Snowmass2021 - Letter of Interest

WIMP 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: One of the most well-motivated dark matter candidates is weakly interacting massive particles. Because their annihilation produces distinct γ-ray signatures, γ-ray observations between 50 MeV and >300 GeV by the *Fermi* Large Area Telescope (*Fermi*-LAT) have provided constraints on the interaction cross sections and lifetimes of WIMP dark matter candidates. Thus far, there are no conclusive detections; however, there is an intriguing γ-ray excess associated with the Galactic Center that could be explained by either WIMP annihilation or astrophysical sources. At energies below 100 MeV, the angular resolution of the *Fermi*-LAT makes source identification challenging, inhibiting our ability to both disentangle the excess at the Galactic Center and to more sensitively probe lower-mass WIMP models. To address both these outstanding questions, a new MeV γ-ray observatory 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 Massive Particles (WIMPs). This dark matter candidate predicts distinct γ-ray signatures primarily in the GeV energy range; however, a powerful tool in distinguishing astrophysical sources from dark matter signatures is observing lower energy γ-rays in the MeV range [13]. Observations at MeV energies come primarily from four instruments (EGRET, COMPTEL, *INTEGRAL*, *Fermi*-LAT), each of which suffer from limited sensitivity. This sensitivity gap particularly affects our sensitivity to WIMP dark matter signatures, as many dark matter models predict sharp spectral signals over relatively narrow energy ranges. A new telescope designed to observe MeV γ rays, such as AMEGO [11], will establish unparalleled sensitivity to the precision of astrophysical emission models to increase the sensitivity of *Fermi*-LAT searches for GeV-scale dark matter candidates, and provide complementarity of MeV indirect detection studies within the context of future direct-detection and collider searches for lighter WIMP dark matter particles.

WIMP Candidates: Despite overwhelming gravitational evidence for dark matter (e.g. CMB, large-scale structure and galactic rotation curves), little is known about the dark matter particle. The observed dark matter relic abundance is similar to the density of baryons, which may provide some indication of early interactions between the dark and visible sectors. Models where dark matter particles enter thermal equilibrium with baryons in the early universe are particularly well motivated, and bound the dark matter mass to lie between approximately 3 MeV [24] and 120 TeV [23]. Fig. 1 (left) provides a cartoon illustrating WIMP interactions with standard model particles. In this broad class of models, residual annihilations are expected to create relativistic standard model particles today, producing observable emission that lies near the dark matter mass. These factors strongly motivate future searches in the MeV through TeV bands.

The scientific justification for GeV-scale γ-ray searches with the *Fermi*-LAT was strengthened by the recognition that the standard thermal-annihilation cross-section had not yet been probed [41;47]. However, a large number of well-motivated MeV to a few GeV mass dark matter models include annihilation or decay rates that depart from standard thermal expectations, and remain viable in light of current constraints see e.g [16;17;25;26;29;34;36;44–46]. In many scenarios, an MeV γ-ray mission will have comparable or better sensitivity than stage-4 CMB experiments, in particular for models where the dark matter particle annihilates primarily into uncharged final states [20].

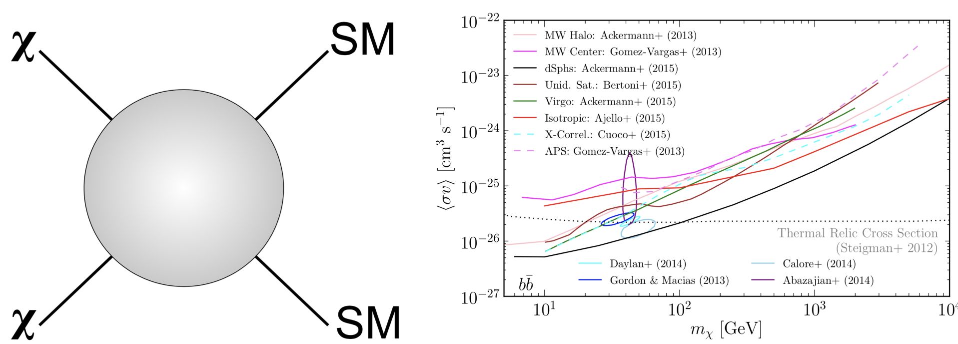

Figure 1: (left) An illustration of WIMP (χ) interactions through an unknown process which yields standard model particles (SM). (right) A summary of dark matter WIMP searches conducted in the GeV band with $Fermi$-LAT data [12]. These observations have strongly constrained portions of the relevant dark matter parameter spaces, but have an energy-ranges that are limited by the GeV-scale sensitivity of the *Fermi*-LAT.

Observational Methods: Galaxy formation models indicate that the single brightest source of WIMP annihilation products – by nearly two orders of magnitude – would stem from the Galactic Center (e.g., [35]). Good angular and energy resolution is needed to disentangle a potential DM signal from the Galactic Center from γ-ray emission by astrophysical mechanisms, including potential contributions from sub-threshold sources densely concentrated around the Galactic bulge, yet this is still poorly understood[7;19;38–40;42;49]. MeV γ-ray telescopes with good energy resolution will be able to use the π^0-bump feature in the energy spectrum of Galactic diffuse emission to disentangle this background component from the dark matter signal. It is worth noting, that compared to GeV searches in the Galactic Center, an MeV-instrument will benefit greatly from the sharp transition in the nature of the diffuse background near the location of the π^0-bump[48], a feature that could provide new constraints on the astrophysical background and illuminate any dark matter signal. All-sky coverage in the MeV energy range is critical to ensure observations of all potential targets as well as unbiased estimates of astrophysical backgrounds.

Despite the lack of a consistent WIMP annihilation signal from dwarf spheriodal galaxies, there is an intriguing excess Galactic Center (GCE) (Fig. 1 right). The spatial and spectral distributions of the GCE match that of a WIMP-like dark matter particle with a mass between 20 and 50 GeV at the thermal relic cross sections (see Ref.[1–3;15;22] and references therein). However, the spectrum is also consistent with a population of pulsars at the very center of the galaxy (see Ref.[4;10] and references therein). A wide-field MeV γ-ray telescope with similar total exposure as that of $Fermi$-LAT will be capable of disentangling the nature of the GCE.

Synergies With Other Search Techniques By improving our sensitivity to indirect signals from dark matter candidates and astrophysical sources by several orders of magnitude, an MeV γ-ray telescope would play an important complementary role in constraining the phase space of WIMP dark matter candidates. Over the last decade, complementarity 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[5]. The combination of these experiments has succeeded in strongly constraining the GeV dark matter parameter space, and motivated new searches in other energy bands[9].

Over the next few years, significant direct detection[6;14;27;28;37;43] and collider efforts[8;18;30–33] are planned to probe light WIMP dark matter. While these techniques will set strong limits, 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[21]. An enhanced MeV γ-ray telescope will provide an important and complementary lever-arm capable of constraining otherwise-hidden MeV 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[47].

Conclusions In this document, we have outlined several scientific motivations supporting the construction of an instrument that significantly increases our sensitivity to MeV γ-rays. In particular, an instrument 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. Moreover, such an instrument would provide critical information capable of constraining the uncertainties in astrophysical γ-ray emission and enhancing the stringency of existing GeV and TeV searches with both the *Fermi*-LAT and existing and upcoming ground-based γ-ray observatories. Finally, we note that such an instrument would provide an indirect-detection handle that is synergistic to ongoing direct detection and collider searches for light WIMP dark matter particles. 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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