Impact of Monte-Carlo System Matrix Completeness on Image Quality in TEP

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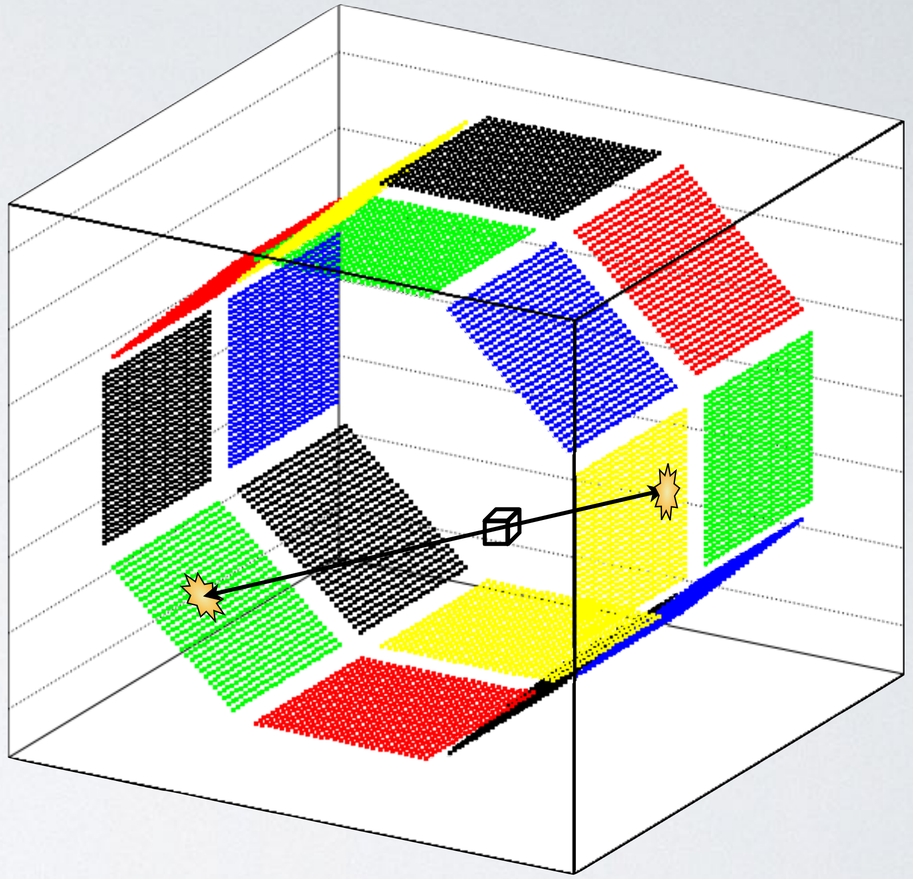
Iterative PET Image Reconstruction Strategy

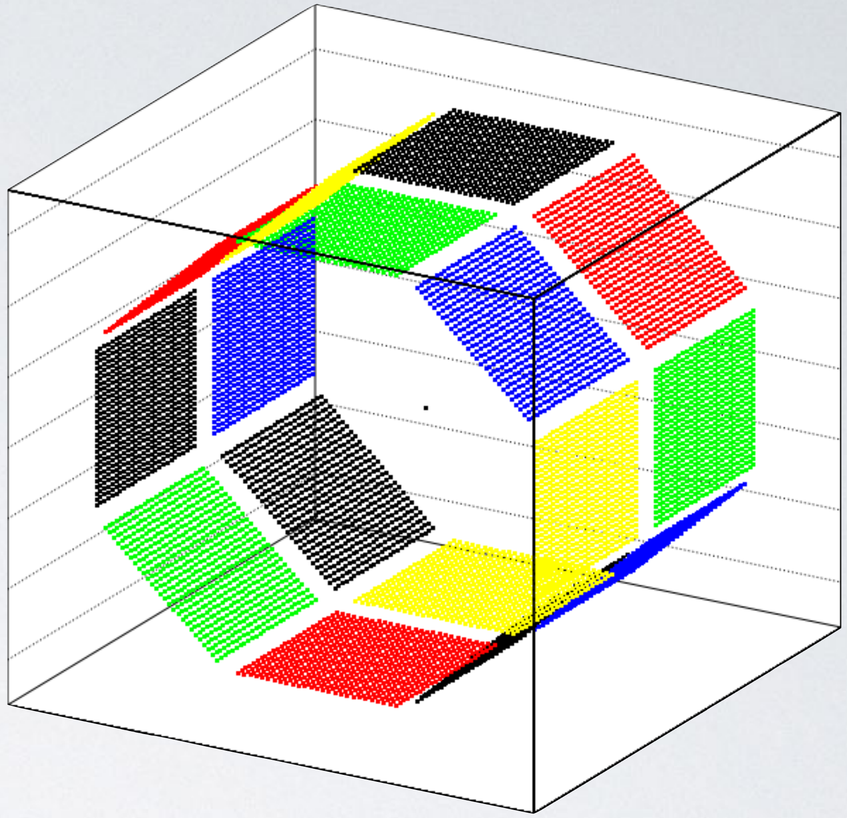
- **Iterative statistical reconstruction**
  - detailed models of the physics of photon propagation and detection
  - description of the read-out electronics
  - benefits from increasing computing ressources

- **System Response Matrix (SRM)**
  - A_{ij} : probability for a pair of γ originating from voxel j in the imaged volume to be detected along LOR i
  - Can be decomposed in different factors, encoding different physical aspects of the detection
  - Determination of SRM:
    - analytically
    - experimentally
    - Monte-Carlo
  - Time consuming to generate, heavy to store, heavy to handle during reconstruction



The IRIS pre-clinical PET/CT

- Commercialised by Inviscan Imaging Systems
- small animal PET/CT
- 2 octogonal rings
- modules of 26x27 crystals
- LYSO:Ce crystals (1.6 x 1.6 x 12) mm3
- 1-6 coincidence detection
- 23654592 possible lines of response



reconstruction :
- OS-EM 8 subset, 8 iteration
- home-made system matrix
- correction of efficiency uniformity
- correction of randoms
- no smoothing, no correction for attenuation

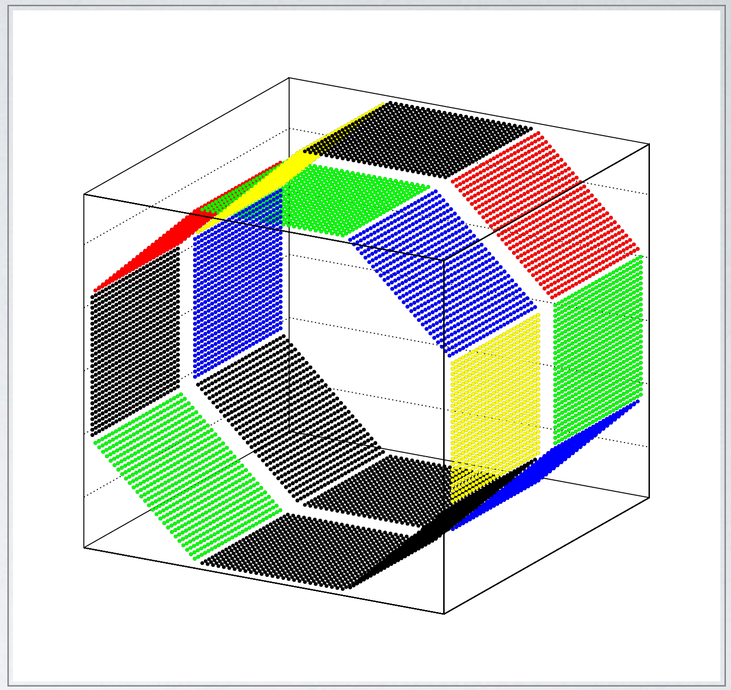
MC matrix generation

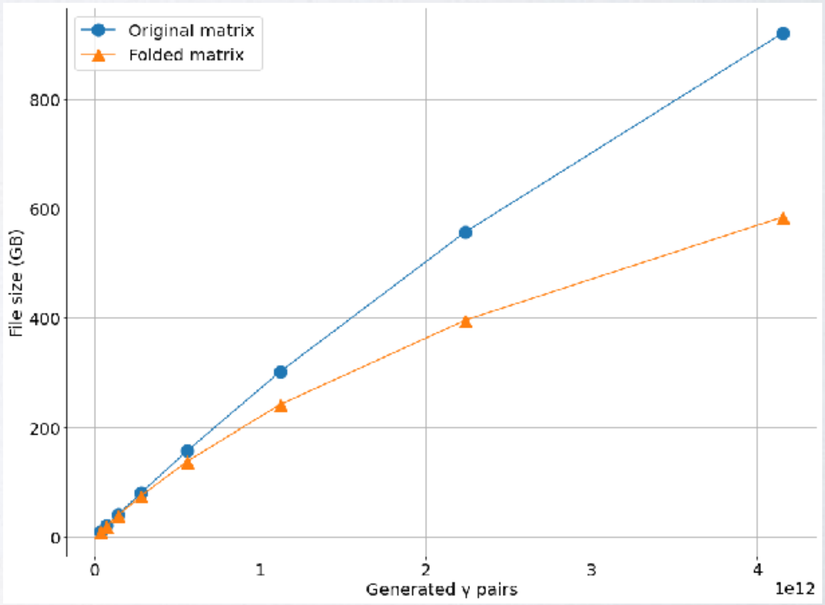
Matrix generation

- Monte-Carlo matrix generation using the **GATE platform**
- Simulate a uniform activity in a cylindrical volume
- Pairs of back-to-back γ emitted at 4π randomly in the volume
- No attenuation
- Each detected pair in a given LOR increment the weight of the voxel of origin for that LOR
- 2 options :
  - **"original" matrix** : keep the voxels and LOR as we generate them
  - **"folded" matrix** : propagate generated voxels to other LOR according to the (xOy), (xOz) and (yOz) planar symmetries (potentially x8 in equivalent statistics?)

Matrix storage

- Hollow matrix
  - List of LOR and number of voxels
  - Voxel index and a weight
- Generated matrices **up to ~1TB for this study**





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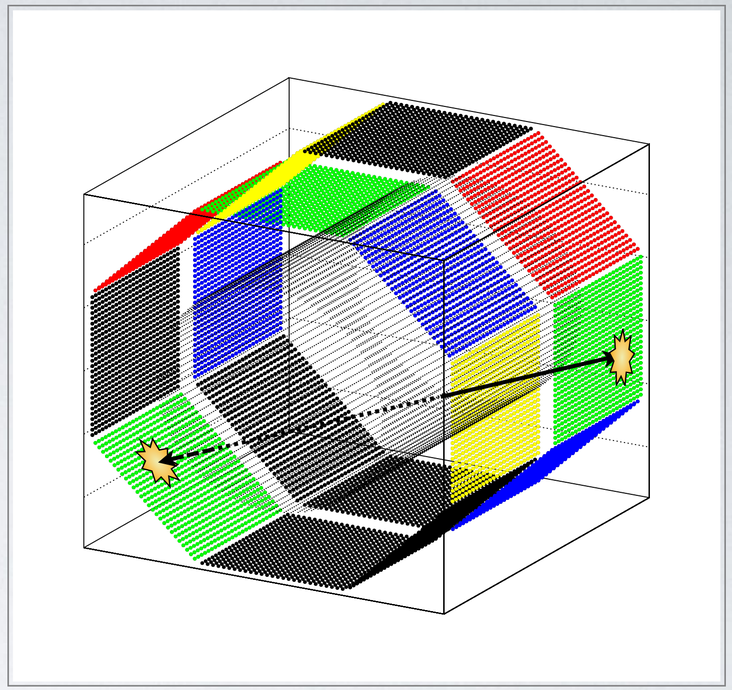
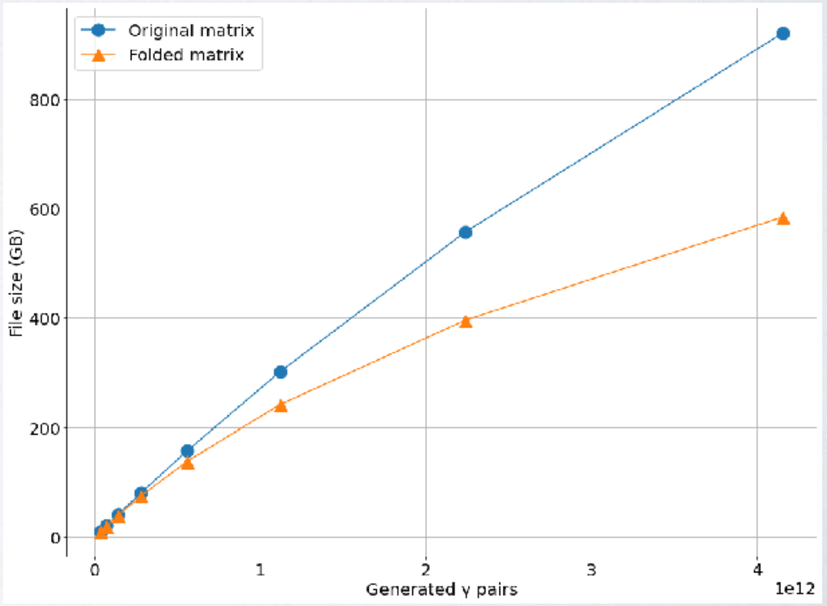
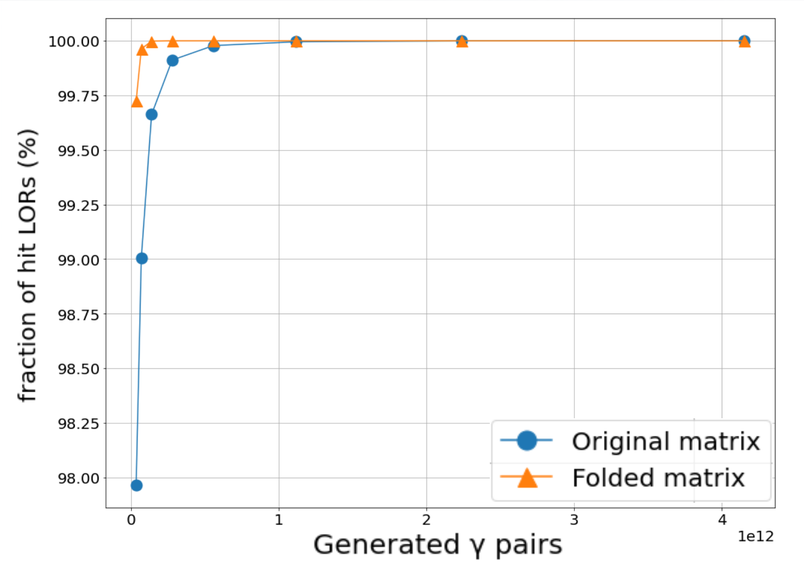
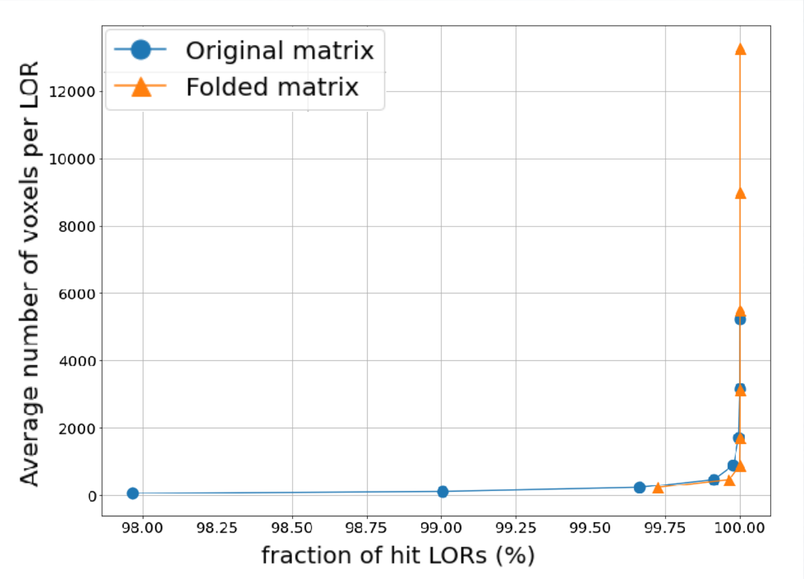
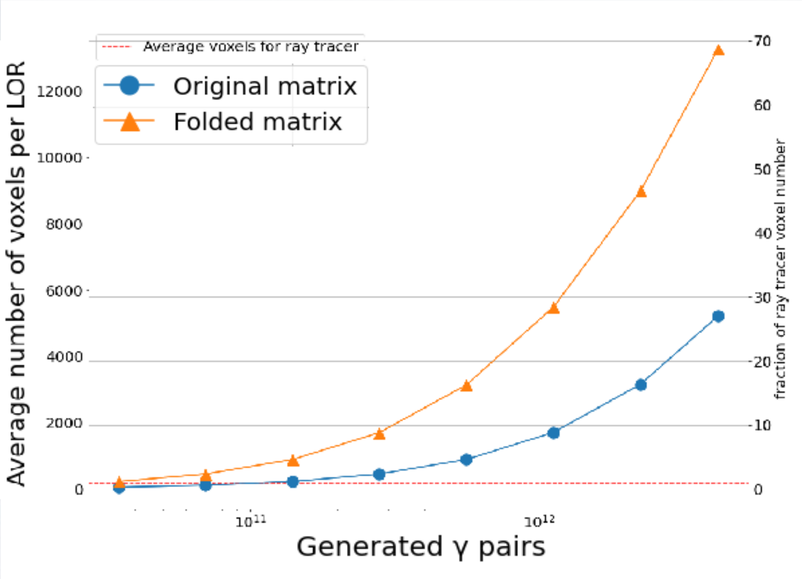




Filling up the matrix

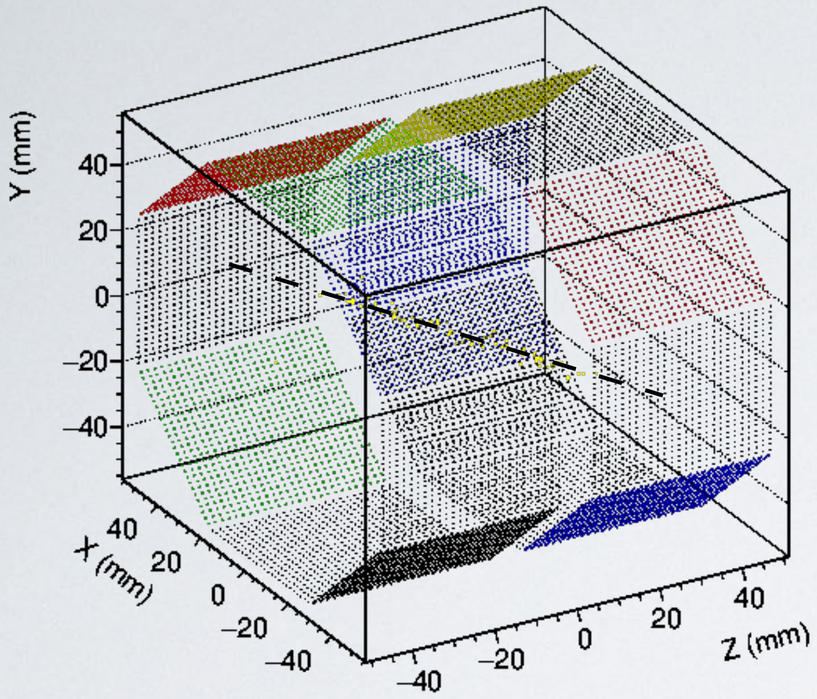


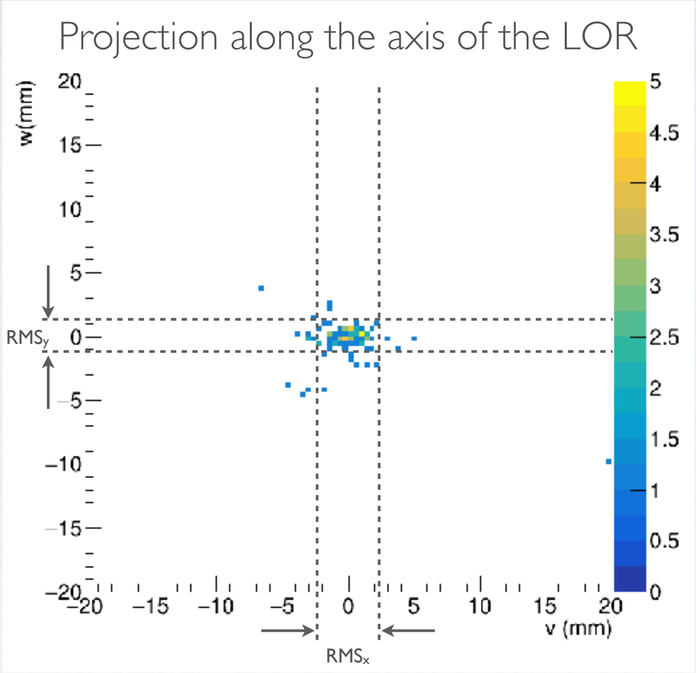


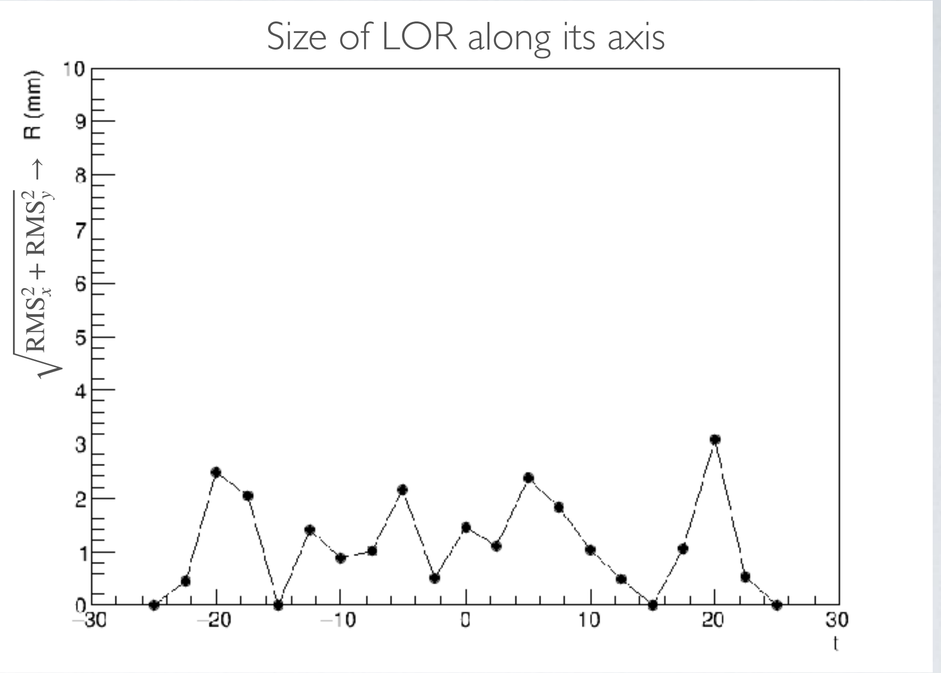


- Number of LOR quickly reaches ~100%
- As no new LOR is available we start finding more and more voxels belonging to a given LOR
- Compare the number of voxel per LOR to the average number of voxel per LOR in a purely geometrical ray-tracer : start filling the diffusion kernel of the LOR

Evolution of the LOR kernel description







First few matrices

- Very low statistics
- Significant gaps in the voxels

Last matrices

- Distributions much more homogeneous
- Reduction on the variance of the width of the LOR

Fill the ray-tracer component, then the width introduced by scatterings : can be decomposed in submatrices?

- Purely geometrical ray tracer
- Diffusion kernel (dependent on the incidence angle on both ends of the LOR)
- Does the kernel remain constant along the LOR?

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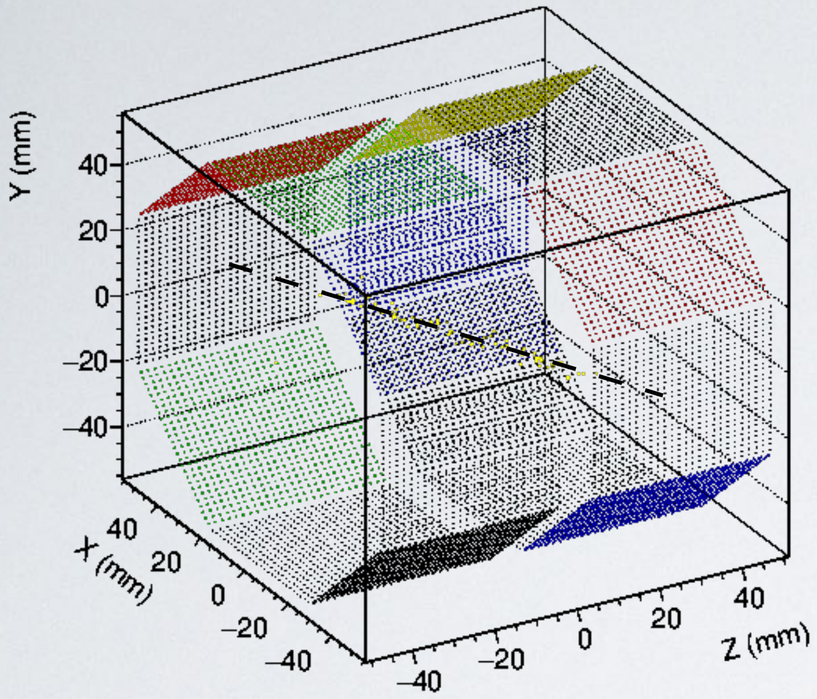

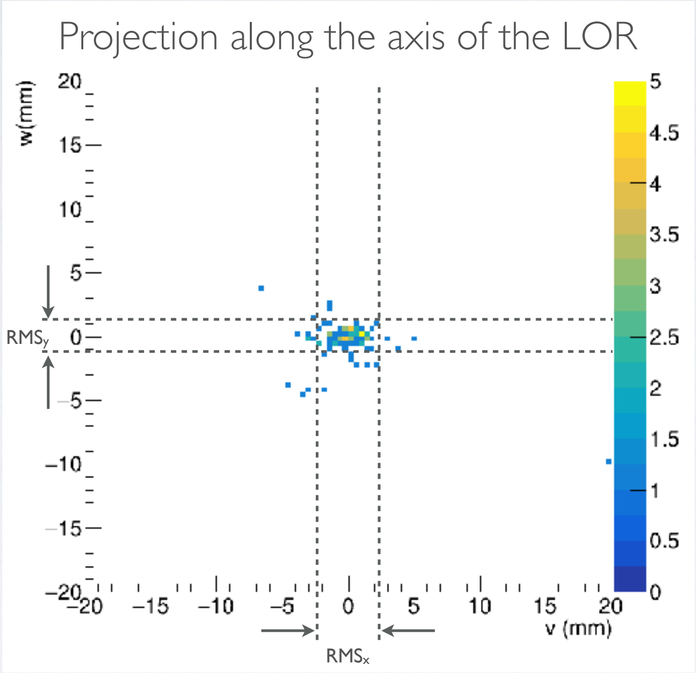

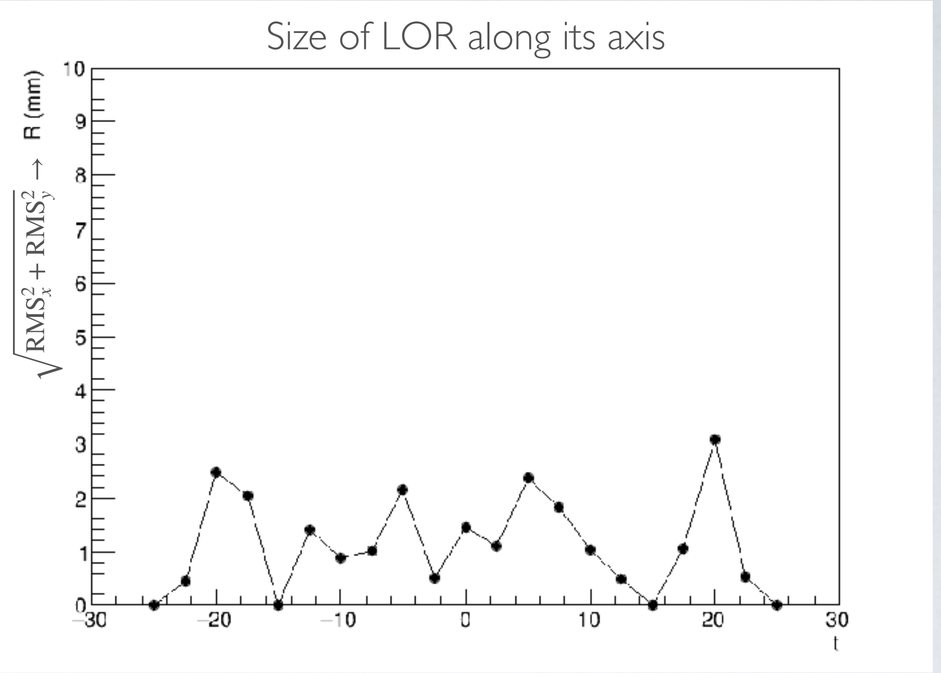

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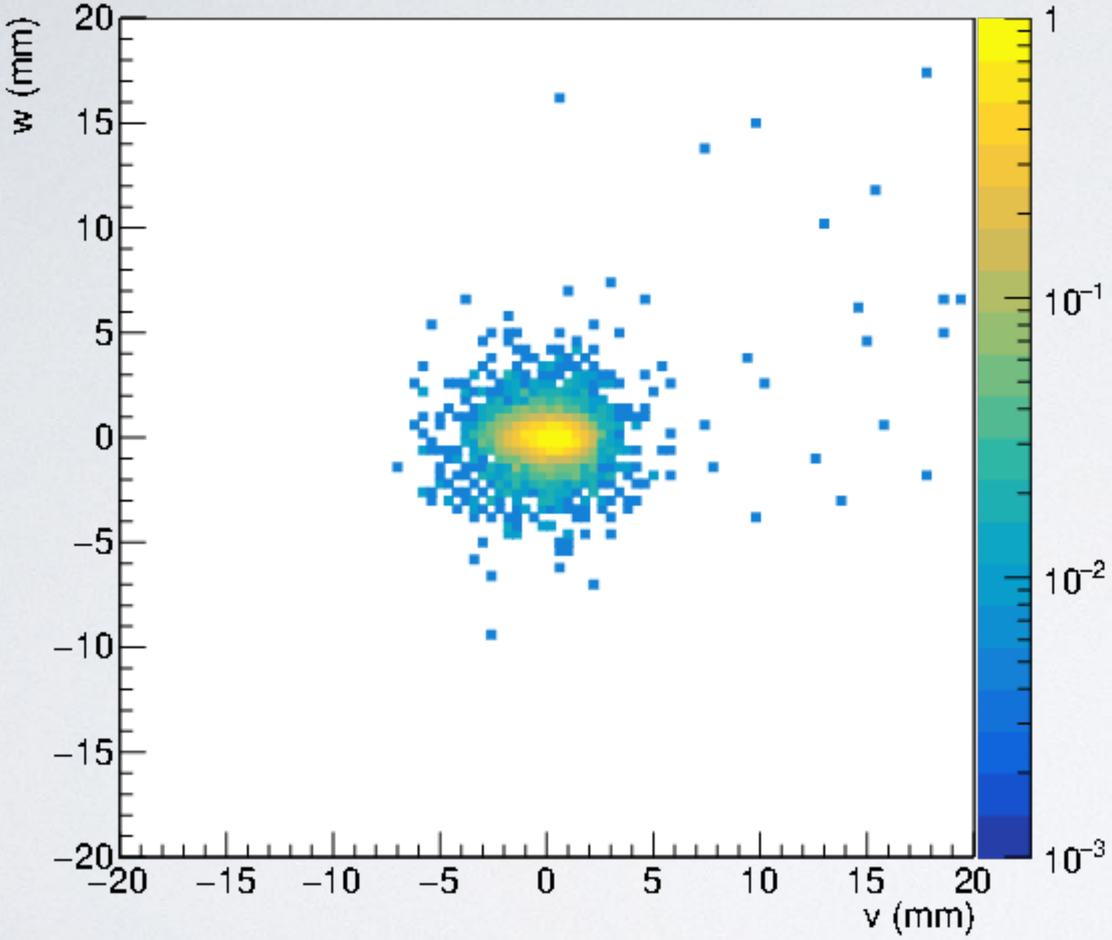
A few examples of LOR projection PDFs



- Large variety of shapes of LOR projection probability density function (scaled to maximum)
- Dependency on incident angle on the LYSO:Ce modules
- Noticeable edge effects for LOR with crystals near the module's sides
- How to account for all these shapes when describing the scattering kernel in image reconstruction?

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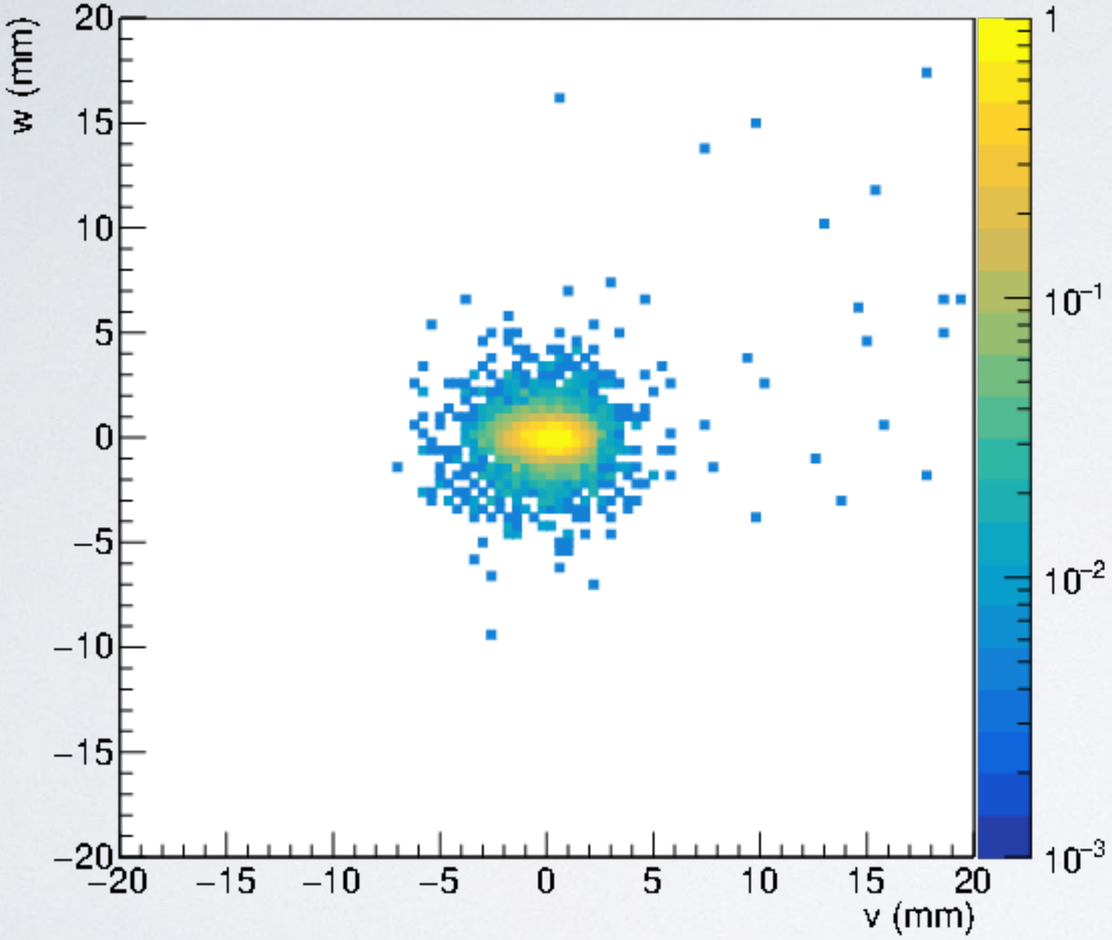

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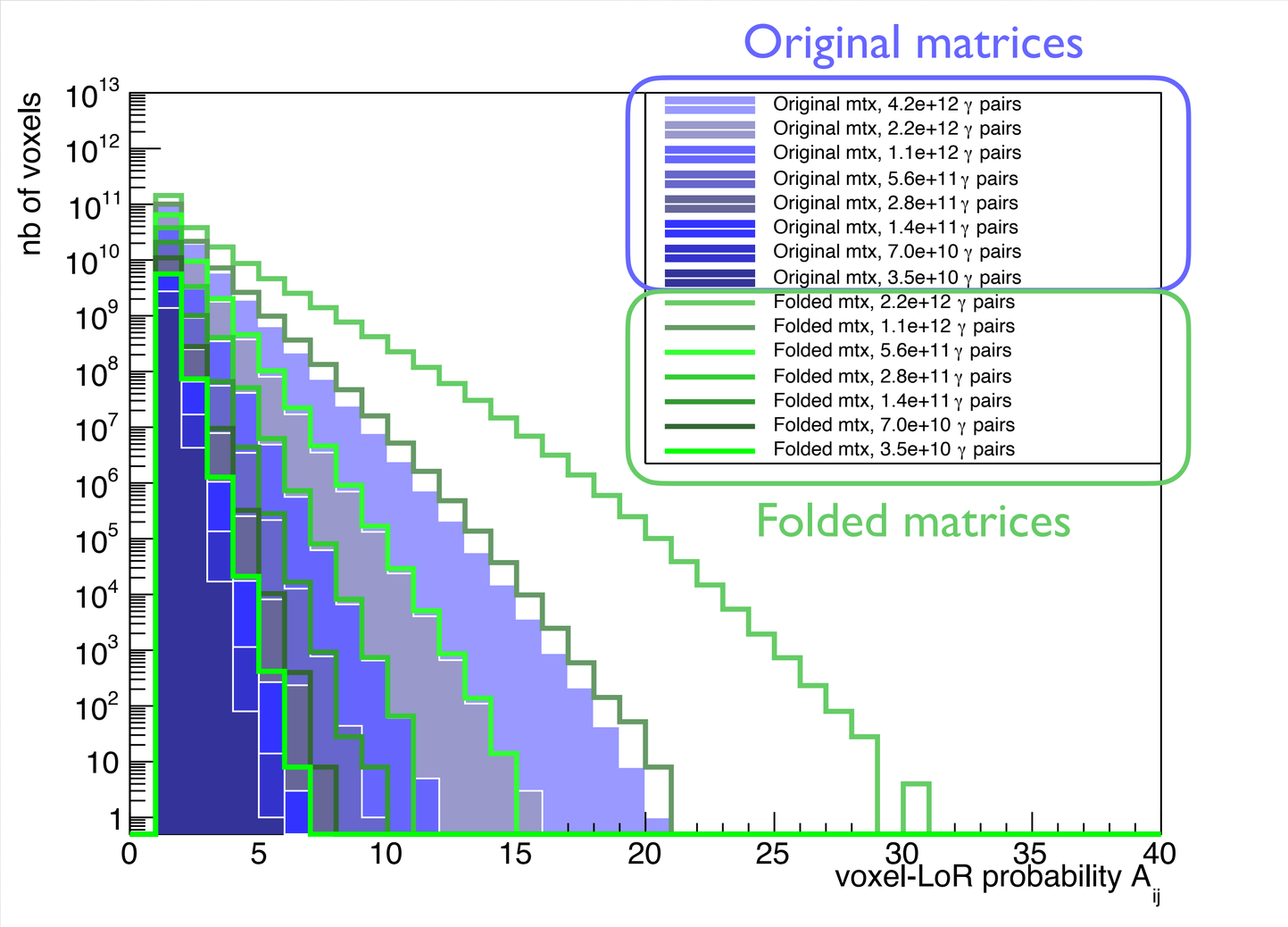
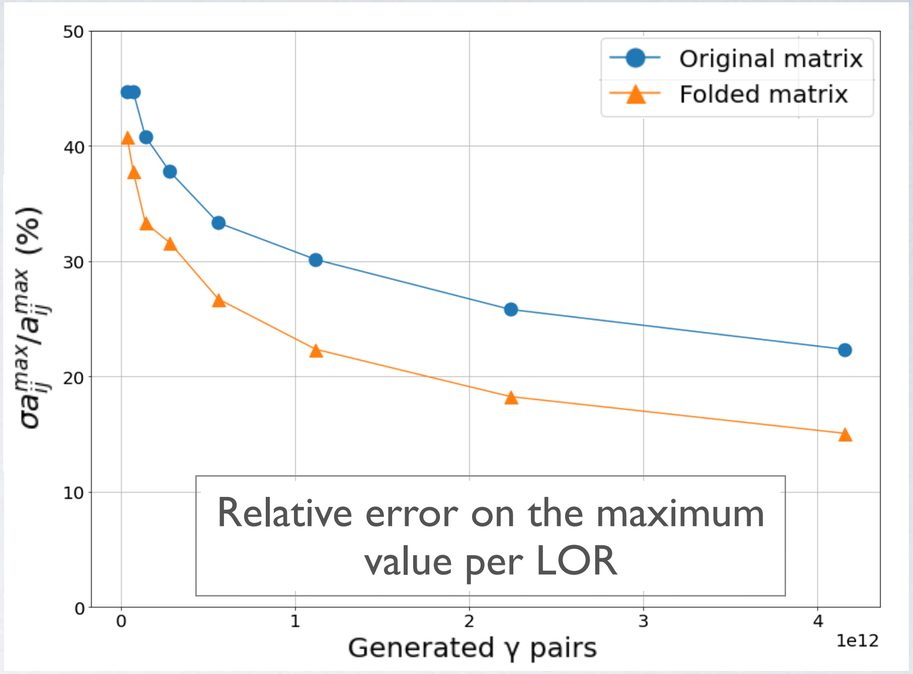
Evolution of MC statistics





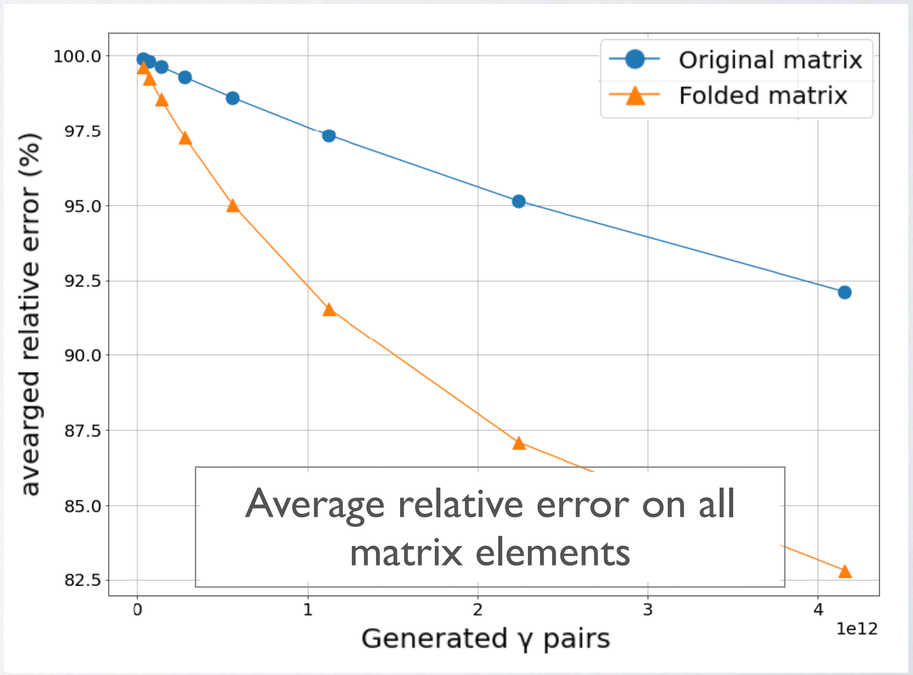
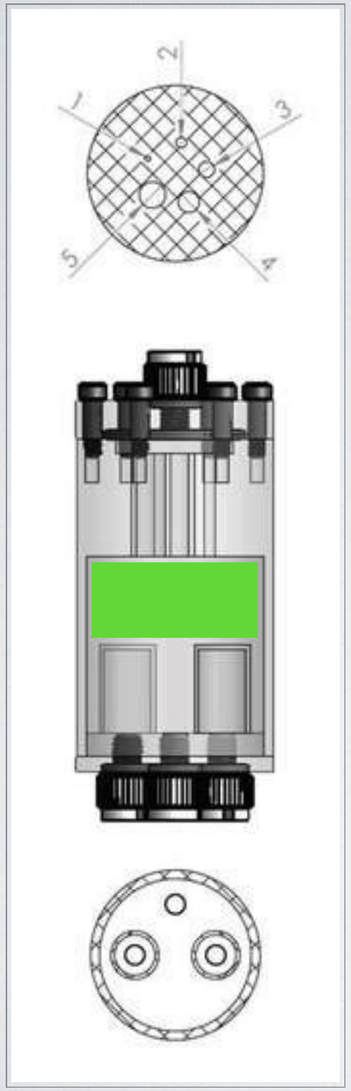
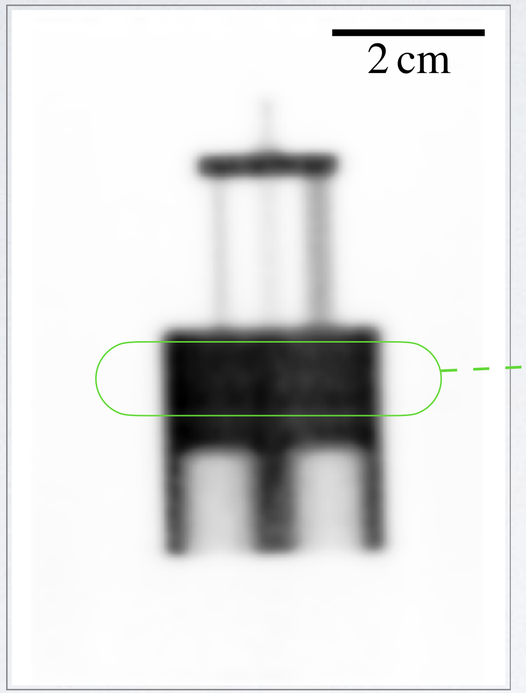
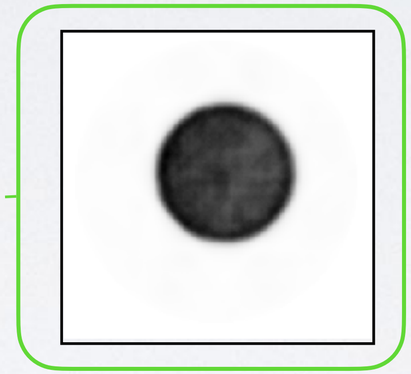


Image Quality Phantom



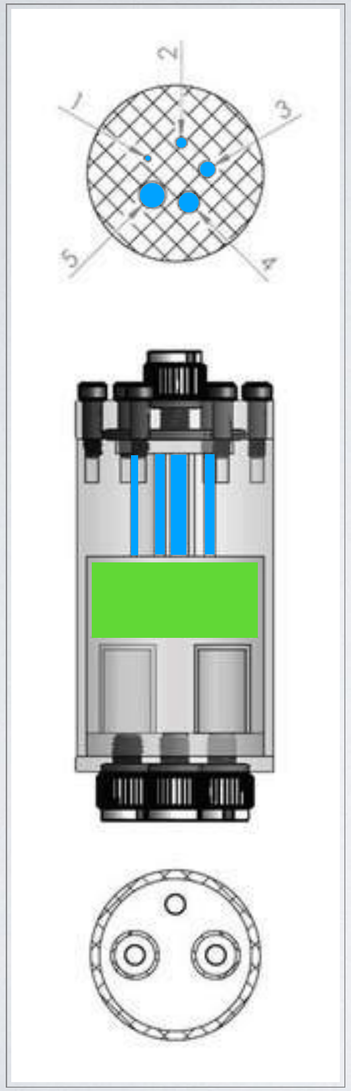


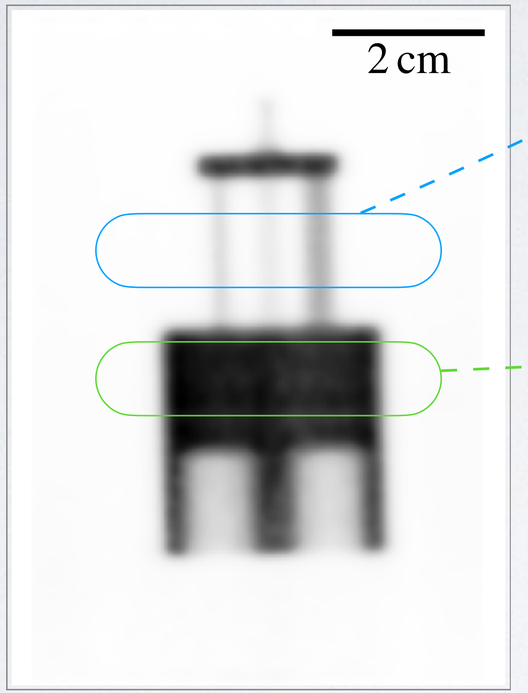


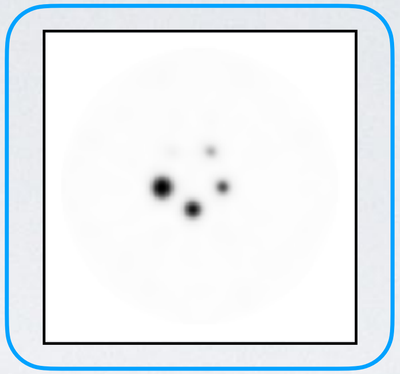
Uniform region

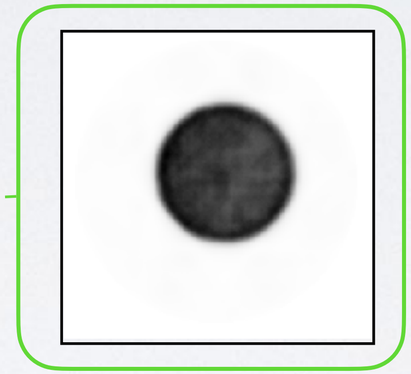
- Mean voxel value
- Variance (in % of mean voxel value)

Image Quality Phantom





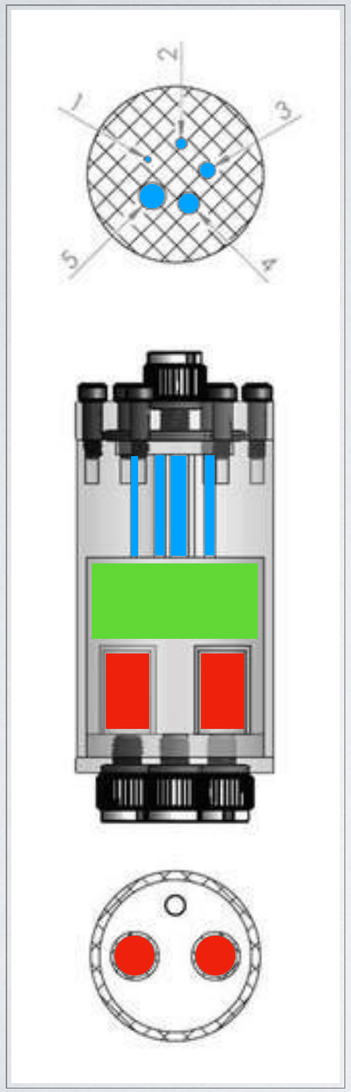


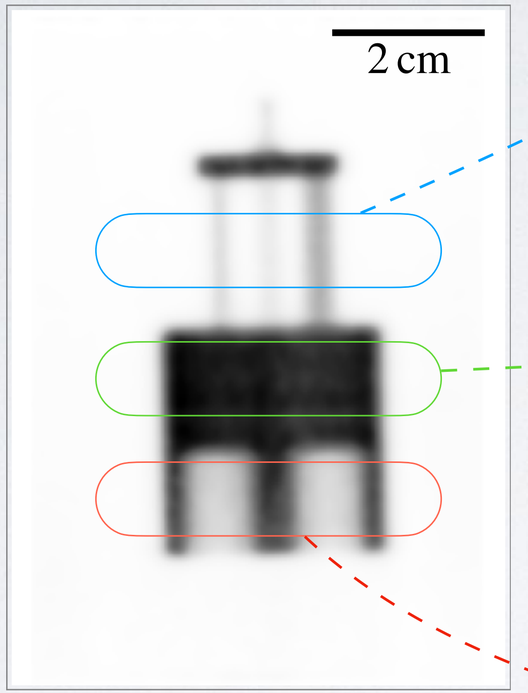


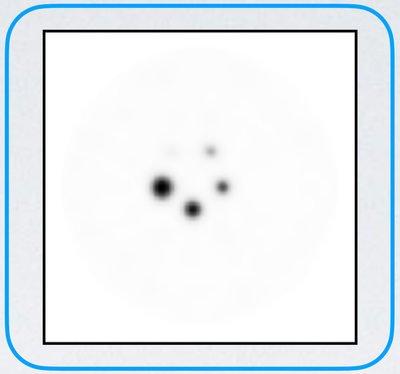
Rod region
- 1-5 mm diameter
- Mean voxel value long the rod
  (in % of mean voxel value of the uniform region)

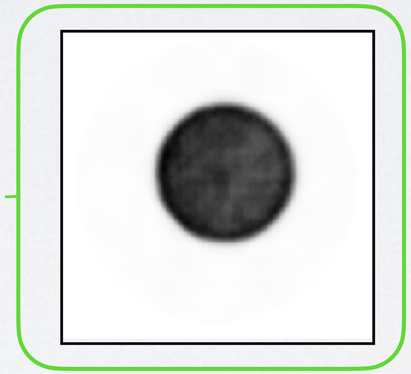
Uniform region
- Mean voxel value
- Variance (in % of mean voxel value)

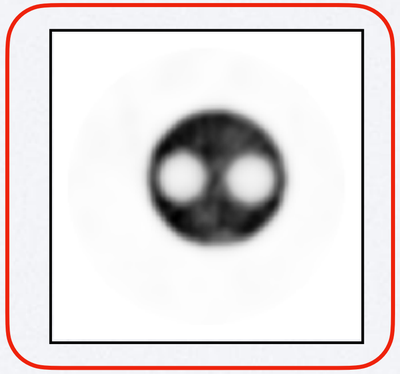
Image Quality Phantom











Rod region
- 1-5 mm diameter
- Mean voxel value long the rod
  (in % of mean voxel value of the uniform region)

Uniform region
- Mean voxel value
- Variance (in % of mean voxel value)

Cavity region
- Filled with air and water (no activity)
- Mean voxel value in cold region
  (in % of mean voxel value of the uniform region)

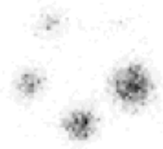
Single IQP slices

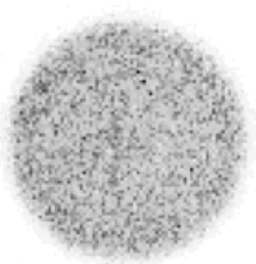
"Original" matrix

3.50e+10 pairs of γ

"Folded" matrix

3.50e+10 pairs of γ





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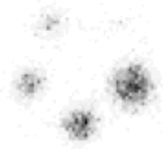
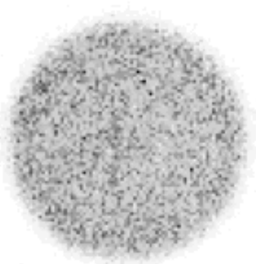
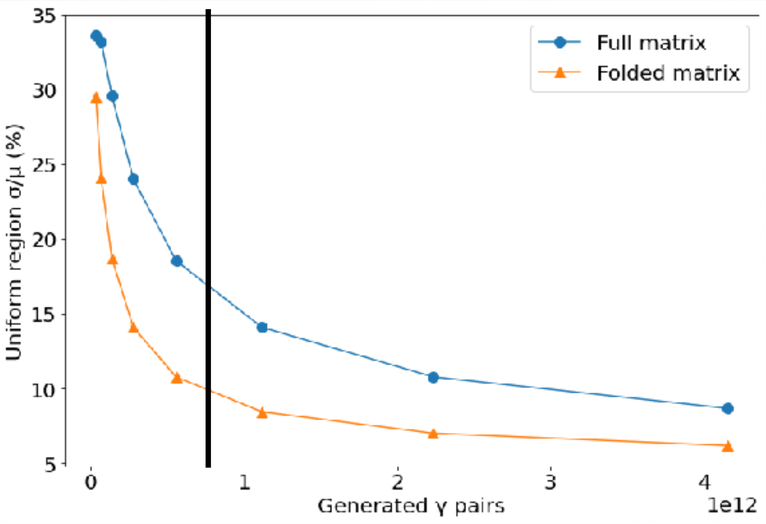
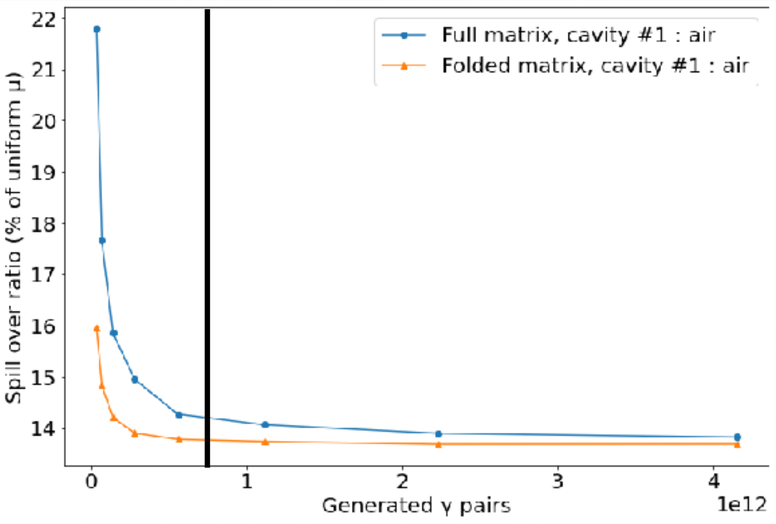
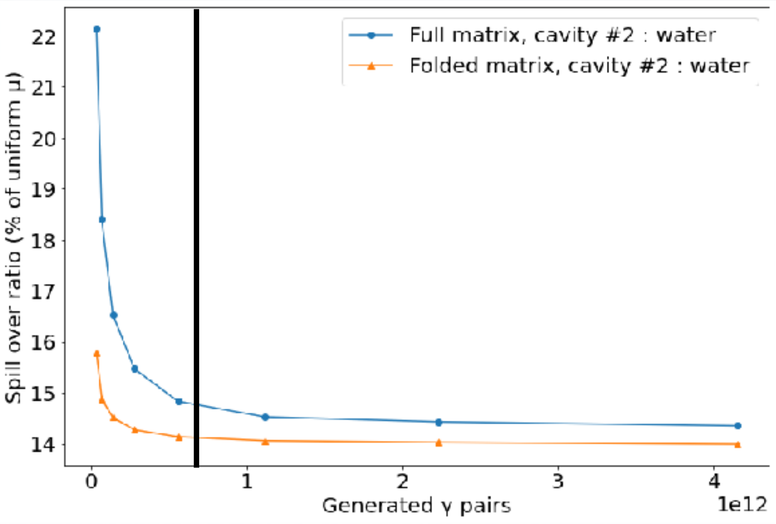


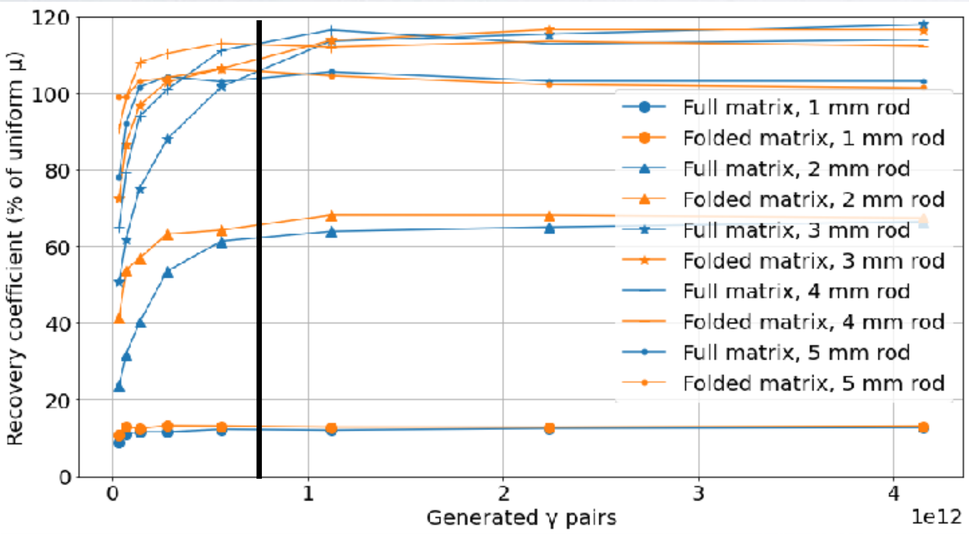


Recovery Coefficients



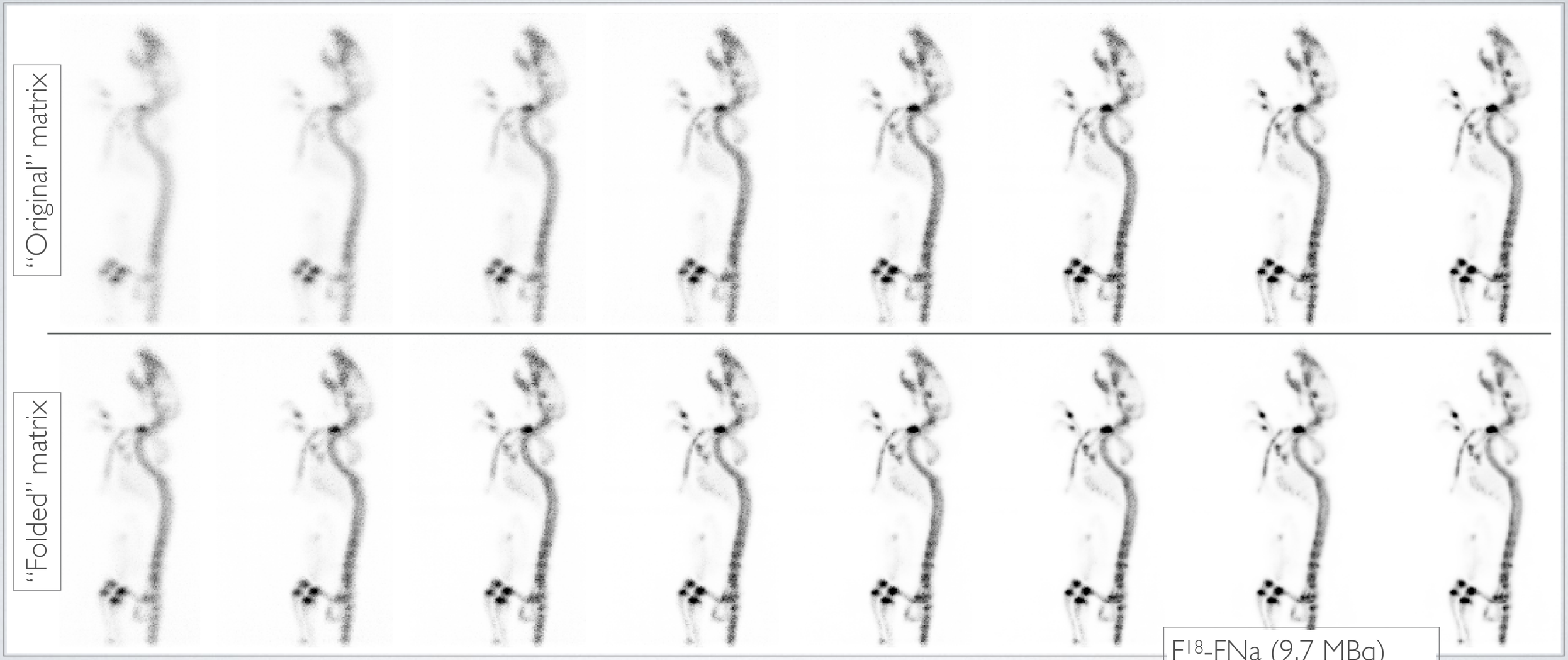






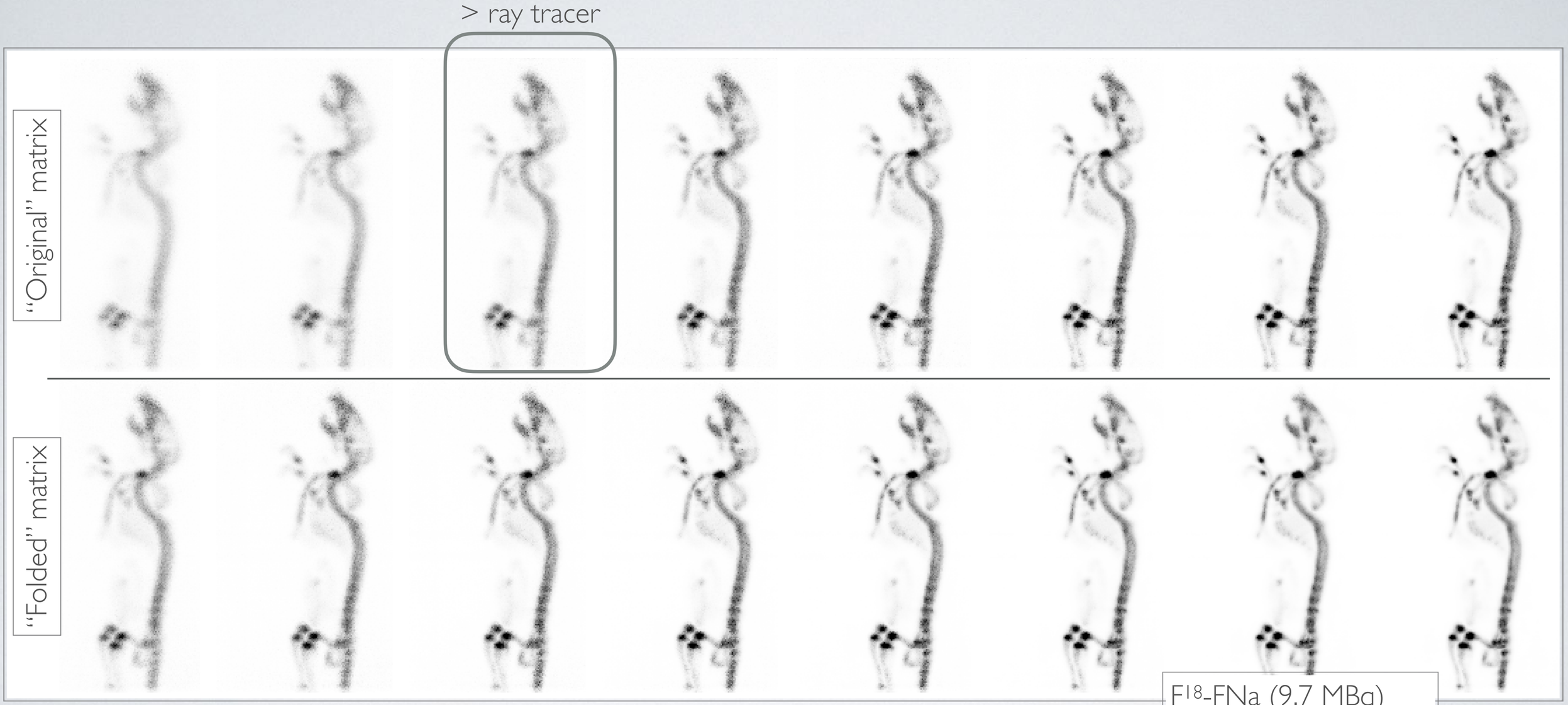
- Spatial resolution parameters converge rather quickly
- Signal/Noise keep on improving, still far from convergence
- Noise can be averaged out by regularization

Visual Impact on FNa Image Reconstruction

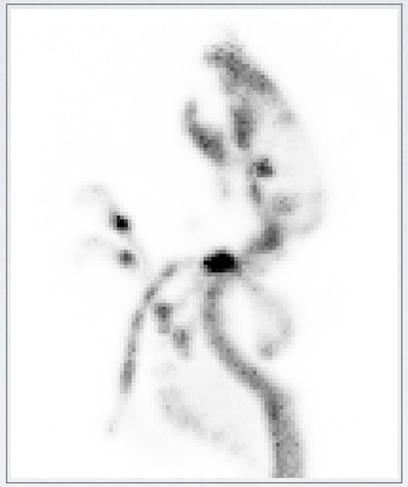


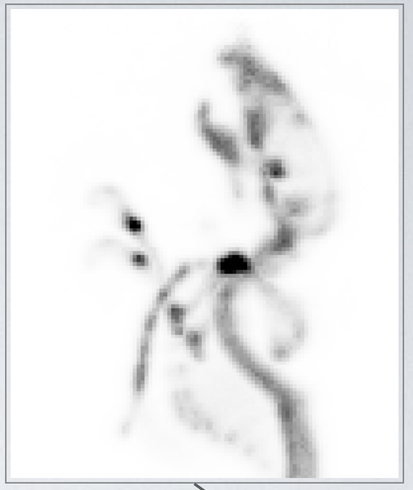
F^{18}-FNa (9.7 MBq)
10 min acquisition
112 min post-injection

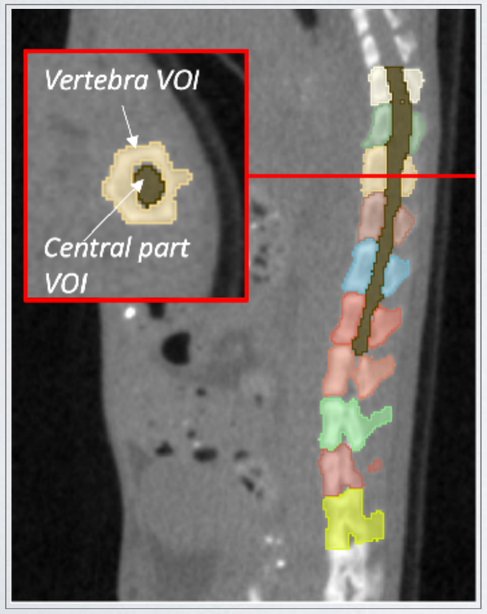
Visual Impact on FNa Image Reconstruction

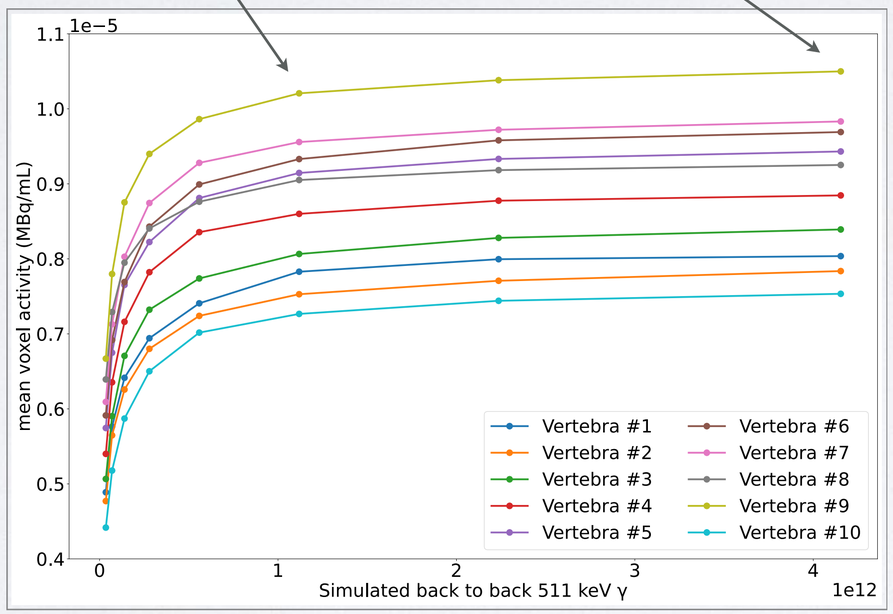


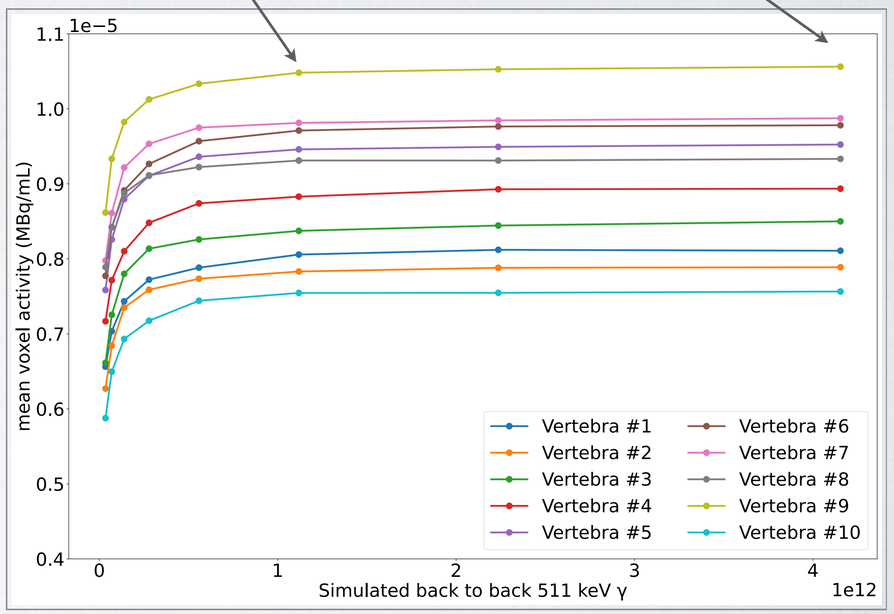
Quantification on vertebrae





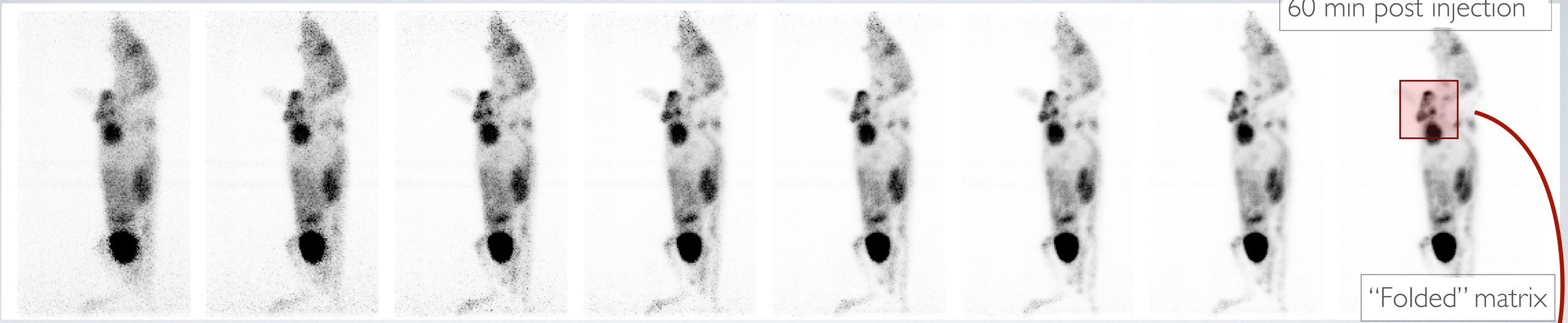






Visual Impact on FDG Image Reconstruction

^{18}F-FDG (4.8 MBq)
10 min acquisition
60 min post injection

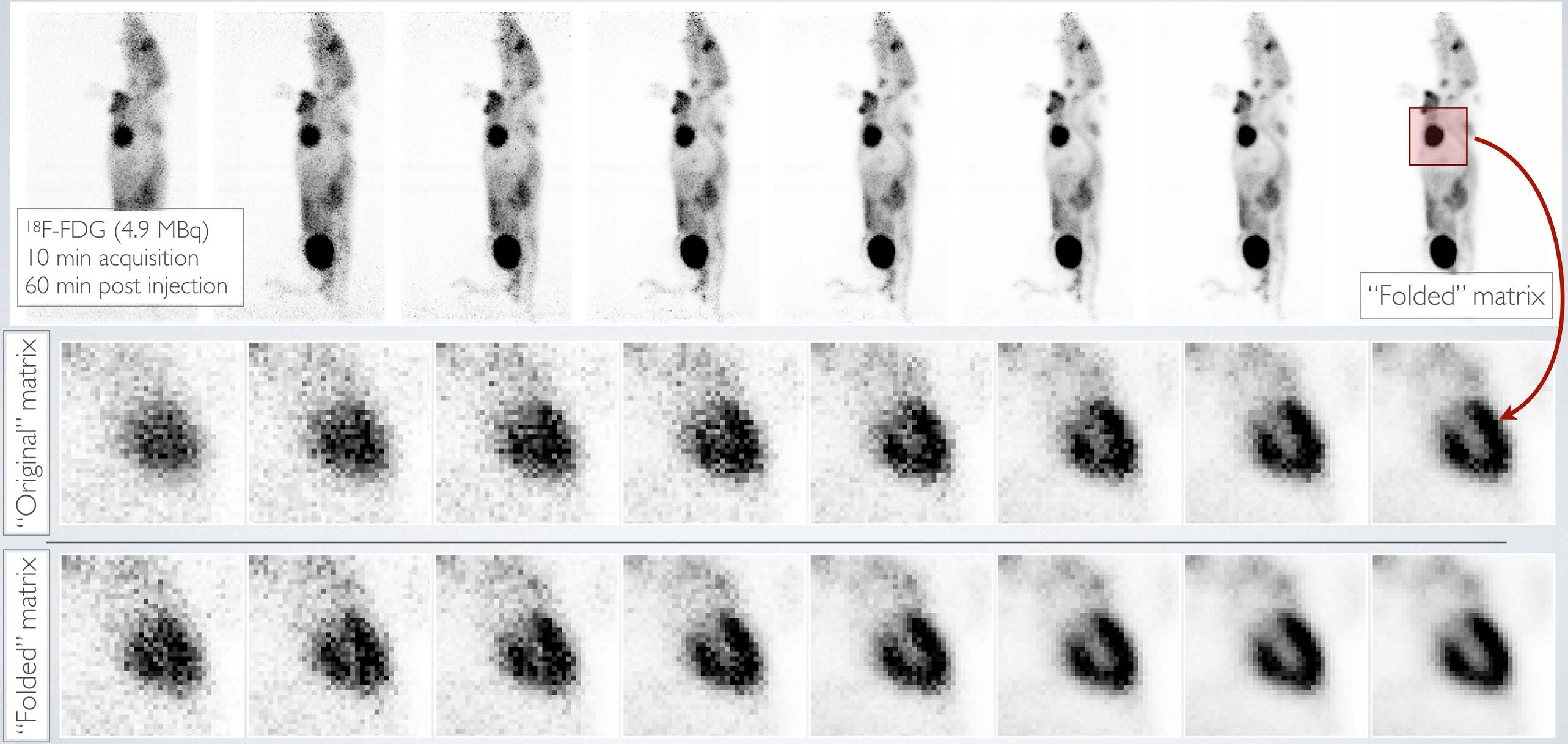


"Folded" matrix

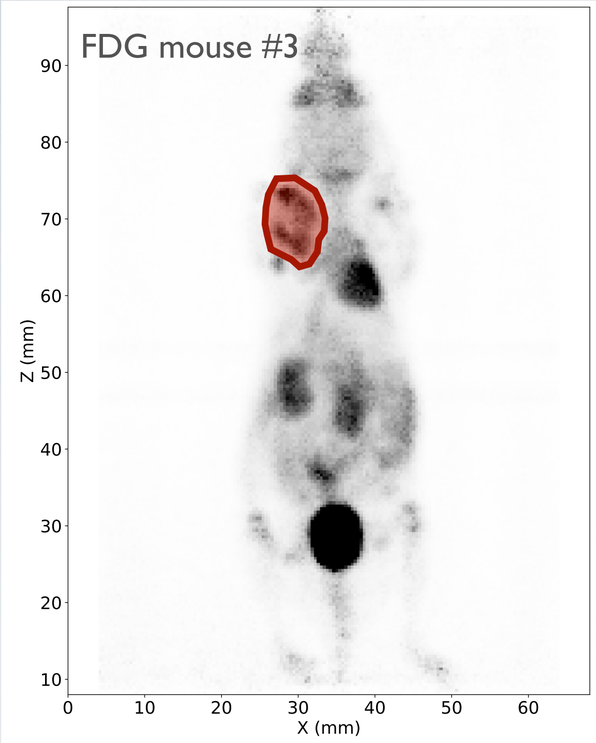
"Original" matrix

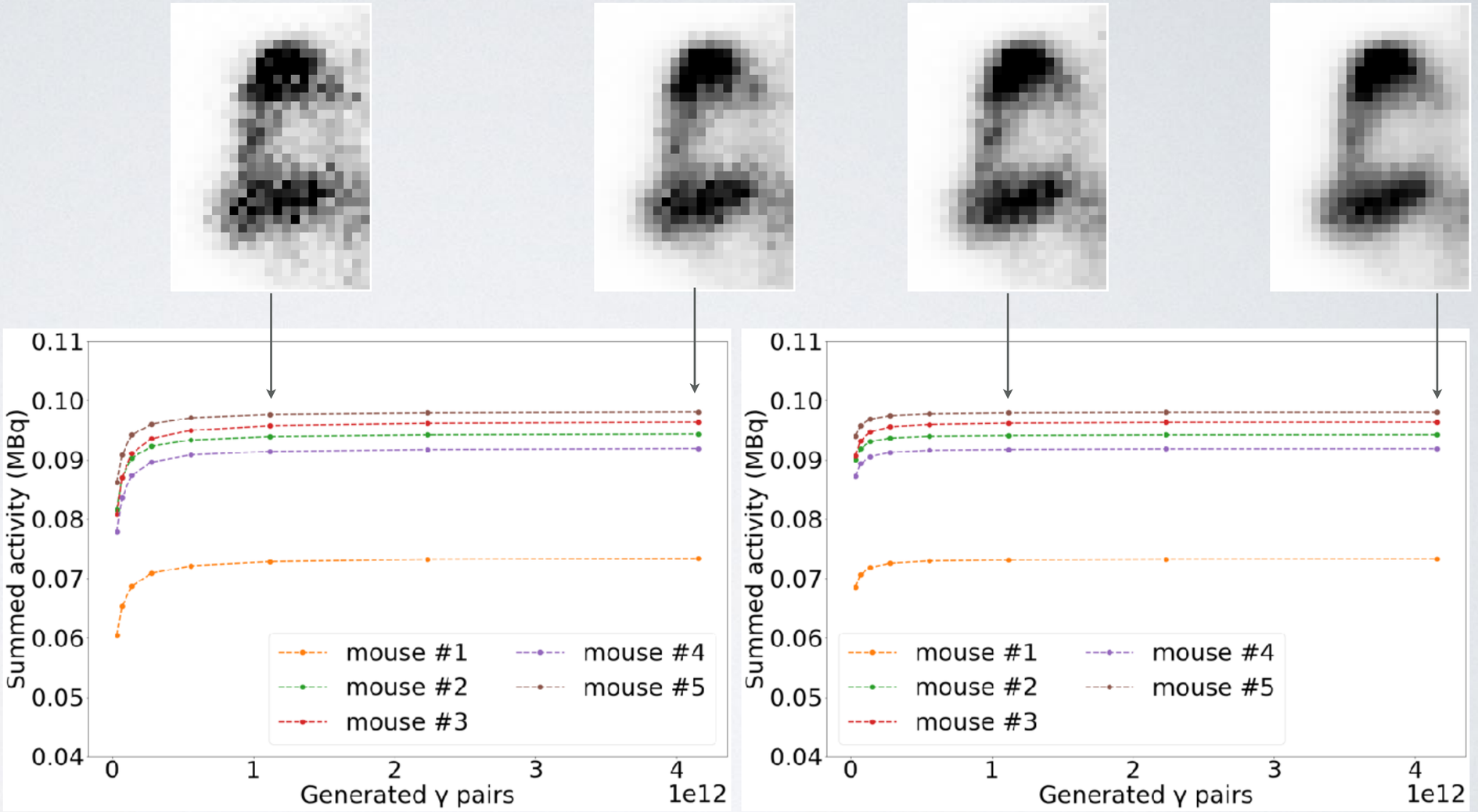
"Folded" matrix

Visual Impact on FDG Image Reconstruction



Quantification on tumors





Summary

- We have studied the impact of Monte-Carlo based system response matrix on the image quality in TEP
- **Quantification metrics** (NEMA NU 4 — 2008) **converge quickly** as we increase the statistics of the SRM
  - impact of modelling other processes become dominant
  - good news! no need to simulate and handle TB matrix files
- Visually, **image quality seems to keep improving** : noise reduction, SNR improves on small structures
  - Balance availability of computing with clinical interest ⇒ application specific
  - Find a better metric to evaluate this effect : perform a radiomics evaluation of tumors
- **Base study to evaluate gains with future reconstructions** based on neural netwotks we will use to increase SRM statistics while keeping reconstruction time manageable

For more details on this study, see https://arxiv.org/abs/2204.10946

IQP reconstructed with IRIS's reconstruction