第２回MeVガンマ線天文学研究会

GRAMSプロジェクトでのダークマター探索とMEVガンマ線観測

TSUGUO ARAMAKI, SLAC

OUTLINE

Dark Matter Search with Antimatter

- Current status and recent results of indirect dark matter search
- Why is antimatter survey important?
- Antimatter-based dark matter search with GRAMS

MeV Gamma-Ray Observations

- Current status of MeV gamma-ray observations
- Why are MeV gamma-ray observations important?
- MeV gamma-ray observations with GRAMS

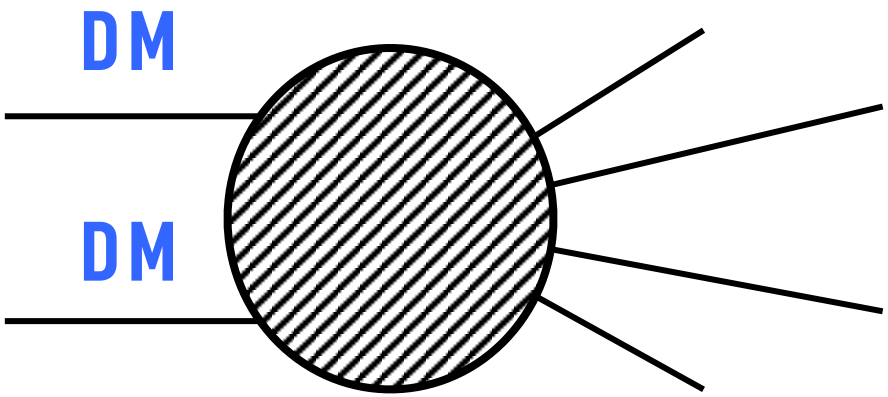
Summary

GRAMS First Paper
accepted in Astroparticle Physics

Aramaki et al., 2019

DARK MATTER SEARCH

MEASURE DM ANNIHILATION/DECAY PRODUCTS



q, h, W,

e^+, γ, ν, $\bar{p}$, $\bar{d}$, $\bar{n}$...

POSITRON:
AMS-02, PAMELA, DAMPE...

GAMMA RAY:
FERMI-LAT, VERITAS, CTA, **GRAMS**...

NEUTRINO:
ICECUBE, ANTARES...

ANTIPROTON:
AMS-02, PAMELA, BESS, **GAPS**, **GRAMS**

ANTIDEUTERON:
AMS-02, BESS, **GAPS**, **GRAMS**

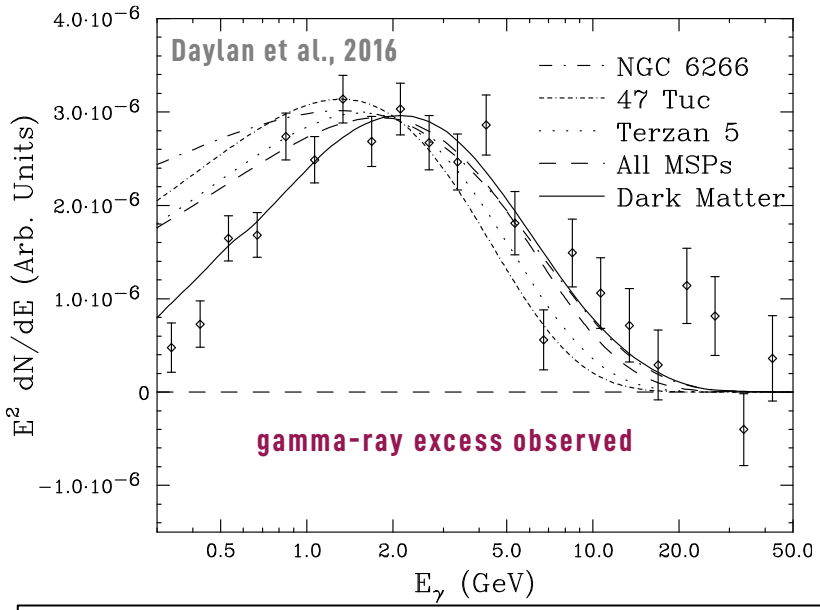
ANTIHELIUM:
AMS-02, **GAPS**, **GRAMS**

COMPLEMENTARY SEARCHES WITH DIFFERENT DETECTION METHODS AND BACKGROUND MODELS ARE CRUCIAL TO VALIDATE DM SIGNATURES

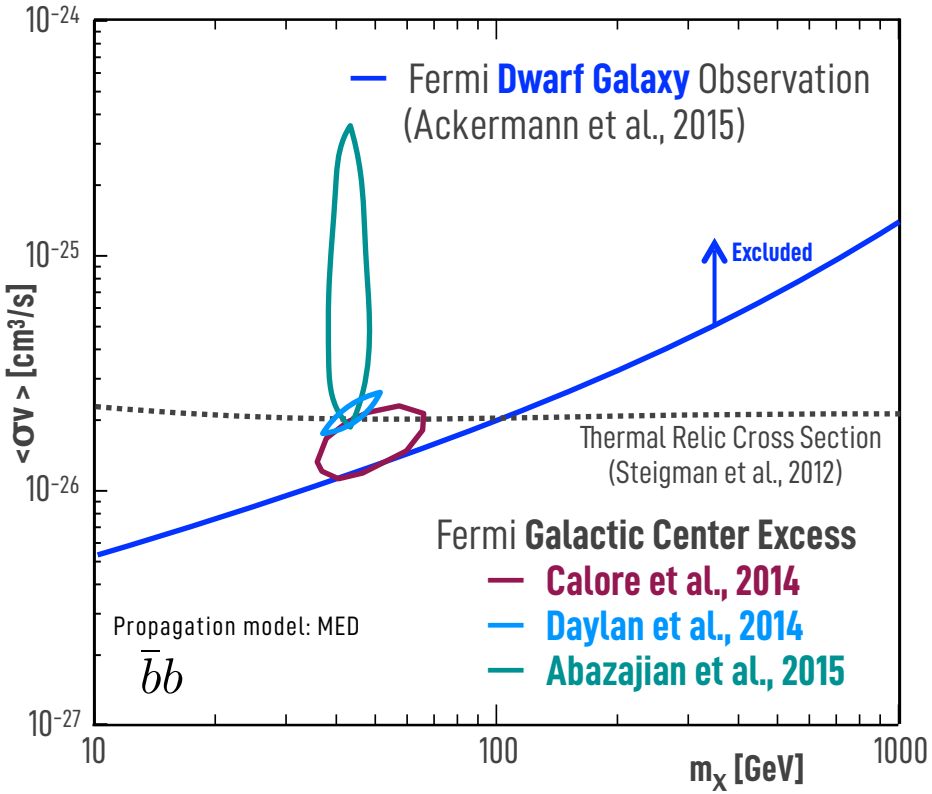
RECENT RESULTS FROM FERMI-LAT

Launched in June 2008, targeting 20MeV - 300GeV gamma-rays

Possible DM signatures from Galactic Center Region (GCE)
Inconsistent with dwarf spheroidal galaxy (dSph) observations
(recent observations for new dSphs show some small excess)



FERMI GALACTIC CENTER EXCESS (GCE)
~50GeV DM or astrophysical objects?

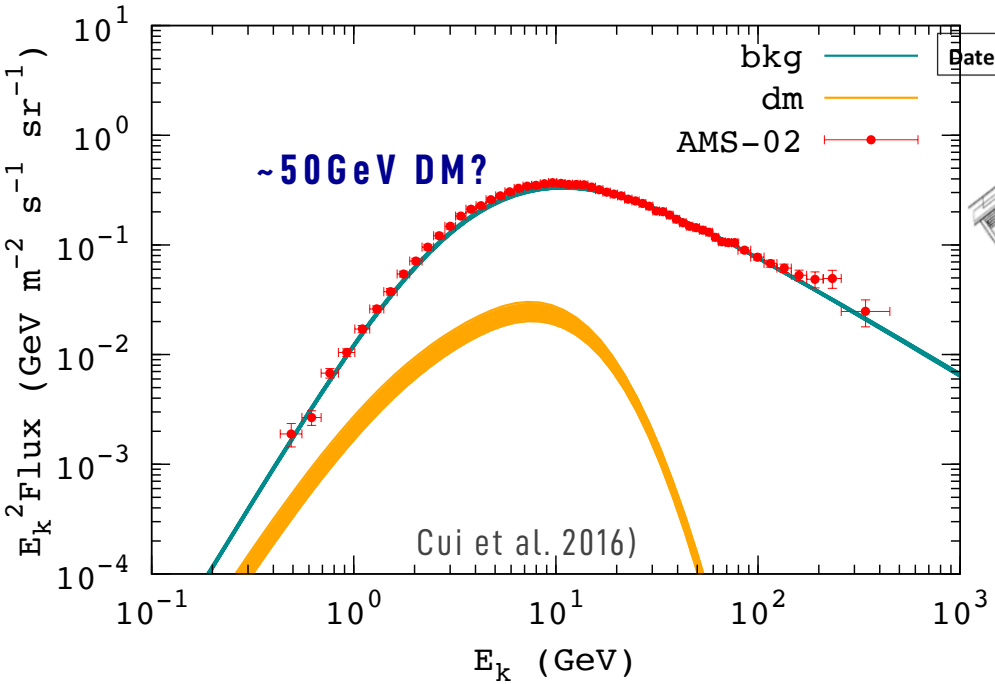


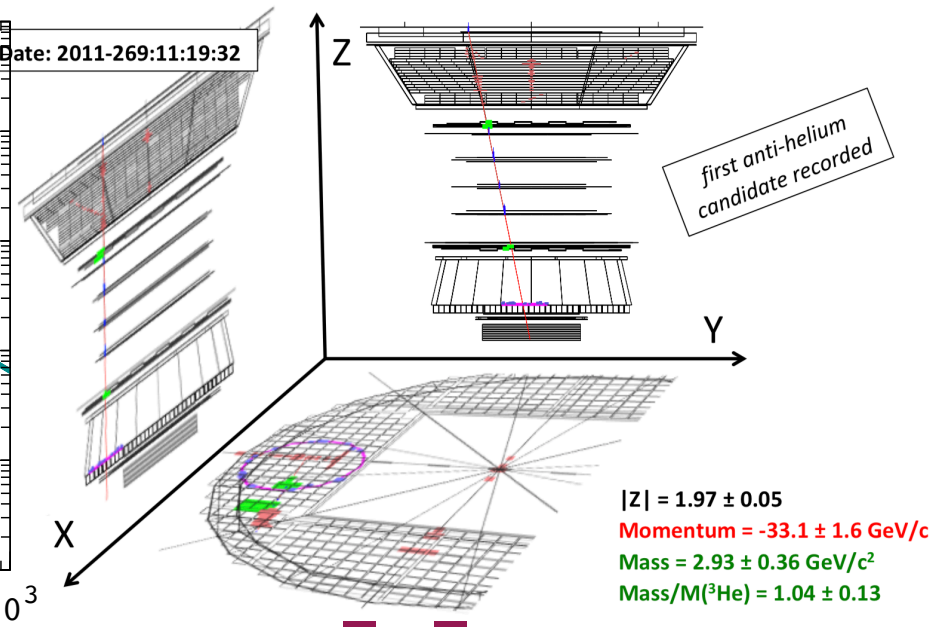
DIFFICULT TO VERIFY DM SIGNATURES DUE TO MIMIC SIGNAL FROM BACKGROUND
NEED A NEW APPROACH/EXPERIMENT TO VALIDATE THE RESULTS

RECENT RESULTS FROM AMS-02

Launched in May 2011, targeting cosmic-rays including antiparticles

Possible DM detection in antiproton measurements
Possible detection of antiheliums and antideutrons





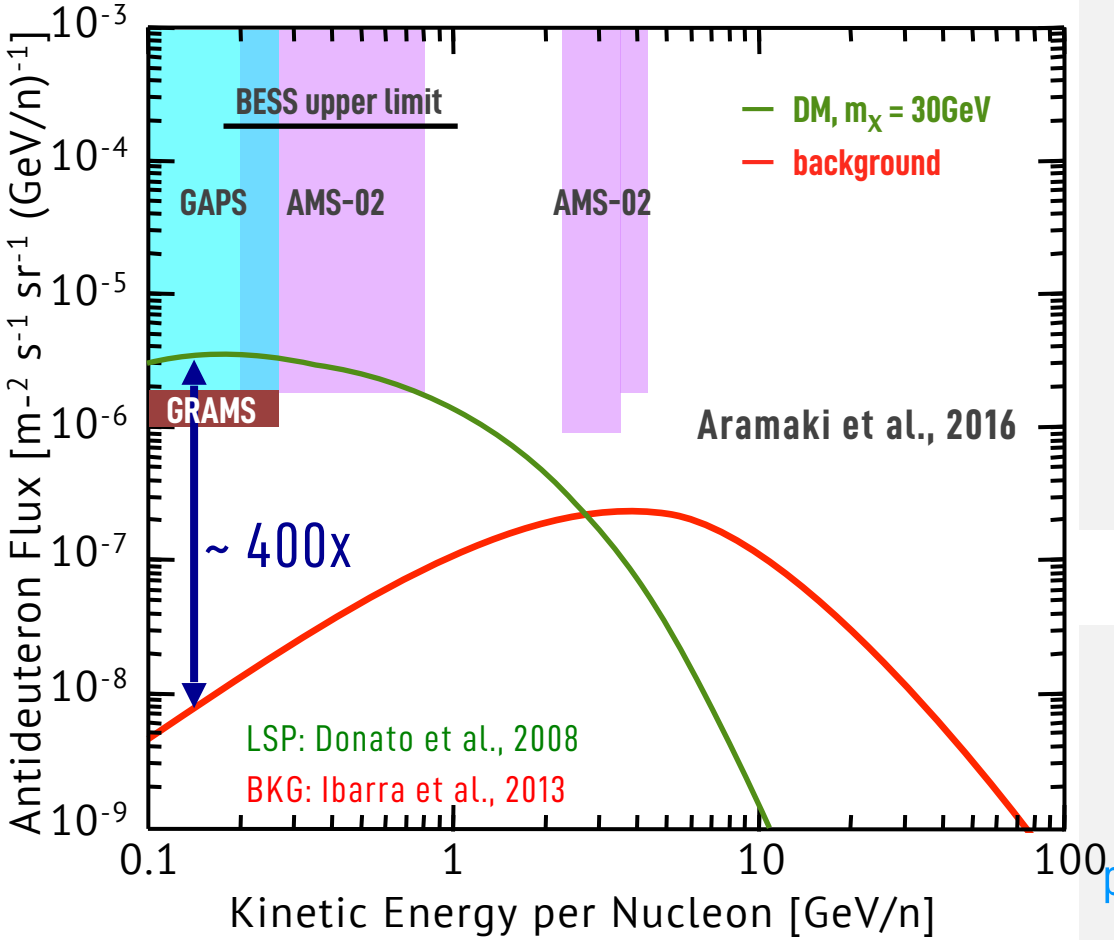
So far, 6 $^{3}\overline{He}$, 2 $^{4}\overline{He}$ candidate events reported

- Antiproton excess: **~50GeV DM** (**consistent with Fermi GCE**) or **cosmic-ray interaction**?
- Antiheluim detection:
  - If from DM, a large excess should be seen in the antiproton/antideuteron fluxes?
  - **antimatter clouds** in our galaxy?

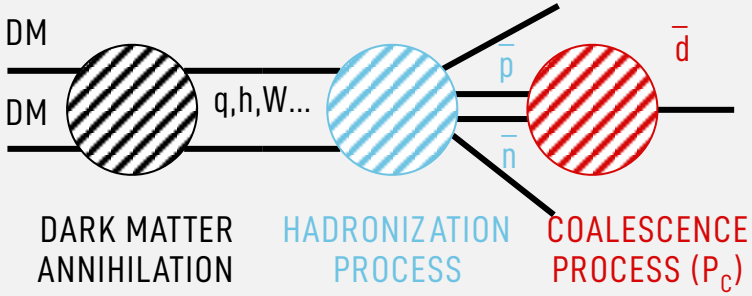
NEED A NEW APPROACH, EXPERIMENT TO VALIDATE THE RESULTS

WHY ANTIDEUTERONS?

BACKGROUND-FREE DM SEARCH AT LOW-ENERGY



PRIMARY FLUX
DM ANNIHILATION/DECAY



SECONDARY FLUX
COSMIC RAY INTERACTION

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

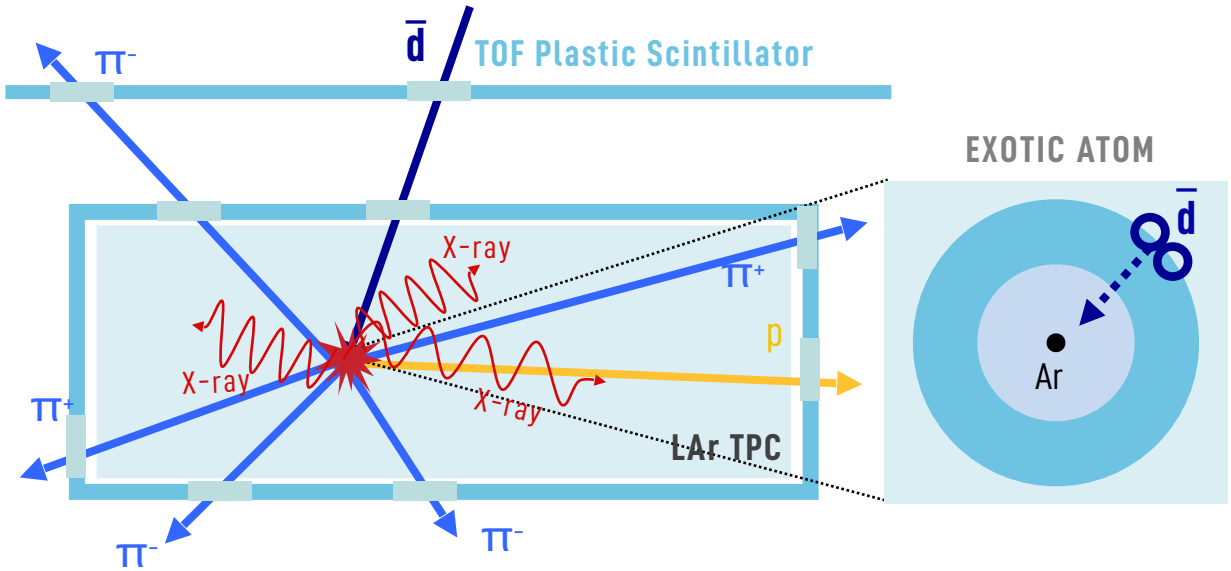
$\bar{d}$

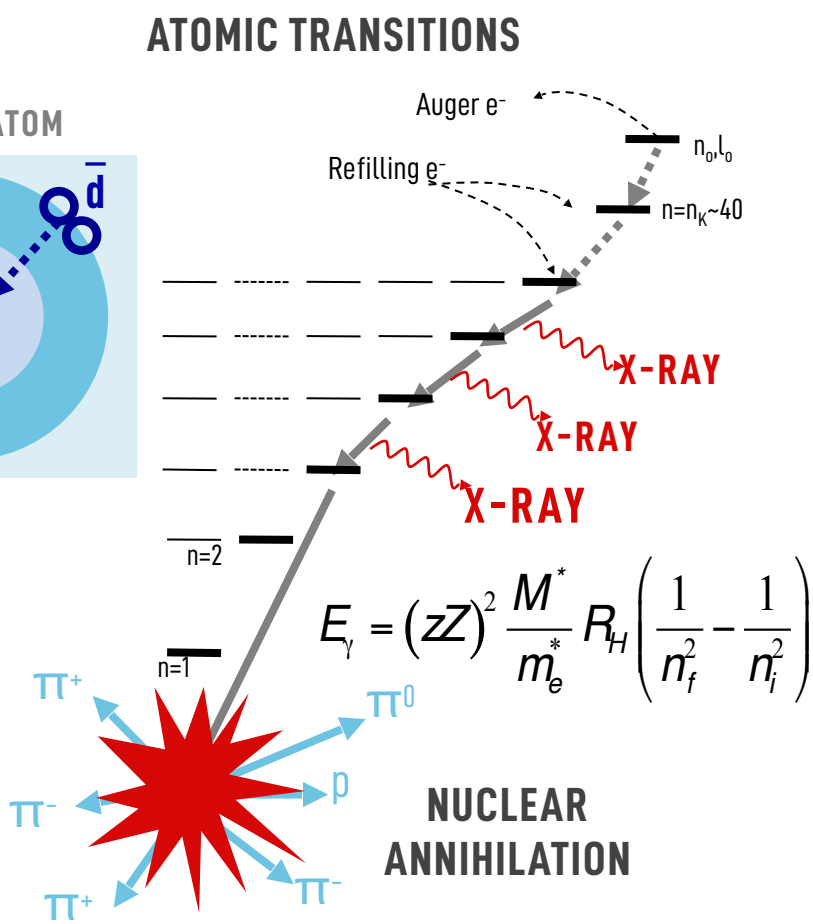
GAPS FIRST SCIENCE FLIGHT IS SCHEDULED FROM ANTARCTIC IN 2021

GRAMS: NEXT GENERATION EXPERIMENT

GRAMS ANTIMATTER DETECTION CONCEPT

MEASURE ATOMIC X-RAYS AND ANNIHILATION PRODUCTS





$$E_\gamma = (zZ)^2 \frac{M^*}{m_e^*} R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

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

Aramaki et al., 2013

Concept proven with accelerator beam test

Cascade model developed for X-ray yields

GRAMS ANTIDEUTERON IDENTIFICATION TECHNIQUE

CR p, e± REJECTION: ANTIPROTON AND ANTIDEUTERON SELECTION

Select **slow particles** with TOF

Simultaneous detection of secondary/**annihilation products (pions/protons)**

- Slow CR p and e± **may not be able to produce secondary particles**

ANTIDEUTERON IDENTIFICATION FROM ANTIPROTONS

Atomic X-rays from exotic atom

- different energy: 58, 97 keV for antiproton, 74, 114 keV for antideuterons

Pion/proton multiplicity

- antideuterons produce more pions and protons

Stopping range (depth sensing)

- antideuterons with the same velocity go deeper before stopping

dE/dX energy deposit in LArTPC

- antideuterons with the same velocity deposit more energy

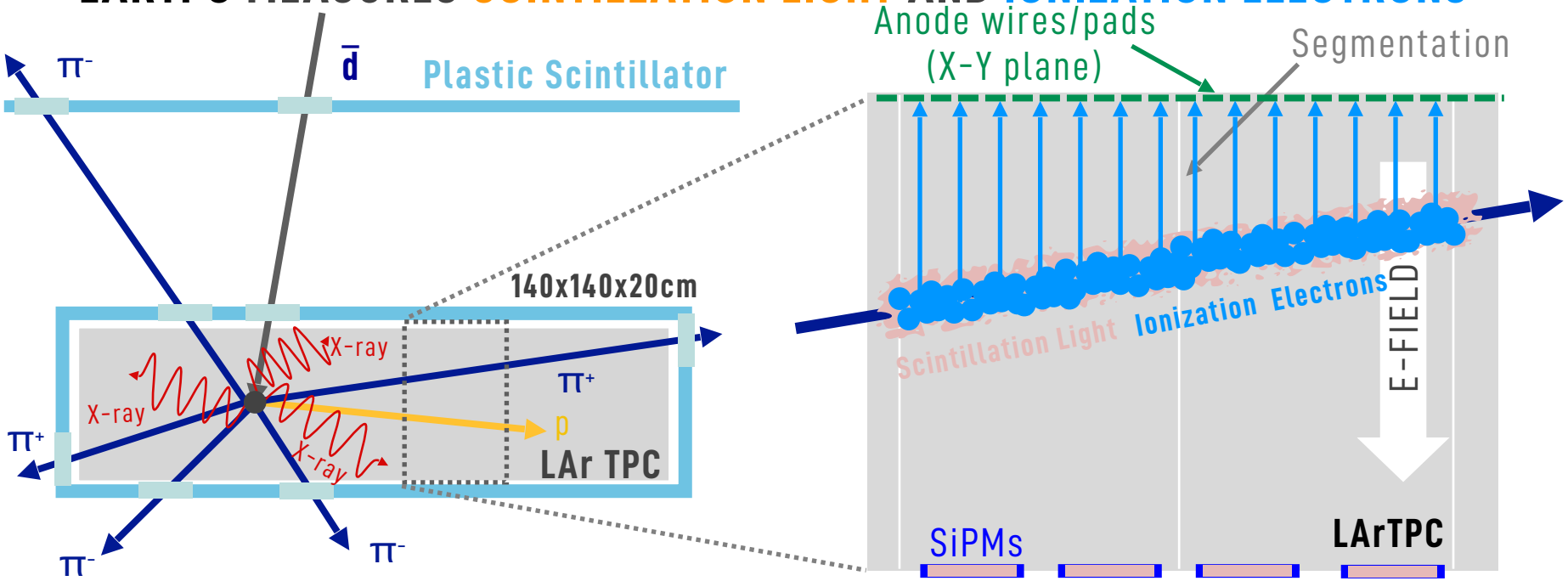
PLANCK

EXPECTED BACKGROUND/MIMIC EVENTS ~0.01

GRAMS DETECTOR DESIGN

LARTPC DETECTOR SURROUNDED BY PLASTIC SCINTILLATORS

LARTPC MEASURES SCINTILLATION LIGHT AND IONIZATION ELECTRONS



Plastic Scintillators: **TOF** – measure velocity and incoming angle

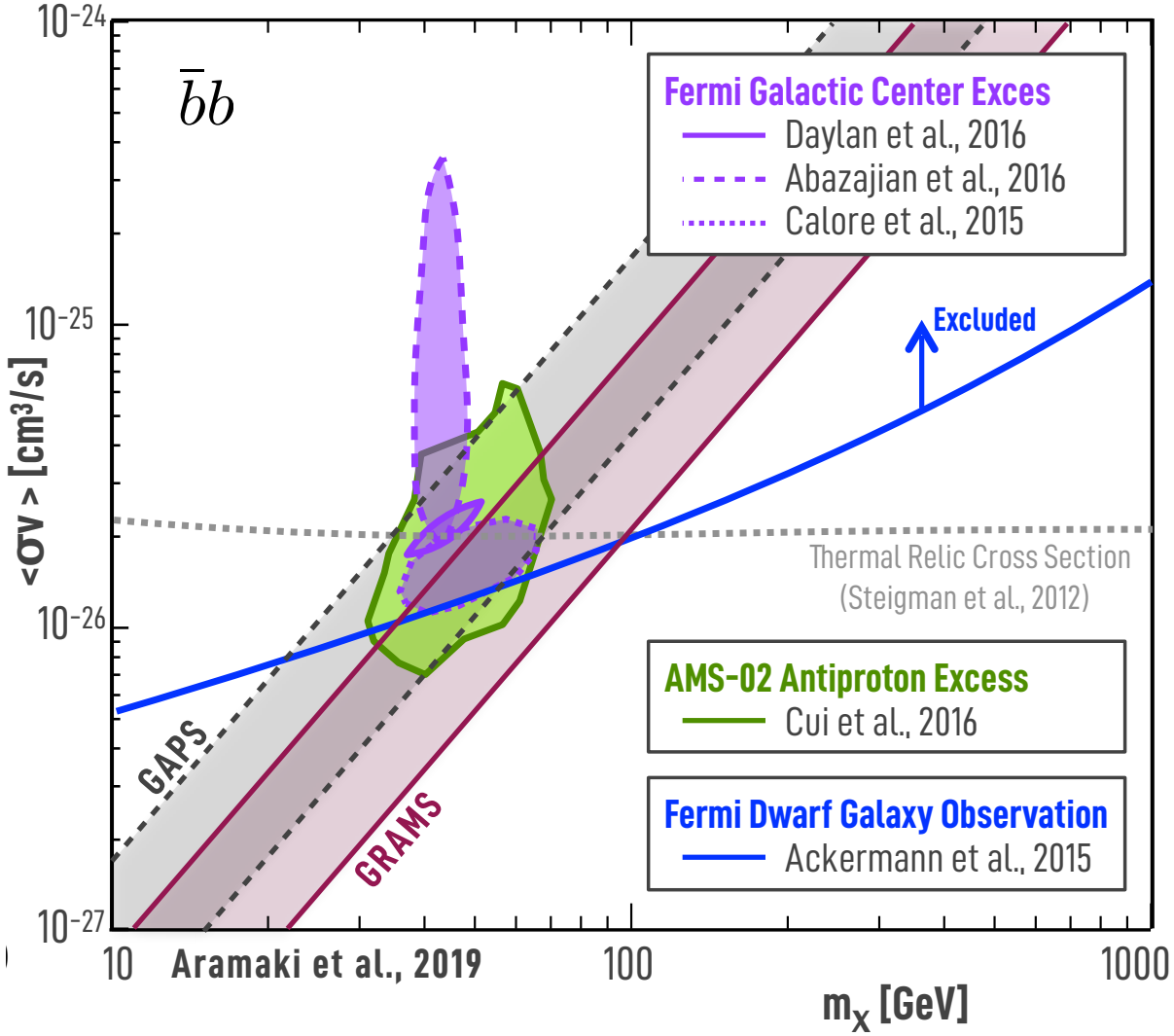
LArTPC: **Calorimeter** and **particle tracker**

- Scintillation light at **SiPMs** **to trigger events**
- Wires/pads on anode plane (X, Y), drift time (Z) to provide a **3D image/track**
- **Well-studied, widely-used** in **large-scale DM/neutrino** experiments

Scintillation light localized by segmentation to reduce coincident background

GRAMS SENSITIVITY IN DM PARAMETER SPACE

STRONG TENSIONS WITH FERMI GCE/DSPHS AND AMS-02



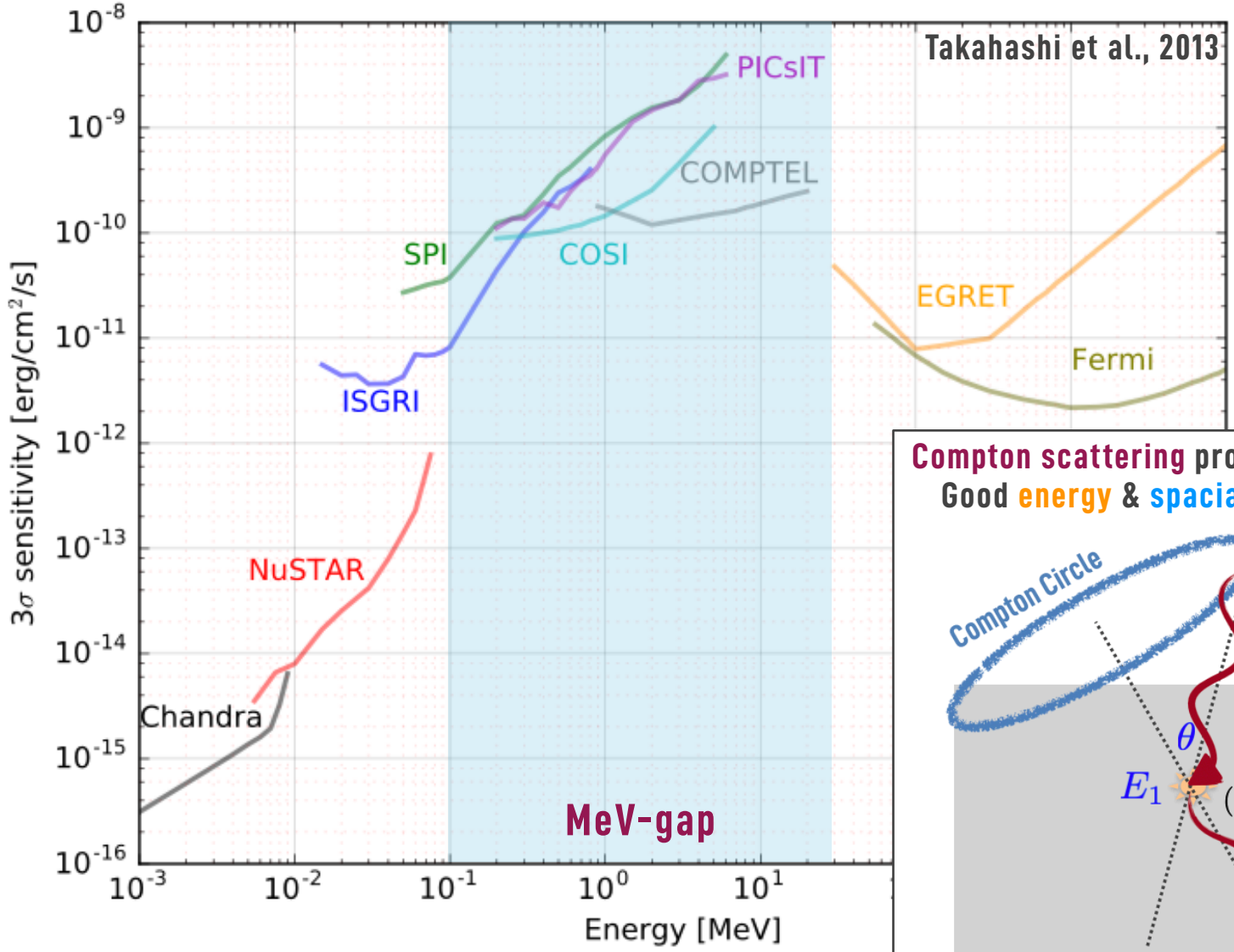
Aramaki et al., 2019

GRAMS COULD DEEPLY INVESTIGATE FERMI GCE, AMS-02 ANTIPROTON EXCESS
CURRENTLY EVALUATING ANTIHELIUM SENSITIVITY

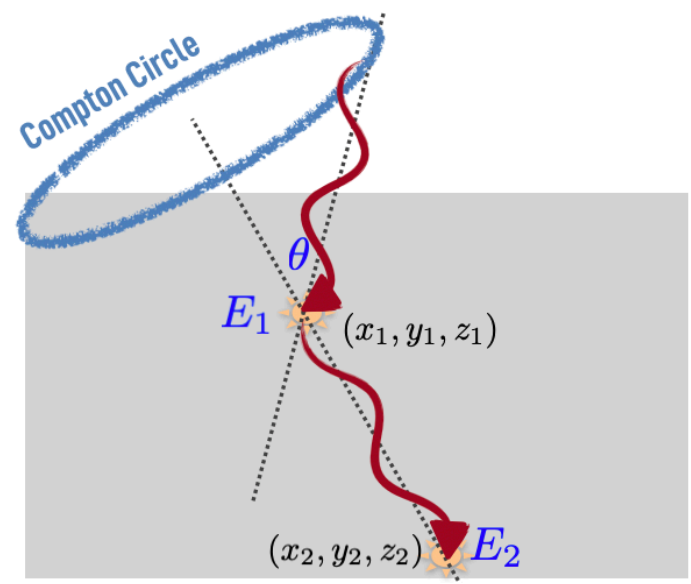
MEV GAMMA-RAY OBSERVATION

CURRENT STATUS OF MEV GAMMA-RAY OBSERVATIONS

GAMMA-RAYS IN MEV REGION POORLY EXPLORED = "MEV GAP"

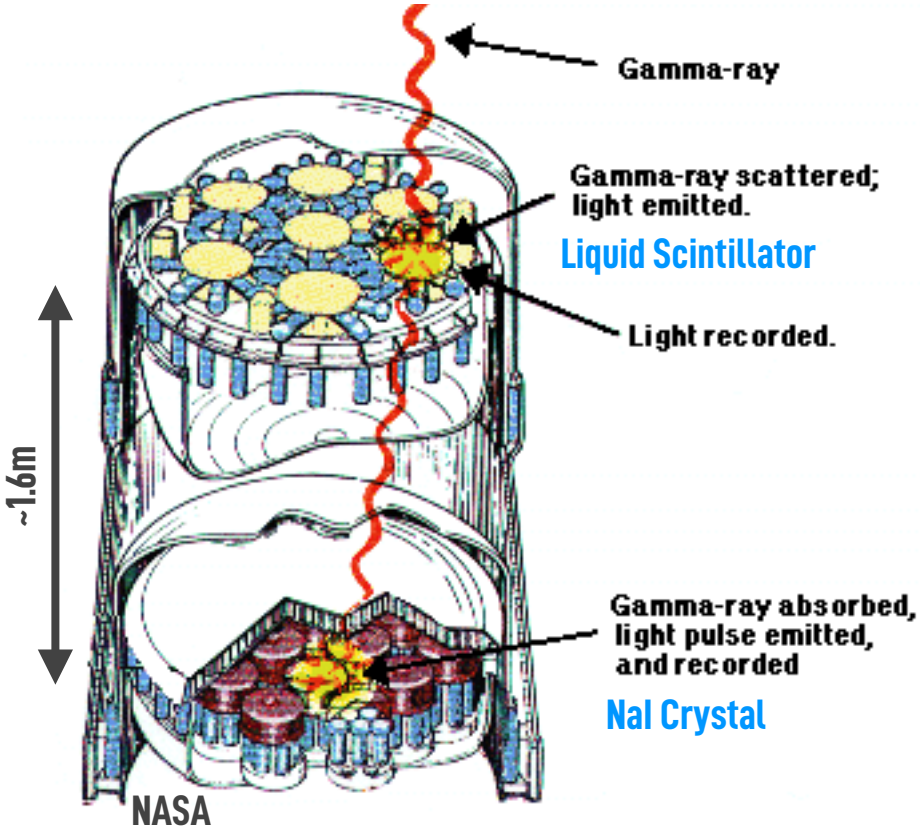


Compton scattering process dominates in MeV
Good **energy** & **spacial** resolution required



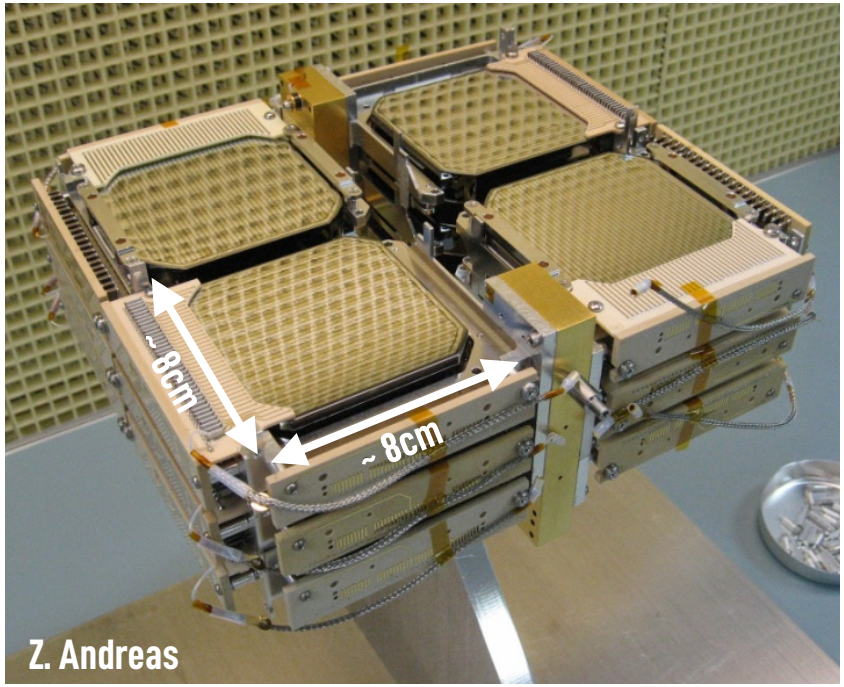
PREVIOUS EXPERIMENTS: COMPTEL AND COSI

COMPTEL
(The Imaging Compton Telescope)



- launched into space in 1991
- installed on Compton Gamma-Ray Observatory
- energy range: 0.75 - 30 MeV
- spacial resolution: ~ 40cm^3
- Detected ~30 sources

COSI
(The Compton Spectrometer and Imager)



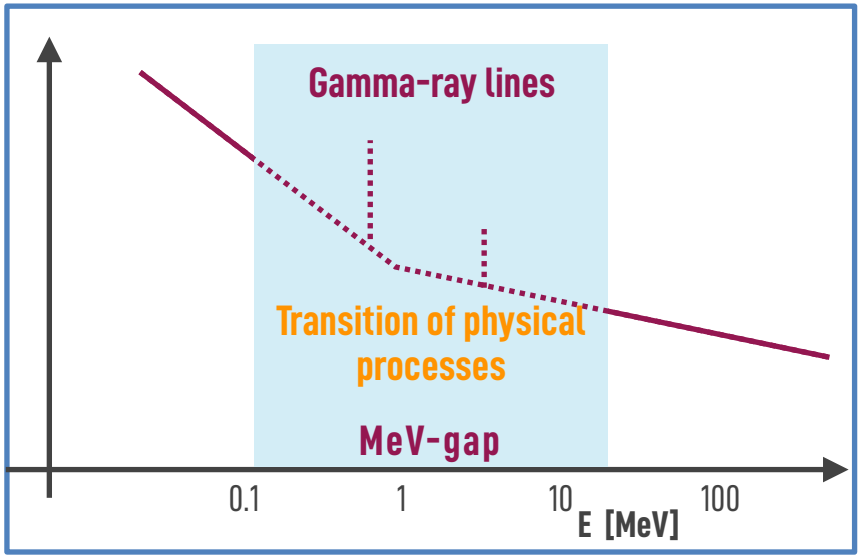
- 12 HPGe crystals (2x2x3), double-sided stripped
- energy range: 0.2 - 5 MeV
- spacial resolution: ~ 2mm^3
- 1st balloon flight from Antarctica in 2014
- 2nd flight from New Zealand in 2016

MEV GAMMA-RAY SCIENCE

GAMMA-RAY SPECTRUM

- Extreme objects
  - **Neutron stars**: high matter density
  - **Magnetars**: strong magnetic field
  - **AGNs/Blazars**: powerful jets
- **Transition** of physical processes
- Cosmic MeV gamma-ray background

Inoue et al., 2019



GAMMA-RAY LINES

- **Positron** annihilation: 511 keV
- **Nuclear lies** are typically in ~MeV
- **Radioactive isotopes** provide physical condition during nucleosynthesis
  - SNe: ^{26}Al (1809keV), ^{60}Fe (1173keV, 1333keV), ^{44}Ti (1157keV), ^{56}Co (847keV)
  - Neutron capture: ^{2}H (2223keV), Cosmic-ray interactions: ^{12}C* (4438keV)

MULTI-MESSENGER ASTRONOMY

- EM counterparts of **NS-NS mergers**
- r-process in **NS mergers/remnants**

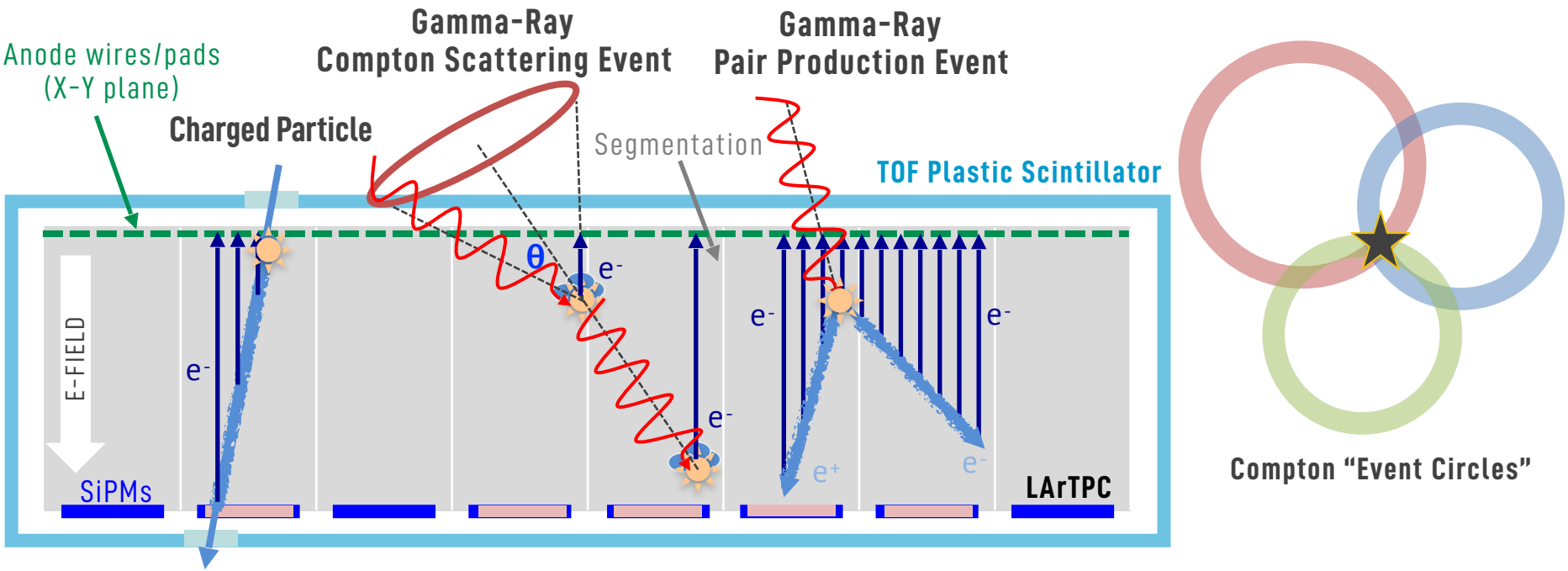
Wu et al., 2019

DARK MATTER SEARCH

- MeV gamma rays from DM annihilation

GRAMS DETECTION CONCEPT: MEV GAMMA-RAYS

LARTPC DETECTOR SURROUNDED BY PLASTIC SCINTILLATORS
LARTPC MEASURES SCINTILLATION LIGHT AND IONIZATION ELECTRONS



Plastic Scintillators: **Veto** incoming charged particles

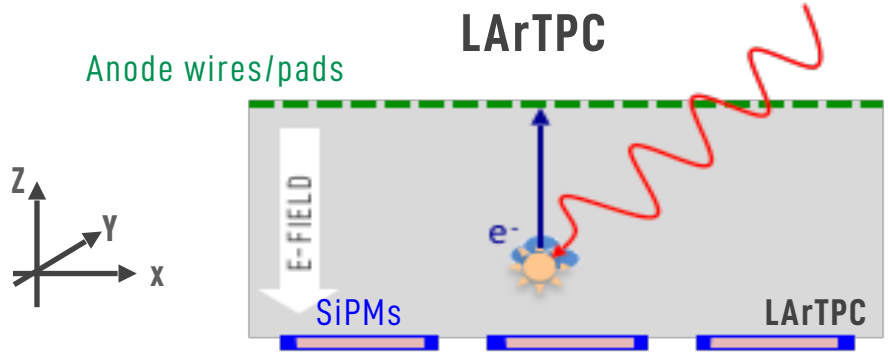
LArTPC: **Compton camera** and **calorimeter** (for pair-production)

- Scintillation light at **SiPMs** **to trigger events**
- Wires/pads on anode plane (X, Y), drift time (Z) to provide a **3D image/track**

Signal localized by segmentation to reduce coincident background

Neutron events can be separated based on the pulse shape

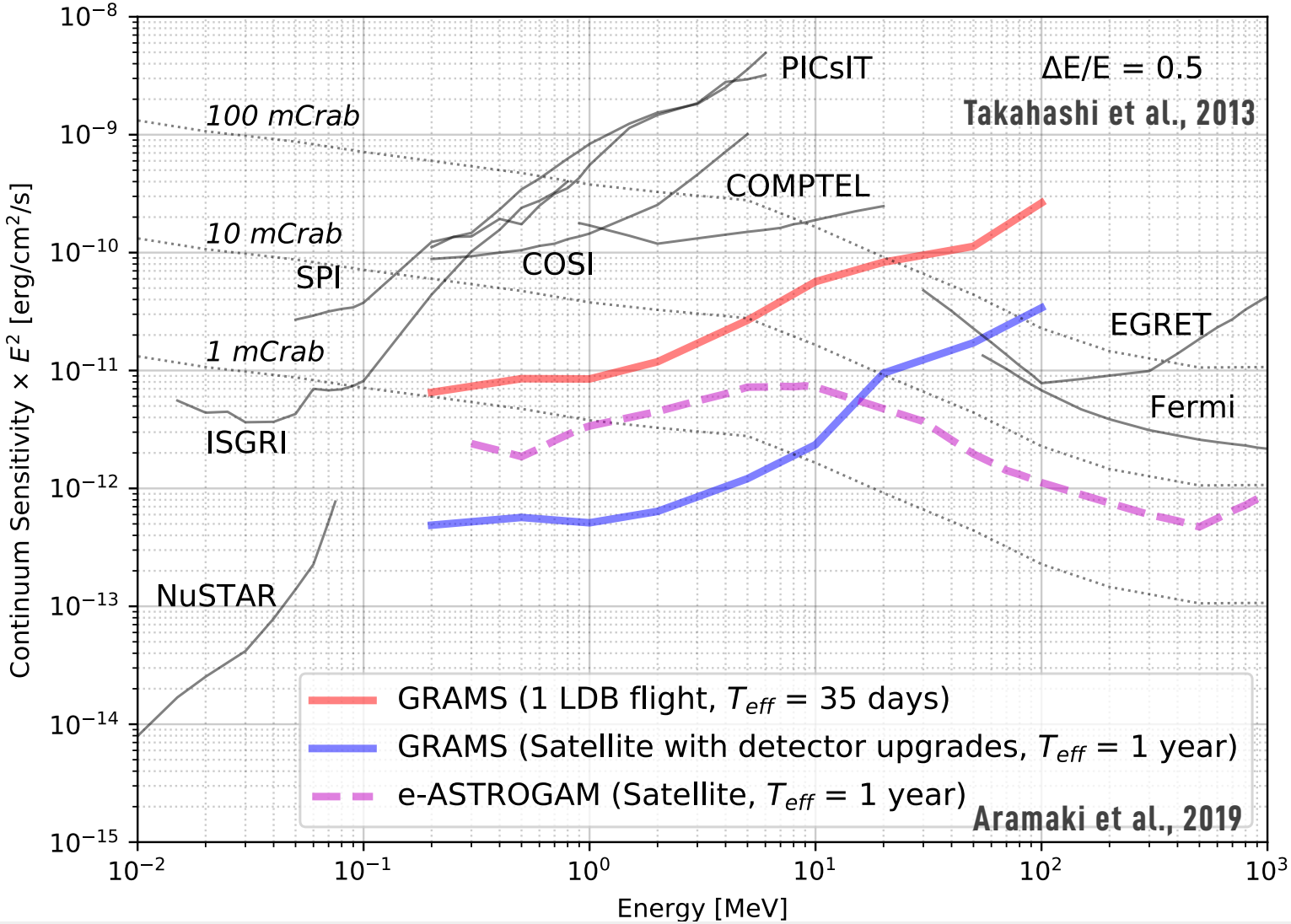
LARTPC VS. SEMICONDUCTOR DETECTOR



	LArTPC	Semiconductor (Si/Ge)
ρ (g/cm³)	1.4	2.3/5.3
$T_{operation}$	~80K	~240K/~80K
Cost	$	$$$
Signal	scintillation light + Ionization electrons	electrons, holes
X, Y Positions	wires on anode plane (X-Y)	double-sided strips
Z position	from drift time	from layer #
# of Layers	1 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 EASILY EXPANDABLE TO A LARGER-SCALE, MUCH LESS CHANNELS/ELECTRONICS REQUIRED, ALMOST NO DEAD VOLUME

GRAMS MEV GAMMA-RAY CONTINUUM SENSITIVITY



SINGLE BALLOON FLIGHT: AN ORDER OF MAGNITUDE IMPROVED

SATELLITE MISSION: COMPARABLE (BETTER) TO FUTURE MISSIONS

FUTURE PROSPECTS

R&D FOR PROOF OF CONCEPT – IN A FEW YEARS

- Validate **detection concept** with a small-scale prototype detector
- Develop **event reconstruction technique**

FIRST BALLOON FLIGHT - IN 5-10 YEARS

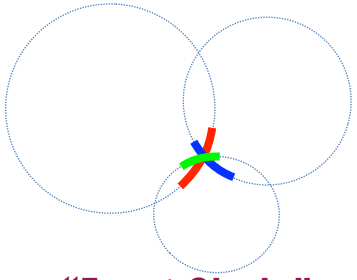
- MeV gamma-ray observations focusing on **bright objects,** nuclear lines
- Antimatter-based **indirect DM search**
  - Possibly detect antideuterons from DM in the first flight
  - Investigate Fermi/AMS-02 results

TPC DESIGN UPGRADE/DEVELOPMENT - IN 10 YEARS

- Improve energy/position resolutions, event reconstruction
  - Finer pitch of anode wires/pads to **track Compton scattered electrons**
  - Add **calorimeters** to improve the performance of Energy measurement

SATELLITE MISSION - IN > 10 YEARS

- **All sky survey** in the MeV energy domain
  - MeV gamma-rays from NS-NS mergers
  - Cosmic MeV gamma-ray background
- Antimatter-based (including **antihelium**) DM search



"Event Circle" becomes "Event Arc"

SUMMARY

- GRAMS is the first experiment to target both **gamma-ray observations** in the poorly explored **MeV energy band** and **antimatter-based dark matter search.**
- 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.
- GRAMS antineutron measurements can provide an **essentially background-free** dark matter signature while deeply investigating and validating the possible dark matter detection indicated in **Fermi GCE** and **AMS-02 antiproton** measurements.
- The project is currently in the **R&D phase** and will demonstrate the detection concept using a small-scale prototype detector.
- Project will then become a **balloon-borne** experiment, as a step forward to a **satellite** mission with detector upgrades.