Development of a compact scintillator-based high-resolution Compton camera for molecular imaging

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Outline

- *Introduction*
- *Handheld Compton camera for environmental measurement*
- *Development of high-resolution Compton camera*
- *3D image reconstruction*
- *Summary*

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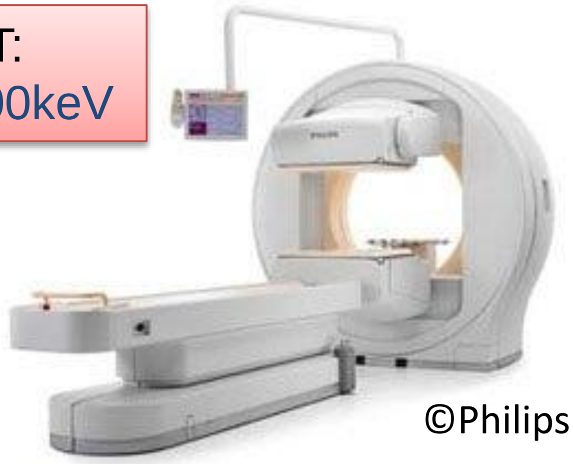
Various molecular imaging devices

Current imaging technique

SPECT:
< ~300keV



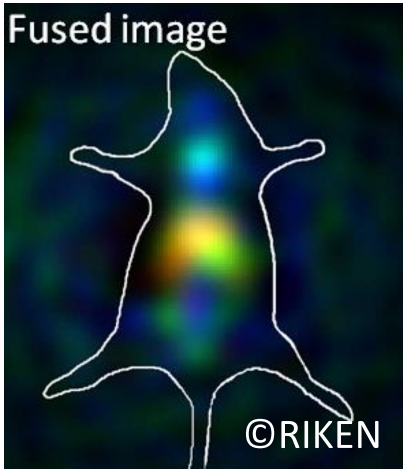
©Philips

©GE

PET:
= 511keV

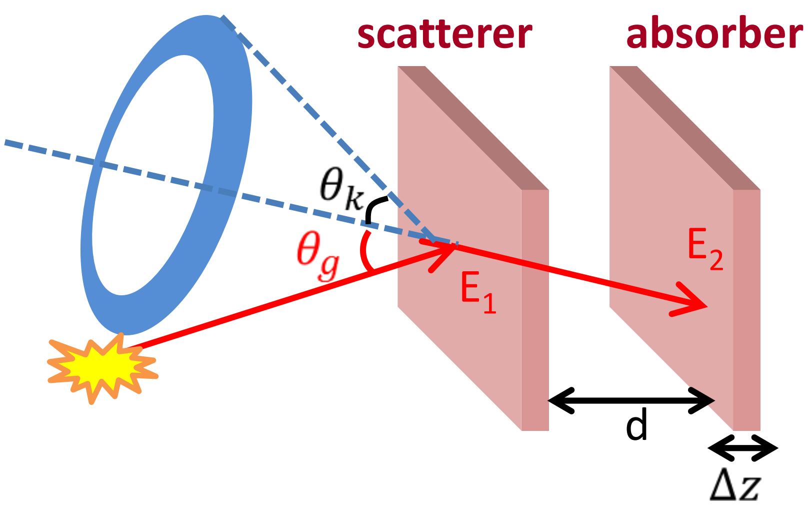
Advantage of Compton camera

- wide energy range (300~2000 keV) → Fused image of different isotopes
- wide field of view (~180 deg) → 3D imaging @ low detector costs



... expected for next-generation imaging instrument !

Principle of Compton camera (CC)



- Compton Kinematics :

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

- γ-ray incident direction is calculated by energy and position information
- $ARM \equiv \theta_k - \theta_g$

For high resolution

- large distance (d)
- thin detectors (Δz)
- good energy resolution (ΔE)

For high efficiency

- small distance (d)
- thick detectors (Δz)
- large effective area

Can achieve good resolution and efficiency at the same time … ?

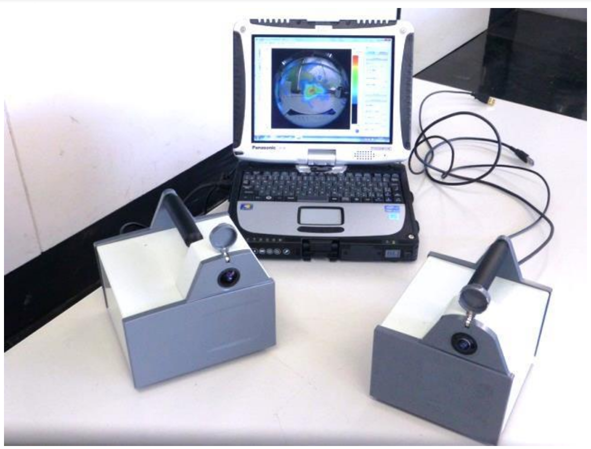
Our Compton camera project

2011-2013
handheld CC (ver.1)

2012-2015
handheld CC (ver.2)

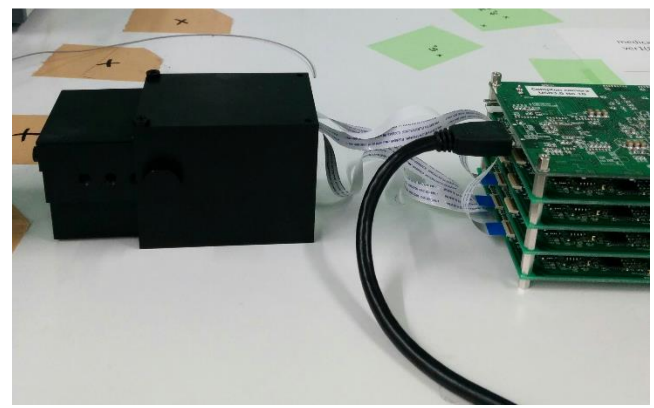
2015-
high-resolution CC

for environmental measurement



To identify radiation hotspots created after the 2011 Japan nuclear disaster

for medical measurement



For molecular imaging, proton therapy monitoring

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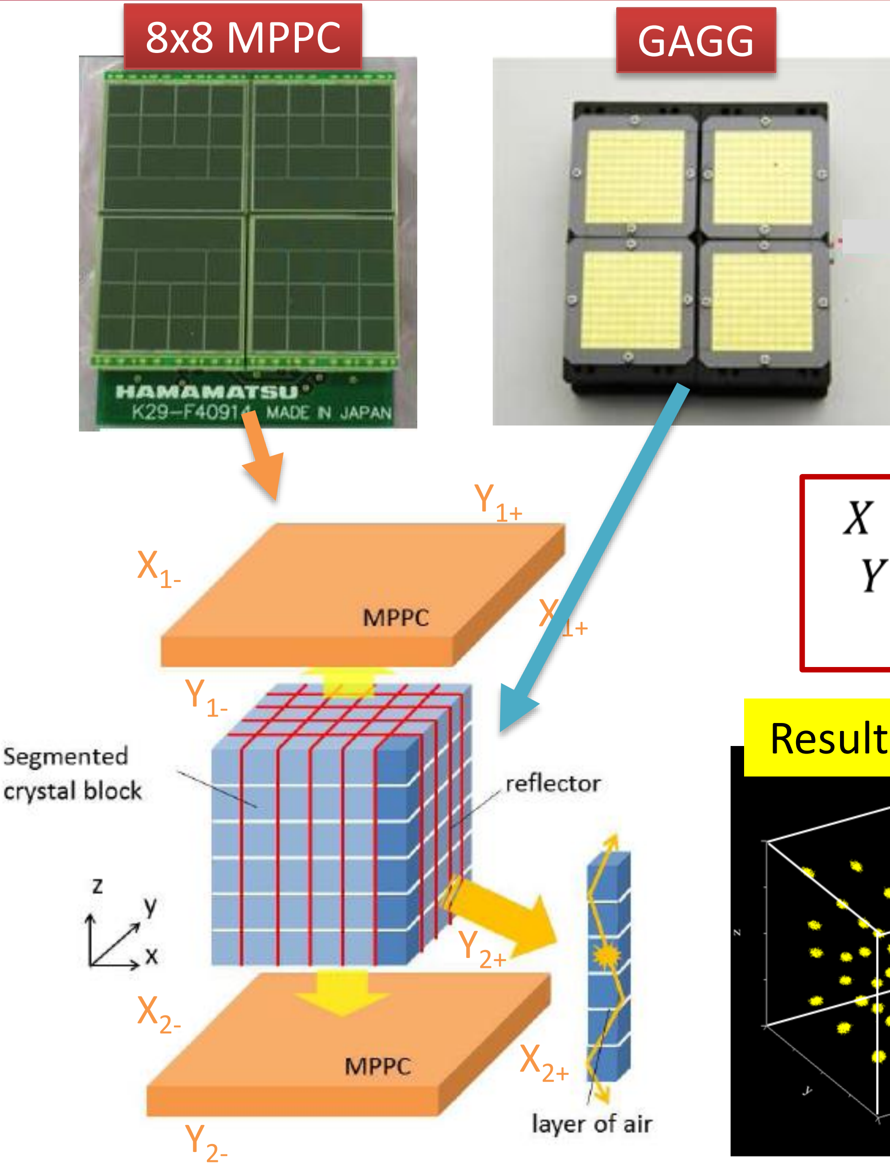
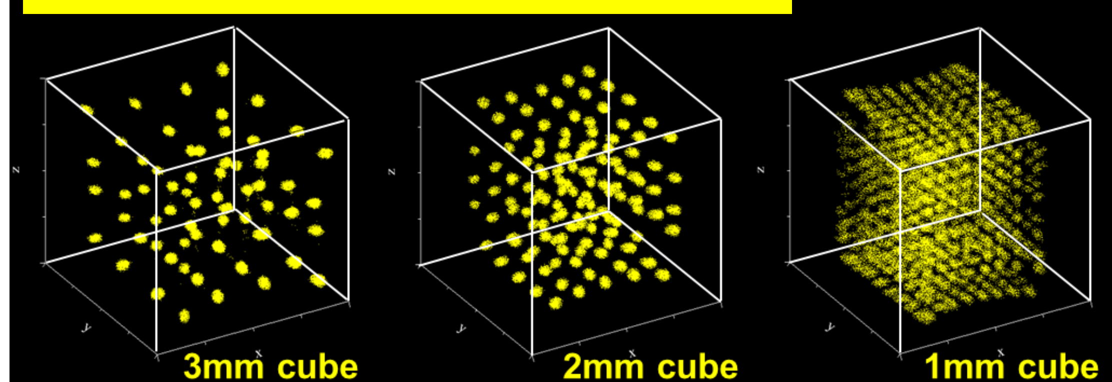
3-D position-sensitive scintillator (DOI)



- ✓ Coupling Ce:GAGG scintillators and 8x8 MPPC arrays
- ✓ Calculate 3D interaction position by centroid method
- ✓ 1mm position resolution can be achieved in scintillator block

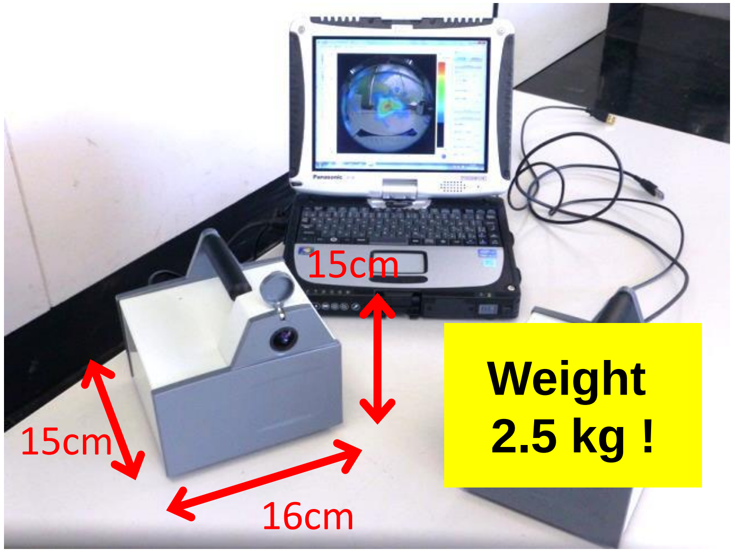
$$X = ((X_{1+} + X_{2+}) - (X_{1-} + X_{2-}))/(S_1 + S_2)$$
$$Y = ((Y_{1+} + Y_{2+}) - (Y_{1-} + Y_{2-}))/(S_1 + S_2)$$
$$Z = LS_1/(S_1 + S_2)$$

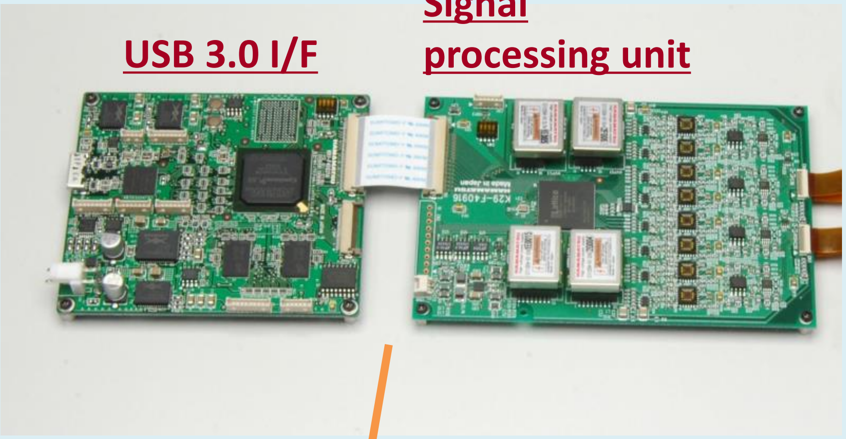
Results of 3D position map @662keV



Kishimoto et al. 2013, IEEE-TNS

Handheld Compton camera



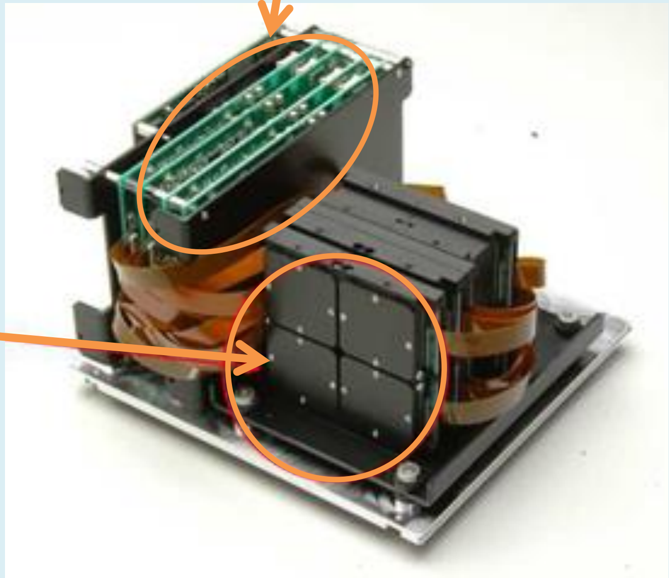


scatterer

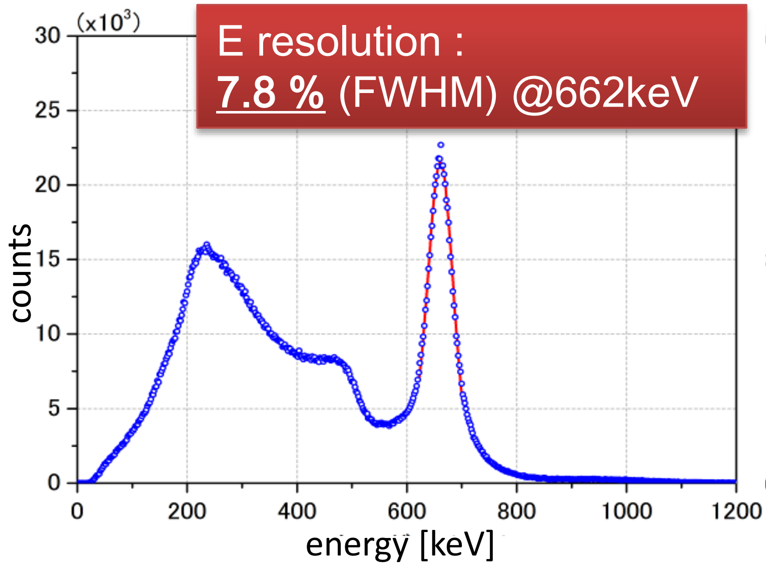
- pixel size : 2x2x4 mm^3
- array : 11x11, 4set
- 2 layer (non DOI)

absorber

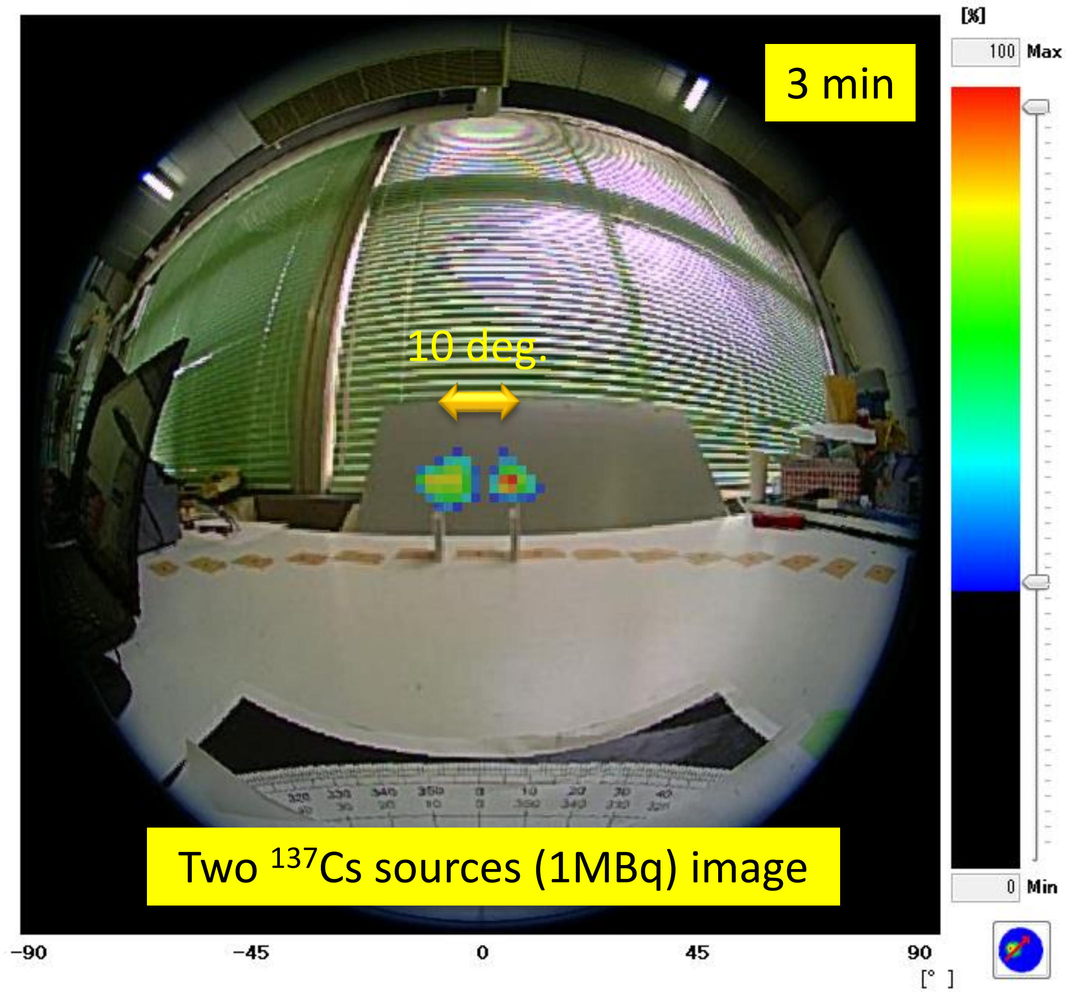
- pixel size : 2x2x2 mm^3
- array : 11x11x10, 4set
- 10 layer DOI



Performance of Handheld CC



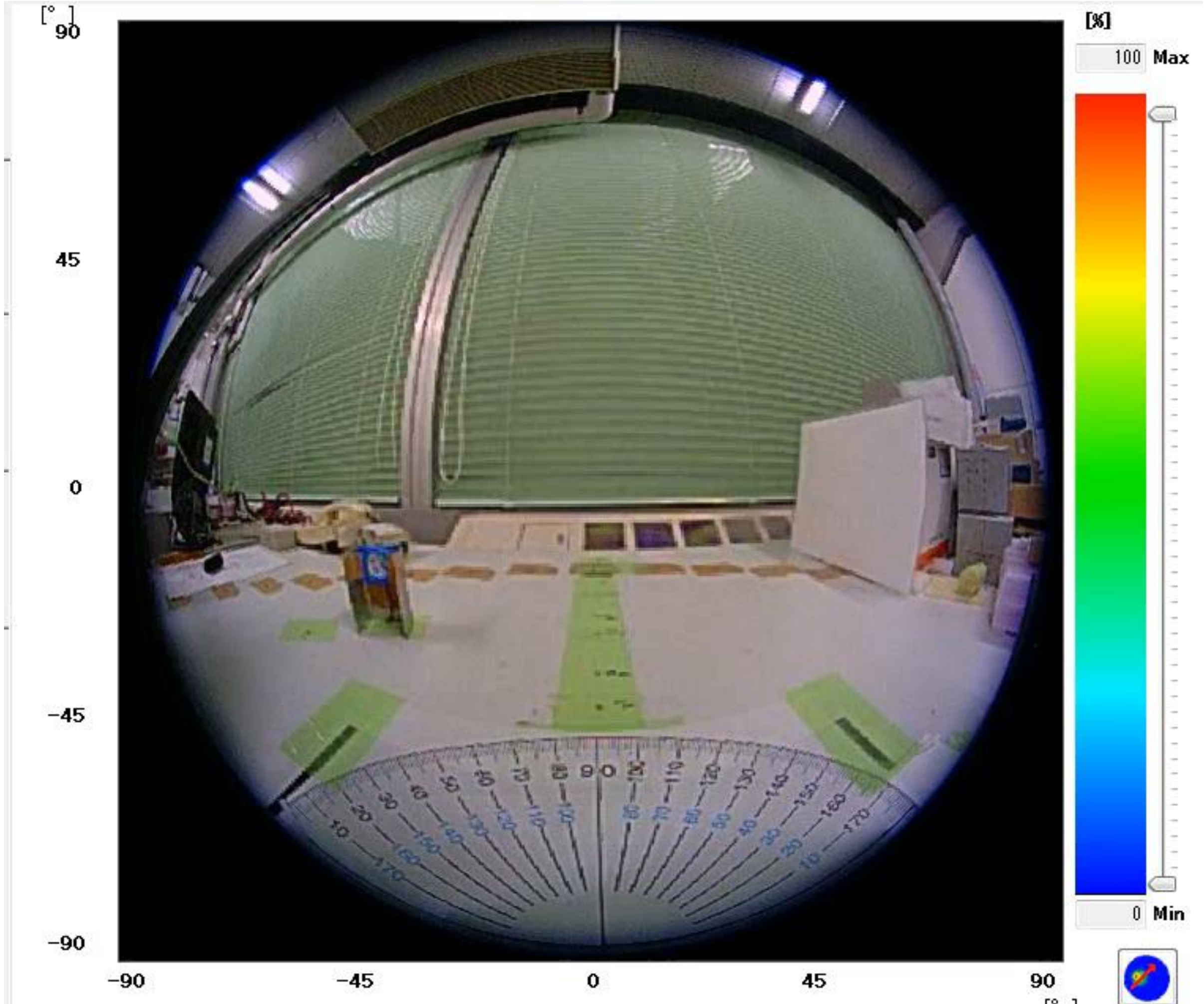
- Angular resolution : 8~9 deg (FWHM)
- Intrinsic efficiency : 0.4 %
- Two sources separated by 10 degrees were clearly distinguished



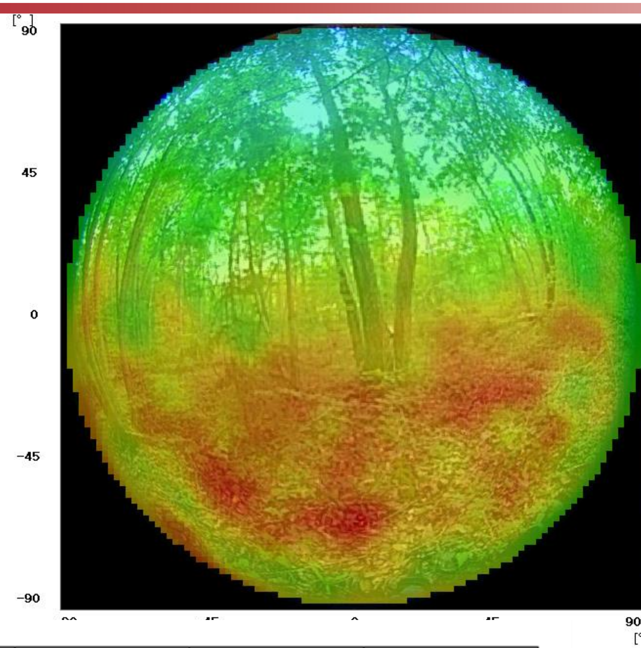
Performance : Real time measurement

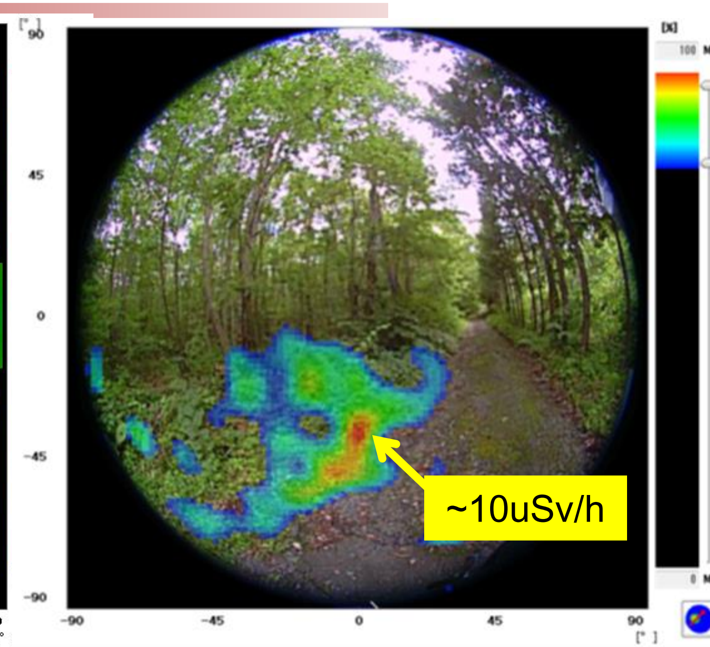
- Intensity of ^{137}Cs : 1 MBq
- Source distance : 30 cm

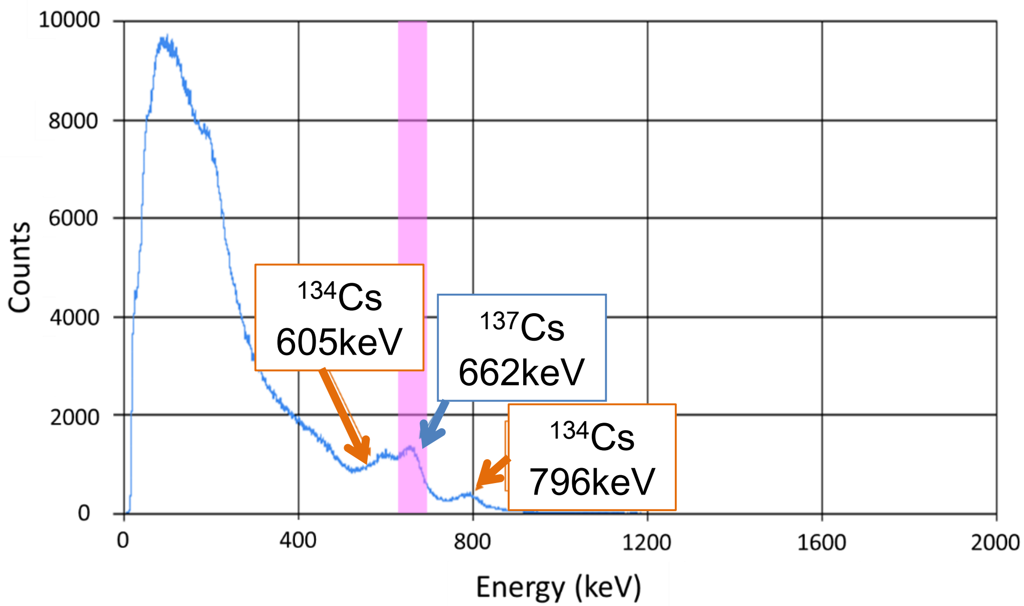
^{137}Cs ^{137}Cs



Field tests at Fukushima







- ✓ Several field tests have been conducted in Fukushima.
- ✓ Typical measurement time is a few min even under the background contamination of ~5μSv/h.

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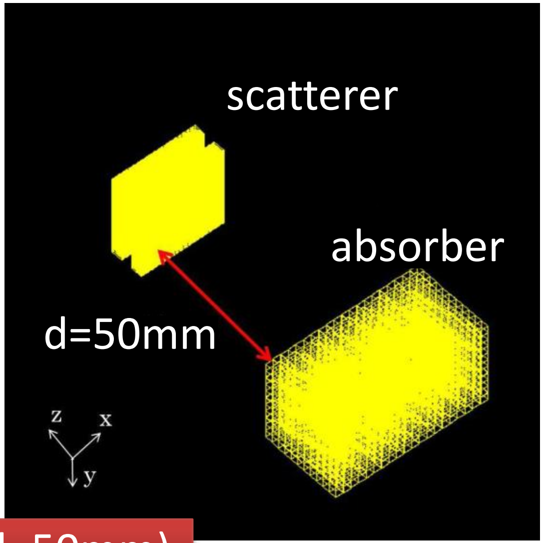
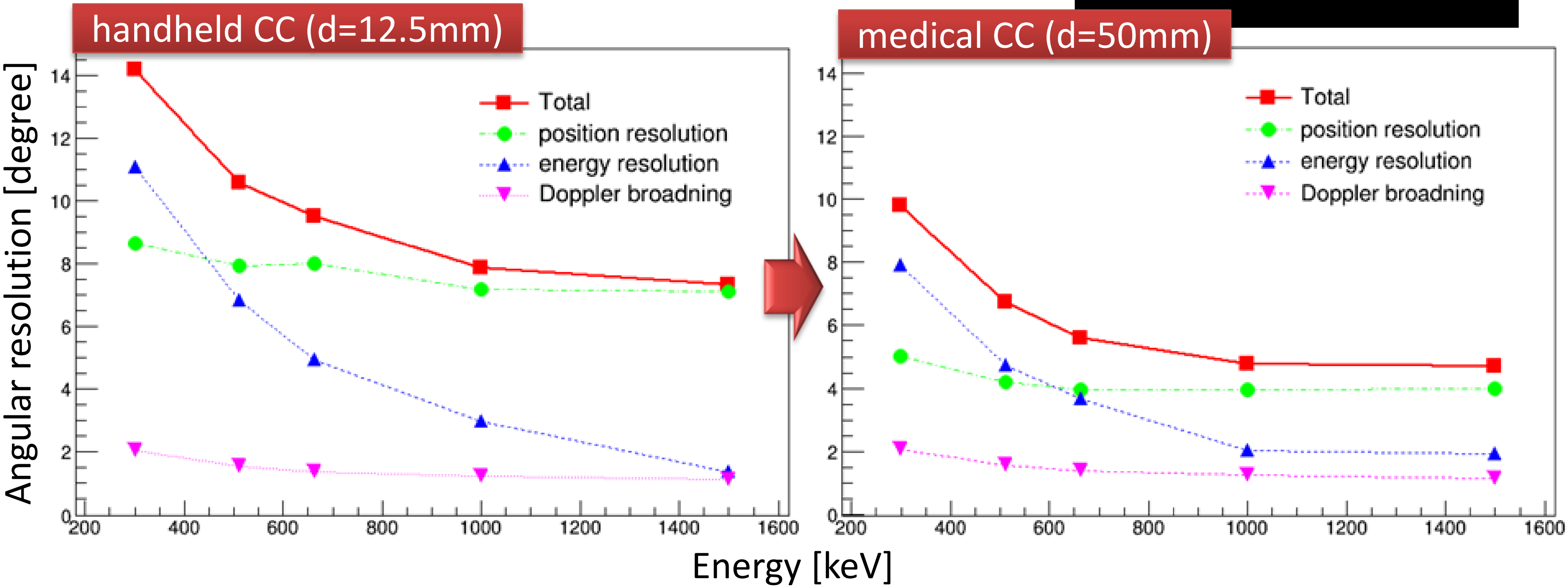
Development of high-resolution CC

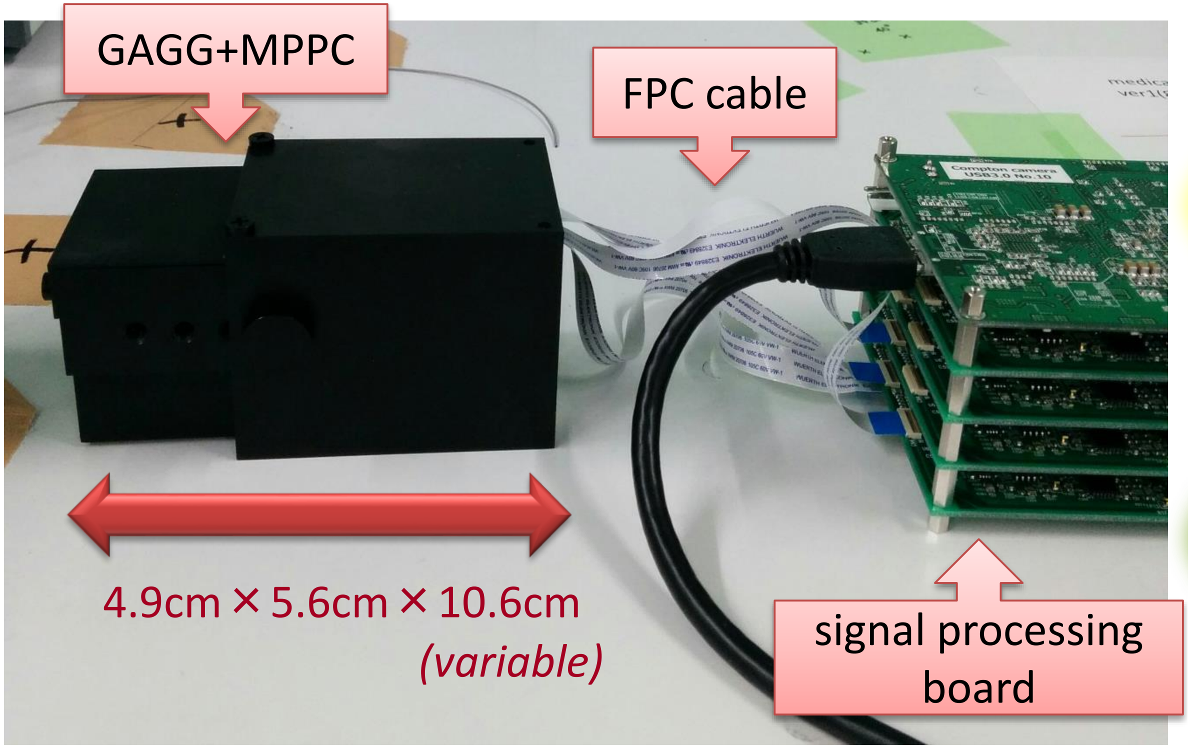
How to improve the resolution … ?

- ✓ In handheld CC, position uncertainty has largest effect on the angular resolution @ 662 keV
- ✓ By optimization of the detector geometry, ~twice improvement in angular resolution can be expected !





Development of high-resolution CC



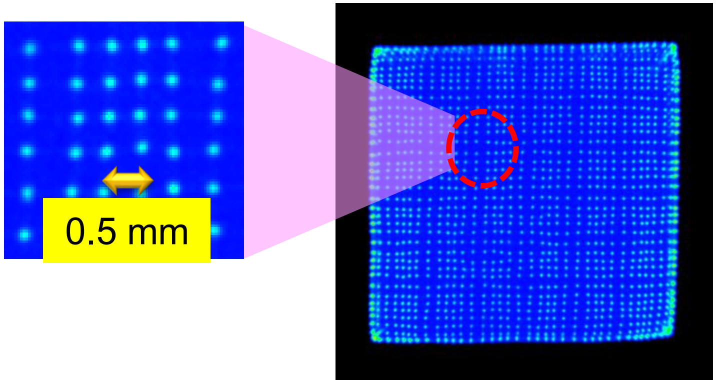
scatterer

- pixel size : 0.5x0.5x3 mm^3
- array : 40x40
- 2 layer (non DOI)

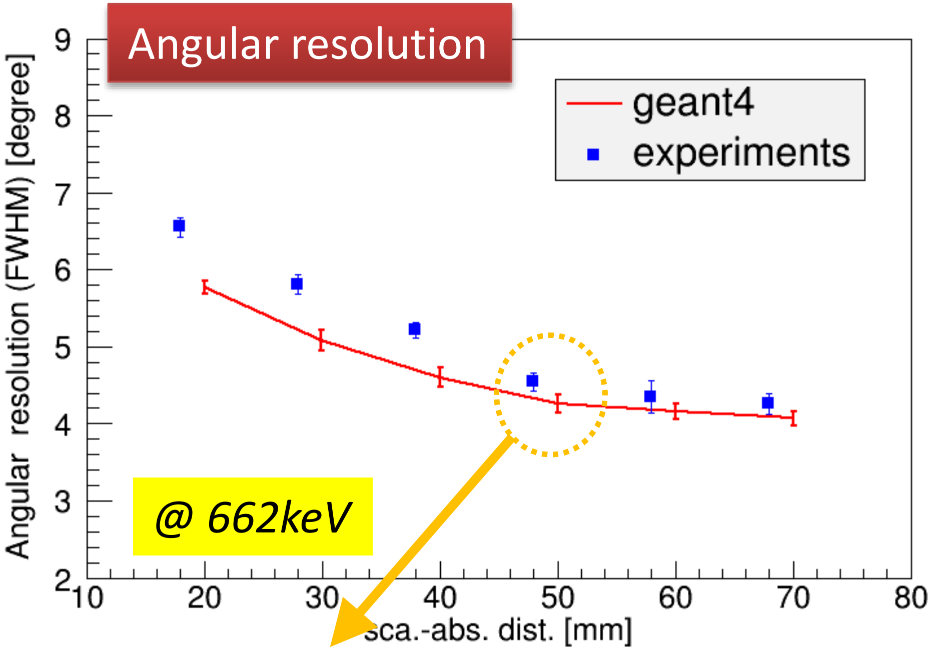
absorber

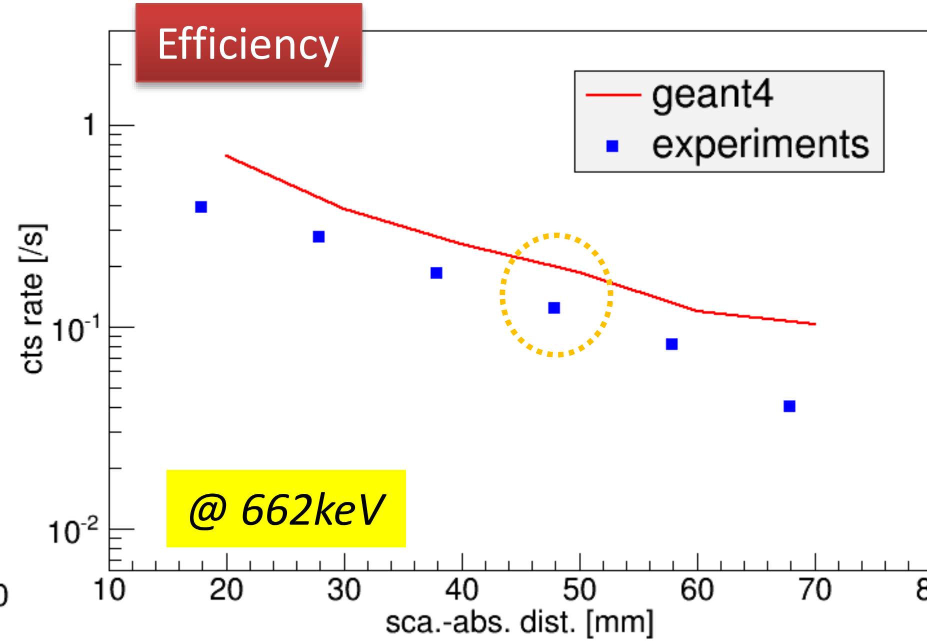
- pixel size : 2x2x2 mm^3
- array : 11x11x10
- 10 layer DOI

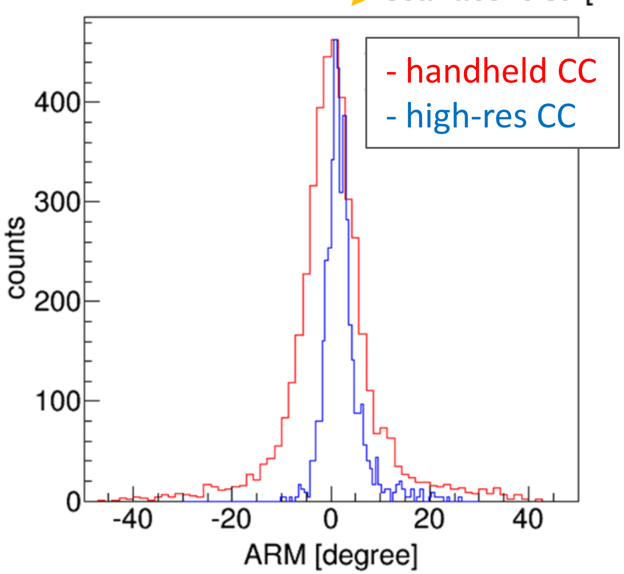
- ✓ More compact & flexible sensor head (1/4 scale)
- ✓ By changing *scatterer-absorber distance*, resolution, efficiency, and FOV are variable to suit the situation

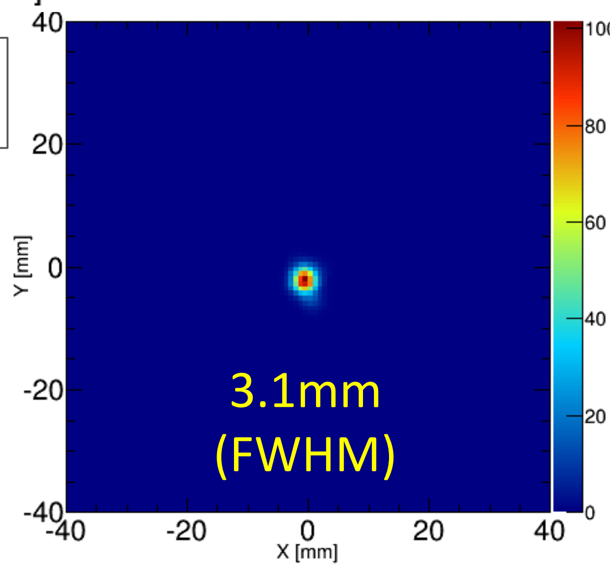


Basic performance of high-resolution CC









- ✓ Angular resolution is ~1.7 times better ! (4.5 deg.)
- ✓ Spatial resolution @40mm apart from detector is 3.1 mm (FWHM)
- ✓ Intrinsic efficiency becomes ~1/4 @662keV

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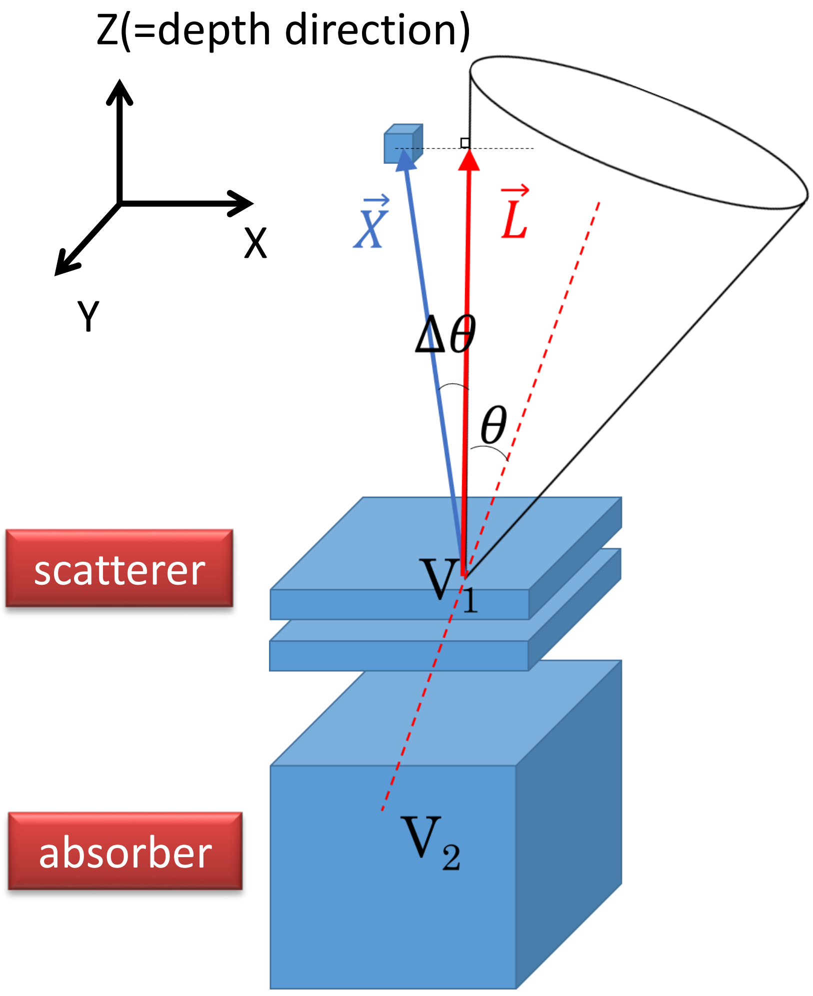
3D reconstruction method (3D MLEM)



3D List-mode MLEM method

Maximum Likelihood Expectation Maximization

$$\lambda_j^{\,n} = \frac{\lambda_j^{\,n-1}}{s_j} \sum_{i=1}^{N} \frac{t_{ij}\, vi}{\sum_k t_{ik} \lambda_k^{\,n-1}}$$

$$t_{ij} = \left|\vec{L}\right|^{-2} \exp\left[-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2\right] \times \frac{1}{\sin^2\theta}$$

$\lambda_j^{\,n}$: the value of the image pixel j at the n[th] iteration

s_j: probability i: event number t_{ij}: weighted likelihood

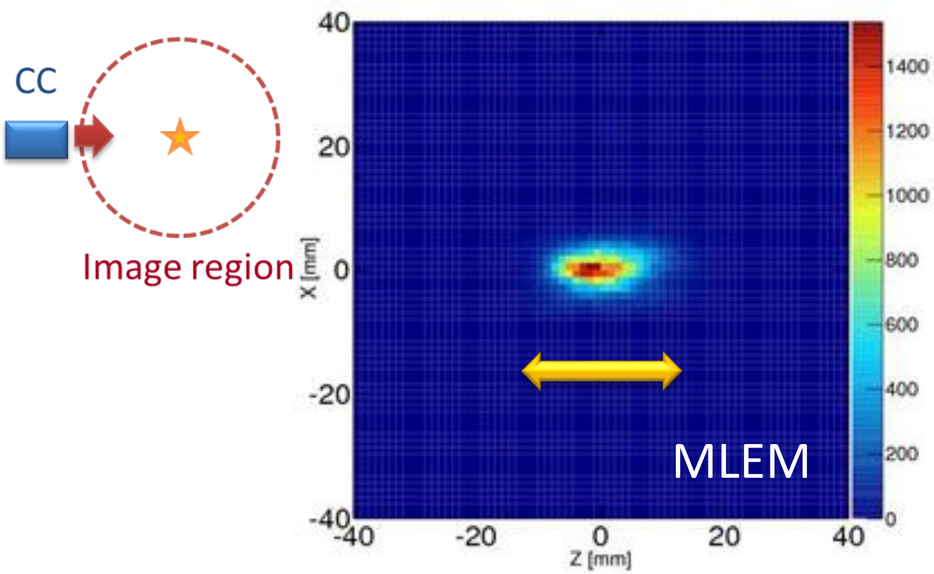
σ: spatial resolution $\Delta\theta$: intrinsic angular resolution

- ✓ Expanded list-mode MLEM to 3D
- ✓ Image region: 8cm x 8cm x 8cm
- ✓ Calculate sensitivity map (s_j) by Geant4

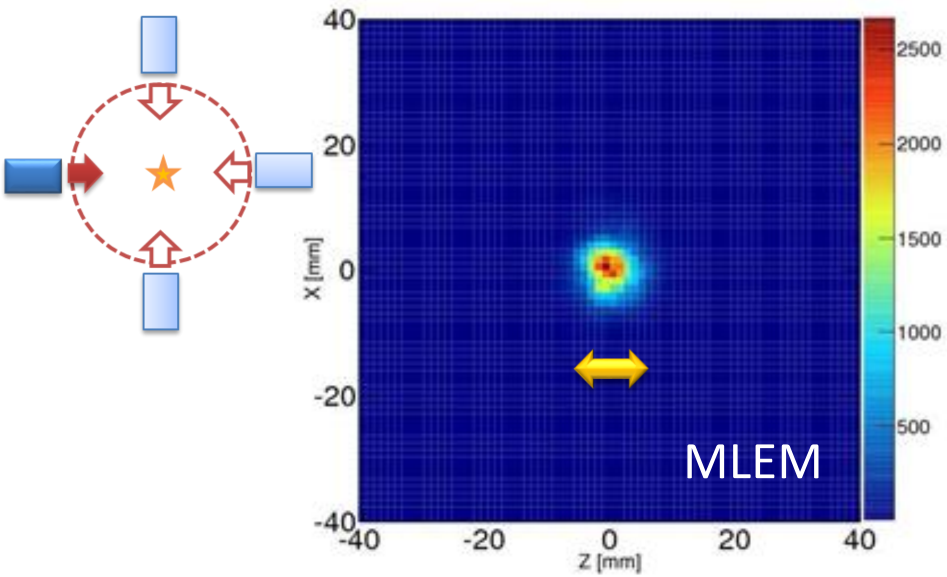
Single angle v.s. Multi angle data acquisition

- ✓ In depth (z) direction, CC image has large position uncertainty because of lack of z intersecting data (single-angle)
- ✓ To compensate for the lack of data, we acquire the data from several angles for imaging region (multi-angle)
- ✓ In multi-angle acquisition, we rotate one Compton camera

single angle

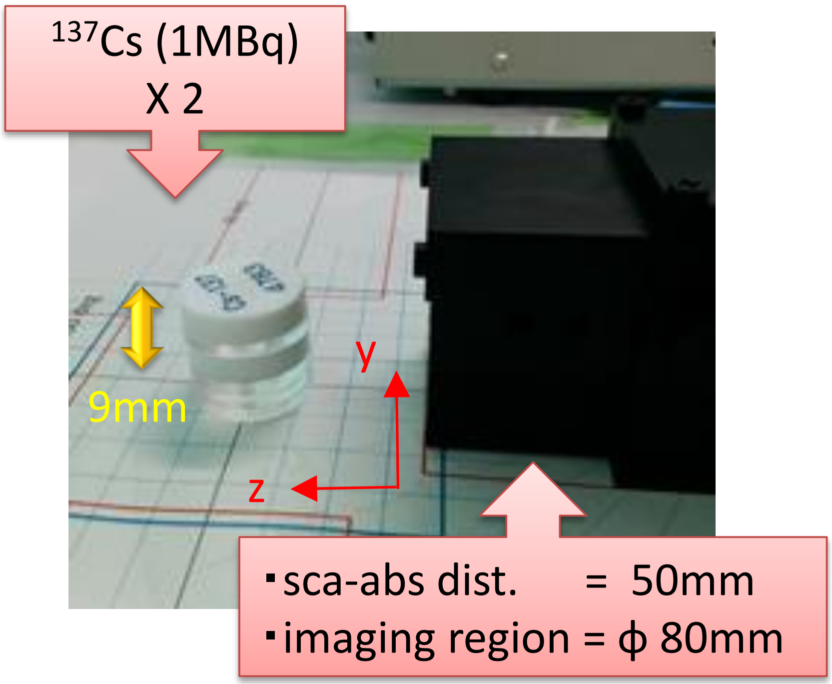


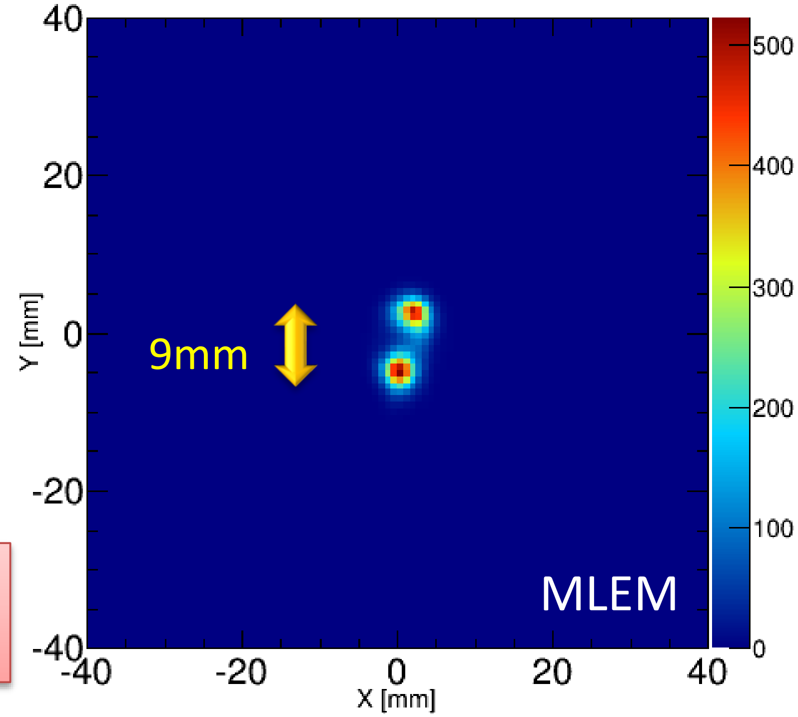
multi angle (4 angle)

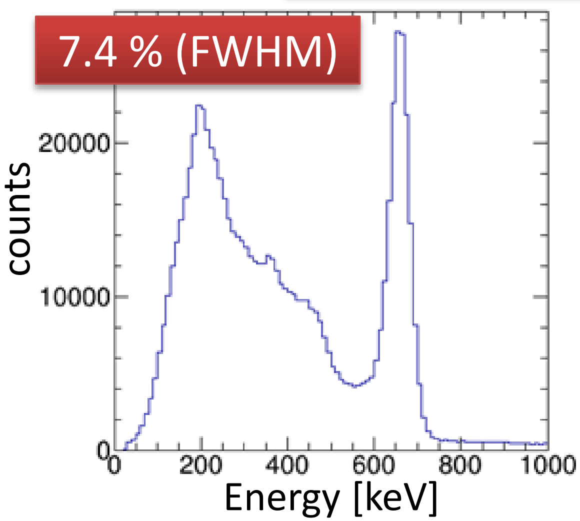


Kishimoto et al. 2015, JINST

Results of 3D imaging: 1 (single color source)



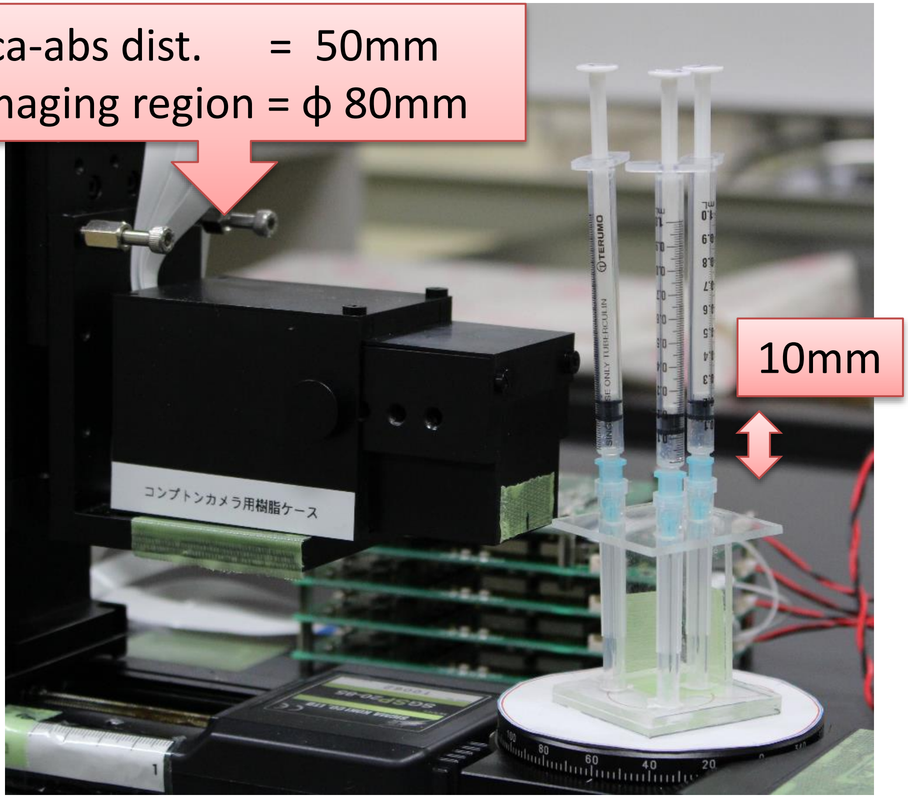


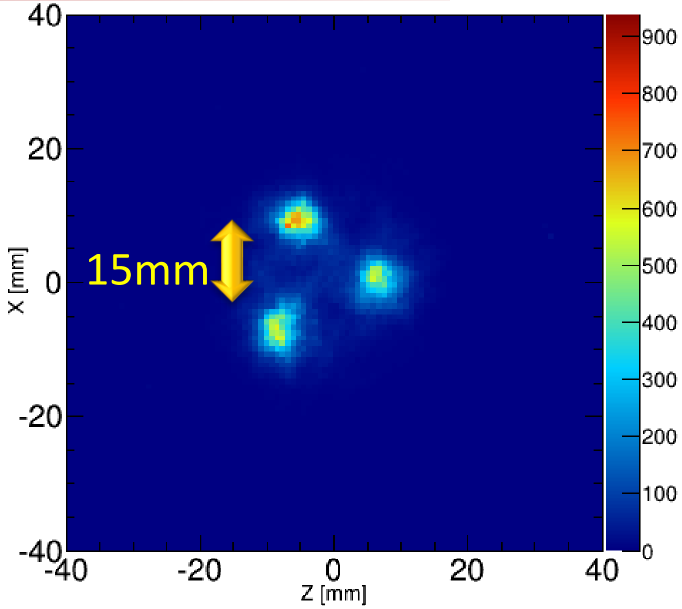


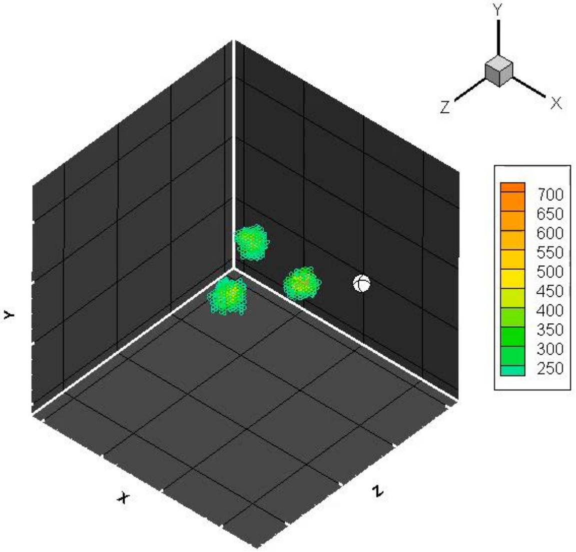
- ✓ single angle data-acquisition
- ✓ Integration time : 5 min.
- ✓ Two sources of 9 mm separation were clearly distinguished

Results of 3D imaging: 2 (phantom imaging)

- sca-abs dist. = 50mm
- imaging region = ϕ 80mm





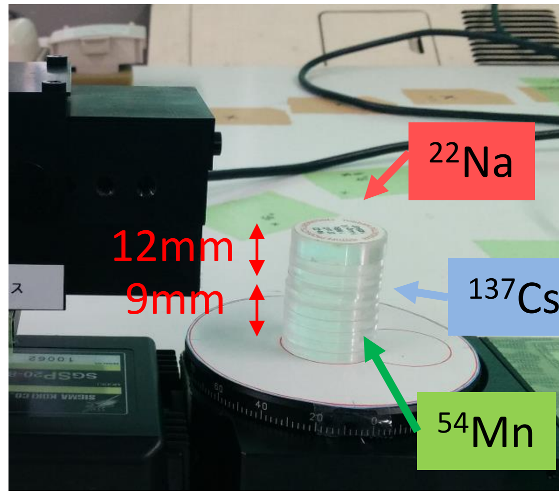


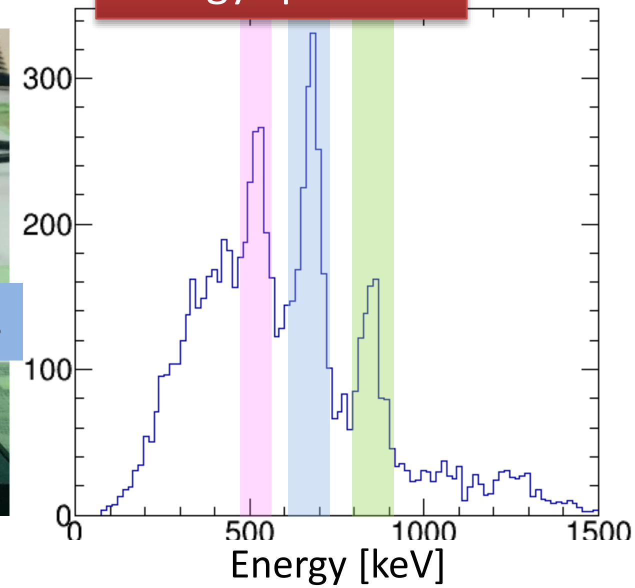
- ✓ 3 syringes (ϕ4.5mm) phantom filled with ^{18}F (~0.75MBq)
- ✓ 12-angle data acquisition
- ✓ Total integration time : 15 m

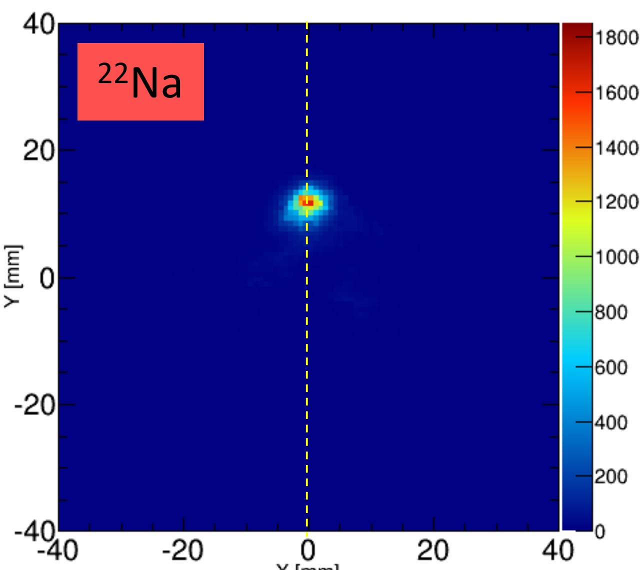
Results of 3D imaging: 3 (multi color source)

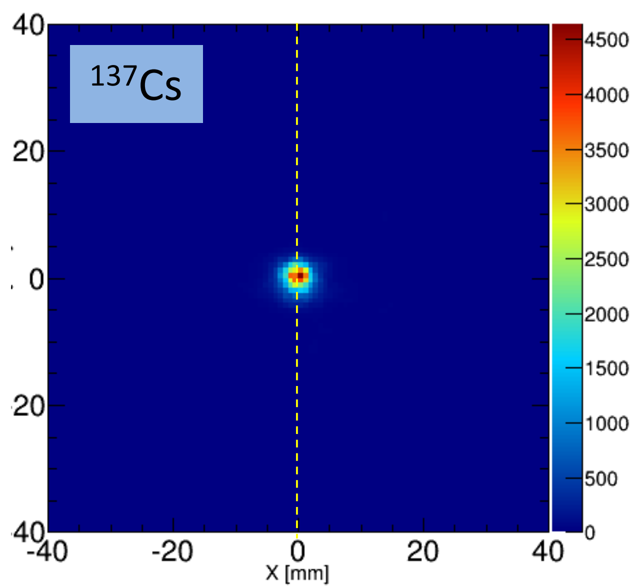
Imaging different-energy sources at the same time !

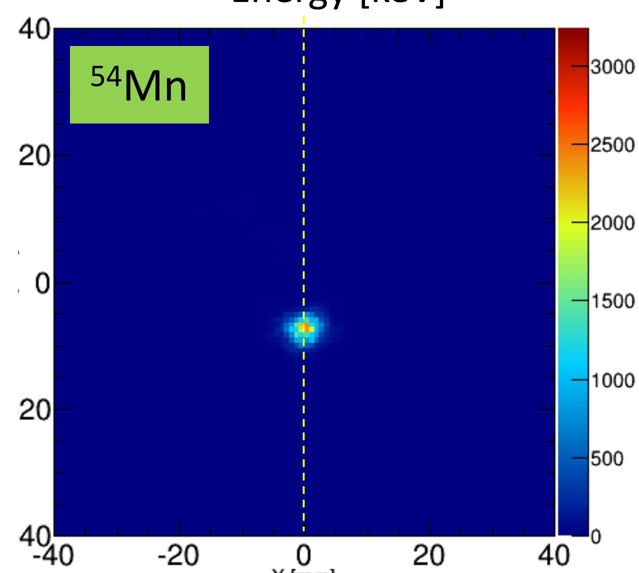
- ✓ ^{22}Na(511keV), ^{137}Cs(662keV), ^{54}Mn(834keV)
- ✓ 12-angle data-acquisition
- ✓ Integration time : 12 x 30sec
- ✓ MLEM : 20 iteration



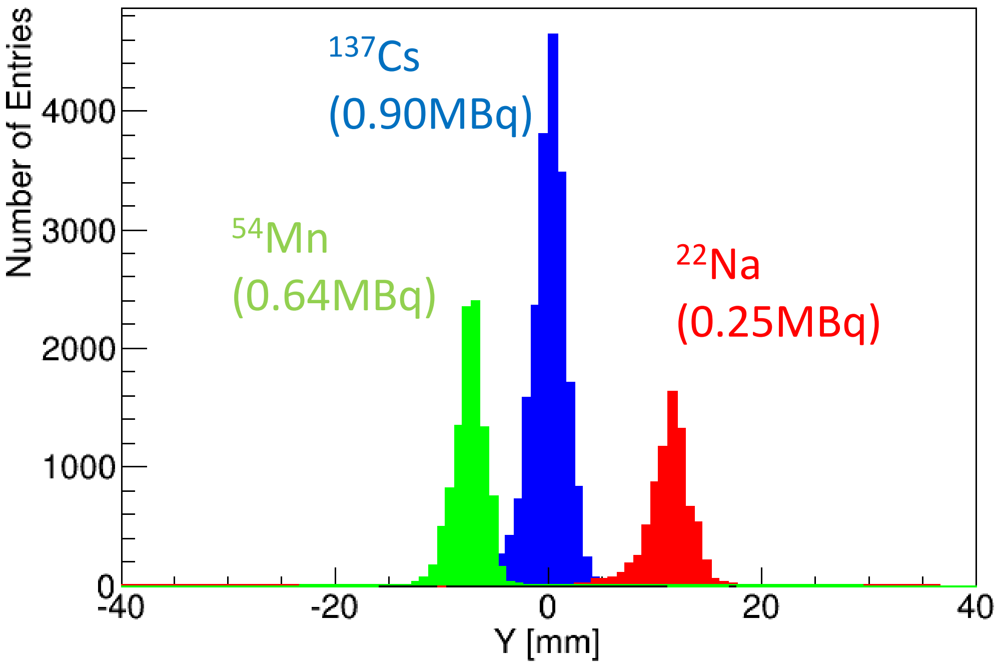


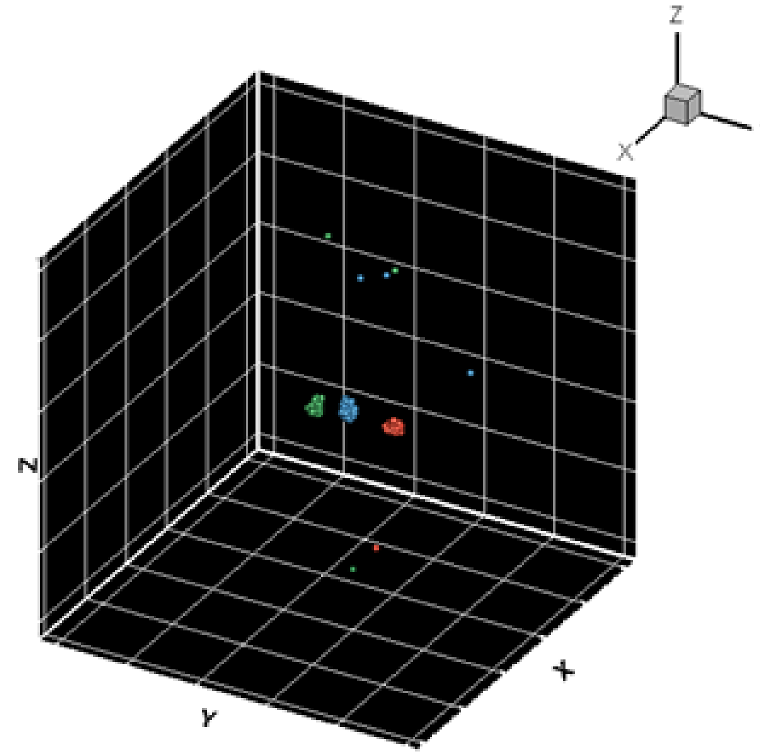






Results of 3D imaging: 3 (multi color source)





- ✓ Each source is imaged in real position
- ✓ Intensity of each source is almost reconstructed correctly
- ✓ By multi-angle data acquisition, colored 3D image can be obtained even at low detector cost

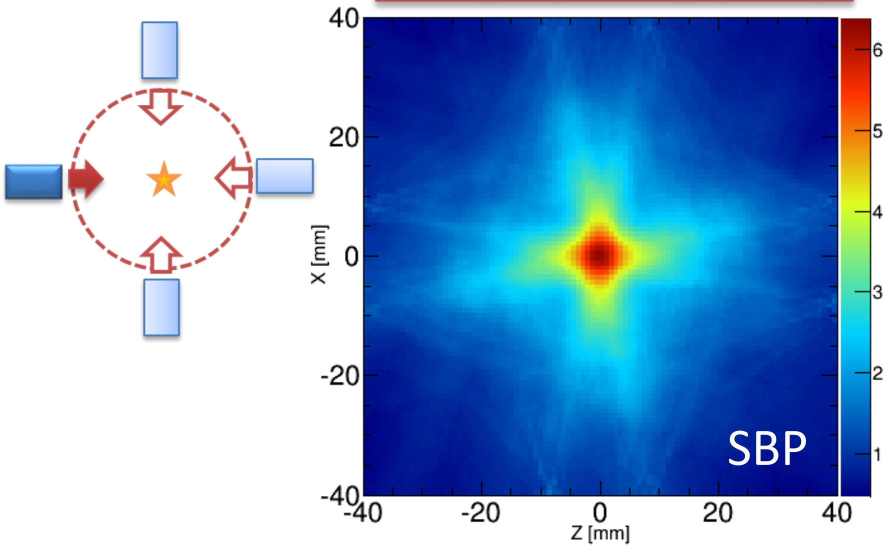
Summary

- ✓ New Compton camera for molecular imaging has achieved more compact size (1/4) and good angular resolution (4.5 deg). ^{137}Cs point source was imaged in spatial resolution of ~3mm.
- ✓ By measuring data from several angles, uncertainty in the depth direction significantly decreased and 3D reconstruction became possible.
- ✓ By the Compton camera, we succeeded 3D multi-color imaging of different-energy sources at the same time.

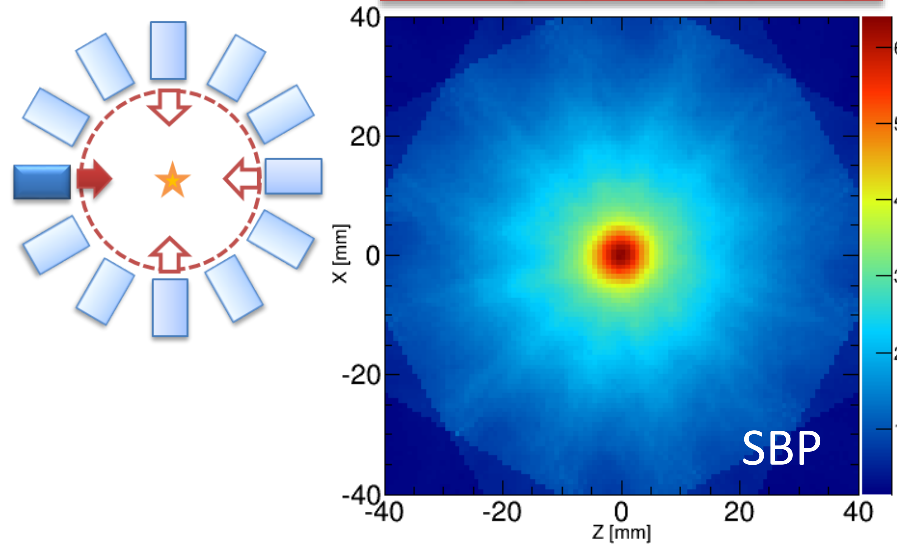
Appendix

Dependence on the number of angle

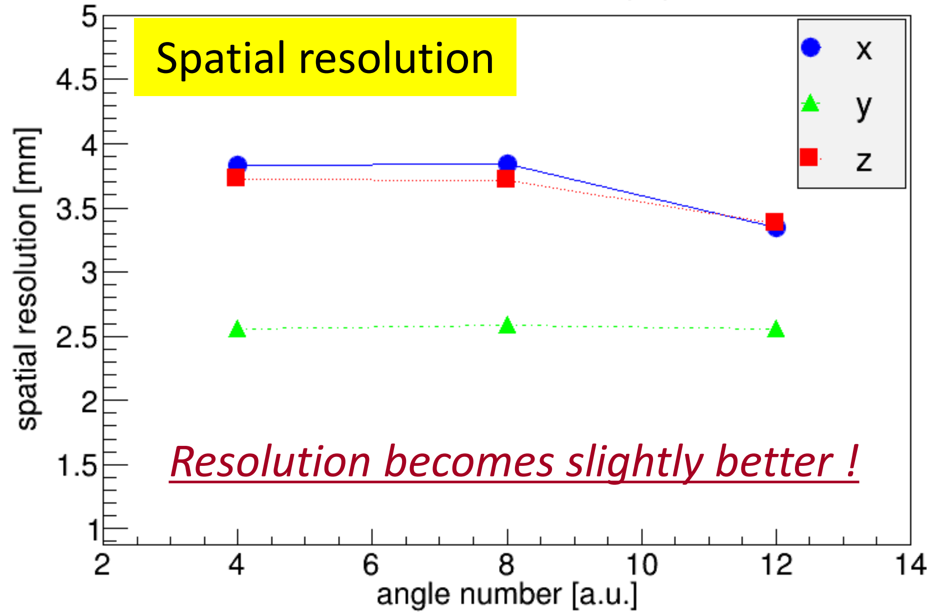
4 angle (90 deg. pitch)



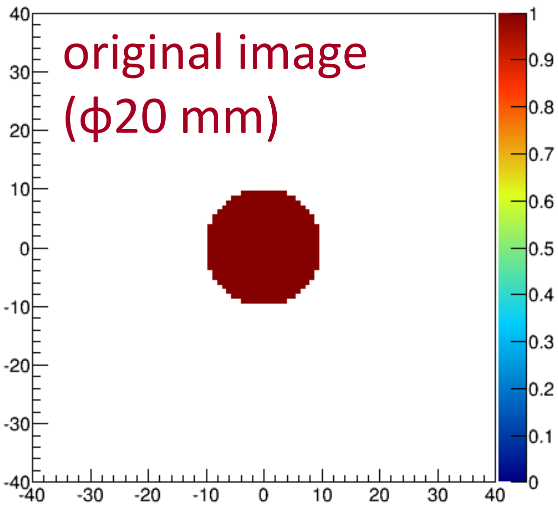
12 angle (30 deg. pitch)



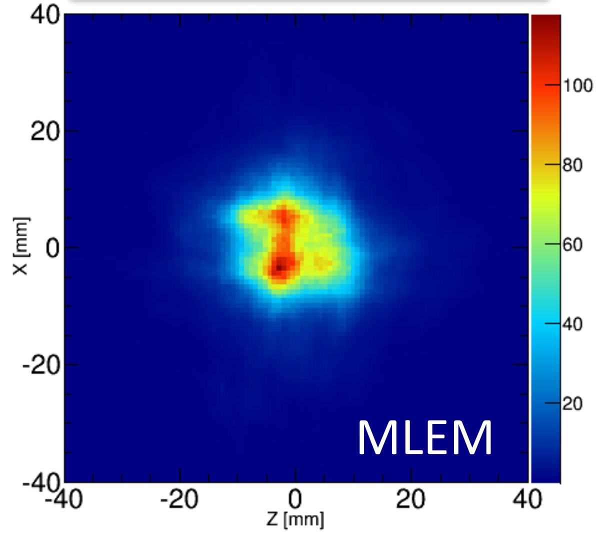
- ✓ Study dependence of spatial resolution on the number of data acquisition step
- ✓ Rotate one detector around the imaging region
- ✓ To compare the image quality fairly, total data acquisition time is same



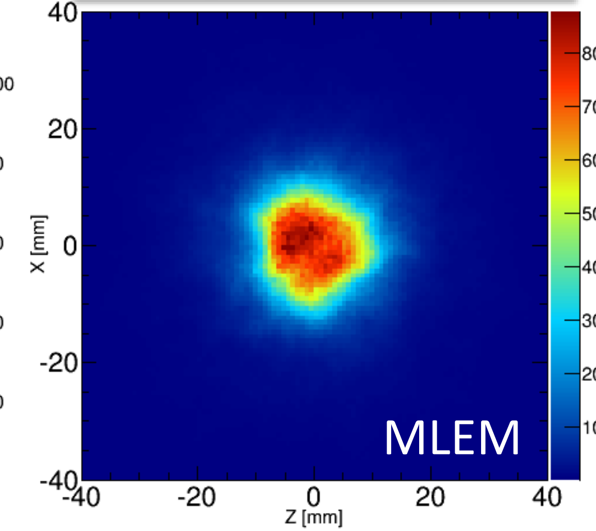
Dependence on the number of angle



4 angle (90 deg. pitch)

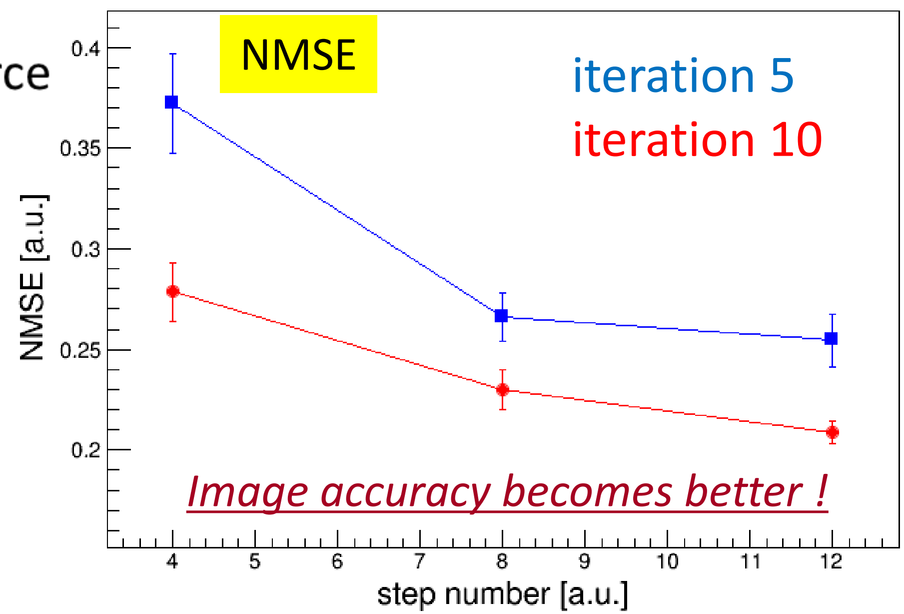


12 angle (30 deg. pitch)

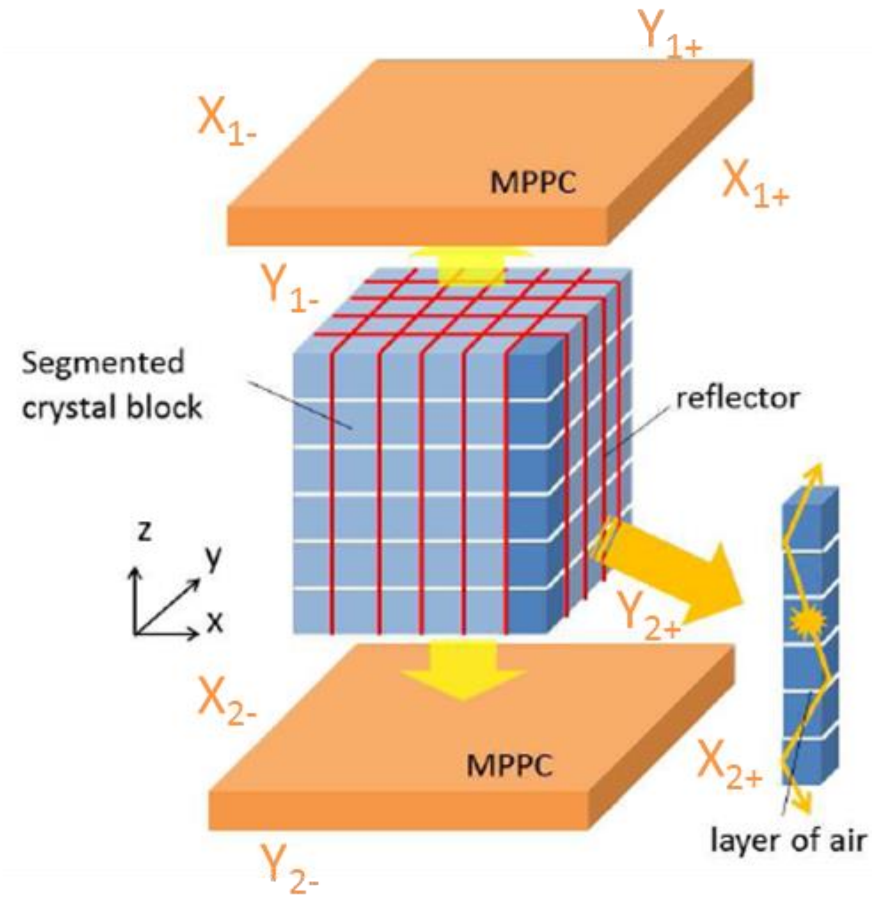


- ✓ Evaluate image accuracy of diffuse source
- ✓ $NMSE = \frac{\sum_x \sum_y \{g(x,y) - f(x,y)\}^2}{\sum_x \sum_y f(x,y)^2}$

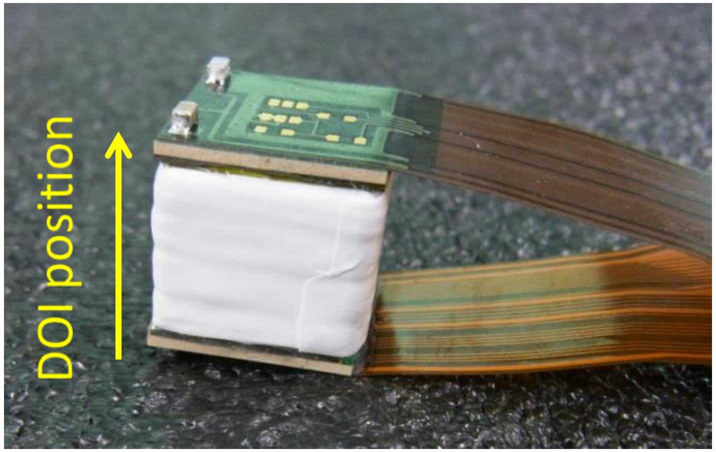
  $f(x, y)$: standard image
  $g(x, y)$: reconstructed image



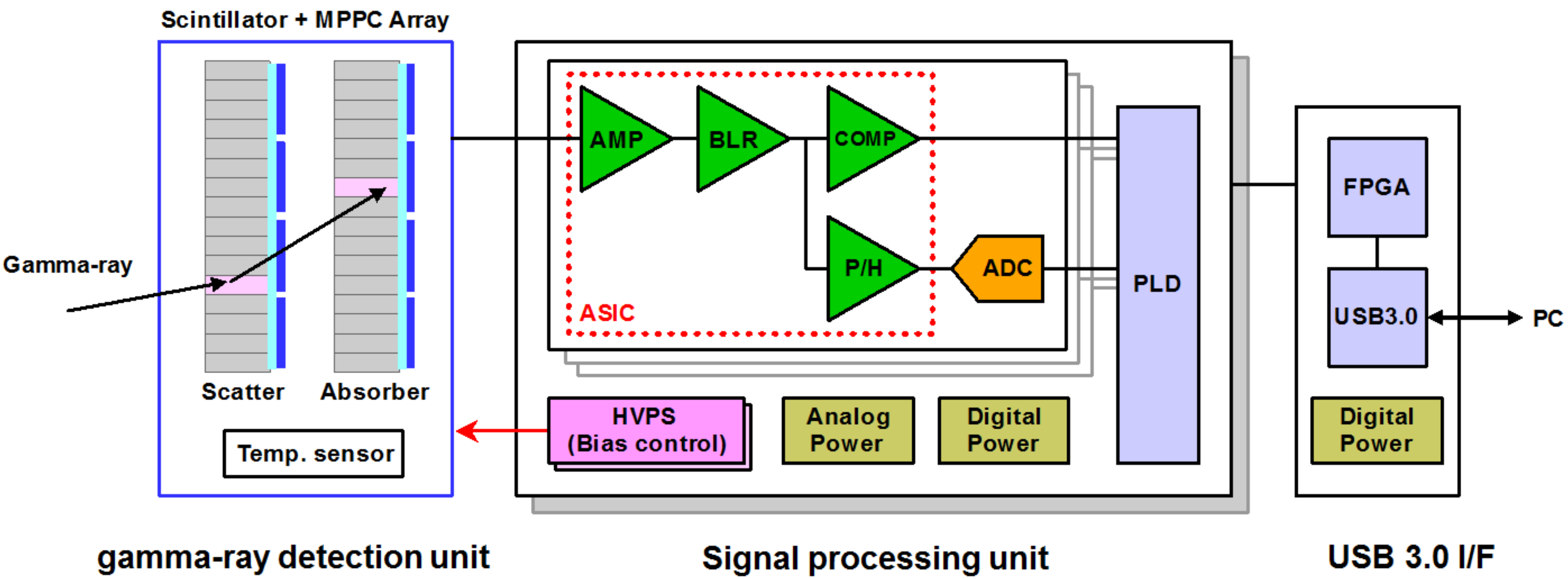
DOI method



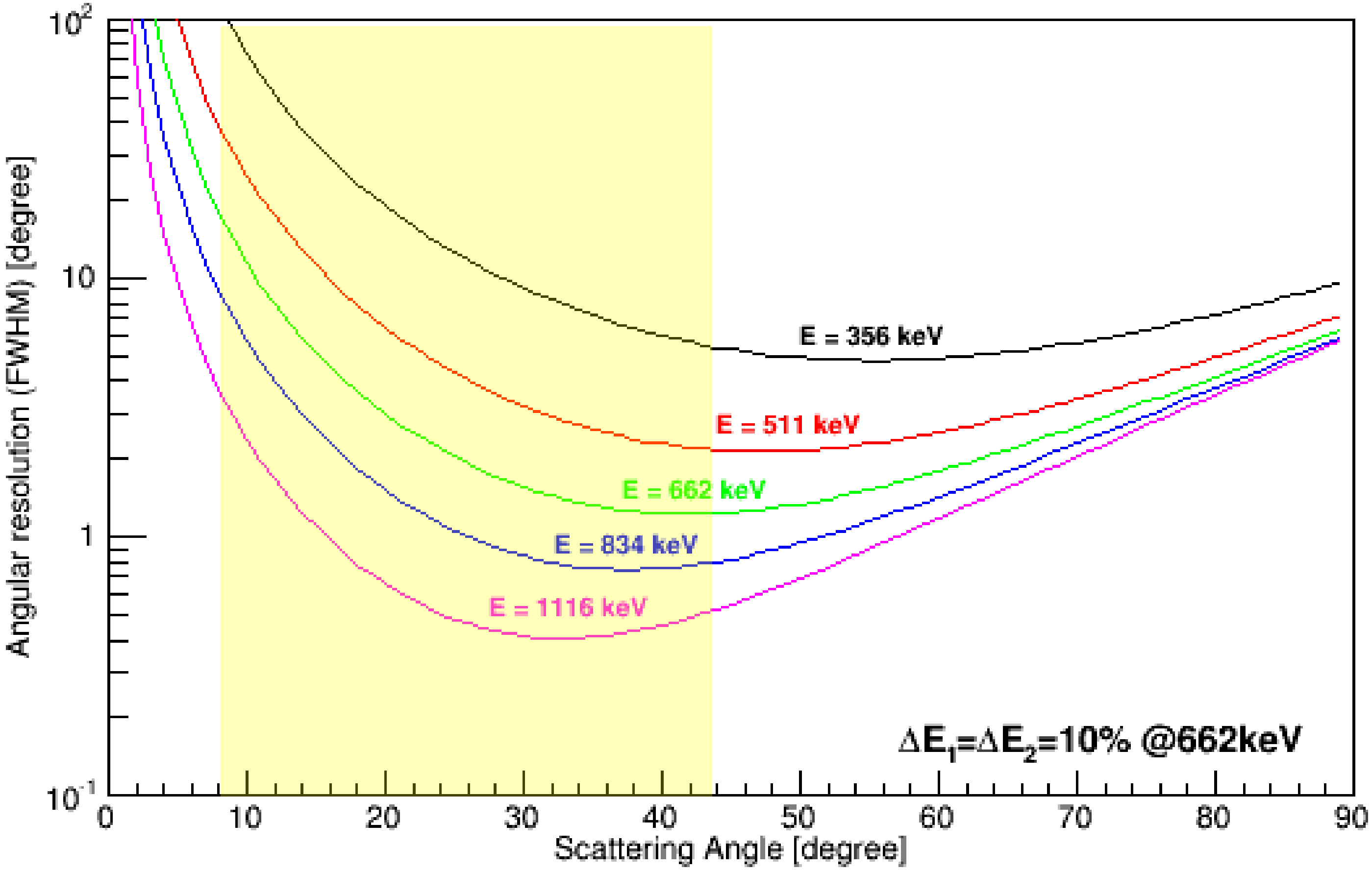
- <u>In the 2D (x,y) direction</u>
  reflectors divide each pixels
- <u>In the DOI (z) direction</u>
  layers of air divide each pixels



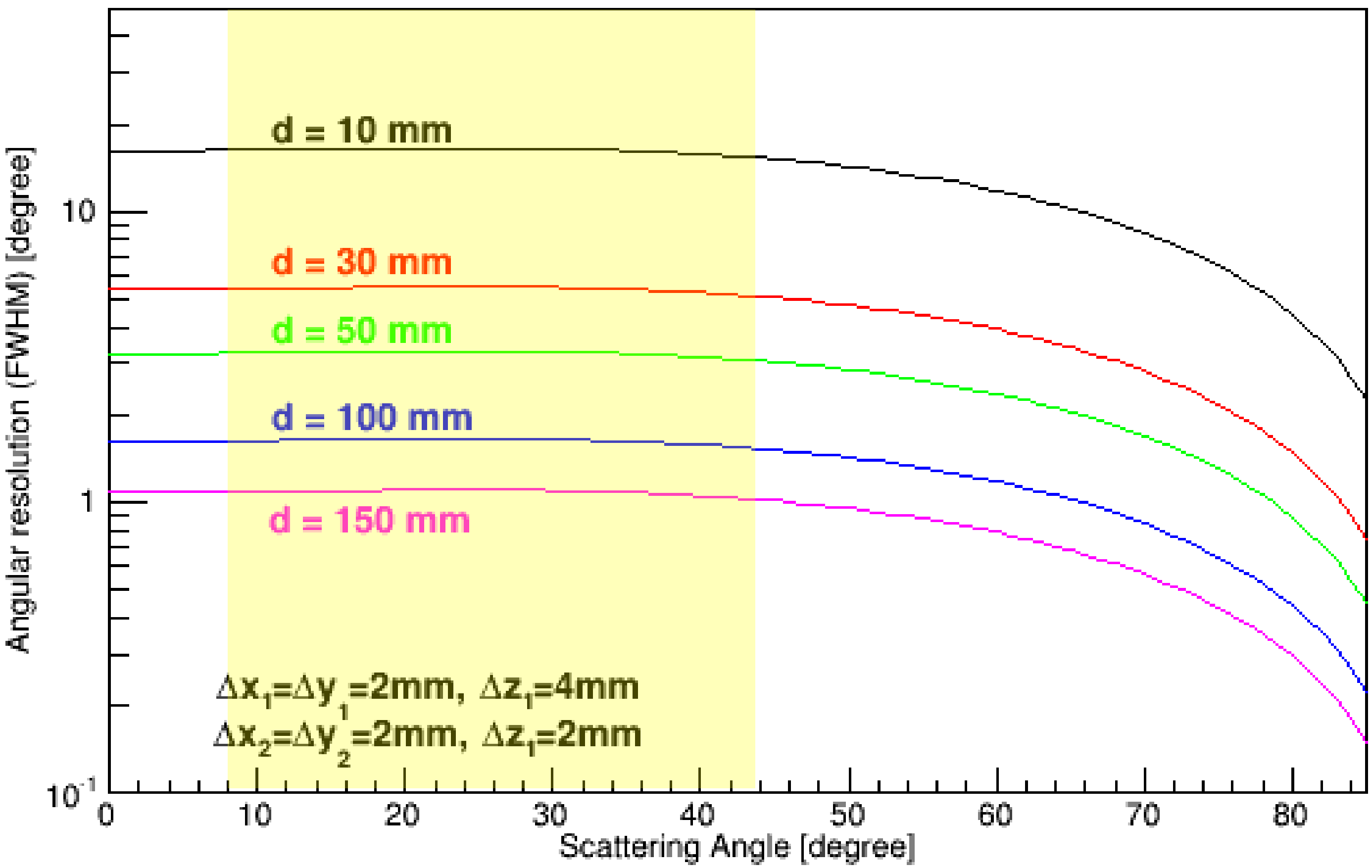
Read-out diagram



The contribution of energy resolution

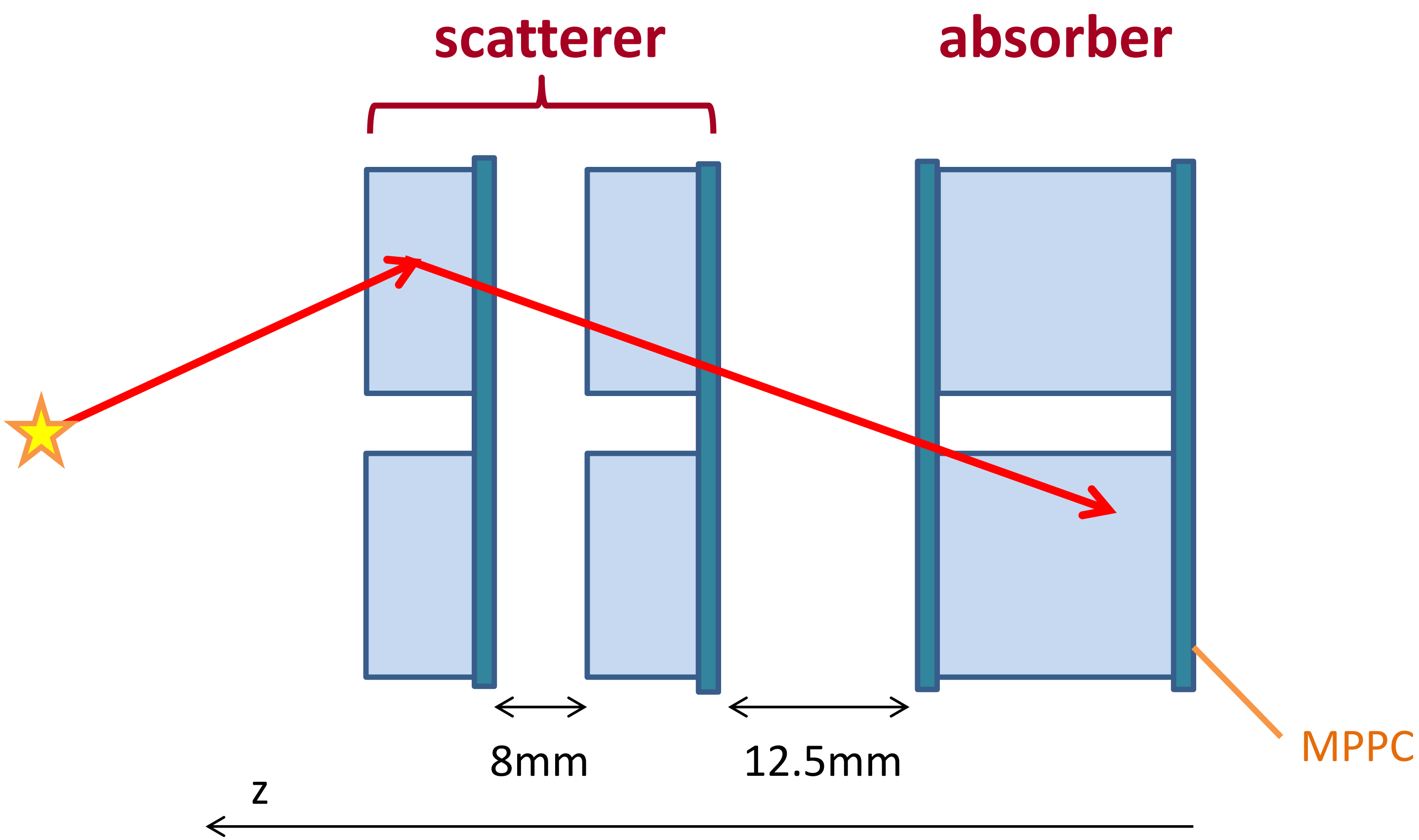


The contribution of geometry



The contribution of geometry

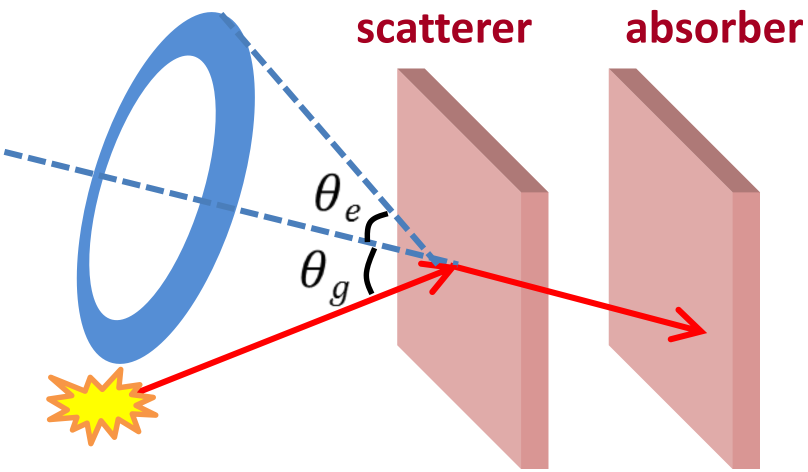
The configuration of 3-D Compton Camera



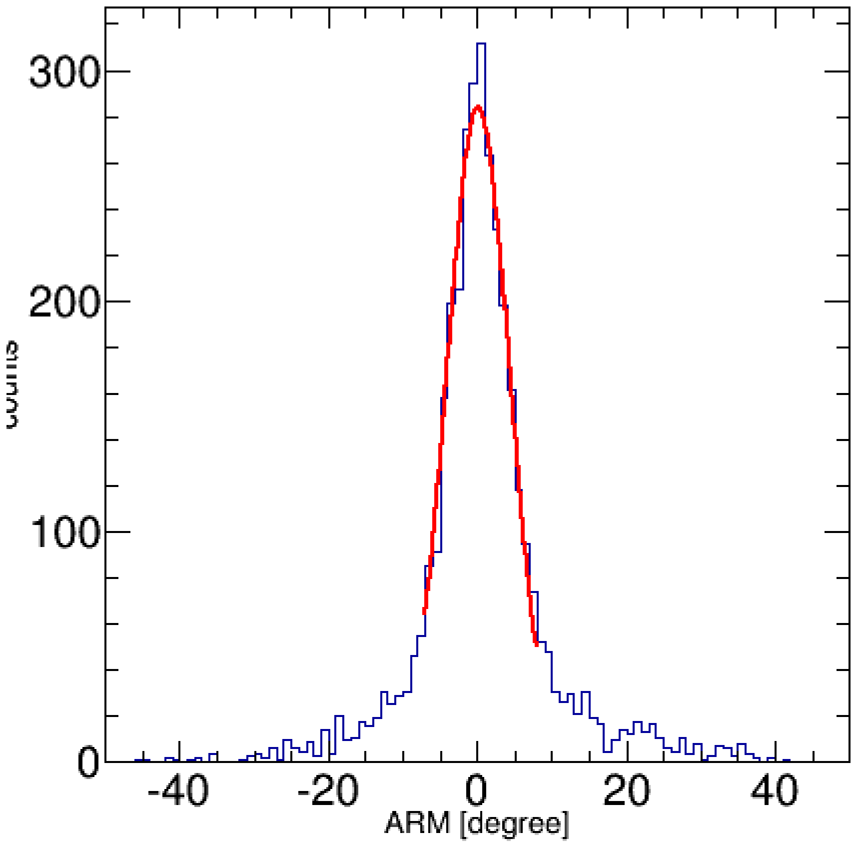
- $2 \times 2 \times 4$ mm^3 pixel
- $11 \times 11 \times 1$ array (8 block)

- 2 mm^3 pixel
- $11 \times 11 \times 10$ array (4 block)

The definition of angular resolution



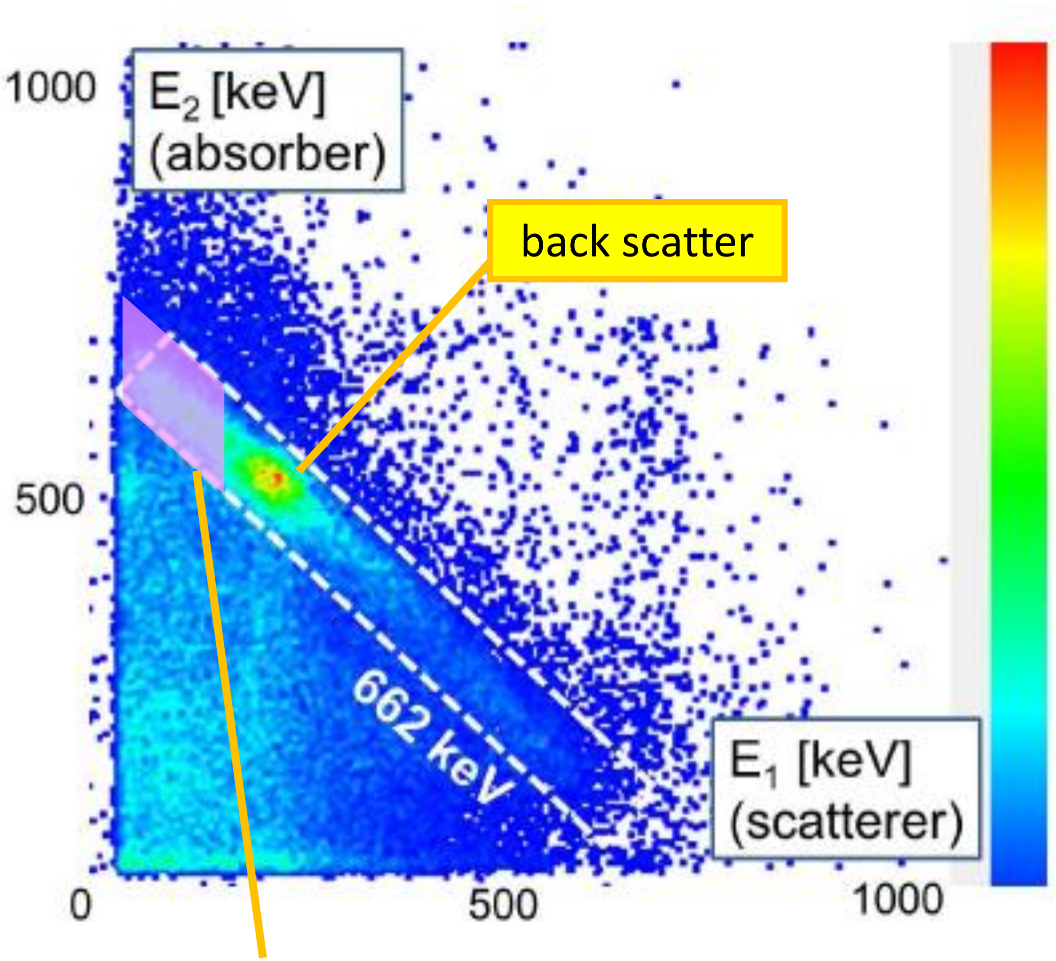
- $ARM \equiv \theta_e - \theta_g$
- $\Delta\theta \equiv \Delta ARM$



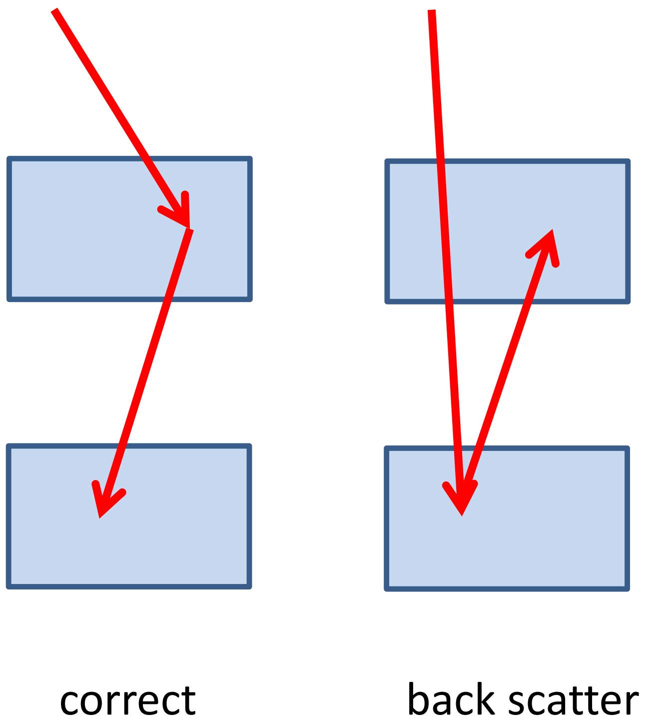
$\Delta\theta$ = 8.8 degree (FWHM)

@3-D, center of the visual field

2D energy spectrum



$10 < Esca < 165\ keV$



Ce: GAGG scintillator

Ce: $Gd_3Al_2Ga_3O_{12}$

scintillator		Ce:GAGG	Tl:NaI	Tl:CsI	BGO
Density	g/cm^3	6.63	3.67	4.53	7.13
Decay constant	ns	88	230	1050	300
Hygro scopic		no	yes	yes	no
Photons per MeV	photon/MeV	60000	45000	56000	8000
Energy resolution	%@^{137}Cs-662keV, 5mm cubic crystal	6.3	5.6	5.7	12
Melting point	°C	1850	651	621	1050
Emission maximum	nm	520	415	550	480