Evaluation of Timepix3 for applications as a Compton scatter polarimeter for hard X- and soft γ-rays

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Outline

- Motivation for X-ray polarimetry
- Timepix3
- Experiment setup
- Compton X-ray polarimetry
- Compton camera
- Conclusions

Hard X-ray polarimetry - Motivation

- A useful tool in study of the most extreme environments in Universe – neutron stars, accretion discs or gamma ray bursts
- Not many hard X-ray polarimetry (> 10 keV) measurements in astrophysics
- Hard X-rays are created close to the compact sources in **the strong gravitational and magnetic fields**
  - synchrotron, cyclotron and curvature radiation are polarized
- Polarization data would test and constrain existing astrophysical models

Source	Expected polarization (10-100 keV)	Measured
BH XRB	~5 %	
AGN	~10 %	
X-ray pulsar	Low 10^1 %	Crab pulsar ~22 %
Accret. pow. pulsar	≤ 30 %	
Pulsar wind nebula	~20-30 %	Crab nebula ~17.4 %
Solar flares	~35-50 % max.	~8-40 %

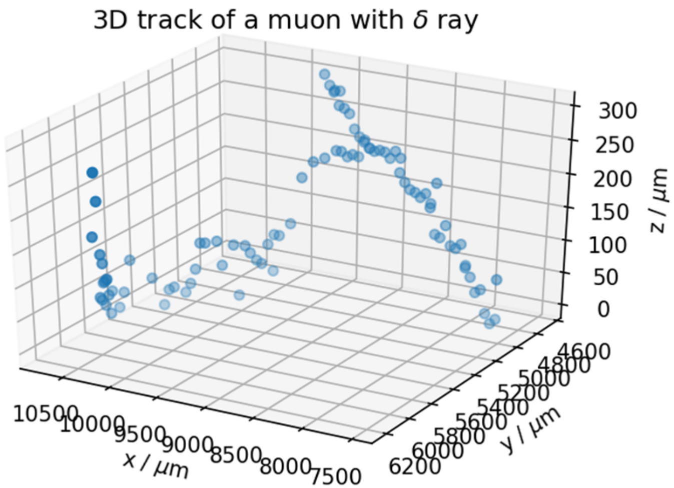
Chattopadhyay, T. *Hard X-ray polarimetry—an overview of the method, science drivers, and recent findings*. J. Astrophys. Astr. (2021)

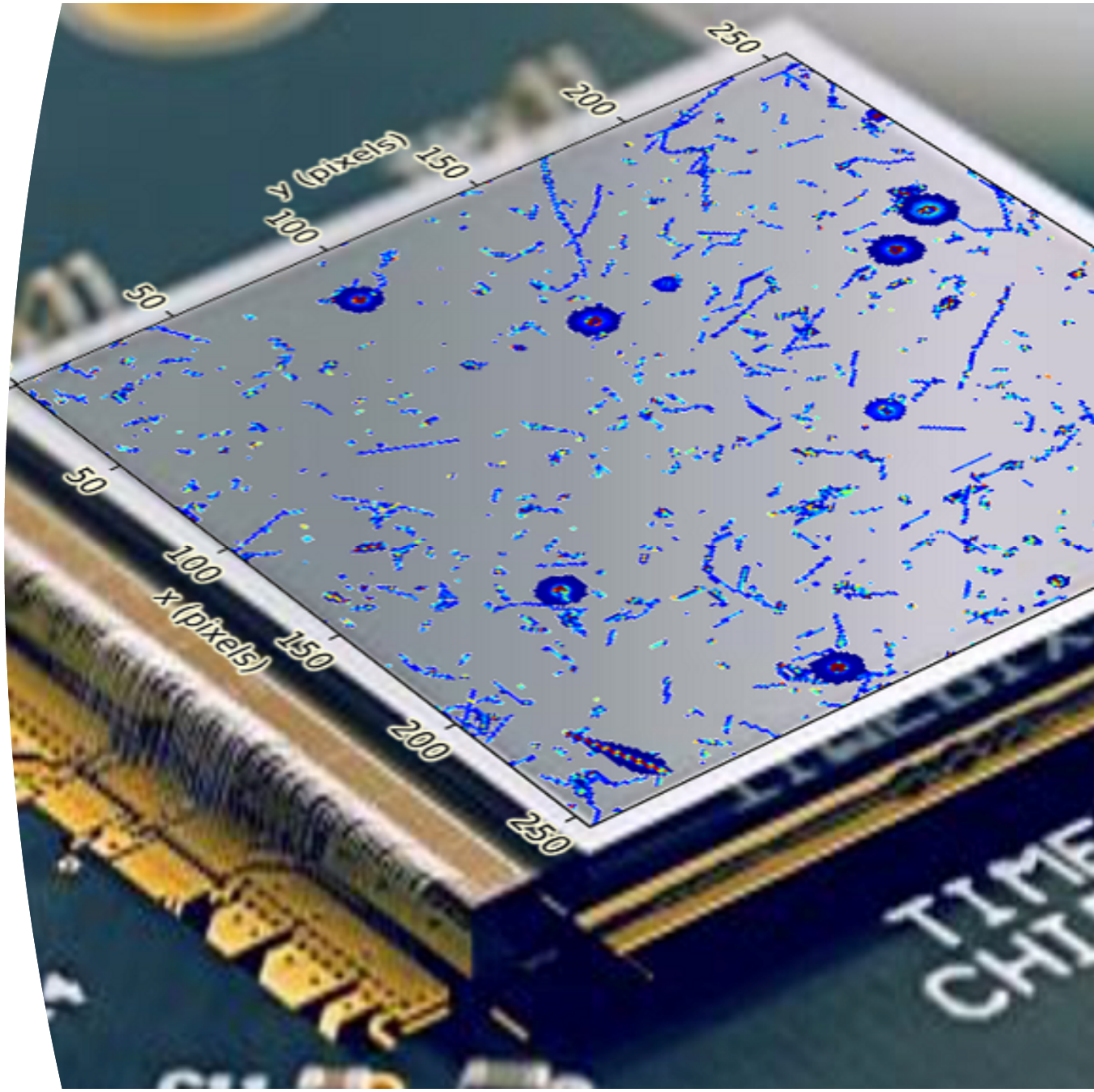
Goals

- Characterize Timepix3 with 1 mm thick Si sensor as a Compton polarimeter to detect linear polarization
- Perform Compton camera imaging using the same data set → Use the geometry of Compton cones to improve polarization measurements

Timepix3

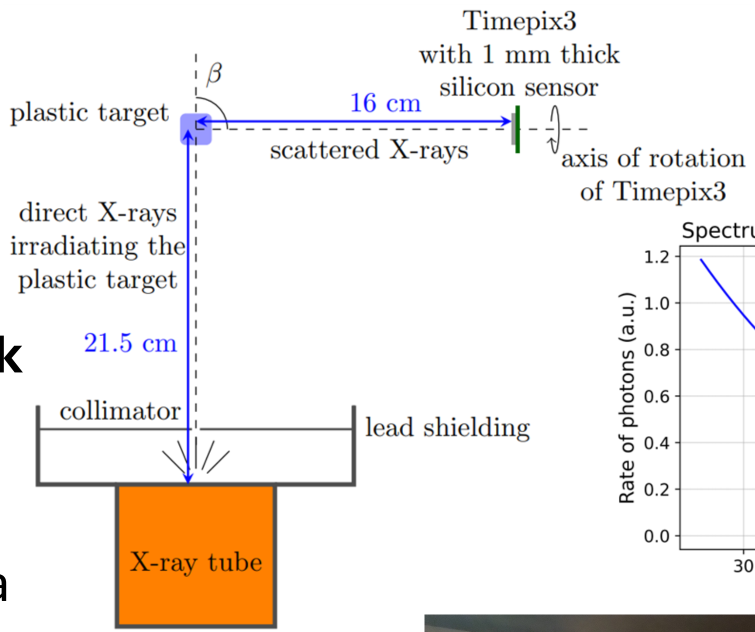
- 256x256 pixel matrix, pixel pitch 55 μm
- Measures simultaneously deposited energy and time of arrival (ToA)
- ToA precision 1.56 ns
- Capability of 3D location reconstruction

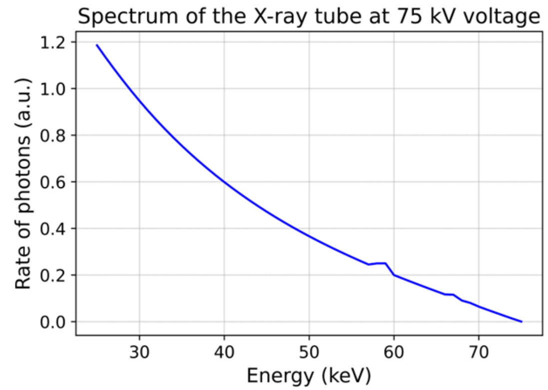


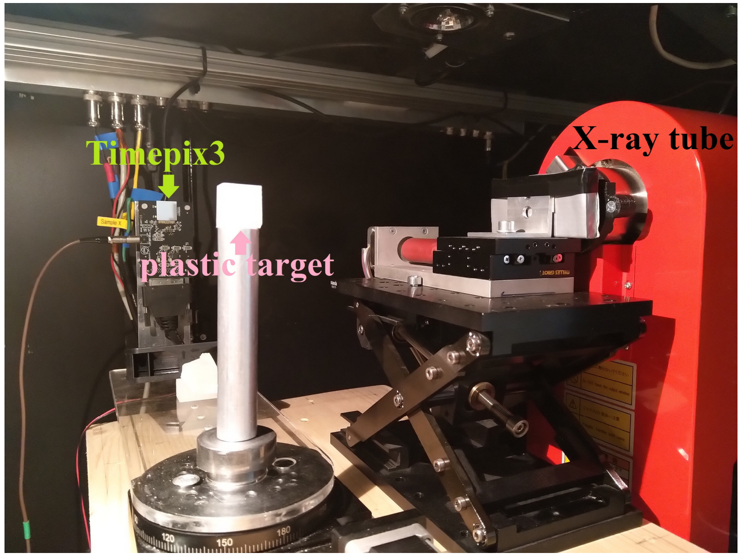


Experiment

- Detector: Timepix3 with **1-mm thick silicon sensor**, bias voltage 400 V
- X-ray tube at voltage 75 kV
- Photons from X-ray tube scatter in a polyethylene target 2x2x2 cm^3
- The scattered photons are polarized – the plastic target is **the source of polarized photons**
- Energy range of interest ~30-65 keV
- Measurements both with and without plastic target (background)







Compton polarimetry – How?

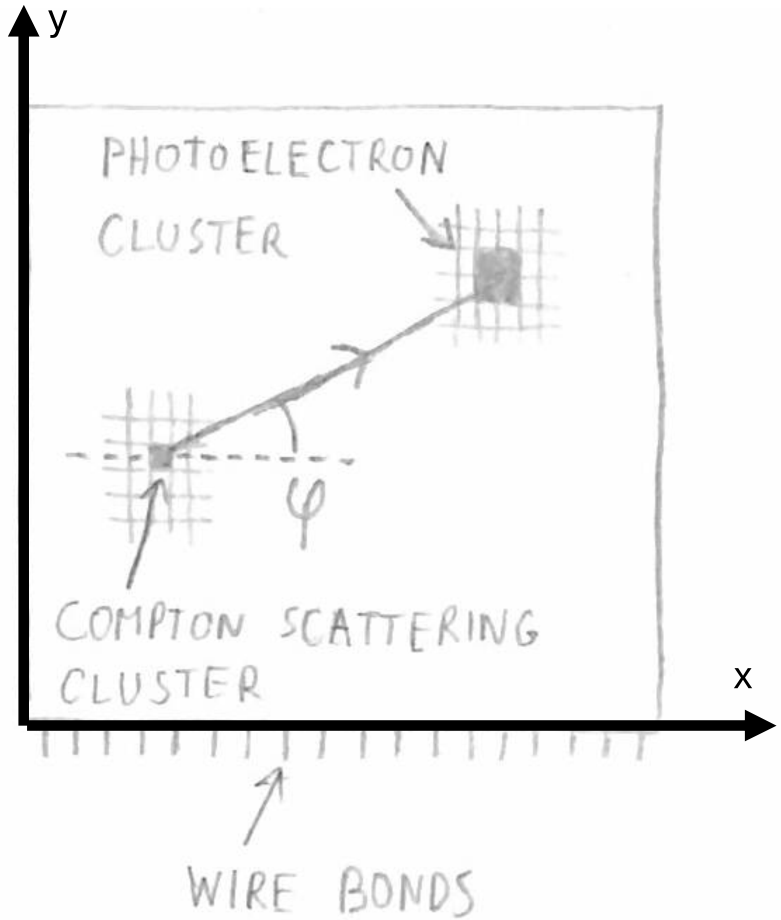
- The photon must interact **two times** in the sensor – Compton scatering followed by photoabsorption
- The distribution $f(\varphi)$ of azimuth scattering angles φ is modulated

  $$f(\varphi) \propto 1 + \mu \cos\big(2(\varphi - \varphi_0)\big)$$

  where μ is **modulation factor** and φ_0 is at 90° to the polarization plane
- **Degree of polarization** P is

  $$P = \frac{\mu}{\mu_{100}}$$

  where μ_{100} is modulation created by 100 % polarized radiation

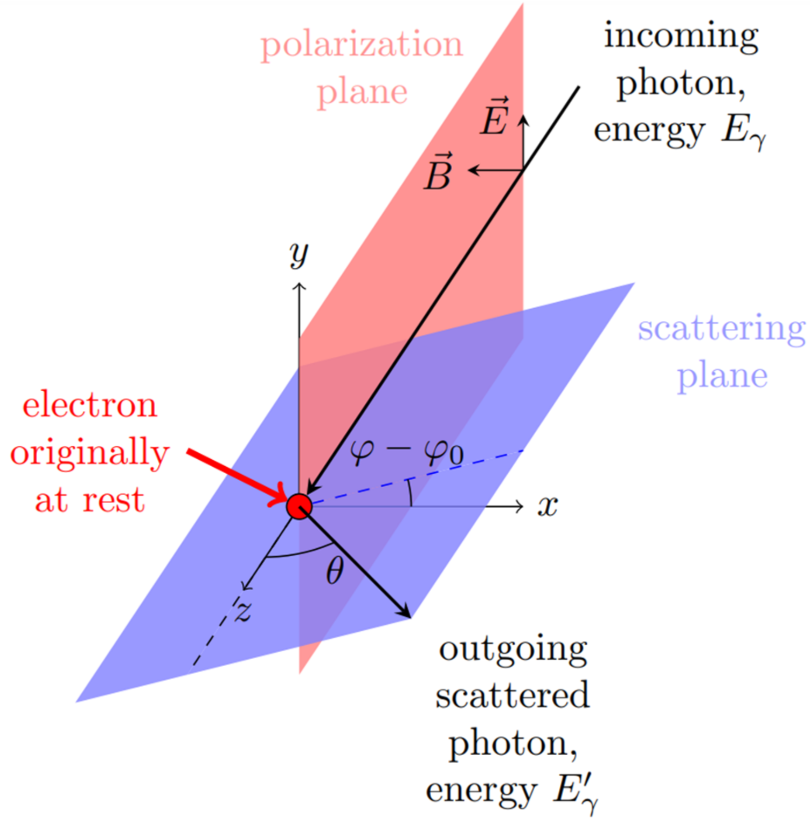


Data analysis

- Looking for coincident pairs clusters that arrived within **time window 65 ns**
- Compton scattering equation:

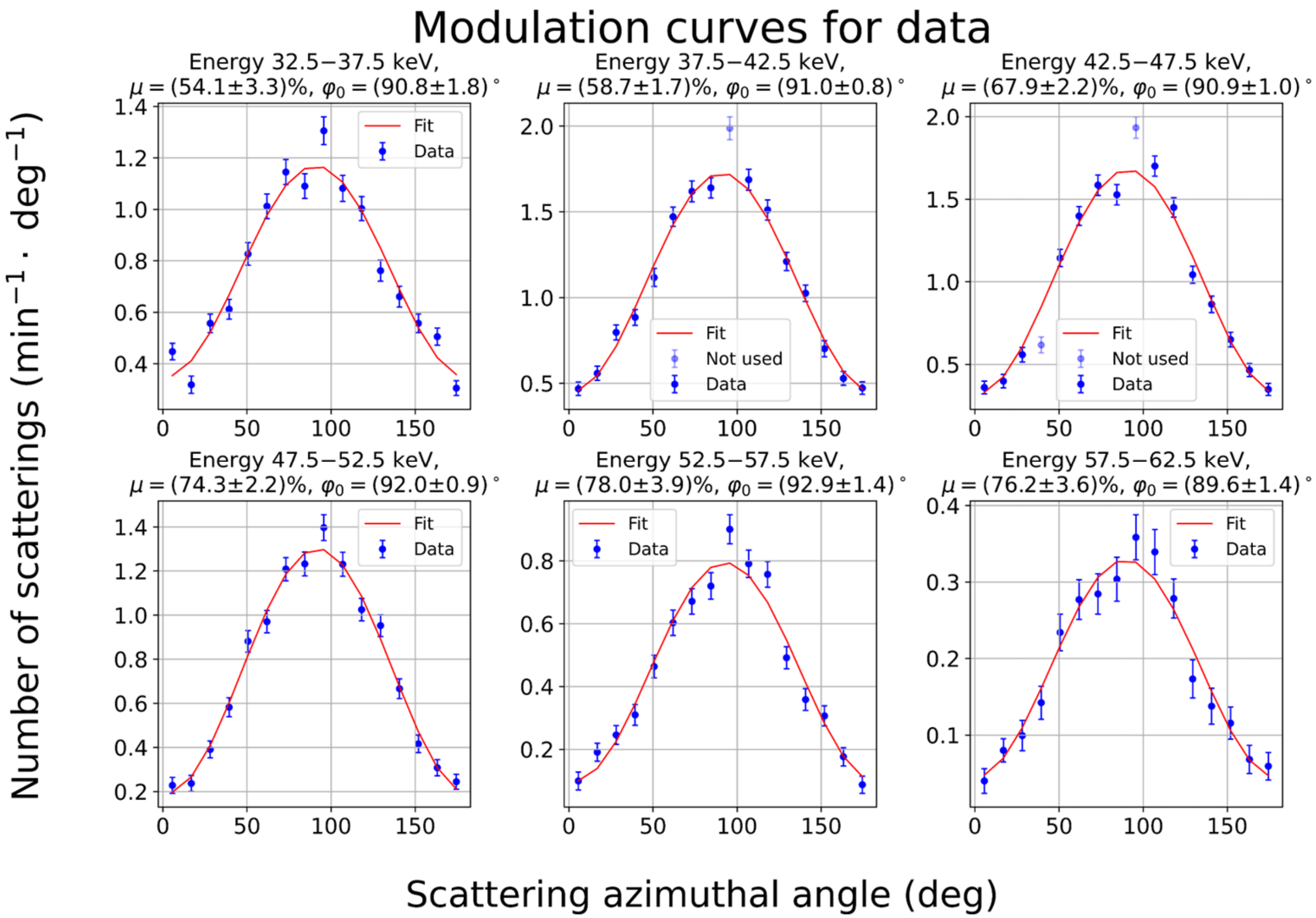
$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E'_\gamma} - \frac{1}{E_e + E'_\gamma} \right) \geq -1$$

  where E'_γ is the energy of photoelectron cluster and E_e is the energy of Compton electron cluster
- Calculate the azimuth scattering angle φ in sensor plane
- Subtract background and random coincidences histograms from the target histogram



Example of modulation curves

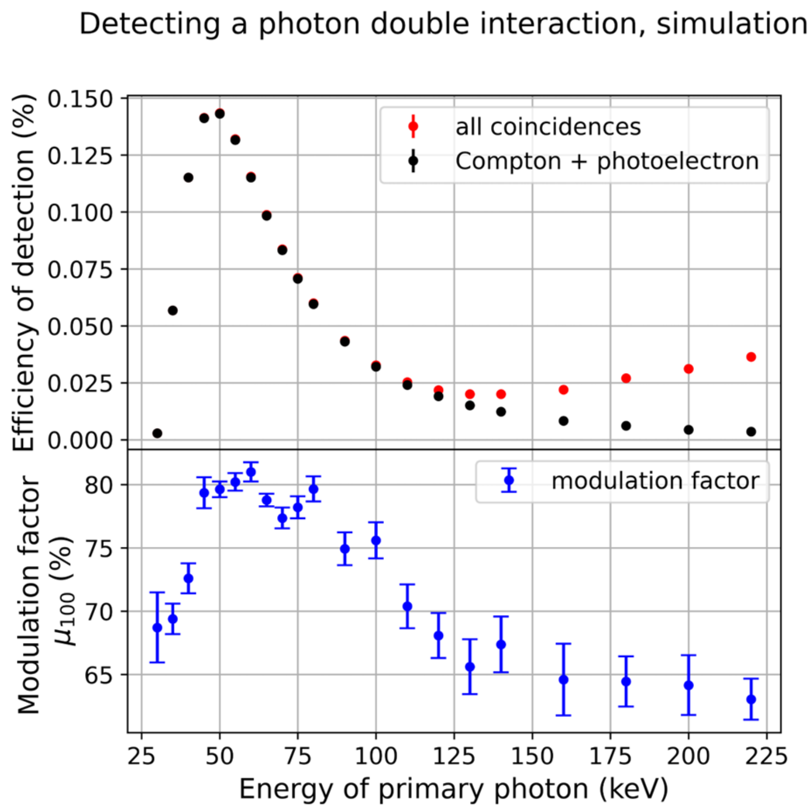
- Energy sensitive polarimetry
- **High modulation factor**
- In the figure: modulation factor 54 % at 32.5-37.5 keV; rising above 70 % at energies >47.5 keV



Simulation to get μ_{100}

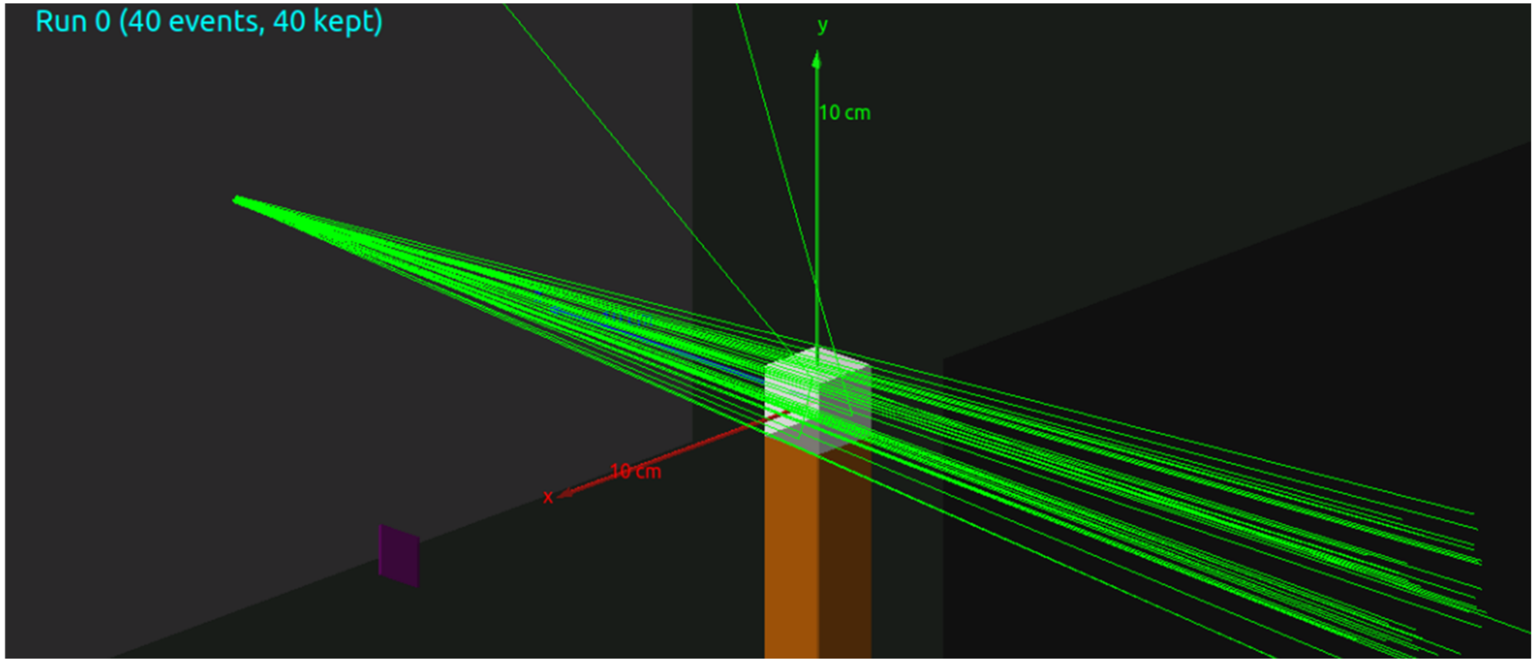
- **Monoenergetic X-ray beams** hitting uniformly the sensor area, **100 % linear polarization**
- Simulated energies 30-220 keV
- **We want to get the modulation factor** μ_{100} caused by 100 % polarized beam
- $\mu_{100} > 77$ % in range 45-80 keV, then decreasing to ~65 % at 200 keV
- Efficiency peaks above 0.14 % in range 45-50 keV

$$\text{eff.} = \frac{\text{number of detected coincident pairs}}{\text{number of photons hitting the sensor}}$$



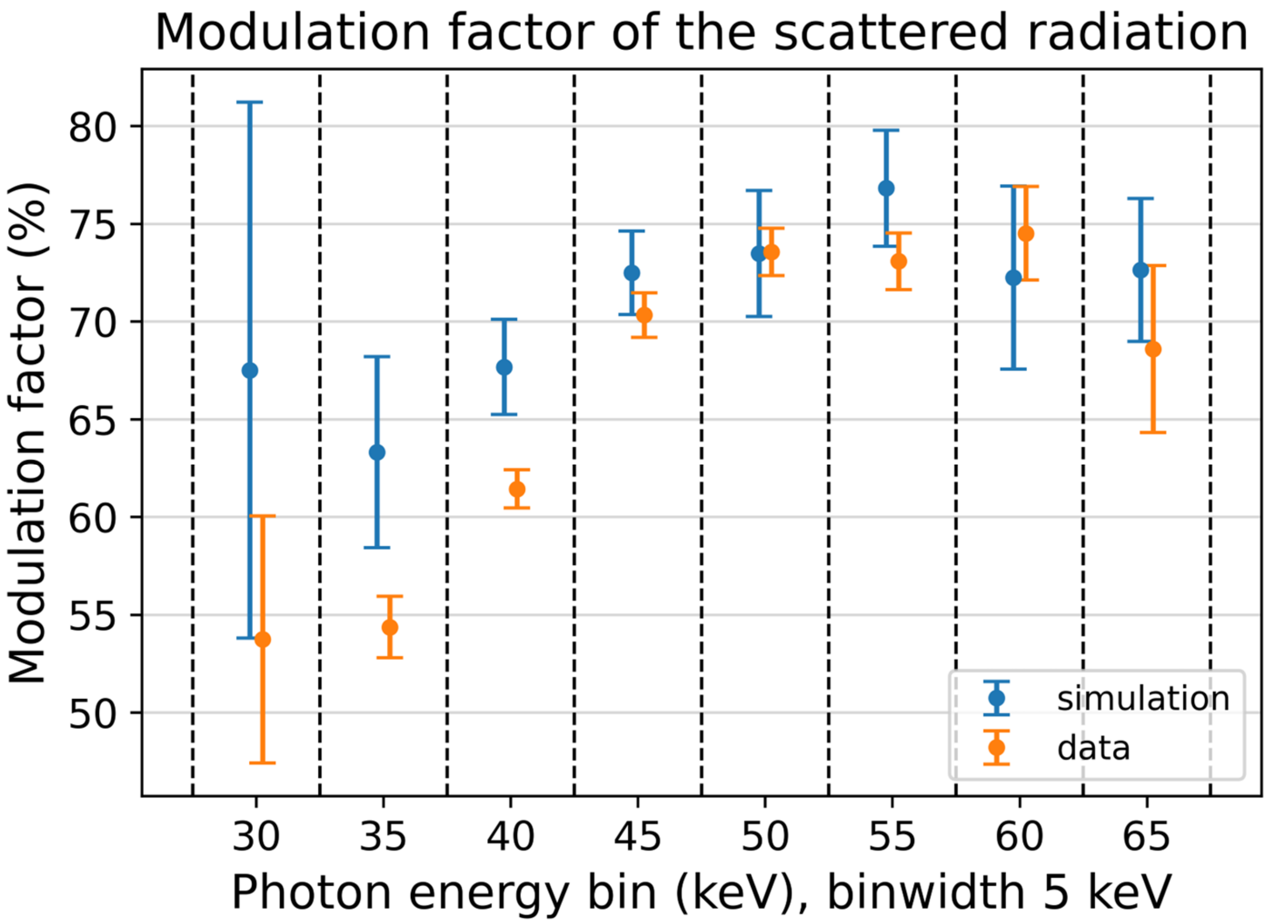
Simulation of the setup

- X-ray beam (same spectrum as X-ray tube) hits a polyethylene target **(white)**
- Scattered photons are detected in 1-mm thick sensor **(purple)**



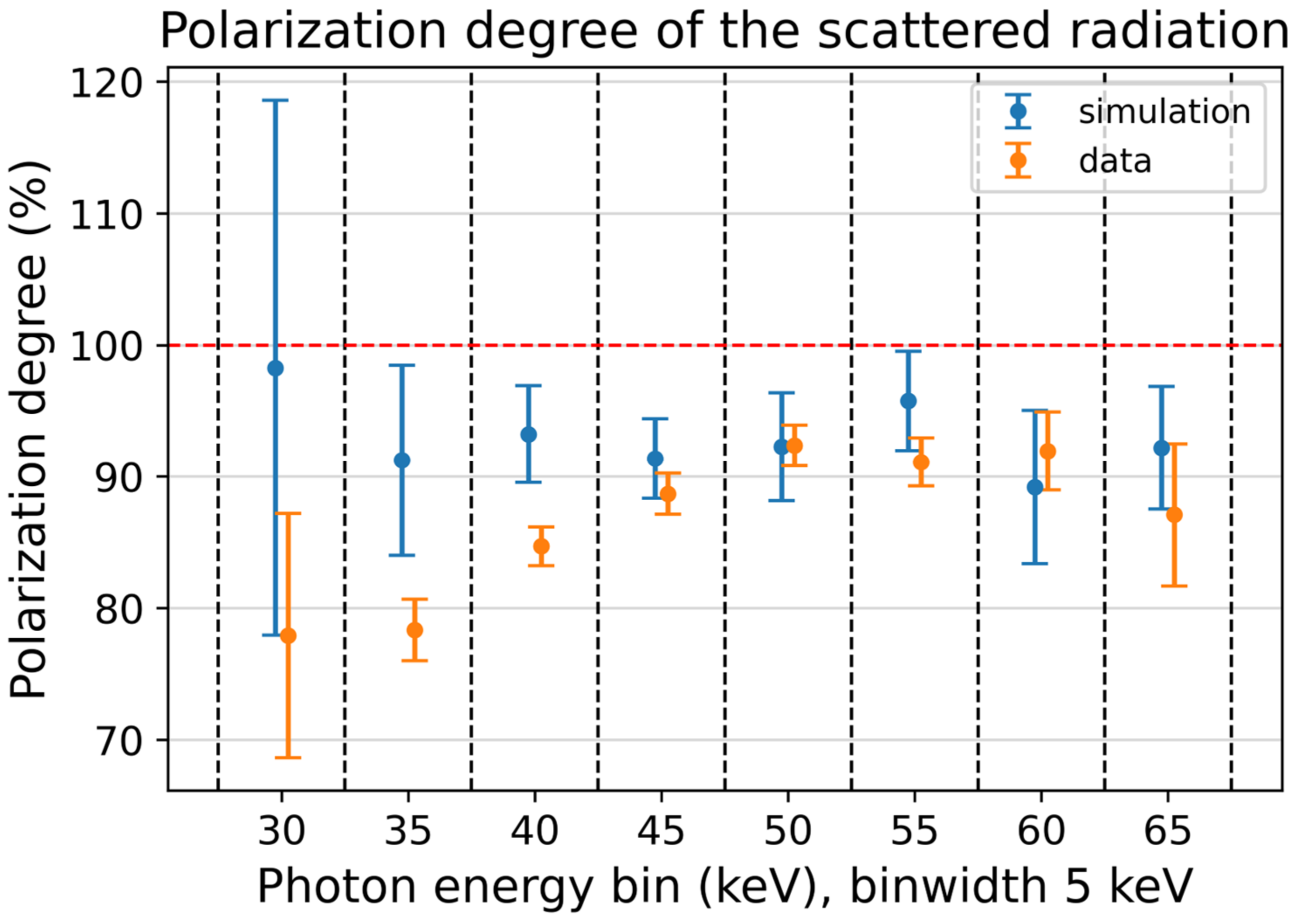
Comparison of simulation with experiment

- Consistent above 45 keV
- Modulation factor is lower in experiment compared to simulation below 45 keV
- *(Small shift in x-axis added to the data points, so that they do not overlap)*



Comparison of simulation with experiment

- Degree of polarization P is
$$P = \frac{\mu}{\mu_{100}}$$
where μ_{100} is modulation created by 100 % polarized radiation
- We use μ_{100} from the simulations of 100 % linearly polarized beams
- *(Small shift in x-axis added to the data points, so that they do not overlap)*

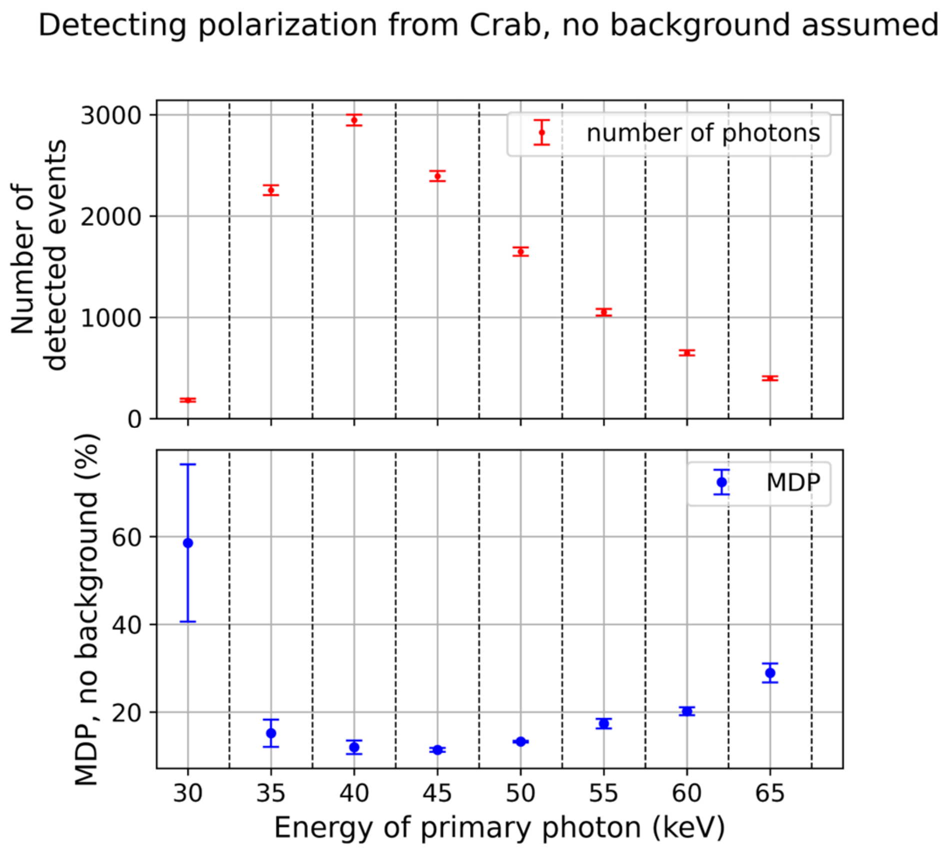


Hypothetical observation of Crab nebula

- 1-mm thick silicon Timepix3 in a focal plane of NuSTAR X-ray mirror, observation time 1,000,000 s
- Performance of polarimeter is quantified by **minimum detectable polarization**

$$\mathrm{MDP}_{99\,\%} = \frac{429\,\%}{\mu_{100} R_{src}} \sqrt{\frac{R_{src} + R_{bcg}}{T}}$$

  where R_{src} is the source rate, R_{bcg} is the background rate and T is measurement time
- Assuming **zero background rate** $R_{bcg} = 0$

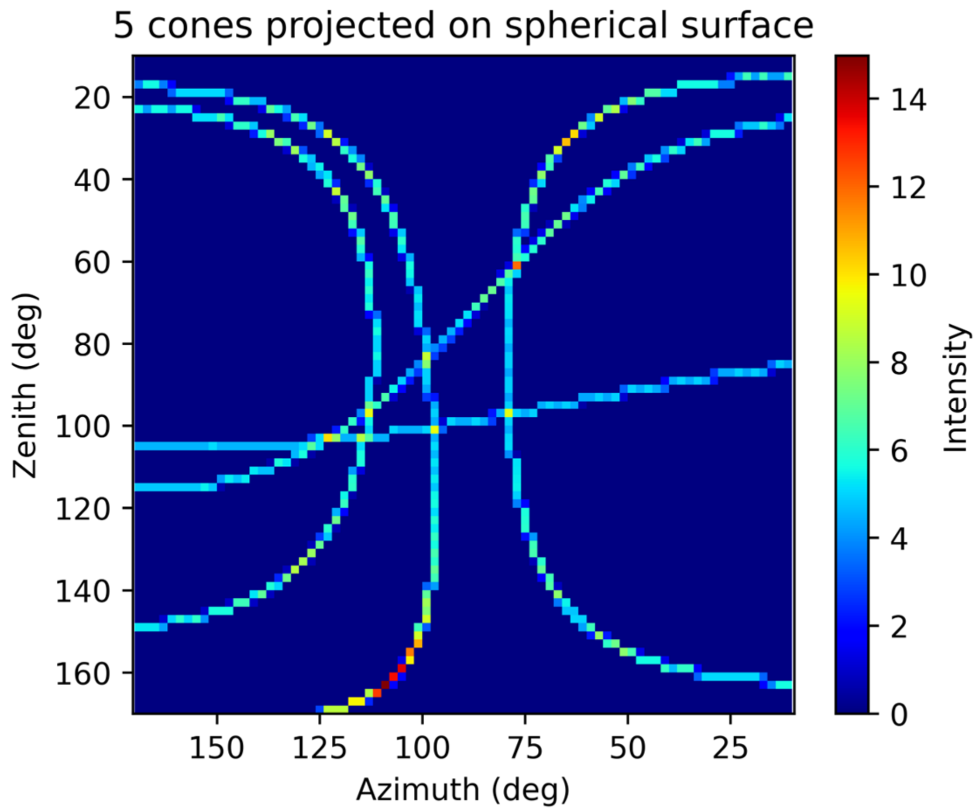


Compton camera

- **Same data set** as for Compton polarimetry – Compton scattering followed by photoabsorption
- We can calculate **opening half-angle of the cone** where the photon must have come from

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E'_\gamma} - \frac{1}{E_e + E'_\gamma} \right)$$

- We use pixel coordinates and ToA difference to get the **cone axis direction** – then we can project the cone



Origin ensemble with resolution recovery

- We used **origin ensemble with resolution recovery** (OE-RR) for image reconstruction
- **Monte Carlo Markov chain method**
- Each photon is assigned a random initial direction, those directions are then updated one by one
- Change of initial direction is accepted or rejected based on likelihood function
- This method **takes into account measurement uncertainties**
- A for loop over all photons = 1 sweep

Compton camera images after 1500 sweeps

- **Images of the plastic target** in coordinate system connected to the detector

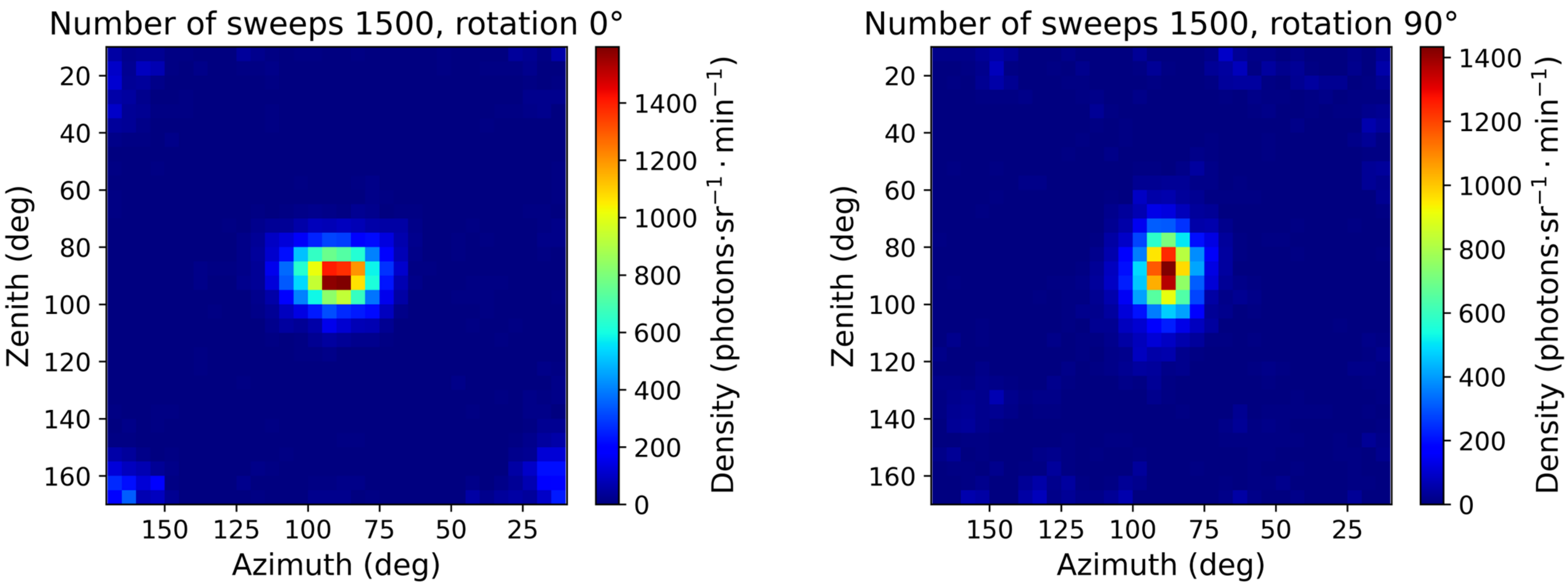
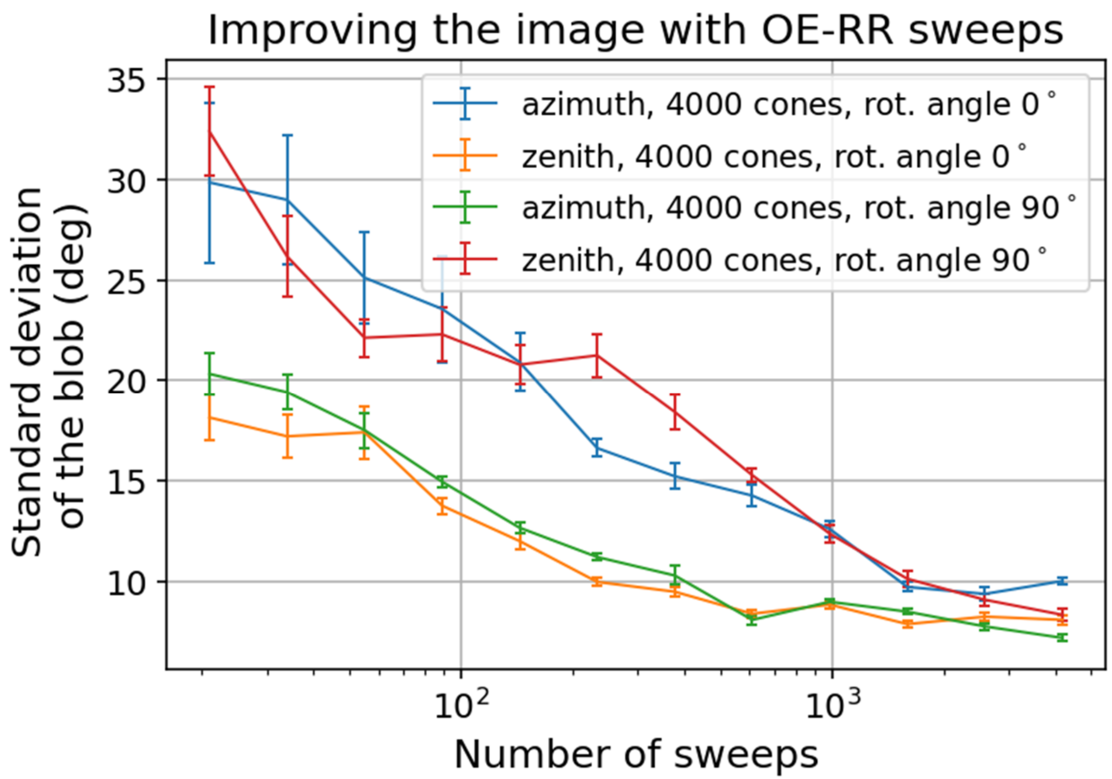


Image size with number of sweeps

- Standard deviation of the image stabilizing at $\sigma_I = 8°\text{-}10°$ after around 1500 sweeps
- Angular radius of the plastic target $\rho \approx 4° \rightarrow$ smearing is
  $$\sigma_S = \sqrt{\sigma_I^2 - \rho^2} = 7°\text{-}9°$$
- **FWHM of the imaging method** estimated to be
  $$\text{FWHM} = 2.36\sigma_S = 16°\text{-}21°$$



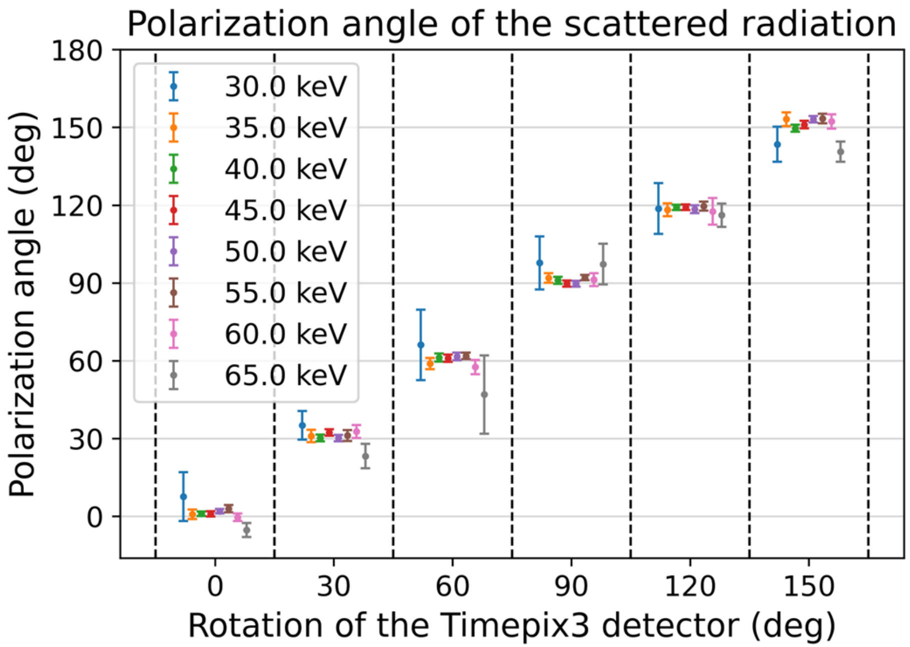
Conclusions

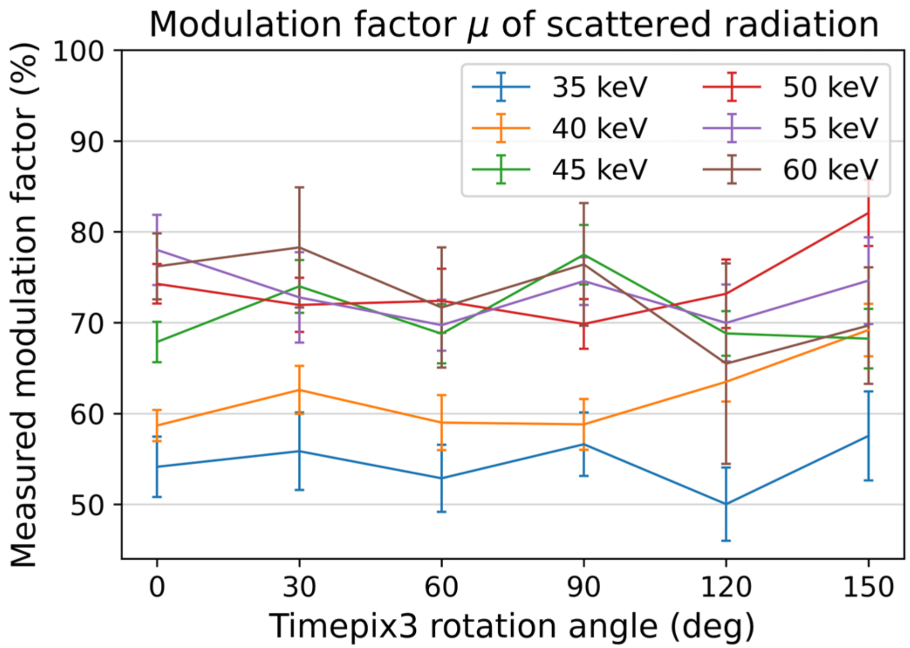
- Timepix3 offers high modulation factor μ_{100} → simulations show above 77 % in range 45-80 keV
- Efficiency of coincident pair detection peaks above 0.14 % at 45-50 keV
- Experiment with X-ray tube at voltage 75 kV → simulation and experiment are consistent in range 45-65 keV
- Compton camera imaging with OE-RR algorithm → we achieved FWHM 16°-21° after more than 1500 sweeps

Thank you for your attention

Rotation around target-Timepix3 axis

- We want to confirm that the modulation curve is static in the laboratory frame
- Results are consistent

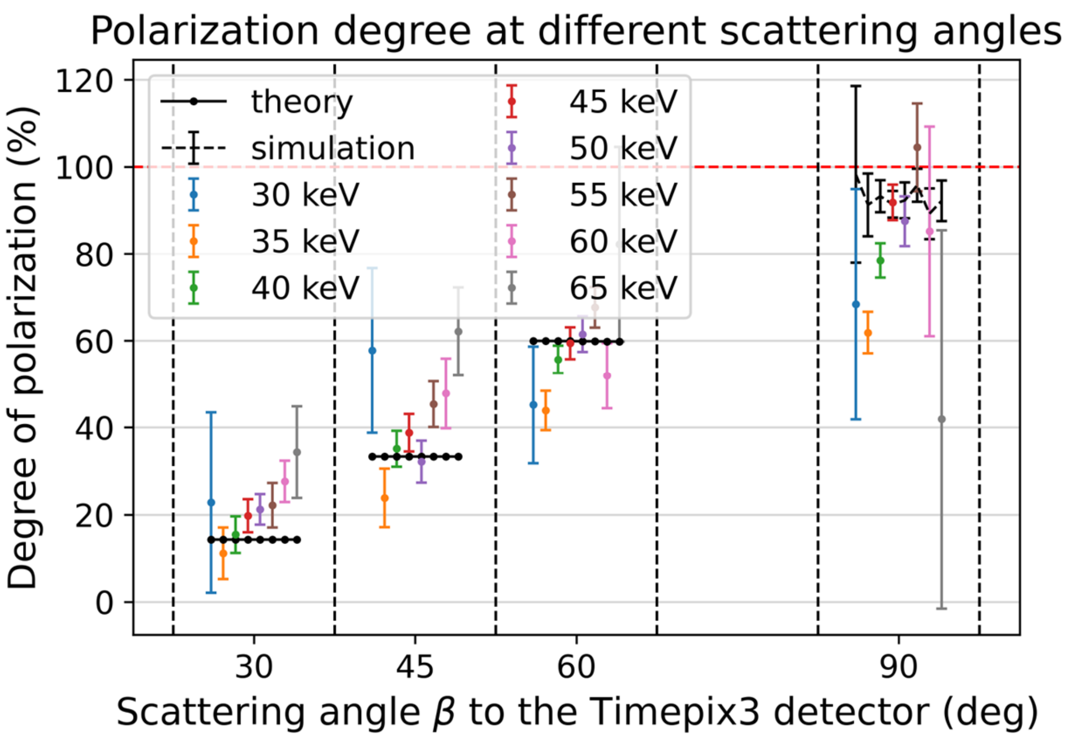




Polarization at different scattering angles

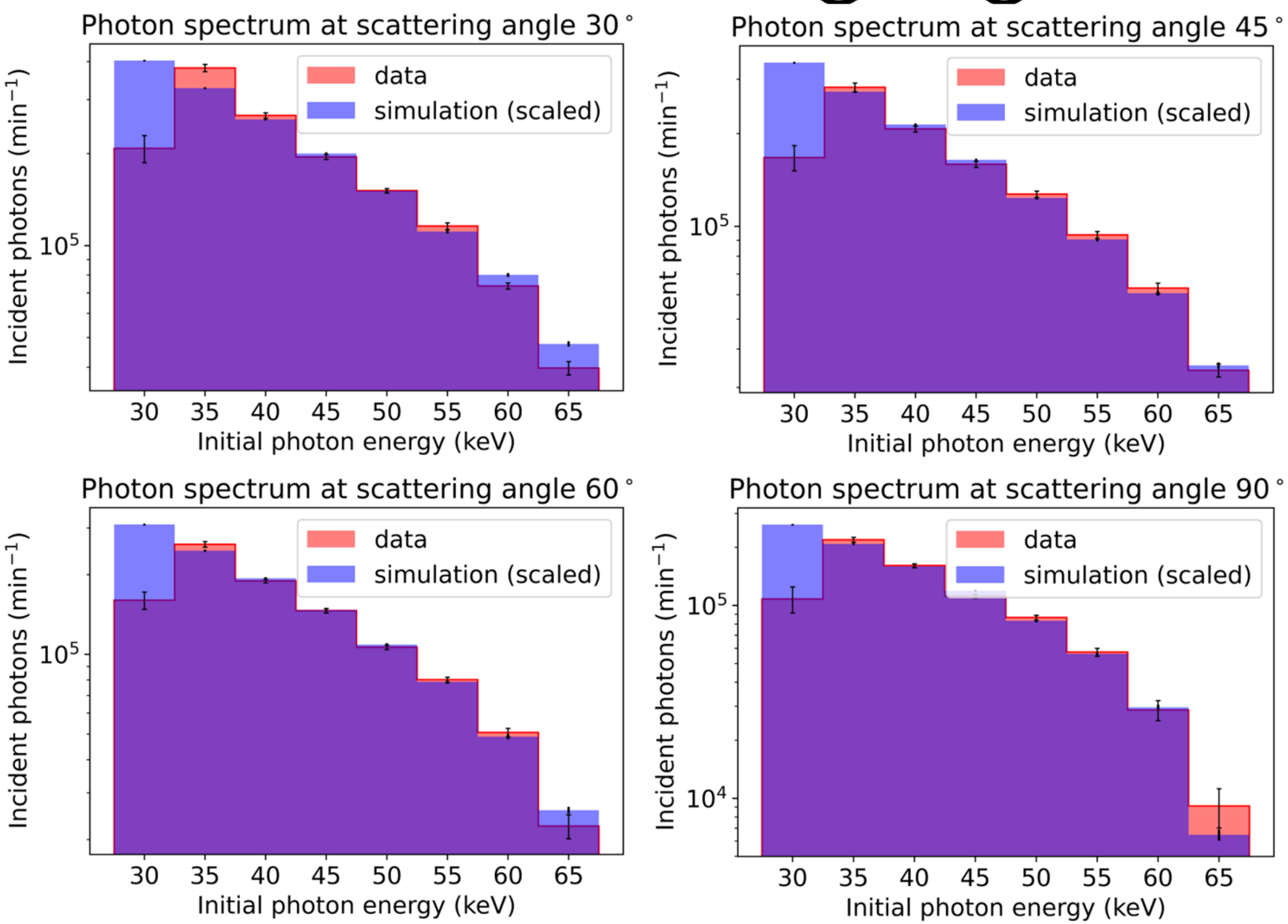
- We did measurements at scattering angles 90°, 60°, 45°, 30° to see how the degree of polarization decreases
- Unpolarized photons of energy E_γ scattering at angle θ carry degree of polarization

$$P = \frac{\sin^2\theta}{\frac{E'_\gamma}{E_\gamma} + \frac{E_\gamma}{E'_\gamma} - \sin^2\theta}$$

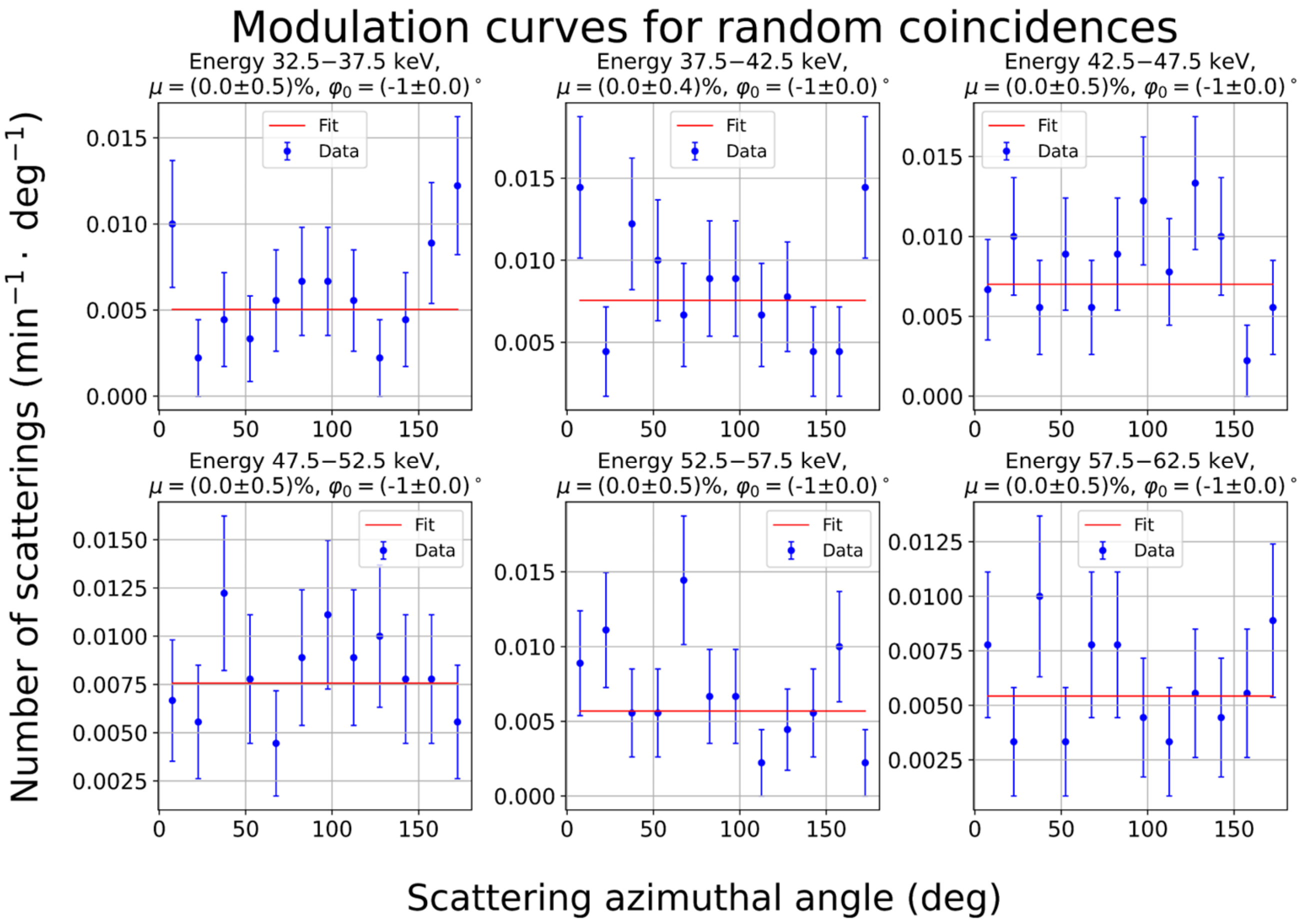


Energy spectrum at different scattering angles

- Using the efficiency from simulation, we can reconstruct the spectrum of photons hitting the sensor
- Good agreement of data with simulation

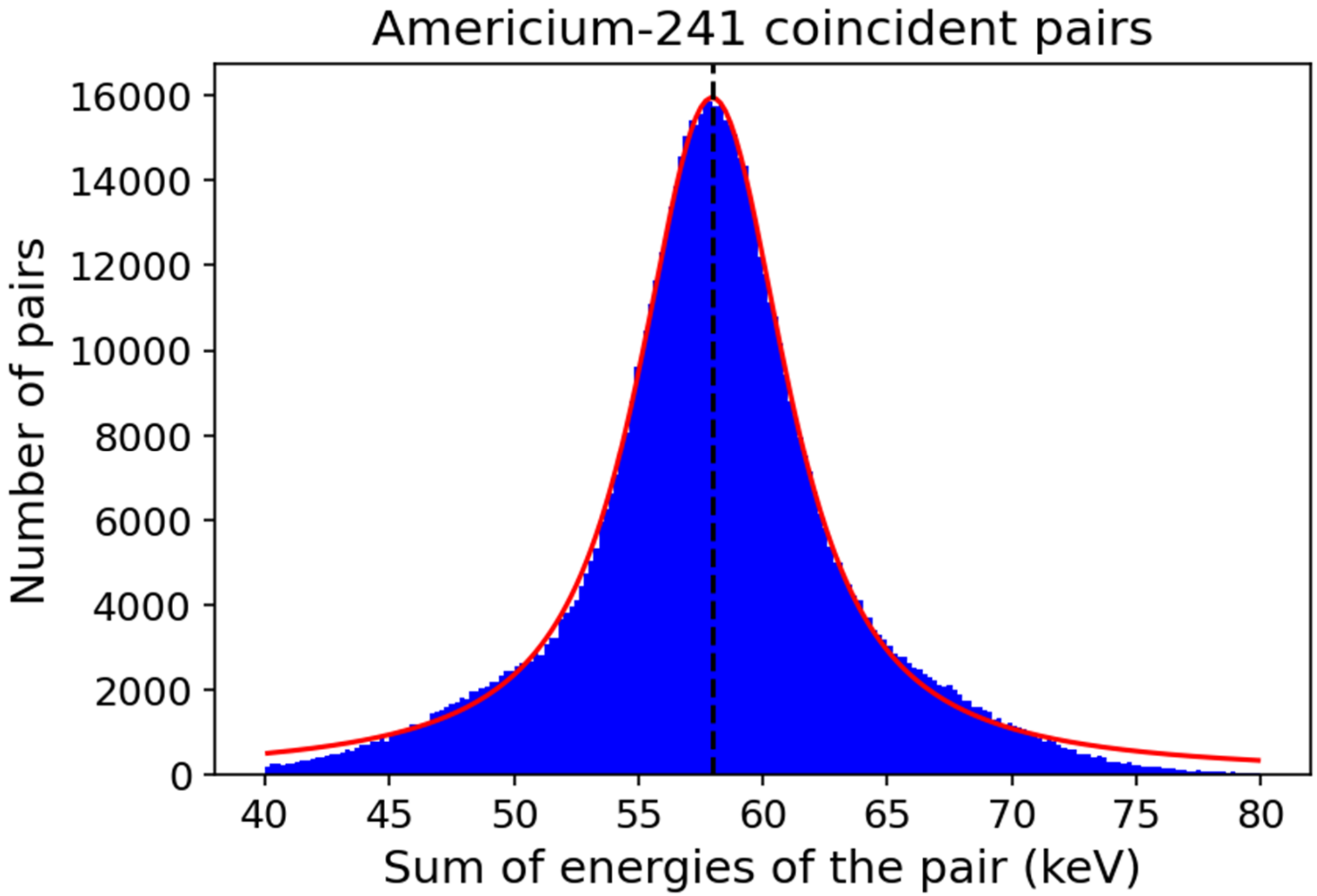


Random coincidences histogram

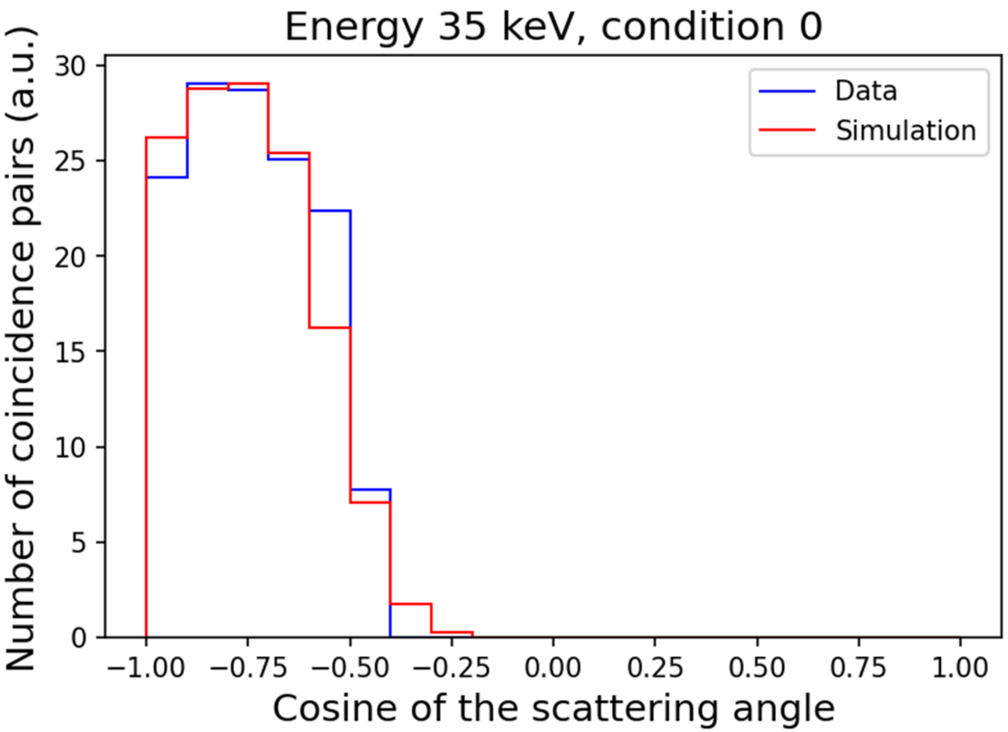


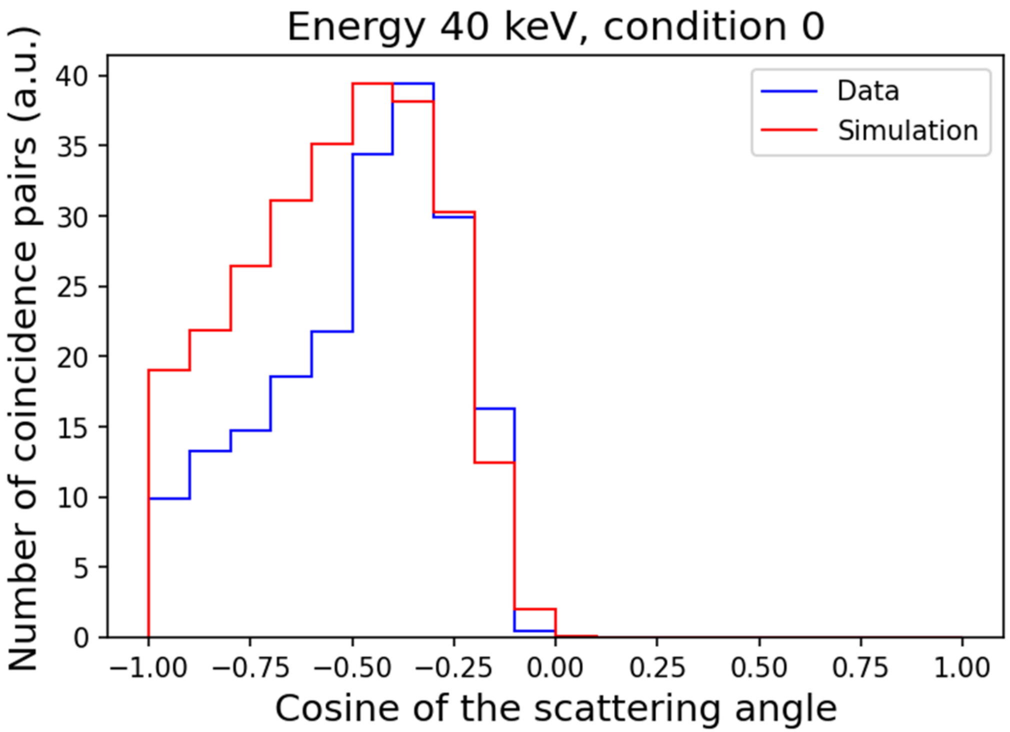
Americium-241 measurement

- Gamma peak: 59.54 keV
- Measured peak: 57.96 keV
- Measured peak 97.3 % of the expected peak

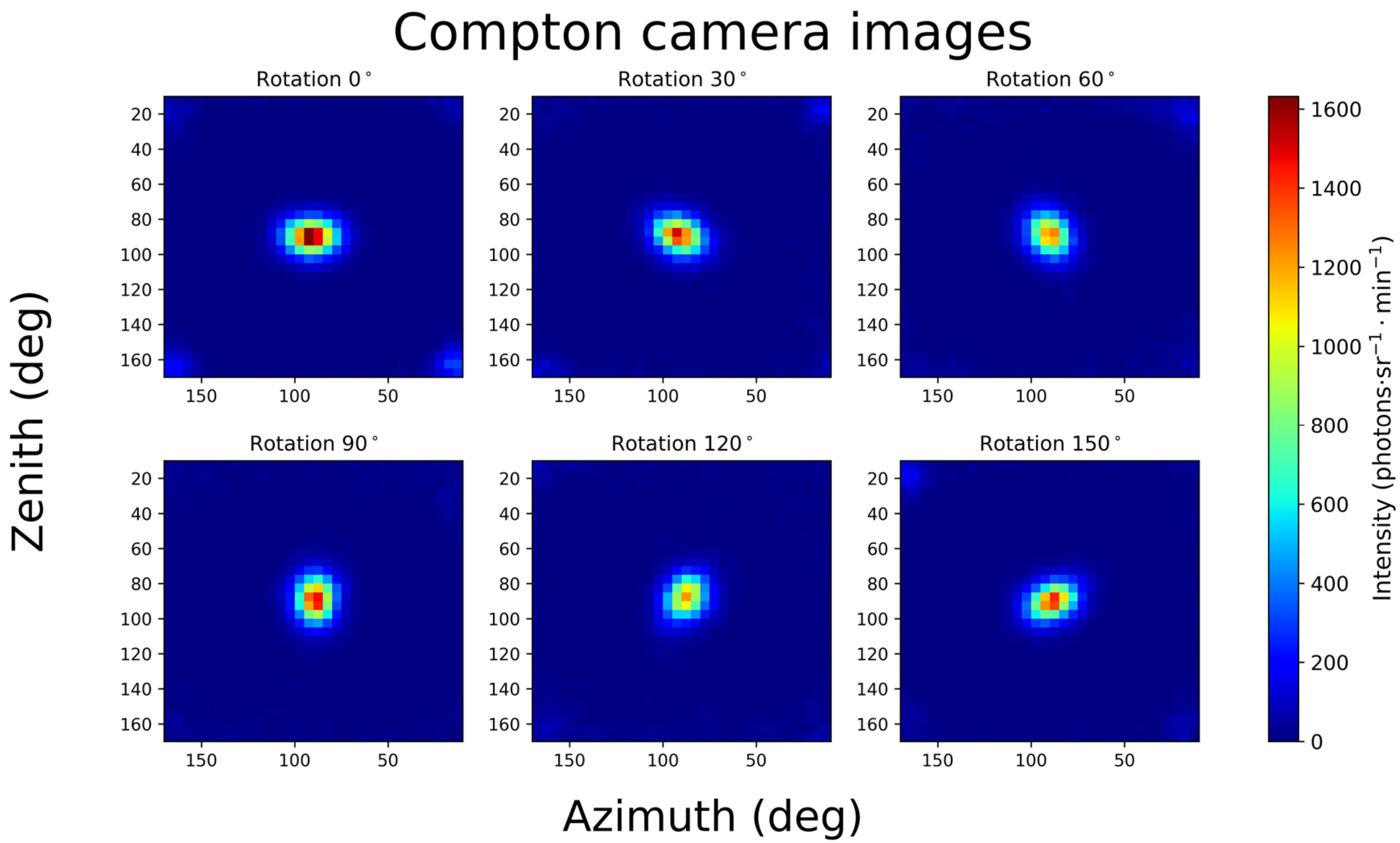


Cosines of scattering angles

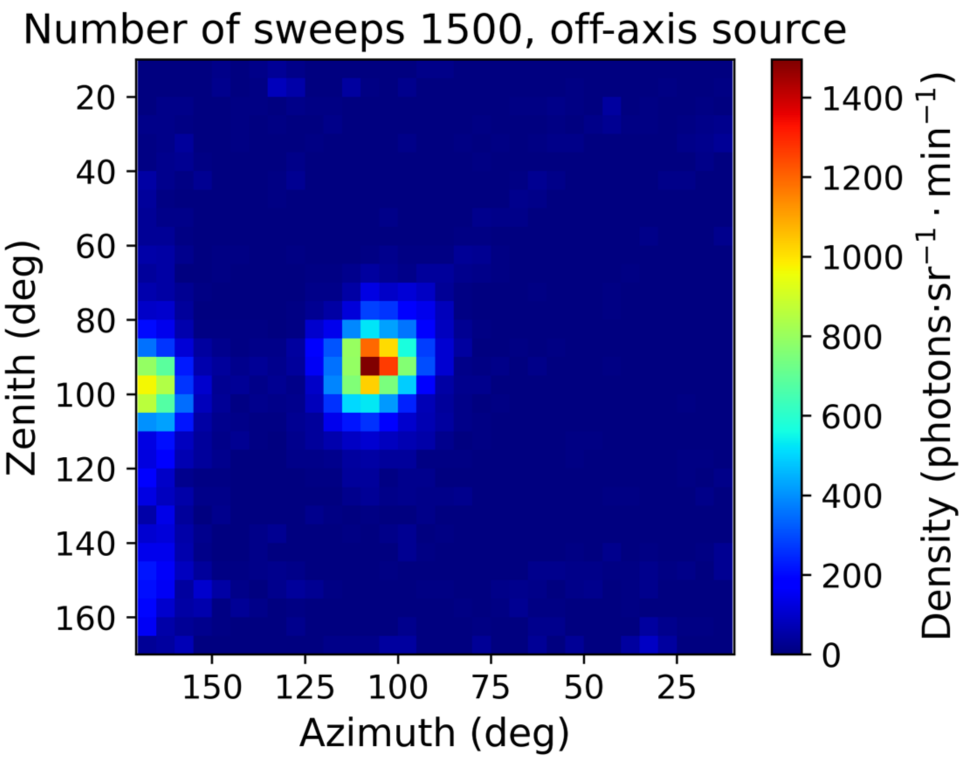


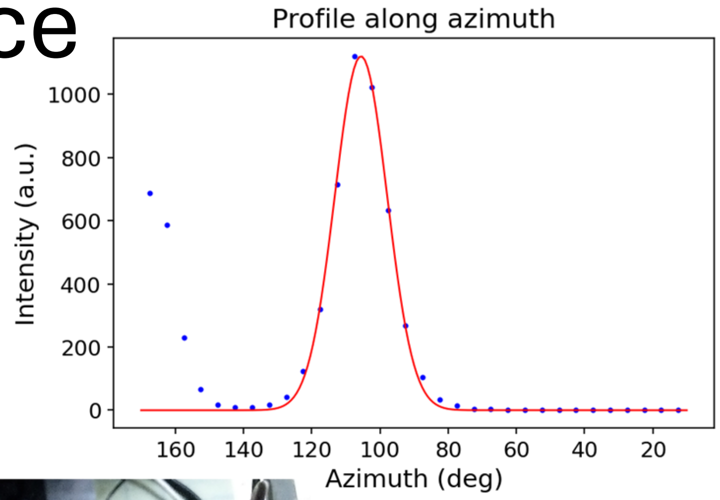


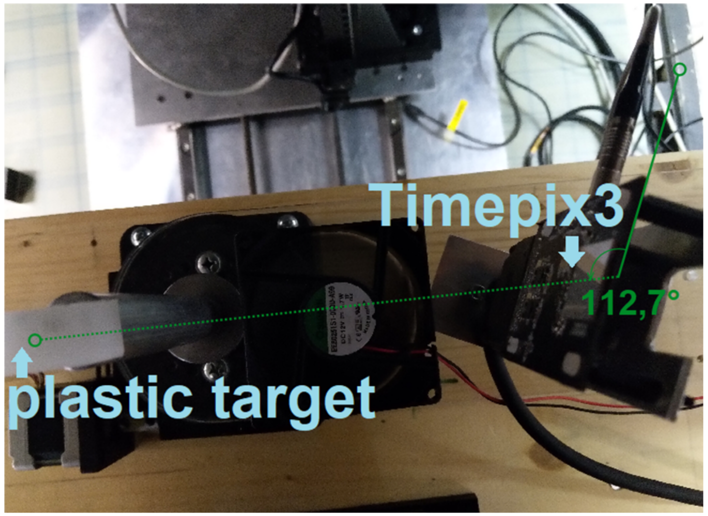
6 reconstructions averaged, 1500 sweeps



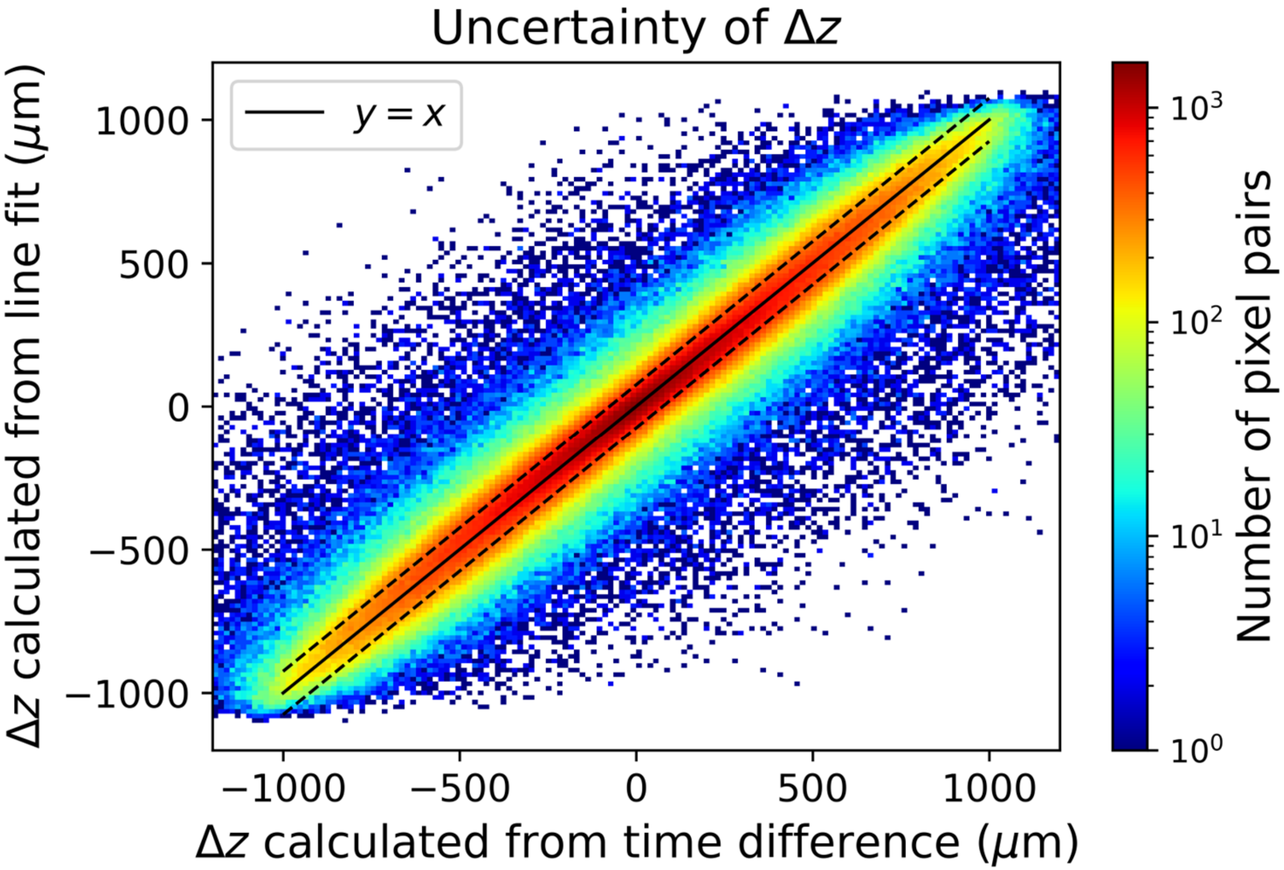
Compton camera: off-axis source







Uncertainty of height difference



Energy uncertainty