Opening the MeV Window

New Technologies and Observing Methods in MeV Gamma-Ray Astronomy

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CDHY Initiative seminars
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Outline

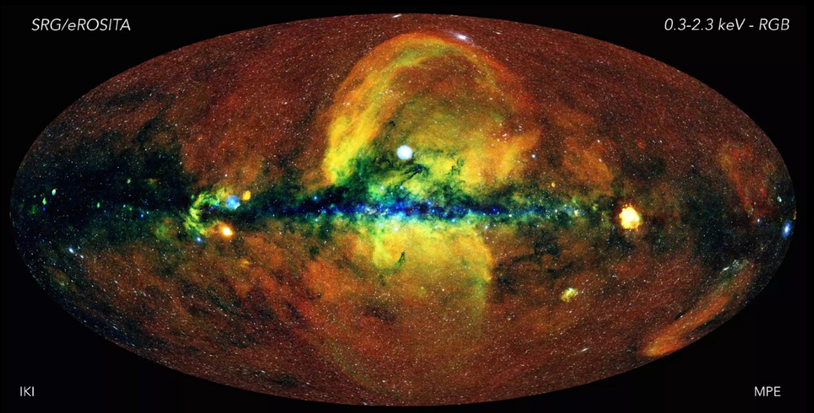
1. Motivation
2. Compton telescopes
3. Data analysis
4. Hardware framework
5. Future directions in MeV telescope design
6. Concluding remarks

1. Motivation

The high-energy universe today

X-ray

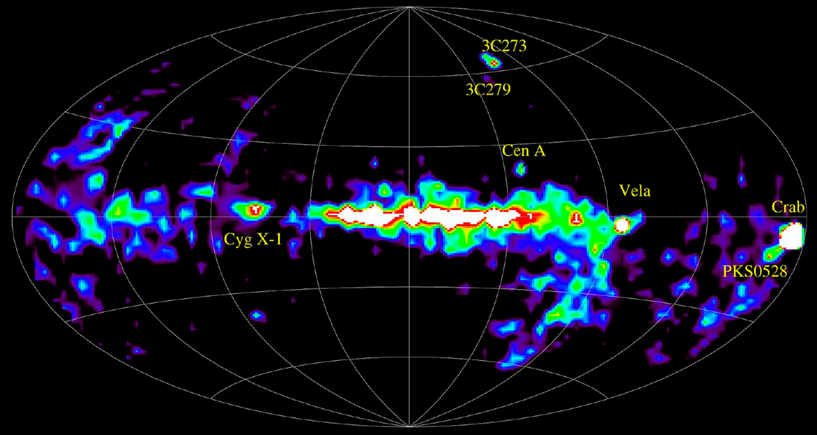
eROSITA



~10^6 objects

MeV

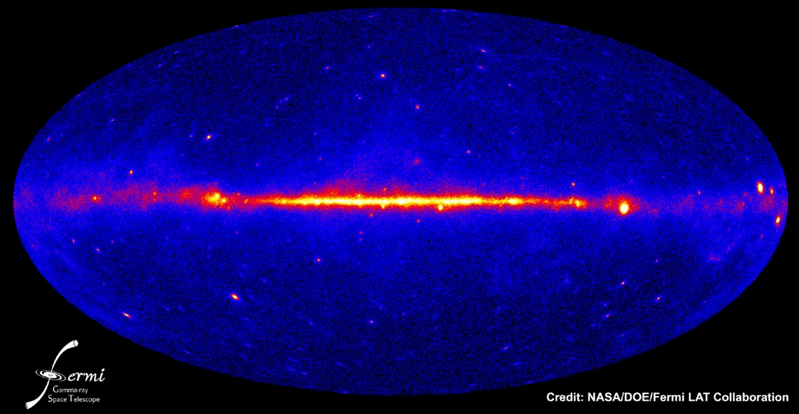
CGRO-COMPTEL



~30 objects

GeV

Fermi-LAT



~7000 objects

X-rays and GeV gamma rays have undergone transformative advances.
But between them, the MeV sky still looks very different.

The MeV universe is special

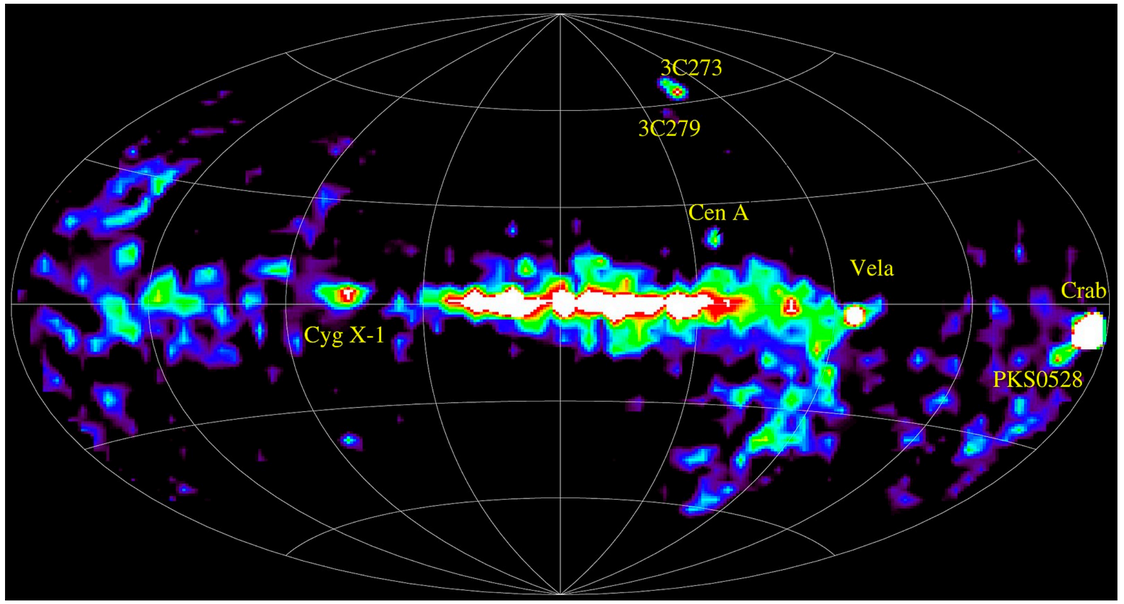
The MeV band provides unique diagnostics of energetic particles, nuclear processes, and nucleosynthesis.

MeV probe	Physical information
Electron emission	electron distribution, temperature, magnetic field
Ion-induced nuclear emission	ion distribution, temperature, composition
Pion-decay emission	relativistic-ion spectrum, acceleration & propagation
Radioactive nuclei	nucleosynthesis, ejecta distribution & dynamics
Positron annihilation	positron origin, transport & annihilation environment

Dark-matter searches: primordial black-hole evaporation, particle dark matter

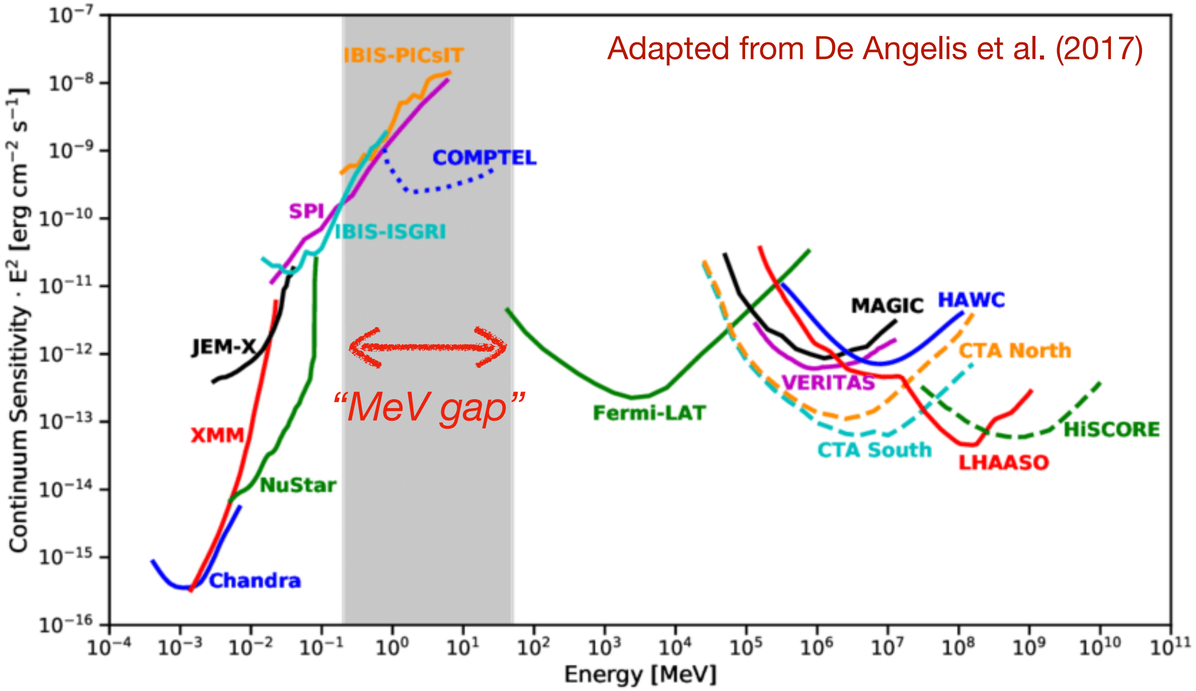
The MeV sky remains largely unexplored

All sky MeV image obtained with CGRO/COMPTEL



Our view of the MeV sky still largely dates back to the COMPTEL era.

Continuum sensitivity of X-/γ-rays



MeV sensitivity has been limited by low detection efficiency for Compton events and high instrumental background in orbit.

The MeV gap also represents a large discovery space.

Why is MeV observation so difficult?

	X-ray (keV)	MeV	GeV
Physical interaction	photoelectric effect	Compton scattering	pair creation
Effective area	**large**	**small**	**small**
Background level	**low**	**extremely high**	**low**
Imaging method	**excellent: 1 arcseceond with reflecting optics**	**poor: ~degrees with Compton telescope**	**good: ~10 arcminutes with pair telescope**

Low detection efficiency: Detecting gamma rays through Compton scattering requires large, complex detectors.

High instrumental background: Cosmic rays and geomagnetically trapped particles produce abundant secondary radiation and induce radioactivation. Atmospheric radiation also contributes.

A simple argument for 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:

  $$\frac{\Delta S}{S} = \frac{\sqrt{bAT}}{\mathrm{flux} \cdot AT} \quad \rightarrow \quad \mathrm{flux} = \left(\frac{S}{\Delta S}\right)\sqrt{\frac{b}{AT}}$$ (simplified argument, depending on the background estimation)

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

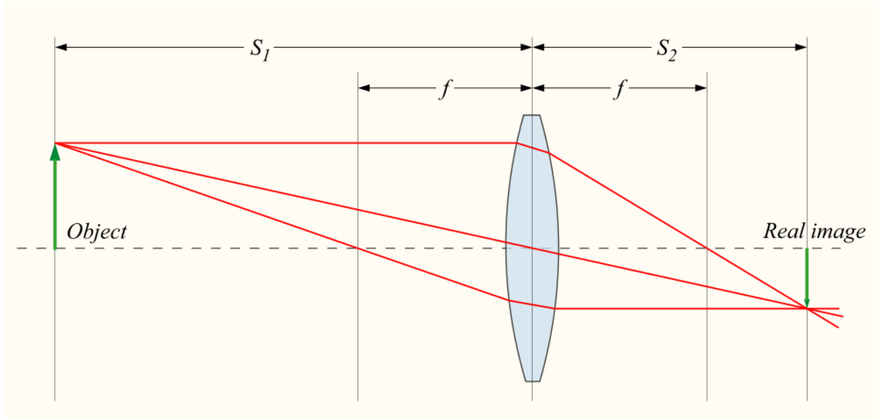
- To have a better sensitivity, **maximize the area**, and **minimize the background level**.

2. Compton telescopes

How can we visualize MeV gamma rays?



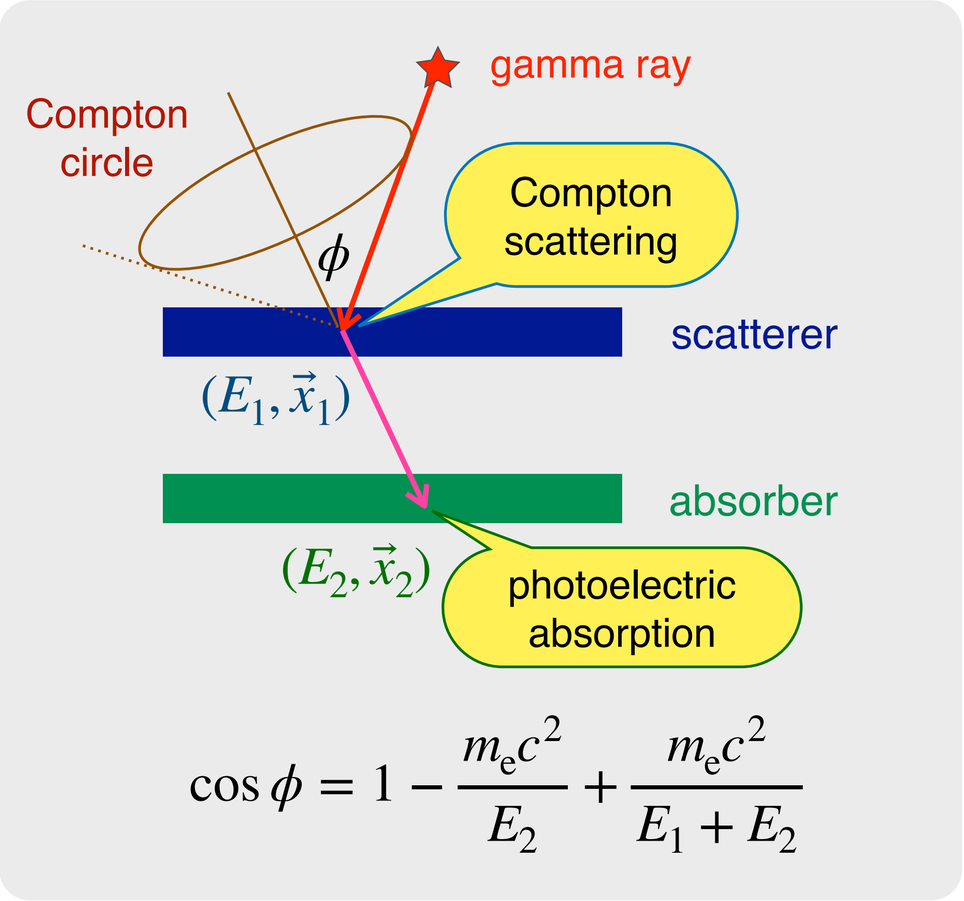




object optics focal plane

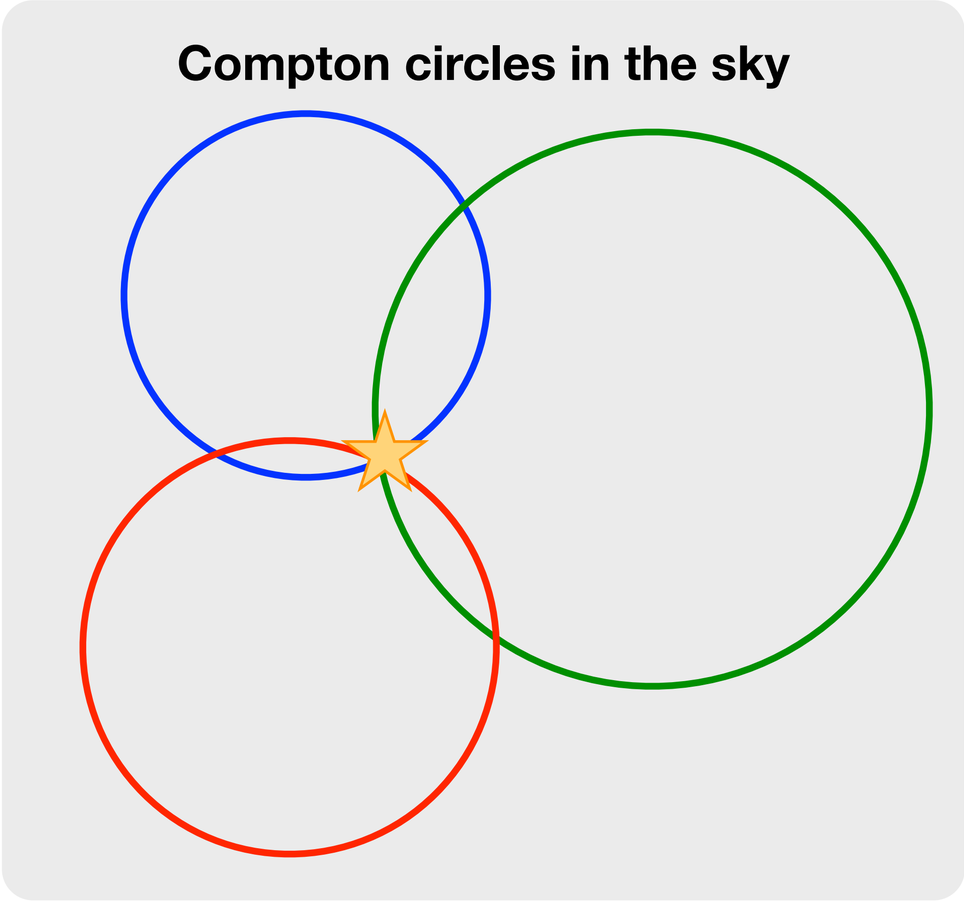
- There is no practical optics for MeV gamma rays...
- What is imaging?
- Imaging is the mapping of incident photon directions onto distinguishable structures in the instrument's data space.
- e.g., in a visible light camera, the lens maps the incident direction onto a point on the imaging sensor.

Compton camera (or Compton telescope)



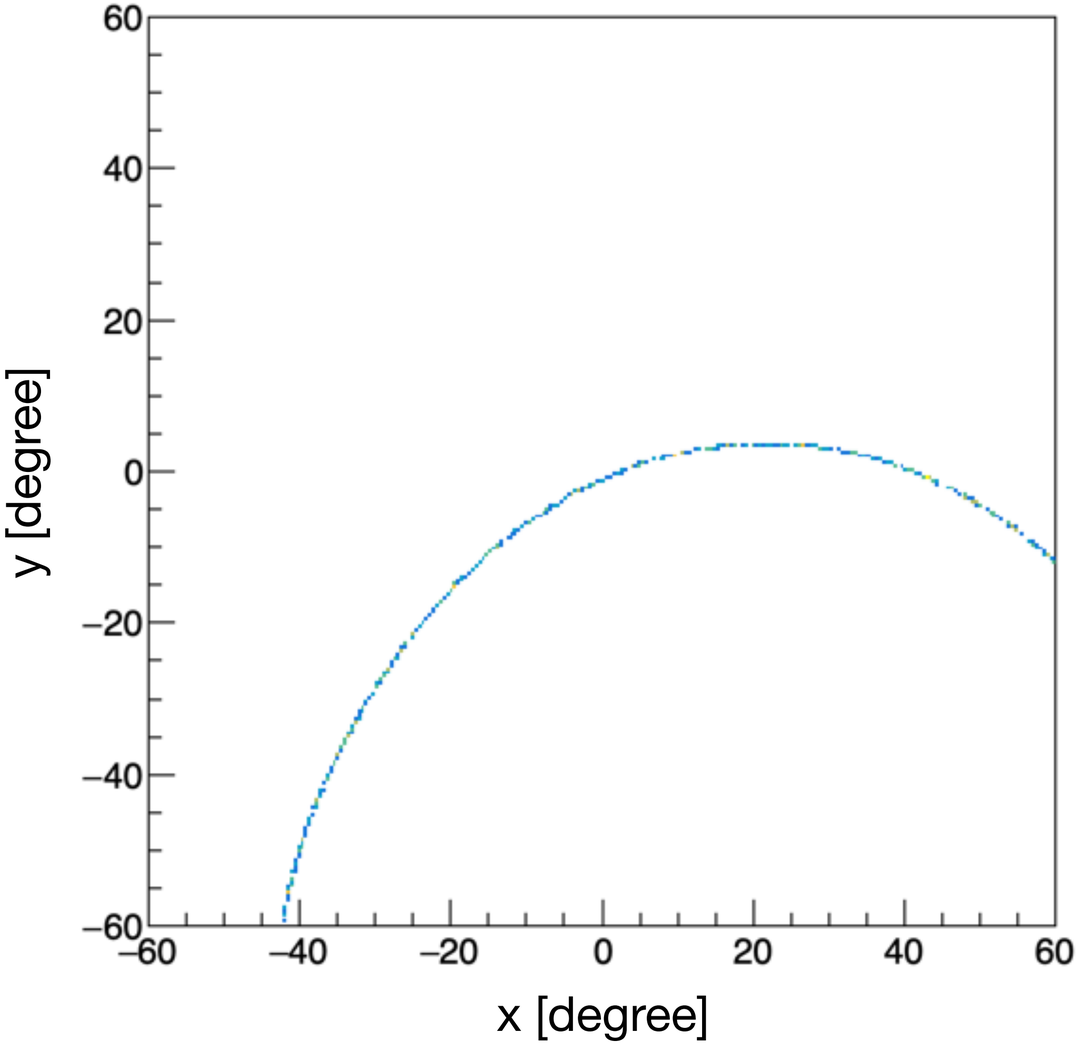
$$\cos\phi = 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2}$$

- The scattering angle can be calculated by the conservation of energy and momentum.



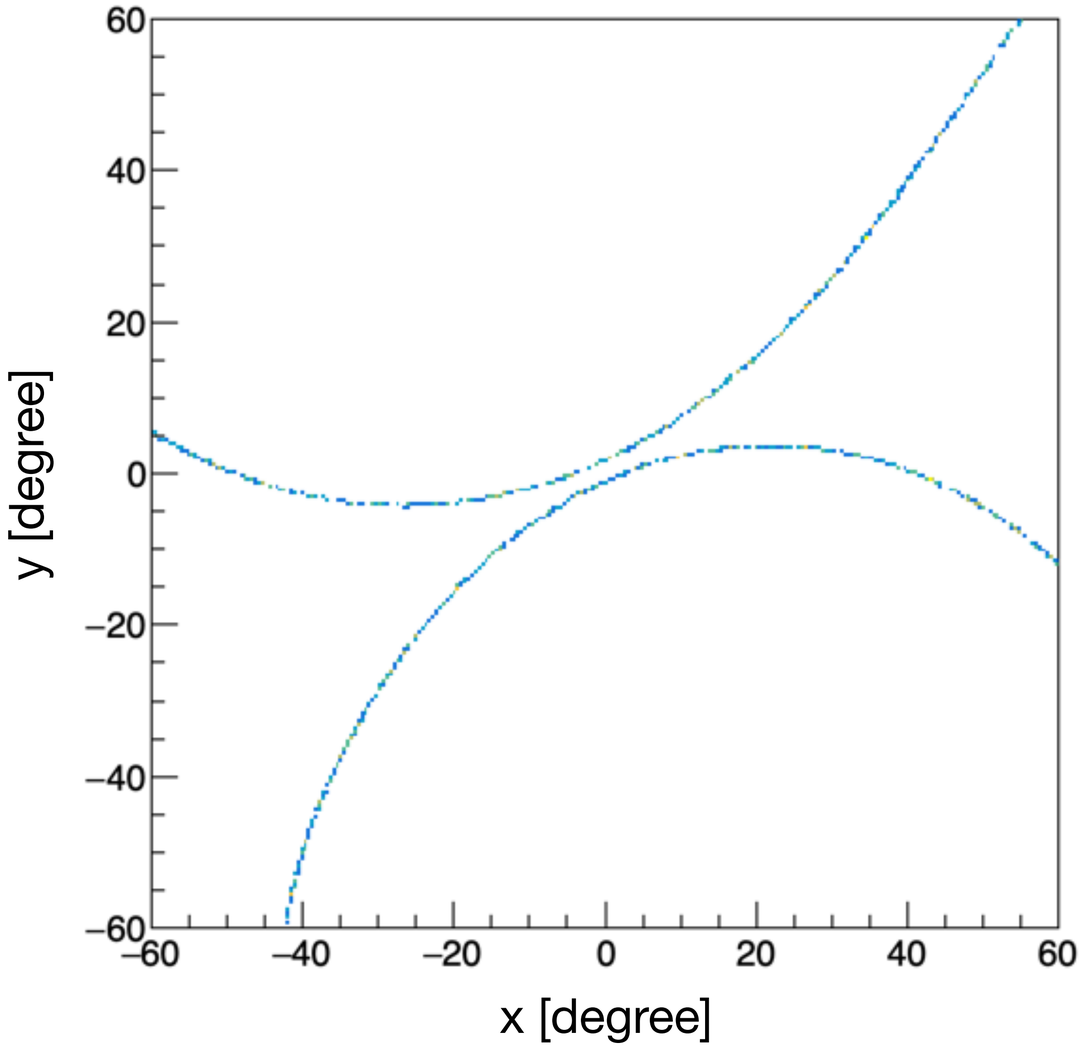
The source is identified as the intersection of independent Compton circles.

Let's see how it works



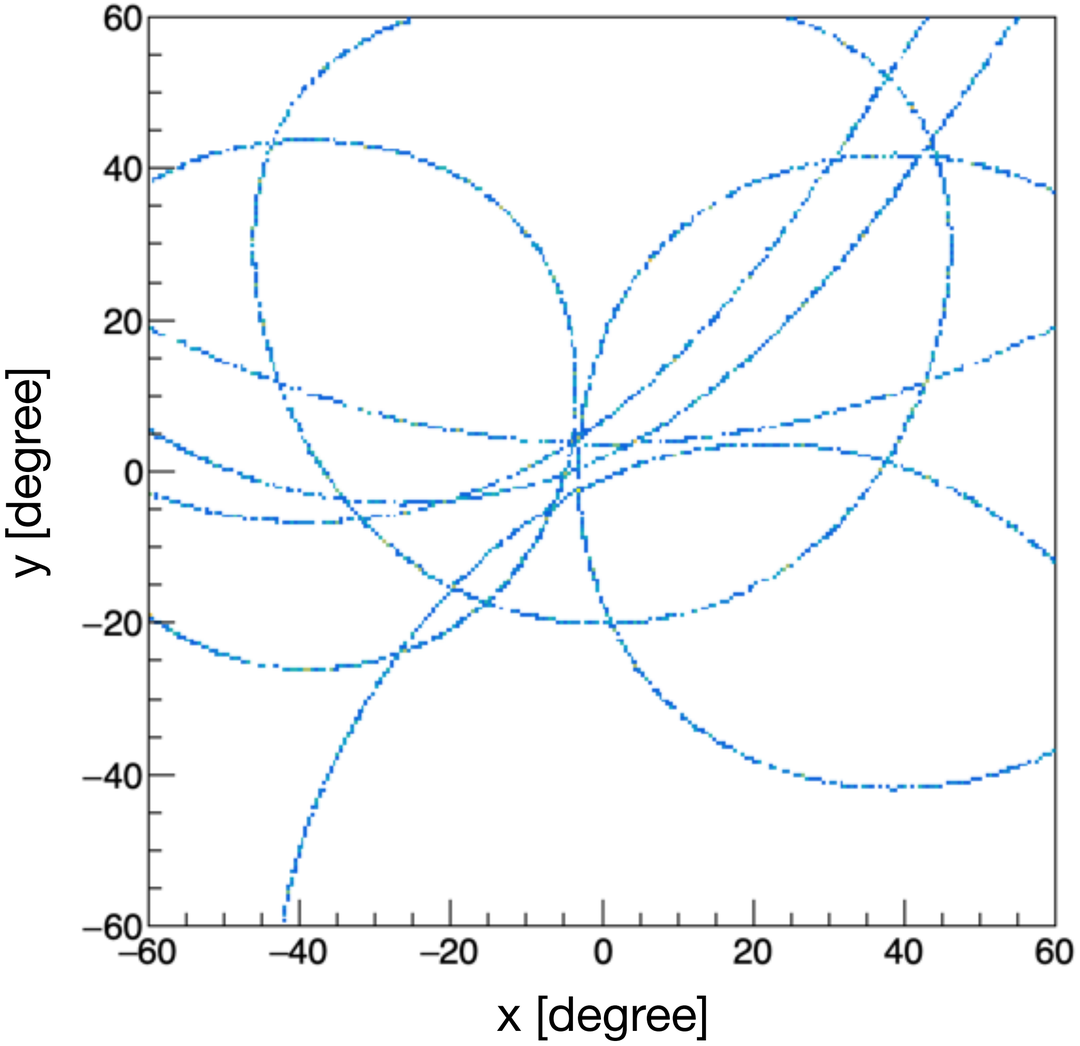
511 keV
1 event

Let's see how it works



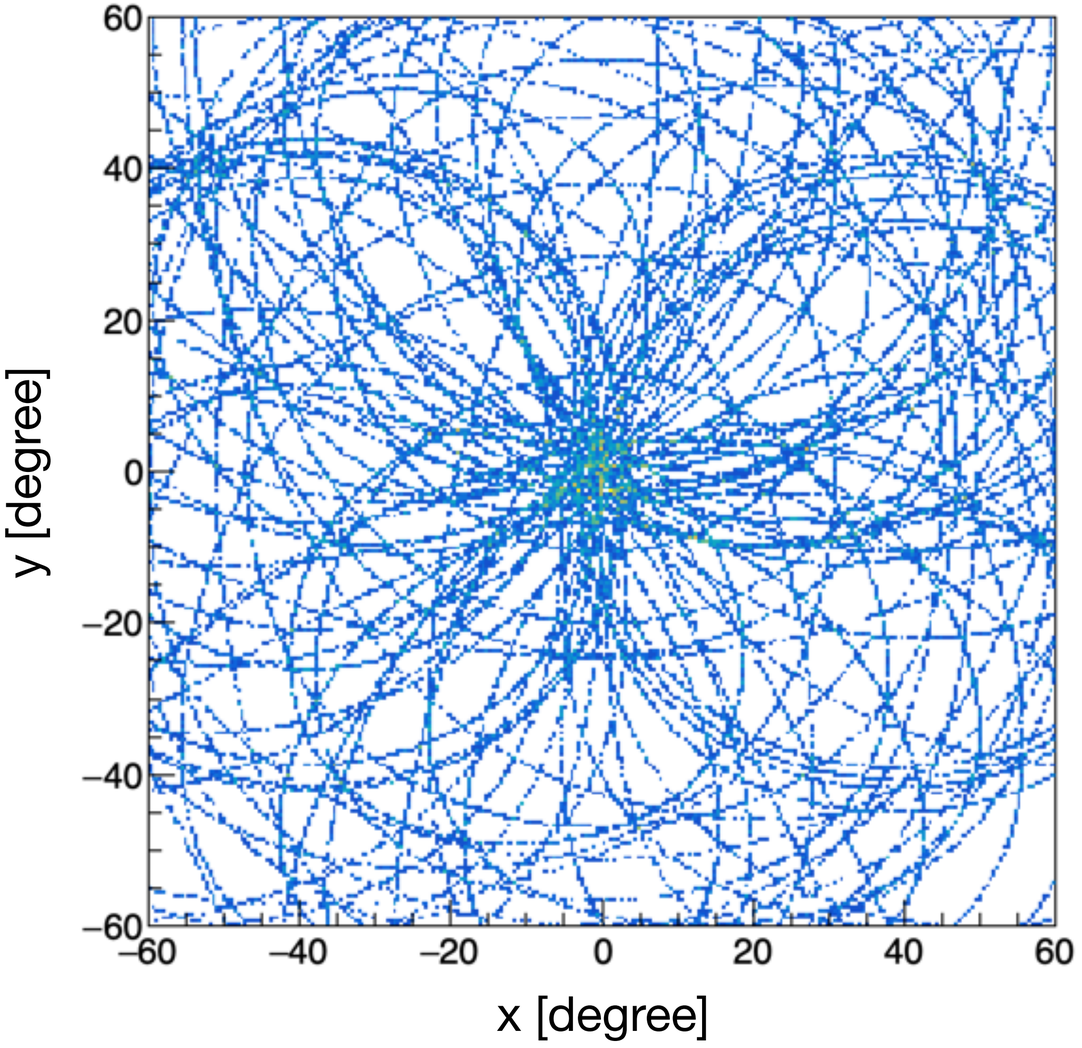
511 keV
2 events

Let's see how it works



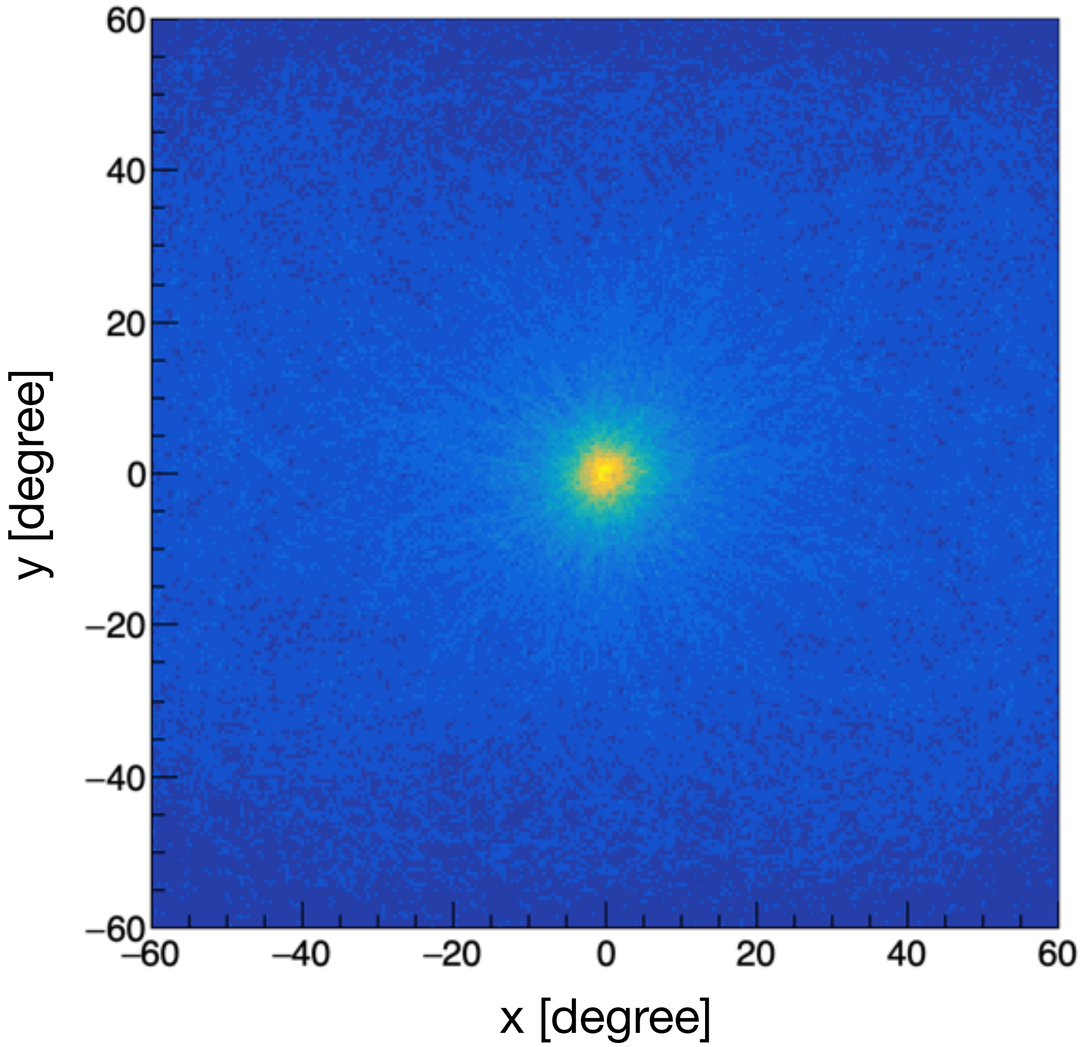
511 keV
10 events

Let's see how it works



511 keV
100 events

Let's see how it works



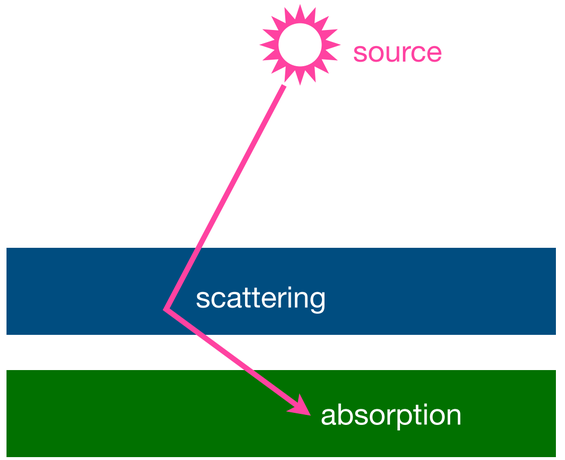
511 keV
10000 events

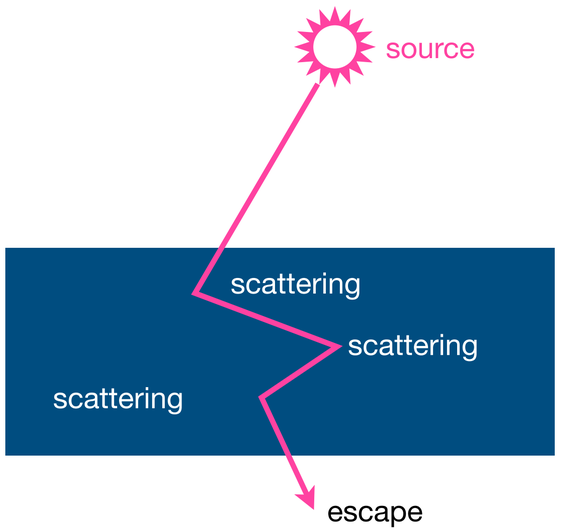
Multiple Compton scattering

Multiple interactions provide additional kinematic constraints.

- Two-hit events: Full energy absorption is generally required to reconstruct the Compton scattering angle.
- Three or more hits: Multiple Compton scatterings can enable reconstruction even when the photon escapes the detector.

Escape events can increase the detection efficiency of Compton telescopes.





2-hit, full-absorption events

$$E_\gamma = E_1 + E_2$$

$$\cos\phi = 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2}$$

3-hits escape events

$$E_\gamma = E_1 + E_2 + E_3'$$

$$\cos\phi = 1 - \frac{m_e c^2}{E_2 + E_3'} + \frac{m_e c^2}{E_1 + E_2 + E_3'}$$

$$E_3' = -\frac{E_2}{2} + \sqrt{\frac{E_2^2}{4} + \frac{E_2\, m_e c^2}{1 - \cos\phi_2}}$$

Angular resolution measure (ARM)

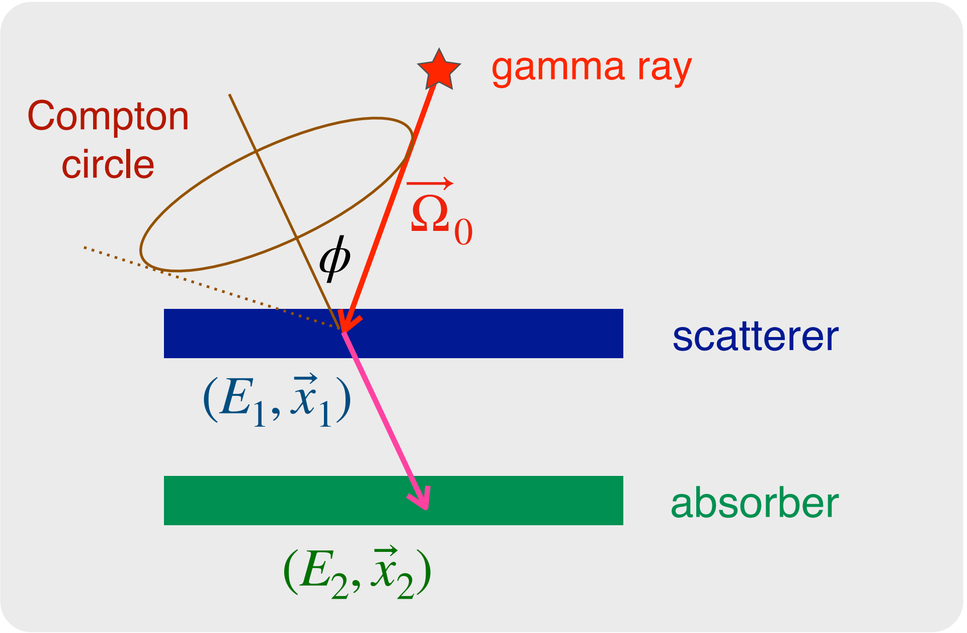
- ARM quantifies the angular accuracy of a reconstructed Compton cone.

$$\mathrm{ARM} = \phi_{\mathrm{kin}} - \phi_{\mathrm{geo}}$$

ϕ_{kin}: Compton scattering angle reconstructed from measured energies

ϕ_{geo}: Geometrical angle between the known incident direction and the measured scattered-photon direction

- Angular resolution is commonly characterized by the FWHM of the ARM distribution.
- Main contributions:
  - Energy resolution → error of ϕ_{kin}
  - Position resolution → error of ϕ_{geo}
  - Doppler broadening due to bound electrons



$$\cos\phi_{\mathrm{kin}} = 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2}$$

$$\cos\phi_{\mathrm{geo}} = \vec{\Omega}_0 \cdot \frac{\vec{x}_2 - \vec{x}_1}{|\vec{x}_2 - \vec{x}_1|}$$

Doppler broadening

Bound electrons are not at rest.

- The Compton scattering formula assumes an electron initially at rest.
- Bound electrons have a finite momentum distribution.
- Their initial momenta introduce uncertainty in the reconstructed scattering angle.

Doppler broadening imposes an intrinsic limit on the angular resolution of Compton cameras.

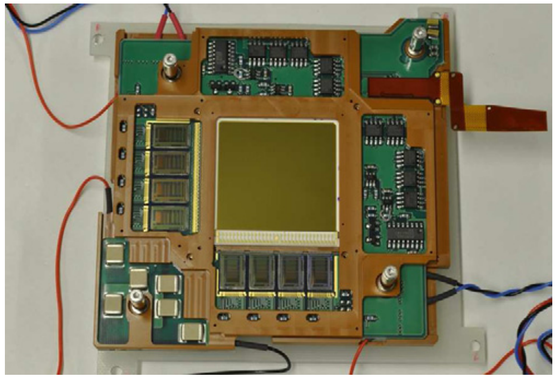
- Doppler broadening depends on photon energy and electron-shell structure.
- Its impact on angular resolution becomes particularly significant at low energies, especially below 1 MeV.
- It cannot be eliminated by improving energy or position resolution alone.

Real Compton camera

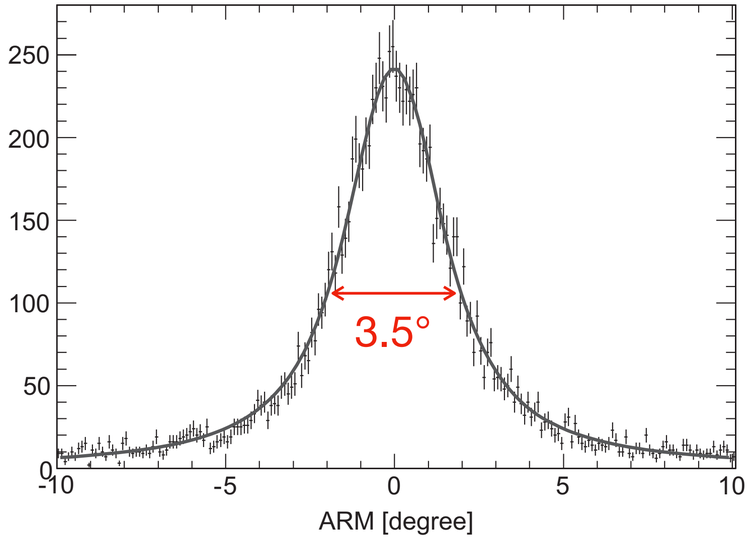
Experimental demonstration with a Si/CdTe Compton camera

- 1 Si layer (scatterer) + 4 CdTe layers (absorber)
- Angular resolution: ARM FWHM of 3.5° at 662 keV
- Compton imaging demonstrated with measured gamma-ray events

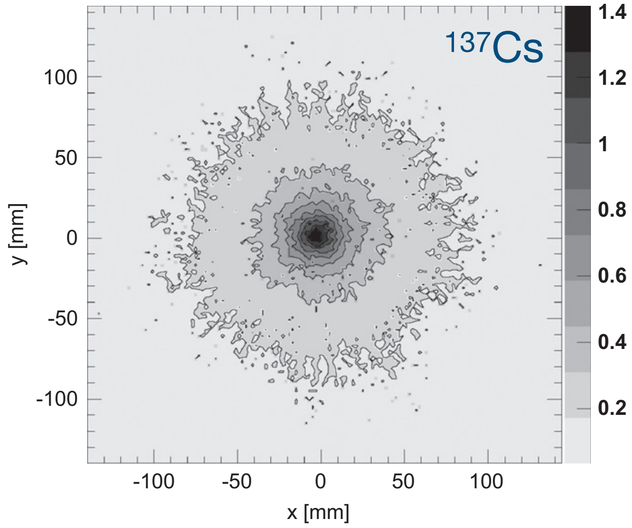
Odaka et al. (2012)



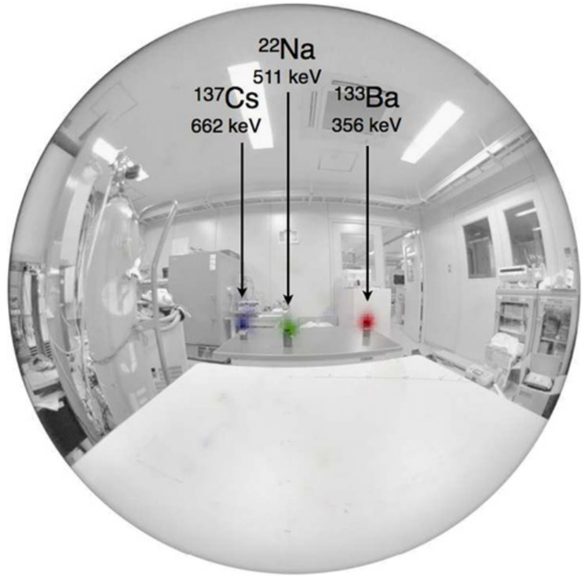
CdTe double-sided strip detector



ARM distribution at 662 keV (^{137}Cs)



Point-source imaging by back projection



Energy-resolved Compton imaging

Mathematical formalism: Compton data space

- Back to the definition of imaging.

  Imaging is the mapping of incident photon directions onto distinguishable structures in the instrument's data space.

- A Compton camera maps the incident photon direction onto a structure in its data space—Compton data space (CDS).

$$(\alpha, \delta) \rightarrow (\phi, \chi, \psi)$$

  (α, δ): incident direction

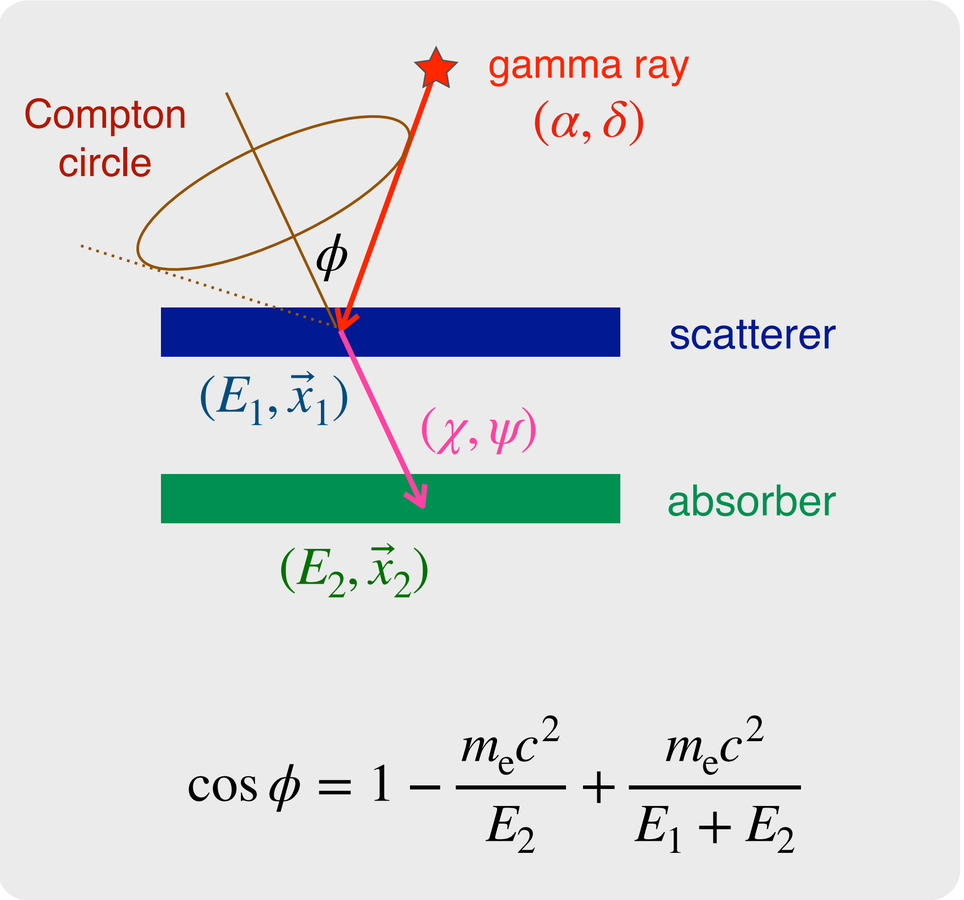
  ϕ: scattering angle determined by kinematics

  (χ, ψ): scattered photon direction

- CDS captures the essential geometry of Compton events in just three dimensions.

A Compton event → A point in CDS

A point source in the sky → A surface-like structure in CDS



$$\cos\phi = 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2}$$

3. Data analysis

Event reconstruction

From detector signals to Compton events

- A gamma-ray photon may produce multiple interactions in the detector.
- The measured hits provide deposited energies and interaction positions.
- The interaction sequence must be reconstructed to determine the Compton scattering geometry.
- Compton kinematics and event topology are used to identify valid events and reject background.

Event reconstruction transforms detector hits into physical events for astronomical analysis.

Need to determine the interaction order：N!

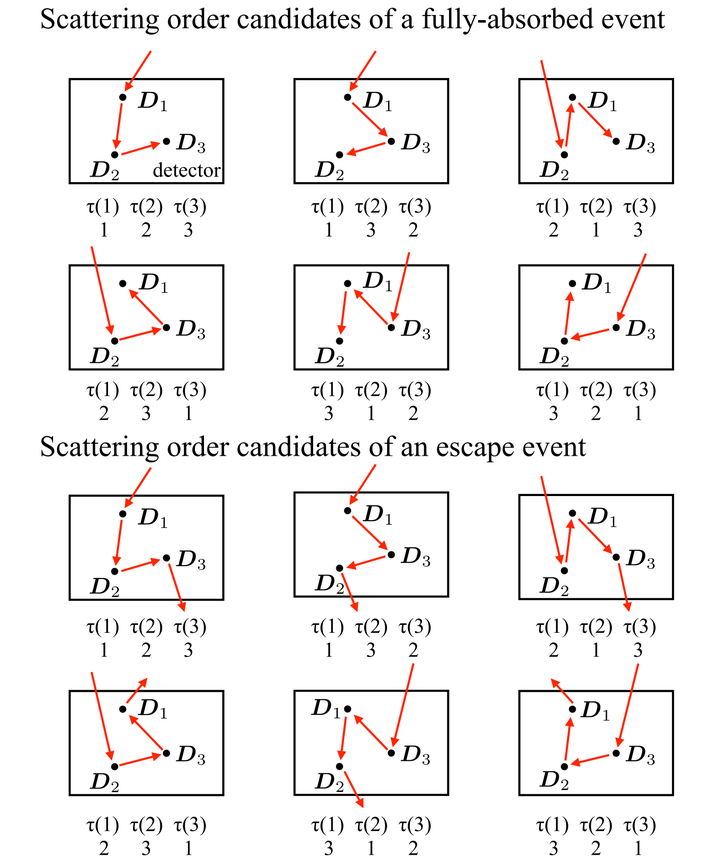


Fig. 1. Scattering order candidates of a 3-hit event and their corresponding map functions $\tau(\cdot)$.

Yoneda, HO et al. (2023)

Event reconstruction: order inference algorithm

Physics-based probabilistic model

Yoneda, HO et al. (2023)

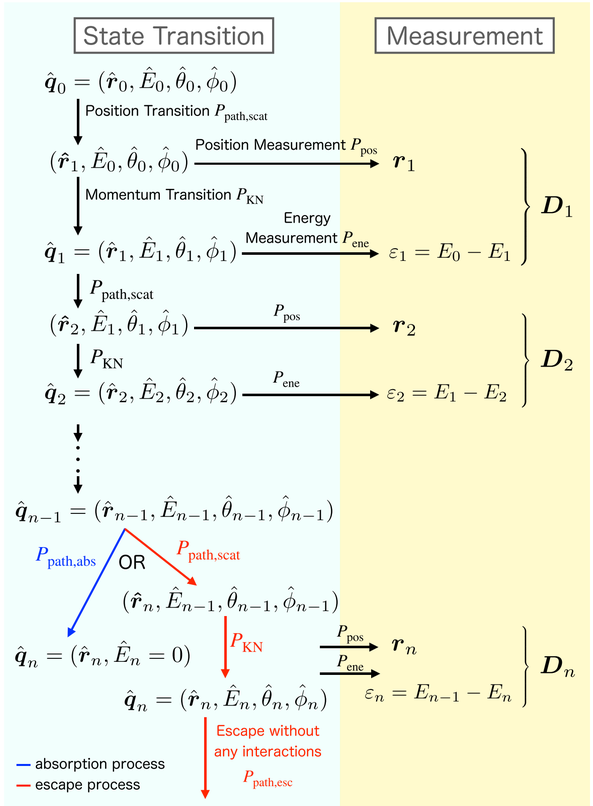


Fig. 3. A graphical representation of Compton scattering in a detector and measurement in a Compton telescope. The red arrows correspond to probabilistic processes that take place only in escape events while the blue arrow corresponds to that for fully-absorbed events. Note again that $\hat{\boldsymbol{q}}_0$ is unknown and $|\hat{\boldsymbol{r}}_0| \to \infty$ in astronomical situations. The approximations implemented for astronomy are explained in Section 4.2.

Neural network

Takashima, HO et al. (2022)

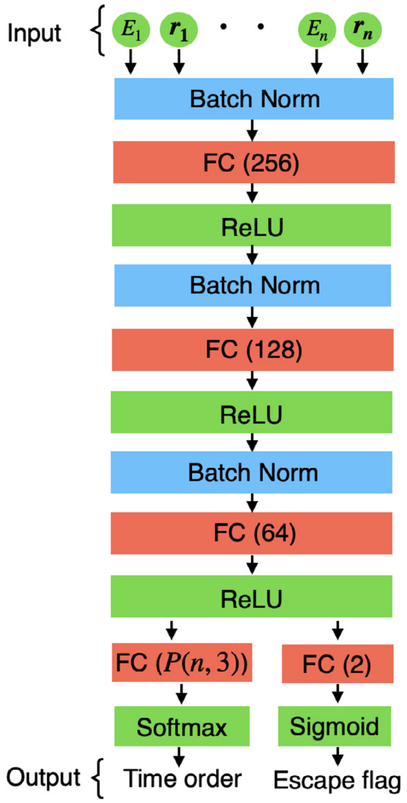


Fig. 2. The network model of the event reconstruction. Three fully connected layers (FCs) are stacked with activation functions and batch normalization layers. The number of each node of fully connected layers is written in a parenthesis after FC.

Forward modeling and instrument response



$$\mu_i = \sum_j R_{ij} f_j + b_i$$

The instrument response can be assumed to be linear.

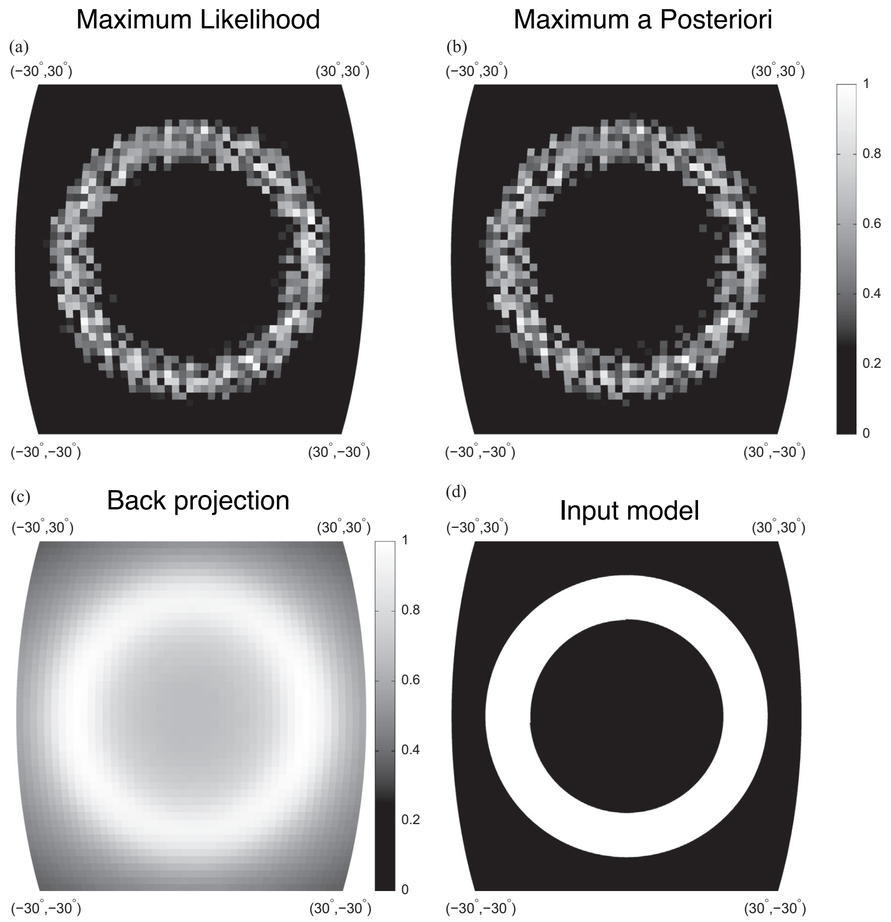
- f_j: Source intensity in sky bin j
- R_{ij}: Instrument response mapping sky bin j to CDS bin i
- b_i: Expected background counts in CDS bin i
- μ_i: Expected total counts in CDS bin i

Statistical inference and image reconstruction

Astronomical information is extracted by fitting models to the observed event distribution in CDS.

- The observed counts n_i follow Poisson statistics:
  $$n_i \sim \mathrm{Poisson}(\mu_i)$$
- Likelihood:
  $$\log \mathscr{L} = \sum_i \left[n_i \log \mu_i - \mu_i - \log(n_i!) \right]$$
- **Source analysis**: Estimate source parameters by maximizing the likelihood.
- **Image reconstruction**: Treat the sky intensities f_j as free parameters.
- **Background**: Included in the expected counts μ_i.

Compton imaging is a statistical inverse problem.



e.g., Richardson–Lucy / Maximum-Likelihood Expectation–Maximization (RL/MLEM)

Ikeda, HO et al. (2014)

Background modeling

- Instrumental background is a major challenge in MeV gamma-ray astronomy.
- Background models require multiple physical components and validation against observational data.

COSI background simulation (Gallego et al. 2026)

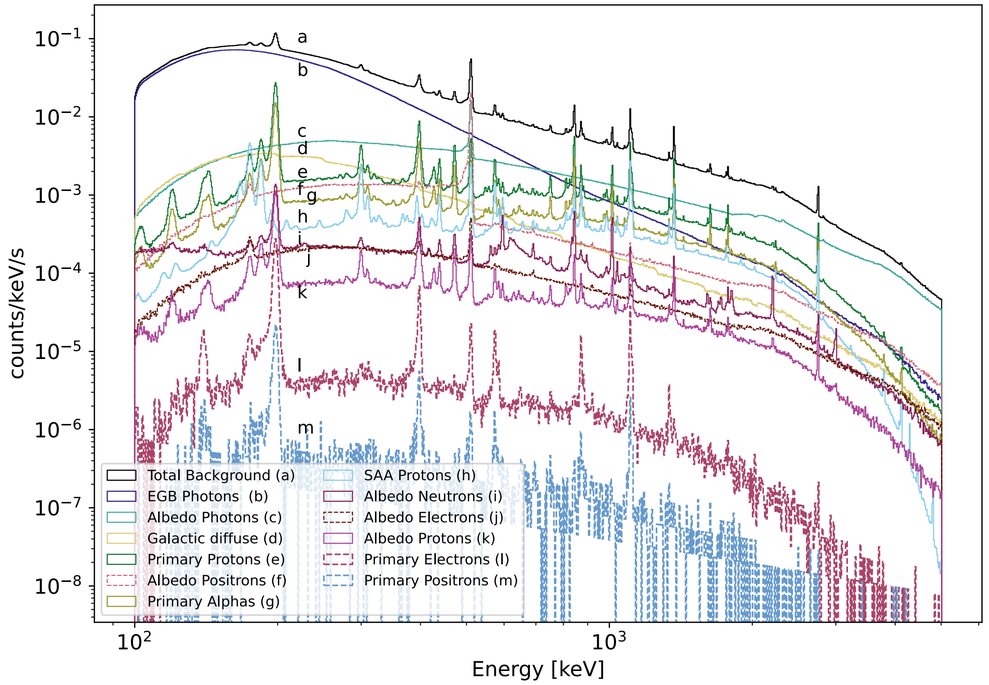
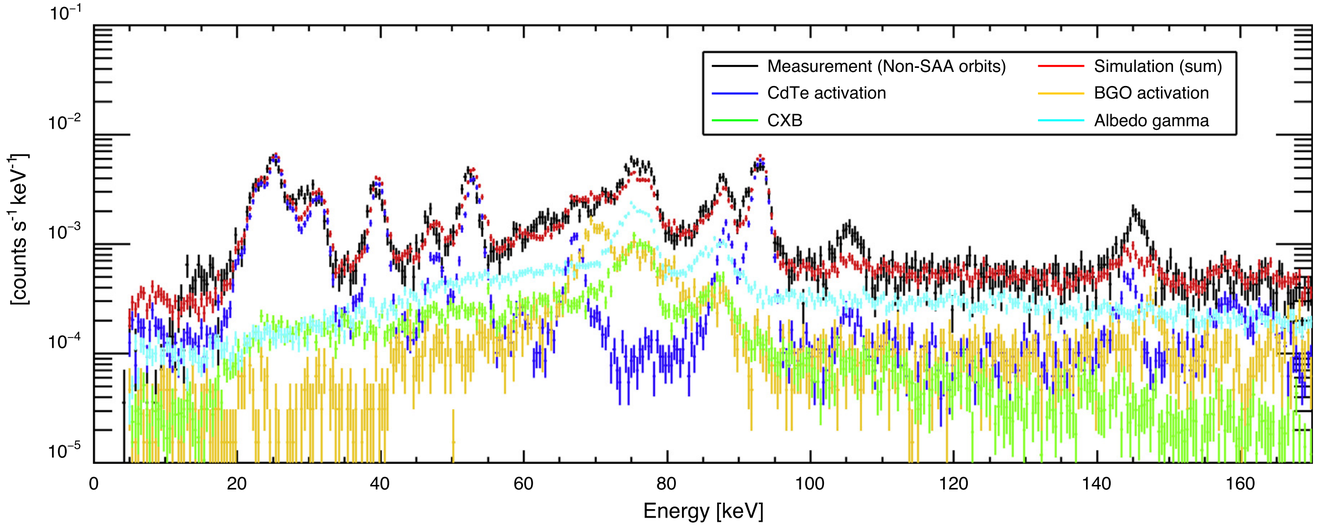


Figure 10. Spectra of the reconstructed Compton events after 3 months of orbit for each background component.

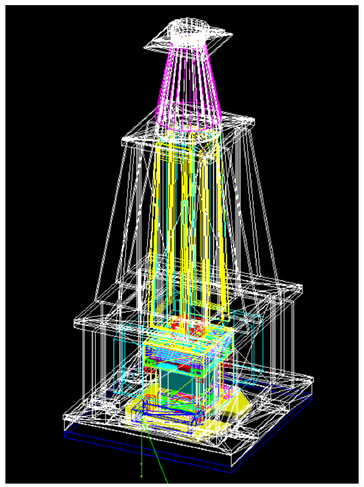
Hitomi-HXI background: measurement vs simulation (Odaka et al. 2018)

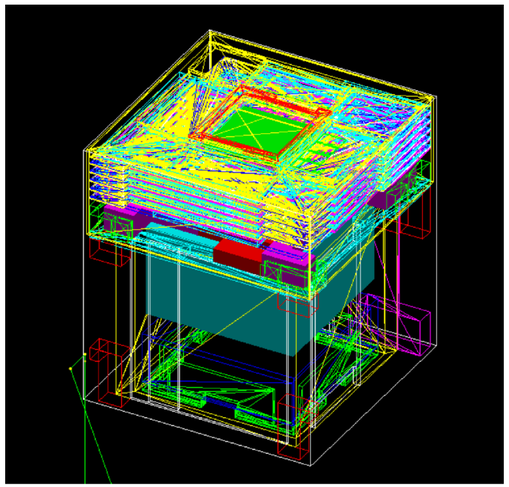


Hitomi: low-Earth orbit 575 km
inclination: 31°

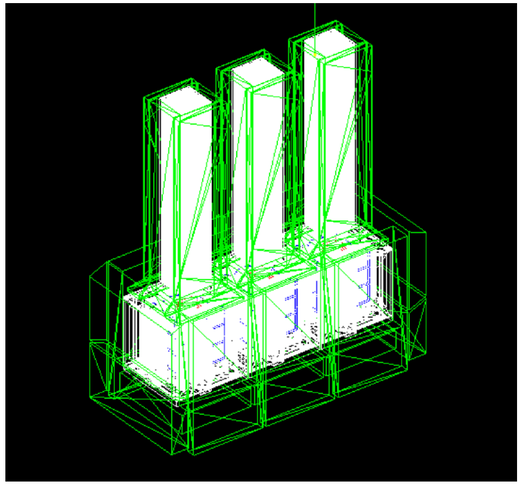
Monte Carlo simulations

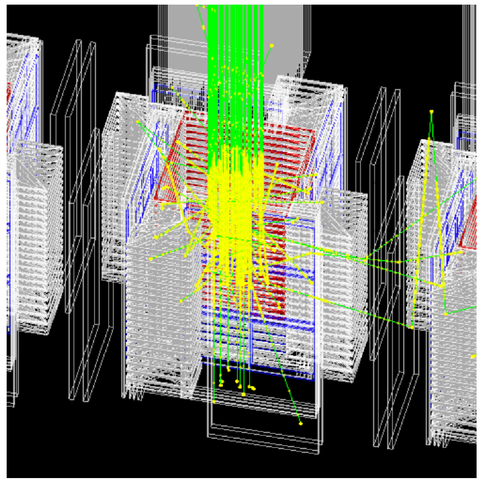
- Detailed simulations are essential for modeling detector responses and instrumental backgrounds.
- Geant4 provides a framework for simulating particle interactions and detector geometries.





Hitomi Hard X-ray Imager (HXI)





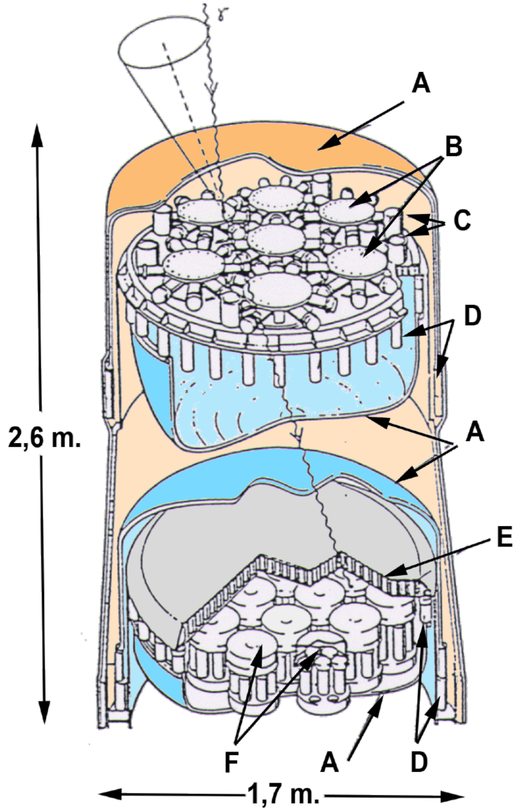
Hitomi Soft Gamma-ray Detector (SGD)

4. Hardware framework

COMPTEL: The Pioneer of MeV telescopes

The first Compton telescope to survey the MeV gamma-ray sky.

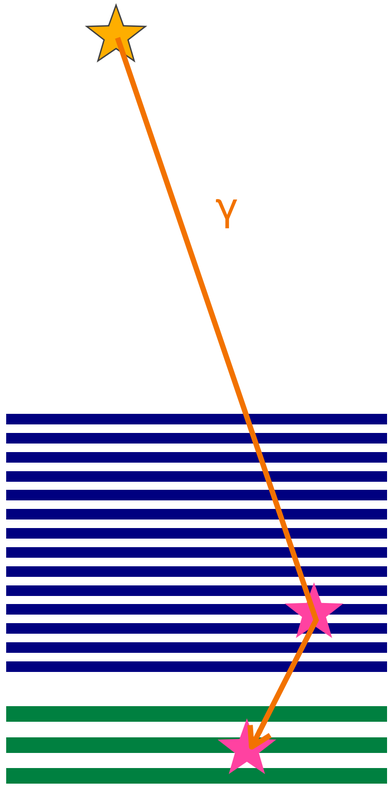
- COMPTEL (1991–2000)
- 0.8–30 MeV
- Two-layer configuration:
  liquid scintillator (D1) and NaI scintillator (D2)
- Time-of-flight (TOF) measurement to
  distinguish downward-going gamma rays
  from upward-going background

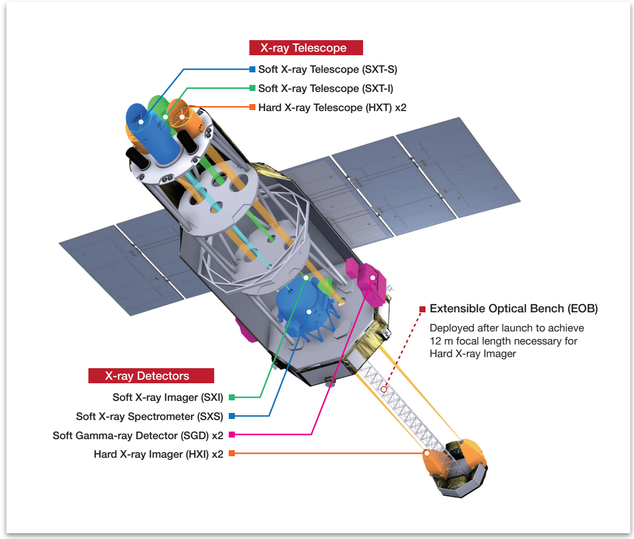




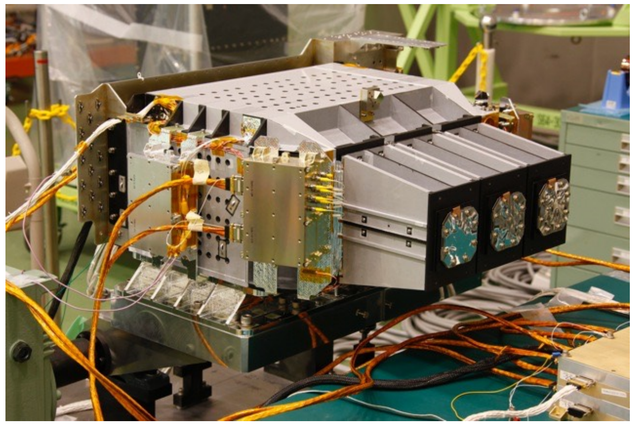
Stacked semiconductor Compton telescopes

Better energy and position resolutions → Semiconductor detectors





Hitomi X-ray observatory
(ASTRO-H, 2016)



Soft Gamma-ray Detector

- Narrow-FOV concept
- Stacked Si pixel detectors
- Surrounding CdTe pixel detectors
- 50–600 keV

Tajima et al. (2018)

COSI: the next major step

Tomsick et al. (2023)

COSI will make a major leap in MeV line sensitivity with a compact Compton telescope based on a densely packed array of 3D Ge detectors.

Energy range	0.2–5 MeV
Spectral resolution	<1.2% at 511 keV
Field of view	>25% of the sky
Survey coverage	full sky every day
Angular resolution	<4.1° at 511 keV
Launch	2027 August (planned)
Mission	> 2 yr



5. Future directions in MeV telescope design

Beyond COSI: what leap is worth going to space for?

Much higher sensitivity

→ Discover much fainter sources and weak nuclear lines

Much larger collecting area

→ Resolve the underlying physics through spectroscopy, polarization, and timing

Much better angular resolution

→ Locate where the emission originates

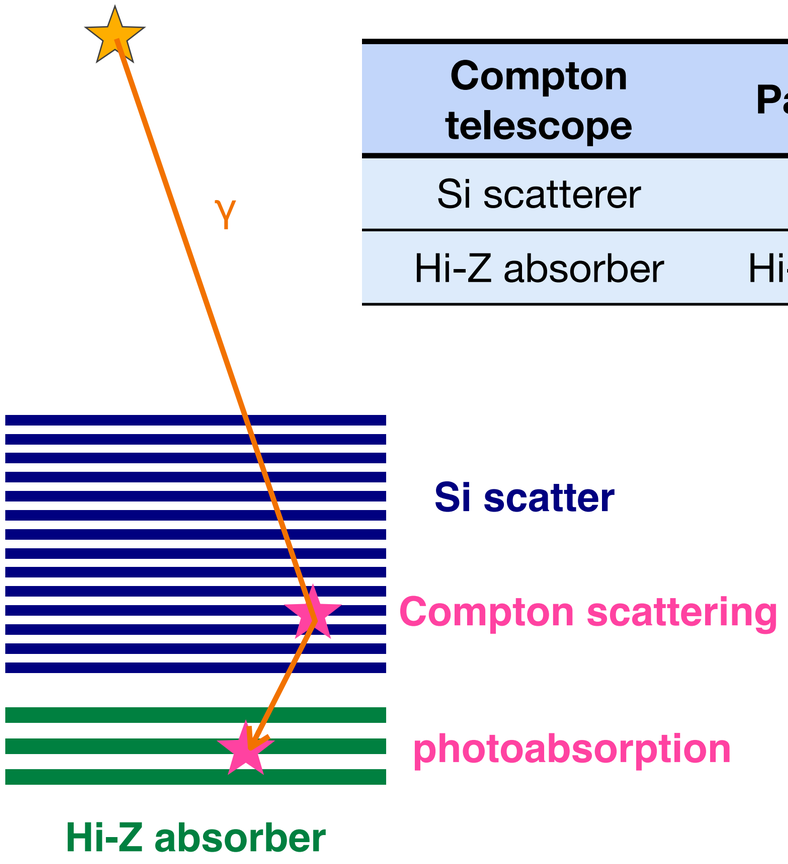
Much broader energy coverage

→ Connect different particle populations and emission processes

Stacked semiconductor Compton telescopes

A natural extension of the established Compton-telescope architecture.

→ Wide-field, broadband Compton + pair telescopes

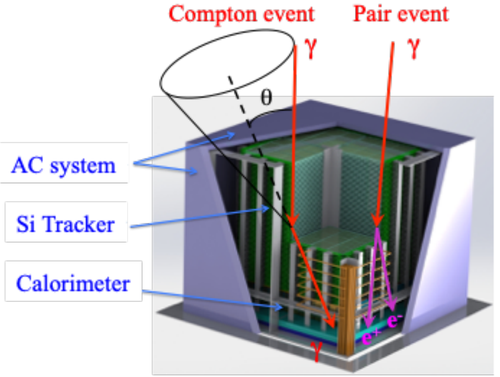


Compton telescope	Pair telescope
Si scatterer	Si tracker
Hi-Z absorber	Hi-Z calorimeter

newASTROGAM

- Stacked double-sided silicon strip detector
- CsI calorimeter
- Coded mask for X-rays
- 15 keV – 3 GeV

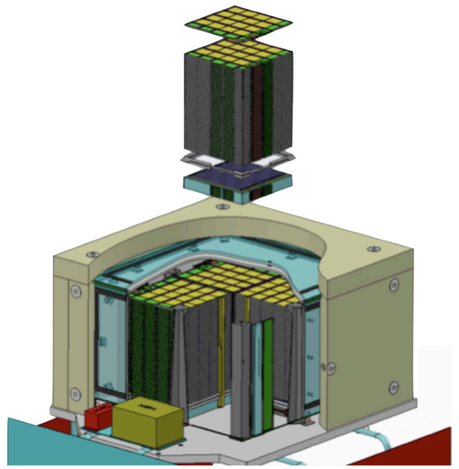
Berge et al. (2025)



AMEGO-X

- Stacked Si active pixel sensors
- CsI calorimeter
- 100 keV – 1 GeV

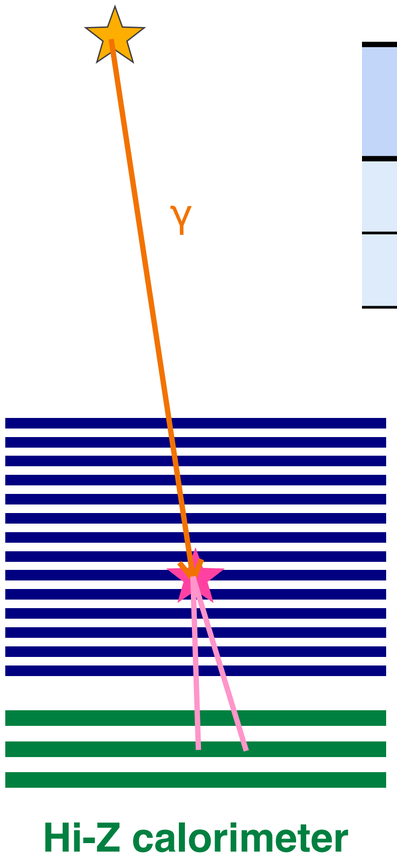
Caputo et al. (2022)



Stacked semiconductor Compton telescopes

A natural extension of the established Compton-telescope architecture.

→ Wide-field, broadband Compton + pair telescopes

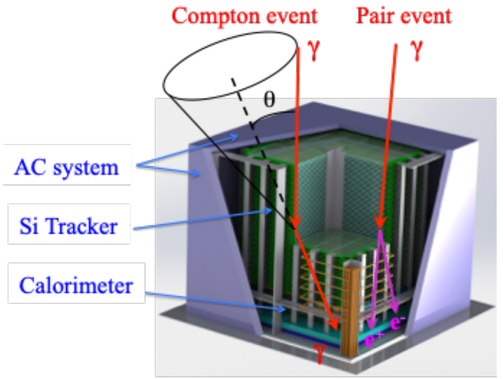


Compton telescope	Pair telescope
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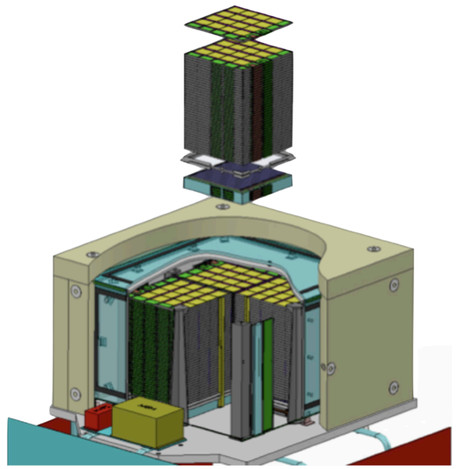
Berge et al. (2025)



AMEGO-X

- Stacked Si active pixel sensors
- CsI calorimeter
- 100 keV – 1 GeV

Caputo et al. (2022)

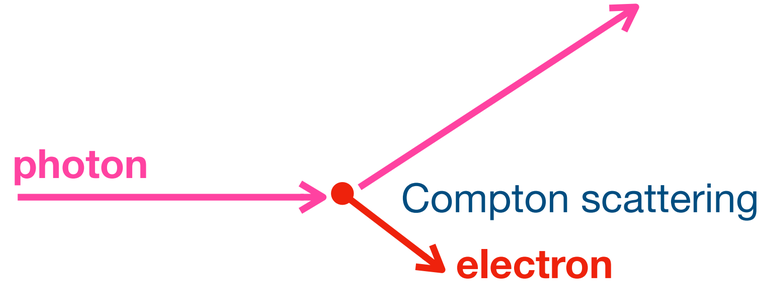


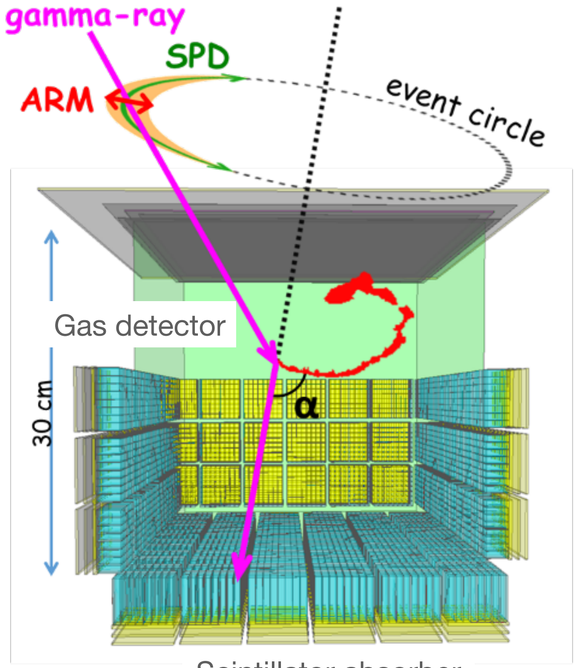
Electron-tracking Compton telescopes

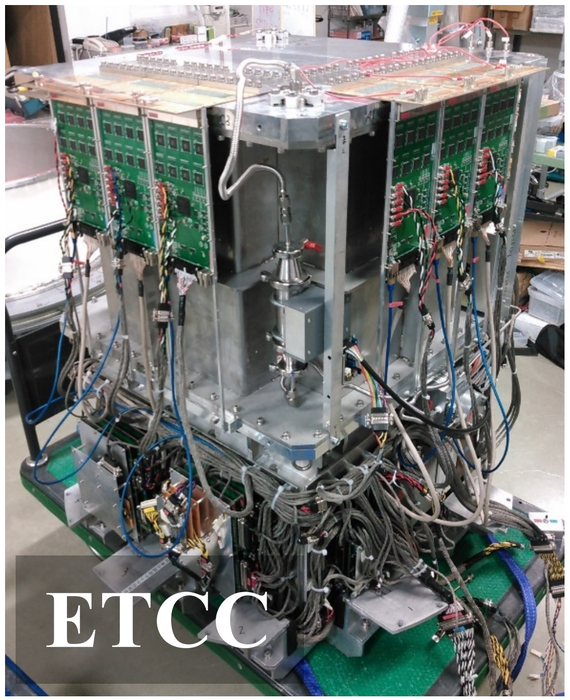
Tracking the recoil electron provides additional information on the incident gamma-ray direction.

- Conventional Compton cameras reconstruct a Compton circle.
- Measuring the recoil-electron direction reduces the directional ambiguity from a circle to an arc.
- Gas detectors are well suited for electron tracking due to their long recoil-electron tracks, as demonstrated by SMILE and further pursued by MeGaT.
- Fine-pitch semiconductor detectors can also enable electron tracking, offering a more compact alternative.

Electron tracking can improve imaging sensitivity by reducing the allowed region on the sky.

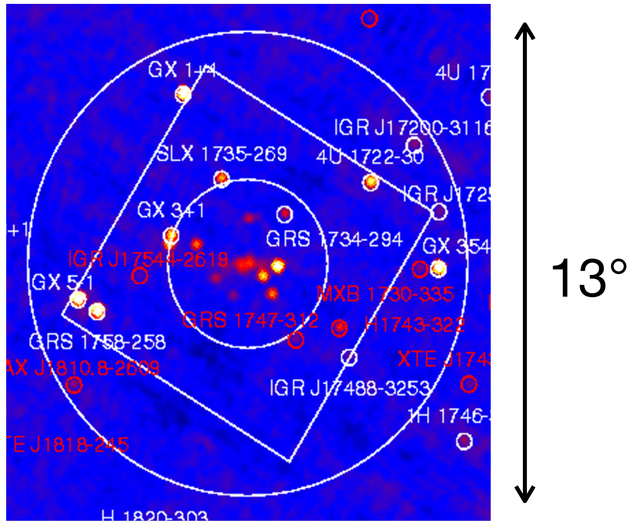






SMILE2+ Takada et al. (2022)

Toward high angular resolution



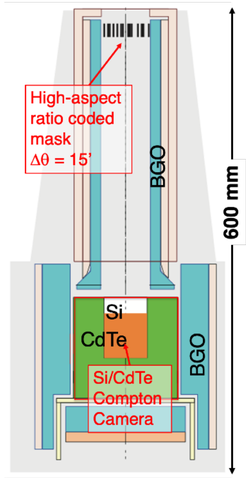
13°

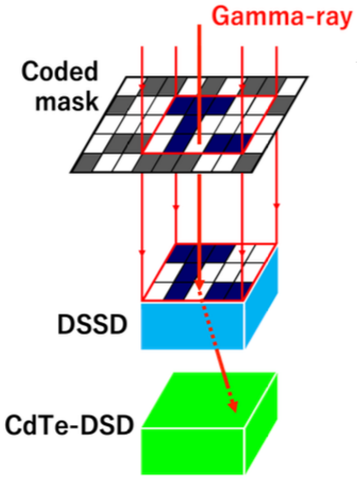
INTEGRAL/IBIS 18-40 keV image of Galactic Center, with 12 arcmin angular resolution. (Kuulkers et al. 2007)

The angular resolution of Compton telescopes is physically limited by Doppler broadening at the ~1° level.

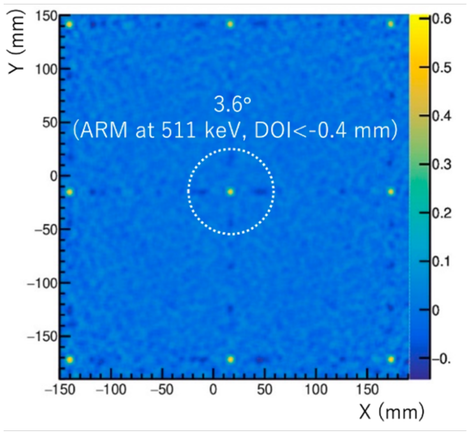
→ Adding coded-aperture imaging can overcome this limit.

SGI

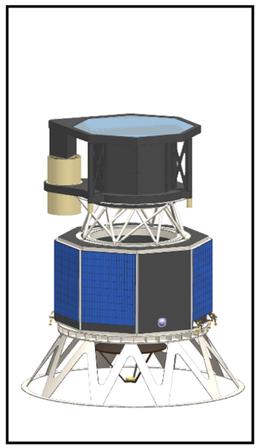


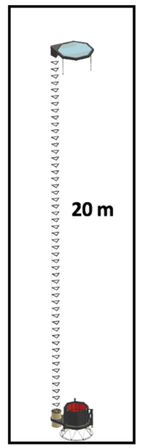


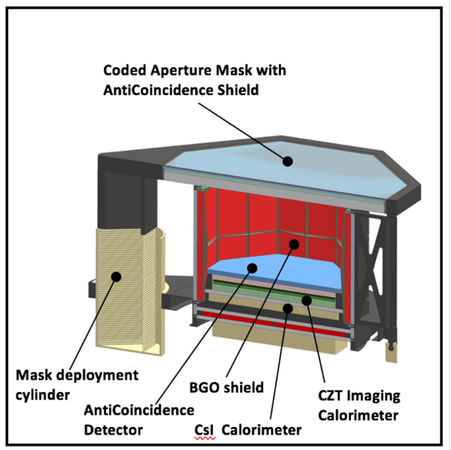
Nakazawa et al. 2026



GECCO

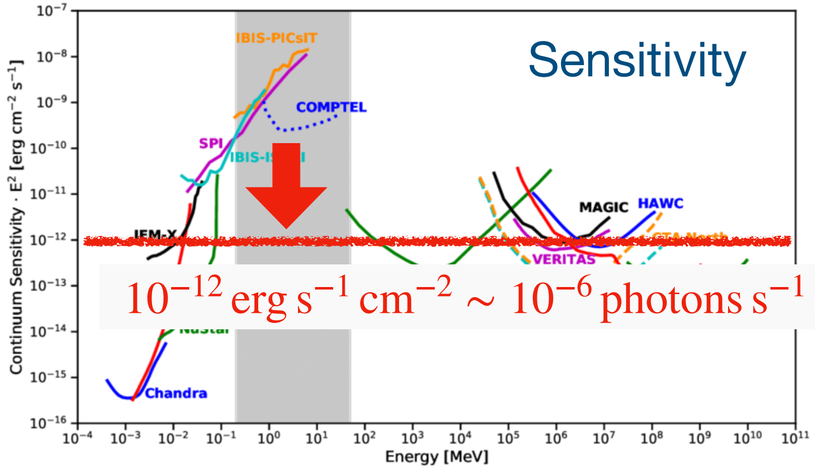






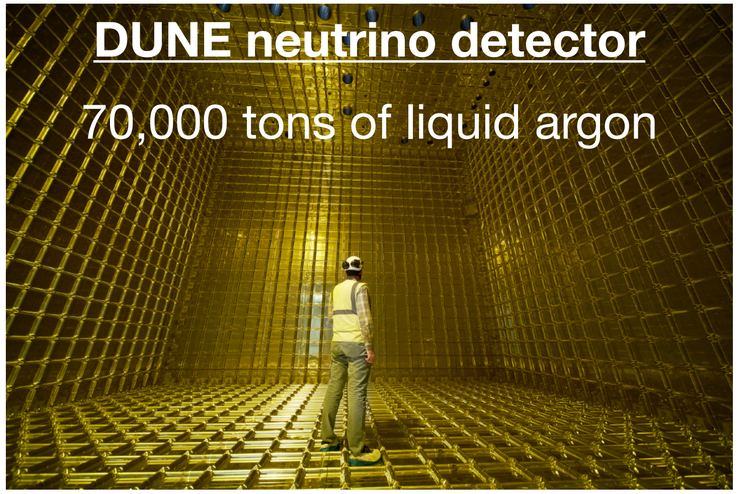
deployable coded mask → ~1′ angular resolution Orlando et al. 2022

Scaling up with liquid argon

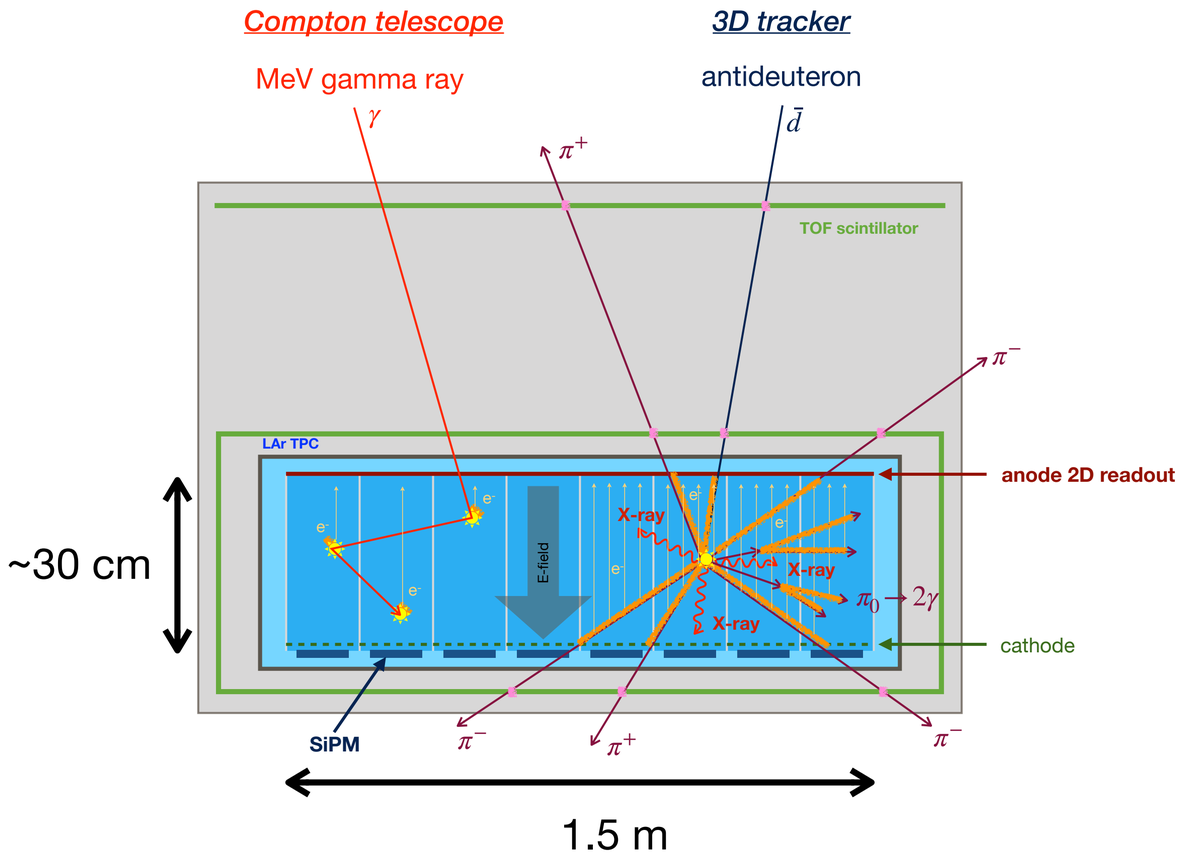


$10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}} \sim 10^{-6}\,\mathrm{photons\,s^{-1}\,cm^{-2}}$ (1 MeV)

We need a much larger collecting area.



This technology will be deployed to space missions.



Liquid-argon time-projection chambers offer a scalable route to very large effective area.

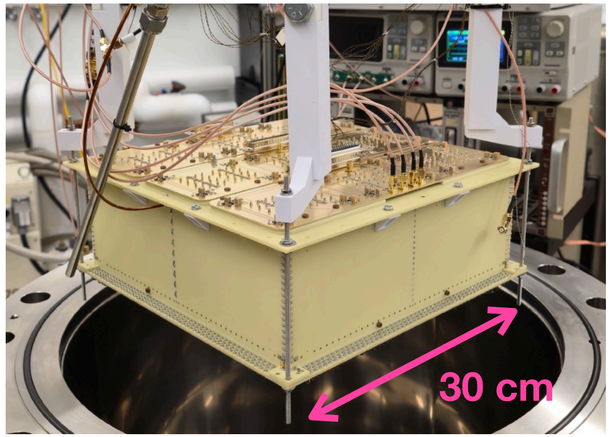
Large, single-volume 3D detector

Liquid-argon gamma-ray telescope concepts

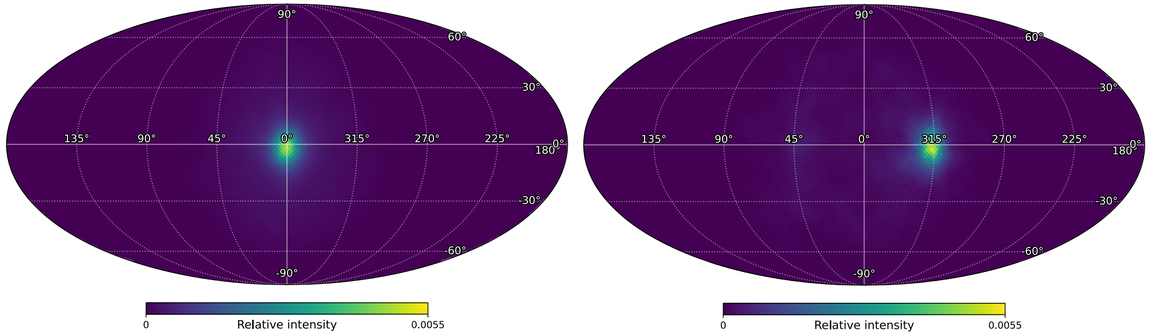
GRAMS Aramaki et al. 2020



World's first LArTPC flight (2023, Japan)

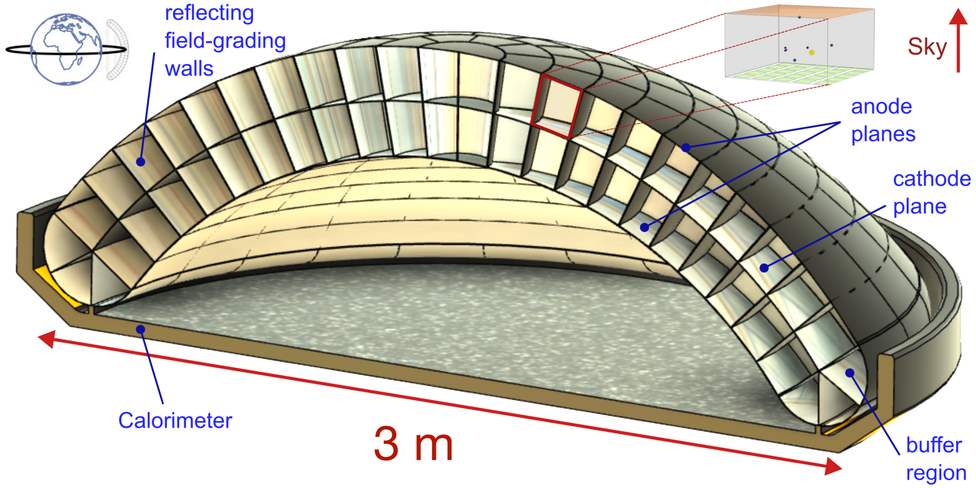


MiniGRAMS detector (2026)



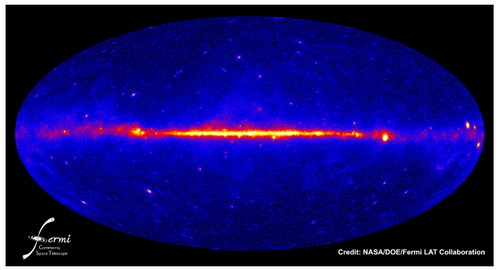
Compton images of ^{22}Na (1.275 MeV)
with a prototype Compton camera (2026)

GammaTPC Shutt et al. 2025



GammaTPC explores the ultimate scalability of this approach, with ~10 m² active area, ~4 metric tons of liquid argon.

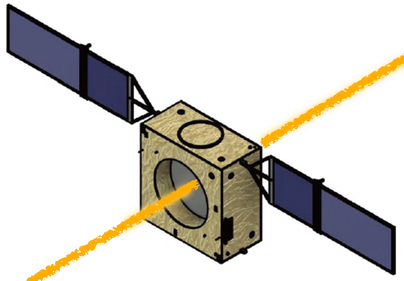
Formation flying opens new observatory architectures



All-sky mode: a few degrees



Pointing mode: 30 arcsec



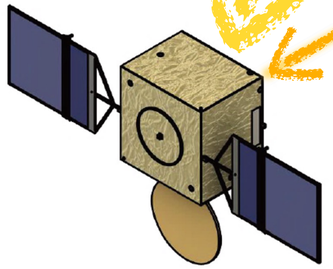
Optics spacecraft

Coded mask / Laue lens

Detector spacecraft

LArTPC

100 m



FF-LAGRAN Concept Mochizuki et al. 2023

Deep gamma-ray observations from a Sun–Earth L2 halo orbit

Formation flying enables long-baseline gamma-ray optics
for high angular resolution and high sensitivity.

The MeV design space remains wide open

Detector/telescope technologies

- Stacked-semiconductor Compton telescopes
- Electron-tracking Compton telescopes
- High-Z photoabsorption detectors
- Coded aperture imaging
- Gamma-ray Laue lenses

Platform / Scale

- Balloons
- Cubesats / CubeSat constellations
- Small satellites
- Large observatories

There is no single obvious path forward.

Where to observe

- Equatorial low-Earth orbit
- Sun-Earth L1 / L2
- Lunar orbit / surface

Data analysis

- Event reconstruction
- Background modeling
- Statistical inference

Concluding remarks

- MeV gamma-ray astronomy remains a largely unexplored frontier, offering unique insights into energetic processes in the universe.
- Sophisticated event reconstruction and data analysis are essential for exploiting the full potential of Compton telescopes.
- New technologies are paving the way for next-generation MeV observatories.

The MeV window is ready to be opened wider.