PROCEEDINGS OF SCIENCE

The GRAMS (Gamma-Ray and AntiMatter Survey) Project

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GRAMS (Gamma-Ray and AntiMatter Survey) is a balloon/satellite mission that will be the first to target both MeV gamma-ray observations and antimatter-based indirect dark matter searches with a LArTPC (Liquid Argon Time Projection Chamber) detector. With a cost-effective, large-scale LArTPC, GRAMS can have extensively improved sensitivities to MeV gamma rays and antinuclei compared with previous missions. GRAMS was recently selected for the NASA APRA-2022 (Astrophysics Research and Analysis) program, which includes the detector development and the prototype flight in the Fall 2025 or Spring 2026.

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1. Introduction

1.1 MeV gamma-ray observations

Multi-messenger and time-domain astronomy are the keys to understanding our Universe, as identified in the recent Decadal Survey (Astro2020) [1]. The Fermi-LAT (Large Area Telescope) and the NuSTAR (Nuclear Spectroscopic Telescope Array) missions have extensively explored astrophysical objects and phenomena via high-energy gamma-ray (above 20 MeV) and X-ray (up to 80 keV) measurements, respectively [2, 3]. Gamma-ray measurements have long been under-explored and overlooked in the so-called *MeV gap* due to the lack of large-scale detectors to efficiently reconstruct the dominant gamma-ray interaction process, Compton scattering, in this energy range (see Figure 2) [4, 5]. COMPTEL (The Imaging COMPton TELescope), onboard the CGRO (Compton Gamma-Ray Observatory) satellite launched in 1991, produced the first catalog of MeV gamma-ray sources but only with approximately 30 objects [6].

Gamma-ray observations in this missing region can potentially provide rich information on astrophysical processes and phenomena, as discussed in Snowmass 2021 White Papers [7–10], including relativistic flows generated in stellar-mass black holes, supermassive black holes in active galactic nuclei, and various types of neutron stars such as radio pulsars and magnetars [11]. Additionally, gamma-ray lines from radioactive isotopes, usually in the MeV range, can offer unique opportunities to directly probe nucleosynthesis processes in astrophysical environments such as in the Galactic Center, classical novae, and the r-process to study the origin of heavy elements. Furthermore, MeV gamma rays could be detected in gravitational wave events produced in neutron star mergers and their remnants, as well as from annihilating and decaying dark matter and evaporating PBHs (Primordial Black Holes) [12]. MeV gamma rays could also be emitted together with high-energy neutrinos originating in the gamma-ray-obscured cores of active galaxies with supermassive black holes [13–15].

1.2 Indirect dark matter searches

Astrophysical observations of gravitational lensing, the Bullet Cluster, and the unexpectedly flat galaxy rotational curves have indicated the existence of dark matter since the 1960s [16, 17]. The recent result of the Planck experiment shows that dark matter comprises roughly a quarter of our universe's energy density, while baryonic matter represents only about 5%. However, the nature and origin of dark matter are still unknown, and many theories and experiments are proposed to solve this problem. WIMPs (Weakly Interacting Massive Particles) are highly-motivated candidates in various dark matter models, including right-handed sneutrinos, Kaluza-Klein particles in extra-dimensional theories, decaying gravitino (SuperWIMPs), and dark photons in hidden sector models [18–22].

The recent results of Fermi-LAT and AMS-02 (Alpha Magnetic Spectrometer) suggested possible dark matter signatures in gamma-ray observations and antiproton measurements, respectively [23–27]. The dark matter models with 50-100 GeV mass could explain both Fermi gamma-ray excess and AMS-02 antiproton excess (see the right panel of Figure 3). These excesses could also be signals from astrophysical objects, such as millisecond pulsars, and uncertainty in antiproton production and propagation models. Additionally, the results are in tension with Fermi-LAT's observations of dwarf spheroidal galaxies [28, 29]. Therefore, new approaches/experiments are necessary to investigate and clarify this issue.

2. GRAMS Mission

The GRAMS project will be the first to target both astrophysical observations and indirect dark matter searches via MeV gamma rays and cosmic-ray antinuclei measurements, respectively, using a LArTPC (a Liquid Argon Time Projection Chamber) detector [30]. GRAMS aims to use a LArTPC as an advanced Compton camera and antimatter detector. The LArTPC technology, successfully developed for underground dark matter/neutrino experiments over the last two decades [31–36], offers an affordable, scalable, and full-sky-reach solution.

2.1 Detector design and detection concept

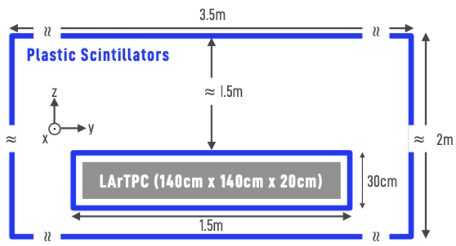

Figure 1: GRAMS detector: LArTPC surrounded by plastic scintillators.

The GRAMS instrument has a single layer of LArTPC (140 cm × 140 cm × 20 cm) surrounded by two layers of plastic scintillators (see Figure 1). Charged particles and gamma rays interact with argon atoms and ionize and excite them. The scintillation light emitted from the excited argon atom can be measured by SiPMs (Silicon PhotoMultipliers) located at the bottom, while the ionized electrons drift to the anode layer due to the applied electric field. The x- and y-coordinates of the interaction point can be identified by the anode wire or pad positions, while the z-coordinate can be estimated based on the drift time after the scintillation light detection. The three-dimensional image of the interaction point can be obtained based on the combination of these signals.

For MeV gamma-ray observations, the plastic scintillators work as veto counters to reject incoming charged particles, while the LArTPC acts as a Compton camera. The LArTPC detector is segmented into *cells* to localize the signals and minimize the coincident background events, such as cosmic-ray and atmospheric photons. These background events are significantly higher during the operation in flight, unlike underground experiments with a shield against cosmic-ray particles. For antimatter measurements, the plastic scintillators work as a TOF (time-of-flight) system to measure the velocity of incoming particles, while the LArTPC acts as a particle tracker or calorimeter.

GRAMS uniquely utilizes LArTPC as a Compton camera and antimatter detector while taking advantage of the LArTPC technology. A LArTPC is cost-effective as argon is one of the most abundant elements on earth, compared to the high-purity semiconductor and scintillation crystals. The single-layer GRAMS LArTPC can efficiently expand the detector size, unlike the conventional multilayer detector configuration with semiconductor or scintillation crystals that requires a large number of readout electronics proportional to the number of layers. Moreover, a LArTPC has much less dead volume as detector mounting frames and preamplifiers are not required inside the TPC, unlike other detectors. Additionally, a LArTPC is capable of distinguishing nuclear recoil events from electron recoil events based on the pulse shape of the light signal, as successfully demonstrated in direct dark matter search experiments. The neutron event, one of the potential background events for gamma-ray measurements, could be identified and rejected with a LArTPC.

2.2 MeV gamma-ray observations

MeV gamma rays tend to undergo multiple Compton scatterings before being photo-absorbed or even escaping from the sensitive volume of the detector. By capturing the accurate position and energy data for the Compton-electron(s) and photo-absorption, the incident gamma-ray energy E and the cone angle θ can be reconstructed via the Compton scattering equation [37, 38]. The measured cone angle defines a *Compton circle* for each event, and the intersection of three or more Compton circles can pinpoint the direction of the gamma-ray source.

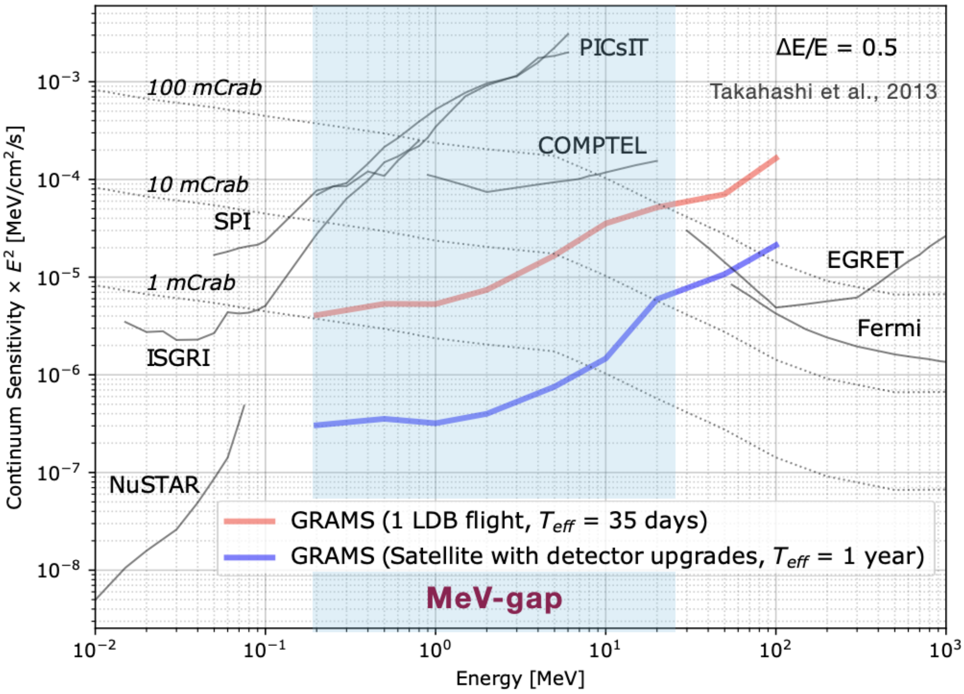

Figure 2: The continuum gamma-ray sensitivities for the GRAMS balloon experiment and the future satellite mission compared to the sensitivities for previous and future experiments. Black dashed lines represent the flux levels of 1-100 mCrab [4, 5].

The cost-effective, large-scale GRAMS detector can deliver unprecedented sensitivity to astrophysical observations of MeV gamma rays. A GRAMS single LDB (Long-Duration Balloon) flight can have an order of magnitude improved sensitivity compared to previous experiments (see Figure 2). The GRAMS satellite mission can provide another order of magnitude enhanced sensitivity comparable and complementary to future proposed projects, such as AMEGO-X [39]. GRAMS can further open up MeV gamma-ray astronomy/astrophysics while filling a gap between X-ray and high-energy gamma-ray observations.

2.3 Antimatter-based indirect dark matter searches

GRAMS aims to measure low-energy antinuclei, especially antideuterons, as it is essentially a *background-free* dark matter search. The primary antideuteron flux can have a relatively flat peak at low energy, $E \sim 0.1\ GeV/n$. The antideuteron flux due to cosmic-ray interactions with the interstellar medium (called secondary flux) is also shown as the solid red line in the left panel of Figure 3 [18, 20, 40–43]. Unlike primary antideuterons, collision kinematics suppress the

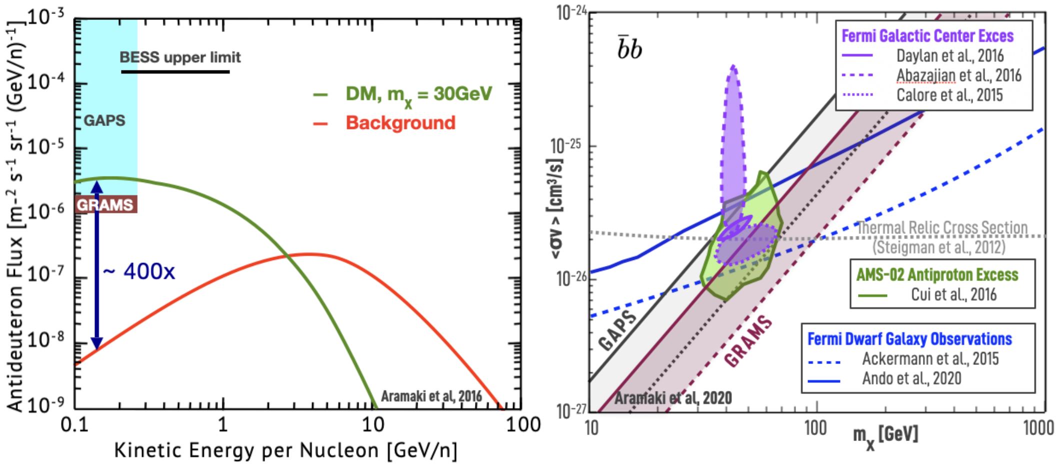

Figure 3: The left figure shows the antideuteron sensitivities for GRAMS and other experiments together with the predicted antideuteron fluxes from dark matter annihilation (primary) and cosmic ray interactions (secondary). The right figure shows the parameter space for the possible dark matter signatures suggested by Fermi and AMS-02, where GRAMS sensitivities are overlaid with an uncertainty of the antideuteron production model

formation of low-energy secondary antideuterons. The primary antideuteron flux can be about two orders of magnitude larger than the secondary antideuteron flux at low energy, providing a high signal-to-background ratio, i.e., a background-free dark matter search.

The GRAMS antimatter detection technique includes the decay of an *exotic atom*. A TOF system with plastic scintillators measures the velocity (energy) and direction of an incoming antiparticle. The antiparticle slows down by the dE/dX energy loss and stops inside the LArTPC, forming an exotic atom in its excited state, where the negatively charged antiparticle is bounded by an argon nucleus. The exotic atom de-excites with the emission of Auger electrons as well as atomic X-rays. Here, the energies of atomic X-rays are unique to the mass of the captured antiparticle and the target atom. At the end of this cascade, the antiparticle is captured by the nucleus, where it annihilates with the emission of annihilation products, such as pions and protons. Here, the pion and proton multiplicities are roughly proportional to the number of antinucleons (see Figure 4).

Antiprotons are the main background for antideuteron measurements, as they can also provide signals from the decay of the exotic atom. GRAMS can, however, identify antideuterons based on

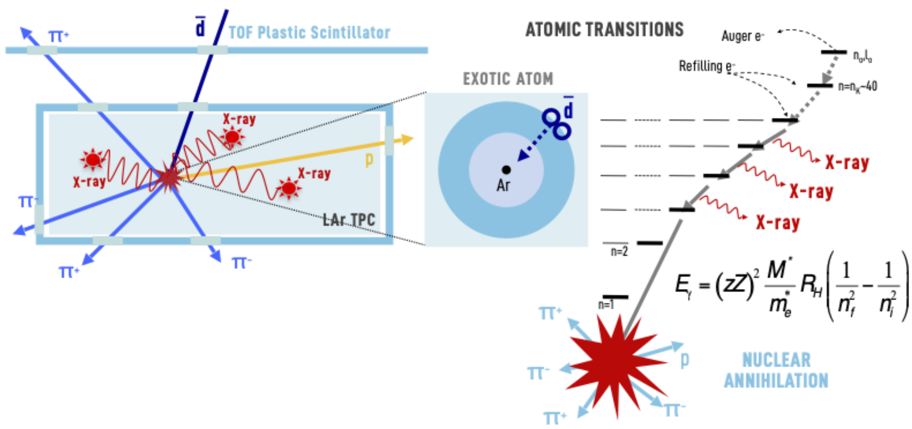

Figure 4: The GRAMS antimatter detection technique. The stopped antimatter forms an excited exotic atom that decays and emits atomic X-rays and annihilation products (pions and protons). The atomic X-rays, pion/proton multiplicities, and the stopping depth in the LArTPC provide the particle identification capability.

atomic X-rays, pion and proton multiplicities, and the dE/dX stopping range, the travel distance of the incoming antinuclei in the medium before stopping. The energies of atomic X-rays are unique to the mass of the captured antiparticle and the target atom, the pion and proton multiplicities are roughly proportional to the number of antinucleons, and the stopping range is approximately proportional to the ratio of mass to the charge squared.

3. Current Status and Future Plans

The GRAMS collaboration is a multidiscipline team, and the members have different backgrounds and expertise while forming an international collaboration. The GRAMS detector R&D is conducted in both US and Japan. A small-scale LArTPC detector, MicroGRAMS (10 cm $\times$ 10 cm $\times$ 10 cm), is currently being tested at Northeastern University (see Figure 5). Low-power, charge-sensitive preamplifiers, pitched by 3 mm on x and y directions, are used to read charge signals, while 16 SiPMs are used to measure light signals. The detector will be scaled to MiniGRAMS, 30 cm $\times$ 30 cm $\times$ 20 cm, that can be segmented into nine cells to demonstrate the gamma-ray measurements with a radioactive source.

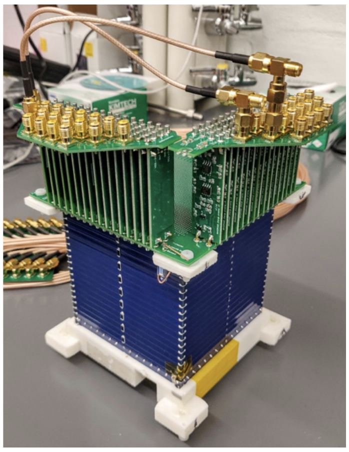

Figure 5: MicroGRAMS at Northeastern.

In the summer of 2023, the engineering flight was successfully conducted at the JAXA (Japan Aerospace Exploration Agency) Taiki Aerospace Research Field, where a small-scale LArTPC with three charge preamplifiers above was operated at flight altitude. The project was recently funded by NASA APRA-2022 for a prototype flight with MiniGRAMS in the Fall of 2025 or Spring of 2026. MiniGRAMS is a larger Compton camera, compared to the previous mission, and can also be used for the future science flight in the late 2020s. Ultimately, the program aims at a satellite mission that will enable transformative research in the 2030s.

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