PROCEEDINGS OF SCIENCE

AMEGO: Dark Matter (ICRC2017)

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The era of precision cosmology has revealed that ∼85% of the matter in the universe is dark matter. Two leading candidates, are weakly interacting massive particles (WIMPs) and weakly interacting sub-eV particles (WISPs) like axions and axionlike particles. Both WIMPs and WISPs possess distinct γ-ray signatures. Data from the *Fermi* Large Area Telescope (*Fermi*-LAT) continues to be an integral part of the search for these dark matter signatures spanning the 50 MeV to >300 GeV energy range in a variety of astrophysical targets. Thus far, there are no conclusive detections; yet, there is an intriguing excess of γ rays associated with the Galactic center that could be explained with WIMP annihilation. The angular resolution of the LAT at lower energies makes source selection challenging and the true nature of the detected signal remains unknown. WISP searches using, e.g. supernova explosions, spectra of blazars, or strongly magnetized environments, would also greatly benefit from increased angular and energy resolution, as well as from polarization measurements. To address these, we are developing AMEGO, the All-sky Medium Energy Gamma-ray Observatory. This instrument has a projected energy and angular resolution that will increase sensitivity by a factor of 20-50 over previous instruments. This will allow us to explore new areas of dark matter parameter space and provide unprecedented access to its particle nature.

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1. AMEGO

The All-Sky Medium Energy Gamma-ray Observatory (AMEGO) is a mission in consideration as a probe for the 2020 Astrophysics Decadal review.[1] AMEGO will survey the entire sky every 3 hours and observe 80% of the sky every orbit with its wide field of view (~ 2.5 sr) and excellent continuum sensitivity between 200 keV and above 10 GeV (see Figure 1). The AMEGO design uses well understood, well tested technologies with significant space heritage. Figure 1 is a diagram of the instrument. For more details please see Ref. [1].

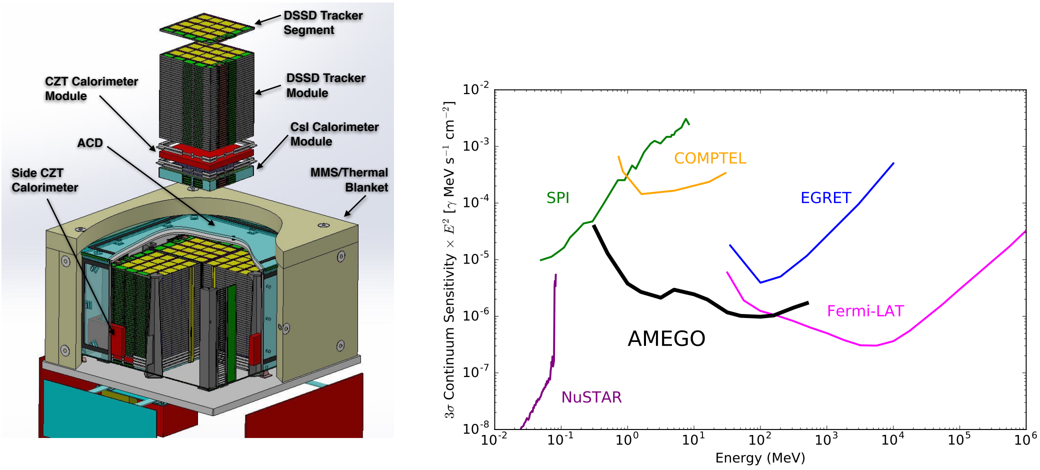

Figure 1: (left) AMEGO hardware design [1]. (right) AMEGO integral flux point source sensitivity between $\sim$ 200 keV and over 10 GeV corresponding to a 3σ detection in 3 years. (Note: Energies up to 1 GeV were simulated; however, the instrument is sensitive above this energy). Also shown in comparison are the sensitivities of previous or current space missions in a similar or complementary energy range.

2. Science Case

The AMEGO energy band represents the transition between the thermal and non-thermal Universe. It is the only part of the electromagnetic spectrum where it is possible to directly observe nuclear processes (atomic nuclei de-excitations and excitations). Specifically, it covers the positron annihilation line at 511 keV. Also, large populations of known sources exist with their peak power output in the MeV range, making its study of extreme relevance to understand source energetics. The AMEGO mission will initiate breakthroughs in our understanding of extreme environments:

- *Astrophysical Jets:* understand their formation and evolution, their acceleration mechanisms.
- *Compact Objects:* identify the physical processes in the most extreme conditions.
- *MeV Spectroscopy:* measure the properties of element formation in dynamic systems.

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[1] https://pcos.gsfc.nasa.gov/physpag/probe/probewp.php

- *Dark Matter:* test models that predict dark matter signals in the MeV band.

These physical properties exist in an array of objects including pulsars and magnetars, γ-ray bursts and multi-messanger astrophysics [2], active galaxies [3], and dark matter.

Dark matter is one of the greatest outstanding mysteries that spans particle physics, astrophysics and cosmology. Data from the *Fermi* Large Area Telescope (LAT) have been used to explore well motivated dark matter candidates such as weakly interacting massive particles (WIMPs) and weakly interacting sub-eV particles (WISPs) like axions and axionlike particles. As ground-based air Cherenkov telescopes push to higher energies, the MeV regime remains largely unexplored. In the following sections, we will discuss the possibilities for both WIMP (Section 3) and WISP (Section 4) searches with AMEGO.

3. WIMP searches with AMEGO

WIMPs are a hypothetical class of particles that could constitute dark matter. They interact via gravity and any force (or forces) which is as weak or weaker than the weak nuclear force. All WIMPs must have been produced thermally in the early Universe, as have all particles of the standard model according to Big Bang cosmology [4]. To be consistent with observations of the cosmic microwave background (CMB) and large scale structure, WIMPs must not travel relativistically (i.e. they should be "cold" instead of "hot"). Obtaining the correct abundance of dark matter today via thermal production requires a self-annihilation cross section of $\langle\sigma v\rangle \simeq 3\times10^{-26}\mathrm{cm}^3\ \mathrm{s}^{-1}$, which is consistent with what is expected for a new particle of mass $\sim$100 GeV that interacts via the electroweak force (see Ref. [4] and references therein). A WIMP annihilating via a a force weaker than the weak nuclear force could subsequently have different masses and still produce the correct relic abundance.

Dark matter searches using data from the *Fermi*-LAT were the first method of indirect detection to be sensitive enough to test thermal relic cross sections for WIMP annihilation for masses between ~ 500 MeV and ~ 100 GeV. Figure 2 is a summary of dark matter searches with the *Fermi*-LAT. The best objects to search for WIMP annihilation are those with low astrophysical γ-ray backgrounds and yet a sufficiently large "J-factor" for the γ-ray signal to be detected with the instrument.[2] Stellar kinematic data (i.e., velocity dispersion profiles) indicate that the dwarf spheroidal satellite galaxies (dSphs) of the Milky Way contain a substantial dark matter component [5]. As of now, however, there is no evidence of dark matter annihilation from dSphs, thus putting into question the thermal relic WIMP in the mass range from 500 MeV to 100 GeV [6]. The largest uncertainty in these constraints comes from the precise determination of the astrophysical J-factor.

The single brightest source of WIMP dark matter annihilation visible from Earth would be the center of the Milky Way [7]. It has a J-factor at least two orders of magnitude larger than that of dSphs; yet, the dark matter density distribution in this region is very uncertain [8]. Despite the lack of a WIMP annihilation signal from dSphs, there is an intriguing excess at the center of the Milky Way (GCE). 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 and $\langle\sigma v\rangle$ at the thermal relic (see Ref. [9] and references therein, and Fig. 2). However the spectrum is also consistent with a population of

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[2] The "J-factor" is the integral along the line of sight of the density of the dark matter squared.

pulsars at the very center of the galaxy (see Ref. [10] and references therein). The limitations of the LAT data in this regime are due in part to the worsening angular resolution at lower energies ($\lesssim$1 GeV). Also, the spectral energy distributions of over 50% of the γ-ray sources peak in the MeV regime, thus data from AMEGO will be critical to disentangle a population of point sources residing at the center of the Galaxy from a dark matter origin of the GCE. This will ultimately lead to an improved detection sensitivity to dark matter annihilation from the Galactic center using both *Fermi*-LAT and AMEGO observations.

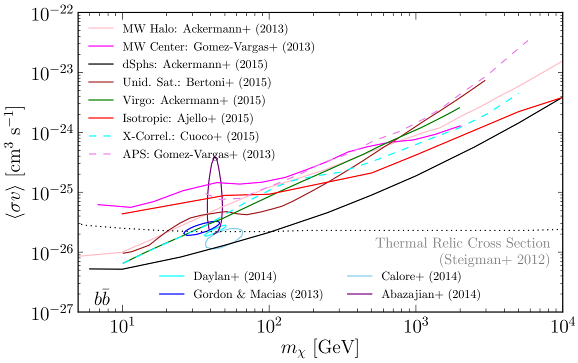

Figure 2: Summary of main dark matter results obtained with *Fermi*-LAT observations of different astrophysical targets (see legend). Lines refer to upper limits on the annihilation cross section while closed contours correspond to the GCE as due to dark matter annihilations. From Ref. [11].

In general, dark matter with any mass from $\sim$MeV to tens of TeV can achieve the correct relic abundance by annihilating directly into standard model particles [12]. Yet, the lower part of this mass range can not be fully explored using existing instruments. Direct dark matter detection experiments, which search for signals of dark matter scattering off nuclei, lose sensitivity to a dark matter particle which is lighter than a few GeV. Collider-based searches for dark matter are also, generally, insensitive to lower masses [13]. Interestingly, limits on dark matter annihilation from the CMB do not exclude many scenarios at low masses, either [12]. To probe the universe for MeV-scale dark matter, AMEGO is needed.

One class of MeV scale dark matter is an electromagnetic-like mediator for dark matter, i.e. a dark photon (A'). The dark photon is a massive hidden sector particle which would couple to both dark matter and to the standard model (see Ref. [14] and references therein). Dark photons would be detectable by mixing with ordinary photons, producing features in the electromagnetic spectrum near the mass of A'. The dark photon would also interact with known particles and therefore produce an enhanced flux of γ rays at around an order of magnitude lower energy than their mass [15].

Progress in searches for MeV mass dark matter is accelerating. Several proposed experiments which focus on MeV dark matter (such as Belle II, fixed target experiments and direct detection experiments) are in their infancy [14]. The time is right for a complementary telescope like AMEGO, to observe the sky in the MeV energy band.

4. WISP searches with AMEGO

As an alternative to WIMPs, dark matter could be made up entirely of WISPs that have masses in the sub-eV range and would be non-thermally produced in the early Universe (see e.g. Ref. [16] for a review). One of the most well motivated hypothetical particles that falls in this category is the axion [17, 18, 19], a by-product of the Peccei-Quinn mechanism proposed to solve the so-called strong CP problem in QCD, but soon realized to be also a viable dark matter candidate [20, 21, 22].

WISPs could be detected through an oscillation to photons in external magnetic fields [23]. For the QCD axion, its mass m_a and photon coupling $g_{a\gamma}$ are proportional,[3] 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 otherwise no emission should be detected, and (3) a change of the photon polarization. The energy at which the spectral features should occur in the case of axions or ALPs is $E_{\rm crit} \sim 2.5\,{\rm GeV}|m^2_{\rm neV} - \omega^2_{\rm pl,\,neV}|/g_{11}B_{\mu{\rm G}}$ (e.g. Ref. [25]), with $m_{\rm neV} = m_a/{\rm neV}$, $\omega_{\rm pl,\,neV}$ the plasma frequency of the medium in neV, $g_{11} = g_{a\gamma}/10^{-11}\,{\rm GeV}^{-1}$, and $B_{\mu{\rm G}}$ the strength of the magnetic field in μG. The search for oscillatory features in spectra of active galactic nuclei (AGN) located in or behind galaxy clusters both at X-ray and γ-ray energies has resulted in stringent limits on the photon-WISP coupling below $m_{\rm neV} \lesssim 10^{-2}$, and $0.5 \lesssim m_{\rm neV} \lesssim 100$, respectively (see e.g. Refs. [26, 27]). The narrow spectral features resemble a chaotic pattern of oscillations which depend on the magnetic field properties. Such patterns are not expected in the non-thermal γ-ray spectra of AGN.

With its wide field of view, AMEGO will observe a plenitude of AGN located in galaxy clusters for which the magnetic fields are often known independently through radio observations.[4] Assuming the same B field along the line of sight towards the radio galaxy NGC 1275 (the central AGN of the Perseus cluster) as in Ref. [27], the green dashed region in Fig. 3 shows the parameters where the axion or ALP-induced spectral irregularities change the photon flux by at least $\sim 10\,\%$ in the AMEGO energy range. With its unprecedented energy resolution of $\sim$1-2 % (Compton events) or $\sim$5 % (pair events) at 10 MeV, AMEGO will be perfectly suited to search for these spectral features and bridge the gap in m_a not accessible to current X-ray or γ-ray missions.

At the moment, this mass range is only probed through the non-observation of an ALP-induced γ-ray burst from SN 1987A [31, 32]. During a core-collapse supernova (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 in coincidence with the SN neutrino burst [33]. The resulting γ-ray spectrum would have a thermal shape and peak around ~ 50 MeV. No such prompt γ-ray signal at such high energies is expected otherwise from an SN, making this feature a smoking gun for WISP detection (which falls under category (2) above). The non-observation of such a burst from SN1987A, which occurred in the Large Magellanic Cloud, with the Solar Maximum Mission resulted in a limit of $g_{11} \gtrsim 0.5$ for $m_{\rm neV} \lesssim 1$ [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 [34]. AMEGO should have a comparable sensitivity to the *Fermi*-LAT for such an event (shown as a dark green shaded region in Fig. 3): the greatly improved point spread function of $\sim 2^\circ$ around 50 MeV compensates for the lower effective area at these energies in comparison to the *Fermi*-LAT. This entails that AMEGO should be able to probe photon-ALP couplings of $g_{11} \gtrsim 0.02$ for $m_{\rm neV} \lesssim 1$ and couplings for which ALPs could constitute the dark matter for masses $0.1 \lesssim m_{\rm neV} \lesssim 10$. It is planned to conduct a dedicated sensitivity study

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[3] 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 [24].

[4] The knowledge of B fields in galaxy clusters will greatly increase in the future due to the all-sky polarization measurements planned with Square Kilometer Array (SKA) [28].

in order to investigate the full WISP parameter space accessible to AMEGO with a Galactic SN.

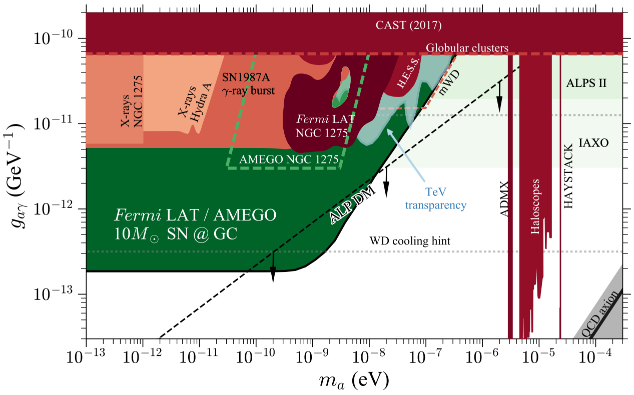

Figure 3: Low mass ALP parameter space. Parameters that will be probed with AMEGO in the case of a Galactic SN are shown as dark green while observations of NGC 1275 should probe parameters within the green dashed lines. Further limits and sensitivities are shown in red and green, respectively (see Ref. [29] and references therein; updated here with the latest CAST bound [30]).

Since the predicted SN rate for the Milky Way amounts to only $\sim 3\,\%$ per year, it will also be investigated if AMEGO can 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. Optical light curves could be used to estimate explosion time [35] from the large number of close-by SN that will be detected in the future Large Synoptic Survey Telescope (LSST) survey [36].

AMEGO will also be able to measure the polarization of γ-rays that are detected as Compton events for energies up to a few MeV. It might thus be possible to search for a WISP-induced change of the polarization. At γ-ray energies, the underlying emission mechanism is of non-thermal nature and in case of e.g. synchrotron radiation, an intrinsic polarization is to be expected. Such an intrinsic polarization would have to be modeled in order to extract a WISP effect, which might be feasible for e.g. the Crab Nebula [37].

5. Summary

The leading candidates for light dark matter (sub-GeV WIMPs and WISPs) are consistent with all current data and possess distinct γ-ray signatures. A new instrument like AMEGO, sensitive in the MeV energy range and with a projected energy and angular resolution that will increase sensitivity by a factor of 20-50 over previous instruments, is now needed in order to properly explore these dark matter candidates. Dark matter searches performed by AMEGO will also be complementary to those carried out by ground-based detectors at much higher energies, thus enabling unprecedented access to its particle nature.

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