Applications of Muography

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Muography School, Muographers 2026, Budapest

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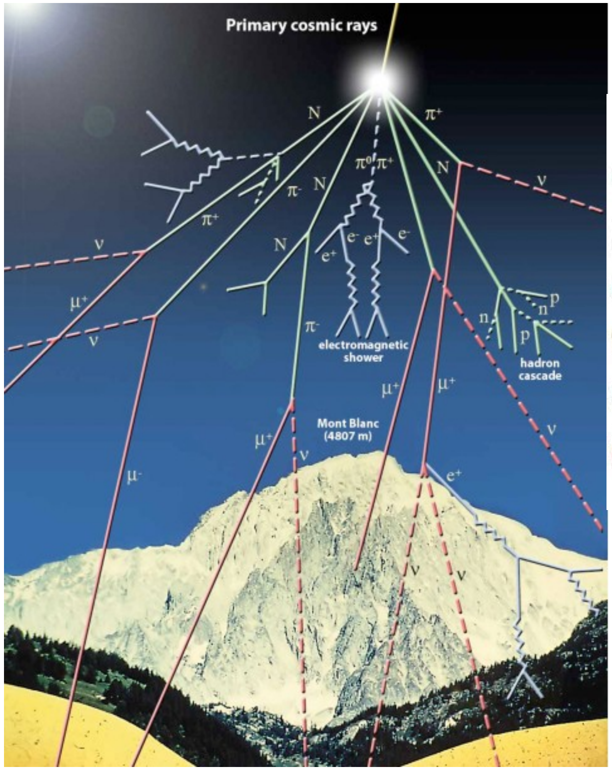
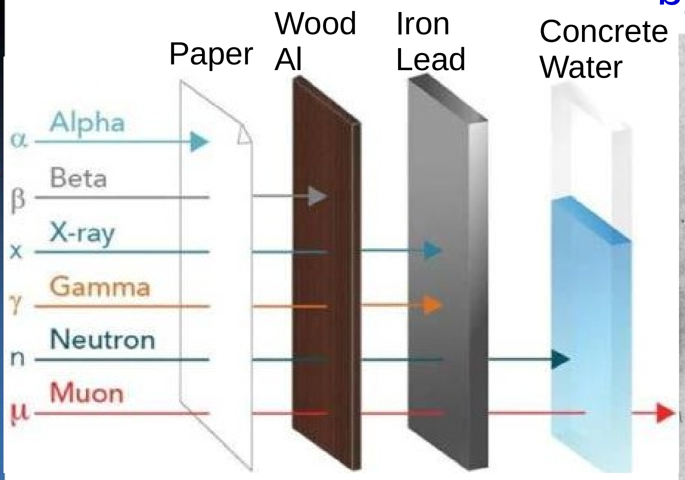
Outline

I. Introduction: Muons and Muography

- **Cosmic-ray muons** continuously produced in the atmosphere and observed everywhere on Earth
- Muons are **highly penetrative particles** which reach down even a few km into Earth's subsurface.
- **Muography**: ”X-raying” of large structures (mountains, volcanoes, pyramids, nuclear reactors, etc.) via tracking of cosmic-ray muons → **non-destructive, non-invasive, passive imaging technique**
- Methodology of muography has been developed before mid 1960s (E.P. George, L.W. Alvarez et al.) but the imaging of large structures was achieved just in mid 2000s thanks to the development of detector technologies

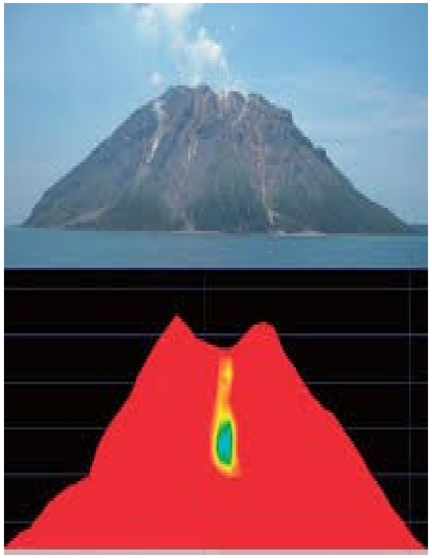


Credit: CERN



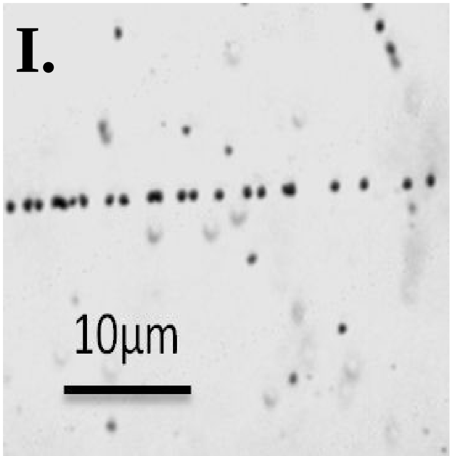
Credit: Decision Sciences

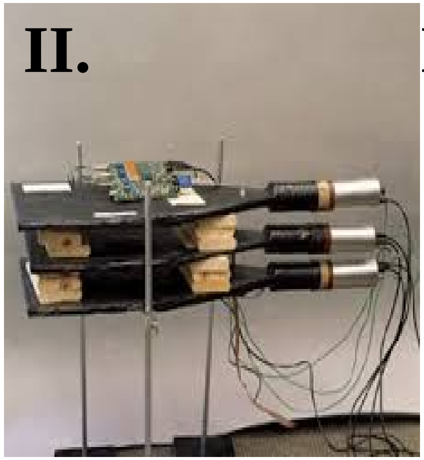
First medical X-ray image by Röntgen (1895)

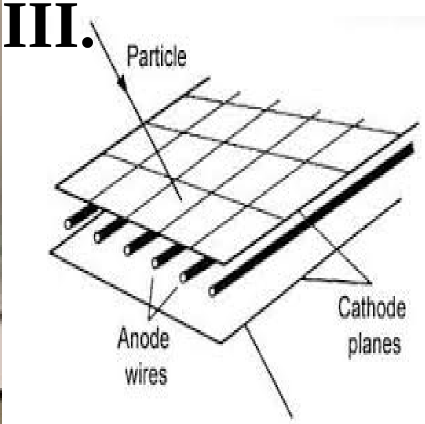


First muon images of volcanoes by Tanaka et al. (mid 2000s)

Technologies for Application-Oriented Detector Development







I. **Emulsion detector:** good positional resolution, but no timing information, offline

II. **Scintillator:** reliable, but positional resolution is costly

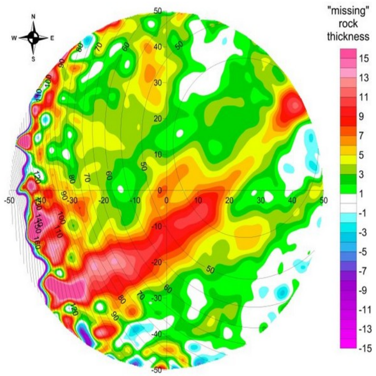
III. **Gaseous detector:** good positional resolution, but needs optimization to environment

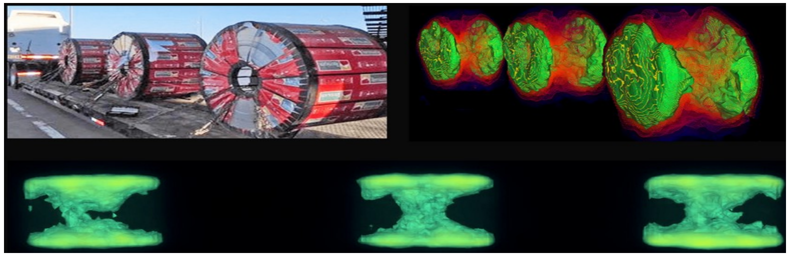
Nagoya University

KEK

HUN-REN Wigner RCP
The University of Tokyo

Arrangements of Muographic Measurements

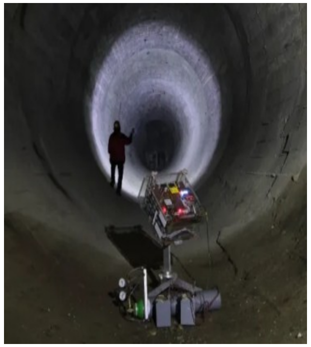




Decision Sciences

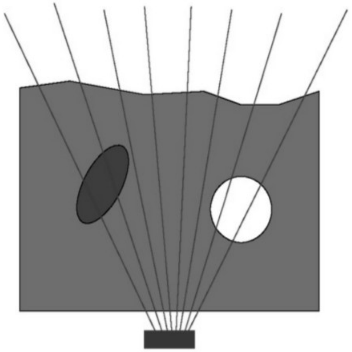
Absorption (reduction of number)

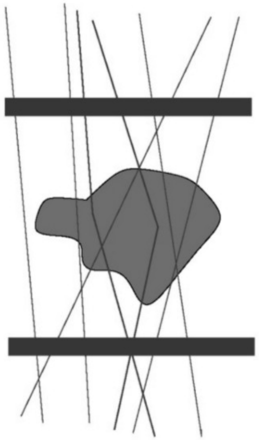
Scattering (directional change)



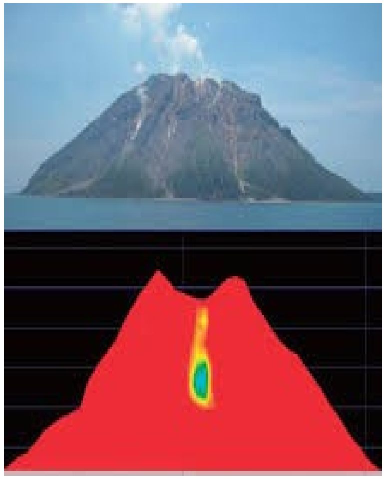
HUN-REN Wigner RCP

Underground (high or low density)





Object inside the detector



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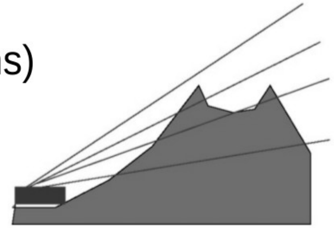
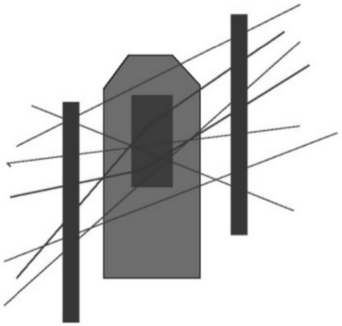
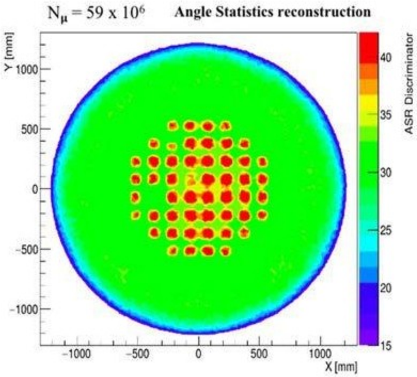
On surface (low angle muons)





Detector "around" object

Credit: D. Varga



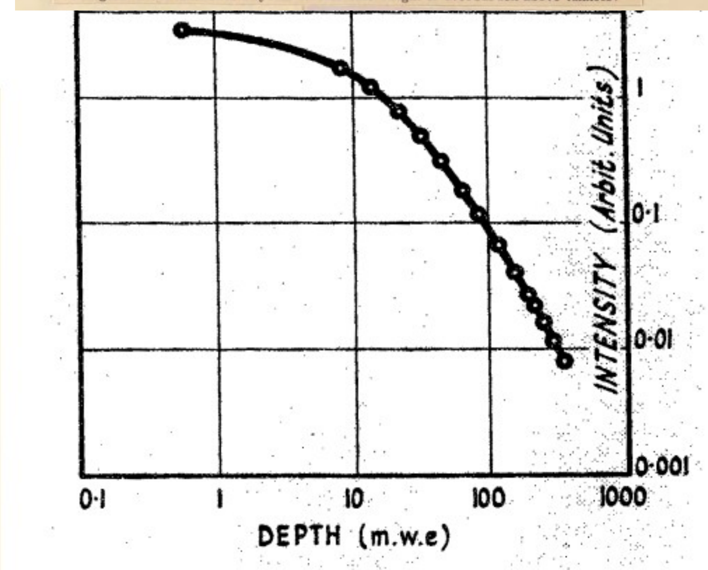
CHANCE Consortium

II. Geotechnics and Civil Engineering

Pioneering Works

E.P. George (1955)

Dr. E. P. George (seated, left) and his team pictured at work in a Snowy Mountain Hydro-Electricity Project tunnel with the "Cosmic Ray Geiger Counter Telescope" designed at the School of Physics to calculate weight of overburden above tunnels.

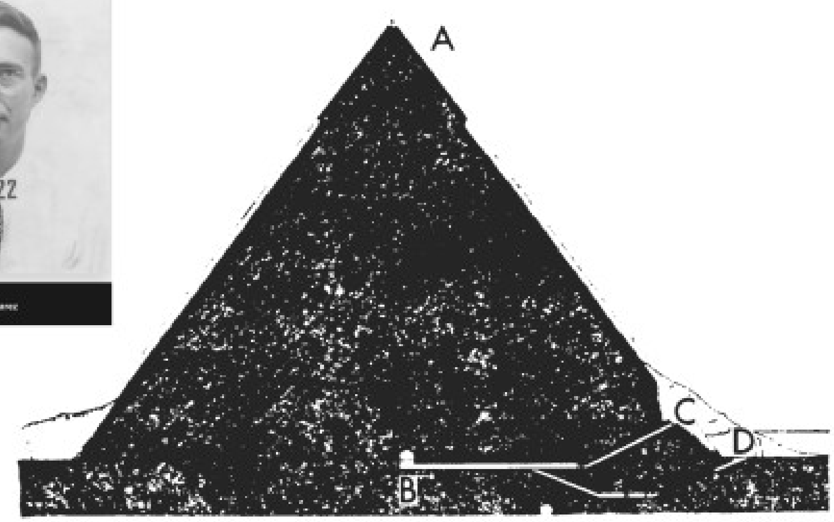


The ratio:

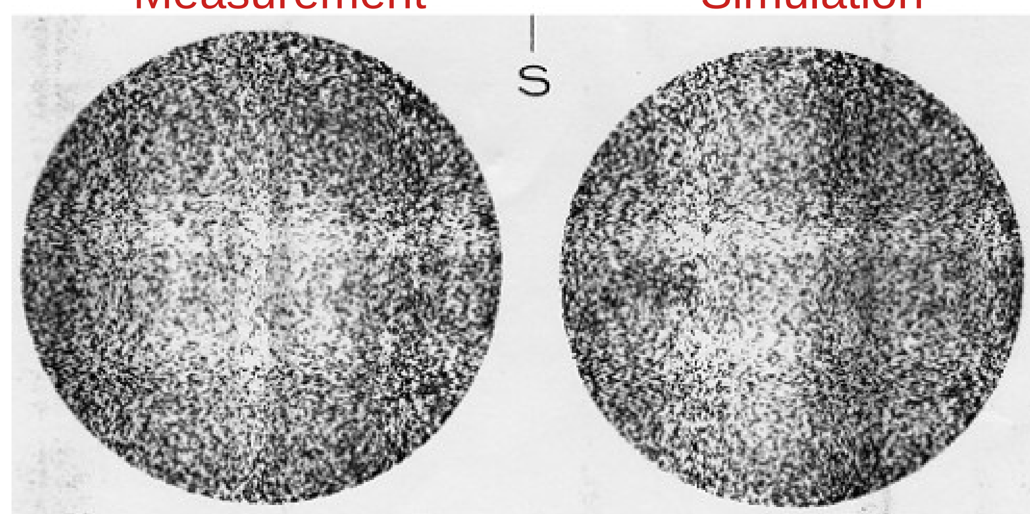
$$\frac{\text{counting rate in tunnel}}{\text{counting rate outside}}$$

was measured and found to be 0.0128. Reading off from Fig. 4, the depth is found to be equivalent to 163 ± 8 metres of water.

Alvarez et al. Science, 167, 832-839 (1970).
https://doi.org/10.1126/science.167.3919.832

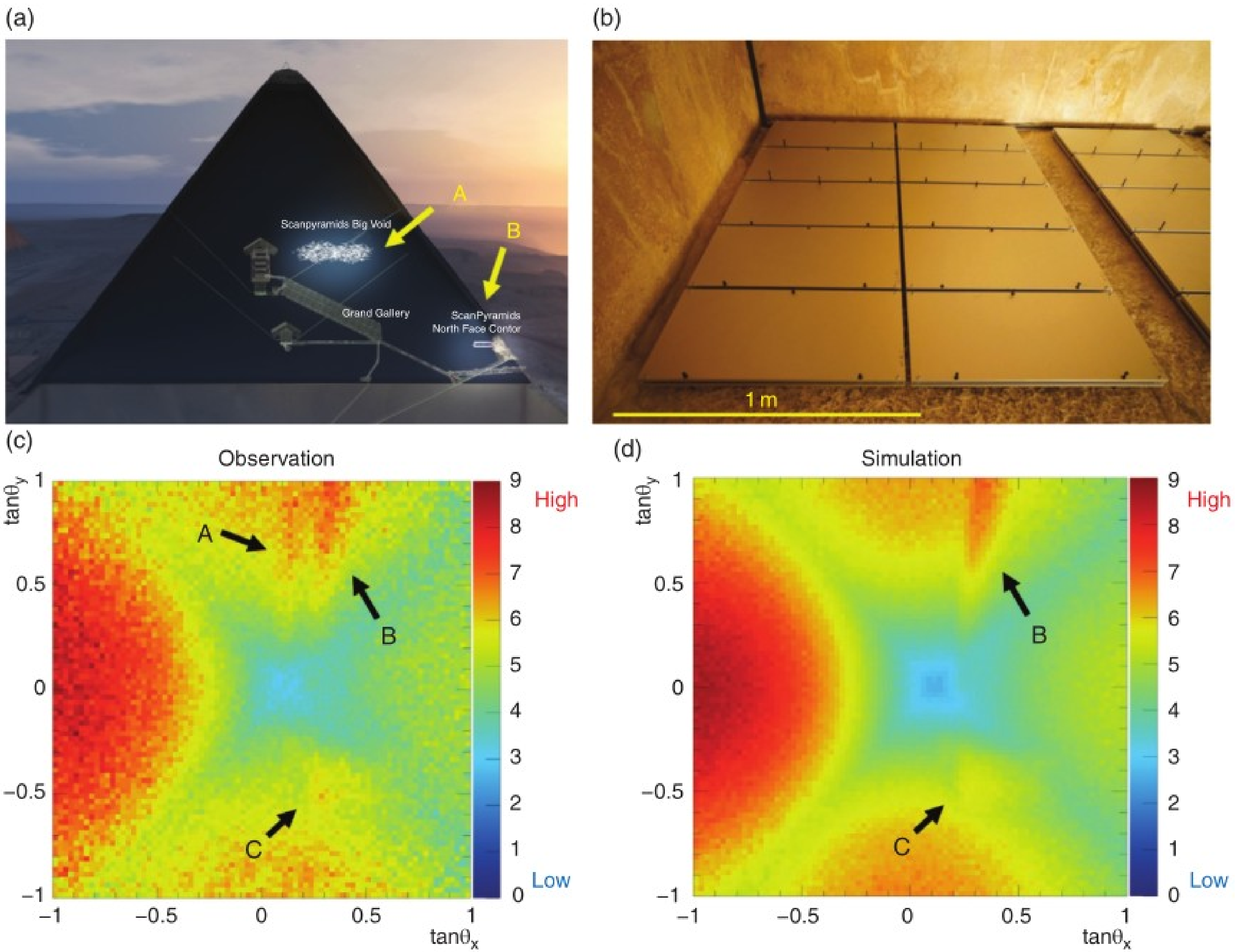


Measurement Simulation

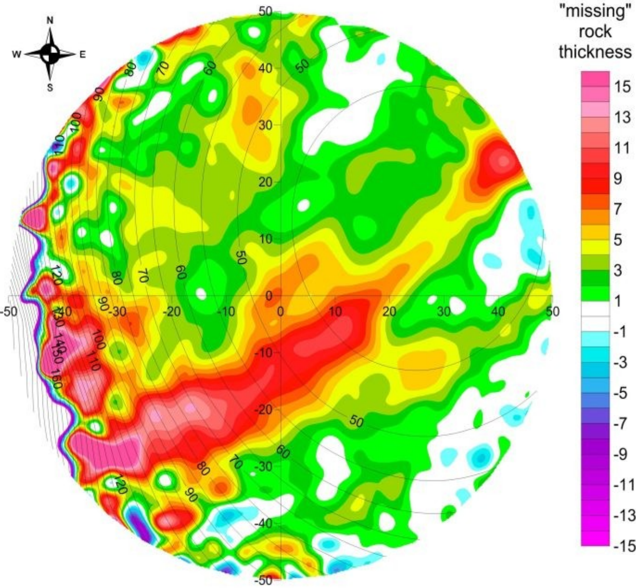


Exploring Hidden Cavities, Fracture Zones

Morishima, K., et al. Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons. Nature 552, 386–390 (2017). https://doi.org/10.1038/nature24647



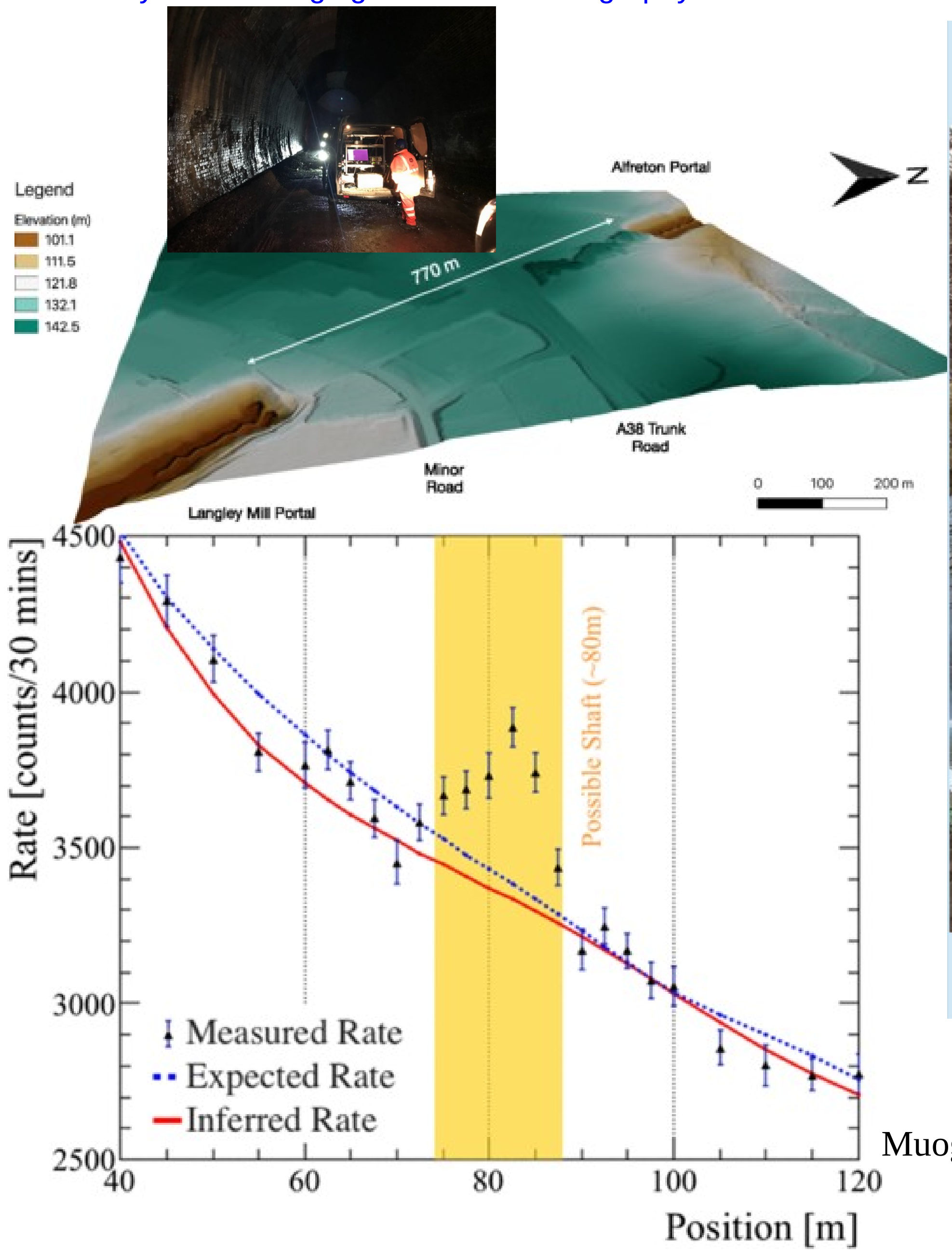
Balázs, L., et al. 3-D muographic inversion in the exploration of cavities and low-density fractured zones. Geophysical Journal International, 236, 700-710 (2024) https://doi.org/10.1093/gji/ggad428

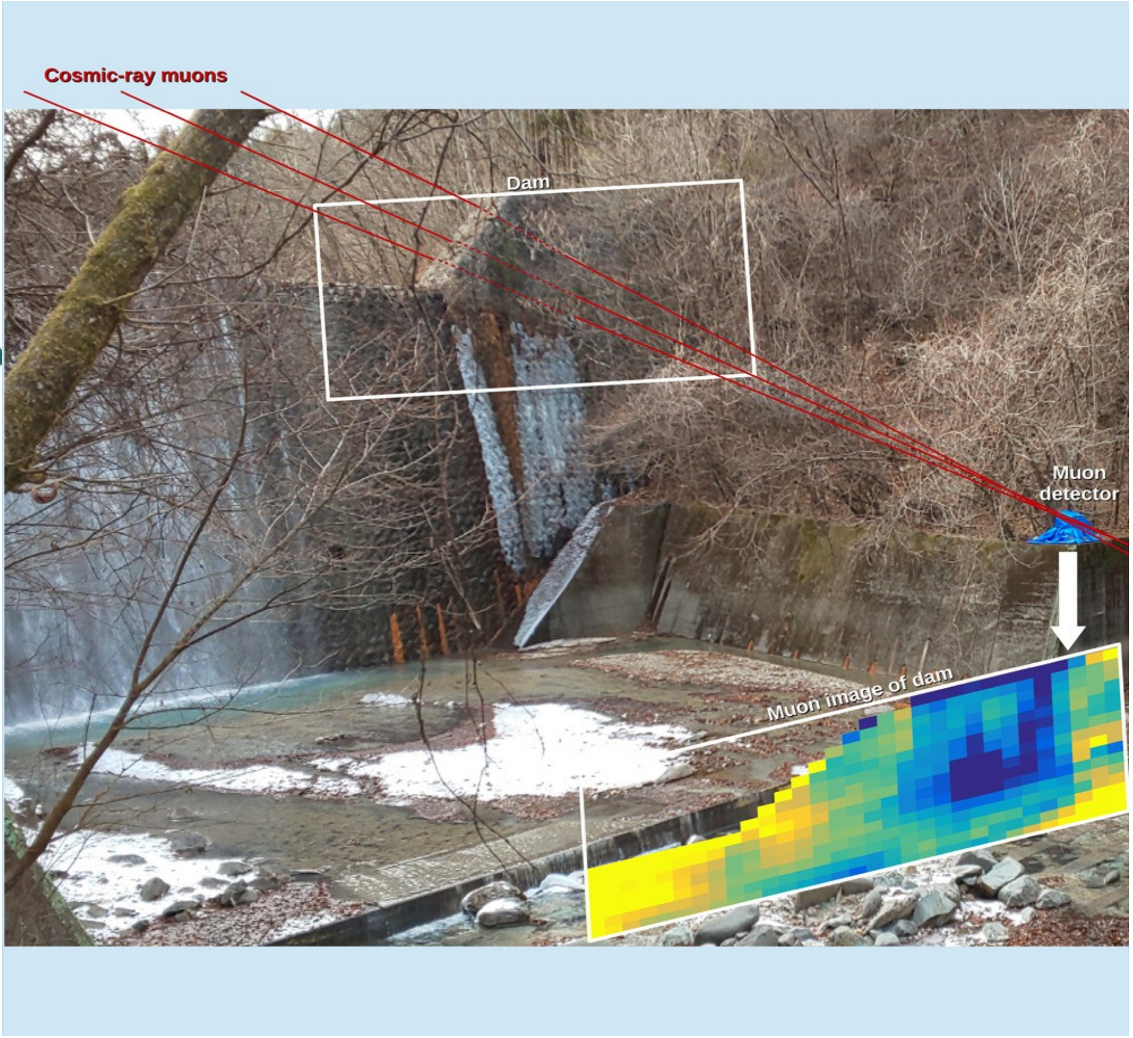


Structural Health Monitoring

Thomson, L. F., et al. **Muon tomography for railway tunnel imaging**. Phys. Rev. Research 2, 023017 (2020)
https://doi.org/10.1103/PhysRevResearch.2.023017
https://www.geplus.co.uk/technical-paper/technical-paper-railway-tunnel-imaging-with-muon-tomography-08-01-2020/

Oláh, L., et al. **Structural health monitoring of sabo check dams with cosmic-ray muography**. iScience 26, 108019 (2023).
https://doi.org/10.1016/j.isci.2023.108019

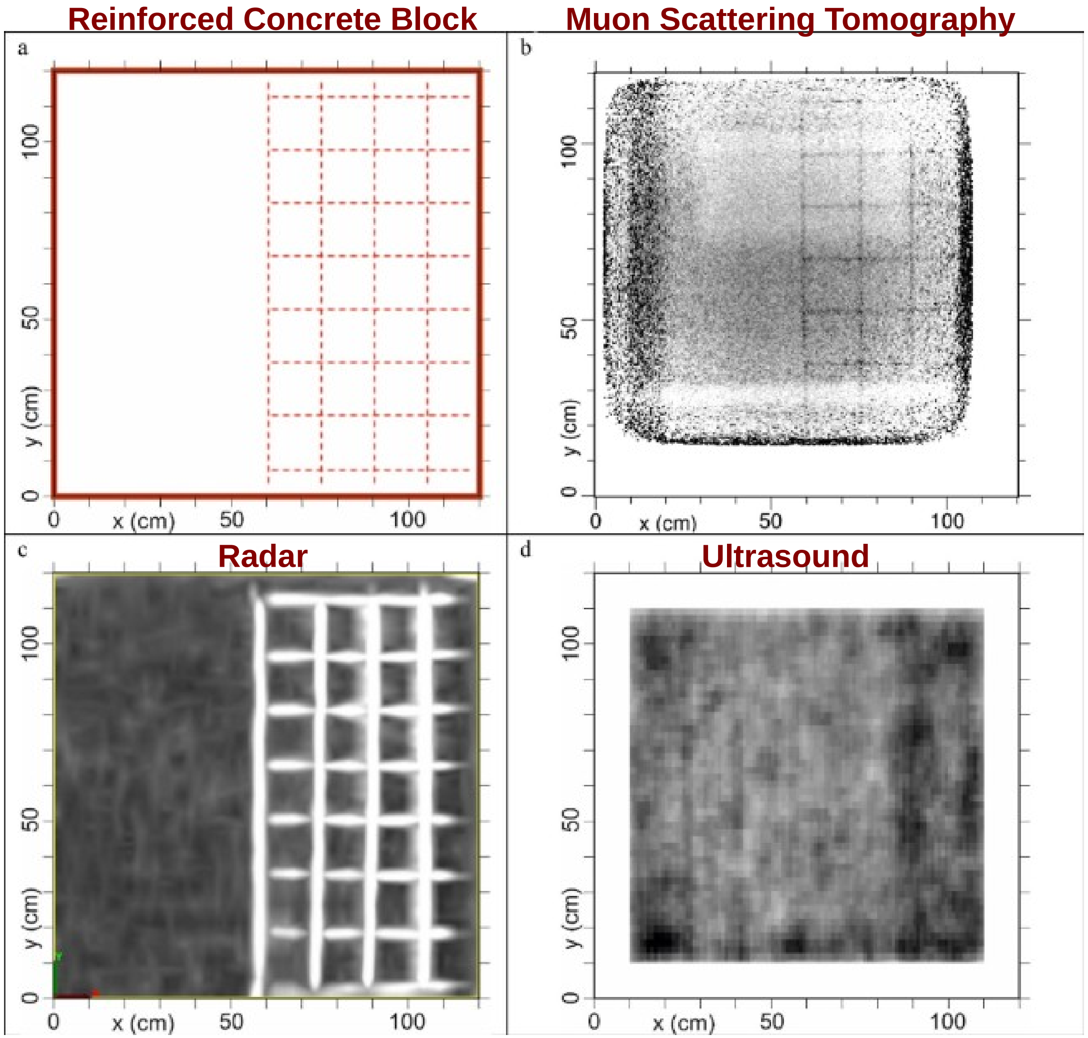


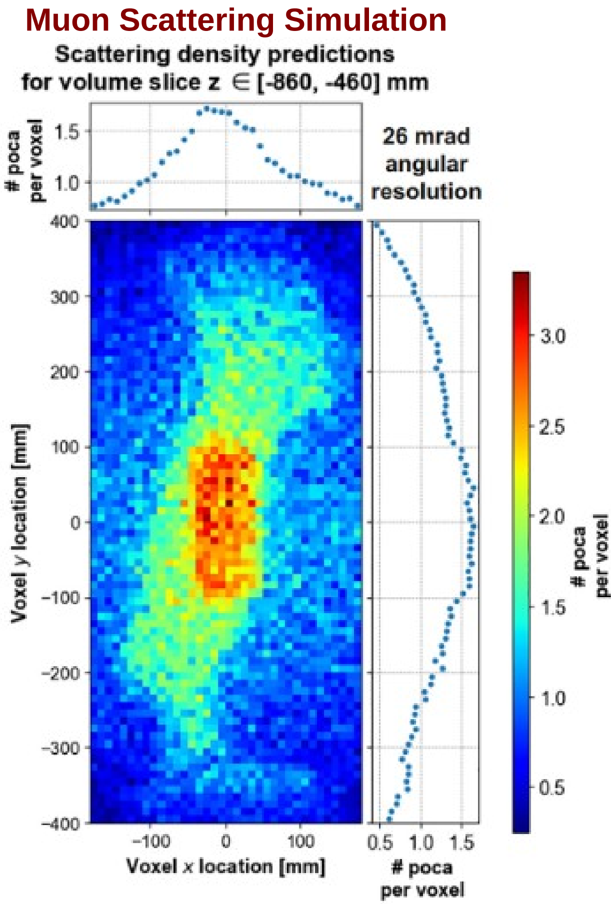


Nondestructive Evaluation

Niederleithinger, E., et al.
Muon Tomography of the Interior of a Reinforced Concrete Block: First Experimental Proof of Concept. J Nondestruct Eval 40, 65 (2021). https://doi.org/10.1007/s10921-021-00797-3

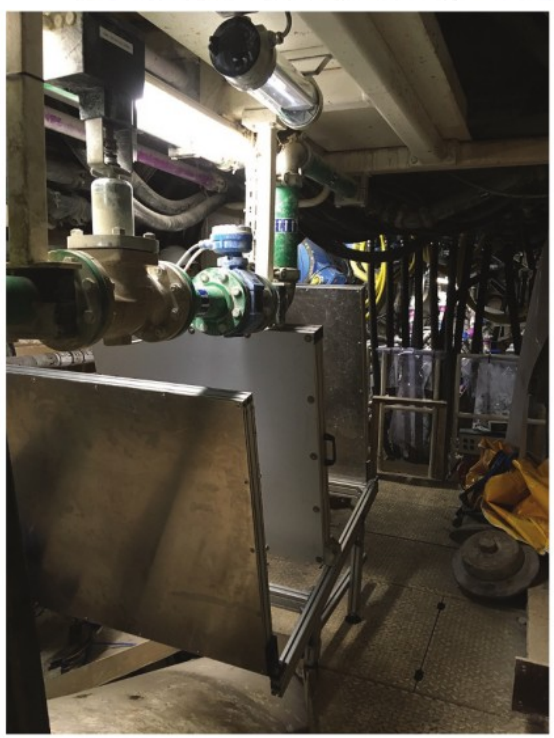
Giammanco, A., et al.
Toward using cosmic rays to image cultural heritage objects, iScience, 28, 112094, (2025) https://doi.org/10.1016/j.isci.2025.112094

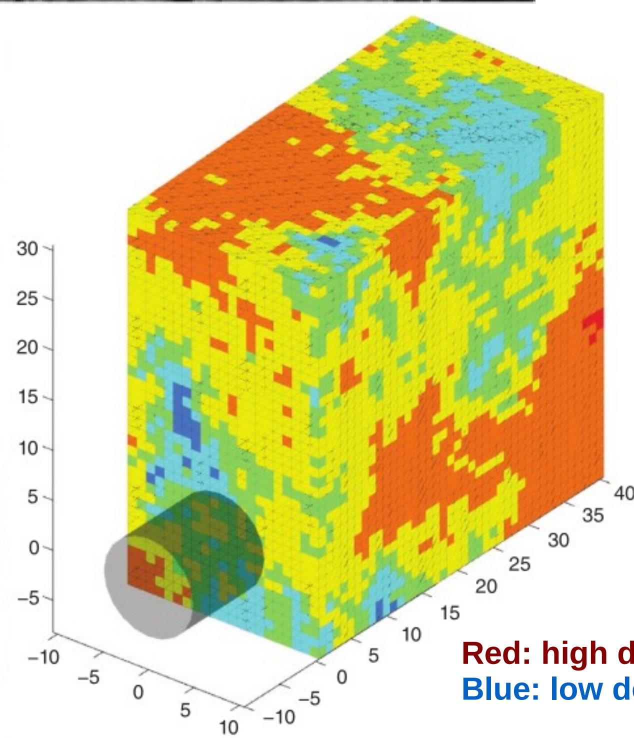




Muography-assisted Tunnel Boring Machine

Marteau, J., et al. Development of Scintillator-Based Muon Detectors for Muography, Geophys. Mon. Ser. 270, 237-252, https://doi.org/10.1002/9781119722748.ch17



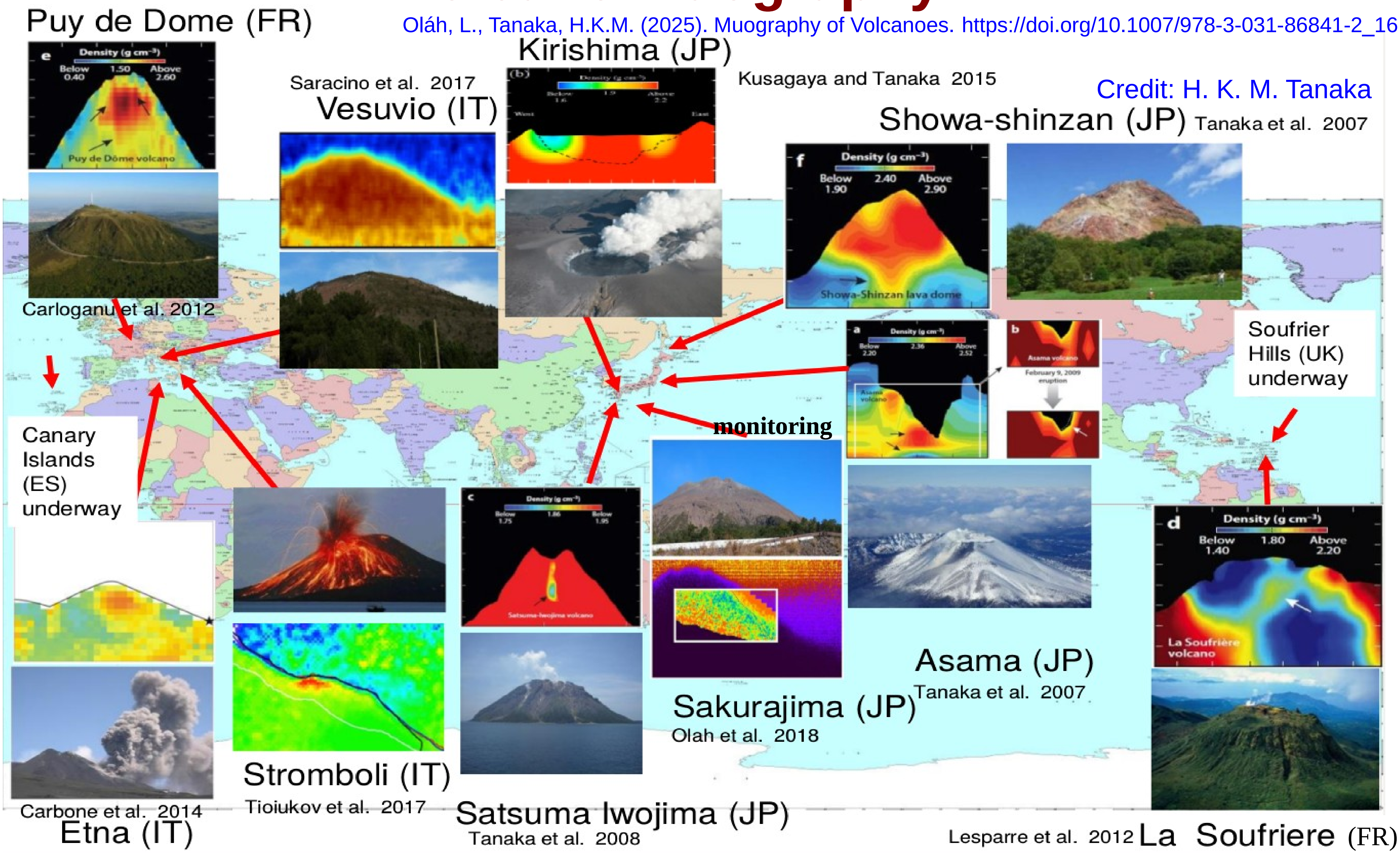


Red: high density
Blue: low density

III. Probing Geological Formations and Earth Phenomena

Volcano Muography

Oláh, L., Tanaka, H.K.M. (2025). Muography of Volcanoes. https://doi.org/10.1007/978-3-031-86841-2_16

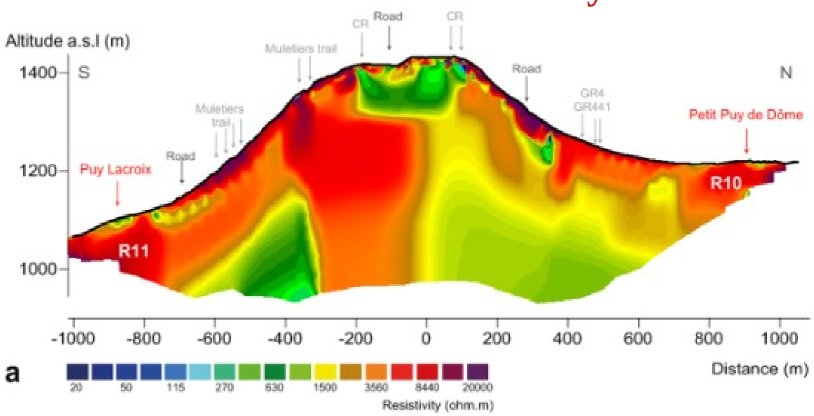


Contributions of Muography to Volcano monitoring and volcanology:
(1) Studying formation and stability of lava domes (Showa-Shinzan, La Soufrière de Guadeloupe),
(2) Exploring conduit structure for eruption modelling (Stromboli, Etna),
(3) Monitoring magma evolution and movement (Asama, Sakurajima, Vesuvio, Puy de Dome),
(4) Assessing the stability of volcanic slopes (Mount Unzen, Copahue).

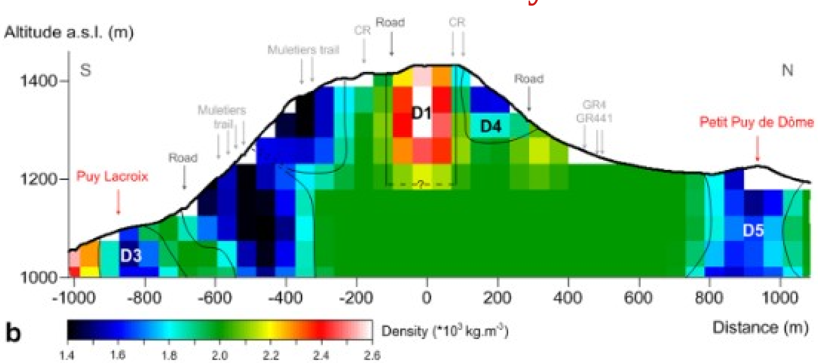
Muography as a complementary technique

Portal, A., et al. **Inner structure of the Puy de Dôme volcano: cross-comparison of geophysical models (ERT, gravimetry, muon imaging)**, Geosci. Instrum. Method. Data Syst., 2, 47–54 (2013) https://doi.org/10.5194/gi-2-47-2013

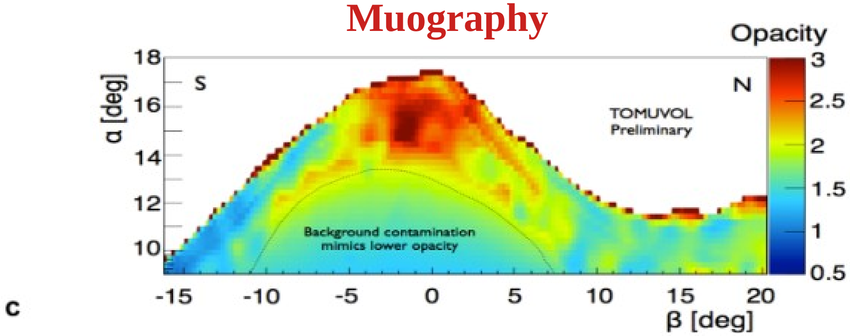
Electrical Resistivity



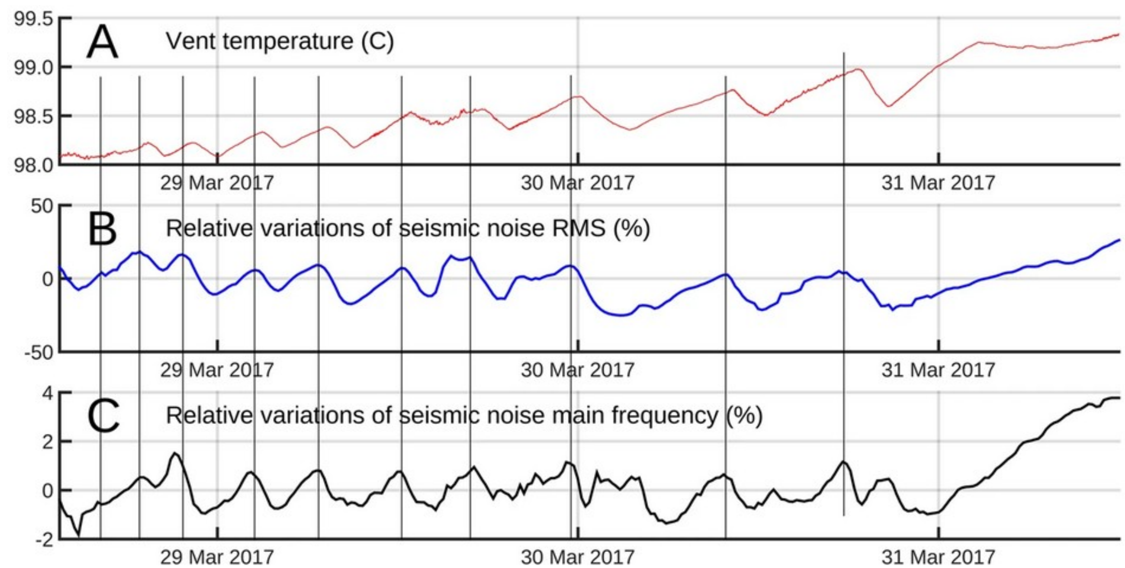
Gravimetry

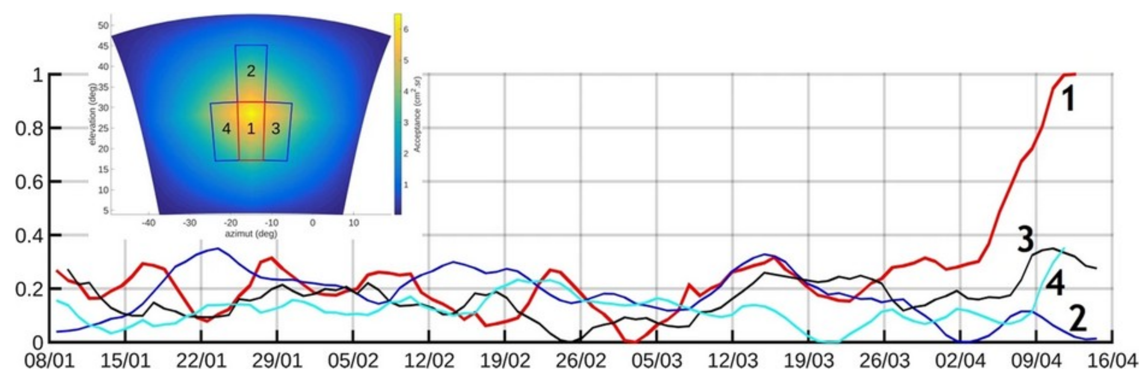


Muography



Le Gonidec, Y., et al. **Abrupt changes of hydrothermal activity in a lava dome detected by combined seismic and muon monitoring**. Sci Rep 9, 3079 (2019). https://doi.org/10.1038/s41598-019-39606-3

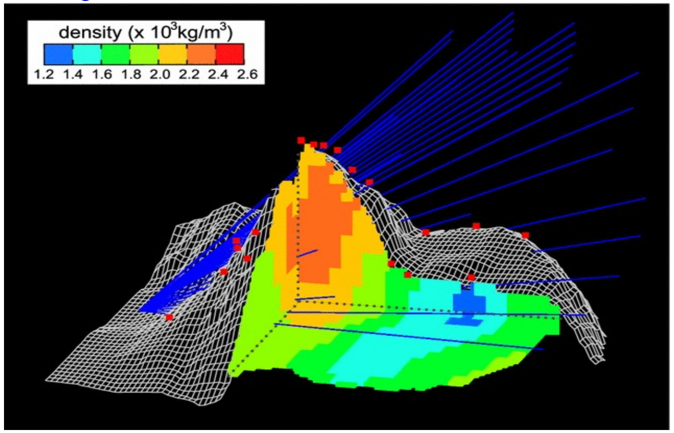




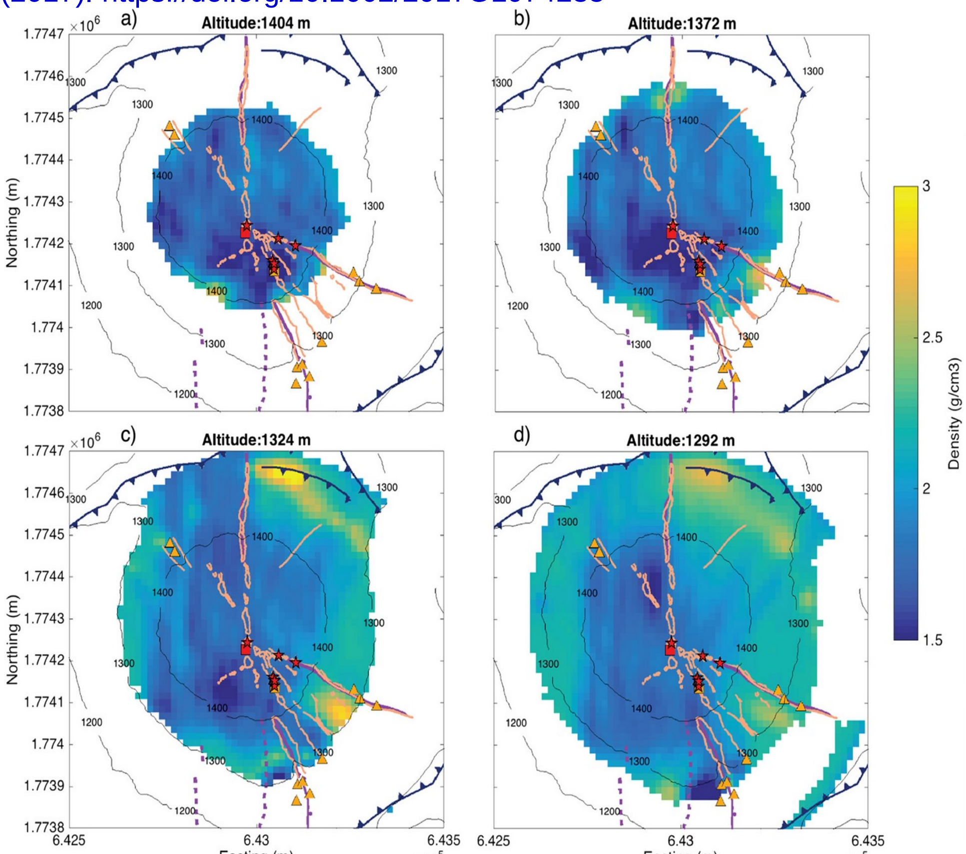
Muography as a complementary technique

Joint processing of muographic and gravimetric data improves the spatial resolution of subsurface exploration.

Nishiyama, R., et al. Pure Appl. Geophys. 174, 1061–1070 (2017). https://doi.org/10.1007/s00024-016-1430-9



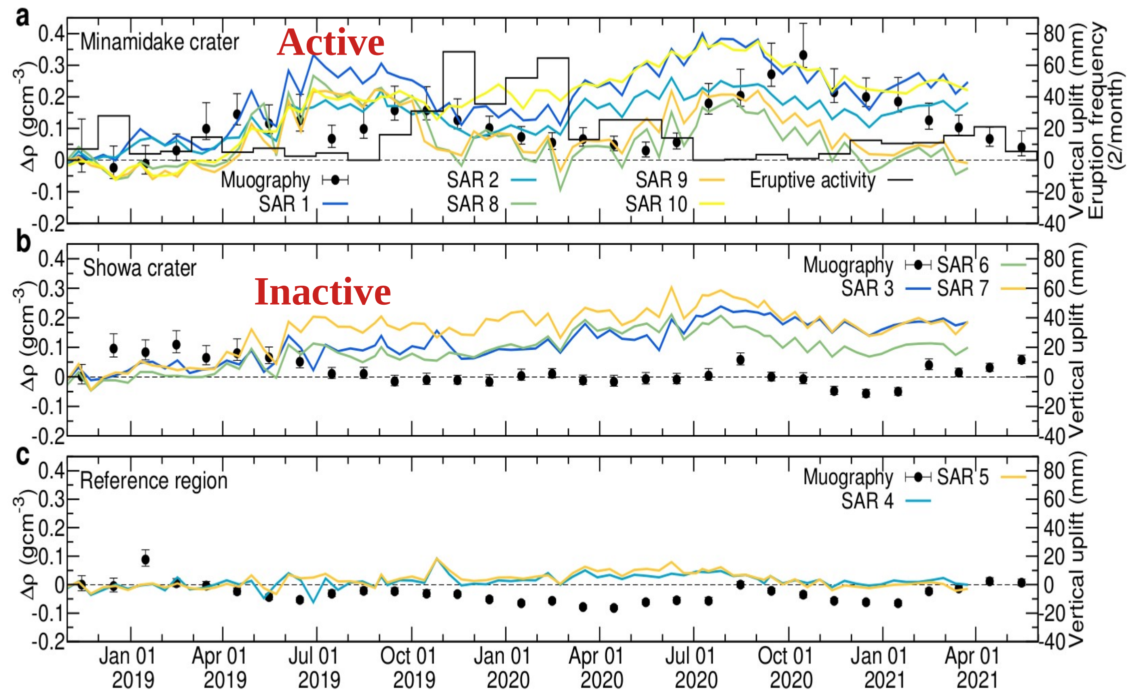
Rosas-Carbajal, M., et al. Geophys. Res. Lett., 44, 6743-6751, (2017). https://doi.org/10.1002/2017GL074285



Muography aids the limitations of ground surface deformation monitoring:

L. Oláh, et al. Geophys. Res. Lett. 50, e2022GL101170 (2023). https://doi.org/10.1029/2022GL101170

Magma migration beneath the active craters of Sakurajima volcano before the 2023 eruption of Showa crater inferred from ground deformation and muon monitoring. Earth Planets Space 77, 196 (2025). https://doi.org/10.1186/s40623-025-02325-3

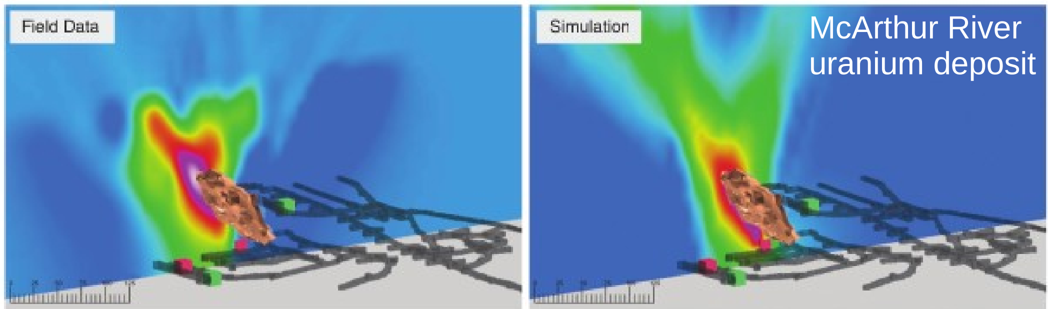


Systematic Coverage	Erupted	Non-Erupted
Deformed	DE 25 True positive	$D\overline{E}$ 29 False positive
Non-deformed	$\overline{D}E$ 9 False negative	$\overline{D}\,\overline{E}$ 135 True negative

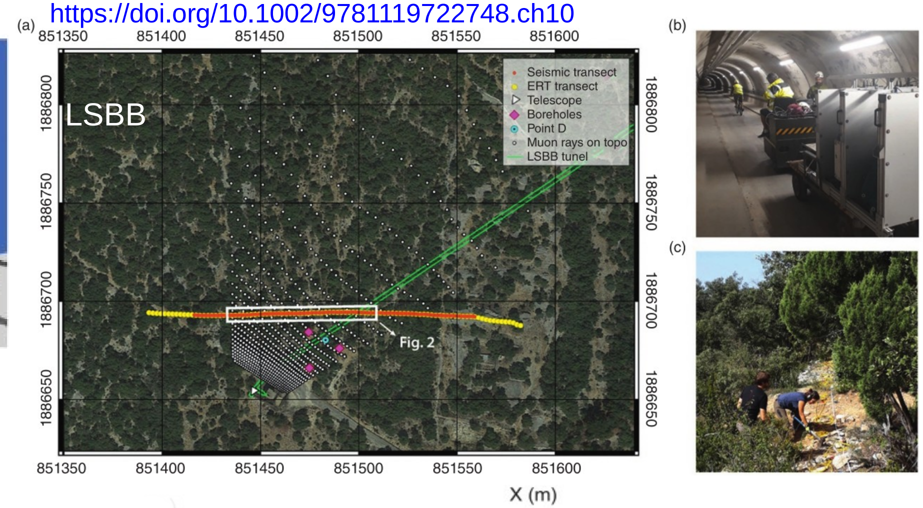
J. Biggs et al.
Global link between deformation and volcanic eruption quantified by satellite imagery.
Nat Commun 5, 3471 (2014).
https://doi.org/10.1038/ncomms4471

Underground Resource Exploration

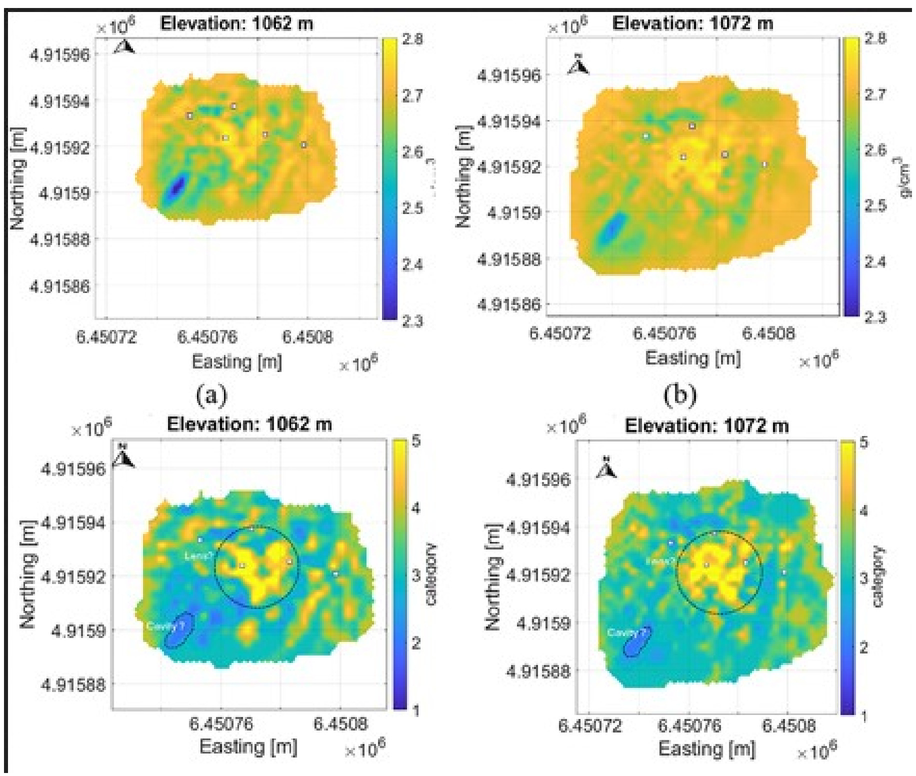
Schouten, D. et al. Muon Tomography for Underground Resources. Mon. Ser. 270,221-235 https://doi.org/10.1002/9781119722748.ch16

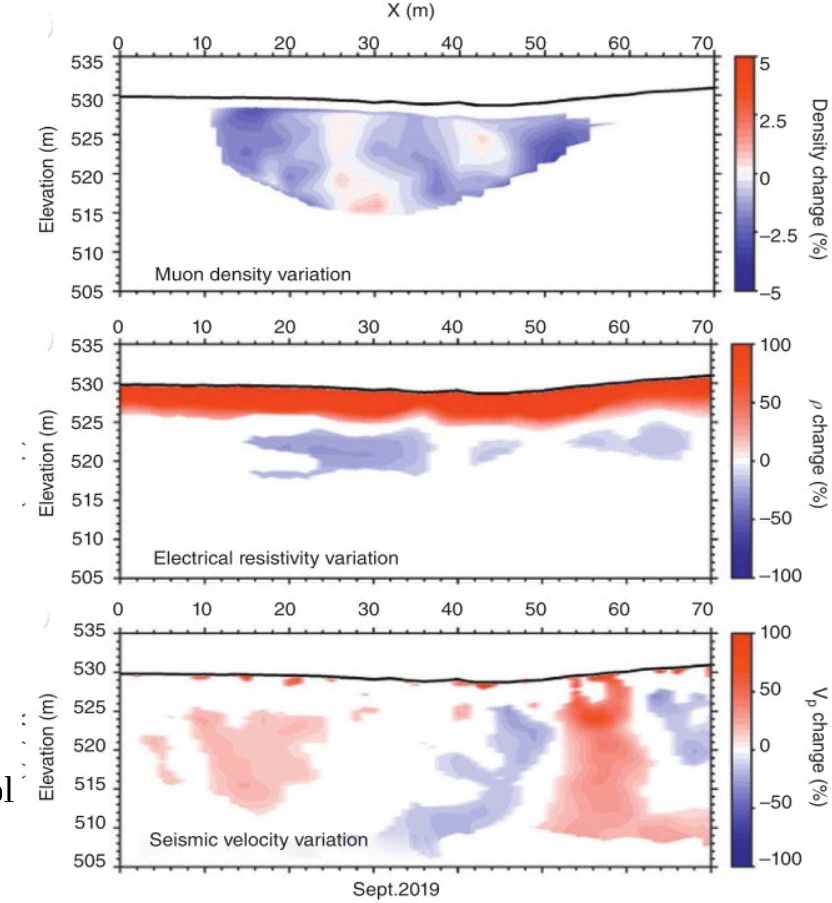


Lázaro Roche, I., et al. Water Resource Management: The Multi-Technique Approach of the Low Background Noise Underground Research Laboratory and its Muon Detection Projects. Geophys. Mon. Ser. 270, 137-152. https://doi.org/10.1002/9781119722748.ch10



Holma, M., et al. Application of muon tomography in bauxite exploration. J. Appl. Phys. 138, 024903 (2025) https://doi.org/10.1063/5.0273513



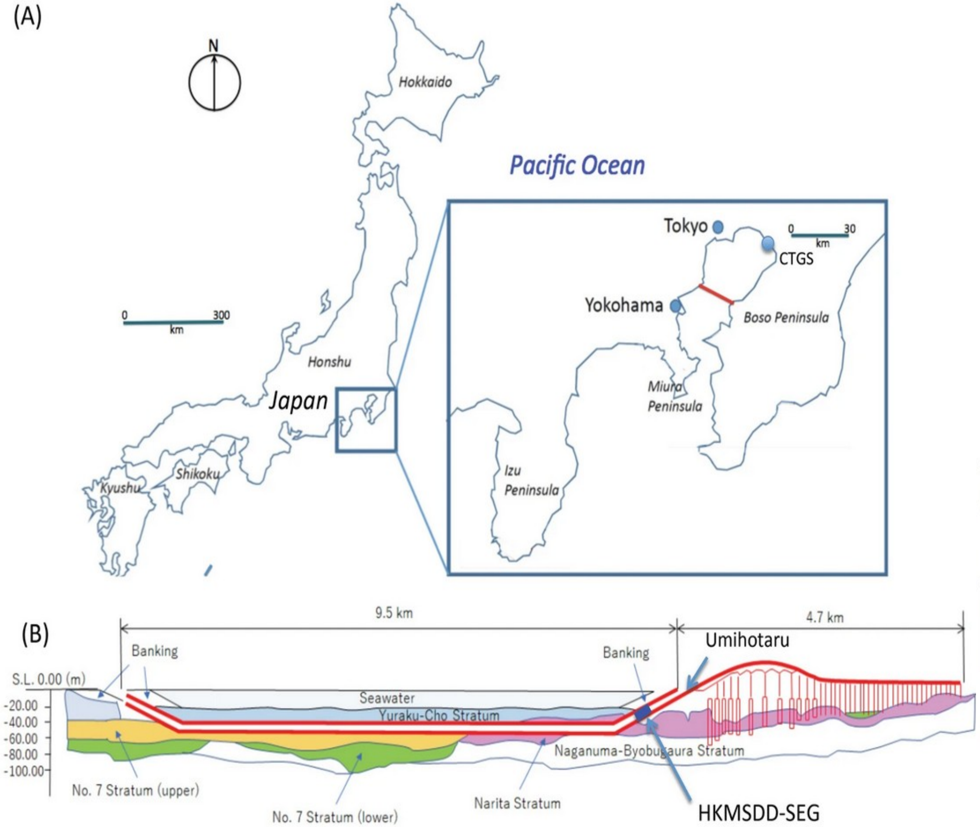


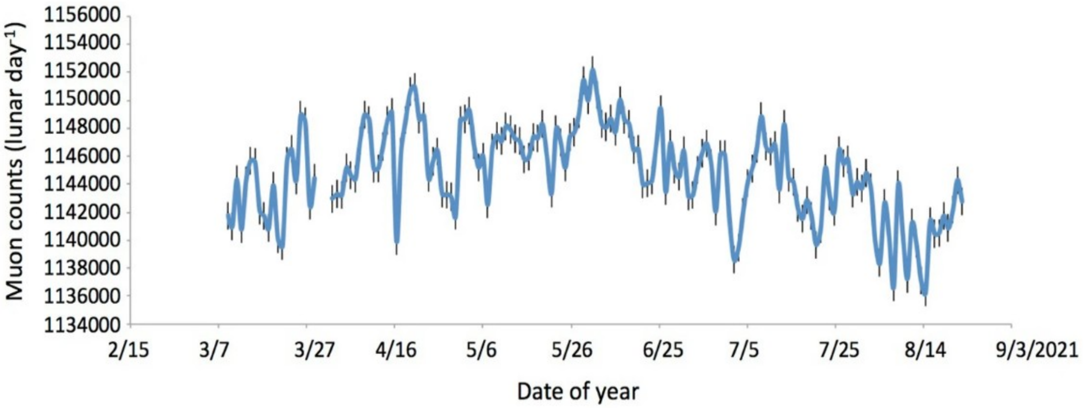
Oláh Muography School

(density categories: 1: cavity, 2: fractured rock, 3: porous limestone 4: compact limestone 5: high density probably bauxite)

Undersea Muography (HKMSDD)

Tanaka, et al. Scientific Reports
https://www.nature.com/articles/s41598-021-98559-8
https://www.nature.com/articles/s41598-022-10078-2

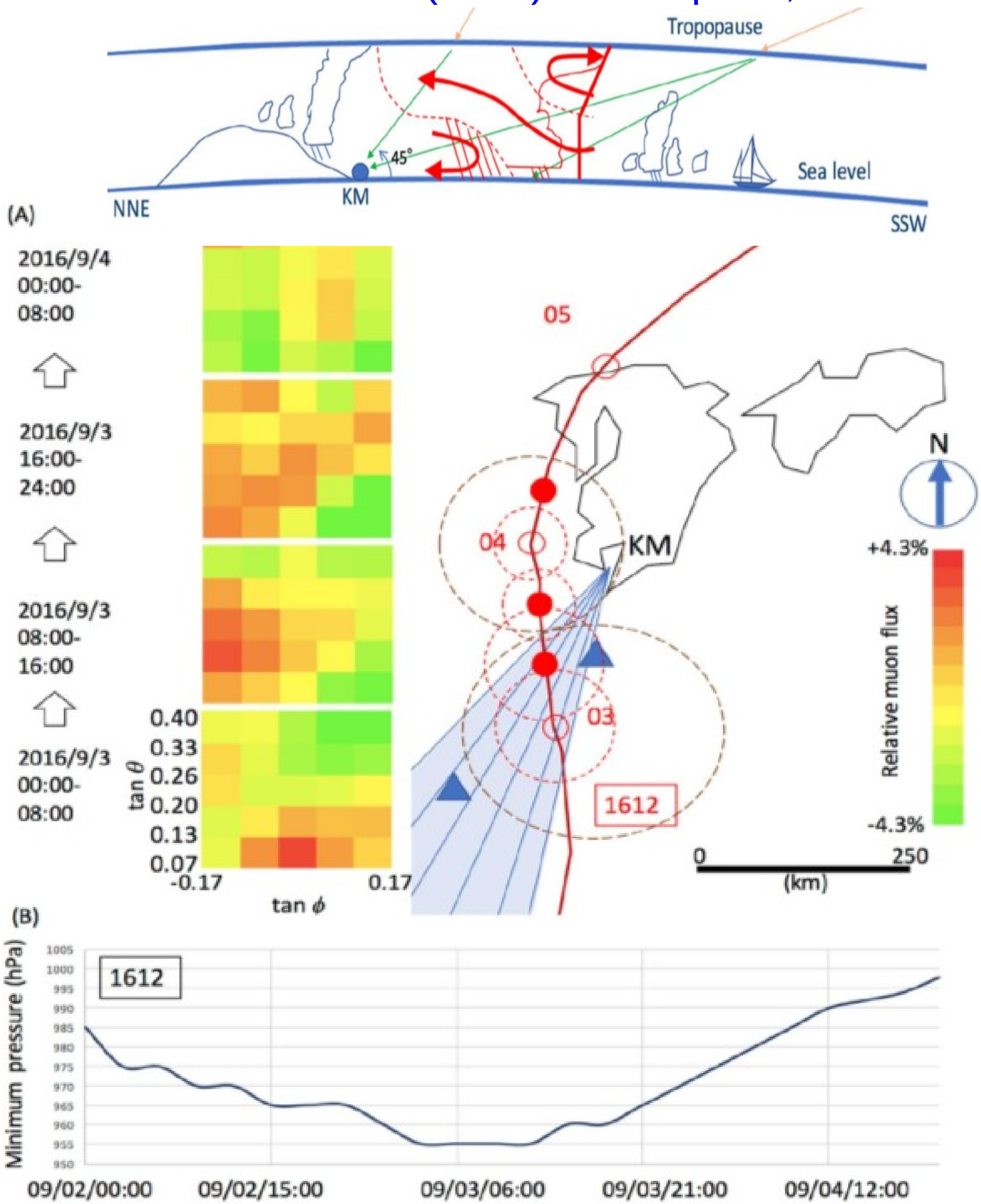




Detector system operated under the Tokyo Bay (HKMSDD):
- water level changes due to periodic effects, typhoons, etc.
- **Application: protection of coastal areas with muographic alarm system**

Muography of Tropical Cyclones

Tanaka et al. (2022) Sci. Rep. 12, 16710 https://doi.org/10.1038/s41598-022-20039-4



- Increase in atmospheric pressure increase the probability of muon decay and interaction

  → **muon flux is inversely correlated with atmospheric pressure**
  (e.g., 1 % pressure drop result in 2 % flux increase)

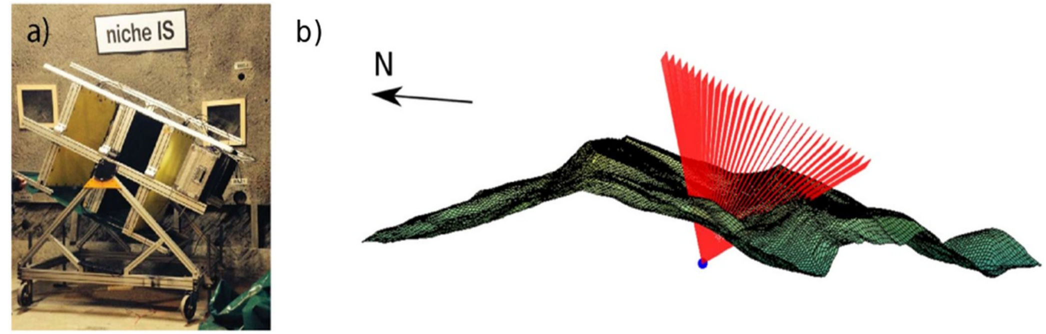
- T-1612 passed across the LOS of SMO from South to North on 2016/09/03 – 2016/09/04
- Angular dependent relative muon flux increased consistently with the passage of typhoon
- **High-resolutional Dynamic Muography:**
  - **Studying the genesis and maintenance of tropical cyclones**

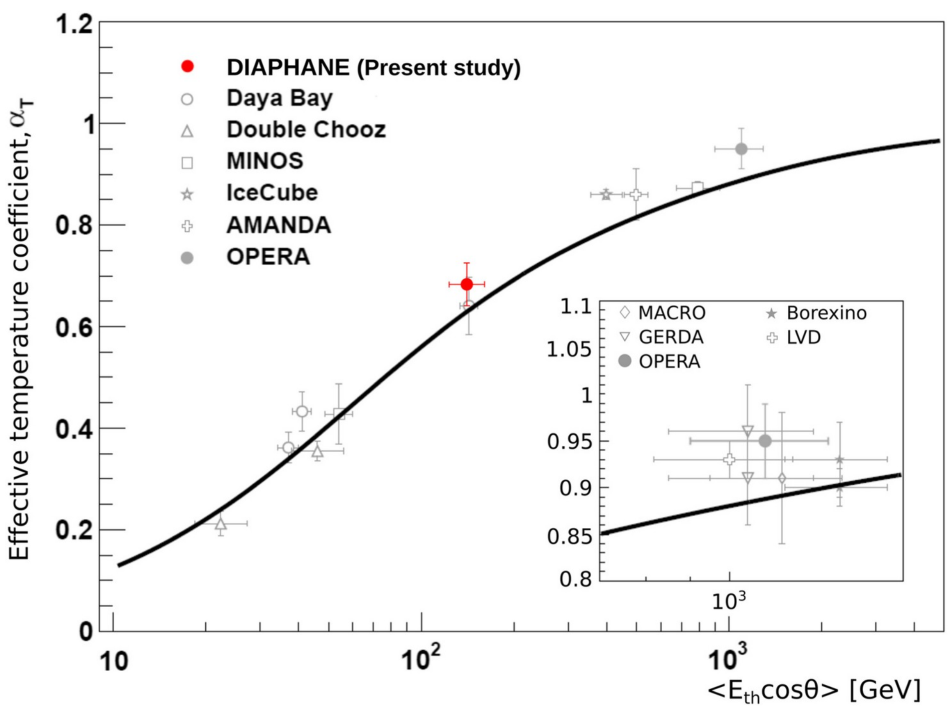
Detecting Sudden Stratospheric Warmings

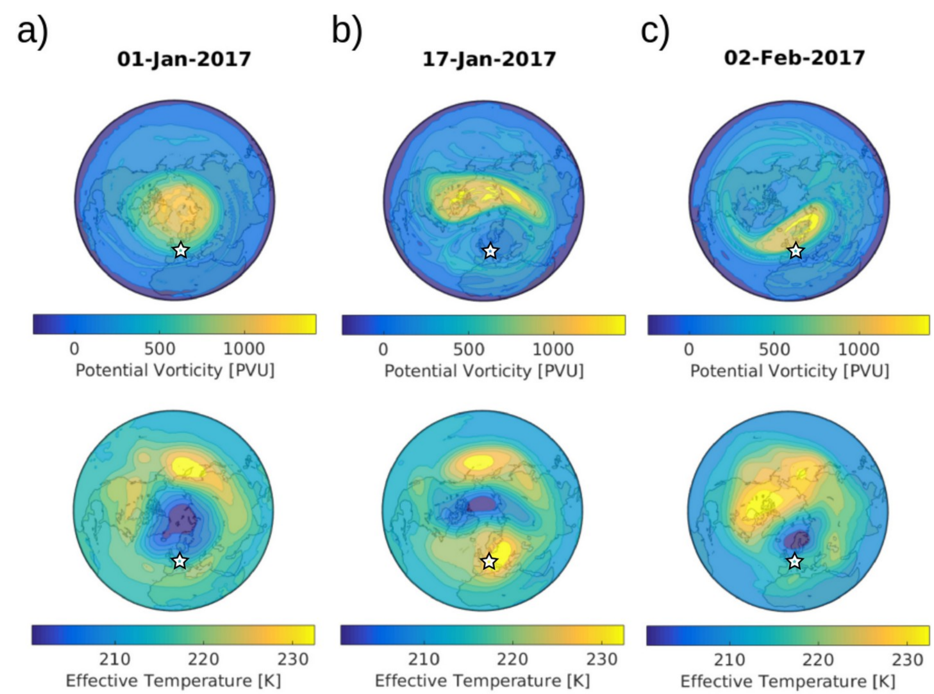
Tramontini, M., Rosas-Carbajal, M., Nussbaum, C., Gibert, D., & Marteau, J. (2019). Middle-atmosphere dynamics observed with a portable muon detector. Earth and Space Science, 6, 1865–1876. https://doi.org/10.1029/2019EA000655

$$\frac{\Delta R}{\langle R \rangle} = \alpha_T \frac{\Delta T_{\mathrm{eff}}}{\langle T_{\mathrm{eff}} \rangle} \qquad T_{\mathrm{eff}} = \frac{\int_0^\infty W(X) T(X) \mathrm{d}X}{\int_0^\infty W(X) \mathrm{d}X}$$

Teff is defined as the temperature of an isothermal atmosphere that produces the same meson intensities as the actual atmosphere.





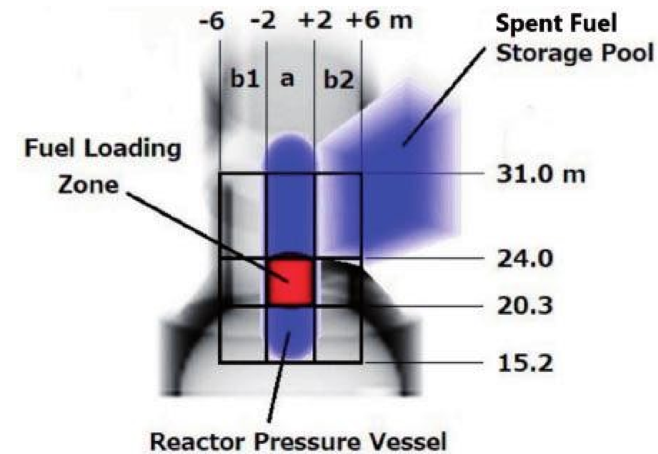


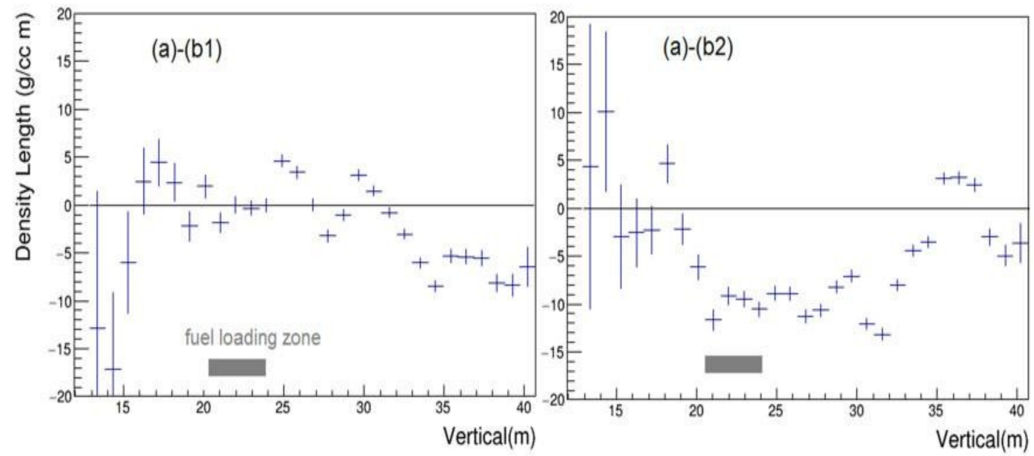
IV. Muons for Safety and Security

Inspection of Fukushima Daiichi Unit-1 Reactor

Fujii et al. Prog. Theor. Exp. Phys. 2020, 043C02
https://doi.org/10.1093/ptep/ptaa027

- Scintillators were operated inside 10-cm-thick iron box for 90 days at a distance of 36 m from the Unit-1
- Nuclear fuel was quantified to 72 tons that is a significantly smaller mass than the expected 160 tons
  → **Unit-1 melted down**





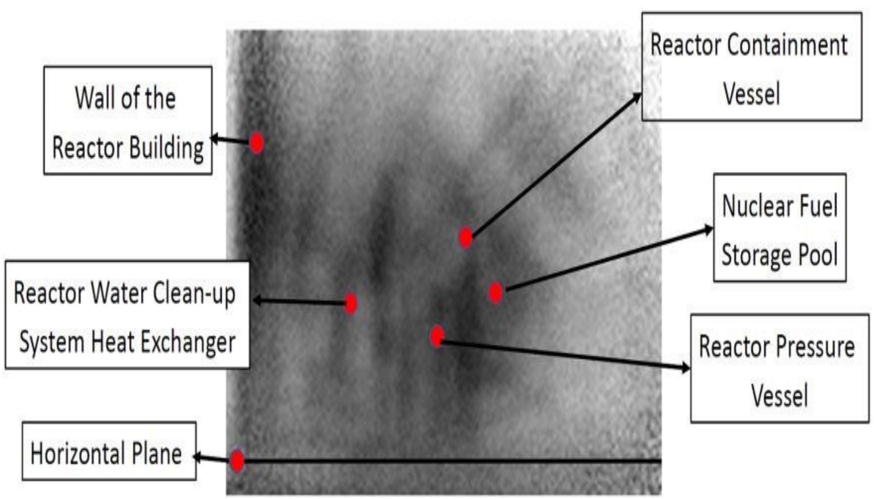


Table 1. Measured amount of material in the RPV for different height regions.

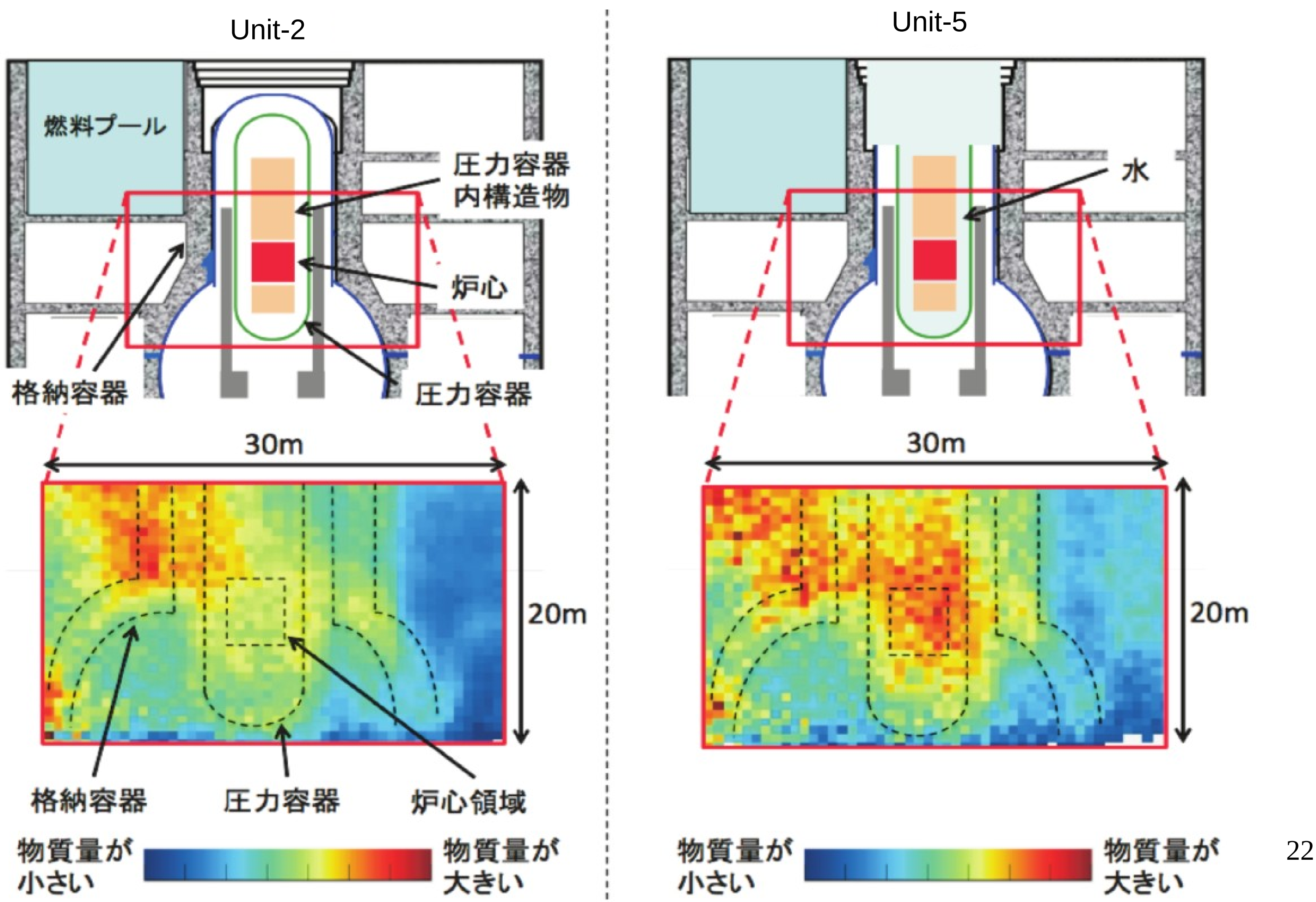
Region	15.2 m < h < 20.3 m (beneath loading zone)	20.3 m < h < 24.0 m (loading zone)	24.0 m < h < 31m (above loading zone)
(a) - (b1)	4±25(stat)±32(syst) tons	1±7(stat)±5(syst) tons	32±6(stat)±11(syst) tons
(a)	33±25(stat)±43(syst) tons	22±7(stat)±22(syst) tons	72*

*Calculated from the engineering drawing.

Inspection of Fukushima Daiichi Unit-2 and Unit-5 Reactors

K. Morishima: Journal of the Photographic Society of Japan, 2016, Vol. 79, No. 1: 42-47

- **Muography data shows that the nuclear fuel may melted down in Reactor No. 2.**



Muon Tomography of a Nuclear Reactor

Muography of G2 reactor located in the CEA, France from 27 positions, with 25-cm side voxels:

Procureur et al., Sci. Adv. 9, eabq8431 (2023).
https://doi.org/10.1126/sciadv.abq8431

A Stands below the graphite cube and shows the concrete base of the reactor.

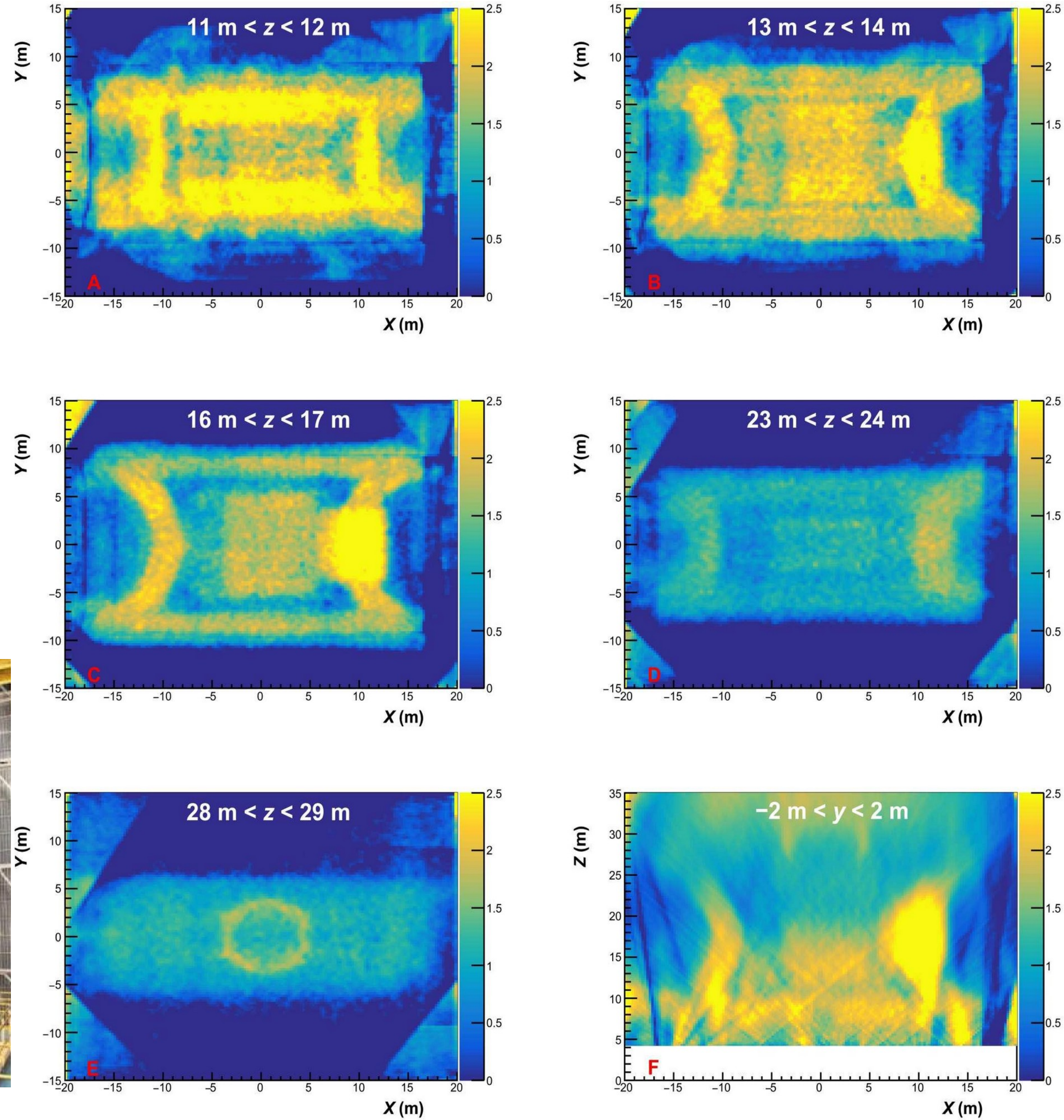
B Lower part of the graphite cube.

C Plane in intersecting the middle of the cylinder.

D Close to the top of the graphite structure where its y dimension is smaller

E taken just above the reactor cylinder. The concrete hat is visible.

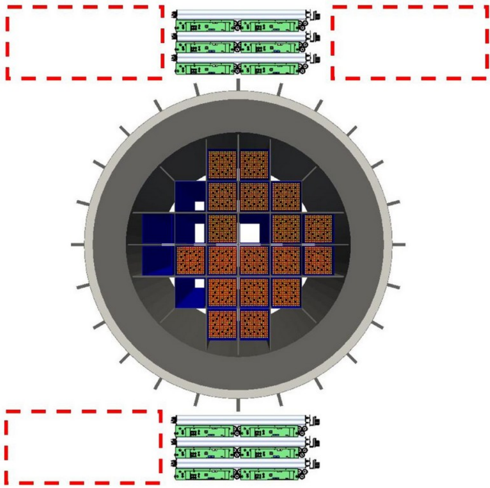
F x-z view of the reconstruction, close to the reactor y center.

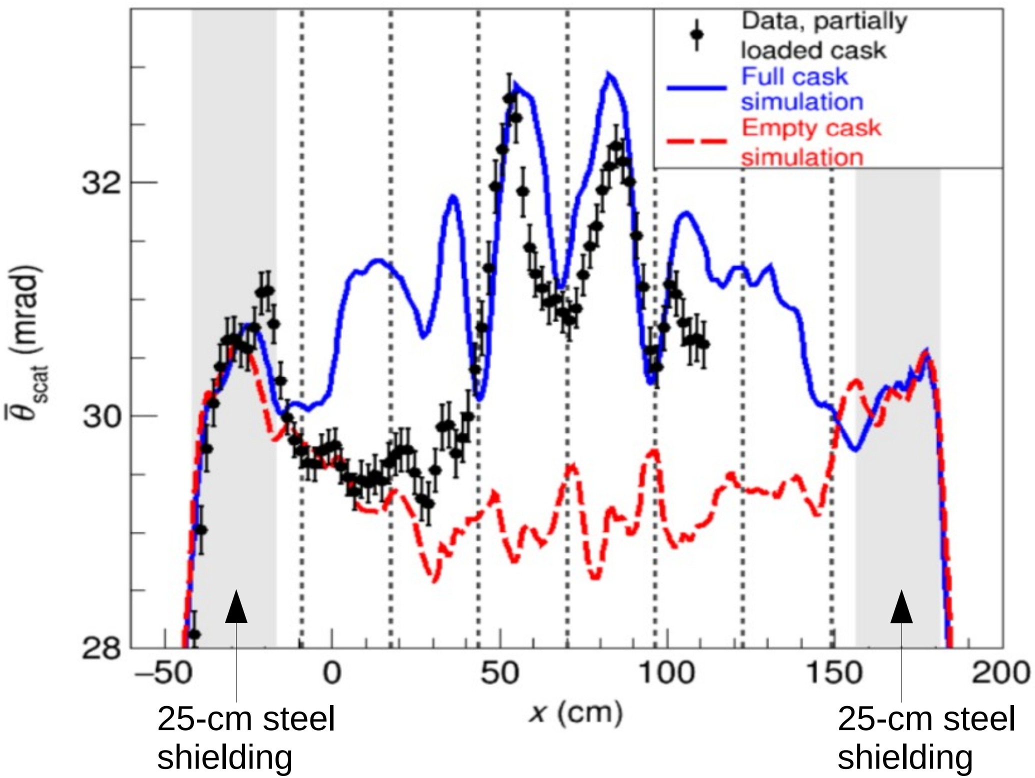


Inspection of Nuclear Fuel Dry Storage Casks

Durham, J. M., et al. PHYS. REV. APPLIED 9, 044013 (2018).
https://doi.org/10.1103/PhysRevApplied.9.044013

- A cask for fuel is a **circular cylinder app. 3 m in diameter and app. 5 m in height and consists of a central basket which holds 20–30 spent fuel assemblies** surrounded by cylindrical layers of neutron and gamma-ray shielding.
- Data are collected in 3 positions for approximately ten days, with samples sizes ranging from 40k to 90k muon tracks in each configuration.
- Stand-alone method to independently determine if fuel assemblies are missing from a sealed dry storage cask
- Muons are an external probe that are not subject to backgrounds from other casks
- Do not require any previous knowledge of the fuel history.



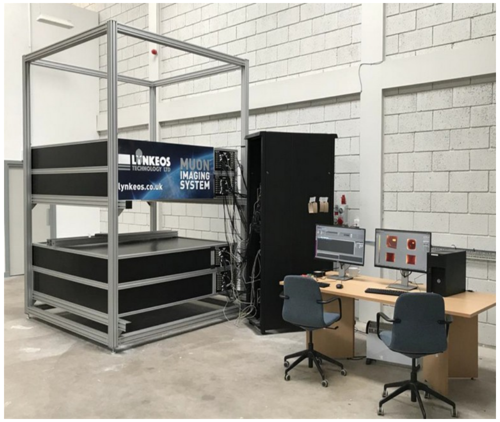


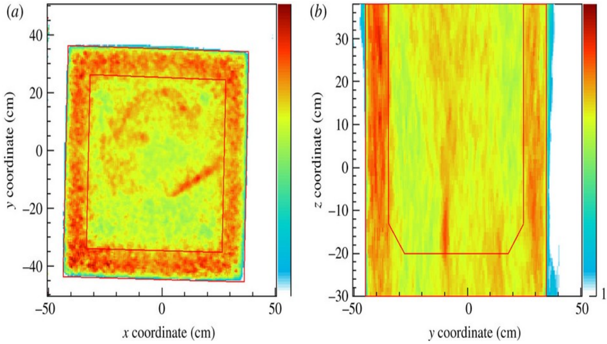
Oláh

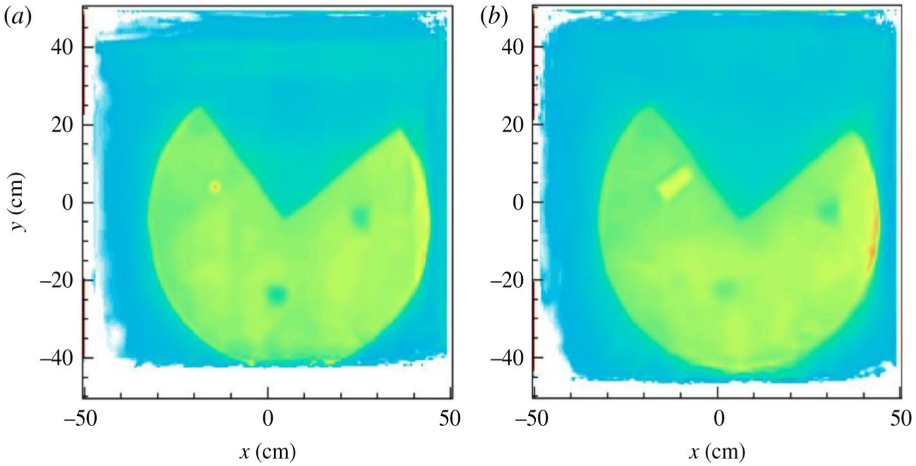
Nuclear Waste Characterization

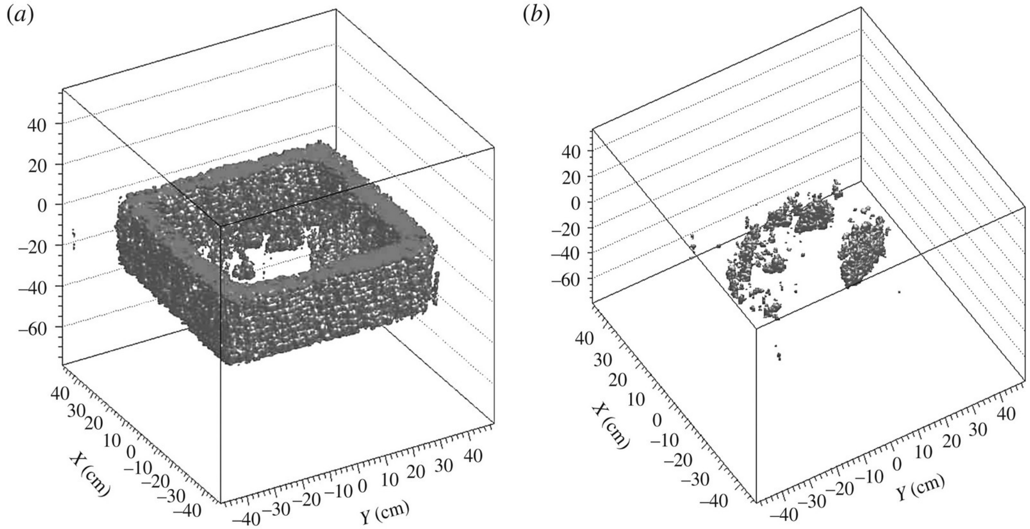
- Nuclear waste containers are typically heavily shielded and highly engineered to contain radioisotopes and attenuate penetrating radiations
- Quality assurrancing by non-destructive testing can reveal the necessity the repacking of waste
- Material discrimination has been conducted in 500 l waste drum and geomelt by Lynkeos

Mahon, D., et al. PRSTA, 377, 20180048 (2019). https://doi.org/10.1098/rsta.2018.0048



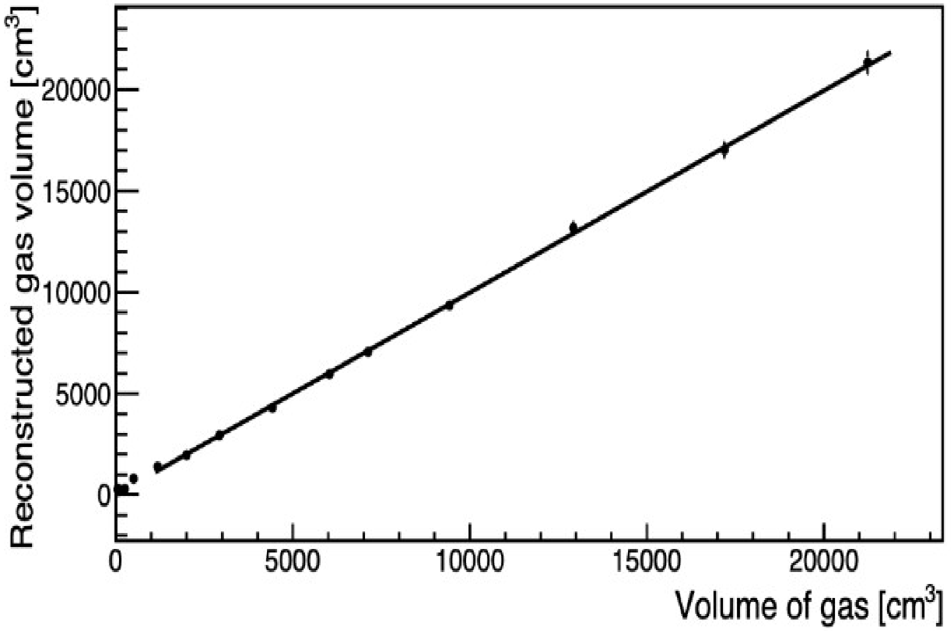


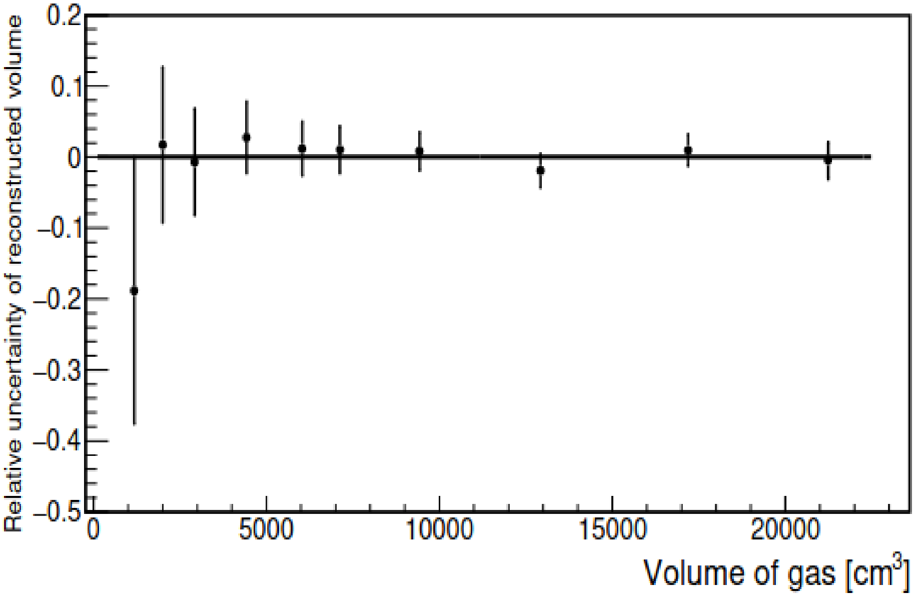




Finding Gas Bubbles in Nuclear Waster Containers

- Nuclear waste is stored in steel containers in which bitumen is used to fill the free volume. Irradiation of the bitumen by radioactive waste can lead to hydrogen production through radiolysis. Since bitumen has very low permeability to water and gases, the generated hydrogen may accumulate in the form of gas bubbles. This can result in swelling, deformation, or potential leakage of the waste containers, thereby complicating their safe handling and long-term storage.
- Gas bubbles with volumes on the order of 1 liter may be detectable using the proposed measurement method.





Dobrowolska, M. J., Velthuis, J., Frazao, L., & Kikola, D. (2018). A novel technique for finding gas bubbles in the nuclear waste containers using Muon Scattering Tomography. Journal of Instrumentation, 13(5), Article P05015.
https://doi.org/10.1088/1748-0221/13/05/P05015

https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5ebd7fff4&appId=PPGMS

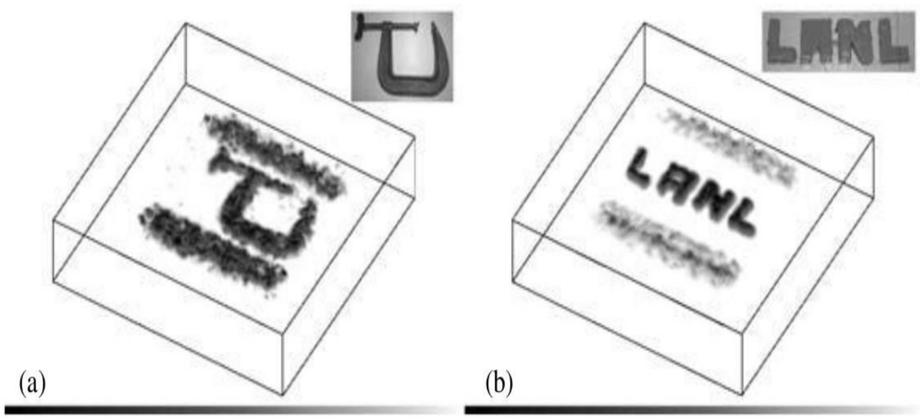
Detection of High-Z Materials by Muon Scattering Tomography

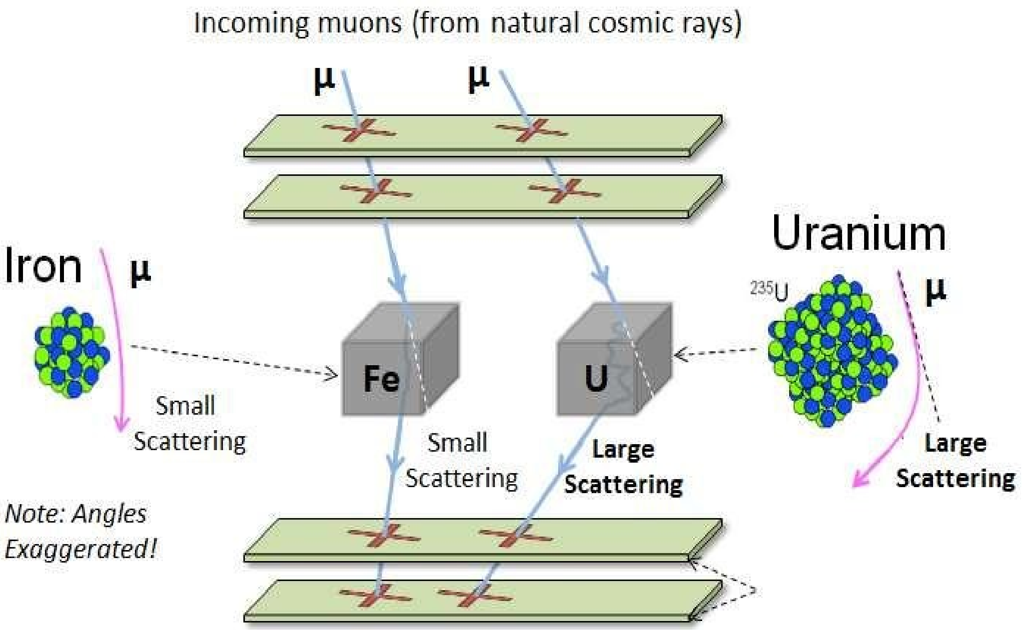
- **Multiple scattering of muons sensitive to atomic number and density**
  → material identification
- **Technical questions:**
  - What is the required inspection time?
  - What is the desired spatial resolution?
  - What do we measure, muons or electrons?
- **A few cargo scanners are operating**

Borozdin, K., et al.: Nature 422, 277 (2003)
https://doi.org/10.1038/422277a

Schultz, L., et al.: NIM A 519, 687 (2004)
https://doi.org/10.1016/j.nima.2003.11.035

Pesente, S., et al.: NIM A 604, 738 (2009)
https://doi.org/10.1016/j.nima.2009.03.017





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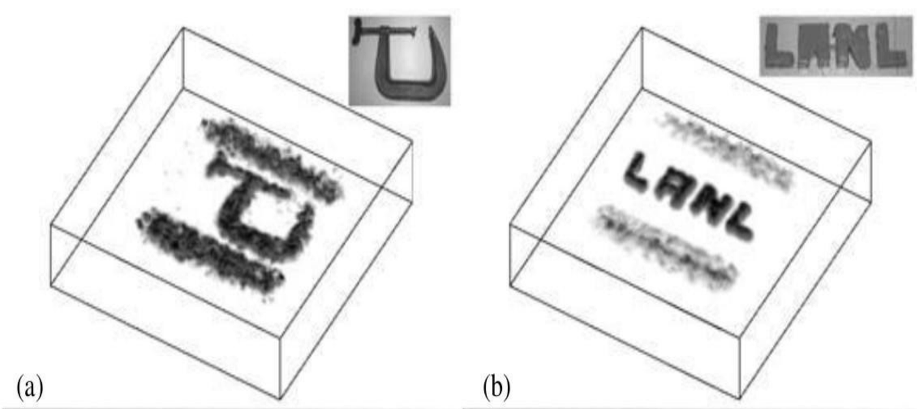
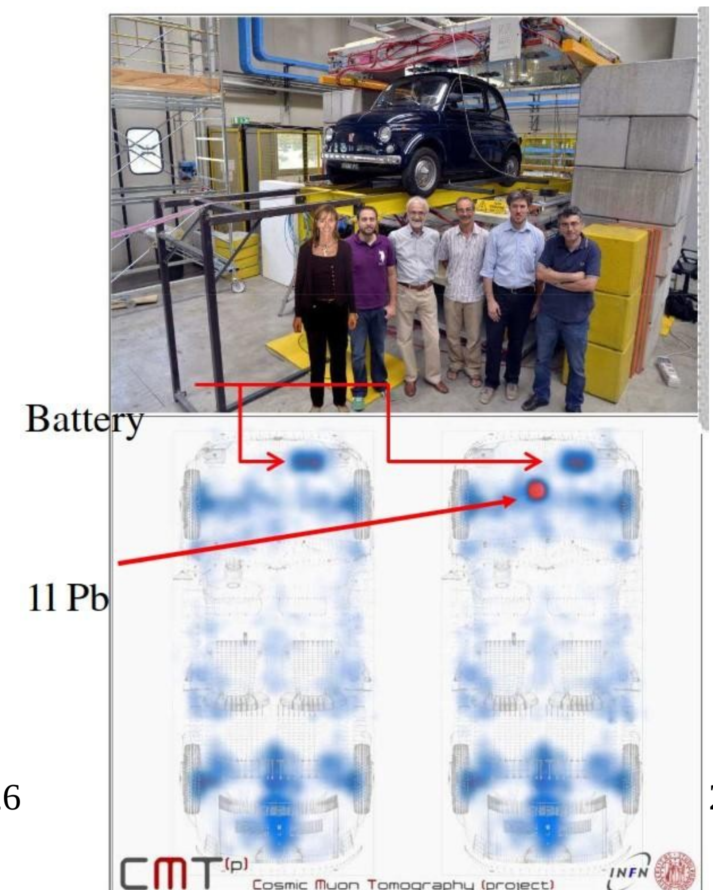
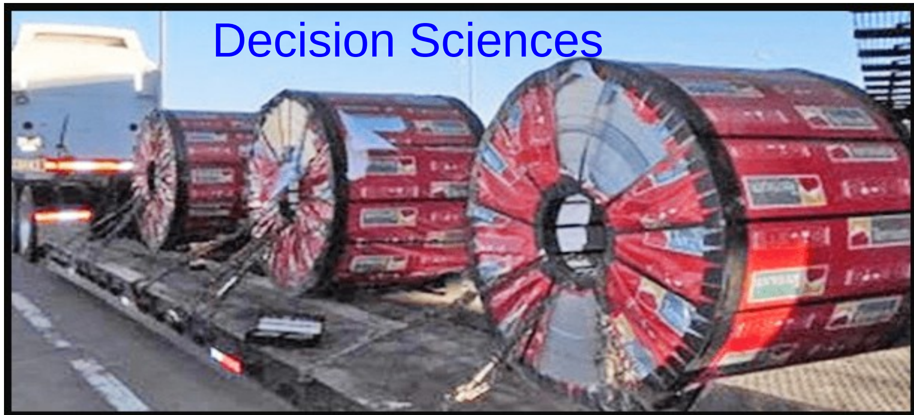
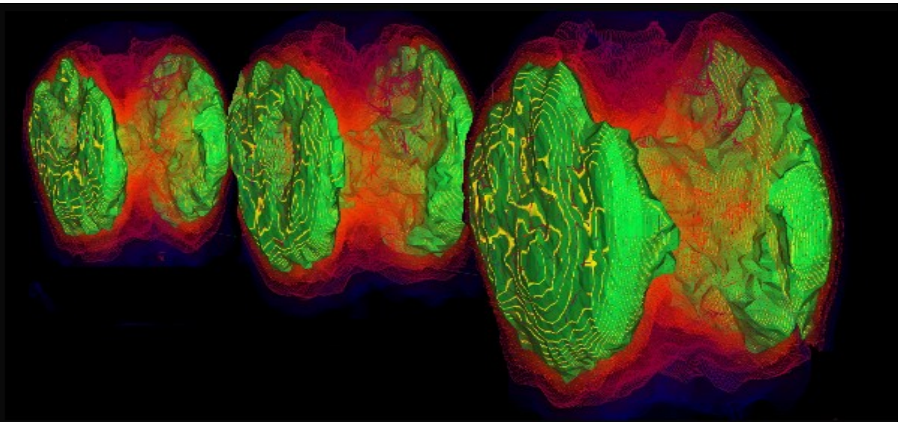


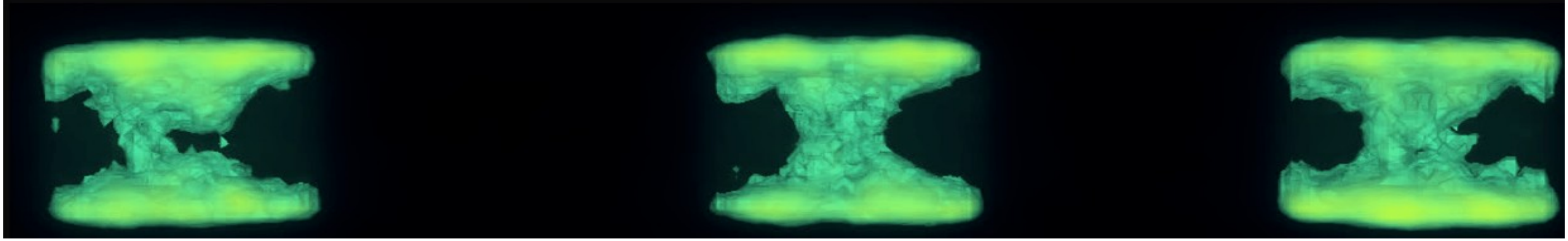


Detection of Smuggled Materials by Decision Sciences

- Muons penetrate all shielding materials used in smuggling.
- 1900 kg of smuggled marijuana with a street value of $20M was detected behind 24 inches of steel by a 4.5 min muon scan
- Explosive precursors were detected in a container among bottled waters and charcoals by a 10 min scan

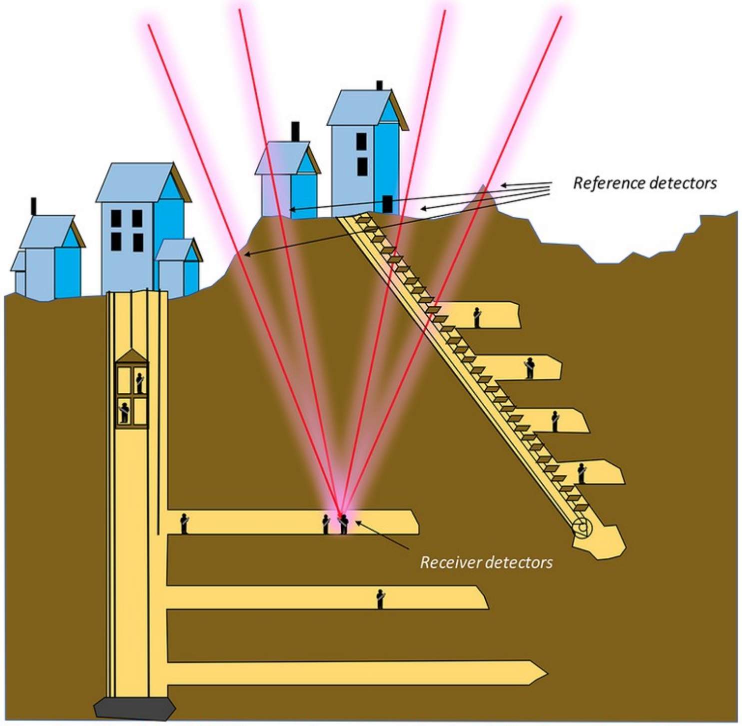






V. Positioning, Navigation, and Timing

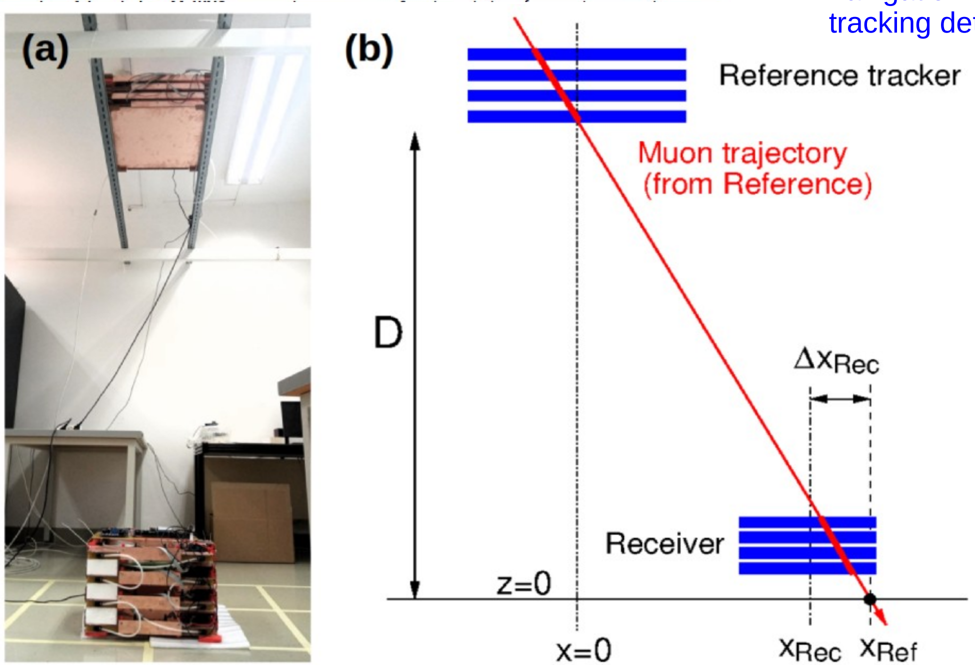
Muon Positioning (muPS) and Navigation

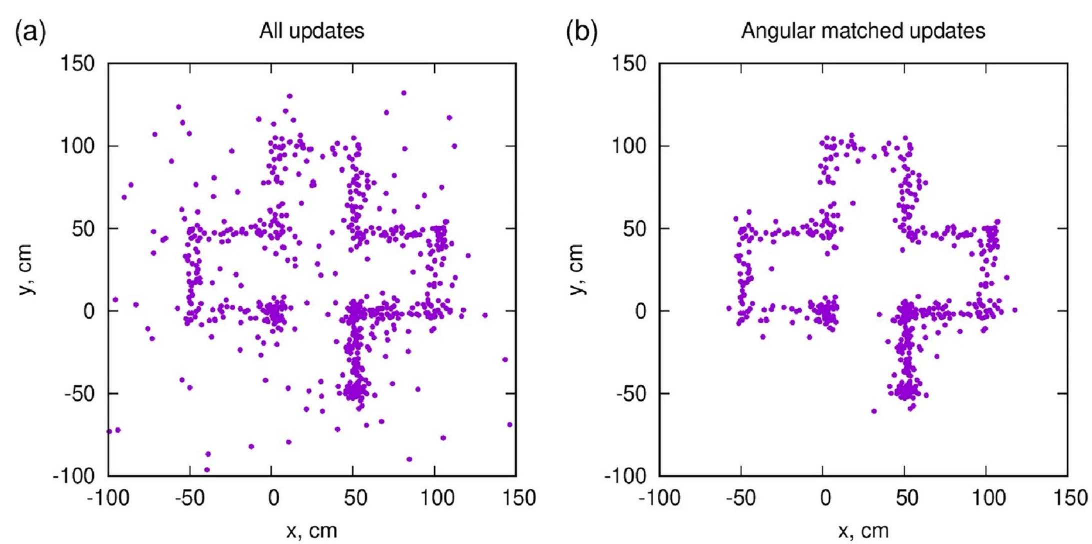


Unlike radio waves, acoustic signals, or laser beams, **muometric positioning accuracy is not influenced by obstacles in its surrounding environment**

Positioning is not required on event-by-event
→ statistics greatly improve accuracy

- Tanaka et al. First navigation with wireless muometric navigation system (MuWNS) in indoor and underground environments. Iscience, 26, 107000 https://doi.org/10.1016/j.isci.2023.107000
- Tanaka, H.K.M. Muometric positioning system (muPS) utilizing direction vectors of cosmic-ray muons for wireless indoor navigation at a centimeter-level accuracy. Sci Rep 13, 15272 (2023). https://doi.org/10.1038/s41598-023-41910-y
- Varga, D., Tanaka, H.K.M. Developments of a centimeter-level precise muometric wireless navigation system (MuWNS-V) and its first demonstration using directional information from tracking detectors. Sci Rep 14, 7605 (2024). https://doi.org/10.1038/s41598-024-57857-7

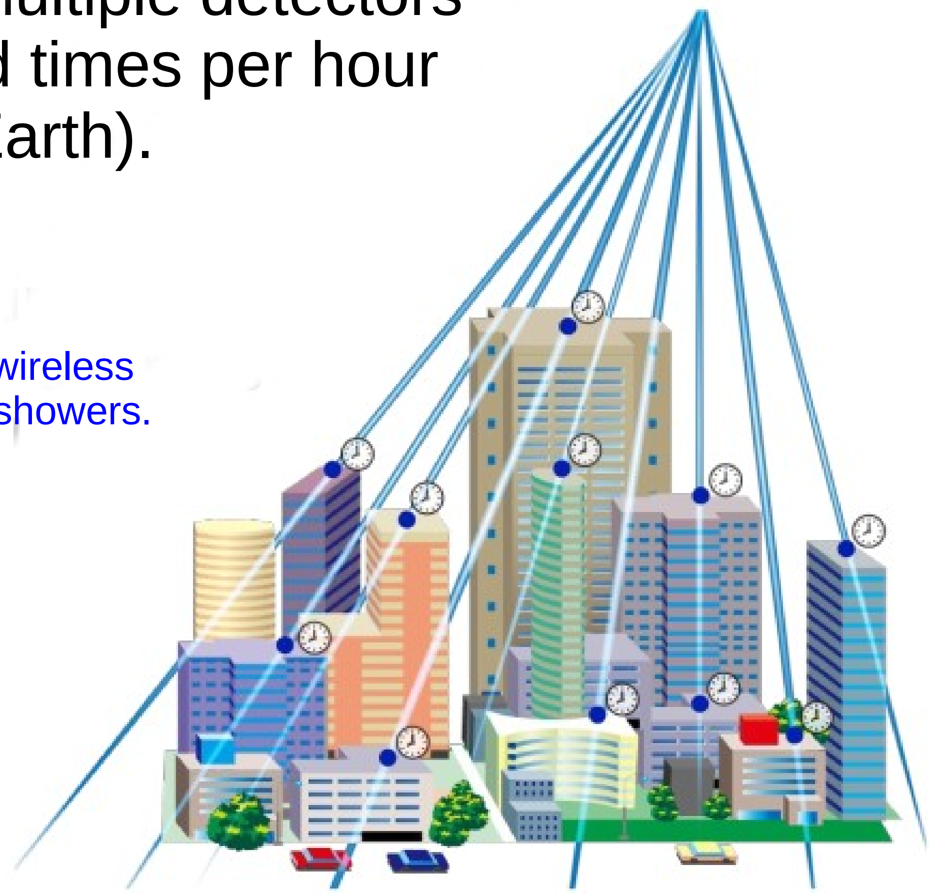




Timing

- Extensive Air Showers (EAS) cover even an area of square kilometres.
- Relativistic particles arrive into multiple detectors simultaneously (about a hundred times per hour over every square kilometer of Earth).
- Time syncronization ~ 100 ns

Tanaka, H.K.M. Cosmic time synchronizer (CTS) for wireless and precise time synchronization using extended air showers. Sci Rep 12, 7078 (2022) https://doi.org/10.1038/s41598-022-11104-z



UTokyo: https://www.u-tokyo.ac.jp/focus/en/press/z0508_00217.html

VI. Summary and Future Perspectives

- Muography is a passive, non-destructive imaging technique capable of scanning large-scale structures.
- Progress in technological development in intersectoral collaborations can contribute to achieve resilient cities (volcano and infrastructure monitoring, muometric positioning) and sustainable resource exploration (underground muography).

Review articles, collections, books:

Tanaka, H.K.M., et al. Nat Rev Methods Primers 3, 88 (2023). https://doi.org/10.1038/s43586-023-00270-7

Lechmann,A., et al. Earth-Science Reviews, 222, 2021, 103842, https://doi.org/10.1016/j.earscirev.2021.103842

Bonomi, G., et al., Prog. Part. Nucl. Phys., 112, 2020, 103768, https://doi.org/10.1016/j.ppnp.2020.103768

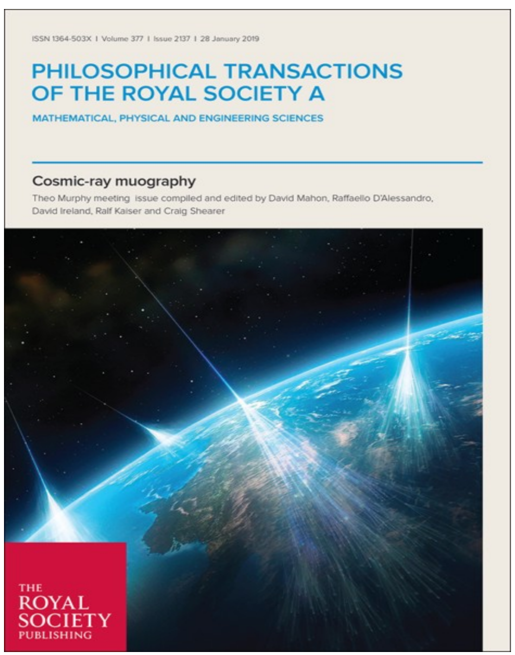
Bonechi, L., et al. Reviews in Physics, 5, 2020, 100038, https://doi.org/10.1016/j.revip.2020.100038

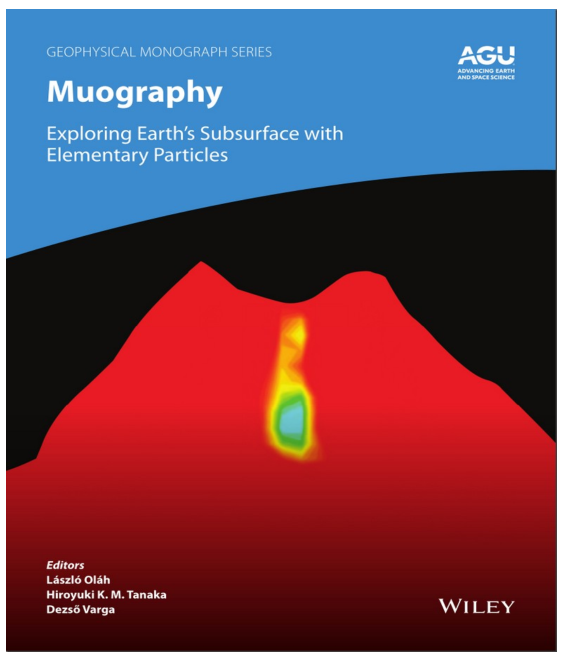
Theo Murphy meeting issue ‘Cosmic-ray muography’: https://royalsocietypublishing.org/rsta/issue/377/2137

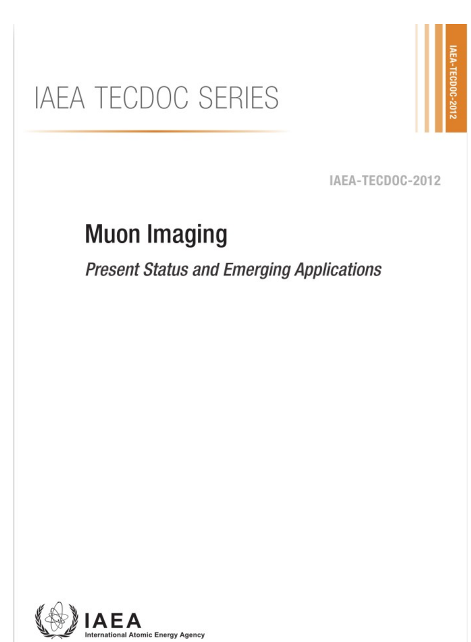
Muography: Exploring Earth's Subsurface with Elementary Particles: https://agupubs.onlinelibrary.wiley.com/doi/book/10.1002/9781119722748

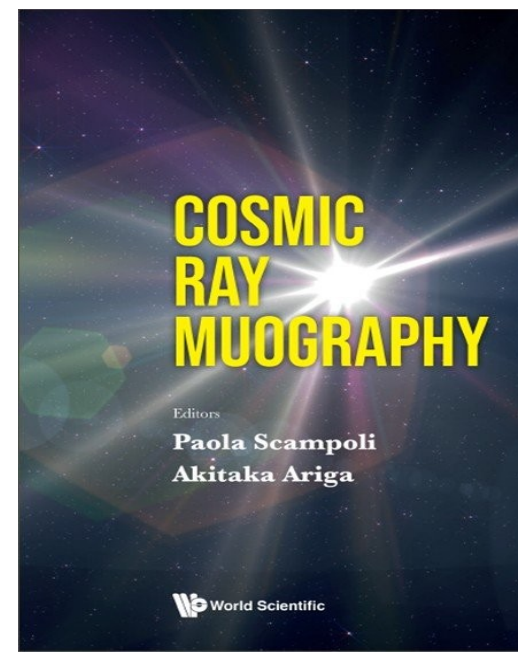
Muon Imaging: https://www.iaea.org/publications/15182/muon-imaging

Cosmic Ray Muography: https://doi.org/10.1142/13102









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Website: https://wigner.hu/s/high-energy-geophysics/

Thank you for your attention!