The TeV Morphology of the Interacting Supernova Remnant IC 443

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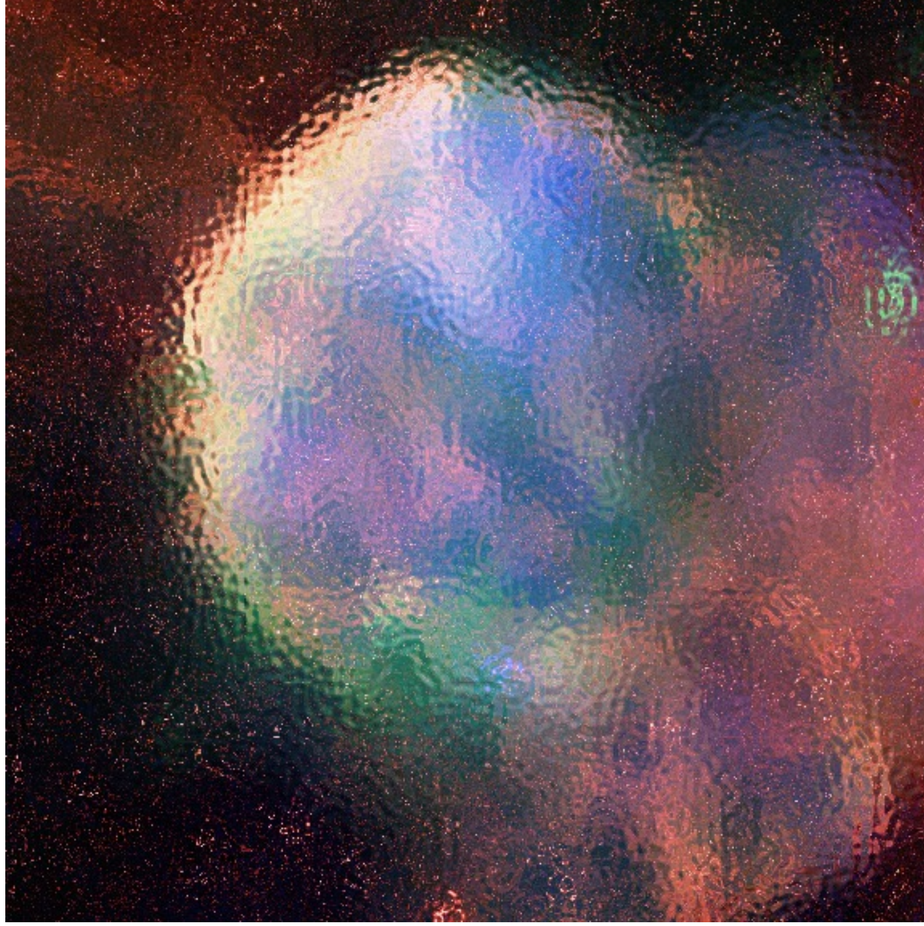
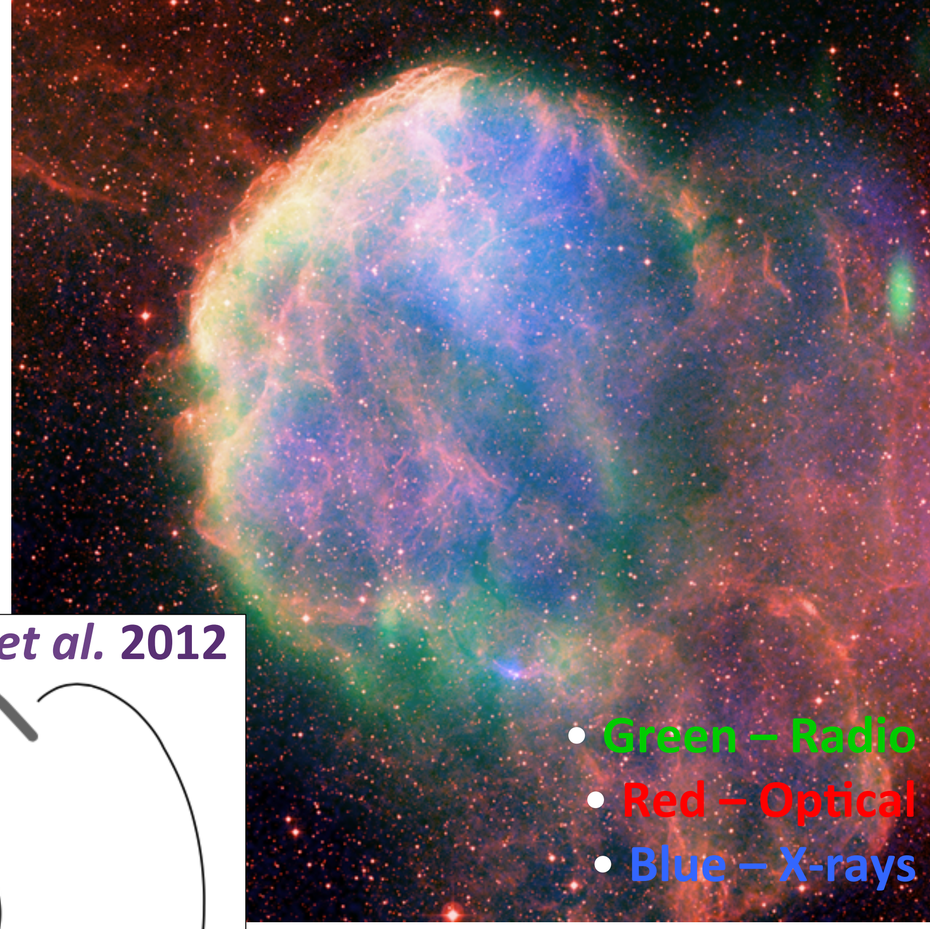
Outline

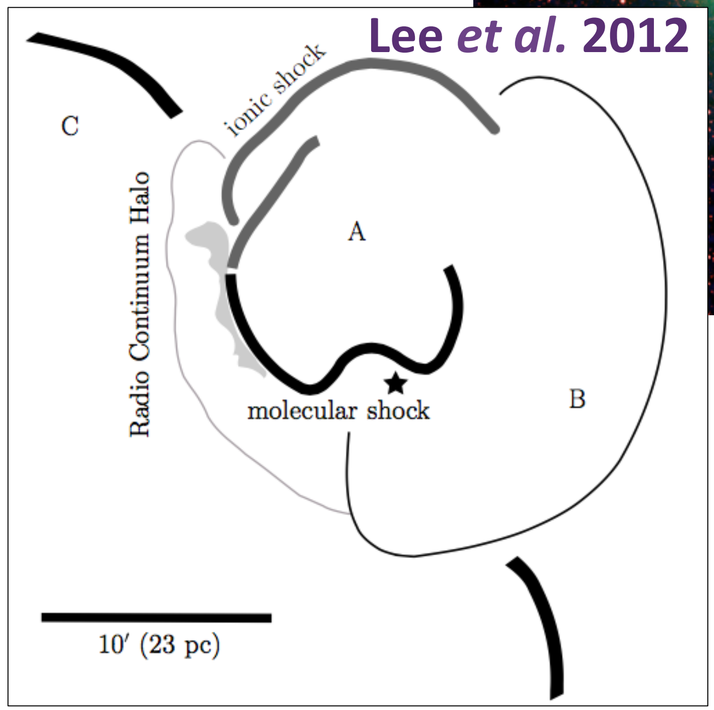
1. Introducing IC 443
2. VERITAS Observations & Analysis
3. Results & Discussion
4. Summary



IC 443 & Neighborhood

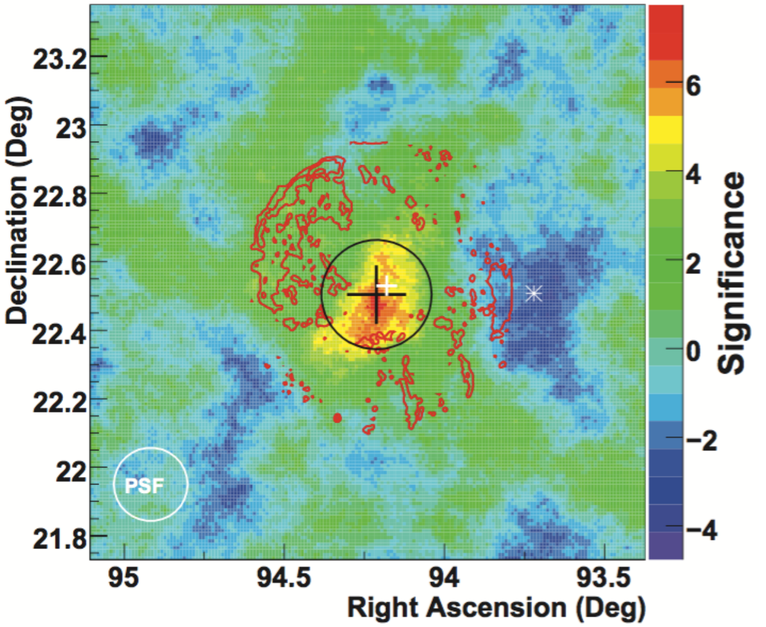
- Remnant of core-collapse SN evolving in inhomogeneous environment.
  - Varying amounts of target material!
- Distance 1.5 kpc, 0.75° diameter
- Age uncertain, 3-30 kyr
- PWN at southern edge of shell

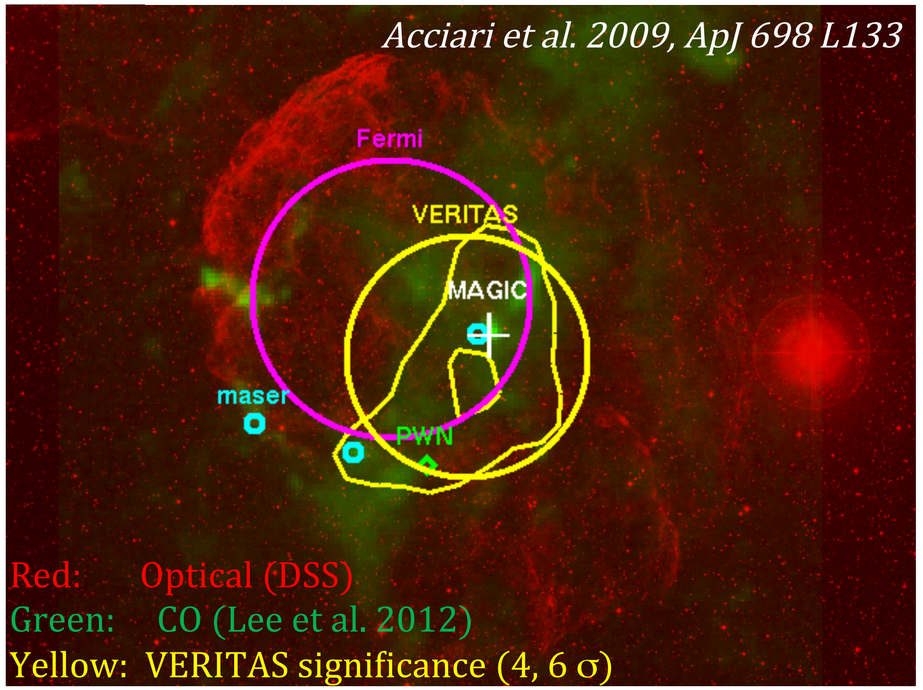




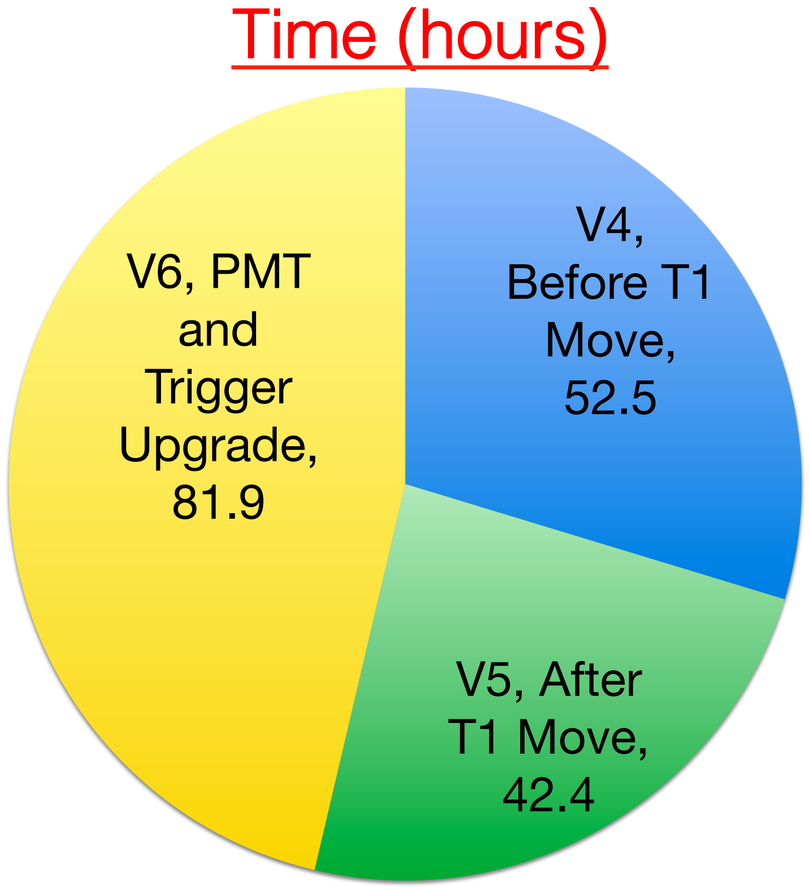
IC 443 in γ rays

- First detected by EGRET in `90s
  - AGILE & Fermi since → detection of pion bump
- VHE: First detected in 2007 by MAGIC and VERITAS
  - Soft-spectrum VHE SNR: $\Gamma \sim 3.0$
- Extended: 2-D Gaussian profile fit:
  - $\sigma \sim 0.16^{\circ} \pm 0.03^{\circ}_{stat} \pm 0.04^{\circ}_{sys}$
  - Correlated with shock/MC interaction





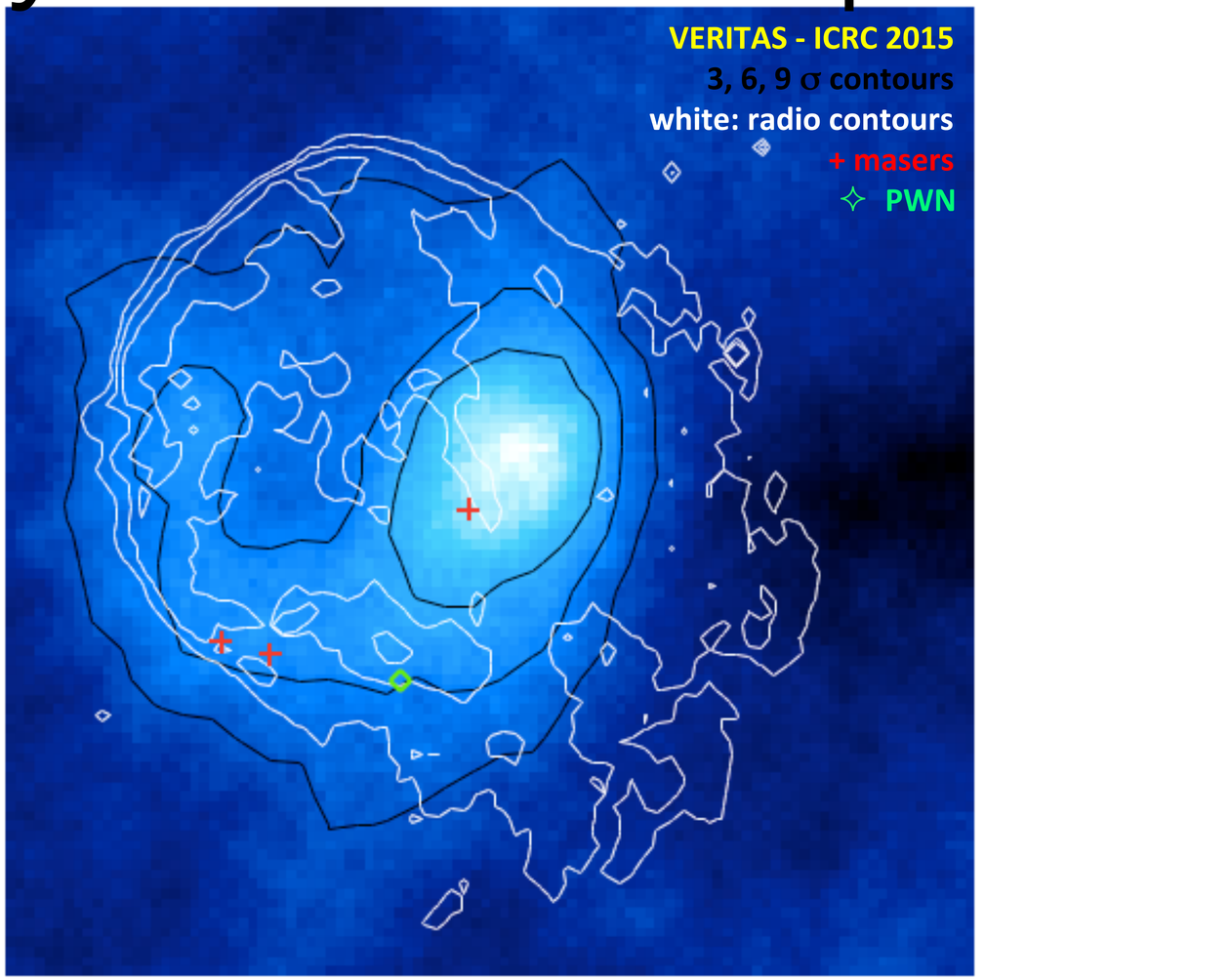
VERITAS Data & Analysis

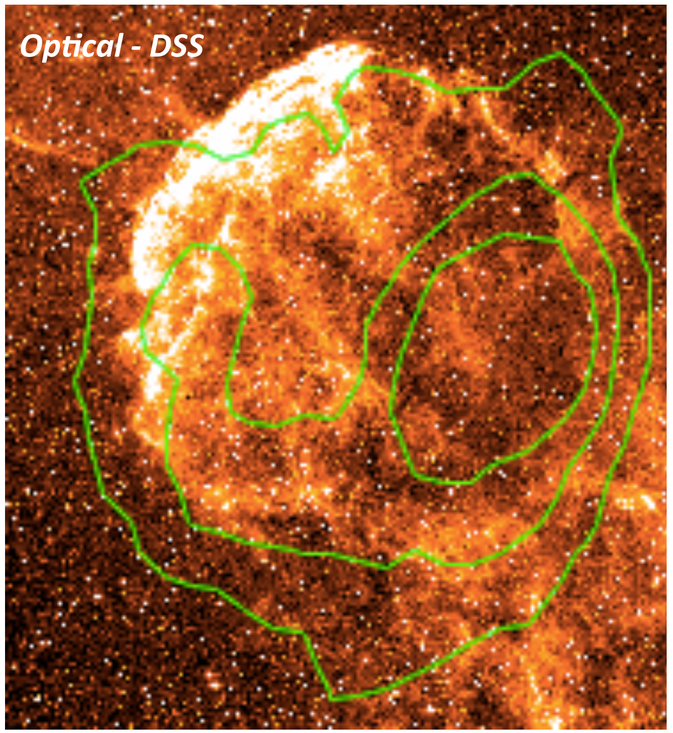


Total Quality-Selected Data
~ 176.8 Hours Duration
(3-Tel & 4-Tel)

- After quality selection & deadtime correction, 155.6 hrs livetime.
  - Compared to published, factor of 4.5 increase in map, factor of 9 in spectrum.
  - Moderate cuts, require 3 images with at least 5 pixels & 600 digital counts.
    - E_{thr} ~ 240 GeV; spectral reconstruction above 190 GeV.
  - Point-source integration radius 0.09°.

γ-ray Excess Map

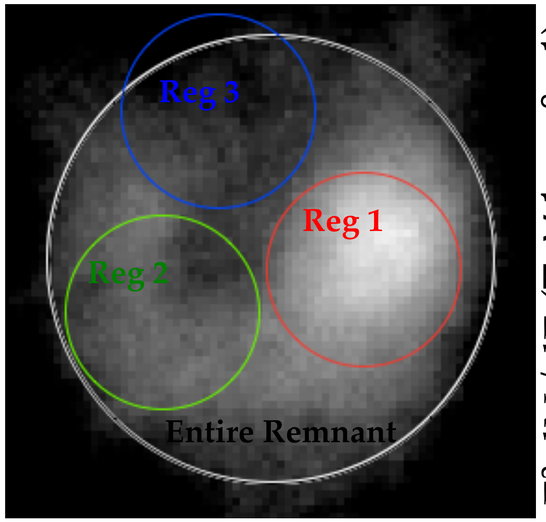


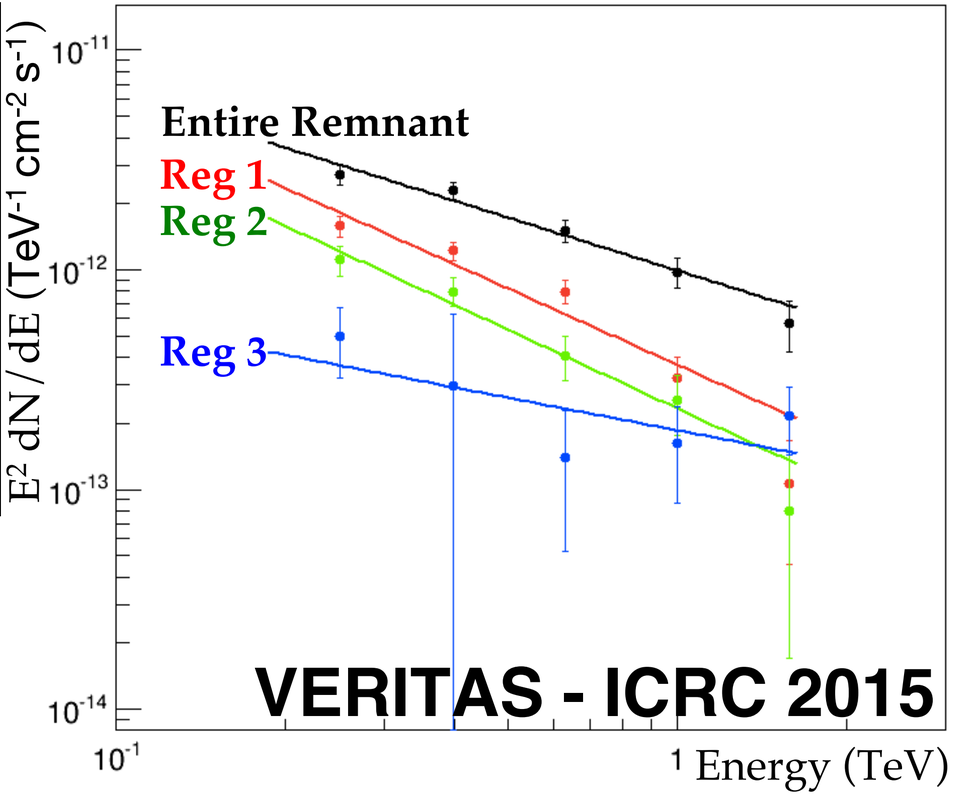


- ✧ TeV emission fills the northeast lobe and SNR/MC interaction regions.
  - ➢ Strongest where maser emission brightest.
- ✧ Entire shell appears to be accelerating particles.

VHE Spectra

- Spectra extracted for entire SNR (0.3° radius) and three regions (0.13° radius):
  1. Brightest maser emission.
  2. Dim, extended maser emission.
  3. Swept-up material; no clouds.



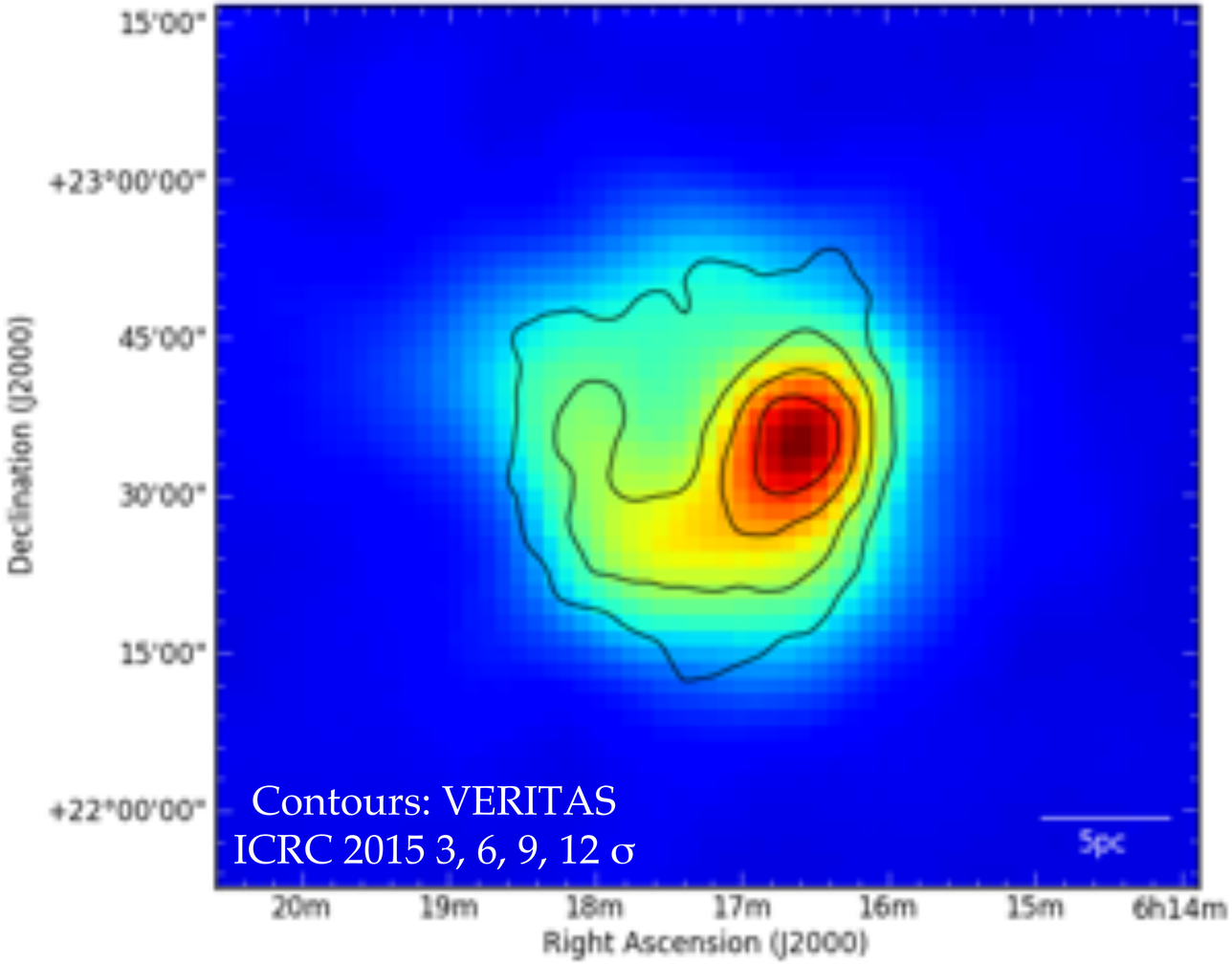


Power-law fit results:

Region	Norm (/550 GeV) * 10^{-13} TeV^{-1} cm^{-2} s^{-1}	Index	χ^2 / ndf
Entire Remnant	9.92 ± 0.90	-2.80 ± 0.09	2.76 / 3
Region 1	3.69 ± 0.42	-3.15 ± 0.11	9.98 / 3
Region 2	2.33 ± 0.42	-3.19 ± 0.17	1.85 / 3
Region 3	1.86 ± 0.49	-2.49 ± 0.42	2.64 / 3

Comparing VERITAS to Fermi-LAT Pass 8

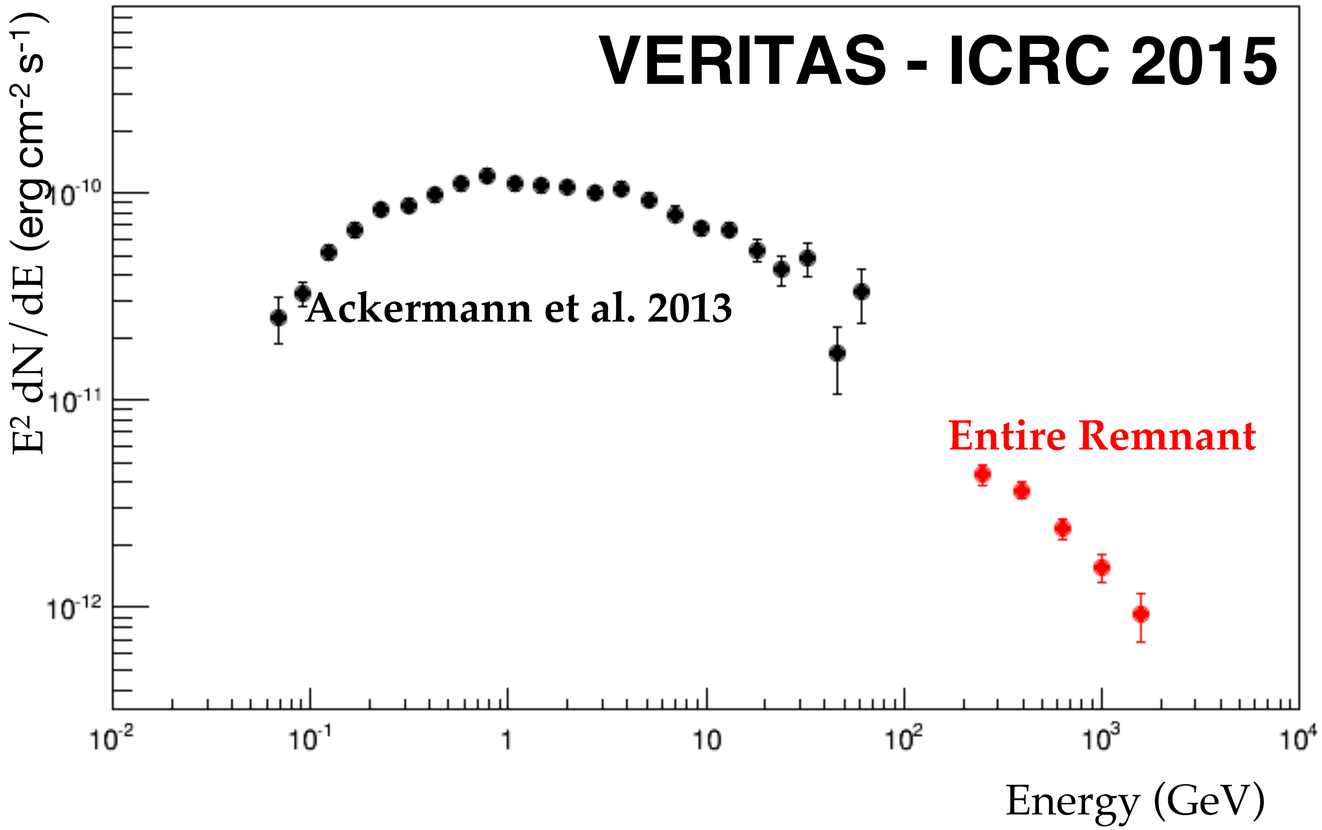
- Counts map: Fermi-LAT photons selected above 5 GeV.
  - 83 months of data; P8R2_SOURCE_V6; Fermi Science Tools v10r0p5
  - Event classes PSF2 and PSF3 (50% events with best PSF).
- GeV, TeV emission show remarkable spatial correlation.
  - Single population of CRs interacting with shocked gas?



courtesy: J. Hewitt for Fermi-LAT Collaboration

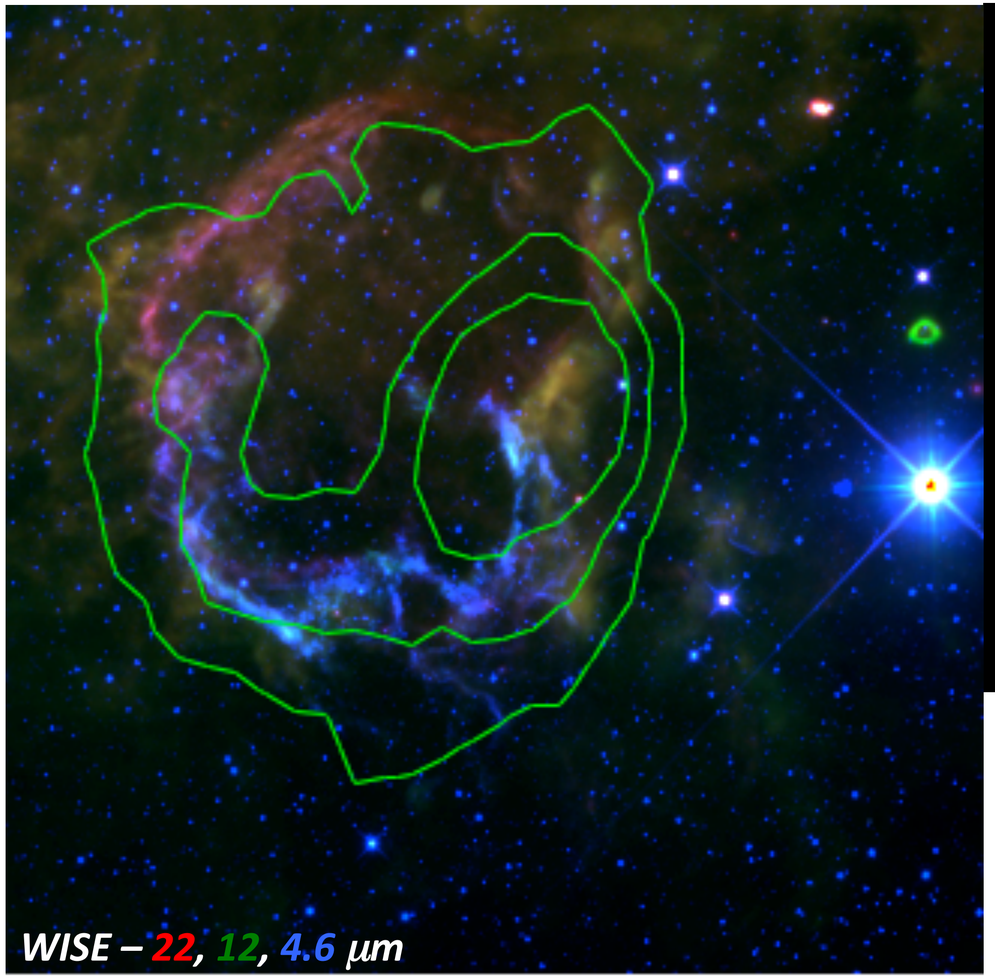
Broadband γ-ray Spectra

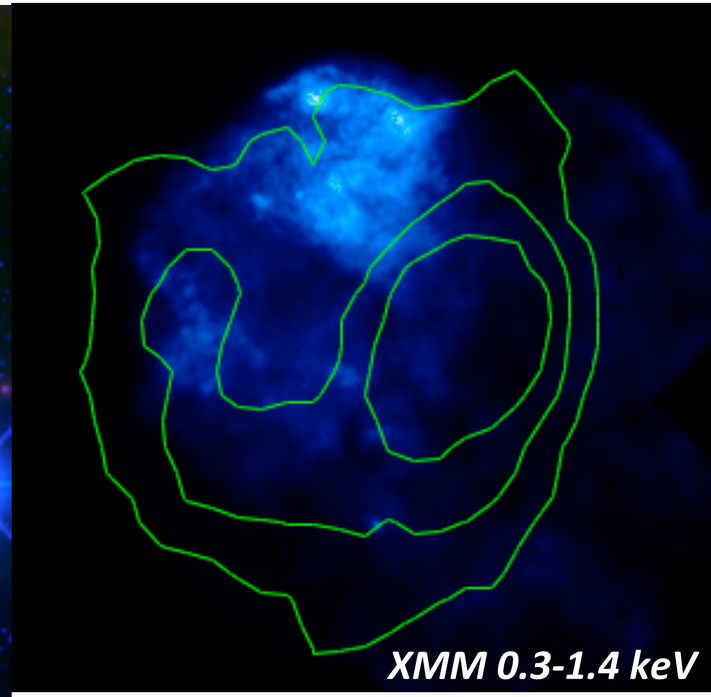
- Fermi-LAT (black) results from Ackermann et al. 2013.
- VERITAS (red) spectrum for entire SNR.
- Smooth transition from GeV to TeV range also suggests a single population of CRs.



γ-rays and Gas Distributions

- Emission anticorrelates with thermal X-rays.
- GeV / TeV emission correlate most strongly with shocked gas.
- Suggests emission dominated by CRs interacting with gas in contact with shock front.





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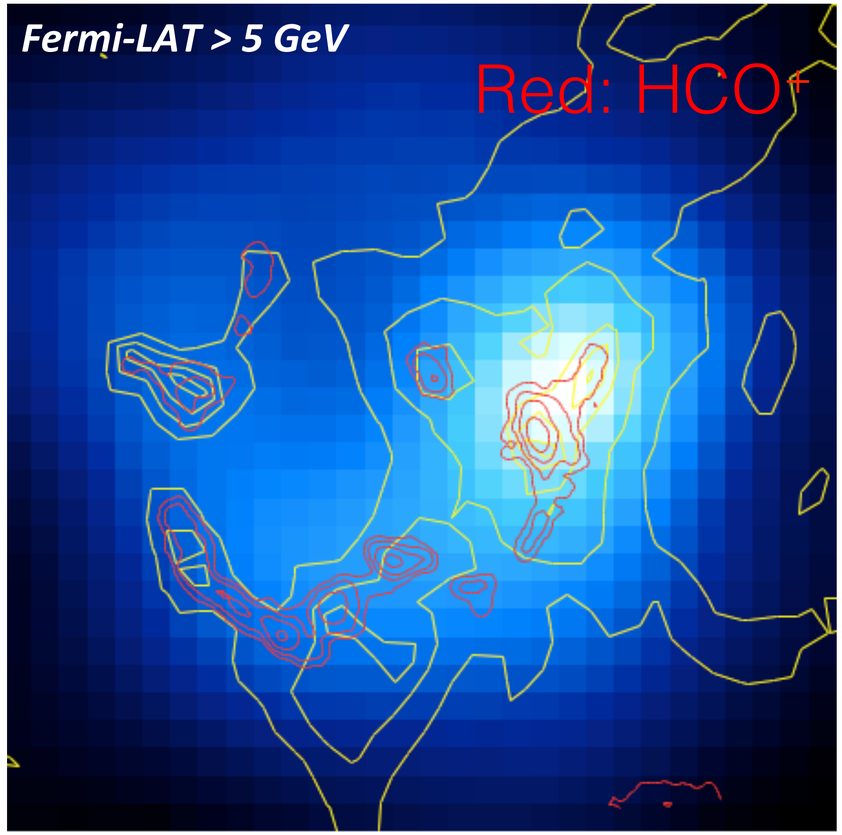
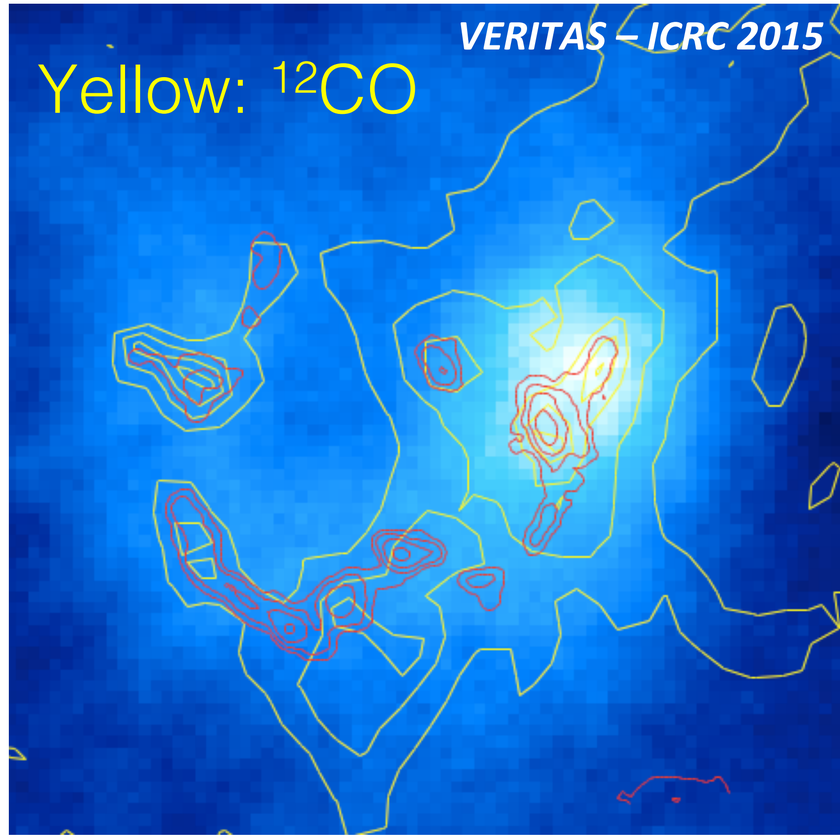
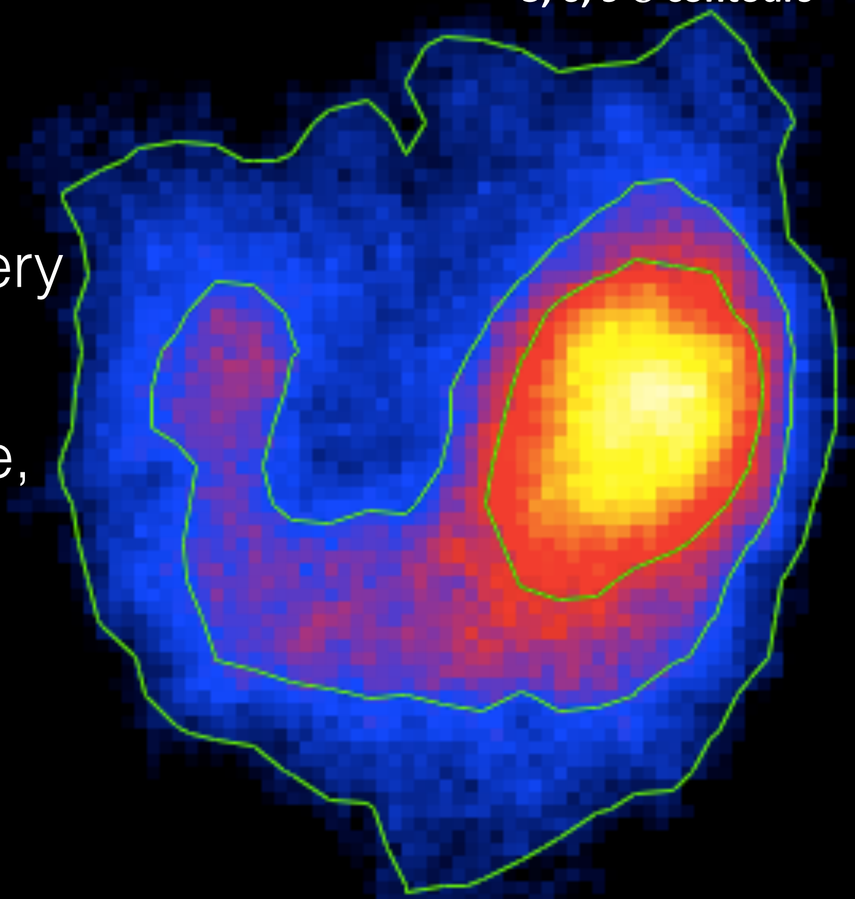
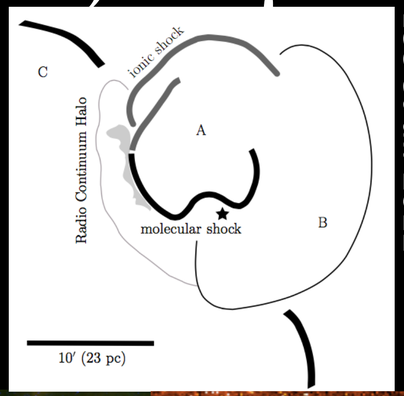




Summary: Resolving the Jellyfish Nebula (IC 443) in γ-rays

- A deep observation of IC 443 with VERITAS has resolved significant VHE emission from the entire northeast lobe.
- Pass-8 Fermi-LAT data reveals very similar morphology above 5 GeV.
- The γ-ray emission spans multiple, very different, environmental conditions.
  - *Can extract spectra from different regions to probe the environmental dependence of cosmic-ray diffusion.*





Lee *et al.* 2012