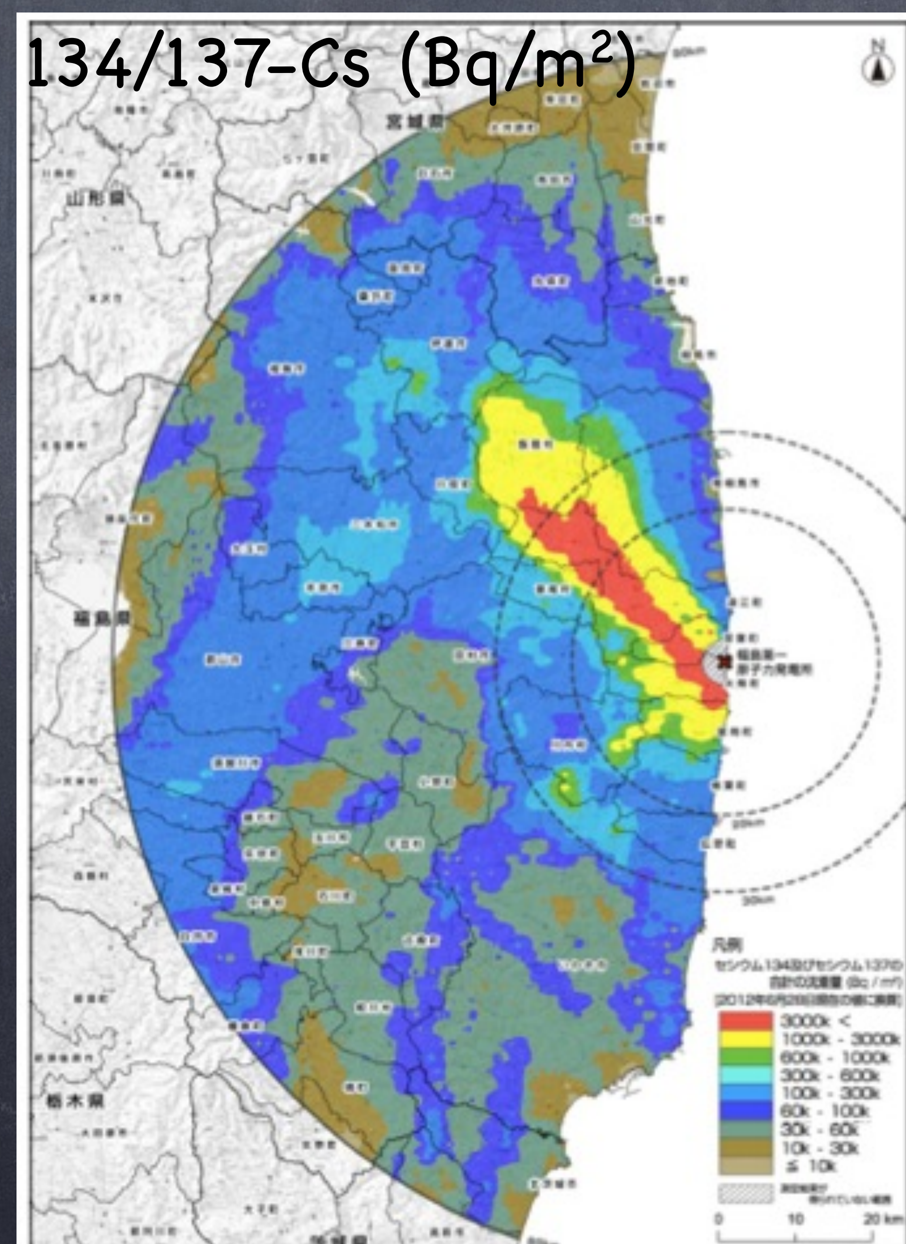
A portable Si/CdTe Compton camera and its applications to visualization of radioactive substances

Shin'ichiro Takeda (ISAS/JAXA)

Atsushi Harayama,
Yoto ichinohe,
Tadayuki Takahashi,
Shin Watanabe
(ISAS/JAXA)
Hiroyasu Tajima
(Nagoya University)
Kei Genba,
Daisuke Matsuura,
Hiroshi Ikebuchi,
Yoshikatsu Kuroda
Tetsuya Tomonaka
(Mitsubishi Heavy Industry)



Urgent problem

Introduction

Imagine ....

The field contaminated by radioactive materials (137/134Cs) with an average intensity of a few 100 kBq/m^2 (a few μSv/h).

A couple of hotspots per about 10x10 m^2 region, which contains several times lager intensity than the average.

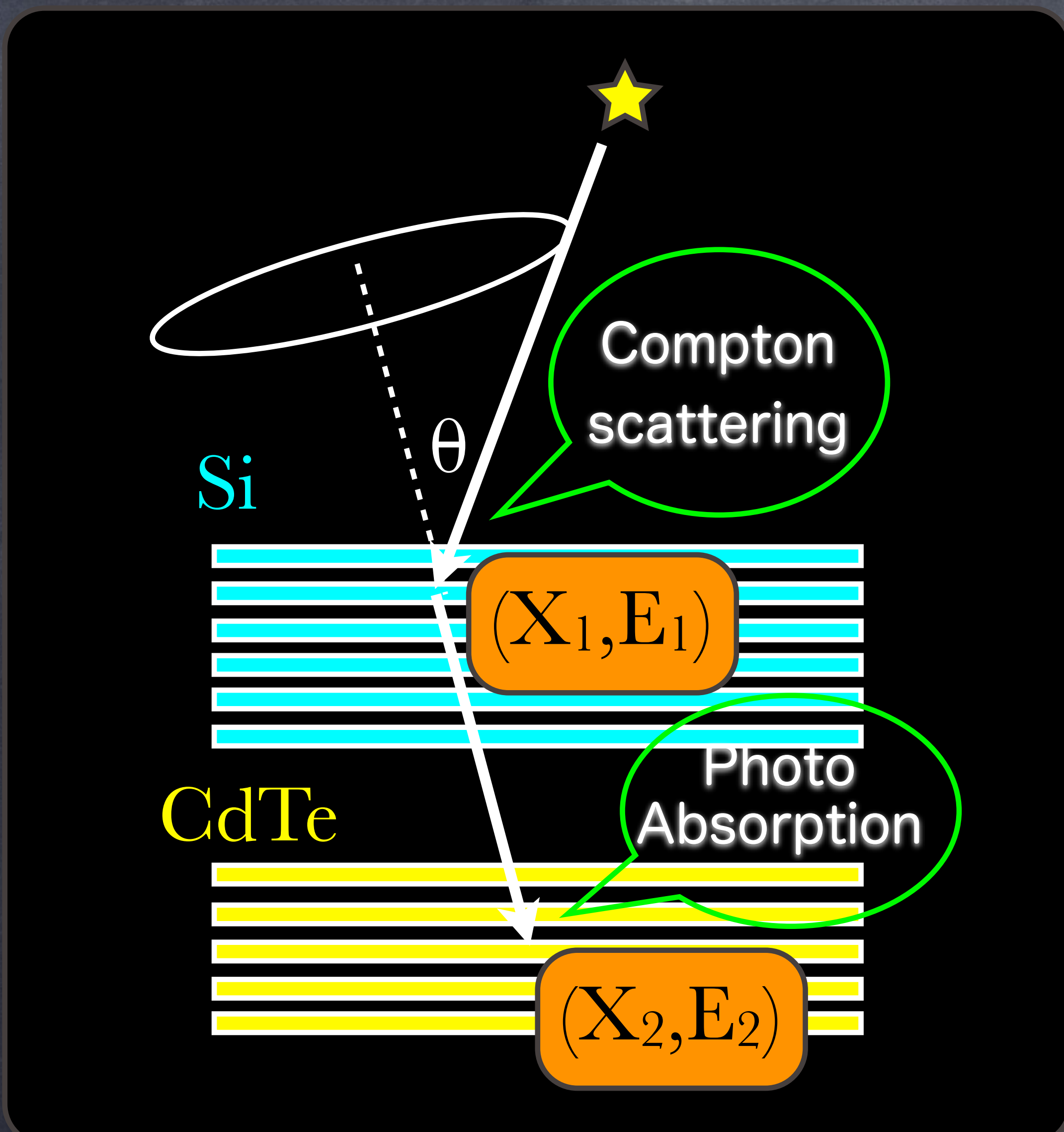
Things that we can do to help the decontamination by using a gamma-ray imaging system.

Env. Rad. Level ~ 5 μSv/h

Env. Rad. Level ~ 2 μSv/h

Approach

Si/CdTe Compton camera



(Takahashi et al. 2003)

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

Advantage ;

- Semiconductor detectors

  Precise gamma tracking (high ΔX, ΔE)

- Low-Z (Si) & High-Z (CdTe)

  Si : small doppler broadening effect

  Good angular resolution (∼1°@500 keV)

  Si : $\sigma_{comp} / \sigma_{photo} >> 1$

  Correct sequence reconstruction (>85%) without Time of Flight

CdTe : High stopping power

(Z=48(Cd), 52(Te), ρ =5.83g/cm3)

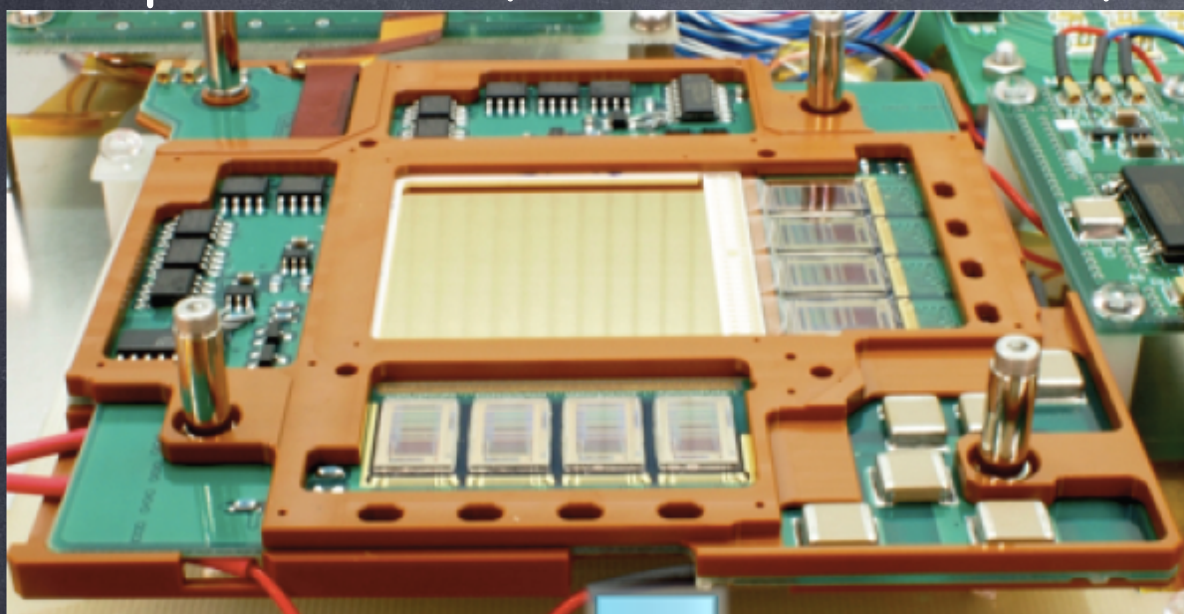
- Collimator-less imaging

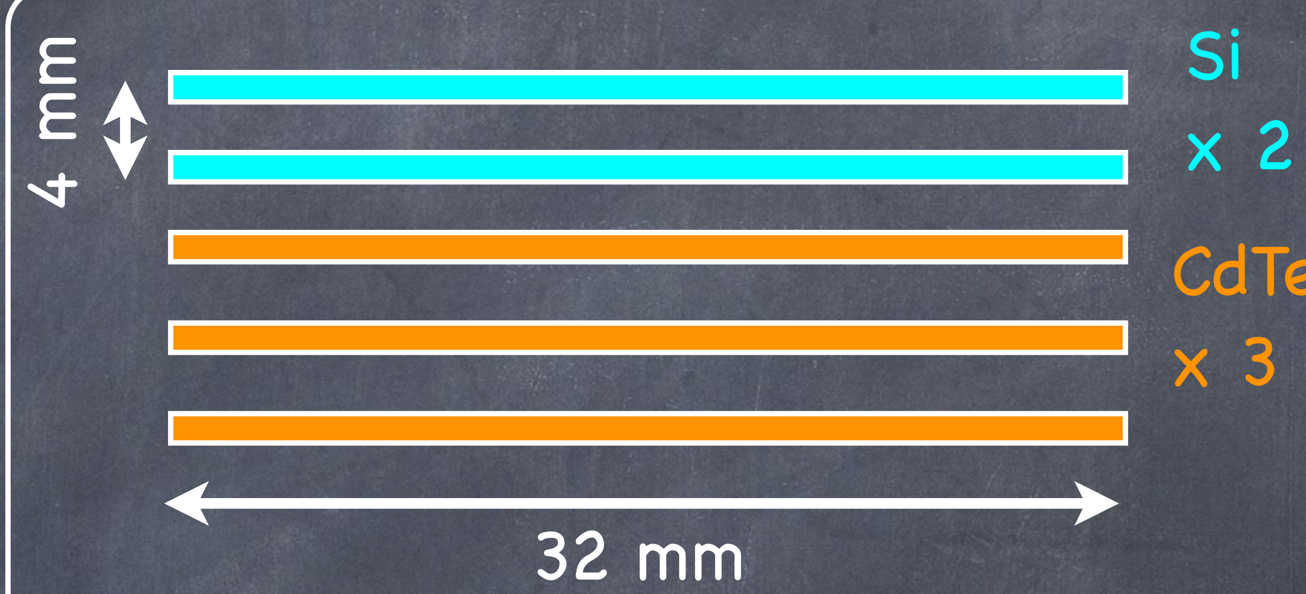
High efficiency, Large field of view
Wide energy band, Light weight

Practice A prototype camera (2012)

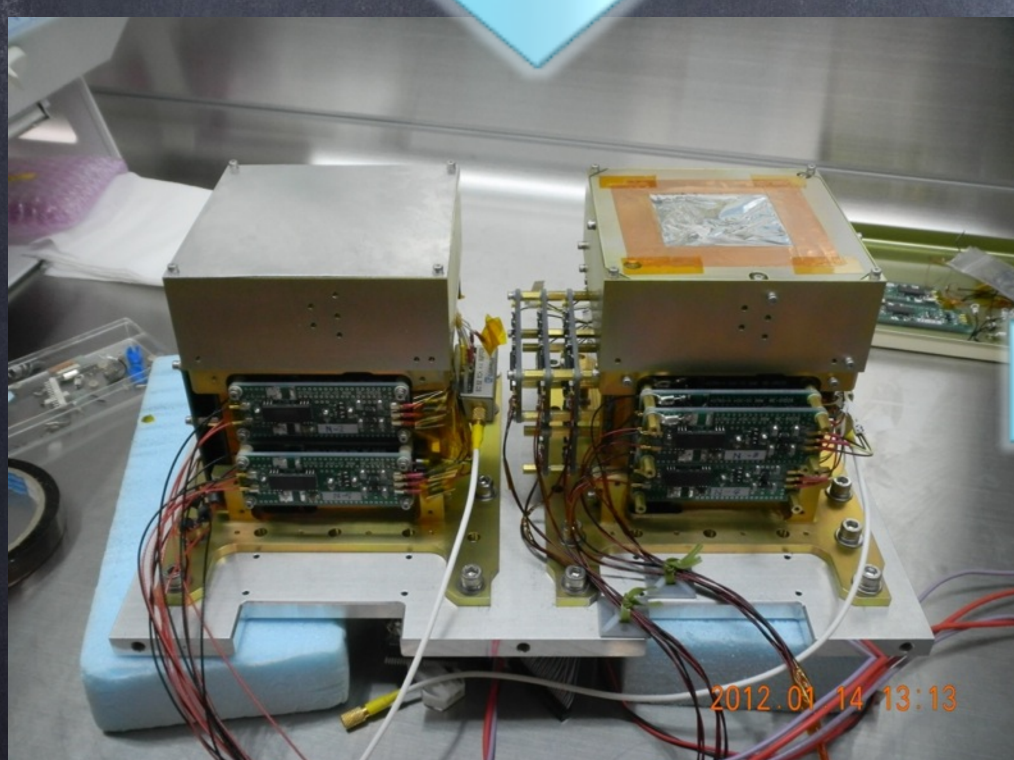
Test system for visualization of radioisotopes in Fukushima

250 μm pitch CdTe Double-sided strip detector (watanabe et al. 2011)





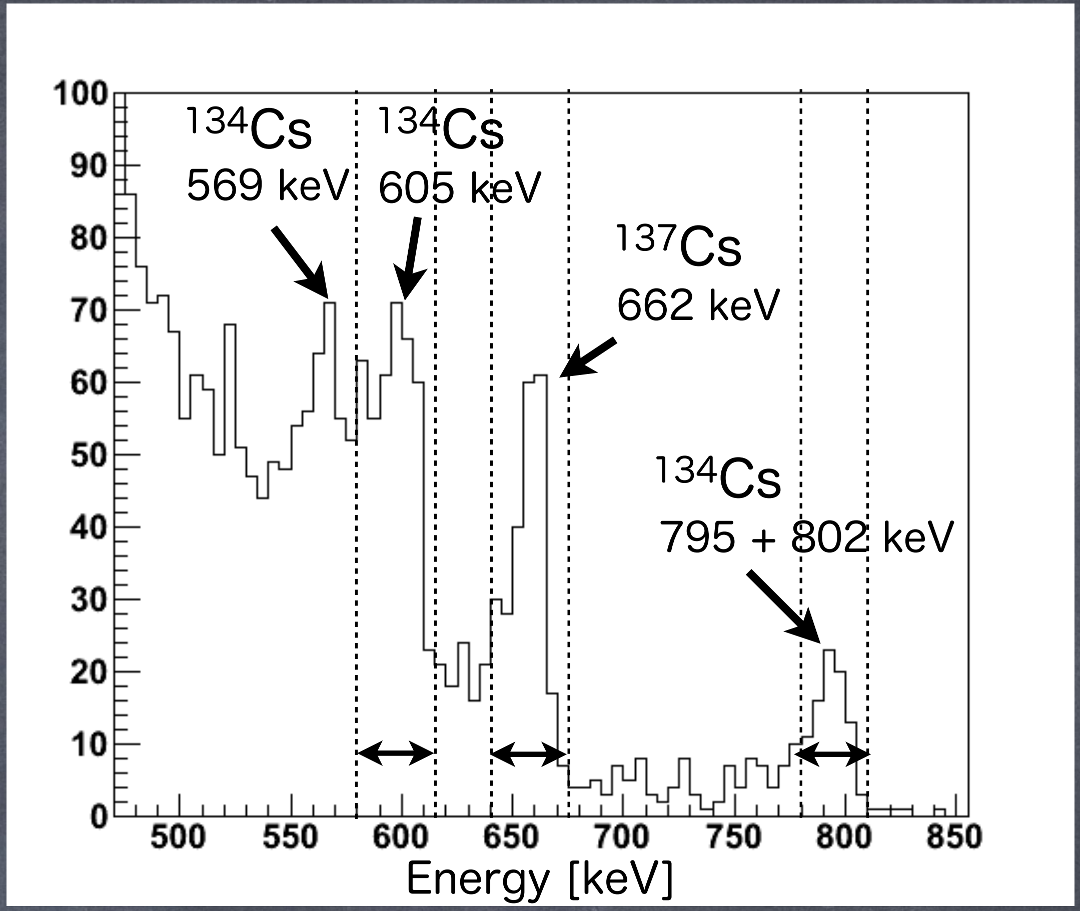
- 250 μm pitch Si-DSSD & CdTe-DSSD
- Thickness : 0.5 mm (Si), 0.75 mm (CdTe)
- ADC implemented VATA ASIC

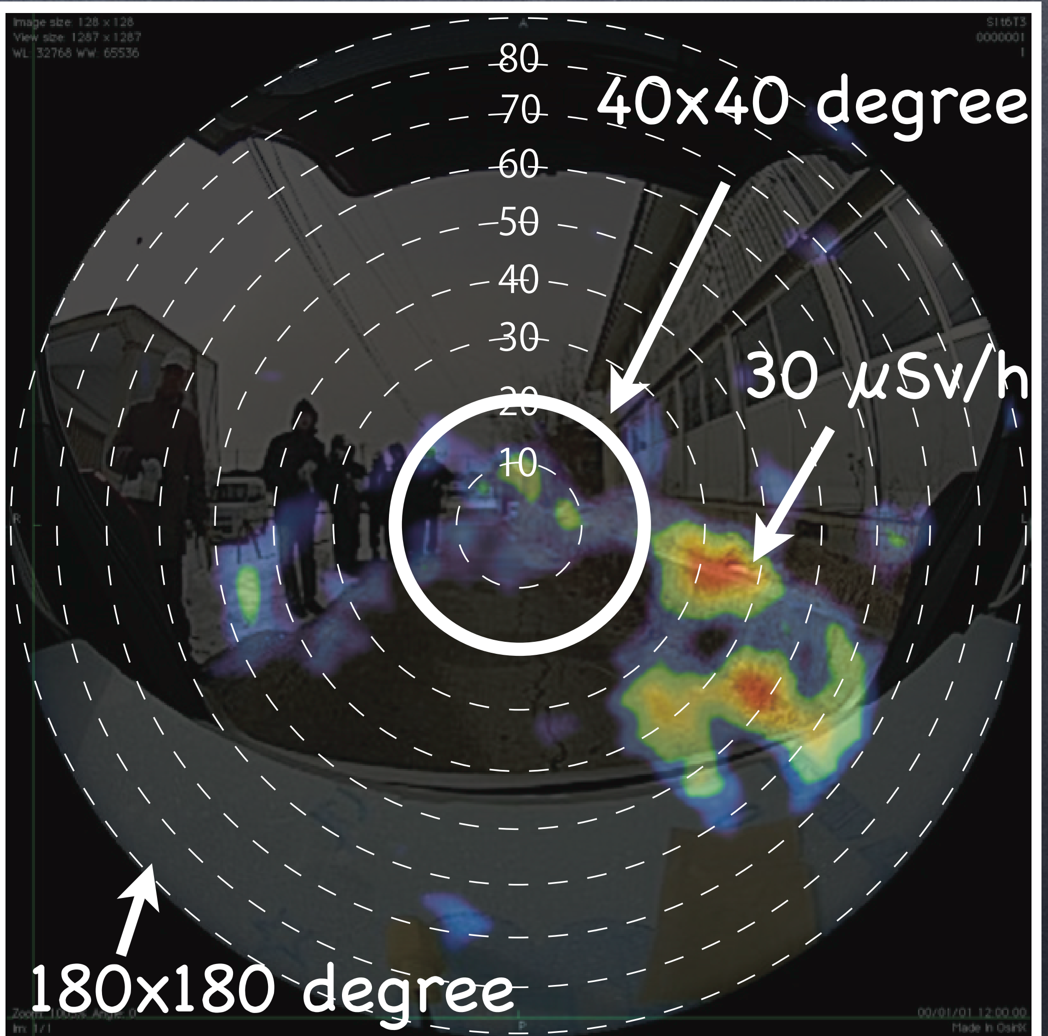


First demonstration in Fukushima

Env. radiation level $\sim$ 3 μSv/h

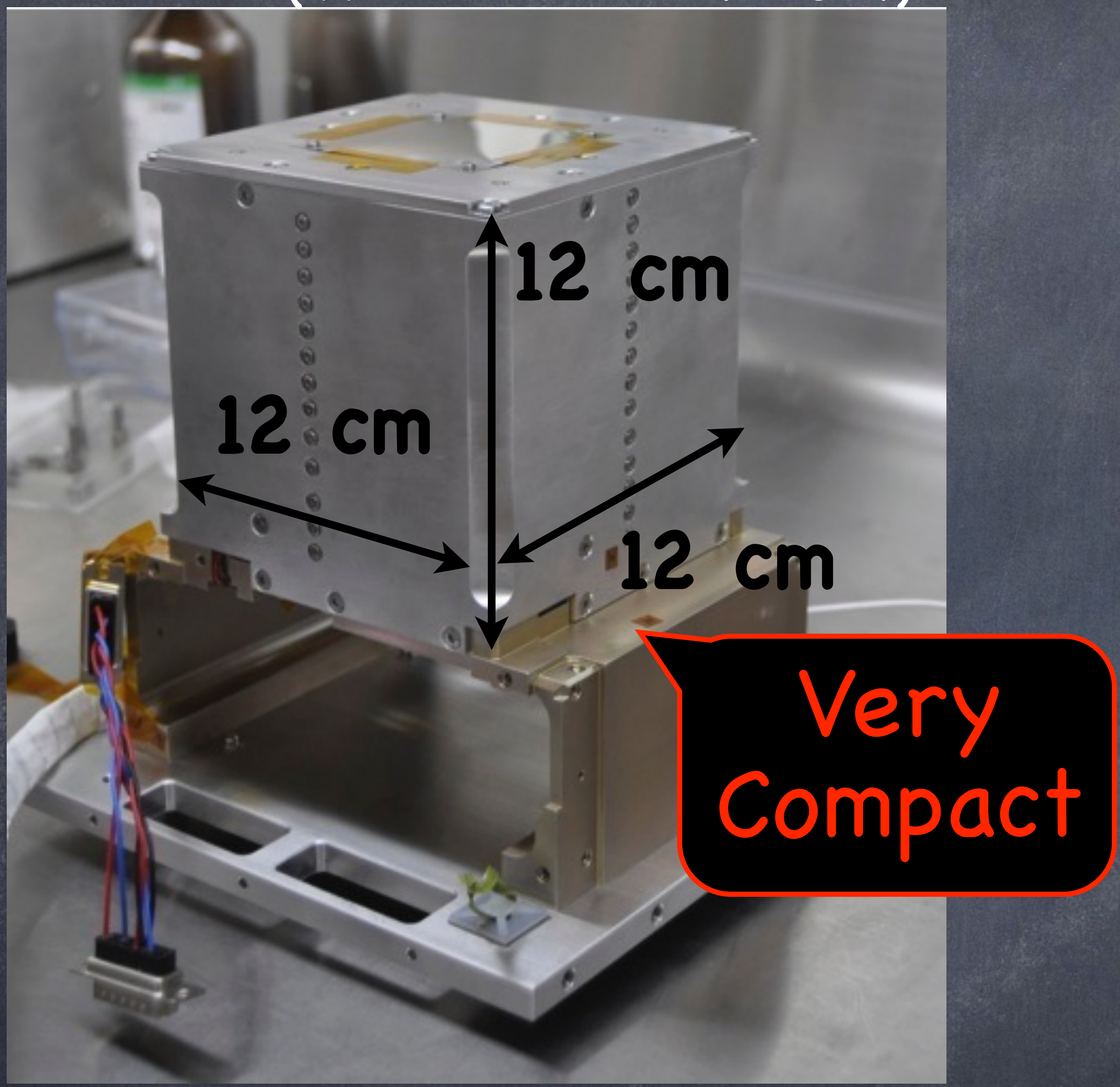
After 60 min exposure

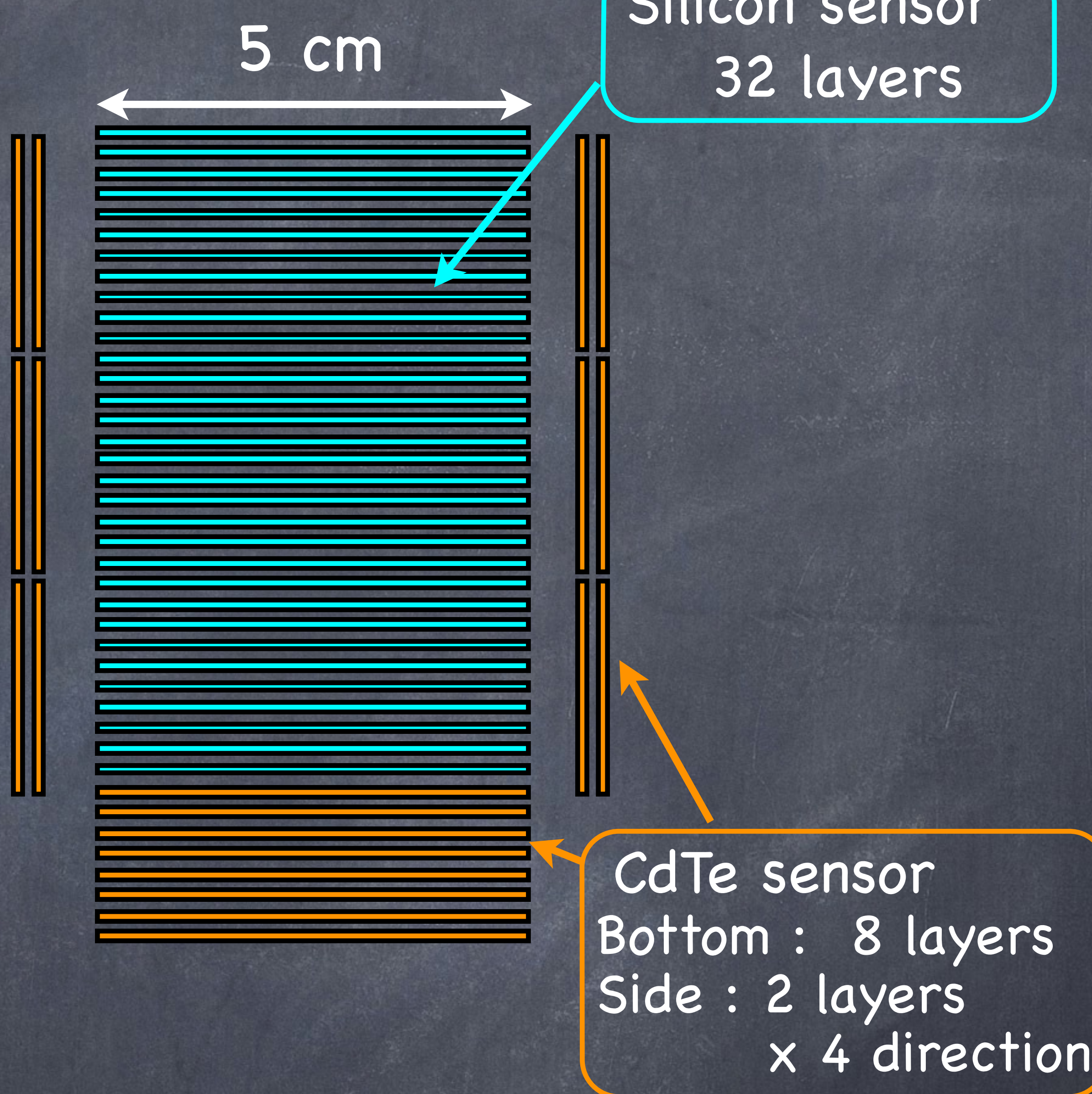




Upgrade High sensitivity Compton camera (2013)

ASTRO-H SGD module
(Watanabe et al. 2014)





- 32 layers of 0.6 mm thick Si Pad
- 8 layers of 0.75 mm thick bottom-CdTe Pad
- 2 layers of 0.75 mm thick side-CdTe Pad
- 3.2 mm pitch pads for Si and CdTe
- Readout channels: 13312 ch / 1 Compton Camera

Prototype

(Takeda et al 2012)

Upgrade

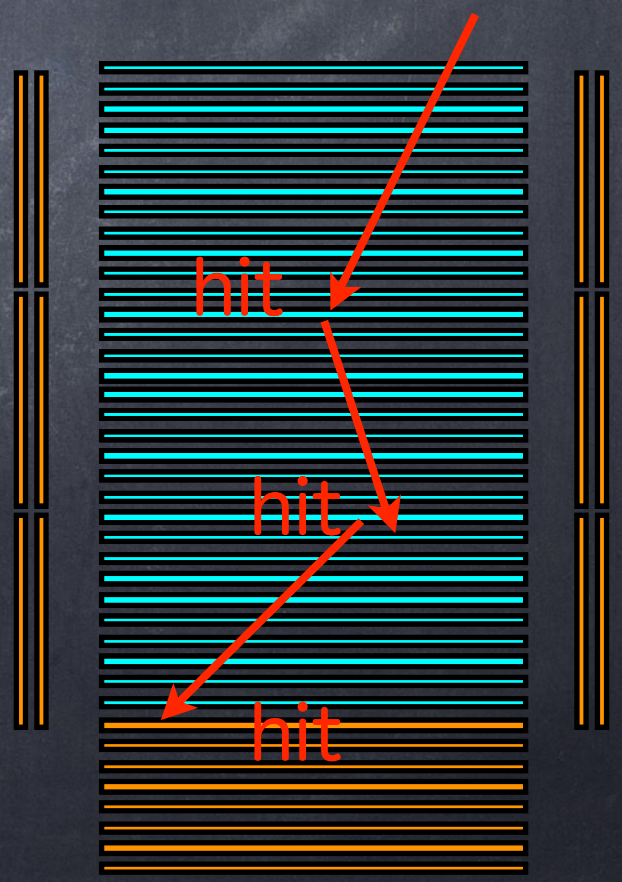
Imaging algorithms

Two important topics in data analysis :

1 Reconstruction of multiple hits event

Gamma-ray energy ↑, Multiple scattering ↑

- Si (1 hit) + CdTe (1 hit) : Only 35 % @ 662 keV
- Requirement : Analysis of num. of total hits ≤ 5



2 Significance of hotspots

to distinguish hotspots from image noises

Why you can say this is hotspots ....

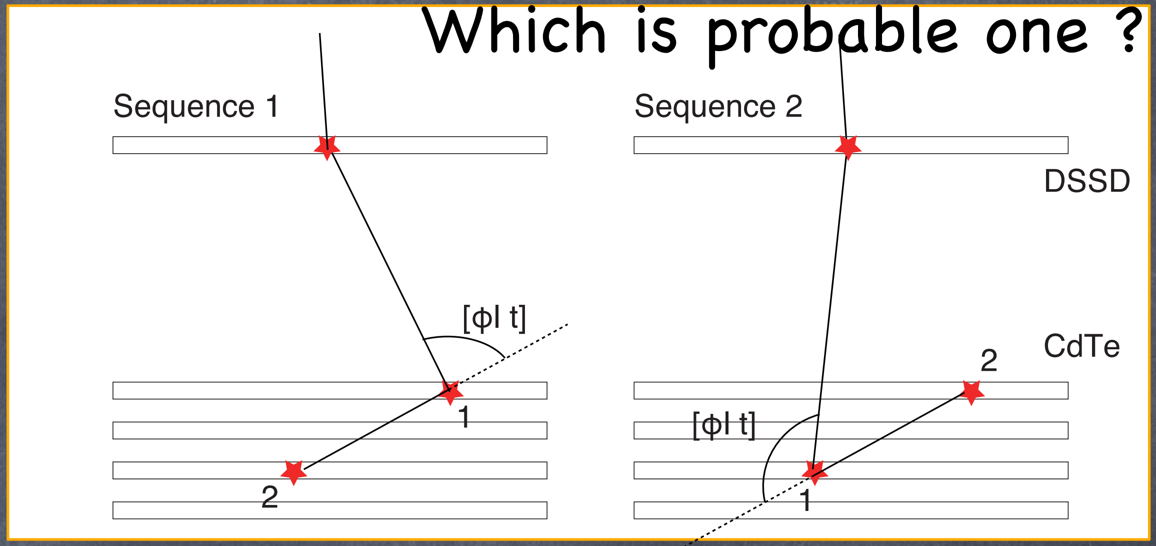
1 Reconstruction of multiple hits event

Correct order is unknown (no ToF) !!
How to select the most probable sequence.

KEY : MC simulator (Odaka et al. 2010)

KEY : Figure of Merits (FoM)
in hits' ordering

(Ichinohe et al. 2014)

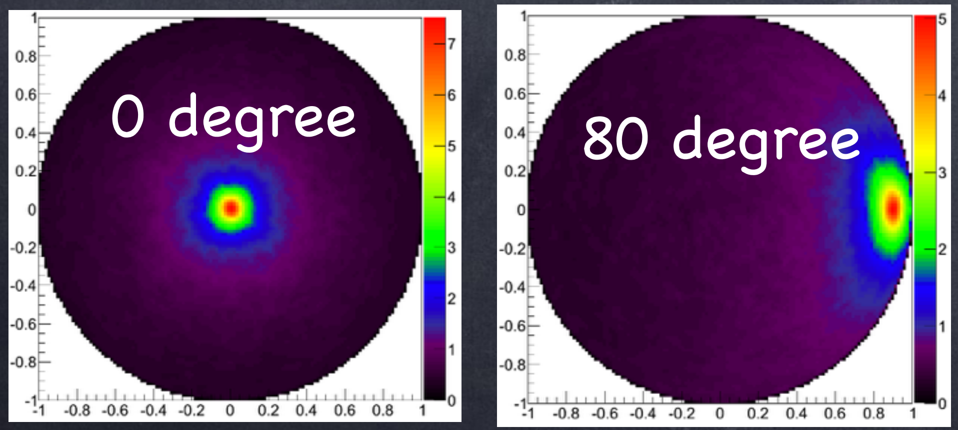


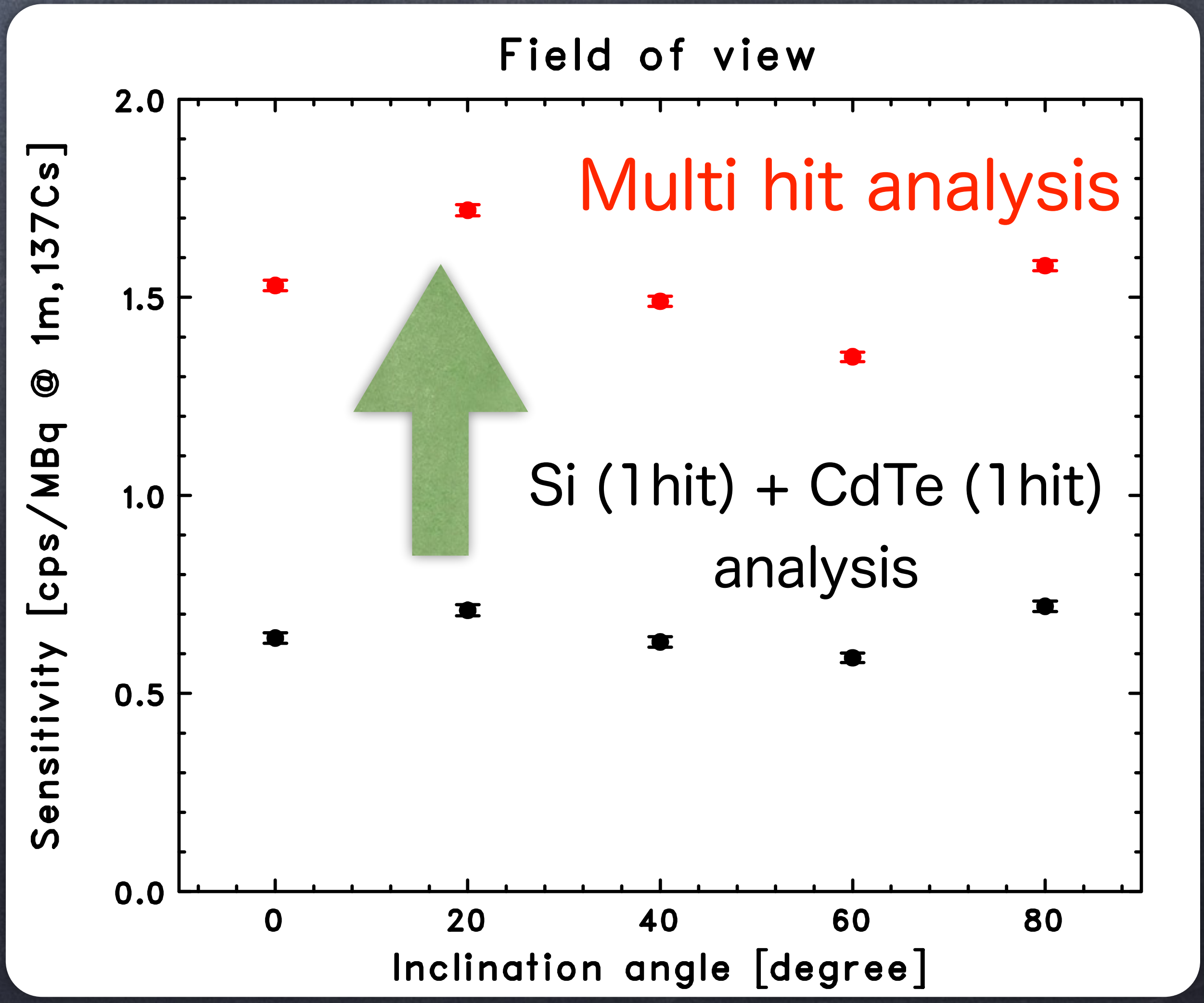
Results :

Efficiency : 2.5 times better

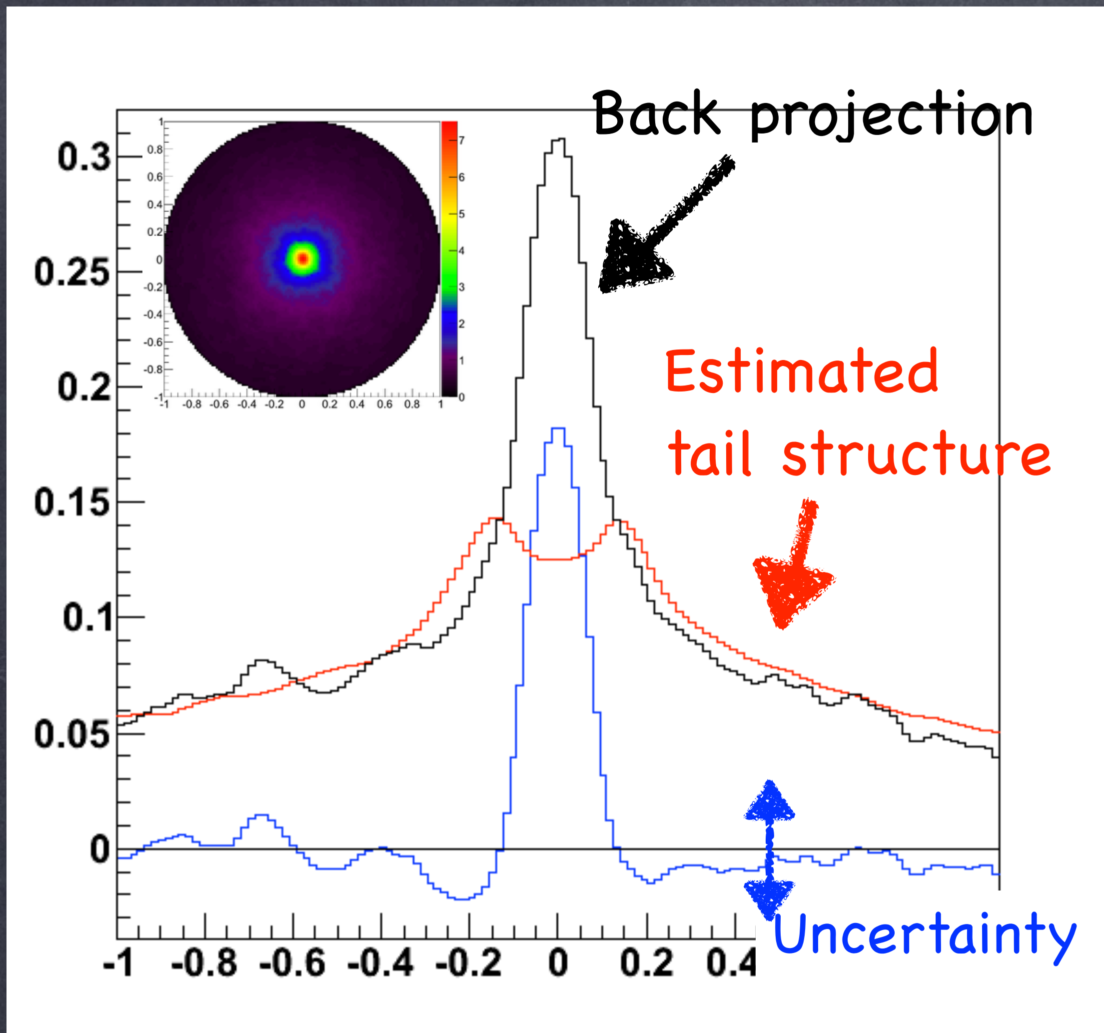
Acceptable reconstruction :

87 % (0 degree), 84 % (80 degree)





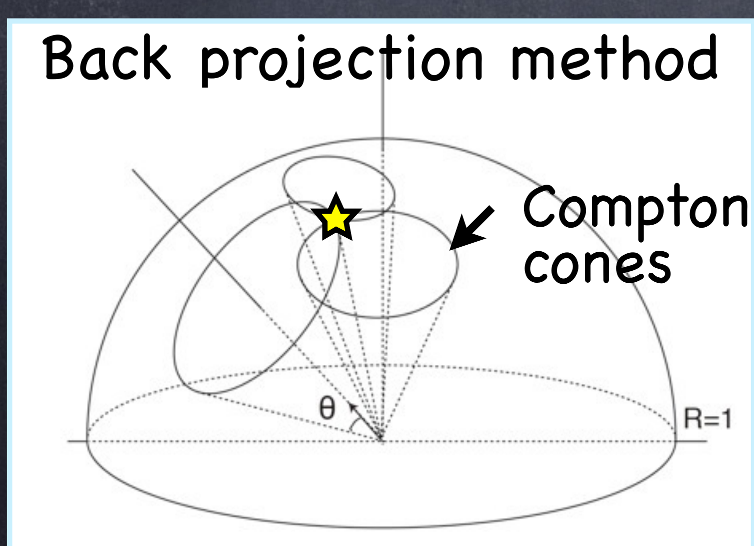
2 Significance of hotspots

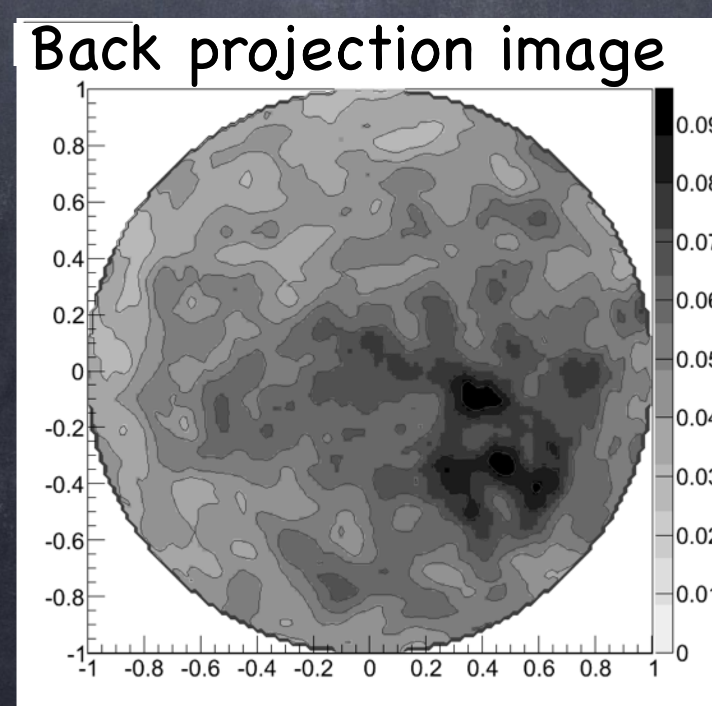


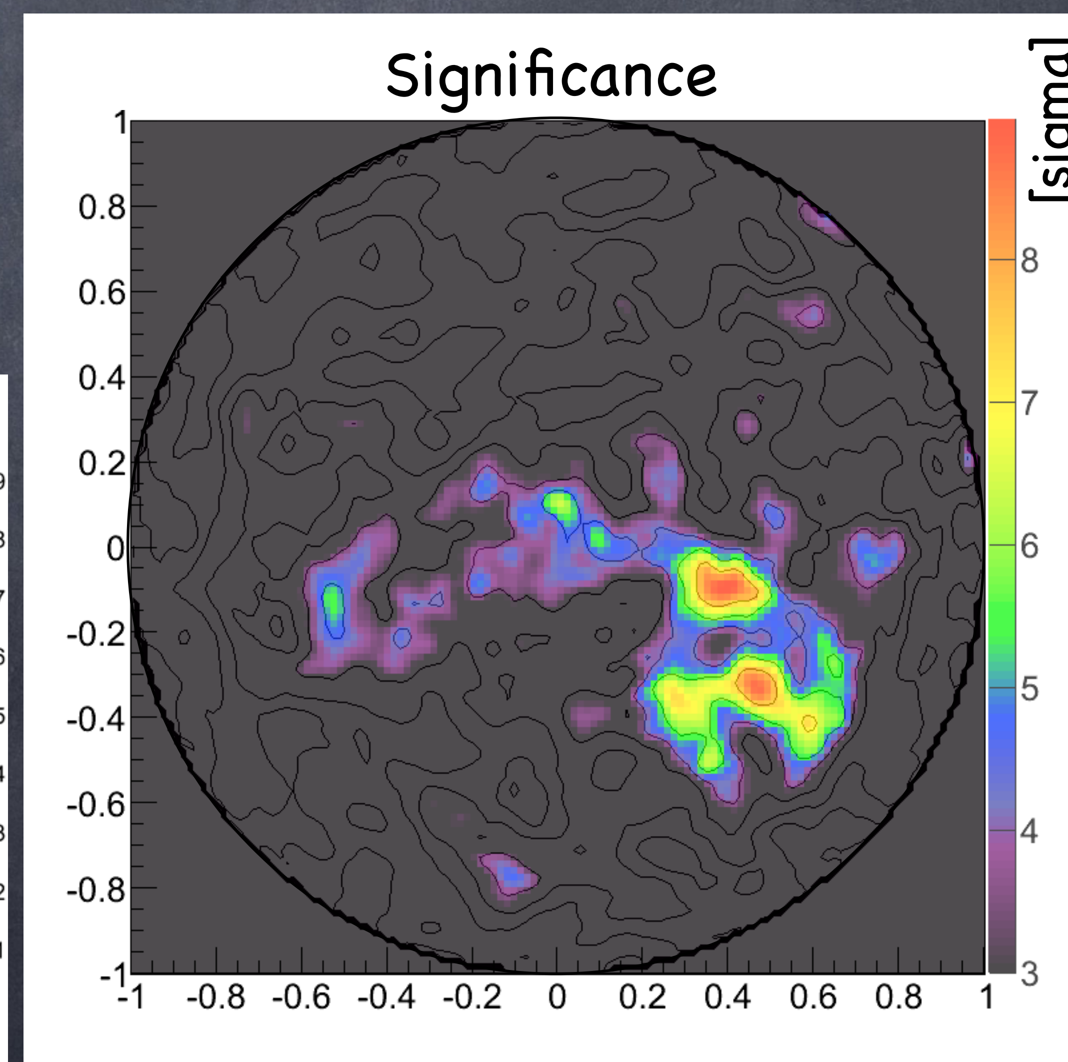
Our approach :

Step 1 : Making image with low systematic error and artifacts. Back projection image is suitable to meet this requirement.

Step 2 : Modeling of tail structure, then calculating uncertainty.



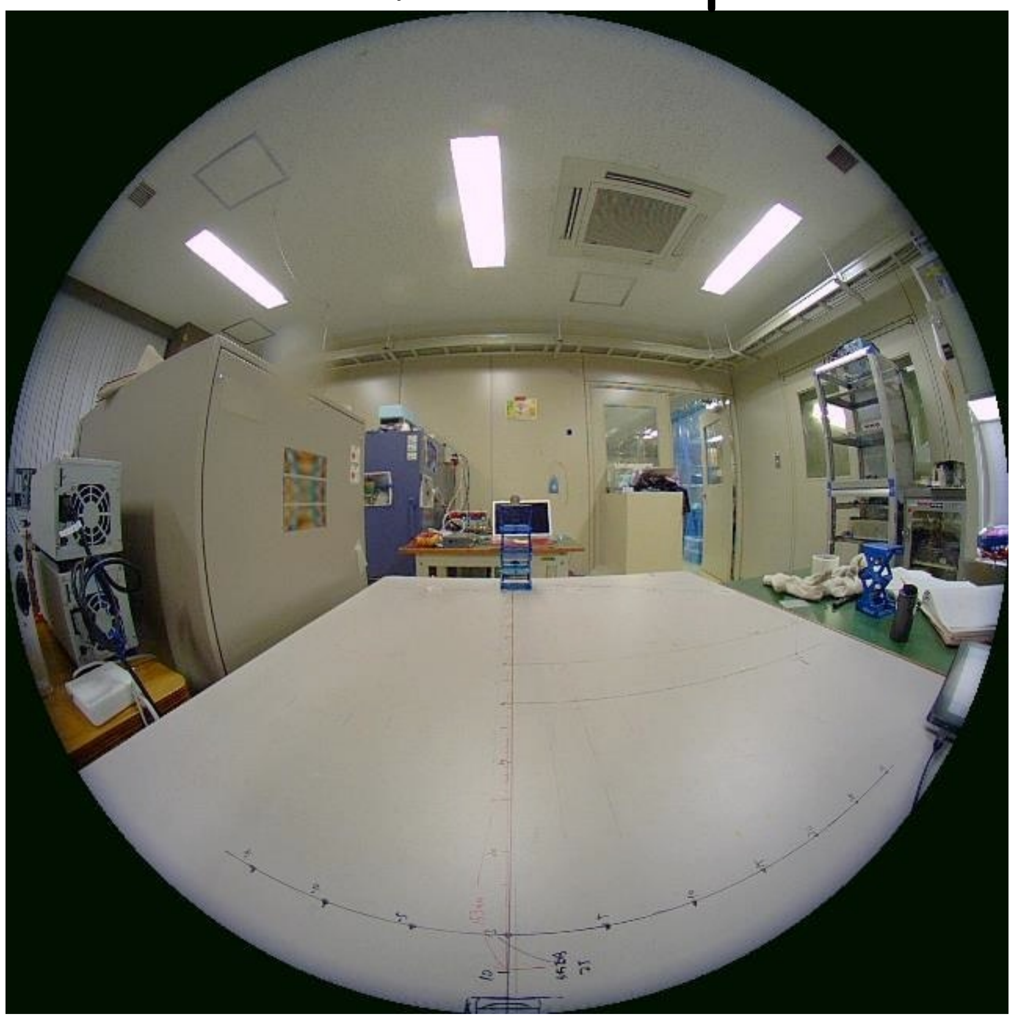


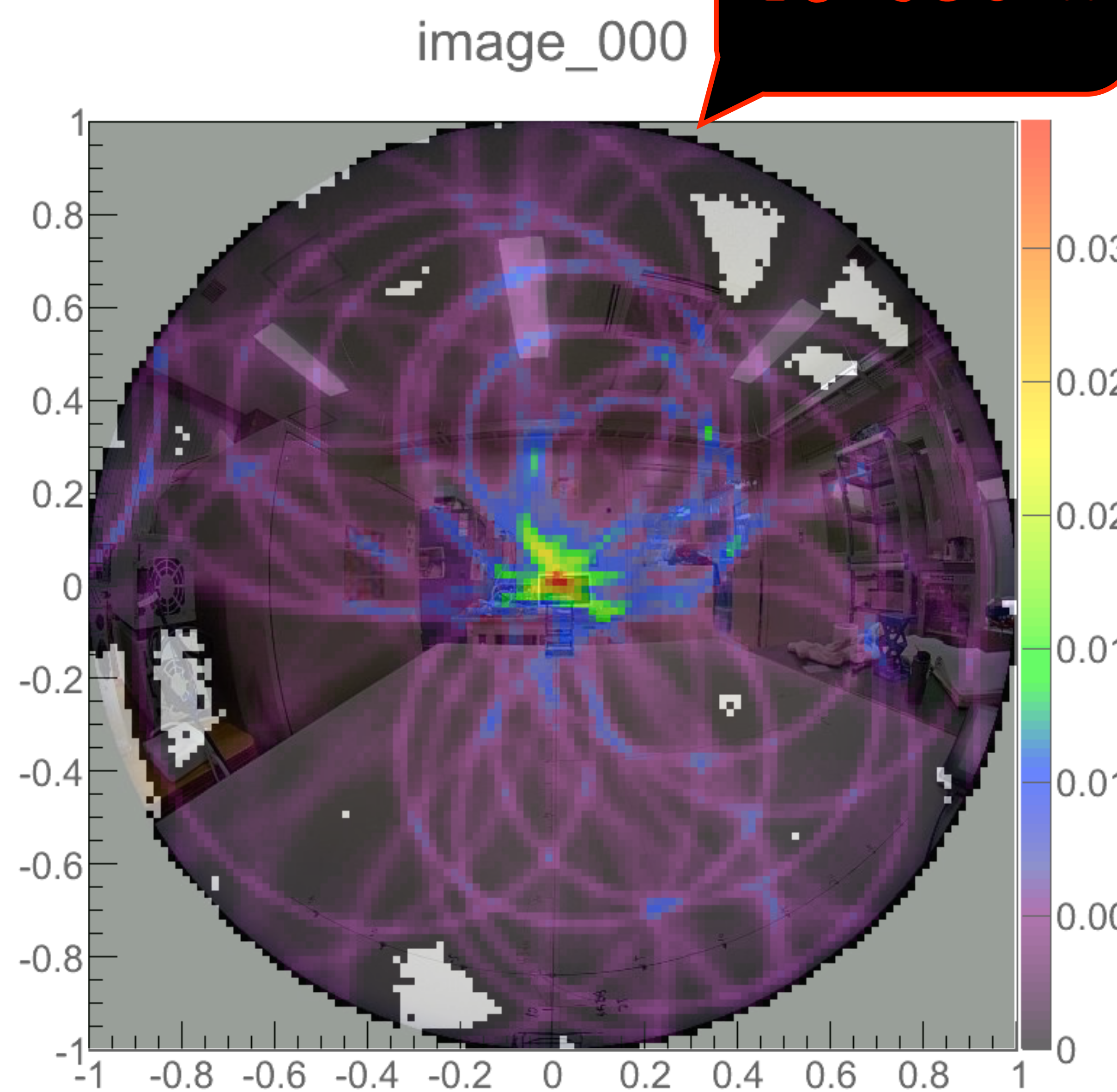


The prototype took 5 minutes

10 sec !!

137-Cs, 2.7MBq @ 1m





40 times better efficiency than the prototype

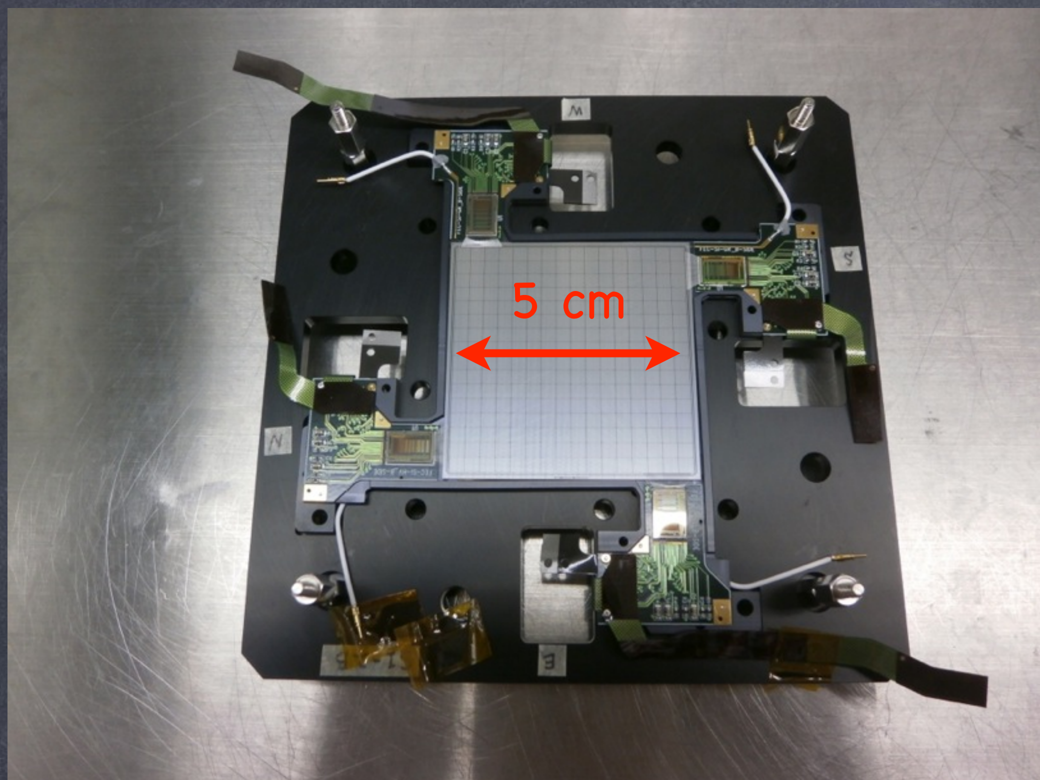
2.8 cps/MBq, 137-Cs 662 ke @ 1m

Release First commercial camera (2013)

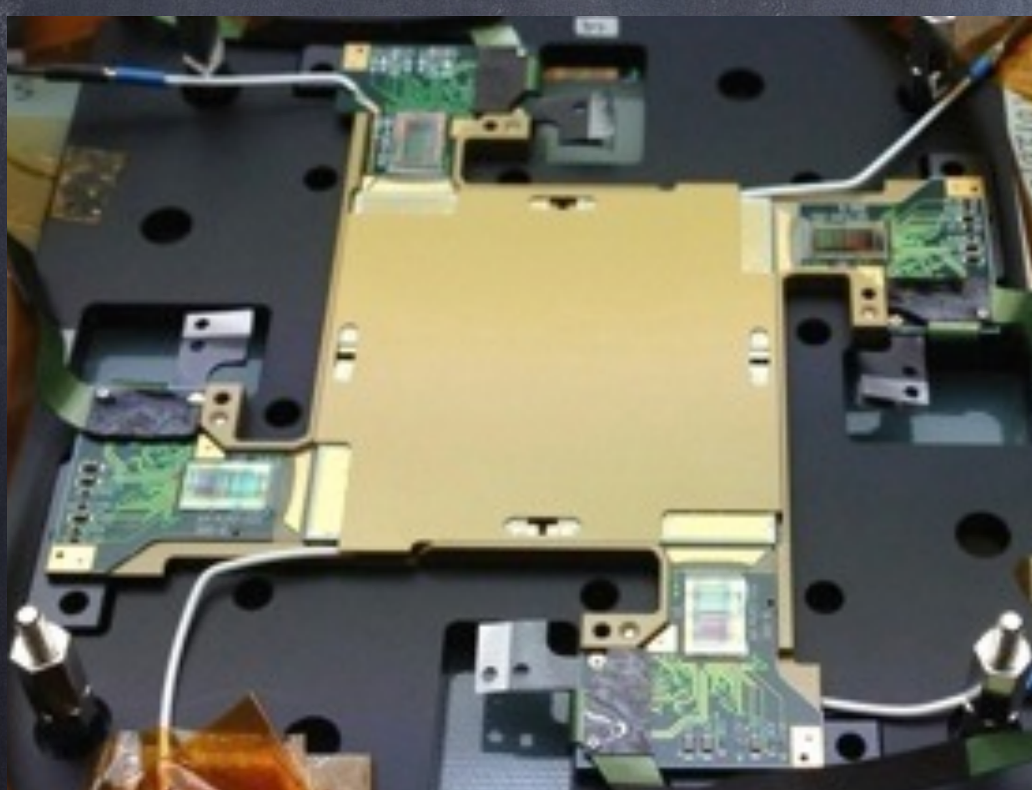
Radiation Visualization Camera

MITSUBISHI HEAVY INDUSTRIES, LTD.
Our Technologies, Your Tomorrow

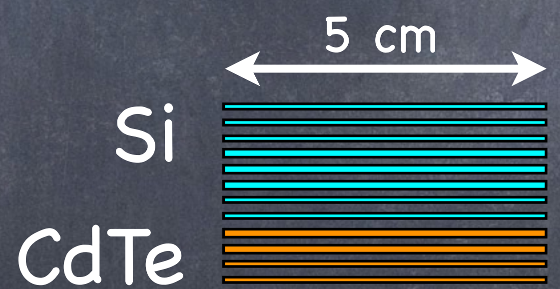
Si Pixel detector



CdTe Pixel detector



Standard Configuration

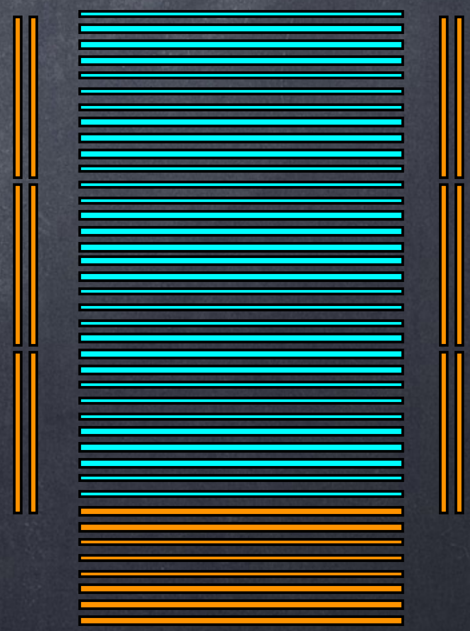


0.16 cps/MBq @1m, 137-Cs

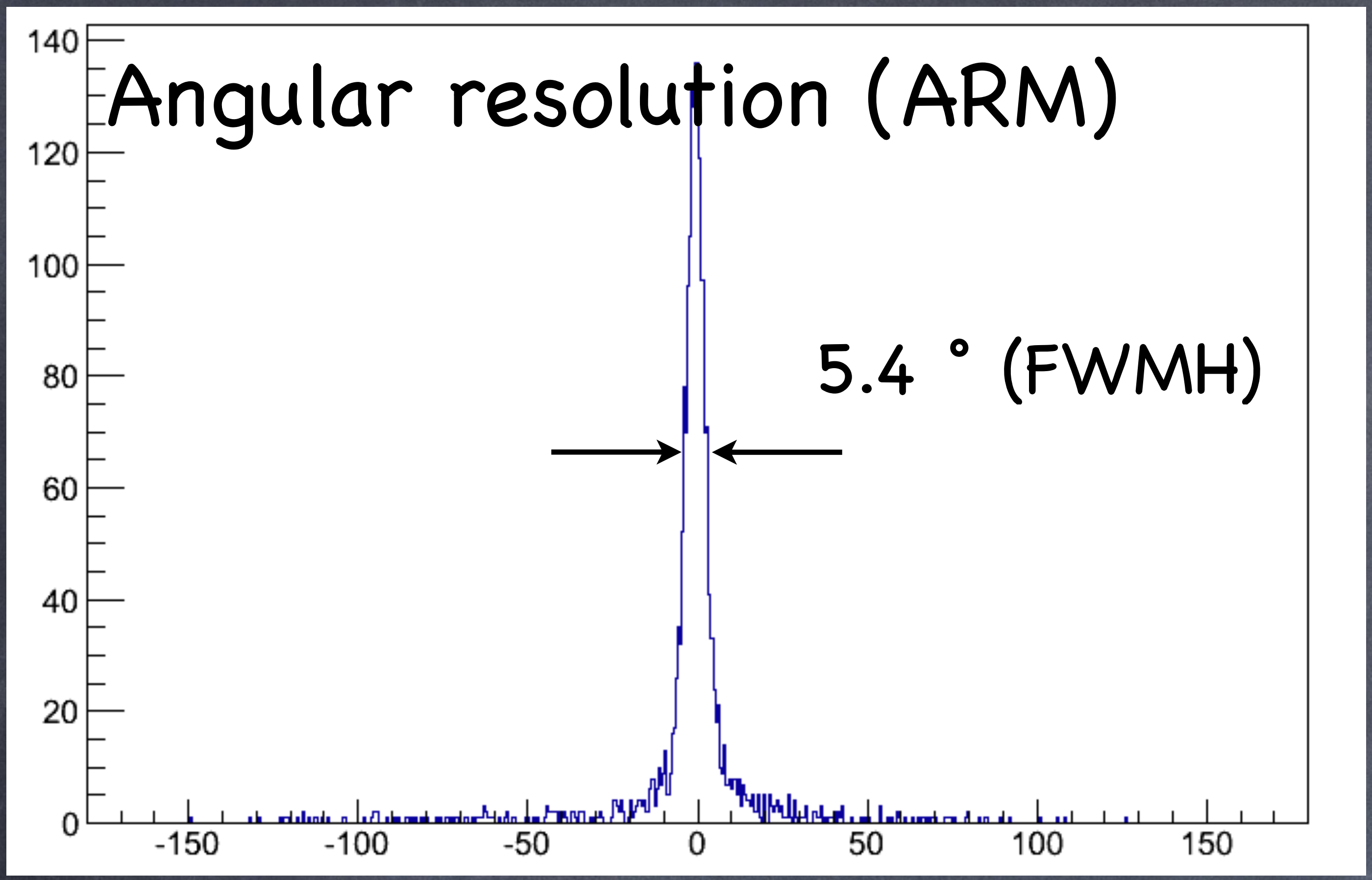
(cf. Prototype)

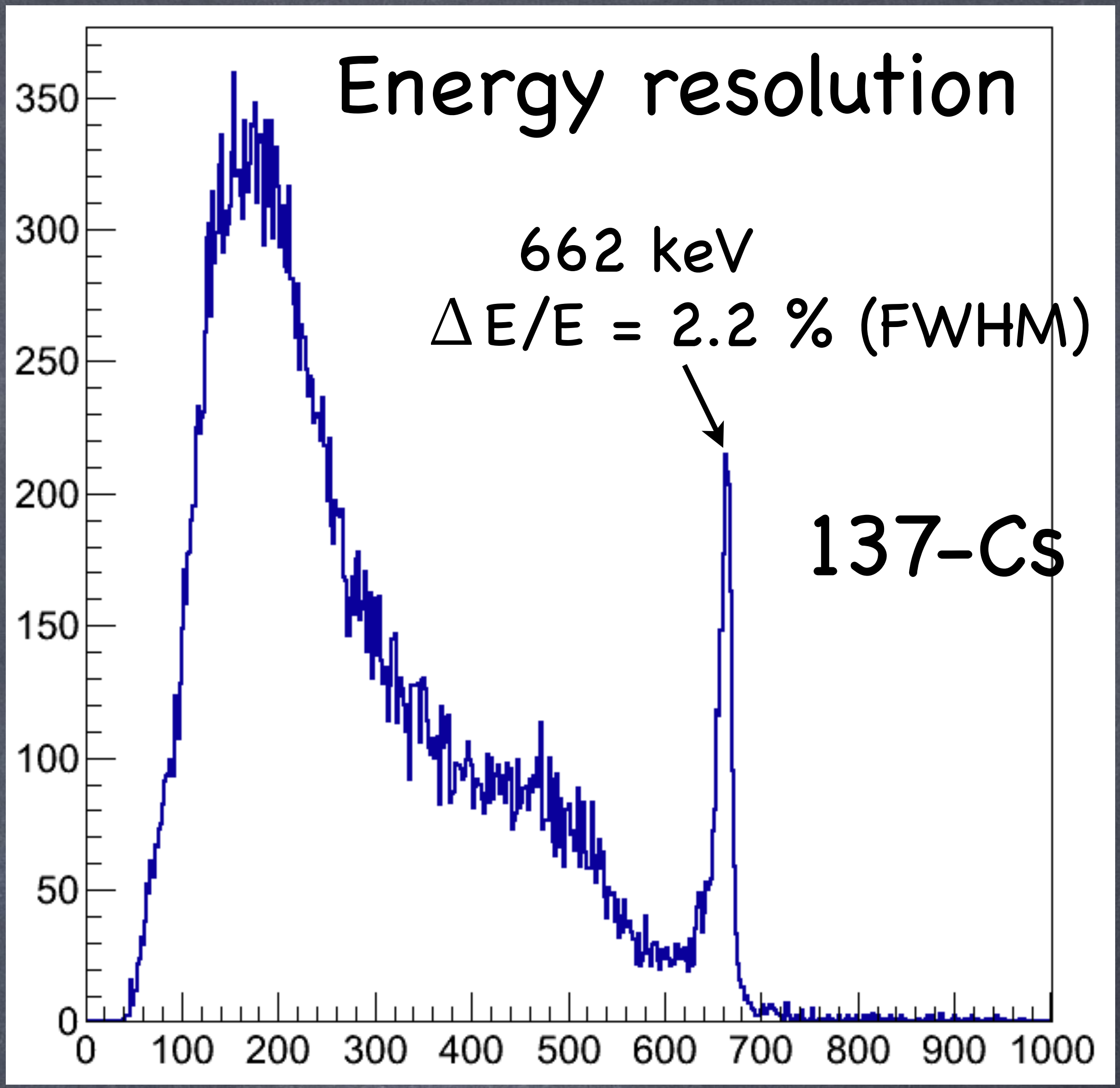
0.035 cps/MBq
@1m, 137-Cs

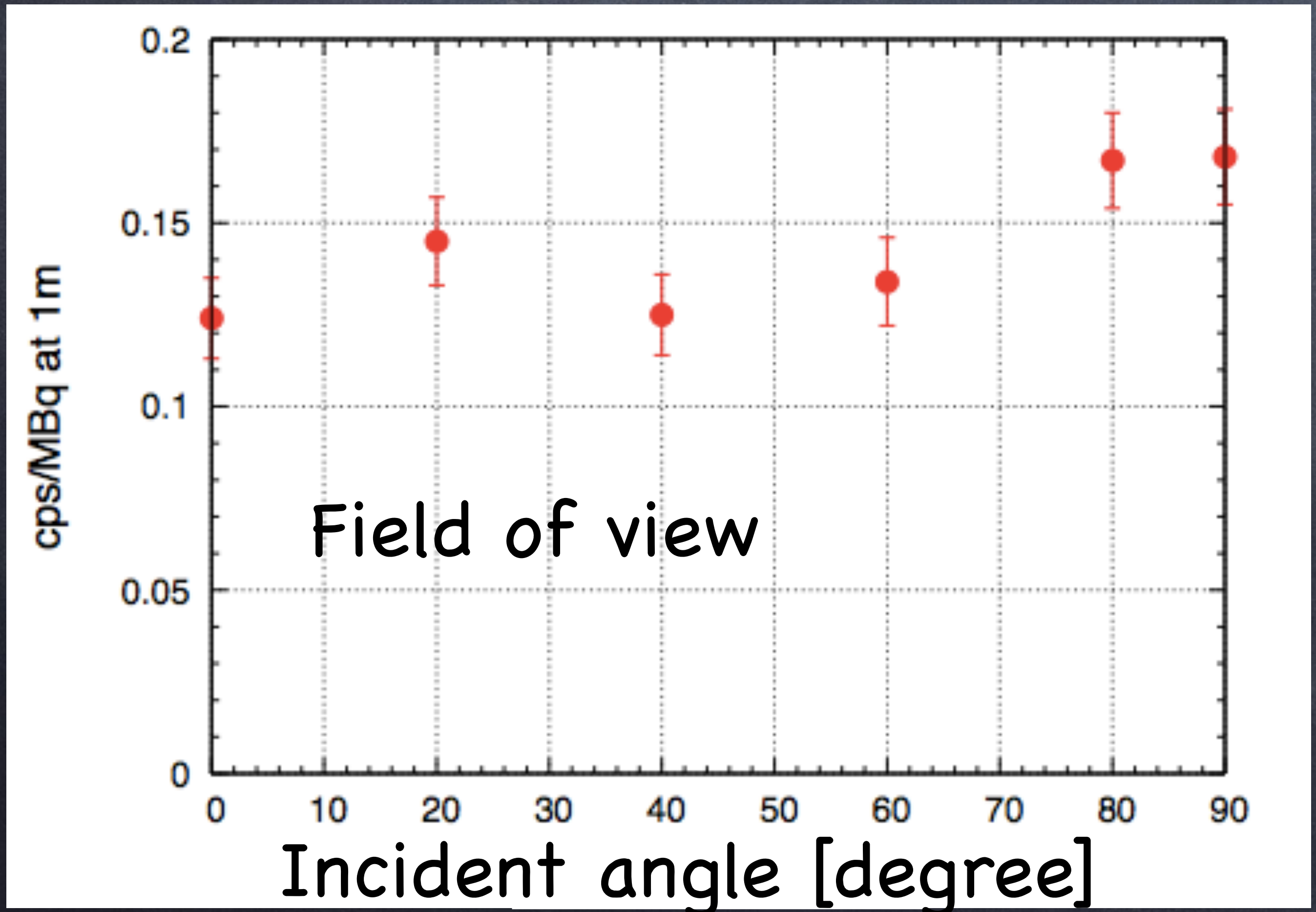
Enhanced Configuration

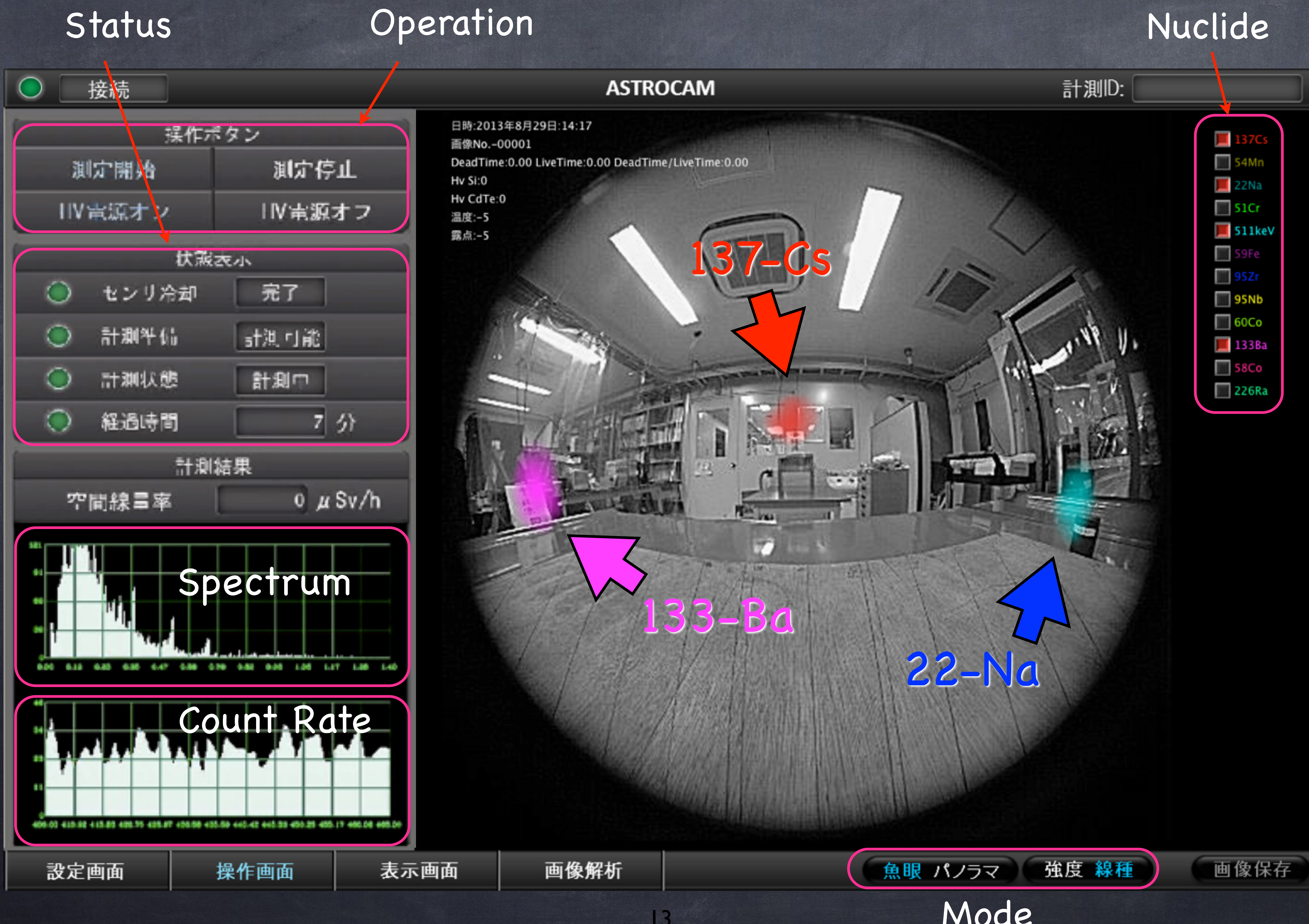


2.8 cps/MBq @1m, 137-Cs


Angular resolution (ARM)
5.4 ° (FWMH)
0
20
40
60
80
100
120
140
-150
-100
-50
0
50
100
150


Energy resolution
662 keV
ΔE/E = 2.2 % (FWHM)
137-Cs
0
50
100
150
200
250
300
350
0
100
200
300
400
500
600
700
800
900
1000


Field of view
cps/MBq at 1m
Incident angle [degree]
0
0.05
0.1
0.15
0.2
0
10
20
30
40
50
60
70
80
90


Status
Operation
Nuclide
接続
ASTROCAM
計測ID:
操作ボタン
測定開始
測定停止
HV電源オン
HV電源オフ
状態表示
センサ冷却
完了
計測準備
計測可能
計測状態
計測中
経過時間
7
分
計測結果
空間線量率
0
μSv/h
Spectrum
Count Rate
日時:2013年8月29日:14:17
画像No.-00001
DeadTime:0.00 LiveTime:0.00 DeadTime/LiveTime:0.00
Hv Si:0
Hv CdTe:0
温度:-5
露点:-5
137-Cs
133-Ba
22-Na
137Cs
54Mn
22Na
51Cr
511keV
59Fe
95Zr
95Nb
60Co
133Ba
58Co
226Ra
設定画面
操作画面
表示画面
画像解析
魚眼
パノラマ
強度
線種
画像保存
Mode

Demonstration in Fukushima

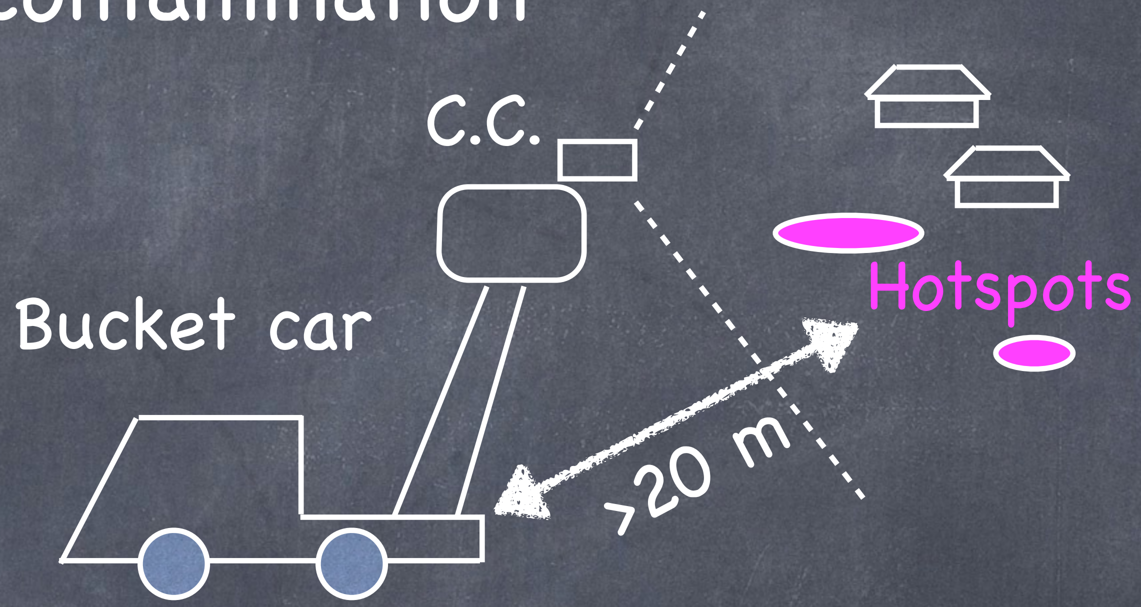
- Inside the 20 km zone from the nuclear plant
- 30 min exposure

Before decontamination (2013.6.21)

After decontamination (2014.1.21)

Demonstration in Fukushima

Tests to visualize a vast expanse of contamination



C.C. altitude ↑ imaging area ↑

Enhancing the merit of Compton imaging
(large field of view)

Merci Beaucuop

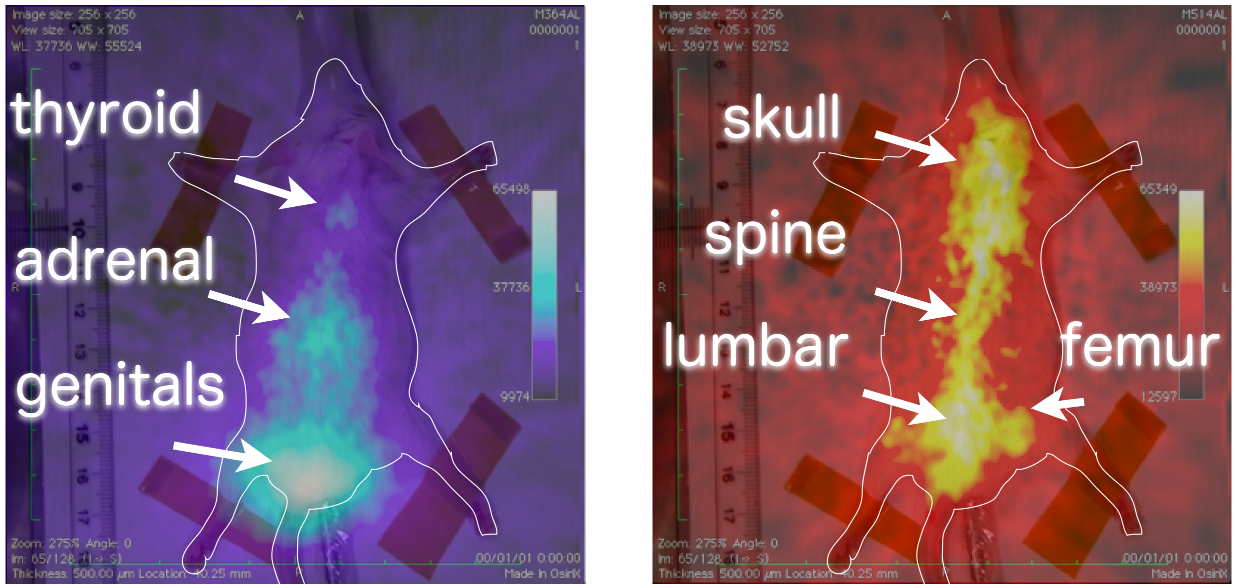
Summary

(1) The first commercial Si/CdTe Compton camera, ASTROCAM, was released.

(2) ASTROCAM is available for hotspot detection and the evaluation of decontamination.

(3) Tests for medical imaging are also ongoing.

^{131}I(364 keV) ^{85}Sr(514 keV)



Results by old prototype (Takeda et al. 2012)

◆ **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

Back up slides

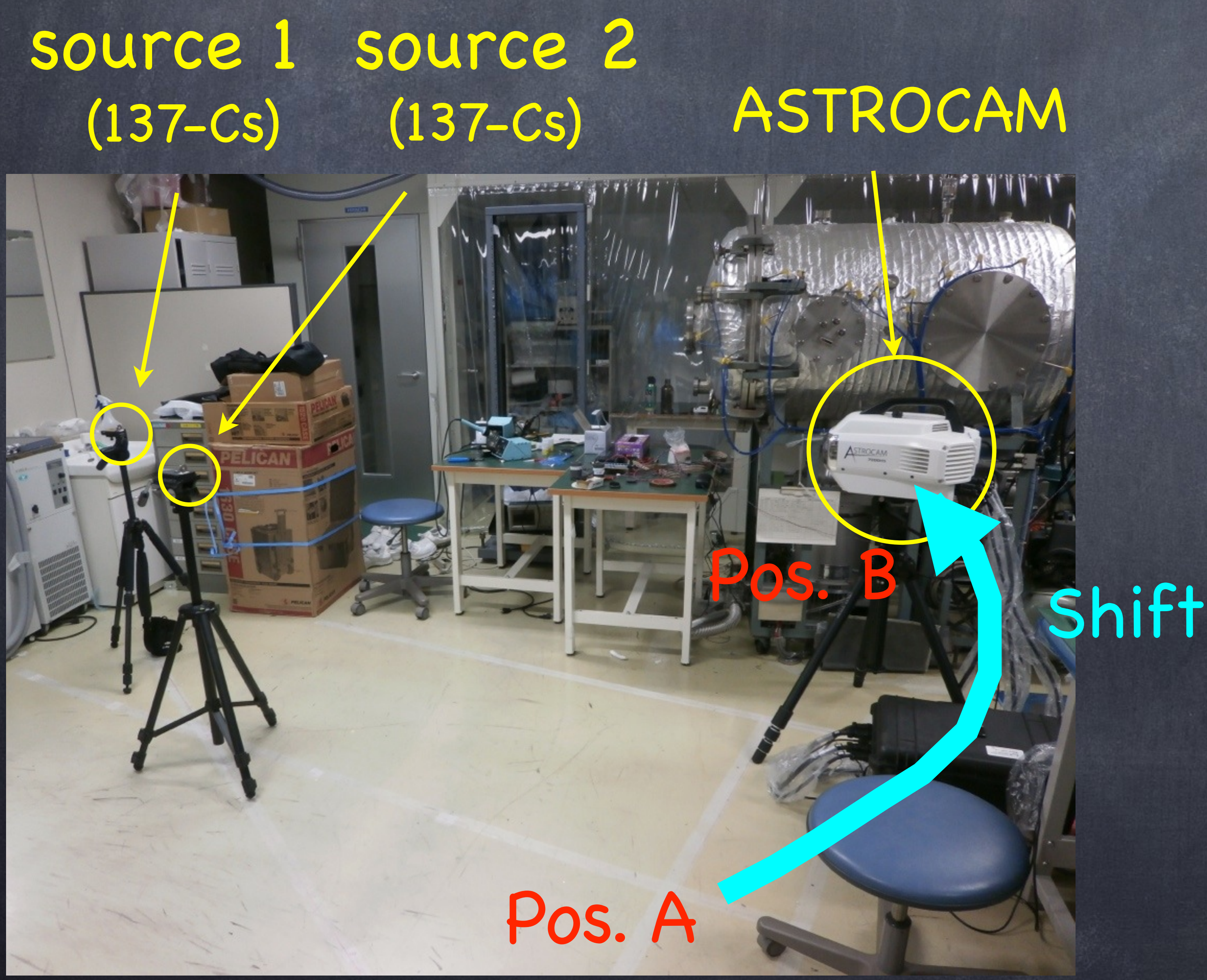
Distance to the hotspots

If possible, we can provide source intensity (Bq).

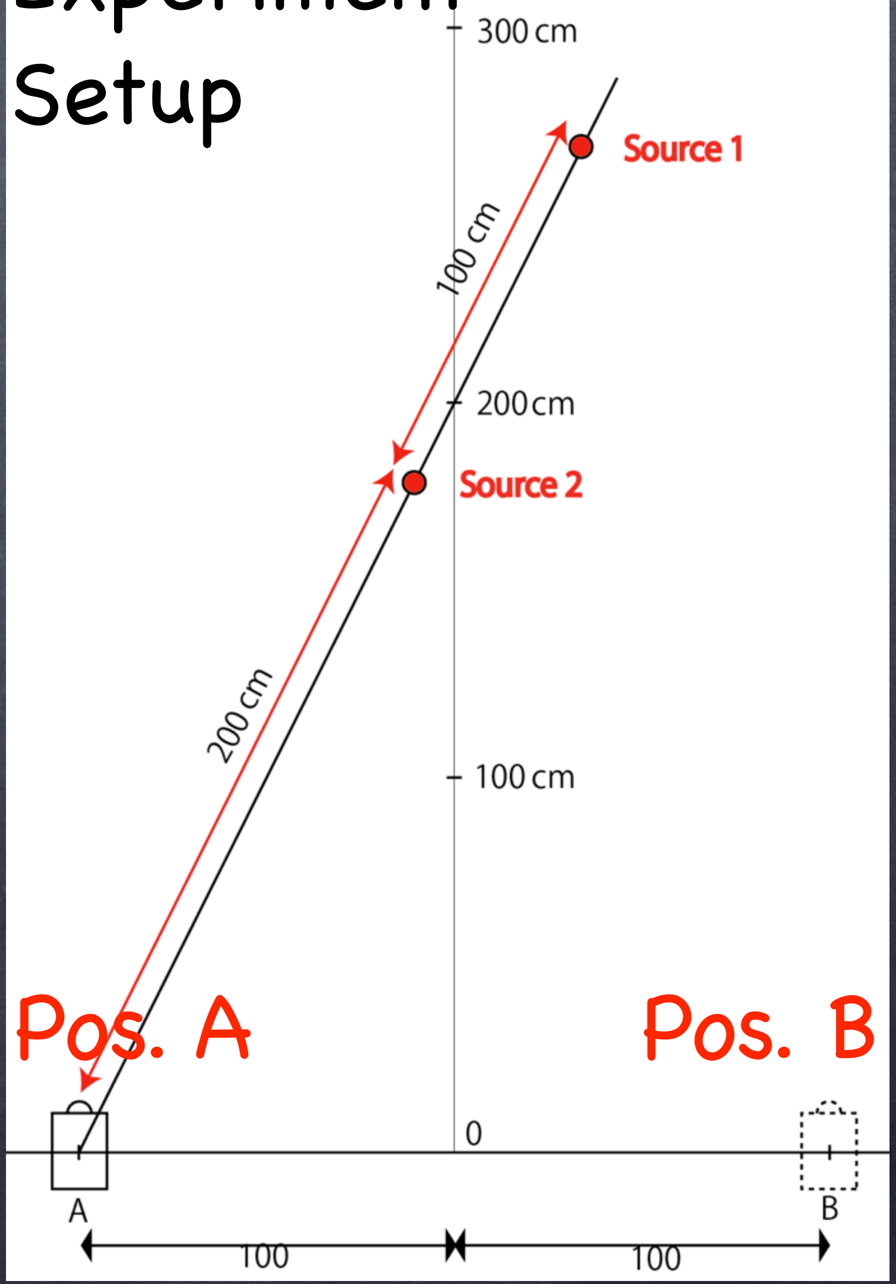
One should locate 3-D position of the hotspots.

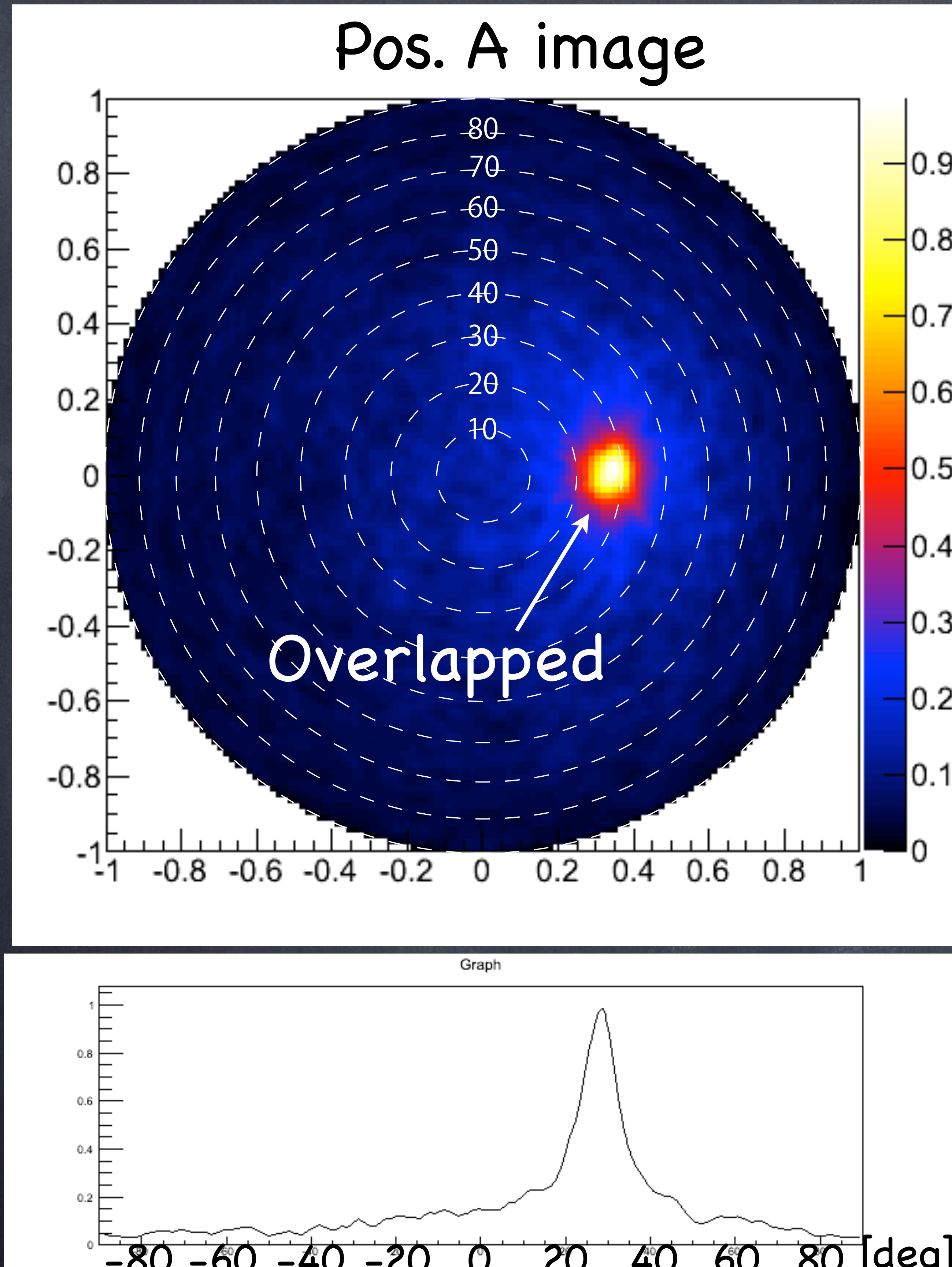
One possibility : Use parallax of 2 camera positions

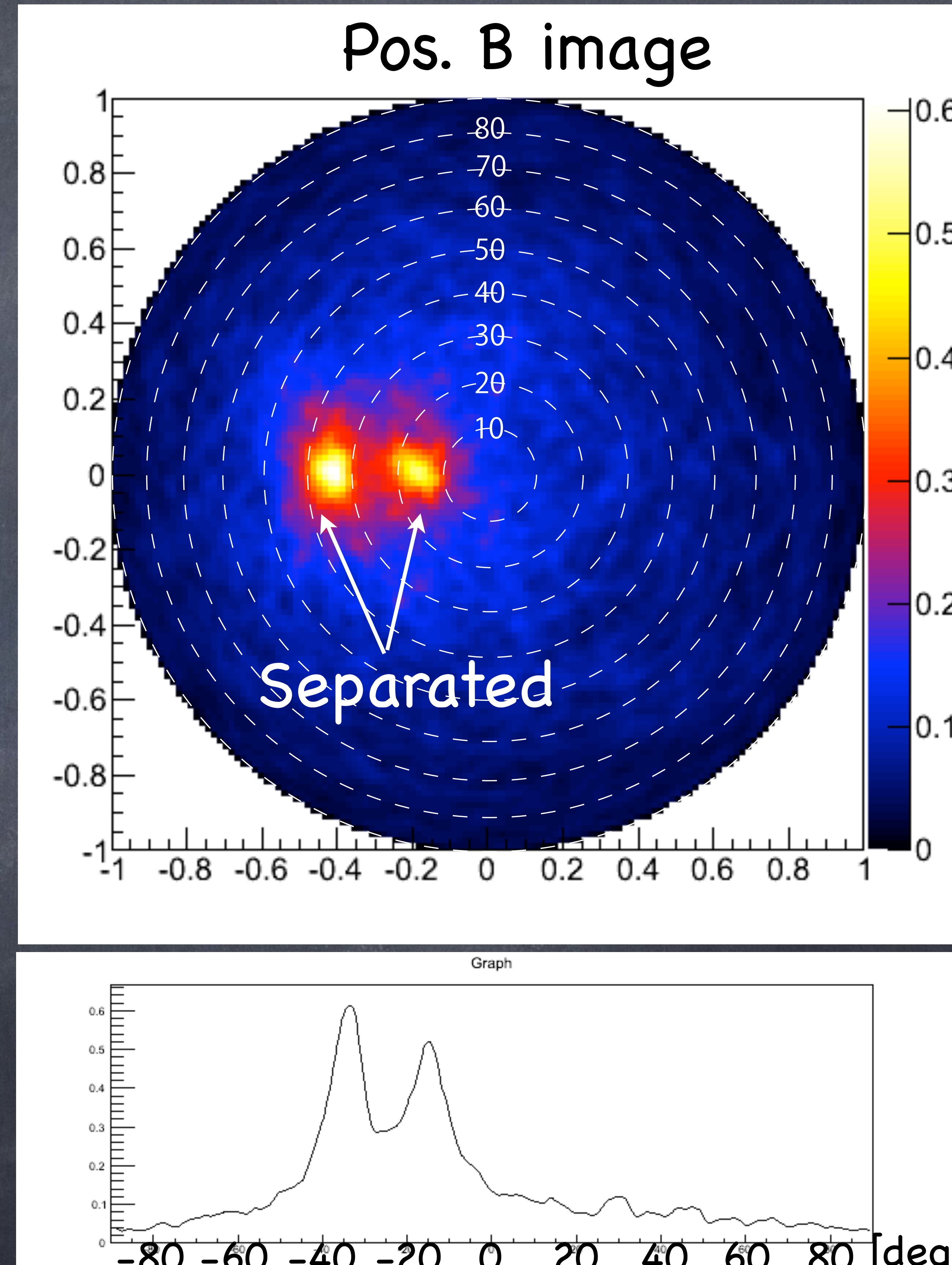
Example :



Experiment Setup

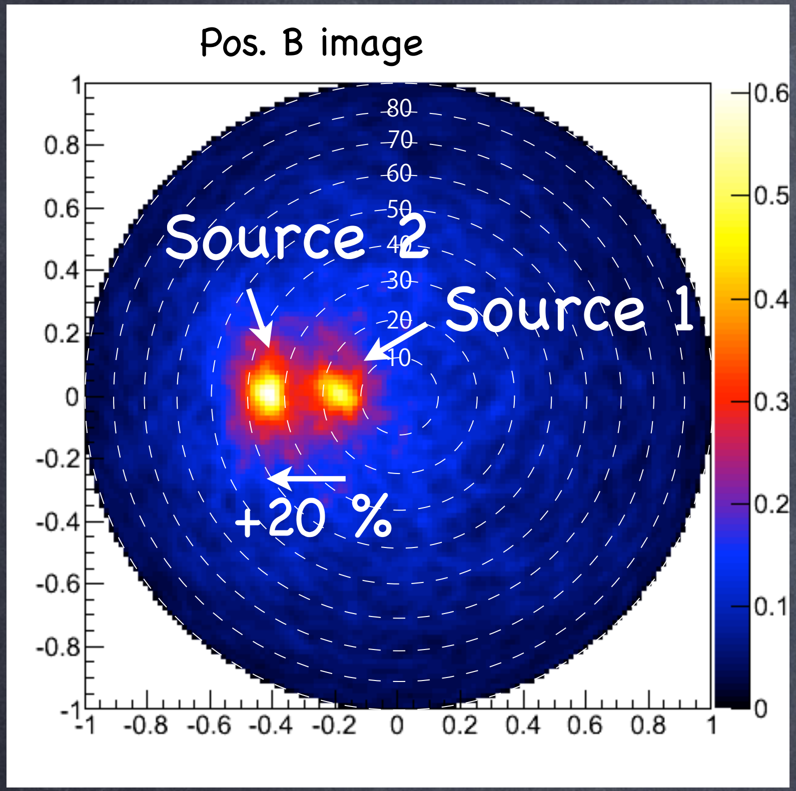



Pos. A image
Overlapped
80
70
60
50
40
30
20
10
Graph
-80 -60 -40 -20 0 20 40 60 80 [deg]


Pos. B image
Separated
80
70
60
50
40
30
20
10
Graph
-80 -60 -40 -20 0 20 40 60 80 [deg]

Distance to the hidden Source 1 is measured. Its distance is 288 cm.

(answer 300cm)



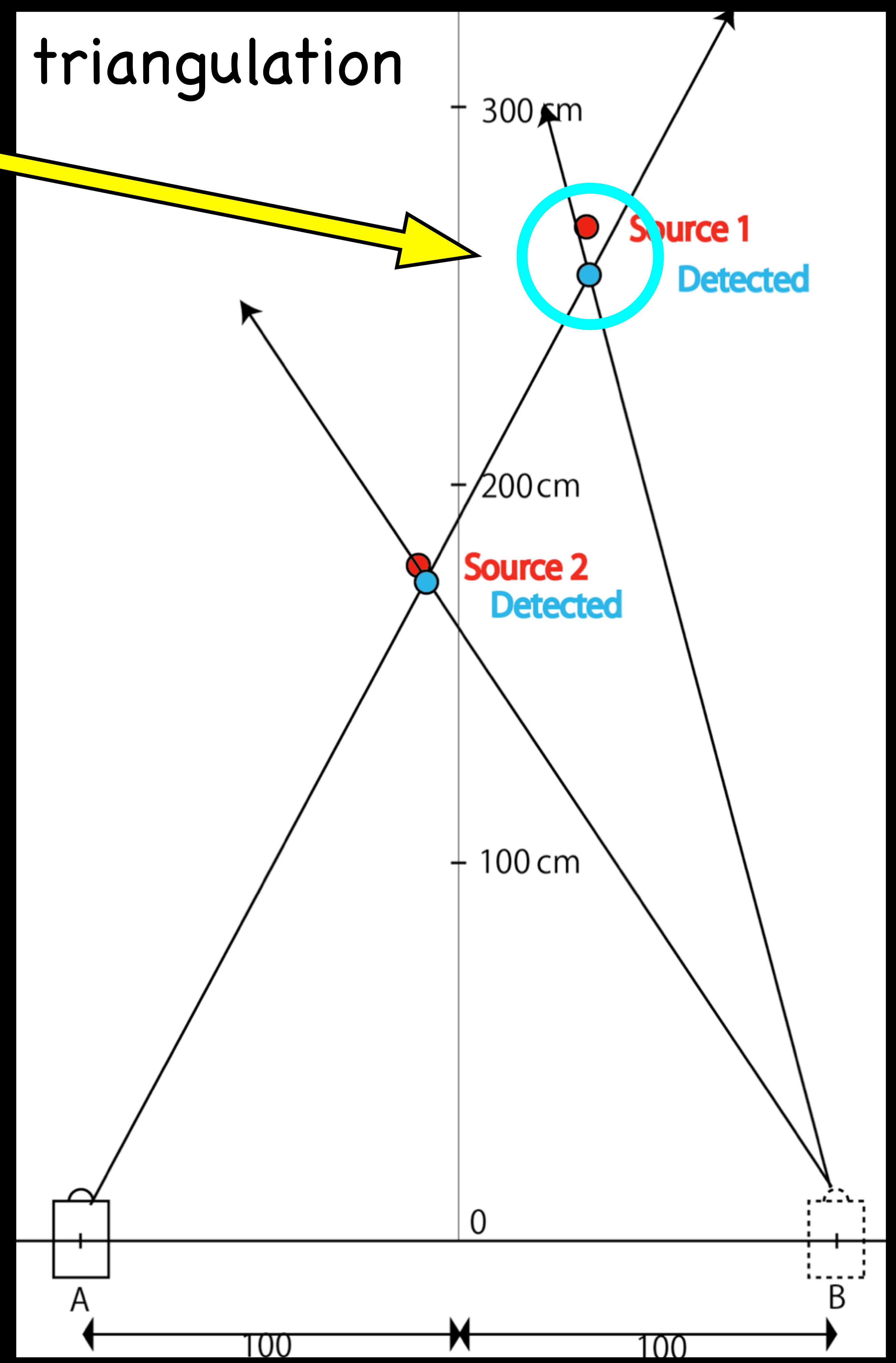
- Image intensity
- FoV data
- Detected positions

Sources intensity

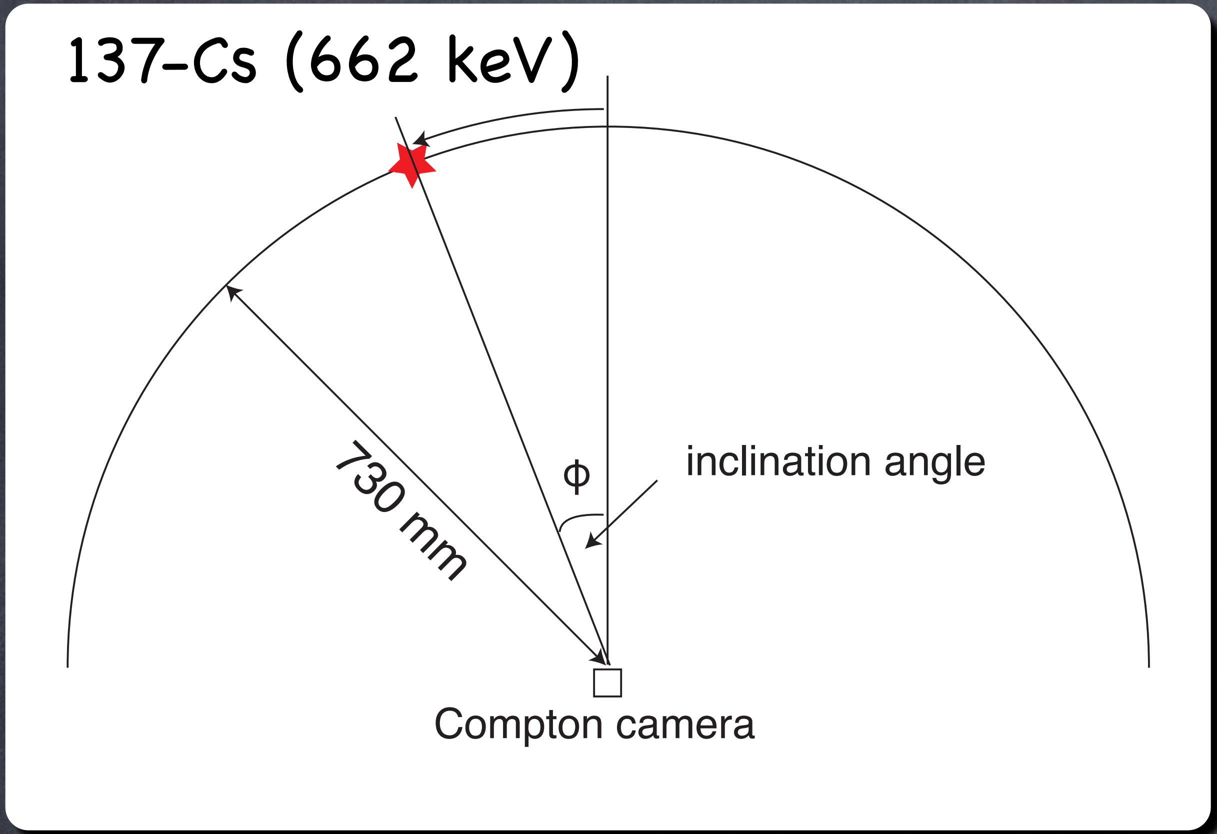
Source 1 : Source 2

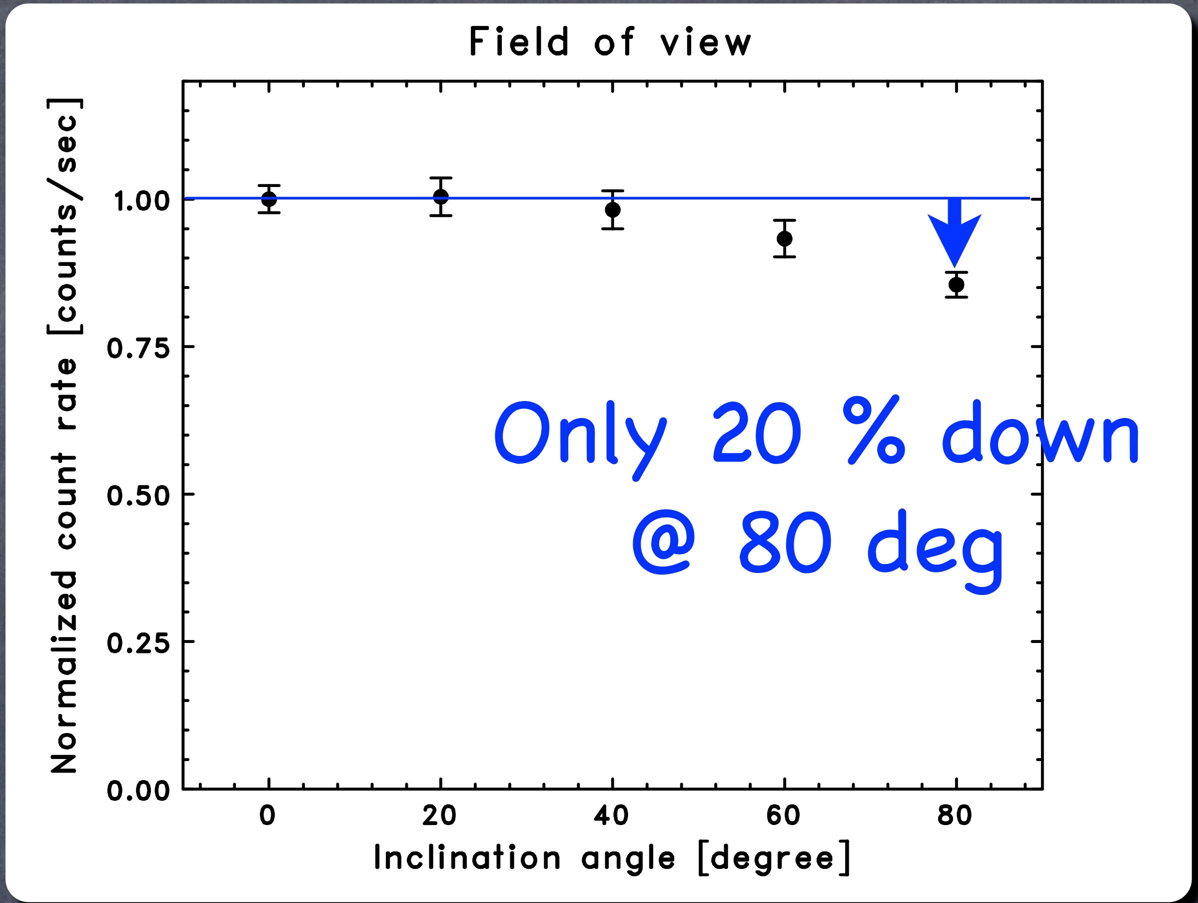
= 1 : 0.94 (answer 1 : 1)

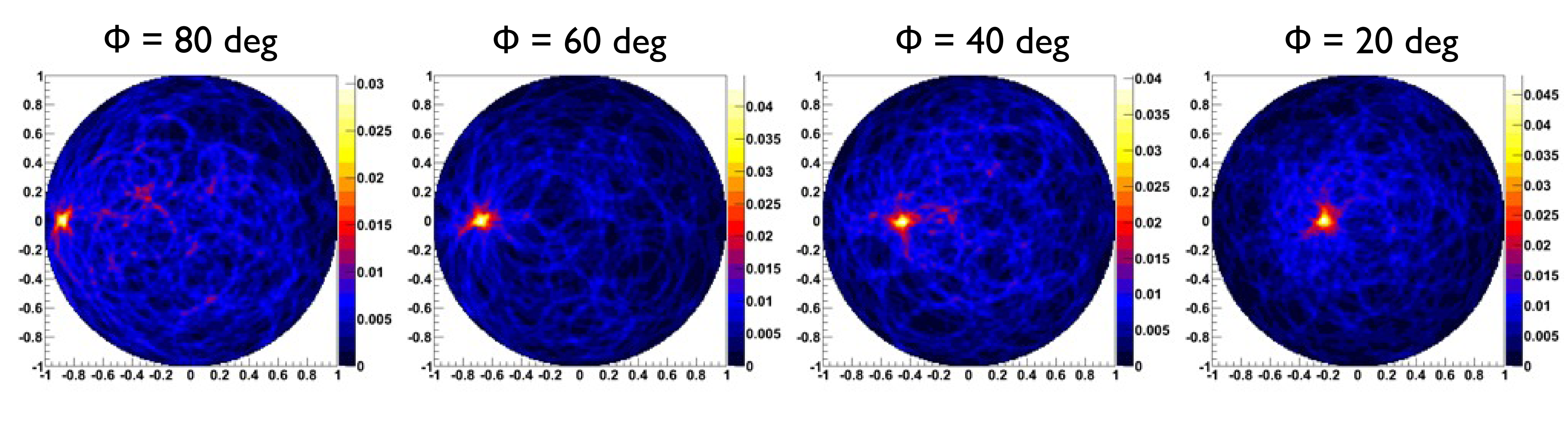
Future : Bq/cm^2 mapping



FOV measurement

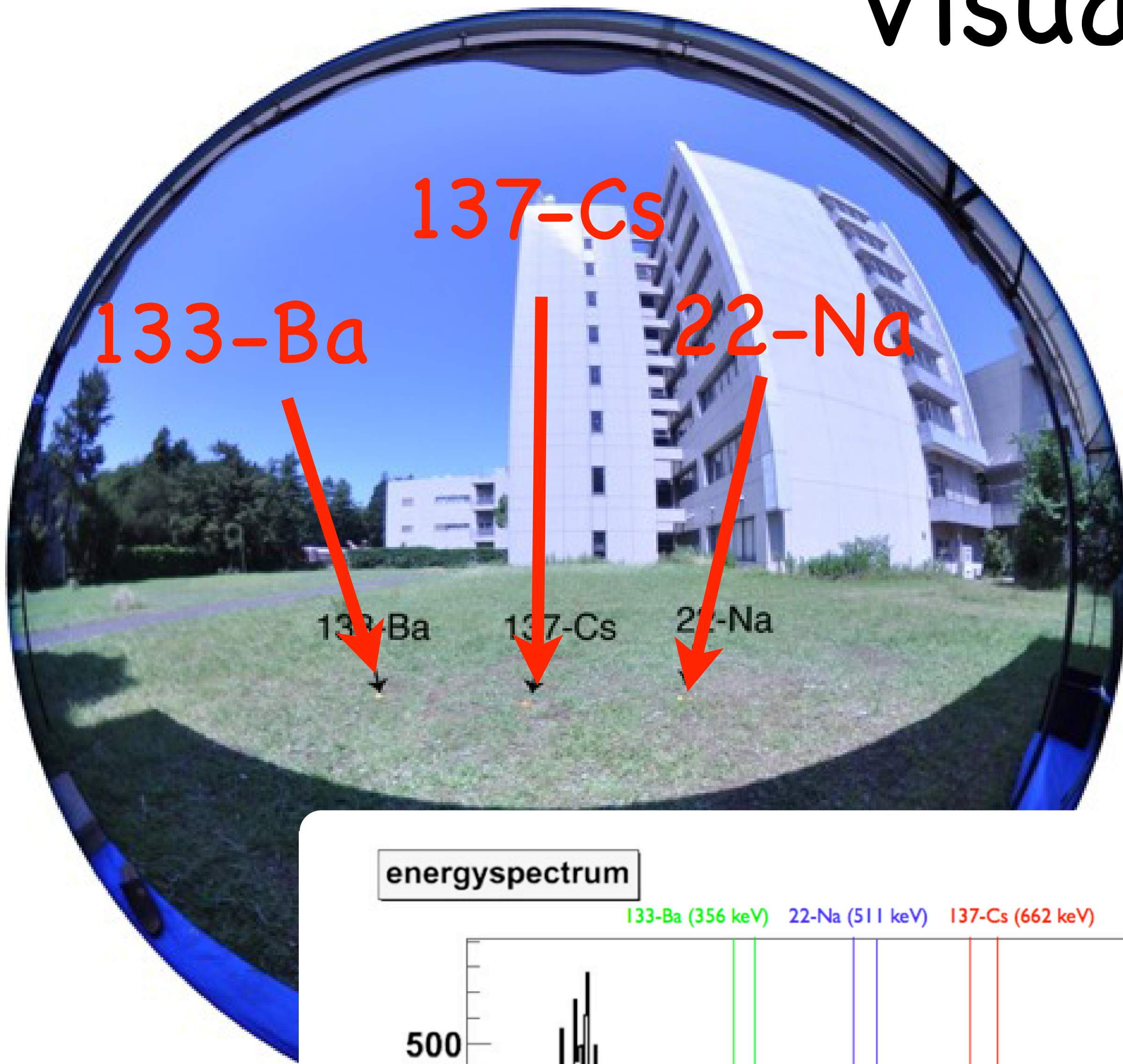


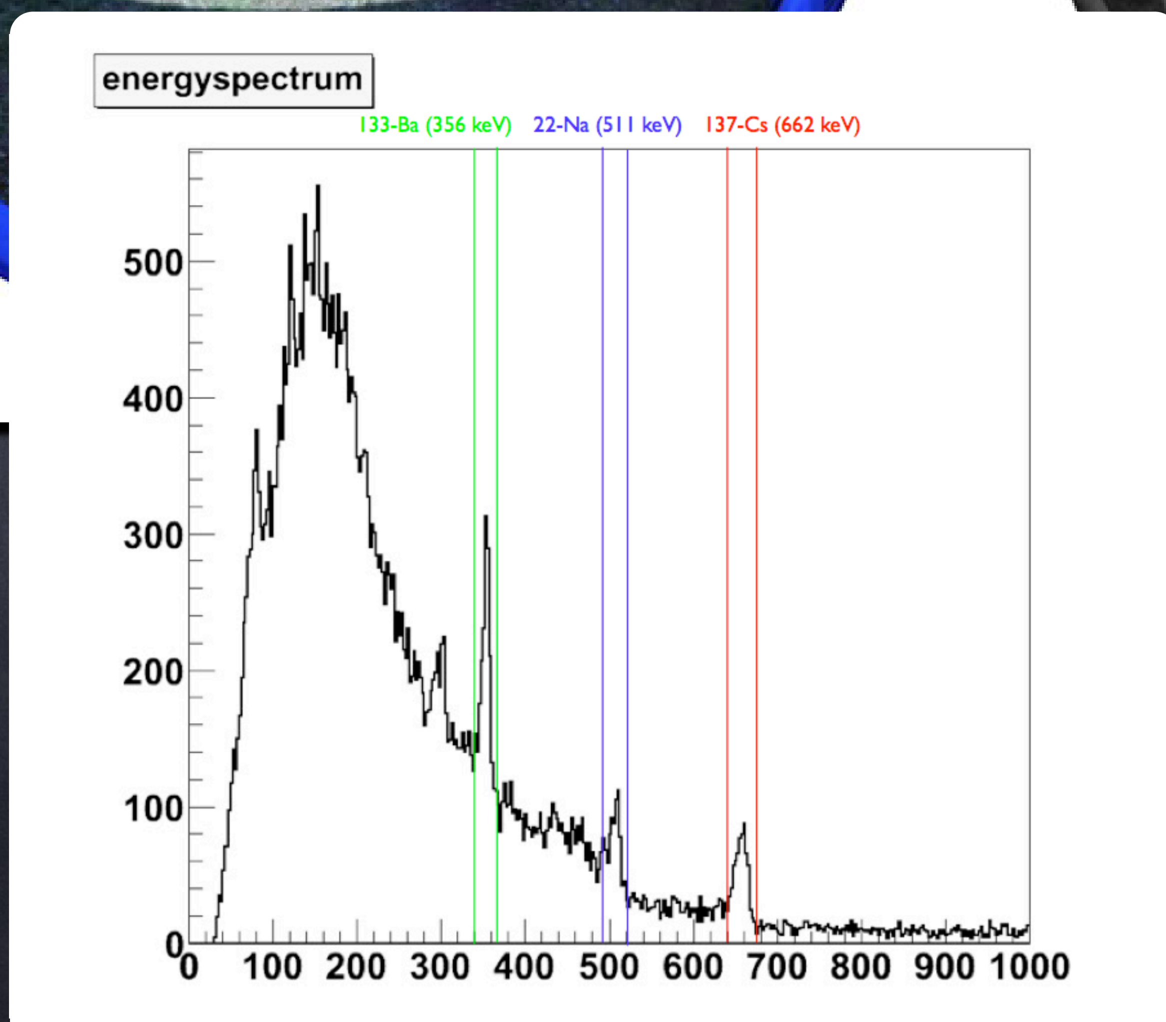




Large FVO corresponding to 2π, Angular resolution 3.8 deg

Visualization





Multi isotope imaging

Good Energy resolution
(2.2 % @ 662 keV)

3D Imaging

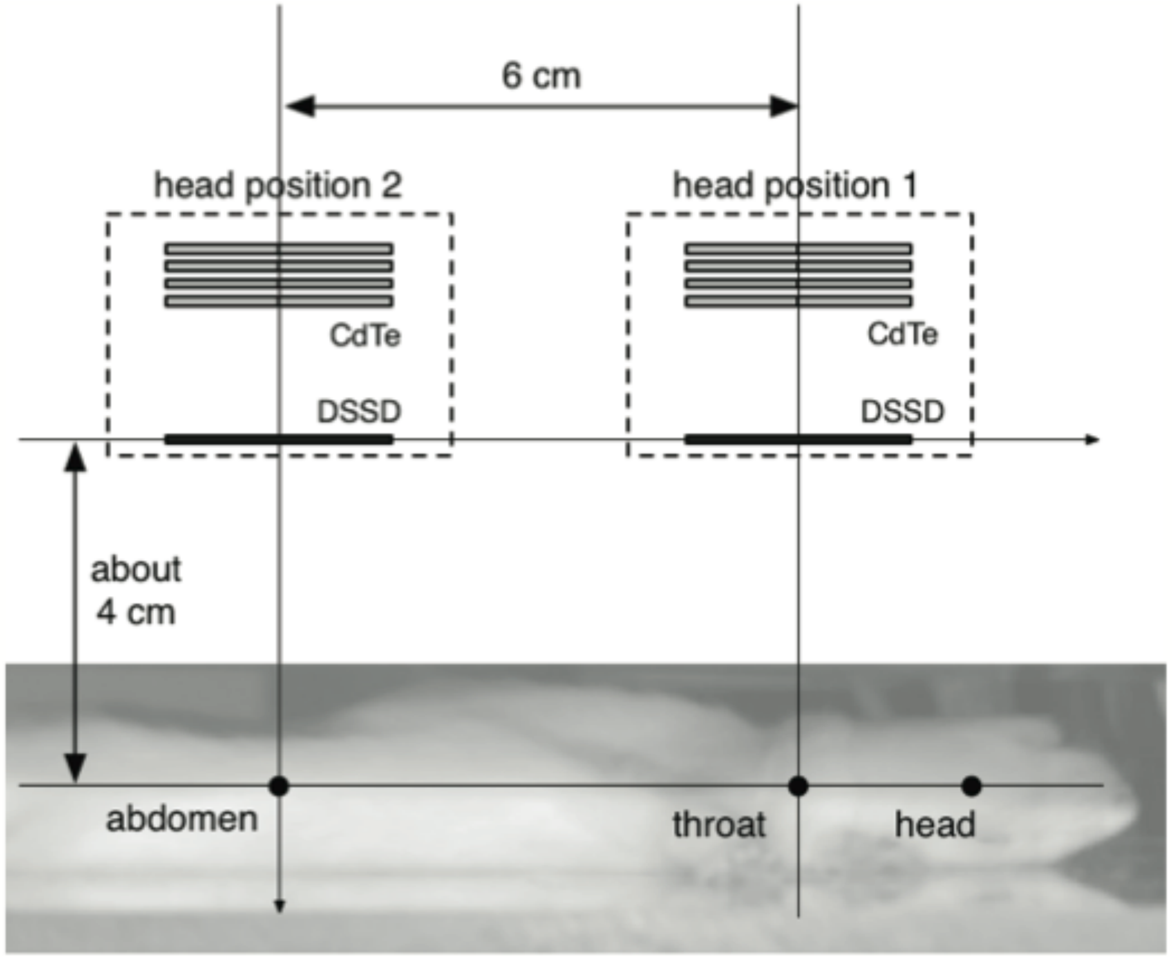


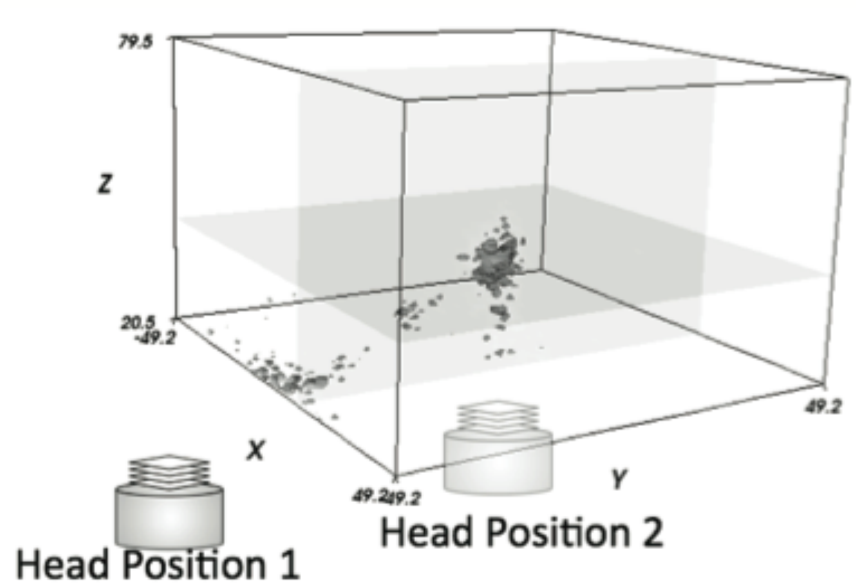
Fig. 3. Relative positions of the camera head against the rat sa

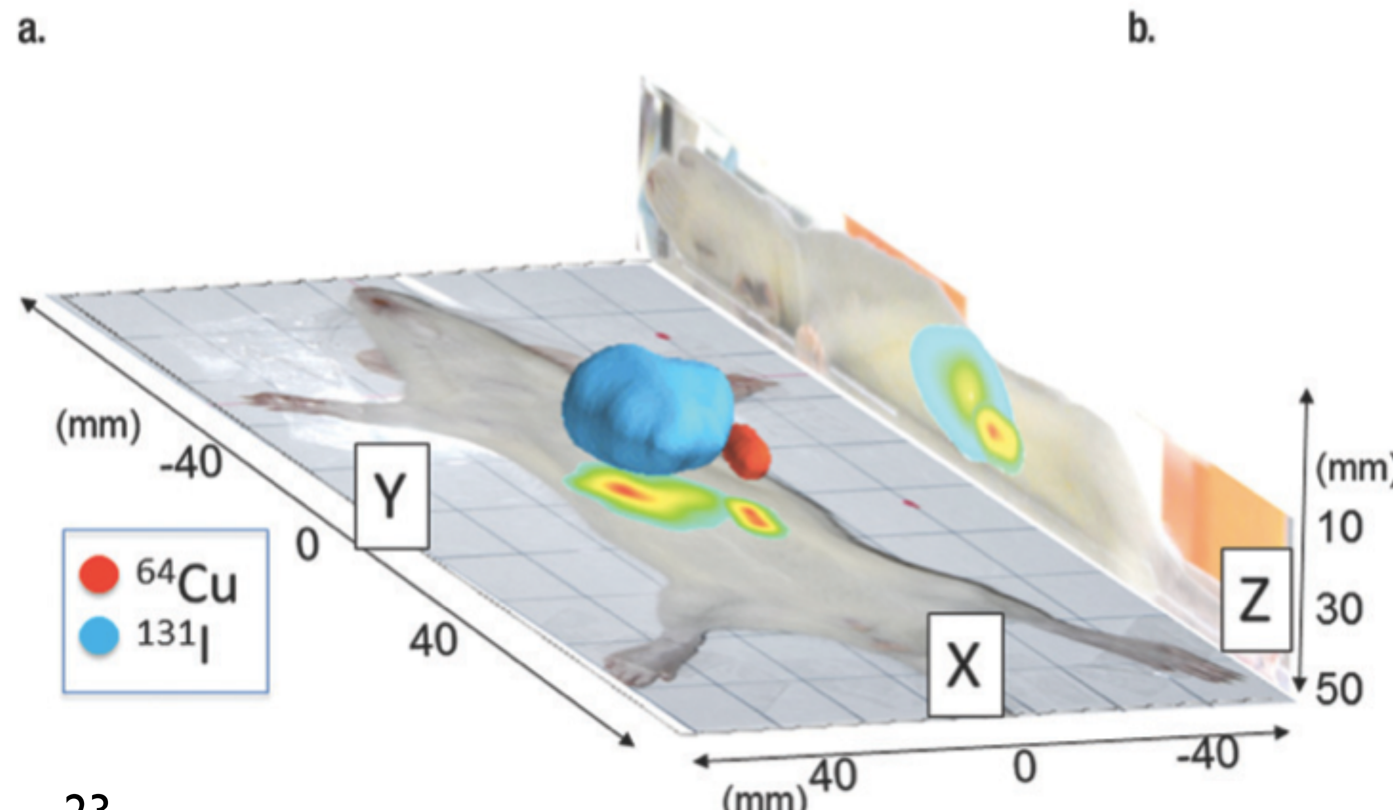
Stereoscopic Observation of Mouse
(ISAS/JAXA, Gunma U.,JAEA)

Yamaguchi et al (2009)

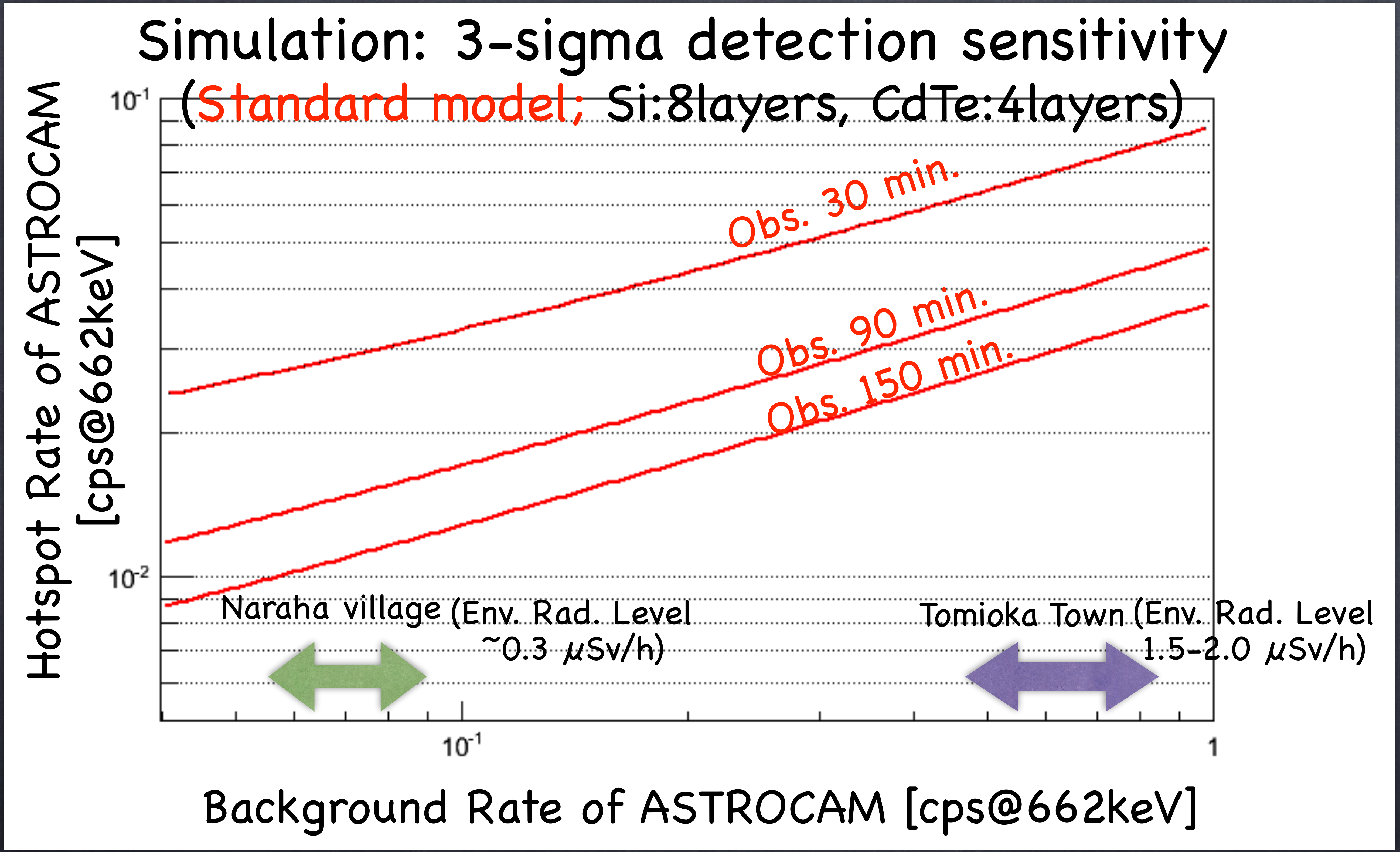
Suzuki et al (2013)

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





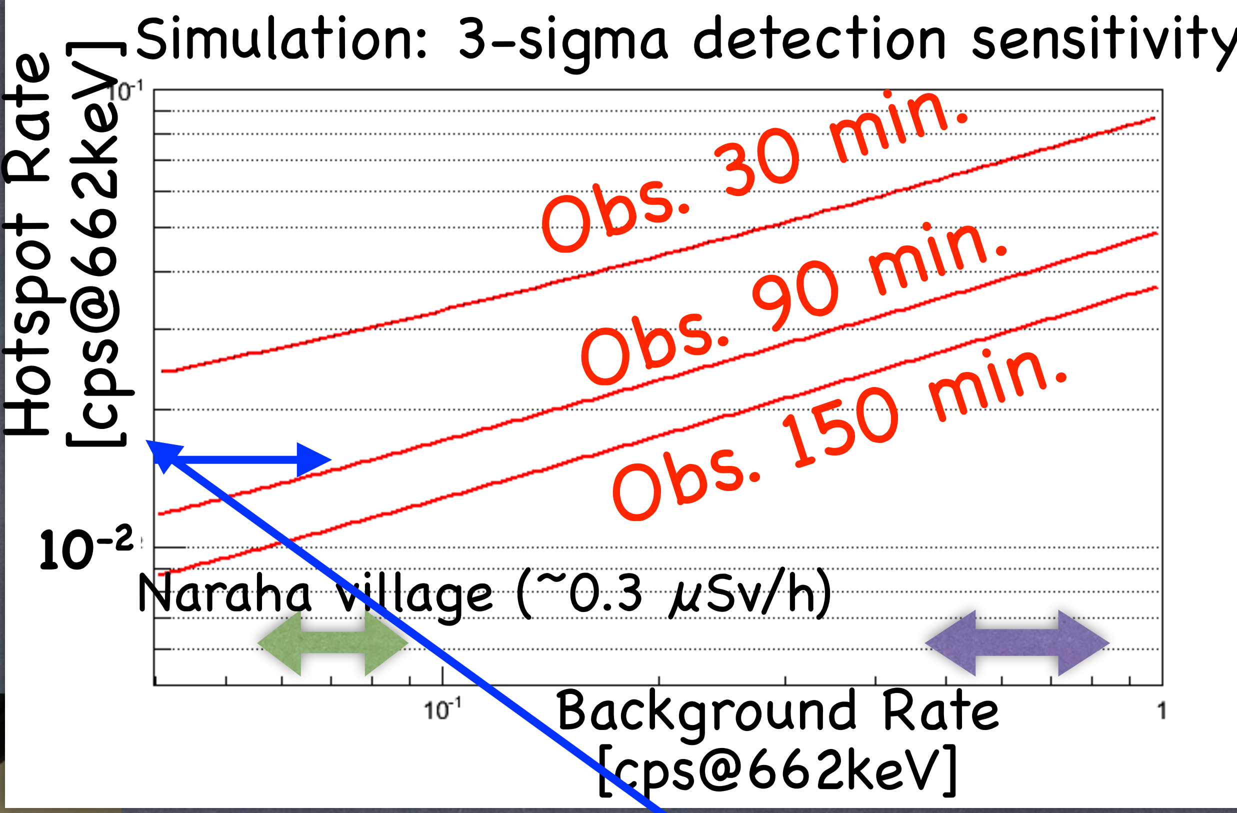
Hotspot detection sensitivity

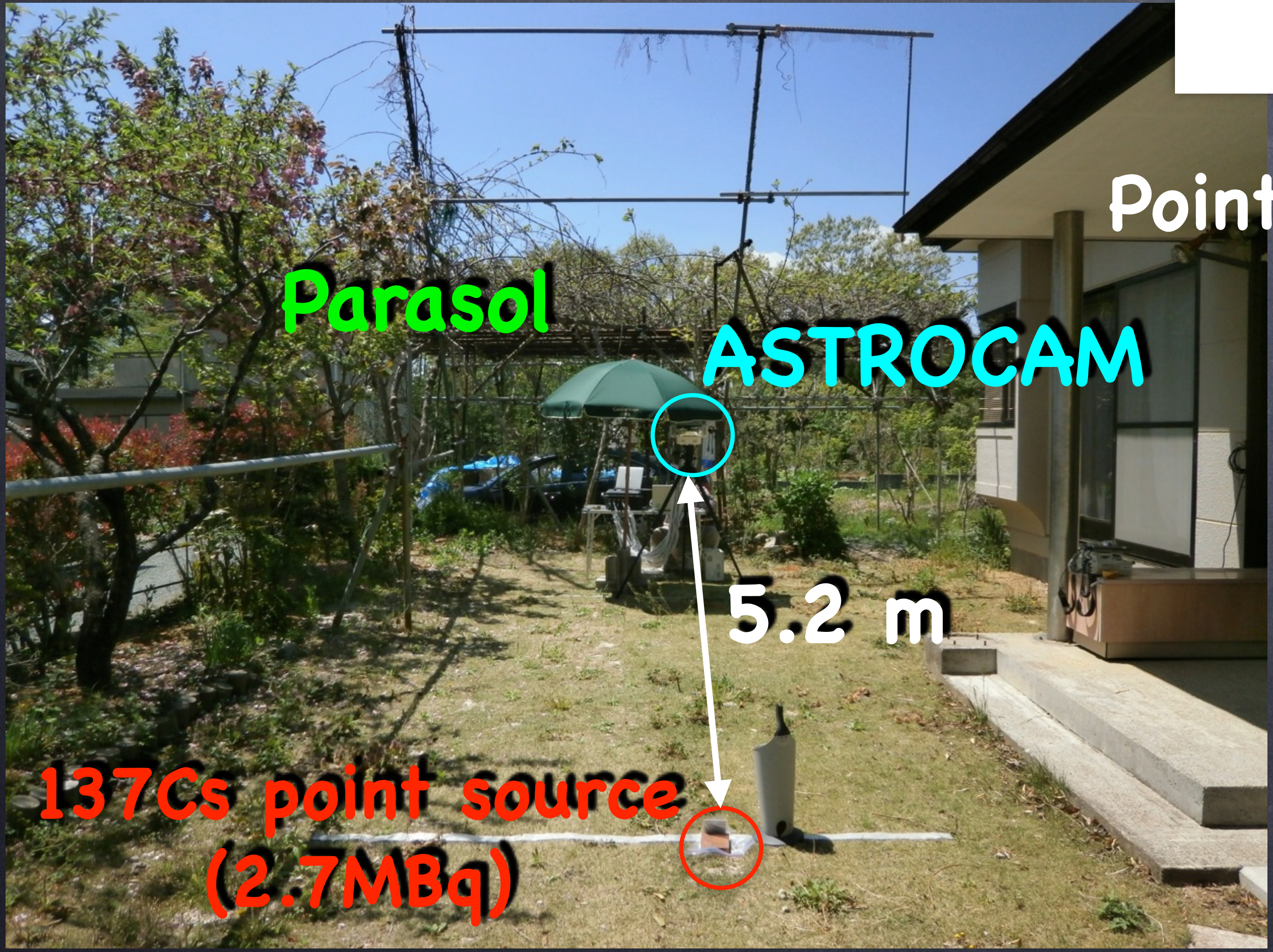


Verification in 0.2-2.0 μSv/h area is very important since the decontamination is now proceeding for inhabitants' return in near future.

Verification in Naraha village

- Inside the 20 km zone from the nuclear plant
- **Env. Rad. Level ~ 0.3 μSv/h**





Point source (2.7MBq, 5.2 m)

- **Rate of ASTROCAM**

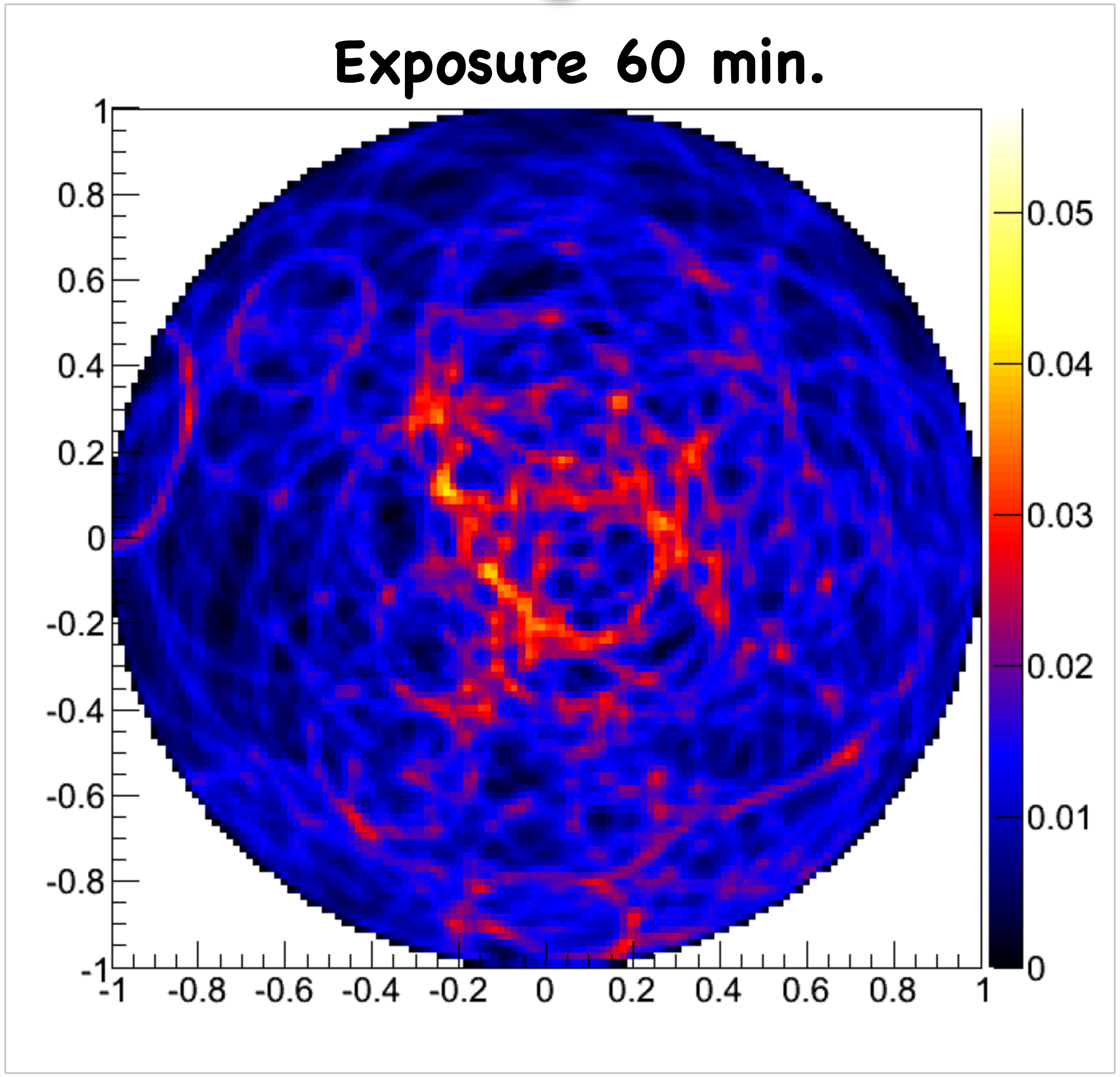
  1.5×10^{-2} cps @ 662 keV

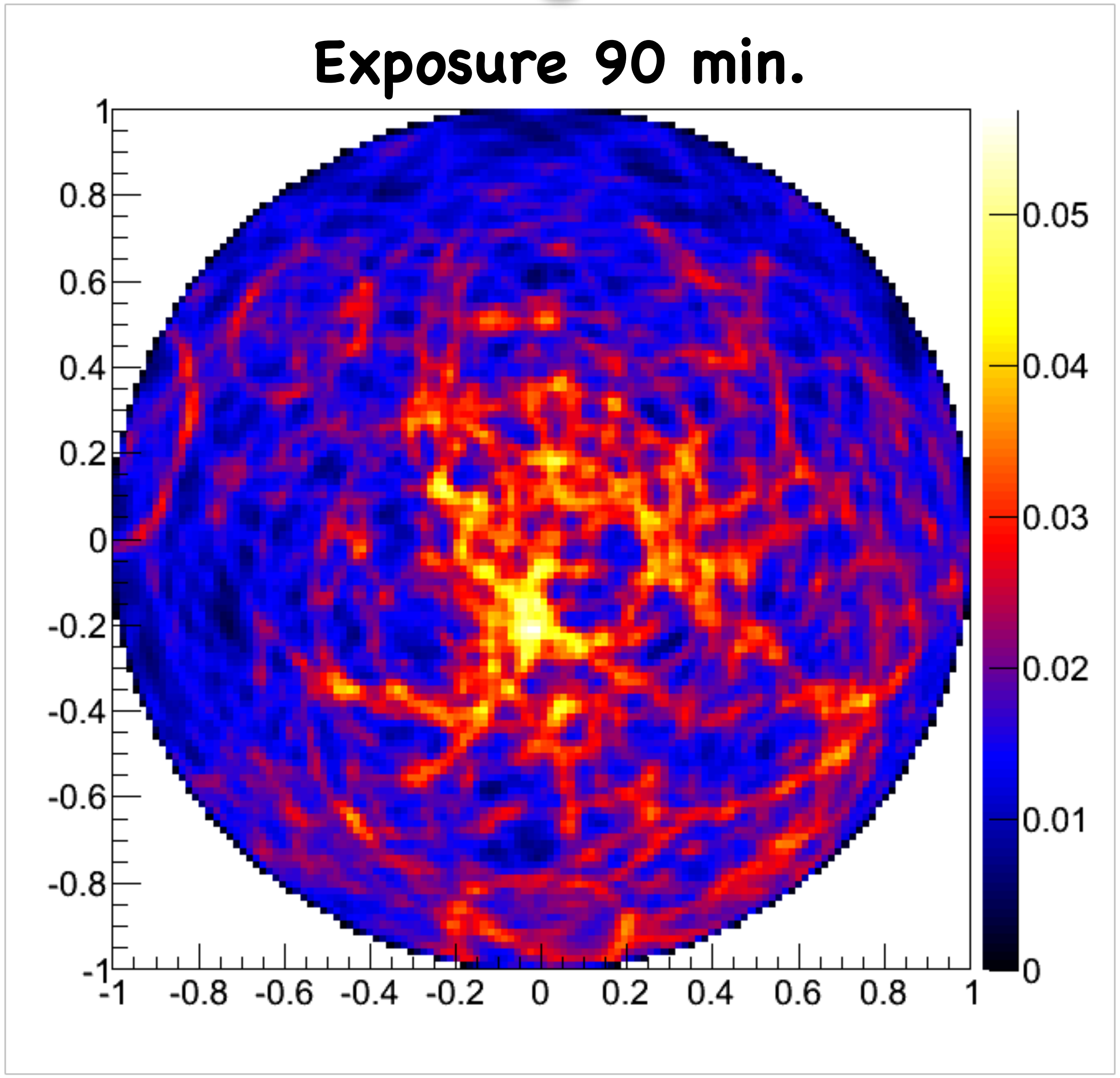
- **Exposure time for 3-sigma detection**

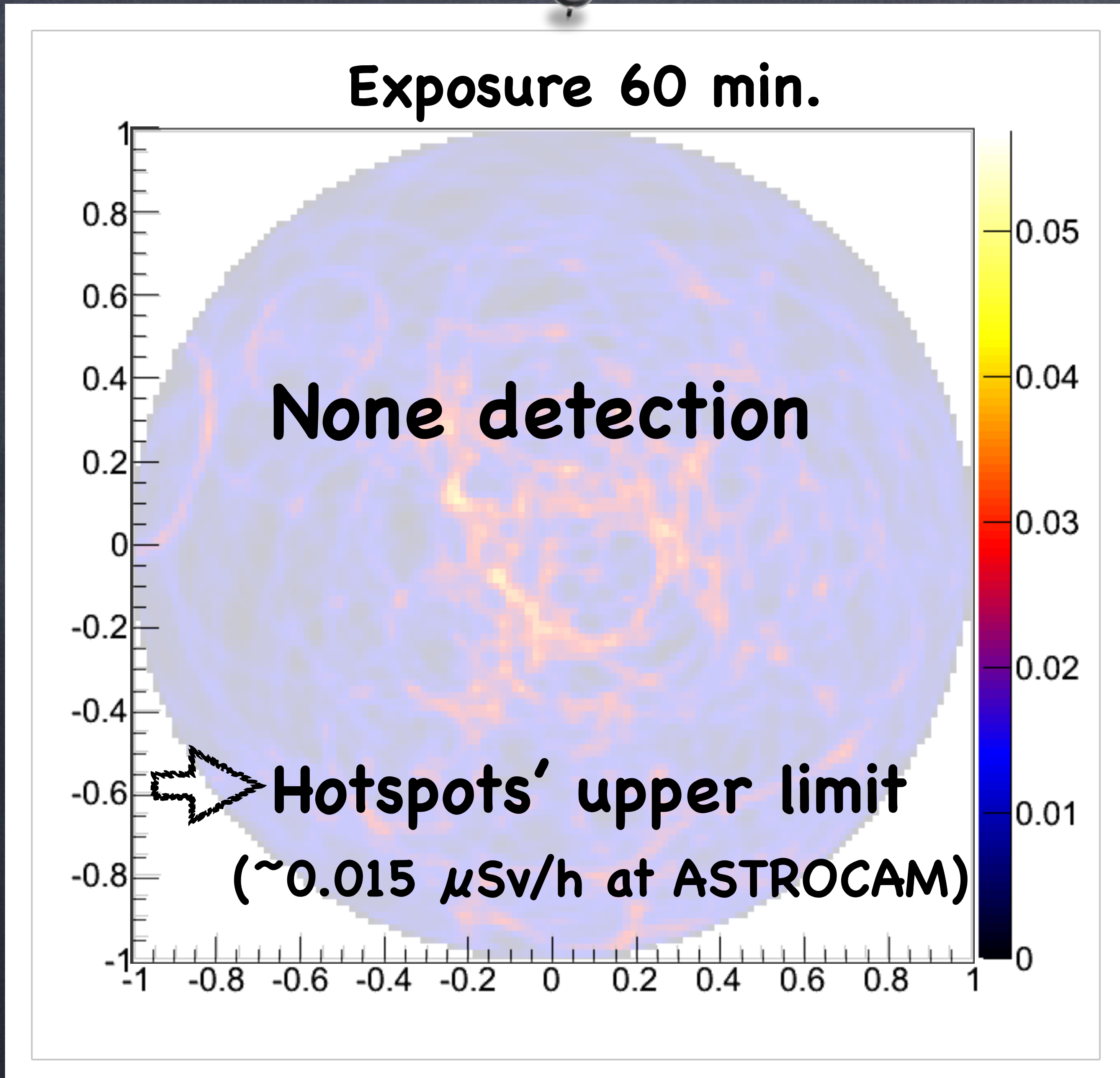
  Expected, around 90 min.

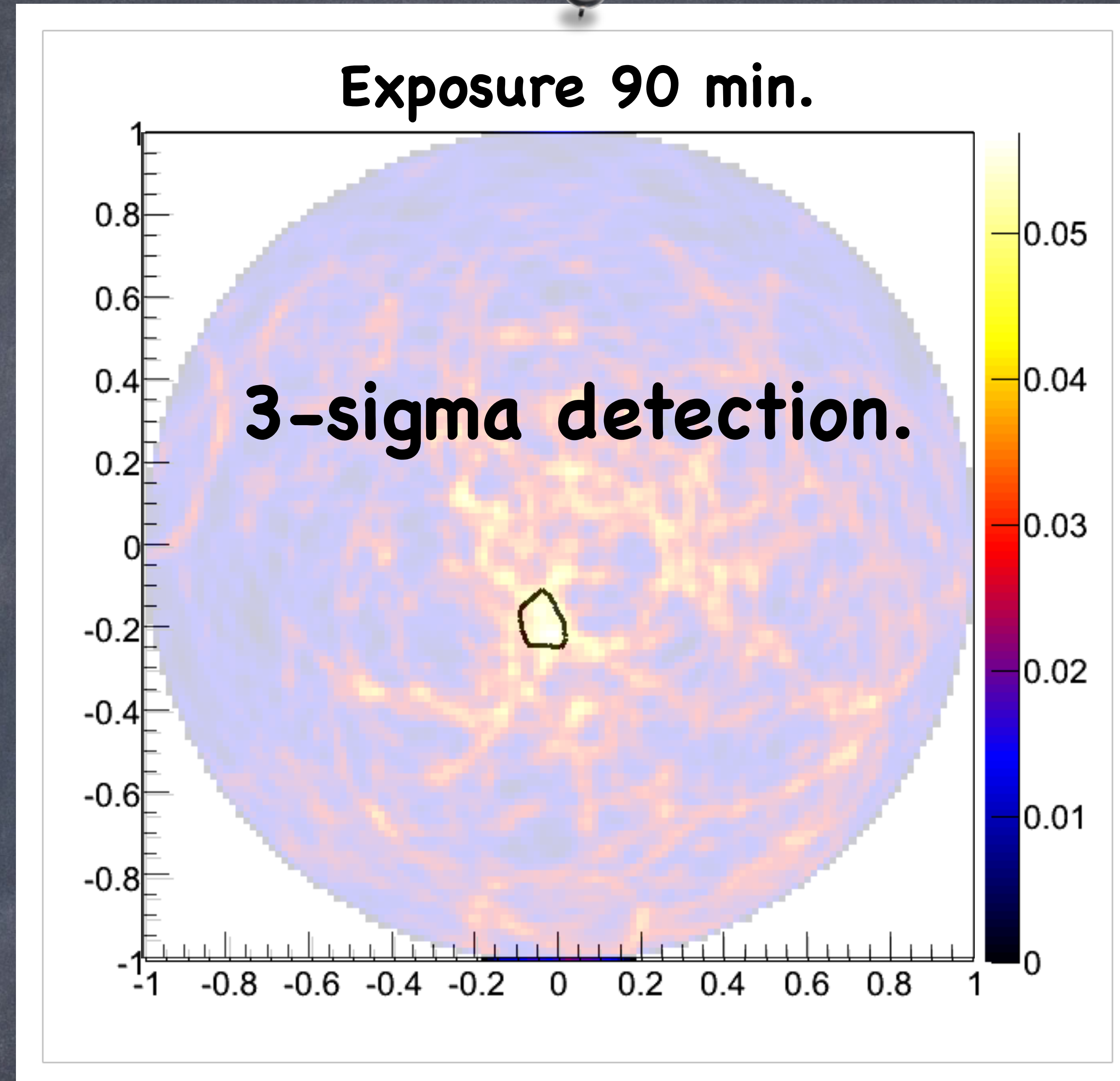
- **Env. Rad. Level**

  ↑ A little rise of 0.01 μSv/h at ASTROCAM


Exposure 60 min.
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
0.05
0.04
0.03
0.02
0.01
0


Exposure 90 min.
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
0.05
0.04
0.03
0.02
0.01
0

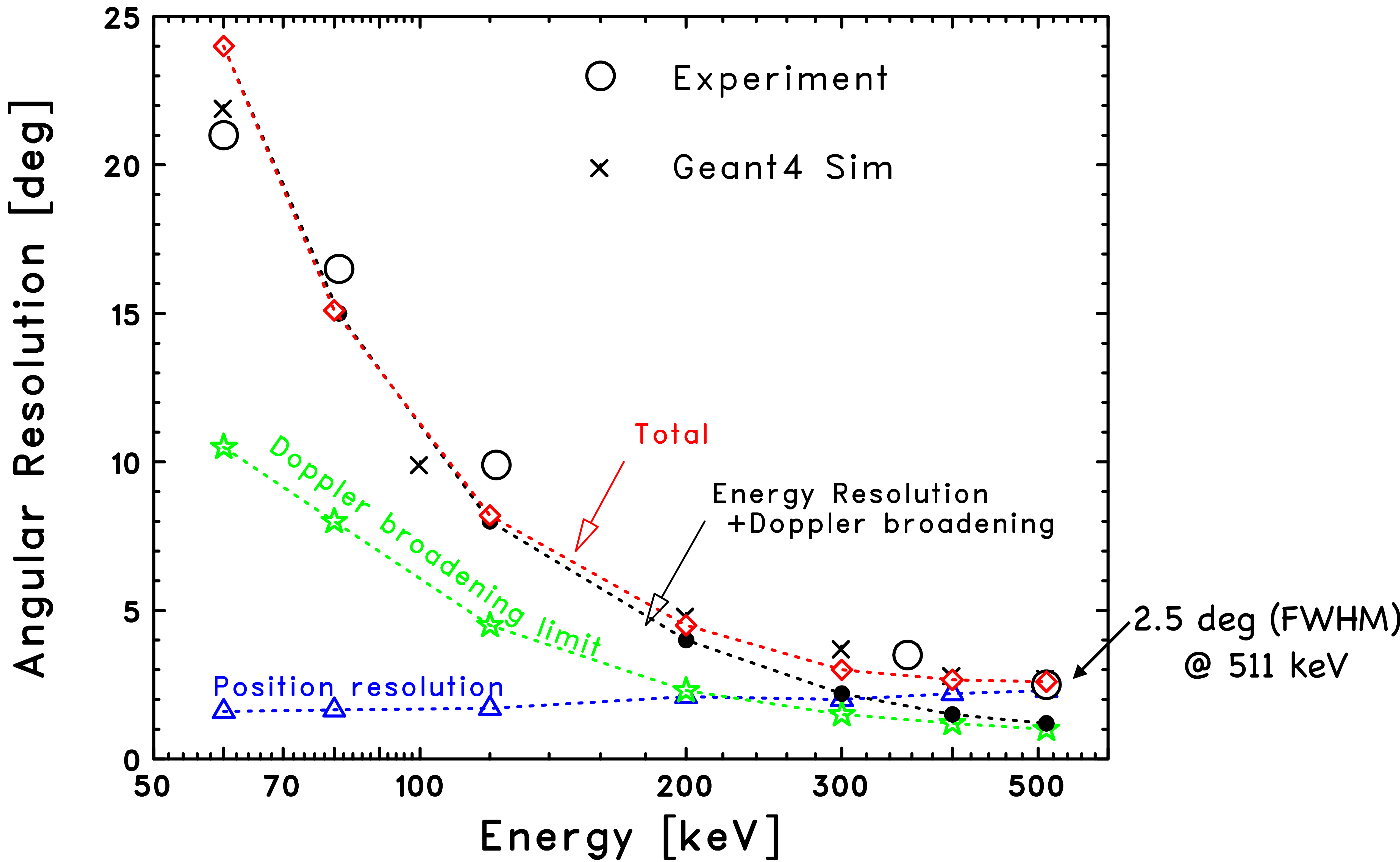




- Weak hotspot that gives ASTROCAM a little rise of Env. Rad. Level of 0.01 μSv/h is detectable. In Naraha village (0.3μSv/h), exposure time is around 90 min, well agrees with the simulation.
- With verified sensitivity curve, hotspots' upper limit was calculated.
- Exposure time can be shortened to 1/16 by the enhanced model of ASTROCAM.

What's a Compton camera ?

Angular resolution achieved by a Si/CdTe Compton camera



Factors of angular uncertainty (Takeda PhD chap 3.4)

- Incomplete measurement by real detectors
  - Finite position resolution (ΔX)

    Uncertainty in photon's scatting direction
  - Finite energy resolution (ΔE)

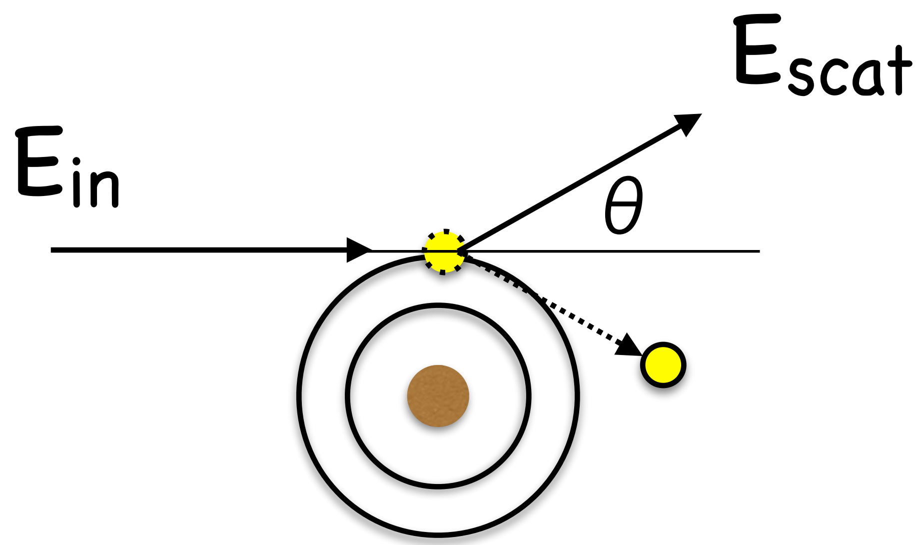
    Uncertainty in photon's scatting angle (θ)
- Momentum of binding electrons (Doppler Broadening Effect)
  - Depend on energy of incident gamma-ray

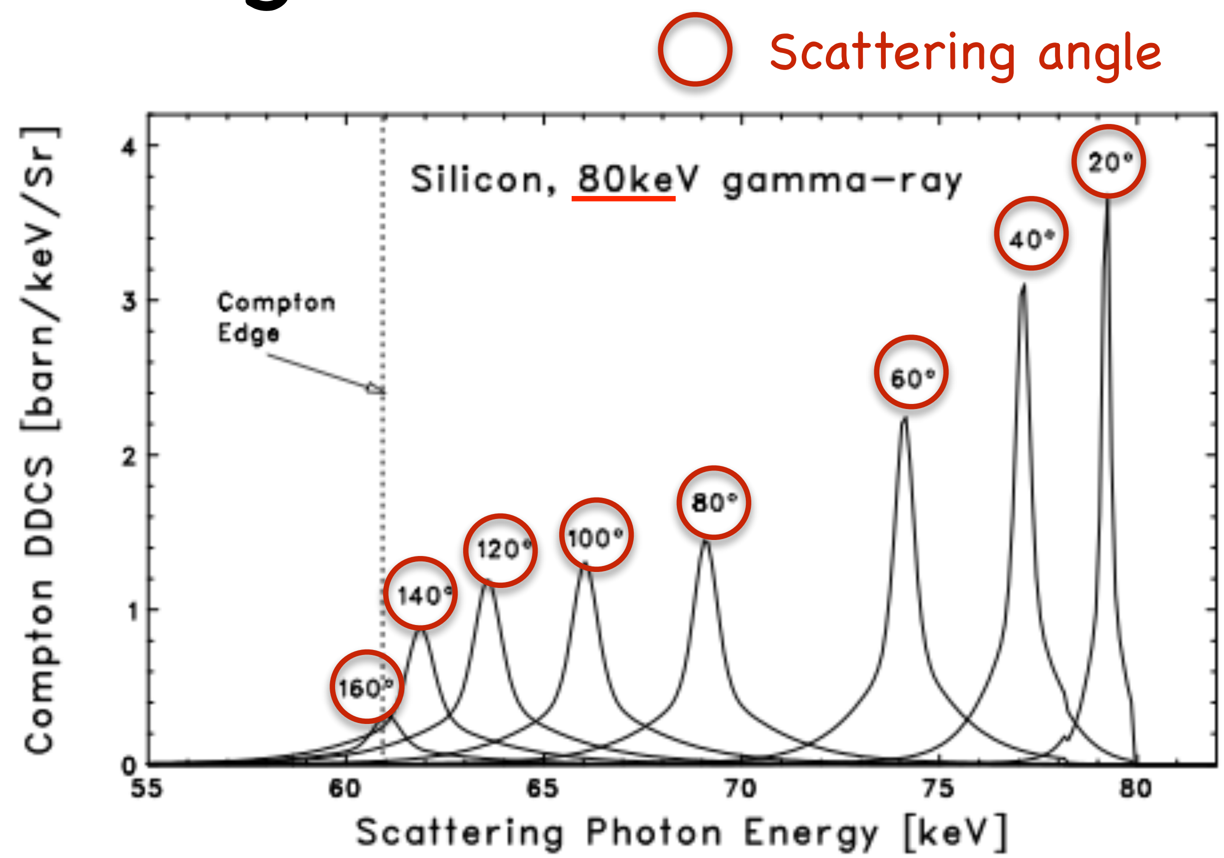
    Energy ↗ DBE ↘ Angular resolution ↗
  - Depend on materials in the scatting part

    Atomic number(Z) ↘ DBE ↘ Angular resolution ↗

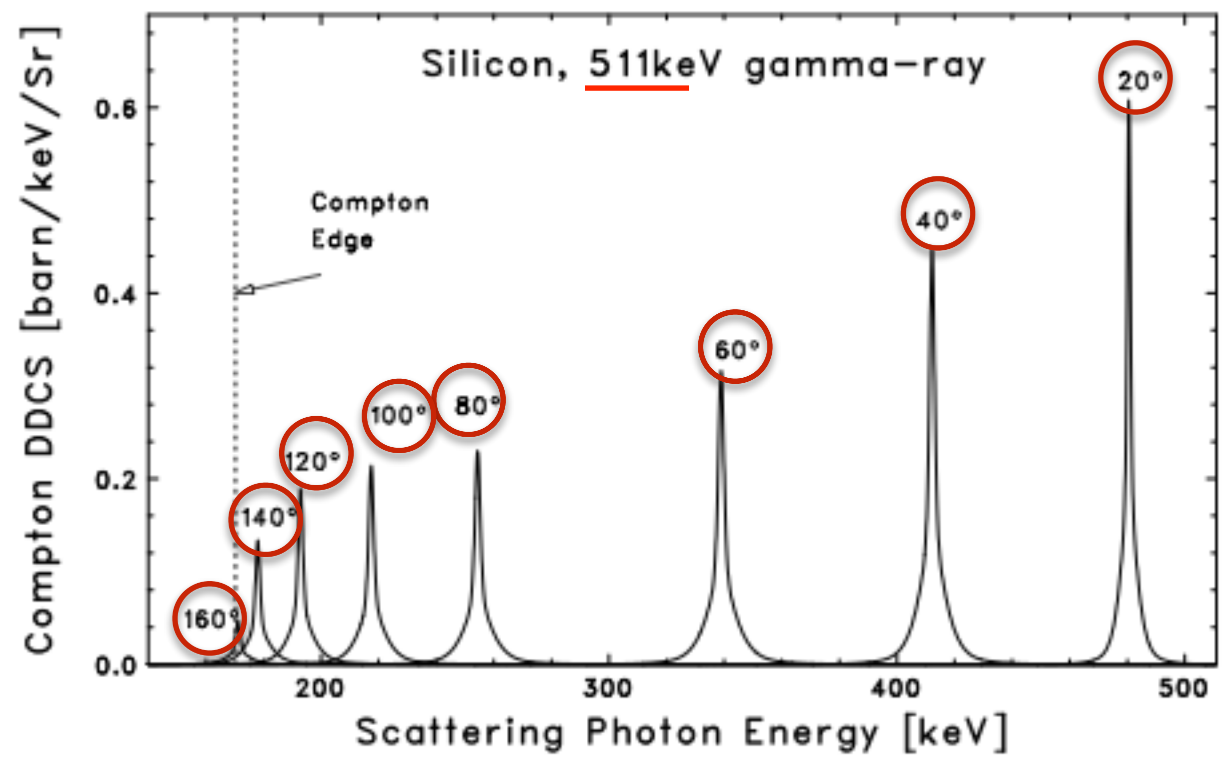
What's a Compton camera ?

Doppler broadening Effect





(a)



(b)

Calculation based on

Numerical Hartree-Fock profile :
F. Biggs et al. (1975)

Simplified analytical equation :
D. Brusa et al. (1996)

What's a Compton camera ?

Doppler broadening Effect