20th WCNDT 20th World Conference on Non-Destructive Testing
Songdo Convensia, Incheon, Korea, 27-31 May 2024

Muography: imaging large objects using cosmic particles

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Abstract: Naturally occuring cosmic particles, mostly muons, reach the Earth surface continuously and
nearly uniformly, and due to their high energy can cross as much as 10-1000m of rock. Since muons propagate along straight lines, one can use these particles for imaging the internal density structure of large objects.
More than five decades ago, this method has been used to search for hidden chambers in a pyramid, and subsequently to study various challenging structures: mines, caves, volcanoes, nuclear reactors. Since the turn of the last century, there has been a rapid increase of interest towards muon imaging – with a new research field, called "Muography" emerging – and the application possibilities broadened along with drastic reduction of instrumentation cost, at improved detection efficiency, portability and imaging resolution.
The talk will introduce the basic physics behind muography, present the possible detection methods, and give an overview how muographic measurements can take place. Muons can either be absorbed, or scattered (slight deviation from a straight line), and both effects can be used for imaging purposes.
The most relevant application possibilities include mining, archeology, volcanology, nuclear industry and border control. Recent investigations revealed voids inside the Great Pyramid of Giza, which remained hidden for millennia. Measurements related to volcanology span three continents, and revealed magma movement, erosion effects and hydrothermal activity, as well as internal (static) structures. Mining applications allow cost reduction (less drilling) and improved operational safety, thus contributing to a sustainable future. Muography allows one to check for high atomic number materials in a short time in large volumes, which is particularly
useful for border control and nuclear waste verification. Muography is not only becoming a consistent research field, but there is an international community which facilitates information exchange, critical assessment of the quality of new results, and promotes technology transfer towards an increasing number of industrial partners.

Muography: imaging large objects using cosmic particles

Dezső Varga
HUN-REN Wigner Research Centre for Physics

WCNDT24 Seoul, 29th May 2024

REGARD
RMKI ELTE Collaboration on Gaseous Detector Research and Development

MŰEGYETEM 1782

All colors of Physics

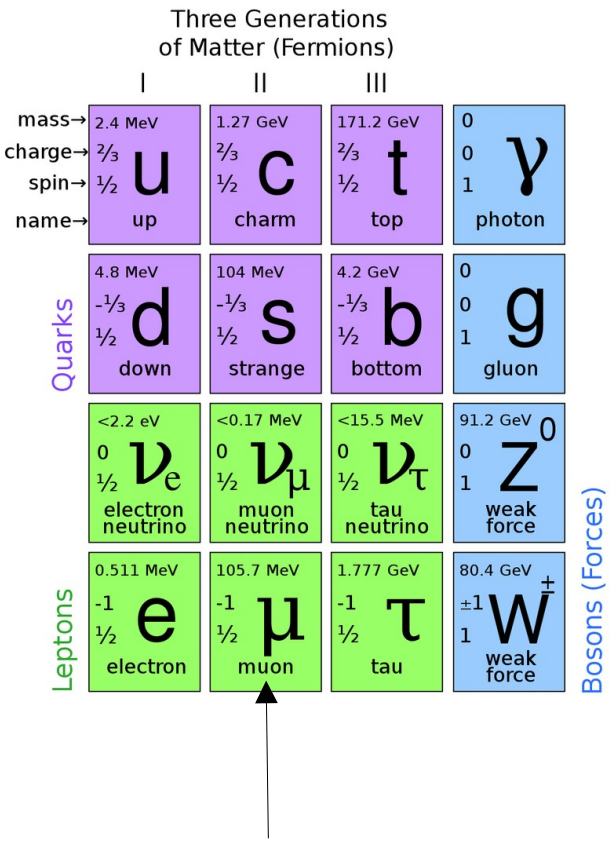
NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION OFFICE HUNGARY
PROJECT FINANCED FROM THE NRDI FUND

Overview

- Muons in science, cosmic muon origins
- Muography: cosmic ray imaging principles
- Community of a new research field: “Muographers”

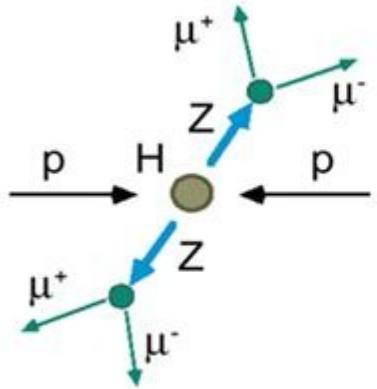
- Earth sciences
- Social sciences: archeology
- Industrial and engineering applications
- Navigation
- Time metrology, information technology

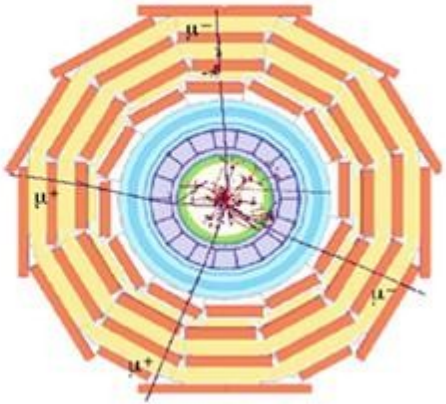
Muon: a fundamental particle in the Standard Model



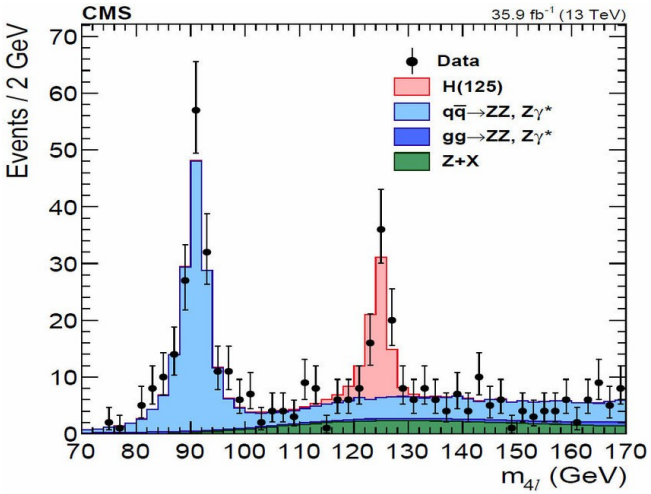
Electron's bigger brother: much less interactions

Decays in 2 microseconds, very characteristic signal in detectors





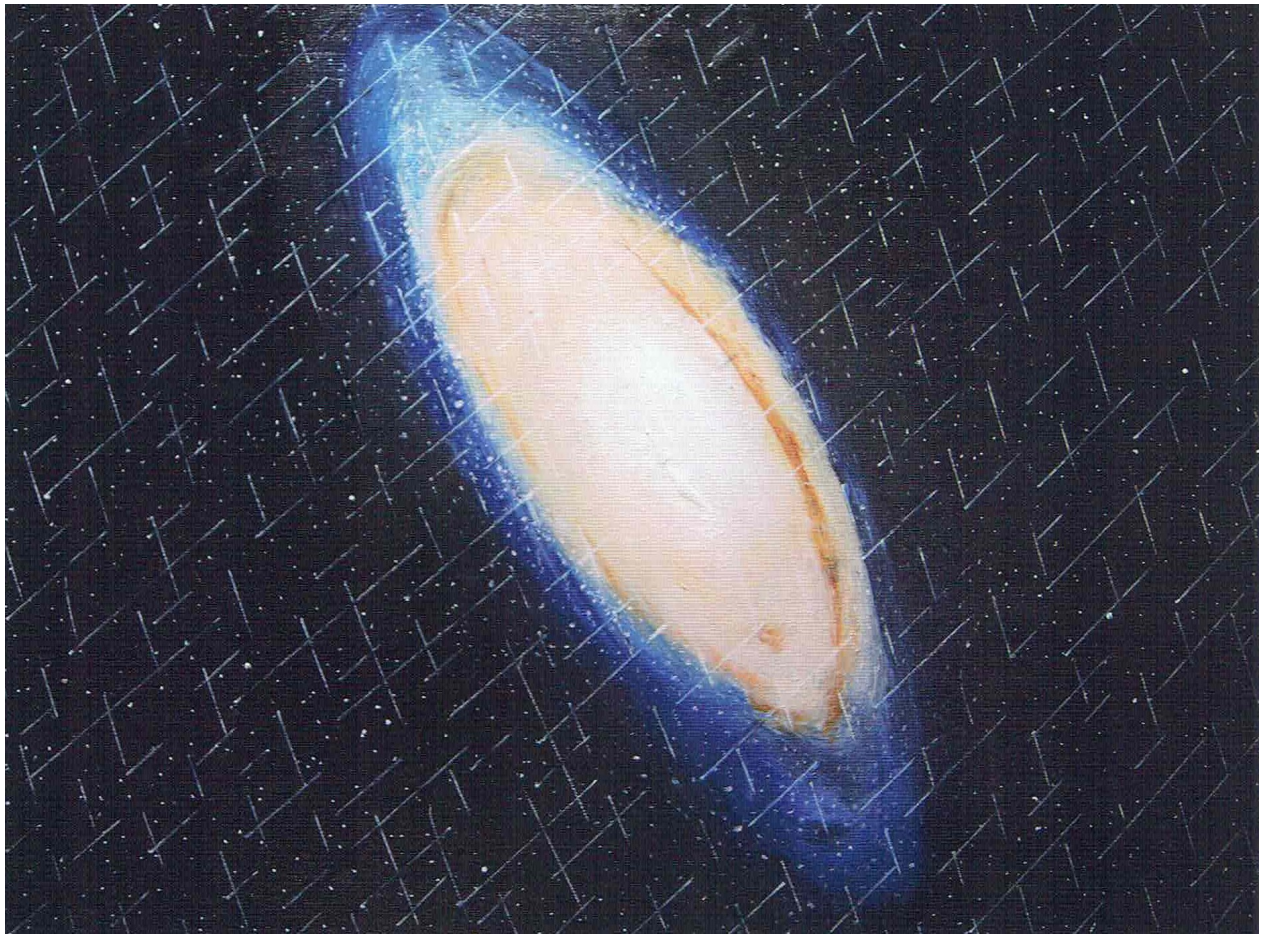
Higgs particle discovery (CERN, 2012)



“Generations” of muography

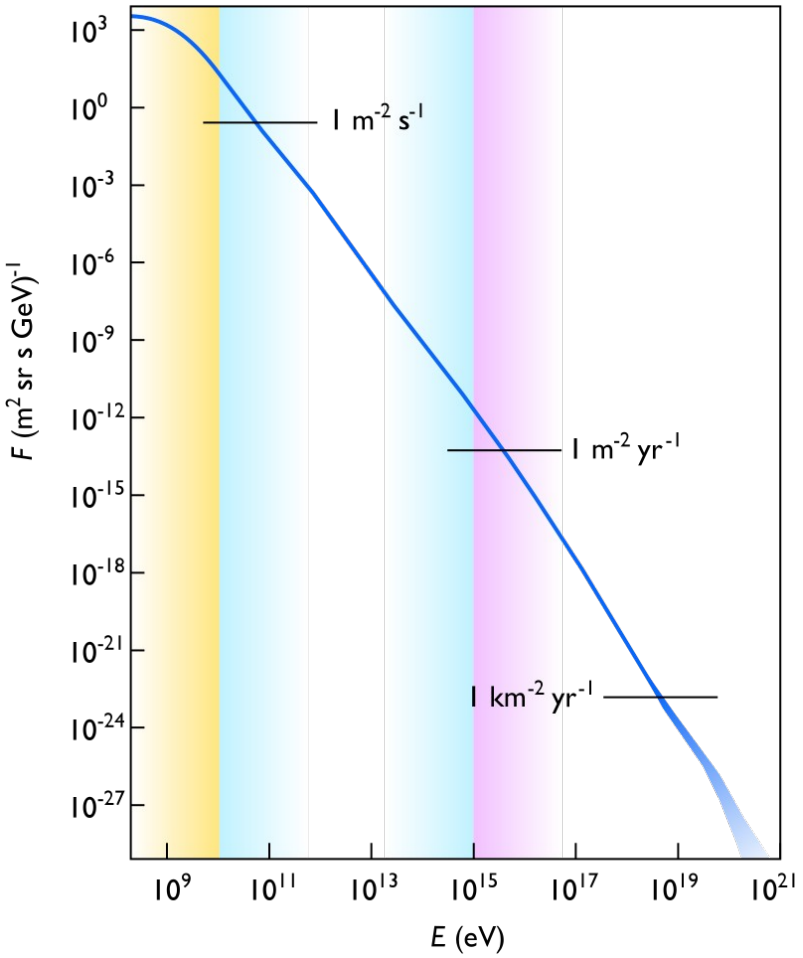
- 1st Generation: **Discovery** and first usage of cosmic rays (Hess 1911 Anderson 1937, George 1955)
- 2nd Generation: Demonstration of the **principles** of underground imaging, expanding possibilities 70s - 90s
- 3rd Generation: **Breakthroughs** in the 2000s. Visualizing magma conduit (2007) and magma movements (2014). From 2D imaging to 3D imaging: scattering tomography (2003) and absorption tomography (2010)
- 4th Generation: **Beyond imaging**: navigation, timing, wireless security… For muography, expanding commercialization and definition of the research field

Cosmic muon origins



Kanji Hatamori: The Universe and Muons

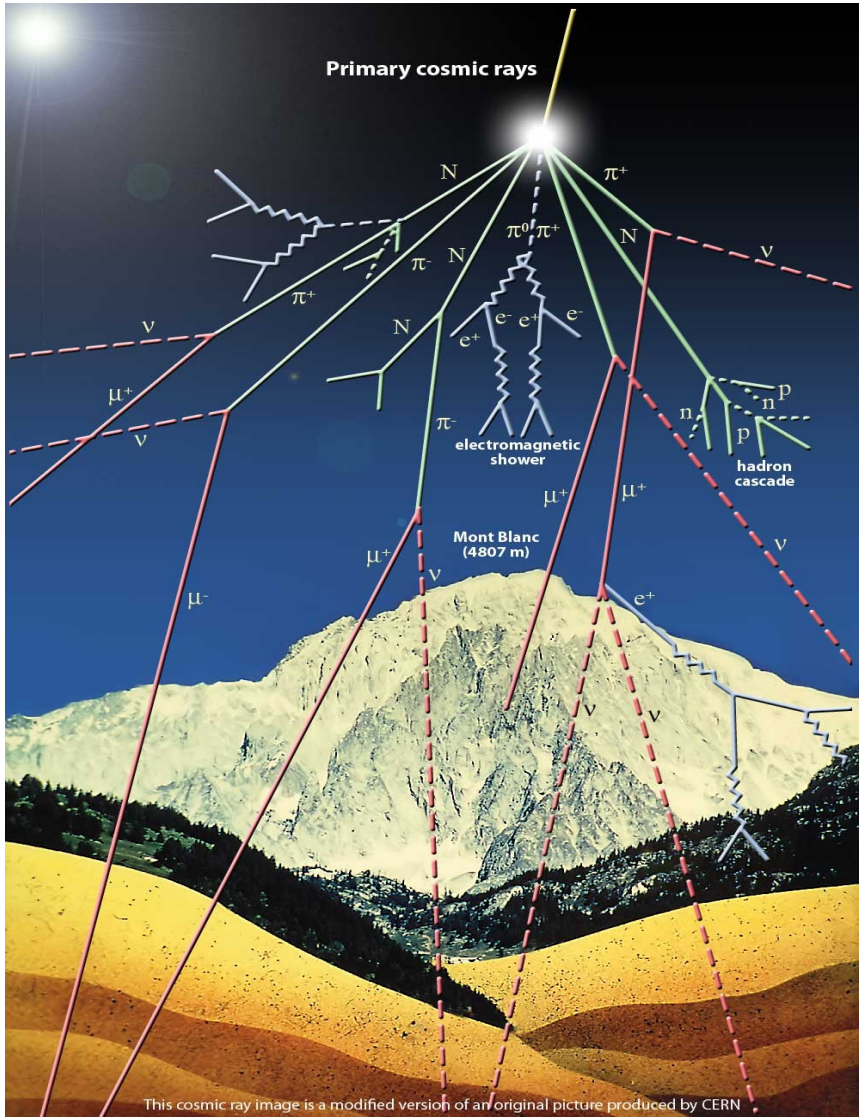
Cosmic particles (rays) from outer space



- Highest energies by far exceeding the largest accelerators
- Part of the natural background radiation
- Astroparticle physics (Pierre Auger Observatory 3000km^2)

Cosmic muons, Nature's gift for Earth

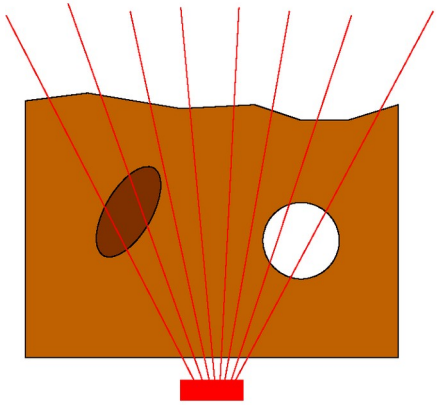
- Cosmic particles reach Earth upper atmosphere
- Muons created in shower-like events, 15-30km altitude, in rather complex series of processes
- Mixed energies 1 -- 1000GeV
- Highest energy muons can cross kilometers of material



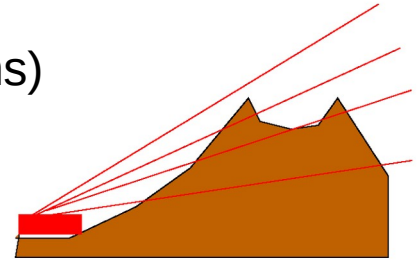
Basic configuration of muography – muon tomography

Absorption (reduction of number)

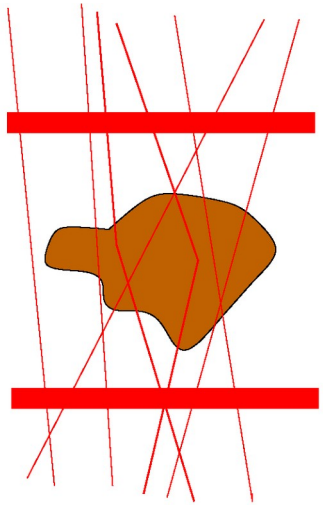
Underground
(high or low density)



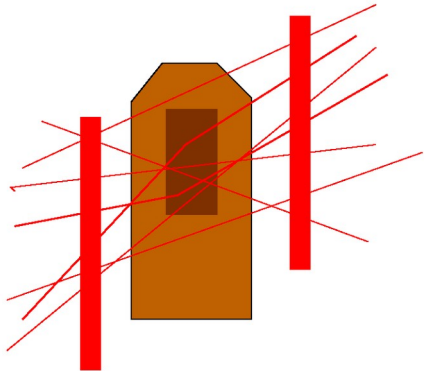
On surface
(low angle muons)



Scattering (directional change)



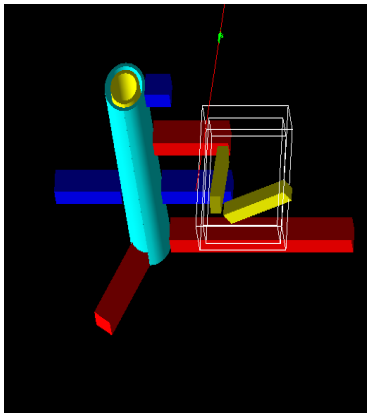
Object inside the detector



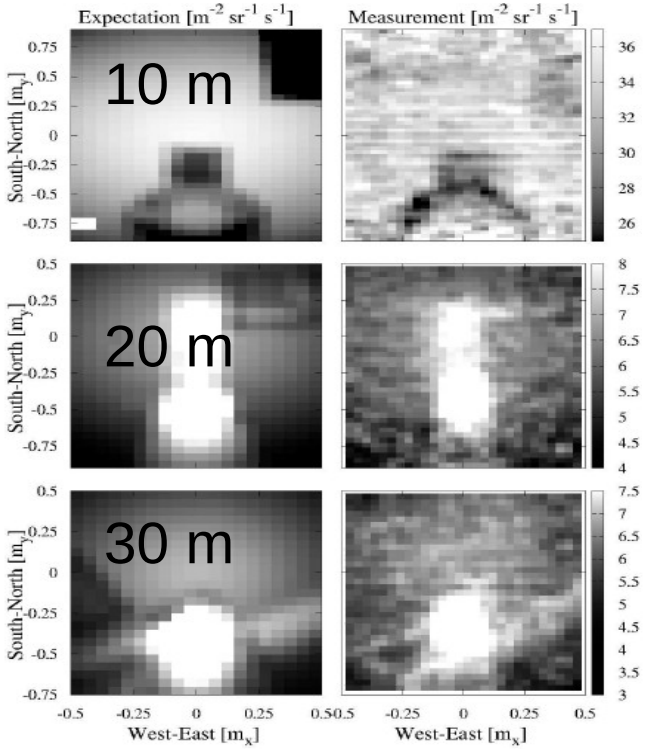
Detector “around” object

MuoGraphy: imaging with cosmic muons

- Underground lab at Wigner RCP

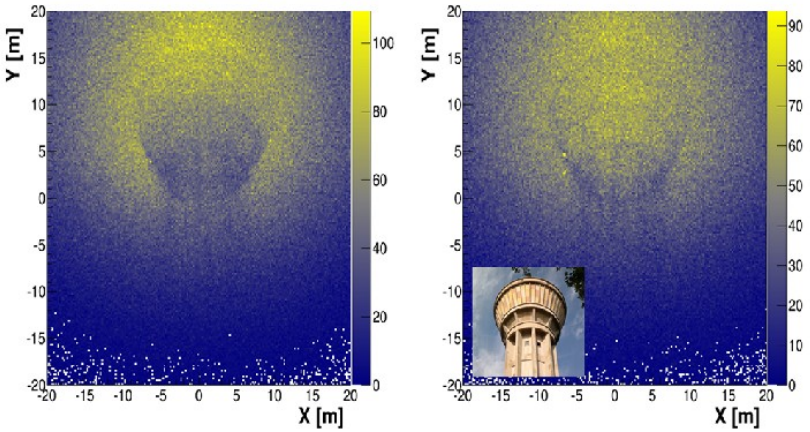


Simulation Measurement



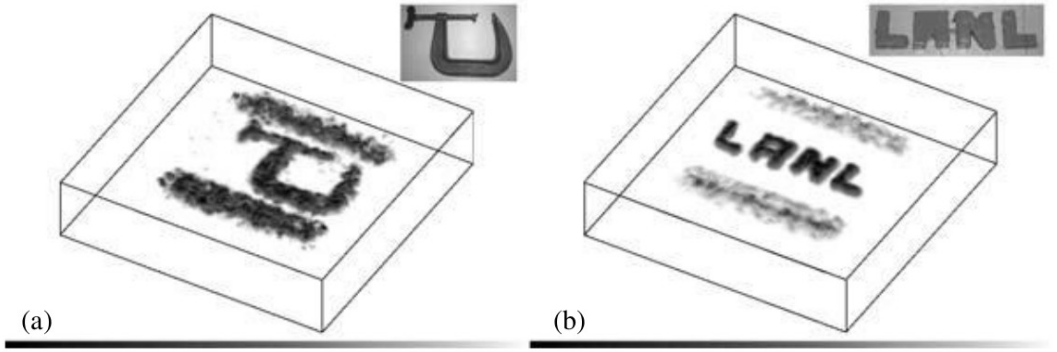
AHEP 2013 560192 (2013)

Water tower at Saclay: full versus empty

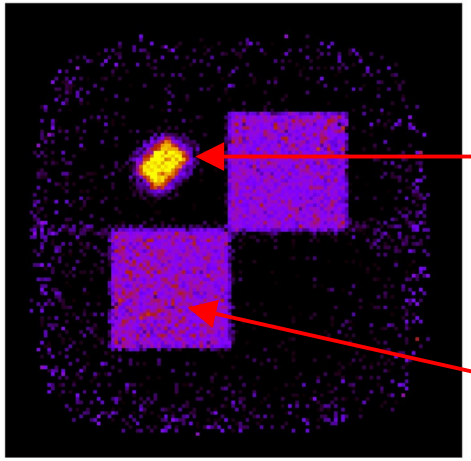


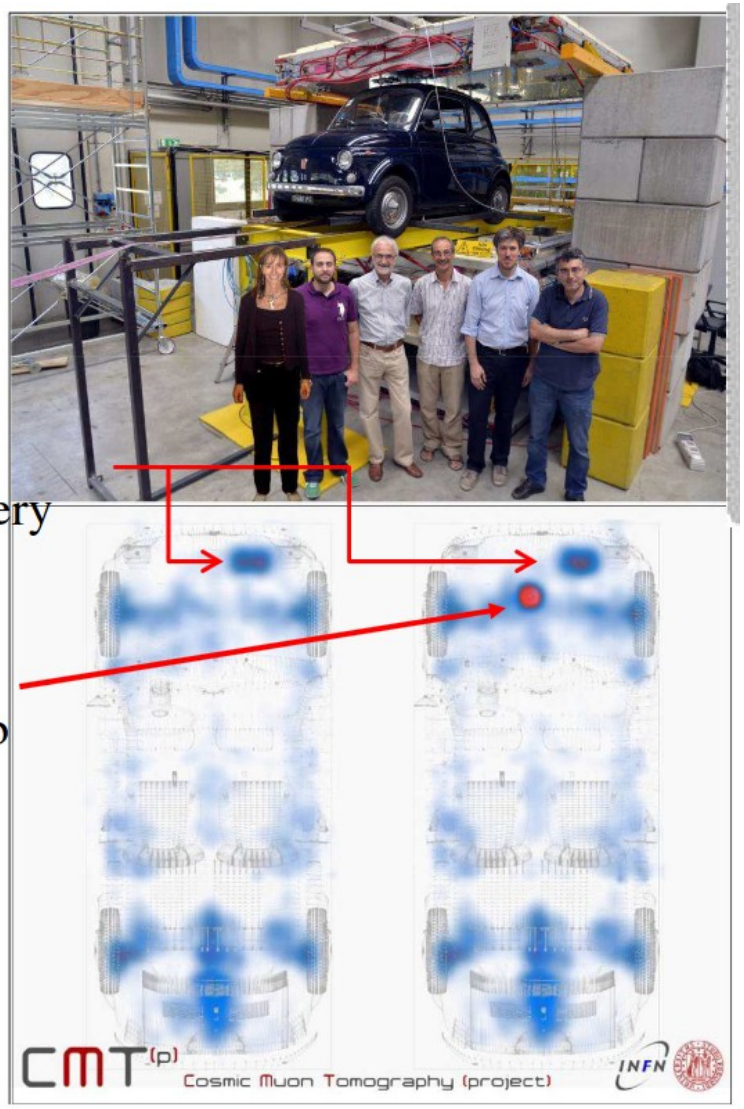
Procureur, NIMA 878. (2017) 10

Scattering muography examples



L.J. Schultz, et al., NIMA, 519, 687–694, (2004)





Muography: science, community and industrialization

- Combination of **very different scientific fields**: High Energy (particle and nuclear), Geosciences, Mining/Geoengineering… took a long time and effort
- Many national projects, **“Innovation gap”** (Research at or below TRL4, commercializaton from TRL7 upwards)
- Scale-up and Start-up companies, difficult to compare performances

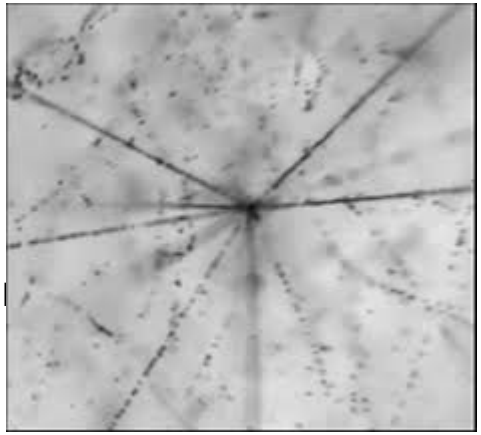
Internatonal Virtual Muography Institute

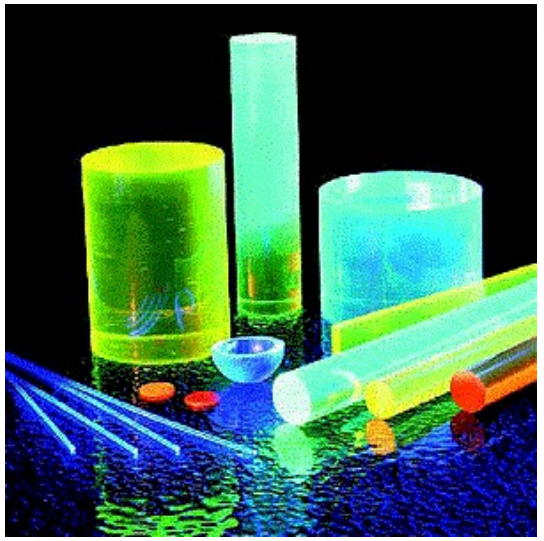
Detection technologies, developed for fundamental science

- Emulsions, thick “photographic films”

  Easy to deploy, high resolutio

  no time resolution



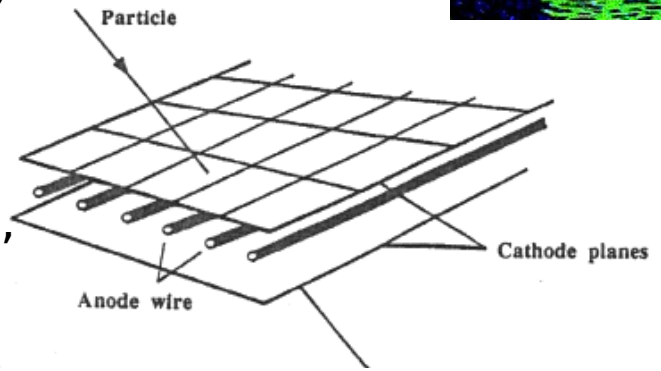


- Scintillators (visible light)

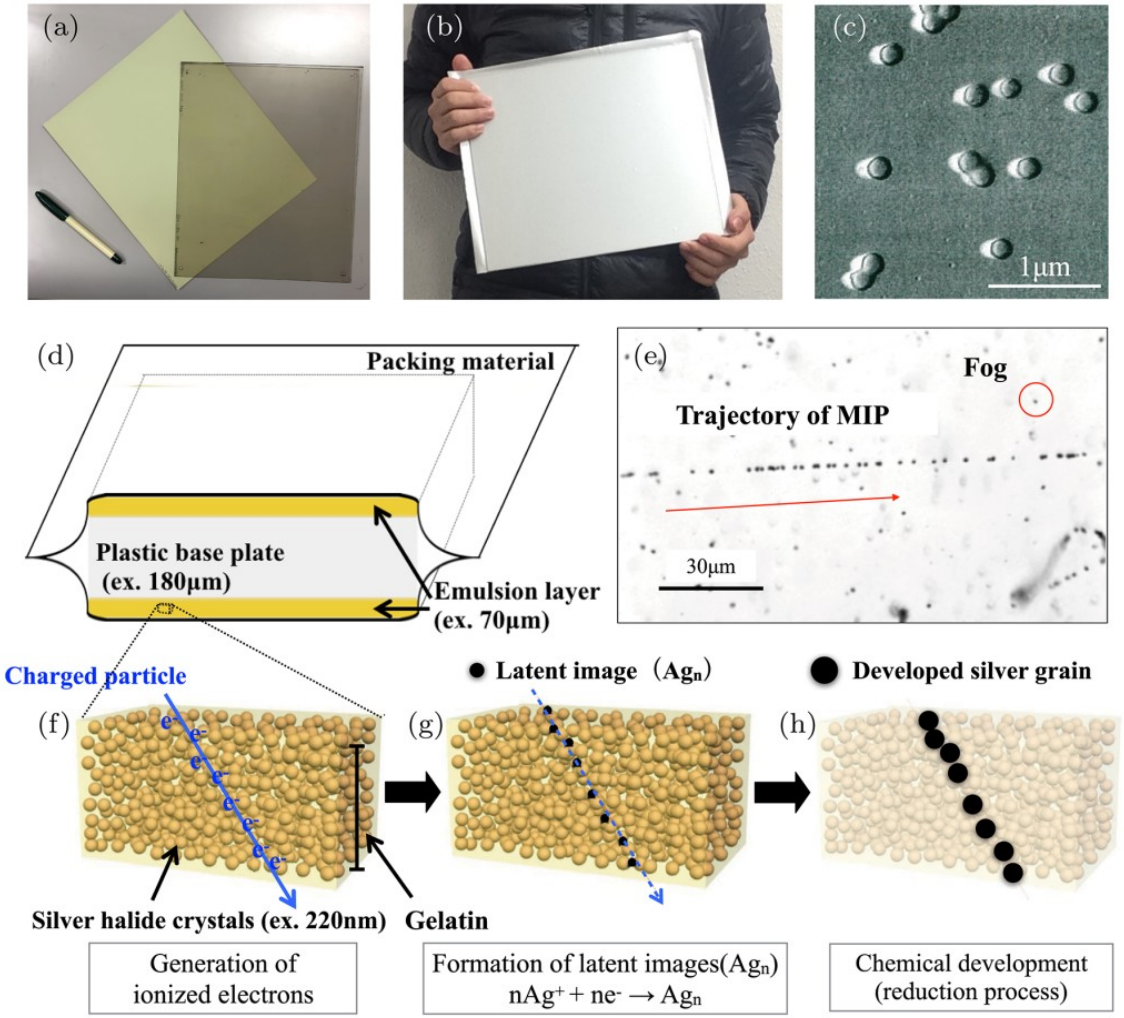
  High efficiency, high reliability

- Gaseous detectors

  High efficiency, cost efficiency, complexity



Emulsions: very precise, very simple to install

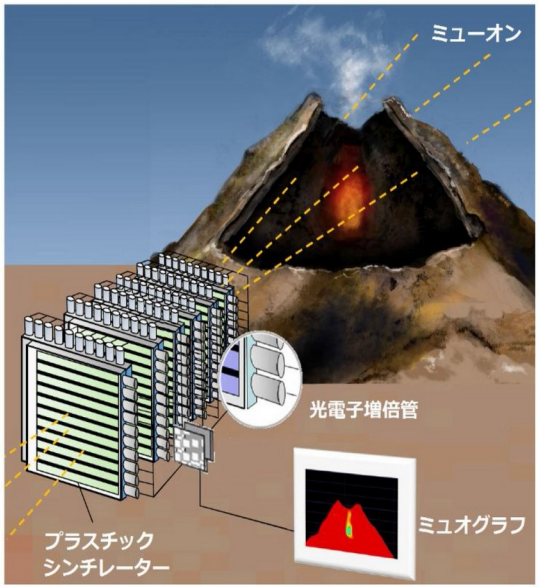


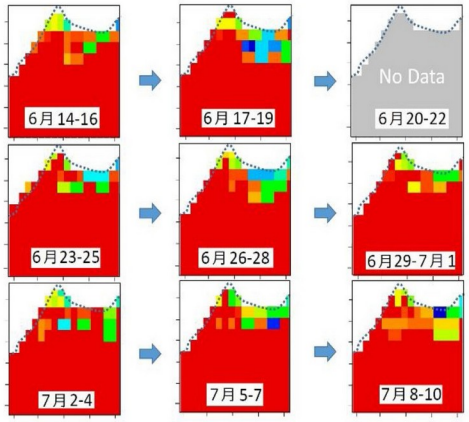
A. Nishio, K. Morishima, et al, NIMA 966 (2020) 163850

Scintillators: reliability

- Efficient, clean signals (low non-muon background)
- Cost and weight needs to be considered

MURAVES (MU-RAY), Saracino et al.





2013年　薩摩硫黄島の噴火の推移

6月	4	6	7	16	17	30
噴煙の高さ	–	300	600	400	100	200
火映	–	–	–	X	–	X

H. Tanaka et al: Nat. Commun. 5:3381 doi: 10.1038/ncomms4381 (2014)

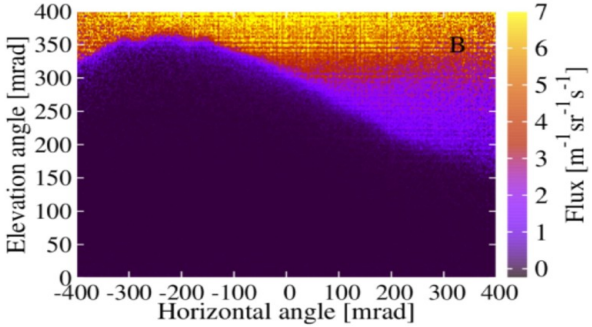
Gaseous: high performance tracking

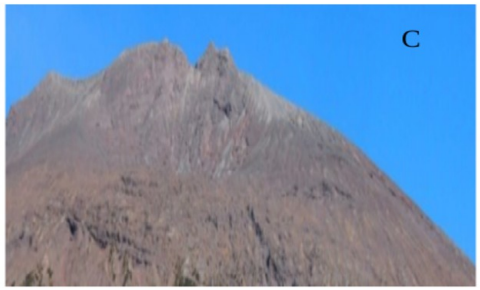
- Precision tracking systems
- Complex setups (readout, gas systems)

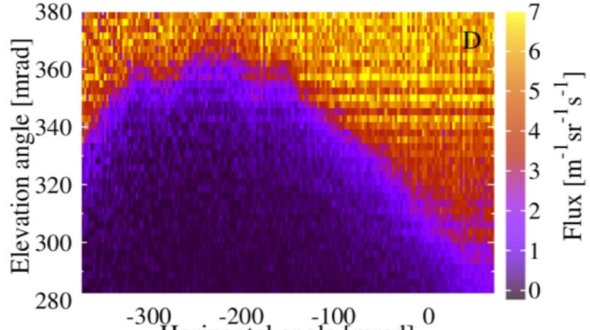
CEA “Pyramid discovery” detectors

Morishima et al, Nature 2017

Detectors at Sakurajima, UT & Wigner







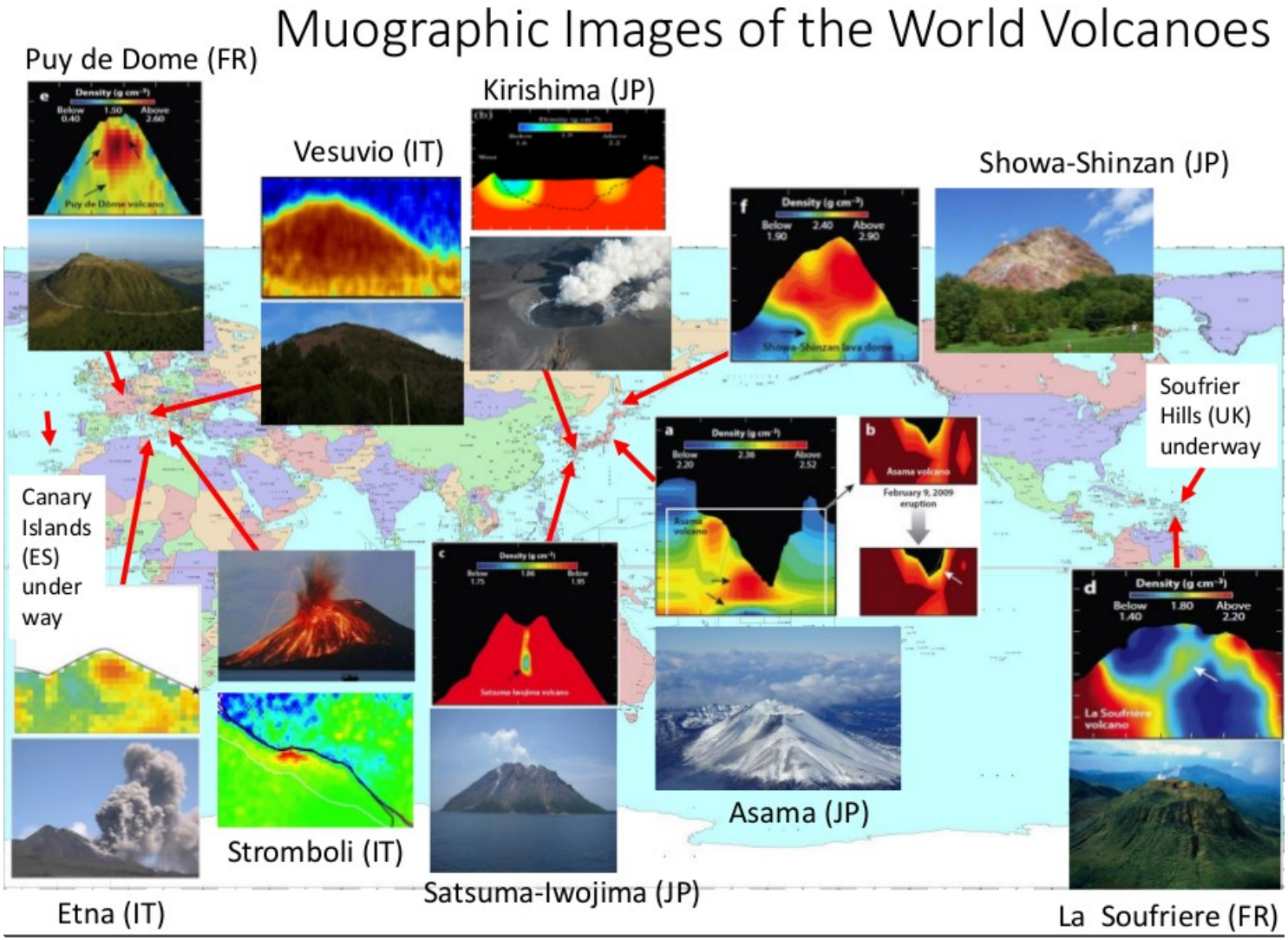
Scientific Reports, Volume 8, Article number: 3207 (2018)

Challenge for particle physicists: from lab to field

Earth sciences: Vulcanology

Hiroshi Nakajima, Volcano Muography

Volcanology applications: a worldwide effort

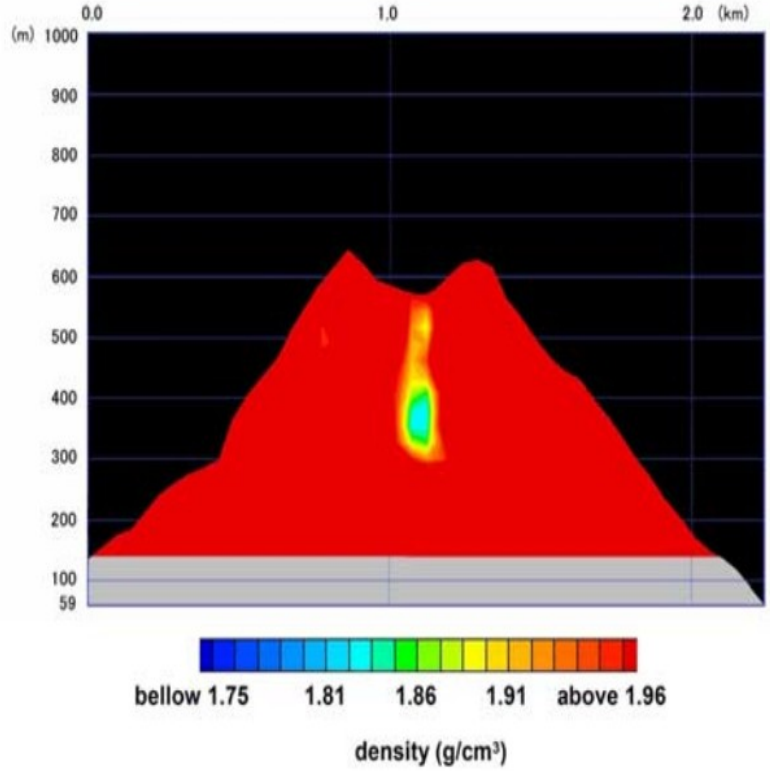


Courtesy: H.K.M. Tanaka

Muography images on Japan volcanoes

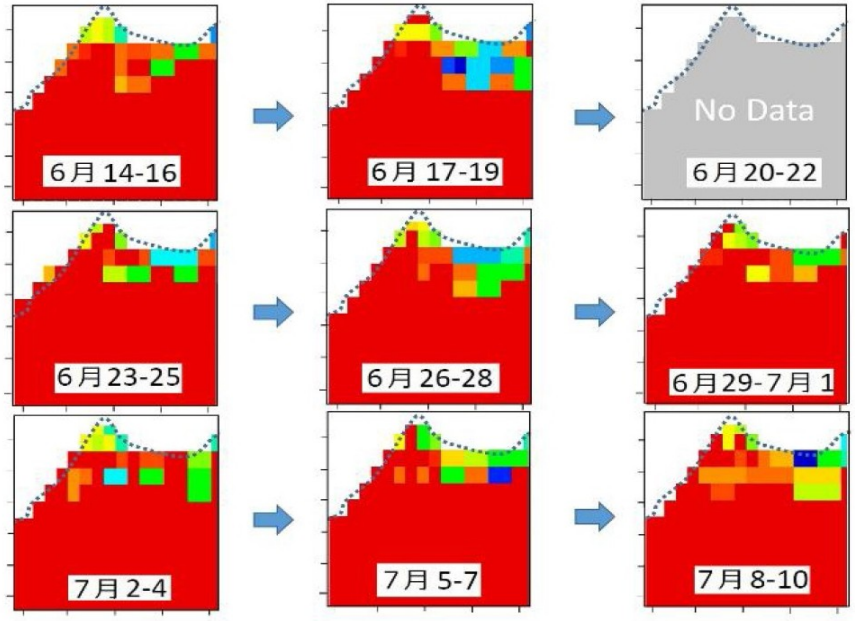
2008: Degassing in Satsuma-Iwojima

H. K. M. Tanaka et al.: GRL. 36, L01304, doi:10.1029/2008GL036451, 2009



2013: Eruption dynamics in Satsuma Iwojima

H. K. M. Tanaka et al: Nat. Commun. 5:3381 doi: 10.1038/ncomms4381 (2014)

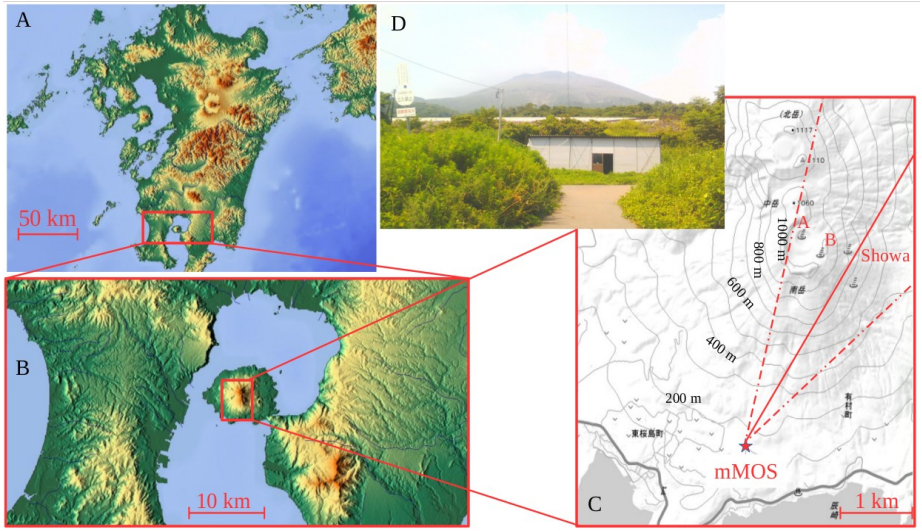


2013年　薩摩硫黄島の噴火の推移

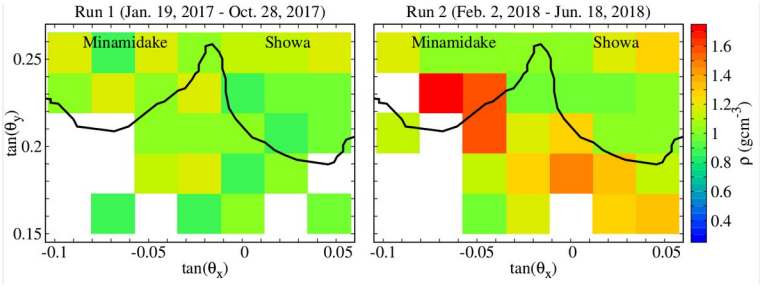
6月	4	6	7	16	17	30
噴煙の高さ	－	300	600	400	100	200
火映	－	－	－	X	－	X

Sakurajima Muography Observatory

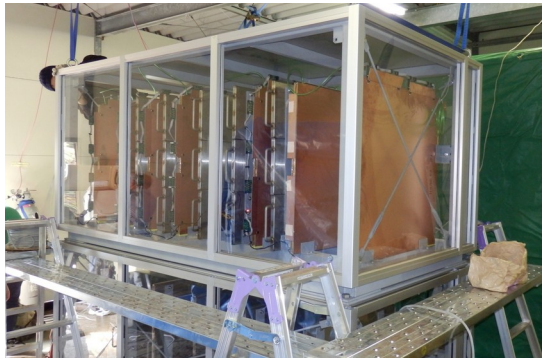
- At Sakurajima (Kyushu), UniTokyo – Wigner collaboration, 8.7 m²



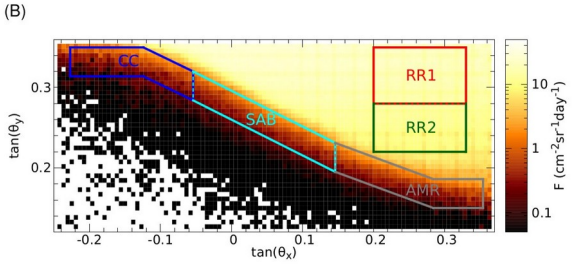
Shift of eruptions from Showa to Minamidake crater: 7Mt “magmatic plug”

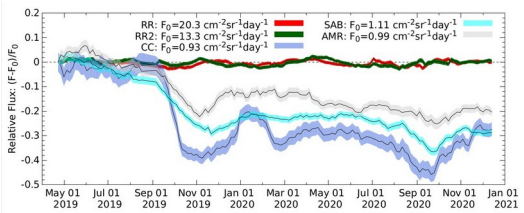


Oláh, **GRL**, 46 (2019) 10417



Tephra deposit quantification: lahars and erosion



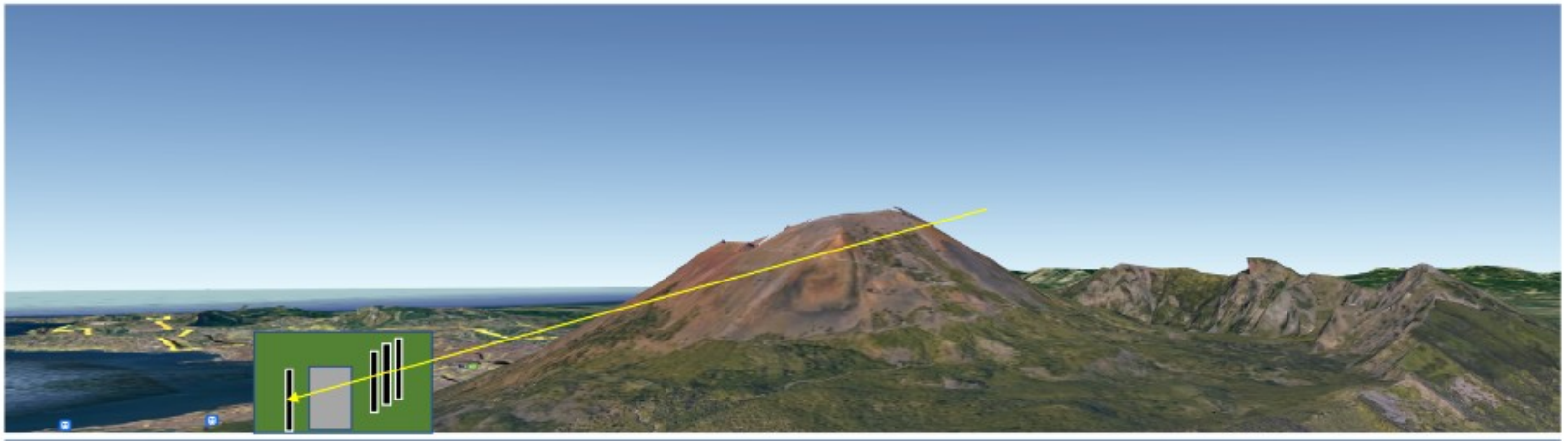


Patent: H. Tanaka, K. Tarou, D. Varga, G. Hamar, L. Oláh: Muographic Observation Instrument, Japanese Ref. No.: 2016-087436, date 25/04/2016

Oláh. **Sci Rep** 11, 17729 (2021).

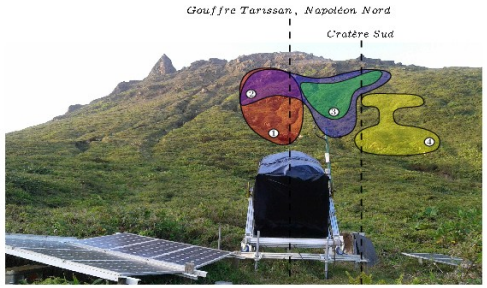
MURAVES Collaboration: Vesuvius cone

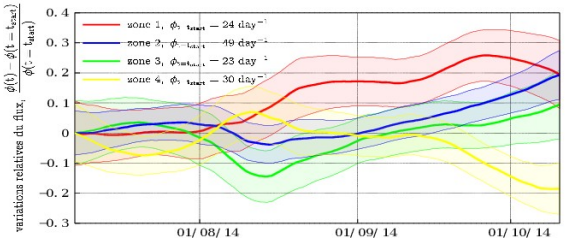
- MUon RAdiography of VESuvius (lead by INFN and Uni.Naples)

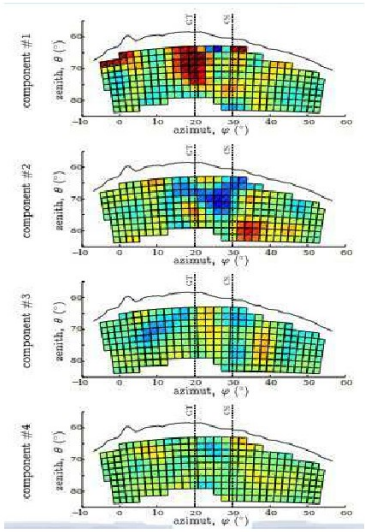


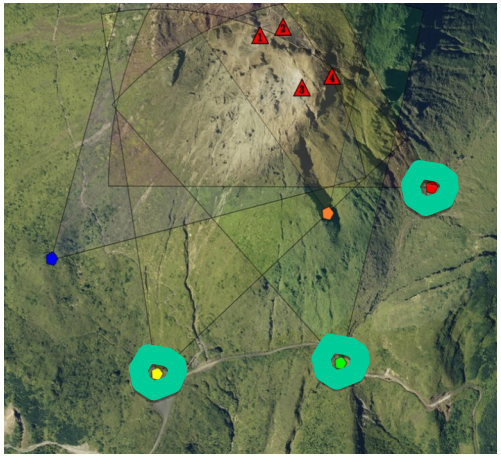
La Soufrière of Guadeloupe: hydrothermal activity

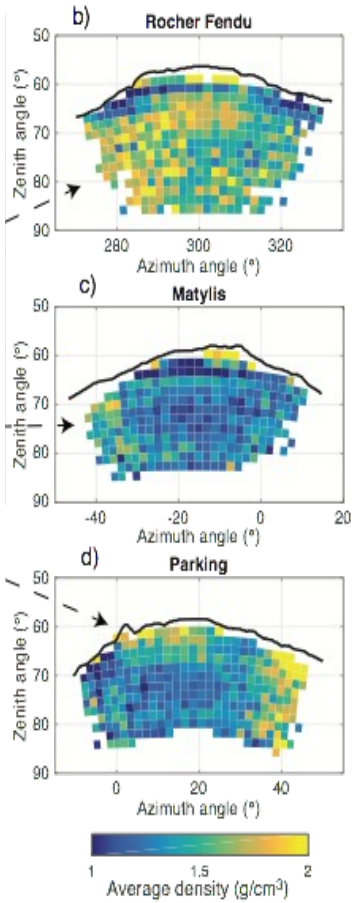
- DIAPHANE collaboration (CNRS, Lyon, Paris) for various muon imaging applications











Multiple views, 3D **gravi-muon joint inversion**

Most diverse measurements available

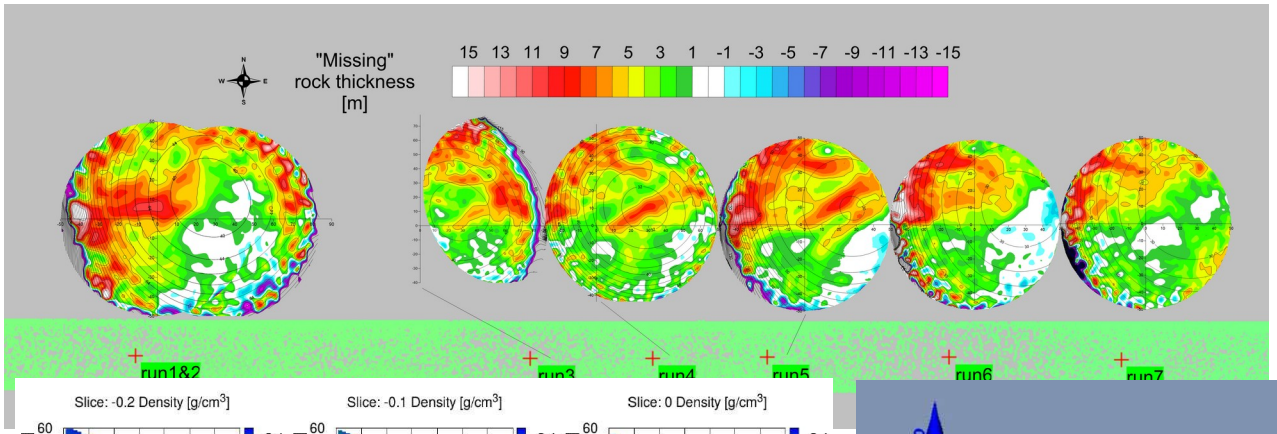
Jourde, K., **Sci Rep** 6, 33406 (2016)

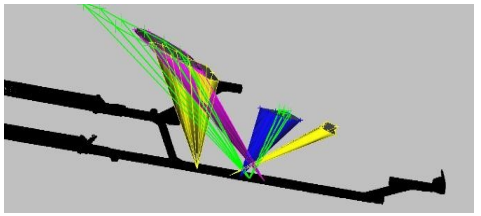
Marteau, **JINST** 12 (2016)

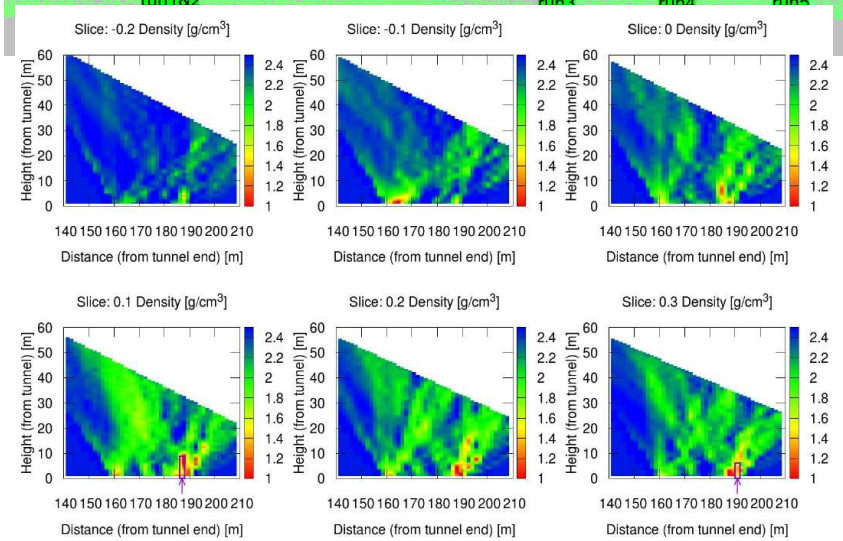
Rosas-Carbajal, 2017

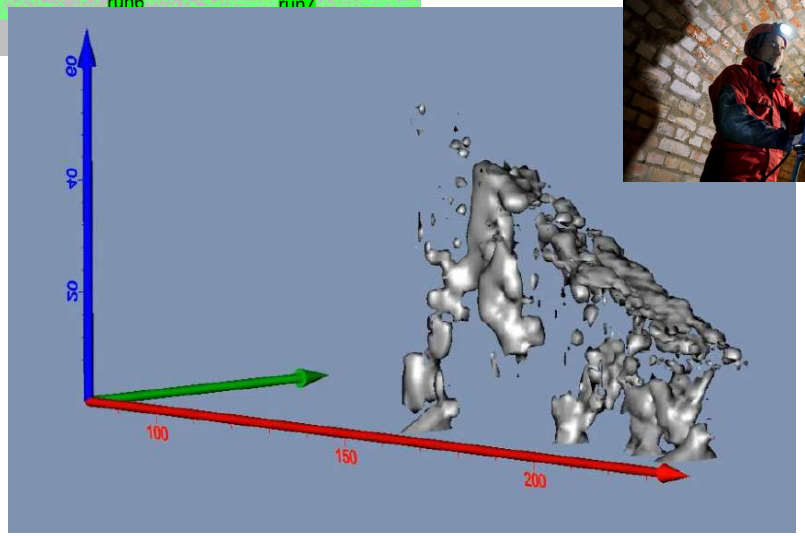
Earth sciences: Geological and geophysical phenomena

- Királylaki cave (Budapest): imaging erosion zone





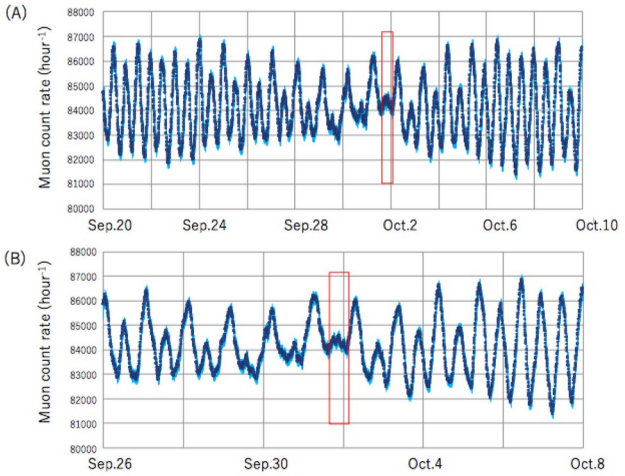




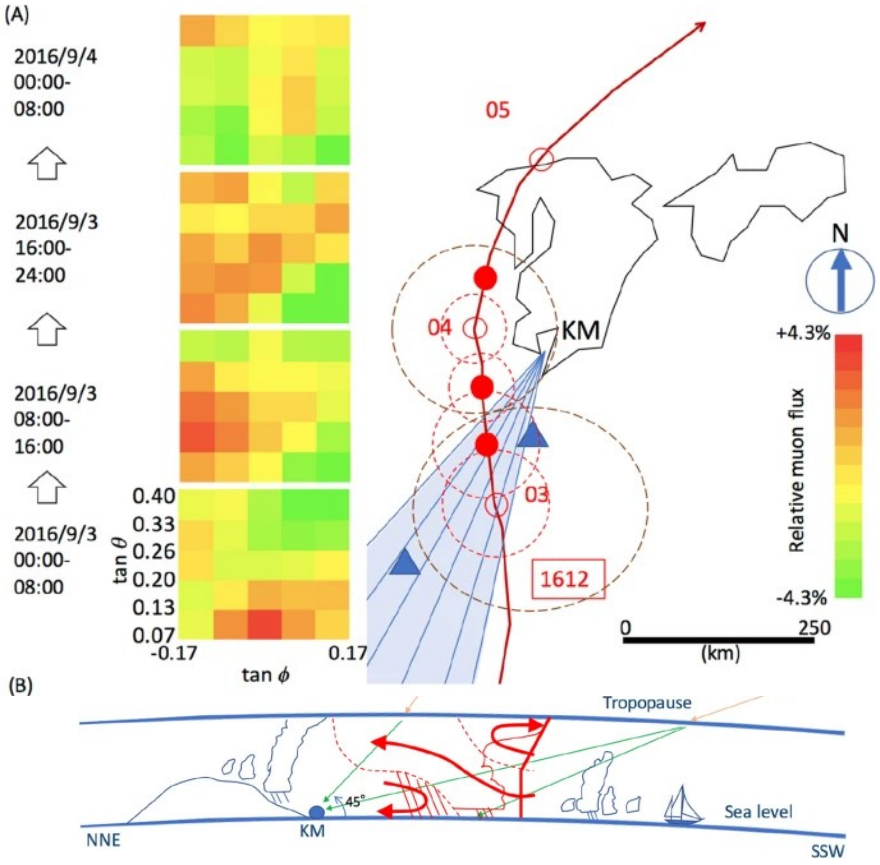
Drilling confirms low density erosion zones (not cave)
Balázs, Nyitrai, Geosci. J. Int. 10.1093/gji/ggad428

Earth sciences: Meteorological tsunami and tropical cyclones

- Tokyo Bay Aqualine HKMSDD (100m)



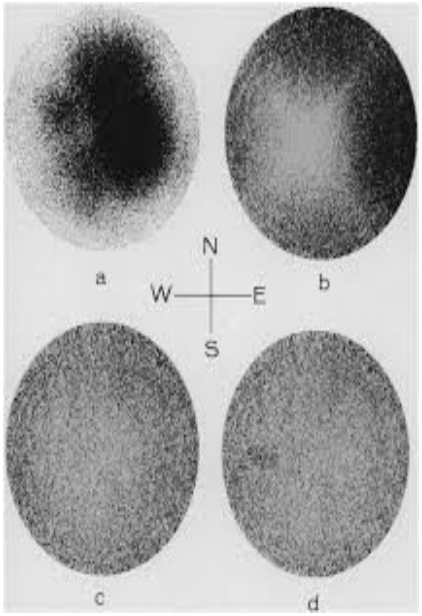
- Internal structure of tropical cyclones



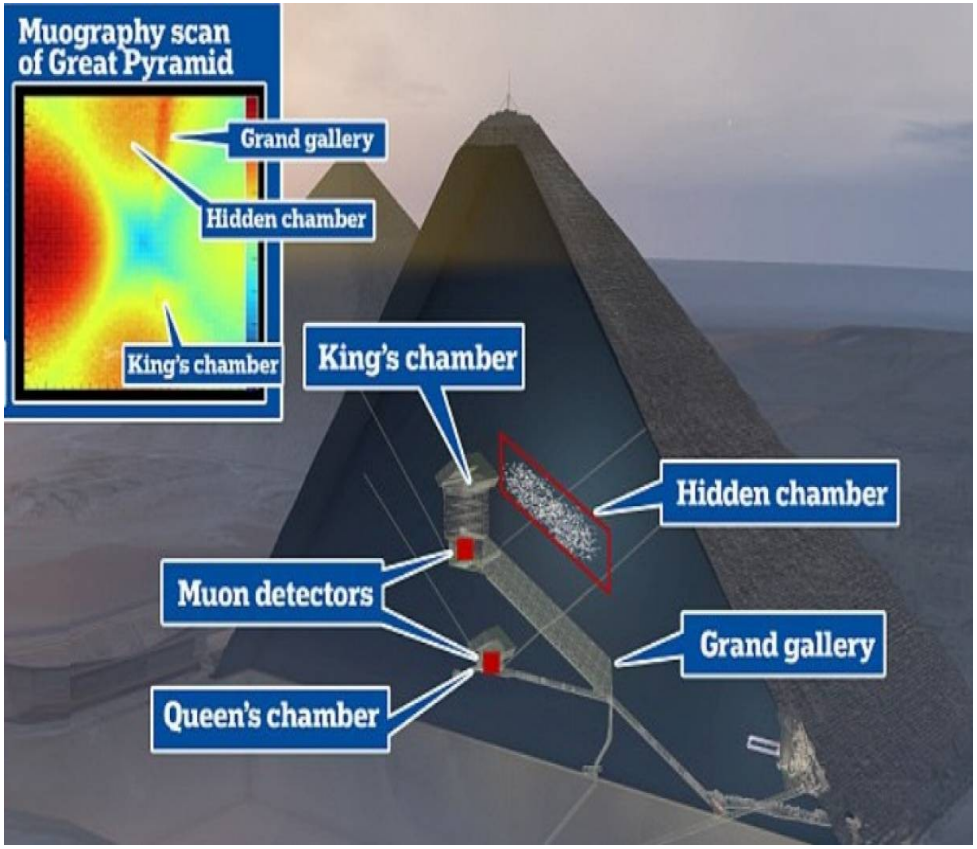
SciRep 12, 6097 (2022)
SciRep 12, 16710 (2022)

Archeology: pyramids

- Alvarez (1970!)



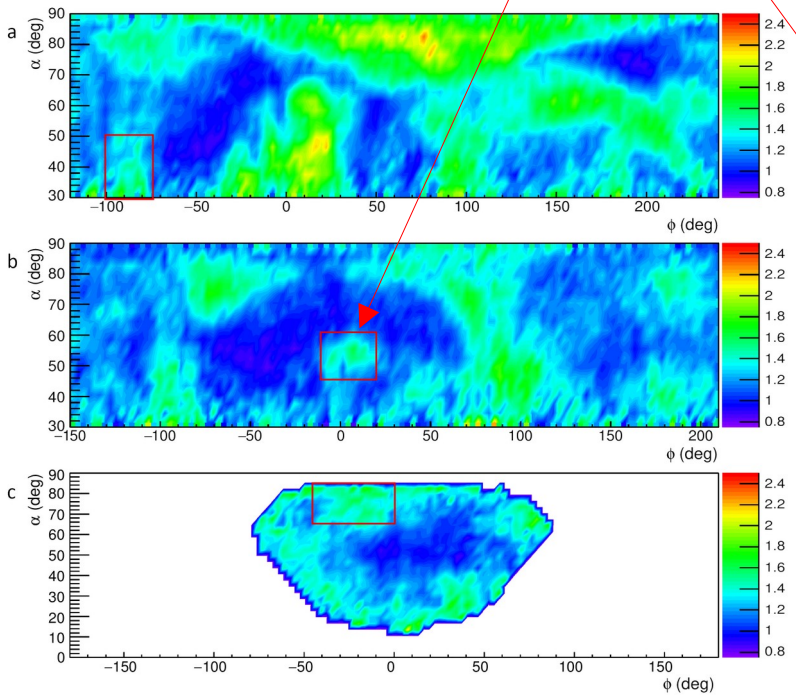
“ScanPyramids” 2018

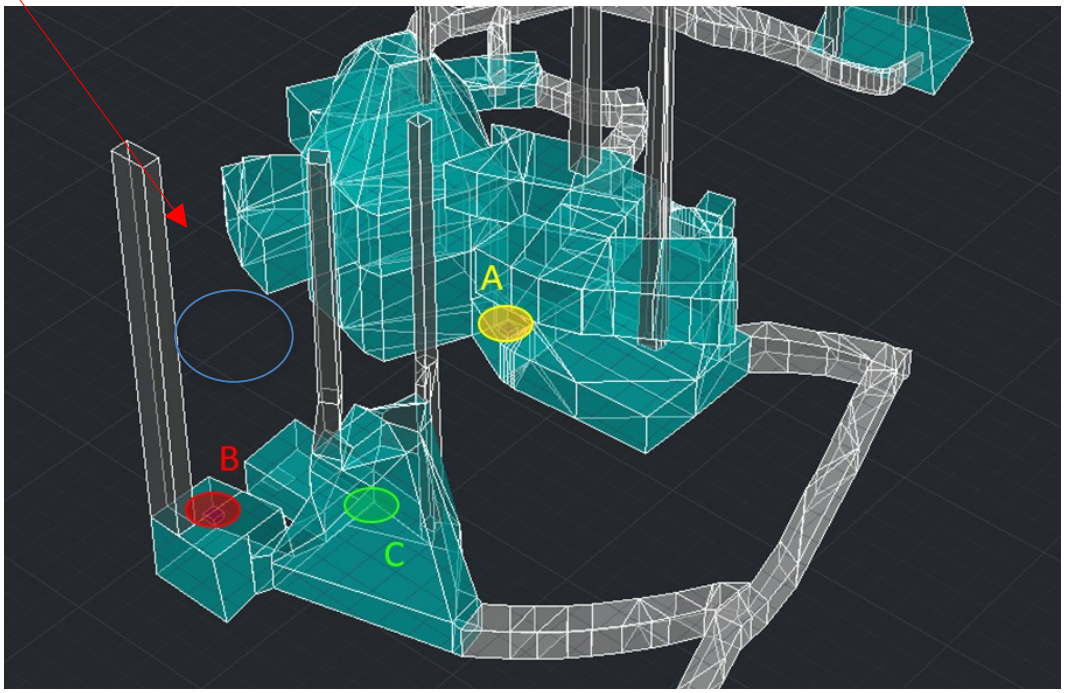


Archeology: Underground structures

Naples, Mt. Etchia

Muography imaging from three different locations reveals a hidden cavity





Cimmino, L., *et al.* *Sci Rep* **9,** 2974 (2019).

Industrial and engineering applications

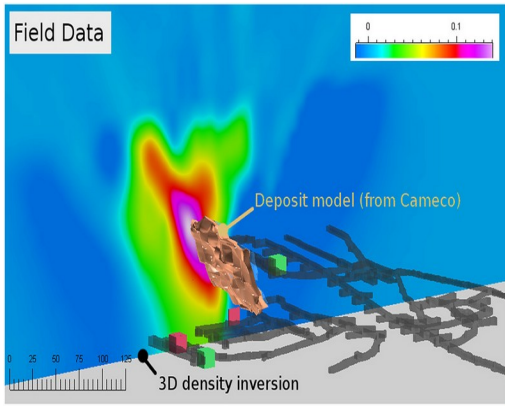
Hiroshi Nakajima: Muography Laboratory II.

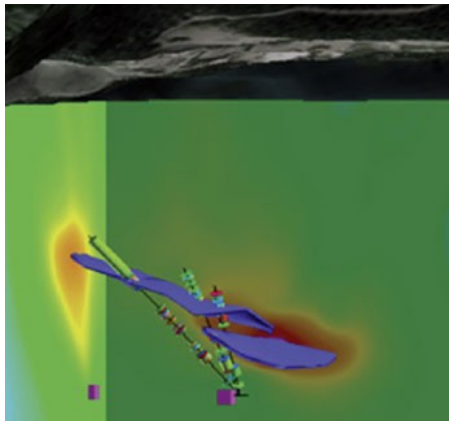
Mining industry

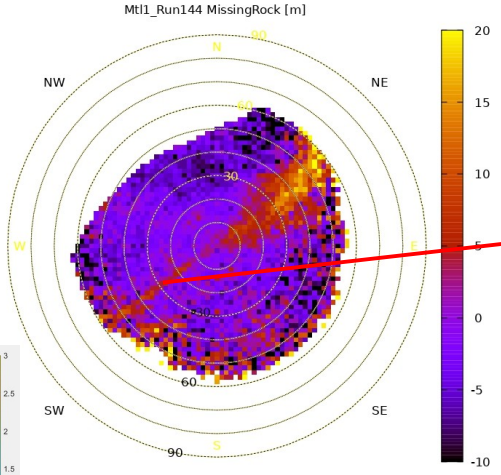
- Canada/Australia: Ore body identification by **density contrast**

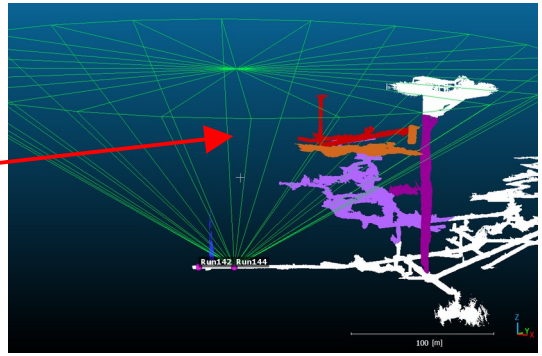
D. Schouten et al, *JGR SE* **123**, 8637 (2018)
D. Schouten, Recorder Vol.43, 5 (2018)

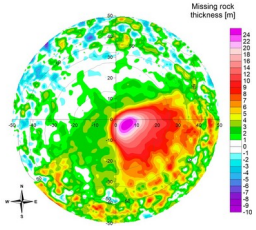
- Identification of **non-collapsed tunnel** in abandoned mine (Hungary)
- **3D imaging** vertical mine shaft

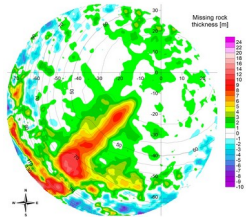


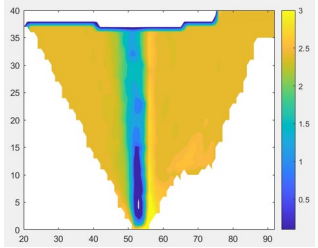








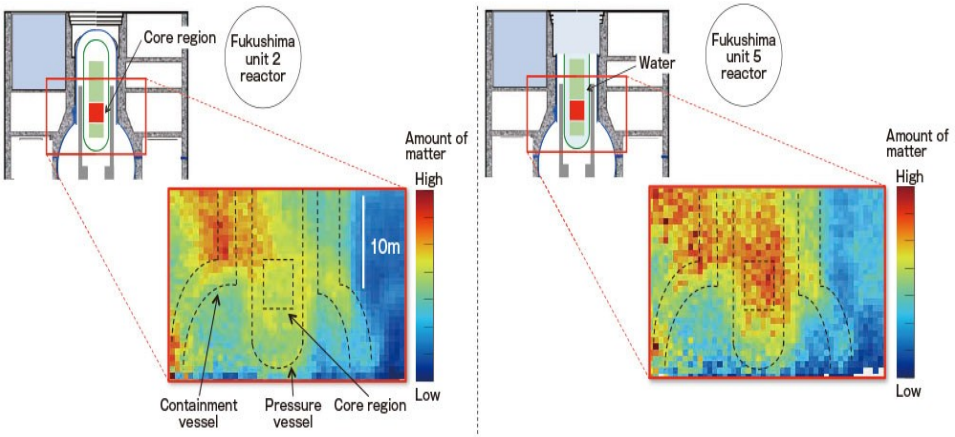




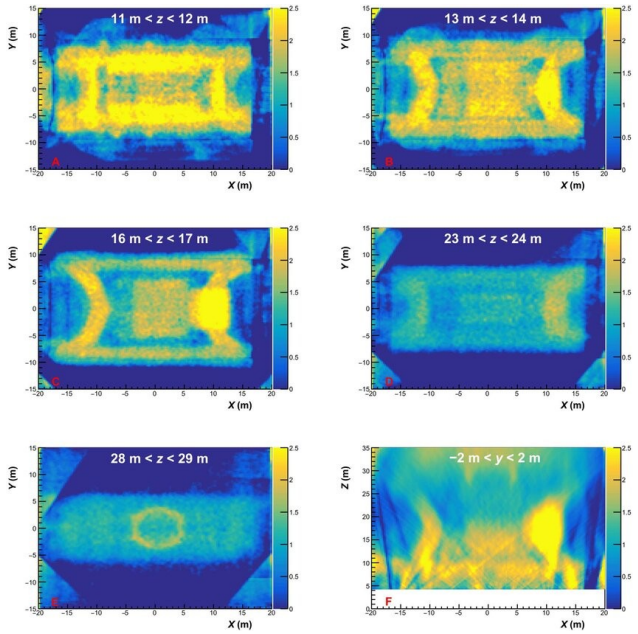
MUON SOLUTIONS

Nuclear reactor imaging

- Post-accident at Fukushima
- 3D tomography by Uni Saclay / CEA

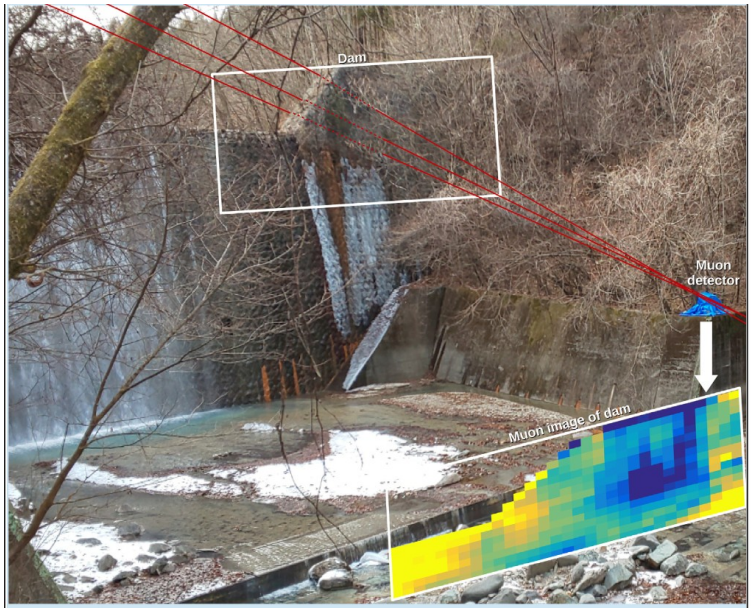


Procureur et al., Sci. Adv 9 (2023)



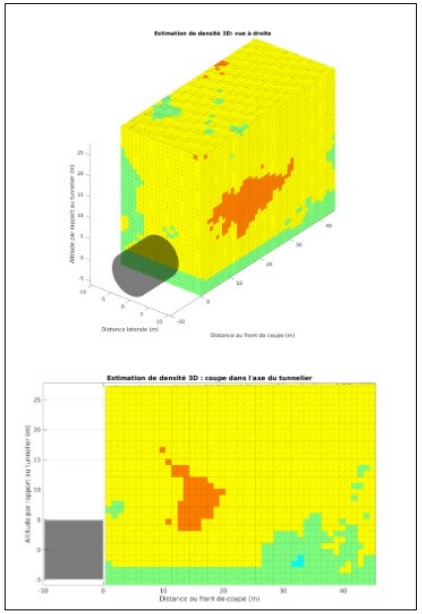
Civil engineering

- Debris (Sabo-) check dam structural health measurement in Japan
- Muography reveals low density region



Olah et al., iScience 26, 108019 (2023), collaboration with Sabo Frontiers Foundation, Japan

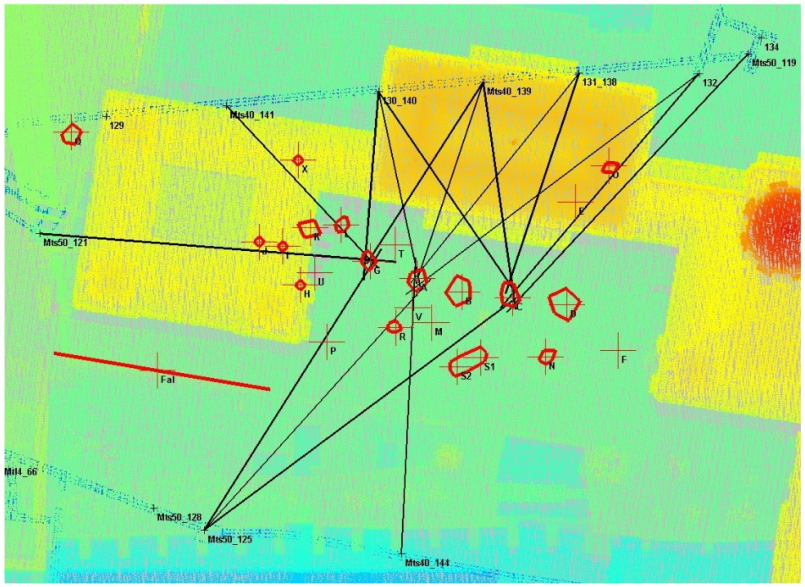
- Soil structure around a tunnel boring machine

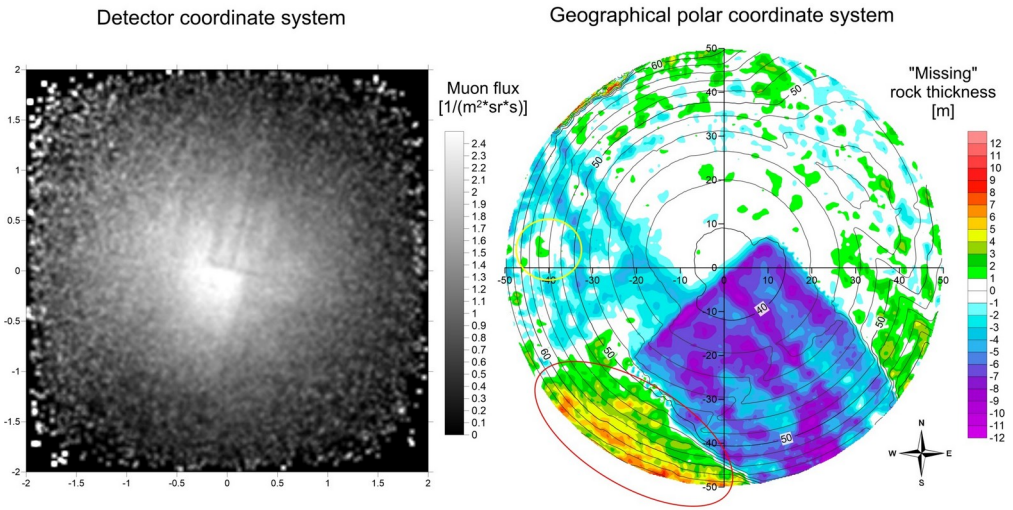


Courtesy: J. Marteau

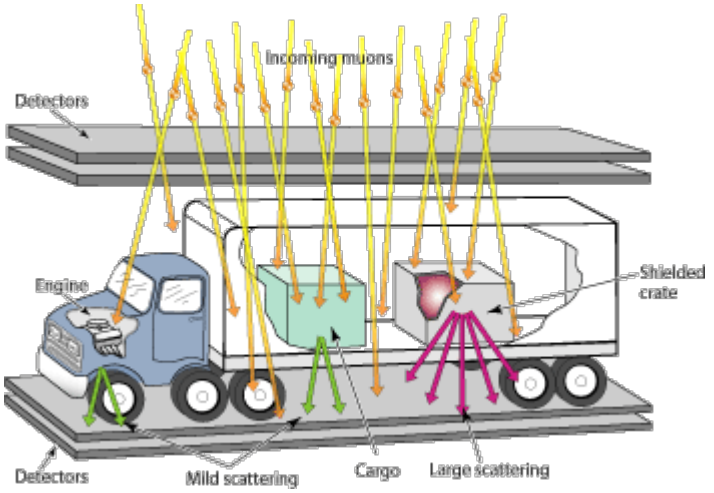
Civil engineering

Searching for geotechnical anomalies at Buda Royal Palace, Budapest, Hungary

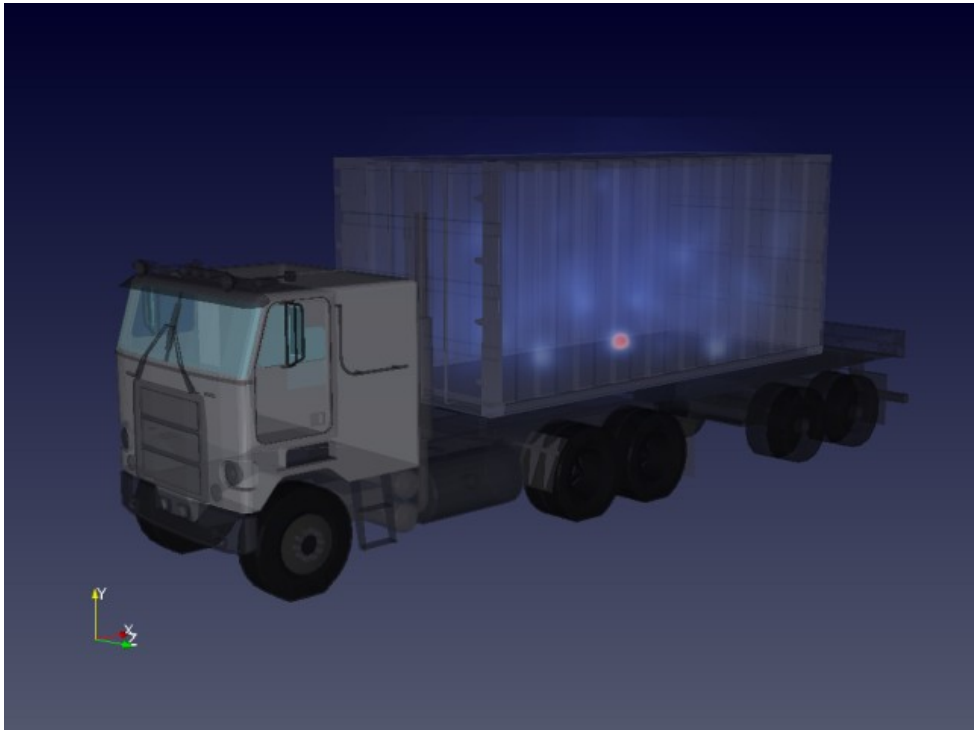




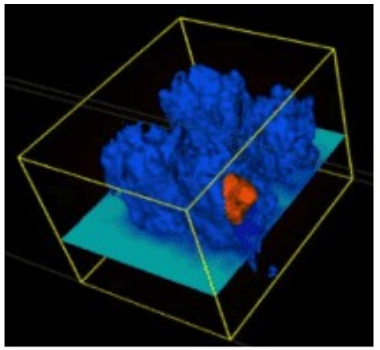
Border control and cargo inspection

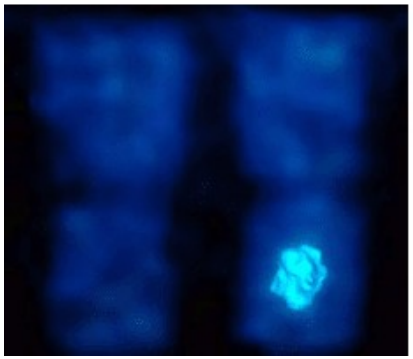


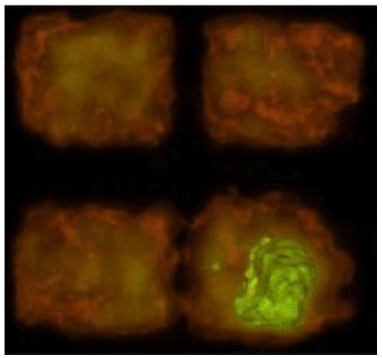
INFN Padova, CMTp



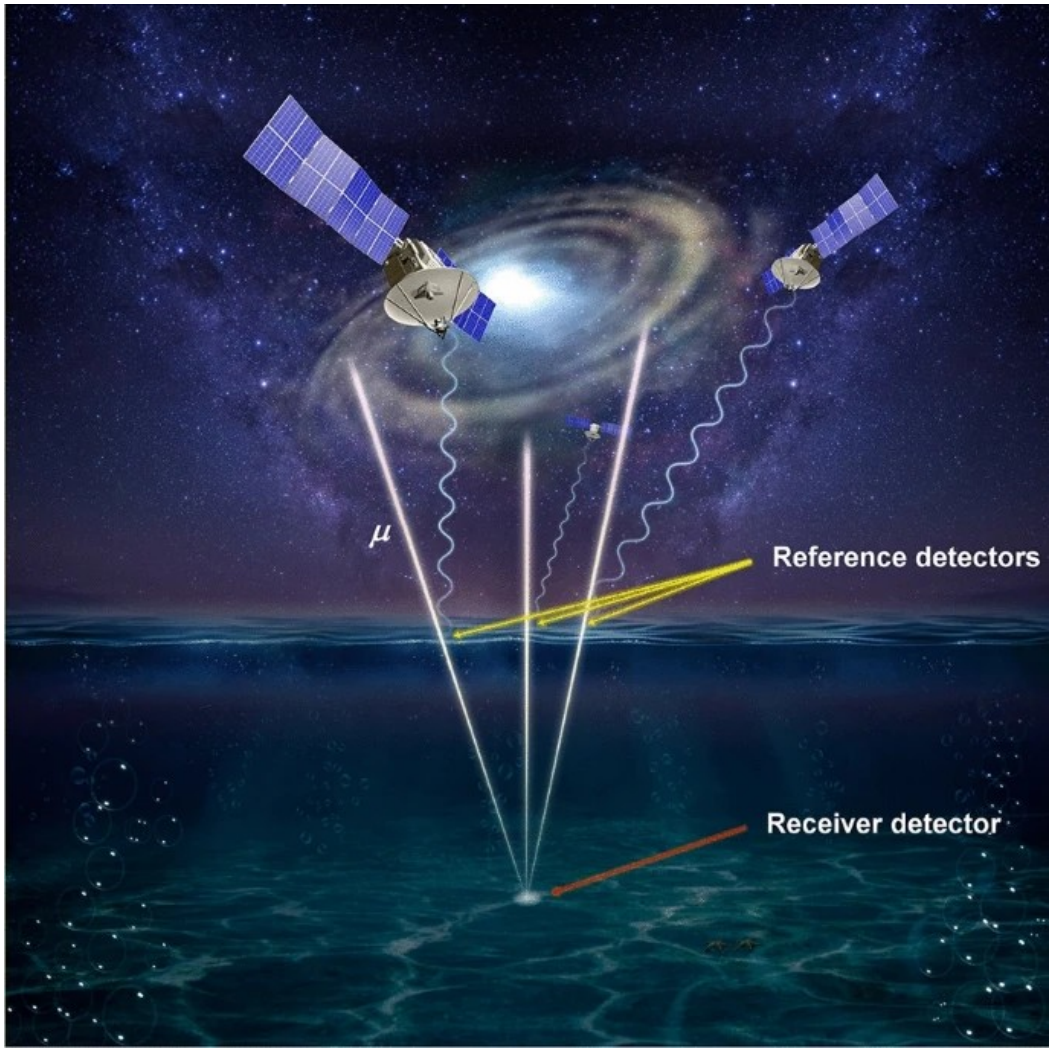
Decisions Sciences, USA







Beyond imaging: navigation, time metrology, secure information

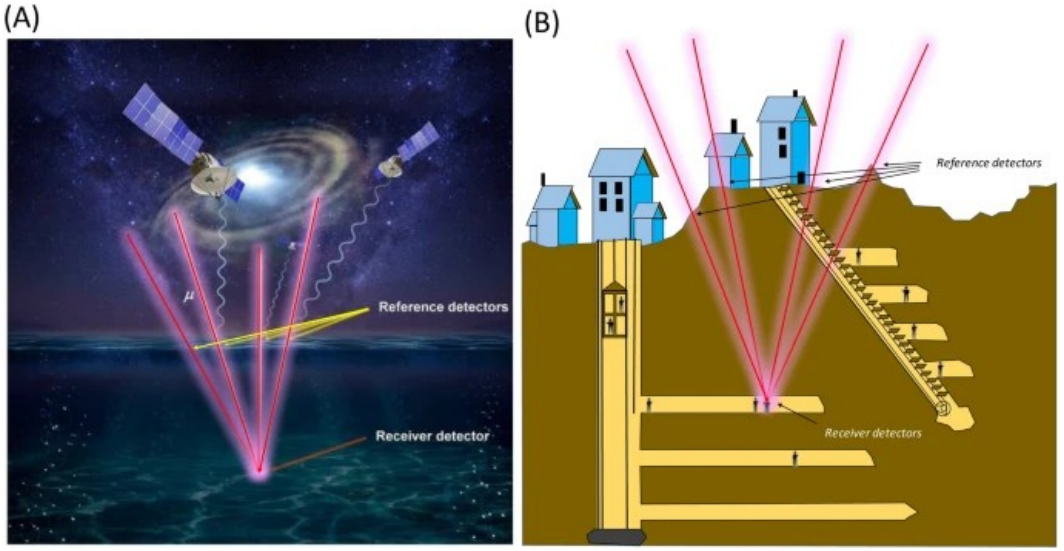


TIME

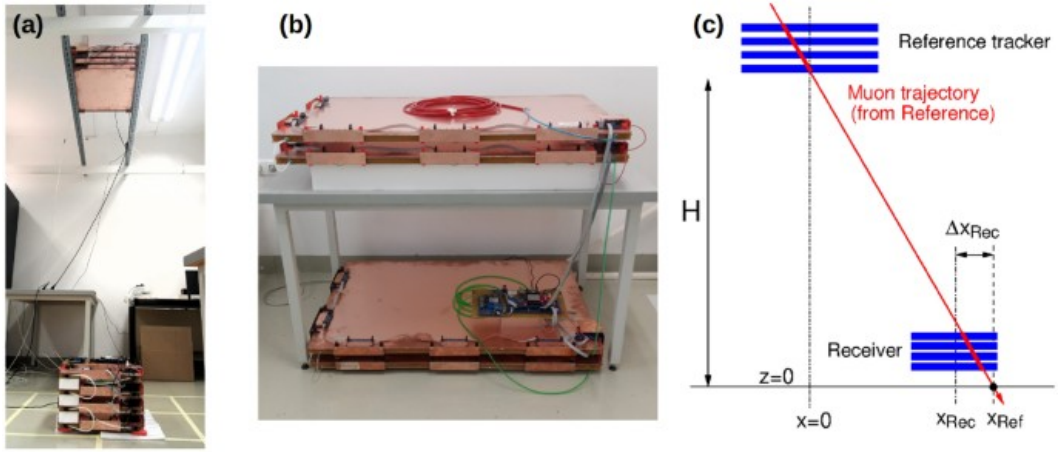
H. K. M. Tanaka,
The Best Inventions of 2023

Muometric Positioning and navigation

- Indoor, Underground, Underwater position information
- Reference stations with known position (GPS or local survey)
- “Receiver” with no GPS, unknown position (underwater, underground...)
- Available low data rate wireless communication: WiFi, ultrasound, infra...
- Sub-cm precision!

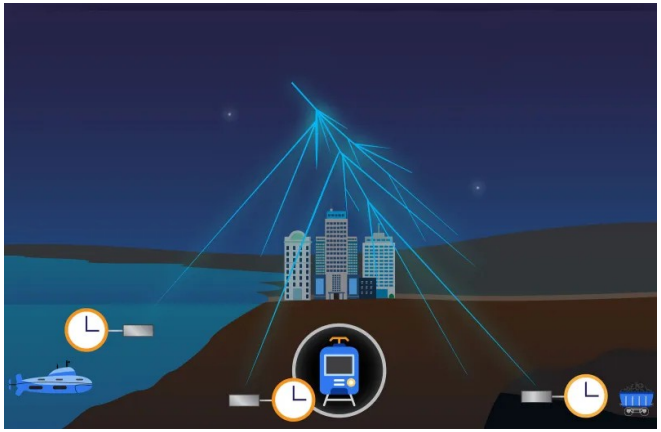


Tanaka 2020, 2022, 2023



Varga, 2024

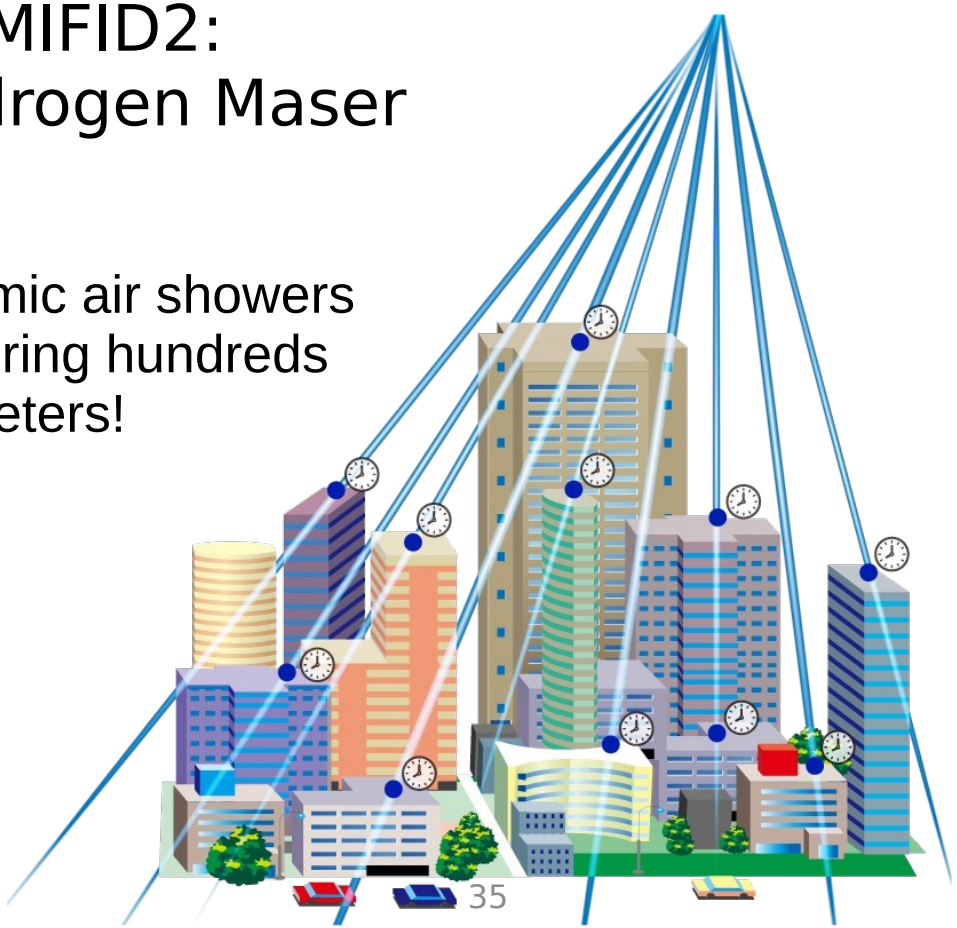
Time metrology



CAT = Cosmic-ray Arrival Time

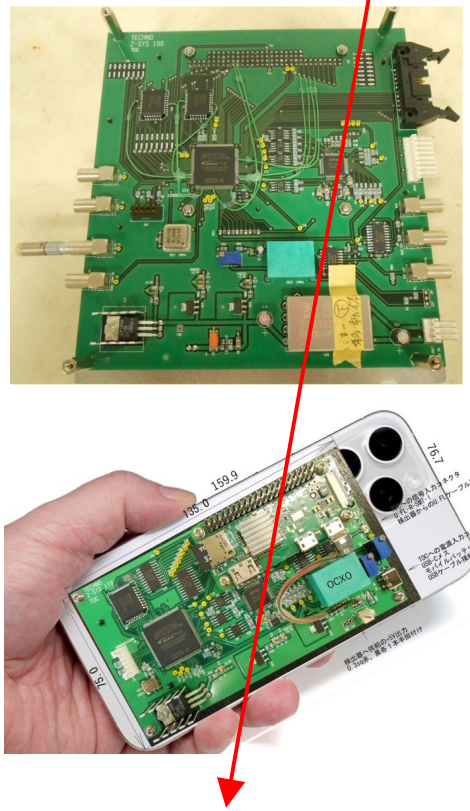
Wireless sharing of UTC – MIFID2:
CTS-disciplined Active Hydrogen Maser

Cosmic air showers covering hundreds of meters!

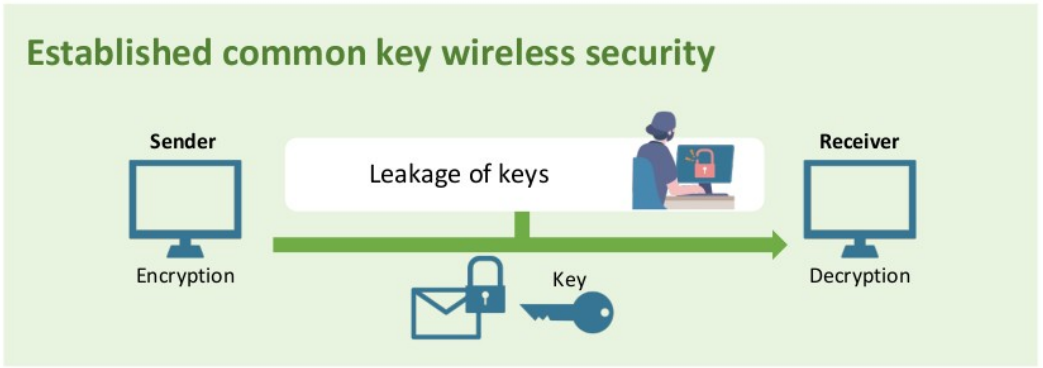


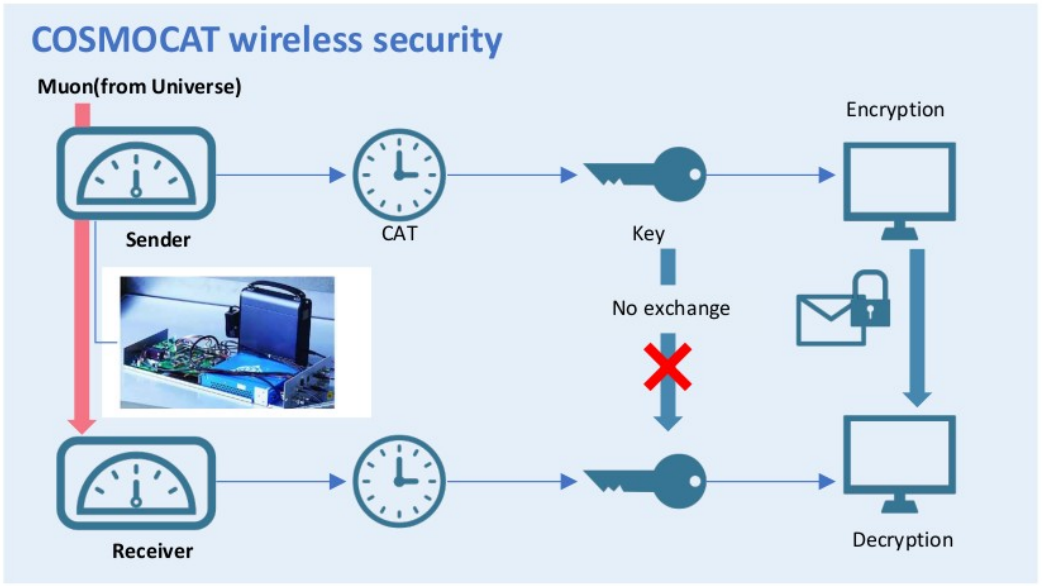
Wireless security

Can be used for secure information exchange!



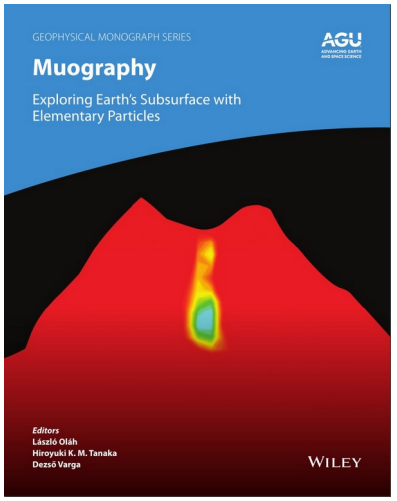
CosmoCAT

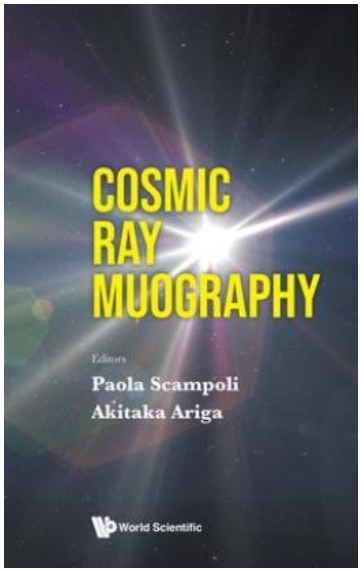




Summary

- Muons can image very large objects, quantify 3D density distribution and reveal internal structures
- Muography is made real by contemporary technology and detector construction methods. Challenge of reliable production and performance is being addressed
- Broad range of applications relevant for NDT community, geosciences, geotechnology, mining, archeology…
- After a long history, now an emerging scientific field and community





Internatonal Virtual Muography Institute

Muographers

Thanks to contributions of H.K.M. Tanaka, J. Marteau, G. Saracino, G. Surányi, M. Holma, L. Oláh, G. Nyitrai, G. Hamar, L. Balázs. and many others

BACKUP SLIDES