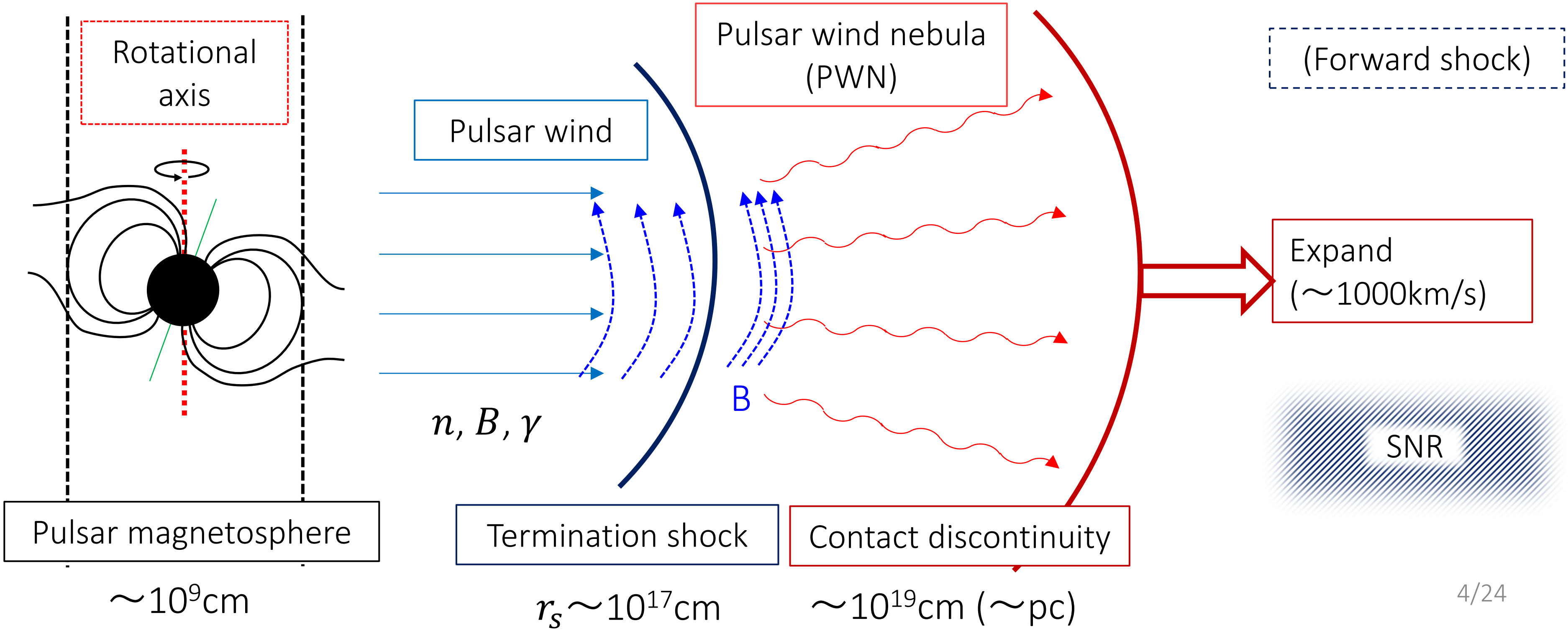
Most simplified spatial model → 1D model!

"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

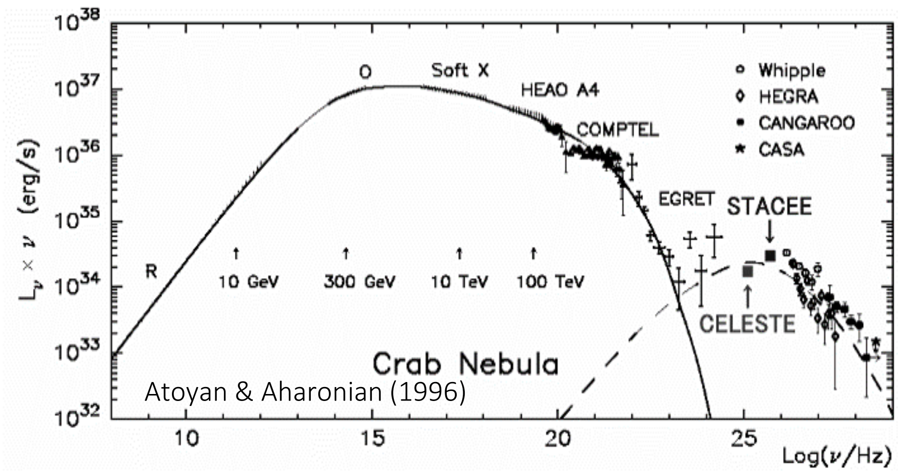


Well explains observed property of the Crab Nebula



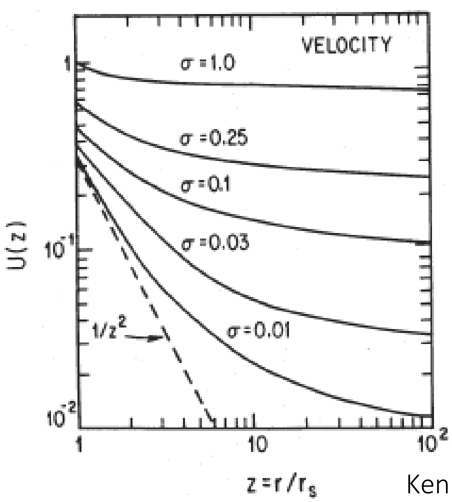
What KC model explains

- SED (Spectrum of the whole nebula)



Atoyan & Aharonian (1996)

- Deceleration of the flow



Kennel & Coroniti (1984)

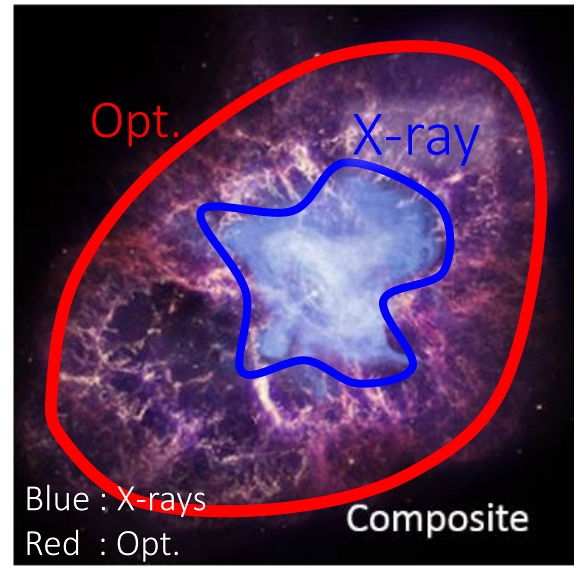
@shock : ~c/3

@edge : ~1000 km/s

Q. How decelerates ?

A. Low sigma flow

- Energy dependent morphology

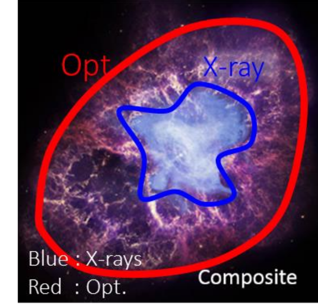


KC model can explain these properties

→ KC model was accepted as a standard model

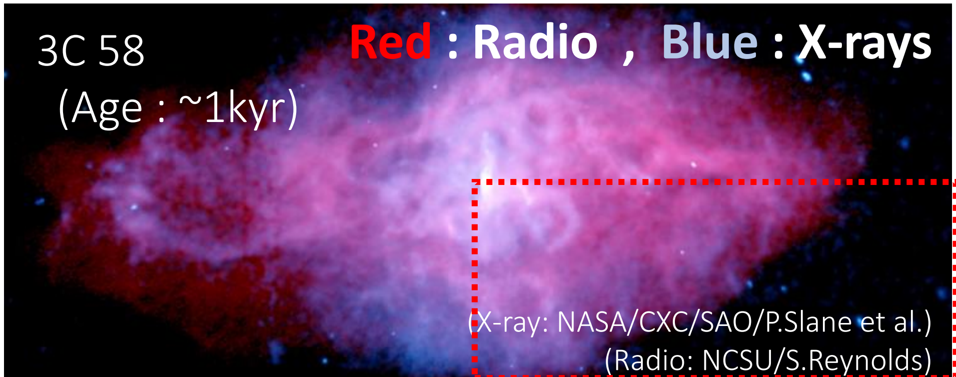
However, such a test has performed for the Crab Nebula **ONLY**.

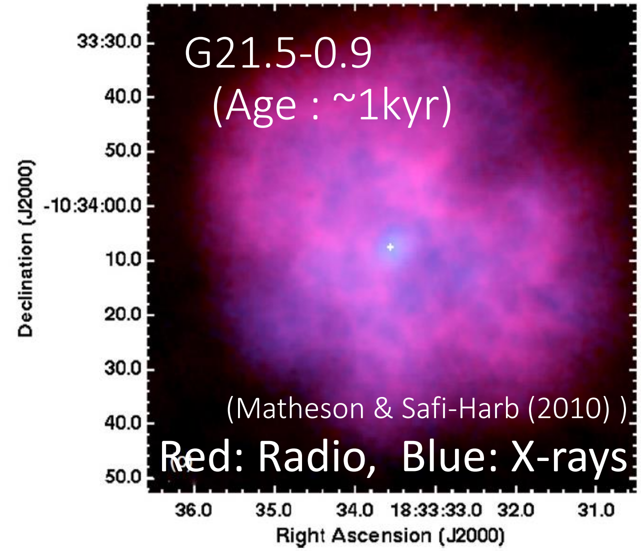
cf. the Crab Nebula

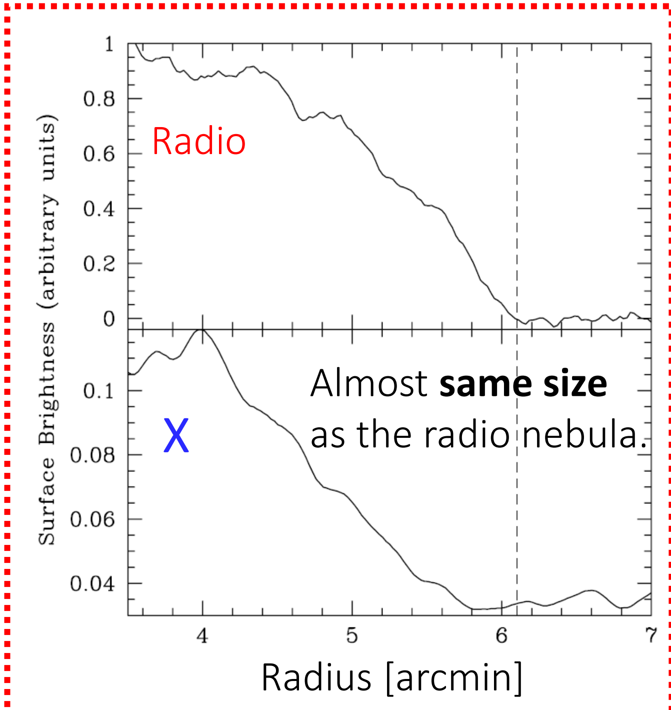


3C 58, G21.5-0.9

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**?

Test of KC model

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

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

Test of KC model

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

- SED : almost reproduced w/ KC model
  - Obtained the parameters almost uniquely
- X-ray surface brightness
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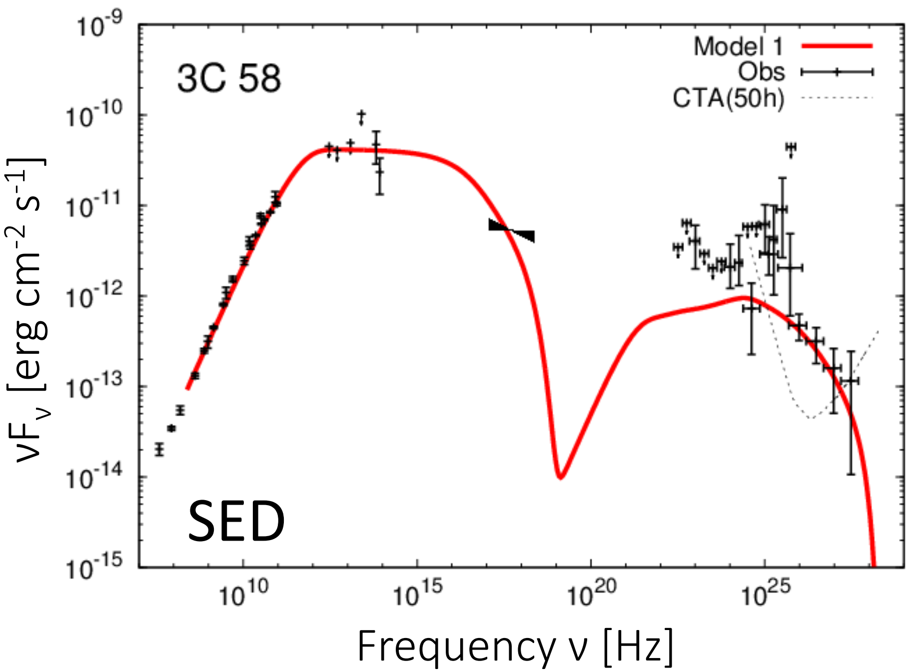

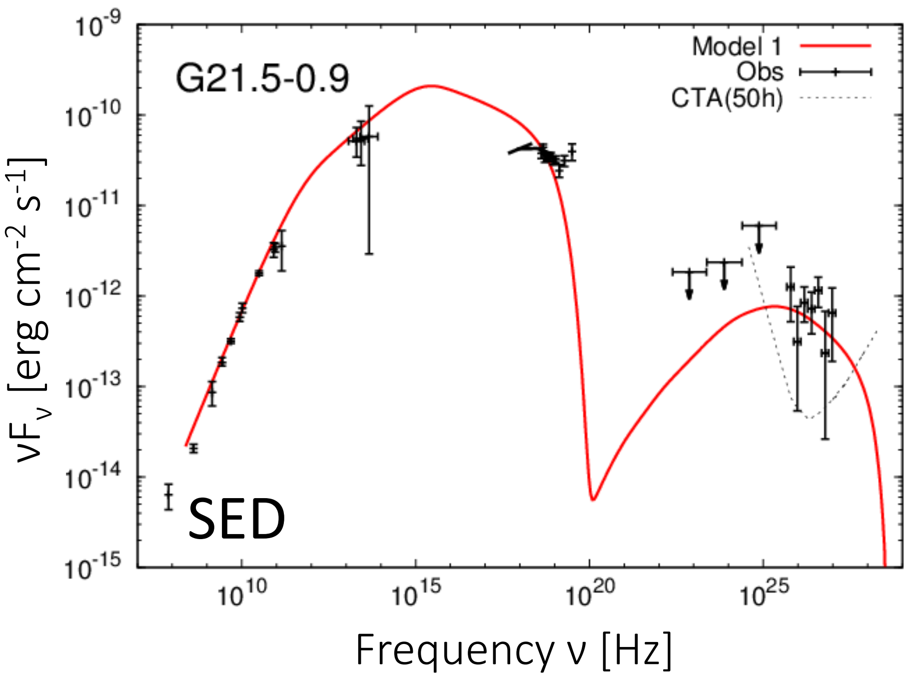

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- SED : almost reproduced w/ KC model
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  - High energy $e^{\pm}$ exhaust their energy by emission.
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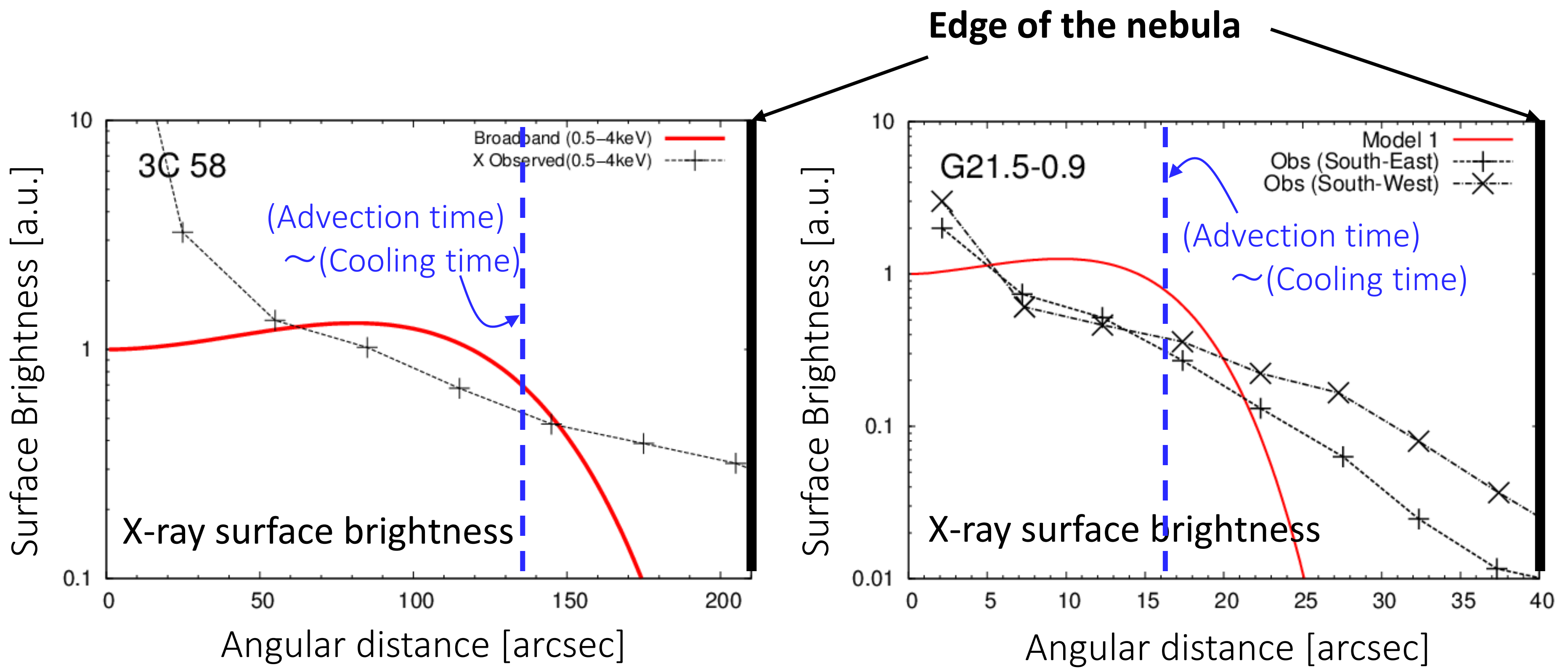

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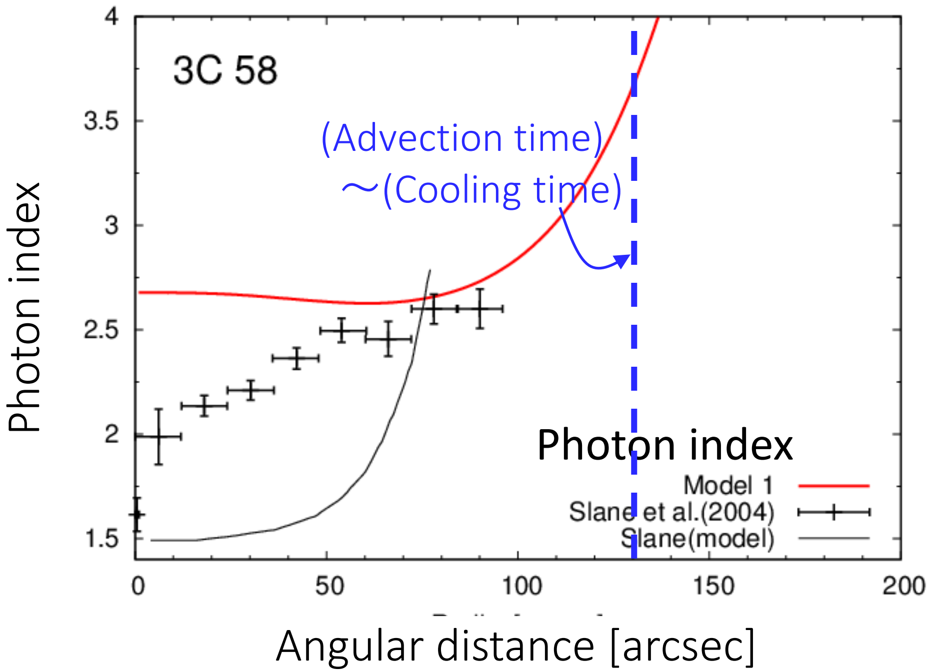

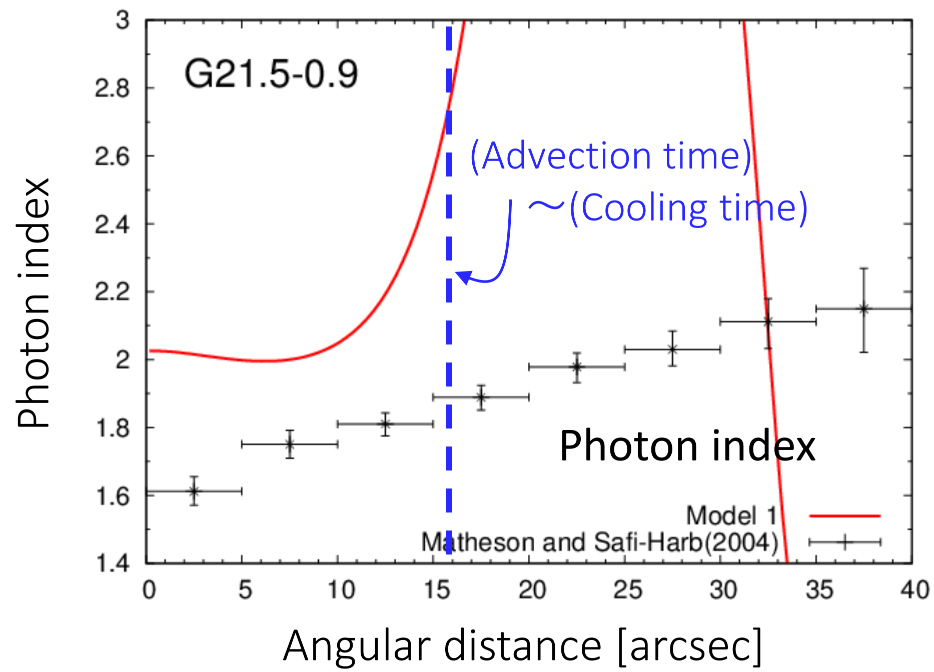

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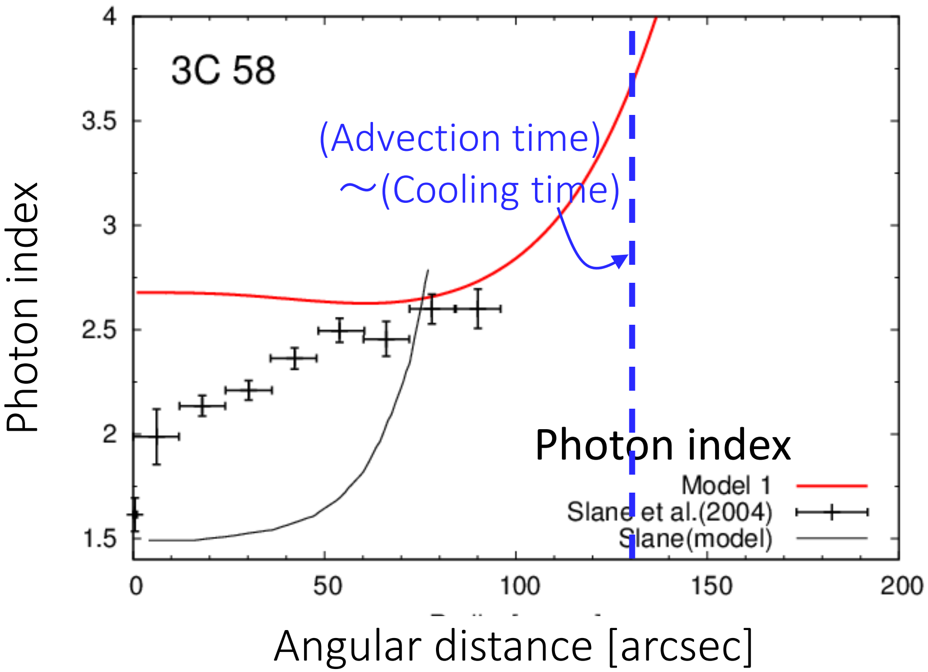

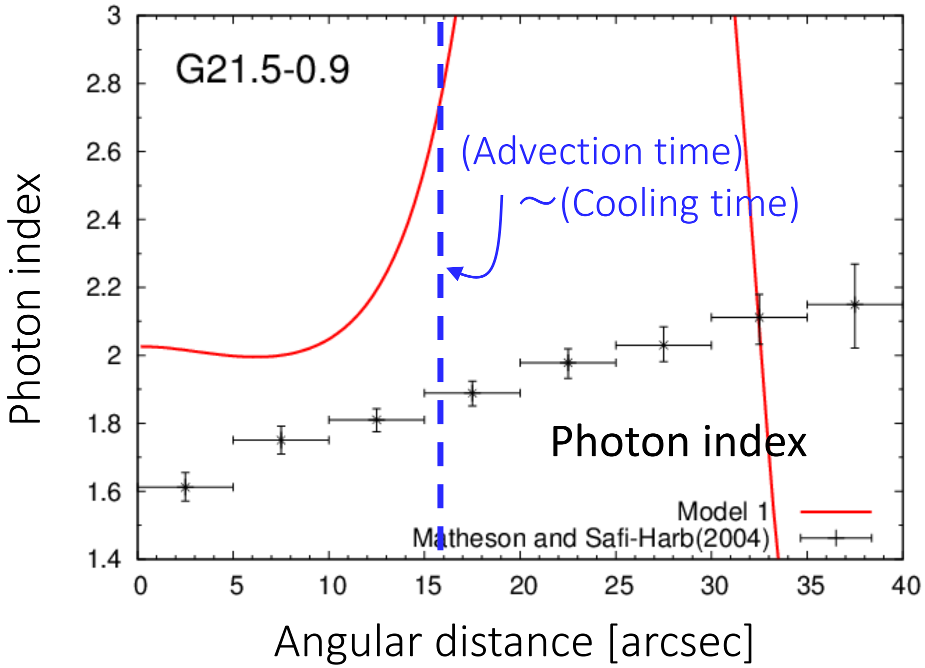

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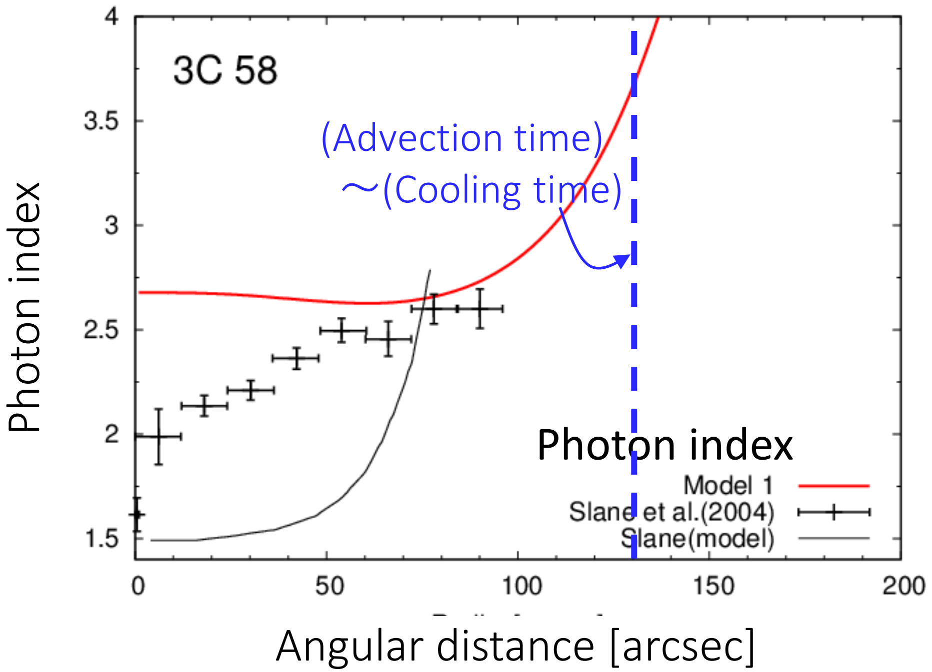
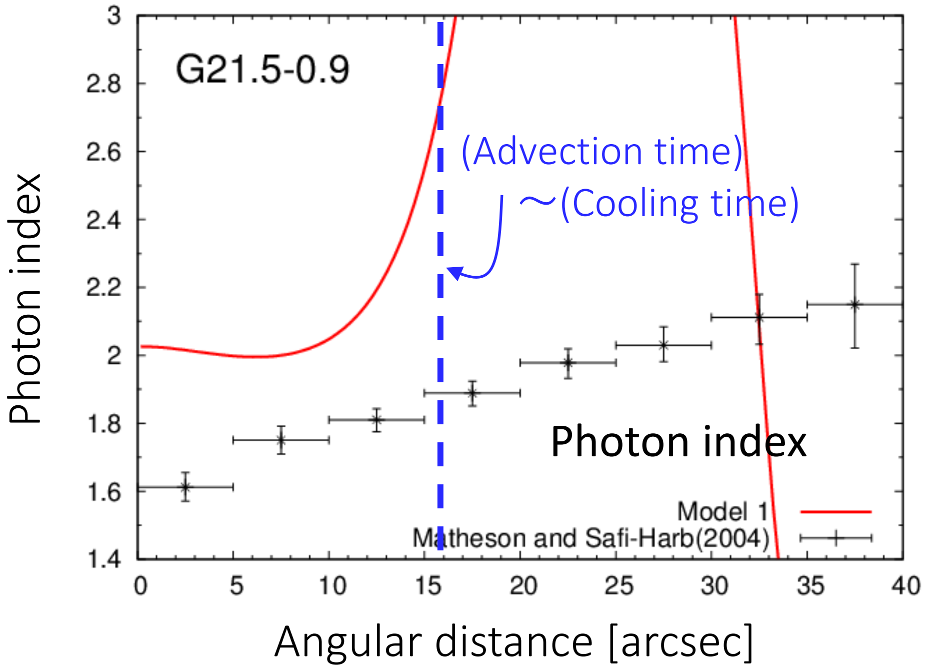
KC model **CANNOT** reproduce SED and X-ray profile **simultaneously**!





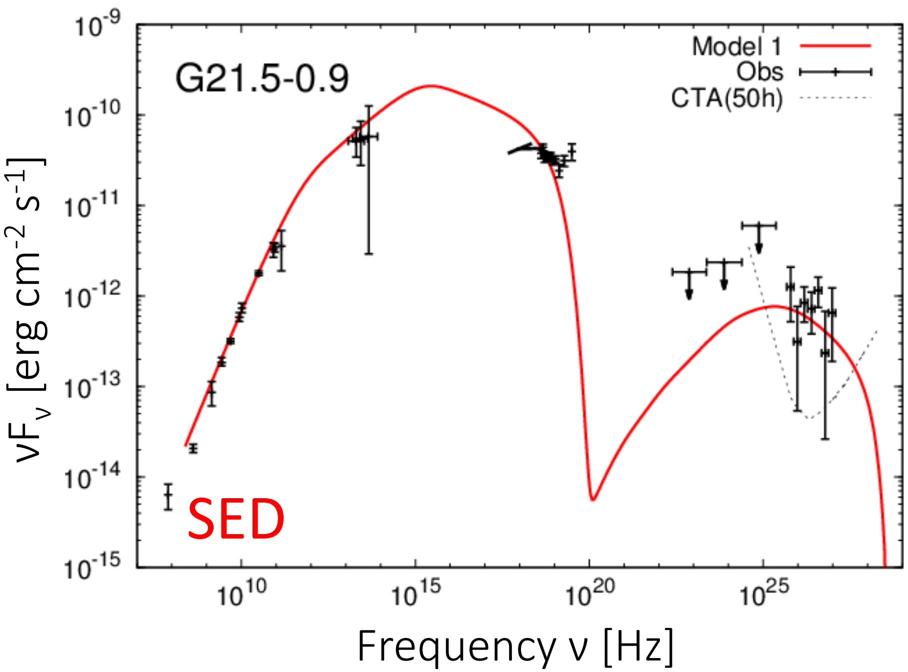
Why cannot?

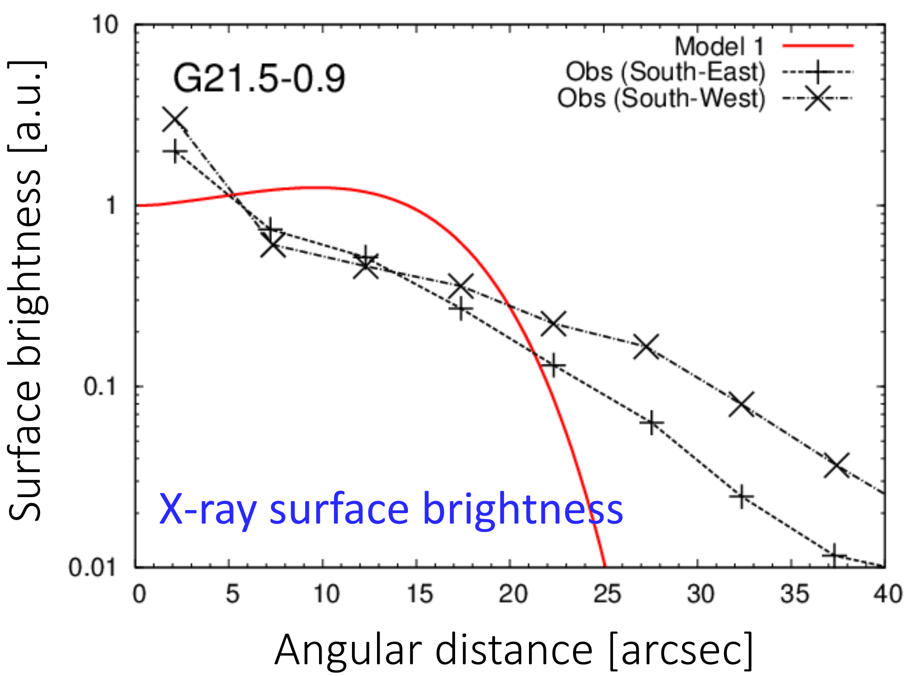
Why cannot?

"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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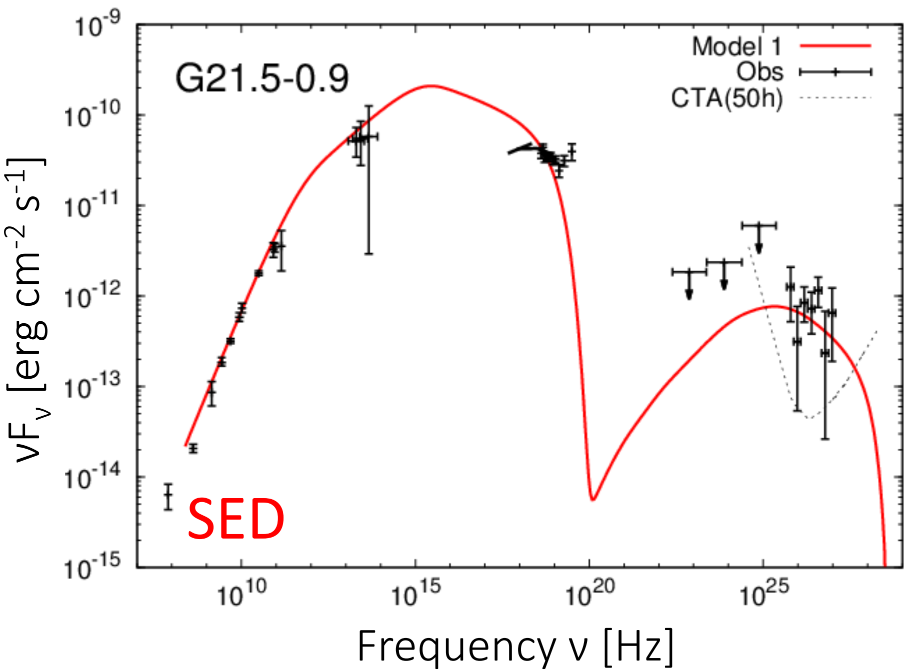

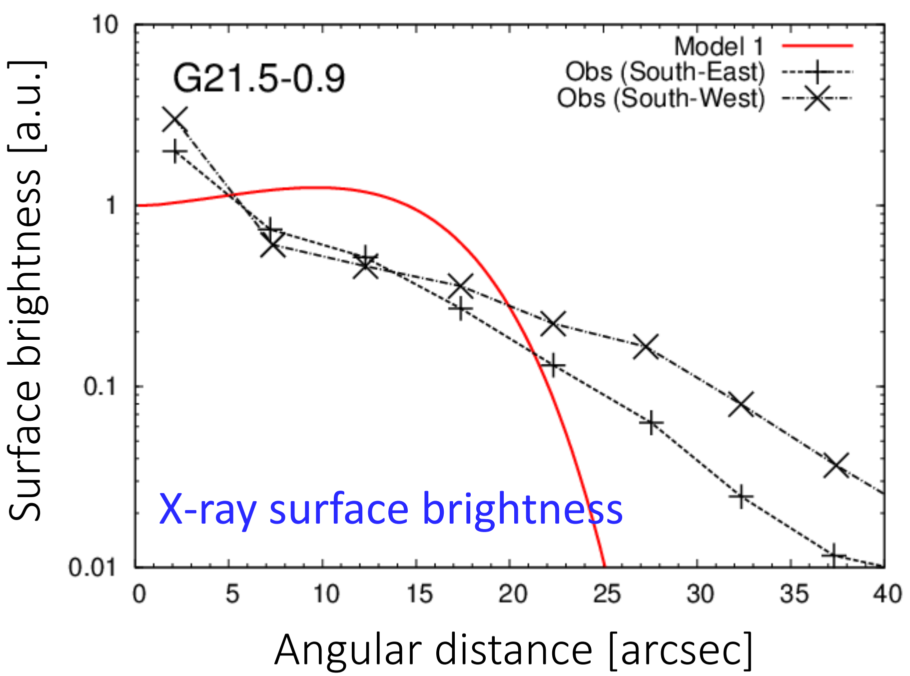

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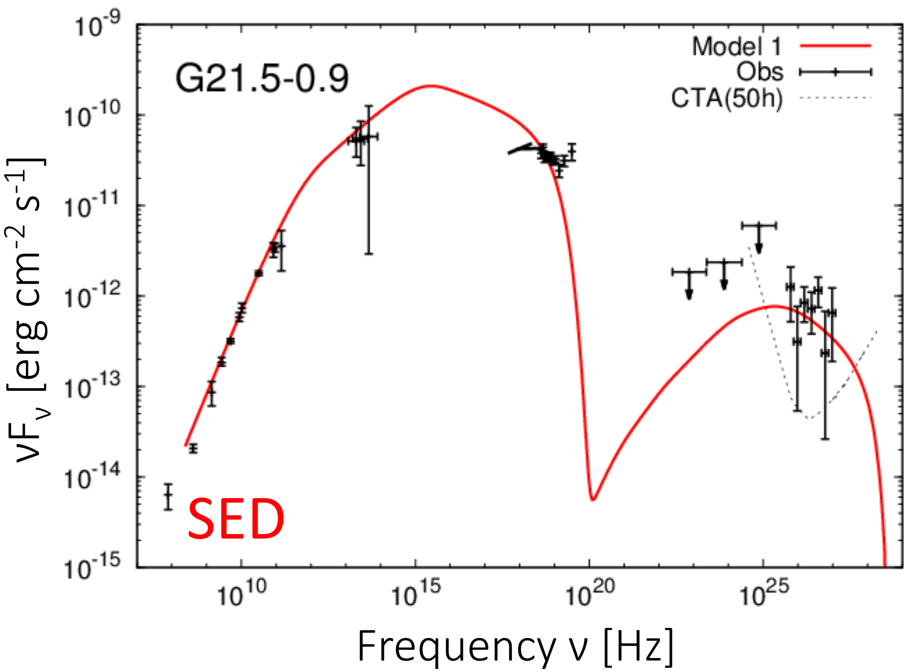

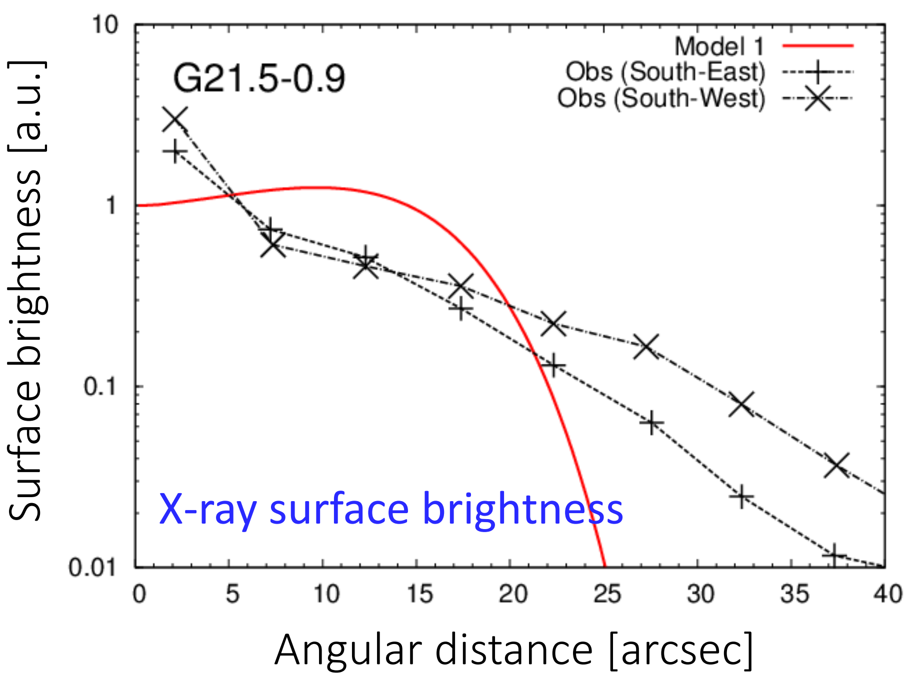

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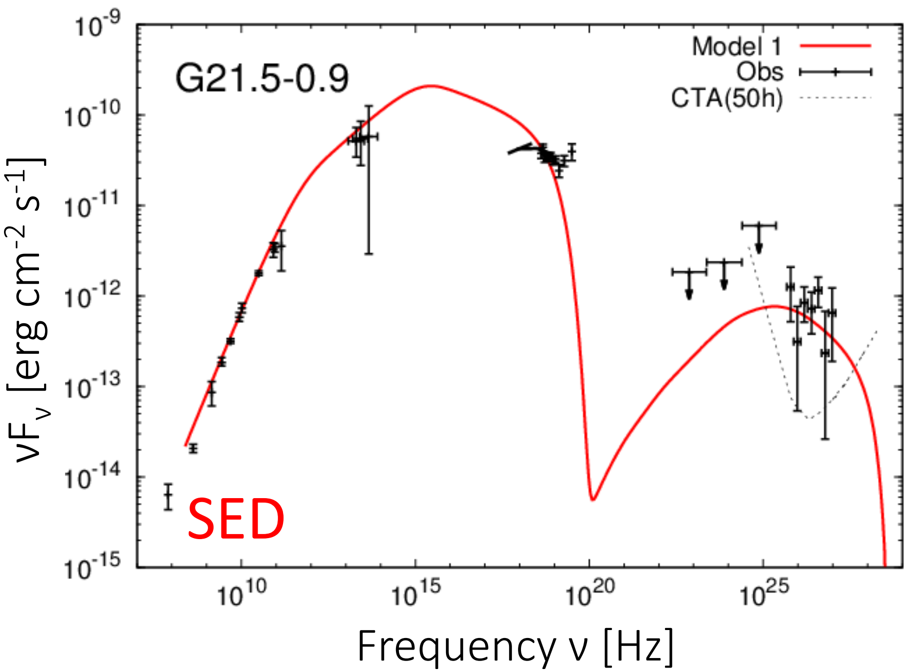
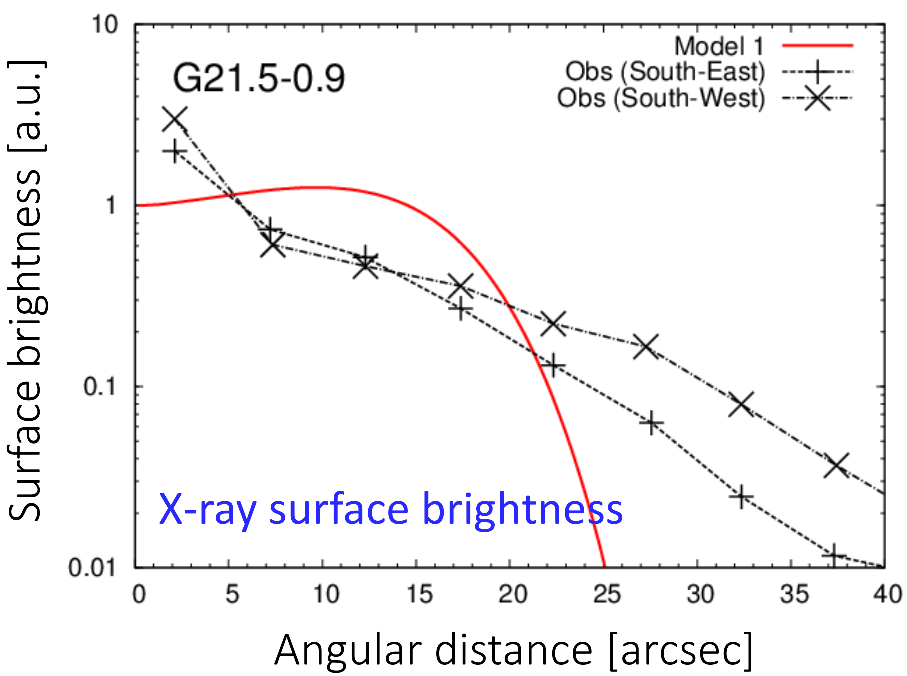
⇒ It is necessary to propagate outward more efficiently. (rather than to suppress cooling)





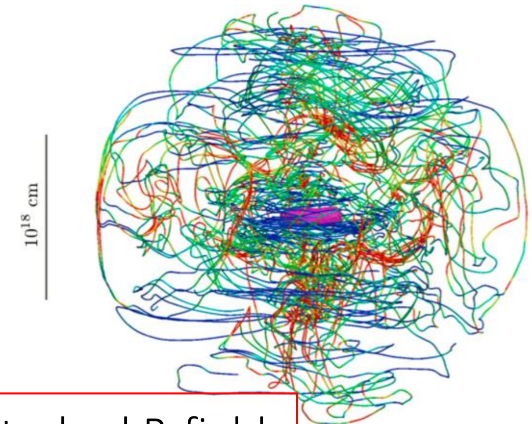
Efficient transport?

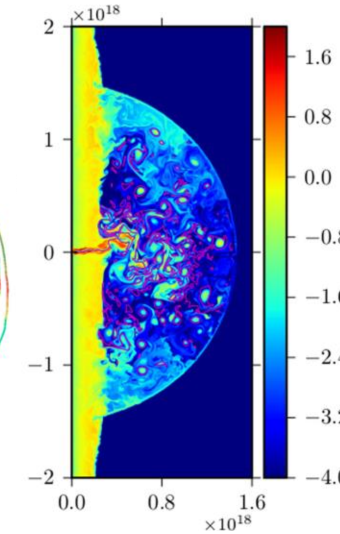
- To solve the problem of X-ray extent...
  - A) Suppress the radiative cooling
  - B) Transport efficiently

⇒ Spatial diffusion by interacting with disturbed B-field

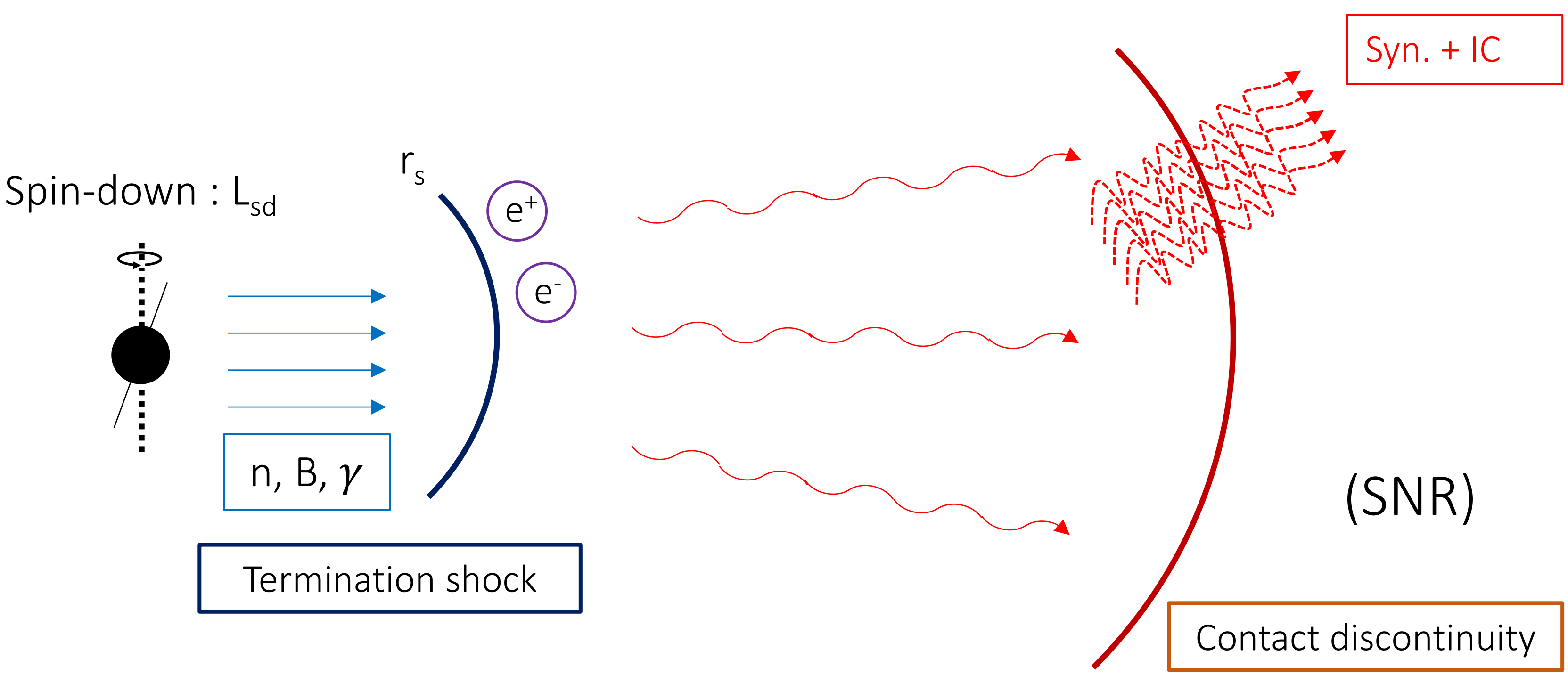
(Tang & Chevalier 2012, Porth+ 2016)

2-D, 3-D simulation





(Porth+ 2014b)



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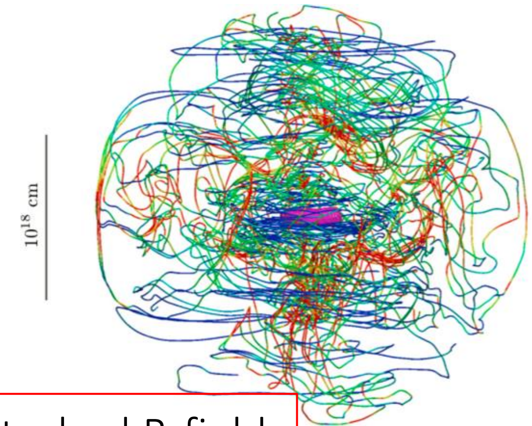
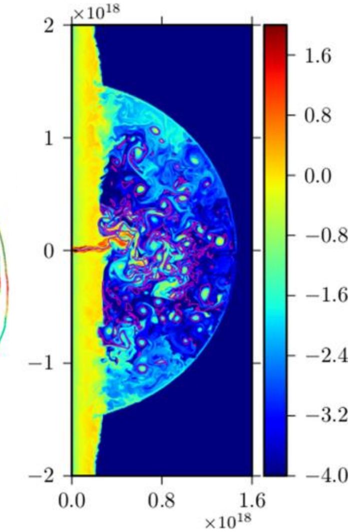


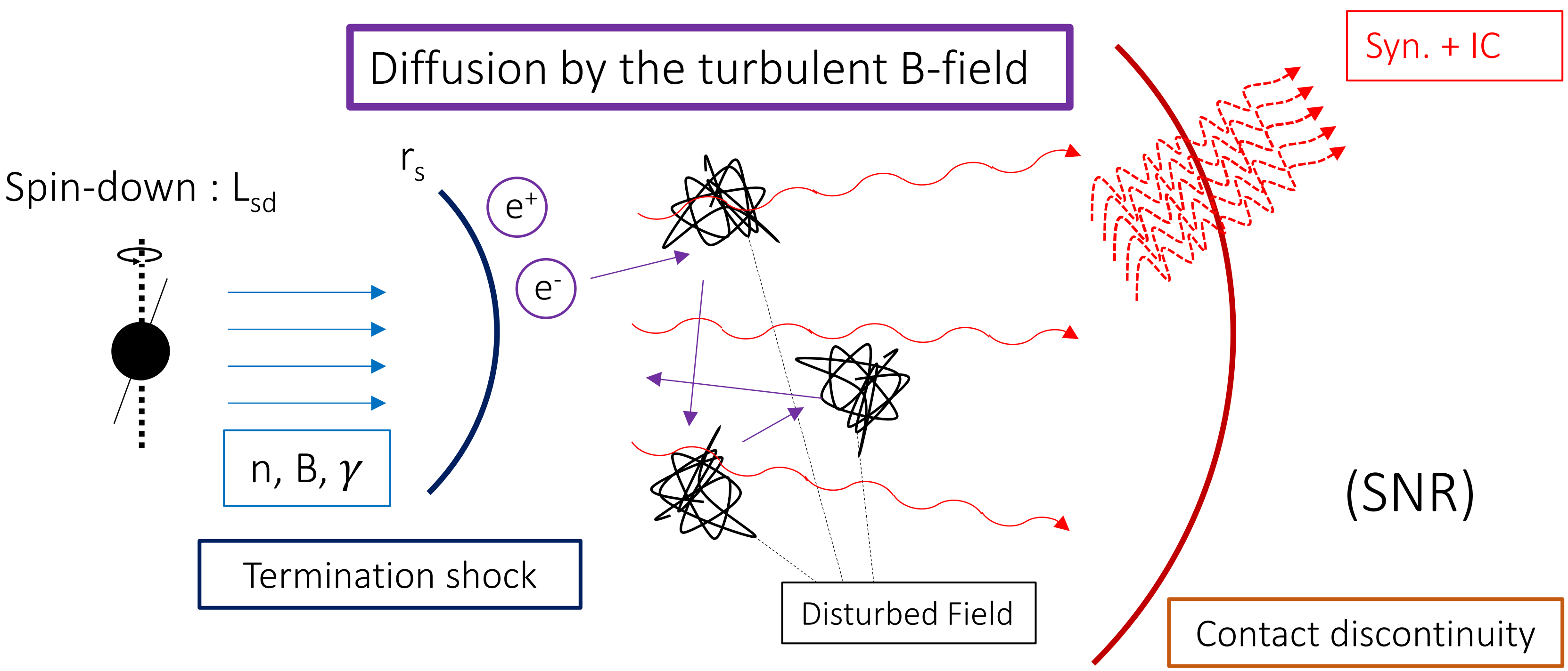


(Porth+ 2014b)

(Tang & Chevalier 2012, Porth+ 2016)

Let us consider the situation

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



Result -G21.5-0.9-

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

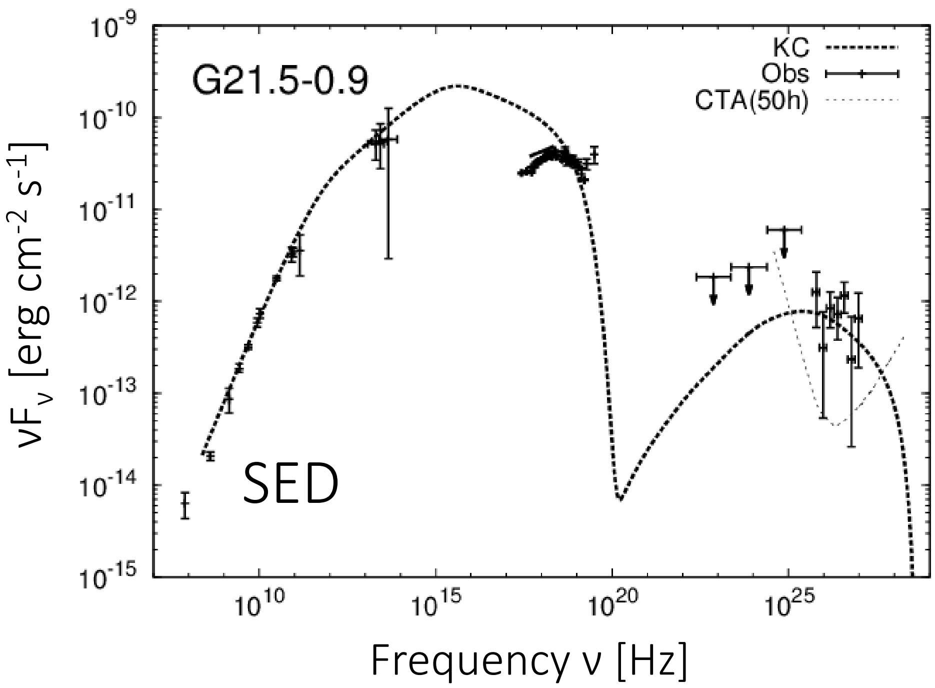
- Result for G21.5-0.9 (Omitted 3C 58)

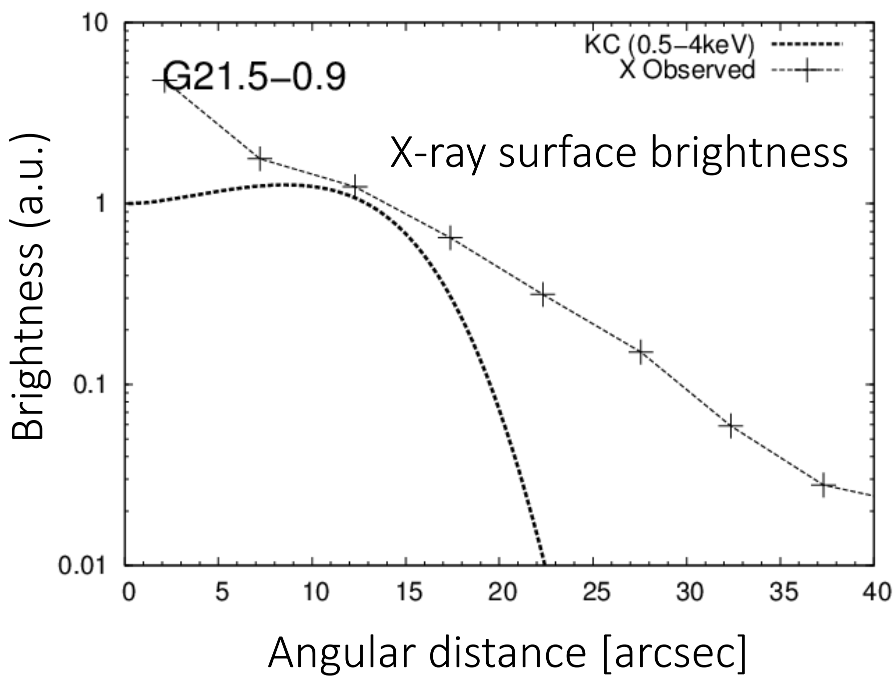
diffusion coefficient of X-ray emitting particles : $\kappa \sim 10^{27}\ \mathrm{cm^2\ s^{-1}}$

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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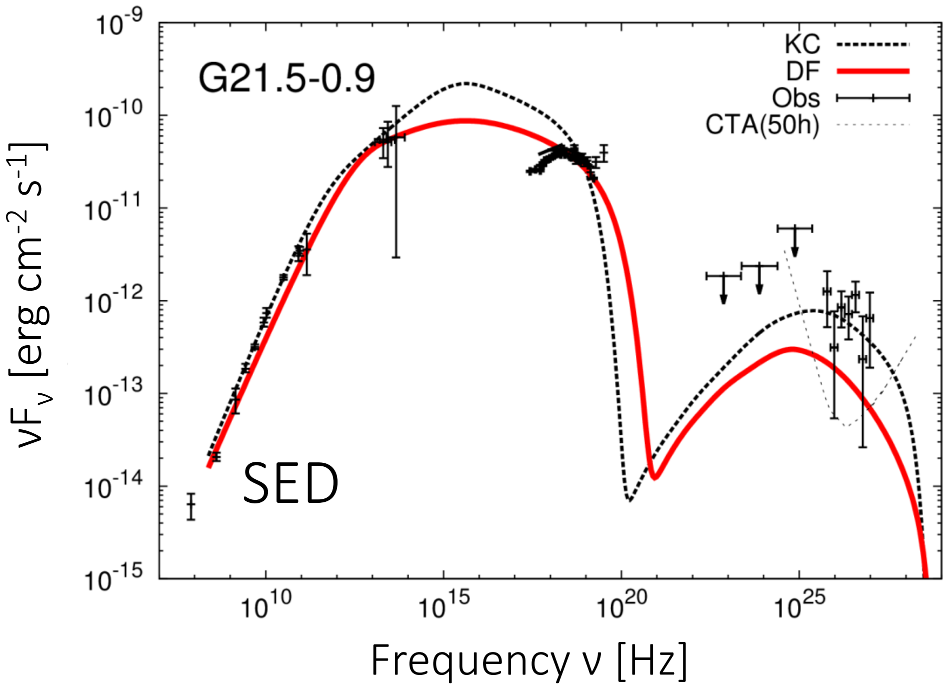

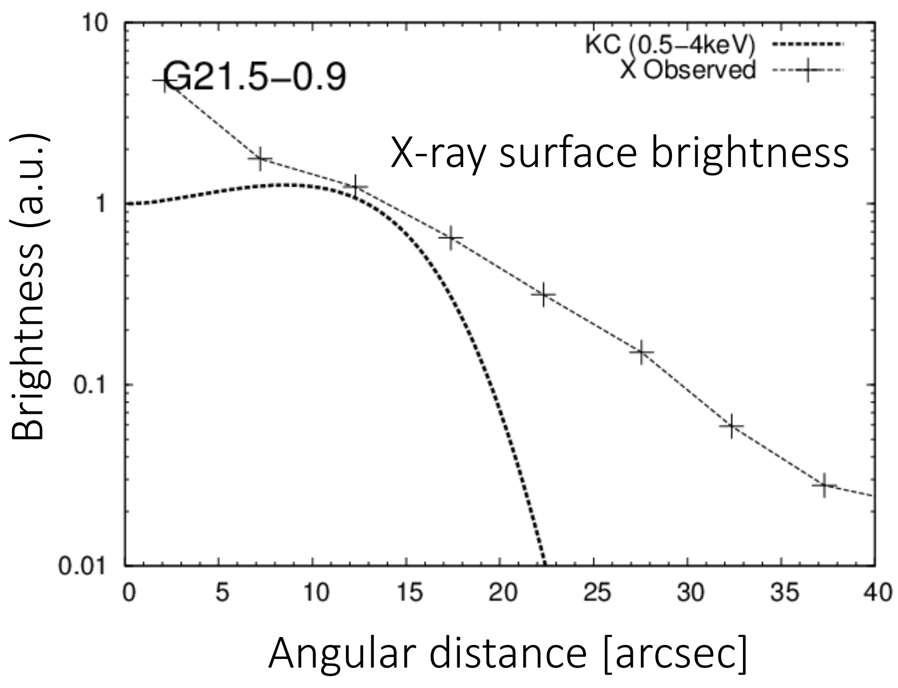

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X-ray surface brightness : **Extends to the edge!**

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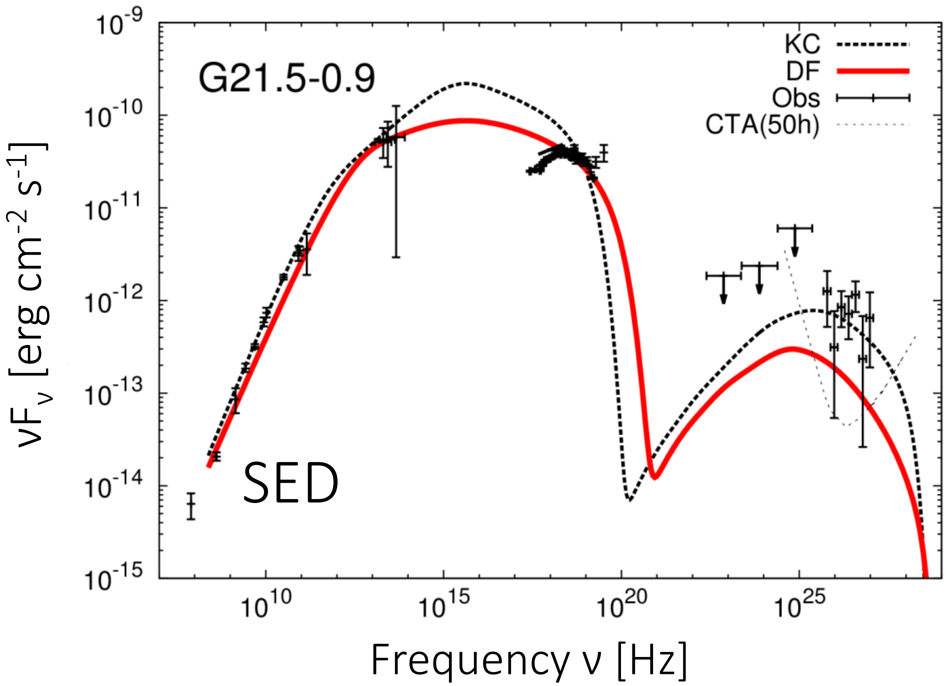

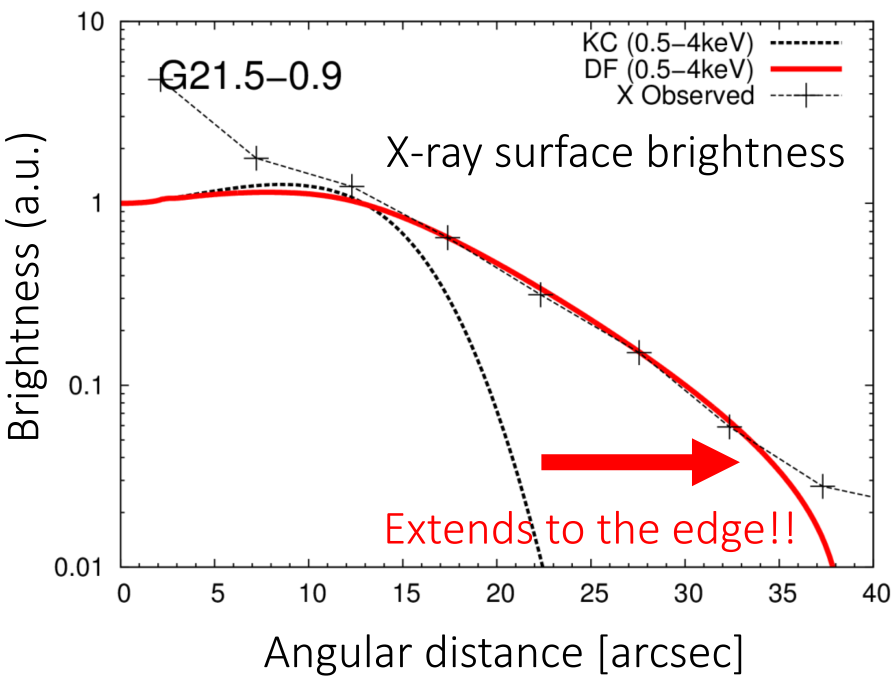

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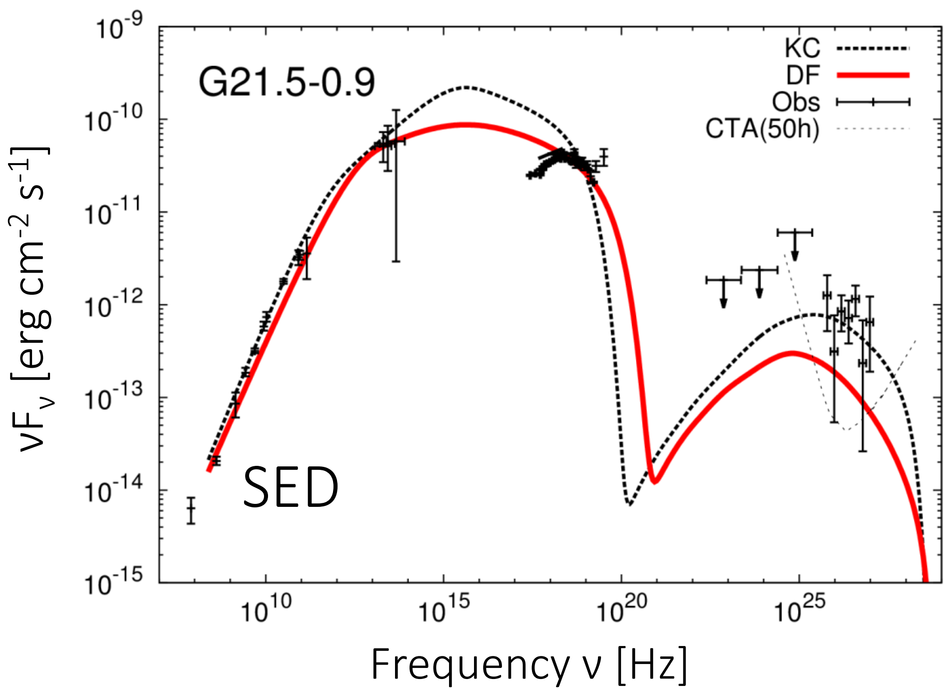
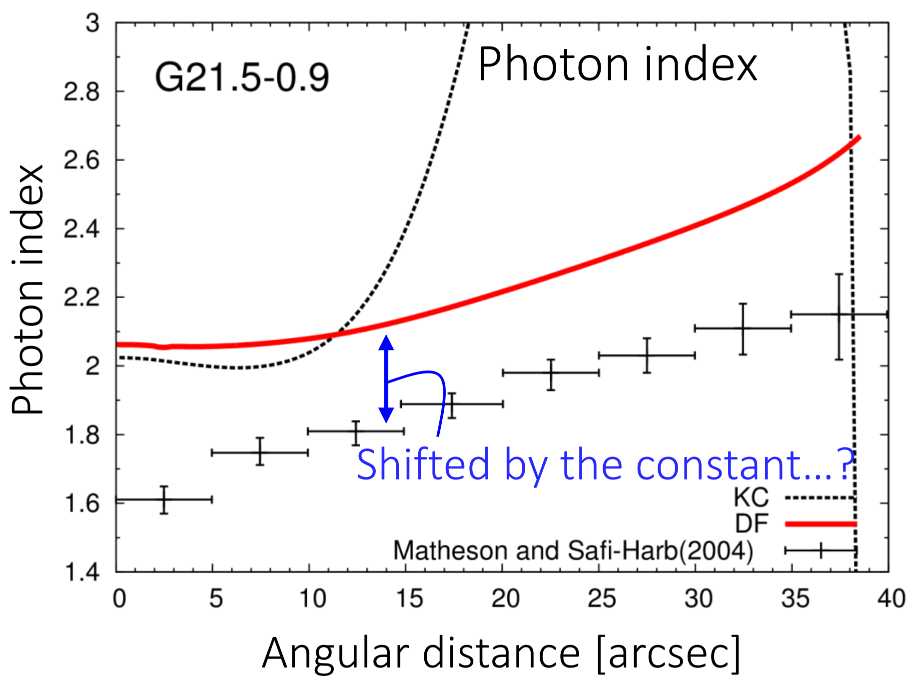
- Result for G21.5-0.9 (continues)

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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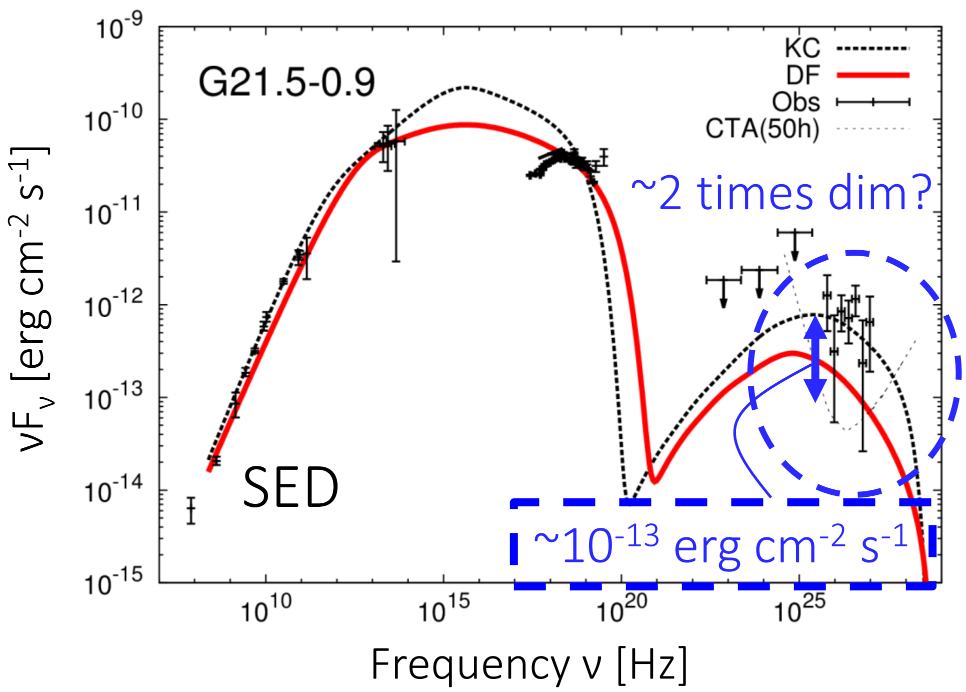
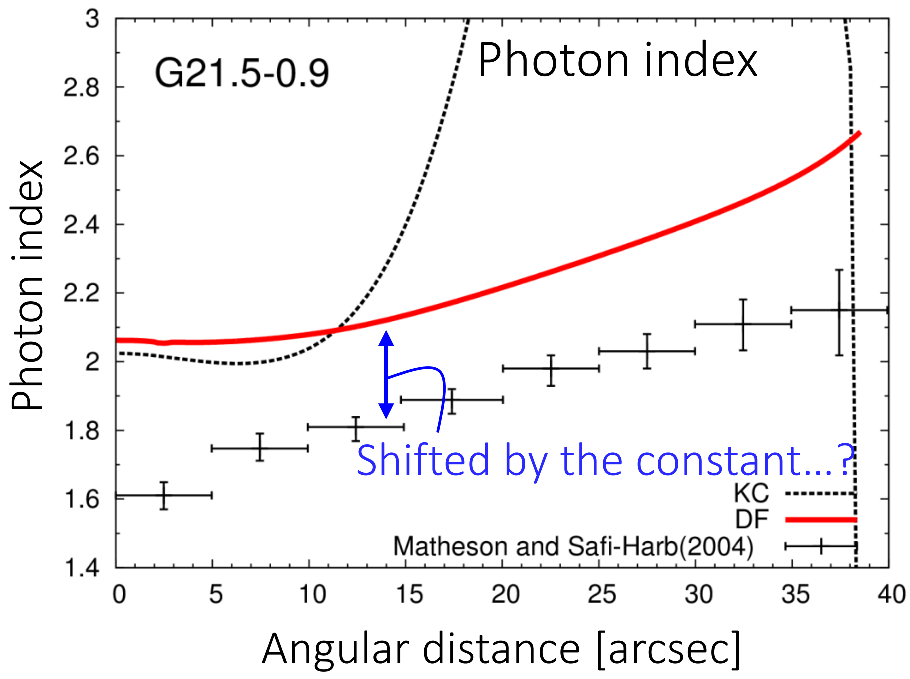




Escaped particles…?

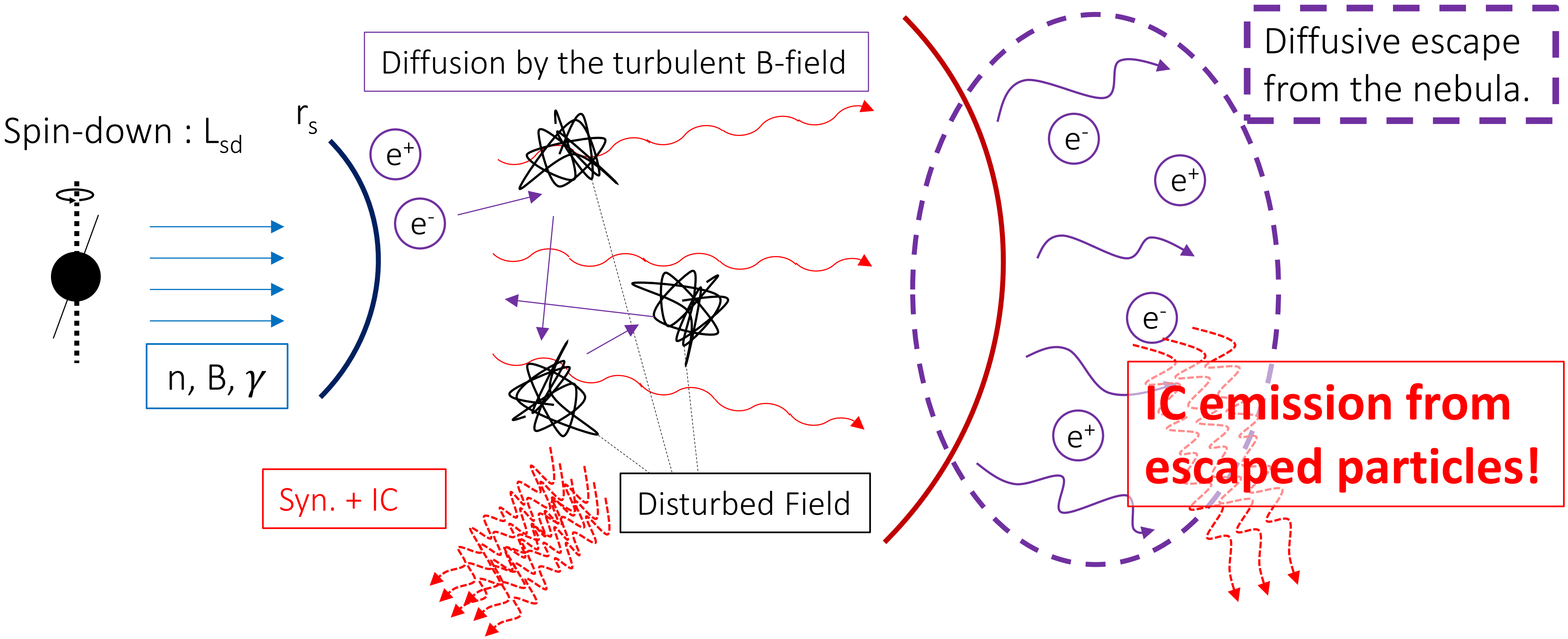
- The γ-ray emission from the particles which escaped out of the nebula.

  → 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 ~ 2 pc (corresponding to $90''$)



Conclusion

- 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.