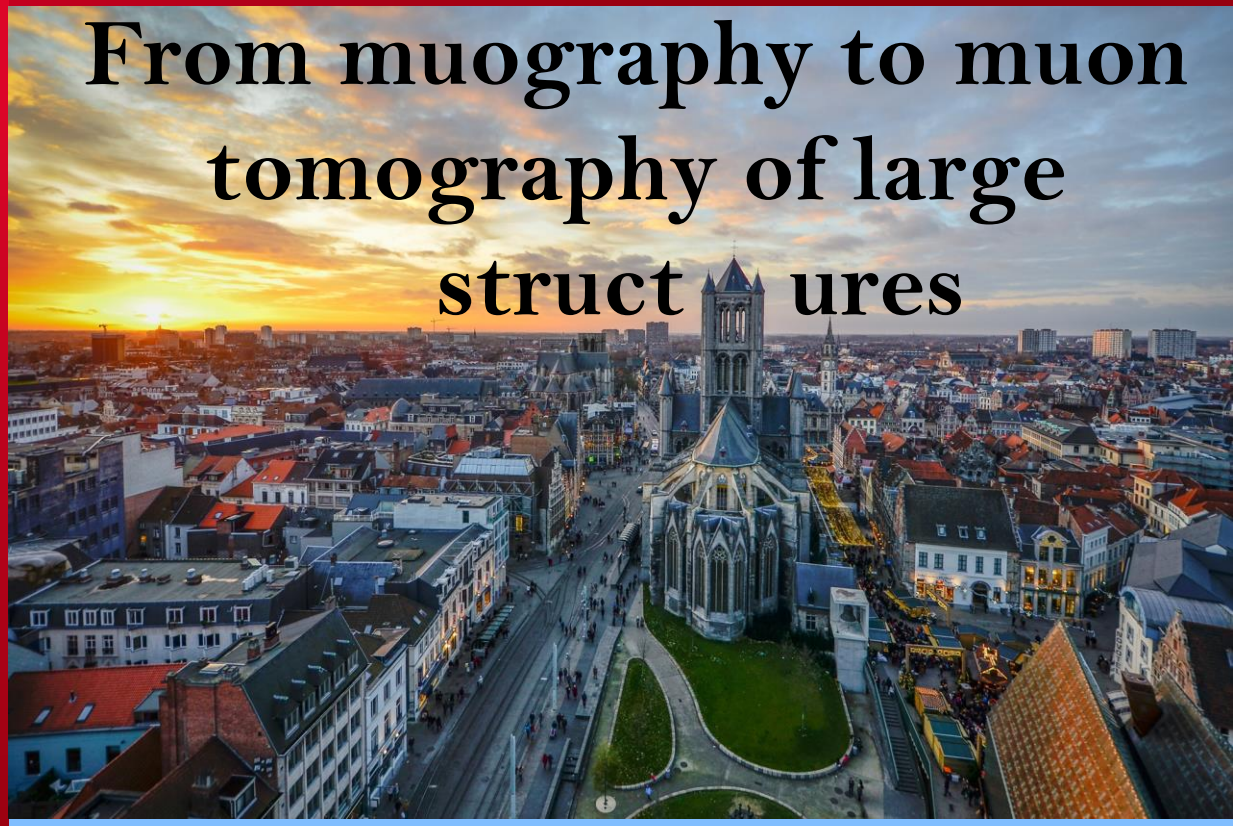
DE LA RECHERCHE À L'INDUSTRIE

From muography to muon tomography of large structures



Sébastien Procureur
CEA Paris-Saclay

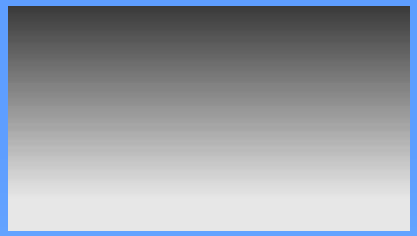
iWoRiD, 29th June 2021

CONTENT

- Muon imaging @ CEA
- Going 3D with SART
- Conclusion & perspectives

MUON IMAGING @ CEA

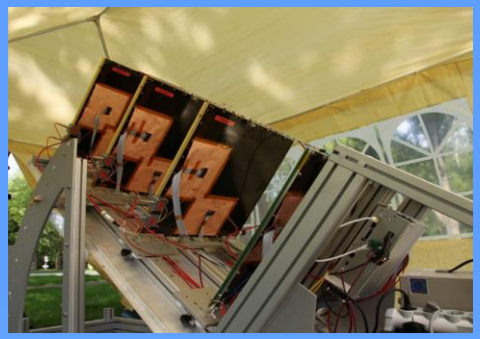
- Muon telescopes based on Micro-Pattern Gaseous Detectors
  - Robust
  - Excellent spatial resolution
  - Real time
  - Very low gas consumption
  - 3 patents



- Industrial manufacturing – many instruments available
  - 12 telescopes of 50x50 cm²
  - 1 scanner of 1mx1m
  - ~ 8 more telescopes and 1 scanner to come soon

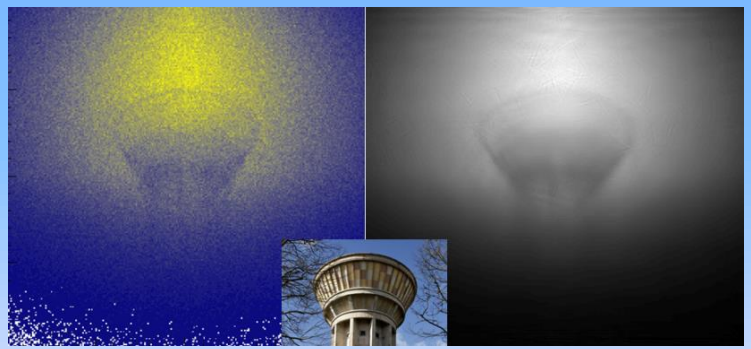
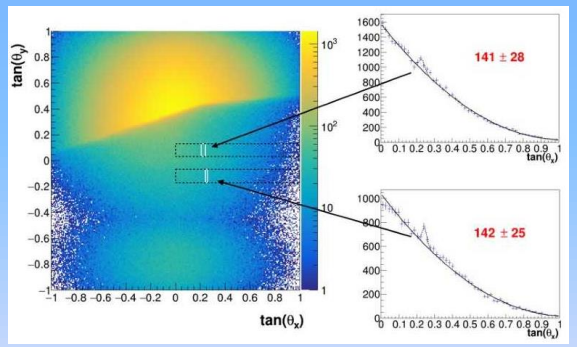
- Operated in many projects, including in harsh environments

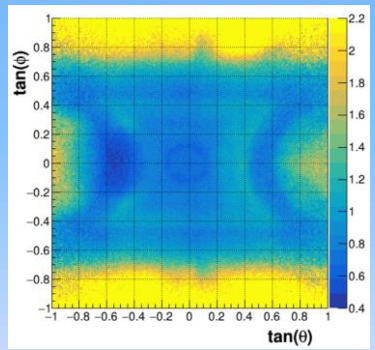
MUON IMAGING @ CEA







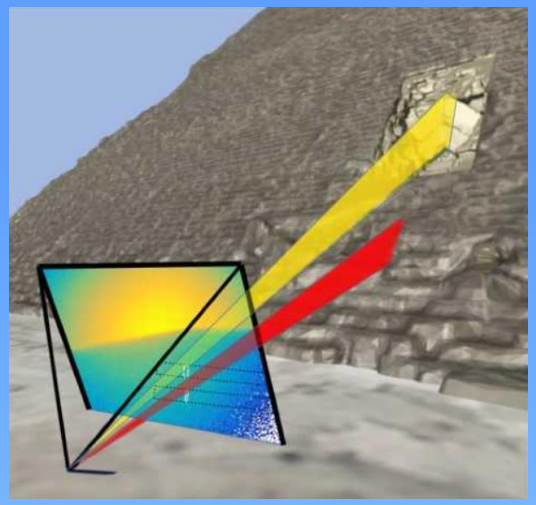






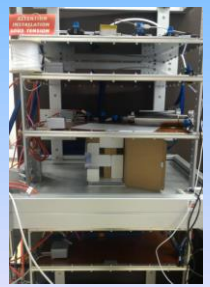
⇒ ***Several projections available for a given structure: 11 for ScanPyramids, 5 for nuclear reactor (~15 by end of 2021)***

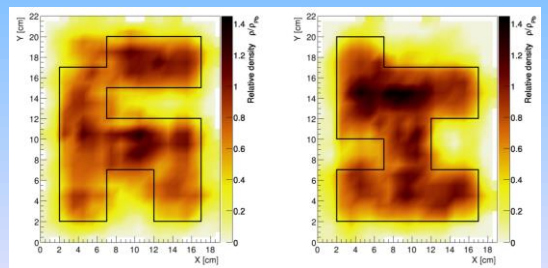
GOING 3D - PRINCIPLE

- Large objects can only be imaged with transmission mode
  - Intrinsically 2D
  - Measures opacity, i.e. 2D density integrated along observation axis



- Muography thus similar to X-ray radiography…
  - Can use algorithms from medical imaging (here SART)
- … with however important differences
  - Size of the volume to image
  - Small number of available projections (a few tens in the best case)
- First implementation in <u>absorption</u> muography (2019):





G. Baccani, JINST 15 P12024 (2020)

GOING 3D - PRINCIPLE

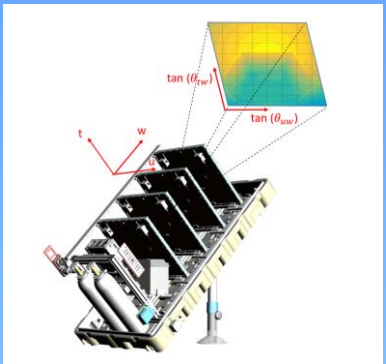
- Same principle in <u>transmission</u> muography…:
  - Split the volume to image in n_v 3D pixels (voxels)
  - Split each muography in n_m independent measurements
  - For a given muography:

$$[a]\vec{\rho} = \vec{o}$$

- Opacity vector, size n_m
- Contains opacity value of each measurement
- Indirectly known from data

- Distance matrix, size $n_v \times n_m$
- Contains mean distance travelled by muons in current voxel
- Calculable

- Density vector, size n_v
- Contains density value of each voxel
- Unknown



- … but (much) more complex:
  - Open-sky flux not measured (≠ absorption mode) ⇒ *Simulation needed for calibration*
  - Much larger objects (~100m vs ~20 cm) ⇒ *Size of the matrix system*
  - Many observation directions are not accessible
  - Need to combine several telescope positions (fixed telescope in absorption)
  - Smaller density contrast ($\Delta\rho \sim 2\ \mathrm{g}/cm^3$ or less vs $\sim 11\ \mathrm{g}/cm^3$)

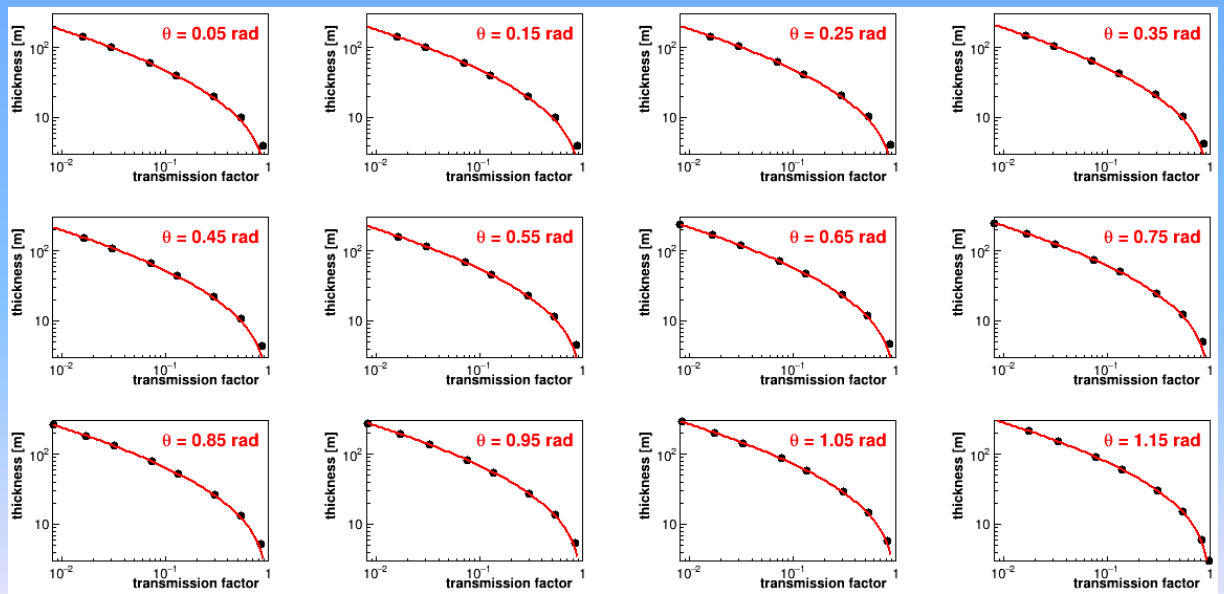
GOING 3D – MUON FLUX VS OPACITY

- Data should be first converted into opacity measurements
  - Calibration with Geant4 simulation
  - Requires very good understanding of telescope performance & muon flux parametrization
  - 1st step: muon flux → transmission factor with open-sky simulation
  - 2nd step: transmission factor → opacity:

$$o = \rho \times f(T;\theta)$$

(θ: zenith angle)

$$f(T;\theta) = L(\theta)\left(e^{A(\theta)\sqrt{-\ln T}} - 1\right)$$



GOING 3D – DISTANCE MATRIX AND MEMORY

- Distance matrix can be calculated once voxels & measurements are defined
  - Need deeply optimized algorithm, e.g. voxel traversal
  - Need special storage method, e.g. YSM (for sparse matrices)

- Just as an example:
  - Volume of 230m x 230m x 140m (pyramid) with 0.5m side voxels
  - Each muography splitted in 200x200 independent measurements
  - 11 projections

⇒ ***Distance matrix has 26 000 000 000 000 elements!! (ok, many zeros, but still…)***

  - After full optimization, CPU to calculate the matrix elements yields ~ 1 day (single thread)
  - Memory (RAM) of 200 Gb

GOING 3D – SOLVING THE SYSTEM WITH SART

- SART algorithm provides update of the density vector at each iteration:

$$\rho_v^j = \rho_v^{j-1} + \Delta\rho_v^j$$

$$\Delta\rho_v^j = \frac{1}{\sum_{m=1}^{N_m} w_m} \sum_{m=1}^{N_m} w_m \frac{O_m - O_m^{j-1}}{|\overrightarrow{A_m}|^2} A_{m,v}$$

$$O_m^{j-1} = \sum_{v=1}^{N_v} A_{m,v} \rho_v^{j-1}$$

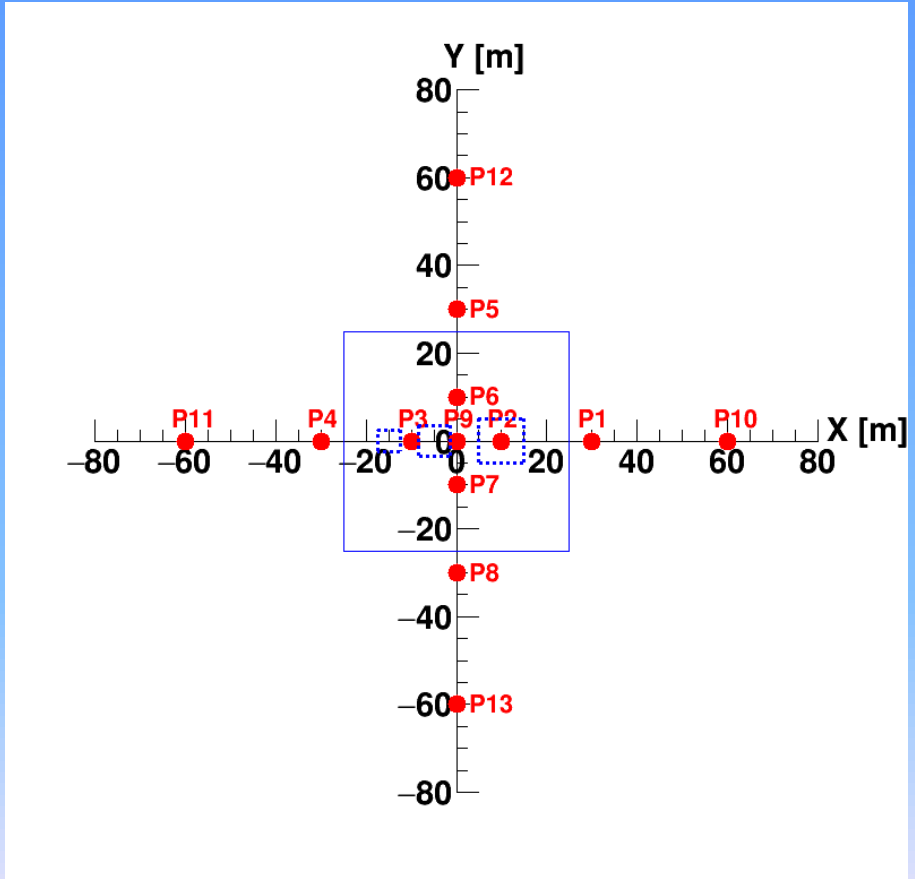
  - Number of effective iterations ~ a few 10,000 for the pyramid case
  - CPU time ~ 0.5 day

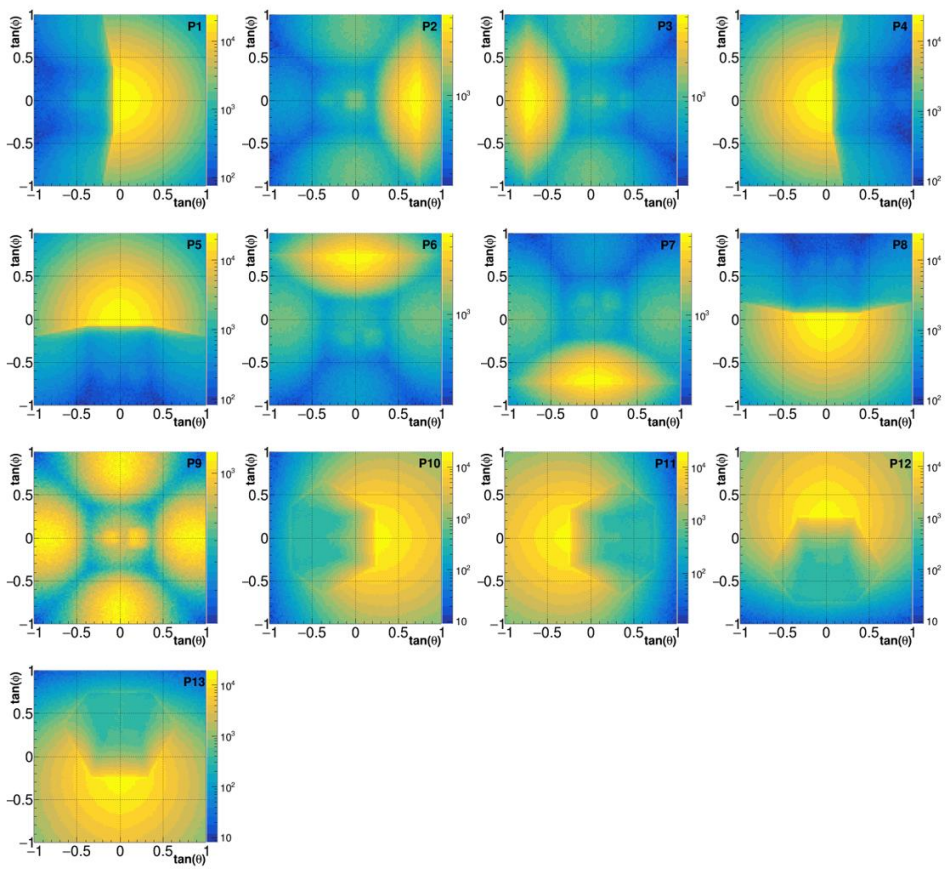
- In practice, limited issue of the initialization of the density vector…

More details in S. Procureur, « Muon tomography of large structures with 2D projections », submitted to Nucl. Inst. & Meth. A

GOING 3D – EXAMPLE FROM SIMULATION

- Framework tested with pseudo-data of a cubic structure with 3 cavities
  - 50m side, concrete material
  - 3 cavities of 10, 7 and 5m side
  - Up to 13 projections below and on the side, 1 month each





GOING 3D – EXAMPLE FROM SIMULATION

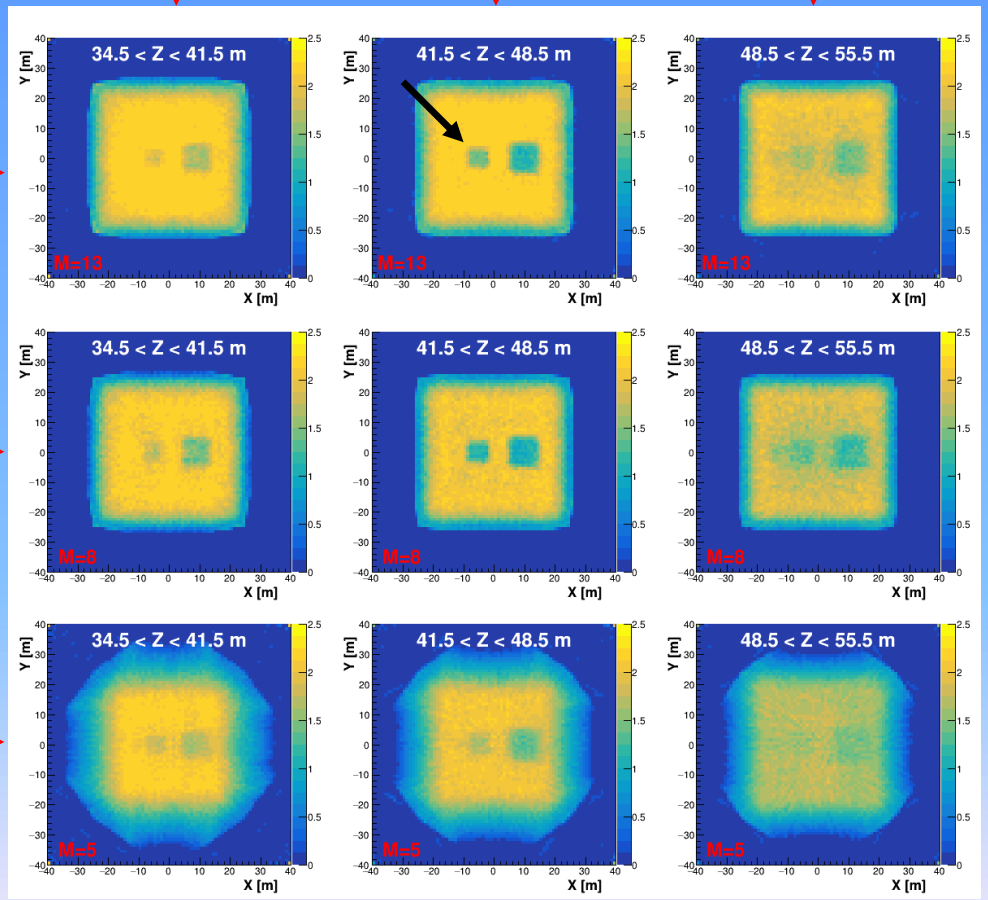
- Tomography obtained in the vicinity of the 7m cavity:

Below cavity *Centered on cavity* *Above cavity*

13 projections

8 projections

5 projections



GOING 3D – EXAMPLE FROM SIMULATION

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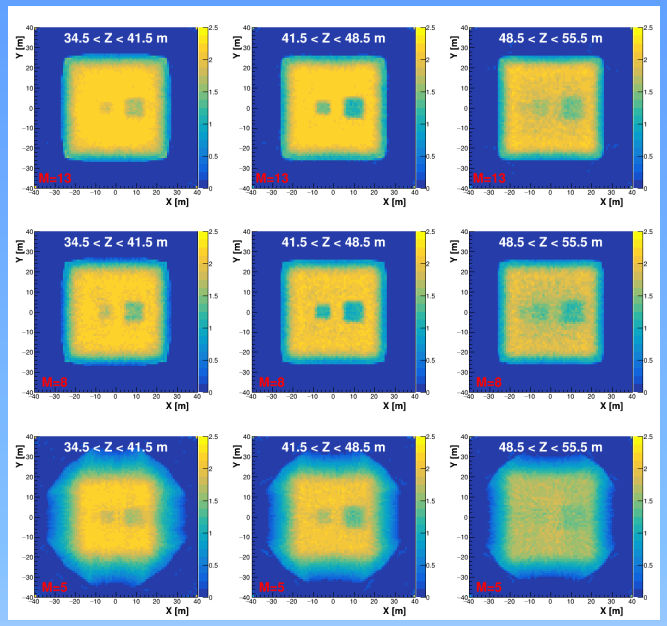
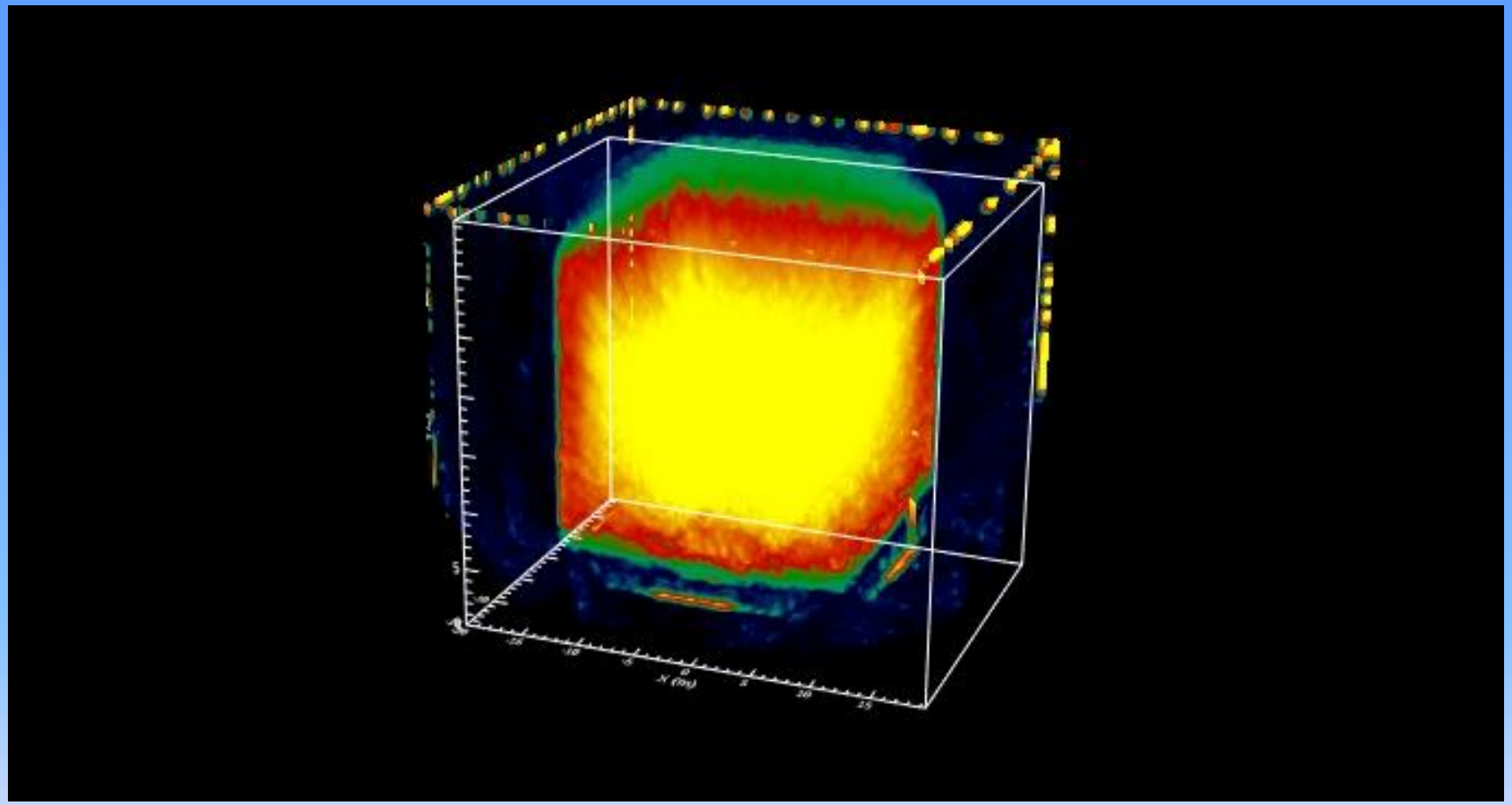


⇒ ***Limit of concrete cube very well defined***
⇒ ***Excellent resolution in x-y (transverse)***
⇒ ***Quite good in z (vertical) as well***
⇒ ***Works with only 5 projections***

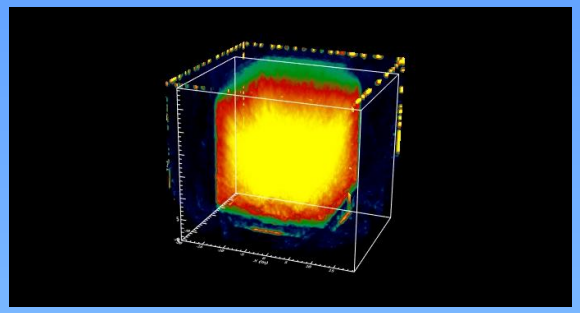
GOING 3D – EXAMPLE FROM SIMULATION

- Using SDvision tool:



CONCLUSION & PERSPECTIVES

- Probably the first SART implementation in transmission muography
  - Most general case in muography (large structures like volcanoes, pyramid, etc.)
- Careful optimization to make the calculation reasonably fast (~1 day)
- Works very well with pseudo-data



- Also successfully tested with pyramid data
  - Requires deep understanding of the instrument (noise, efficiency, acceptance)
  - Added in the ScanPyramids latest paper, submitted to Science recently
- Very recently applied to our nuclear reactor data (only 5 projections so far!)
  - Many internal structures properly localized and reconstructed
  - Probably a paper by the end of the year

THANK YOU FOR YOUR ATTENTION