

Indirect Dark Matter Search using MeV Gamma-Ray Observations of the Galactic Center

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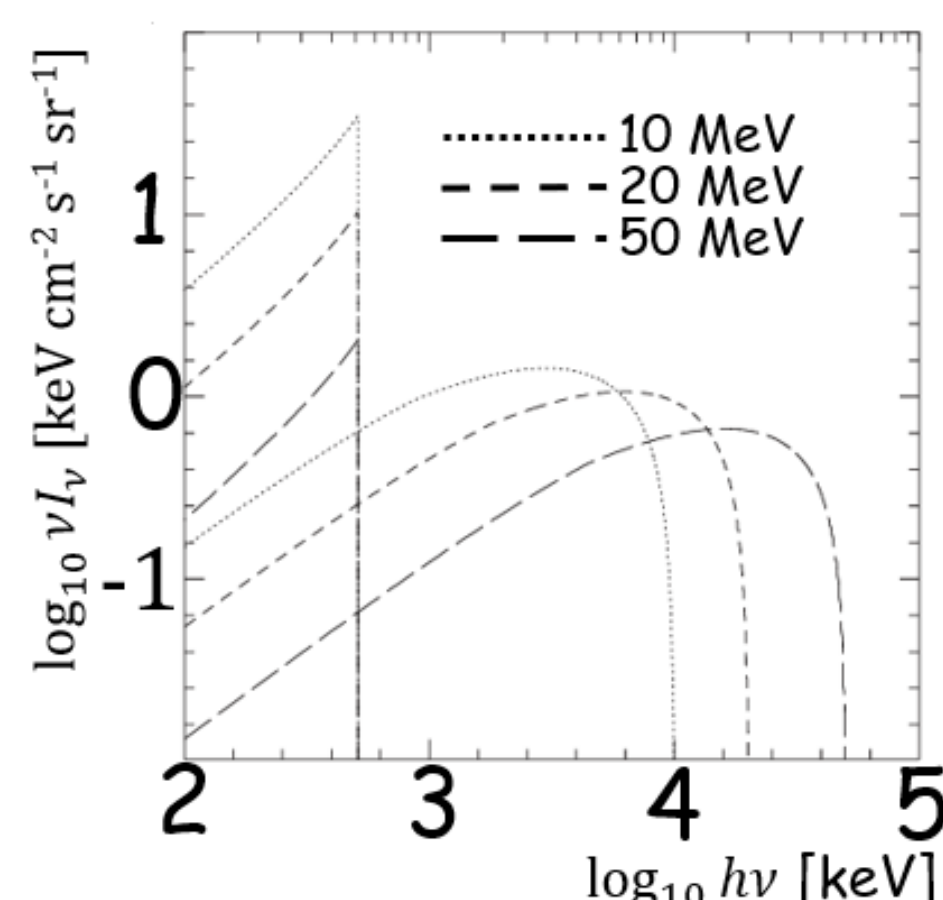
Why use MeV Gamma-rays?

Particle Dark Matter

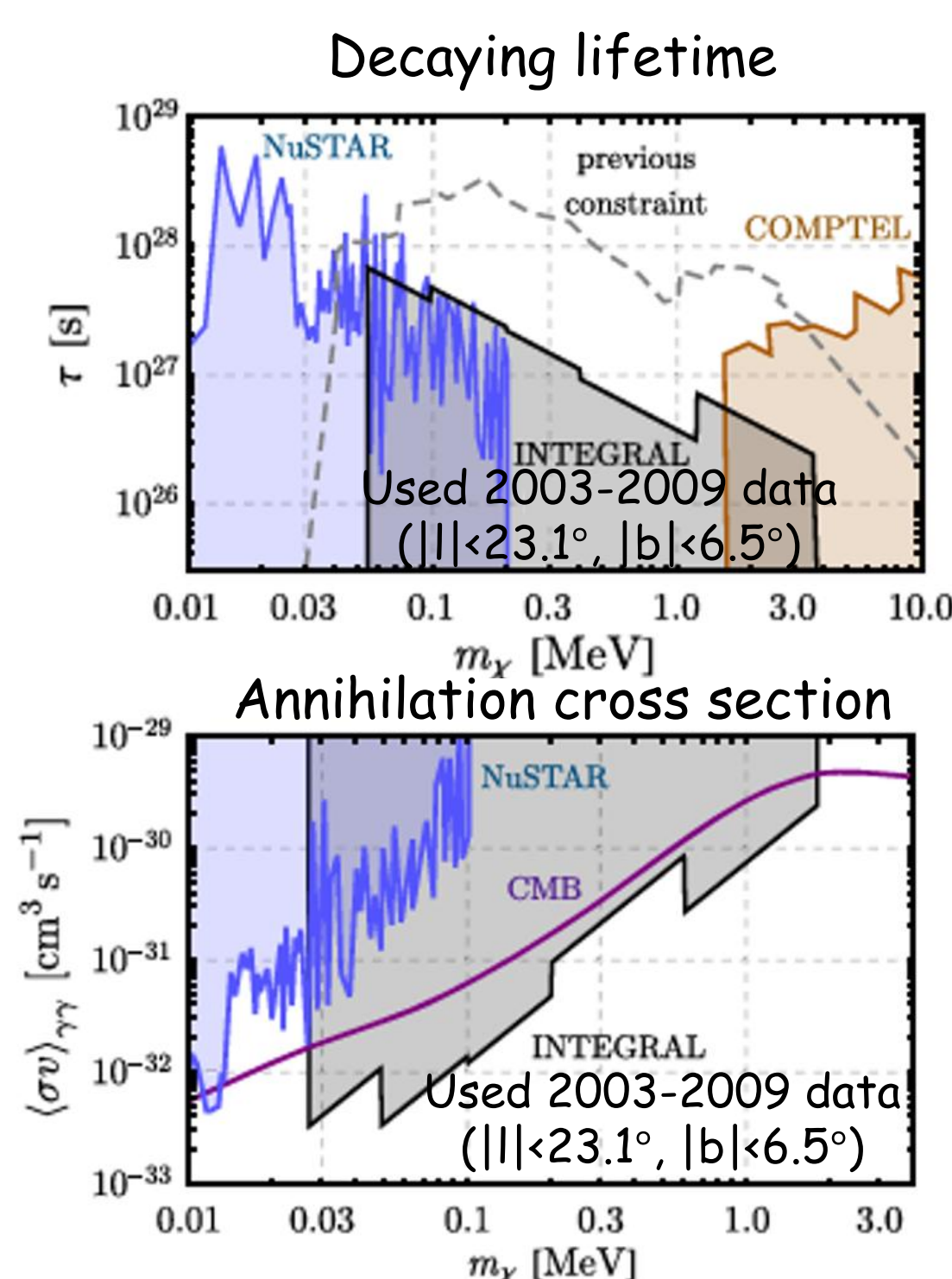
➤ Motivation for Indirect Detection

- Constrains parameters different from direct detection (e.g., annihilation cross-section)
- Enables validation across multiple targets (e.g., Milky Way and external galaxies)

Existence of MeV-scale DM predicts positron annihilation and MeV band continuum emission



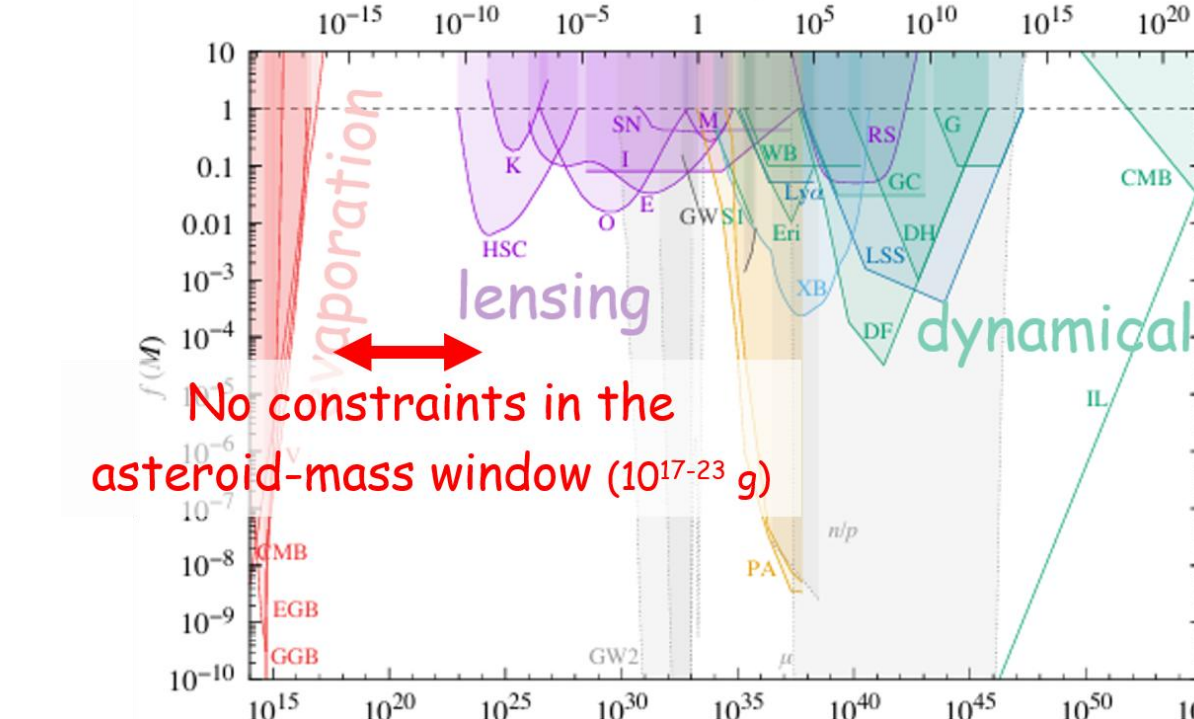
Predicted dark matter annihilation spectrum (K. Ahn, 2005, PRD)



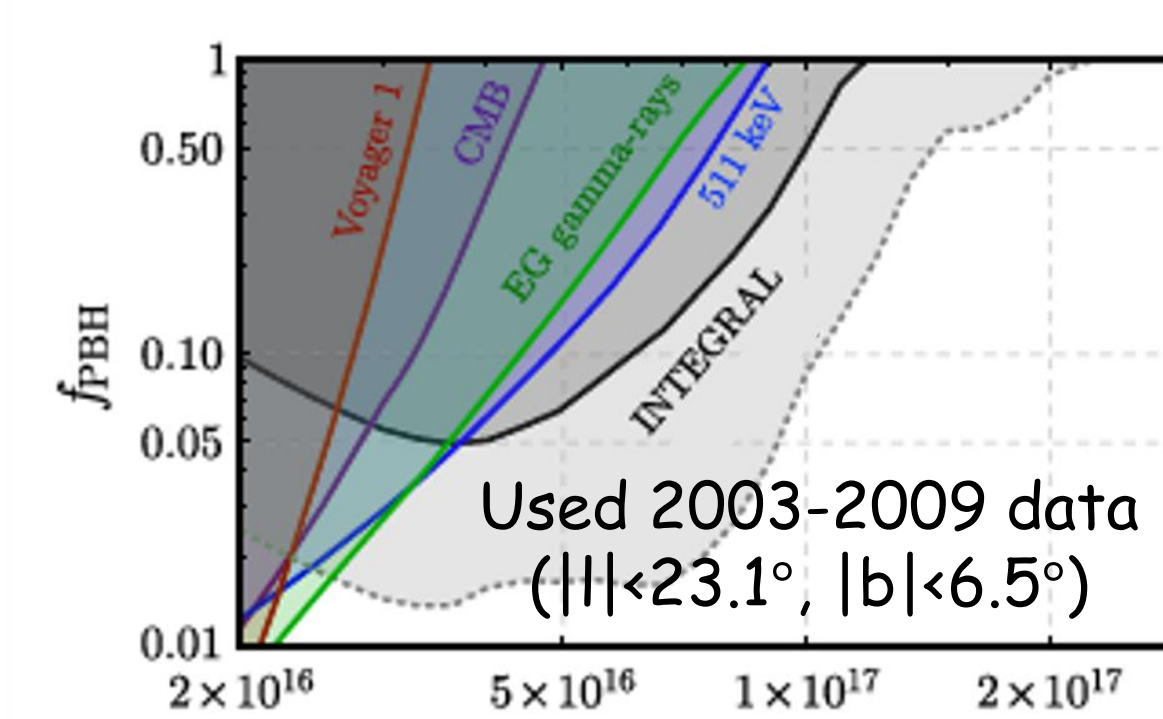
(R. Laha et al., 2020, PRD)

Primordial Black Hole(PBH)

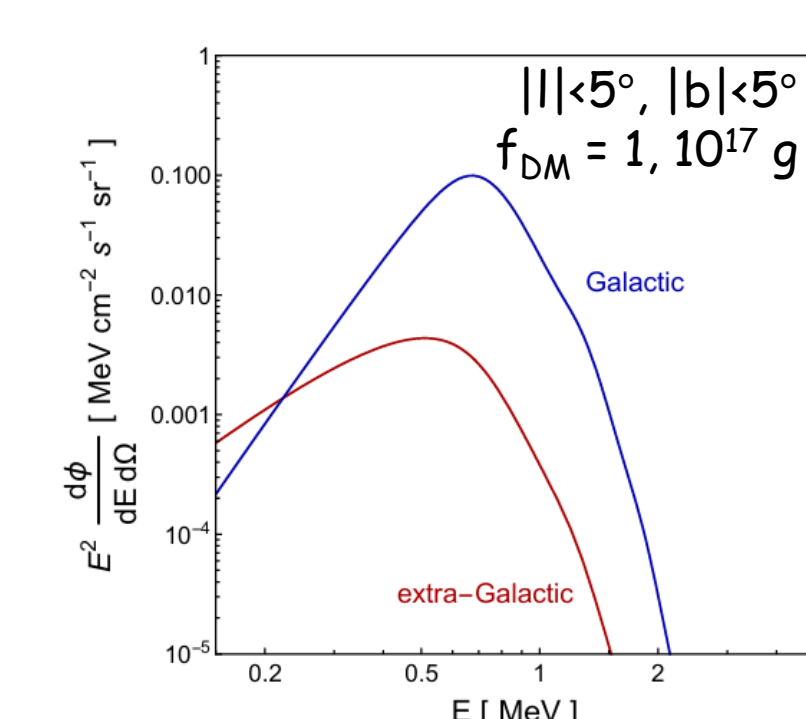
- Black holes formed in the early universe from quantum density fluctuations
 - The unique candidate for directly observing Hawking radiation
 - $T_{\text{BH}} \sim 10.6 \text{ MeV} \times (10^{16} \text{ g} / M)$
 - $\tau \sim 13.8 \text{ Gyr} \times (M/M_\star)^3$ ($M_\star = 5.1 \times 10^{14} \text{ g}$; τ = age of the Universe)



Constraints on mass fraction of dark matter halo (B. Carr et al., 2021, Rep. Prog. Phys.)



Constraints on mass fraction of dark matter halo (R. Laha et al., 2020, PRD)



Expected photon flux spectrum from PBHs (A. Ray et al., 2021, PRD)

Our Strategy

➤ Spatial Distribution Analysis

- Utilizing few-MeV continuum and positron annihilation in Galactic Center region
- Astrophysical sources: Distributed along the Galactic plane (Sources characteristically bright in the MeV band remain unidentified)
- Dark matter decay / PBH Hawking radiation $\propto \rho$
- Dark matter annihilation $\propto \rho^2$

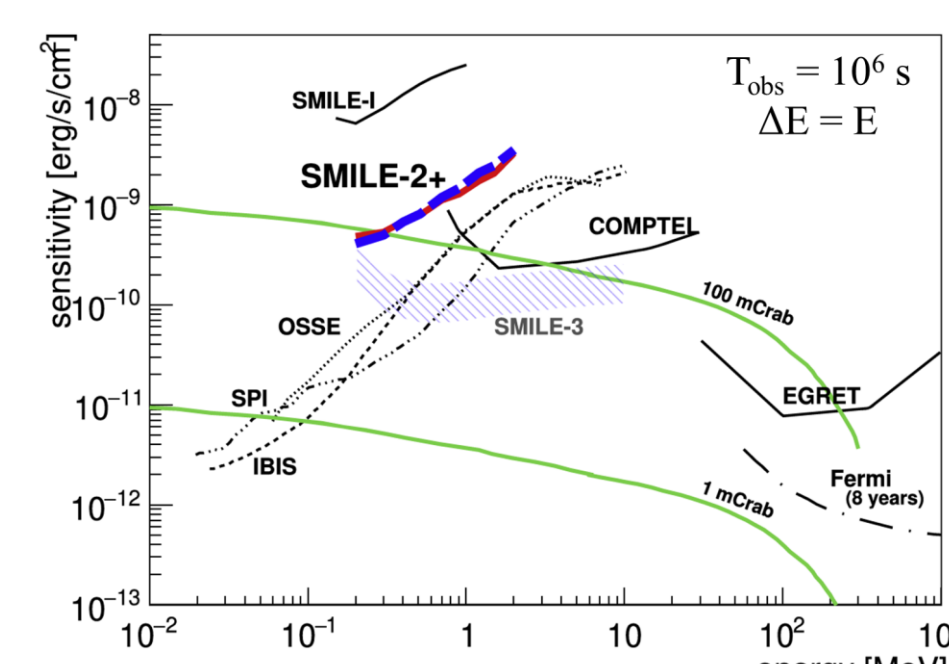
Essential to develop a next-generation detector with high spatial resolution capability

Challenges in MeV Gamma-ray Observation and the ETCC Solution

MeV Gap

➤ MeV Band : Insufficient Sensitivity

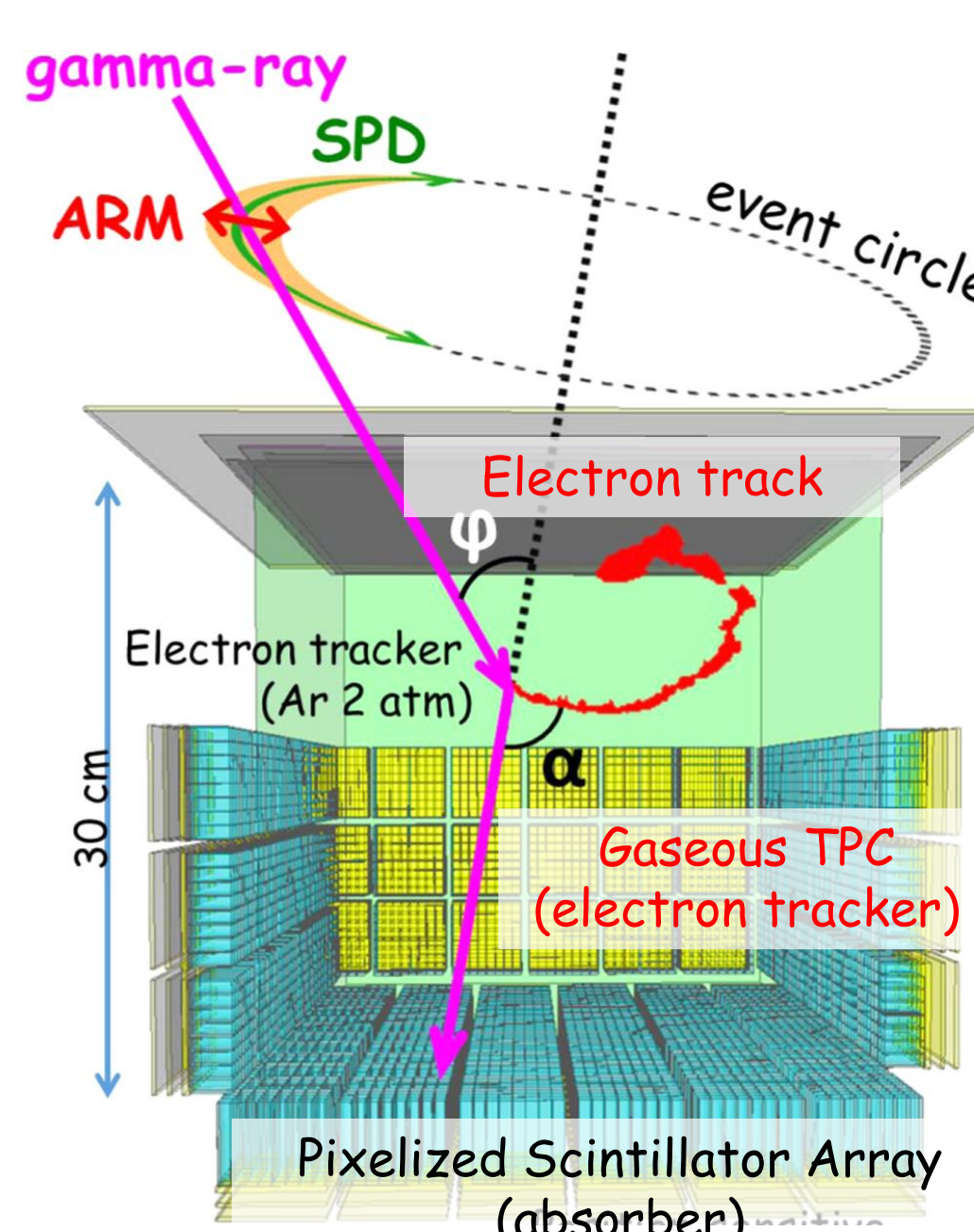
- Difficulty in focusing photons ($\lambda \sim 10^{-12} \text{ m}$)
- Dominance of Compton scattering
- High background generated in structural materials (structural mass $\gg$ detector mass)



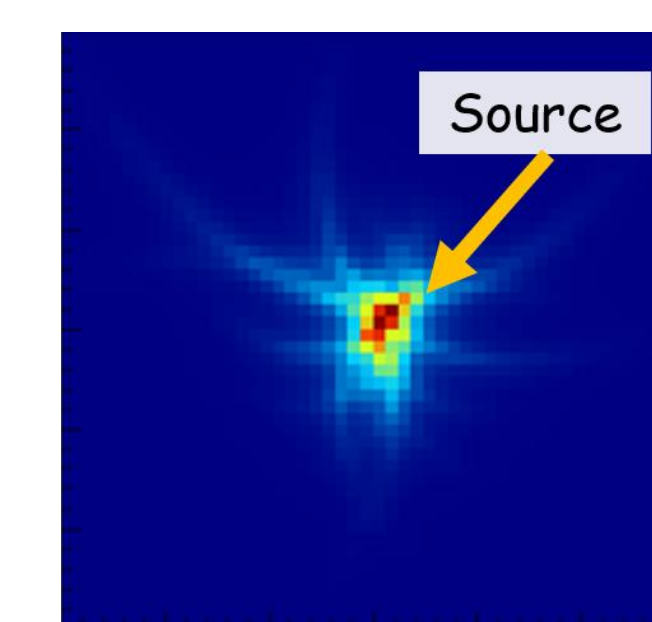
3σ detection sensitivity for the continuum spectrum (A. Takada et al., 2022, ApJ)

Electron Tracking Compton Camera (ETCC)

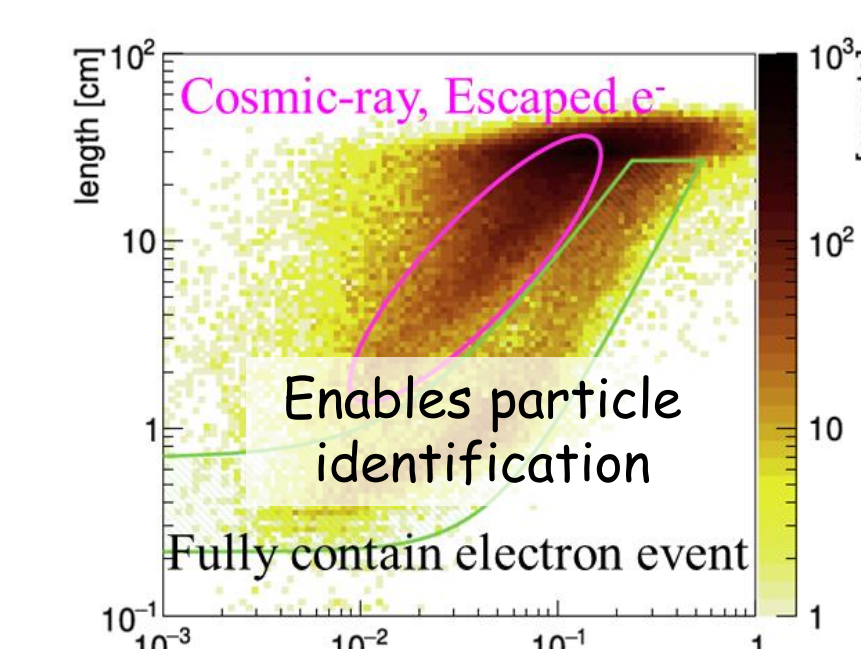
- Measures recoil electron track and energy using gaseous TPC (Enables use of momentum conservation) $\Rightarrow$ Point-like event reconstruction



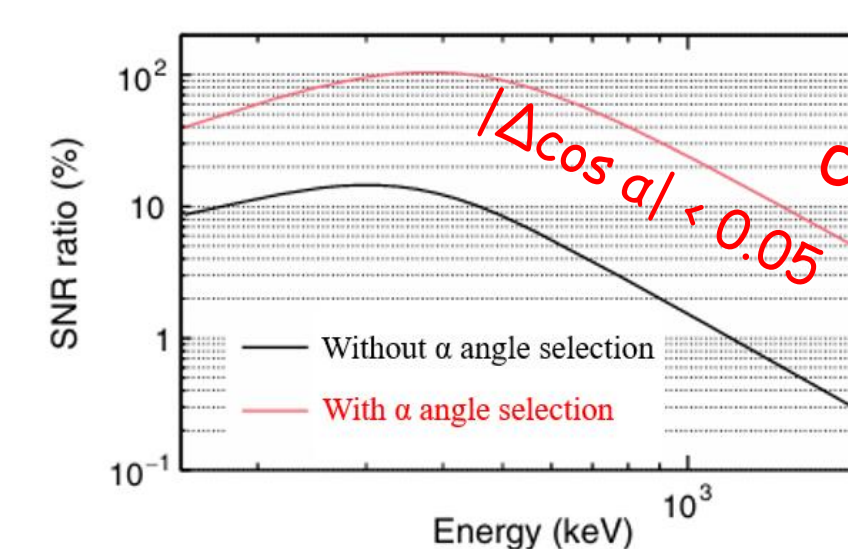
Schematic view of ETCC (T. Tanimori et al., 2020, JPCS)



ETCC Reconstructed image of point source (T. Tanimori et al., 2020, JPCS)

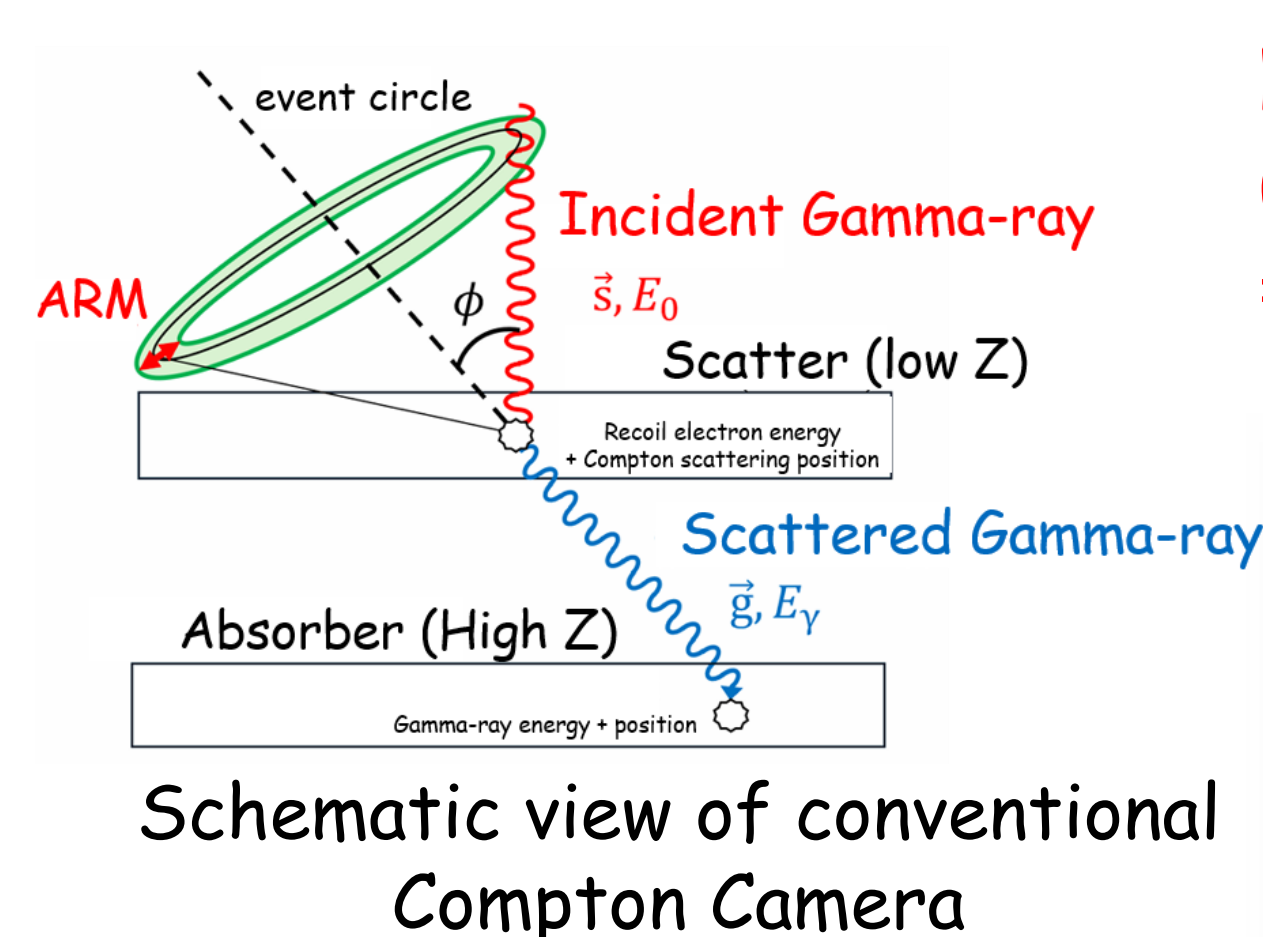


Energy loss rates acquired by ETCC (A. Takada et al., 2022, ApJ)



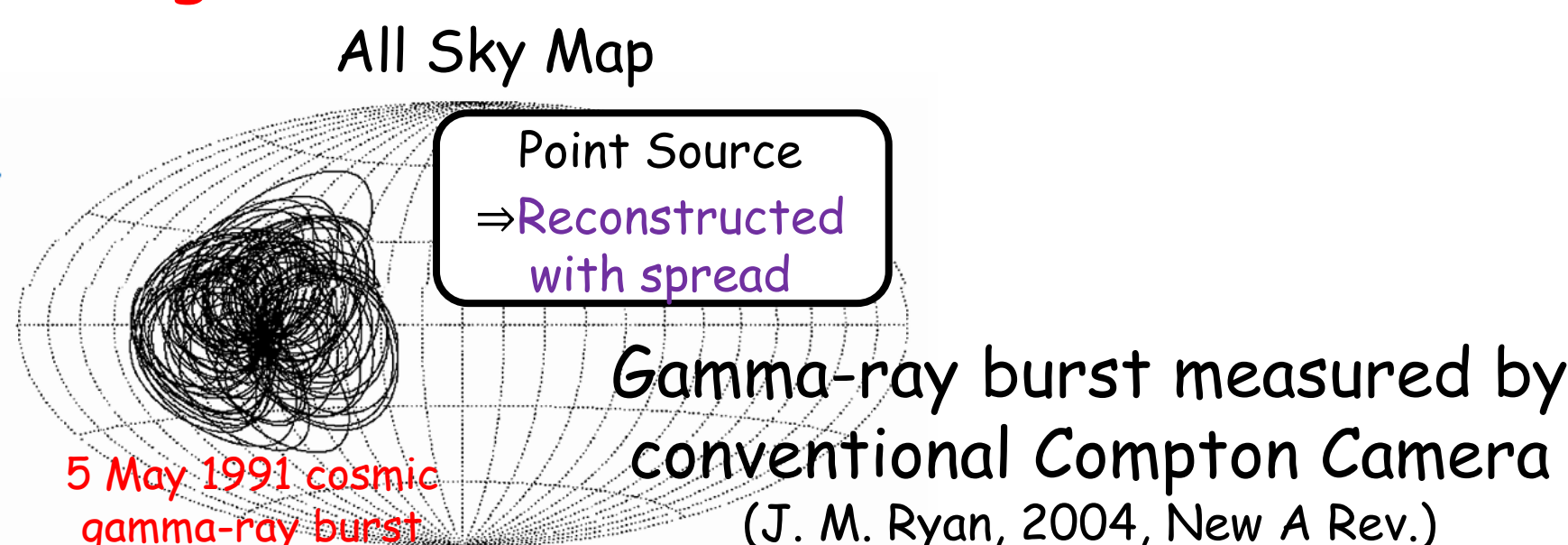
cosa is determined via two methods: geometrical and kinematical. Signal-to-noise ratio of ETCC within the FOV using atmospheric gamma-ray (T. Ikeda et al., 2023, PRD)

Conventional Methods (Compton Camera)



Schematic view of conventional Compton Camera

No recoil electron direction info (Cannot use momentum conservation) $\Rightarrow$ Ring-like event reconstruction



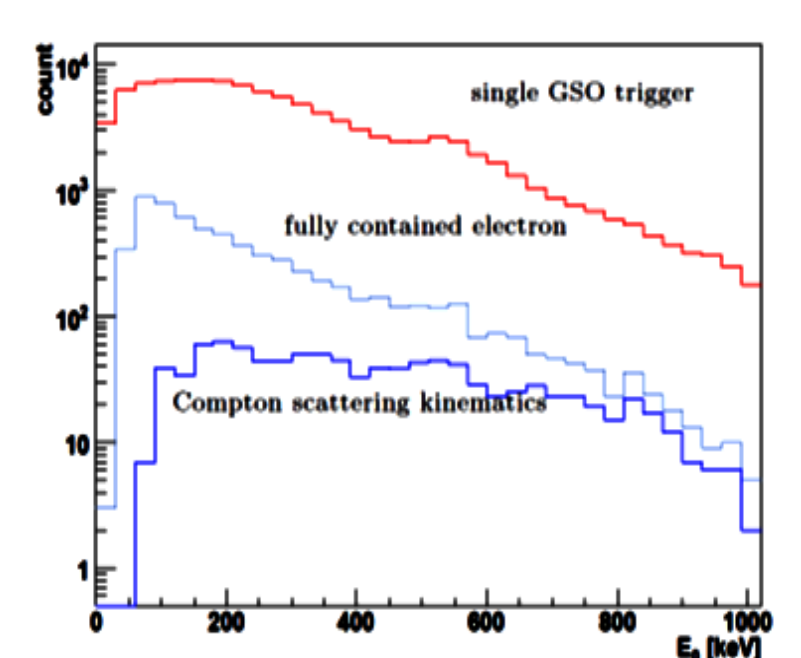
Gamma-ray burst measured by conventional Compton Camera (J. M. Ryan, 2004, New A Rev.)

SMILE (Sub-MeV/MeV gamma-ray Imaging Loaded-on-balloon Experiment)

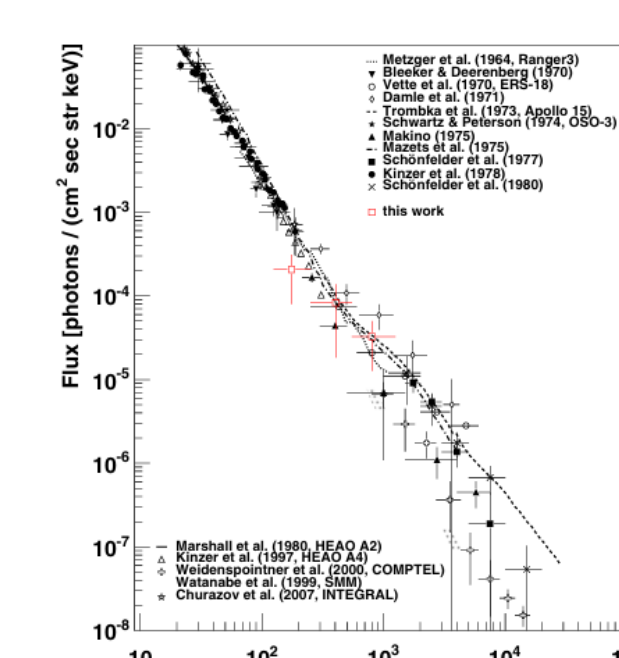
https://kurs10699.sakura.ne.jp/MeV/wiki.cgi?page=Top_en

➤ Past flight: Demonstration of the ETCC

- SMILE-I (2006, Sanriku, Japan, 32-35 km, 4 hours) (A. Takada, et al., 2011, ApJ)
 - Demonstration of strong background rejection capability of the ETCC

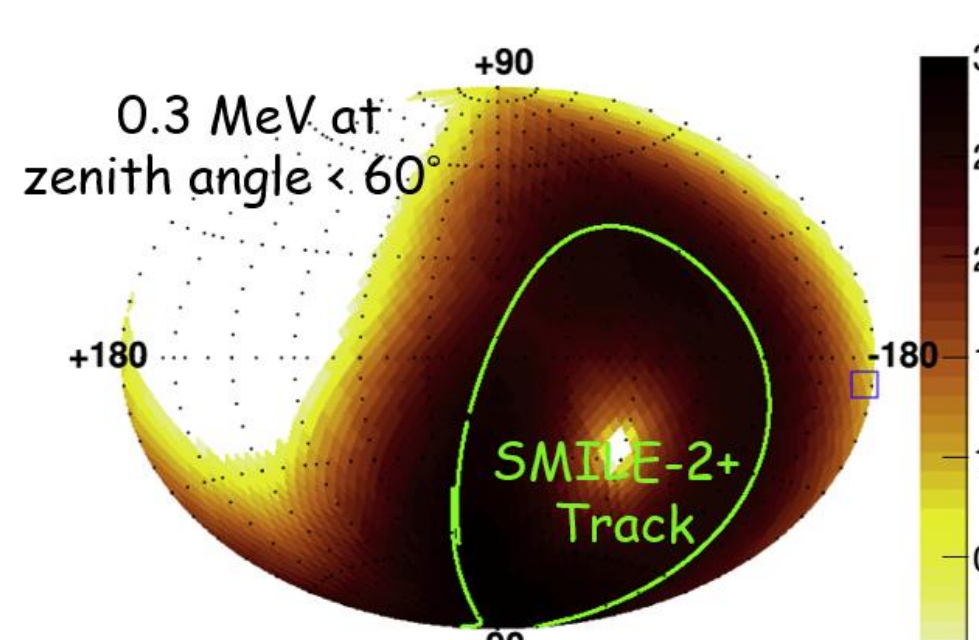


Comparison of counts before and after noise reduction (A. Takada et al., 2011, ApJ)

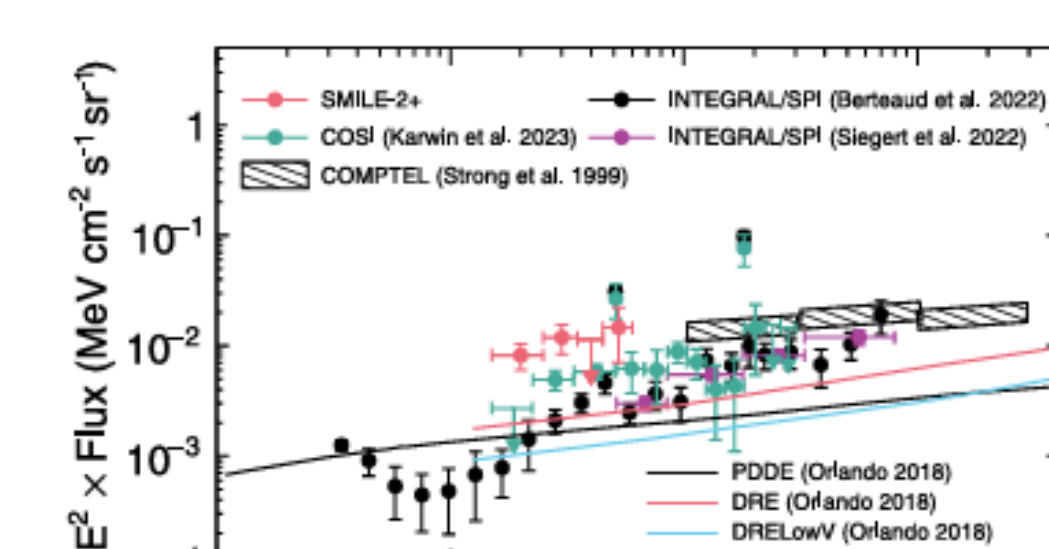


Differential fluxes of diffuse cosmic gamma rays (A. Takada et al., 2011, ApJ)

- SMILE-2+ (2018, Alice Springs, Australia, 37.8-40.4 km, 26 hours) (A. Takada et al., 2022, ApJ)
 - Demonstration of astronomical observation capabilities.



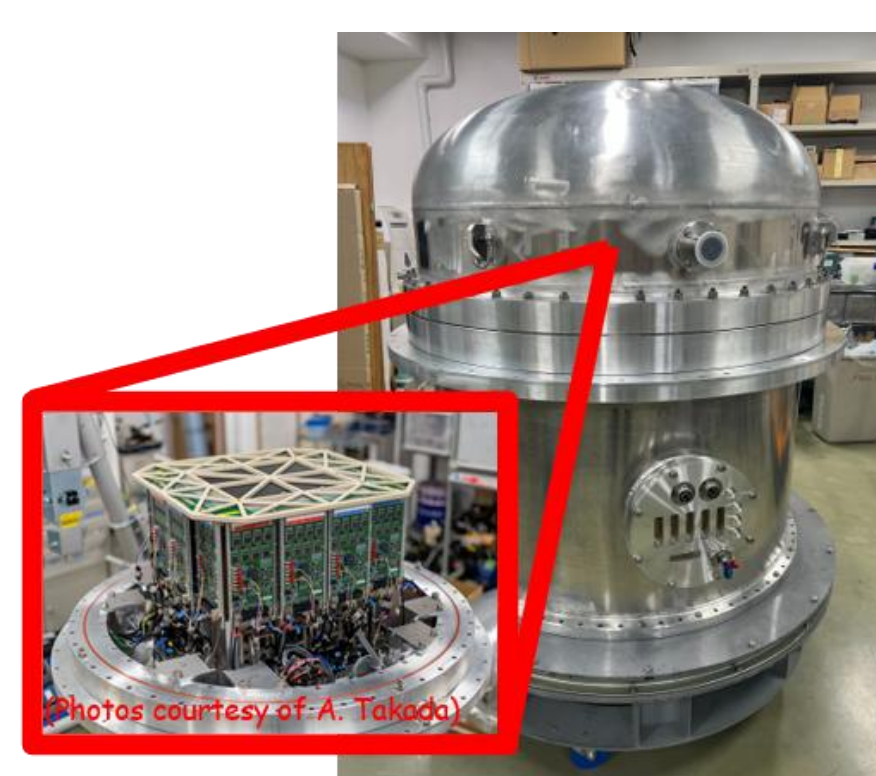
Exposure map of SMILE-2+ (A. Takada et al., 2022, ApJ)



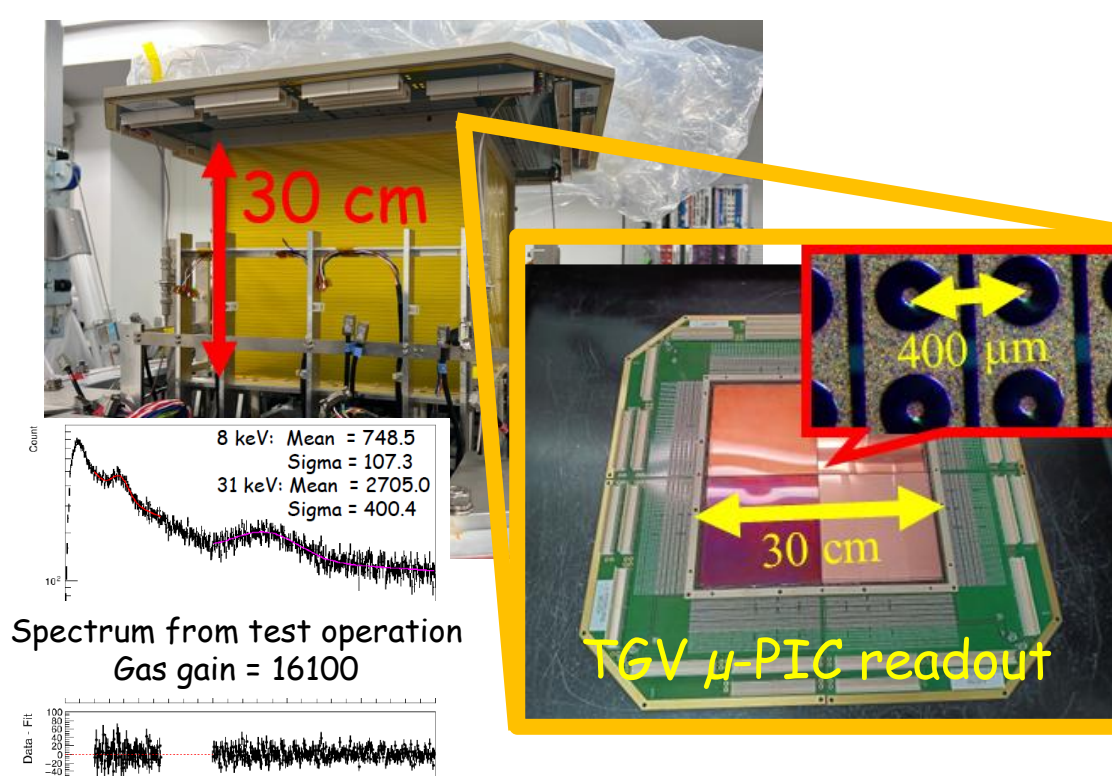
Intensity in the Galactic Center region obtained with the SMILE-2+ (T. Ikeda et al., 2026, PRD)

➤ SMILE-3: Scientific Observation Flight

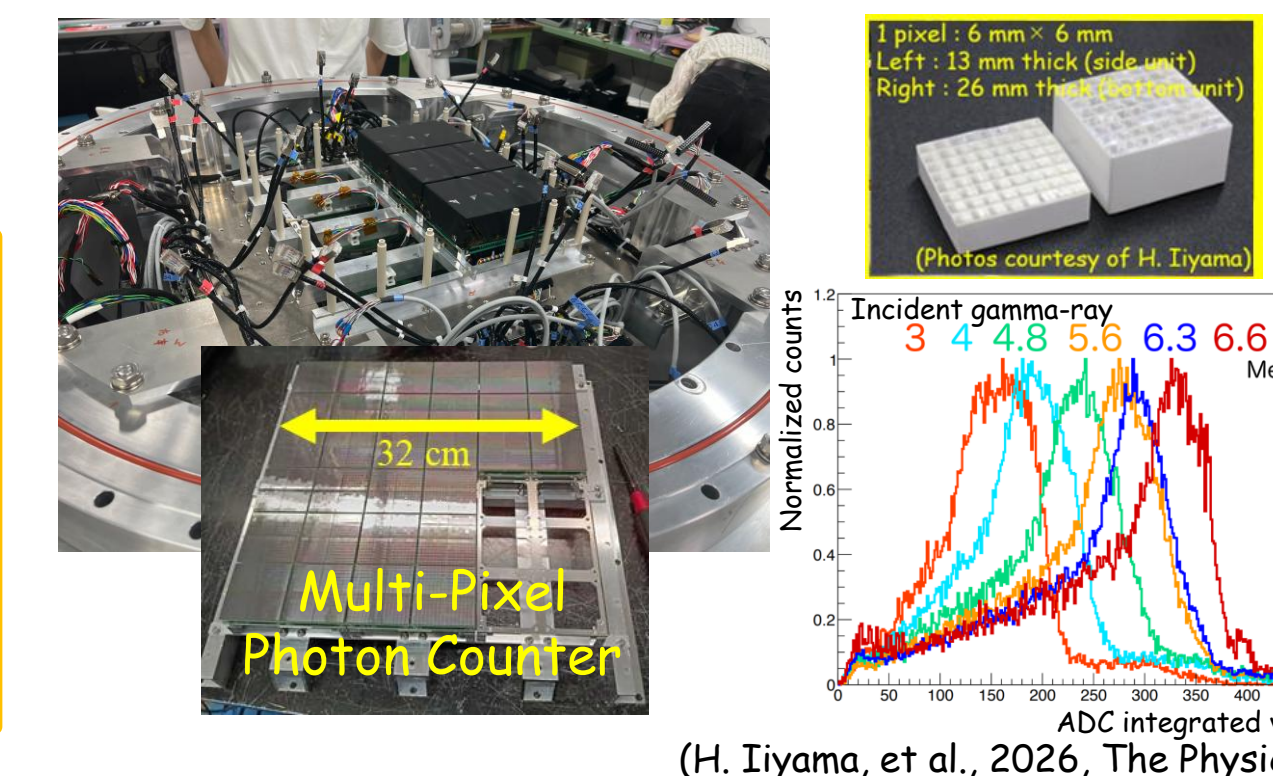
- (First flight of SMILE-3 is planned for 2028, Alice Springs, Australia, 1 day)
- Scientific Targets: Galactic diffuse gamma-ray emission and positron annihilation (To constrain the existence of Dark Matter and PBH)
- Requirements for SMILE-3
 - Effective area : $\sim 5 \text{ cm}^2$
 - Point spread function : $\sim 10^\circ$ at 0.5 MeV



SMILE-3 Vessel



SMILE-3 Gaseous TPC



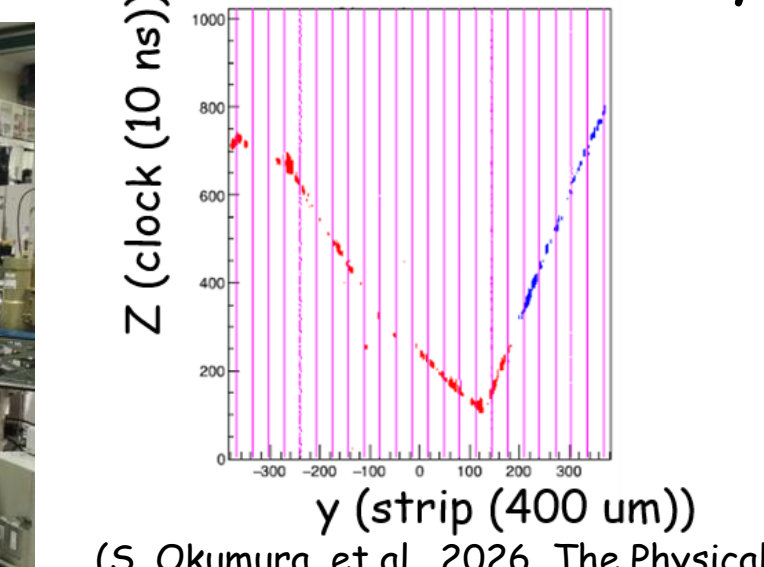
SMILE-3 Pixelized Scintillator Array

➤ Preparation for the next flight

- Beam Test at UVSOR (Institute of Molecular Science, National Institutes of Natural Science)
 - Tested the operation of the gaseous TPC (done)
- Balloon experiment for star tracker (done)
- Thermal vacuum test



Setup for the first beam test of SMILE-3 at UVSOR



Track of Pair production obtained by SMILE-3