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Indirect Dark-Matter Searches in VHE Gamma Rays with Legacy VERITAS Dwarf Spheroidal Observations

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In the current cosmological theory, the existence and contribution of dark matter (DM) is inevitable. The weakly interacting massive particle (WIMP), expected mass in the range of tens of GeV to tens of TeV, is a DM candidate which can annihilate and/or decay into secondary particles, sequentially producing very-high-energy gamma rays (VHE; above 100 GeV). The Very Energetic Radiation Imaging Telescope Array System (VERITAS; sensitive to 100 GeV to 30 TeV gamma rays) is a ground-based VHE telescope array and can look for or detect gamma-ray signatures resulting from the annihilation of WIMPs. Since dwarf spheroidal galaxies (dSphs) are DM-rich regions, they are one of the best targets to look for indirect DM annihilation signatures. Compared to the previous DM search in dSphs, we significantly extend the observational dataset and improve our method of constraining the WIMP annihilation cross section by considering the dSph angular extension.

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1. Introduction

A variety of observational phenomena (e.g., galaxy rotational curves, bullet cluster, etc.) can be explained by the presence of invisible matter, so-called Dark Matter (DM) [1]. According to the current cosmological scenario, about 27% of the matter-energy density in the universe is made up of DM. DM is thought to be stable on cosmological timescales and to interact gravitationally and (possibly) weakly. There are lots of candidates, but none of them has been discovered.

The dwarf Spheroidal Galaxies (dSphs) are some of the best targets to search for an indirect DM signal for the following reasons. First of all, there is a clear evidence of the prevalence of dark matter, where the mass-to-light ratios (*M/L*) are large, implying a large amount of DM (*M/L* = 4000 for Segue 1). The fact that they are nearby systems (order of 10's kpc away) without known background sources makes it easier to search for a possible DM signal.

One DM candidate is the weakly interacting massive particles (WIMPs), which can decay and/or annihilate into standard model particles that produce gamma-ray lines or continuum emission. The produced gamma-rays, whose energies are in the GeV to TeV range, will propagate and be observed at Earth.

2. The VERITAS Observatory

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array of four Imaging Atmospheric Cherenkov Telescopes (IACTs) located in Arizona, USA, which is designed for observing very-high-energy (>100 TeV) gamma rays from the sky. One of its scientific programs is to search for indirect DM signals from astrophysical objects such as dSphs and the Milky Way galactic center. VERITAS is sensitive to gamma rays with energies from 85 GeV to above 30 TeV, which makes it possible to hunt for a gamma-ray signal from WIMPs. Regarding the point source sensitivity, VERITAS can detect a flux of 1% of the Crab Nebula flux in ~25 hours of observation [2].

3. Data reduction and method

In this study, we exploit observations of 17 dSphs, taken between 2007 and 2018 (630 hours in total; Table 1). Note that the previous VERITAS publication on dSphs [3] uses 230 hours of observations of five dSphs. The data are reduced with the official VERITAS analysis tools with improved reconstruction methods [4], compared to the original publication (including boosted decision trees for gamma/hadron separation). We especially optimize the size of the source region to boost the sensitivity.

In order to estimate flux from the WIMP annihilation, we need two ingredients: the DM spectrum and its density profile. For the DM spectrum, we exploit PPPC4DMID (dN_γ/dE) [5], which is widely used for the WIMP search. For the density profile, we adopt the generalized NFW profile (ρ) [6, 7]. With these two components, the expected DM counts convolved with the VERITAS response function (R) given the region of interest ($\Delta\Omega$) and the line of sight (los; $l\hat{n}'$) can be described as

$$\frac{dN_s}{dE} = \frac{\langle\sigma v\rangle}{8\pi M_\chi^2}\int_{E'} dE' \frac{dN_\gamma(E')}{dE'}\left(\iint_{\Delta\Omega,\mathrm{los}} \rho^2(l\hat{n}')R(E,\Omega|E',\Omega')d\Omega' dl\right) \tag{1}$$

Dwarf	Exposure (hr)	Sigma	Dwarf	Exposure (hr)	Sigma
Bootes	13.98	0.8	Coma Berenices	39.76	-0.2
CVn I	9.72	0.3	CVn II	8.14	1.6
Draco II	8.02	0.0	Hercules I	9.46	0.2
Leo I	5.66	-0.1	Leo II	11.31	0.2
Leo IV	0.48	-1.2	Leo V	1.38	-0.5
Segue 1	126.29	0.2	Segue II	12.51	-0.5
Sextans I	7.45	0.2	Triangulum II	29.51	-2.0
Ursa minor	135.3	-0.2	Ursa Major I	6.63	0.6
Ursa Major II	212.32	-0.8			

Table 1: The VERITAS observations of dSphs from 2007 to 2018 (total 630 hours). The left column shows the object name, the middle column the exposure time, and the right column the detection significance.

where $\langle \sigma v \rangle$ is the DM thermally averaged velocity-weighted cross section, and M_χ is the DM mass. Note that the quantities, E (E') and Ω (Ω'), are the reconstructed (true) photon energy and solid angle, respectively.

With the obtained DM spectrum, we perform a maximum Likelihood Estimation (MLE) analysis, where the likelihood is as follows

$$\mathcal{L}(\langle \sigma v \rangle; b|D) = \frac{(N_s + \alpha\, b)^{N_{\rm on}}\, e^{-(N_s+\alpha b)}}{N_{\rm on}!} \frac{b^{N_{\rm off}} e^{-b}}{N_{\rm off}!} \prod_{i=1}^{N_{\rm on}} \frac{N_s p_s(E_i) + \alpha\, b\, p_b(E_i)}{N_s + \alpha\, b}, \tag{2}$$

where N_{on} and N_{off} are the number of events from ON and OFF regions, and p_s and p_b are the probability density functions for the signal and background, respectively. The parameter α is the relative exposure time. The nuisance parameter b, the expected background counts, is included in this likelihood function.

4. Results

We do not observe any excess above the background level, as shown in Table 1. Here, we present upper limits on the DM thermally averaged velocity-weighted cross section obtained from the Segue 1 observation (126 hours) alone. As seen in Figure 1, our upper limit, quoted at the 95% confidence level, provides a more stringent constraint compared to previous VERITAS results and those from other VHE observatories [e.g., 3, 8–10]. The combined analysis with 17 dSphs will further constrain the DM thermally averaged velocity-weighted cross section.

5. Conclusion

VERITAS (10+ yrs of operation) has searched for indirect DM signals using observations of dSphs. A DM signal is not observed. However, with improved analysis methods and an extended dataset, we provide competitive upper limits on the DM velocity-weighted cross section. In the near future, a new combined analysis with the full extended dataset will be presented, which will

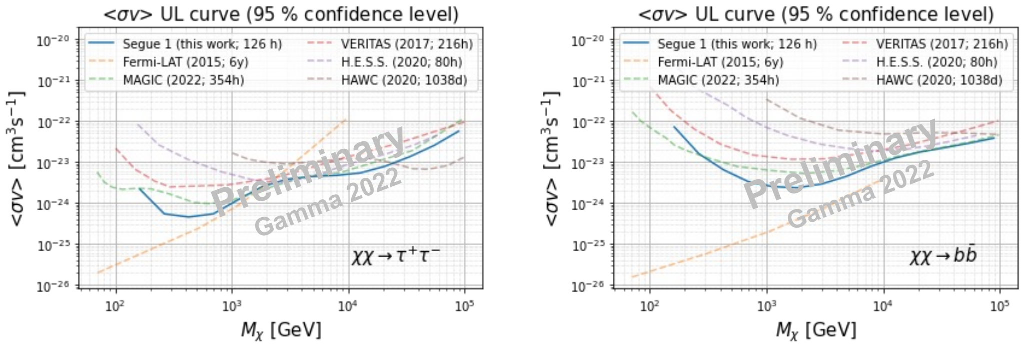

Figure 1: The upper limits on the DM annihilation cross section obtained from the extended Segue 1 observation. The VERITAS result (solid blue) is shown with other publications (dashed lines). The left (right) panel show ULs from the $\tau^+\tau^-$ ($b\bar{b}$) annihilation channel. All upper limits have been computed at a 95% confidence level.

give a boost to DM sensitivity by about a factor of two in some cases.

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