Gamma-Ray and AntiMatter survey(GRAMS) experiment

Sep, 2025, USTC seminar

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On behalf of GRAMS collaboration

About me

- ❑Grow up in Chuzhou, Anhui （滁州）
  - ❑ Been to USTC for 30th Chinese Physics Olympiad, CPhO（高中生物理竞赛）
- ❑Physics Undergrade at Sun Yat-sen University(China) 中山大学
- ❑Seventh year grad student at Northeastern department of physics.
- ❑Worked on Bio-Physics for 2 years, designing electronics readout(FPGA).
- ❑Currently working on indirect DM search and comic-ray antinuclei in GAPS and **GRAMS** experiment

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What is GRAMS?

GRAMS = Gamma-Ray and AntiMatter Survey

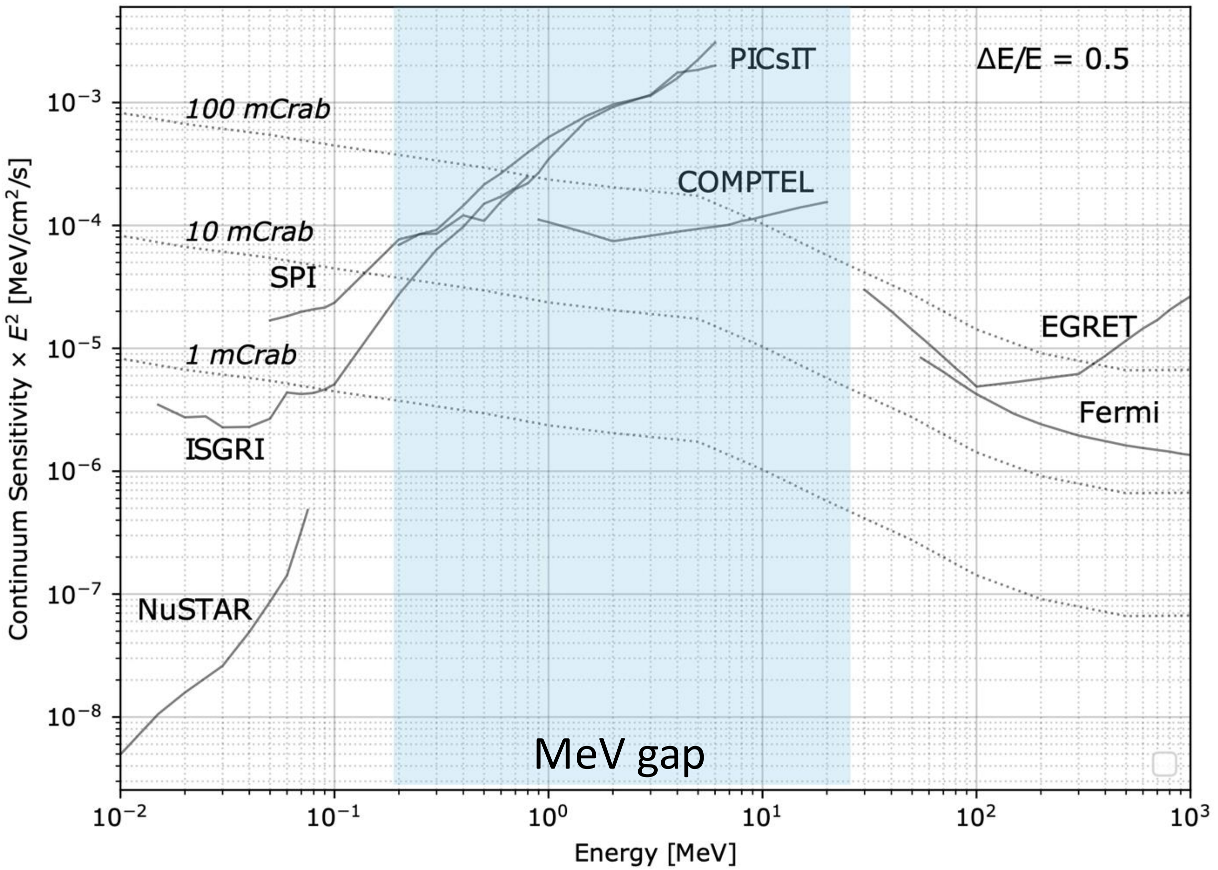
- First balloon/satellite experiment to target both
  - Astrophysical observations with **MeV gamma rays**
  - Indirect dark matter searches with **cosmic antinuclei**

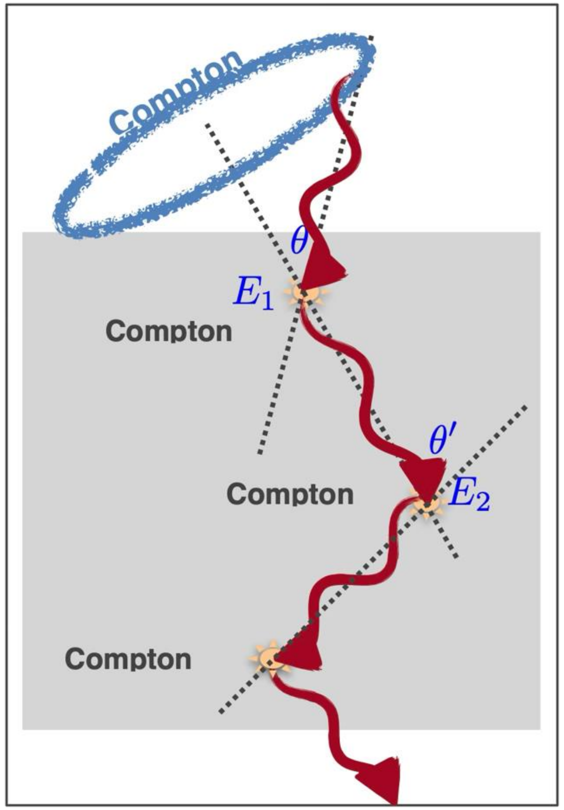
- First balloon/satellite mission with a low-cost, large-scale **LArTPC** (liquid argon time projection chamber) detector

- Funded by **NASA** as a **Physics of the Cosmos** suborbital experiment

MeV Gamma-Ray Observations

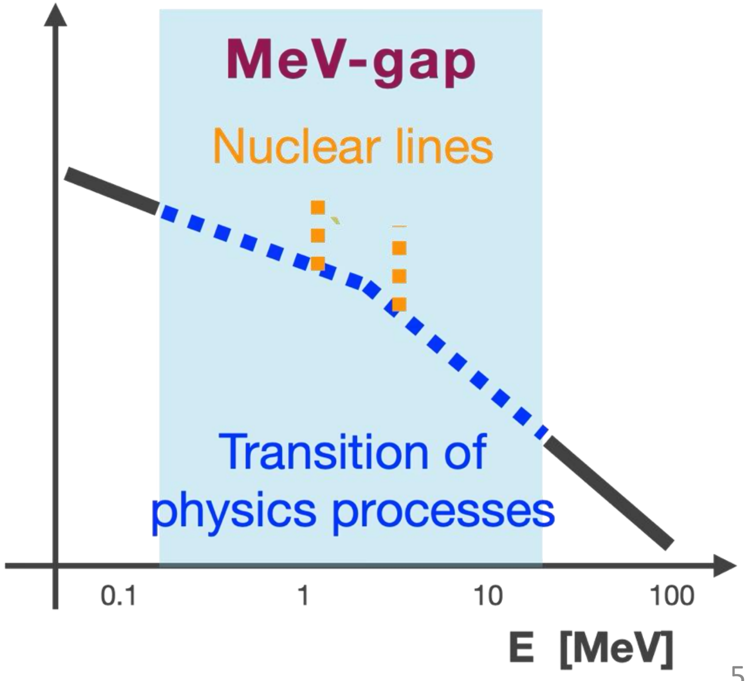
- ❑MeV region is poorly measured due to domination of Compton scattering. Detectors require good spatial and energy resolution





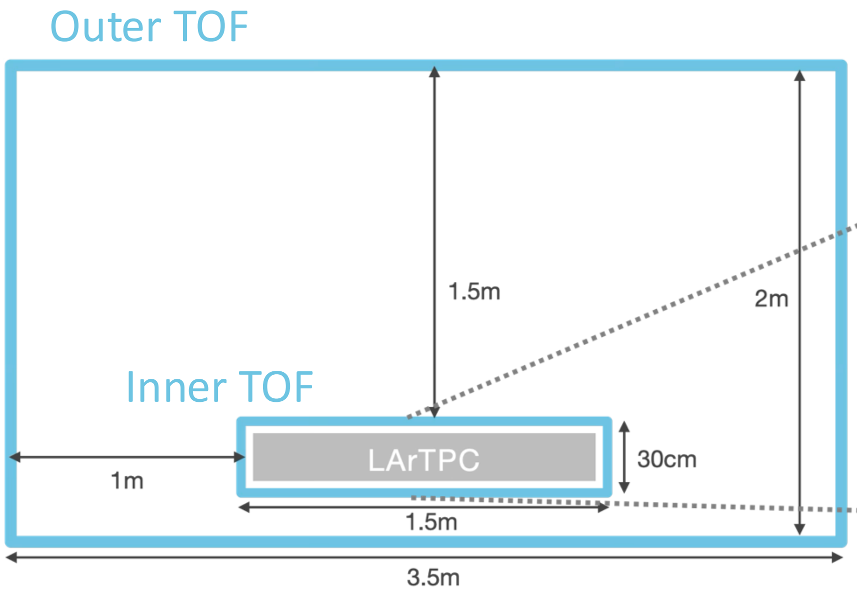
MeV Gamma-ray Science

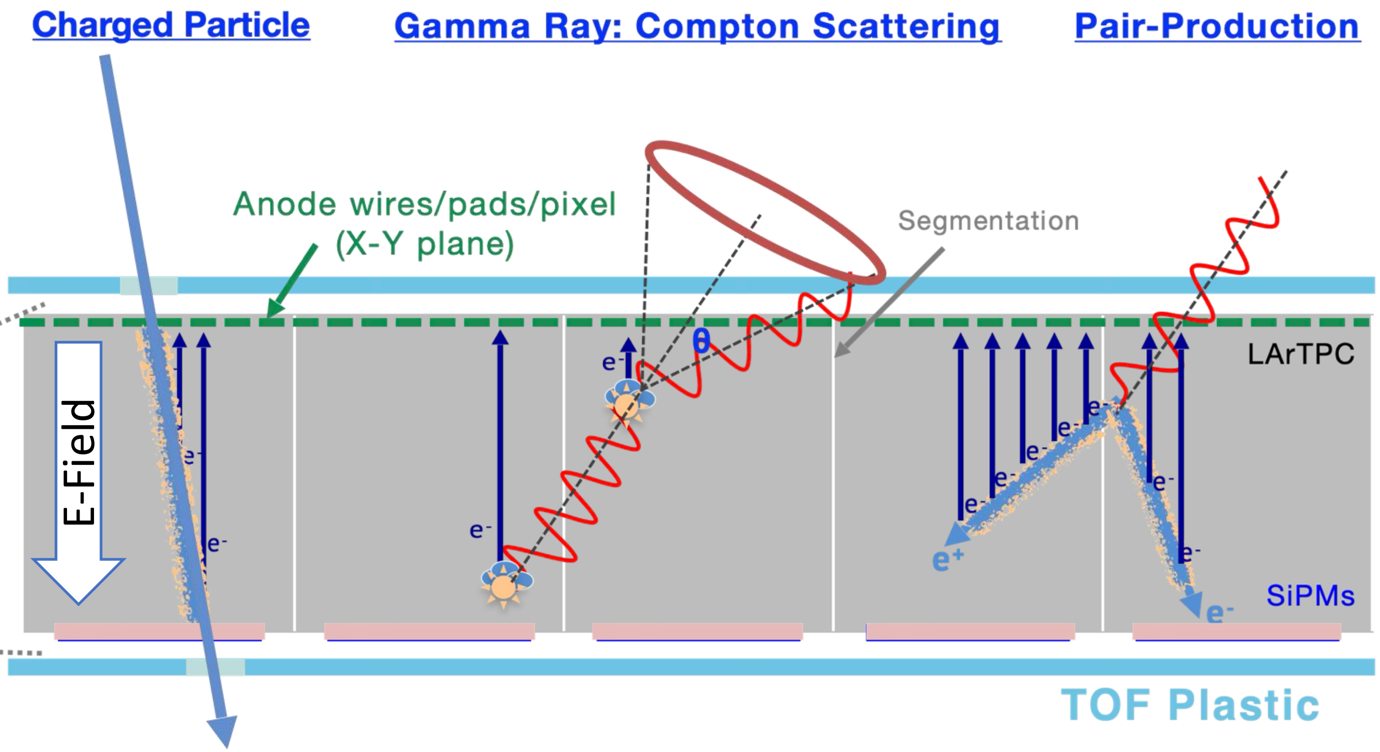
- **Physics processes/nucleosynthesis**
  - Transition of physics processes in MeV
    - Particle acceleration in Pulsar Wind Nebula
    - Relativistic flows in stellar/super-massive BHs, pulsars, magnetars
  - **Nuclear lines** from radioactive isotopes in astrophysical environments
    - Galactic center, classic novae, SNe, etc
    - r-process for the origin of heavy elements
- **Multi-messenger astrophysics**
  - MeV gamma rays + GWs
  - MeV gamma rays + high-energy neutrinos
    - NS/BH mergers, GRBs, SNe, AGNs
- **Indirect Dark Matter and PBH searches**



GRAMS detector design

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



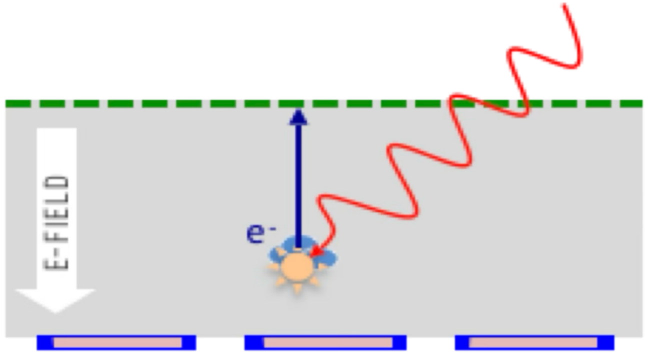


Multiple Compton reconstruction, Hiroki Yoneda et al, https://doi.org/10.1016/j.astropartphys.2022.102765

Why LArTPC?

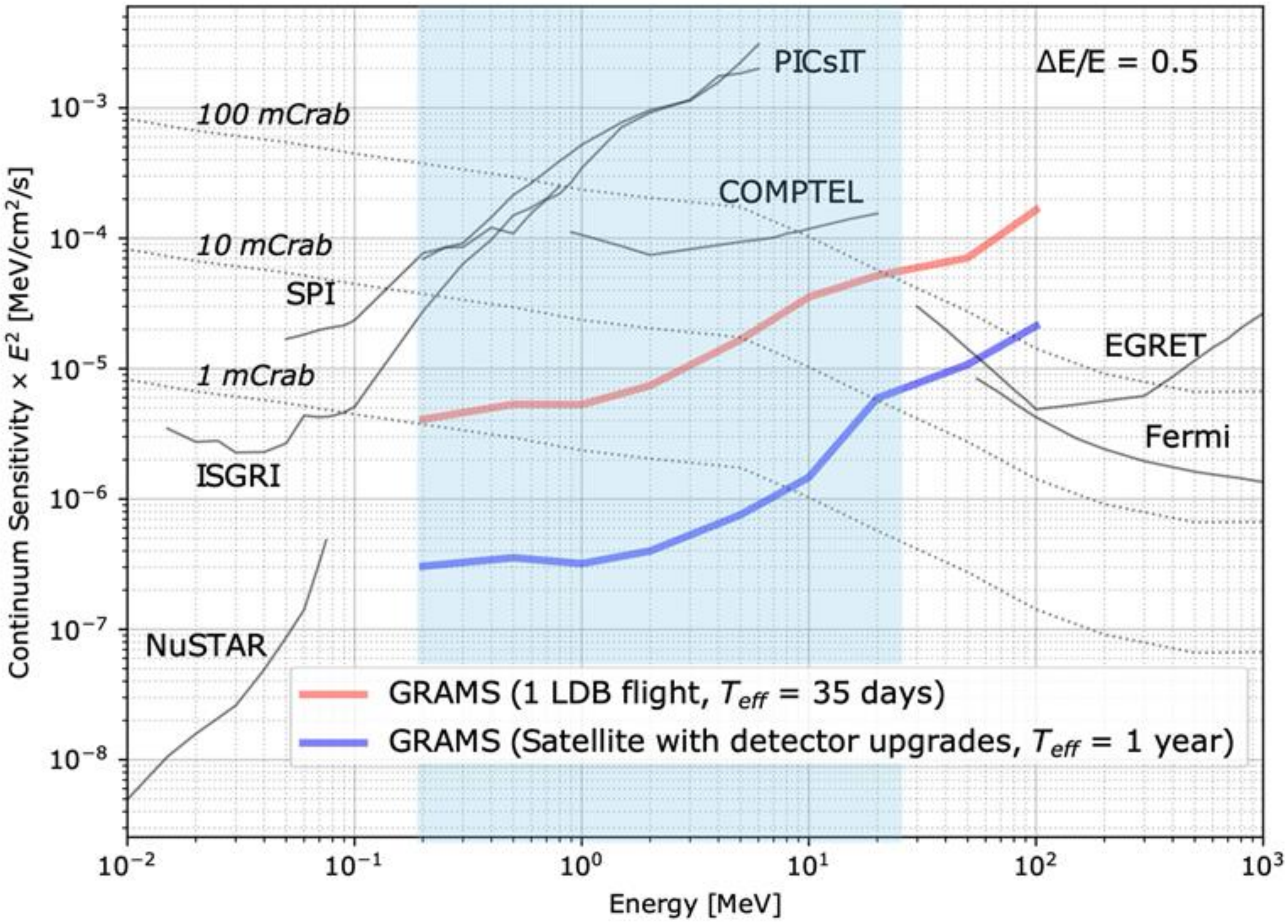
❑LArTPC is **cost-effective** and easily expandable to a **larger scale**, Almost **no dead volume** and **high detection efficiency**

	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



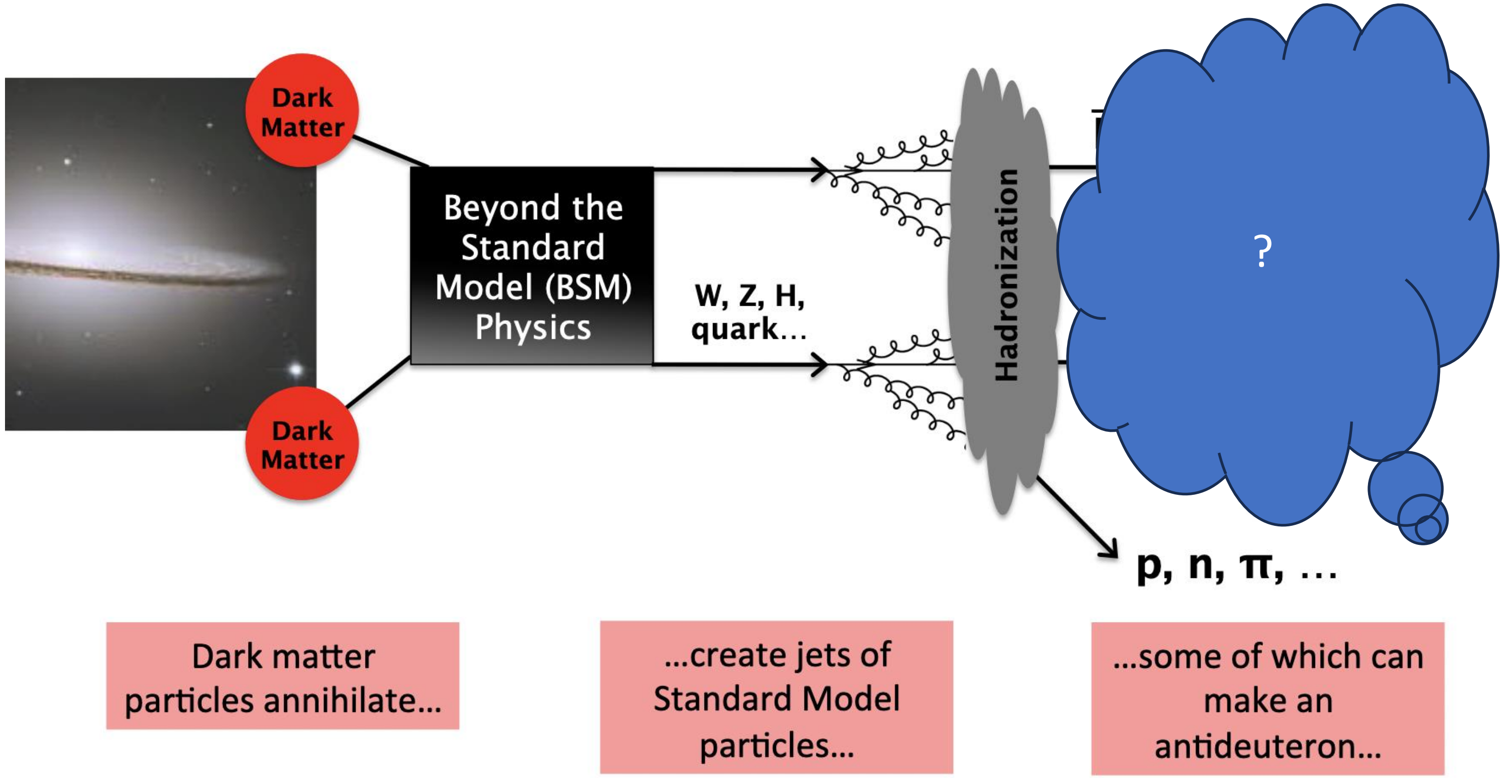
MeV Gamma-ray Observations

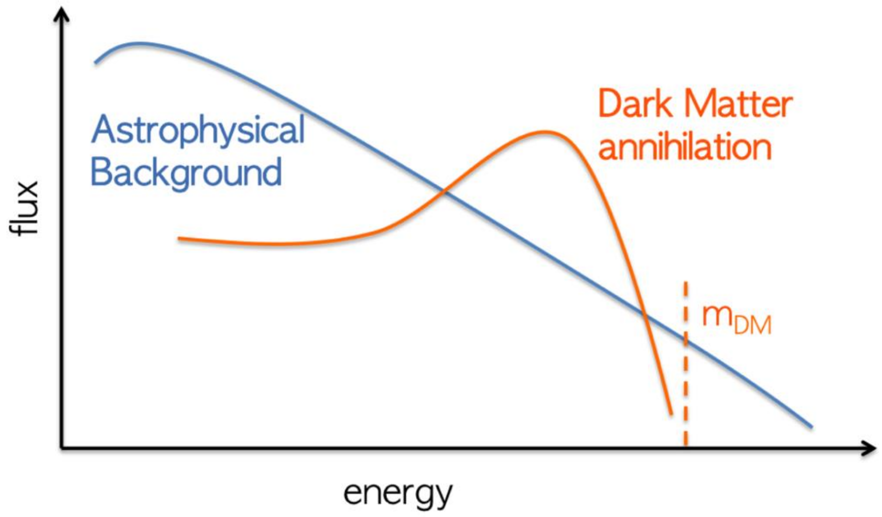
- **Single balloon** flight:
  - Order of magnitude improved
- **Satellite** mission:
  - Comparable to future missions



T.Aramaki et al 10.1016/j.astropartphys.2019.07.002

Indirect DM Searches

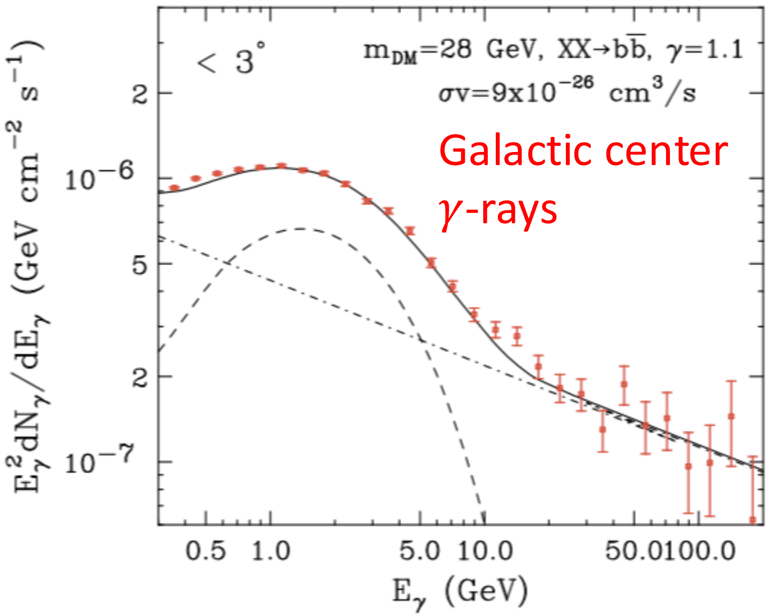




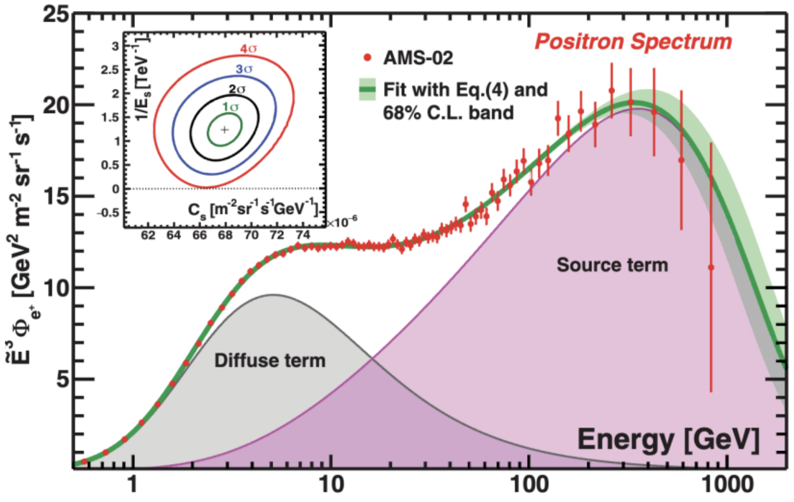
Finding products generated by DM self interaction

Indirect DM Searches

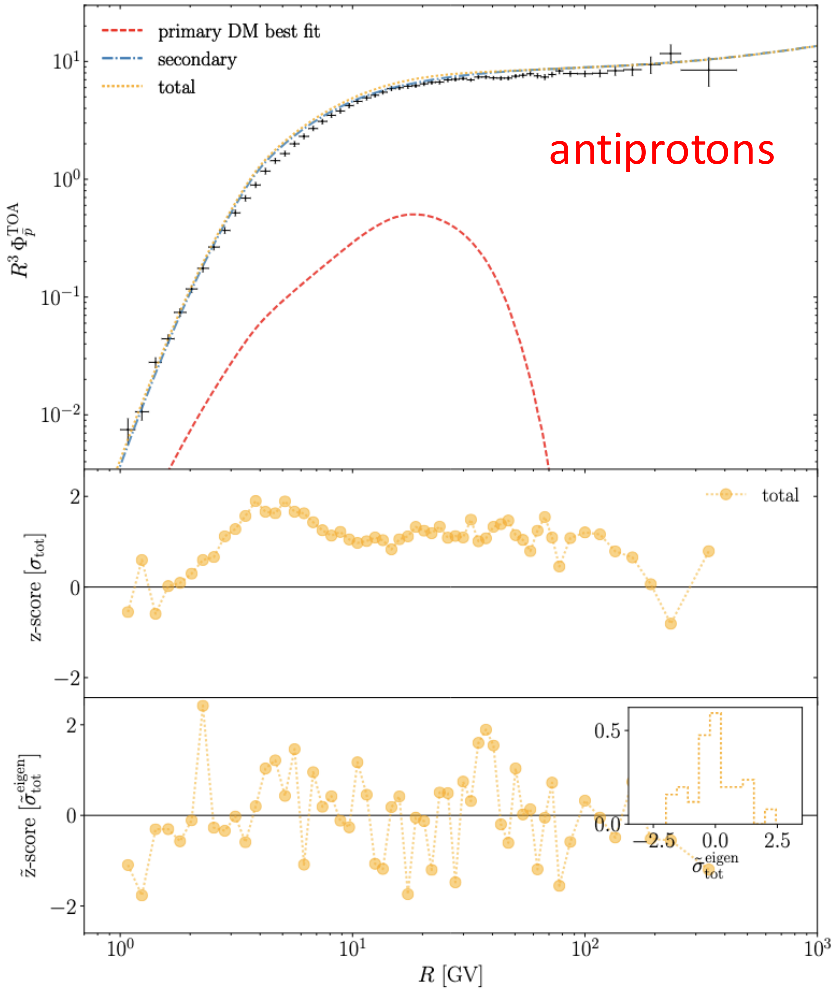
- ❑Uncertain astrophysical backgrounds make indirect searches harder



Lisa Goodenough et al, https://arxiv.org/abs/0910.2998



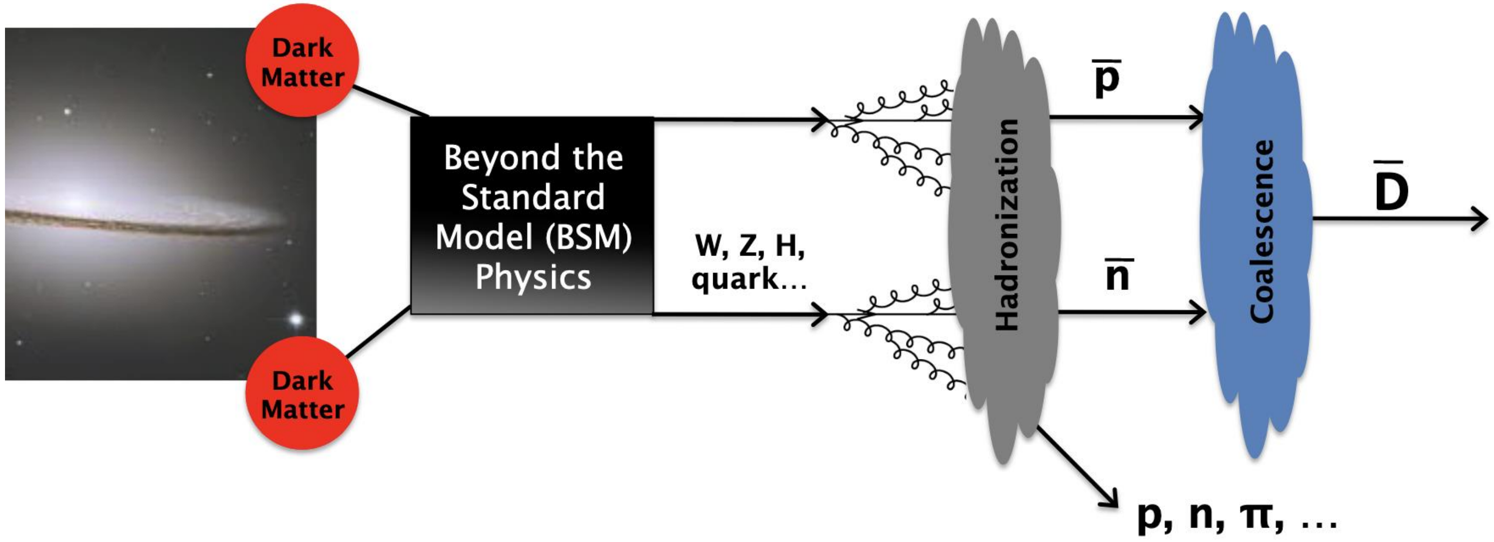
M. Aguilar et al, https://doi.org/10.1103/PhysRevLett.122.041102

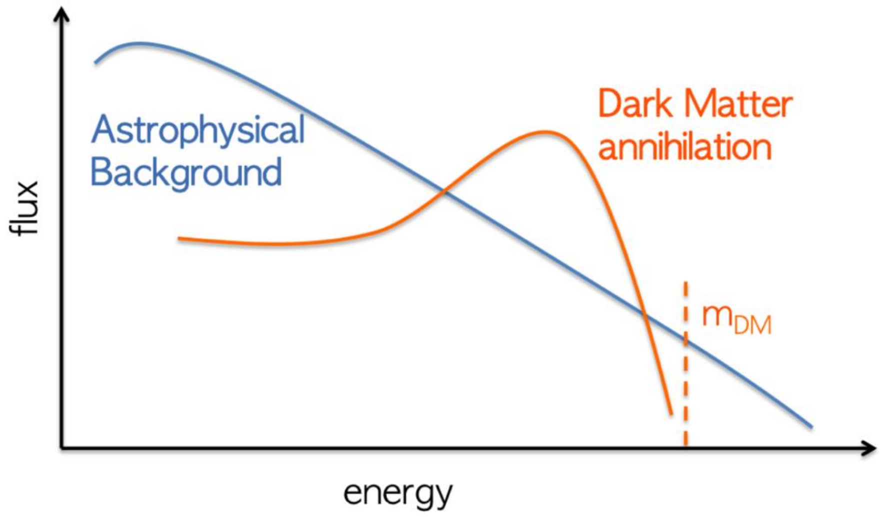


Francesca Calore et al, https://scipost.org/10.21468/SciPostPhys.12.5.163

We need background-free searches!

Indirect DM Searches





Dark matter particles annihilate…

…create jets of Standard Model particles…

…some of which can make an antideuteron…

Finding products generated by DM self interaction

Indirect DM Searches

- ❑Low energy antideuteron give an essentially astrophysical background-free new physics signature

Antiproton Production:

$$p + p \rightarrow p + p + \boxed{p + \overline{p}}$$

Anti-deuteron Production:

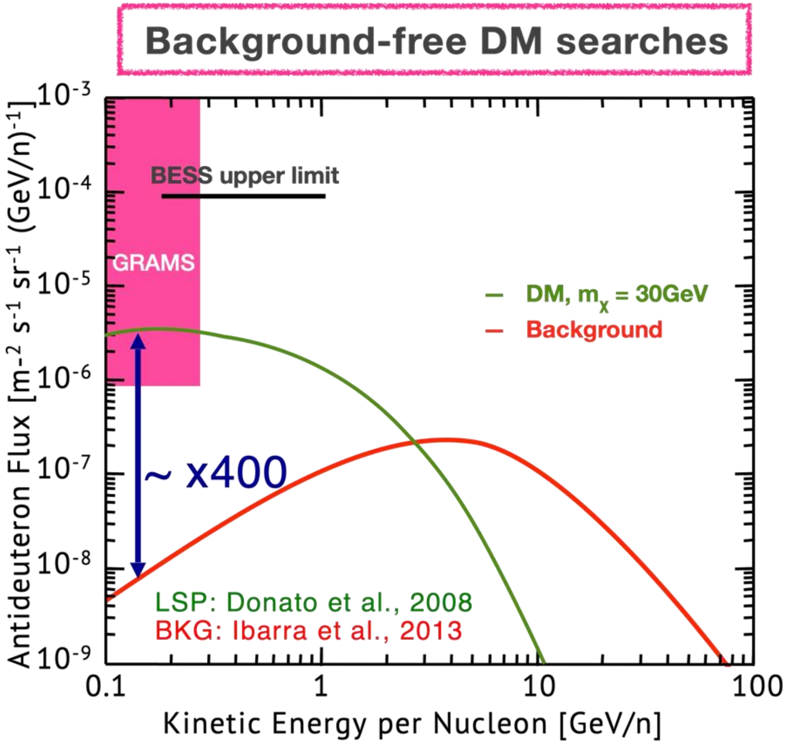
$$p + p \rightarrow p + p + \boxed{p + \overline{p} + n + \overline{n}}$$

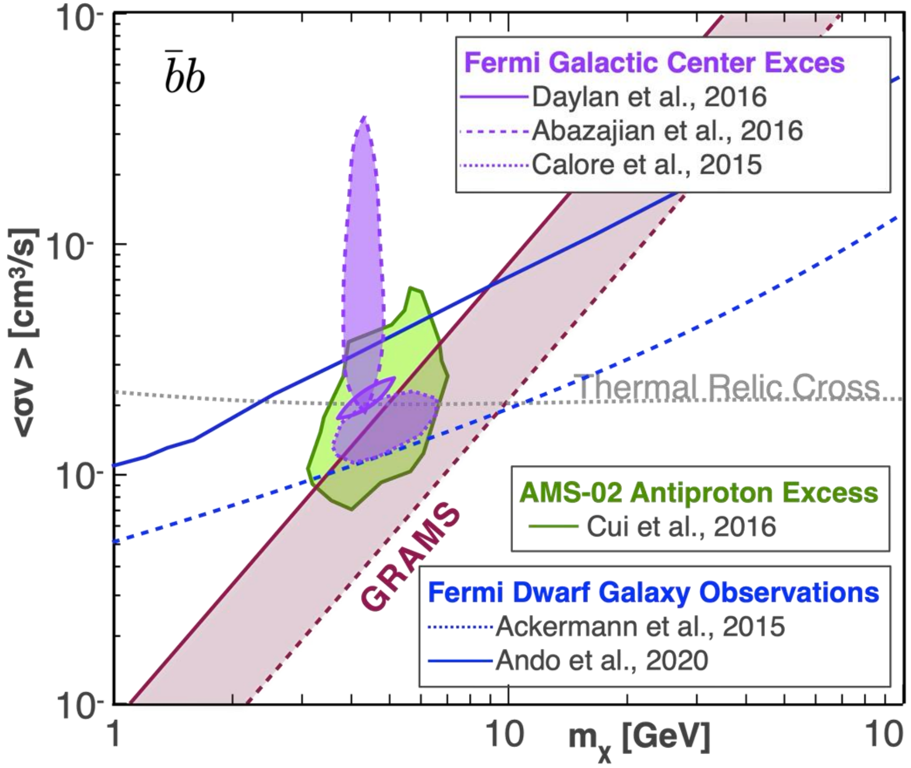
$$\overline{p} + \overline{n} \rightarrow \overline{d}$$

- ❑Threshold exist• Expect most antideuteron to come out with a few GeV
- ❑**Almost impossible to produce low energy anti-deuterons from standard astrophysics**

GRAMS Antideuteron Sensitivity

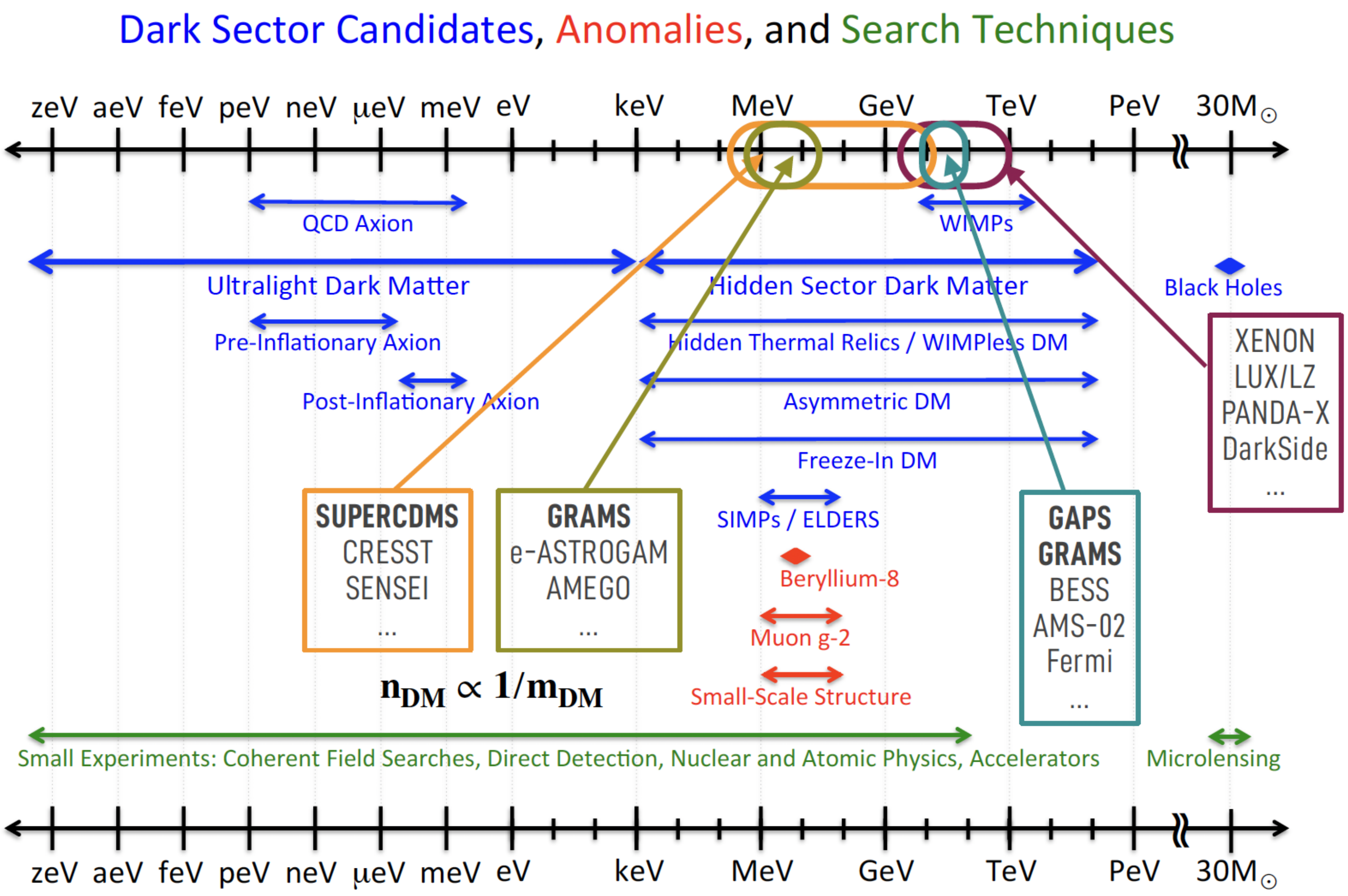
- ❑Low energy $\bar{D}$ gives an essentially background-free signature
- ❑Extensively explore DM parameter space and validate Fermi/AMS-02 results





Next generation measurement beyond GAPS

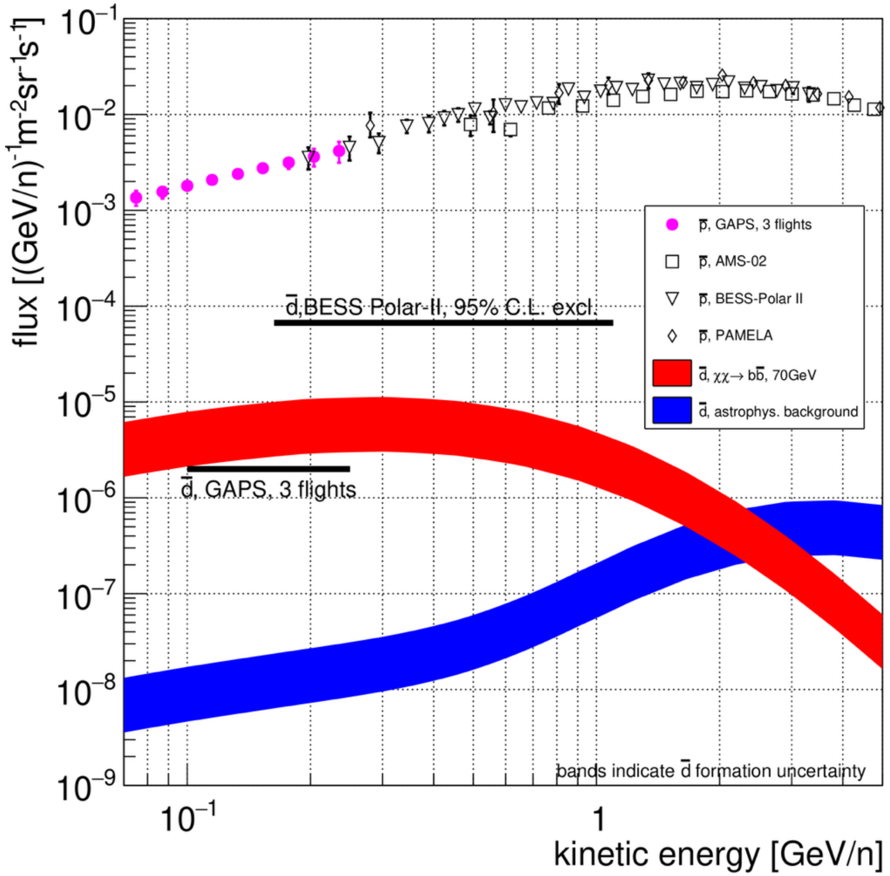
GRAMS DM searches

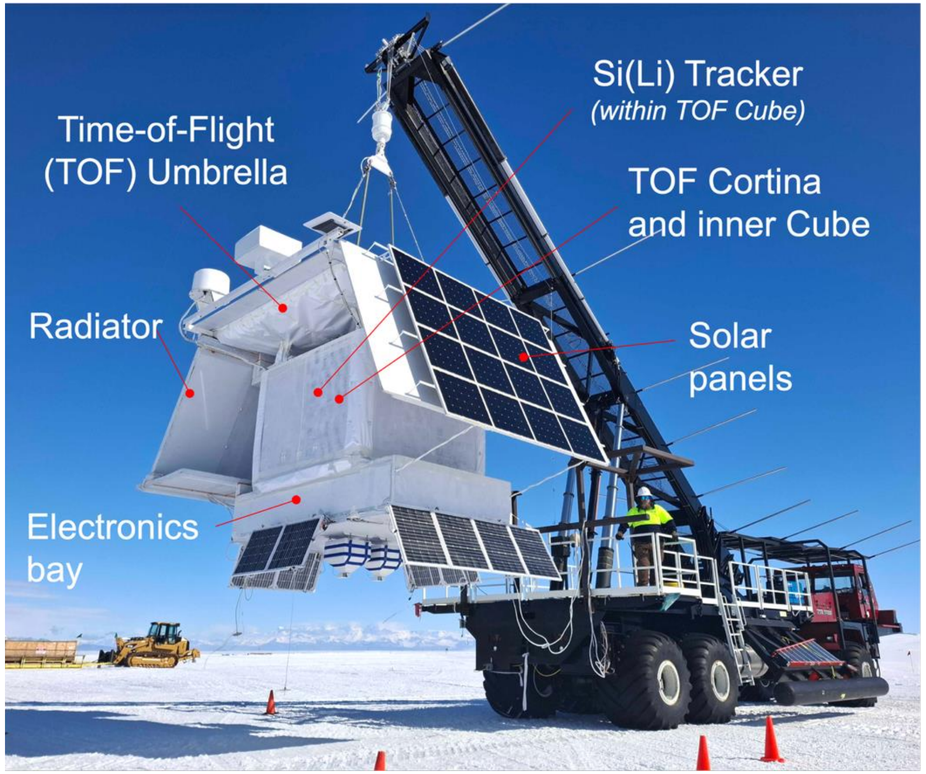


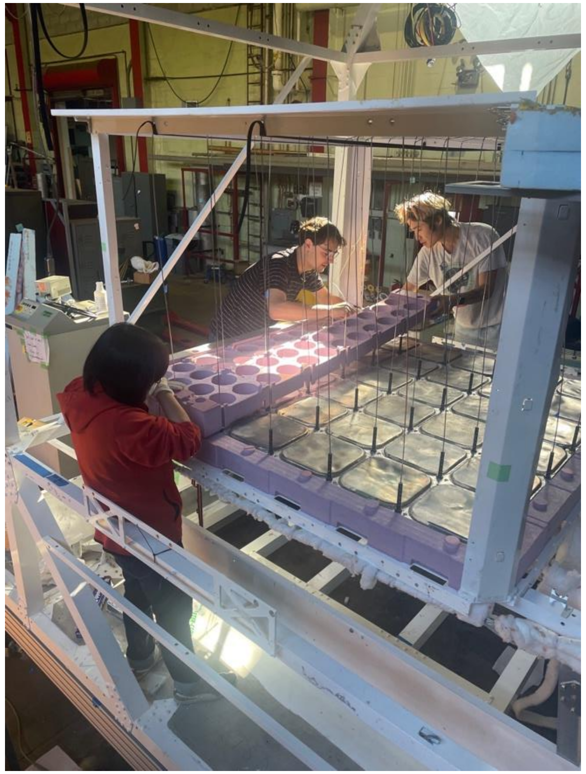
Marco Battaglieri et al, https://arxiv.org/abs/1707.04591

General AntiParticle Spectrometer

- Current generation low energy antiparticles experiment



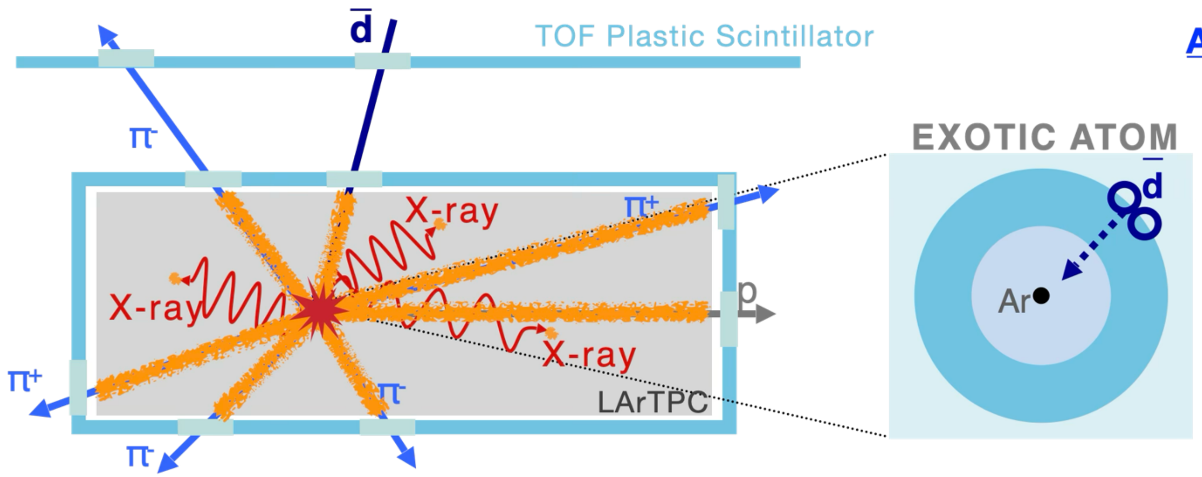


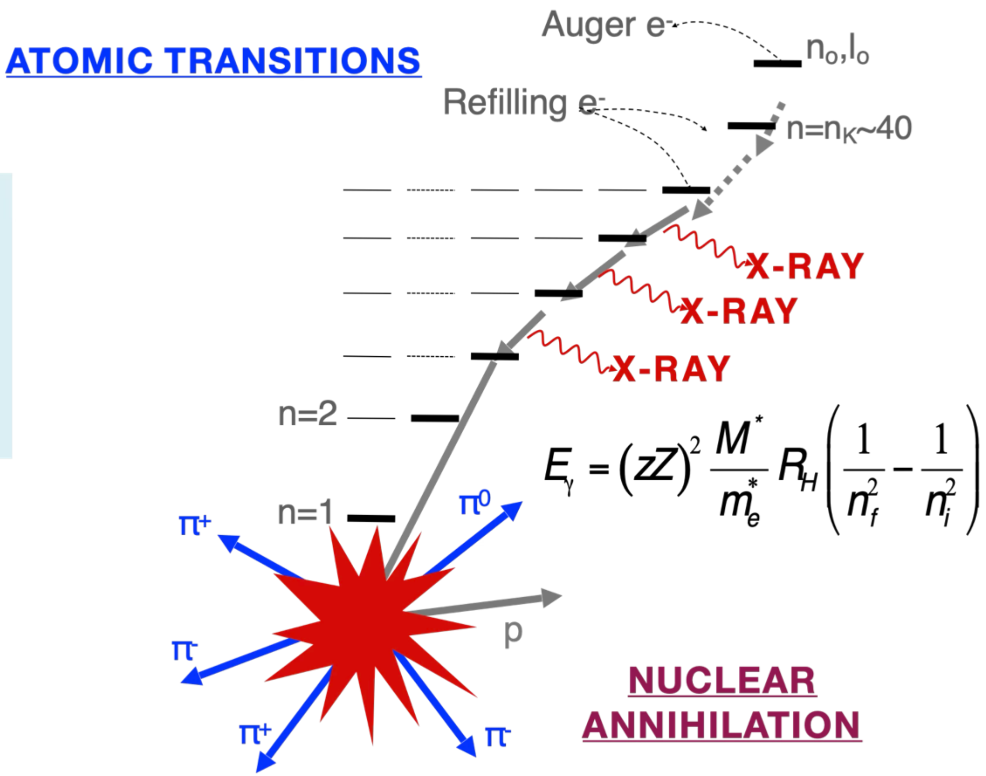


GAPS instrument is READY in Antarctica planed for flight in late 2025

GRAMS Antimatter detection

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

Particle identification with the combination of
TOF timing, stopping range, pion/proton multiplicities, energy depositions in plastic/LArTPC, atomic X-rays

Antimatter separation

- ❑Primary goal is antideuteron and antihelium-3
- ❑Main background would be normal particles and antiproton

Use antihelium-3 as an example

Respect to normal particles $(p, d, He, e^{\pm})$:

$\bar{d}$	$^{3}_{2}\overline{He}$
Secondary profile	Secondary profile

- Time of Flight targeting on low energy incoming particles $(\sim 250 MeV/n)$
- Normal particles could not produce annihilation product, making secondary profile unique

Use antihelium-3 as an example

Respect to antiproton:

$\bar{d}$	$^{3}_{2}\overline{He}$
Secondary profile	Secondary profile
atomic X-ray	atomic X-ray
Depth sensing	dE/dx in TOF
dE/dx in LArTPC	…

GRAMS antihelium-3

❑GRASP or Geometric acceptance

❑Simulation critiria

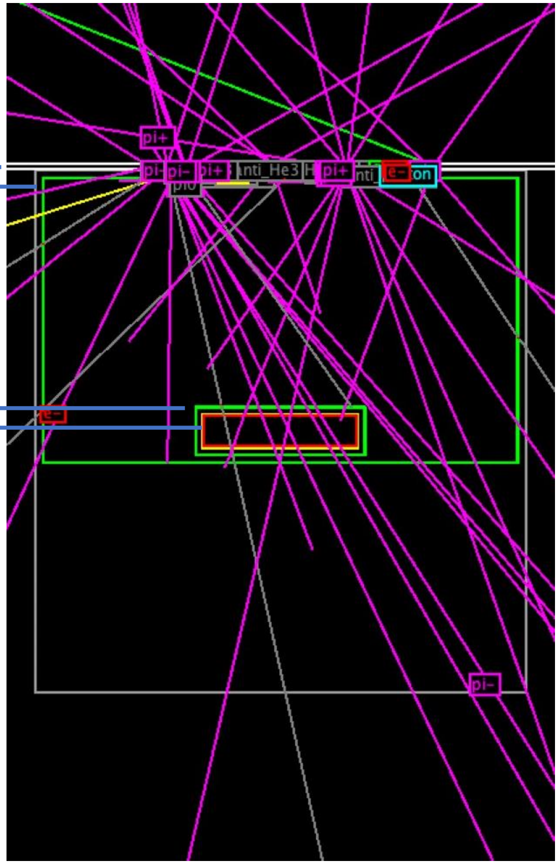
Geant4 simulation, https://github.com/Eclipsedclaw/GRAMS

Compressed air

Outer TOF(3.6m×3.6m×1.6m)

Inner TOF(1.5m×1.5m×0.3m)

LArTPC(1.4m×1.4m×0.2m)

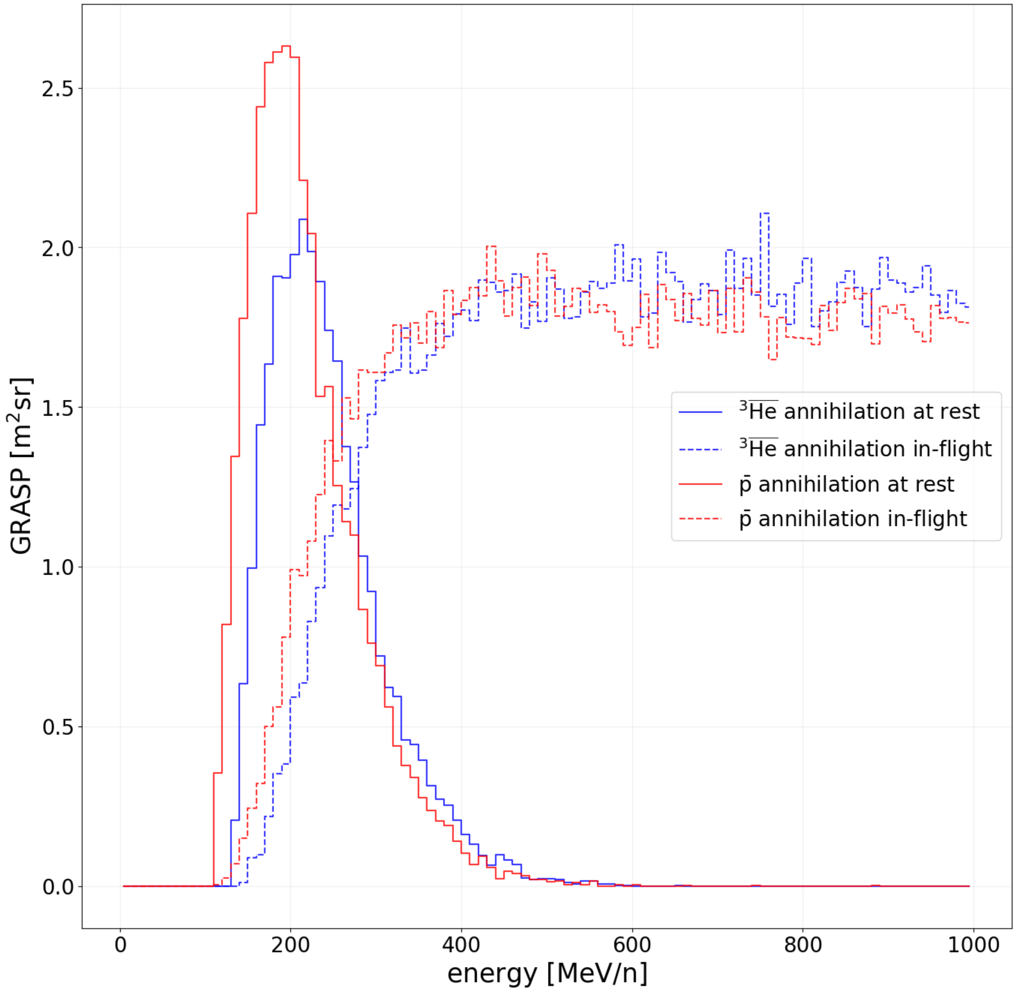


❑Generate large amount of antiparticles from top of instrument. Count how many of them stop inside LArTPC detector to get the geometrical acceptance.

$$G_{stop} = G_{ref} \cdot \frac{N_{stop}}{N_{total}} = A \cdot \pi \cdot \frac{N_{stop}}{N_{total}}$$

GRAMS antihelium-3

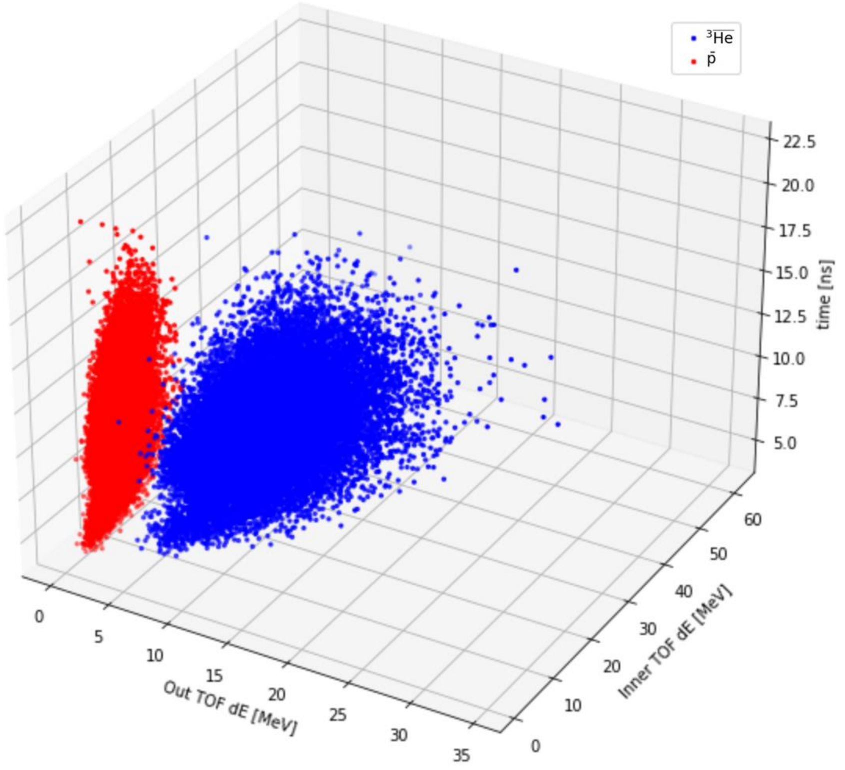
- GRASP, or geometric acceptance
  - Simulation antiproton and antihelium-3 from 0 to 1000 MeV/n
  - Almost no stopping events after 500MeV/n
  - Time of flight timing resolution regulate higher kinetic energy particle being distinguished



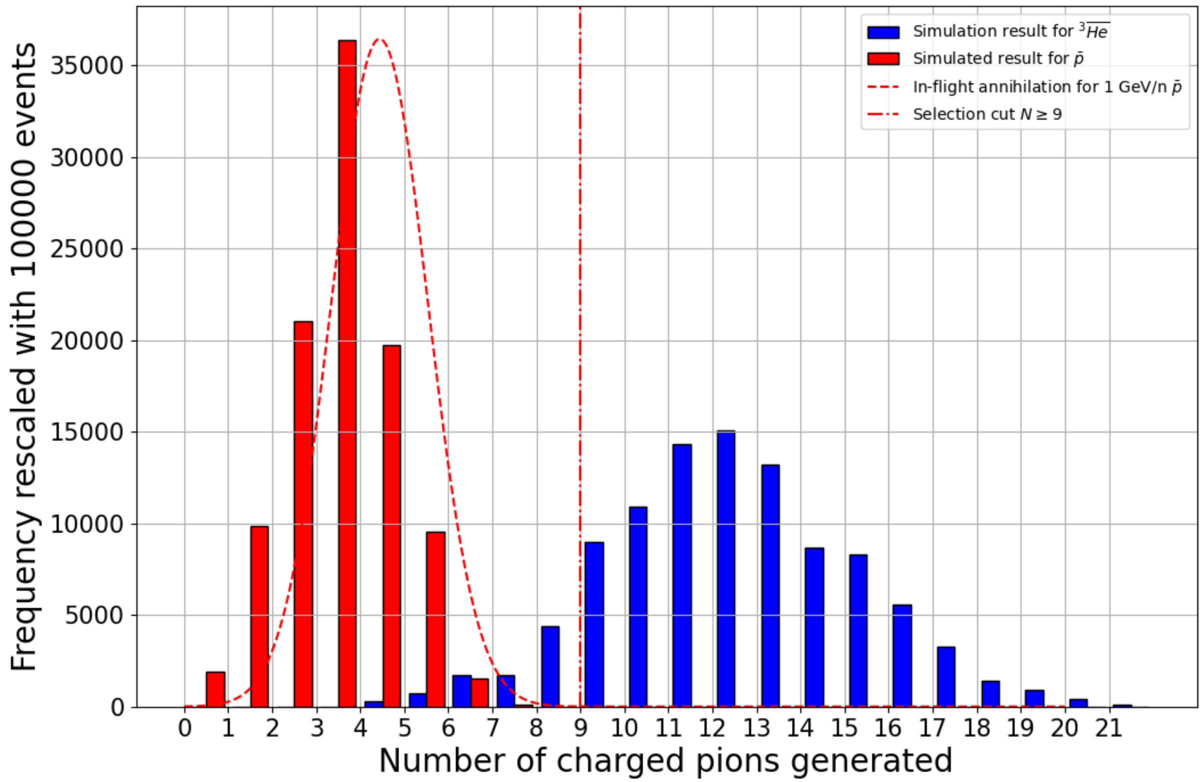
J. Zeng et al, https://doi.org/10.1016/j.astropartphys.2025.103152

GRAMS antihelium-3

- AMS reported antihelium-3 possible events, it could come from DM channels



Charge-2 CRs particles tend to deposit more energy in TOF detector



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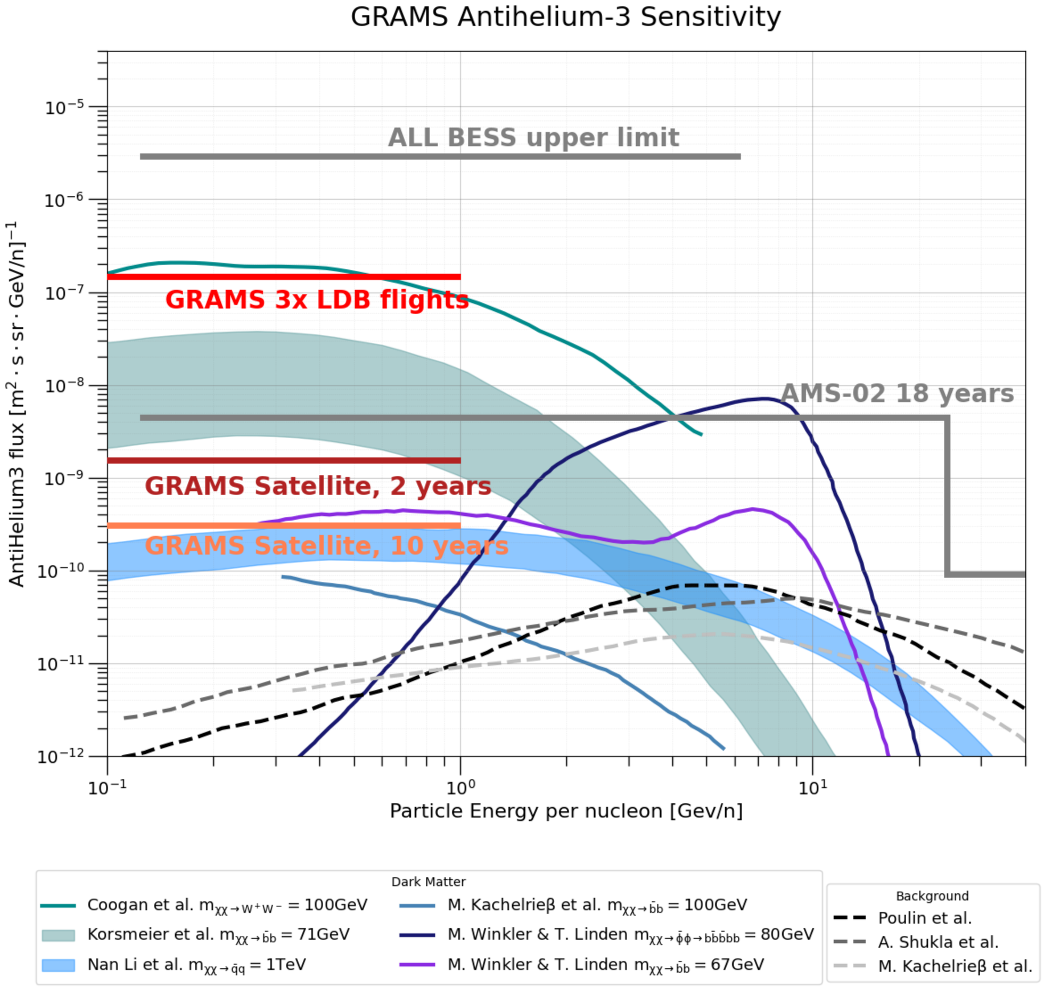
GRAMS antihelium-3

- GRAMS could investigate a variety of DM models, complementary to AMS-02



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Antihelium-3 sensitivity for the GRAMS experiment

J. Zeng [1,*], T. Aramaki [1], K. Aoyama [2,3], S. Arai [4], S. Arai [2], J. Asaadi [5], A. Bamba [4], N. Cannady [6], P. Coppi [7], G. De Nolfo [6], M. Errando [8], L. Fabris [9], T. Fujiwara [10], Y. Fukazawa [11], P. Ghosh [6], K. Hagino [4], T. Hakamata [10], N. Hiroshima [12], M. Ichihashi [4], Y. Ichinohe [13], Y. Inoue [10,14,15], K. Ishikawa [2], K. Ishiwata [10], T. Iwata [4], G. Karagiorgi [16], T. Kato [4], H. Kawamura [10], D. Khangulyan [17,18], J. Krizmanic [6], J. LeyVa [1], A. Malige [16], J.G. Mitchell [6], J.W. Mitchell [6], R. Mukherjee [19], R. Nakajima [2], K. Nakazawa [21], H. Odaka [10], K. Okuma [21], K. Perez [16], N. Poudyal [1], I. Safa [16], K. Sakai [20], M. Sasaki [6], W. Seligman [16], J. Sensenig [16], K. Shirahama [10], T. Shiraishi [22], S. Smith [23], Y. Suda [11], A. Suraj [1], H. Takahashi [11], S. Takashima [4], T. Tamba [4,3], M. Tanaka [2], S. Tandon [16], R. Tatsumi [10], J. Tomsick [24], N. Tsuji [22], Y. Uchida [25], Y. Utsumi [2], S. Watanabe [23], Y. Yano [2], K. Yawata [26], H. Yoneda [27], K. Yorita [2], M. Yoshimoto [10]

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ABSTRACT

The Gamma-Ray and AntiMatter Survey (GRAMS) is a next-generation balloon/satellite mission utilizing a Liquid Argon Time Projection Chamber (LArTPC) detector to measure both MeV gamma rays and antinuclei produced by dark matter annihilation or decay. The GRAMS can identify antihelium-3 events based on the measurements of X-rays and charged pions from the decay of the exotic atoms, Time of Flight (TOF), energy

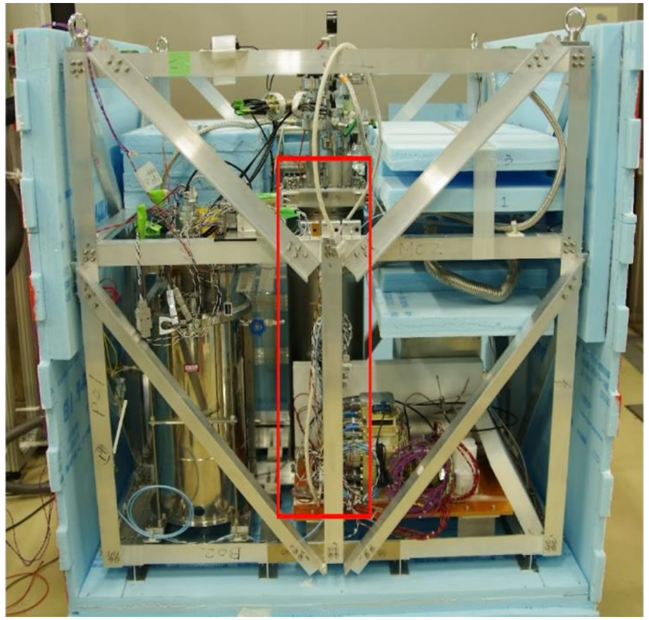
J. Zeng et al, https://doi.org/10.1016/j.astropartphys.2025.103152

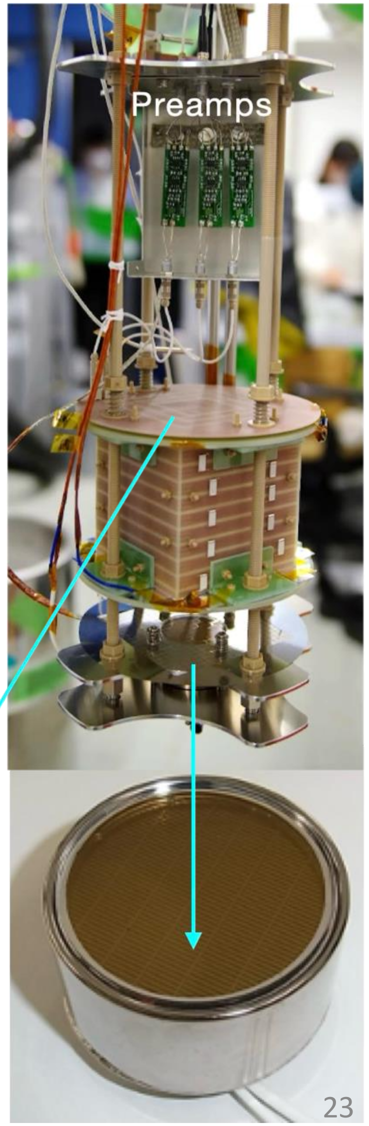
GRAMS timeline

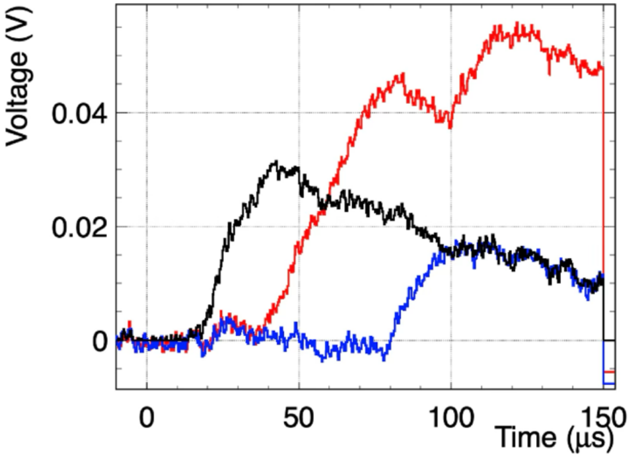
- 2019: concept paper
  - https://doi.org/10.1016/j.astropartphys.2019.07.002
- 2021: Founded in Japan by JSPS
  - 2023 eGRAMS engineer flight
  - 2025 Beam test
- 2022: Founded in US by NASA APRA
  - 2026 pGRAMS prototype flight
- …

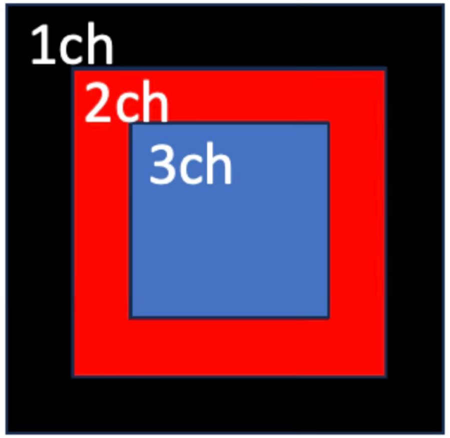
Engineer flight eGRAMS

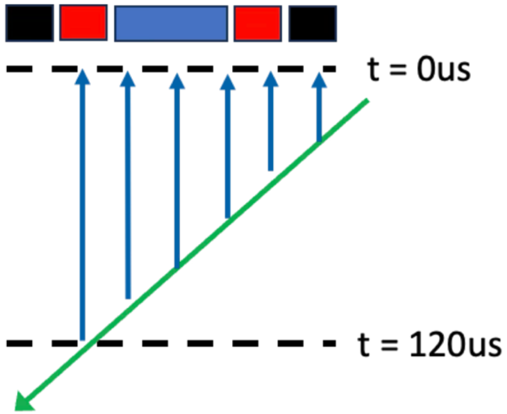
- **Successful engineering flight @JAXA TARF**
  - **First** LArTPC operation at stratosphere
  - TPC: 10 x 10 x 10 cm^3
    - 1 PMT (Hamamatsu R6041-06) at the bottom
    - 3 charge channels (pGRAMS preamps)
    - No cooling/circulation system
  - Pressure vessel for RPi/DAQ
  - Obtained ~400k stable events with light + charge







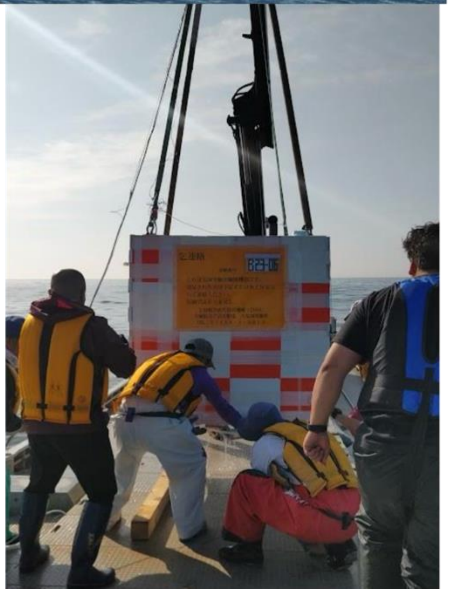




R. Nakajima, *et al.* 10.1093/ptep/ptae179

eGRAMS in July 2023

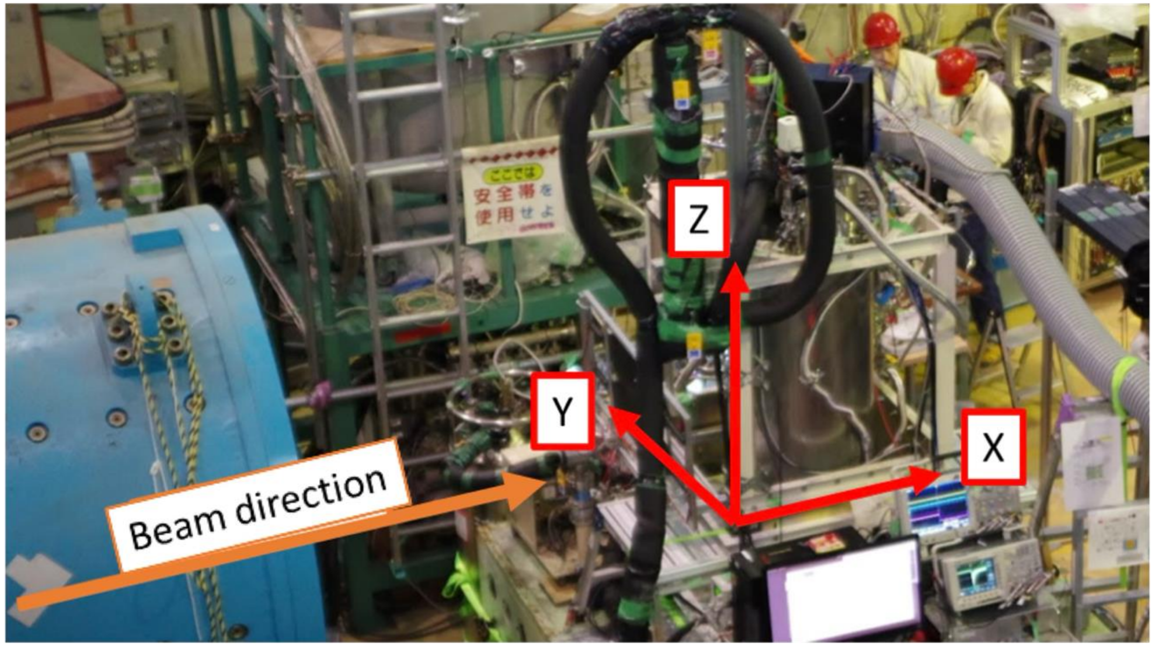
Led by the **GRAMS Japanese team**

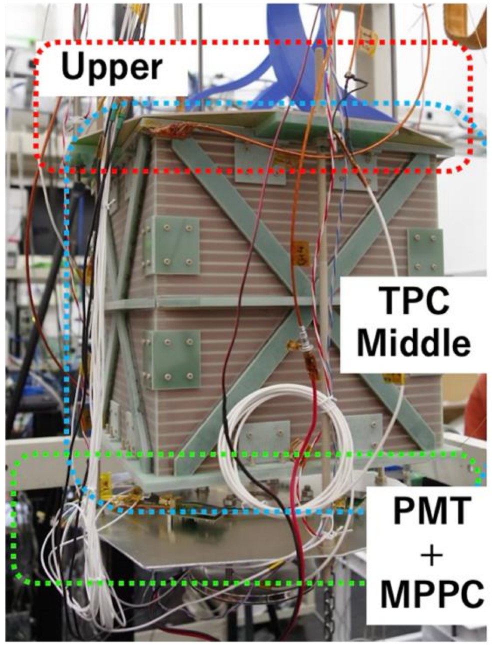


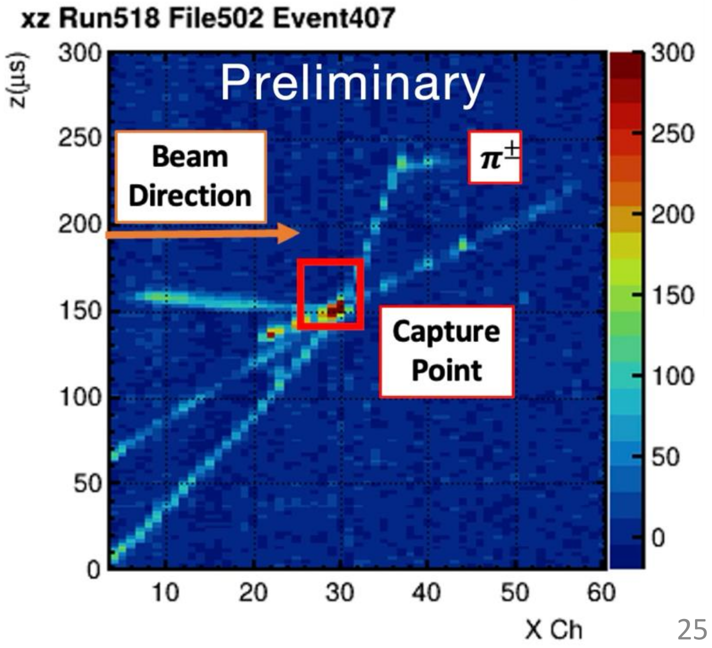
Antiproton Beam Test at J-PARC, February 2025

- ❑@J-PARC in Feb 2025
  - ❑**Antiprotons** with 0.7 GeV/c
  - ❑**Validated** LArTPC performance as an antimatter detector
    - ❑ TOF + Aerogel Chrenkov detector to reject pion events
    - ❑ Waseda TPC: 30 cm x 30 cm x 30 cm
    - ❑ Measure annihilation products: pions (and protons)

Led by the **GRAMS Japanese team**



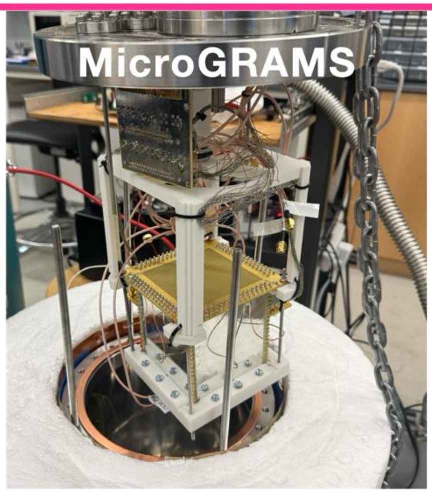


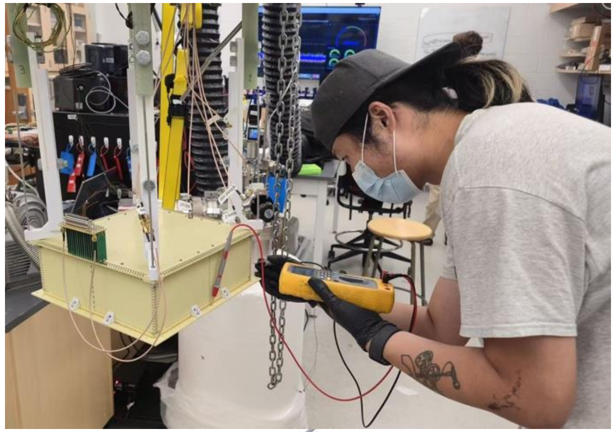


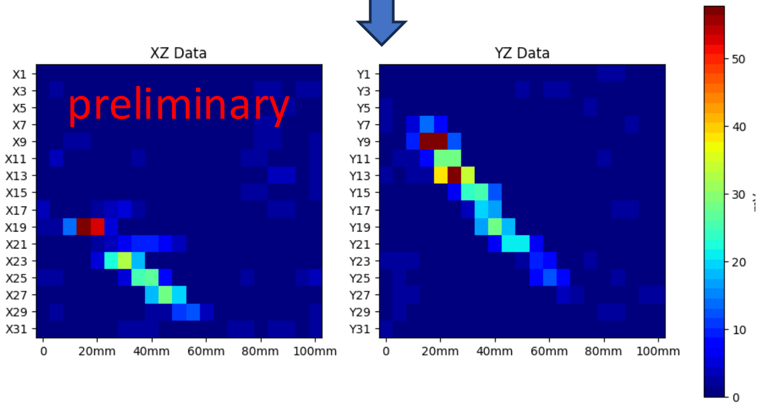
Prototype Flight (pGRAMS), Spring 2026

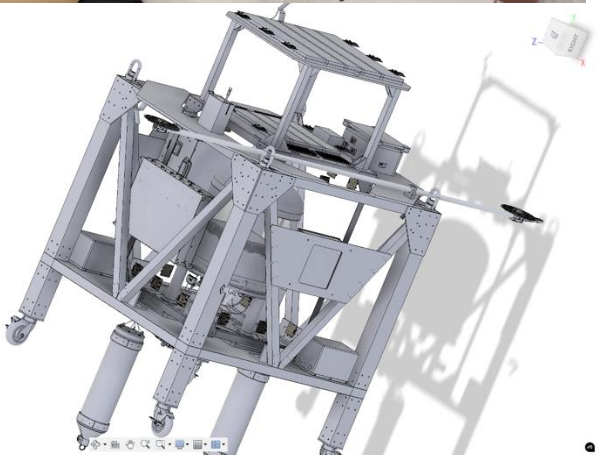
- ❑Scheduled @Arizona in **Spring 2026**
  - ❑ Demonstrate LArTPC performance in flight
    - ❑ **Particle tracking** for charged particles
    - ❑ **Gamma-ray detection**
  - ❑ **MiniGRAMS**: 30 x 30 x 20 cm^3 segmented into **9 cells**
    - ❑ Tile/pads (~3mm pitch) for x/y directions
    - ❑ 180 charge channels, 36 light channels
  - ❑ Currently testing **MicroGRAMS** @Northeastern
    - ❑ TPC size: 10 x 10 x 10 cm^3
    - ❑ Demonstrate the particle tracking and event reconstruction
- ❑Science flights with **MiniGRAMS**
  - ❑ One of the **largest** Compton cameras
  - ❑ Cooling/circulation system onboard

Funded by **NASA APRA2022**









Gondola and cryostat designed by NASA GSFC group

pGRAMS flight will focus on MeV gamma-ray and particle tracking

pGRAMS team

Senior Advisor/Institutional PIs
John Mitchell, Reshmi Mukherjee
John Tomsick, Makoto Sasaki, Manel Errando, Lorenzo Fabris

PI: Tsuguo Aramaki
Spokes person: Georgia Karagiorgi

Japanese Support/Institutional PIs
Hirokazu Odaka, Naomi Tsuji, Yoshiyuki Inoue, Kohei Yorita, Masashi Tanaka, Yasushi Fukazawa, Hiroki Yoneda, Yuto Ichinohe

pGRAMS Subsystem Integration Coordinator
Jiancheng Zeng

WBS 1: LArTPC
Tsuguo Aramaki
Georgia Karagiorgi
(Waseda Group)

WBS 2: TOF
Makoto Sasaki

WBS 2: MPD
Nicholas Cannady

WBS 3: Cryostat
John Mitchell
Sonya Smith
Shun Okazaki

WBS 4: Power
John Mitchell

WBS 5: Gondola
John Mitchell

WBS 6: Flight Computer/Telemetry
Hirokazu Odaka
John Mitchell

WBS 1.1: TPC
Jonathan Leyva
Jiancheng Zeng

WBS 1.2: Cold Electronics (charge)
Jiancheng Zeng

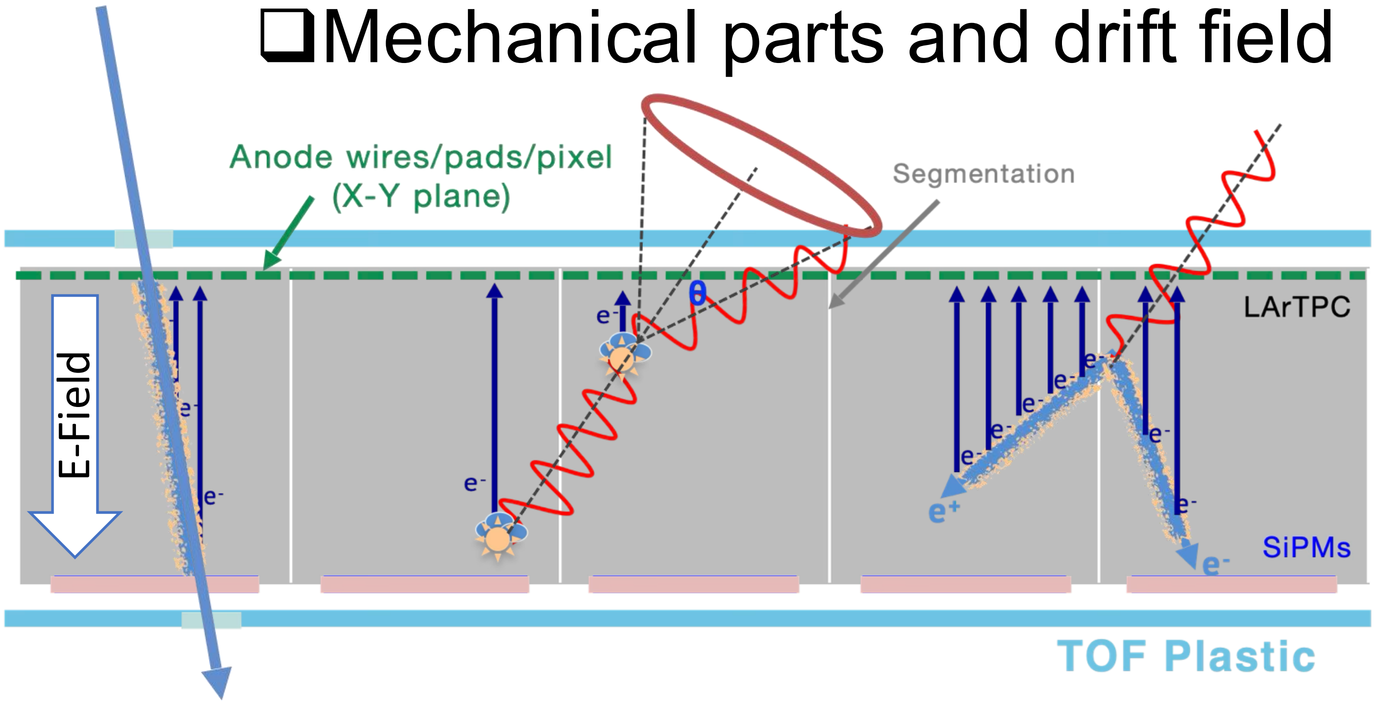
WBS 1.3: Cold Electronics (light)
Jonathan Leyva

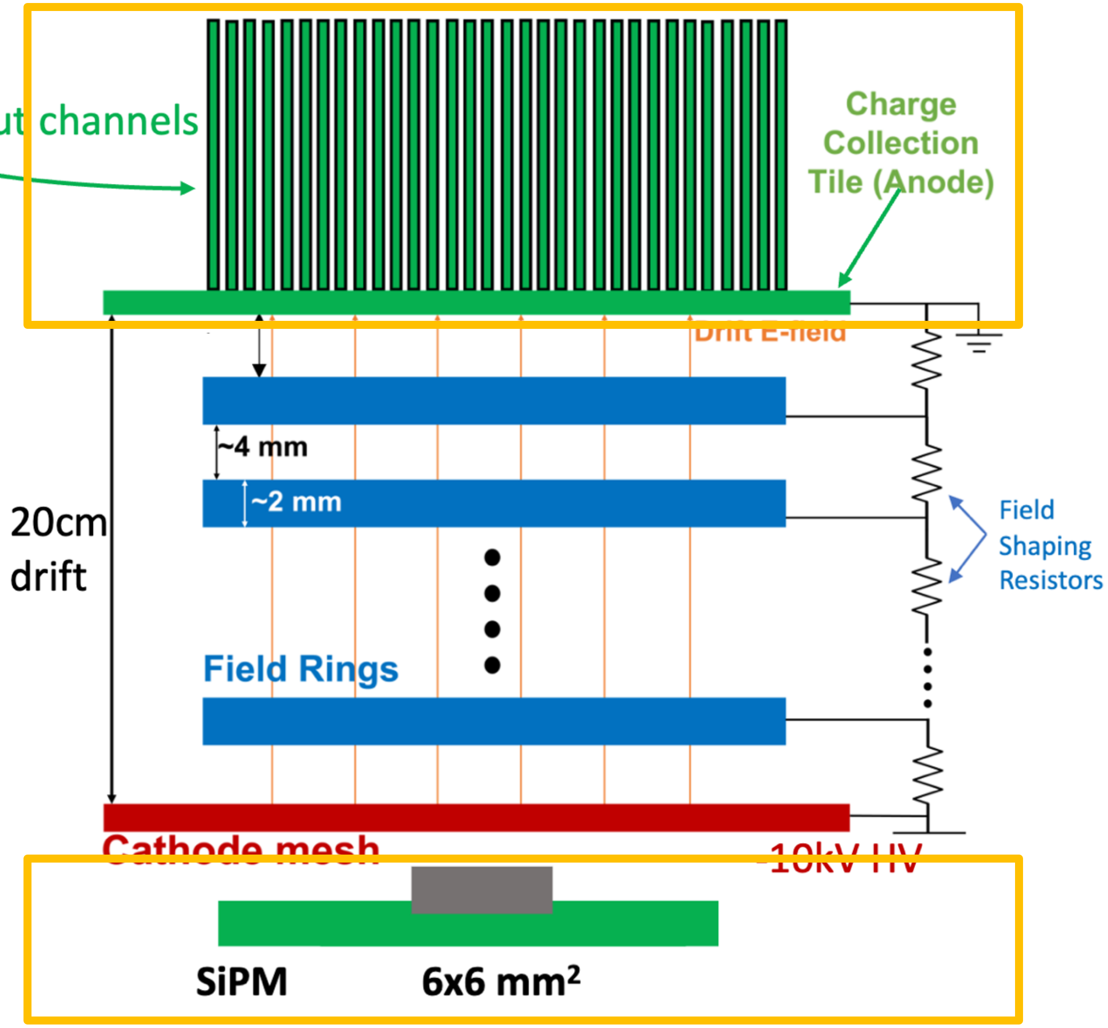
WBS 1.4: Warm Electronics (CAEN)
Nabin Poudyal

WBS 1.5: Warm Electronics (Columbia)
Akshay Malige

pGRAMS detector TPC design

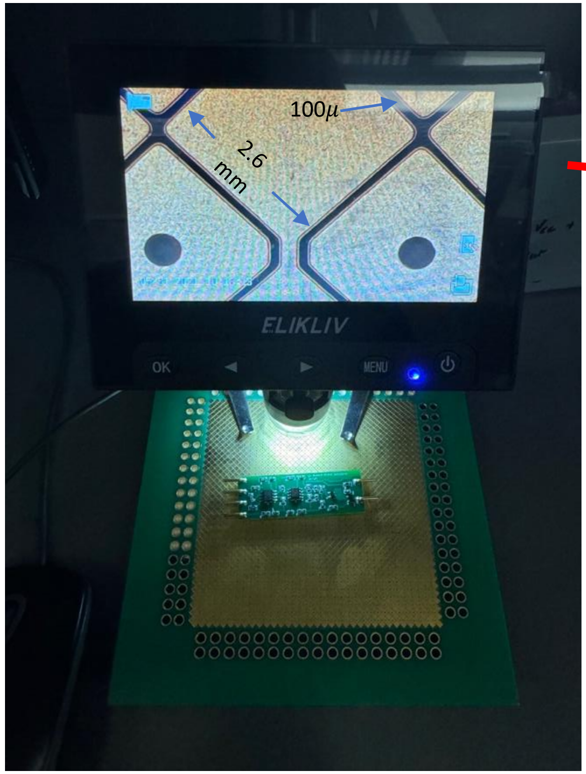
- ❑TPC composed with
  - ❑Top charge readout
    - ❑Tile + CSP
  - ❑Bottom light readout
  - ❑Mechanical parts and drift field

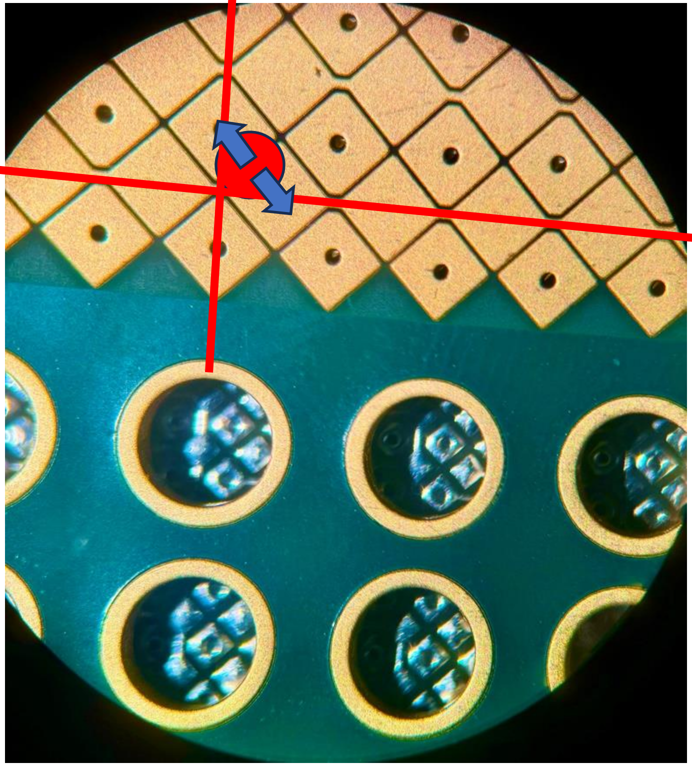


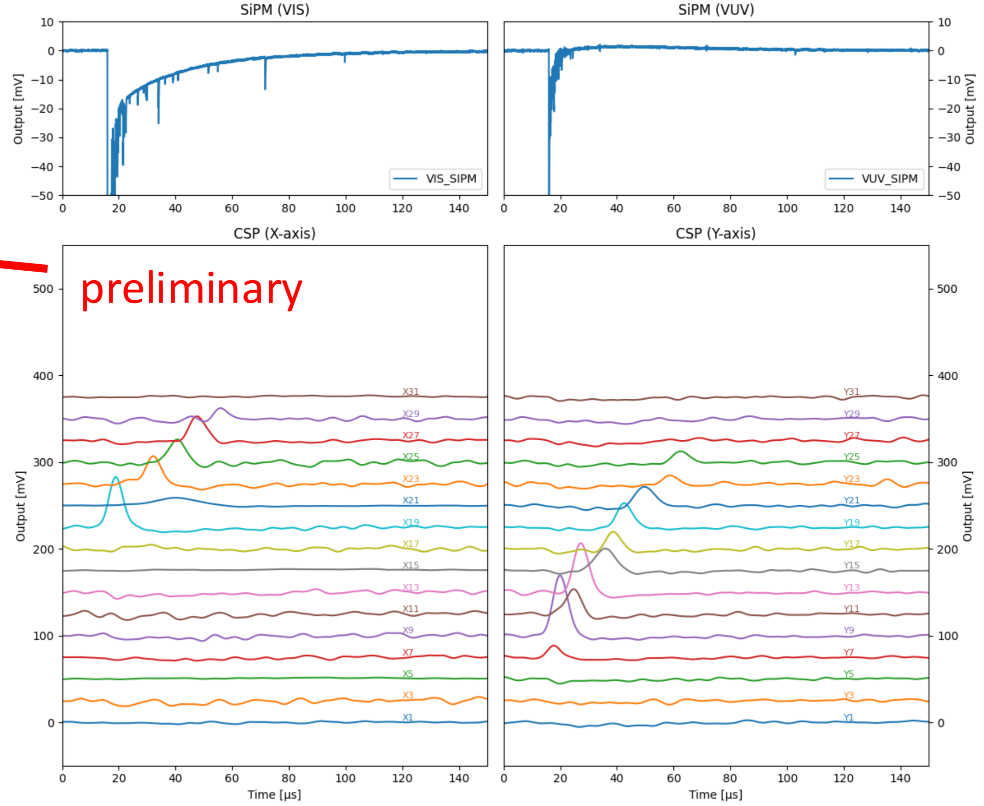


Charge readout tile

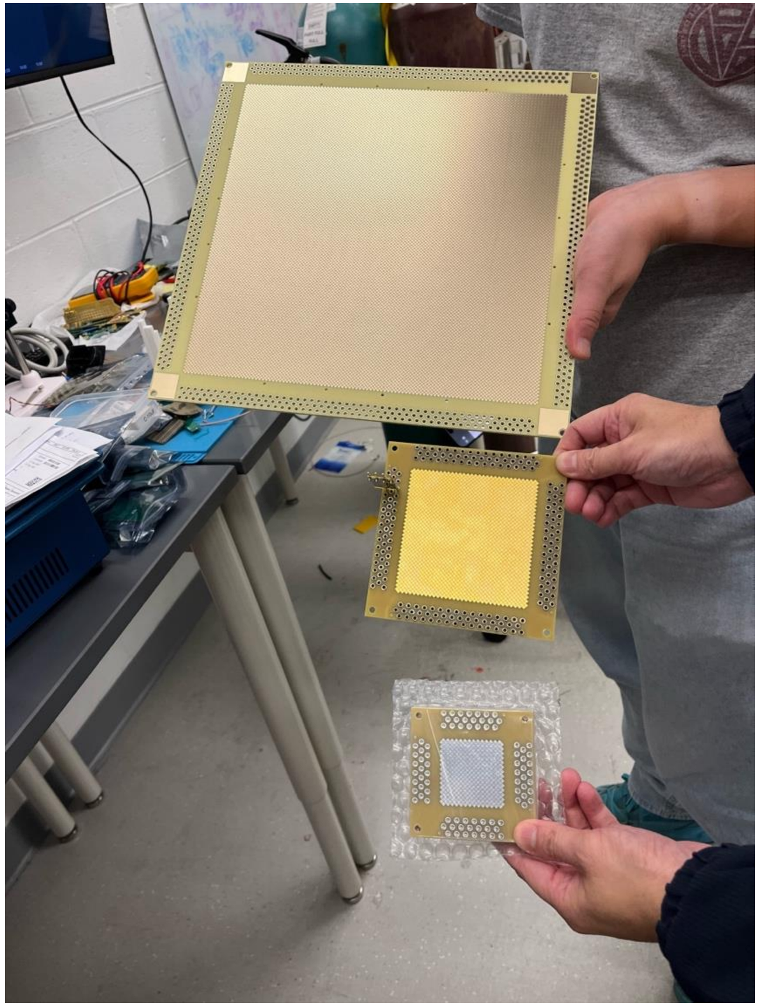
- 2D readout tile
  - More stable than wire-mesh readout for balloon payload
  - Power saving comparing to pixel readout

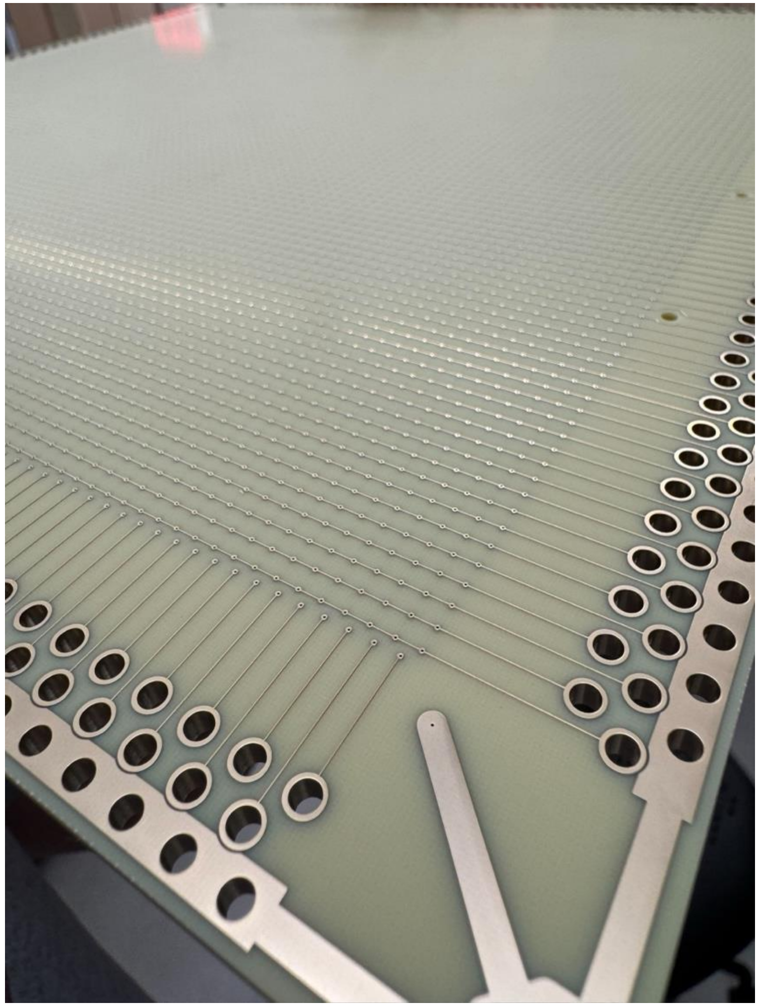


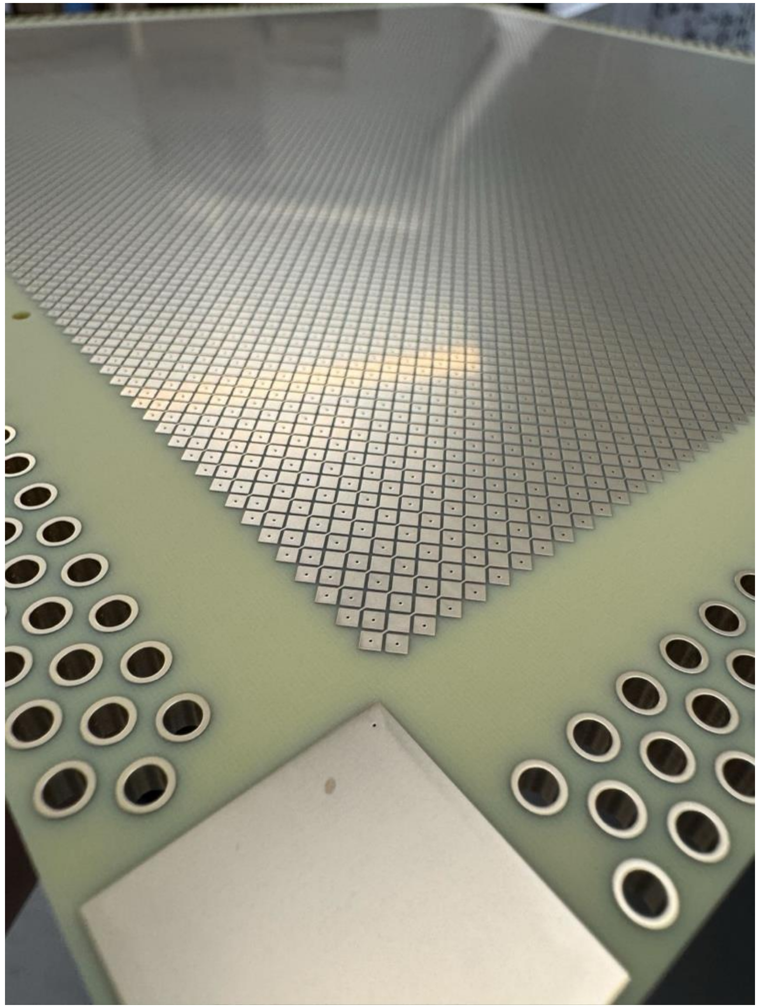




Charge readout tile

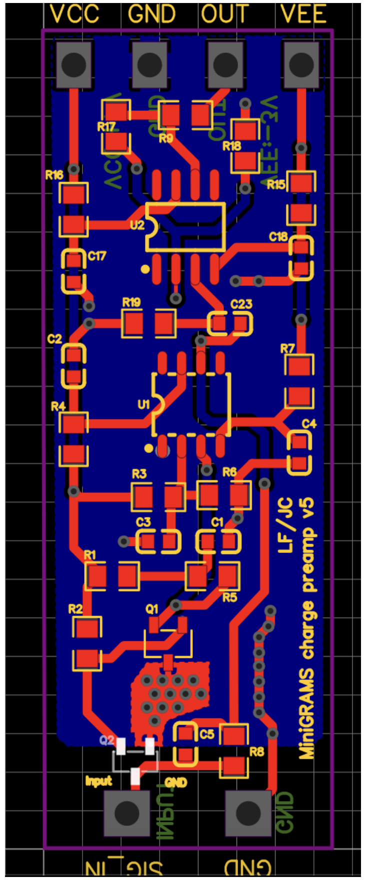


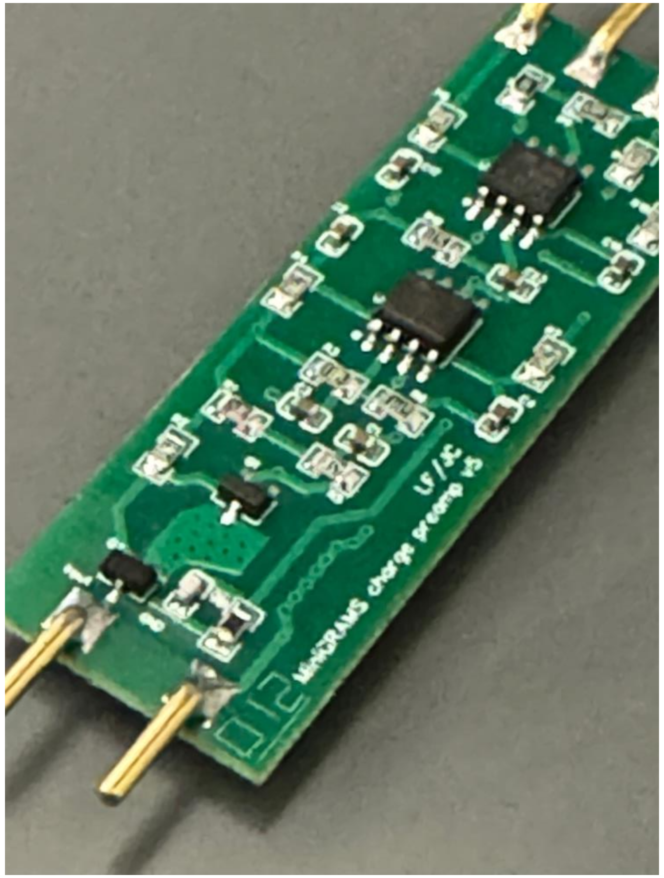




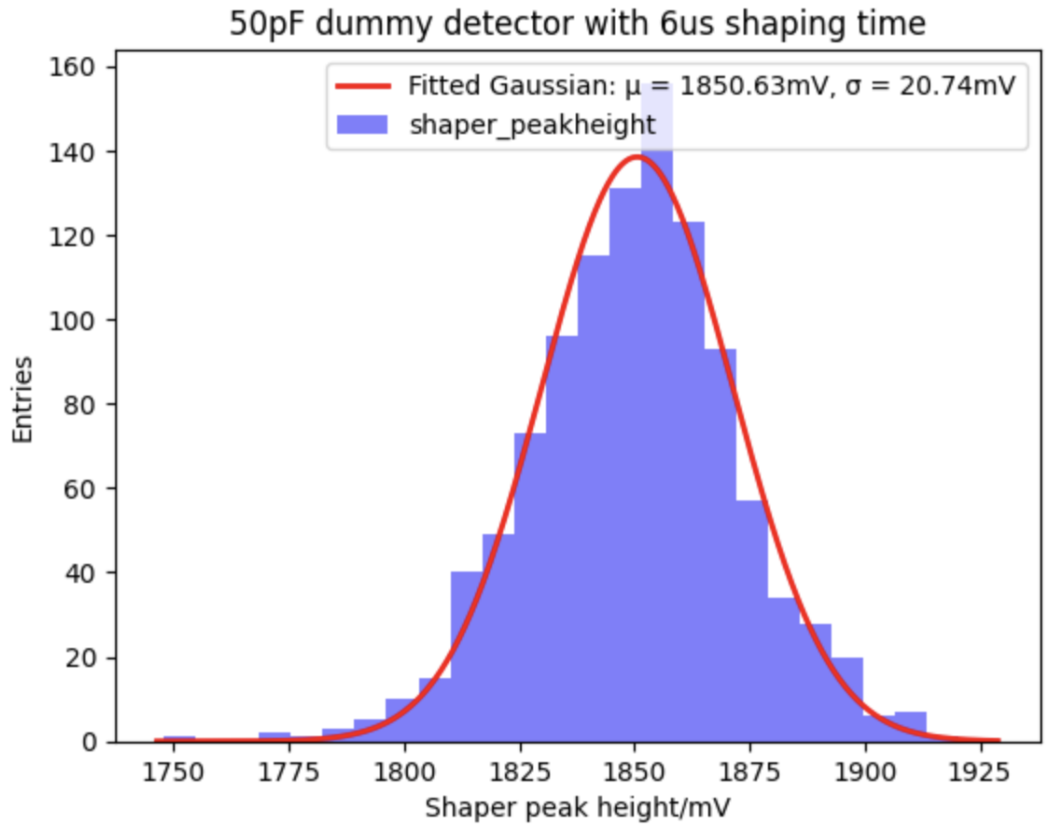
Charge readout CSP

- Charge sensitive preamp, adopted from nEXO, modified for cryo usage





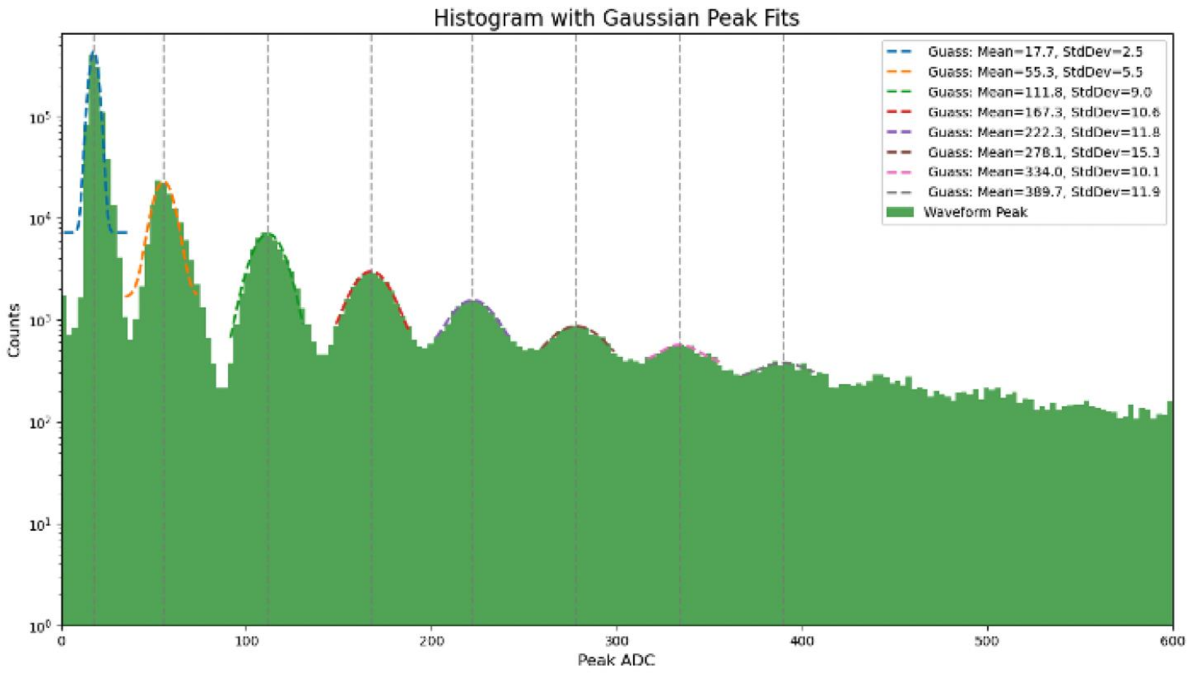
Fitted Average (mu): 1850.631828722438
Fitted Standard Deviation (sigma): 20.735336939507086



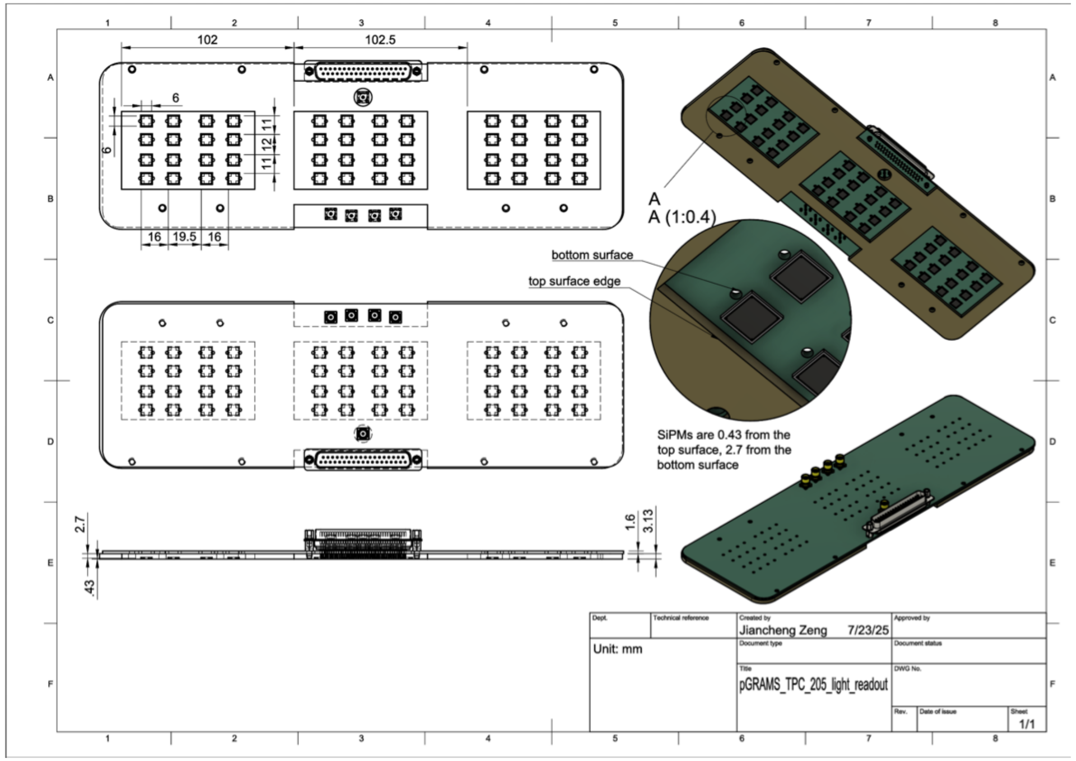
Reached 10keV resolution!!

light readout

- ❑9x SiPM cell array
  - ❑more compact than PMT

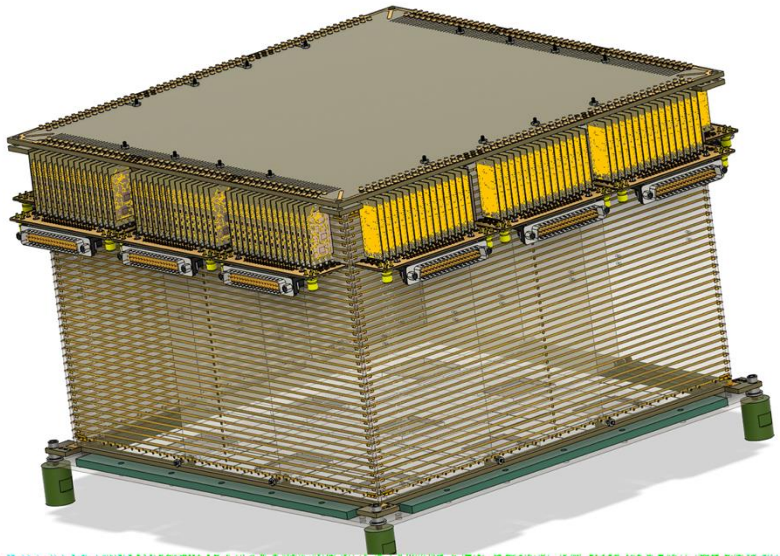


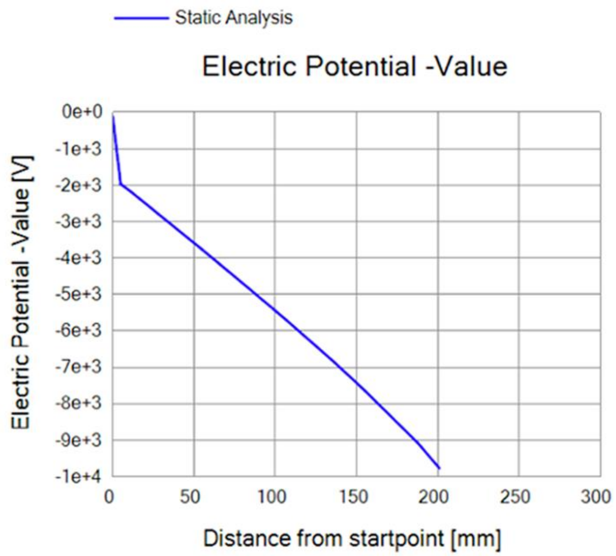
One VIS SiPM channel P.E spectrum, cr: Jon Sensenig

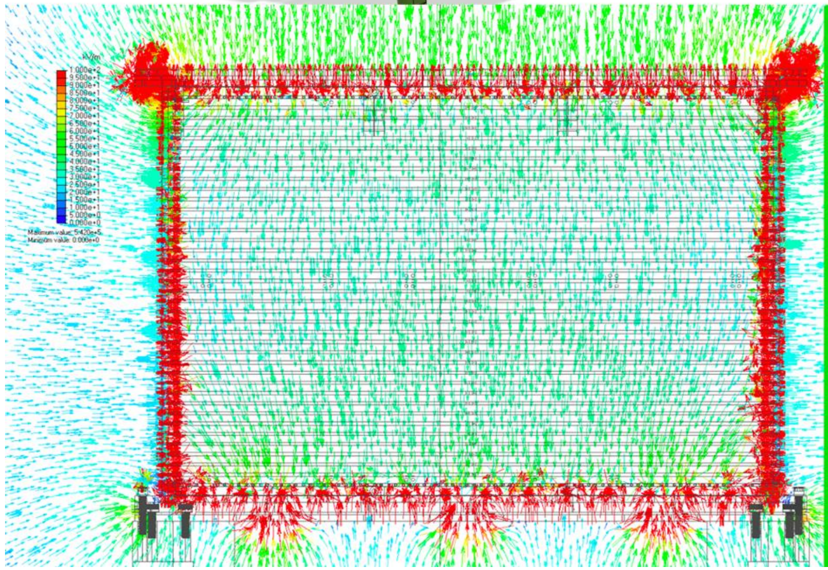


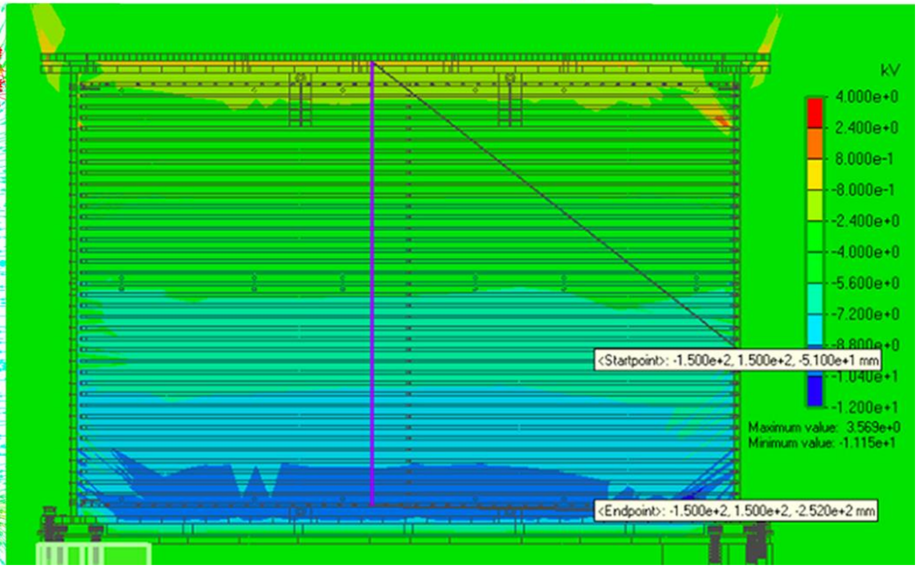
SiPM board designed by Jonathan LeyVa

Mechanical parts and drift field

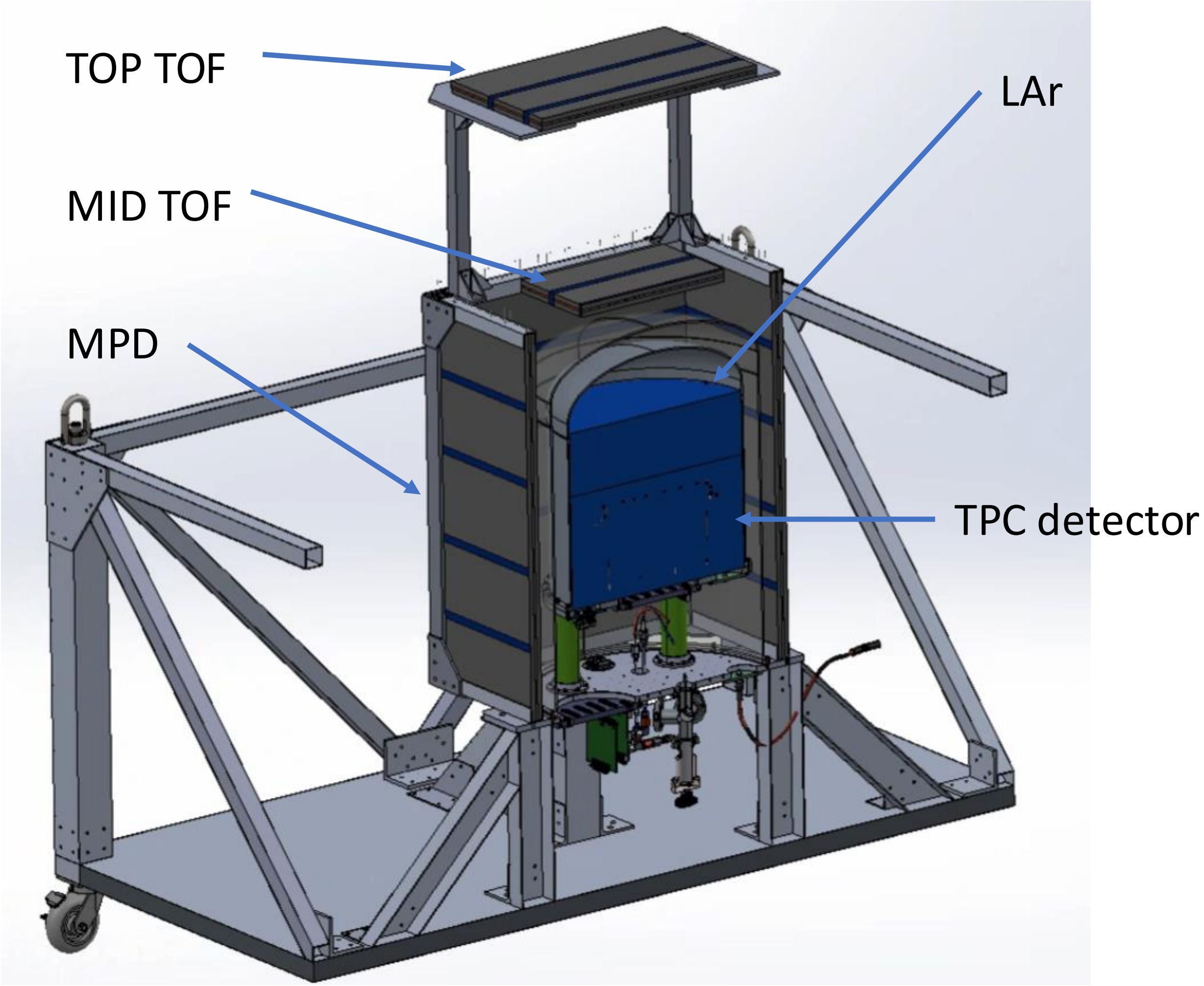








pGRAMS payload



GRAMS collaboration and timeline

International collaboration with different backgrounds/expertise
Gamma-rays, X-rays, Cosmic-rays, Neutrinos, Direct/Indirect DM searches

❑ International

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

❑ USA

- ❑ Barnard College
- ❑ Columbia University
- ❑ Howard University
- ❑ NASA GSFC
- ❑ Northeastern University
- ❑ Oak Ridge National Lab
- ❑ University of California, Berkeley
- ❑ University of Chicago
- ❑ UT Arlington
- ❑ Washington University
- ❑ Yale University

Summary

- GRAMS aims for both **gamma-ray** observations in the **poorly explored MeV** range and **indirect dark matter searches** with **antimatter**. The project started with a **balloon** experiment and will be expanded 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 **antinuclei** 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 successfully demonstrated the LArTPC detector performance during the **engineering flight** from the JAXA balloon facility and the **antiproton beam test** at J-PARC.
- As a step forward for future science flights, we will have a **prototype flight** scheduled for Spring 2026, supported by the NASA APRA program.

Thanks!

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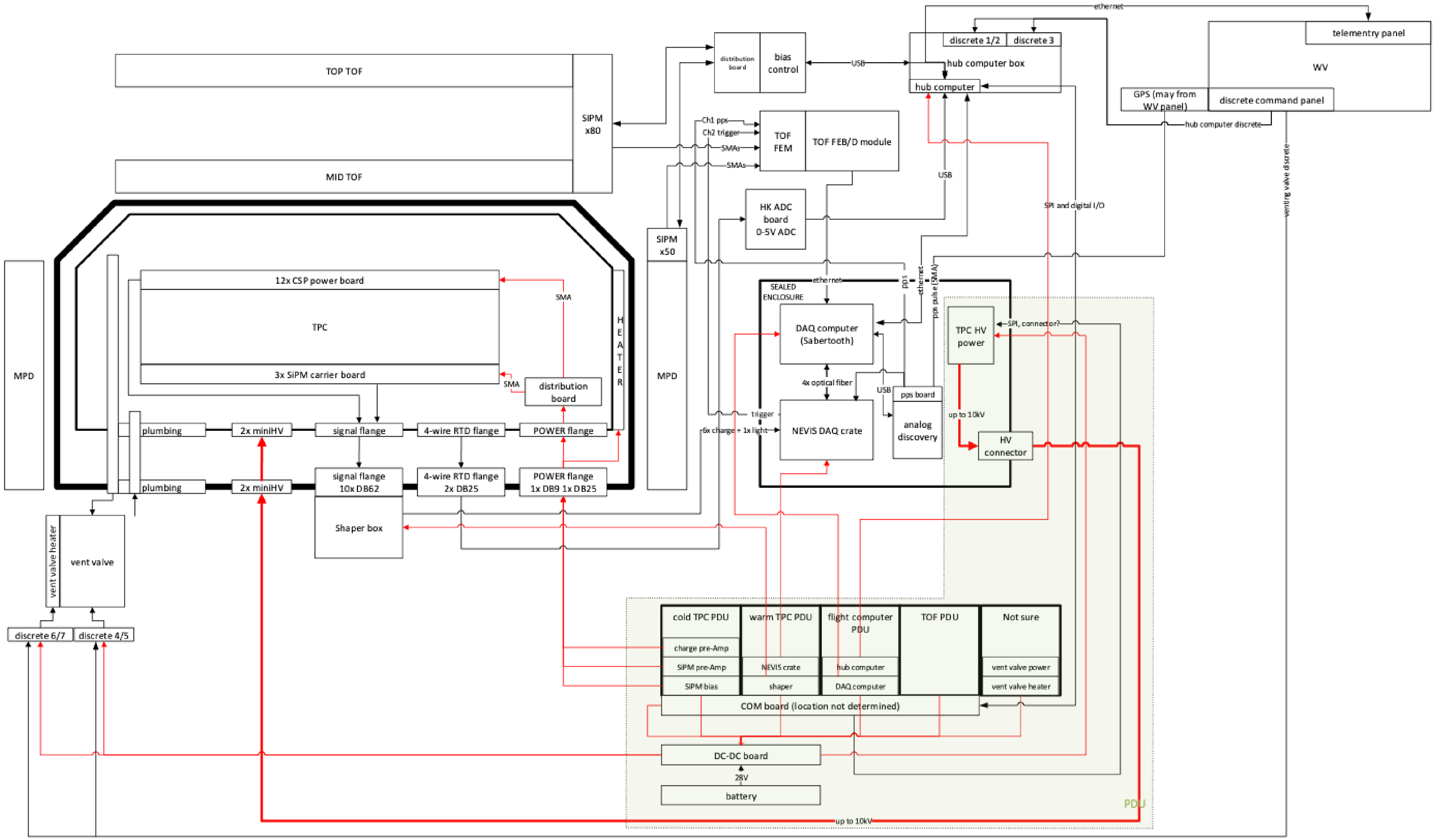
JCZeng1412@gmail.com

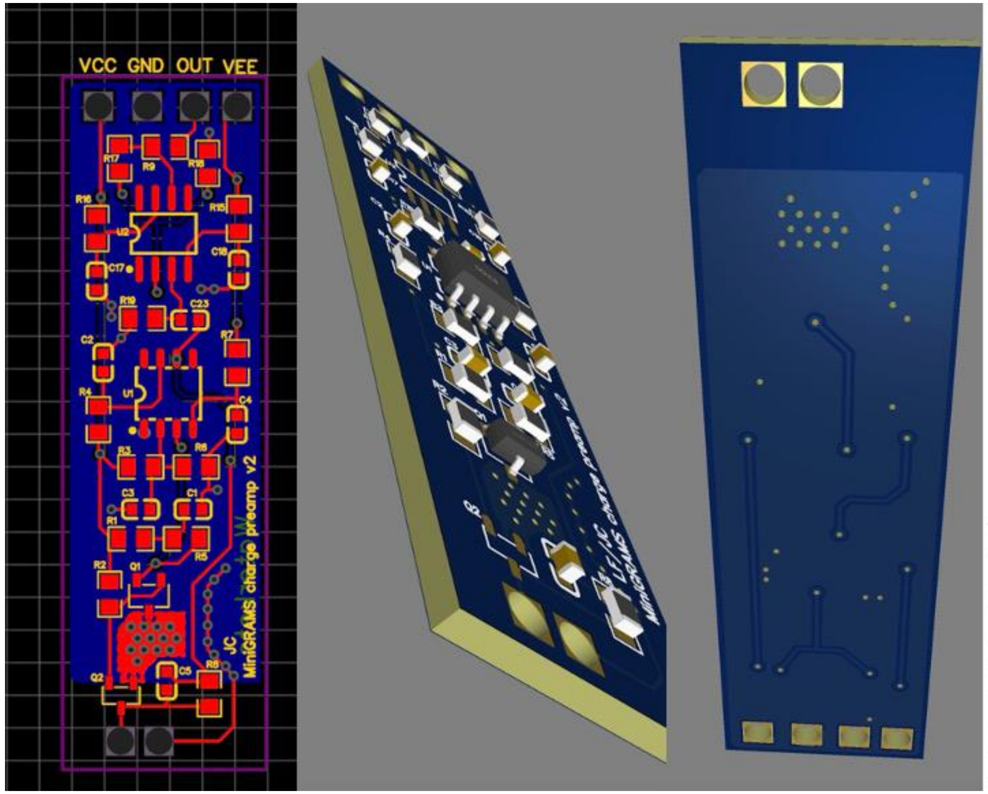
Backup slides

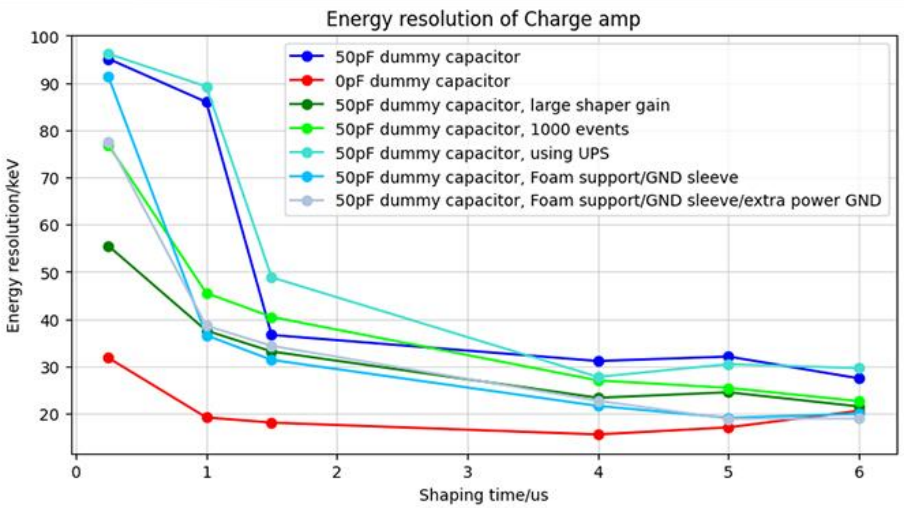
pGRAMS system diagram



pGRAMS electronics

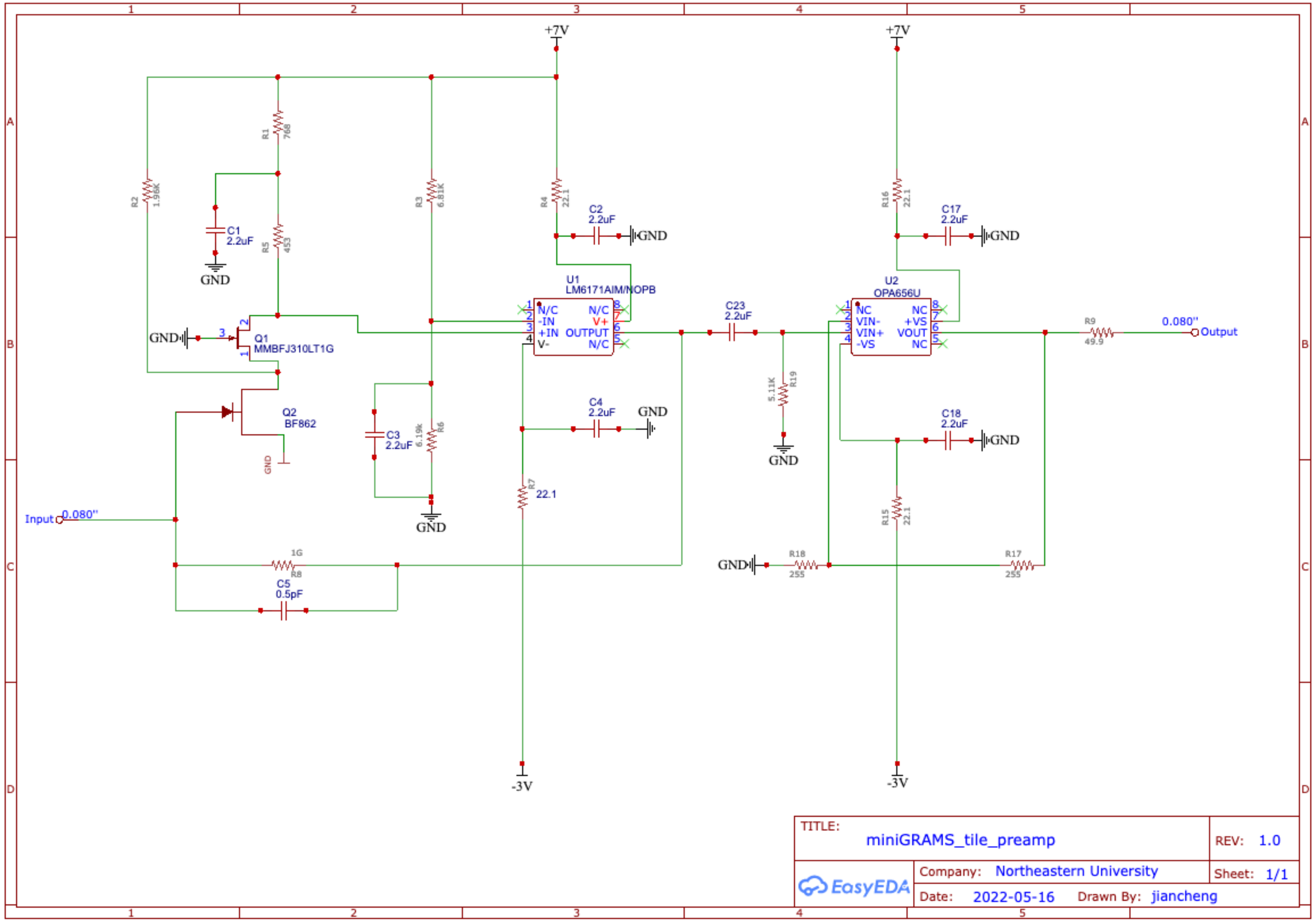
- Charge Sensitive Pre-amp(CSP) that works in cryo front end, minimize the pickup noise after readout tile





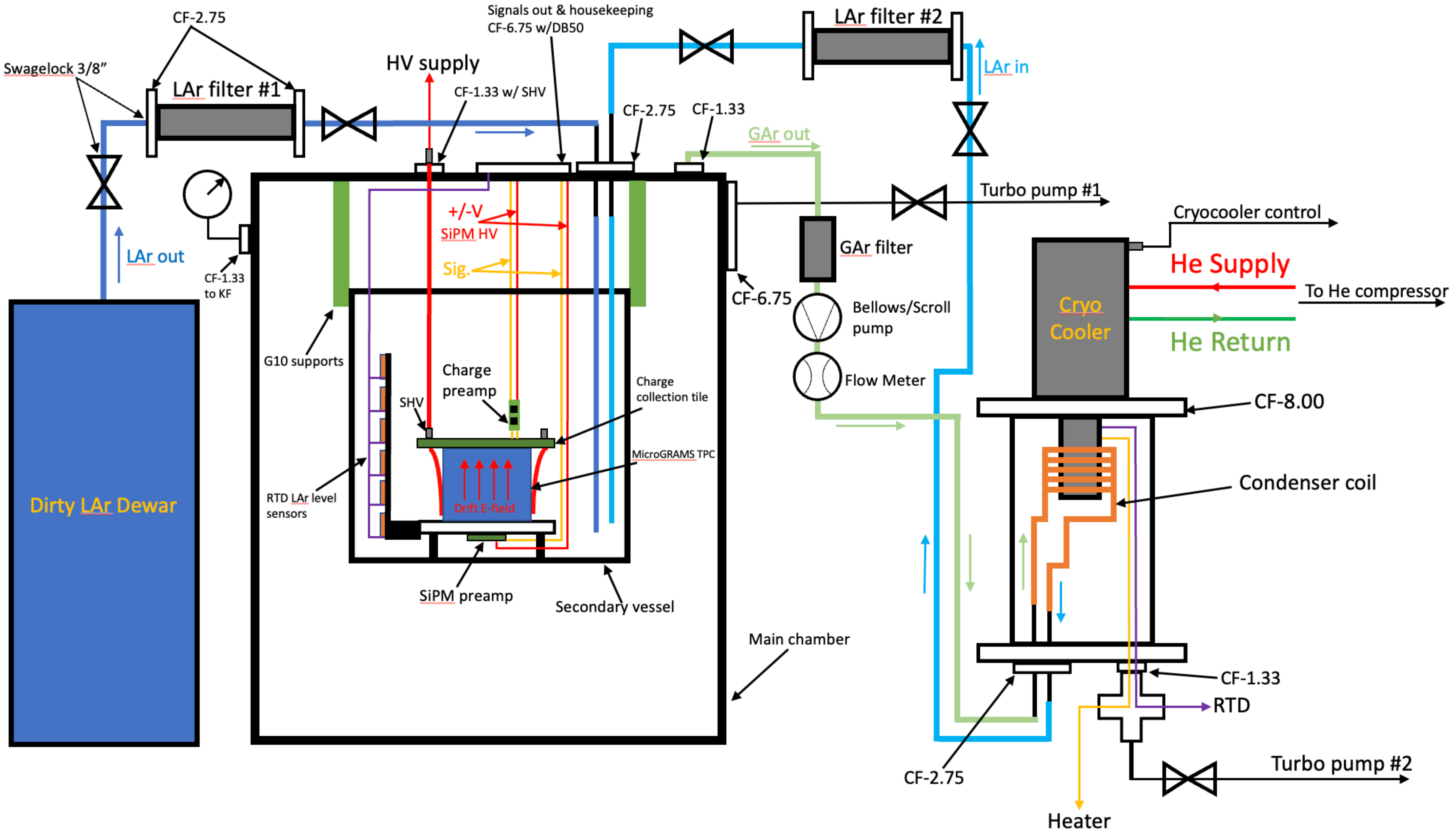
	0.25us/keV	1us/keV	1.5us/keV	4us/keV	5us/keV	6us/keV
0pF dummy	31.8	19.2	18.1	15.6	17.1	20.6
50pF dummy	55.517	37.58	33.165	23.363	24.528	21.523
50pF 1000 events	76.872	45.527	40.48	27.033	25.46	22.642
50pF no pump	185.83	43.64	47.49	25.89	21.3	21.35
50pF UPS	96.17	89.26	48.86	27.78	30.48	29.64
50pF celling GND	66.66	37.06	NaN	22.53	24.7	22.71
50pF foam/sleeve/celling GND	91.32	36.58	31.38	21.64	19.13	19.95
50pF extra power GND	77.54	38.6	34.35	22.72	18.92	18.98

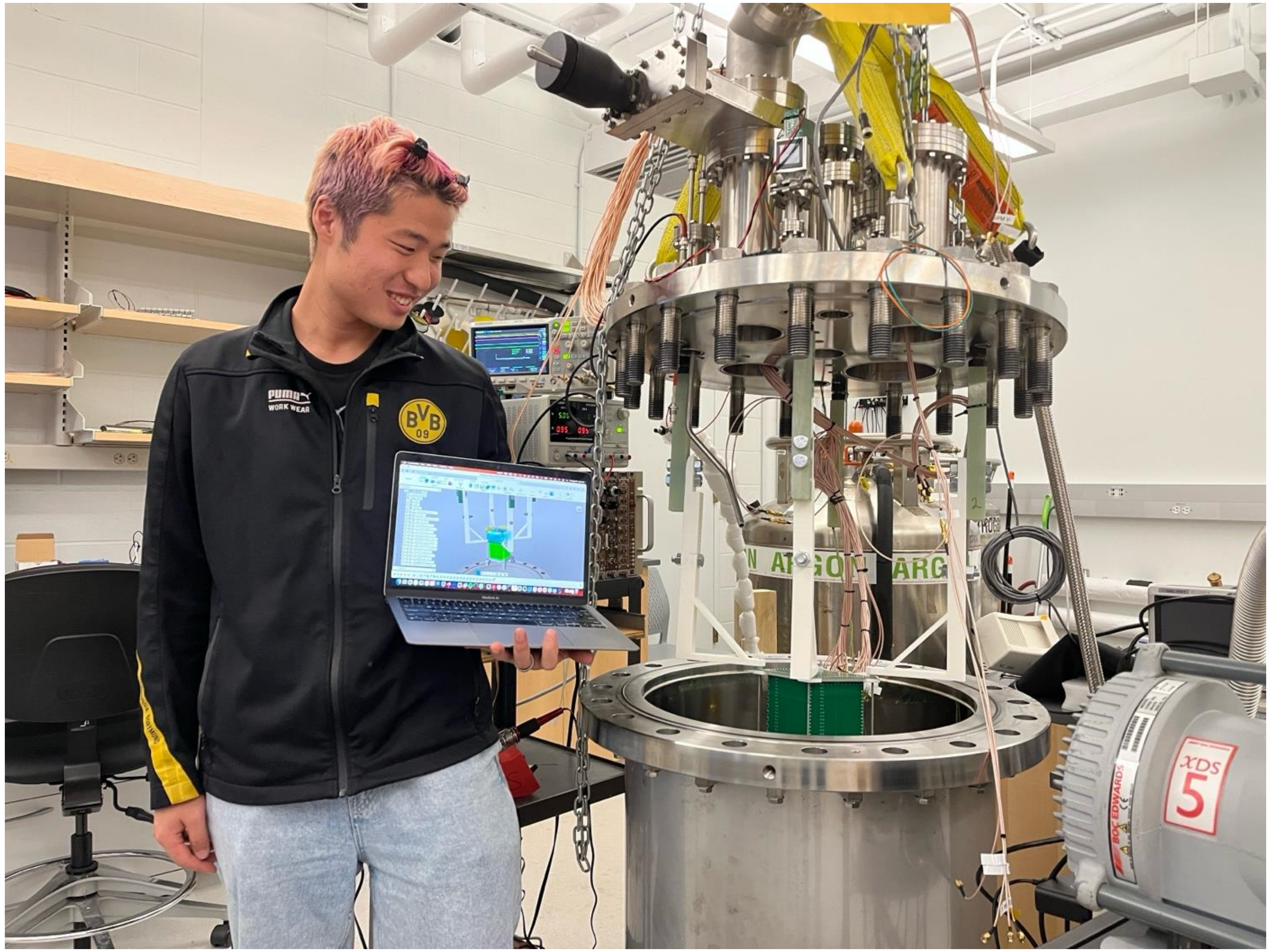
S. Arathi preparing performance analysis paper

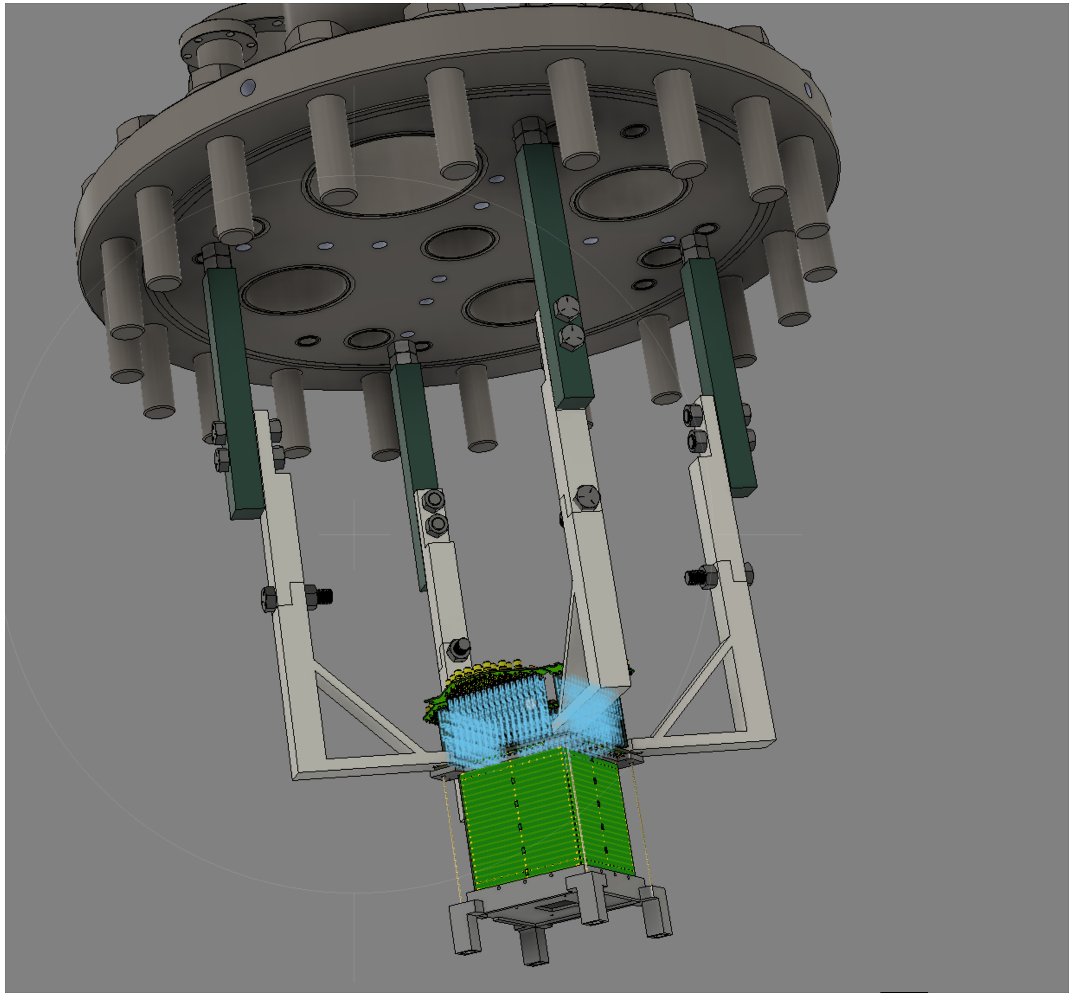


+7V
R1 768
R2 1.96K
R3 6.81K
R4 22.1
C1 2.2uF
R5 453
C2 2.2uF
GND
U1 LM6171AIM/NOPB
Q1 MMBFJ310LT1G
Q2 BF862
C3 2.2uF
R6 6.19K
C4 2.2uF
R7 22.1
Input 0.080"
R8 1G
C5 0.5pF
-3V
C23 2.2uF
R19 5.11K
U2 OPA656U
R16 22.1
C17 2.2uF
C18 2.2uF
R15 22.1
R18 255
R17 255
R9 49.9
0.080" Output
TITLE: miniGRAMS_tile_preamp
REV: 1.0
Company: Northeastern University
Sheet: 1/1
Date: 2022-05-16
Drawn By: jiancheng
EasyEDA

miniGRAMS

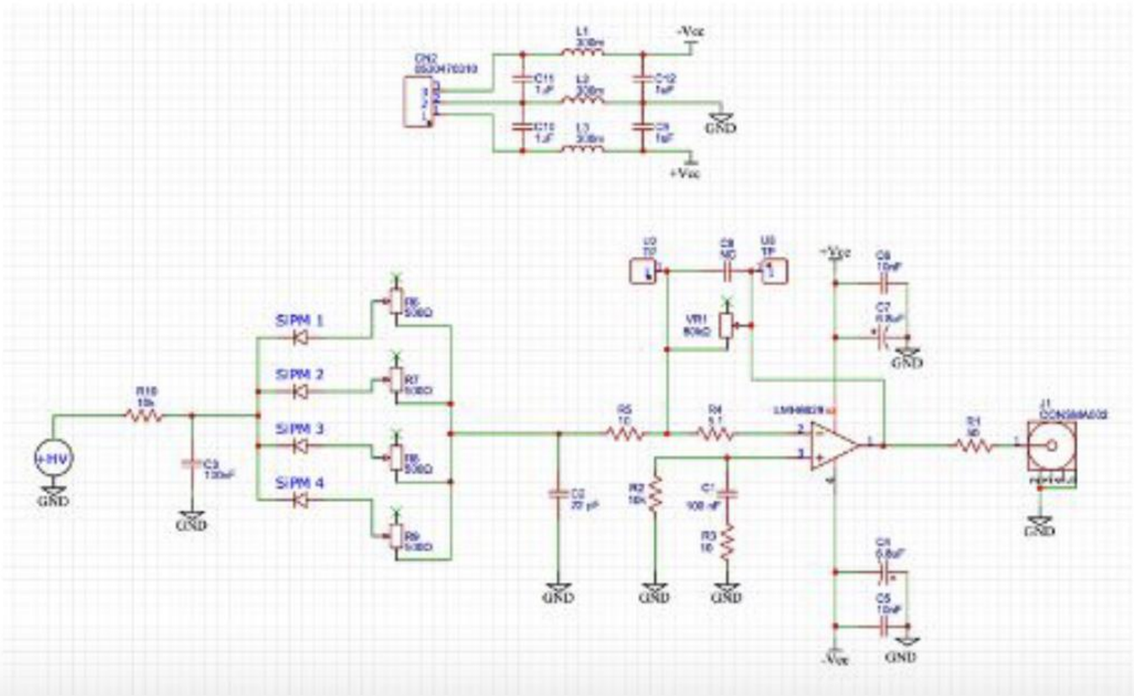

Swagelock 3/8"
CF-2.75
LAr filter #1
HV supply
CF-1.33 w/ SHV
Signals out & housekeeping
CF-6.75 w/DB50
LAr filter #2
LAr in
CF-2.75
CF-1.33
GAr out
Turbo pump #1
Cryocooler control
LAr out
CF-1.33
to KF
+/-V
SiPM HV
Sig.
GAr filter
He Supply
To He compressor
CF-6.75
Bellows/Scroll
pump
Cryo
Cooler
He Return
G10 supports
Charge
preamp
Charge
collection tile
Flow Meter
CF-8.00
SHV
MicroGRAMS TPC
Condenser coil
Dirty LAr Dewar
RTD LAr level
sensors
Drift E-field
SiPM preamp
Secondary vessel
Main chamber
CF-1.33
RTD
Turbo pump #2
CF-2.75
Heater

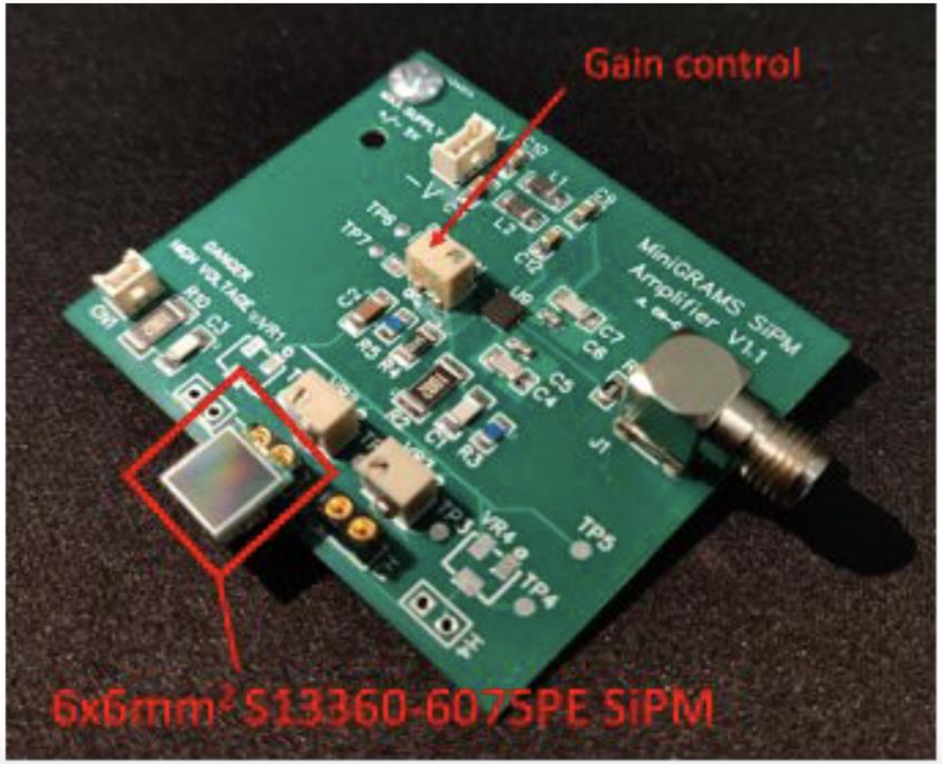

PUMA
WORK WEAR
BVB
09
XDS
5
BOC EDWARDS



Proto type SiPM board

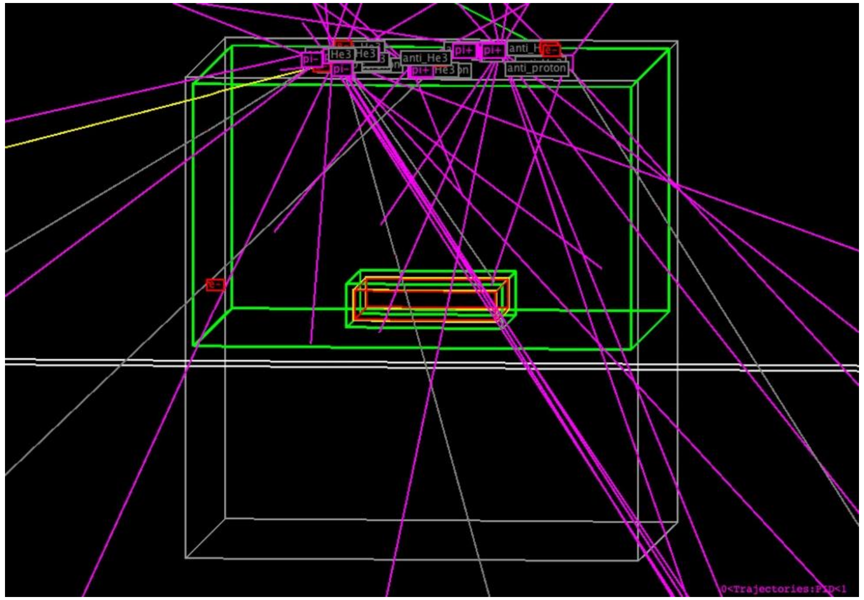
- Texas Instruments LMH6629
  - Input noise: 0.69 nV/√Hz and 2.6 pA/√Hz
  - 900 MHz bandwidth (includes controllable compensation feature that sacrifices bandwidth for improved stability at gains as low as 4V/V)
  - 1600 V/μs slew rate
  - Hetero-junction BJT, good for low temp stability
  - Typical power consumption with 3.4V (+/- 1.7V) of dynamic range → ~30 mW @ T=87K

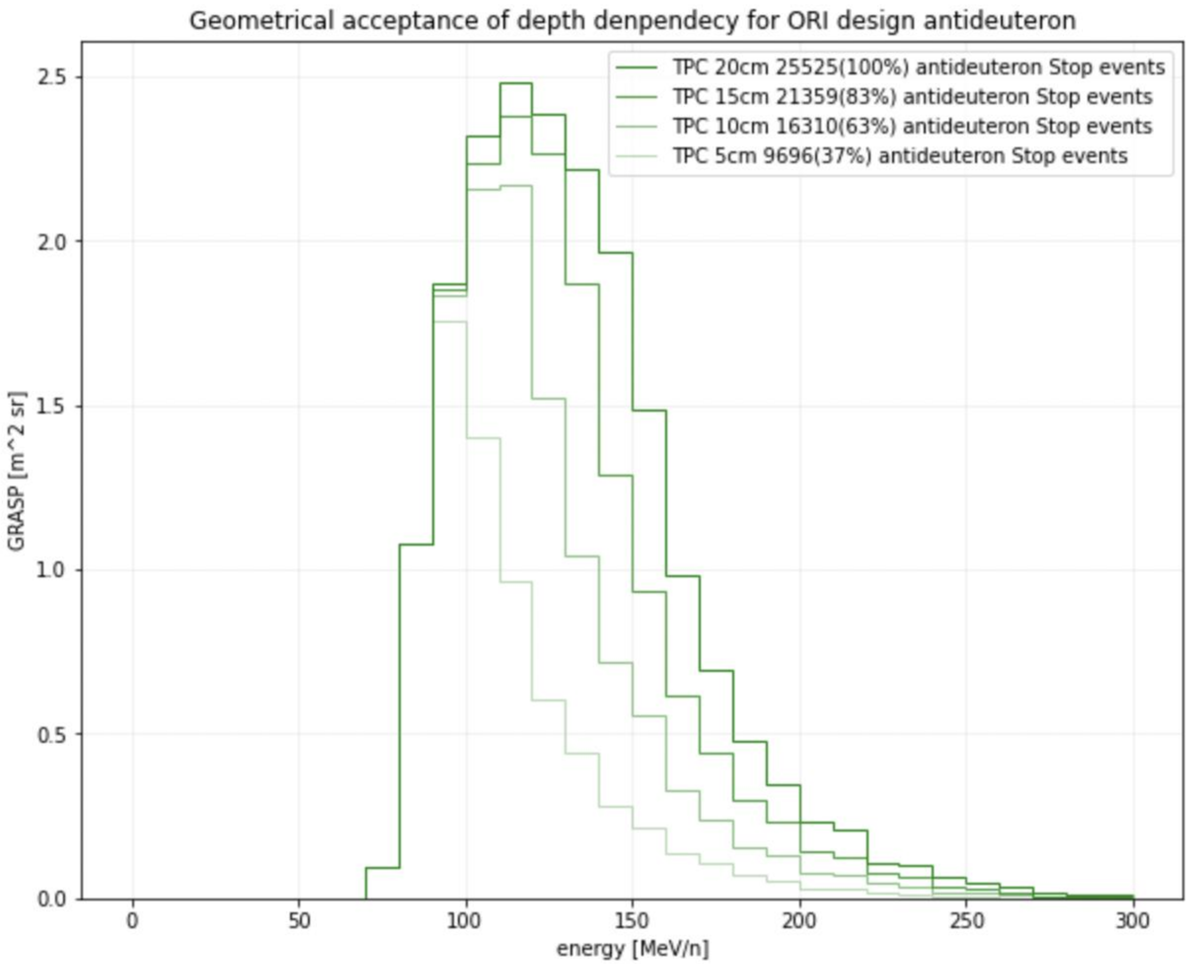




Impact of LArTPC thickness

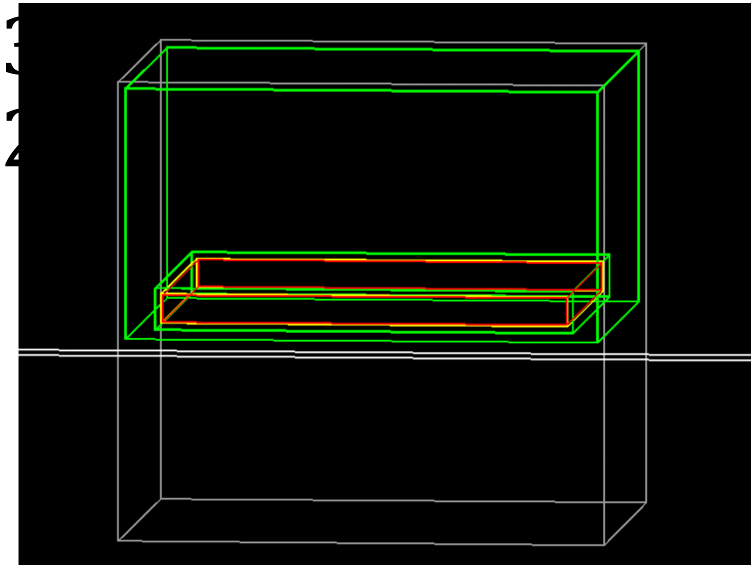
- Randomly generate antideuteron from the sky and collect events that stop and annihilate inside LArTPC.

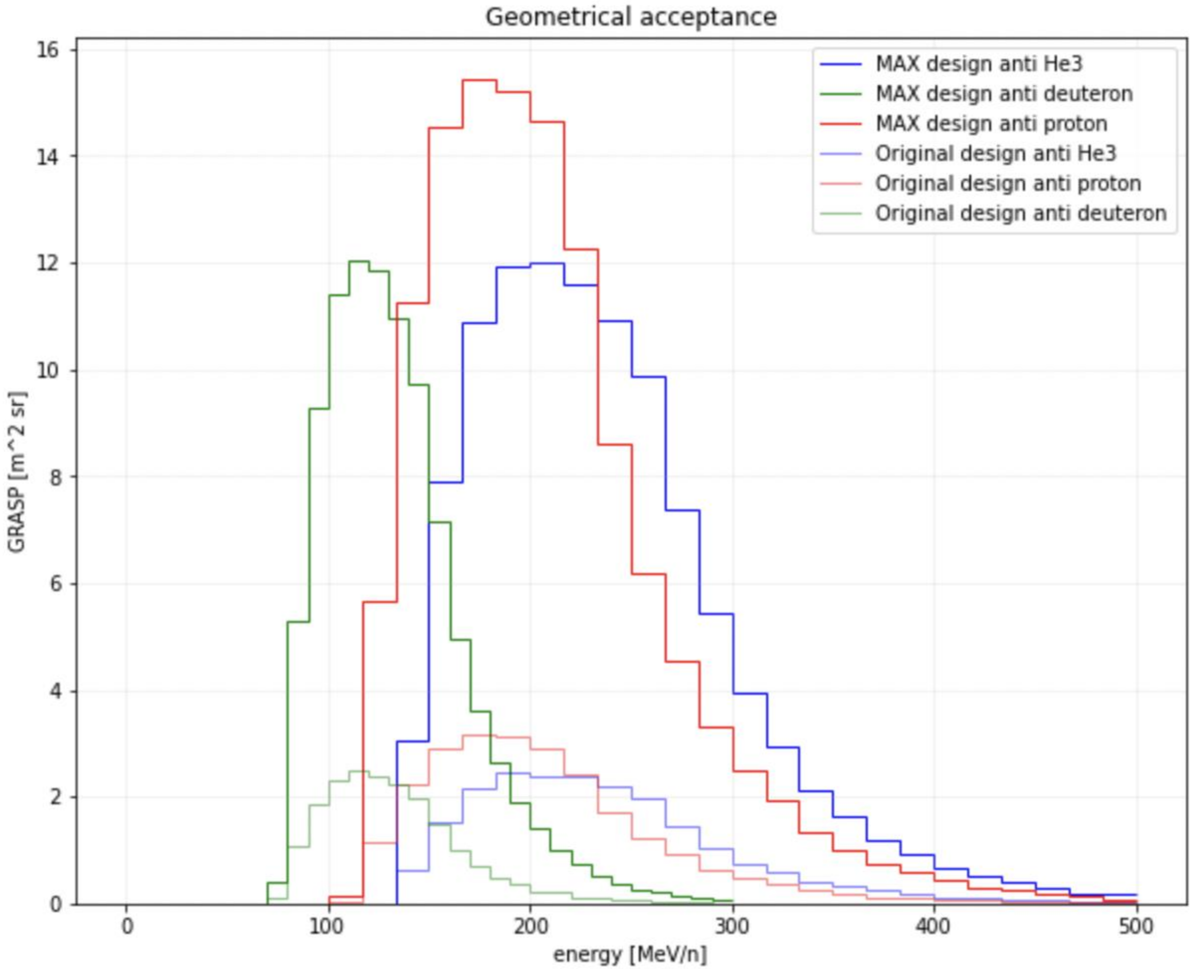




Detector horizontally expand

- Original design: $140cm \times 140cm \times 20cm$
- MAX design:





TPC shape

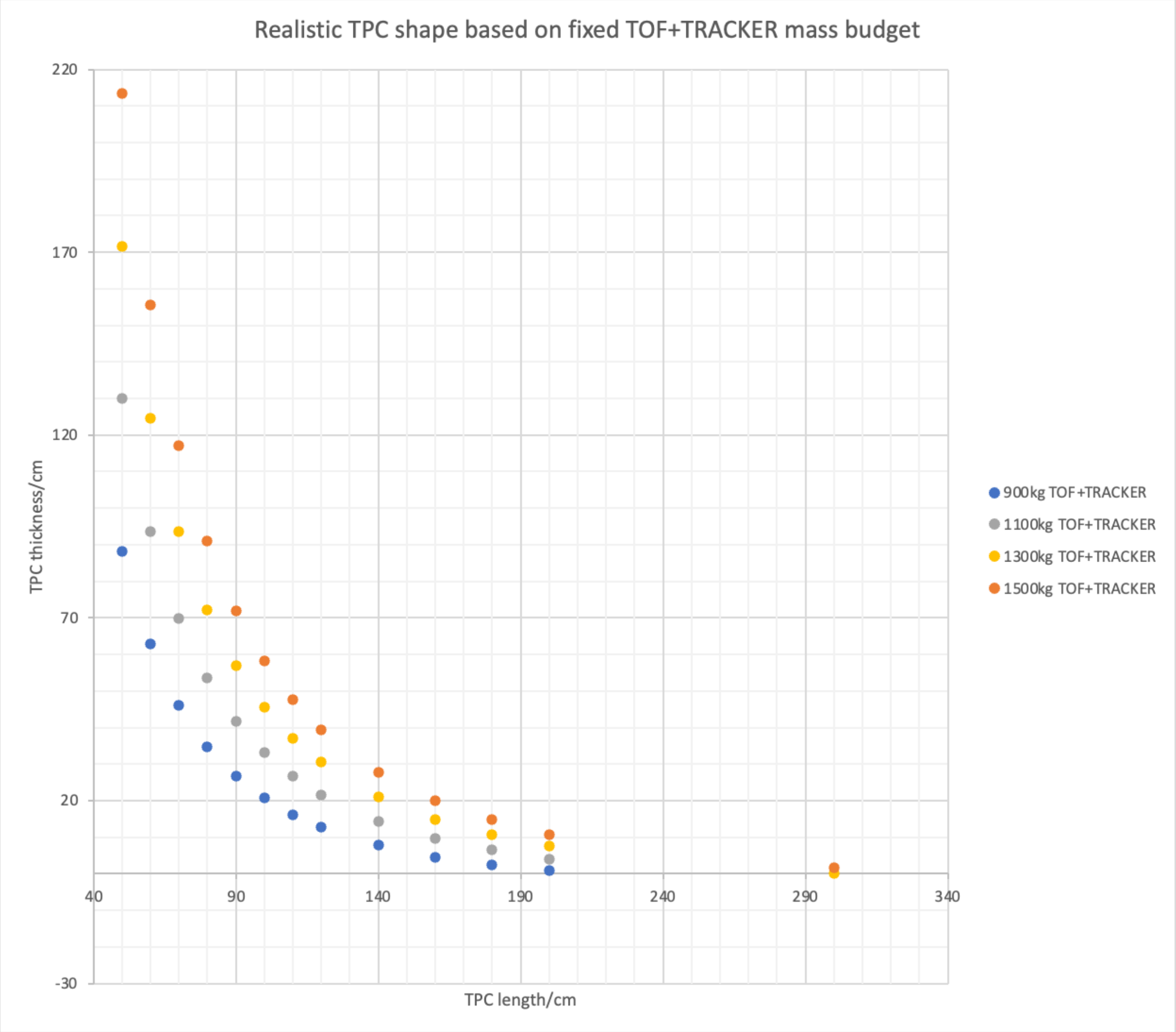
Tracker + TOF 900kg	TOF CONF 1424
TPC length [cm]	TPC thickness [cm]
50	88.2
60	62.8
70	46.2
80	34.8
90	26.6
100	20.7
110	16.2
120	12.7
140	7.8
160	4.6
180	2.3
200	0.8
300	-2.9
600	-4.8

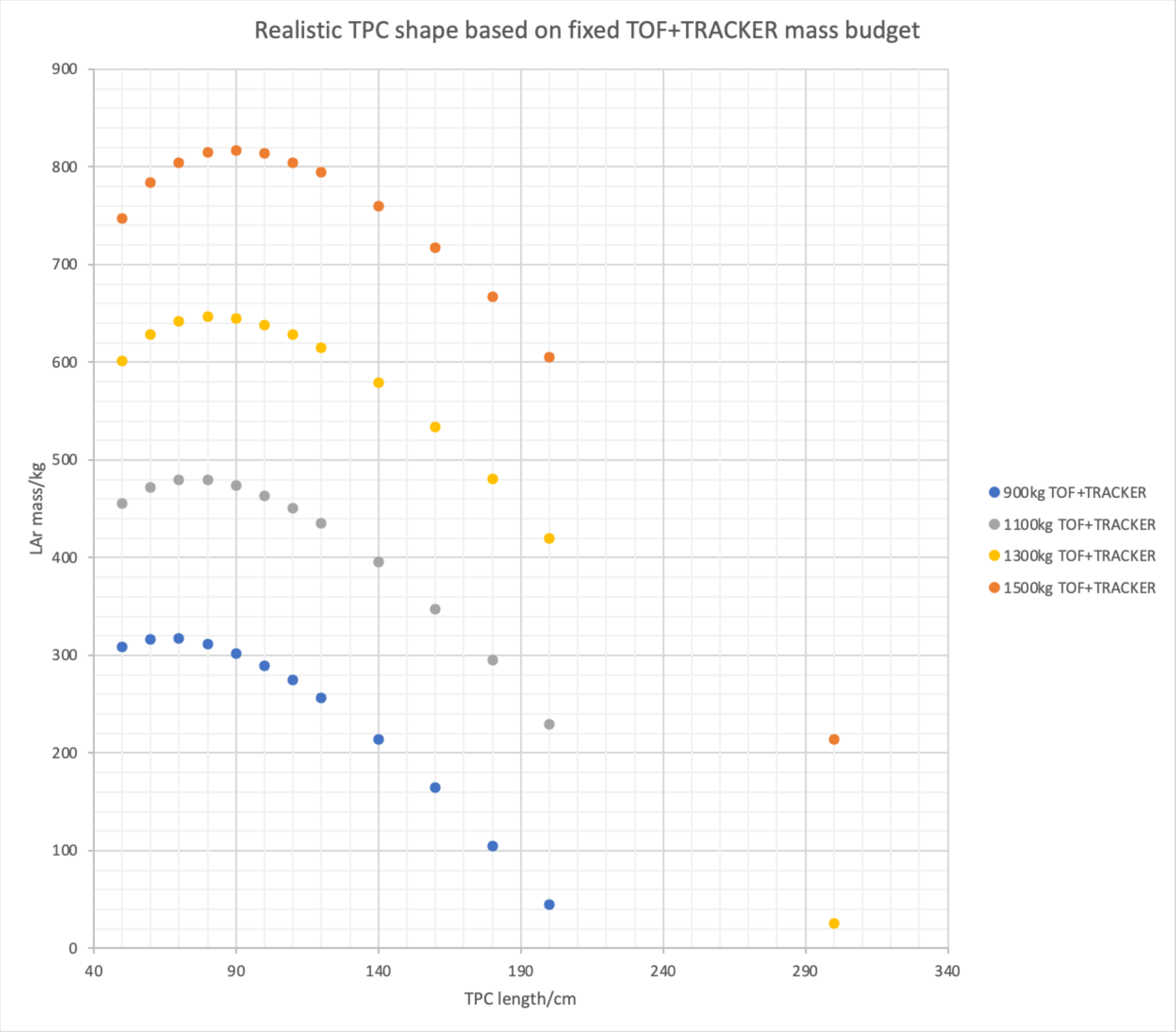
Tracker + TOF 1100kg	TOF CONF 1424
TPC length [cm]	TPC thickness [cm]
50	130
60	93.7
70	69.9
80	53.5
90	41.8
100	33.1
110	26.6
120	21.6
140	14.4
160	9.7
180	6.5
200	4.1
300	-1.4
600	-4.4

Tracker + TOF 1300kg	TOF CONF 1424
TPC length [cm]	TPC thickness [cm]
50	171.7
60	124.6
70	93.6
80	72.2
90	56.9
100	45.6
110	37.1
120	30.5
140	21.1
160	14.9
180	10.6
200	7.5
300	0.2
600	-4

Tracker + TOF 1500kg	TOF CONF 1424
TPC length [cm]	TPC thickness [cm]
50	213.5
60	155.5
70	117.2
80	90.9
90	72
100	58.1
110	47.5
120	39.4
140	27.7
160	20
180	14.7
200	10.8
300	1.7
600	-3.7

TPC Shape


Realistic TPC shape based on fixed TOF+TRACKER mass budget
220
170
120
70
20
-30
TPC thickness/cm
40
90
140
190
240
290
340
TPC length/cm
900kg TOF+TRACKER
1100kg TOF+TRACKER
1300kg TOF+TRACKER
1500kg TOF+TRACKER


Realistic TPC shape based on fixed TOF+TRACKER mass budget
900
800
700
600
500
400
300
200
100
0
LAr mass/kg
40
90
140
190
240
290
340
TPC length/cm
900kg TOF+TRACKER
1100kg TOF+TRACKER
1300kg TOF+TRACKER
1500kg TOF+TRACKER

Mass budget comparison