The VERITAS Dark Matter Program

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In the cosmological paradigm, cold dark matter (DM) dominates the mass content of the Universe and is present at every scale. Candidates for DM include many extensions of the standard model, with a weakly interacting massive particle (WIMP) in the mass range from ∼10 GeV to greater than 10 TeV. The self-annihilation or decay of WIMPs in astrophysical regions of high DM density can produce secondary particles including very high energy (VHE) gamma rays with energy up to the DM particle mass. VERITAS, an array of atmospheric Cherenkov telescopes, sensitive to VHE gamma rays in the 85 GeV - 30 TeV energy range, has been utilized for DM searches. The possible astrophysical objects considered to be candidates for indirect DM detection are VERITAS dwarf spheroidal galaxies (dSphs) of the Local Group and the Galactic Center, among others. This presentation reports on our extensive observations of these targets and constraints of the dark matter physics from these objects, including the methodology and preliminary results of a combined DM search of five dSphs.

1. INTRODUCTION

The search for Standard Model (SM) particles resulting from the annihilation of Dark Matter particles provides an important complement to that of direct searches for DM interactions and accelerator production experiments. Among the theoretical candidates for the DM particle [1], weakly interacting massive particles are well motivated since they naturally provide the measured present day cold DM density [2]. Candidates for WIMP dark matter are present in many extensions of the SM of particle physics, such as supersymmetry (SUSY) [3] or theories with extra dimensions [4]. In such models, the WIMPs either decay or self-annihilate into standard model particles, most of which produce either a continuum of gamma rays with energies up to the DM particle mass, or mono-energetic gamma-ray lines.

Attractive targets for indirect DM searches are nearby massive objects with high inferred DM density which are not expected to be sources of VHE gamma rays. The Galactic Center is likely the brightest source of gamma rays resulting from DM annihilations, however the detected VHE gamma-ray emission is coincident with the supermassive black hole Sgr A* and a nearby pulsar wind nebula [5], motivating searches for DM annihilation in the Galactic Center halo where the VHE gamma-ray background is expected to be significantly lower [6]. Galaxy Clusters have a large DM content. However, they are extended for VERITAS, and the possibility exists of a VHE background from conventional processes [7] [8], although not yet detected. Galactic DM sub-halos would appear as unidentified objects (UNIDs) without multi-wavelength counterparts in Fermi-LAT data. If a Fermi UNID were detected in VHE, it could potentially be from DM. Dwarf spheroidal galaxies (dSphs) are additional attractive targets for DM searches. Dwarf spheroidal galaxies are relatively close (∼50 kpc), and have a low rate of active or recent star formation, which suggests a low background from conventional astrophysical VHE processes [9].

The following sections describe the status of observations and data analysis of each of the DM targets described above as of fall 2014, followed by conclusions and a discussion of the future of the VERITAS DM program.

2. SUB-HALOS

Recent cosmological N-body, high-resolution simulations [10] indicate that DM halos are populated with a wealth of substructures [11]. Because of tidal disruption near the Galactic disk, most of the sub-halos are thought to survive at high Galactic latitude. The lack of material in these regions prevents the DM overdensities from attracting enough baryonic matter and trigger star formation. DM clumps would therefore be invisible to most astronomical observations from radio to X-rays. DM structures residing in the the Milky Way halo can be nearby the Sun and therefore have a bright gamma-ray annihilation signal [12]. These clumps would likely be only visible at gamma-ray energies and therefore may not have shown up in astronomical catalogs yet. Since gamma-ray emission from DM annihilation is expected to be constant, DM clumps could then appear in all-sky monitoring programs [14] done at gamma-ray energies. These can be best provided by the Fermi-LAT instrument. Very likely, the distinct spectral cut-off at the DM particle mass is located at energies too high to be measurable by Fermi within a reasonable timescale (see, e.g., the WIMP mass lower limits in [13]) and can only be detected by ground-based telescopes, such as VERITAS. Furthermore, detection of this spectral cut-off at the same energy in multiple objects would stand as a visible signature of DM. The Second Fermi-LAT Catalog (2FGL) contains 1873 high energy gamma-
ray sources detected by the LAT instrument after the first 24 months of observations. For each source, positional and spectral information are provided as well as identification or possible associations with cataloged sources at other wavelengths. Although Fermi-LAT has a good angular resolution, a firm identification based on positional coincidence alone is not always feasible. Thus, 576 sources in the 2FGL lack any clear association. These are the so-called unassociated Fermi objects (UFOs), a population among which DM clumps might be represented [16]. In order to extract possible DM clump candidates out of the 2FGL UNIDs, we adapt the selection criteria from [17], selecting sources by requesting them:

- to lie outside the Galactic Plane,
- to be non-variable,
- to exhibit a power law spectra, and
- to not have possible counterparts.

The original list obtained from the 2FGL catalog is then filtered to select only sources observable with VERITAS with a maximum zenith angle at culmination of 40°, in order to pursue the lowest energy threshold. Additionally, an estimate of required observation time for a 5σ detection, dubbed detectability, is computed based on a 2FGL Catalog flux extrapolation to the VERITAS energy range.

The preliminary results of the VERITAS observations shown in Table 1 are in tension with the extrapolation of the gamma-ray spectra from the Fermi-LAT to very high energies. Additional data from these UNIDs and others by VERITAS and other Cherenkov telescopes may completely completely rule out a direct extrapolation of the Fermi-LAT which would give strong DM model constraints or potentially detect a DM signature, provided that they are truly without counterparts at other wavelengths.

### Table I Preliminary DM Sub-halo Results.

Flux upper limits are given in units of Crab Nebula flux.

| 2FGL Name | Exposure (hrs) | Significance (σ) | Excess Counts | $E_{tr}$ (GeV) | $E^{99\text{\% CL}}_{\gamma}$ (C.U.) |
|-----------|---------------|------------------|---------------|--------------|----------------------------------|
| J0312.8+2013 | 9.7           | -1.5             | -26 ± 17      | 220          | < 0.9%                           |
| J0746.0−0222 | 9.1           | -0.9             | -15 ± 16      | 320          | < 1.1%                           |

![Figure 1: Dark Matter velocity-averaged cross-section limits from the Coma galaxy cluster. Figure taken from [19].](image)

**Figure 1:** Dark Matter velocity-averaged cross-section limits from the Coma galaxy cluster. Figure taken from [19].

3. GALAXY CLUSTERS

Clusters of galaxies are the largest virialized objects in the Universe, with typical sizes of a few Mpc and masses on the order of $10^{14}$ to $10^{15} M_\odot$. Most of the mass ($\sim$ 80%) is dark matter, as indicated by galaxy dynamics and gravitational lensing [18]. Aside from DM annihilation, it is possible to have gamma-ray emission from cosmic-ray interactions, producing neutral pions [7], or inverse Compton of ambient photons [8].

VERITAS has taken 18.6 hours of dedicated observations of the Coma cluster between March and May 2008. The Coma cluster is a close ($z=0.023$) and massive ($M\sim 10^{15} M_\odot$) cluster which has been thoroughly studied across all wavelengths. The standard analysis of the Coma cluster data using point-source cuts for the core of the cluster yielded 17 excess counts, with a significance of 0.84σ, indicating a non-detection. Upper limits of 0.83% of the Crab Nebula flux were placed for the core of the Coma cluster with 95% confidence, assuming a powerlaw spectral index of -2.3. With the absence of a signal from the Coma cluster, limits of the velocity-averaged cross-section for DM annihilation were placed at $O(10^{-21})$, as shown in Figure 1 [19].

An archival VERITAS galaxy cluster search is also in the works, looking for galaxy clusters that have happened to overlap in the same FOV as other targeted observations. ROSAT and SDSS galaxy cluster catalogs are being used to cross-check with other VERITAS observations. Most notably M87 in the Virgo cluster of galaxies [20] and NGC 1275 in the Perseus cluster [21].
4. GALACTIC CENTER

The center of our galaxy, SgrA*, is a strong VHE source, along with several other VHE sources nearby \[22\] and possible diffuse emission \[23\], making Dark Matter detection in that region a complicated, but not impossible, prospect.

The Galactic center was observed by VERITAS in 2010-2014 for \(\sim 80 \text{hrs} \) (good quality data) at zenith angles of \(z = 60 - 66 \text{deg}\) (average threshold of \(E_{\text{thr}} \approx 2.5 \text{TeV}\)). The higher effective areas due to the large zenith angle observations make the VERITAS observations now the most sensitive instrument for the Galactic Center region above 2 TeV. The detection of SgrA* by VERITAS and VHE emission in the region through conventional processes are discussed in greater detail elsewhere in these proceedings \[24\].

The DM signal and background regions for the Galactic center region will use arc-shaped regions north and south of the Galactic plane to avoid diffuse emission and VHE sources, as shown in Figure 2. The VERITAS observations were accompanied by off-source observations of a field located in the vicinity of the Galactic center region (with similar zenith angles and sky brightness) without a known TeV \(\gamma\)-ray source. These observations are used to study the background acceptance throughout the field of view and will assist in the identification of a diffuse \(\gamma\)-ray component surrounding the position of the Galactic center.

The DM search for the Galactic center region is still in the preliminary stages. Work is currently underway for computing J factors for the signal and background regions for the arc-shaped regions described above.

5. DWARF GALAXIES

Dwarf spheroidal galaxies (dSphs) best meet the criteria for a clear and unambiguous detection of dark matter. They are gravitationally-bound objects and contain up to \(\mathcal{O}(10^3)\) times more mass in DM than in visible matter \[1\]. As opposed to the Galactic center, globular clusters and clusters of galaxies, dSphs present the clear advantage of being free of any significant astrophysical emission. Their high Galactic latitude and relative proximity to Earth \(\sim 50 \text{kpc}\) make them very good targets for high signal-to-noise detection.

Between the start of full VERITAS array operations and Summer 2013, five dSphs have been observed with VERITAS: Segue 1, Ursa Minor (UMi), Draco, Boötes 1, and Willman 1. The VERITAS collaboration has previously published a 48 hour exposure on Segue 1 \[20\] and \(\sim 15 \text{hour} \) exposures on the other four mentioned here \[25\]. Deeper exposures on Segue, UMi and Draco have been taken after these publications. To obtain the lowest possible energy threshold for DM searches, looser cuts optimized \textit{apriori} on soft spectral VHE sources were used for the collective data set. The combination of looser cuts and deeper exposures revealed certain systematic effects in the cosmic-ray (CR) background data. The first is a gradient in the VERITAS cameras dependent on the zenith angle of observations across the FOV. The second systematic effect results from bright stars in the VERITAS FOV that cause the high voltage to pixels in the cameras to be suppressed. Both of these systematic effects have been corrected for and the results are summarized in Table 2. The ‘crescent’ background method which also developed for dSph analysis \[27\] was also used for the Table 2 results.

The first background systematic effect, relating to the zenith gradient, was corrected using a zenith-dependent acceptance map. The standard VERITAS analysis uses only a radially-dependent acceptance, i.e. the angle between the reconstructed event direction and the array pointing direction. Measuring the gradient utilized a map that is the ratio of the number of all reconstructed events in a sky map within a given search radius (defined as 0.17 degree in this work) to the (radial only) acceptance in that same bin, a parameter we will refer to as \textit{flatness} in the rest of this work. If the acceptance adequately describes the CR background, then excluding any stars or known VHE sources, it should not correlate with any external parameters. However, a strong correlation was seen with the mean zenith angle of each reconstructed event position in the skymap bin. This correlation in the skymap bins is shown in Figure 3. This gradient is corrected in the data by fitting the correlation with a fourth-degree polynomial and using that to re-weight the acceptance map. The \(\alpha\) parameter from Li & Ma equation 17 is then re-calculated \[28\], \[29\].

Figure 2: Skymap of the galactic center region using a subset of the VERITAS data. DM signal and background regions are indicated north and south of SgrA*.
Table II Preliminary DM DSph Results

| DSph Name    | Exposure (hrs) | Significance (σ) | Excess Counts | $E_{tr}$ (GeV) | $F^{99\%\text{CL}}$ (C.U.) |
|--------------|----------------|------------------|---------------|----------------|--------------------------|
| Segue 1      | 92.0           | 0.7              | 94.4 ± 134.1  | 150            | < 0.4%                   |
| Ursa Minor   | 59.7           | -0.1             | -7.2 ± 68.5   | 290            | < 0.3%                   |
| Draco        | 49.9           | -1.0             | -73.2 ± 69.1  | 220            | < 0.3%                   |
| Boötes 1     | 14.0           | -1.0             | -38.5 ± 36.7  | 170            | < 0.3%                   |
| Willman 1    | 13.7           | -0.6             | -28.7 ± 46.2  | 180            | < 1.0%                   |

Figure 3: Scatter plot of the flatness parameter on the y-axis, and the mean zenith difference between the array tracking direction and event reconstruction direction on the x-axis for the Segue 1 data summarized in Table 2. A fit of this scatter to a fourth-degree polynomial is shown in red.

It should be noted that the difference of the adjusted value of $\alpha$ to the non-adjusted value is typically less than 1%. However, the difference to the $\gamma$-ray excess and significance becomes larger over time as statistics accumulate.

The second background systematic effect is due to “holes” that are seen in the data relating to bright stars in the FOV that would trip the high voltage of camera pixels or raise cleaning thresholds due to higher night-sky background levels. Missing pixels would in turn effect both energy and gamma-ray position reconstruction. A method of using a 2D Gaussian likelihood fit to each shower image is utilized here, called HFit [30]. Standard VERITAS analysis uses the moments of the shower images, commonly referred to as Hillas parameters. By using the 2D elliptical fitting to each image, missing data from disabled or broken PMTs are effectively interpolated around, as are images truncated by the edge of the cameras, as shown in Figure 4. This has been shown to reduce both the size and the depth of the holes due to bright stars seen in the data, including but not limited to the B magnitude 3.4 star Eta Leonis which is located 0.68° away from the center of the Segue 1 dSph. The effectiveness of HFit on an independent data sample is shown in Figure 5, which shows the apparent surface brightness in the CR background (which is in reality a deficit for reasons described above) at a star location in the FOV of the blazar RGB J1058+564 (Merak, 2.4 B magnitude).

Work is currently underway to utilize the data for the previously published papers plus additional data for a combined DM physics result. This result will use the methodology developed by Geringer-Sameth et al. [31] to utilize both the individual energy and event reconstruction information as well as astrophysical “J factors” from a generalized NFW profile by Geringer-Sameth and Walker [32].
Figure 5: Apparent surface brightness of background cosmic ray events as a function of angle $\theta$ from the bright star, Merak, in the FOV of RGB J1058+564 using both the HFit algorithm and the standard Hillas shower image characterization. The VERITAS data analysis typically excludes regions around bright stars or known VHE sources from cosmic-ray background characterization. The default radius for background exclusion region for Merak is also shown as the dashed blue line.

6. CONCLUSIONS

New DM publications from the VERITAS collaboration are forthcoming: the combined analysis of the dSphs should be publically available within the next six months, which promises to be the most robust result of any DM result in VHE gamma rays so far, while DM results for the Galactic Center, Fermi UNIDs and the archival galaxy cluster search should be ready on longer timescales. New analysis techniques are being developed by the VERITAS collaboration which promise large gains to our DM sensitivity, as an example an extended analysis of the dSphs which would incorporate longer tails of the DM density profile, which would in turn give a boost to the $J$ factors by as much as a factor of $\sim 2$. A combined analysis with Fermi-LAT, or other $\gamma$-ray instruments could potentially provide a boost to DM sensitivity.

The VERITAS collaboration has a historical commitment to substantial DM observations and plans to do so in the foreseeable future. Recently, a new long-term plan for VERITAS has gone into effect, which has a significant fraction (15-20%) of the total dark observation time dedicated to DM observations. The focus of this long-term plan is dSphs; however the galactic center, Fermi UNIDs and galaxy clusters will not be completely ignored. If executed consistently over the expected lifetime of VERITAS, these observations will form the basis of an important and unique contribution to the field of indirect DM detection.

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