Snowmass2021 - Letter of Interest

Searching for Axion-Like Particles 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]*

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Abstract: Axion-Like Particles (ALPs), a generalization of standard axions, are well motivated dark-matter candidates. ALPs convert to gamma rays in the presence of a magnetic field. Therefore, ALPs would be found at extragalactic gamma-ray sources like Active Galactic Nuclei. Once generated, these ALPs would then travel without experiencing attentuation by the extragalactic background light like gamma rays do. When encountering the Galactic magnetic field, ALPs could convert back to gamma rays. In this scenario, gamma-ray observatories would observe high-energy gamma rays beyond the expected cutoff of the host source. Detection of these high-energy gamma rays from extragalactic sources would be a strong indication of ALPs. In this letter, we discuss the impact of the proposed Southern Wide-field Gamma-ray Observatory (SWGO) on ALP searches with cosmic gamma rays.

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

Axion-like Particles (ALPs) are hypothesized in many theories beyond the Standard Model[3]. They are similar to axions (which were theorized to solve the "Strong CP Problem" in particle physics[4]), except their mass and coupling strength to photons are independent of each other. ALPs would be produced non-thermally in the early Universe and could constitute some or all of the dark matter that exists today[5] according to their mass and interaction strength. These particles could also be formed today through high-energy interactions with magnetic fields.

One potential ALP signature would be the detection of an unexpected contribution of $\gtrsim$10 TeV photons from an extragalactic source. Very-high-energy photons produced in extragalactic sources are difficult to observe at Earth since they suffer extinction through interactions with the Extragalactic Background Light (EBL). However, gamma rays produced at the source could convert into ALPs in its strong magnetic fields or the intergalactic magnetic field. These ALPs would then travel to us unimpeded. They would then convert back into gamma rays in the Milky Way's magnetic field and then be detected at Earth[6;7].

We propose a next-generation gamma-ray observatory that will have the best sensitivity at high energies ($>$ 10 TeV), making it well equipped to search for these ALP gamma-ray signatures. The Southern Wide-field Gamma-ray Observatory (SWGO)[8;9] 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[10]. Both measure 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, operating all the time with a near-100% duty cycle. They complement Imaging Atmospheric Cherenkov Telescopes (IACTs), which have smaller fields-of-view and only a nocturnal duty cycle. Also, air-shower arrays are more sensitive than IACTs at higher energies (see Figure 1).

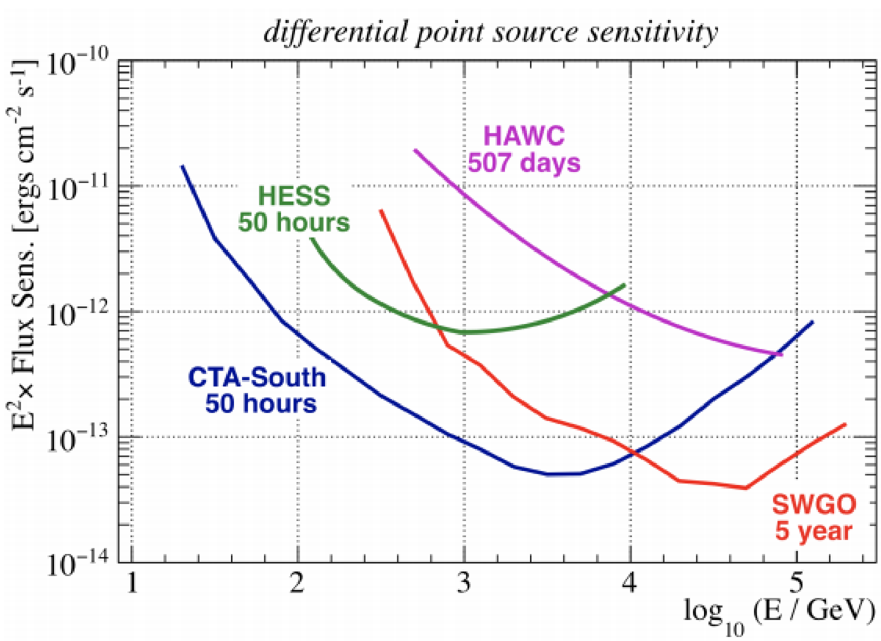

Figure 1: Gamma-ray source sensitivity of current and future gamma-ray observatories. H.E.S.S.[11] is a current IACT array and CTA[12] is a future IACT array currently being constructed. 50 hours is a typical exposure of a single source. HAWC is a current air-shower array and SWGO is a future air-shower array.

Several extragalactic sources that are promising for ALP searches are present in the Southern Hemisphere; e.g. PKS 0447-439 (z = 0.343)[13;14] and 1RXS J023832.6-311658 (z = 0.232)[15]. Observations of many sources of this nature by a wide-field-of-view observatory like SWGO would also allow for a stacked analysis to improve the search. As a concrete example, we consider 1RXS J023832.6-311658. We match an EBL-corrected[16] spectrum to the observed spectrum[17] to produce the expected observed emission in Figure 2. We include the case where no ALPs are produced at the source and the case where ALPs are produced assuming an ALP mass of $m_a = 5$ neV and ALP-photon coupling constant of $g_{a,\gamma} = 5 \times 10^{-11}\mathrm{GeV}^{-1}$ (values that are allowed with current ALP constraints[18]). Because SWGO's sensitivity would be the world's best for E $>$ 10 TeV, the difference between a cutoff or flattening of the observed spectrum would be clearly distinguishable.

It should be noted that ALP conversions could also produce sharp spectral features in the observed spectrum of extragalactic sources[18;19]. However, excellent energy resolution ($\lesssim 10\%$) is needed to resolve these features, while SWGO's energy resolution is predicted to be $\sim 35\%$.

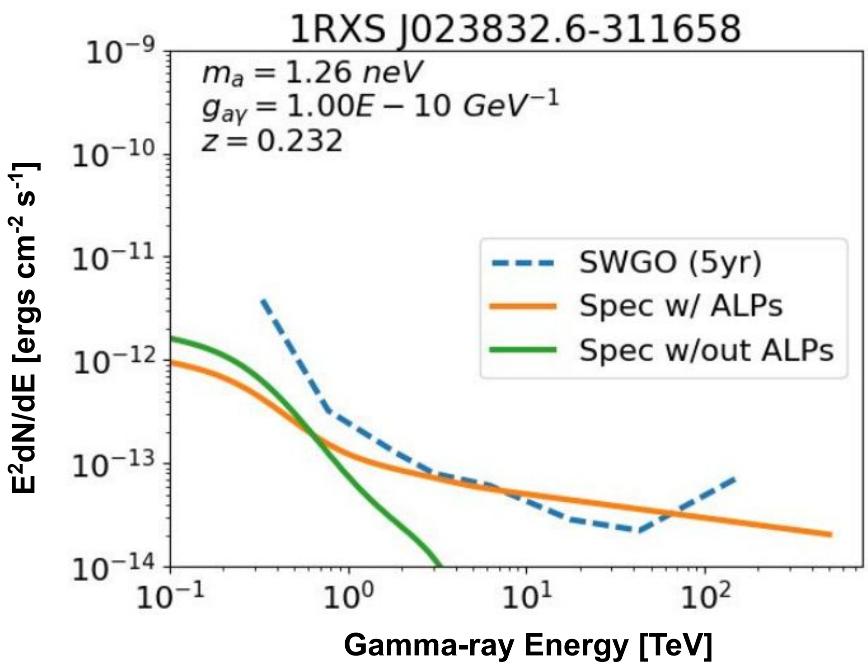

Figure 2: The RXJ1713.7-3946 source reported by H.E.S.S. gamma-ray spectrum with and without ALPs[20]. Also shown is the expected differential sensitivity of SWGO.

References

[1] J. Patrick Harding, A. Albert, C. Alvarez, R. Arceo, K. S. Caballero-Mora, G. Cotter, B. L. Dingus, K. L. Engel, H. Fleischhack, J. A. Goodman, T. Greenshaw, B. Hona, P. Huentemeyer, J. S. Lapington, J. Lundeen, J. Martinez-Castro, H. Martinez-Huerta, K. Murase, M. U. Nisa, H. Schoorlemmer, K. Tollefson, A. Viana, and A. Zepeda. Exploring Beyond-the-Standard-Model Physics with TeV Gamma-rays. , 51(3):272, 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] Joerg Jaeckel and Andreas Ringwald. The Low-Energy Frontier of Particle Physics. *Ann. Rev. Nucl. Part. Sci.*, 60:405–437, 2010.

[4] R. D. Peccei and Helen R. Quinn. CP Conservation in the Presence of Instantons. *Phys. Rev. Lett.*, 38:1440–1443, 1977. [,328(1977)].

[5] Paola Arias, Davide Cadamuro, Mark Goodsell, Joerg Jaeckel, Javier Redondo, and Andreas Ringwald. WISPy Cold Dark Matter. *JCAP*, 1206:013, 2012.

[6] Dieter Horns, Luca Maccione, Manuel Meyer, Alessandro Mirizzi, Daniele Montanino, and Marco Roncadelli. Hardening of TeV gamma spectrum of AGNs in galaxy clusters by conversions of photons into axion-like particles. *Phys. Rev.*, D86:075024, 2012.

[7] Manuel Meyer, Dieter Horns, and Martin Raue. First lower limits on the photon-axion-like particle coupling from very high energy gamma-ray observations. *Phys. Rev.*, D87(3):035027, 2013.

[8] 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.

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

[10] 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.

[11] Markus Holler et al. Observations of the Crab Nebula with H.E.S.S. Phase II. *PoS*, ICRC2015:847, 2016.

[12] Valentina Fioretti, Deivid Ribeiro, Thomas B. Humensky, Andrea Bulgarelli, Gernot Maier, Abelardo Moralejo, and Cosimo Nigro. The Cherenkov Telescope Array sensitivity to the transient sky. *PoS*, ICRC2019:673, 2020.

[13] A. Abramowski et al. Discovery of TeV γ-ray emission from PKS 0447-439 and derivation of an upper limit on its redshift. *Astron. Astrophys.*, 552:A118, 2013.

[14] H. Muriel, C. Donzelli, A. C. Rovero, and A. Pichel. The BL-Lac gamma-ray blazar PKS 0447-439 as a probable member of a group of galaxies at z = 0.343. *Astron. Astrophys.*, 574:A101, 2015.

[15] Florian Gaté and Thomas Fitoussi. H.E.S.S. observations of very-high-energy emission from 1RXS J023832.6-311658. *PoS*, ICRC2017:645, 2018.

[16] Alberto Franceschini, Giulia Rodighiero, and Mattia Vaccari. The extragalactic optical-infrared background radiations, their time evolution and the cosmic photon-photon opacity. *Astron. Astrophys.*, 487:837, 2008.

[17] Florian Gaté and Thomas Fitoussi. H.E.S.S. observations of very-high-energy emission from 1RXS J023832.6-311658. *PoS*, ICRC2017:645, 2018.

[18] M. Ajello et al. Search for Spectral Irregularities due to Photon–Axionlike-Particle Oscillations with the Fermi Large Area Telescope. *Phys. Rev. Lett.*, 116(16):161101, 2016.

[19] A. Abramowski et al. Constraints on axionlike particles with H.E.S.S. from the irregularity of the PKS 2155-304 energy spectrum. *Phys. Rev.*, D88(10):102003, 2013.

[20] H. Abdalla et al. (H.E.S.S. Collaboration). H.E.S.S. observations of RX J1713.7-3946 with improved angular and spectral resolution; evidence for gamma-ray emission extending beyond the X-ray emitting shell. *ArXiv e-prints*, September 2016.

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