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

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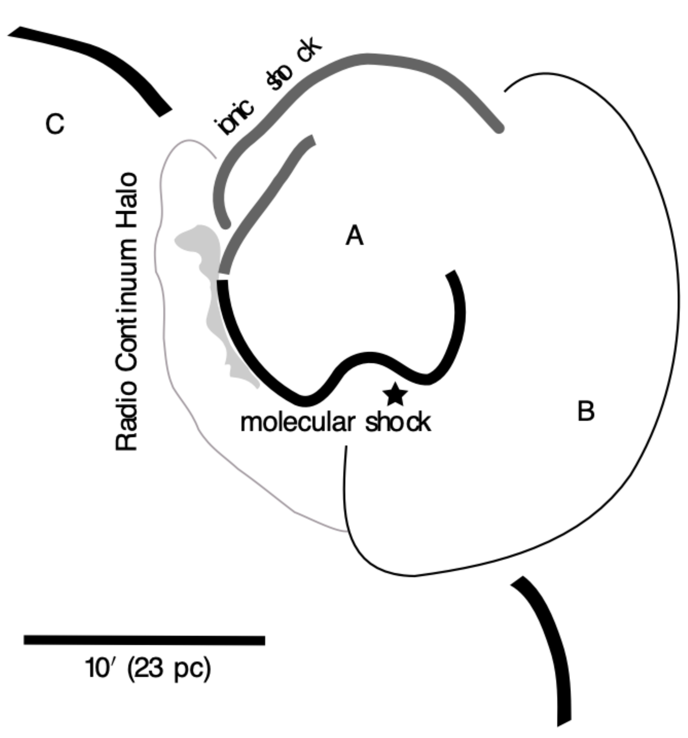
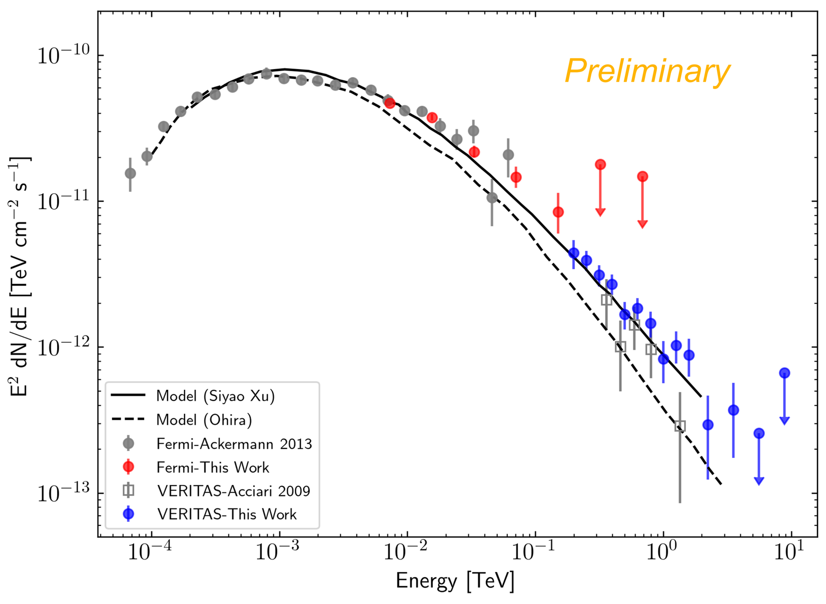
IC 443 is among the closest and best-studied cases of a supernova remnant interacting with a molecular cloud. The gamma-ray spectrum shows evidence of a cutoff at low energies, interpreted as evidence of a hadronic origin. A new Fermi and VERITAS spatially-resolved study from GeV to TeV energies reveals evidence for multiple components contributing to the SNR shell. This allows the first spatially-resolved study of gamma-ray emission from GeV to TeV energies. A spectral break is evident for both the entire remnant and individual regions. The brightest region appears to cutoff near an energy of 1 TeV.

SNR-molecular cloud interaction

IC 443 (SNR G189.1+3.0) is known to be interacting with a dense molecular cloud ~10^5 M_{sun} along the south and west. To the northeast is lower density ionized gas, and a large very low density cavity is present in radio continuum emission extending behind and to the west of the SNR (diagram from [1]). This environment is a laboratory to study the diffusion of accelerated protons as they diffuse away from an old SNR.

IC 443 has been detected by many γ-ray observatories [2,3,4]. The SED shows a low-energy decrease consistent with a hadronic origin [5]. Our updated spectrum for the entire SNR using 15 years of *Fermi* LAT and 155 hours of VERITAS data is consistent with both compressed cosmic rays (CRs) [6] or runaway CRs illuminating the adjacent clouds [7].





Figures. (Top) Schematic diagram of IC 443 [1]. An ionic shock is present in low density atomic gas in the NE. A slower molecular shock is present to the S and W. Further W is a breakout bubble producing prominent radio emission. (Left) Spectral energy distribution of the entire SNR IC 443 with updated LAT (red) and VERITAS (blue) data compared to past work.

Asymmetric γ-ray Shell

We analyzed 15 years of Fermi-LAT Pass8r3v3 Source data using the 4FGL-DR4 model [8] and 155 hours of VERITAS data from 2007-15 using standard "wobble" mode. Images from energies of 5-300 GeV and 0.2-5 TeV, respectively, show an identical shell structure with brightness that generally correlates with the amount of shocked molecular gas.

VERITAS observes a change in morphology at >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)

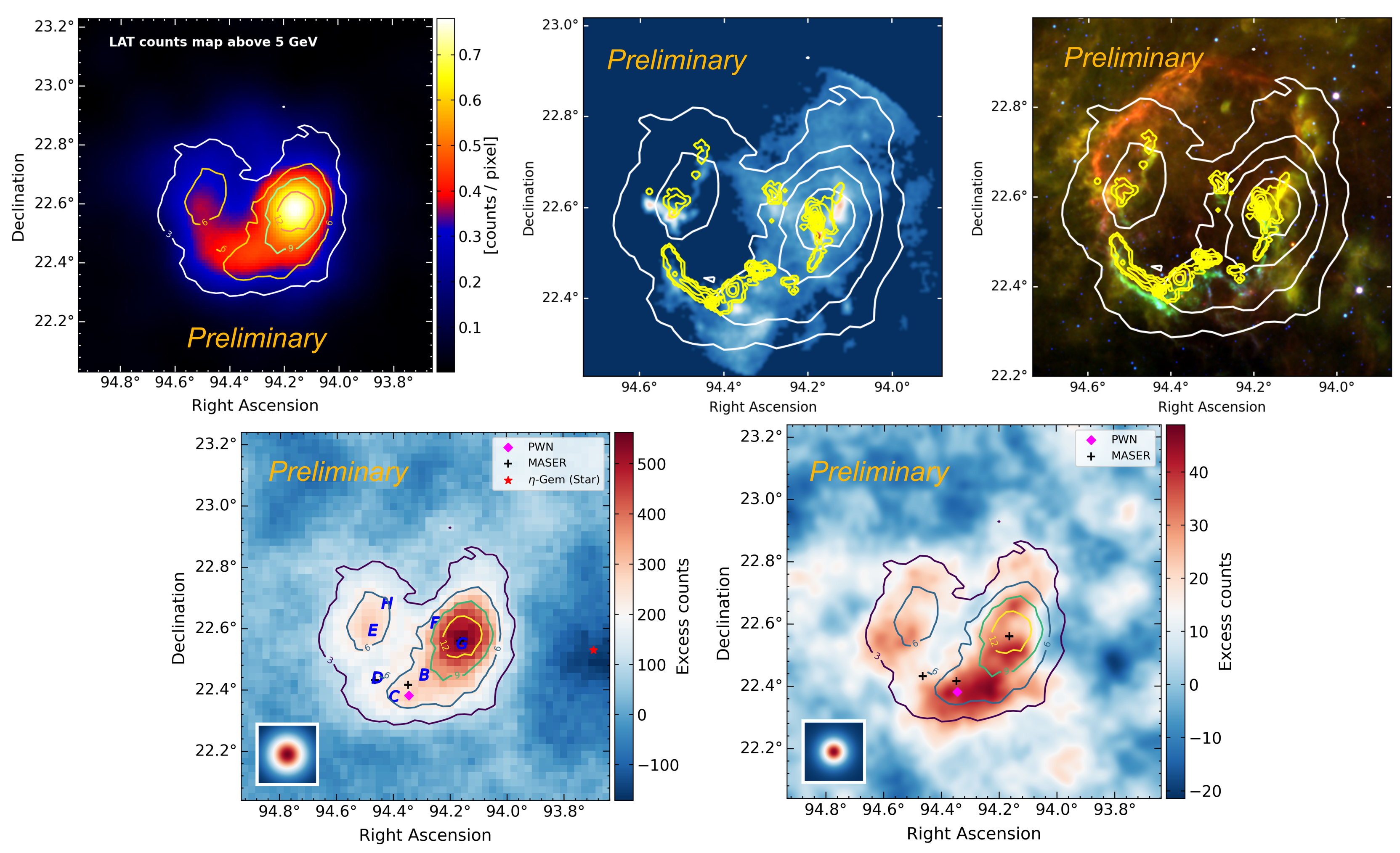


Figure. (Top Left) LAT counts map >5 GeV, with VERITAS contours at 3, 6, 9, and 12 σ levels also present in all images. (Top Center) CO map overlaid with contours from VERITAS (white) and HCO+ 1-0 shocked gas (yellow). (Top Right) WISE infrared images, 22 μm (red), 12 μm (green), and 4.6 μm (blue), overlaid with same contours. (Bottom Left) VERITAS excess map >180 GeV. OH maser positions in black. Magenta diamond at the PWN position. Nearby bright star η-Gem indicated by a red star. Blue letters (B-H) indicate shocked molecular clumps. Energy-averaged angular resolution of VERITAS in 0.2-5 TeV shown in the lower left corner. (Bottom right) VERITAS excess map for energies > 1 TeV.

Acknowledgments

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Spatially-resolved γ-ray Spectra

IC 443 is divided into four regions, for which SEDs are extracted using spatial templates (LAT, [9]) and 0.13° circular radii (VERITAS). 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.

Spectral indices of all regions match within errors. The spectrum of Region 1 is best-fit by a smoothly broken power law (ΔBIC = -6.5), with a break energy of 0.5 TeV, consistent with the change in morphology seen at >1 TeV. Region 1 (brightest) is coincident with a large foreground, unshocked cloud, so the decrease in flux may be due to either an additional runaway-CR component from outside the SNR, or different CR diffusion conditions in this region.

Regions 1-3, coincident with prominent molecular clouds [10], contain ~100 times more mass than the atomic neutral hydrogen found coincident with Region 4 [1]. Yet Region 4 is only 8-15x fainter than the combined flux from Regions 1-3, suggesting the CRs are unevenly distributed or do not fully illuminate all molecular material.

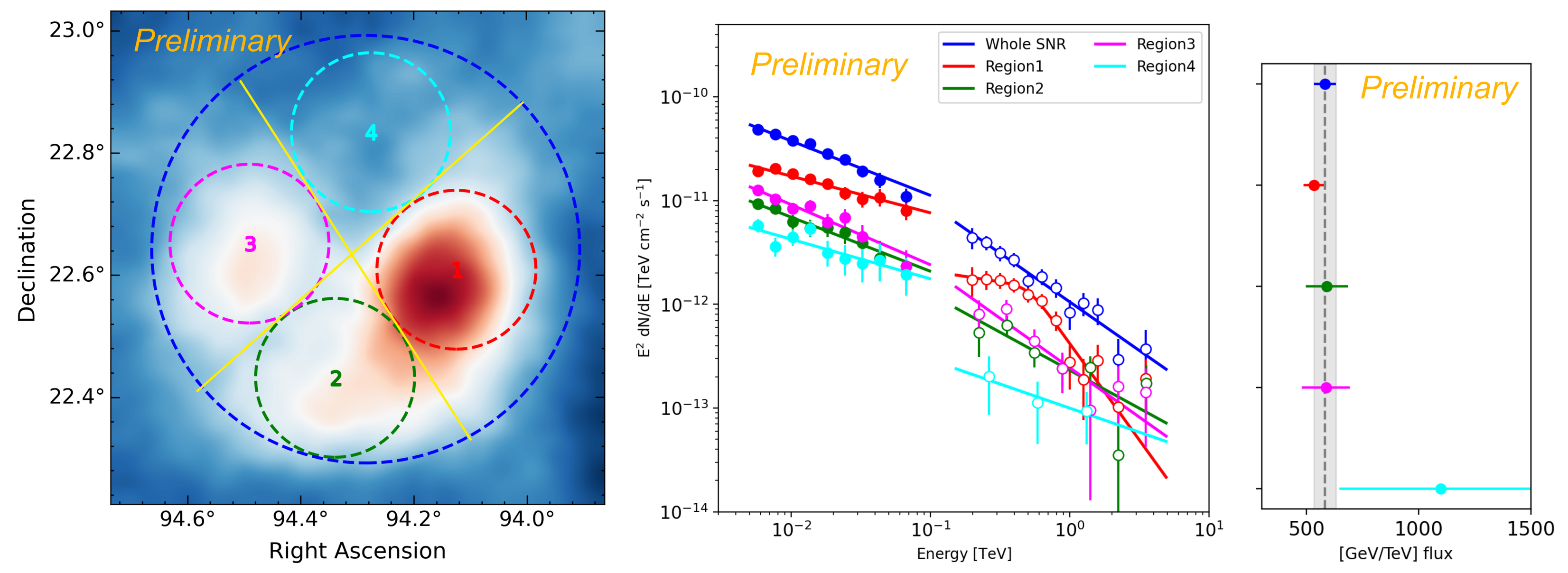

Figure. (Left) Regions from which spectra were extracted overlaid on the VERITAS excess map. The VERITAS spectrum is derived from circular regions, while the Fermi-LAT spectrum is extracted from wedges. Scaling factors derived from the LAT spatial template, are applied between LAT and VERITAS to correct for differences in the spectrum due to different extracted area. (Center) Best-fit spectral models for each individual instrument. Filled points are from LAT and non-filled points are from VERITAS. (Right) The ratio of GeV to TeV flux for each of the four regions and the whole-SNR.

Table. Best-fit model parameters and GeV/TeV ratio for four regions. Region 1 is most accurately described by a smooth broken power law (SBPL), while other regions are best represented by a simple power law (PL) model.

Preliminary

Region	VERITAS Model (Best)	VERITAS Parameters	VERITAS Integral Flux (0.2–10 TeV)	Fermi-LAT Model (Best)	Fermi-LAT Parameters	Fermi-LAT Integral Flux (5–100 GeV)	Flux Ratio (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

Conclusions

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 well 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 gamma-ray-to-gas ratio.

References

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