A Joint Gamma-ray Search for Dark Matter in Dwarf Spheroidal Galaxies with Fermi-LAT, HAWC, H.E.S.S., MAGIC and VERITAS

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Weakly Interacting Massive Particles (WIMPs) in the GeV–TeV mass range could produce gamma rays through self-annihilation or decay, offering potential observational signatures for indirect dark matter (DM) searches. Dwarf spheroidal galaxies (dSphs) of the Milky Way are prime targets for such studies due to their high inferred DM-induced gamma-ray fluxes and minimal astrophysical background.

In this contribution, we present the final results of the first constraints on DM annihilation in dSphs obtained by combining data from five leading gamma-ray observatories: the space-based Fermi-LAT (100 MeV–100 GeV), the ground-based H.E.S.S., MAGIC, and VERITAS (100 GeV–10 TeV), and the water Cherenkov detector HAWC (>10 TeV).

Each experiment analyzed its respective dataset using a coordinated statistical approach, ensuring a consistent treatment of systematics and background estimation. The individual results were then combined in a joint likelihood analysis, significantly improving sensitivity to potential DM signals.

By integrating these independent datasets, we derive stringent upper limits on the velocity-weighted annihilation cross-section $\langle \sigma v \rangle$ over a broad DM mass range of 5 GeV to 100 TeV. The obtained constraints improve with respect to the individual searches by a factor of 2–3, depending on the DM mass and annihilation channel. For instance, the observed 95% confidence level upper limits for a 2 TeV dark matter particle annihilating into $\tau^+\tau^-$ pairs range between 1.5×10^{-24} cm^3 s^{-1} and 3.2×10^{-25} cm^3 s^{-1} depending on the assumed dark matter distributions.

These results set some of the most stringent constraints on DM annihilation in dSphs to date, showcasing the power of multi-instrument synergy. Our findings underscore the critical role of cross-collaboration among gamma-ray observatories and establish a methodological framework for future analyses, including those incorporating next-generation gamma-ray and neutrino telescopes.

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1. Introduction

Understanding the nature of dark matter (DM) remains one of the challenges in astrophysics and cosmology. Among the many indirect detection strategies, the search for gamma rays from self-annihilating DM particles offers a promising observational window, especially in regions of the sky where conventional gamma-ray backgrounds are minimal.

Dwarf spheroidal galaxies (dSphs) orbiting the Milky Way are among the most favorable targets for this purpose. Their high dark matter content and lack of significant astrophysical gamma-ray sources make them prime candidates to search for weakly interacting massive particles (WIMPs). If WIMPs annihilate into Standard Model particles, gamma rays may be among the final decay products, providing a detectable signal.

This work presents a joint likelihood analysis that combines observations from five gamma-ray instruments: Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS. By integrating datasets across a wide energy range and combining statistical power from 20 dSphs, we set stringent constraints on the DM annihilation cross section.

2. Instruments and Data Sets

The five instruments involved in this analysis cover complementary energy regimes and utilize distinct detection methods:

Fermi-LAT is a pair-conversion telescope onboard the *Fermi* satellite. It continuously scans the sky, detecting photons from 20 MeV up to beyond 1 TeV with excellent exposure uniformity and minimal atmospheric interference [1]. For this work, 10 years of Pass 8 data were used, with dedicated regions of interest (ROIs) around each dSph and careful modeling of astrophysical backgrounds.

HAWC is a water Cherenkov detector located in Mexico that operates continuously and is sensitive to gamma rays above 300 GeV [2]. Its wide field of view and high duty cycle allow for extensive monitoring of the sky. A data set spanning approximately 1000 days was analyzed.

H.E.S.S, **MAGIC**, and **VERITAS** are ground-based imaging atmospheric Cherenkov telescopes (IACTs) that detect gamma-ray-induced air showers in the atmosphere. These instruments provide high sensitivity in the range from tens of GeV to tens of TeV. They contribute deep, targeted observations of individual dSphs, with exposure times ranging from 50 to over 300 hours per target across the three observatories [3–5].

Each collaboration analyzed their own datasets using common DM spectral and morphological models and common conventions on the statistical analysis, including the treatment of the relevant statistical uncertainties. The result of those analyses are binned likelihood values for individual targets and annihilation channels, profiled for the nuisance parameters relevant to the instrument. These profiles were later combined without sharing raw data or internal instrument calibrations.

3. Dark Matter Content and Target Selection

The intensity of the DM gamma-ray signal is proportional to the so-called J-factor, defined as the integral over the line of sight (los) and the observing cone ($\Delta\Omega$) of the square of the dark matter

density (ρ), i.e.:

$$J(\Delta\Omega) = \int_{\text{los}} dl \, d\Omega \, \rho^2 \tag{1}$$

A total of 20 dSphs were selected based on data availability and the quality of their dark matter halo modeling. Both classical and ultra-faint dSphs were included, with J-factors integrated up to the outermost observable star between $\sim 10^{17}$ and $\sim 10^{20}$ GeV^2 cm^{-5}.

J is fully degenerate with the annihilation cross section $\langle\sigma v\rangle$ in the computation of the expected dark matter flux. Two independent sets of J-factor estimates were employed to assess systematic uncertainties: one based on analyses by Geringer-Sameth et al. [6], and the other by Bonnivard et al. [7]. These differ in their assumptions and statistical treatments of stellar kinematics. The uncertainties in J-factors were incorporated into the likelihood framework as nuisance parameters, allowing for profiling over astrophysical uncertainties.

4. Statistical Framework

The analysis uses a profile likelihood approach. For each dSph, a combined likelihood is formed by multiplying the likelihoods from each participating instrument. The global likelihood function is given by:

$$L(\langle\sigma v\rangle) = \prod_l \left[L_l(\langle\sigma v\rangle, J_l) \times \mathcal{L}_J(J_l) \right], \tag{2}$$

where L_l is the joined likelihood value for $\langle\sigma v\rangle$ given the observed counts in all the considered energy and spatial bins for all instruments, for dSph l; the likelihood function for the J-factor, $\mathcal{L}_J(J_l)$, is obtained by fitting a log-normal function to the posterior distribution of J_l. The nuisance parameters, including J_l and background normalizations, are profiled over in the construction of the likelihood ratio test statistic.

The predicted gamma-ray counts are derived by convolving the instrument response functions (including detection efficiency, angular resolution, and energy resolution) with the expected flux from DM annihilation, calculated as:

$$\frac{d\Phi}{dE \, d\Omega} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2} \sum_f \text{BR}_f \frac{dN_f}{dE} \times \frac{dJ}{d\Omega}, \tag{3}$$

where m_χ is the WIMP mass, BR_f is the branching ratio for channel f, and dN_f/dE is the gamma-ray yield per annihilation, tabulated from simulations [8].

Each collaboration independently generated likelihood curves over a grid of DM masses (from 5 GeV to 100 TeV) and for several standard annihilation channels: $b\bar{b}$, $t\bar{t}$, W^+W^-, ZZ, e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$. These were shared in standardized format and combined using open-source tools such as `gLike` [9] and `LklCom` [10].

The 95% confidence level upper limits on $\langle\sigma v\rangle$ were obtained by identifying the cross-section value at which the likelihood falls by 2.71 units with respect to its maximum, assuming Wilks' theorem holds.

5. Results

The joint analysis yields significantly improved limits relative to individual experiments. At low masses ($\lesssim 100$ GeV), Fermi-LAT data dominate, with the combined analysis achieving sensitivity to $\langle \sigma v \rangle$ below the canonical thermal relic value of 3×10^{-26} cm^3 s^{-1} for the $b\bar{b}$ and $\tau^+\tau^-$ channels.

At higher masses (above 1 TeV), ground-based instruments—HAWC and the IACTs—become essential, achieving up to a factor of three more stringent limits on $\langle \sigma v \rangle$ compared to the most sensitive single-instrument results. For instance, the combination achieves limits of the order of 10^{-23} cm^3 s^{-1} at 10 TeV for hadronic channels and about 10^{-24} cm^3 s^{-1} at 1 TeV for leptonic channels.

The use of multiple instruments also reduces statistical fluctuations and strengthens constraints across different channels. The impact of systematic uncertainties from J-factors was also evaluated. Limits obtained using the Geringer-Sameth et al. J-factors are generally stronger than those using the Bonnivard et al. set, though differences remain within a factor of two, depending on the mass and channel.

6. Conclusion

This joint effort demonstrates the power of multi-instrument collaboration in the search for dark matter. By combining data from five gamma-ray telescopes and applying a consistent statistical framework, the analysis achieves the most stringent constraints to date on WIMP annihilation in dwarf spheroidal galaxies across a wide mass range.

The methodology is flexible and scalable, and thus applicable to future instruments like the Cherenkov Telescope Array Observatory (CTAO) and to other messengers such as neutrinos or cosmic rays. The approach also highlights the importance of sharing high-level likelihoods and J-factor models to enable robust joint analyses.

As gamma-ray observations continue and more dSphs are discovered through optical surveys, the sensitivity of this strategy will only improve. Joint analyses like this will remain a cornerstone of indirect dark matter searches in the years ahead.

7. Acknowledgements

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