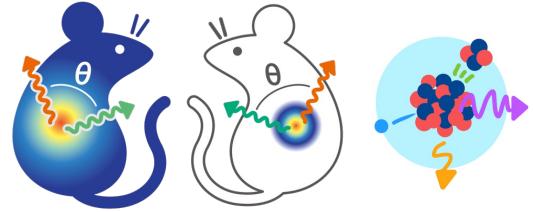


SOIPIX医療用コンプトンカメラの開発と 今後の展望

島添健次

東京大学

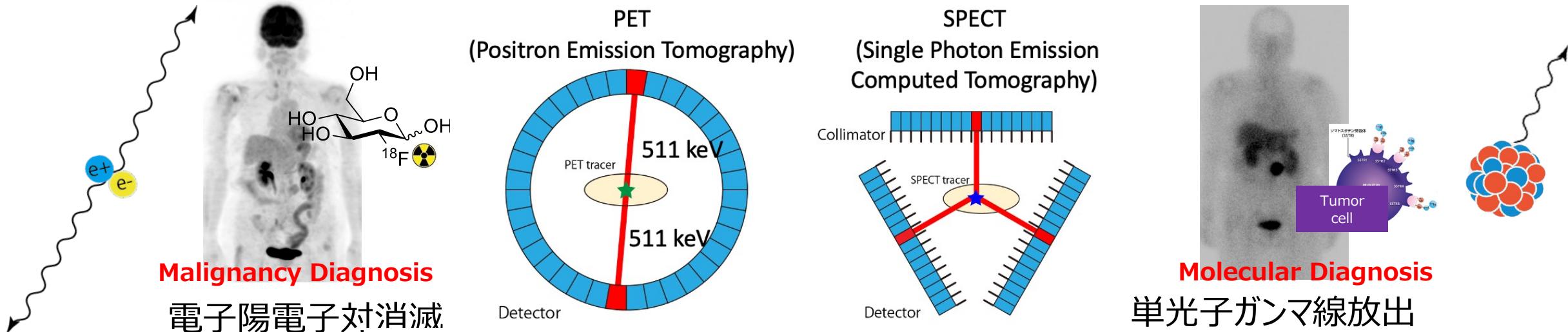
2025.12.02@石川県政記念 しいのき迎賓館
SOIPIX量子イメージング研究会2025



核医学イメージング PET & SPECT



イメージング手法の観点



分子の時空間的な集積を可視化



超高感度 (<p mol)、高分解能



陽電子放出核種のみ (単色)

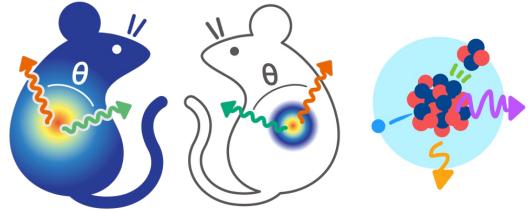


感度



集積のみ

1950年代に手法の発明～原理はずっと変わっていない



核医学イメージング PET & SPECT

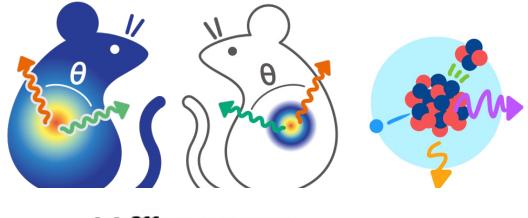


診断核種

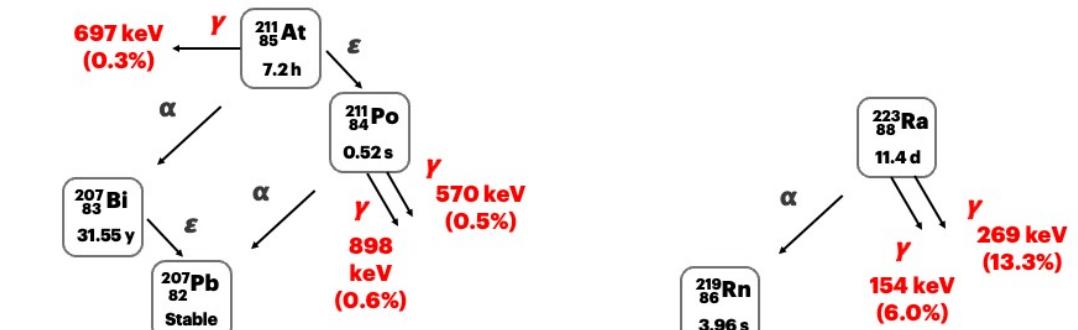
装置	核種	半減期	ガンマ線 エネルギー	臨床応用
PET	¹⁸ F	110 m	511keV	悪性腫瘍・グルコース代謝 Tumor/Myocardium/Brain imaging、Glucose imaging
	¹⁵ O	2 m		Oxygen consumption, lung function etc.
SPECT	^{99m} Tc	6 h	141 keV	Brain, thyroid gland, blood flow, tumor, etc.
	¹²³ I	13 h	159 keV	Thyroid function, cerebral blood flow, etc.
	¹¹¹ In	2.8 d	171, 245 keV	bone marrow imaging, inflammation , etc.

PET核種のエネルギー = 511 keV

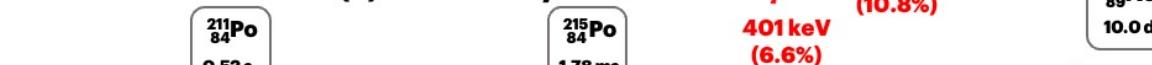
SPECT核種のエネルギー = a few 100 keV



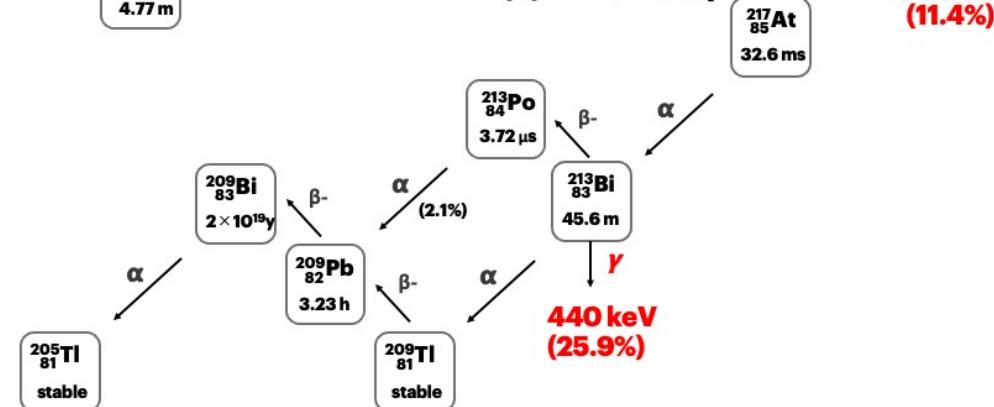
(1) ^{211}At Decay



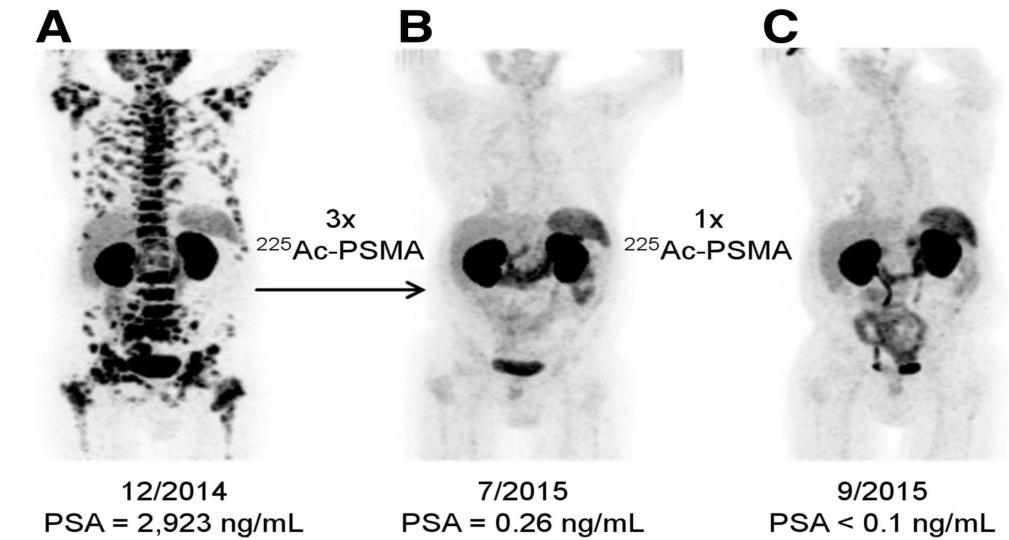
(2) ^{223}Ra Decay



(3) ^{225}Ac Decay

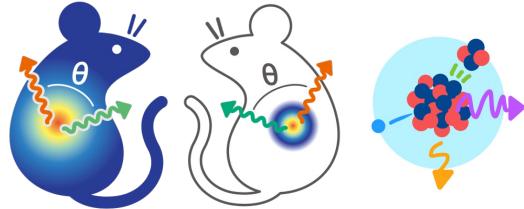


核医学治療



Kratochwil et al. J Nucl Med 2016;57:1941-1944

α線放出治療核種の直接観測の要望



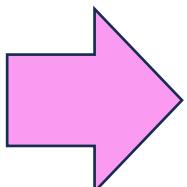
核医学イメージング 治療核種



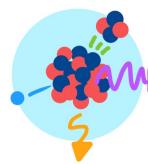
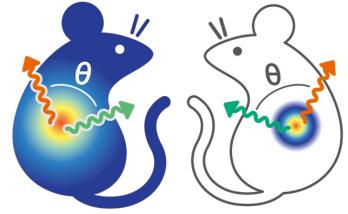
治療核種

Nuclide	Half life	β -ray (keV)	α -ray (MeV)	X-ray (keV)	γ -ray (keV)	Clinical application	
^{131}I	8 d	606			364	thyroid cancer, etc.	臨床応用
^{177}Lu	6.73 d	497			113, 208	neuroendocrine tumors, etc.	
^{223}Ra	11.4 d		5~8		154, 324 etc.	prostate cancer, etc.	
^{225}Ac	10 d		6~8		218, 440 etc.	prostate cancer, etc.	研究
^{211}At	7 h		~6	70-90	570, 687, 898	pheochromocytoma, etc.	

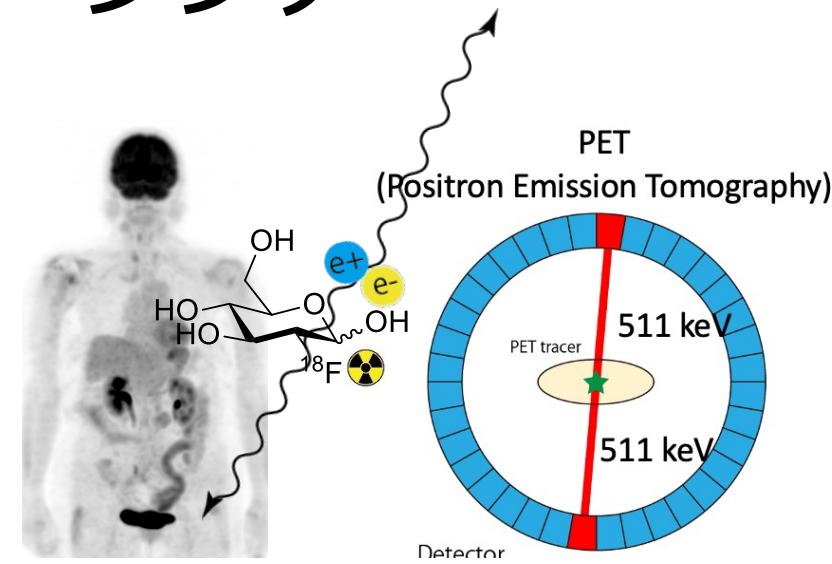
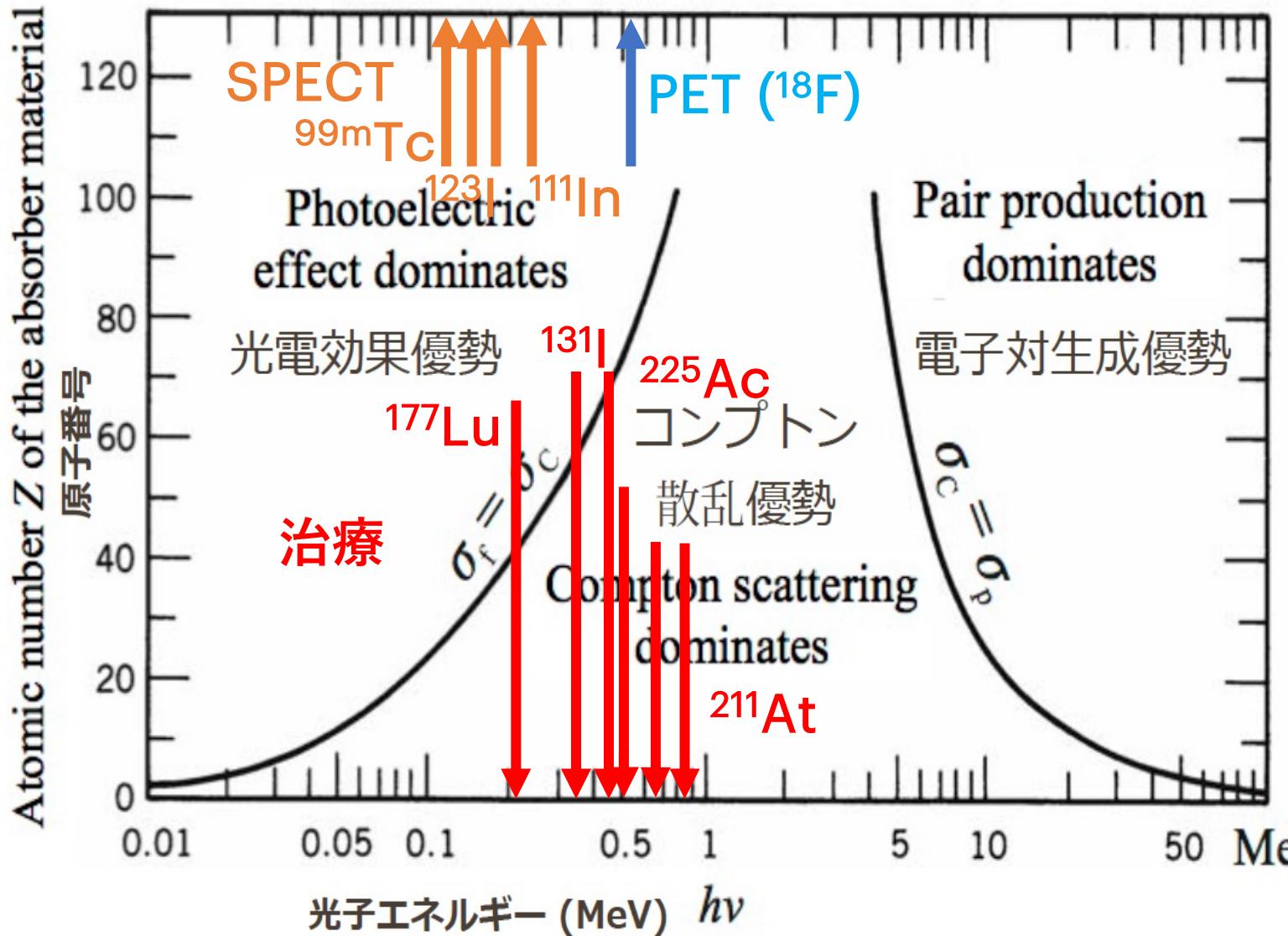
ラジオセラノスティクス =治療と診断の融合 =診断核種治療核種の同時撮像



多色(多分子同時)イメージング
ラジオセラノスティクス
～コンプトンPETハイブリッドカメラ



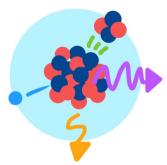
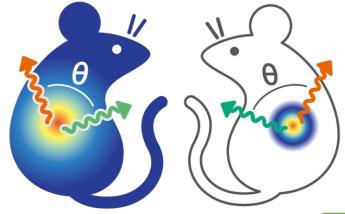
核医学における多色イメージング



イメージング手法の観点では
光電吸収のみが利用されてきたが、

コンプトン散乱は
広帯域のエネルギーで発生する。
→ コンプトン散乱の利用

原理的にはSPECTより高感度
高解像度

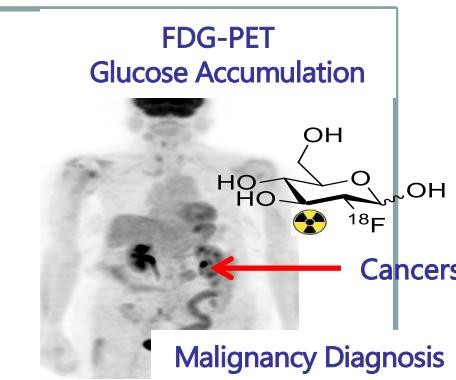
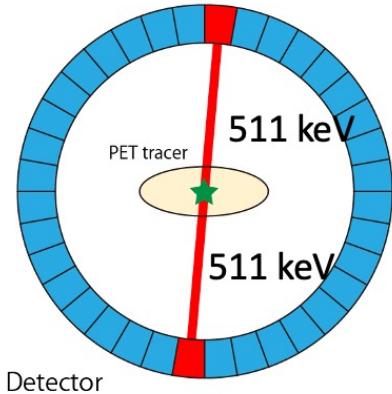


コンプトンPETハイブリッドカメラ

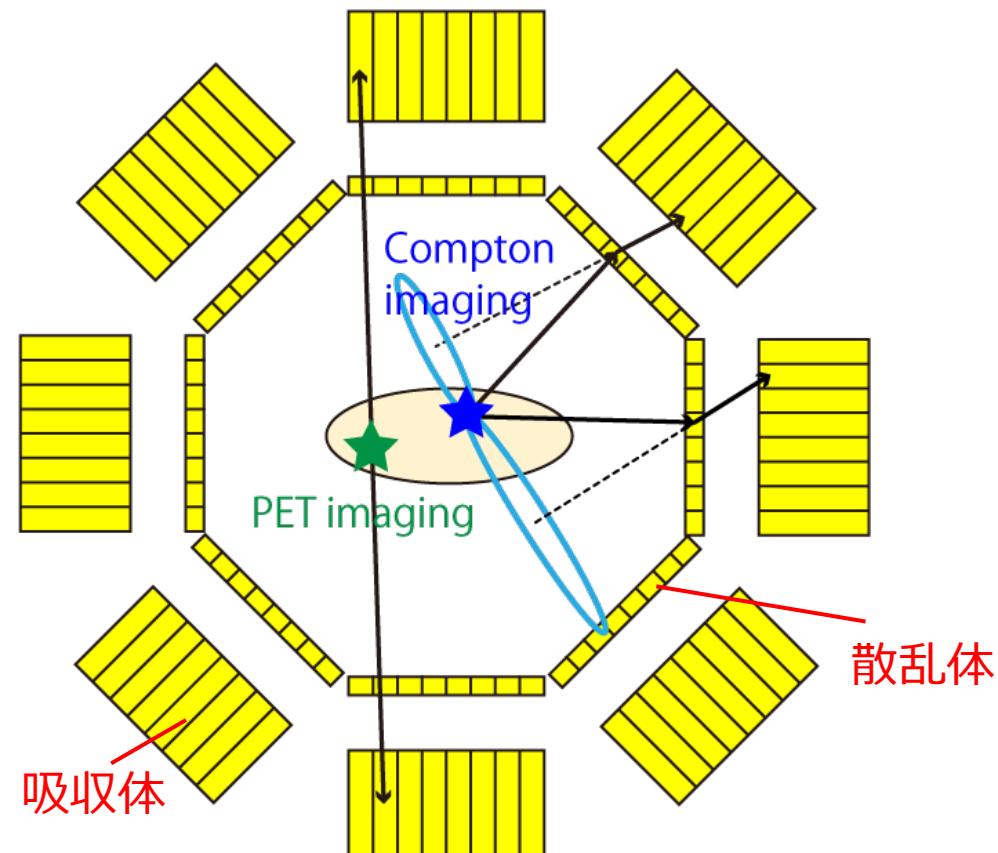


高感度PET × 高感度コンプトンカメラ = 多分子撮像

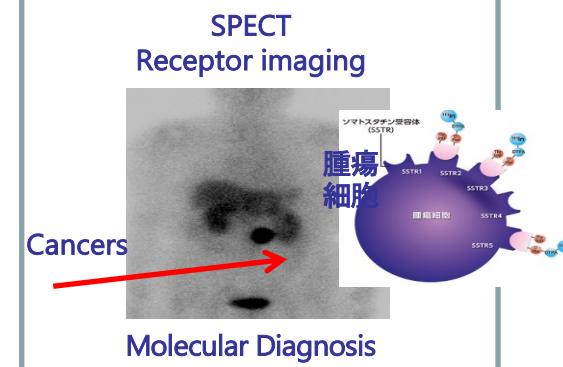
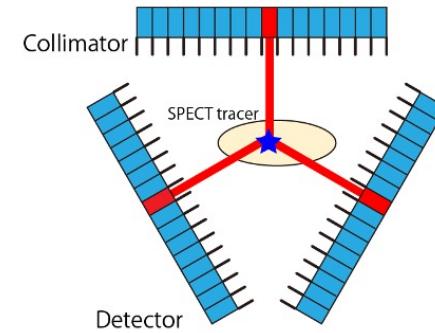
PET
(Positron Emission Tomography)

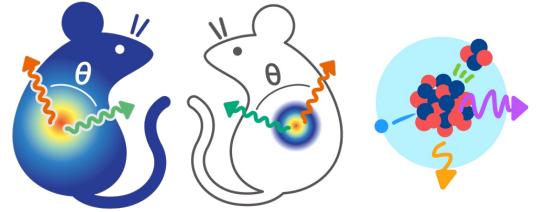


コンプトンPETハイブリッドカメラ



SPECT
(Single Photon Emission
Computed Tomography)

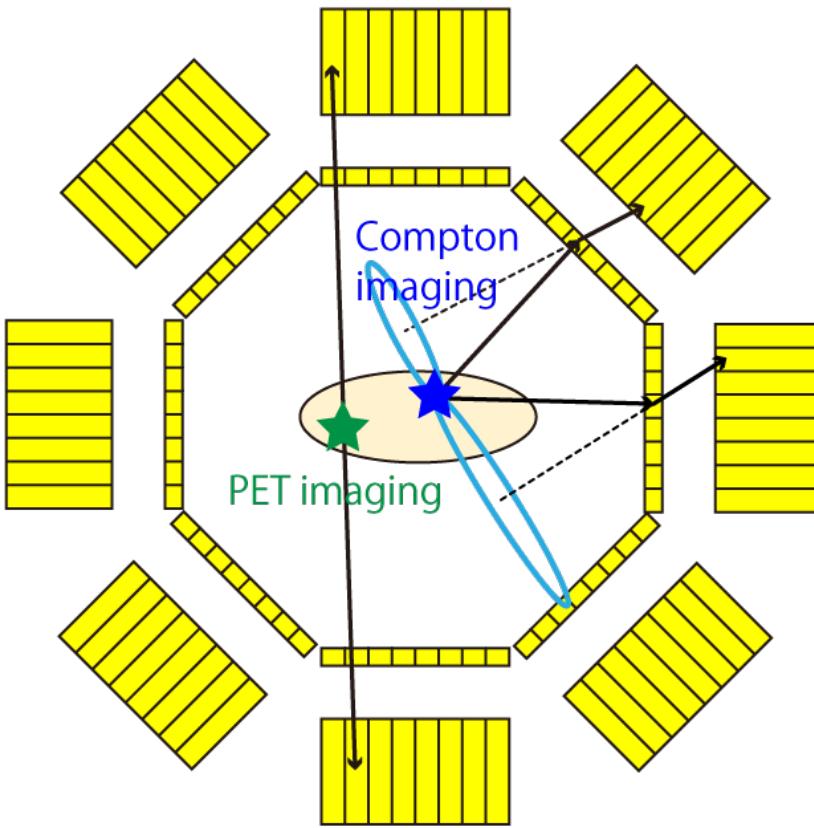




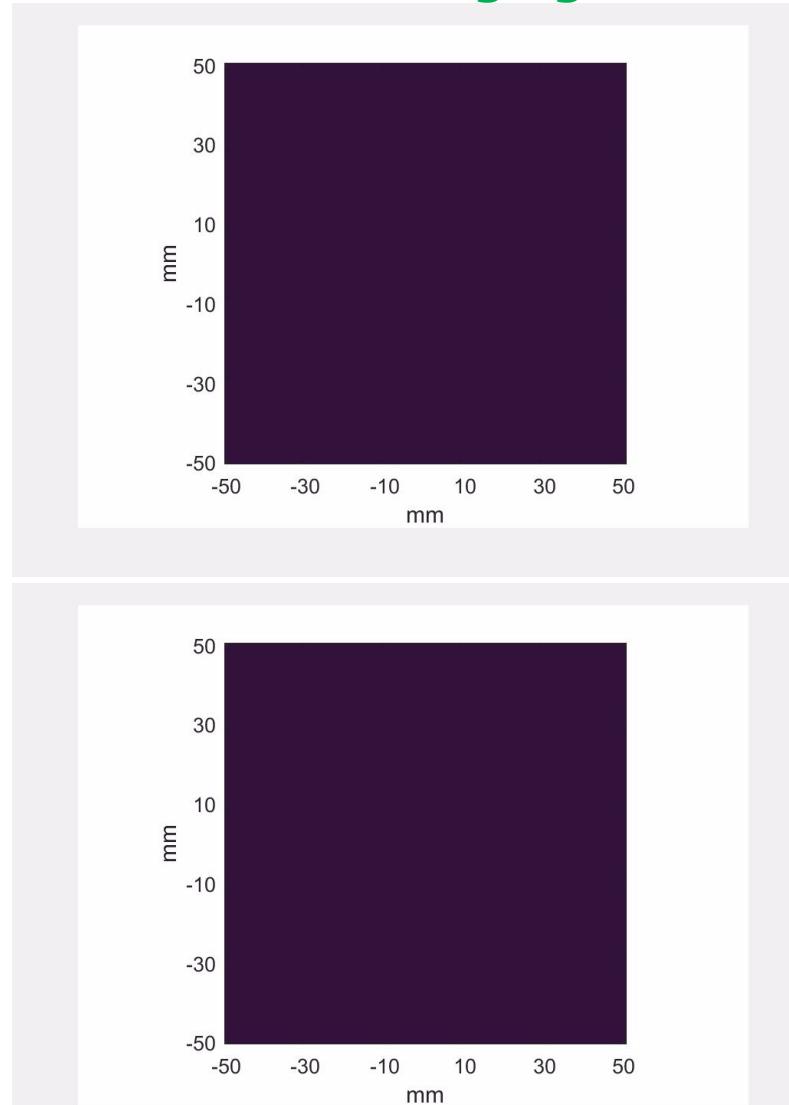
コンプトンPETハイブリッドカメラ



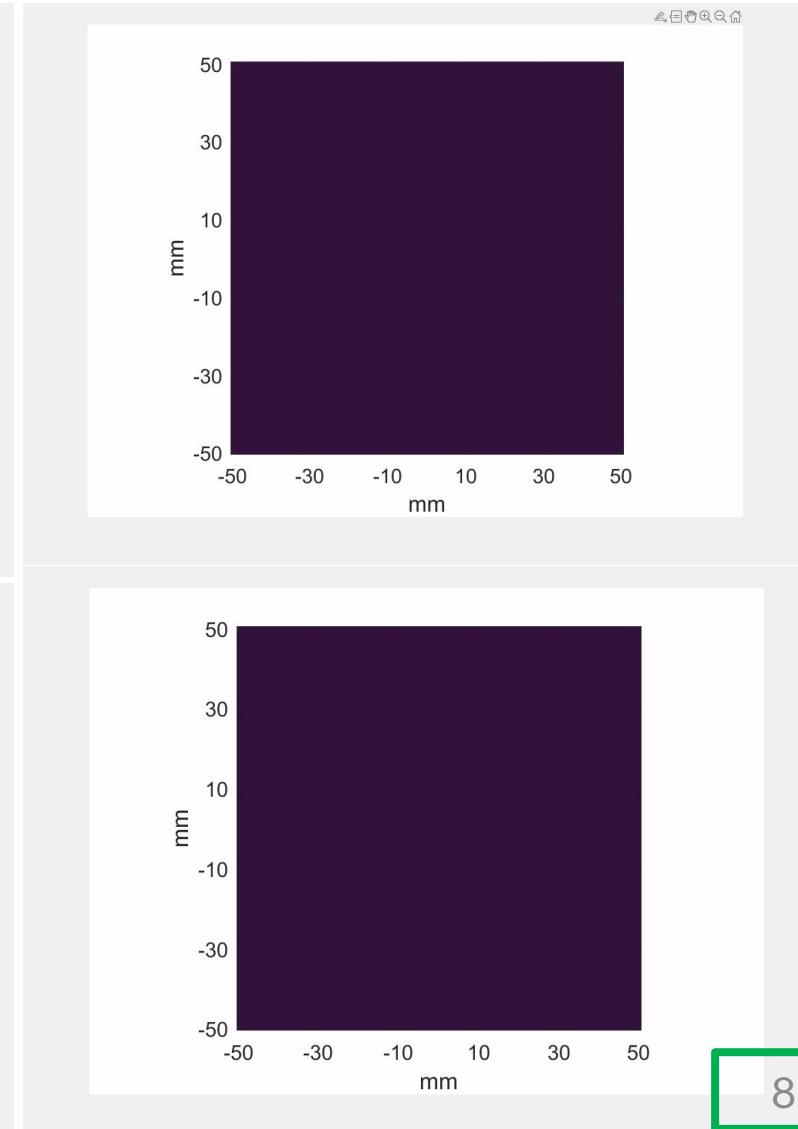
Compton-PET hybrid camera

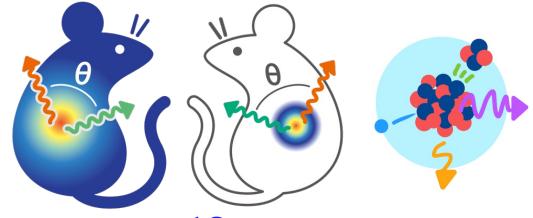


PET imaging



Compton Imaging

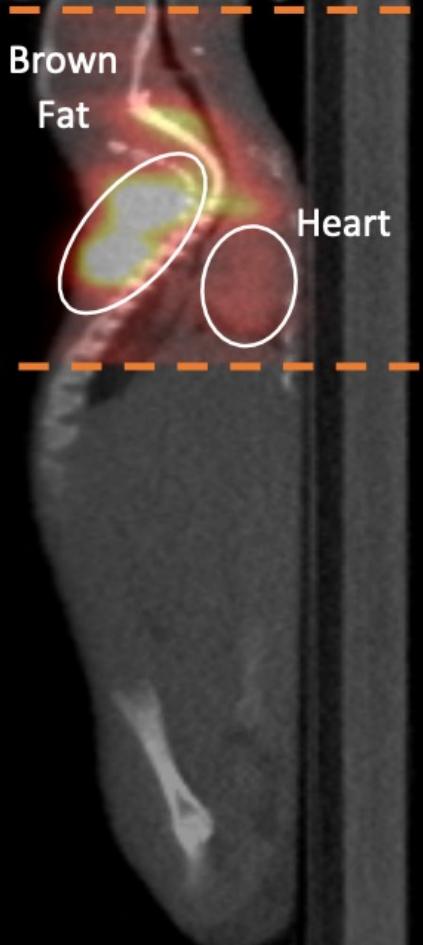




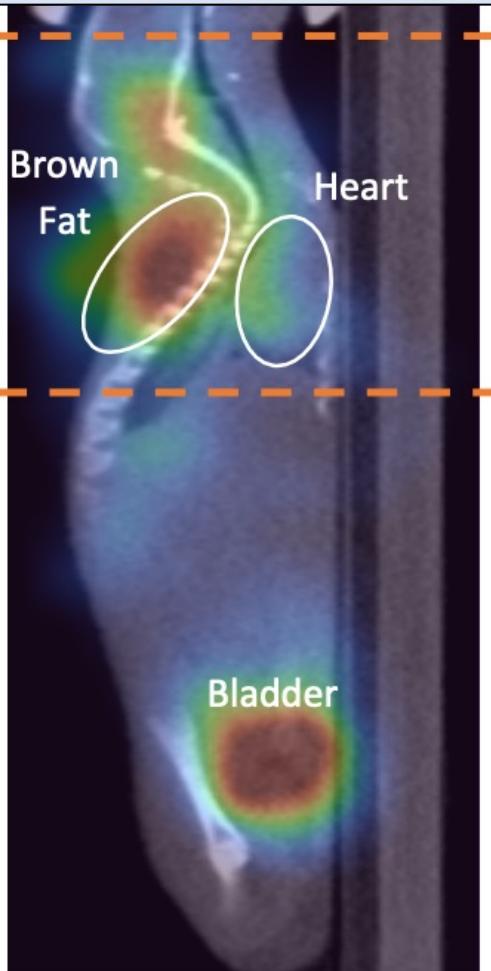
コンプトンPETカメラ

■ ^{18}F -FDG(PET) and Na^{131}I (Therapeutic) *in vivo* Imaging

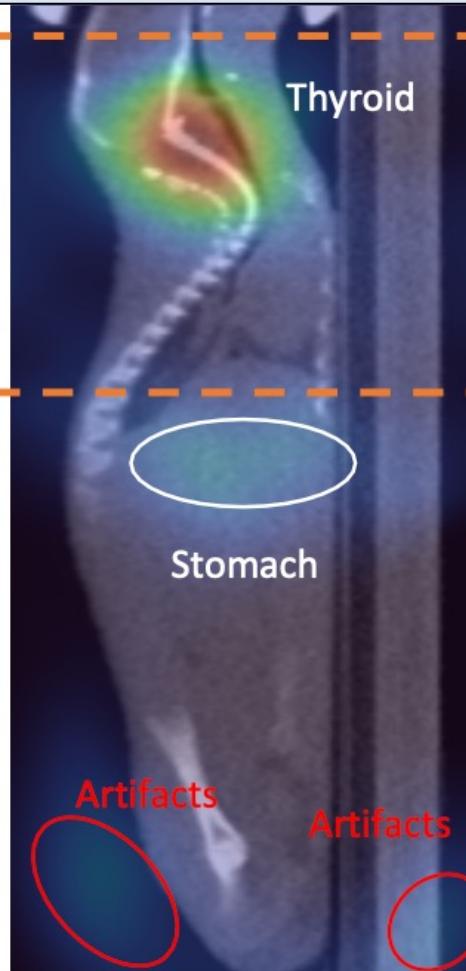
PET imaging
(511 keV)



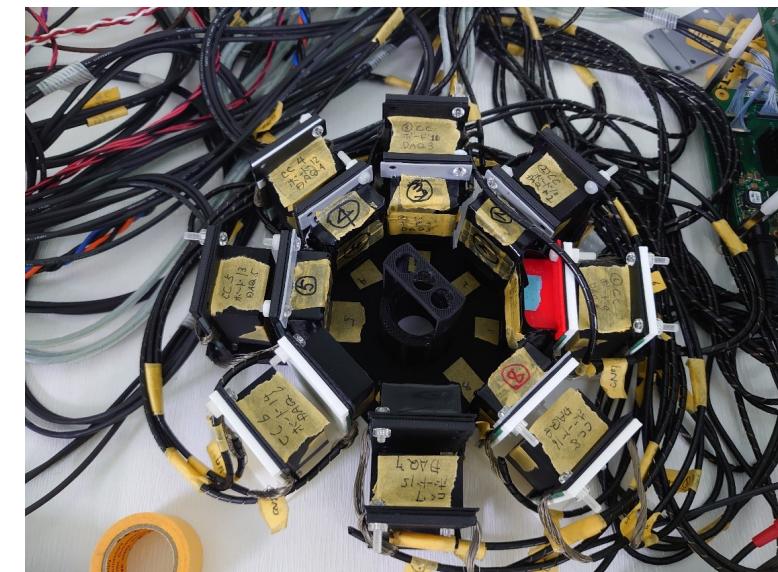
Compton imaging
(^{18}F -FDG 511 keV)



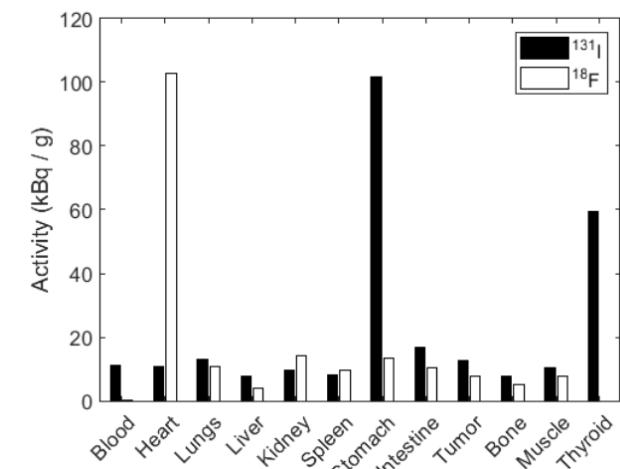
Compton imaging
(Na^{131}I 356 keV)

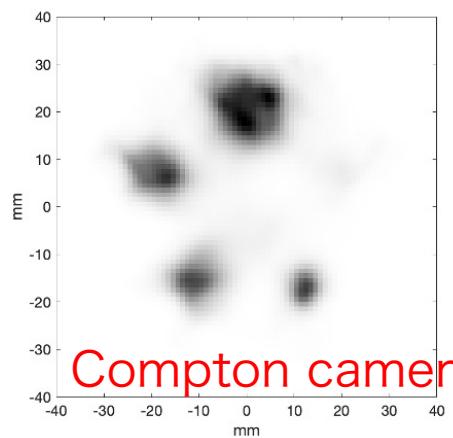
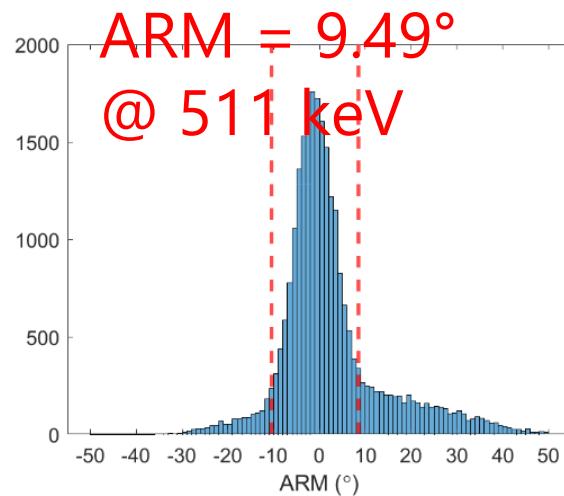
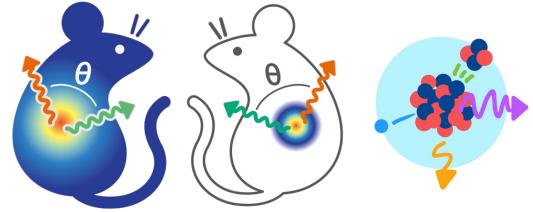


HR-GAGG CC



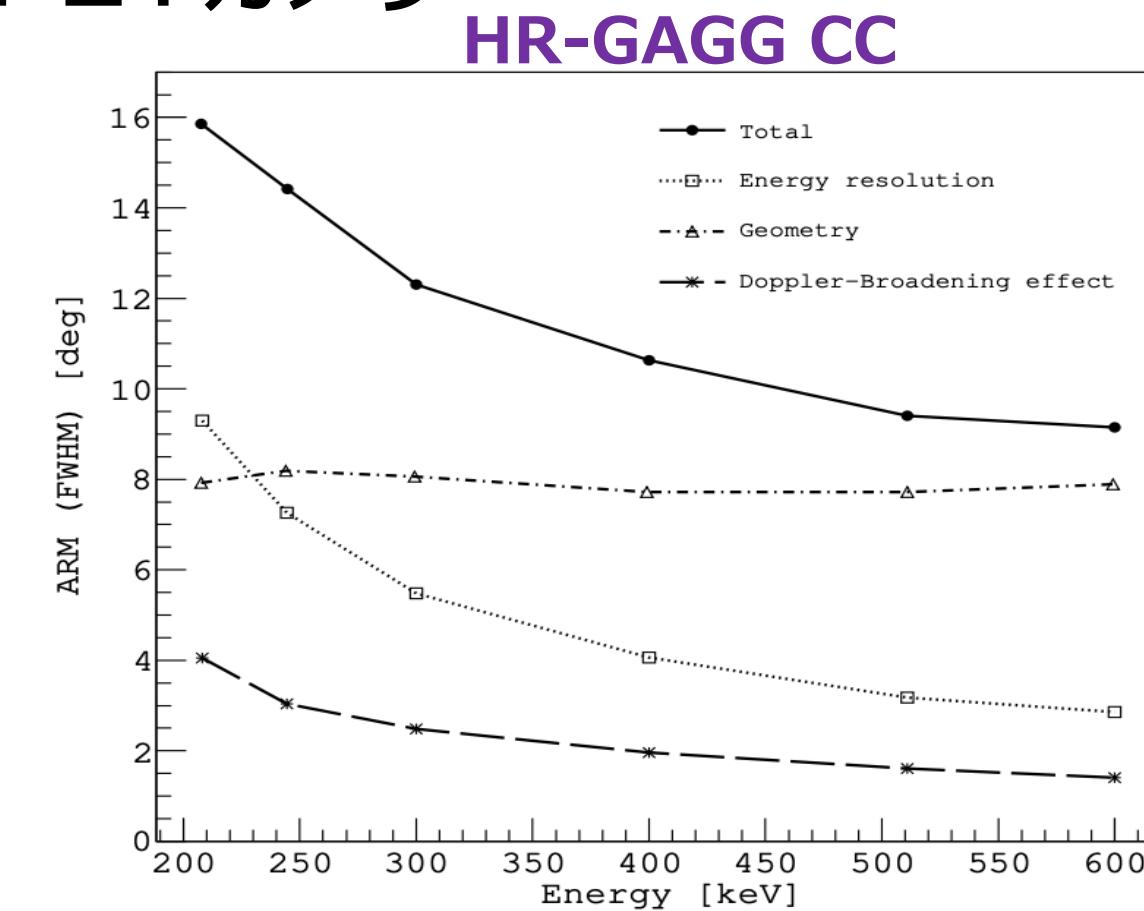
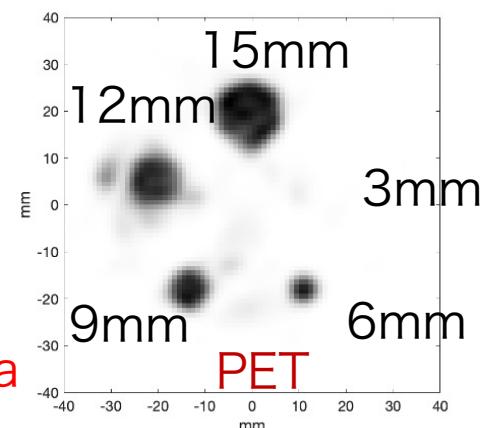
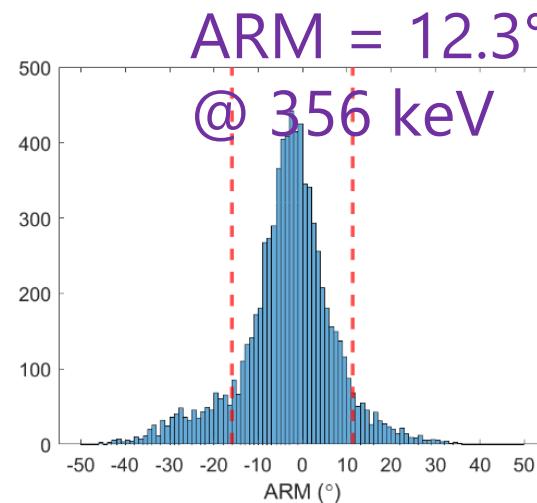
Accumulation in Organs





PETに近い画像が得られる
事を確認

コンプトンPETカメラ

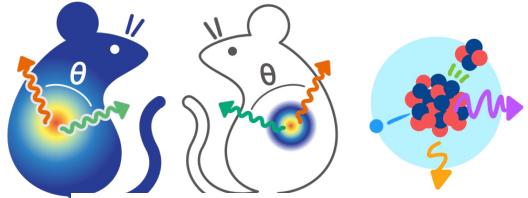


$$9.49^\circ = 10 \text{ cm} \text{で} 16.6 \text{ mm}$$

$$2^\circ = 10 \text{ cm} \text{で} 3.5 \text{ mm}$$

$$1^\circ = 10 \text{ cm} \text{で} 1.75 \text{ mm}$$

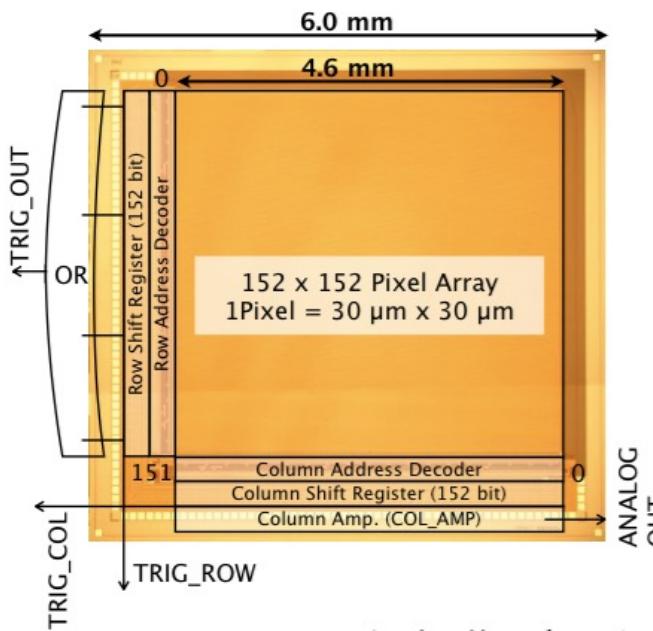
エネルギー分解能の向上と低エネルギー撮像



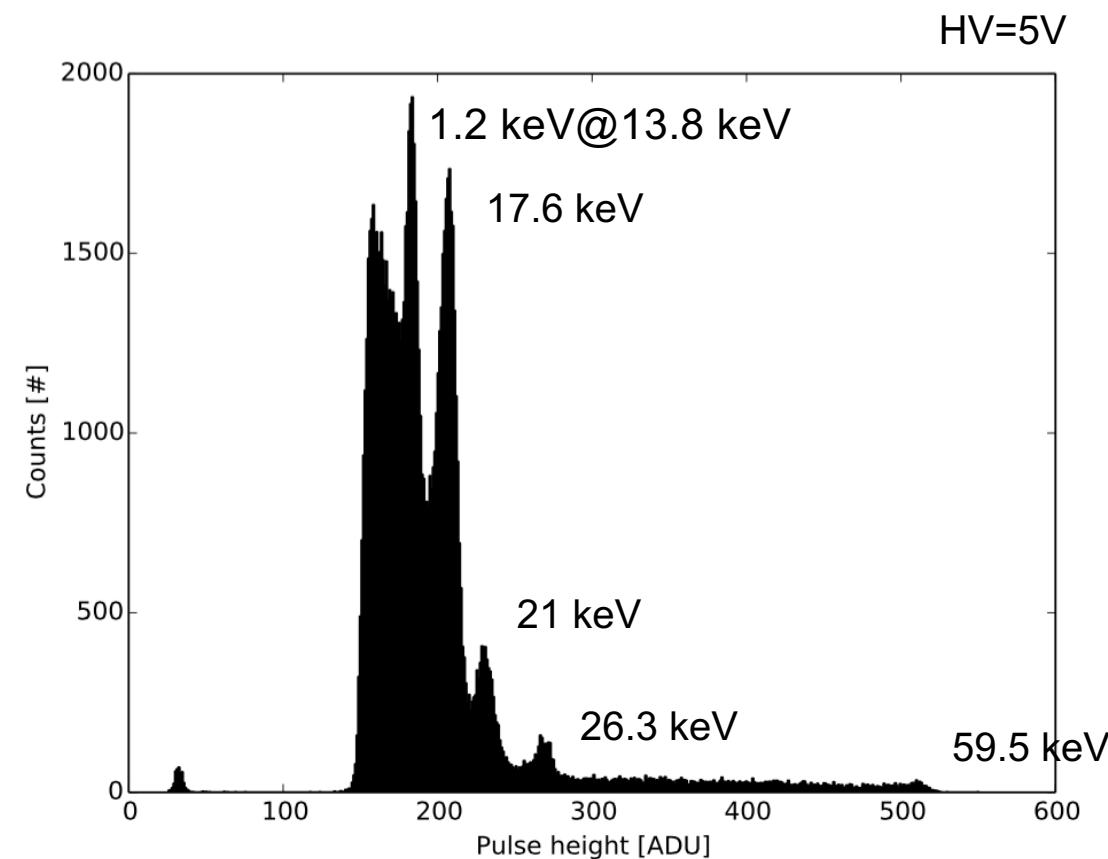
SOIPIXコンプトンカメラ

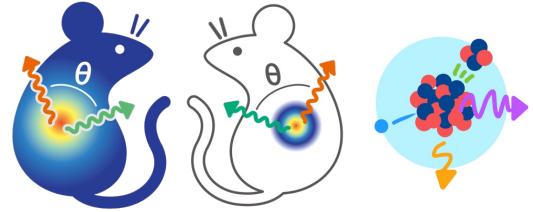


	NHR1(CZ)	NFZ
Chip Size	6.0 mm sq.	
Pixel Size	30 μm sq.	
BPW Size	12 μm sq.	
# of pixel ***	152 x 152	
Effective Pixel	144 x 144 (= 20,736)	
Effective Area	4.3 mm x 4.3 mm	
Thickness of Sensor ****	250 μm	500 μm
Resistivity	1.5 k Ω · cm	5 k Ω · cm
Power Supply *****	1.8V @ Core / 3.3V @ IO	
Back Bias (sensor)	5 - 500V <	

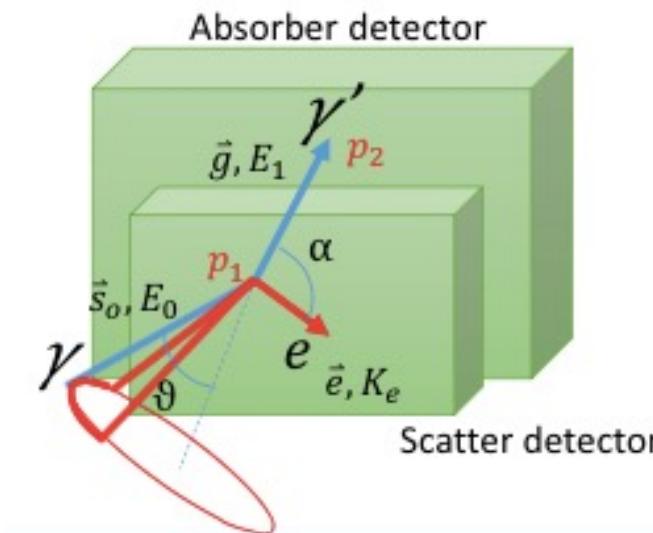


XRPIX2b(小型デバイス)
@ 新井先生新学術 2013-2019年





SOIPIXコンプトンカメラ



コンプトンカメラ

反跳電子
トラッキング

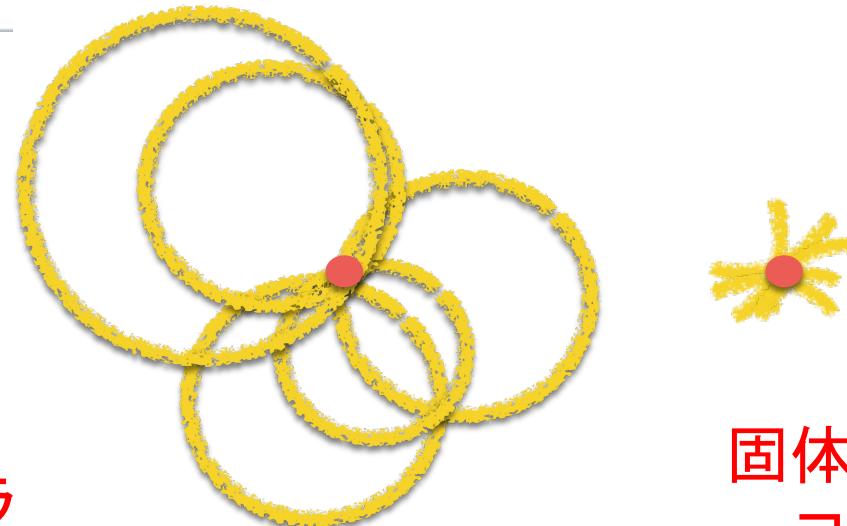
$$\vec{s}_o = \left(\cos\vartheta - \frac{\sin\vartheta}{\tan\alpha} \right) \vec{g} + \frac{\sin\vartheta}{\sin\alpha} \vec{e}$$

direction of
the incident
gamma-ray

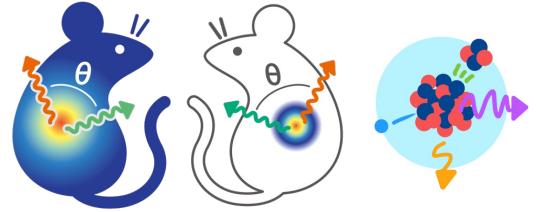
differential angle
between \vec{g} and \vec{e}

unit vector
of the scattering
direction

unit vector
of the recoil
direction



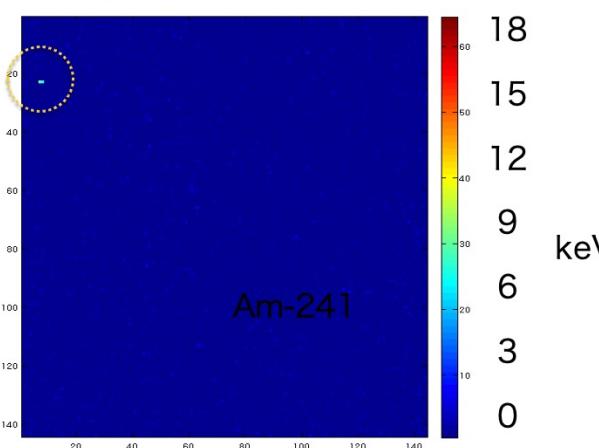
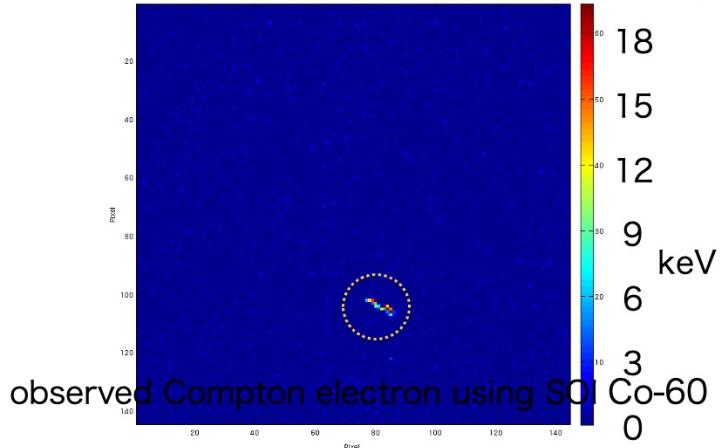
固体電子トラッキング
コンプトンカメラ



SOIPIXコンプトンカメラ

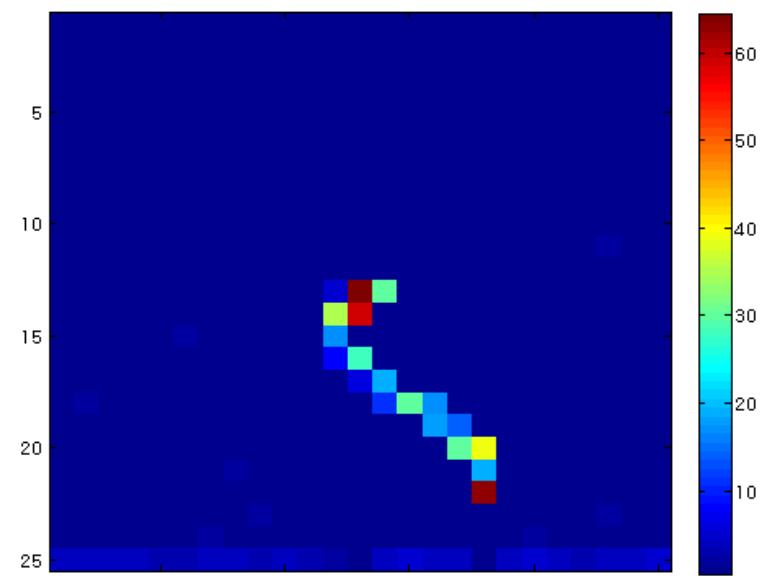
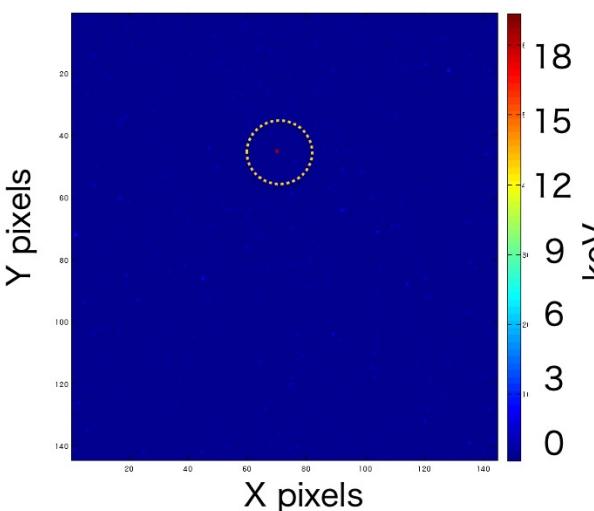
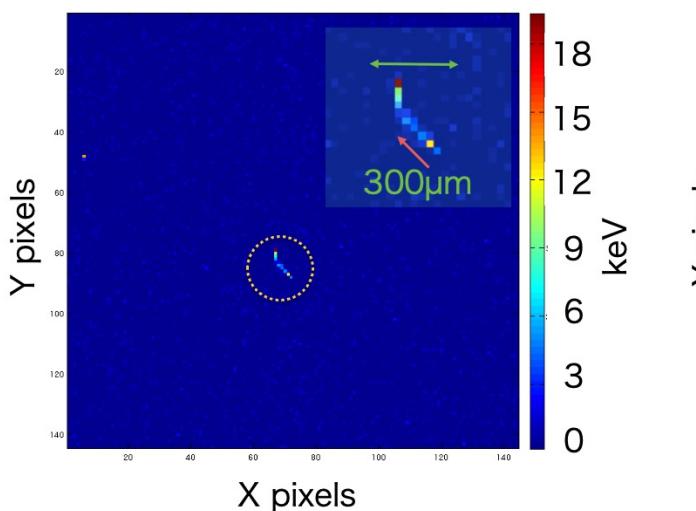


CZ wafer Vbias=5V room temperature integration time = 1000us

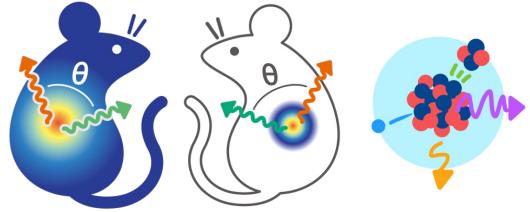


Trigger mode (25 x 25 pixels)
pattern readout

750μm x 750 μm



Shimazoe, K., et al. "Electron Pattern Recognition using trigger mode SOI pixel sensor for Advanced Compton Imaging." *Journal of Instrumentation* 11.02 (2016): C02030.



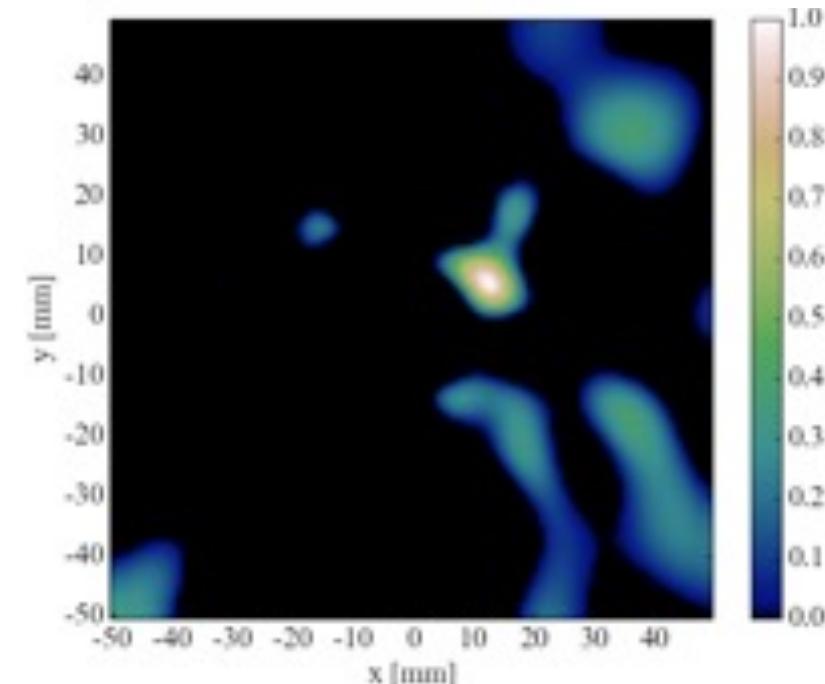
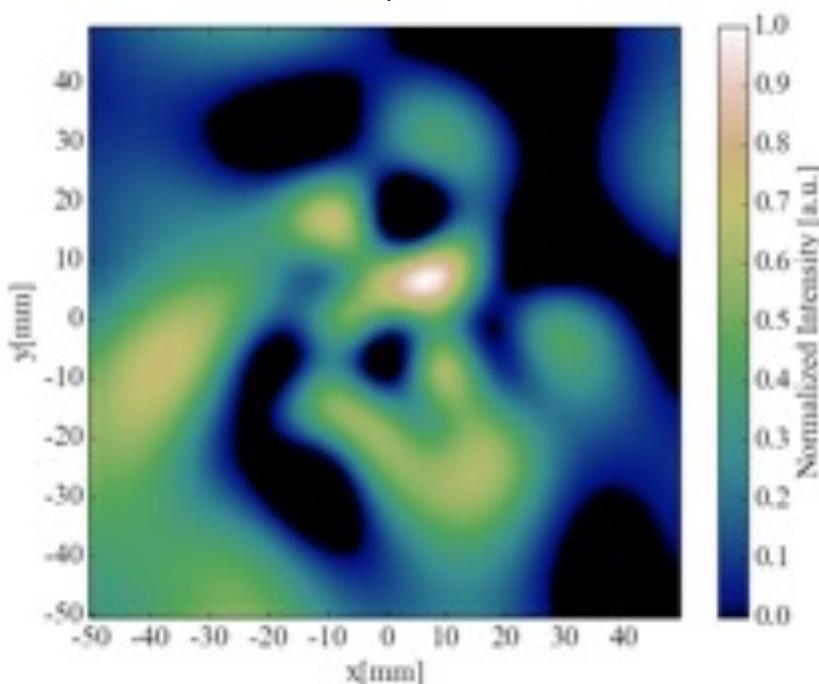
XRPIX2b-電子トラッキングCC



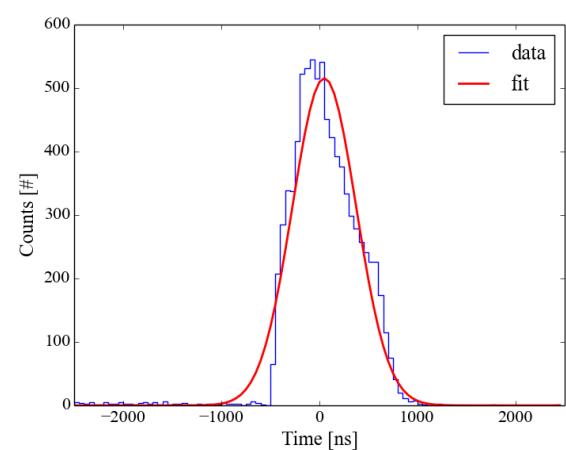
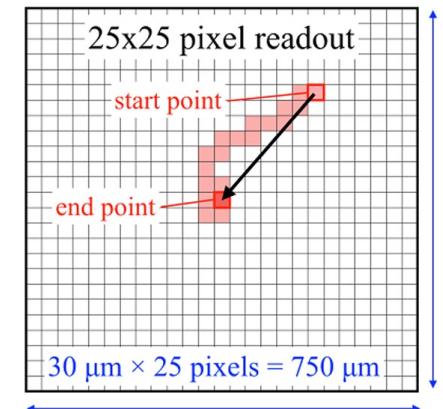
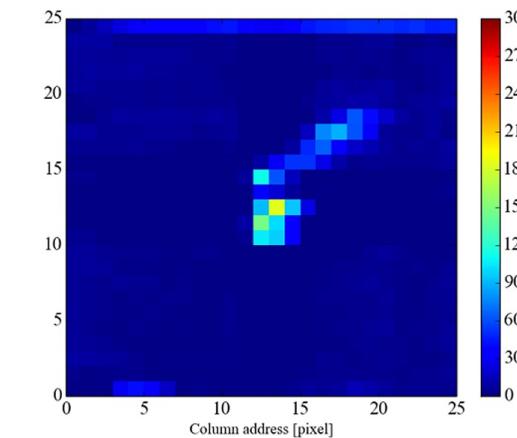
XRPIX2b + GAGG-MPPC Compton Camera

1MBq ^{137}Cs (検出器中心, 散乱体表面から距離3cm)
コインシデンスイベント検出率 : ~1 cps
フレームセレクト率: 0.6 %

従来

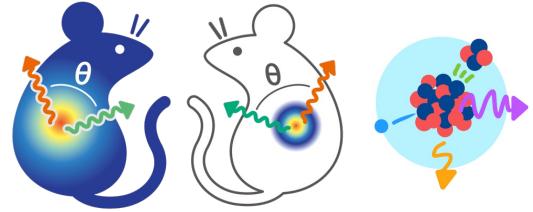


電子トラッキング



Timing spectrum: FWHM=1128 ns

Yoshihara, Y., et al. "Development of electron-tracking Compton imaging system with 30-μm SOI pixel sensor." *Journal of Instrumentation* 12.01 (2017): C01045.



反跳電子方向推定

Method	Pixel Size	SPD (alpha)	SPD (beta)
MLP	10 μm	68.8°	41.2°
MLP	30 μm	79.1°	35.8°
CNN	10 μm	57.5°	36.3°
CNN	30 μm	73.0°	35.6°

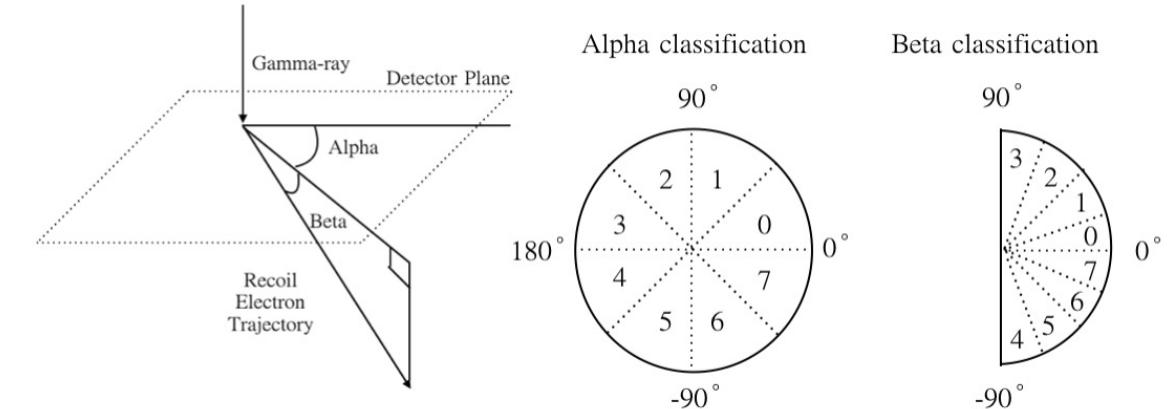


Figure 2. Definition of alpha and beta angle and its classification.

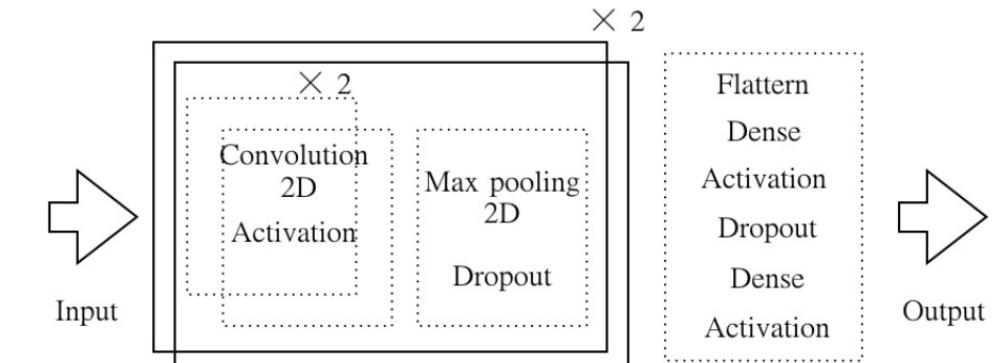
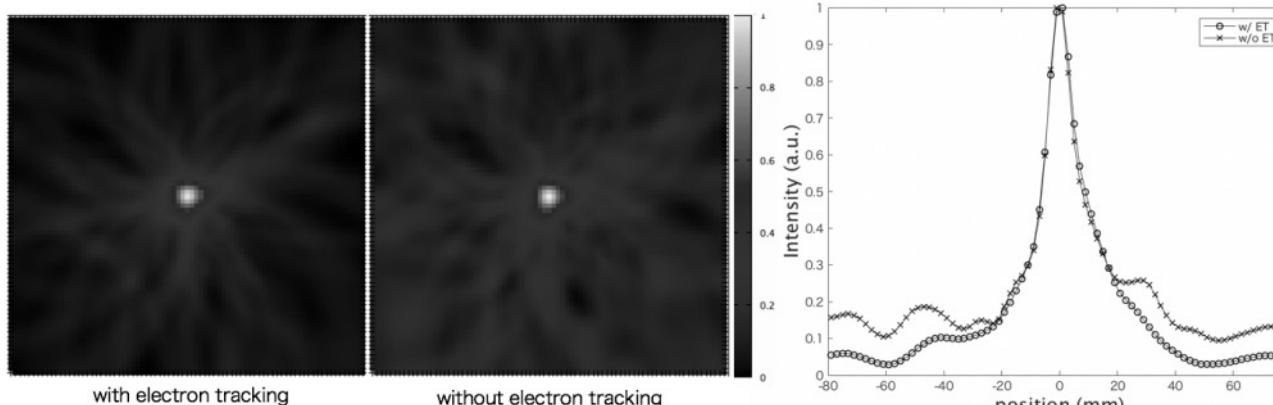
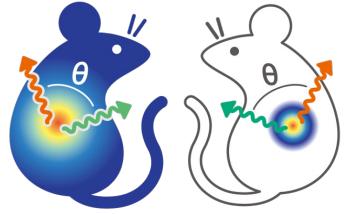


Figure 3. Diagram of convolutional neural network used in this machine learning.

Shimazoe, K., et al. "Simulation study on SOI based electron tracking Compton camera using deep learning method." *Journal of Instrumentation* 15.02 (2020): C02010.



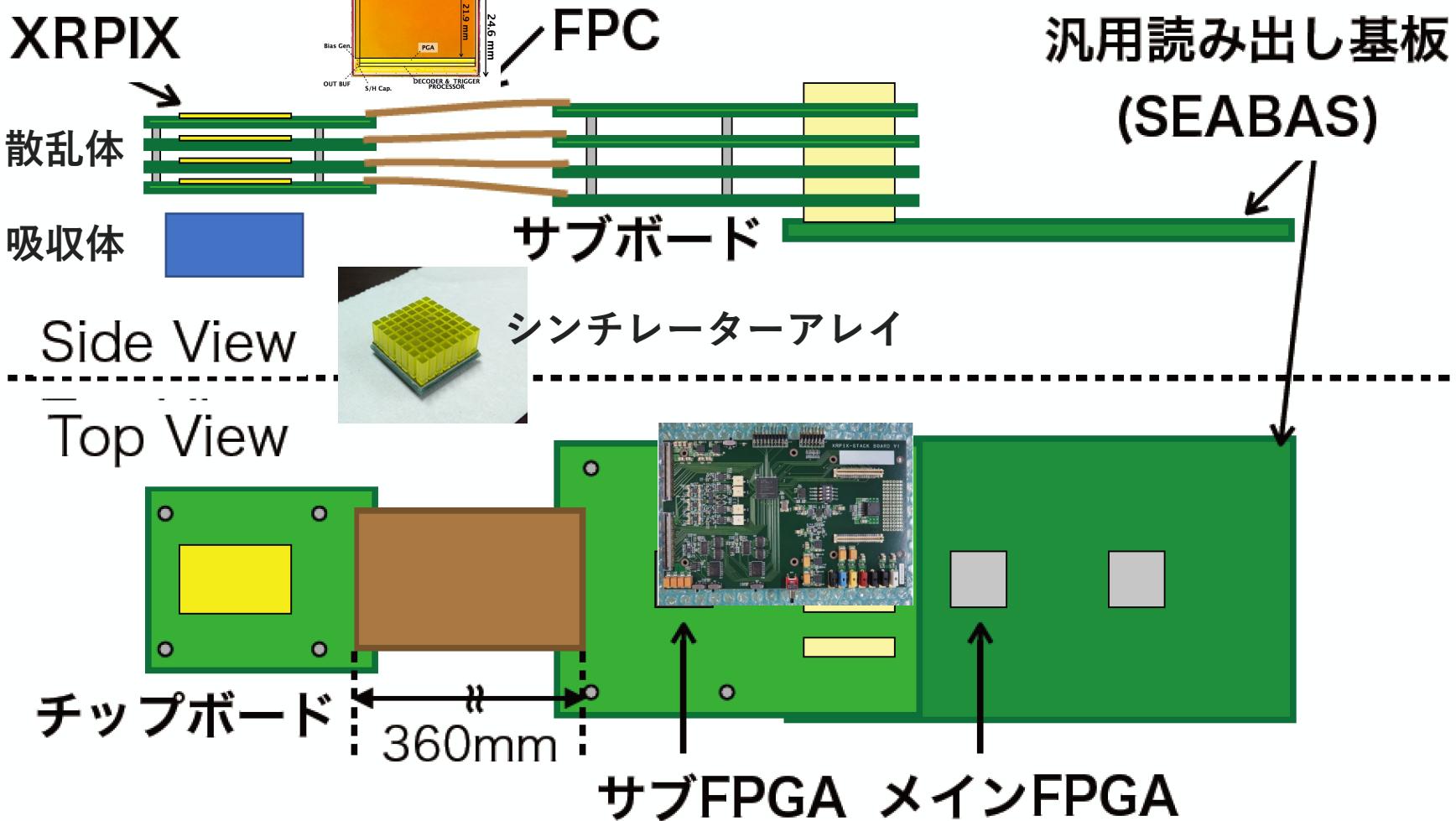
大型化への流れ



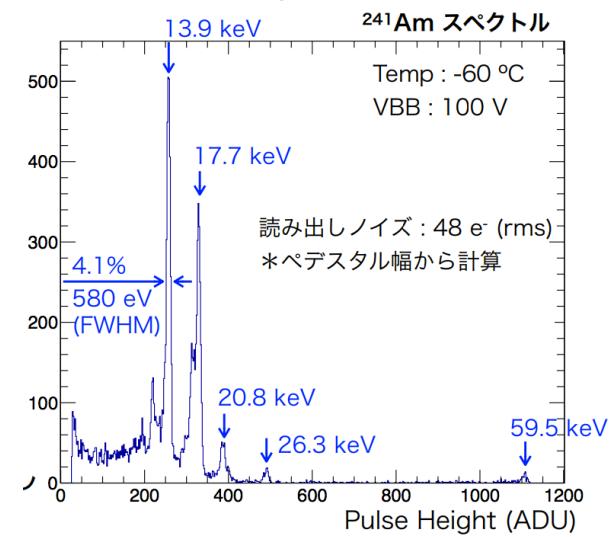
XRPIX5..

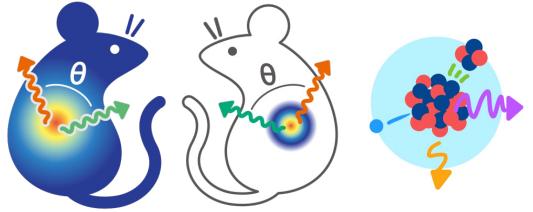
XRPIXシリーズの大面積素子

- チップサイズ : 24.6 mm x 15.3 mm
(有効領域 : 21.9 mm x 15.3 mm)
- ピクセルサイズ : 36 μm 角
- ピクセル数 : 608 x 384
- センサ層厚 : 310 μm (CZ)
500 μm (FZ)



イベントがあった素子の ①素子ID, ②タイミング, ③アドレス, ④エネルギー を全て計測 + 吸収体との同期

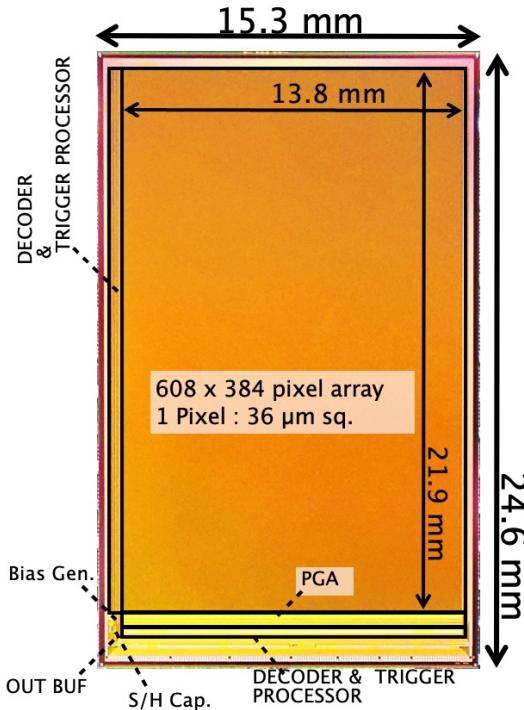




XR7-GFAGコンプトンカメラ



Large area X-ray SOI sensor + GFAG

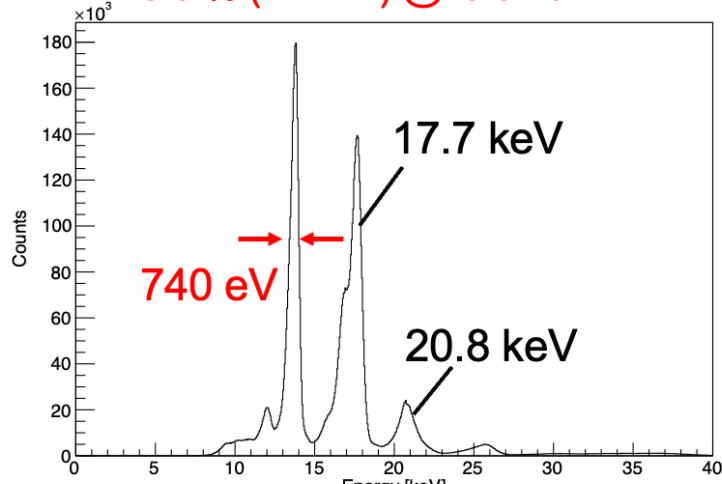


Sensor information

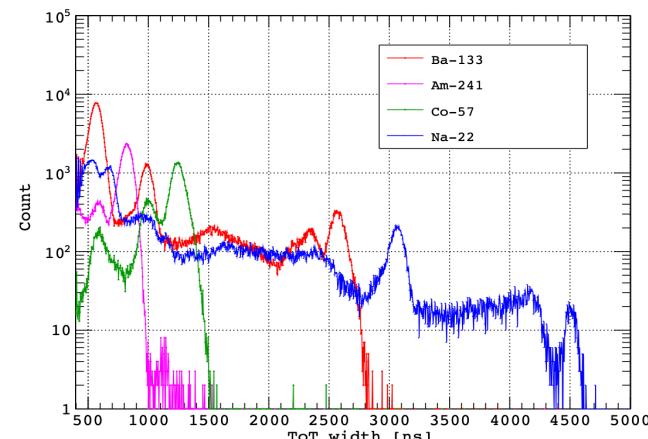
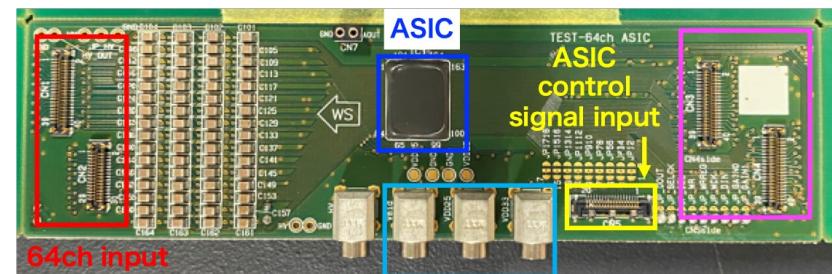
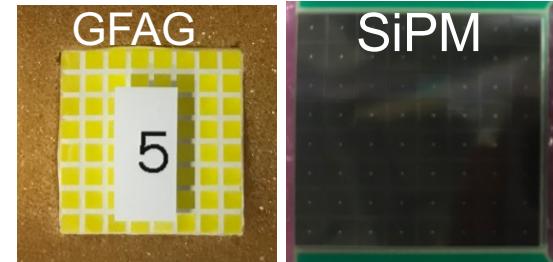
- Chip size : 24.6 mm x 15.3 mm
(Active area : 21.9 mm x 13.8 mm)
- Pixel size : 36 μm sq.
- Pixel number : 608 x 384 (= ~233k)
- Sensor thickness : 300 μm - 500 μm

イベント駆動 → 同時計測

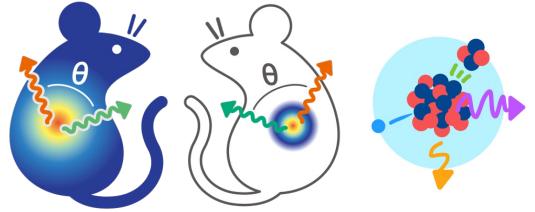
5.3 % (FWHM) @13.9 keV



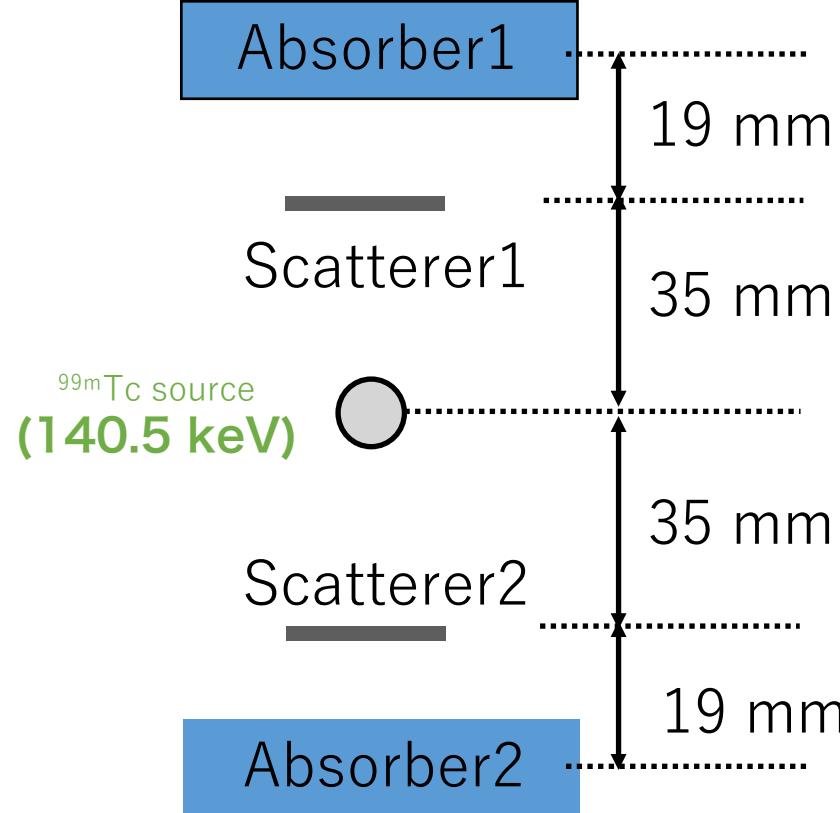
- Temperature : 0 deg
- V_{det} : -25V (not full depletion)



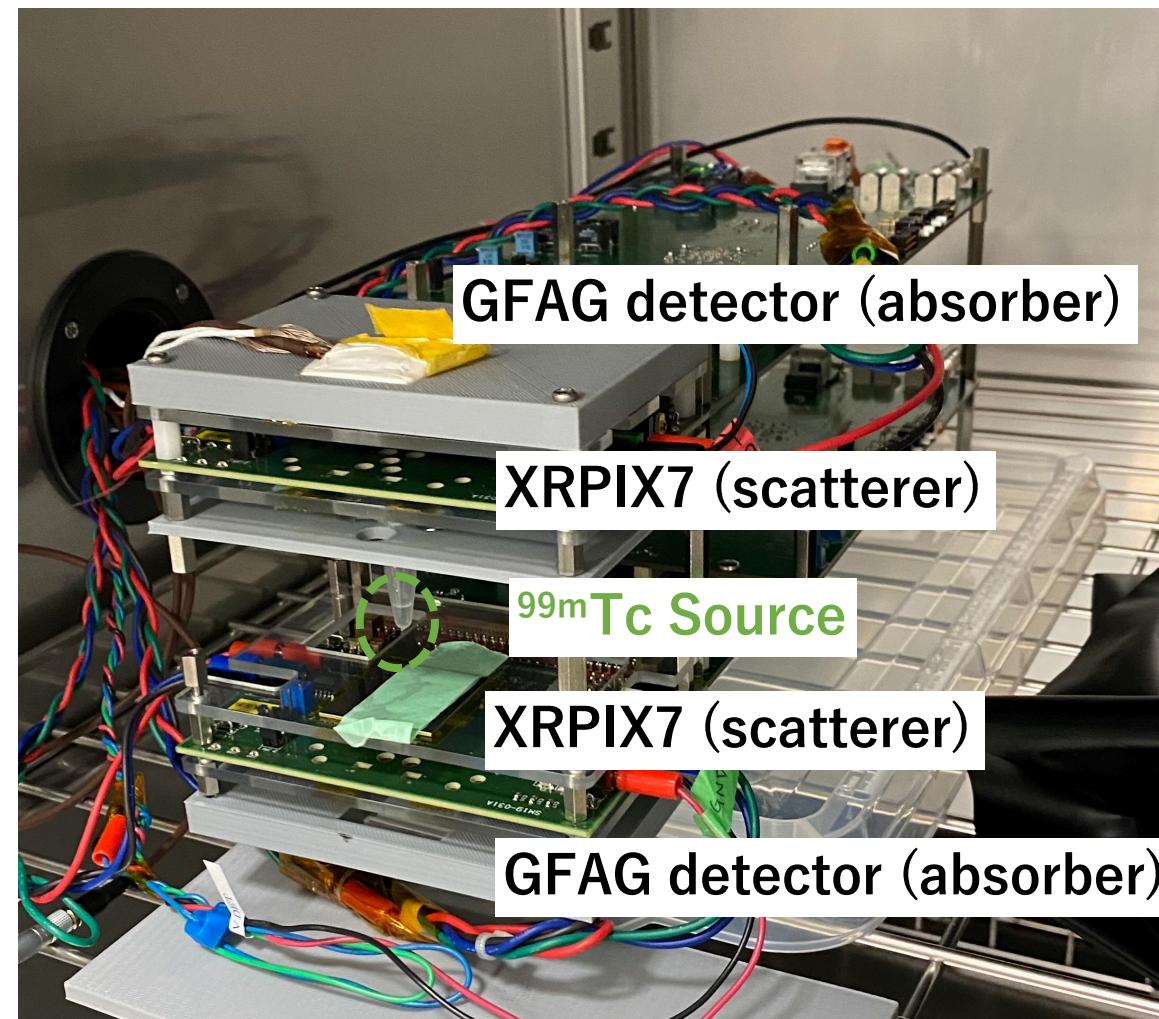
Energy [keV]	Energy resolution (FWHM) [%]
122	18.2
511	11.7
1274.5	5.6



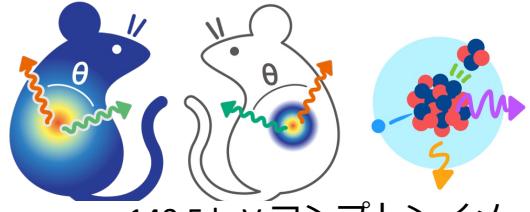
XR7-GFAGコンプトンカメラ



- Temperature: 0 deg
- XRPIX Bias: -25V
- SiPM Bias: -55V



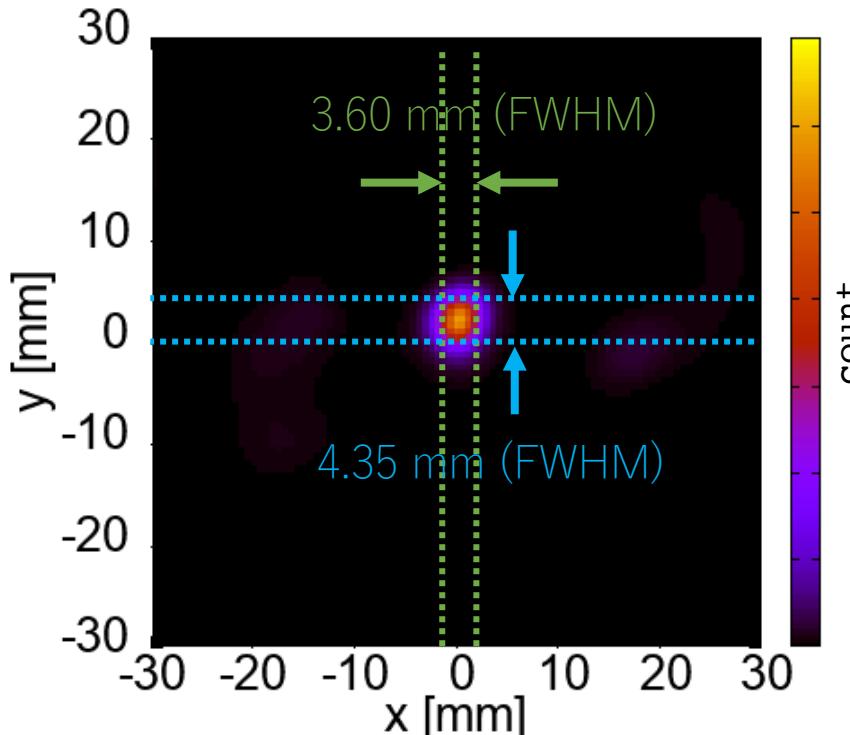
- Activity: ~1 MBq
- Measurement time: ~12.8 h



XR7-GFAGコンプトンカメラ



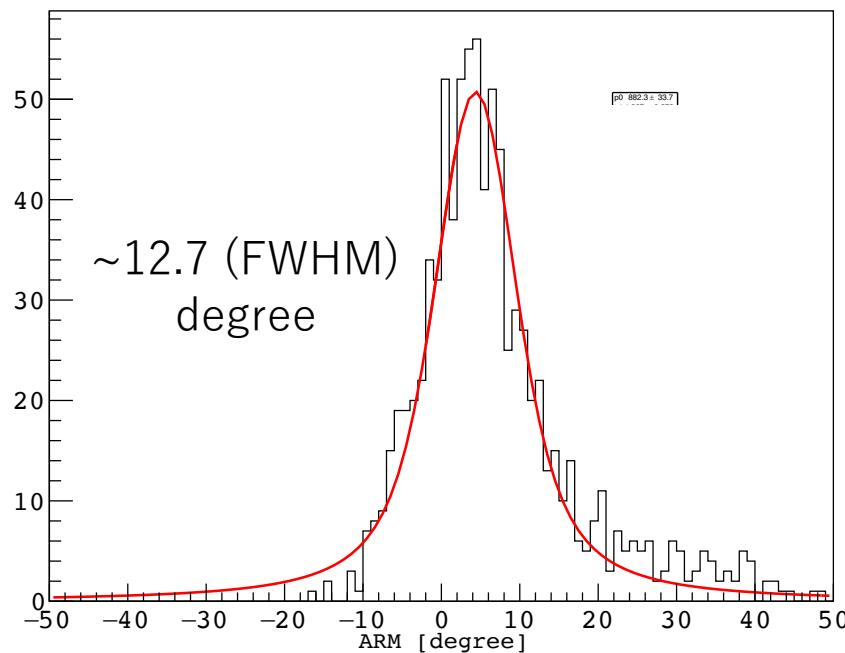
140.5 keV コンプトンイメージング



Reconstruction parameters

- MLEM*
- Iteration number: 100
- $5 \text{ keV} < E_{\text{sc}} < 20 \text{ keV}$
- $126.5 \text{ keV} < E_{\text{total}} < 154.6 \text{ keV}$

角度分解能

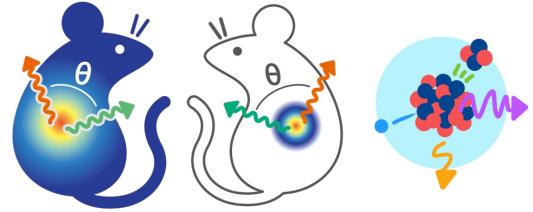


検出効率

Intrinsic detection efficiency	SOI-GFAG Compton-PET camera	GAGG Compton-PET camera
140.5 keV Compton imaging	4.3×10^{-6}	-
511 keV Compton imaging	1.7×10^{-6}	7.0×10^{-4}

低エネルギーガンマ線(140.5 keV)の
コンプトンイメージングに成功

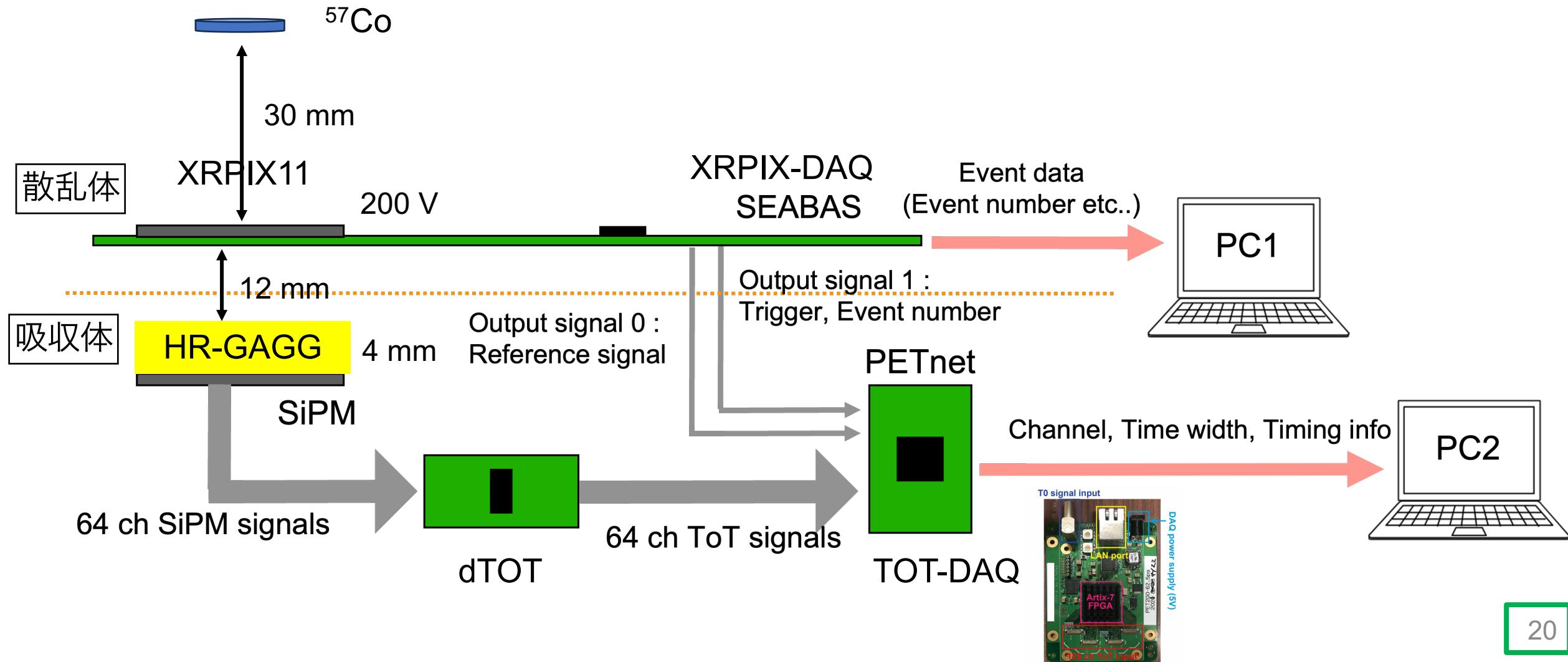
*Maximum likelihood estimation method

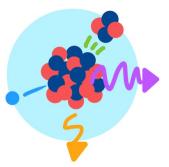
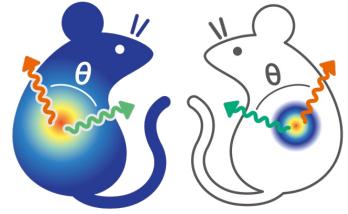


XR11-GAGGコンプトンカメラ



実験体系

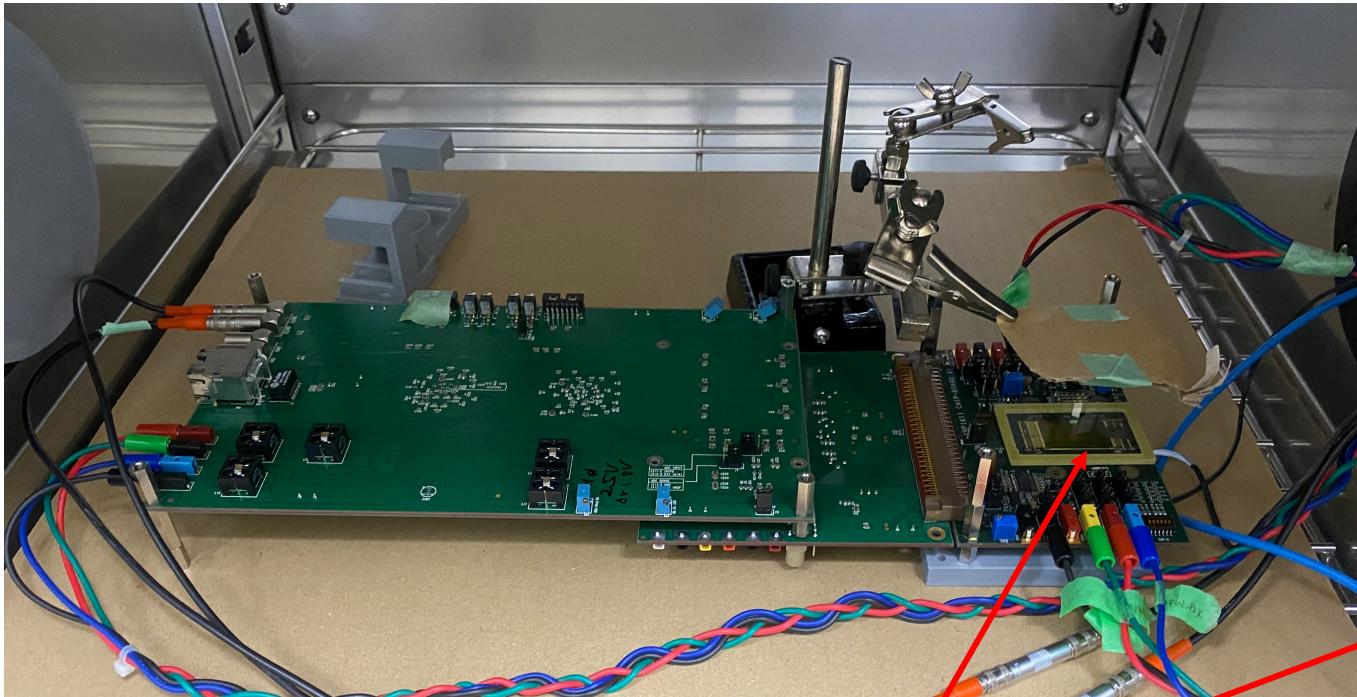




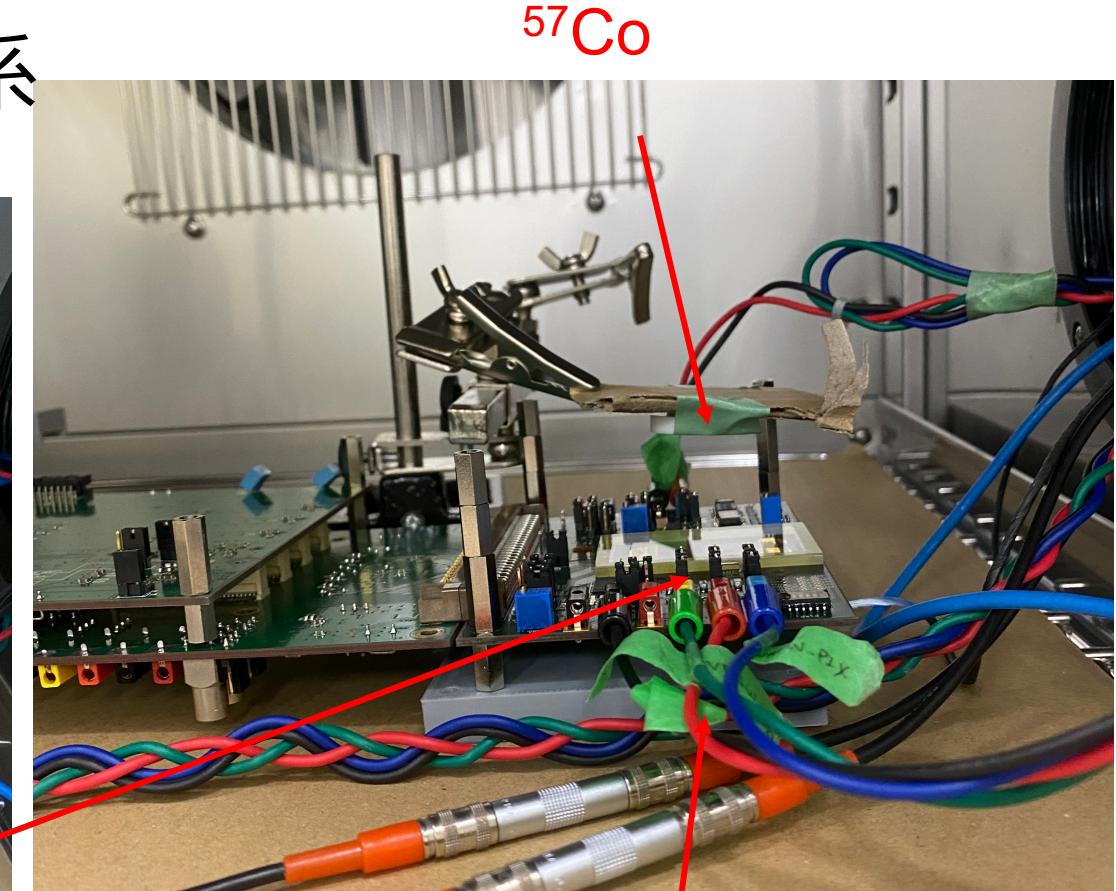
XR11-GAGGコンプトンカメラ



実験体系

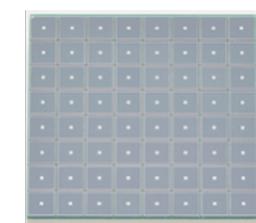
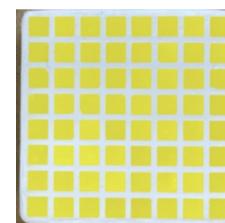


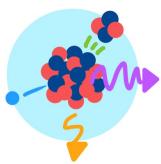
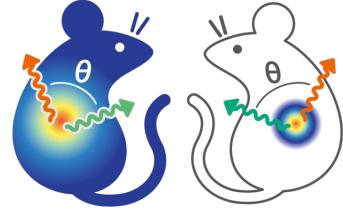
XRPIX11



^{57}Co

HR-GAGG (4mm厚)
3.2 mmピッチ8×8



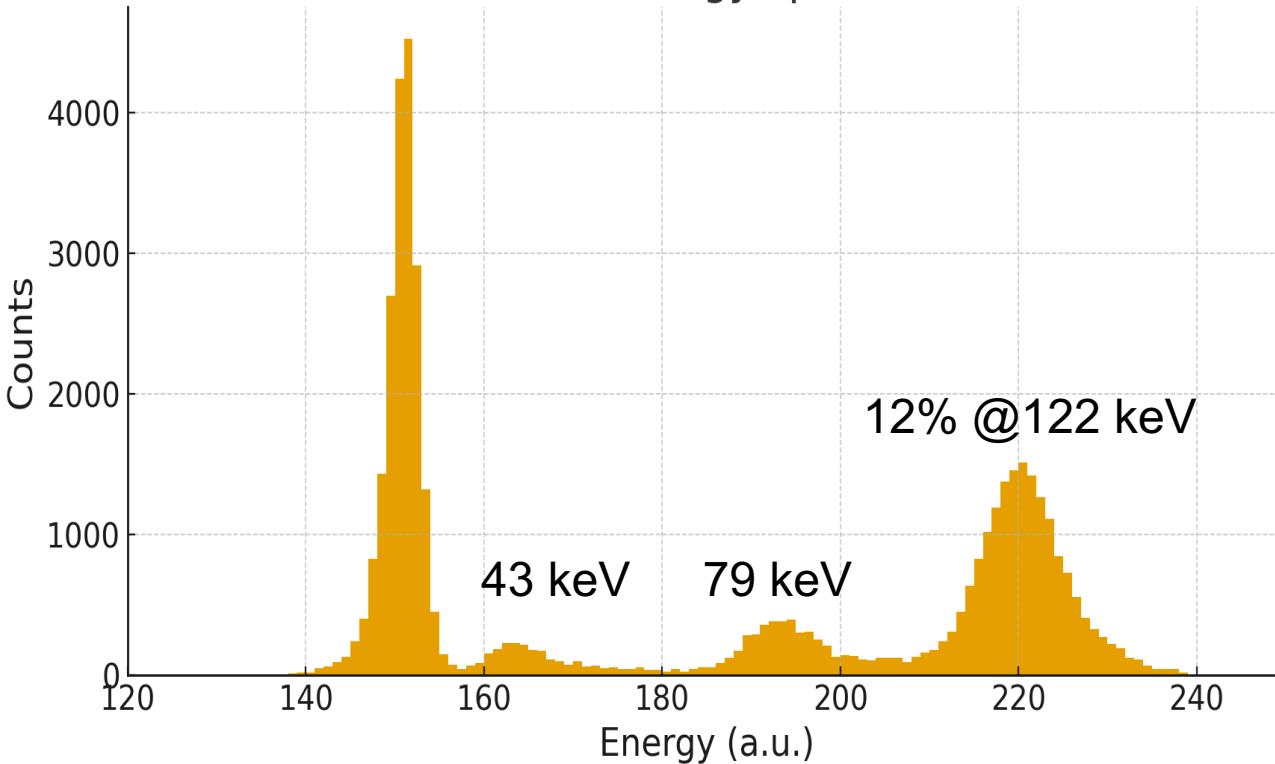


XR11-GAGGコンプトンカメラ



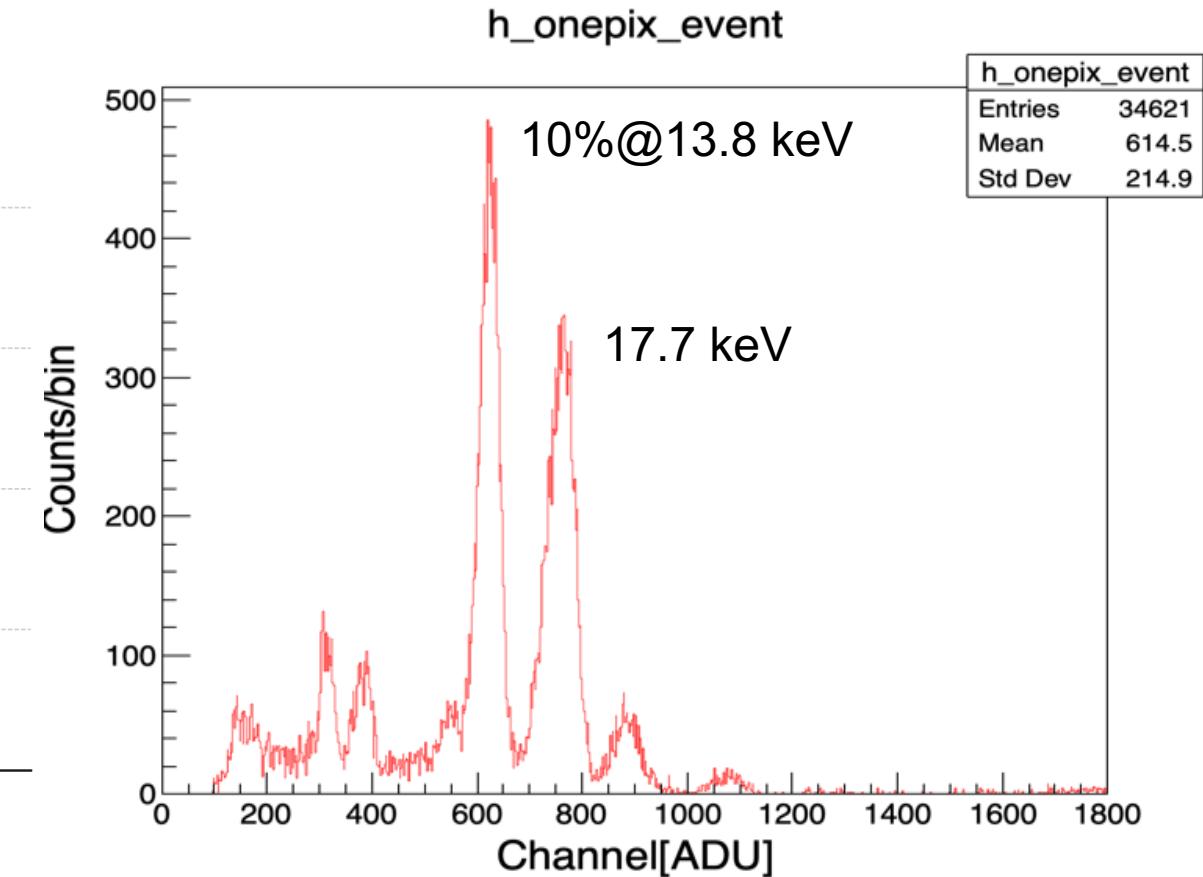
エネルギー応答(GAGG, XR11)

HR-GAGG-SiPM Energy spectrum (Co-57)

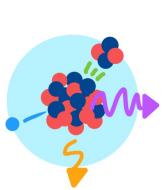
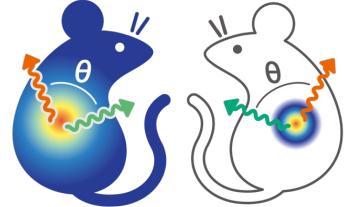


54.5V-SiPM-HR-GAGG @ room temperature

h_onepix_event



-200 V @ room temperature

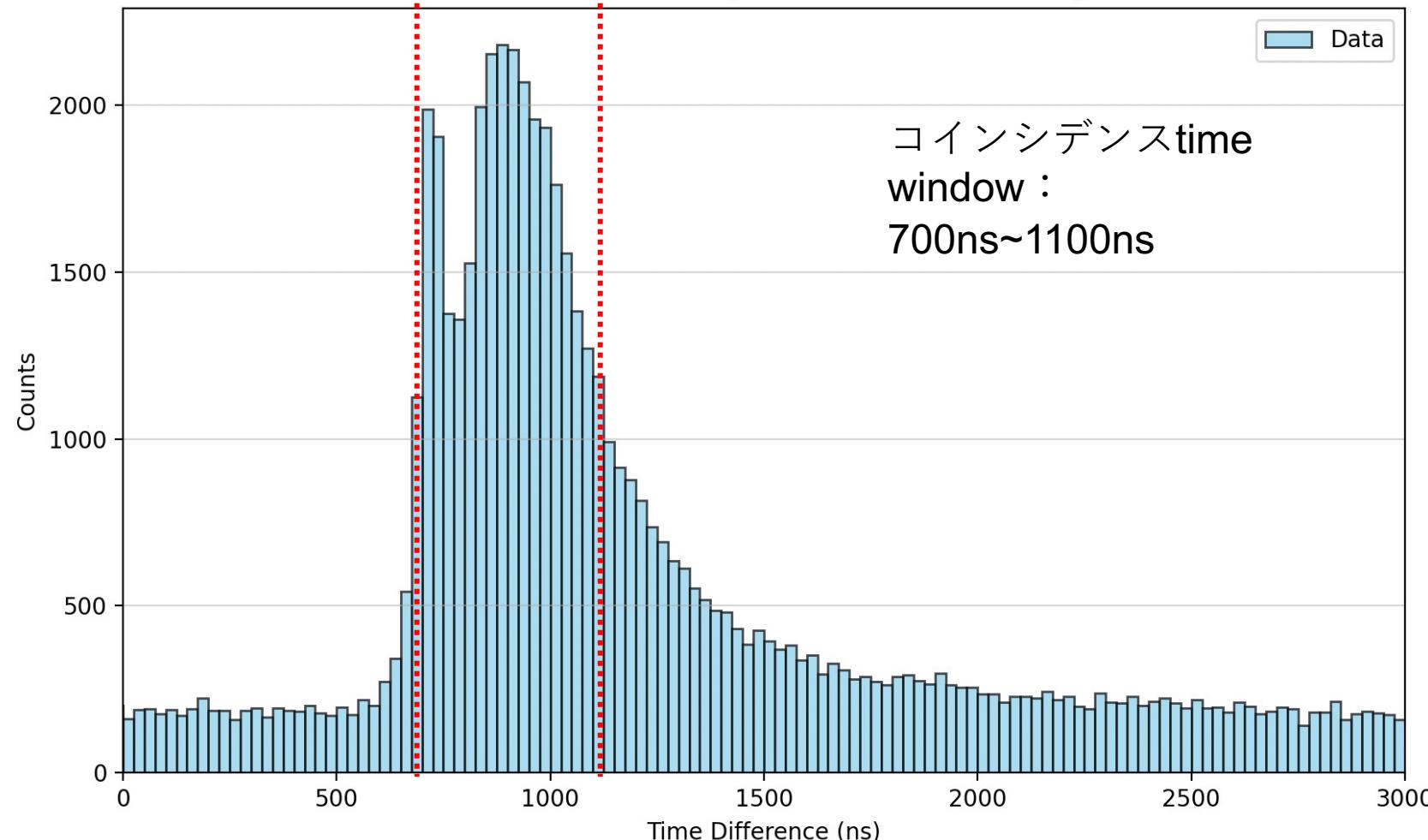


XR11-GAGGコンプトンカメラ

時間応答(コインシデンス)

時間差ヒストグラム timestamp(XRPIX11) - timestamp(HR-GAGG)

Time Difference Histogram (Coincidence Timing)

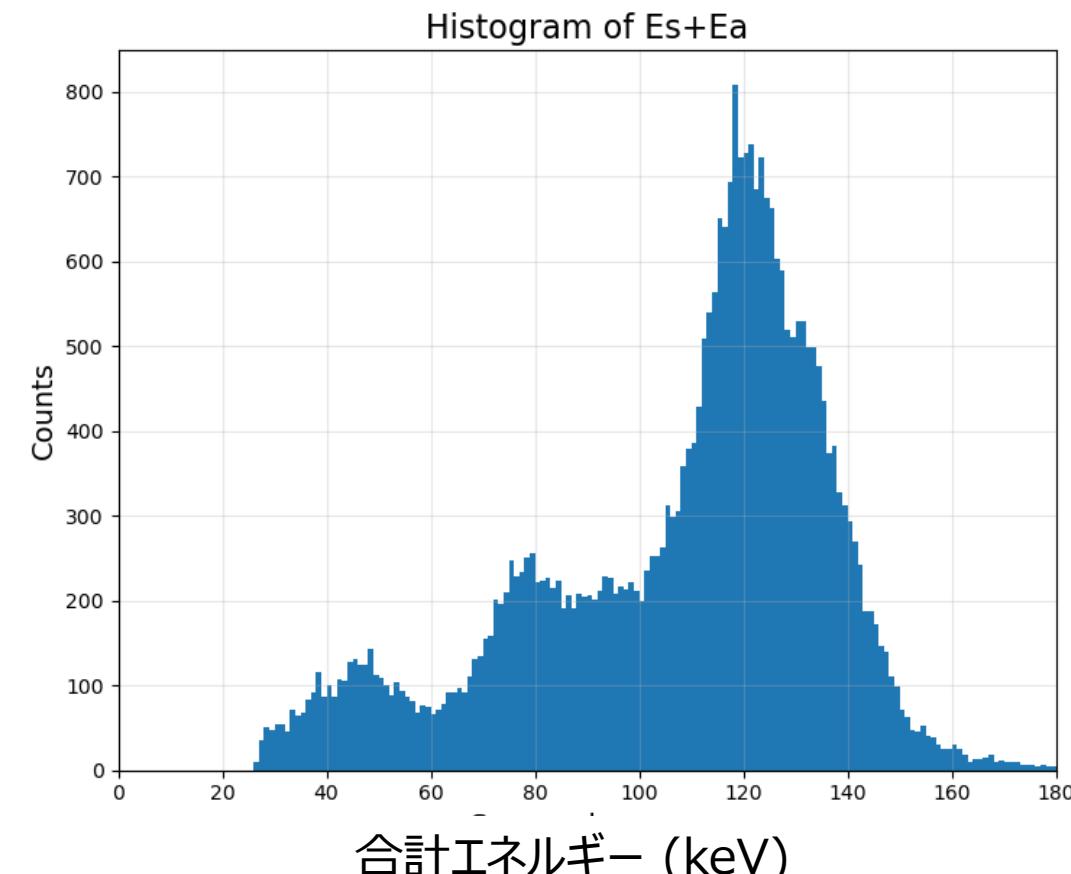
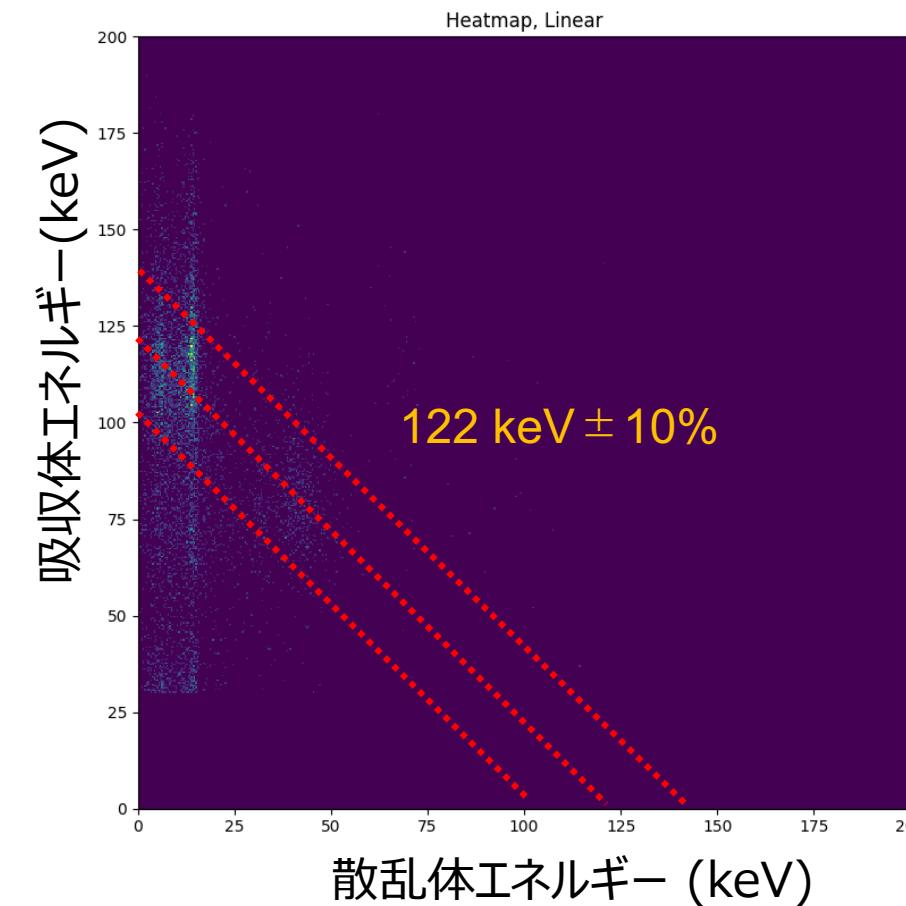


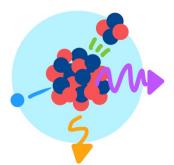
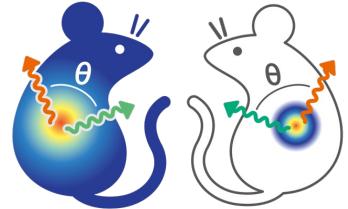


XR11-GAGGコンプトンカメラ



Es + Ea 合計エネルギースペクトル



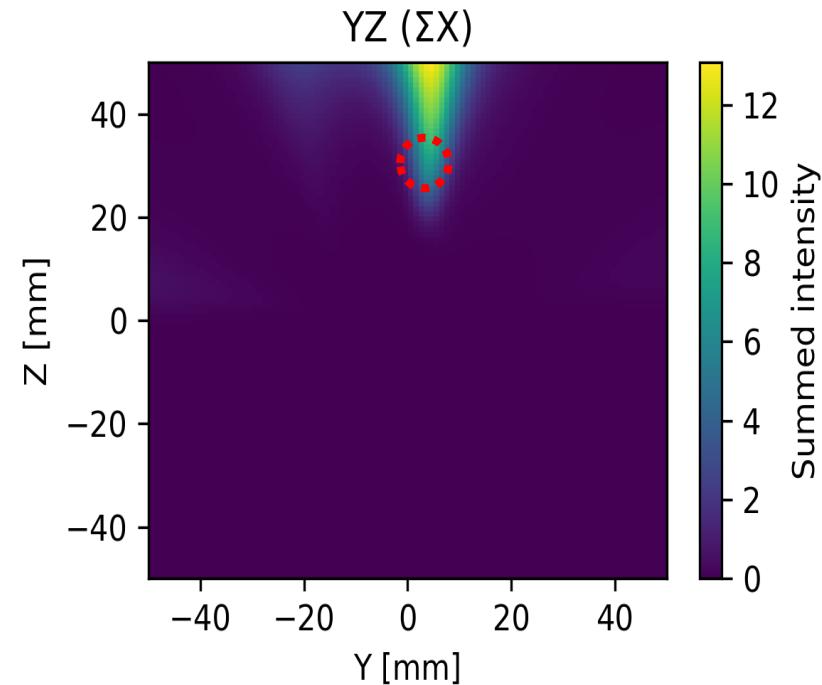
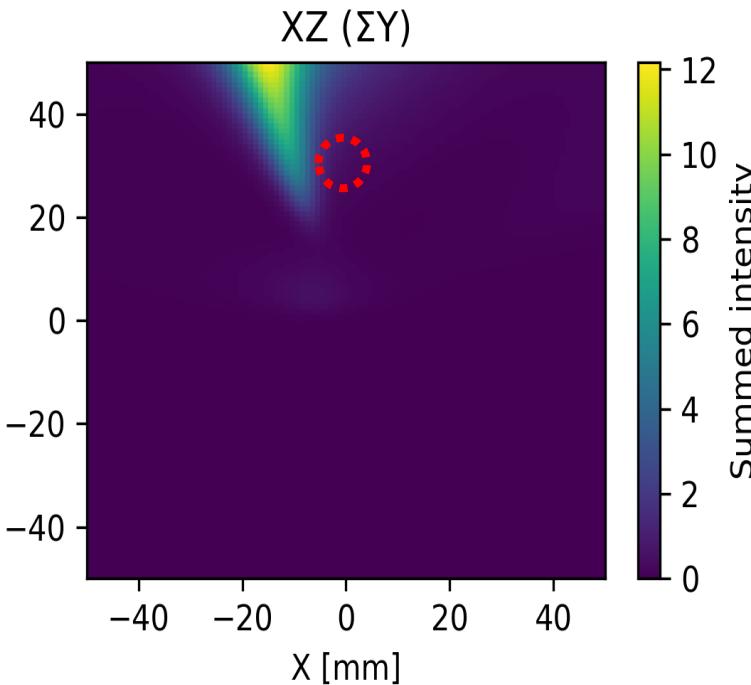
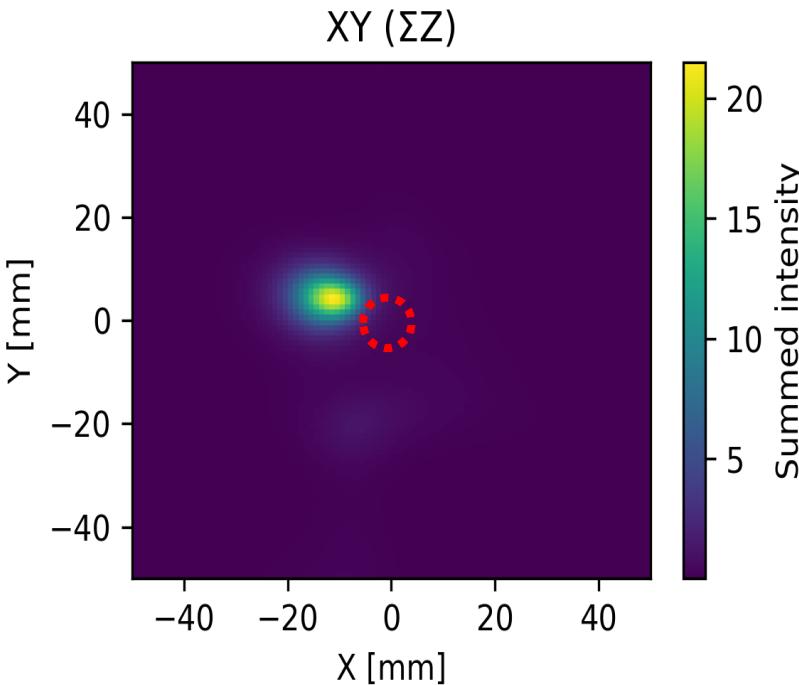


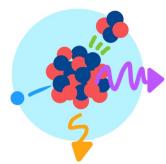
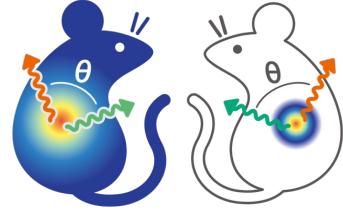
XR11-GAGGコンプトンカメラ



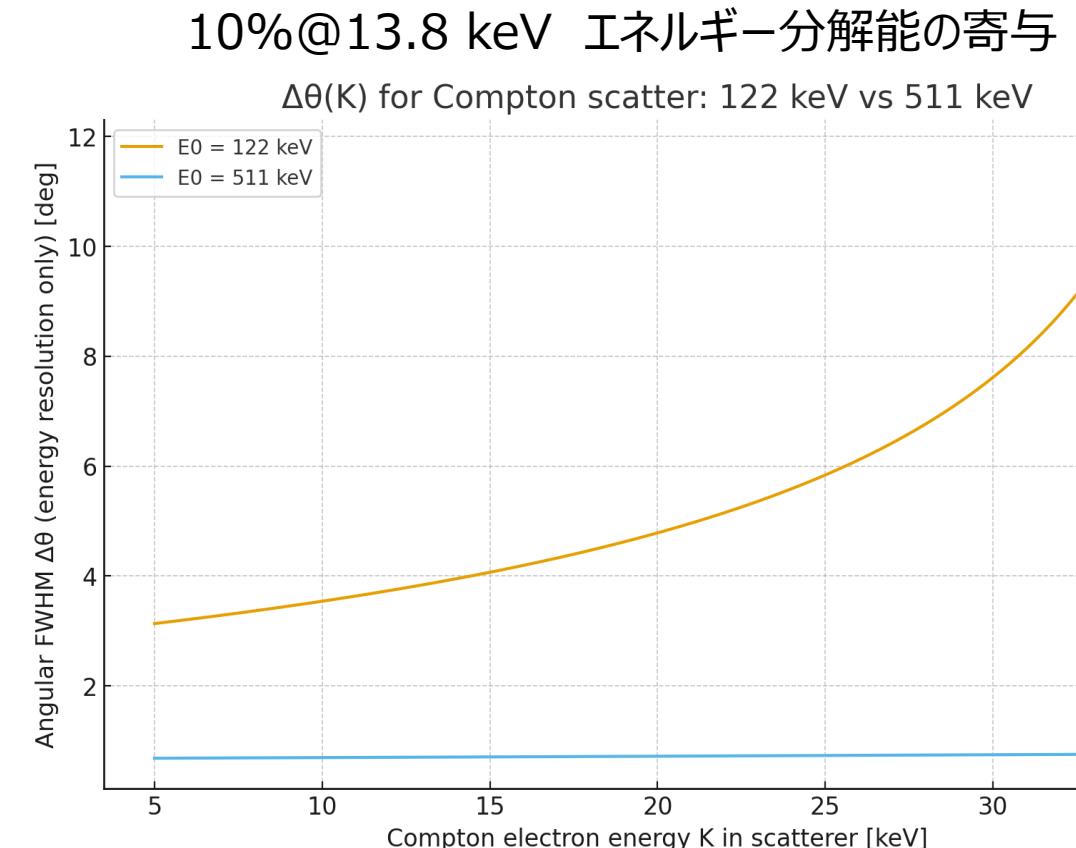
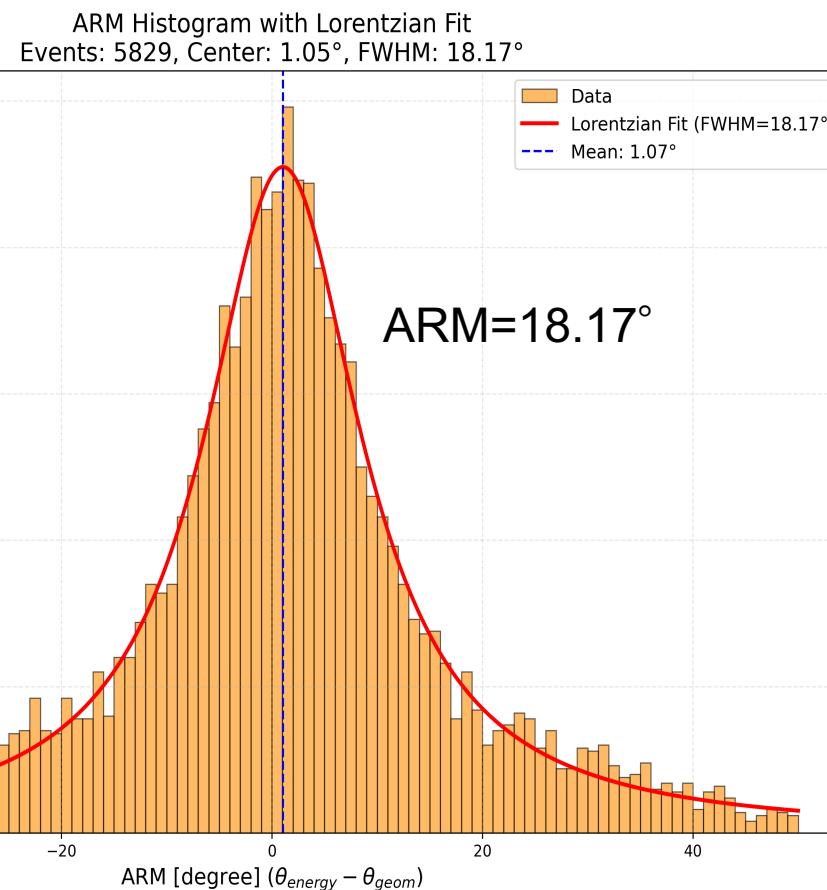
再構成条件（カスケード放射除外）

- $5 \text{ keV} < E_{\text{sc}} < 12.6 \text{ keV}, 15.4 \text{ keV} < E_{\text{sc}} < 30 \text{ keV}$
- $E_{\text{sum}} = E_{\text{sc}} + E_{\text{abs}} = 122 \text{ keV} \pm 10\%$

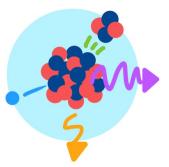
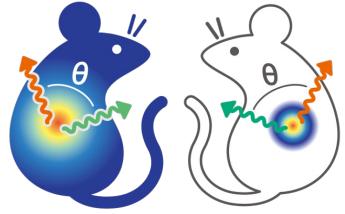




XR11-GAGGコンプトンカメラ



XR11素子で初めてのコンプトンカメラ画像を得た。(常温、完全空乏で動作)
今後電子トラッキング、他のエネルギーでの試験、分解能改善、in vivoへの展開を行う

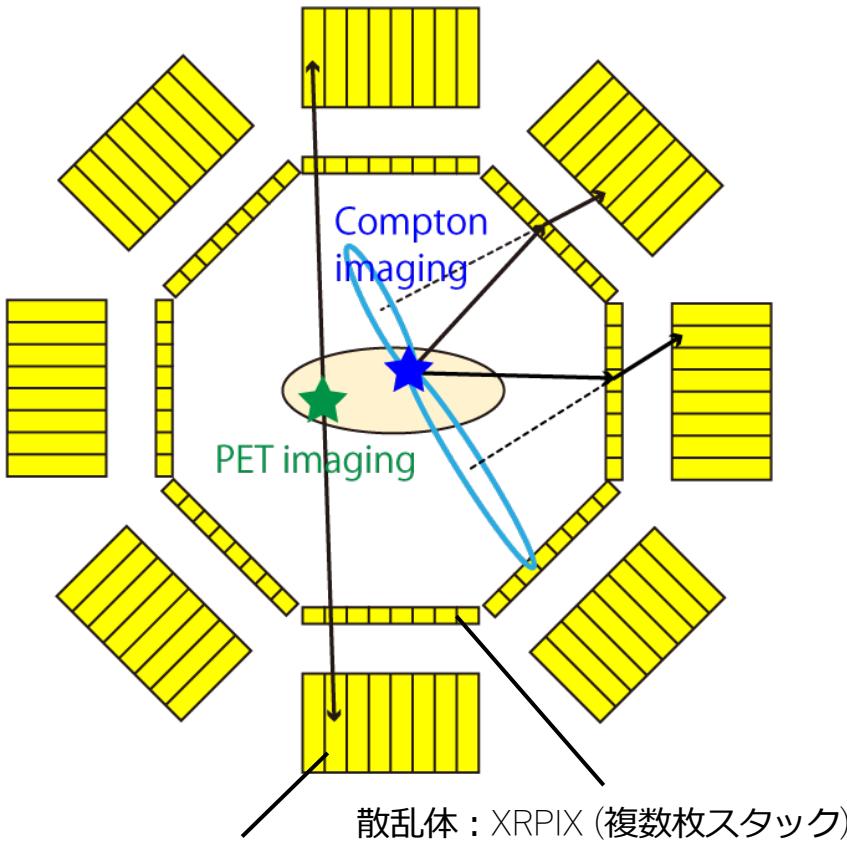


SOI-GAGGコンプトンカメラ



将来目標：リング型のイメージングシステムの構築

Compton-PET hybrid camera



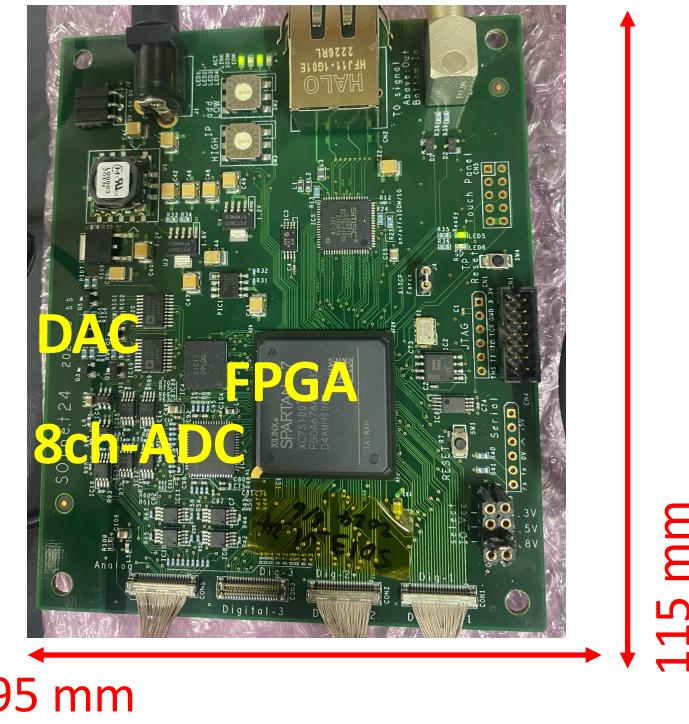
吸収体: GAGG検出器

チップ基板とDAQシステムの小型化（東大・佐藤）

XRPIXチップ基板



FPGA-based DAQ “SOInet”



- SOInet (XRPIXのDAQ) と PETnet (GAGGのDAQ) の同期が可能
- 8ch-DACを搭載、極細同軸ケーブルで信号・設定電流/電圧を伝達