Probing Cosmic Ray Transport around Pulsar Halos with CTAO

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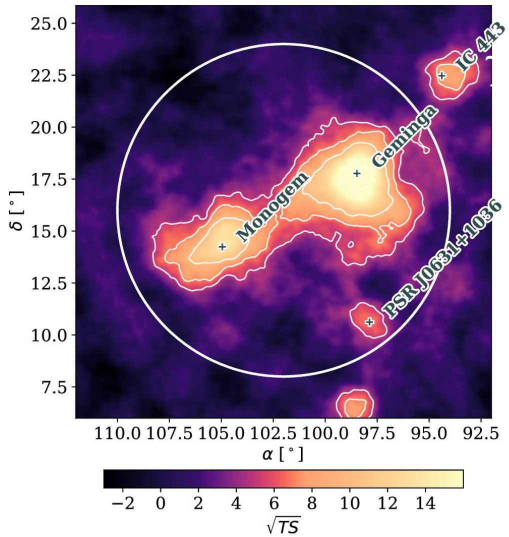
GRAPPA
GRavitation AstroParticle Physics Amsterdam

TeV Particle Astrophysics
TeVPA
Valencia 2025

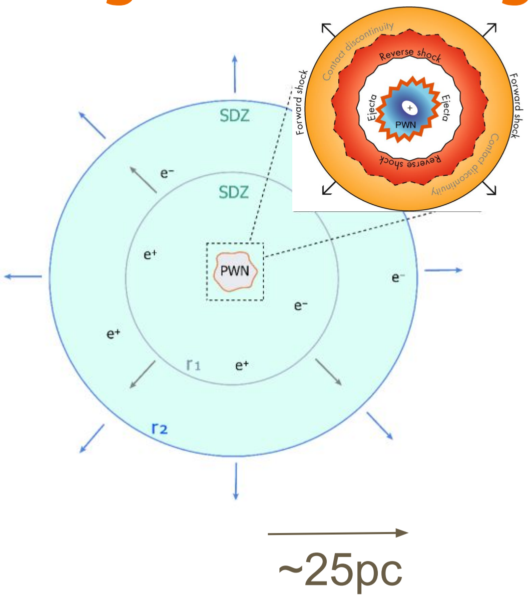
Content

- TeV halo around Geminga and Monogem
- How can CTAO help?
- Modeling the TeV-halo
- Simulate the Observation with CTAO
- Observation results

TeV-halos around Geminga nad Monogem



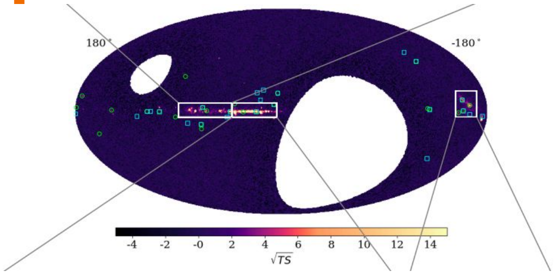
2024, HAWC Collaboration



$$R_{\text{diff}}(E) = \sqrt{4D(E)\min[\mathrm{t_{loss}(E)}, \mathrm{t_{inj}}]}$$

- 1-2 orders of magnitude suppression of diffusion coefficient is measured in pulsar halos compared to the Galactic average (Di Mauro et al. 2020)
- However, the Galactic average is measured by AMS-02 for up to 2 TV rigidity (Genolini et al. 2019)

Updated Views on TeV-halos



- Observed TeV halos:
  HAWC
  Geminga, Monogem,
  PSR B0540+23, J0633+0632,
  J0359+5414 (radio-quiet)
  LHAASO
  J0621+3755

- ~40% of LHAASO first source catalogue (TeV-PeV) coincides with pulsars (2024)

…05.00175v1 [astro-ph.HE] 30 Apr 2025

Extended TeV halos may commonly exist around middle-aged pulsars

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- TeV halos detected through stacking analysis of 36 isolated pulsars (HAWC)

What Can CTAO Contribute?

- better sensitivity than the current imaging Cherenkov telescopes

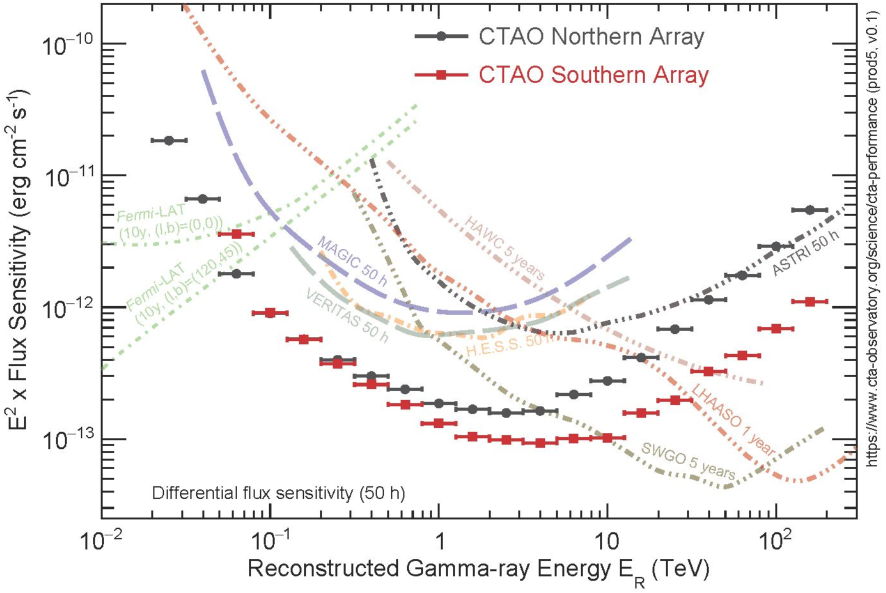
  -> detecting fainter halos

- $\lesssim$ 0.05–0.1° angular resolution at multi-TeV

  -> resolving energy dependent morphology

- Large energy range (20GeV-300TeV)

  -> captures more spectral features



Methodology

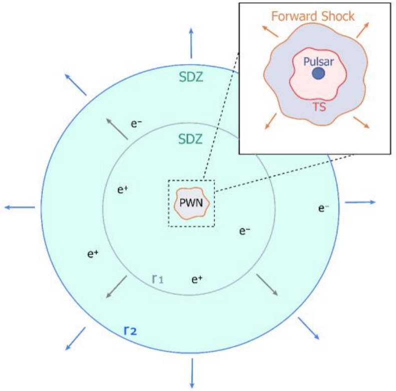
1) Build a sky model = source emission + background emission

2) Forward folding the sky model using the CTAO instrumental response function (IRFS)

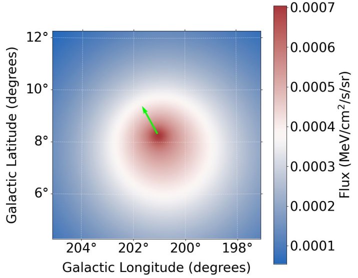
3) Obtain test statistics from template fitting

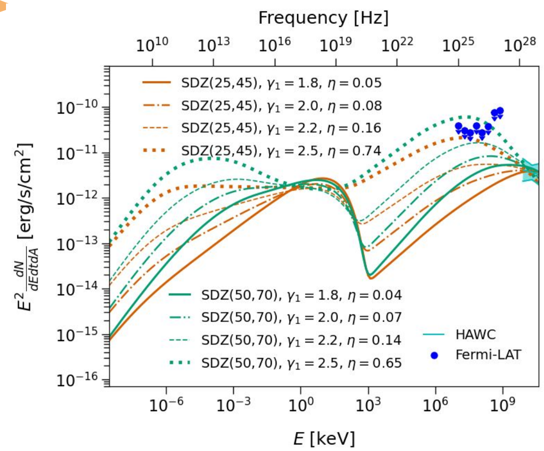
Source Modeling of PWN TeV-halos

2-zone diffusion model



Monogem halo at 50 GeV



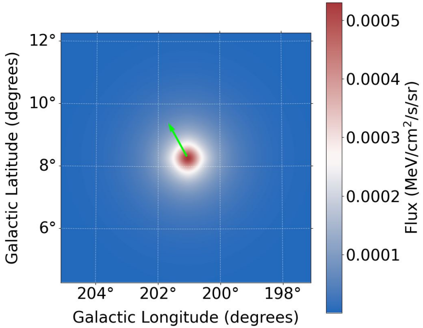


- High resolution numerical simulation of propagation of relativistic charged particles in the Galactic scale
- Using a single node with 224 GB of memory and 128 CPUs. Each simulation took around ~ 5 hours

For more details!

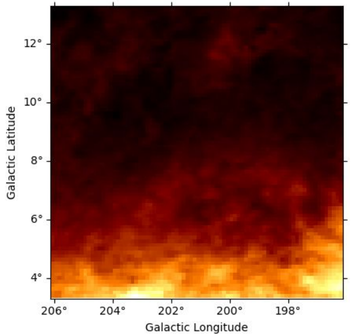
Li et al. 2025

Sky Region Modeling for CTAO Observation



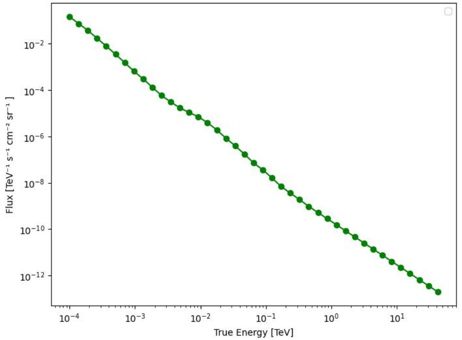
Geminga and Monogem TeV-halo

\+



Galactic Diffuse Background

\+



Isotropic Diffuse Background

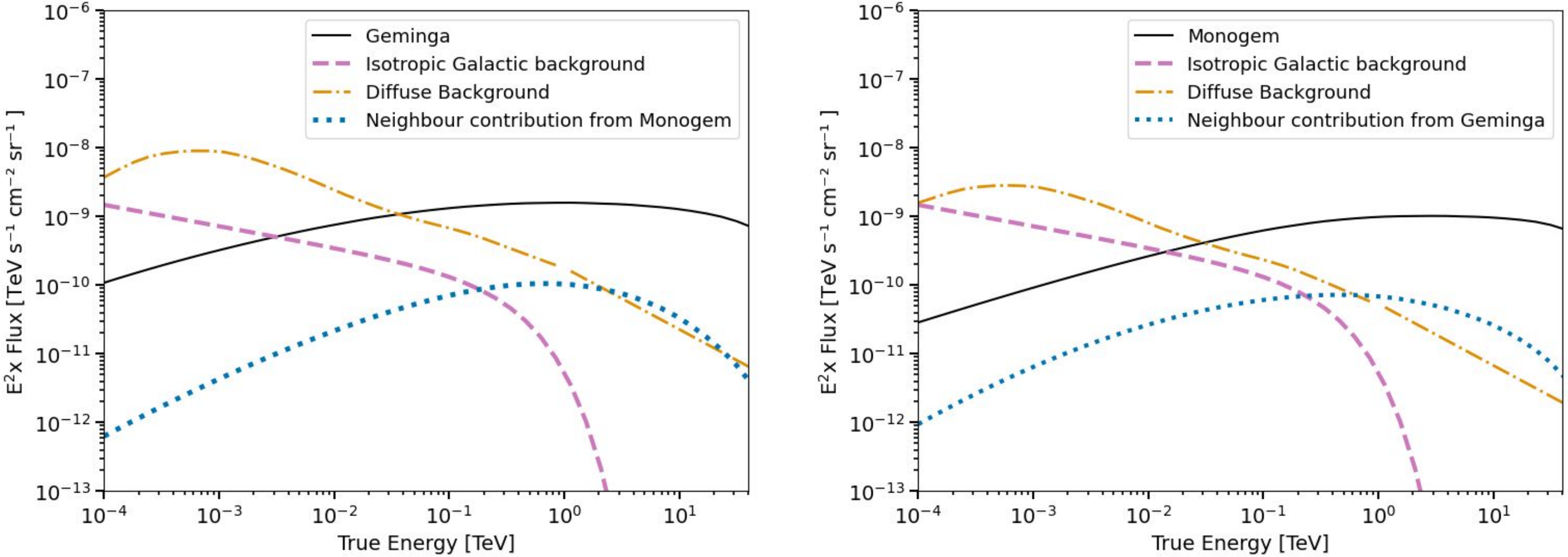
\+ Irreducible Cosmic Ray Background

\+ FoV (Field of View) Background

\+ Neighbour Source Contribution

A **Python** package for
gamma-ray astronomy

Flux Contribution from the FoV



Average flux of 2.15◦ radius region centered at the Geminga halo (left panel), and Monogem halo (right panel)

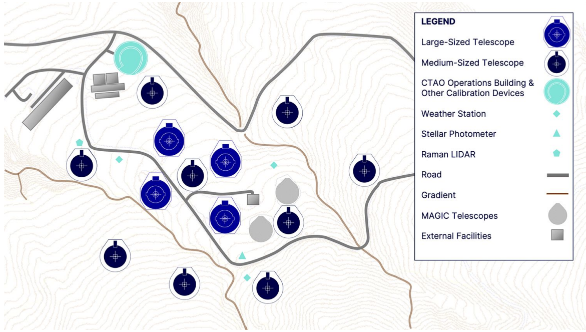
Simulating the Observation

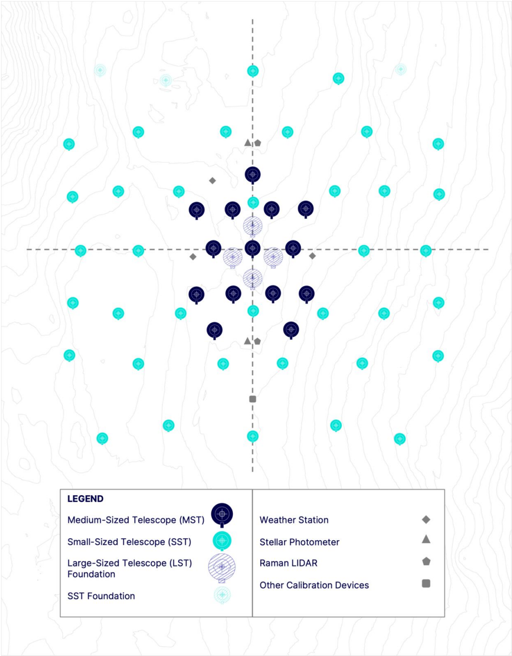
IRFS of **alpha configuration**:

- The **"Alpha Configuration"** is the current official configuration

- An array configuration of 4 LSTs and 9 MSTs in the northern site **(CTAO-North)**,

  and 14 MSTs and 37 SSTs in the southern site **(CTAO-South)**

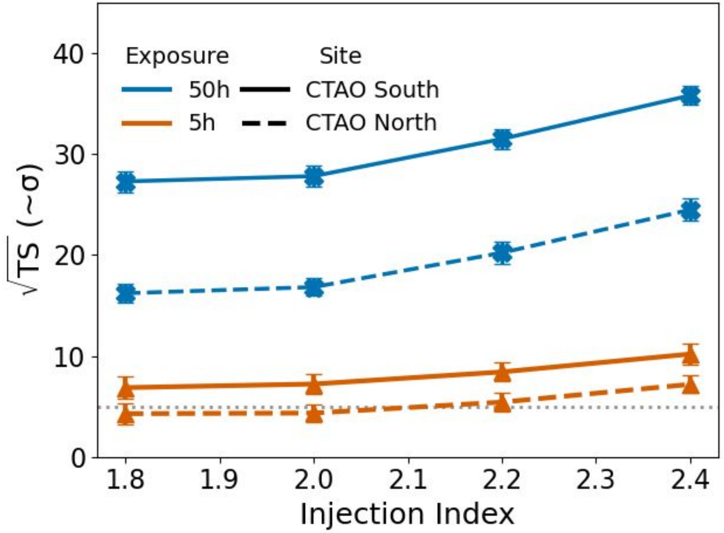




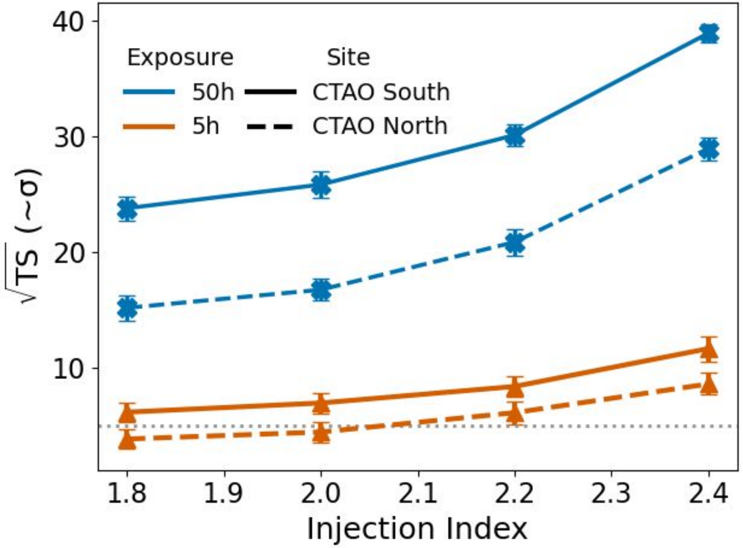
Simulating the Observation

- Both North and South sites are tested
- Observation time of 5h and 50h at each site
- For each source model, we generated 50 realizations (observations)

Detection Results



Geminga halo



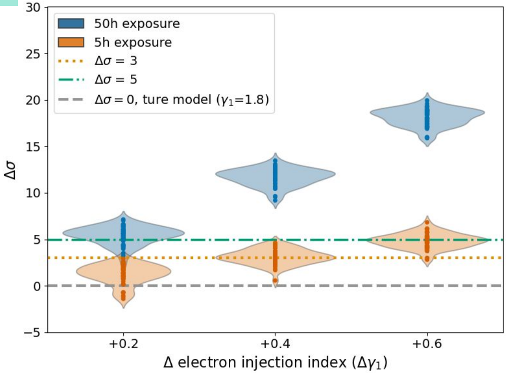
Monogem halo

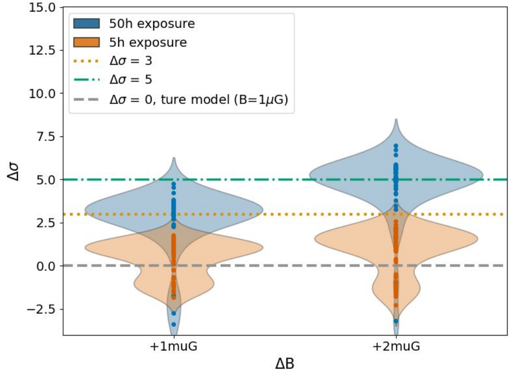
- For best case scenario (perfect modeling), both Geminga and Monogem are detected on both sites for > 5h observation

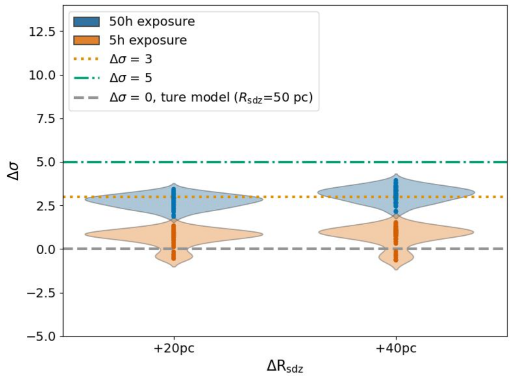
Probing CR Properties with CTAO Observations

CTAO South

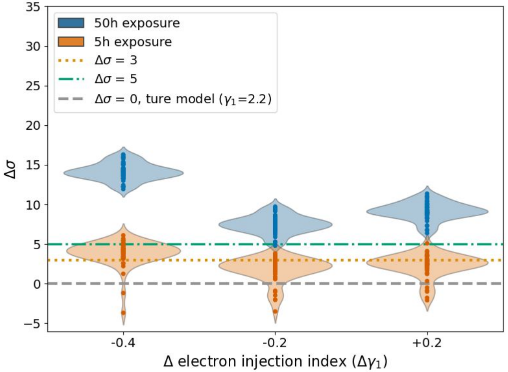
Geminga Halo

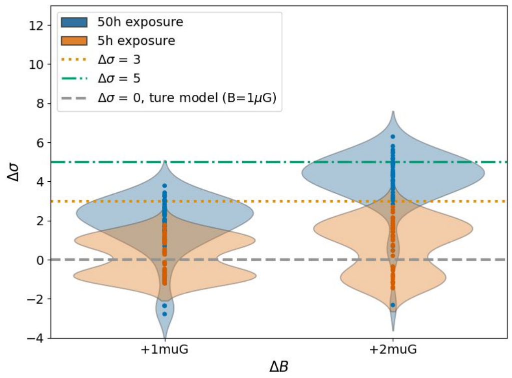


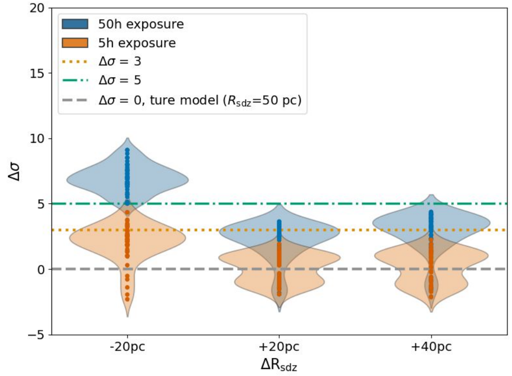




Monogem Halo







Take Home Messages

- CTAO will detect and resolve Geminga and Monogem with high significance, in 50h exposures.

- Forward-folding simulations show that CTAO can quantitatively distinguish between different diffusion and injection scenarios.

- Longer exposures greatly enhance parameter distinguishability.