Image credit: Giuseppe Donatiello

PennState

Observations of the IC 443 region with HAWC

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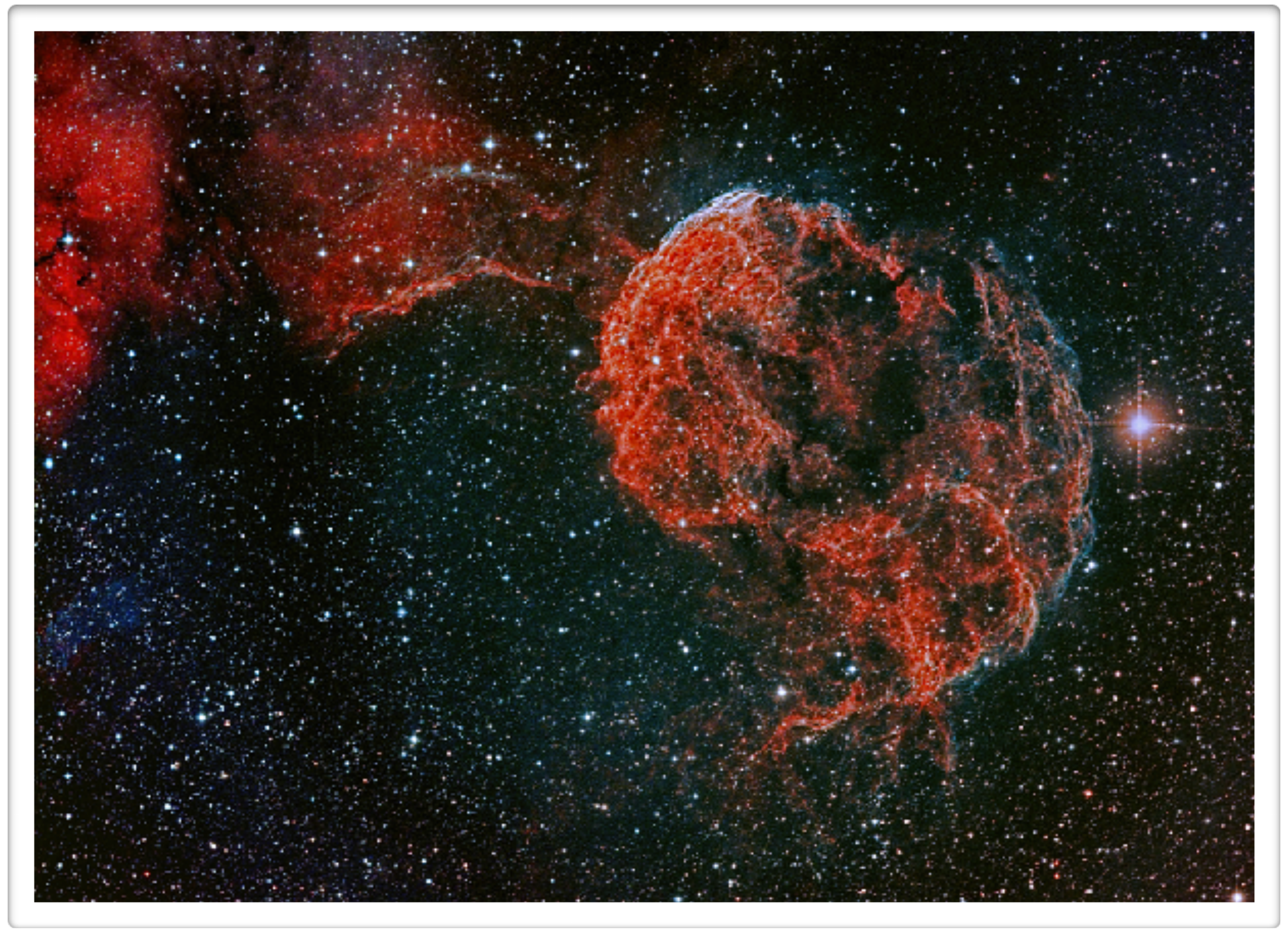
HAWC
High Altitude Water Cherenkov
Gamma Ray Observatory

Supernova remnants as Cosmic-ray accelerators



- Supernova Remnants (SNRs) are the aftermaths of the catastrophic explosions of massive stars or white dwarfs after accreting enough mass
- They are capable of accelerating cosmic rays (CRs)
  - Candidates to be PeVatrons, i.e. CRs at PeV energies.

Image credit: Giuseppe Donatiello

IC 443 Nebula

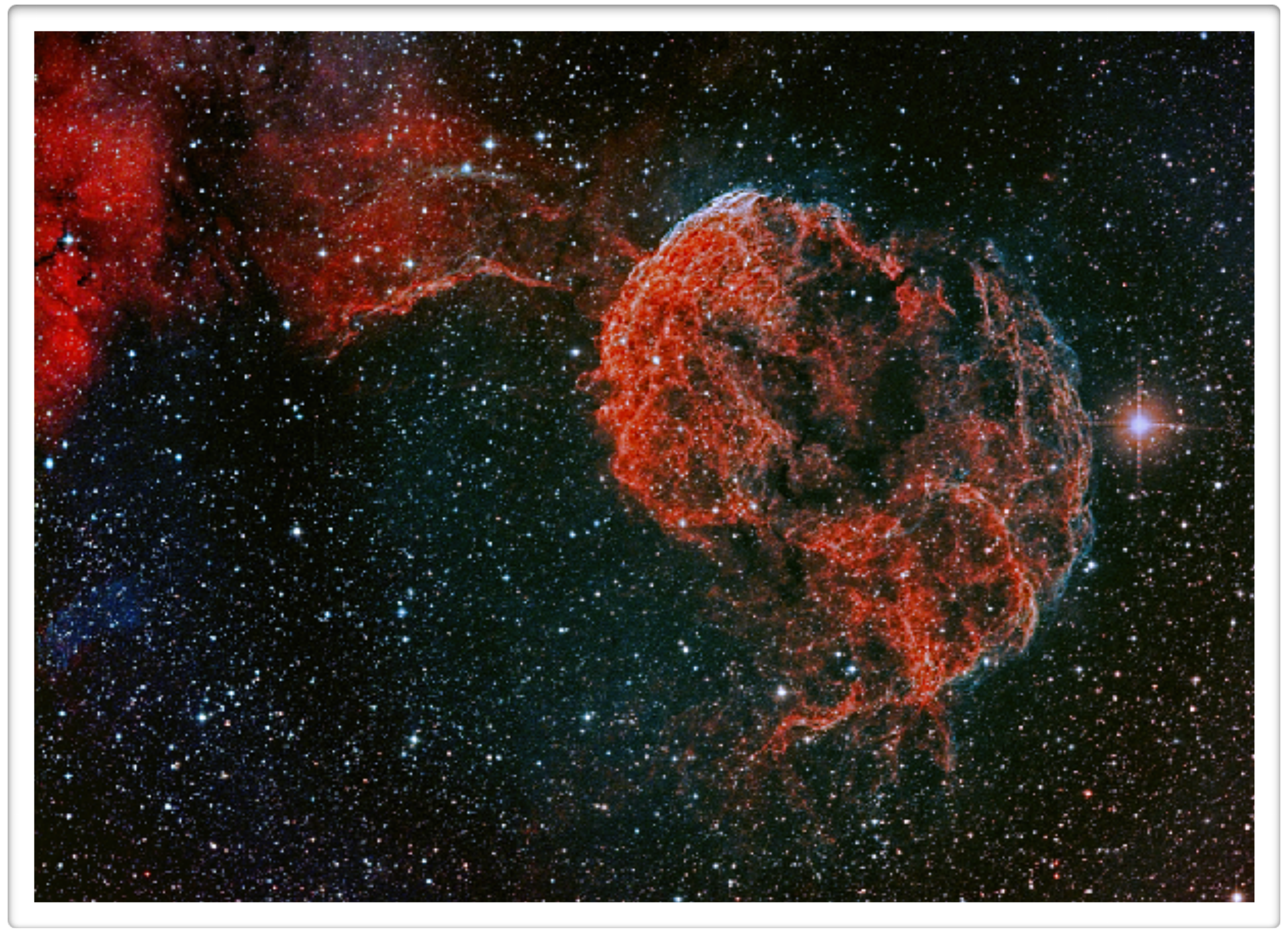
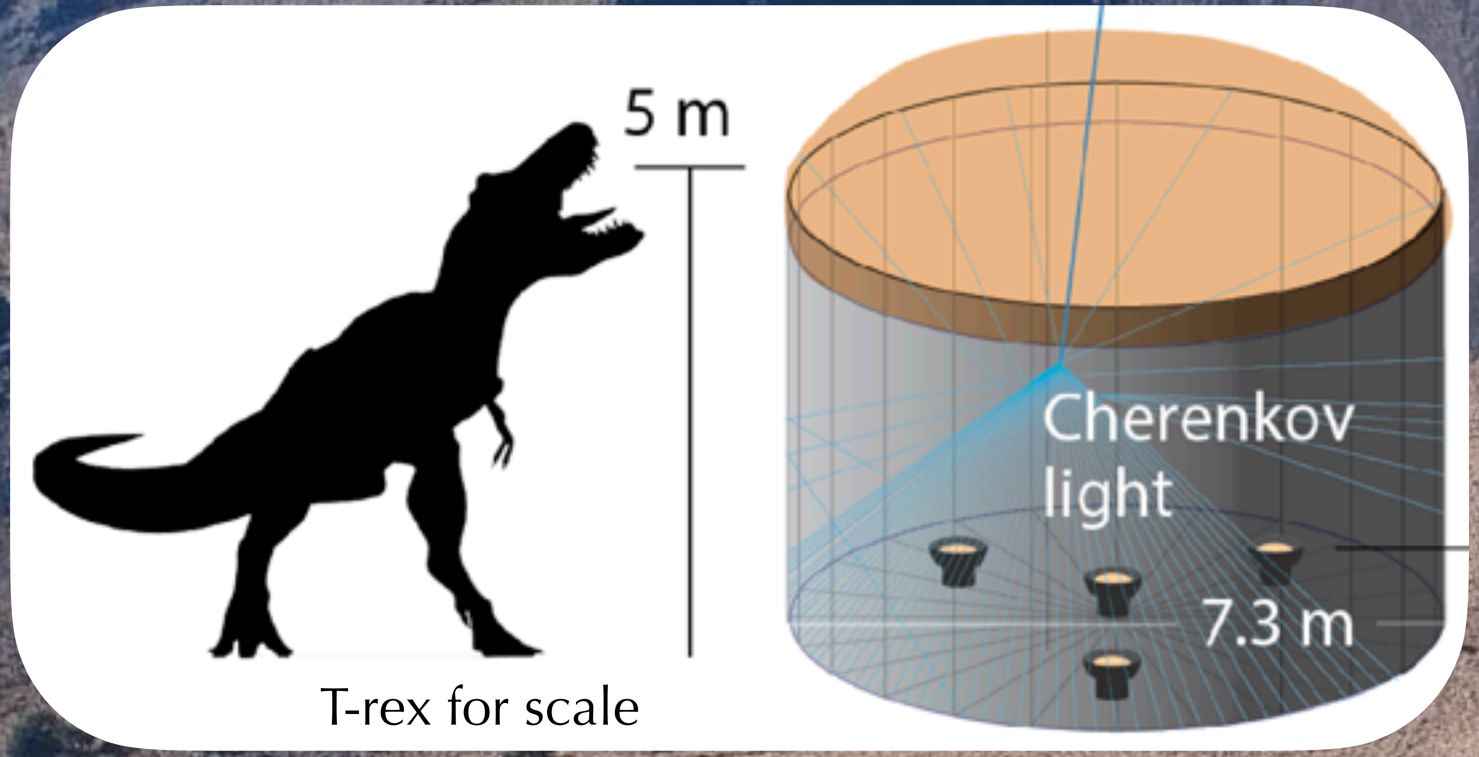


Image credit: Giuseppe Donatiello

- One of the most studied SNRs. Observed for the first time in 1892.
- Located at ~1.8 kpc (Ambrocio-Cruz et al. 2017)
- Detected in radio, IR, optical, x-rays and gamma rays:
  - Radio highlights regions of synchrotron radiation (Castelletti et al. 2011, and others).
  - Optical helps delineate the boundaries and the region of the interaction of the shock wave and the ISM (Li et al. 2022, and others)
  - X-rays reveal the hot gas heated by the shock wave. Also found the progenitor of the SNR, a pulsar named CXOU J061705.3+222127 (Swartz et al. 2015)
  - Gamma rays alludes to particle acceleration and type of particles (Ackermann et al. 2013, and others)

High Altitude Water Cherenkov Observtatory

HAWC
High Altitude Water Cherenkov Gamma-Ray Observatory



Energy range: ~300 GeV — 100 TeV
Angular resolution: ~0.2°
Field of View: ~2 sr
>95% Uptime

Main array completed March 2015
Outriggers deployed 2018

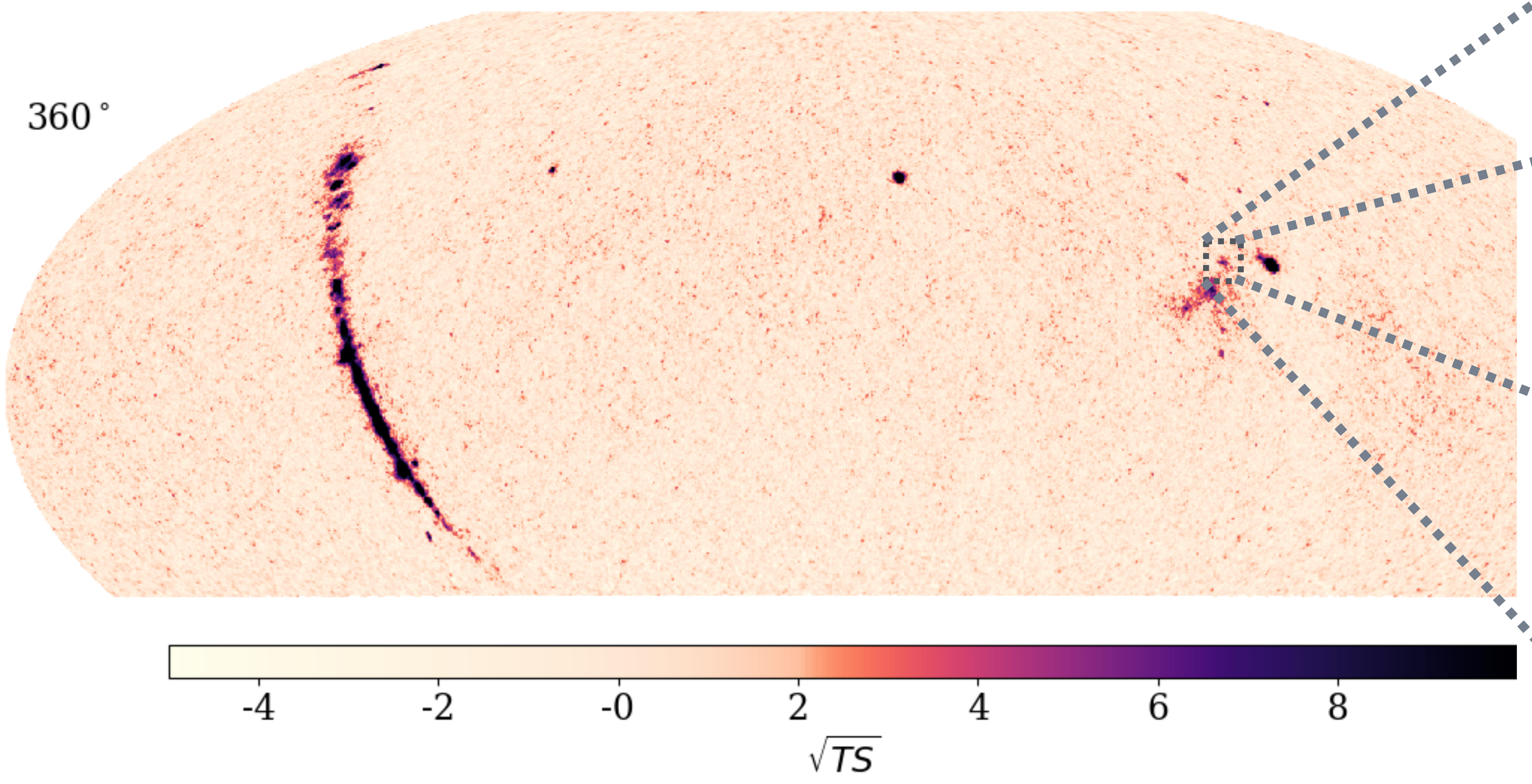
100,000 m^2

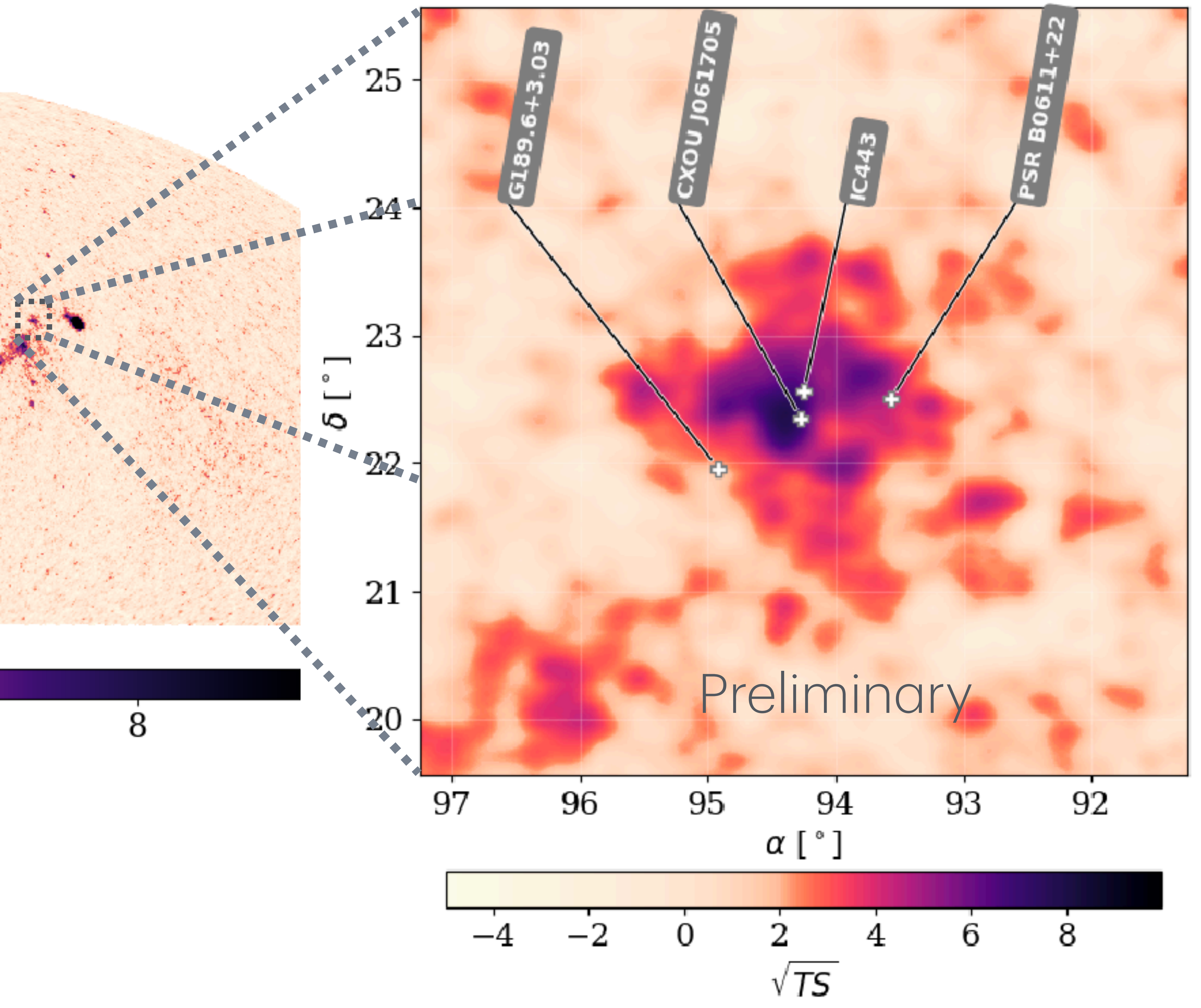
4100 m elevation

22,000 m^2

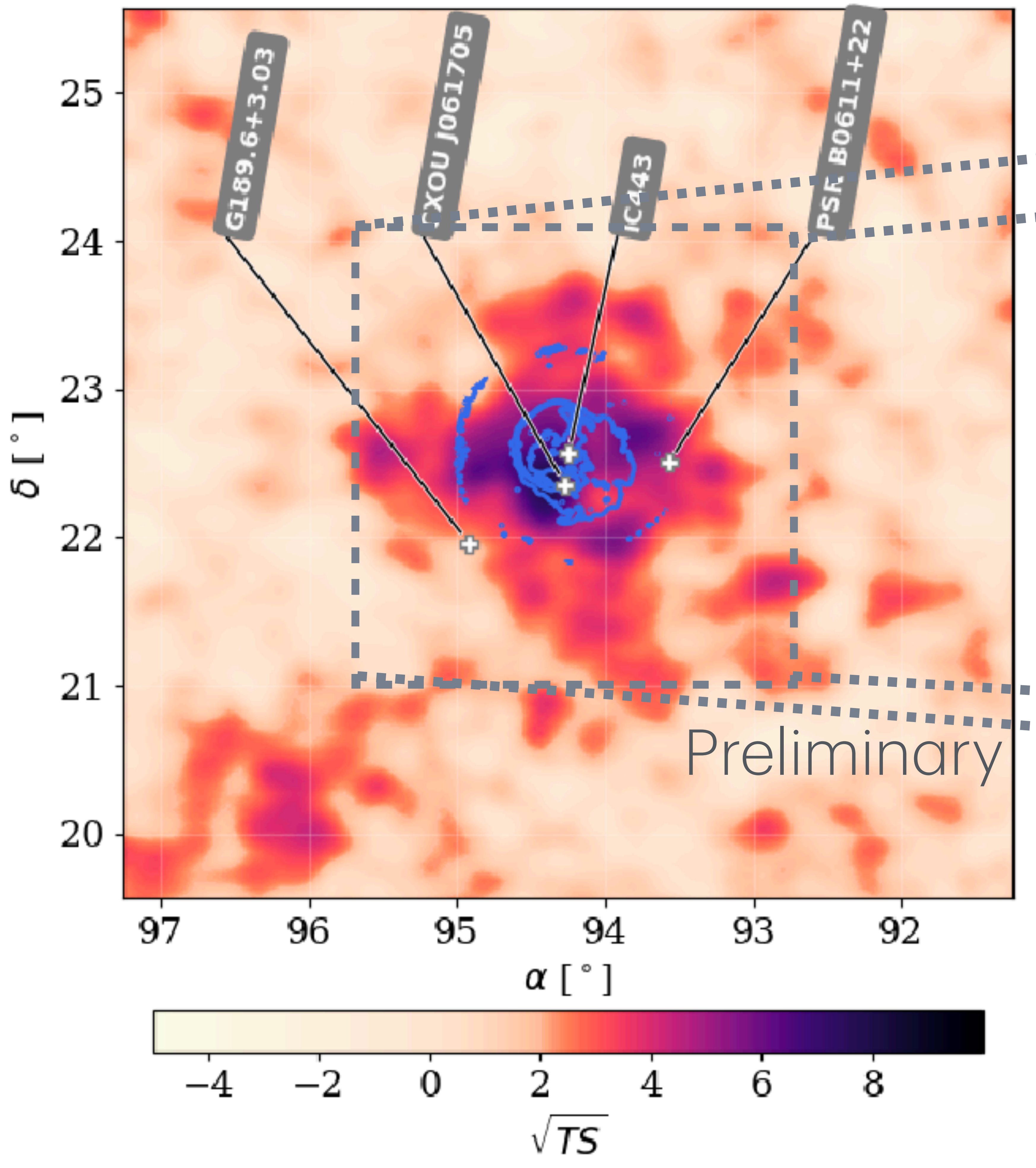
HAWC NIM paper 2023

HAWC observations of the IC 443 region

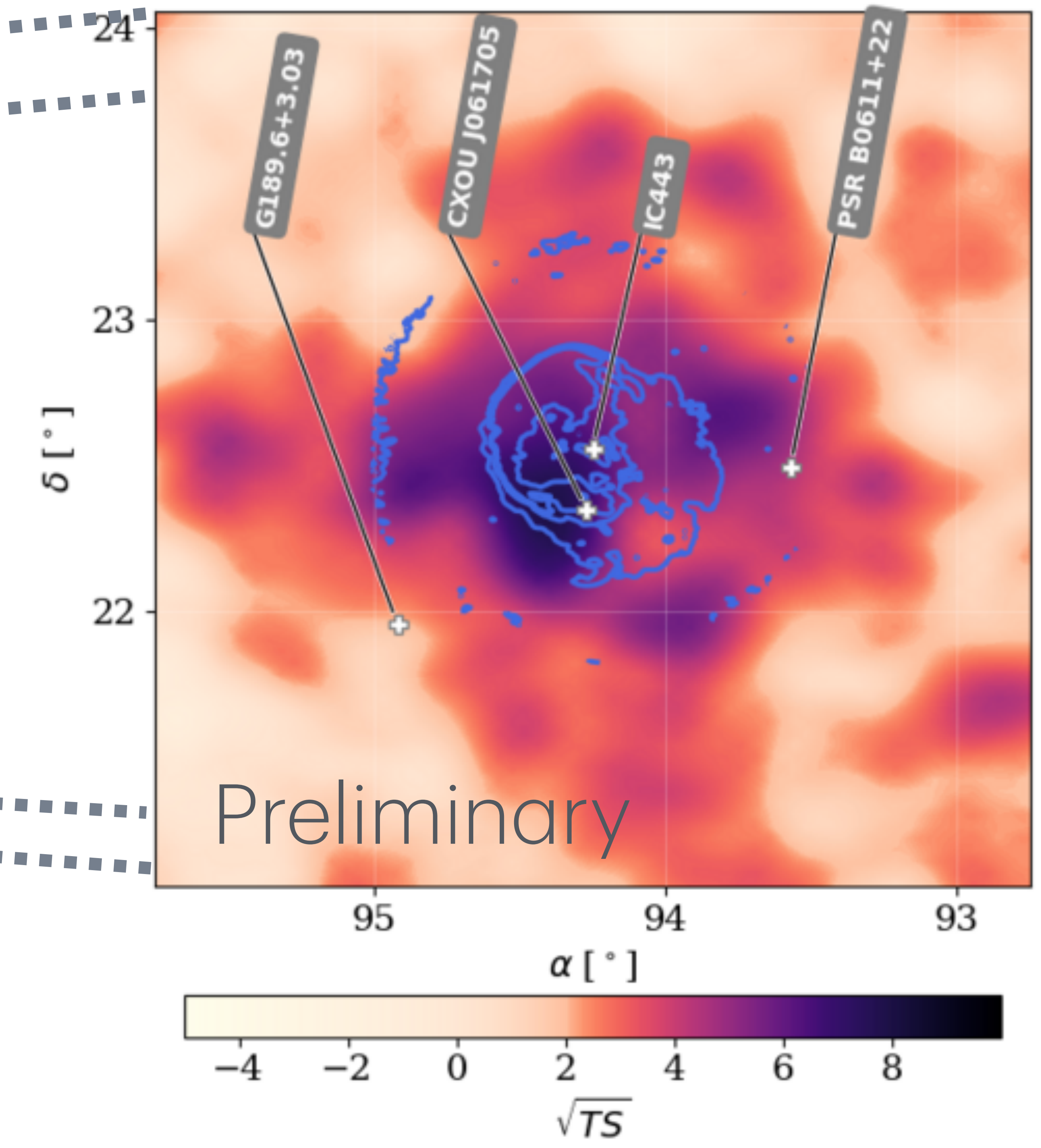




HAWC observations of the IC 443 region



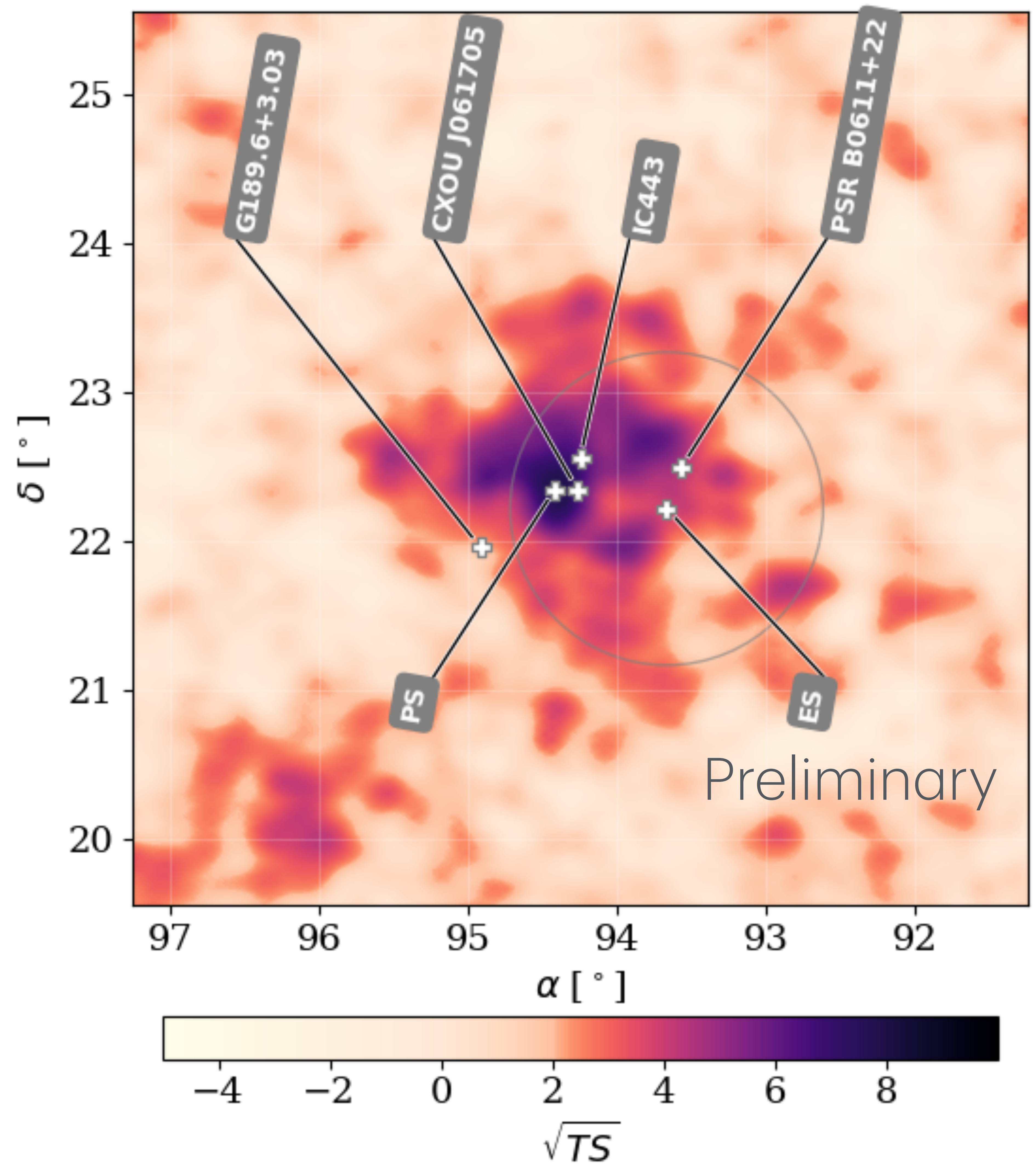
- Contours from Lee, Jae-Joon, et al. 2008.



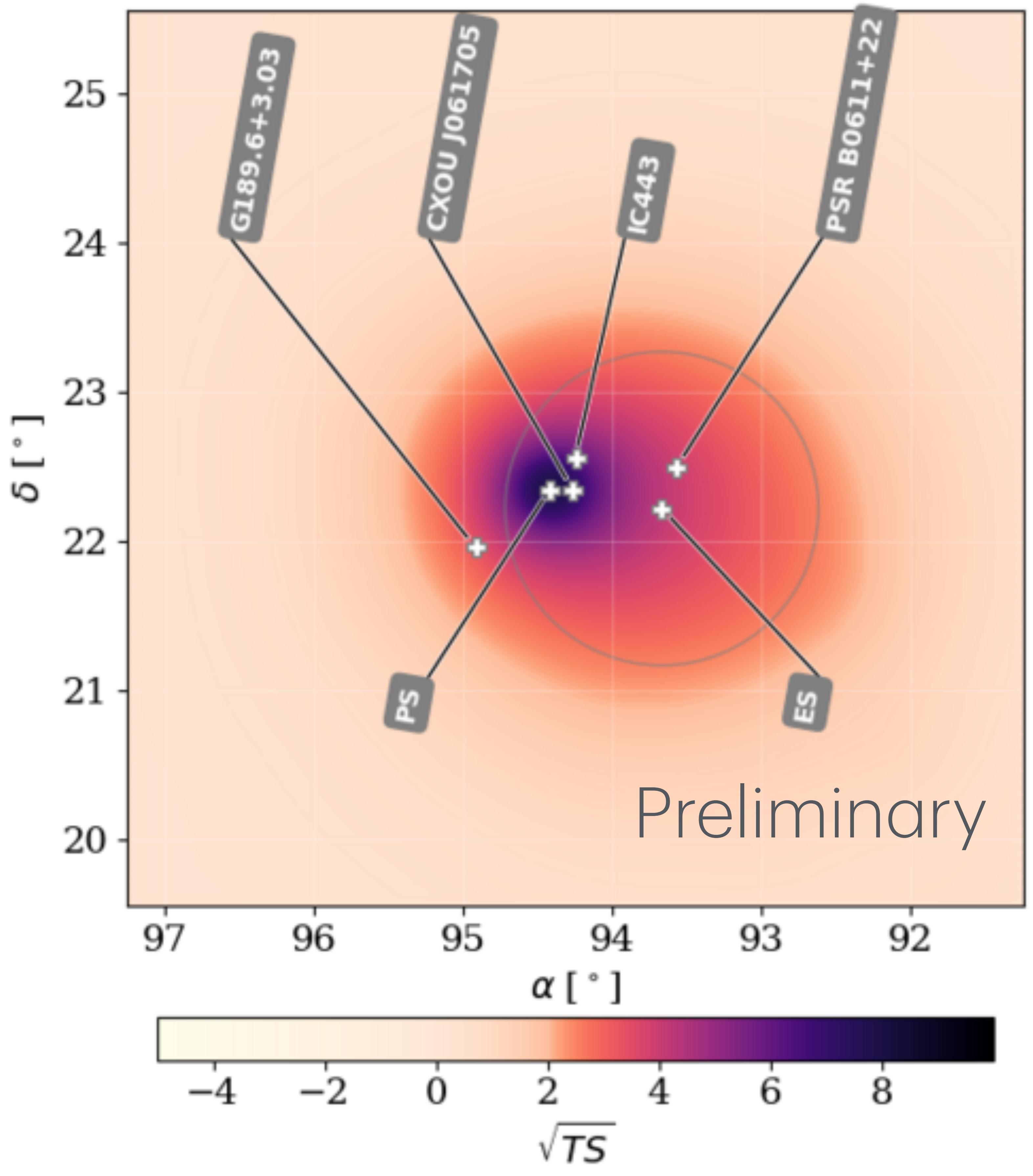
- Angular resolution of HAWC is ~0.2 deg above 10 TeV.

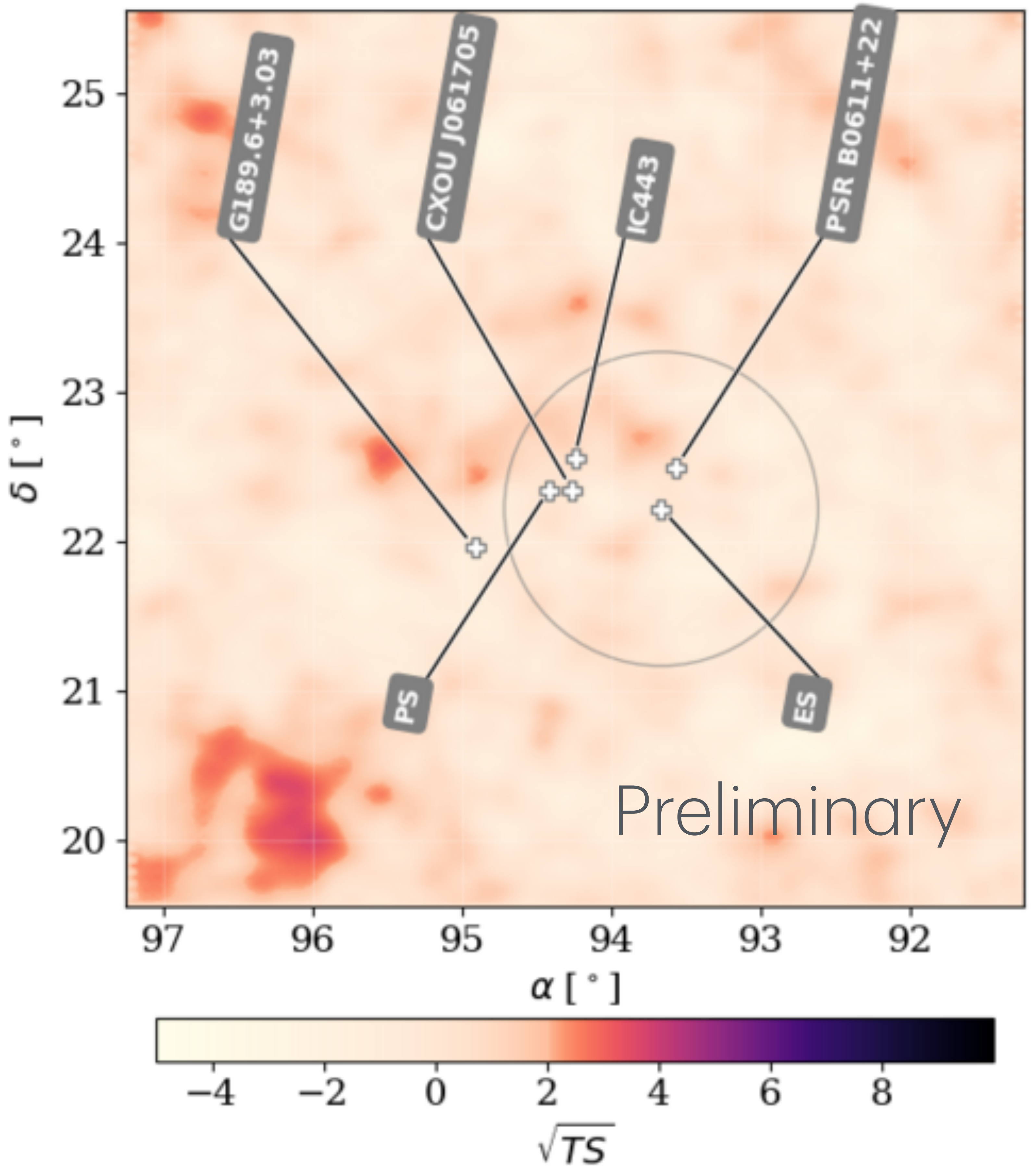
Analysis of the region

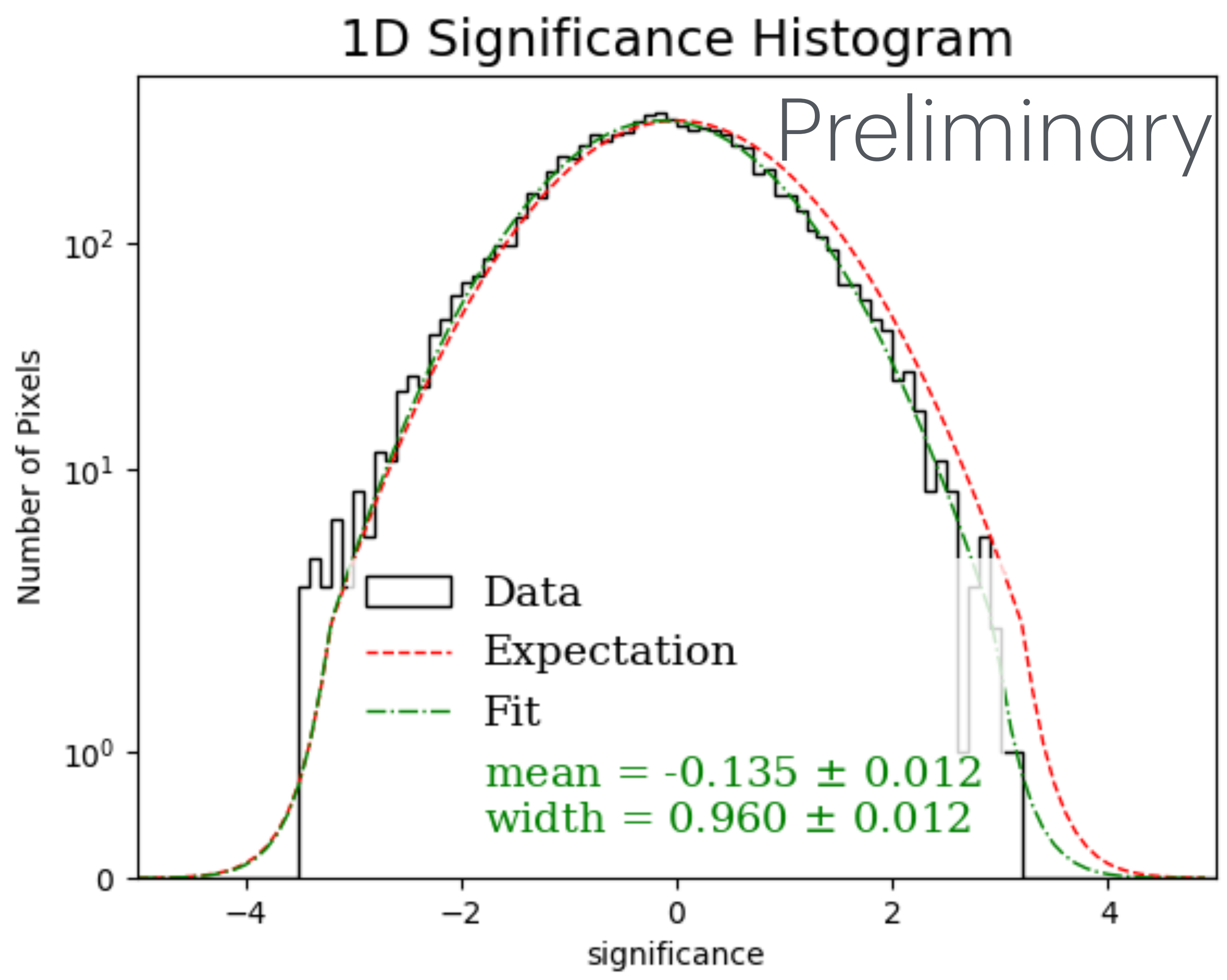
- Use likelihood method (3ML, Vianello et al. 2015; Abeysekara et al. 2022)
  - Find morphology and spectrum that best describes the data:
    - Iterative process similar to Fermi-LAT catalog construction
  - Best model: a point source close to IC 443 and an extended source (Gaussian shape).
    - Both prefer a power-law spectrum.
    - Includes Galactic Diffuse Emission from Hermes model (Dundovic et al. 2021)



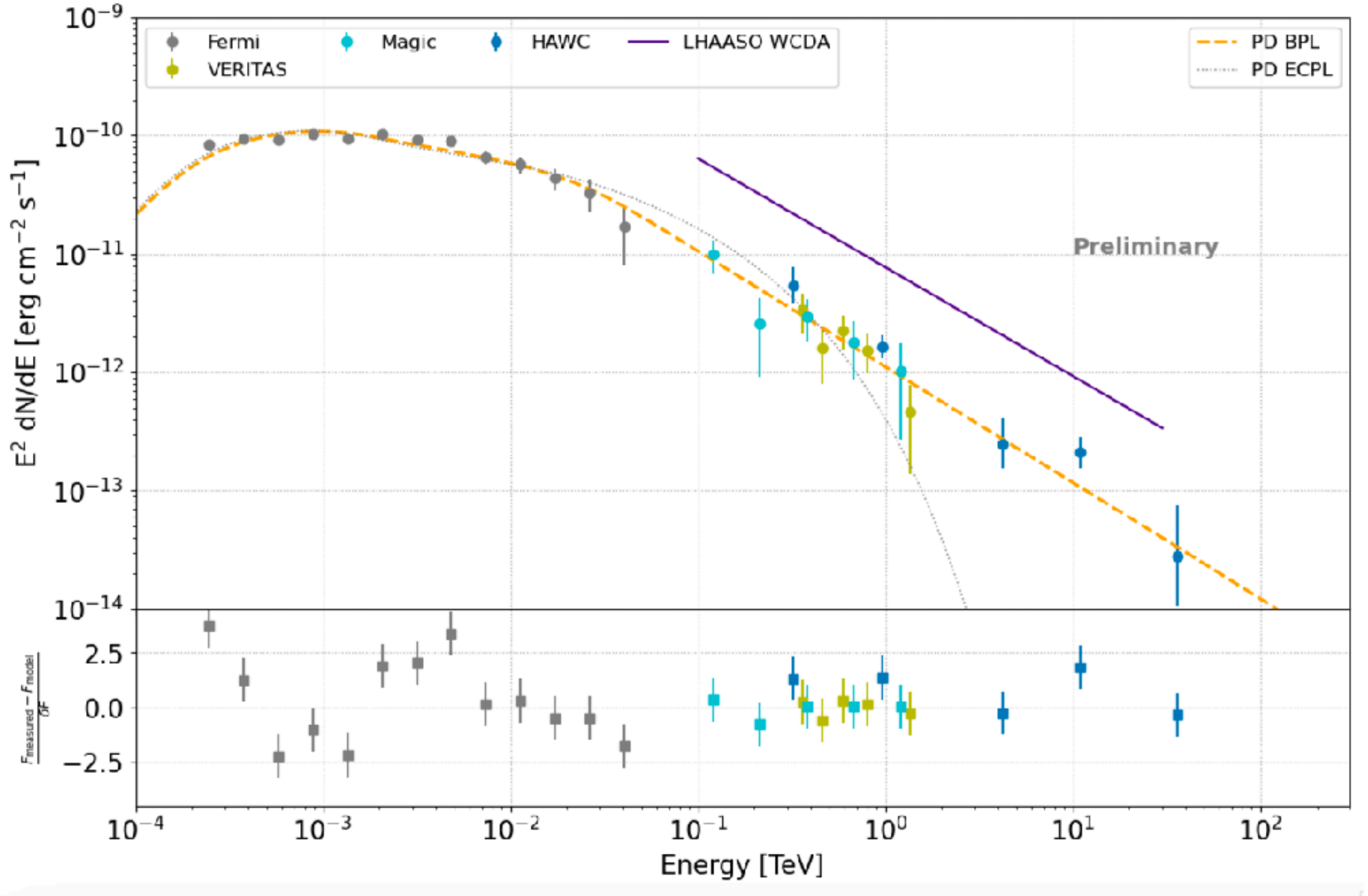
Analysis - Model and residual maps





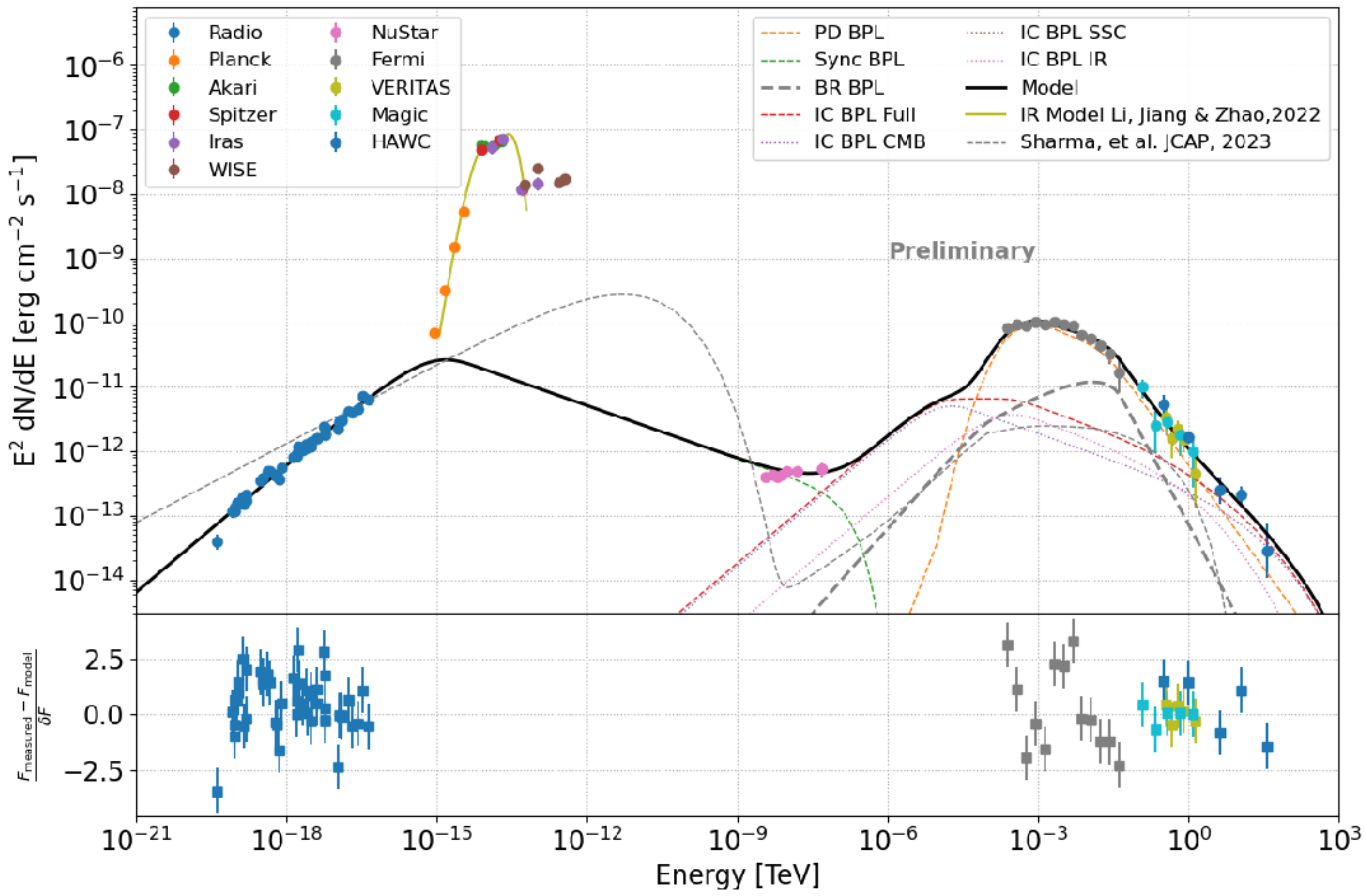


IC 443 - VHE



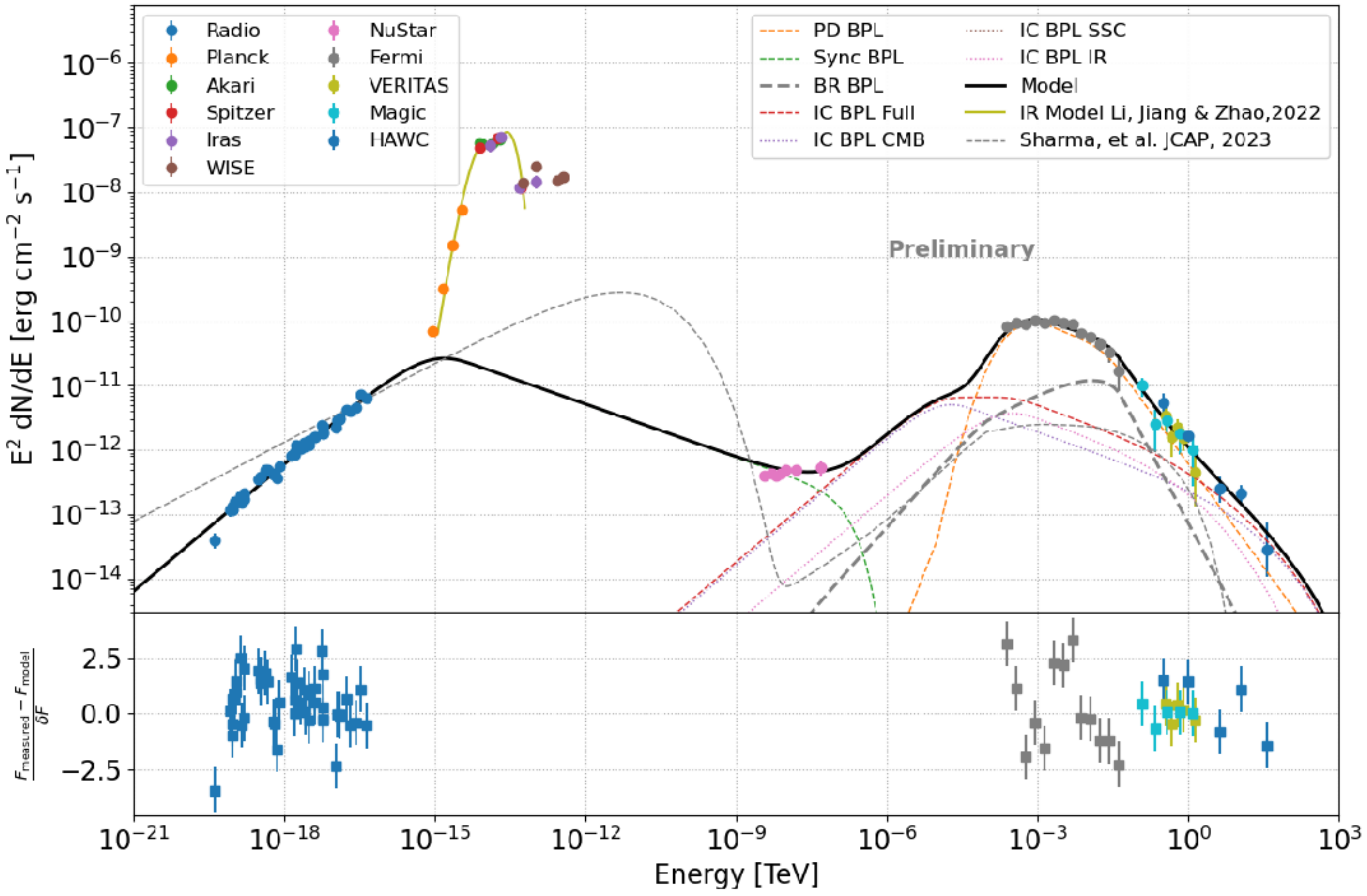
- Fermi confirmed hadronic acceleration after observing pionic gamma rays (2013)
- HAWC observations increase the energy range of the observed gamma rays
  - PL with index of -3.14 and normalization of $(5.9\pm1.3)\times10^{-13}$ $[\mathrm{TeV\ cm^2\ s}]^{-1}$ at 1 TeV.
- Non-thermal emission model prefers a broken power law function for the CR spectra.
- LHAASO flux from catalog. Their search found one extended source. A detailed analysis is needed for proper comparison.
- Not enough evidence to tell if it is a PeVatron

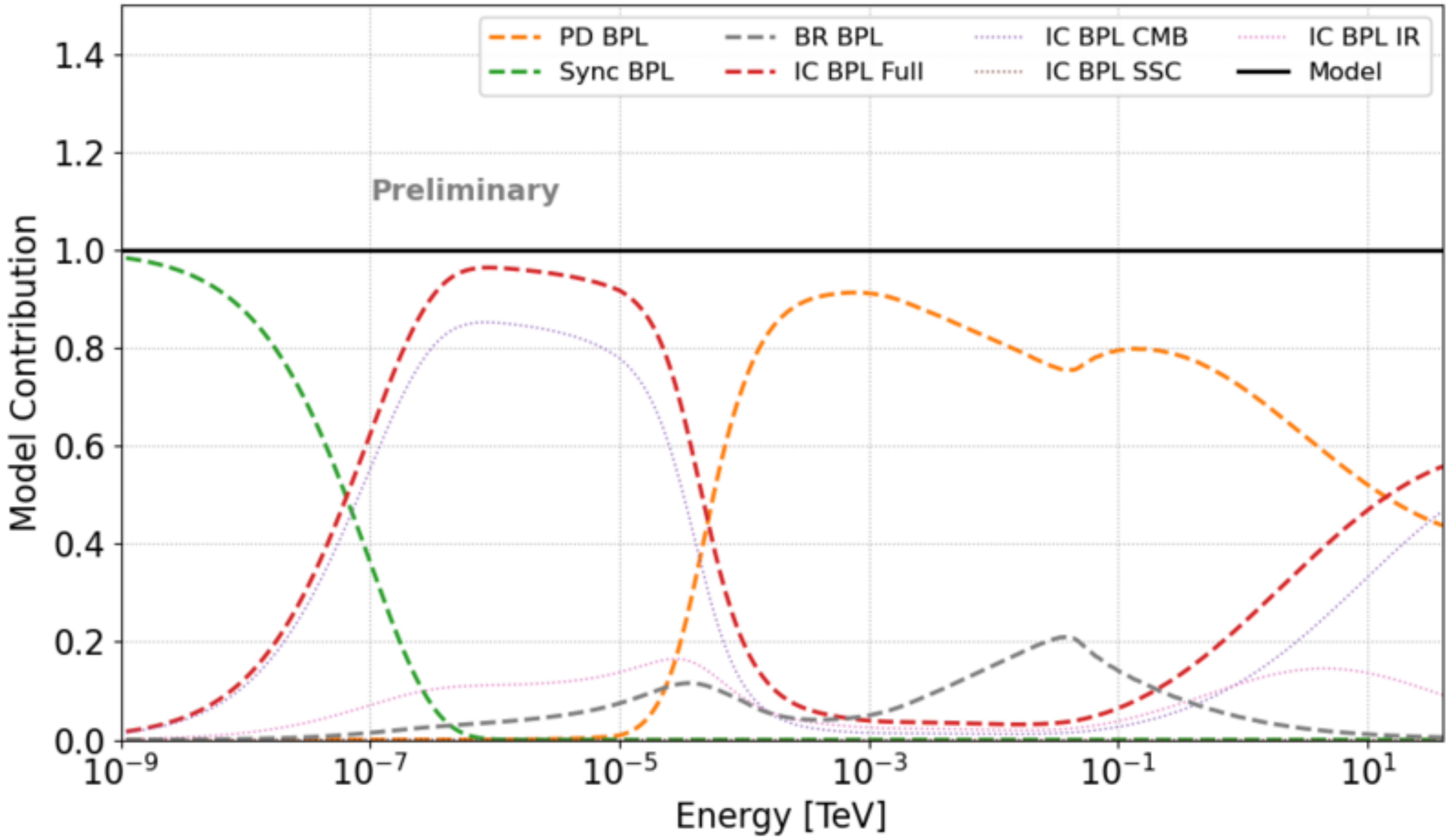
IC 443 - MW picture



- Non-thermal emission model
  - IR data is thermal emission so it's not part of the final model, but used as a photon seed for inverse Compton.
  - X-ray observations are from the PWN so are not considered in the Fit

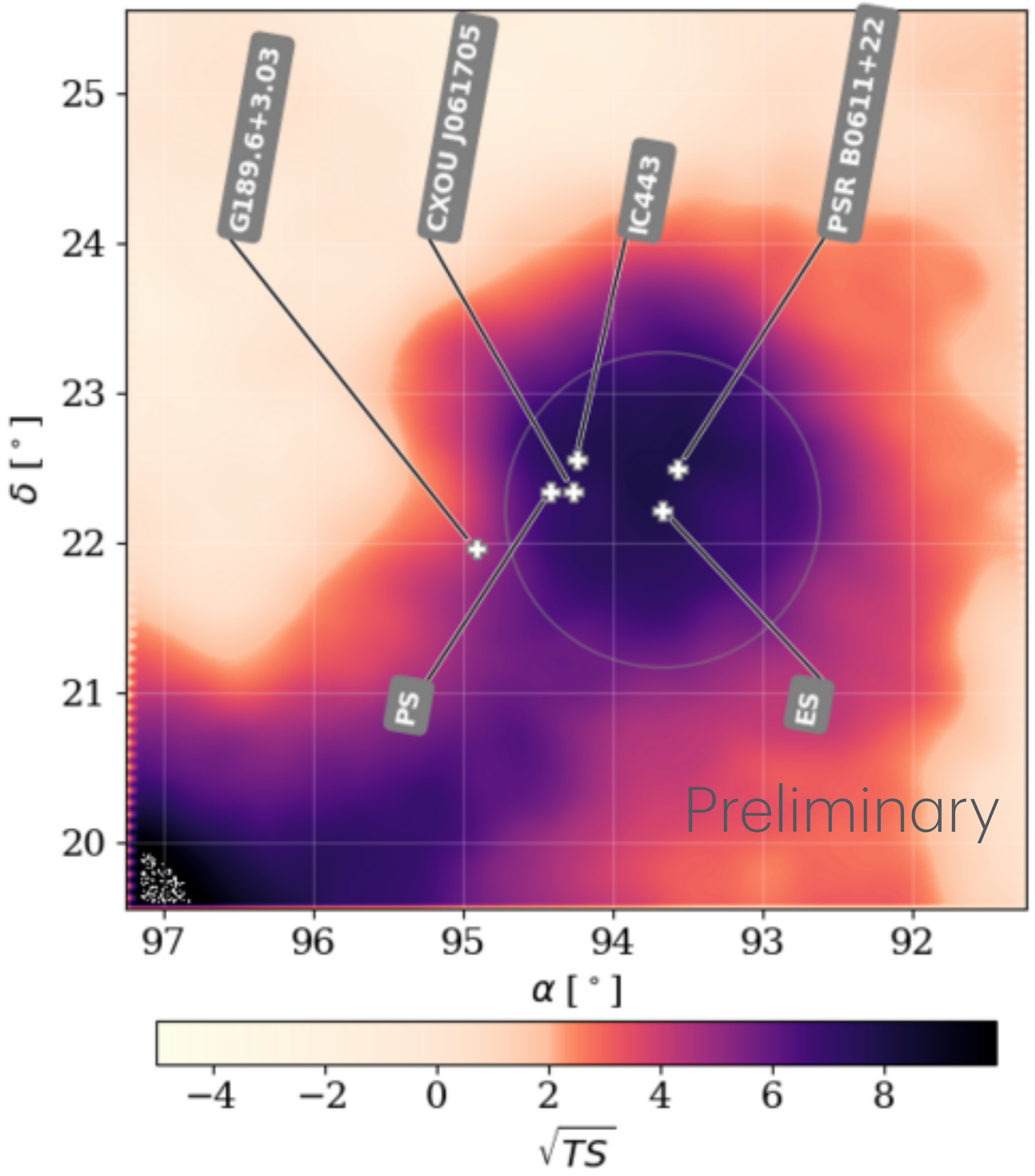
IC443 - MW picture





- In this lepto-hadronic model, IC and Pion decay both contribute to the VHE emission above 10 TeV.

Extended source - a new TeV Halo?

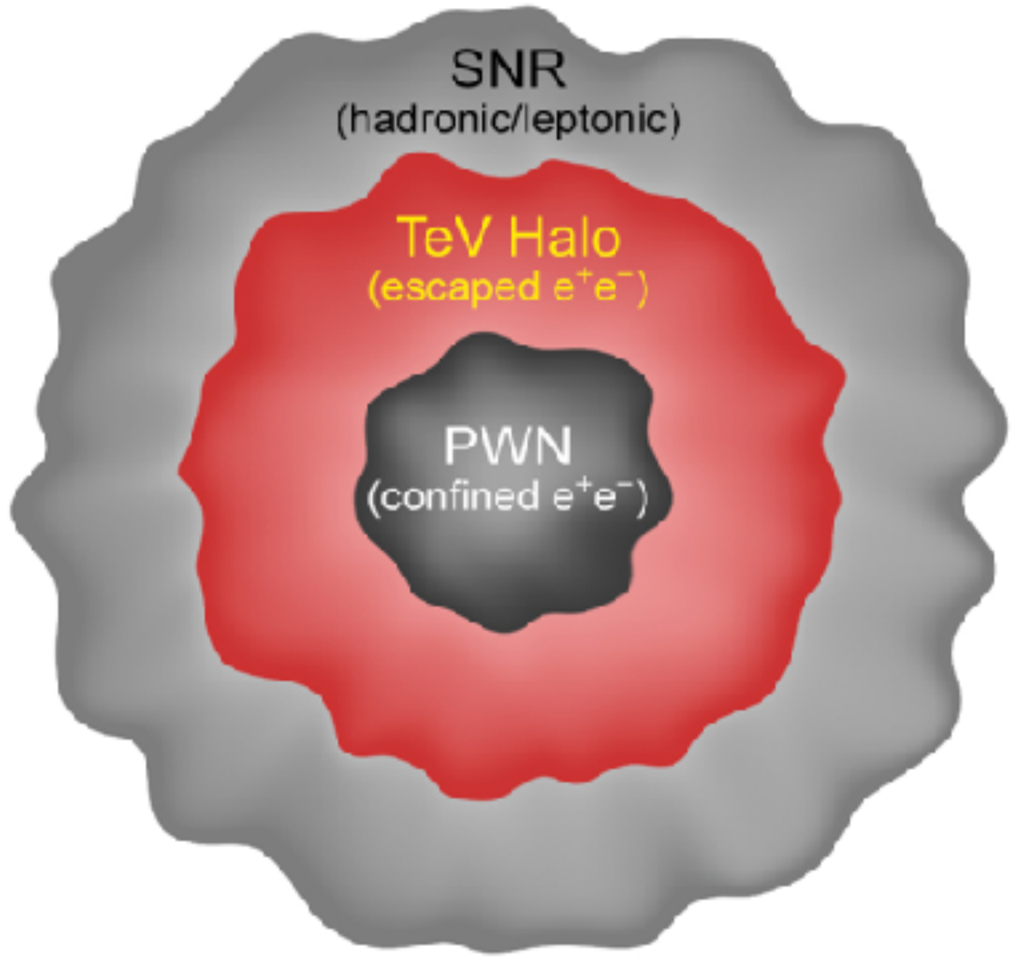


- The extended emission is around PSR B0611+22 (or J0614+2229)
  - Old pulsar with 89kyr of age
  - Located at 3.55kpc away
  - $\dot{E} = 6.24 \times 10^{34}\,\mathrm{erg\,s^{-1}}$
  - $P_0 = 0.3349\,\mathrm{s}$

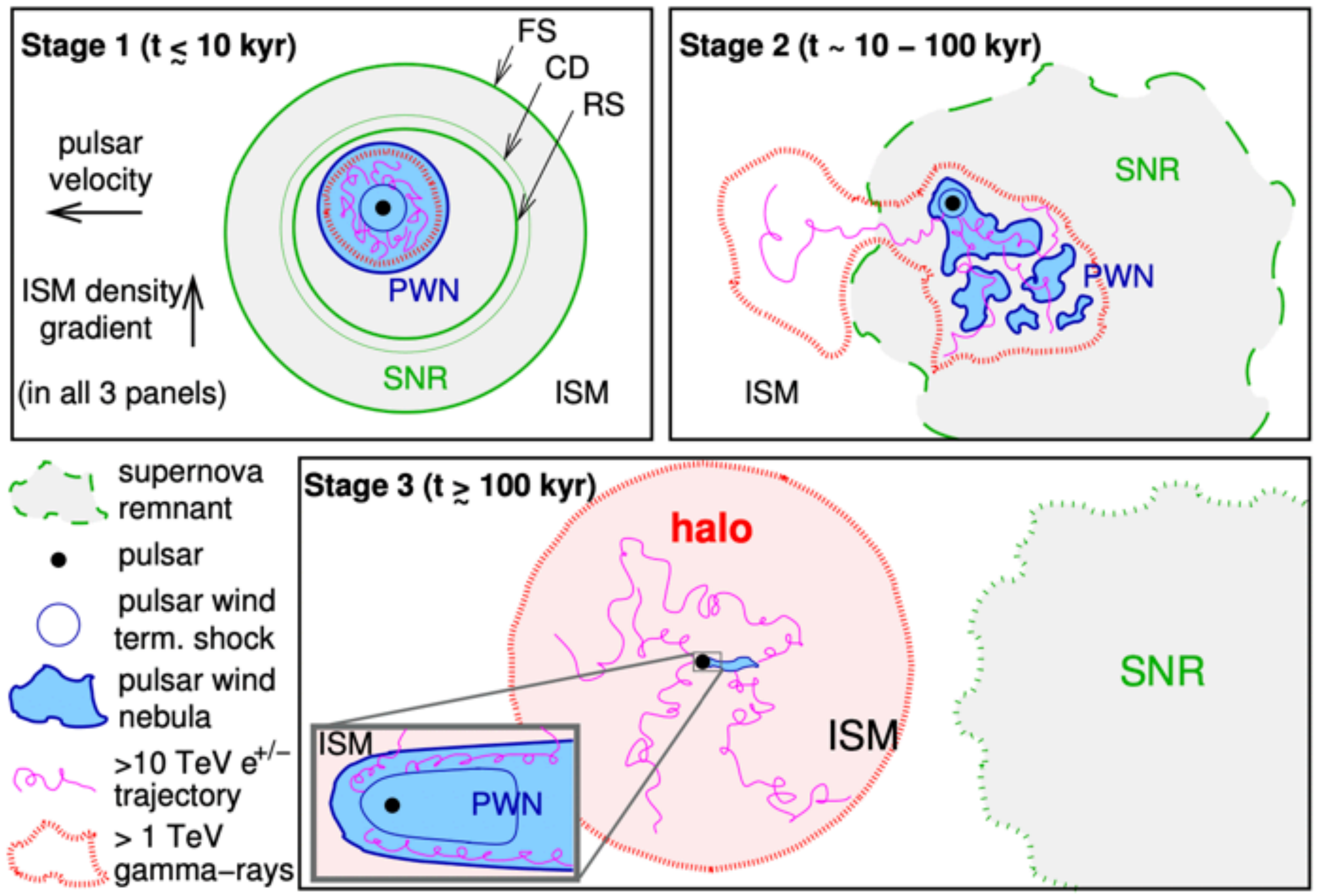
VHE Halos in a nutshell

- “Inverse Compton” halos: gamma rays emitted by inverse Compton scattering of electrons and positrons accelerated in the pulsar wind nebulae

- A couple of models:



Sudoh et al. 2019

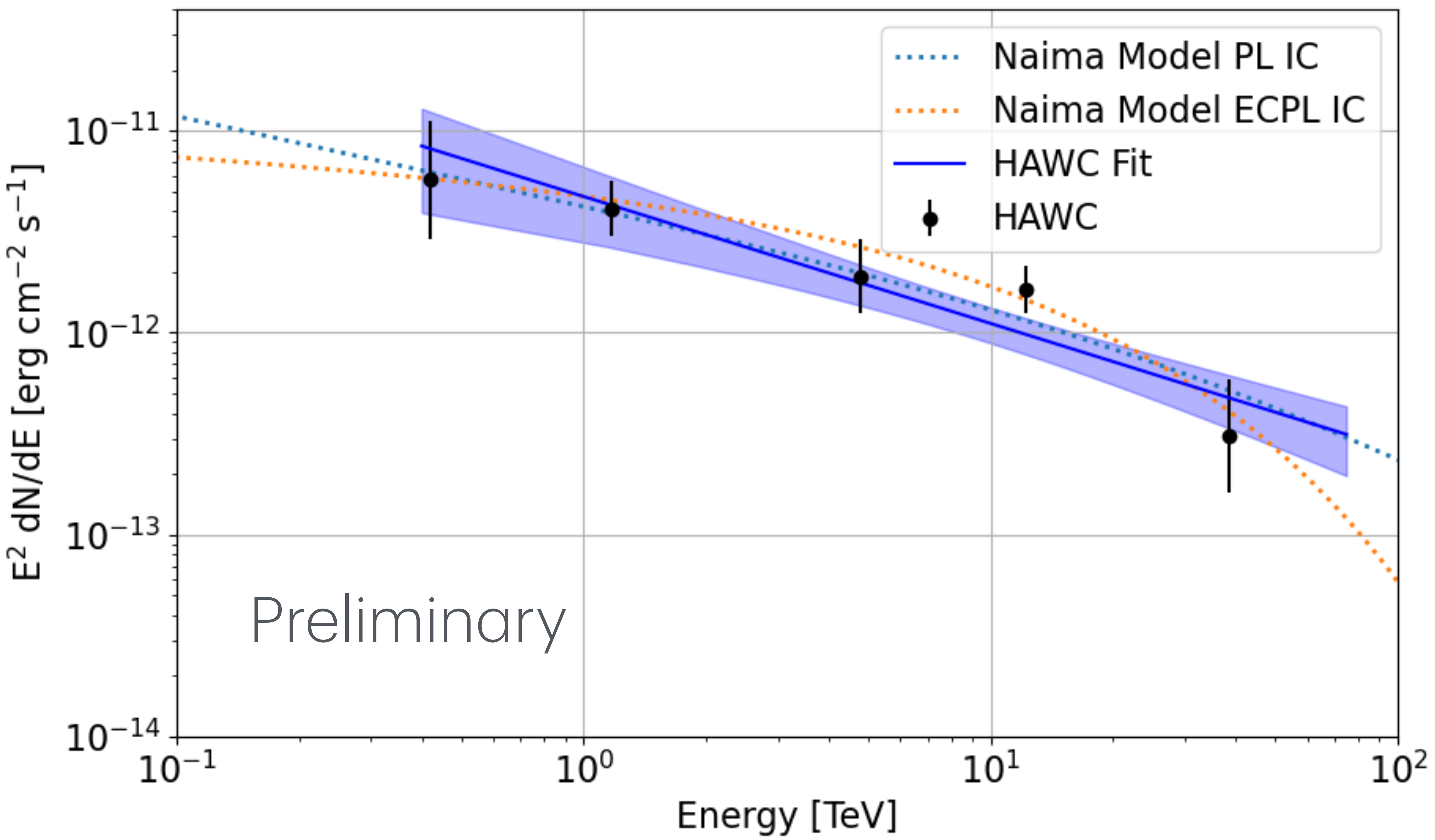


Giacinti et al. 2020

- Test evolution of particle acceleration and escape from PWN and pulsars

- Study propagation of electrons and positrons in the ISM

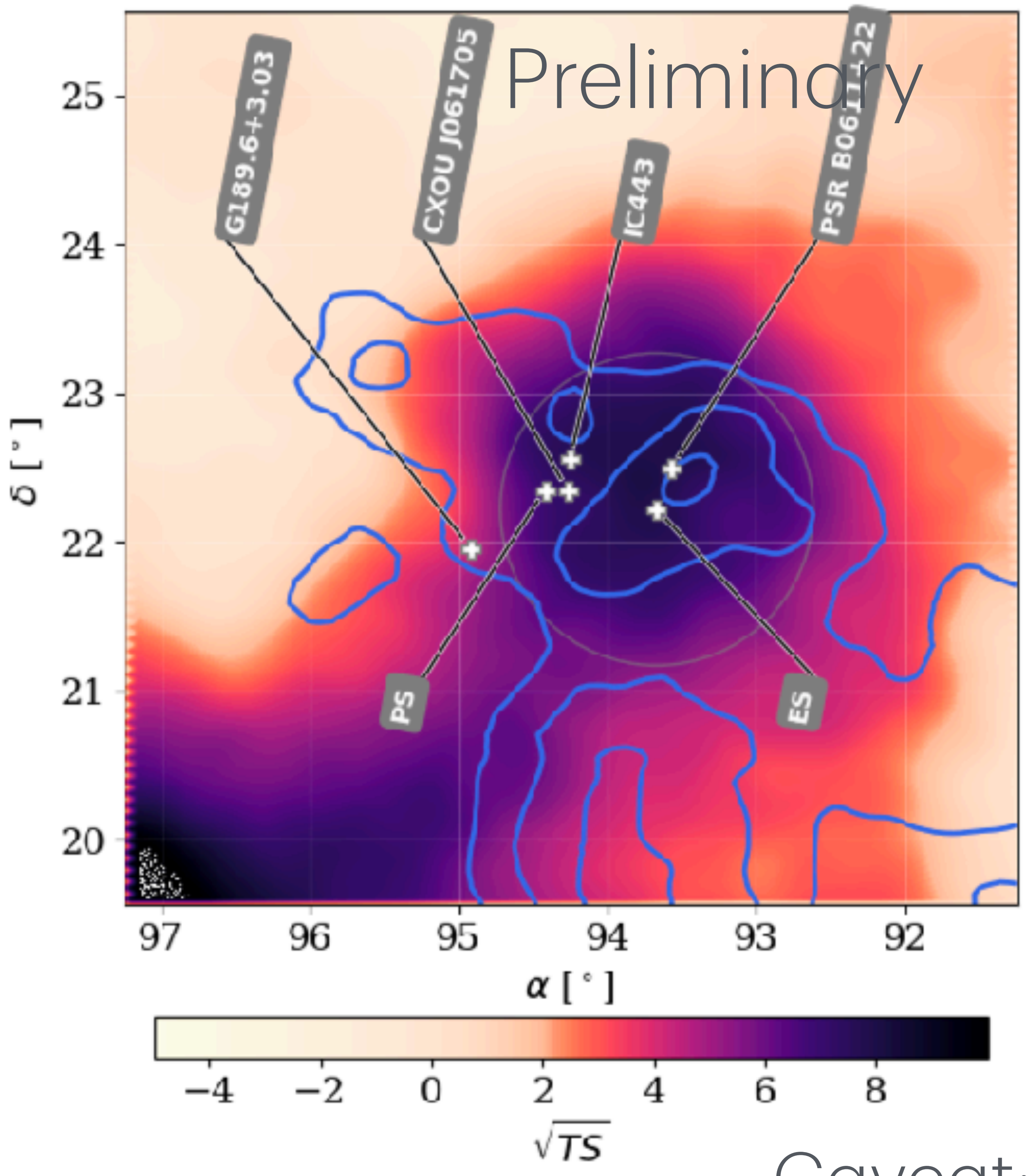
Extended source - a new TeV Halo?



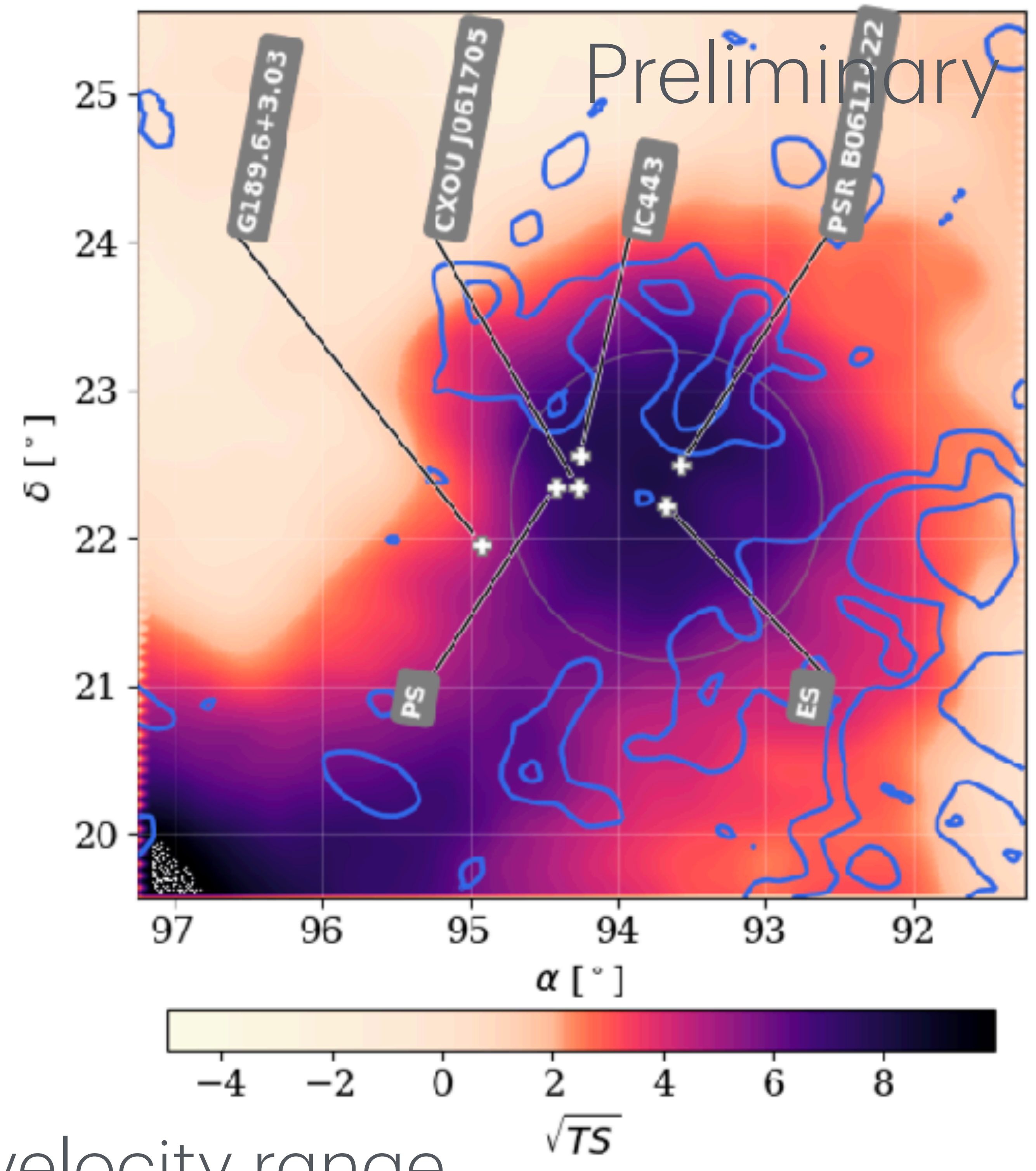
- Simple inverse Compton model
- Use the fitted electron spectrum to find energy density of electrons
  - Smaller than the ISM -> Evidence that this is a electron (TeV) halo.
  - Current estimates with HAWC data put this value between 10^{-3} and 10^{-5} eV cm^{-3}

Extended source - CR illumination of Gas?

- Another hypothesis, accelerated CR interacting with gas.
  - Diffuse gamma-ray emission from sea of CRs interacting with the gas included in the model
  - Fresh CRs accelerated in the region could produce this emission. Calculations in progress.



HI (HI4PI survey)



H2 (Dame CO survey)

Caveat: integrated over full velocity range

Summary

- HAWC Observations of IC 443 up to 40 TeV.
  - Consistent with other VHE observations. Data can be described by a lepto-hadronic model
- An extended source is observed in the region. Emission could come from
  - Halo around pulsar B0611+22
  - CR illumination of gas

Thank you

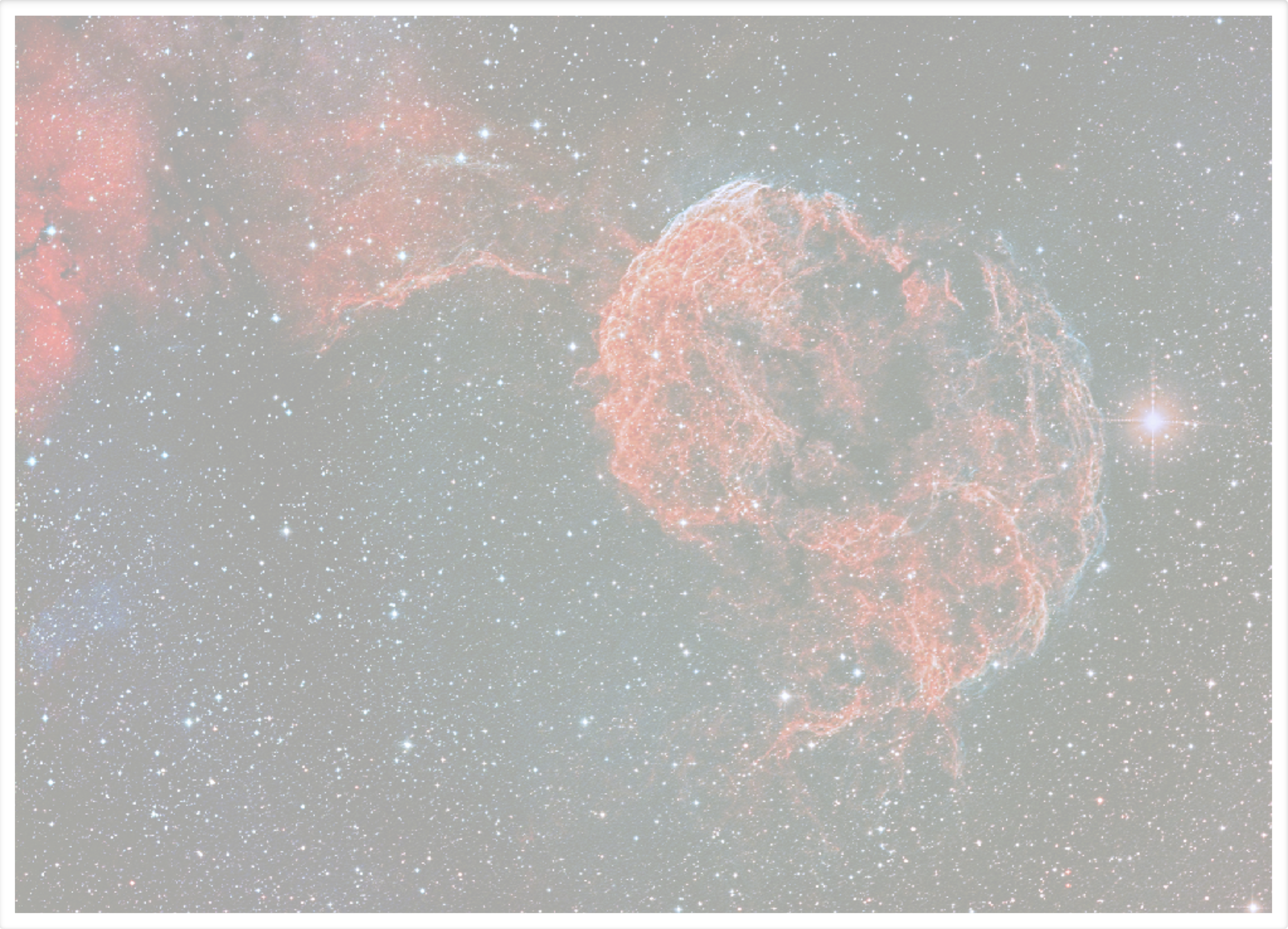


Image credit: Giuseppe Donatiello

Back-up

Numbers

Table 1. Results of the analysis in the region of IC 443 using the f_{hit} scheme.

Source	K [$TeV^{-1}cm^{-2}s^{-1}$]	Index	R.A. [deg]	Decl. [deg]	σ [deg]
IC 443	$(5.9 \pm 1.3^{+0.21}_{-0.86}) \times 10^{-14}$	$-3.14 \pm 0.18^{+0.08}_{-0.09}$	$94.42^{+0.07+0.009}_{-0.05-0.008}$	$22.35^{+0.06+0.035}_{-0.07-0.003}$	–
E.S.	$(3.18^{+1.37+0.19}_{-0.92-0.37}) \times 10^{-13}$	$-2.49 \pm 0.08^{+0.009}_{-0.028}$	$93.67 \pm 0.19^{+0.016}_{-0.004}$	$22.22 \pm 0.20^{+0.015}_{-0.007}$	$1.05^{+0.21+0.004}_{-0.18-0.013}$

Naima Models

- IC 443 - Hadronic Model:
  - SBPL: log(N)=47.34+0.09-0.06; idx1 = 2.36±0.04; idx2 = 3.04±0.05; E_{break} = 100±30 GeV
  - ECPL: log(N)=49.58±0.03; idx1 = 2.34±0.03; E_{cutoff} = 71±9 GeV
- IC 443 - Lepto Hadronic Model:
  - SBPL proton: log(N)=47.11+5.6-0.1; idx1 = 2.35±0.08; idx2 = 3.15±0.2; E_{break} = 174±30 GeV; N_H = 188±12 cm^2
  - SBPL electron: log(N)=48.6±0.2; idx1 = 1.68±0.04; idx2 = 3.61±0.2; E_{break} = 50±15 GeV; B=10.4±1.0 uG
- Halo - IC model:
  - SPL = log(N)=47.7±0.3; idx=3.42±0.18
  - ECPL = log(N)=47.7±0.5; idx=2.87±0.73; E_{cutoff} = 66±20 TeV

Importance of Halos

- Test evolution of particle acceleration and escape from PWN and pulsars
- Study propagation of electrons and positrons in the ISM

Halo Comparisons