IC443 Analysis With Gammapy

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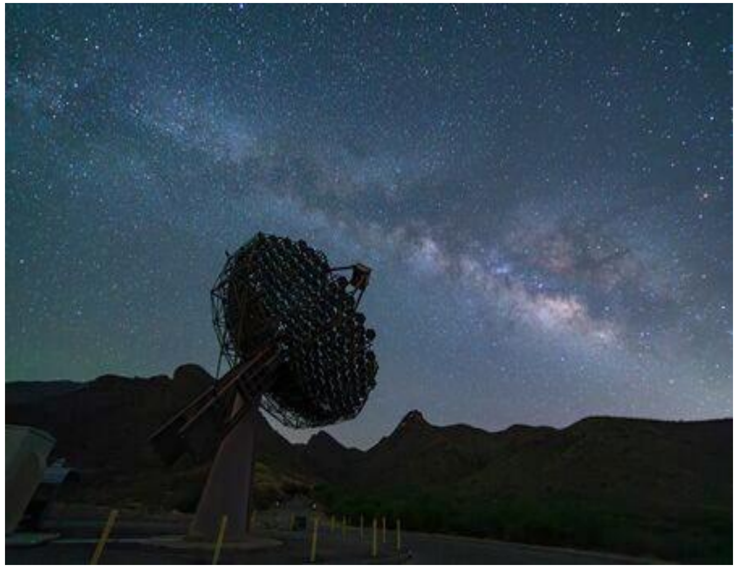
10-6-2025

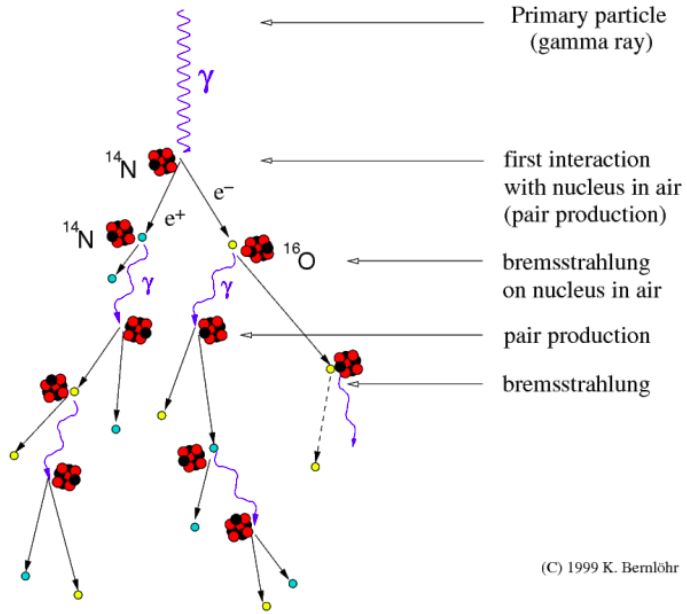


VERITAS

(Very Energetic Radiation Imaging Telescope Array System)

- Gamma-ray telescope, started operations in 2007
- Energy range: 85 GeV to 30 TeV
- Spatial resolution: 0.1 degree at 1 TeV
- Field of view: 3.5 degrees
- Utilizes Cherenkov radiation produced by gamma-ray induced air showers for gamma-ray detections

Development of gamma–ray air showers



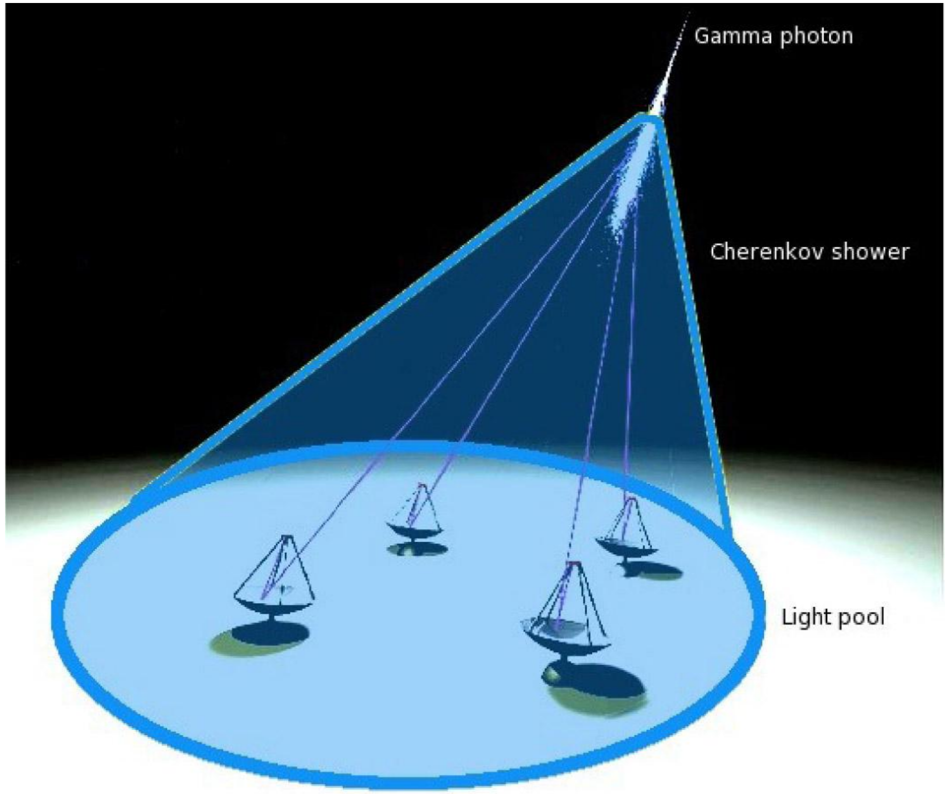
https://www.mpi-hd.mpg.de/hfm/CosmicRay/Showers.html

Gamma-ray Air Showers

- Cosmic ray background
  - Cosmic ray induced air showers
  - Detection rate ~450Hz
  - Source rate ~10Hz (Crab)

- Detection of Cherenkov radiation from air shower (VERITAS)
  - Angular resolution: 0.1 degree at 1 TeV
  - Energy range: ~85 GeV to ~30 TeV
  - Energy resolution: ~17%
  - Night observations only

- Detection of air shower byproducts (HAWC)
  - Angular resolution: 1 degree at 1 TeV
  - Energy range: ~100 GeV to 100 TeV
  - 24 hours observation window



Reflecting surfaces of novel Cherenkov telescopes

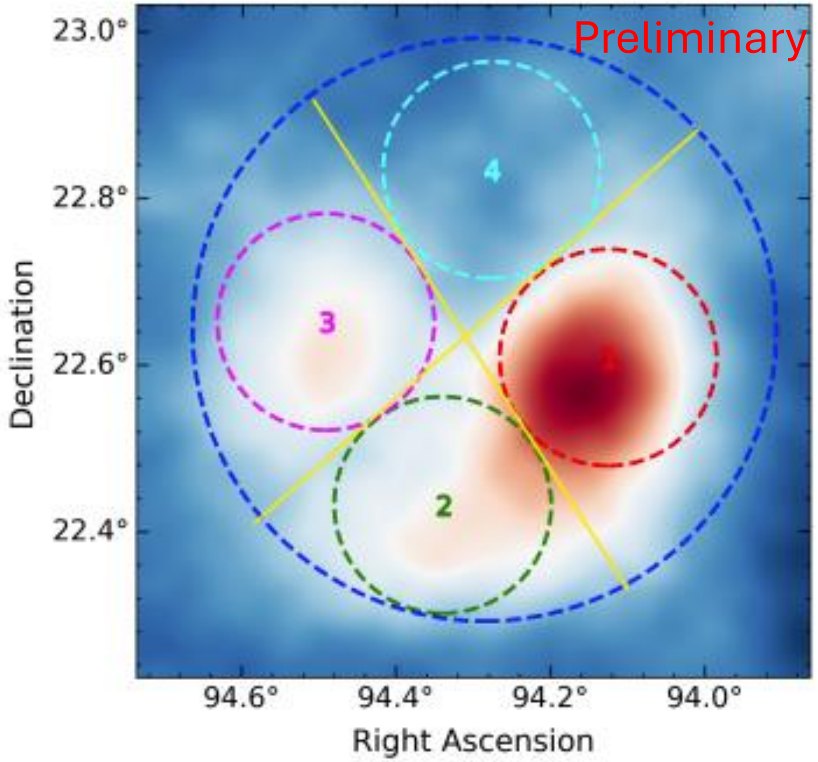
IC443 (aka Jellyfish nebula)

- Acts as a Galactic-scale particle accelerator
  - Boosting protons and electrons to TeV energies
- Accelerates both protons and electrons
  - Electrons produce gamma-rays through Bremsstrahlung radiation
  - Protons produce gamma-rays through $p\text{-}p \rightarrow {}^{0}\pi \rightarrow 2\gamma$
- Detected across the electromagnetic spectrum
  - radio, X-ray, GeV (Fermi-LAT), TeV (VERITAS, MAGIC, H.E.S.S.)
- Ideal target for extended source studies

https://anunakiobservatory.es/en/ic-443-jellyfish-nebula/

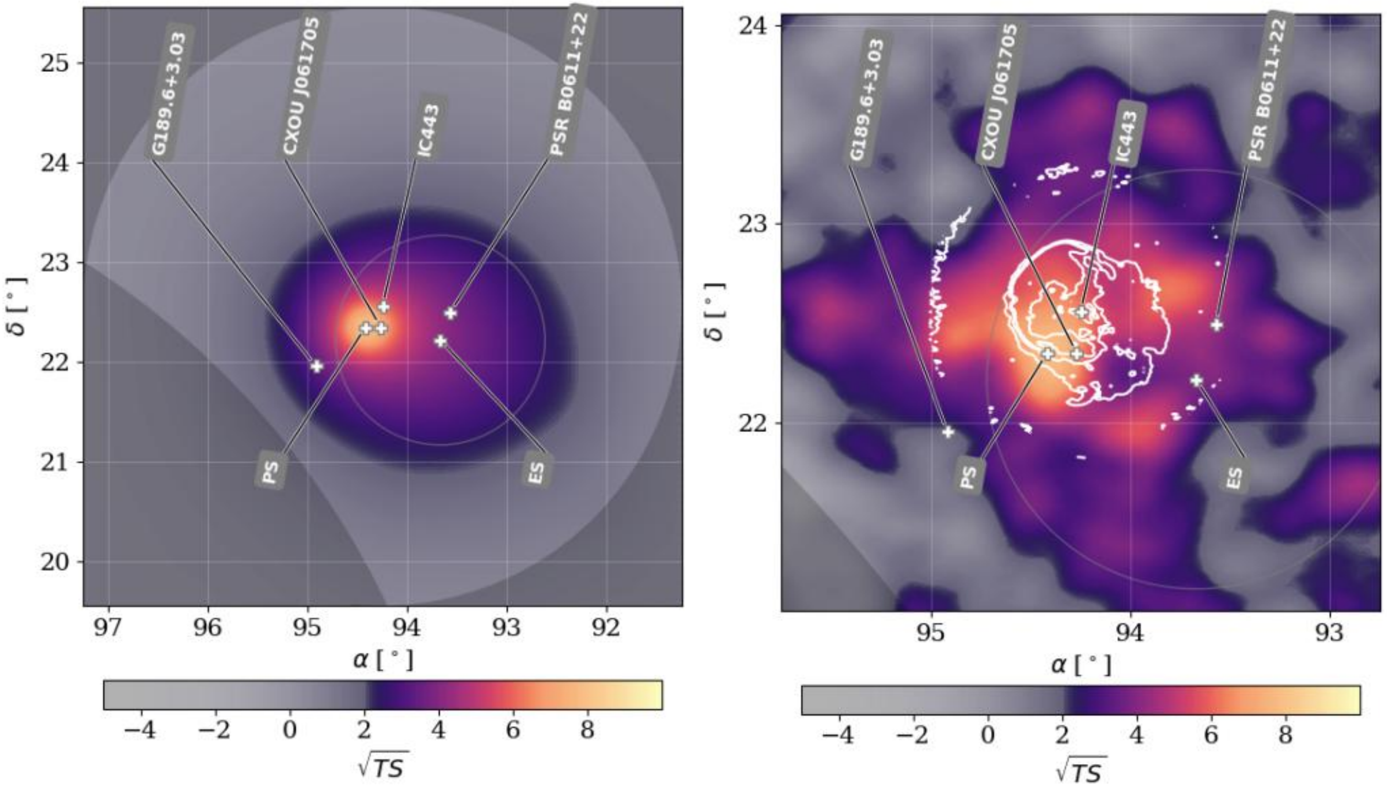
Current Measurements of IC443

- VERITAS analysis of IC443
- Energy range of ~ 200GeV to 4 TeV
- Extended source was detected
  - Previous detection was non-extended
- Analyzed 4 regions along the remnant to probe for different production mechanisms
- Analysis is on going



HAWC Analysis

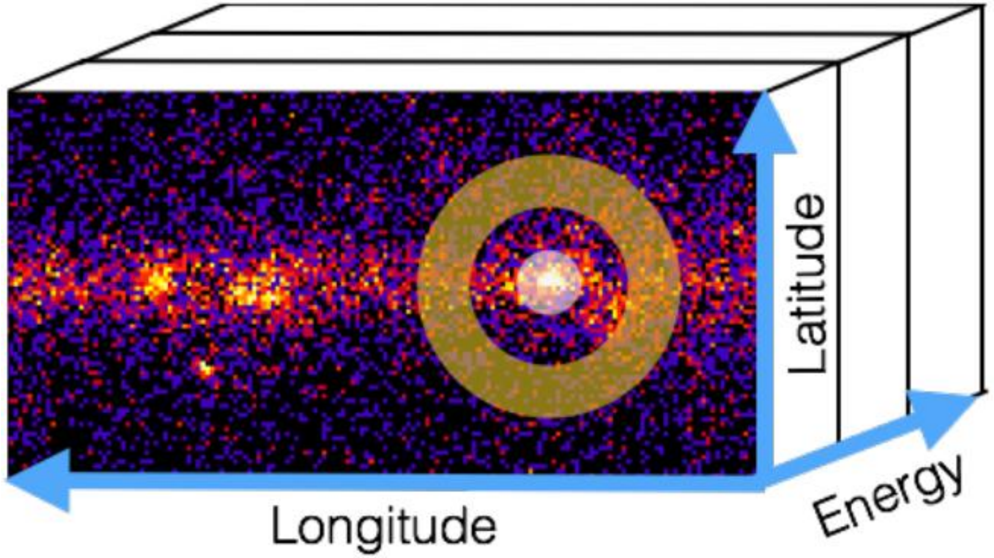
- HAWC (High Altitude Water Cherenkov)
- Performed a high energy analysis on IC443 region
  - Paper released 22 Jan 2025
  - Energy range of 300GeV to ~30TeV
- Had a detection of two sources
  - The known source of IC443, seen as a point-like
  - An extended gaussian source



Alfaro, R. et al. (2025)

Gammapy

- Open-Source gamma-ray astronomy python-based analysis package
- Built for the next generation of gamma-ray astronomy
  - Cherenkov Telescope Array Observatory (CTAO) starting in 2028
- Adds more capabilities compared to VERITAS standard analysis packages
  - 3D analysis
  - Morphological fitting
- Still under development and validation



Gammapy - A Python package for γ-ray astronomy

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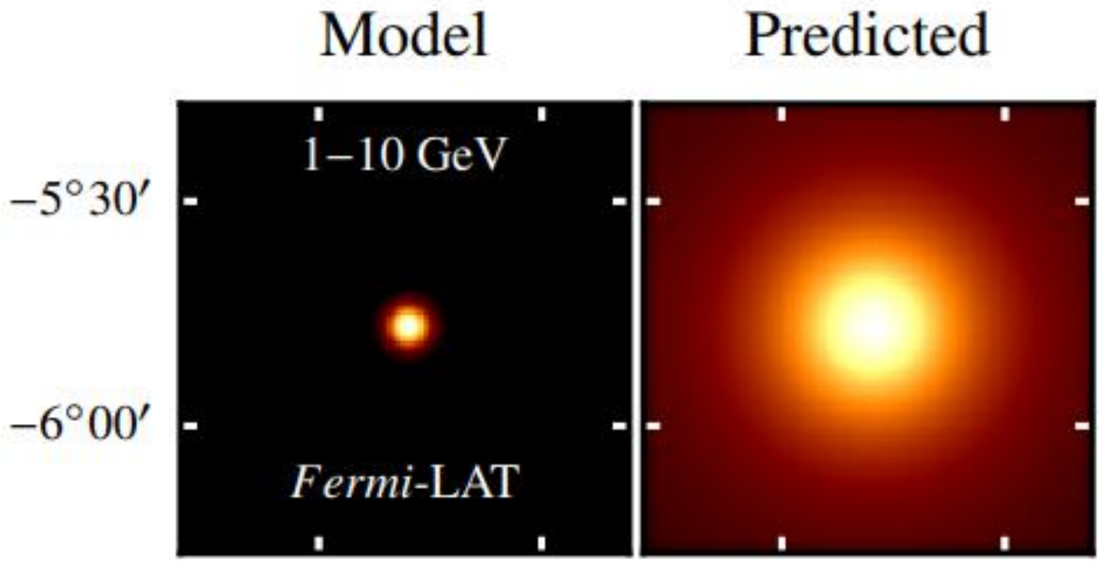
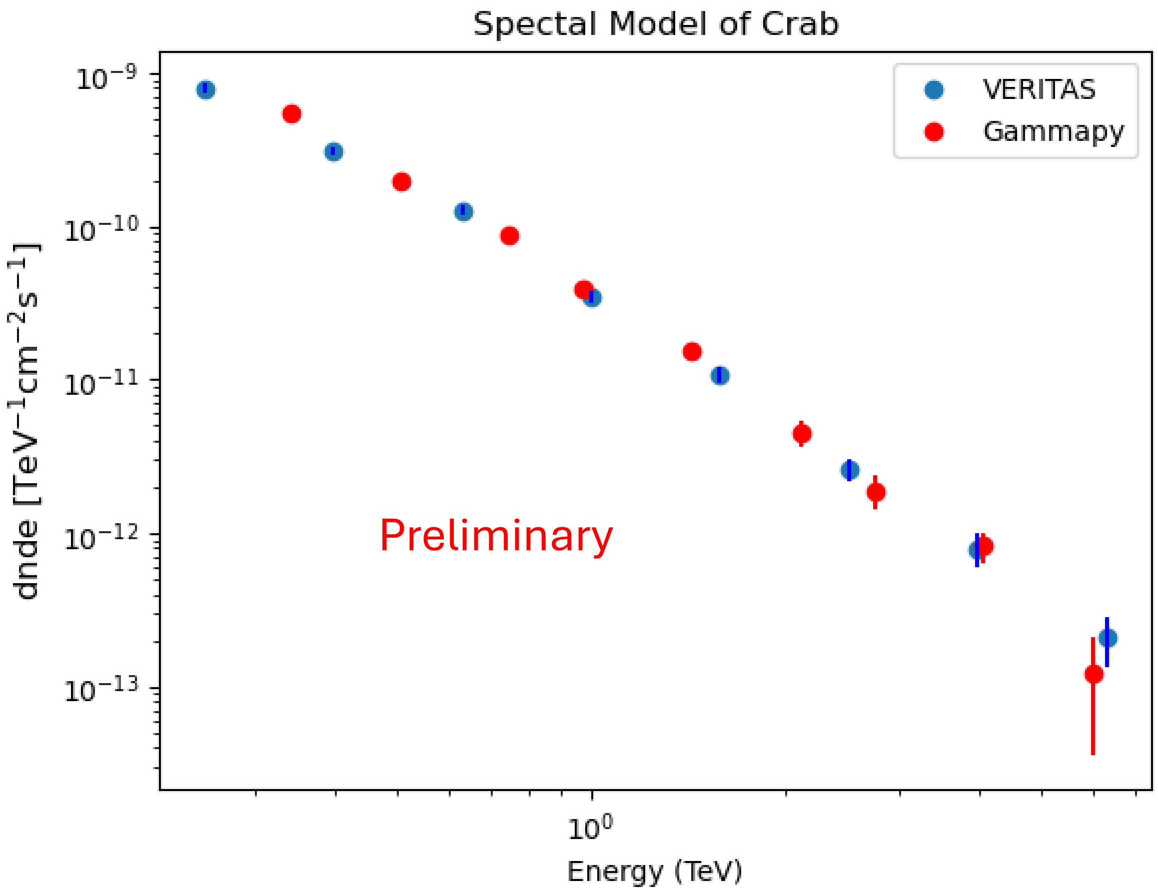


Spectrum and extension of the inverse-Compton emission of the Crab Nebula from a combined Fermi-LAT and H.E.S.S. analysis

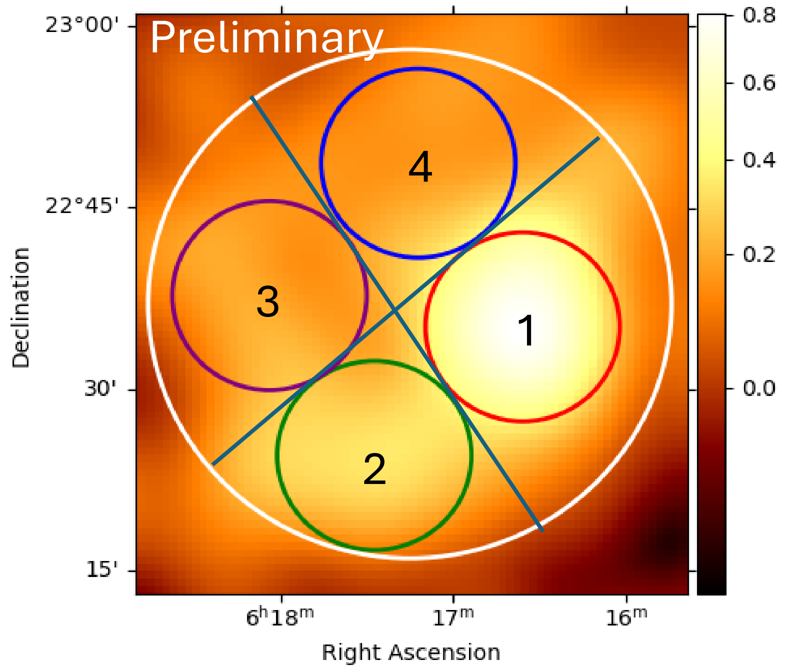
Gammapy Analysis Validation

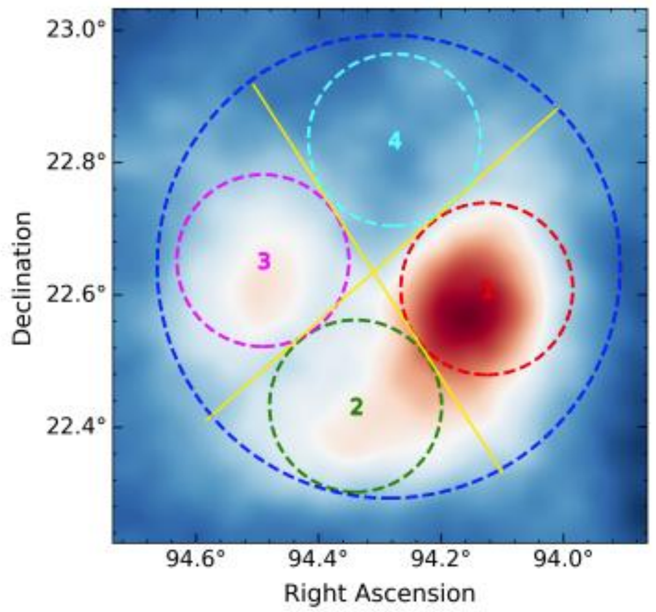
- Validating Gammapy 3D analysis techniques using VERITAS data
- Utilizing stable source Crab nebula
- Comparing standard VERITAS spectral analysis to Gammapy
- Within agreement between the two packages



Gammapy IC443 Validation

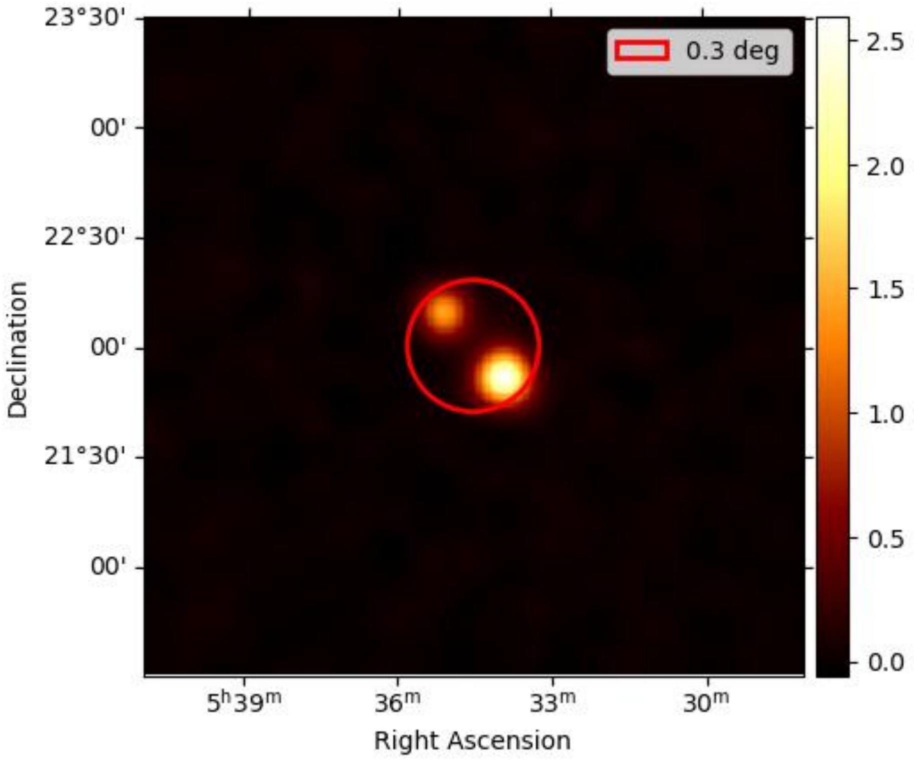
- Analysis of IC443 utilizing VERITAS data using Gammapy
- Four 0.13 degree circular integration regions and one 0.35 degree region
- Agreement with VERITAS analysis





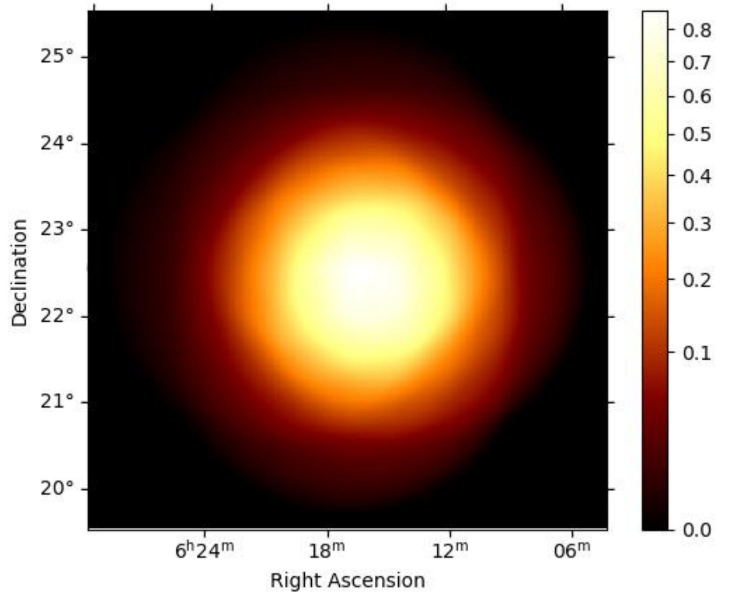
Simulating Gamma-Ray Observations with Gammapy

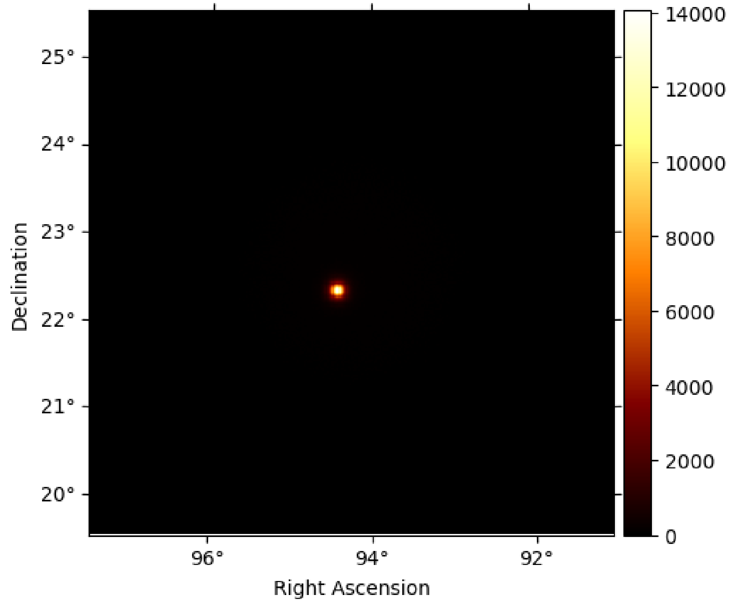
- Simulates realistic gamma-ray detections based on astrophysical source models
- Accounts for key instrumental effects: angular resolution (PSF), energy dispersion, background
- Uses Poisson statistics to model photon fluctuations — just like real data
- Critical for validating analysis methods before applying to real VERITAS observations



3D Simulations

- Differentiating two sources
  - Gaussian and point-like source
  - Similar to HAWC source
- Spatial and spectral models taken from HAWC IC443 paper (Alfaro et al. 2025)
- Using separate IRF, analyze the source and recover original models
- Simulate very extended gaussian
  - test if VERITAS could measure the new HAWC source with point source on top
- Resulting analysis was a success, reproducing both spectral and spatial components





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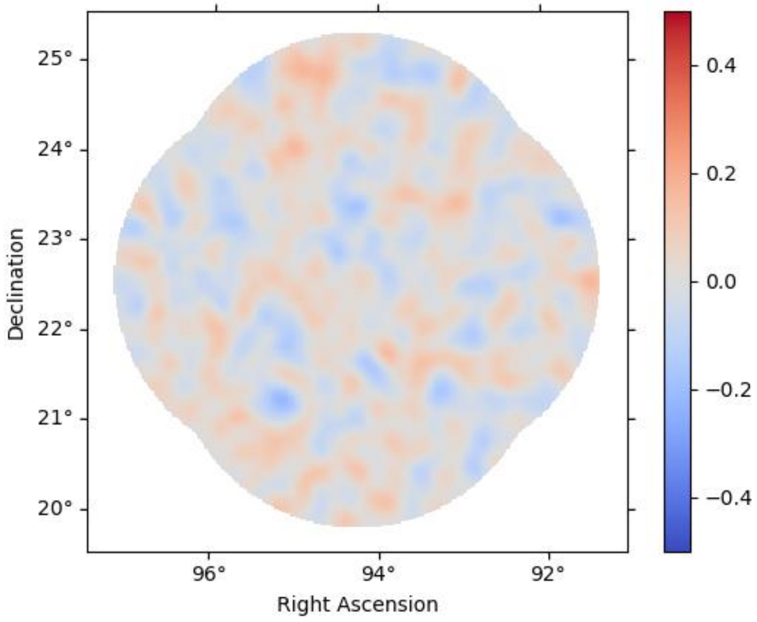
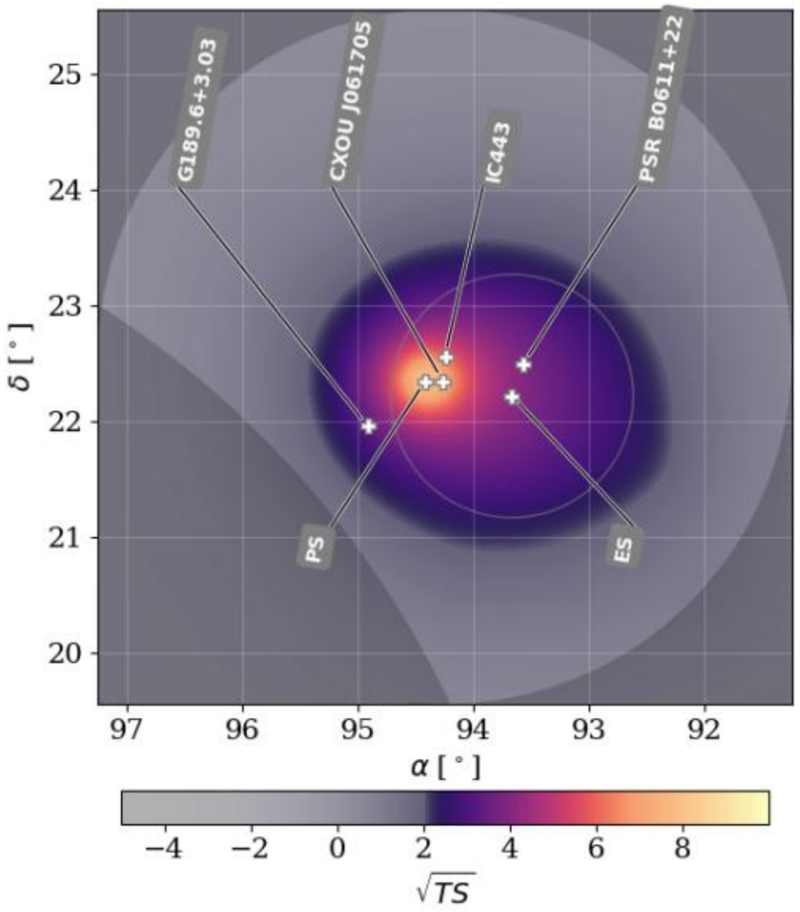


Future Analysis

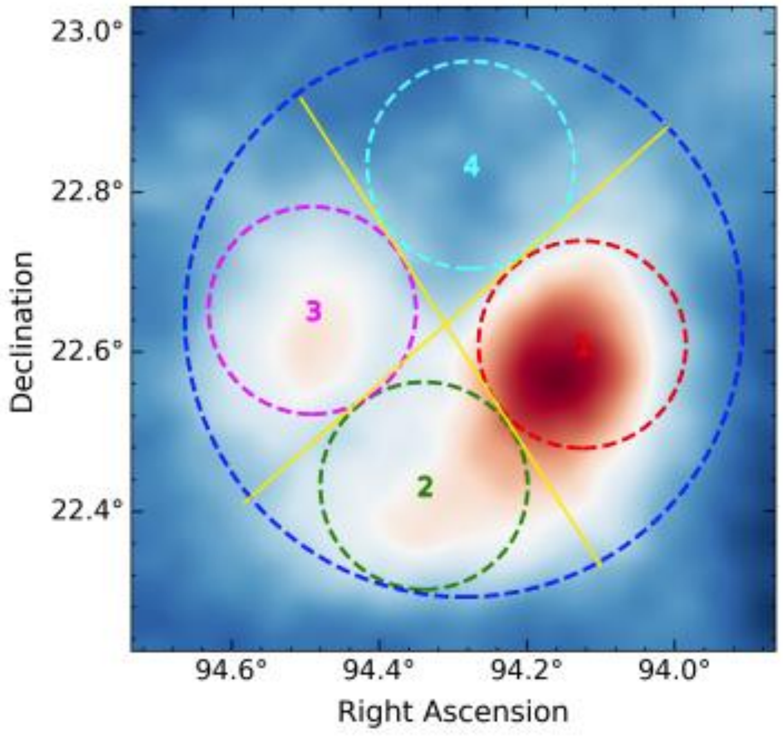
- Extend the IC 443 study by replicating HAWC's two-source analysis
- Use Gammapy's 3D analysis tools with VERITAS data
- Test if VERITAS can identify the same two emission regions seen by HAWC
- Leverage VERITAS's finer angular resolution to improve source separation



Alfaro, R. et al. (2025)

Conclusion

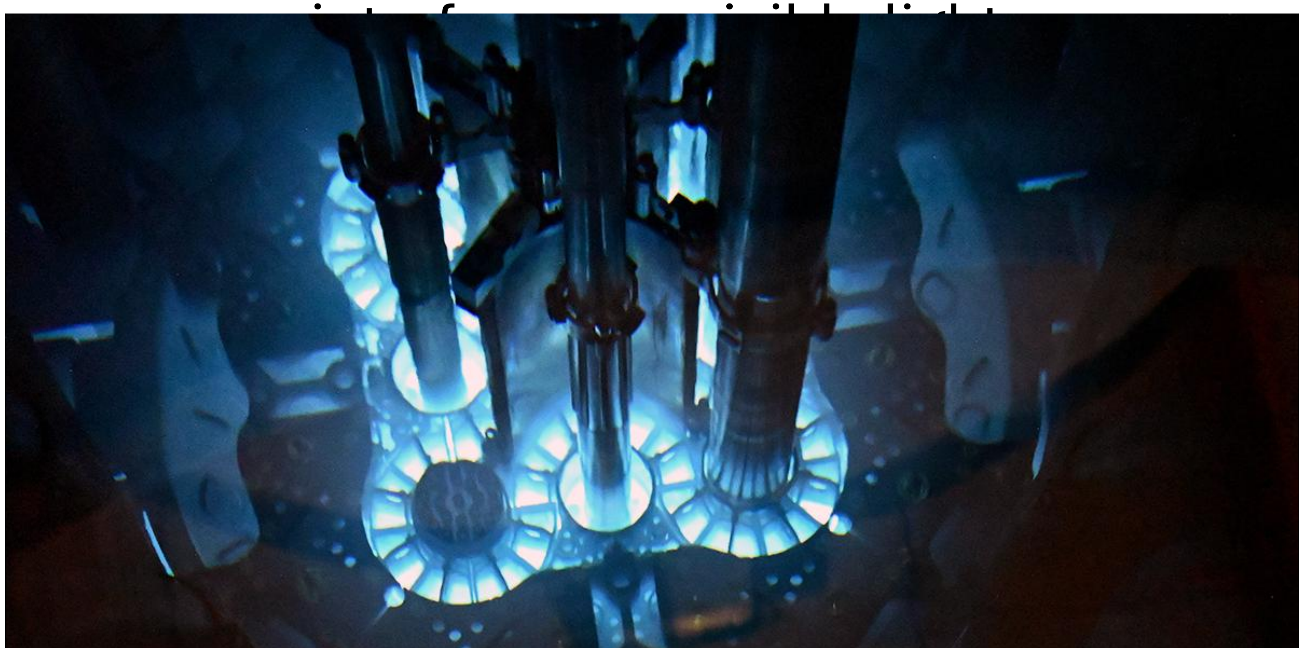
- IC 443 remains a compelling target for extended source studies across the gamma-ray spectrum
- Gammapy enables flexible and new analysis techniques, including 3D and morphological fitting
- Simulations confirm that VERITAS has the potential to probe new source seen by HAWC
- Future work will focus on refining spectral analysis and validating detection of multiple components

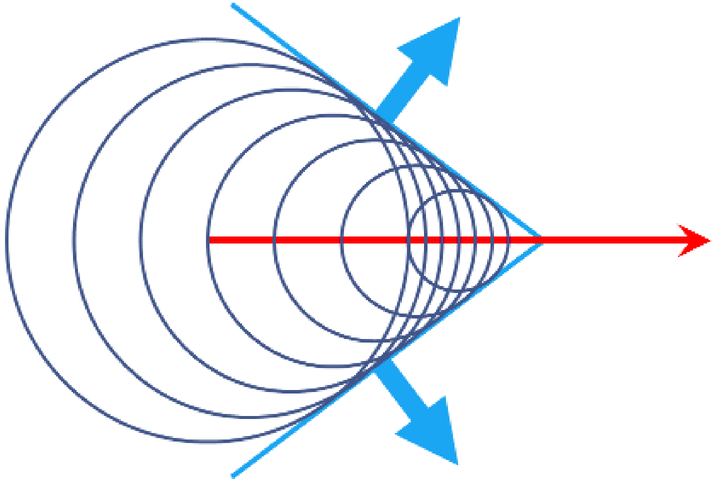


Back-up slides

Cherenkov Radiation

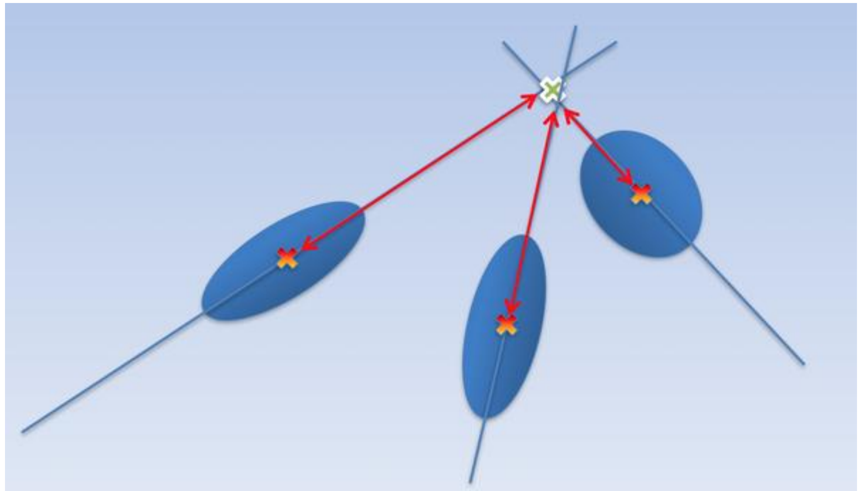
- Occurs when a particle travels faster than light in a given medium
    - Atmosphere in case of IACT
- Similar to sonic boom
    - Moving charged particle excites particles in medium
    - Particles return to ground-state - emit photons
    - Asymmetric polarisation - overlapping emitted waves - constructive

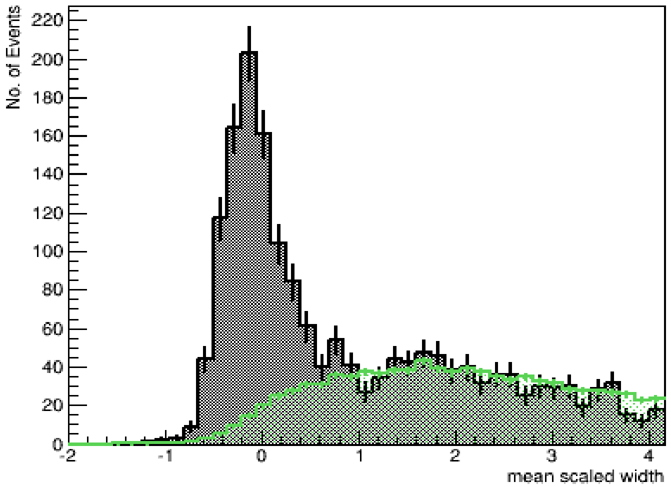


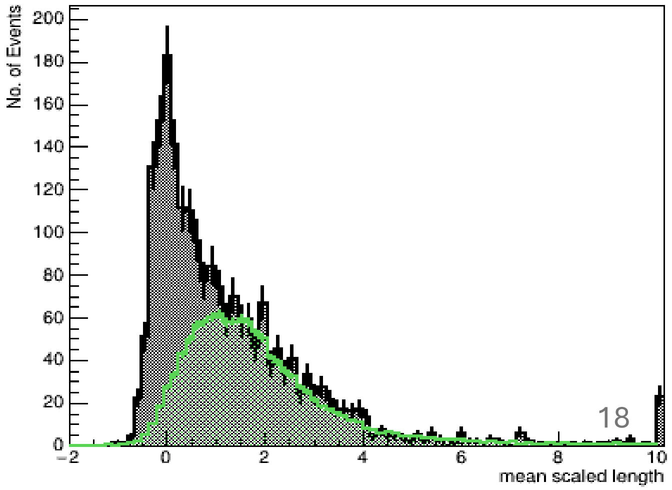


Reconstructing a Gamma-Ray

- Gamma-ray showers will appear as narrow ellipses
  - Major axis gives vertical extension and direction of source
  - Height estimated from the distance of the shower location to telescope on ground plane (Impact Parameter)
- Energy estimated from brightness of shower image and impact parameter
  - Brighter image - more energetic
  - Monte Carlo lookup tables used for estimation
- Hadron rejection
  - Cuts applied to shape of showers
  - Gamma-ray showers : longer and more narrow - not an exact science

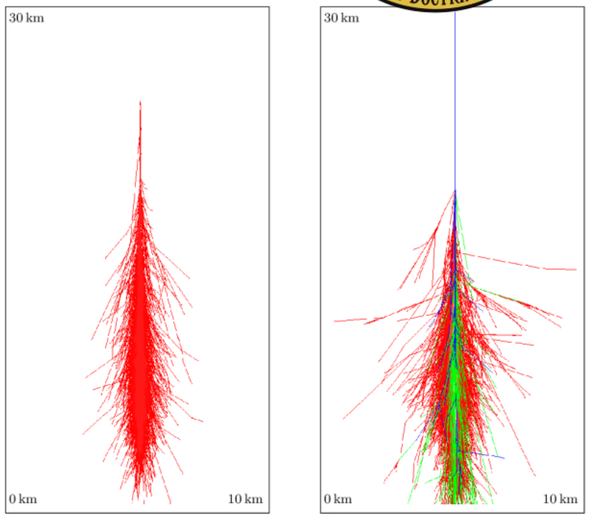






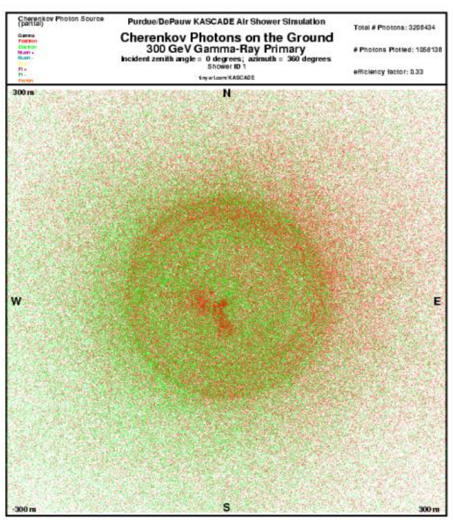
Hadronic Showers

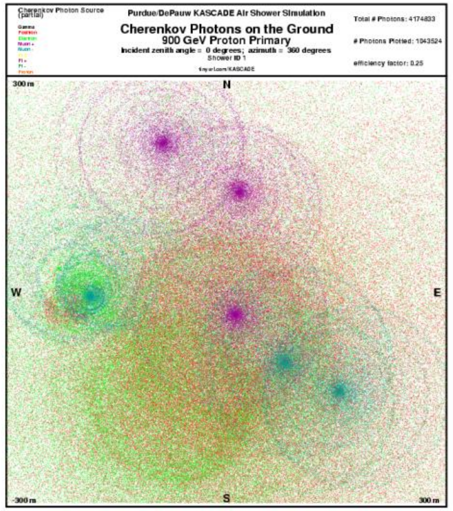
- Similar process as gamma ray
- Major source of background
- Pions most commonly produced upon entering atmosphere
    - π^0 quickly produce 2 gamma rays which undergo PP -> bremsstrahlung
    - Nearly indistinguishable from a shower produced by a single gamma ray
- Cosmic electrons and positrons can also induce an EAS
    - Further background



(a) γ-ray induced air shower with 300 GeV and first interaction in 23 km height

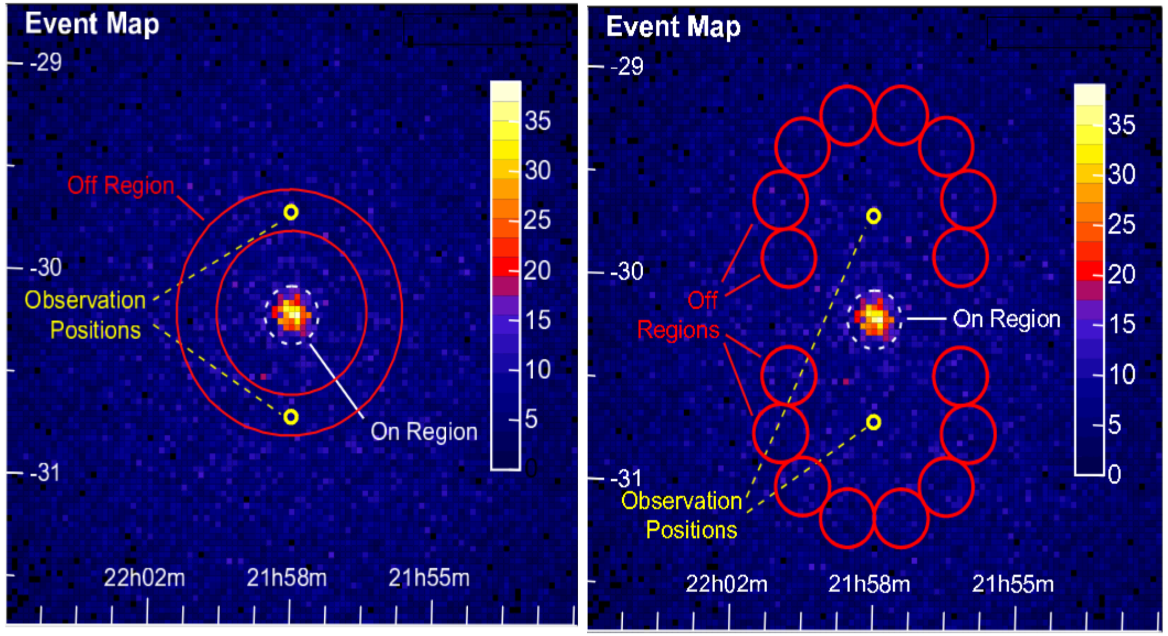
(b) hadron induced air shower with 1 TeV and first interaction in 18 km height





Background Estimation

- Data still not background free
  - Remainder must be estimated
- Determine statistical significance of observation with Li & Ma equation 17 (Li and Ma 1983)
  - 5σ required for a statistically significant detection of target over the background



$$S = \sqrt{2}\left\{N_{on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{on}}{N_{on}+N_{off}}\right)\right] + N_{off}\ln\left[(1+\alpha)\left(\frac{N_{off}}{N_{on}+N_{off}}\right)\right]\right\}^{\frac{1}{2}}$$