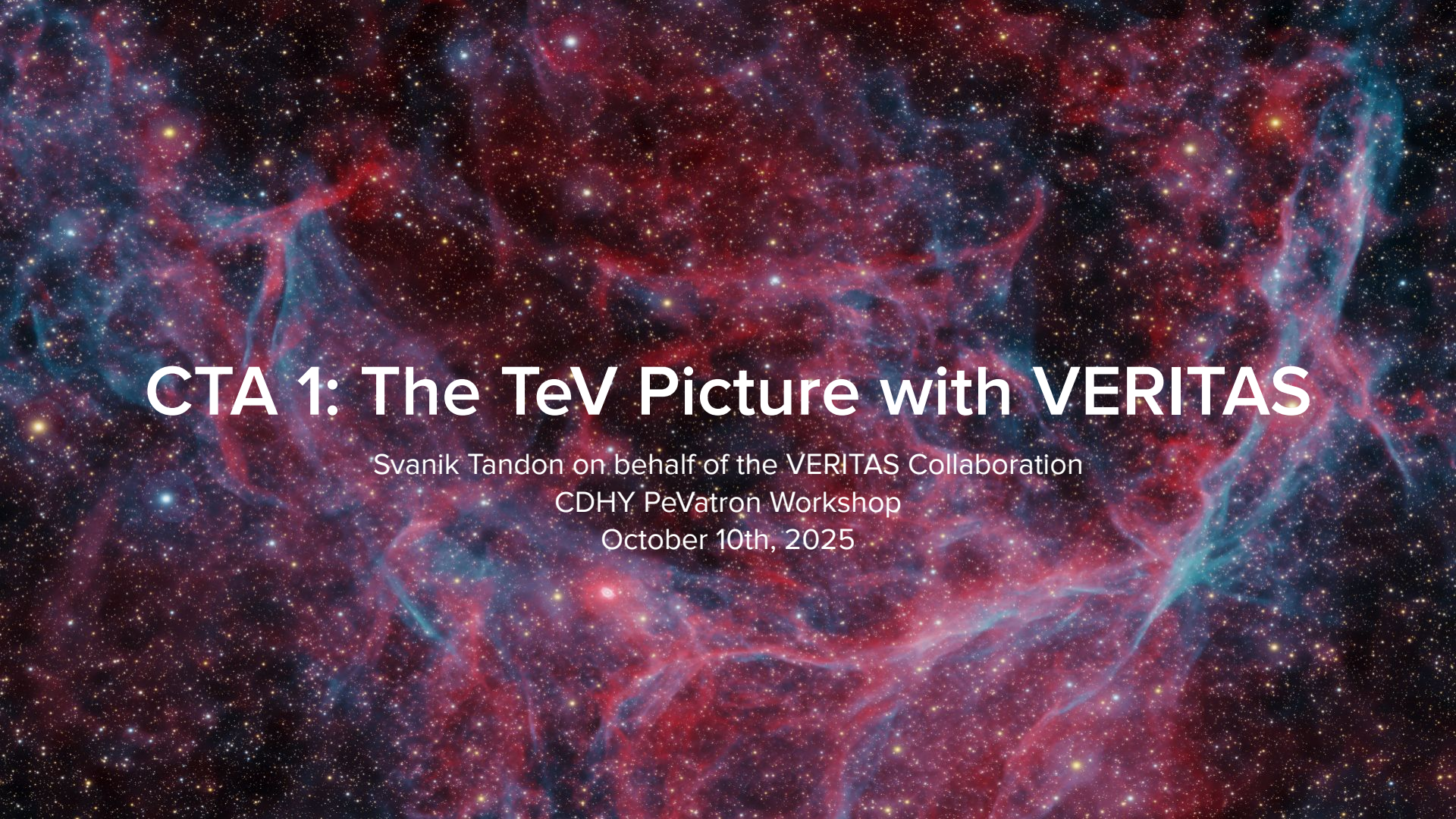


CTA 1: The TeV Picture with VERITAS

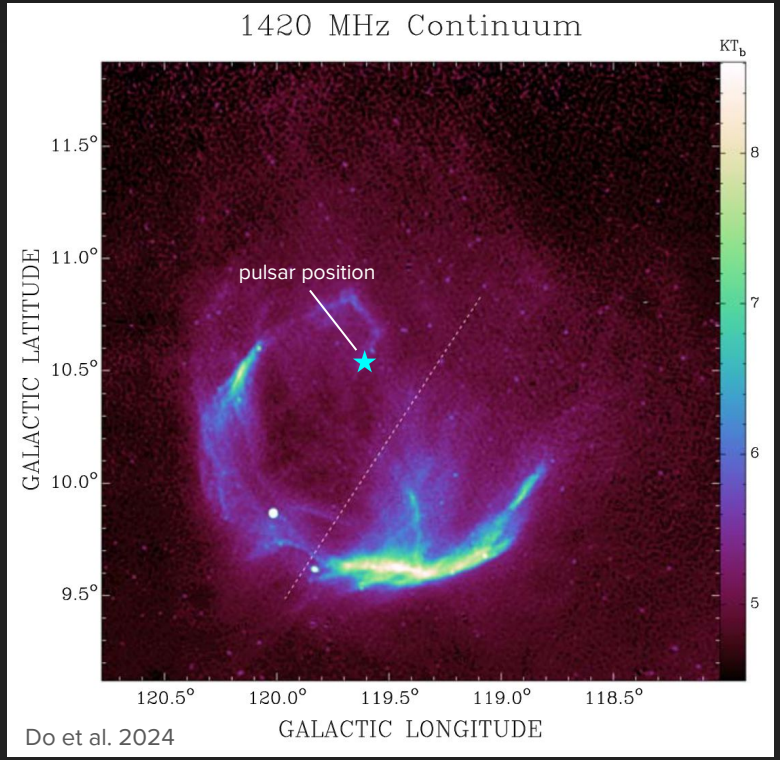
Svanik Tandon on behalf of the VERITAS Collaboration

CDHY PeVatron Workshop

October 10th, 2025

CTA 1 Overview

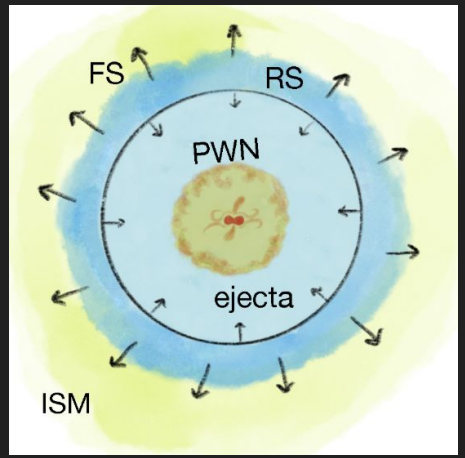
- Galactic object first discovered and proposed as SNR in 1960 by Caltech Radio Observatory
- Composite SNR system, consisting of:
  - Radio SNR shell, 1.8° diameter
  - Central X-ray & γ-ray pulsar J0007+7303
  - X-ray & γ-ray PWN
- Distance: **1.09 ±0.2 kpc** (Do et al. 2024)
- Age: **~13 kyr** (Caraveo et al. 2010)
- High galactic latitude (10.5°), low background region
  - Ideal testbed for studying PWN/SNR evolution + particle transport



Continuum skymap of CTA 1 at 1420 MHz, from Dominion Radio Astrophysical Observatory (DRAO) Synthesis Telescope

PWN + SNR Evolution

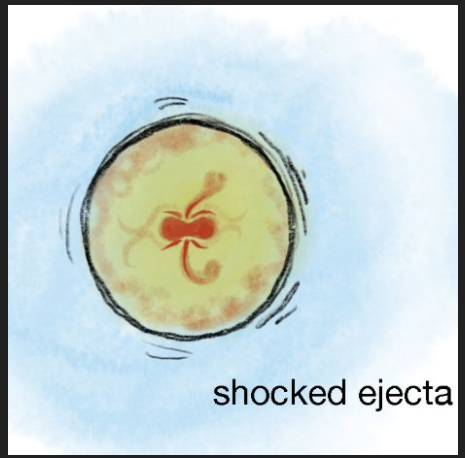
Stage I: <10kyr



free expansion

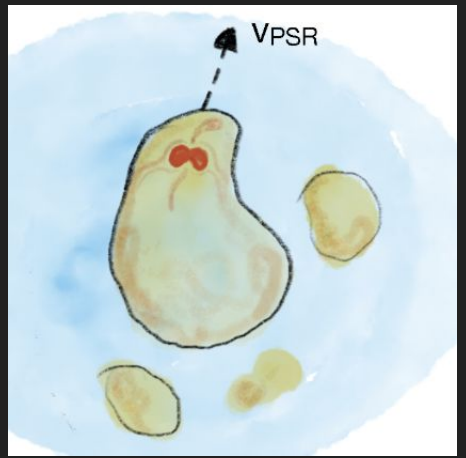
CTA 1
13 kyr

Stage II: 10kyr-100kyr



PWN compression + reverberation

Stage III: >100kyr



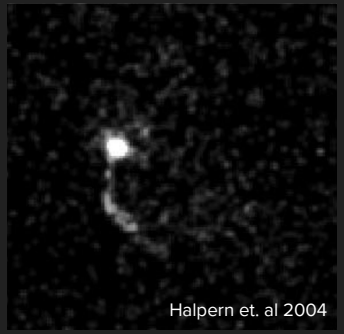
separate relic + new PWNe

CTA 1 likely transitioning between evolutionary stages with reverse shock interaction + particle diffusion out of the PWN.

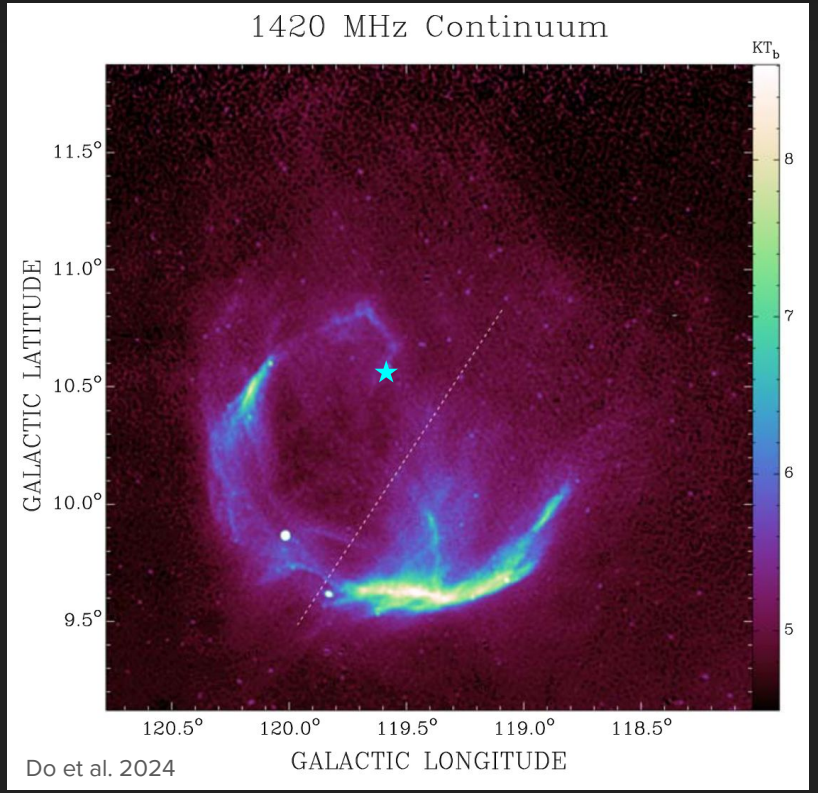
Images: B. Olmi 2023

X-Ray and Radio Morphology

- Asymmetric SNR shell, due to lower density CSM in NW region
- X-ray emission consists of pulsar, torus, bent jet, and diffuse PWN component
  - See Seth Gagnon's talk
- If jet bending is caused by ram pressure from pulsar motion, find very modest pulsar speed



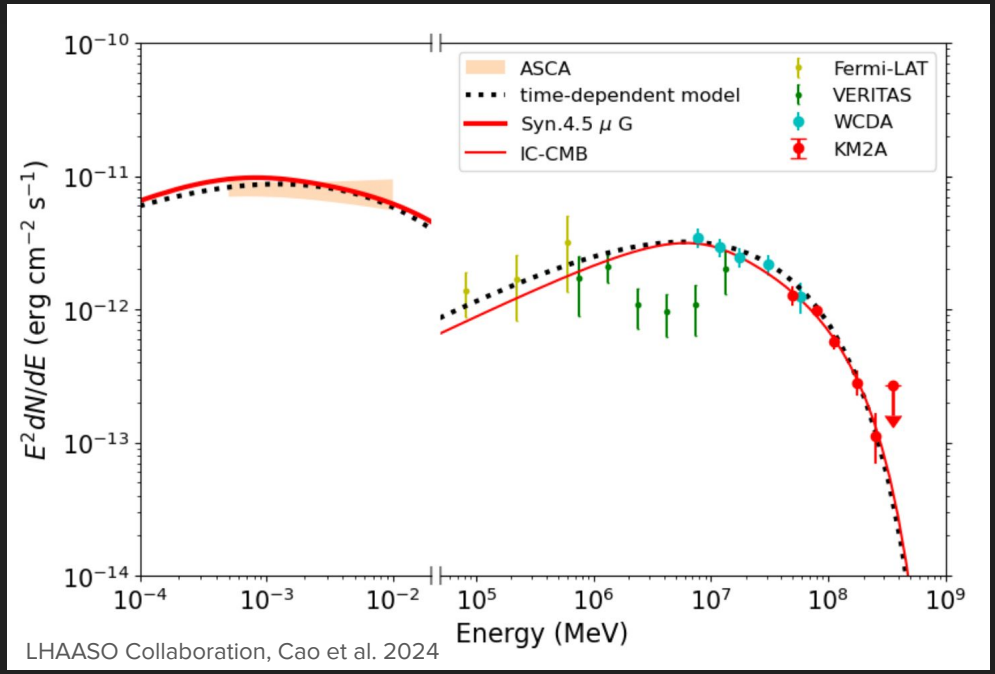
Chandra ACIS Image; 0.5-8 keV



Do et al. 2024

Recent Observations from Fermi and LHAASO

- Masking out emission from GeV-bright pulsar, Fermi-LAT detects PWN-associated emission above 50 GeV
- LHAASO also detects extended symmetric emission centered around the pulsar position
    - Maximum parent electron energy estimated to be around 350 TeV – ***not a PeVatron***
- Absence of molecular cloud + low CSM density rules out hadronic emission scenario

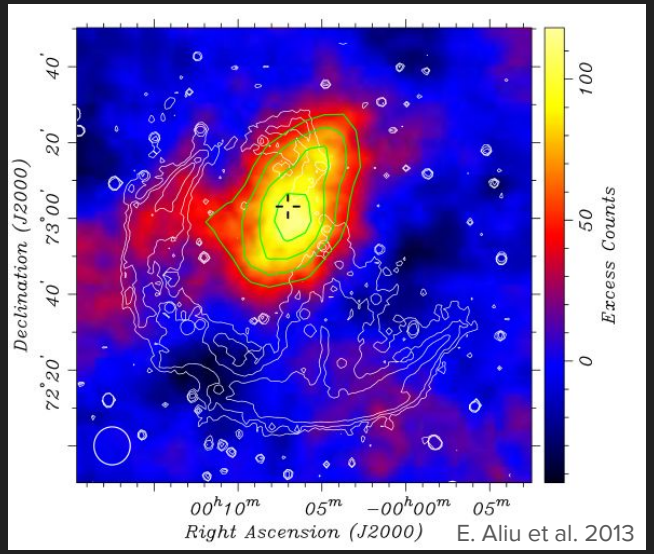


Spectrum of CTA 1 including Fermi, LHAASO, and 2013 VERITAS points. Red line represents the expectation from a one-zone leptonic model, considering only CMB target photons.

The TeV Picture With VERITAS

- VERITAS is well-positioned to study CTA 1
  - First detected extended TeV emission in 2013 with 41 hrs exposure
  - Concluded to be a PWN of leptonic origin
- Recently tripled dataset:
  - 41 hrs ➔ 119 hrs
  - Deepest VHE exposure on the source
  - Increased statistics allow for a more in-depth study of the energy-dependent morphology

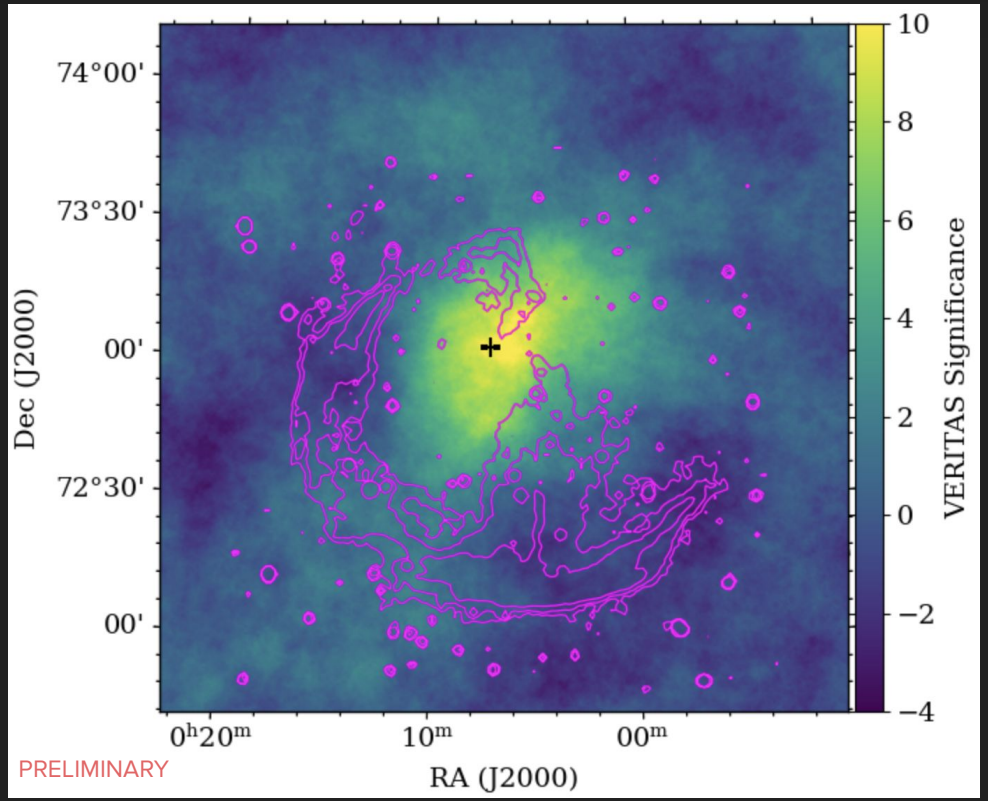
One of four VERITAS IACTs in southern Arizona.



2013 VERITAS excess map: VERITAS 3σ ,4σ ,5σ ,and 6σ significance contours in green, 1420 MHz radio contours in white

2025 VERITAS Skymap

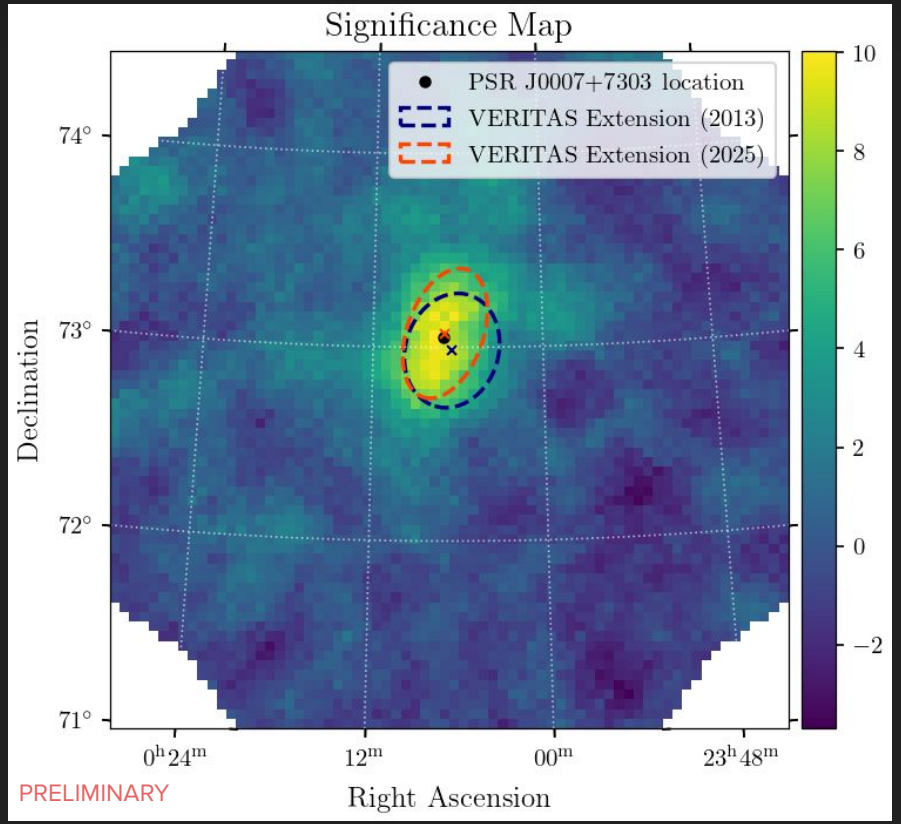
- Updated VERITAS skymap using full dataset
- Pink lines show 1420 MHz radio contours (SNR shell structure)
- Black cross is pulsar position
- Region of highest significance is around the pulsar position and near the “breakout” section of the SNR



2025 VERITAS Skymap

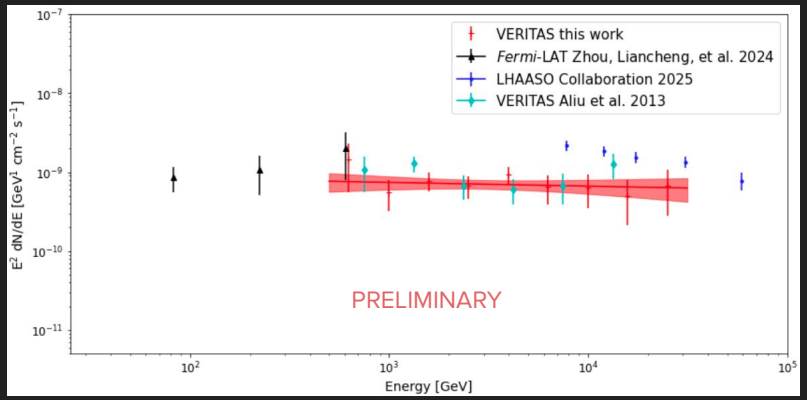
- Extent of the excess emission was fit to a two-dimensional Gaussian
- Measured extension is highly coincident with pulsar, exhibits asymmetric morphology
    - Could indicate interaction of PWN with reverse shock of SNR, asymmetry intrinsic to the pulsar wind

Parameter	Value	Uncertainty
Centroid RA (deg)	1.7296	0.0256
Centroid DEC (deg)	73.0722	0.0167
σ_x (deg)	0.3486	0.0278
σ_y (deg)	0.1966	0.0157
θ (deg)	−19.4212	5.1225

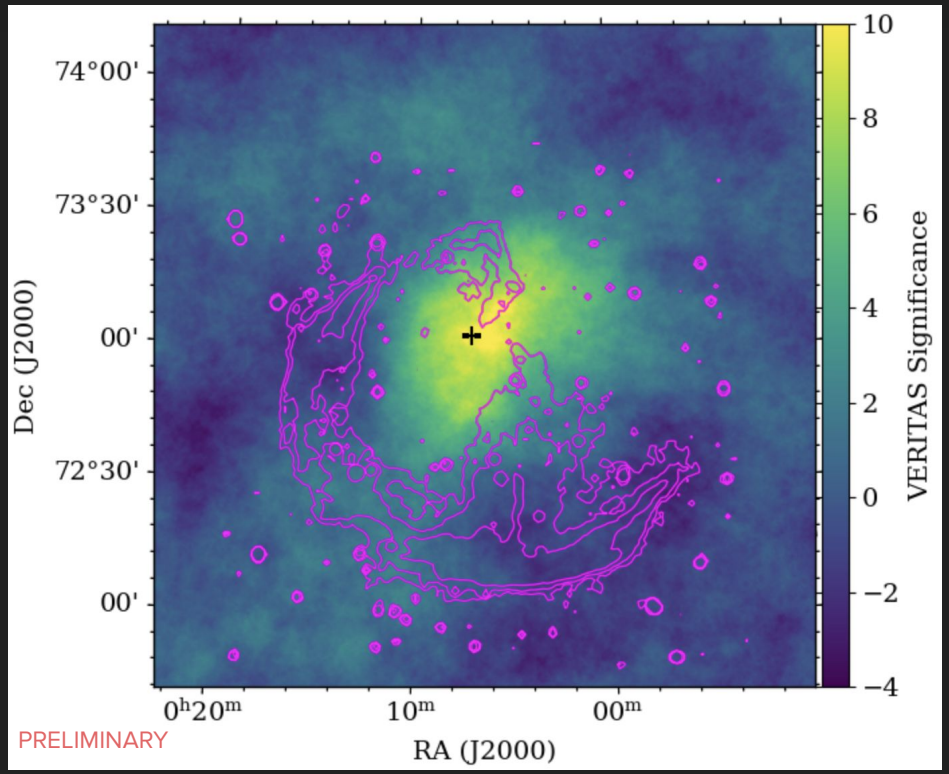


PWN + SNR Evolution

- Latest spectrum finds a hard spectral index of Γ=2.0±0.1.
- CTA 1 evolution study from Martin et al. 2016 finds that VERITAS flux could not be fit to compression phase model
- Indication that the evolution of CTA 1 is complex and asymmetric – some parts of the PWN may be further evolved than others

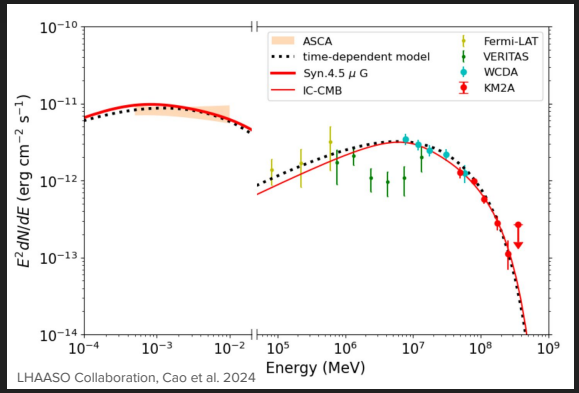


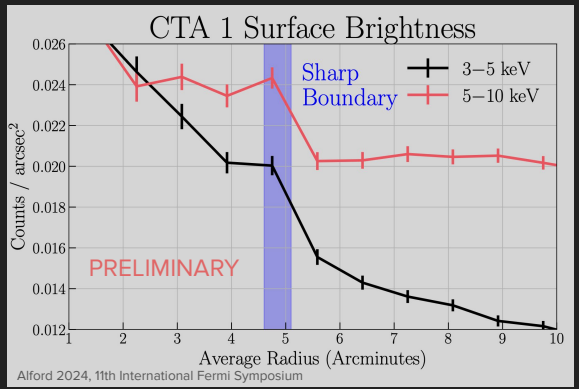
Full multi-wavelength SED including 2013 and 2025 VERITAS points.



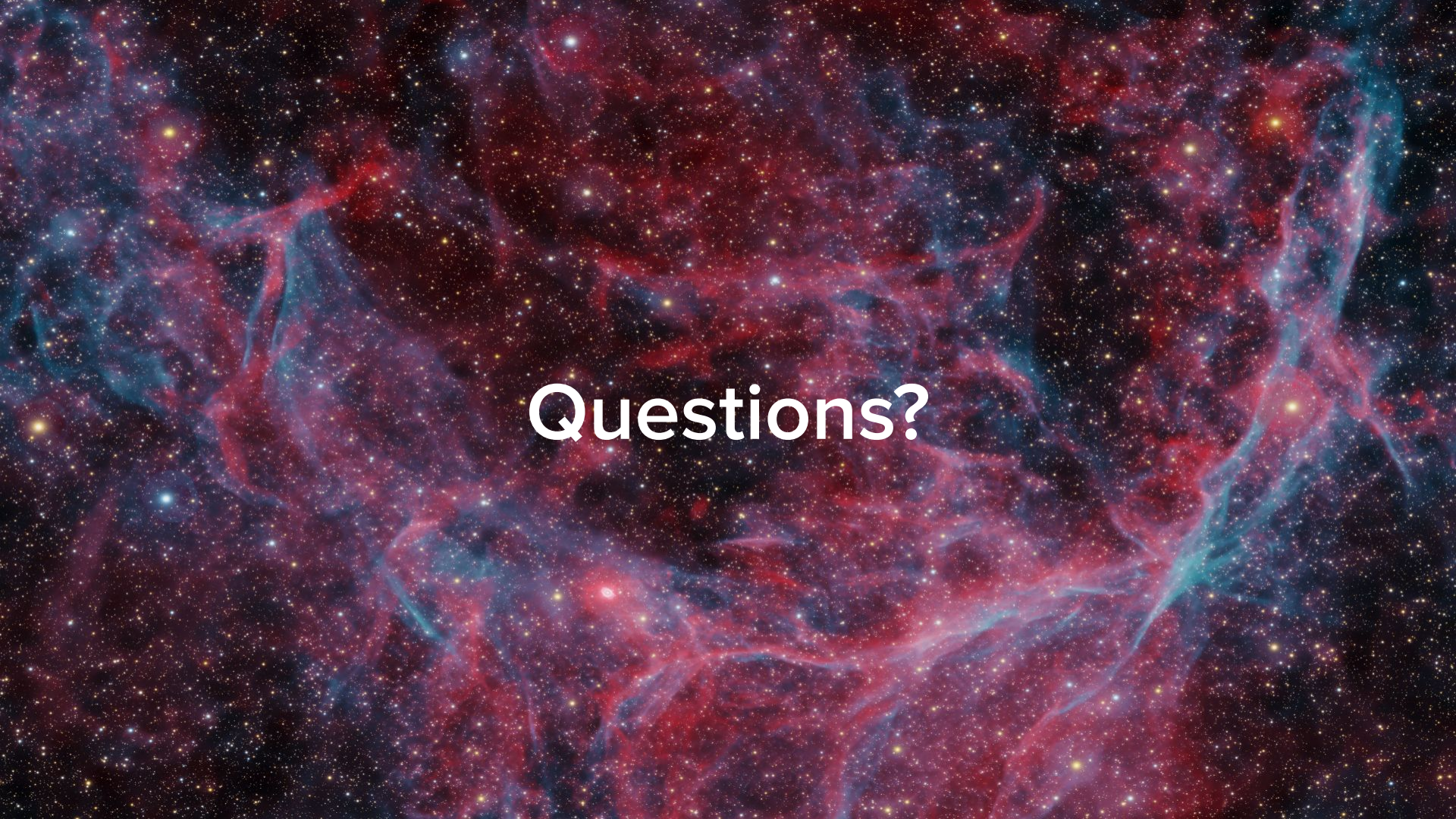
Particle Transport and Escape

- Under assumption that CTA 1 is in free-expansion phase, LHAASO finds that particle transport is dominated by advection
  - Model neglects the possibility of escaping particles
- Preliminary results from archival XMM data show a sharp boundary in surface brightness with no energy dependence
  - TeV emission appears to extend out several arcminutes beyond this X-ray boundary
  - Possible indicator of electron/positron escape – spectral/morphological analysis to investigate this is ongoing





XMM radial profiles indicating X-ray PWN boundary.


Questions?