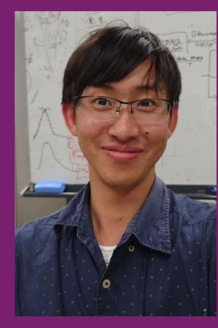
Charge Response Simulation of Liquid Argon Compton Cameras for Precise MeV Gamma-Ray Event Reconstruction



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1. Introduction

- MeV gamma-ray opens new perspectives
  - Nucleosynthesis of heavy elements
  - Nuclear reactions in black hole accretion disks
  - Particle acceleration
  - Transition from thermal to non-thermal emission

Why still unexplored? — The "MeV Gap"
- **Insufficient effective area**
  → MeV band remains poorly explored ("MeV gap", Fig. 1).
- **High instrumental and environmental backgrounds**
- Difficulties in event reconstruction

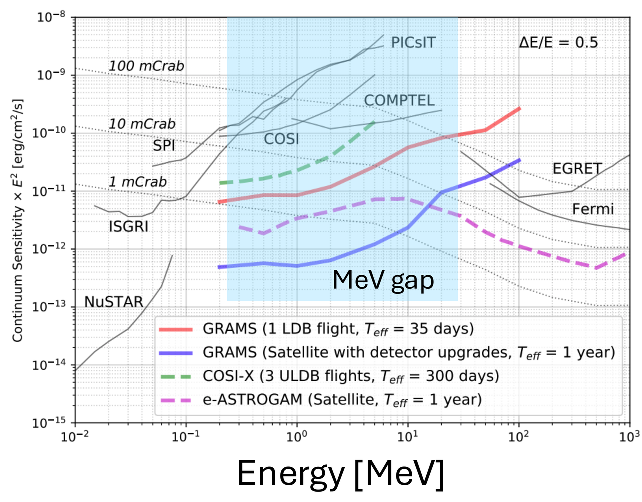


Fig. 1 Continuum sensitivity around MeV Band[1]

- Gamma Ray and AntiMatter Survey (GRAMS)
  - A balloon-borne / satellite-based mission for **MeV gamma-ray observations and dark-matter searches** via antiparticles.
  - A liquid argon time-projection chamber provides **superior sensitivity** in the MeV band
  - A prototype balloon experiment (pGRAMS) is scheduled for **Spring 2026 in Arizona, USA**.
  - A detector for the demonstration of Compton imaging, NanoGRAMS, is under development. (S. Takashima's presentation on Nov. 21th for details)
  - In this study, we aim to **explore the feasibility of using not only GRAMS but also general LArTPCs as Compton cameras**.
- LArTPC:
  - A promising technology for next-generation MeV Compton cameras.
  - **Scalable and cost-effective**, enabling a large effective area (**~1000 cm^2** for GRAMS).
  - Acts as both a **Compton camera** and a **3D particle tracker**, enabling **clear discrimination between charged-particle backgrounds and gamma-ray events.**

2. Detector Concept of LArTPC

- Incident gamma rays interact with LAr via:
  - Compton scattering
  - Photoelectric absorption
  } "Hits"
- LArTPC measurement:
  - **3D hit positions:**
    - z-axis from the time difference between scintillation light and ionization charge
    - $x-y$ plane from the 2D charge readout
  - **Energy deposition** from the charge-signal pulse height
- Event with (> 3 hits) or (a Compton Scattering + a Photoelectric absorption)
  → Enable reconstruction of the **incident gamma-ray energy and direction** using Compton kinematics (Right).
- A single event constrains the source direction to a ***Compton cone***.
- **Overlapping multiple cones** provides the final direction reconstruction (Fig. 3).

$$E = \sum_{i=1}^{N} \Delta E_i + E_{esc},$$ Where N: number of hits

$$E_{esc} = -\frac{\Delta E_{N-1}}{2} + \sqrt{\frac{\Delta E_{N-1}^2}{4} + \frac{\Delta E_{N-1} m_e c^2}{1-\cos\theta_{N-1}}}$$

$$\cos\theta_1 = 1 - m_e c^2 \left(\frac{1}{E-\Delta E_1} - \frac{1}{E}\right)$$

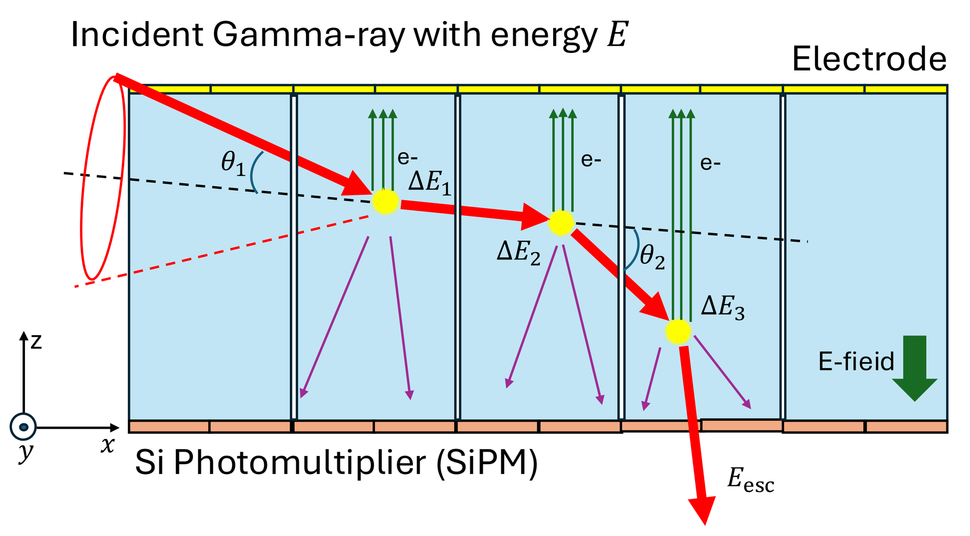


Fig. 2: Schematic of LArTPC

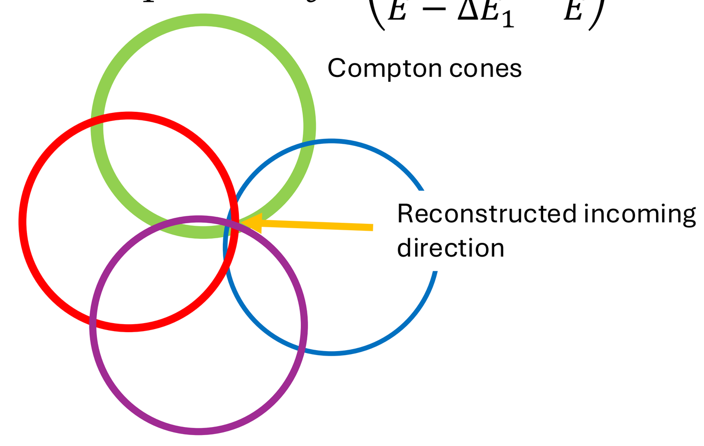
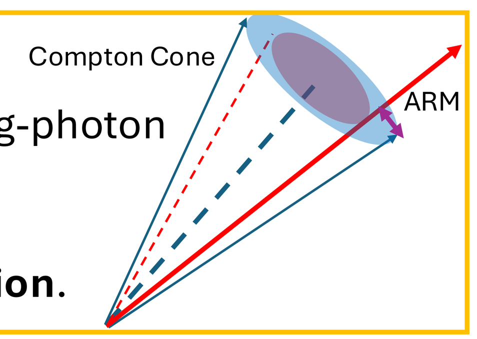


Fig. 3 Schematic of the estimation of the direction

3. Performance Evaluation of a Compton Camera

Performance of a Compton camera is measured by ARM, and energy resolution (typically evaluated using FWHM).

ARM (Angular Resolution Measure)
- Difference between the **true** direction and **reconstructed** incoming-photon direction
- The overlap of Compton cones determines the source direction
  →The cone-overlap sharpness directly reflects the **angular resolution**.



Candidate effects to make ARM & energy resolution worse

Effects we considered in this study

- Position resolution of energy deposition
  - Pixel Pitch
  - Distortion of electric field (geometrical effects, space charge effect, etc.)
  - Diffusion (longitudinal and transverse)
  - Clustering / hit-finding method
- Energy resolution of energy deposition
  - Recombination of ionized electrons (and its fluctuation)
  - Electrical & statistical fluctuations
  - Charge collection efficiency (CCE) ←Ar ions drift much more slowly than electrons
  - Liquid-argon purity
- Performance of reconstruction algorithms

Precise event reconstruction requires both **good energy resolution** and **sharp ARM**.
→ How do these detector effects impact the performance of an LArTPC as a Compton camera?

4. Simulation

Geant4-based simulation
- Detector-response modeling implemented using the semiconductor-detector framework **ComptonSoft** [2].
- **Recombination** modeled with the **Modified Box (MB)** approach [3,4]
- **Longitudinal and transverse diffusion** included following the formulation in [5].
- **Modified charge-collection efficiency (CCE)** calculation tailored for LArTPC.
- Geometry: **30 cm** × **30 cm** × **30 cm** LAr volume, voxelized.
- **Monochromatic photons** at various energies are injected into the LArTPC.

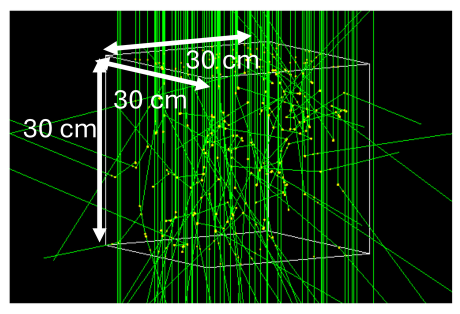
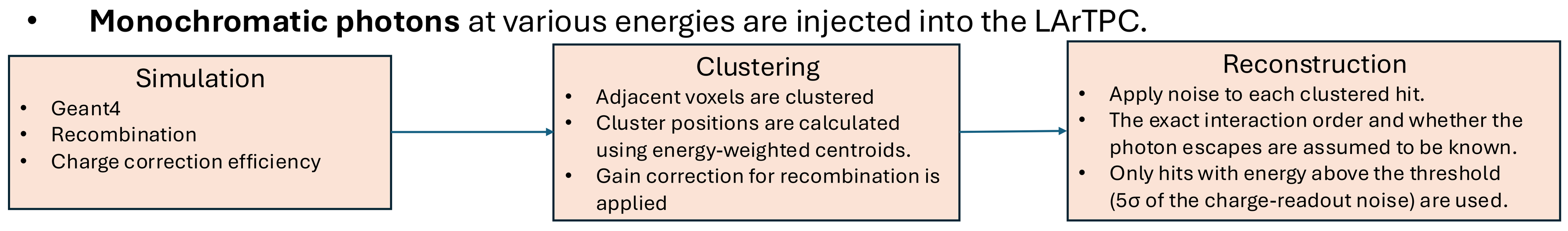


Fig. 4: Geometry of simulation



Recombination model implementation

Multiple recombination models exist, but the microscopic nature remains uncertain.
→ We adopt the **Modified Box (MB)** model, using **dE/dx from ESTAR** [6] for each step.

$$R = \frac{\log\left(\alpha + \frac{dE}{dx}\frac{\beta}{\epsilon\rho}\right)}{\frac{dE}{dx}\frac{\beta}{\epsilon\rho}}$$

R: Ratio of electron to photon
$\alpha = 0.93$ [4]
$\beta = 0.184$ kV g cm^{-3} MeV^{-1} [4]
$\rho = 1.396$ g cm^{-3}: Density of Argon
$\epsilon = 0.5$ kV cm^{-1}: Electric Field

Gain Correction
- A phenomenological gain correction is applied.
- Voxels are grouped along the z-axis to derive the correlation between **true energy deposition** and **signal height** (after recombination) (Fig. 5).
  →For each signal height, the **mean true energy** is used as the corrected value.
- The upper region of the sensitive volume is excluded.

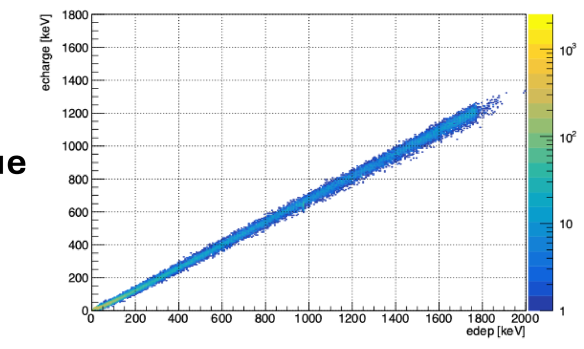


Fig. 5: Correlation between energy deposition and signal height

Simulation condition
- We made the simulation changing conditions and compared the results:
  - With/without recombination
  - Pixel pitch, 0.5, 1, 2, 3mm
  - Noise parameter: p_0 = 10, 5, 2, 0.472 keV (Charge readout noise)
    p_1 = 0.05 keV$^{0.5}$= limitation by Fano factor (0.107)

Underbar: Nominal condition

Noise Parameter = $[p_0, p_1]$

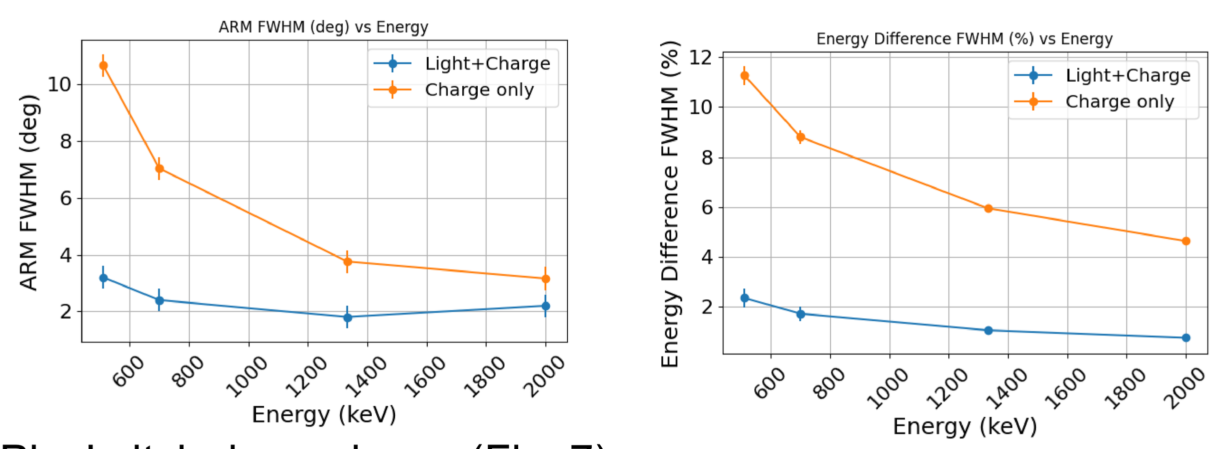
$$\sigma = \sqrt{p_0^2 + p_1^2 E}$$

E: energy deposition [keV]

5. Results

- We evaluated the simulation results by FWHM of ARM and energy difference ($E_{rec} - E_{true}$)
  Reconstructed energy

With recombination at **500 V/cm** (Fig. 6)
- **ARM** degrades ~ x 2.1 at 1.3 MeV.
- **Energy resolution** worsens ~ x 5 at 1.3 MeV.
  ➡ The spectroscopic performance can be improved by using the light signal in addition to the charge signal.
- Even if the charge signal is used alone, we can achieve an **excellent ARM of 3°** and an **acceptable energy resolution of 5% at 2 MeV.**



More realistic energy measurement methods using both the light and charge will be studied in future.

Fig. 6: FWHM of ARM (left) and energy resolution (right) with/without recombination

Pixel pitch dependence (Fig. 7)
- For **pixel pitch < 1 mm**, the **ARM** shows almost no degradation.
- Reconstructed **energy resolution** shows little dependence on pixel pitch.

➡ **A pixel pitch of 1 mm is sufficient for high-resolution Compton imaging** unless we measure the tracks of recoiled electrons. 2 mm still yields very good angular resolution.

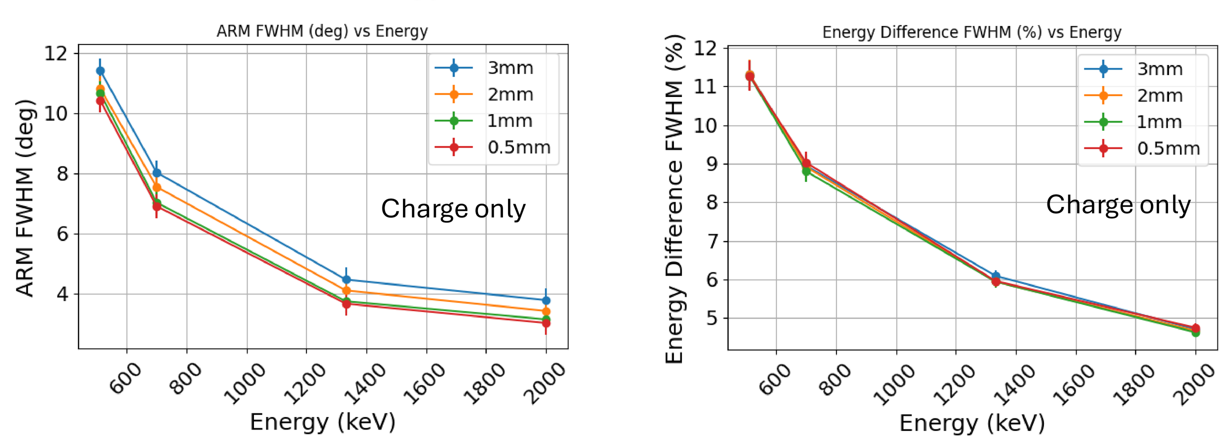


Fig. 7: FWHM of ARM (left) and energy resolution (right) at several pixel pitch.

Charge readout noise dependence (Fig. 8)
- **Charge readout noise significantly affects the ARM**, particularly for low-energy photons.
- While the charge readout noise affects the energy resolution, **the improvement of the electronics noise below 2 keV does not contribute to the spectroscopic performance.**

➡ **A noise level of 2 keV can be regarded as the development goal of charge readout electronics.**

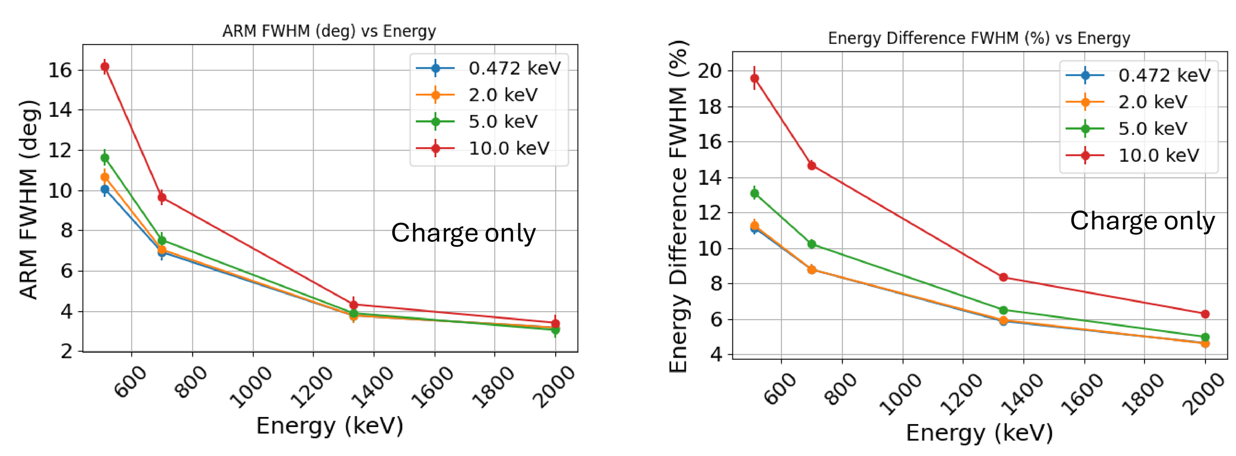


Fig. 8: FWHM of ARM (left) and energy resolution (right) at several charge readout noise

5. Conclusion

- **LArTPCs are promising next-generation Compton cameras** for MeV gamma-ray astronomy.
- To evaluate their performance, we conducted Geant4-based simulation and postprocessing of realistic detector effects such as recombination and charge readout noise.
- Excellent Compton reconstruction performance will be achievable by the electron signal readout with:
  - **Pixel pitch: 1~2 mm**
  - **Electronic noise: ~2.0 keV**
- There remains strong potential for further improvement through the **combined use of light and charge signals**, while **charge-only readout** still delivers good performance for high-energy photons (>1MeV).

References

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