Modelling the X-ray Emission of Boomerang Nebula

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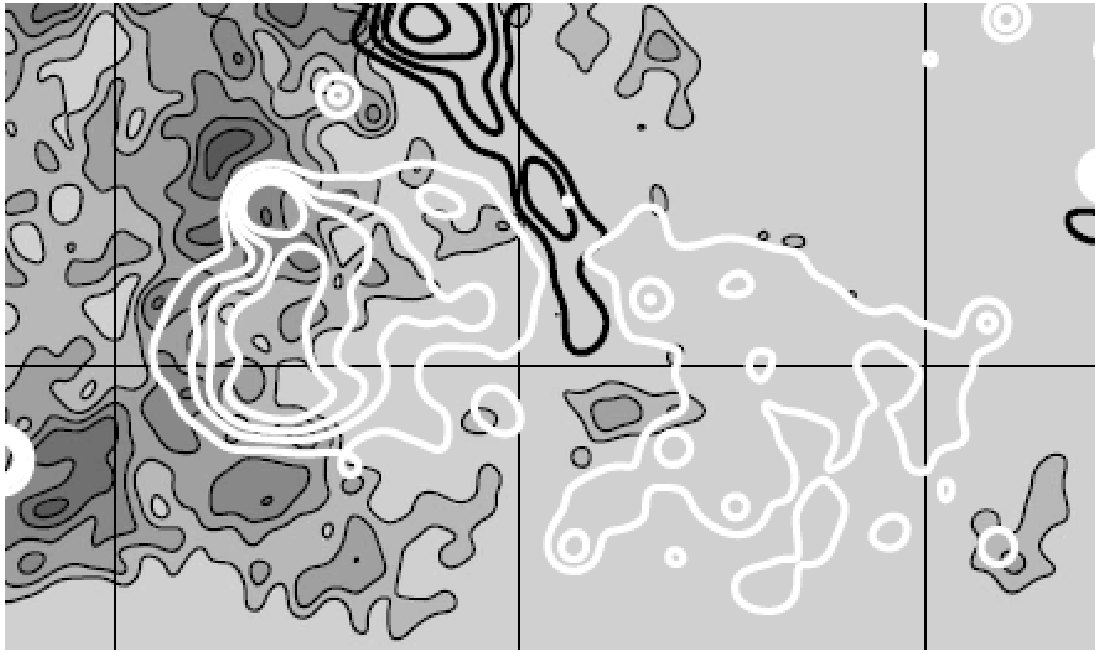
1. Introduction of the Boomerang Nebula

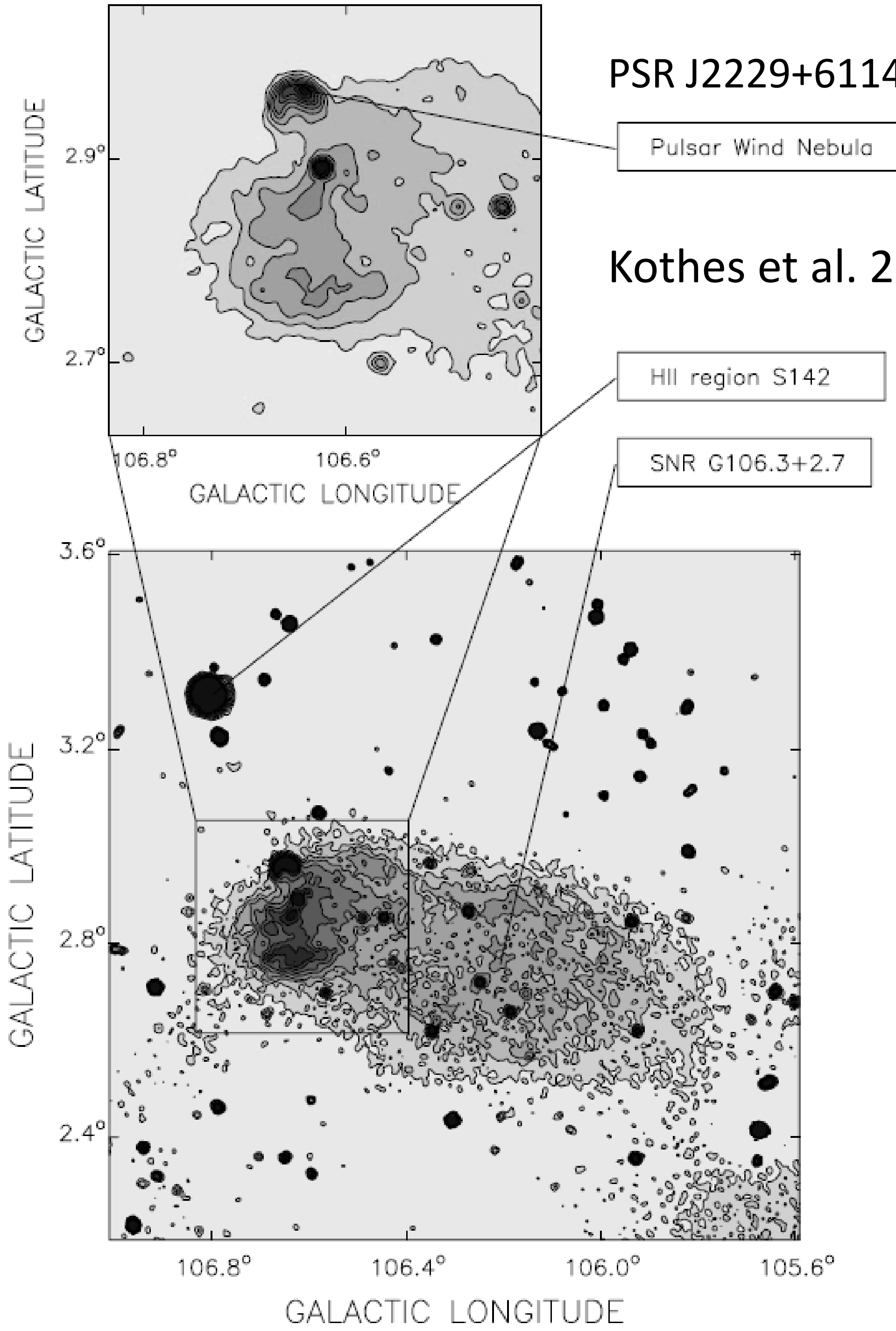
2. Modelling the X-ray Emission

3. Discussion & Summary

supernova remnant (SNR) G106.3+2.7

- Head -- brighter northeast component, interacting with HI cloud
- Tail -- fainter, more extended, southwest component, expanding into a cavity





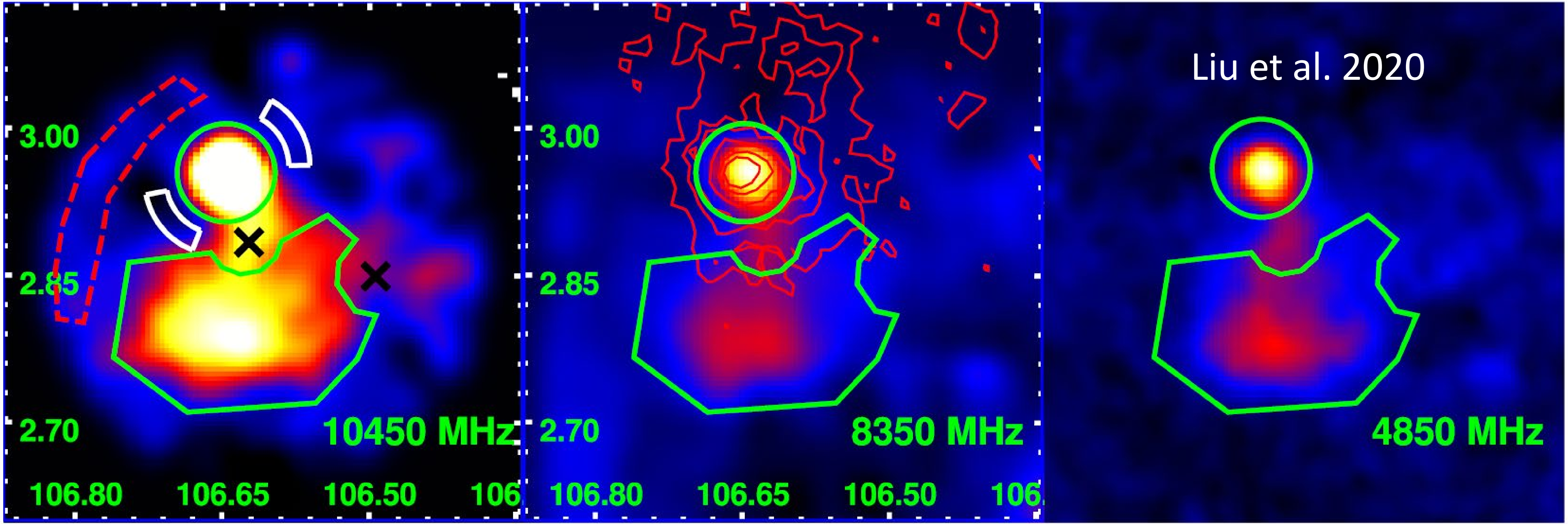
PSR J2229+6114

Kothes et al. 2001

pulsar PSR J2229+6114 & pulsar wind nebula (PWN) “Boomerang”

Period (*s*)	0.0516
Period derivative ($s\ s^{-1}$)	7.827×10^{-14}
Distance (*pc*)	800
Spin − down luminosity ($erg\ s^{-1}$)	2.2×10^{37}
Characteristic age (*yr*)	10460

Parameters (Halpern et al. 2001, Kothes et al. 2001)



Observations

Fermi-LAT, 3-500GeV (Xin et al. 2019)

VERITAS, 1-15TeV (VERITAS Collaboration 2009)

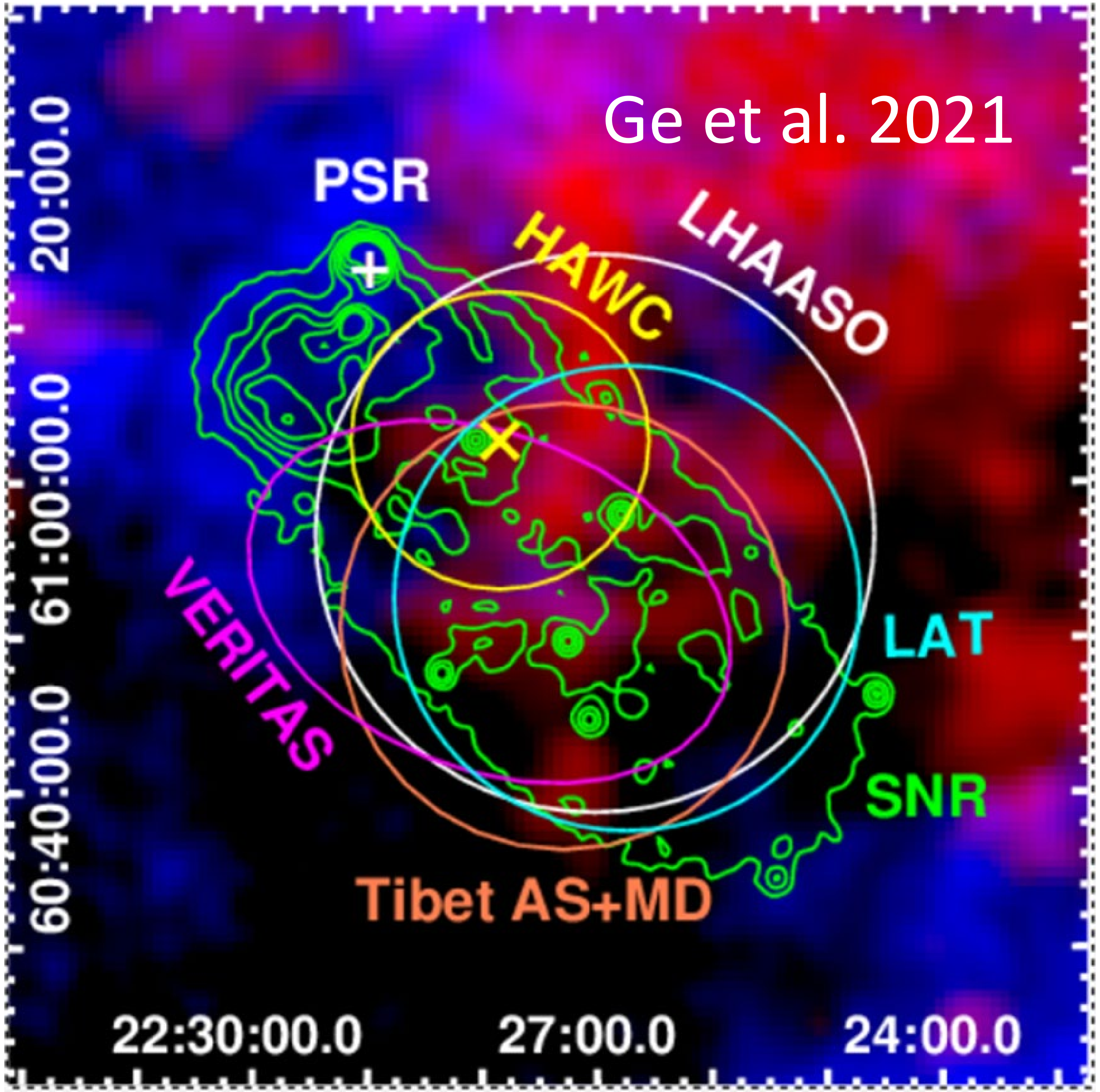
HAWC, 40-110TeV (HAWC Collaboration 2020)

Tibet AS+MD, 10-110TeV (Asγ Collaboration 2021)

LHAASO, 20-500TeV (LHAASO Collaboration 2021)

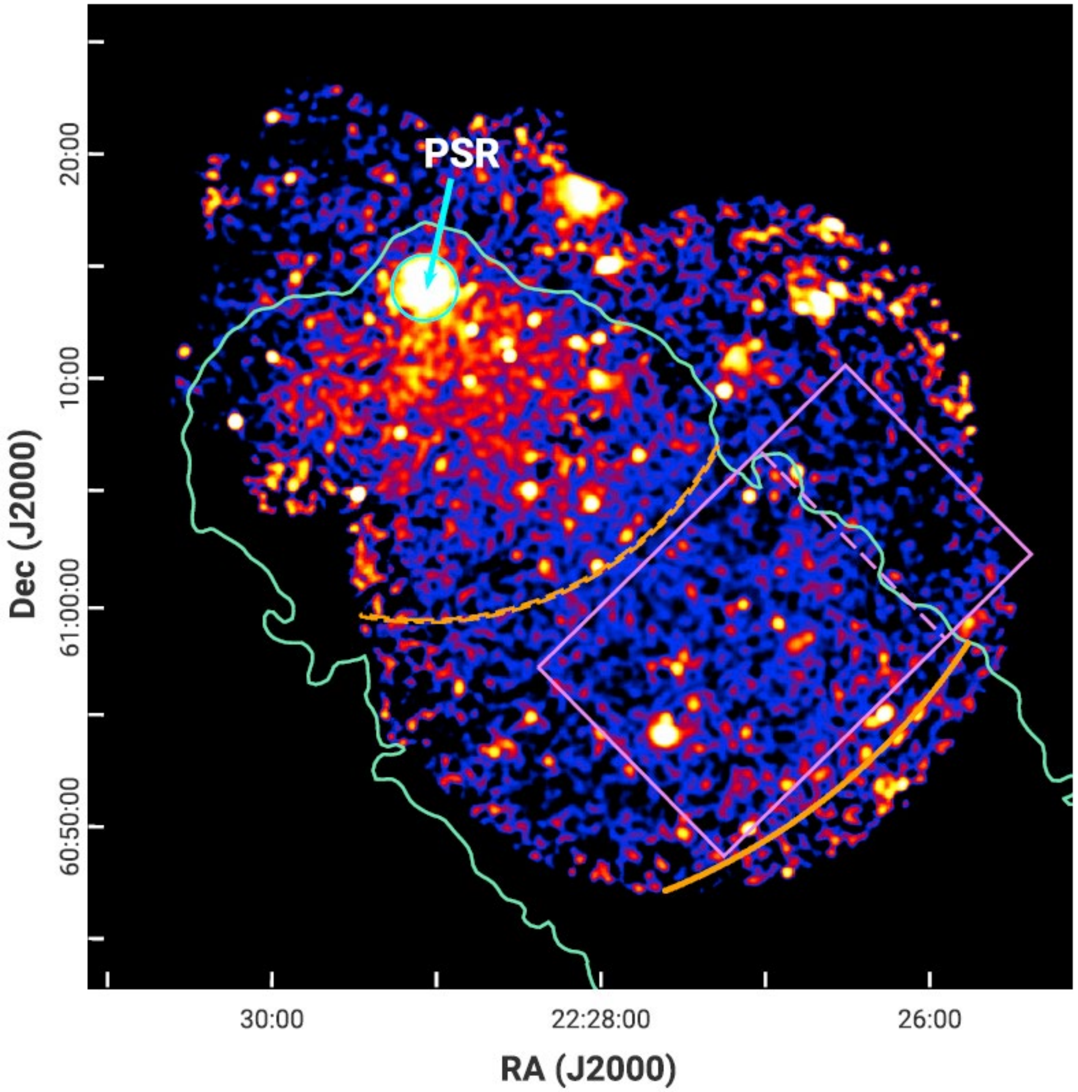
White +: PSR J2229+6114
Blue: atomic (HI) cloud
Red: molecular cloud
Green contours: the 1.4 GHz radio continuum of the SNR

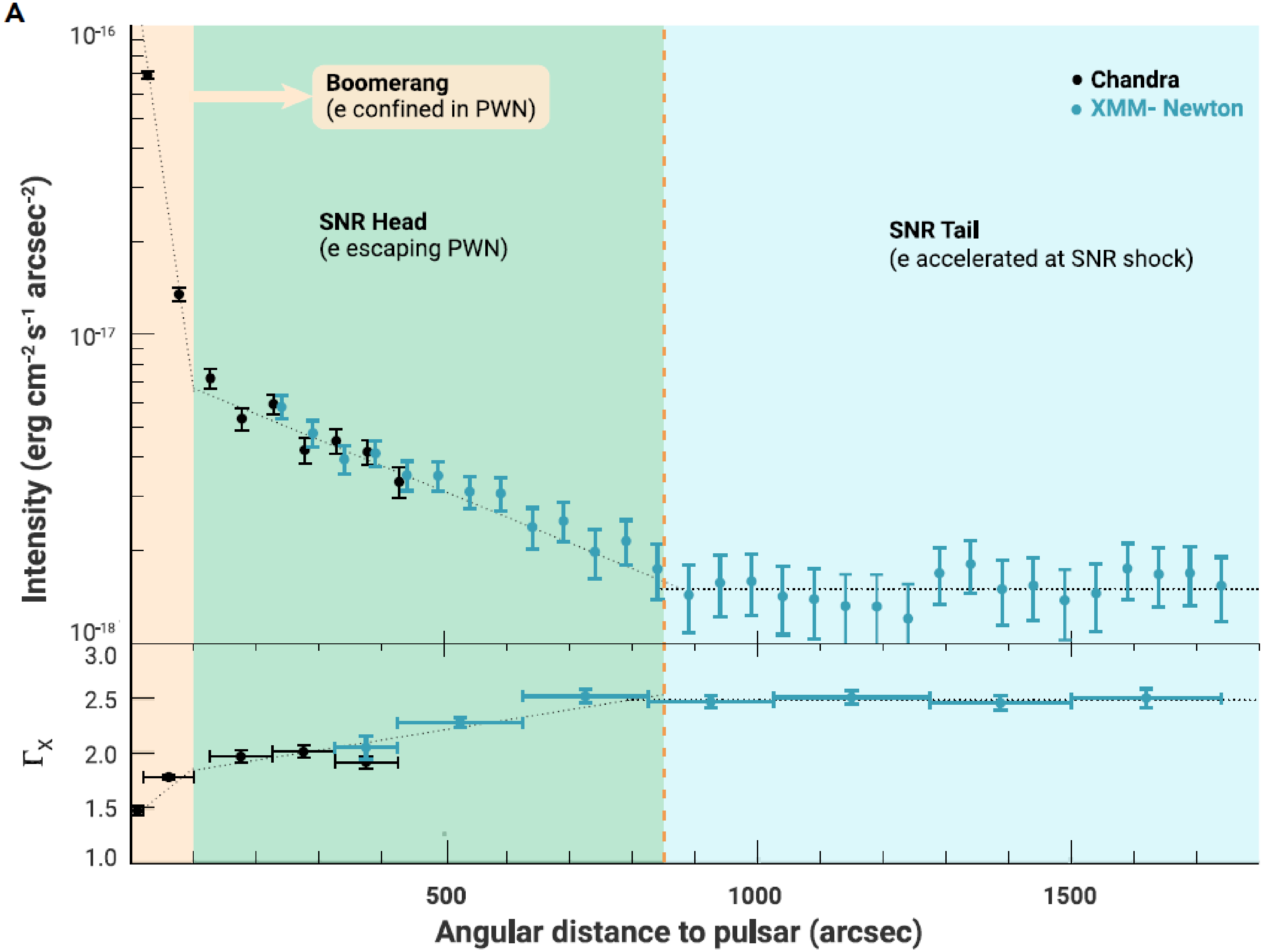
γ-ray coincident with the molecular cloud



Milagro, 20, 35 TeV (Abdo et al. 2007, 2009, not shown)

Radial profiles of X-ray intensity and the spectral index (Ge et al. 2021)





- "Since the X-ray-emitting electrons cool rapidly, the electrons in the tail region should be accelerated in situ."
- Two electron components are suggested.
- Details of the Suzaku data can be found in Fujita et al. 2021.

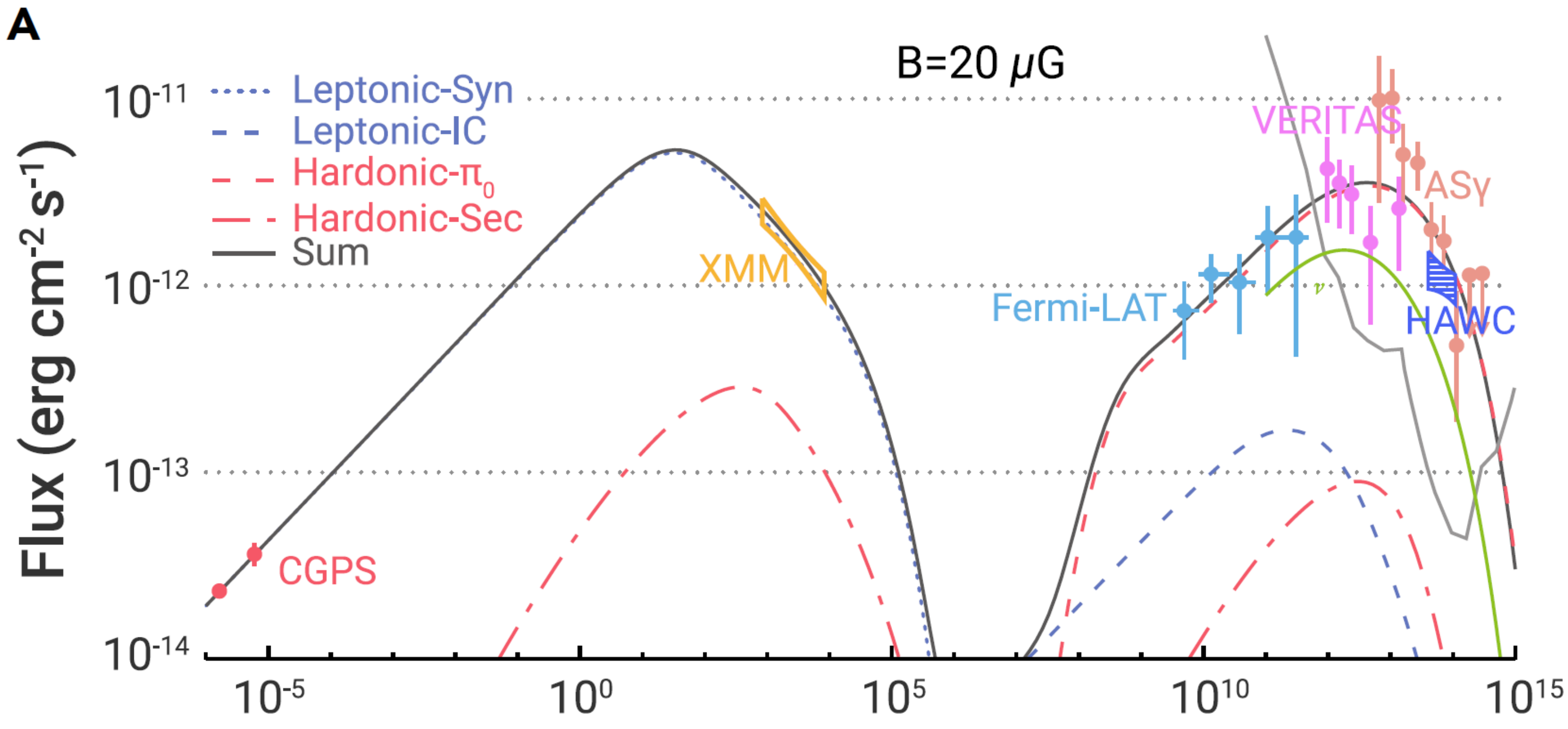
How to fit the profiles?

$$D(E) = D_0(E/100TeV)^{delta}$$

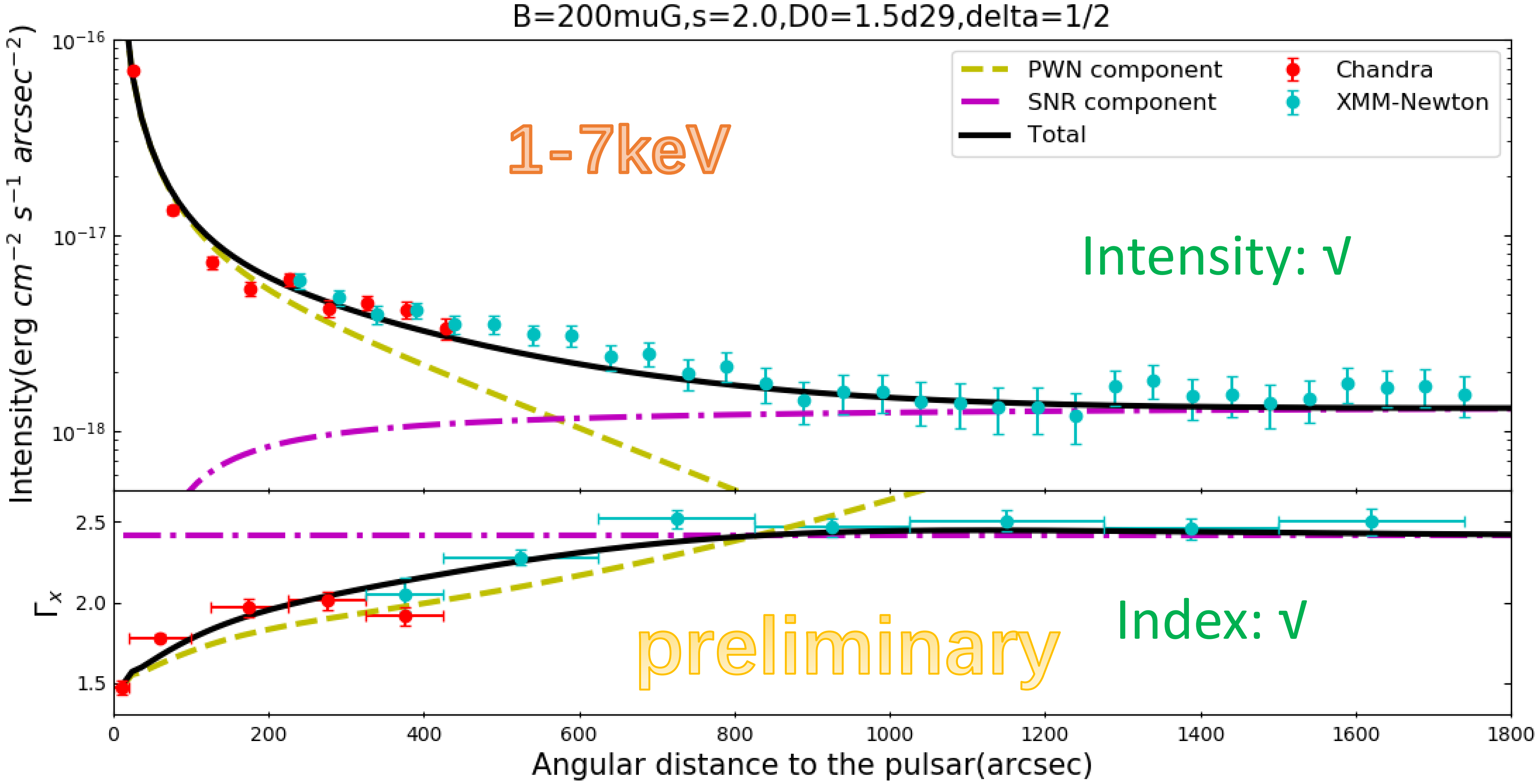
PWN component: ballistic + diffusive propagation

$$N(\gamma)_{inj} = (\gamma/\gamma_c)^{-s} e^{-\gamma/\gamma_{max}}$$

SNR component:
(Ge et al. 2021)

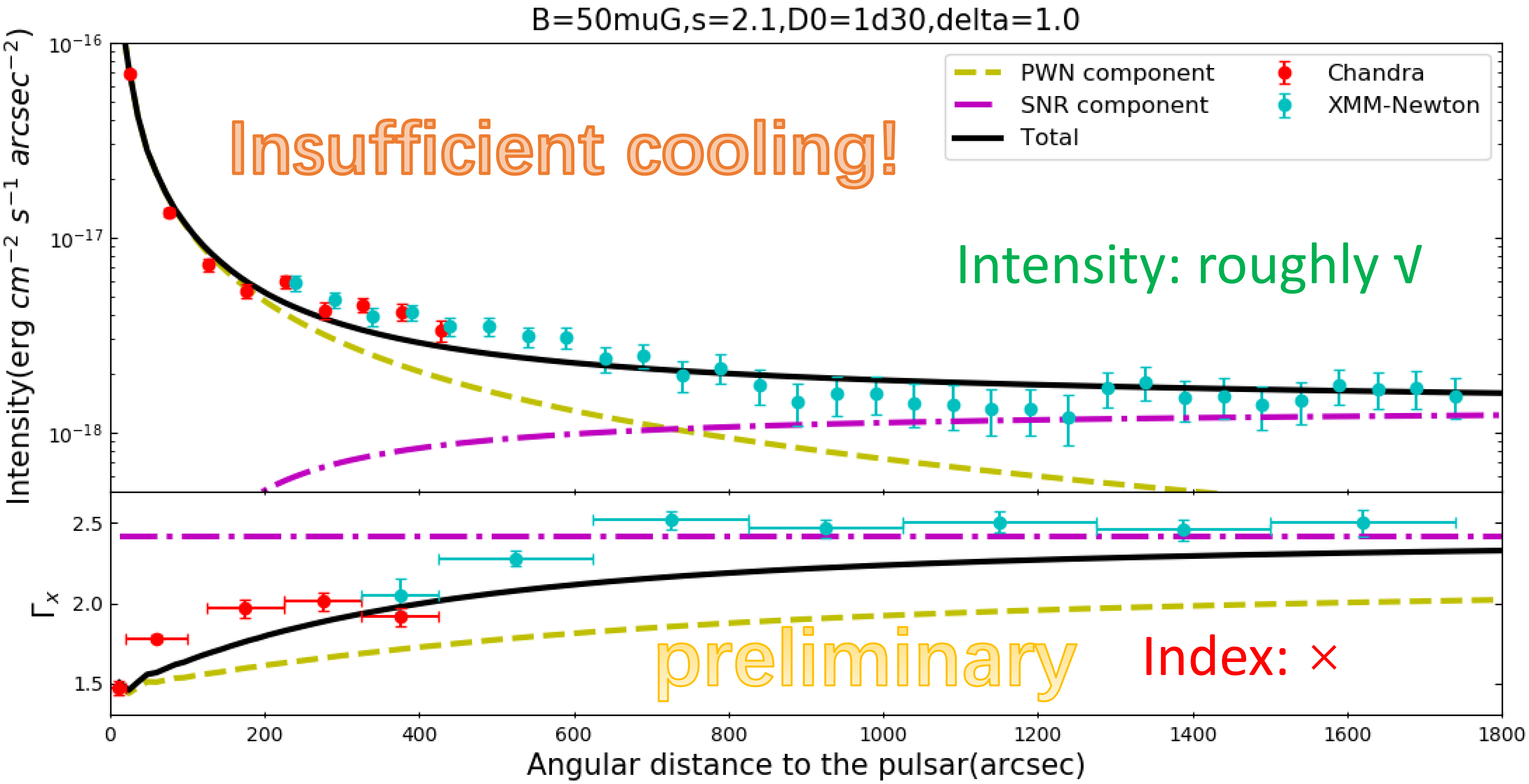


A solution with a strong magnetic field



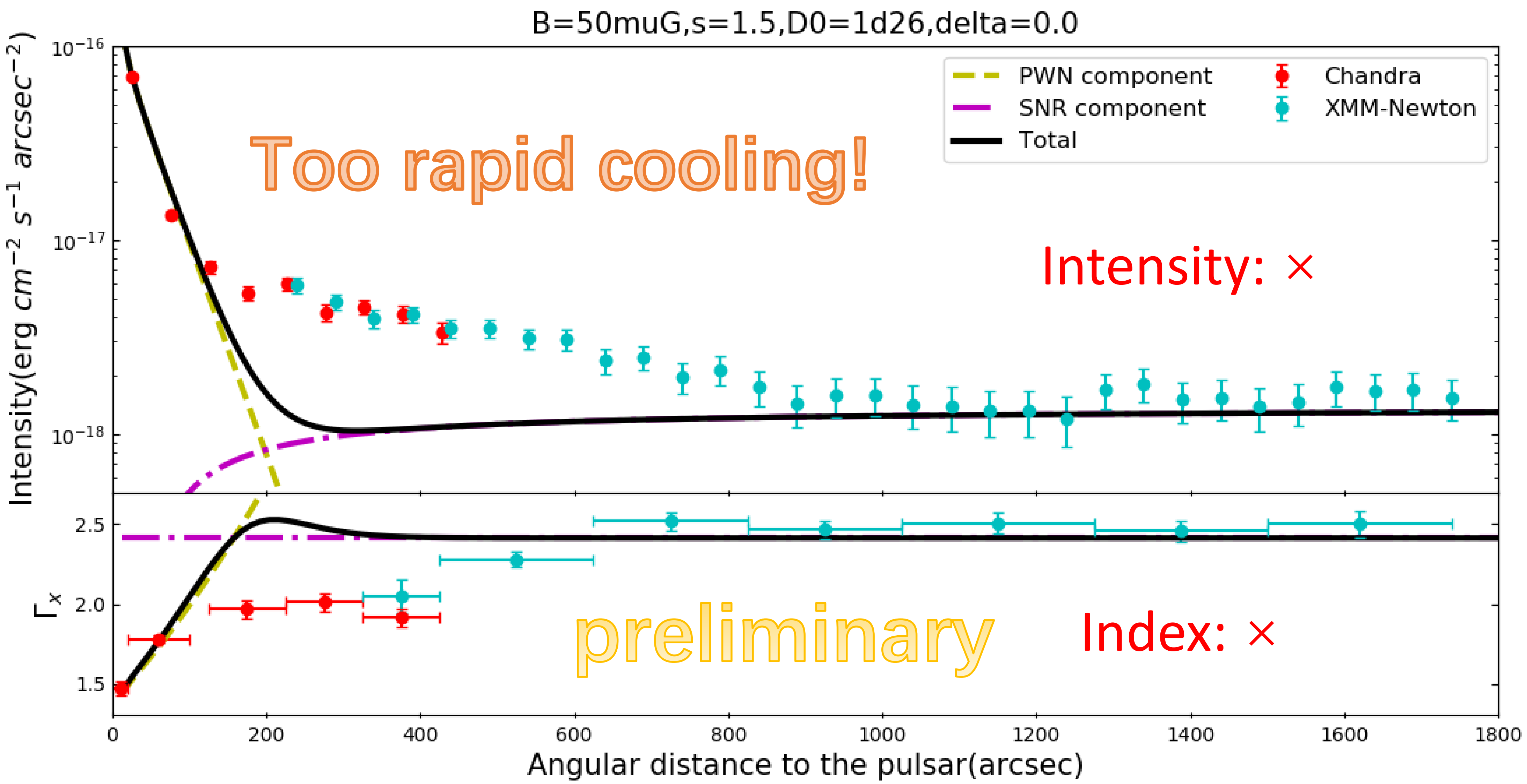
What about a weaker magnetic field?

- Large D0 & delta are conducive to diffusion.
- The change of spectral index is not enough.

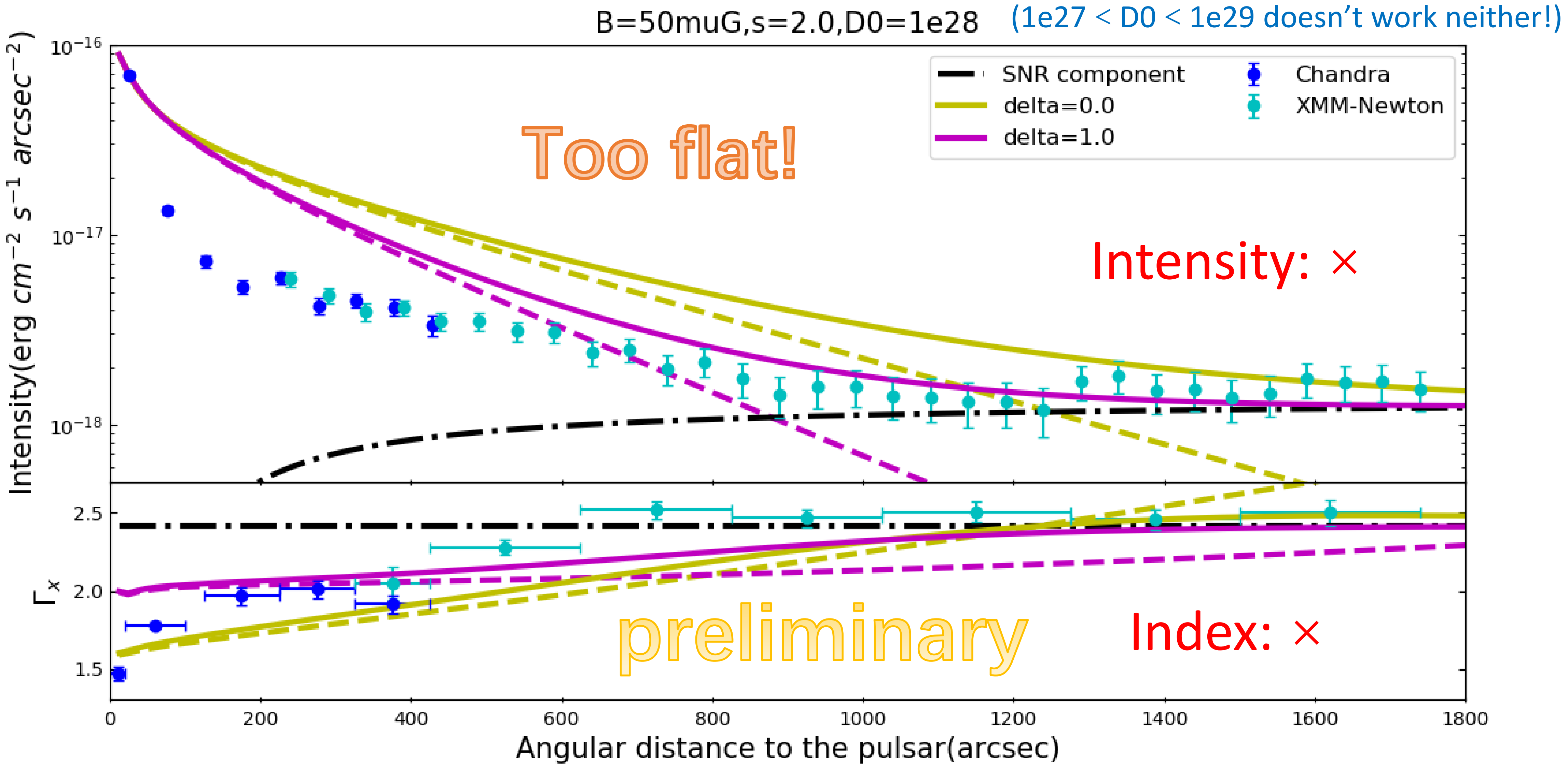


Cool!!!

- Smaller D0 & delta are adopted.
- The changes of both parameters are extreme.

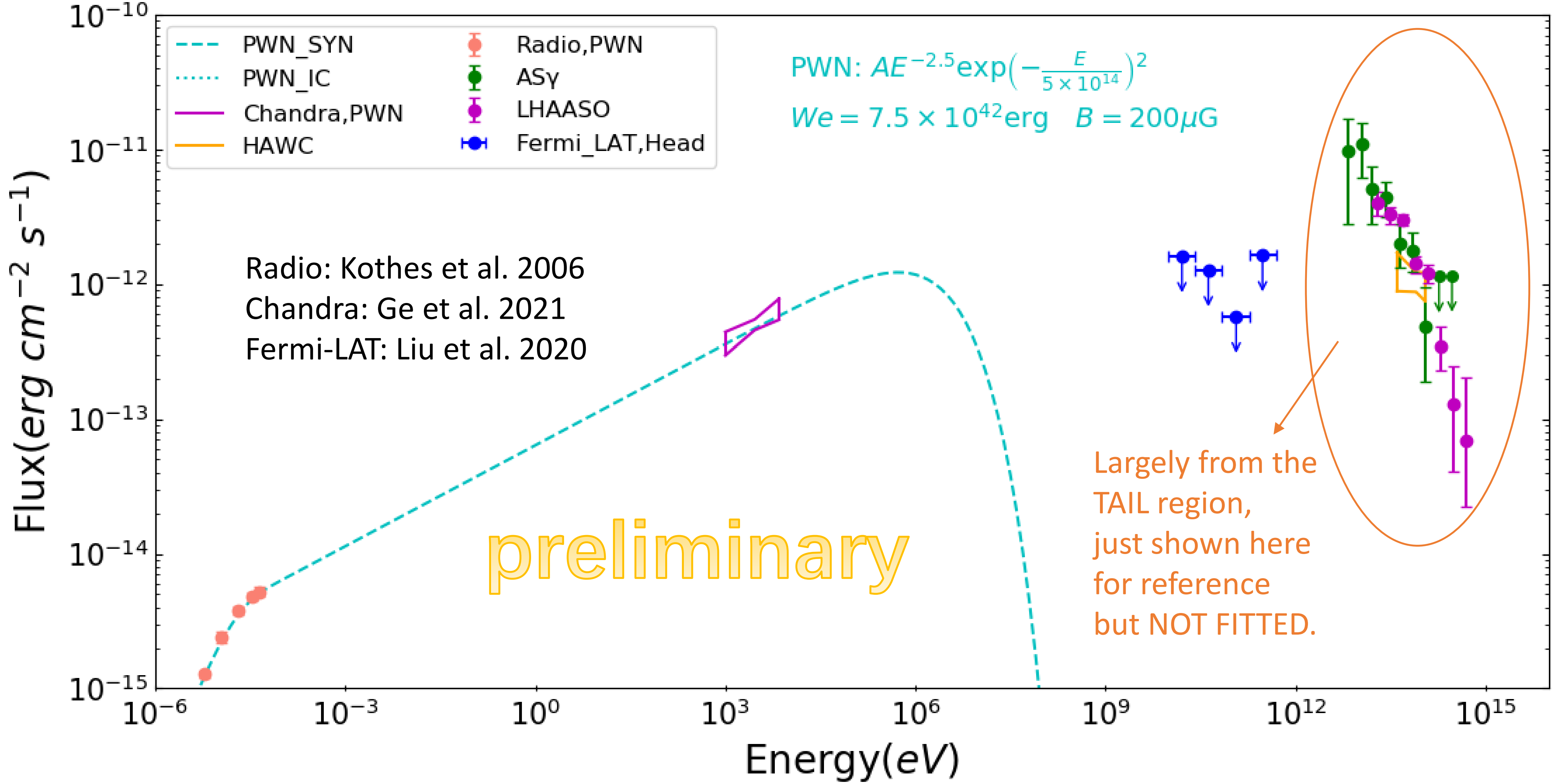


An intermediate case? Unfortunately no.



SED of PWN

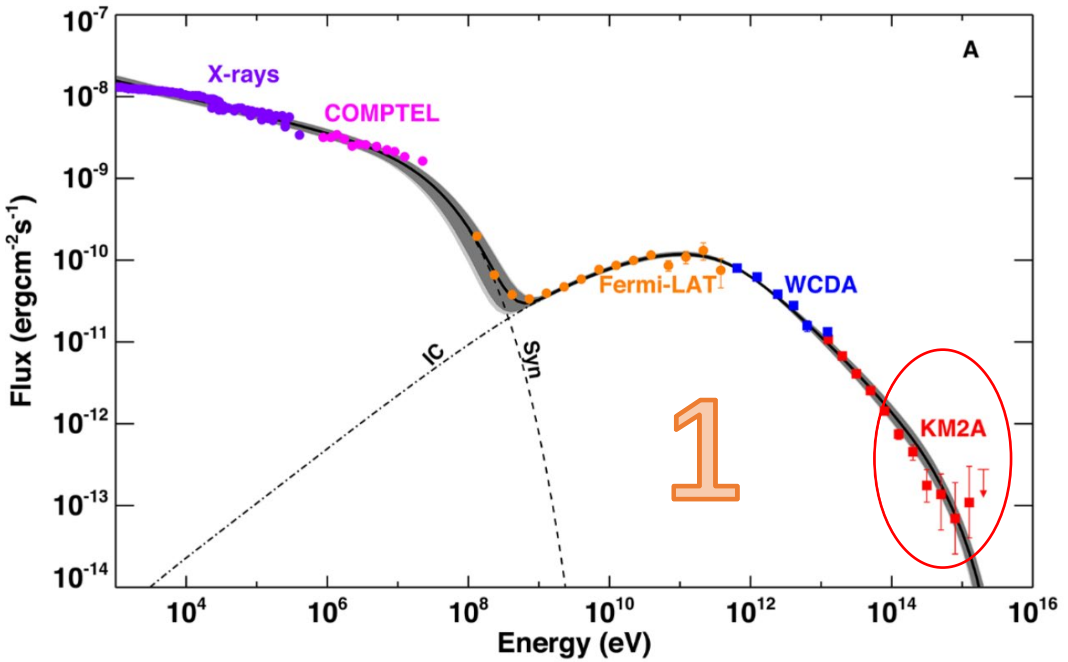
- The IC radiation inside the PWN is severely suppressed.
- $U_B \sim 1000, U_{CMB} \sim 0.26, U_{Syn} \sim 8.3 \times 10^{-5}\ (eV\ cm^{-3})$

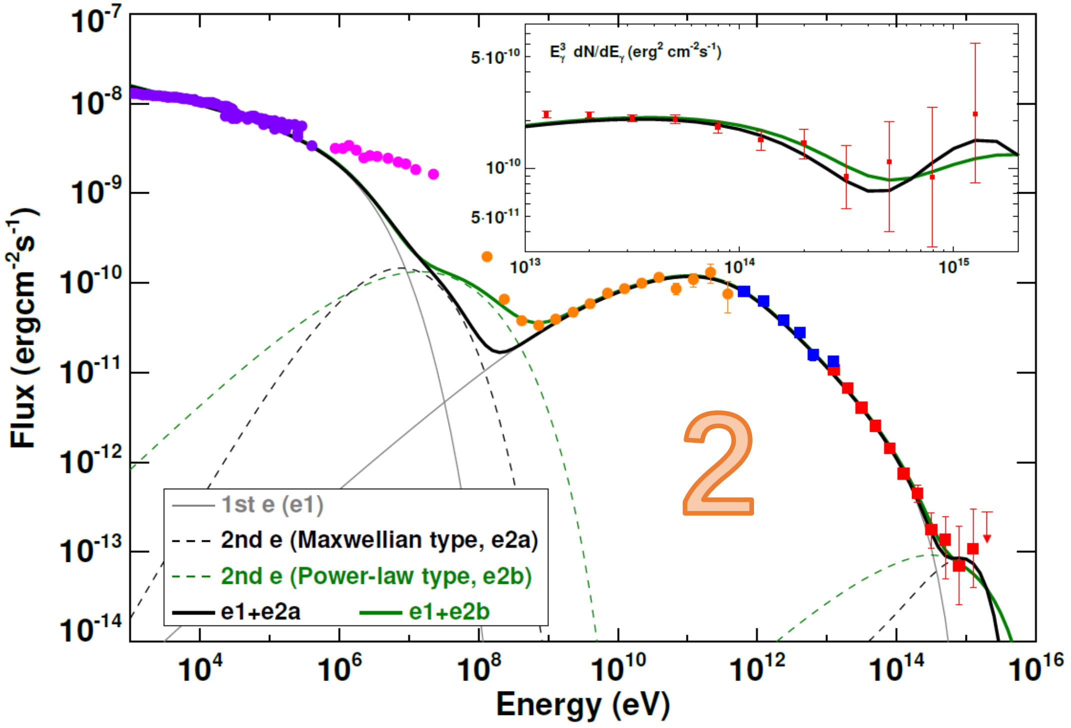


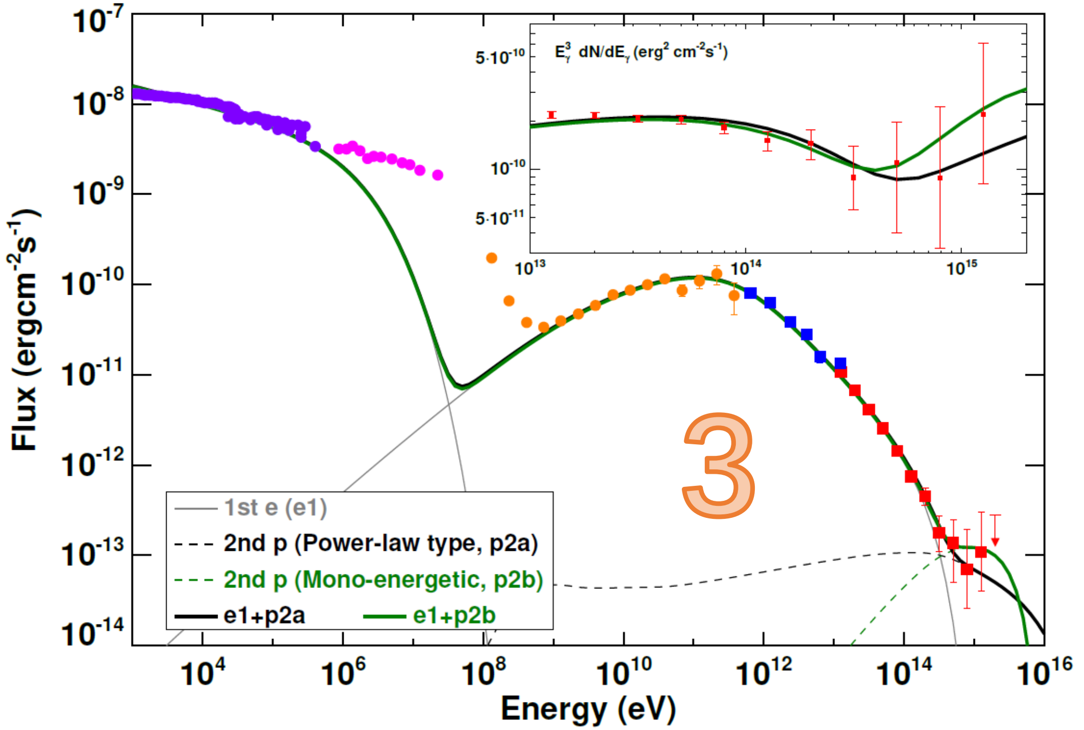
A second spectral component like Crab?

1. One-zone scenario
2. Two-zone scenario: two electron populations
3. Two-zone scenario: electron + proton

LHAASO Collaboration 2021

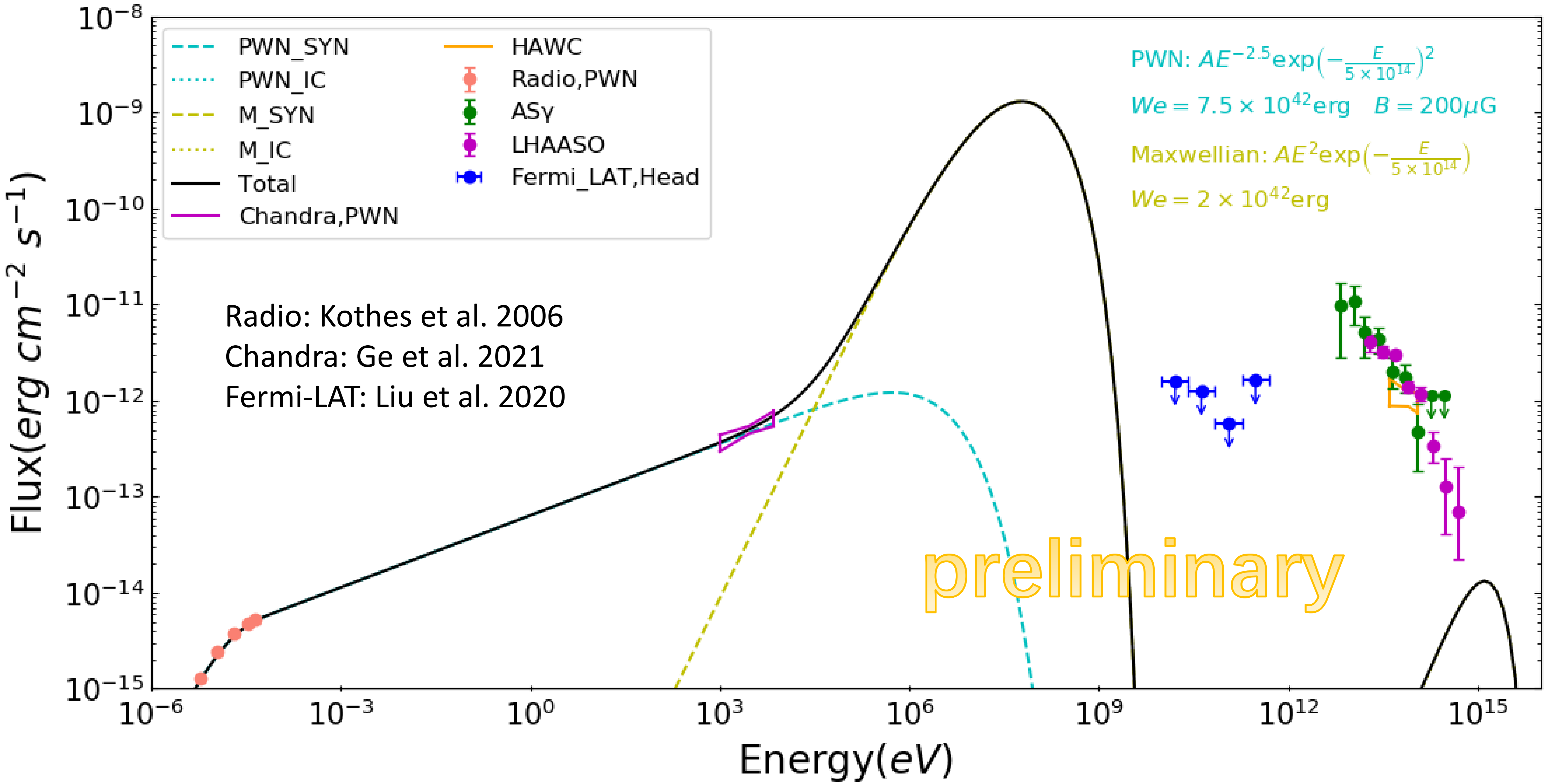






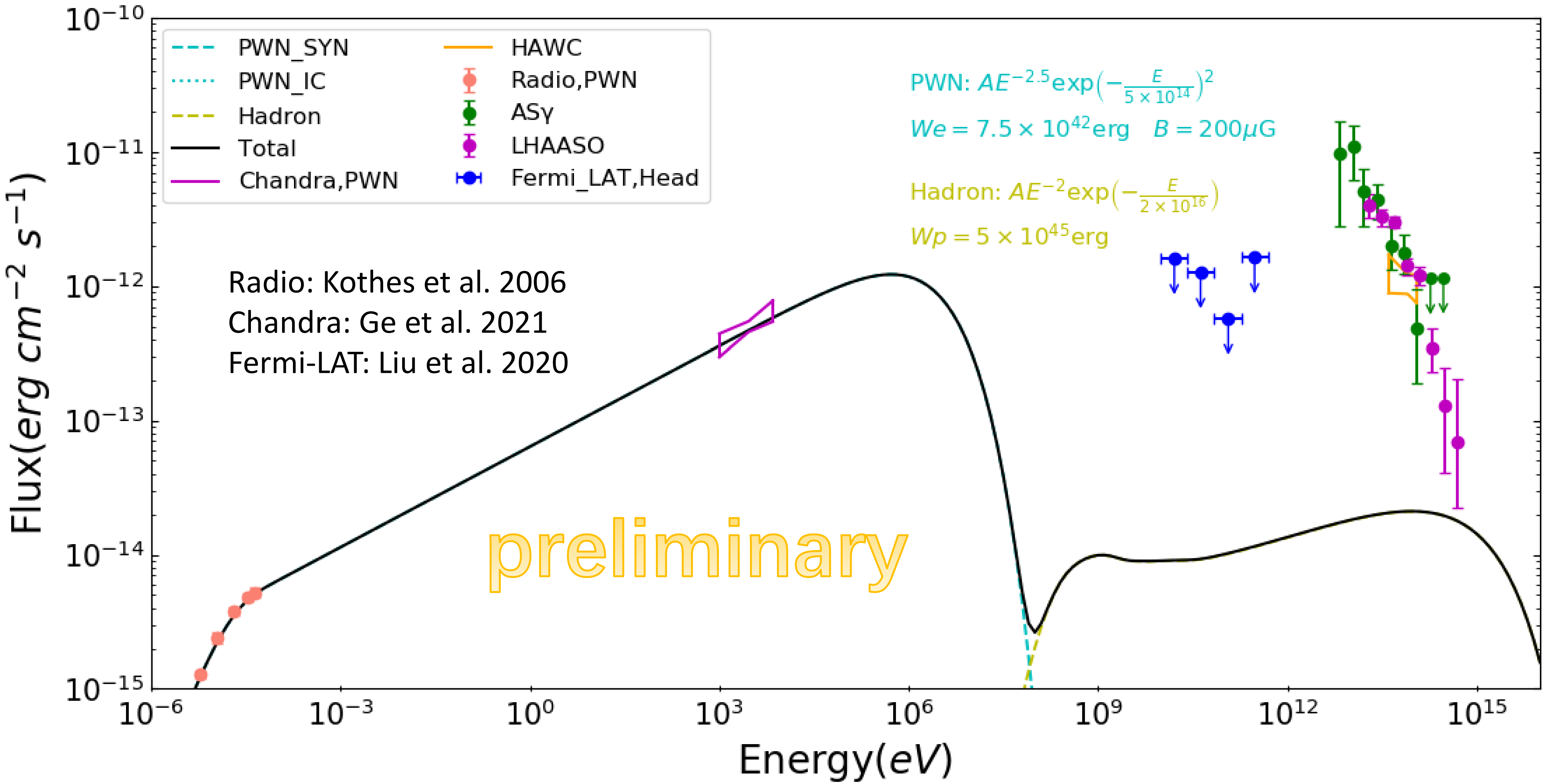
Two-component leptonic scenario

- extend the SED to a few PeV but not much further
- can be verified via hard X-ray observation



Leptonic-hadronic scenario

- extend the SED to well beyond 1 PeV
- can be verified via VHE γ-ray observation



Summary

- The X-ray intensity profile and the spectral index profile of the SNR-PWN complex can be explained with two components.
- A ballistic-diffusive transition is taken into account for electrons from the PWN.
- $B \sim 200 \mu G$: √ Much smaller B is disfavored.
- IC radiation inside the Boomerang nebula is severely suppressed.
- If a second leptonic population or a hadronic population exists, the Boomerang nebula may still be a gamma-ray emitter.
- The requirement for the magnetic field may be different in a different model (e.g. advection).

Thanks!