GRAMS

A Liquid Argon Telescope for MeV Gamma-Ray Astronomy and Dark Matter Searches

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GRAMS

Gamma-Ray and AntiMatter Survey

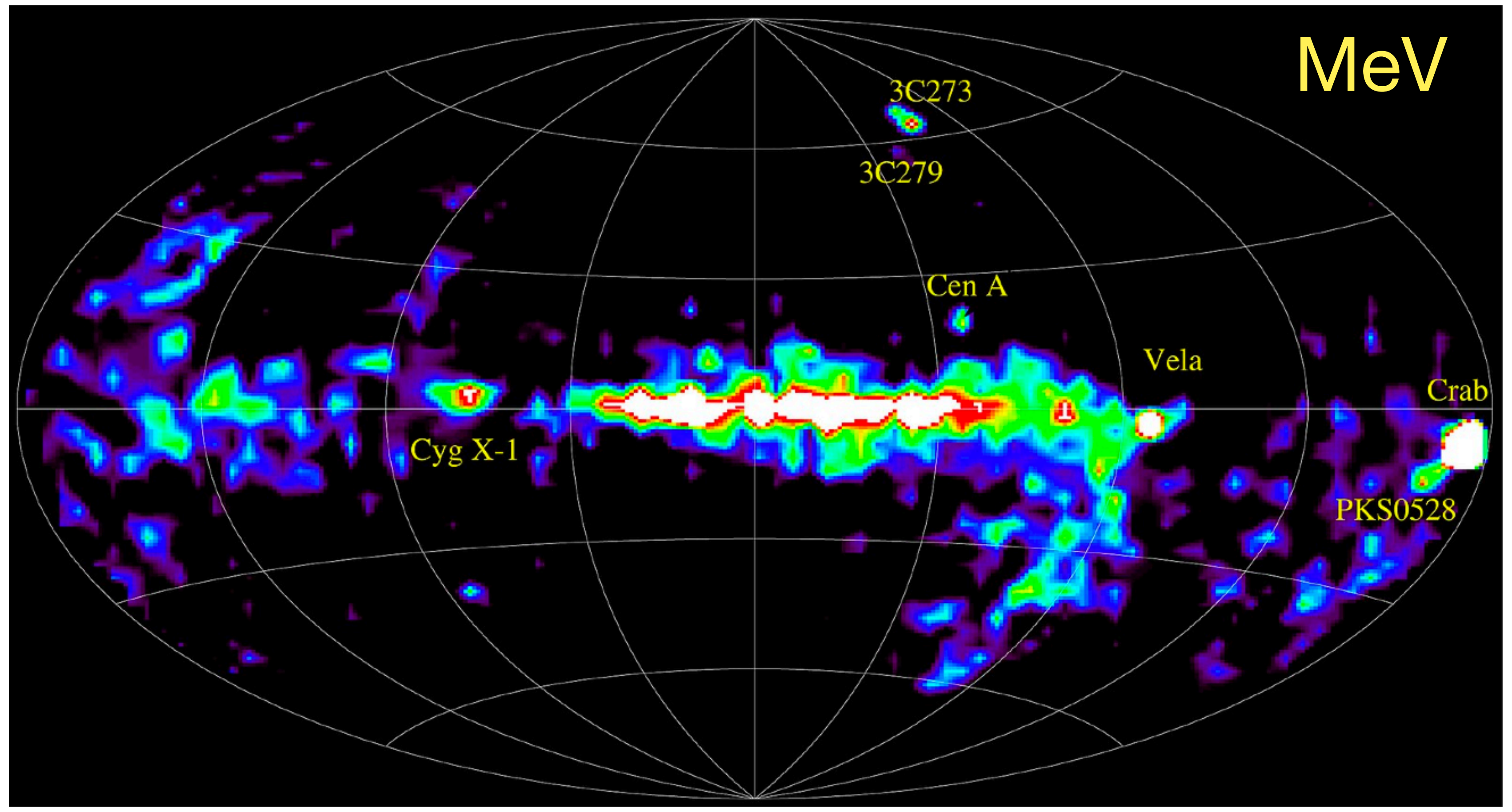
Deploying a huge liquid argon detector into the sky

1. ultra-long duration balloon flights around late 2020s–early 2030s
2. a satellite-based deep all-sky survey mission in 2030s–2040s

MeV gamma-ray astronomy

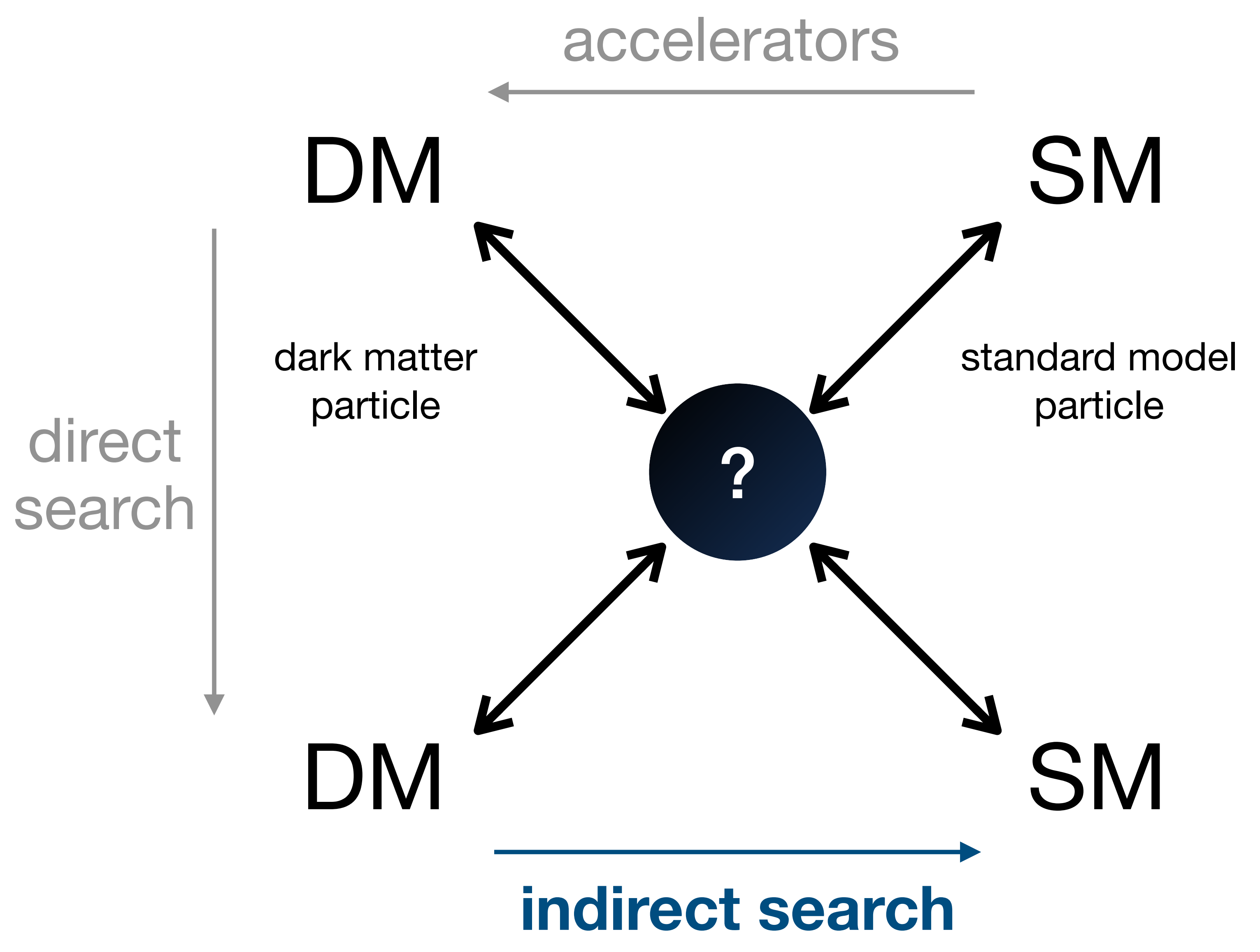
✓ Nuclear astrophysics

✓ Particle acceleration—particularly focusing on the thermal-to-nonthermal transition

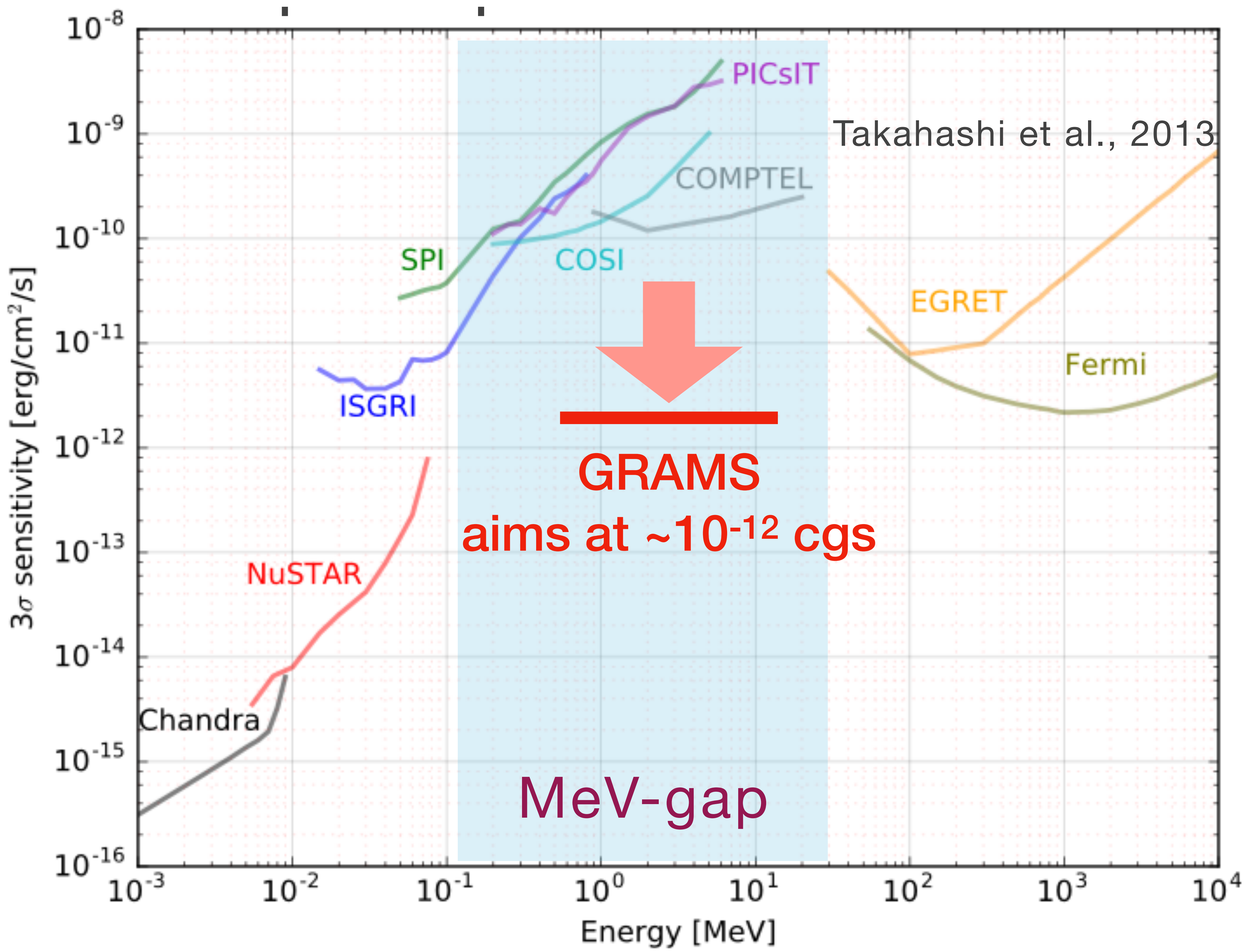


Indirect dark matter search

background-free search via hadronic channels using antideuteron/antihelium



Sensitivity gap at the MeV band



$10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}} \sim 10^{-6}\,\mathrm{photons\,s^{-1}\,cm^{-2}}$ for 1 MeV

r-process site candidates

Supernova

Neutron star mergers

MeV gamma rays give us unique probes of cosmic nuclear reactions.

However, nuclear lines are very faint.

For high sensitivity, we need a **large effective area**
to obtain **high photon statistics**, and to obtain **precise background estimate**.

Quick summary of MeV science

There is enormous discovery space in the unexplored MeV/sub-GeV bands.

- Nucleosynthesis in supernovae and neutron star mergers
- Nuclear reactions in black hole accretion flows
- Cosmic ray interactions in interstellar medium
- Energy peak of synchrotron radiation from the most efficient cosmic accelerators
- Transition from thermal to non-thermal distribution of particles (triggers or initiation of particle acceleration)
- Low energy limit of cosmic rays
- Probes of cosmic neutrino generation sites
- Dark matter particles and primordial black holes

Quick note on sensitivity

- We measure events as the sum of the signal and background.

  $$C = S + B_{\mathrm{True}}$$

- The signal is obtained by

  $$S = C - B_{\mathrm{Estimate}}$$

- The error of the signal:

  $$\Delta S = \Delta C \oplus \Delta B_{\mathrm{Estimate}}$$

  $$\Delta S \simeq \Delta B_{\mathrm{True}} \oplus \Delta B_{\mathrm{Estimate}}$$ Recall $S \ll B_{\mathrm{True}}$ for MeV faint sources

- This error gives our sensitivity:

  $$\frac{\Delta S}{S} = \frac{\sqrt{bAT}}{\text{flux} \cdot AT} \qquad \therefore \text{flux} = \left(\frac{S}{\Delta S}\right)\sqrt{\frac{b}{AT}}$$

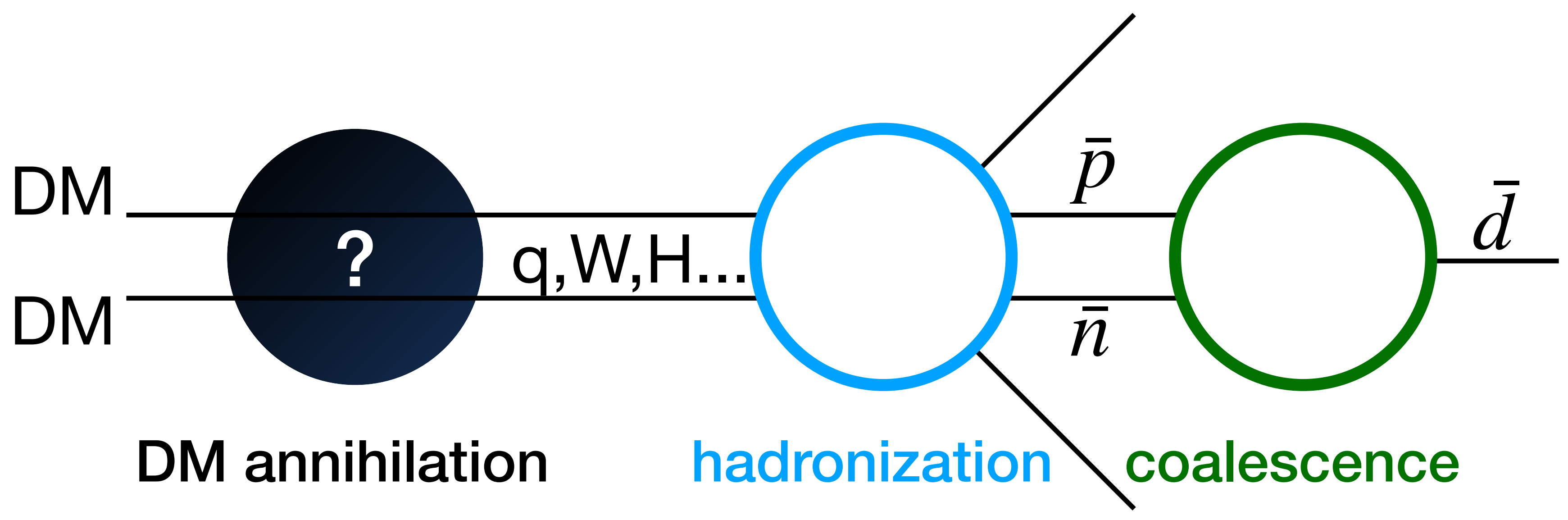
  (simplified argument, depending on the background estimation)

  where A: effective area, T: observation time, b: background rate per effective area

- To have a better sensitivity, maximize the area, and minimize the background level.

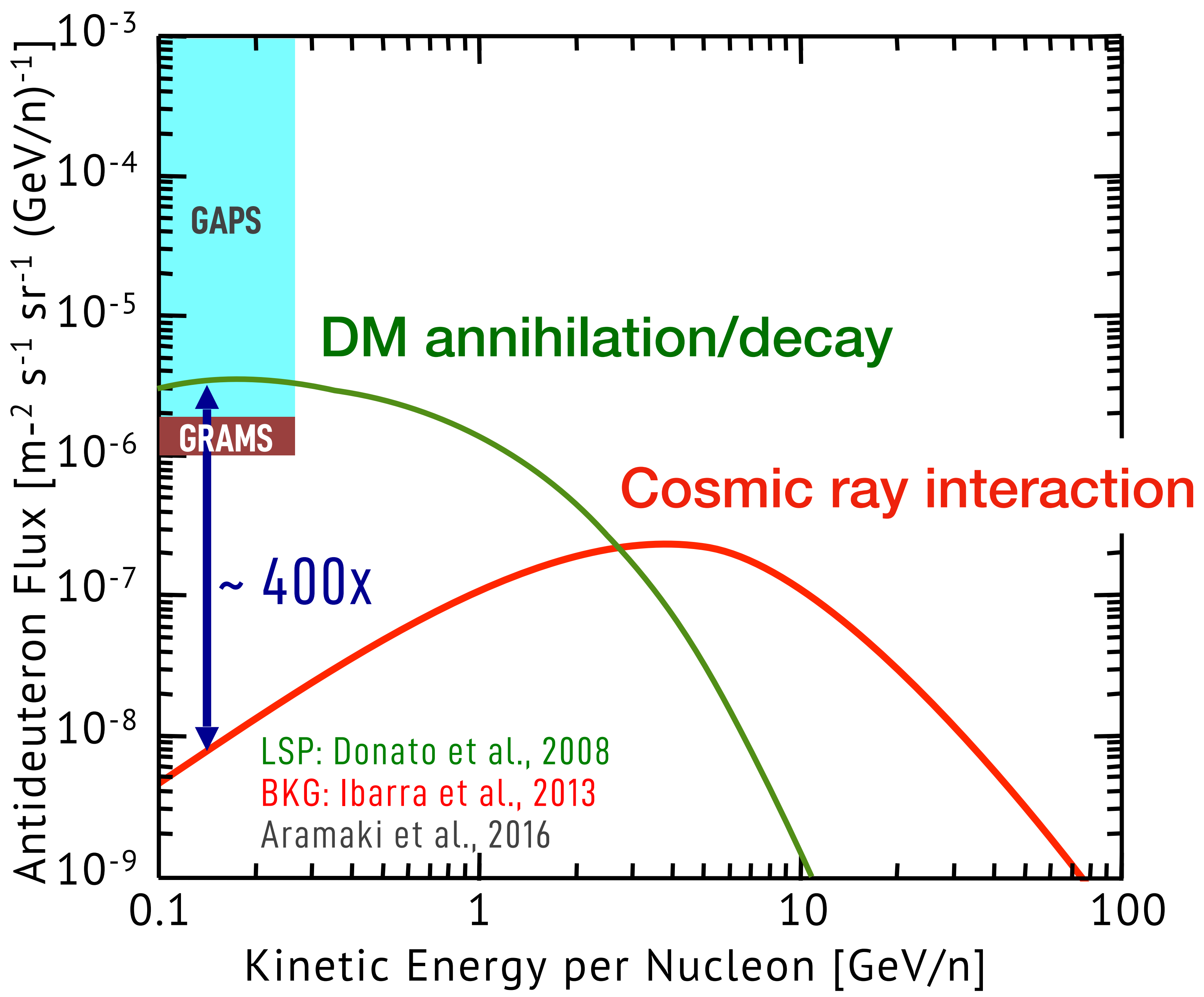
Dark matter search with antideuteron

Primary: dark matter annihilation



Secondary: cosmic ray interaction

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

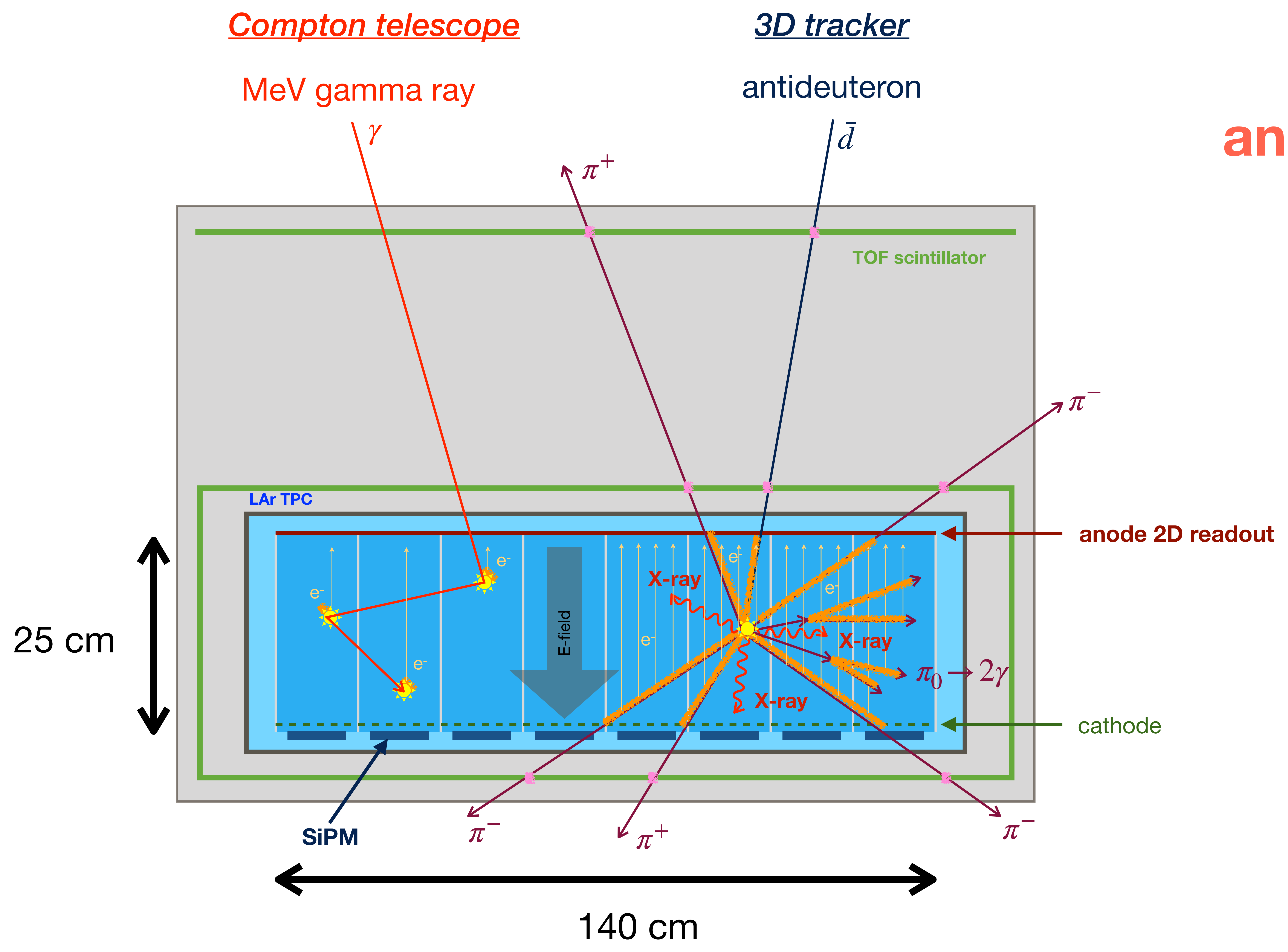


For low-energy antideuterons, the secondary flux is expected to be very low.

→ detection would give a strong evidence of dark matter = background-free search

GAPS experiment in Antarctica (2024–) → GRAMS (next generation)

Liquid argon time projection chamber



Novel approach to realize an extremely large effective area

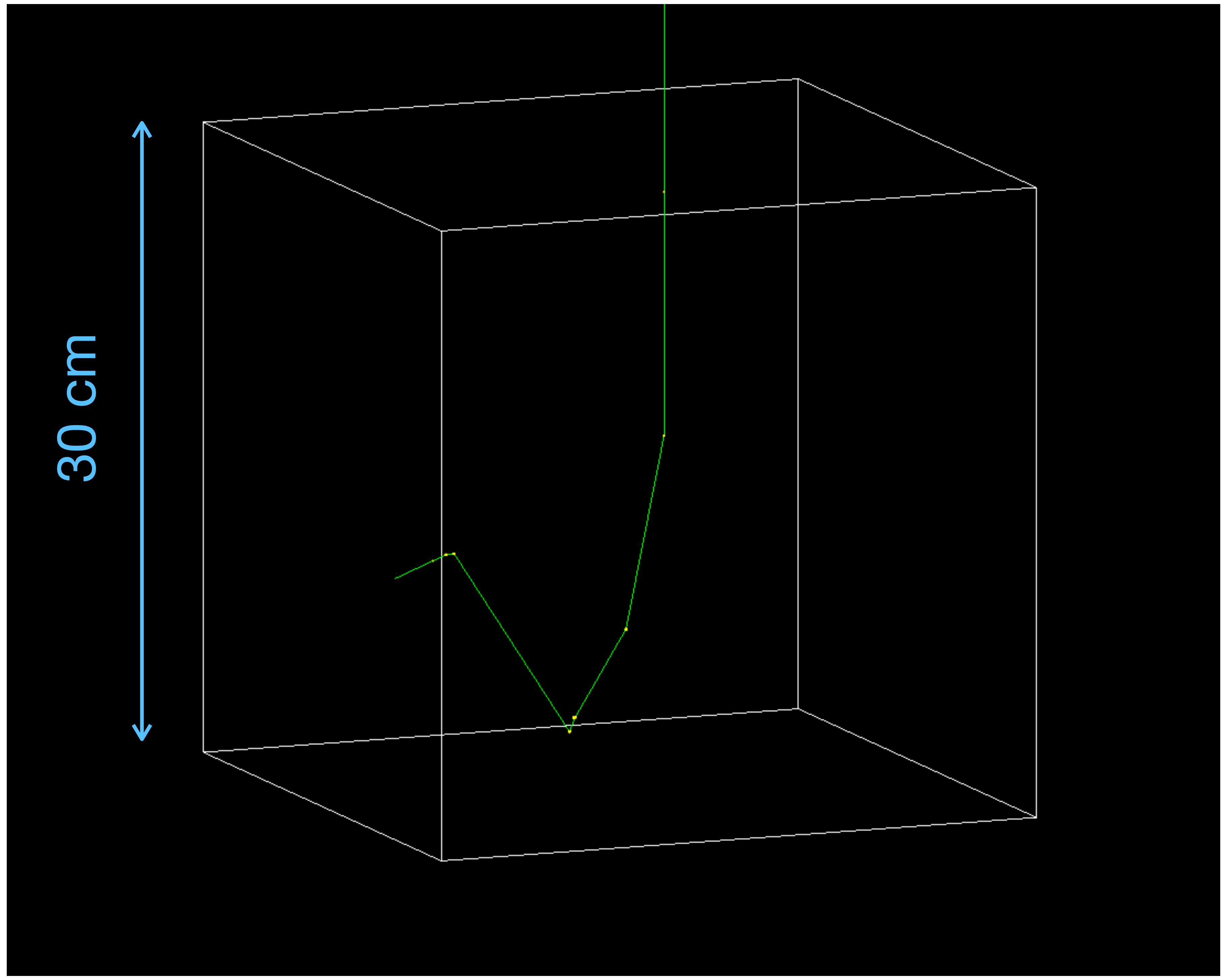
~2000 cm²

1. Adoption of liquid detector
- high density and large volume

2. Use in particle physics experiments
- neutrino physics
- direct dark matter search
- this technology will be deployed to space missions (balloon/satellite)

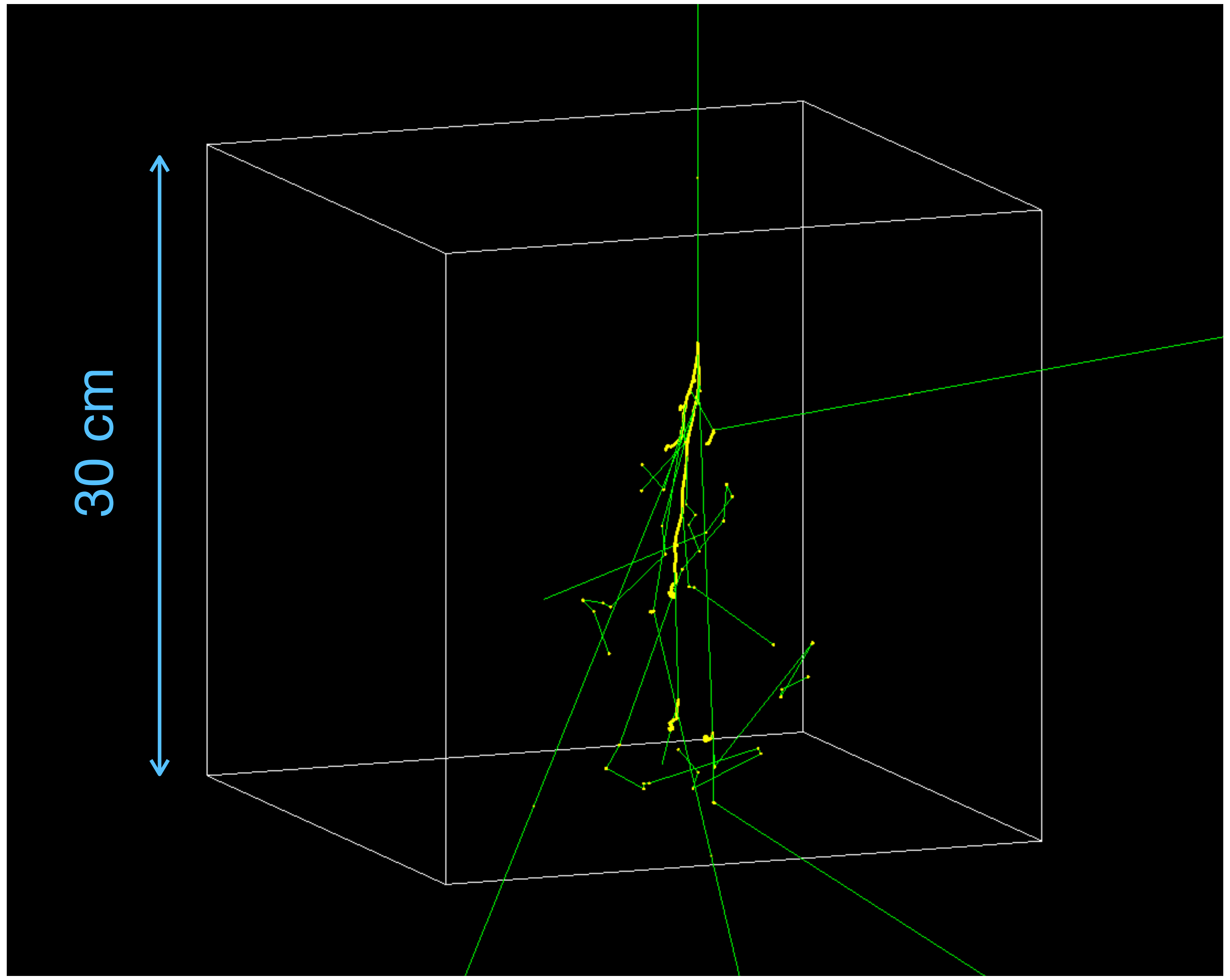
Interactions in liquid argon

1.3 MeV ~ nuclear line



LArTPC efficiently detects 1.3 MeV gamma rays via **multiple Compton scattering interactions**.

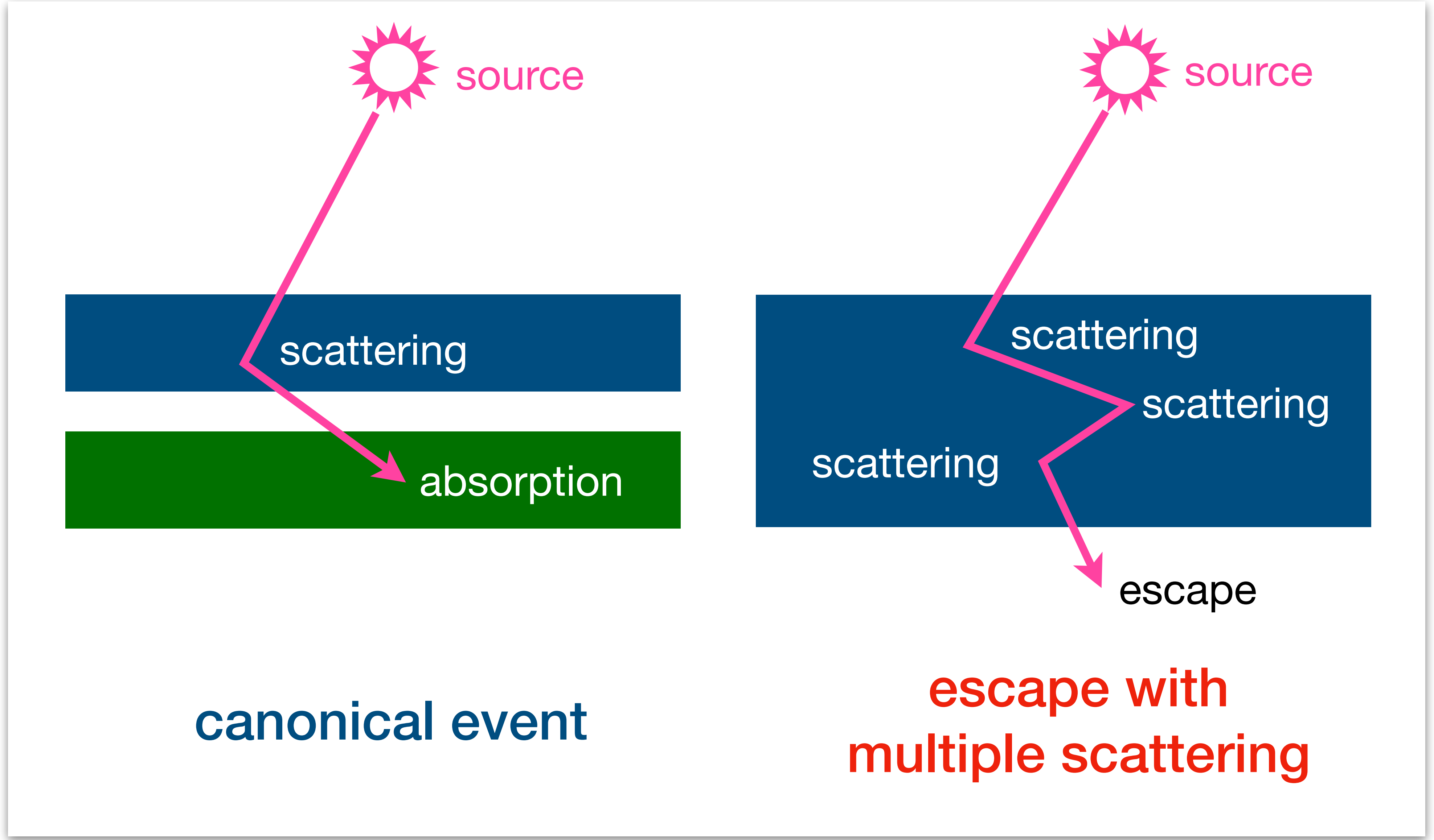
70 MeV ~ pion bump



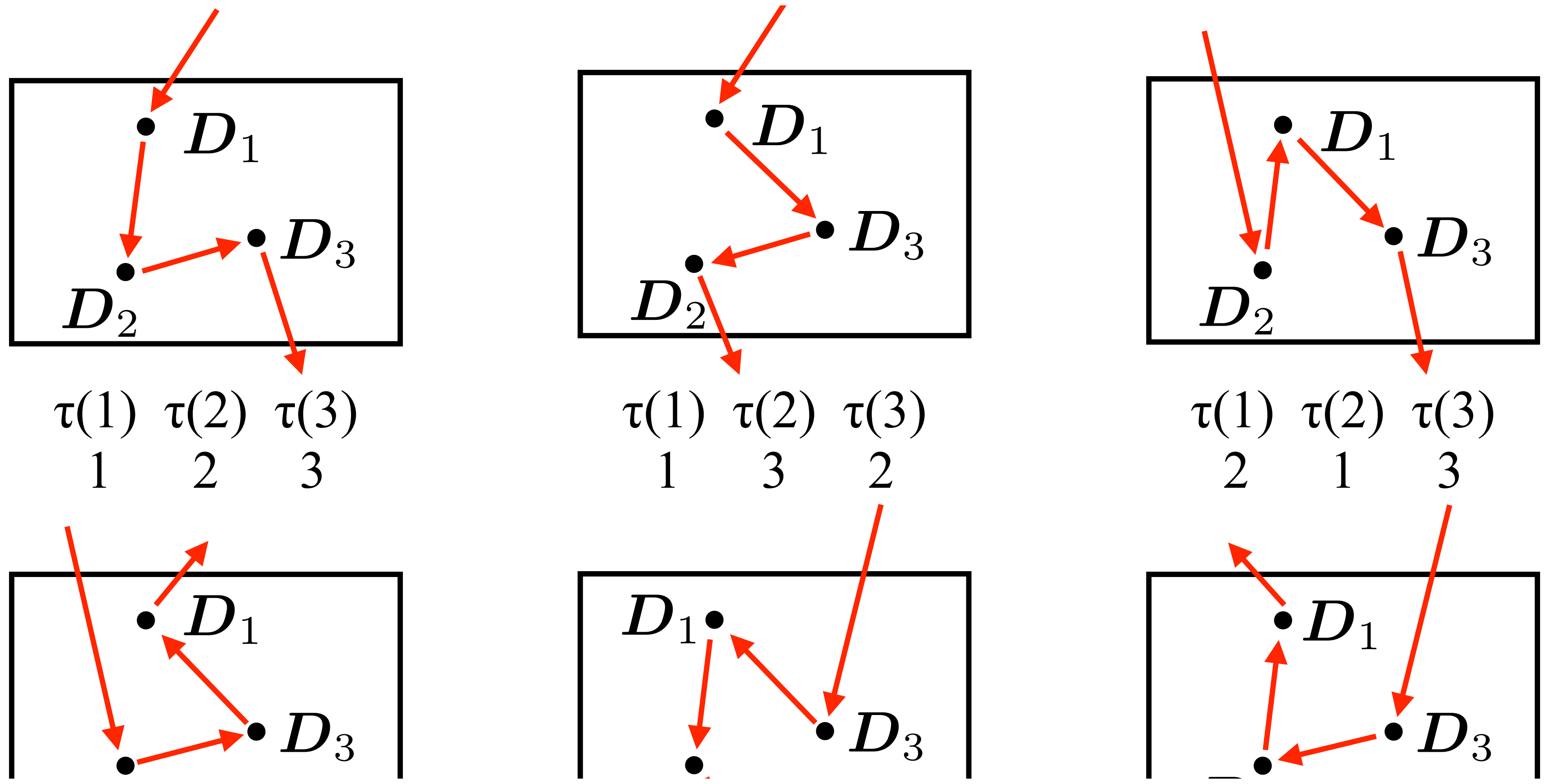
LArTPC accurately measures 70 MeV gamma rays via **pair production with small effects of multiple scattering**.

A thick volume of liquid argon is promising for a high efficiency gamma-ray detector of 1–100 MeV.

Event reconstruction technique



Need to determine the interaction order : N!



GRAMS employs a new Compton camera concept made of only a single **Compton-thick** scatter with **no dead volume** inside the detector.

→ GRAMS detects multiple scattering events with high efficiency.

→ We have developed new Compton reconstruction algorithms to treat multiple scattering with escaping.

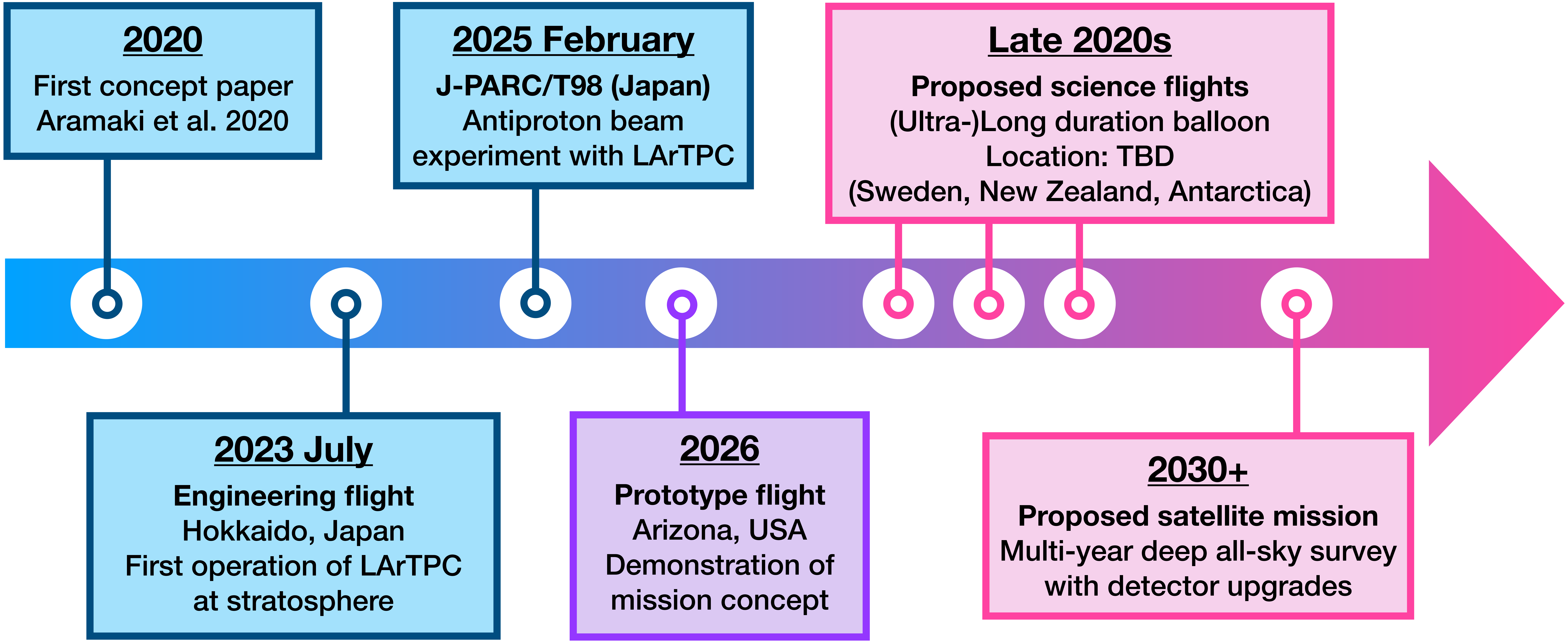
<u>1. Physics-based probabilistic model</u>

- Yoneda et al. 2023
- giving a benchmark model

<u>2. Multi-task neural network</u>

- Takashima et al. 2022
- outperforming after simulation learning

Timeline: achievements and plan



GRAMS Collaboration

Barnard College
Columbia University
Hiroshima University
Howard University
JAXA
Kanagawa University
Kyoto University
Nagoya University
NASA/GSFC
National Defense Medical College
Northeastern University
Oak Ridge National Lab
RIKEN
University of California, Berkeley
University of Chicago
University of Osaka
University of Tokyo
University of Texas at Arlington
Washington University
Yale University
Yokohama National University

US-Japan Interdisciplinary Team

X-ray/gamma-ray astronomy, accelerator, neutrino/dark matter experiments

7th Collaboration Meeting, May 2024, Boston

eGRAMS: Engineering flight in Japan

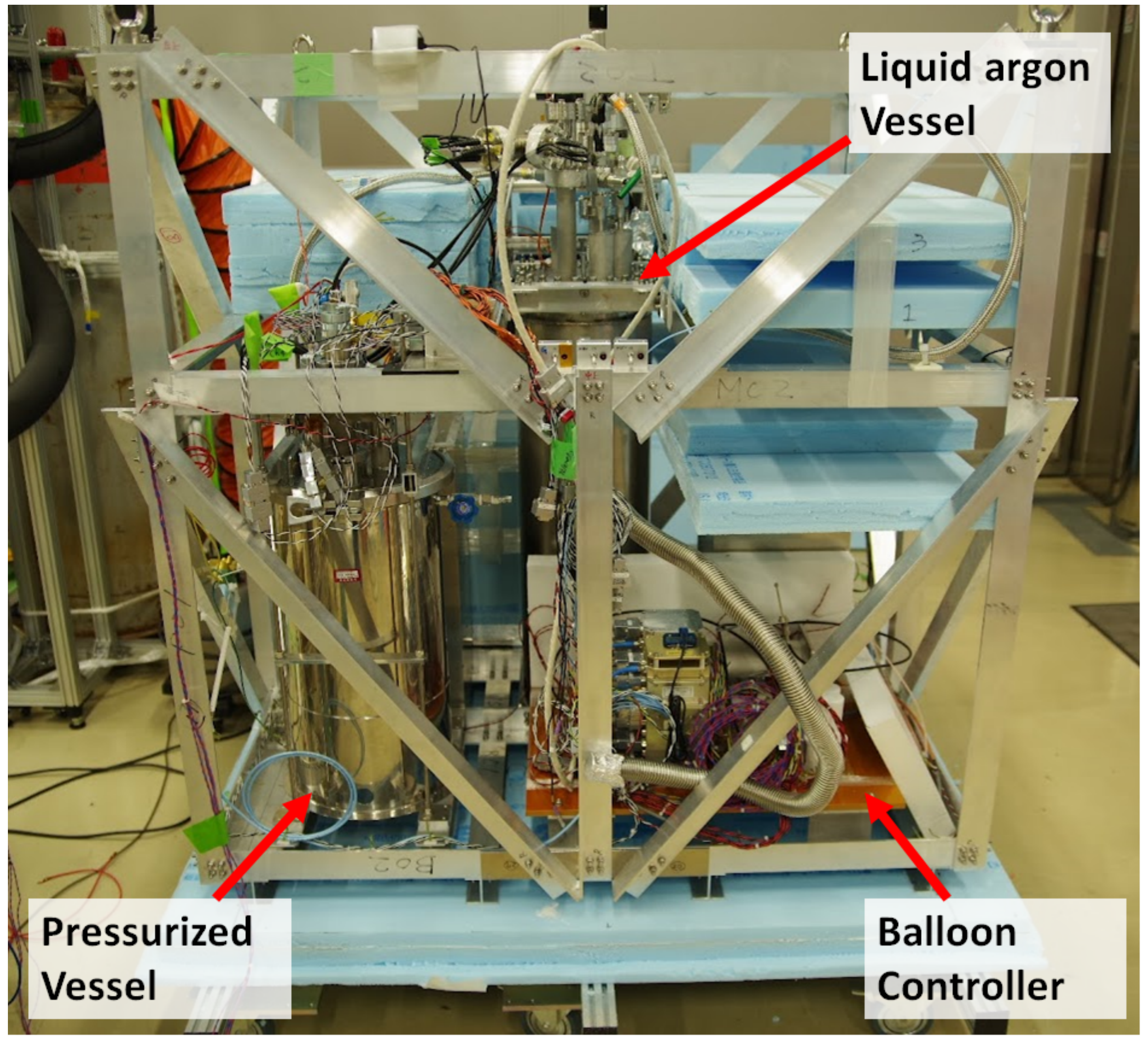
2023 July

The world's first balloon flight of a LArTPC

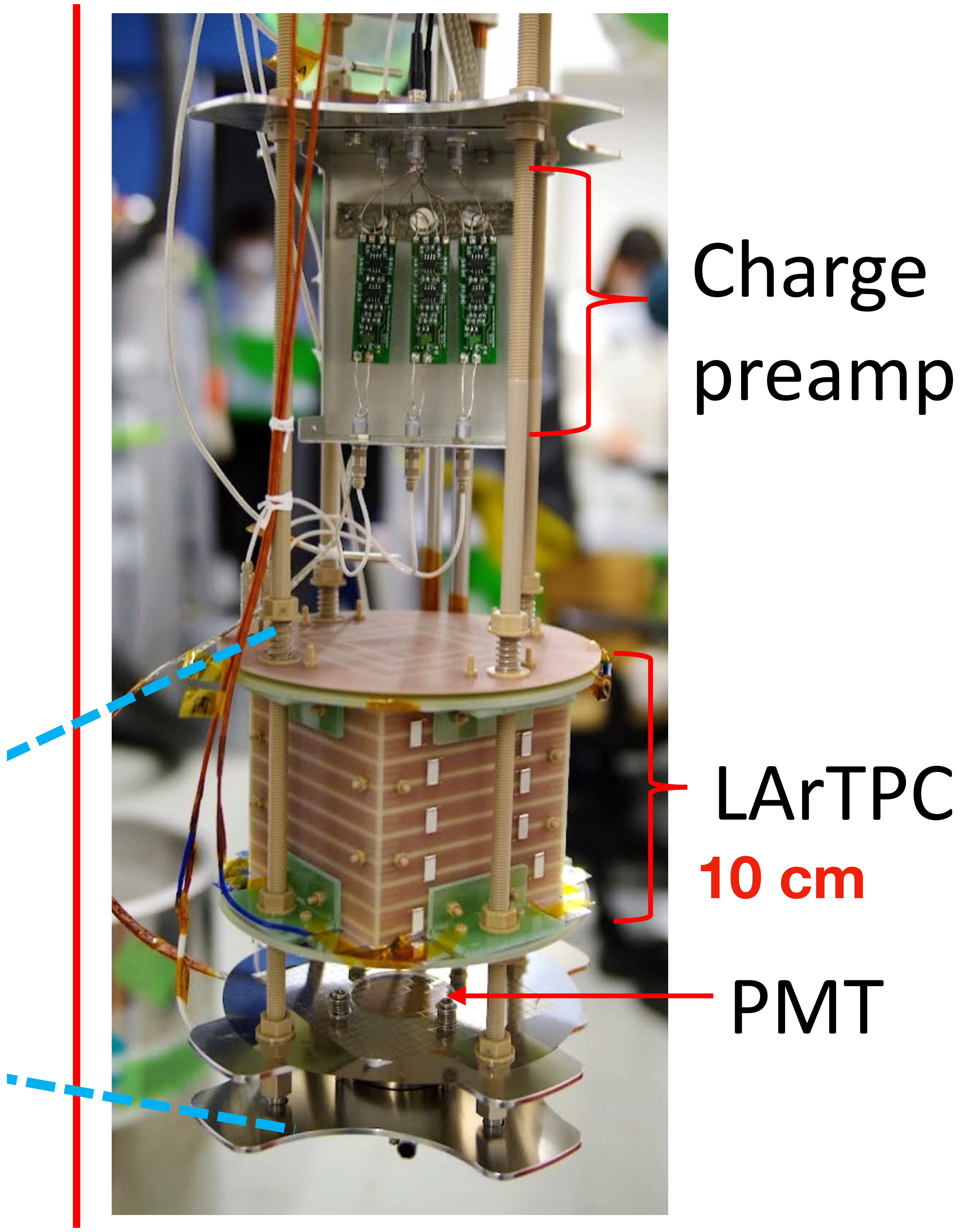
Nakajima et al. 2024

- ✓ a minimal configuration of a LArTPC for an engineering test
- ✓ to establish safe and stable operations of LArTPC on a flying balloon
- ✓ launched from JAXA balloon facility on 2023 July 27

Hokkaido, Japan



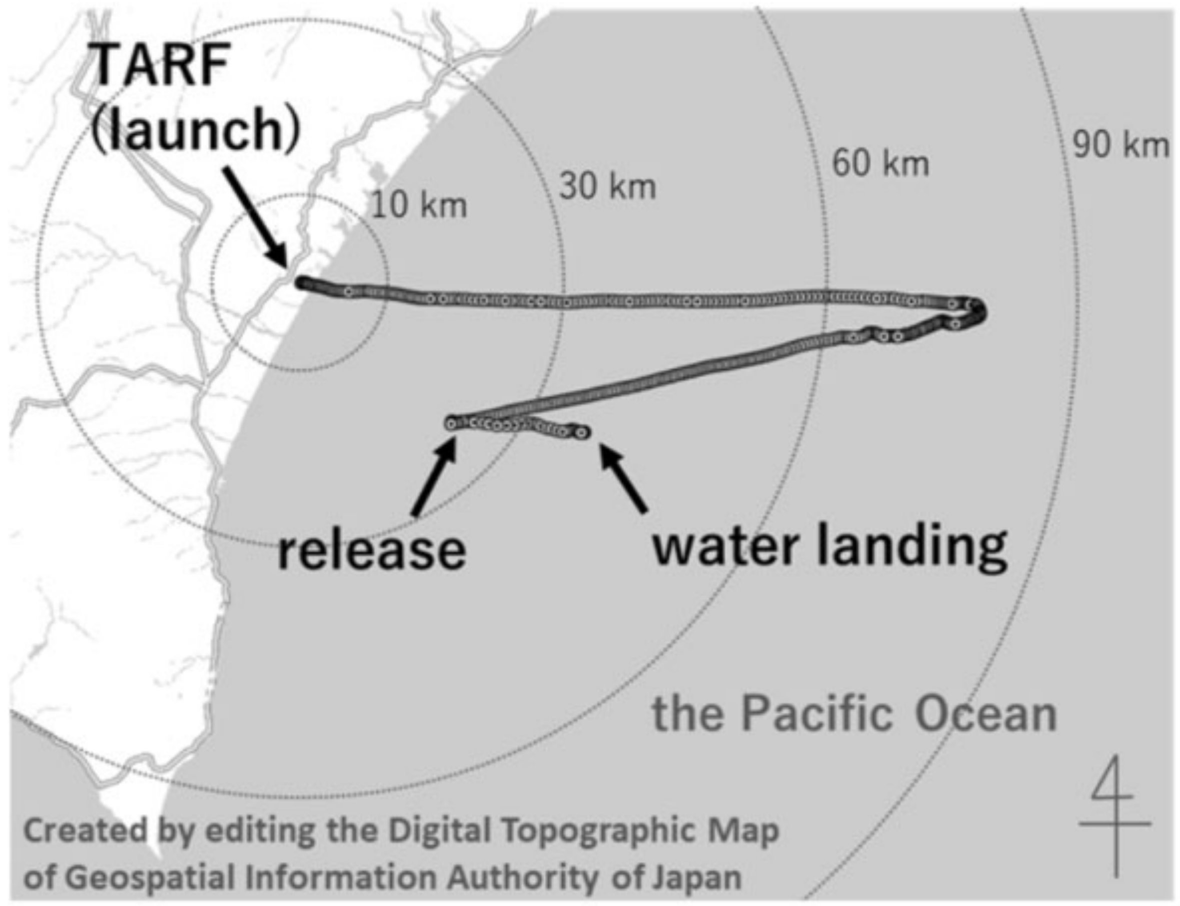
Gondola: 1.2 m

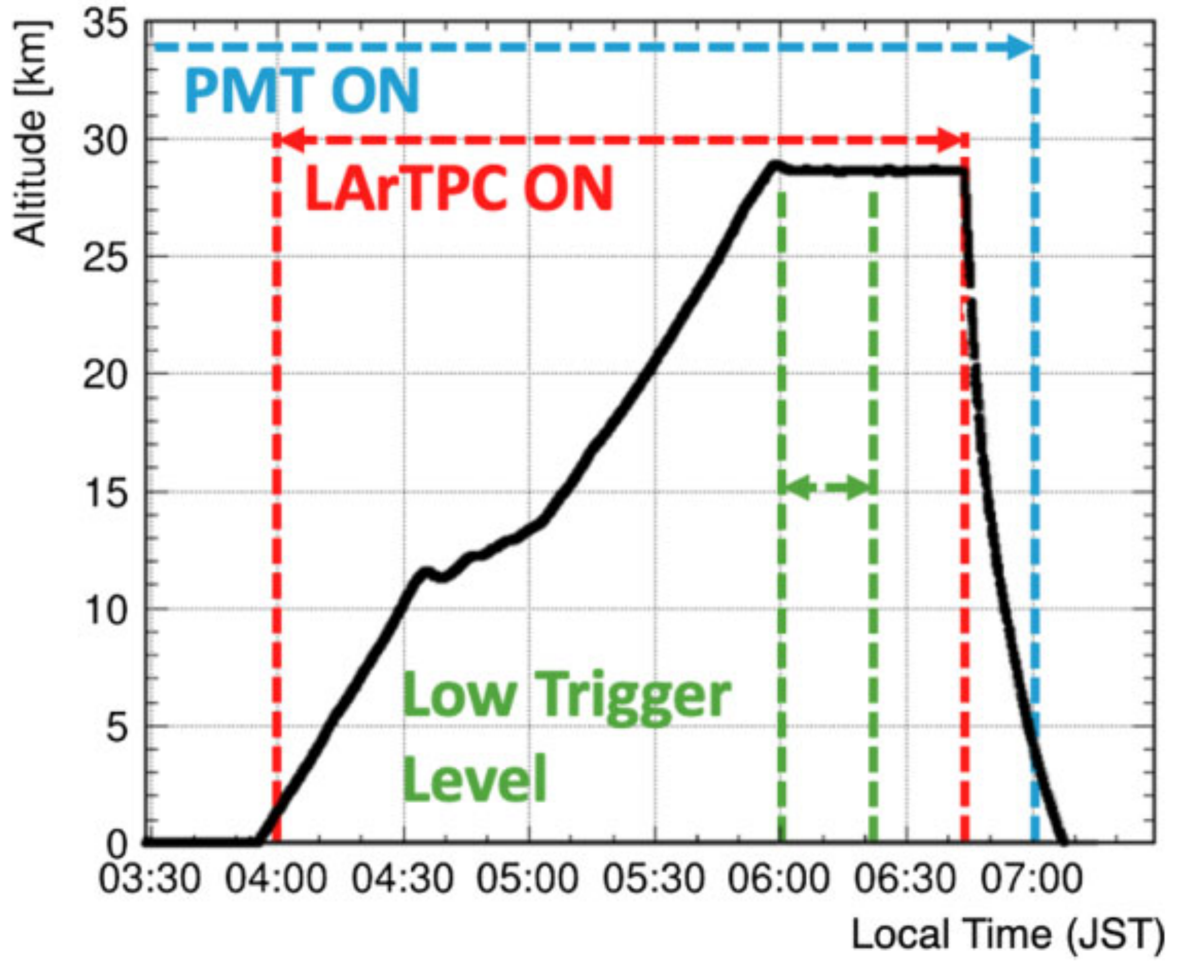


LArTPC

eGRAMS: Engineering flight in Japan

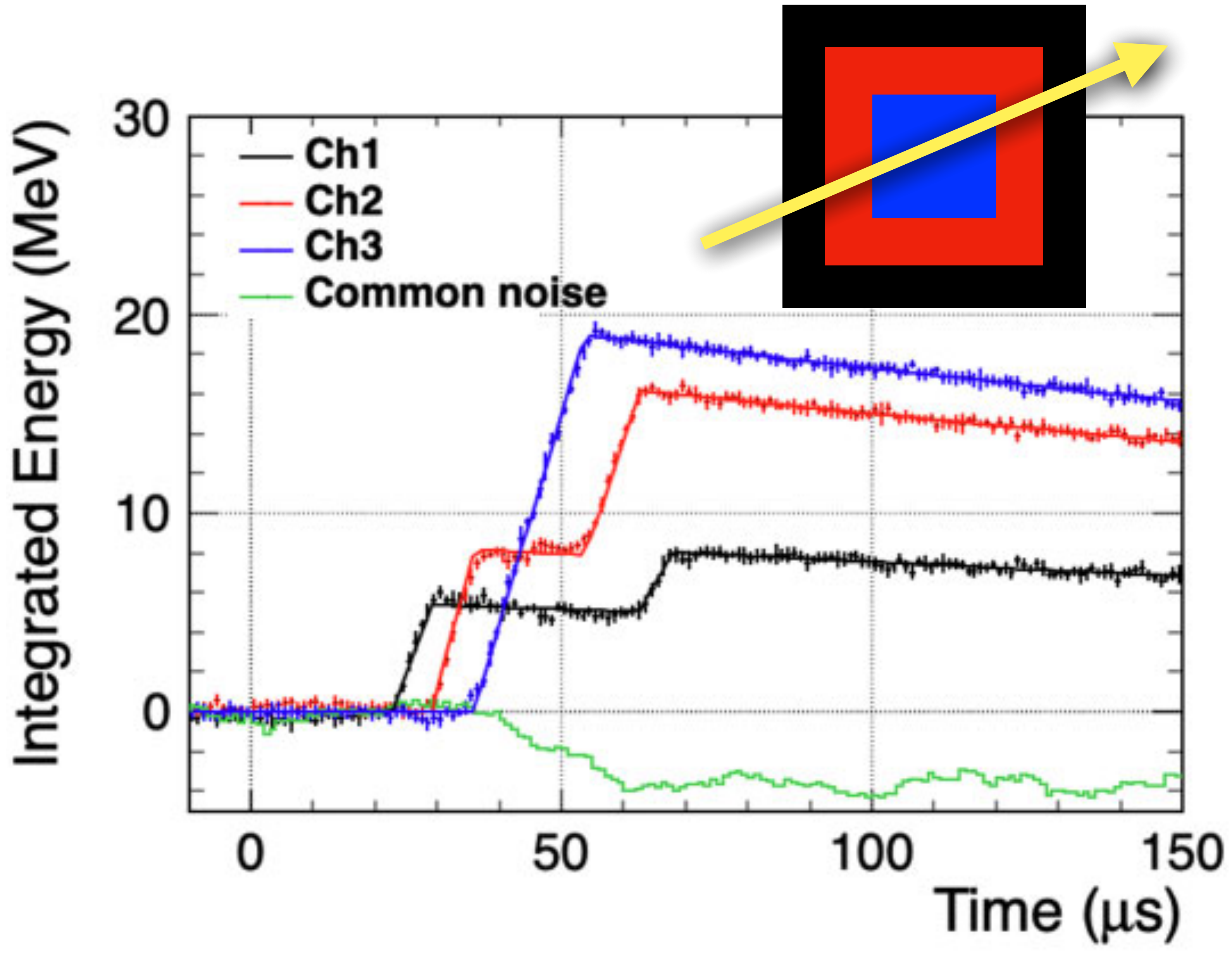
2023 July





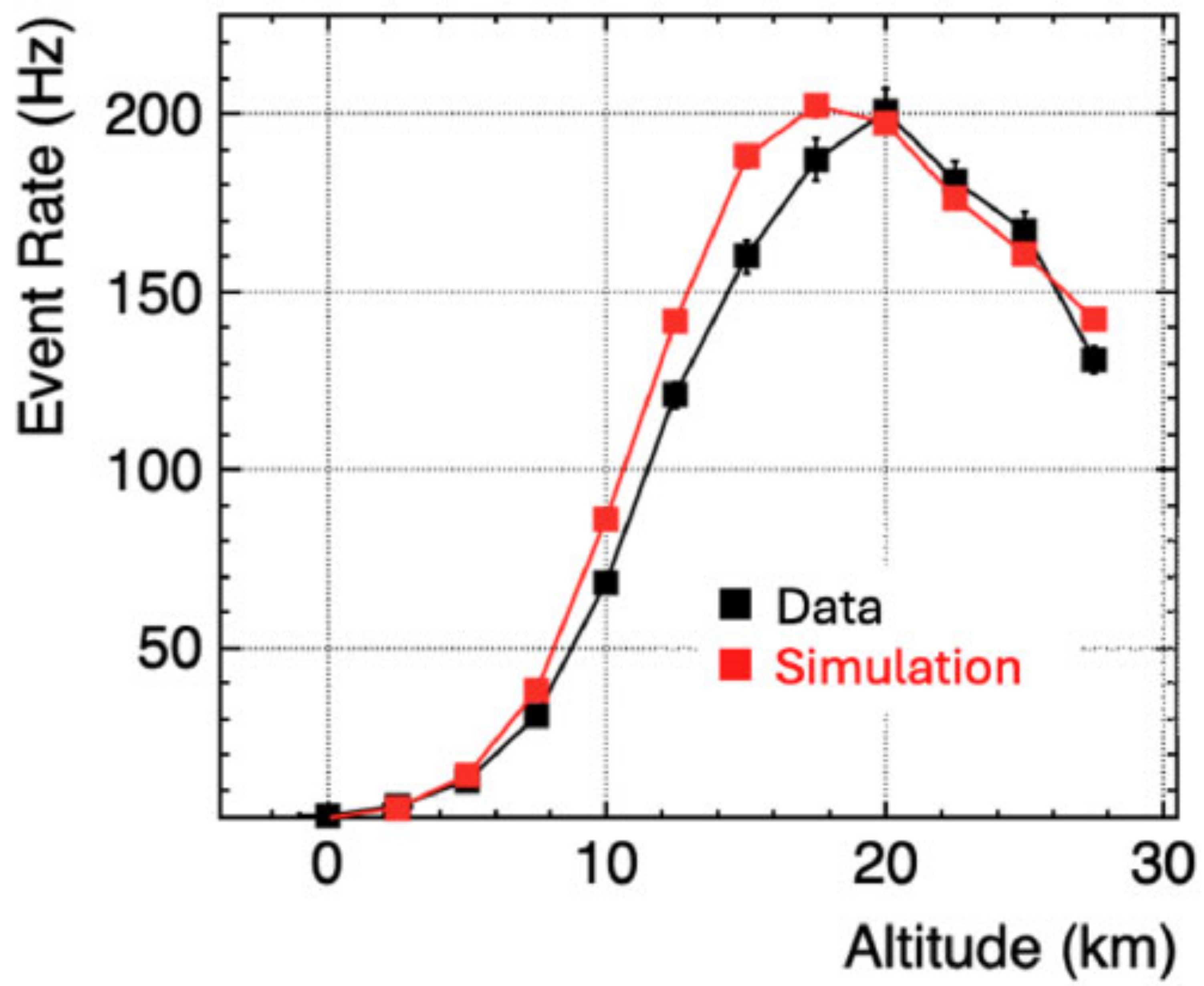
level flight at 29 km for 40 min

Waveforms of a cosmic ray penetrating the LArTPC



Nakajima et al. 2024

Event rates



✓ successful operations and in-flight measurement of cosmic rays and gamma rays in stratospheric radiation environments

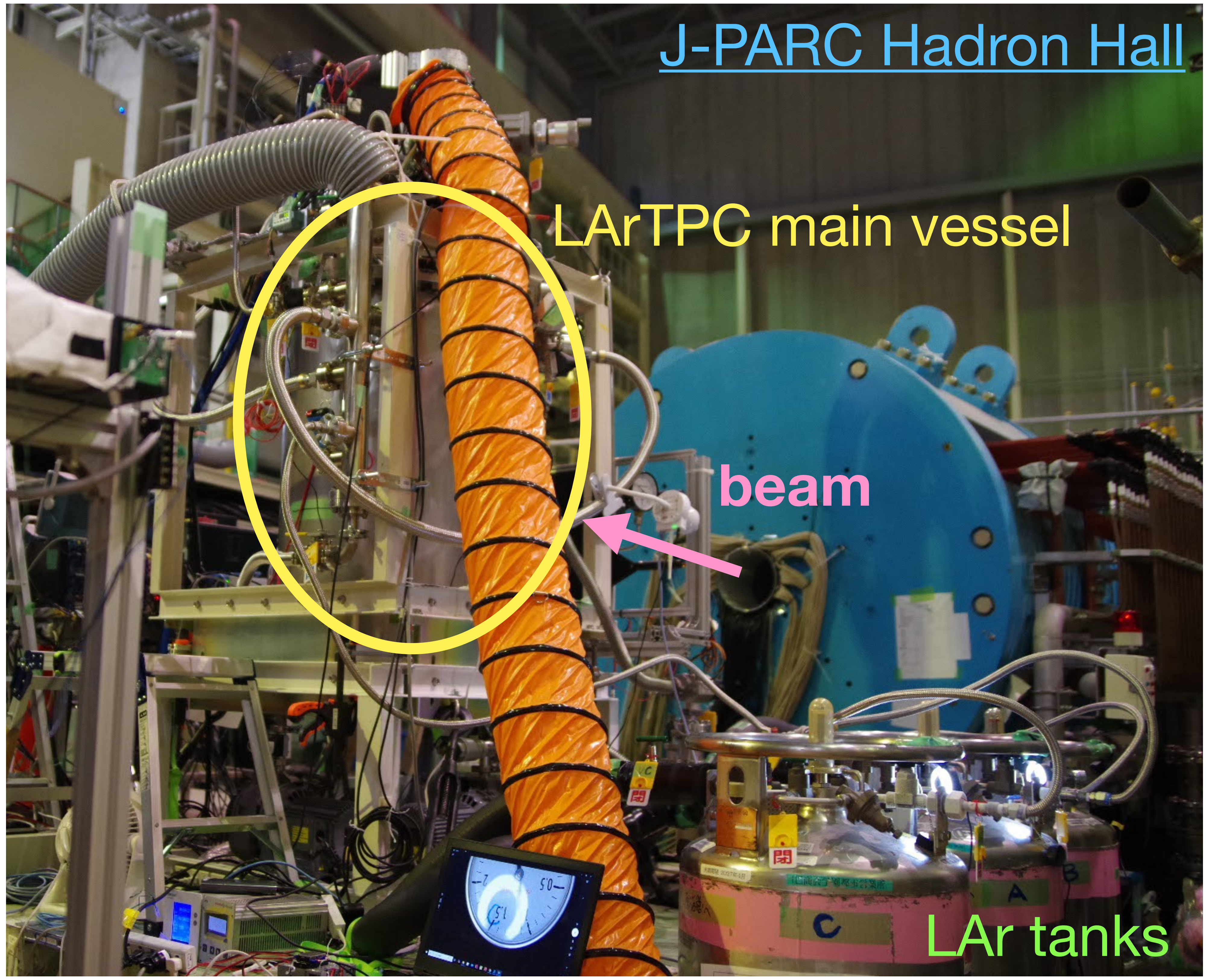
✓ safe recovery of the instrument and data

Anti-proton beam test at J-PARC

2025 February

Purpose: performance evaluation of anti-particle identification by LArTPC

Method: we measured anti-protons at J-PARC K1.8BR beam line

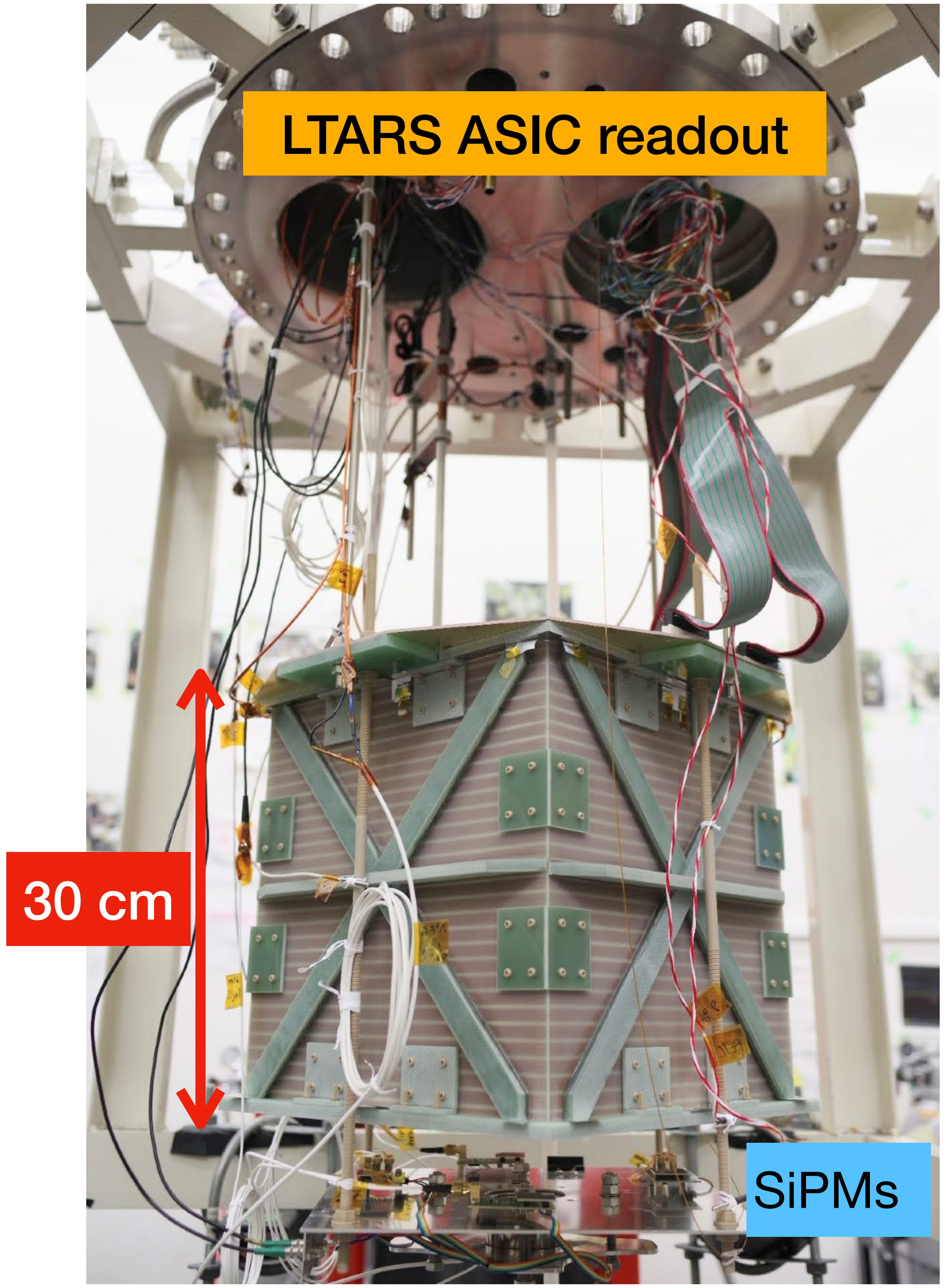


LArTPC

- 30 cm × 30 cm × 30 cm
- 5 mm electrode pitch
- LTARS ASIC readout
- SiPM light readout

Beam

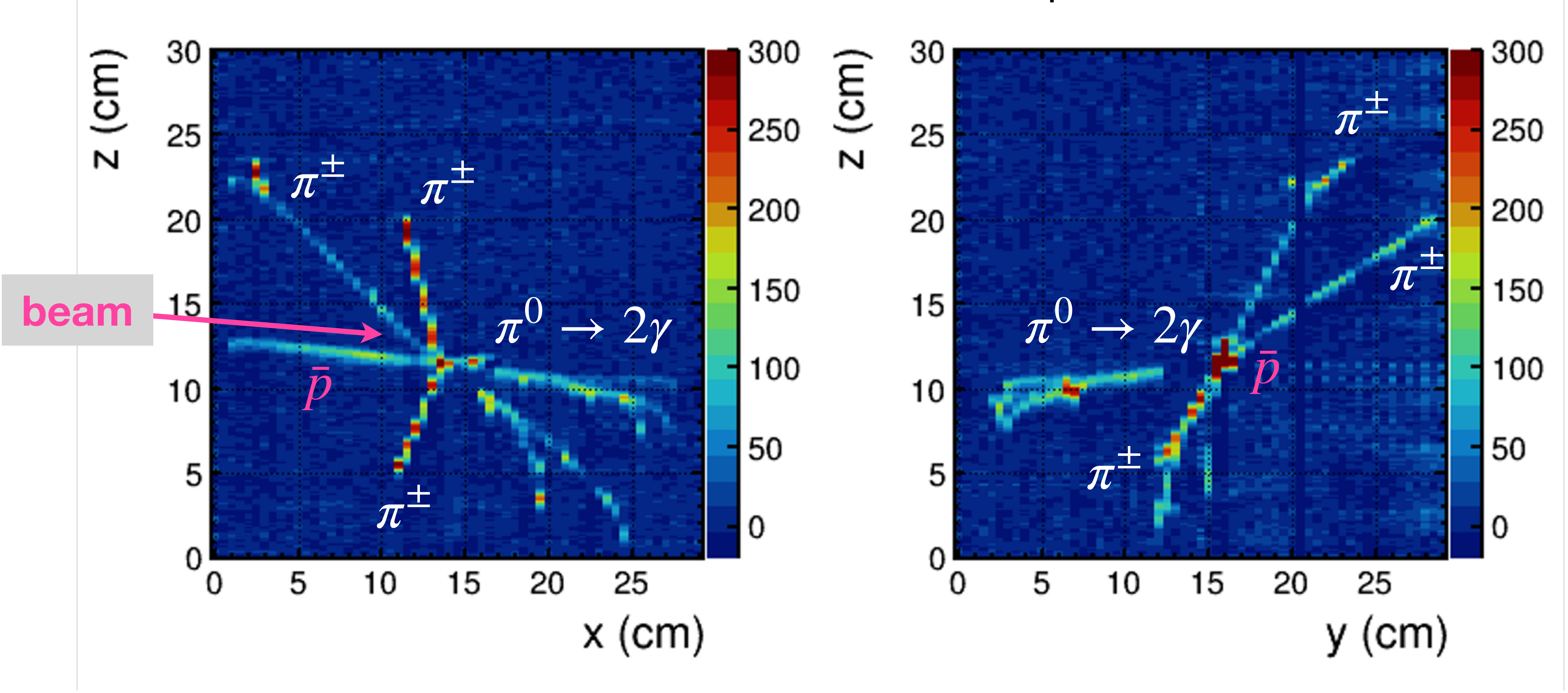
- antiproton
- proton
- deuteron
- K^-



Anti-proton beam test at J-PARC

2025 February

Annihilation event tracks of an incident antiproton of $0.7\ \mathrm{GeV}/c$

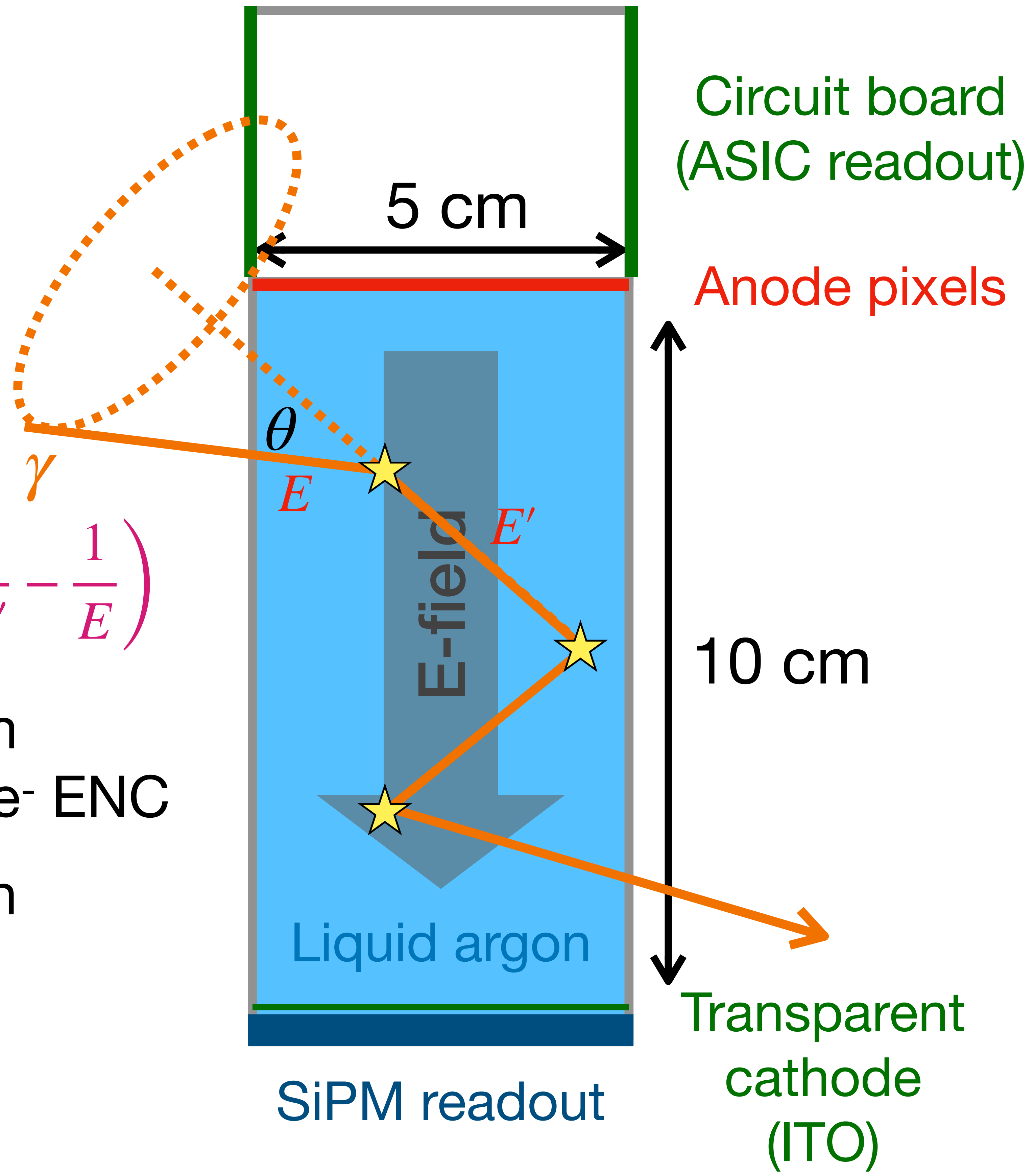


We demonstrated the high capability of particle tracking and particle identification of LArTPC.

Imaging experiment: NanoGRAMS

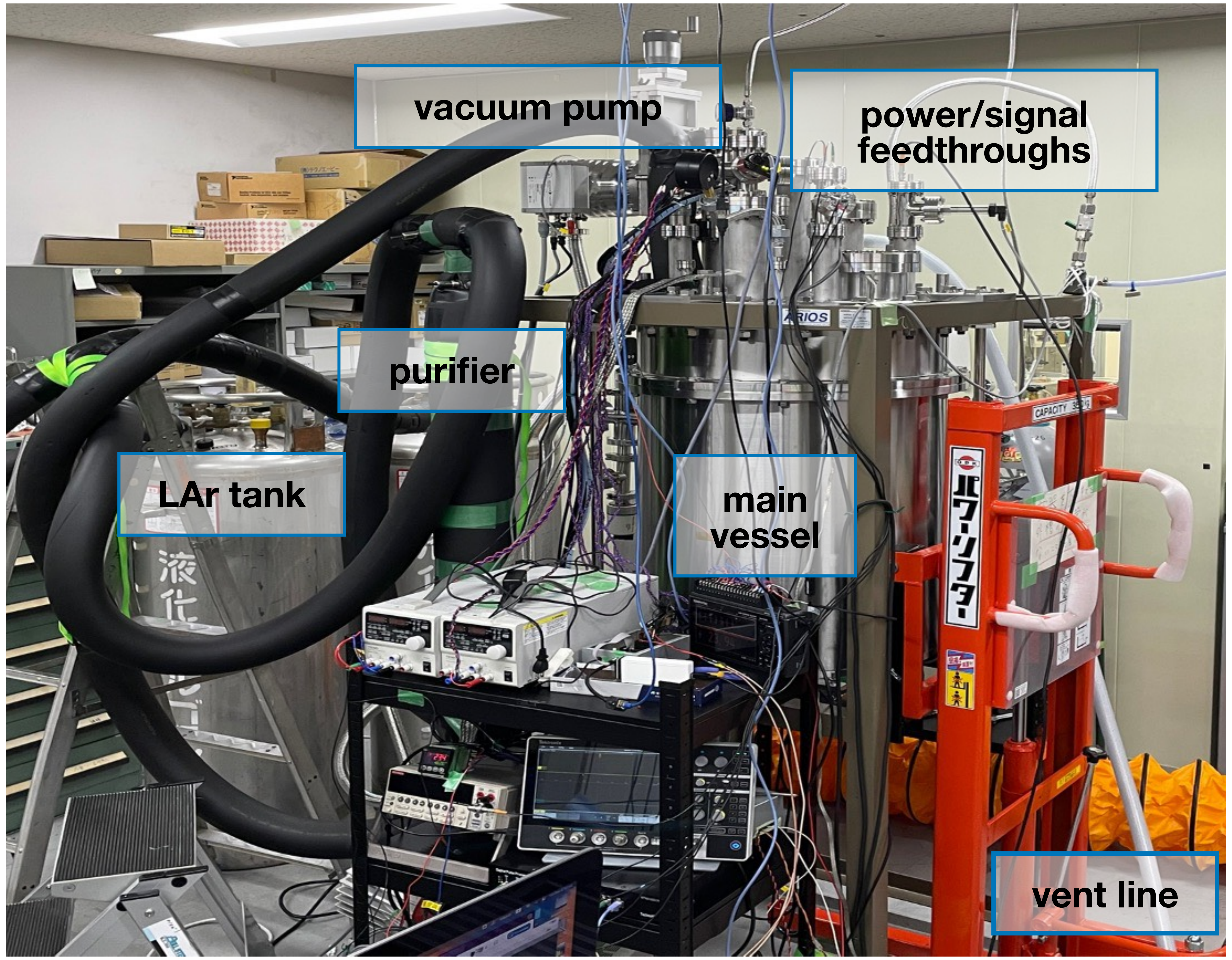
Evaluate gamma-ray imaging capability with a small LArTPC
with high-energy resolution pixel ASIC and high-gain SiPM arrays

→ feedback for a large-size detector

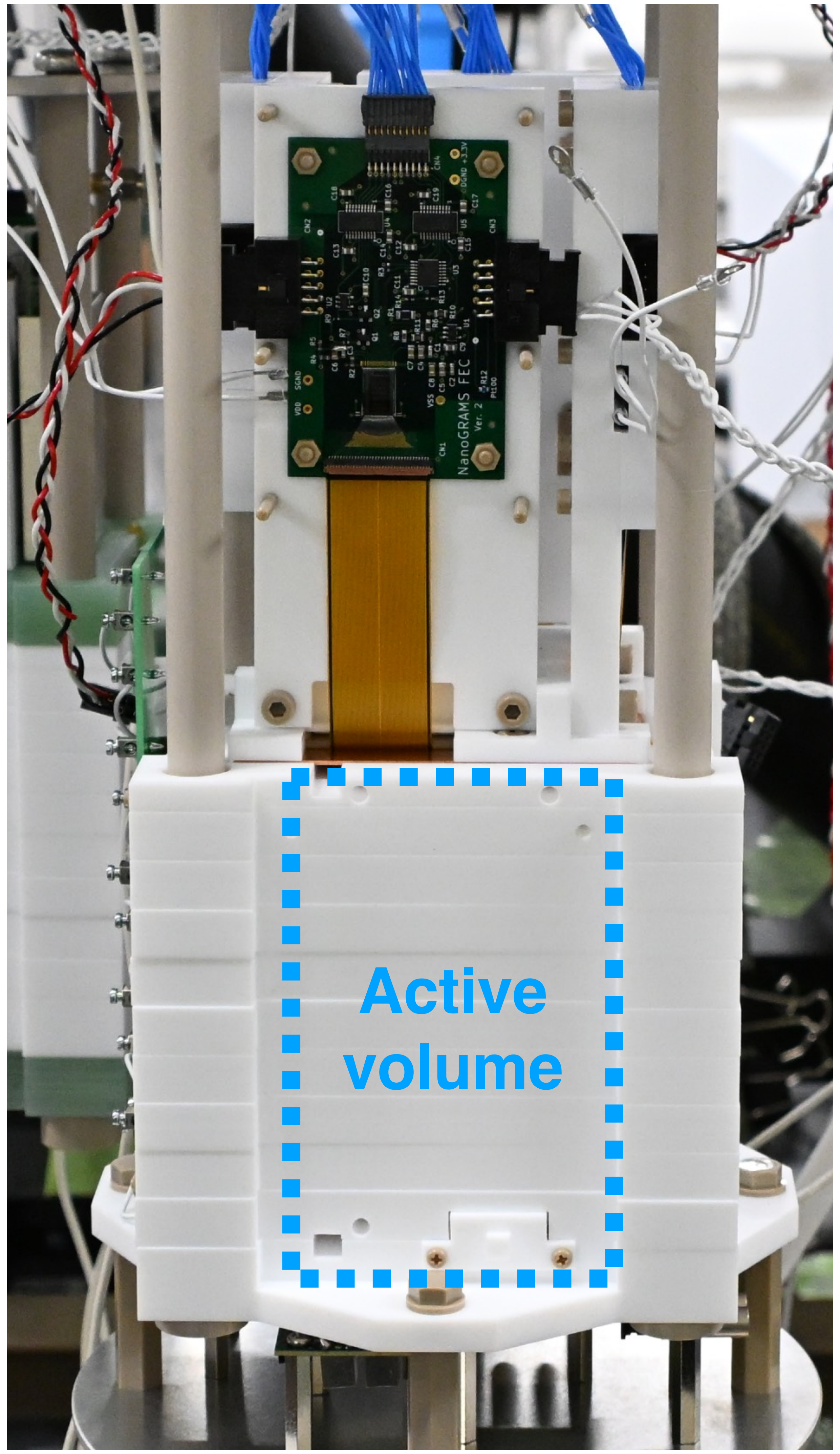


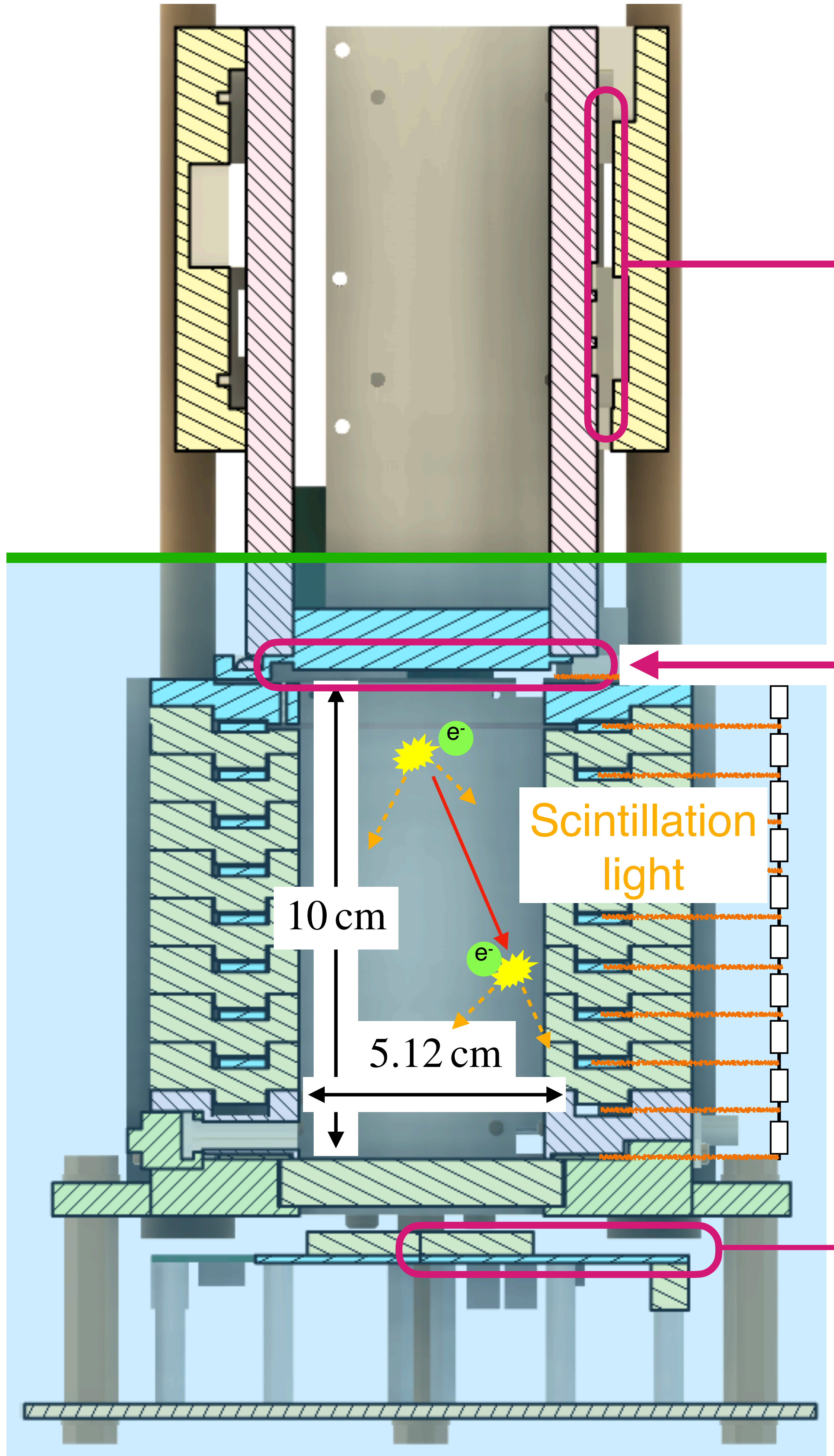
$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E'} - \frac{1}{E} \right)$$

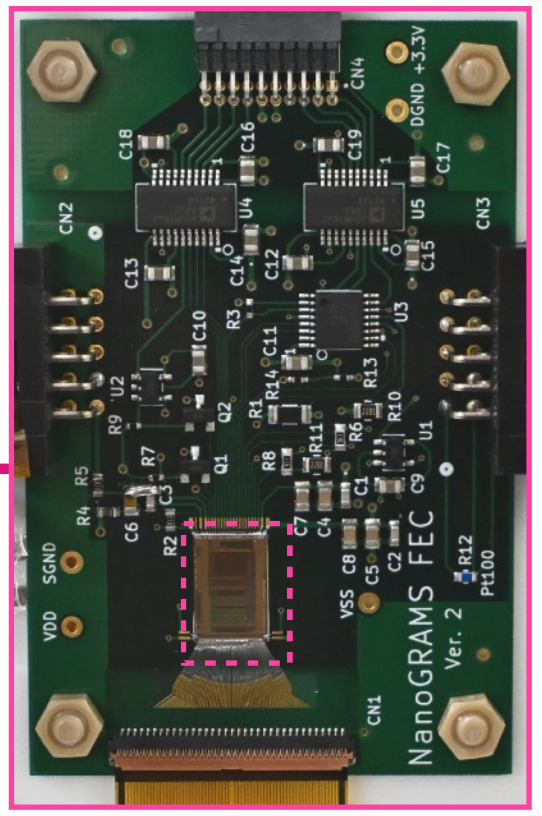
- Energy resolution
  5 keV (1σ) ~200 e^- ENC
- Spatial resolution
  3 mm

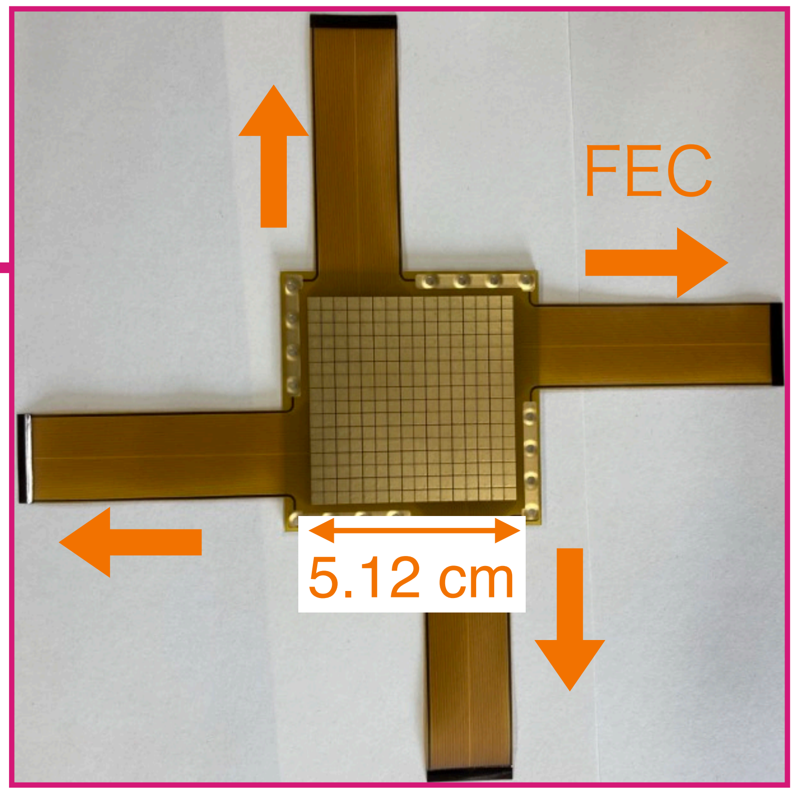


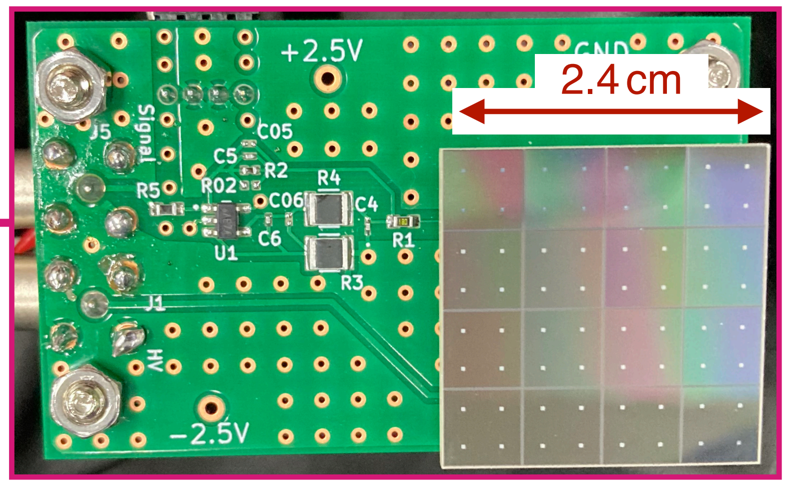
Imaging experiment: NanoGRAMS











Arrayed SiPM board

Electron readout

- VATA-SGD ASIC
- 64 channels/chip
- ENC: 180 e^- at 6 pF

Anode pad

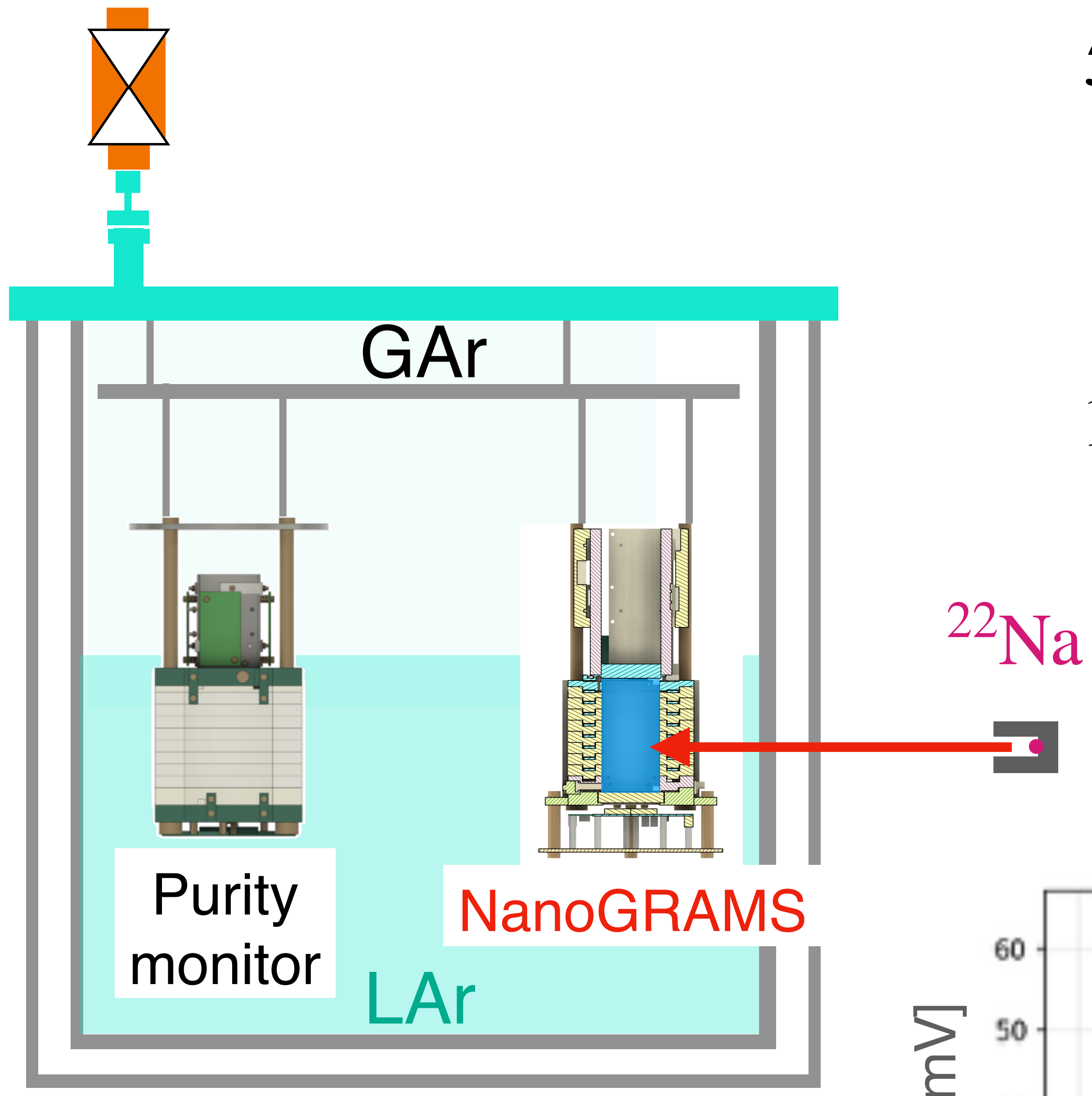
- 16 × 16 pixels
- 51.2 × 51.2 mm^2
- pixel pitch: 3.2 mm

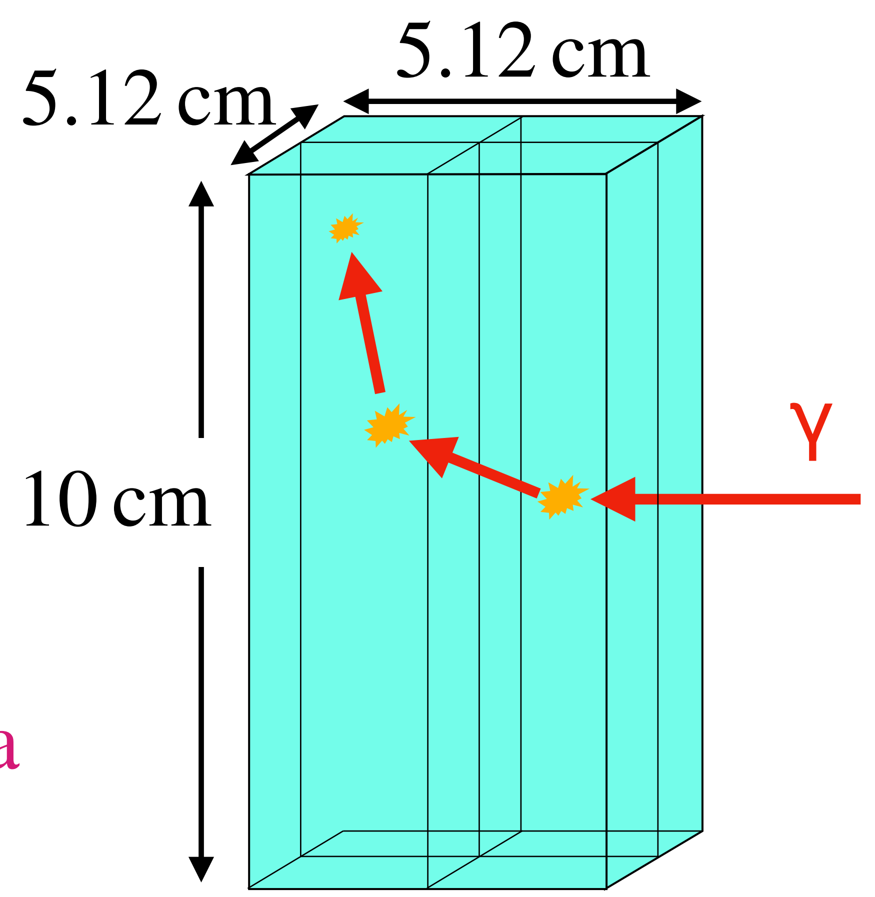
SiPM array

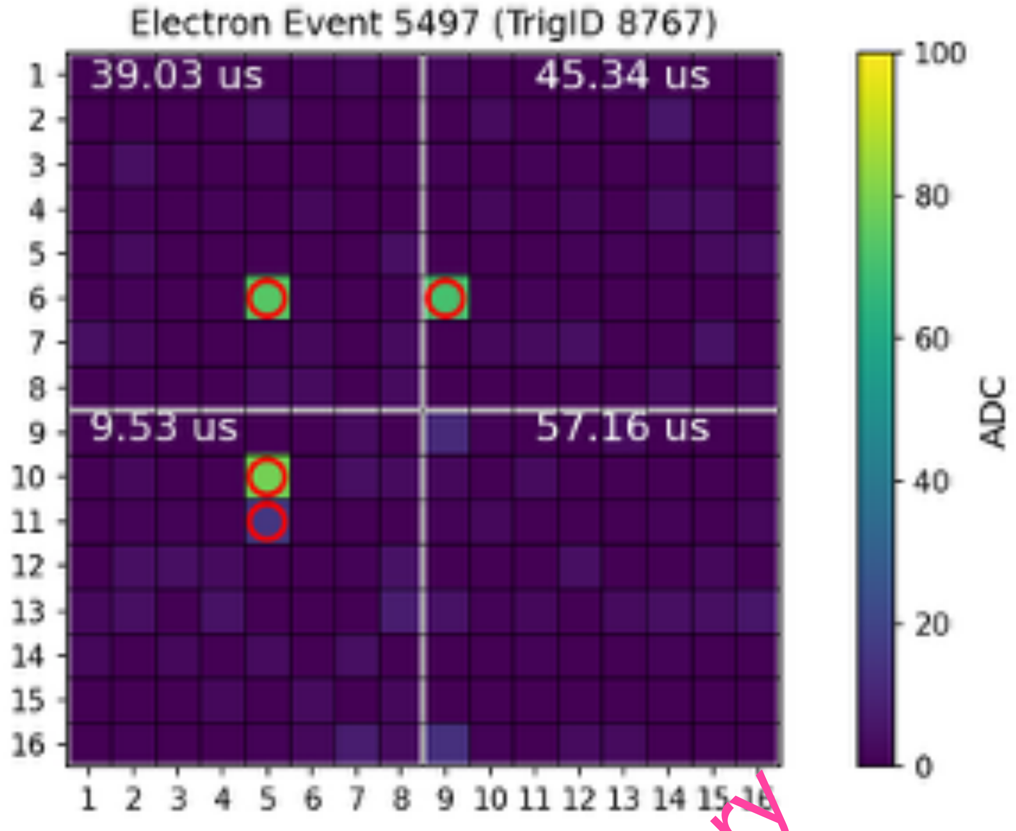
- Four 4×4 arrays covers 5×5 cm^2
- Hamamatsu S13361-6075AE-04 × 4

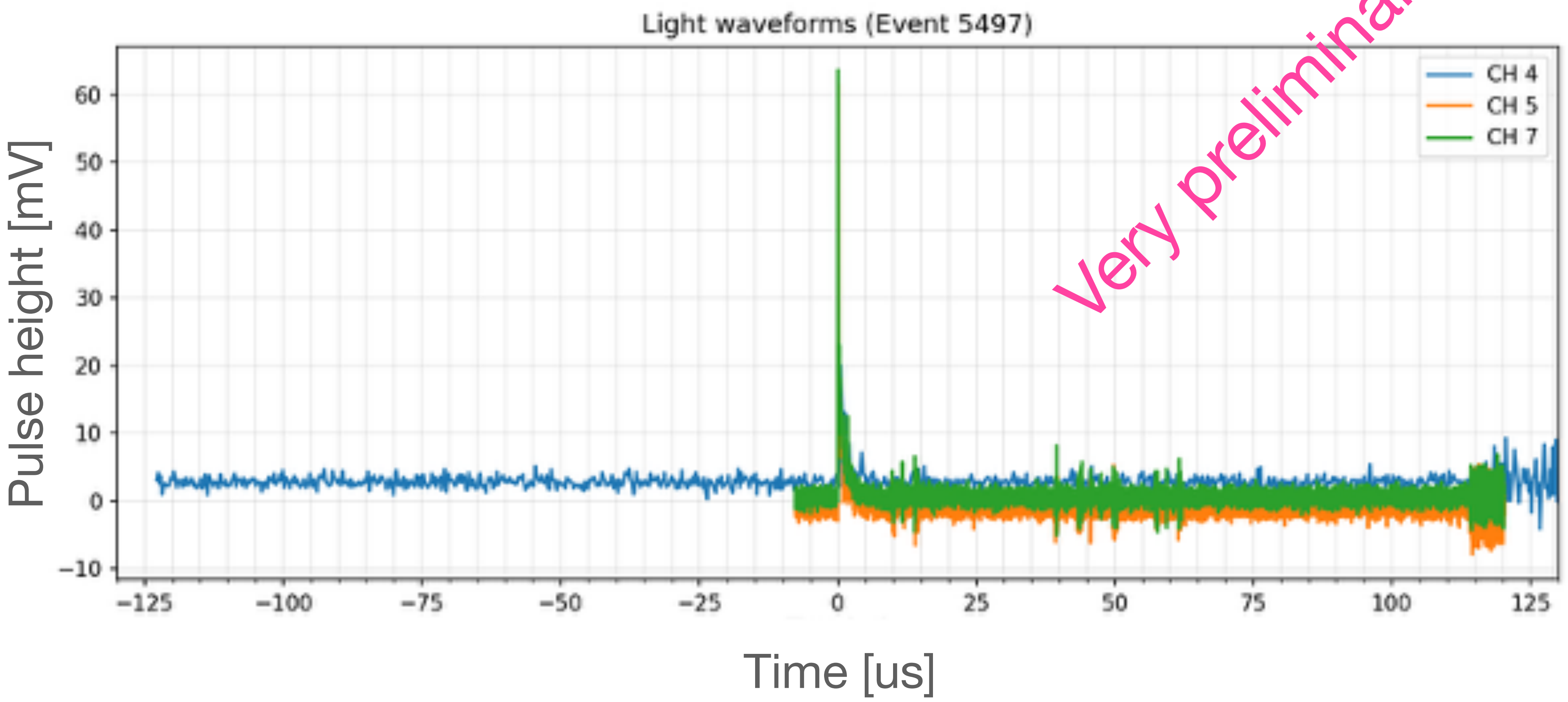
Imaging experiment: NanoGRAMS

2025 December



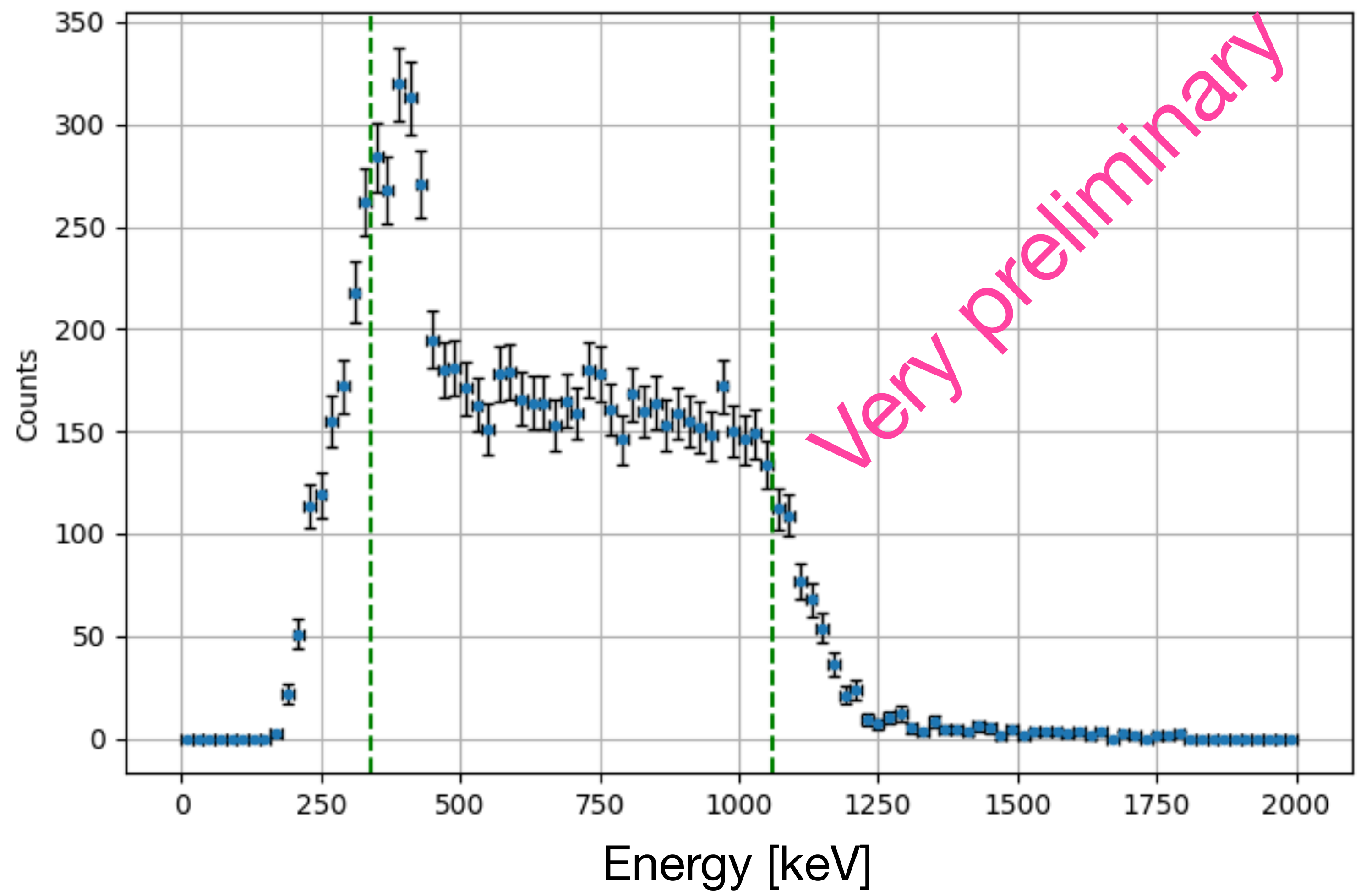






3-hit events for Compton reconstruction successfully obtained.

Spectrum of ^{22}Na (0.511/1.274 MeV)



- Clearly see Compton spectrum with the Compton edges of 0.511/1.274 MeV.
- ASIC operations, energy gain calibration, and data acquisition system are not yet optimized.

pGRAMS: Prototype flight

Scheduled for launch in 2026

The next important step is a prototype flight of a scientific LArTPC called MiniGRAMS.

✓ NASA/APRA funded in 2023

✓ demonstration of the mission concept

✓ planned for launch in 2026 in Arizona

MiniGRAMS—a prototype LArTPC

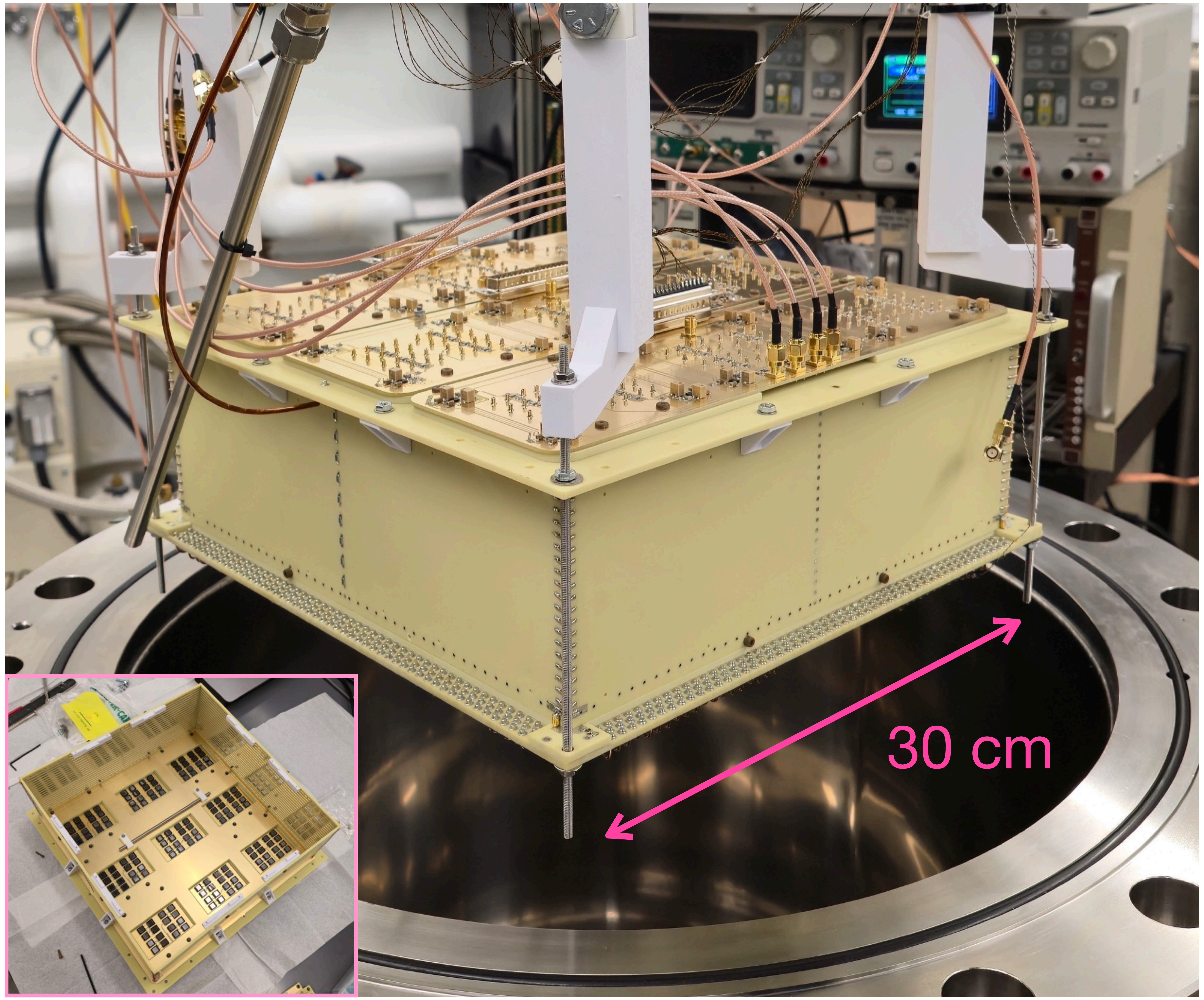
✓ TPC size: 30 × 30 × 20 cm^3

✓ **Scalable design**

✓ Tile/pads for x-/y-directions ~3 mm pitch

✓ **180 cryogenic charge preamps** operated in 87K liquid argon

✓ 32 SiPMs at the bottom



Concluding remarks

- GRAMS aims to deploy a large liquid-argon time projection chamber (LArTPC) in sub-orbital and space missions to explore **MeV gamma-ray astronomy** and perform **background-free dark-matter searches**.
- The LArTPC offers an **unprecedented effective area** for both gamma rays and antiparticles.
- The first engineering balloon flight in Japan (2023) was successfully completed.
- In February 2025, we demonstrated excellent antiparticle tracking and identification by using the J-PARC antiproton beam.
- Prototype developments are ongoing in the U.S. and Japan.
- As the next step toward future science missions, a prototype flight supported by the NASA/APRA program is planned for launch in Arizona in 2026.

GRAMS is establishing itself as a leading mission for MeV gamma-ray and dark-matter exploration.

Quick note on sensitivity

- We measure events as the sum of the signal and background.
  $$C = S + B_{\text{True}}$$
- The signal is obtained by
  $$S = C - B_{\text{Estimate}}$$
- The error of the signal:
  $$\Delta S = \Delta C \oplus \Delta B_{\text{Estimate}}$$
  $$\Delta S \simeq \Delta B_{\text{True}} \oplus \Delta B_{\text{Estimate}}$$ Recall $S \ll B_{\text{True}}$ for MeV faint sources
- This error gives our sensitivity:
  $$\frac{\Delta S}{S} = \frac{\sqrt{bAT}}{\text{flux} \cdot AT} \quad \therefore \text{flux} = \left(\frac{S}{\Delta S}\right)\sqrt{\frac{b}{AT}}$$
  where A: effective area, T: observation time, b: background rate per effective area
- To have a better sensitivity, maximize the area, and minimize the background level.