

Supernova Remnants at TeV Energies with VERITAS Array



Sajan Kumar for VERITAS Collaboration

TeVPA 2022, Kingston, Canada

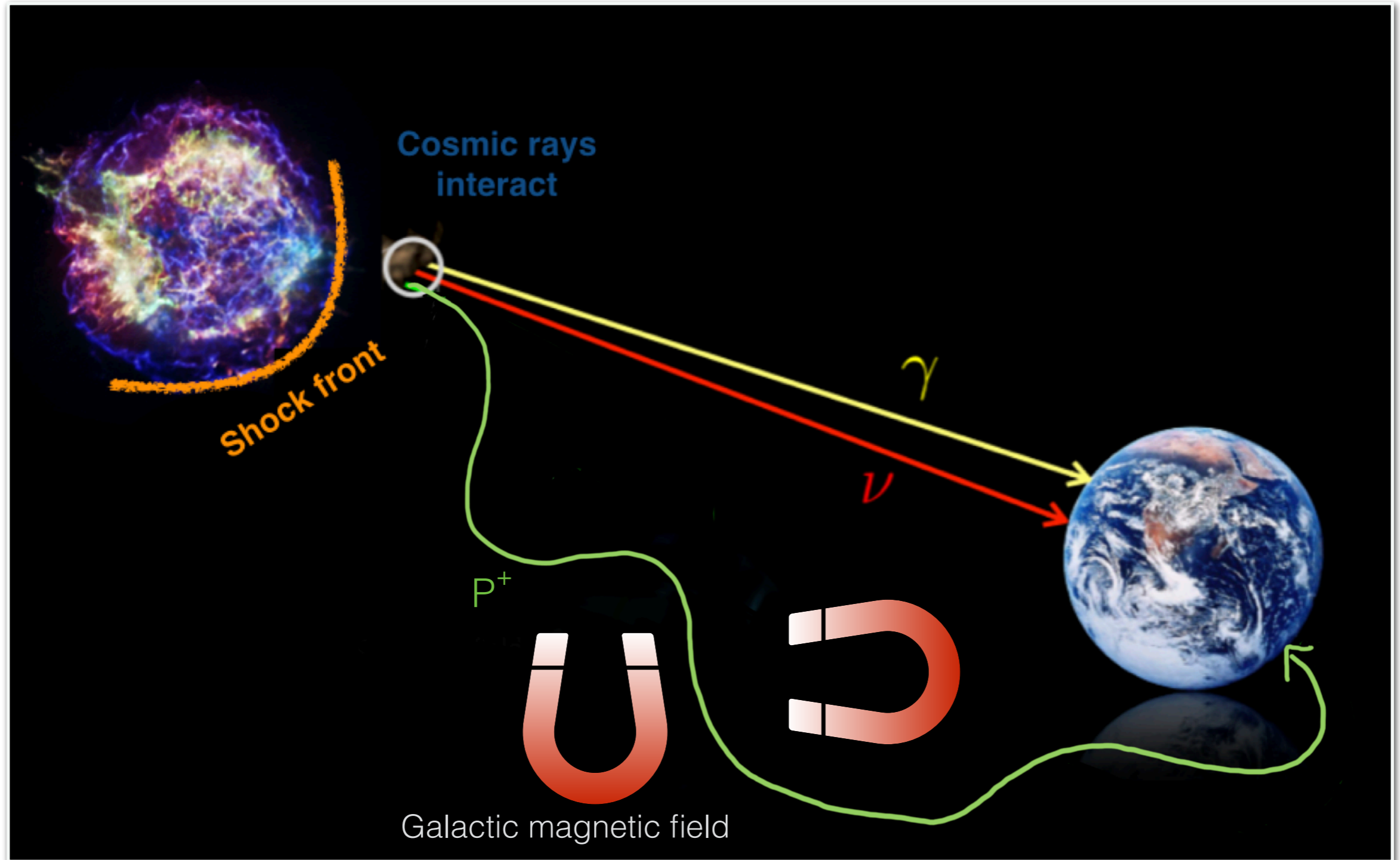
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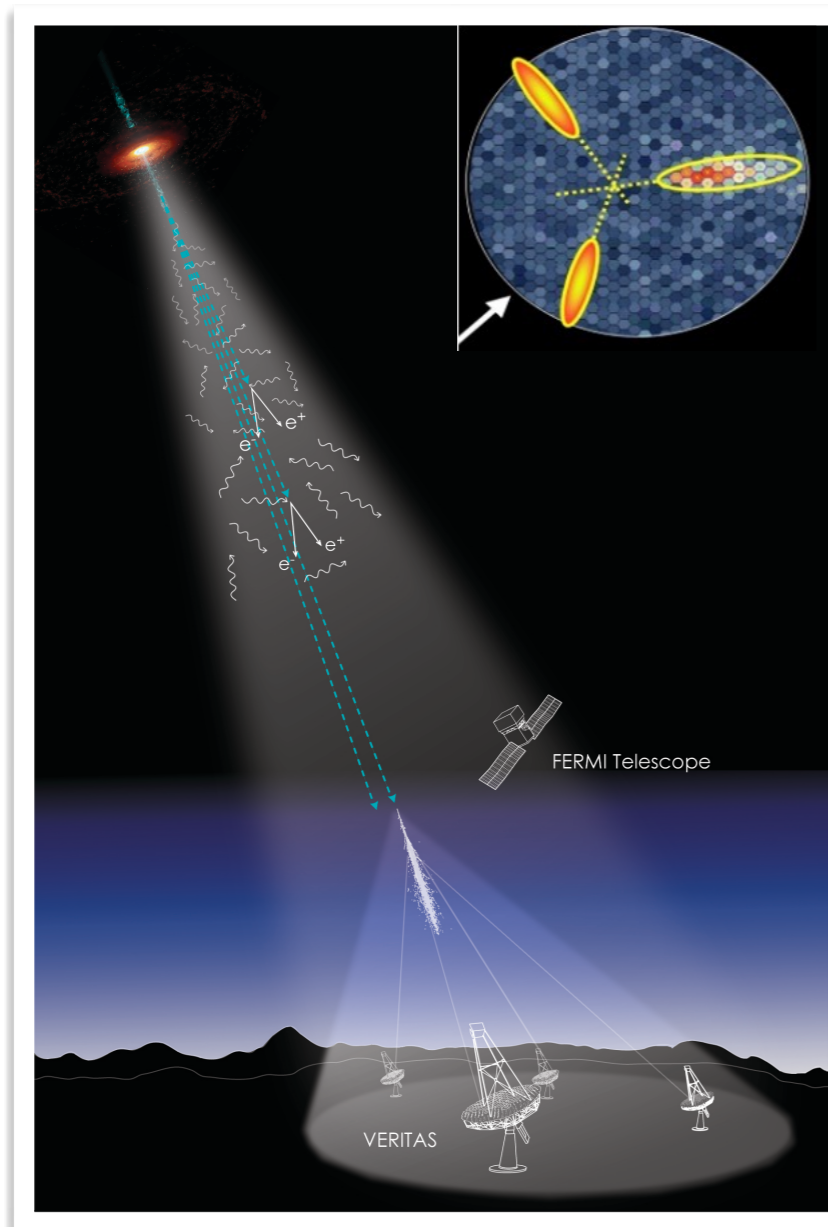
Outline

- Motivation for gamma-ray astronomy
- Technical details about VERITAS array
- **Supernova remnants study with VERITAS**
 - ✓ Cassiopeia A
 - ✓ IC 443

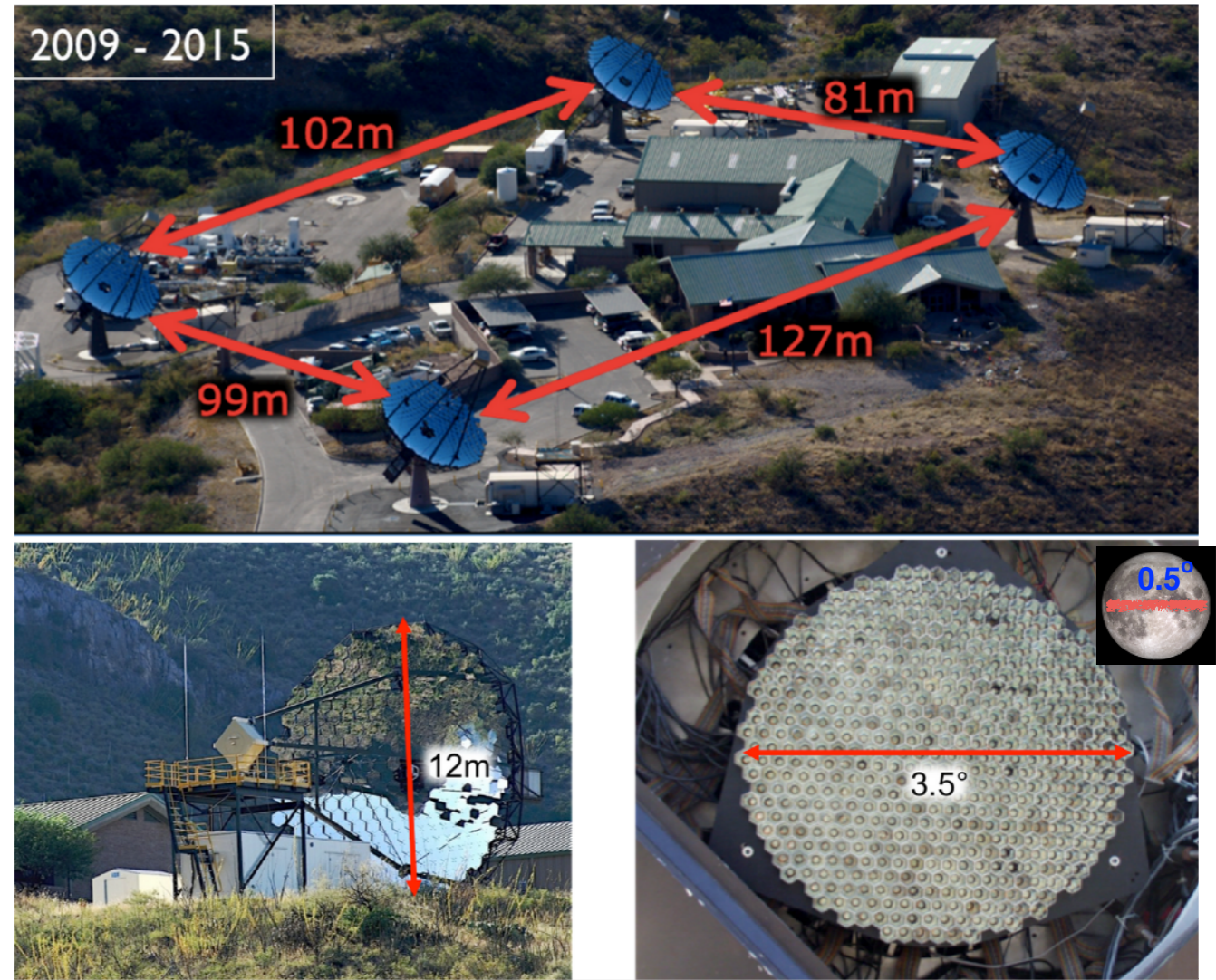
Cosmic rays and γ -rays



VERITAS array



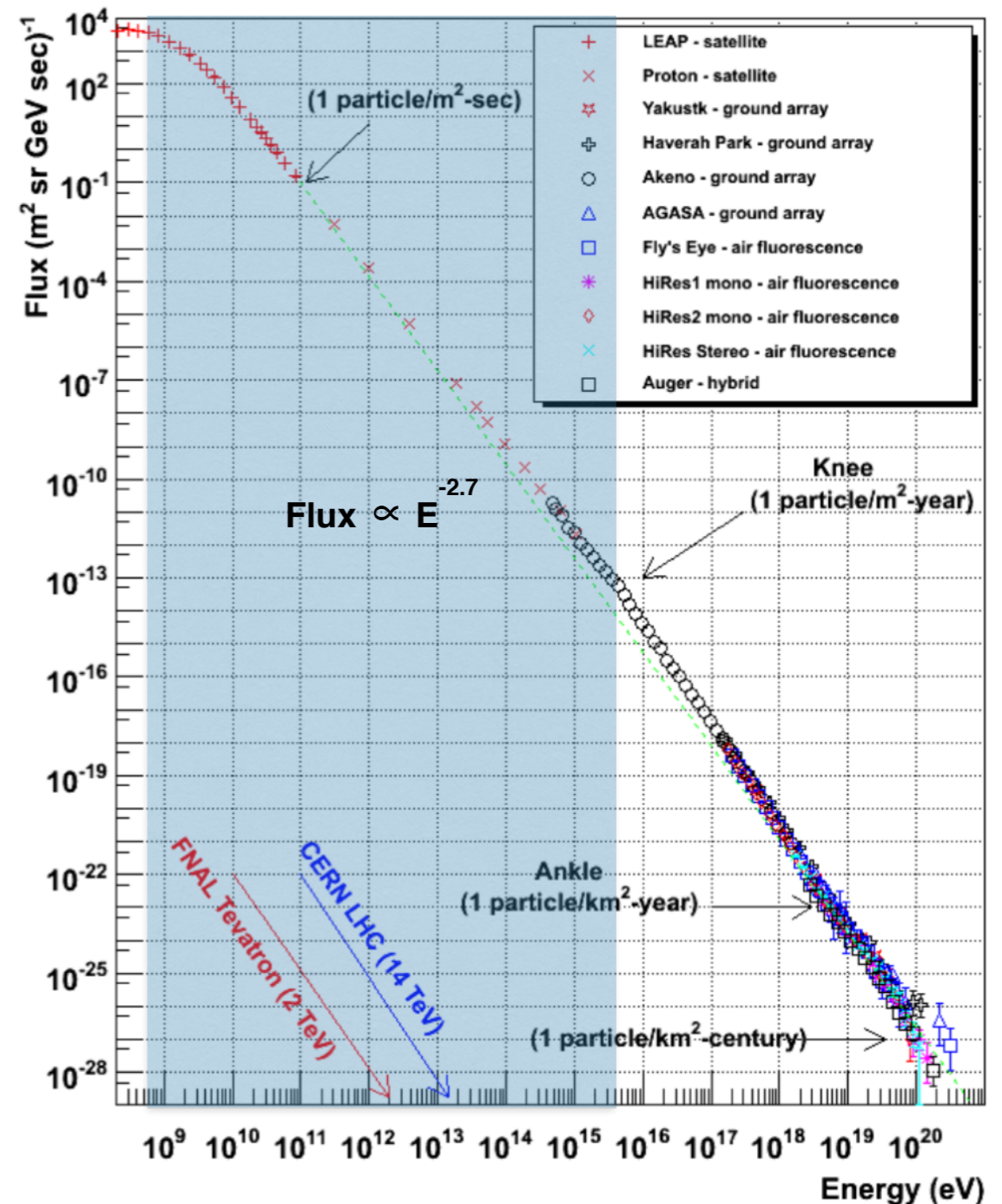
- Cherenkov light is emitted from EM shower
- Light is focussed onto a fast-response camera
- Analysis of images is done to reconstruct properties of shower; energy, direction, timing



- Four telescopes
- Each telescope has a diameter of 12 m
- PMT camera with a field of view of 3.5 degrees
- **Energy range:** 85 GeV to > 30 TeV
- **Angular resolution:** ~ 5 arc minute at 1 TeV

SNRs as origin of Cosmic rays

- Cosmic rays are mainly charged particles that contribute an energy density of 1 eV cm^{-3} in our Galaxy
- **SNRs** are considered as the best candidates for the origin of Galactic CRs up to 10^{15} eV (PeVatron)
 - ➔ **Power required** to maintain the cosmic ray flux in our galaxy can be supplied by supernova explosions if 2-3 SNe happen per century and converted 10% of their energy into CRs
 - ➔ **Diffusive shock acceleration** naturally explains the power-law spectrum of cosmic rays ($\alpha = -2.7$ up to PeV energies)

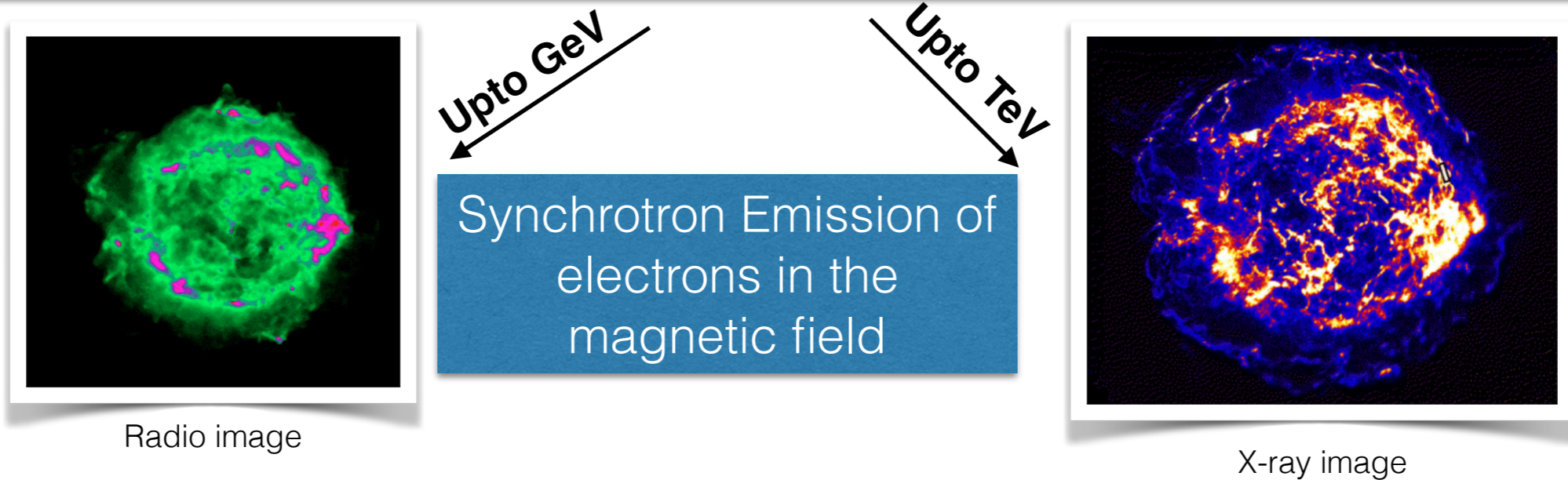


Blasi et al. 2013

SNR: Cassiopeia A

- ◆ Young SNR (~ 350 years) results from the type IIb explosion of a massive star
- ◆ Explosion drives shock waves into the circumstellar medium
- ◆ Particles get accelerated at the shocks by *diffuse shock acceleration (DSA)*

Observational evidence of acceleration of electrons at the shocks

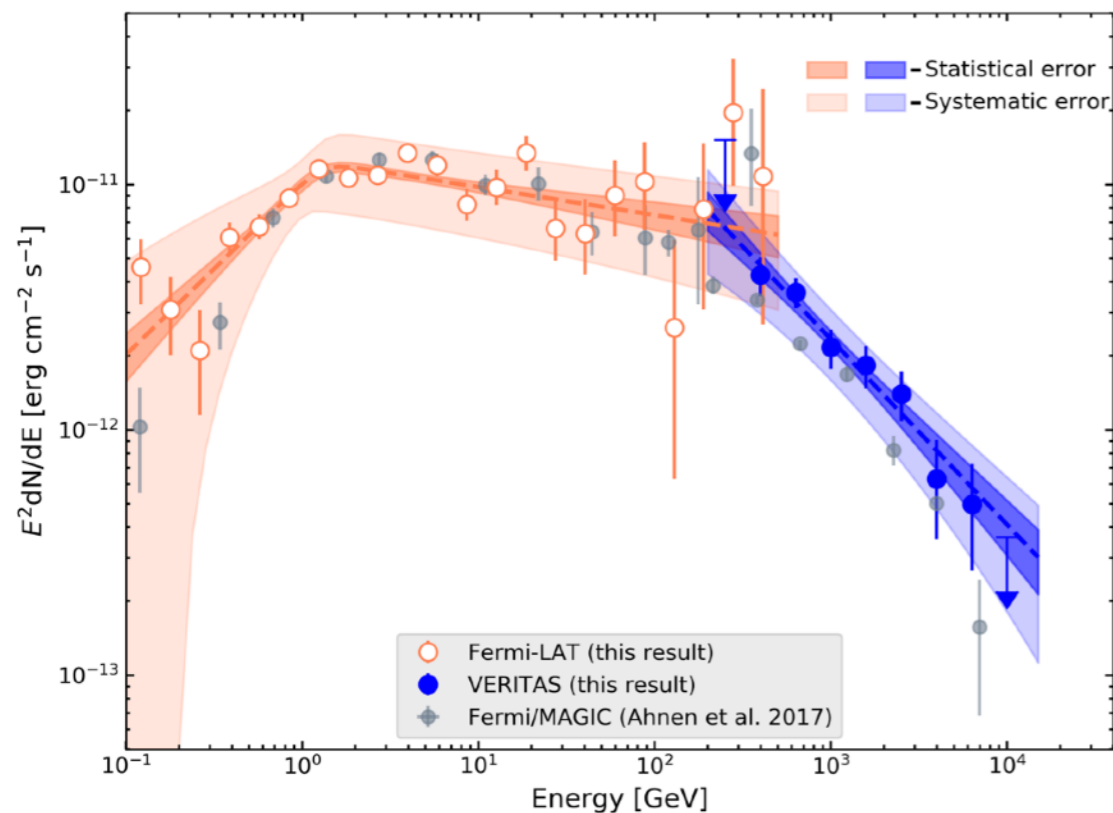


Can SNR also accelerate protons ? To test this, observations in gamma-ray regime can be helpful

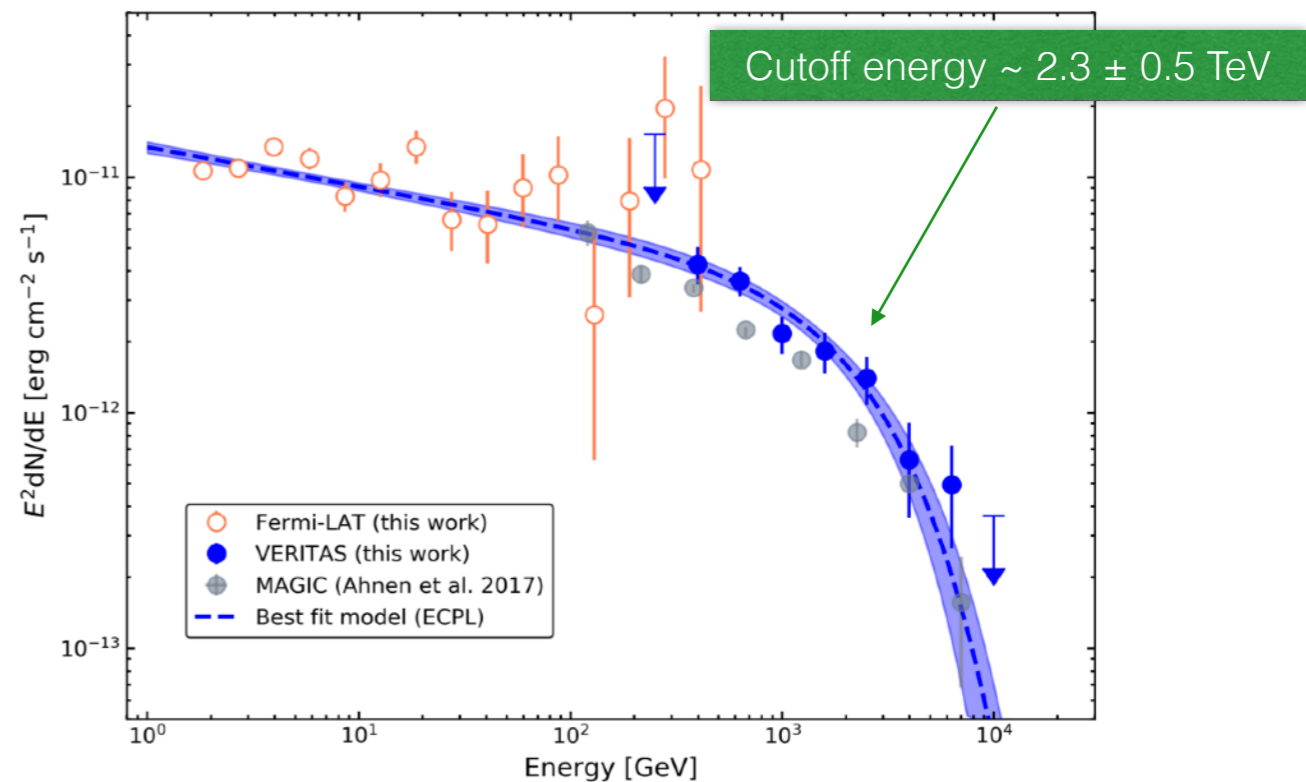
VERITAS and Fermi-LAT spectral measurements of Cas A

- ~65 hours of VERITAS data (200 GeV - 10 TeV)
- ~11 years of Fermi-LAT data (100 MeV - 500 GeV)

Spectral energy distribution



Joint fit of LAT-VERITAS points above 1 GeV

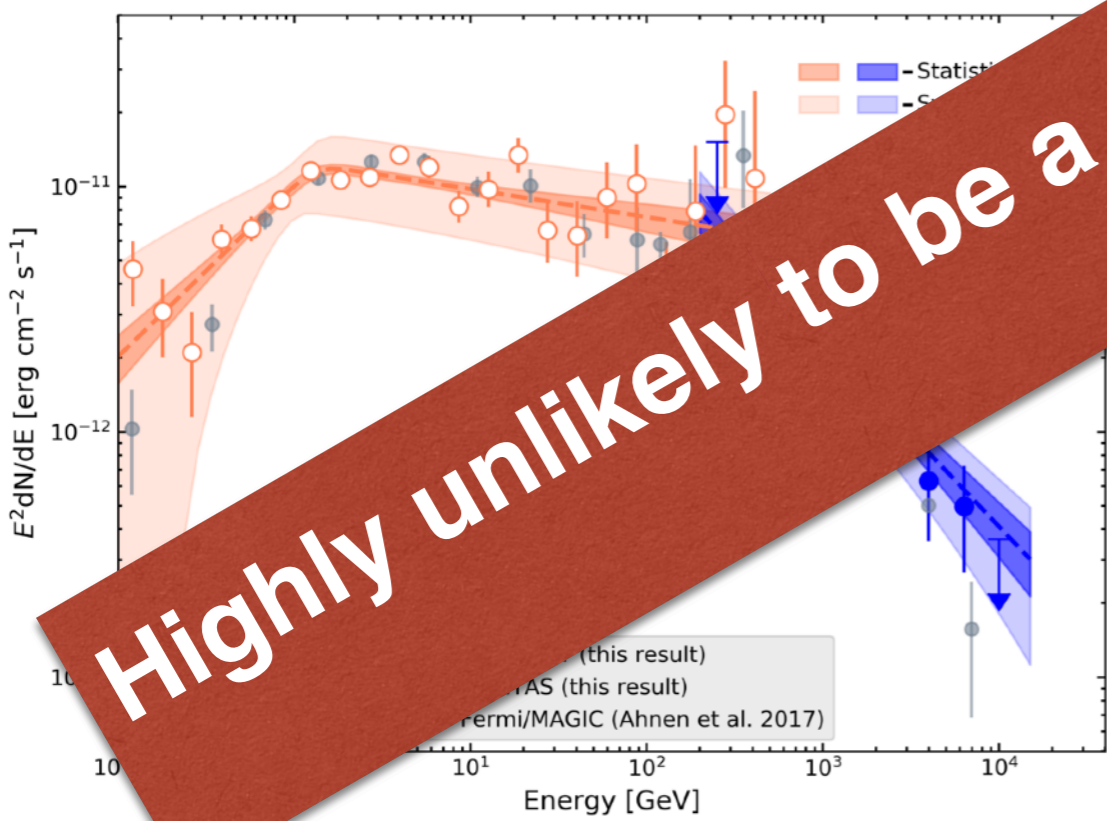


A. U. Abeysekara *et al* 2020 *ApJ* **894** 51

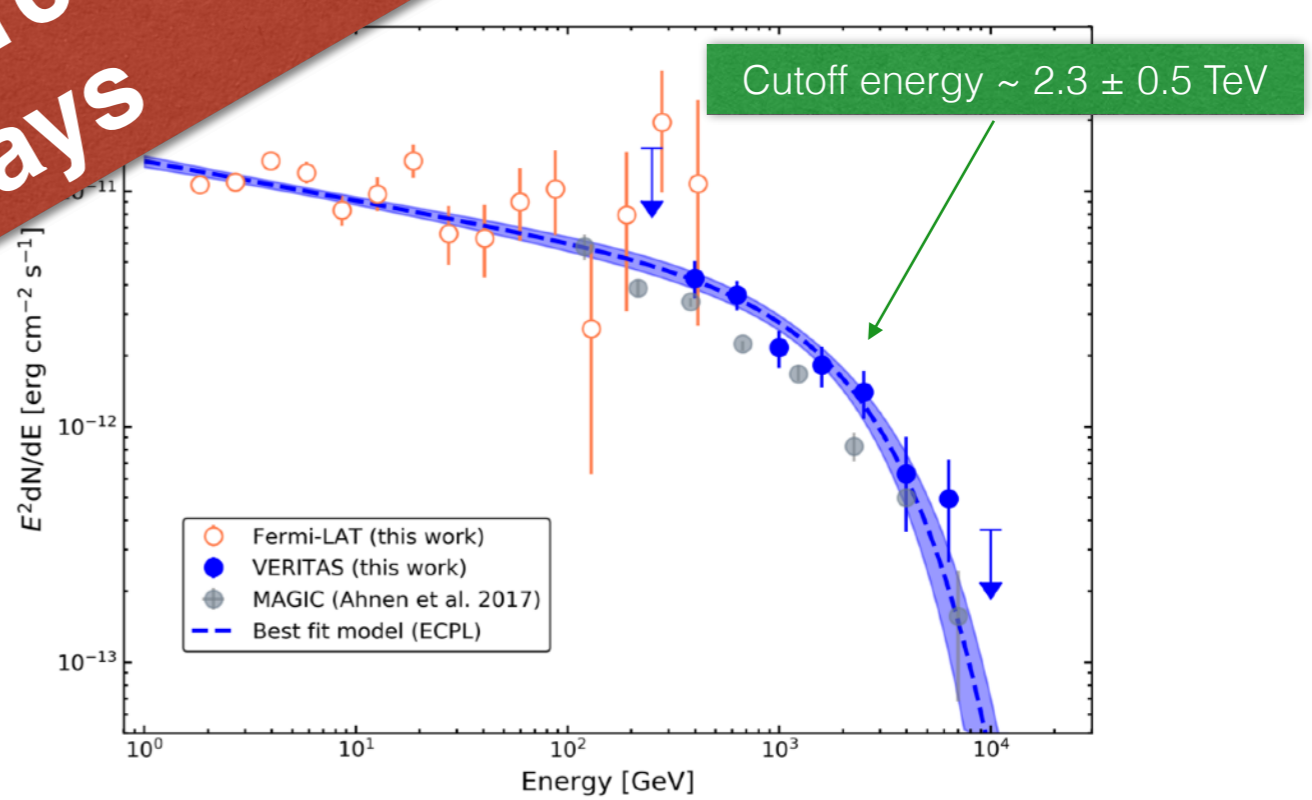
VERITAS and Fermi-LAT observations of Cas A

- ~65 hours of VERITAS data (200 GeV - 10 TeV)
- ~11 years of Fermi-LAT data (100 MeV - 300 GeV)

Spectral energy distribution



VERITAS points above 1 GeV



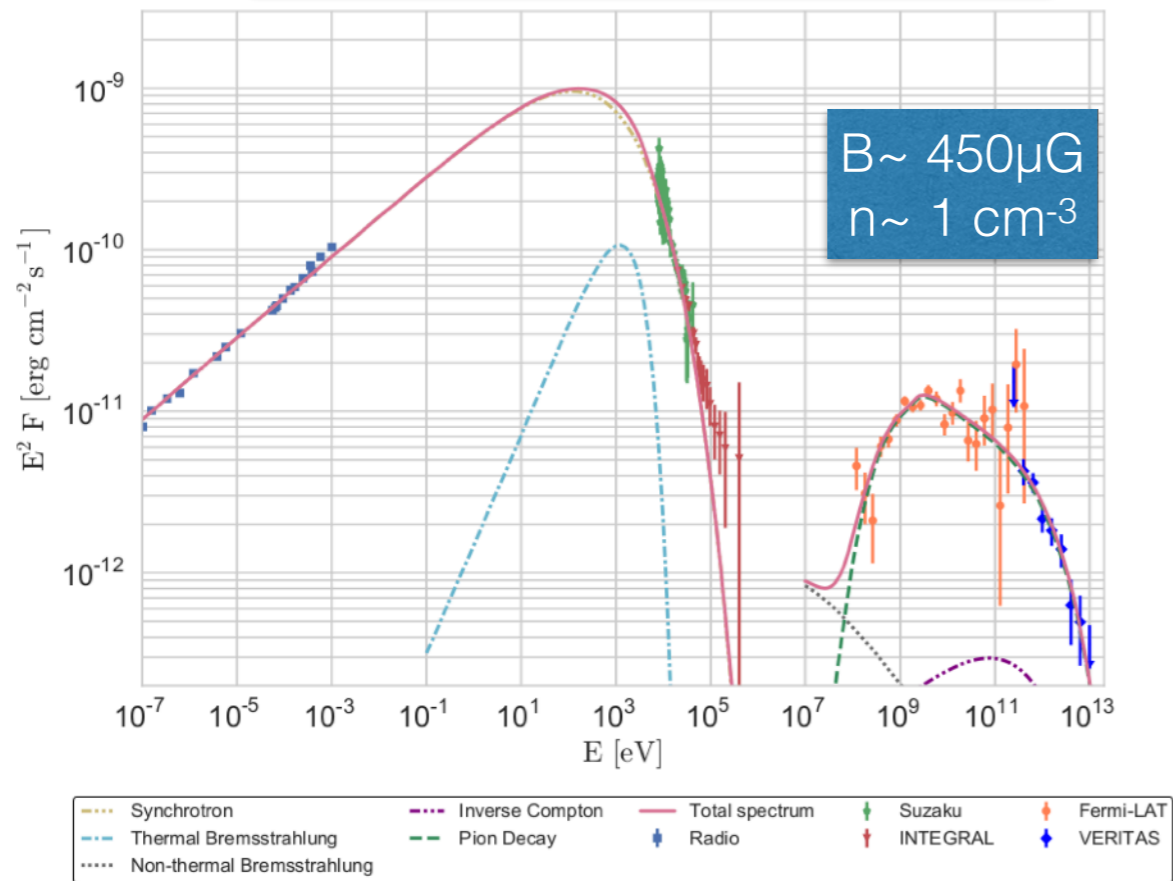
Highly unlikely to be a source of PeV (10^{15} eV) cosmic rays

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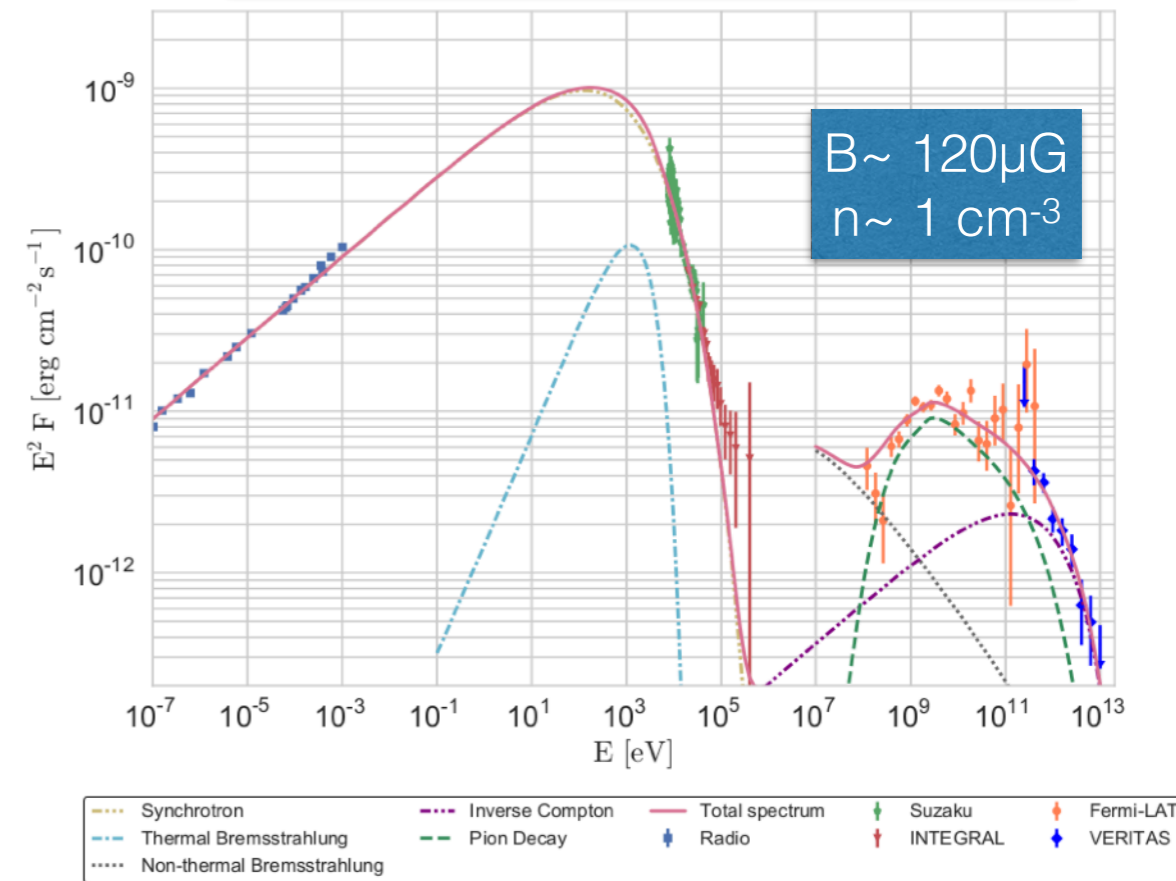
....SED Modelling

Emission Processes : Synchrotron, Bremsstrahlung, Inverse Compton, Pion Decay

Proton dominated emission



Electron dominated emission

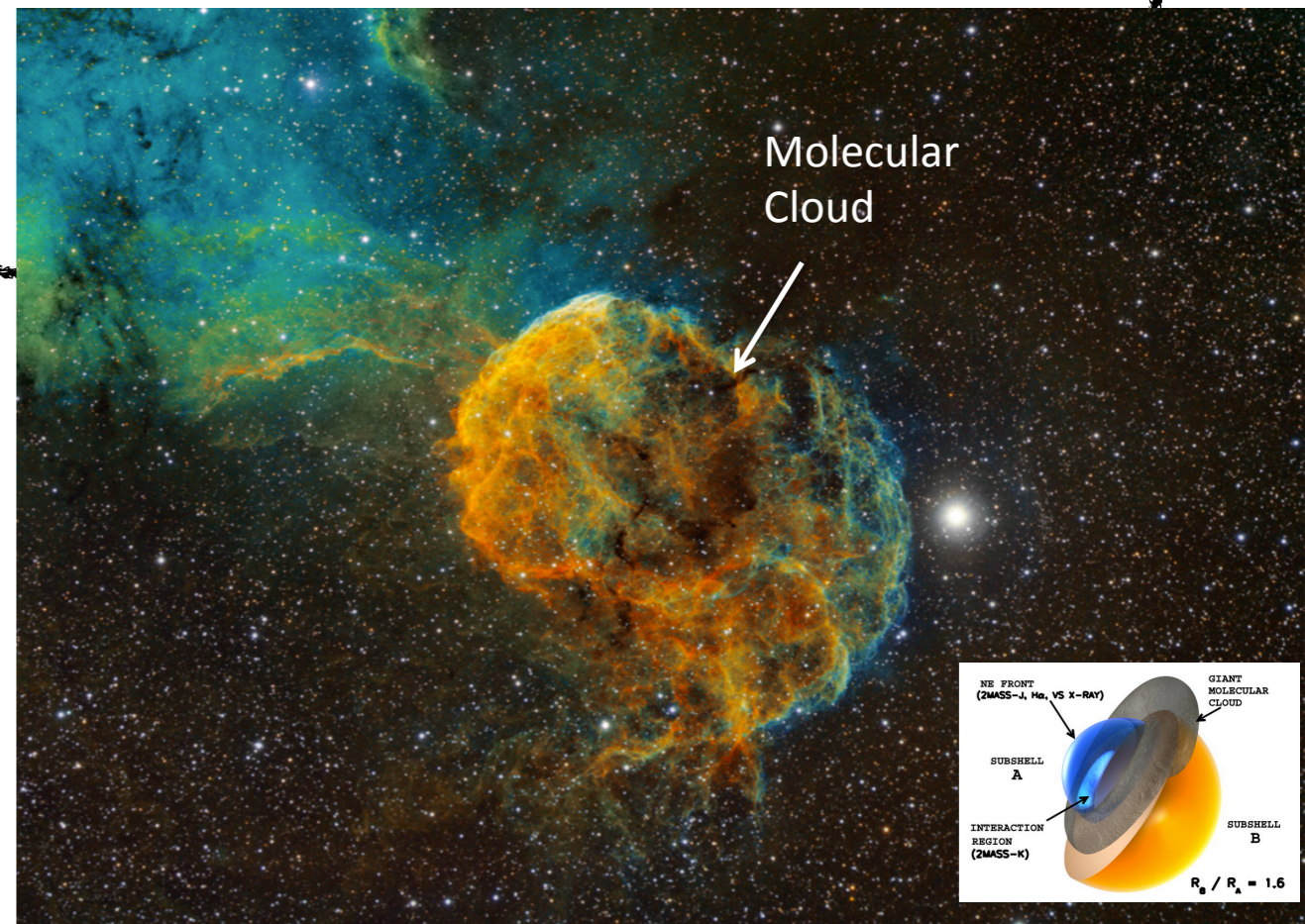
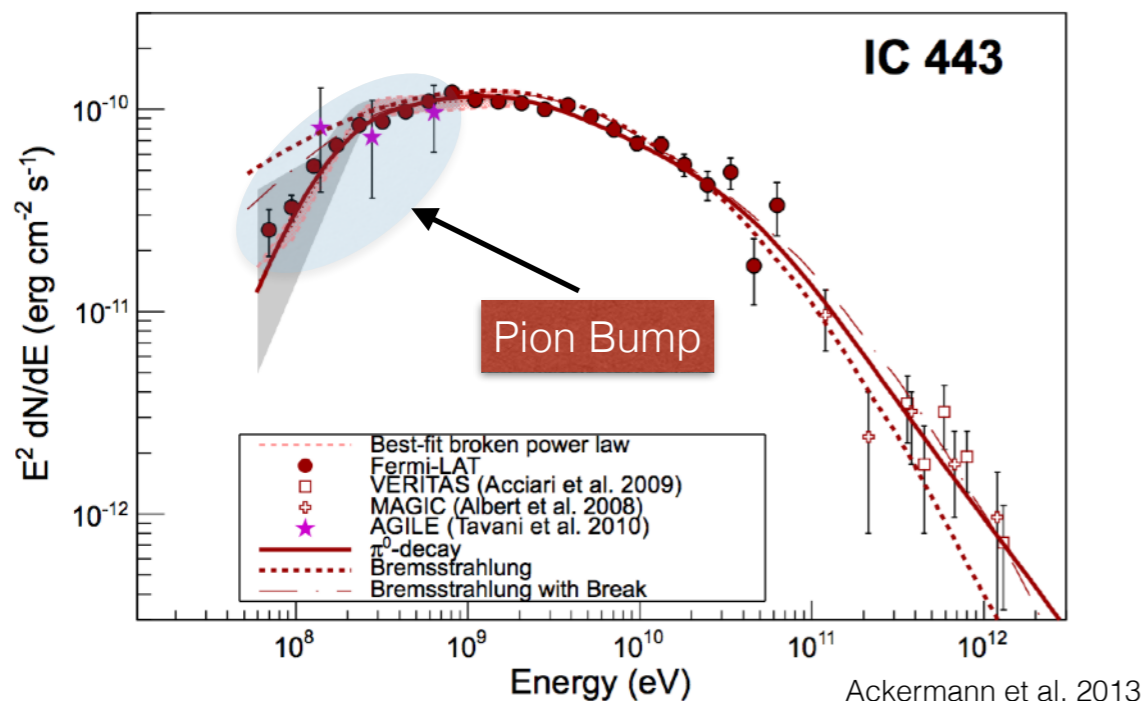


Conclusion: Acceleration of protons up to TeV is required for any scenario, however gamma-ray spectrum still not showing energies up to 100 TeV

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Middle aged SNR: IC 443

- Remnant of core collapse SN evolving in inhomogeneous environment
 - varying amount of target material
- Interacting with a molecular cloud (average density of particles $\sim 200 \text{ cm}^{-3}$)
- Distance of 1.5 kpc, 0.75°
- Age uncertain, 3-30 kyr



http://en.wikipedia.org/wiki/Jellyfish_nebula

Observations

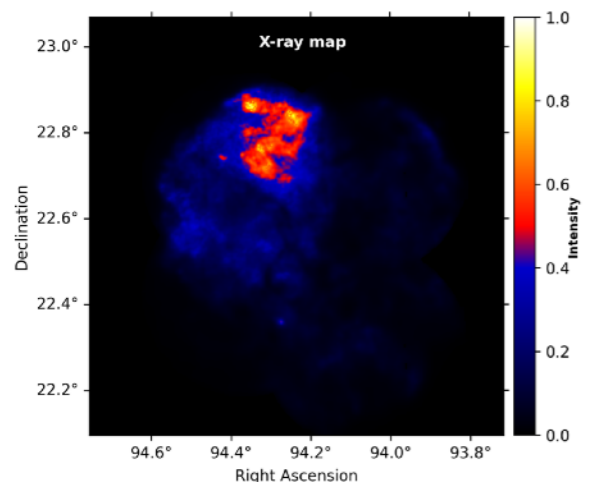
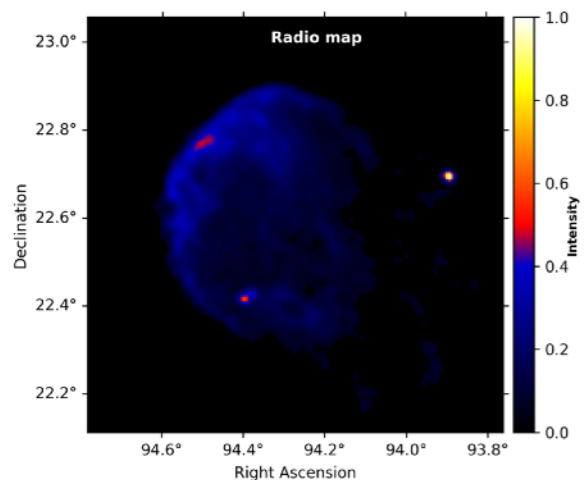
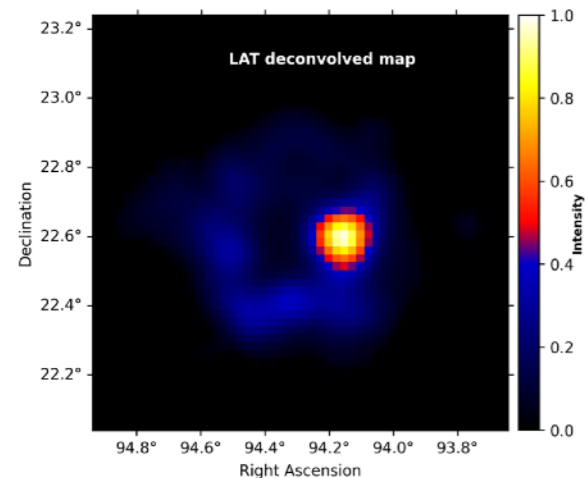
- **Fermi-LAT**

- 10.5 years of data 2008-08-04 to 2019-02-28, pass8r3
- To match VERITAS PSF, events above 5 GeV in two best PSF classes (PSF2, PSF3) are selected

- **VERITAS**

- 155 hours of quality data
- To improve angular reconstruction, events with images in at least three telescopes are selected
- Energy threshold ~ 180 GeV

Templates used

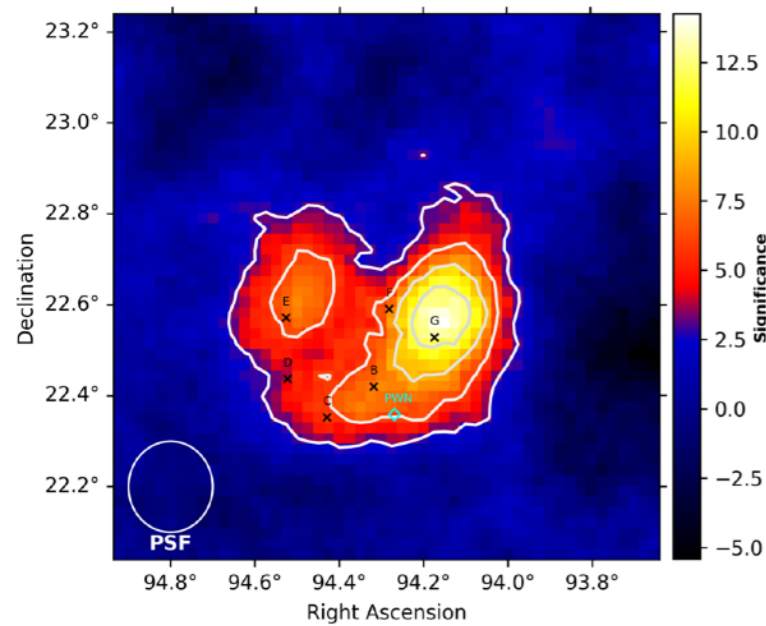


- Choose different spatial templates to understand morphology of IC 443 emission
- Akaike information criterion = $2k - TS$ is used to find the best-fit model
- **LAT deconvolve** model is the best model

Spatial model	$\ln \mathcal{L}$	TS	k	Δ AIC	Ref.
Null	-15070.437	-	-	-	
LAT deconvolution	-10729.047	8682.780	3	-17359.560	
LAT 4 regions	-10725.472	8689.930	12	-17355.860	
Point source	-12660.859	4819.156	3	-9632.312	
Uniform disk	-10882.574	8375.726	3	-16745.452	
Gaussian	-10839.263	8462.348	3	-16918.696	
Gaussian+Point source	-10781.674	8577.526	5	-17145.052	
HCO+ template	-11545.793	7049.288	3	-14092.576	
X-ray template	-11214.903	7711.068	3	-15416.136	
Radio template	-11198.363	7744.148	3	-15482.296	
VERITAS template	-10889.611	8361.652	3	-16717.304	
IR templates					
X-ray + HCO+	-10951.103	8238.668	6	-16465.336	

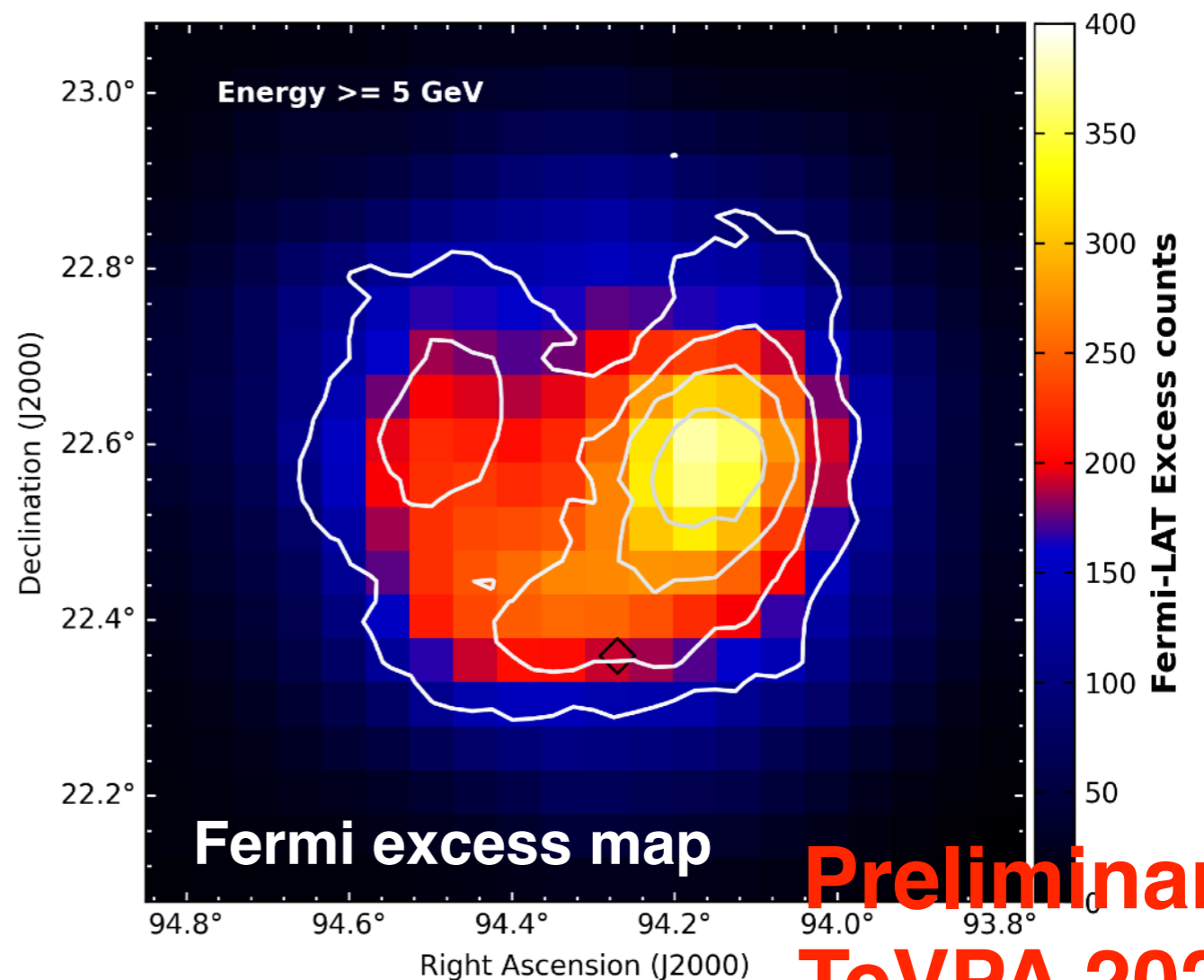
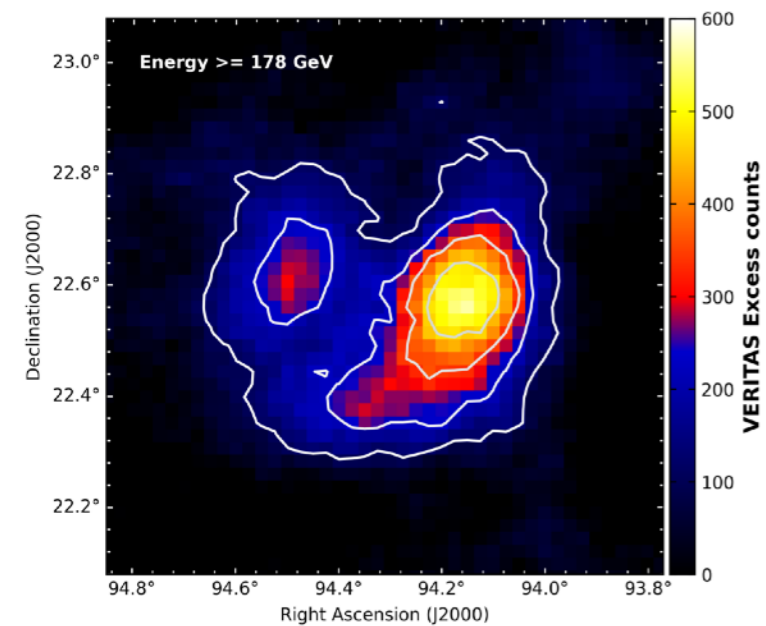
Fermi-LAT and VERITAS skymaps

VERITAS Significance map



- Morphology between TeV and GeV emission matches
- Indicate that same type of particles are producing both GeV/TeV emission

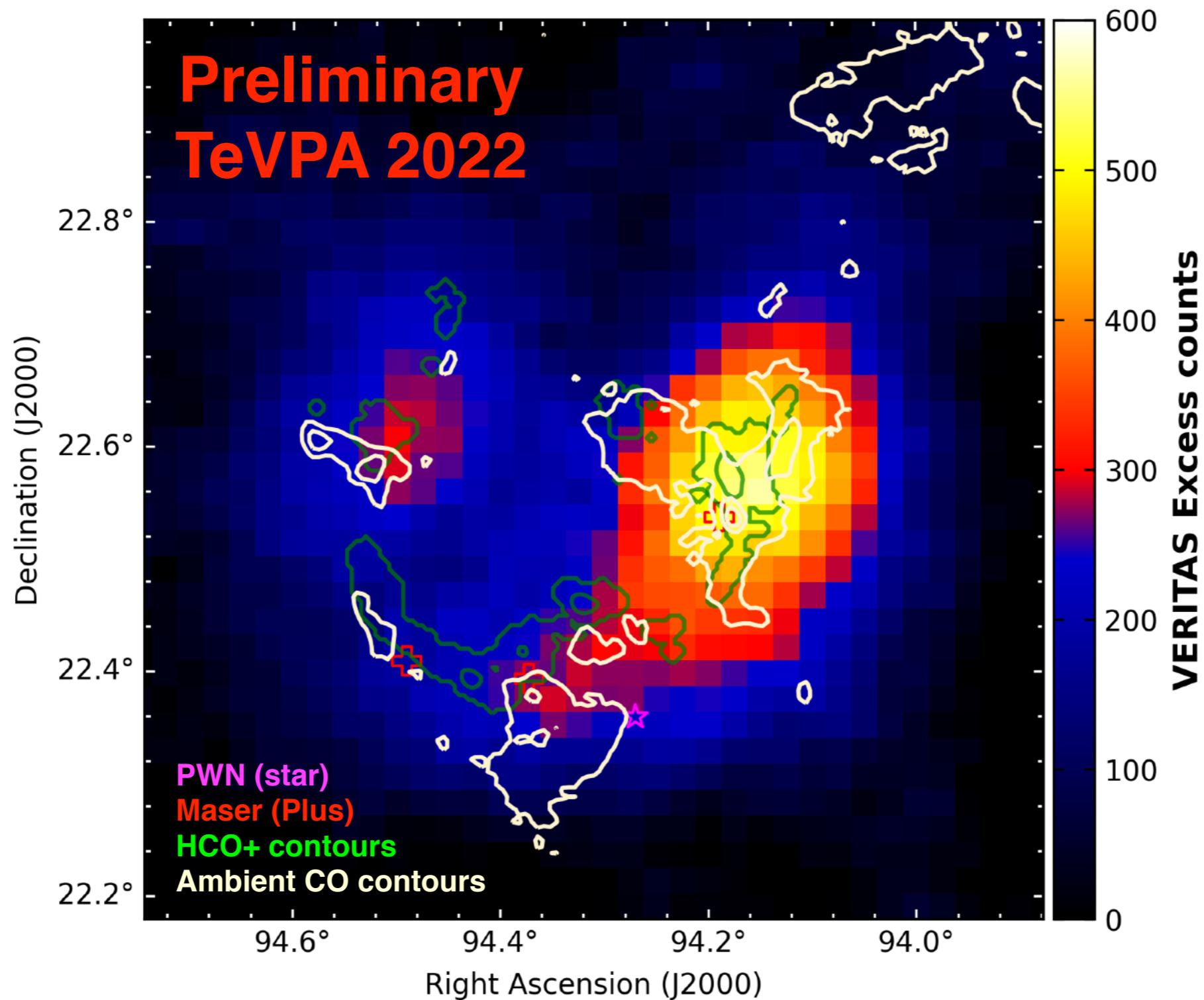
VERITAS excess map



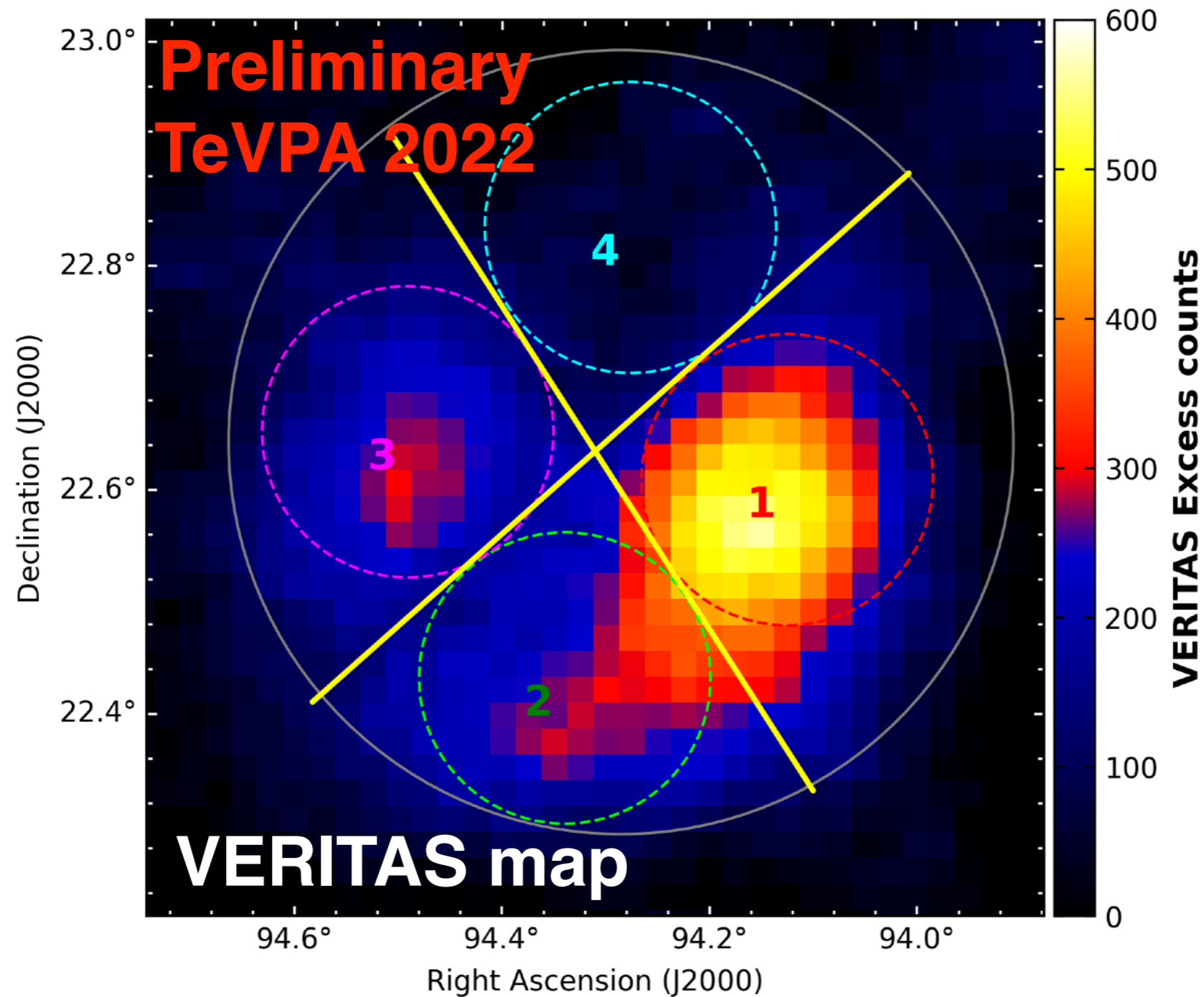
Contours are at 3,6,9 and 12 sigma level from left most plot

Preliminary
TeVPA 2022

Morphology comparison at other wavelengths

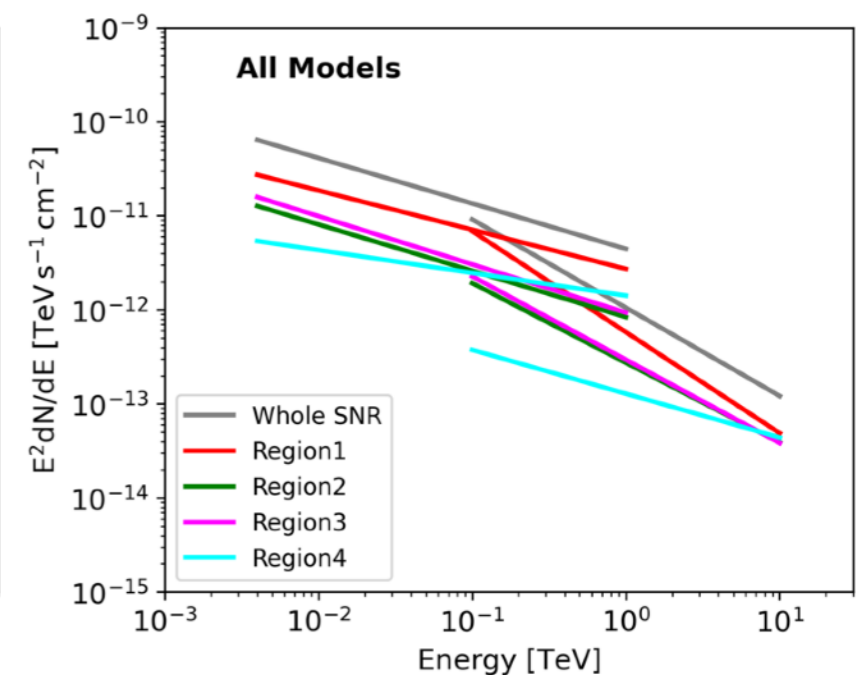
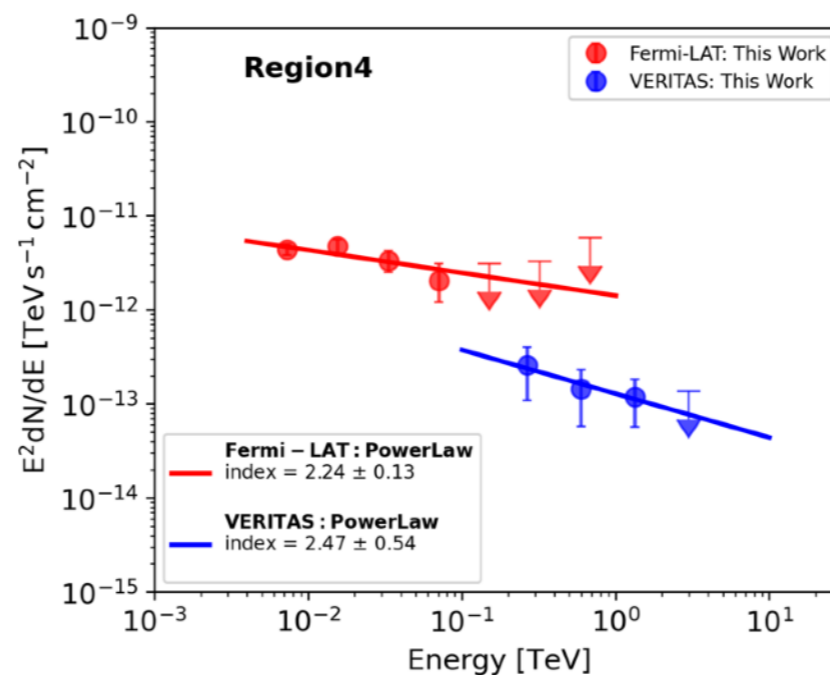
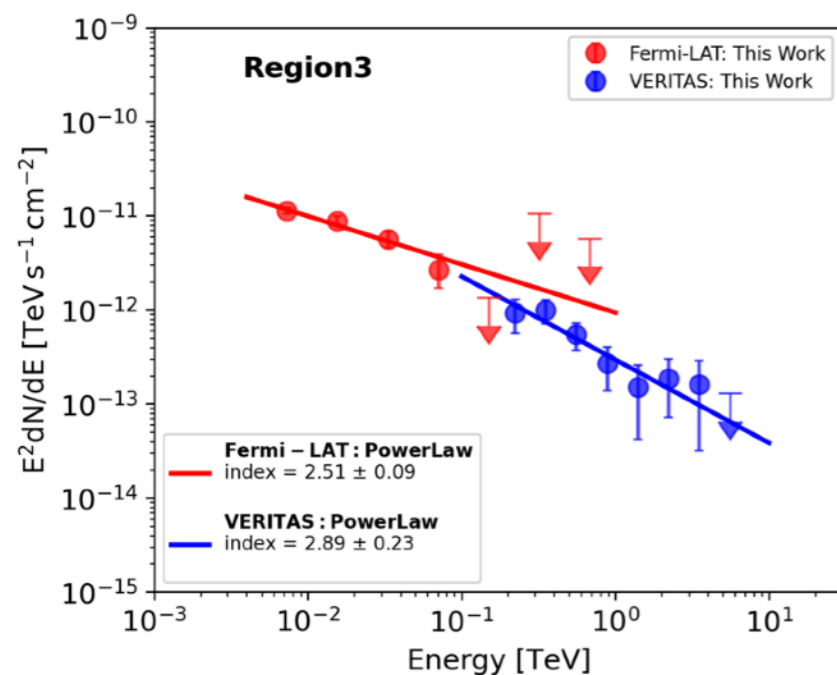
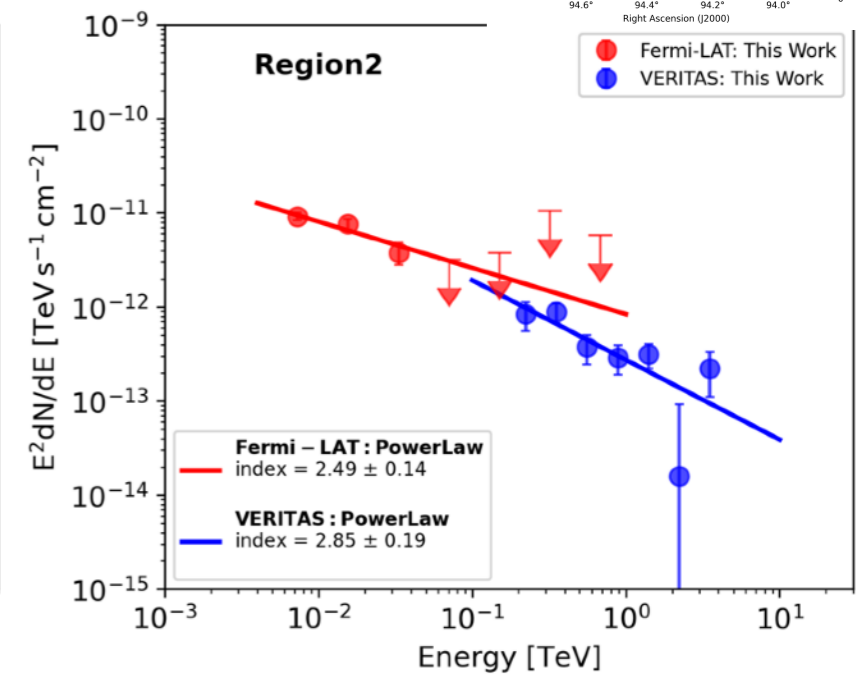
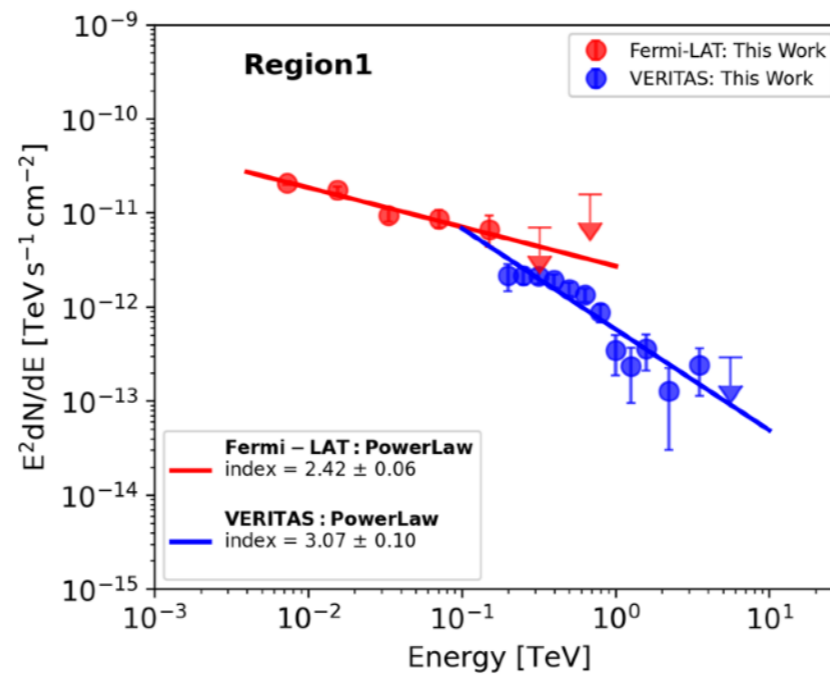
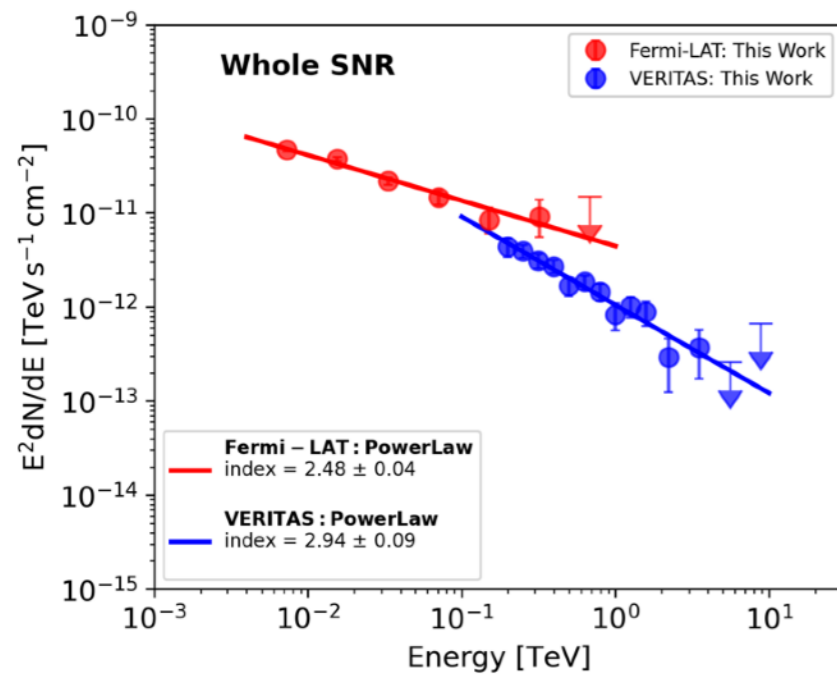
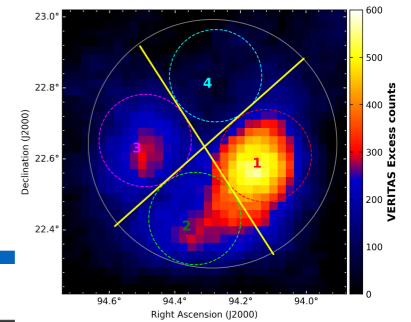


Spectral studies



Spectral Modelling

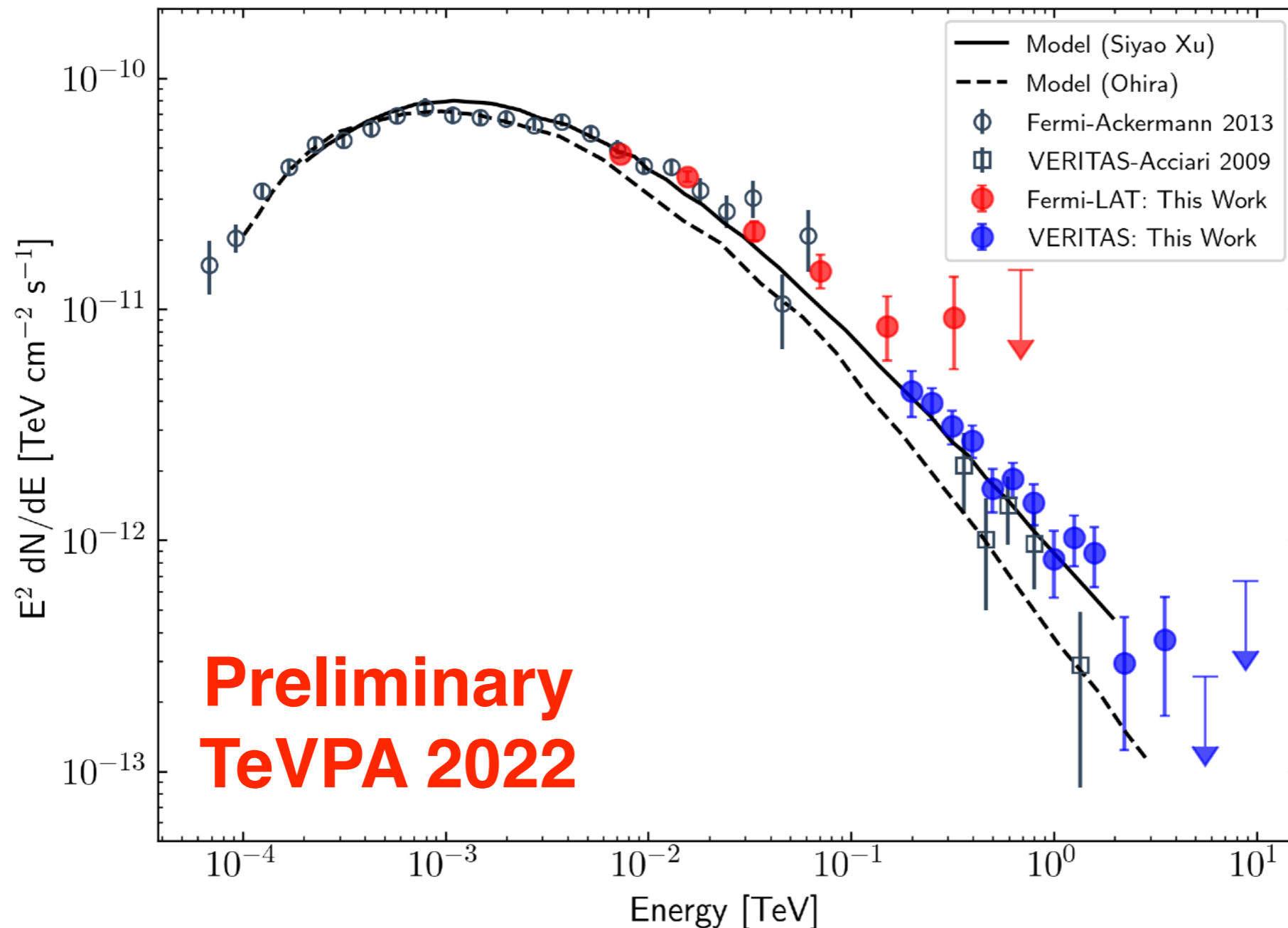
Preliminary
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The spectrum softens from a power-law index of ~ 2.4 in GeV band to ~ 3.0 in the VHE band in each region, and for the entire SNR

Broad band picture for entire SNR

- Smooth rollover of PL index from 2 (GeV) to 3 (TeV)
- Spectrum agrees with model from literature



Summary

- We have a proof of cosmic ray acceleration in SNRs (pion bump in IC 443, Cas A)
 - There is still a lack of evidence of energy reaching 10^{15} eV
- Resolved morphology and getting spectrum from different parts help to understand acceleration mechanism under different environmental conditions

Thank you