Latest results from the IKP Compton camera

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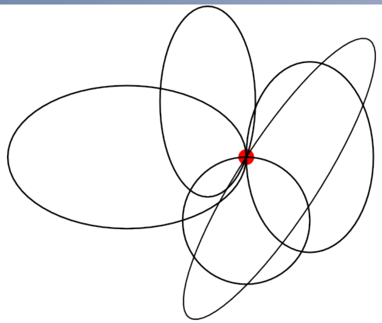
B. Weiler, M. Winkel
E12, TU München

12.09.2017

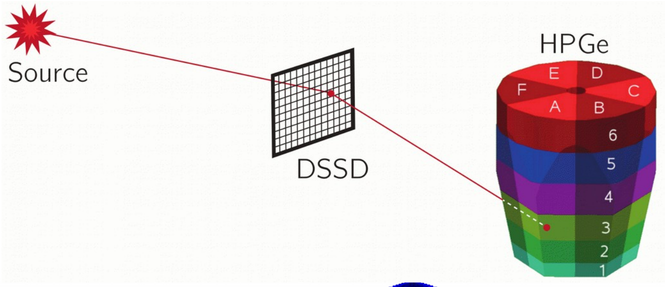
PSeGe workshop, Milano, 2017

Overview

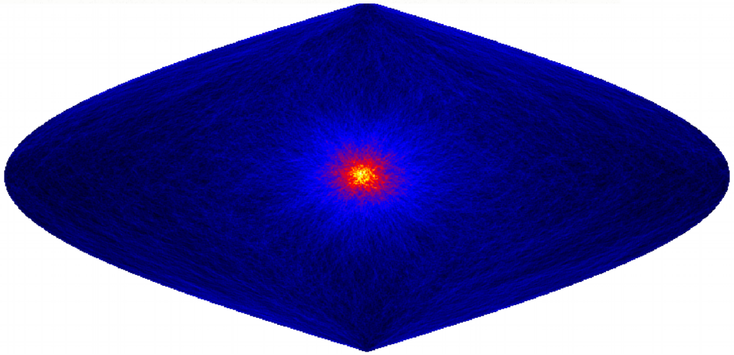
- **Compton camera principle**



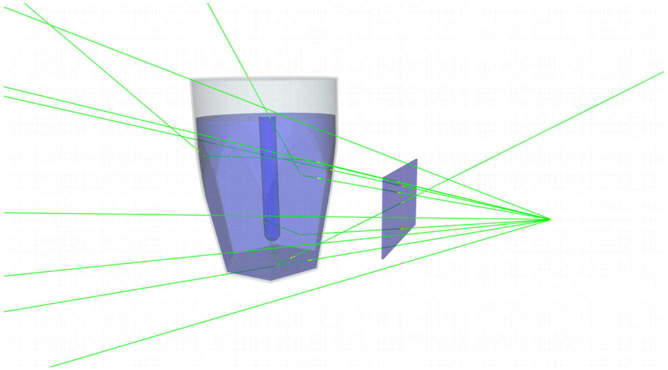
- **Experimental setup**
  - Detector setup
  - Digital electronics



- **Achieved results**
  - Coincidence mode
  - High efficiency mode



- **Outlook**
  - Simulation
  - New HPGe Detector

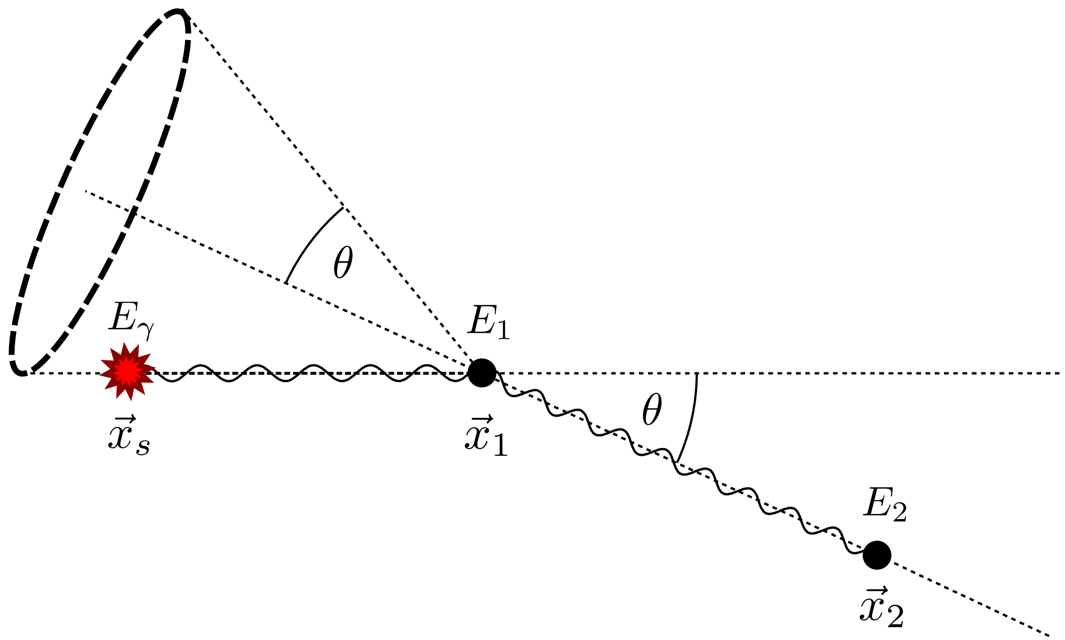


Compton camera principle

Imaging requires:

- Energy E_γ
- Energy loss due to Compton scattering E_1
- Interaction points and sequence
- Multiple events

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



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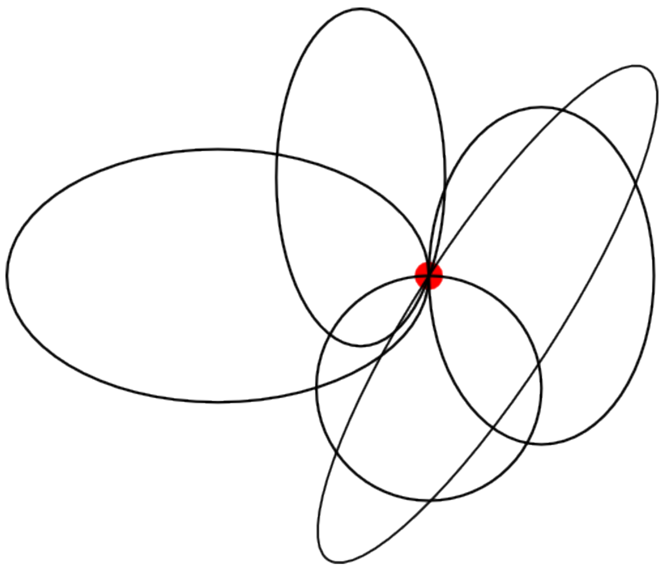
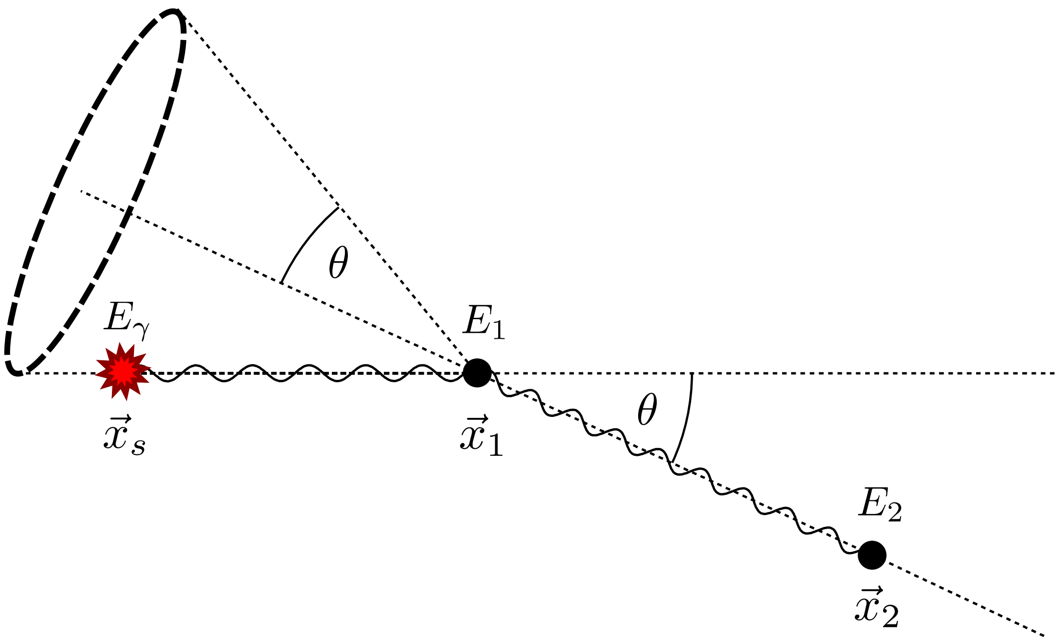
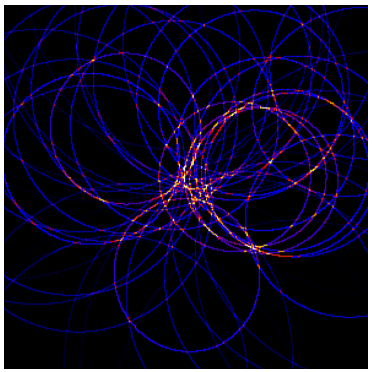
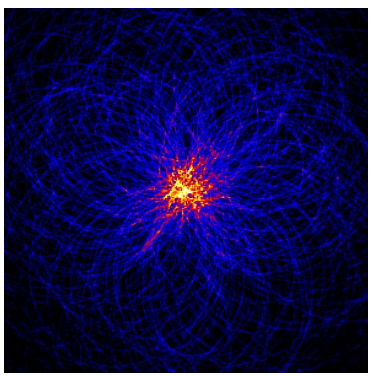




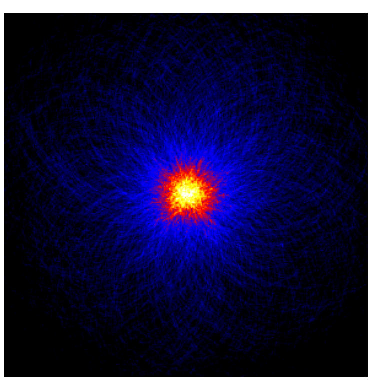
Compton camera principle



50 events



500 events



5000 events

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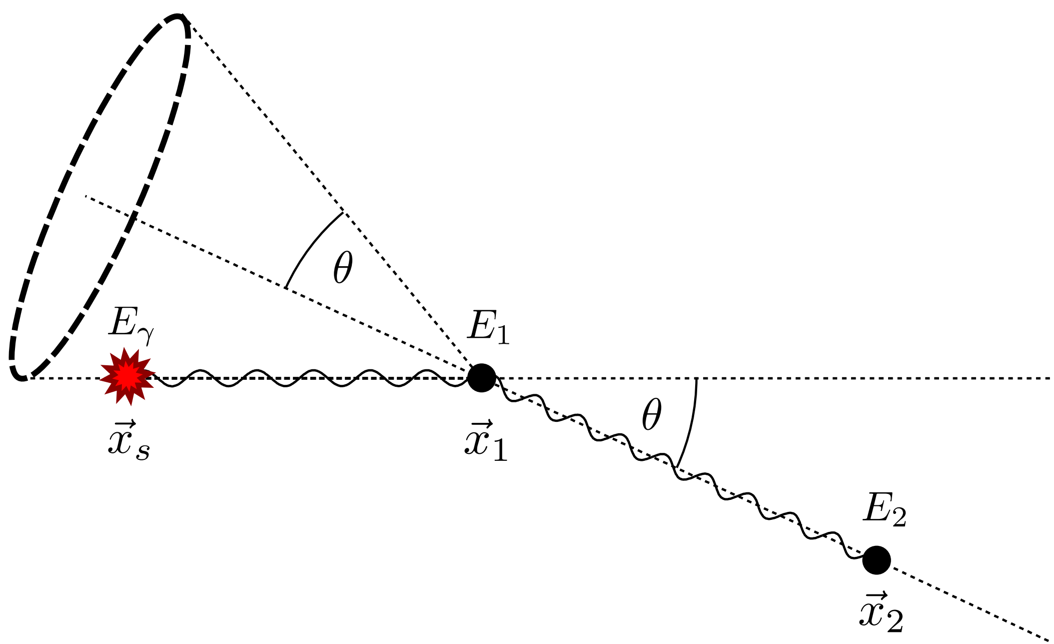


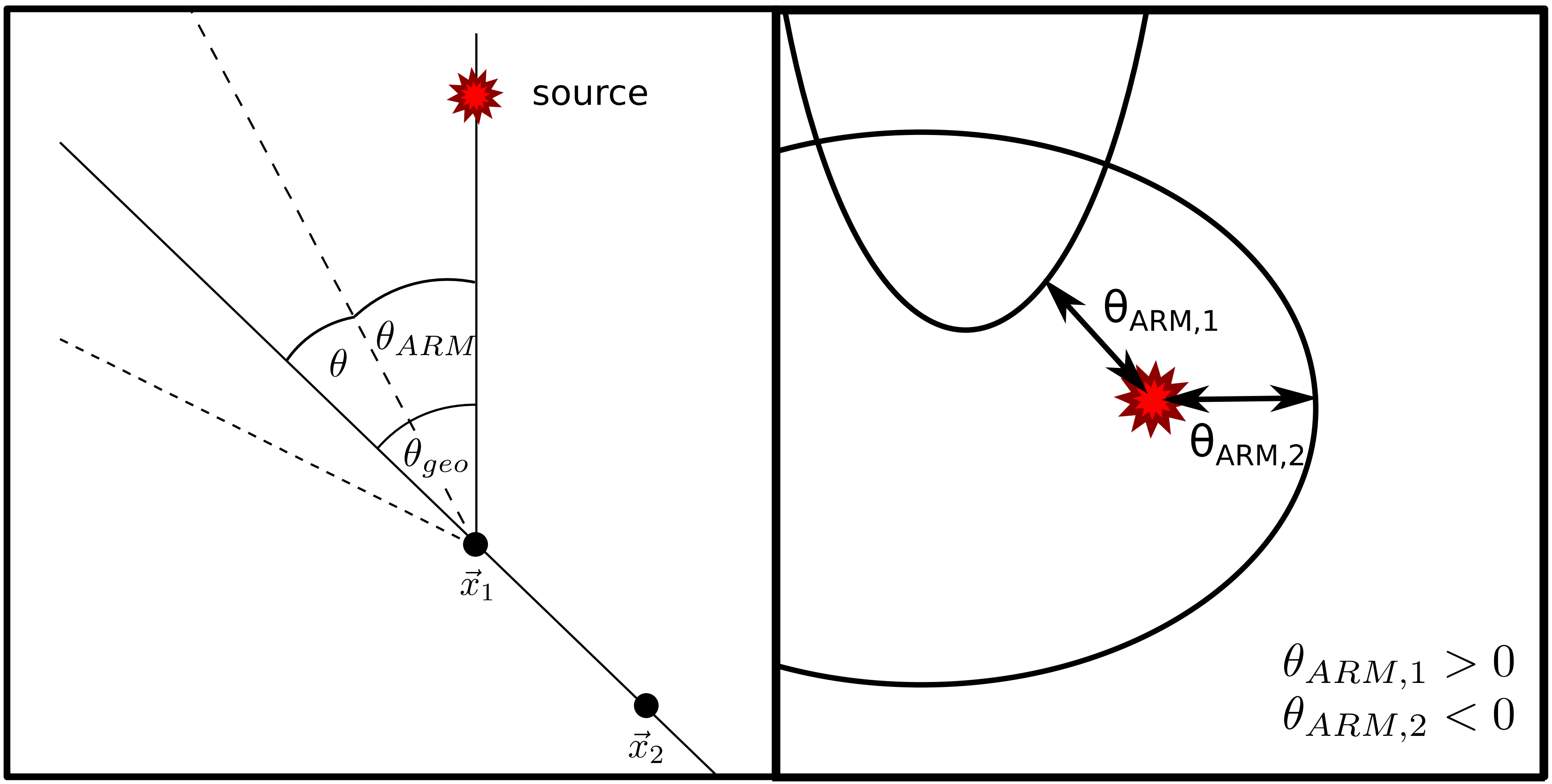
Angular Resolution Measure (ARM)

θ_{ARM} minimal angular distance

- Compton cone intersection
- Known source position

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

$$\theta_{\mathrm{ARM}} = \theta_{geo} - \theta$$



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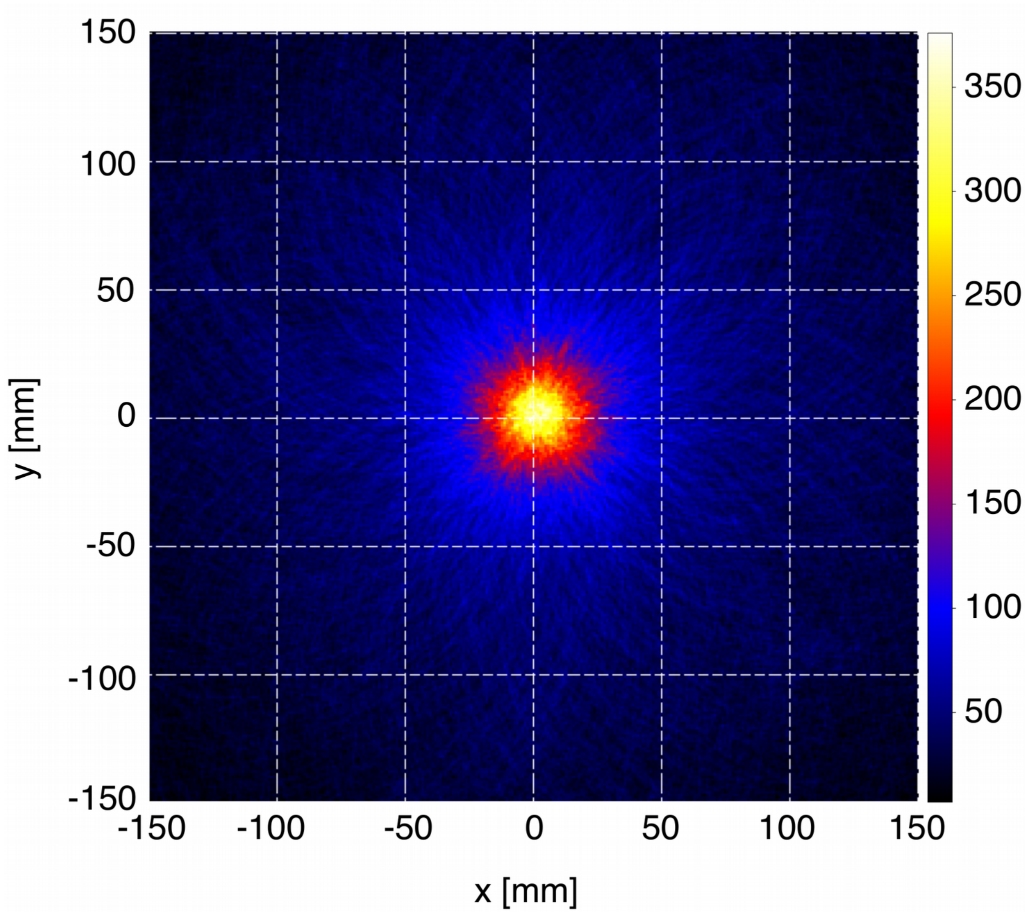
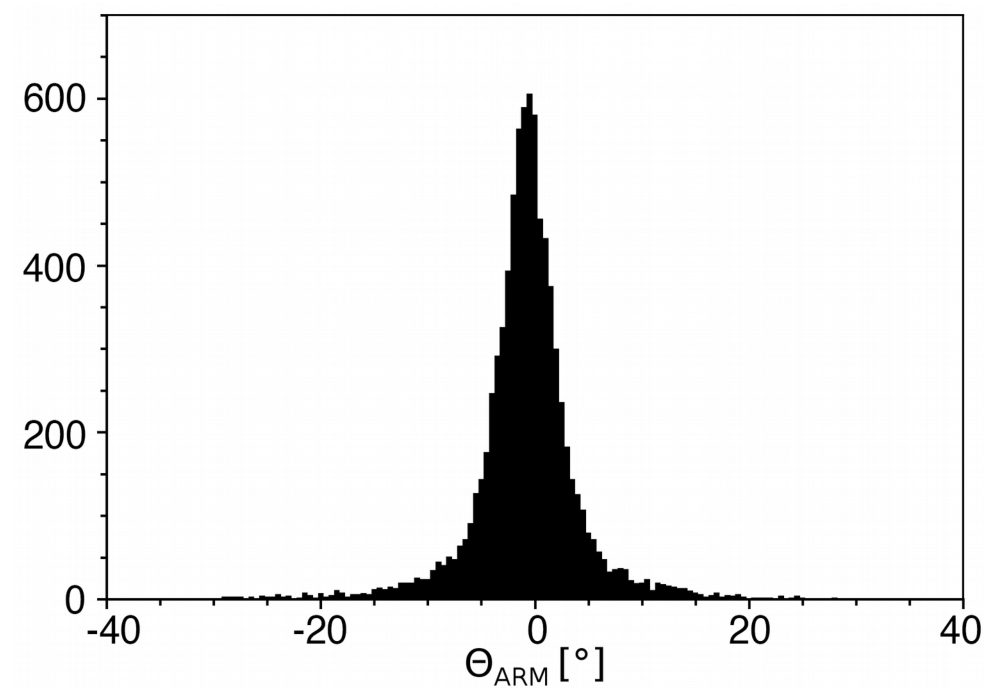
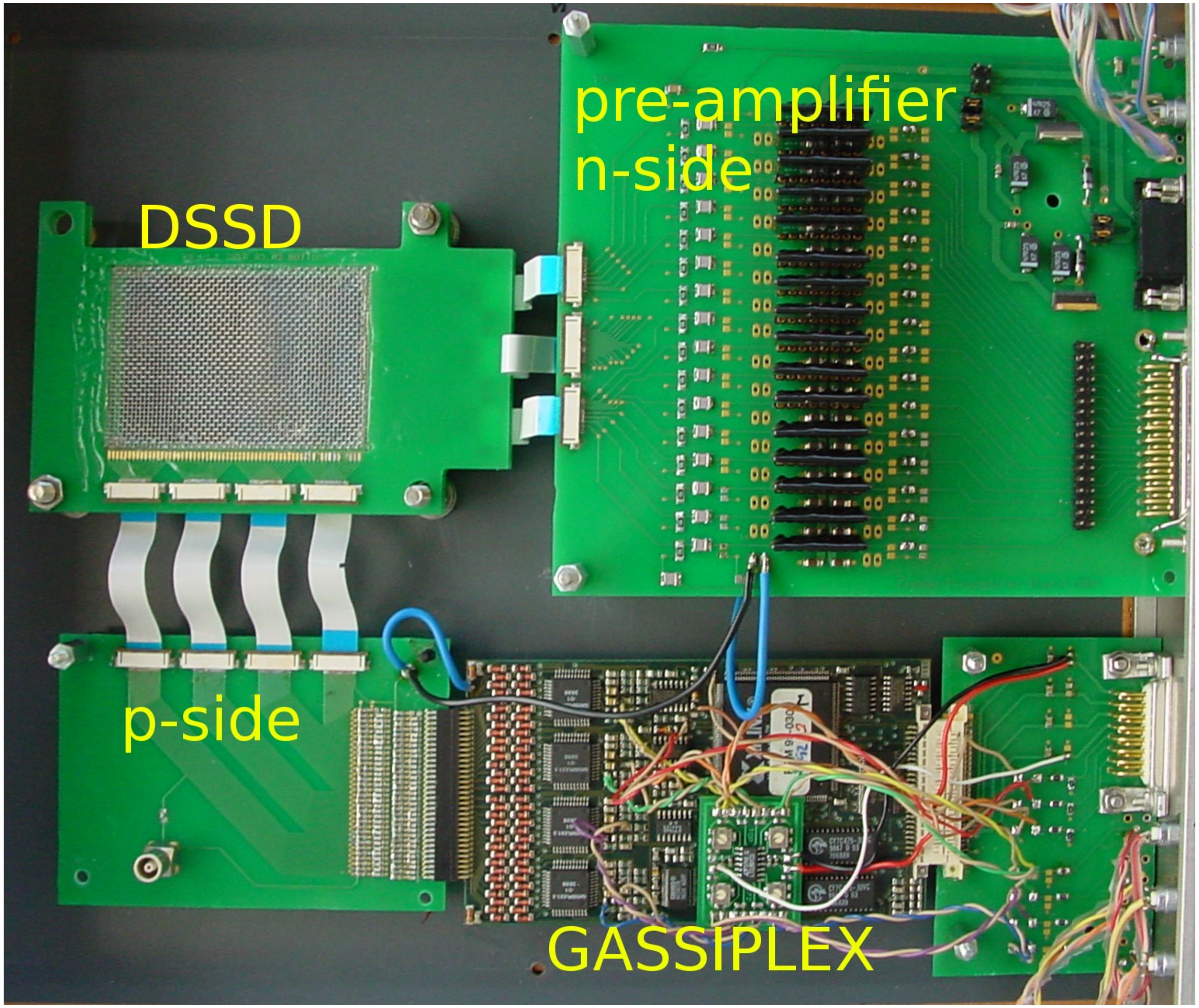




$$\Delta\theta = 4.6^\circ$$

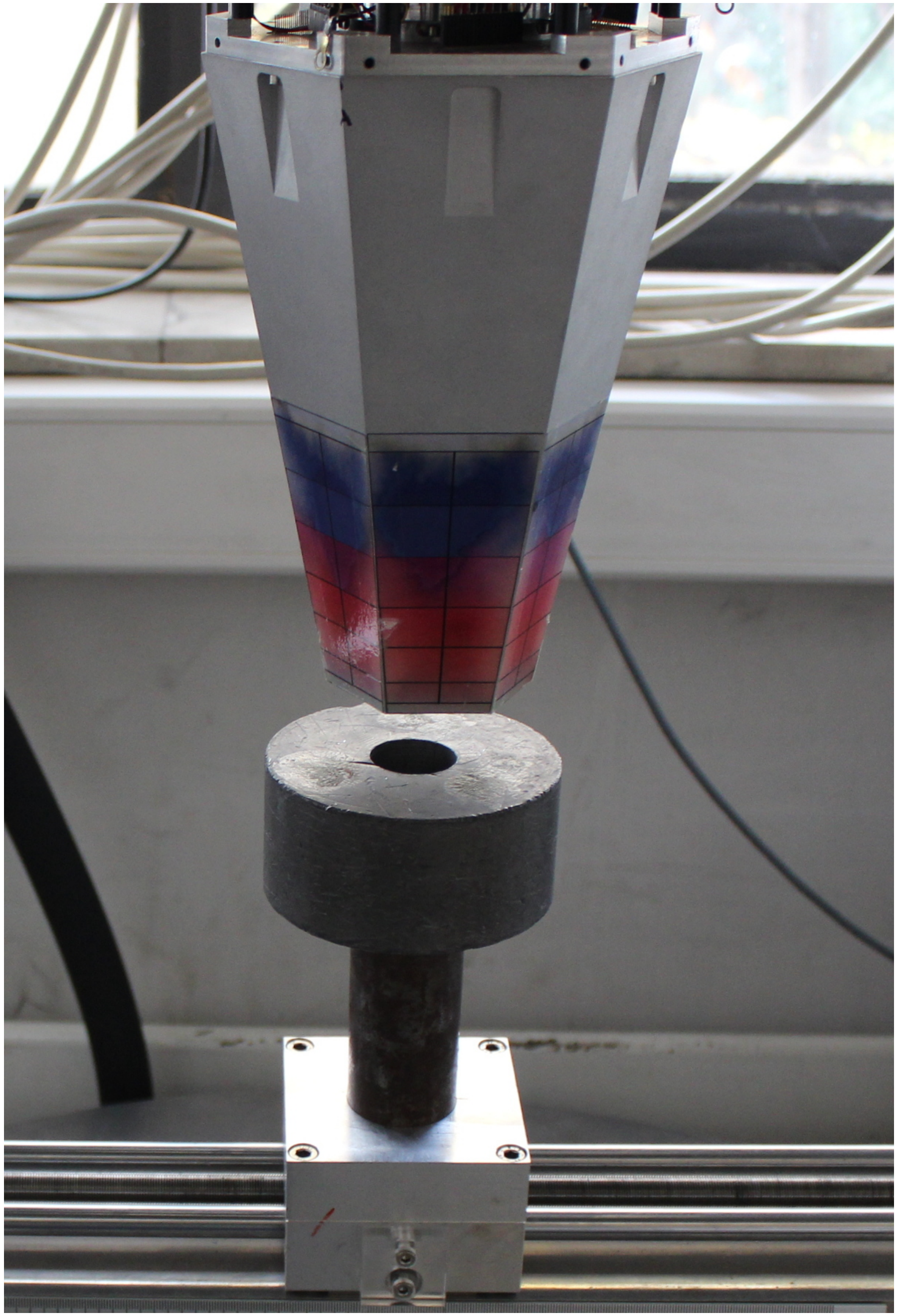
Detector setup



Double-sided silicon strip detector (DSSD)

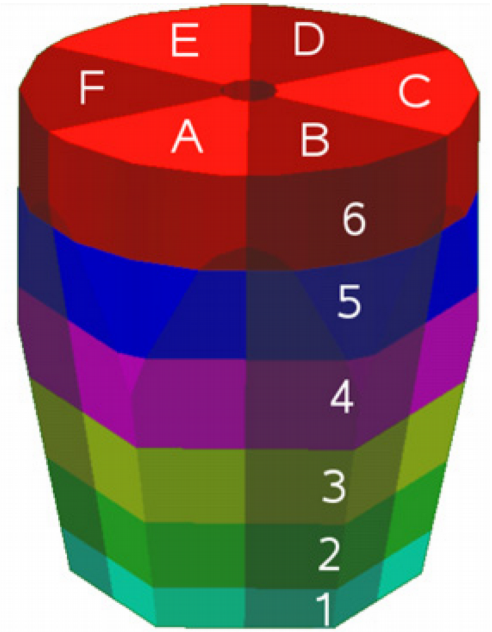
- 60x40x1 mm^3
- 1 mm strips
- n-doped side
  - 32 charge-sensitive preamplifiers
- p-doped side
  - 4 GASSIPLEX chips
  - multiplexed energy information of 15 strips

Detector setup

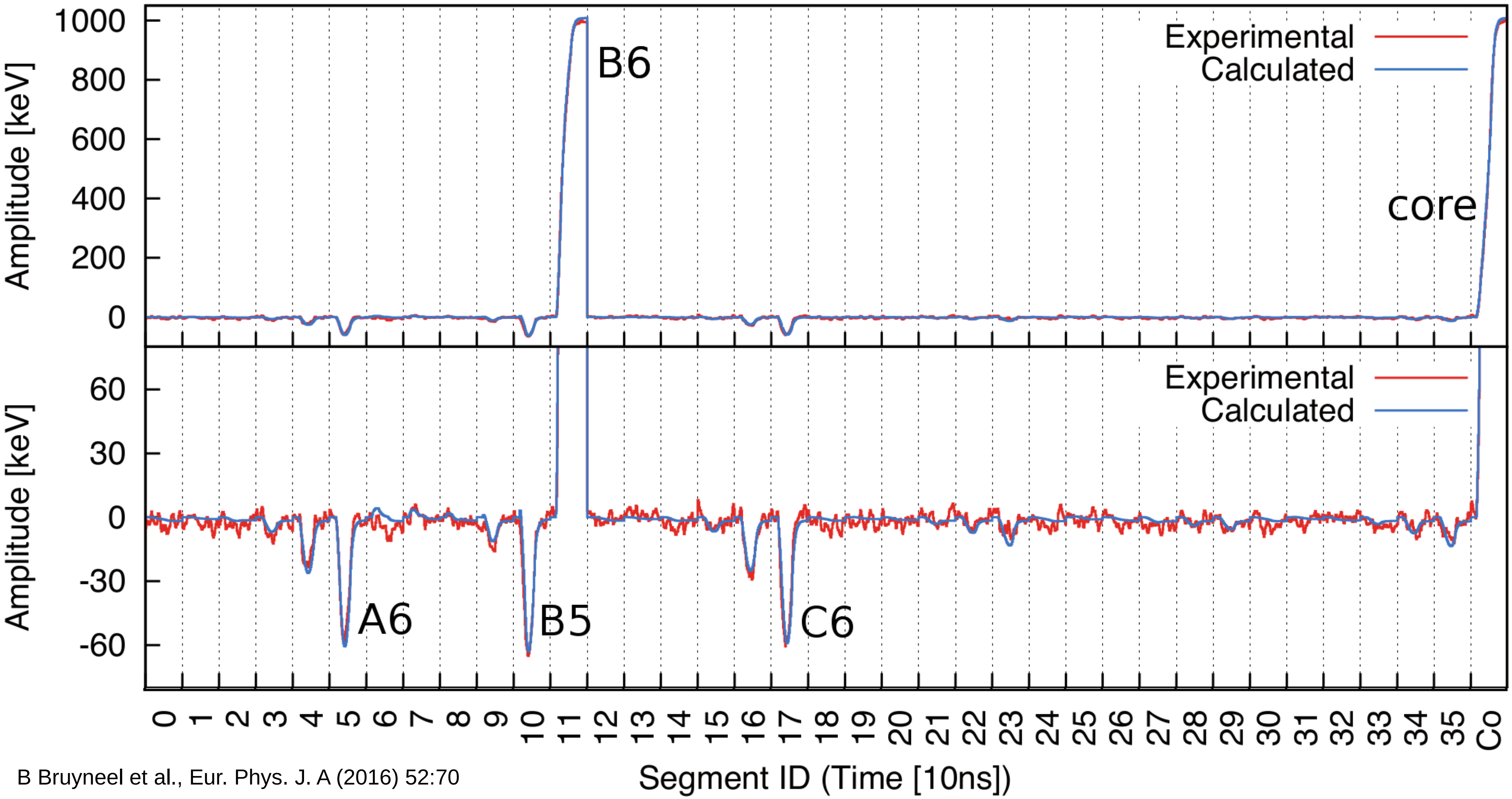


Highly segmented HPGe detector

- AGATA detector S001
- h=89mm Ø=80mm
- 71.1% efficency
- 36 segments
- 10° symmetric hexagonal tapered
- Sub segment spacial resolution due to pulse-shape analysis (PSA)



Pulse-shape analysis



B Bruyneel et al., Eur. Phys. J. A (2016) 52:70

Database of simulated signals

- Grid of interaction points
- Simulated with ADL

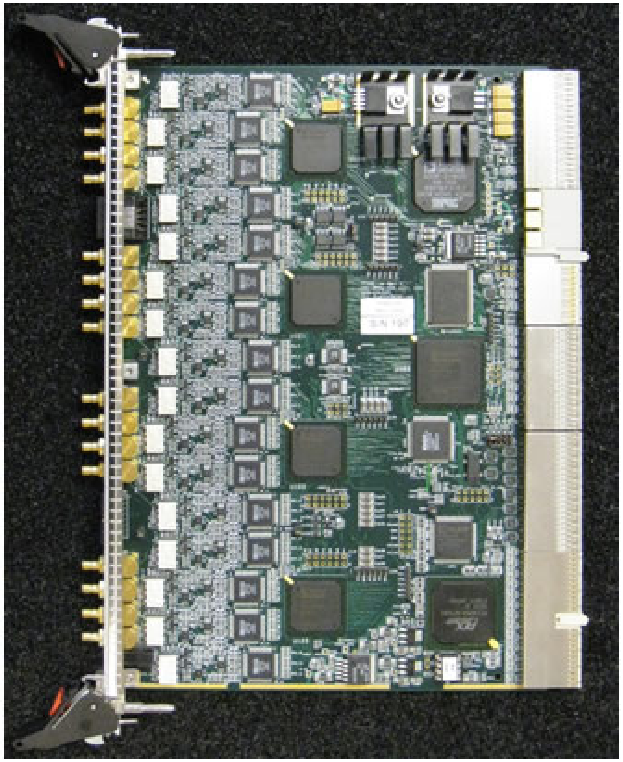
Comparison of measured and simulated signals with AGAPRO

$$\text{Figure of Merit} = \sum_{i,j} |A^m_{i,j} - A^s_{i,j}|^p$$

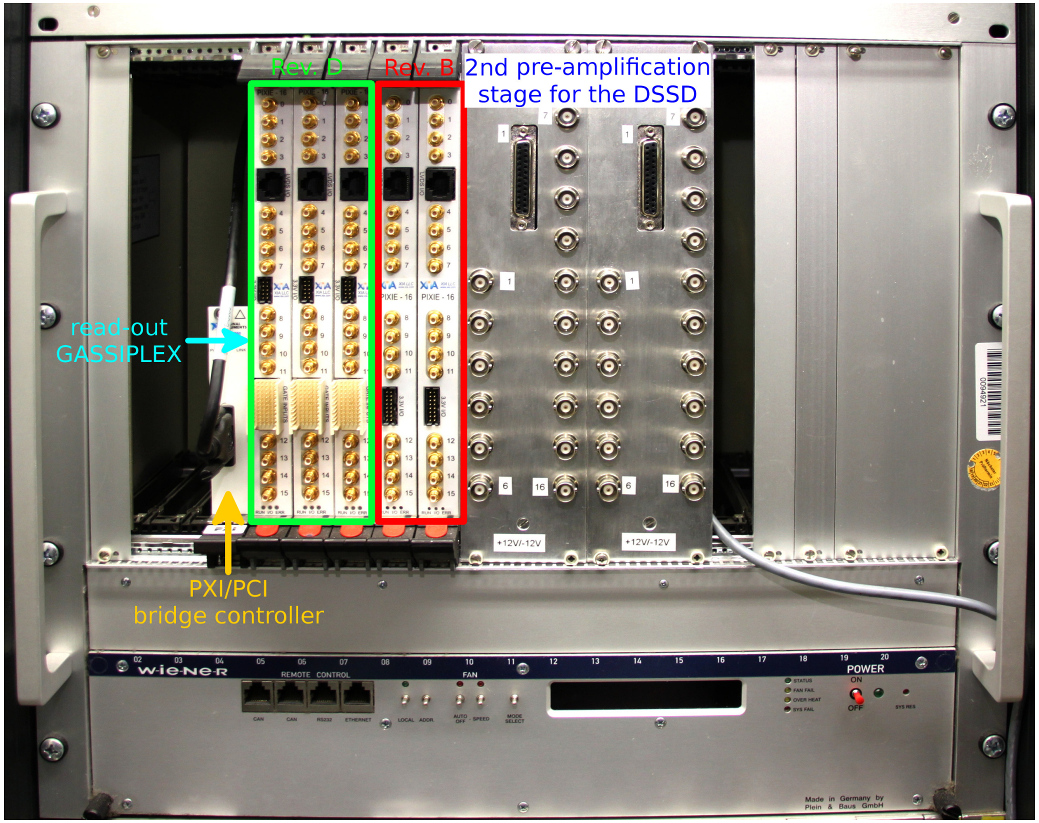
Digital electronics

Pixie-16 modules from XIA

- 16 channels per module
- 12-bit ADC
- 100-MHz sampling rate
- Custom firmware
- Data Converter to AGAPRO

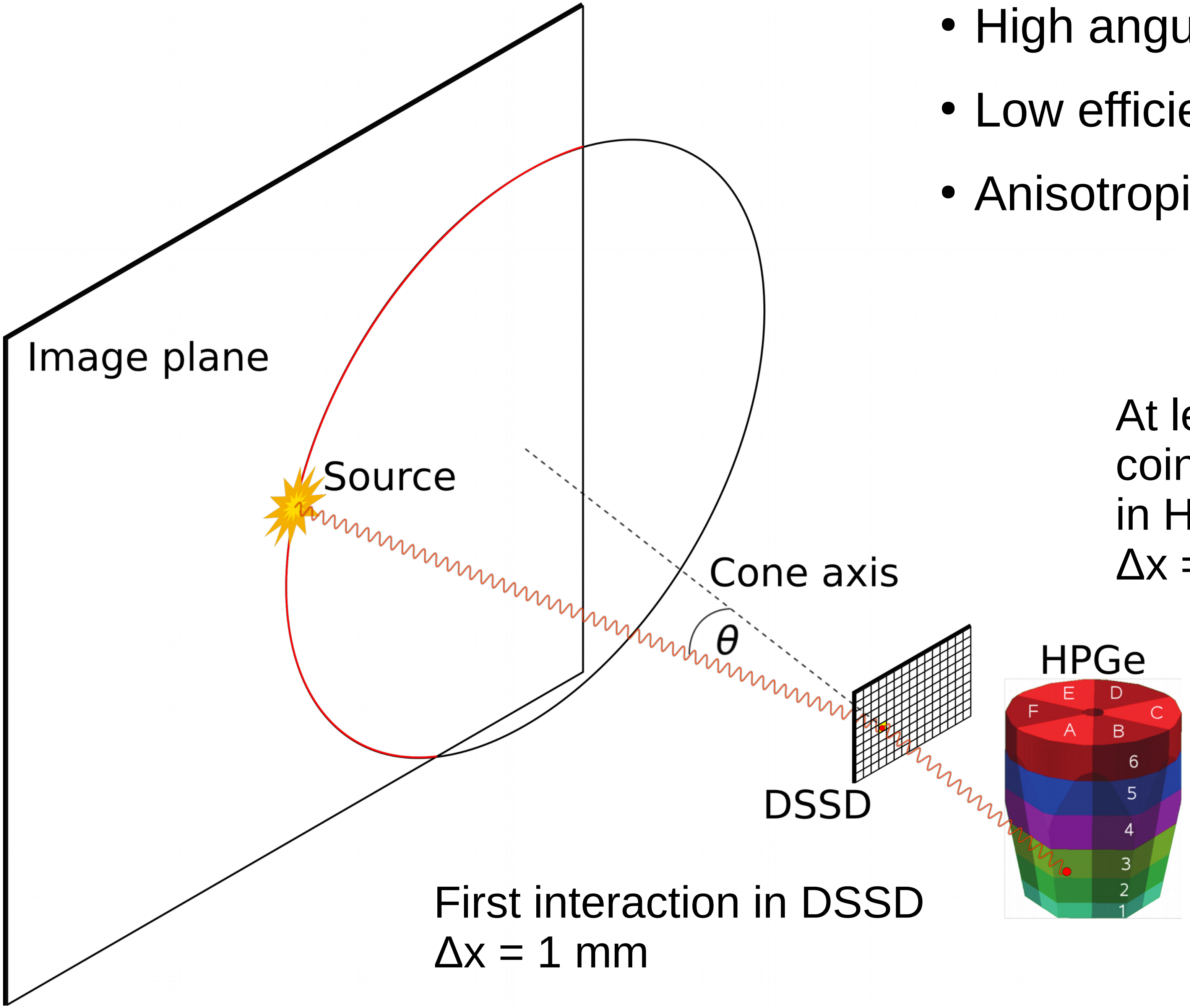


www.xia.com



Coincidence mode DSSD + HPGe

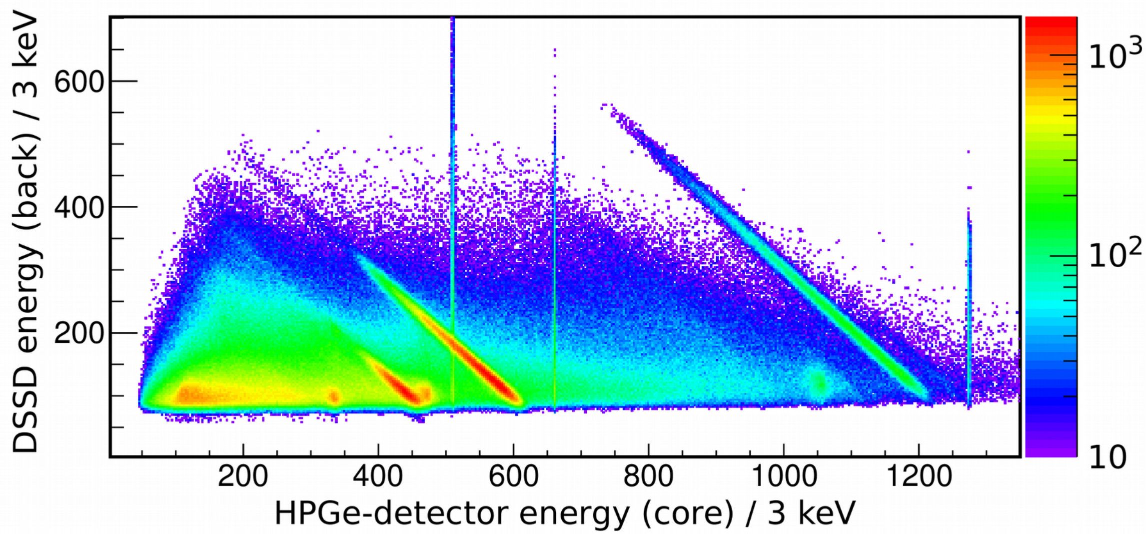
- High angular resolution
- Low efficiency
- Anisotropic sensitivity



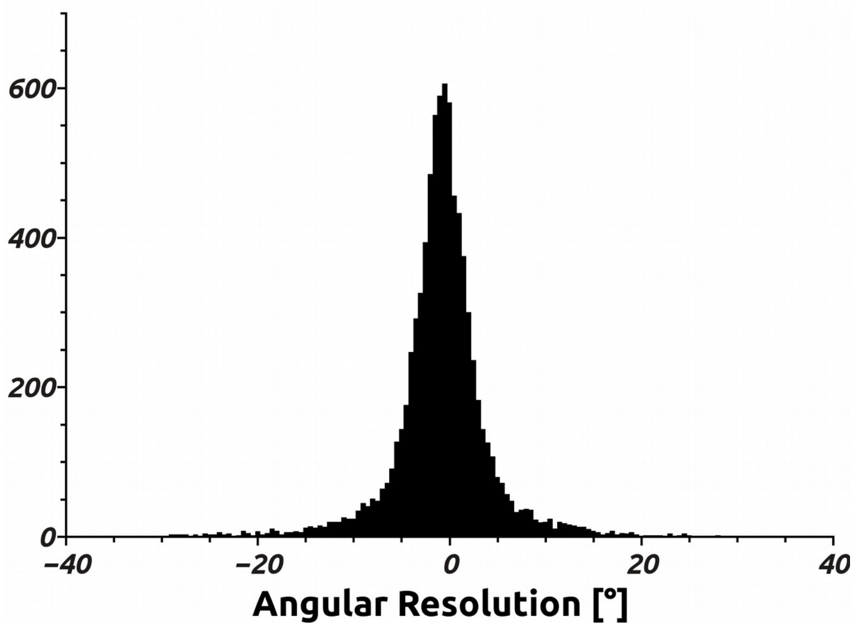
At least one coincident interaction in HPGe-detector
Δx = 4-5 mm

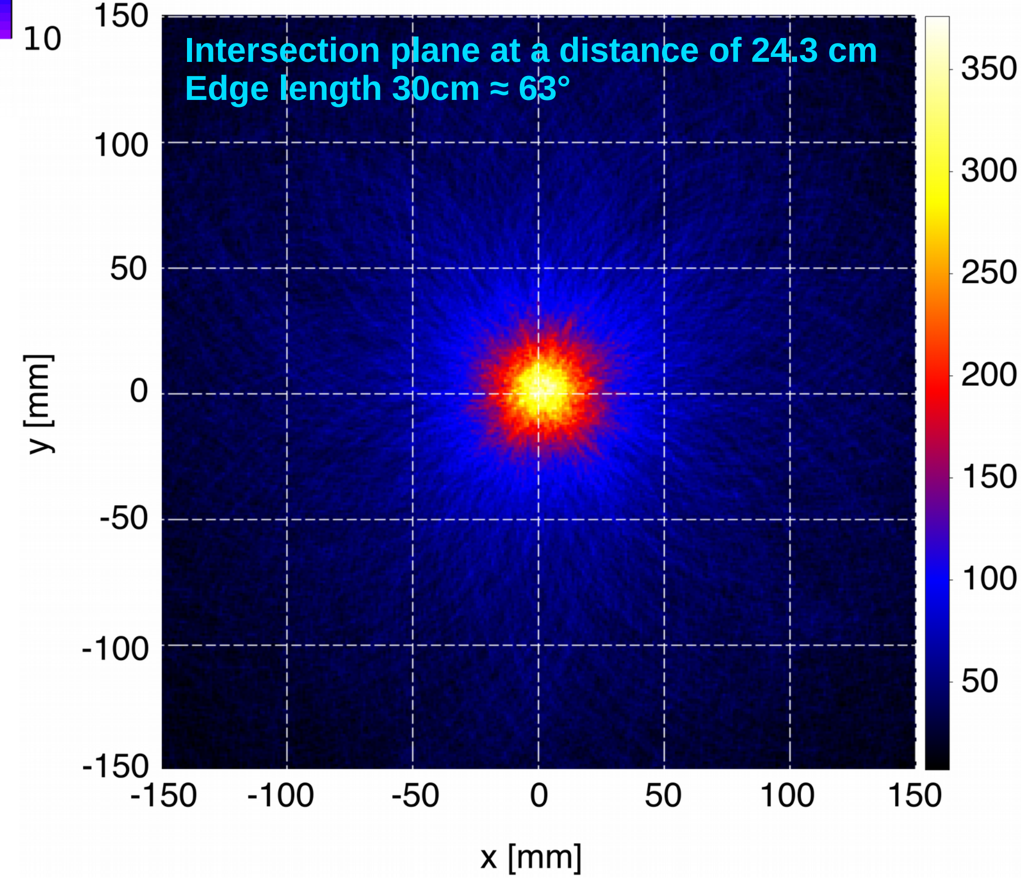
First interaction in DSSD
Δx = 1 mm

Coincidence mode DSSD + HPGe



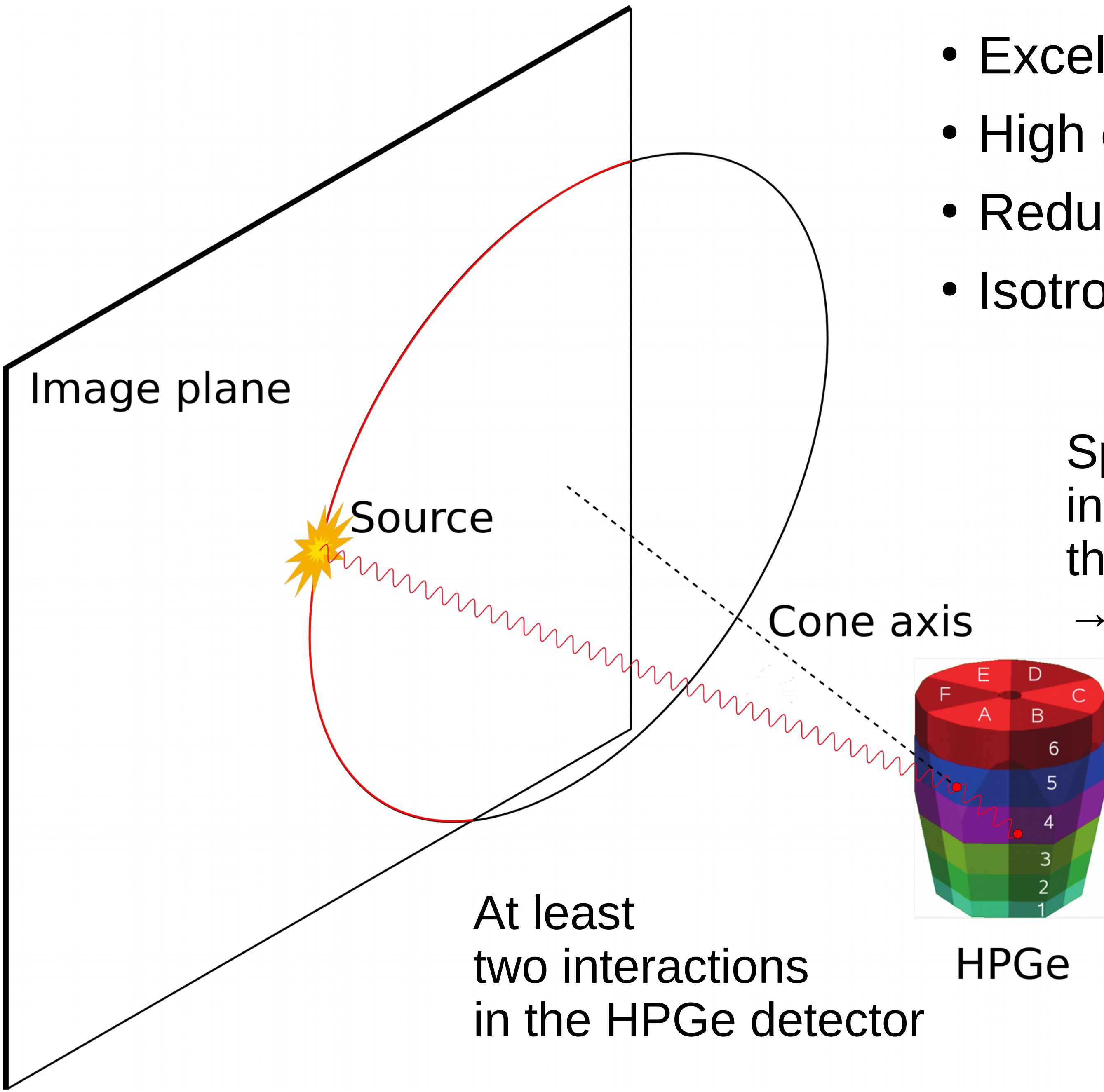
Source: Na-22 (E_γ = 1275 keV)
Activity: 450 kBq
Distance source ↔ DSSD: 24.3 cm
Efficiency: ~ 1.7x10^{-5}
Angular resolution (AR): $\Delta\theta = 4.6^\circ$





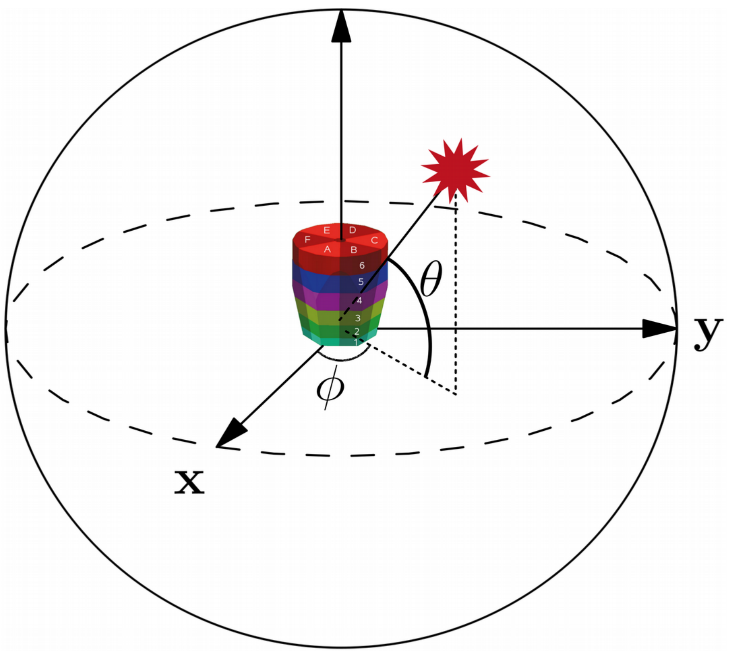
HPGe stand-alone mode

- Excellent energy resolution
- High efficiency
- Reduced angular resolution
- Isotropic sensitivity



Spacial resolution of the interaction points dominate the angular resolution
→ highly sensitive on PSA performance

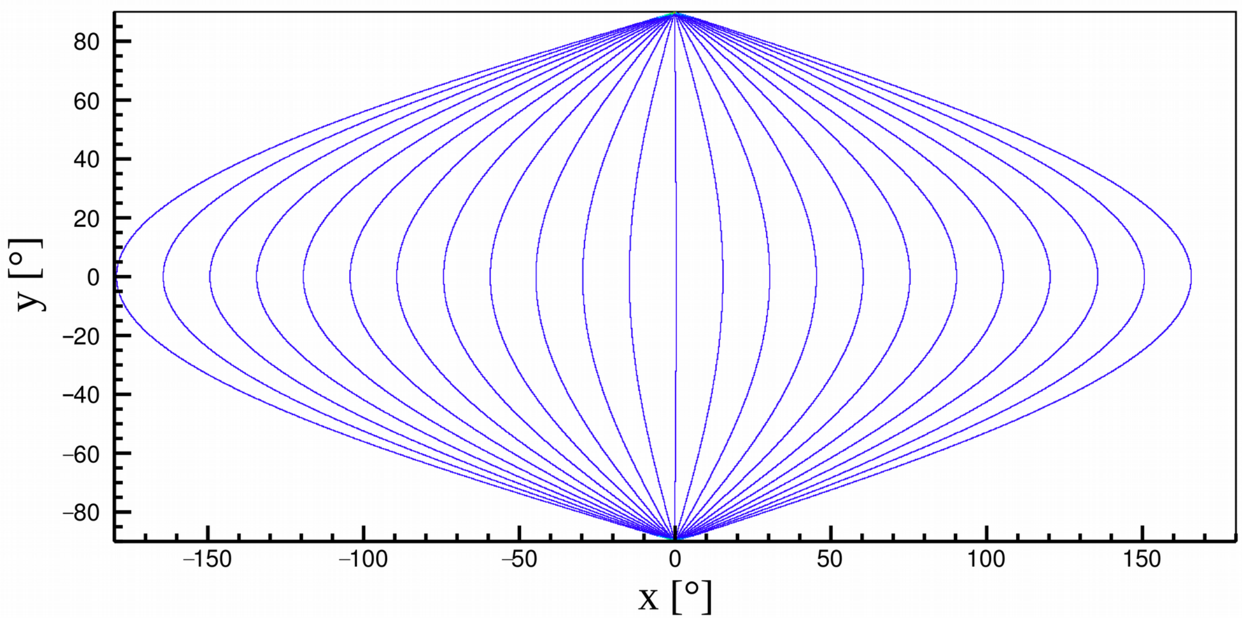
Near-field imaging



Cone intersection with a sphere

- Near-field imaging
- Full solid angle coverage
- No solid angle dependence
- Walking algorithm
- S. J. Wilderman et al., IEEE Transactions on Nuclear Science 45 (3) (1998) 957–962.

Sinusoidal map projection
lines of longitude



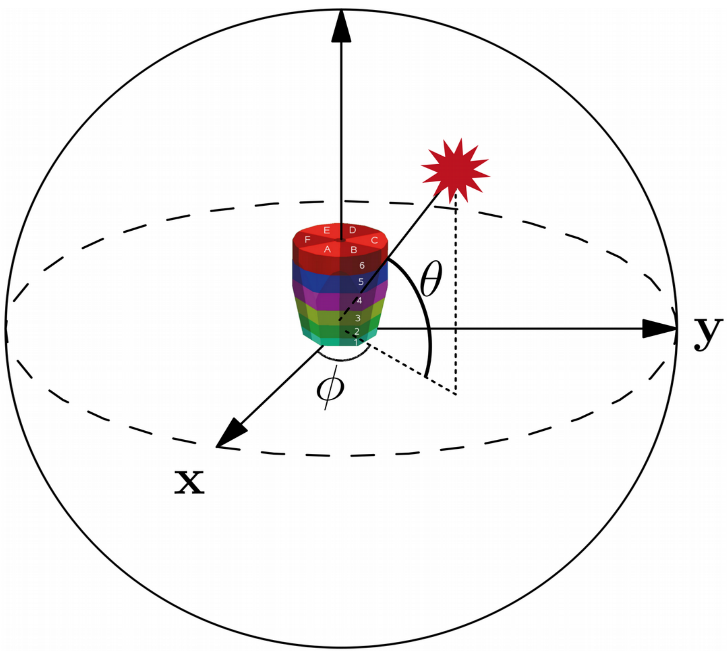
2D representation of the sphere surface

- Sinusoidal map projection
- Area conserving
- Straight forward calculation

$$x = \phi \cdot \cos(\theta)$$

$$y = \theta$$

Near-field imaging



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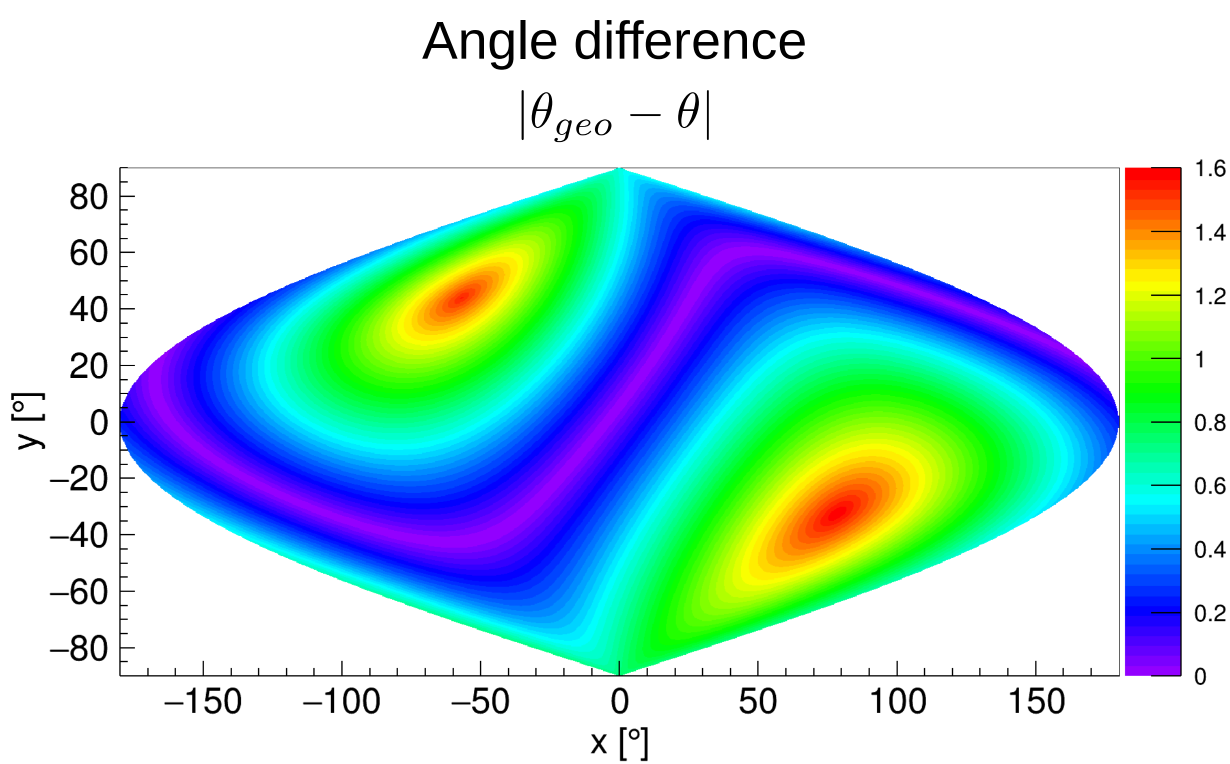
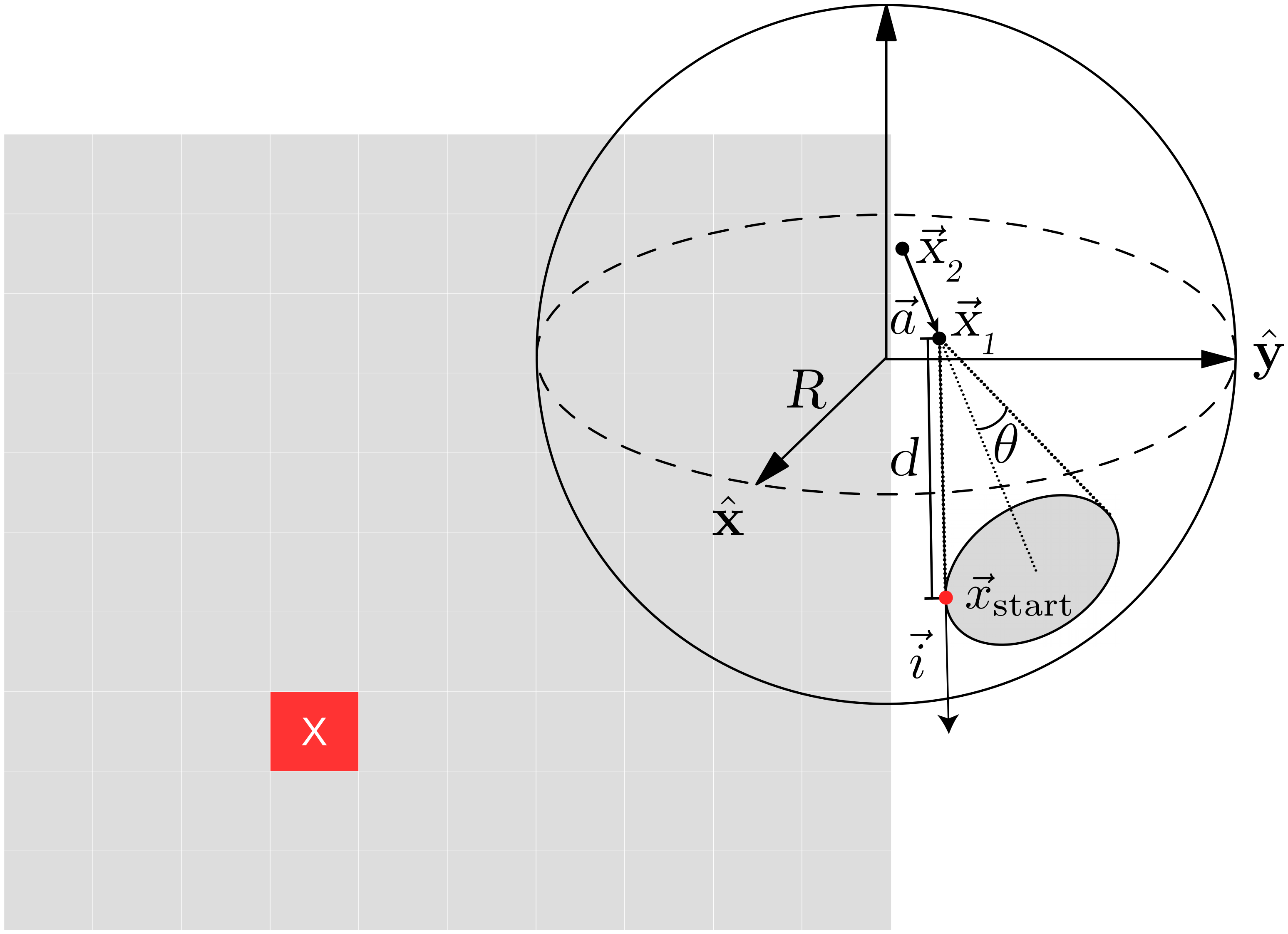


Walking algorithm



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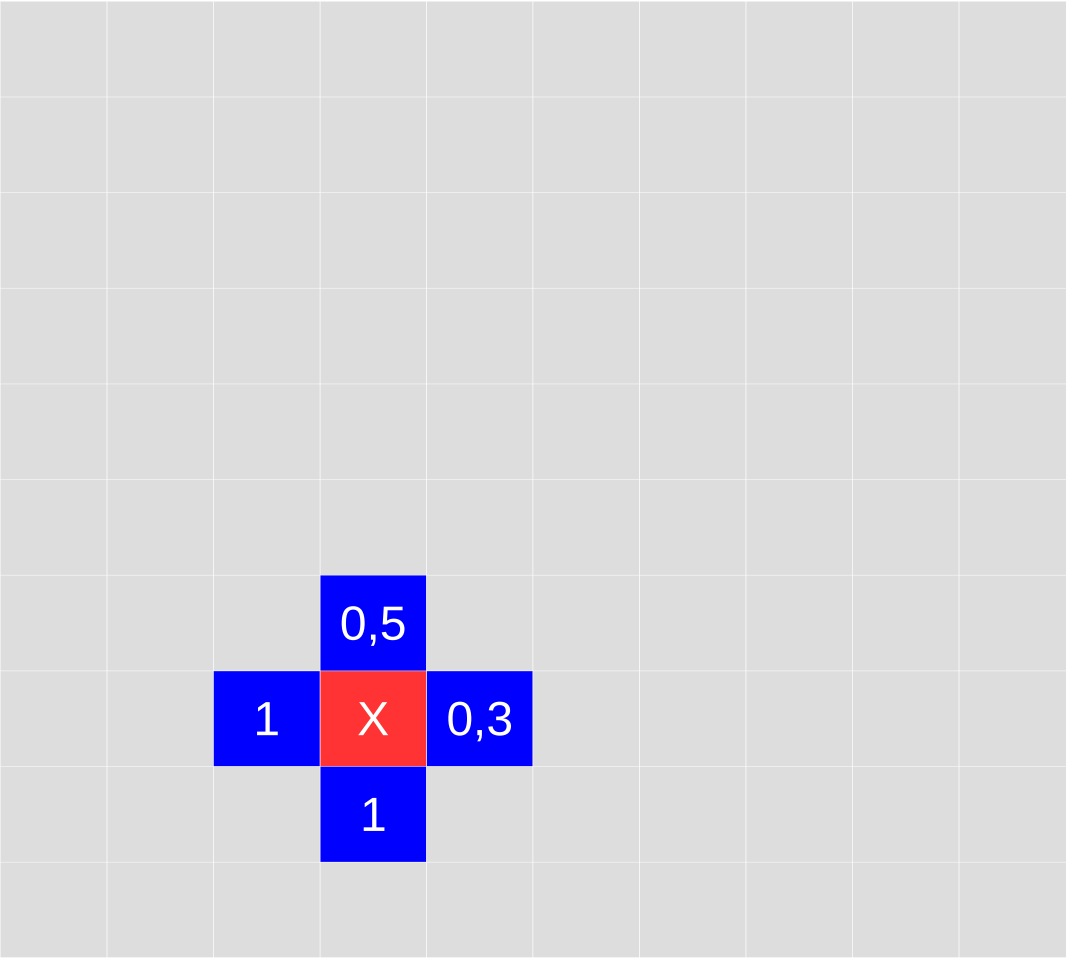

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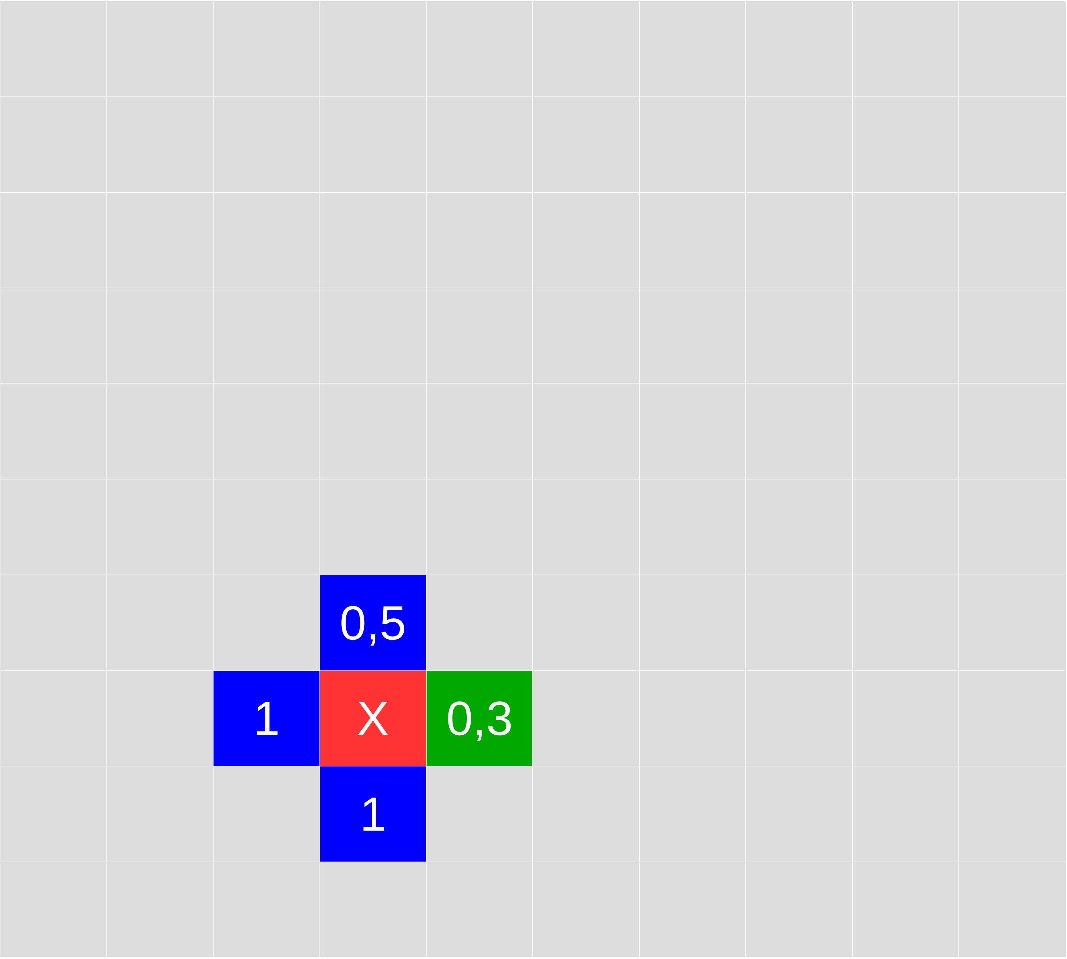

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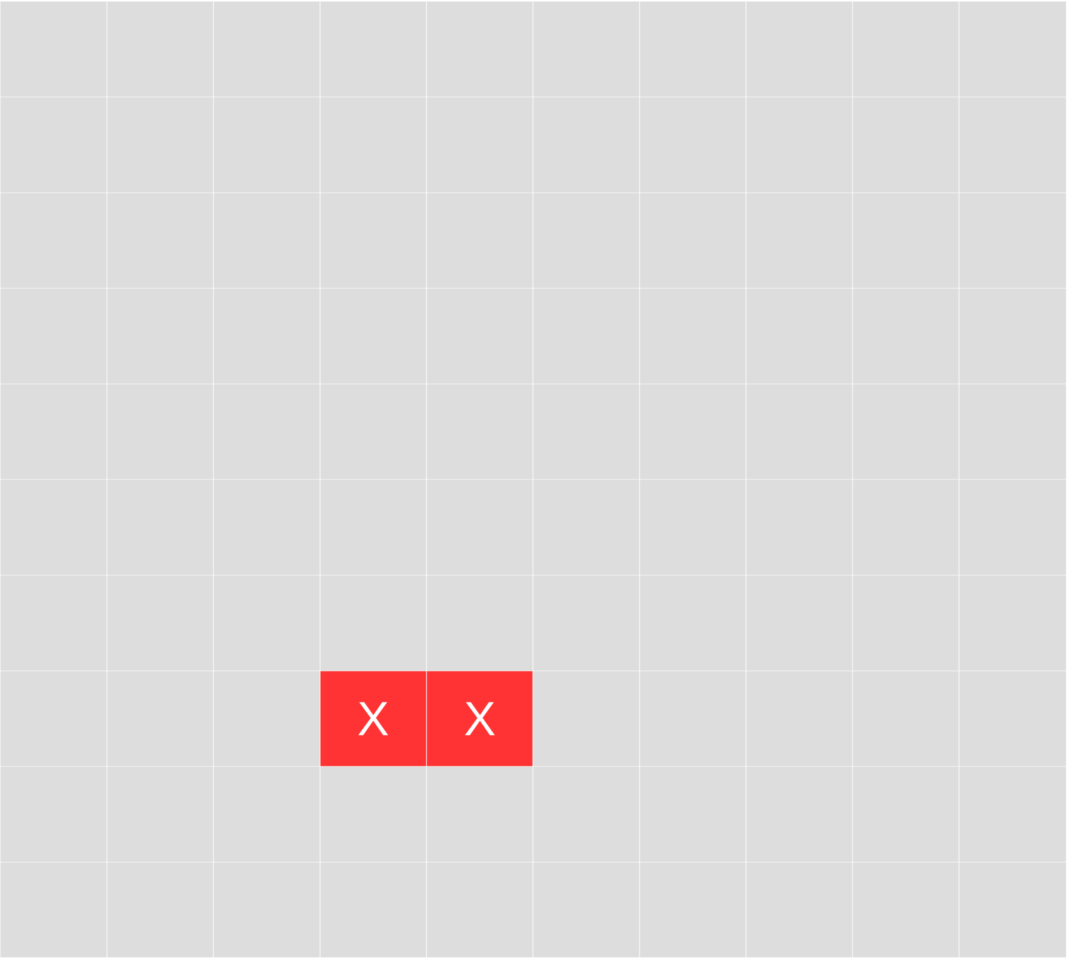

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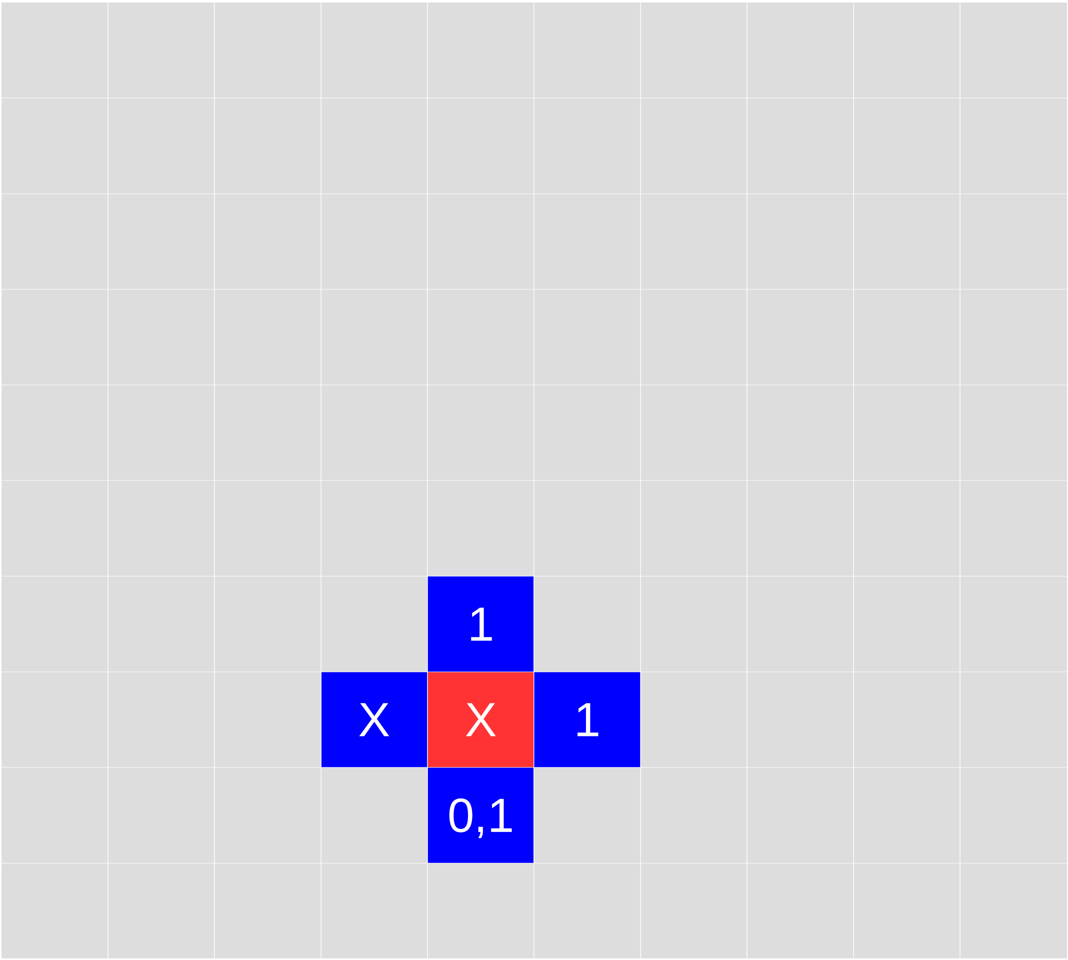

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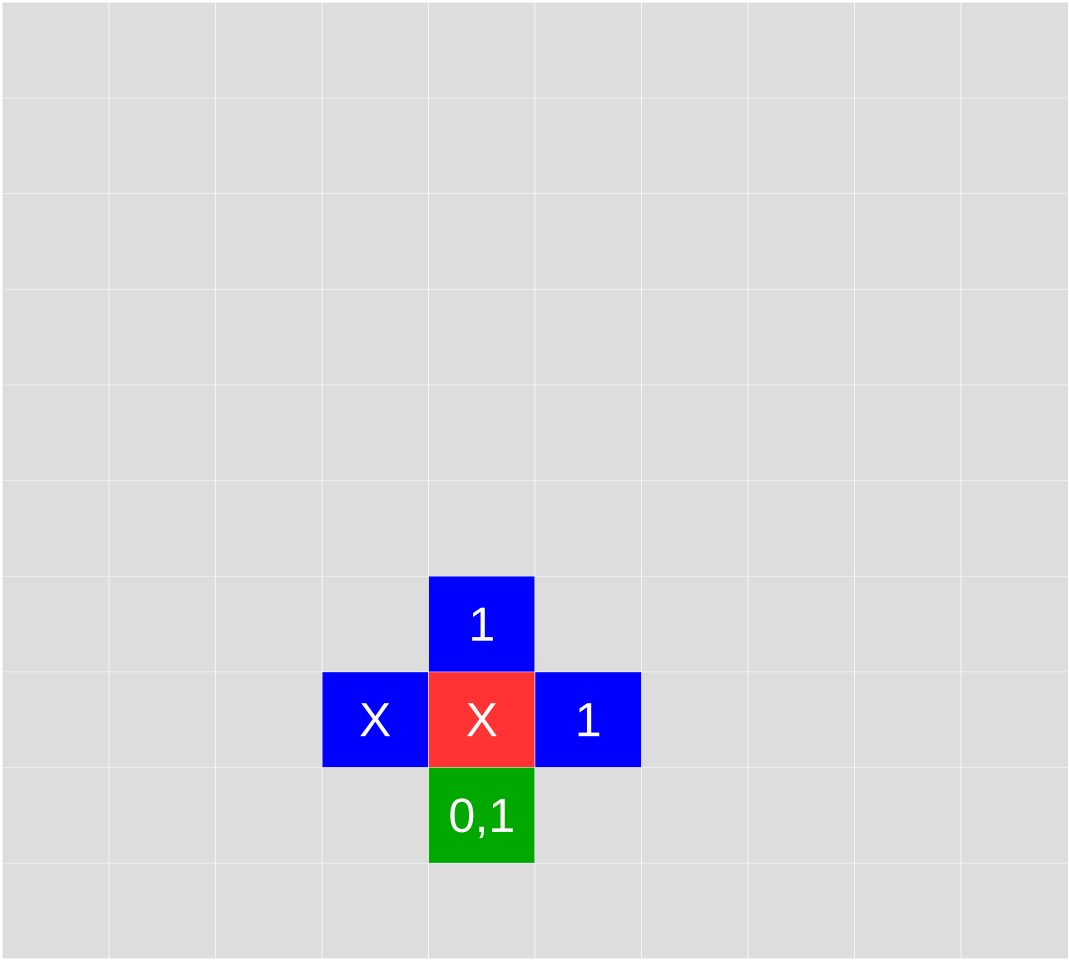
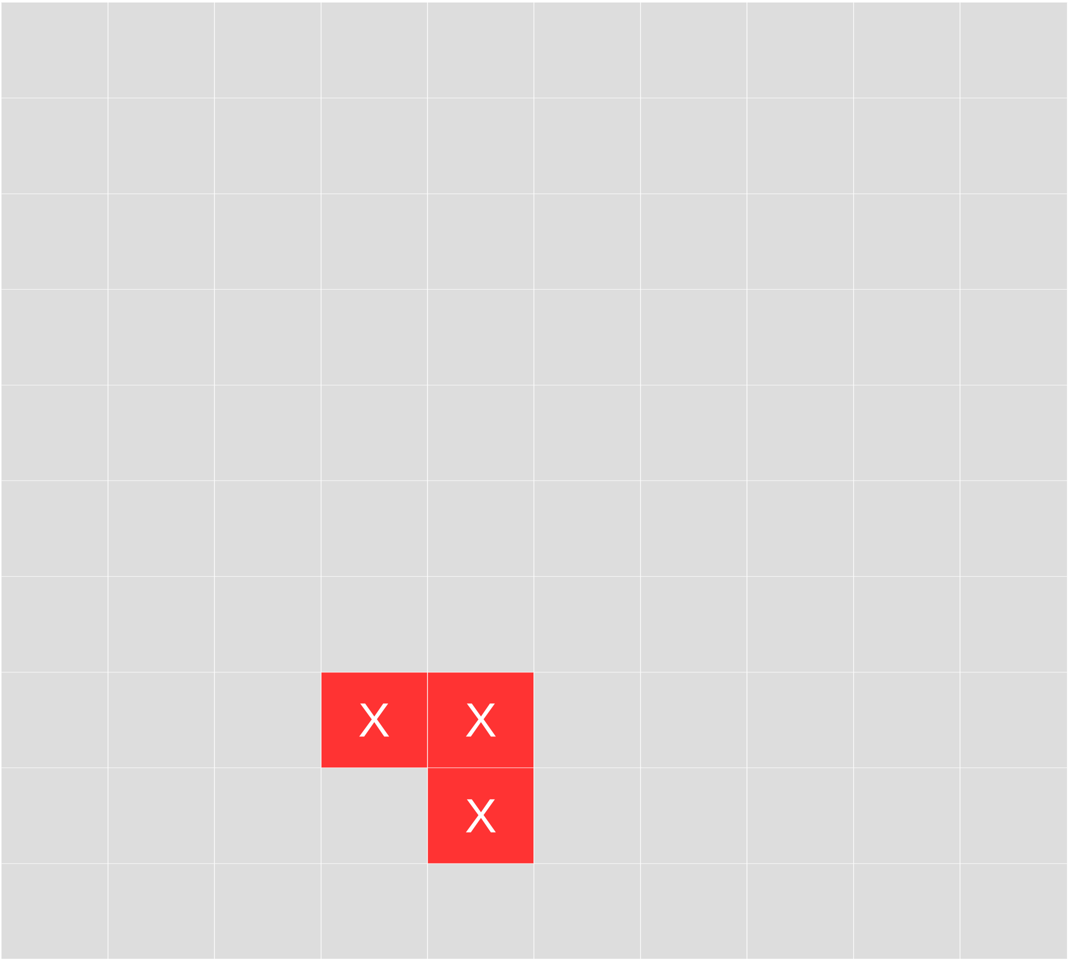


Walking algorithm



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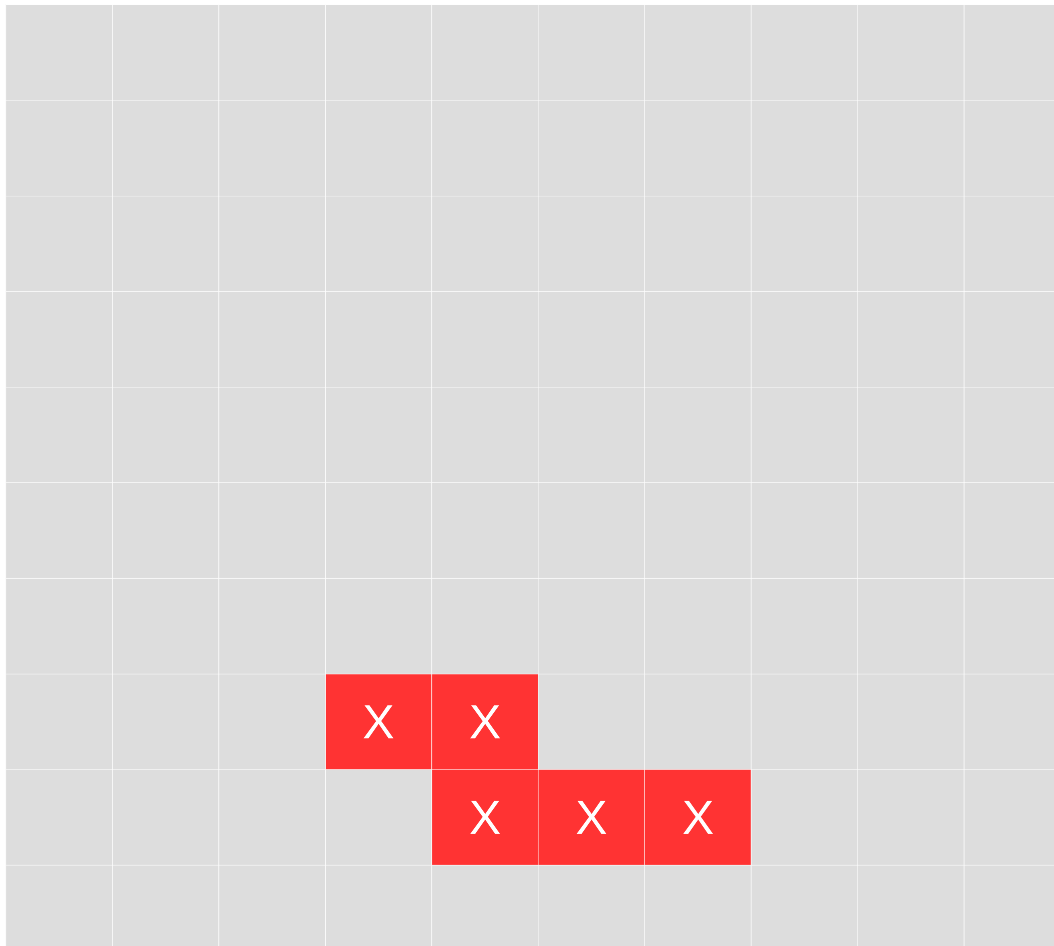

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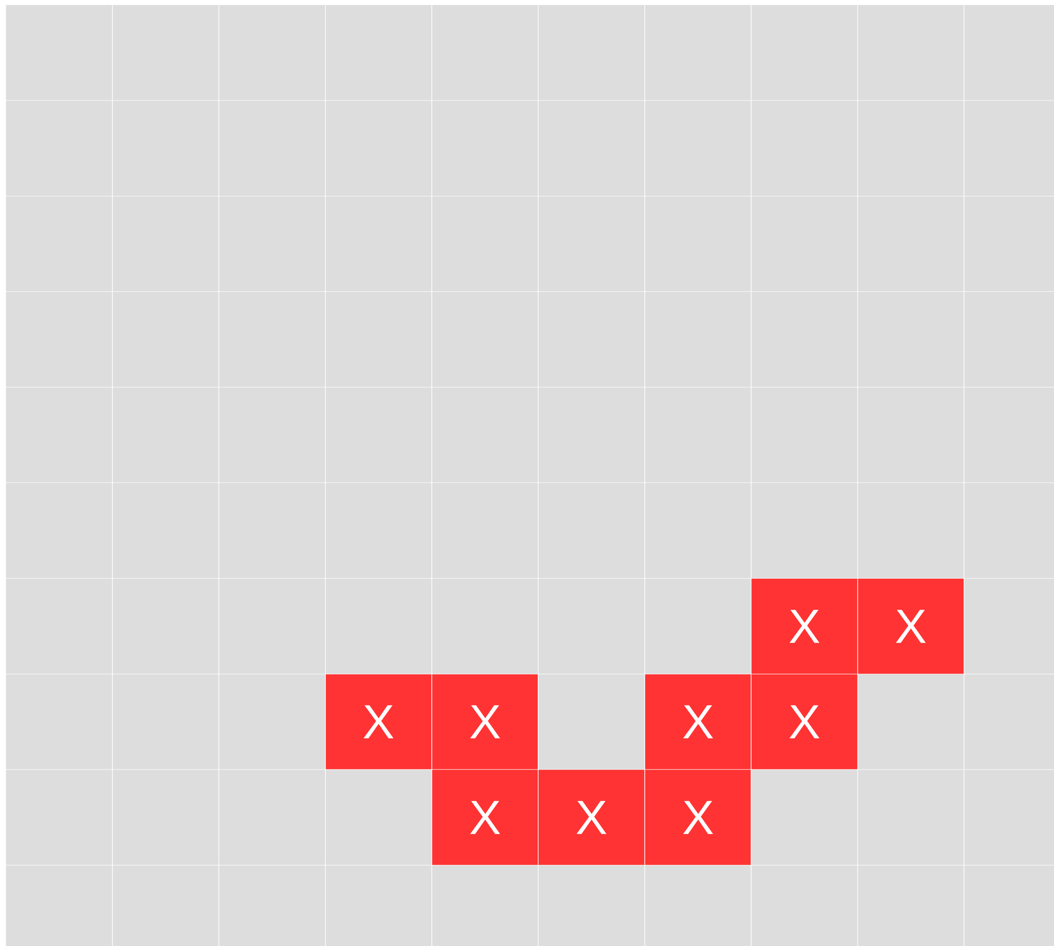

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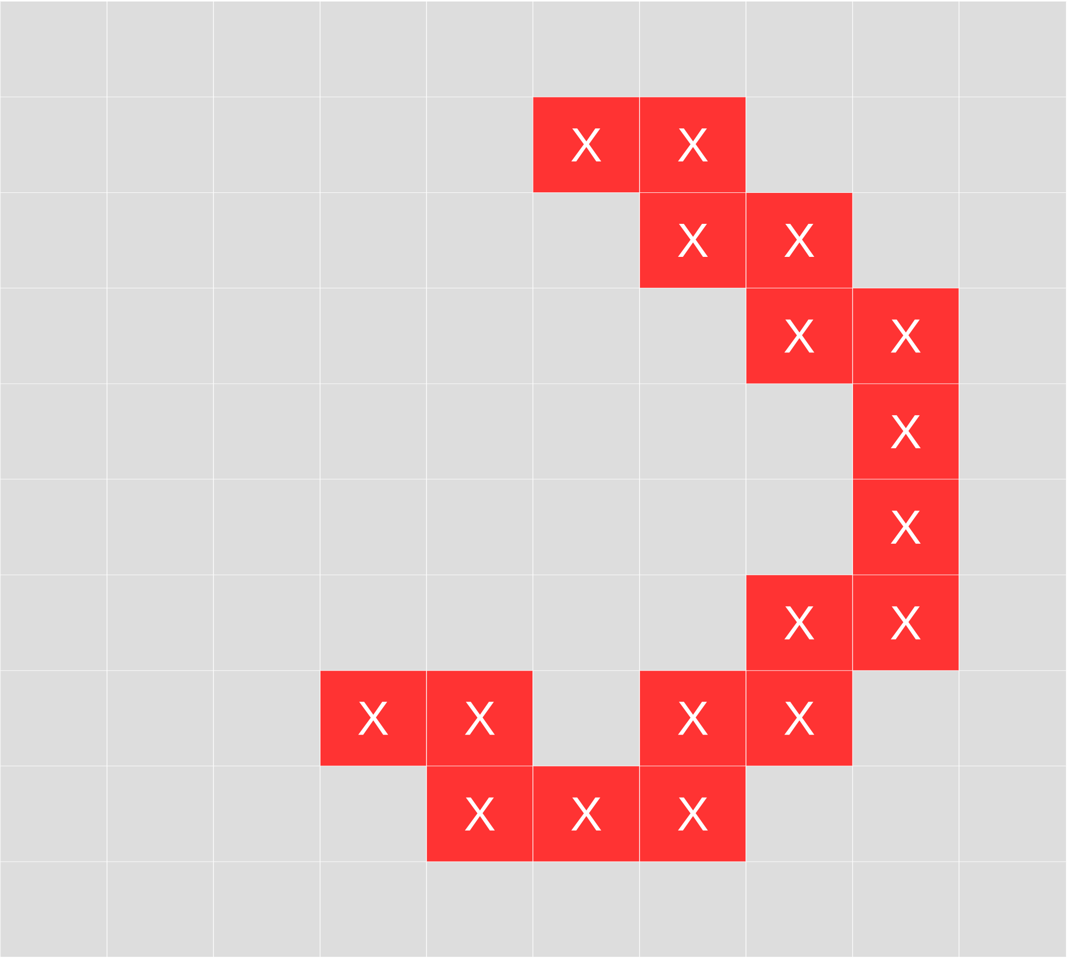
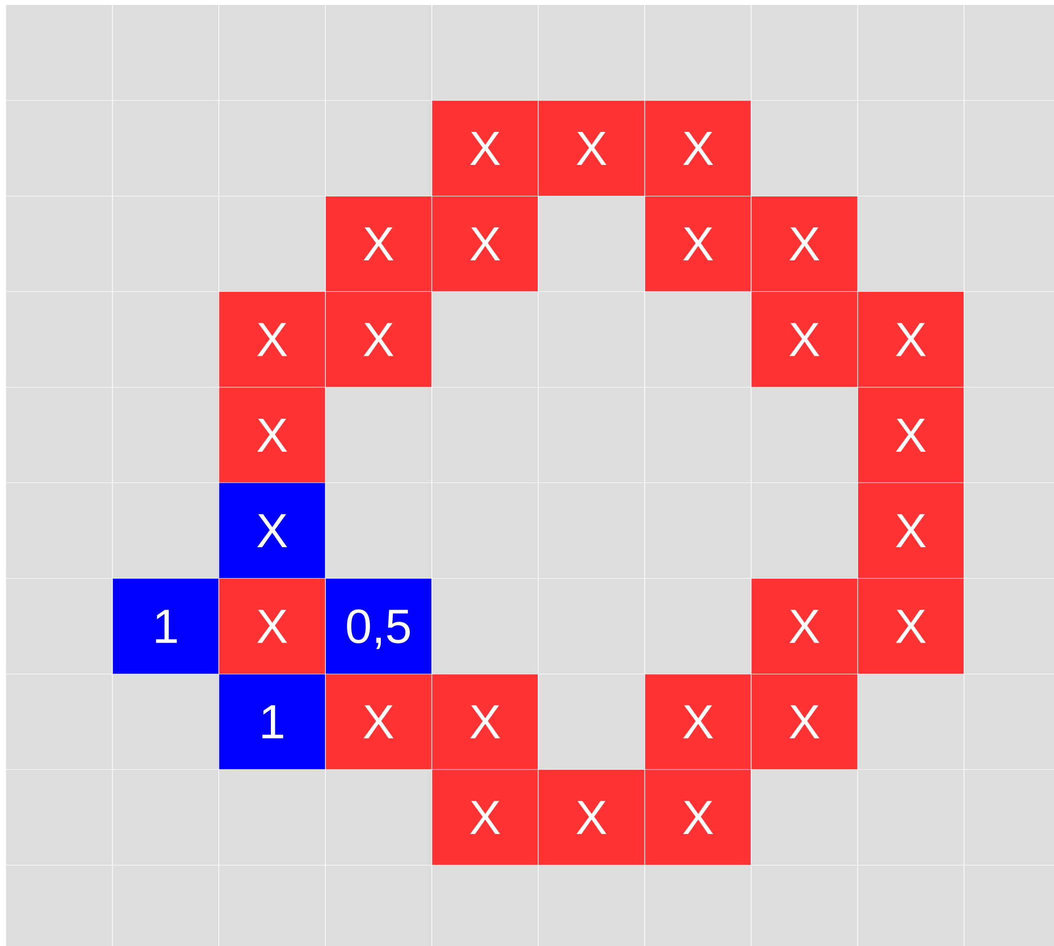


Walking algorithm

				X	X	X			
			X	X		X	X		
		X	X				X	X	
		X						X	
		X						X	
		X					X	X	
			X	X		X	X		
				X	X	X			

Walking algorithm



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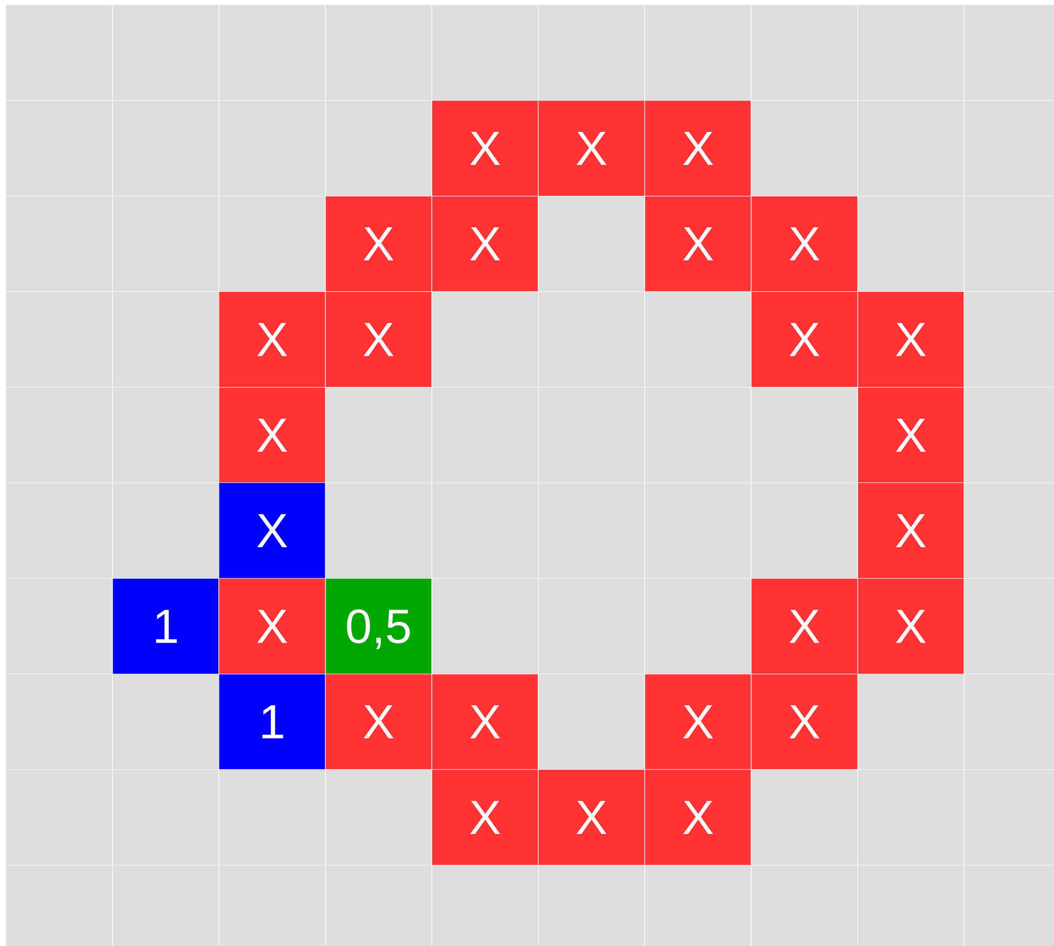

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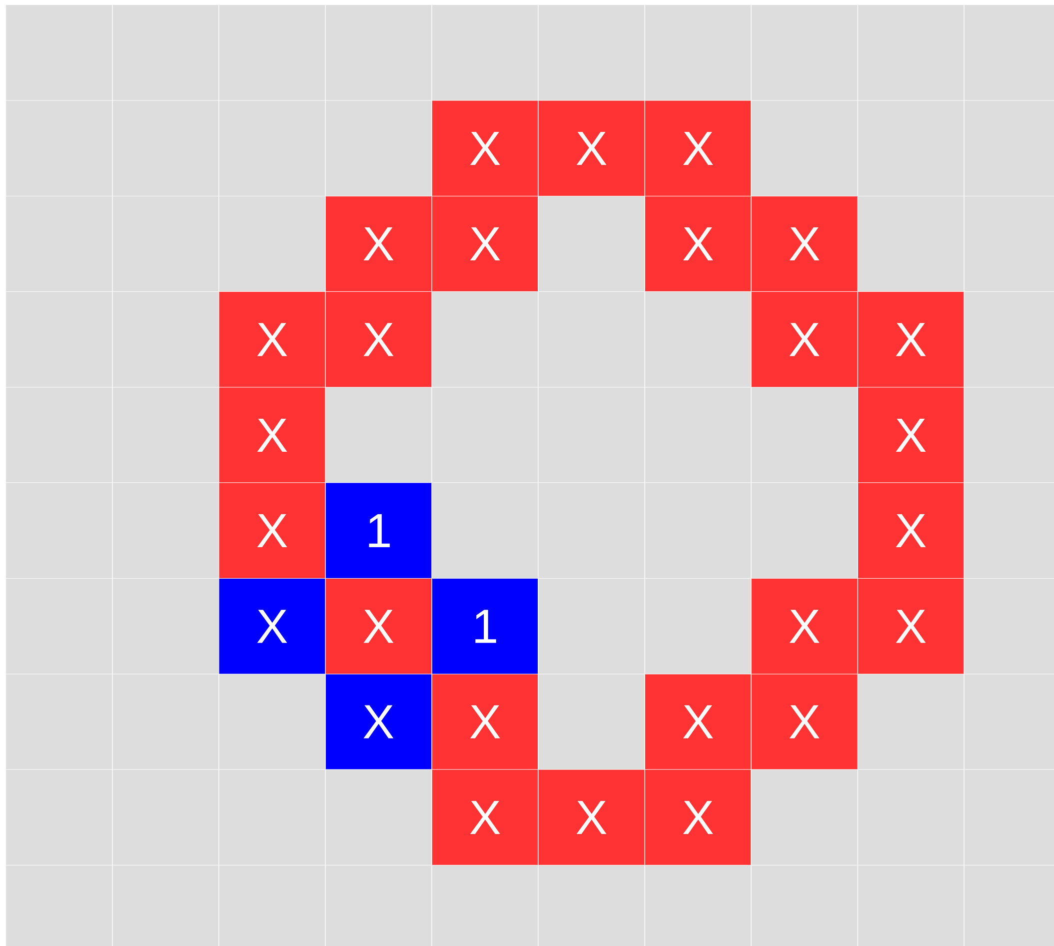
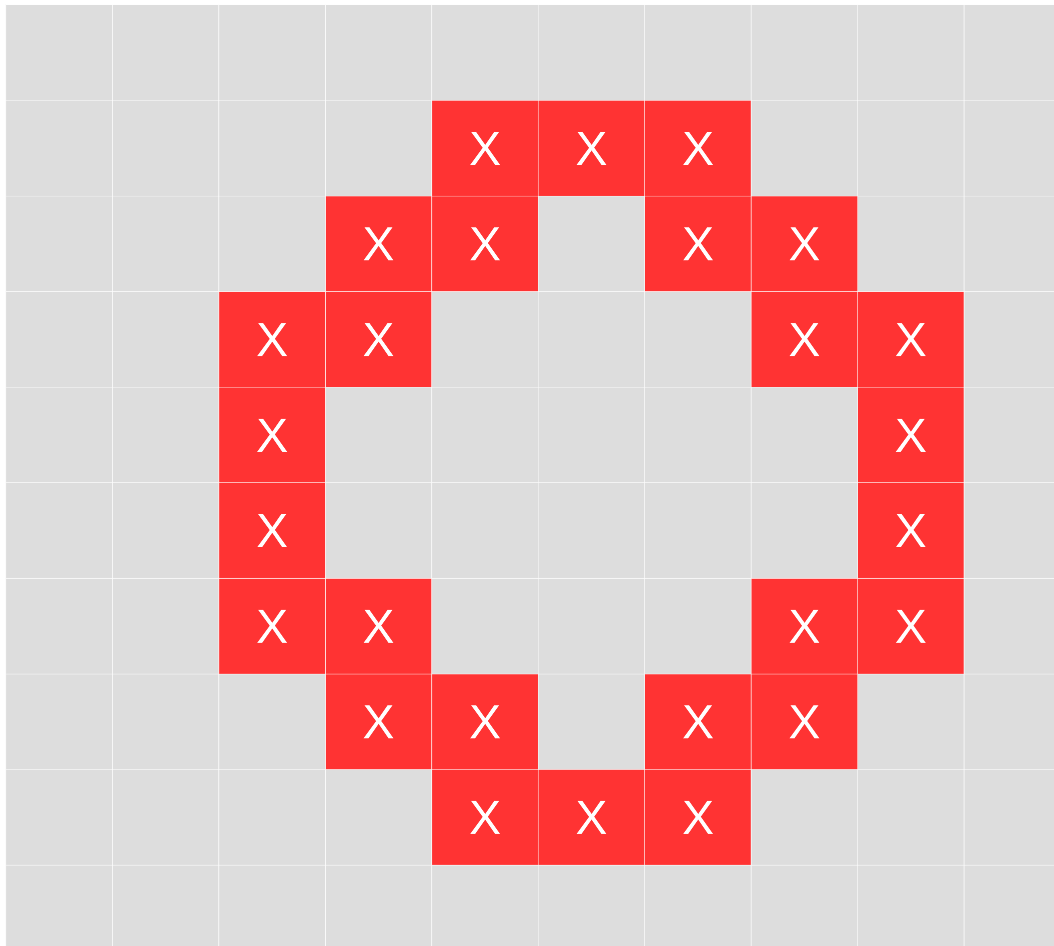
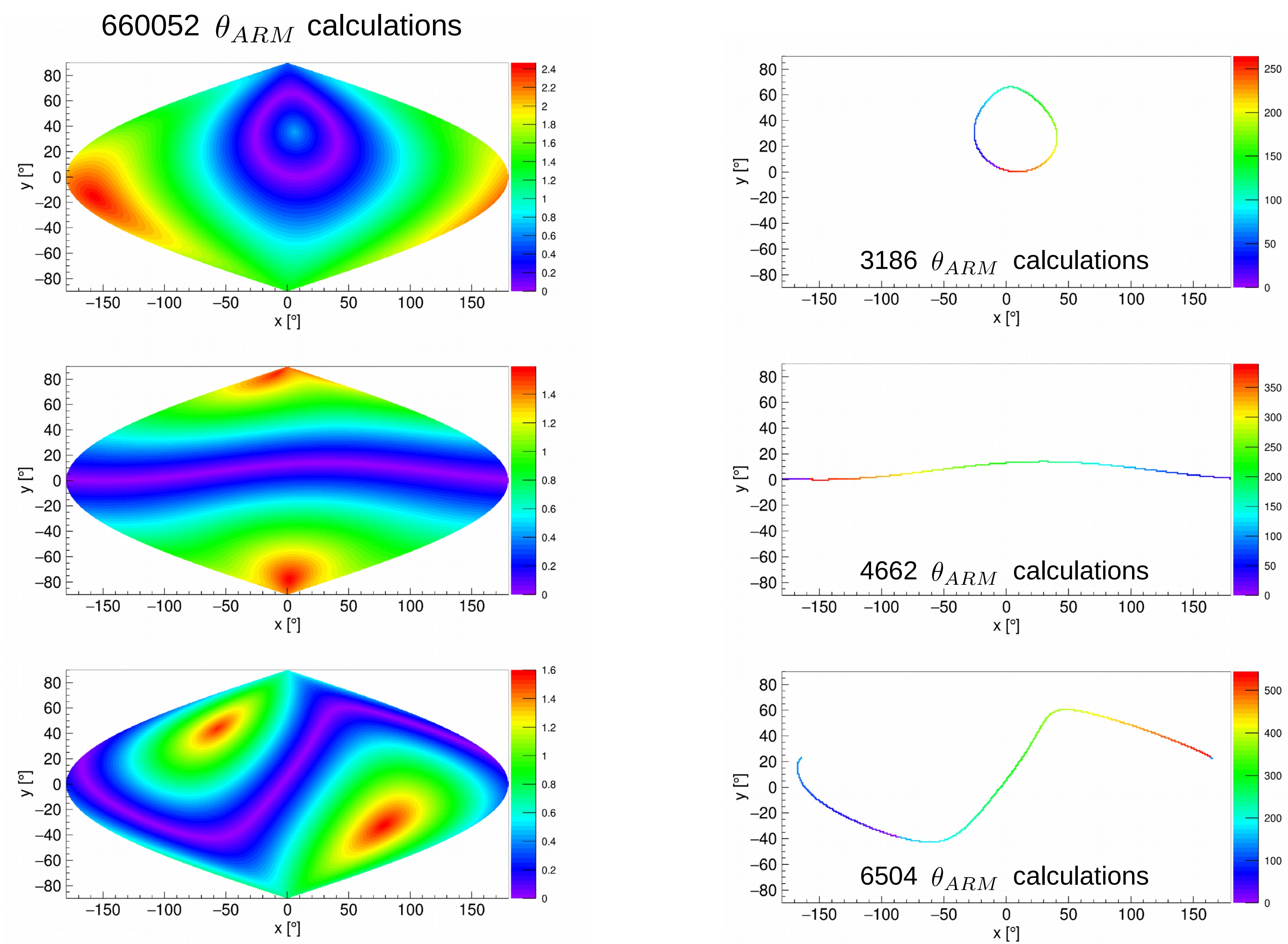


Walking algorithm



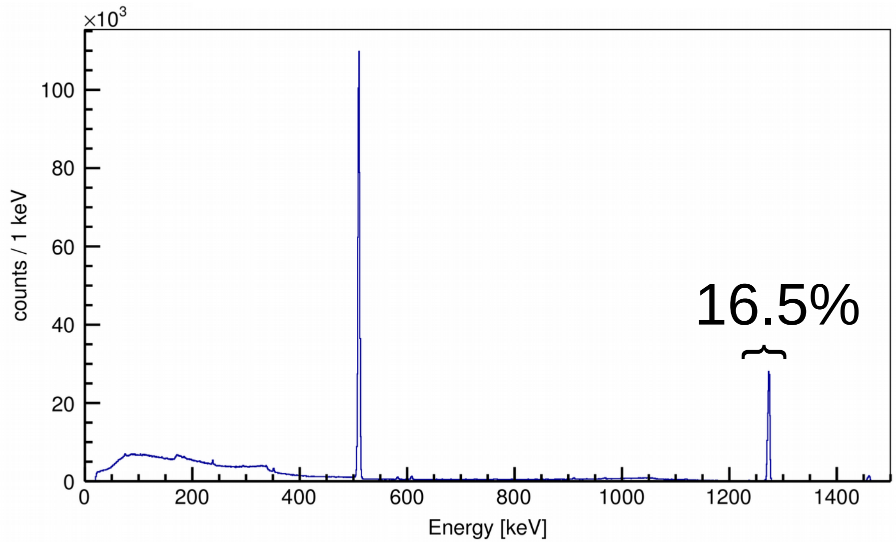
Walking algorithm : 78 calculations
Brute force : 100 calculations

Walking algorithm example



Imaging

Energy ~ 1274.5 keV



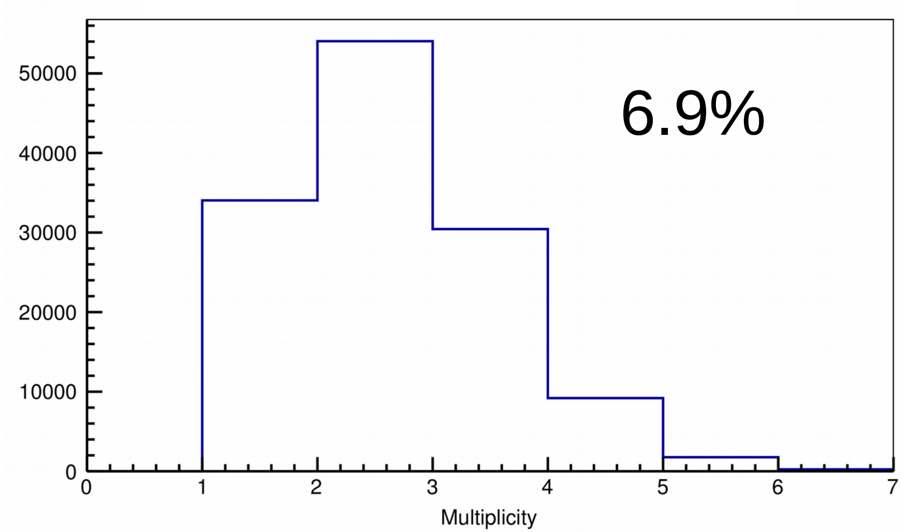
Source: Na-22 (75 kBq)

Time of measurement: 30 min

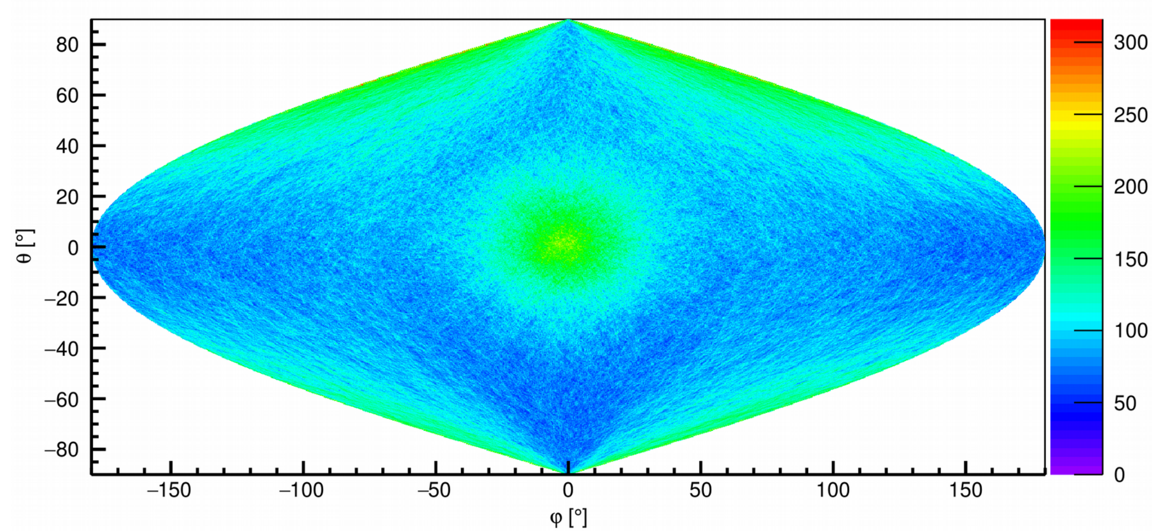
Distance: Source ↔ HPGe: 33 cm

Efficiency: 6.9 % (corrected for activity and geometry)

Multiplicity = 2



Compton image

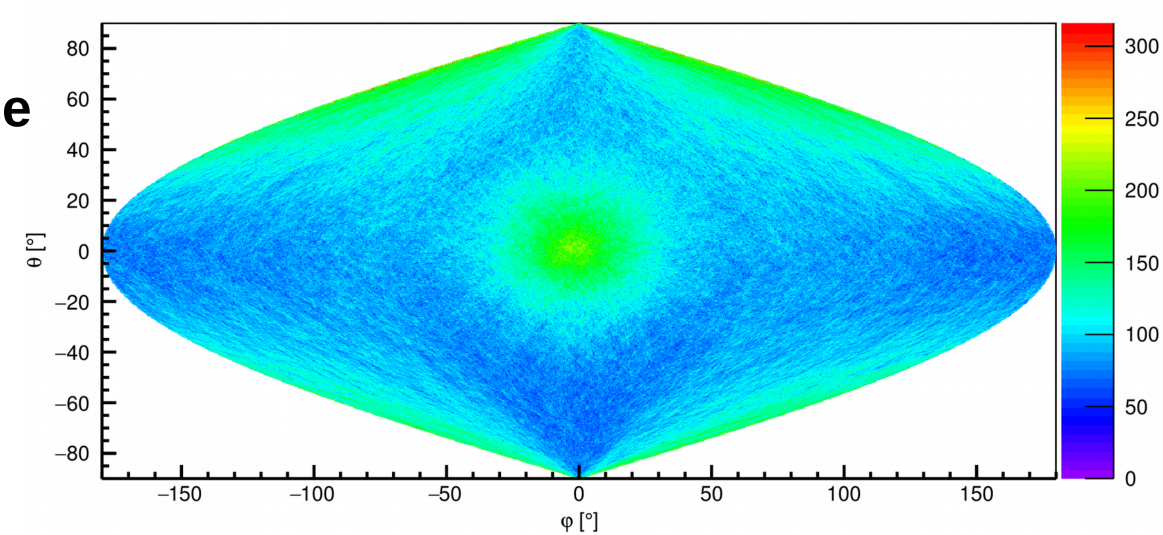


Interaction point sequence

Segment multiplicity = 2

Most probable interaction sequence

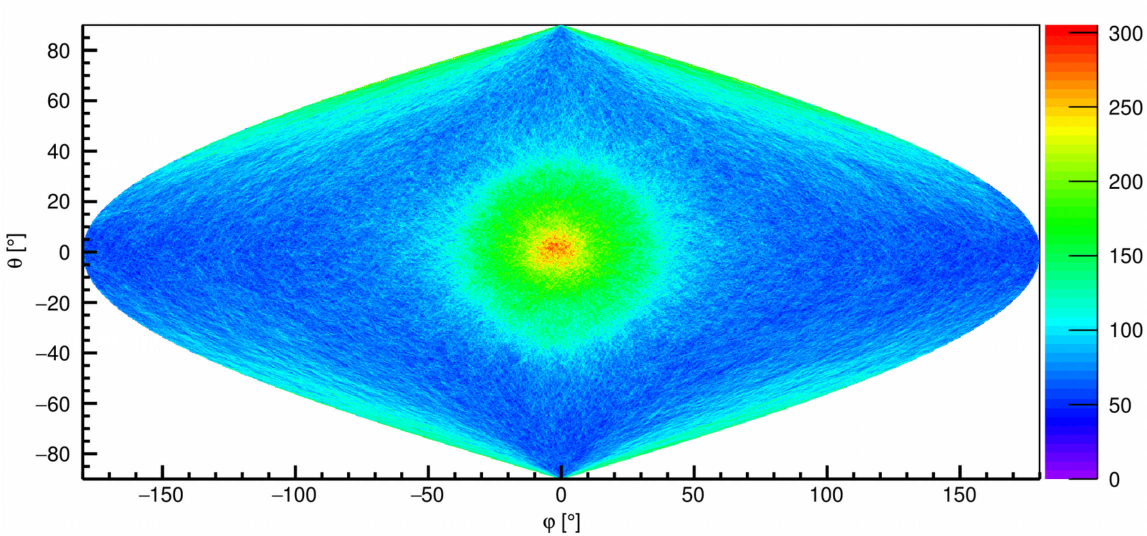
- Higher energy deposition at the first Interaction position $E_1 > E_2$
- Exception E_1 > Compton edge at ~1060 keV



Angular resolution = 31.8°

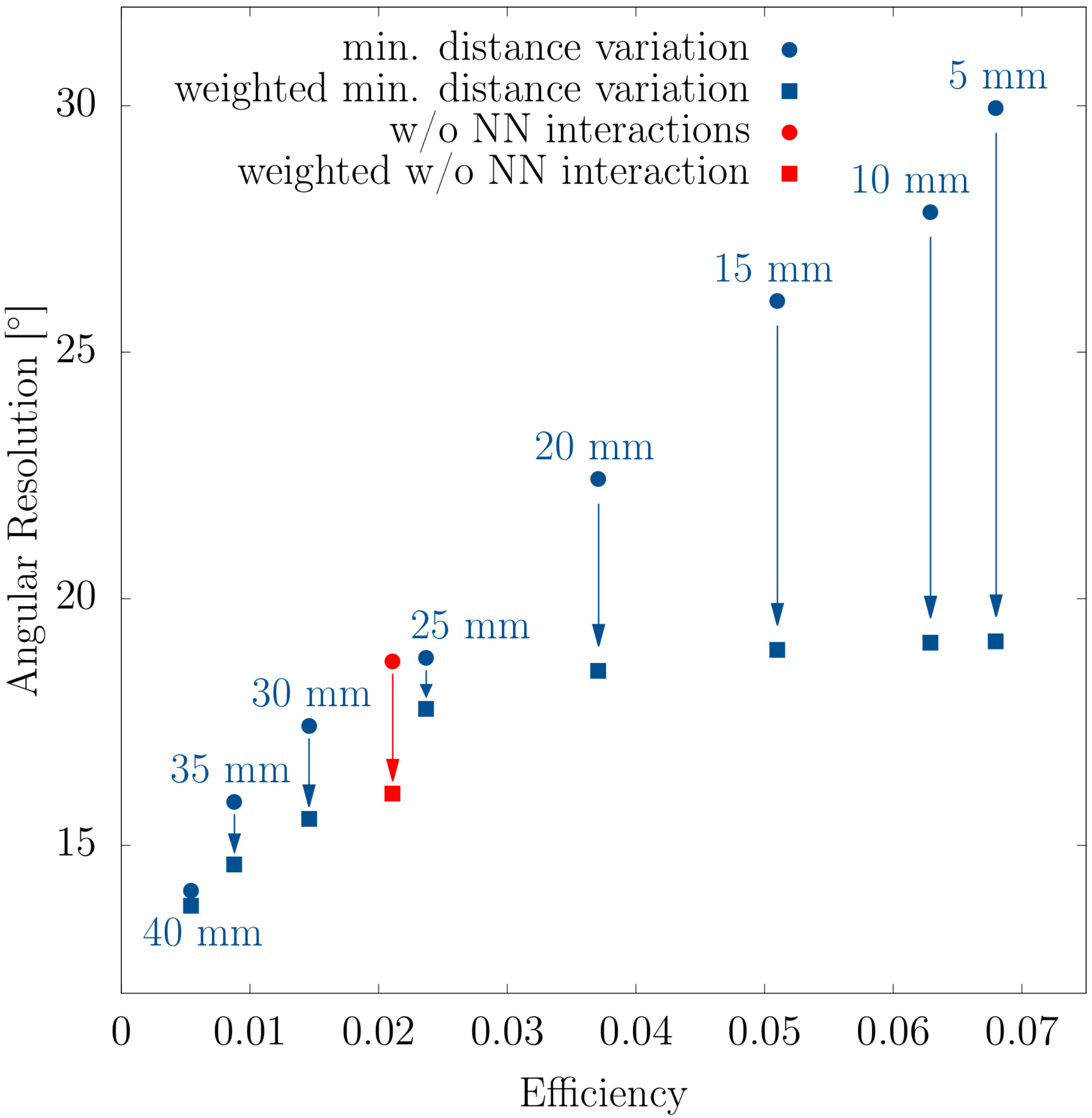
Tracking

- Point source
- Accumulation point roughly known
- Change interaction point sequence if:
  - $|\theta_{ARM}| > 35°$
  - $|\theta_{ARM}|$ is reduced

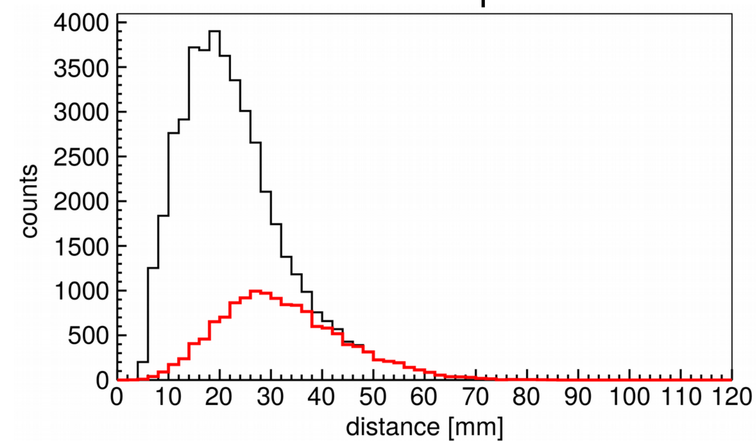


Angular resolution = 30.9°

Angular resolution vs. efficiency



Distribution of interaction point distances

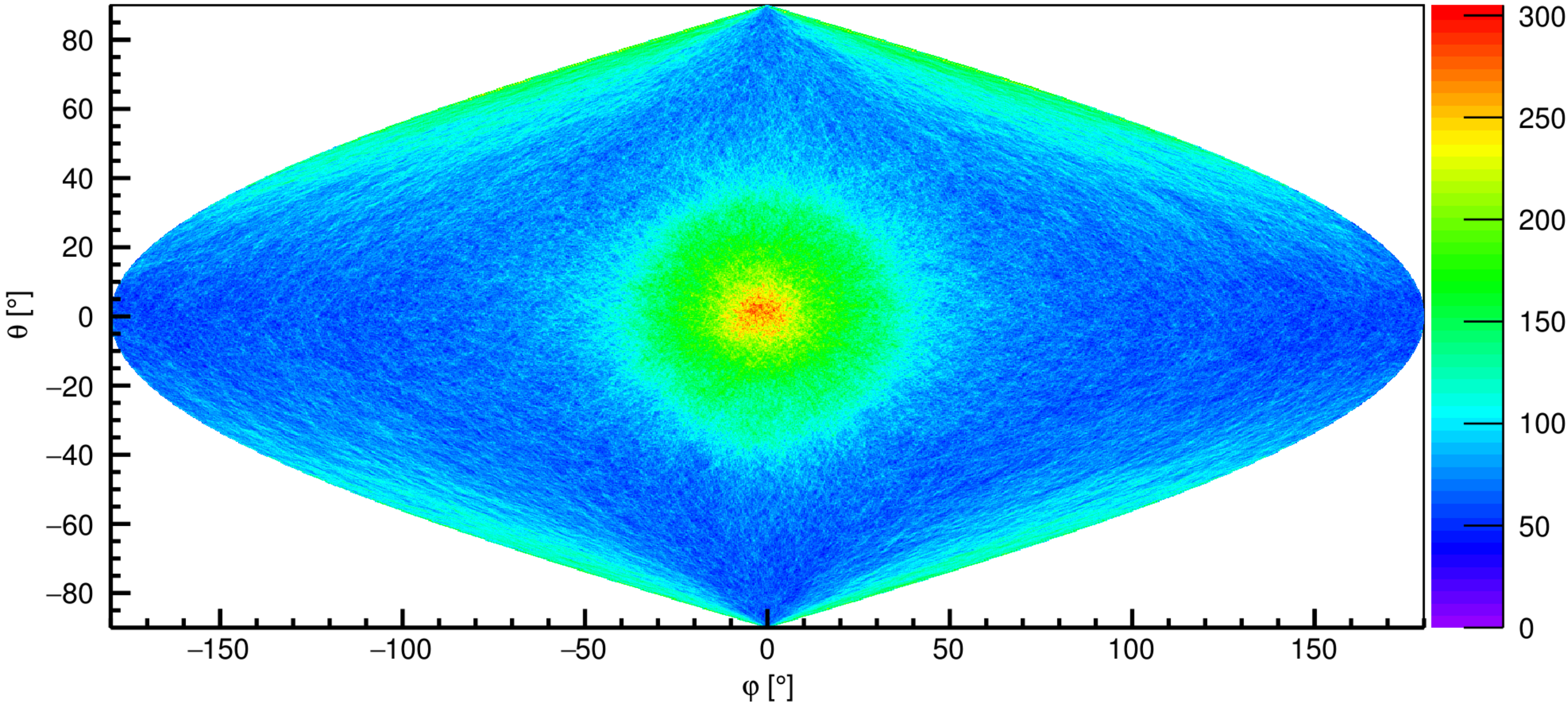


Weighting by interaction point distance

$$w = \frac{1}{\Delta_{axis}} \approx \frac{r_{1,2}}{\sqrt{\delta r_1^2 + \delta r_2^2}} \propto r_{1,2}$$

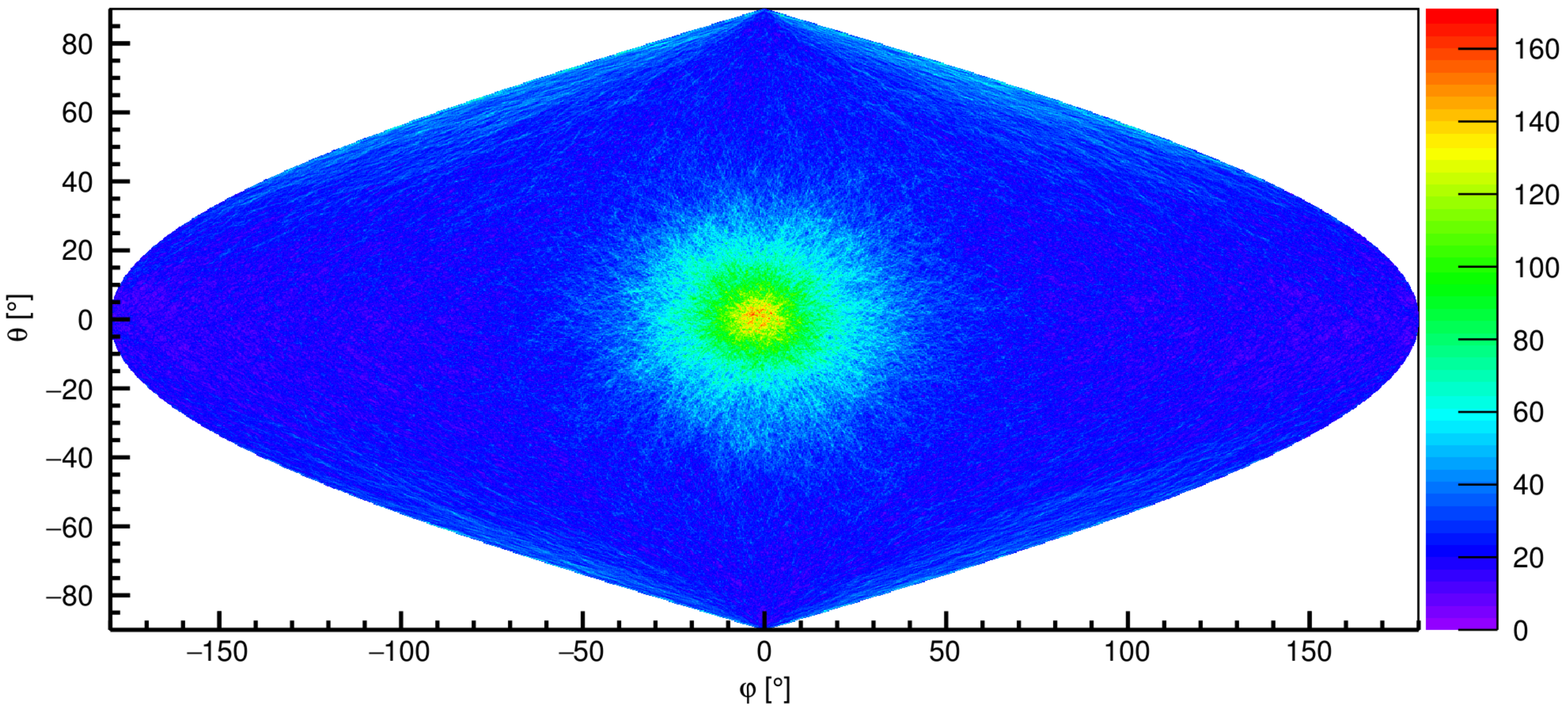
F. Recchia et al.,
Nucl. Instr. Meth. Phys. Res. A 604 (12) (2009) 60 – 63.

No distance cut



Efficiency: 6,9 % Angular Resolution: Δθ = 30,9°

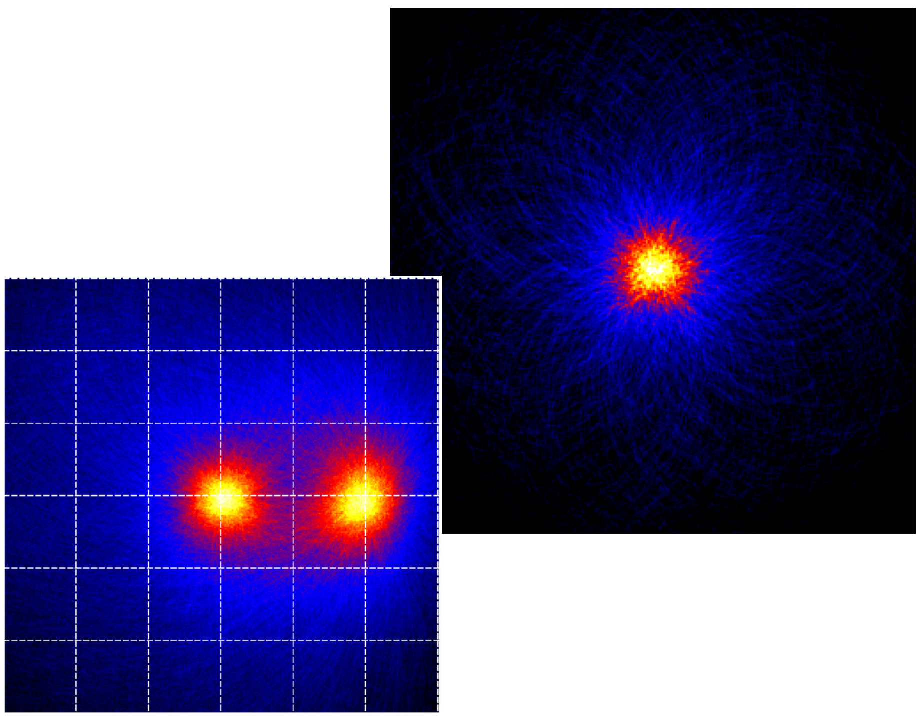
Next neighbor cut



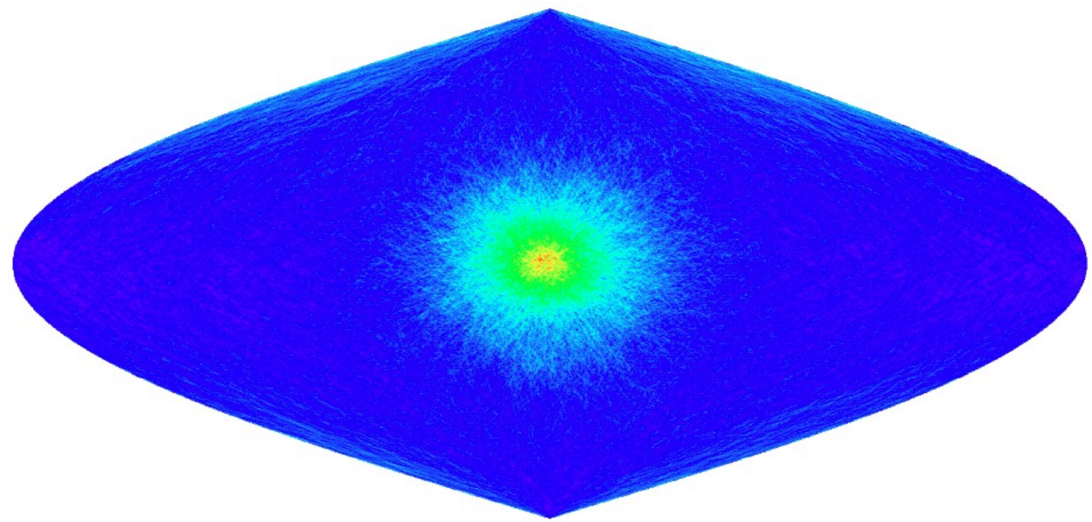
Efficiency: 2,1 % Angular Resolution: $\Delta\theta$ = 16,1°

Summary

- Coincidence mode
  - Angular resolution 4.6°
  - Low efficiency (1.7×10^{-5})



- High-Efficiency mode
  - Higher efficiency (up to 6.9%)
  - Lower angular resolution (between 19° and 14°)



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THE EUROPEAN PHYSICAL JOURNAL A

Special Article – Tools for Experiment and Theory

Compton imaging with a highly-segmented, position-sensitive HPGe detector

T. Steinbach[1], R. Hirsch[1], P. Reiter[1,a], B. Birkenbach[1], B. Bruyneel[1], J. Eberth[1], R. Gernhäuser[2], H. Hess[1], L. Lewandowski[1], L. Maier[2], M. Schlarb[2], B. Weiler[2], and M. Winkel[2]

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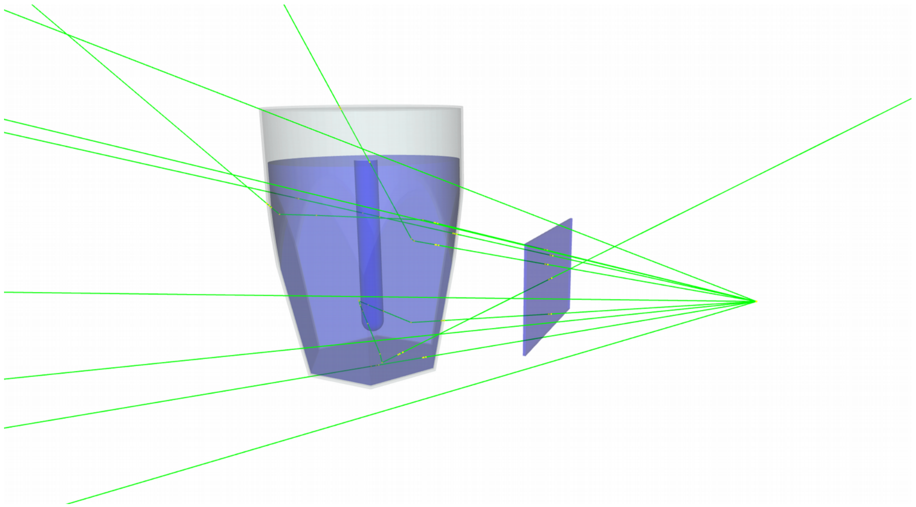
Abstract. A Compton camera based on a highly-segmented high-purity germanium (HPGe) detector and a double-sided silicon-strip detector (DSSD) was developed, tested, and put into operation; the origin of γ radiation was determined successfully. The Compton camera is operated in two different modes. Coincidences from Compton-scattered γ-ray events between DSSD and HPGe detector allow for best angular resolution; while the high-efficiency mode takes advantage of the position sensitivity of the highly-segmented HPGe detector. In this mode the setup is sensitive to the whole 4π solid angle. The interaction-point positions in the 36-fold segmented large-volume HPGe detector are determined by pulse-shape analysis (PSA) of all HPGe detector signals. Imaging algorithms were developed for each mode and successfully implemented. The angular resolution sensitively depends on parameters such as geometry, selected multiplicity and interaction-point distances. Best results were obtained taking into account the crosstalk properties, the time alignment of the signals and the distance metric for the PSA for both operation modes. An angular resolution between 13.8° and 19.1°, depending on the minimal interaction-point distance for the high-efficiency mode at an energy of 1275 keV, was achieved. In the coincidence mode, an increased angular resolution of 4.6° was determined for the same γ-ray energy.

Geant4 simulation

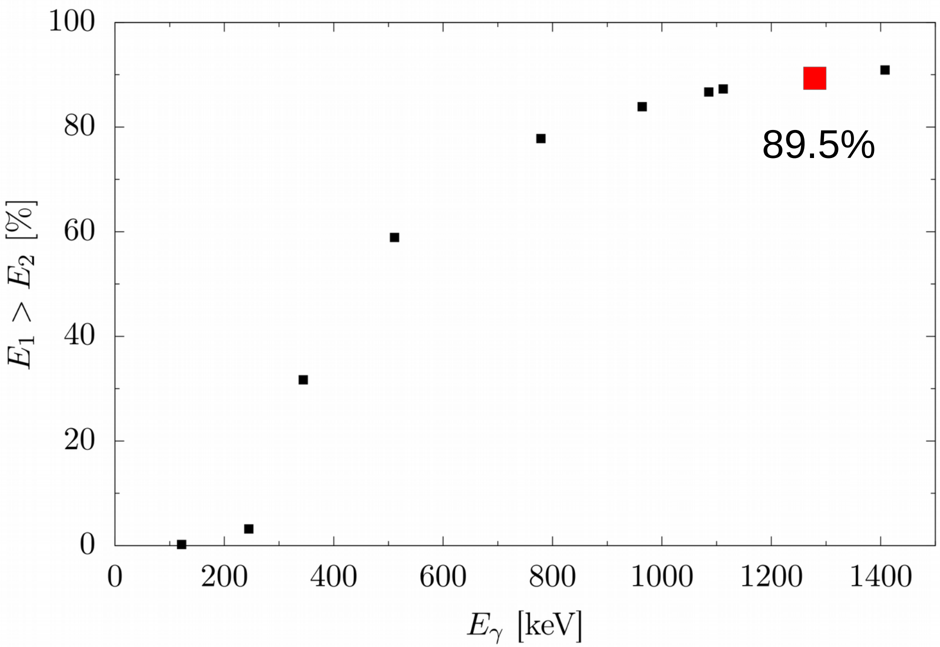
Geant4 simulation

- Both operation modes
- Energy depositions at interaction points
- Interaction sequence tracking

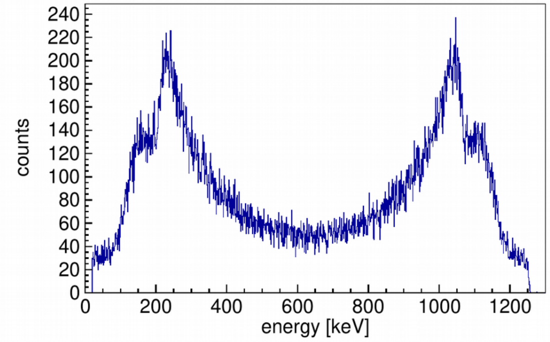


Energy depositions multiplicity = 2
Energy: 1275 ± 5 keV

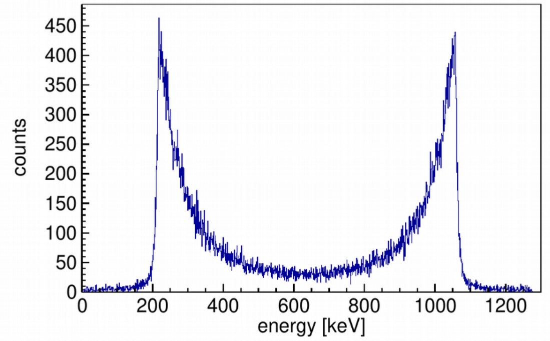
Interaction sequence probability
HPGe stand-alone mode



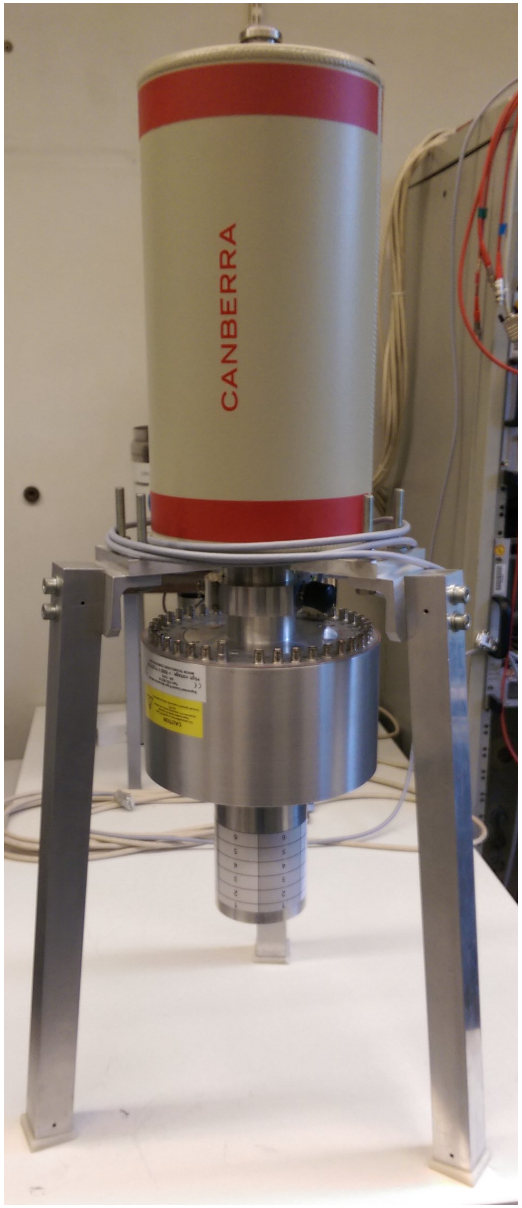
Experiment



Simulation



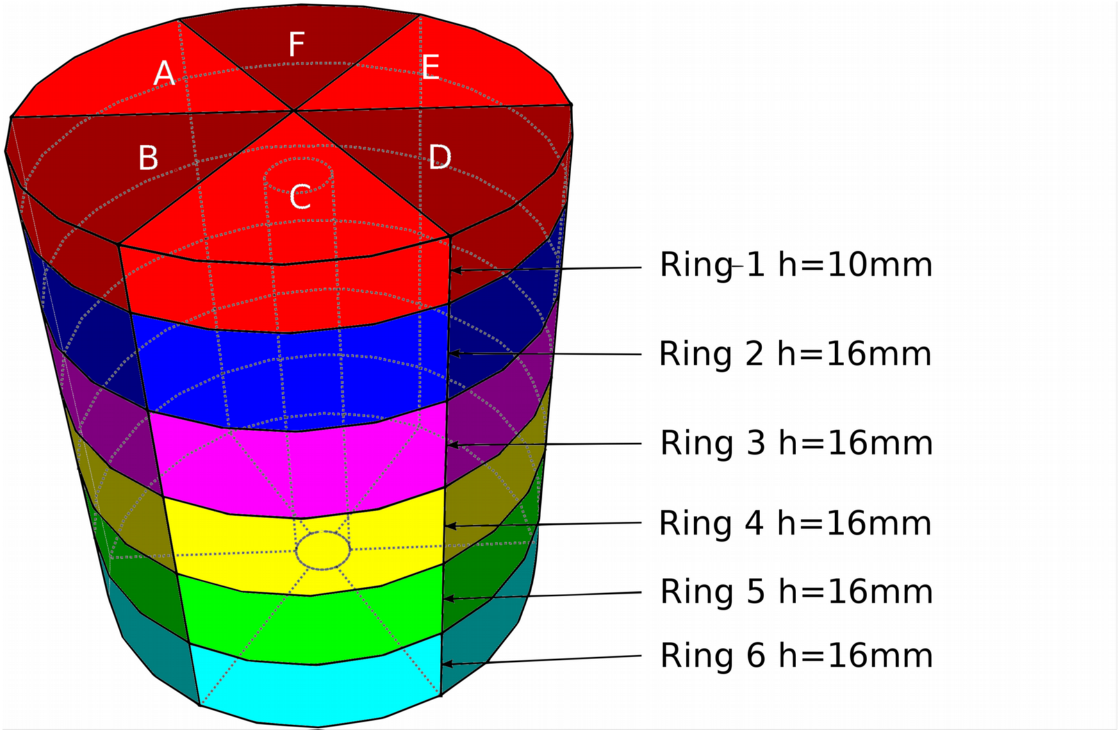
New HPGe-Detektor



Canberra EGC-36

- Closed-ended coaxial shape
- 36 Segments
- h=89mm Ø=80mm
- Average signal risetime 26 ns
- 109% efficiency

For comparison: Efficiency of AGATA/S001 71.1%



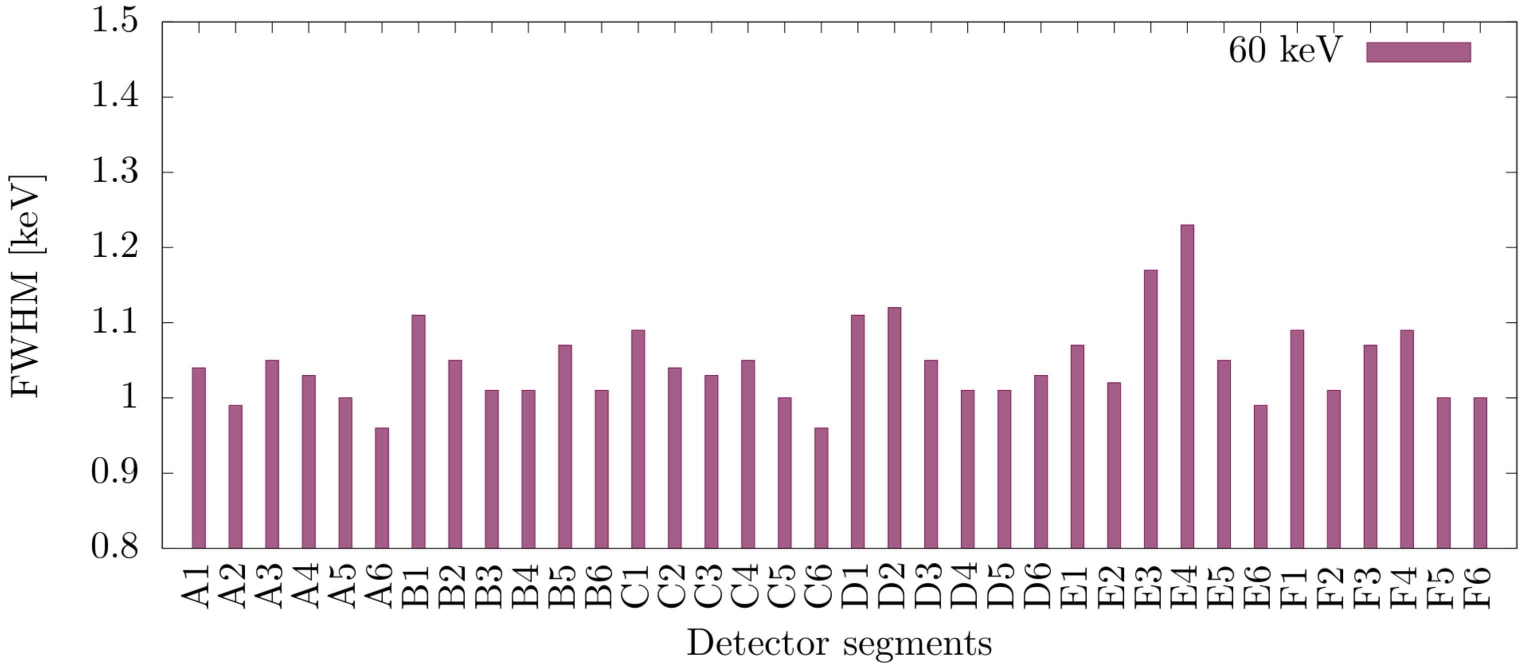
Energy resolution

Am-241

Specification:
ΔE < 1.2 keV

Segments Avg.:
ΔE = 1.045 keV

Core:
ΔE = 1.00 keV

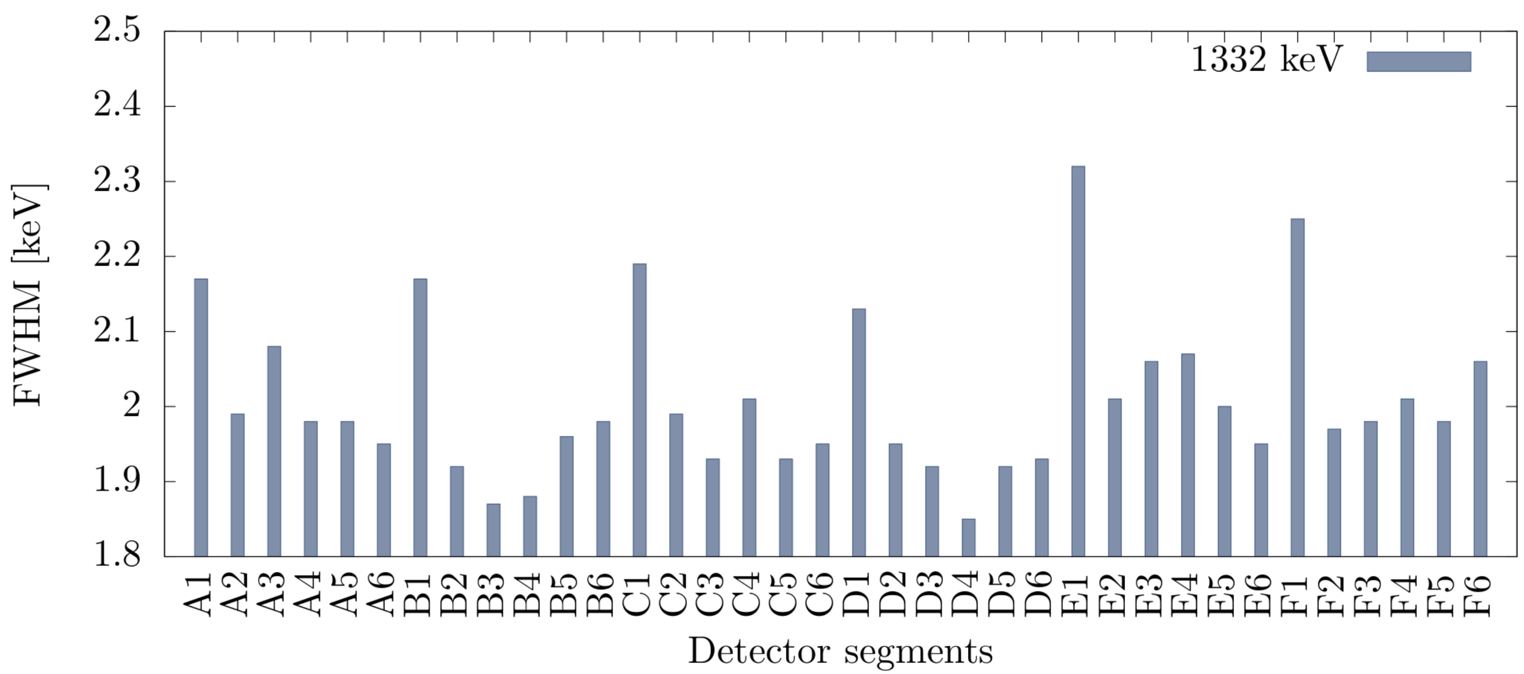


Co-60

Specification:
ΔE < 2.1 keV

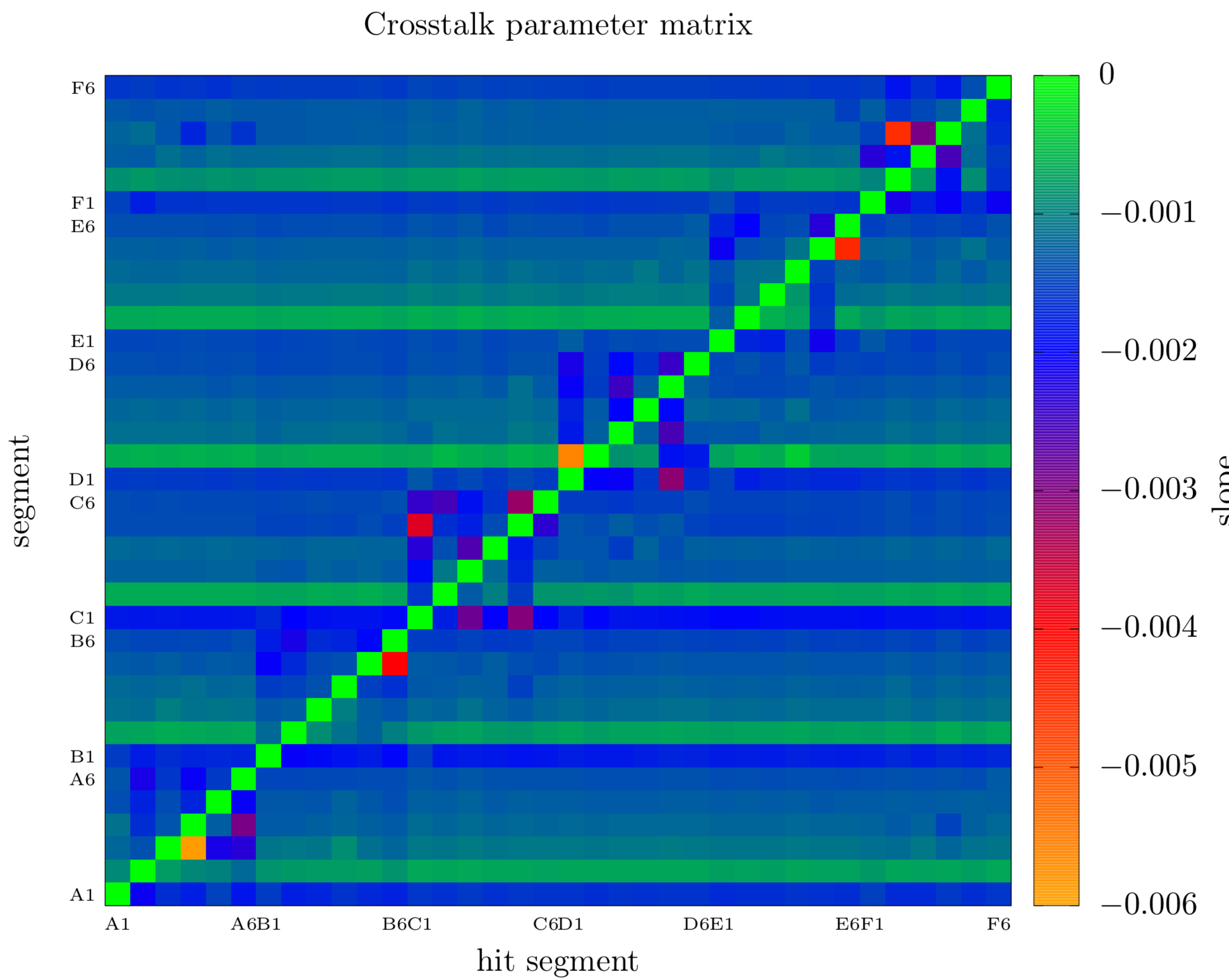
Segments Avg.:
ΔE = 2.008 keV

Core:
ΔE = 2.21 keV



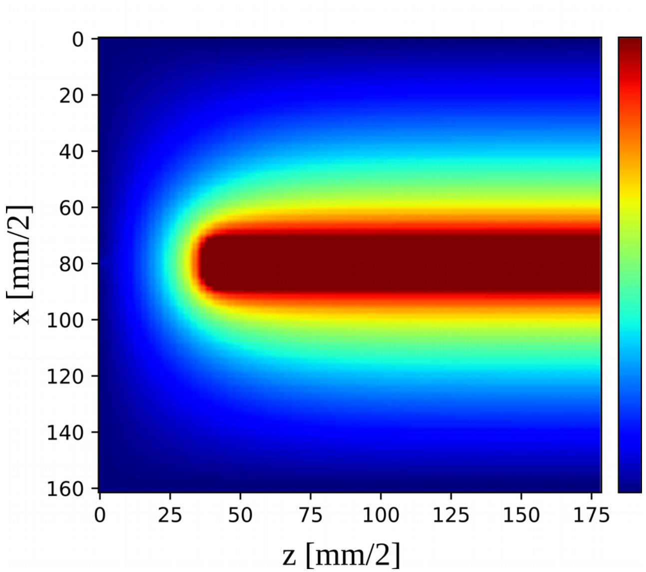
Crosstalk measurement

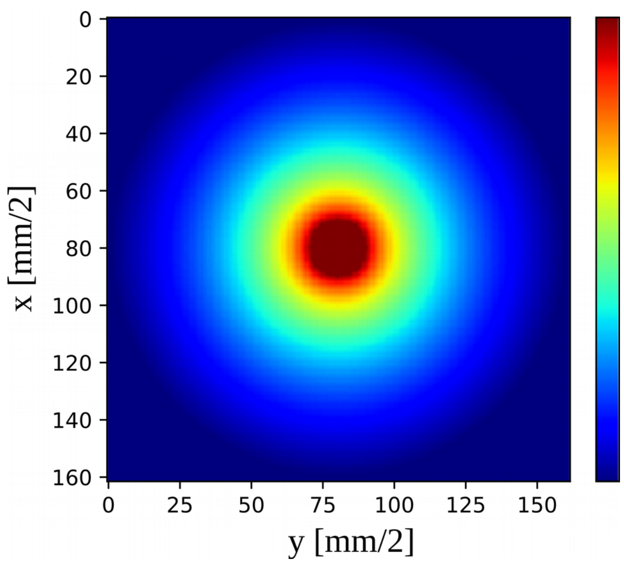
Average:
slope = -0.0013



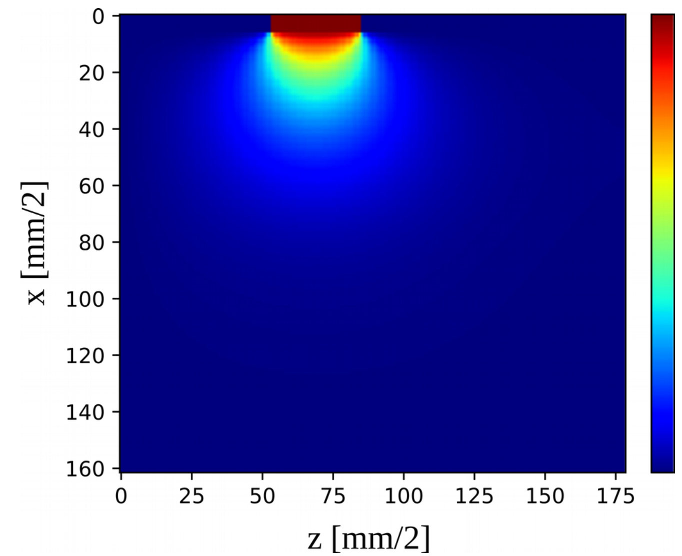
ADL3 – Weighting potentials

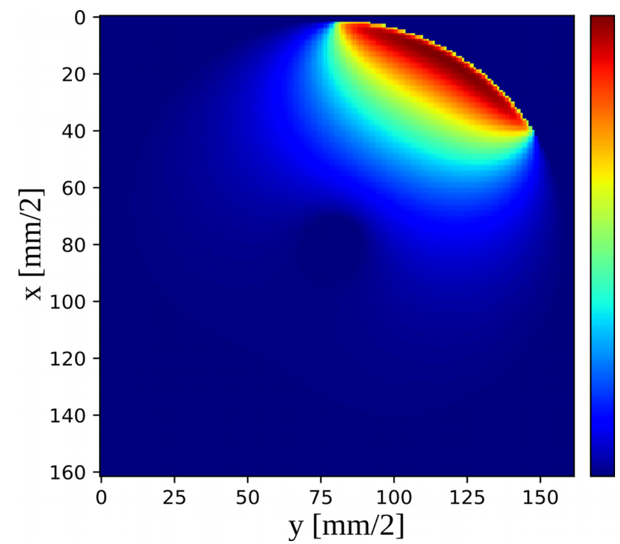
Core electrode





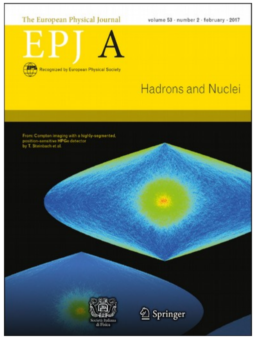
Segment C3



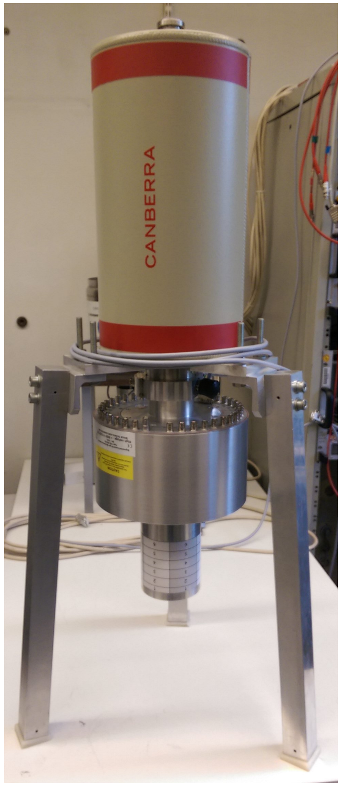


Summary and Outlook

- IKP Compton camera
  - Successful operation
  - Two operation modes



- New detector
  - Implementation
  - Preparation Data Library



- Development of Geant4 simulation

- Implement advanced imaging algorithms

Thank you for your attention!

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