Magyar Magfizikus Találkozó 2024

Nuclear Safety and Security by Measuring Cosmic Muons

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HUN-REN Magyar Kutatási Hálózat

Wigner

NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION OFFICE HUNGARY

PROJECT FINANCED FROM THE NRDI FUND

Outline

I. Introduction

II. Muon imaging for Nuclear Safety

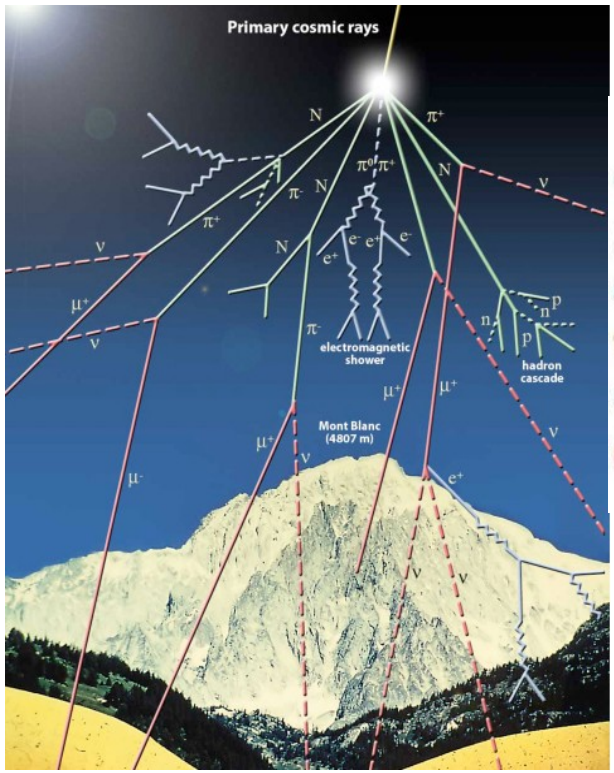
III. Muon Tomography for Security

IV. Recent Developments in HUN-REN Wigner RCP

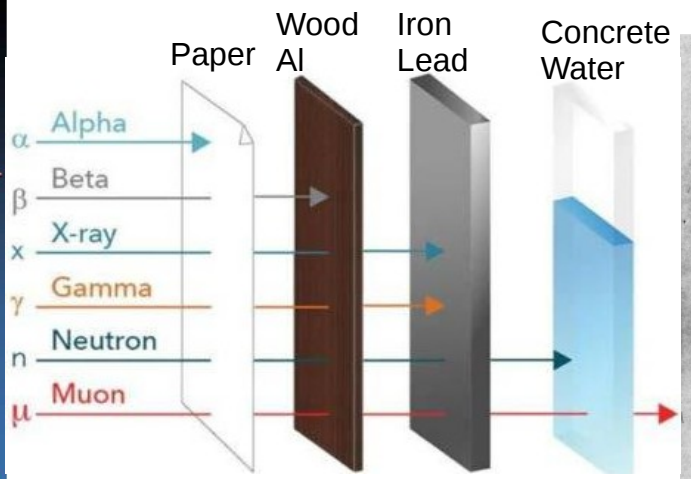
V. Summary and Future Perspectives

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

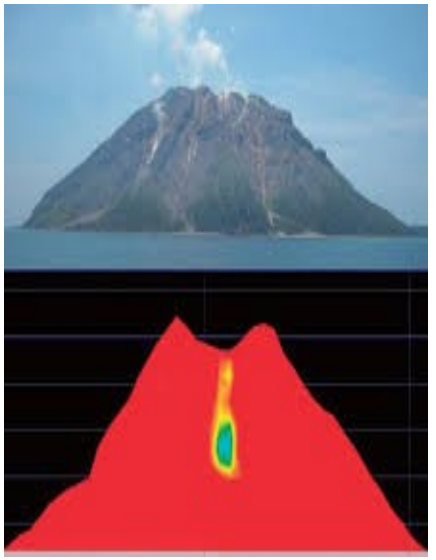


Credit: CERN



Credit: Decision Sciences

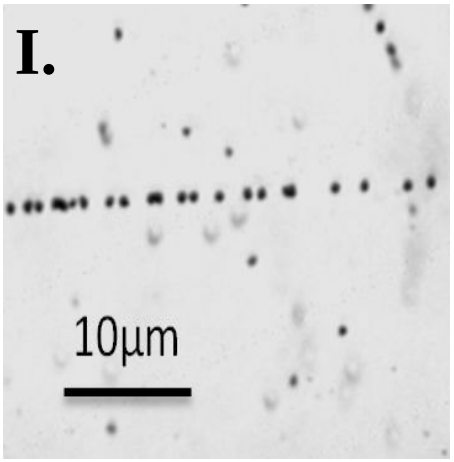
First medical X-ray image by Röntgen (1895)



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

Muon Detector Technologies

I.



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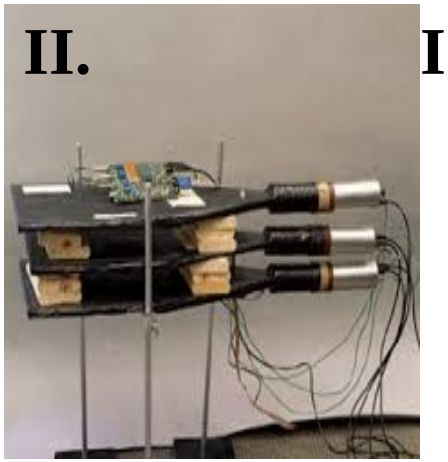
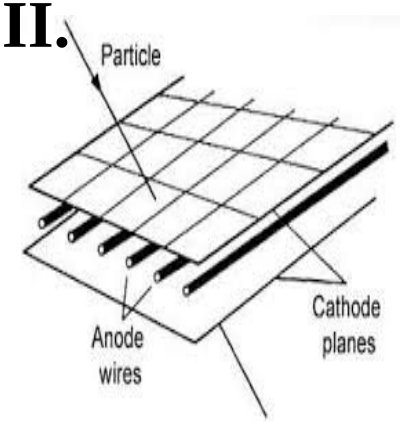


III.



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

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

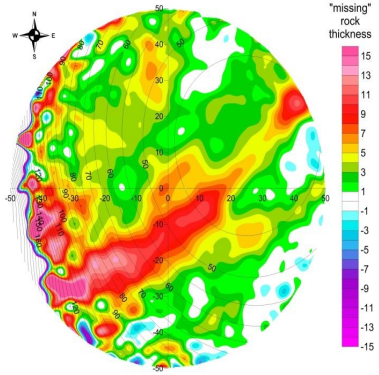
III. **Gaseous detector:** good positional resolution, but needs optimization to environment

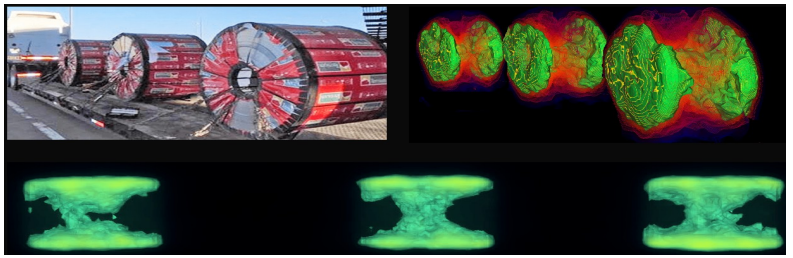
Nagoya University

KEK

HUN-REN Wigner RCP
The University of Tokyo

Muon Imaging Techniques

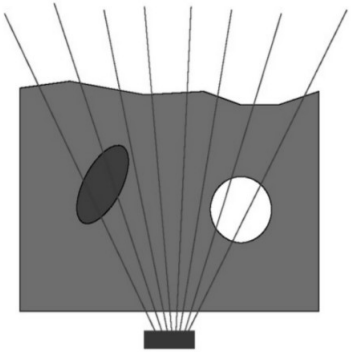


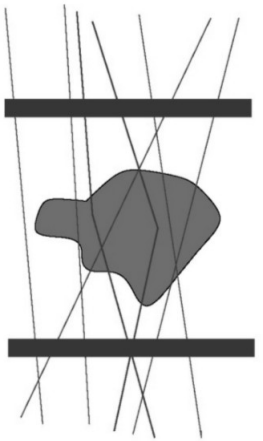


Absorption (reduction of number) **Scattering** (directional change)

Decision Sciences

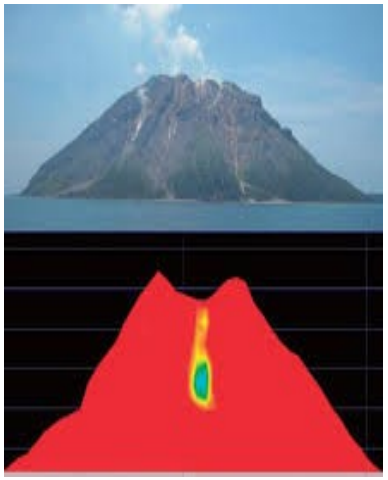
Underground
(high or low density)



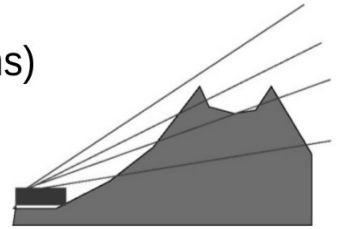


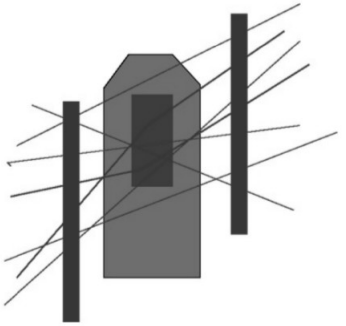
Object inside the detector

HUN-REN Wigner RCP



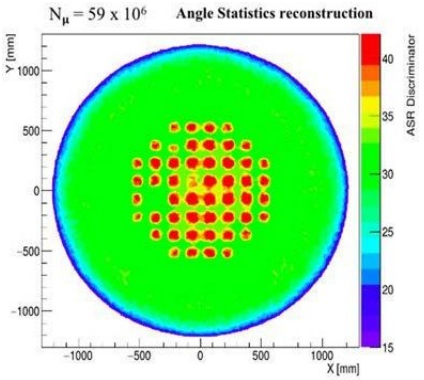
On surface
(low angle muons)





Detector "around" object

Credit: D. Varga



The University of Tokyo

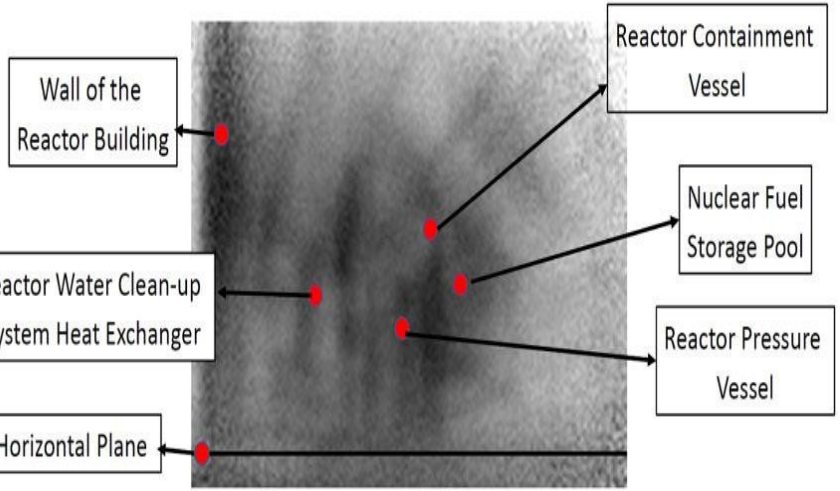
CHANCE Consortium

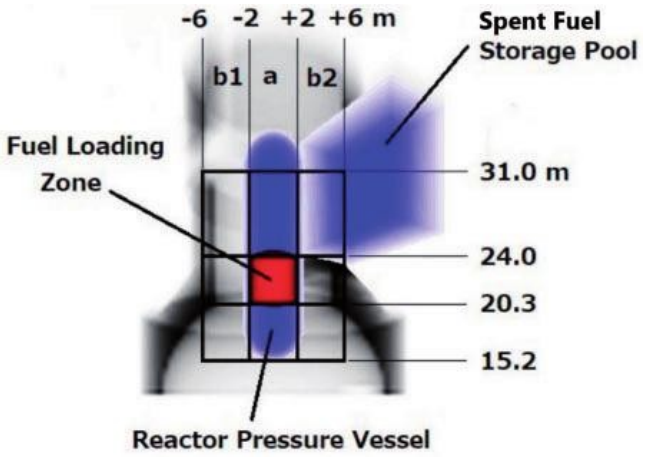
II. Muon Imaging for Nuclear Safety

Inspection of Fukushima Daiichi Unit-1 Reactor

Fujii et al. Prog. Theor. Exp. Phys. 2020, 043C02

- 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**





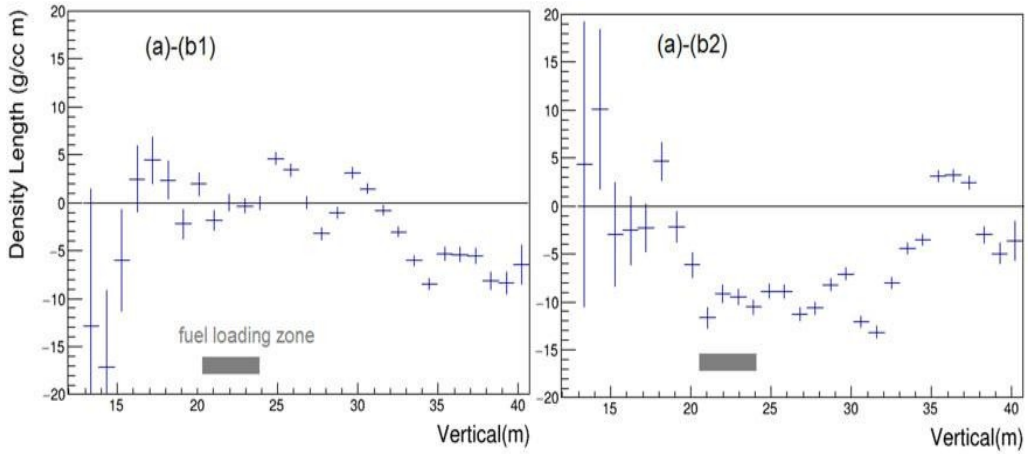


Table 1. Measured amount of material in the RPV for different height regions.

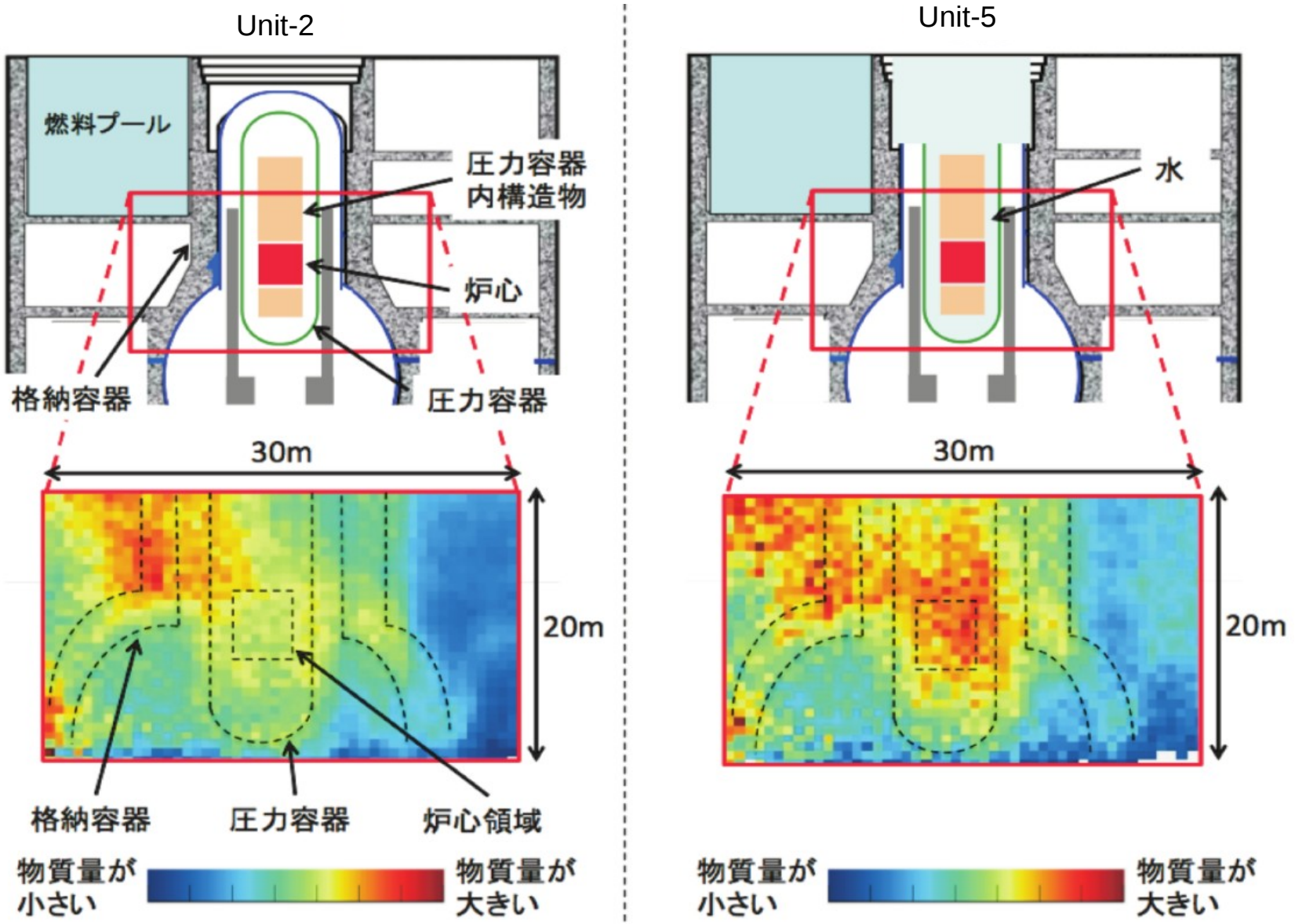
Region	15.2 m < h < 20.3 m (beneath loading zone)	20.3 m < h < 24.0 m (loading zone)	24.0 m < h < 31m (above loading zone)
(a) - (b1)	4±25(stat)±32(syst) tons	1±7(stat)±5(syst) tons	32±6(stat)±11(syst) tons
(a)	33±25(stat)±43(syst) tons	22±7(stat)±22(syst) tons	72*

*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)

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

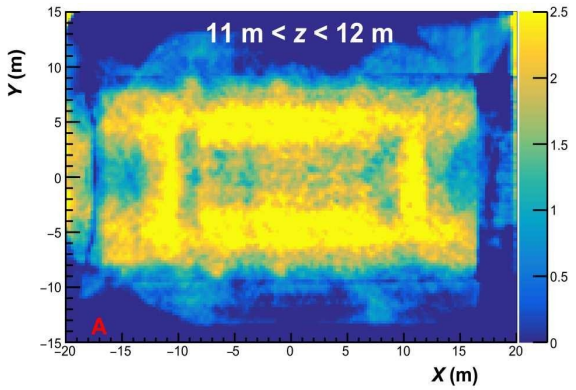
B Lower part of the graphite cube.

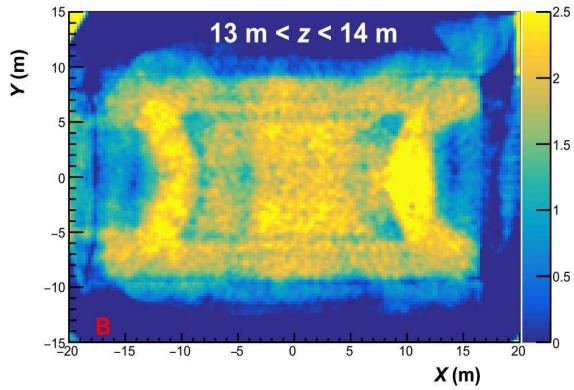
C Plane in intersecting the middle of the cylinder.

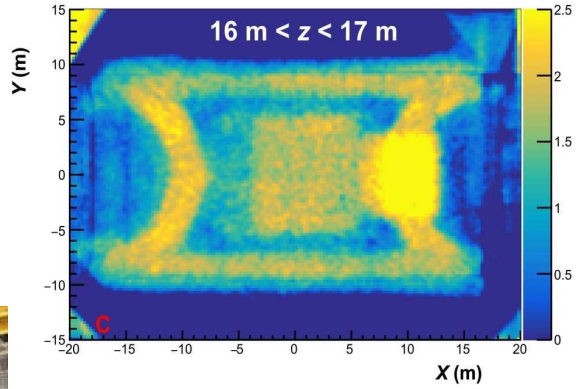
D Close to the top of the graphite structure where its y dimension is smaller

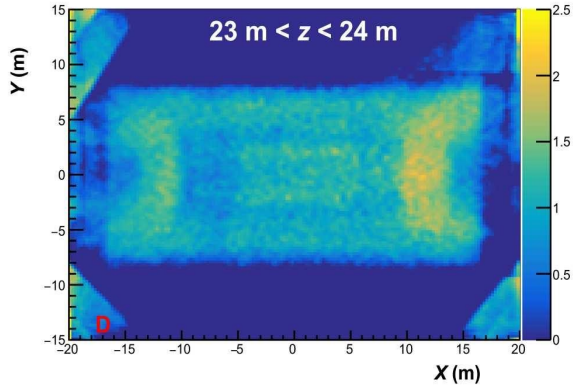
E taken just above the reactor cylinder. The concrete hat is visible.

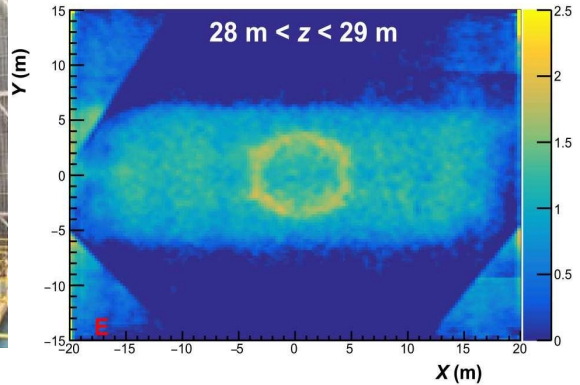
F x-z view of the reconstruction, close to the reactor y center.

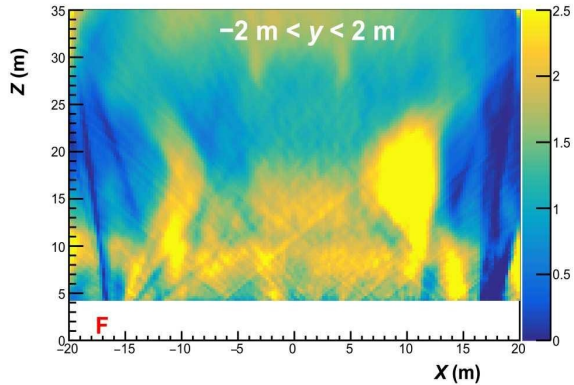








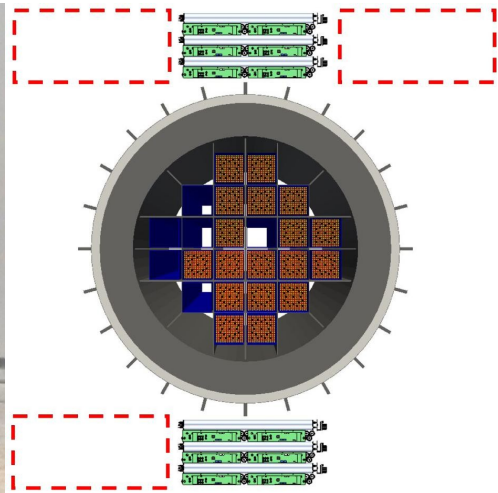


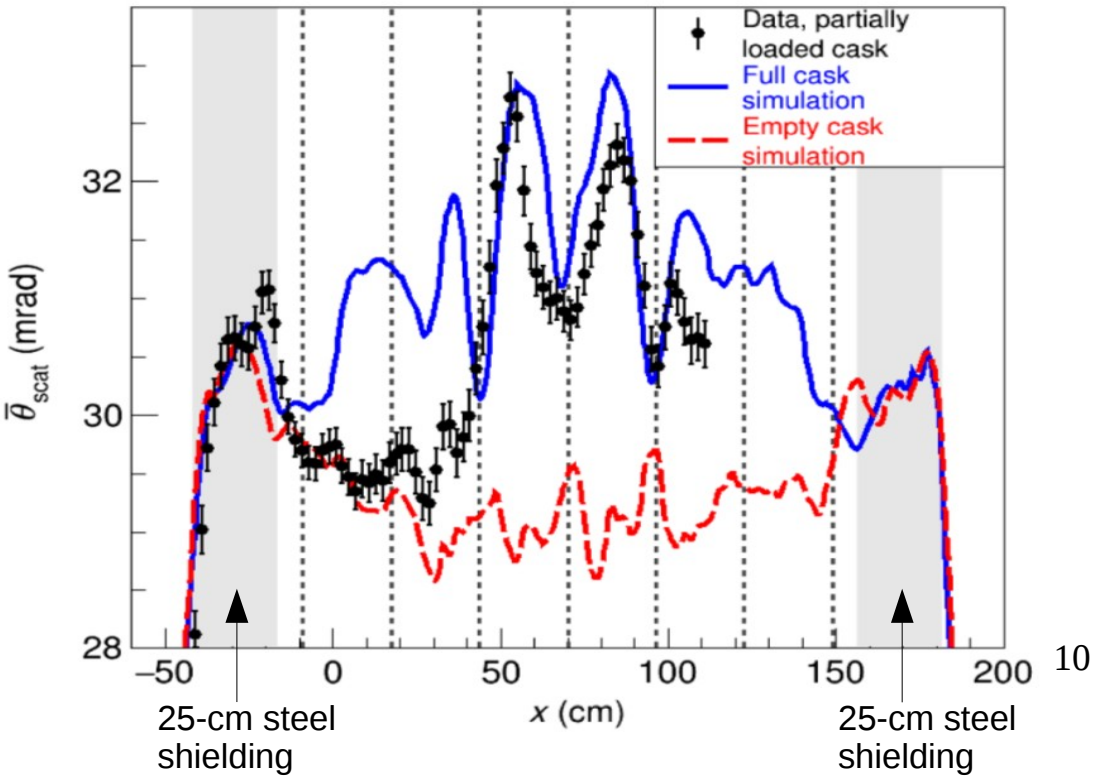


Inspection of Nuclear Fuel Dry Storage Casks

J. M. Durham et al. PHYS. REV. APPLIED 9, 044013 (2018)

- 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.

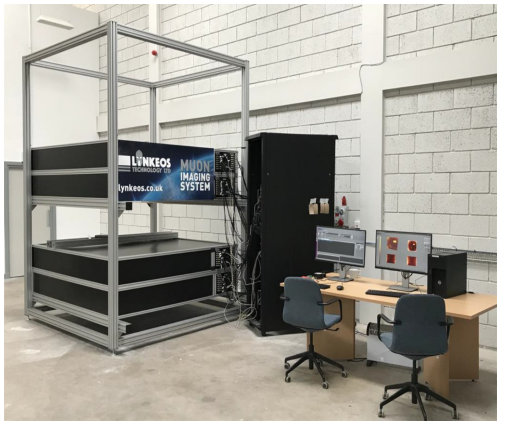


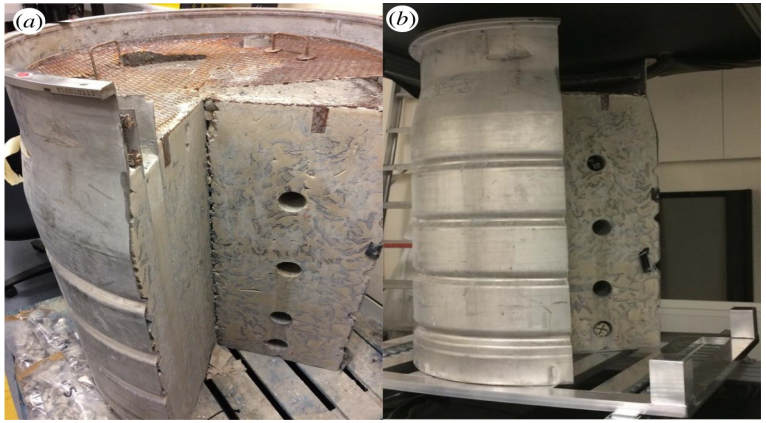


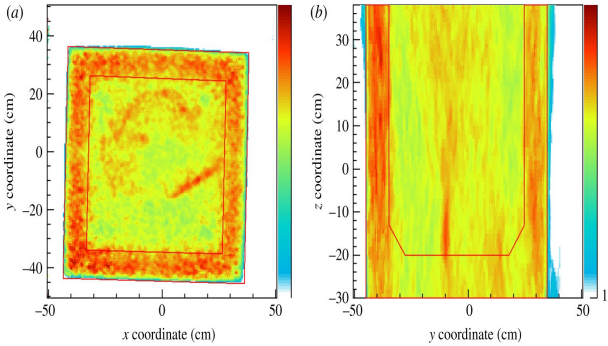
Nuclear Waste Characterization

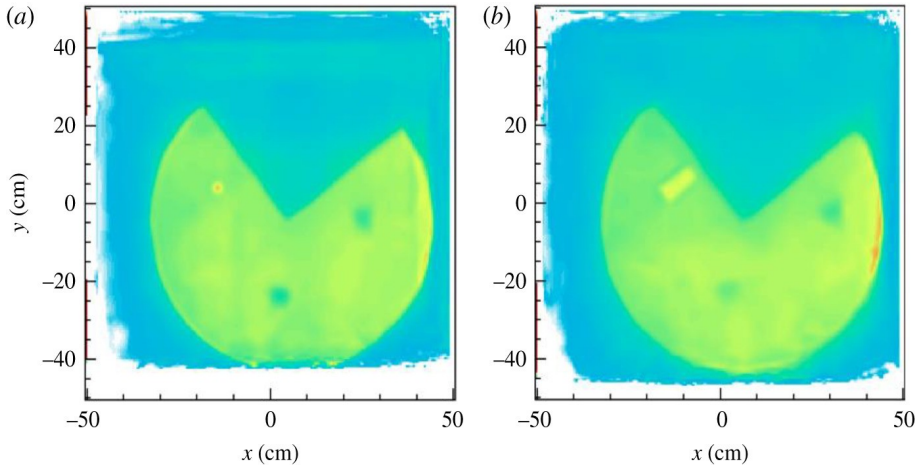
- Nuclear waste containers are typically heavily shielded and highly engineered to contain radioisotopes and attenuate penetrating radiations
- Quality assurrancing by non-destructive testing can reveal the necessity the repacking of waste
- Material discrimination has been conducted in 500 l waste drum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

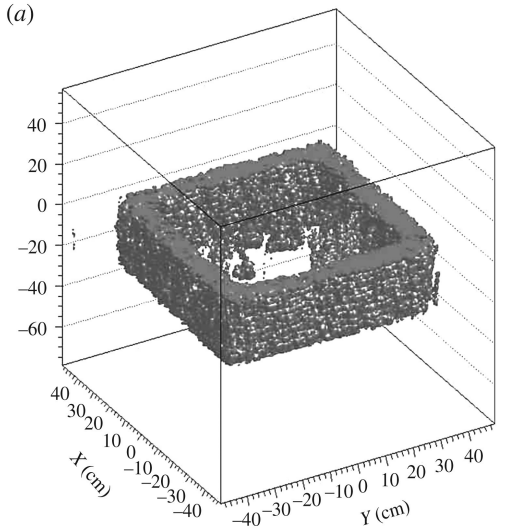
D. Mahon et al. PRSTA, 377, 20180048

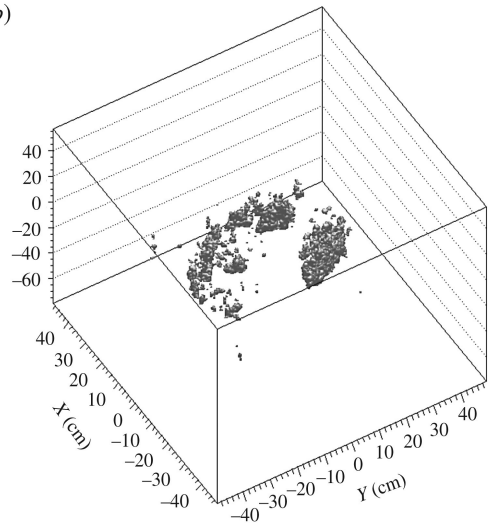










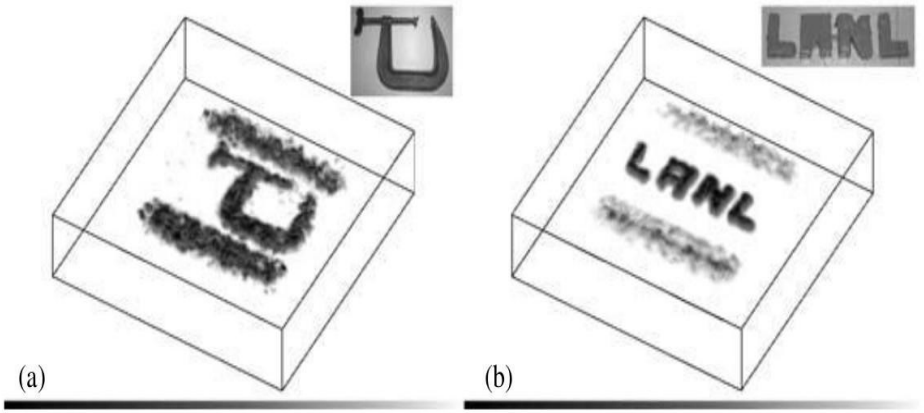


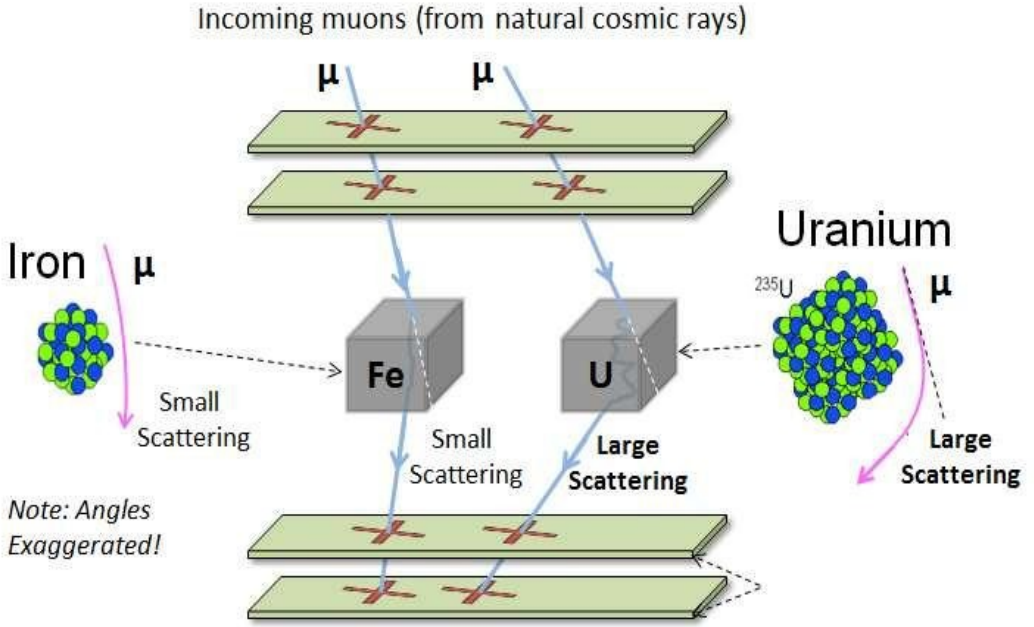
III. Muon Tomography for Security

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**

K. Borozdin et al.: Nature 422, 277 (2003)
L. Schultz et al.: NIM A 519, 687 (2004)
Pesente et al.: NIM A 604, 738 (2009)





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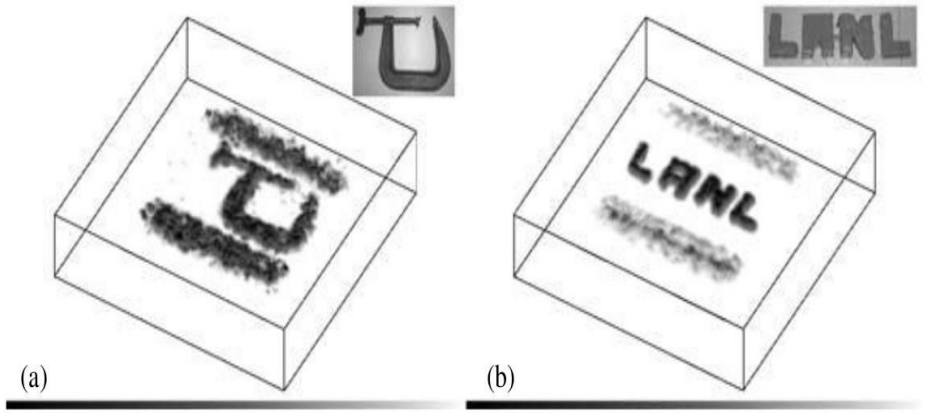
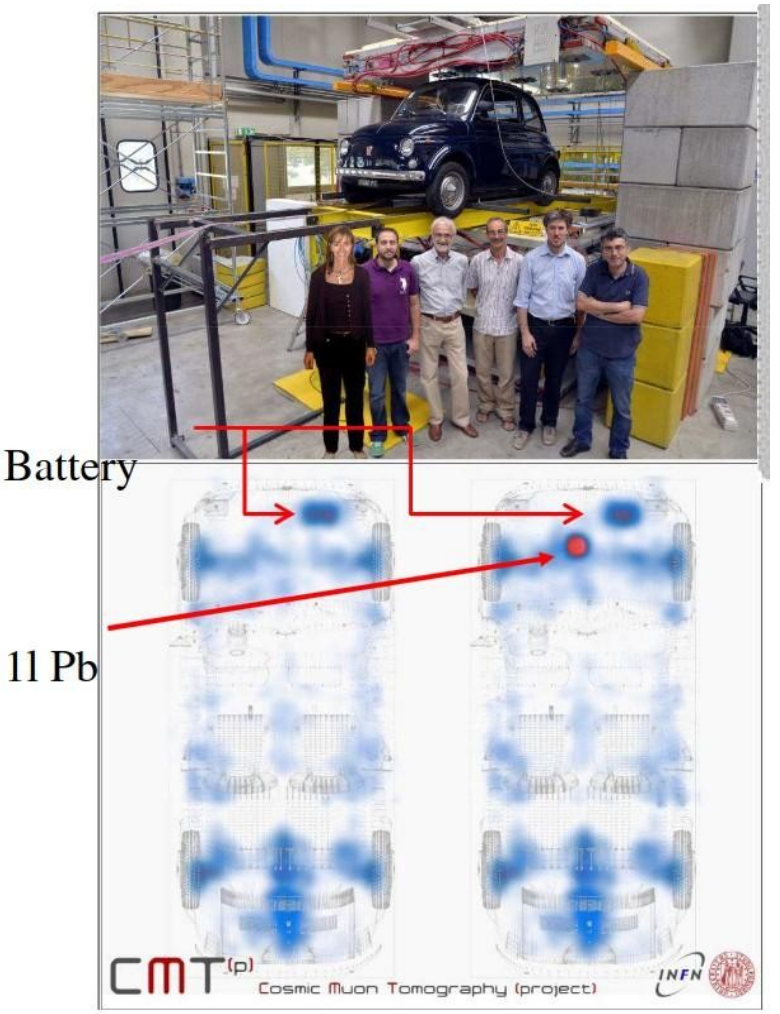
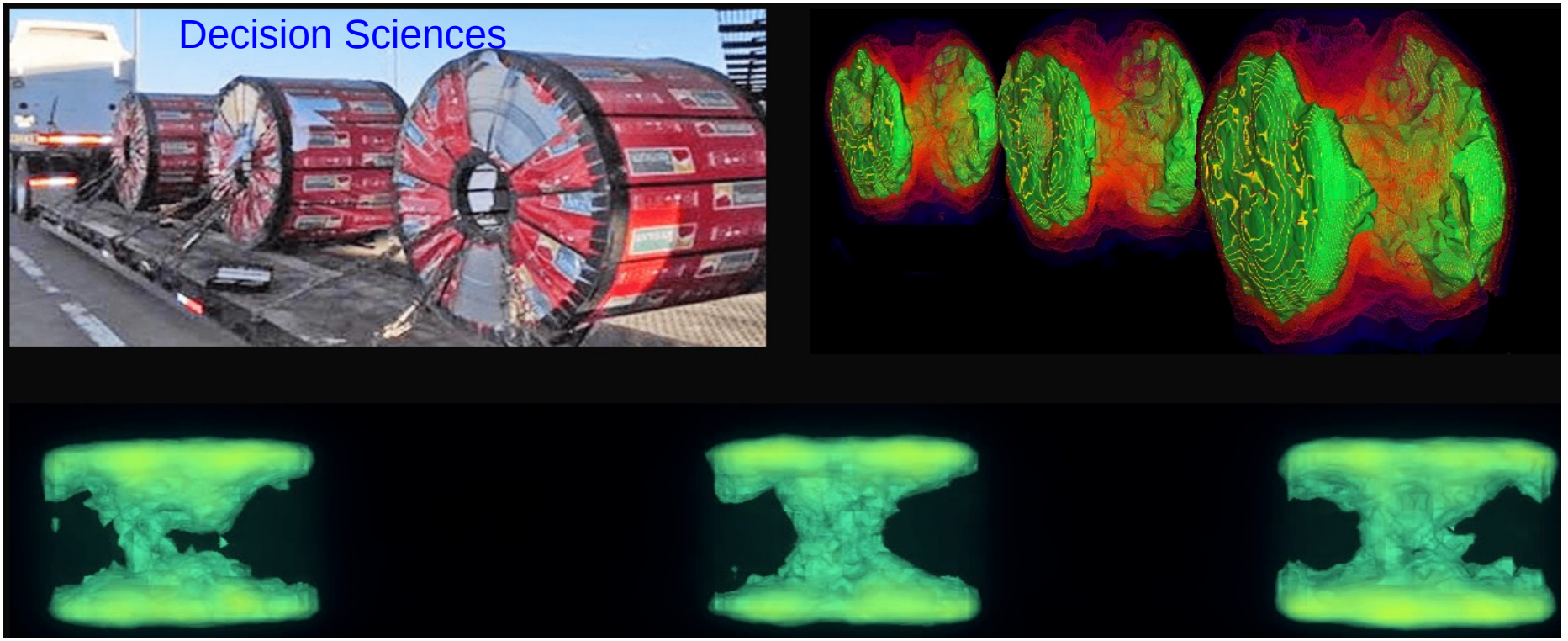




Detection of Smuggled Materials by Decision Sciences

- 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



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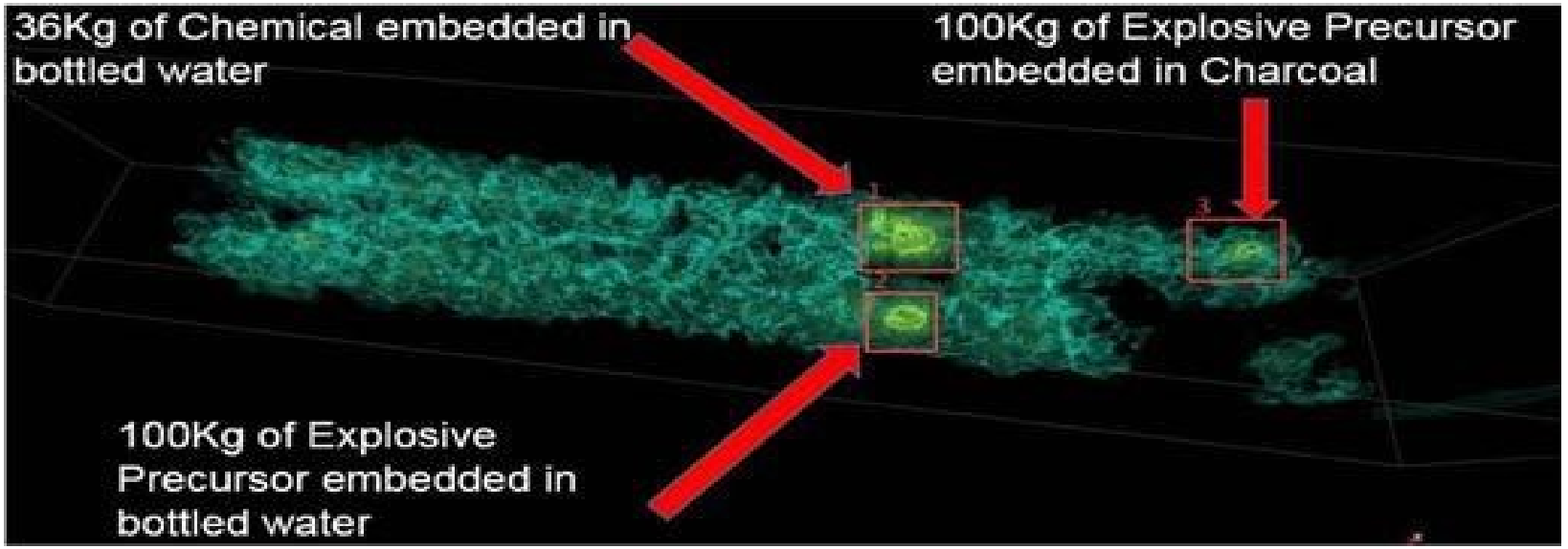
Decision Sciences



IV. Recent Developments in HUN-REN Wigner RCP

Research Infrastructures and Instrumentation for HEP Research and Applications

Vesztergombi High Energy Physics Laboratory (VLAB)
involves clean rooms, construction labs, underground labs, etc.
→ Application oriented R&D of gaseous tracking detectors for HEP Experiments (ALICE, CMS, NA61, etc.) and applications

International Virtual Muography Institute (VMI)

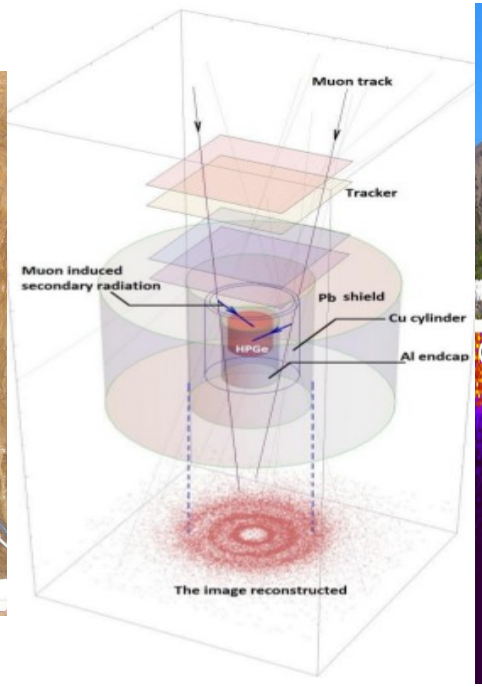
→ Joint laboratories and muography observatories in Japan, Italy, Oman, etc.
→ Common frameworks for data storage, monitoring and simulation

Muography Project Portfolio

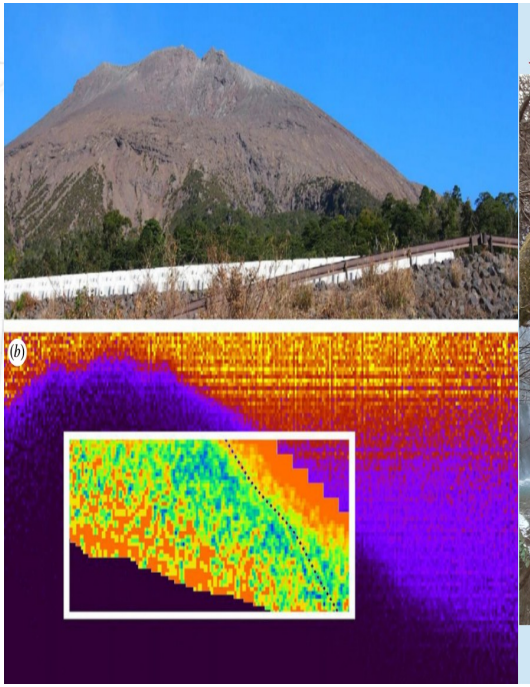
- R&D for Muography has been launched in HUN-REN Wigner RCP 15 years ago
- **Innovative Detector R&D Momentum Research Group** (https://regard.wigner.hu/ 2013-)
- **High-Energy Geophysics Research Group** (https://wigner.hu/s/high-energy-geophysics/ 2024-)
- International and intersectoral collaborations in Europe and Asia

Application oriented R&D of Instrumentation

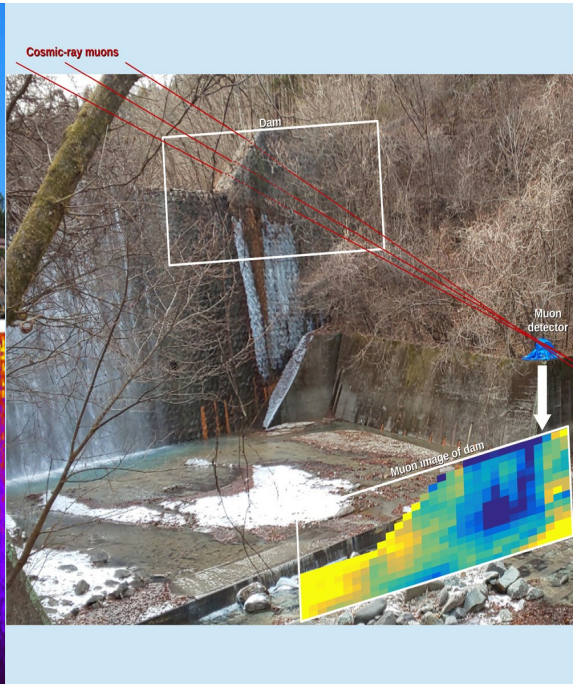
Development of novel imaging techniques



Geophysical Applications: volcanology, geology



Geotechnics and civil engineering



R&D towards Scattering Tomography

- **First small-sized prototype and proof-of-concept with Pb, Fe and Al plates**

  L. Oláh et al. Journal of Physics: Conference Series 632 (2015) 012020

- **Large-sized, robust and high-performance Multi-wire Proportional Chambers**

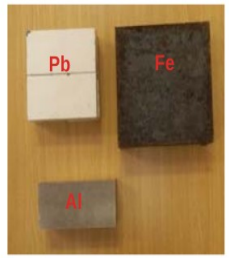
  D. Varga et al. AHEP, 2016, 1962317

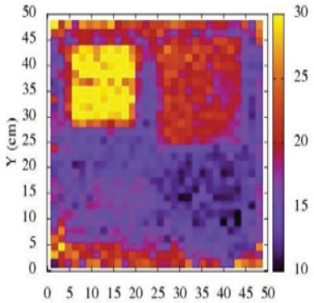
  Muograpic Observation Instrument WO2017187308

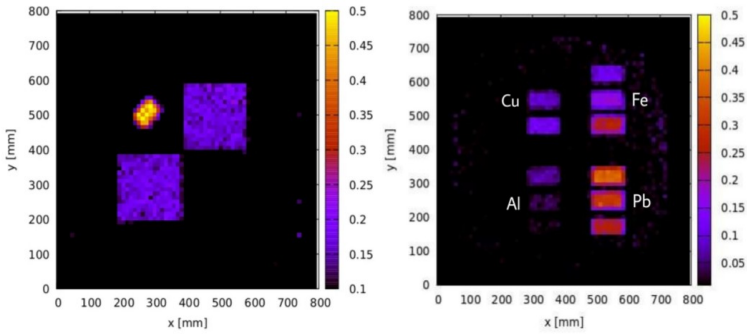
  https://patentscope2.wipo.int/search/en/detail.jsf?docId=WO2017187308

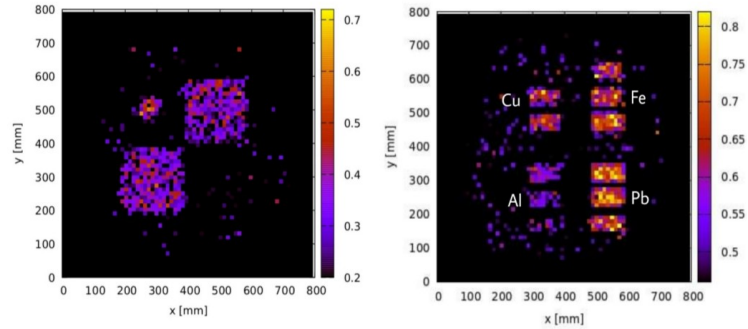
- **Experimental Momentum Binning**

  B. Csatlós et al. JAIS-496, 2024









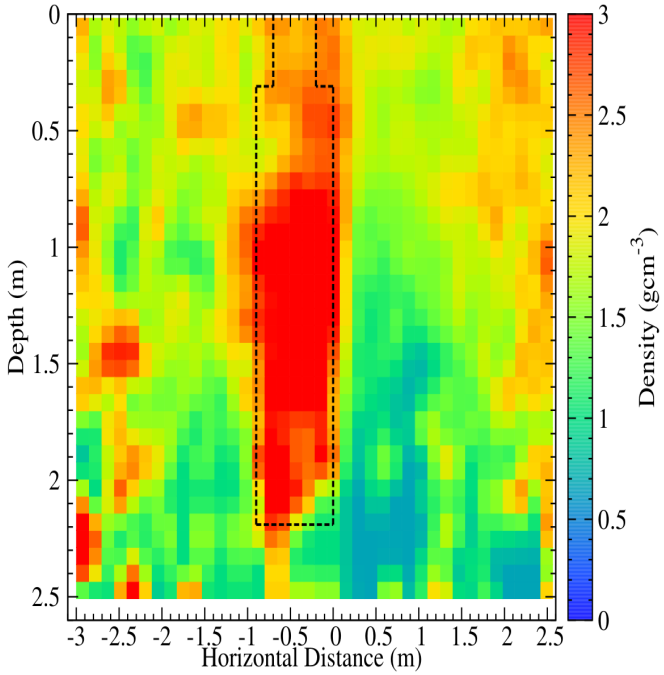
Structural Health Monitoring (SHM)

Inspecting a **buried reinforced concrete railway pillar**
by NEC, UTokyo and Wigner RCP

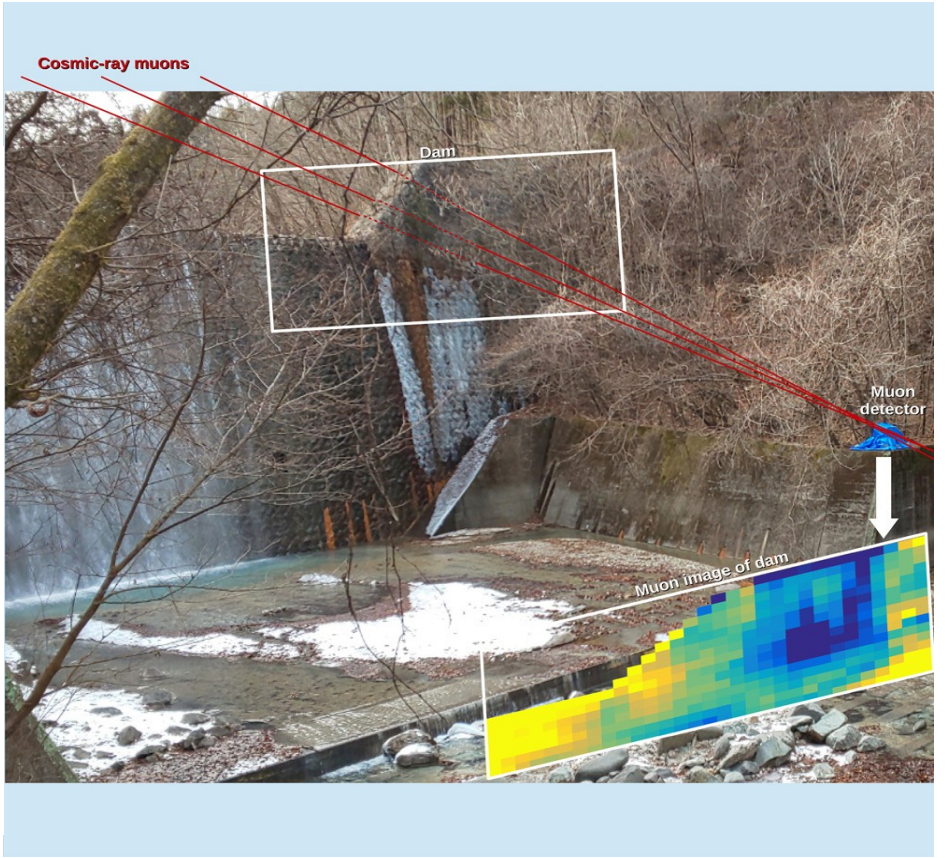
Imaging the internal structure of a **rock-filled sabo check dam**
by Sabo FF, Utokyo and Wigner RCP

L. Oláh et al.: Geophysical Exploration 71, 161-168

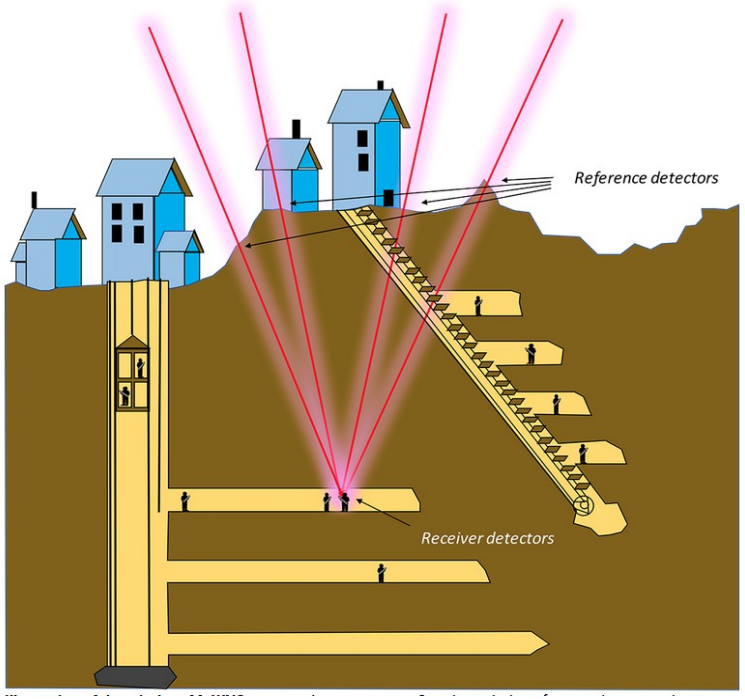
Undeground state observation device JP2020085732A
https://patents.google.com/patent/JP7269595B2/en



L. Oláh et al. (2023) iScience 26, 108019



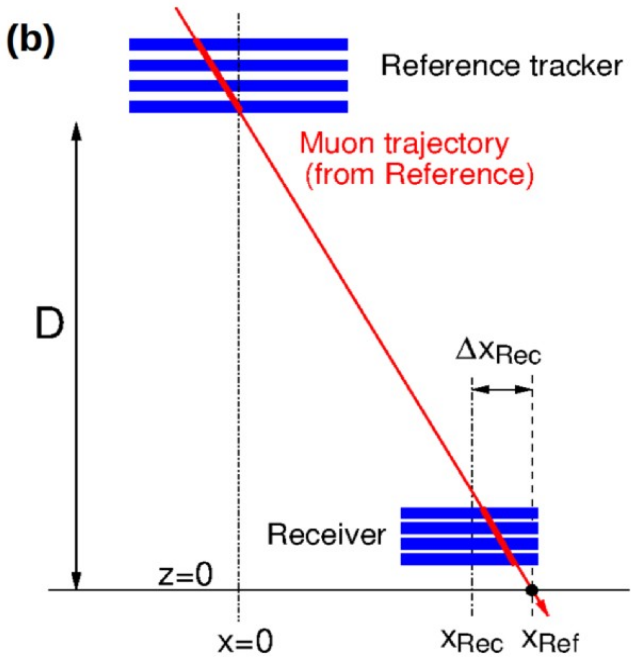
Navigating With Muometric Positioning

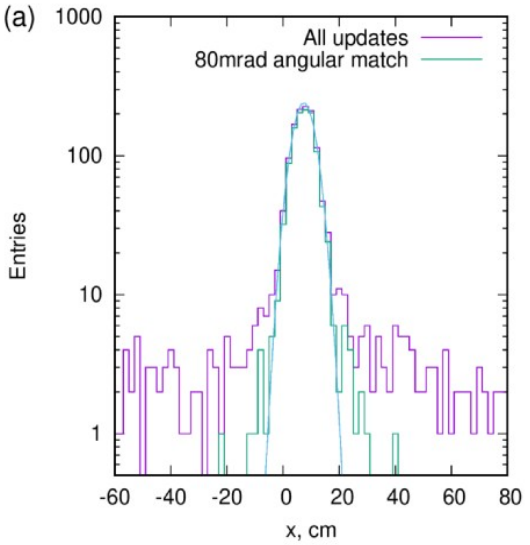


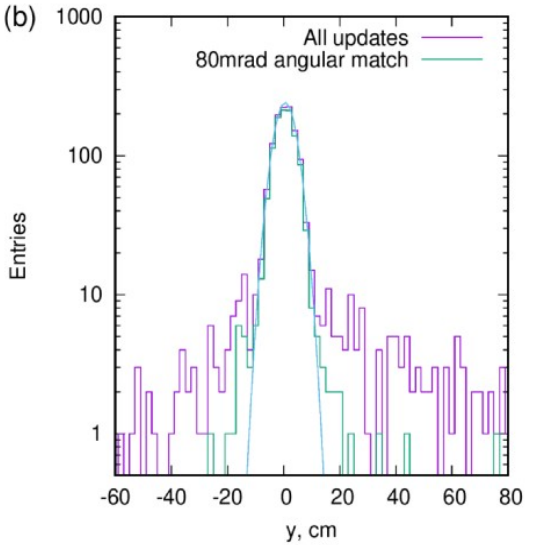
Navigation with muons in underground, underwater environments, such as under damaged nuclear reactors.

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

- 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
- Submitted patent by Tanaka, Varga et al.







V. Summary and Future Perspectives

- Muon imaging, based on either transmission or scattering, allows non-destructive, remote and passive inspection of large-sized structures.
- Progress in muon imaging in intersectoral collaborations can contribute to **nuclear safety** (fuel cask and nuclear waste monitoring), **disaster mitigation** (reactor imaging, navigation of robots in damaged plants) **and security** (detecting smuggled nuclear materials).

Supporters:

- **Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT) Integrated Program for the Next Generation Volcano Research** https://kazan-pj.bosai.go.jp/next-generation-volcano-pj-2019-jun
- **Joint Usage Research Project (JURP) from the ERI, University of Tokyo** https://www.eri.u-tokyo.ac.jp/en/joint-usage-top/
- **"INTENSE" H2020 MSCA RISE, GA No. 822185 in Horizon 2020 from European Comission** https://cordis.europa.eu/project/id/822185
- **TKP2021-NKTA-10 , OTKA Grant FK-135349 and other grants for instrument development from National Research, Development and Innovation Office, Hungary** https://nkfih.gov.hu/english-nkfih
- **HUN-REN Welcome Home and Foreign Researcher Recruitment Programme KSZF-144/2023**

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Thank you for your attention!