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# A Search for Dark Matter from Dwarf Galaxies using VERITAS

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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 are found in many extensions of the standard model with weakly interacting massive particles (WIMPs) 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 indirect DM searches. The astrophysical objects considered to be candidates for indirect DM detection by VERITAS are dwarf spheroidal galaxies (dSphs) of the Local Group and the Galactic Center, among others. This presentation reports on the observations of five dSphs, and the results from a joint DM search from these objects.

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## 1. Introduction

The composition of the particle candidates comprising dark matter (DM) is still a large open question. Extensions of the standard model (SM) such as supersymmetry (SUSY) [1] or theories with extra dimensions [2] including weakly interacting massive particles (WIMPs) would annihilate or decay into standard model particles, and this would produce a continuum of $\gamma$ rays with energies up to the DM particle mass [3] or mono-energetic $\gamma$-ray lines [4]. The indirect search for SM particles from astrophysical objects with a large inferred DM density is an important complement to direct searches for DM interactions and accelerator production experiments.

Attractive objects for indirect DM detection by $\gamma$-ray instruments are massive, relatively close objects likely not to be $\gamma$-ray emitters. Dwarf spheroidal galaxies (dSphs) fit all of these criteria: they are relatively close (~50 kpc) with high mass-to-light ratios, and have low rates of active star formation, suggesting a low background from conventional astrophysical VHE processes [5]. This work reports the results of observations of dwarf galaxies with the Very Energetic Radiation Imaging Telescope Array System (VERITAS).

VERITAS is a Imaging Atmospheric Cherenkov Telescope (IACT) located in southern Arizona, USA. VERITAS is sensitive to very-high energy (VHE) $\gamma$ rays in the energy range between 85 GeV and 30 TeV. The point-spread function (PSF) of VERITAS is ~0.1° with 68% containment at 1 TeV and the pointing accuracy is better than 50 arc seconds.

## 2. VERITAS Data and Analysis

In the period between 2007 and 2013, VERITAS observed five dSphs: Boötes I, Draco, Ursa Minor, Willman I and Segue I, accumulating a total of ~230 quality hours, including 92 hours devoted to Segue I. The total observing time for each dSph is listed in Table 1. The quality selection for the data requires nominal operations of all four telescopes and clear moonless skies.

The inferred DM annihilation luminosity is referred to as the ‘J factor’ or ‘astrophysical factor’ is defined as:

$$J_{ANN} = \int\int \rho(l,\Omega)^2 dl d\Omega \tag{2.1}$$

where $\rho(l,\Omega)$ is the DM density profile and $l$ is the distance along the line of sight. The J factor for the dSphs studied in this work are also listed in Table 1, using the values from [6]. This work will later refer to a ‘J profile’ which is the J factor per solid angle: $dJ_{ANN}/d\Omega$.

Data analysis mostly uses the standard techniques [7], with a few notable exceptions. In order to construct a background spectrum, which is required by the event weighting method described later in the text, the cosmic-ray background was subtracted using an annulus around the telescope array tracking direction [8]. Also, in this work looser cuts optimized for soft spectrum sources were used, in order to obtain the lowest possible energy threshold. The combination of deep exposures and the lower-energy-threshold cuts revealed background systematics in the cameras, namely a gradient along the direction of zenith angle of observation and deficit regions in the camera due to optically bright stars. The 3.8 magnitude star $\eta$-Leonis located 0.68° away from Segue I was of particular concern. The zenith gradient was corrected for by using a zenith-dependent acceptance

| Dwarf | Live time [hrs] | $\log_{10} J$ [$\mathrm{GeV}^2\mathrm{cm}^{-5}$] | Significance [$\sigma$] | $F^{95\%}_{-12}$ [$10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] |
|---|---|---|---|---|
| Segue 1 | 92.0 | $19.36^{+0.32}_{-0.35}$ | 0.7 | 0.34 |
| Ursa Minor | 60.4 | $18.93^{+0.27}_{-0.19}$ | -0.1 | 0.37 |
| Draco | 49.8 | $18.84^{+0.10}_{-0.09}$ | -1.0 | 0.15 |
| Boötes | 14.0 | $18.24^{+0.40}_{-0.37}$ | -1.0 | 0.40 |
| Willman 1 | 13.7 | N/A | -0.6 | 0.39 |

**Table 1:** Summary of dSph data used in this work. $J$ factors are from [6] with an integration radius of 0.5° around each Dwarf. Dwarf galaxy detection significance is calculated from Li & Ma equation 17 [12] and integral upper 95% confidence level flux limit in units of $10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ above 300 GeV, assuming a spectral index of -2.4, using the Rolke method with bounded intervals [13]

function [9][10]. The bright stars were corrected for using a 2D elliptical fit to each shower image, as opposed to a moment analysis [11]. This had the benefit of being unbiased towards camera pixels that were shut off due to high currents or had raised cleaning thresholds due to higher night-sky background levels and improving the PSF, particularly at higher energies. Detection significances are calculated using Li&Ma equation 17 [12]. No significant $\gamma$-ray emission was found in the direction of any of the dSphs. Flux upper limits were calculated above 300 GeV using the Rolke method [13].

## 3. Dark Matter Search

To search for dark matter in several dSphs simultaneously, an event weighting method is employed. The full details of the method are in [14] and are only summarized here. It improves on conventional IACT techniques for DM searches by utilizing the energies and spatial properties of the individual events, as well as the instrumental and astrophysical background properties. Each event in the region-of-interest around the dSphs (defined as the ON region in most IACT analysis) is assigned a weight, $w_i$, based on the dwarf field it originates from, $\nu$, reconstructed energy $E$, and reconstructed angular direction away from the direction of the center of the dwarf, $\theta$. The test statistic for the hypothesis of $\gamma$ rays being produced by dark matter is the sum of the weights from all events: $T = \sum w_i$. The index $i$ is summed over all ON events for all dSphs. The form of the weight function is:

$$w(\nu,E,\theta) = \log\left[1+\frac{s(\nu,E,\theta)}{b(\nu,E,\theta)}\right] \tag{3.1}$$

where $s(\nu,E,\theta)$ and $b(\nu,E,\theta)$ are the total number of expected signal and background events with those properties, respectively. The number of expected background events is extracted by a spectrum generated from the OFF data for each data run using the method described in the previous section. The background is assumed to be isotropic within this region, so $b(\nu,E,\theta)$ is proportional to $\sin(\theta)d\theta$.

The expected signal $s(\nu,E,\theta)$ is determined by a convolution of the dark matter annihilation flux with the VERITAS instrument response

$$s(\nu,E,\theta) = \frac{dN(\nu,E,\theta)}{dEd\Omega} dE 2\pi \sin(\theta) d\theta \tag{3.2}$$

where the number of events reconstructed with energy $E$ and angular separation $\theta$ is given by the equation:

$$\frac{dN(\nu,E,\theta)}{dEd\Omega} = \int_{E_t}\int_{\Omega_t} dE_t d\Omega_t \frac{F(E_t,\theta_t)}{dE_t d\Omega_t} R(E,\theta|E_t,\theta_t) \tag{3.3}$$

where the subscript $t$ denotes true energies and directions and the $R$ is the VERITAS instrument response function which is a function of the effective area, live time, instrument PSF, and energy dispersion (the probability to measure $E$ given $E_t$). Effective area, PSF and energy dispersion are generated from $\gamma$-ray Monte Carlo. The function $F$ is the $\gamma$-ray flux from dark-matter annihilation:

$$\frac{dF(E_t,\theta_t)}{dE_t d\Omega_t} = \frac{\langle\sigma v\rangle}{8\pi M^2}\frac{dN_\gamma(E)}{dE}\frac{dJ(\theta)}{d\Omega} \tag{3.4}$$

where $dN_\gamma(E)/dE$ is the number of $\gamma$ rays produced per annihilation, $dJ(\theta)/d\Omega$ is the DM density profile, $M$ is the dark matter particle mass, $\langle\sigma v\rangle$ is the velocity-weighted annihilation cross section (later referred to as simply 'cross section'). The single annihilation spectrum used in this work is from PPP4 [15] and the DM density profile from [6].

In order to search for annihilation or set limits on the cross section, we need to compute a probability distribution for $T$, with the null hypothesis that the observed test statistic, $T_{obs}$, is due to only background processes. The detection significance is defined as the probability that $T$ is less than $T_{obs}$ under the background-only hypothesis (equivalent to $\langle\sigma v\rangle$ =0). The description of computing the probability distributions is too lengthy to be included here, and is detailed in [14]. This distribution is computed for different values of $M$ and choice of DM annihilation channels.

## 4. Limits to Annilhation Cross-section

With the absence of a DM signal, we compute the limits to the annihilation cross section. The 95% confidence limits are generated by performing the hypothesis test at several values of the cross section. The $\langle\sigma v\rangle$-space is divided into two regions where the hypothesis can and cannot be rejected at 95% confidence. The hypothesis test is performed by asking, for a given value of $\langle\sigma v\rangle$, whether the probability that $T < T_{obs}$ is less than 5%. The boundary between the two regions represents the 95% upper limit to the cross section.

Figure 1 shows the 95% confidence limit obtained with the 216 hours of dSph data. Willman I was not used for the combined search or the annihilation cross section limits, because the J factor could not be reliably calculated. Each panel shows a 100% branching fraction into various Standard Model final states. The shaded band for the limits represents the $1\sigma$ systematic uncertainty that exists because of imperfect knowledge of the dSph density profiles which is the dominate systematic effect in this work. Figure 2 shows the median observed DM limit for the $\tau^+\tau^-$ and $b\bar{b}$ channels with $1\sigma$ and $2\sigma$ statistical uncertainties (the limit has a 68% and 95% chance to be within the red and green bands, respectively). Note that the observed limit does not exceed $\pm 2\sigma$ of the expectation limit for any value of the DM mass, indicating a non-detection of DM.

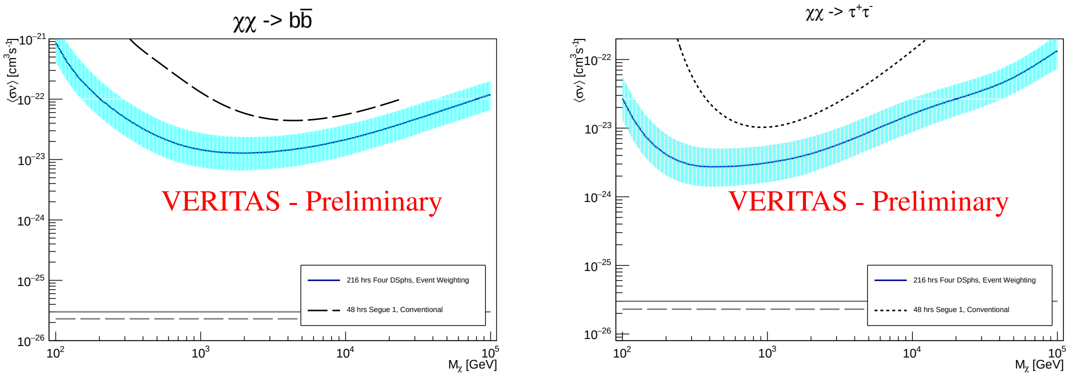

**Figure 1:** Preliminary observed cross section exclusion limits as a function of DM particle mass with 95% confidence for annihilation channels $b\bar{b}$ (left), $\tau^+\tau^-$ (right). The blue bands indicate the $1\sigma$ systematic uncertainty in the dark matter profile. The cross section limits for the previously published 48 hour exposure VERITAS observations of Segue I are also shown [16].

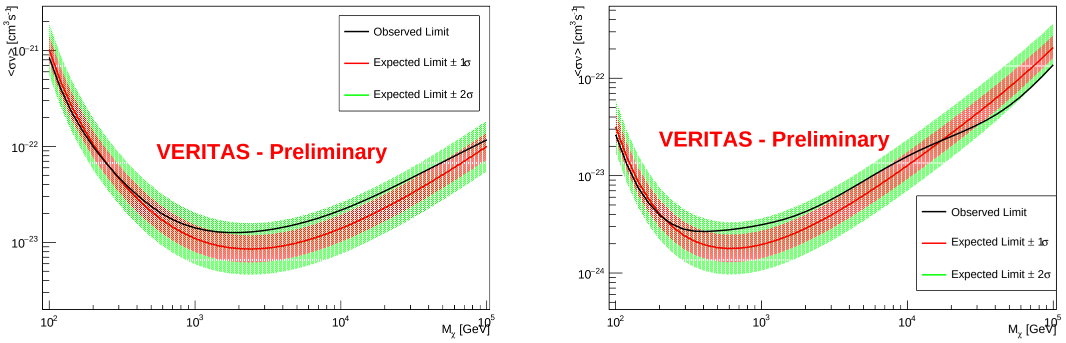

**Figure 2:** Preliminary observed cross section exclusion limits with the $1\sigma$ and $2\sigma$ statistical uncertainties.

## 5. Conclusions

Presented here are the results for IACT analysis using the event weighting method that has been successful for Fermi-LAT, which uses information from several objects to compute a combined search and cross section limits. No evidence of a DM annihilation signal is found in 216 hours of combined dSph data, and limits on the annihilation cross section have been computed. The Event Weighting method has the added benefit of using the VERITAS PSF and individual event reconstruction direction in addition to using the individual energies of each event, leading to much more robust cross section limits. The combination of softer cuts used for the analysis, roughly twice the exposure for Segue I, and the event weighting method leads to much more improved cross section limits compared to previous VERITAS results [16], as shown in Figure 1. This method can at some point in the future be applied to other $\gamma$ ray instruments such as CTA and combine results with several instruments into a single result.

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## References

[1] Jungman, G., et al. 1996, PhR, 267, 195

[2] Servant, G., et al. 2003, Nuclear Physics B, 650, 391

[3] Bertone, G., et al., 2009, Phys.Rev. D80, 023512.

[4] Bringmann, T., et al., 2008, JHEP 0801, 049.

[5] Baltz, E. A., et al., 2000, prd, 61, 023514

[6] Alex Geringer-Sameth et al., 2015, ApJ 801 74.

[7] Cogan, P. 2008, International Cosmic Ray Conference, 3, 1385

[8] Zitzer, B., for the VERITAS Collaboration 2013, arXiv:1307.8367

[9] Zitzer, B. for the VERITAS Collaboration 2015, arXiv:1503.00743

[10] Rowell, G. P., 2003, aap, 410, 389

[11] Christiansen, J., et al., American Institute of Physics Conference Series, 1505, 709

[12] Li, T.-P., & Ma, Y.-Q., 1983, ApJ, 272, 317

[13] Rolke, W. A., et al., 2005, Nuclear Instruments and Methods in Physics Research A, 551, 493

[14] Geringer-Sameth, A., Koushiappas, S. M., & Walker, M. G. 2015, prd, 91, 083535

[15] Cirelli, M., et al. arXiv 1012.4515, JCAP 1103 (2011) 051. Erratum: JCAP 1210 (2012) E01.

[16] Aliu, E., et al., 2012, PRD, 85, 062001. Erratum: PRD, 91, 129903 (2015)