13th International Conference on Position Sensitive Detectors

Evaluation of Compton recoil electron tracking capability of fine-pitch pixel silicon detector with a Monte Carlo simulation

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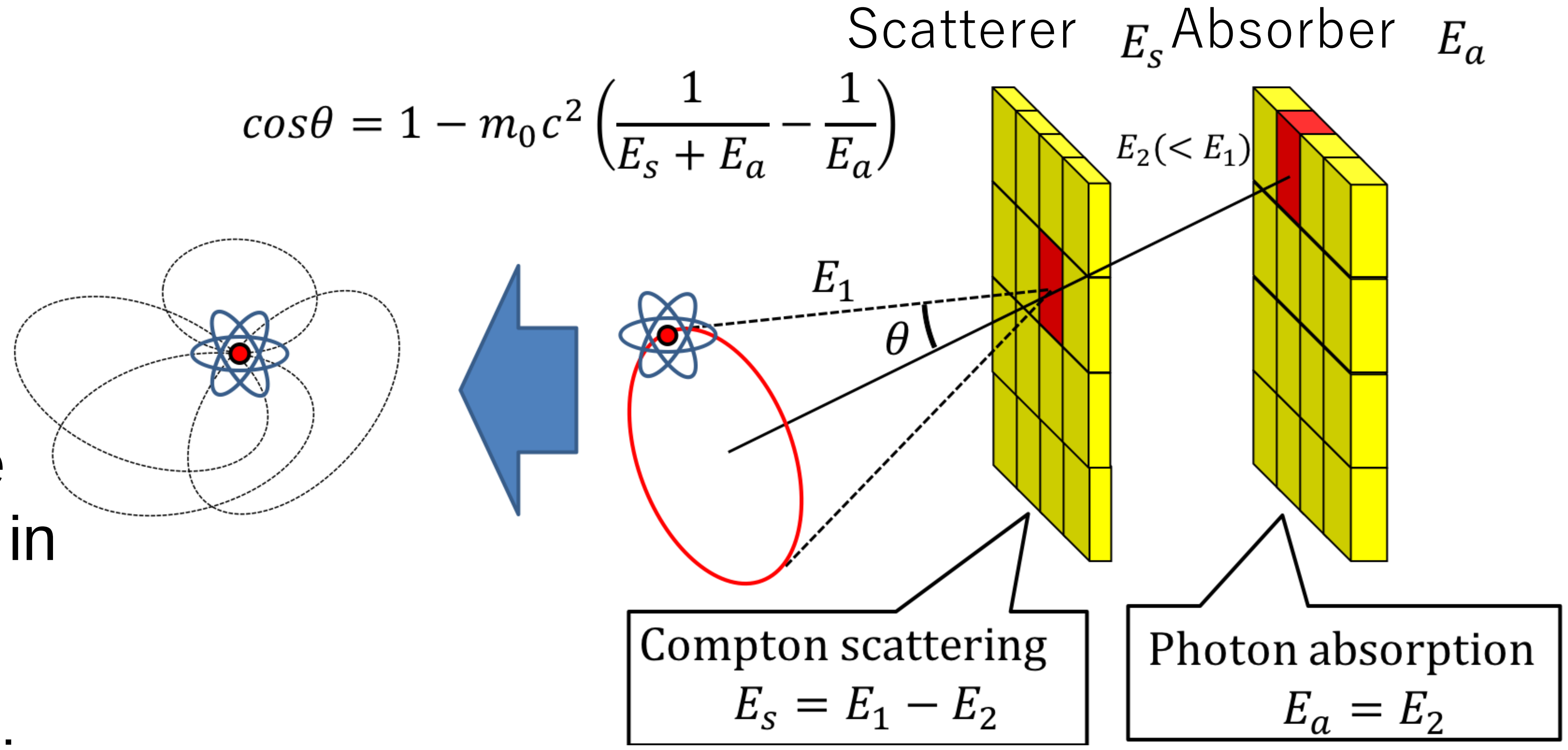
2023.09.07

◆ Compton imaging

- One of gamma-ray imaging techniques based on Compton scattering kinematics
- Scattering angle information can be calculated from deposited energies in a scatterer and an absorber
- No collimators required
- Wide photon energy range for imaging
- Wide field of view

$$\cos\theta = 1 - m_0 c^2 \left(\frac{1}{E_s + E_a} - \frac{1}{E_a} \right)$$



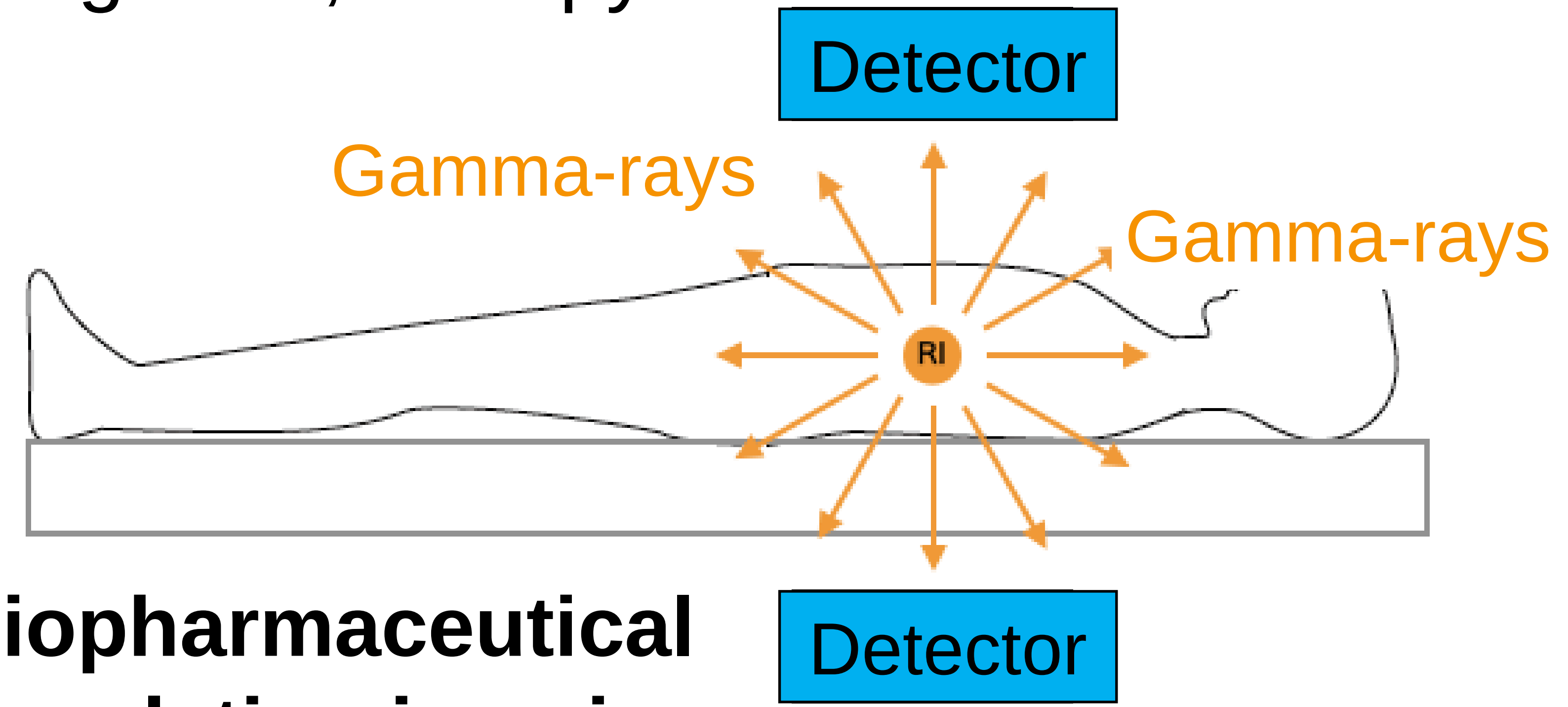
Application

Astrophysics, Medical field, Nuclear field

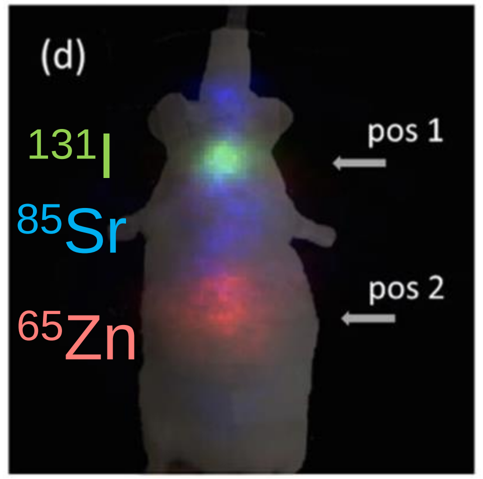
◆ Compton imaging in medical field

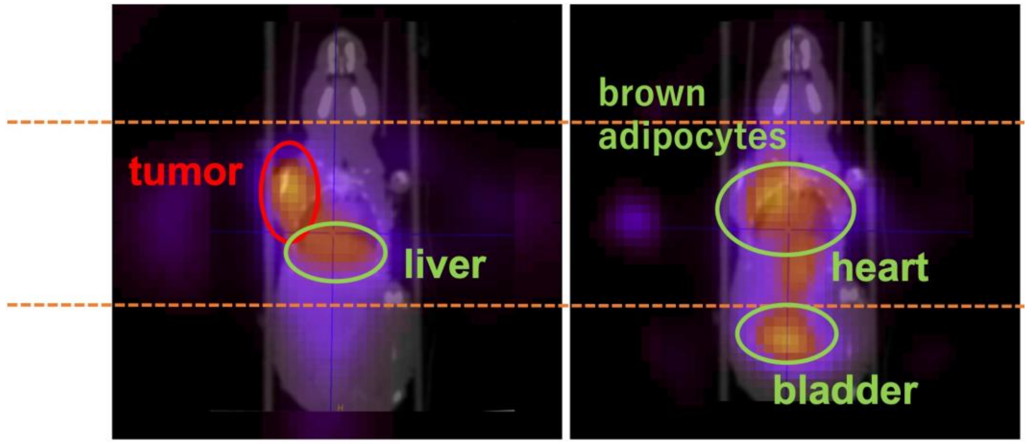
Nuclear Medicine

→Diagnosis, therapy



Radiopharmaceutical accumulation imaging

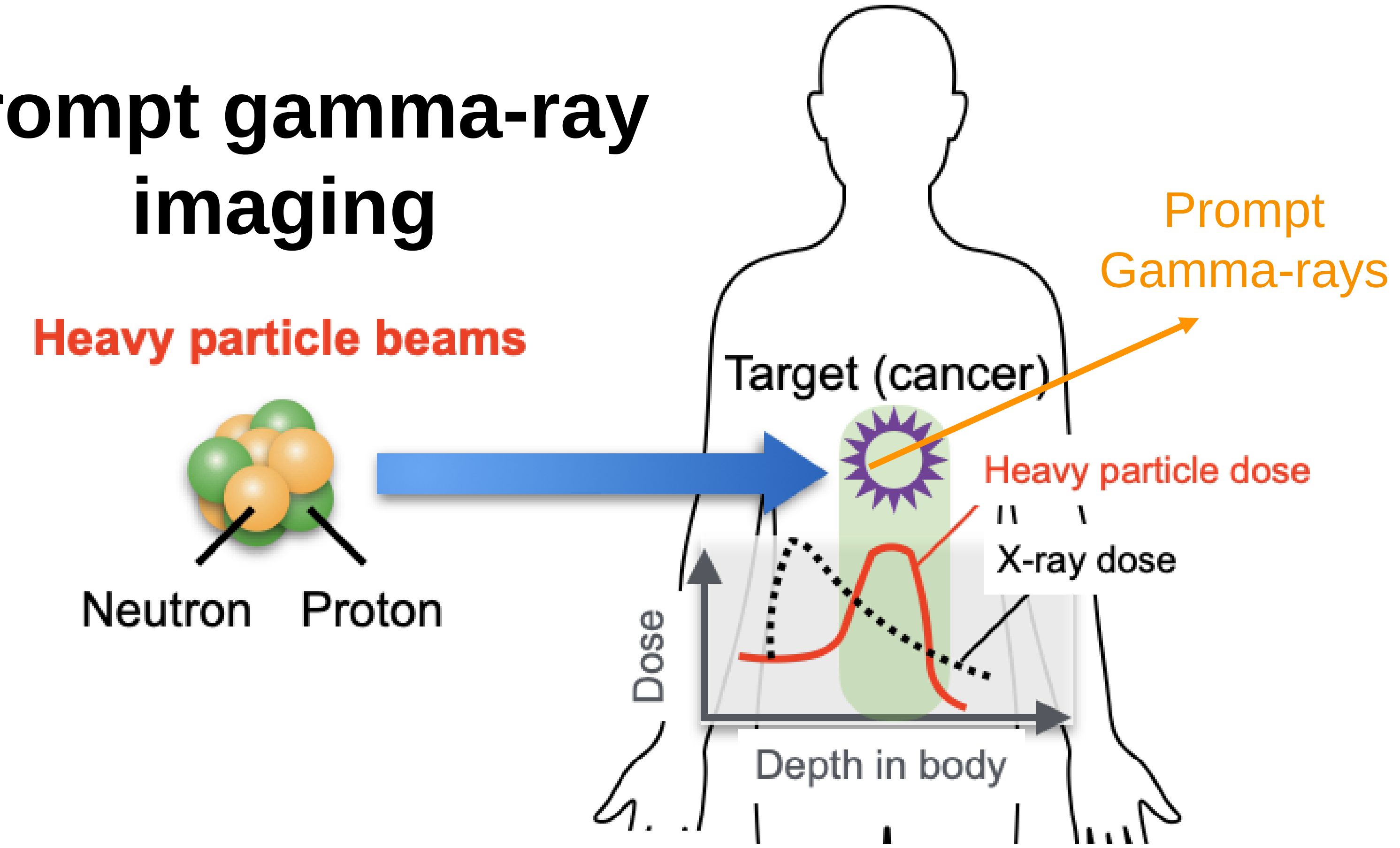


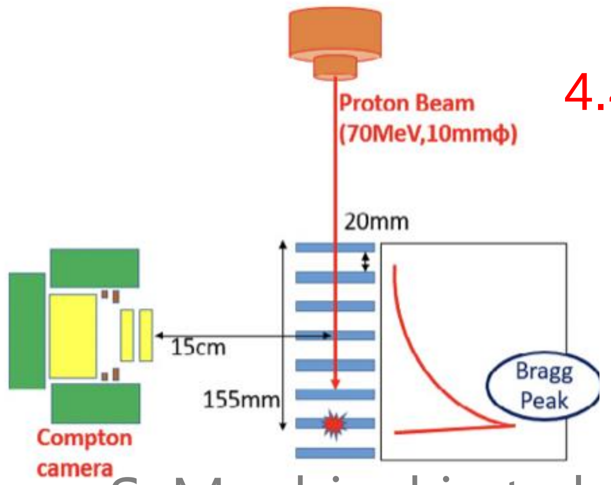


. Kishimoto et al., Sci. Rep., (2017):2110
M. Uenomachi et al., Sci. Rep., (2021):17933

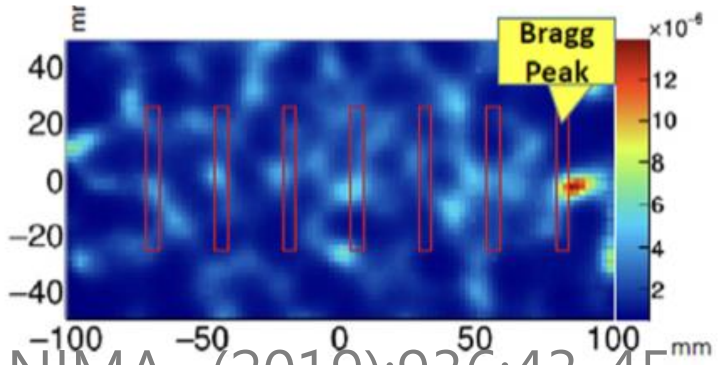
Heavy particle therapy

Prompt gamma-ray imaging





4.4 MeV Prompt gamma imaging



S. Mochizuki et al., NIMA., (2019);936:43-45

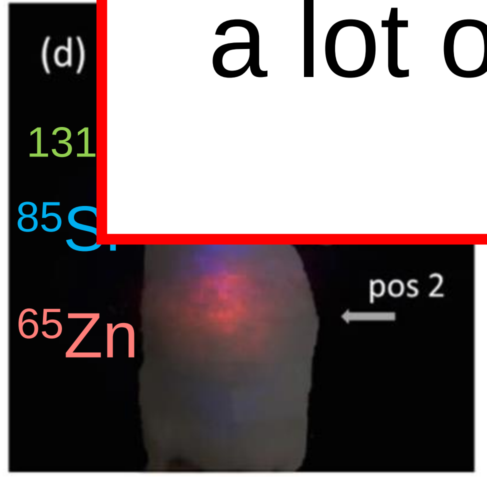
◆ Compton imaging in medical field

Nuclear Medicine

→Diagnosis, therapy

Detector

Radioph
accumul

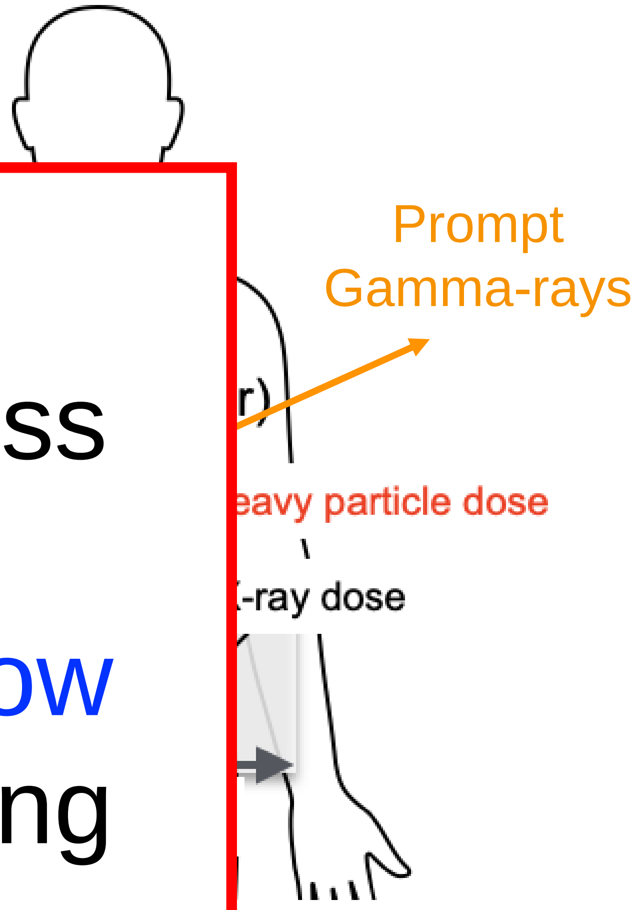


A. Kishimoto et al., Sci. Rep., (2017):2110

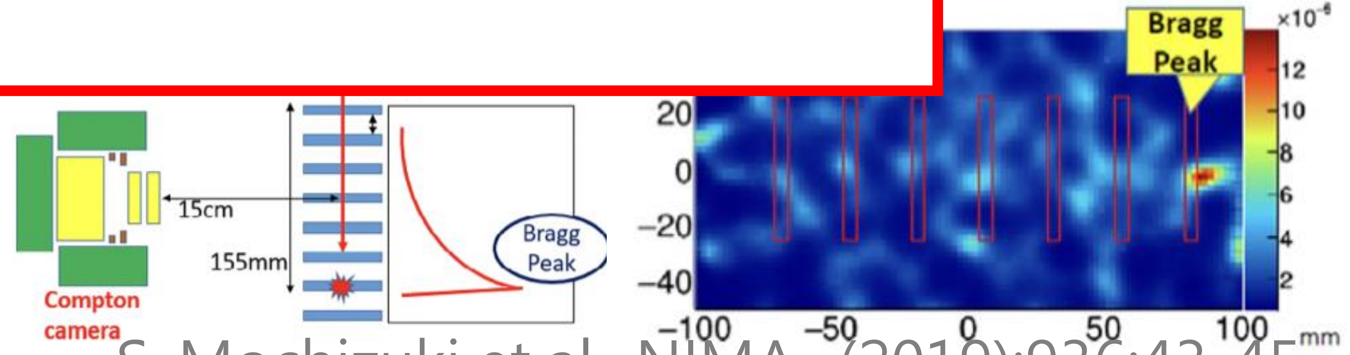
M. Uenomachi et al., Sci. Rep., (2021):17933

Heavy particle therapy

Prompt gamma-ray



t gamma imaging



S. Mochizuki et al., NIMA., (2019);936:43-45

Compton imaging is a promising method in medical field due to the wide energy range and collimator-less imaging

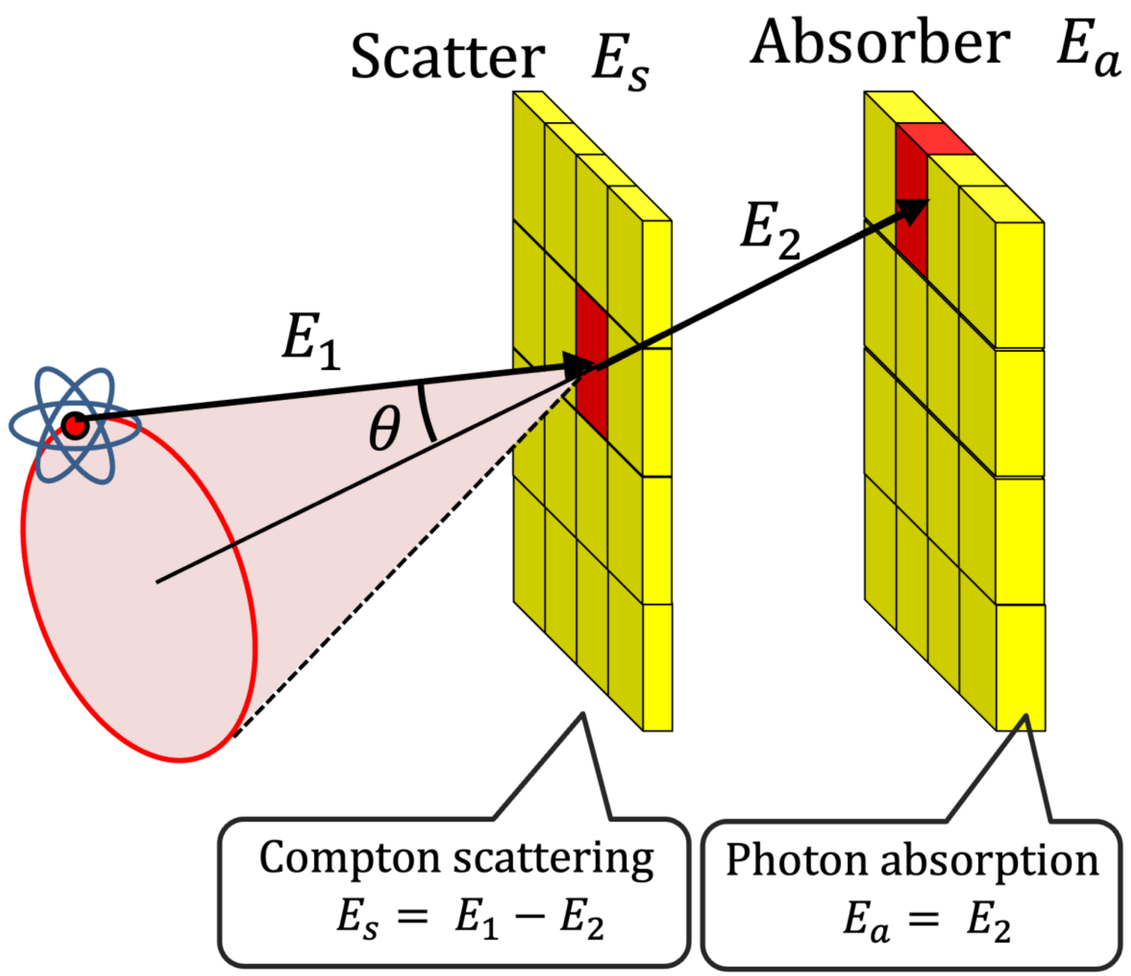
However, still in under research because of the low signal-to-background ration (SBR) caused by drawing a lot of Compton cones.

Recoil electron tracking Compton imaging

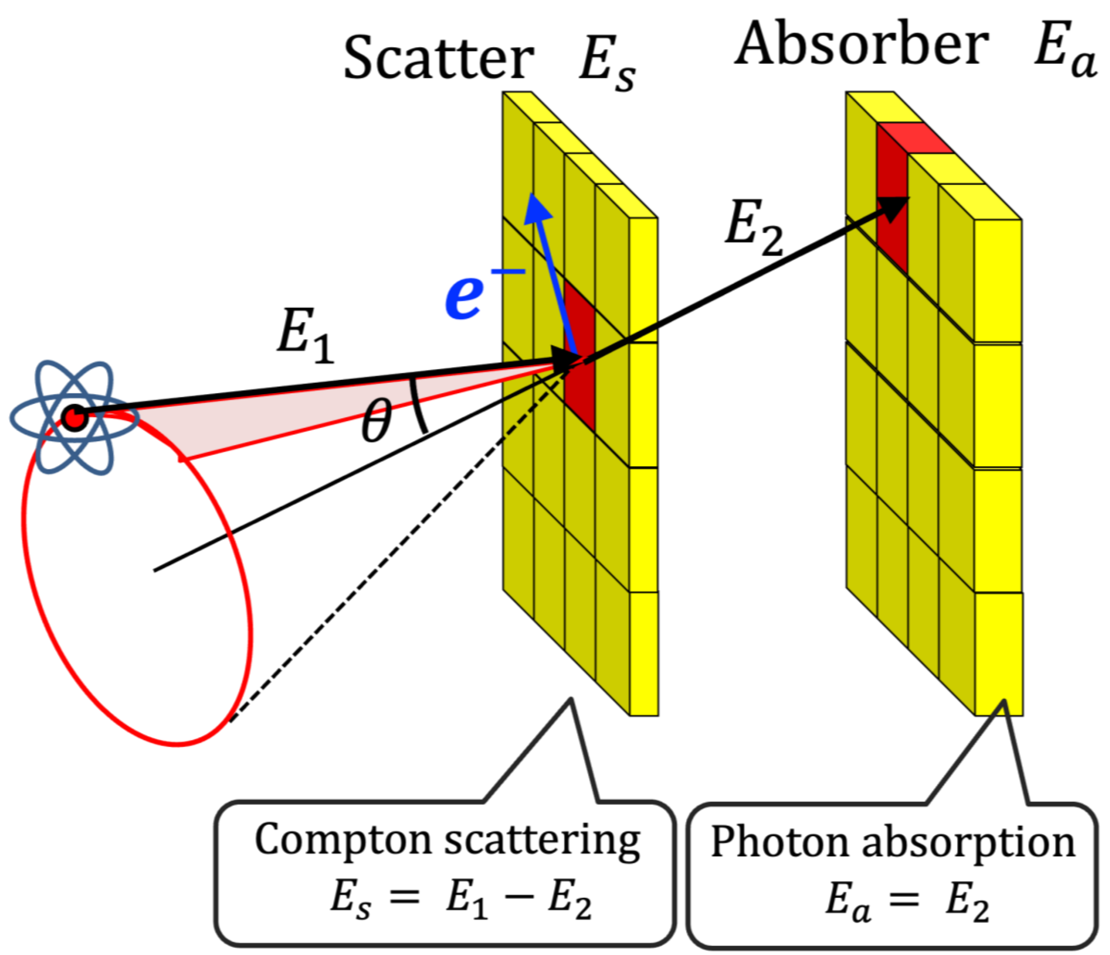
Measurement of a recoil electron trajectory when a photon is Compton scattered in a scatterer

→ Constrains the radionuclide position on from a Compton conical surface to **an arc surface**

Conventional imaging



Electron tracking imaging



Recoil electron tracking Compton imaging

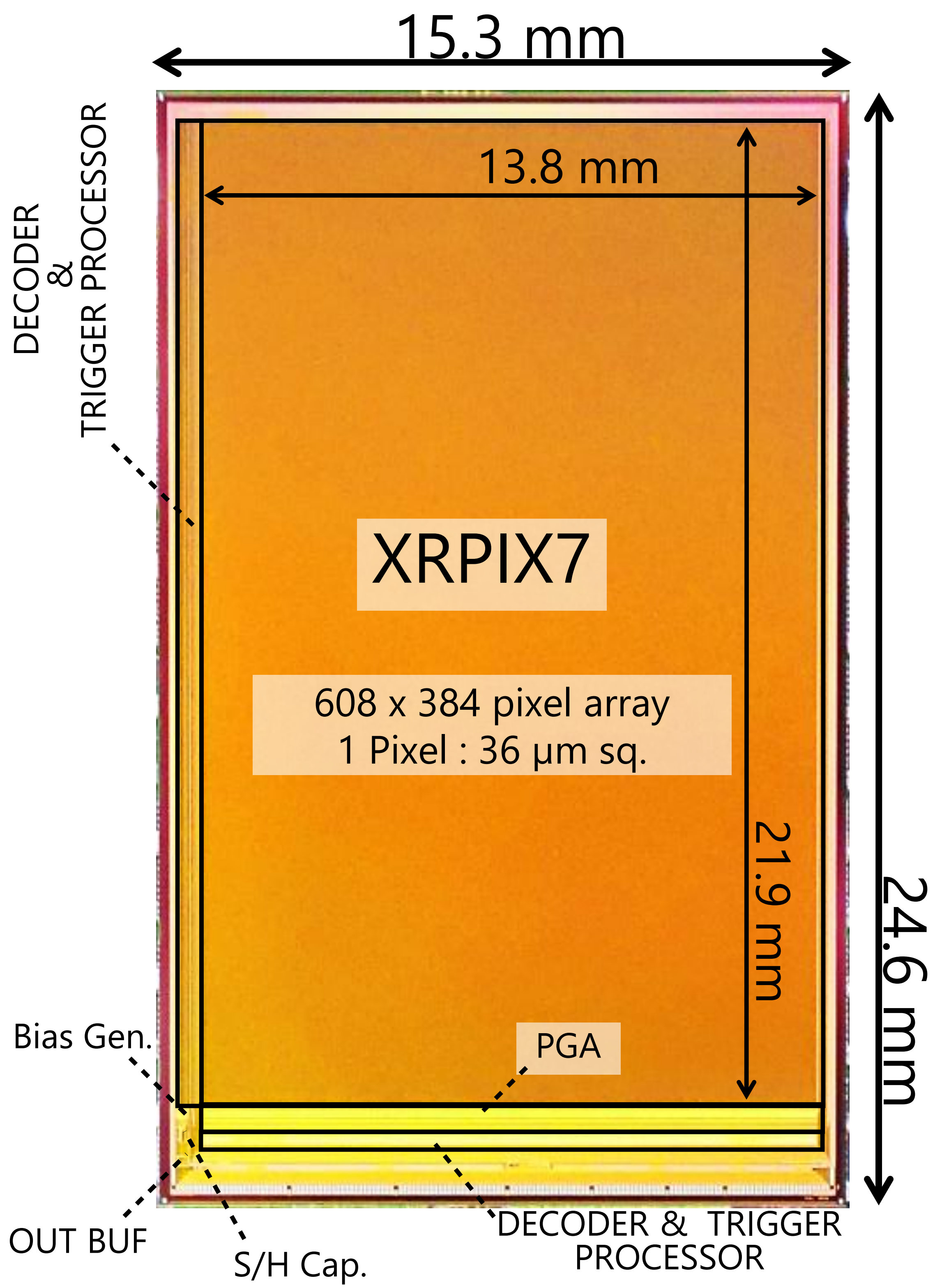
- Electron tracking Compton camera succeeded to be developed with gaseous detectors by Kyoto University Tanimori group for high energy gamma-ray astrophysics.
- For medical imaging, semiconductor detector is ideal
- However, the high spatial resolution (a few tens of μm) is required for electron tracking with a semiconductor detector

Objective

In this study, we developed a Compton imaging system with SOI (silicon on insulator) fine-pitch pixel sensor and GFAG scintillator detector for electron tracking Compton imaging

SOI pixel sensor with 36 µm pixels

Silicon on Insulator (SOI) technique → Monolithic circuit integrated silicon sensor

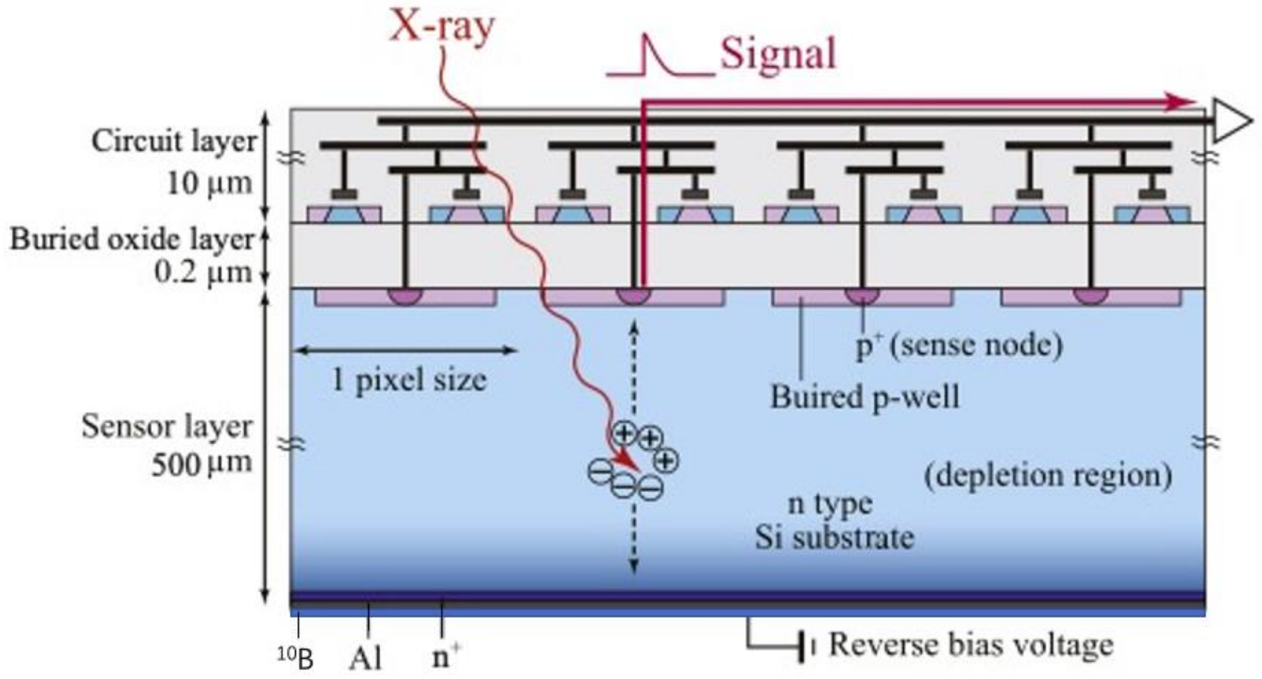


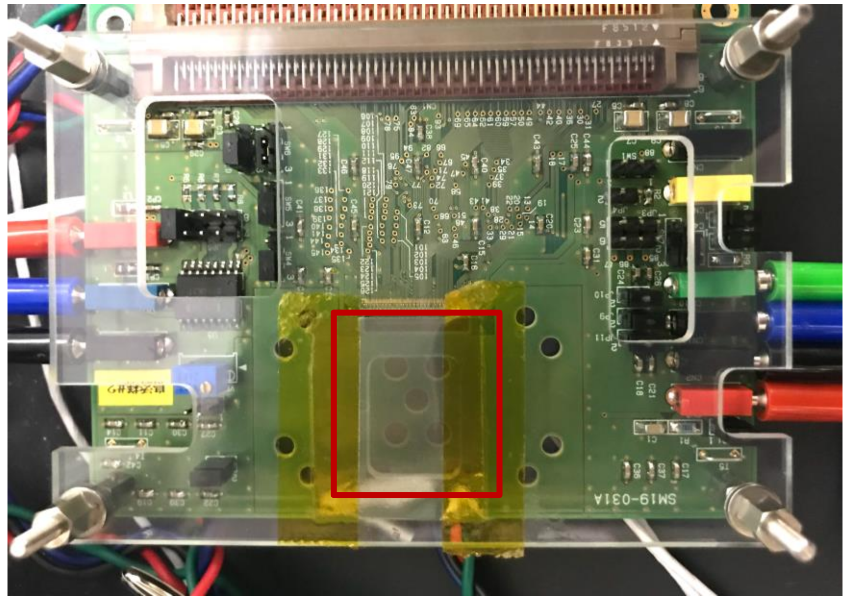
Large area X-ray SOI sensor "XRPIX7"

Sensor information

- Chip size： 24.6 mm x 15.3 mm
  (Active area： 21.9 mm x 13.8 mm)
- Pixel size： **36 µm sq.**
- Pixel number： 608 x 384 (= ~233k)
- Sensor thickness： 300 µm

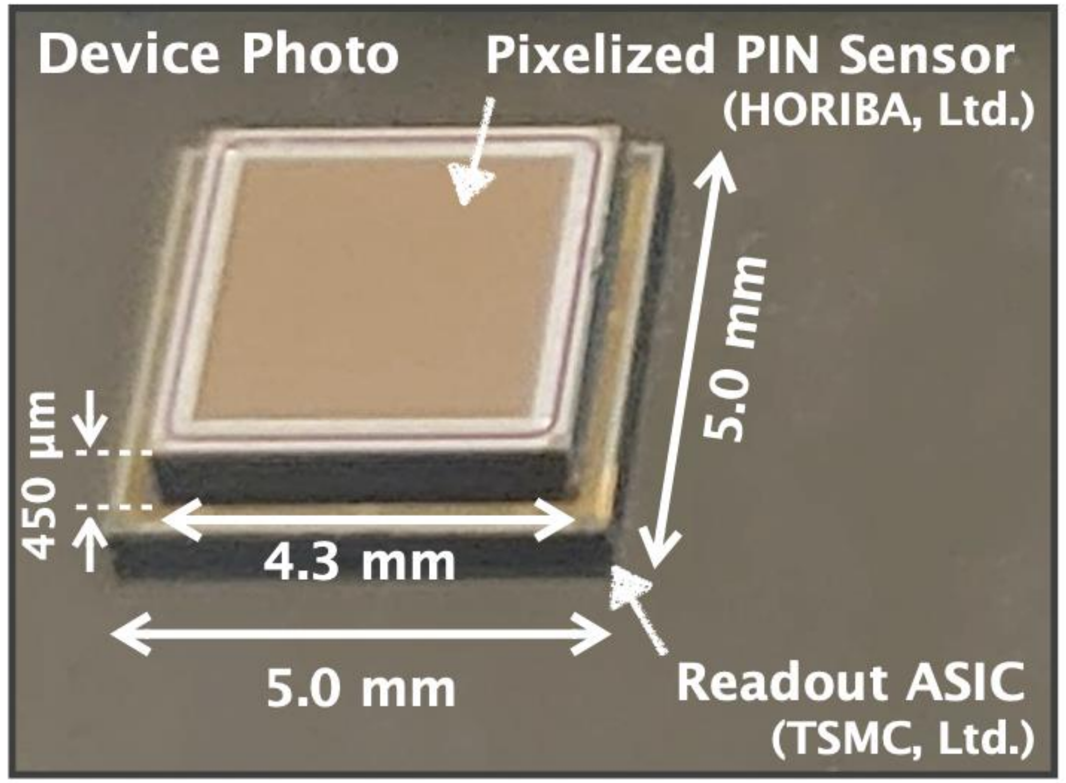
Event driven mode → coincidence detection





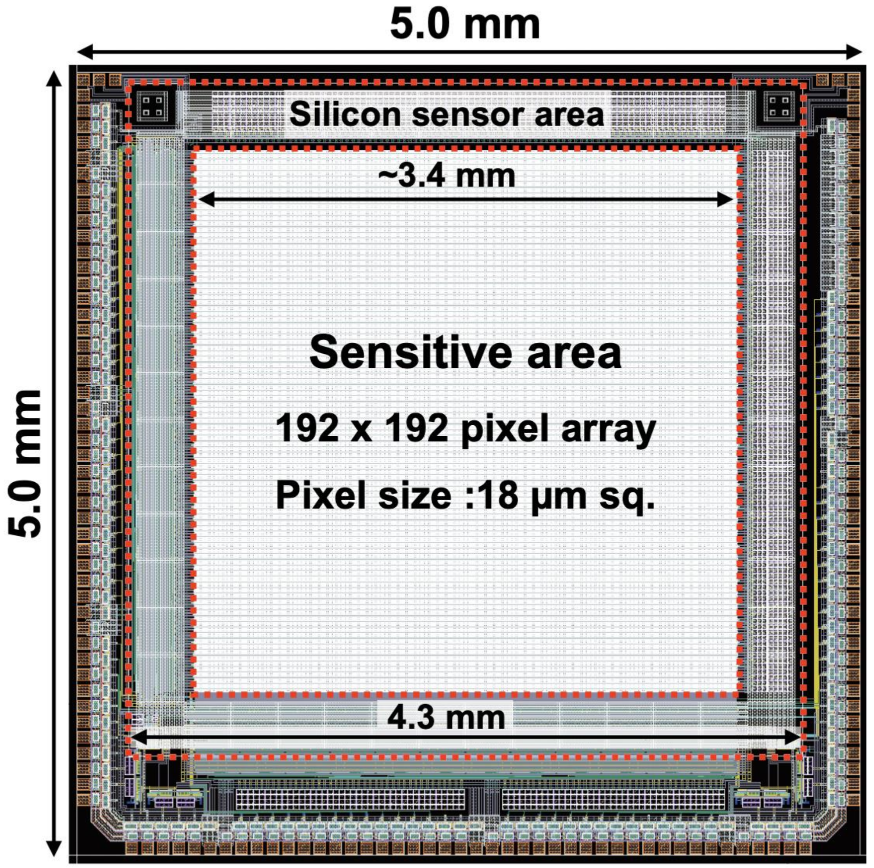
Si-ASIC hybrid pixel sensor with 18 μm pixels

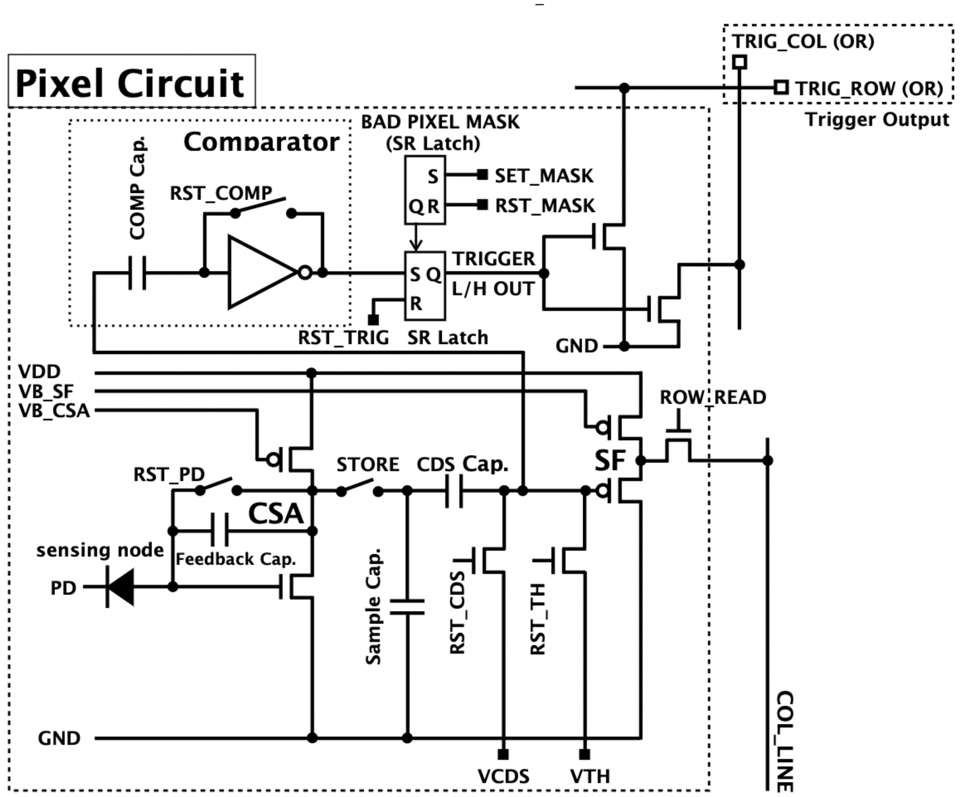
Hybrid pixel sensor → Si sensor coupled to pixel ASIC with 18 μm pixels

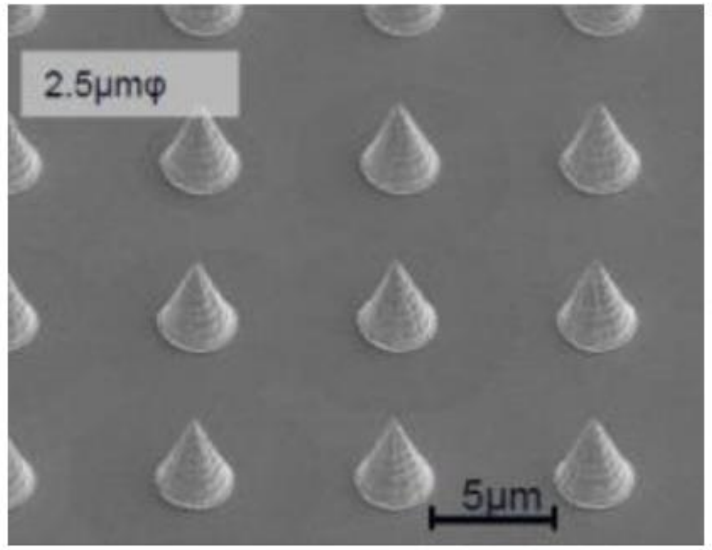


Sensor information

- Chip size (Si)： 4.3 mm x 4.3 mm
- Sensor thickness： 450 μm
- ASIC size : 5.0 mm x 5.0 mm
- Pixel size： **18 μm sq.**
- Pixel number： 192 x 192 (= ~233k)



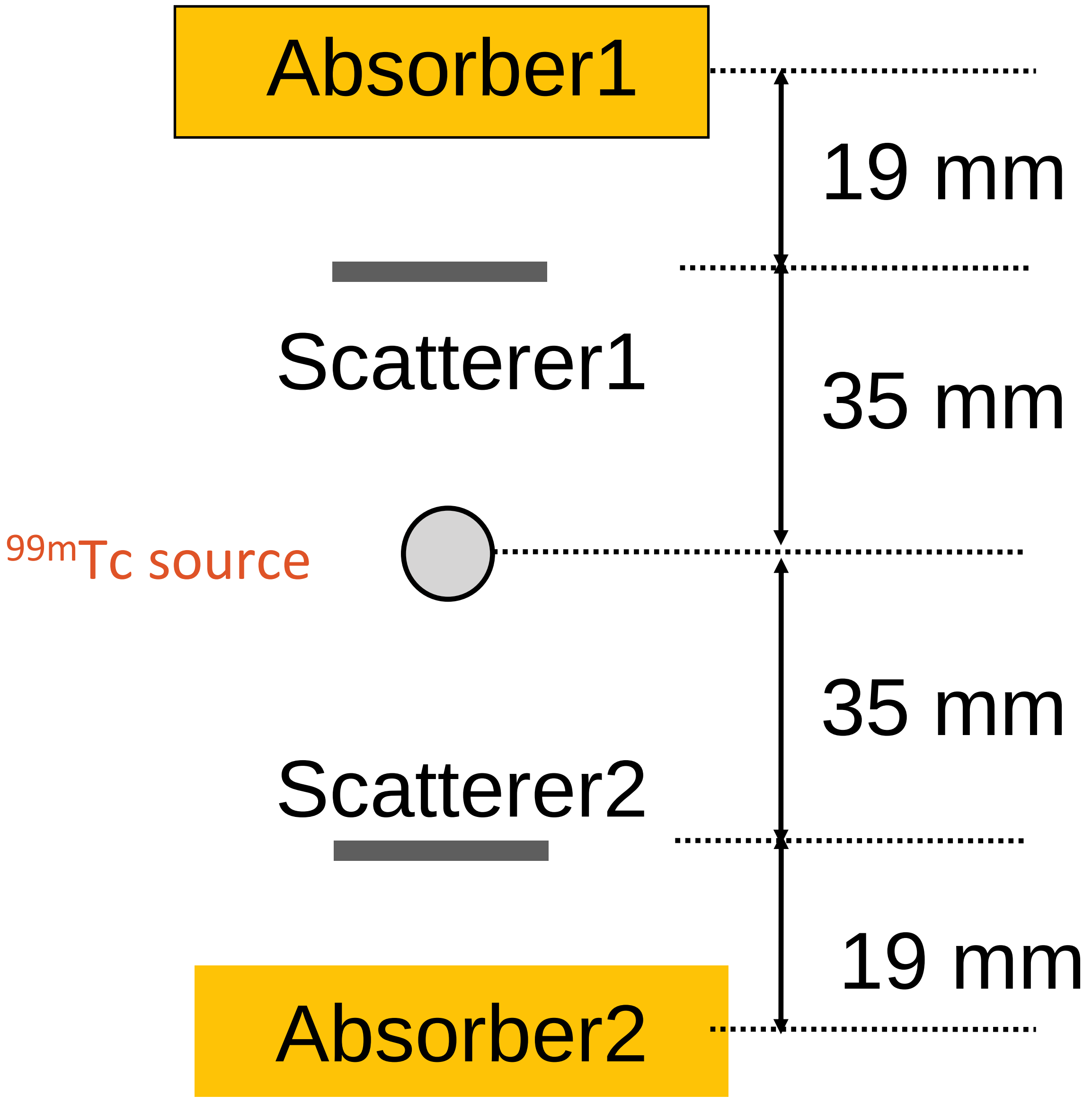




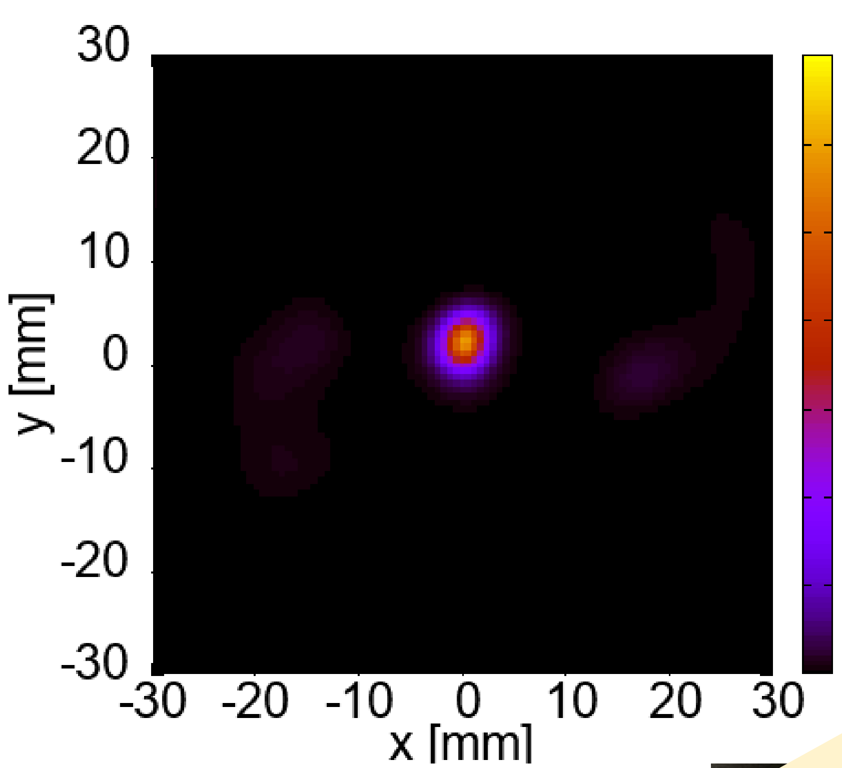
Au Micro-bump
(Tohoku MicroTec Co., Ltd.)

Development of SOI-GFAG Compton camera

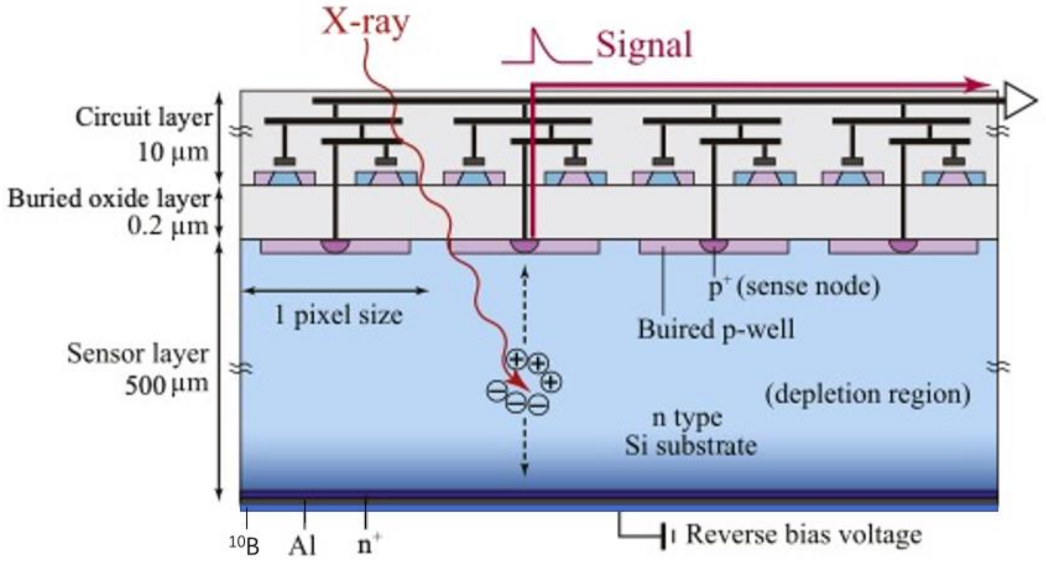
Experimental Setup



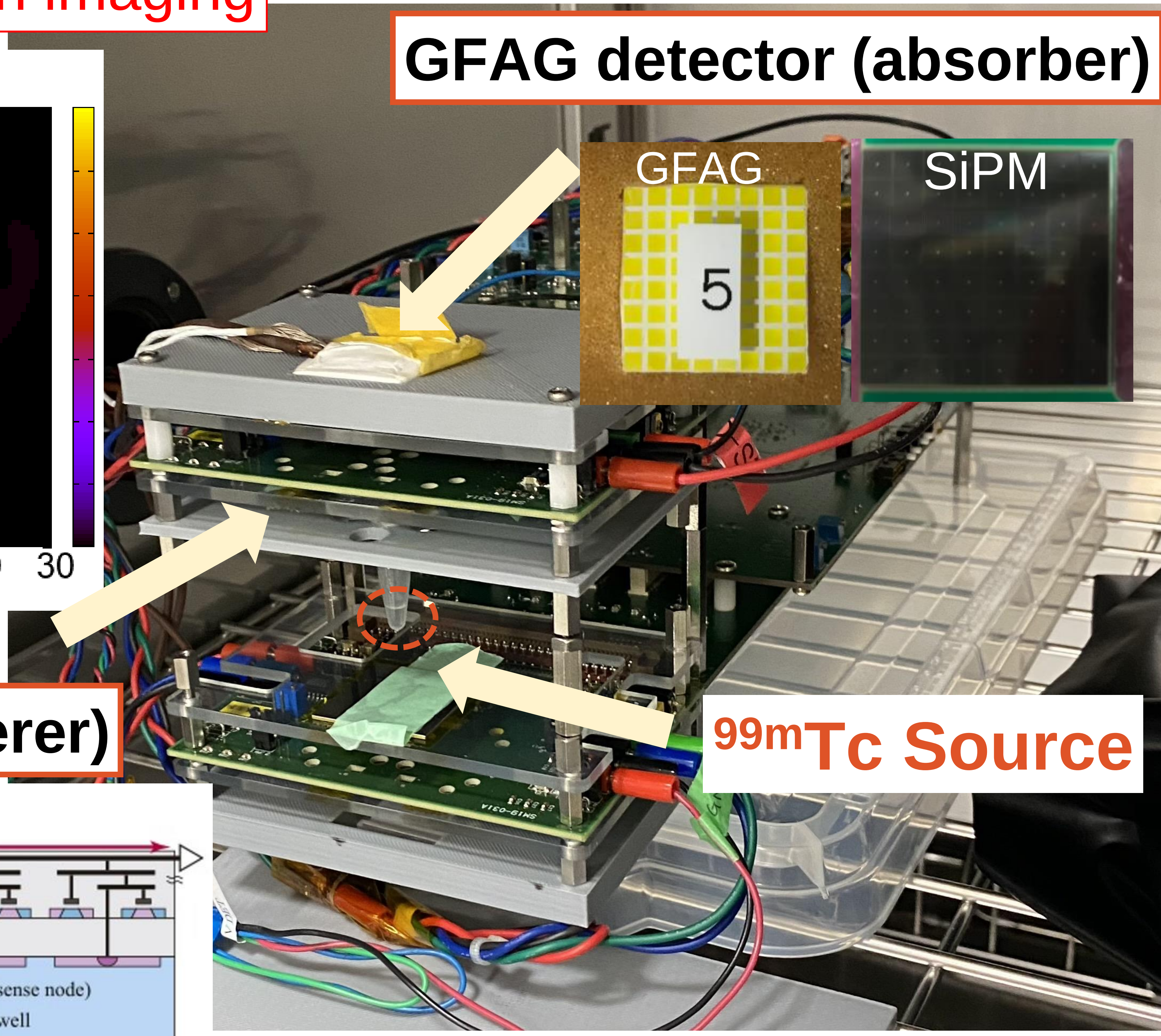
140.5 keV Compton imaging



XRPIX7 (scatterer)

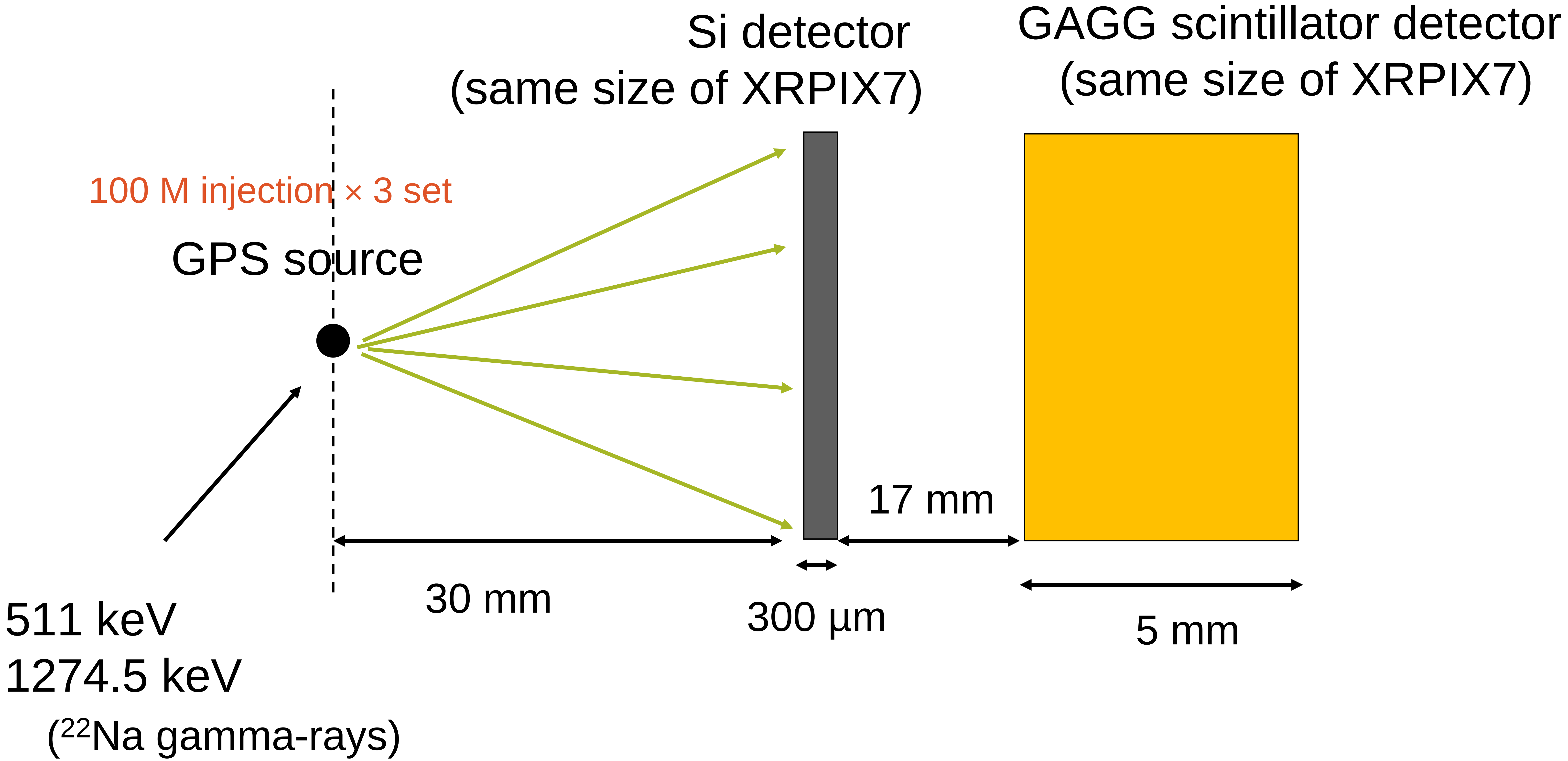


GFAG detector (absorber)



A Monte Carlo simulation by geant4 toolkit

Simulation setup



A Monte Carlo simulation by geant4 toolkit

Data format Si + GAGG Coincidence data

[event ID, track ID, parent ID, process name, detector name, deposit energy,
step start position (x,y,z) [mm] , step end position (x,y,z) [mm], momentum direction (x,y,z), kinetic energy]

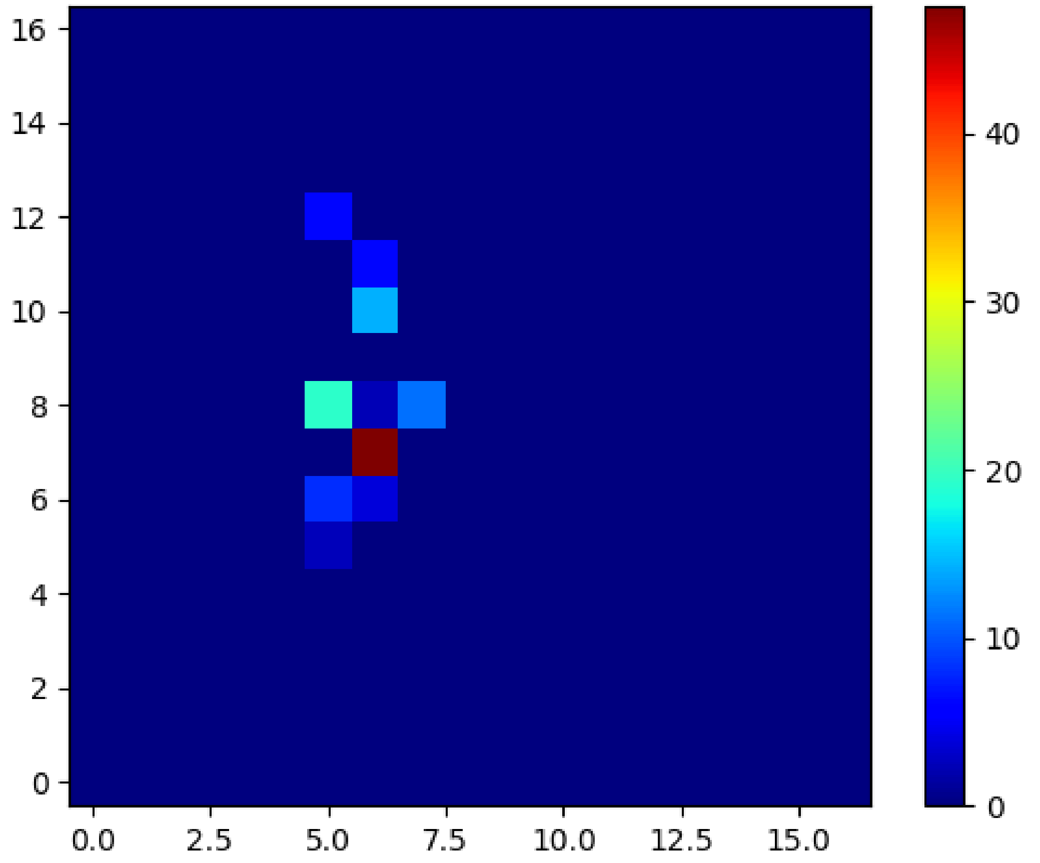
```
150787 1 0 gamma SiLogical compt 55.6403 30 -4.93426 5.16096 30.2006 -4.96725 5.19547 0.934857 0.334142 0.119965 455.36
150787 1 0 gamma GAGGLogical phot 455.36 47.3 1.14454 7.38974 50.3461 2.2333 7.78063 0.934857 0.334142 0.119965 0
150787 2 1 e- SiLogical eIoni 12.6608 30.2006 -4.96725 5.19547 30.2029 -4.97487 5.19648 -0.440073 -0.433698 0.786284 42.8708
150787 2 1 e- SiLogical eIoni 26.7524 30.2029 -4.97487 5.19648 30.2002 -4.97758 5.20139 0.792296 0.372711 0.483067 16.1184
150787 2 1 e- SiLogical eIoni 5.84556 30.2002 -4.97758 5.20139 30.201 -4.9772 5.20187 0.521554 0.178869 0.834258 10.2729
150787 2 1 e- SiLogical eIoni 4.14641 30.201 -4.9772 5.20187 30.2012 -4.97713 5.2022 0.760945 0.193592 -0.619262 6.12647
150787 2 1 e- SiLogical eIoni 2.47519 30.2012 -4.97713 5.2022 30.2013 -4.9771 5.20211 -0.499787 -0.342218 -0.795676 3.65128
150787 2 1 e- SiLogical eIoni 3.65128 30.2013 -4.9771 5.20211 30.2012 -4.97713 5.20204 -0.499787 -0.342218 -0.795676 0
```

Recoil direction = (x_end, y_end, z_end) - (x_start, y_start, z_start)

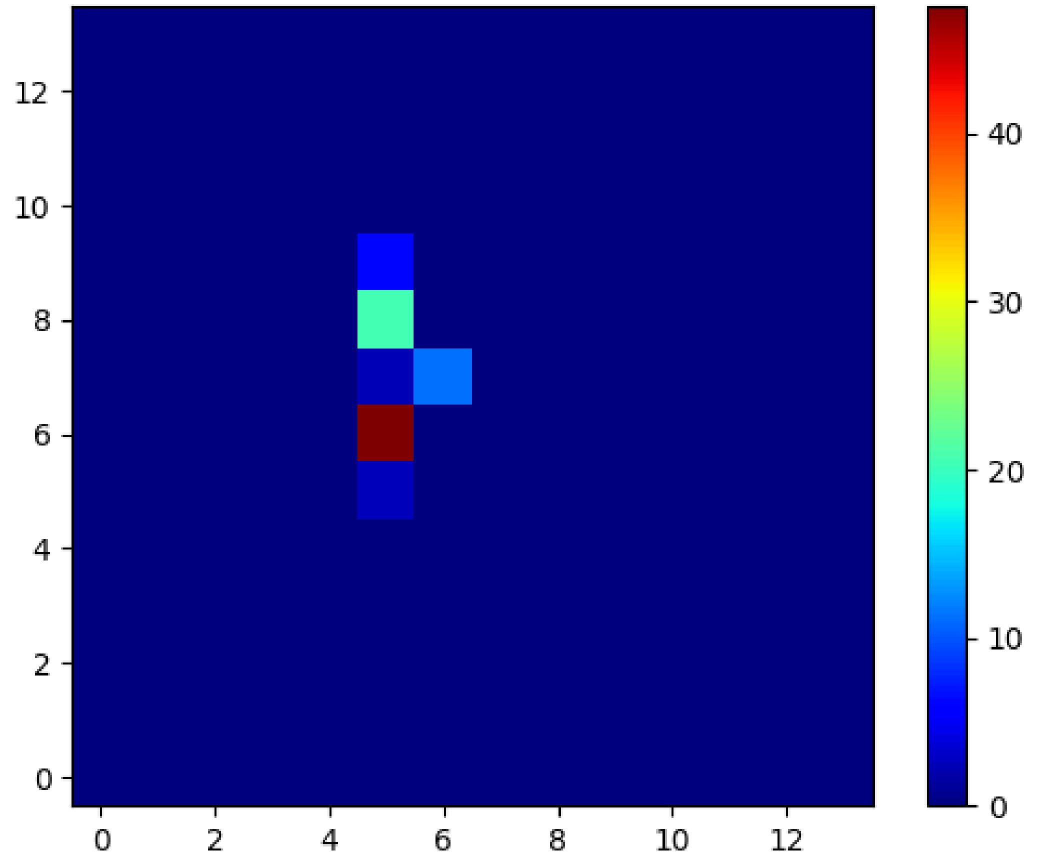
2D image of electron trajectory

511 keV

18 µm pixels



36 µm pixels

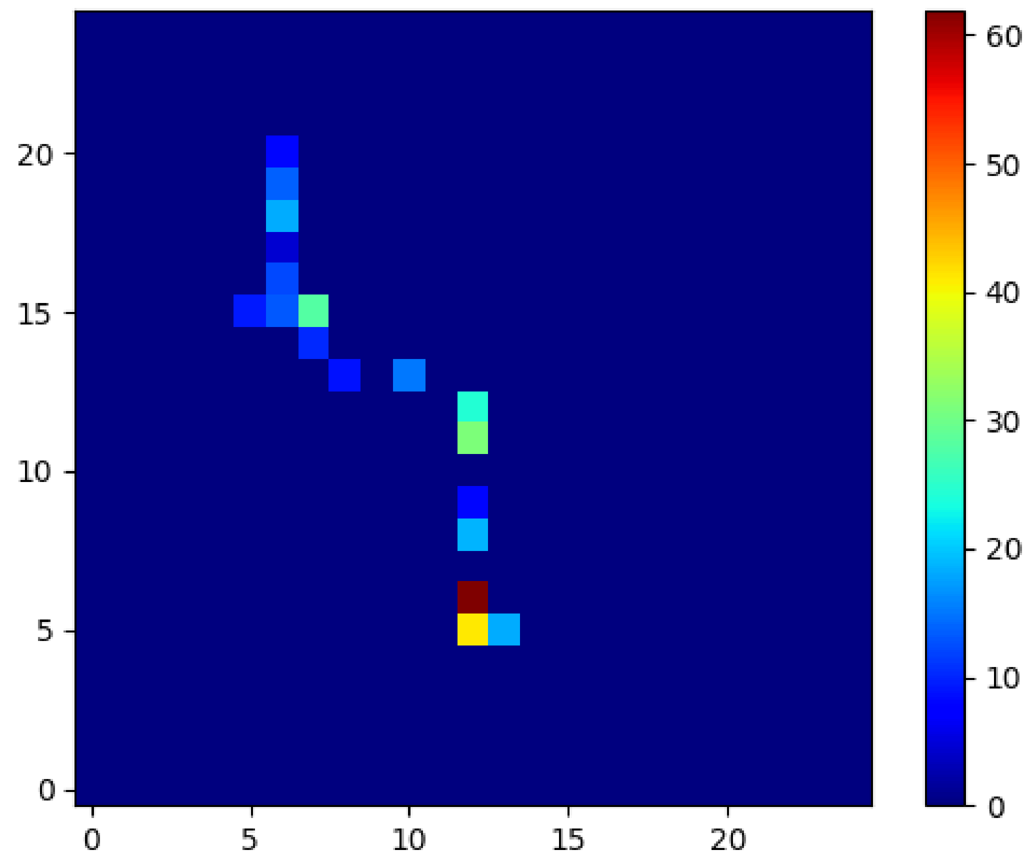


	Coincidence events	1-2 pixels event	3 < pixels event
18 µm pixels	8166	3220	4946
36 µm pixels		1564	6602

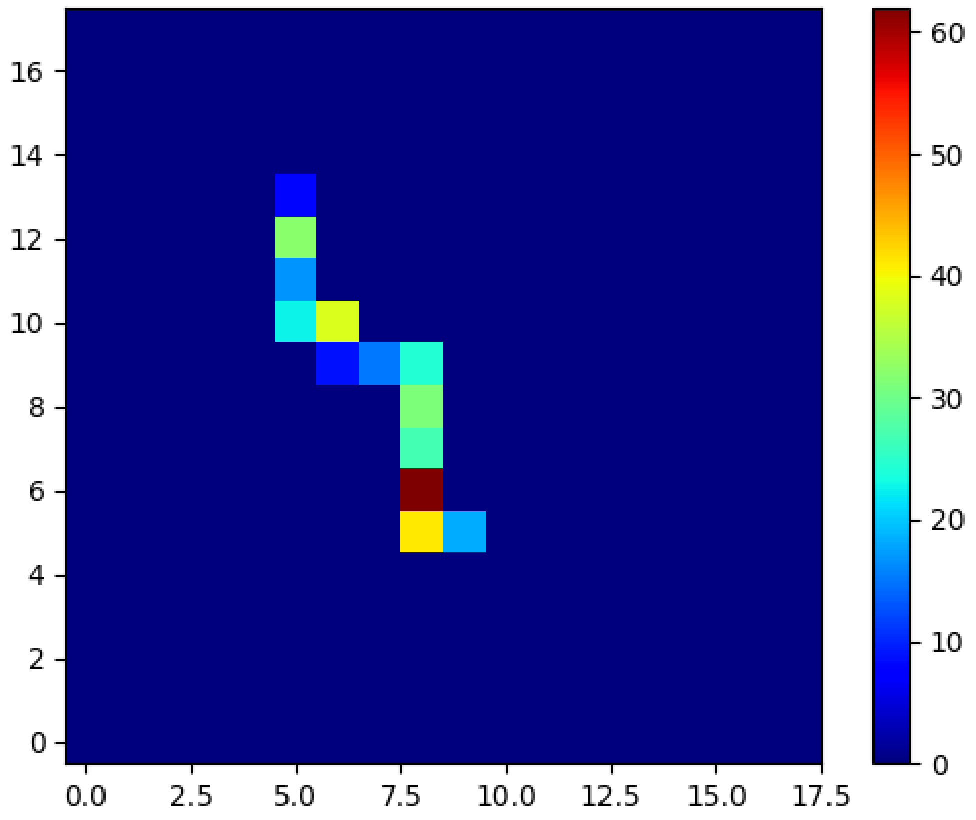
2D image of electron trajectory

1274.5 keV

18 µm pixels



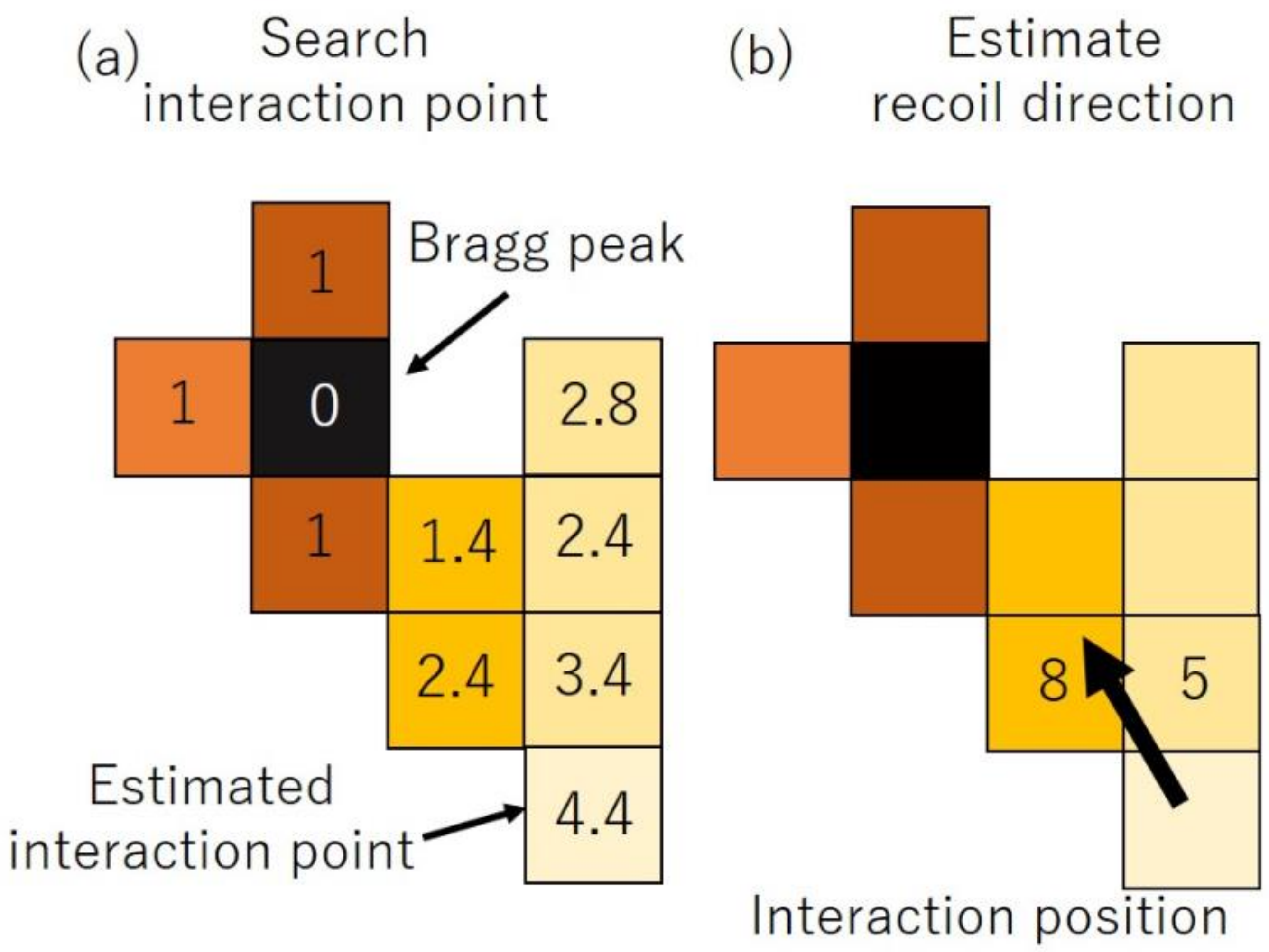
36 µm pixels



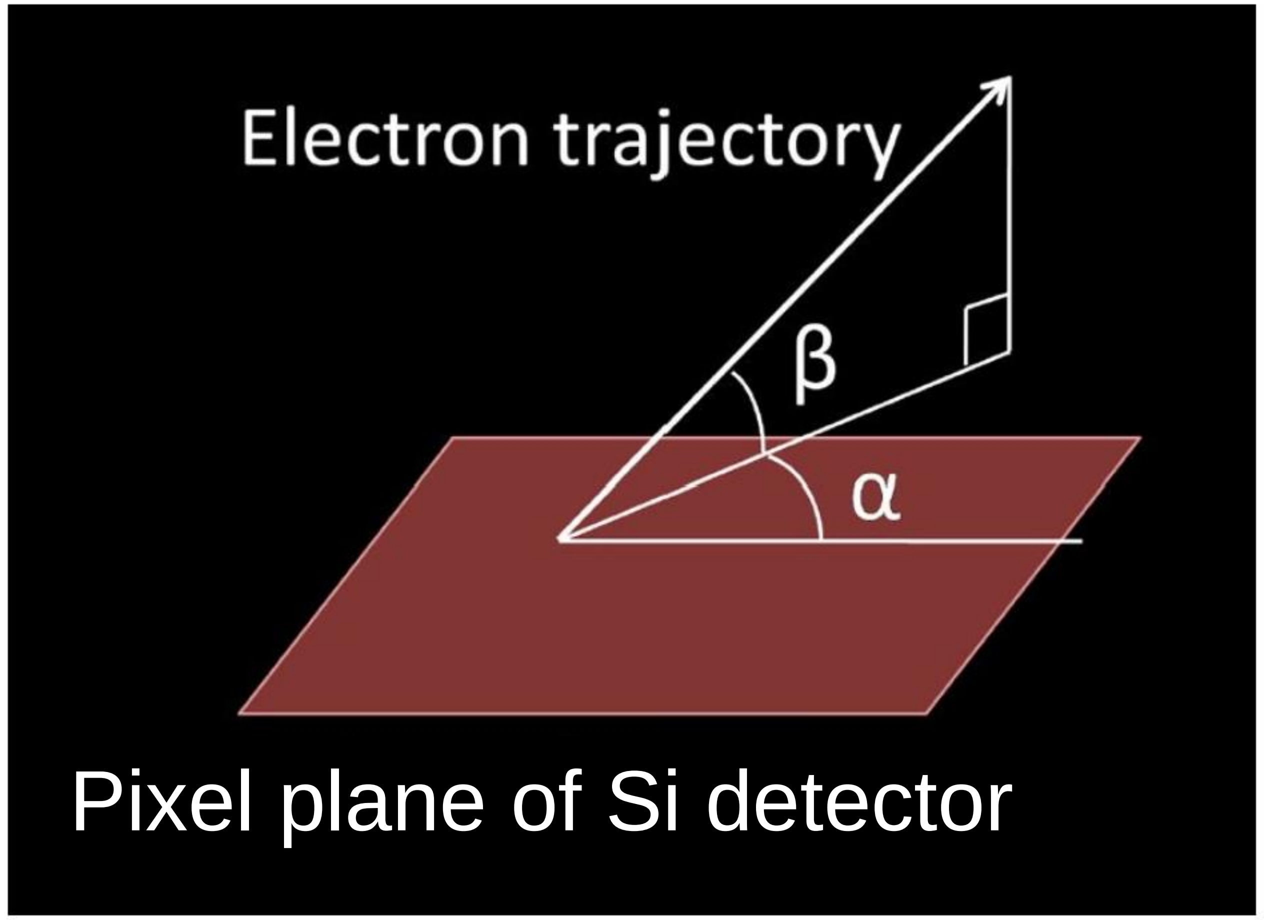
	Coincidence events	1-2 pixels event	3 < pixels event
18 µm pixels	1886	71	1815
36 µm pixels		16	1870

Estimation of 2D recoil direction

Estimation method of α angle



M. Kagaya et al., proceedings of 2021 IEEE NSS/MIC, (2021)



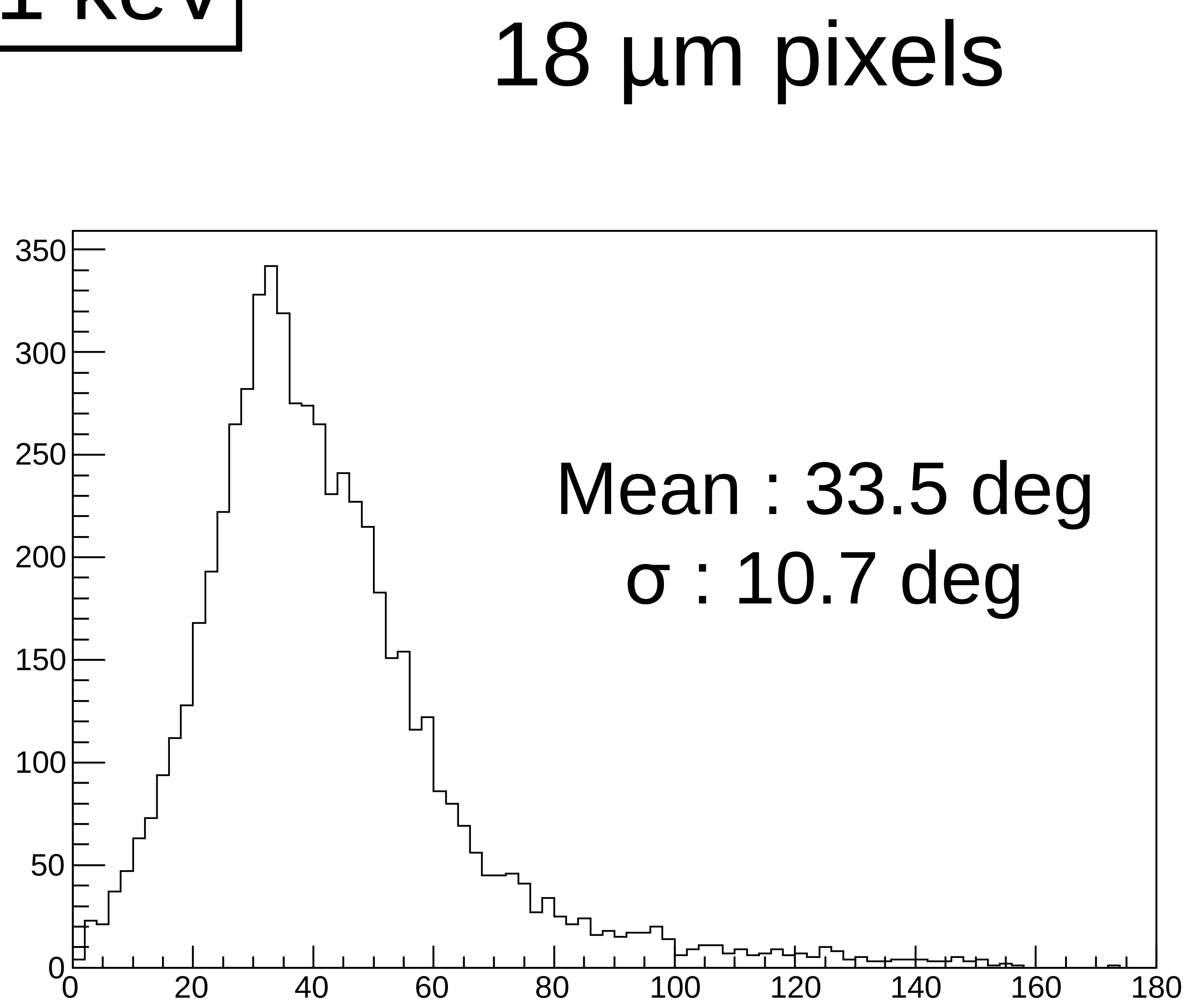
Vector of the adjacent pixel from start pixel

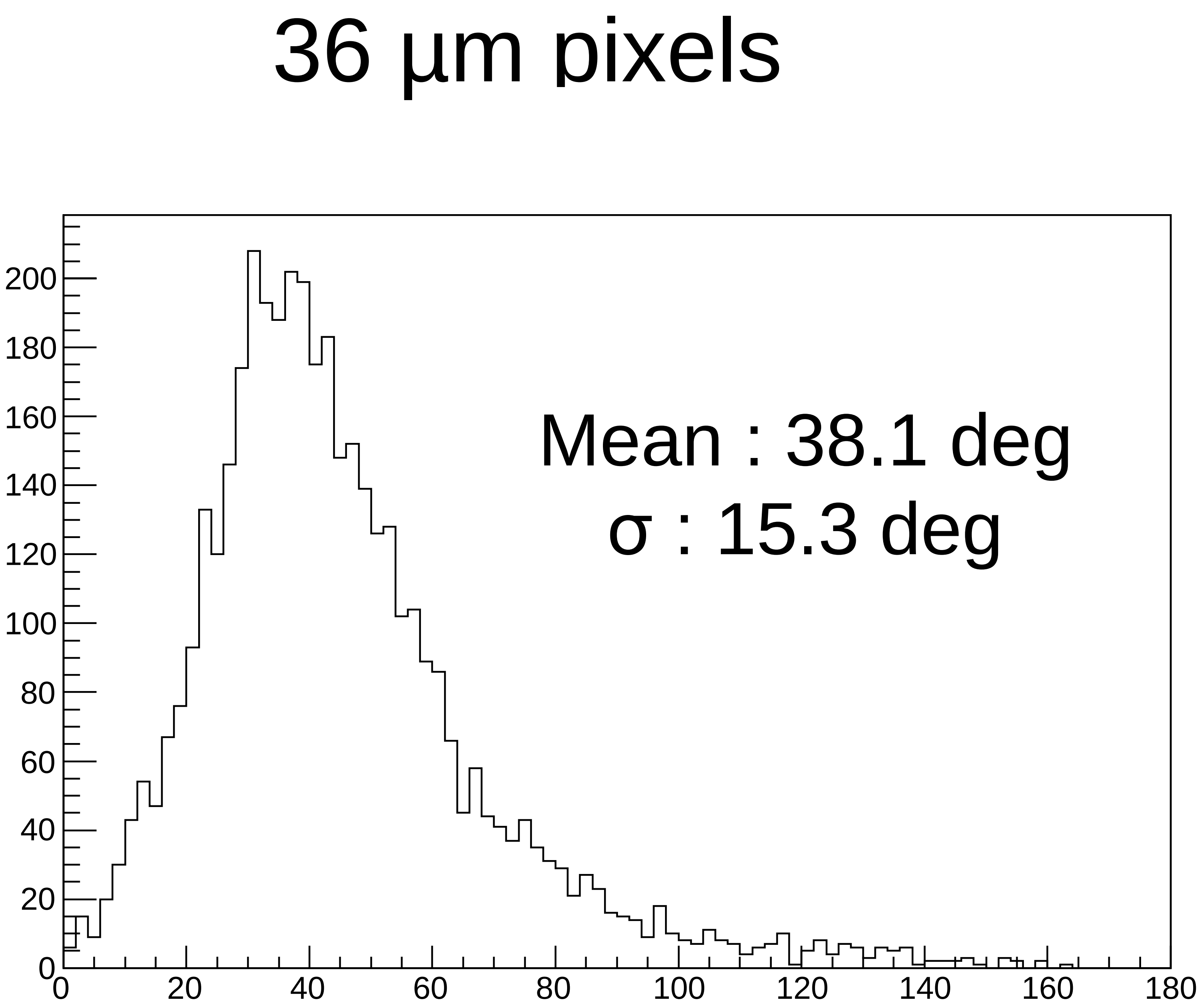
$$\vec{x} = \frac{\sum_{i=1}^{N} w_i \vec{x_i}}{\sum_{i=1}^{N} w_i},$$

Deposited energy in a pixel

Accuracy of 2D recoil direction

511 keV



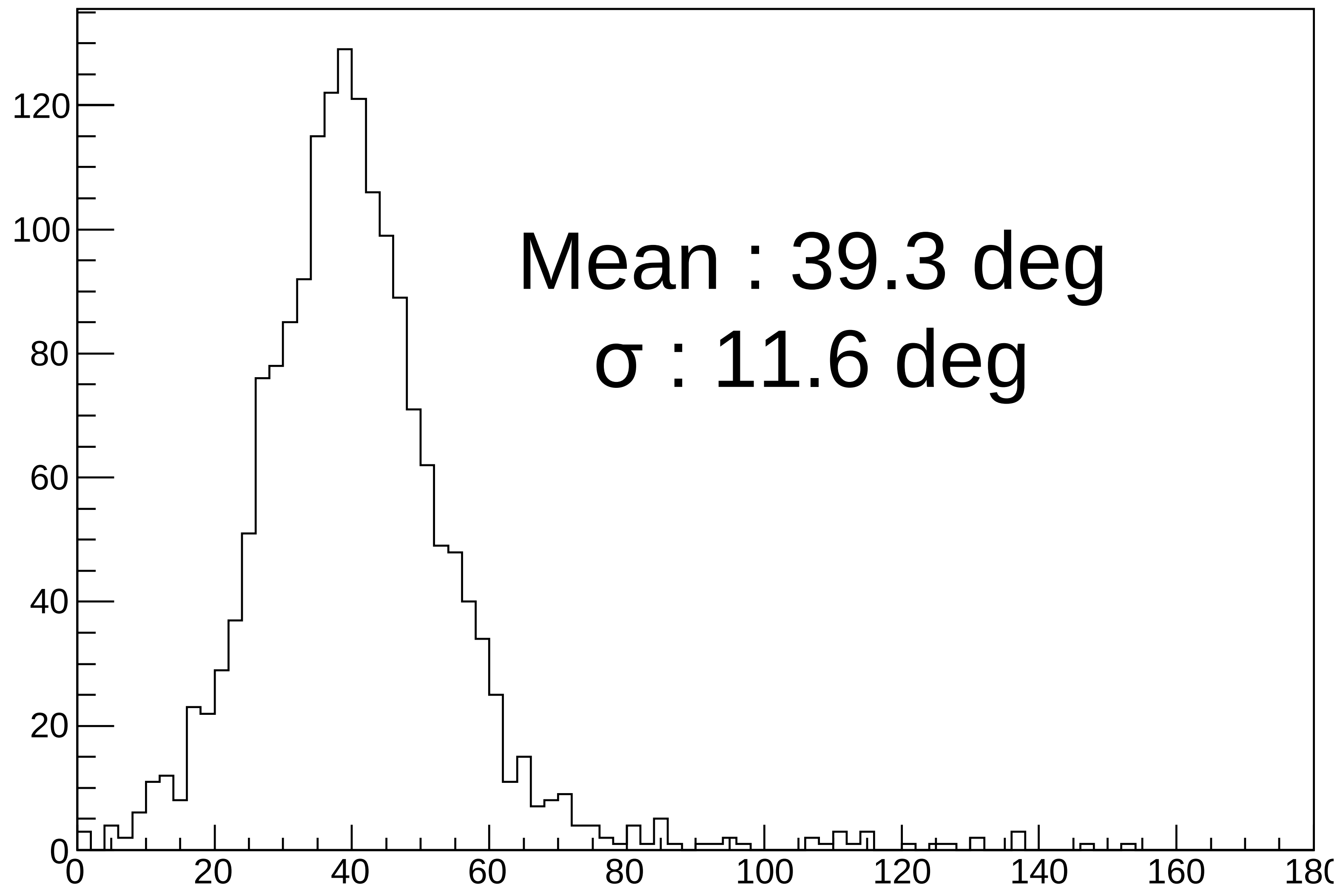


Difference of simulated and calculated α angles [degree]

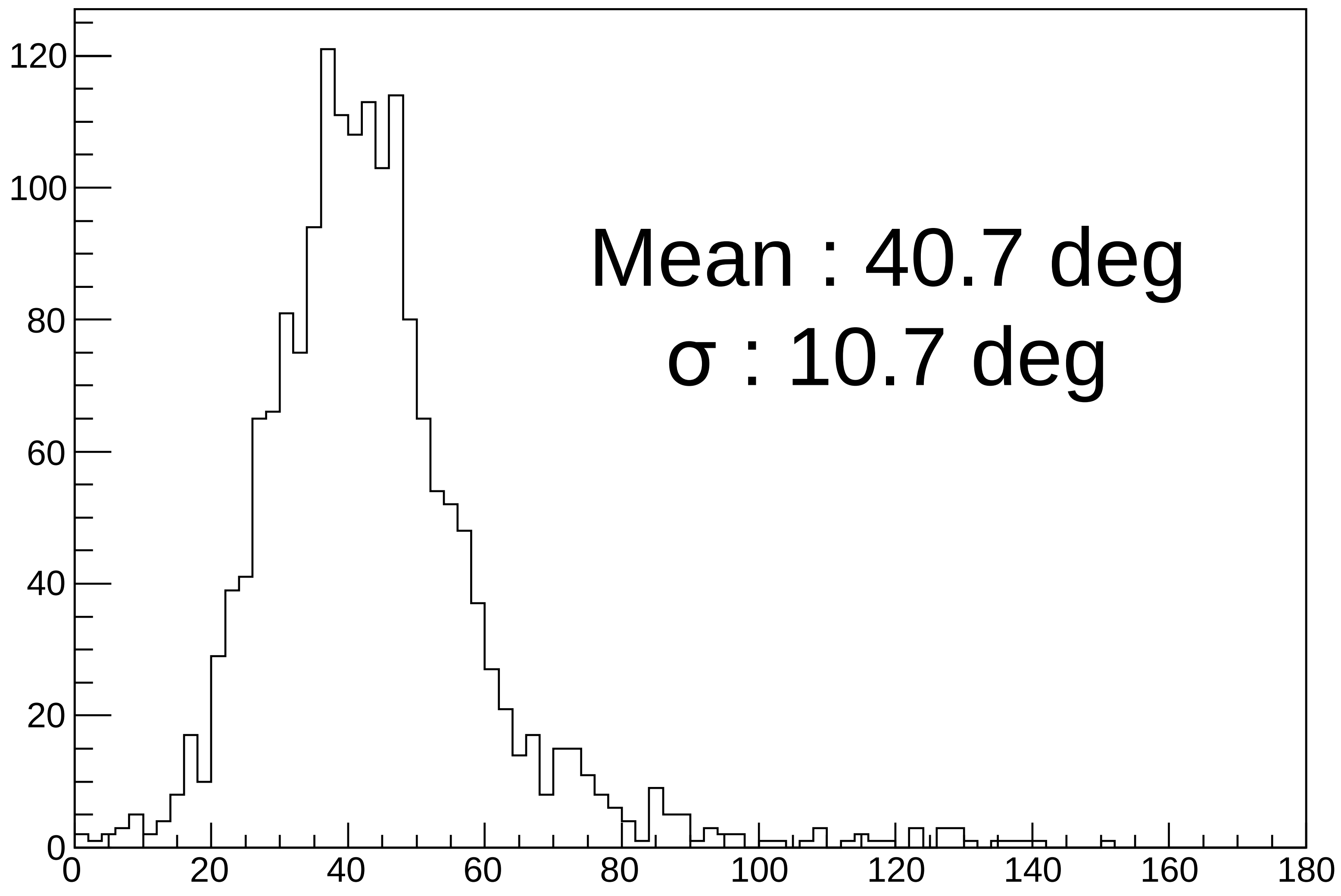
Accuracy of 2D recoil direction

1274.5 keV

18 µm pixels



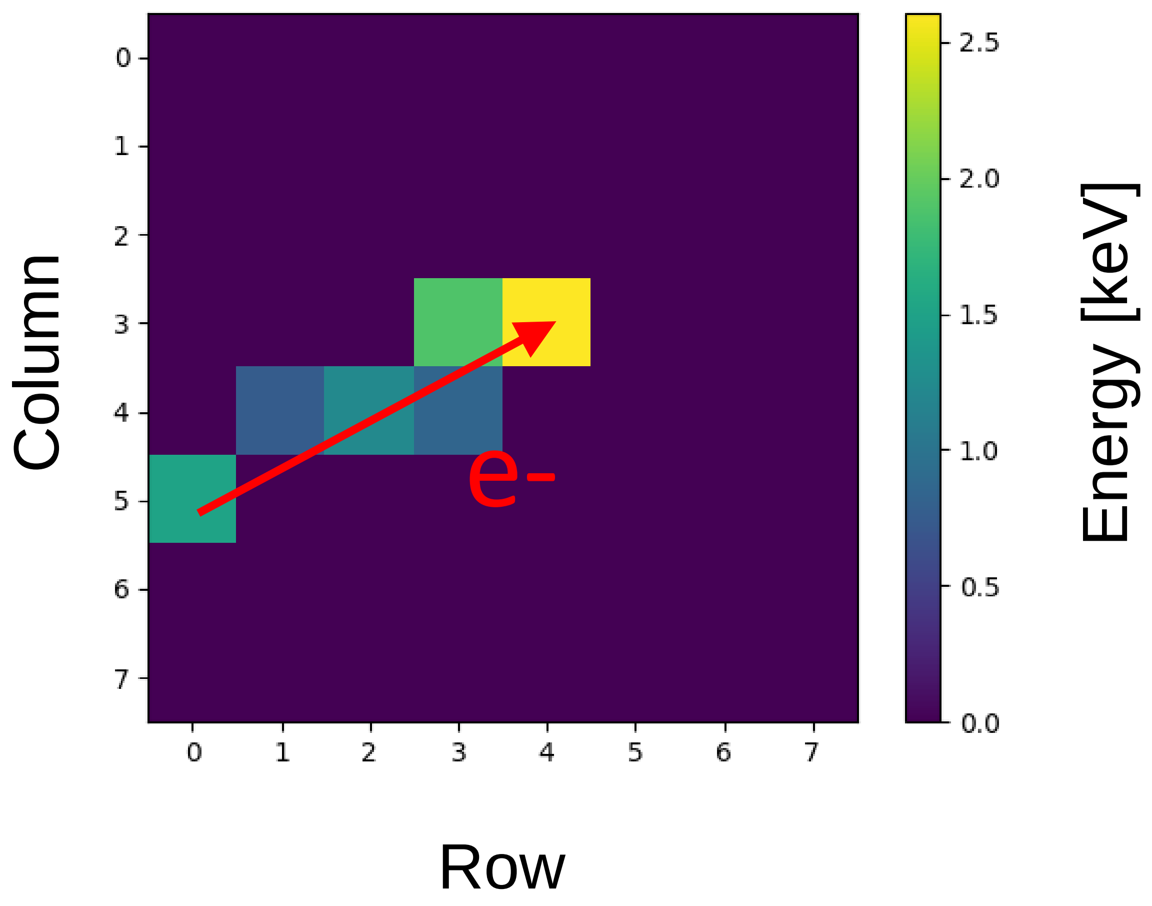
36 µm pixels

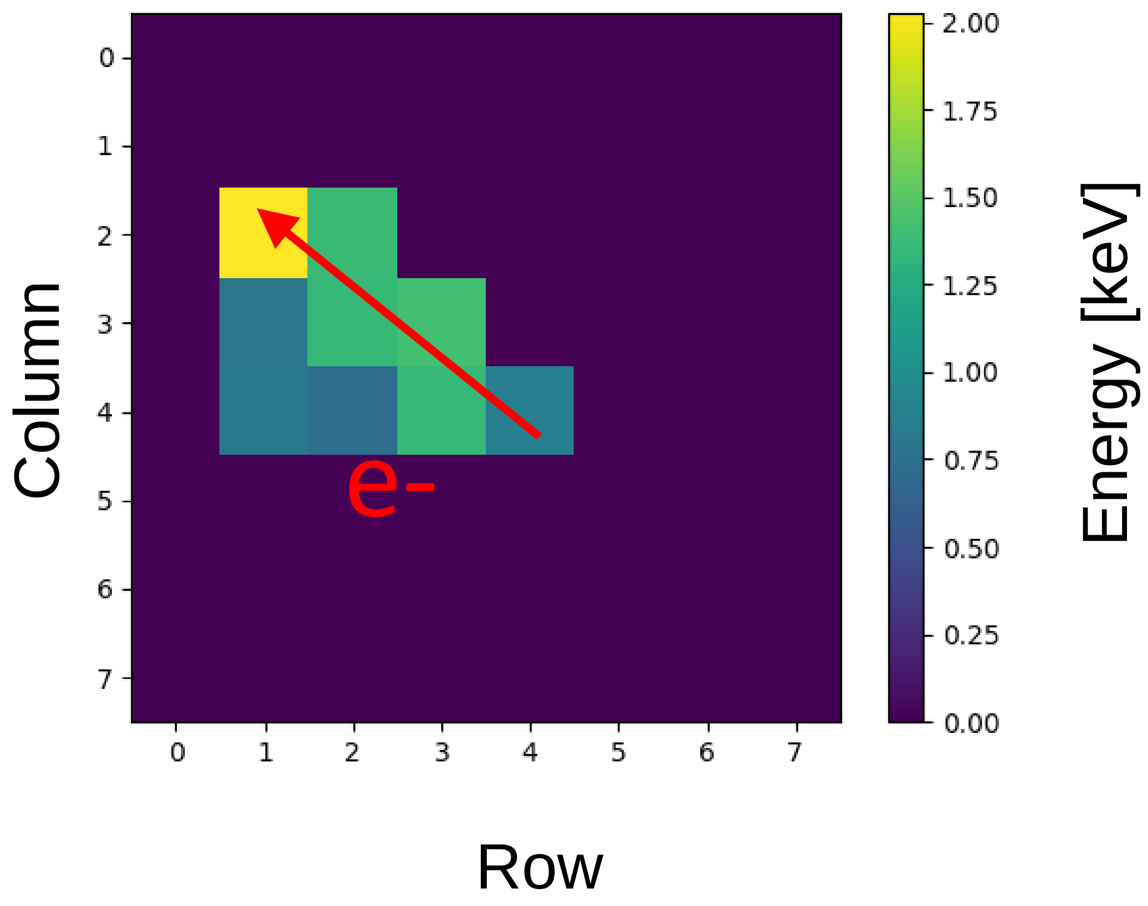


Difference of simulated and calculated α angles [degree]

Electron Trajectory in XRPIX7

Recoil electron trajectories of 511 keV gamma-ray (^{22}Na)





XRPIX7 could detect some of recoil electron trajectories of 511 keV gamma-ray.
For future work, we need to establish the method to extract the correct electron trajectory because XRPIX7 can measure only 2D trajectory.

Summary and future works

- We are developing SOI pixel detectors with pixel size of 36 μm

- We also developed Si-ASIC hybrid sensor with pixel size of 18 μm

- The Monte Carlo simulation by geant4 shows that the estimation accuracy of 2D recoil direction is not significantly improved by 18 μm measurements compared to by 36 μm measurements although the recoil trajectory can be measured more finely.

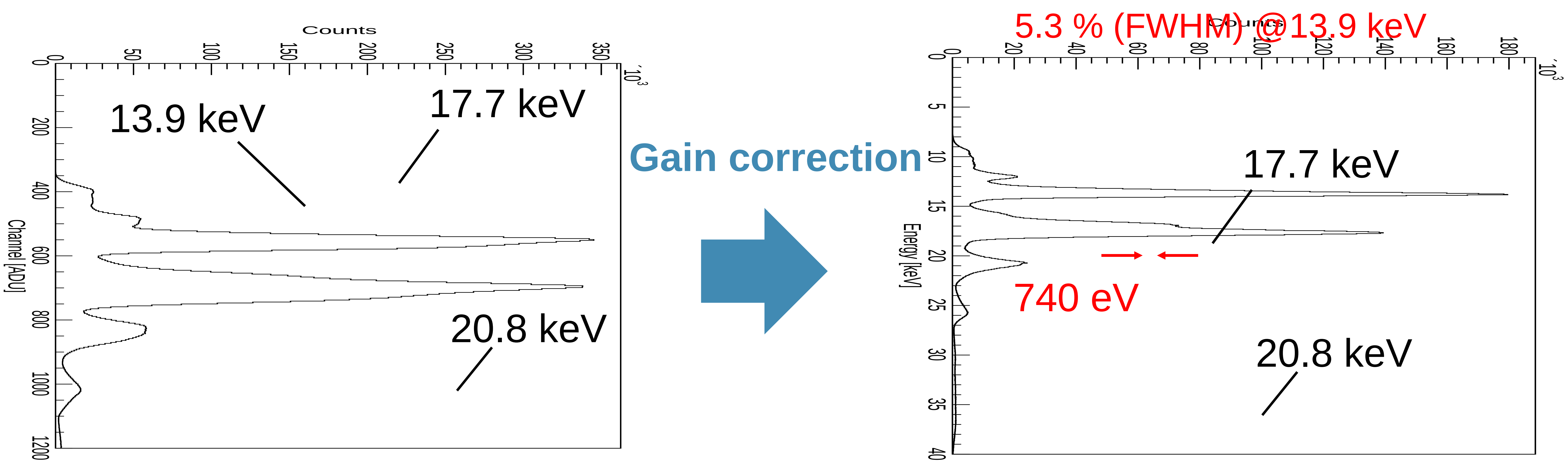
- The estimation method of 3D recoil direction (B.C Plimley, UC Berckley Ph.D thesis, 2014) will be implemented

- XRPIX7 can detect a recoil electron trajectory of 511 keV gamma-ray (but not full depletion)

Thank you for your attention

Basic performance of XRPIX7

^{241}Am spectrum of all pixels



- Temperature : 0 deg
- Vdet : -25V (not full depletion)