The VERITAS Dark Matter Program

Benjamin Zitzer
For The VERITAS Collaboration
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

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
γ-rays from Dark Matter Annihilation

- Well-motivated theoretically by extensions of the SM (SUSY, Kaluza-Klein) by a weakly-interacting massive particle (WIMP)
- WIMP annihilation production of gamma-rays
  - Gamma-ray line from direct annihilation
  - Gamma-ray continuum from hadronization
  - Enhanced near DM mass from internal Bremmstraung.
- DM gamma-ray flux:

\[
\frac{dF(E, n)}{dE d\Omega} = \frac{\langle \sigma v \rangle \frac{dN_\gamma(E)}{dE}}{8\pi M^2} \frac{1}{4\pi l^2} \int d\ell \rho^2(\ell n)
\]

Almost all roads lead to gamma rays!

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VERITAS Dark Matter Targets

Galactic Center (GC)
- Close By (~8kpc)
- Large DM Content
- Astrophysical Backgrounds

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

Galaxy Clusters
- Distant
- Large DM Content
- Many are extended
- Astrophysical Background (?)
**VERITAS Dwarf Galaxy Observations: 2007 to 2013**

### Recent VERITAS Publication:
- Archambault et al. Phys. Rev. D 95, 082001

### Five dSphs observed by VERITAS between 2007 and 2013
- Total of 230 hours after data quality selection
- 92 hours Segue 1
- Crescent-shaped region used for background subtraction
- No gamma-ray detection
- Integral flux upper limits above 300 GeV for each dSph
- J Factors from Geringer-Sameth et al.

<table>
<thead>
<tr>
<th>DSph</th>
<th>$N_{ON}$ [counts]</th>
<th>$N_{OFF}$ [counts]</th>
<th>$\bar{\alpha}$</th>
<th>Significance $[\sigma]$</th>
<th>$N^{95%}$ [counts]</th>
<th>$\Phi^{95%}$ [10^{-12} \text{cm}^2 \text{s}^{-1}]</th>
<th>Distance [kpc]</th>
<th>$\log_{10} J(0.17^\circ)$ [GeV^2 \text{cm}^{-5}]</th>
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<tbody>
<tr>
<td>Segue 1</td>
<td>15895</td>
<td>120826</td>
<td>0.131</td>
<td>0.7</td>
<td>235.8</td>
<td>0.34</td>
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<td>91.6</td>
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<td>Boötes 1</td>
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<td>0.39</td>
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</table>
Dark Matter Search/Limits from Dwarf Galaxies

• Each event in each ON region gets a weight based on the energy, angular distance from dwarf center and dwarf field
  • proportional to probability of event being produced by DM
• Test statistic for detection of DM at a given mass is the sum of weights from all dwarfs
• PDF generated from background from compound Poisson distributions
• PPP4 DM model used for single annihilation spectra
• Limits produced by repeating over several test mass and <σν> values
  • Limits on plots where DM hypothesis is rejected at 95% confidence for a given mass

\[ w = \log \left[ 1 + \frac{s}{b} \right] \]

\[ s(\nu, E, \theta) = \frac{dN(\nu, E, \theta)}{dE d\Omega} dE \ 2\pi \sin(\theta) d\theta \]

\[ \frac{dF(\hat{E}, \hat{n})}{dE d\Omega} = \frac{\langle \sigma v \rangle}{8\pi M^2} \frac{dN_\gamma(E)}{dE} \frac{dJ(\hat{n})}{d\Omega} \]

\[ R(E, \hat{n}|E_t, \hat{n}_t) = \sum_{\text{runs}} \tau A_{\text{eff}}(E_t) \text{PSF}(\hat{n}|E_t, \hat{n}_t) D(E|E_t) \]
Dark Matter Search from Dwarf Galaxies

Combined Search

Individual Dwarf Search
- Velocity-averaged cross section with 95% C.L.
- Each panel assumes 100% annihilation into a different SM particle
- Band represents 1σ systematic error in J-Factor
- Limits shown with and without Segue 1 included in combined limit
Comparison with other Experiments

$\chi \chi \rightarrow b \bar{b}$

$\chi \chi \rightarrow \tau^+ \tau^-$

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# A Decade of VERITAS Dwarf Observations

<table>
<thead>
<tr>
<th>Dwarf</th>
<th>$\log_{10} A_1(0.5^\circ)$ [GeV$^2$ cm$^{-2}$]</th>
<th>$\log_{10} J_2(0.5^\circ)$ [GeV$^2$ cm$^{-2}$]</th>
<th>$\log_{10} D_1(0.5^\circ)$ [GeV cm$^{-2}$]</th>
<th>Exposure v4 [min]</th>
<th>Exposure v5 [min]</th>
<th>Exposure v6 [min]</th>
<th>Total Exposure [min]</th>
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<tr>
<td>Segue 1</td>
<td>19.4$^{+0.3}_{-0.4}$</td>
<td>17.0$^{+1.2}_{-1.2}$</td>
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<td>Draco II</td>
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<tr>
<td>Ursa Major I</td>
<td>17.9$^{+0.6}_{-0.3}$</td>
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<td>17.6$^{+0.4}_{-0.4}$</td>
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<td>Leo I</td>
<td>17.8$^{+0.2}_{-0.2}$</td>
<td>17.8$^{+0.2}_{-0.2}$</td>
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<td>Leo V</td>
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<td>16.1$^{+1.2}_{-1.0}$</td>
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<td>Leo IV</td>
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<td>16.1$^{+0.7}_{-1.1}$</td>
<td>0</td>
<td>0</td>
<td>151</td>
<td>151</td>
</tr>
</tbody>
</table>

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VERITAS Dwarf Observations Divided into two Classes:

- **Deep Exposure** – dSphs with typically the best J-Factors in the literature

- Deep Exposure dSphs are a combination of ‘Classical’ (i.e. Draco, Ursa Minor) and ‘Ultra-faint’ (i.e. Segue I, Ursa Major II) dSphs

- **Survey** - dSphs covering nearly all Northern Hemisphere dSphs

- Strategy ensures the program is not severely impacted if one of the dSphs is no longer considered a viable indirect DM target.

- The analysis of the Dwarf Galaxies are preliminary and work is ongoing

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- Dwarf Spheroidal Galaxy discovered by SDSS (Zucker et al. 2007)
- 145 hours of quality-selected data between 2013 and 2017
- Limit computed using unbinned Maximum Likelihood (Aleksic, Rico and Martinez, 2012, jcap, 10, 32)
- band represents 1sigma uncertainty in the J factor
- Preliminary limit exceeds 216 hour combined limit at all masses for tau lepton and b quark channels
Recent VERITAS publication: Archer et al. 2016, apj, 821, 129

~85 hours of quality-selected data between 2010 and 2014

Galactic Center region does not transit above 30° elevation at VERITAS site
  - To overcome angular resolution degradation, we the Displacement method for gamma-ray reconstruction (Kosack et al. 2004), giving a PSF of ~0.12° with 68% containment
  - Raised energy threshold for galactic center analysis: ~2 TeV
- Raised energy threshold for VERITAS Observations
- Effective area for IACTs proportional to size of Cherenkov light pool
- Larger effective areas for higher energies
- VERITAS can do a very sensitive DM search for the highest WIMP masses (M \geq 10 \text{ TeV})
- Search regions in annuli above and below the SgrA*, excluding the galactic plane
- Work is still ongoing, search regions being finalized
It has been suggested that Fermi unassociated objects are actually DM subhalos (Pieri et al. 2008)

- VERITAS Candidates are:
  - Non-variable
  - Have powerlaw spectra extending to VHE
- Two suitable candidates in 2FGL
  - Each observed by VERITAS for ~10hrs each
- 2FGL J1115.0-0701 was found later to be variable
- 2FGL J0545.6+6018, fit to curved PL, W boson or b quark spectra
  - VERITAS Upper Limit ~0.6% of the Crab Flux
  - No X-ray counterparts found by Swift
  - New UV source found within error circle
Conclusions and Future Work

- VERITAS Primordial Black Hole search at this conference: S. Archambault [GA249]

- Dwarf Galaxies:
  - VERITAS Observations of 230 hours of dwarf galaxies between 2007 and 2013
  - Combined search and limits using 216 hours from 100 GeV to 100 TeV
  - Method utilizing individual event energies and directions
  - VERITAS has a larger data set with data taken after 2013
  - Fermi – VERITAS – HAWC working group for standardization and combination of DM searches

- Galactic Center:
  - VERITAS sensitivity for Dark Matter competitive at the highest WIMP masses