

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

Javier Rico,^{a,*} Celine Armand,^b Eric Charles,^c Mattia Di Mauro,^d Chiara Giuri,^e J. Patrick Harding,^f Daniel Kerszberg,^{a,l} Tjark Miener,^{g,m} Emmanuel Moulin,^h Louise Oakes,ⁱ Vincent Poireau,^b Elisa Pueschel,^j Lucia Rinchiuso,^h Daniel Salazar-Gallegos^k and Kirsten Anne Tollefson^k on behalf of the Fermi-LAT, HAWC, H.E.S.S., MAGIC and VERITAS Collaborations.

^a*Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology (BIST)
E-08193 Bellaterra (Barcelona), Spain*

^b*Université Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3
74000 Annecy, France*

^c*W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology,
Department of Physics and SLAC National Accelerator Laboratory, Stanford University
Stanford, CA 94305, USA*

^d*Istituto Nazionale di Fisica Nucleare, Sezione di Torino
I-10125 Torino, Italy*

^e*DESY
Platanenallee 6, 15738 Zeuthen, Germany*

^f*Los Alamos National Laboratory
Los Alamos, NM, USA*

^g*IPARCOS Institute and EMFTEL Department, Universidad Complutense de Madrid
E-28040 Madrid, Spain*

^h*IRFU, CEA, Université Paris-Saclay
F-91191 Gif-sur-Yvette, France*

ⁱ*Institut für Physik, Humboldt-Universität zu Berlin
Newtonstr. 15, D 12489 Berlin, Germany*

^j*Fakultät für Physik & Astronomie, Ruhr-Universität Bochum
D-44780 Bochum, Germany*

^k*Department of Physics and Astronomy, Michigan State University
East Lansing, MI, USA*

^l*Now at Sorbonne Université, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies,
LPNHE
4 place Jussieu, 75005 Paris, France*

^m*Now at Département de physique nucléaire et corpusculaire, University of Genève, Faculté de Sciences
1205 Genève, Switzerland*

E-mail: jrico@ifae.es

*Speaker

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 $1.5 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1}$ and $3.2 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ 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.

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.:

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

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 $\sim 10^{20}$ $\text{GeV}^2 \text{cm}^{-5}$.

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 Bonnavard 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:

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

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:

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

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 $3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ 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 $10^{-23} \text{ cm}^3 \text{ s}^{-1}$ at 10 TeV for hadronic channels and about $10^{-24} \text{ cm}^3 \text{ s}^{-1}$ 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

The Fermi-LAT Collaboration acknowledges generous ongoing support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as scientific data analysis. These include the National Aeronautics and Space Administration and the Department of Energy in the United States, the Commissariat à l’Energie Atomique and the Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules in France, the Agenzia Spaziale Italiana and the Istituto Nazionale di Fisica Nucleare in Italy, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), High Energy Accelerator Research Organization (KEK) and Japan Aerospace Exploration Agency (JAXA) in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the Swedish National Space Board in Sweden. Additional support for science analysis during the operations phase is gratefully acknowledged from the Istituto Nazionale di Astrofisica in Italy and

the Centre National d'Études Spatiales in France. This work performed in part under DOE Contract DE-AC02-76SF00515.

The HAWC collaboration acknowledges the support from: the US National Science Foundation (NSF); the US Department of Energy Office of High-Energy Physics; the Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory; Consejo Nacional de Ciencia y Tecnología (CONACyT), México, grants 271051, 232656, 260378, 179588, 254964, 258865, 243290, 132197, A1-S-46288, A1-S-22784, cátedras 873, 1563, 341, 323, Red HAWC, México; DGAPA-UNAM grants IG101320, IN111716-3, IN111419, IA102019, IN114924, IN110521, IN102223; VIEPBUAP; PIFI 2012, 2013, PROFOCIE 2014, 2015; the University of Wisconsin Alumni Research Foundation; the Institute of Geophysics, Planetary Physics, and Signatures at Los Alamos National Laboratory; Polish Science Centre grant, DEC-2017/27/B/ST9/02272; Coordinación de la Investigación Científica de la Universidad Michoacana; Royal Society - Newton Advanced Fellowship 180385; Generalitat Valenciana, grant CIDEAGENT/2018/034; The Program Management Unit for Human Resources & Institutional Development, Research and Innovation, NXPO (grant number B16F630069); Coordinación General Académica e Innovación (CGAI-UdeG), PRODEP-SEP UDG-CA-499; Institute of Cosmic Ray Research (ICRR), University of Tokyo, H.F. acknowledges support by NASA under award number 80GSFC21M0002. We also acknowledge the significant contributions over many years of Stefan Westerhoff, Gaurang Yodh and Arnulfo Zepeda Dominguez, all deceased members of the HAWC collaboration. Thanks to Scott Delay, Luciano Díaz and Eduardo Murrieta for technical support.

The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the German Research Foundation (DFG), the Helmholtz Association, the Alexander von Humboldt Foundation, the French Ministry of Higher Education, Research and Innovation, the Centre National de la Recherche Scientifique (CNRS/IN2P3 and CNRS/INSU), the Commissariat à l'énergie atomique et aux énergies alternatives (CEA), the U.K. Science and Technology Facilities Council (STFC), the Irish Research Council (IRC) and the Science Foundation Ireland (SFI), the Knut and Alice Wallenberg Foundation, the Polish Ministry of Education and Science, agreement no. 2021/WK/06, the South African Department of Science and Technology and National Research Foundation, the University of Namibia, the National Commission on Research, Science & Technology of Namibia (NCRST), the Austrian Federal Ministry of Education, Science and Research and the Austrian Science Fund (FWF), the Australian Research Council (ARC), the Japan Society for the Promotion of Science, the University of Amsterdam and the Science Committee of Armenia grant 21AG-1C085. We appreciate the excellent work of the technical support staff in Berlin, Zeuthen, Heidelberg, Palaiseau, Paris, Saclay, Tübingen and in Namibia in the construction and operation of the equipment. This work benefited from services provided by the H.E.S.S. Virtual Organisation, supported by the national resource providers of the EGI Federation.

The MAGIC collaboration would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The financial support of the German BMBF, MPG and HGF; the Italian INFN and INAF; the Swiss National Fund SNF; the grants PID2019-107988GB-C22, PID2022-136828NB-C41, PID2022-137810NB-C22, PID2022-138172NB-C41, PID2022-138172NB-C42, PID2022-138172NB-C43, PID2022-

139117NB-C41, PID2022-139117NB-C42, PID2022-139117NB-C43, PID2022-139117NB-C44, CNS2023-144504 funded by the Spanish MCIN/AEI/ 10.13039/501100011033 and "ERDF A way of making Europe; the Indian Department of Atomic Energy; the Japanese ICRR, the University of Tokyo, JSPS, and MEXT; the Bulgarian Ministry of Education and Science, National RI Roadmap Project DOI-400/18.12.2020 and the Academy of Finland grant nr. 320045 is gratefully acknowledged. This work has also been supported by Centros de Excelencia "Severo Ochoa" y Unidades "María de Maeztu" program of the Spanish MCIN/AEI/ 10.13039/501100011033 (CEX2019-000920-S, CEX2019-000918-M, CEX2021-001131-S) and by the CERCA institution and grants 2021SGR00426 and 2021SGR00773 of the Generalitat de Catalunya; by the Croatian Science Foundation (HrZZ) Project IP-2022-10-4595 and the University of Rijeka Project uniri-rirod-18-48; by the Deutsche Forschungsgemeinschaft (SFB1491) and by the Lamarr-Institute for Machine Learning and Artificial Intelligence; by the Polish Ministry Of Education and Science grant No. 2021/WK/08; and by the Brazilian MCTIC, CNPq and FAPERJ.

The research of VERITAS is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, and by the Helmholtz Association (including the Young Investigators Program of the Helmholtz Association) in Germany. This research used resources provided by the Open Science Grid, which is supported by the National Science Foundation and the U.S. Department of Energy's Office of Science, and resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument.

References

- [1] W. B. Atwood et al., "The Large Area Telescope on the Fermi Gamma-ray Space Telescope Mission," *Astrophys. J.* **697**, 1071–1102 (2009), [arXiv:0902.1089](#).
- [2] A. U. Abeysekara et al., "Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory," *Astrophys. J.* **843**, 39 (2017), [arXiv:1701.01778](#).
- [3] M. L. Ahnen et al., "Limits to dark matter annihilation cross-section from a combined analysis of MAGIC and Fermi-LAT observations of dwarf satellite galaxies," *JCAP* **02**, 039 (2016), [arXiv:1601.06590](#).
- [4] S. Archambault et al., "Dark Matter Constraints from a Joint Analysis of Dwarf Spheroidal Galaxy Observations with VERITAS," *Phys. Rev. D* **95**, 082001 (2017), [arXiv:1703.04937](#).
- [5] H. Abdallah et al., "Search for dark matter annihilations towards the inner Galactic halo from 10 years of observations with H.E.S.S.," *Phys. Rev. Lett.* **117**, 111301 (2018), [arXiv:1607.08142](#).
- [6] A. Geringer-Sameth, S. M. Koushiappas, and M. Walker, "Dwarf galaxy annihilation and decay emission profiles for dark matter experiments," *Astrophys. J.* **801**, 74 (2015), [arXiv:1408.0002](#).

- [7] V. Bonnivard et al., “Dark matter annihilation and decay in dwarf spheroidal galaxies: The classical and ultrafaint dSphs,” *Mon. Not. Roy. Astron. Soc.* **453**, 849–867 (2015), [arXiv:1504.02048](#).
- [8] M. Cirelli et al., “PPPC 4 DM ID: A poor particle physicist cookbook for dark matter indirect detection,” *JCAP* **03**, 051 (2011), [arXiv:1012.4515](#).
- [9] J. Rico et al., “gLike: Numerical Maximization of Heterogeneous Joint Likelihoods,” Zenodo (2022), [doi:10.5281/zenodo.7342721](#).
- [10] T. Miener and D. Nieto, “LklCom: Combining Likelihoods from Different Experiments,” Zenodo (2021), [doi:10.5281/zenodo.4597500](#).