Muons for Geoscience and Archaeology

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Laser-Driven GeV Muon Sources at ELI (LAMU)
March 20, 2025

ChatGPT's view on this topic

Outline

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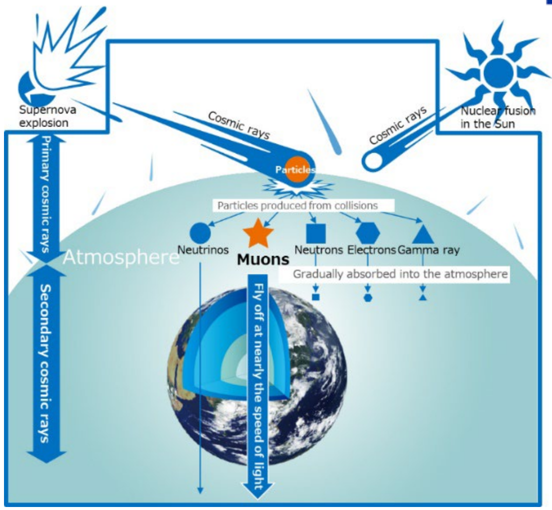
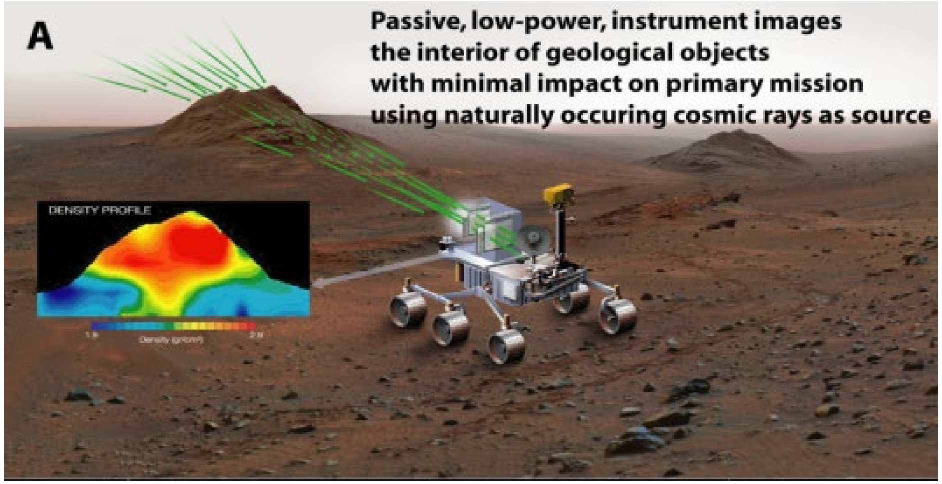
- ❑ Selected applications in
  - Geoscience
  - Archaeology
- ❑ Concluding remarks on muon sources

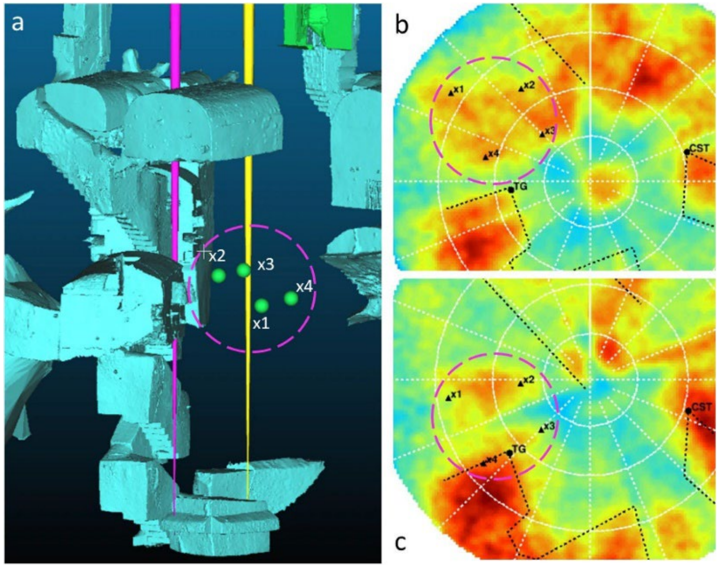


[https://www.nec.com/en/global/insights/article/2021100001/index.html]

Disclaimer: list of projects & scenarios much longer than what is covered here …



[https://blogs.egu.eu/geolog/2013/06/19/muon-musings-how-penetrating-particles-could-let-us-peer-beneath-mars-surface/]



[https://www.heritagedaily.com/2023/04/archaeologists-use-muography-to-reveal-hidden-chamber-in-naples/147137]

Muons for Geoscience (I)

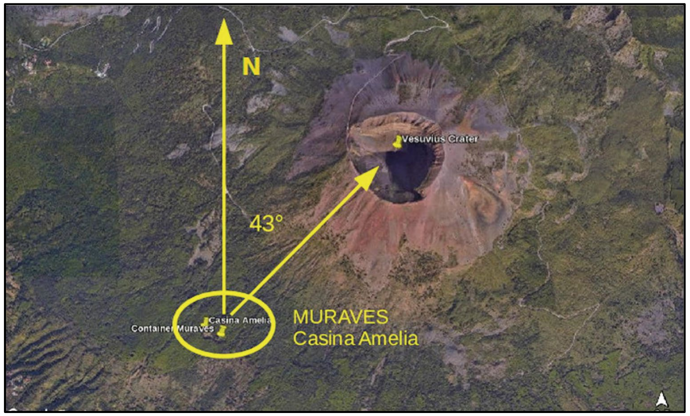
Study of volcanic systems

- Static, dormant vs. dynamic, active systems
- Muon telescopes usually positioned far away from target (safety, site accessibility)
- Usually, long exposure times up to years required
- Simultaneous measurement of free sky and transmitted muon flux
- Many features observed already, e.g. conduit size, plug formation and explosion, magma ascent during eruption, degassing process, hydrothermal changes in lava dome …; more and more combination with geoscience data

Examples of past/ongoing projects at various locations:

- Sakurajima, Japan
  - e.g. [L. Oláh *et al*, Sci. Rep. 8 (2018) 3207]
- Vesuvius, Italy
  - e.g. [M. Al Moussawi *et al*, J. Adv. Instrum. Sci. (2024) 501]
- Stromboli, Italy
  - e.g. [V. Tioukov *et al*, Sci Rep 9 (2019) 6695]
- Etna, Italy
  - e.g. [D. Lo Presti et al, https://doi.org/10.1002/9781119722748.ch7]
- Omuroyama scoria cone, Japan
  - e.g. [S. Nagahara *et al*, Bull. Volcanol. 84 (2022) 94]
- La Soufrière, Guadeloupe
  - e.g. [D. Gilbert *et al*, https://doi.org/10.1002/9781119722748.ch5]

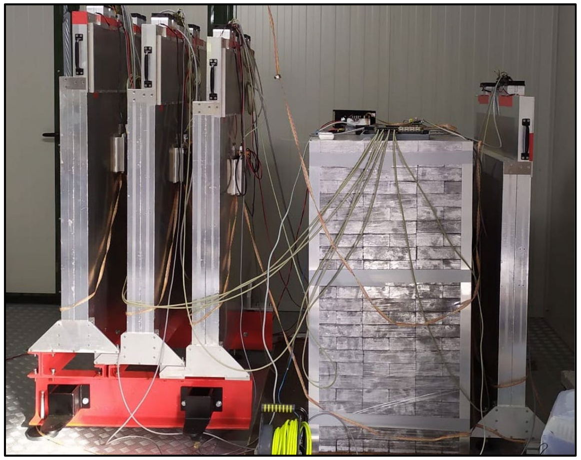
Muraves project @ Mt. Vesuvius



Located 1500m away from crater and ~640m asl, i.e. slightly below bottom of Vesuvius crater

Solar panel system (5.4 kW peak power) on the container roof connected to array of batteries

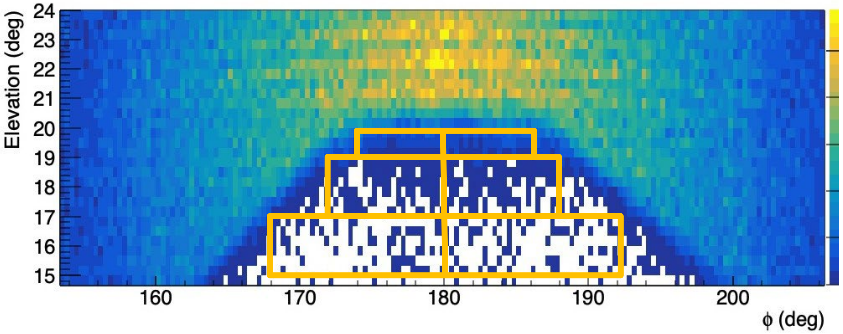
3 muon trackers (including 60cm lead wall for suppression of <0.9GeV muons)



Δy	Δx	$\bar{L} = 500\,\mathrm{m}$	$\bar{L} = 1000\,\mathrm{m}$	$\bar{L} = 3000\,\mathrm{m}$
9 m	9 m	8 months	3 years	100 years
9 m	26 m	3 months	1 year	33 years
9 m	130 m	15 days	2.5 months	6 years
26 m	130 m	5 days	1 month	2 years
52 m	260 m	2 days	6 days	16 months

Expected exposure times for 10% mean density uncertainty

Initial result with 1-2 months of exposure time



[M. D'Errico et al, J. Adv. Instrum. Sci. (2022) 273]

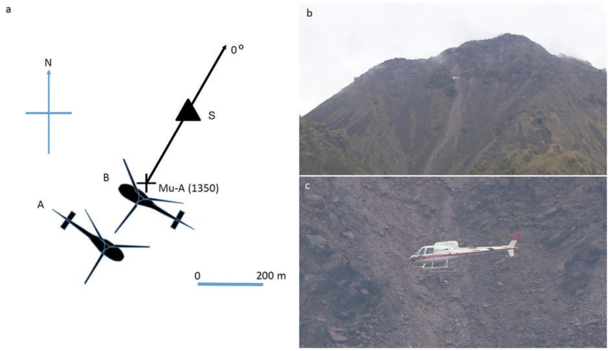
High fluxes would reduce exposure time, but need to rethink geometry

Airborne (heliborne) muography

Positioning of muon detectors not always easy due to geographical and infrastructural conditions

Airborne (heliborne) muography

- allows to bring the detectors close to target object, in optimal position for muon collection, shortening the required exposure time
- has no issue with availability of electricity (as long as the aircraft keeps flying …)
- allows fast transportation and easy "installation" of the detector



First trial on the Heisei-Shinzan lava dome of the Unzen volcano, Japan; <u>observation point only ~200m away from the peak</u>; <u>157min data taking</u>, (muon trans. + open-sky); control of the aircraft position via GPS monitoring; positional variation during data taking was below detector position resolution

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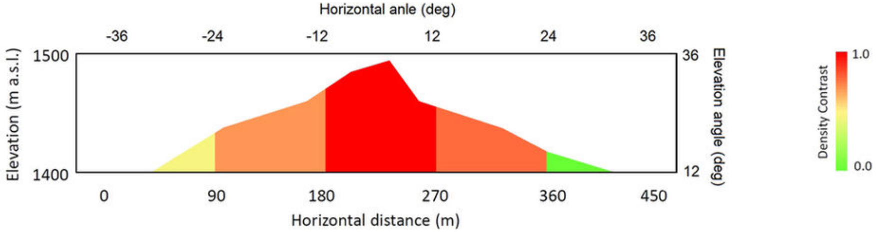
Density contrast of the HS lava dome



[H. Tanaka, Sc. Rep. 6 (2016) 39741]

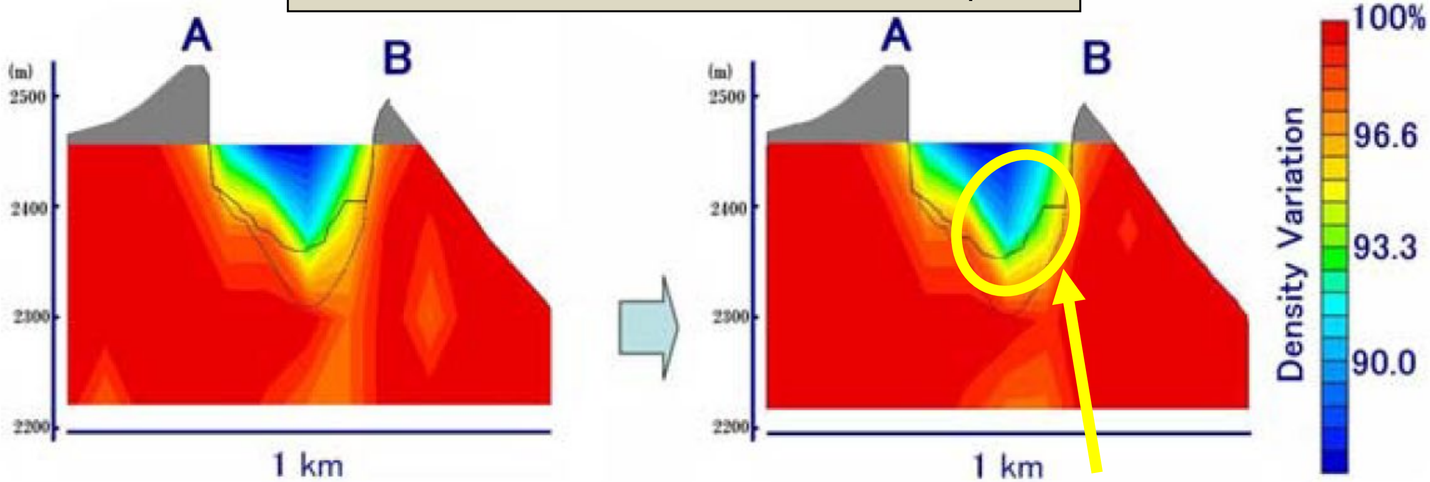
Dynamic muography

While static muographic images provide structural information, dynamic, i.e. sequential images of temporal variations of a target object provides more insight into ongoing processes

High fluxes would improve monitoring of fast evolving systems

Mt. Asama, Japan, effectively erupted on Feb. 2, 2009, during an ongoing muography scan

Before and after the 2009 Asama eruption



Mass loss observed only in certain crater region; no large mass change below crater

The image was interpreted that magma did not flow up the pathway in the 2009 eruption, but instead, high-pressure vapor simply blasted through the old magma deposit that acts as a "plug" of the pathway

Mass movement can be estimated from measured changes in average density length:

$\Delta\langle\rho\rangle \cdot L \cdot A$ = 22.5 tons m^{-2} x (58 x 50) m^2 = 65 ktons

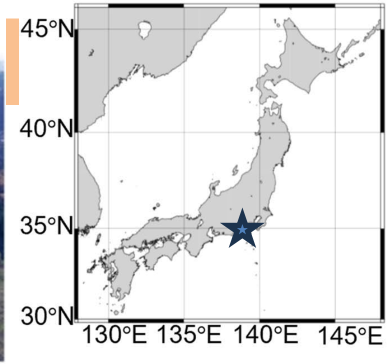
↔ Total volume of ash and other ejecta estimated ~50 ktons

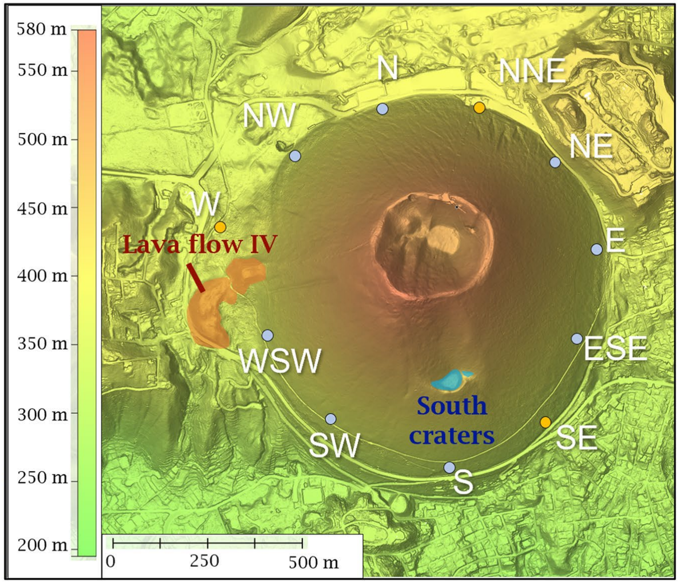
[H.K.M. Tanaka *et al.*, GeoPhys. Res. Lett. 36 (2009) L17302]

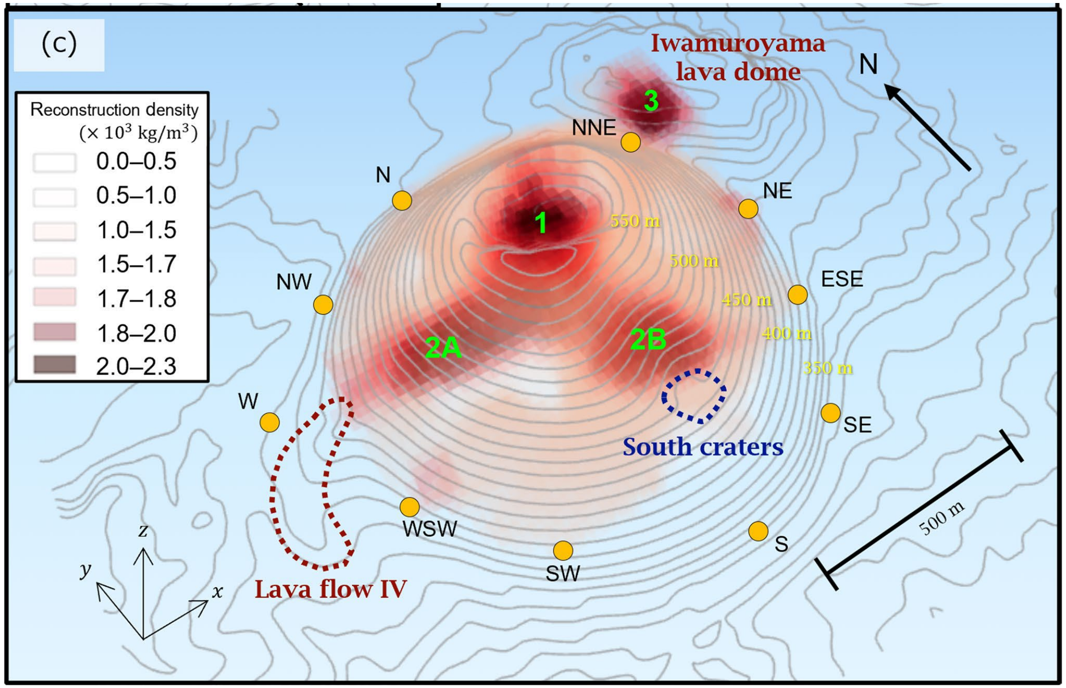
3D Muography

Izu-Omuroyama scoria cone, Japan

Multi-directional muography using nuclear emulsions at <u>11 different sites around target</u>







- Relatively high contrast expected, i.e. density of non-welded scoria deposits expected ~0.5–1.0x10³ kg/m3, density of lava flows and welded scoria expected >2.0x10³ kg/m³
- no other mountains within 4km radius that interfere with muographic observations

Detector site ID	Effective area ($\times 10^{-4}$ m^2)	Exposure time (d)
W, SE, and NNE (2018)	120	60
N, NW, WSW, SW, S, ESE, E, and NE (2019)	240	90

Rethink layout of setup for 3D imaging; beam angular coverage

[S. Miyamoto *et al*, Geosci. Instrum. Method. Data Syst. 11 (2022), 127–147]

Muons for Geoscience (II)

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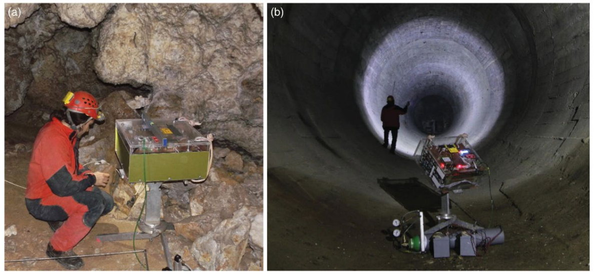
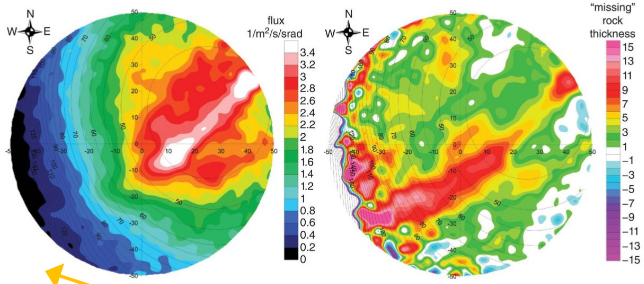
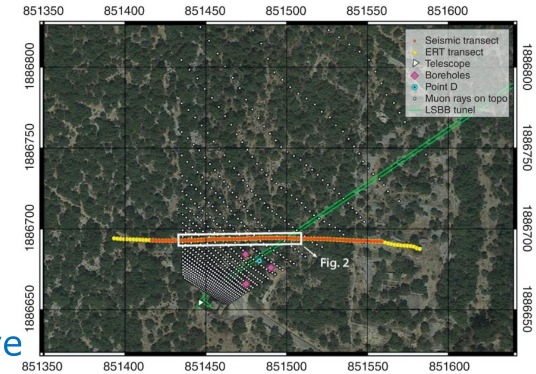
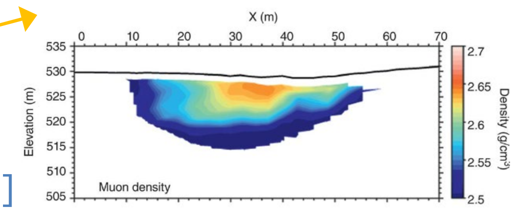
General environmental applications

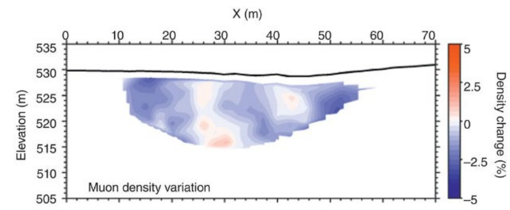
- Many applications involving underground detection systems (borehole or portable systems)
- Absorption muography only; multiple viewpoints











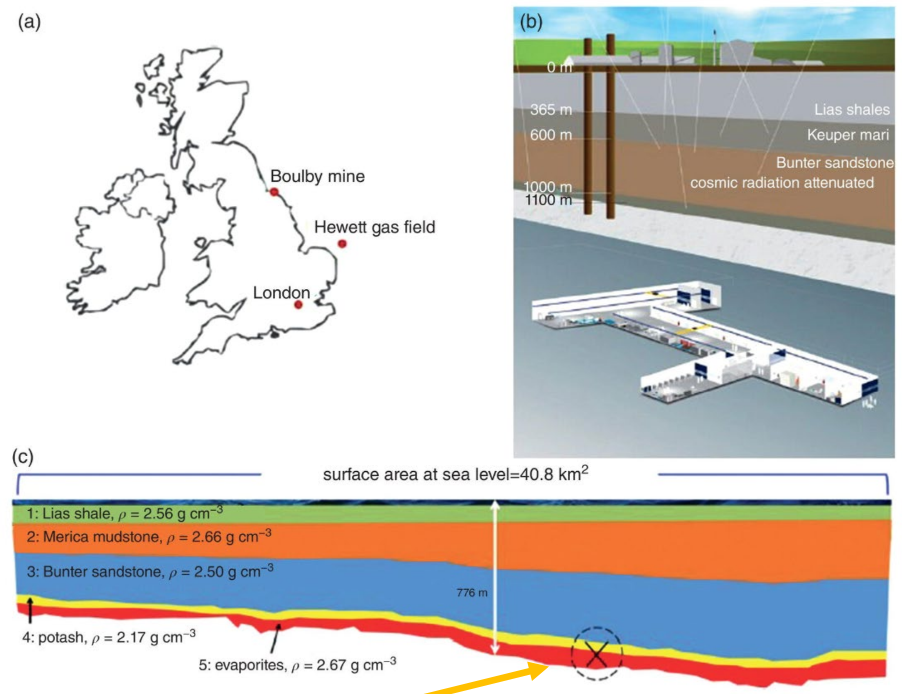
Application examples:

- Exploration of underground cave systems, e.g. Királylaki cave and tunnel region near Budapest, Hungary
  [G. Surányi *et al*, Karsztfejlődés 2016, 203]
- Study of groundwater hydrodynamics, e.g. Buissonnière area case study near LSBB (low-noise underground lab), France
  [I.L. Roche *et al*, https://doi.org/10.1002/9781119722748.ch10]
- Monitoring of carbon geostorage
  [J. Gluyas *et al*, Phil Trans. R. Soc. A 377 (2019) 20180059]
- Mining and underground resources exploration and monitoring, e.g. McArthur River Uranium Mine, Canada
  [D. Schouten *et al*, JGR Solid Earth 123 (2018), 8637–8652]

Geocarbon Storage

- **Carbon Capture and Storage (CCS)**, i.e. CO_2 capture at e.g. power stations and industry; compression to vapor phase or super critical fluid; transport to storage site for injection deep underground (below 800m) into pore spaces of either deep saline aquifers or depleted oil and gas fields
- CO_2 needs to remain there for centuries or millennia; with time, injected CO_2 may dissolve into the interstitial connate water or react with the rock to form a solid carbonate precipitate, i.e. CO_2 is locked into the rock system
- Long-term monitoring is essential, i.e. the fluid phase CO_2 at injection is buoyant and will migrate in the subsurface, driven either by buoyancy or a pressure gradient (natural or induced), within the natural rock system and/or within the vicinity of the injection wellbore
- Traditional monitoring based on CO_2 detection, or seismic data (expensive, noise issues due to weather …)

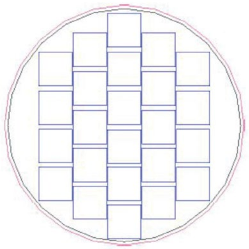
➢ Muon radiography for cheap, long-term monitoring ?



Muography @ Boulby Mine test site

Geocarbon Storage

Scintillator bar borehole detector to be installed underneath CO_2 reservoir

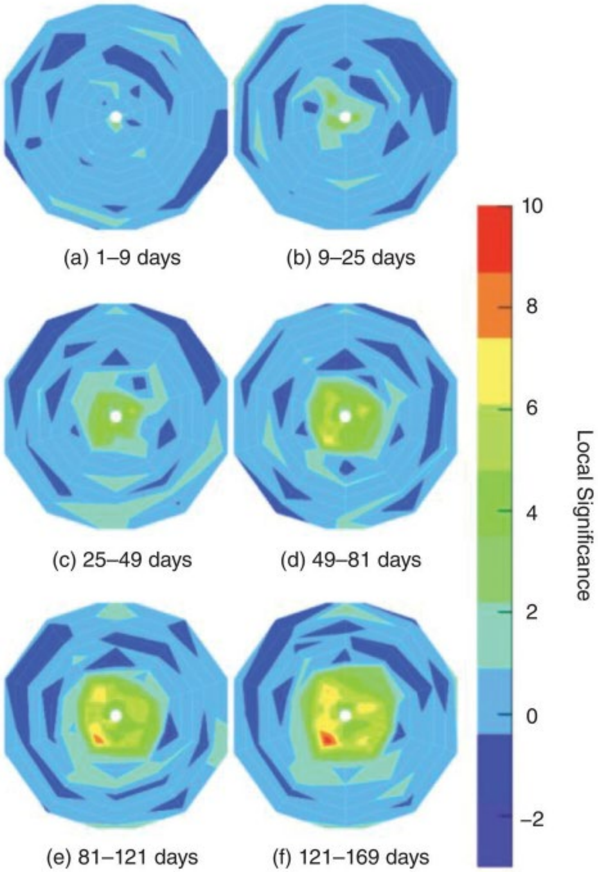


Muons reaching the detector site below CO_2 reservoir:

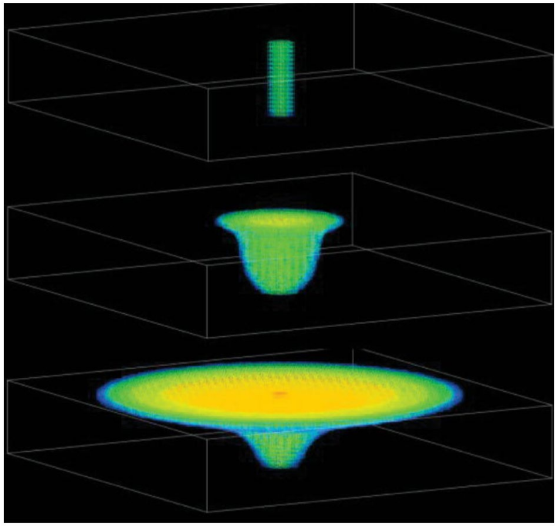
$$\langle E_\mu^{sea\ level} \rangle \approx 1500\ \text{GeV},\ \langle E_\mu^{detector\ site} \rangle \approx 220\ \text{GeV}$$

Suppression of natural radioactivity background via #hit bars and E-threshold

High energy muons required to reach underground setup



Post-injection CO2 plume modelling (20kg/s injection, after 441 days, plume of 170m height and 375m radius)



Simulation of significance of change in detected muon rate due to constant CO_2 injection

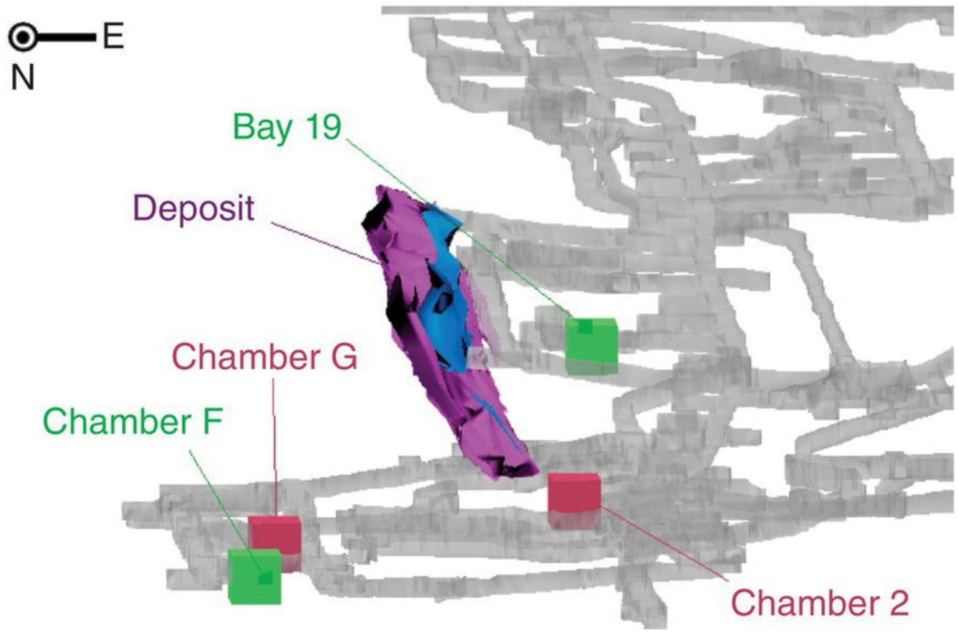
[J. Klinger *et al*, Int. J. Greenhouse Gas Control 42 (2015) 644–654]

McArthur River Uranium Mine

- McArthur River high-grade uranium deposit located ~500m underground, below Athabasca Basin, northern Saskatchewan, Canada; largest high-grade uranium deposit in the world, i.e. significant fraction of global uranium production

- Uranium mineralization occurs at depths between 500 meters and 640 meters around the unconformity; this particular deposit is not surrounded by extensive alteration that is common to other unconformity associated uranium deposits

➢ a very compact, dense uranium ore body at depth as test case for muography



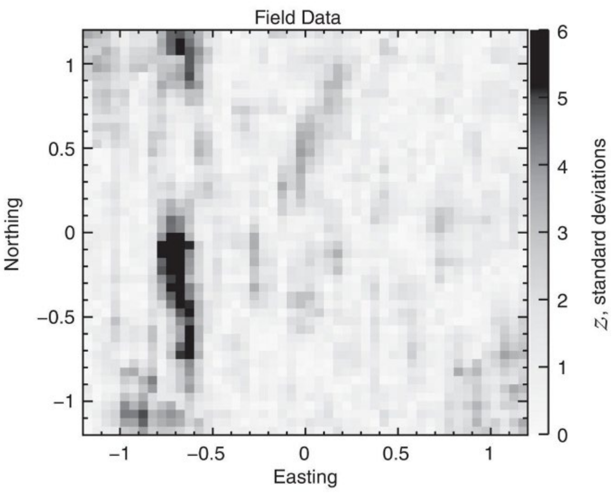
- Two muon trackers used in four locations

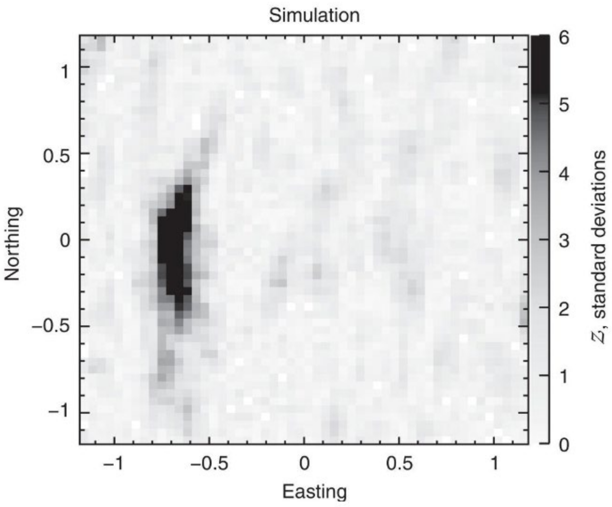
- Model of the thick sandstone overburden constrained using data of Bay 19 location above the uranium deposit

[D. Schouten *et al*, JGR Solid Earth 123 (2018), 8637–8652]

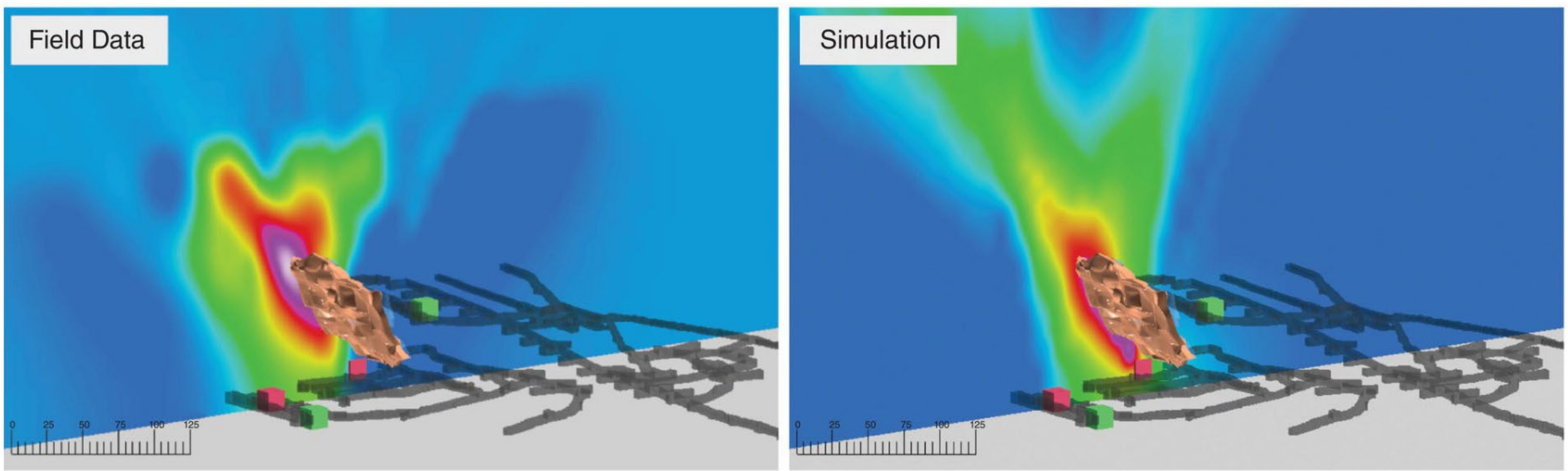
In ideal case, muon source would illuminate underground target and all muon trackers

McArthur River Uranium Mine





Expected anomaly from know deposit, in simulation and data; differences likely due to large density variations within uranium ore versus, uniform density in simulation

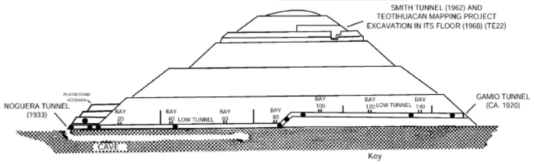


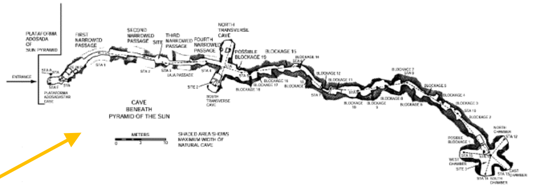
Density inversion from muon data and simulation; <u>show case study for improved tomographic reconstruction via images acquired at multiple depths and locations</u>

Muons for Archaeology (I)

Searching for hidden structures in ancient moments and sites

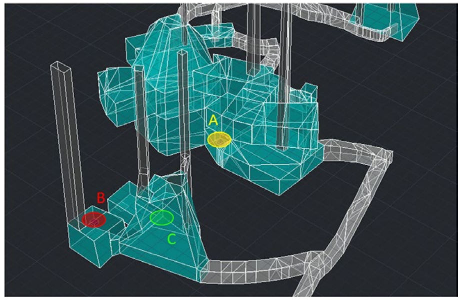
- Absorption muography only; sometimes long exposure times due to underground locations and/or near horizontal muon flux
- Objects ranging from *O*(100m) to *O*(km)
- Ideal cases with multiple viewpoints for 3D reconstruction of hidden space





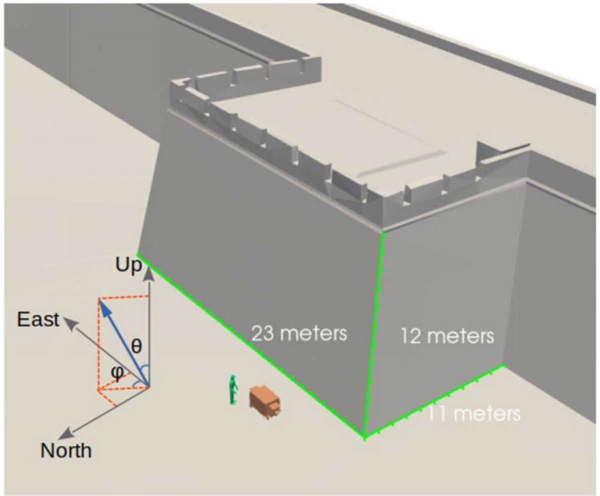
Examples of past projects:

- First muographic imaging of Egyptian pyramids in 1970
  [L.W. Alvarez *et al*, Science 167 (1970) 832]
- Pyramid of the Sun, Mexico
  [S. Aguilar *et al*, Proc. 33rd ICRC (2013) 0364]
- ScanPyramids project at Giza, Cairo, Egypt
  [K. Morishima *et al*, Nature 552 (2017) 386-390]
- Palazzone Necropolis Etruscan site, Perugia, Italy
  [D. Borselli *et al*, J. Adv. Instrum. Sci. (2024) 467]
- Early settlements of city of Naples at Mt. Echia
  [L. Cimmino *et al*, Sci. Rep. 9 (2019) 2974]
- Xi'an defensive walls, China
  [L. Guorui *et al*, J. Appl. Phys 133 (2023) 014901]
- Tumuli, e.g. Apollonia tumulus, Greece

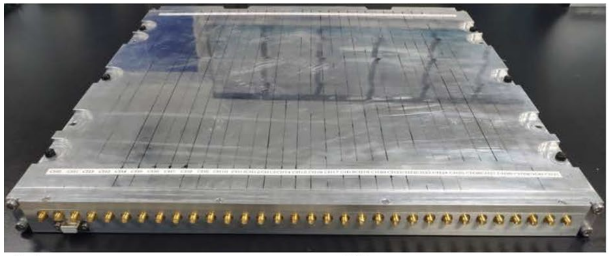


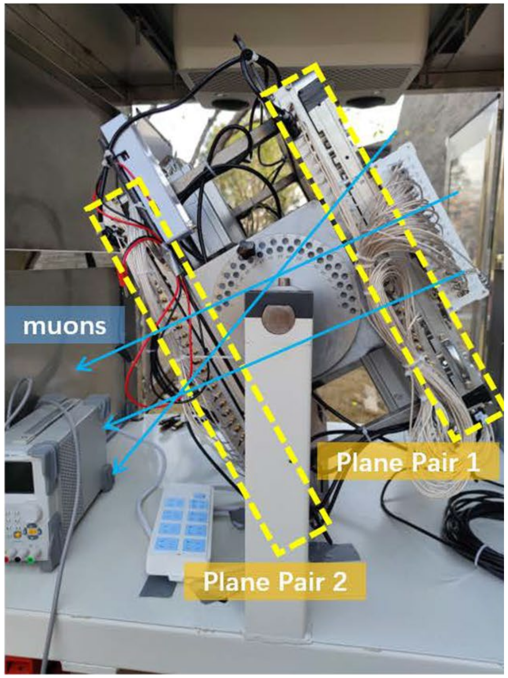
Xi'an Defensive Walls

- Ancient city of Xi'an (Shaanxi Prov., China) famous for terracotta warriors of the Qin Dynasty (BC221–BC207)



- Xi'an defensive wall one of the most complete ancient city wall structures in China; rectangular shape, perimeter ~13.74 km





- Many incidents due to structural damage; recent survey results indicated 214 cracks over 1cm, many areas of settlement, spalling, large bulges, and nearly 2000 holes of all sizes in the wall

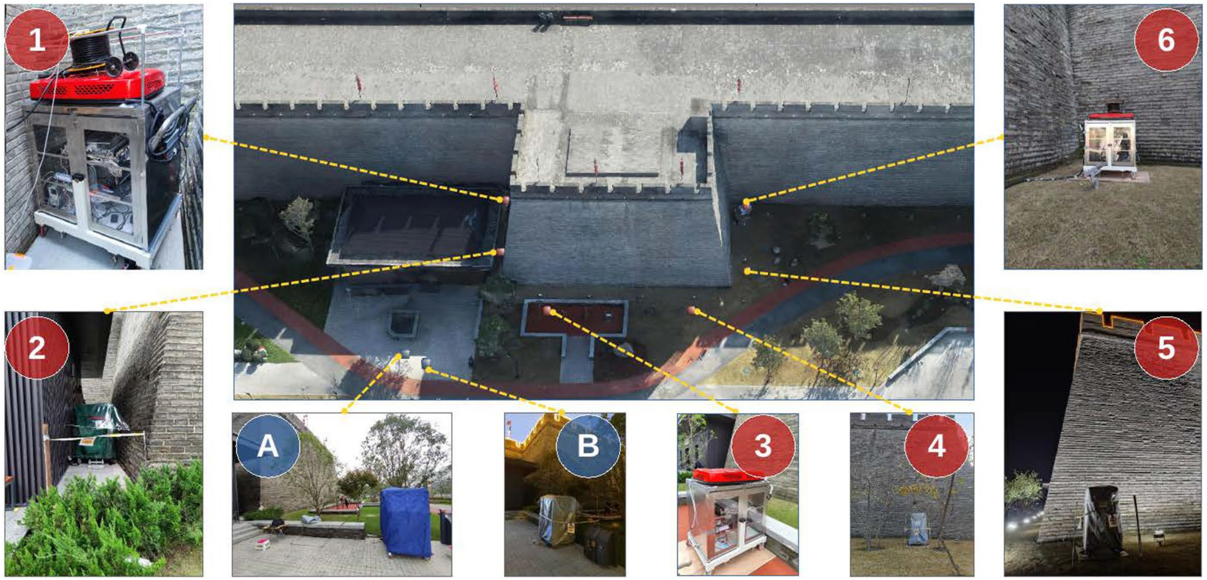
➢ Mobile, 2XY station, scintillator-based telescope; 48x48cm^2 active area; 2.3mm (10mrad) spatial (angular) resolution; SPIROC-based DAQ

Ideal case for a muon source …

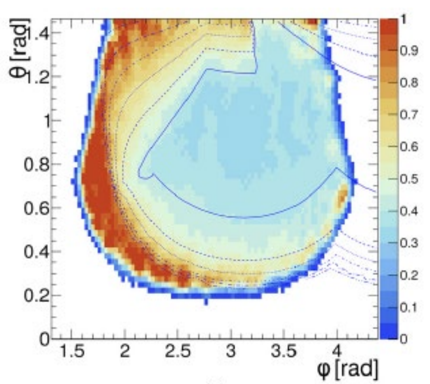
Xi'an Defensive Walls

Target was 12m high Rampart No. 58 (north side) of the wall; 6 viewpoints + 2 open sky points, <u>one week of exposure per measurement position</u>

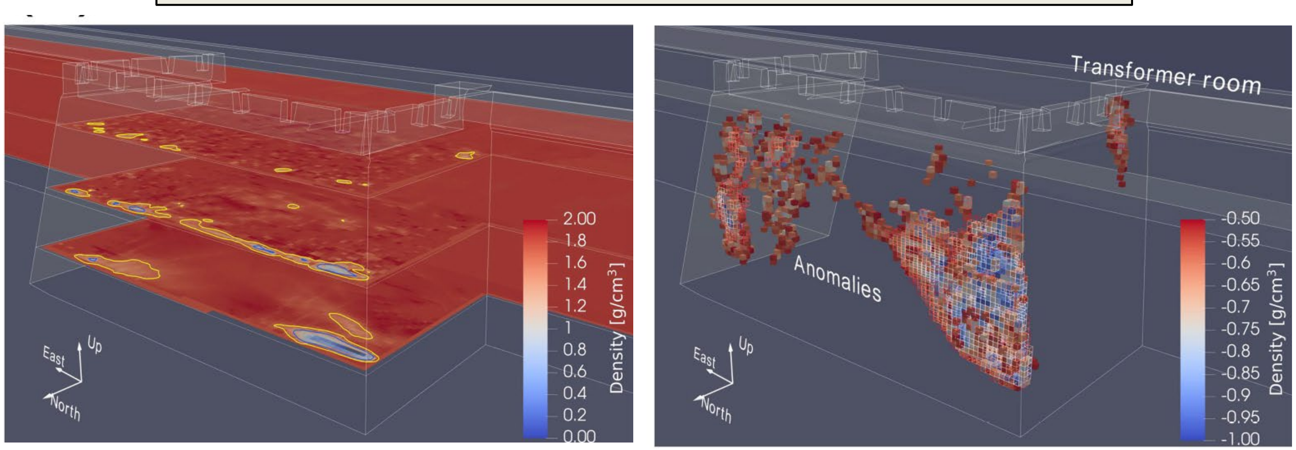
Location	Azimuth angle (°)	Zenith angle (°)	Duration (days)	Total count	Count rate (h^{-1})
1	163.10	69.70	7.8	664 708	4455
2	178.20	69.57	9.7	1 168 963	5769
3	270.66	60.55	13.9	1 772 770	8608
4	268.74	58.94	9.0	2 040 626	9287
5	−9.10	69.96	8.2	1 171 220	6738
6	27.60	59.47	8.8	1 761 860	8698
A	≈25.00	60.00	3.0	1 175 291	15 366
B	≈90.00	70.00	2.8	911 615	10 752



Measured survival rate compared to prediction (contours) for Point 1



Examples of inversion results

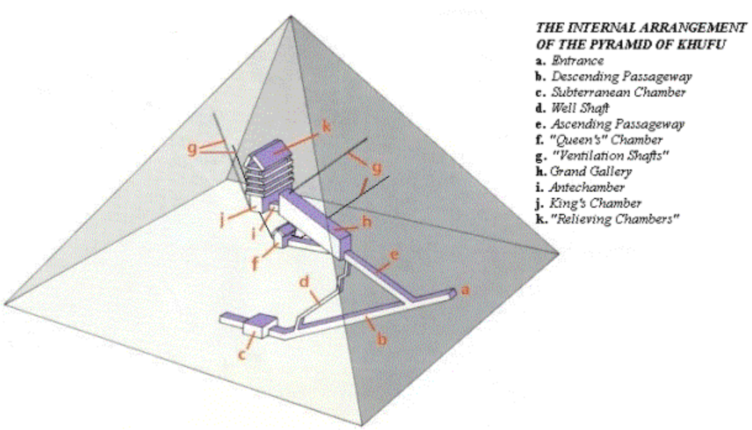


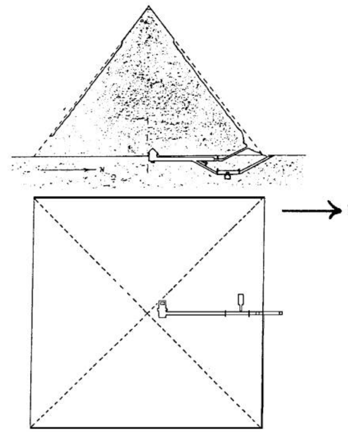
[L. Guorui *et al*, J. Appl. Phys 133 (2023) 014901]

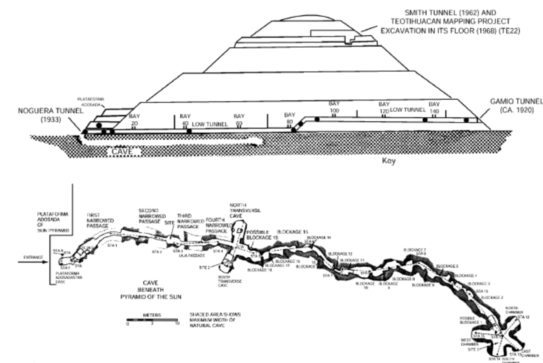
Searching for hidden structures inside pyramids

Pyramids of Khufu and Khafre @ Giza plateau near Cairo, Egypt

Pyramid of the Sun @ Teotihuacán - “The City of the Gods”, near Mexico City

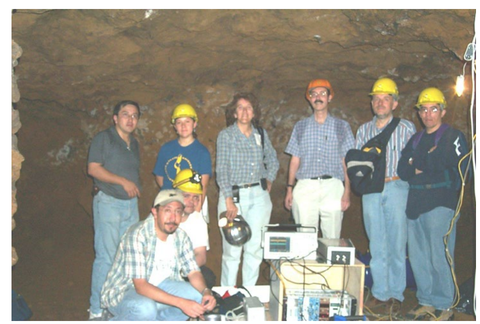






Typical dimensions: base ~210-230m; height: ~65-140m; **detectors inside and/or outside**

Gaseous detectors outside & **emulsion films** and **scintillator detectors** inside Queen Chamber of Khufu Pyramid

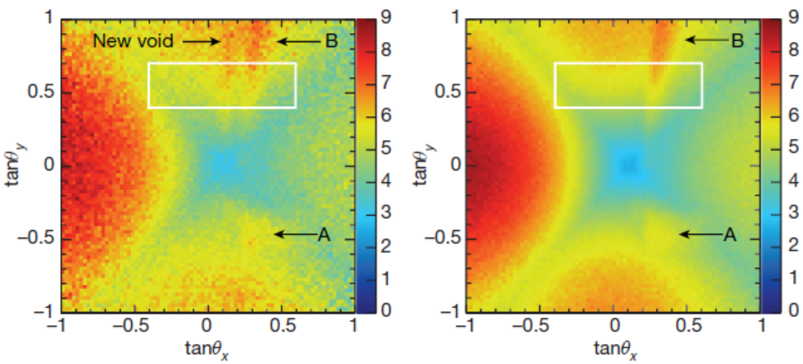


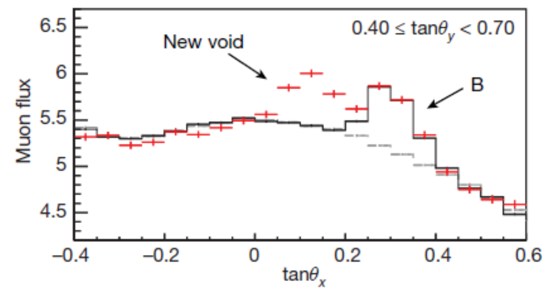
Inside 100m tunnel undernearth Pyramid of the Sun

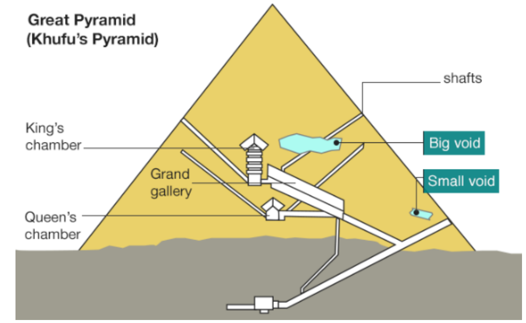
Installation of elevated muon trackers ?

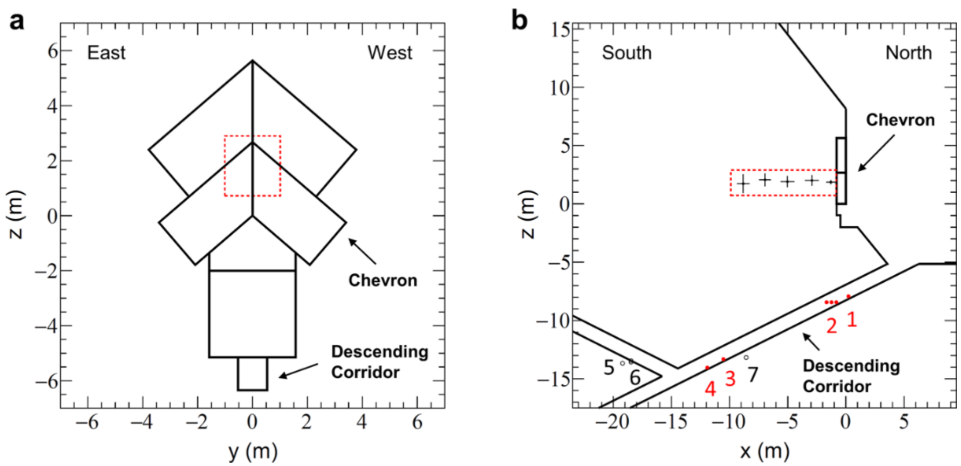
Hidden structures inside Khufu Pyramid

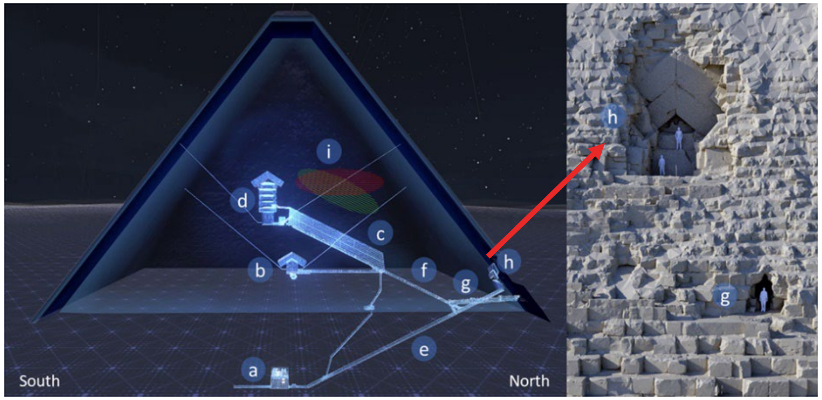
Discovery of new void above known chambers in Khufu pyramid; “big void” is ~30m long and several meters high; 3 months of data taking in 2017
[K. Morishima *et al*, Nature 552 (2017) 386]











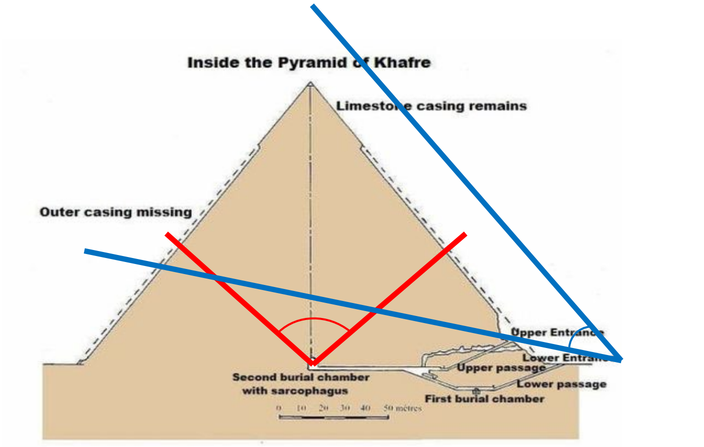
Downward pointing source could reach underground trackers

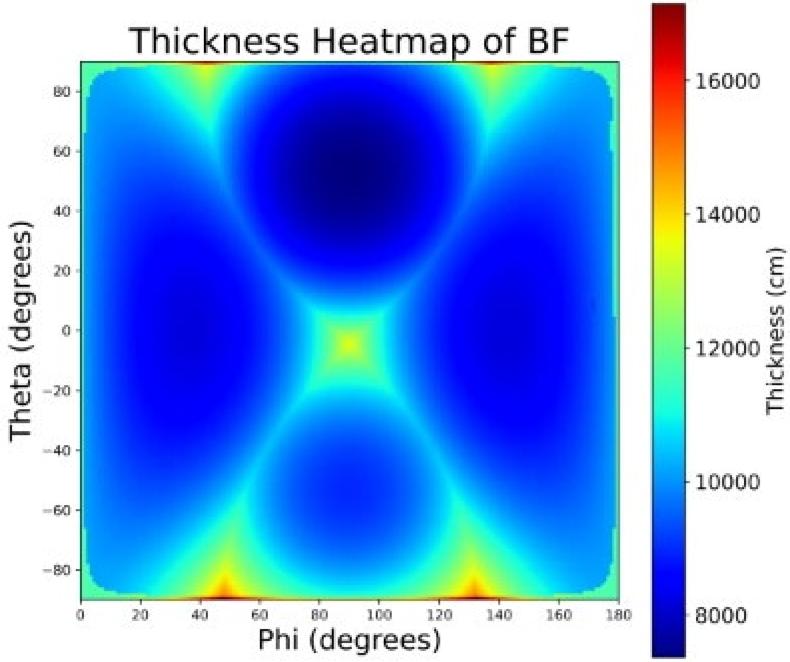
Precision measurement of newly discovered North Face Corridor in Khufu pyramid
[S. Procureur *et al*, Nature Comm. 14 (2023) 1144]

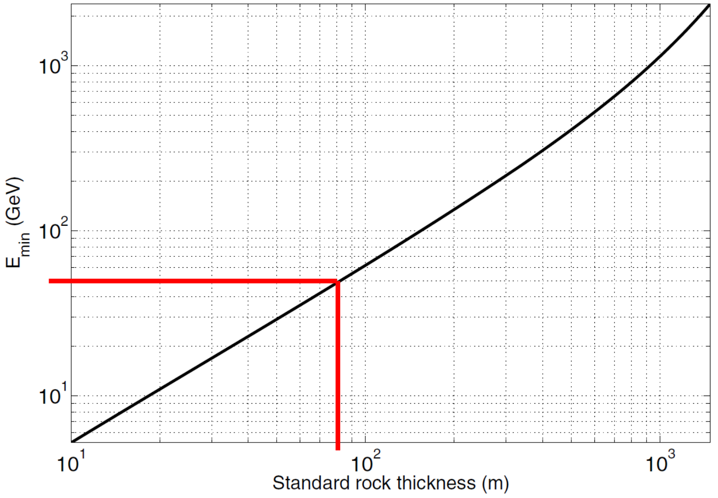
Simulations studies for Khafre Pyramid

New campaigns planned @ Khafre pyramid
e.g. [M. Tytgat *et al*, J. Adv. Instrum. Sci. (2024) 470]

Muon trackers placed outside and/or inside central burial chamber; <u>energy threshold for muons to reach the inside detector >50 GeV</u>





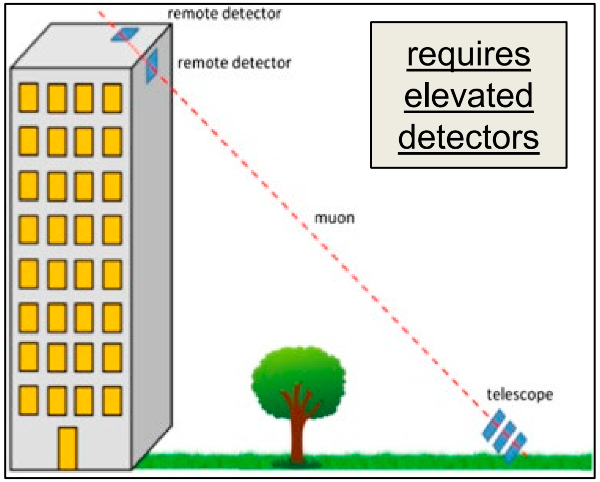


High energy muons needed

[N. Lesparre *et al*, Geophys. J. Int. 183 (2010) 1348-1361]

Monitoring stability of large structures

Idea: use cosmic ray muons to monitor the alignment and stability of a given structure, e.g. tower, pillar, mechanical press, historical buildings …



Palazzo della Loggia in Brescia, Italy:

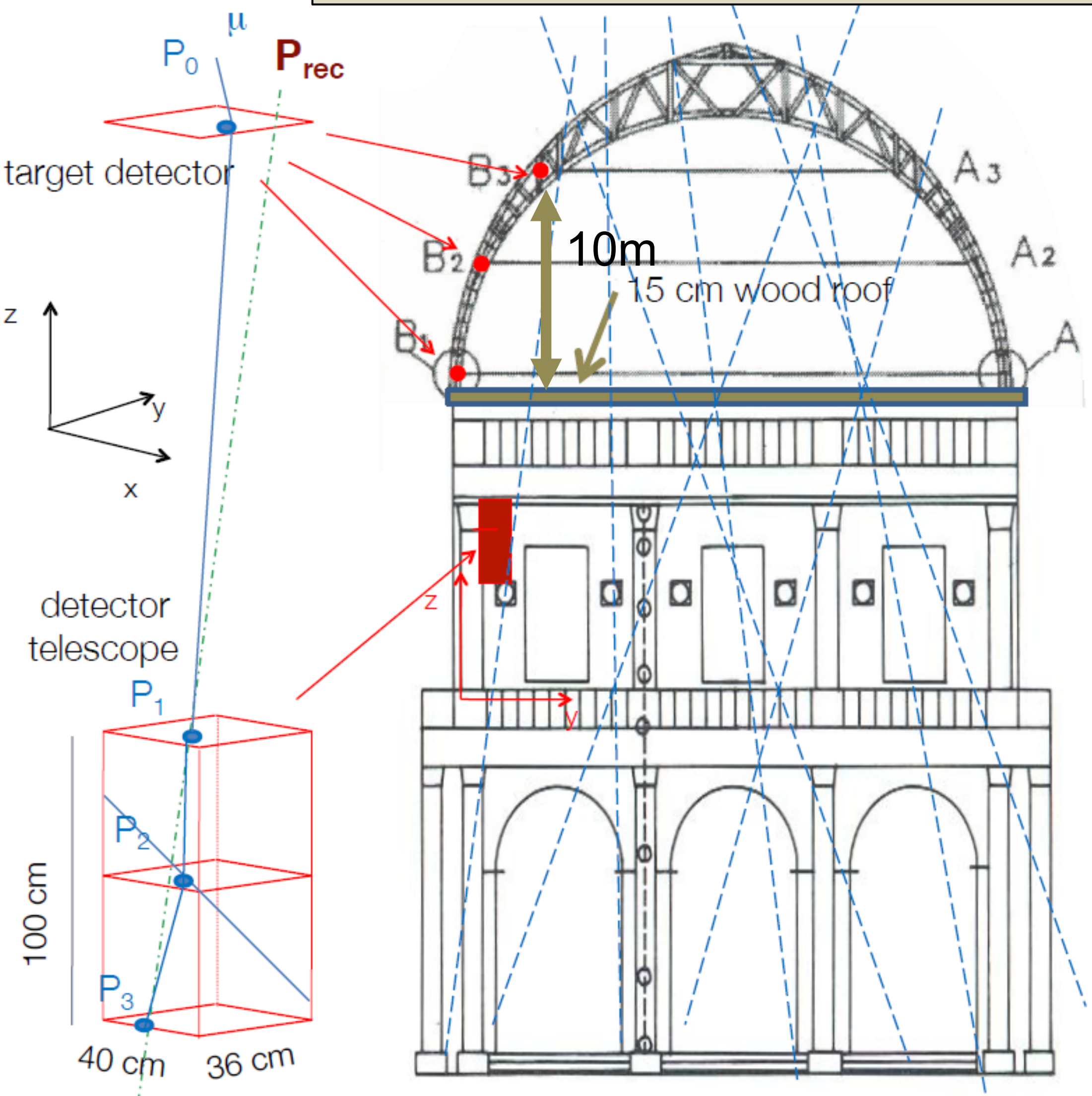
- Built in 1574, several structural stability problems due to repairs and transformations
- Wooden vaulted roof fully reconstructed in 1914, exhibits progressive deformation, in particular the top beam, i.e. 19cm in 1923, 80cm in 1980 !

Monitor stability and progressive deformation of wooden vaulted roof

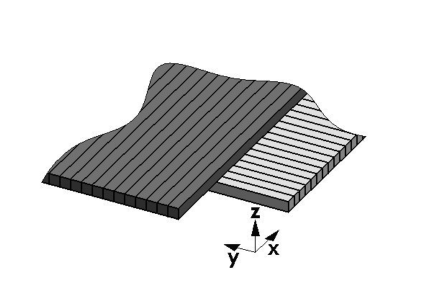
[A. Zenoni *et al*, "Historical building stability monitoring by means of cosmic ray tracking system", arXiv:1403.1709 [physics.ins-det]]

Monitoring stability of large structures

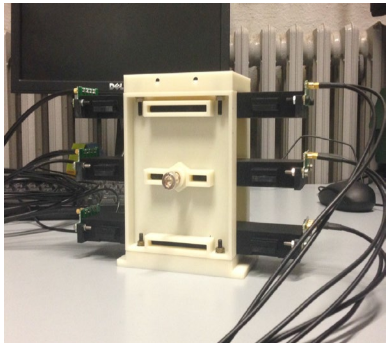
Feasibility study with Geant4 Monte Carlo simulation

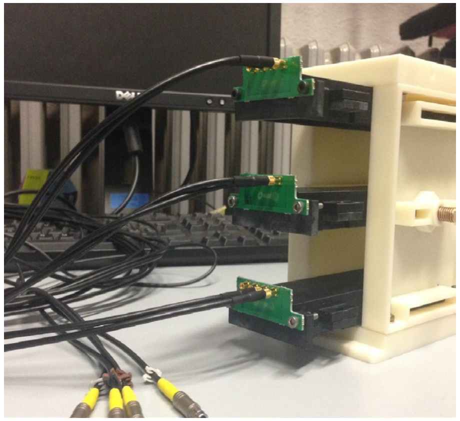


Feasible with upward point muon source



Small size prototype detectors based on 3x3 mm square scintillating fibers readout by SiPMs





Muons for Archaeology (II)

Investigation of (small) cultural heritage objects

- Border region of applicability of traditional X-rays for *O*(m)-sized objects
- Muon transmission vs. scattering, or combination of both
- Objects might be moveable or fixed (too fragile, heavy and/or precious to move to laboratory for imaging with *X*-rays, neutrons or electrons)
- Need for portable detectors

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:

- No information available on **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.

Going from large to small size objects

Portable, compact devices are required for such cases, but …

- *X*-ray fluorescence analysis (XRF) → limited to shallow depths by the high absorption rate of *X*-rays
- Portable fast-neutron sources are hazardous to humans, strictly regulated, and could cause undesirable activation of material

➢ Cosmic muons ? They penetrate deeper than *X*-rays and neutrons, and pose no hazard to humans and artifacts

Adjustable muon energy would help

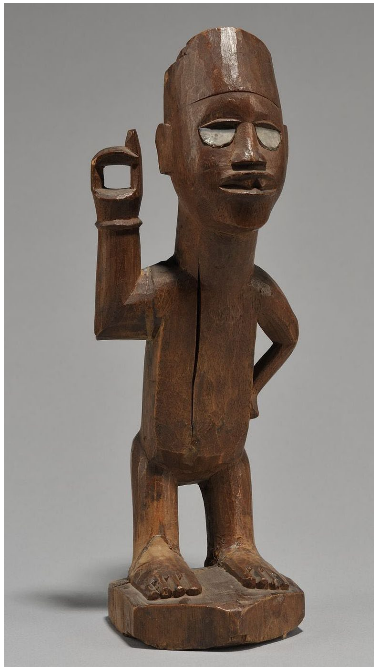
Large-size objects require sometimes months of data taking because most muons are absorbed, which is different for small statues, i.e.

- 1 m of stone ($\rho \sim 2.5$ g/cm^3) stops muons below ~0.5 GeV
- At sea level, only ~10% of the muon energy spectrum is below 0.5 GeV, i.e. a fraction f ~90% of the free-sky muon flux survives the passage through the statue

➢ <u>Larger muon statistics, but density discriminating power (i.e. getting good contrast in image) depends on f and tends to vanish for f→0 and f→1</u>

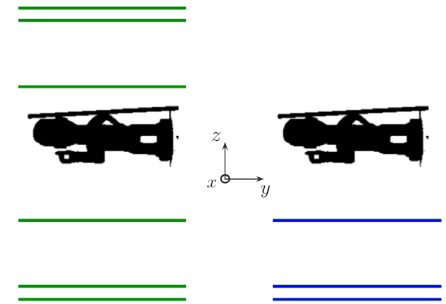
➢ Low-momentum muons undergo a lot of scattering in the object and detector itself, degrading the image resolution

Case study via simulations



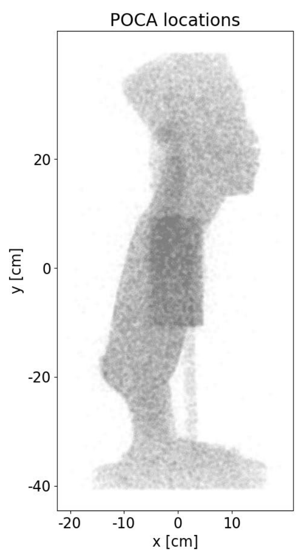
Wooden statue as test case, simulating different object sizes (from 80x30x30cm^3 to 320×120×120 cm^3); considering both scattering and absorption muography

Insert a hidden bronze cylinder inside the statue; simulate e.g. 8 hours of data taking with different detector scenarios

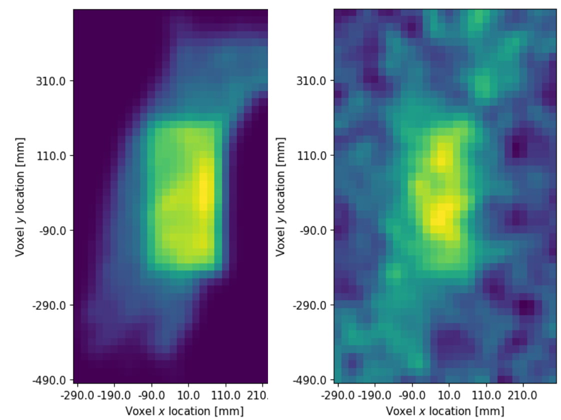


Certain objects could be scanned in a lab

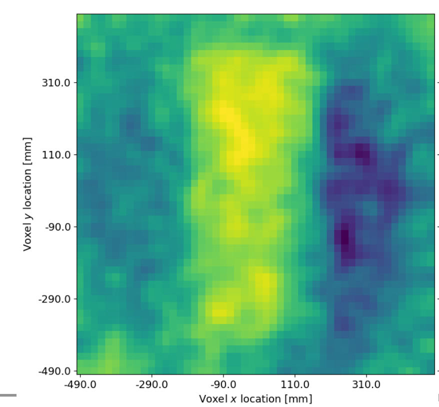
HardWood (oak: 687.25 kg/m³) statue as model courtesy of the TOCOWO project (https://tocowo.ugent.be/) and the Africa Museum of Tervuren (Belgium)



Small statue, scattering



Medium statue, scattering (left) vs. absorption (right)



Large statue, absorption

[A. Giammanco *et al*, iScience 28 (2025) 112094]

Concluding remarks on muon sources

Points to consider regarding applicability of muon sources

- Tunability of muon energy for different applications (from GeV to TeV)
- Need precise knowledge of incoming muon flux
- Beam-induced background ?
- Directionality & angular aperture of muon beam (need sufficient irradiation area, i.e. usually no narrow beams, to cover target and multiple detector sites simultaneously)
- Rethink the geometry of setup, i.e. now "point-like" muon source, positioning of muon detectors wrt. source
- Consider maximum rate capability of muon detectors (#muons/spill, spill rate)
- Accessibility of the (outdoor, remote) application site for mobile muon sources
- Power consumption of muon source at remote locations

Possible benefits of muon sources

- Detector calibration, bench marking of detectors & algorithms
- Increased statistics, especially for cases relying on (near) horizontal muons, i.e. weak natural muon flux, theoretical flux uncertainty, other unwanted targets in line of sight, scattering of low energy muons …, or highly dynamic targets
- Removal of low energy muons (<~1 GeV), for scattering/absorption muography

Extensive list of applications to consider

- Study and long-term monitoring of volcanic systems (how to place detectors ?)
- Underground applications in mining, caving (downward pointing muon beam ?)
- Internal structure of monuments, building stability, structural defects (upward pointing muon beam, with elevated muon detectors ?)
- Small object muography (cultural heritage example, in lab or remote locations)
- ...