Snowmass2021 - Letter of Interest

Searching for TeV Gamma-Ray Dark Matter Signals from Galactic Substructure with the Southern Wide-field Gamma-ray Observatory (SWGO)[*]

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

Contact Information: (authors listed after the text)
Submitter Name/Institution: Andrea Albert (Los Alamos National Laboratory)
Collaboration (optional): HAWC, SWGO
Contact Email: amalbert@lanl.gov

Abstract: Evidence suggests that the majority of the mass in the Universe is dark matter. Many promising models hypothesize that dark matter is a particle that can annihilate or decay and produce secondary gamma rays. Several searches have been performed by GeV and TeV gamma-ray experiments, none of which have detected a definitive signal. The Southern Hemisphere is home to many key dark-matter targets, like the dwarf galaxy Reticulum II and the Large Magellanic Cloud. So far, only a few Southern Hemisphere targets have been observed by the current H.E.S.S. observatory due to its limited field-of-view. A wide-field-of-view survey observatory, like the Southern Wide-field Gamma-ray Observatory (SWGO), is needed to survey the many dark-matter targets in the Southern Hemisphere. We show that such an observatory would produce competitive, if not the best, limits for dark matter from Galactic substructure targets with masses from 100 GeV to several PeV.

[*]This Letter contains excerpts and material from White Papers submitted for the Astro2020 Decadal Survey [1;2]

Astronomical observations suggest that the majority of mass in the Universe is composed of non-baryonic dark matter[3–5]. There are several well-motivated theories that predict dark matter is a fundamental particle such as a Weakly Interacting Massive Particle[6]. In these models, the dark matter annihilates or decays, producing Standard Model particles that would be observed by astrophysical observatories. Typically, the dark-matter interactions produce unstable particles that produce a spectrum of Standard Model particles, including gamma rays (e.g., $\chi\chi \rightarrow b\bar{b}$).

If the dark matter has a mass well above the TeV scale, the only discovery space is astrophysical— these particles would be well above achievable collider searches for dark matter and would have number densities too low for direct-detection searches. However, with the high-dark-matter-density regions observed astrophysically and the high-energy reach of astrophysical experiments, dark-matter masses much greater than 1 TeV can be probed. Dark matter clumps on subgalactic scales, producing substructure in the Galactic Halo. These targets are promising for searches of gamma rays from particle-dark-matter interactions since they are dark-matter rich and nearby. Specifically, dozens of dwarf galaxies and the Large and Small Magellanic clouds are good dark-matter targets in the Southern Hemisphere.

We propose a next-generation gamma-ray observatory that will have the best sensitivity at high energies ($>$10 TeV). The Southern Wide-field Gamma-ray Observatory (SWGO)[7;8] is planned to be located in the Southern Hemisphere and have a sensitivity $\sim 10\times$ better than the High-Altitude Water Cherenkov (HAWC) Observatory[9]. Both detect radiation produced by relativistic particles in extensive air showers caused by cosmic-ray and gamma-ray interactions in the atmosphere. These arrays have a wide field-of-view and observe $\sim 2/3$ of the sky every day with a near-100% duty cycle. They complement Imaging Atmospheric Cherenkov Telescopes (IACTs), which have smaller fields-of-view. Therefore, SWGO would observe several Southern Hemisphere dark-matter targets every day.

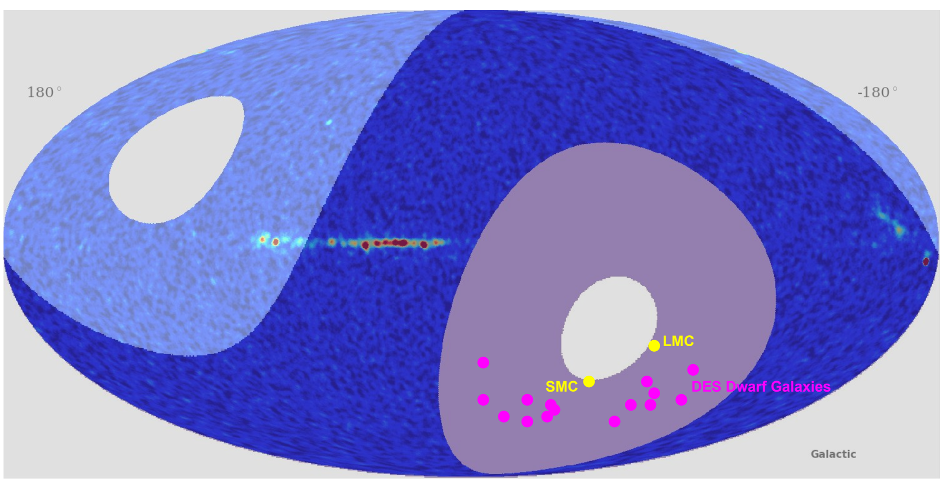

Figure 1: HAWC skymap with the SWGO field-of-view overlaid. Shown are new targets avalible to SWGO. The pink targets are new dwarf galaxies discovered by the Dark Energy Survey[10]. This assumes SWGO is located at latitude 20° South

Dwarf spheroidal galaxies (dSphs) are some of the most dark-matter-dominated objects known. Dozens are known to exist nearby in the Milky Way dark-matter halo. Given their proximity and low astrophysical backgrounds, Milky Way dSphs are excellent targets for searching for gamma-ray emission from dark-matter annihilation or decay. For example, HAWC has derived competitive limits on dark-matter annihilation and decay using 14 dSphs with known dark-matter content[11].

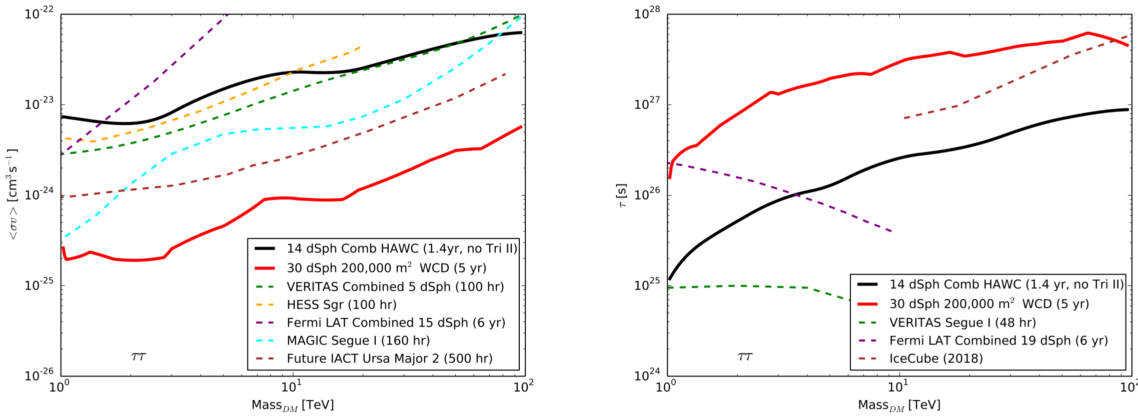

Figure 2: (Left) Expected 95% confidence level dark-matter-annihilation cross-section upper limits in dSphs with a 200,000 m^2 water Cherenkov detector (WCD) (10 times the HAWC area, similar to SWGO). Also shown are the observed dSph limits from VERITAS[39], H.E.S.S.[40], *Fermi*-LAT[38], MAGIC[41], and the expected limits from CTA[42]. (Right) Expected 95% confidence level dark-matter decay lifetime lower limits for dark-matter decay in dSphs. Also shown are the observed dSph limits from VERITAS[43], *Fermi*-LAT[44], and IceCube[45].

Recent deep observations with wide-field optical imaging surveys have discovered 33 new ultra-faint Milky Way satellites[12–26], mostly in the Southern Hemisphere. These objects are potentially dark-matter-dominated dSphs, but this needs to be confirmed with spectroscopic follow-up observations. Fifteen of the new satellites have already been spectroscopically confirmed as dSphs[19;26–37]. These add to the existing 18 well-characterized dSphs known before these surveys[38].

Figure 2 shows the expected improvement in the dark-matter annihilation and decay limits relative to the current HAWC limits for a HAWC-like array with $10\times$ better sensitivity in the Southern Hemisphere and an increased number of dSphs. We assume the dark-matter amount and distribution in the new dSphs matches that of the previously known dSphs. With the next generation of observations, we expect to be able to improve the present limits by nearly an order of magnitude. We also expect such an array's dSph searches to be more sensitive than dSph searches from current and future IACTs like H.E.S.S. and CTA.

Additionally, with a survey instrument examining the sky every day, additional dSphs that haven't been discovered yet will have already been observed with the instrument's full sensitivity. The Rubin Observatory[46] will survey the Southern Hemisphere sky with unprecedented sensitivity and is expected to find hundreds of new dSphs[47]. Legacy data from SWGO at these locations could easily and immediately be analysed when new dSphs are found.

Two other promising Southern Hemisphere dark-matter targets are the Large (LMC) and Small (SMC) Magellanic Clouds. The LMC is the largest Milky Way satellite and rich in dark matter. It also is likely on its first in-fall, meaning it has not been tidally stripped by the galaxy and still contains most of the its initial dark-matter density. The SMC is in a complicated orbit around the LMC, but also likely on its first in-fall and therefore not tidally stripped. Though its dynamics are more complicated than the LMC, the SMC's rotations curves show that it is dark-matter dominated. Since it is extended by $\sim 10^{\circ}$, a wide-field-of-view observatory would uniquely observe the entire LMC dark-matter subhalo at TeV energies.

References

[1] Andrea Albert, K. S. Caballero, P. M. Chadwick, B. L. Dingus, K. L. Engel, J. A. Goodman, T. Greenshaw, J. P. Harding, P. Huentemeyer, J. S. Lapington, J. Lundeen, J. Martinez-Castro, M. U. Nisa, H. Schoorlemmer, K. Tollefson, A. Viana, and A. Zepeda. Searching for Sources of TeV Particle Dark Matter in the Southern Hemisphere. , 51(3):202, May 2019.

[2] P. Abreu et al. The Southern Wide-Field Gamma-Ray Observatory (SWGO): A Next-Generation Ground-Based Survey Instrument for VHE Gamma-Ray Astronomy. 7 2019.

[3] P. A. R. Ade et al. Planck 2013 results. XVI. Cosmological parameters. *Astron. Astrophys.*, 571:A16, 2014.

[4] Douglas Clowe, Marusa Bradac, Anthony H. Gonzalez, Maxim Markevitch, Scott W. Randall, Christine Jones, and Dennis Zaritsky. A direct empirical proof of the existence of dark matter. *Astrophys. J.*, 648:L109–L113, 2006.

[5] Yoshiaki Sofue and Vera Rubin. Rotation curves of spiral galaxies. *Ann. Rev. Astron. Astrophys.*, 39:137–174, 2001.

[6] Jonathan L. Feng. Dark Matter Candidates from Particle Physics and Methods of Detection. *Ann. Rev. Astron. Astrophys.*, 48:495–545, 2010.

[7] P. Abreu et al. The Southern Wide-Field Gamma-Ray Observatory (SWGO): A Next-Generation Ground-Based Survey Instrument for VHE Gamma-Ray Astronomy. 7 2019.

[8] A. Albert et al. Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere. 2 2019.

[9] A.U. Abeysekara et al. (HAWC Collaboration). Observation of the crab nebula with the hawc gamma-ray observatory. *The Astrophysical Journal*, 843(1):39, 2017.

[10] A. Drlica-Wagner et al. Eight Ultra-faint Galaxy Candidates Discovered in Year Two of the Dark Energy Survey. *Astrophys. J.*, 813(2):109, 2015.

[11] A. Albert et al. Dark Matter Limits From Dwarf Spheroidal Galaxies with The HAWC Gamma-Ray Observatory. *Astrophys. J.*, 853(2):154, 2018.

[12] K. Bechtol et al. Eight New Milky Way Companions Discovered in First-Year Dark Energy Survey Data. *Astrophys. J.*, 807(1):50, 2015.

[13] V. Belokurov, M. G. Walker, N. W. Evans, G. Gilmore, M. J. Irwin, D. Just, S. Koposov, M. Mateo, E. Olszewski, L. Watkins, and L. Wyrzykowski. Big Fish, Little Fish: Two New Ultra-faint Satellites of the Milky Way. , 712:L103–L106, March 2010.

[14] A. Drlica-Wagner et al. Eight Ultra-faint Galaxy Candidates Discovered in Year Two of the Dark Energy Survey. *Astrophys. J.*, 813(2):109, 2015.

[15] A. Drlica-Wagner et al. An Ultra-Faint Galaxy Candidate Discovered in Early Data from the Magellanic Satellites Survey. *Astrophys. J.*, 833(1):L5, 2016.

[16] Daisuke Homma et al. A New Milky Way Satellite Discovered In The Subaru/Hyper Suprime-Cam Survey. *Astrophys. J.*, 832(1):21, 2016.

[17] D. Homma et al. Searches for new Milky Way satellites from the first two years of data of the Subaru/Hyper Suprime-Cam survey: Discovery of Cetus III. , 70:S18, January 2018.

[18] Dongwon Kim, Helmut Jerjen, Dougal Mackey, Gary S. Da Costa, and Antonino P. Milone. A Hero's Dark Horse: Discovery of an Ultra-faint Milky way Satellite in Pegasus. *Astrophys. J.*, 804(2):L44, 2015.

[19] S. E. Koposov, M. G. Walker, V. Belokurov, A. R. Casey, A. Geringer-Sameth, D. Mackey, G. Da Costa, D. Erkal, P. Jethwa, M. Mateo, E. W. Olszewski, and J. I. Bailey. Snake in the Clouds: a new nearby dwarf galaxy in the Magellanic bridge*. , 479:5343–5361, October 2018.

[20] Benjamin P. M. Laevens et al. A New Faint Milky Way Satellite Discovered in the Pan-STARRS1 3 pi Survey. *Astrophys. J.*, 802:L18, 2015.

[21] Benjamin P. M. Laevens et al. Sagittarius II, Draco II and Laevens 3: Three new Milky way Satellites Discovered in the Pan-starrs 1 3π Survey. *Astrophys. J.*, 813(1):44, 2015.

[22] E. Luque et al. The Dark Energy Survey view of the Sagittarius stream: discovery of two faint stellar system candidates. , 468:97–108, June 2017.

[23] Nicolas F. Martin et al. Hydra II: a faint and compact Milky Way dwarf galaxy found in the Survey of the Magellanic Stellar History. *Astrophys. J.*, 804(1):L5, 2015.

[24] G. Torrealba et al. Discovery of two neighbouring satellites in the Carina constellation with MagLiteS. , 475:5085–5097, April 2018.

[25] G. Torrealba, S. E. Koposov, V. Belokurov, and M. Irwin. The feeble giant. Discovery of a large and diffuse Milky Way dwarf galaxy in the constellation of Crater. , 459:2370–2378, July 2016.

[26] G. Torrealba, S. E. Koposov, V. Belokurov, M. Irwin, M. Collins, M. Spencer, R. Ibata, M. Mateo, A. Bonaca, and P. Jethwa. At the survey limits: discovery of the Aquarius 2 dwarf galaxy in the VST ATLAS and the SDSS data. , 463:712–722, November 2016.

[27] N. Caldwell, M. G. Walker, M. Mateo, E. W. Olszewski, S. Koposov, V. Belokurov, G. Torrealba, A. Geringer-Sameth, and C. I. Johnson. Crater 2: An Extremely Cold Dark Matter Halo. , 839:20, April 2017.

[28] D. Kim, H. Jerjen, M. Geha, A. Chiti, A. P. Milone, G. Da Costa, D. Mackey, A. Frebel, and B. Conn. Portrait of a Dark Horse: a Photometric and Spectroscopic Study of the Ultra-faint Milky Way Satellite Pegasus III. , 833:16, December 2016.

[29] E. N. Kirby, J. G. Cohen, J. D. Simon, P. Guhathakurta, A. O. Thygesen, and G. E. Duggan. Triangulum II. Not Especially Dense After All. *Astrophys. J.*, 838:83, 2017.

[30] E. N. Kirby, J. D. Simon, and J. G. Cohen. Spectroscopic Confirmation of the Dwarf Galaxies Hydra II and Pisces II and the Globular Cluster Laevens 1. , 810:56, September 2015.

[31] S. E. Koposov et al. Kinematics and Chemistry of Recently Discovered Reticulum 2 and Horologium 1 Dwarf Galaxies. , 811:62, September 2015.

[32] T. S. Li et al. Farthest Neighbor: The Distant Milky Way Satellite Eridanus II. *Astrophys. J.*, 838(1):8, 2017.

[33] T. S. Li, others, and MagLiteS Collaboration. Ships Passing in the Night: Spectroscopic Analysis of Two Ultra-faint Satellites in the Constellation Carina. , 857:145, April 2018.

[34] N. F. Martin et al. Is Draco II one of the faintest dwarf galaxies? First study from Keck/DEIMOS spectroscopy. , 458:L59–L63, May 2016.

[35] J. D. Simon et al. Stellar Kinematics and Metallicities in the Ultra-Faint Dwarf Galaxy Reticulum II. *Astrophys. J.*, 808(1):95, 2015.

[36] J. D. Simon et al. Nearest Neighbor: The Low-Mass Milky Way Satellite Tucana III. *Astrophys. J.*, 838(1):11, 2017.

[37] M. G. Walker, M. Mateo, E. W. Olszewski, S. Koposov, V. Belokurov, P. Jethwa, D. L. Nidever, V. Bonnivard, J. I. Bailey, III, E. F. Bell, and S. R. Loebman. Magellan/M2FS Spectroscopy of Tucana 2 and Grus 1. , 819:53, March 2016.

[38] M. Ackermann et al. Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data. *Phys. Rev. Lett.*, 115(23):231301, 2015.

[39] S. Archambault et al. Dark Matter Constraints from a Joint Analysis of Dwarf Spheroidal Galaxy Observations with VERITAS. *Phys. Rev.*, D95(8):082001, 2017.

[40] A. Abramowski et al. Search for dark matter annihilation signatures in H.E.S.S. observations of Dwarf Spheroidal Galaxies. *Phys. Rev.*, D90:112012, 2014.

[41] J. Aleksić et al. Optimized dark matter searches in deep observations of Segue 1 with MAGIC. *JCAP*, 1402:008, 2014.

[42] Valentin Lefranc, Gary A. Mamon, and Paolo Panci. Prospects for annihilating Dark Matter towards Milky Way's dwarf galaxies by the Cherenkov Telescope Array. *JCAP*, 1609(09):021, 2016.

[43] E. Aliu et al. VERITAS Deep Observations of the Dwarf Spheroidal Galaxy Segue 1. *Phys. Rev.*, D85:062001, 2012. [Erratum: Phys. Rev.D91,no.12,129903(2015)].

[44] Matthew G. Baring, Tathagata Ghosh, Farinaldo S. Queiroz, and Kuver Sinha. New Limits on the Dark Matter Lifetime from Dwarf Spheroidal Galaxies using Fermi-LAT. *Phys. Rev.*, D93(10):103009, 2016.

[45] M. G. Aartsen et al. Search for neutrinos from decaying dark matter with IceCube. 2018.

[46] David Alonso et al. The LSST Dark Energy Science Collaboration (DESC) Science Requirements Document. 9 2018.

[47] Jonathan R. Hargis, Beth Willman, and Annika H. G. Peter. Too Many, Too Few, or Just Right? The Predicted Number and Distribution of Milky Way Dwarf Galaxies. *Astrophys. J.*, 795(1):L13, 2014.

Authors: A.M. Albert (Los Alamos National Laboratory), L.H. Arnaldi (CNEA/IB, Argentina), J.C. Arteaga-VelÁzquez (Universidad Michoacana, Mexico), H.A. Ayala Solares (Pennsylvania State University, University Park), U. Barres de Almeida (CBPF, Brazil), C.A. Brisbois (University of Maryland, College Park), K.S. Caballero-Mora (UNACH, México), A. Carramiñana (INAOE, México), A. Chiavassa (Torino University, IT), R. Conceição (LIP/IST, Lisbon, Portugal), J.C. Díaz-Vélez (University of Wisconsin–Madison), B.L. Dingus (University of Maryland), M. Doro (University of Padova, IT), M. Durocher (Los Alamos National Laboratory), R.W. Ellsworth (University of Maryland, College Park), K.L. Engel (University of Maryland, College Park), C. Espinoza (UNAM, México), K.L. Fan (University of Maryland, College Park), K. Fang (Stanford University, University of Wisconsin-Madison), N. Fraija (IA-UNAM, México), J.A. García-González (ITESM-EIC), G. Giacinti (MPIK, Germany), J.A. Goodman (University of Maryland, College Park), J.P. Harding (Los Alamos National Laboratory), R.N. Hix (University of Maryland, College Park), D.Z. Huang (Michigan Technological University, Houghton), P. Huentemeyer (Michigan Technological University, Houghton), F. Hueyotl-Zahuantitla (UNACH, México), G. La Mura (LIP, Lisbon, Portugal), F. Longo (University and INFN Trieste), I. Martinez-Castellanos (NASA-GSFC/CRESST/UMD), J.A. Morales-Soto (Universidad Michoacana, Mexico), E. Moreno (BUAP, México), L. Nellen (ICN-UNAM, México), E. Orlando (University of Trieste and Stanford University), M. Pimenta (LIP/IST, Lisbon, Portugal), A. Sandoval (UNAM, México), M. Santander (University of Alabama, USA), M. Schneider (University of Maryland, College Park), A.J. Smith (University of Maryland, College Park), K. Tollefson (Michigan State University, East Lansing), B. Tomé (LIP/IST, Lisbon, Portugal), R. Torres Escobedo (Universidad de Guadalajara, Mexico/Texas Tech University, Lubbock TX), J. Vícha (FZU, Prague, Czech Republic), E.J. Willox (University of Maryland, College Park)