Liquid Argon TPCs in space: The Gamma-Ray and AntiMatter Survey (GRAMS) Project

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for the GRAMS Collaboration

Gamma2024 @Milano, Sep 2-6, 2024

What is GRAMS?

GRAMS = Gamma-Ray and AntiMatter Survey

One of the NASA Physics of Cosmos Missions

First experiment to target both astrophysical observations with **MeV gamma rays** and indirect dark matter searches with **antimatter**

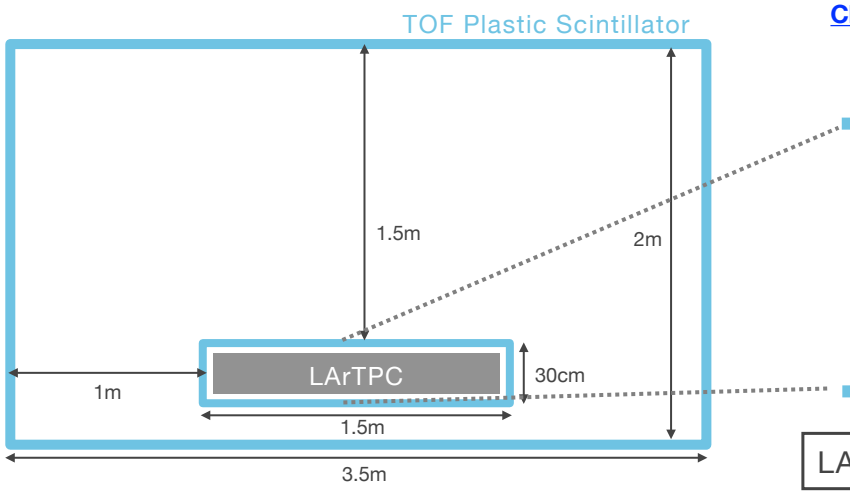
First balloon/satellite mission with a low-cost, large-scale **LArTPC** (Liquid Argon Time Projection Chamber) detector

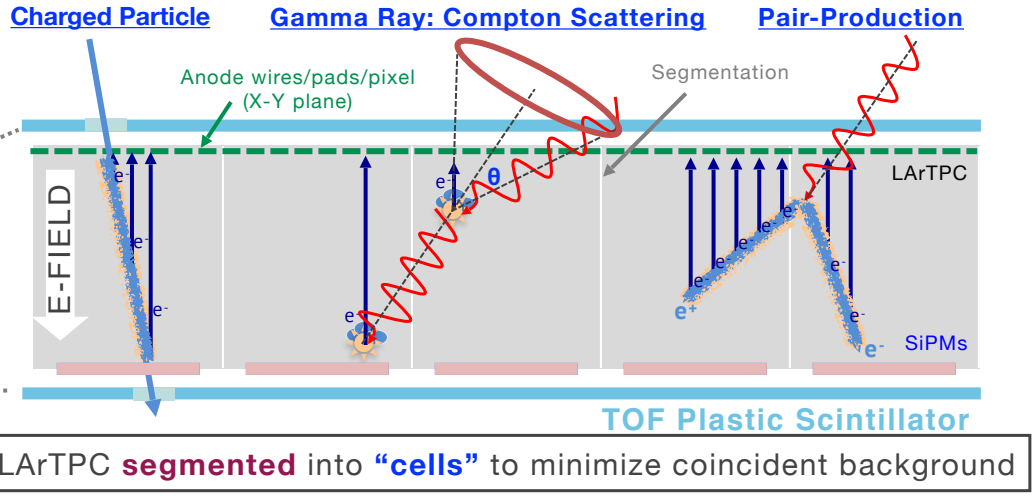
A prototype flight is scheduled in 2025/2026 under **NASA APRA22**

GRAMS detector design

LArTPC surrounded by plastic scintillators

	Antimatter	Gamma ray
Plastic Scintillator	Time of Flight to measure velocity	VETO Counter to reject charged particles
LArTPC	Particle Tracker, Calorimeter	Compton Camera, Calorimeter

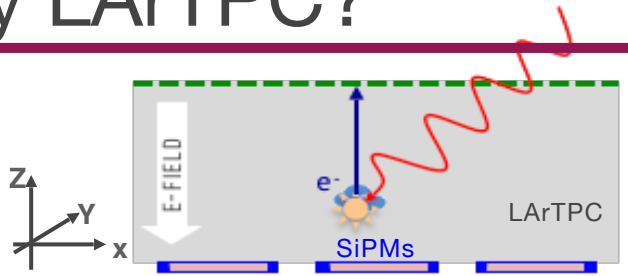




LArTPC **segmented** into **"cells"** to minimize coincident background

Large-scale, low-energy threshold LArTPC has been **well-studied** and **widely-used** in underground **dark matter** and **neutrino** experiments

Why LArTPC?



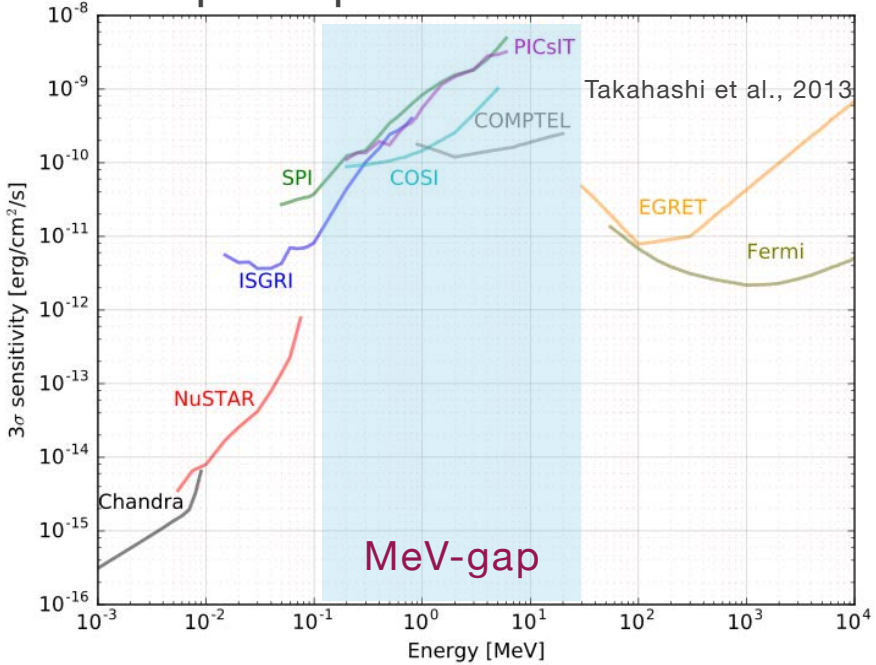
	LArTPC	Semiconductor/Scintillator
ρ (g/cm^3)	1.4	2.3/5.3 (Ge/Si)
$T_{operation}$	~80K	~240K/~80K
Cost	$	$$$
Signals	scintillation light + ionization electrons	electrons, holes
X, Y positions	Wires/pads on anode plane (X-Y)	double-sided strips
Z position	From drift time	from layer #
# of layers	Single layer	multi-layers
# of electronics	#	###
Dead volume	Almost no dead volume	detector frame, preamps
Neutron bkg	Identified with pulse shape	no rejection capability

LArTPC is **cost-effective** and almost **no dead volume**

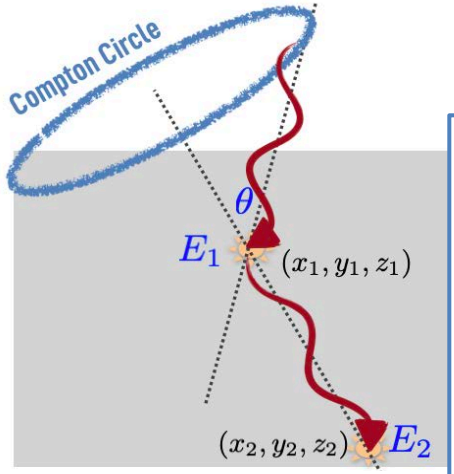
Easily expandable to a **larger scale** with **high detection efficiency**

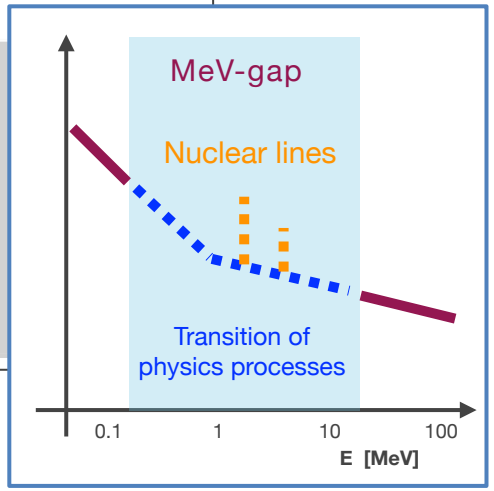
MeV gamma-ray Observations

Open up a new window into the **poorly-explored** MeV sky region



Compton scattering process dominates in MeV range
Good energy & spatial resolution required



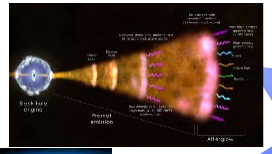


MeV gamma-ray continuum/line spectrum

- Physics processes/**nucleosynthesis**
- **Multi-messenger** astronomy: EM counterparts of GWs and high-energy neutrinos
- Indirect **dark matter** searches/**PBH** searches

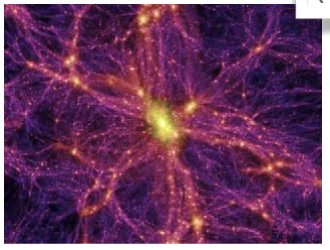
MeV gamma-ray Science

Gamma-ray bursts



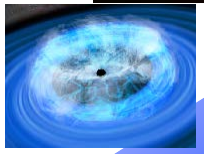
Blazars

Dark Matter

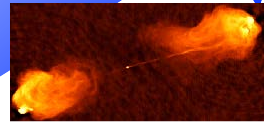


Q-ball
(Shinta Kasuya's poster)

Seyferts

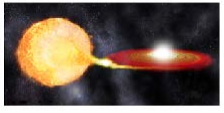


Starburst Galaxies



Radio Galaxies

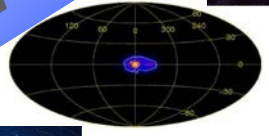
NS merger



Type-Ia SNe

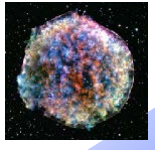
X-ray/γ-ray Binaries

DISTANCE



Galactic Center

SNRs & PWN



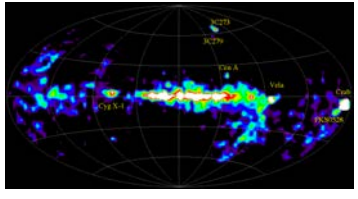
Pulsars & Magnetars

Sun

Novae

Terrestrial Flashes

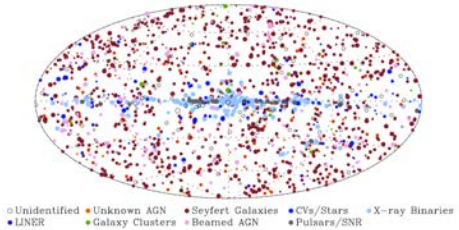
Background



MeV gamma-ray all sky

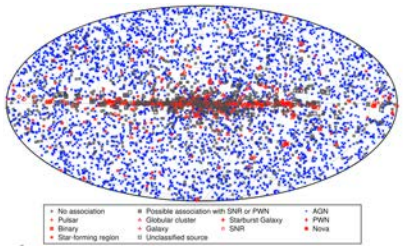
Swift-BAT 105-month

(1632 sources in 14 to 195 keV)



4FGL-DR2

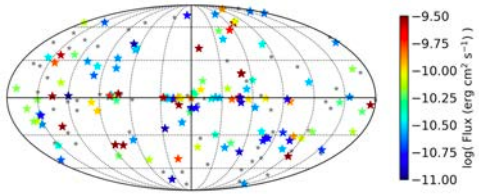
(5788 sources in 50 MeV to 1 TeV)



Catalog cross-match

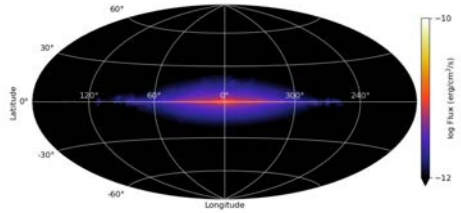
Sources

(Tsuji+ 2021; 2023)



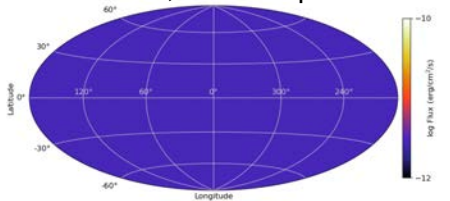
Galactic diffuse emission

(Ackermann+ 2012; Orlando 2018)



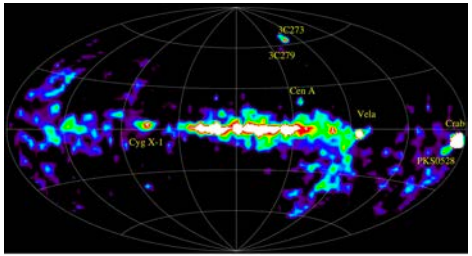
Extragalactic emission

(Watanabe 2000; Weidenspointner 2000)

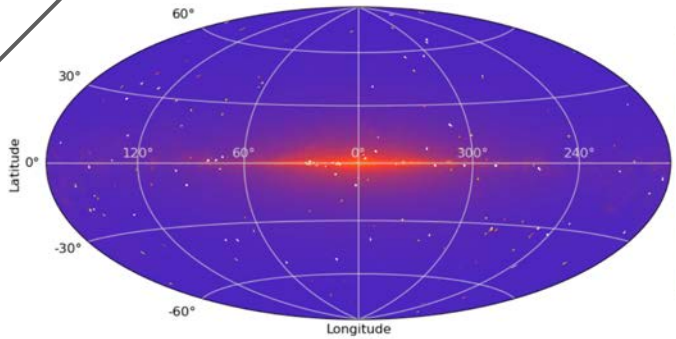


COMPTEL all-sky map

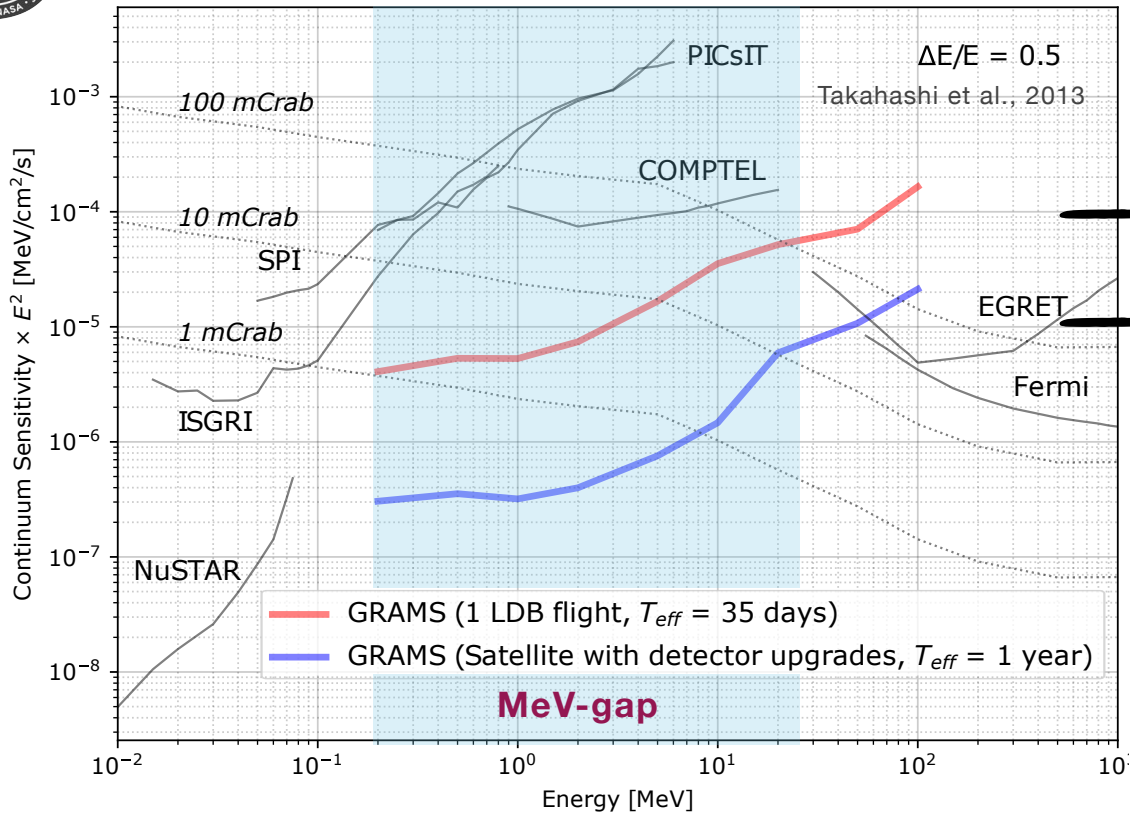
(Strong et al. 1999)



1-10 MeV all sky



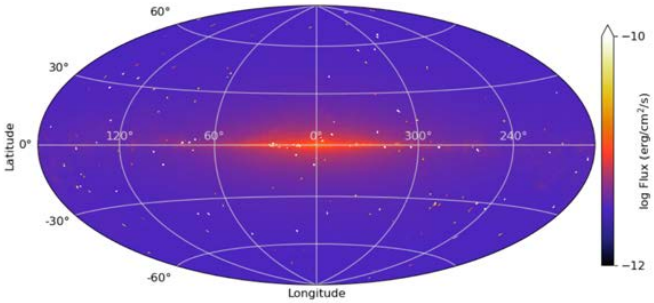
MeV gamma-ray sensitivity



~30 sources

~100 sources

1-10 MeV all sky

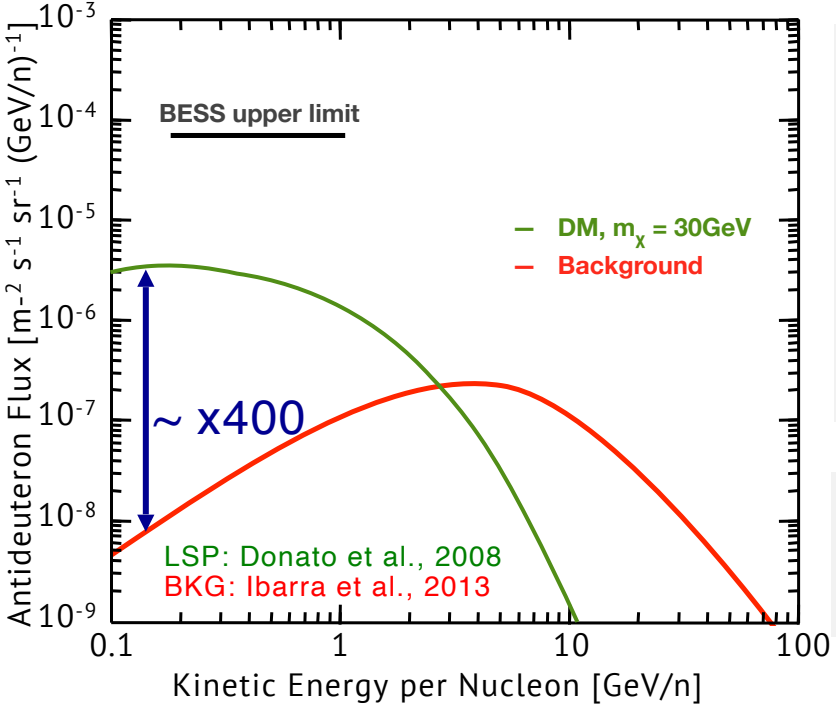


LDB Balloon flight: an order of magnitude improved

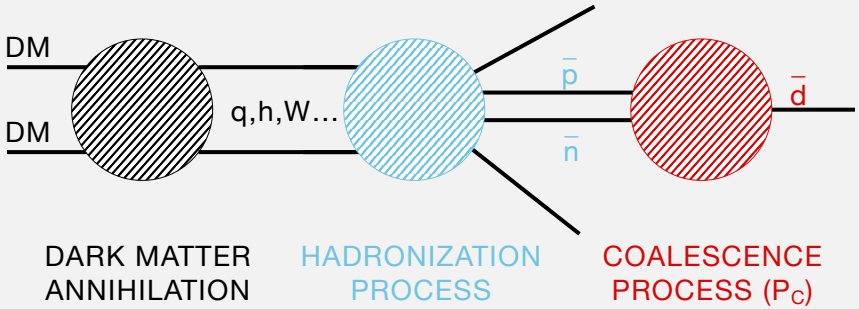
Satellite mission: comparable to future missions

Low-energy antideuteron measurements

Background-free DM search



PRIMARY FLUX = DM ANNIHILATION/DECAY



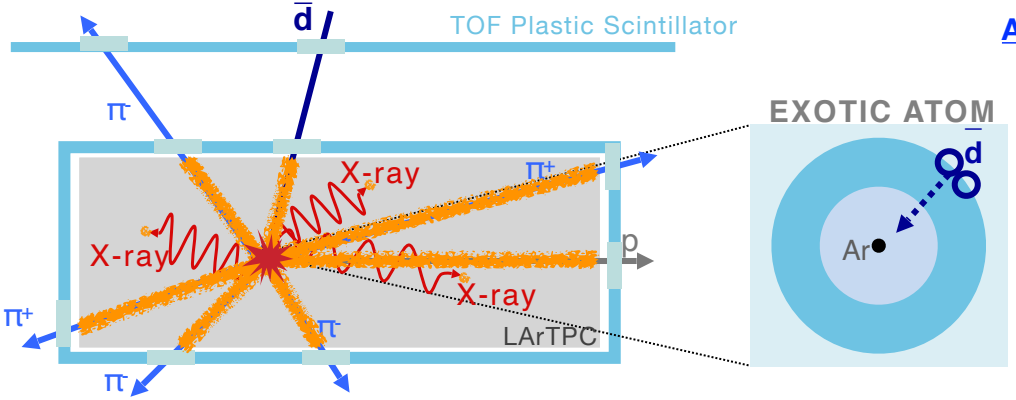
SECONDARY FLUX = COSMIC RAY INTERACTION

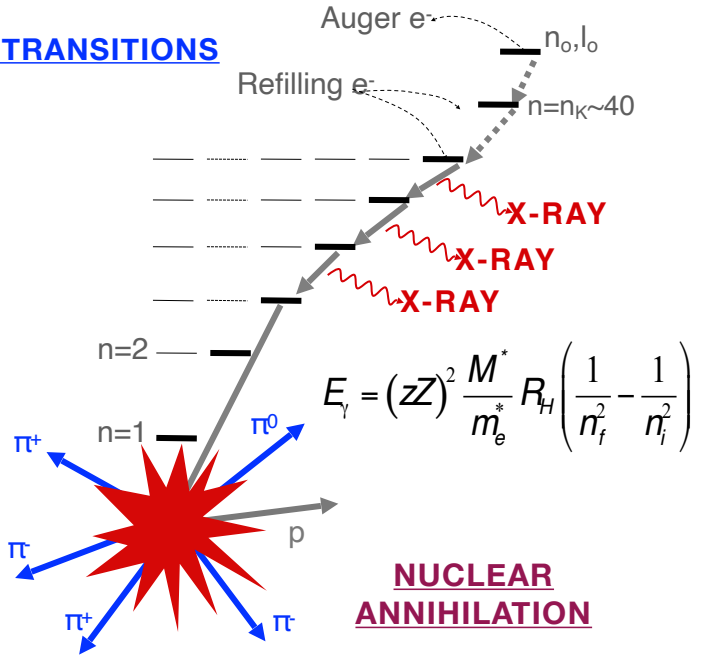
$$p\ (CR) + H\ (ISM) \rightarrow p + H + p + n + \bar{p} + \bar{n}$$ $\bar{d}$

Balloon experiments from the Antarctic are optimized for low-energy antideuteron measurements considering geomagnetic cut-off

GRAMS antimatter detection concept

Measure atomic X-rays and annihilation products



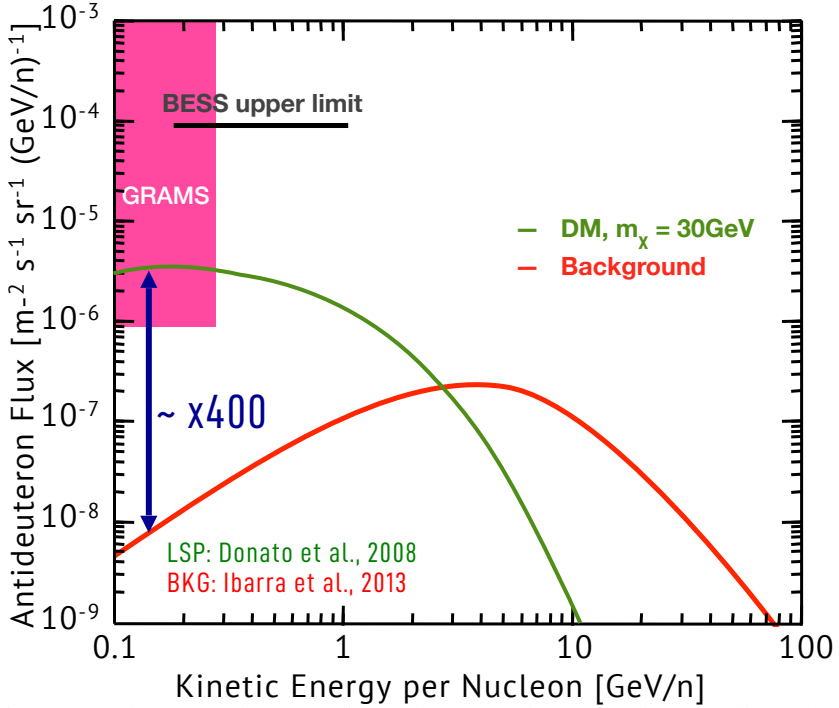


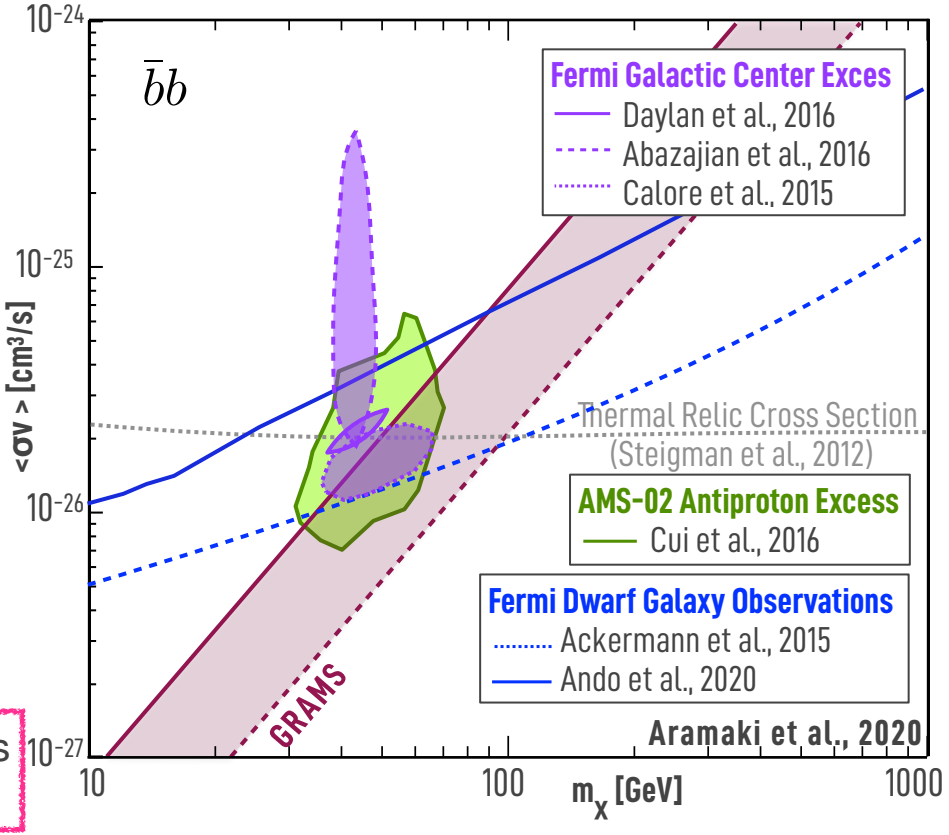
- A time of flight (TOF) system tags candidate events and records velocity
- The antiparticle slows down & stops, forming an excited exotic atom
- De-excitation X-rays provide signature
- Annihilation products provide additional background suppression

LArTPC (almost no dead volume) provides
- **Excellent** 3D particle tracking capability
- **High** particle detection efficiency

GRAMS Sensitivity in DM Parameter Space

Extensively explore DM parameter space and validate Fermi/AMS-02 results



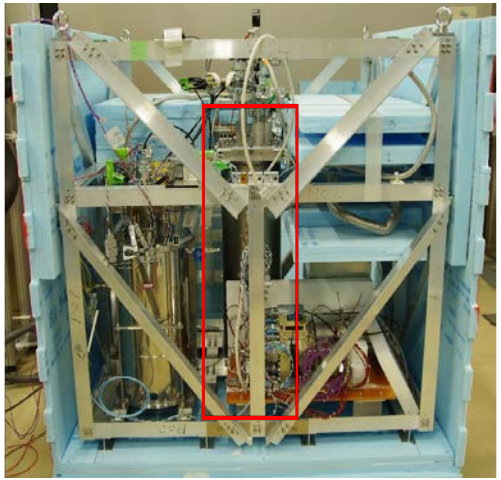


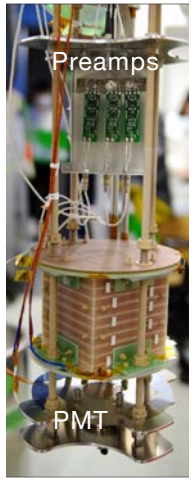
Cost-effective/fast recovery/more frequent flights with LArTPC can further enhance the sensitivity

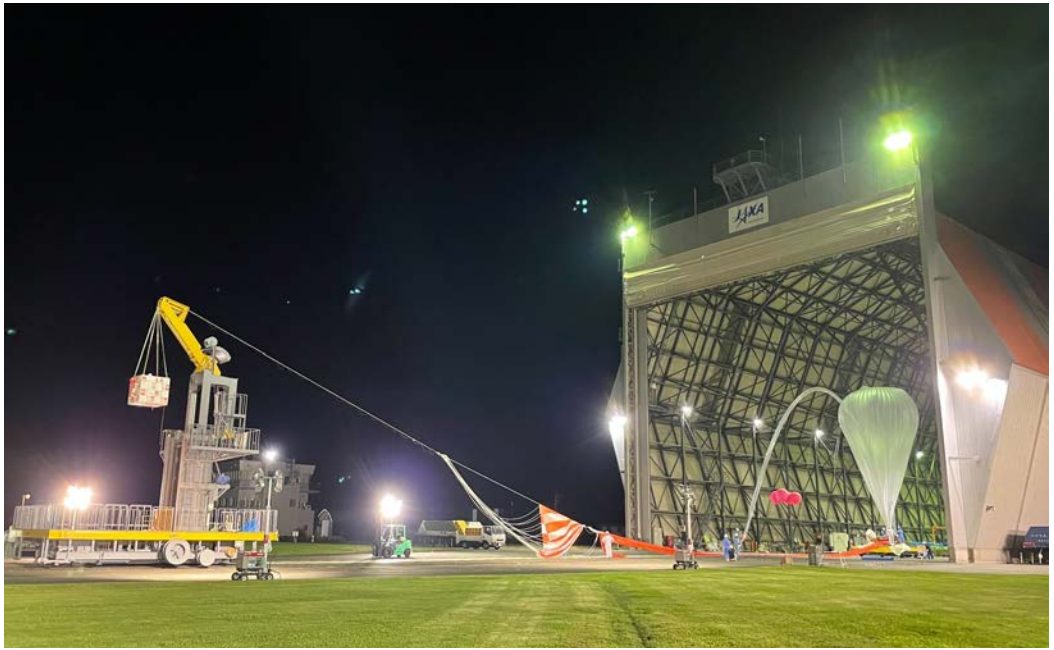
Engineering Flight and Beam Test in Japan

Successful Engineering flight

- Launched in **July 2023** @JAXA TARF
- **First** LArTPC operation in flight
- TPC: 10 x 10 x 10 cm^3
  - 3 charge channels, 1 PMT
- Obtained ~400k stable events







Antiproton beam test @J-PARC in Dec 2024

- **Validate** LArTPC performance as an antimatter detector
  - Measure annihilation products (and atomic X-rays)
- May include some **antideuterons**

Prototype flight (pGRAMS)

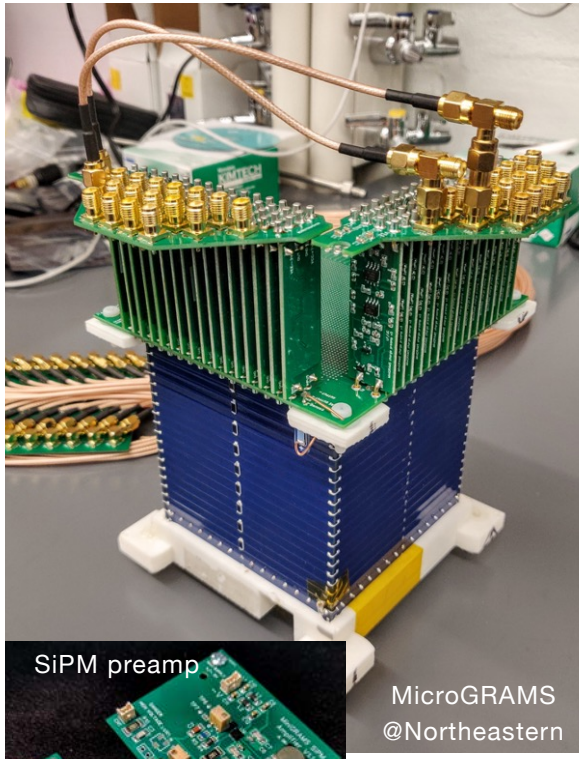
Funded by NASA APRA2022

Prototype flight scheduled **in 2025/2026**

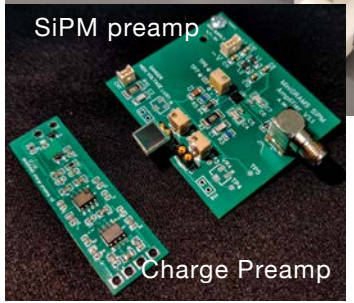
- Demonstrate LArTPC performance in flight
  - **Particle tracking** for charged particles
  - **Gamma-ray detection**
- **MinGRAMS**: 30 x 30 x 20 cm^3 segmented into **9 cells**
  - Tile/pads (~3mm pitch) for x/y directions
  - 180 charge preamps in total
  - 16 SiPMs (6 mm x 6mm each) per cell
- Currently testing **MicroGRAMS** @Northeastern
  - TPC size: 10 x 10 x 10 cm^3 (TPB inside TPC)
  - Demonstrate the particle tracking capability and event reconstruction techniques with gamma-ray sources

Followed by science flights with **MiniGRAMS**

- One of the **largest** Compton cameras
- Cooling/circulation system onboard



MicroGRAMS @Northeastern



GRAMS Collaboration

International collaboration with different backgrounds/expertise

Gamma-rays, X-rays, Cosmic-rays, Neutrinos, Direct/Indirect DM searches

USA

- Barnard College
- Columbia University
- Howard University
- NASA GSFC
- Northeastern University
- Oak Ridge National Lab
- UCB/SSL
- UT Arlington
- Washington University
- Yale

2024 May Collaboration Meeting

International

- Hiroshima University
- Tokyo University of Science
- Kanagawa University
- Nagoya University
- National Defense Medical College
- Osaka University
- Universität Würzburg
- RIKEN
- Rikkyo University
- University of Tokyo
- JAXA
- Yokohama National University
- Waseda University

Summary

- GRAMS aims for both **gamma-ray** observations in the **poorly-explored MeV** range, as well as **indirect dark matter searches** with **antimatter**. The project will begin with a **balloon** experiment as a step forward to a **satellite** mission.

- With a cost-effective, large-scale LArTPC detector, the sensitivity to MeV gamma rays can be **an order** (**two orders**) of magnitude improved with a **single balloon flight** (**Satellite**) compared with the previous missions.

- GRAMS low-energy **antideuteron** measurements can be essentially **background-free** dark matter searches while investigating and validating the possible dark matter signatures indicated in **Fermi** GCE (Galactic Center Excess) and **AMS-02** antiproton excess.

- We are currently testing **MicroGRAMS** for the particle tracking capability and gamma-ray event reconstruction techniques and preparing for the **antiproton beam test** (late 2024),

- We will have a **prototype flight** with **MiniGRAMS** in 2025/2026, funded by the **NASA APRA (2022)** program.

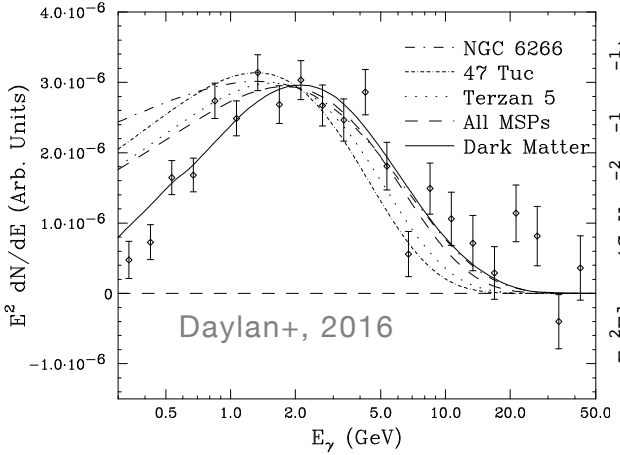
Backup

Puzzling excesses in indirect DM searches

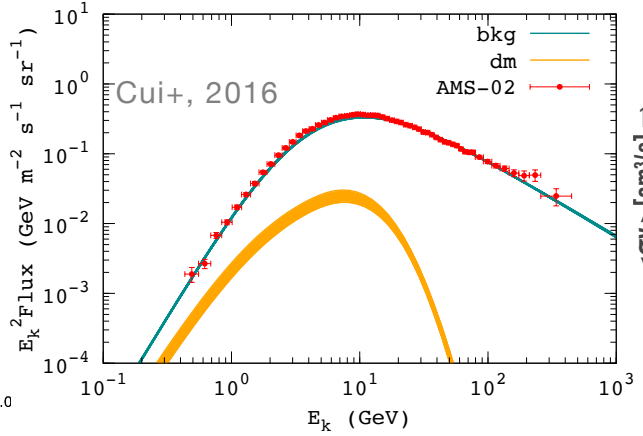
Snowmass2021 CF White Paper

- arXiv:2209.07426: Report of the Topical Group on Particle Dark Matter for Snowmass 2021
- arXiv:2203.06859: Puzzling Excesses in Dark Matter Searches and How to Resolve Them:
- arXiv:2203.06894: The landscape of cosmic-ray and high-energy photon probes of particle dark matter

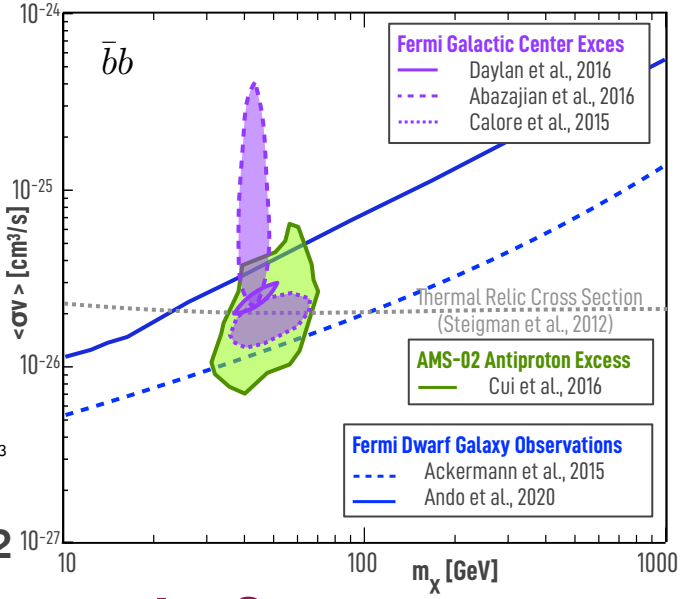
Fermi gamma-ray excess



AMS-02 antiproton excess



Detection of antideuteron/antihelium-like events in AMS02



How do we validate these results?