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

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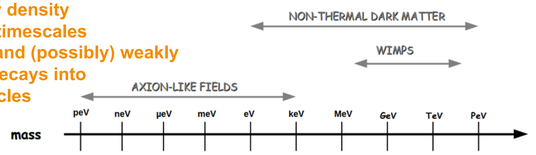
Dark Matter in a nutshell

Lots of observational phenomena (e.g., galaxy rotational curves) necessitate invisible matter

- 27% of the matter-energy density
- Stable on Cosmological timescales
- Interacts gravitationally and (possibly) weakly
- Possibly annihilates or decays into the standard model particles
- Lots of candidates



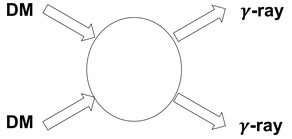
Dwarf Spheroidal Galaxies (dSphs)

- Evidence of the prevalence of dark matter
- Nearby systems (about 10's kpc away)
- Mass-to-light ratios (M/L) are large (4000 for Segue 1)
- No known background sources

One of the best targets for studying indirect DM signal

Expected DM Flux at Earth

WIMPs decay or annihilate into standard model particles that **produce gamma-ray lines or continuum.** The produced gamma-rays will propagate and be observed at Earth.



Very Energetic Radiation Imaging Telescope Array System (VERITAS)

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.

Key properties

- Energy range: 85 GeV to > 30 TeV
- Field of view: 3.5°
- Energy resolution: 15-25%
- Angular resolution: <0.1° @ 1 TeV
- Point source sensitivity: 1% Crab in ~25h

No evidence of indirect dark matter signal above background

Data selection

- 17 dSph observations from 2007 to 2018 (630 hours in total); note that VERITAS et al. (2017) uses 230 hours of observations.
- Observation data is reduced with the official VERITAS analysis tools with the improved reconstruction method (e.g., BDT).
- Optimize the size of a source region to boost the sensitivity.

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

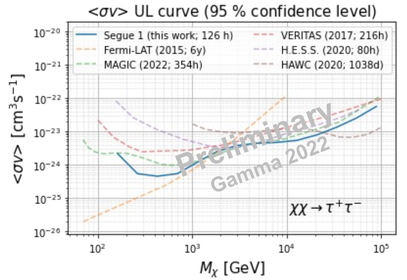
Methods

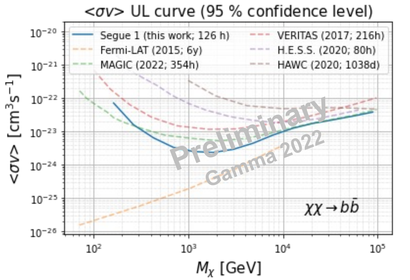
- PPPC4DMID (dN_γ/dE; Cirelli et al. 2012) and the generalized NFW profile ($dJ/d\Omega$; Geringer-Sameth et al. 2015)
- Maximum Likelihood Estimation (MLE) method.
- Since the DM density profile implies the angular dependence in signal, the 2D analysis method is introduced.

$$L = \frac{(g+\alpha b)^{N_{on}} e^{-(g+\alpha b)}}{N_{on}!} \frac{b^{N_{off}} e^{-b}}{N_{off}!} \prod_{i=1}^{N_{on}} P_{on}(E_i, \theta_i | M, \langle\sigma_v\rangle) \prod_{j=1}^{N_{off}} P_{off}(E_j, \theta_j),$$

E: the energy of an event
θ: the angular distance (deg) from the center of a region
M: mass of the dark matter
$\langle\sigma v\rangle$: cross section of the dark matter
N_{on}: the number of observed ON-region (source) events
N_{off}: the number of observed OFF-region (background) events
g: expected DM signal counts
b: expected background counts
P_{on}: Probability density function for the ON region (signal + background)
P_{off}: Probability density function for the OFF region (background)

Upper limits on the DM annihilation cross section





Here we present **upper limits on the DM cross section obtained from the Segue 1 observation (126 hours) alone**; it already provides a better constraint compared to our previous result and those from other VHE observatories.

The combined analysis with 17 dSphs will further constrain the DM cross section.

Conclusion

- VERITAS (10+ yrs of operation) has searched for indirect DM signals from WIMPs.
- A DM signal is not observed: with improved methods and extended dataset, we provide competitive upper limits on the DM cross section.