NDIP 2011
4-8 July 2011 at Lyon

Development of High-Resolution Compton Cameras Based on Si/CdTe Imaging Detectors

Hirokazu Odaka (ISAS/JAXA)

Y. Ichinohe, S. Takeda, T. Fukuyama, K. Hagino, S. Saito, T. Sato,
G. Sato, S. Watanabe, M. Kokubun, T. Takahashi (ISAS/JAXA),
M. Yamaguchi (JAEA),
H. Tajima (Nagoya University), T. Tanaka (Stanford University),
K. Nakazawa (University of Tokyo), Y. Fukazawa(Hiroshima University)

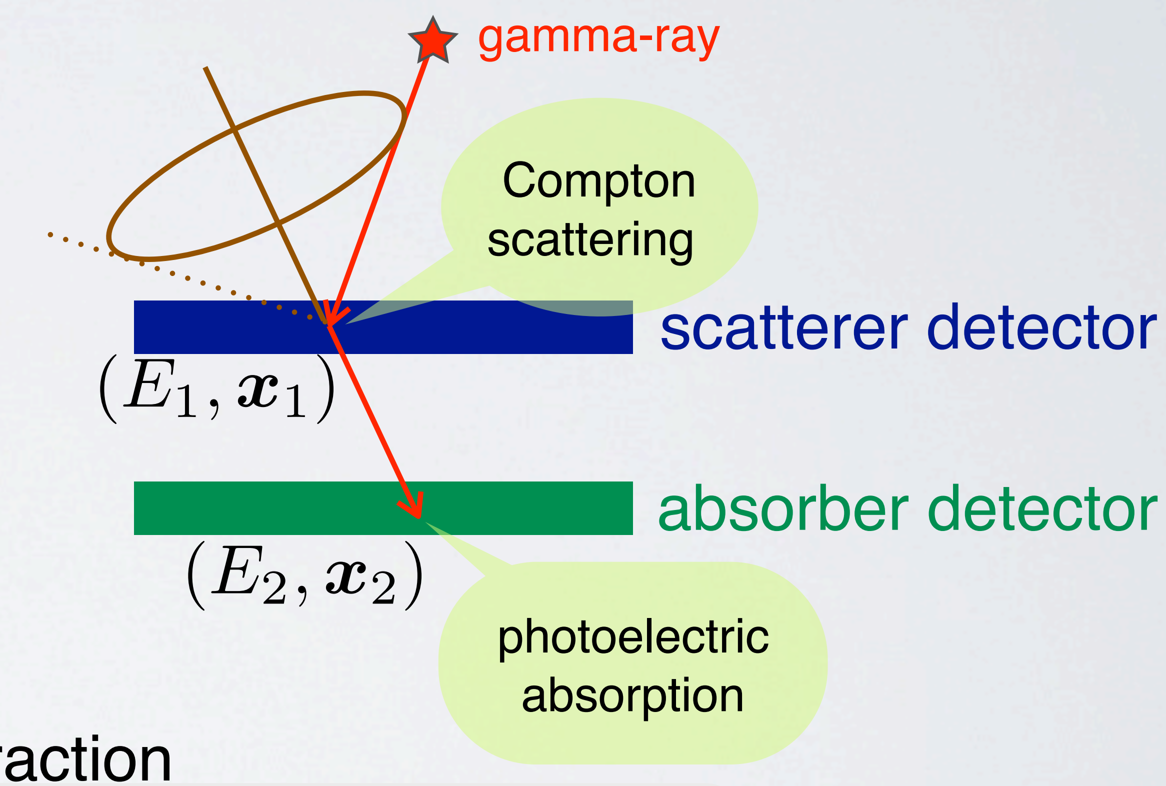
Compton Camera

Energy band from 100 keV to 10 MeV

Compton scattering is dominant over all other interactions of a photon with detector material.

Promising sub-MeV/MeV gamma-ray imaging spectrometer for

- Astrophysical observation
- Medical imaging
- Nondestructive inspection
- Search for radioactive isotopes



Energy and direction of the incident photon are determined by Compton kinematics.

E_i : Energy deposited

$\boldsymbol{x}_i$: Position of an interaction

$$E = E_1 + E_2, \quad \cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

Accurate measurement of energy and position is important to obtain high angular/spatial resolution.

Advantage of Si/CdTe

Semiconductor imaging detectors are the most suitable.

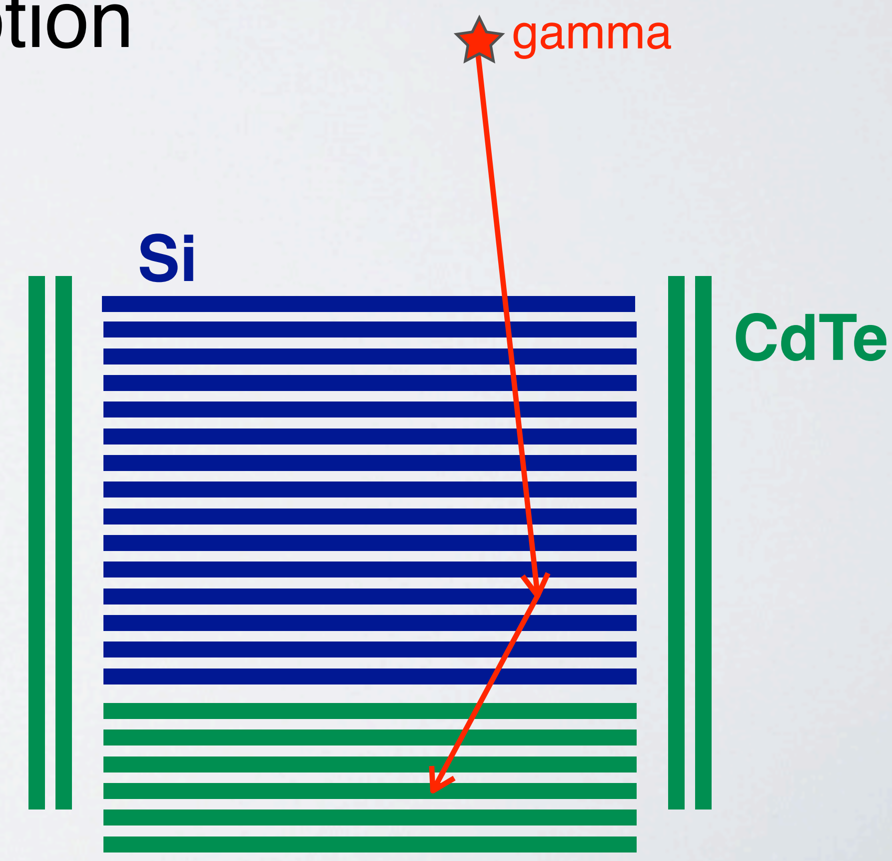
High Energy/Position Resolution

1) Si detector as the scatterer [Low-Z: Z=14]

- High probability of Compton scattering
- Small Doppler broadening effect (by target electron momentum)

2) CdTe detector as the absorber [High-Z: Z=48,52]

- Large cross section of photoelectric absorption
- High density (5.85 g/cm^3)
- Schottky diode electrode configuration
  reduced low-energy tail (high bias voltage)
  Takahashi+ (2002)



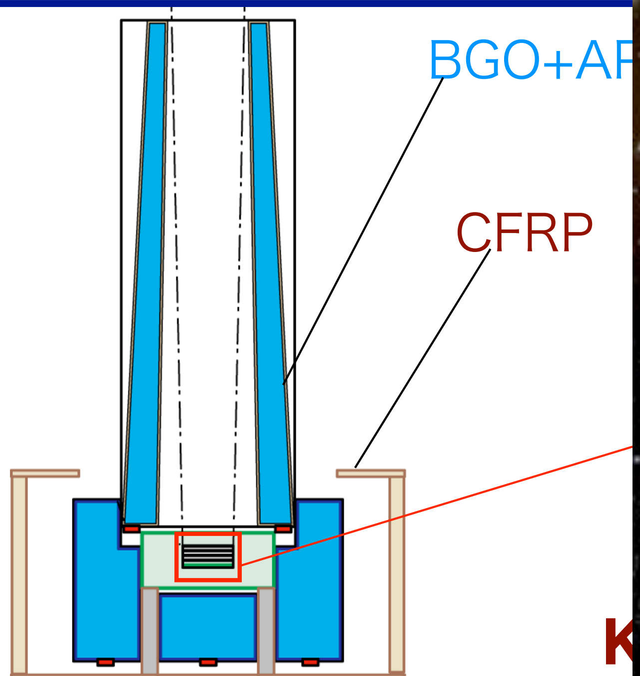
Design of Si/CdTe Compton cameras

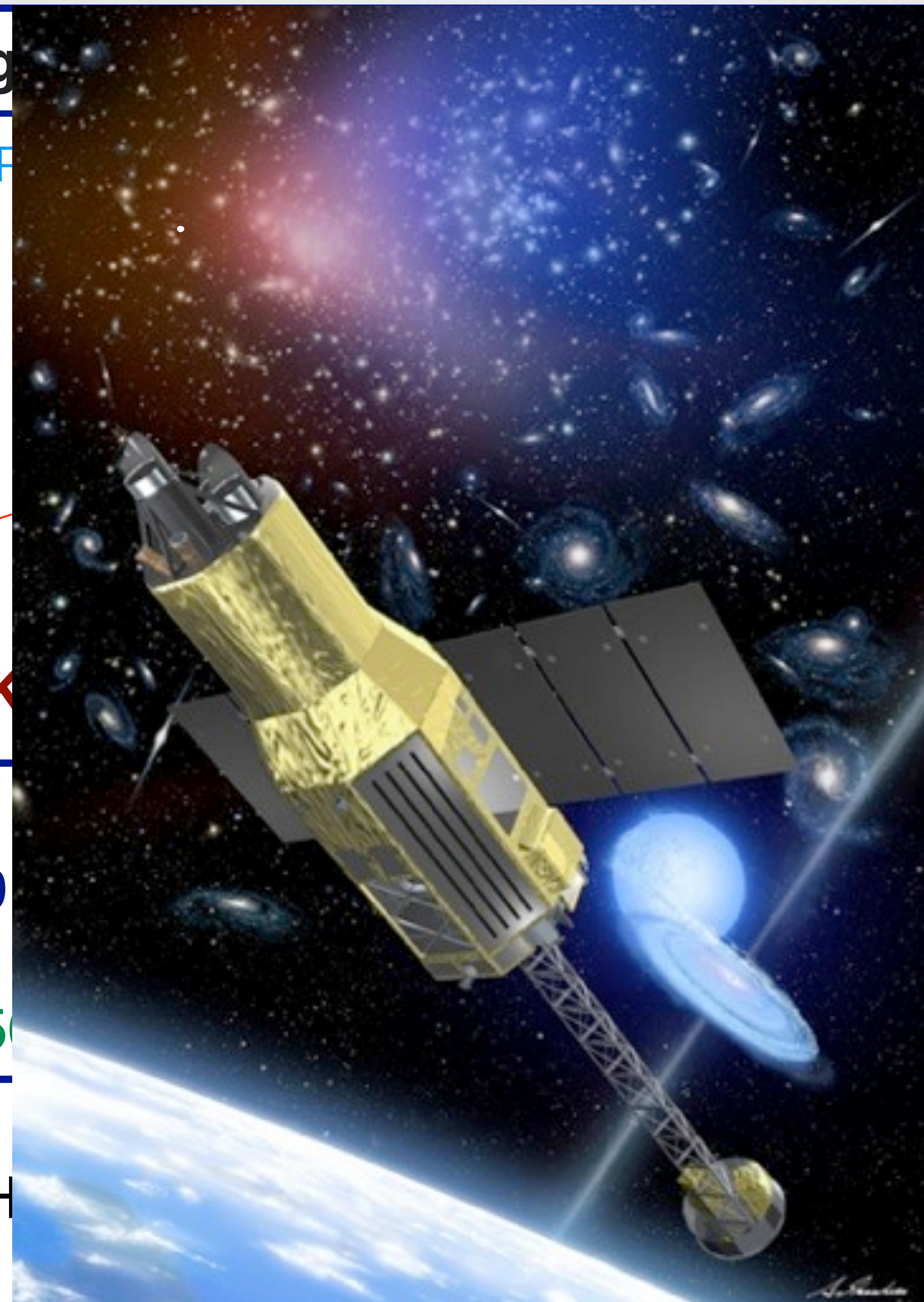
✓ Combination of Si and CdTe detectors with high resolution

✓ Many-layer stack structure with small pitch

ASTRO-H X-ray Observatory

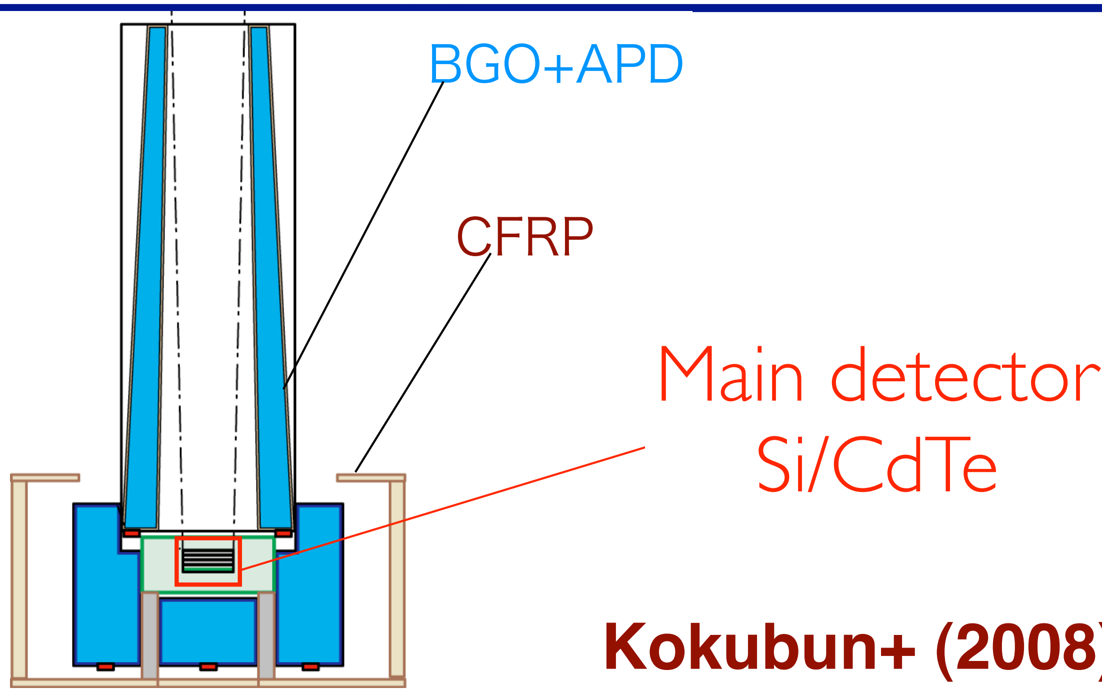
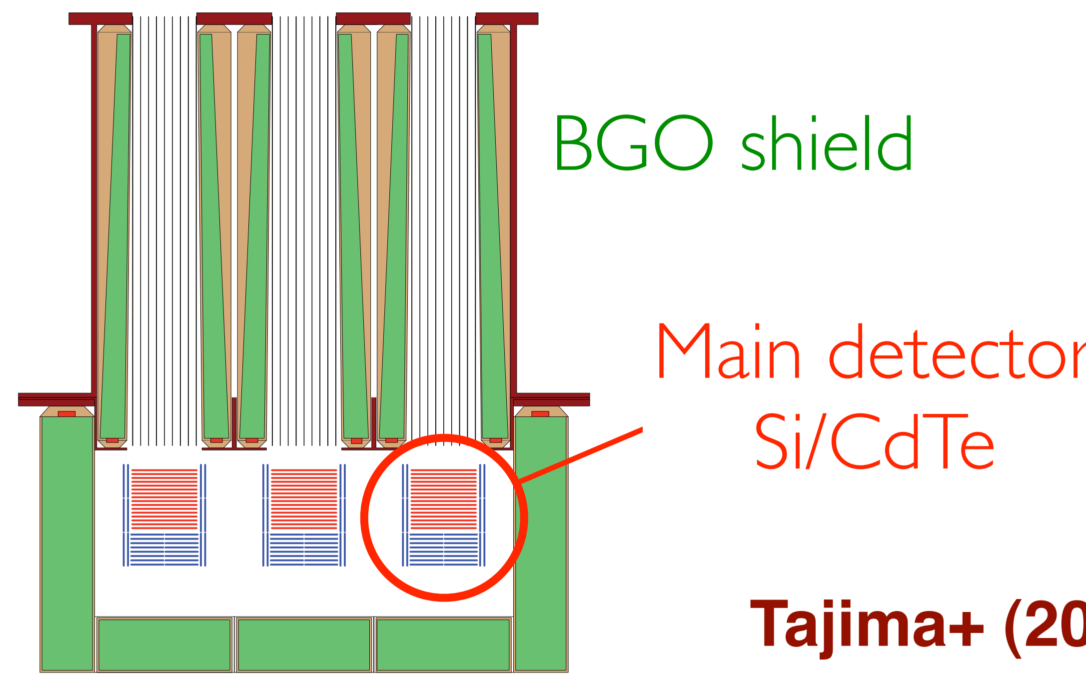
ASTRO-H is the next X-ray satellite led by JAXA, scheduled for launch in 2014. (Takahashi+ 2010)

Hard X-ray Imag	-ray Detector (SGD)
	
4-layer Si-DSD 32.0 x 32.0 x 0.5 mm, 250 1-layer CdTe-DSD 32.0 x 32.0 x 0.75 mm, 25	ick, 32 layers m thick, , 2 layers at each sides CC unit × 6 CC
• 5 - 80 keV • Focal plane detector of H mirror	mpton telescope



ASTRO-H X-ray Observatory

ASTRO-H is the next X-ray satellite led by JAXA, scheduled for launch in 2014. (Takahashi+ 2010)

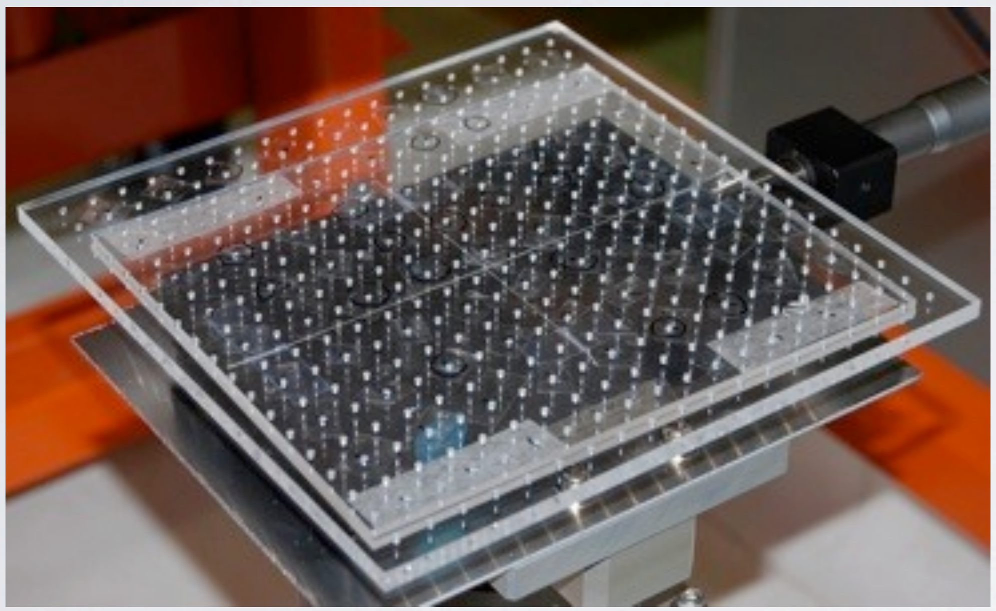
Hard X-ray Imager (HXI)	Soft Gamma-ray Detector (SGD)
 **Kokubun+ (2008)**	 **Tajima+ (2008)**
4-layer Si-DSD 32.0 x 32.0 x 0.5 mm, 250 um strip pitch 1-layer CdTe-DSD 32.0 x 32.0 x 0.75 mm, 250 um strip pitch	Si-Pad 0.6 mm thick, 32 layers CdTe-Pad 0.75 mm thick, 8 layers at bottom, 2 layers at each sides 13321 channels/CC unit × 6 CC
• 5 - 80 keV • Focal plane detector of Hard-X-ray super mirror	• 10 - 600 keV • Narrow-FOV Compton telescope

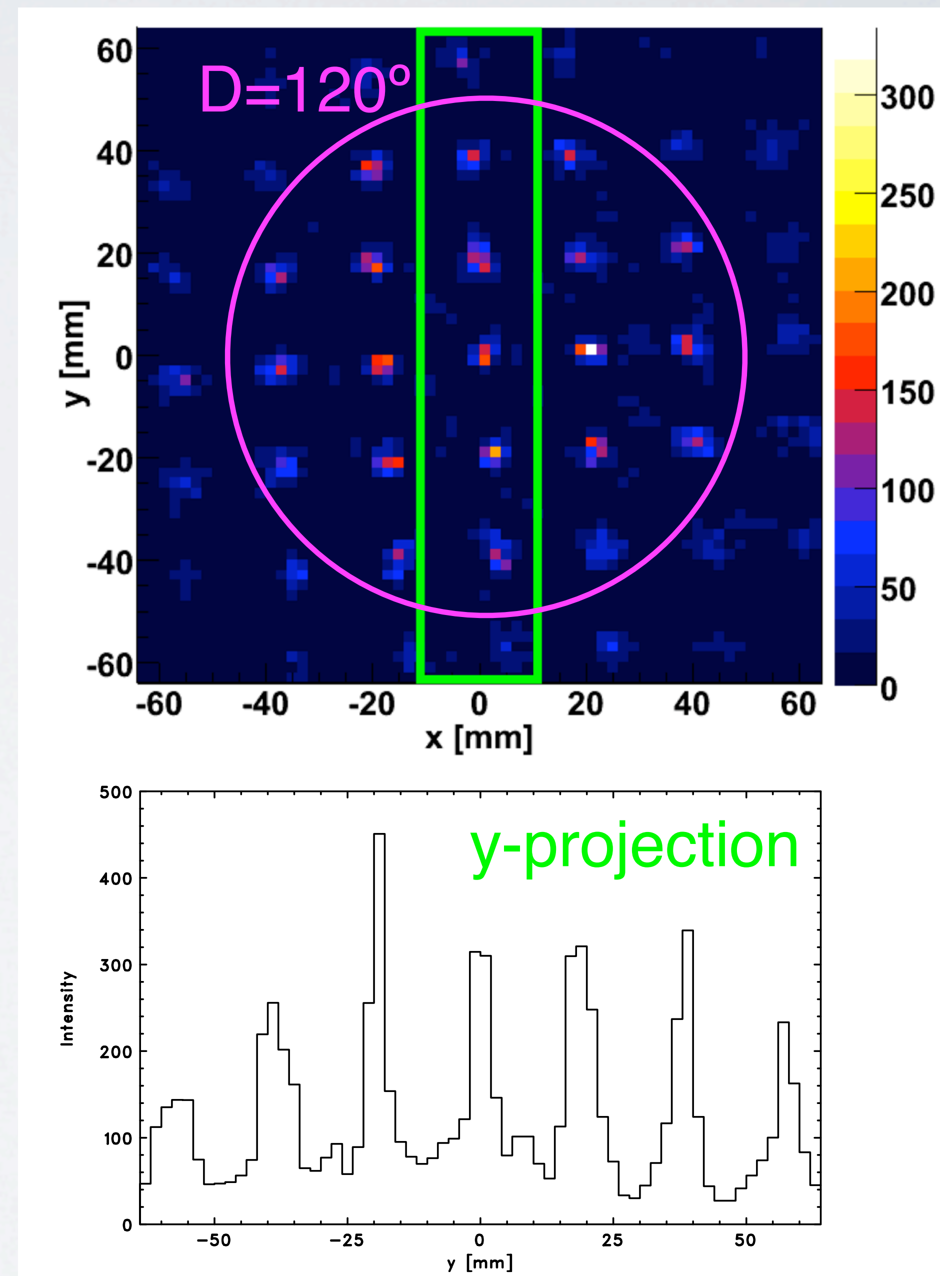
Results from Prototypes
Compton Imaging

Takeda+ (2009) collaboration with Gunma Univ. & JAEA

1-layer Si + 4-layer CdTe

Multiple point sources





- Liquid ^{131}I source (364 keV)
- Grid with a gap of 20 mm
- Distance of 60 mm from the camera top

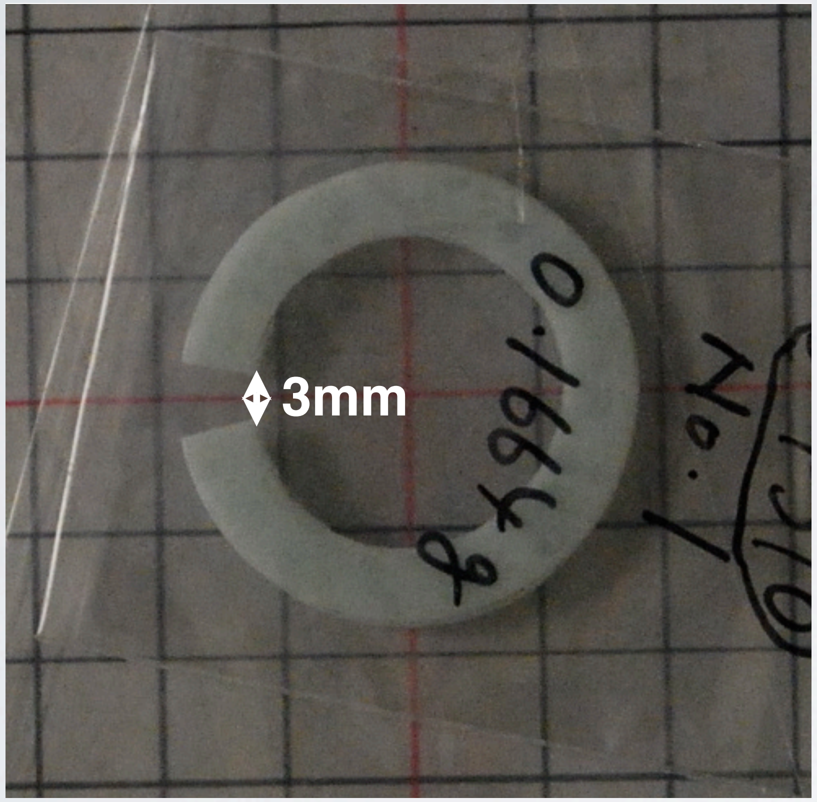
- 1 mm position accuracy (distance: 60 mm)
- FOV > 120°

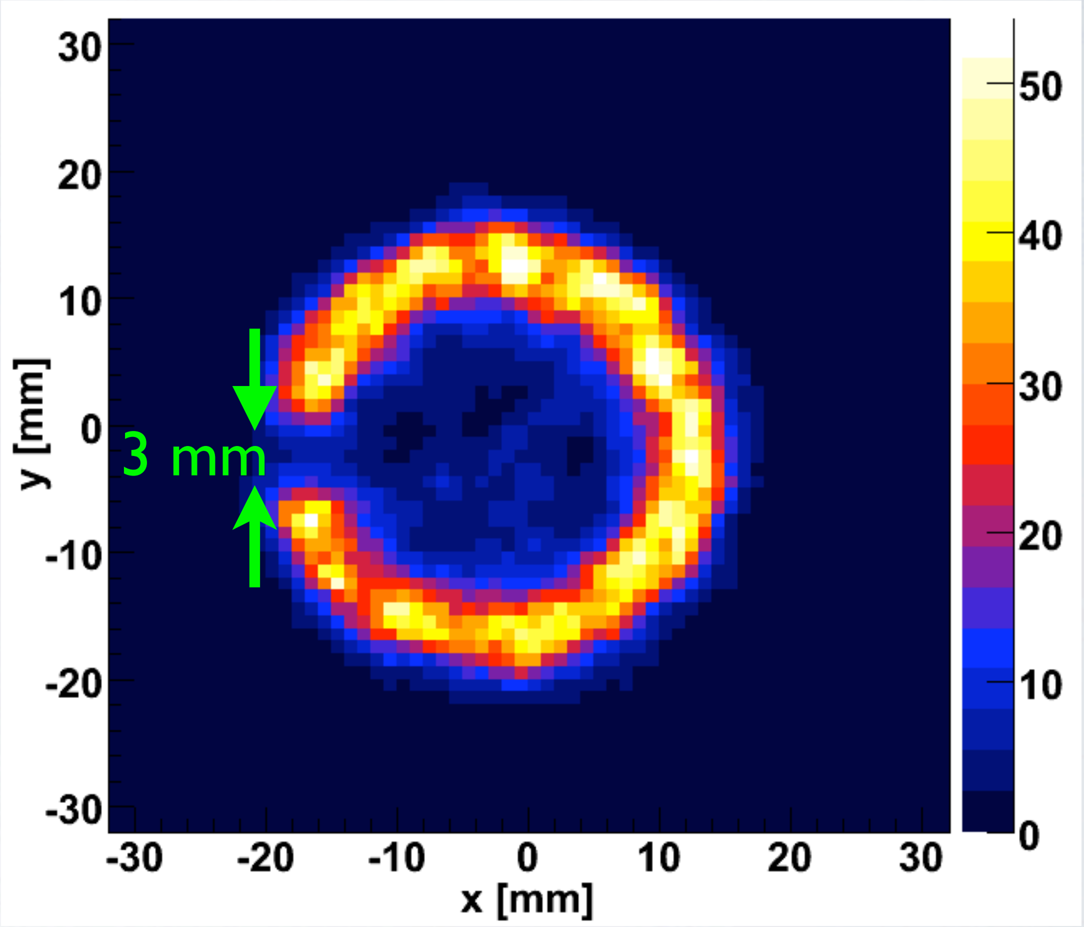
Results from Prototypes
Compton Imaging

Takeda+ (2009) collaboration with Gunma Univ. & JAEA

1-layer Si + 4-layer CdTe

Extended sources





- Liquid ^{131}I source (364 keV)
- reverse "C" shape
- Distance of 30 mm from the top

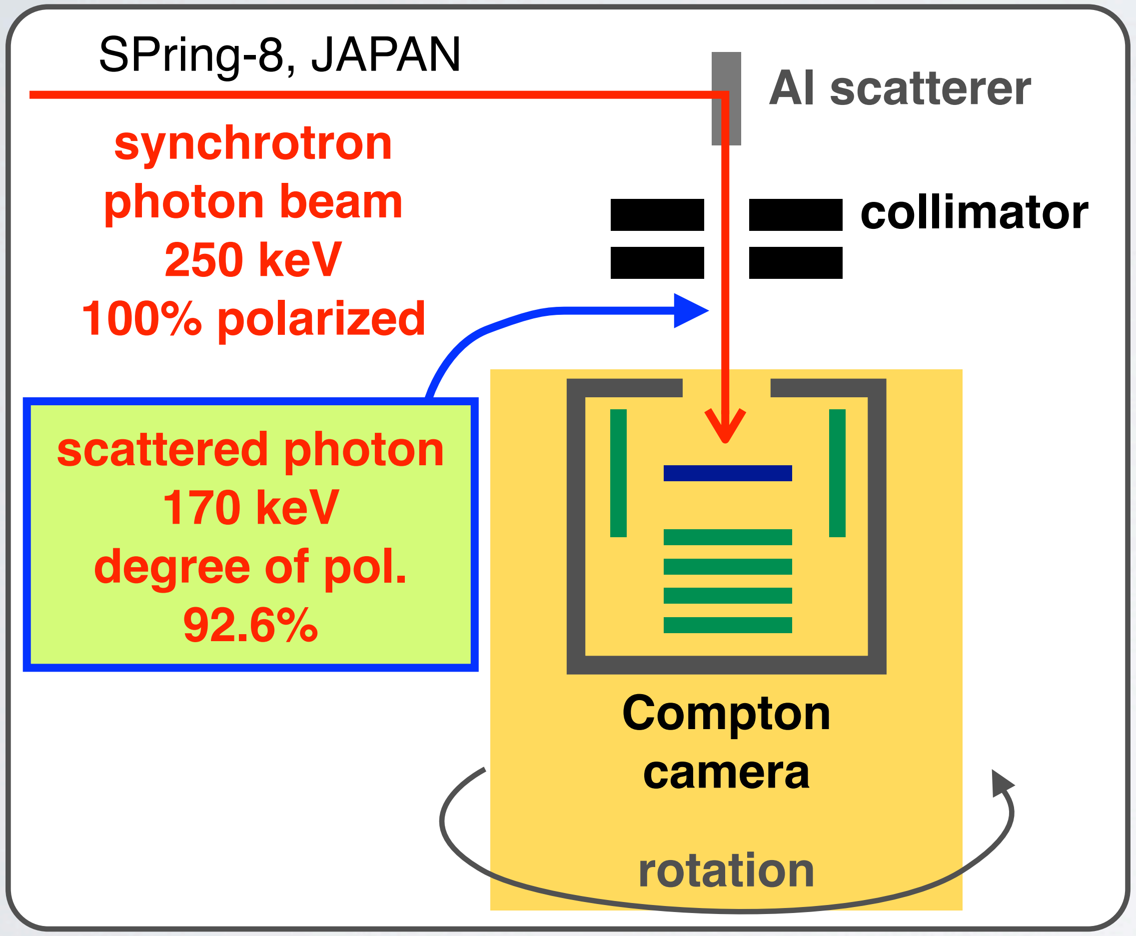
- Imaging of diffuse emission is well performed.
- Spatial resolution is better than 3 mm. (distance: 30 mm)

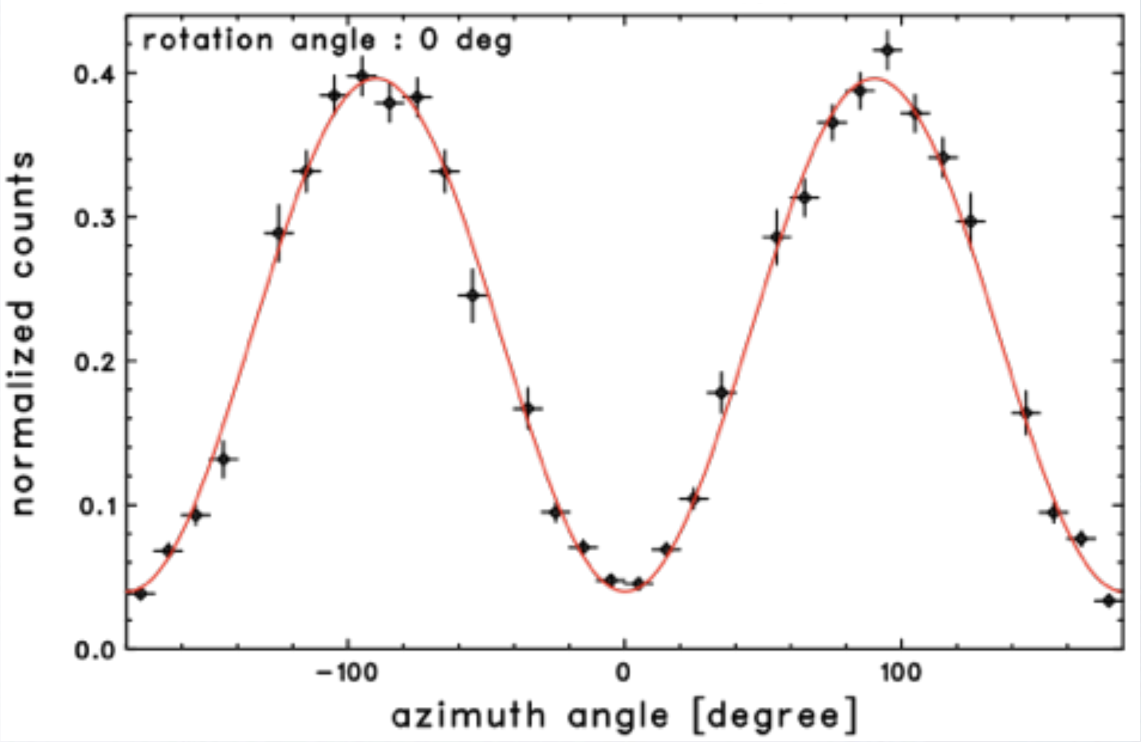
Results from Prototypes
High-Precision Polarimetry

Principle: anisotropy of the azimuth angle distribution of Compton scattering

<u>Advantage over conventional Compton polarimeters</u>

- High precision measurement of the azimuth angle
- Restrict the incident direction of photons (Background rejection)





Modulation factor = 0.82 ± 0.01
Polarization angle = 0.2° ± 0.4°

- The measured modulation factor agrees with the theoretical value.
  0.83 = 0.926 × 0.90 (modulation factor for 100% polarized beam)
- Polarization angle is determined to a precision of 1°.

Takeda+ (2010)

Strategy for Higher Performance

Two important performance keys:

1) Angular/Spatial Resolution

	Energy	Position
Precise measurement	**New ADC-included low-noise readout ASICs VATA 450/460/461**	**New fine-pitch CdTe double-sided strip detectors**
Detailed data reduction	**Efficient calibration method using Compton events**	**Depth sensing & inter-strip events using multi-strip information**

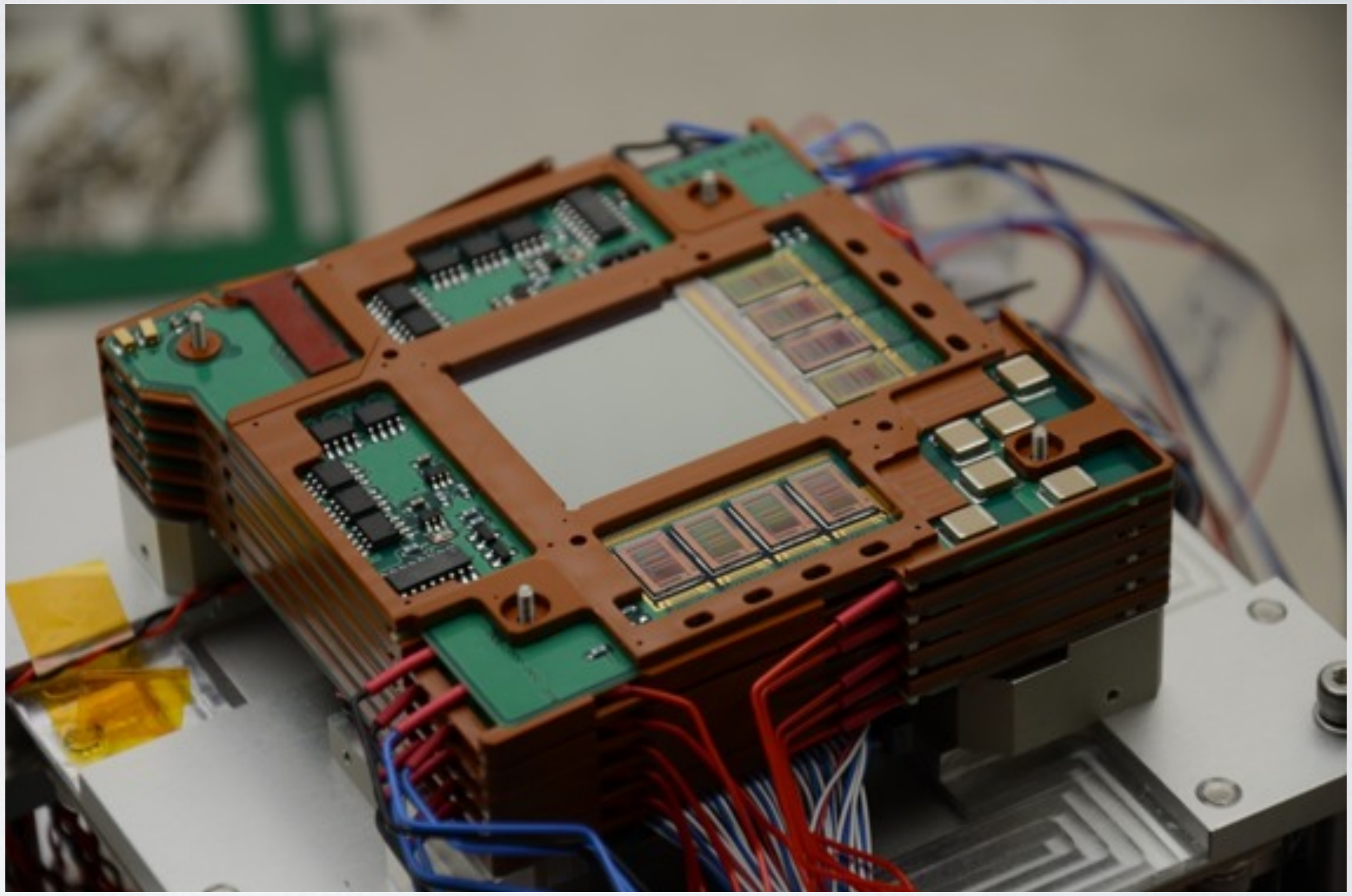
2) Detection Efficiency

- Large-area & multi-layer stacking of double-sided strip detectors
- Modular design → flexible & scalable configuration

New Camera Module

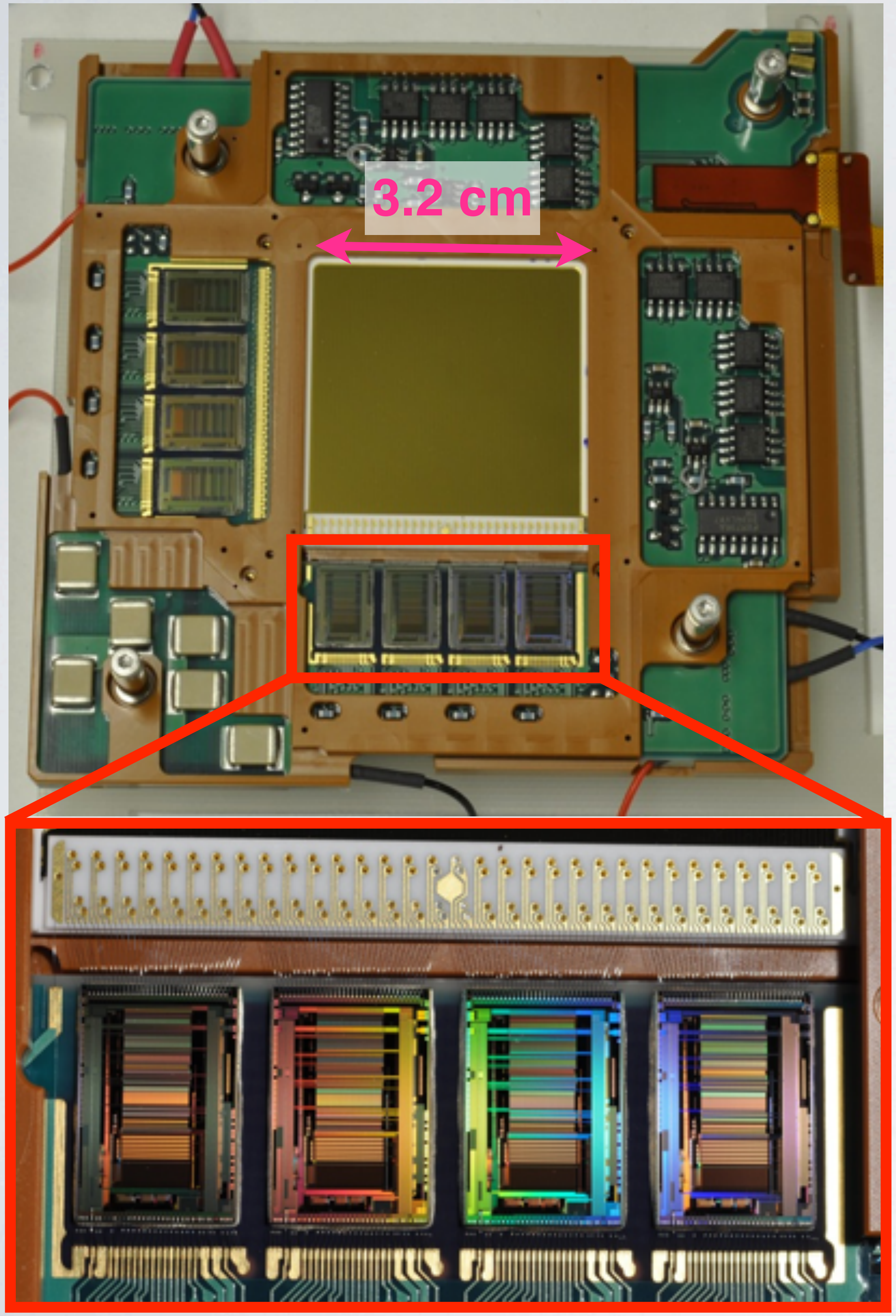
- ✓ Stack of DSDs with high energy/position resolutions
- ✓ Highly modular design
- ✓ The detector configuration is flexible and scalable for specific applications. Example: 1 Si + 4 CdTe

assembled by MHI



Common spec.	DC-coupled floating readout with VATA 460/461 Active area: 3.2 x 3.2 cm^2 128 strips in each side with 250-um pitches
Si-DSD	ΔE: 1.5 keV at 60 keV (FWHM) Thickness: 500 um Hamamatsu
CdTe-DSD	ΔE/E: 1% at 500 keV (FWHM) Thickness: 750 um ACRORAD

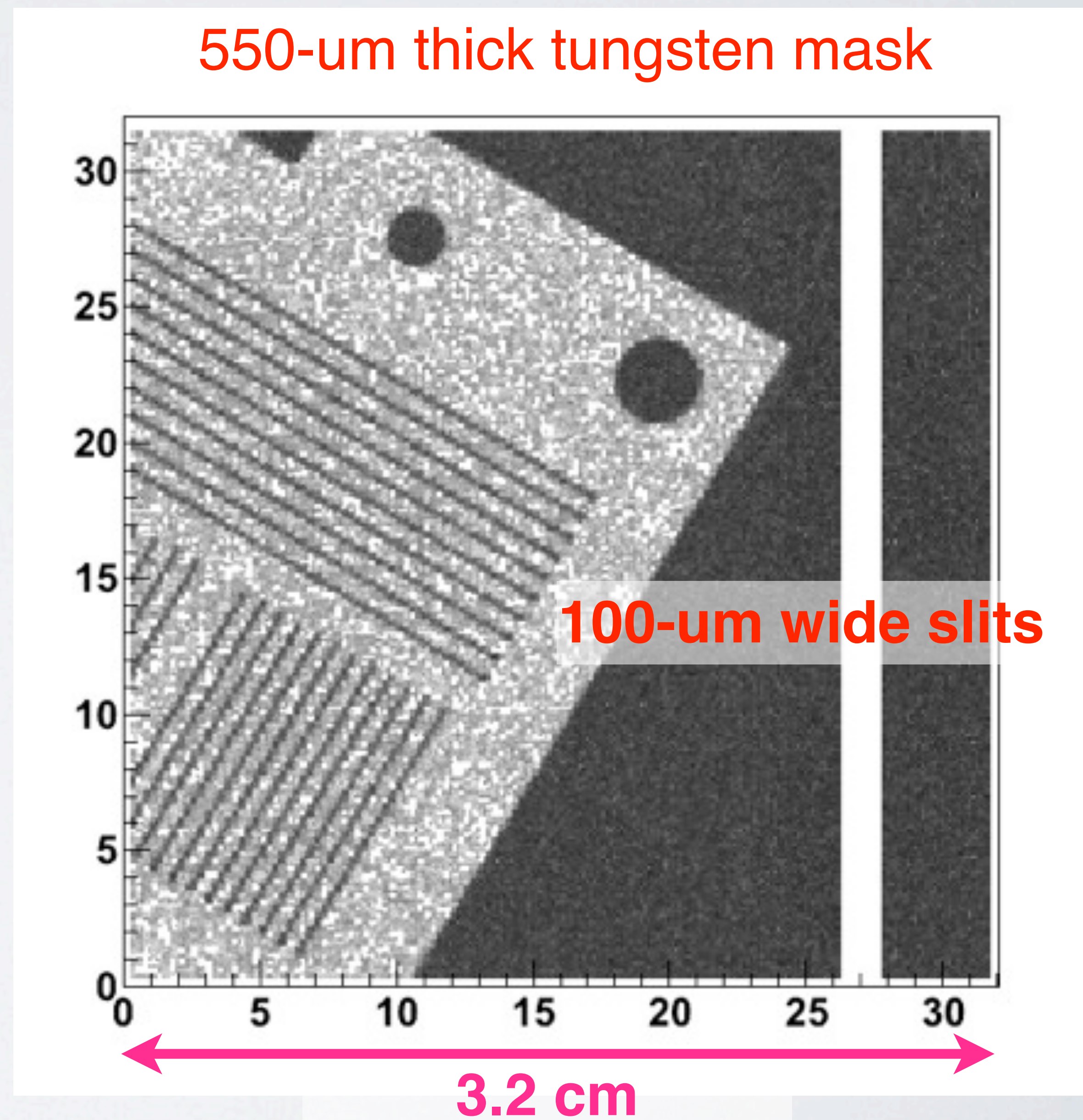
250-um Pitch CdTe-DSD



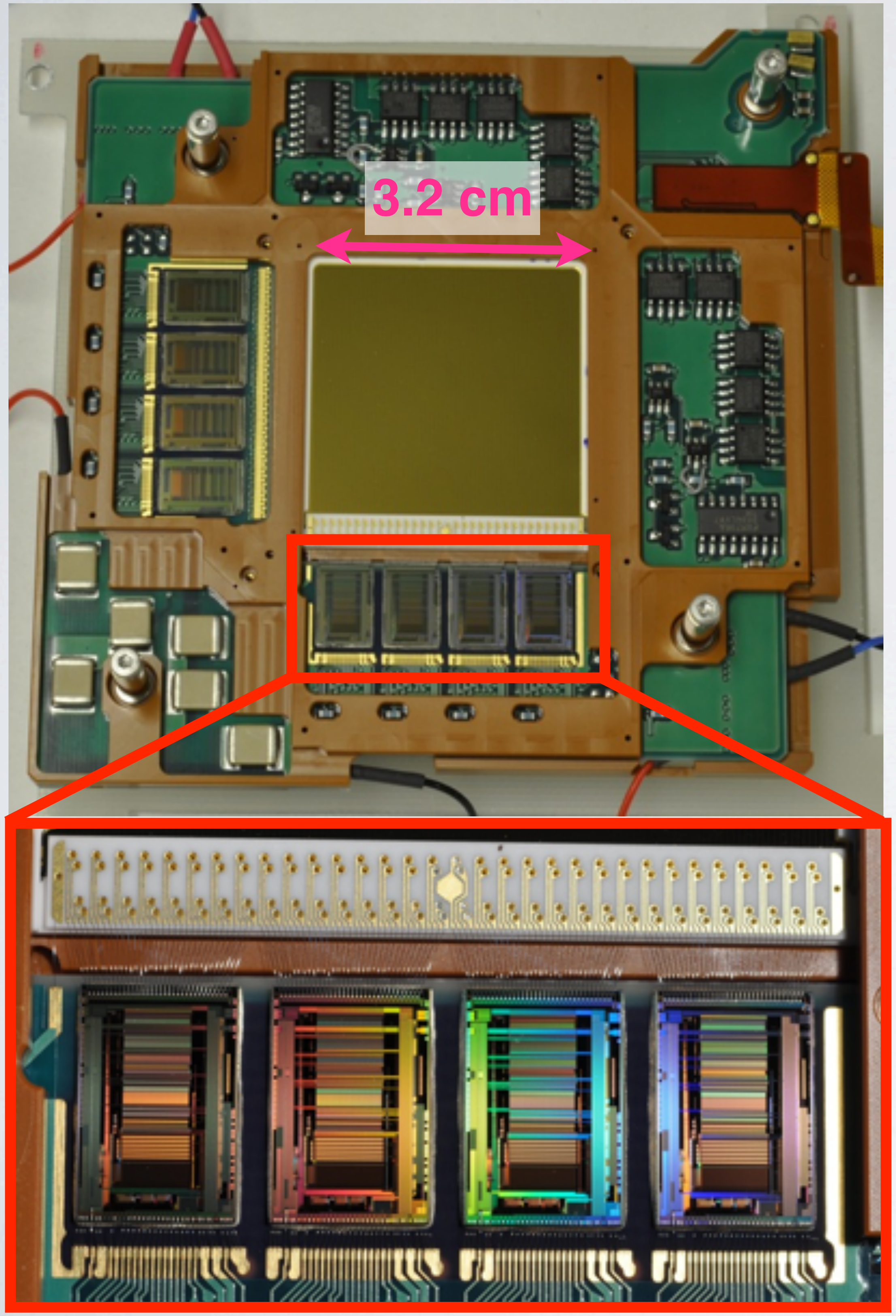
Key detector of the Si/CdTe system

Watanabe+ (2009), Ishikawa+ (2010)

Shadow image (28-33 keV)



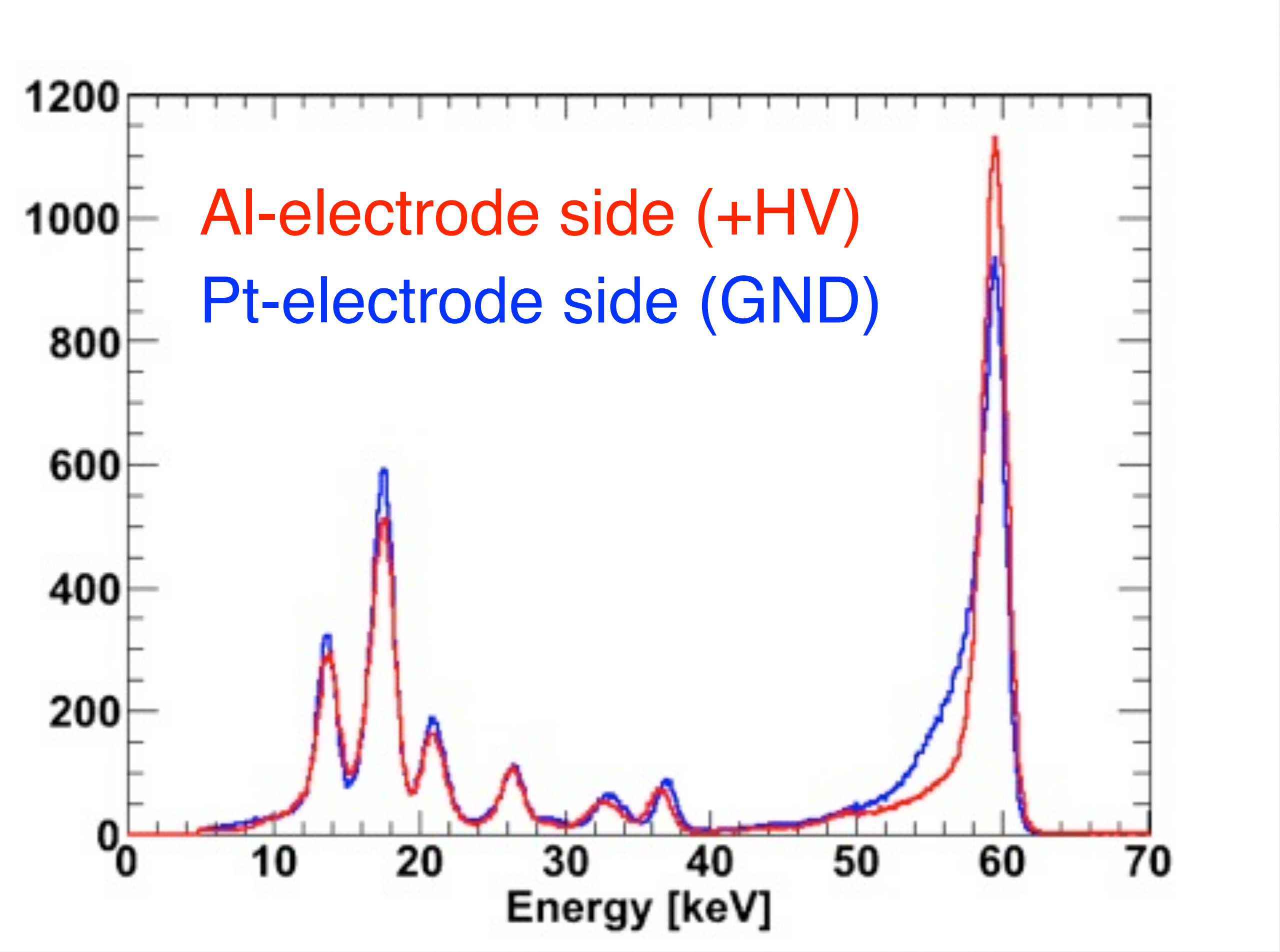
250-um Pitch CdTe-DSD



Key detector of the Si/CdTe system

Watanabe+ (2009), Ishikawa+ (2010)

Am-241 spectrum



Applied bias: 250 V

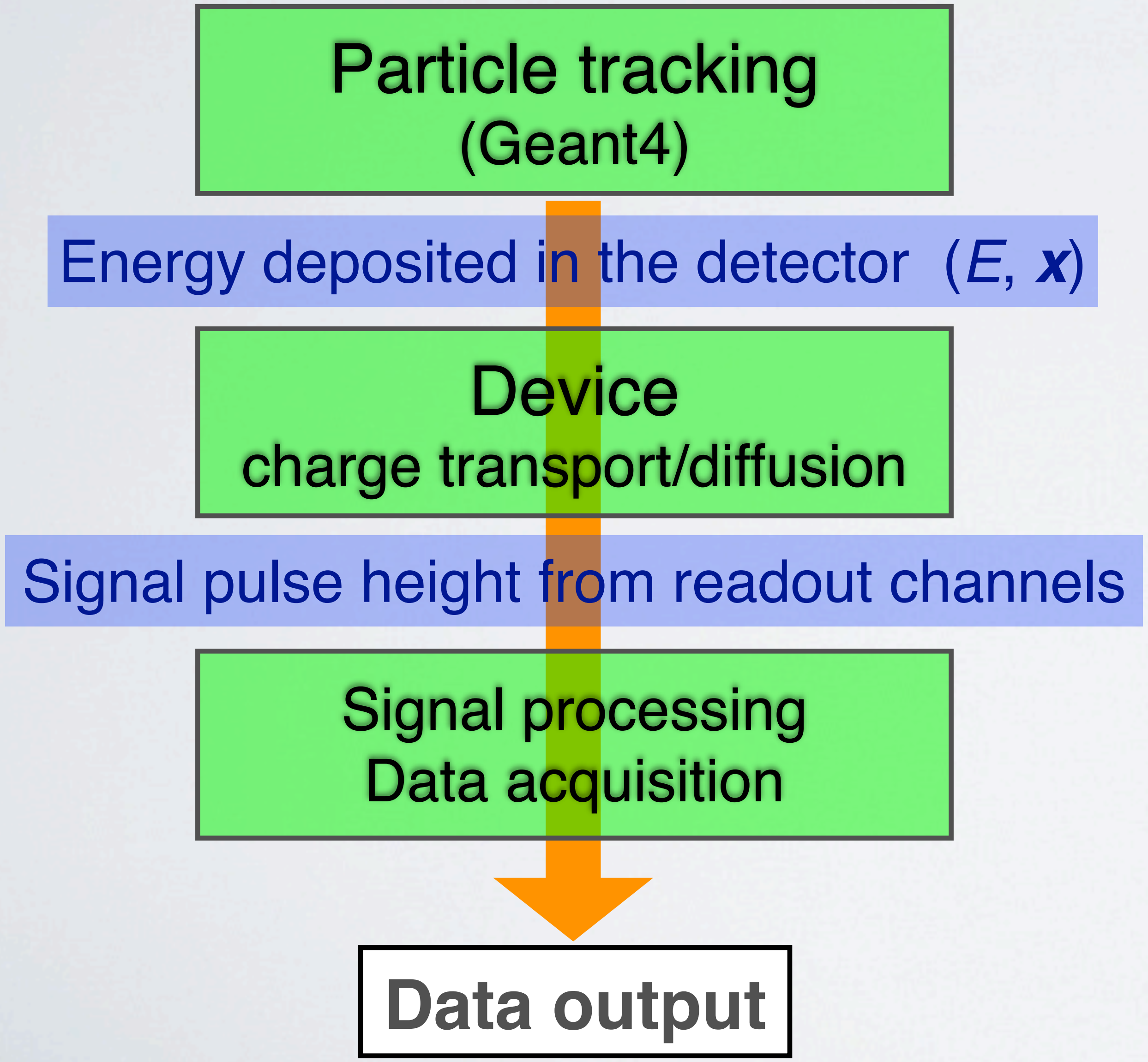
ΔE: 1.7-1.9 keV at 60 keV (FWHM)

Low threshold: 5 keV

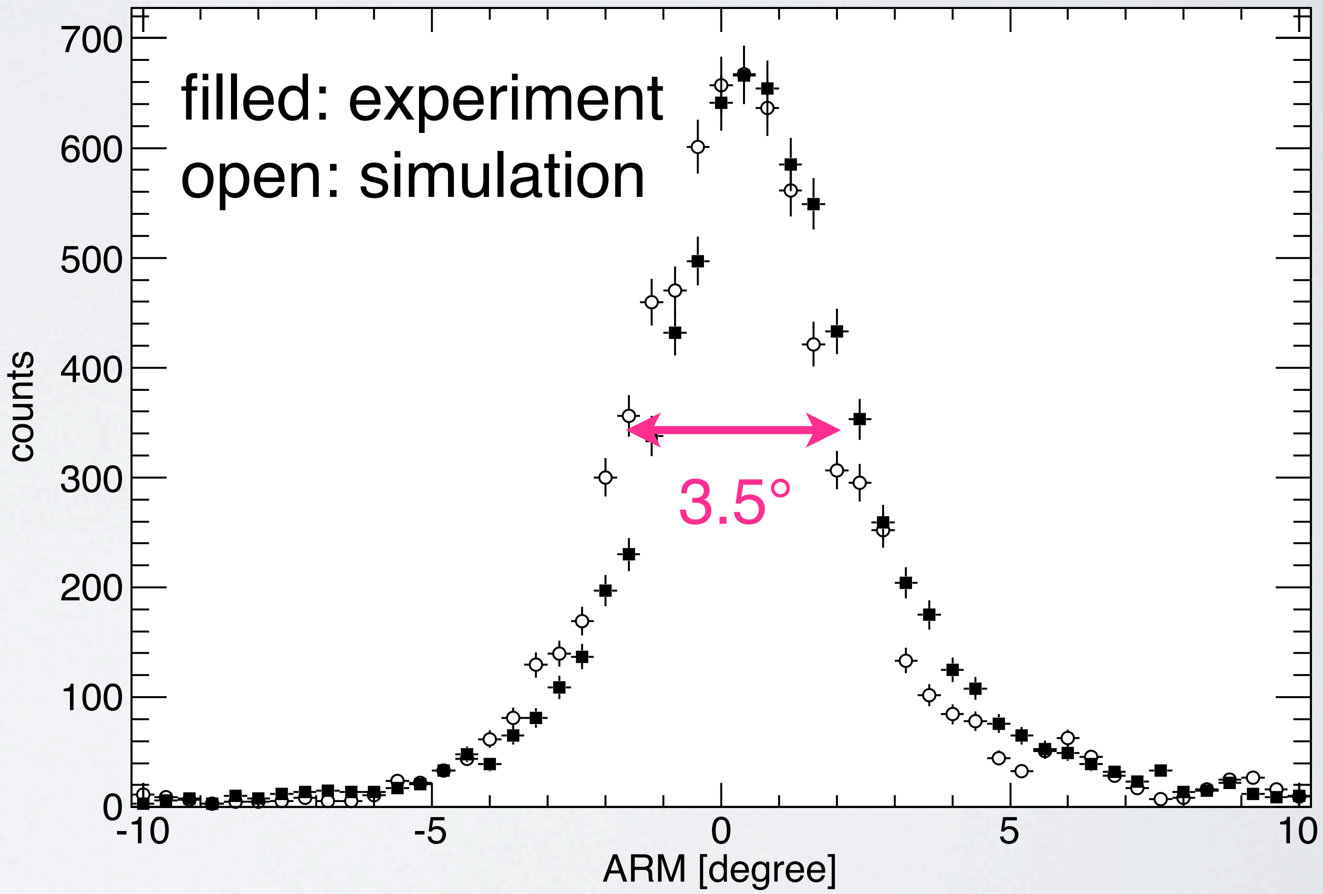
Detector Response

For scientific applications (spectral fitting, image deconvolution,...), correct understanding of the detector response is required.

To handle complex response of the Si/CdTe Compton camera, we have developed a full Monte Carlo simulator. (Odaka+ 2010)



same format as the real experimental data

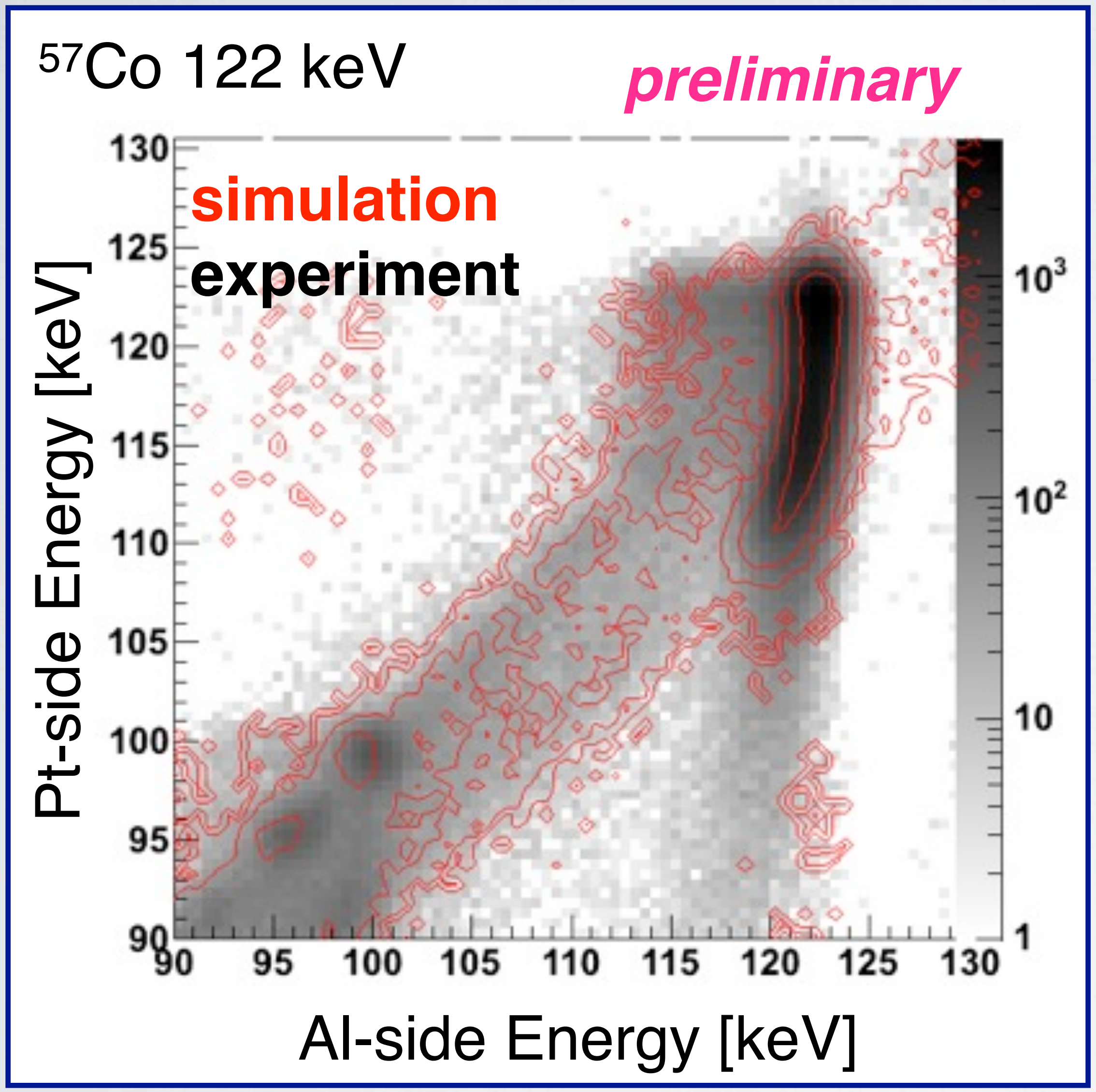


Angular response (ARM) at 356 keV

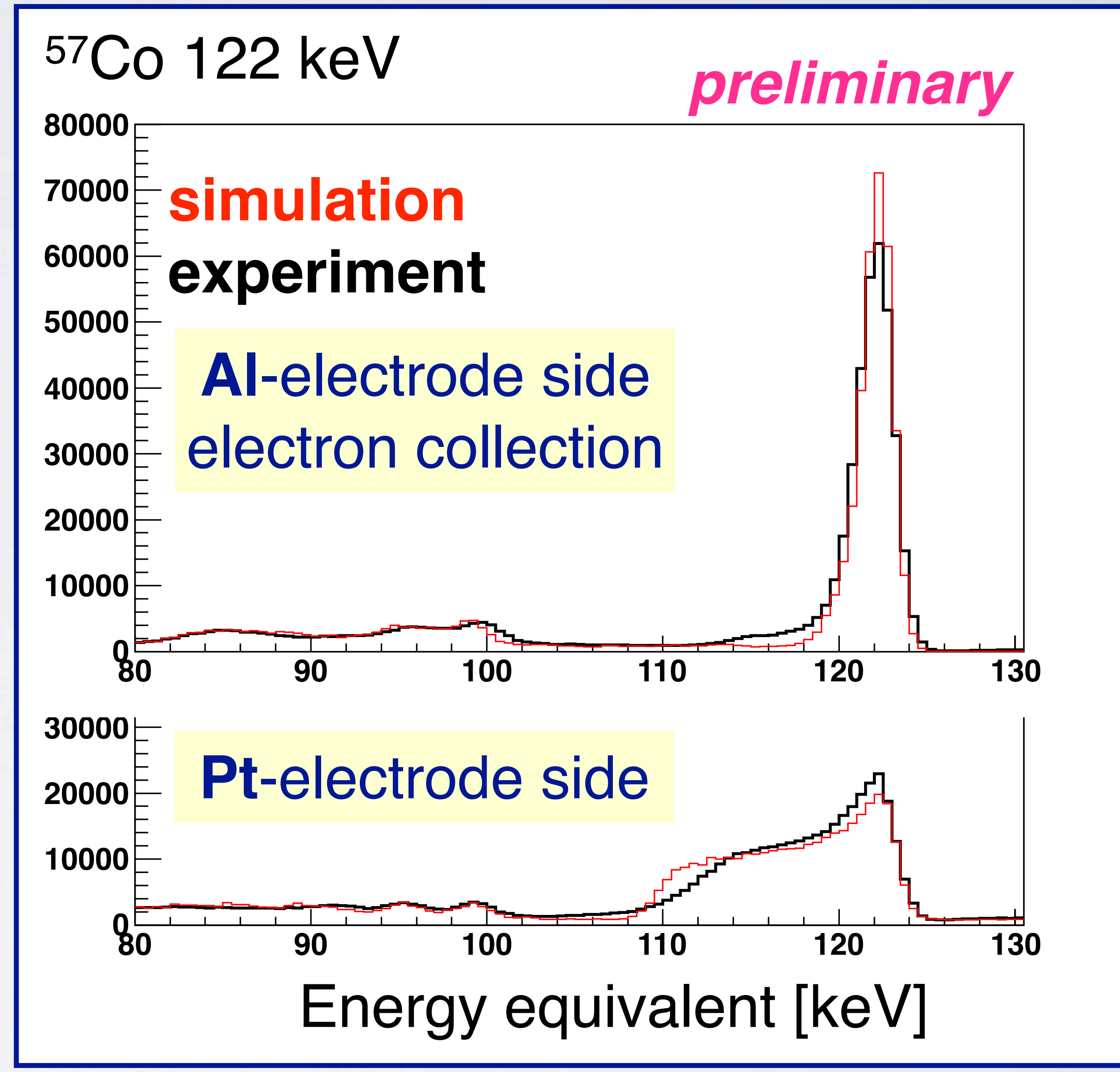
Good agreement with an experimental result from the prototype

Response of CdTe

Complex detector response due to incomplete charge collection
(small mobility-lifetime product of hole)



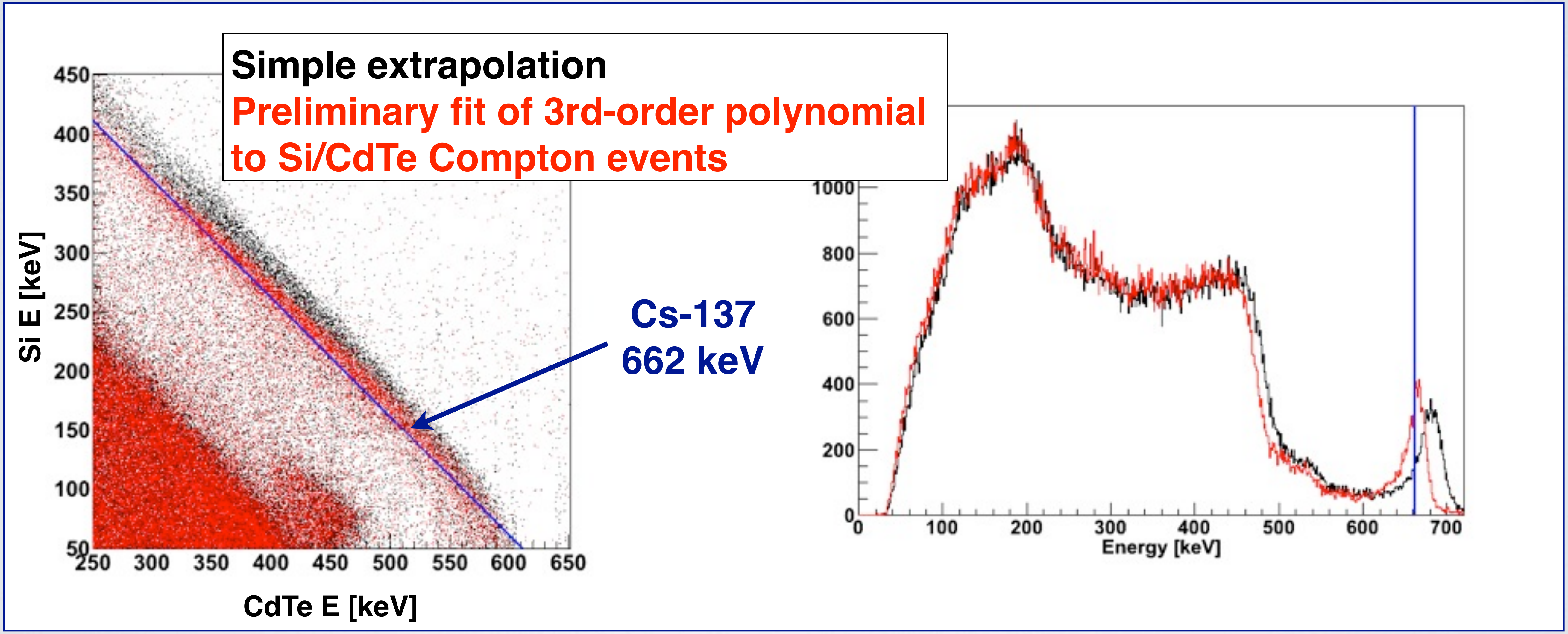
projection



- We are now investigating inter-strip events, which can produce charge-shared events and/or low-energy tail structure.
- Polarization of CdTe is also an important issue. We established long-term stability at the ASTRO-H operation temperature, –20°C. (Sato+ 2010)

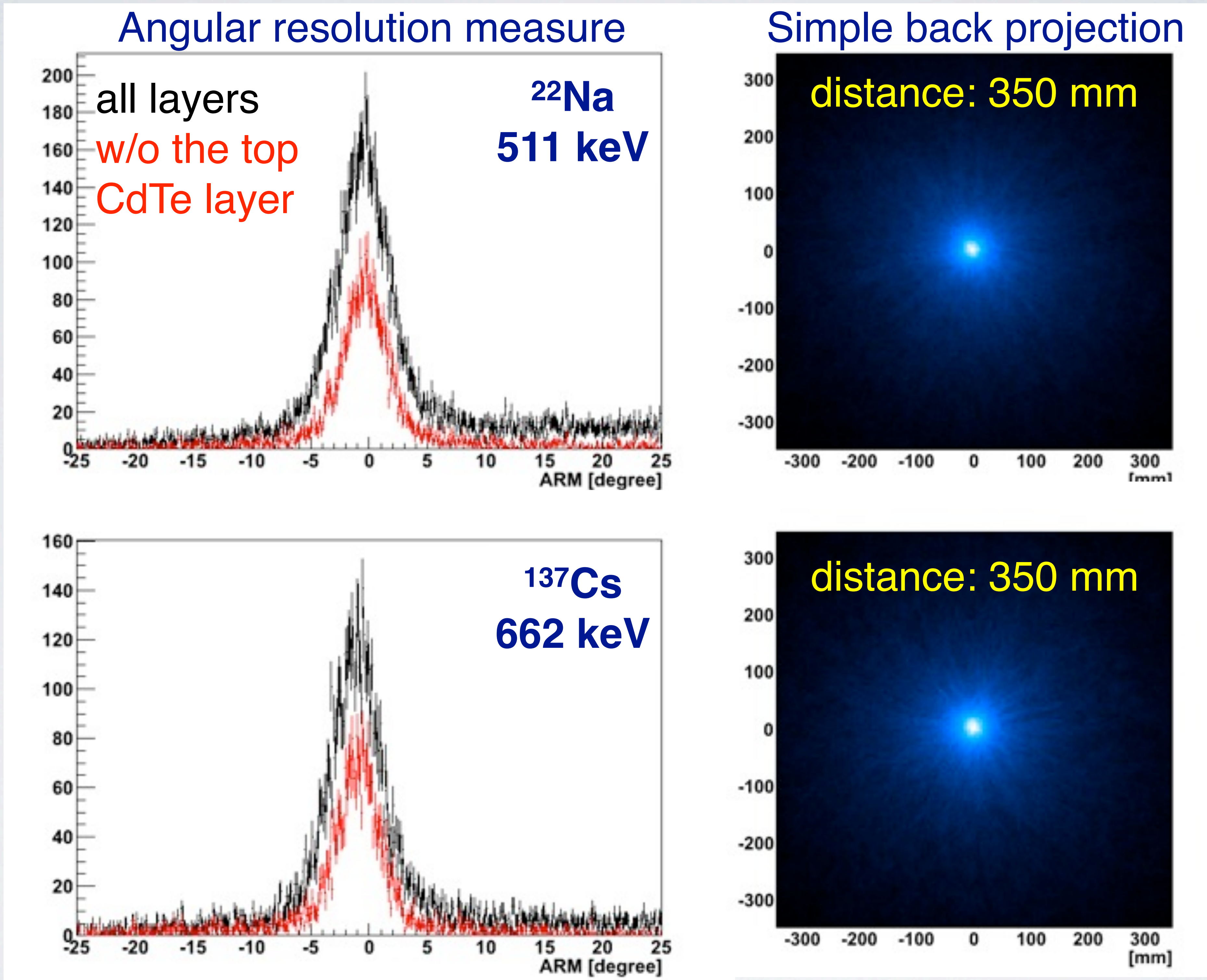
Calibration

High resolution detectors require accurate calibrations!
Calibration using gamma-ray lines is not realistic at high energies for Si detectors because photoelectric absorption hardly occurs.
→ Use two-hit Compton events



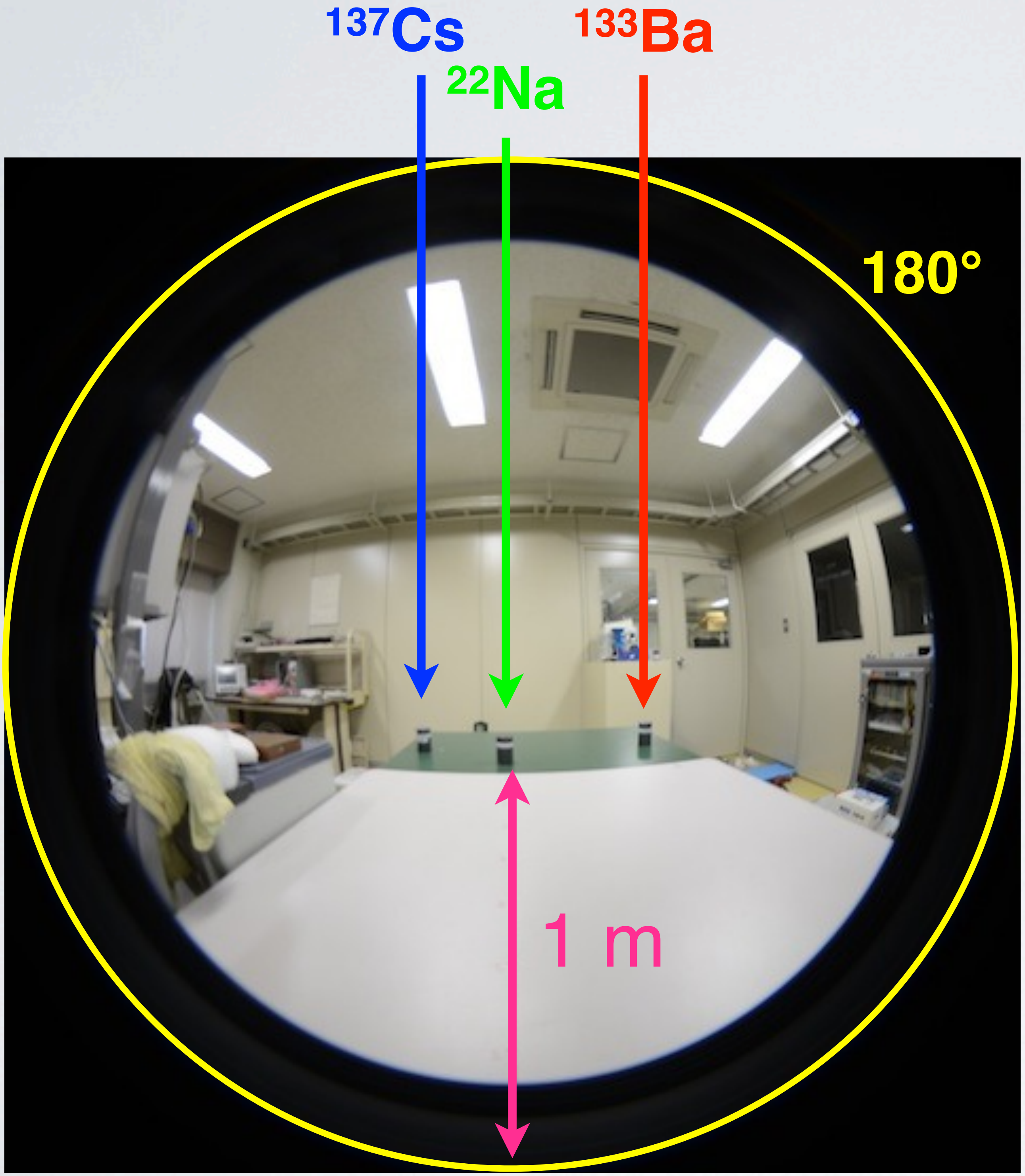
This method can be cross-checked by test pulses.
VATA 450/460 series has a function to operate calibration test pulses.

Initial Results



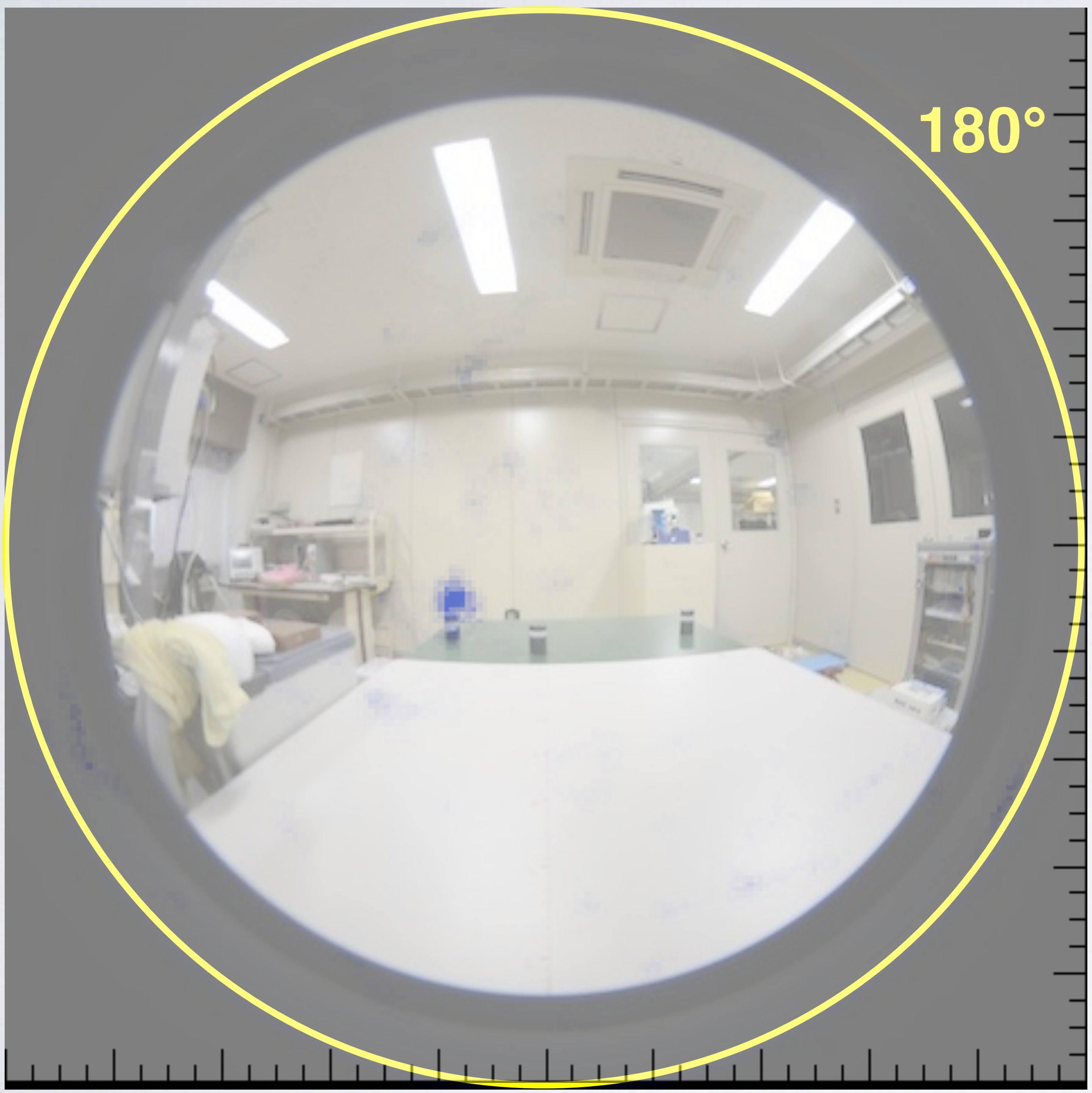
Angular resolution is 4-6 degrees, depending on event selection criteria.

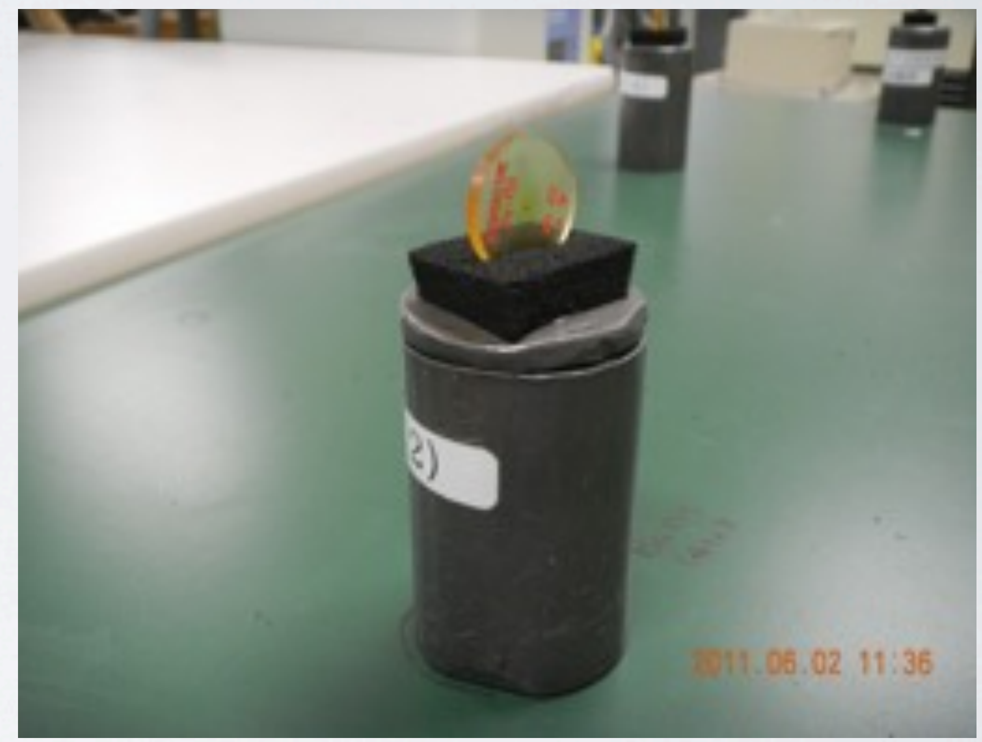
Simultaneous Multi-RI Imaging



Simultaneous Multi-RI Imaging

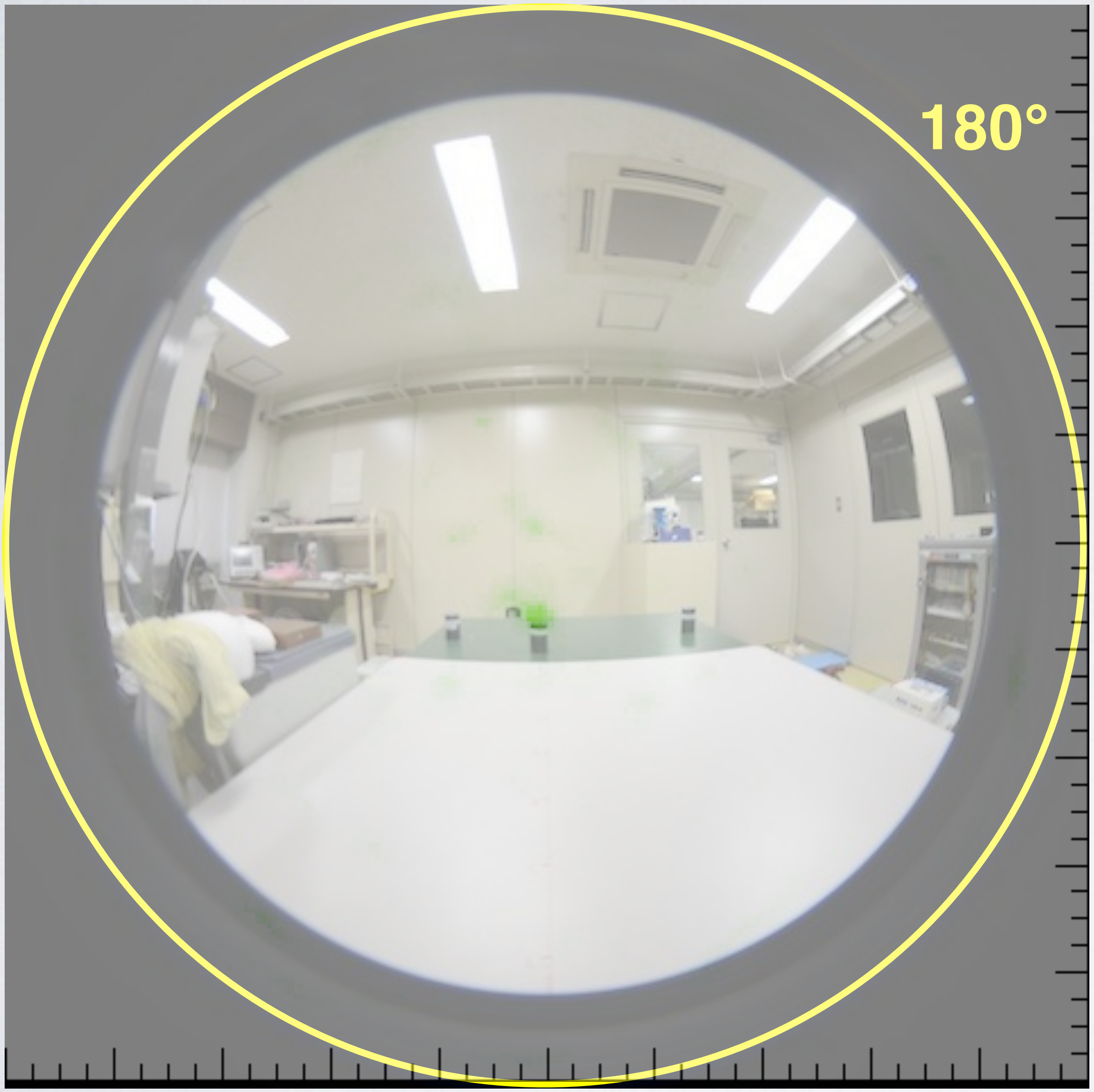
^{137}Cs 662 keV (2.8 MBq)





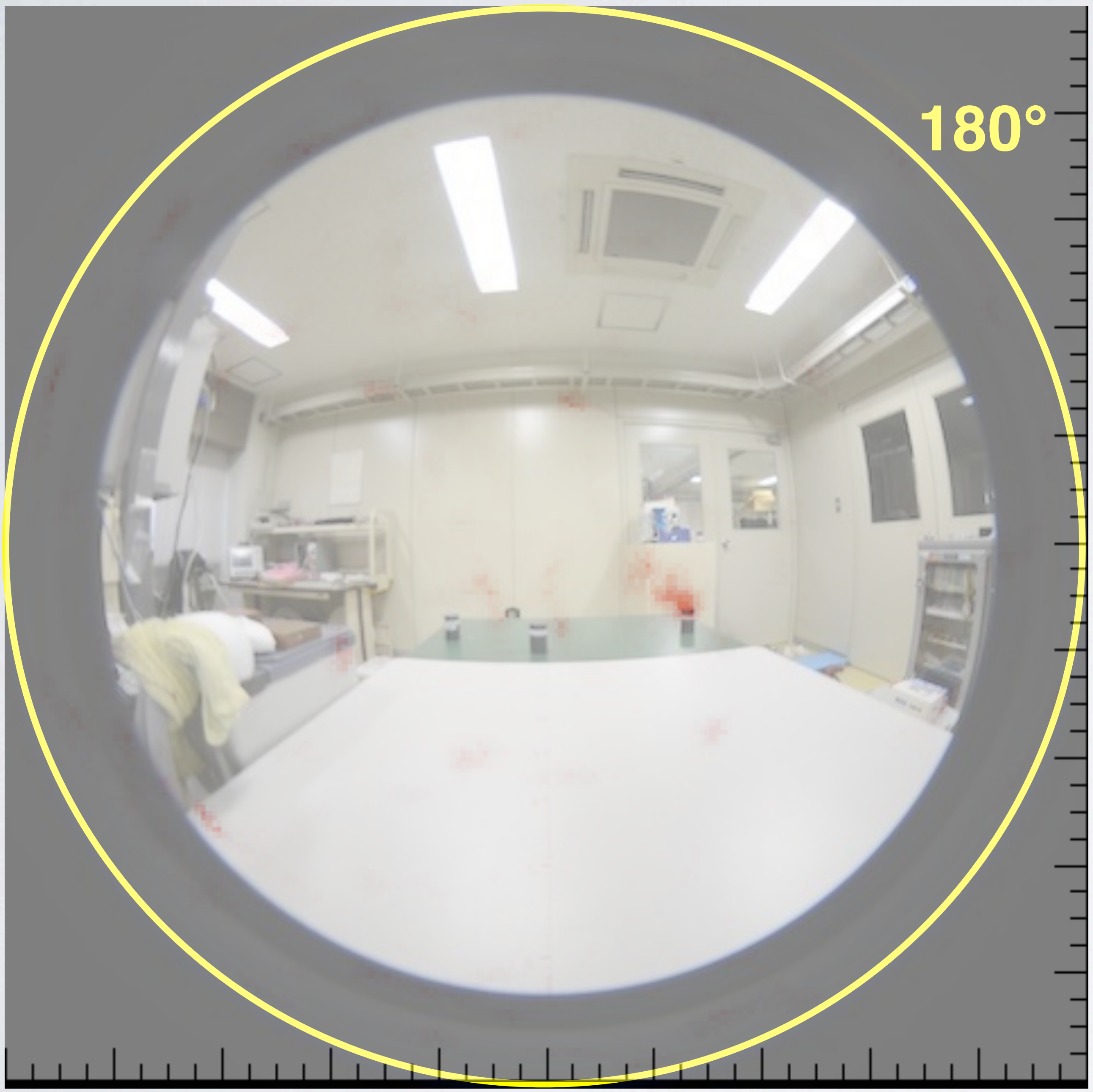
Simultaneous Multi-RI Imaging

^{22}Na 511 keV (0.5 MBq)



Simultaneous Multi-RI Imaging

^{133}Ba 356 keV (2.3 MBq)



We successfully obtained multi-RI gamma-ray images with the new camera.

Summary

- **Prototype camera**
  - ✓ **High-spatial resolution Compton imaging**
    1 mm accuracy, better than 3 mm precision
  - ✓ **High-precision polarimetry**
    degree of polarization ~1 %, angle ~1°

- **New Si/CdTe module**
  - ✓ **Flexible and scalable structure**
  - ✓ **New ADC-included readout ASICs VATA 450/460/461**
  - ✓ **250-um-pitch double-sided strip detectors**
  - ✓ **High energy resolution CdTe-DSD: 1%**
  - ✓ **We demonstrated good Compton-imaging performance from the initial data analysis.**