Snowmass2021 - Letter of Interest

Light Dark Matter Candidates with MeV gamma-ray signatures

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: Weakly interacting sub-eV particles (WISPs) (e.g. axions and axion-like particles) are an increasingly explored dark matter candidate which produces distinct γ-ray signatures. Over the last decade, data taken between 50 MeV to $>$300 GeV by the Fermi Large Area Telescope (*Fermi*-LAT) has only recently begun exploring the phase space of interest for these models and thus far, there are no conclusive detections. At lower energies, the angular resolution of the *Fermi*-LAT makes source identification challenging, inhibiting our ability to more sensitively probe WISP models. Additionally, targeted WISP searches (e.g., those probing supernovae (SN) and blazars) would greatly benefit from enhanced energy resolution and polarization measurements in the MeV range. To address these issues, a new telescope that is optimized for MeV observations is needed. Such an instrument would allow us to explore new areas of dark matter parameter space and provide unprecedented access to its particle nature.

Introduction: The era of precision cosmology has revealed that ∼85% of the matter in the universe is dark matter. A leading candidate motivated by both particle physics and astronomical considerations is Weakly Interacting Sub-eV Particles (WISPs), e.g., axions and axion-like particles. This dark matter candidate provides distinctive MeV γ-ray signatures; however, the MeV energy range remains largely unexplored due to challenges in telescope design. The combination of accurate theoretical modeling and improved observational capabilities thus offer an intriguing opportunity for transformative progress in the near future.

At present, indirect sub-eV dark matter constraints stem primarily from four instruments (EGRET, COMPTEL, INTEGRAL, *Fermi*-LAT), each of which suffer from limited sensitivity in the MeV γ-ray range. This missing capability limits our sensitivity to these dark matter signatures, as many dark matter models predict sharp spectral signals over relatively narrow energy ranges. Establishing unparalleled sensitivity to sub-thermal dark matter candidates and optimizing the energy window for axion searches in blazars and SN is a strong motivation for improvements in MeV γ-ray instrumentation. A new telescope designed to observe MeV γ rays, such as AMEGO[9], will establish unparalleled sensitivity to sub-thermal MeV dark matter candidates, optimize the energy window for axion searches in blazars and SNe, and provide complementarity of MeV indirect detection studies within the context of future direct-detection and collider searches for light dark matter particles.

WISP and Axion-like Particle Candidates: Dark matter could be composed of WISPs that have masses in the sub-eV range and would be non-thermally produced in the early Universe (see e.g. Ref.[22] for a review). One of the most well motivated hypothetical particles that falls in this category is the axion[34;38;39], a by-product of the Peccei-Quinn mechanism that was proposed to solve the strong-CP problem in QCD, but was soon realized to additionally provide a viable dark matter candidate[1;13;35]. WISPs could be detected through an oscillation to photons in external magnetic fields[36]. Fig. 1 (left) illustrates an example of this interaction. For the QCD axion, its mass m_a and photon coupling $g_{a\gamma}$ are proportional,[1] whereas this is not the case for general WISPs such as axionlike particles (ALPs). In general, the photon-WISP oscillation could lead to three observables: (1) spectral features around a specific energy, (2) a photon flux from sources for which no emission should otherwise be detected, and (3) a change of the photon polarization. The narrow spectral features resemble a pattern of oscillations which depend on the magnetic field properties. Such patterns are not expected in the non-thermal gamma-ray spectra of AGN, SN, magnetars or other high-energy astrophysical sources[3;28;29;40].

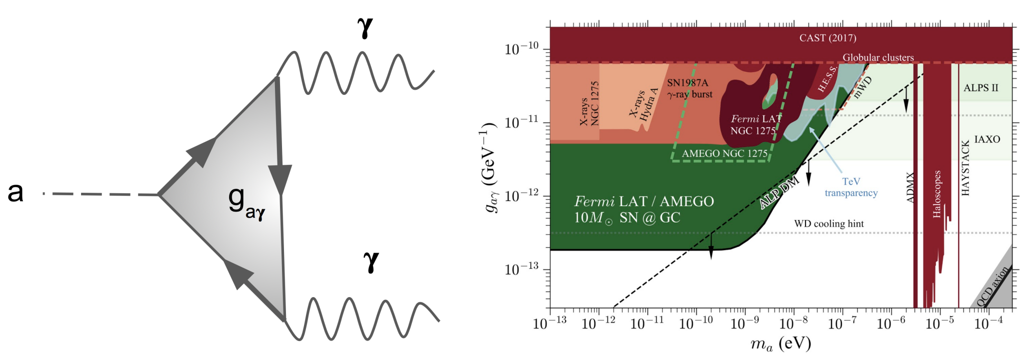

Figure 1: (left) WISP (a) interactions with a coupling $g_{a\gamma}$ producing gamma rays. (right) A summary of dark matter ALP searches conducted in the GeV band with $Fermi$-LAT data[10]. These observations have constrained portions of the relevant dark matter parameter spaces, but have an energy-ranges that are limited by the GeV-scale sensitivity of the *Fermi*-LAT.

[1]The $(m_a, g_{a\gamma})$ parameter space for the axion could be greatly enlarged, however, in the case that the axion couples exponentially strong to photons[14].

Observational Methods: WISP searches require high energy resolution to detect the sharp spectral features that arise axion-like particle oscillations in magnetic fields. In particular, WISP searches would benefit tremendously from an energy resolution of $\sim$1-5 % from 1-100 MeV. An MeV γ-ray instrument would bridge an important gap for WISP masses that are not accessible to current X-ray or γ-ray missions. A wide field-of-view will also allow us to make observations of many potential WISP targets, while high angular resolution will improve our sensitivity at low WISP masses.

Currently constraints on WISP parameters come only from the non-observation of an ALP-induced γ-ray burst from SN 1987A[8;17]. During a core-collapse SN, ALPs would be produced in the SN core through the conversion of thermal photons in the electrostatic fields of protons and ions. They would quickly escape the core and subsequently convert into γ-rays in the magnetic field of the Milky Way. This would lead to a short burst lasting tens of seconds that would arrive concurrently with the SN neutrino burst[33]. The resulting γ-ray spectrum would have a thermal shape and peak around $\sim 50\,$MeV. No other prompt γ-ray signal at such high energies is expected from an SN, making this feature a smoking gun for WISP detection. The non-observation of such a burst from SN1987A with the Solar Maximum Mission resulted in a limit of $g_{11} \gtrsim 0.5$ for $m_{\mathrm{neV}} \lesssim 1$[33]. It has been recently shown that in the event of a Galactic SN observed with the *Fermi*-LAT, and in the absence of the detection of a prompt γ-ray burst, these limits could be improved by more than an order of magnitude[31] (Fig. 1 (right)).

Since the predicted SN rate for the Milky Way amounts to only 0.03 per year, it will also be important for a mission to probe ALP-induced γ-ray bursts from extragalactic SN. For an extragalactic SN, current neutrino detectors will probably not detect a signal and thus will not provide a time stamp when to look for the γ-ray burst; however, there is potential with future neutrino observatories such as the Deep Underground Neutrino Experiment (DUNE)[2]. The explosion time can also be estimated from optical light curves[11;32] from the large number of nearby SN that will be detected in the future Rubin Observatory (nee: LSST) survey[27].

Synergies With Other Search Techniques: By improving our sensitivity to indirect signals from light dark matter candidates by several orders of magnitude, an MeV γ-ray instrument would play an important complementary role. Over the last decade, complementary between collider, direct, and indirect dark matter searches has served as a guiding principle in the GeV range, an approach that was strongly advocated during the Cosmic Frontier studies at Snowmass 2013[4]. The combination has succeeded in strongly constraining the GeV dark matter parameter space, and motivated new searches in other energy bands[7].

Over the next few years, significant direct detection[5;12;18;19;25;30] and collider efforts[6;15;20;21;23;24] are planned to probe WISP dark matter. While these techniques will set strong limits on light dark matter, each has fundamental limitations that preclude important regions of the dark matter parameter space. For example, many direct detection experiments are significantly less sensitive to spin-dependent dark matter interactions, while collider constraints depend strongly on the form factor of the dark matter coupling to quarks and gluons[16]. An enhanced MeV γ-ray instrument will provide an important and complementary lever-arm capable of constraining otherwise-hidden dark matter models. In particular, indirect detection signatures are unique in their ability to map any dark matter signature over the universe and associate any new particle with its well-measured gravitational effects. Moreover, indirect detection signatures directly probe the thermal-annihilation cross-section that is required if dark matter achieves its relic abundance through thermal processes[26;37].

Conclusions An MeV telescope with a wide-field-of-view, broad energy-range and high spatial- and energy-resolution, would be uniquely capable of enhancing our sensitivity to important regions of the dark matter parameter space by orders of magnitude. The push for three-dimensional complementarity (collider, direct and indirect-detection) has been critical for constraining GeV dark matter over the last decade, and strongly motivates our continuation of this process in the MeV band over the upcoming decade.

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