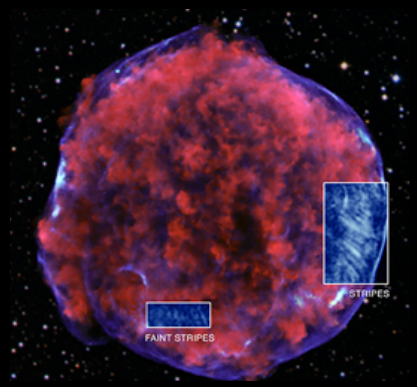
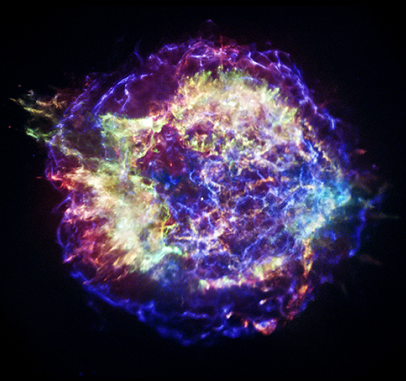
Young and Hard-Spectrum Supernova Remnants with VERITAS





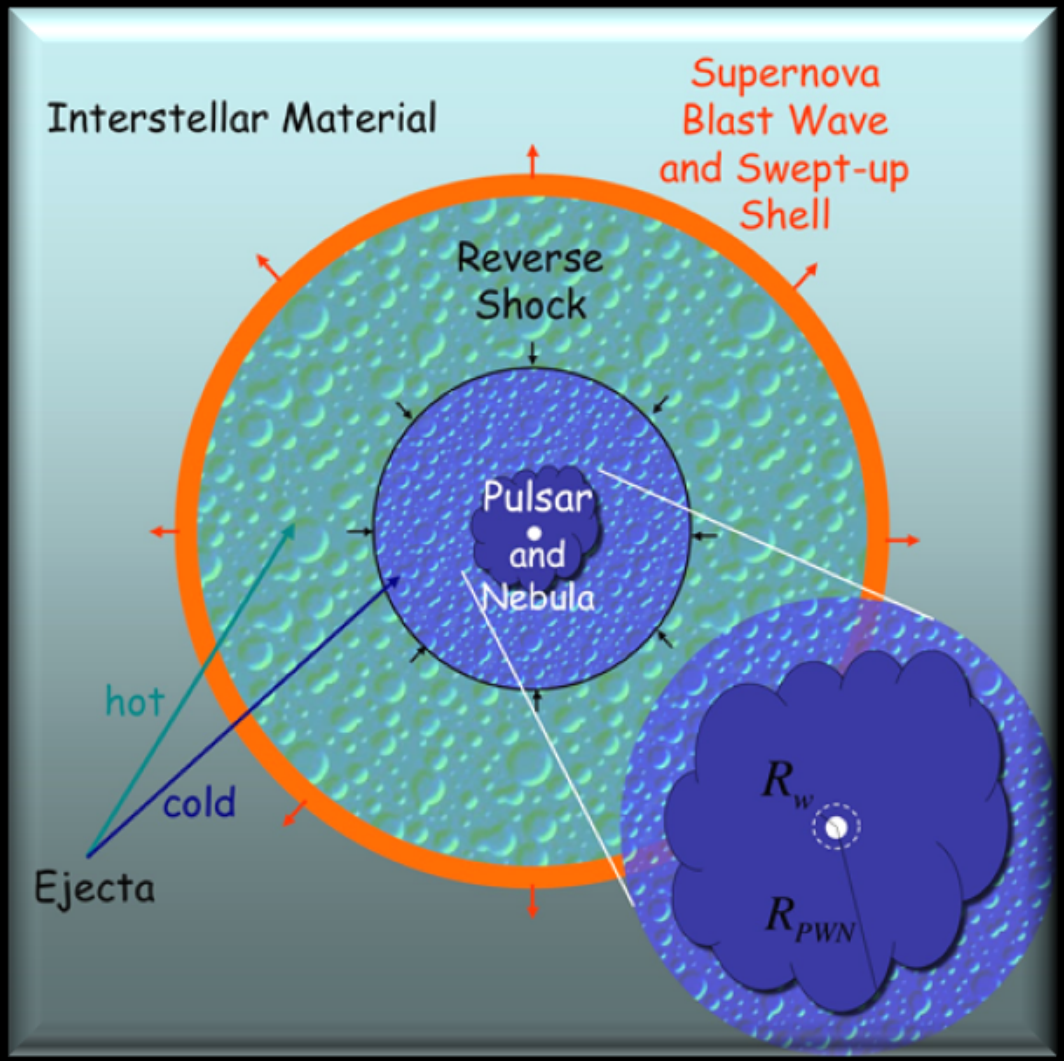
Amanda Weinstein
for the VERITAS Collaboration

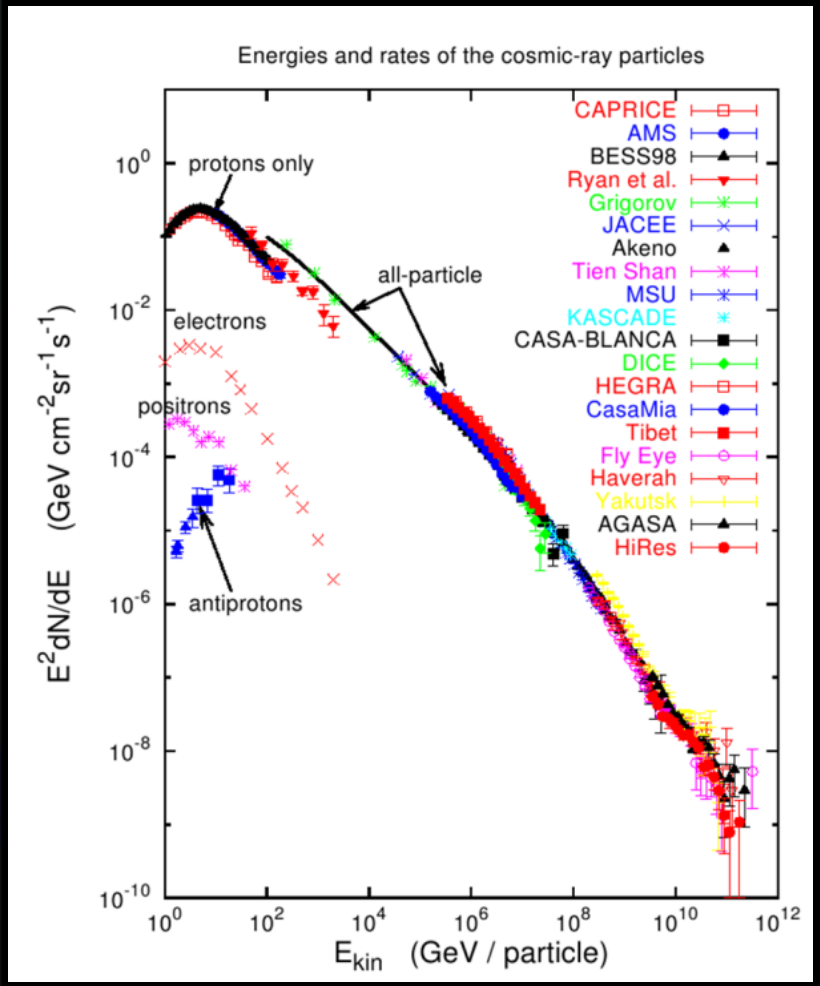
Supernova Remnants: An Odyssey in Space after Stellar Death
June 9, 2016

Overview

- Brief motivation
- Updates on VERITAS observations of two young, historial SNRs
  - Tycho
  - Cas A
- Additional comments

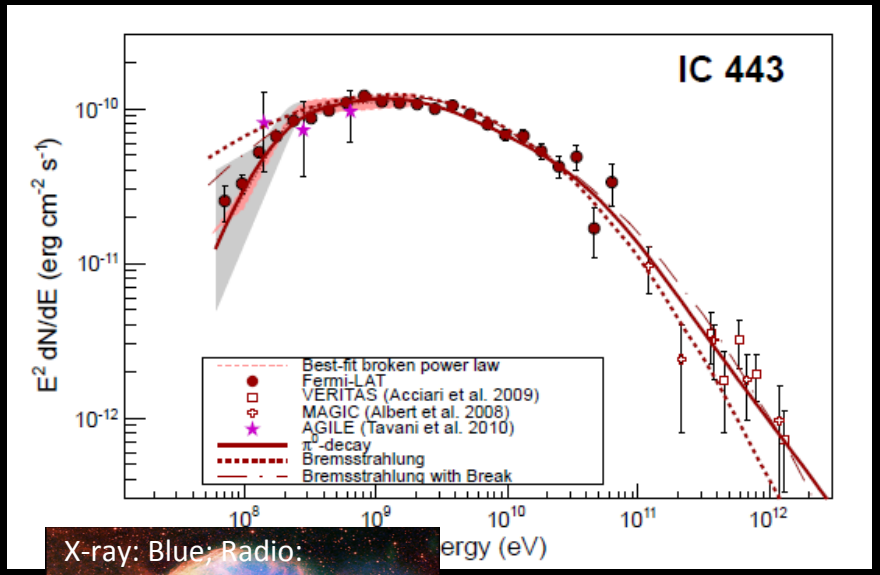
Stellar Death = CR Acceleration?



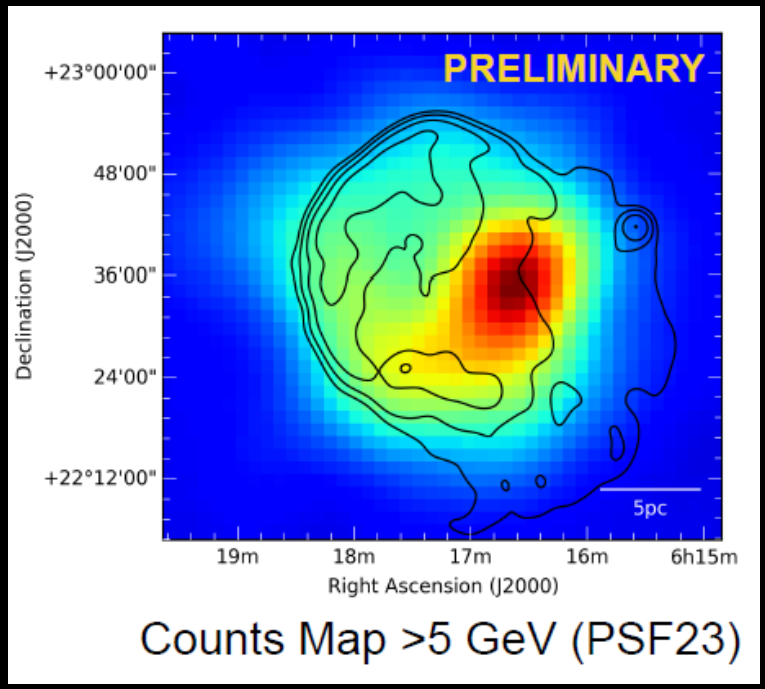


- SNRs favored candidates for CR acceleration below the “knee”

(some) SNRs are hadron accelerators



IC443 and the "pion decay bump"

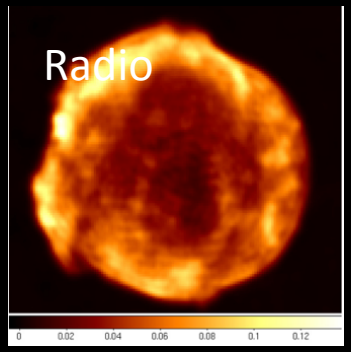


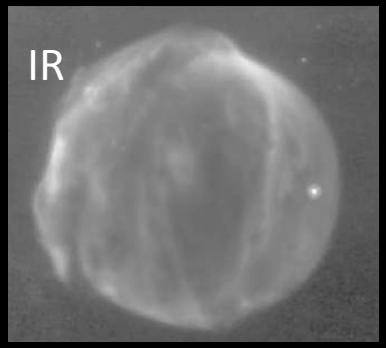
See poster (B. Humensky, S1.9) for detailed update!

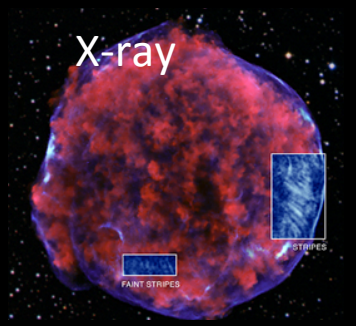
- But gamma-ray spectra of these few middle-aged SNR are steep
  - Highest CR energies generally reached very early on and escape first

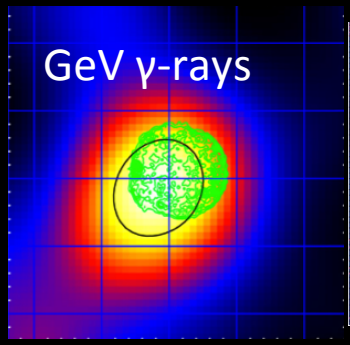
Tycho's SNR

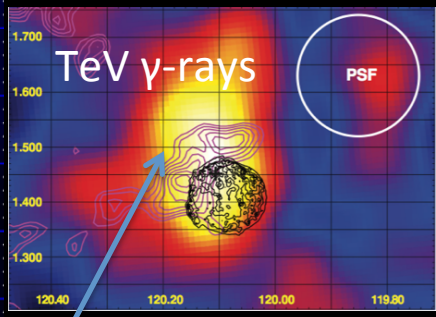
- Historical Type 1a SNR (age: 440 kyr; distance: 2-5 kpc)
  - Well-studied at all wavelengths (radio to gamma rays)
  - Explosion took place in relatively clean environment









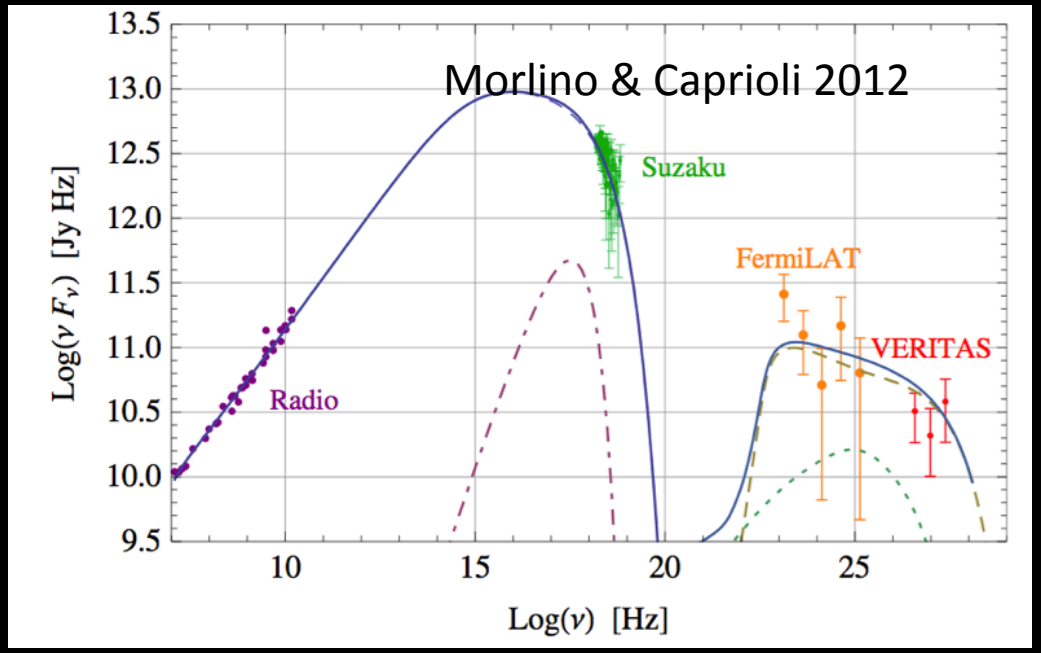


- Broadband spectra
  - Inference of high B fields (S. Reynolds, this meeting)
  - Inference of maximal proton energy

≥5 talks at this meeting

Relationship to molecular cloud to northeast? (Ishihara et al 2010)

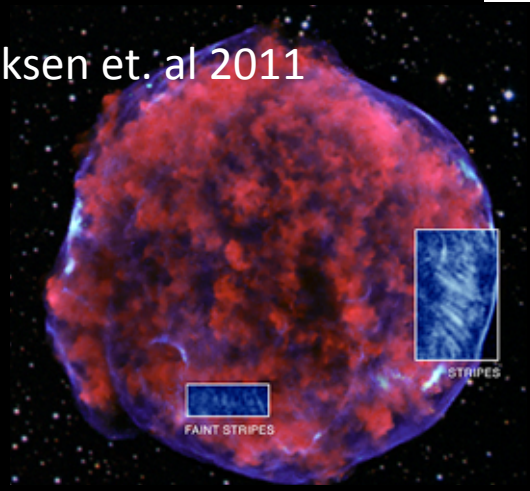
Tycho as Potential PeVatron I



Synchrotron
Thermal e- bremsstrahlung
Pion decay
IC

- Argues for a maximal proton energy of 500 TeV

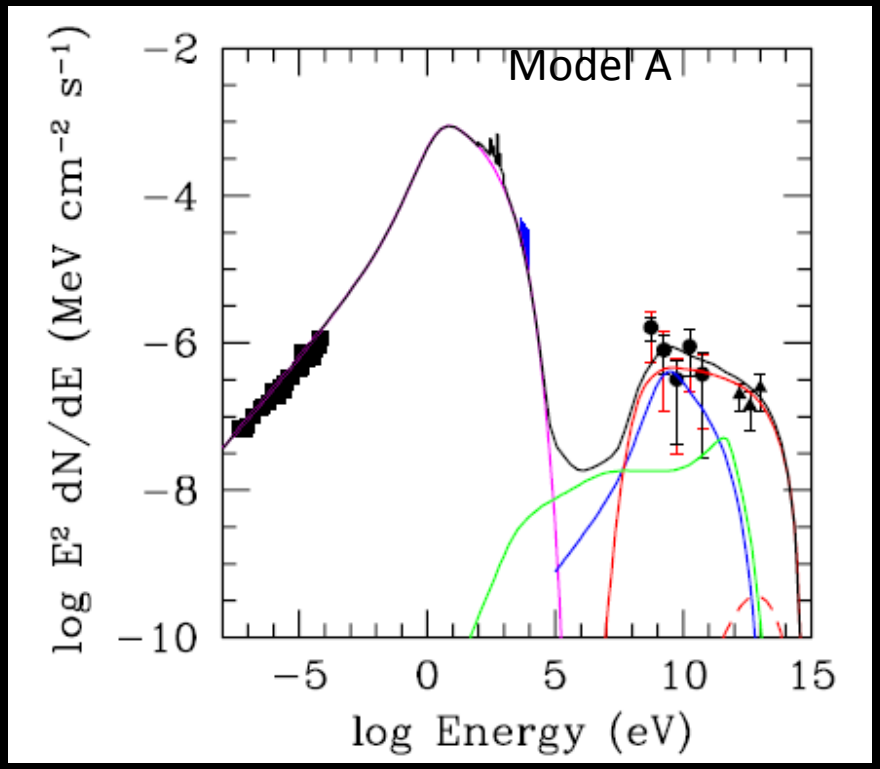
Eriksen et. al 2011



- Spacing of non-thermal striping
  - Gyroradii of 10^{14}-10^{15} eV protons?
  - Anisotropic magnetic turbulence? (Bykov 35 al. 2011)

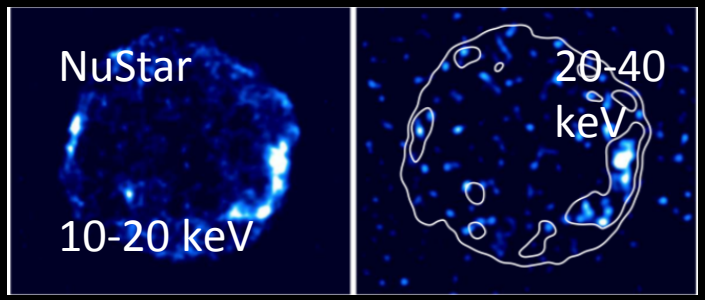
A deeper look

Slane et al. 2014



- One two-zone leptonic model (Atoyan and Dermer 2012)
- Gamma-ray data from Fermi and VERITAS plays a critical role in constraining these models

- Range of models (different handling of ISM, zones,hydrodynamics)
  - Majority do have gamma-ray emission dominated by pion decay
  - Mo, Berezhko et al. 2013, Zhang et al 2013
  - Maximal proton energies ~50 TeV-500 TeV depending on model
- X-ray data suggests lower numbers?



Lopez et al 2015

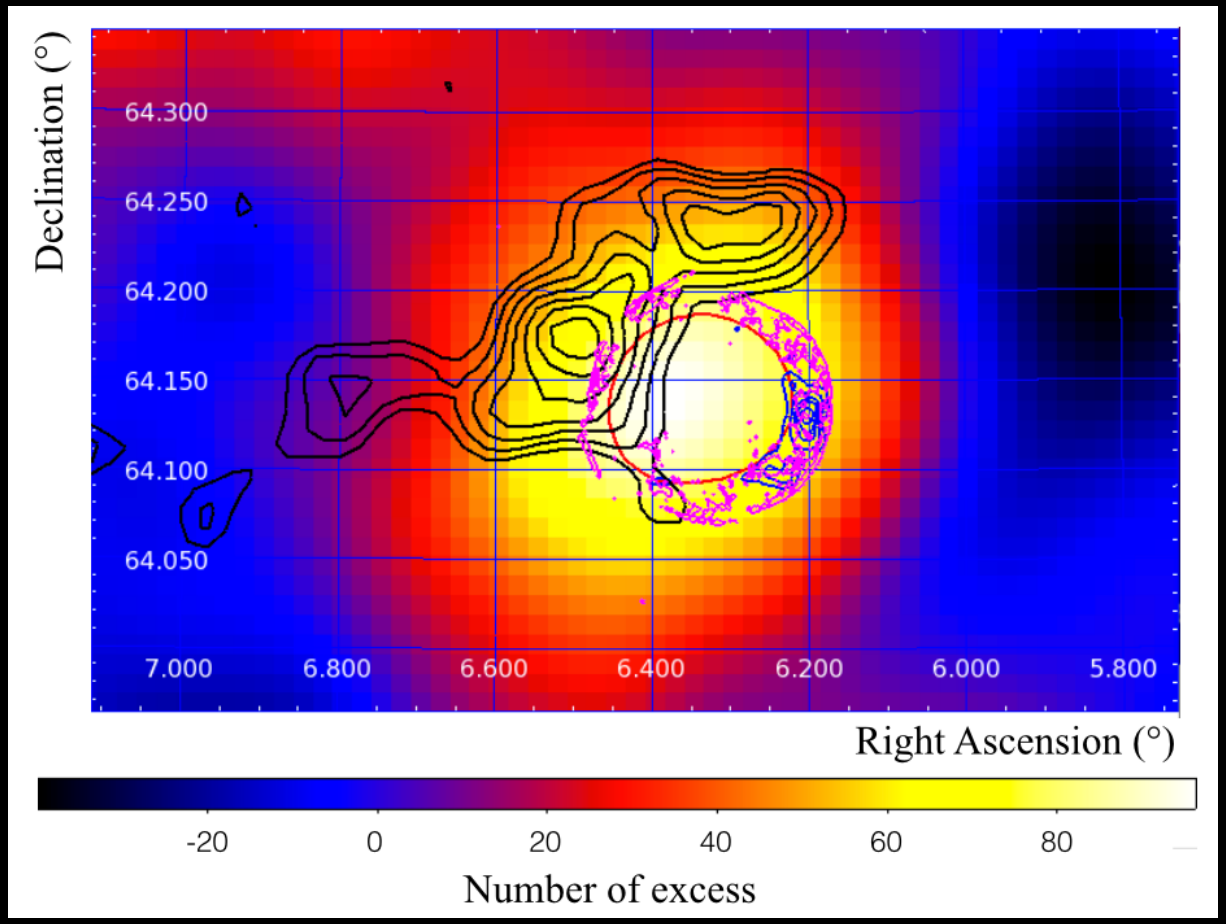
Updated Results: Tycho's SNR

- Program of deep VERITAS observations (150 Hours)
  - More recent VERITAS observations (~74 hours) have a signficantly lower energy threshold
  - Extended spectral measurement down to 400 GeV
- Combined with larger and improved Fermi-LAT dataset
  - 77 months of Pass 7 reprocessed data using 3FGL catalog
  - Consistent with past results
    - 100 MeV < E < 300 GeV : power-law with index of $1.8 \pm 0.2_{stat} \pm 0.1_{sys}$
    - 300 MeV < E < 300 GeV : power-law with index of $2.3 \pm 0.2_{stat} \pm 0.1_{sys}$

Tycho Update: Morphology

- No strong indication of energy dependence in centroid

No evidence of MC illumination in GeV or TeV

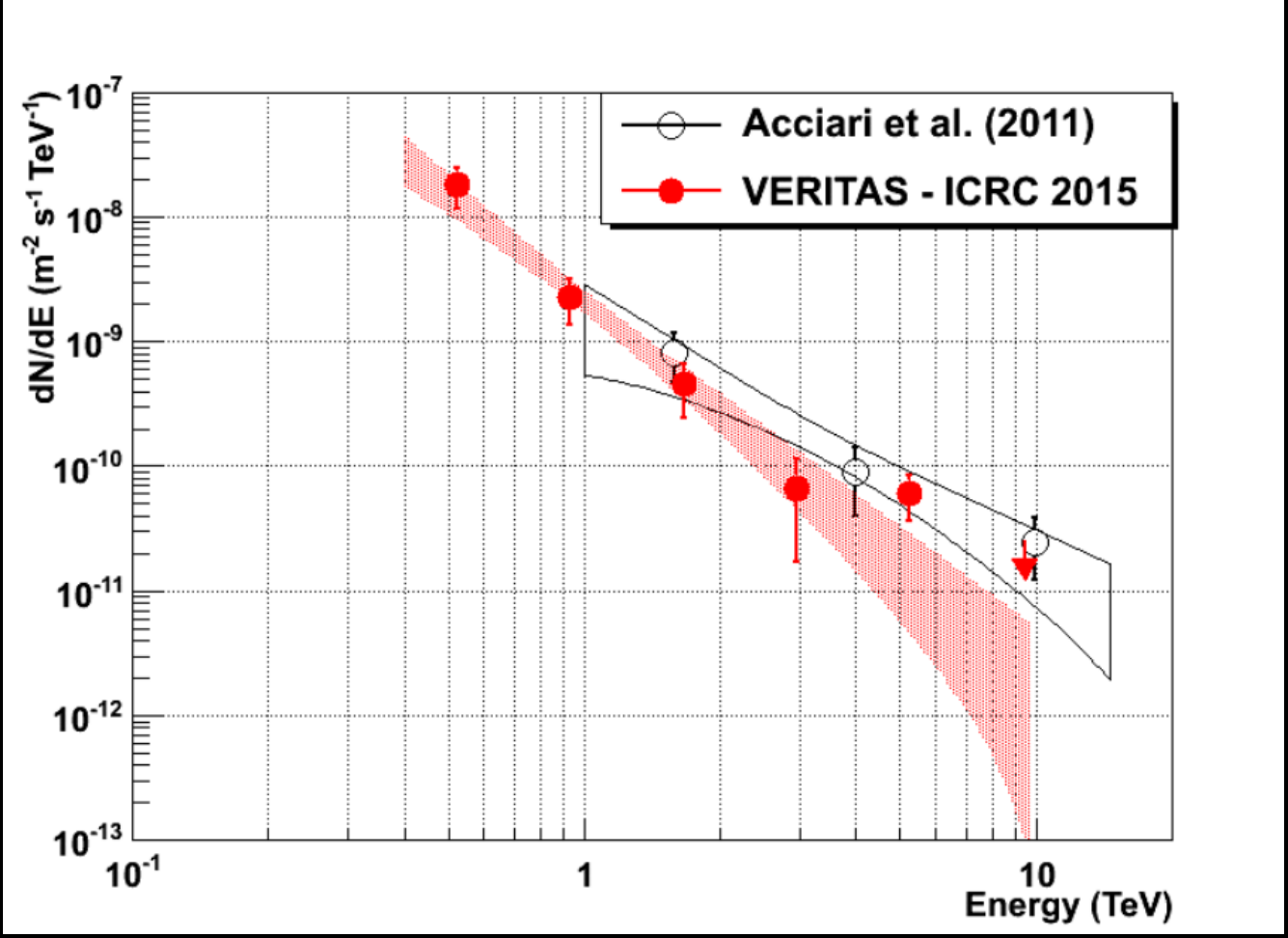


CO cloud / X-ray (Chandra, E>4.1 keV) / X-ray (NuSTAR, 20 keV<E<40 keV)/ Red (Fermi, 95% C.L. centroid, this study)

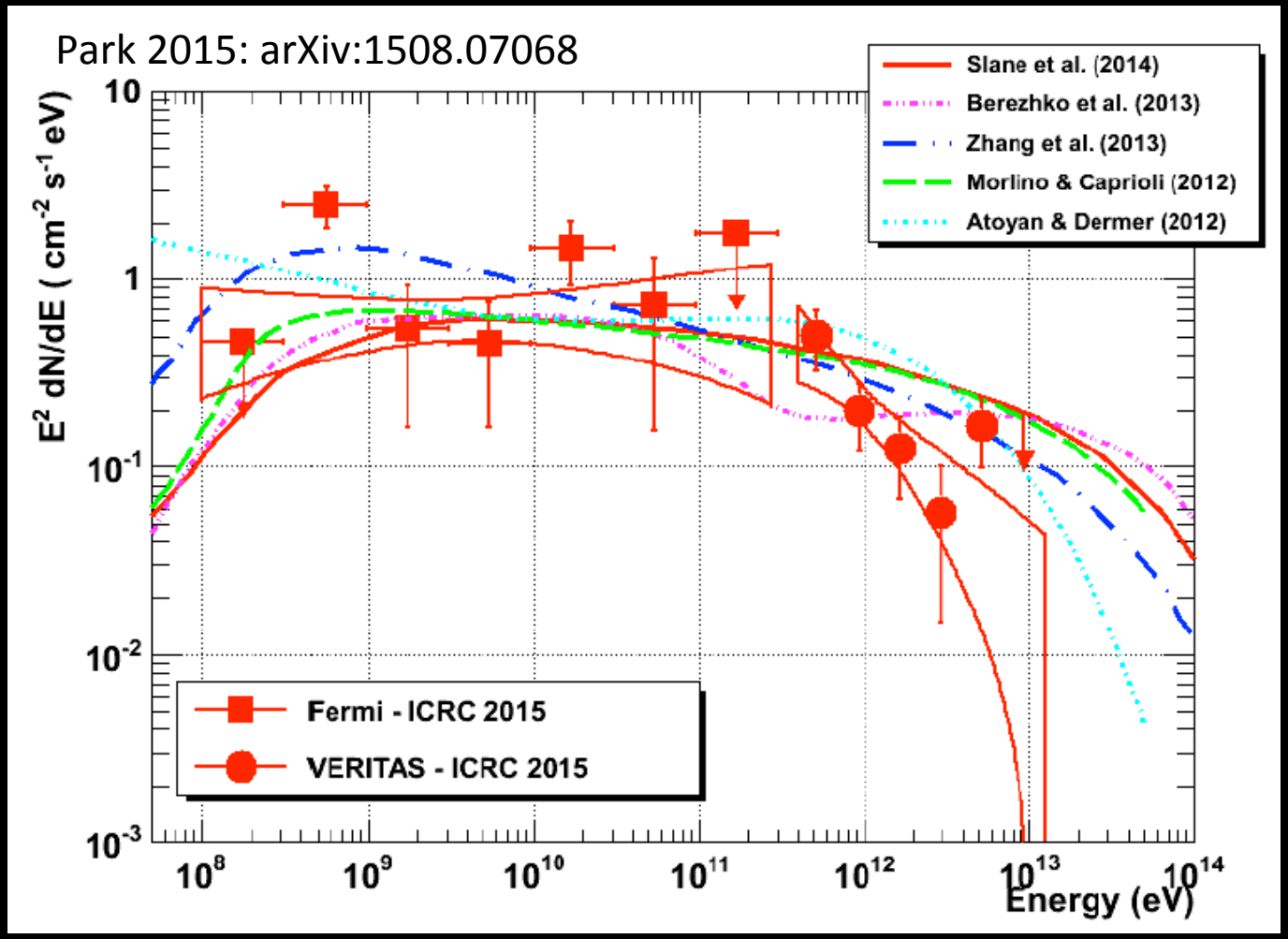
(^{12}CO: FCRAO survey; Heyer et 1998)

Updated Tycho Spectrum

- New power law index: $2.92 \pm 0.42_{stat}$, 0.8% Crab (E > 400 GeV)
- Old power law index: $1.95 \pm 0.51_{stat} \pm 0.30_{sys}$



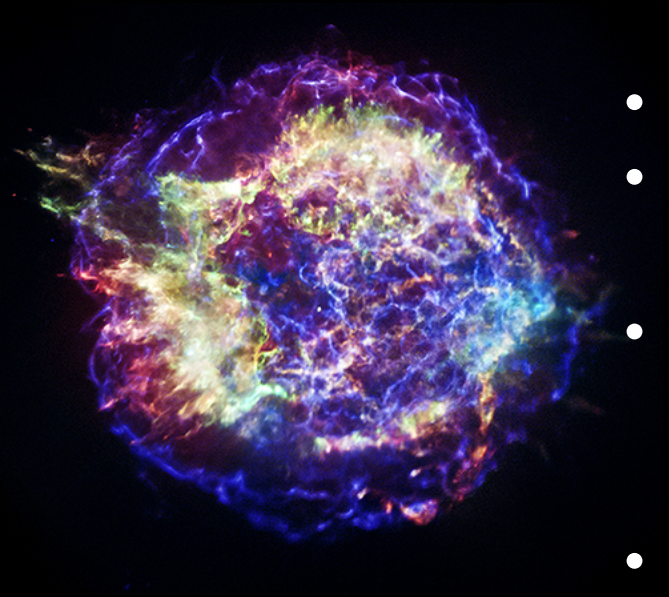
Tycho Spectrum: New Model Constraints



- Deep VERITAS observations in tension with all extant models

Cas A

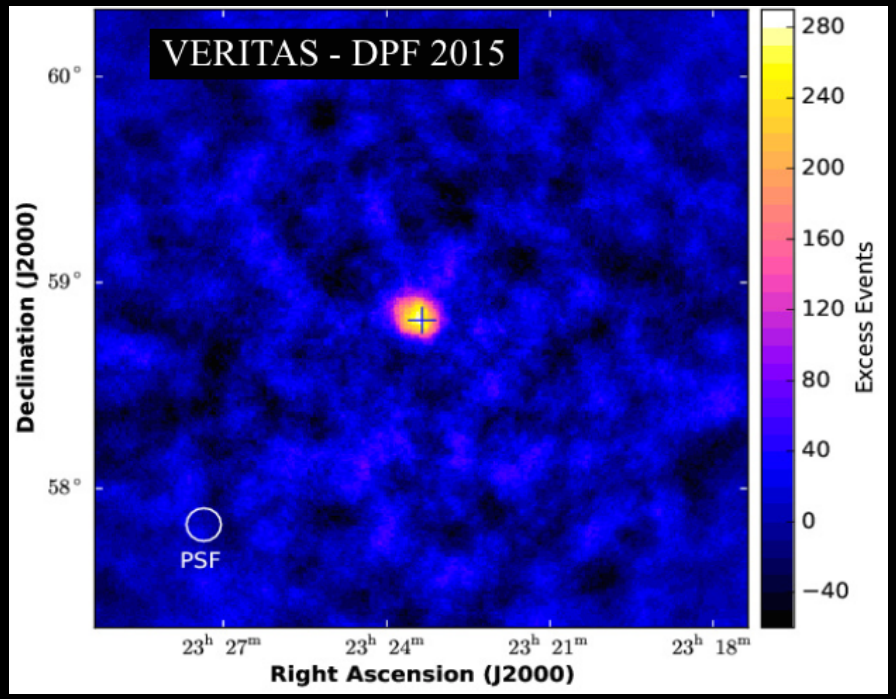
- 350 yr old remnant bright in radio, X-rays, and gamma rays (HE and VHE)
- Core-collapse supernova, Type IIb

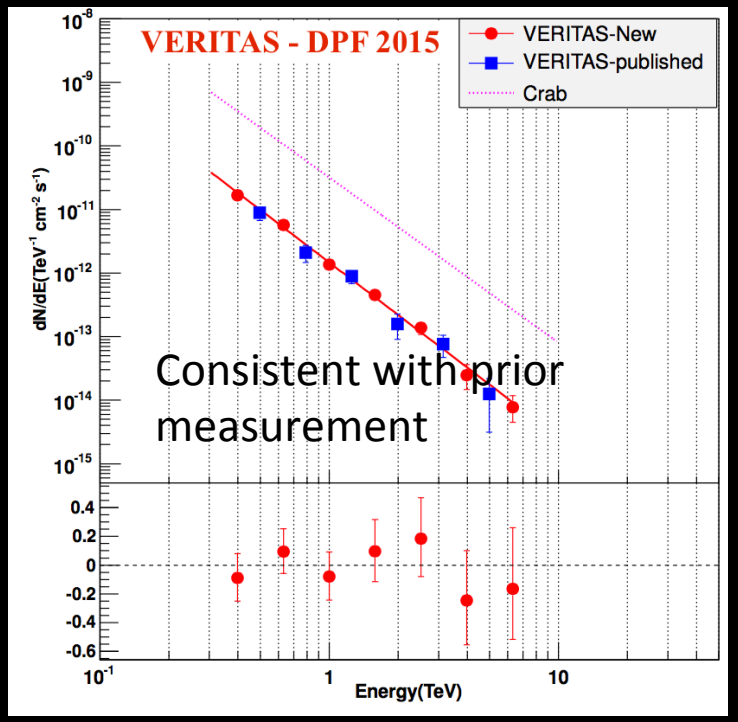


≥4 talks at this meeting

- Close (~3.4 kpc)
- Also extremely-well studied at most wavelengths
- Bright ring dominates radio emission, thought to be associated with reverse shock
- CO line emission broadening (Spitzer) suggests interaction between shock front and molecular clouds

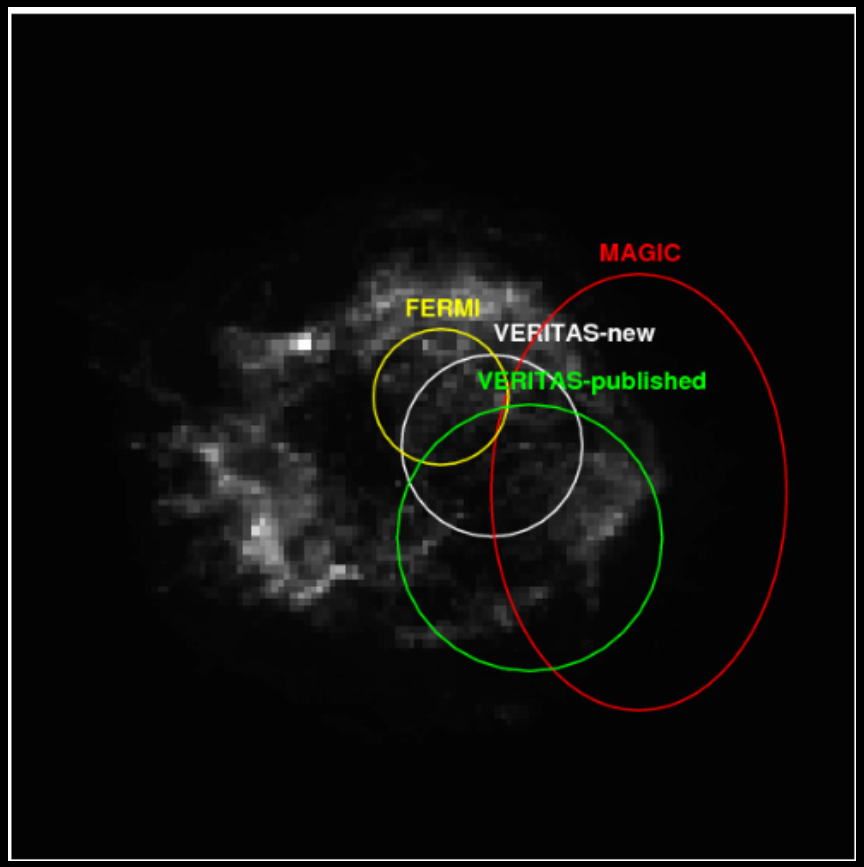
Deep VERITAS observations of Cas A





- Triple previously published VERITAS exposure (now ~60 hrs)
- A substantial fraction of dataset taken at large zenith angle to boost effective area above a few TeV
- Centroid: $23^h23^m20.4^s \pm 0^\circ.006_{stat} \pm 0^\circ.014_{sys}$ $+58.817 \pm 0^\circ.006_{stat} \pm 0^\circ.014_{sys}$

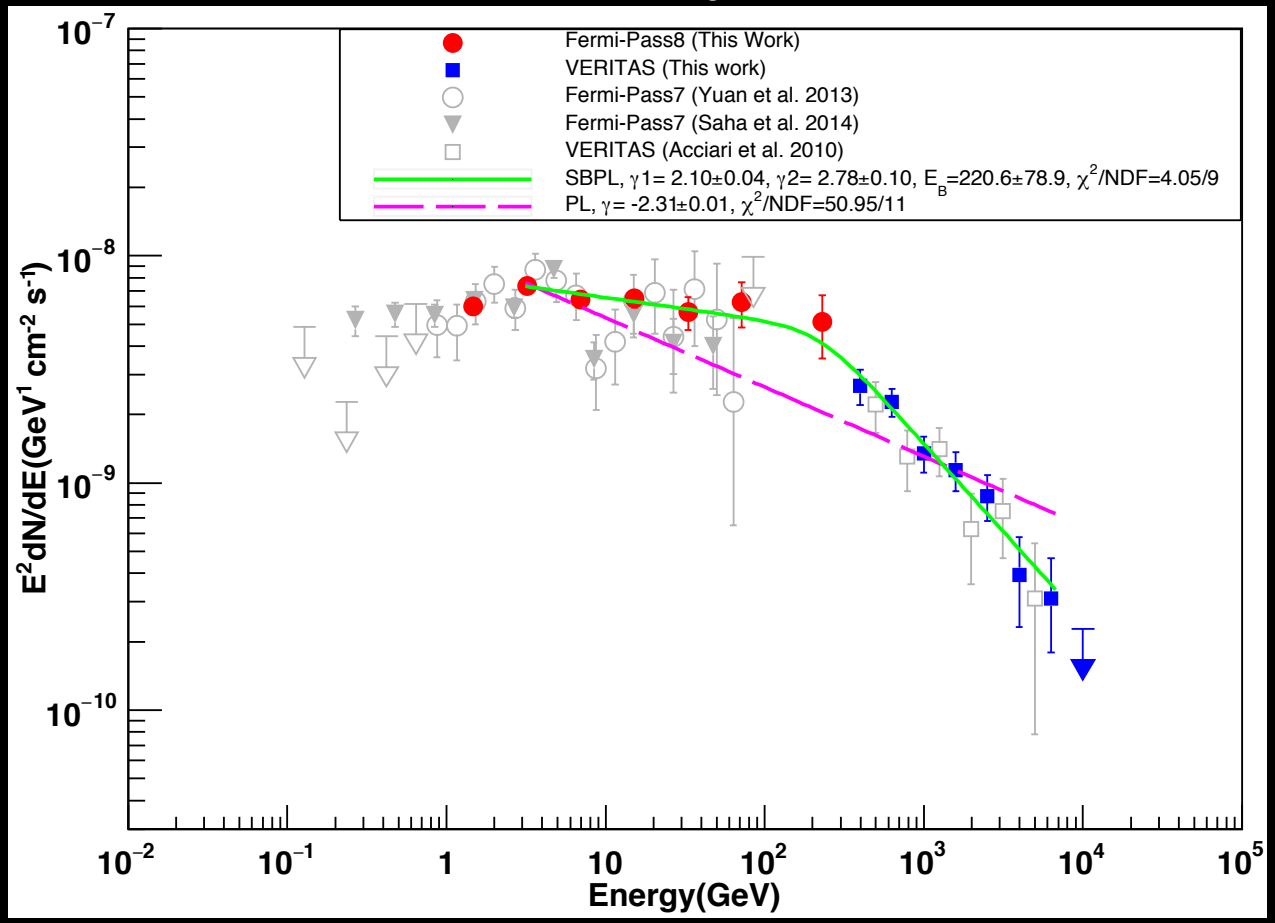
Cas in VHE Y-rays: updated position



- Comparison of centroids from Fermi, VERITAS, and MAGIC, overlaid on *Chandra* map

- Centroid: $23^h23^m20.4^s \pm 0^\circ.006_{stat} \pm 0^\circ.014_{sys}$ $+58.817 \pm 0^\circ.006_{stat} \pm 0^\circ.014_{sys}$
- Now limited by systematics in the telescope pointing (50 arcseconds)

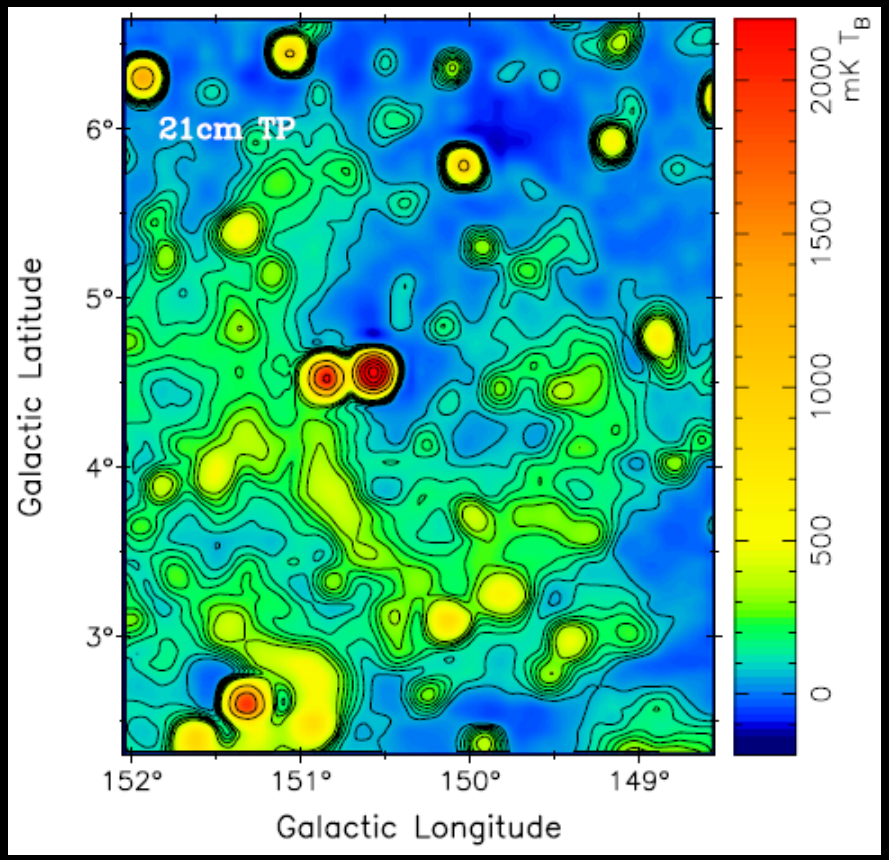
Cas A Spectrum



- Broken power law model favored at the >4.9 σ level over a single power law (3.5 σ after accounting for syst. uncertainties)
- Modeling in process---extension to lower and higher energies promise strong constraints on models.

New Target of Opportunity: G150.3+4.5

Gao and Han, A&A 567, A59 (2014)

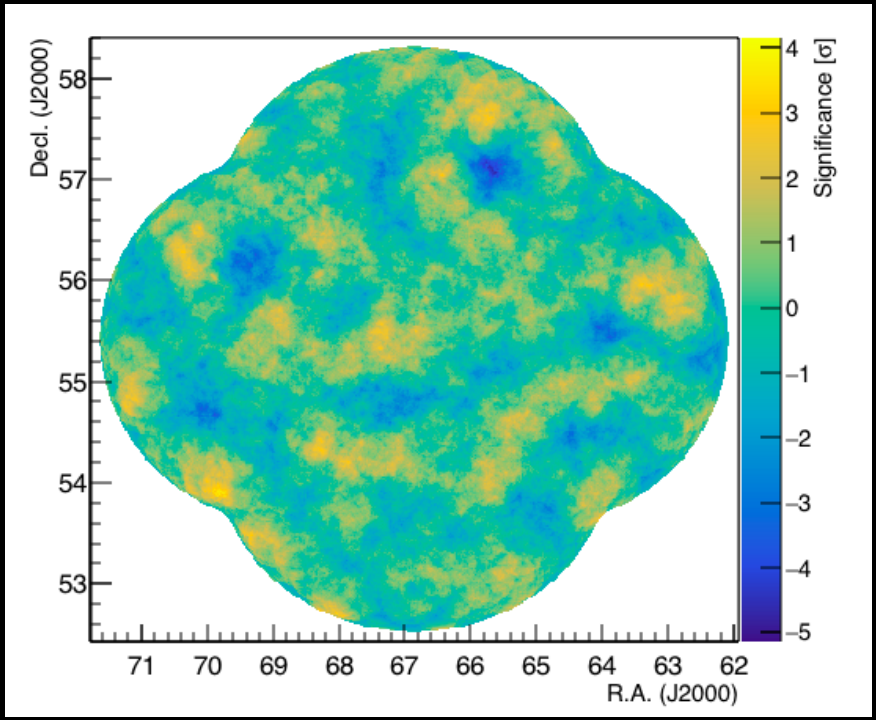


- Very large radio SNR (2.5°x3°): seen in 6, 11, 21, 74.5 cm
- Co-located hard PL spectrum ($\Gamma \sim -1.9$) gamma-ray source of similar extent between 10 GeV and 2 TeV (M.H. Grondin, this conference)
- TeV detection challenging due to large size
- Not very well characterized in X-rays

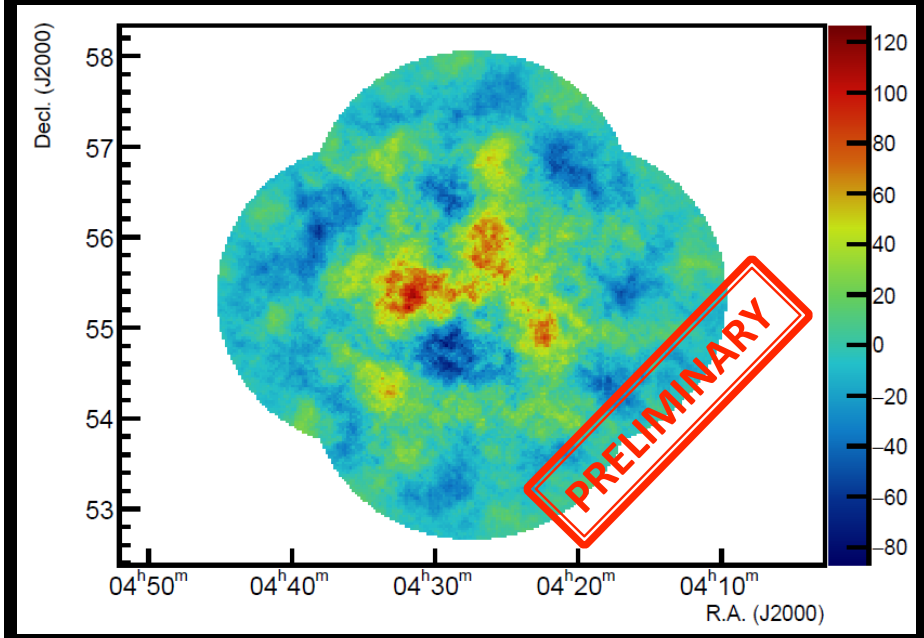
2FHL J0431.2+5553E: Toy Monte-Carlo

- ~20 hours of **simulated** VERITAS(like) observations (500 GeV – 5 TeV)

NO ACTUAL DATA WAS HARMED IN THE MAKING OF THIS SLIDE



Skymap: Standard Ring Background Method
No detection



Skymap: Maximum likelihood method
Significant detection for 1000 separate toys
Recover spectral parameters to 10-15%

Summary

- Successful program of deep VERITAS observations of Tycho and Cas A

- Strong constraints on emission models
  - ➨ Tension between extant models and Tycho spectrum

- Even young SNR have steep VHE spectra
  - ➨ Looking too late and/or too early
  - ➨ A hard-spectrum gamma-ray SNR like G150.3+4.5 could have much to tell us

BACKUP

The VERITAS Instrument

Specifications:

- Energy range: ~85 GeV to ~30 TeV
- Energy resolution ~ 15 % at 1 TeV
- Angular resolution (68% containment): <0.1^{o} at 1 TeV, 0.14^{o} at 200 GeV
- Source location accuracy: <50 arcseconds

Instrument design:

- Four 12-m imaging atmospheric Cherenkov telescopes
- 499-pixel cameras (3.5° FoV)
- FLWO,Mt. Hopkins, Az (1268 m)

Sensitivity:

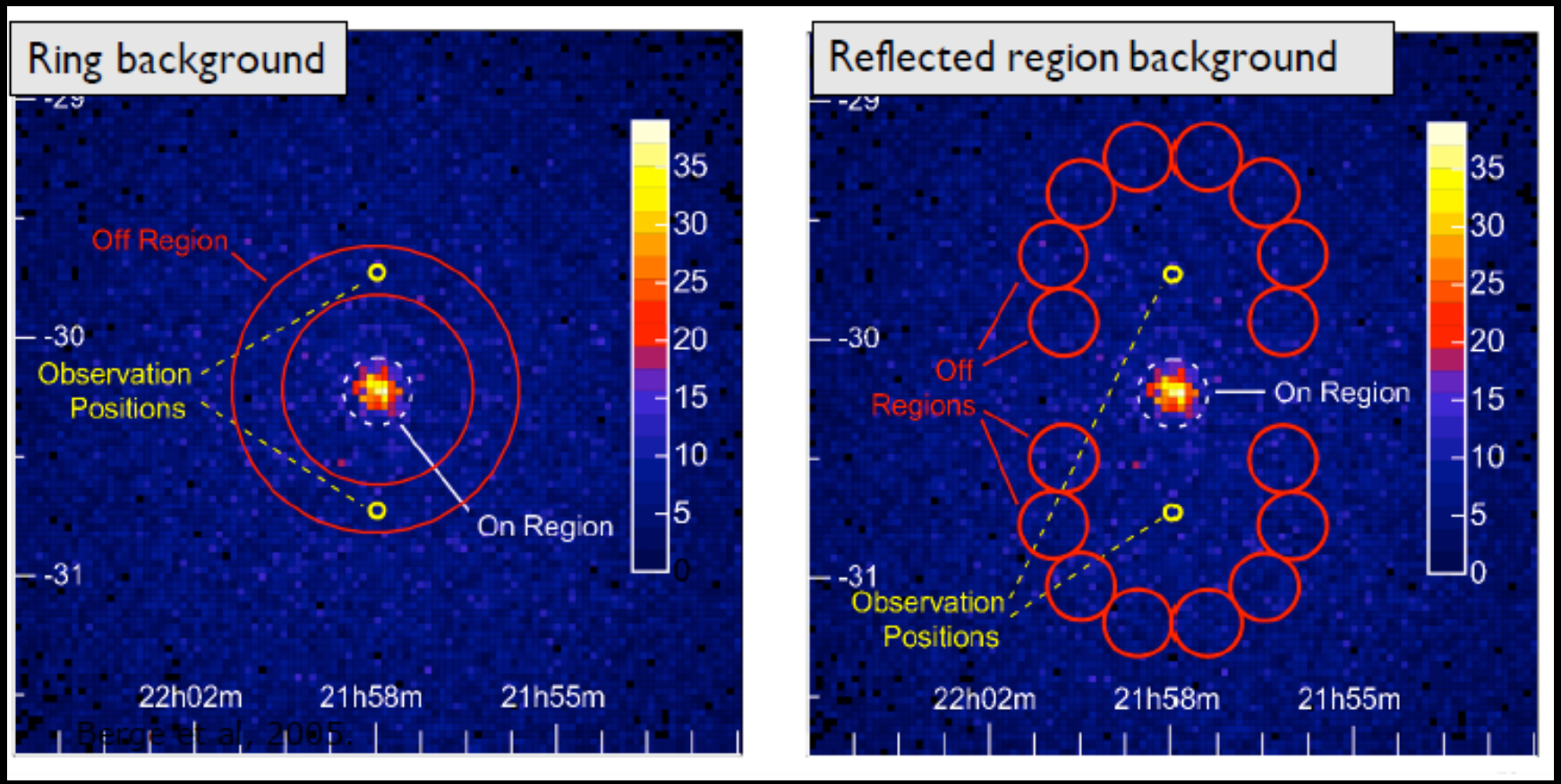
- 1% Crab in < 30 hrs
- 10% Crab in < 30 min

Yearly observing (good weather):

- **Dark time ~800 hours**
- **Moonlight ~400 hrs additional**

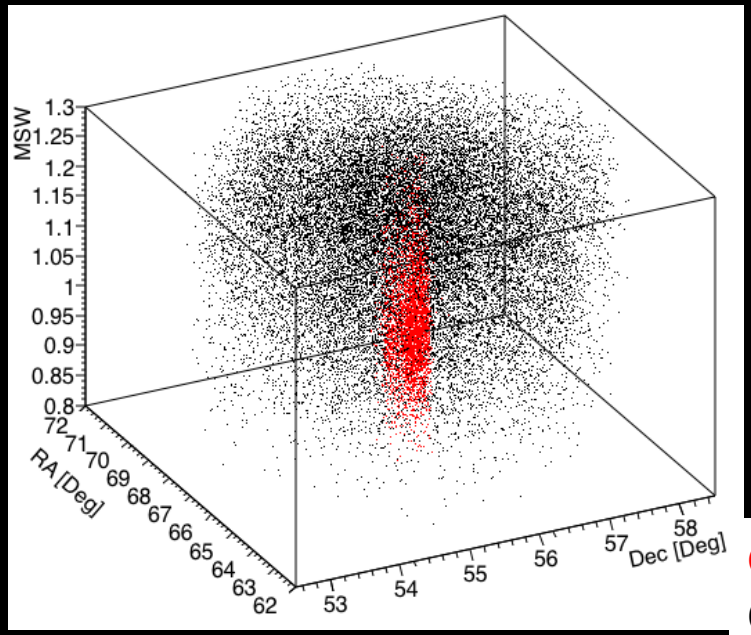
Supported by: NSF/DOE/Smithsonian, SFI(Ireland), NSERC(Canada), STFC (UK)

Large Sources are Challenging

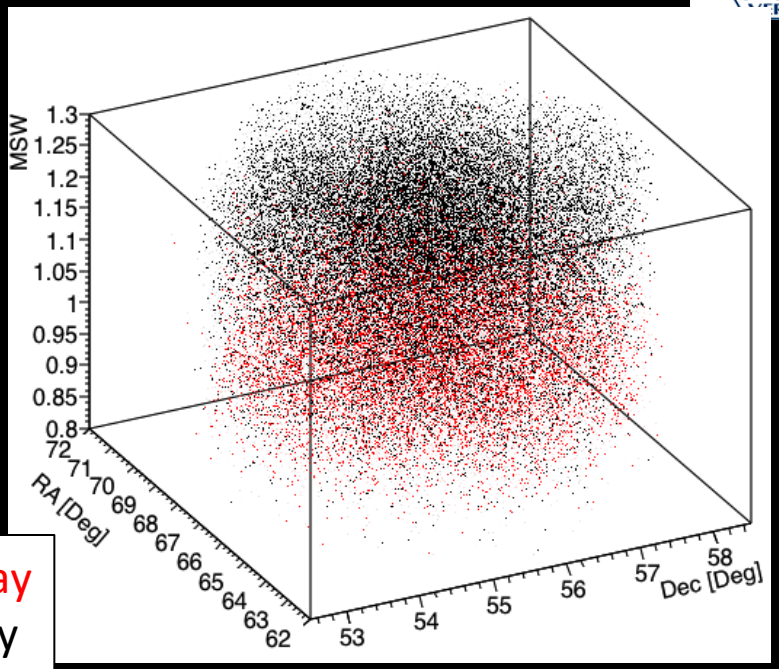


VERITAS standard analysis approaches rely on a region of the field of view away from the source to estimate background

“3D” approach

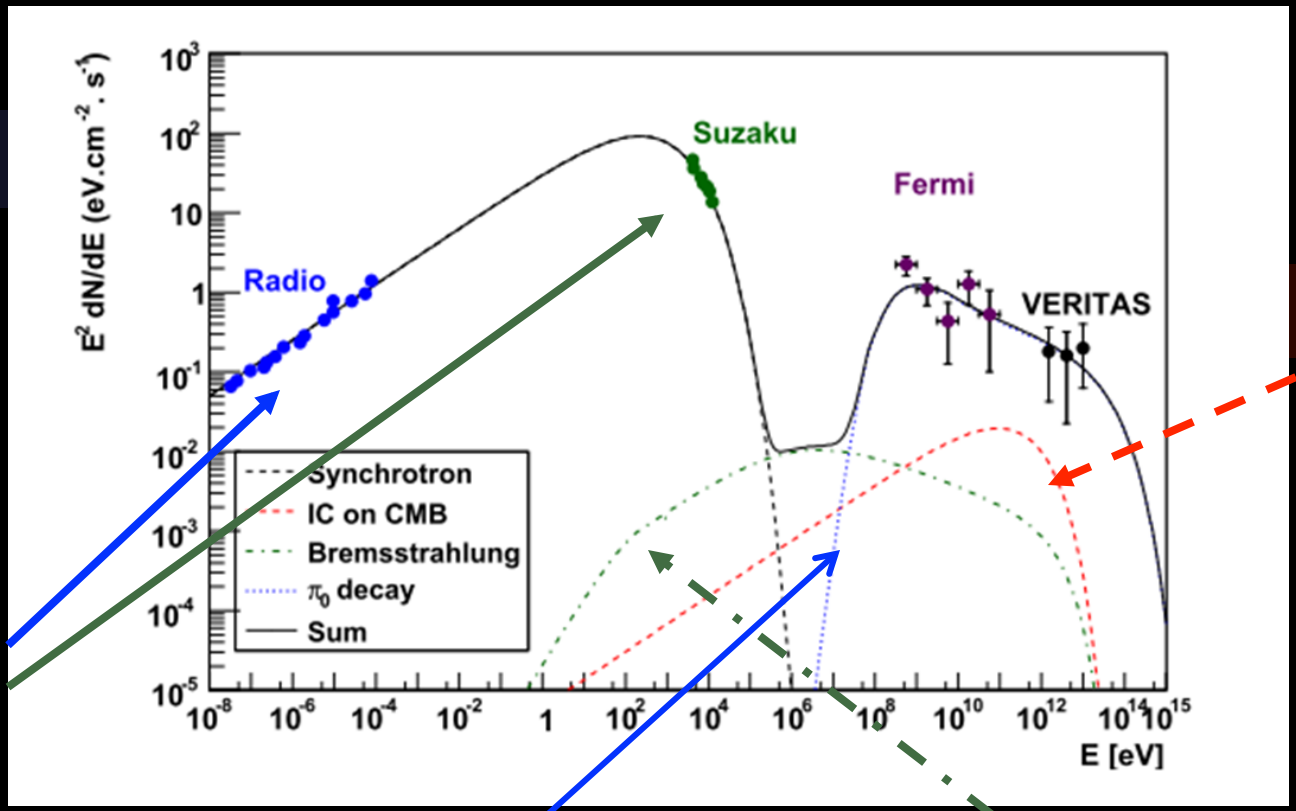


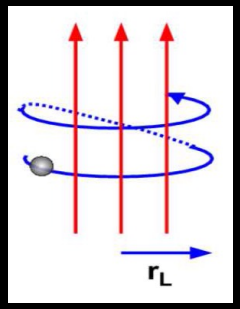
Gamma-ray
Cosmic-ray



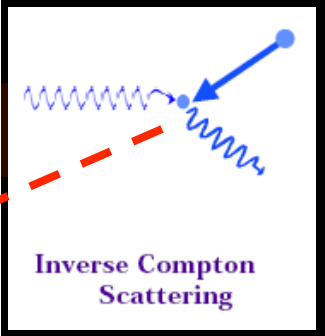
- Essential feature: model signal and background distributions in
  - Spatial dimensions (i.e. the VERITAS “camera”)
  - A parameter that separates gamma-ray- and (hadronic) cosmic-ray-initiated air showers (Mean-scaled width)
  - Fit unbinned in these parameters, binned in reconstructed energy
- Sensitive to distribution of photons spatially similar to the background

Need detailed measurements to disentangle contributions to spectrum





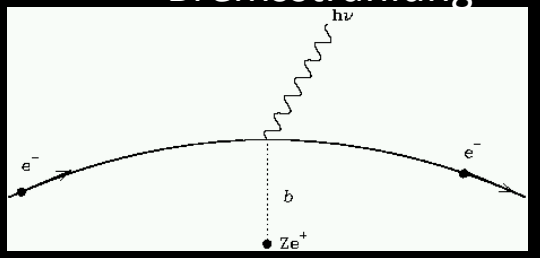
Synchrotron



Giordano et al

$$p + \text{target material} \rightarrow \pi^0 \rightarrow \gamma\gamma$$

Bremsstrahlung



Toy Model Simulations Cont.

- Need much deeper observations to get a clear image