Indirect searches for Dark Matter annihilations toward dSph galaxies with VERITAS

M.Vivier [1] for the VERITAS collaboration[2]

(1) Department of Physics & Astronomy and the Bartol Research Institute, University of Delaware, Newark DE 19716

(2) http://veritas.sao.arizona.edu

Abstract: 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 50 GeV to greater than 10 TeV. The self-annihilation of WIMPs in astrophysical regions of high DM density can produce secondary particles, including Very High Energy (VHE) gamma rays, with energies up to the DM particle mass. The VERITAS array of Cherenkov telescopes, designed for the detection of VHE gamma rays in the 100 GeV-10 TeV energy range, is an appropriate instrument for the detection of DM and is complementary to Fermi-LAT. Dwarf spheroidal galaxies (dSphs) of the Local Group are potentially the best targets to search for the annihilation signature of DM due to their proximity and large DM content. This poster reports on the latest VERITAS observations of dSphs and discusses the results in the framework of WIMP models.

The VERITAS Cherenkov telescope array

The VERITAS array of Cherenkov telescopes is located in southern Arizona at the Fred Lawrence Whipple Observatory. VERITAS consists of four Imaging atmospheric Cherenkov telescopes, which collect the Cherenkov light emission from particle cascades initiated by cosmic-rays in the upper atmosphere. VERITAS is designed to detect very high energy (VHE) γ-rays with energies between 100 GeV and 30 TeV. The stereoscopic reconstruction of showers allows for an enhanced background rejection, with an energy resolution of 15 – 25 % and an angular resolution < 0.1 deg. In its current configuration, VERITAS is able to detect 1% of the Crab Nebula flux in less than 30 h of observations.

Dwarf spheroidal galaxies

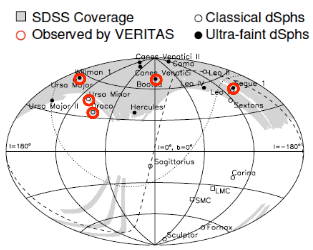


Figure: A non-exhaustive list of the known Milky Way satellites with their location shown in Galactic coordinates. Filled circles are dSphs discovered by the Sloan Sky Digital Survey (SDSS), unfilled circles are the previously known dSph. From Belokurov et al. (2007)

Dwarf spheroidal galaxies are DM dominated objects orbiting around the Milky Way. Embedded in the Milky Way DM halo, they are believed to be the remnants of smaller DM halos formed in hierarchical clustering scenarios. Dsphs are generally high latitude objects with very poor gas content and no VHE γ-ray sources. These galaxies are environments with a favorably low γ-ray astrophysical background, and are therefore promising targets for the indirect detection of DM. Interest in dSphs as DM target has been recently enhanced by the discovery of a number of new ultra-faint dSphs in the SDSS survey of the northern sky (see figure above). VERITAS has started a deep observation campaign on the closest and best-studied ones, namely **Draco, Ursa Minor, Bootes 1, Willman 1, and Segue 1.**

VERITAS observations and analysis

VERITAS has been observing dSphs since early 2007, immediately after the full array was commissioned. The so-called wobble pointing mode, where the pointing position is shifted by ± 0.5 deg from the target position, has been used. This pointing strategy is used to minimize the systematic uncertainties in the background determination. After calibration of the data, the γ-rays are selected by calculating the Hillas parameters of the recorded images. The selection cuts were optimized for the detection of a 3.5 % Crab-like source. After the γ-ray selection, the residual background in a circular region of 0.1 deg radius centered on the target position (called the ON source region) is estimated using the reflected background model.

The analysis of the data did not reveal any significant excess over the estimated background in any of these observations. The table below displays the measured γ-ray excesses for each of the dSphs, along with the corresponding significance and the resulting upper limits in terms of number of of γ-rays in the ON source region and of integrated flux above the analysis energy threshold.

Quantity/dSph	Draco	Ursa Minor	Boötes 1	Willman 1	Segue 1
Excess [counts]	-28.4	-30.4	28.5	-1.45	-17.5
Significance[a] [s]	-1.51	-1.77	1.35	-0.08	-1.1
95% CL upper limit[b] [counts]	18.8	15.6	72.0	36.7	13.4
E_{th} [GeV]	340	380	300	320	300
Flux upper limit 95 % CL[c] [$cm^{-2}\ s^{-1}$]	0.5×10^{-12}	0.4×10^{-12}	2.2×10^{-12}	1.2×10^{-12}	0.2×10^{-12}

[a] Li and Ma method (Li & Ma 1983)
[b] Rolke method (Rolke et al. 2005)
[c] Above energy threshold, for a Crab-like spectrum

The limits are comparable to the observations conducted by MAGIC on the same dSphs, and are better than the Whipple limits by a factor of 40.

Constraints on DM models

The upper limits on the number of γ-rays can be converted to bounds on the annihilation cross-section $\langle\sigma v\rangle$ as a function of the hypothetical DM particle mass m_χ. The expected γ-ray flux from DM annihilation can be expressed as:

$$\frac{d\phi}{dE} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\left[\frac{dN(E,m_\chi)}{dE}\right]_{DM}\langle J\rangle$$

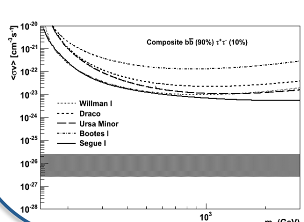
where <J> is the squared DM density integrated along the line of sight and dN/dE the DM annihilation spectrum. Every dSph DM distribution has been modeled with an Navarro, Frenk & White (NFW) profile, except Segue 1 for which an Einasto profile provides a better match to the data.

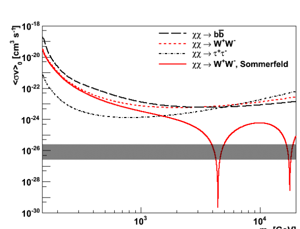
Quantity/dSph	Draco	Ursa Minor	Boötes 1	Willman 1	Segue 1
Distance [kpc]	80	66	62	38	23
<J> [$GeV^2\ cm^{-5}$]	1.5×10^{18}	2.7×10^{18}	1.1×10^{18}	8.4×10^{18}	10^{19}

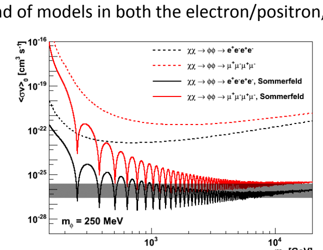
Having the value of the astrophysical factor for each dSph in hand, one can compute bounds on the DM self annihilation cross-section, assuming a typical DM annihilation spectrum.

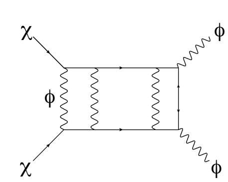
The figure on the left summarizes the current bounds on DM annihilations obtained with all the dSphs observed with VERITAS so far, for a composite DM annihilation spectrum (90% bbar, 10% $\tau^+\tau^-$). The figure on the right shows the VERITAS constraints with the observations of Segue 1, the most promising dSph, for different annihilation channels.

The last figure below place the Segue 1 bounds in the context of leptophilic DM models, recently proposed to explain the cosmic-ray lepton excesses reported in different experiments (ATIC, PAMELA, Fermi,…) in the 100-1000 GeV energy range. In such models (namely the Arkani-Hamed et al. models)., a new force carried by a mediator ϕ, is present in the dark sector (with a mass and couplings to standard model particles chosen to prevent the overproduction of antiprotons). In these models, the WIMPS annihilate into ϕ particles, which themselves decay predominantly into leptons. These models naturally comprise a **Sommerfeld enhancement**, giving a boost (inversely proportional to the DM particles relative velocity) to the present-day annihilation cross-section. Depending on the mass and the coupling of the exchanged boson, the Sommerfeld enhancement can exhibit a series of resonances for specific values of the DM particle mass, giving very large boost factors up to 10^6. As shown by the figure, VERITAS starts to disfavor such kind of models in both the electron/positron, and muon channels.









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