IPMU
APEC Seminar

July 22nd
2019

THE GRAMS PROJECT

DUAL MEV GAMMA-RAY AND DARK MATTER OBSERVATORY

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 GAPS and 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

GRAMS Current Status and Future Prospects

- R&D Program
- Application to other fields

Summary

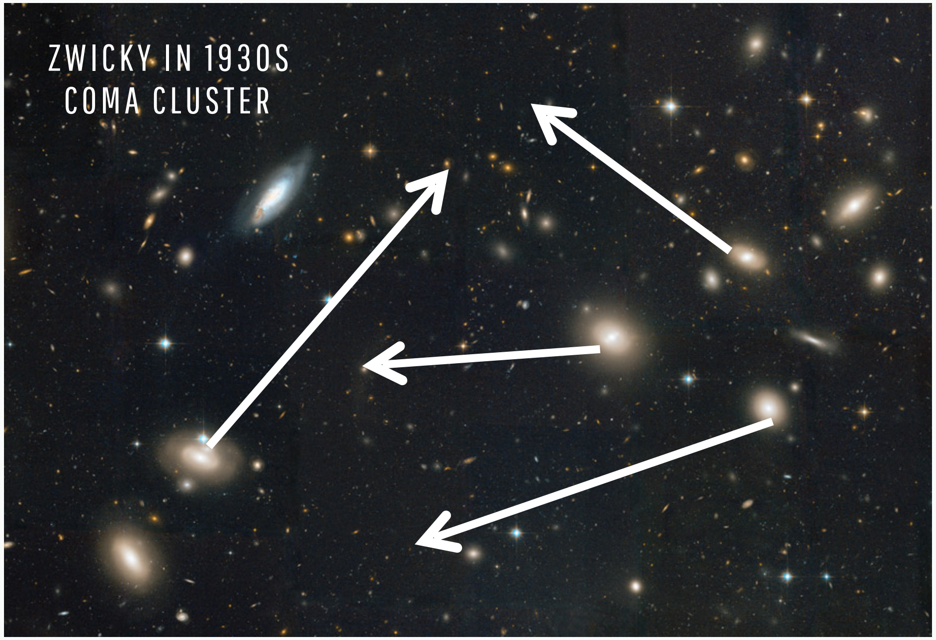
GRAMS First Paper: arXiv:1901.03430
Accepted in Astroparticle Physics
Aramaki et al., 2019

DARK MATTER SEARCH

DARK MATTER IN ASTROPHYSICAL PHENOMENA

EVIDENCE FOR DARK MATTER

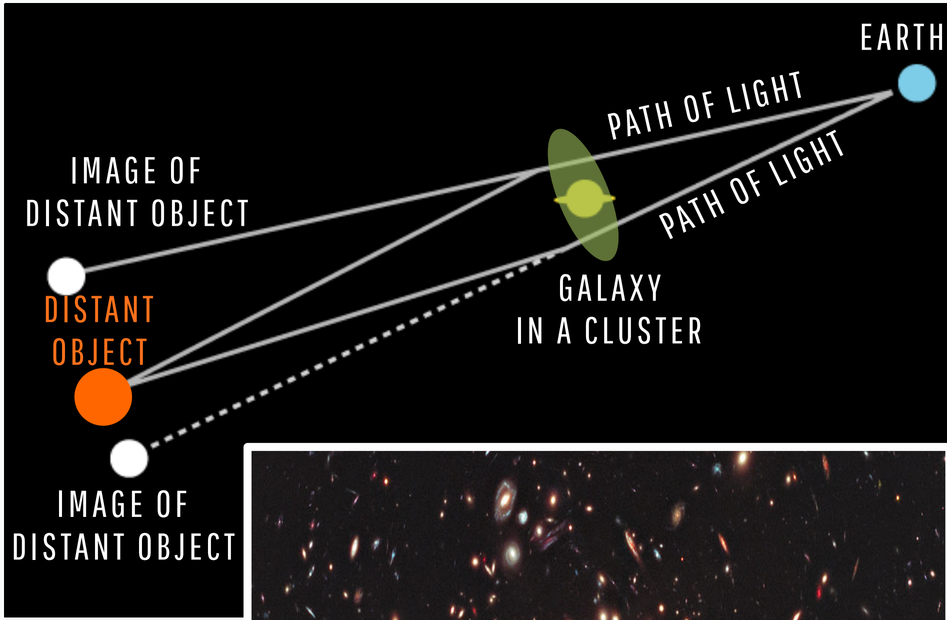
GALAXY CLUSTERS



GALAXIES MOVING TOO FAST!

INVISIBLE/MISSING MASS FOR HIGH VELOCITY

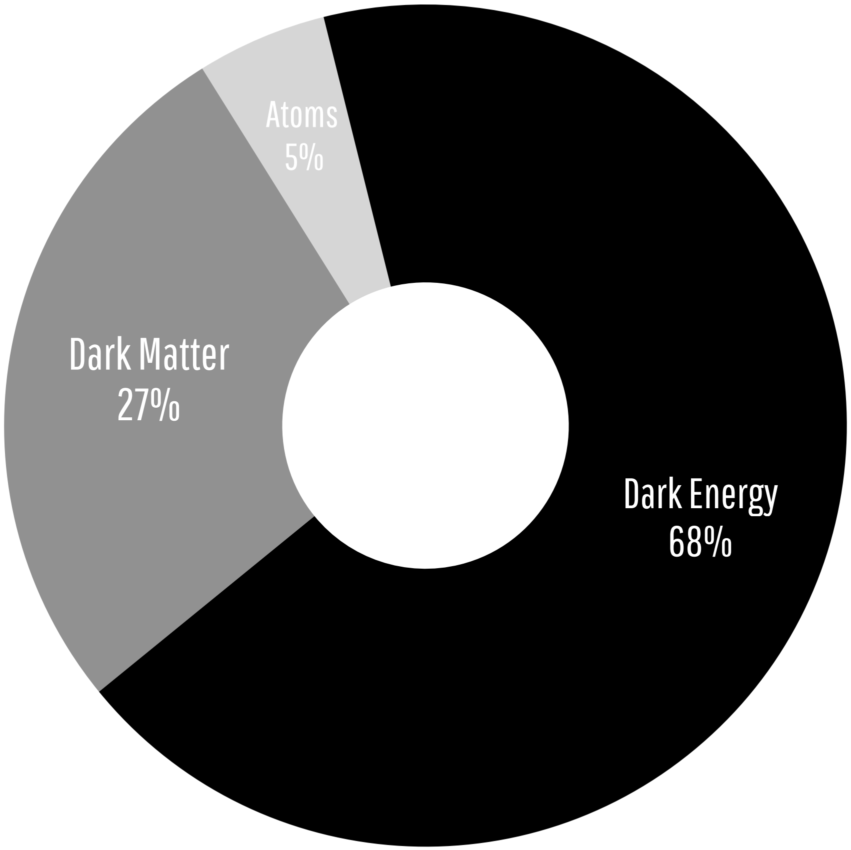
GRAVITATIONAL LENSING



INVISIBLE/MISSING MASS FOR DISTORTED FIELD

INVISIBLE/MISSING MASS = DARK MATTER

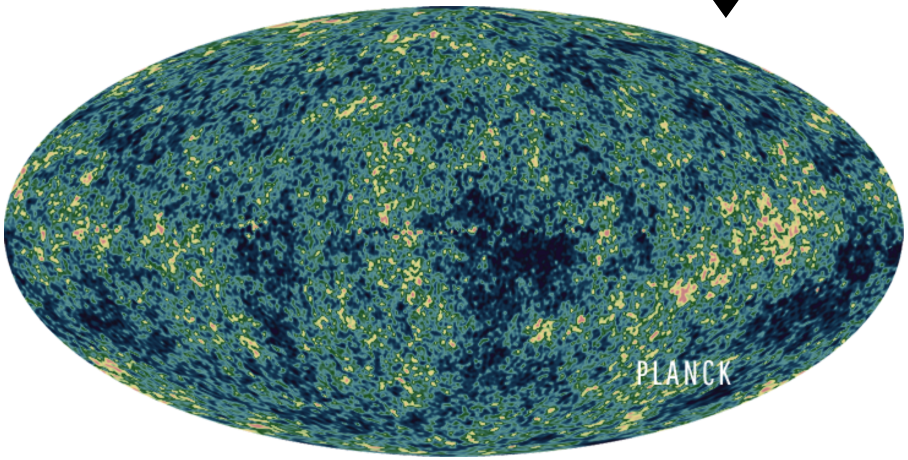
COMPOSITION OF THE UNIVERSE



COSMIC MICROWAVE BACKGROUND

SNAPSHOT OF THE EARLY UNIVERSE
when electrons and protons were recombined

NO DM, NO LIFE.



TEMPERATURE FLUCTUATION PROVIDES
COMPOSITION/EVOLUTION OF THE UNIVERSE

27% OF OUR UNIVERSE IS DARK MATTER (DM)

Large scale structure and galaxy clusters were created
by dark matter density fluctuation in early universe

DARK MATTER PROFILE

ASTROPHYSICAL PHENOMENA INDICATE THAT DM SHOULD BE:

1) LONG LIFETIME

Stable particle on galactic time scale

Otherwise DM wouldn't be seen in Astrophysical phenomena

2) VERY SMALL INTERACTION WITH NORMAL MATTER

Or else DM would have been easily detected long time ago

3) NON RELATIVISTIC (SLOW)

Otherwise there would be lower density fluctuation in the early universe and less large scale structures in the present

VARIOUS DM MODELS ARE PROPOSED TO EXPLAIN ASTROPHYSICAL PHENOMENA

POPULAR DARK MATTER CANDIDATES (M>10 GEV)

WEAKLY INTERACTING MASSIVE PARTICLE = WIMP (> 10 GeV)

(I) THERMAL (CHEMICAL) EQUILIBRIUM

IN EARLY UNIVERSE

SM = Standard Model Particle
DM = Dark Matter Particle

DM DM	⟷	SM SM

MIXED IN HOT SOUP

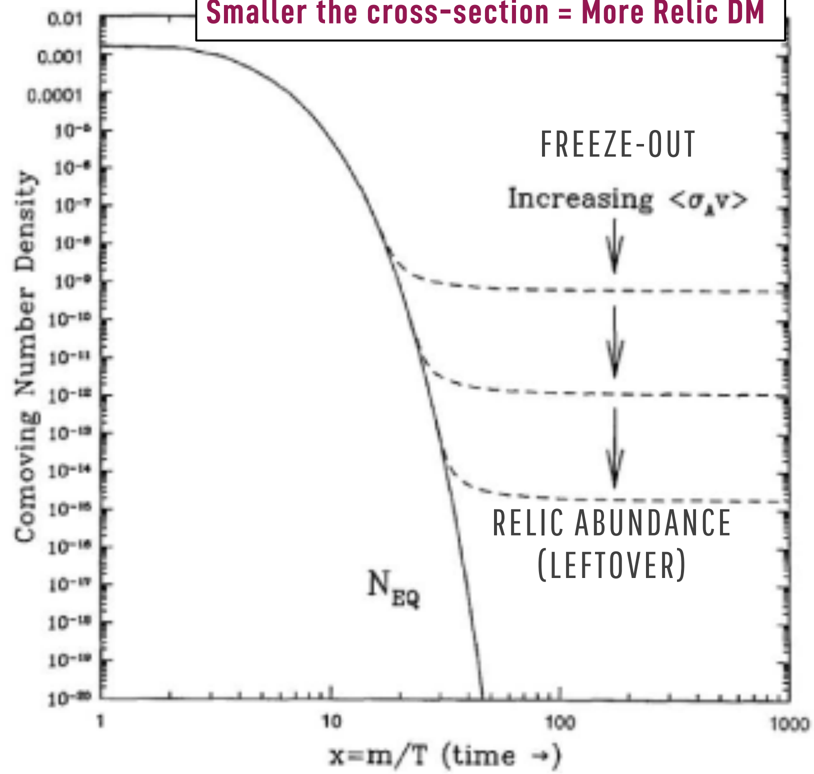
(II) UNIVERSE EXPANDED AND COOLED DOWN

LEFTOVER	DM DM	⊘	SM SM

ISOLATED THEN
DM IS FROZEN OUT

DM Relic Abundance

Larger the cross-section = Less Relic DM
Smaller the cross-section = More Relic DM



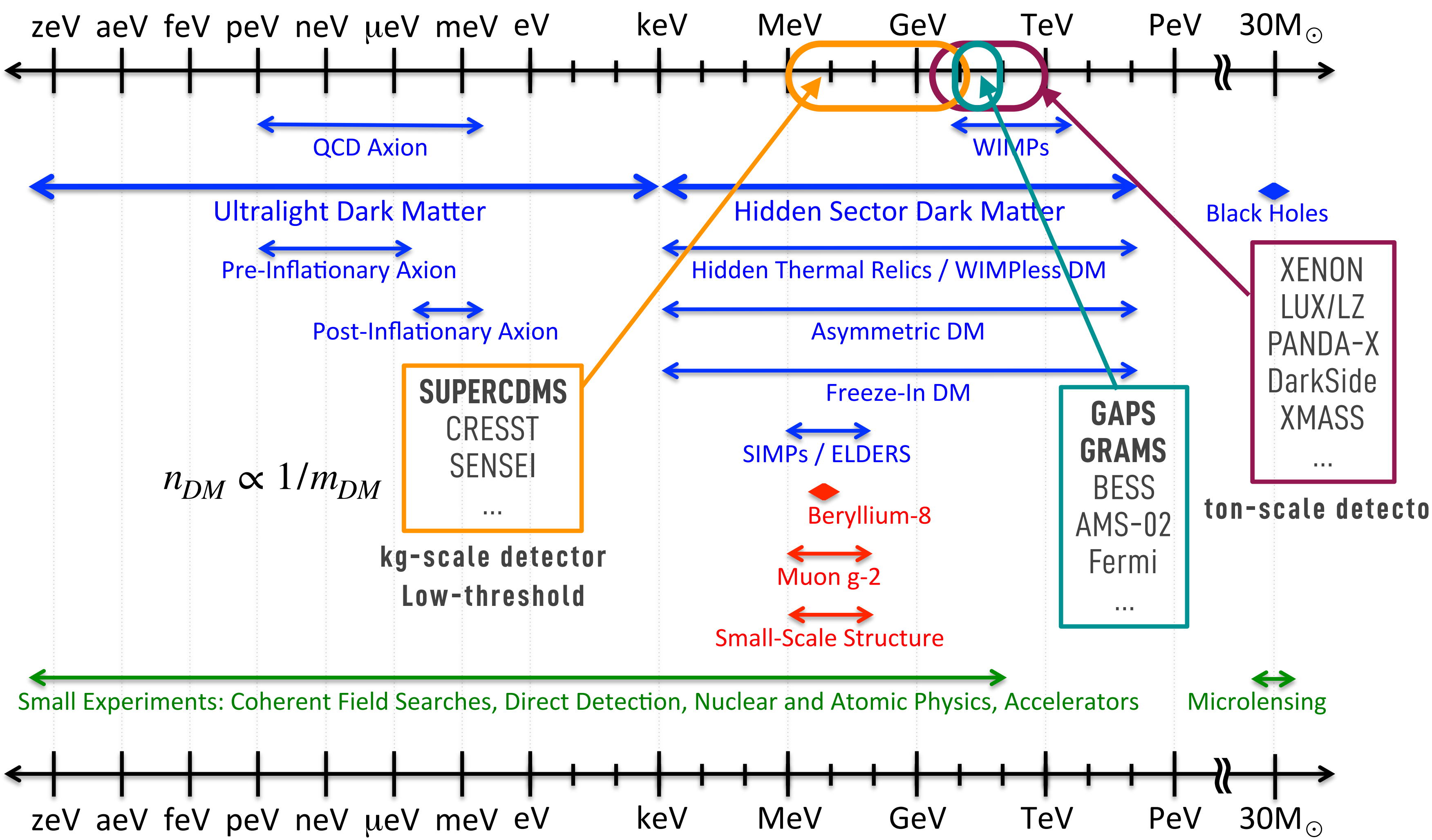
WIMP weak-scale interaction cross-section coincidentally gives right dark matter relic abundance seen in astrophysical phenomena

NO SIGNS OF DETECTION IN DM SEARCH → MORE FOCUS ON LOW-MASS DM

OTHER DARK MATTER CANDIDATES

US COSMIC VISIONS 2017 (arXiv:1707.04591)

Dark Sector Candidates, Anomalies, and Search Techniques



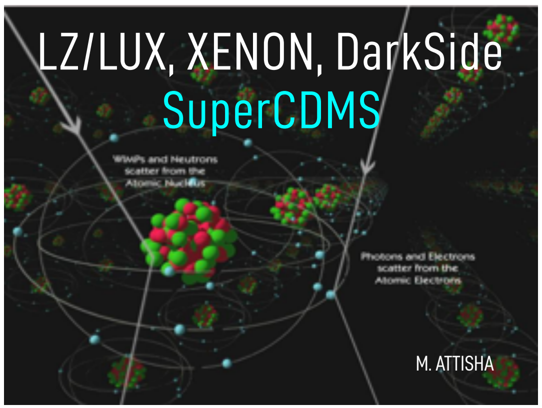
DARK MATTER SEARCHES

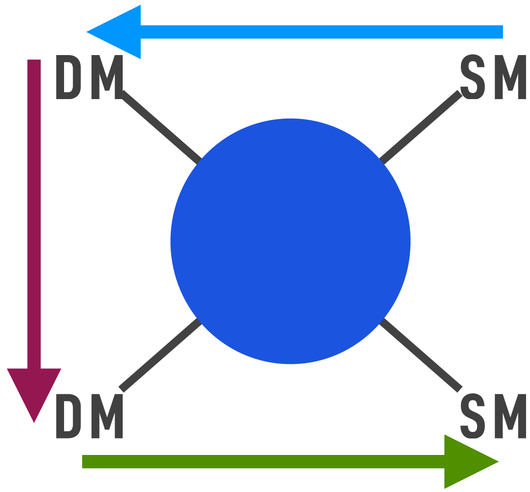
DIRECT DM SEARCH

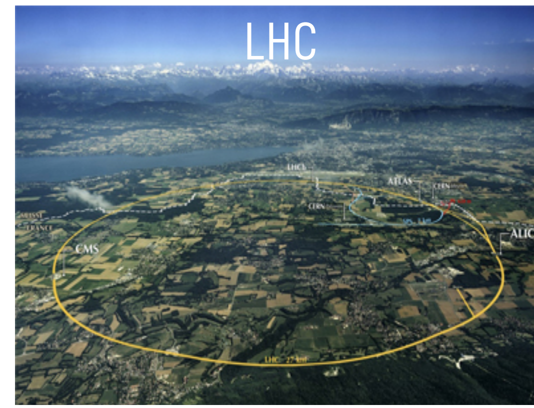
- DM interaction inside the detector
- Measure scintillation, charge, phonon
- Underground lab to minimize cosmic-rays

COLLIDER SEARCH

- Artificially produce DM particles
- Measure missing energy/momentum
- Mono-X search to trigger events

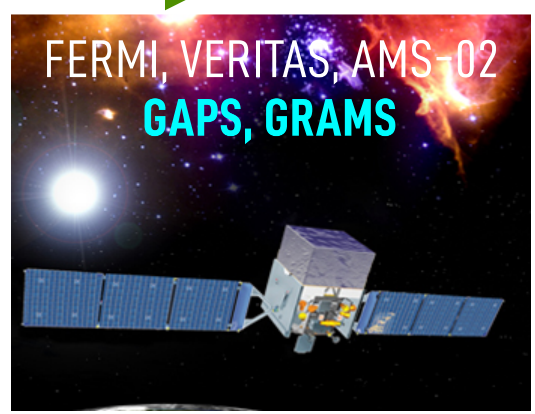






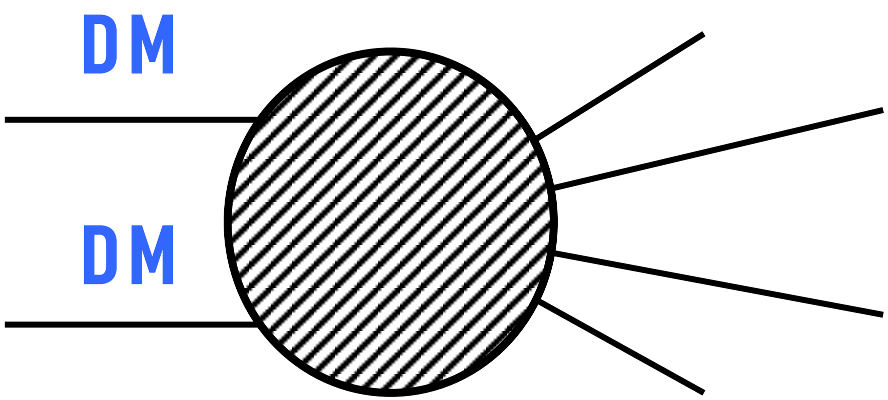
INDIRECT DM SEARCH

- Measure DM annihilation/decay products



COMPLEMENTARY SEARCHES ARE CRUCIAL TO ILLUMINATE THE NATURE OF DM

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**

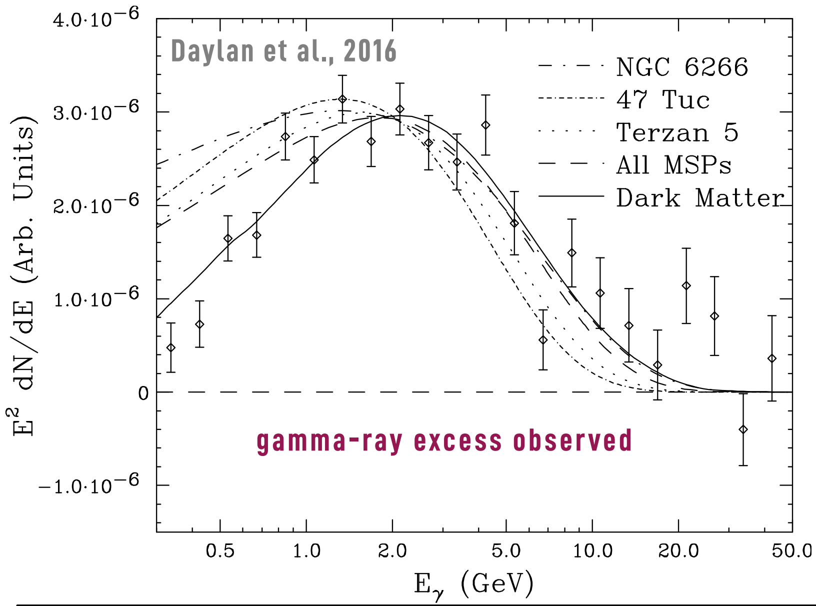
ANTIHELIUM:
AMS-02, **GRAMS**

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

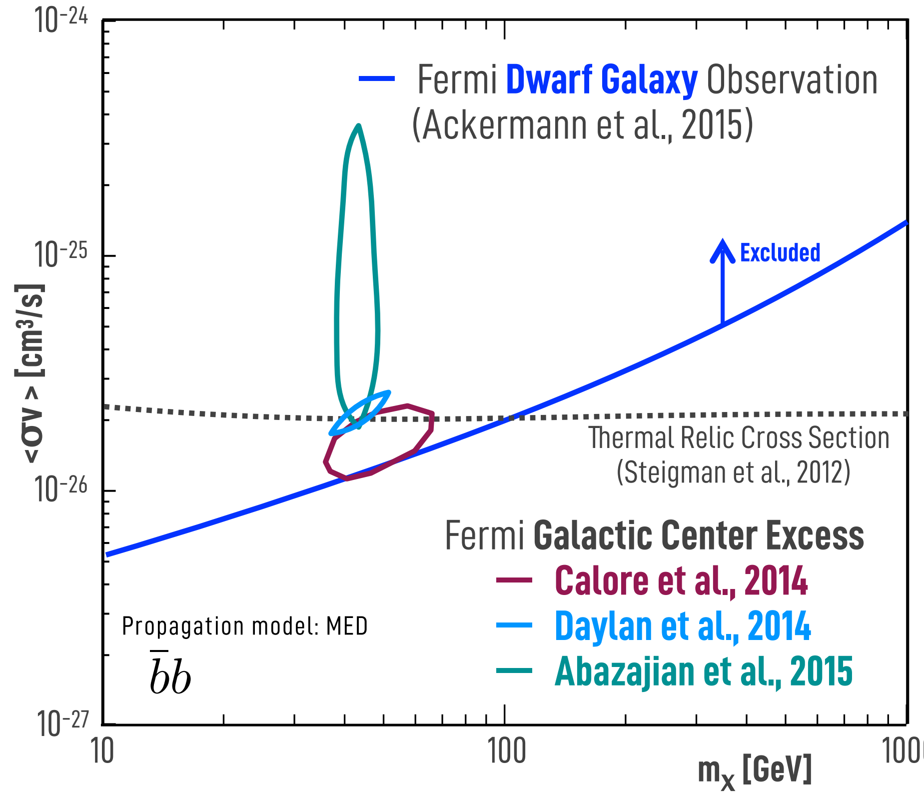
RECENT RESULTS FROM FERMI-LAT

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)



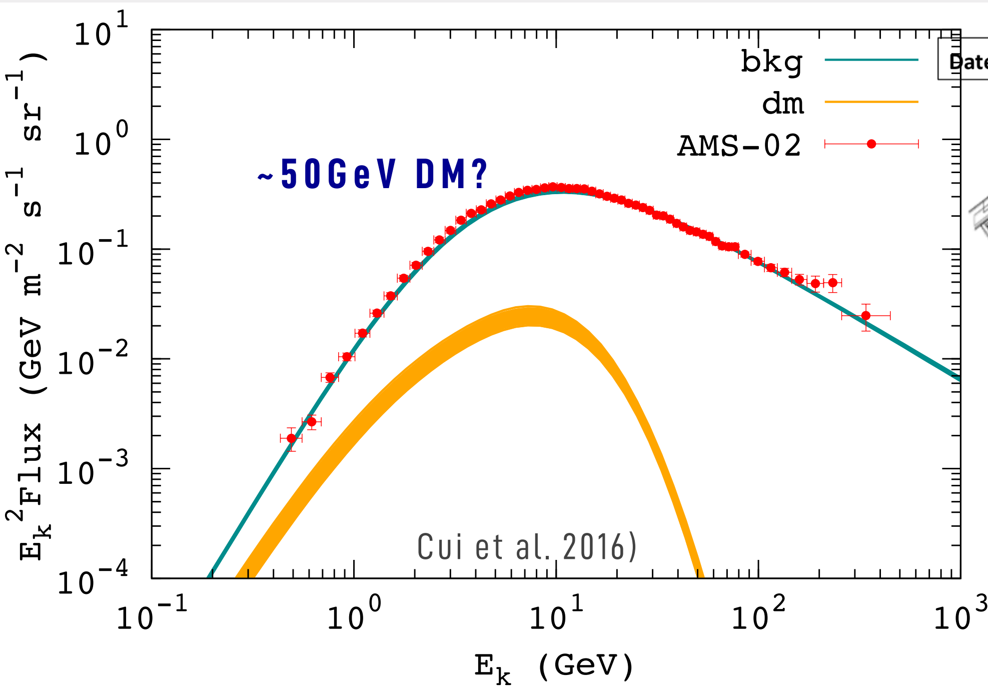
FERMI GALACTIC CENTER EXCESS (GCE)
~50GeV DM or **astrophysical objects**?

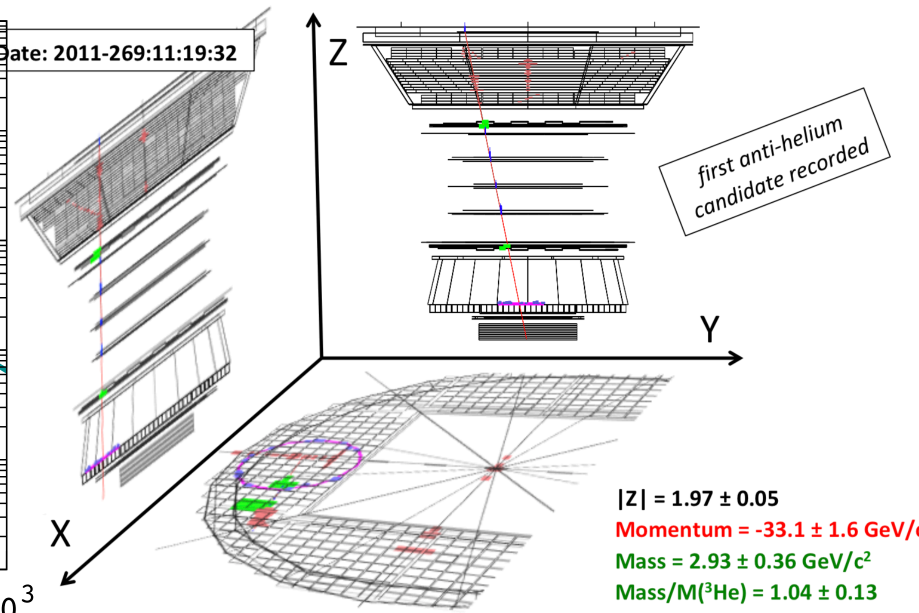


DIFFICULT TO VERIFY DM SIGNATURES DUE TO MIMIC SIGNAL FROM BACKGROUND
NEED A NEW APPROACH/EXPERIMENT TO VALIDATE THE RESULTS

Launched in May 2011, targeting cosmic-rays including antiparticles

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





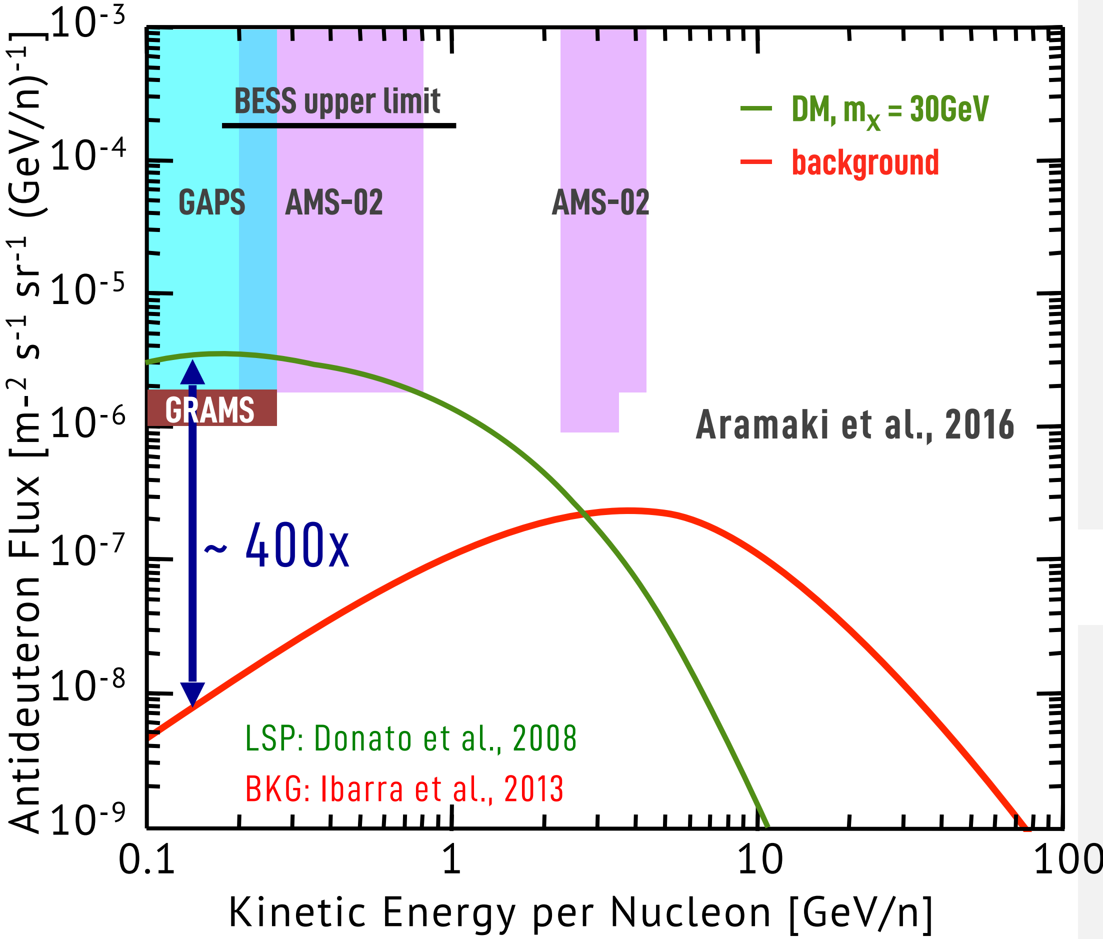
So far, 6 $^3\overline{\mathrm{He}}$, 2 $^4\overline{\mathrm{He}}$ candidate events reported

- 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

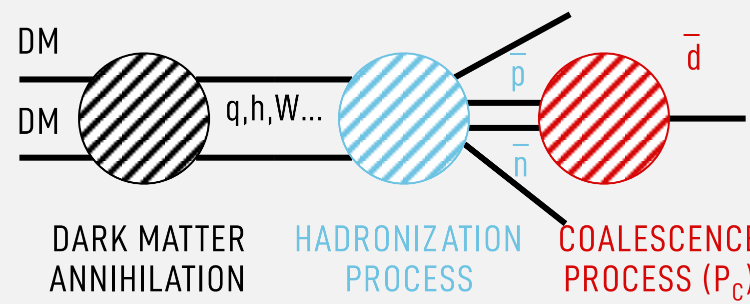
WHY ANTIDEUTERONS?

BACKGROUND-FREE DM SEARCH AT LOW-ENERGY



PRIMARY FLUX

DM ANNIHILATION/DECAY



SECONDARY FLUX

COSMIC RAY INTERACTION

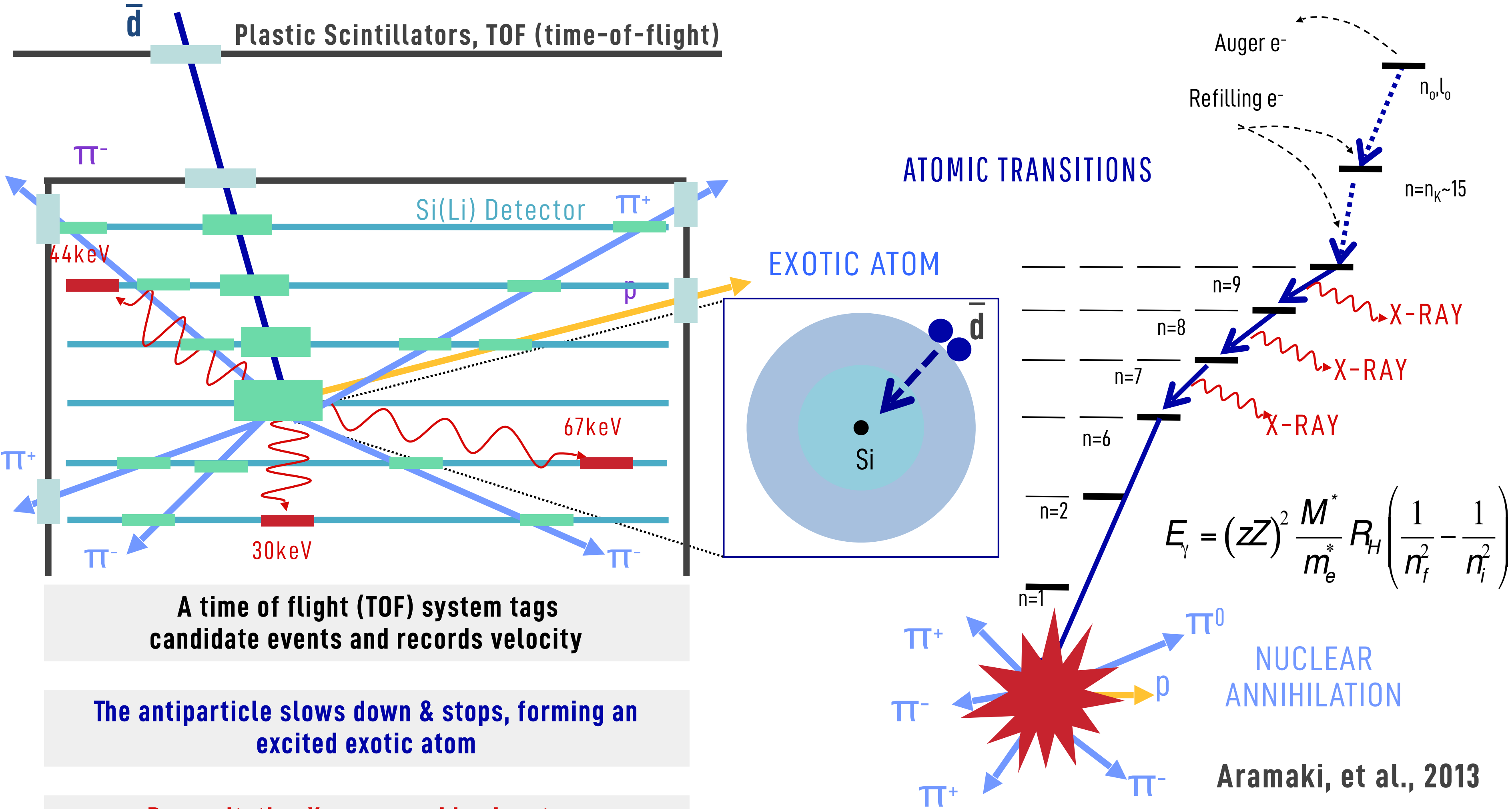
$$p\ (CR) + H\ (ISM) \rightarrow p + H + p + n + \underbrace{\bar{p} + \bar{n}}_{\bar{d}}$$

GAPS FIRST SCIENCE FLIGHT IS SCHEDULED FROM ANTARCTIC IN 2021

GRAMS: NEXT GENERATION EXPERIMENT

GAPS/GRAMS DETECTION CONCEPT

MEASURE ATOMIC X-RAYS AND ANNIHILATION PRODUCTS



Aramaki, et al., 2013

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

Concept proven with accelerator beam test
X-ray yields measured with different targets
Cascade model developed to predict X-ray yields

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**

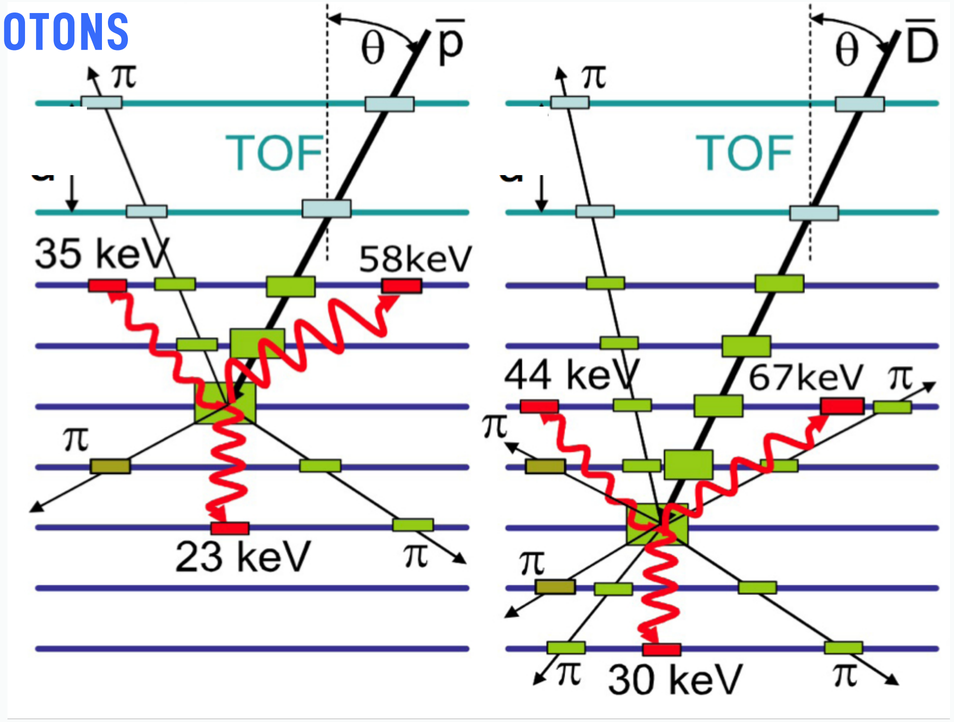
ANTIDEUTERON IDENTIFICATION FROM ANTIPROTONS

atomic X-rays from exotic atom
- different energy

pion/proton multiplicity
- more for antideuterons

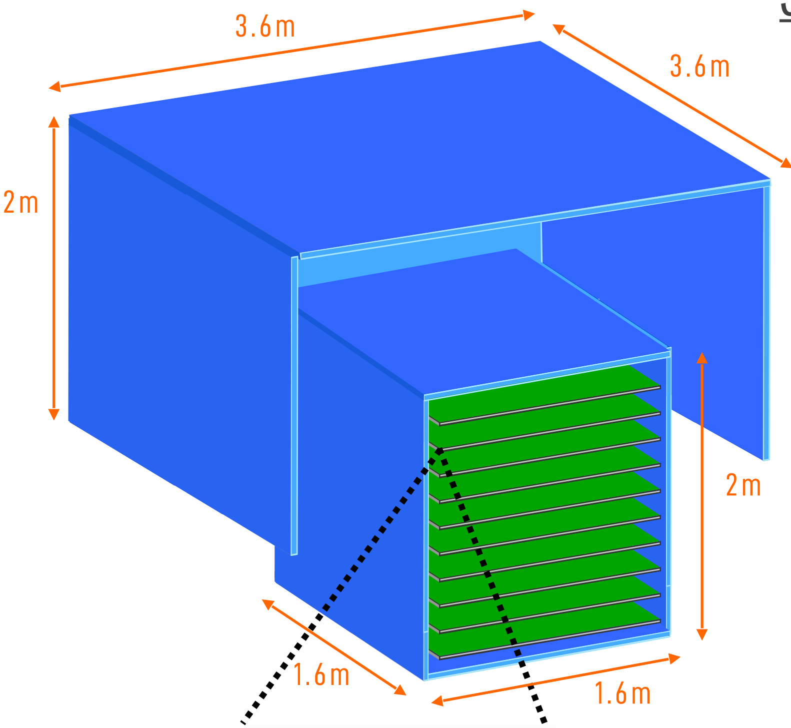
stopping range (depth sensing)
- antideuterons go deeper

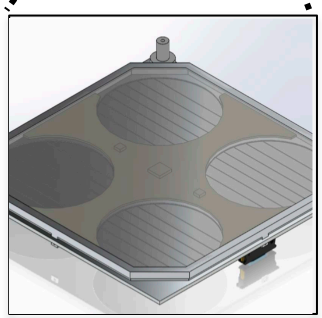
dE/dX energy deposit in layers
- more for antideuterons



EXPECTED BACKGROUND/MIMIC EVENTS ~0.01

GAPS DETECTOR





Si(Li) DETECTOR: 4 inch, 2.5mm thick wafer

- 10 layers, about 140 Si(Li) detectors/layer
- Segmented into 8 strips
  >3D particle tracking
- Energy/timing resolution: 4 keV, ~100 ns
- Operation temperature: -40C
  cooled with oscillating heat pipe (OHP)
- Dual channel electronics
  20-80 keV: X-rays
  0.1-50MeV: charged particles

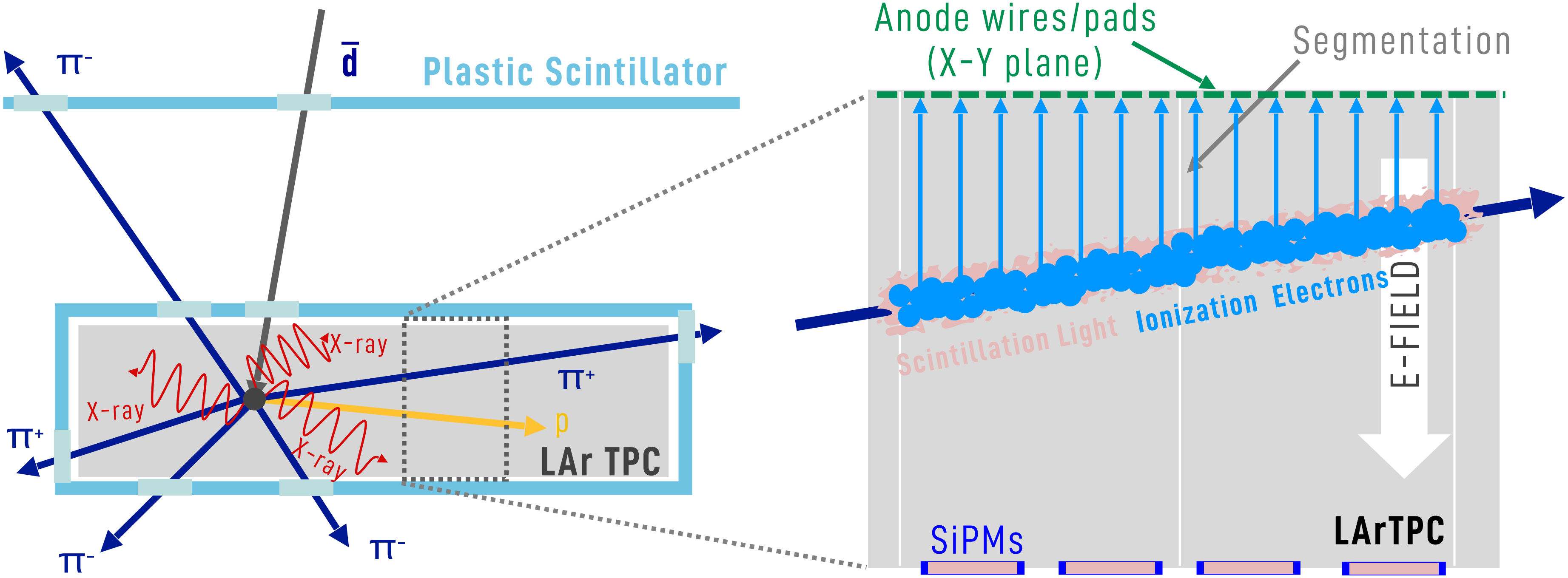
TOF PLASTIC SCINTILLATORS: 18cm x 1.6m x 5mm

- Identify incoming charged particles
- 1m separation between inner/outer TOF
- Timing resolution: 0.5ns, SiPMs on each end

WELL-STUDIED, WIDELY-USED SI(LI) AND PLASTIC SCINTILLATORS SUCCESSFULLY DEMONSTRATED THE PERFORMANCE IN THE ENGINEERING FLIGHT

GRAMS DETECTOR

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



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

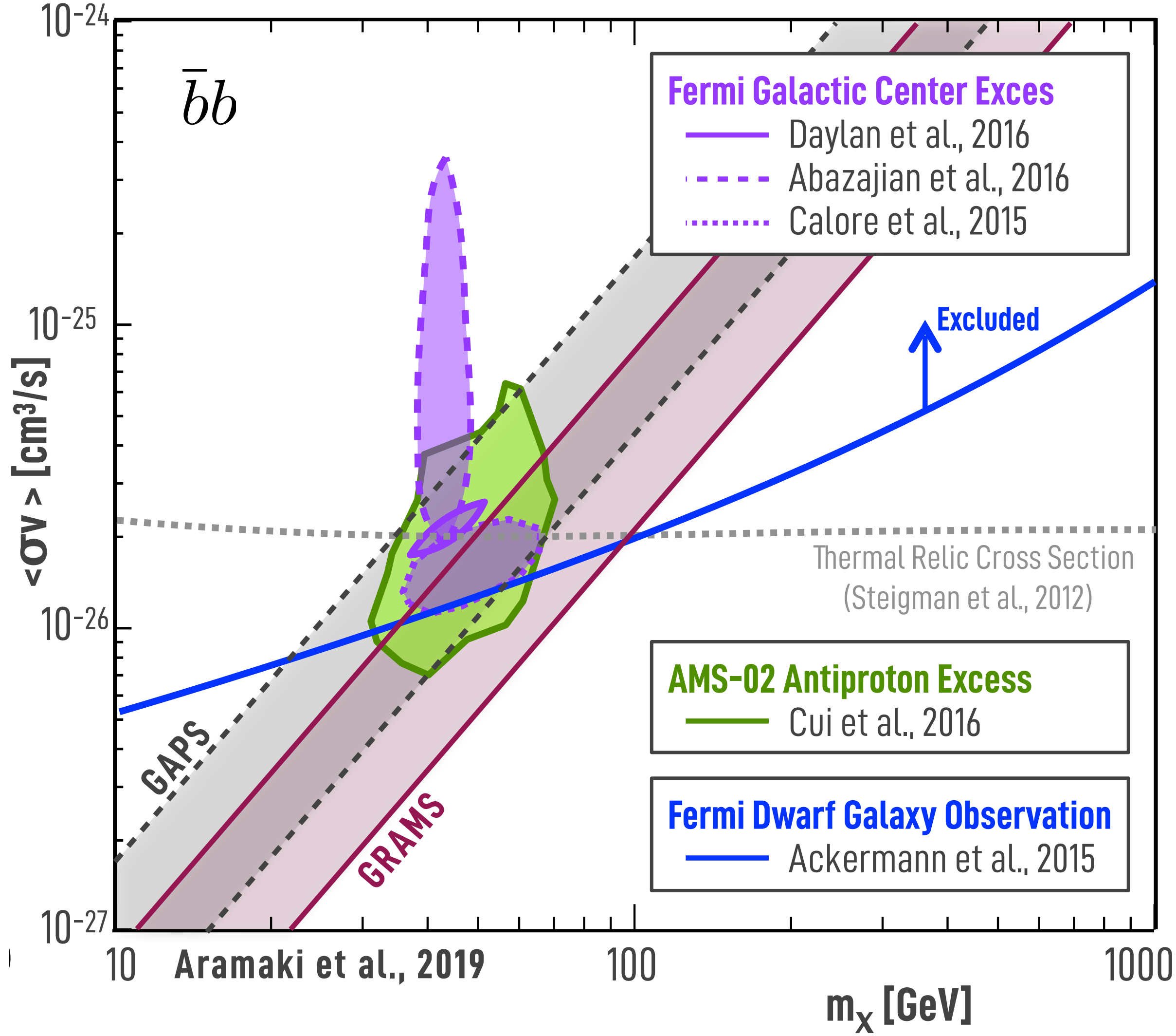
LArTPC: **Calorimeter** and **particle tracker**

- 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

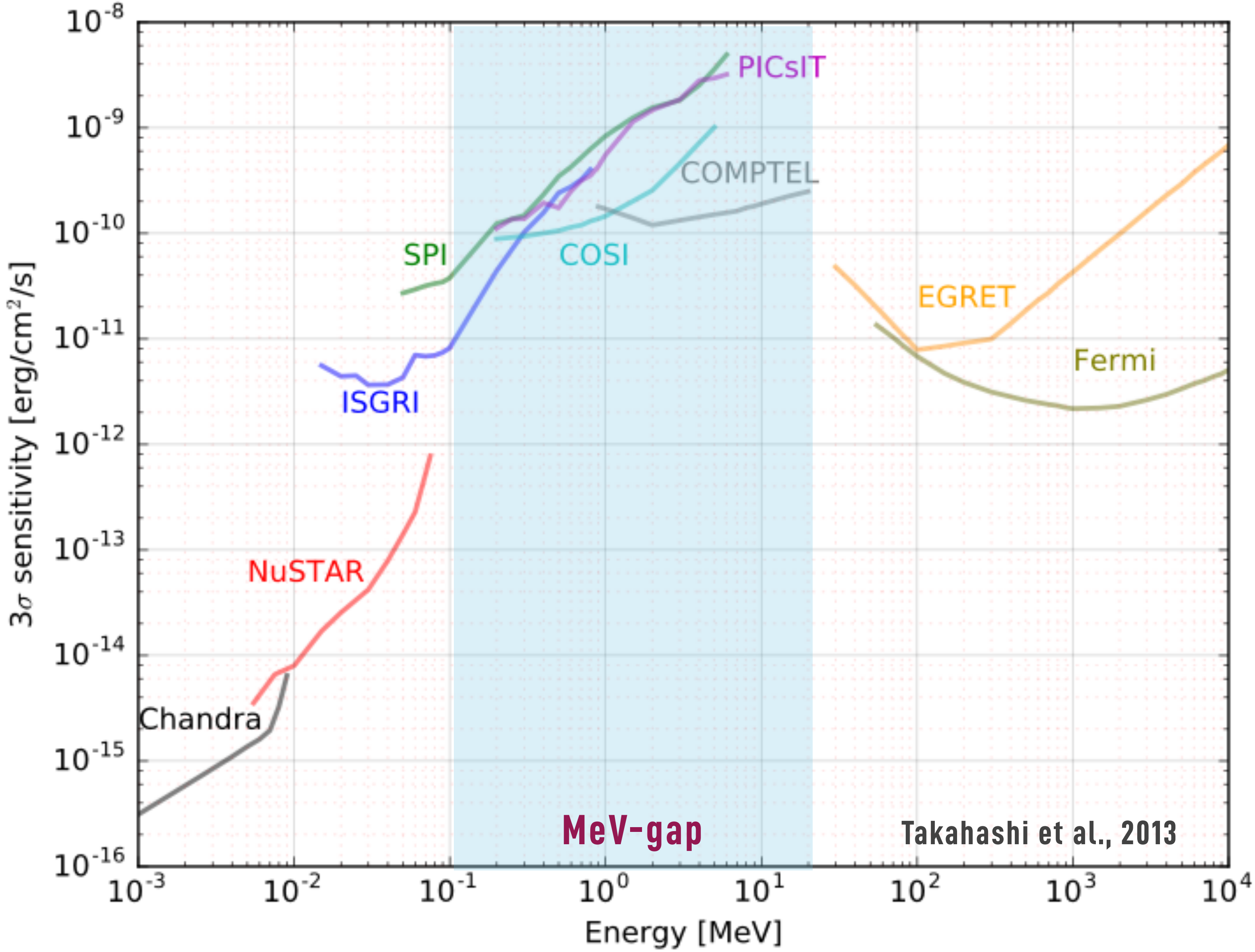
GRAMS COULD FULLY INVESTIGATE FERMI GCE AND AMS-02 ANTIPROTON EXCESS

CURRENTLY EVALUATING GRAMS ANTIHELIUM SENSITIVITY

MEV GAMMA-RAY OBSERVATION

CURRENT STATUS OF MEV GAMMA-RAY OBSERVATIONS

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

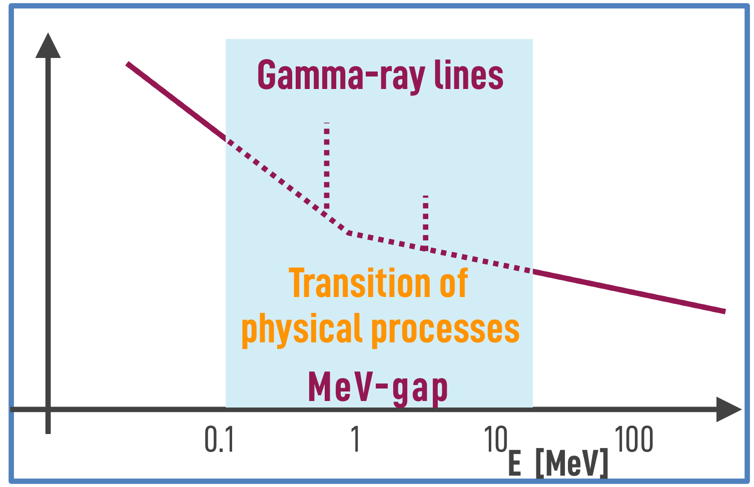


MEV GAMMA-RAY SCIENCE

ASTROPHYSICAL OBJECTS

- Neutron stars: high matter density
- Magnetars: strong magnetic field
- AGNs/Blazars: powerful jets
- Cosmic MeV gamma-ray background

Inoue et al., 2019



GAMMA-RAY LINE STUDY

- Positron annihilation: 511 keV
- Nuclear lies are typically in ~MeV
- Radioactive isotopes provide physical condition during nucleosynthesis
  - Core-collapse SNe: ^{26}Al (1809keV), ^{60}Fe (1173keV, 1333keV), ^{44}Ti (1157keV)
  - Thermonuclear SNe: ^{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 neutron star mergers/remnants

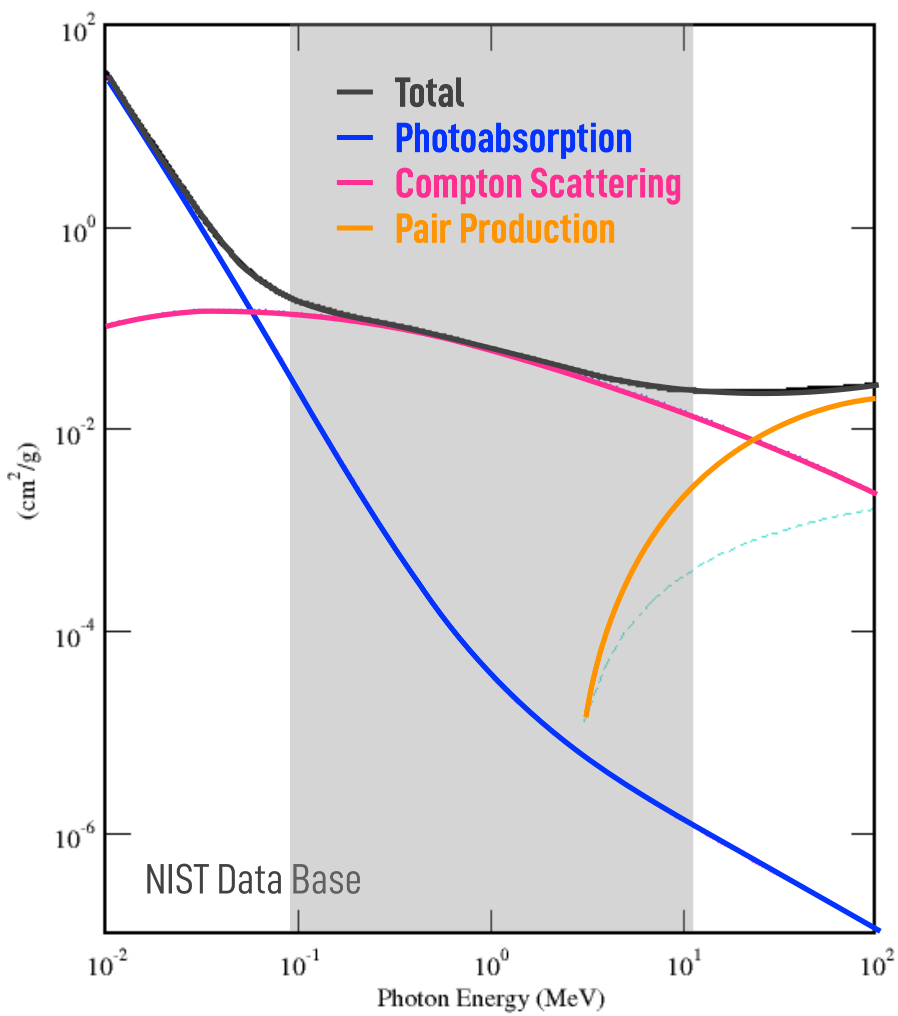
Wu et al., 2019

DARK MATTER SEARCH

- MeV gamma rays from DM annihilation

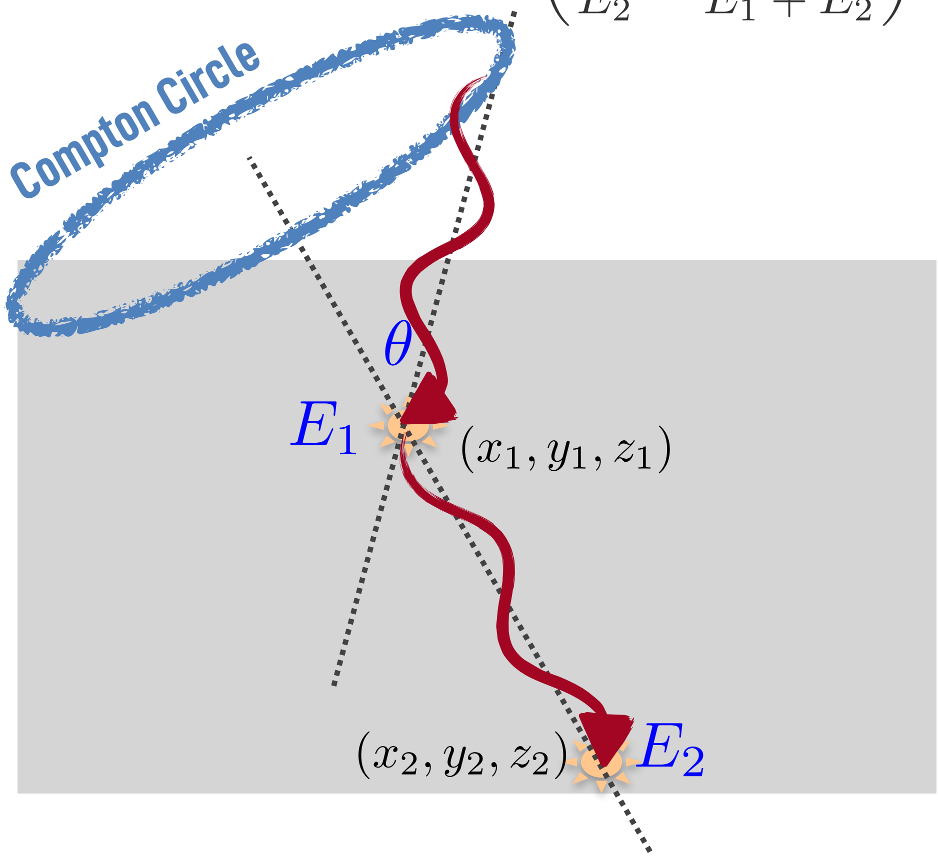
WHY IS IT DIFFICULT TO MEASURE MEV GAMMA-RAYS?

- **Compton scattering** dominates in the MeV energy region
- Both **energy** & **position** resolutions need to be good for event reconstruction
  - Challenging to have a **large-scale** detector



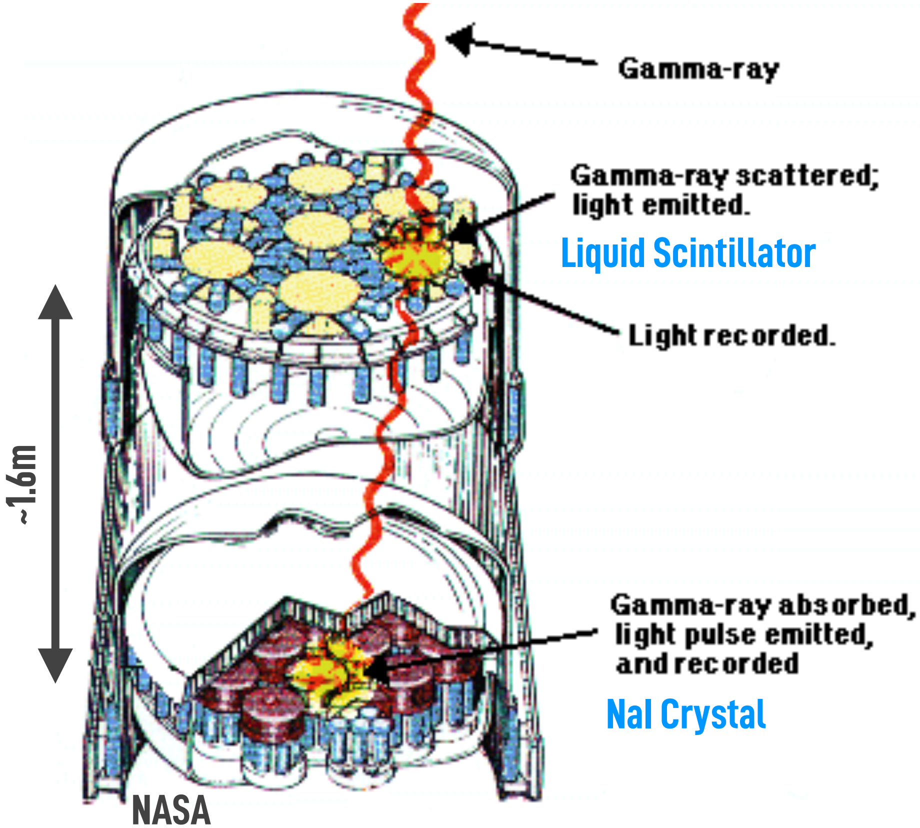
$$E = E_1 + E_2$$

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



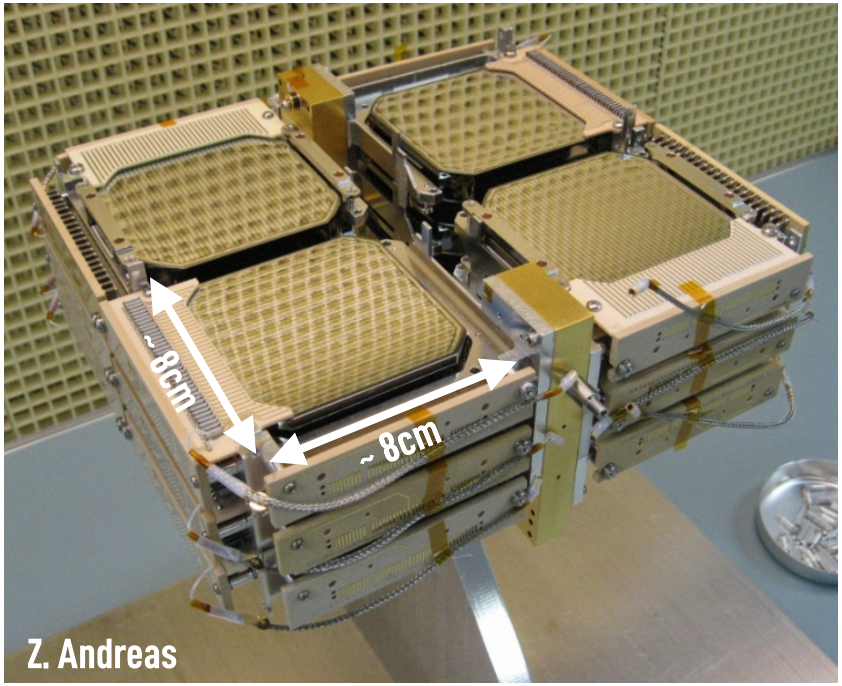
PREVIOUS EXPERIMENTS: COMPTEL AND COSI

COMPTEL
(The Imaging Compton Telescope)



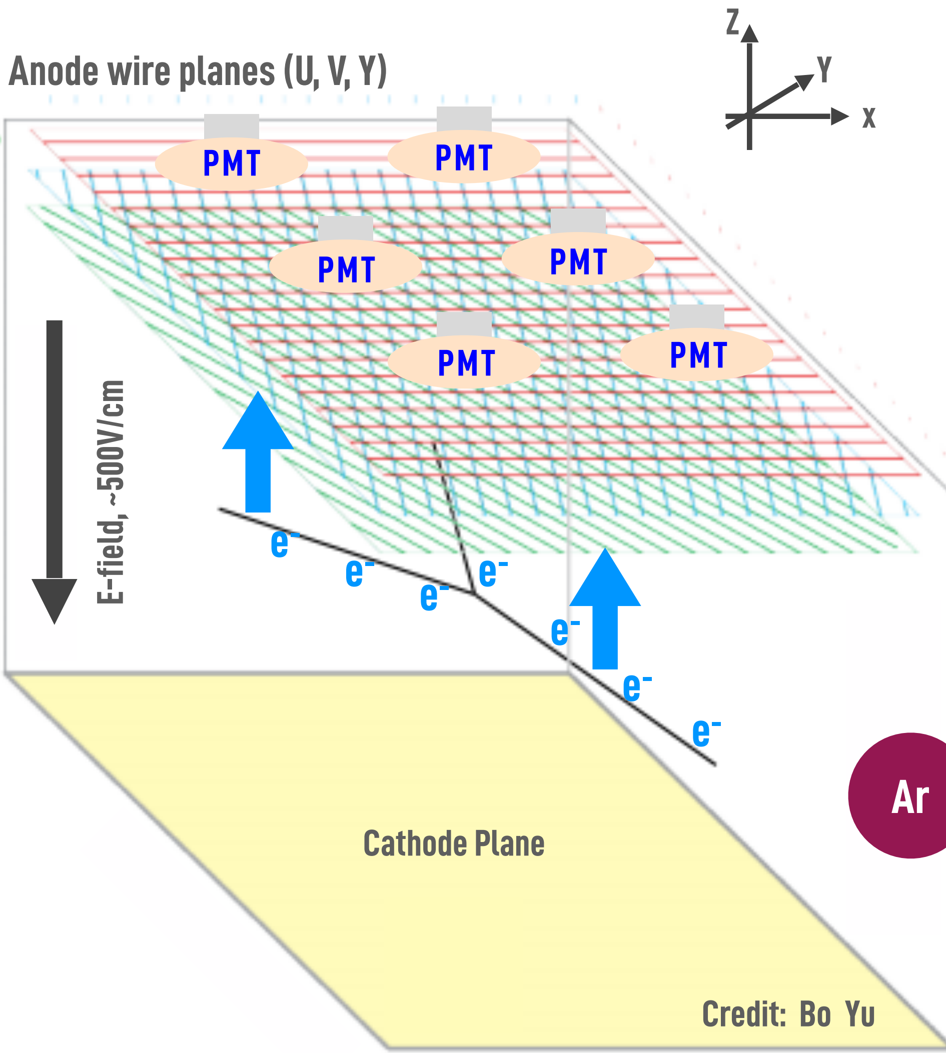
- launched into space in 1991
- installed on Compton Gamma-Ray Observatory
- energy range: 0.75 - 30 MeV
- spacial resolution: ~ 40cm^3
- Detected ~30 sources

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

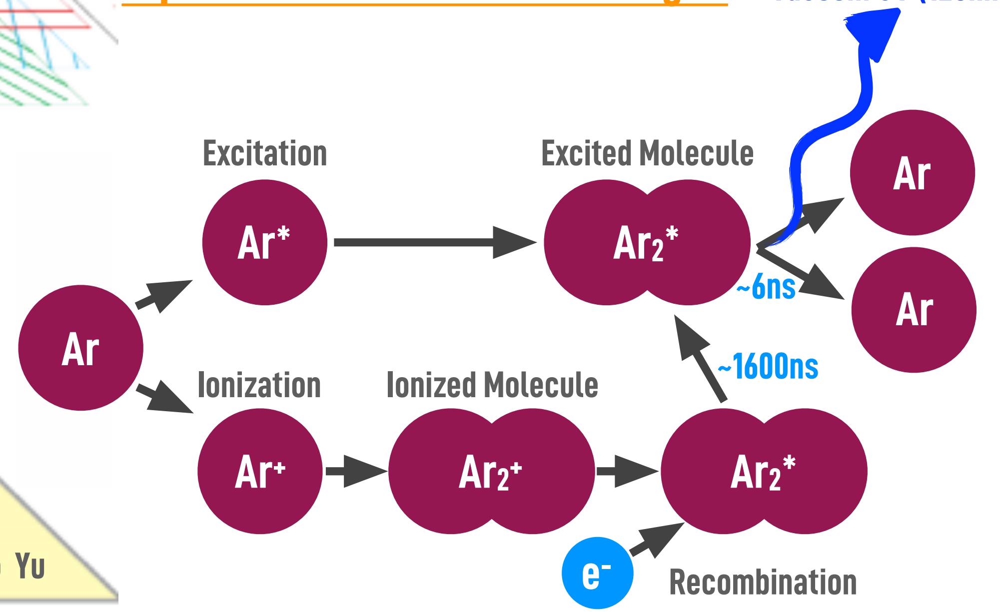
LArTPC DETECTORS HAVE BEEN WELL-STUDIED AND WIDELY-USED FOR LARGE-SCALE NEUTRINO/DARK MATTER SEARCH EXPERIMENTS



3D particle tracking in LArTPC

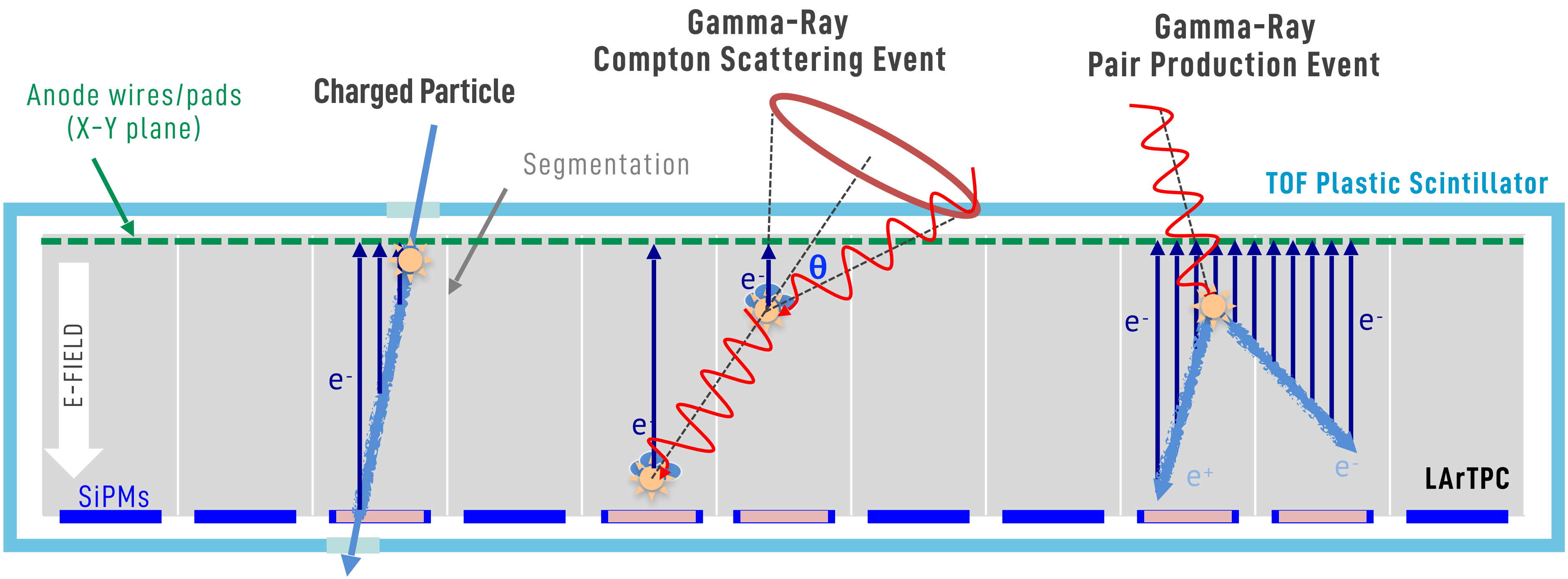
- Measure both scintillation light and ionization electrons
- Scintillation light is detected in PMTs
- Ionization electrons drift and are collected in anode wire planes

2 paths for scintillation light



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)

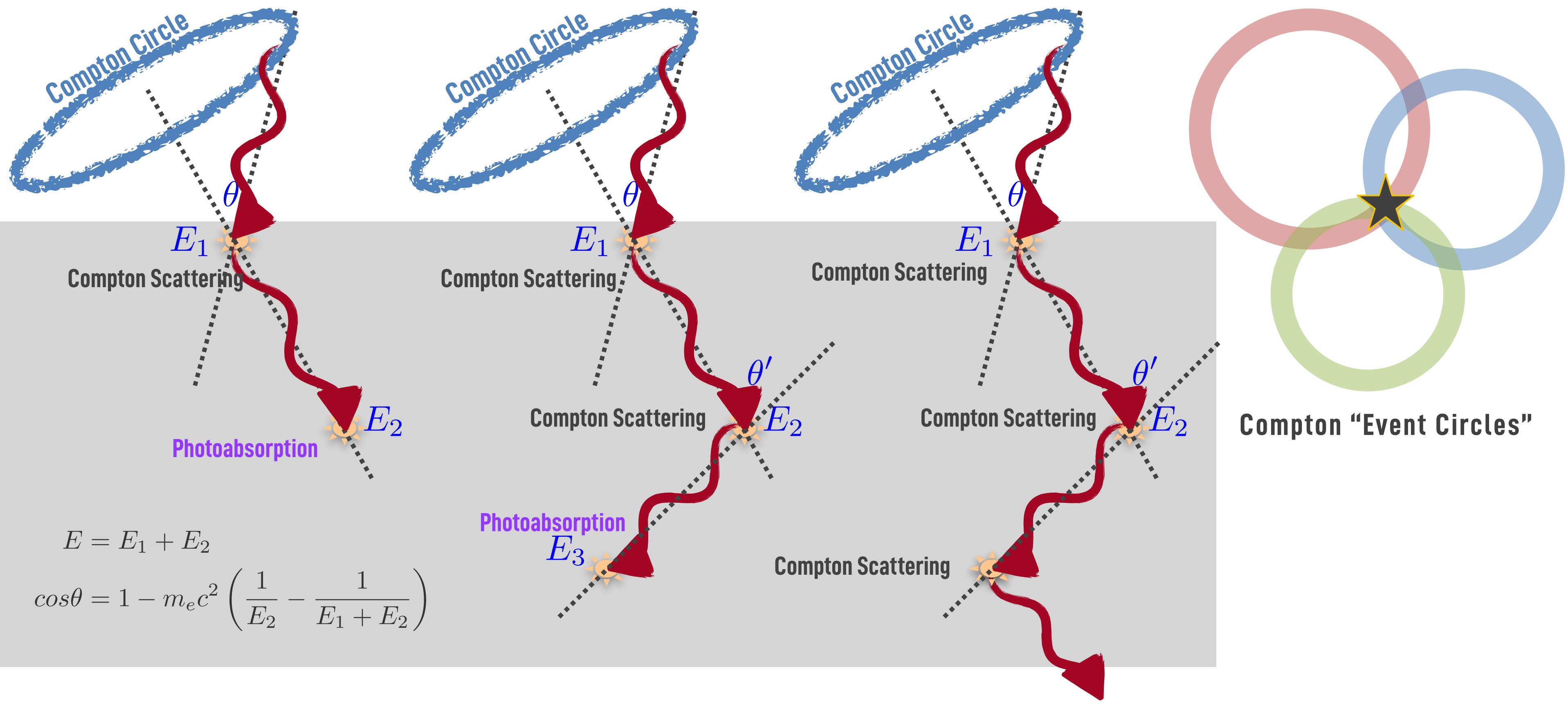
- Scintillation light at **SiPMs to trigger events**
- Wires/pads on anode plane (X, Y), drift time (Z) to provide a **3D image/track**

Signal localized by segmentation to reduce coincident background

Neutron events can be separated based on the pulse shape

EVENT RECONSTRUCTION FOR COMPTON SCATTERING

One Compton Scattering + Photoabsorption | **Two Compton Scatterings + Photoabsorption** | **Three Compton Scatterings + Escaping Photon**



$$E = E_1 + E_2$$

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

$$E = E_1 + E_2 + E_3$$

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

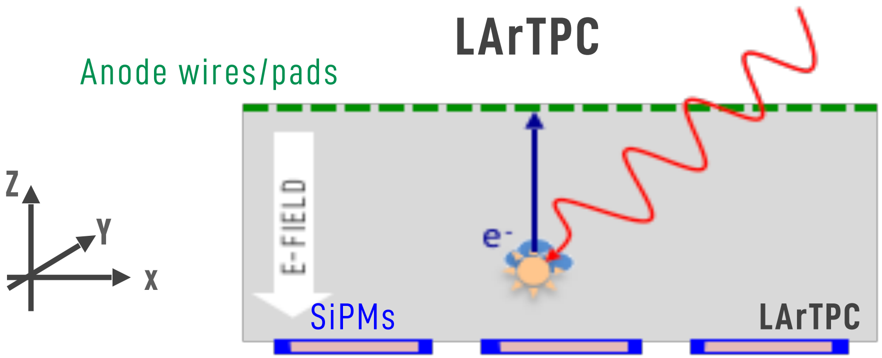
$$cos\theta' = 1 - m_e c^2 \left(\frac{1}{E_3} - \frac{1}{E_2 + E_3}\right)$$

$$E = E_1 + E_2 + E_3'$$

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

$$E_3' = -\frac{E_2}{2} + \sqrt{\frac{E_2^2}{4} + \frac{E_2 m_e c^2}{1 - cos\theta'}}$$

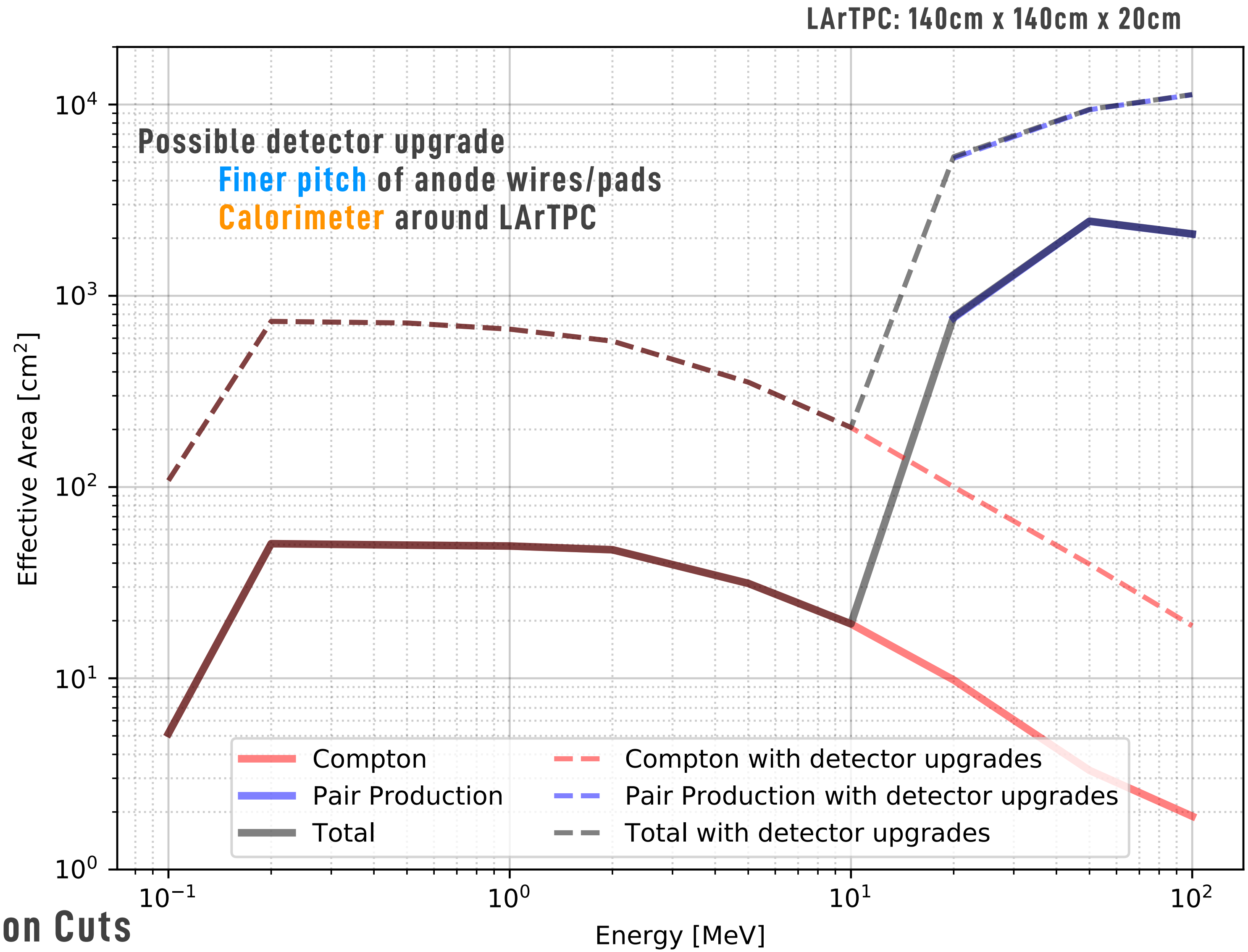
LARTPC VS. SEMICONDUCTOR DETECTOR



	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

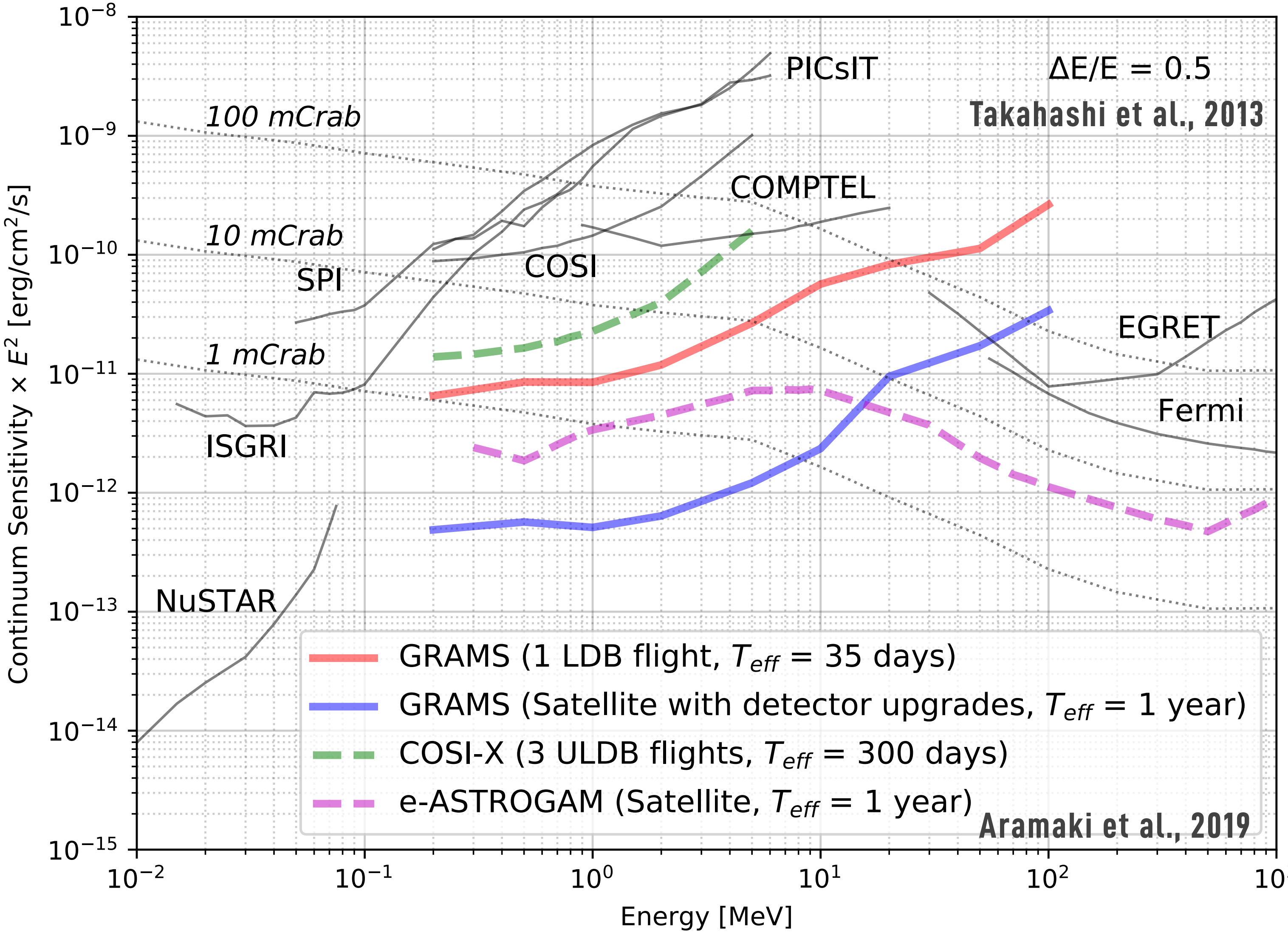
GRAMS EFFECTIVE AREA



Selection Cuts

- **Compton scattering**: interaction points should be separated by > 10cm
- **Pair production**: both e^+ and e^- should stop within detector, leave tracks > 2cm

GRAMS MEV GAMMA-RAY CONTINUUM SENSITIVITY



SINGLE BALLOON FLIGHT: AN ORDER OF MAGNITUDE IMPROVED

SATELLITE MISSION: COMPARABLE (BETTER) TO FUTURE MISSIONS

CURRENT STATUS AND FUTURE PROSPECTS

GRAMS COLLABORATION

Tsuguo Aramaki, SLAC
GAPS, SuperCDMS
GRAMS antimatter search

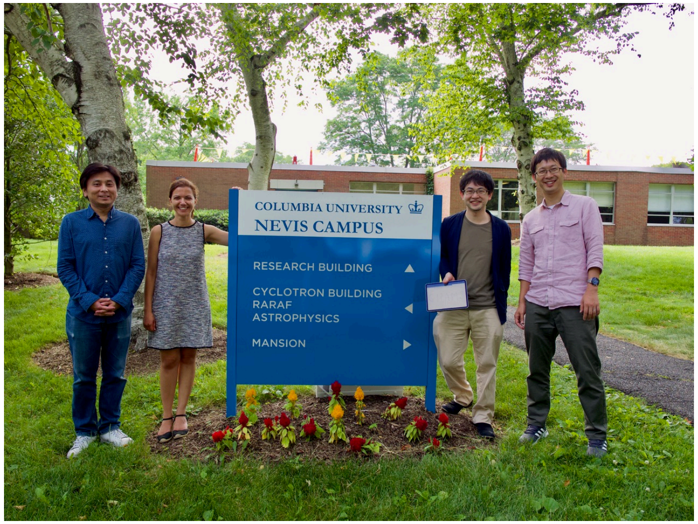
Hirokazu Odaka, U of Tokyo
Astro-H, Suzaku
GRAMS event reconstruction

Georgia Karagiorgi, Columbia U
MicroBooNE, SBND, DUNE
GRAMS LArTPC design

Yoshiyuki Inoue, RIKEN
Astrophysics theorist (AGN etc.)
GRAMS MeV gamma-ray science

Charles Hailey: professor at Columbia U, GAPS PI, NuSTAR Co-I
Pelle Hansson: former SLAC physicist/engineer, ATLAS, SuperCDMS, DUNE

First collaboration meeting in July 2019 at Columbia University, Nevis Lab



Possible Future Collaborations

SLAC **DUNE**, **LZ**, Stanford **nEXO**, MIT/UCLA/UCSD/Hawaii **GAPS**, Columbia theory group ...

TIMESCALE

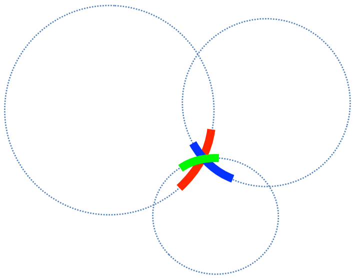
R&D FOR PROOF OF CONCEPT – IN A FEW YEARS

- Validate **detection concept**
- Develop **event reconstruction technique**

Submitted proposals to NASA APRA, SLAC LDRD programs

FIRST BALLOON FLIGHT (STARTING WITH AN ENGINEERING 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



"Event Circle" becomes "Event Arc"

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
- Antimatter-based (including **antihelium**) DM search

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 antideutron measurements can provide **essentially background-free** **dark matter signatures** while deeply investigating and validating the possible dark matter detection indicated in **Fermi GCE** and **AMS-02 antiproton** excess.
- The project is currently in the **R&D phase** and will demonstrate the detection concept using a small-scale prototype detector, **MiniGRAMS**.
- Project will then become a **balloon** experiment, as **a step forward to** a **satellite** mission with detector upgrades.
- GRAMS detector technology can also be **applicable to** other fields, such as **nuclear medicine** and **homeland security**.