Resolving the gamma-ray SNR IC 443 with *Fermi*-LAT and VERITAS

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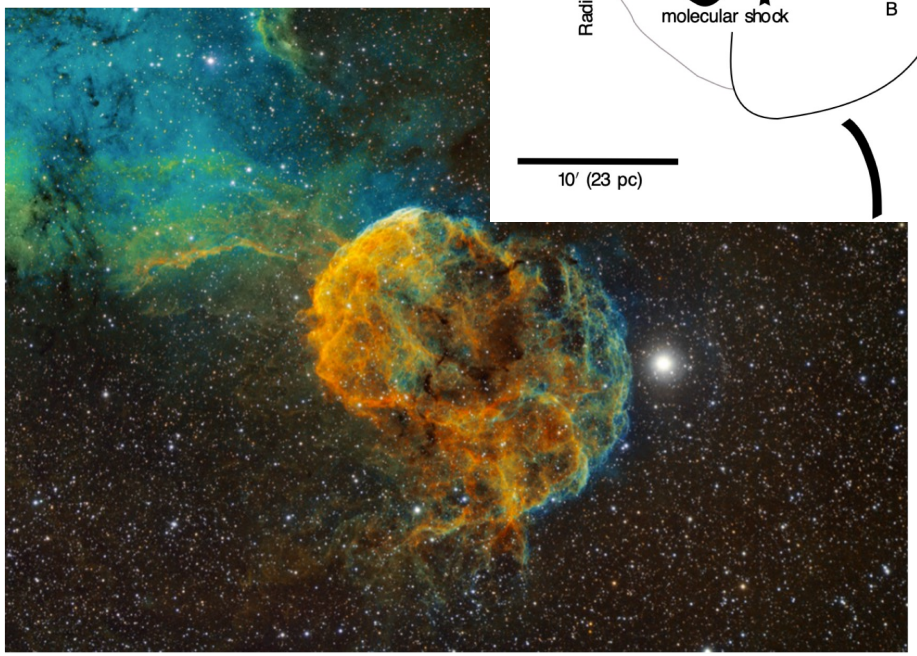
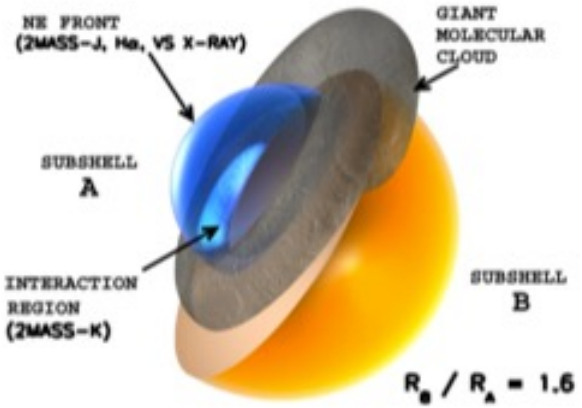
IC 443 – The Jellyfish Nebula

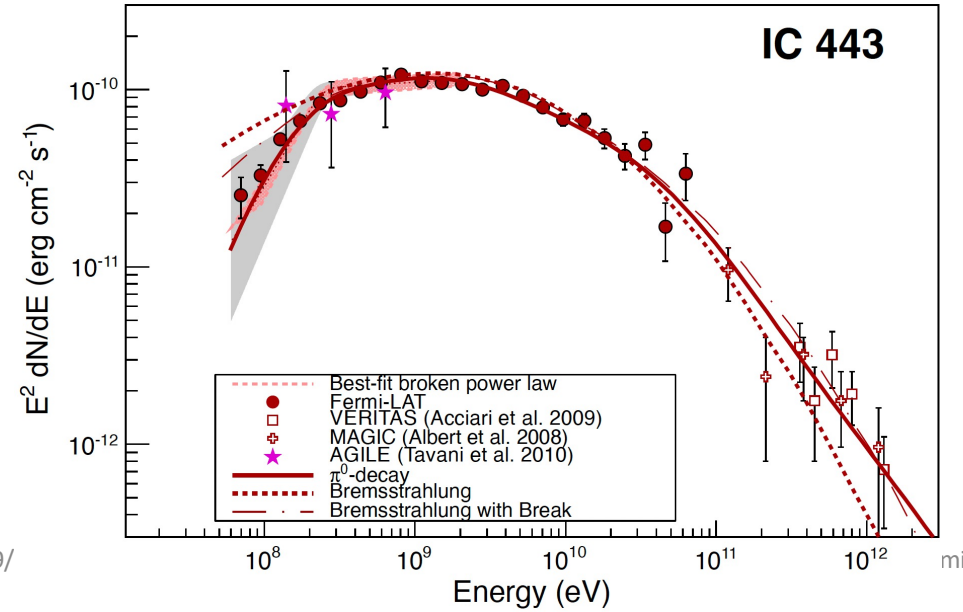


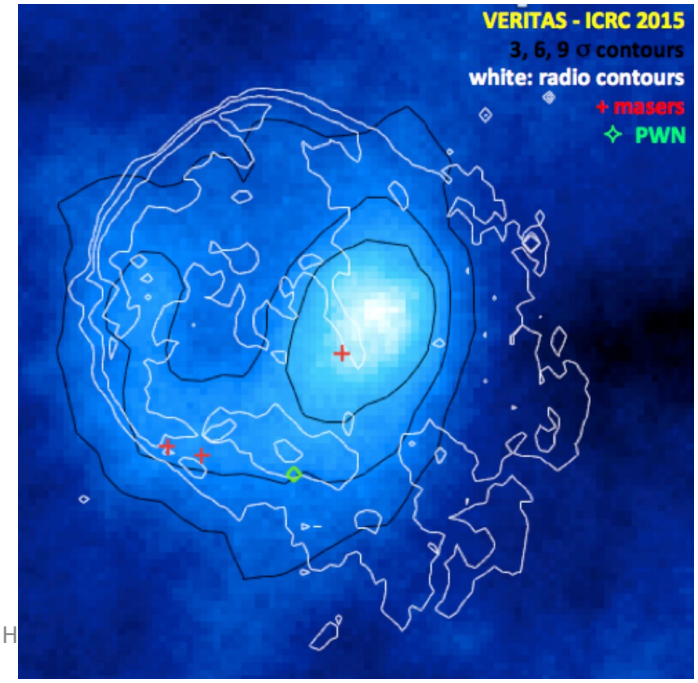
- Remnant of a core-collapse SN interacting with surrounding material.
  - Interacting with a dense molecular cloud ~10^5 M_{sun} along the south and west.
  - Lower-density ionized gas to the northeast.
  - Large, very low-density cavity is present in radio continuum emission extending behind and to the west of the SNR.
  - Evolving in a very inhomogeneous environment!
- An uncertain age that is likely around 8 kyr (Ustamujic+ 2021).
- At a distance of 1.5 kpc, ~45’ diameter → 20 pc.

IC 443 – The Jellyfish Nebula

- Detected in γ-rays by EGRET, MAGIC, VERITAS, *Fermi*-LAT, AGILE, HAWC, LHAASO.
- Previously:
  - Low-energy decrease in the SED consistent with a hadronic origin (Ackermann+ 2013).
  - Shell resolved in GeV/TeV γ-rays (Humensky+ 2015).







VERITAS

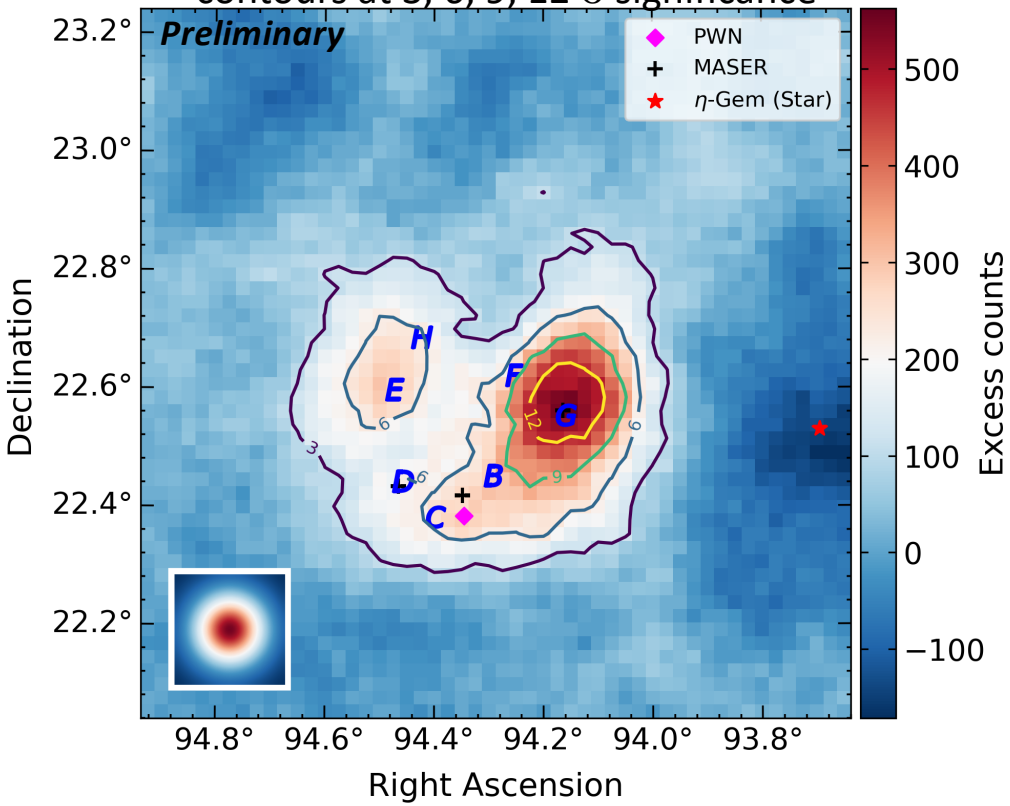
- Full-array operations begin: 2007 - 16 years of operation.
- Energy range: ~85 GeV to ~30 TeV.
- Sensitivity: 1% Crab in 25 hr, 10% in 25 min, Ang. resolution: 0.08° resolution @ 1 TeV.
- Prototype SCT telescope for CTA on site.
- Funded by National Science Foundation (USA), Smithsonian Astrophysical Observatory (USA), Natural Sciences and Engineering Research Council (Can), Helmholtz Association (Ger).

Sajan Kumar, Maryland

VERITAS, Fermi Images of IC 443

- VERITAS analysis using 155 hr taken 2007-2015.
  - 0.18 – 4.5 TeV.
- Fermi analysis above 5 GeV using 15 years of Fermi-LAT Pass8r3v3 Source data using the 4FGL-DR4 model
  - PSF classes 2, 3 to match VERITAS PSF.

VERITAS Excess Map,
contours at 3, 6, 9, 12 σ significance



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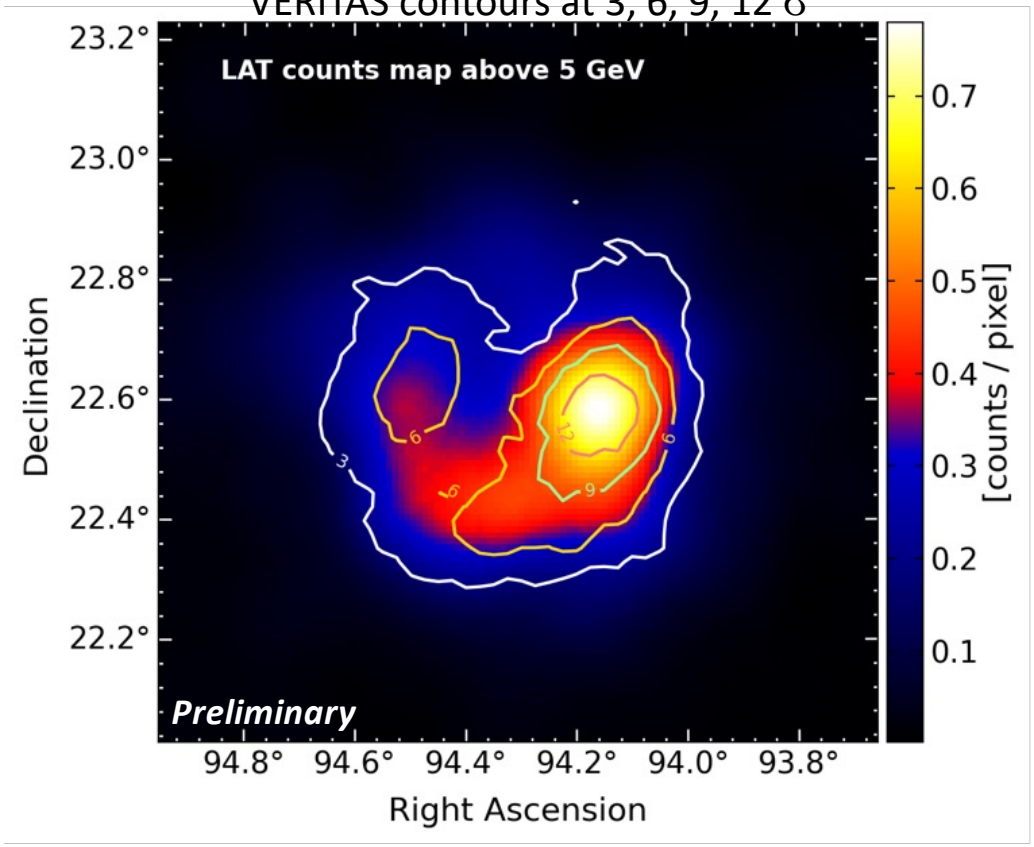
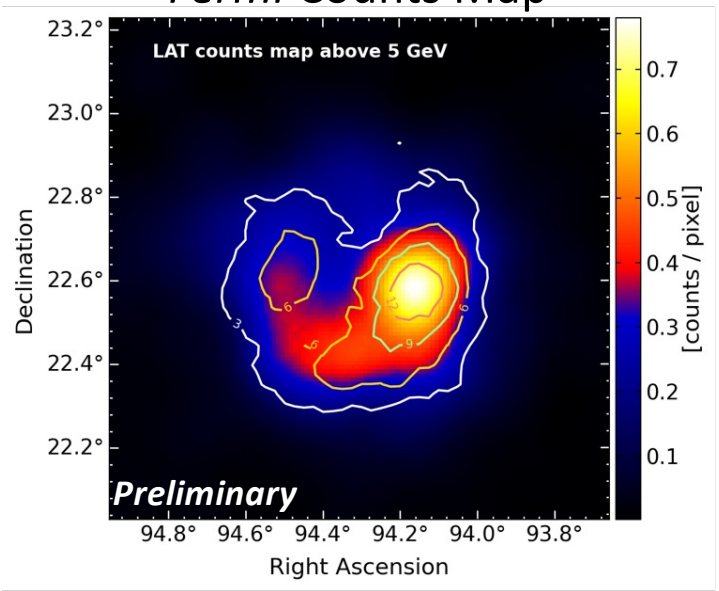
Fermi Counts Map,
VERITAS contours at 3, 6, 9, 12 σ



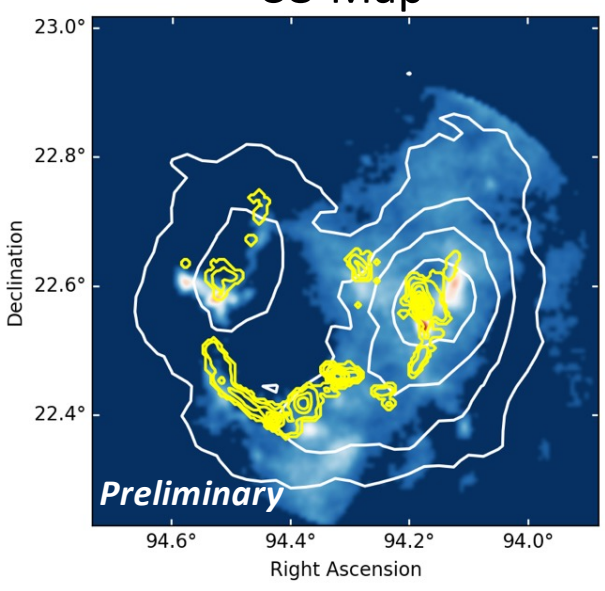
Comparison with Gas Tracers

- Gamma-ray emission broadly traces dense and shocked gas surrounding IC 443 but not perfectly, particularly in the north.

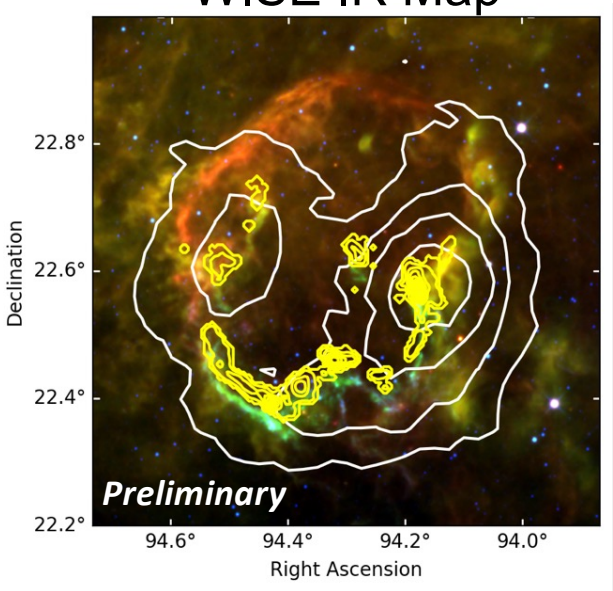
Fermi Counts Map



CO Map

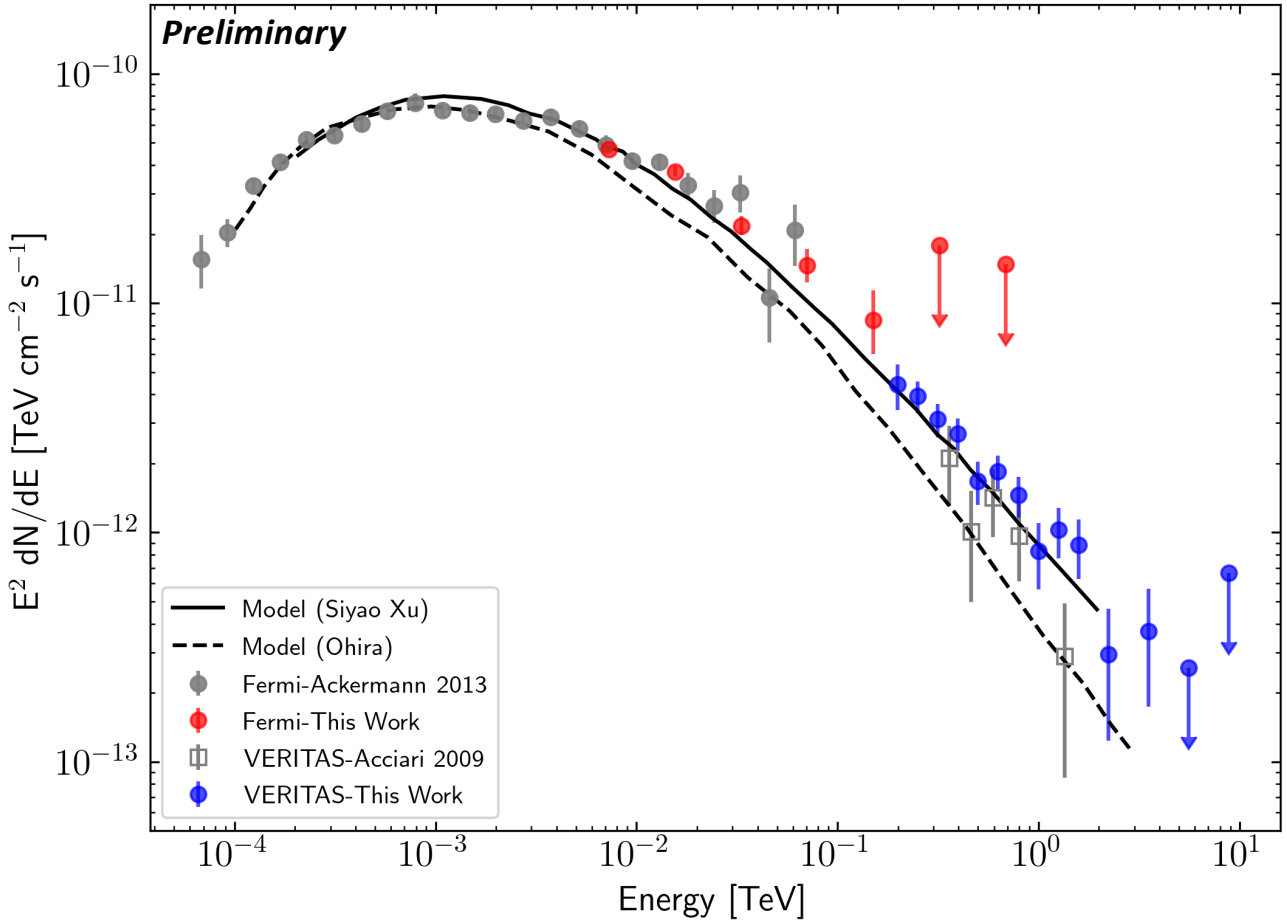


WISE IR Map



All maps: white contours are VERITAS at 3, 6, 9, 12 σ, yellow contours are HCO+ 1-0 shocked gas.

Gamma-ray Spectrum of Entire IC 443

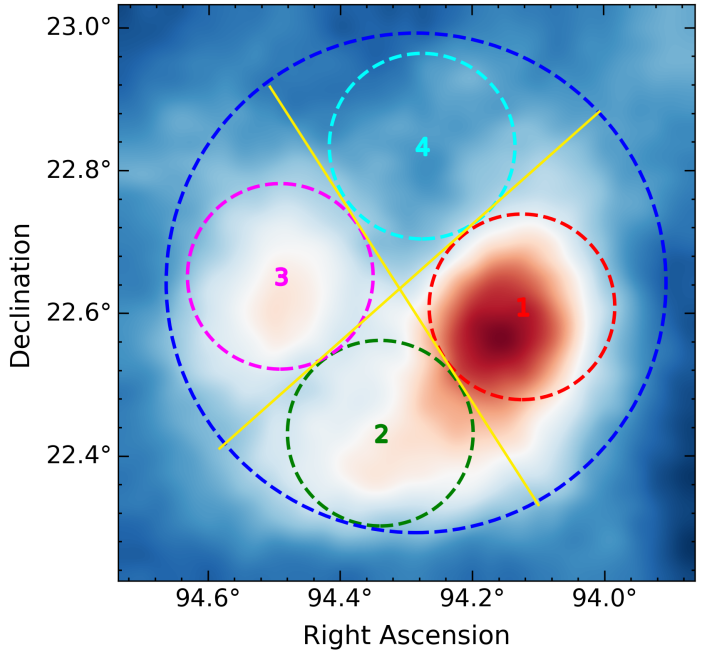


- Broad-band γ-ray spectrum integrated over entire SNR aligns well with previous measurements.
  - VERITAS: used 0.35º radius region.
- Spectrum extends smoothly from Fermi to VERITAS range, with index gradually softening from -2.4 to -2.9.

Regional Spectra

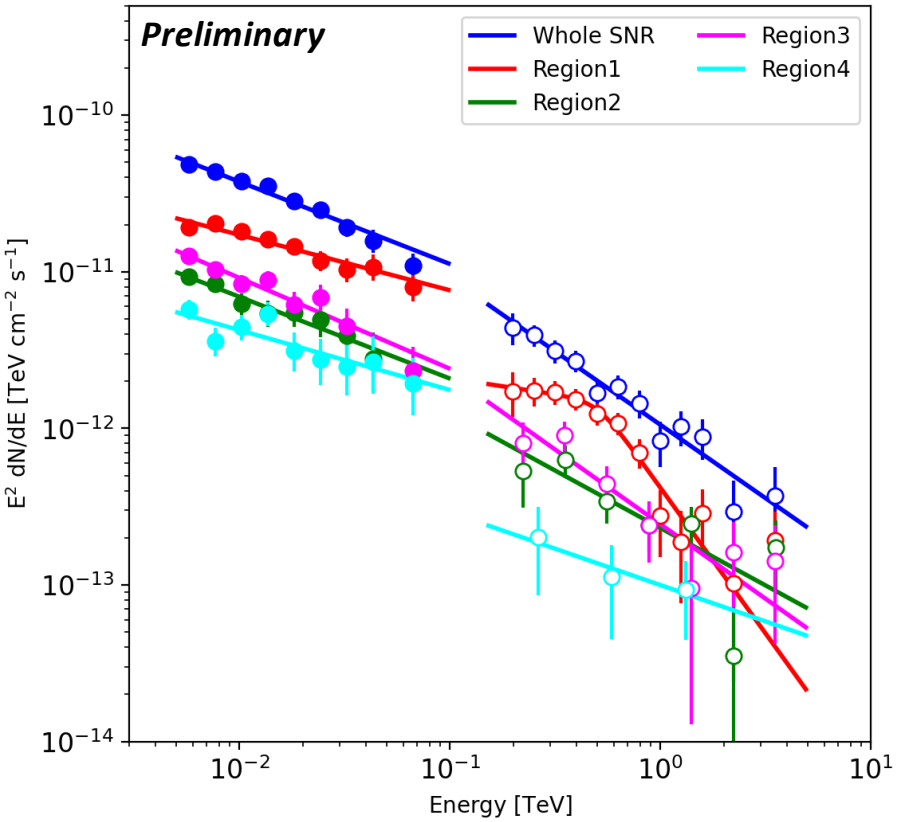
- IC 443 is divided into four regions, for which SEDs are extracted using spatial templates (LAT, Tajima+ 2007) and 0.13° circular radii (VERITAS).
  - Regions selected to follow the gas distribution:
    - Region 1 – shocked molecular cloud.
    - Regions 2&3 – shocked molecular/atomic/ionized gas.
    - Region 4 – no shocked gas observed.

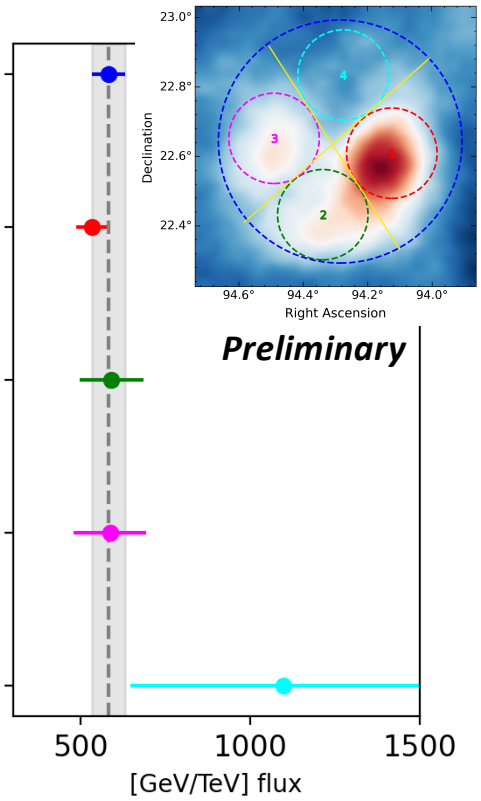
- Because the shapes of the regions are slightly mismatched, we apply a scaling factor calculated from the LAT spatial template, to slightly increase the VERITAS fluxes.



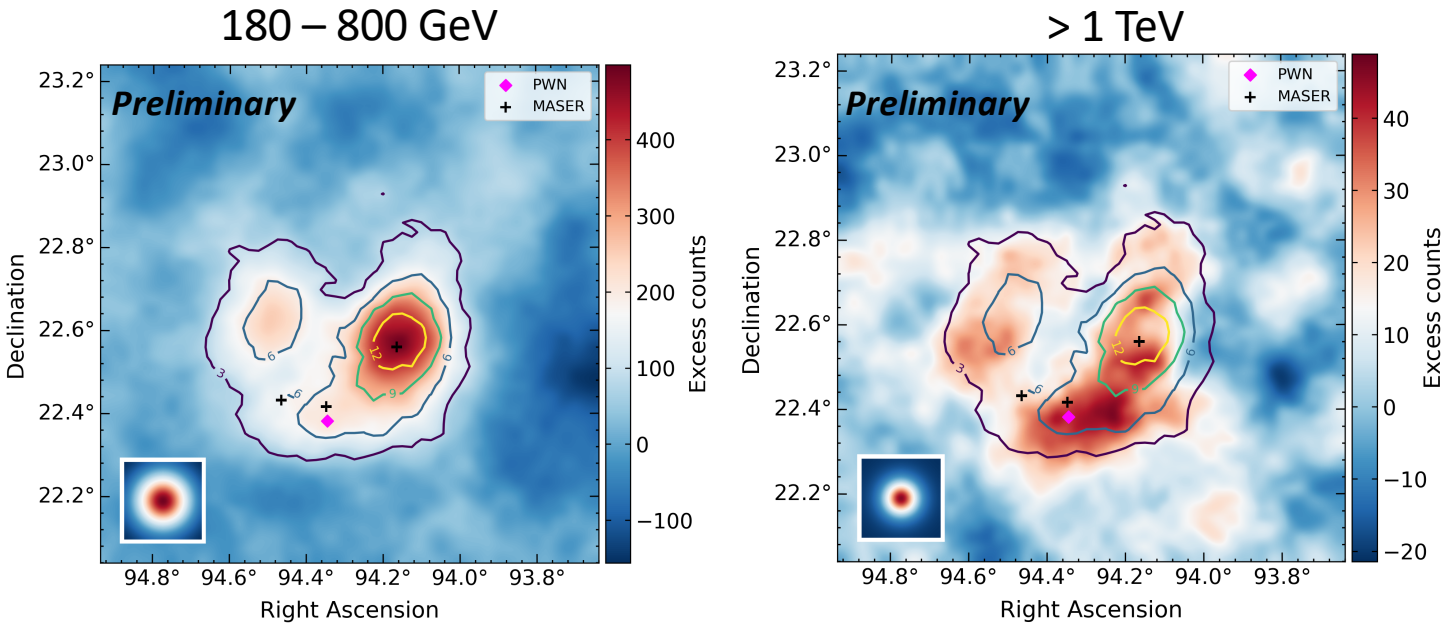
Regional Spectra

- Spectral shapes consistent within errors across regions, well fit by simple power laws.
  - LAT : indices 2.35-2.58.
  - VERITAS : indices 2.7-3.0.
- Exception: Region 1 (red) in the VERITAS range prefers a broken power law, steepening around 500 GeV to an index of 3.9.
- Integral flux ratio is constant across all bands.





Energy-Resolved VERITAS View of IC 443



- Contours are VERITAS 3, 6, 9, 12 σ from all-energy map.
- Change in morphology around 1 TeV where the brightest region decreases significantly in comparison to the rest of the shell. By fitting the LAT data as a spatial template, we find that the bright spot decreases by ~40% in brightness relative to the shell (ΔAIC = -8.4).

Summary

- IC 443 is resolved as an asymmetric shell with a very similar morphology at GeV (*Fermi*-LAT) and TeV energies (VERITAS).
- The γ-ray morphology is not completely explained by any multi-wavelength spatial template (radio, X-ray, shocked gas).
- This motivates a spatially-resolved analysis of four distinct regions of the SNR.
- The regions vary greatly in flux but show largely the same spectra.
  - However, we see evidence for a decrease in the flux of the brightest region at the highest energies seen by VERITAS.
  - The faintest region 4 is devoid of molecular gas yet has the largest the γ-ray-to-gas ratio.

Backup

Little Variation in Spectra across Remnant

Region	VERITAS			Fermi-LAT			Flux Ratio
	Model (Best)	Parameters	Integral Flux (0.2−10 TeV)	Model (Best)	Parameters	Integral Flux (5−100 GeV)	(GeV/TeV)
1	SBPL	$\Gamma_1 = 2.20 \pm 0.45$ $\Gamma_2 = 3.86 \pm 0.53$ $E_b = 0.5 \pm 0.2$ TeV	$(6.0 \pm 0.5) \times 10^{-12}$	PL	$\Gamma = 2.35 \pm 0.05$	$(3.2 \pm 0.1) \times 10^{-9}$	533 ± 47
2	PL	$\Gamma = 2.73 \pm 0.17$	$(2.2 \pm 0.3) \times 10^{-12}$	PL	$\Gamma = 2.52 \pm 0.11$	$(1.3 \pm 0.1) \times 10^{-9}$	591 ± 93
3	PL	$\Gamma = 2.95 \pm 0.21$	$(2.9 \pm 0.5) \times 10^{-12}$	PL	$\Gamma = 2.58 \pm 0.08$	$(1.7 \pm 0.1) \times 10^{-9}$	586 ± 107
4	PL	$\Gamma = 2.46 \pm 0.53$	$(7.2 \pm 2.9) \times 10^{-13}$	PL	$\Gamma = 2.38 \pm 0.12$	$(7.9 \pm 0.6) \times 10^{-10}$	1097 ± 450
Whole-SNR	PL	$\Gamma = 2.94 \pm 0.09$	$(1.2 \pm 0.1) \times 10^{-11}$	PL	$\Gamma = 2.52 \pm 0.03$	$(7.0 \pm 0.1) \times 10^{-9}$	583 ± 49