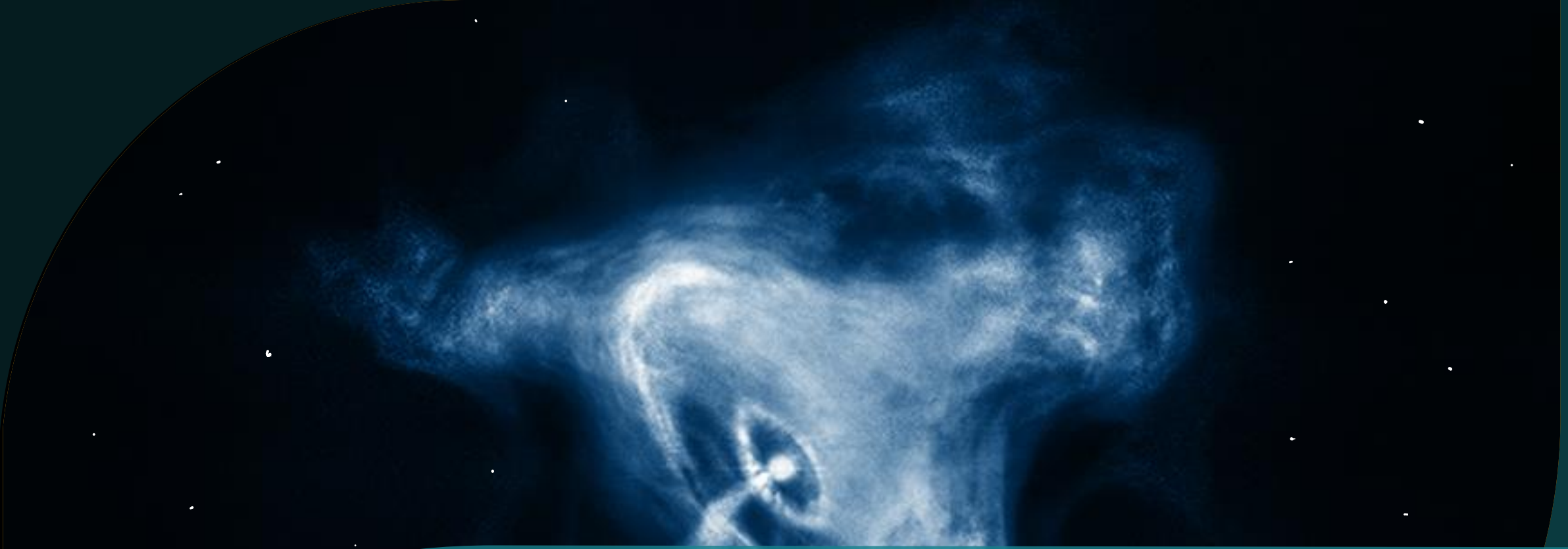

Multi-wavelength modeling of Pulsar Wind Nebula Halo

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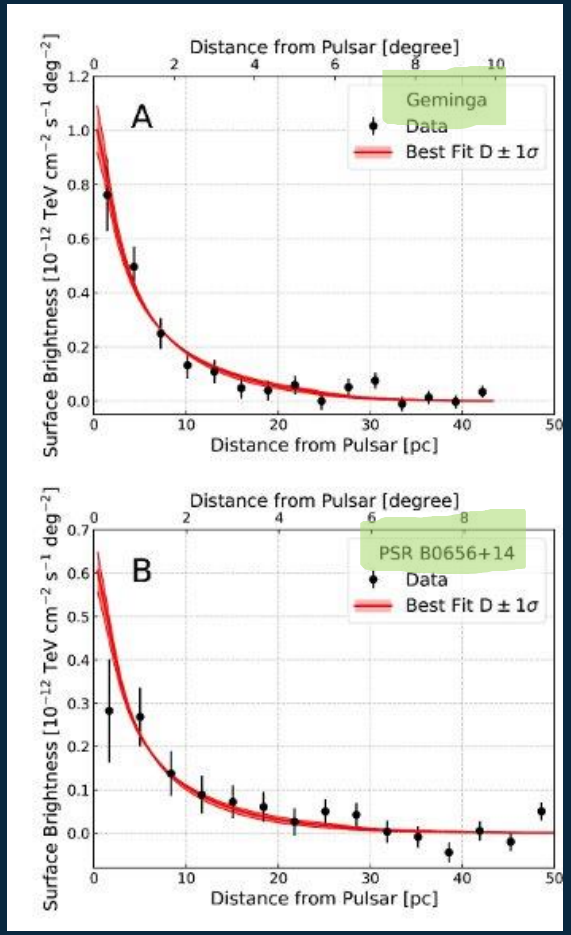
University of Amsterdam

Observational Motivation: TeV γ-ray Halos Around Pulsars

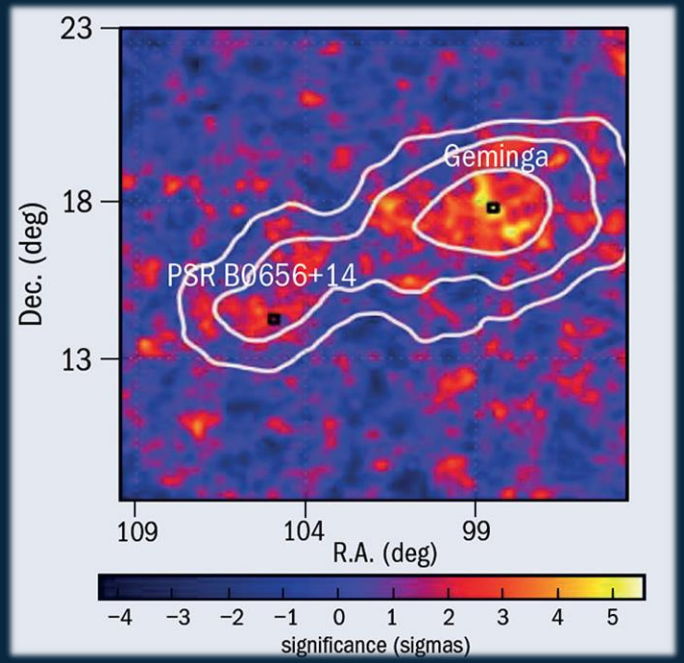


- HAWC observed extended γ-ray emission around Geminga pulsar and PSR B0656+14 (2016)

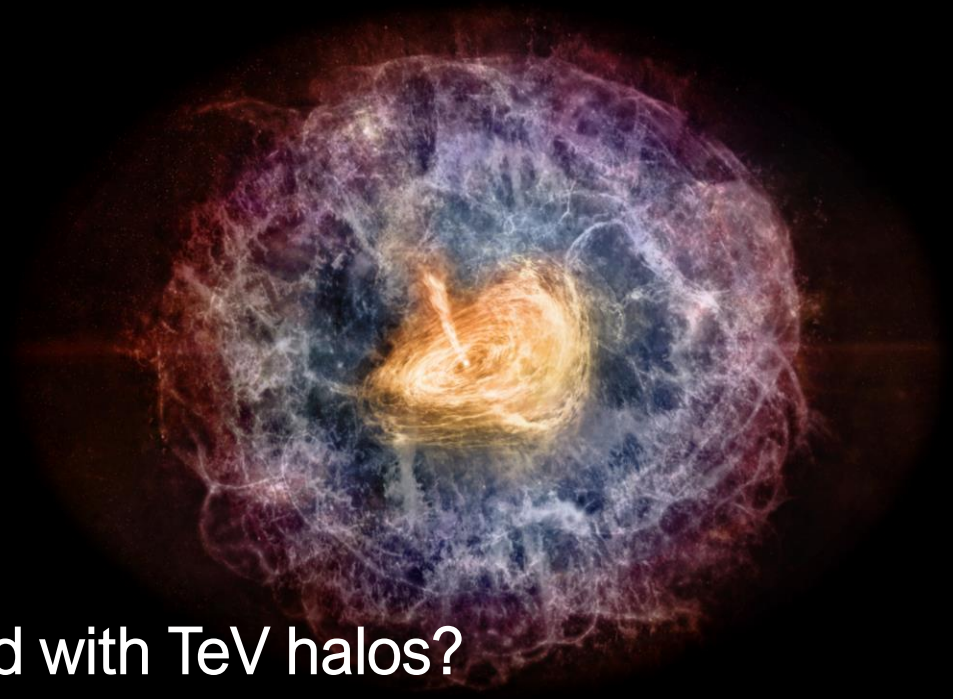
Energy: 4-50 TeV

Size: ~10 pc

- **Suggestion:** Inverse-Compton (IC) emission from escaped electrons/positrons accelerated at the termination shock of pulsar wind nebula (PWN)

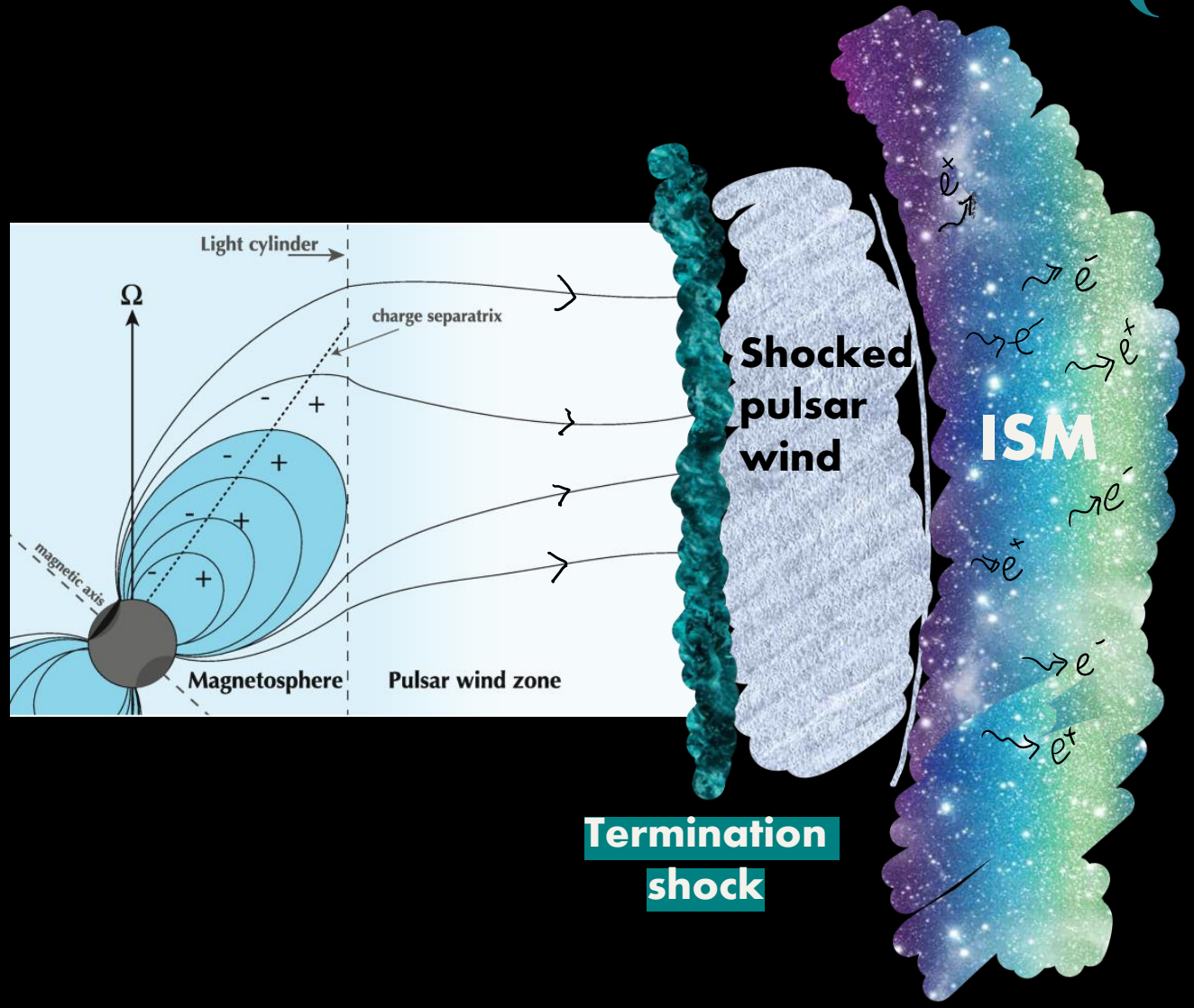


Open Questions



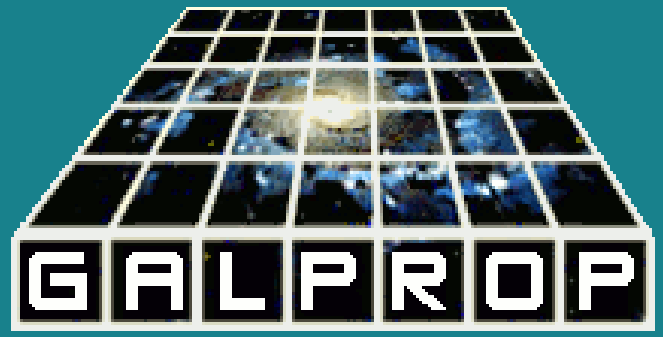
- What is the origin of TeV-halos?
- How often are pulsars/PWN associated with TeV halos?
- What can we learn about leptonic/hadronic particle acceleration in these systems?
  - Can PWN explain the cosmic ray positron excess?
  - Can PWN be hadronic PeVatron?

Pulsar Wind Nebula (PWN)

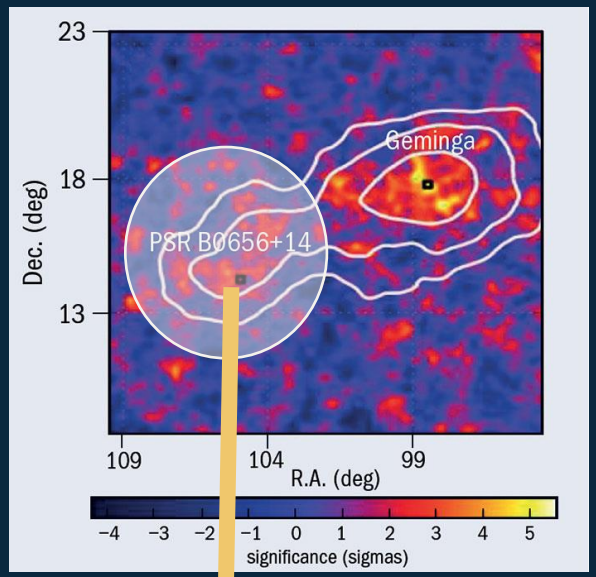


- The pulsar wind is driven by the pulsar spin-down power $\dot{E}$
- The pulsar wind forms termination shock at the contact with circumstellar medium
- PWN has been detected across the EM spectrum: from the lowest frequency $\nu \leq 100$ MHz radio waves PeV energy γ-rays

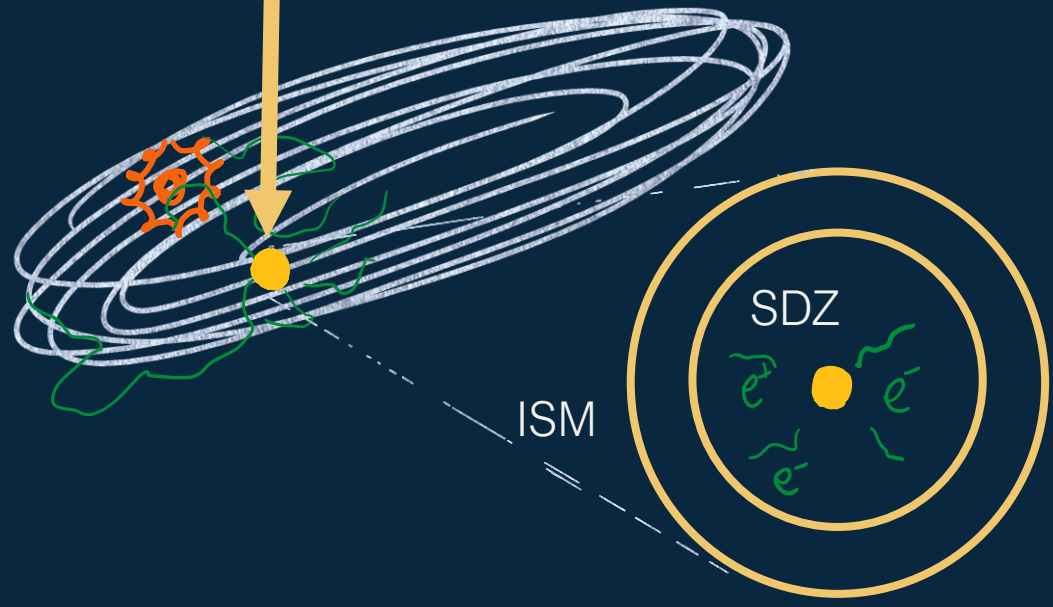
Simulating TeV-halo of Monogem Pulsar with



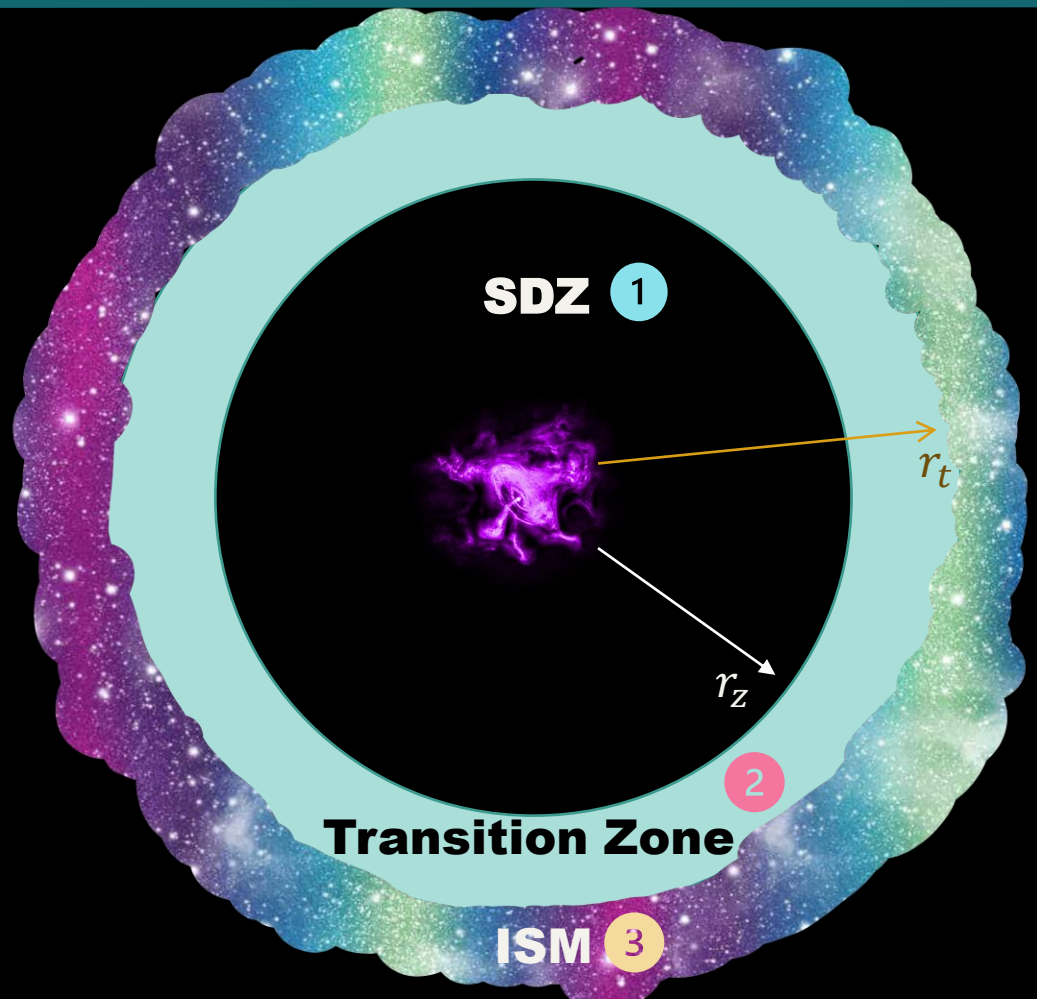
GALPROP is a numerical code for calculating the propagation of relativistic charged particles in the Galactic scale and the diffuse emissions produced during their propagation



- Mid-aged pulsar associated with the Monogem ring (~65pc radius in X-ray)
- The power-law component of X-ray from the PWN of PSR 0656+14 is observed by CHANDRA
- TeV-halo observed by HAWC have an extension of ~25pc across around the PWN



Slow Diffusion Zone (SDZ) Model



$$r_z, r_t \sim O(10^1 - 10^2 \text{ pc})$$

$$D = \beta \left(\frac{R}{R_0}\right)^{\delta} \begin{cases} D_z & , \quad r \le r_z \quad (1) \\ D_z \left[\frac{D_0}{D_z}\right]^{\frac{r - r_z}{r_t - \gamma_z}} & , \quad r_z \le r \le r_t \quad (2) \\ D_0 & , \quad r \ge r_t \quad (3) \end{cases}$$

$D_z = 1 \times 10^{26} \quad cm^2 s^{-1} \quad @R_0 = 4\text{GV}$
Abeysekara et al. (2017)

$D_0 = 4.5 \times 10^{28} \quad cm^2 s^{-1} \quad @R_0 = 4\text{GV}$

$\delta = 0.35$ (Kolmogorov − like diffusion regime)

e^-/e^+ injection by the source

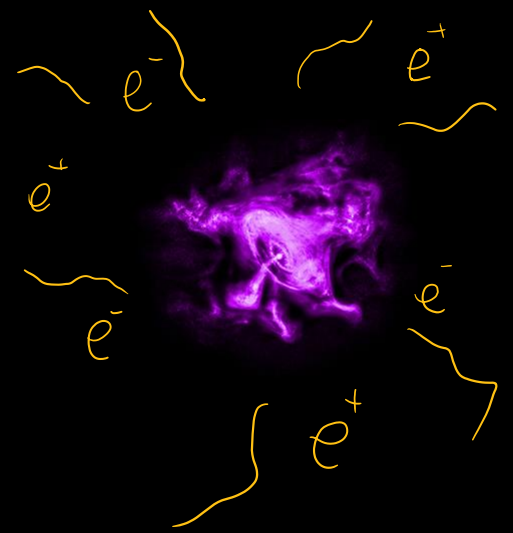
- We inject e^- that follow a broken power-law energy spectrum:

Power-law index: 1.8, 2.0, 2.2

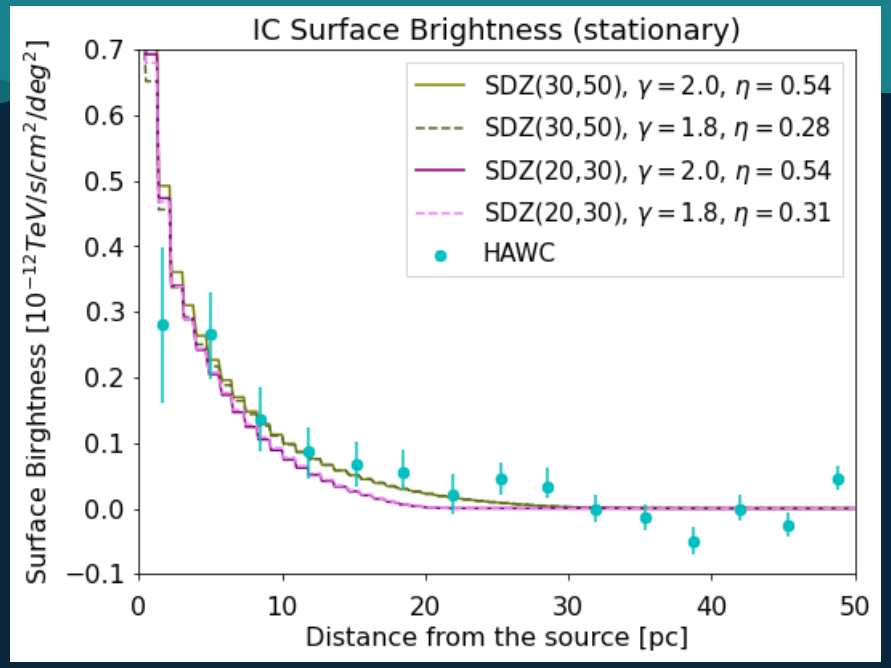
- A fraction of the pulsar spin-down power ($\dot{E}$) converts to total e^- luminosity L_{e^-}:

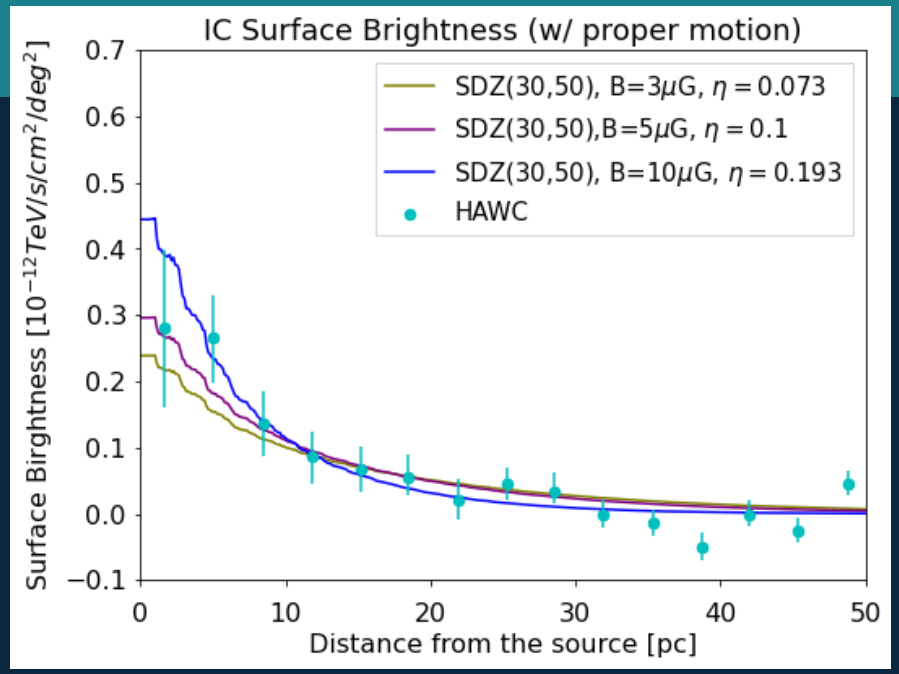
$$L_{e^-}(t) = \eta \dot{E}_0 \left(1 + \frac{t}{\tau_0}\right)^{-2}$$

Free Parameter



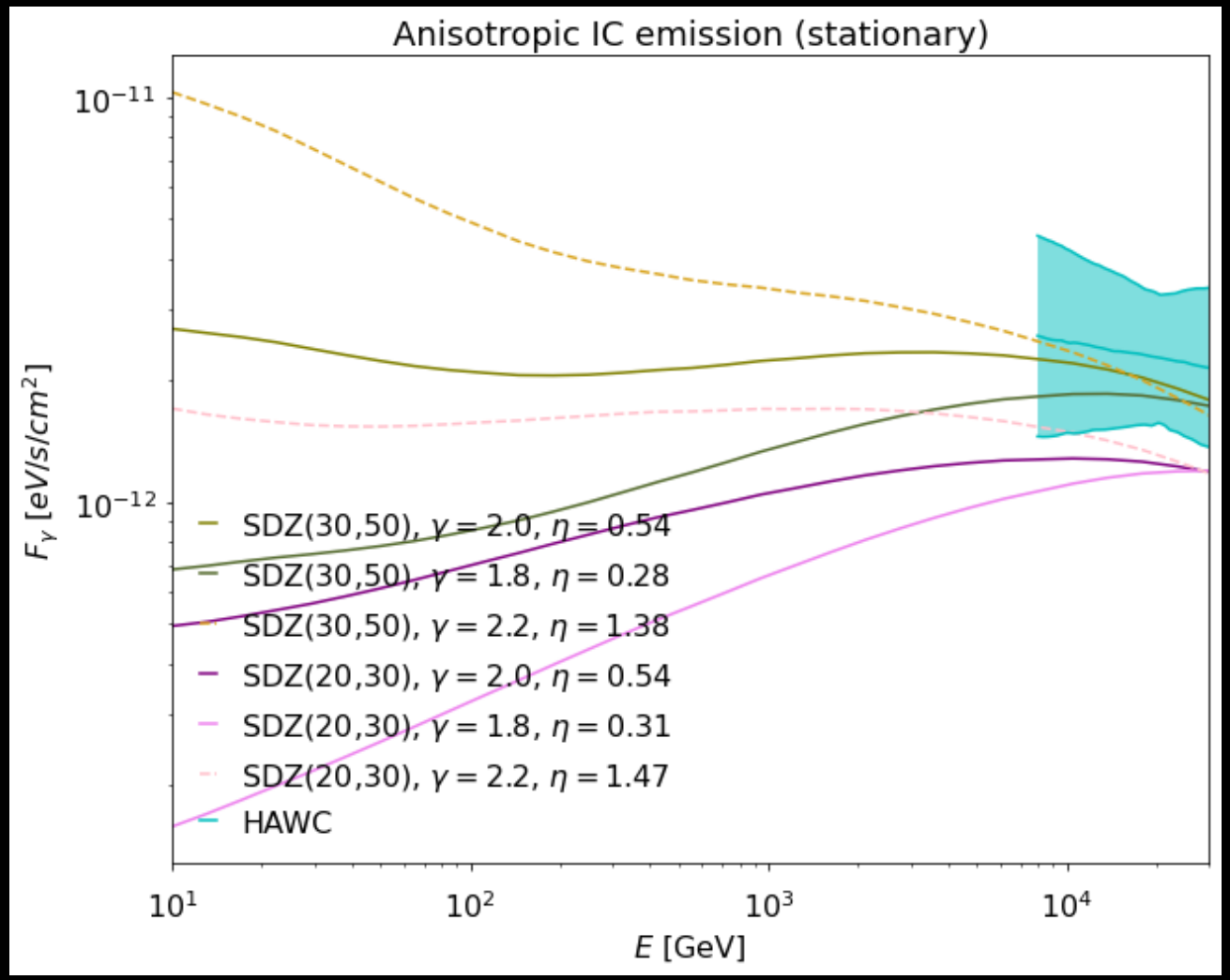
Inverse Compton Emission (8-40 TeV)





- A smaller SDZ yields a cuspier profile of the surface brightness
- A higher acceleration efficiency is required to describe the surface brightness for a softer injection spectrum
- A stronger magnetic field around the source also leads to cuspier surface brightness in the TeV range

Inverse Compton Emission (8-40 TeV)



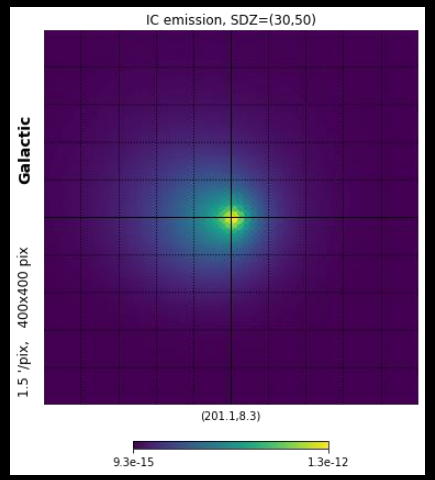
- The SDZ size of ~50 pc radius leads to an agreement with the energy spectrum of the HAWC observation

Proper Motion of B0656+14

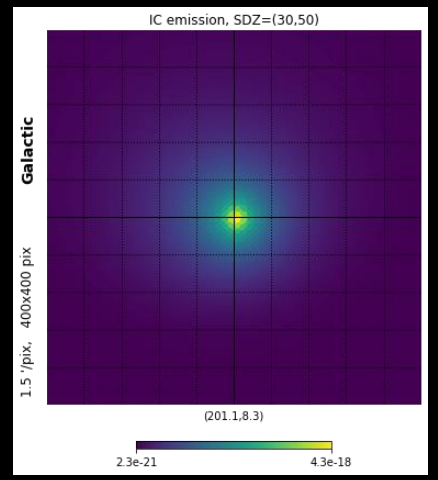
IC- Emission

- We expect asymmetry in GeV gamma-ray halo, but not significantly in TeV halo

γ -ray(30GeV)



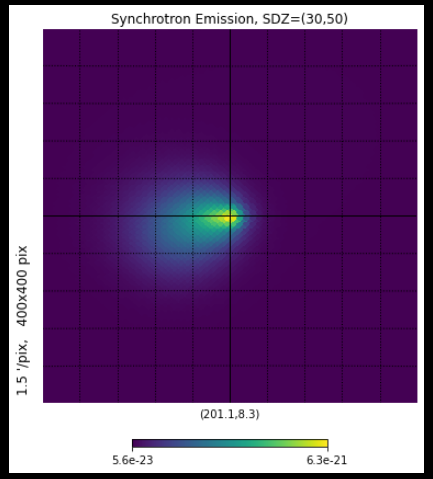
γ -ray(30TeV)



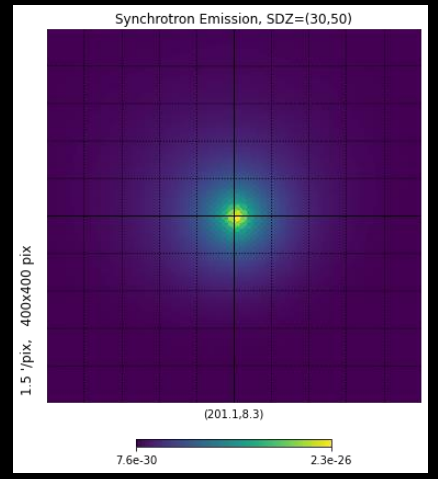
Synchrotron Emission

- We also expect corresponding radio and X-ray halo w/ extension of ~10s pc

Radio (1GHz)

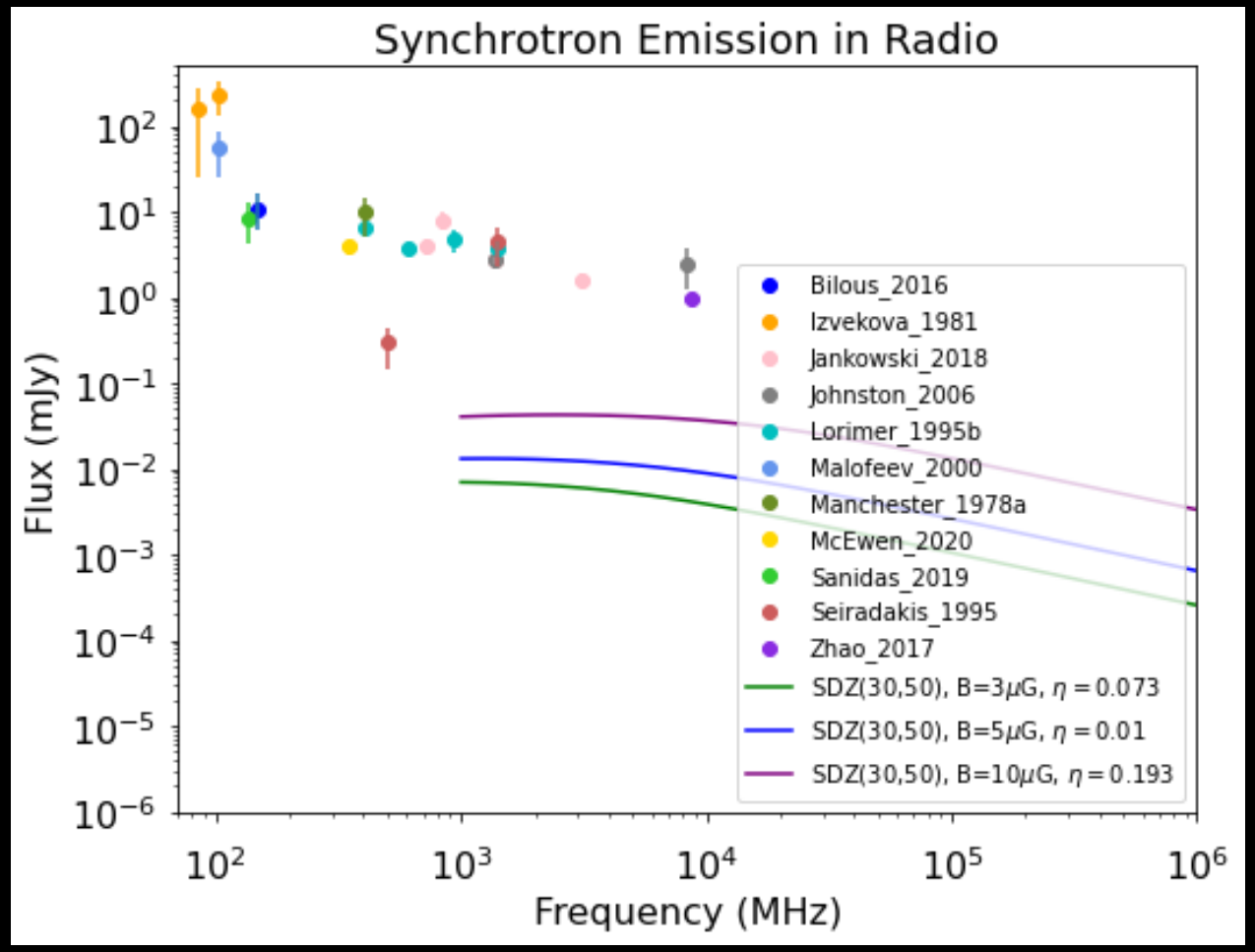


X-ray (4keV)



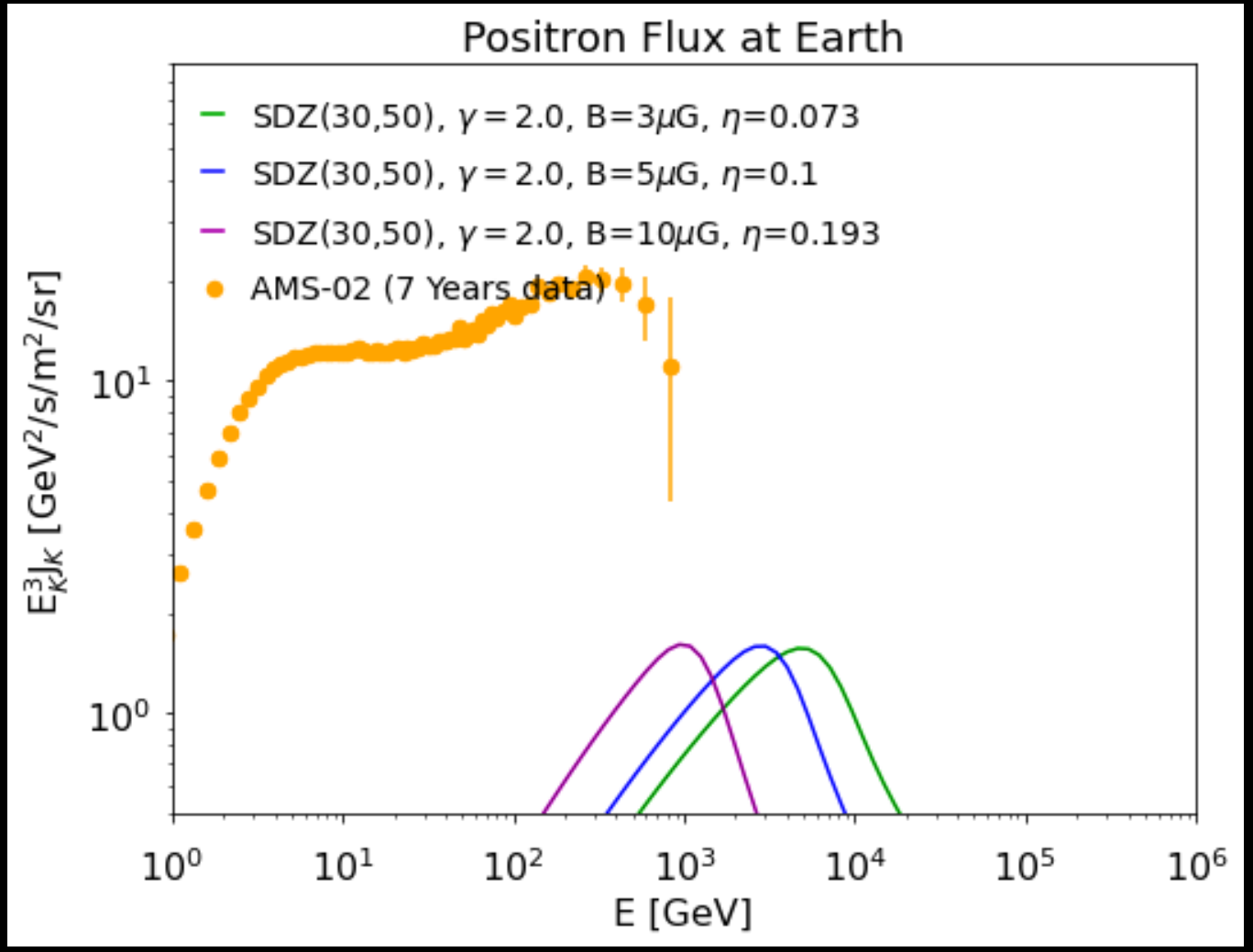
grid size:5pc

Synchrotron Emission (Radio)



- The observed radio emission from B0656+14 could be from jet component of the pulsar or/and the PWN component or/and the halo component
- The flux of the synchrotron halo component in radio frequency from the simulation is well below the observation

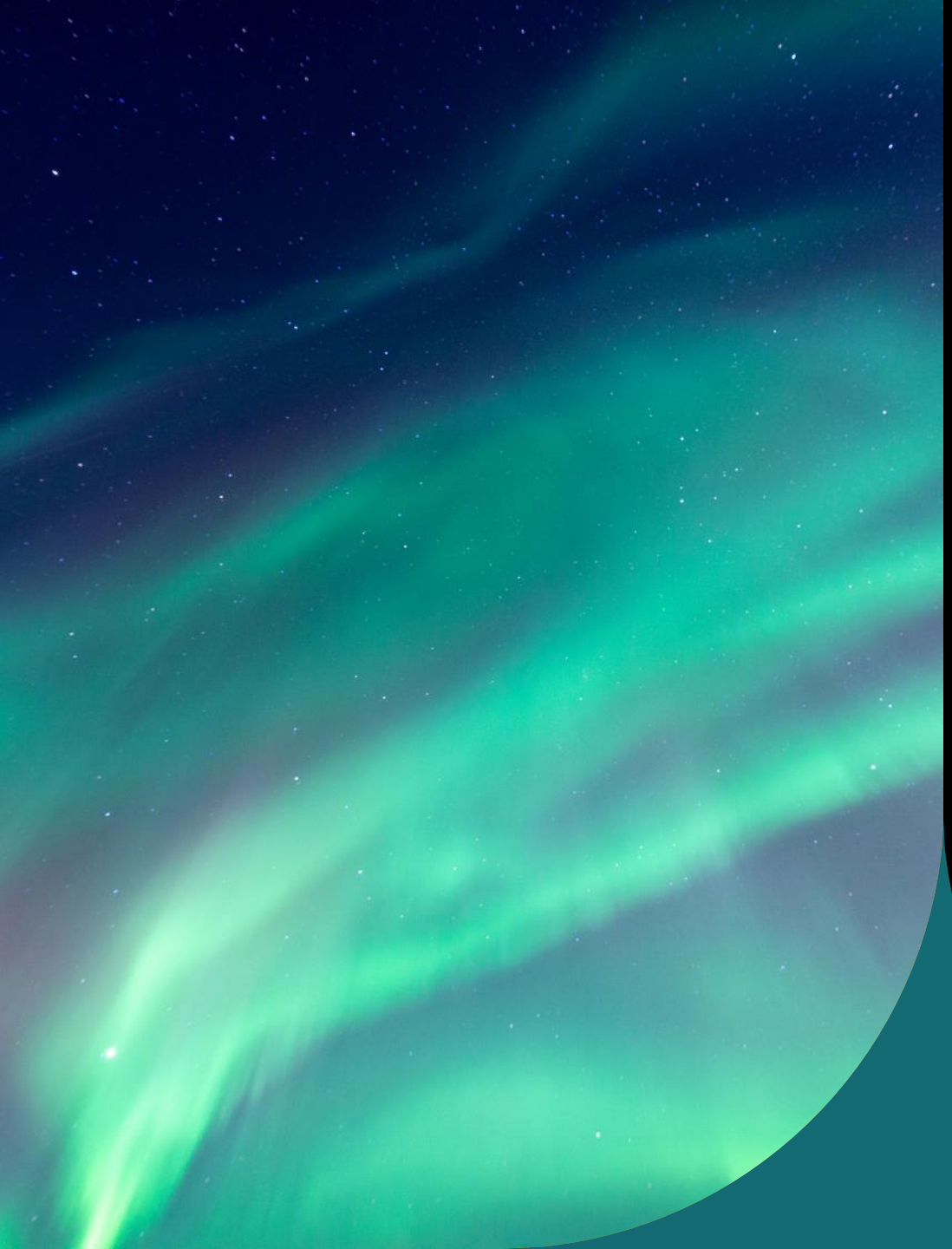
Positron Flux at Earth



- The positron contribution from B0656+14 is NOT significant
- The higher the magnetic field around the source, the positron flux at Earth peaks at a lower energy

Take-home Message

- TeV halo can be reproduced by introducing slow diffusion zone of $O(10^1)$pc size region around the PWN
- Observations of the extended emission in radio and X-ray are crucial to understand the origin of TeV-halos
- B0656+14 alone has no significant contribution to the positron flux at Earth
- Theoretical investigations in these regions are important e.g. magnetic field strength, magnetic turbulence, self-induced turbulence ⟶ CR acceleration, CR diffusion



Thank You!

Questions?