Optimizing the design of a Timepix4 based compact gamma camera with validated Geant4 Monte Carlo simulations

Laura Antonia Cerbone[1,2,5], Antonio Sarno[1,2], Massimiliano Fiorini[3,4], Nicolò Vladi Biezus[3,4], Riccardo Bolzonella[3,4], Giovanni Mettivier[1,2], Paolo Russo[1,2]

1. Dipartimento di Fisica “Ettore Pancini”, Università di Napoli Federico II
2. Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Napoli
3. Dipatimento di Fisica e Scienze della Terra, Università di Ferrara
4. Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Ferrara
5. Scuola Superiore Meridionale, Napoli

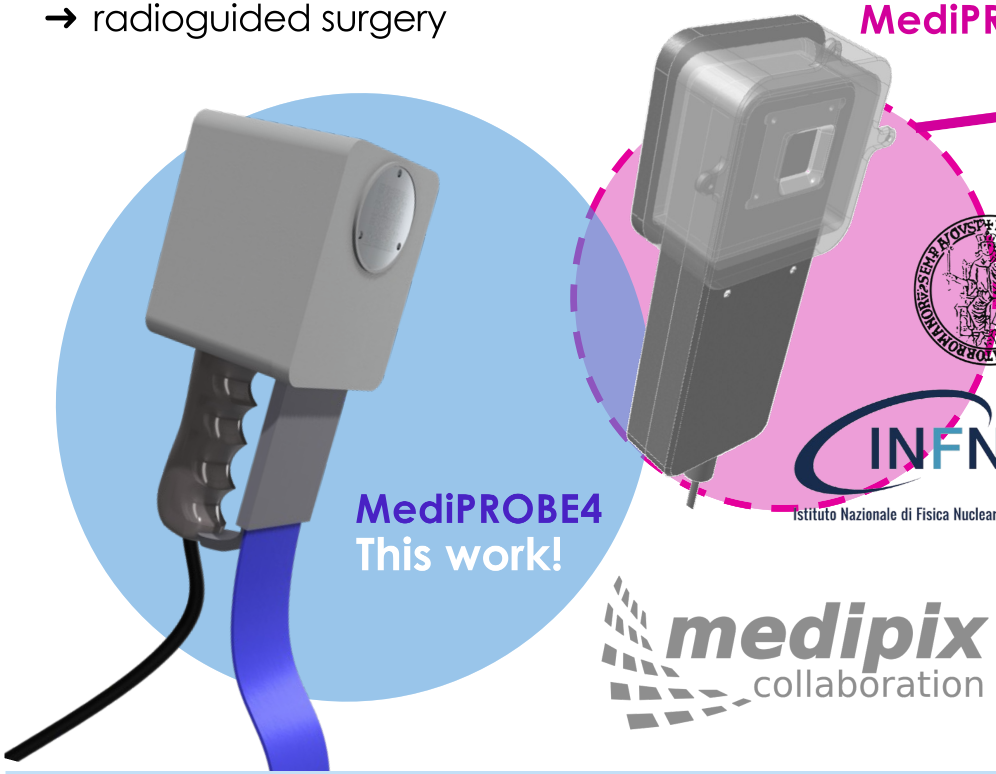
Geant4 based optimization for semiconductor hybrid pixel detector for nuclear medicine imaging

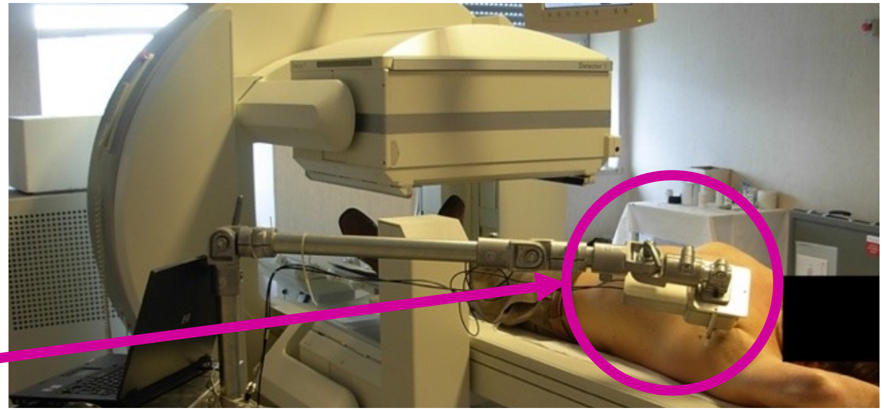
A **portable gamma camera** is a small, light-weight gamma ray detector that can be used for pre- and intra-operative clinical procedures, tipically with Tc-99m radiotracers

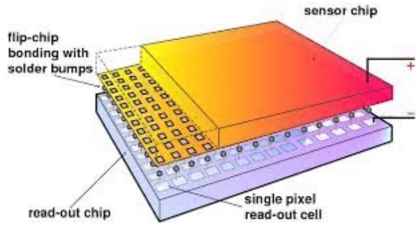
→ sentinel lymph node scintigraphy

→ radioguided surgery

MediPROBE2







Hybrid pixel detectors
Semiconductor sensor bump-bonded to a readout chip.

MediPROBE2 (2011)

Medipix2 ASIC (256 x 256 pixels, 55 μm pitch).
1-mm-thick CdTe sensor (sensitive area 1.98 cm^2).
Readout mode: frame based (Imaging).
FOV: 40 x 40 mm^2 at 50-mm skin-to-collimator distance.
Spatial Resolution: 5.5 mm FWHM (0.94 mm pinhole) at 50-mm skin-to-collimator distance.

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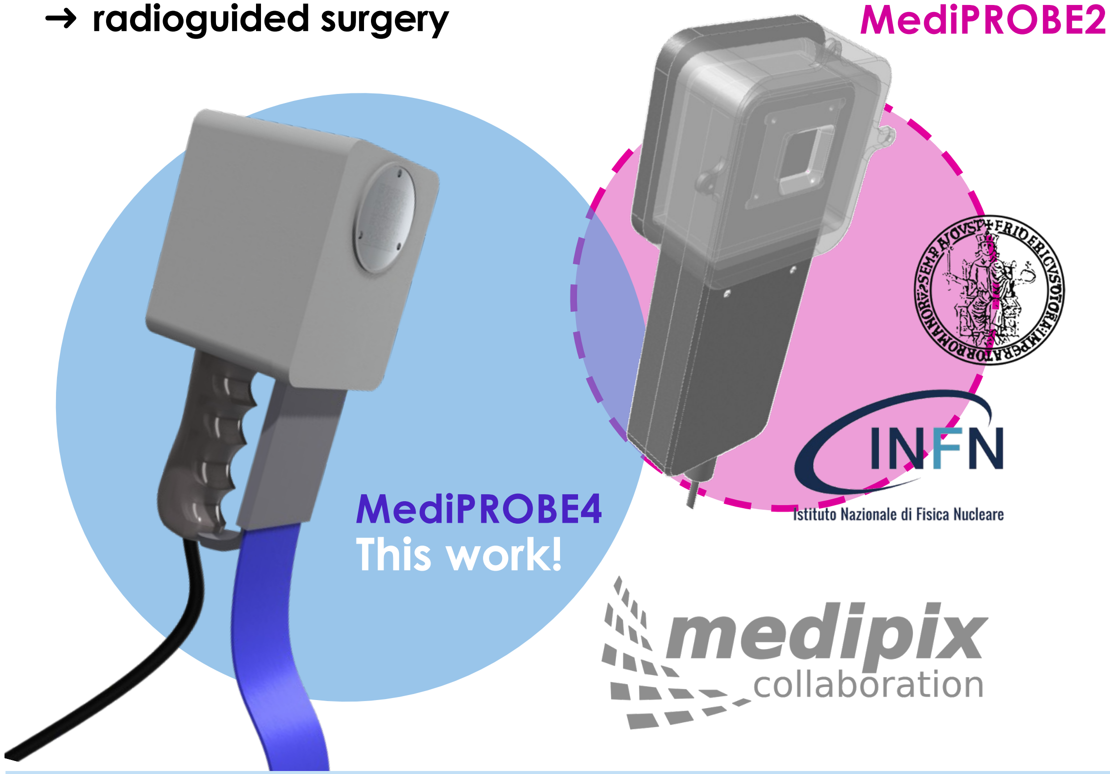

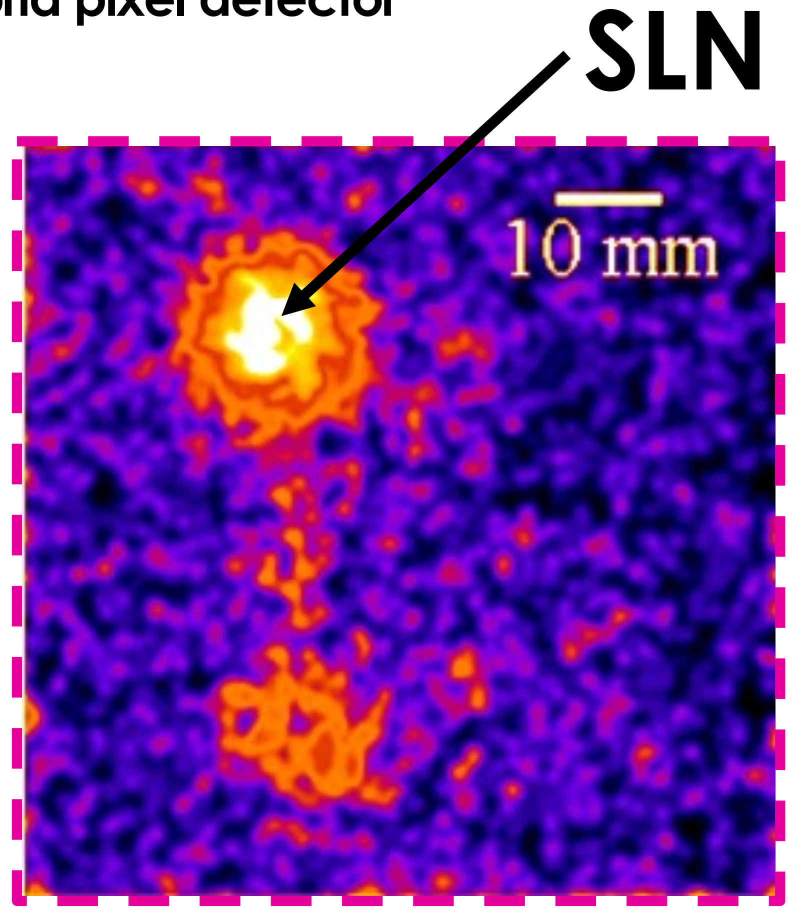

Image of two lymph nodes acquired with MediPROBE2 (pinhole 0.94 mm aperture)

Geant4 based optimization for semiconductor hybrid pixel detector for nuclear medicine imaging

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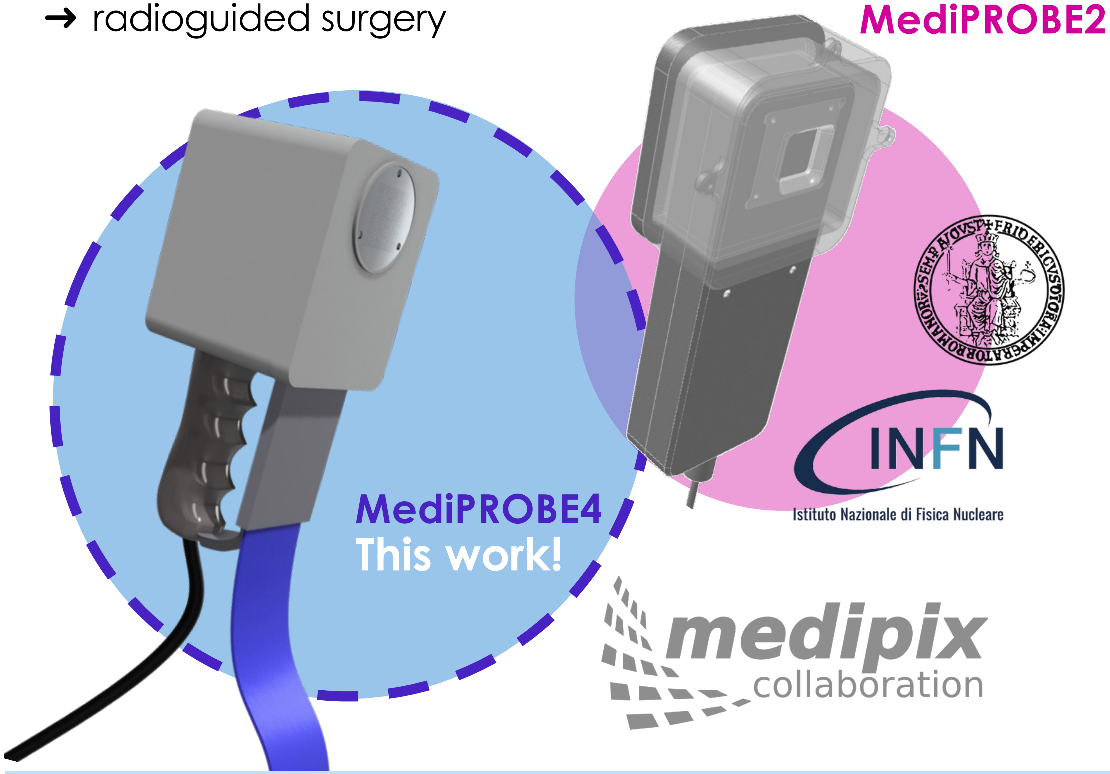
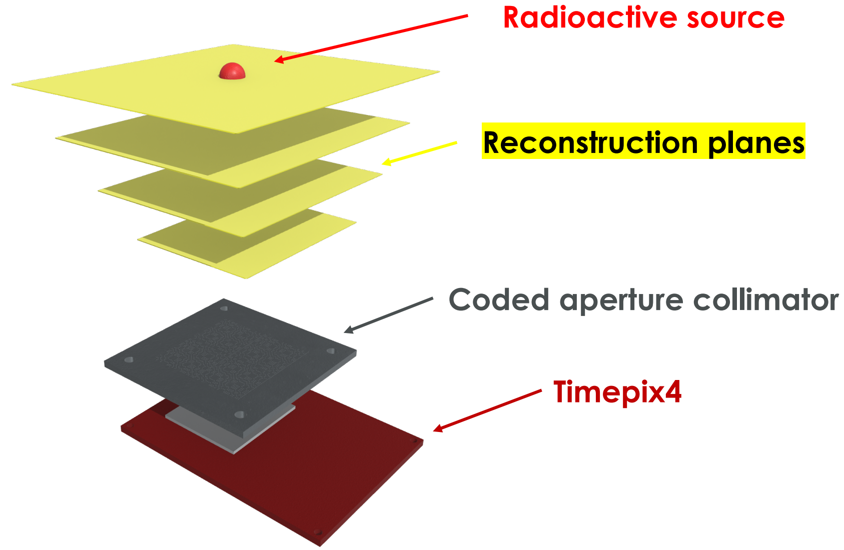
➜ sentinel lymph node scintigraphy

➜ radioguided surgery



MediPROBE4 (2022) with Timepix4

Timepix4 ASIC (448 x 512 pixels, 55 µm pitch).
0.3-mm-thick Si sensor (sensitive area 6.93 cm^2).
Readout modes: Frame based + Data Driven (tracking).
Coupled to a Coded Aperture (CA) collimator.



With CA mask, from 2D data, one can obtain a 3D reconstruction of the emitting object (through a deconvolution algorithm).

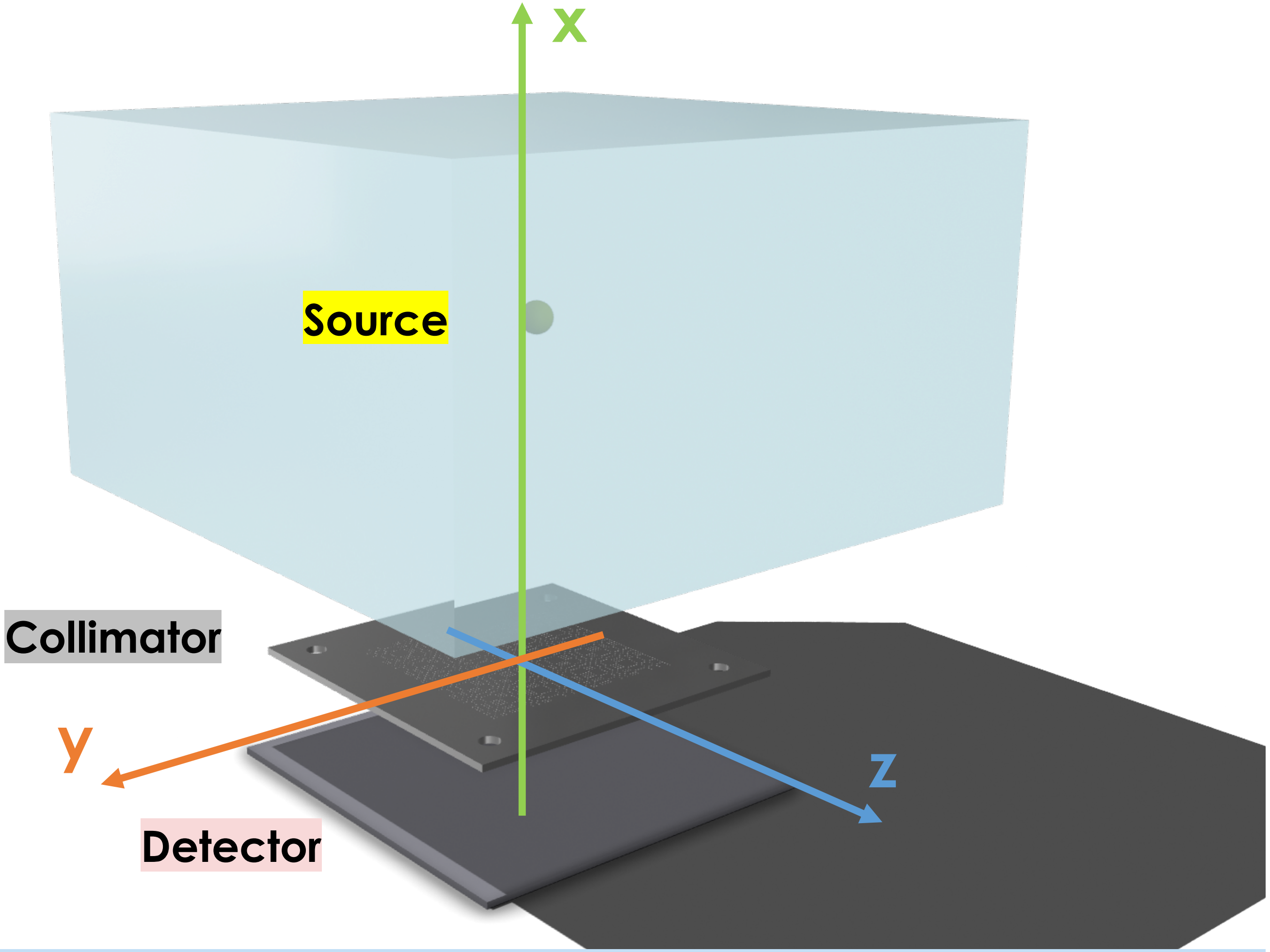
Monte Carlo simulations with Geant4

Version 10.6
PhysicsListStdOpt4()

Simulated processes
◎ Photoelectric absorption
◎ Coherent and incoherent scatter
◎ Deexitations processes

Electron range cut-off: 1 μm

We used Geant4 MC simulation to simulate images acquired by our imaging system to later decode them using a deconvolution algorithm and study them.



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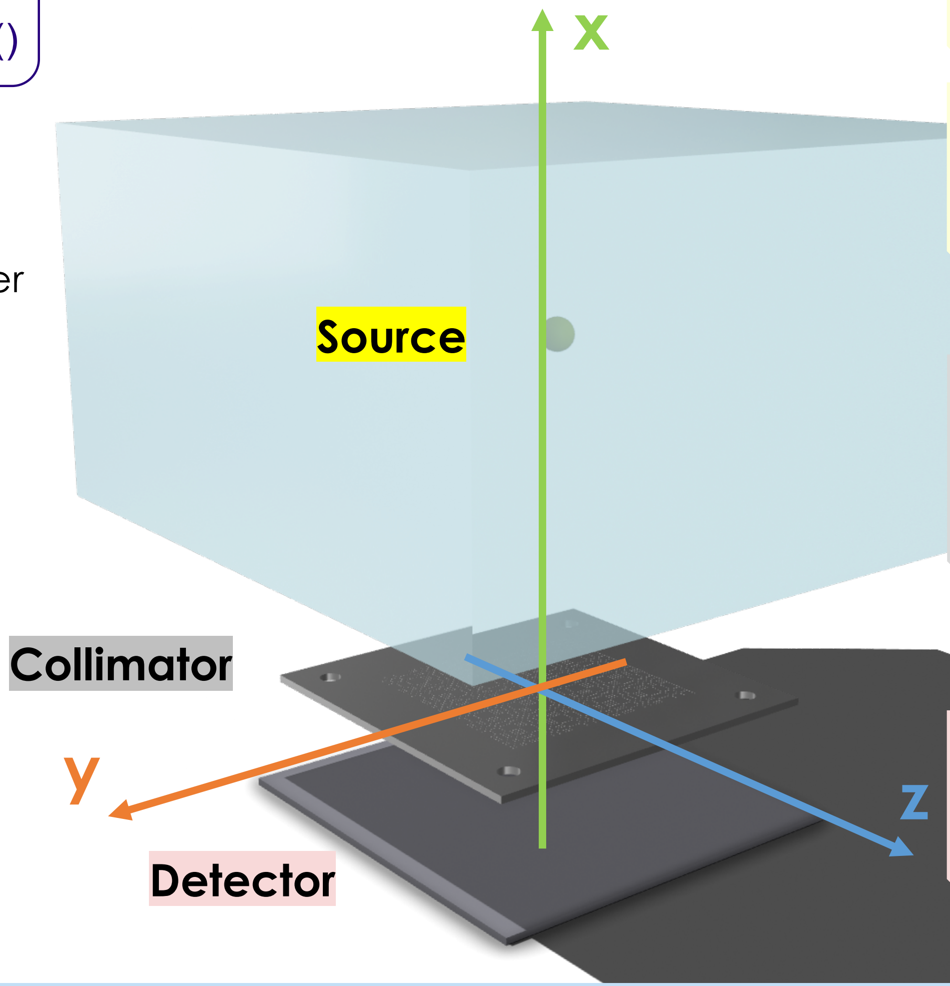


Geometry
- Planar round source
- Spherical source

Photon energy
- Monoenergetic
- Radioactive sources spectra (Tc99m, Ba133, Am241)

Coded Aperture Collimator
Interactions with the collimator were simulated, as well as with the interposed material (e.g. water phantom simulating tissue)

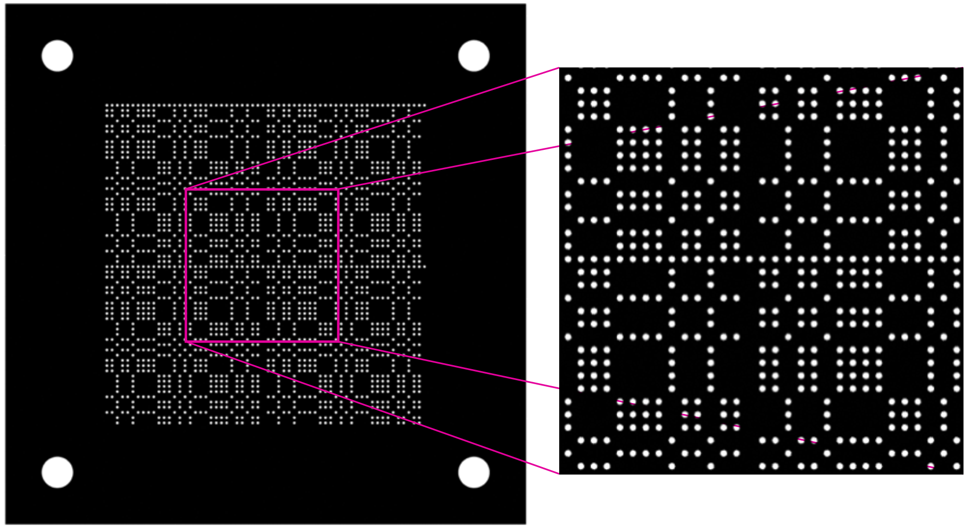
Detector
CdTe (1 or 2 mm thick) or Si sensor (300 µm thick) (55µm x 55µm pixel)

Monte Carlo simulations for collimator optimization

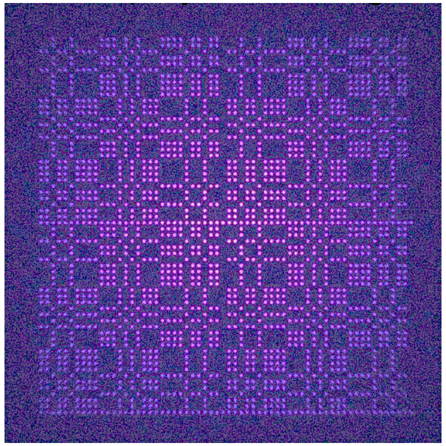
Geant4 simulations to study the collimator.

Anti-symmetric NTHT 62 × 62 MURA mask.

Hole aperture diameter [mm]	0.25
Collimator thickness [mm]	1
Total no. of apertures in the collimator	4 x 480
Collimator material	W



140.5 keV 1-mm source at 50 mm from the collimator



Output image obtained from the Monte Carlo simulation, i.e. **projection image of the coded aperture collimator** on the detector

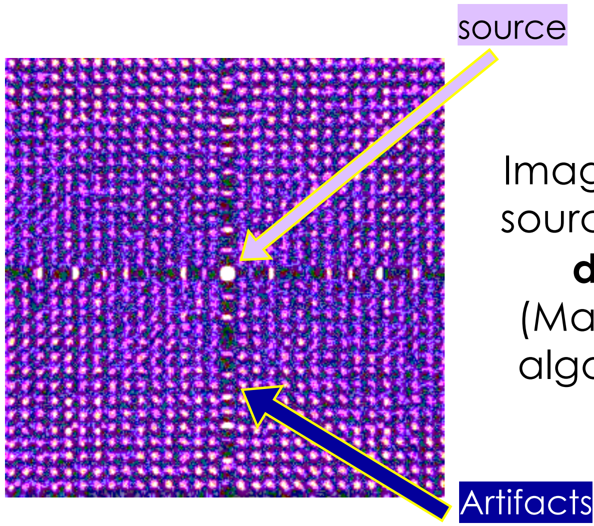


Image of the radioactive source obtained **after the decoding process** (MatLab deconvolution algorithm by R. Accorsi)

Monte Carlo simulations for collimator optimization

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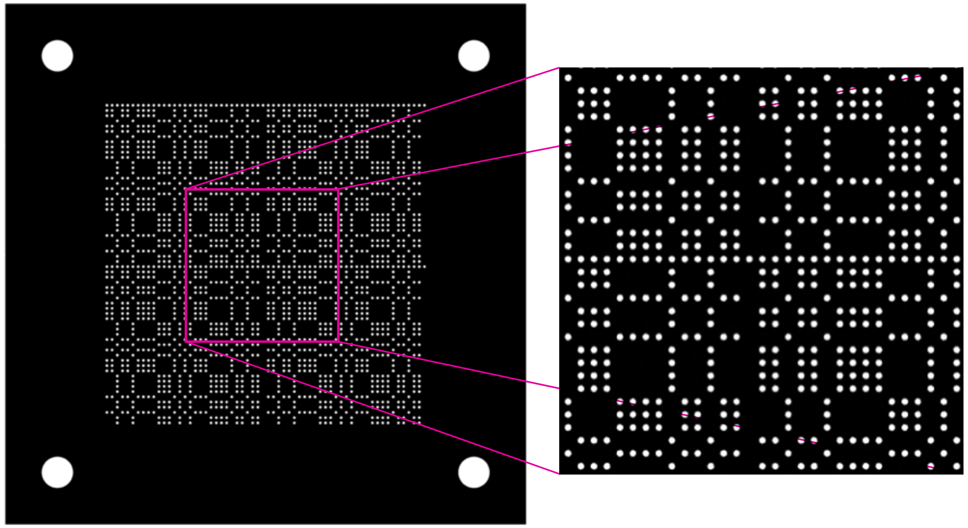


(for a 140 keV source at 50 mm from the collimator and detector at 10 mm from the collimator)

	MC simulations	Theory
Transmittance W sheet	2.8%	2.6%
FOV	90 x 90 mm^2	90.3x90.3 mm^2
Sensitivity	4 x 10^{-4} (290 times that of single aperture in the mask)	480 times that of single aperture in the mask
Collimator lateral spatial resolution FWHM	(1.7±0.7) mm	1.44 mm

Good agreement between MC and collimator theory

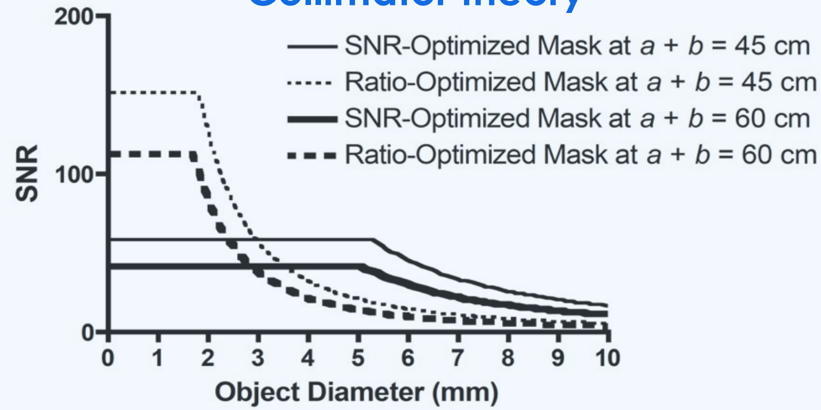
Image quality for extended sources

SNR for CA mask depends linearly on the **concentration parameter** (= 1 for point sources and approaches zero for extended sources)

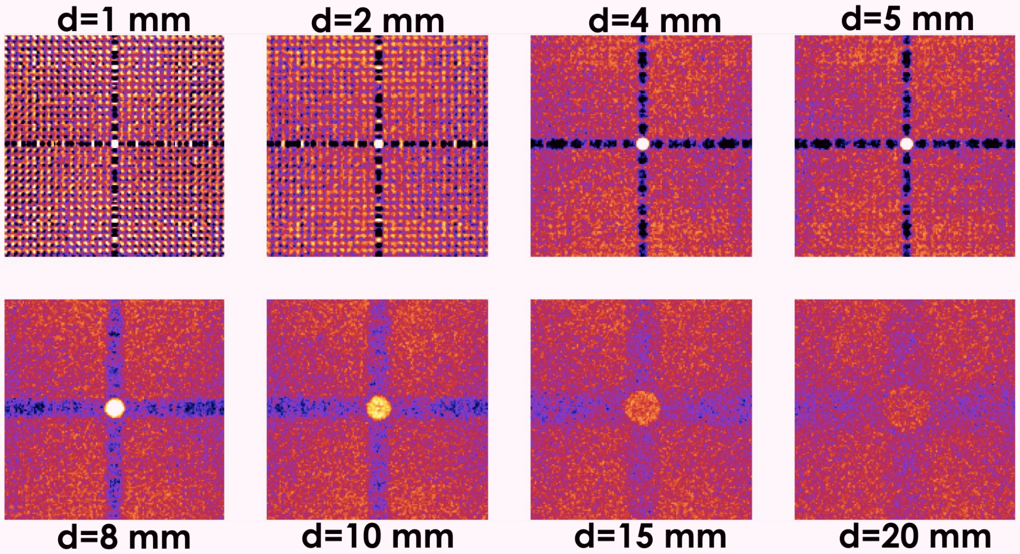
Circular planar sources of various diameters were simulated (**photon flux on the detector is constant**)

Detail SNR was computed for each of the decoded images

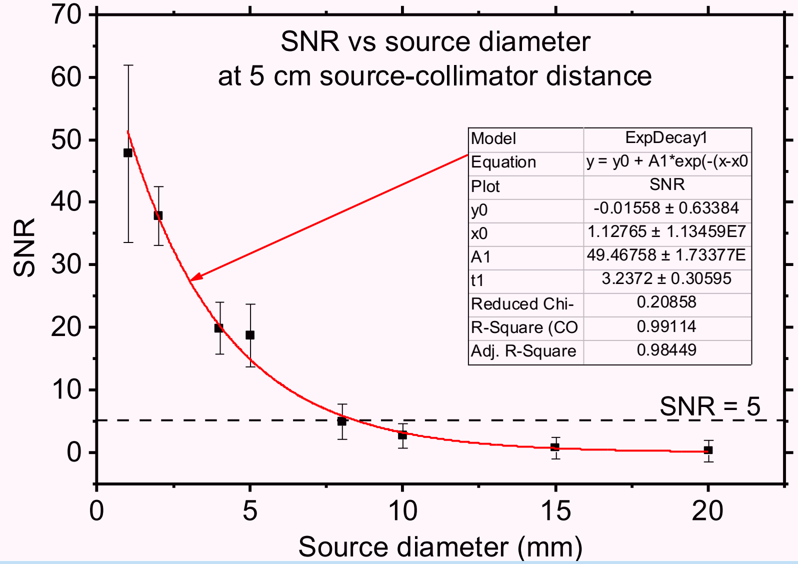
Collimator theory



Decode images of simulated radioactive sources



MC simulations

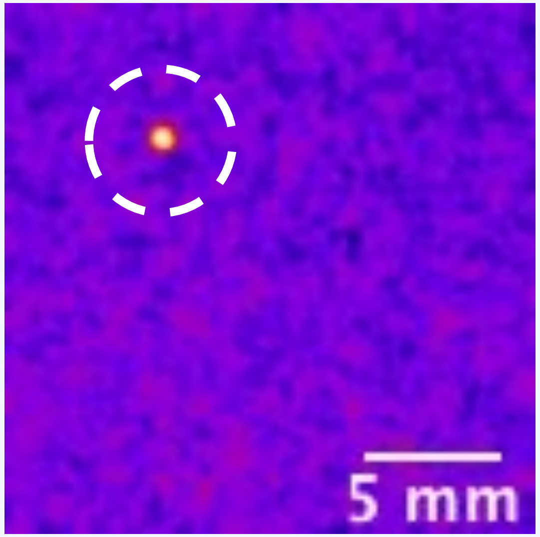


Laboratory tests with Timepix4 (Data Driven mode)

Spectral imaging of radioactive sources using Timepix4 coupled to a coded aperture collimator.

- Timepix4v1 bump bonded with a **300 µm Silicon** sensor
- Spidr4 hardware and in-house software (Nikhef)
- Coded aperture collimator physically available at the lab (NTHN MURA mask, rank 31, **0.08 mm holes, 0.110 mm** thickness)
- Radioactive source: Ba-133 (0.6 mm diameter)

$\alpha = 1.96 \quad a = 63.2mm$



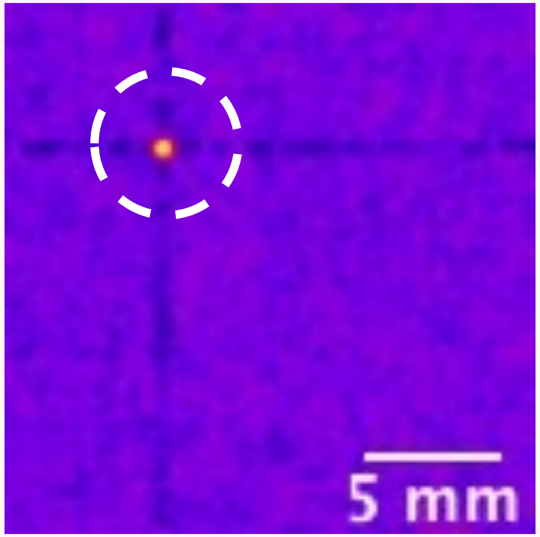
$\boldsymbol{SNR \approx 100}$

Geant4 simulations

Imaging of a monoenergetic source taking into account interactions inside the sensor.

- **300 µm Silicon** sensor (energy deposition in the sensor are computed each 10µm along the ionization track)
- Coded aperture collimator (NTHN MURA mask, rank 31, **0.08 mm holes, 0.110 mm** thickness)
- Monoenergetic source 30.85 keV (planar round source, 0.6 mm, placed at 5mm from the FOV center)

$\alpha = 1.96 \quad a = 63.2mm$



$\boldsymbol{SNR \approx 80}$

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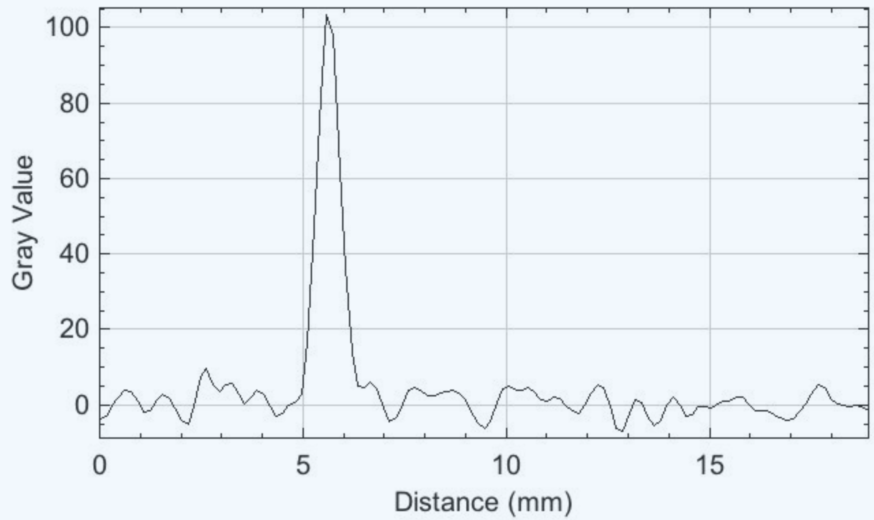

$SNR \approx 100$

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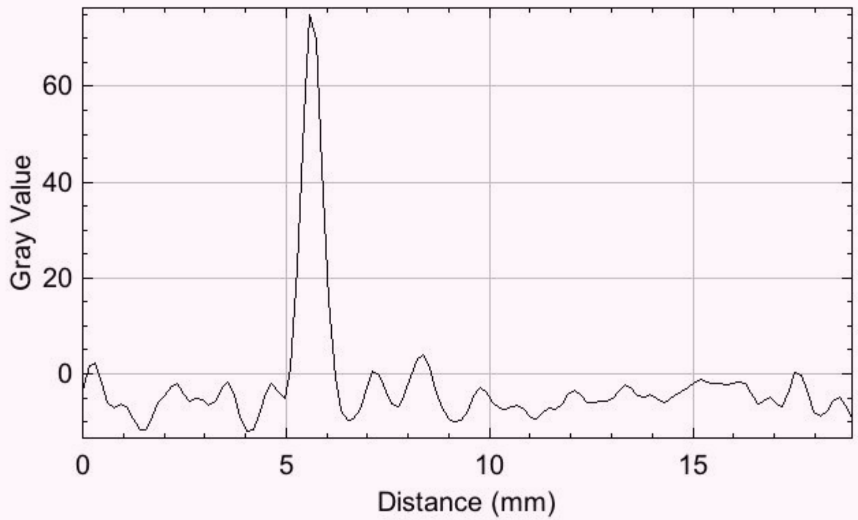


$SNR \approx 80$

Thank you for your attention!

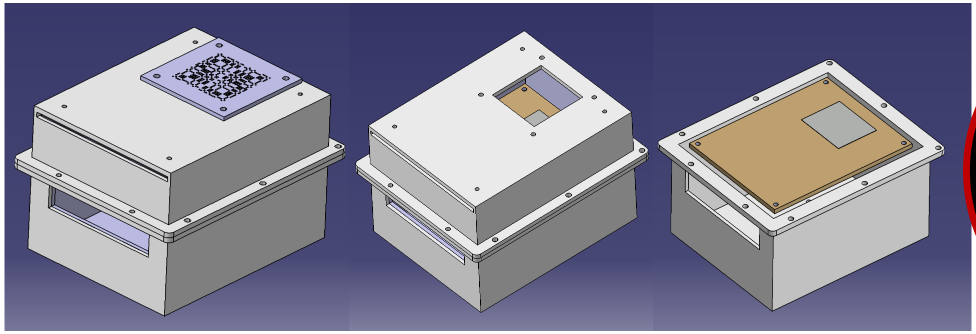
Laura Antonia Cerbone
Contact: cerbone@na.infn.it

Back-up slides

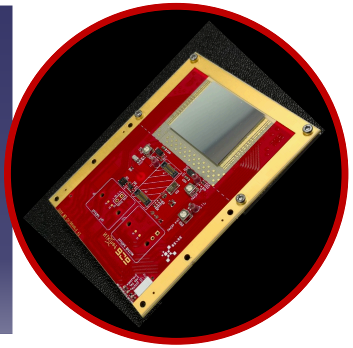
MediPROBE4 scheme

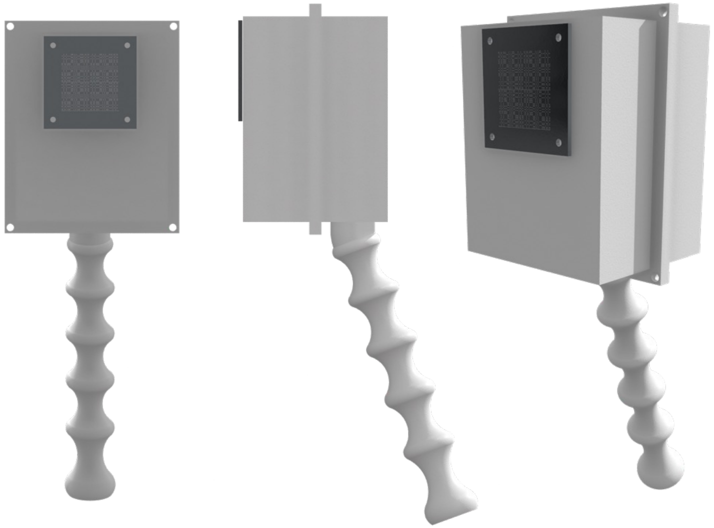
- 3D printed ABS box (≈ 9 x 11 x 7 cm^3)
- 2-mm-thick lead shielding
- Chipboard adjustable position
- Overall weight of ≈ 1 kg
- External readout electronics box
- PC notebook operated

3D model of the camera head



Timepix4





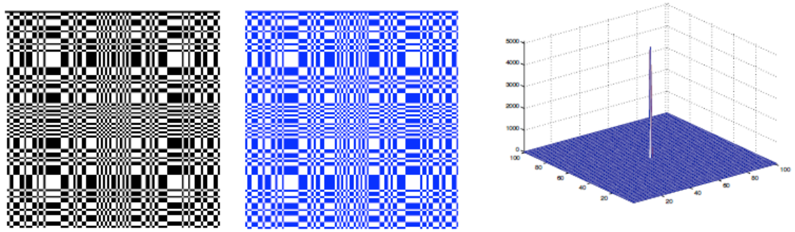
Portable gamma camera:
must be **compact** and **lightweight**

Overall weight around **1 kg**

Total length of the device (with the handle) around **22 cm**

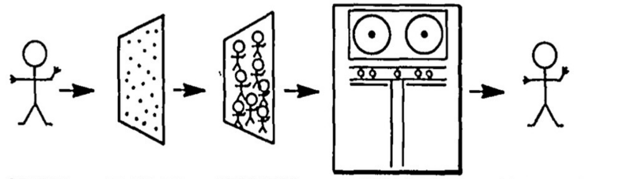
How do CA masks work?

$$\boxed{P = O * A + N}$$



A $\quad$ G $\quad$ $A * G = \delta$

Reconstruction process



$$\hat{O} = \mathrm{P} * G = O * (A * G) + N * G$$

$*$: *convolution*
P: recorded picture
O: emitting object

A: encoding pattern
N: noise function
G: decoding pattern

Decoding algorithm:
MURA Decoding (inverse filtering)

A decoding pattern (G) can be associated to each MURA (Modified-Uniformly-Redundant-Array) mask.

$$A \otimes G = \delta$$

$\otimes$ *correlation*

$$\hat{O} = O * \delta + N * G$$

By convolving the recorded image with the decoding pattern (G), the recontructed object image is obtained. Reconstruction artifacts may appear.

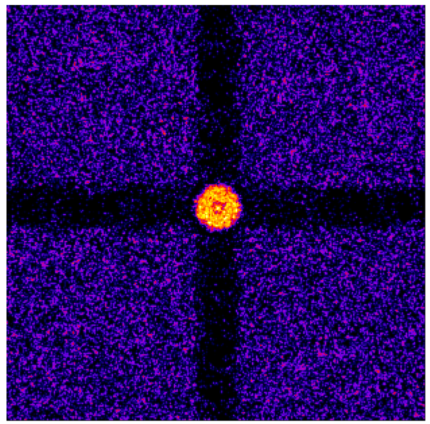
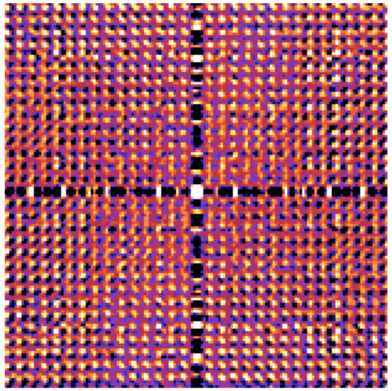
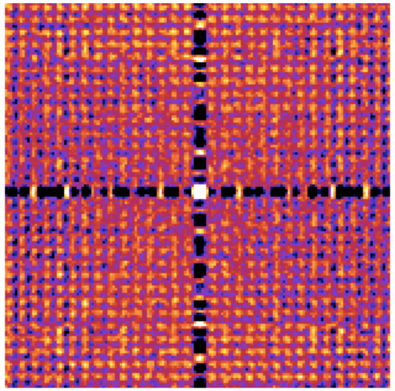


Image quality for extended sources

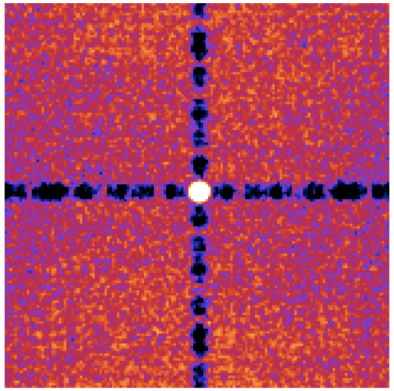
d=1 mm



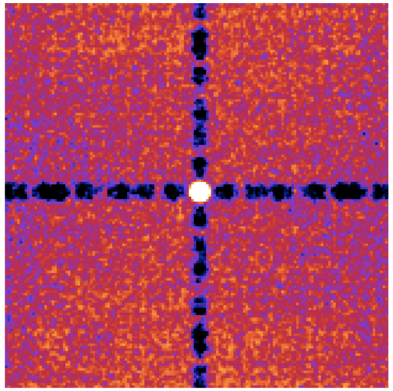
d=2 mm

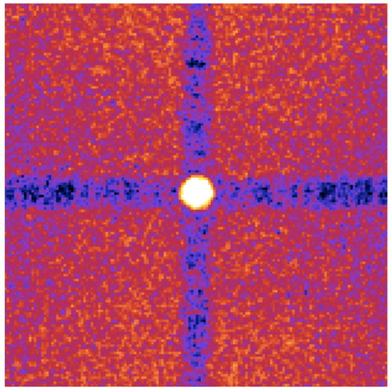


d=4 mm

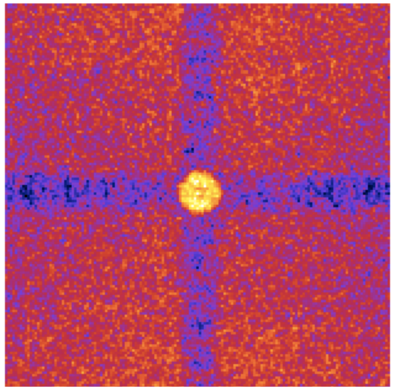


d=5 mm

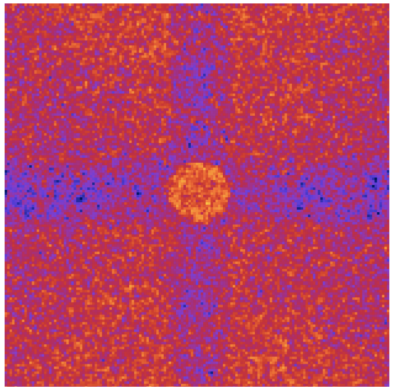




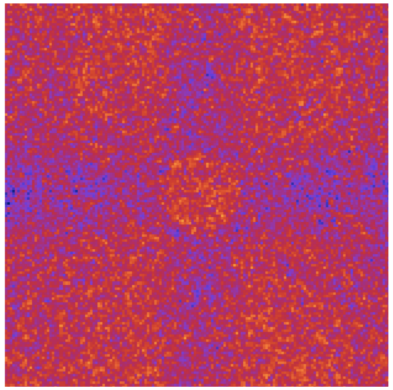
d=8 mm



d=10 mm



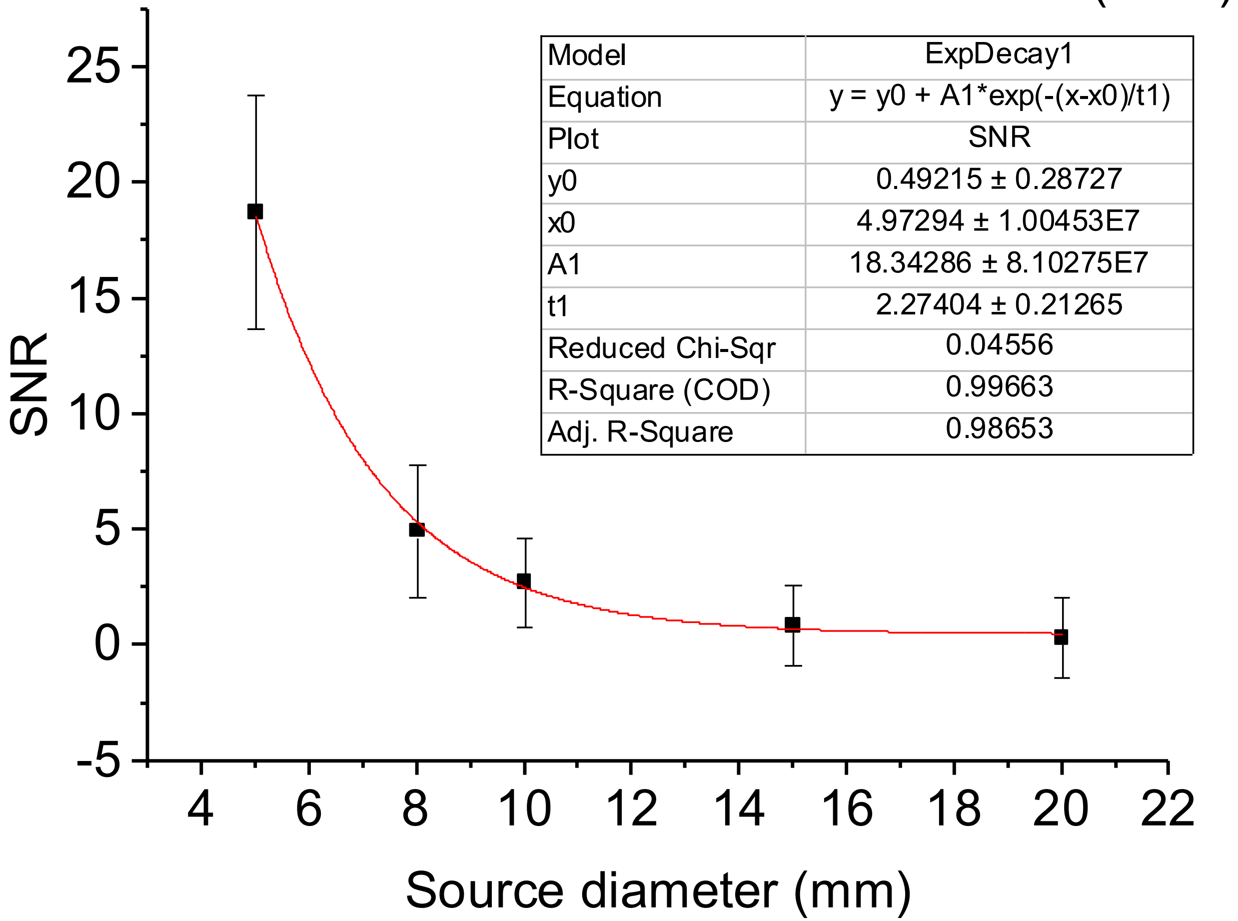
d=15 mm



d=20 mm

Image quality for extended sources

SNR vs Source Diameter
at a fixed Source to collimator distance (5 cm)



Model	ExpDecay1
Equation	y = y0 + A1*exp(-(x-x0)/t1)
Plot	SNR
y0	0.49215 ± 0.28727
x0	4.97294 ± 1.00453E7
A1	18.34286 ± 8.10275E7
t1	2.27404 ± 0.21265
Reduced Chi-Sqr	0.04556
R-Square (COD)	0.99663
Adj. R-Square	0.98653

Spatial Resolution

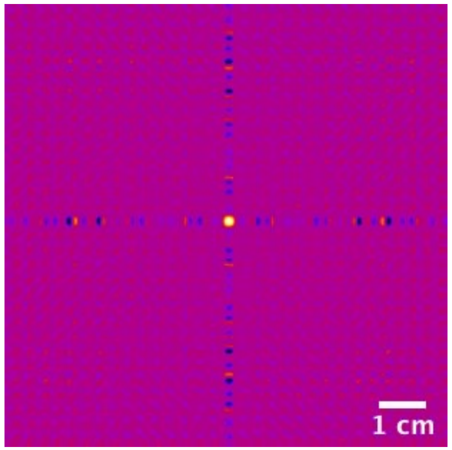
Back-up

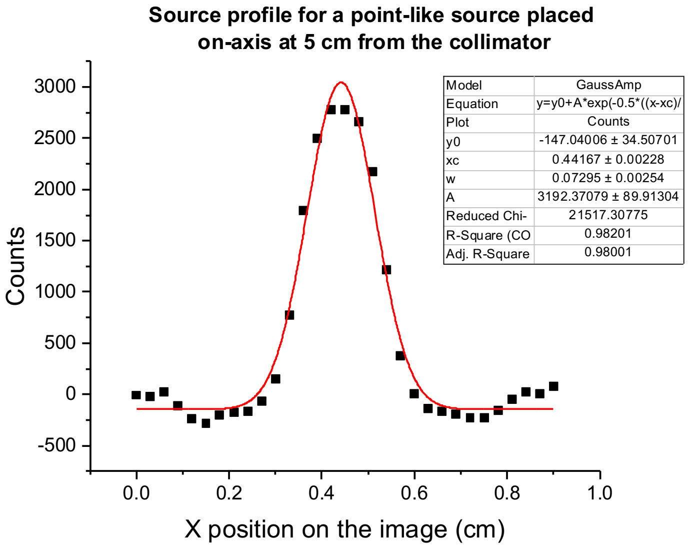
CA mask is expected to have an SR comparable to that of a single pinhole in the mask. When *mt* is not negligible, SR can be computed usign this formula

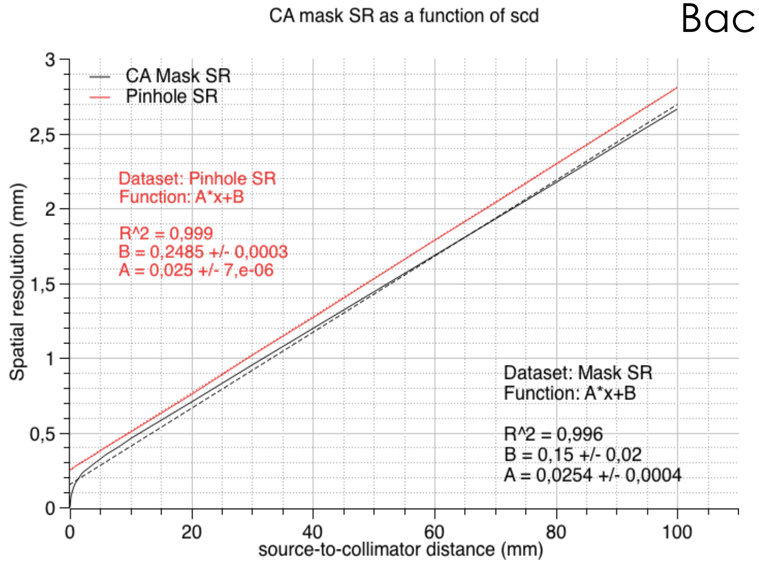
$$SR_{mask} = \sqrt{\left(IR\times\frac{a}{b}\right)^2 + \left[\frac{Pa\times a\times(a+b)}{\left(a+\frac{mt}{2}\right)\left(b+\frac{mt}{2}\right)}\right]^2}$$

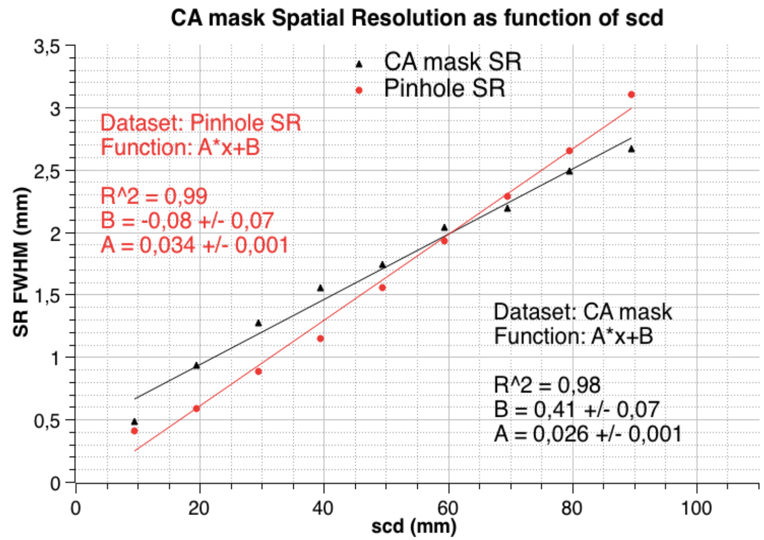
IR: intrinsic SR of the detector (55µm in our case)
Pa: aperture diameter (250µm in our case)

Spatial resolution from MC simulations was obtained assessing the FWHM of the source profile from decoded images for various scd.







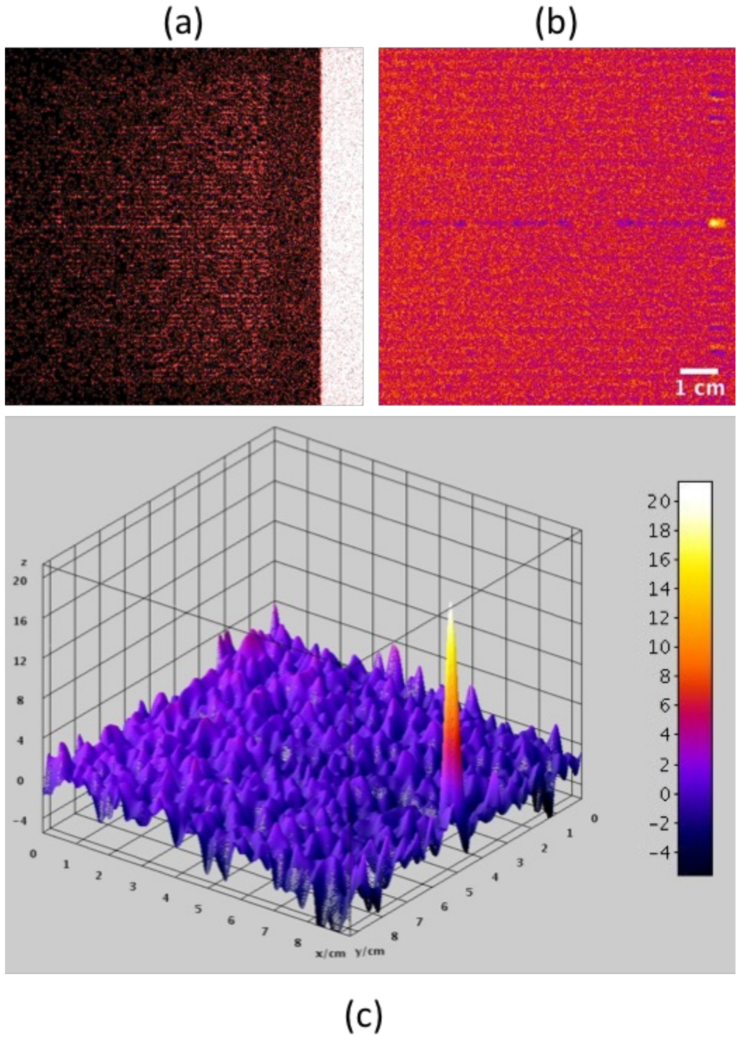


FOV assessment

Back-up

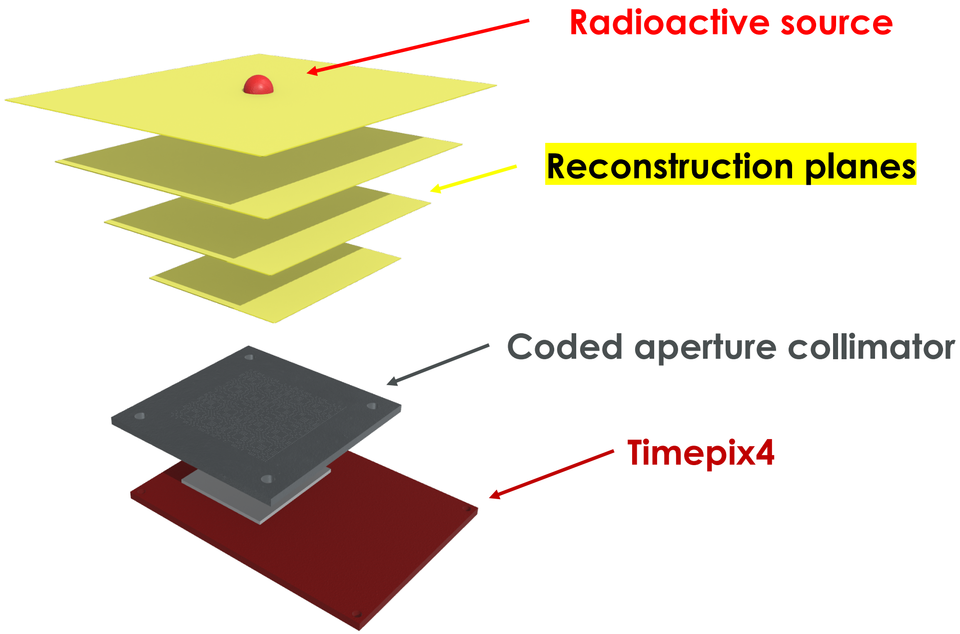
MC simulation with Geant4

Source	• Point-like (0.003mm) • 4 cm from FOV center (zp=+40mm) • 5 cm from the collimator • 10^7 photons (cone beam 3*semidetector_lenght) • Monoenergetic (140.5keV)
Background	None
Medium **Interposed material**	Air/Vacuum



3D imaging: laminography

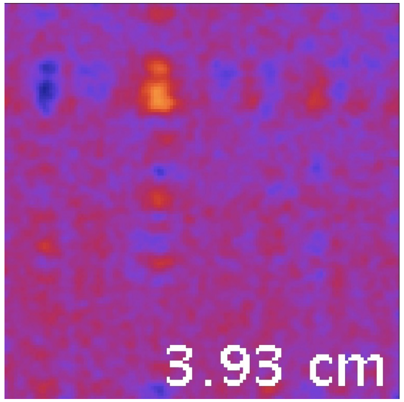
With CA mask, from 2D data, one can obtain a 3D reconstruction of the emitting object.

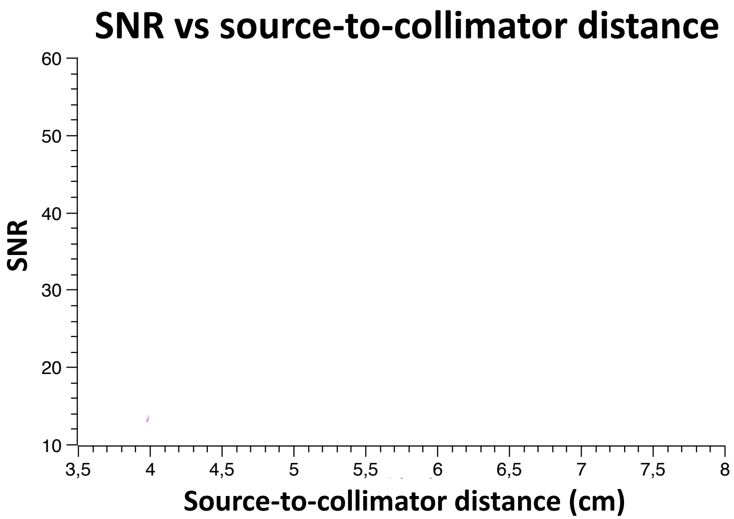


Lateral Spatial Resolution FWHM	1.7 mm
Longitudinal Spatial Resolution FWHM	5 mm

Lab measurements with an Am-241 source

Off-axis point-like source (60 keV)
at 5.5 cm from the collimator (Data acquired from Timepix4)

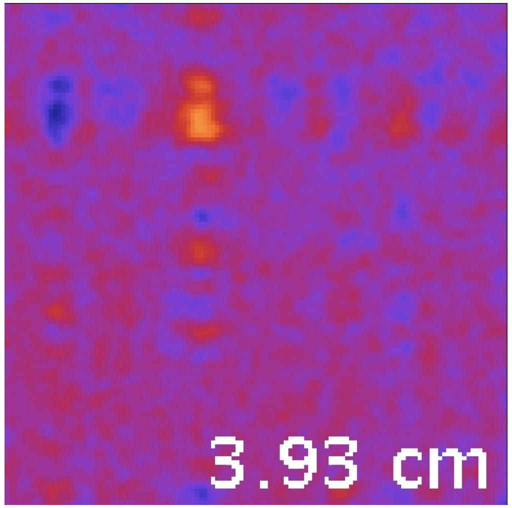


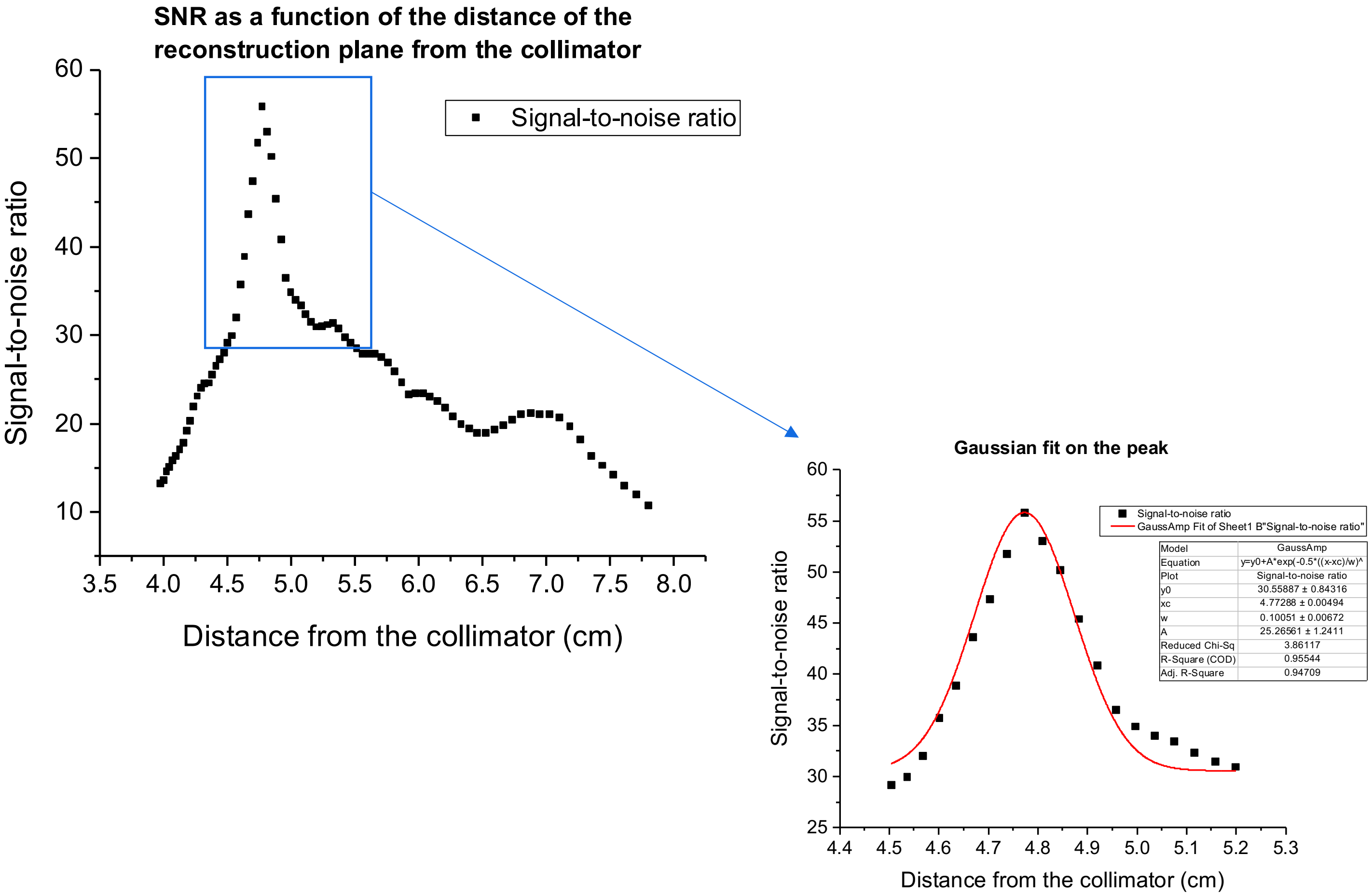


Longitudinal Spatial Resolution

To derive the longitudinal SR we used data acquired with Timepix4 (300 μm Si sensor) for a Am-241 radioactive source (approximately point-like).

The image was acquired using a CA mask available at the lab (80μm diameter holes).
We decoded the image for 80 reconstruction planes between 4 cm and 8 cm.

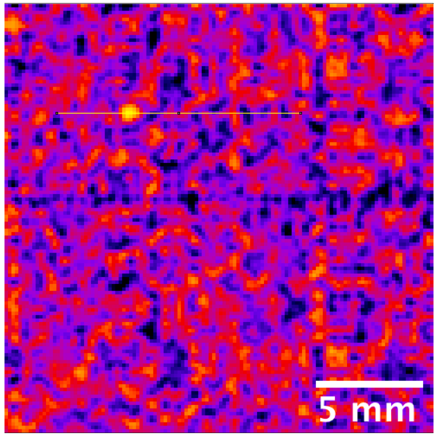




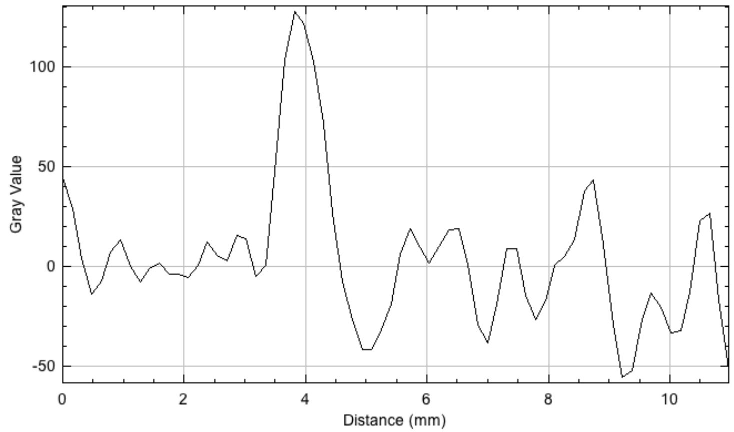
Test with Ba-133

Spectral imaging of radioactive sources using Timepix4 coupled to a CA mask

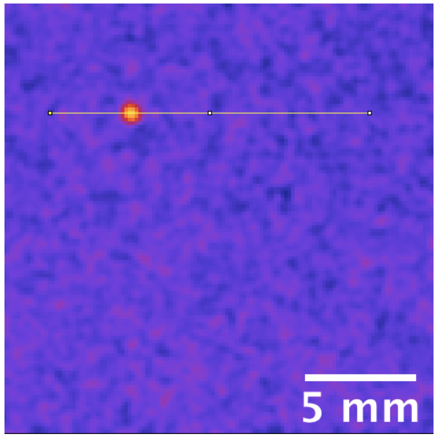
$\alpha = 1.96 \quad a = 63.2mm$



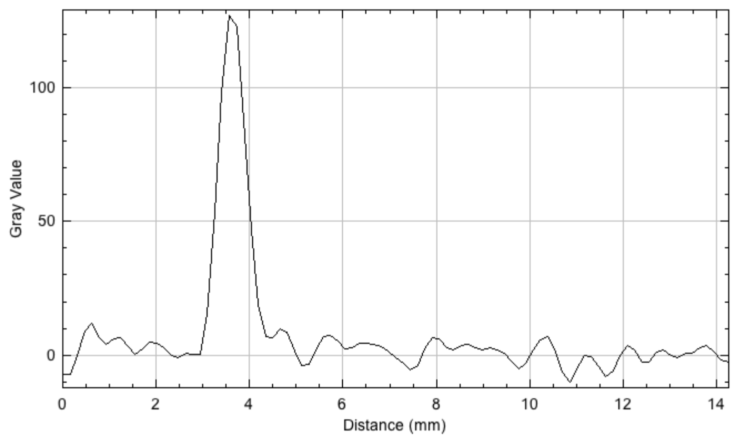
$SNR = 9 \pm 3$



$\alpha = 1.96 \quad a = 63.2mm$



$SNR = 104 \pm 24$

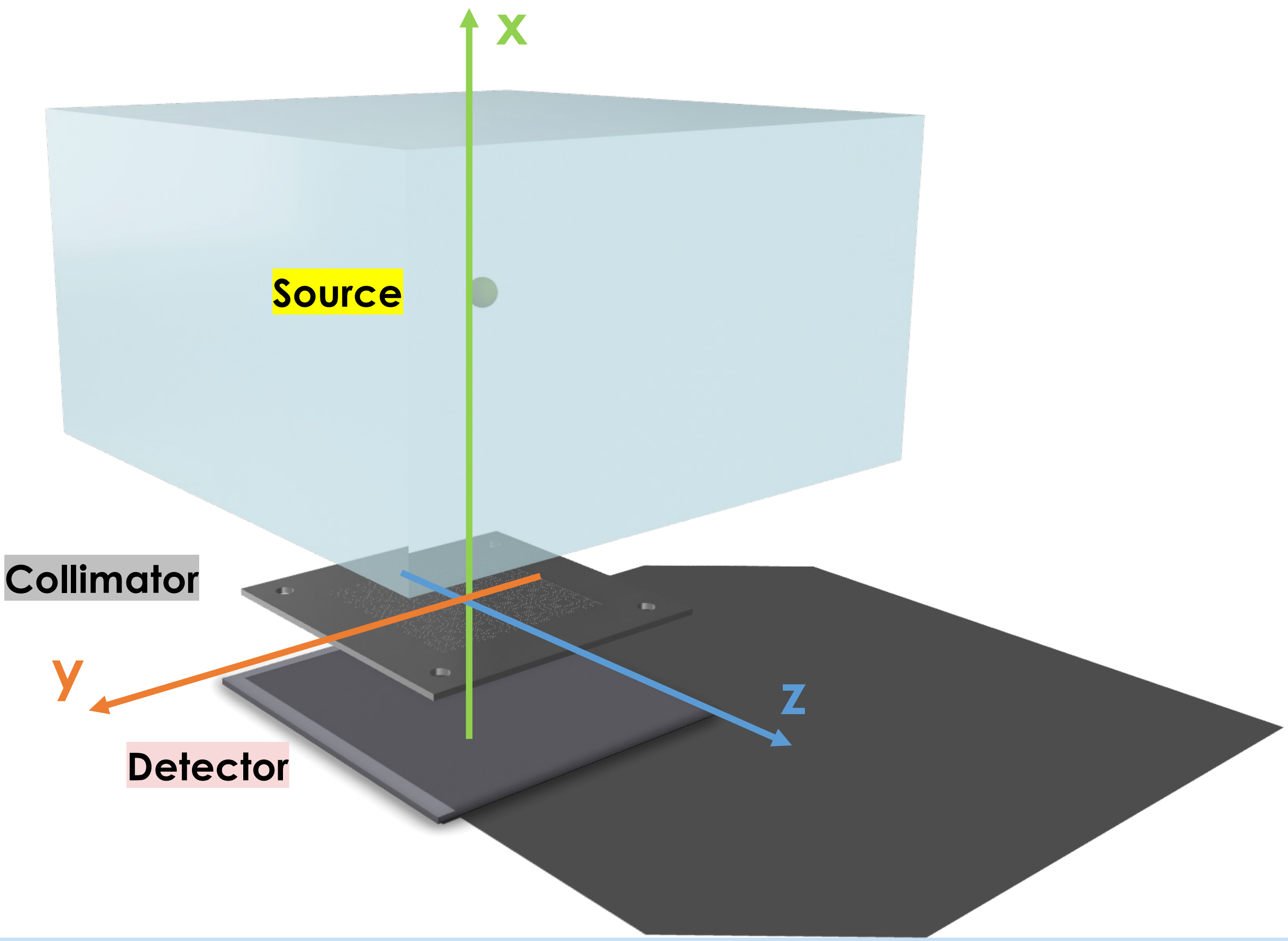


ToT selection allows to **remove scattered gamma rays** and **background radiation** from the acquired image

Image quality is enhanced

For the Ba-133 source, ToT selection lead to a improvement in the SNR.

Configuration for MC simulations



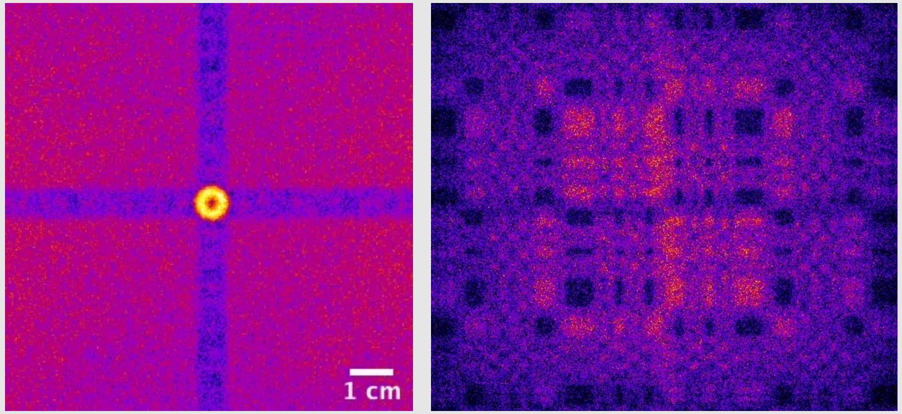
Background Activity

Back-up

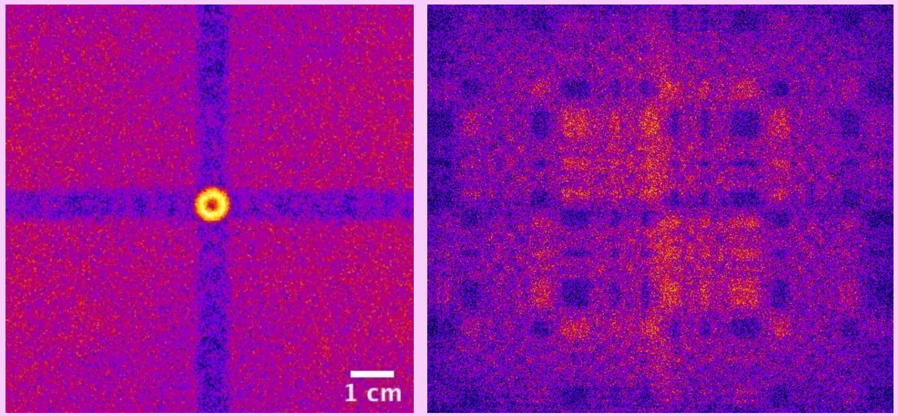
MC simulation with Geant4		
October 2022		
Source	• Spherical (1 cm) • On axis • 5 cm from the collimator • 10^7 photons (cone beam) • Tc99m spectrum	
Background	None	$3*10^8$ (source to bkg 10:1)
Medium Interposed material	Water 5 x 9 x 9 cm^3 (source placed in the center of the water box)	
SNR	Without BKG	With BKG
	7.7	5.8

Background activity deteriorates the SNR

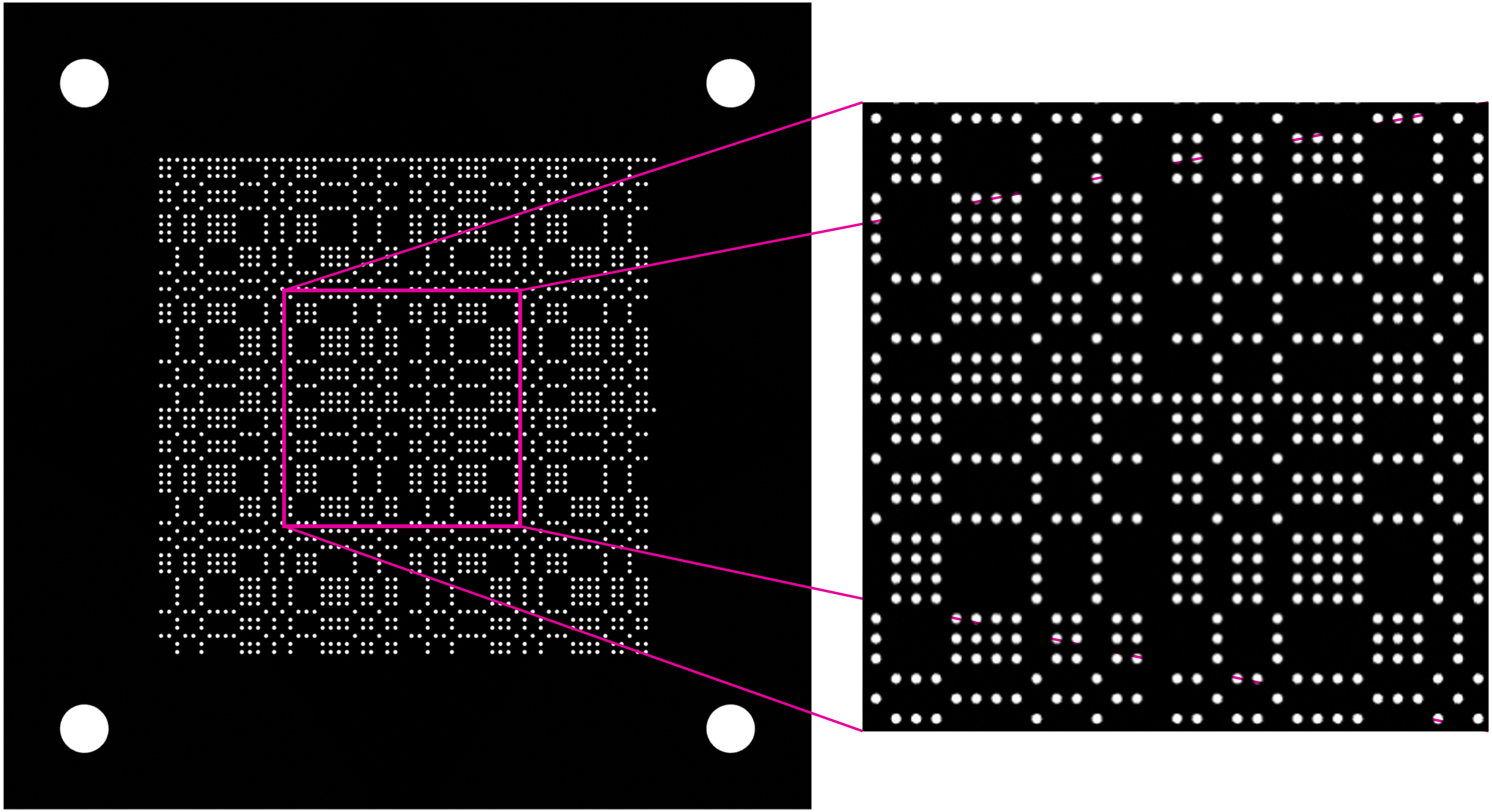
With Water – NO background activity

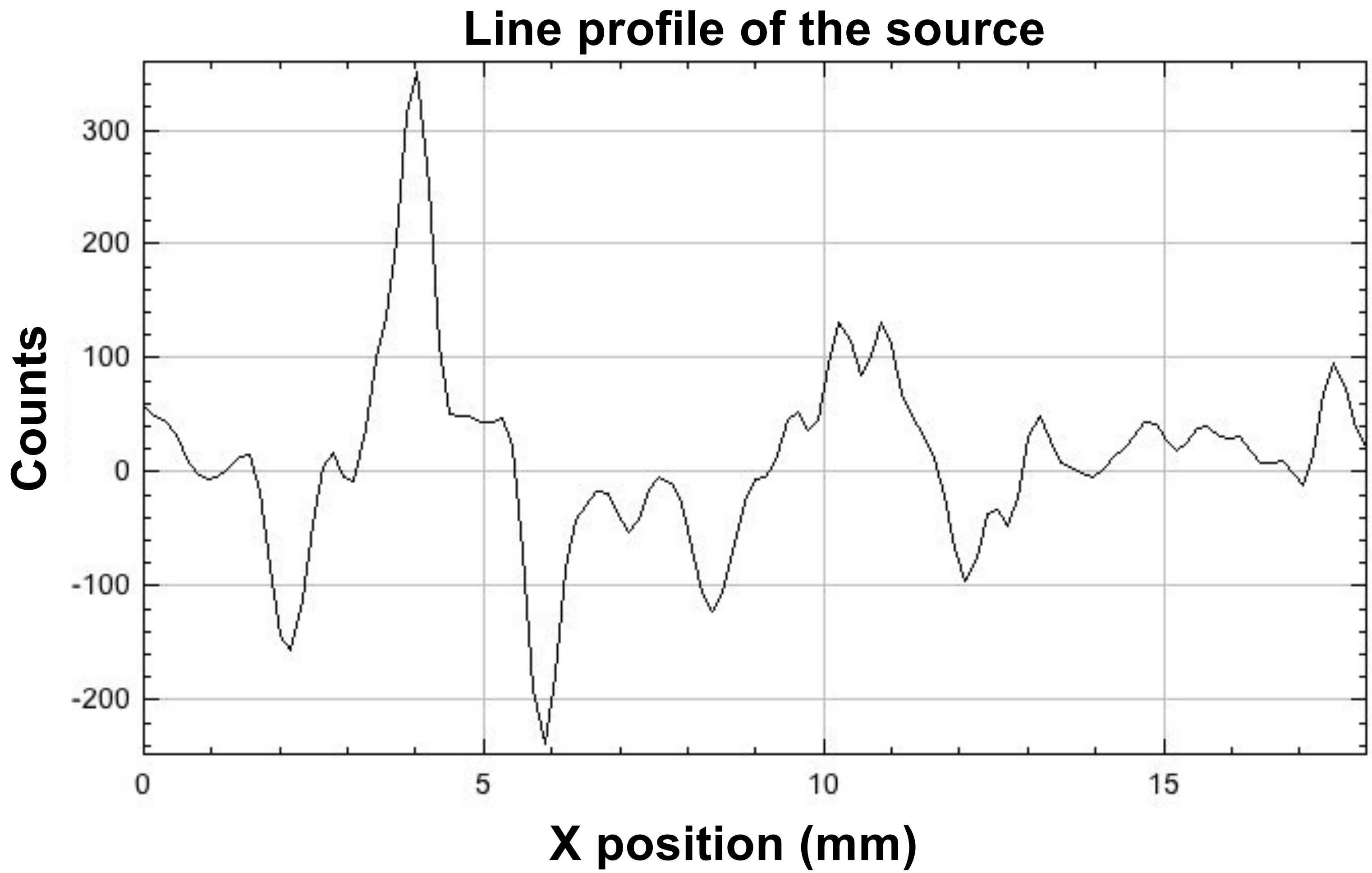


With Water – Background activity



These images can be found in the folder «Background_Activity» in Articolo MediPROBE




Line profile of the source
Counts
300
200
100
0
-100
-200
0
5
10
15
X position (mm)