The VERITAS Dark Matter Program

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VERITAS Introduction

- Very Energetic Radiation Imaging Telescope Array System
- Employs ~100 scientists in five countries
- Full Array Operations since fall 2007
- Four 12m Davies-Cotton Telescopes in Southern AZ
- Upgrades:
  - Move of T1 in Summer 2009
  - Trigger Upgrade in November 2011
  - Camera Upgrade in Summer 2012

- Support From:
  - US DOE
  - US NSF
  - Smithsonian Inst.
  - STFC (UK)
  - SFI (Ireland)
  - NSERC (Canada)

- Performance:
  - Energy Range: 0.85 – 30 TeV (Post-Upgrade)
  - Energy Res: \( \Delta E/E \sim 0.2 \)
  - Angular Res: \( \sim 0.1 \) deg (68%)
  - Angular Accuracy: 50 arcsec
  - FOV: 3.5 deg
Gamma Rays from Dark Matter

Dark Matter is well described theoretically by extensions of the Standard Model of Particle physics (Supersymmetry, Kaluza-Klein) by a Weakly Interacting Massive Particle (WIMP) in the mass range of ~10 GeV – 10 TeV.

- WIMP annihilation production \( \gamma \)-rays
- Gamma-ray line from direct annihilation (higher order process)
- Gamma-ray continuum from hadronization
- Enhanced near \( M_{WIMP} \) from internal brems
- DM gamma-ray flux:

\[
\frac{dF(E, \hat{n})}{dE d\Omega} = \int d\ell \frac{\ell^2}{4\pi} r(\ell \hat{n}) \frac{dN_\gamma(E)}{dE} \frac{1}{4\pi \ell^2}
\]

\[
\left< \sigma v \right> \frac{dN_\gamma(E)}{dE} \frac{8\pi M^2}{dE} = \int d\ell \rho^2(\ell \hat{n})
\]

(Nearly) All Roads lead to Gamma Rays!

Particle Physics  Astrophysical Factor
VERITAS Dark Matter Targets

**Galactic Center (GC):**
- Close by
- Astrophysical backgrounds

**Dwarf Spherioidal Galaxies (DSphs):**
- Low Astrophysical Backgrounds
- High M/L
- Low Flux

**Galaxy Clusters:**
- Large DM Content
- Large Distance
- Potentially Extended
- Astrophysical backgrounds

**Unassociated Fermi Sources**
- Potentially DM Sub-halos?
DM Sub-Halo Candidates

- N-Body simulations predict the existence of DM sub-halos
  - Potentially close enough for VHE detection
  - Too small to attract Baryonic matter for star formation
    - Invisible at other wavelengths
- Selection Criteria for VERITAS Observations:
  - Lies outside the Galactic Plane
  - No variability
  - No spectral curvature
  - Detection feasible by extrapolation of Fermi-LAT spectra to VHE
  - No counterparts at other wavelengths
DM Sub-Halo Candidates

**2FGL J0312.8+2013**

- Exposure Time: 9.1 hrs
- Excess: $-25.7 \pm 16.9$
- Significance: $-1.5\sigma$
- Energy Threshold: 220 GeV
- Flux UL (99% CL): $< 1.78 \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}$
- $< 0.9\%$ Crab Nebula

**2FGL J0746.0-0222**

- Exposure Time: 9.1 hrs
- Excess: $-14.5 \pm 15.8$
- Significance: $-0.9\sigma$
- Energy Threshold: 320 GeV
- Flux UL (99% CL): $< 1.23 \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}$
- $< 1.1\%$ Crab Nebula
Galaxy Clusters

- 21 hrs on Coma Galaxy Cluster, low Zn observations
- No Detection with VERITAS or Fermi-LAT
- $\langle \sigma v \rangle^{95\% CL} \sim O(10^{-21}) \text{ cm}^{-3} \text{s}^{-1}$
- Archival Galaxy Cluster search currently underway
- Search for clusters that have overlapped in same FOV as previous VERITAS observations
- Cluster list from ROSAT and SDSS

![X-ray contours](image1.png)

![Radio contours](image2.png)

![Graph](image3.png)
Sgr A* Observation Strategy

- 18σ detection of SgrA*, 46 hours observation
- Large Zenith Observations → ~2 TeV threshold
- Increased CR density in GC, diffuse gamma-ray emission, SNR & PWNe in GC
- Two different ON/OFF pointings
  - Define signal/bg regions in ON/OFF maps, excluding SgrA* and other gamma-ray sources
  - Use OFF map to determine energy-dependent acceptance
DM Constraints from the Galactic Center

Preliminary Estimate
For 80 hour exposure

Sommerfeld-Boosted Cross Section

Natural Cross Section

$\langle \sigma v \rangle$ (cm$^3$ sec$^{-1}$)

$M_x$ (GeV)
DM Constraints from DSphs

- Already published shown here:
  - 15 hours on four DSphs
    - $\langle \sigma v \rangle \sim 10^{-23} \, \text{cm}^3\text{s}^{-1}$ at min $M_x$
  - 48 hours Segue 1
    - $\langle \sigma v \rangle \sim 10^{-24} \, \text{cm}^3\text{s}^{-1}$ at min $M_x$

Equation for cross-section:

$$<\sigma v>^{95\%CL} = \frac{8\pi}{J(\Delta \Omega)} \frac{N_\gamma^{95\%CL} m_X^2}{t_{obs} \int_0^{m_X} A_{eff}(E) \frac{dN_\gamma}{dE} dE}$$

- $N_\gamma^{95\%}$: counts UL, calculated from Rolke
- $A_{eff}(E)$: Effective area
- $J(\Delta \Omega)$: line of sight integral of DM density squared
- $t_{obs}$: Observation time on target
- $dN_\gamma/dE$: Single annihilation spectra for a WIMP
Segue 1 Results

- CR electron excess seen by Pamela/Fermi/HESS could be explained by a Sommerfeld enhancement
  - Arises when two DM particles interact though a attractive potential, mediated by a third particle.
- Velocity dependent, modifying cross-section
- Constraints on models of Lattanzi & Silk (2009), bottom left, and Arkani-Hamed et al (2009), bottom right
DSph Results of other IACTs

MAGIC: 160 hours on Segue 1
Full Maximum Likelihood method
ArXiv: 1312.1535

HESS: 141 hours combined on five dSphs
90 hours on Sagittarius
Maximum Likelihood Method
Deep exposure on Galactic Center as well
arXiv: 1410.2589
Deep Exposure Systematics

- 92 hours of data quality selection for Segue 1 from period of 2009 to 2013
  - Deepest VERITAS Observation \textit{without} seeing a strong gamma-ray signal

- Softer cuts used, improves statistics, but increases systematics
  - Wider significance distributions of backgrounds (Gaussian sigma > 1.0)

- Gradient correlating with Zenith angle of observations (above, right)
  - Fit of Non/Acc (Flatness) – Zenith curve used to re-weight acceptance
Deep Exposure Systematics (cont.)

- Bright stars are problematic for IACT data
- Suppressed pixels in cameras for analysis
  - Holes in skymaps
- Segue 1 has bright star (Eta Leonis, 3.8 BMag)
  - located 0.68 deg away
- New HFit algorithm - 2D Gaussian fit of all pixels in camera, no cleaning
- Tested on independent data set - RBG J1058
### DSph Results after Systematic corrections:

<table>
<thead>
<tr>
<th>DSph</th>
<th>Exposure (hrs)</th>
<th>( \log_{10} J ) (GeV²cm⁻⁵)</th>
<th>Significance (( \sigma ))</th>
<th>Eth (GeV)</th>
<th>Flux UL, 95% CL (&gt; 300 GeV), Index = -2.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segue 1</td>
<td>91.9</td>
<td>19.0</td>
<td>0.7</td>
<td>150</td>
<td>( 4.2 \times 10^{-9} ) cm⁻²s⁻¹, ( \sim 0.3 % ) CU</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>59.7</td>
<td>18.9</td>
<td>-0.1</td>
<td>290</td>
<td>( 3.4 \times 10^{-9} ) cm⁻²s⁻¹, ( \sim 0.2 % ) CU</td>
</tr>
<tr>
<td>Draco</td>
<td>49.9</td>
<td>18.4</td>
<td>-1.0</td>
<td>220</td>
<td>( 3.4 \times 10^{-9} ) cm⁻²s⁻¹, ( \sim 0.2 % ) CU</td>
</tr>
<tr>
<td>Boötes 1</td>
<td>14.3</td>
<td>17.9</td>
<td>-1.0</td>
<td>170</td>
<td>( 5.0 \times 10^{-9} ) cm⁻²s⁻¹, ( \sim 0.3 % ) CU</td>
</tr>
<tr>
<td>Wilman 1</td>
<td>13.7</td>
<td>18.9</td>
<td>-0.6</td>
<td>180</td>
<td>( 1.1 \times 10^{-8} ) cm⁻²s⁻¹, ( \sim 0.7 % ) CU</td>
</tr>
</tbody>
</table>
Future Work: Combined DM Analysis

- VERITAS DM results shown previously do not use individual photon information, one limit per source

- Event Weighting method used for Fermi-LAT data of DSphs (Geringer-Sameth et al. arXiv:1410.2242)
  - Authors working with VERITAS Collaboration
  - Each event is assigned a weight as a function of energy and position, increased sensitivity
  - Events closer to target with lower energy more likely to be from DM annihilation
  - Sum of weights is test statistic to test hypothesis of events existing due to DM annihilation with given $M$ and $<\sigma v>$
  - Able to combine multiple sources and instruments into a single DM limit
  - Very close to having new DM physics results ready (~1 month)
  - J factors to be used from Geringer-Sameth et al. [arXiv:1408.0002]

arXiv:1408.0002
Concluding Remarks

VERITAS dark matter program is ongoing:
- Observations of dSphs, GC, Fermi UNIDs, galaxy clusters
- No detections of DM (yet!)
- Gaining better understanding of systematics, utilizing new techniques
- Segue 1 Flux UL reduced with longer exposure: \(~0.5\%\) Crab \(\rightarrow\) \(~0.3\%\) Crab

Future Plans:
- Continuing observations of dark matter targets
- Significant portion of VERITAS observing time (~170 hrs/year)
- Analysis of dSphs for combined analysis paper ongoing (~230 hours!)
  - Gamma-ray analysis/Flux UL complete
  - Dark Matter physics limits soon, including line search
- Galactic center
  - SgrA* detection paper complete
  - Work on DM limits of halo ongoing
- Fermi UNIDs
  - More data to be taken, search for more feasible Fermi UNIDs
- Galaxy Clusters
  - Archival work underway, work on extended source systematics