Very-high-energy γ-ray Astronomy with the VERITAS Observatory

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Cosmic Accelerators and Atmospheric Calorimeters

- Learn about
  - Particle sources/Acceleration processes at sources
  - Other particle sources (i.e. dark matter annihilation/decay)
  - Properties of intervening medium (e.g. magnetic fields)
The Imaging Atmospheric Cherenkov Technique

Atmospheric Cherenkov Gamma-ray Telescopes

Fig. 5. An illustration of the stereoscopic imaging technique. A gamma-ray triggers an electromagnetic cascade in the Earth's atmosphere, which generates Cherenkov radiation in a light pool on the ground. Telescopes within this light pool are used to form an image of the shower, which allows reconstruction of the arrival direction of the incident primary photon.

The requirement for a very large field-of-view for each telescope dictates a small impact parameter $a$. The angular distance of the set is proportional to the shower impact parameter $a$ (Figure 5). Even a point source of gamma-rays, therefore, requires a field-of-view of a few degrees diameter. In reality, many known sources of gamma-ray emission (particularly supernova remnants and pulsar wind nebulae) have a large angular extent. Additionally, analysis of ACT data typically uses a portion of the field-of-view in which there are no known gamma-ray sources to estimate the background of remaining cosmic ray showers. Currently operating arrays have fields-of-view of 3-5, while plans for the next generation of instruments reach 8-10.

VERITAS
FLW Observatory in southern AZ
Energy range: ~85 GeV - 30 TeV
Angular resolution: 0.1° @ 1 TeV
Field of view: 3.5°

Multiple telescopes for stereoscopic imaging

Credit: J. Holder

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VERITAS Collaboration

- ~60 active members
  - >15% associated with DESY and/or University of Potsdam
The γ-ray Sky

Population of confirmed TeV emitters small but growing
Extragalactic sky dominated by blazars

Fermi-LAT sky
https://svs.gsfc.nasa.gov/11342

TeV sky
http://tevcat.uchicago.edu
Galactic Science

Understanding High-energy Emitters
Gamma-ray Binary PSR J2032+4127

- Pulsar / Be star binary system with 50 year orbital period
  - Pulsar located near steady, extended, unidentified TeV-emitter
- Periastron in November 2017
  - Strongly variable γ-ray emission from pulsar detected
- 2nd VHE γ-ray binary with identified compact object

Abeysekara et al. arxiv:1810.05271
Gamma-ray Binary PSR J2032+4127

• Lightcurve modelling challenging
  • Inverse Compton efficiency & γγ-absorption major factors
• Unexpected spectral cutoff in low state
**VERITAS Observations of HAWC Sources**

- VERITAS follow-up of 14 HAWC sources without TeV association
  - 507 days HAWC observation
  - Fermi-LAT + VERITAS + HAWC cover <10 GeV - 100 TeV
  - VERITAS sensitivity & angular resolution complementary

**HAWC**
Puebla, Mexico
Energy range: ~300 GeV - 100 TeV
Angular resolution: ~0.1°
Field of view: ~2 sr

Abeysekara et al.
arxiv:1808.10423

VERITAS flux limits < HAWC fluxes
Spectral change and/or extended source
VERITAS + HAWC: SNR G54.1+0.3 Region

- (new) Fermi-LAT + (previous) VERITAS + HAWC detection in same region
  - Likely association: pulsar wind nebula with young, energetic pulsar
VERITAS + HAWC: DA 495

- New VERITAS detection of extended source in 72 hours of data
- No Fermi-LAT detection of extended source, point source detection in region
- Likely association with pulsar wind nebula DA 495
  - Aging PWN with no evidence for supernova remnant shell
- Possible contamination by nearby source
Extragalactic Science

Understanding High-energy Emitters
Radio Galaxy 3C 264

- “Distant” (z=0.0217) Faranoff-Riley I galaxy with resolved radio jet
- VERITAS detection: hard-spectrum, weakly variable (~monthly time scales) emitter
  - Usually high synchrotron & $\gamma$-ray peak
- Follow-up radio (VLBI, HST), optical, X-ray observations - radio knots & core stable
BL Lacertae Flare

• Rapid 1.8 Crab flare in 2016
• Usual asymmetric flare profile
  • $t_{\text{rise}} \sim 140$ mins, $t_{\text{fall}} \sim 36$ mins
• GeV, X-ray, optical variable, optical & radio polarization variable
  • Time lags between bands
• Radio (VLBA) observations show emergence of new superluminal knot

Abeysekara et al. arxiv:1802.10113
Other Particle Sources
Cosmic-ray Electron Spectrum

- AMS measurements of cosmic-ray electron & positron spectra
  - Positrons - expect majority secondaries
  - Measurements test diffusion/propagation models & for sources in local universe
- Rising positron flux observed, contrary to expectation
  - Dark matter annihilation? Local source?
VERITAS All Electron Spectrum

Archer et al. arxiv:1808.10028

- VERITAS measurement on ~300 hours observations (off galactic plane)
  - Boosted decision trees to distinguish electromagnetic from hadronic showers (γ-ray contamination minimal)
  - Spectral break measured at 710 ± 40 (stat) ± 140 (syst) GeV
Indirect Astrophysical Dark Matter Searches

Appealing to consider GeV-TeV mass, weakly-interacting particle

“WIMP Miracle”

$<\sigma v> \sim 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$

Astrophysical signal from annihilation or decay to standard model particles
Predicted Signal

\[
\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \frac{< \sigma v > dN_\gamma}{\delta m^2_\chi dE_\gamma} \int \int \rho^2 d\sigma d\Omega
\]

Particle physics
Spectral information: lines or cut-offs

Theoretical uncertainty on DM profiles

Astrophysics
“J factor”: DM distribution, distance to source, instrument response

Dark matter profiles
- NFW ($\gamma=1$)
- Einasto ($\alpha=0.17$)
- ISO ($\gamma=0$)

J-factors with $\alpha_{int} = 0.1$ deg
VERITAS limits with Dwarf Spheroidal Galaxies

<table>
<thead>
<tr>
<th>Target</th>
<th>Exposure [hrs]</th>
<th>log$_{10}J$(0.17$^\circ$) [GeV$^2$ cm$^{-5}$]</th>
<th>Significance $\sigma$</th>
<th>$\Phi^{95%}$ $10^{-12}$cm$^{-2}$s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segue 1</td>
<td>92.0</td>
<td>$19.2^{+0.3}_{-0.3}$</td>
<td>0.7</td>
<td>0.34</td>
</tr>
<tr>
<td>Draco</td>
<td>49.8</td>
<td>$18.3^{+0.1}_{-0.1}$</td>
<td>-1.0</td>
<td>0.15</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>60.4</td>
<td>$18.9^{+0.3}_{-0.3}$</td>
<td>-0.1</td>
<td>0.37</td>
</tr>
<tr>
<td>Boötes 1</td>
<td>14.0</td>
<td>$18.3^{+0.3}_{-0.4}$</td>
<td>-1.0</td>
<td>0.40</td>
</tr>
<tr>
<td>Willman 1</td>
<td>13.6</td>
<td>N/A</td>
<td>-0.6</td>
<td>0.39</td>
</tr>
</tbody>
</table>

- J-factor estimation challenging
  - Observe multiple targets, **classical** and **ultra-faint** dSphs

- Event-weighting analysis with spatial and spectral information

Archambault et al. arxiv:1703.04937
VERITAS limits with Dwarf Spheroidal Galaxies

\( \chi \chi \rightarrow \text{SM SM} \)

- Median limits plotted
- Benchmark cross section @ 3x10\(^{-26}\) cm\(^3\)s\(^{-1}\) (thermal relic abundance)
- Update underway: larger datasets, broader survey, analysis improvements
Conclusions

• VERITAS performing well after 10+ years of operation
• Expanding sparse VHE source populations
  • Gamma-ray binaries, radio galaxies
• Multiwavelength observations provide interesting datasets for modelling
  • PSR J2032+4127, HAWC follow-up, 3C 264, BL Lac flare
• Good understanding of instrument enables “precision” measurements
  • Electron spectrum, limits on dark matter annihilation
Thank you
Backup