Introduction to VERITAS

- Array of four IACTs in Southern AZ, USA
- Employs ~100 Scientists in five countries
- Full Array Operations in Fall 2007
- Upgrades:
  - Move of T1 in Summer 2009
  - Level-2 Trigger upgrade in Fall 2011
  - Camera Upgrade with High-QE PMTs in Summer 2012
- See overview talk by Nahee Park

- Support From:
  - NSF (USA)
  - DOE (USA)
  - Smithsonian Institution
  - NSERC (Canada)
VERITAS Performance

- **V6**: Mid – 2012 to Present
- **Energy Range**: 85 GeV to > 30 TeV
- **Energy Resolution**: 15-25%
- **Sensitivity**: 1% Crab in ~25 hrs
- **Angular Resolution**: <0.1 at 1 TeV (68%)
- **Pointing Accuracy**: Error < 50 arcsec
VERITAS Dark Matter Targets

Galactic Center (GC)
- Close By
- Large DM Content
- Astrophysical Backgrounds

Dwarf Galaxies (DSphs)
- No Astrophysical Backgrounds
- Close By (~10’s kpc)
- High M/L

Fermi Unidentified Objects
- Potentially DM Subhalos?

Galaxy Clusters
- Distant
- Large DM Content
- Many are extended
- Astrophysical Background (?)
VERITAS Dwarf Galaxy Observations

<table>
<thead>
<tr>
<th>Dwarf</th>
<th>Live time [hrs]</th>
<th>$\log_{10} J$ [GeV$^2$cm$^{-5}$]</th>
<th>Significance $\sigma$</th>
<th>$F_{95%}^{\delta_{12}}$ [$10^{-12}$cm$^{-2}$s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segue 1</td>
<td>92.0</td>
<td>$19.4^{+0.3}_{-0.4}$</td>
<td>0.7</td>
<td>0.34</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>60.4</td>
<td>$18.9^{+0.3}_{-0.2}$</td>
<td>-0.1</td>
<td>0.37</td>
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<tr>
<td>Draco</td>
<td>49.8</td>
<td>$18.8^{+0.1}_{-0.1}$</td>
<td>-1.0</td>
<td>0.15</td>
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<tr>
<td>Boötes</td>
<td>14.0</td>
<td>$18.2^{+0.4}_{-0.4}$</td>
<td>-1.0</td>
<td>0.40</td>
</tr>
<tr>
<td>Willman 1</td>
<td>13.7</td>
<td>N/A</td>
<td>-0.6</td>
<td>0.39</td>
</tr>
</tbody>
</table>

- Five dSphs observed by VERITAS between 2007 and 2013
- Total of 230 hours
  - Deepest exposure on Segue 1: 92 hours
- No gamma-ray detection
- Flux upper limits above 300 GeV

Benjamin Zitzer, TeVPa 2015
• Using Methodology of Geringer-Sameth et al.
  • Each event is assigned a weight which is proportional to the probability of photon originating from DM annihilation
  • Function of Energy and angular distance from dwarf galaxy
• J Factors from Geringer-Sameth et al.
Dark Matter Search/ Limits from Dwarf Galaxies

Combined Search

Individual Dwarf Search

Benjamin Zitzer, TeVPa 2015
- 216 hours combined limit
  - Willman 1 not used
  - Band represents uncertainty in J factor
  - Substantial improvement over 48 hour Segue 1 result
Observations of two Fermi-LAT UNIDs from 2FGL

- Selection criteria: Power-law spectra, not variable, no counterparts, observable by VERITAS

- 2FGL J1115.0-0701 found to be variable in 3FGL catalog, likely a blazar

- 2FGL J0545.6+6018 curved power-law in 3FGL

- Fit of 2FGL J0545.6+6018 with Dark Matter model
  - Assume $<\sigma v> = 2.2 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$
  - Mass and J factors are free fit parameters
- Interaction of CRs with the interstellar medium and unresolved point source leads to predictions of VHE emission from M31
- Number of CR accelerators scales with star formation rate
- M31 is extended and optically bright, both of which have been issues for IACTs
- Upper limits in several test regions of interest
  - Extended and point-like test regions
296 hours of data between 2009 and 2012

- Electron-like events selected by boosted decision trees and extended likelihood fitting
- Agreement with other experiments within systematic uncertainties
- Break at 710 ± 40 GeV
- Index below break: -3.2 ± 0.1_{stat}
- Index above break: -4.1 ± 0.1_{stat}
- Confirms the existence of at least one nearby CRE emitter
- Second high-statistics measurement of a break above 1 TeV

Benjamin Zitzer, TeVPa 2015
IGMF Measurements

- IGMF provides clues for large-scale structure and CR propagation
- Pair production with EBL produces cascade
  - Secondary particles bent by IGMF
  - Broadening of Blazar VHE emission
- No extension seen in 7 blazars
- Limits on IGMF magnitude set for model-dependent extended emission by comparing to simulated blazars and using 3D semi-analytical code
  - T. Weisgarber 2012
- VERITAS disfavors IGMF strength of $\sim 10^{-14}$ G

Benjamin Zitzer, TeVPa 2015
Follow-up of Icecube events

- TeV emission associated with astrophysical flux of high-energy neutrino events provides evidence of the site of CR acceleration

- Observation of 22 $\nu_\mu$-induced muon-track showers for combined 40 hours exposure
  - Muon tracks have good angular reconstruction: ~1 deg
  - Flux upper limits in the 2-10% Crab level
Other VERITAS Dark Matter/ Astroparticle Projects

- Dark Matter:
  - Archival Galaxy cluster search (arXiv: 1508.07197)
  - Galactic Center (arXiv: 1508.07197)

- Astroparticle topics:
  - Lorentz Invariance Violations (arXiv: 1307.8382)
  - Measurement of positron fraction with Moon Shadow Observations (arXiv: 1508.07197)
Dark Matter/Astroparticle physics is a key science topic for VERITAS

Active and diverse group within the collaboration

VERITAS (and IACTs in general) can provide important dark matter physics constraints (or possible detection) at masses of ~1 TeV and above, particularly with Sommerfeld boosts

Provide input on many areas of New/Fundamental physics