High Resolution CdTe detectors and Applications to Gamma-ray Imaging

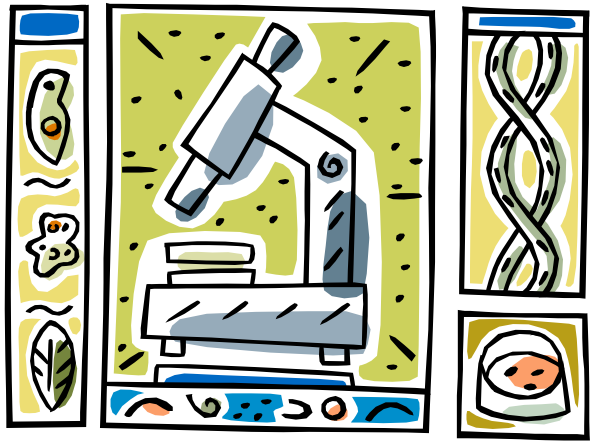
Tadayuki Takahashi

Shin Watanabe, Yuto Ichinohe, Hirokazu Odaka,
Goro Sato, Shin'ichiro Takeda,
Institute of Space and Astronautical Science (ISAS),JAXA
&
Department of Physics, Univ. of Tokyo

Acknowledgement
ACRORAD
MHI
IDEAS
Nagoya U.
Gunma U.
JAEA

Need Good Detectors

Good Energy Resolution similar to Ge (0.2%@662keV)
High Efficiency, above 10 keV upto 1 MeV
Position resolution a few hundred micron
A detector which can be operated at “room temperature”



Situation is same in the fields of

- **Astronomical Observation (gamma-ray astronomy)**
- **Medical Application**
- **Homeland Security**
- **Monitoring (Radioisotopes)**

2. CdTe (CdZnTe) Semiconductor in Space

2002

Nuclear Astrophysics INTEGRAL (ESA)
- 16,384 CdTe detectors in the IBIS instrument
- total area 2620 cm^2

coded mask

2003

Study of γ-ray Bursts: Swift (NASA)
- 32,768 CdZnTe detectors in the BAT instrument
- total area 5240 cm^2

X-ray Observatory

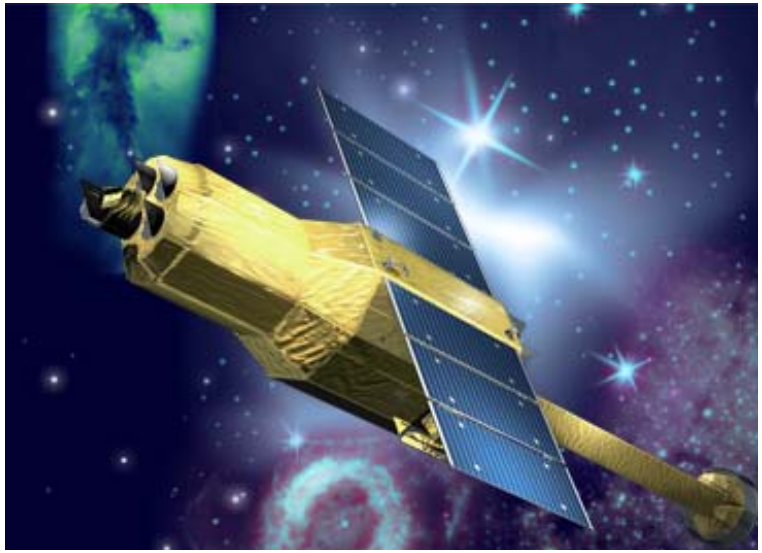
ASTRO-H (JAXA)

CdTe pad/strip detectors

total area 3457 cm^2

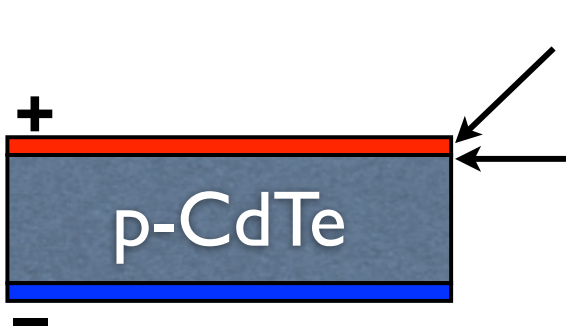
readout channels 31,232

2014



3. Schottky CdTe diode

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



Low work function metal (In or Al)

Schottky barrier

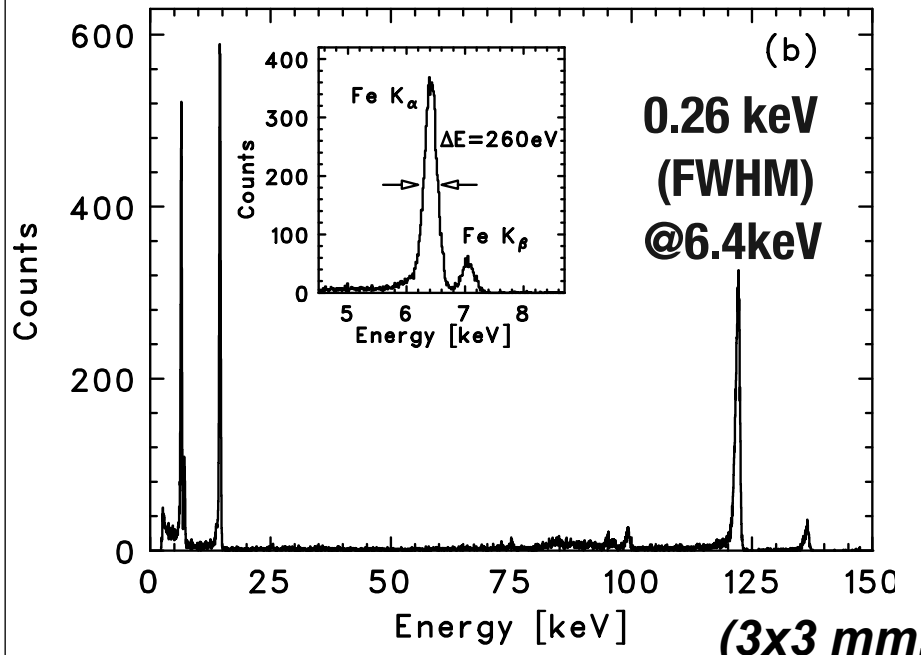
Takahashi et al. 1998

with ACRORAD

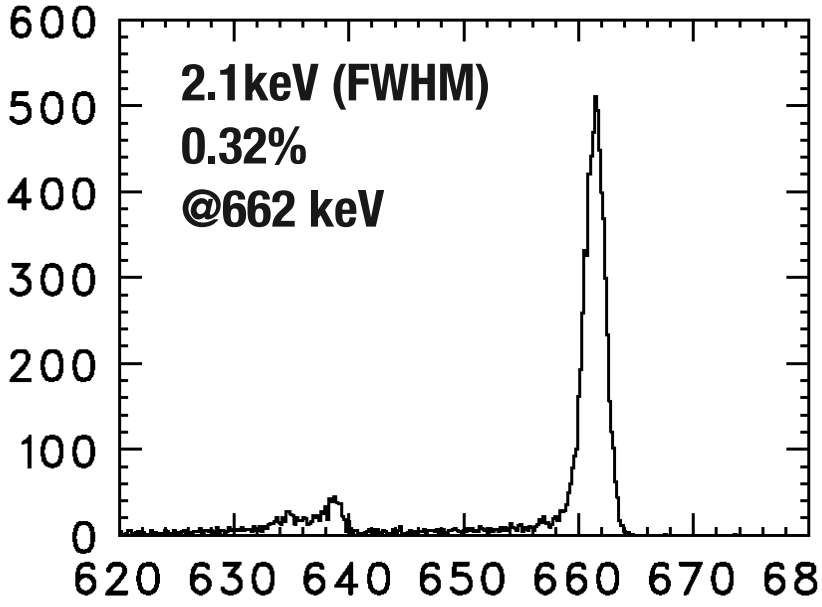
- Extremely low leakage current
- High bias voltage

→ Full charge collection (NO TAIL)

Best spectra we presented 10 years ago.



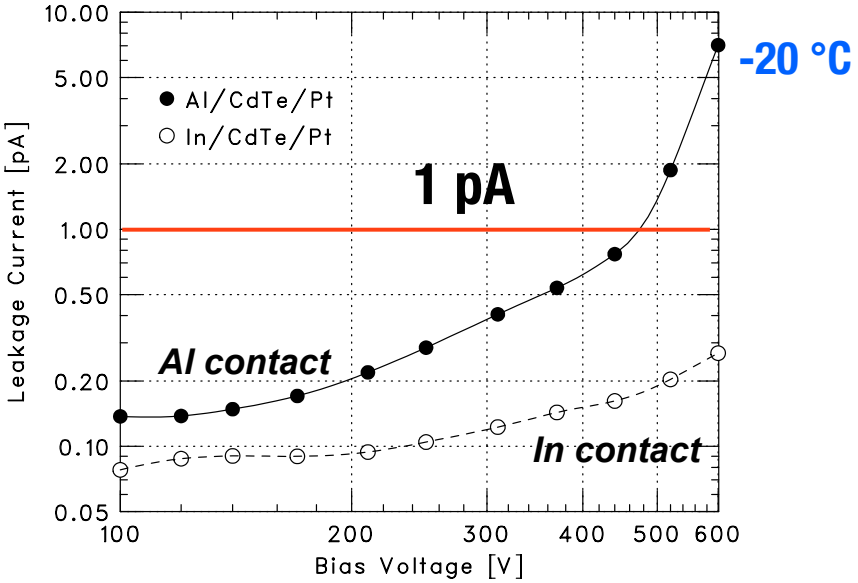
(3x3 mm, 1 mm^t)

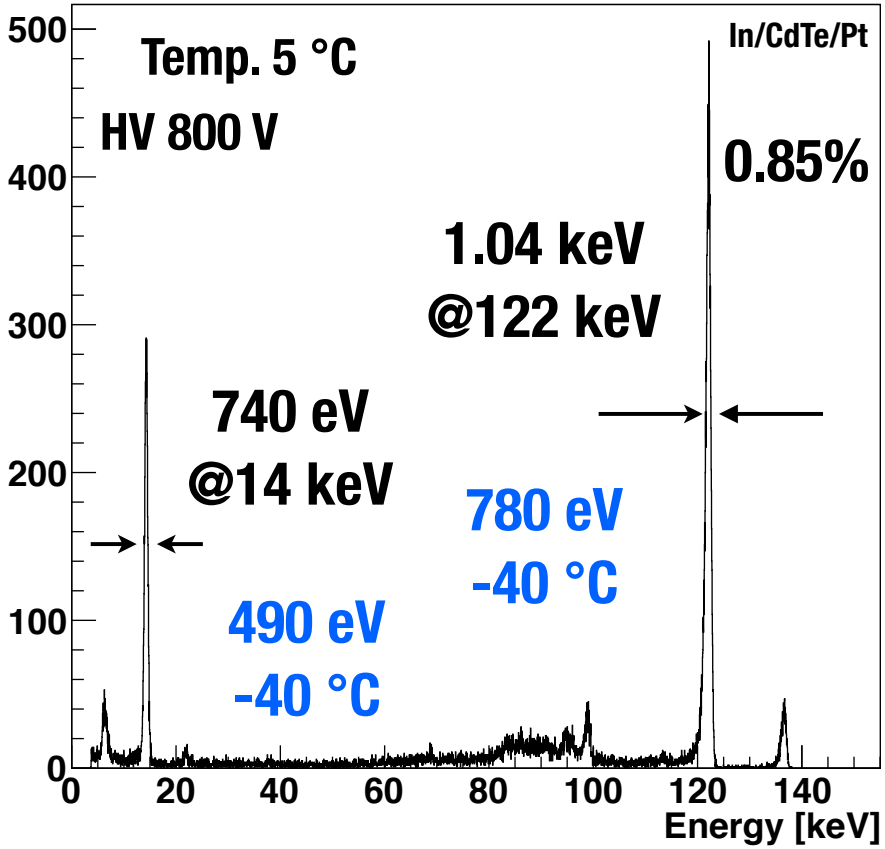


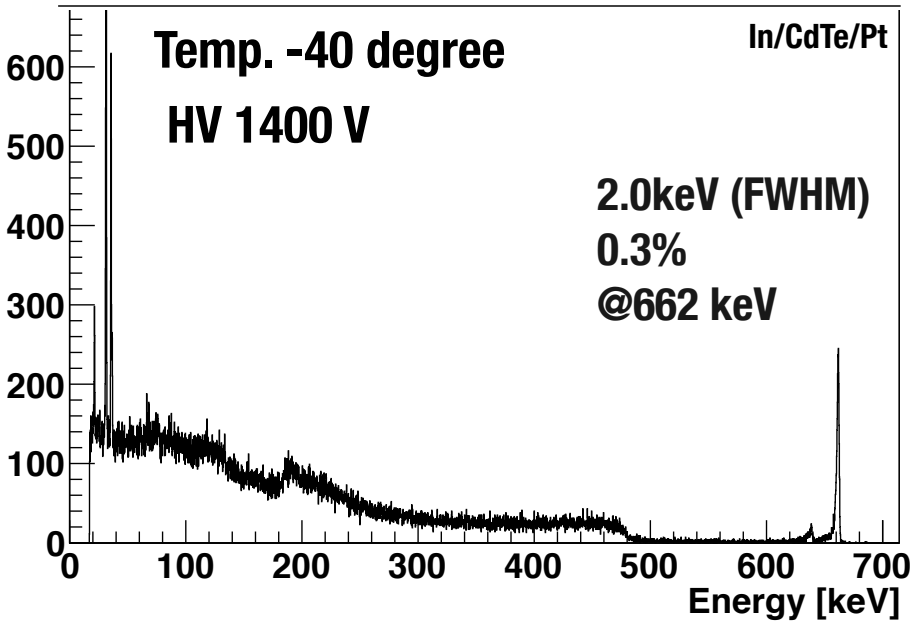
(2x2 mm, 0.5 mm^t)

4. Even better performance - the recent production

Typical Spectra we can obtain, today
(2 x 2 mm, 0,5 mm)

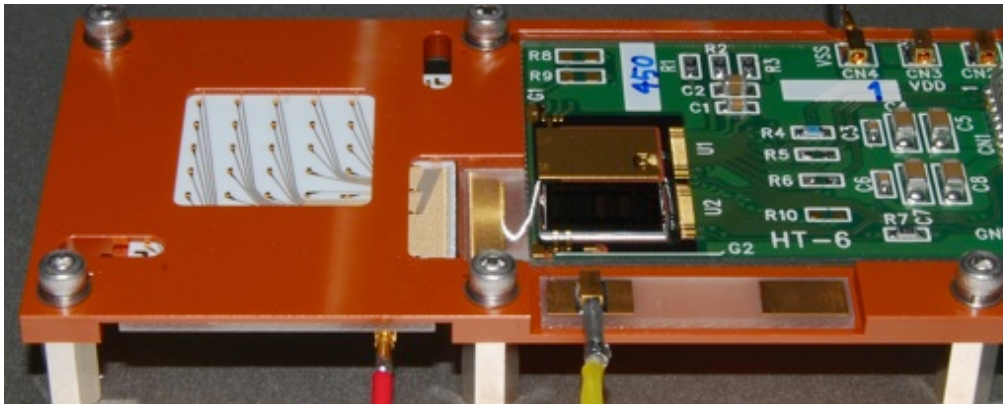






CdTe manufactured by ACRORAD, 2011

5. Application to Large Area Pixel Detectors



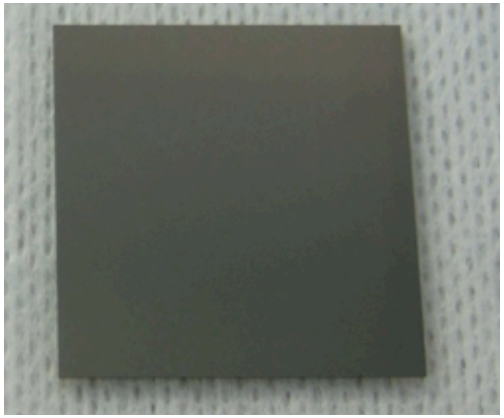
In/CdTe/Pt Diode

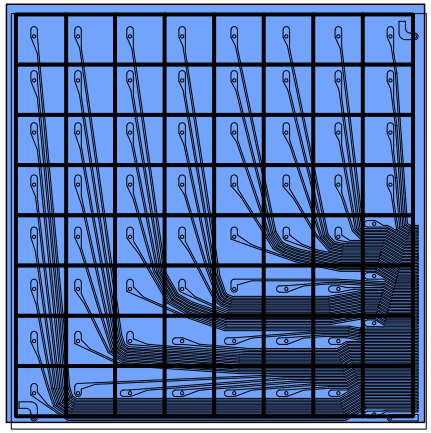
2.56 x 2.56 cm, 0.75 mm^t

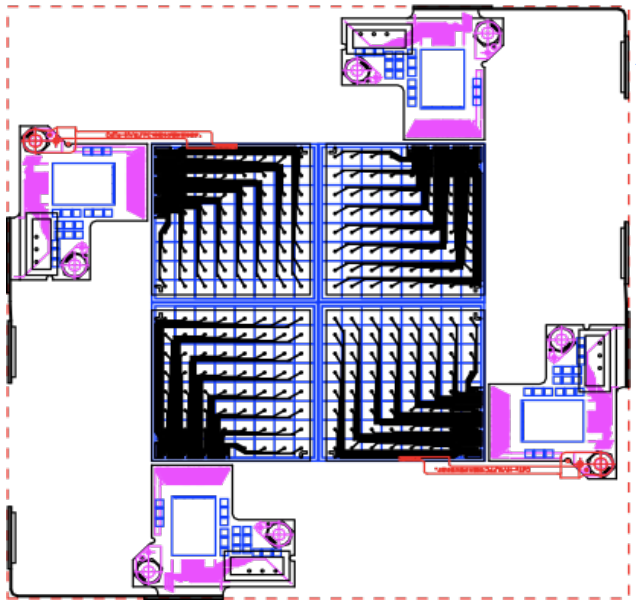
64 pixels (8x8)

pixel size 3.2mm x 3.2 mm

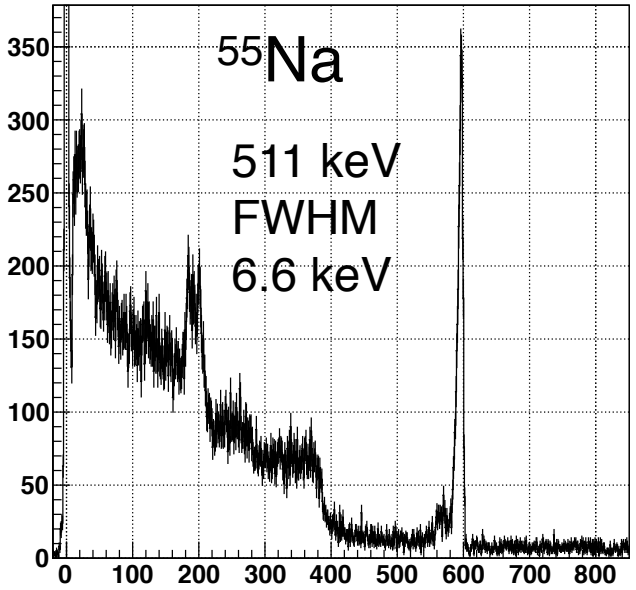
Read out by a 1-dim ASIC







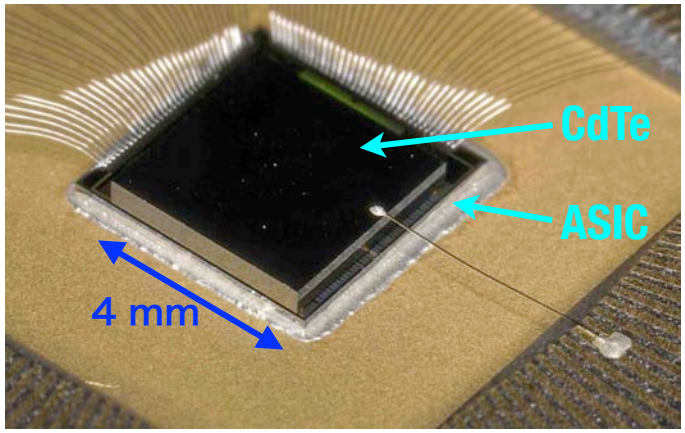
5.12 x 5.12 cm detector array



Energy Resolution (FWHM)

$$\sqrt{(1.5\text{-}2)^2 + (E\ (\text{keV}) * 0.0125)^2}$$

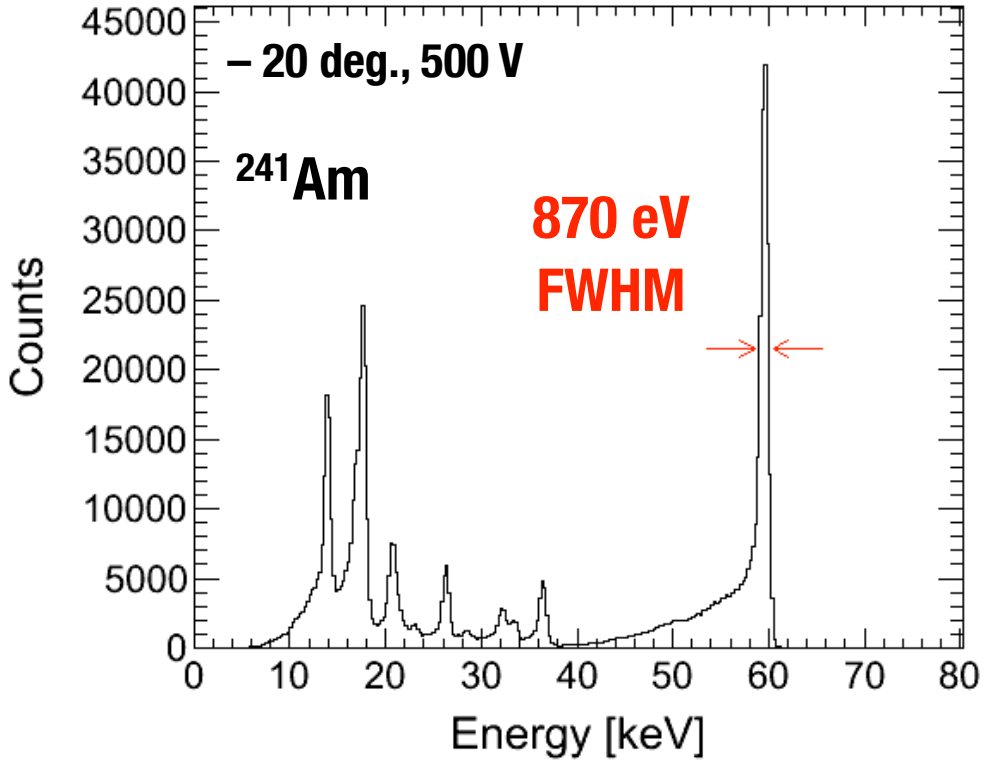
6. Application to Fine pitch pixel detector



A hybrid CdTe/ASIC
270 μm pixels
144 ch

Good performance
both for imaging & spectroscopy
in self-trigger mode

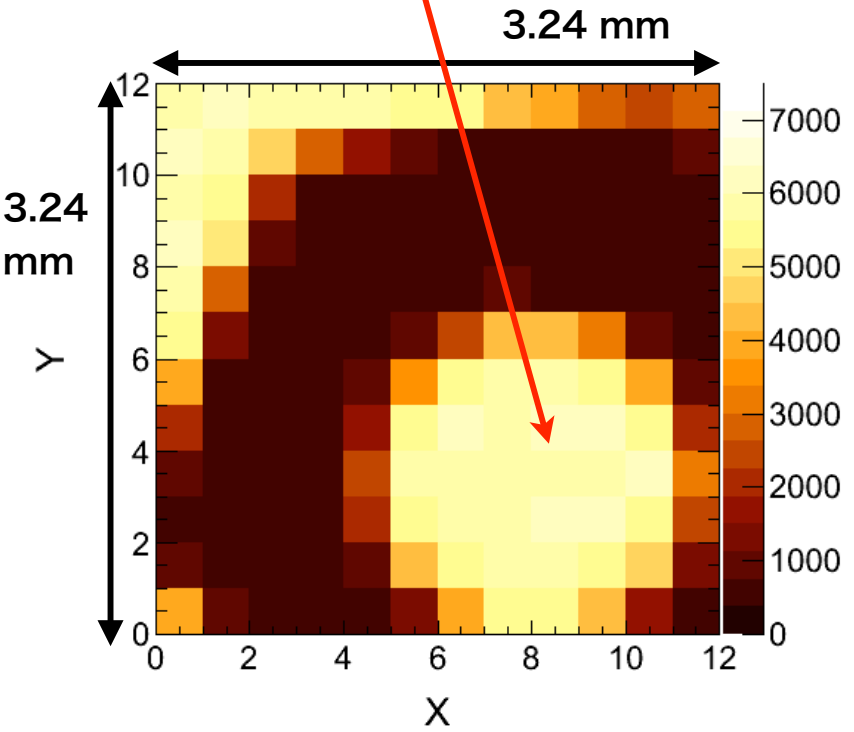
Composite spectrum of the 144 ch (single hit)



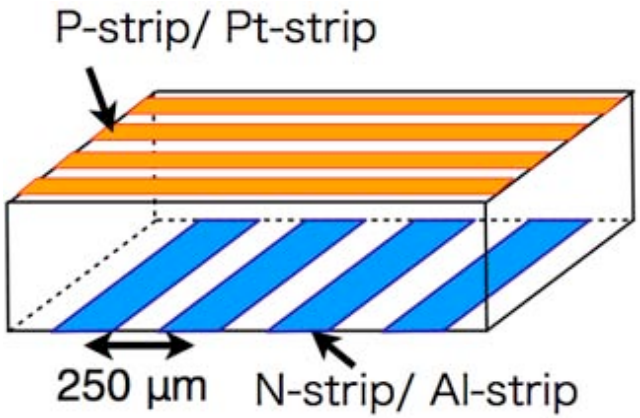
Sato et al. 2010
IEEE TNS

Nut
Φ 2 mm

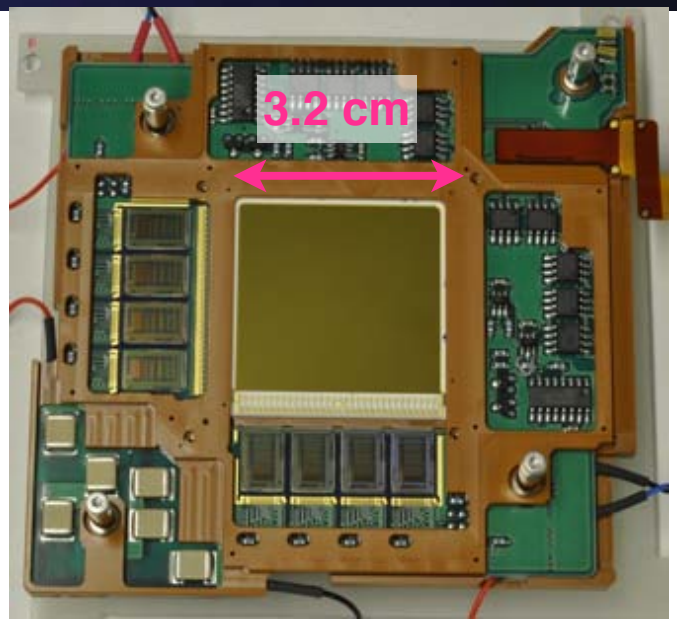
59.5 keV
shadow image



7. CdTe double side strip (3.2cm x 3.2 cm)

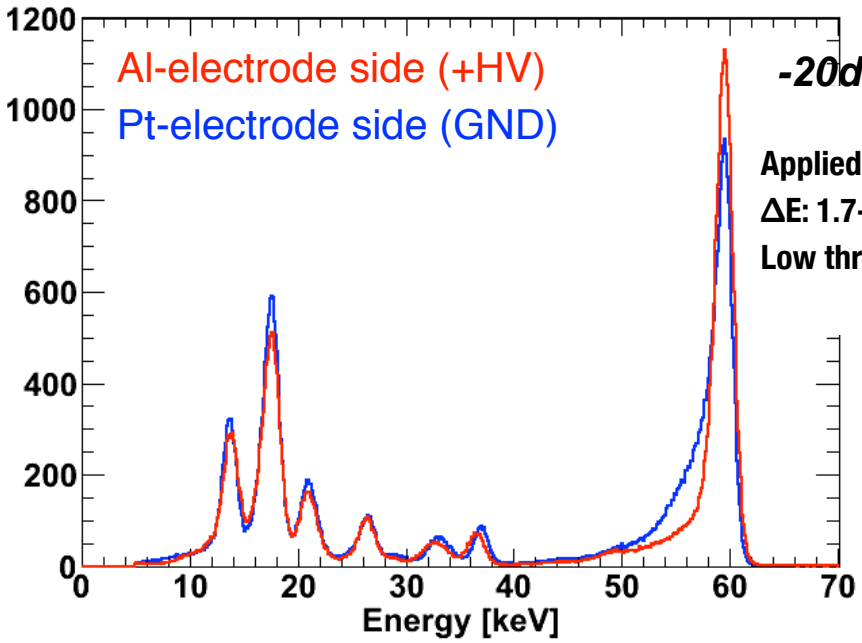


250 micron pitch strips for both side



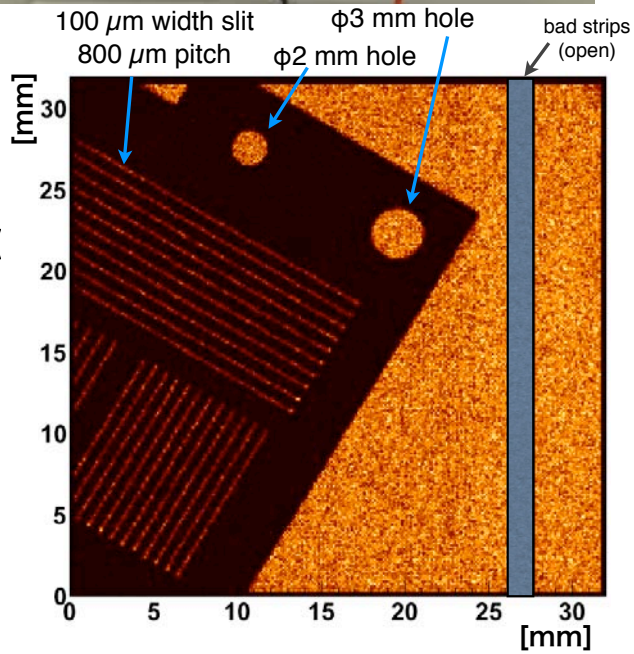
Al-strip (+)
(Schottky barrier)

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



-20deg

Applied bias: 250 V
ΔE: 1.7-1.9 keV at 60 keV (FWHM)
Low threshold: 5 keV

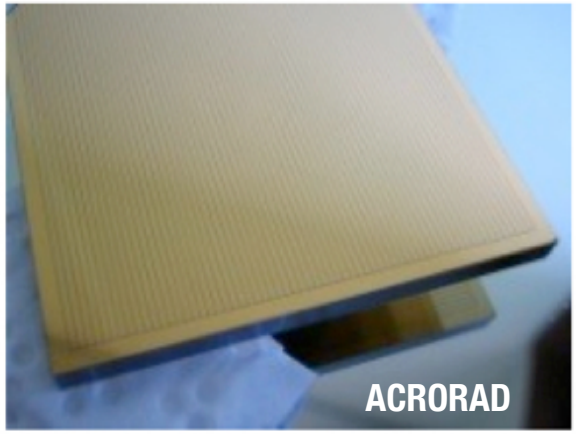


Watanabe et al., 2011

8. Now, we have a full set of technologies

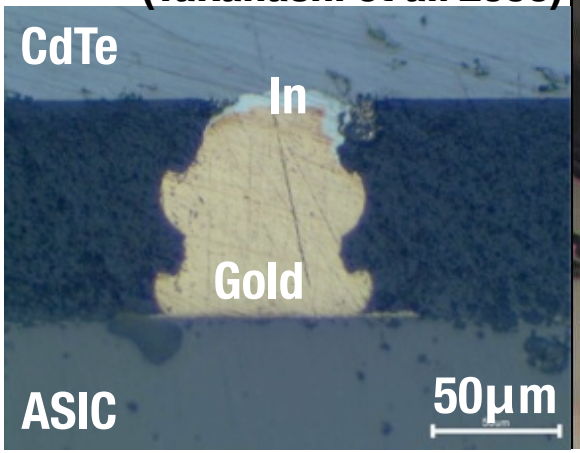
Good Material

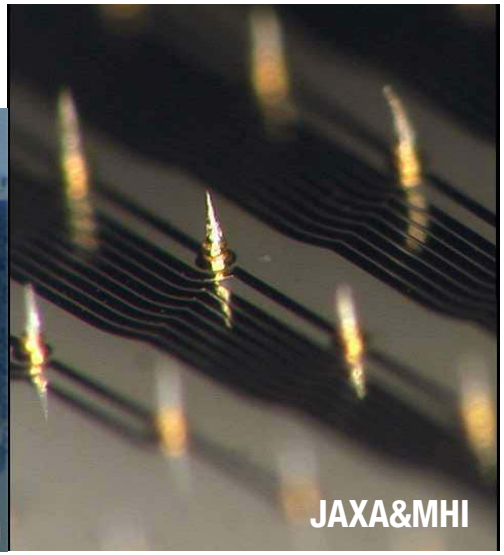
Single Crystal CdTe(Cl) (1,1,1)



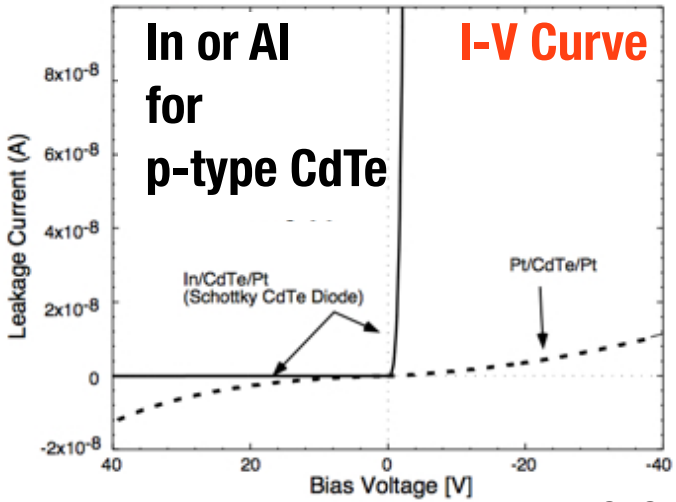
Hybridization

In/Gold Stud Bump
(Takahashi et al. 2000)



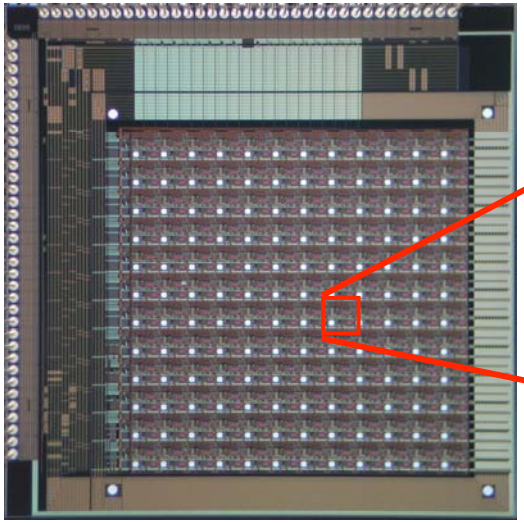


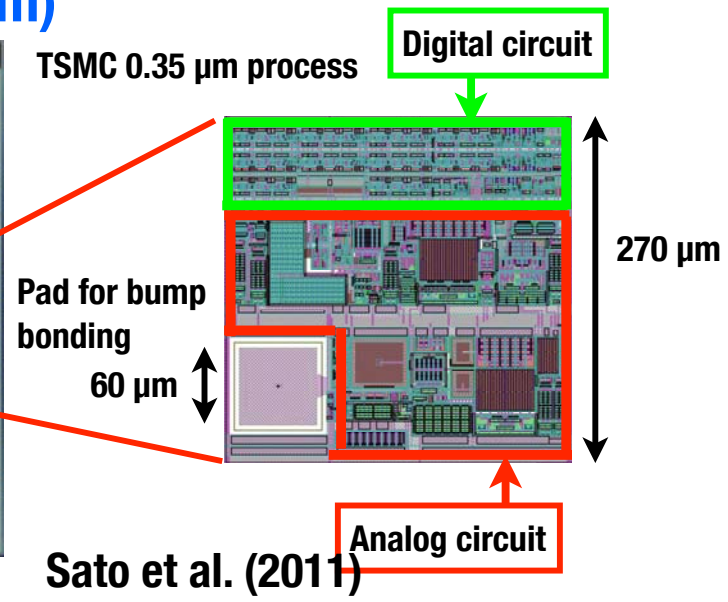
Blocking Electrode



Takahashi et al. (2000) with ACRORAD

ASICs (1 dim & 2 dim)





Sato et al. (2011)

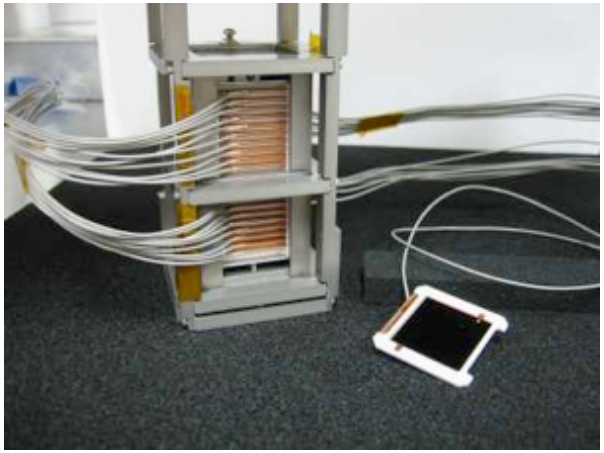
9. Efficiencies?

A Solution : Stack

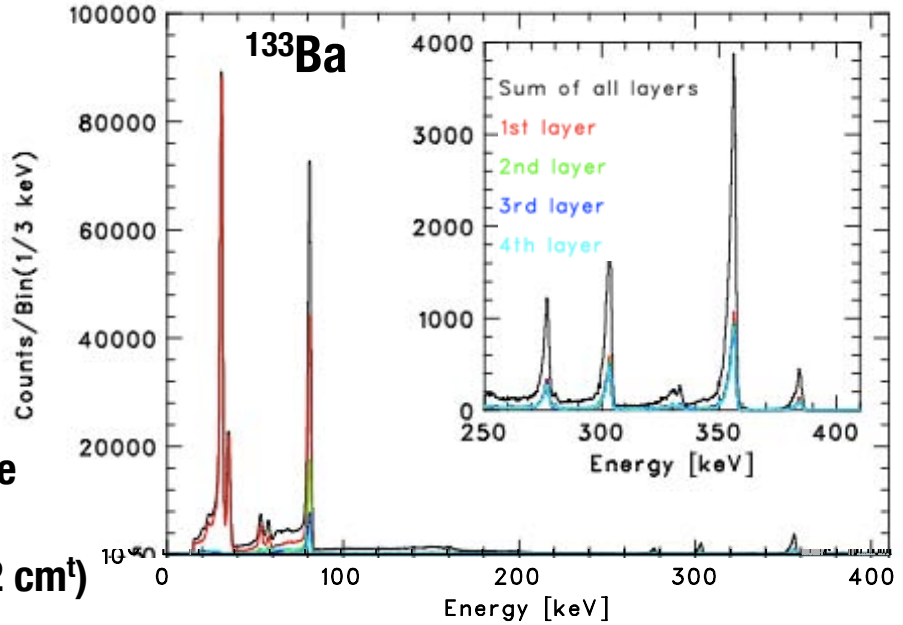
Easy. If we have corresponding technologies.

In 2000

only with Planar detectors

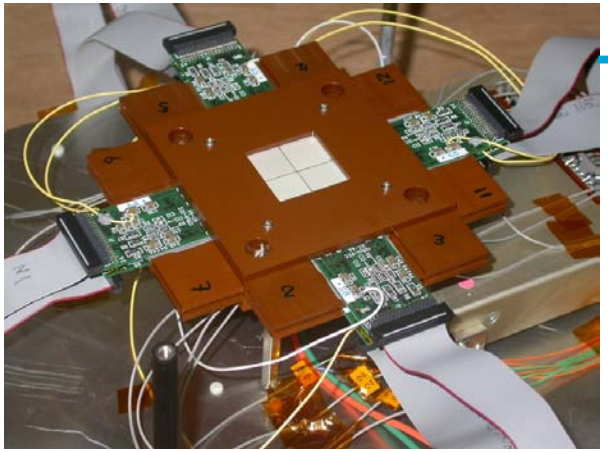


40 CdTe Layers (total 2 cm^t)

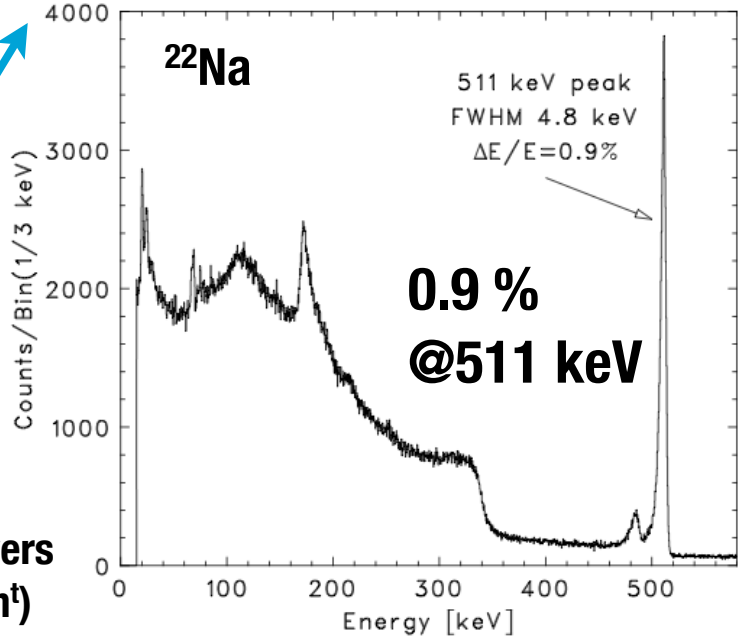


In 2007

with Imaging Capability

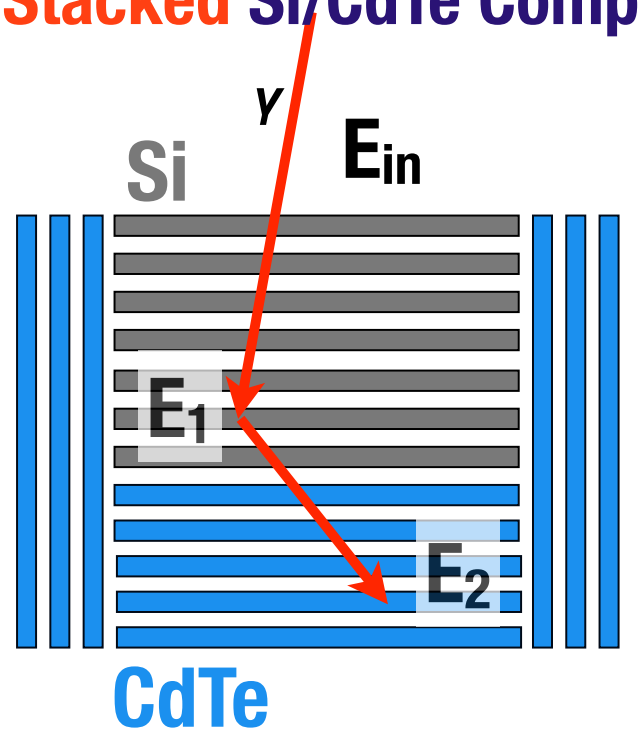


Four CdTe Image Layers (total 2mm^t)



10. The next-generation gamma-ray Imager

Stacked Si/CdTe Compton Camera

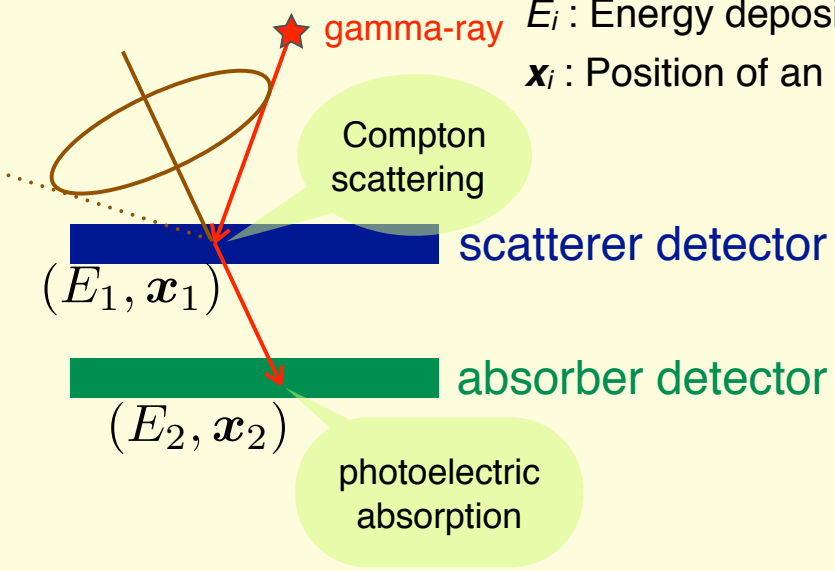


2001, 2002
Takahashi et al.

2005
Watanabe et al.

2008, 2011
Takeda et al.

Compton Camera



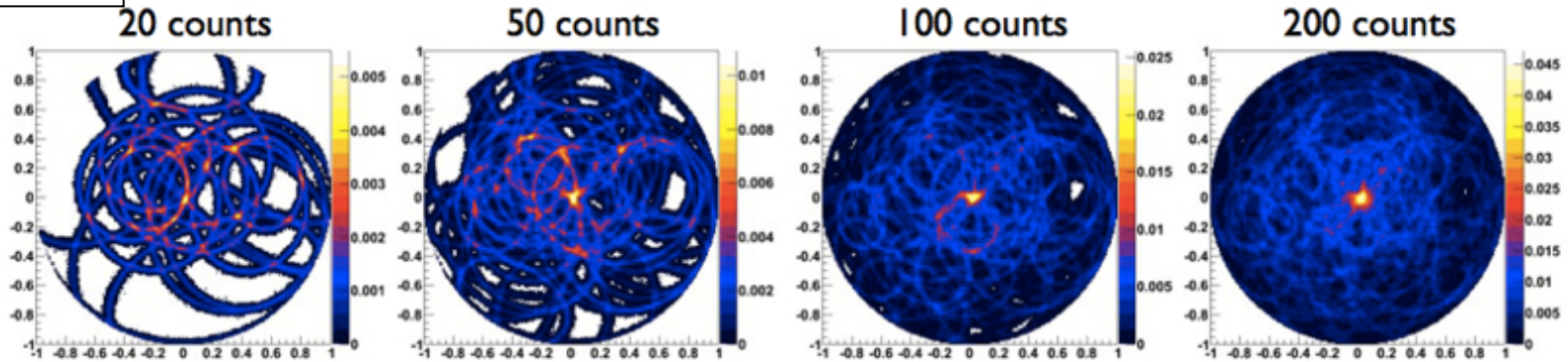
E_i : Energy deposited

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

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

Imaging ^{137}Cs

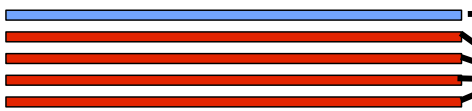
By a simple back projection method



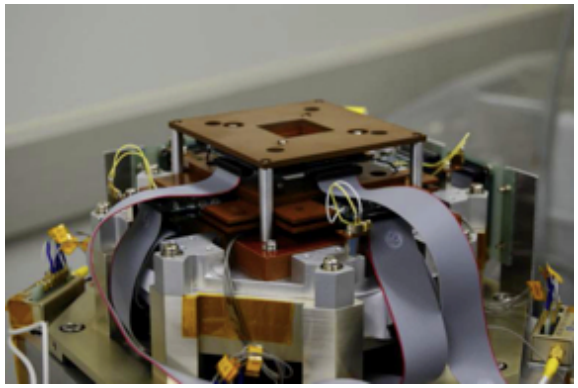
11. Si/CdTe Compton Camera - Spectrum -

Semiconductor is best suited for Compton Camera :High Energy/Position Resolution

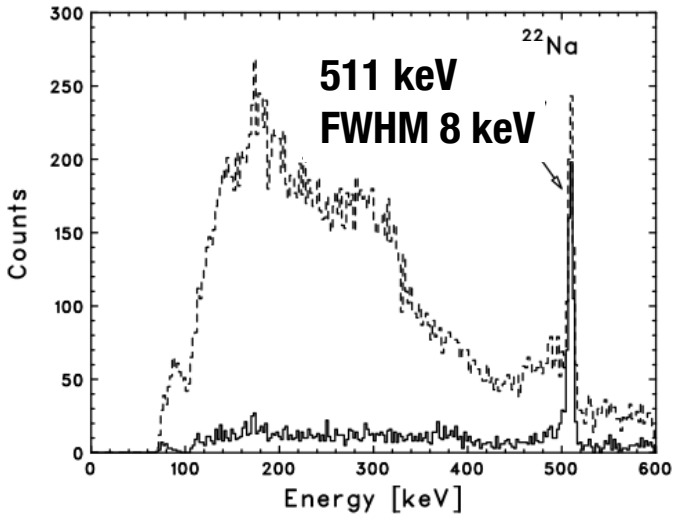
1st Prototype

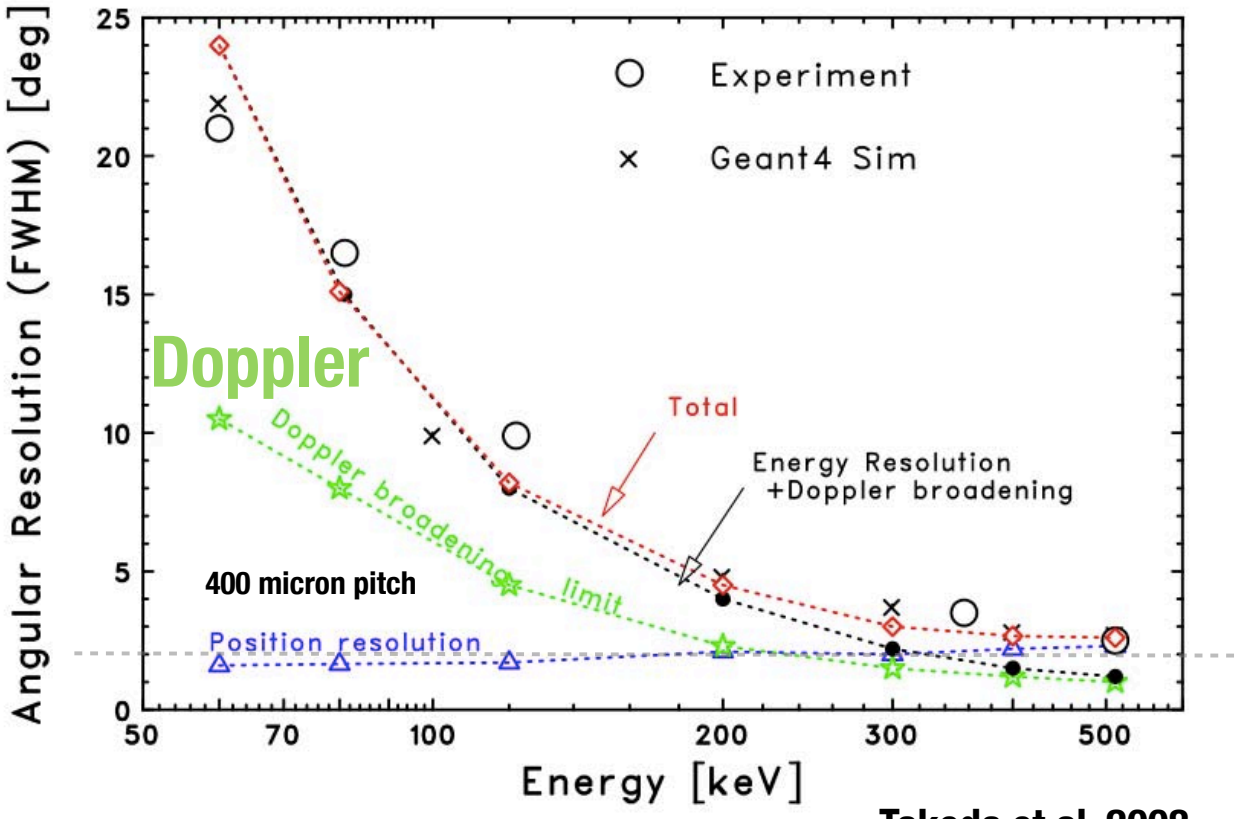


- ★ Si (Z=14): Small momentum of target electrons
  Small Doppler effects
- ★ CdTe (Z=48,52) works better as an absorber



Spectrum (511 keV)





Takeda et al. 2008

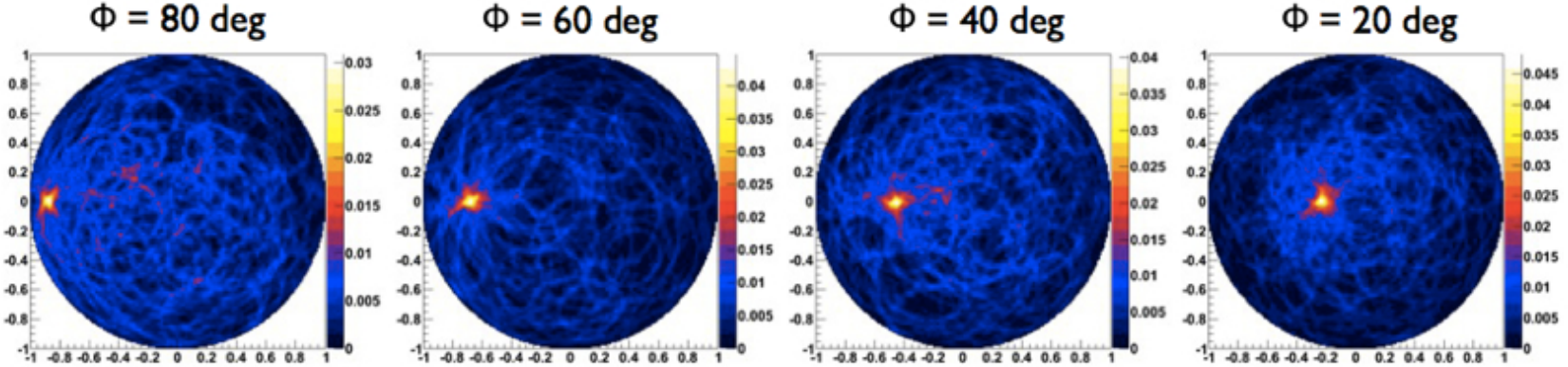
11. Compton Camera - Advantage -

Large FOV and good energy resolution

Takeda et al. 2008,2011

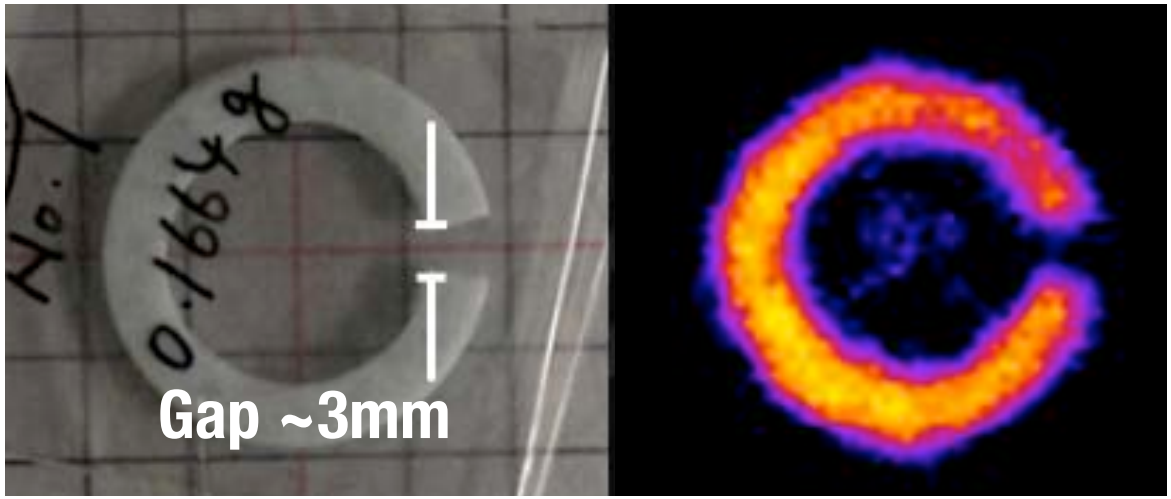
Imaging a moving ^{137}Cs source

Large FOV > 160deg (80% at ±80 deg)



Takeda et al. 2008

Good performance for a diffuse source.



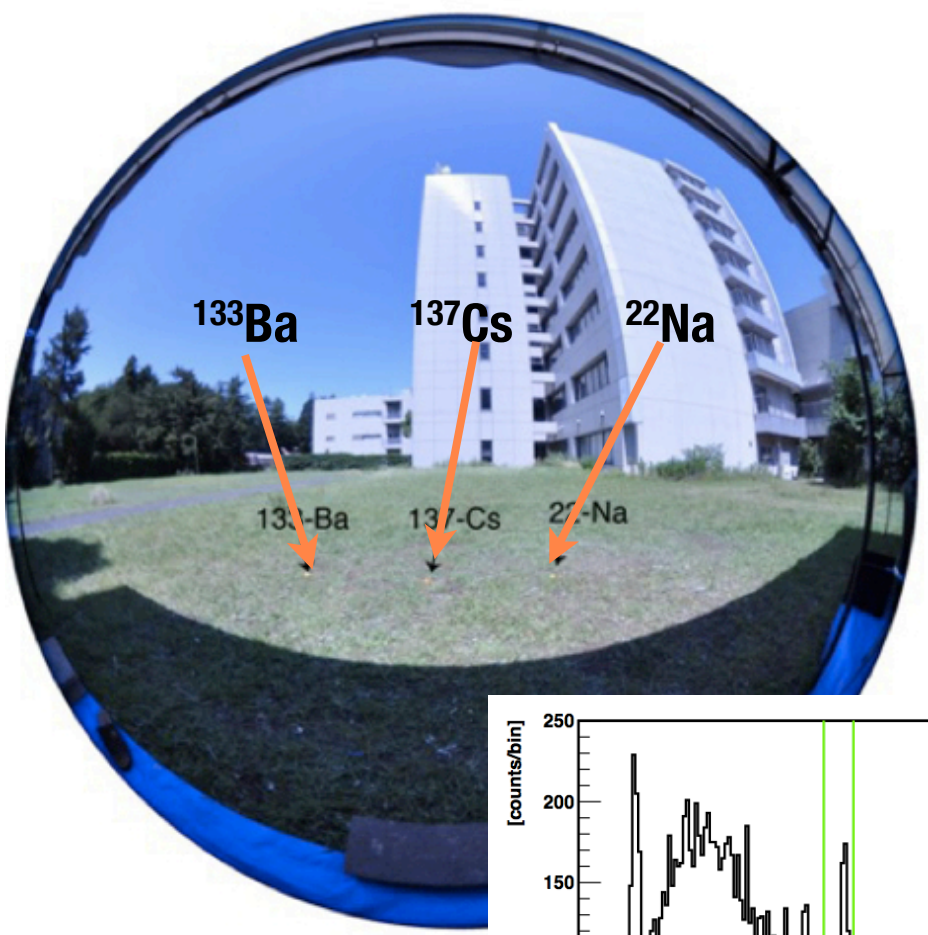
JAXA/Gunma U./JAEA(2008)

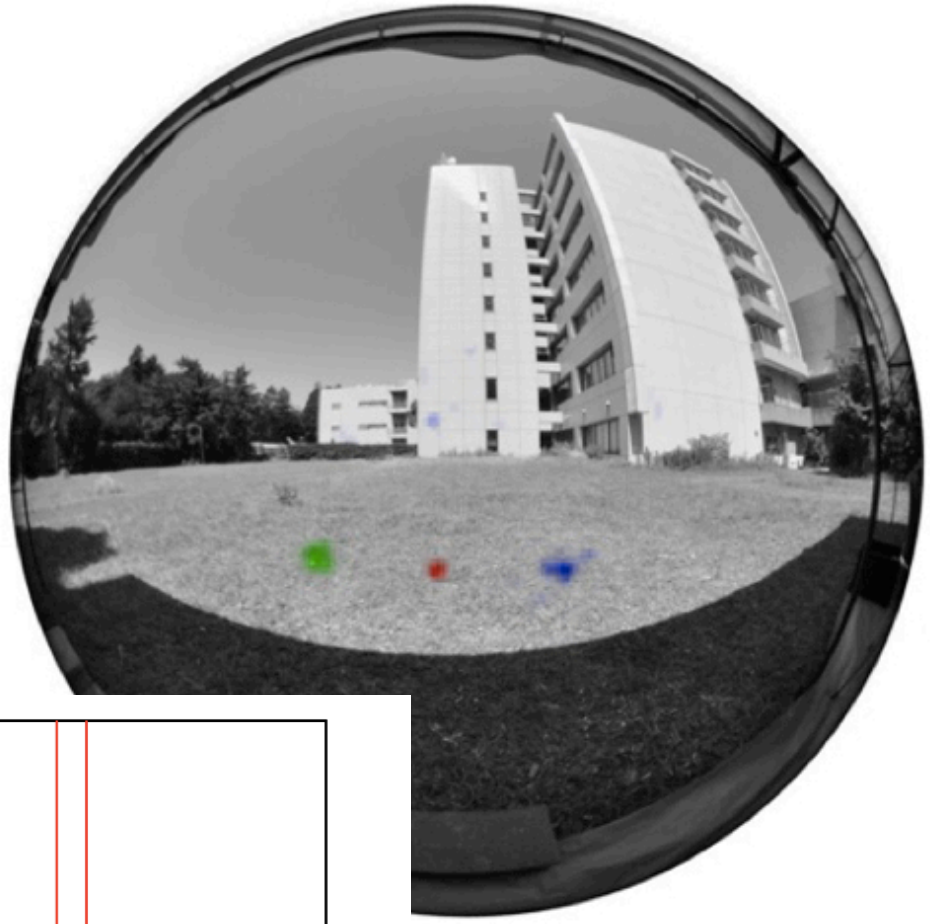
Image taken at 3 cm

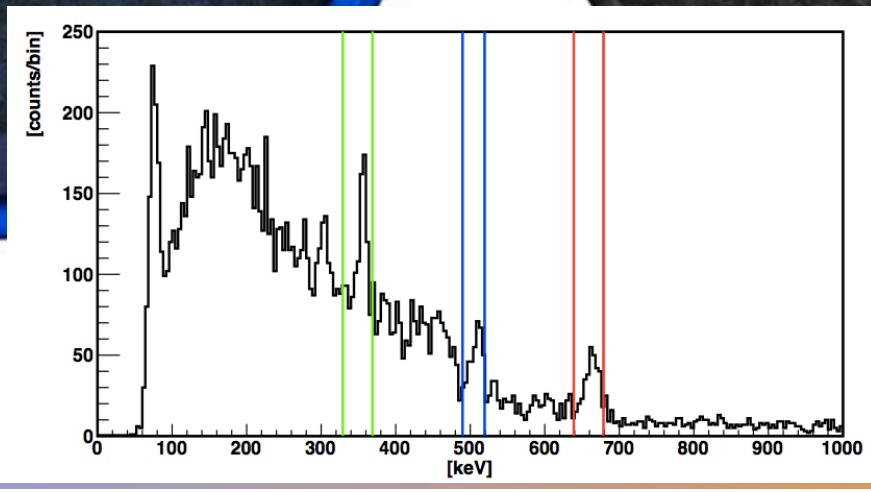
^{131}I

364 keV, 1.6 MBq

13. Si/CdTe Compton Camera - Searching for Hot Spots -





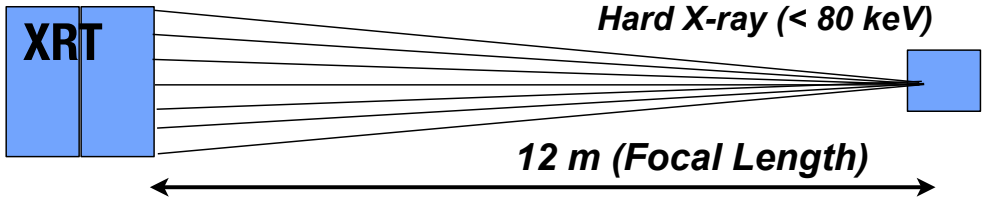


13. Si/CdTe Compton Camera - Searching for Hot Spots -

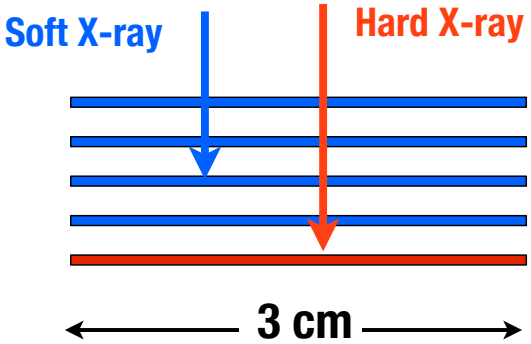
Hide ^{137}Cs

Found out ^{137}Cs

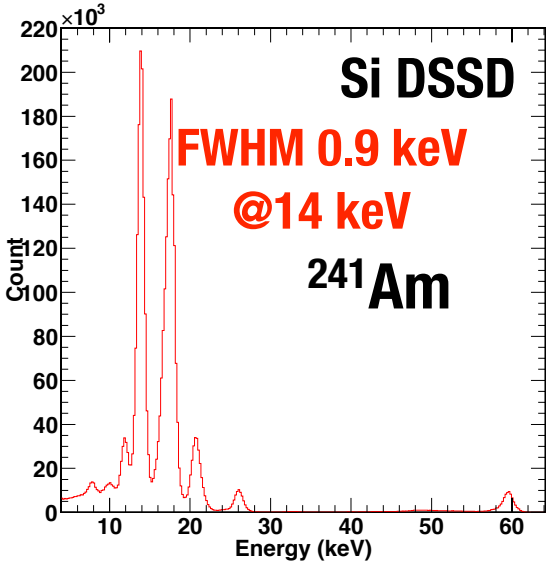
14. Our technology goes to space - ASTRO-H -

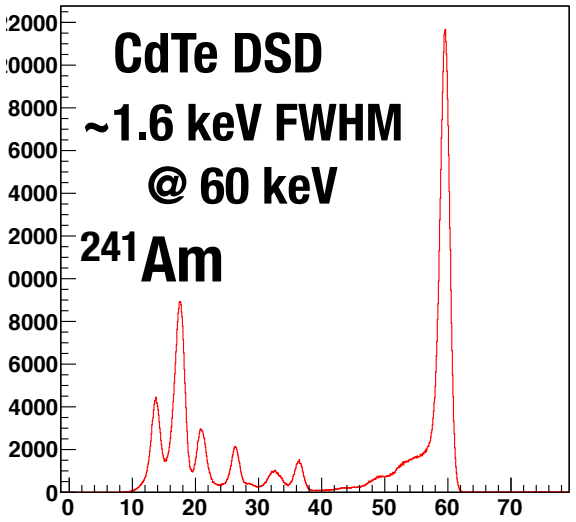


Si and CdTe Hybrid Imager (5 - 80 keV):



Size 3cm x 3cm
Resolution
250 μm pitch
Double Side
Si & CdTe



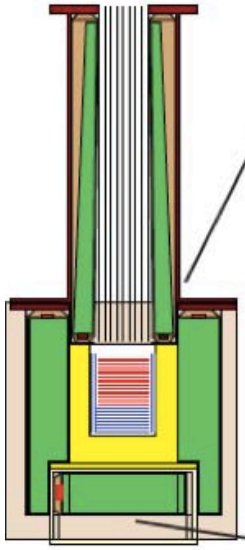


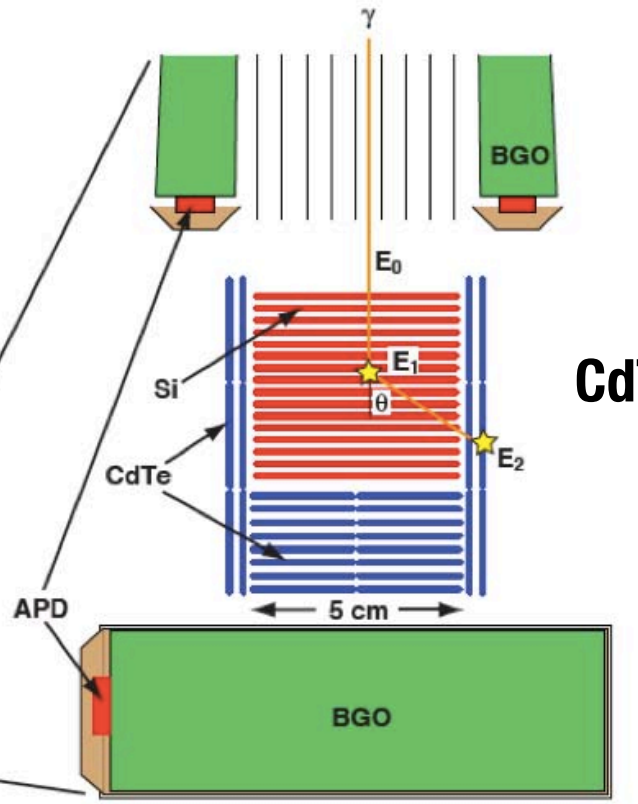
Kokubun et al. 2010

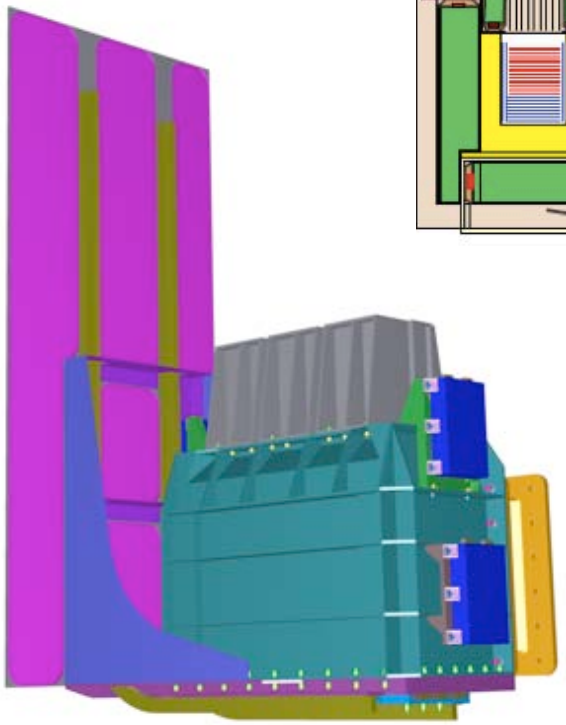
16. ASTRO-H - Soft Gamma-ray Detector (SGD) -

Concept:

Narrow FOV Si/CdTe Compton Camera to achieve extremely low background







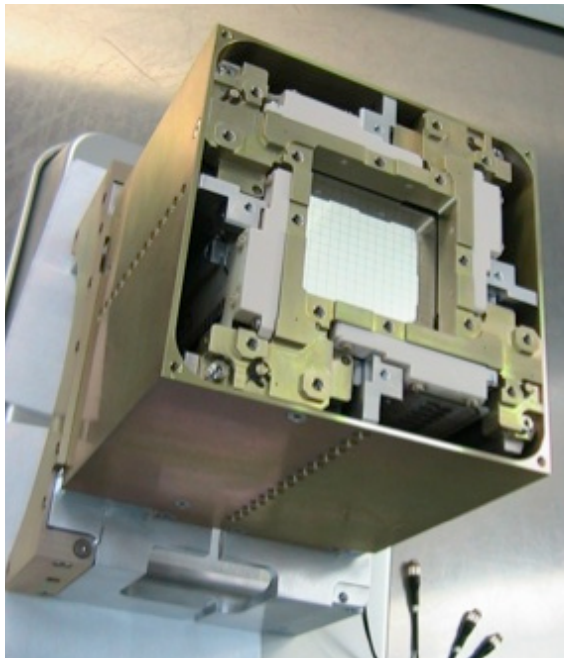
32 layers of Si (2 cm thick)
8 layers of CdTe (Bottom)
2 layers of CdTe (Side)

CdTe : pixel size 3.2x3.2 mm

: thickness 0.75 mm

50 keV - 600 keV

Compton Efficiency 10-20 % (more than 100 times efficient than our prototypes shown before)



Tajima et al. 2010

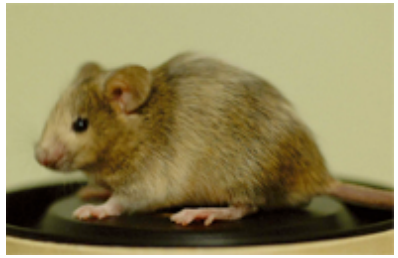
17. Summary

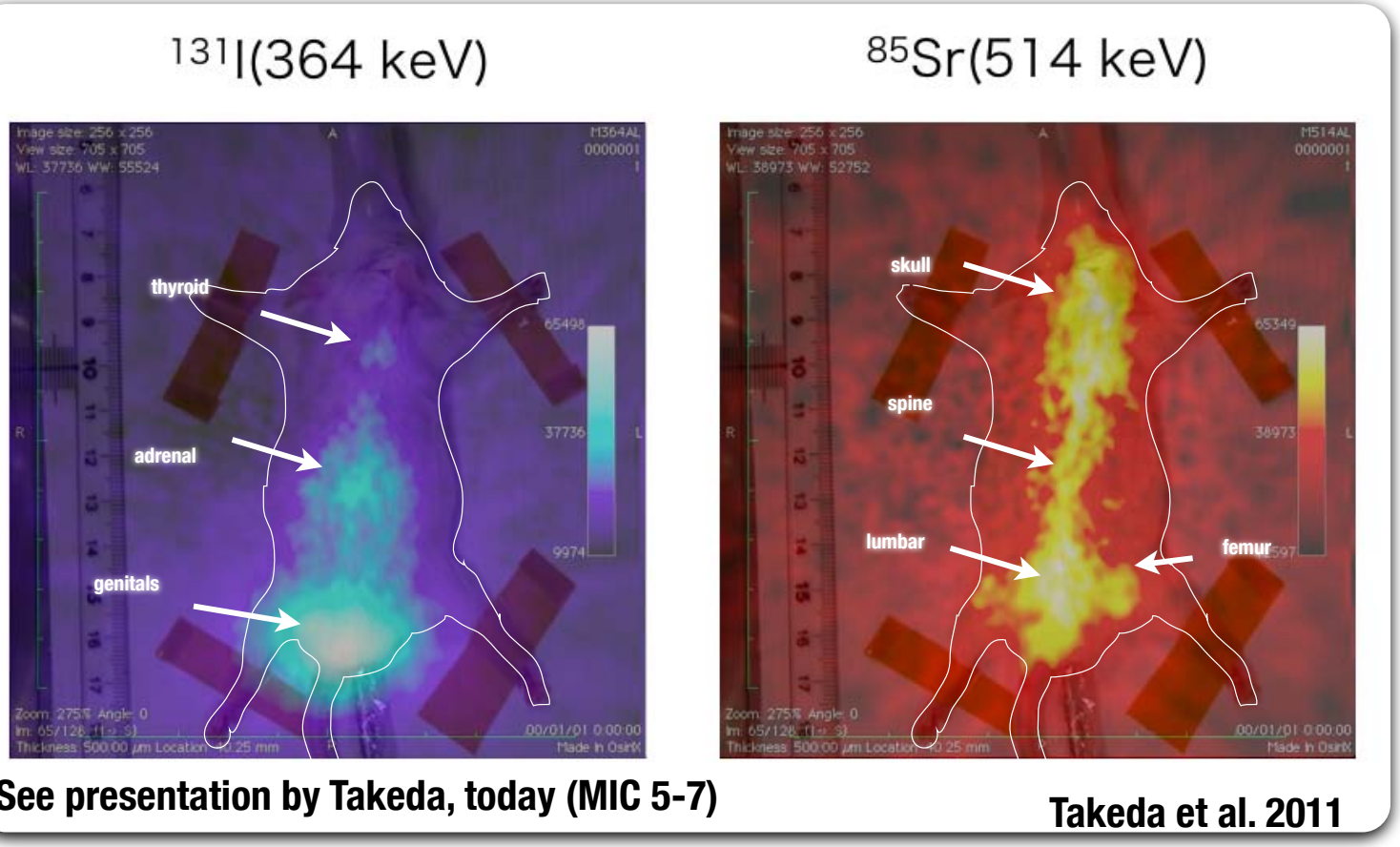
1) Space science mission requires cutting edge technology due to its high Scientific Requirements

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)

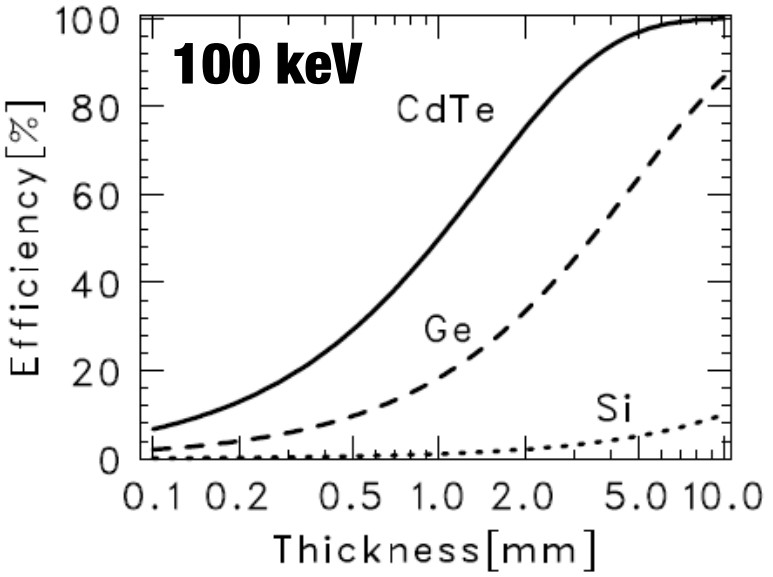
Takeda et al. 2011

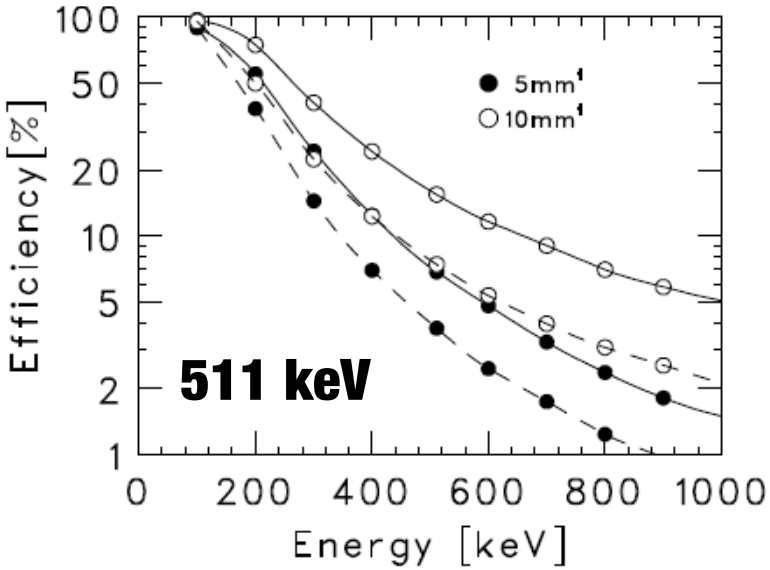
CdTe/CdZnTe seem to be the only candidate *at least, at this moment*

- High Z semiconductor (Z_{Cd} = 48, Z_{Te} = 52), ρ =5.9 g/cm³
- Room Temperature Operation or Cool Environment

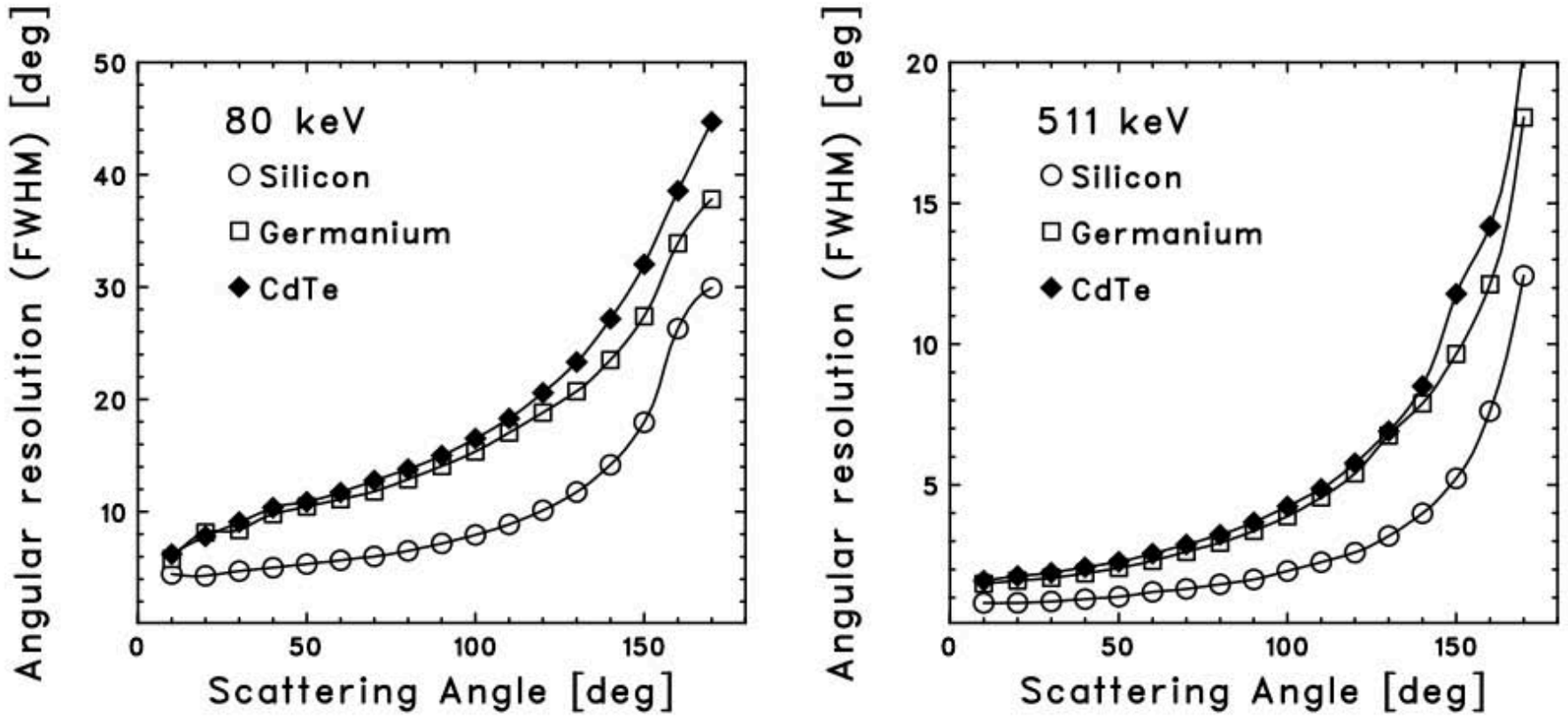
Material	Ge (77K)	HgI_2	CdTe	CdZnTe
Atomic number	32	80, 53	48, 52	48, 30, 52
Band gap (eV)	0.74	2.13	1.50	1.57
Energy per e-h pair (eV)	2.97	4.2	4.4	4.6
Fano factor	0.08	0.19	0.11	0.09
μ_e (cm²/Vs)	40,000	100	1100	1000
μ_h (cm²/Vs)	40,000	4	100	10
τ_e (s)	10^{-3}	10^{-5}	10^{-6}	10^{-5}
τ_h (s)	10^{-3}	10^{-5}	10^{-6}	10^{-6}

P. Luke (2006)





Takahashi and Watanabe (2000)



(a) 80 keV

(b) 511 keV

Figure 3.11: The contribution of Doppler broadening effect to the angular resolution.

Solution 1 : High Resolution CdTe Diode

Schottky diode (In/CdTe/Pt) (e.g. Takahashi et al.)
p-i-n diode (e.g. Khusainov et al. , Niraula et al.)
all based on high quality THM-CdTe wafer

Low leakage current

↓

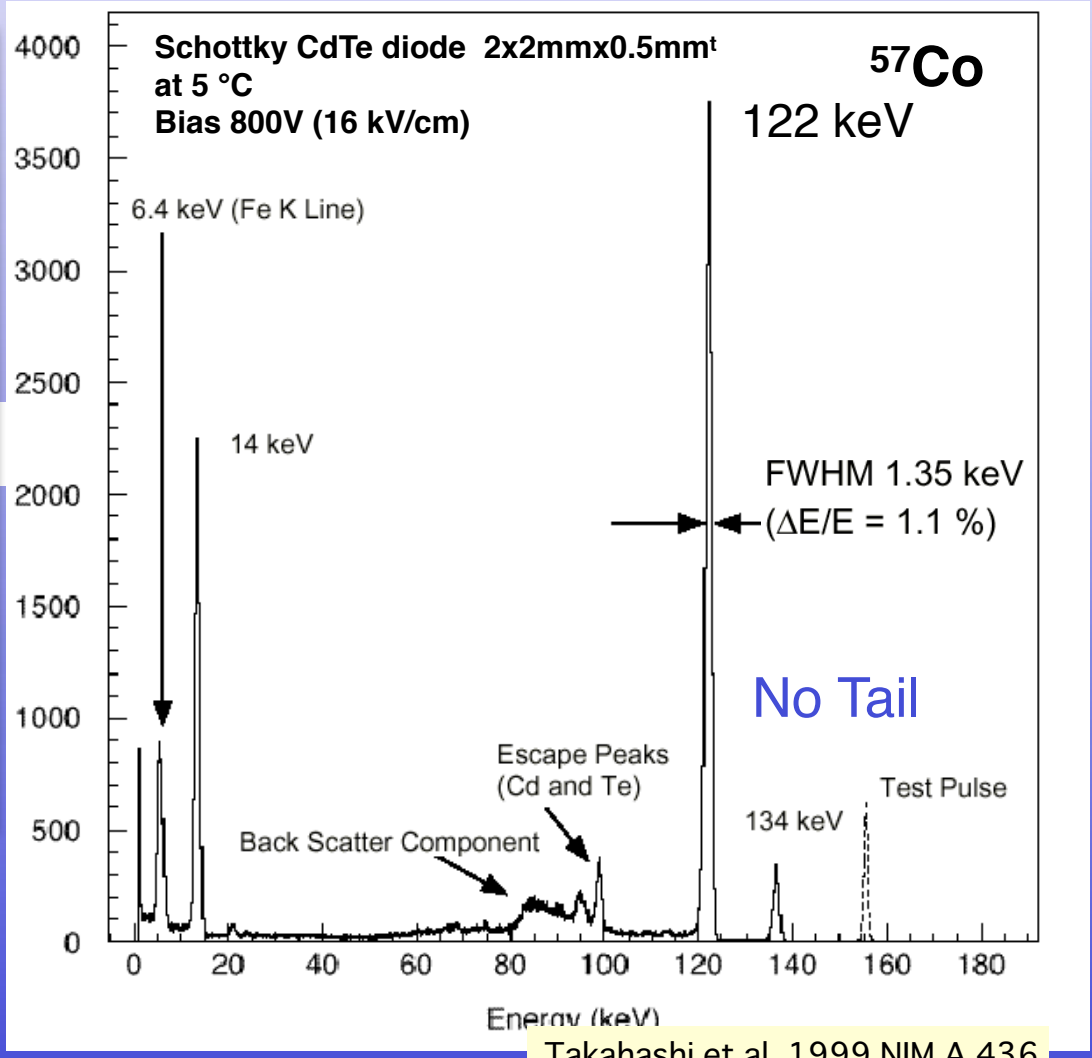
High bias voltage

↓

With Bias >800 V, charge collection is complete for a detector with a thickness of 0.5 mm

↓

If this thickness (90 % at 40 keV, 30 % at 100 keV) is sufficient for the purpose of the detector, best energy resolution is obtained from this approach.



Takahashi et al. 1999 NIM A 436