

GRAMS Project



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COSPAR2024 @Busan, South Korea, July 13-21, 2024



What is GRAMS?

2

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**



Outline

3

MeV gamma-ray observations with GRAMS

- Current status
- Detection concept and sensitivity

Antimatter measurements with GRAMS

- Current status
- Detection concept and sensitivity

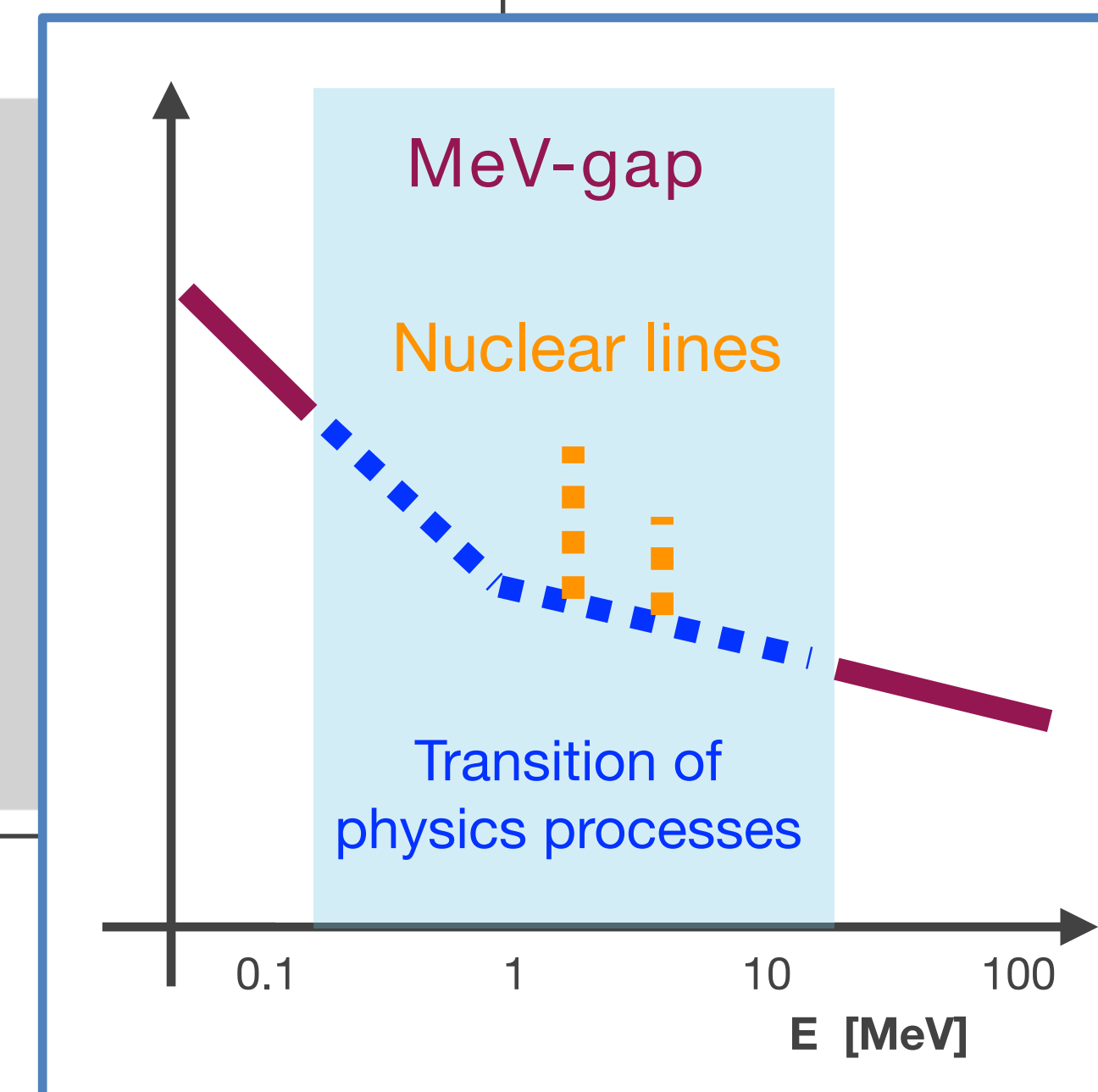
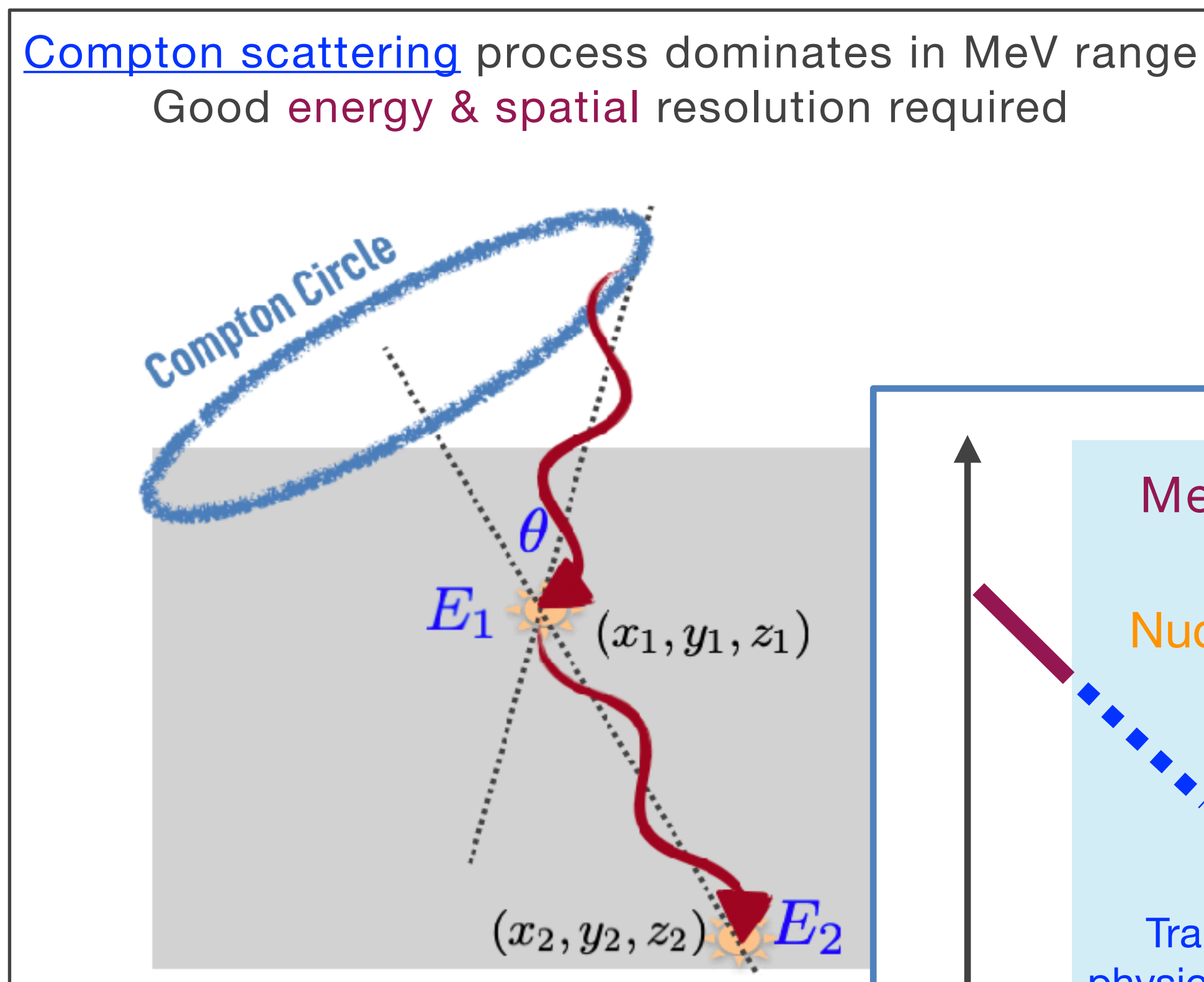
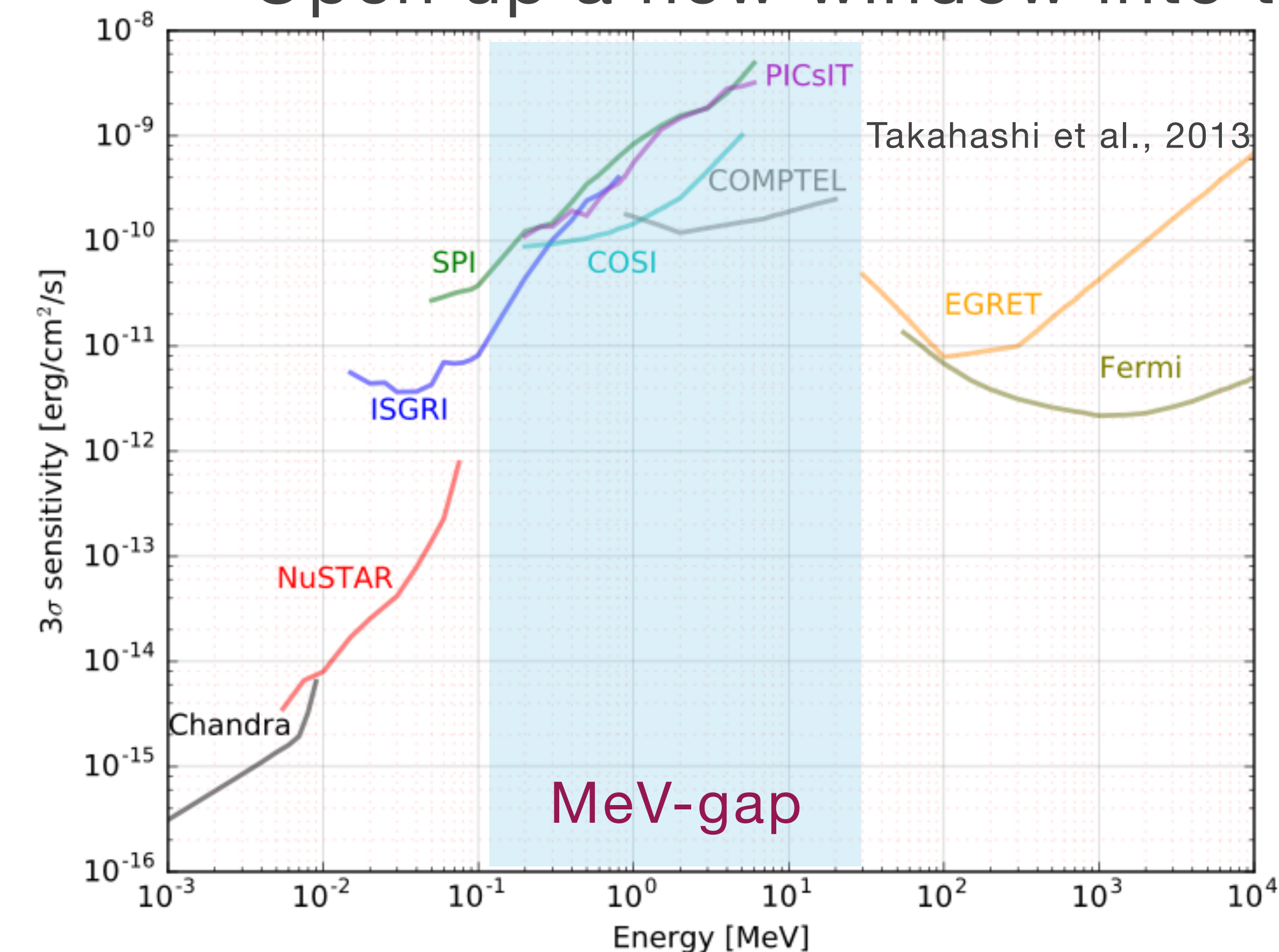
Current status and future plan

- Engineering flight (eGRAMS)
- Beam test
- Prototype flight (pGRAMS)

Outlook/Summary

MeV Gamma-Ray Observations

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



MeV gamma-ray continuum/line spectrum

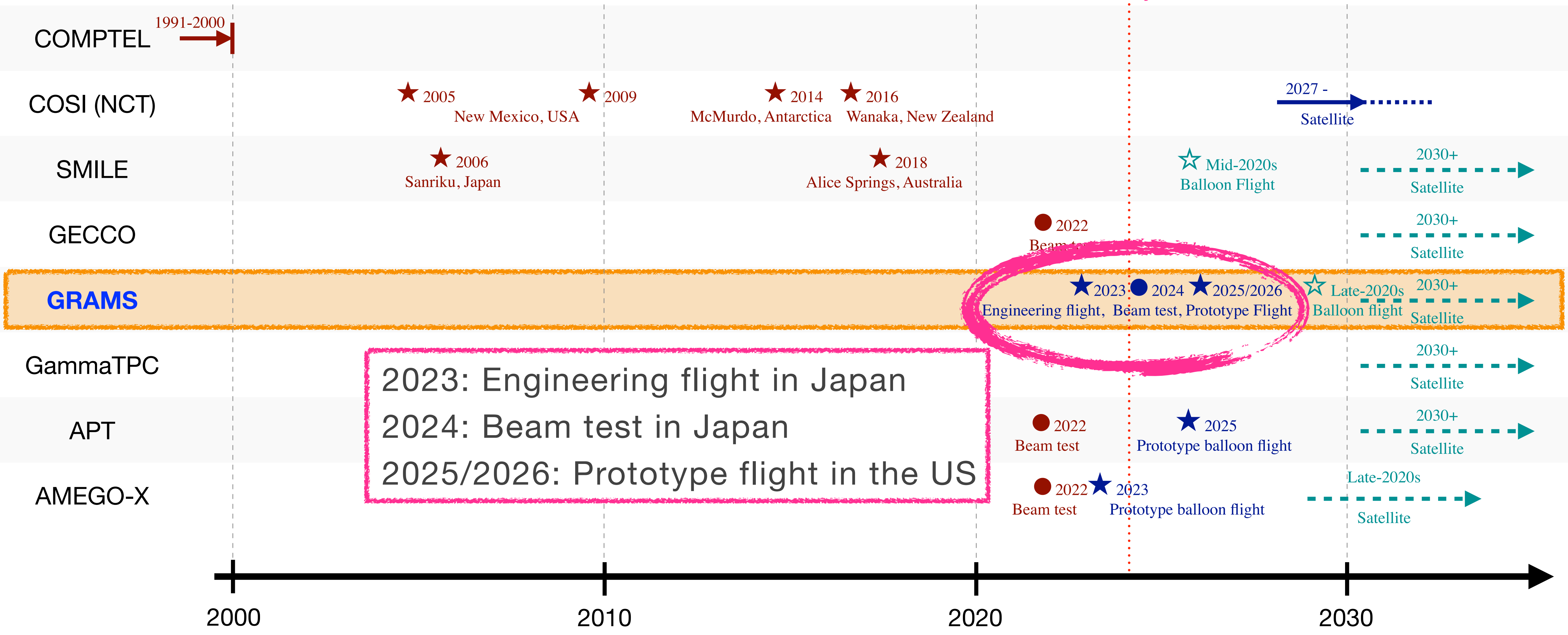
- Physics processes/**nucleosynthesis**
- **Multi-messenger** astronomy: EM counterparts of GWs and high-energy neutrinos
- Indirect **dark matter** searches/**PBH** searches



MeV gamma-ray missions (Snowmass 2021+)

Past, near-term, and long-term future plans

Snowmass White Paper:
Aramaki+, 2022





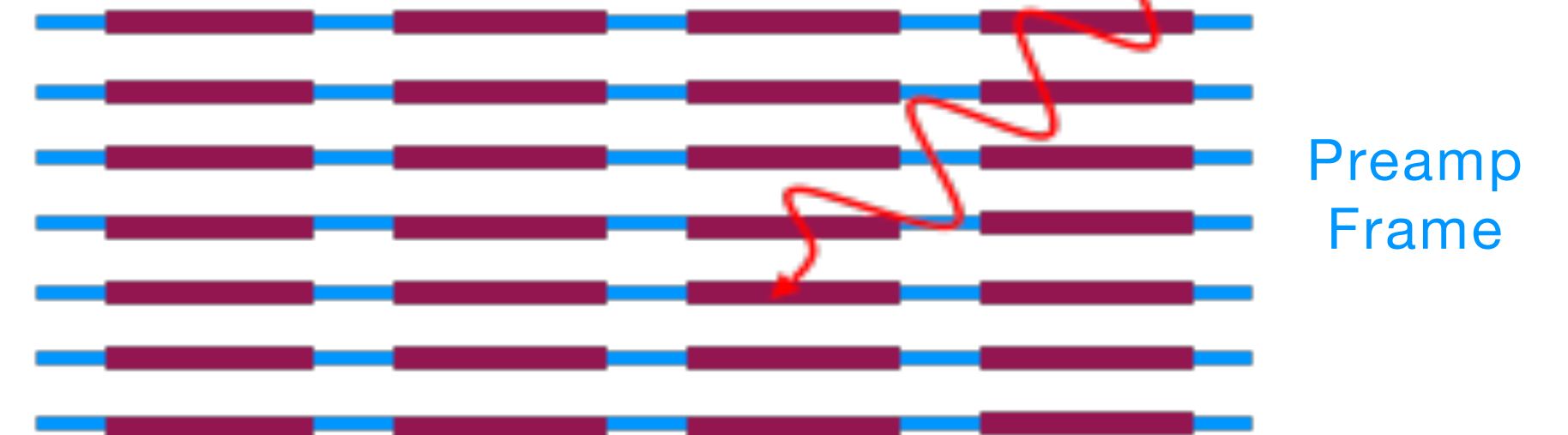
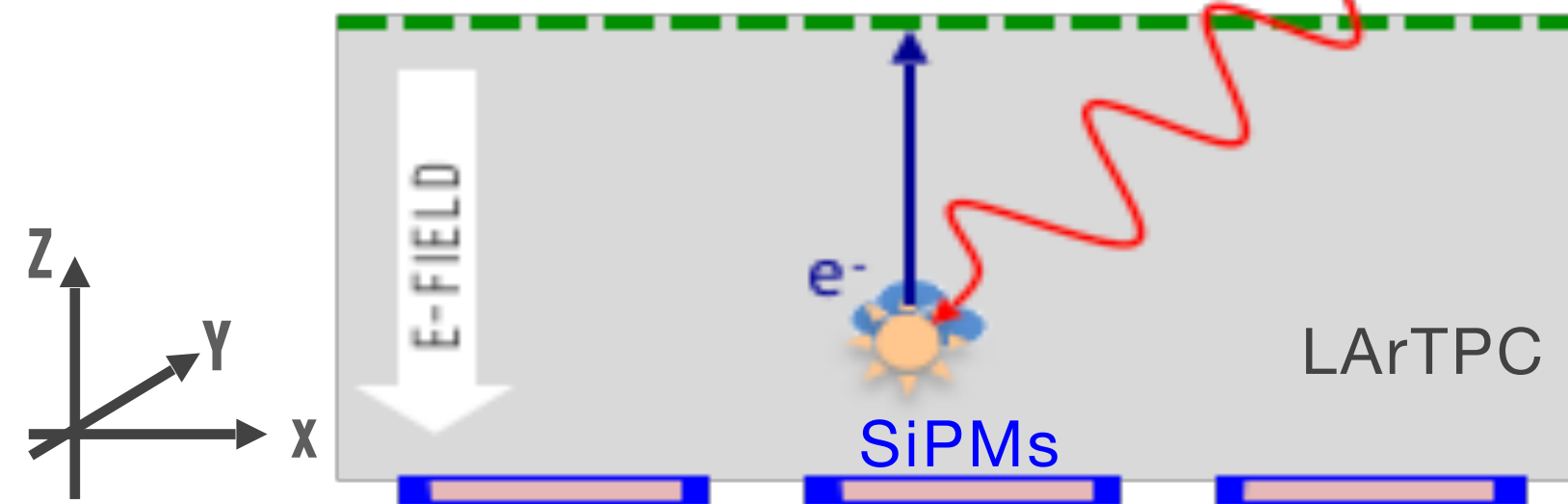
The diagram illustrates the LArTPC detector structure and its segmentation. The left part shows the overall dimensions: a 3.5m wide TOF Plastic Scintillator surrounding a 1.5m wide LArTPC, which is 30cm high. The right part is a detailed view of the LArTPC segmented into "cells". It shows an E-FIELD pointing downwards, anode wires/pads/pixel in the X-Y plane, and SiPMs at the bottom. Three interaction types are depicted: a Charged Particle (blue line), Gamma Ray Compton Scattering (red wavy line with angle θ), and Pair-Production (red wavy line with e^+ and e^-). The segmentation is indicated by vertical lines between the cells.

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



Why LArTPC?

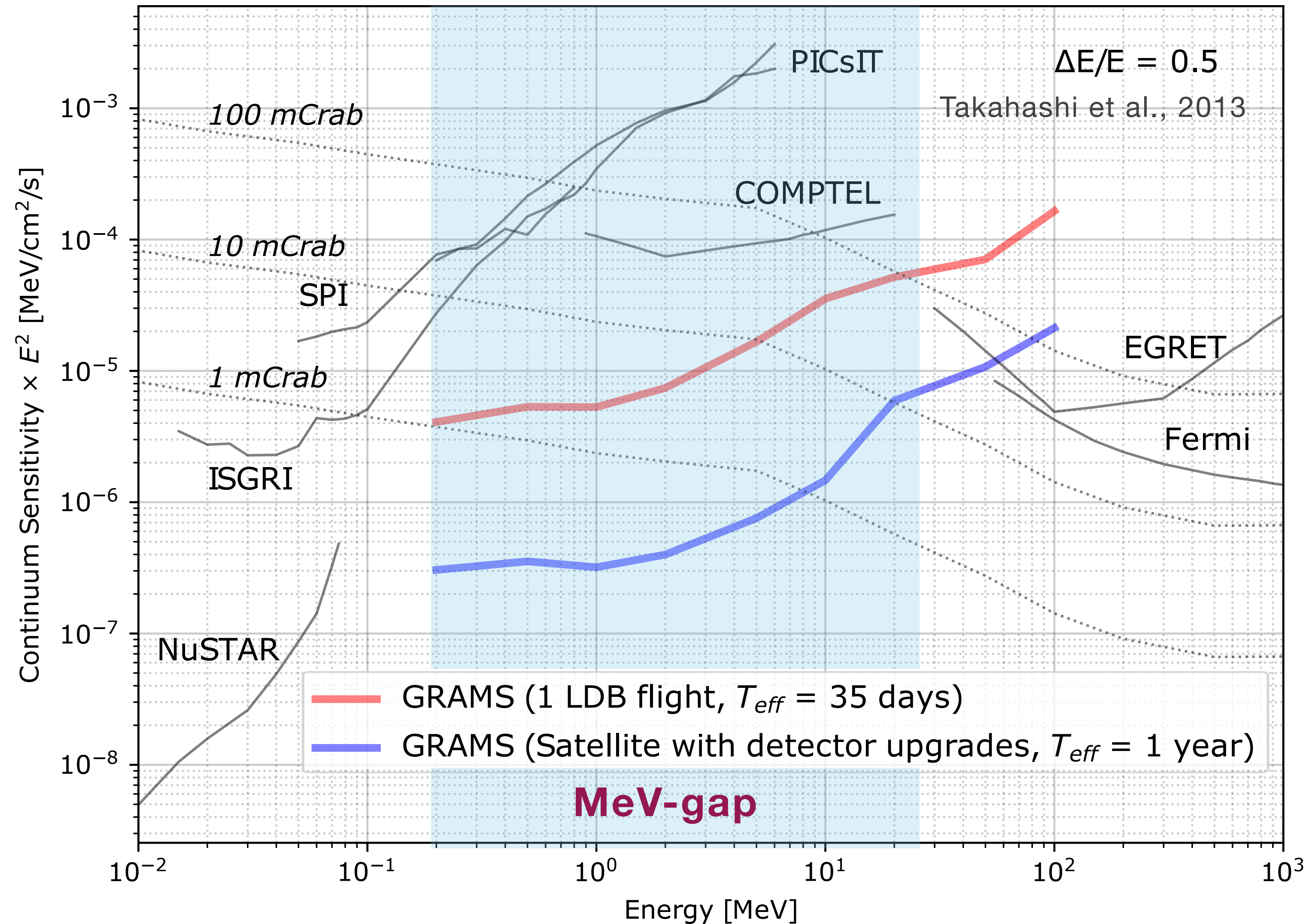
7



	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 sensitivity



Updating sensitivity

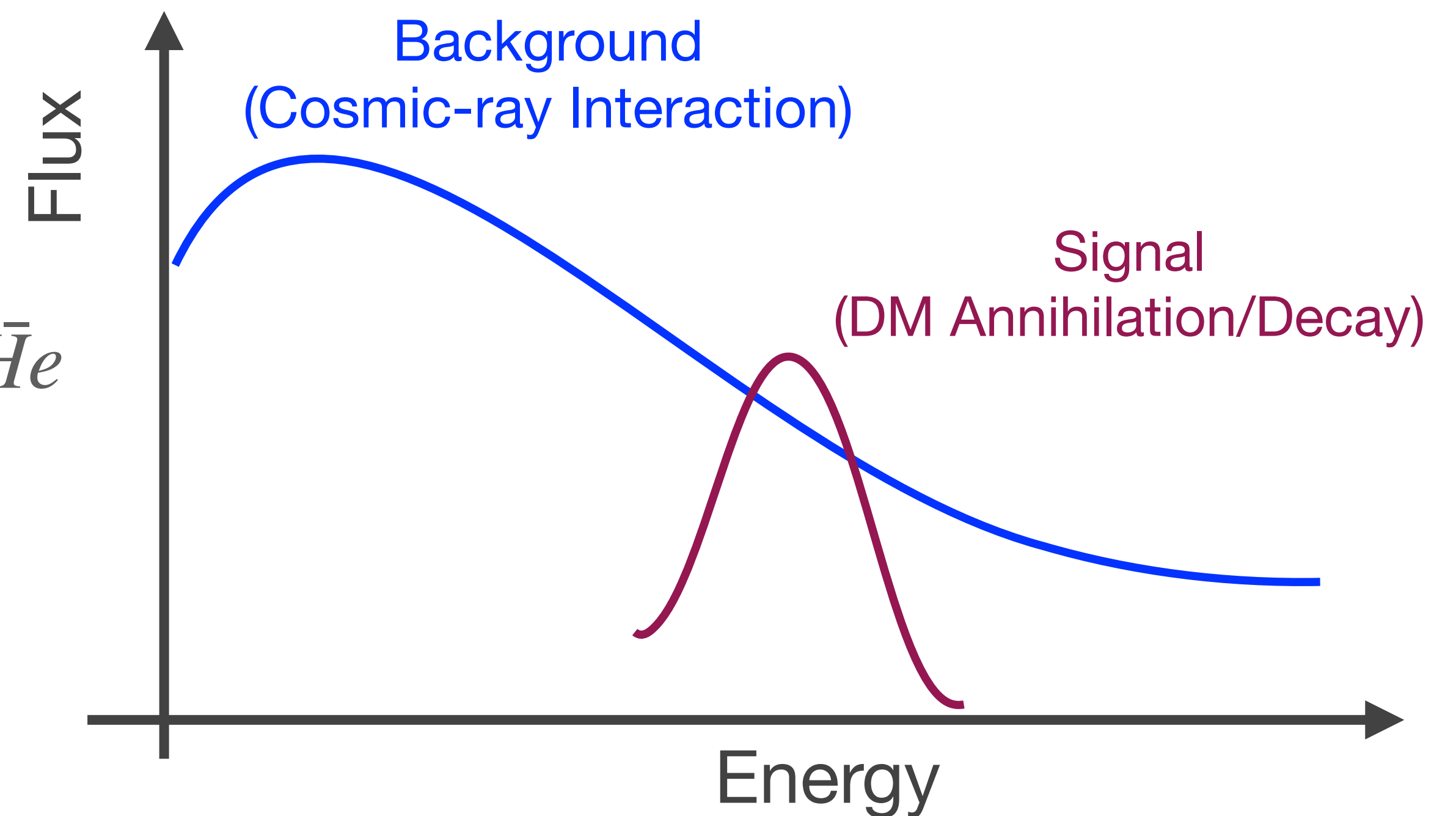
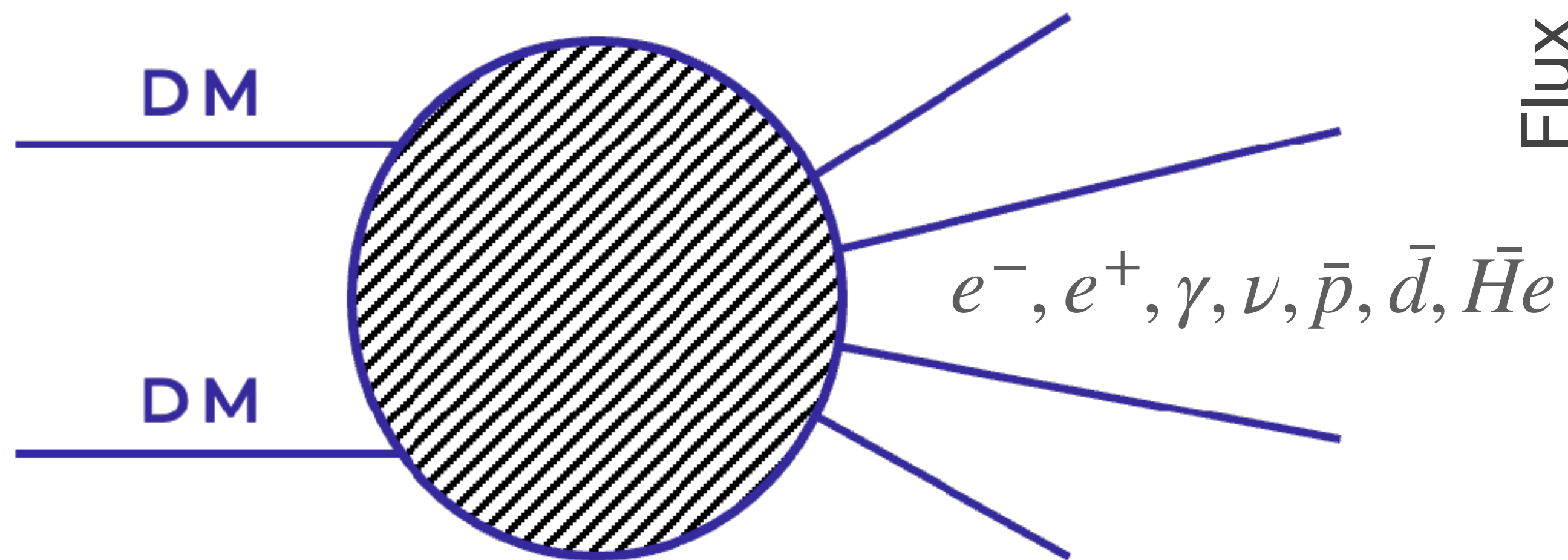
New event reconstruction methods

- 3+ Compton scatterings events
- Physics probability
- Machine learning

LDB Balloon flight: an order of magnitude improved

Satellite mission: comparable to future missions

Measure DM annihilation/decay products



- Positron: AMS-02, PAMELA, Fermi-LAT ...
- **Gamma-ray**: Fermi-LAT, CTA, **GRAMS**, VERITAS...
- Neutrino: IceCube, ANTARES...
- **Antiproton**: AMS-02, BESS, GAPS, **GRAMS**
- **Antideuteron** : AMS-02, BESS, GAPS, **GRAMS**
- **Antihelium**: AMS-02, GAPS, **GRAMS**



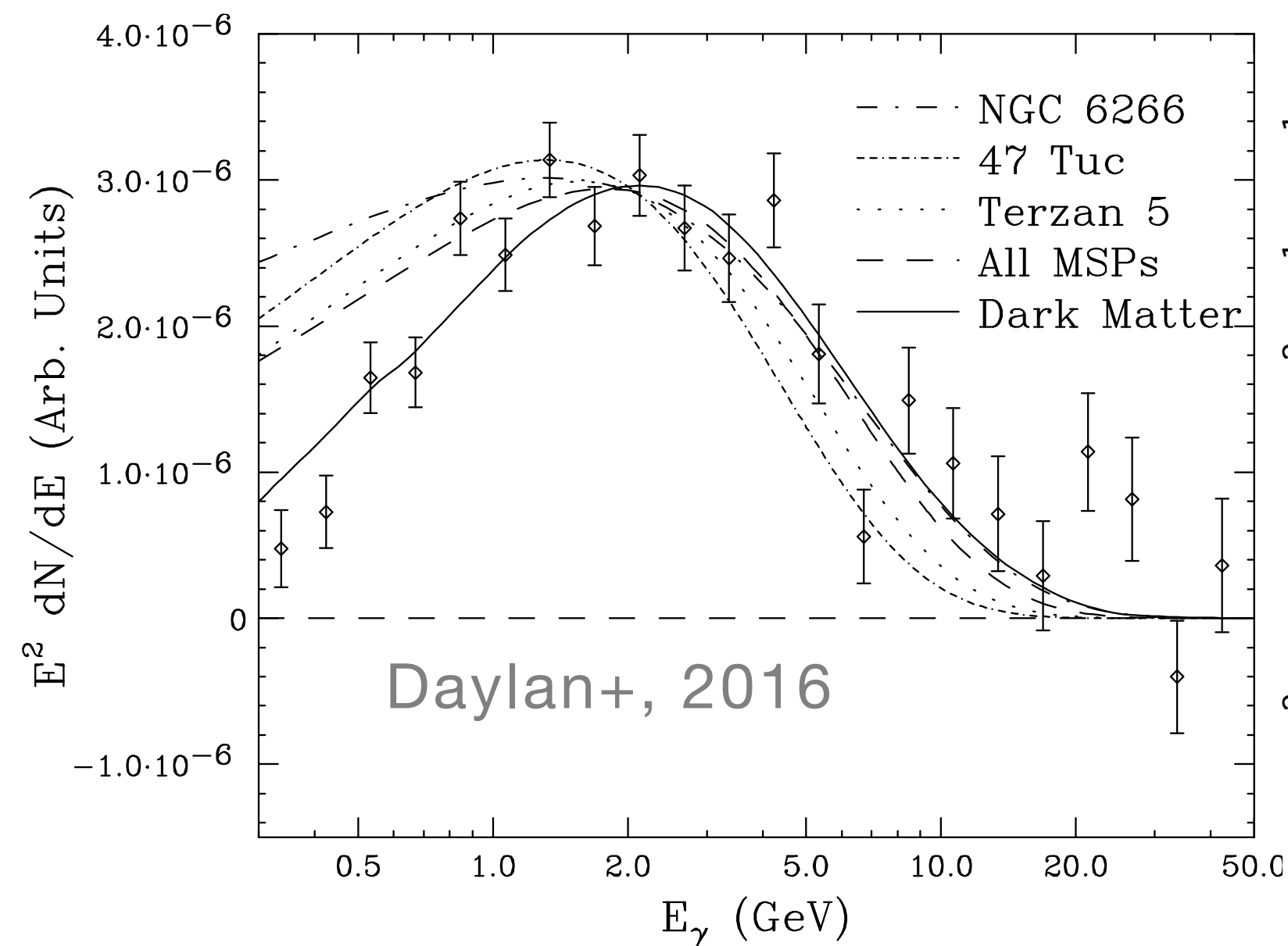
Puzzling excesses in indirect DM searches

10

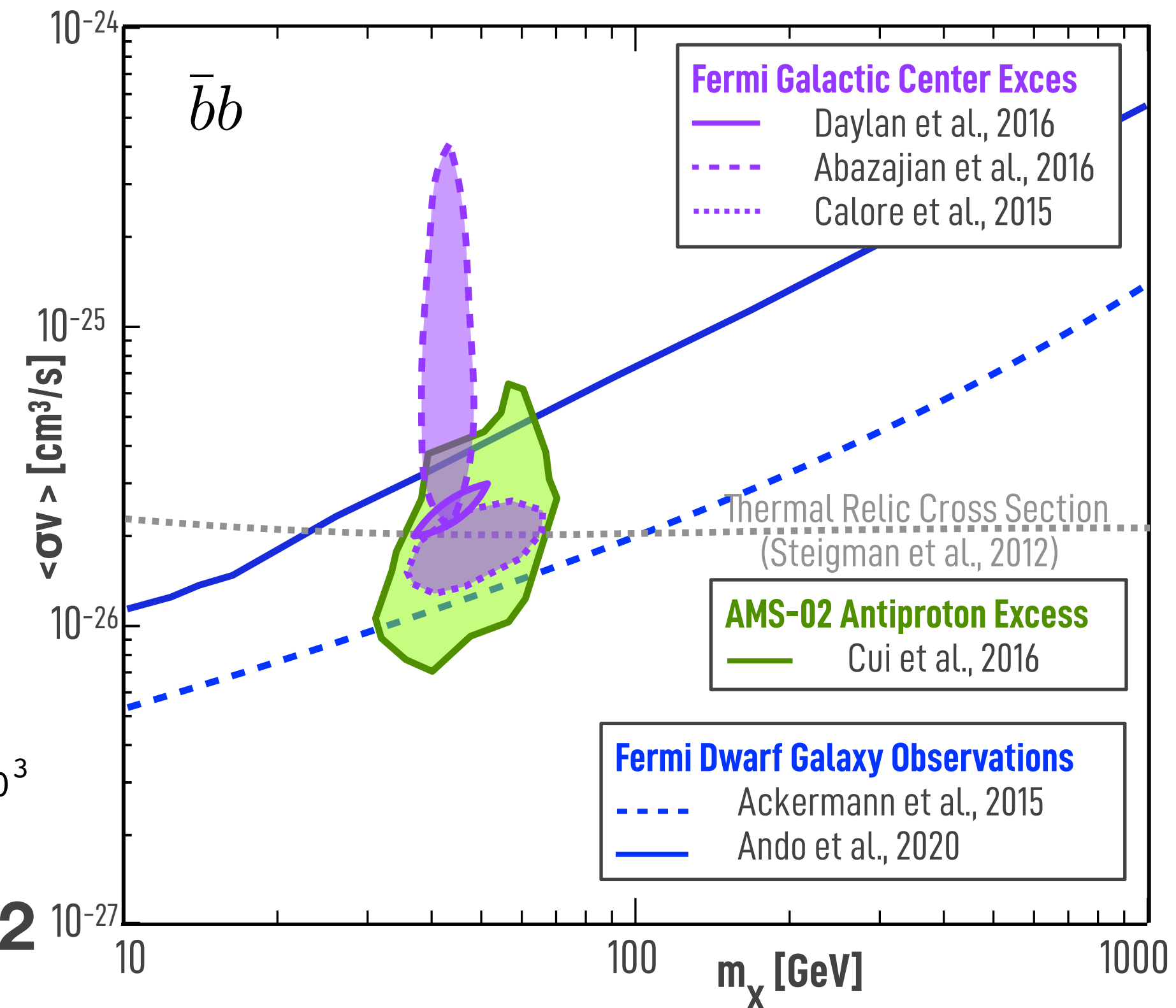
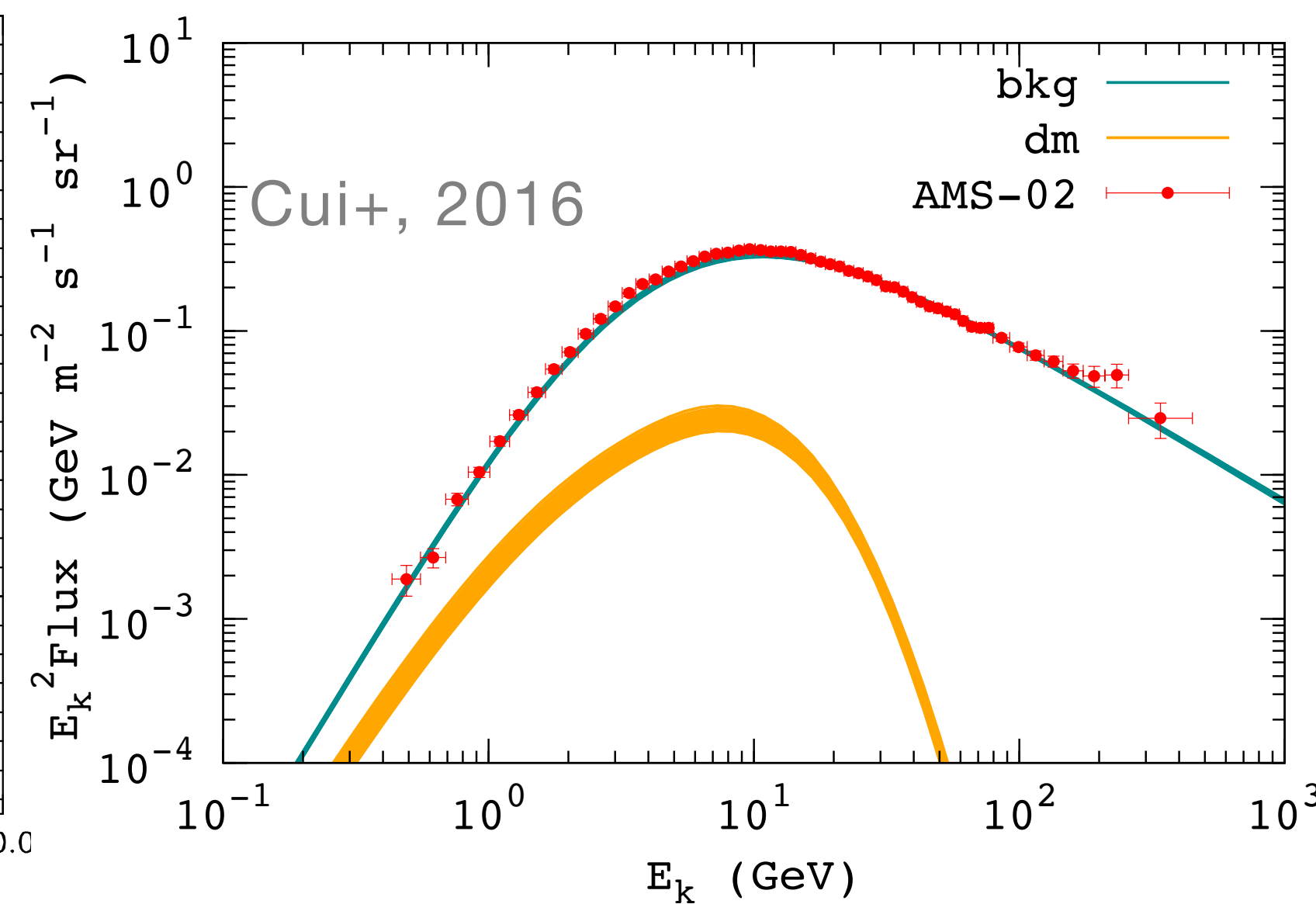
Snowmass2021 CF White Paper

- 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



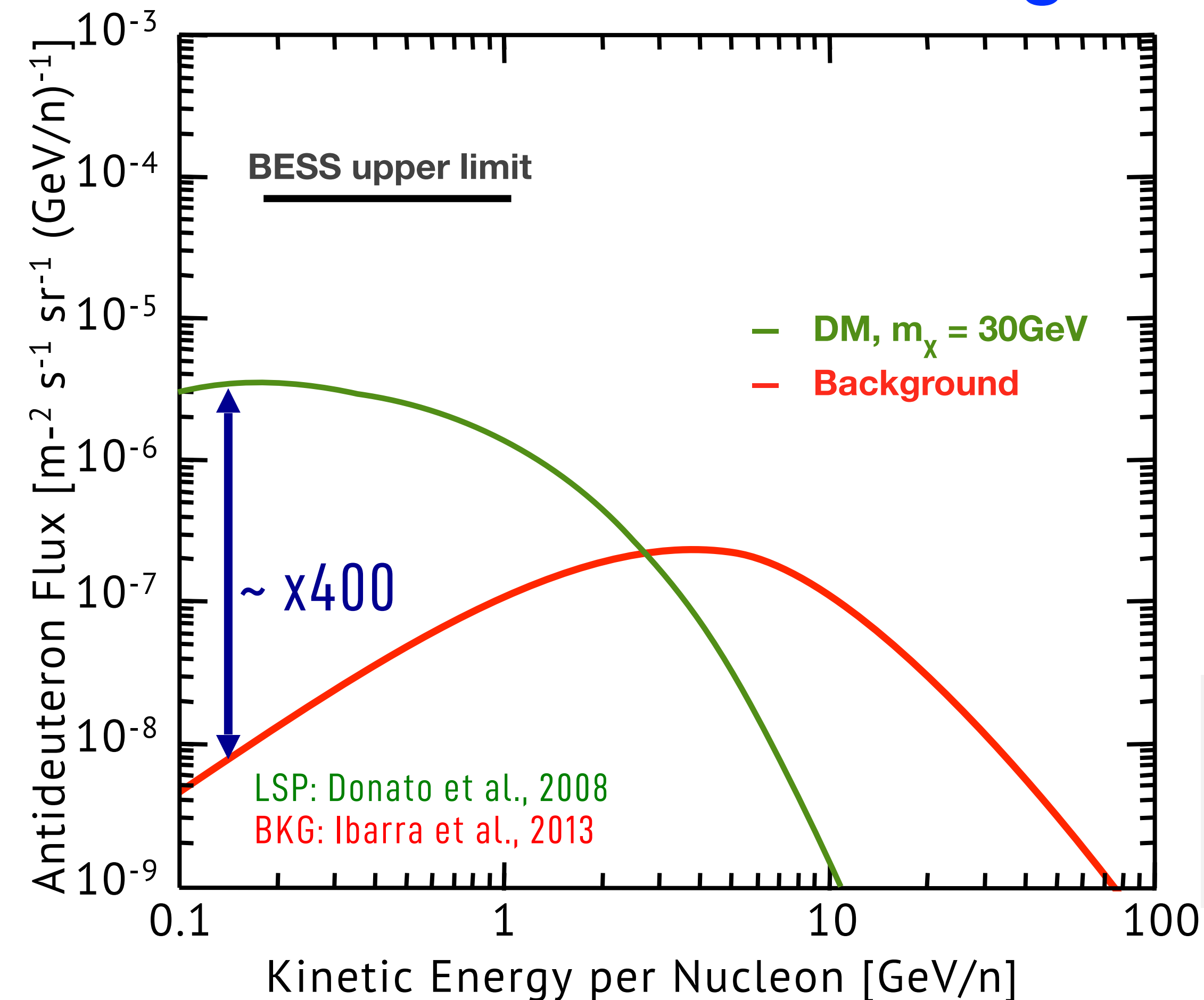
AMS-02 antiproton excess



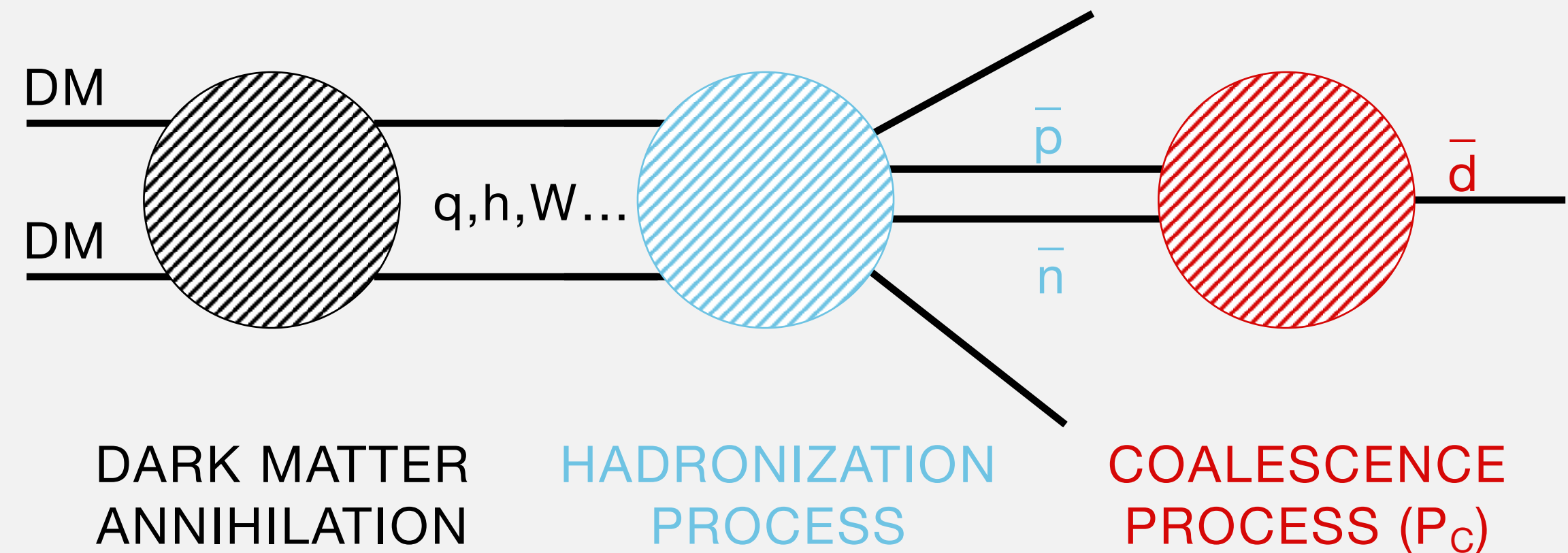
Detection of antideuteron/antihelium-like events in AMS02

How do we validate these results?

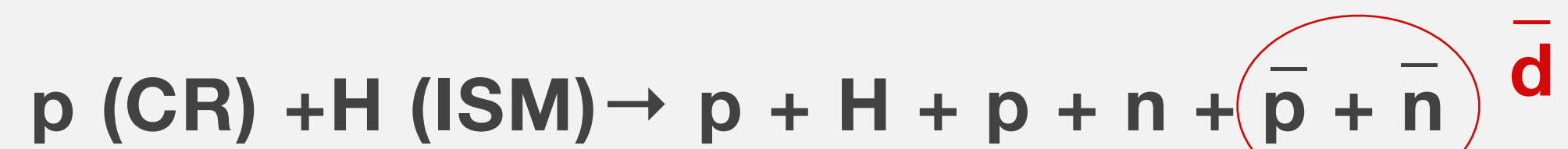
Background-free DM search



PRIMARY FLUX = DM ANNIHILATION/DECAY

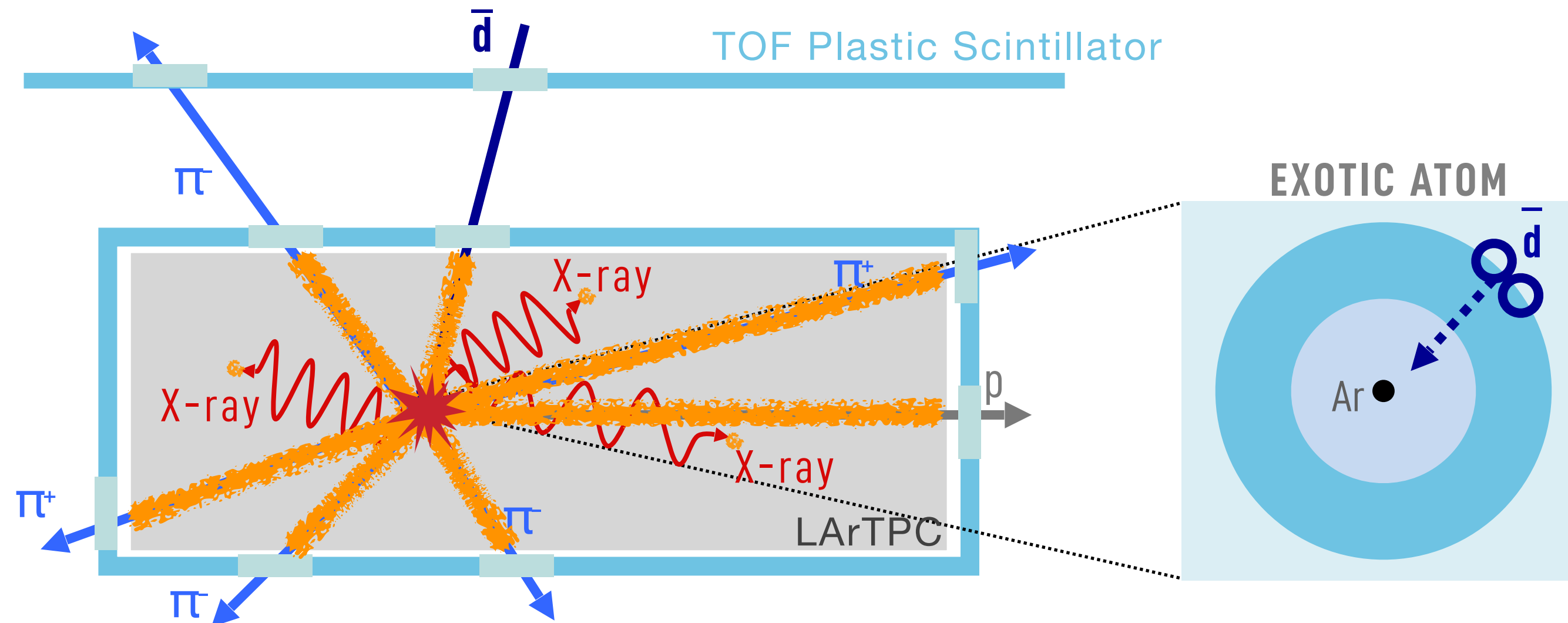


SECONDARY FLUX = COSMIC RAY INTERACTION



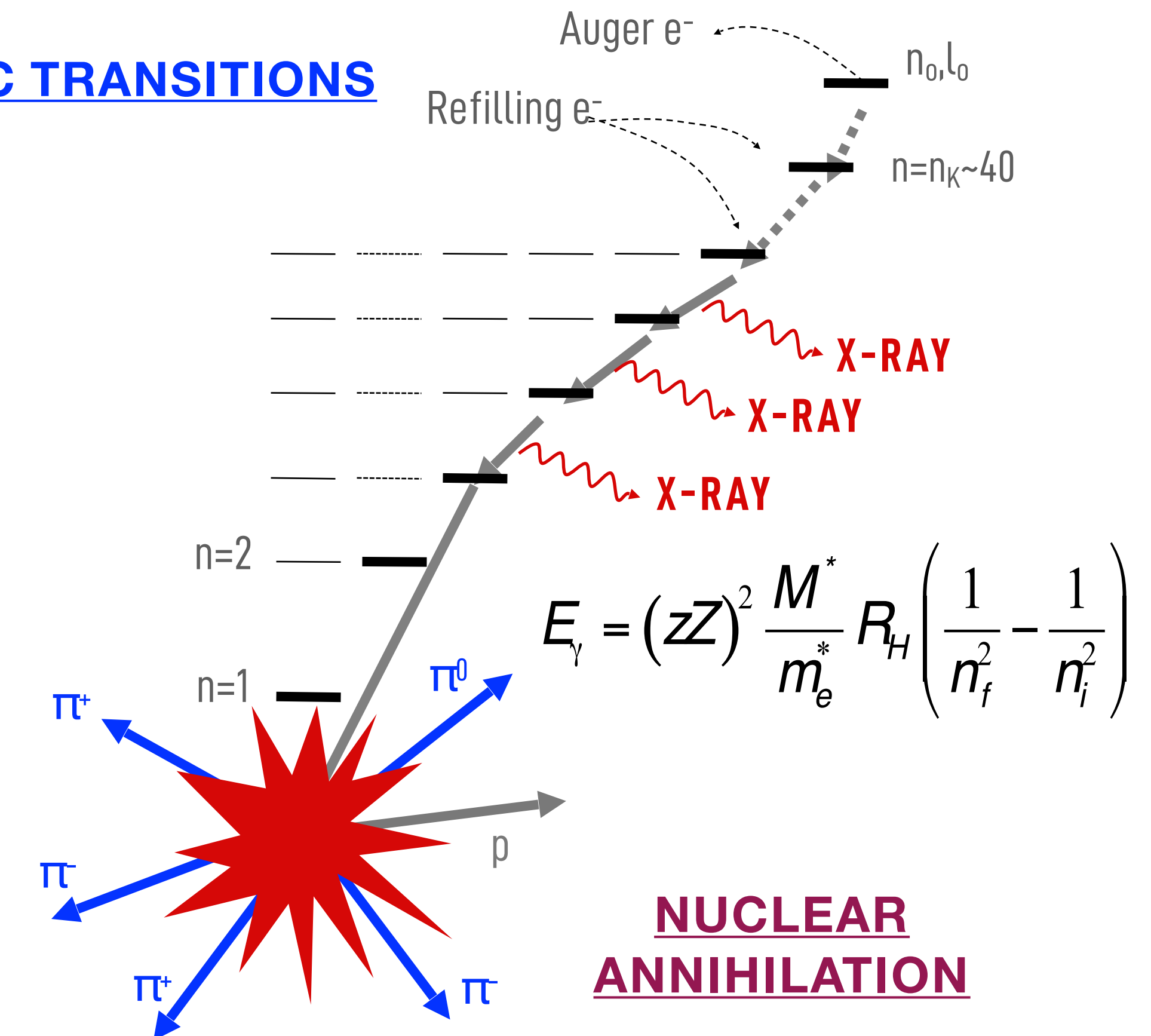
Balloon experiments from the Antarctic are optimized for low-energy antideuteron measurements considering geomagnetic cut-off

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

ATOMIC TRANSITIONS



LArTPC (almost no dead volume) provides

- **Excellent** 3D particle tracking capability
- **High** particle detection efficiency



GRAMS antideuteron/antihelium identification

13

CR p, $e^\pm$ rejection (= antimatter selection)

- Select **slow** particles with TOF that can stop inside LArTPC
- Simultaneous detection of secondary/annihilation products (pions/protons)
 - **No secondary particles** from slow CR p and $e^\pm$

Antideuteron (vs. antiproton)

- **Atomic X-rays** from exotic atom
 - 74, 114 keV for antideuterons
 - (58, 97 keV for antiprotons)
- **Pion/proton** multiplicity
 - More pions and protons
- **Stopping range** (depth sensing)
 - Longer stopping ranges
- **dE/dX energy deposit** in LArTPC
 - More energy deposit in LArTPC

Antihelium-3 (vs. antiproton)

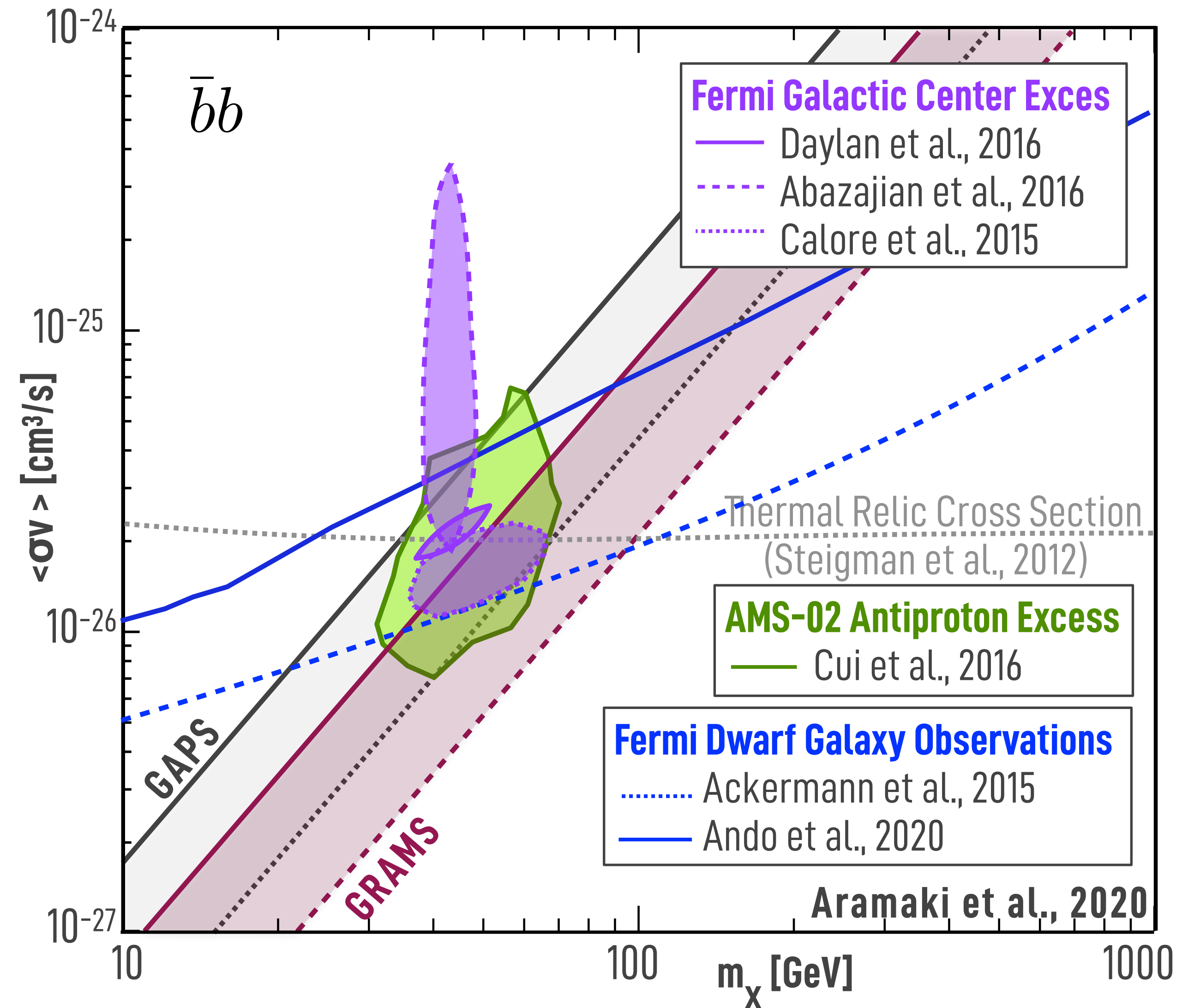
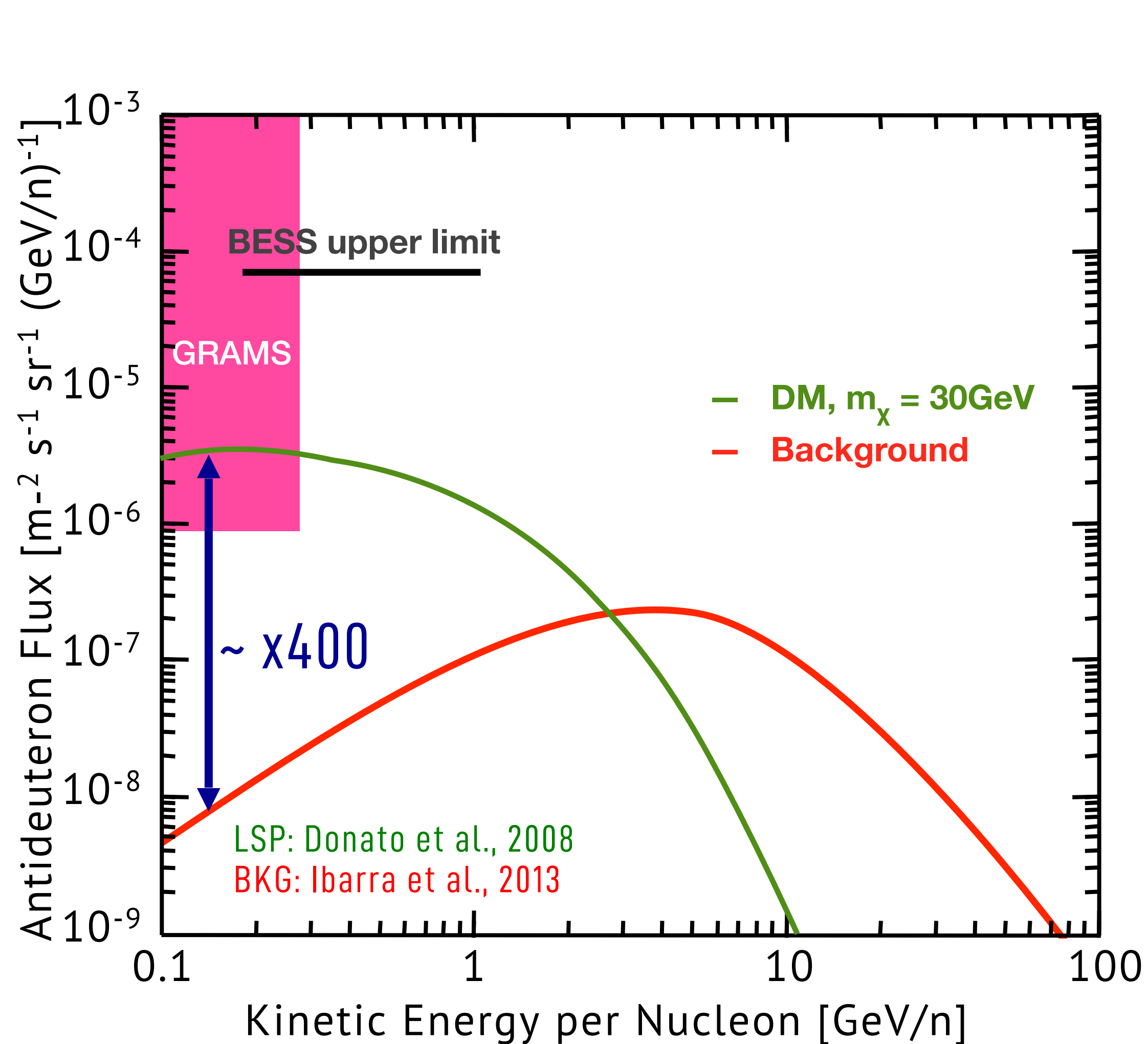
- **Atomic X-rays** from exotic atom
 - 119, 156 keV for antiheliums
 - (58, 97 keV for antiprotons)
- **Pion/proton** multiplicity
 - More pions and protons
- ~~Stopping range~~ (depth sensing)
- **dE/dX energy deposit** in LArTPC/TOF
 - More energy deposit in LArTPC
 - More energy deposit in TOF



GRAMS Sensitivity in DM Parameter Space

14

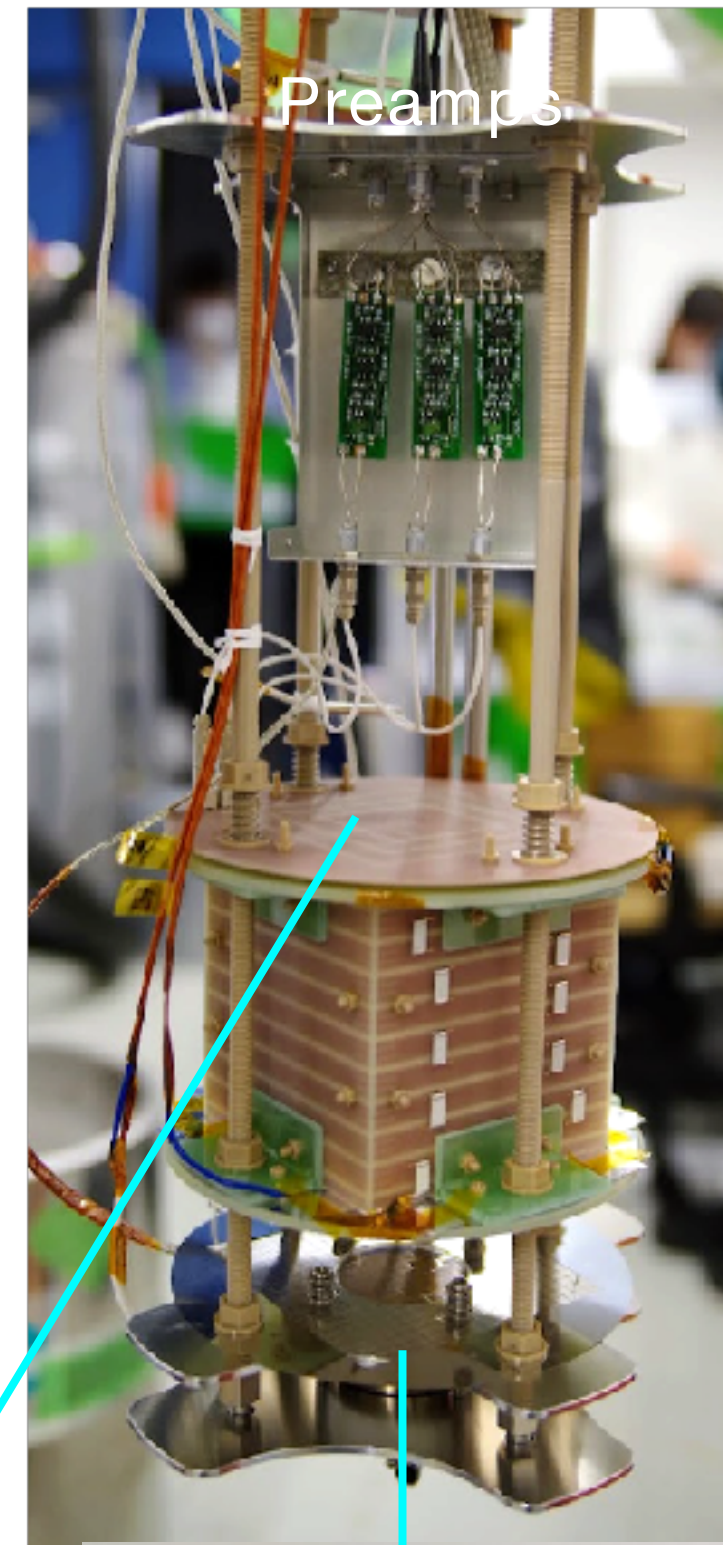
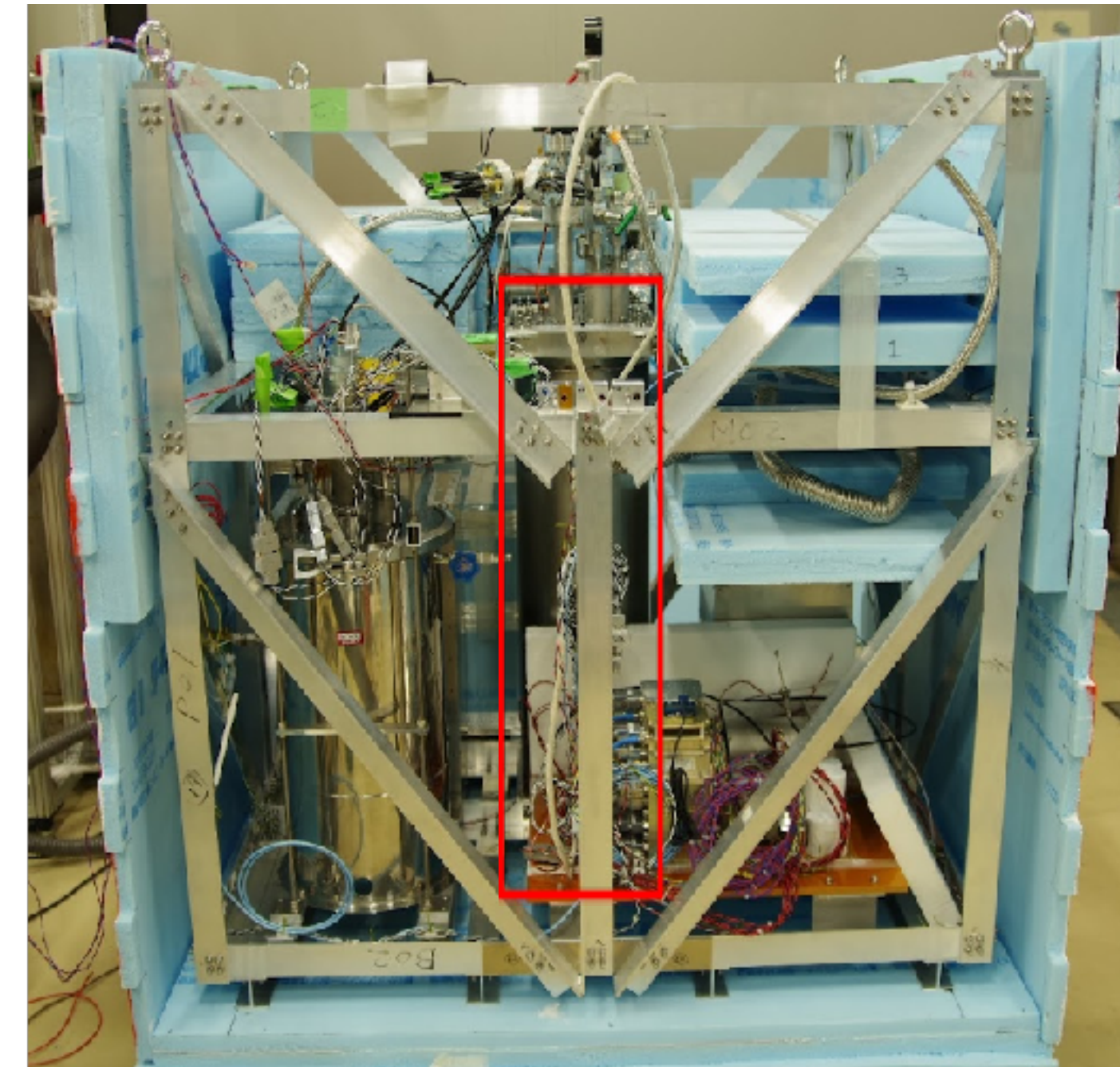
Extensively explore DM parameter space and validate Fermi/AMS-02 results



Masa's talk in PSB.1 (Tue)

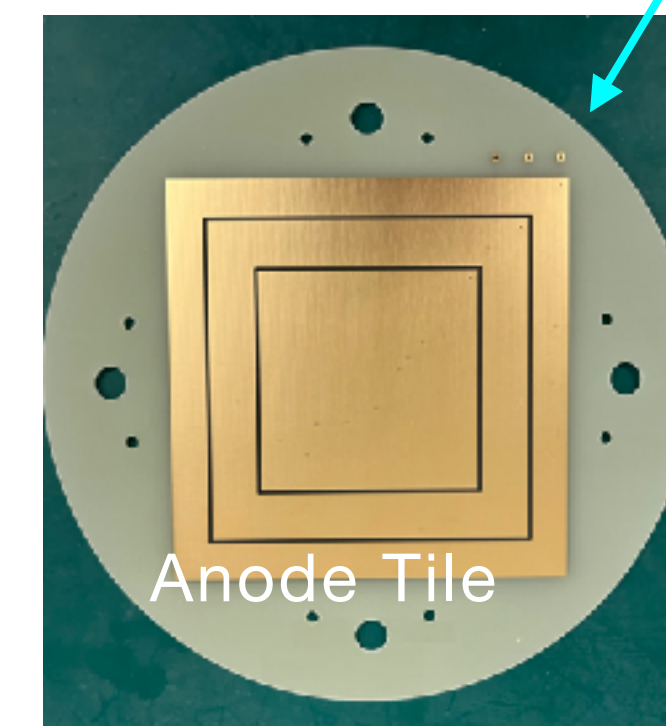
Engineering flight

- Launched in **July 2023** @JAXA TARF
- **First** LArTPC operation at stratosphere
- TPC: $10 \times 10 \times 10 \text{ cm}^3$
 - PMT (Hamamatsu R6041-06) at the bottom
 - 3 charge channels (pGRAMS preamps)
 - No cooling/circulation system
- Pressure vessel for RPi/DAQ
- Obtained ~400k stable events with light + charge



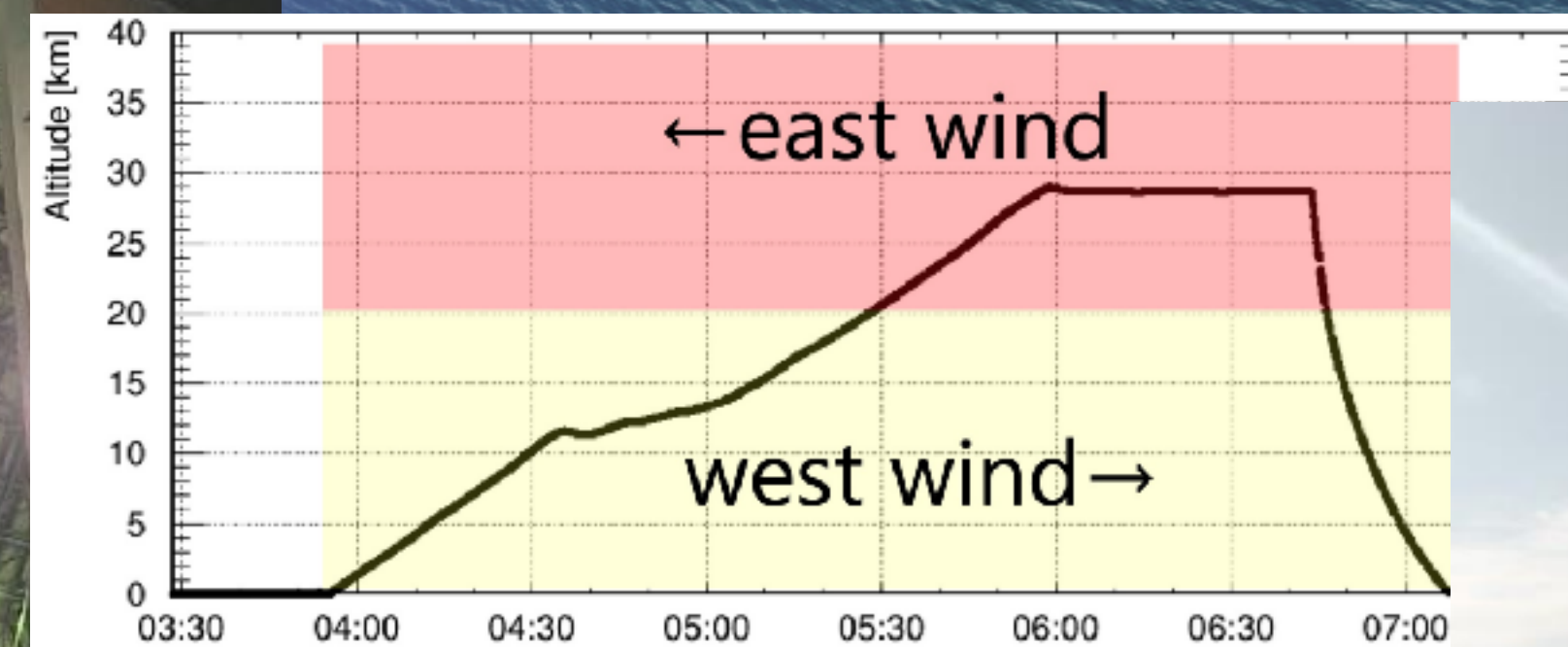
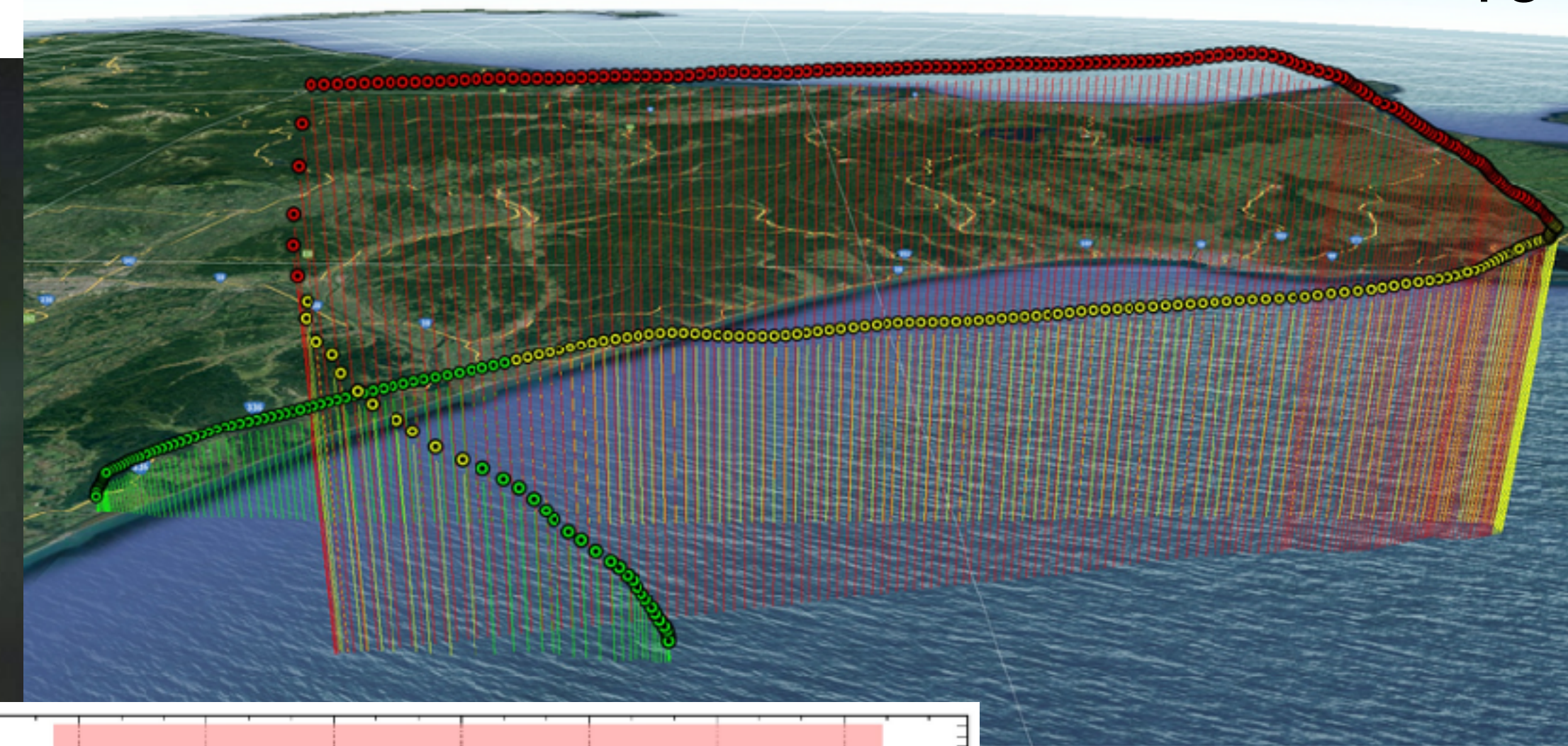
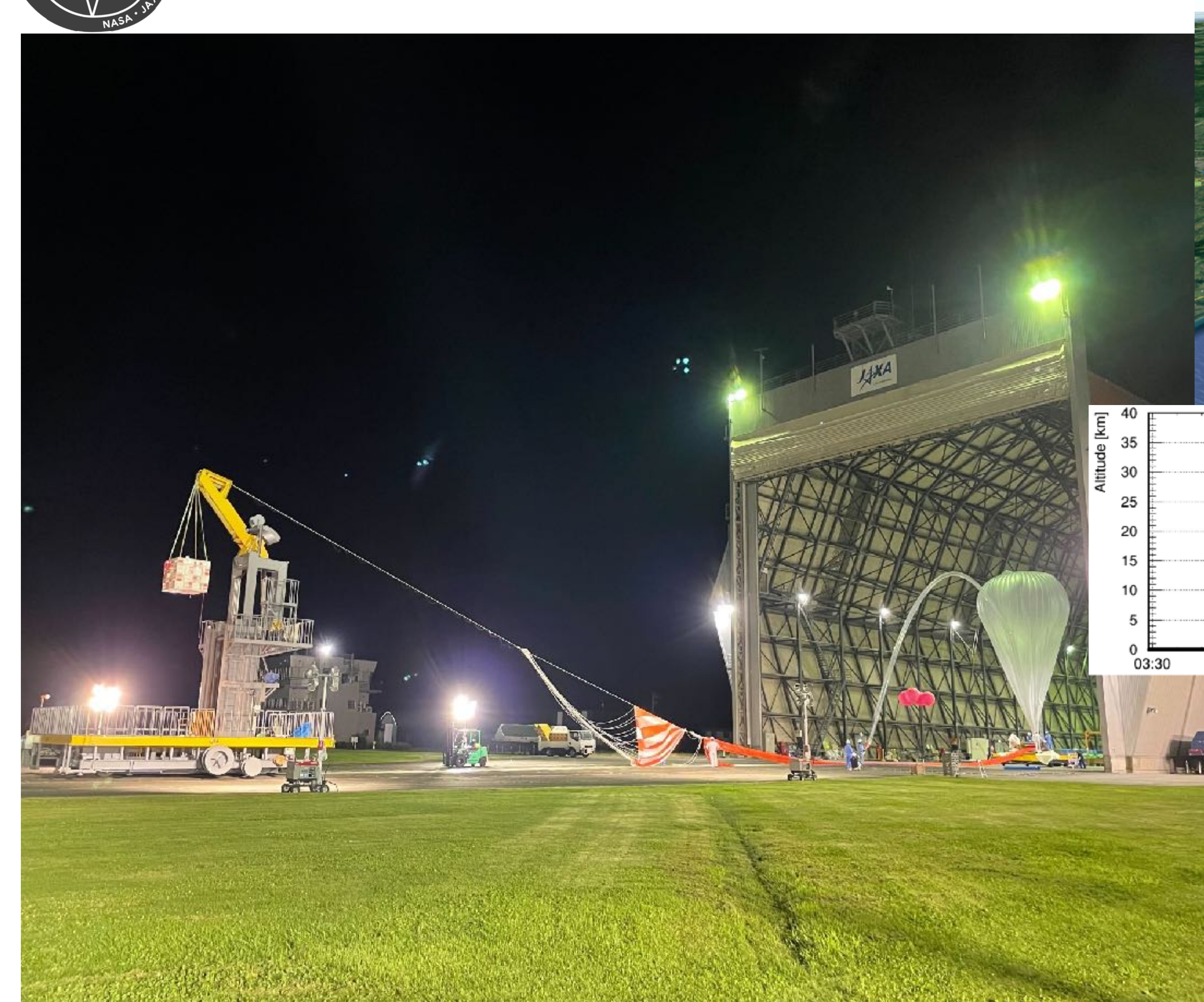
Antiproton beam test

- Scheduled @J-PARC in **2024**
- **Validate** LArTPC performance as an antimatter detector
 - Measure annihilation products (and atomic X-rays)
- May include some **antideuteron**s



Engineering flight (eGRAMS) in Japan

16





Prototype flight (pGRAMS)

Funded by NASA APRA2022

17

Currently testing **MicroGRAMS** @Northeastern

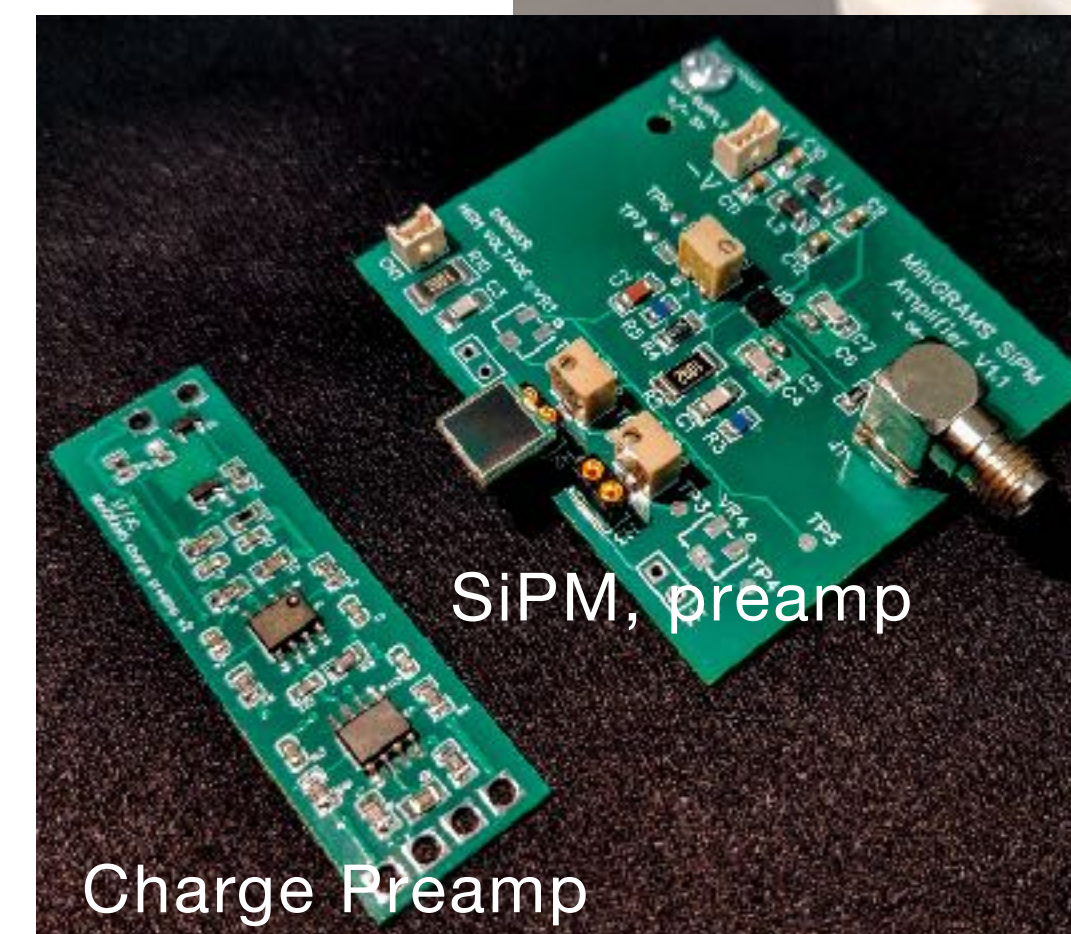
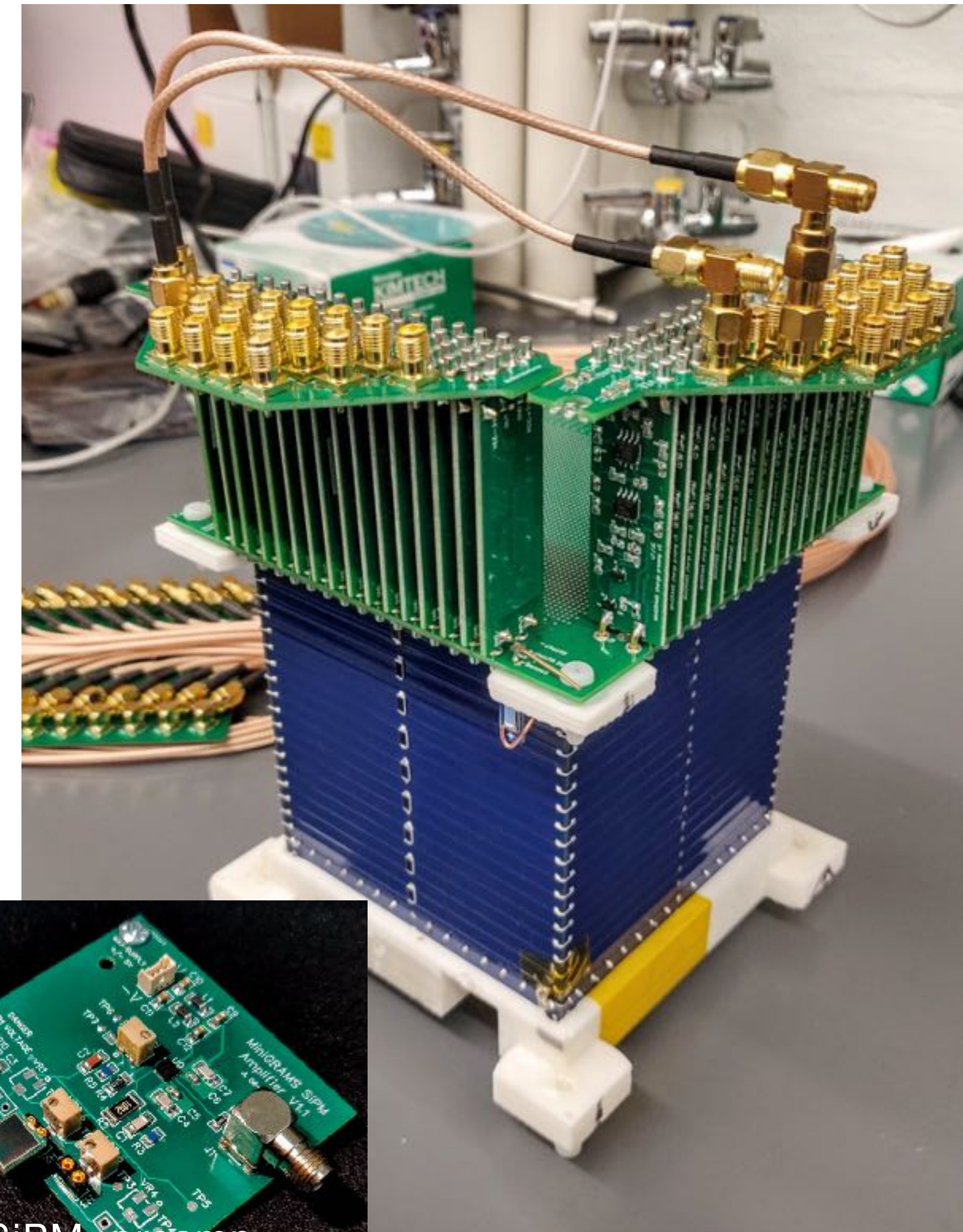
- TPC size: $10 \times 10 \times 10 \text{ cm}^3$ (TPB inside TPC)
- Demonstrate the **particle tracking capability** and **event reconstruction techniques** with gamma-ray sources

Prototype flight scheduled **in 2025/2026**

- Demonstrate LArTPC performance in flight
 - Particle tracking for charged particles
 - Gamma-ray detection
- **MinGRAMS**: $30 \times 30 \times 20 \text{ cm}^3$ segmented into **9 cells**
 - Tile/pads ($\sim 3\text{mm}$ pitch) for x/y directions
 - 180 charge preamps in total
 - 16 SiPMs (6 mm x 6mm each) per cell

Followed by science flights with **MiniGRAMS**

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





GRAMS Collaboration

18

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

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

2024 May Collaboration Meeting





Summary

19

- 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 **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.

