

GRAMS Project Overview



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IDM2022 @Vienna, Austria, July 18-22, 2022



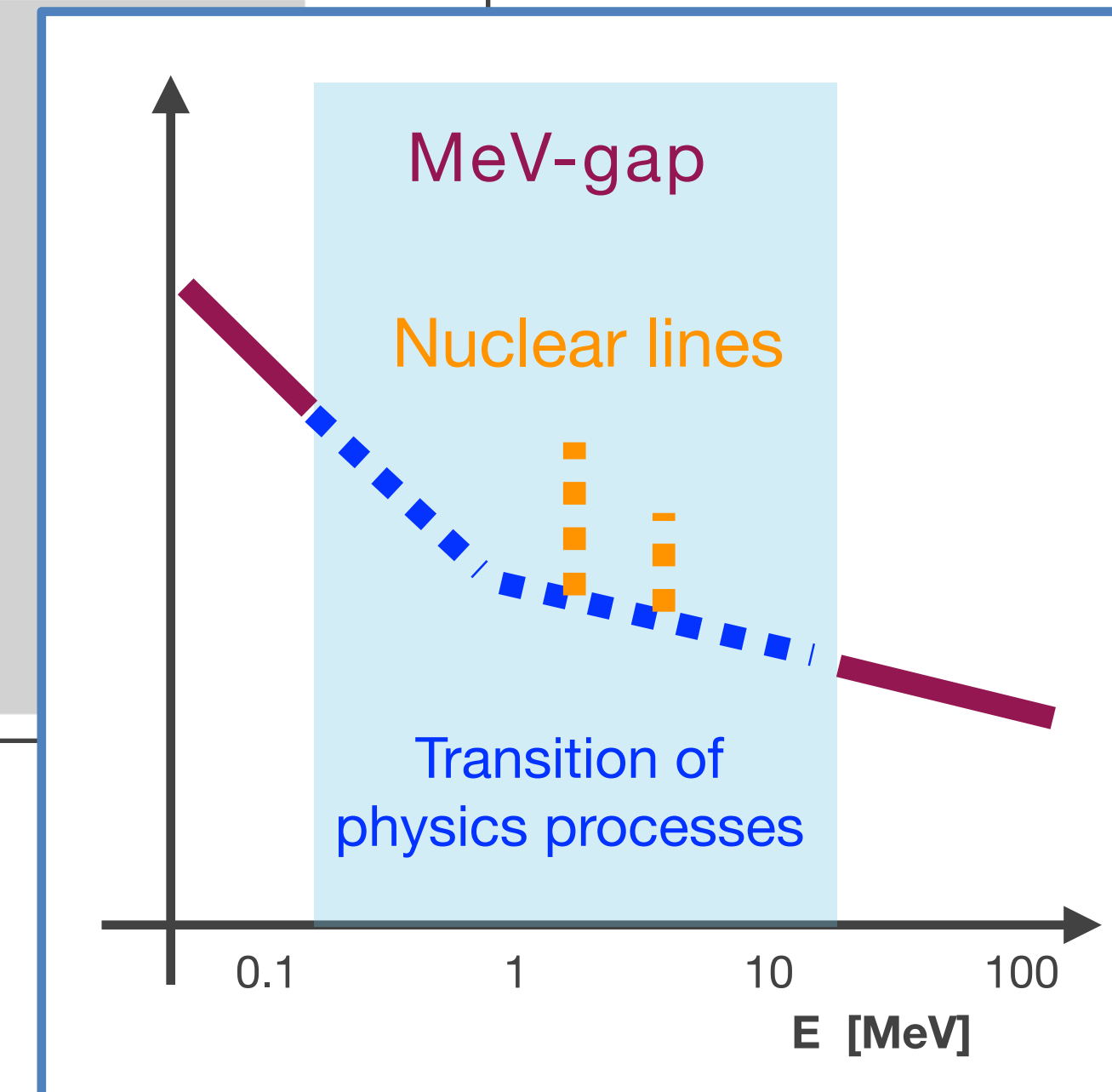
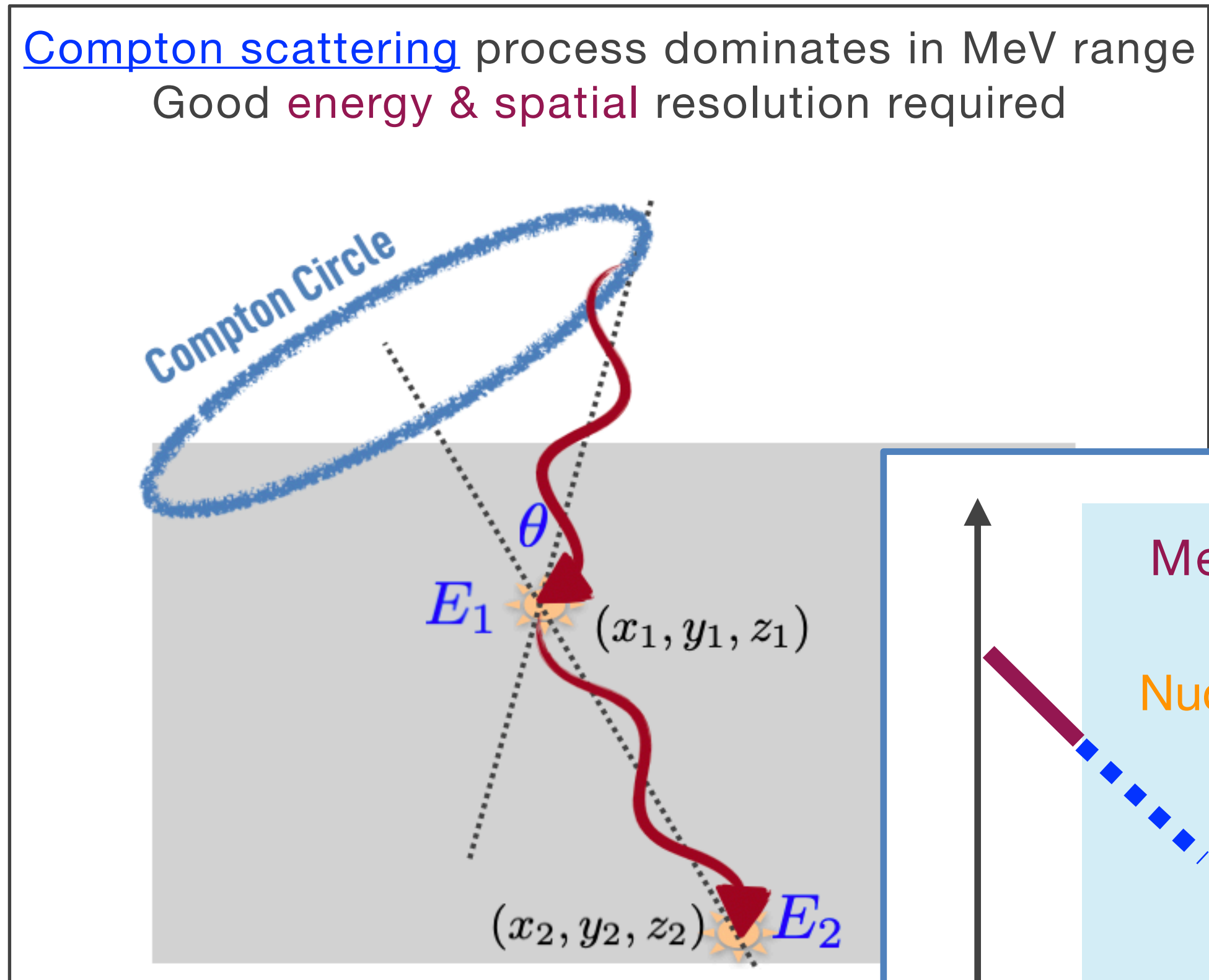
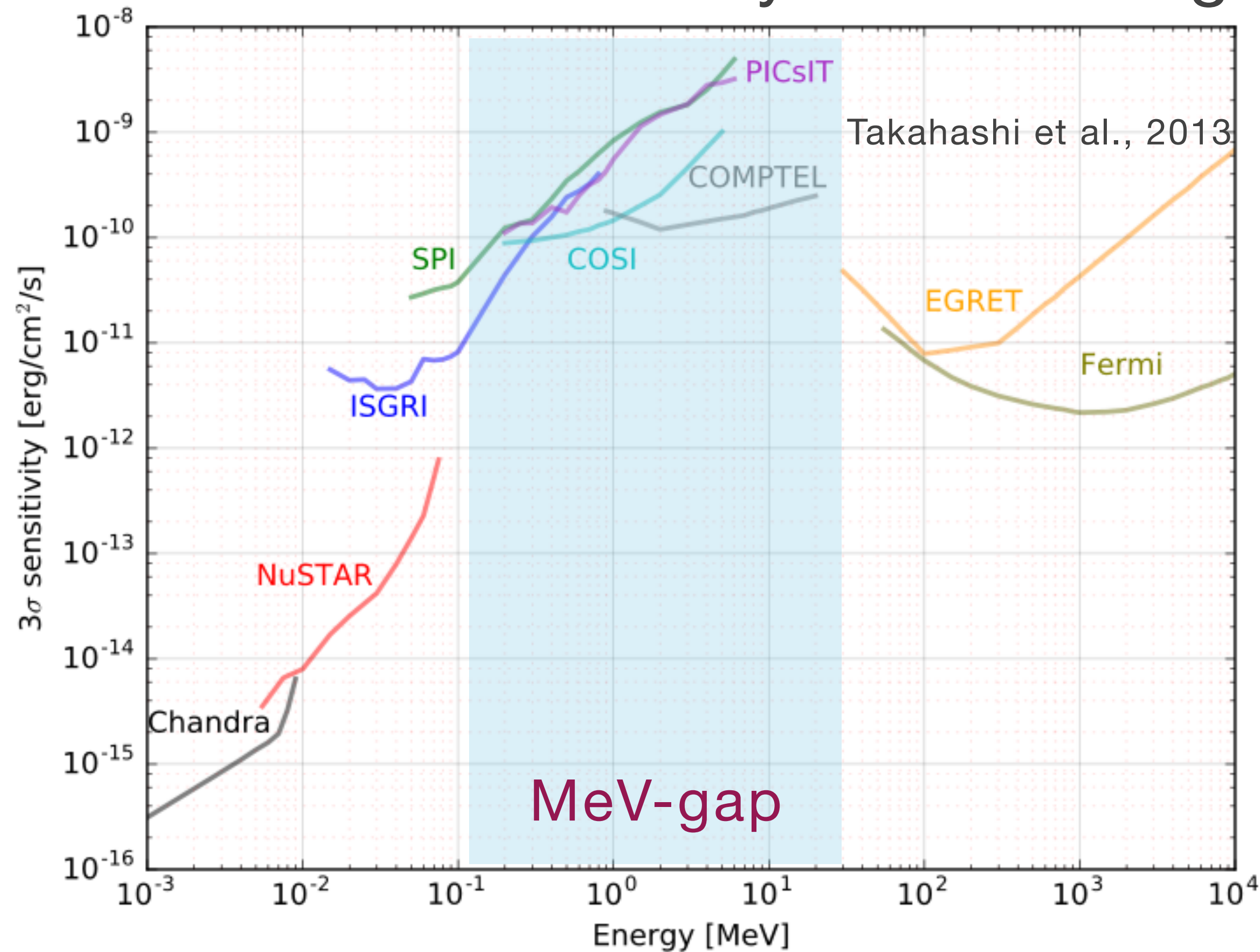
GRAMS = Gamma-Ray and AntiMatter Survey

A newly proposed project with an international collaboration

First balloon/satellite mission with a **low-cost**, **large-scale** LArTPC detector

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

Gamma-rays in MeV region poorly explored: **“MeV Gap”**



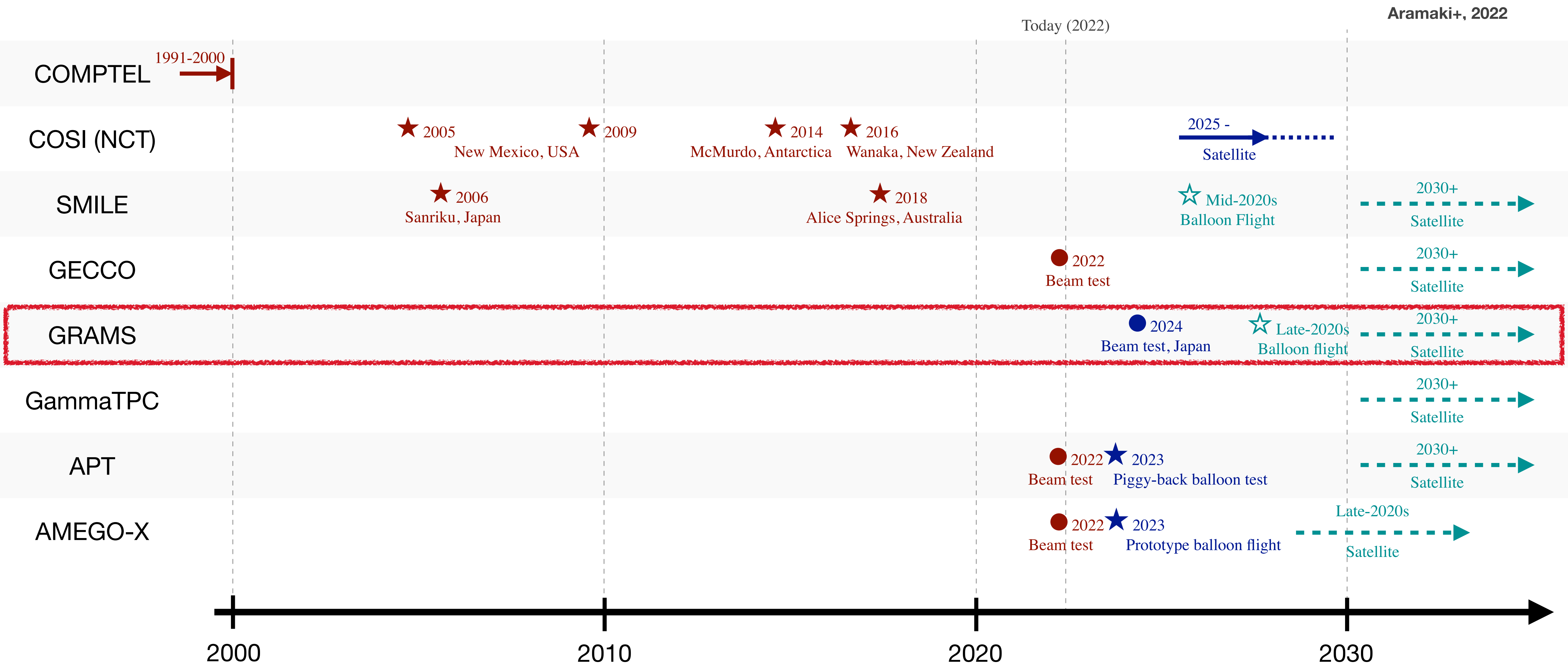
MeV gamma-ray continuum/line spectrum

- Physics processes/**nucleosynthesis**
- **Multi-messenger** astronomy
- Indirect **dark matter** searches/**PBH** searches



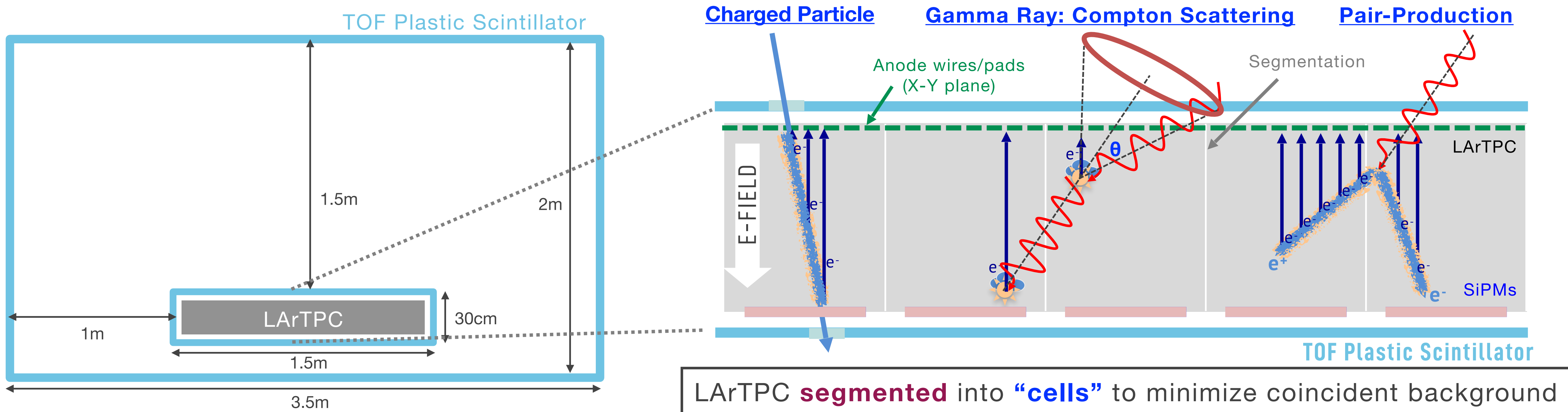
MeV Gamma-ray Missions

Past, near-term, and long-term future plans (Snowmass CF1 WP5)



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



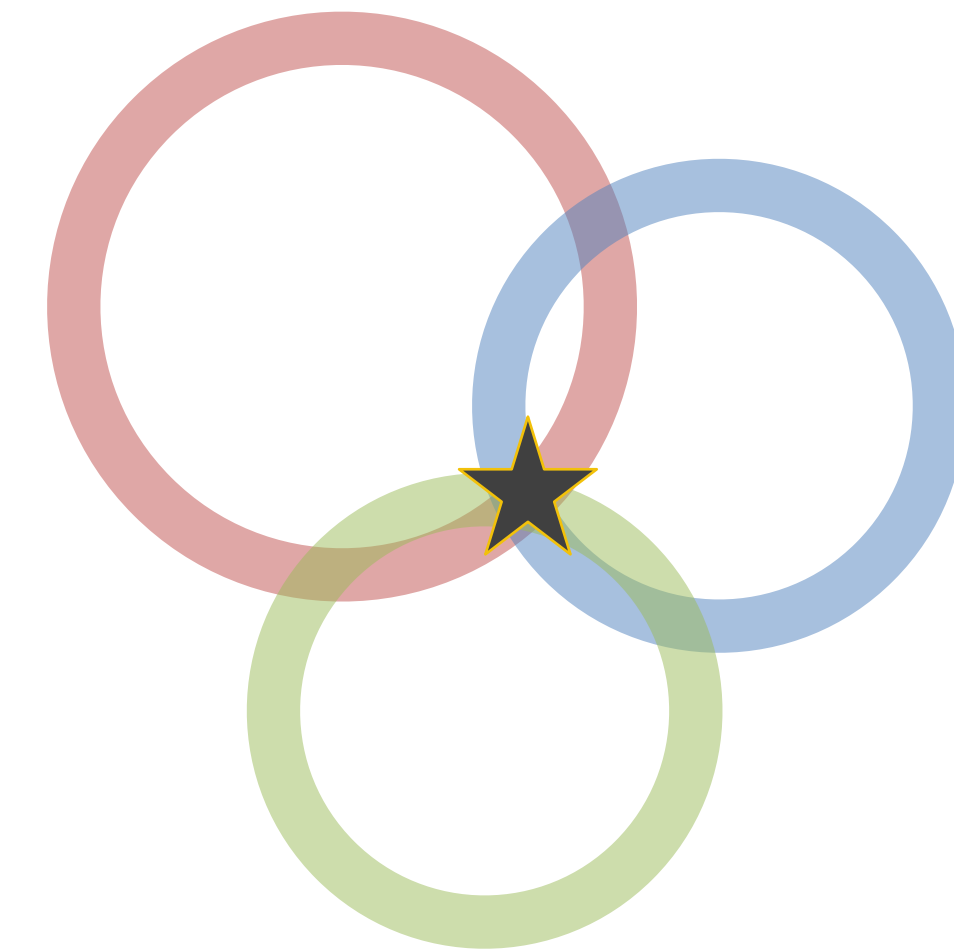
- Large-scale, low-energy threshold LArTPC has been **well-studied/widely-used** in underground **dark matter/neutrino** experiments

One Compton Scattering + Photoabsorption

Two Compton Scatterings + Photoabsorption

Three Compton Scatterings + Escaping Photon

Compton "Event Circles"

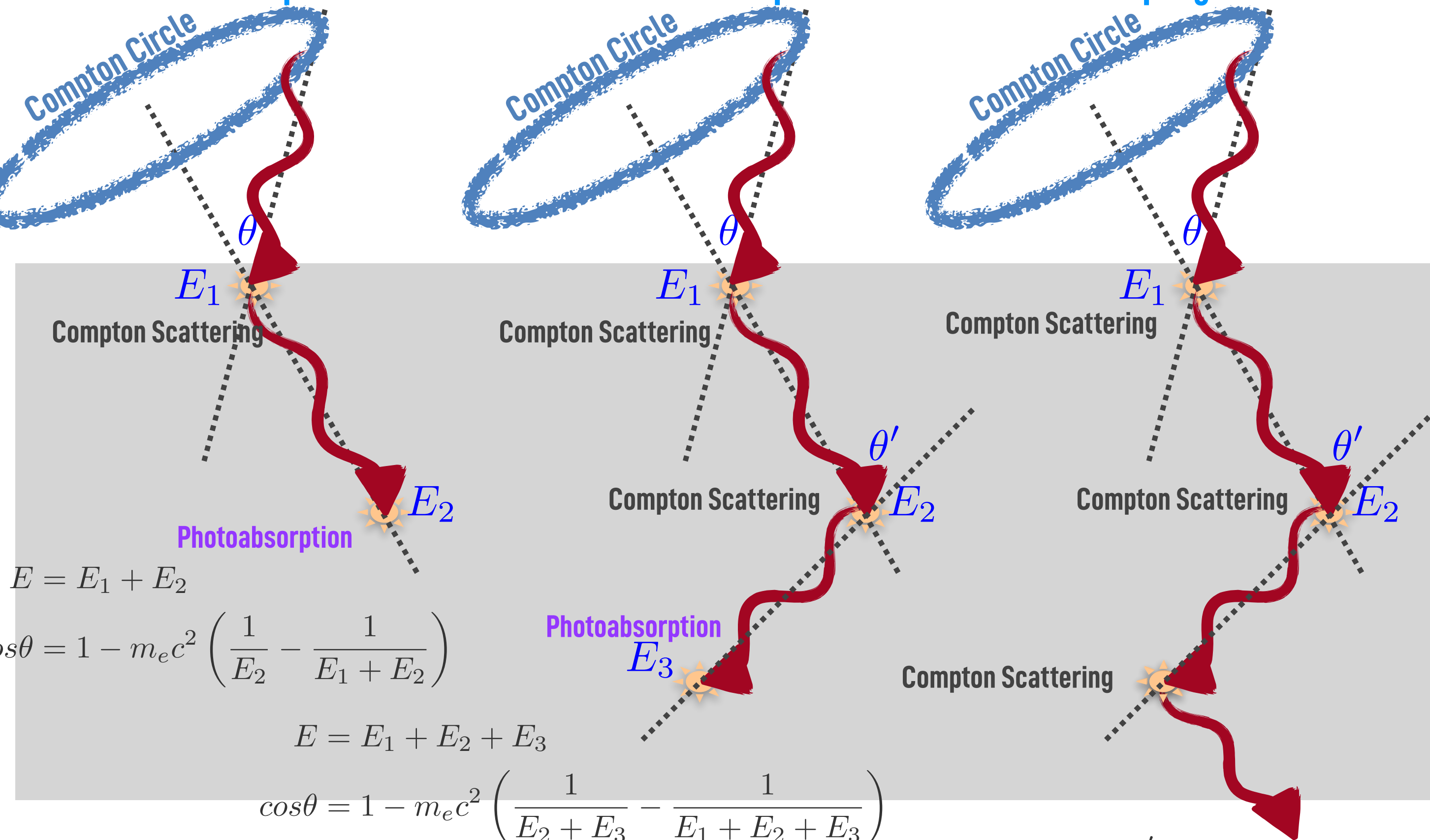


Multiple Compton Scatterings

- **3+ scatterings dominates** for $E > 1$ MeV
- Event reconstruction methods developed for 3+ scatterings (including **escaping**)
- \rightarrow ~50% efficiency

(Physics-based: Yoneda+, 2022)

(Machine learning: Takashima+ 2022)



$$E = E_1 + E_2$$

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

$$E = E_1 + E_2 + E_3$$

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2 + E_3} - \frac{1}{E_1 + E_2 + E_3} \right)$$

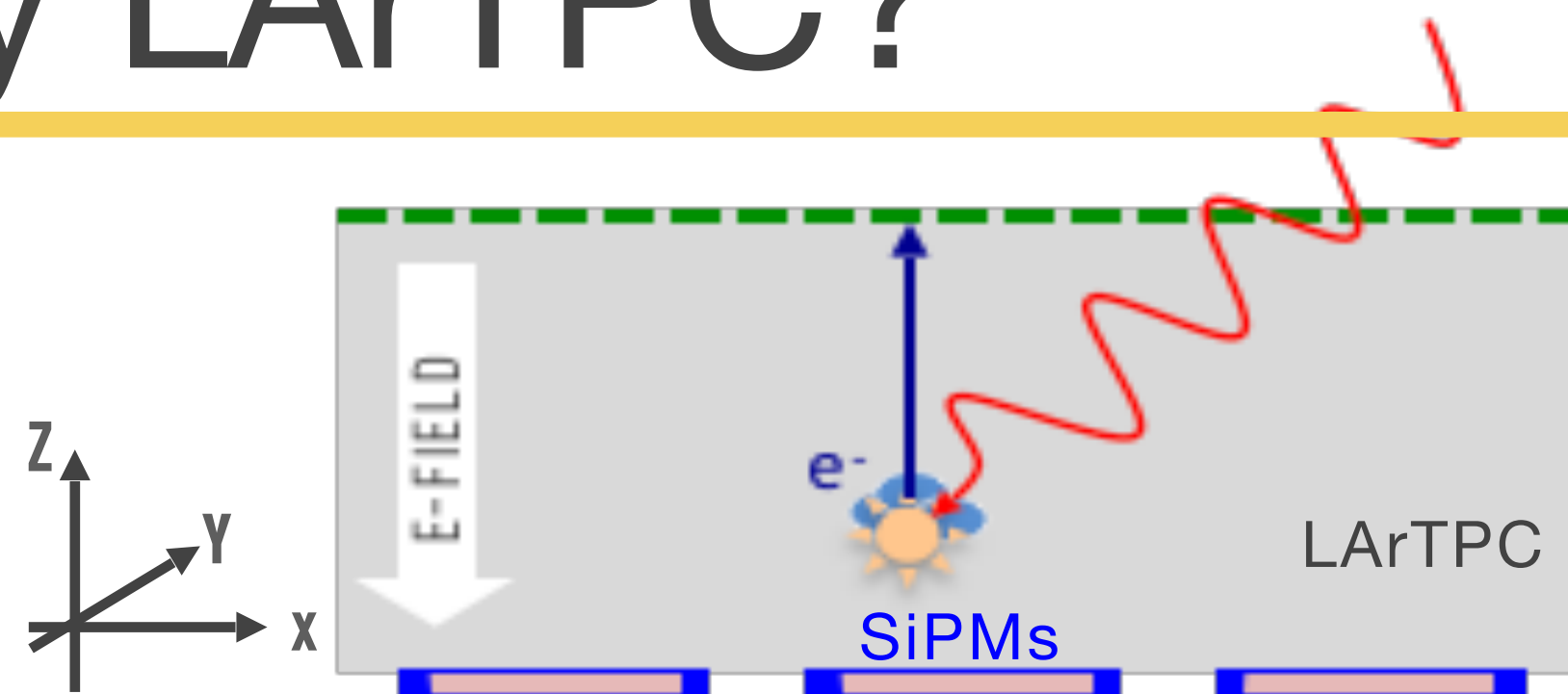
$$\cos\theta' = 1 - m_e c^2 \left(\frac{1}{E_3} - \frac{1}{E_2 + E_3} \right)$$

$$E = E_1 + E_2 + E'_3$$

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2 + E'_3} - \frac{1}{E_1 + E_2 + E'_3} \right)$$

$$E'_3 = -\frac{E_2}{2} + \sqrt{\frac{E_2^2}{4} + \frac{E_2 m_e c^2}{1 - \cos\theta'}}$$

Why LArTPC?

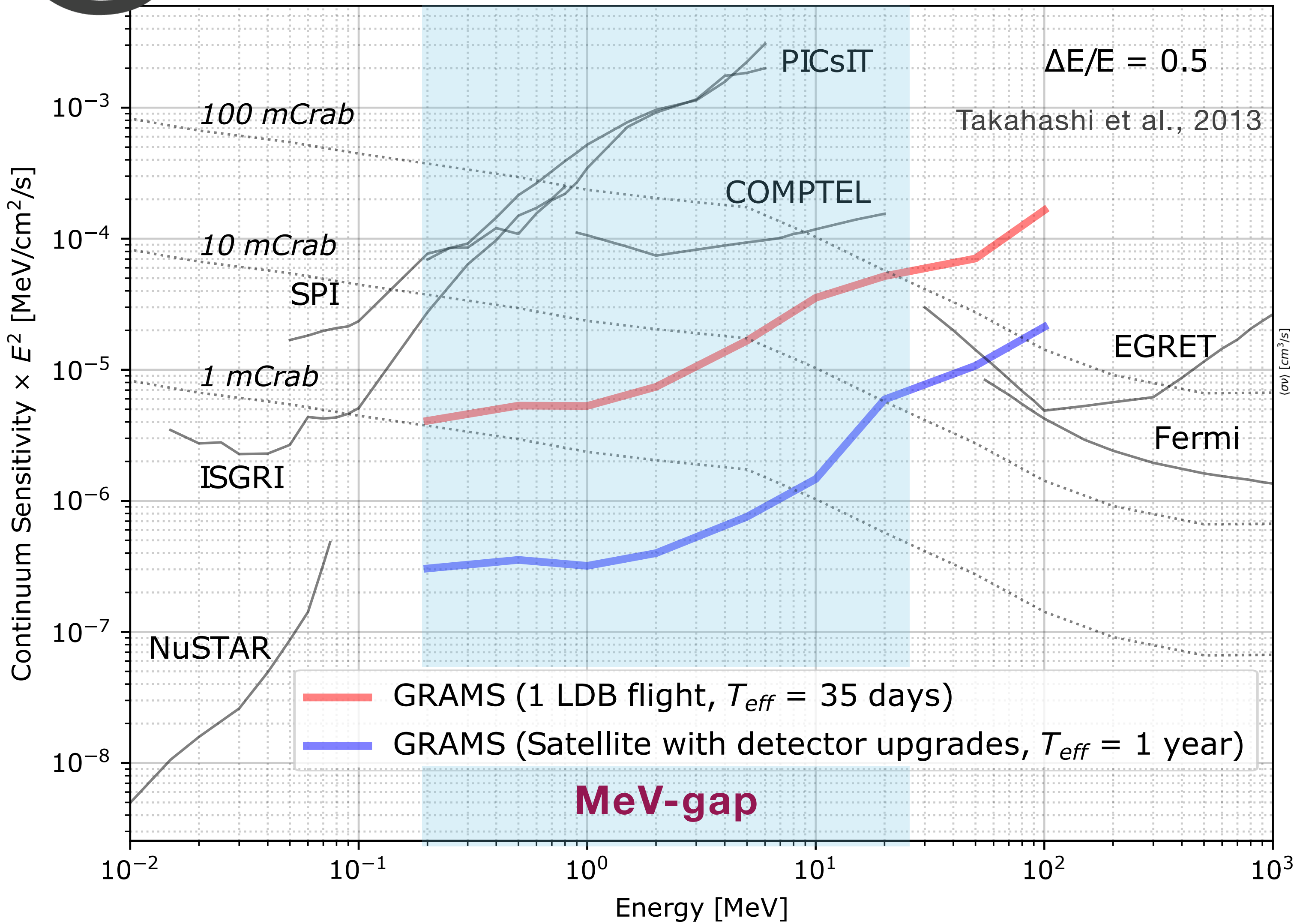


	LArTPC	Semiconductor/Scintillator
ρ (g/cm ³)	1.4	2.3/5.3 (Ge/Si)
T _{operation}	~80K	~240K/~80K
Cost	\$	\$\$\$
Signals	scintillation light + ionization electrons	electrons, holes
X, Y positions	Wires/pads on anode plane (X-Y)	double-sided strips
Z position	From drift time	from layer #
# of layers	Single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

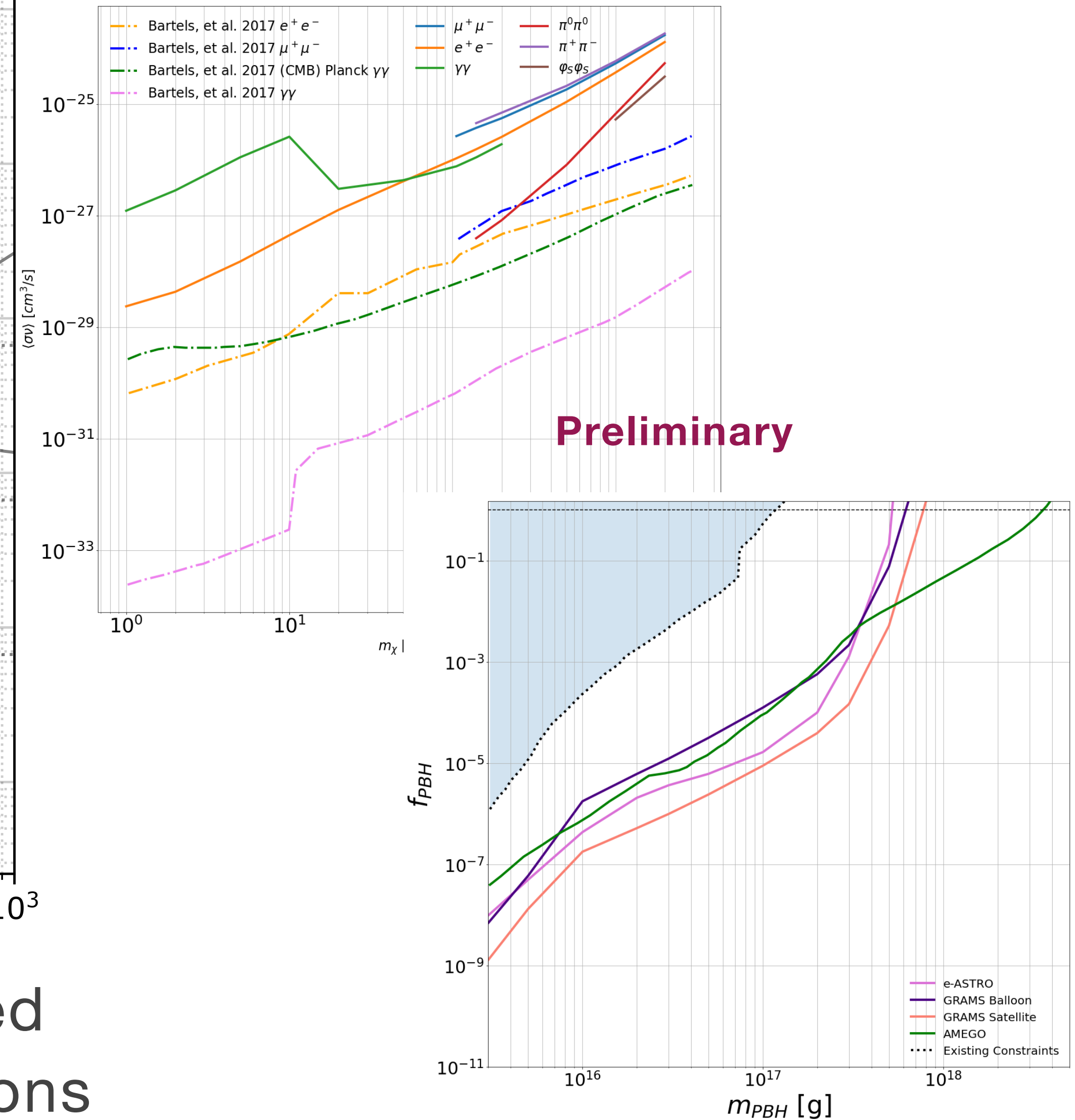
- LArTPC is **cost-effective** and almost **no dead** volume
- Easily **expandable** to a larger scale with **high detection efficiency**



MeV Gamma-ray Observations



Annihilating DM and evaporating PBHs



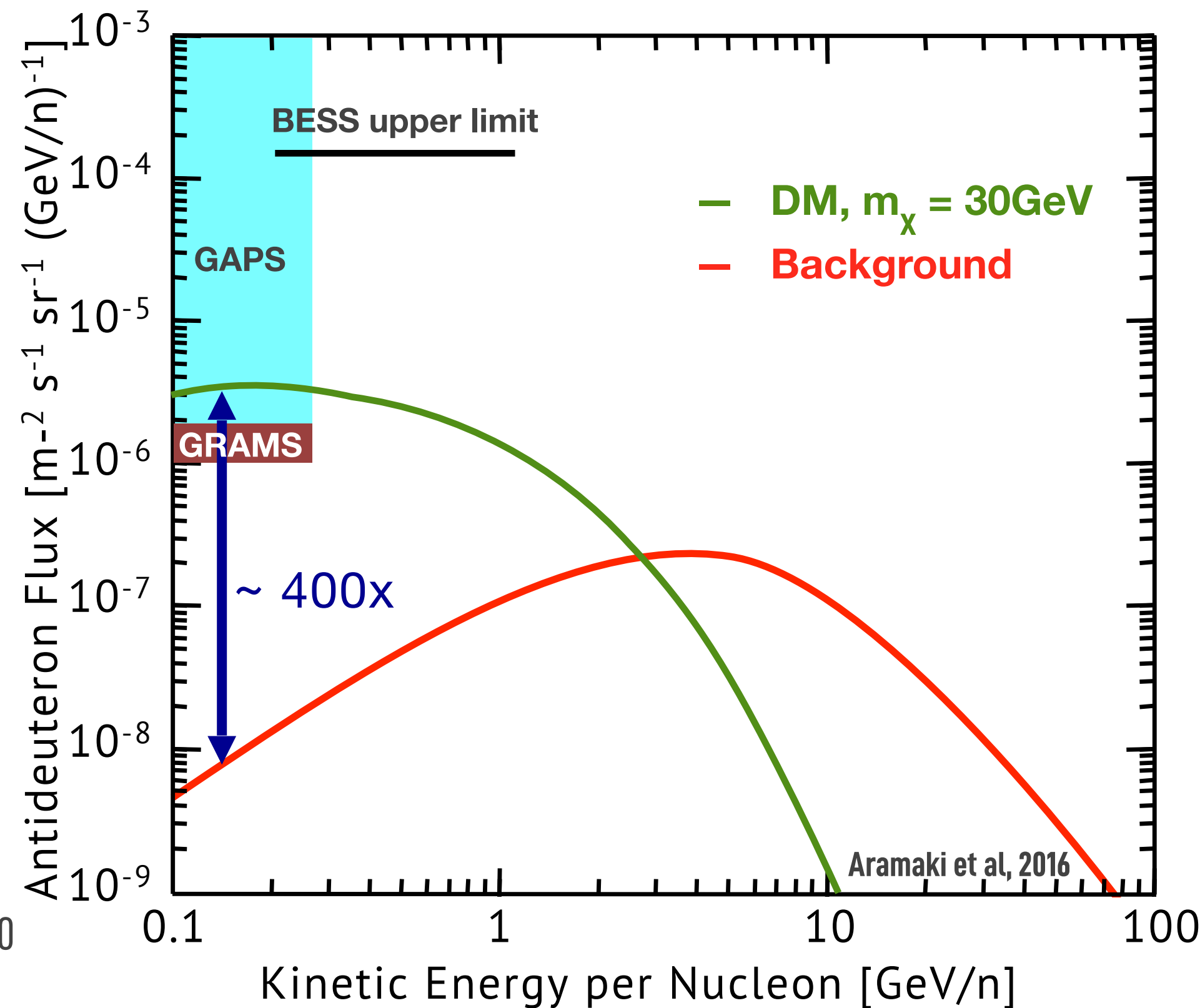
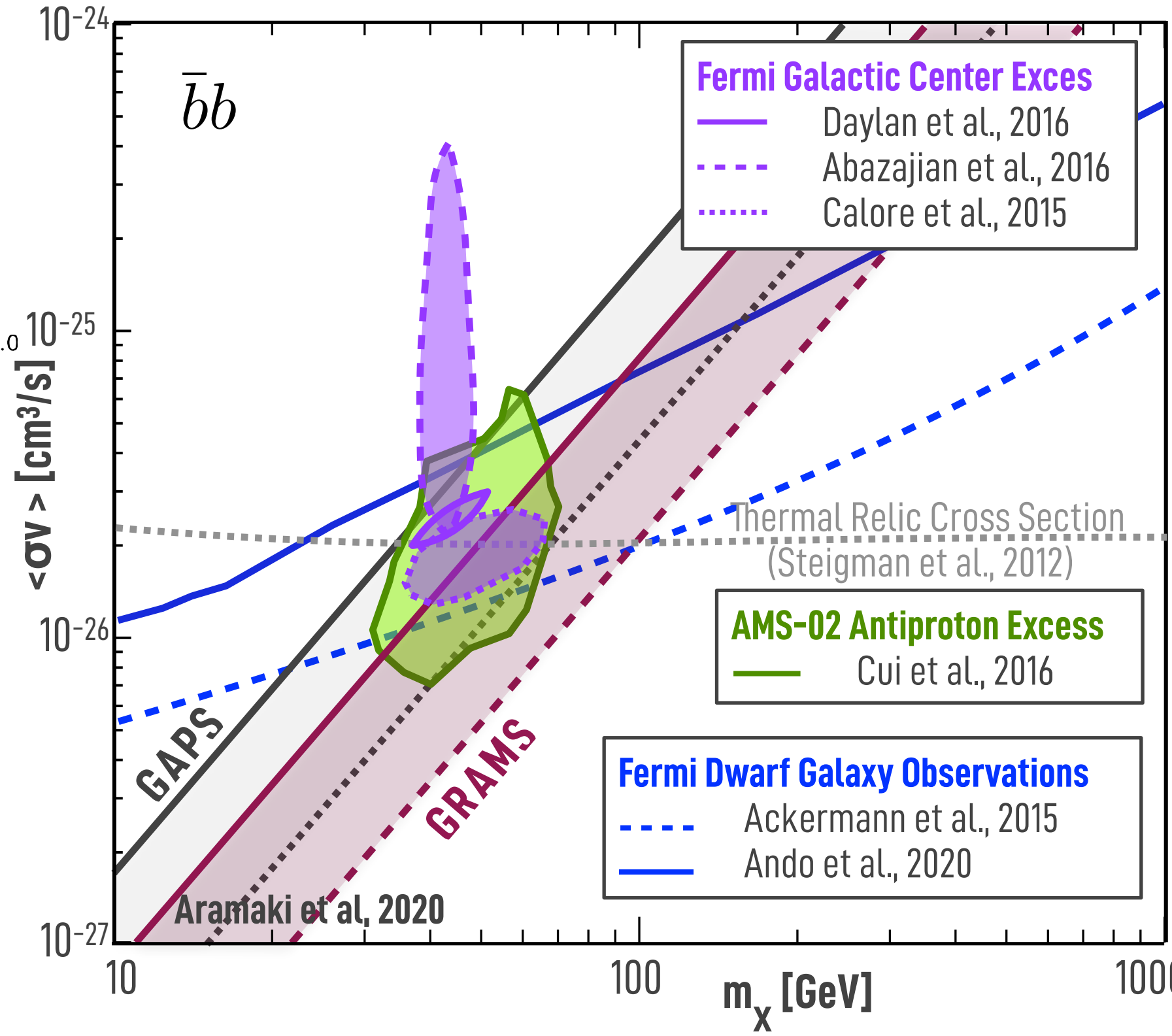
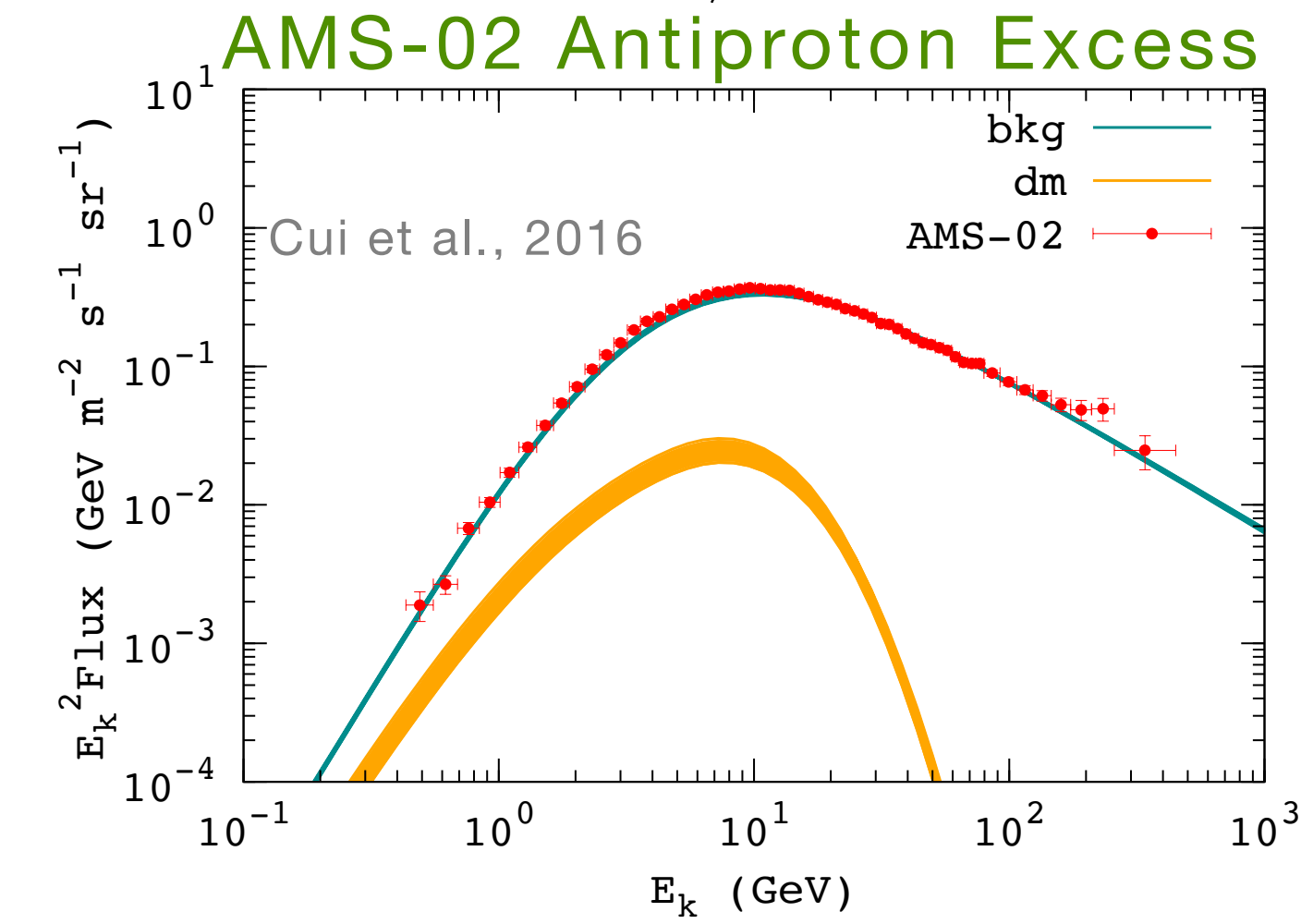
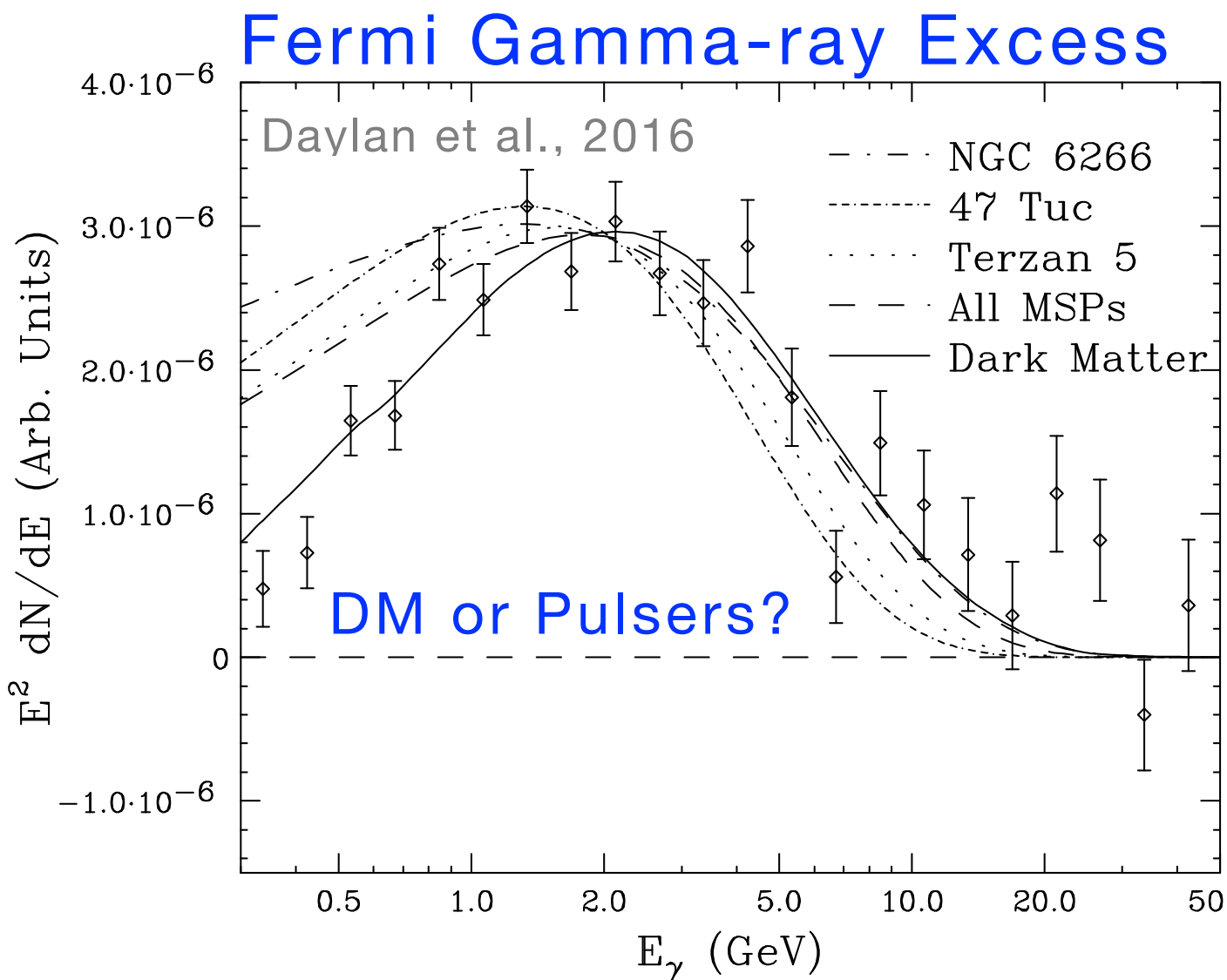
- **Balloon** flight: an order of magnitude improved
- **Satellite** mission: comparable to future missions



Indirect DM Searches with Antinuclei

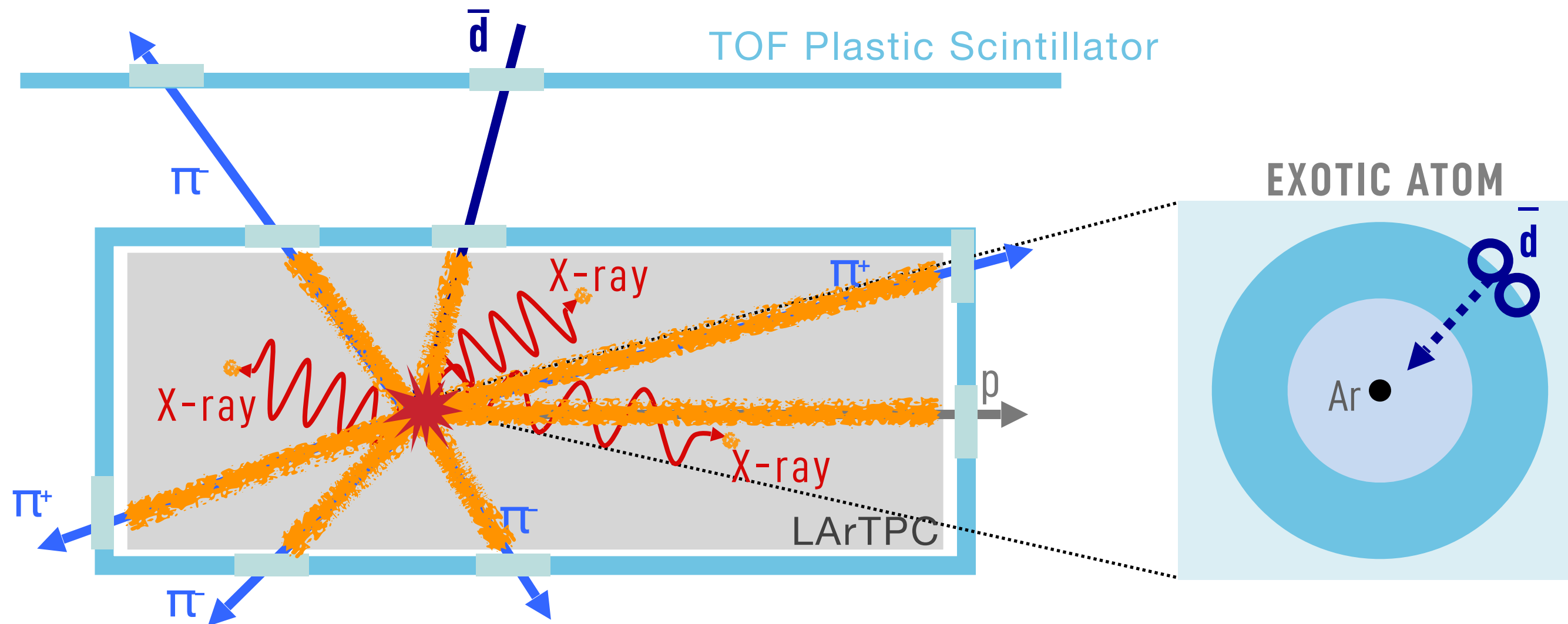
- Possible DM signature in **FERMI GCE**, **AMS-02 antiproton** excess
- AMS-02 detected **antihelium-like** events

How do we validate these results?

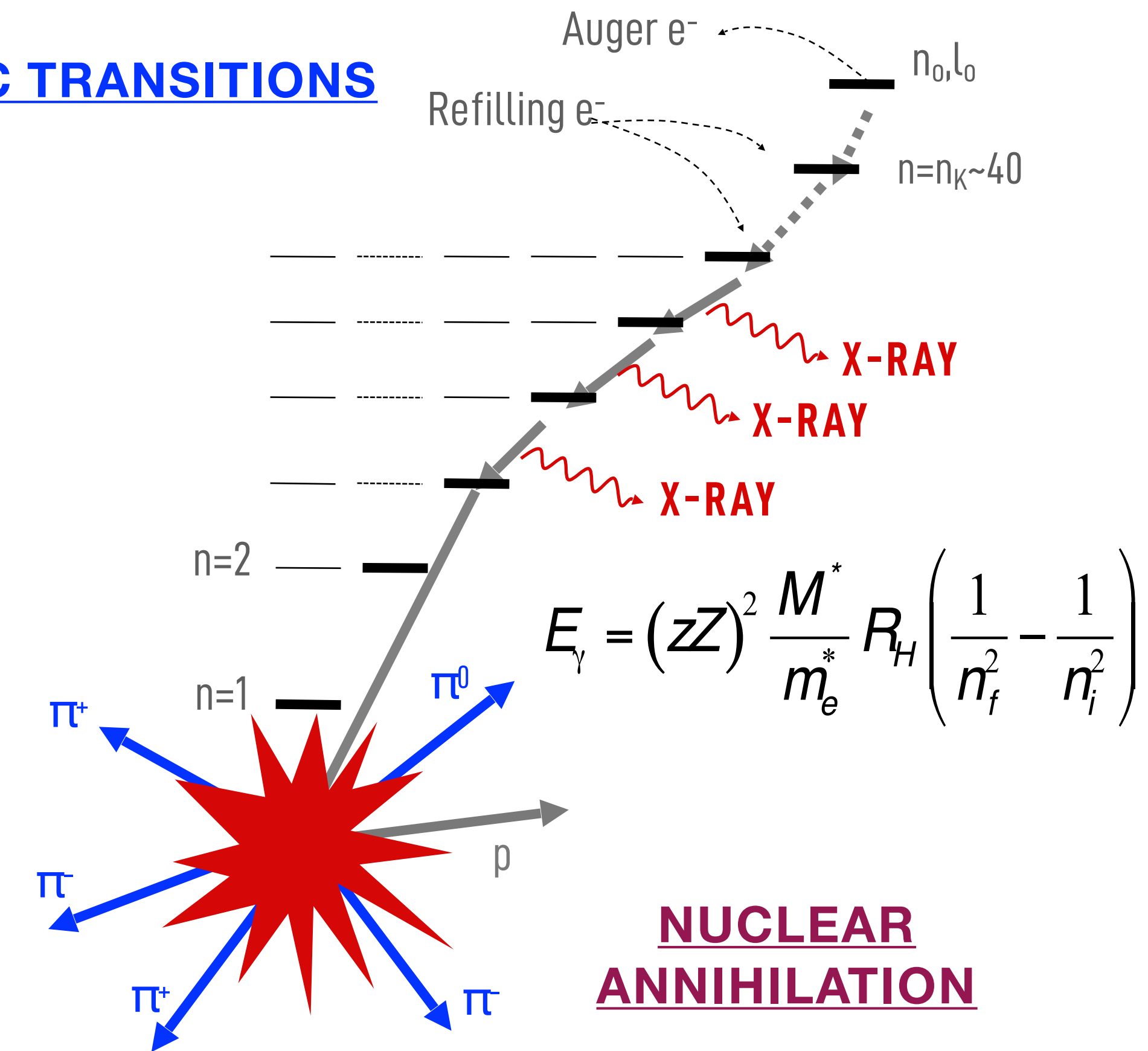


- **Background-free** DM search with low-energy antideuterons
- GRAMS can **extensively** explore DM parameter space

Measure atomic **X-rays** and **annihilation** products



ATOMIC TRANSITIONS



- 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



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

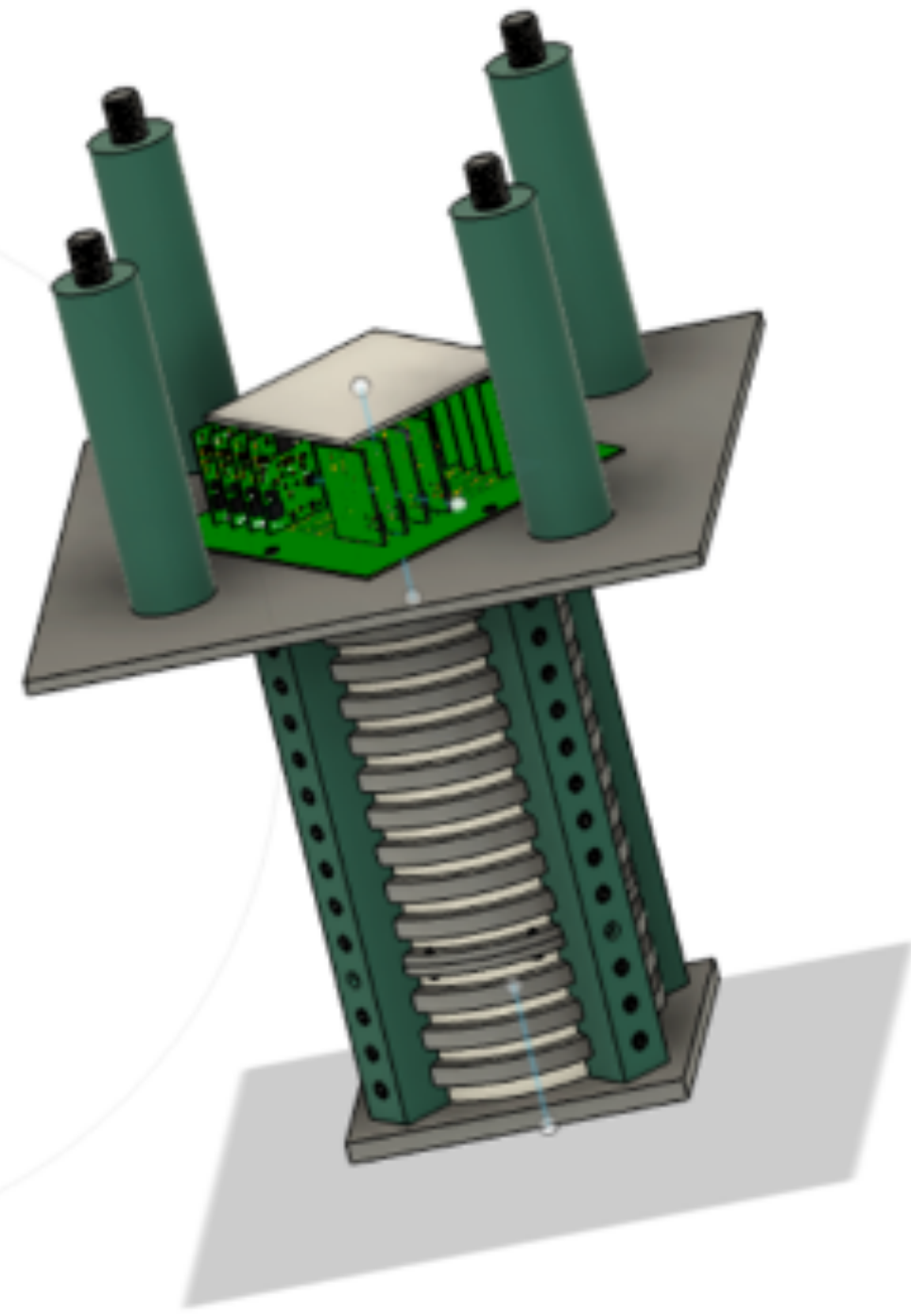
- Select **slow** particles with TOF that can stop inside LArTPC
- Simultaneous detection of secondary/annihilation products (pions/protons)
 - **No secondary particles** from slow CR p and e^\pm

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



MiniGRAMS construction: Northeastern

- TPC: $10 \times 10 \times 20 \text{ cm}^3$
 - > $30 \times 30 \times 20 \text{ cm}^3$ with segmentation
- PCB tile (nEXO-like) instead of wires
 - Charge-sensitive amp (ORNL)

Readout system: Columbia

- **MicroBooNE** ADC/digitizer

TOF/Ballooning system: NASA GSFC (TBD)

- Scintillator, DAQ, telemetry, gondola designs

U Tokyo

- Currently building MiniGRAMS with ASICs developed for ASTRO-H SGD
- Developed **event reconstruction algorithms** (neural network, probabilistic methods)

Waseda

- LArTPC development for the ANKOK direct DM search experiments
- Optimization of TPB evaporation for high light-yield

-> **Beam test in 2024**



GRAMS Collaboration

Multidisciplinary team with different backgrounds/expertise

Gamma-rays, X-rays, Cosmic-rays, Neutrinos,
Direct DM search, Indirect DM search

USA

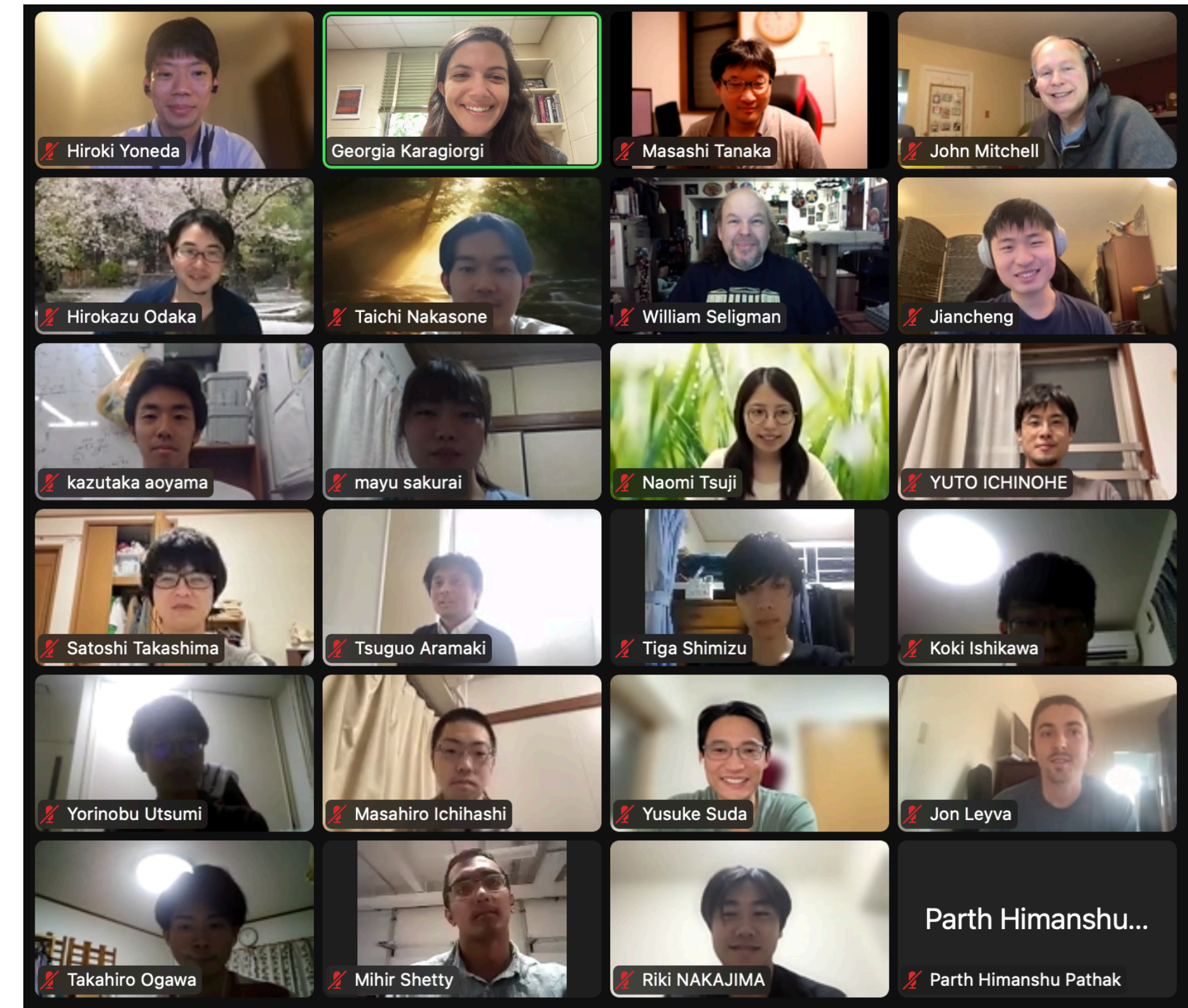
- Barnard College
- Columbia University
- MIT
- NASA GSFC
- Northeastern University
- Oak Ridge National Lab
- UT Arlington

International (Japan)

- Hiroshima University
- Kanagawa University
- Osaka University
- RIKEN
- Rikkyo University
- University of Tokyo/NDA
- Waseda University

We are expanding the collaboration.

Please contact me: t.aramaki@northeastern.edu



5th Collaboration Meeting, June 2022



Summary

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- GRAMS is a proposed next-generation mission to target both **gamma-ray** observations in the poorly explored **MeV** energy band and **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 **more than an order of magnitude improved** compared to previous experiments with a **single** balloon flight.
- We have developed the **event reconstruction algorithms** for multiple Compton scattering events, based on multi-task neural network/physics-based probabilistic methods.
- GRAMS **antideuteron** measurements can be essentially **background-free** dark matter searches while investigating and validating the possible dark matter detection indicated in Fermi GCE and AMS-02 antiproton excess.
- We are currently building a small-scale LArTPC detector, **MiniGRAMS** that can be deployed in the **beam test** (2024) and the prototype flight (TBD).