To uncover hotspots of radiation with a Si/CdTe Compton Camera
-- Recovering from the tragedy --

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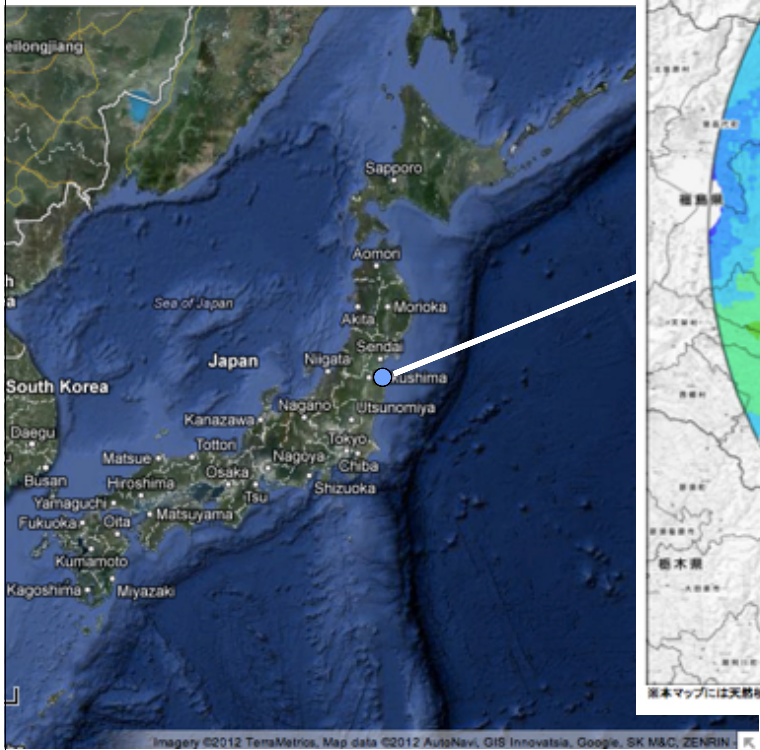
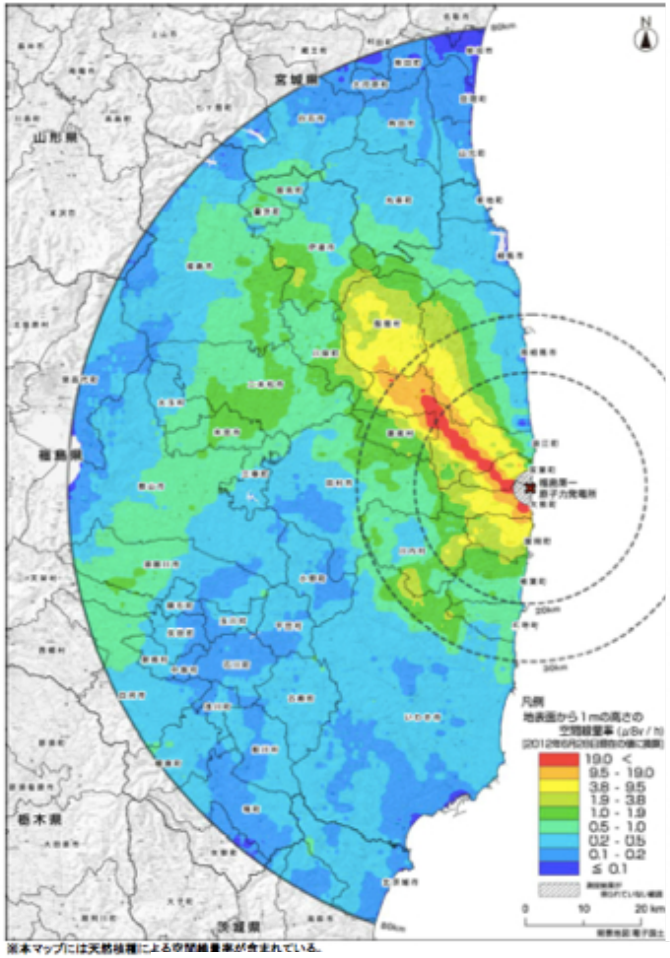
1. Effects caused by the nuclear accident at Fukushima

http://radioactivity.nsr.go.jp

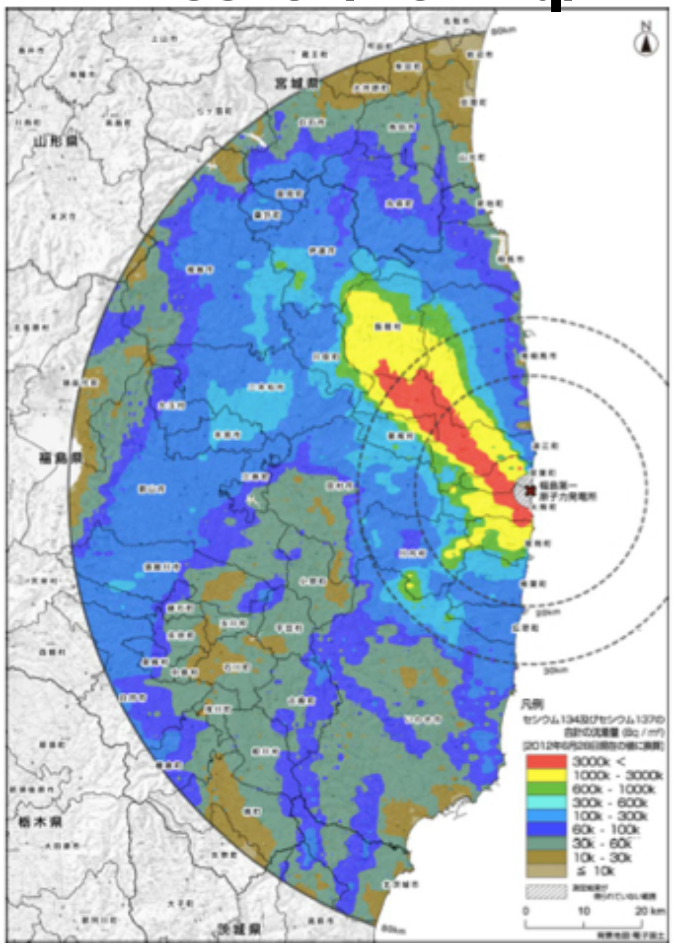
2012/June 22-28



Radiation Level

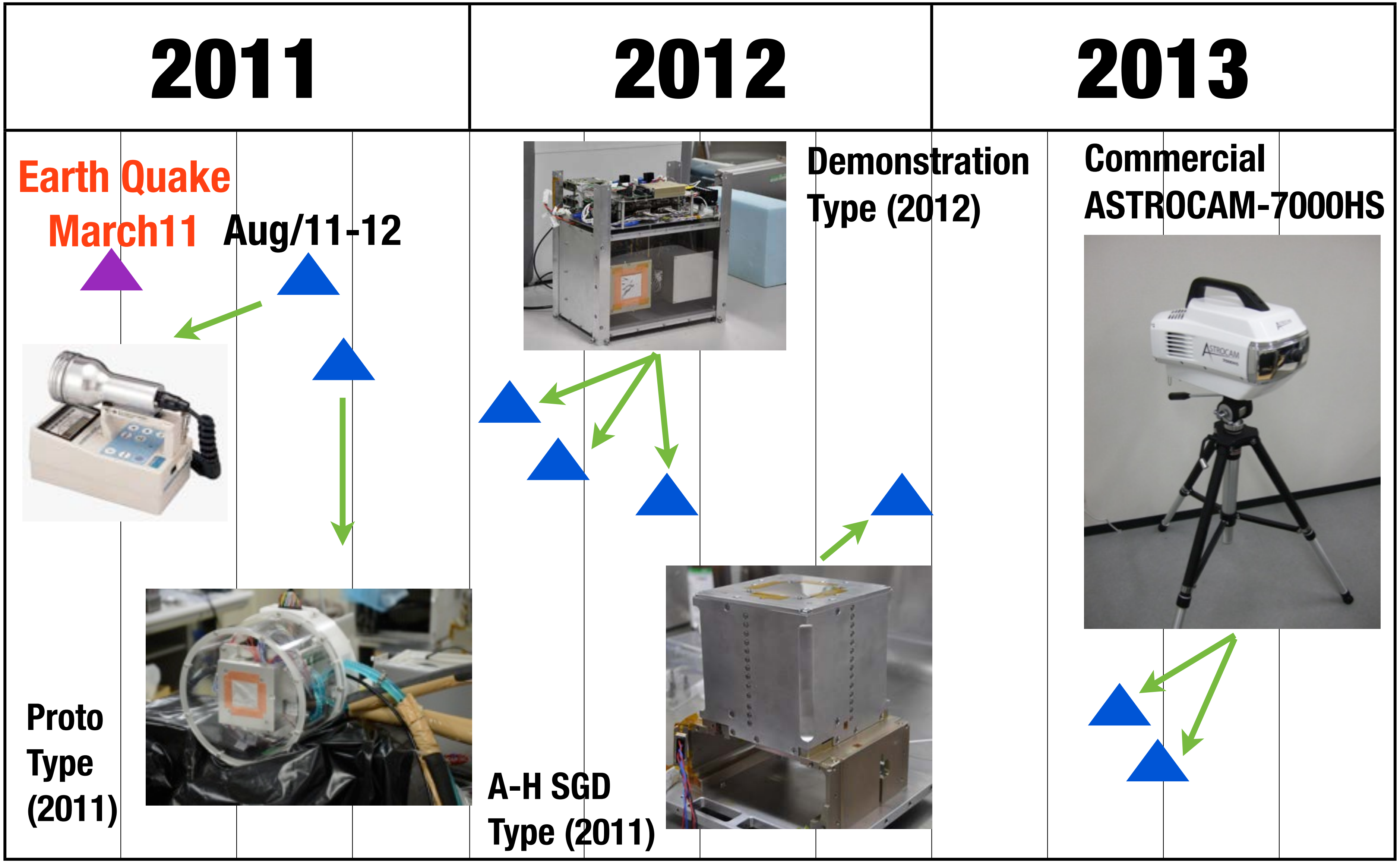


Cs134/137 Bq/m^3



Quick removal of dust with radioactive materials (decontamination) is essential

3. Our Challenges, since the first e-mail in April/2011

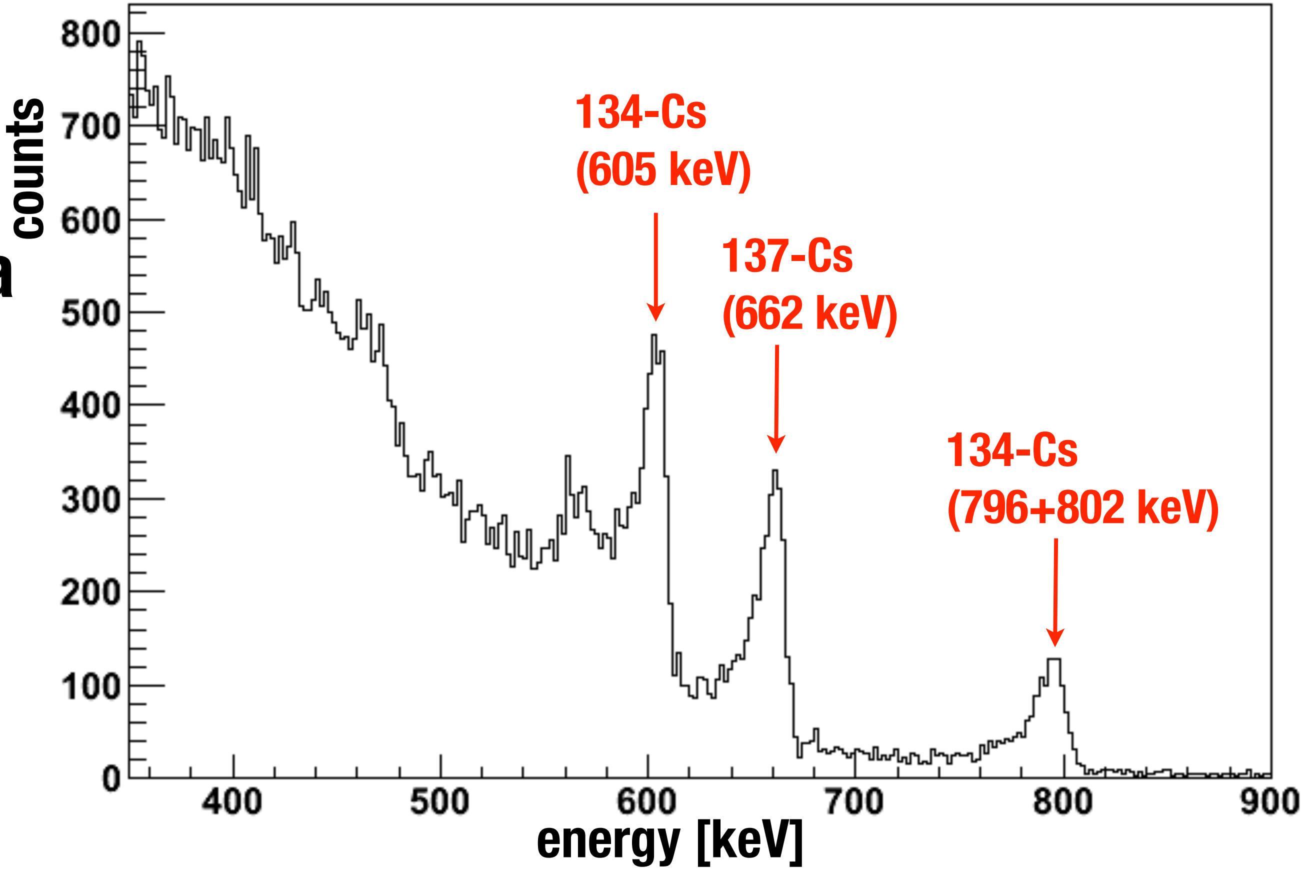


4. Requirments for "Gamma-Camera" in Fukushima

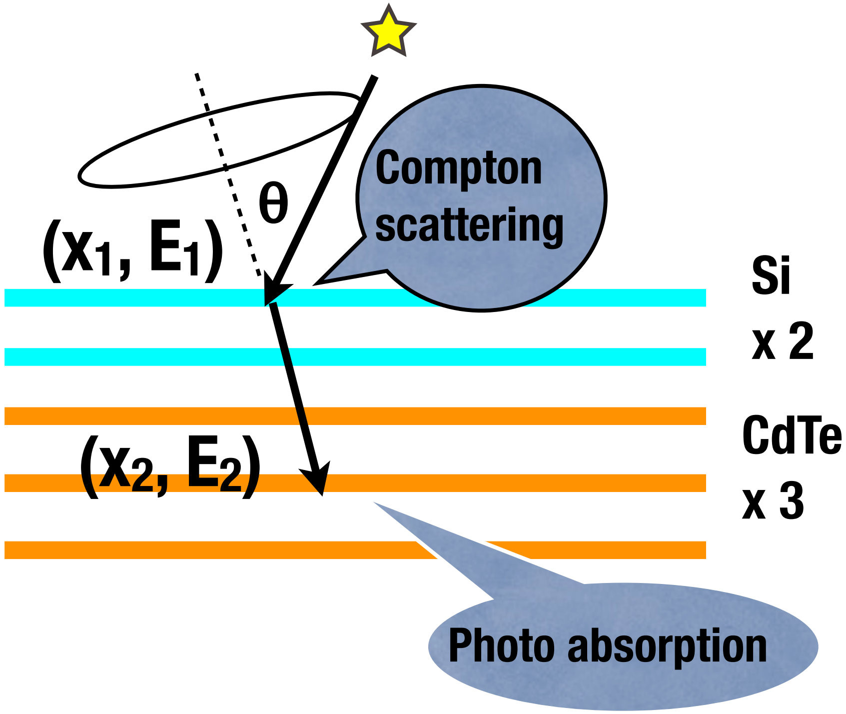
1. Spectral Resolution (need to identify 134-Cs, 137-Cs : ~3%)
2. Image (Larger FOV is better)
3. Angular Resolution (a few degrees)
4. Efficiency (Shorter exposure is better)
5. Portability

6. Availability
(People in Fukushima really need this kind of device, now.)

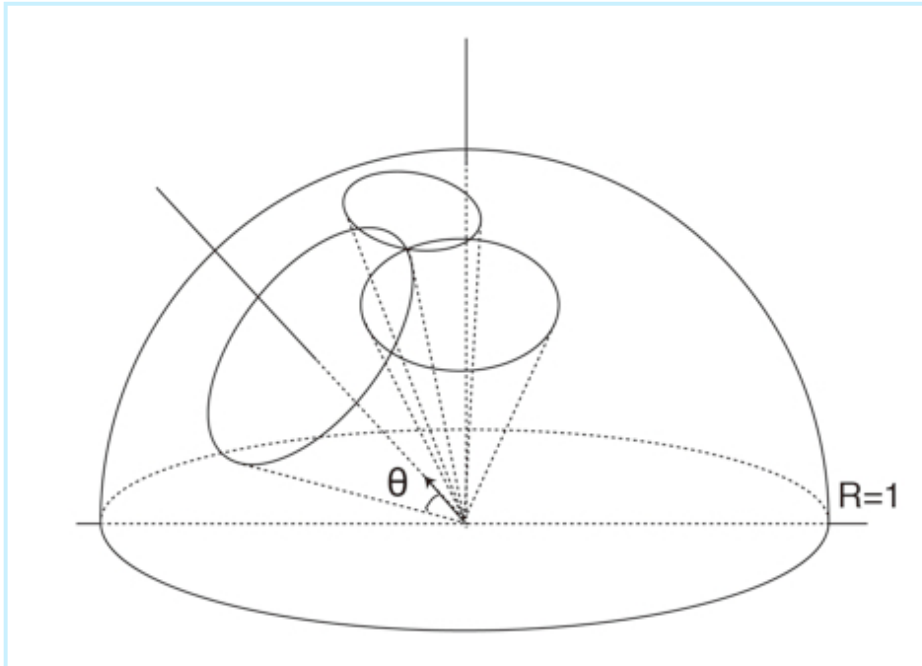
Spectrum taken in Fukushima



5. Our technology - Si/CdTe Compton Camera -



Back-Projection to the Sky



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

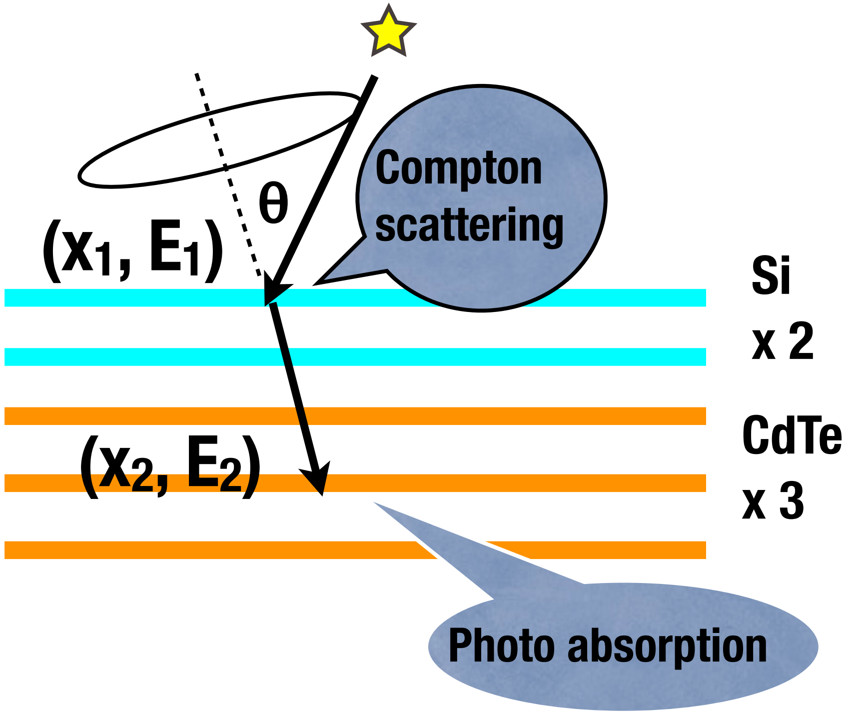
Si and CdTe are the best match to realize semiconductor based Compton Camera (Si/CdTe Compton Camera)

Si : Good scatterer←High $\sigma_{Compton}/\sigma_{PhotoAbs}$ Ratio

CdTe : Good absorber←High stopping power.

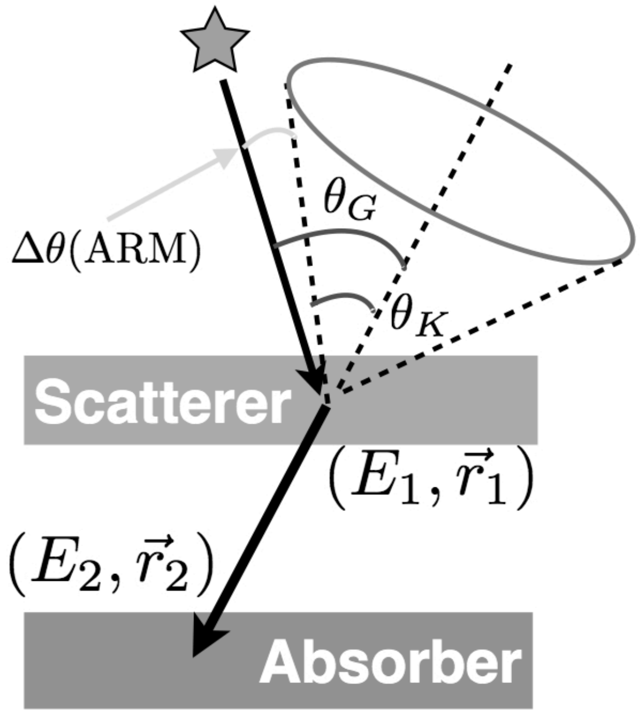
(Takahashi et al. 2001 ,2002, Watanabe et al. 2005, Takeda et al. 2012)

5. Our technology - Si/CdTe Compton Camera -



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

Angular Resolution (ARM)

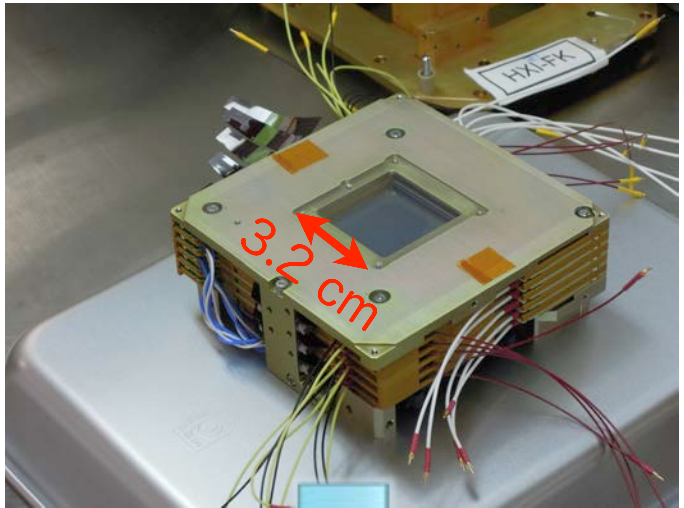


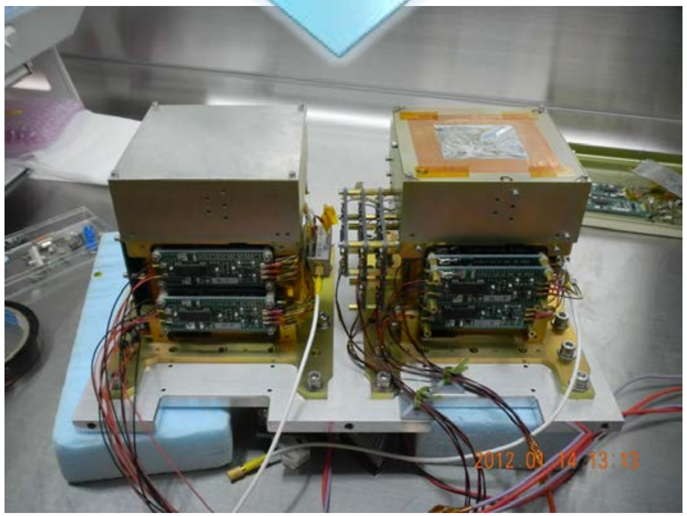
Si and CdTe are the best match to realize semiconductor based Compton Camera (Si/CdTe Compton Camera)

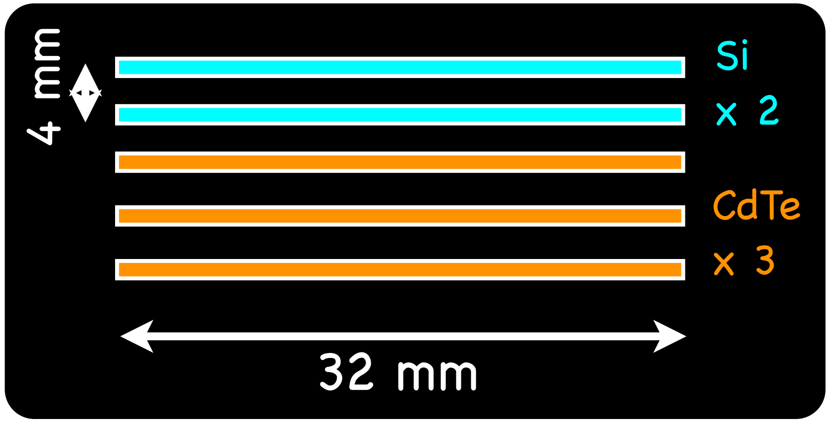
(Takahashi et al. 2001 ,2002, Watanabe et al. 2005, Takeda et al. 2012)

Si : Good scatterer←Low Doppler Effect (Low Z)

5. Our technology - Si/CdTe Compton Camera -





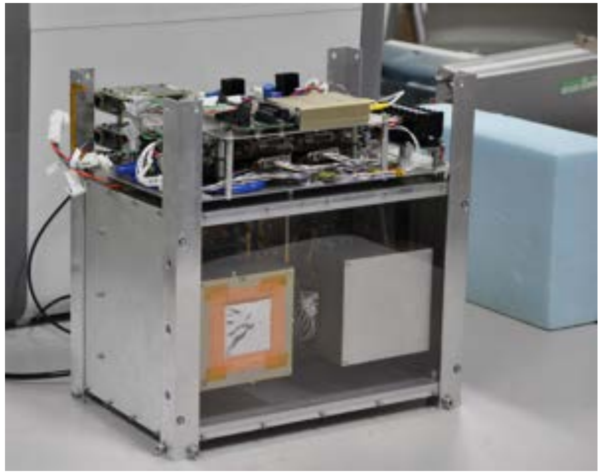


0.5 mm thick

0.7 mm thick

Large FOV (180x180 deg)
10 times larger than existing gamma cameras

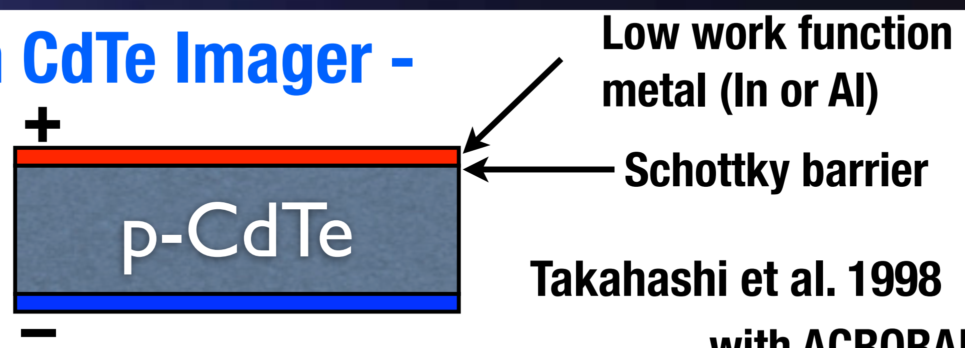
Good Energy resolution
(2.2 % @ 662 keV)



5. Our technology - Si/CdTe Compton Camera -

Key Technology - High Resolution CdTe Imager -

1. Thin device (0.5 – 2.0 mm)
2. Schottky diode
3. Guard ring

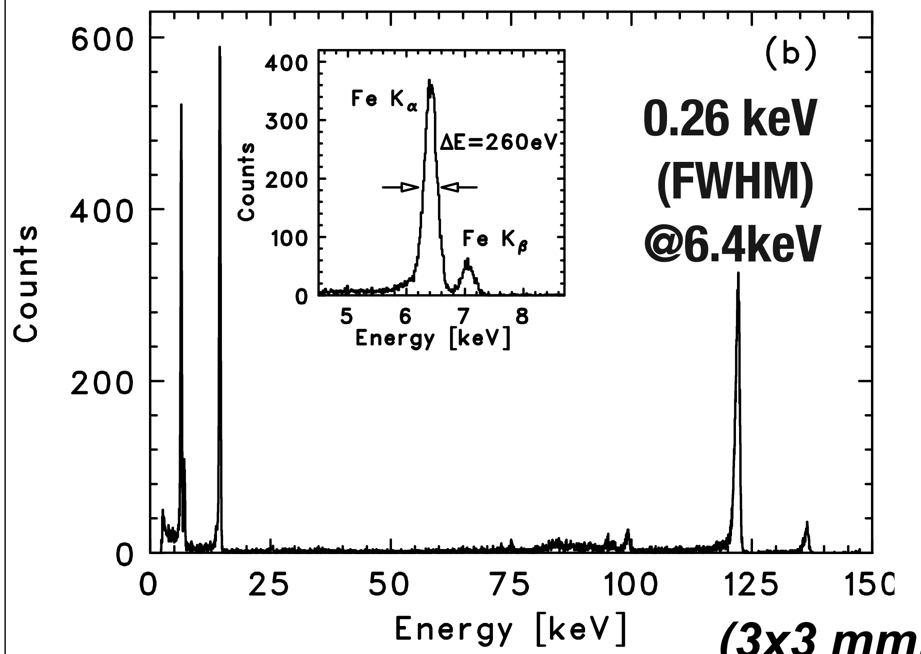


Takahashi et al. 1998 with ACRORAD

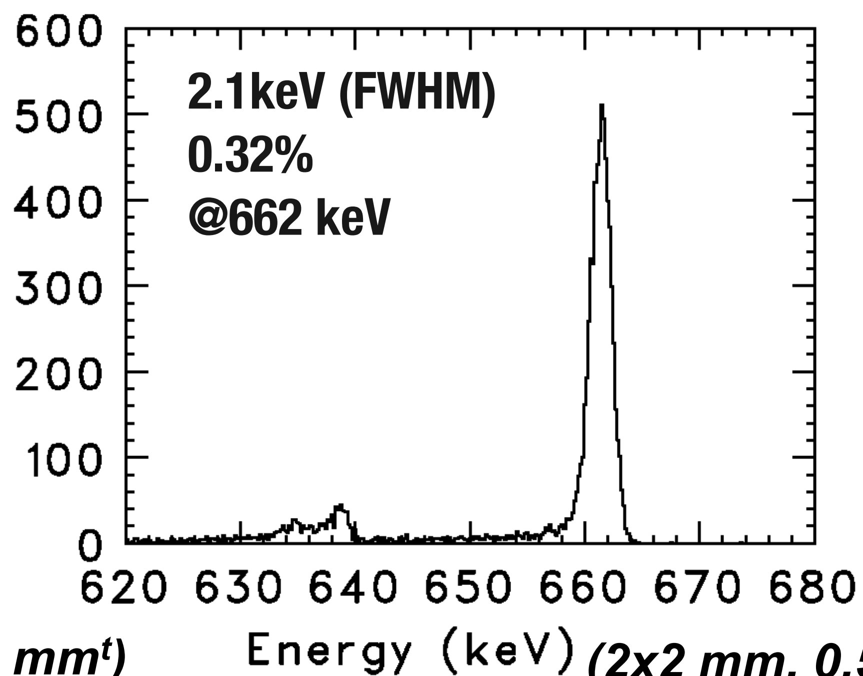
- Extremely low leakage current
- High bias voltage

→ Full charge collection (NO TAIL)

Best spectra we presented 10 years ago.



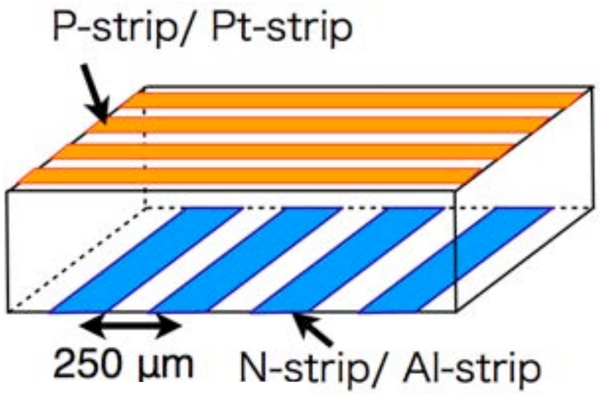
(3x3 mm, 1 mm^t)



(2x2 mm, 0.5 mm^t)

5. Our technology - Si/CdTe Compton Camera -

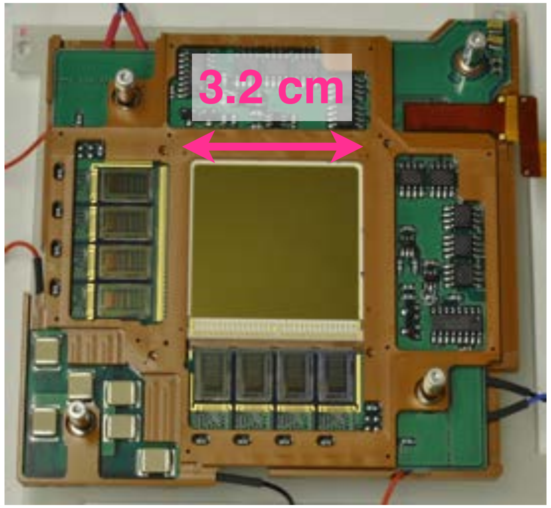
- High energy/position resolution & high uniformity are quite important.

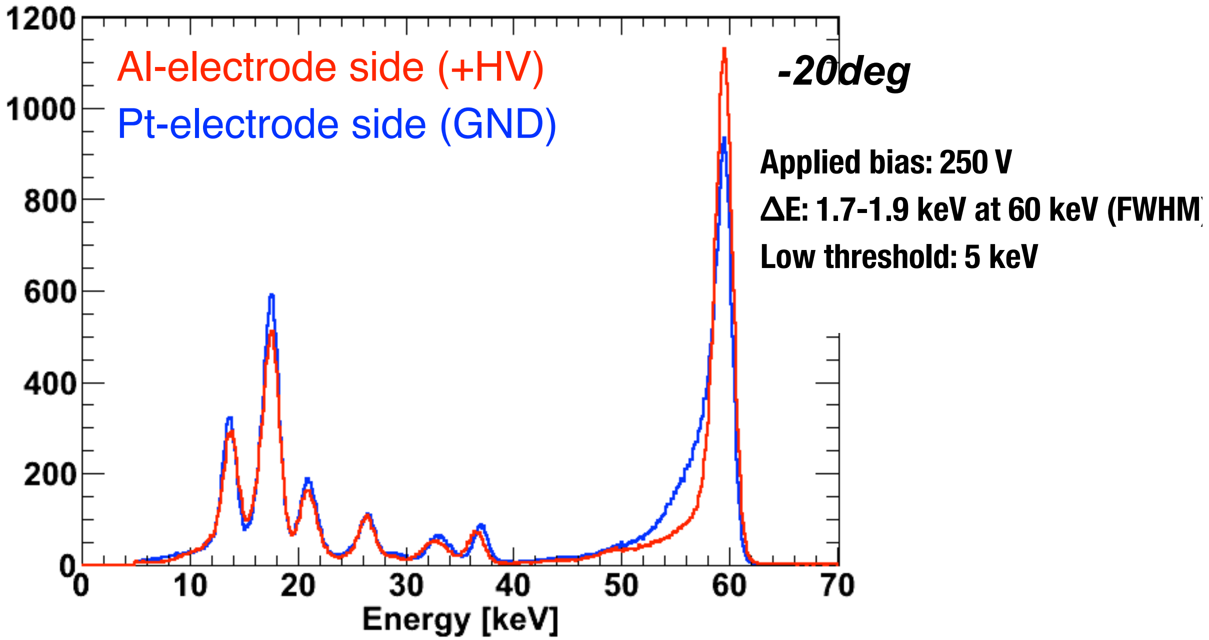


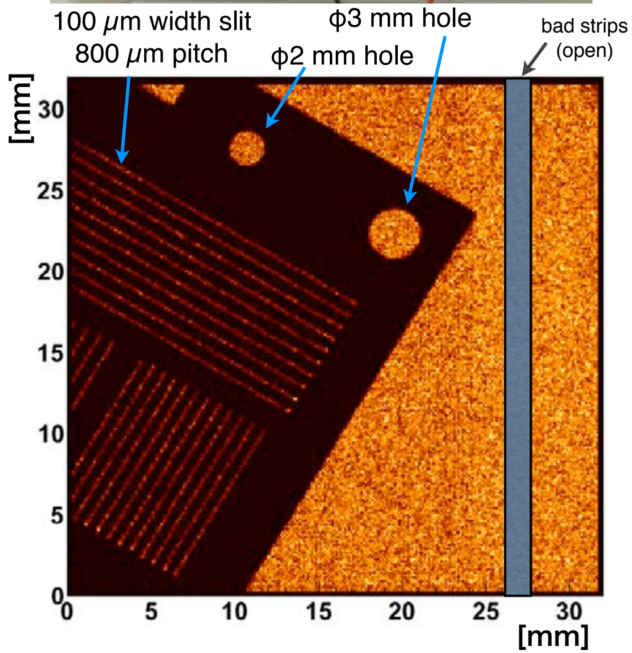
250 micron pitch strips for both side

Al-strip (+)
(Schottky barrier)

2 x 128 = 256 channels
(<<128*128=16,384)



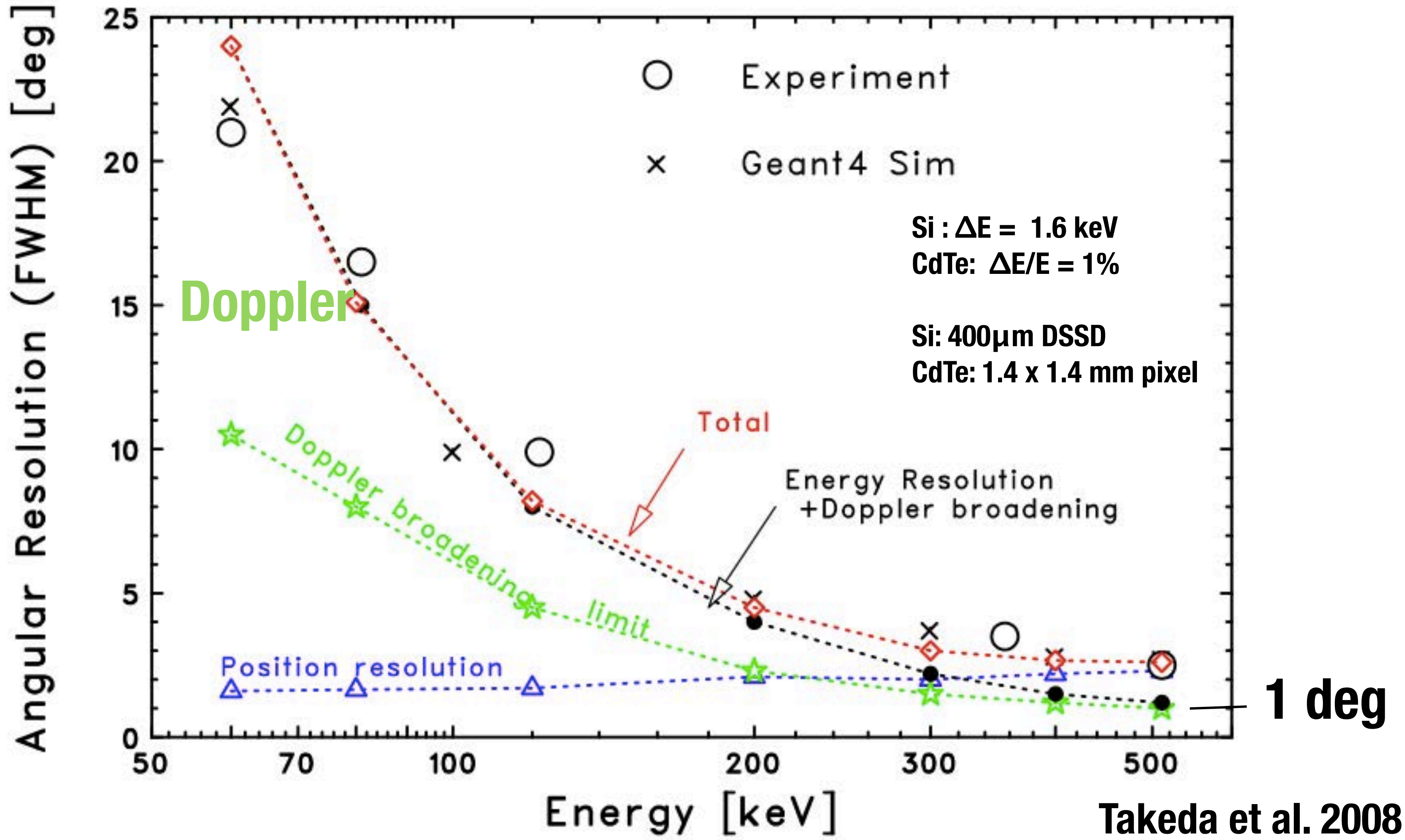




Watanabe et al., 2011

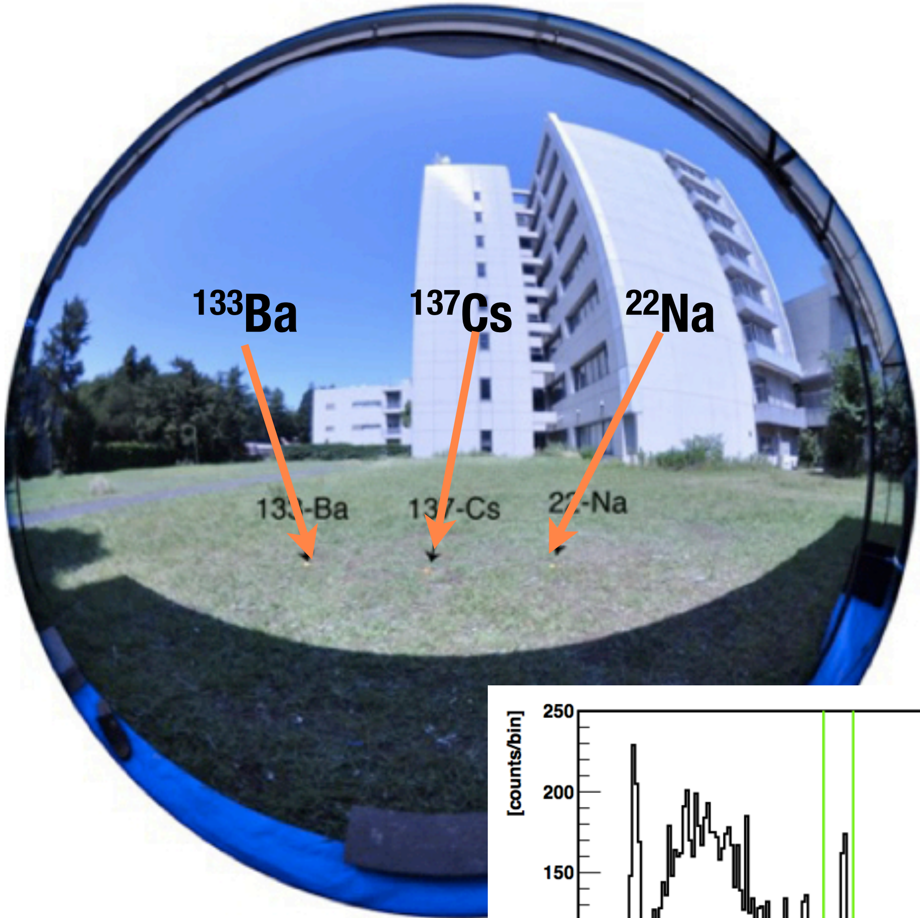
6. Angular Resolution of a Si/CdTe Compton Camera

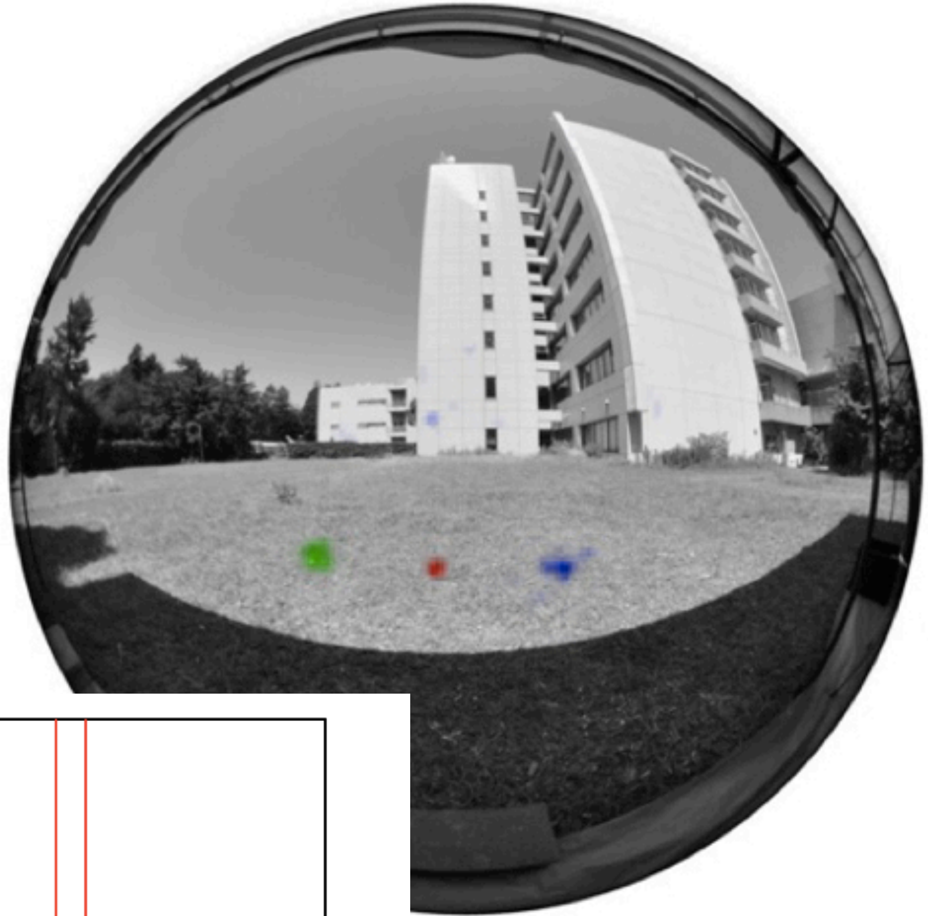
Doppler effect in Si limits the angular resolution

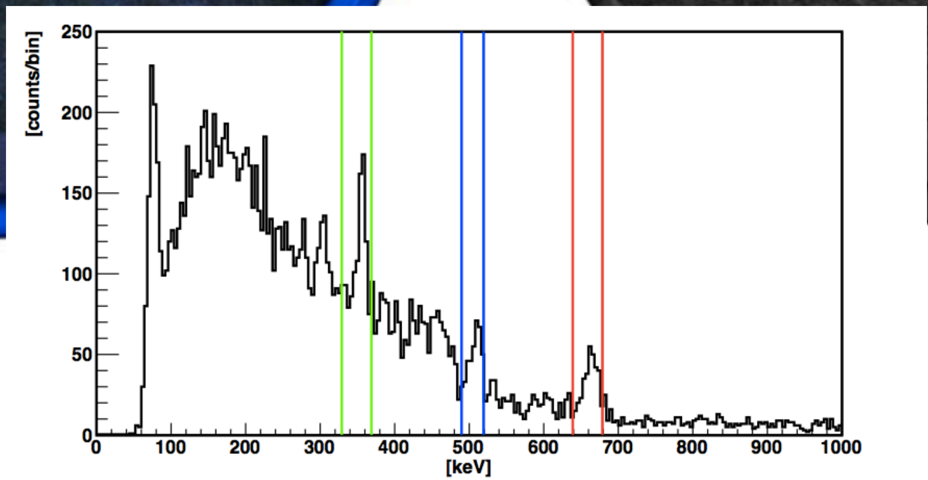


Takeda et al. 2008

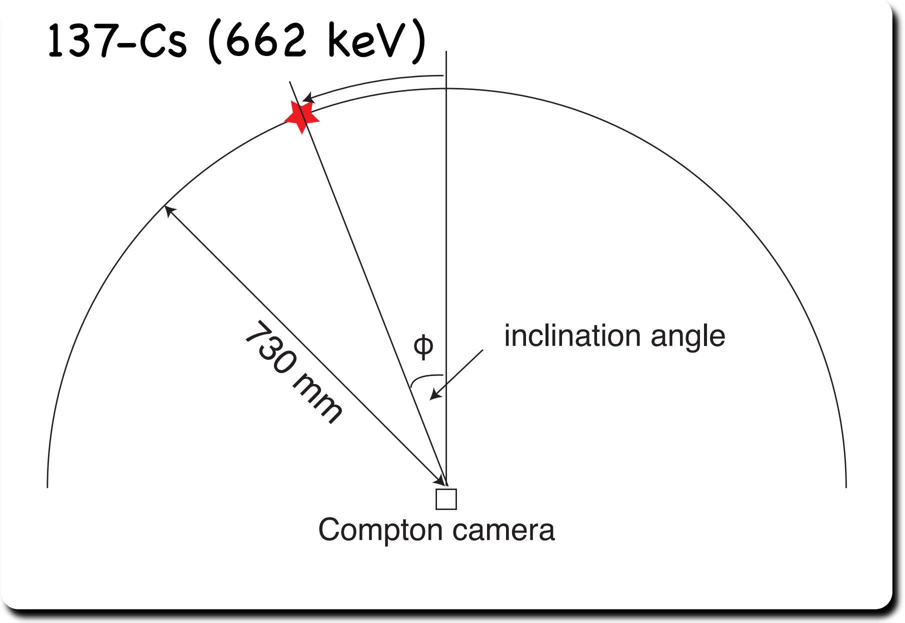
7. Performance of the first prototype

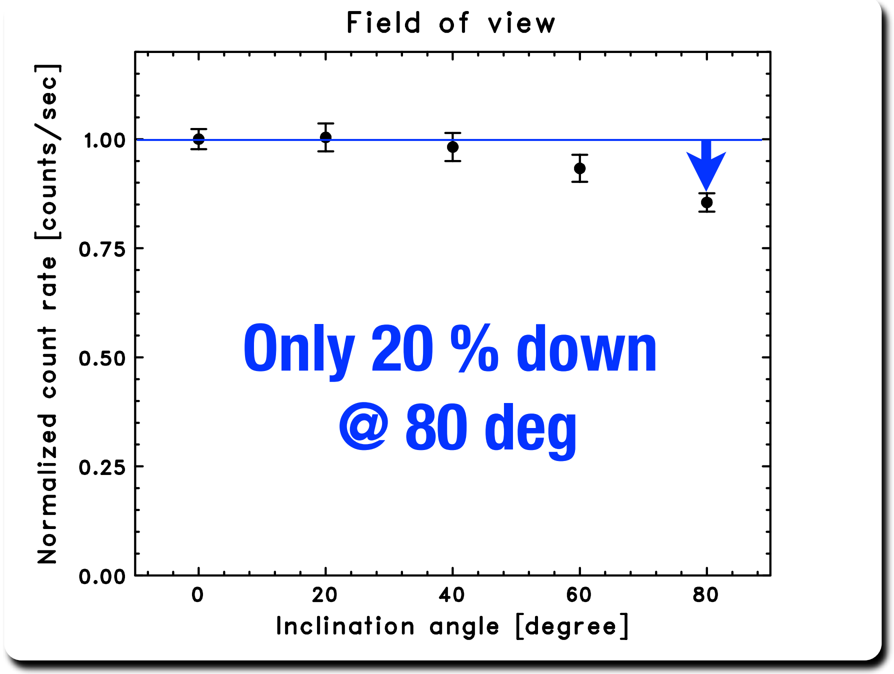




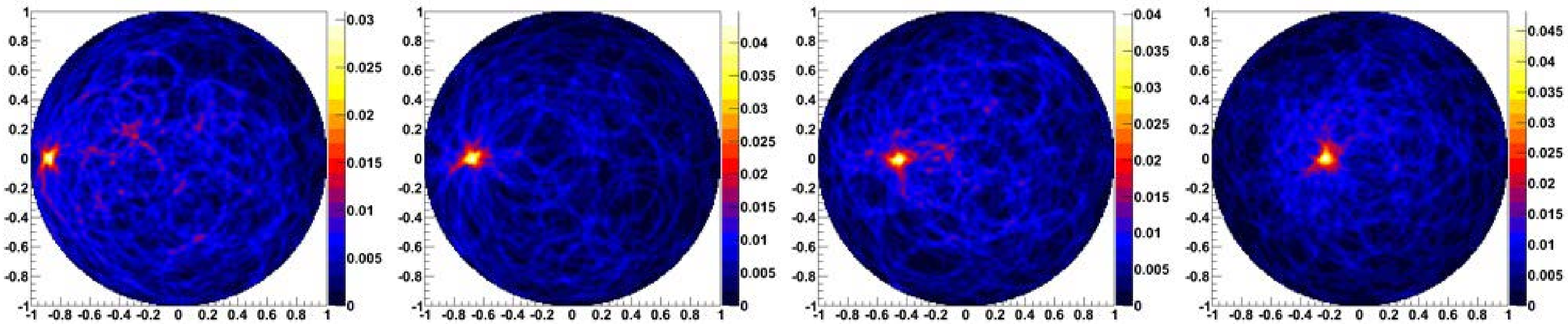


7. Performance of the first prototype





Φ = 80 deg　Φ = 60 deg　Φ = 40 deg　Φ = 20 deg

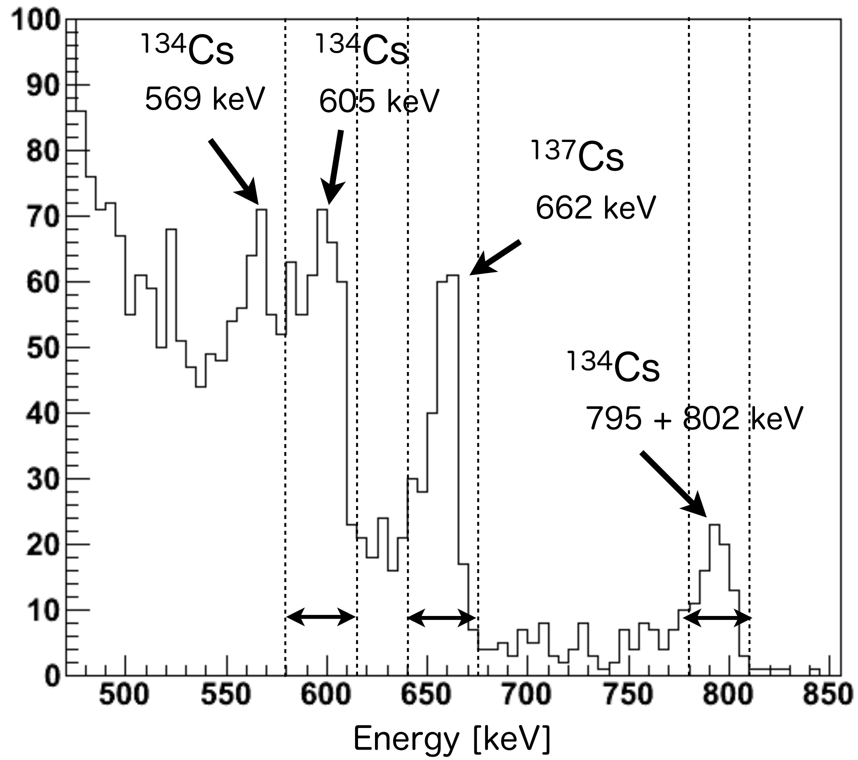


Large FOV of ~2π str., Angular resolution 3.8 deg

Takeda et al. (2012)

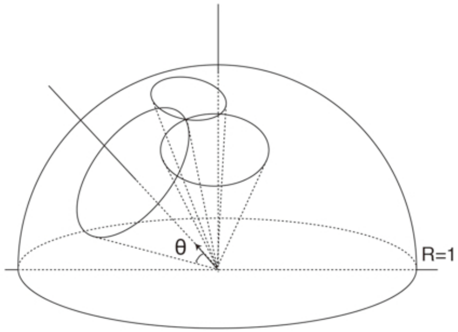
Si/CdTe Compton Camera went to Fukushima.

Optical image taken with a fish-eye lens



Select lines, directly emitted from Cs, to avoid scattered component

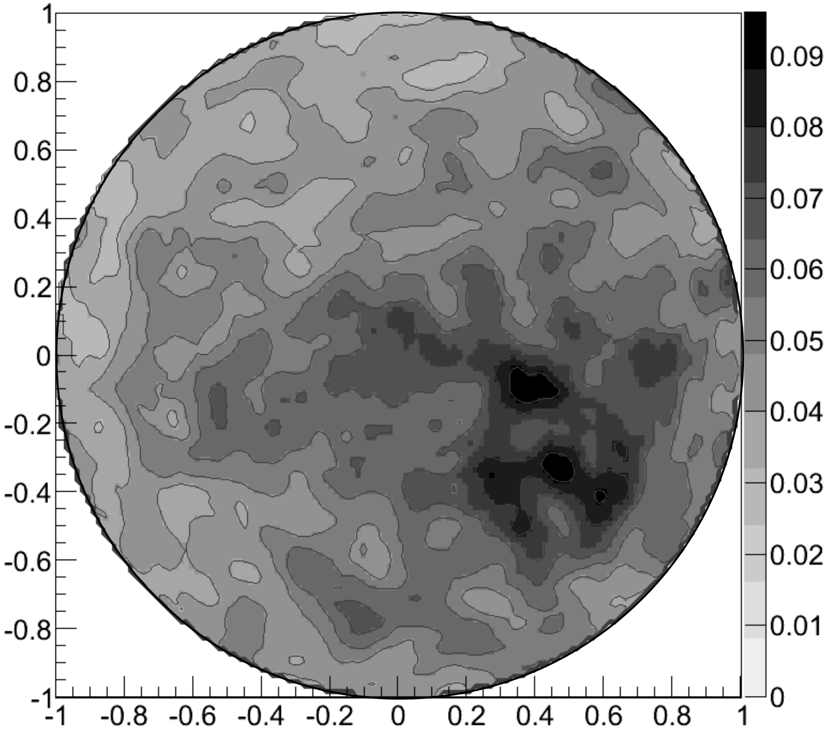
8. Demonstration in Fukushima - Part 1-



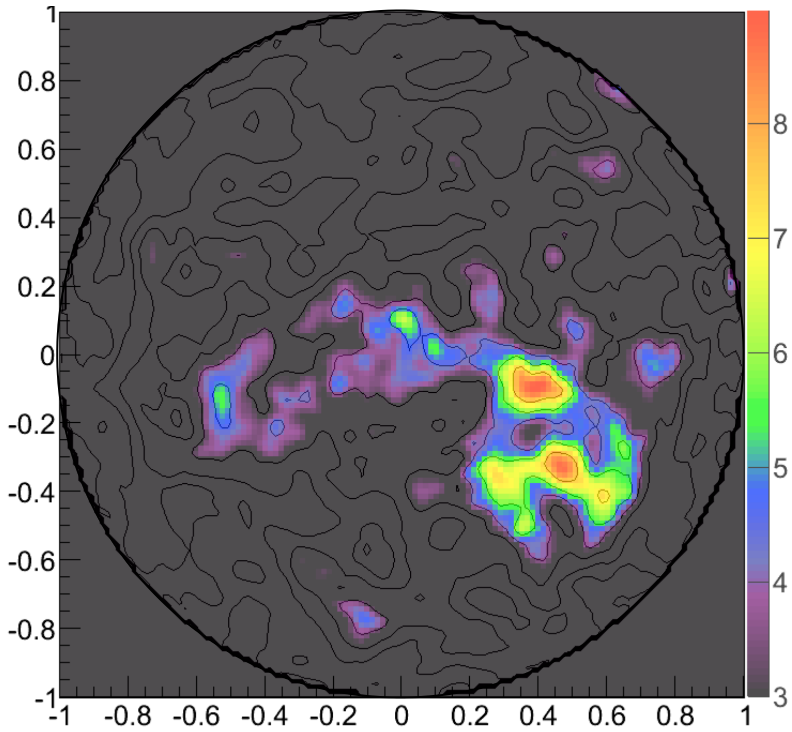
Contour on the Backprojection Image

An image shot by the Ultra-Wide-Angle Compton Camera showing the intensity (flux) distribution of gamma rays of 605, 662, 796, and 802 keV directly emitted from Cesium-134 and 137. Red is high intensity while blue is low.

Intensity



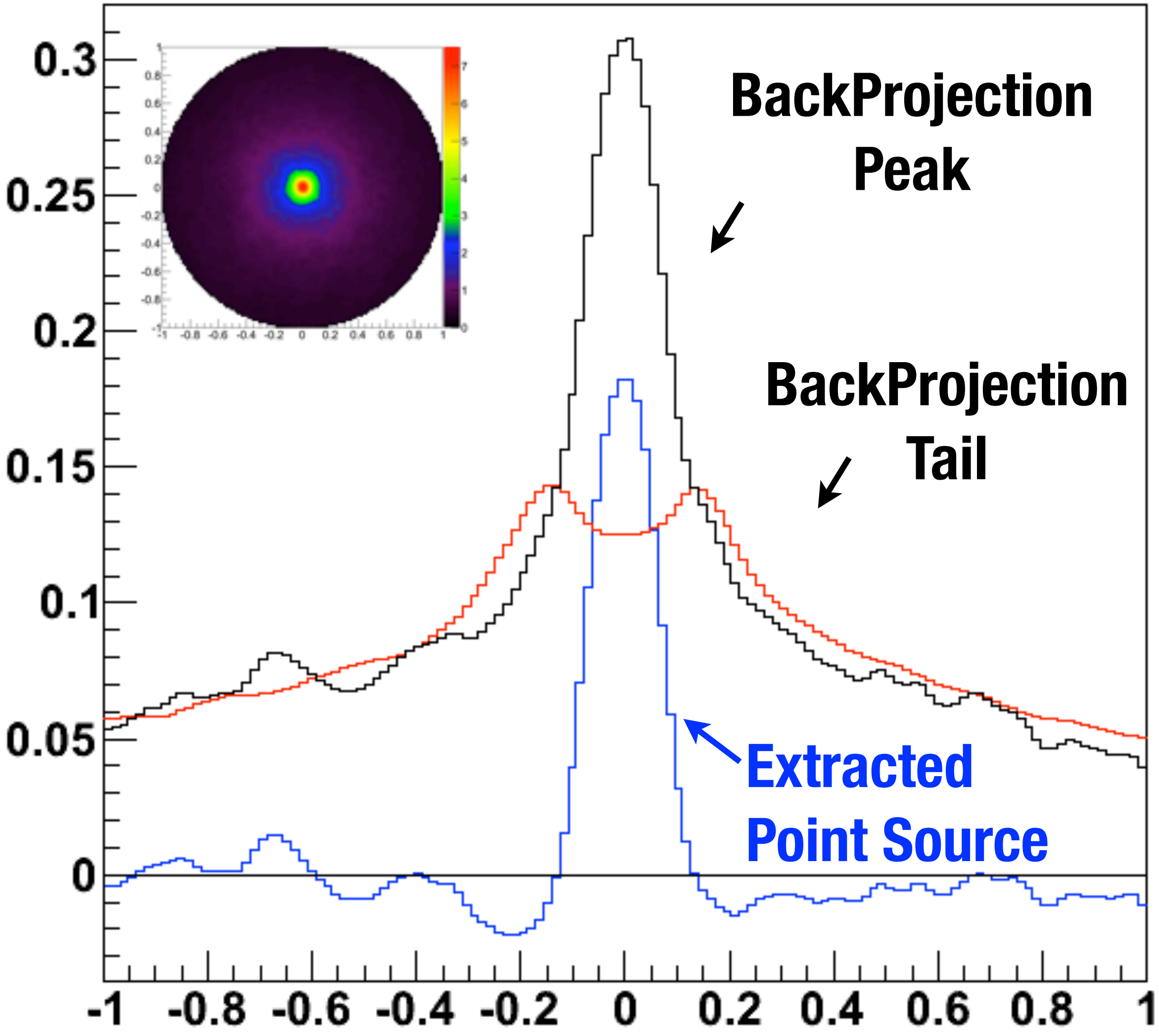
Significance



3 sigma

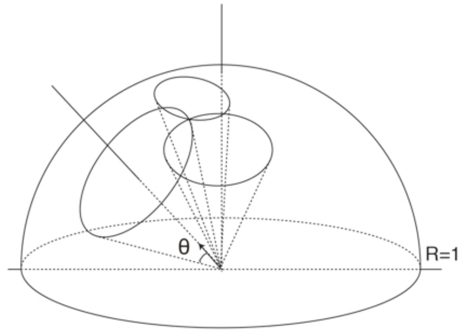
8. Demonstration in Fukushima - Part 1-

Point Spread Function for a point source



Takeda et al. (2013)

8. Demonstration in Fukushima - Part 1-

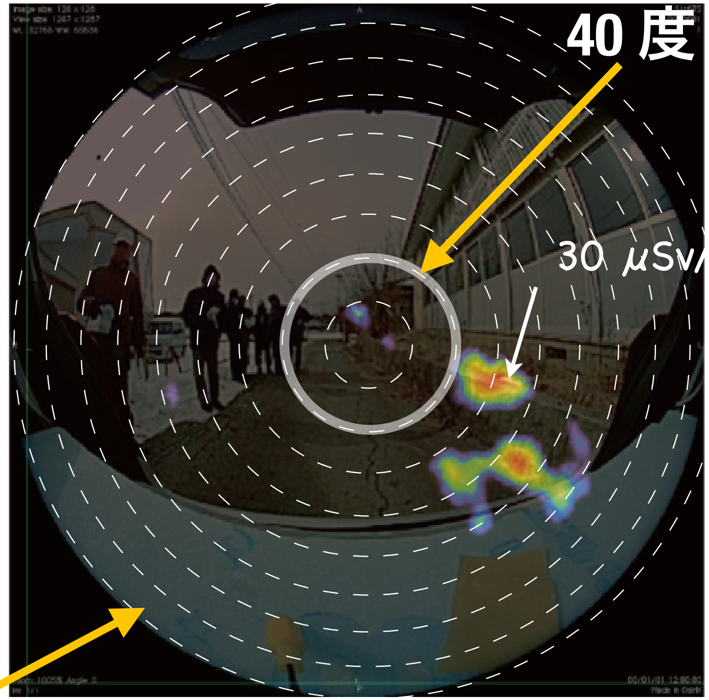


Contour on
the Back projection
Image

Intensity

An image shot by the Ultra-Wide-Angle Compton Camera showing the intensity (flux) distribution of gamma rays of 605, 662, 796, and 802 keV directly emitted from Cesium-134 and 137. Red is high intensity while blue is low.

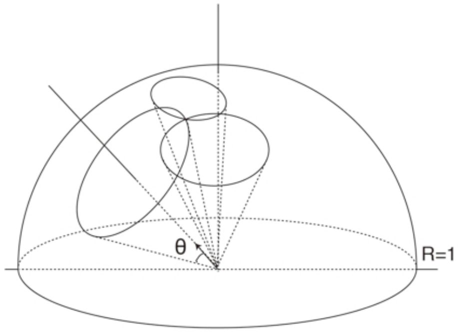
Significance



180 deg

(back ground ～3 μSv/h)

8. Demonstration in Fukushima - Part 1-



Contour on
the Backprojection
Image

Intensity

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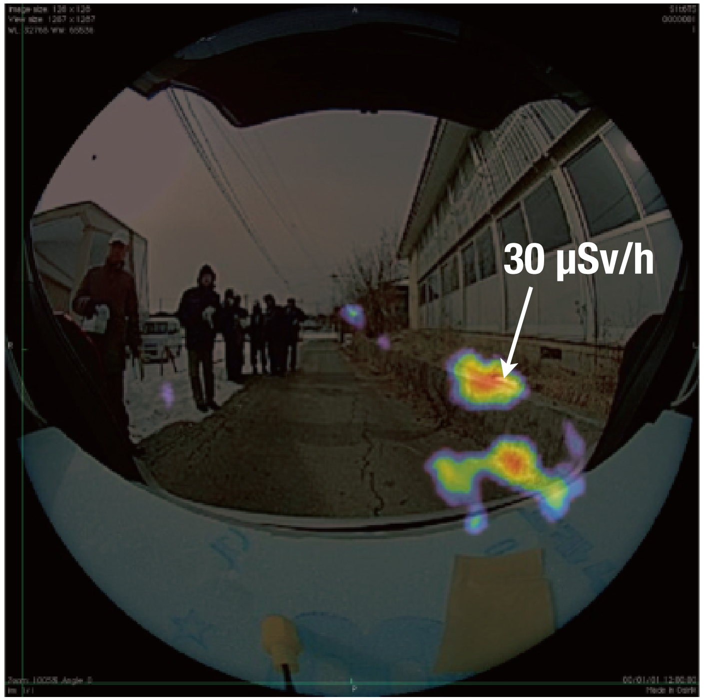
Significance



9. Further Improvements

✤ Higher sensitivity (Shorter Exposure)

✤ Portability

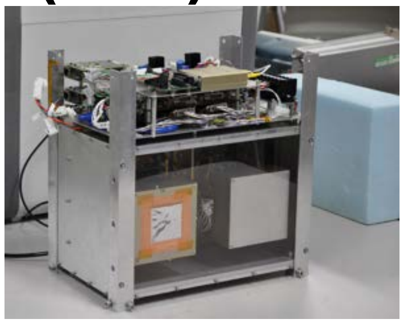
• 0.6 mm thick Si Pixel + 0.75 mm thick CdTe Pixel

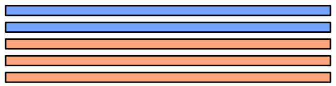
• 3.2 by 3.2 mm pixel size for Si and CdTe

Use the design of
the ASTRO-H SGD Compton Camera

see Watanabe's talk
in this session

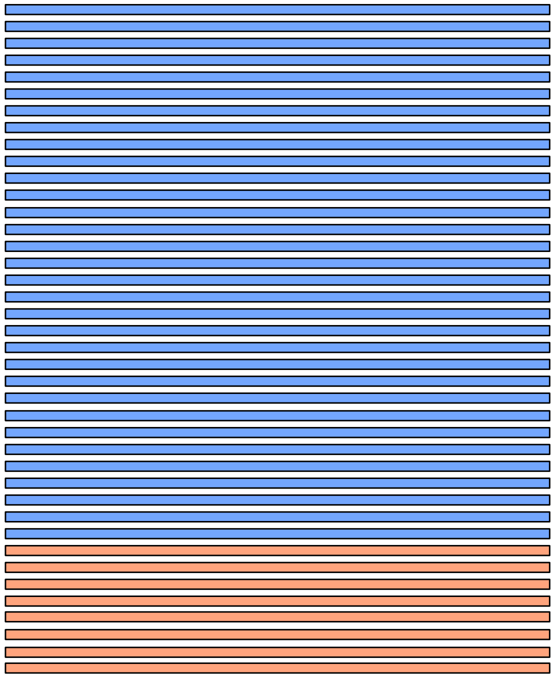
First
Demonstration
Type (2011)





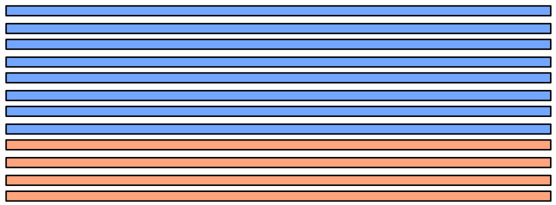
x2

30 times higher sensitivity



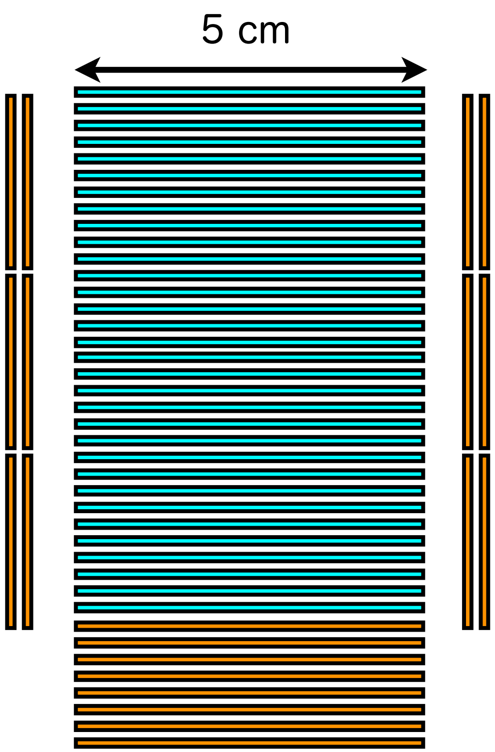
ASTRO-Hに搭載される軟ガンマ線検出器

10 times higher sensitivity
(reasonable price))

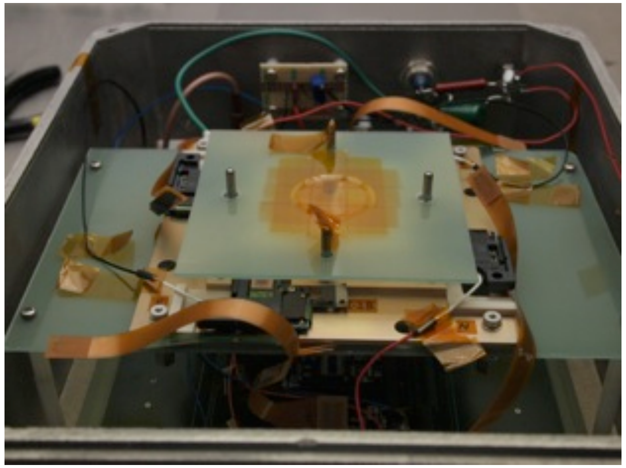


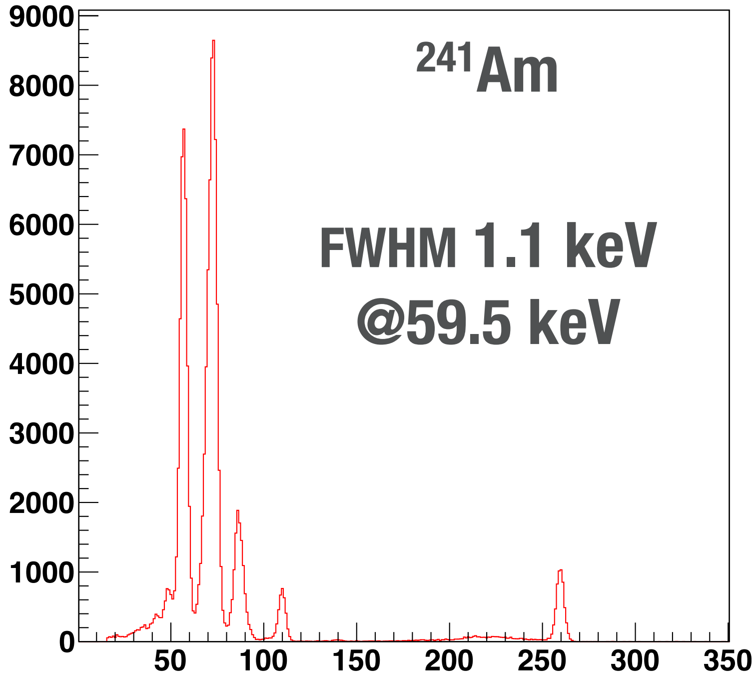
Supported by the JST Program
"development of systems and technology for advanced measurement and analysis" (2012-)

9. Further Improvements (Same design as the ASTRO-H SGD Compton Camera)

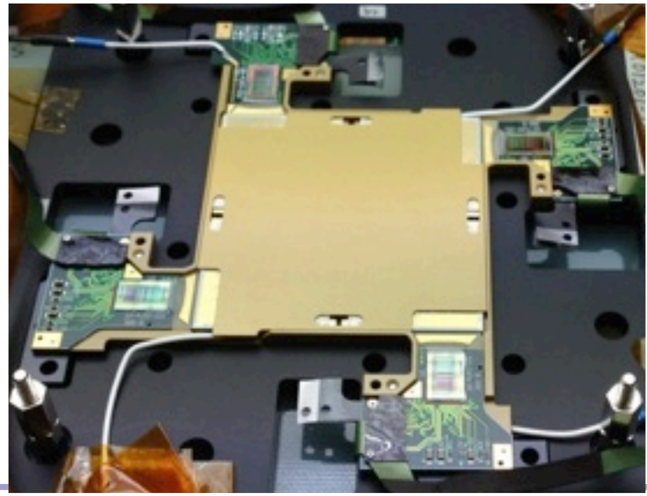


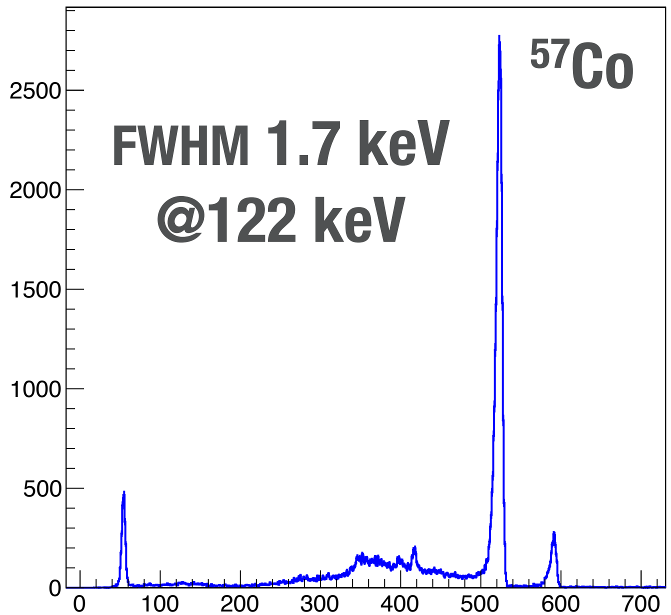
Si Pixel (Pad) detector





CdTe Pixel (Pad) detector

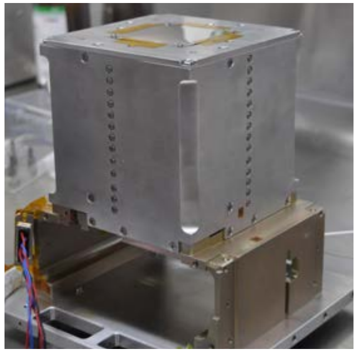




- 32 layers of Si (~2 cm in total)
- 8 layers of CdTe
- 2 layers of side CdTe

see Watanabe's talk in this session

10. Vast Improvements (Same design as the ASTRO-H SGD Compton Camera)

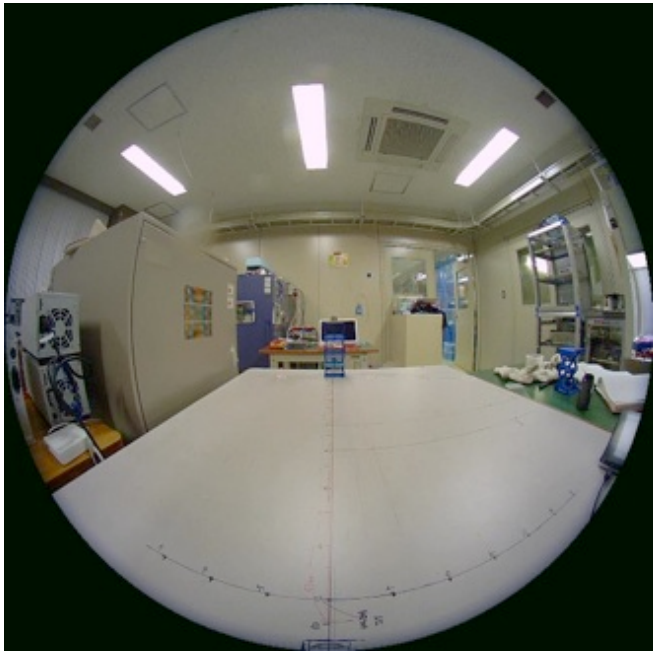


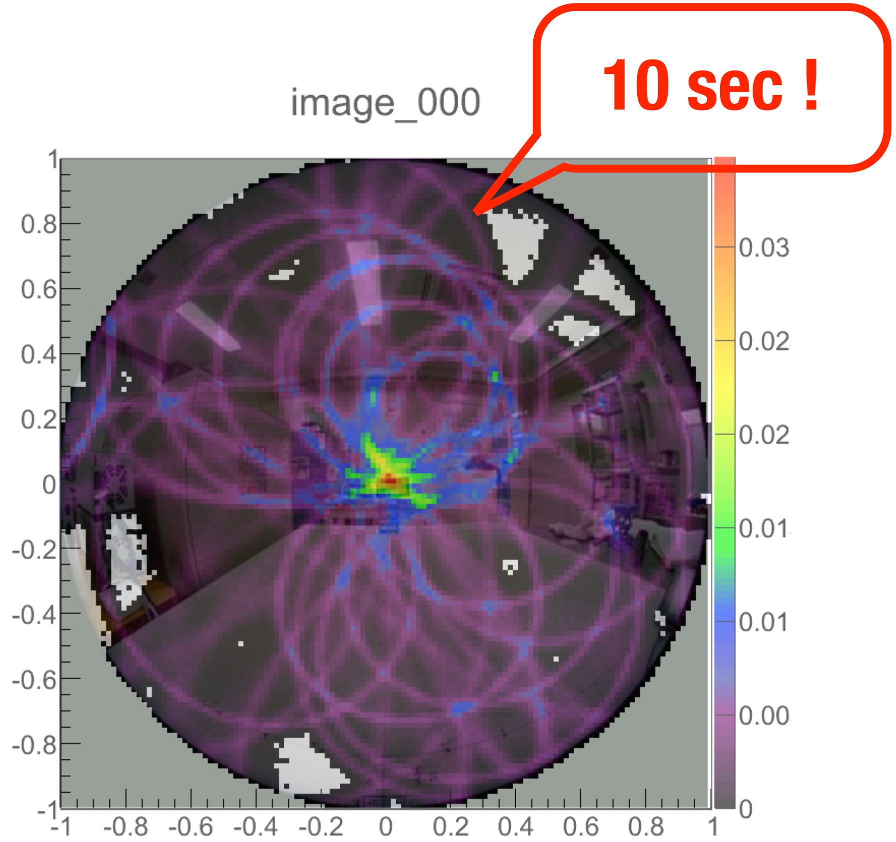
10 cm

Still very comact

※First Prototype (2012) took 5 min.

137-Cs, 2.7 MBq @ 1 m

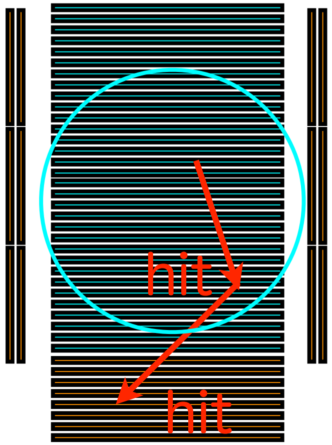




Efficiency 0.03 cps/MBq @ 137-Cs, 1m

→1.1 cps/MBq @ 137-Cs, 1m

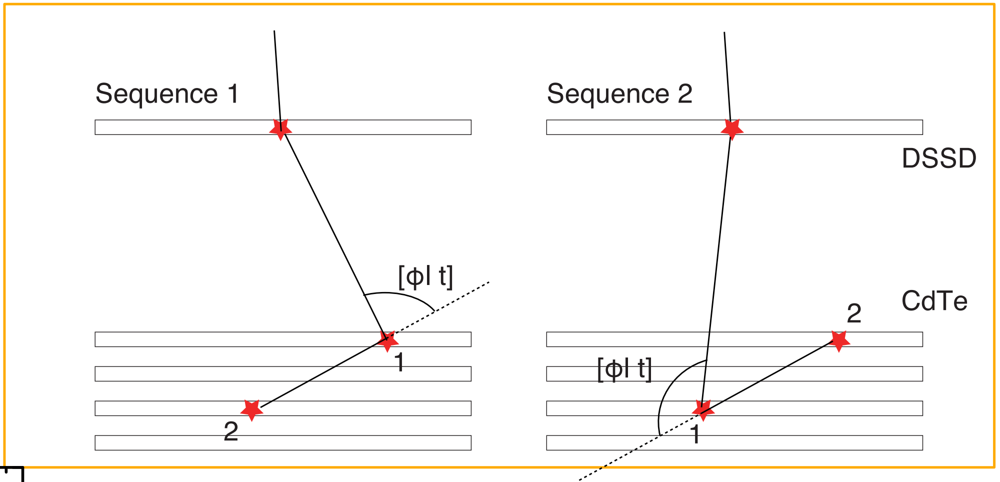
10. Vast Improvements (ASTRO-H SGD type)



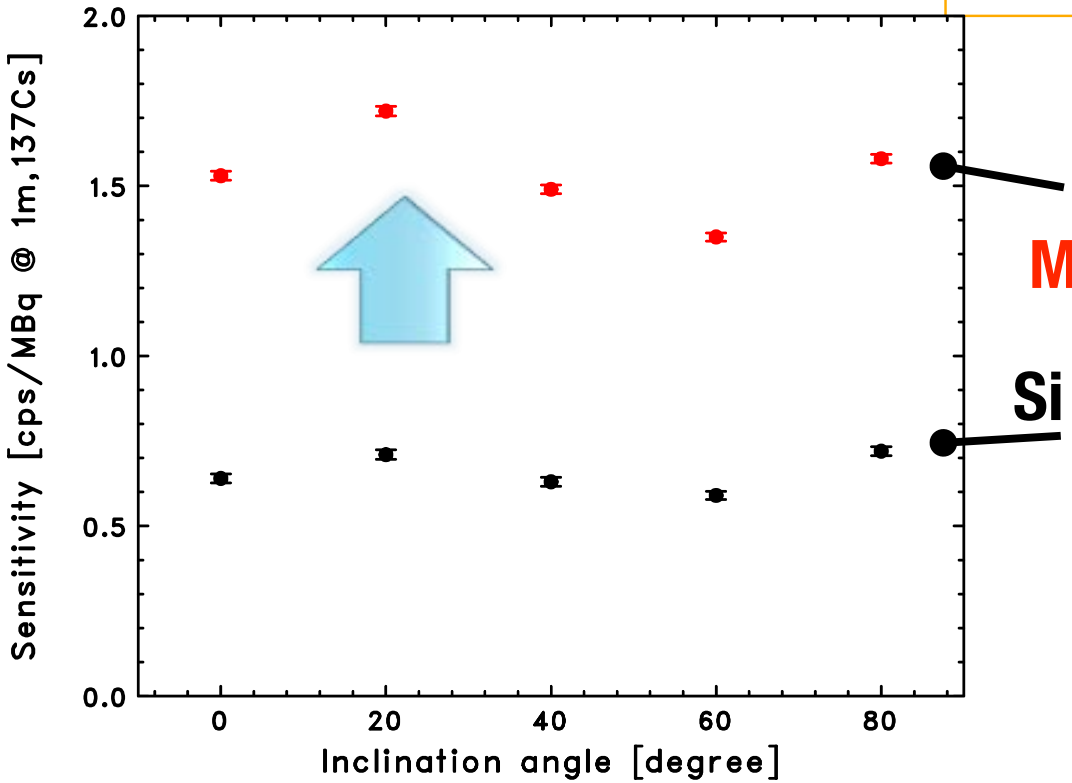
We can learn a lot from the real detector

Ex. Scattering Sequences

Multi Hit Analysis



Field of view



Multi Hit Analysis Included

Si (1hit) + CdTe (1hit) event only

Ichinohe et al. (2013)

12. ASTROCAM-7000HS (Our technology goes to the market)

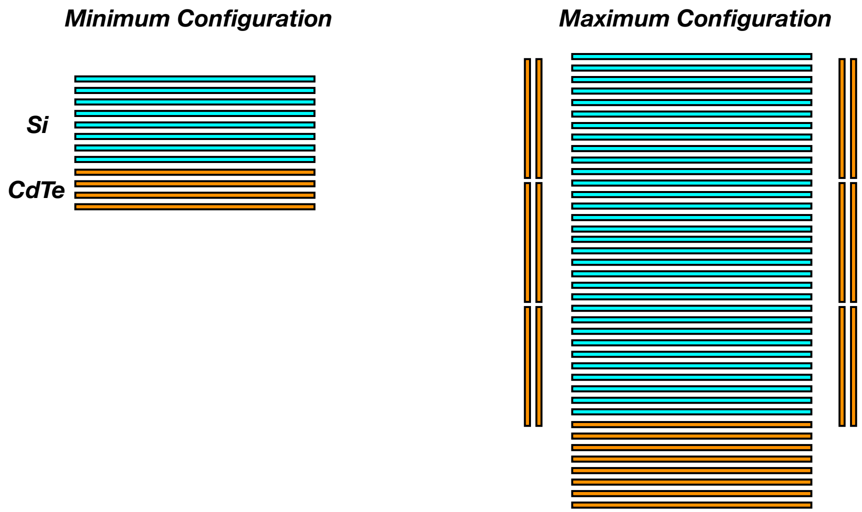
Radiation Visualization Camera

MITSUBISHI HEAVY INDUSTRIES, LTD.
Our Technologies, Your Tomorrow

◆ Specifications

Dimensions	445L x 340W x 235H (mm)
View Angle	**180 degrees (ultra-wide)** <detection efficiency depending on angular positions>
Weight	Approximately 8 ~ 13kg (Camera Unit Only) < depending on specifications>
Power Source	AC100V~240V and Battery
Operating Temperature	0 to 40 degrees Celsius
Storage Temperature	0 to 50 degrees Celsius
Operating Humidity	35 to 80% (Non-condensing)
Auxiliaries	Camera Controller Box, Laptop PC, Visualization Software

All specifications may be changed without notice

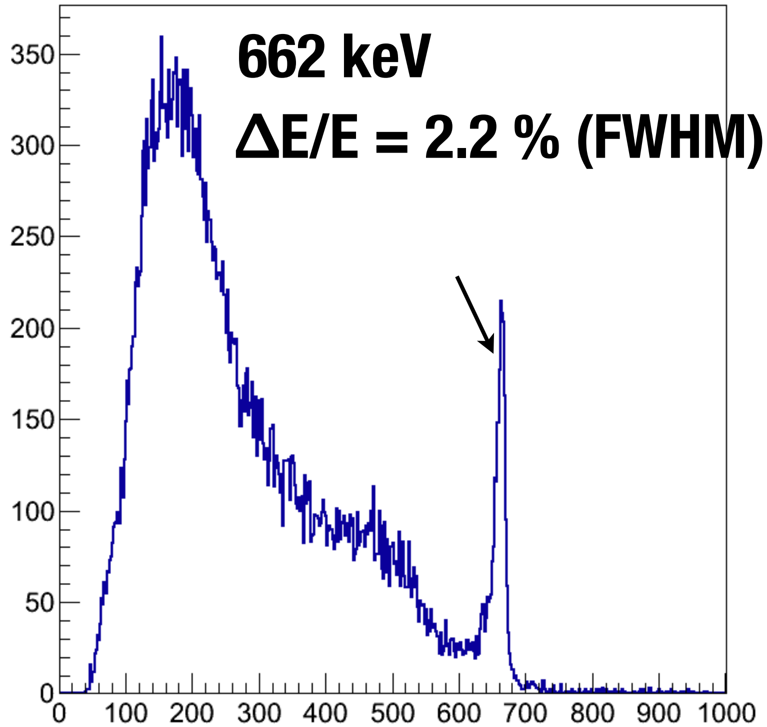


12. ASTROCAM-7000HS (Our technology goes to the market)

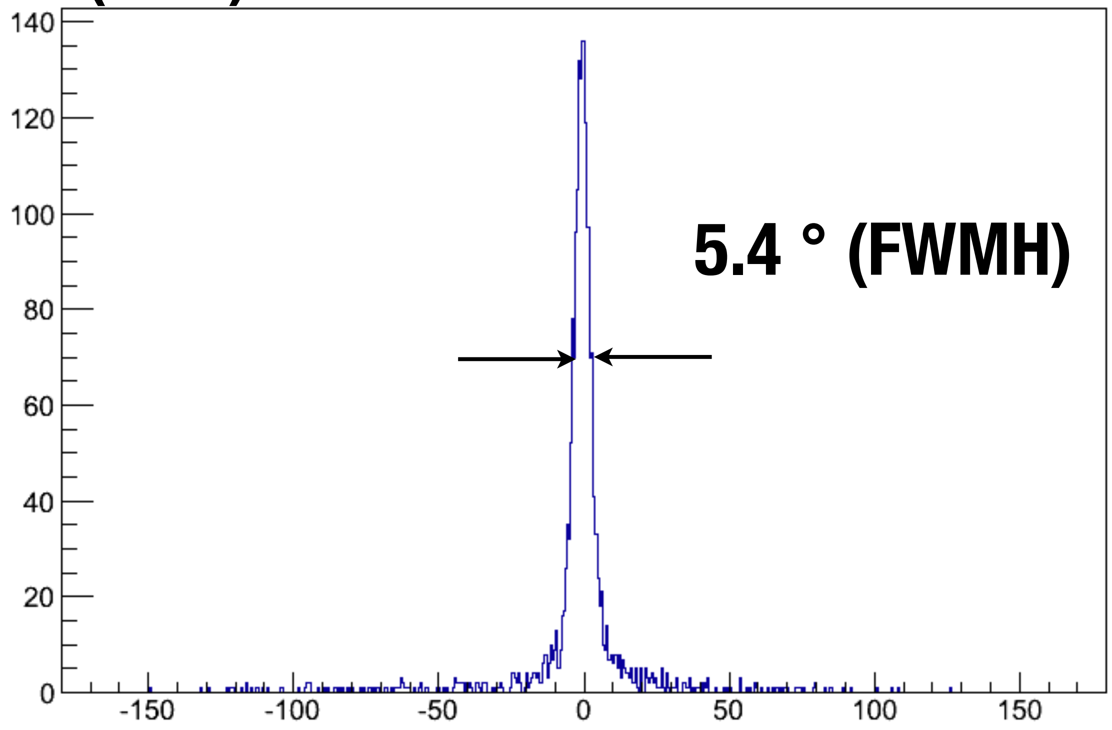
12. ASTROCAM-7000HS (Our technology goes to the market)

Performance

137-Cs



Angular Resolution (ARM)



Pixel size (~3 mm) is optimized to get required angular resolution

14. Summary

1) **Space science missions require cutting edge technology due to its high scientific requirements (e.g. X-ray Satellite ASTRO-H)**

2) **We are now able to access all the technologies which are necessary to make the next-generation CdTe-based gamma-ray imager (ASTRO-H Hard X-ray Imager & Soft Gamma-ray Compton Camera)**

3) **Si/CdTe Compton camera has been demonstrated in Fukushima as a "Gamma Camera" with high angular resolution (a few degrees at ~600 keV).**
The camera meets the requirements.
3D Imaging is possible by multiple pointing.

4) **Our technology has been transferred to the industry.**
"Ultra-wide angle Compton Camera" is now commercially AVAILABLE.

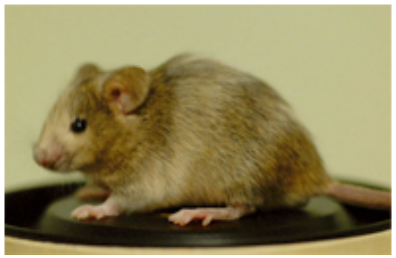
A. Appendix

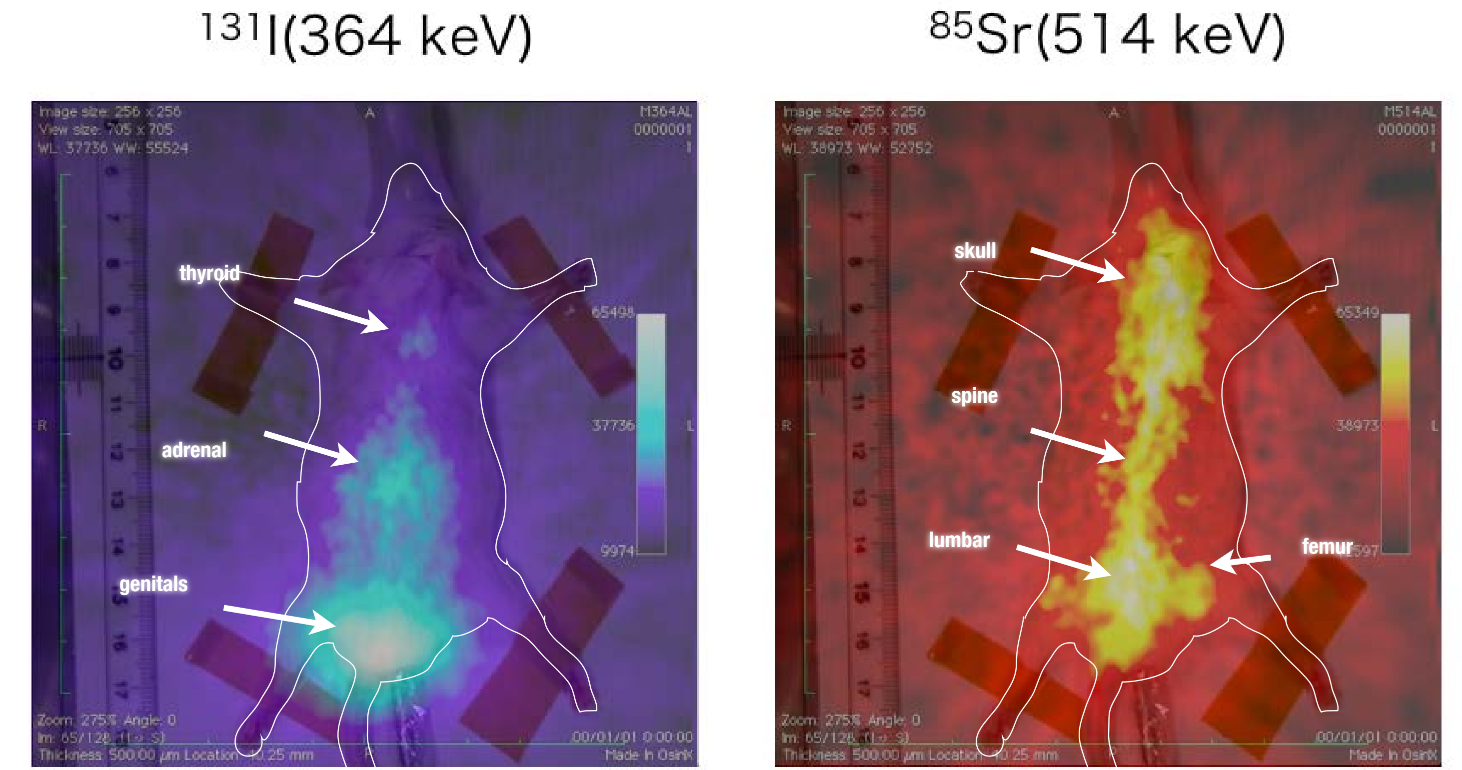
1) Space science mission requires cutting edge technology due to its high Scientific Requirements

2) We are now able to access all the technologies which are necessary to make the next-generation CdTe-based gamma-ray imager (ASTRO-H HXI&SGD)

3) Our Si/CdTe Compton Camera can be applied to various fields. One example is...

4) Still need further efforts to reach the final goal.





See presentation by Takeda, today (MIC 5-7)

Takeda et al. 2011

3D Imaging

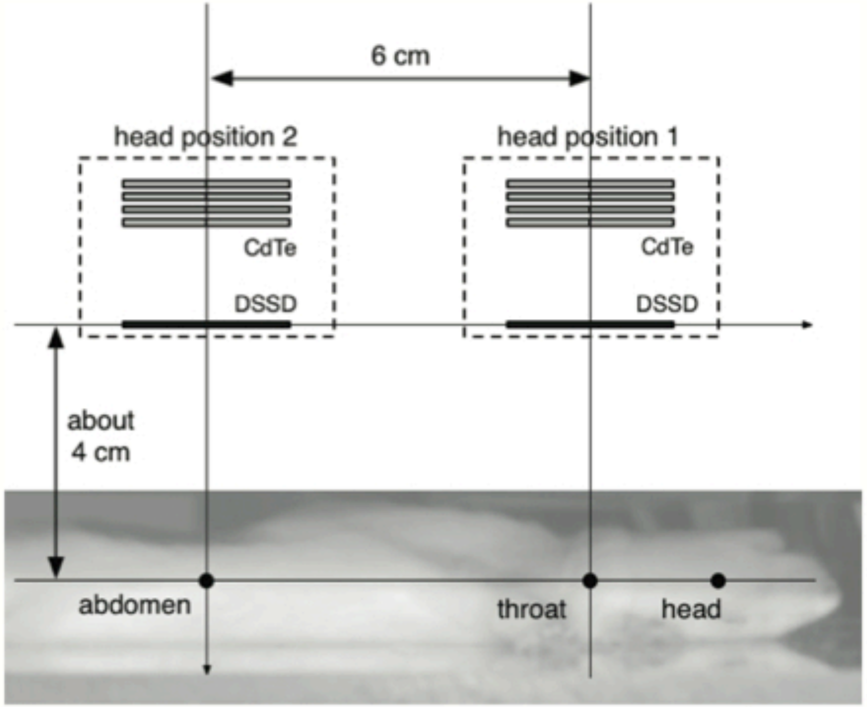


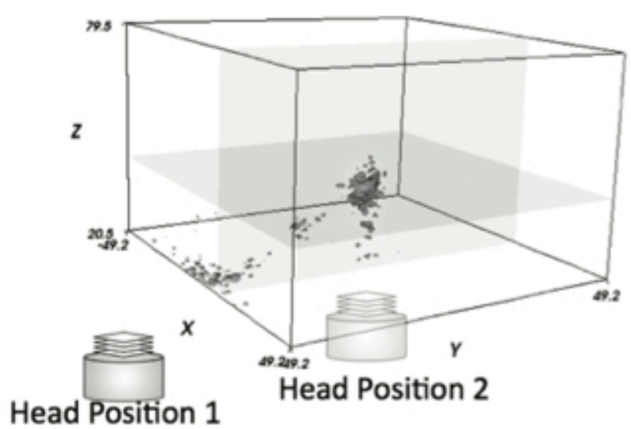
Fig. 3. Relative positions of the camera head against the rat sa

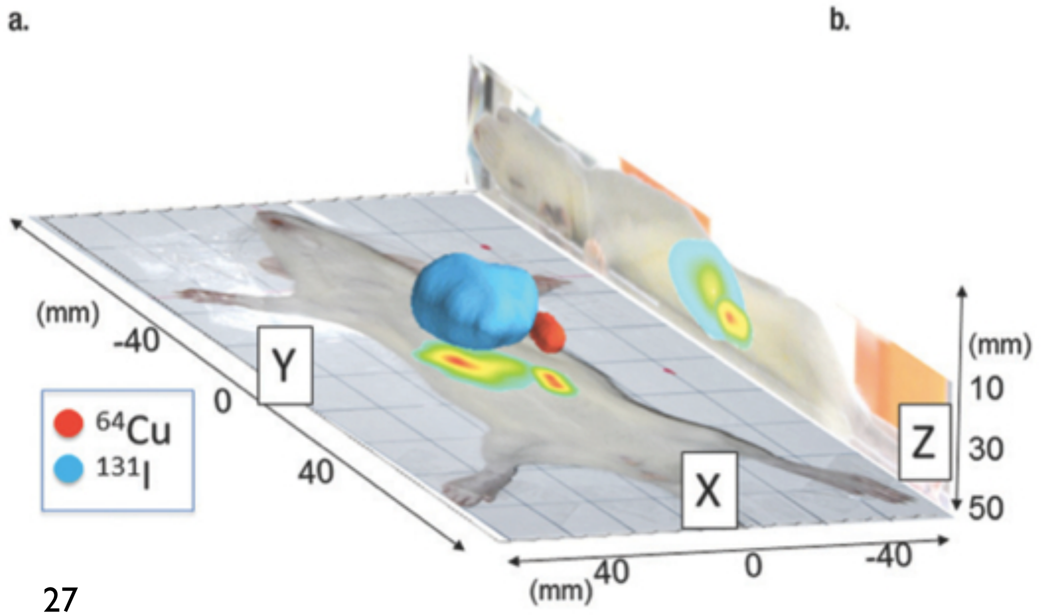
Stereoscopic Observation of Mouse
(ISAS/JAXA, Gunma U.,JAEA)

Yamaguchi et al (2009)

Suzuki et al (2013)

Radiology. 2013 Jun;267(3):941-7.
doi: 10.1148/radiol.13121194. Epub 2013 Feb 15.





NDIP08

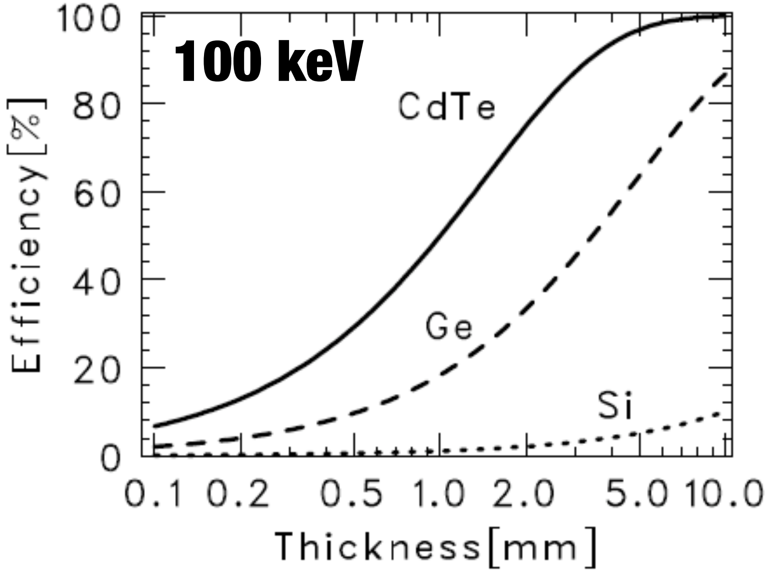
CdTe/CdZnTe seem to be the only candidate *at least, at this moment*

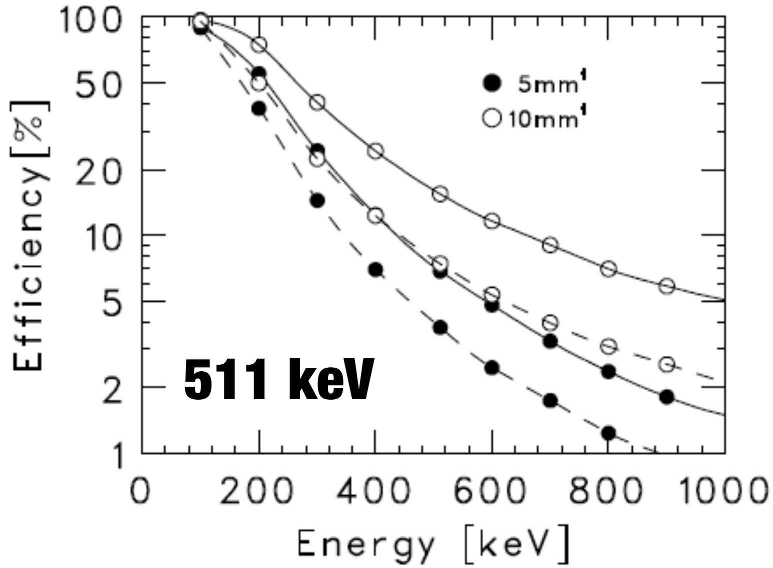
- High Z semiconductor (Z_{Cd} = 48, Z_{Te} = 52), ρ =5.9 g/cm³

- Room Temperature Operation or Cool Environment

Material	Ge (77K)	HgI_2	CdTe	CdZnTe
Atomic number	32	80, 53	48, 52	48, 30, 52
Band gap (eV)	0.74	2.13	1.50	1.57
Energy per e-h pair (eV)	2.97	4.2	4.4	4.6
Fano factor	0.08	0.19	0.11	0.09
μ_e (cm^2/Vs)	40,000	100	1100	1000
μ_h (cm^2/Vs)	40,000	4	100	10
τ_e (s)	10^{-3}	10^{-5}	10^{-6}	10^{-5}
τ_h (s)	10^{-3}	10^{-5}	10^{-6}	10^{-6}

P. Luke (2006)





Takahashi and Watanabe (2000)