Cosmic muons for Cultural Heritage

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Including material and ideas also from:
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Judy De Roy and Sam Huysmans (Royal Institute for Cultural Heritage, Belgium)

Muography for large structures

- Muography already showed its value for **very large** cultural heritage structures

LETTER

doi:10.1038/nature24647

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

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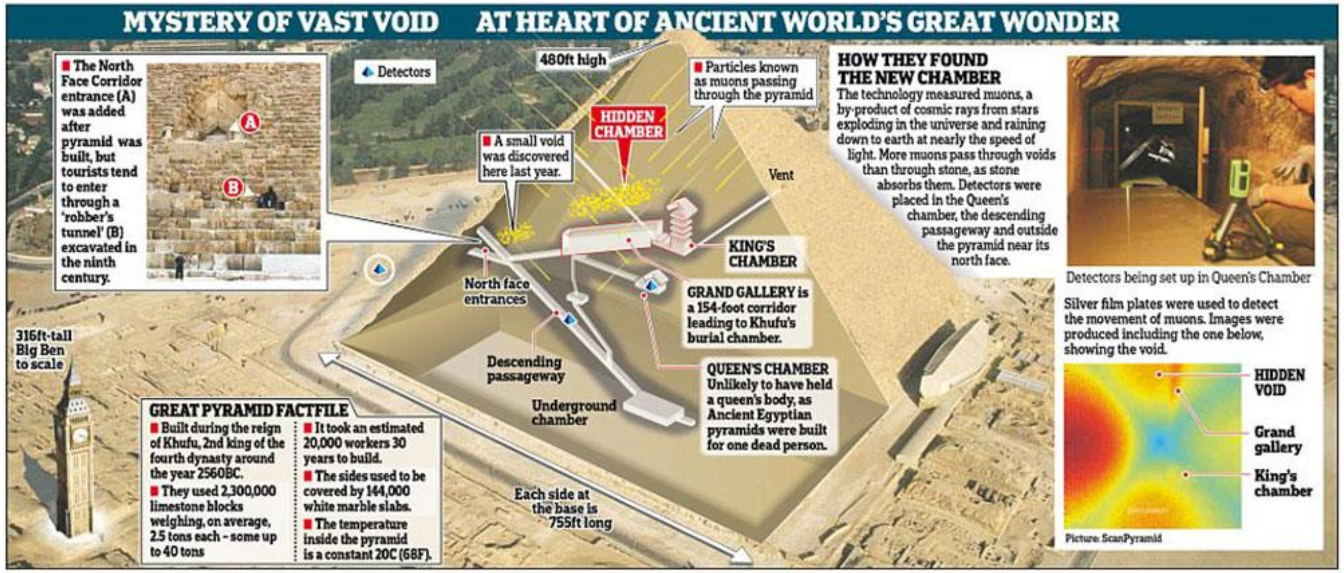

Research article

Imaging the dome of Santa Maria del Fiore using cosmic rays

E. Guardincerri, J. D. Bacon, N. Barros, C. Blasi, L. Bonechi, A. Chen, R. D'Alessandro, J. M. Durham, M. Fine, C. Mauger, G. Mayers, C. Morris, F. M. Newcomer, J. Okasinski, T. Pizzico, K. Plaud-Ramos, D. C. Poulson, M. B. Reilly, A. Roberts, T. Saeid, V. Vaccaro and R. Van Berg See fewer authors

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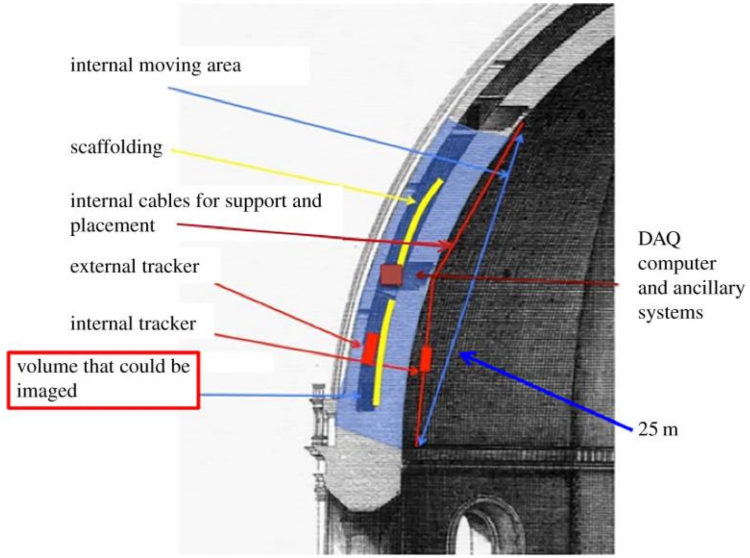
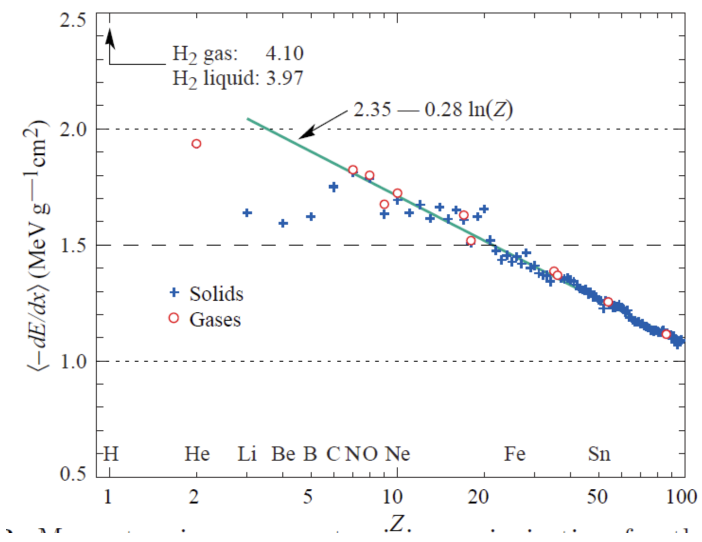
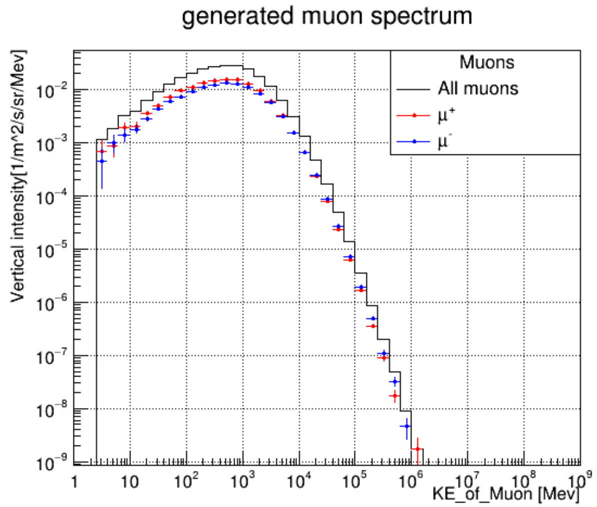


The small-size limit of (absorption-based) muography

- With a pyramid one needs months of data taking because most muons are stopped; but e.g. with statues the situation is different:
  - 1 m of stone (ρ ~ 2.5 g/cm^3) stops muons up to ~0.5 GeV
  - At sea level, only ~10% of the μ spectrum is < 0.5 GeV
- Which means a fraction f~90% of the free-sky flux survives the passage through the object
  - Larger muon statistics may sound like an advantage of small objects, but it's actually too much of a good thing!
  - Discriminating power depends on f(1-f): so it tends to 0 for f→0 and f→1
- This regime is challenging for muography
  - Also because low-momentum implies a lot of Coulomb scattering in the detector itself, degrading the resolution





What we call small, is someone else's huge

- "blind spot" in standard cultural heritage (CH) imaging methods
  - O(m)-sized objects (e.g., human-sized statues)
  - They may be too fragile, too heavy and/or too precious to be moved to a laboratory for imaging by beams of X or gamma rays, neutrons or electrons
- Portable and compact devices solve this problem, but they bring new issues
  - X-ray fluorescence analysis (XRF) → limited to shallow depths by the high absorption rate of X rays
  - Portable fast-neutron sources → hazardous to humans, strictly regulated, can cause activation of material
  - Cosmic muons reach deeper than X-rays and neutrons, and pose no hazard to humans and artifacts

TRACER 5 XRF

https://doi.org/10.3390/s20020502

Some interesting use cases in Brussels

Angels in Notre Dame aux Riches Claires:

- Reparations after a fire were not properly documented.
- Important (and **currently unfeasible!**) to assess number and positions of iron threaded bars/dowels inserted in the '90s.

Fountain of the Three Graces:

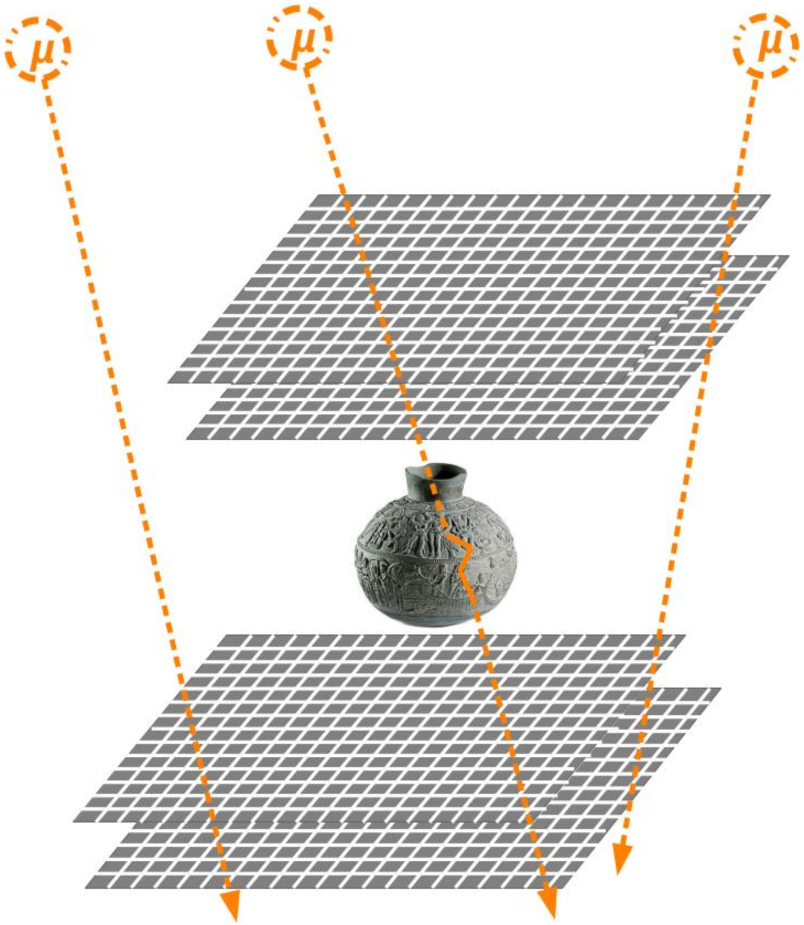
- we have **no information** on the inner tube system/fountain system that is probably still present in the core center of the column, and other hidden internal features.

Tomb of von Turn und Taxis:

- The subsidence has caused deformation in the marble structure of the tomb beneath the sculptures
- it would be valuable to assess the condition of the tomb's inner structure through visualization
- Dismantling the sculptures poses a risk to their preservation.

Scattering-based muography

Detector area needs to be large with respect to the volume of the object, as the acceptance must include muons scattered at large angles.



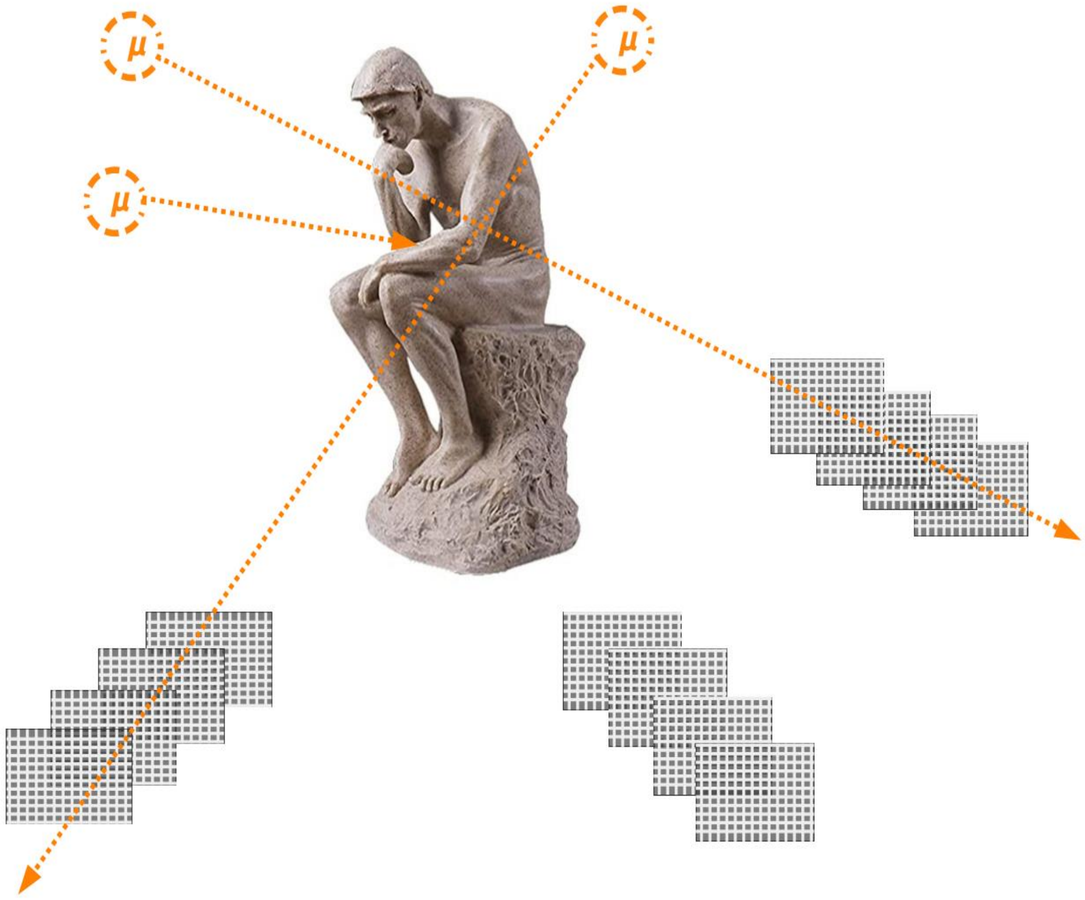
- Appealing option for small cultural heritage items, e.g. terracottas, figurines, small statues
- Muon scattering is sensitive to the atomic number Z, this property allows material discrimination: particularly interesting for multi-material objects where experts are not sure about some inner (and hidden) component

Limitations :

- Impractical for human-sized (or larger) statues
- The object of interest must be moved → a problem for fragile or very precious objects
- Complexity of the installation → Placing a muon detector on top of the object and others on the ground
- Cost (with respect to absorption muography)
  → relatively large detectors needed for full acceptance

Absorption-based muography

There is no specific limitations on the size of the detector plates, this technique is effective for larger targets

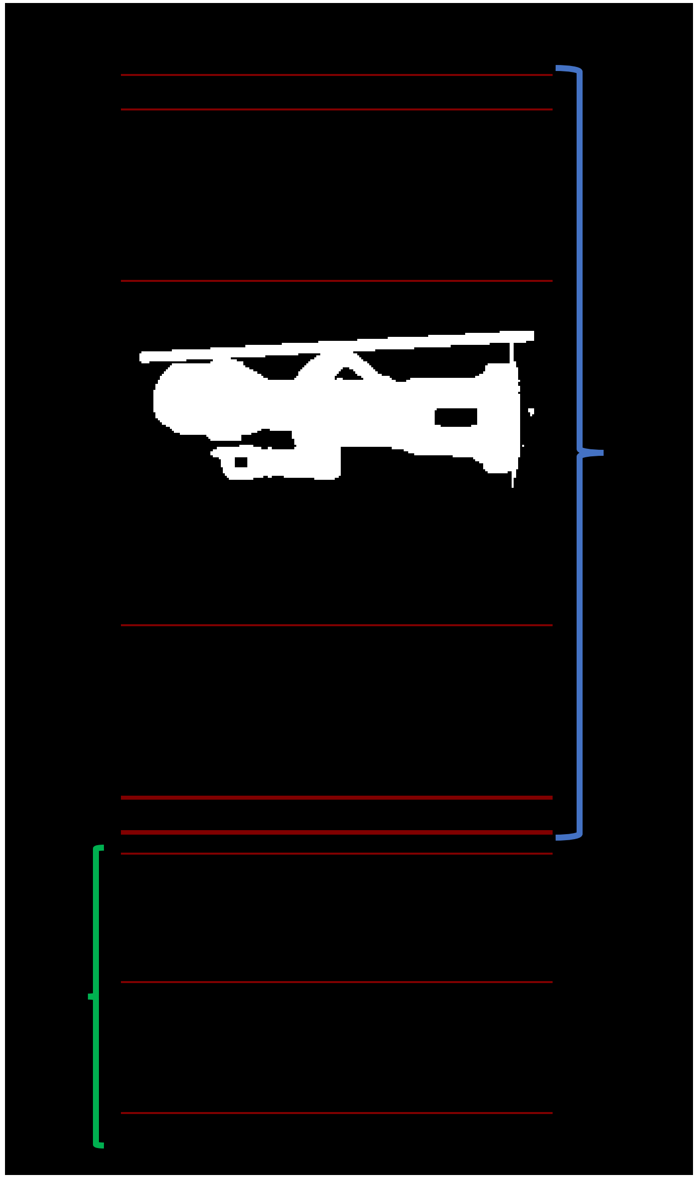


- Appealing option for large cultural heritage items, practical for example for human-sized (or larger) statues
- Sensitive to the matter density of the material, which gives the possibility to discriminate between different hypotheses on the inner composition of a large object, and also assess specific conditions like the moisture content

Limitations :

- No material discrimination (apart from density)
- the small size / low density of the object of interest compared to the usual absorption muography targets

Simulation setup



- Starting with a MC study, using Geant4 model of an object that has been imaged with X-rays but was at the limit of the technique.
- Changing its scale in MC until it's too big for X-rays but just a bit too small for our muography setup

Detector panels:

- 6 detection planes close to the target are used for **scattering** reconstruction
- 3 detection planes for **absorption** reconstruction
- detector panels are 'ideal' (with infinite resolution)
- They record the true muon position, strips and pixels will be simulated further in the analysis

Statue:

- 3D voxelized volume for an african statue made of HardWood (oak: 687.25 kg/m³)
- Courtesy of the TOCOWO project (https://tocowo.ugent.be/) and the Africa Museum of Tervuren (Belgium)

Muon source:

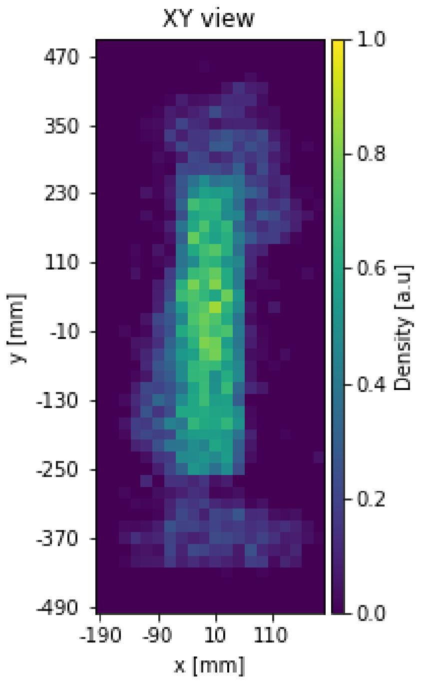
- Realistic cosmic muons using CRY generator

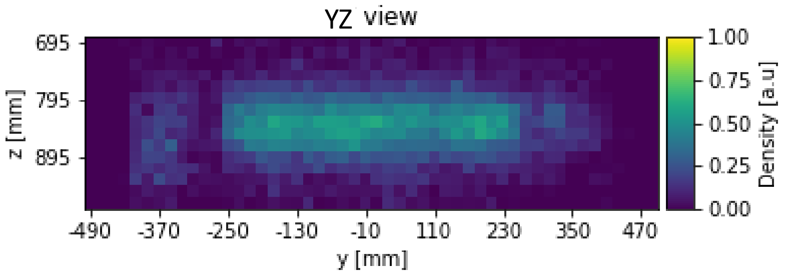
Simulation setup

Setup	Size [cm³]	Additives	Pixels size [mm]	# of pixels / plane
A	80*30*30	Copper bar	1 mm	1000x1000
B (Backup)	80*30*30	Copper bar	10 mm	100x100
C	160*60*60	Bronze bar	Perfect resolution	/

Scattering reconstruction: POCA

Scenario A: Statue (80*30*30cm³)



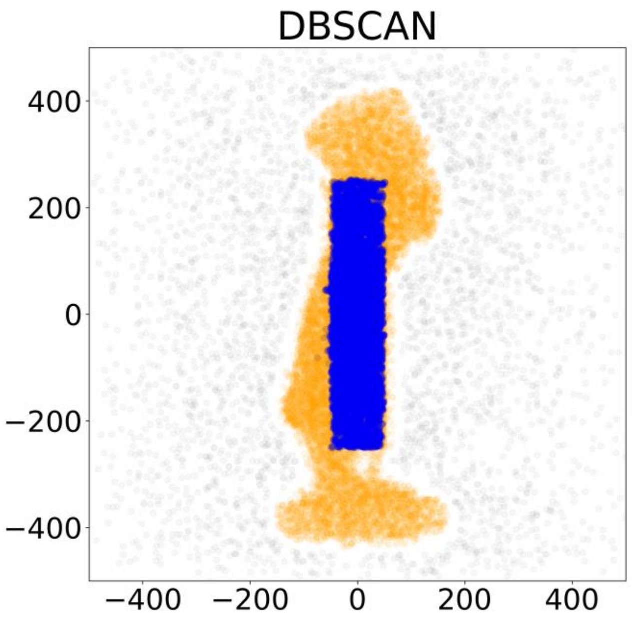


- We associate the value of the scattering angle to each POCA points
- Then for each voxel, we associate a score corresponding to the median of the scattering angles of all the POCA points of the voxel
- The quality of the image is good
- The shape of the wooden statue can be identified
- Conclusion: the POCA approach is good at identifying high density object within low density objects

Clustering algorithm

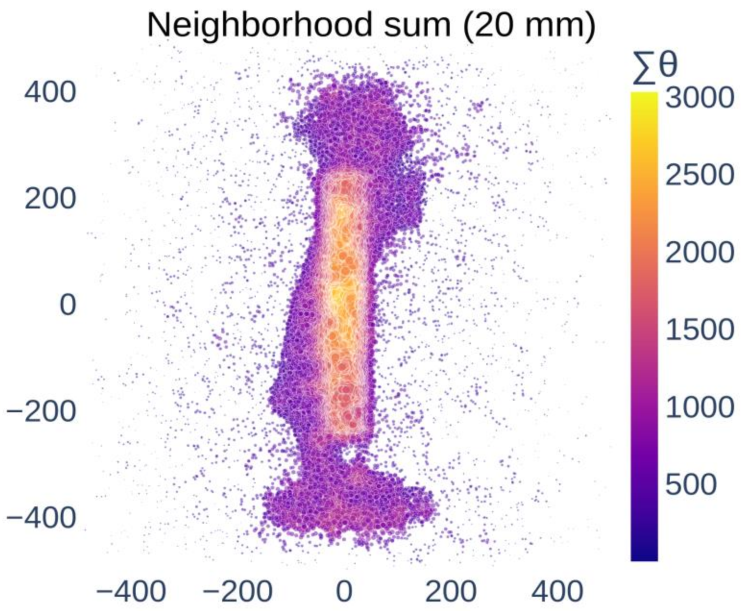
Density-Based Spatial Clustering of Applications with Noise:

Condition : Clustering of POCA points based on density



- DBSCAN is a density based clustering algorithm.
- It requires 2 input parameters: distance of a cluster point (ϵ) and a minimum number of points within the neighbourhood i.e., within ϵ.
- Depending on cluster condition, a point in DBSCAN is classified as a core or noise point.

Neighborhood sum:



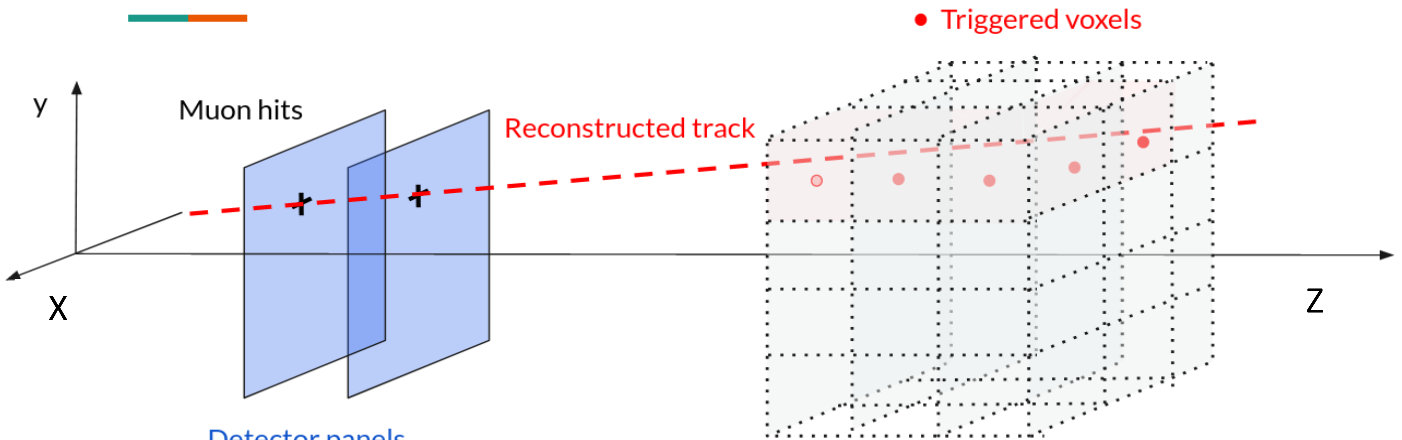
- The sum of all the θ values (where θ is the scattering angle) of points within a circle of radius ϵ is taken as the weight of the point around which the circle has been constructed.
- This process is repeated for all the points
- This approach assigns greater weight to points located in **high-density regions** surrounded by points with large θ values. Conversely, points surrounded by small θ values in **low-density regions** receive relatively suppressed weights.

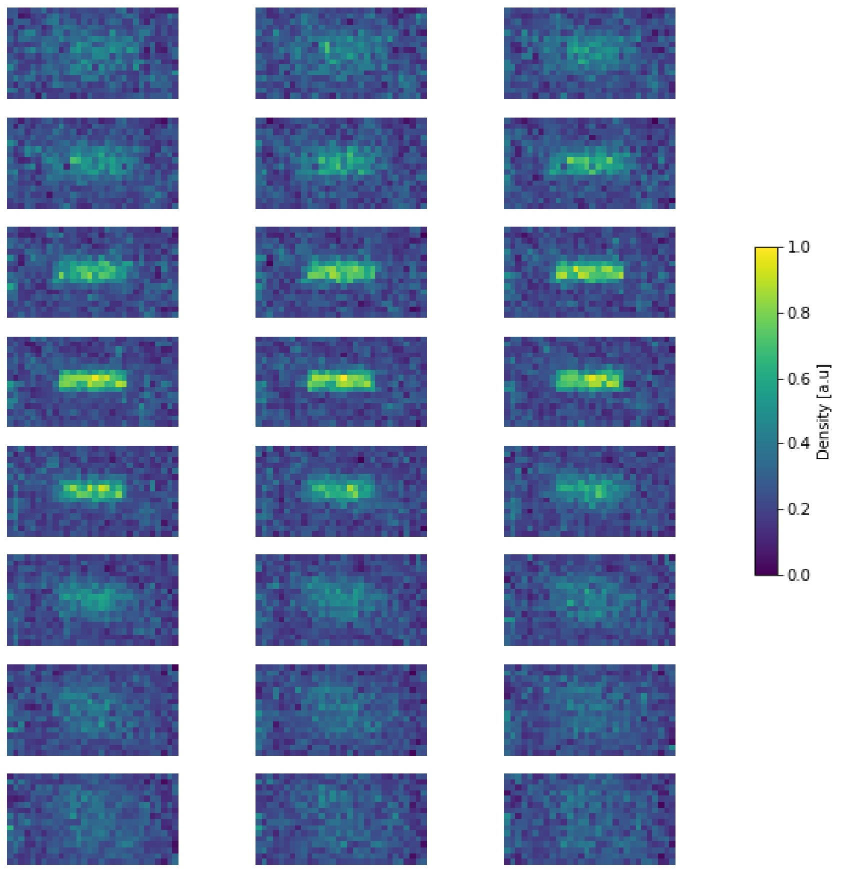
Absorption reconstruction: Back-Projection method

<u>Scenario C:</u> Statue (160*60*60cm³)

Challenging regime:

- For scattering based muography: large volume
- For absorption based muography: small volume with low density object





transmission map slice by slice

- Take into account only muons with E< 800MeV
- 2 minutes exposition time is enough for identifying a bronze bar hidden in the statue
- Custom back-projection ASR reconstruction algorithm

(L. Bonechi et al 2015 JINST 10 P02003 and M. Stapleton et al. 2014 JINST 9 P11019)

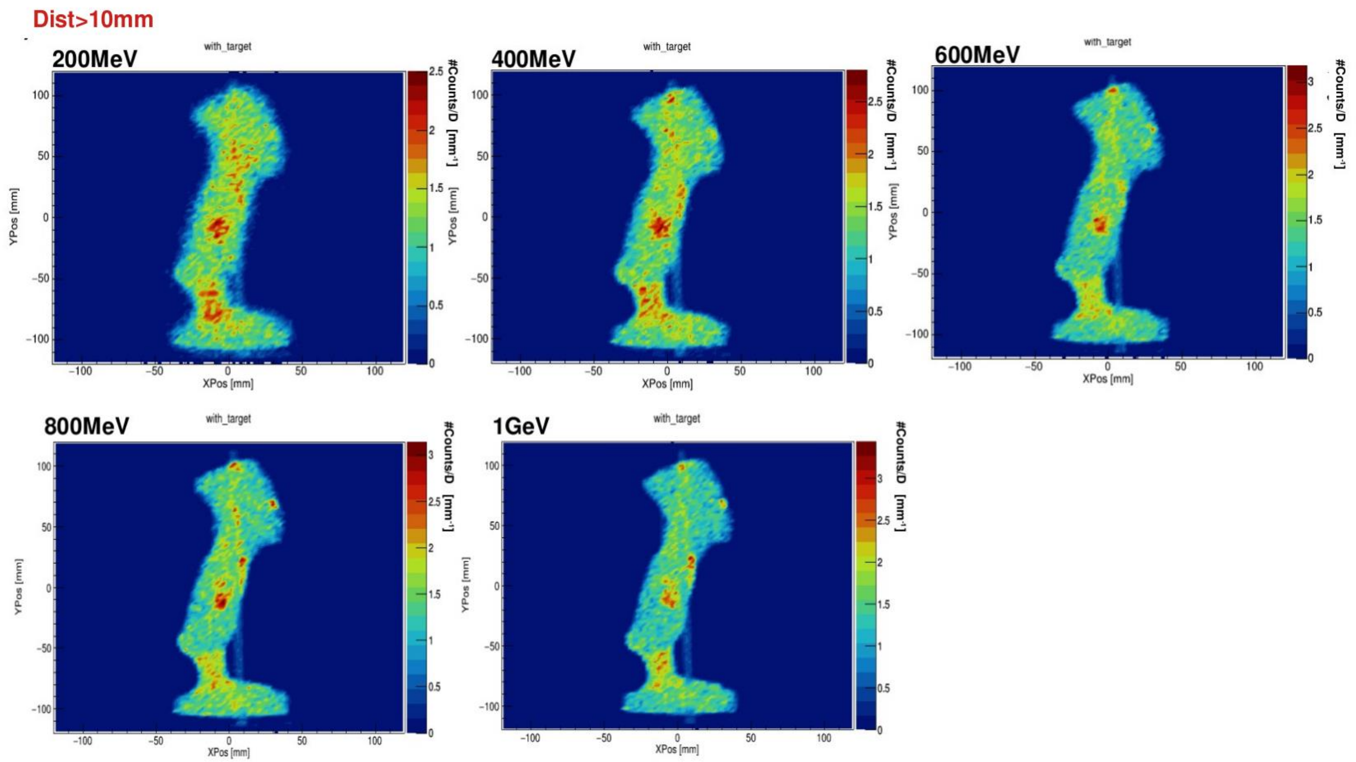
What about artificial muon beams?

Everything shown so far assumes **cosmic** muons. While it has several advantages (radiologically safe, cheap, sustainable, and **portable**), cosmic-ray muography has also two severe limitations:

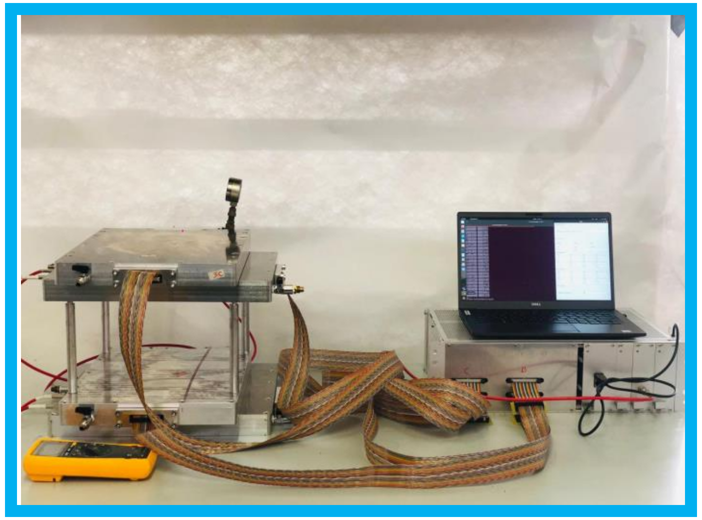
- Long acquisition times
- Extremely broad energy spectrum (and incoming angular distribution)

None of these limitations exist if muons are produced by accelerators. In case a **portable** artificial muon source becomes available, we would get the best of the two worlds.

This figure shows, for the same object modeled in the previous slides, what we could get very quickly with a controlled perpendicular beam of muons at a few fixed energies (200,400,600,800,1000 MeV)

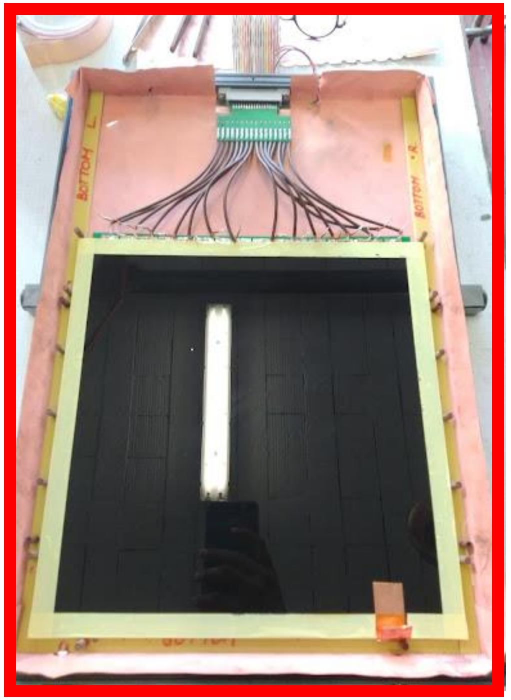


Our detectors: Resistive Plate Chambers



Design goals:

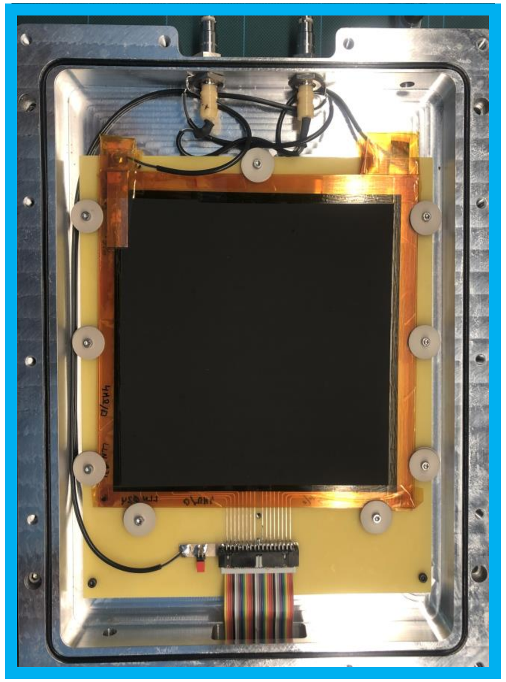
- Small, light, robust
- Modular (flexibility to change the general setup based on the use case)
- Cheap, easy to assemble
- Collaboration established :
  - Ghent and Louvain : glass electrodes
  - NISER: bakelite electrodes



Property	UGent (Prototype 1.G)	UCLouvain (Prototype 1.L)
Size	30×30 cm^2	16×16 cm^2
Gas Flow	Continuous	Sealed
Gas Mixture	95.2% Freon, 0.3% SF_6 4.5% isobutane	95.2% Freon, 0.3% SF_6 4.5% isobutane
Readout	1.5cm width Cu strip	1cm width Cu strip
Semi-resistive coating	Using hand sprayer ($\sim$ 650 K$\Omega/\square$)	Serigraphy method ($\sim$ 4 M$\Omega/\square$)
DAQ	NIM + CEAN integrated	Custom made
Portability	Not yet	Portable

Table : Properties of the two RPC prototypes

From R.M.I.D Gamage et al., E3S Web of Conf. 357 (2022) 01001



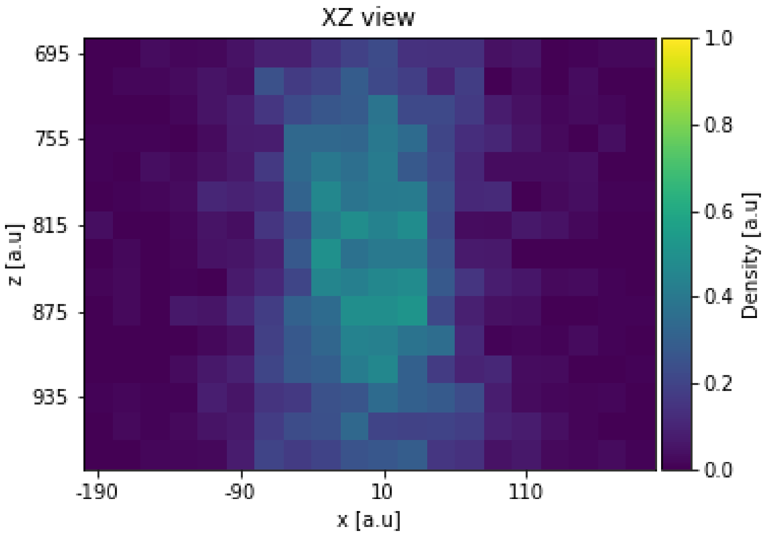
Summary

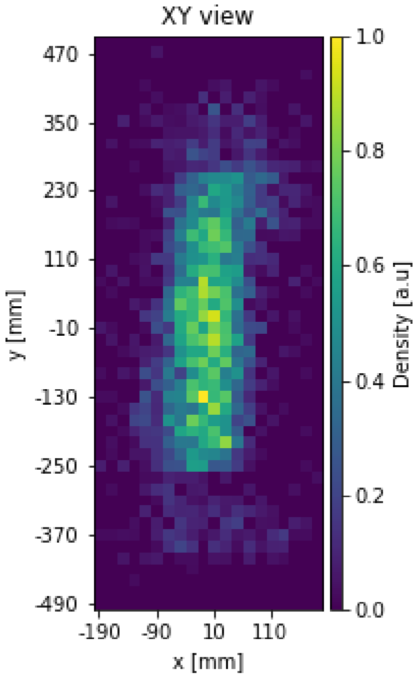
- Cosmic-ray muography, with the absorption method, has already proven its usefulness for the study of large-scale cultural heritage
- It is harder to apply to **small-scale** objects; however, we argue that it is worth the extra work necessary to adapt it also to this regime, given potential applications of cultural heritage importance
- We started a series of MC studies in collaboration with cultural heritage experts in Belgium; a "white paper" is upcoming
- Exploring two methods: scattering-based (appropriate for small items) and absorption-based (appropriate for human-sized or larger)
- Interdisciplinary "white paper" in preparation with cultural heritage experts, containing recommendations based on rough simulations

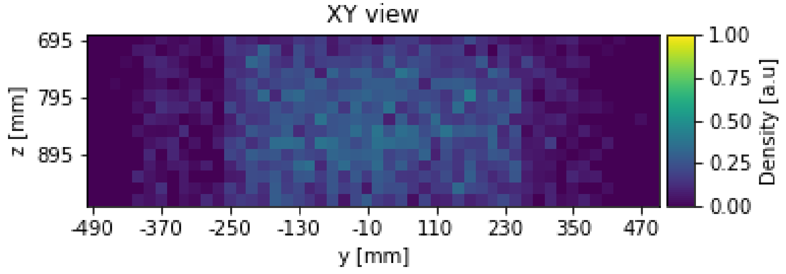
Backup slides

Scattering reconstruction: POCA

Scenario B:





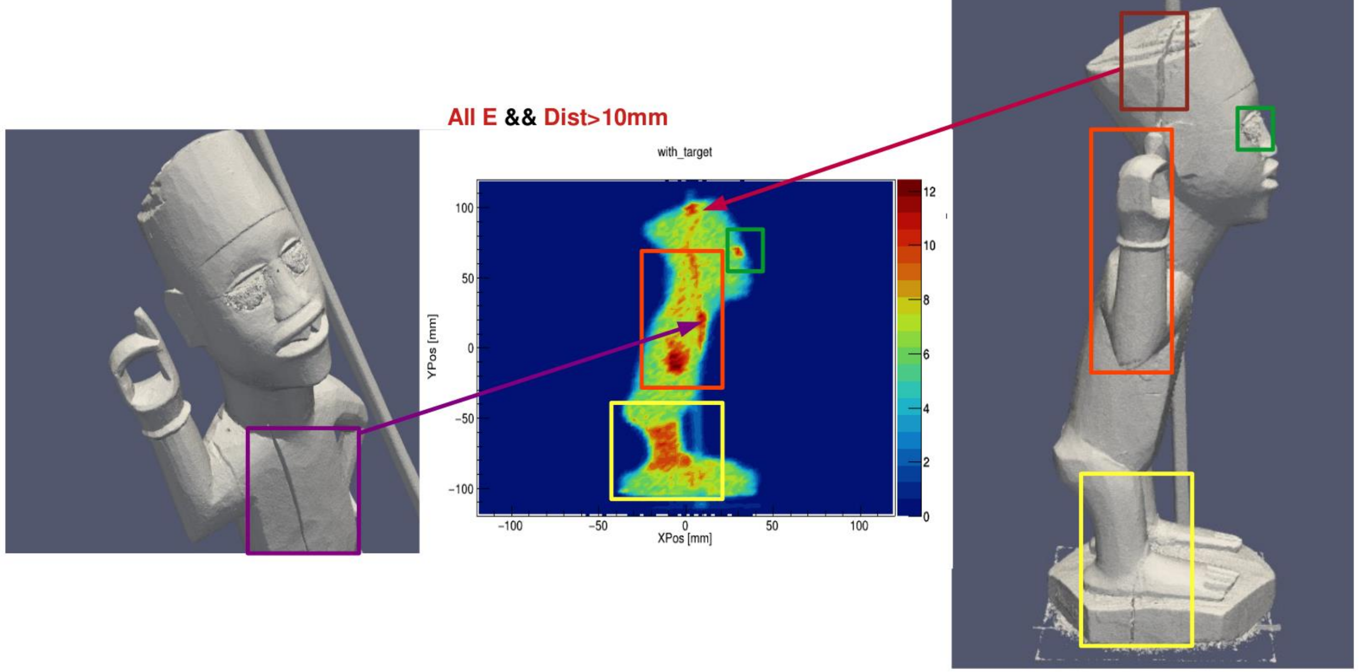


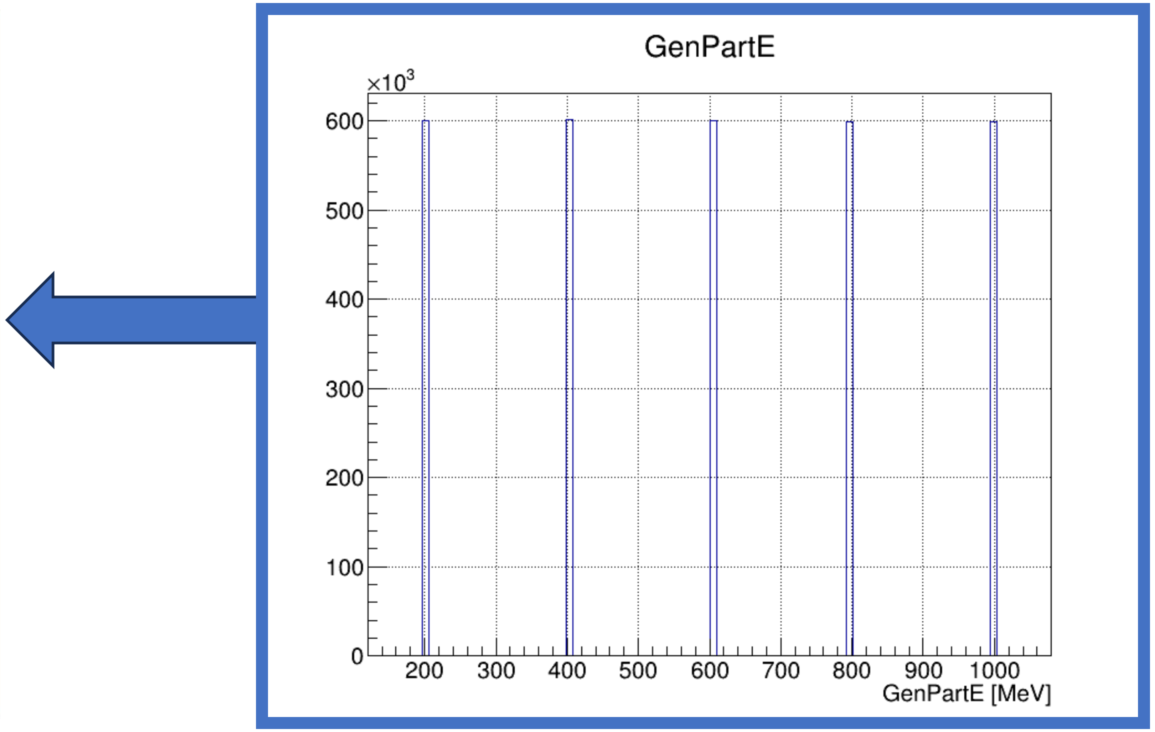
- Whenever the spatial resolution of the detector decreases (pixel size = 1cm), the resolution along the z axis becomes worst
- Including the scattering angles in the analysis adds a lot of noise

Artificial muon beam (additional details)

- Fixed energies (200,400,600,800,1000 MeV)
- Perpendicular beam
- Homogeneous generation surface = 24x24 cm
- Real statue size

Mesh geometry VS 2D plot :





- Compute the average hit position from the true GEANT4 hits x_mean and y_mean and then normalize it with respect to the traveled distance of muons "D" inside the statue (when D>10mm)

Portable artificial beam

DAPRA: MuS2 program:

- The MuS2 program seeks to develop a directional source of muons produced at relevant energies and intensities and in sufficient quantities to support demonstrations of National Security and scientific applications.

- with **10 to 100 GeV** energies while showing a clear path to a practical design for a transportable system.

↓

High energy not efficient for small objects

↓

What we need : Low energy (sub-GeV)

↓

A lot of Coulomb scattering in the object of interest as well as in the detector (not an issue if muon energy is precisely controlled or at least measured in the detector itself – which makes it more expensive)

Back-Projection method