Detections, constraints, and future aspect of TeV halos

3rd CDHY workshop

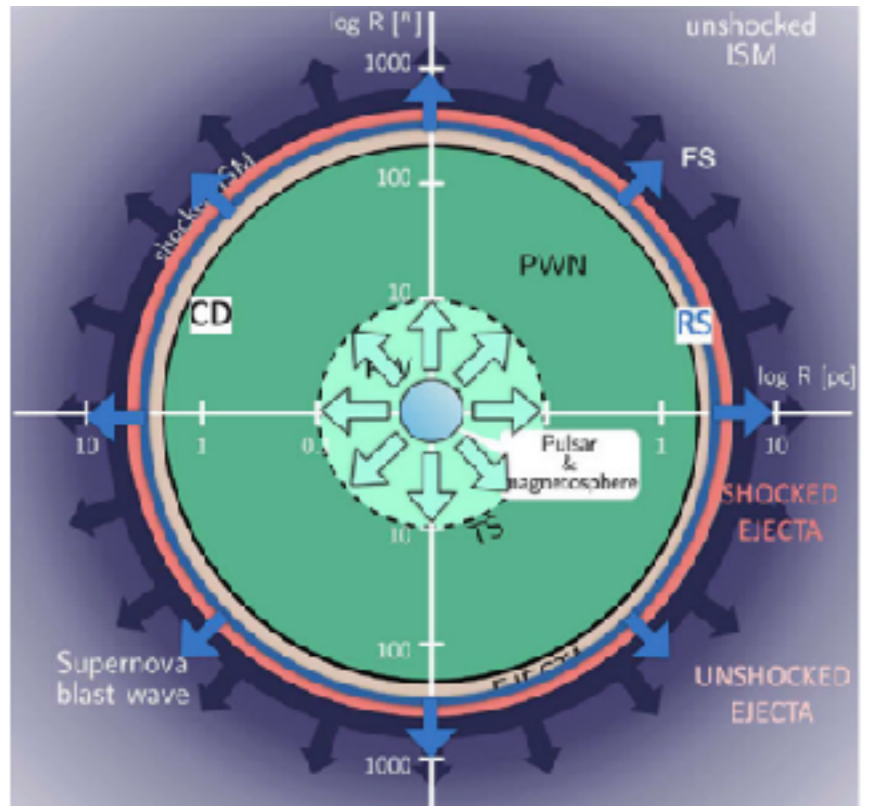
Ruo-Yu Shang

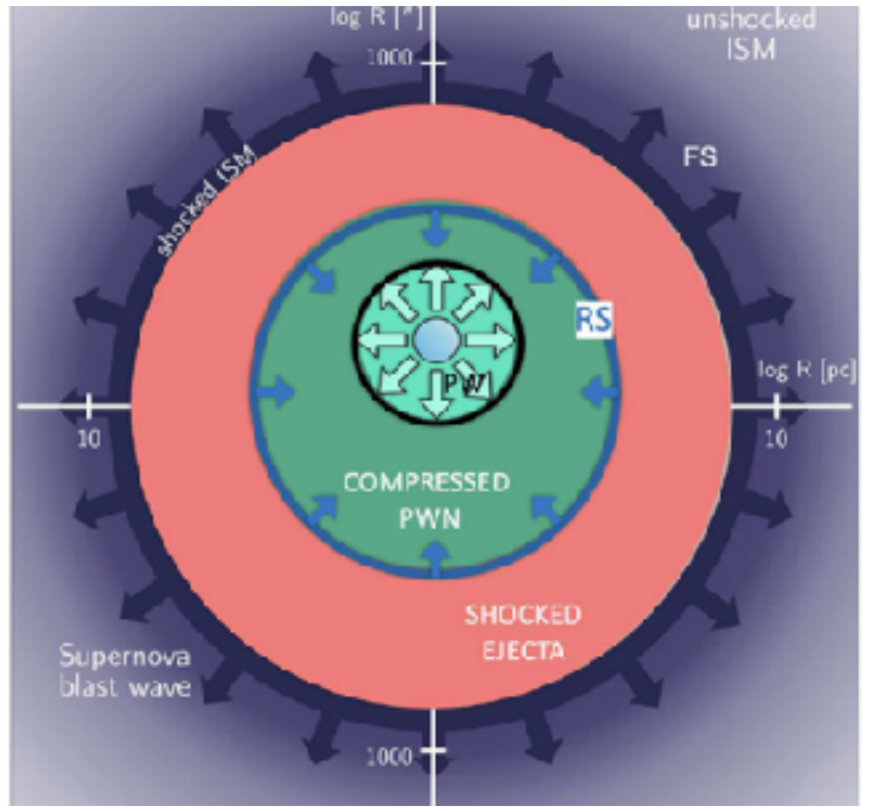
Outline

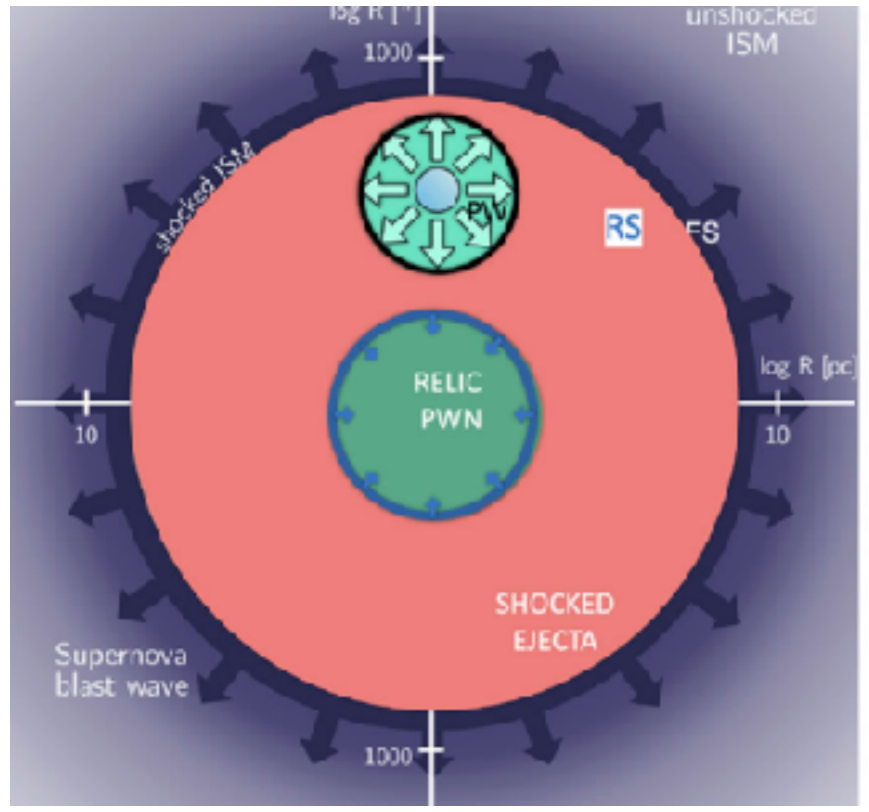
1. Evolution of PWNe and TeV haloes
2. Geminga halo
    1. HAWC / LHAASO detection
    2. Fermi and HESS detection
    3. X-ray upper limits
3. Other TeV halo
4. Future and challenges

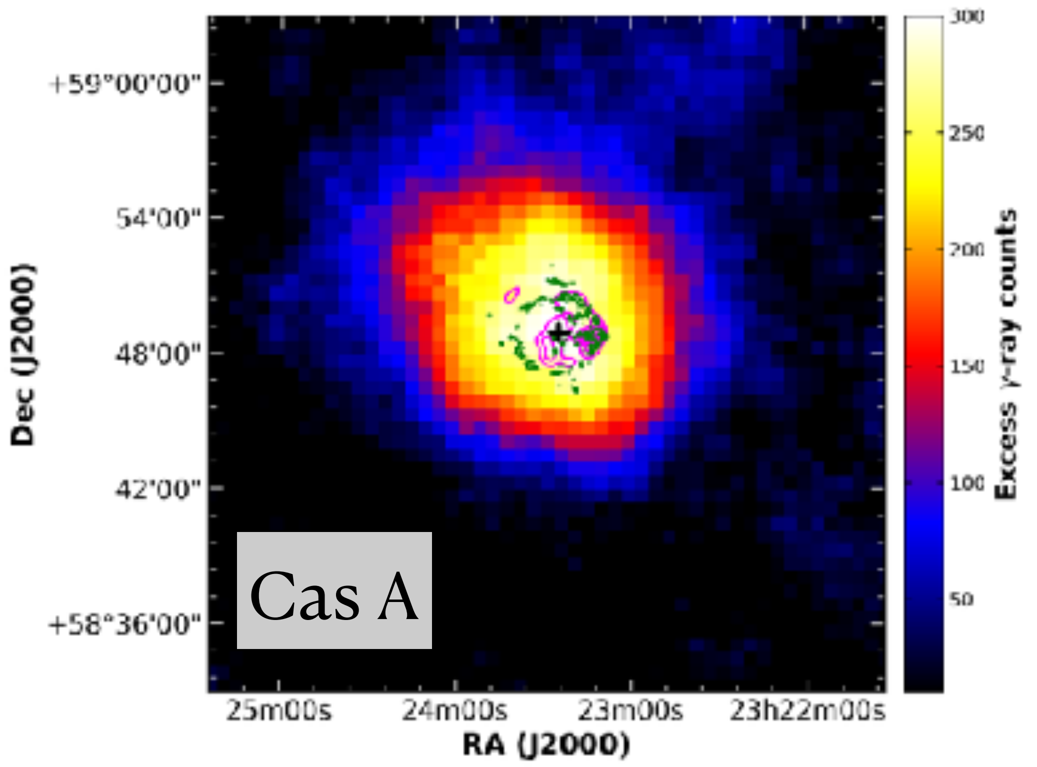
Evolution of PWNe observed by VERITAS

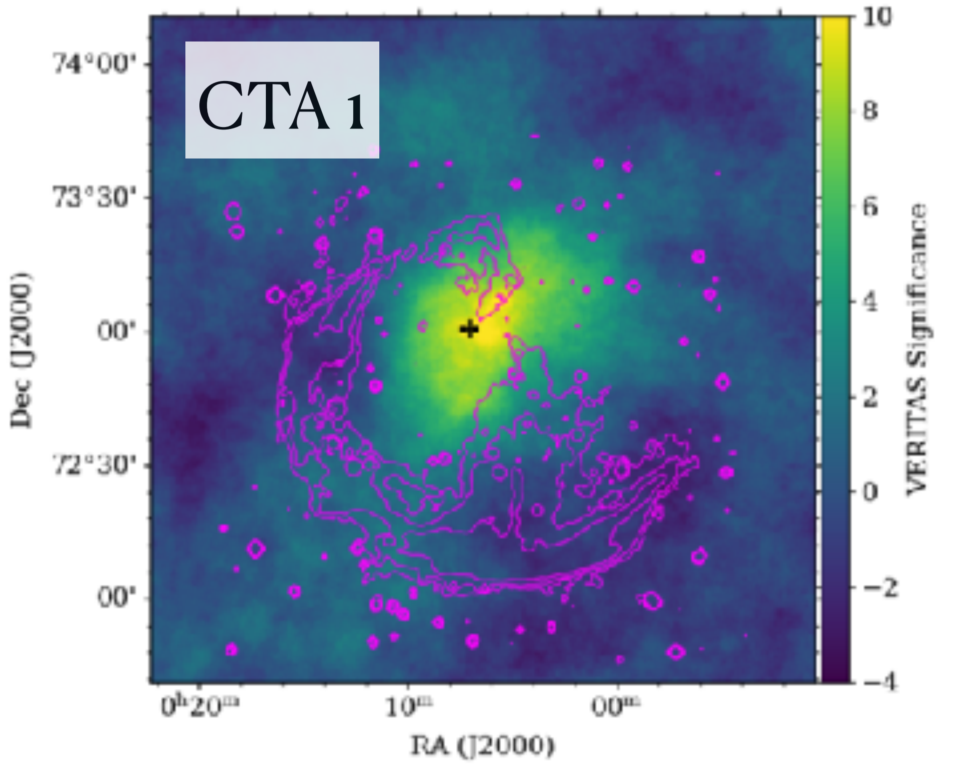
Free expansion < 1 kyr	Reverse shock compression 1 kyr - 10 kyr	New and relic PWNe 10 kyr - 100 kyr

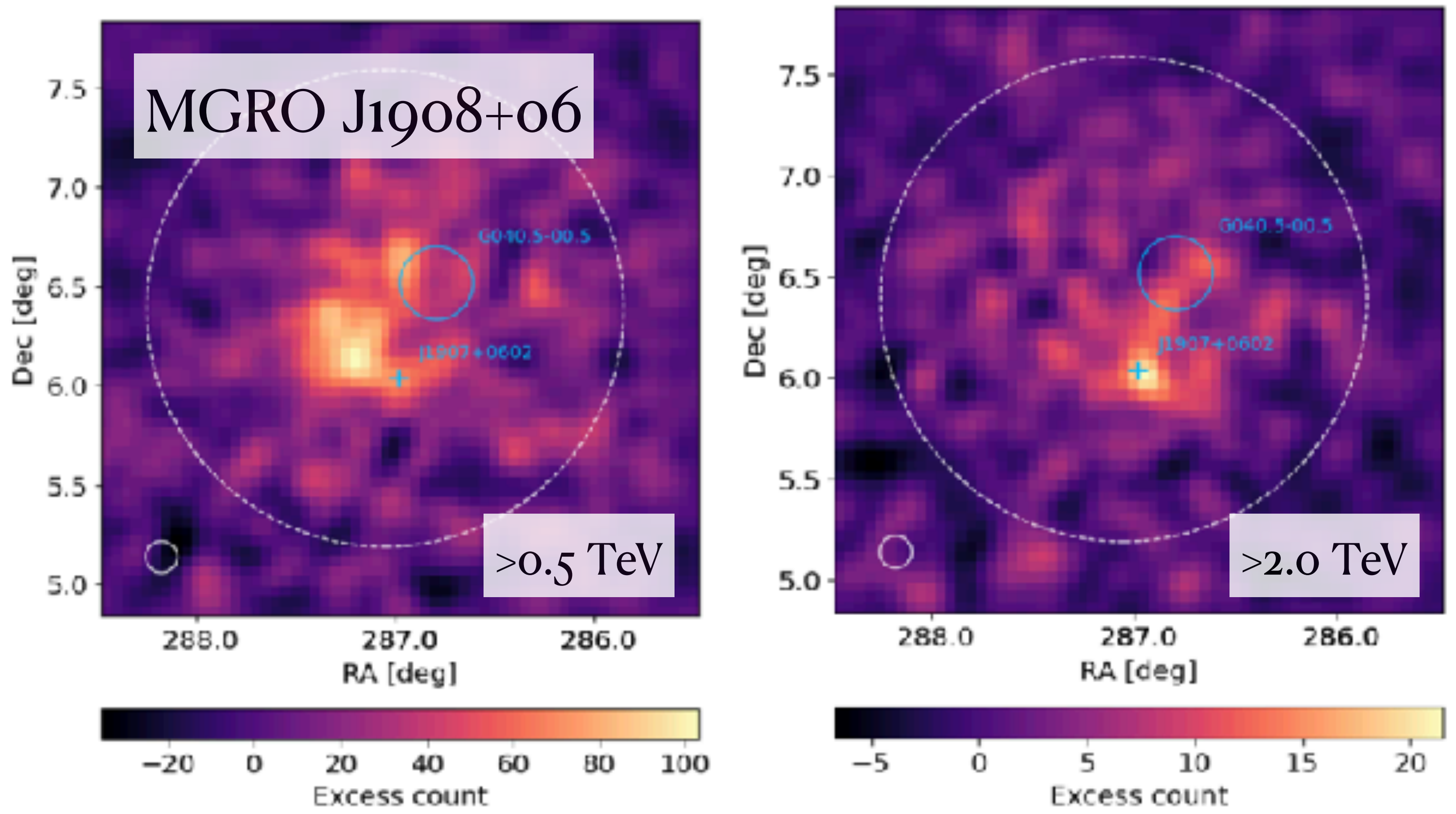








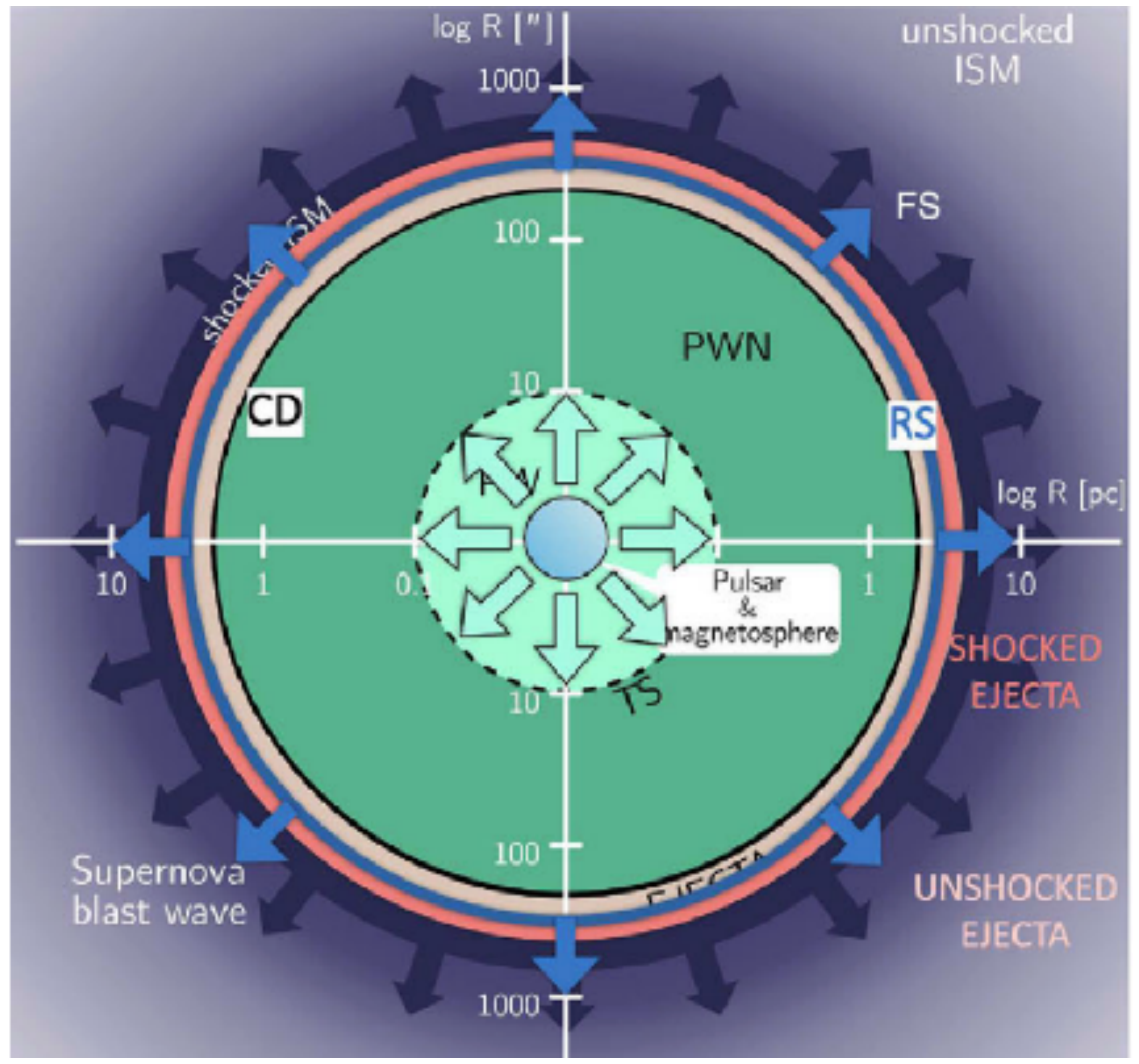




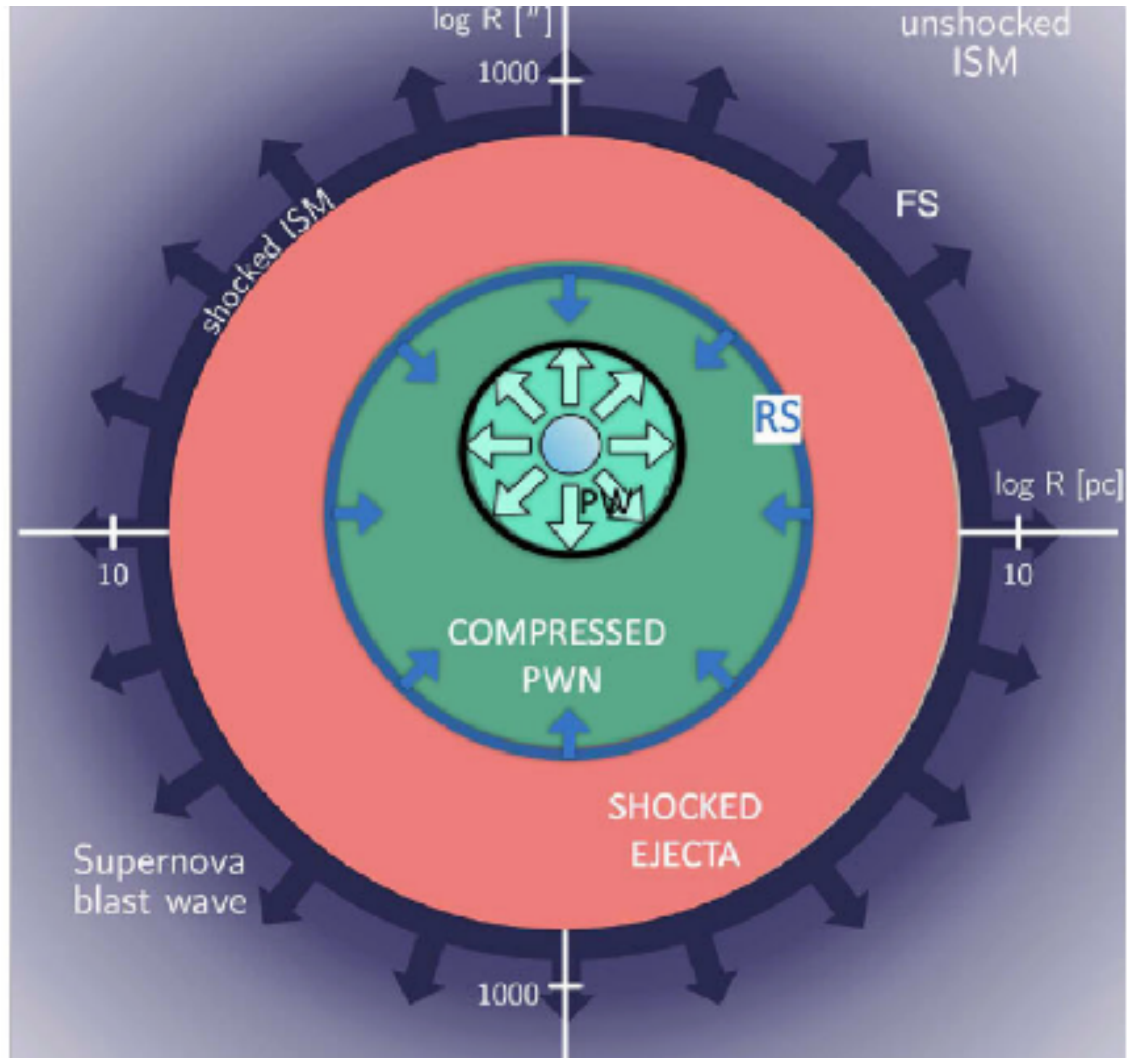
The Astrophysical Journal 974.1 (2024): 61

Evolution of a PWN: becoming a halo

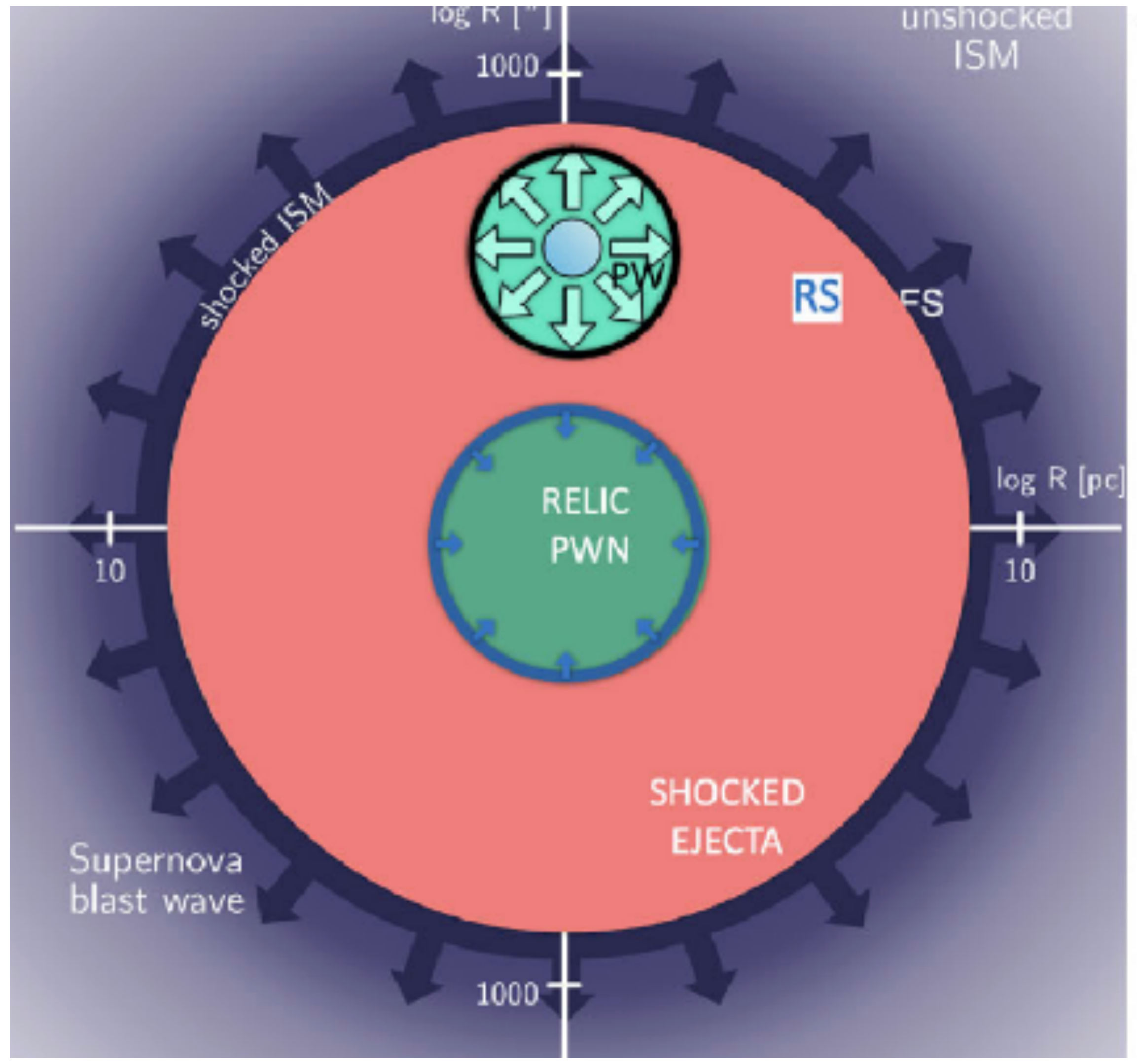
Free expansion
< 1 kyr



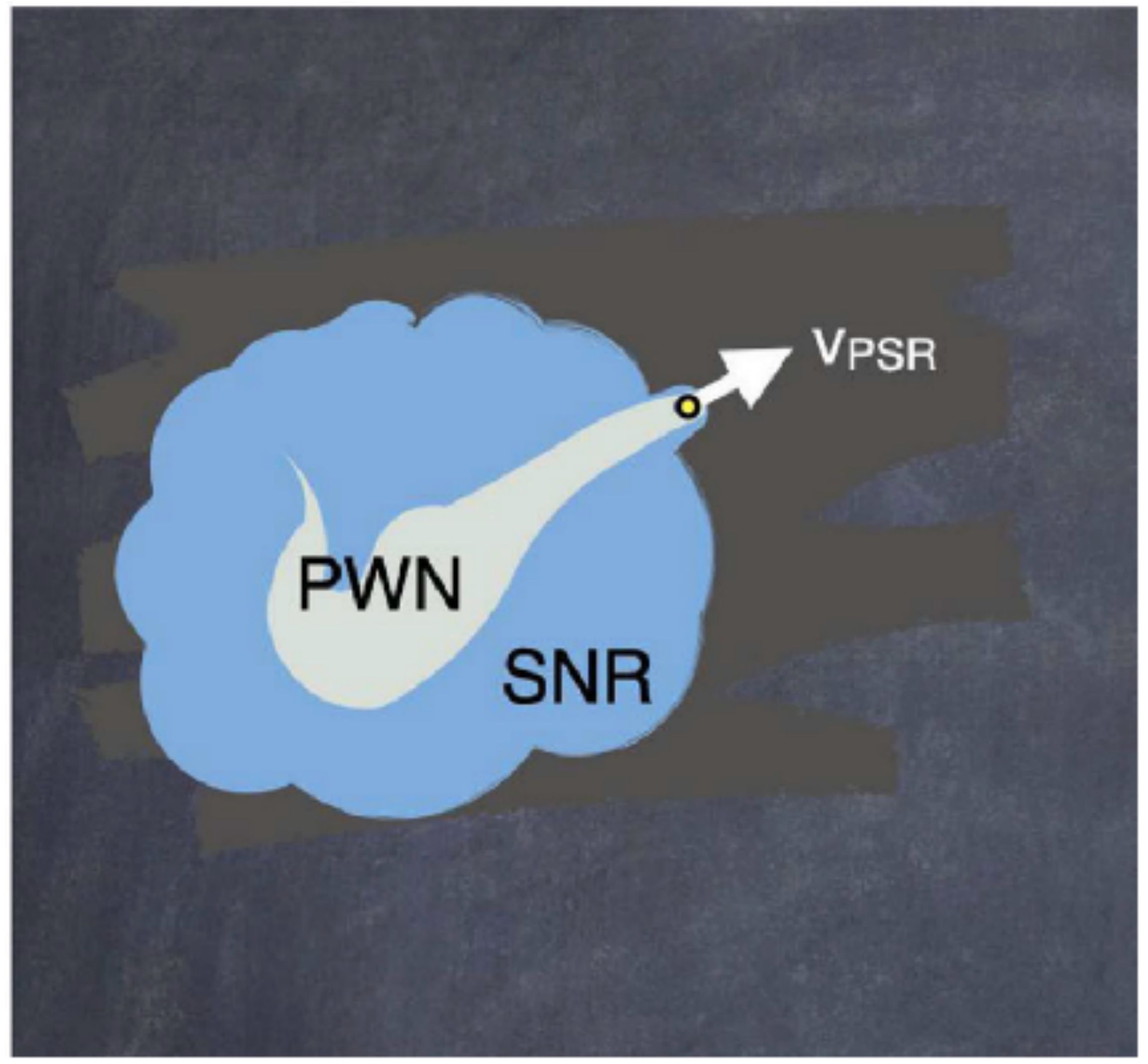
Reverse shock compression
1 kyr - 10 kyr



New and relic PWNe
10 kyr - 100 kyr



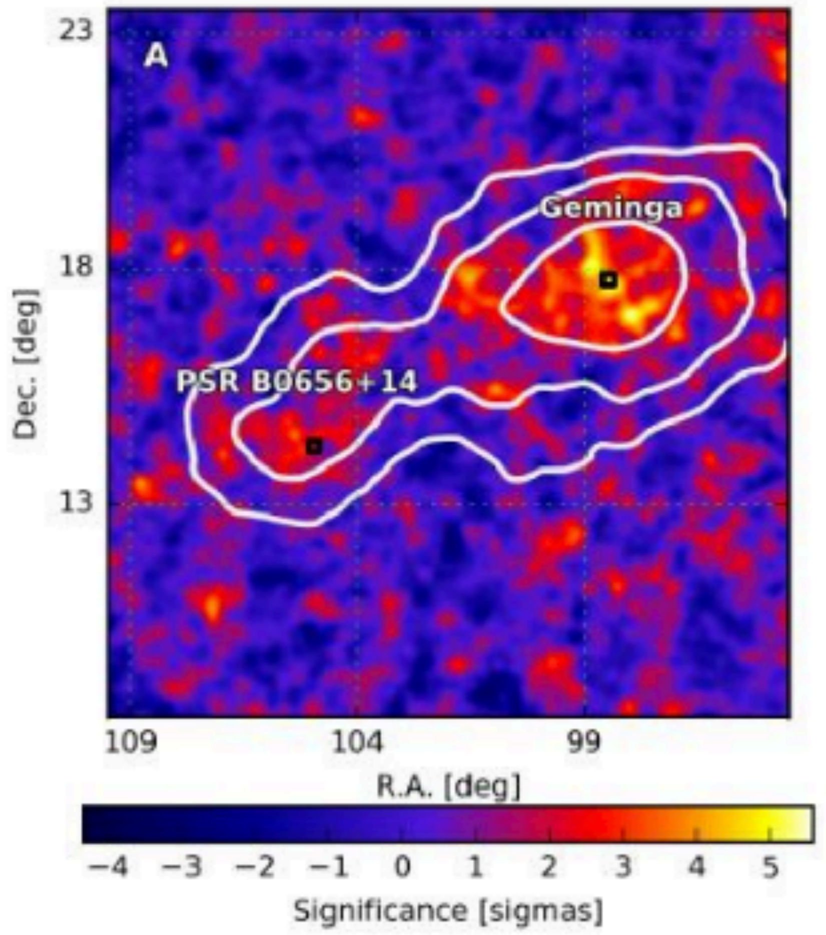
Halo
> 100 kyr

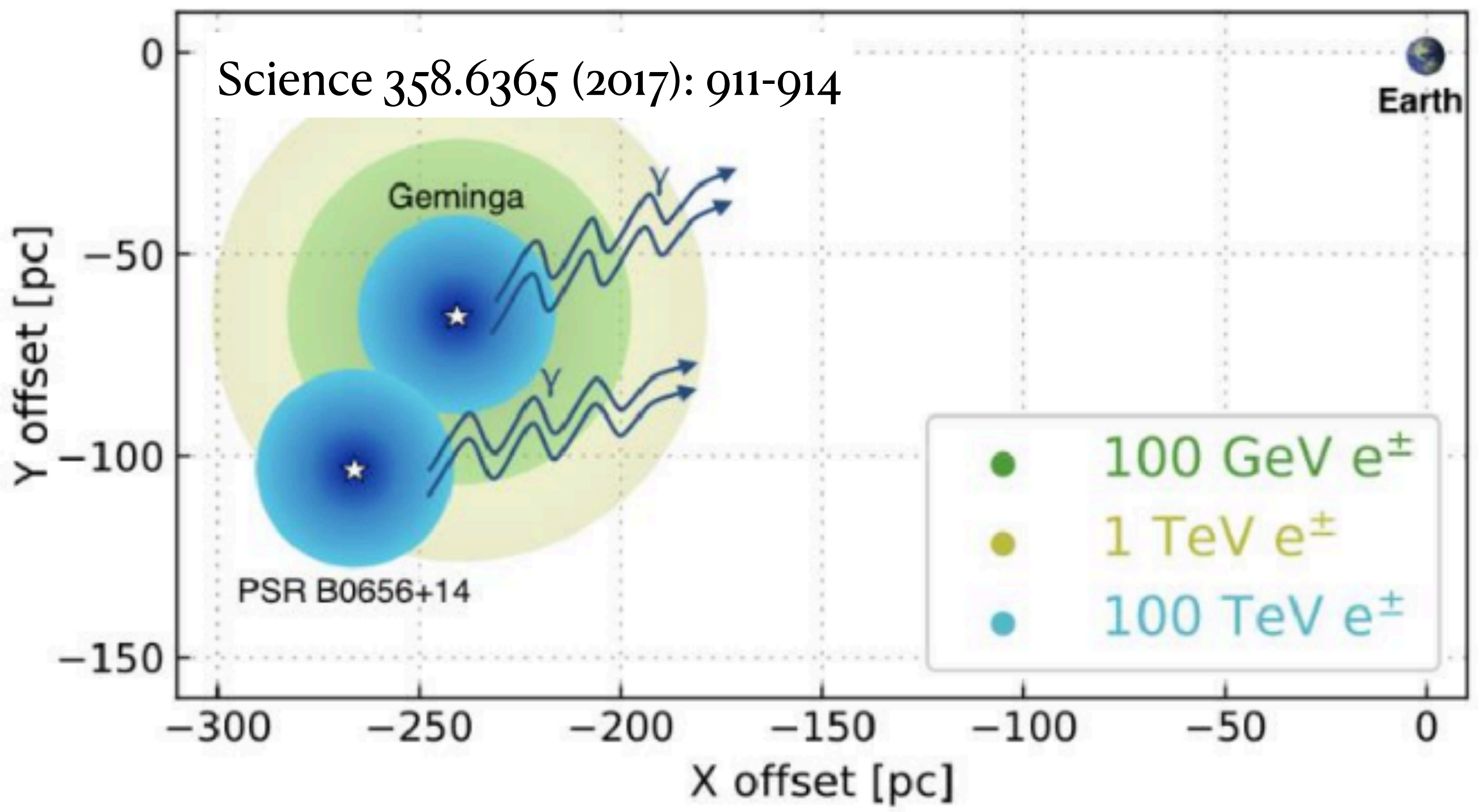


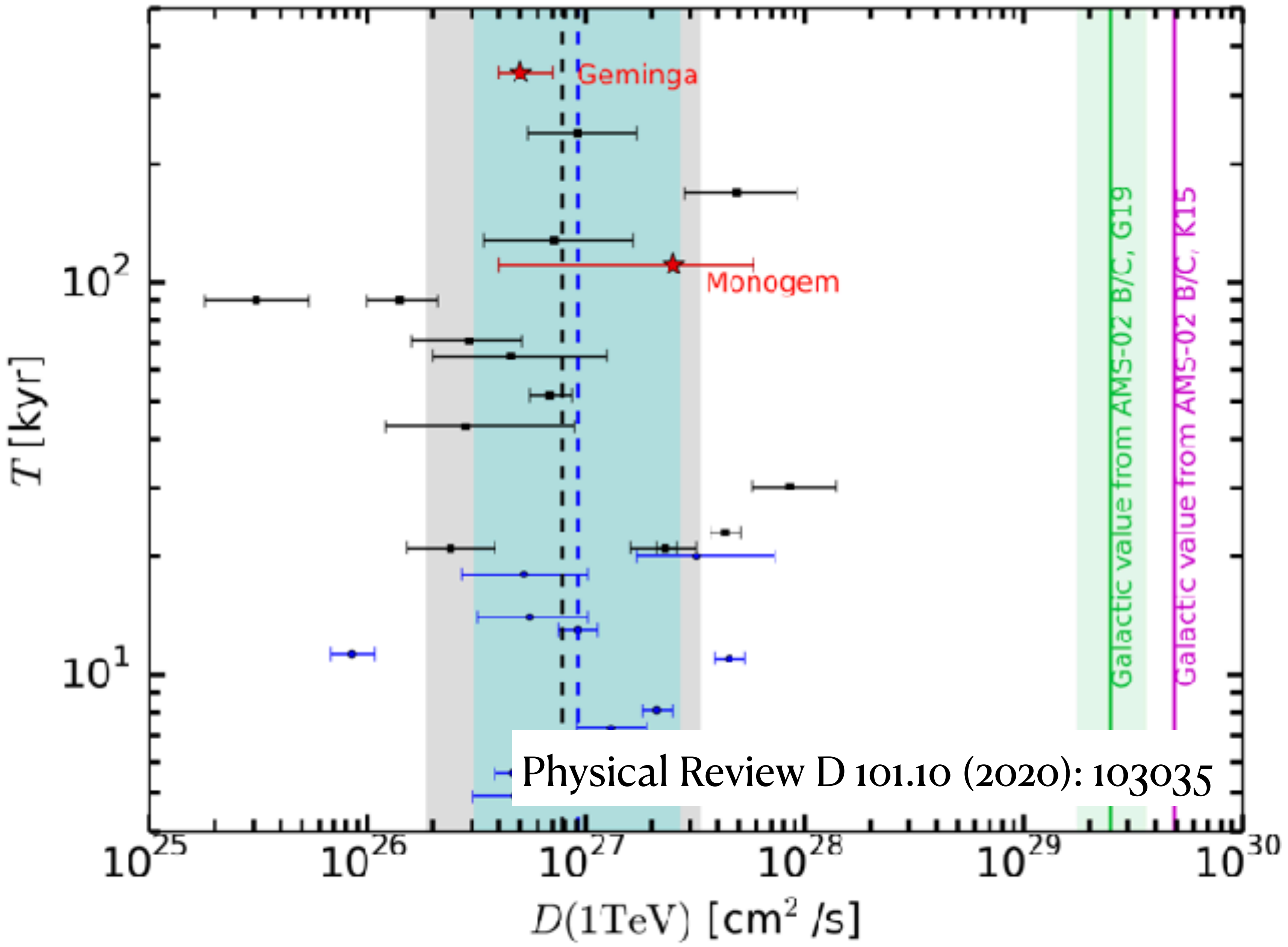
Elena Amato, Sarah Recchia (2024)

Geminga halo detection by HAWC

1. First definitive detection of a TeV halo, a new class of astrophysical objects.
2. Electrons and positrons escaping from the Geminga pulsar were diffusing through the interstellar medium much more slowly than previously thought.
3. Origin of the Positron Excess: Geminga could be the source of the cosmic-ray positron excess measured by experiments like AMS-02.



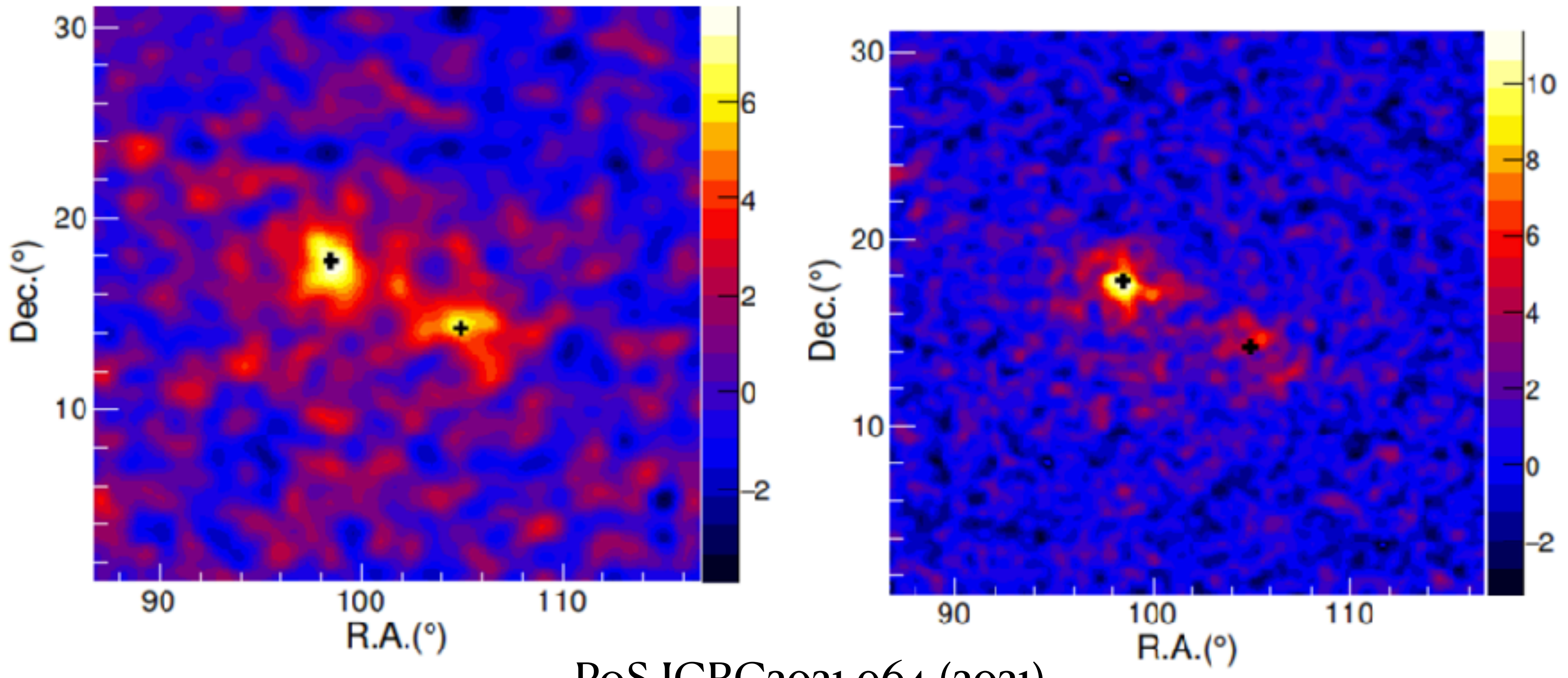




Geminga halo detection by LHAASO

1. Confirmation of Extended Emission
2. Offer more precise measurement above 100 TeV of the spectral cutoff:
    1. Maximum energy of the electrons and positrons accelerated
    2. Cooling processes

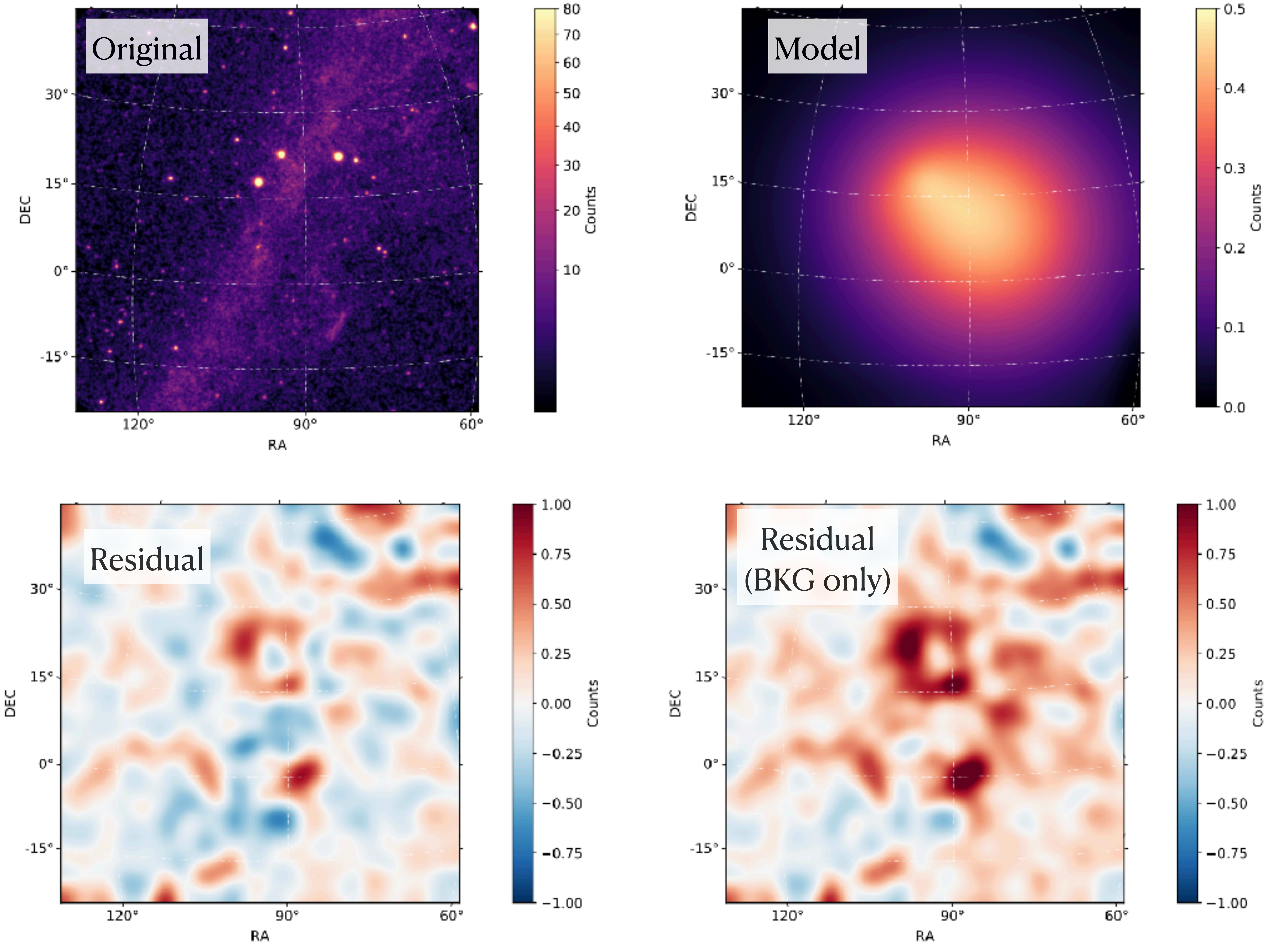
15-25 TeV 25-65 TeV



PoS ICRC2021 964 (2021)

Geminga halo detection by Fermi-LAT

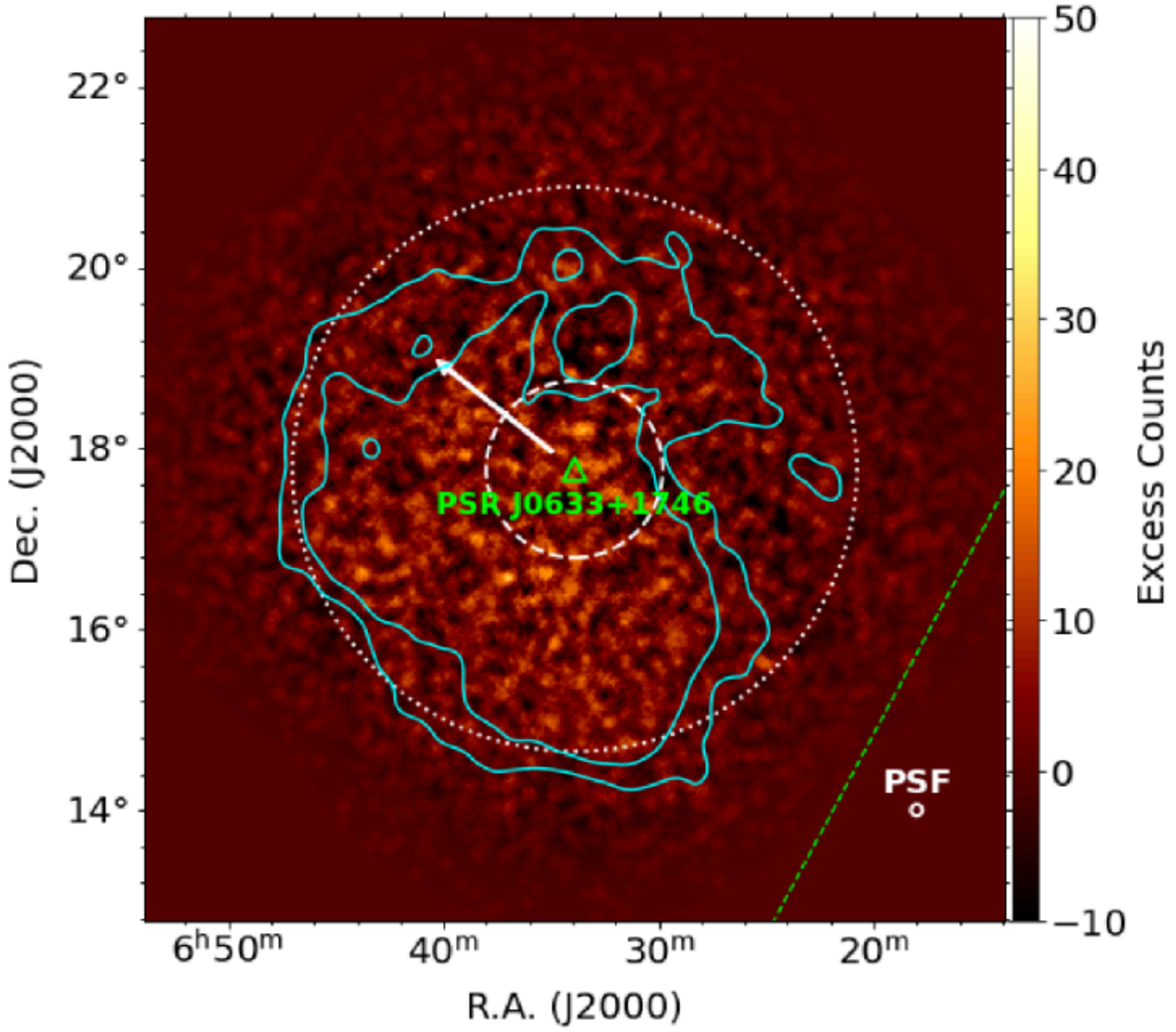
1. Much larger size:
    1. 20 deg at 10 GeV,
    2. Expected because of longer cooling time
2. Confirmation of Slow Diffusion:
    1. Hundreds of times slower than ISM.
    2. High-energy electrons from the pulsar can remain trapped in the region
3. Positron Excess Connection:
    1. The pulsar alone could be responsible for up to 20% of the cosmic-ray positron excess observed by experiments like AMS-02



Physical Review D 100.12 (2019): 123015

Geminga halo detection by HESS

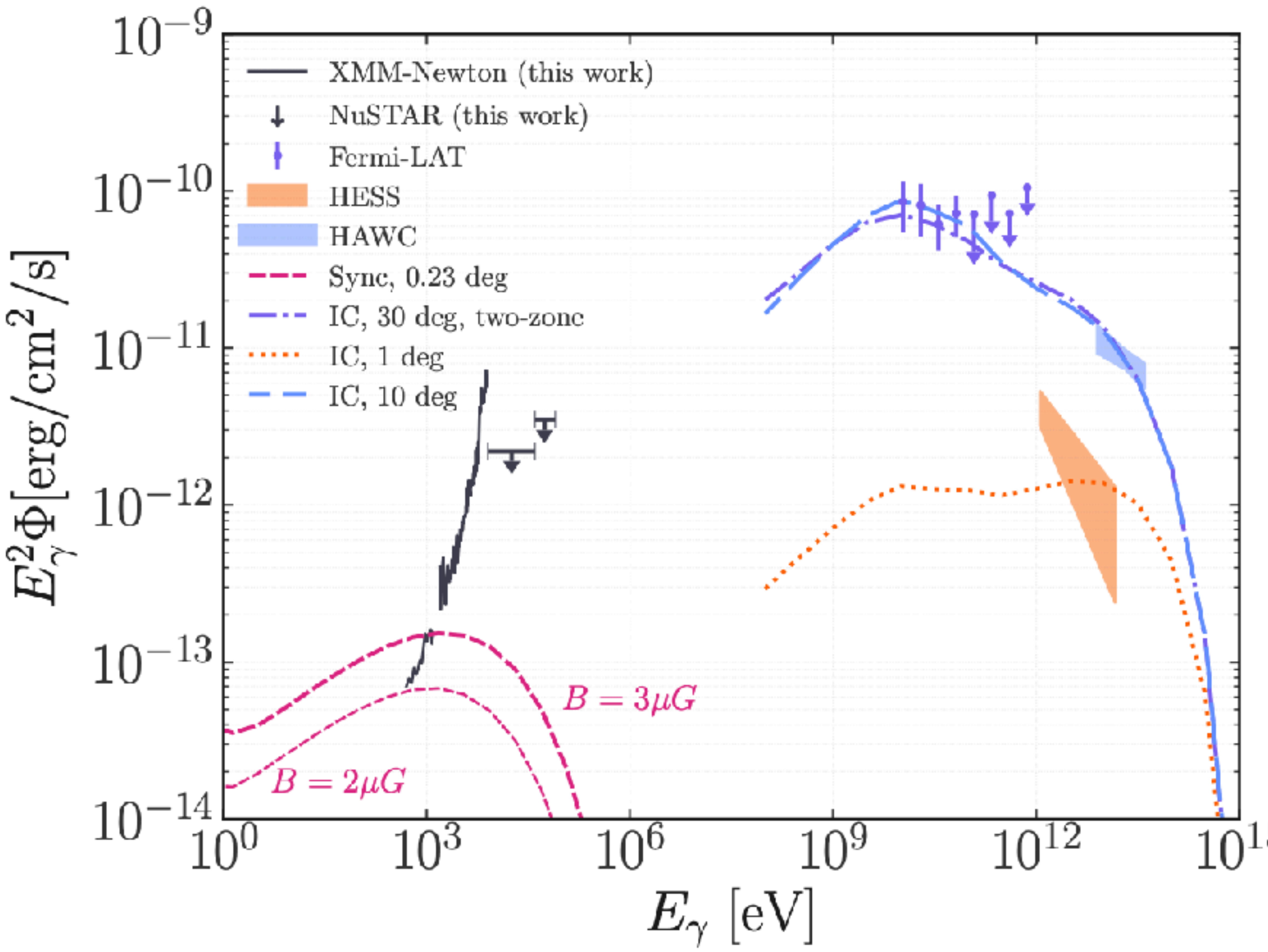
1. Confirmation of a TeV Halo:
    1. Emission with a radius of at least 3 degrees in the energy range of 0.5–40 TeV.
2. Complementary Data:
    1. IACT offers superior angular resolution and spectral information,
    2. Detailed look at the morphology and energy distribution of the particles within the halo



Astronomy & Astrophysics 673 (2023): A148

Constraints by X-ray observations

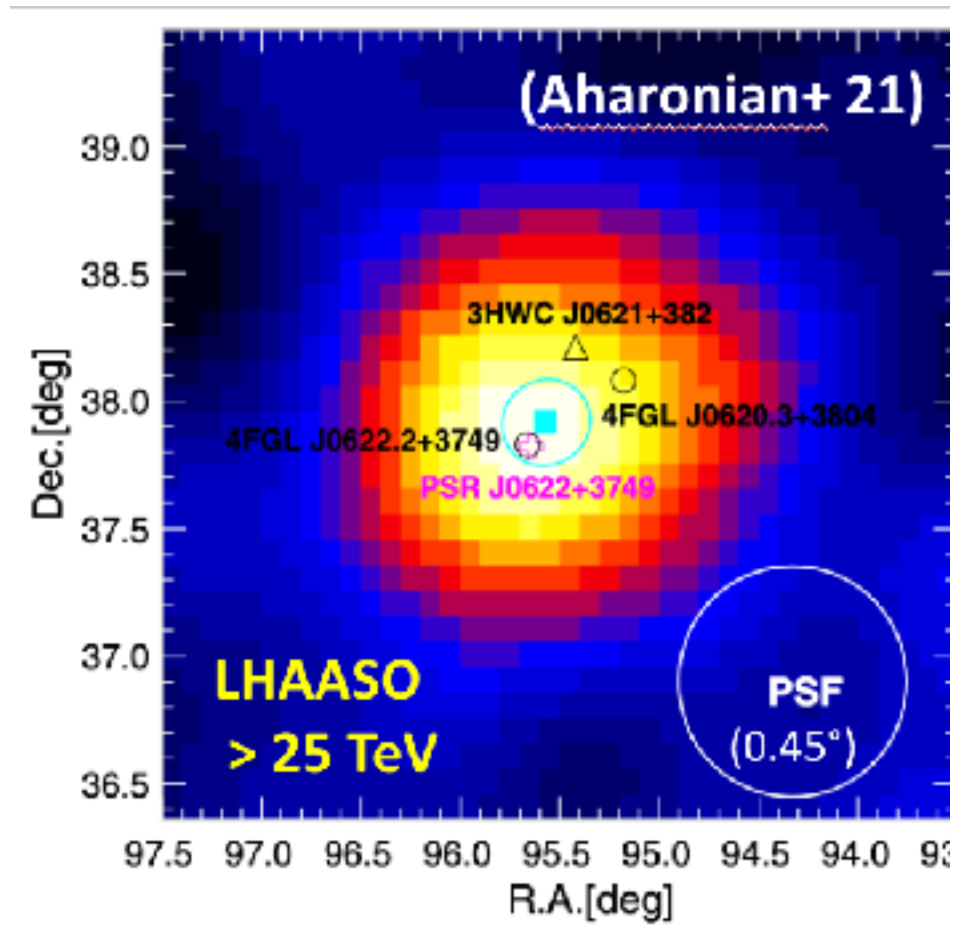
1. Alternative channel:
    1. Gamma-rays: inverse Compton scattering
    2. X rays: synchrotron radiation
    3. Detecting this X-ray halo would provide a direct measure of the magnetic field strength in the region.
2. A diffuse X-ray halo has not been detected
3. Constraining the Magnetic Field:
    1. The lack of a detection suggests that the magnetic field in this region is weak, less than a few μG

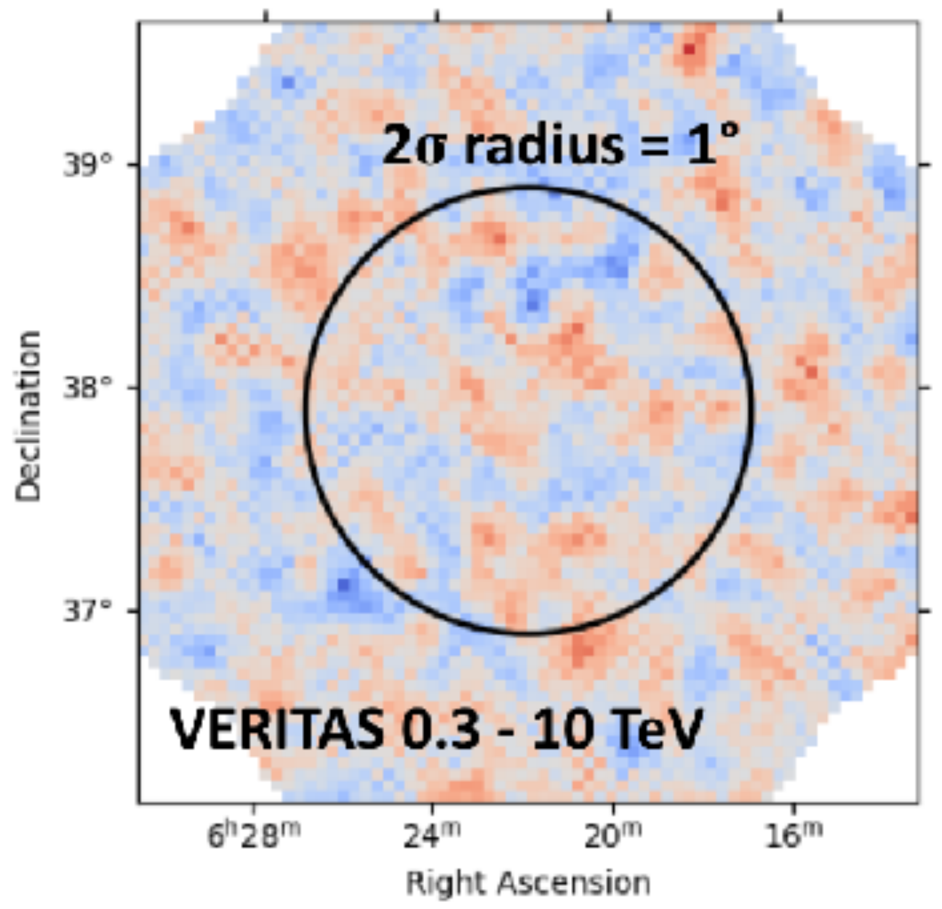


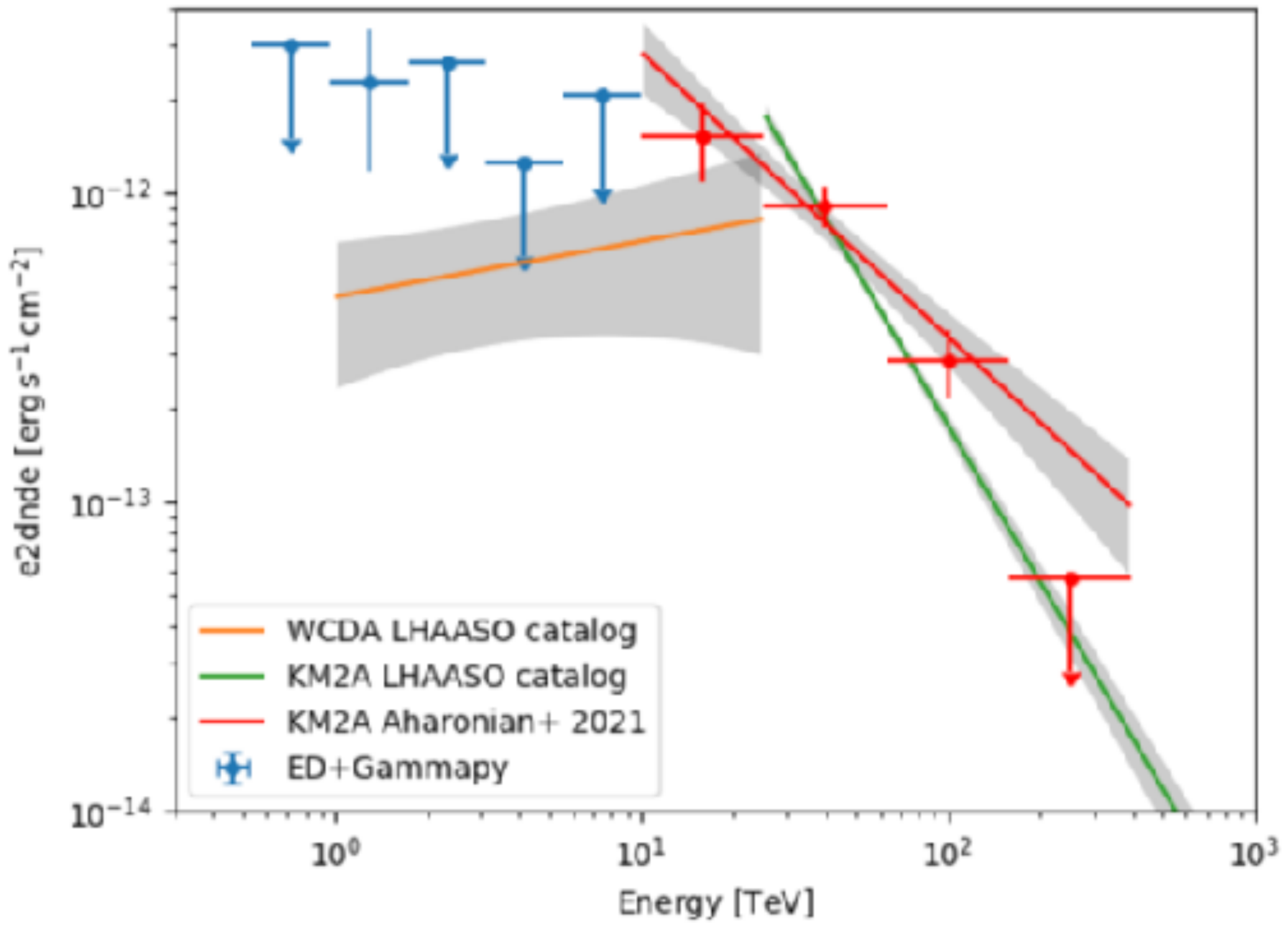
Astronomy & Astrophysics 689 (2024): A326

Dark PeVatron halo observed by VERITAS

1. LHAASO J0621+3755:
   1. No identified counterparts in TeV band.
   2. High-energy emissions >25 TeV.
2. Large angular extents
   1. LHAASO J0621+3755 is a TeV halo candidate with size ~10 of pcs
3. Search in VERITAS data yields null detection:
   1. These mysterious sources have peak emission at >TeV!

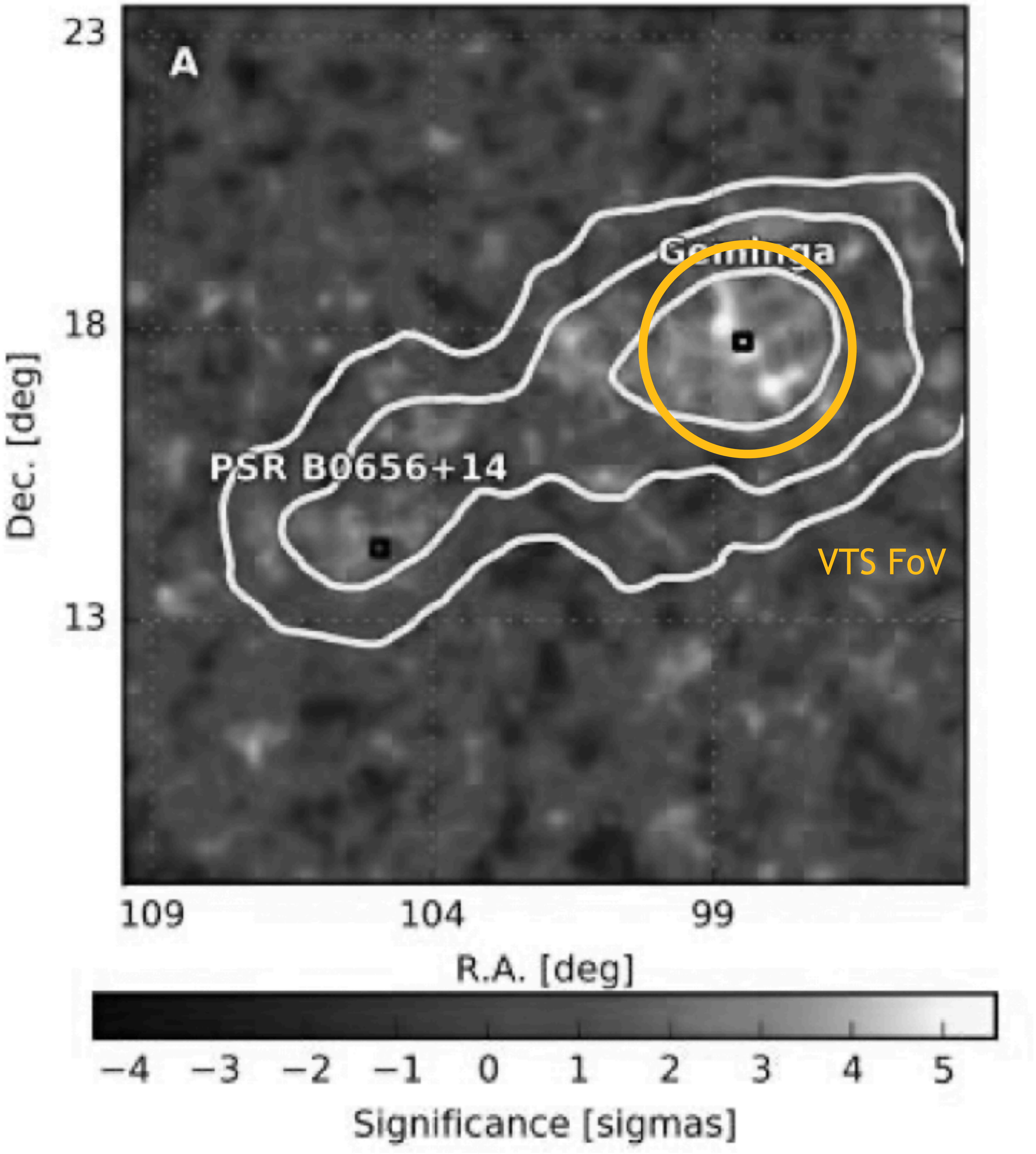






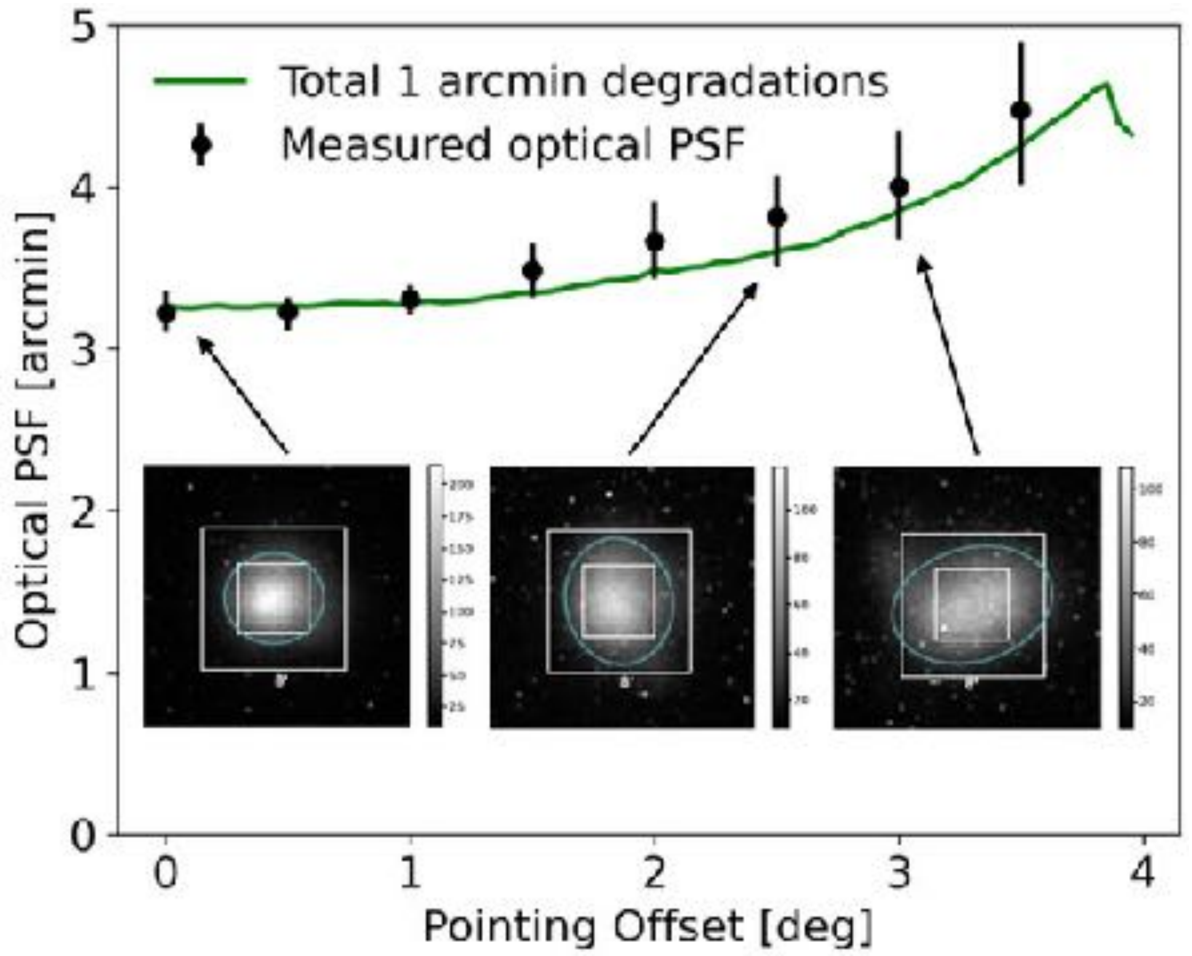
Future and challenges

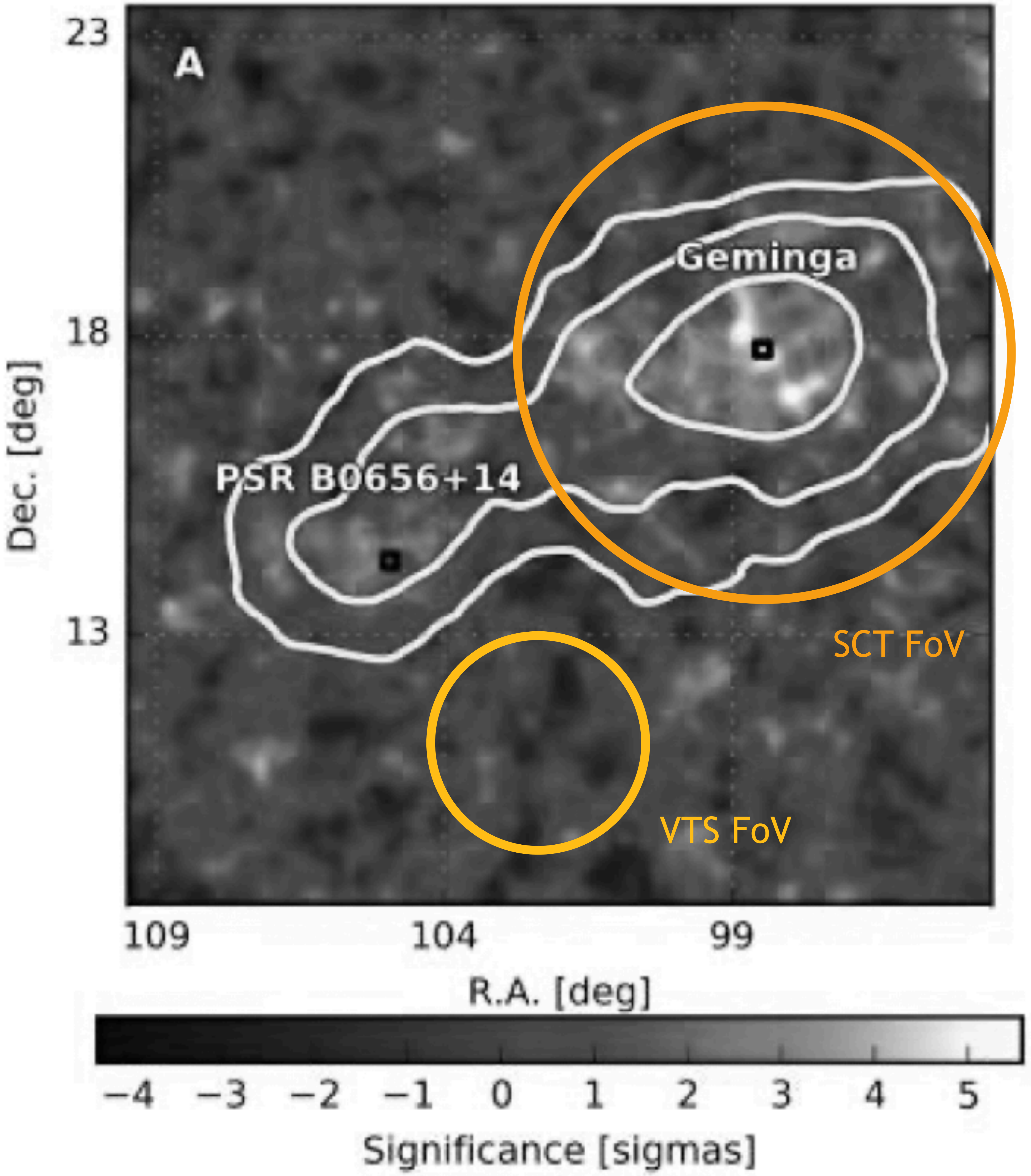
1. TeV halos are large in physical and angular sizes that can exceed the field of view of X-ray and gamma-ray telescopes
2. This leads to lacking signal-free region for background estimation
3. Two approaches to address this issue:
    1. Improving instrument field of view
    2. Improving analysis method



Future instruments: CTAO and SCT

1. Schwarzschild-Couder telescope
    1. Dual-mirror design
    2. Correct for spherical and comatic aberrations
    3. Small plate scale
    4. Large field of view
2. Improve extended-source sensitivity:
    1. Divergent pointing observation to maximize the advantage of SCT FoV
    2. Allow background region for extended sources

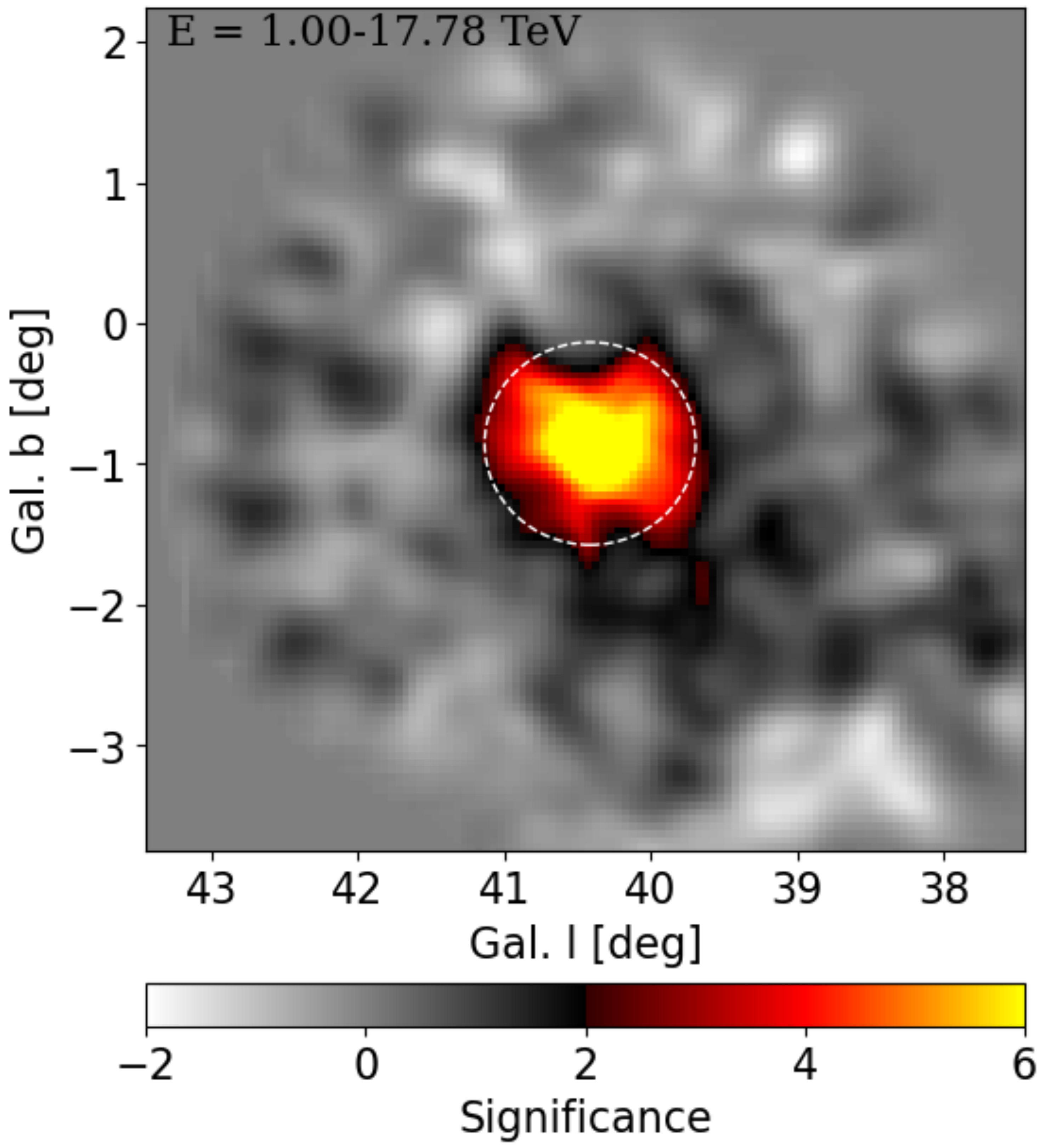


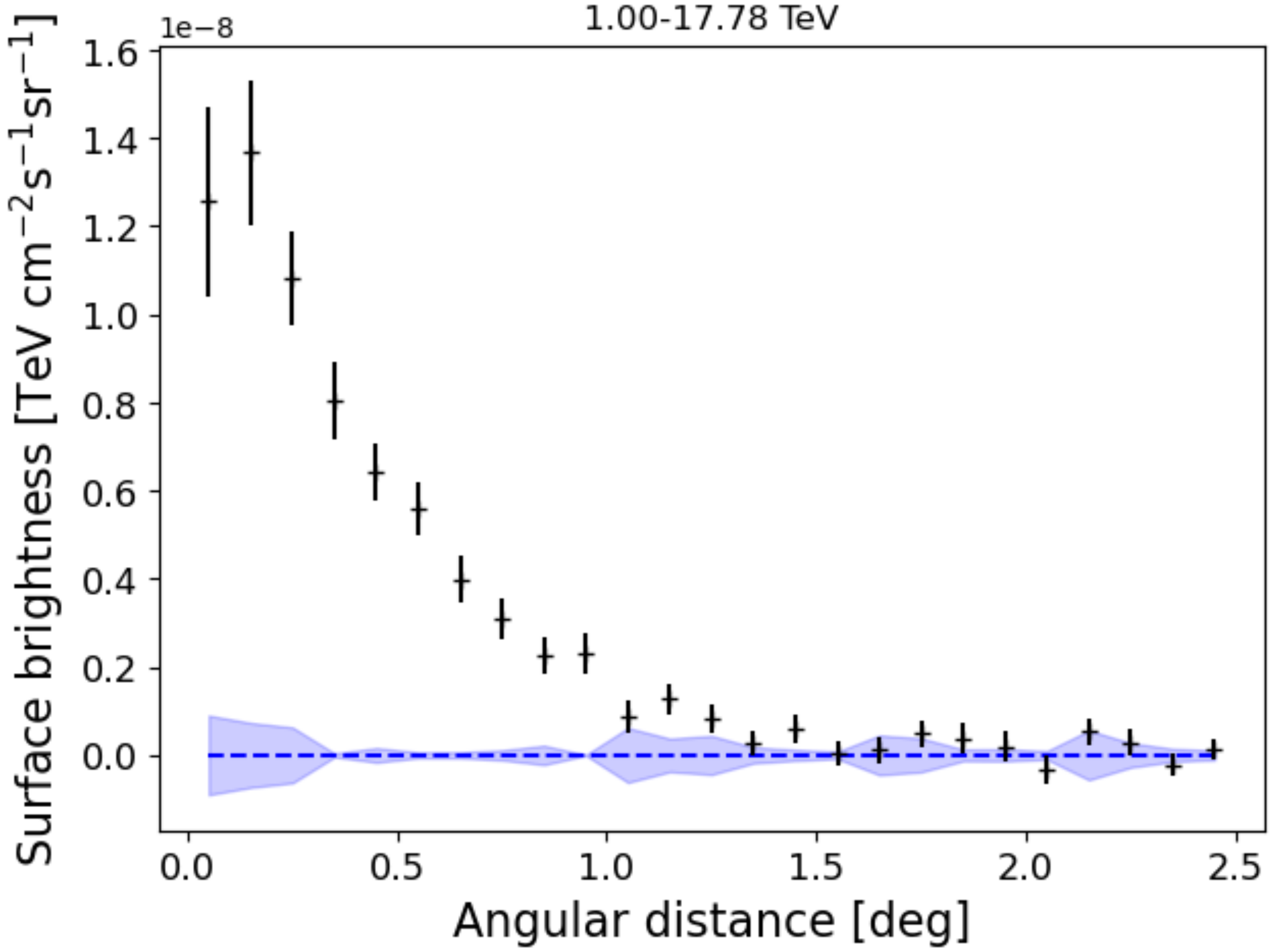


New background estimation technique

Singular Template of Imaging Cherenkov Showers (STOICS)

1. Numerical solution for analyzing extended γ-ray sources with size > FoV
2. Learn low-dimension representation from archival cosmic-ray data
3. Predict γ-like background across given observed cosmic-ray-like events
4. Enable analyses of source size > FoV
5. Goal: establishing this as a standard CTAO algorithm





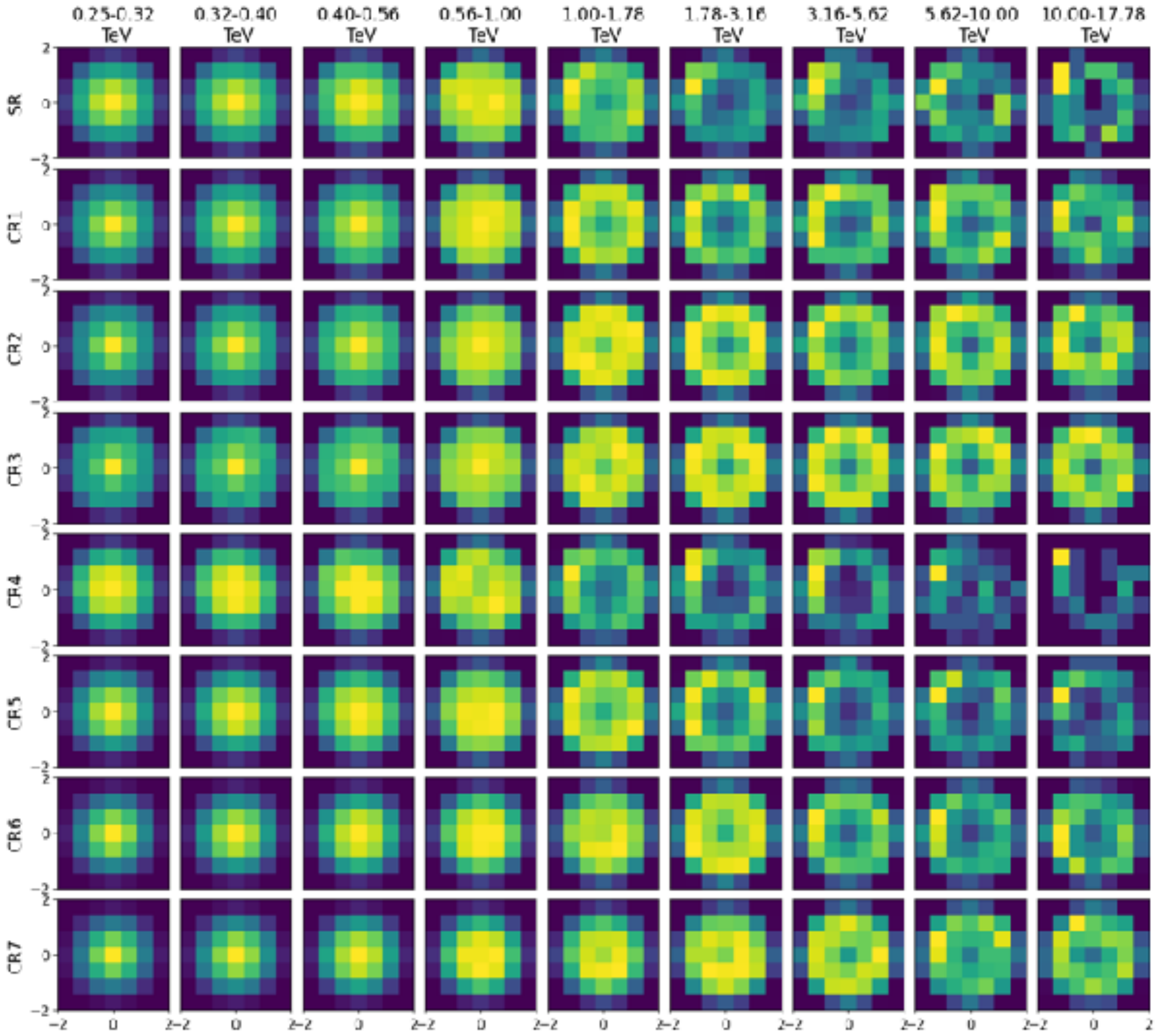
Application example: MGRO J1908+06

Summary

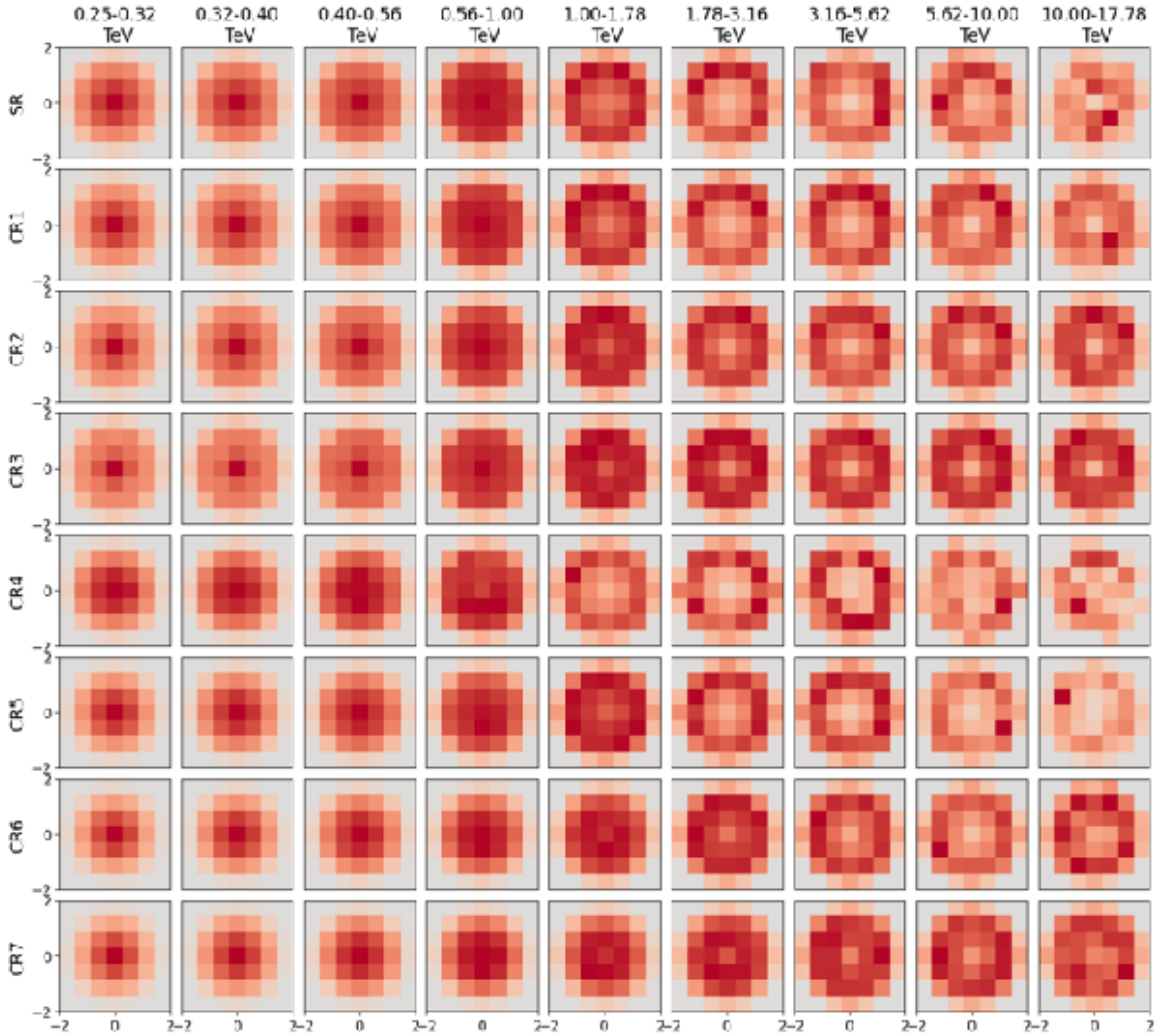
1. HAWC detection of Geminga opens a new research field on TeV halos
2. Geminga has been further detected at higher energies by LHAASO and at lower energies by Fermi-LAT and H.E.S.S.
3. X-ray observations by XMM and NuSTAR put strong constraints on magnetic field around the Geminga pulsar
4. VERITAS observations put upper limits on other TeV halo candidates
5. Development on future instruments and analysis methods will advance the science on TeV halos

Backup

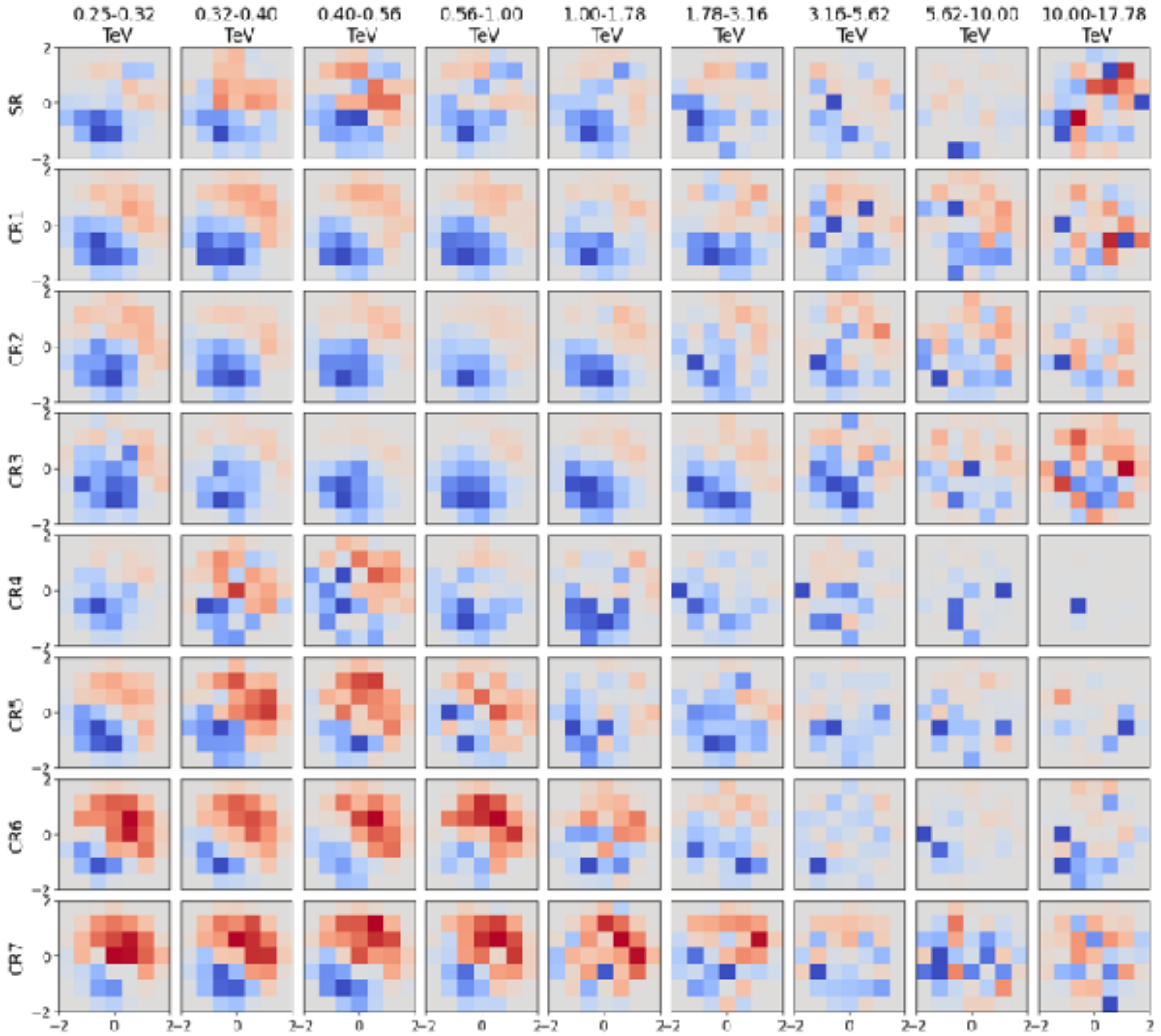
Original data



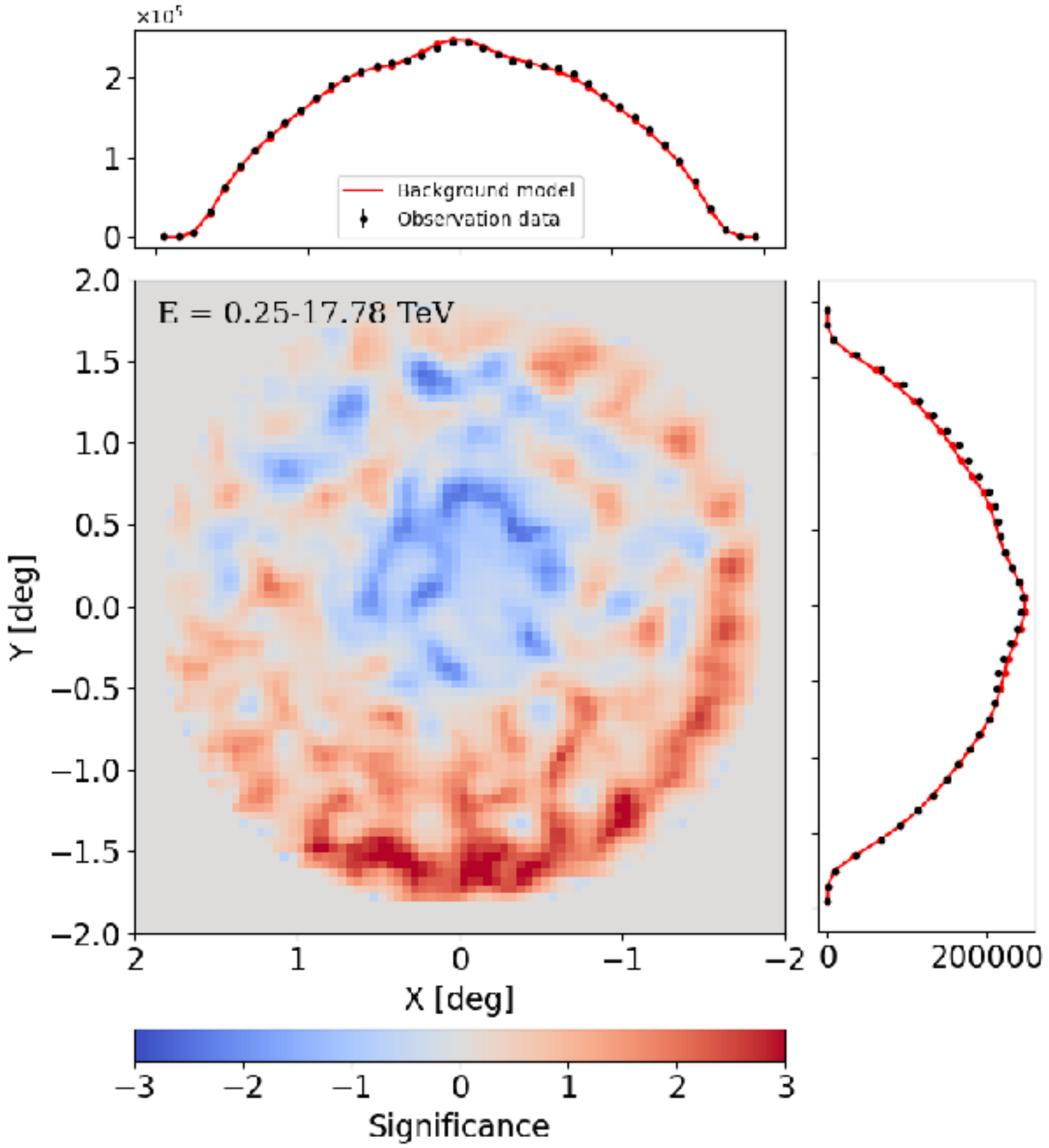
First singular template



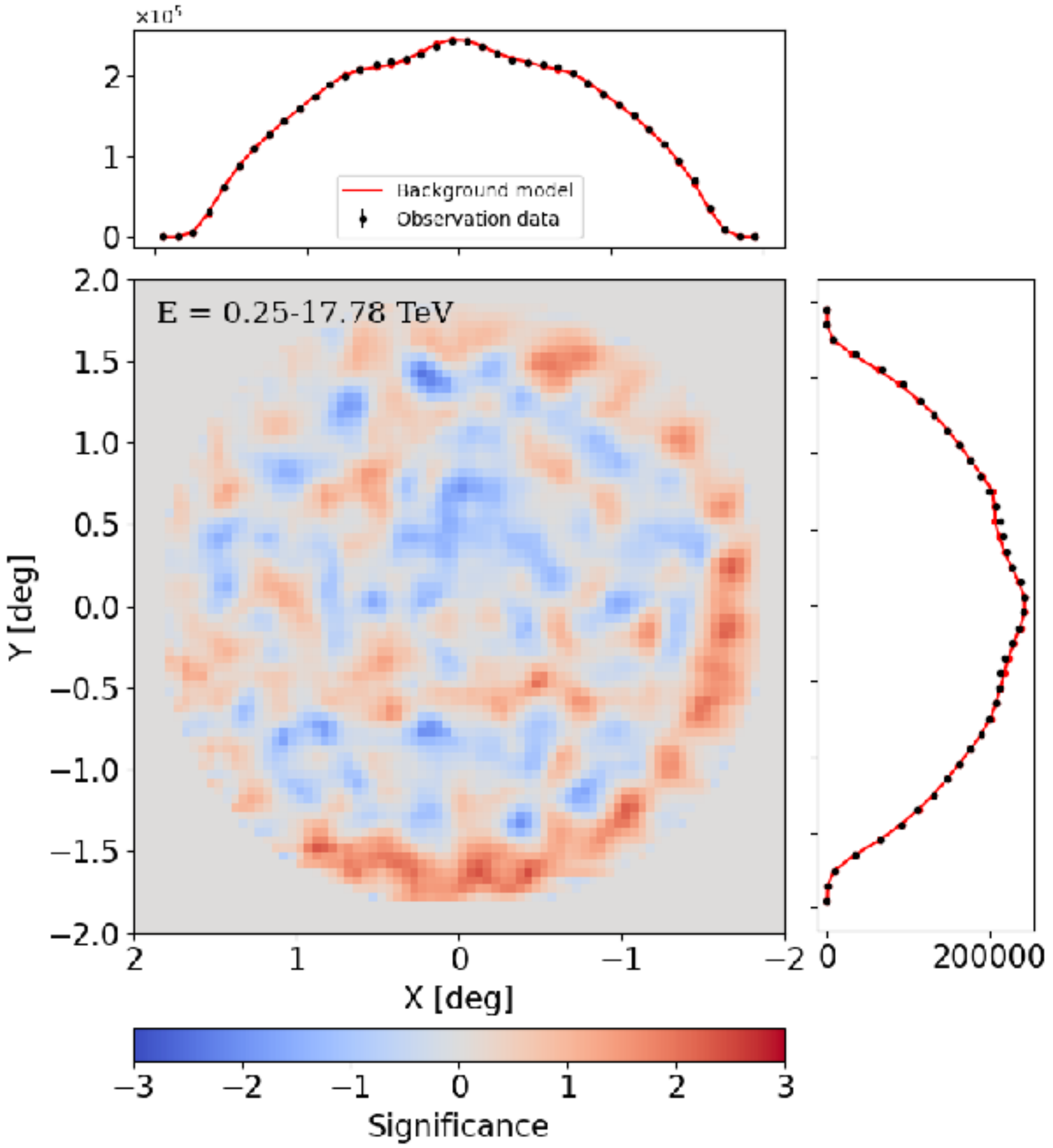
Fifth singular template



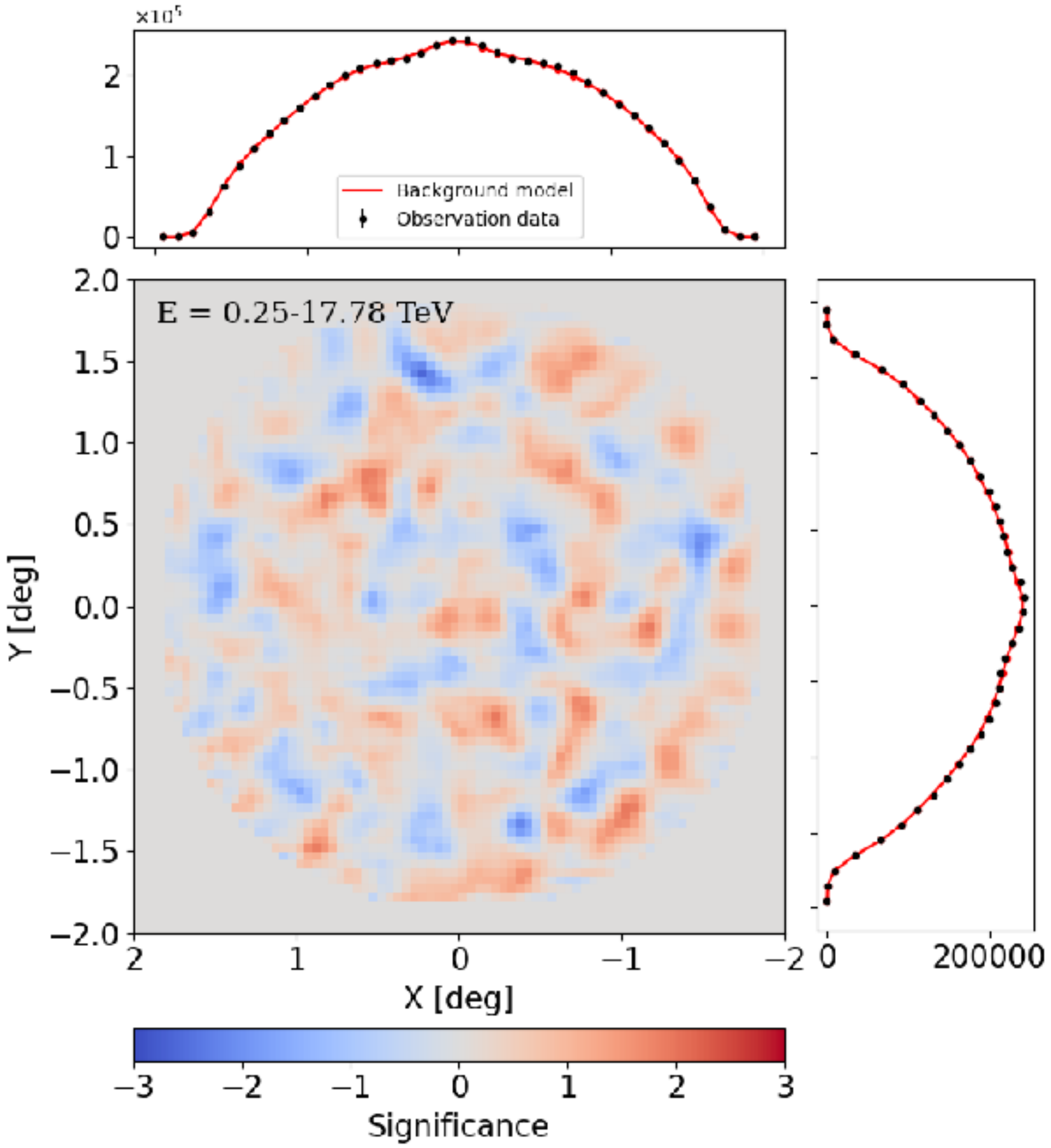
Include 1 template



Include 4 templates



Include 32 templates



The most-extended gamma-ray source