Secondments from Wigner RCP to TokyoU, and resulting scientific outcomes

European Commission

INTENSE MidTerm meeting, 2022

Pisa, Italy

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wigner REGARD INNOVATIVE GASEOUS DETECTORS MŰEGYETEM 1782 MUOGRAPHY

Outline

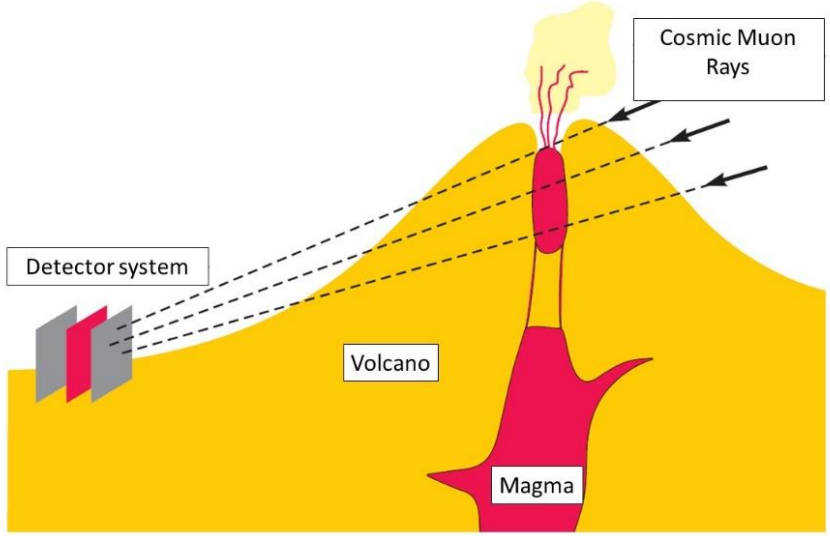
- **Muography detectors**
- **Secondment projects**
- **Sakurajima muography results**
- **Developments** during and after secondments
- **Summary, Secondment progress**

Muography detectors

Characteristics of muography

Conditions of muographic survey:

- Positions (detector altitude **below object**, on surface or underground)
- Exposition time (10-30 days)
- Infrastructure (power, net, transportation)
- DEM/DTM surface map, tunnel maps
- Flux and uncertainty calculations, simulations

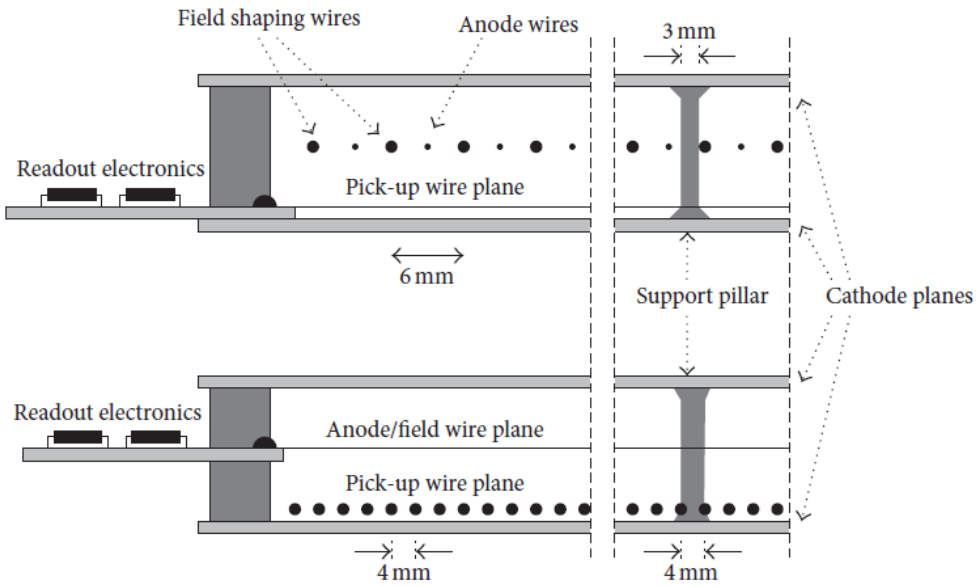


Requirements for detector design:

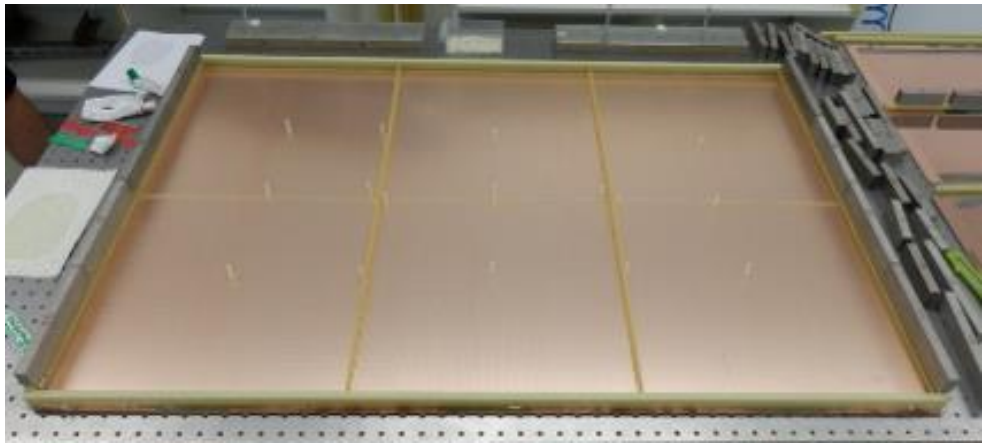
- Resolution (5-50 mrad)
- Size (available space vs. cost)
- Robustness (mechanical, environmental)
- Background suppression (eg. lead, on surface)
- Mobility, Autonomy, Consumption
- Cost-efficiency

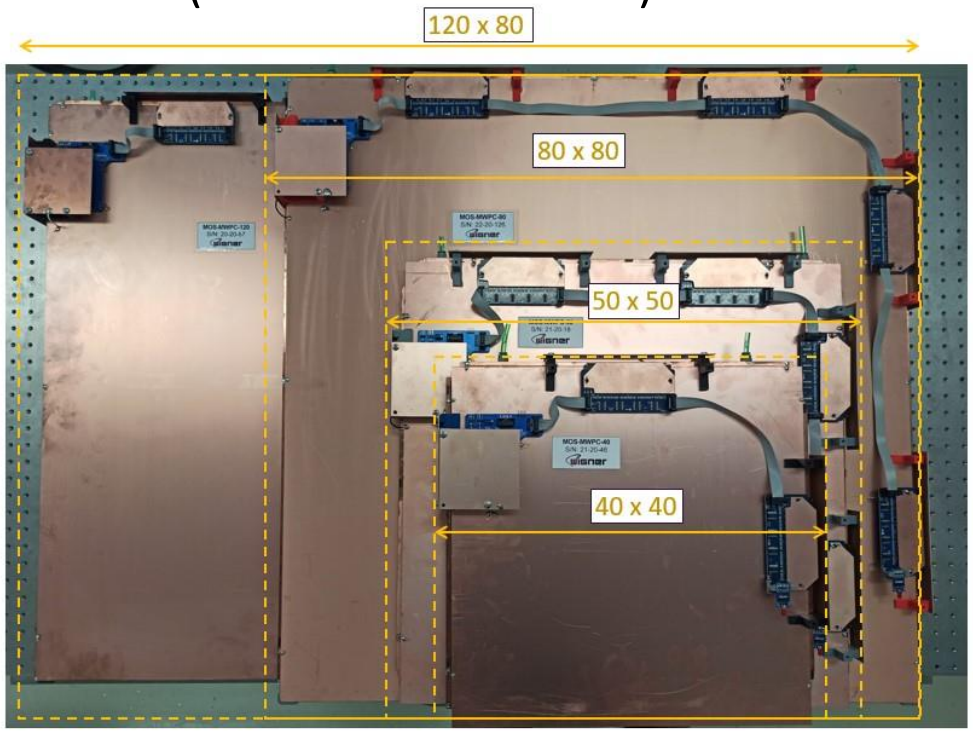
Muography detectors

Advanced MWPC detectors from Wigner RCP



- Gaseous detector (**M**ulti-**W**ire **P**roportional **C**hamber)
- >98% tracking efficiency, 9 mm FWHM position resolution
- Gas: nontoxic, non-flammable, commercial welding gas ($Ar:CO_2$ 82:18)
- Wide range of sizes (40x40 – 120x80 cm^2)

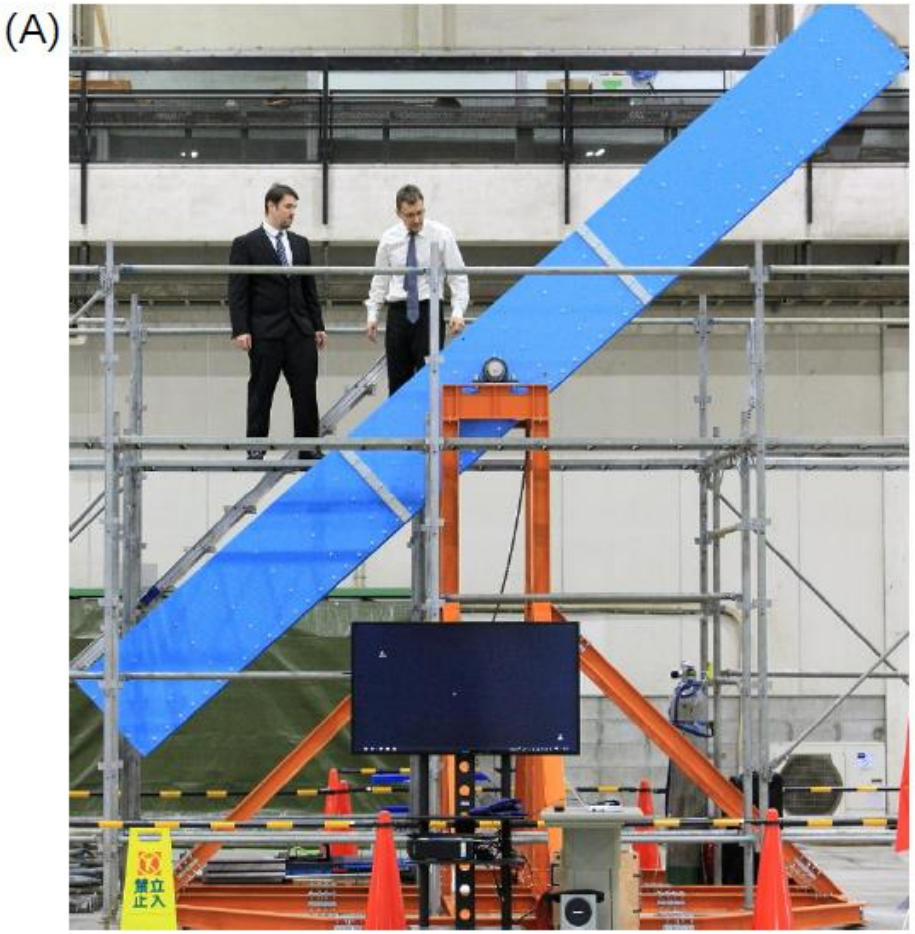


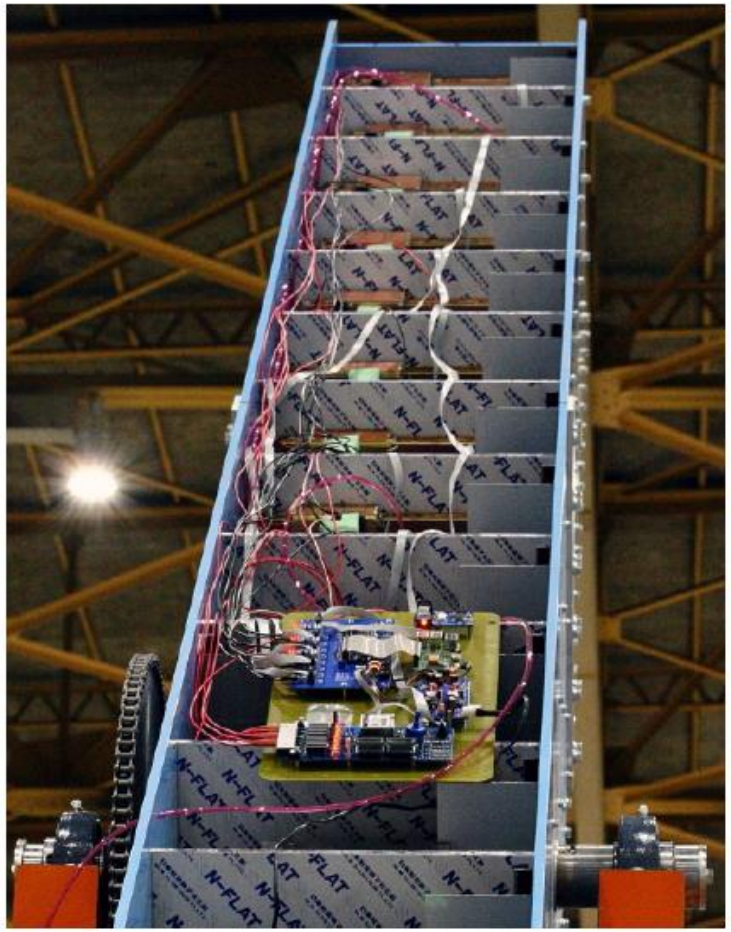


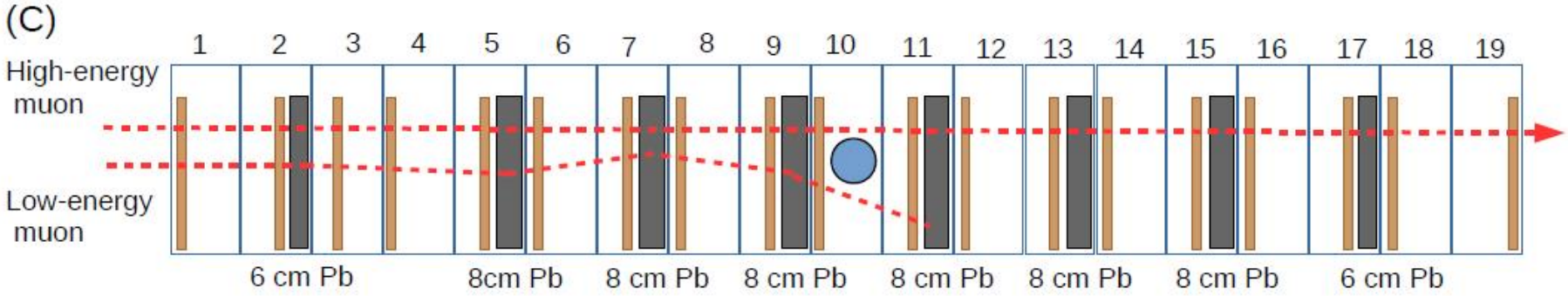
Secondment projects

NEWCUT

- Low E muon spectra
- For better imaging smaller objects
- 6 m, rotatable
- 19 MWPC + Pb walls
- Optimization: Neural network GEAN4 simulation







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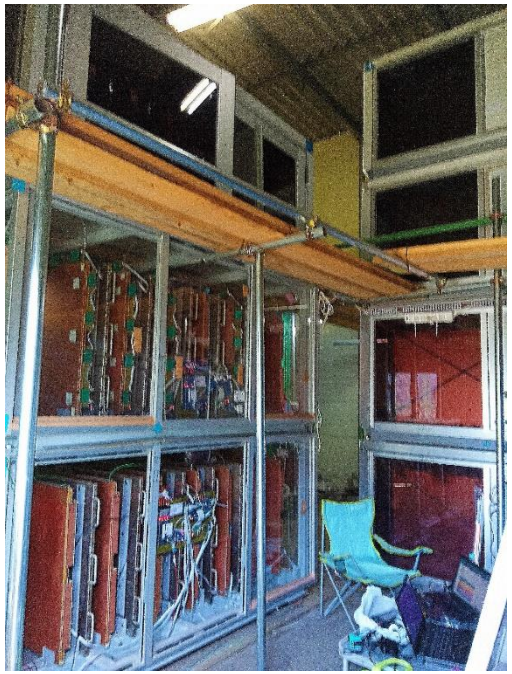
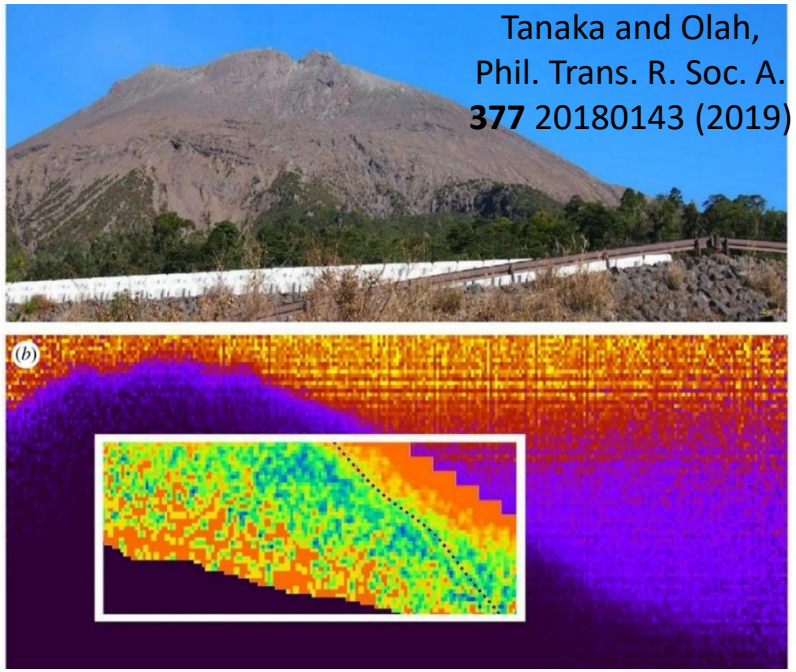
Secondment projects

Muography **O**bservation **S**ystem at the Sakurajima volcano

- Collaboration and patent[1] with the University of Tokyo since 2016
- Continuous extension of the observatory
- 8.7 m^2 total, 11 detector module

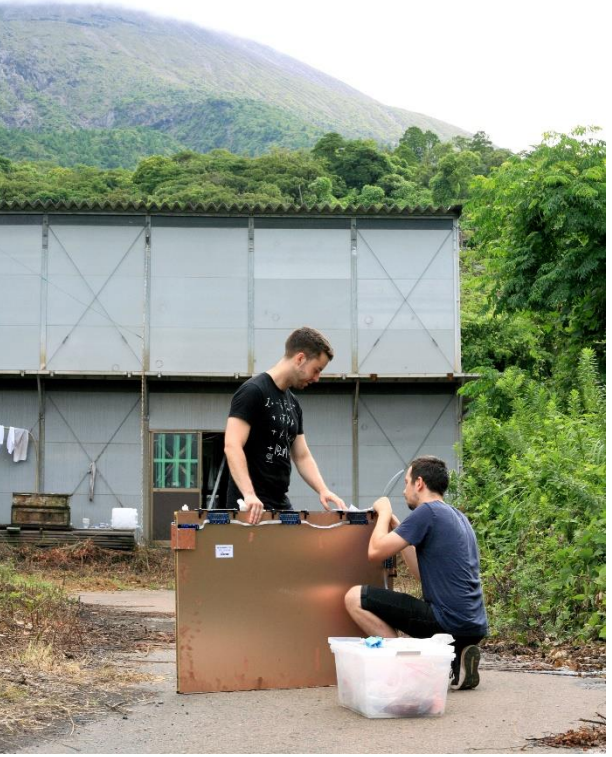


[1]H. Tanaka, K. Tarou, D. Varga, G. Hamar, L. Oláh: Muographic Observation Instrument, Japanese Ref. No.: 2016-087436, date 25/04/2016



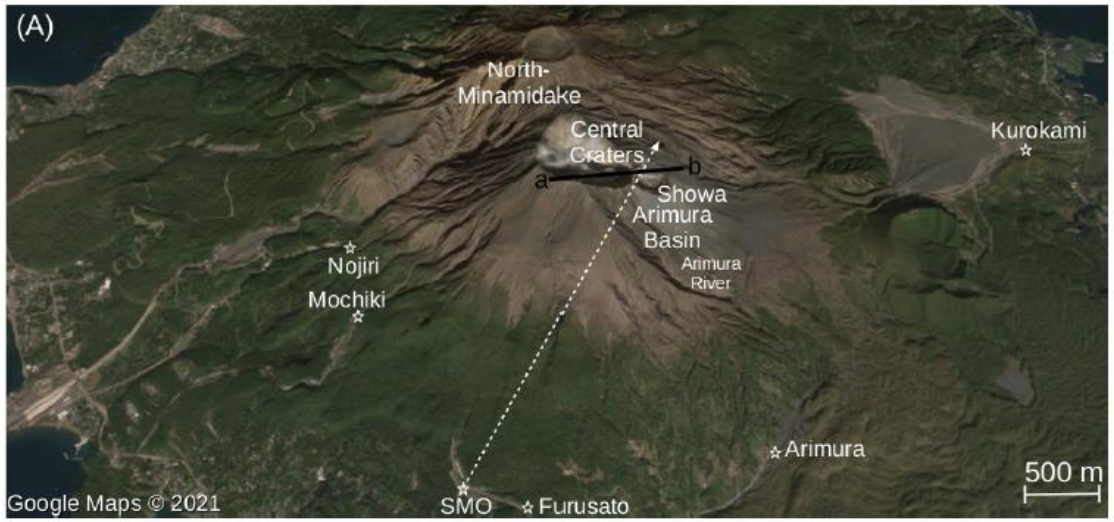
Tanaka and Olah, Phil. Trans. R. Soc. A. **377** 20180143 (2019)

Secondment projects: Installations

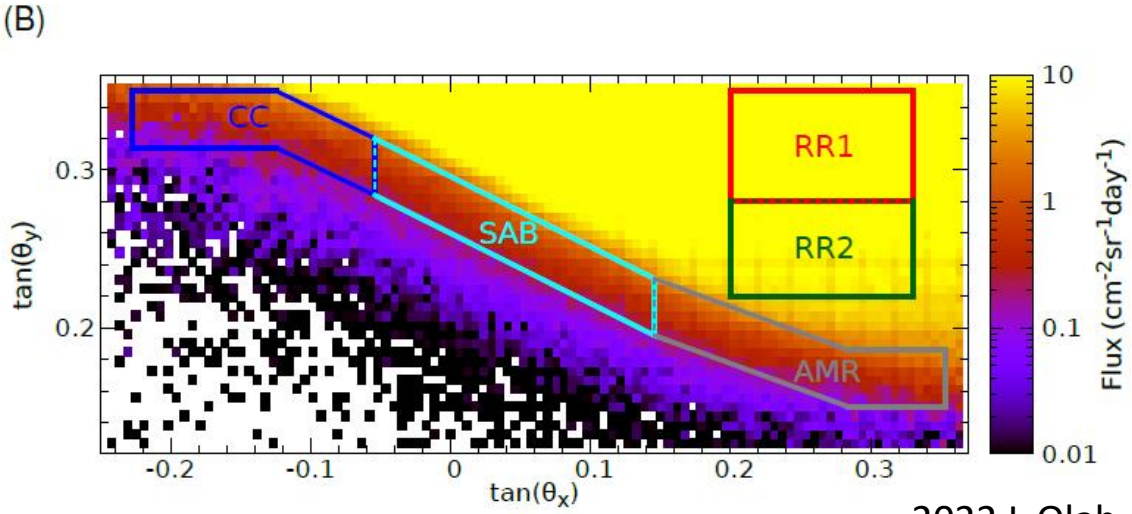


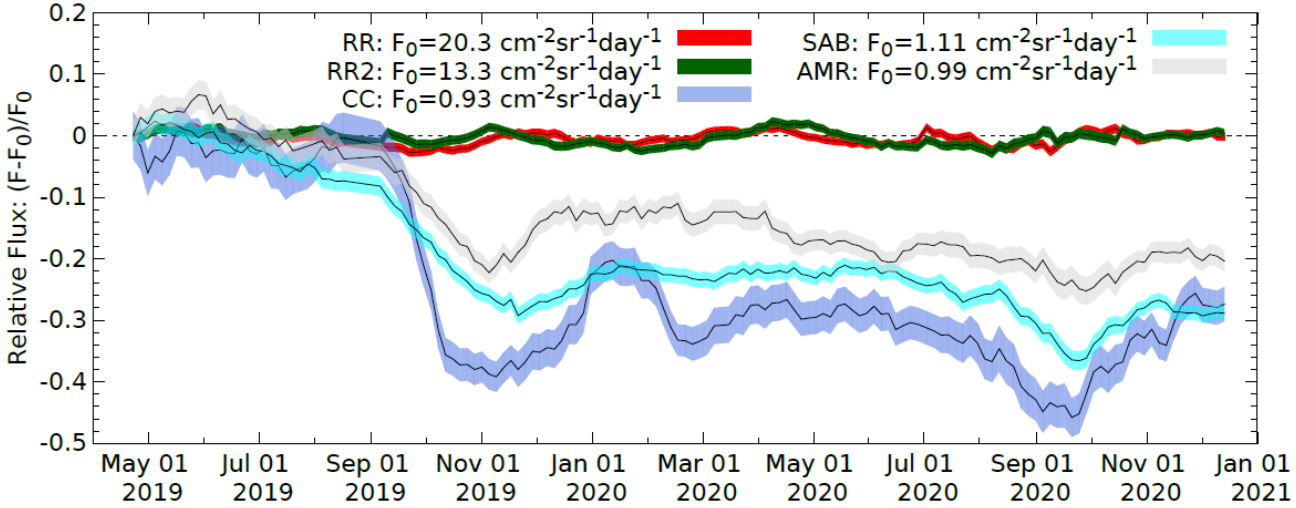
Sakurajima muography results

Lahar monitoring



- Danger: rain triggered lahars (volcanic sediment movement)
- Mass changes by muography
- Better understanding volcanic post activities
- Assessment of hazard levels





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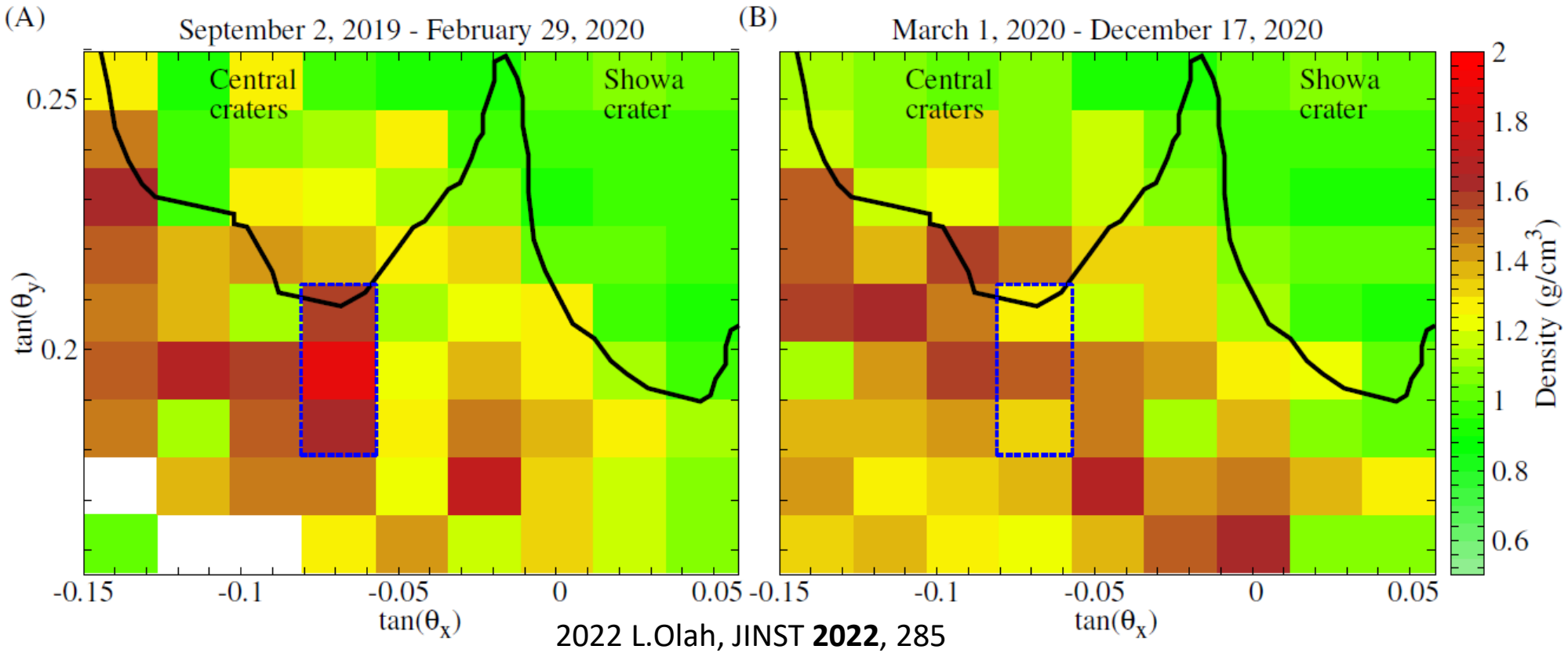
Sakurajima muography results

Plug formation

- Density change under crater regions -> explanation for eruption shift



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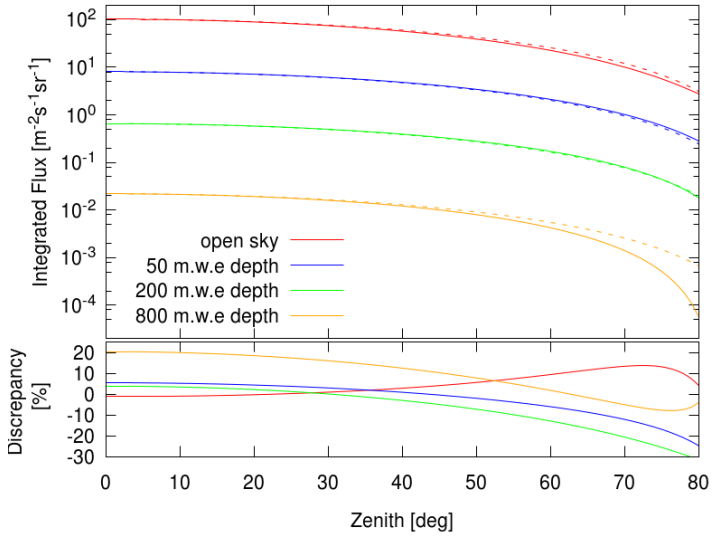
Developments

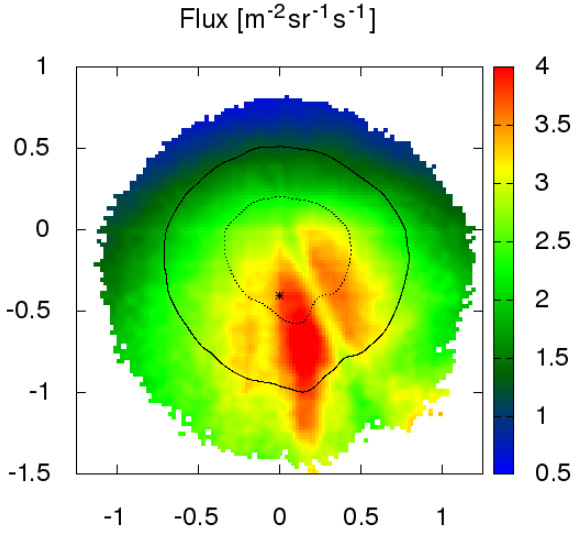
Software

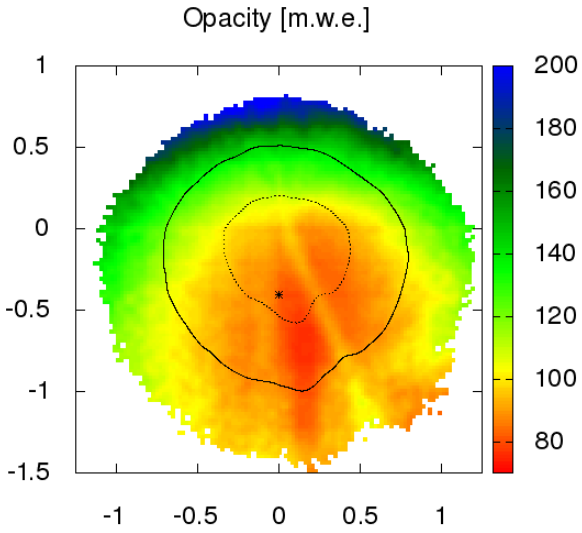
Under the University of Tokyo secondments (supervision: prof. HKM.Tanaka and L.Oláh)

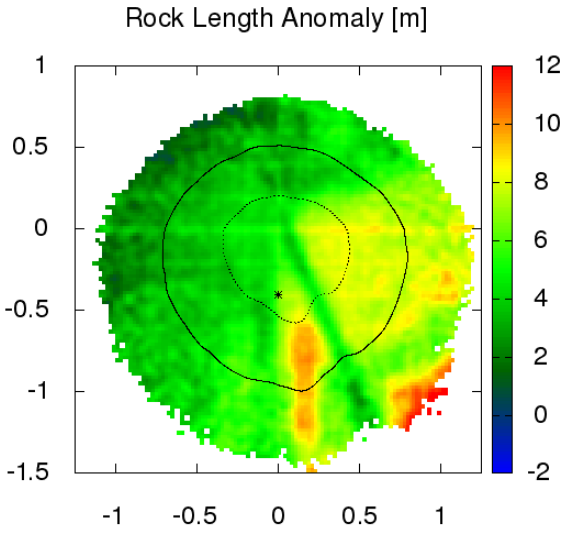
- Precise flux calculation and comparison of rock-thickness data from DEM
- Machine learning as software tool for improved muon tracking

➢ Quantitative evaluation of muographic data





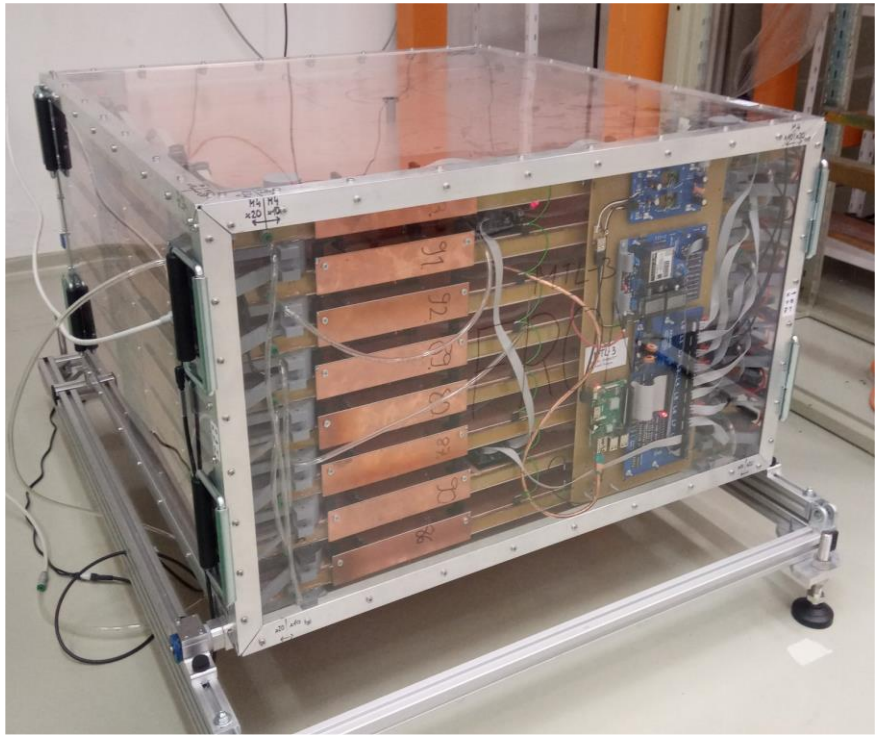




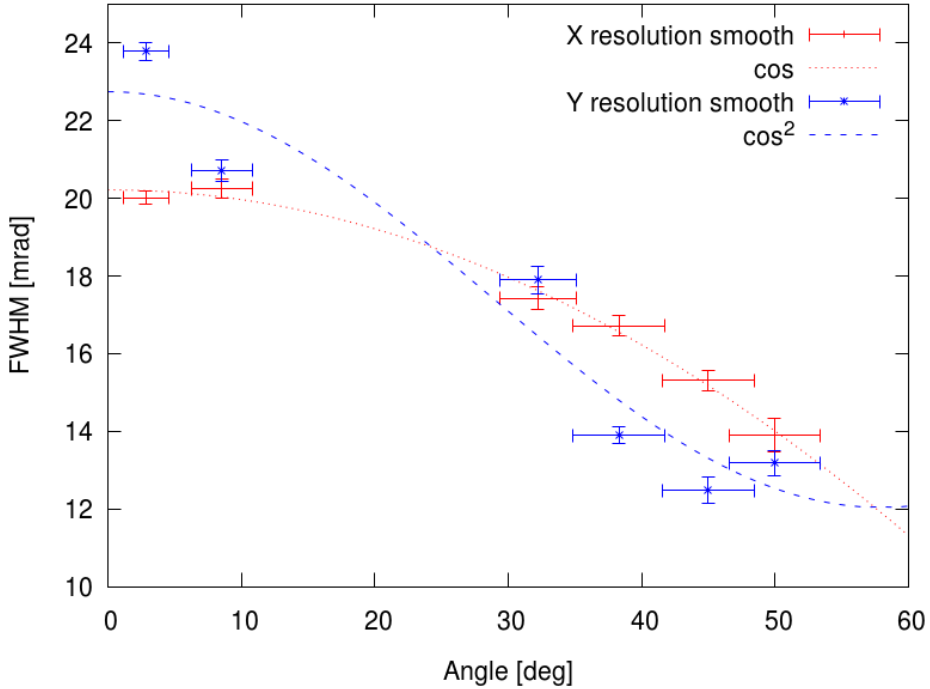
Developments

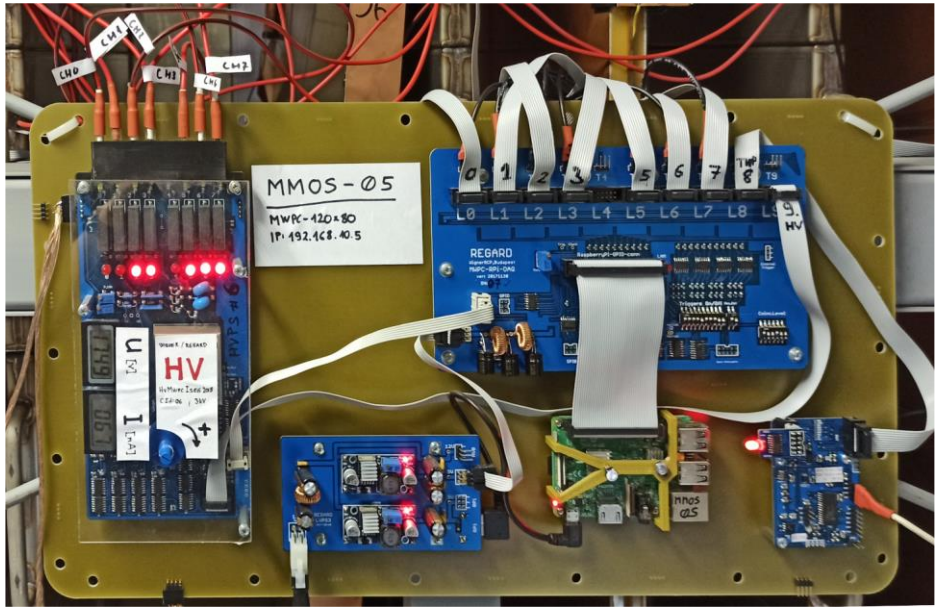
Hardware

For new underground application
(Mining, Archaeology, Civil engineering)



2022 D.Varga, JINST **2022**, 307





Developments

Low gas consumption

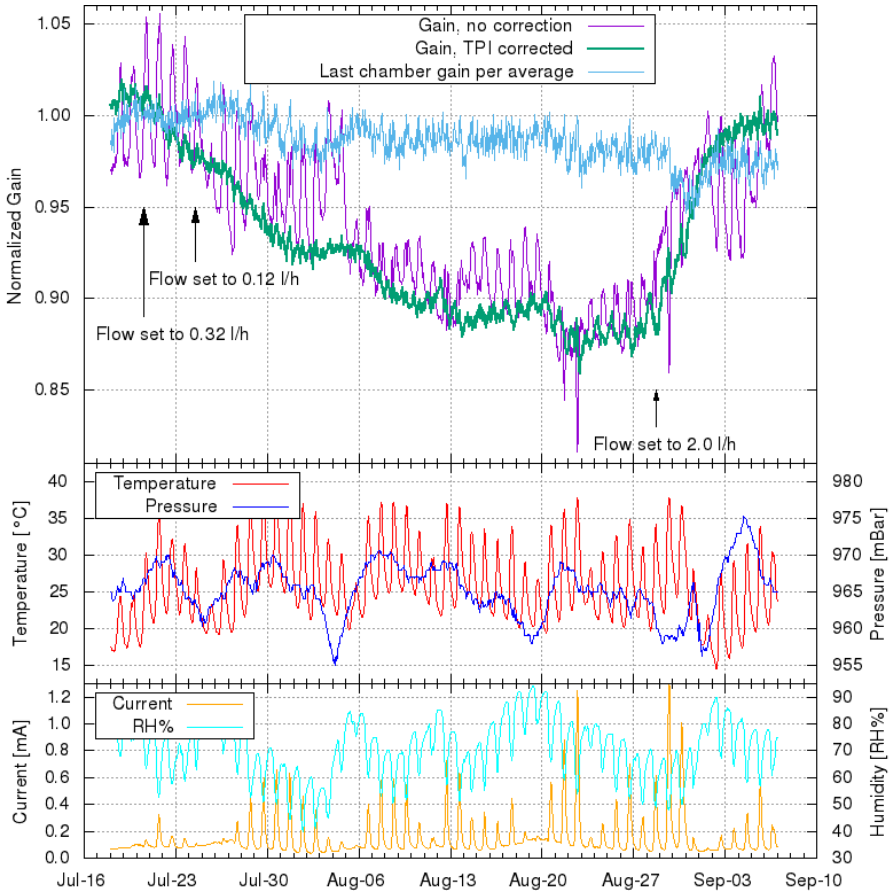
G.Nyitrai
TIPP (2021)

Gas system:

- Open outlet → no stress due to atm. pressure change
- Daily temperature change could cause air backflow → properly designed buffer tube solves the issue
- Low intrinsic outgassing → low input flow possible
- Generally used 1—2 l/h can be decreased to **0.12 l/h**

➢Less maintenance (10 l bottle for a year)

➢More autonomy



2021 G.Nyitrai, *JAP* **129,** 244901

Summary

- Multiple detector technologies in muography. Ours: advanced MWPC (gaseous)
- Important developments thanks to the experiences gathered during the secondments
  - NEWCUT spectrometer upgrade
  - Sakurajima Muography Observatory extension
  - Detection software and hardware developments for better imaging and new applications

- **Geoscientific results shown** (eg. Lahar movements, Plug formation)

Secondment progress

Seconded	Date	Target	Status
G. Galgóczi	31 July 2019 – 31 Aug. 2019	Detector installation, Simulation development	Completed
G. Nyitrai	1 Aug. 2019 – 30 Aug. 2019	Detector installation, Software development	Completed
G. Galgóczi	1 March 2020 – 18 March 2020	Detector installation, Simulation development	Completed
G. Nyitrai	1 March 2020 – 1 Apr. 2020	Detector installation, Software development	Completed
G. Hamar	*2023, 1 month*	*Joint developments*	*Planned*
G. Hamar	*2023, 1 month*	*Joint developments*	*Planned*
G. Galgóczi	*2023, 1 month*	*Detector installation, Simulation development*	*If possible*
G. Nyitrai	*2023, 1 month*	*Detector installation, Software development*	*If possible*

Thank you for your attention!

INTENSE Acknowledged scientific releases:

List of publications since 2019

- 2021 L.Oláh „Muographic monitoring of hydrogeomorphic changes…” SciRep **11**, 17729
- 2021 G.Nyitrai „Toward low gas consumption…” JAP **129**, 244901
- 2021 G.Hamar „Gaseous Tracking Detectors at the Sakurajima…” TIPP’21
- 2022 D.Varga „Construction and readout system…” JAIS **2022**, 307
- 2022 L.Oláh „Development of Machine Learning…” JAIS **2022**, 264

5 best international presentations

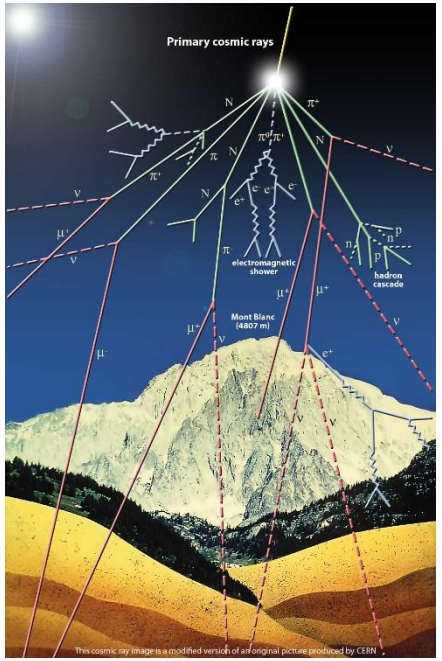
- 2021 G.Hamar „Underground Muography with Portable Gaseous Detectors” TIPP’21 online
- 2021 G.Nyitrai „Low gas consumption in tracking detectors for outdoor applications” TIPP’21 online
- 2021 D.Varga „Construction and readout systems of gaseous muography detectors” Muographers (Ghent, Belgium)
- 2022 G.Nyitrai „Overview of muography in geoscientific research” EGU’22 (Vienna, Austria)
- 2022 G.Nyitrai „ Volcano muography with MWPC cosmic ray detectors” CoV’22 (Heraklion, Greece)

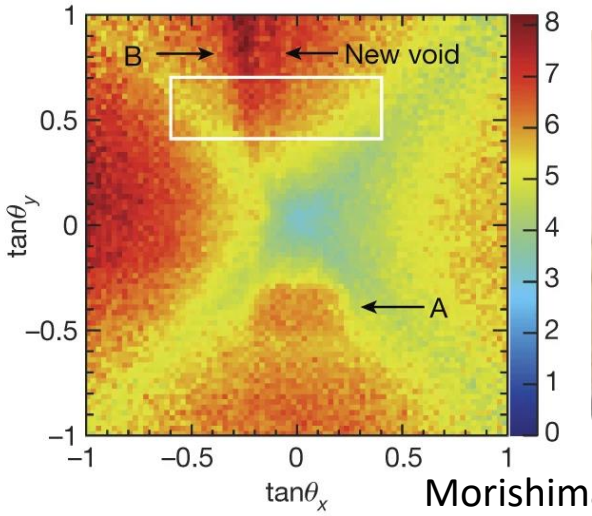
Backup slides

Muography principles

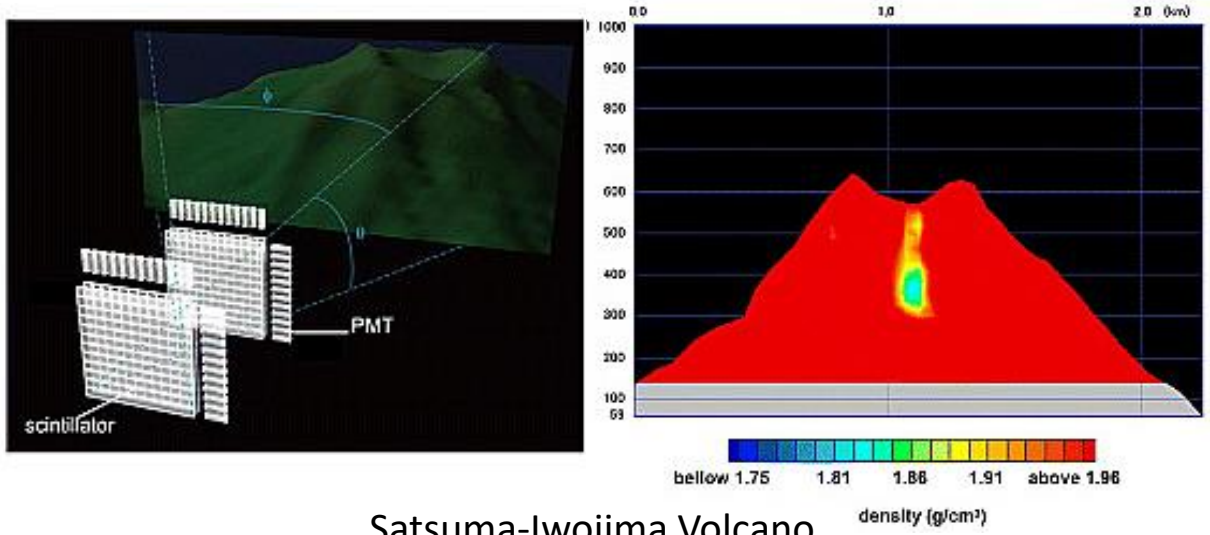
Imaging with cosmic muons

- High energy cosmic particle collisions in the upper atmosphere
  → **Muons**
- Muon flux can be measured in a direction by tracking
  → **Detectors**
- Flux is proportional to the integrated density-length (absorption)
  → **X-ray-like images**
- Imaging static **density anomalies** or
  dynamic **density changes** in high resolution



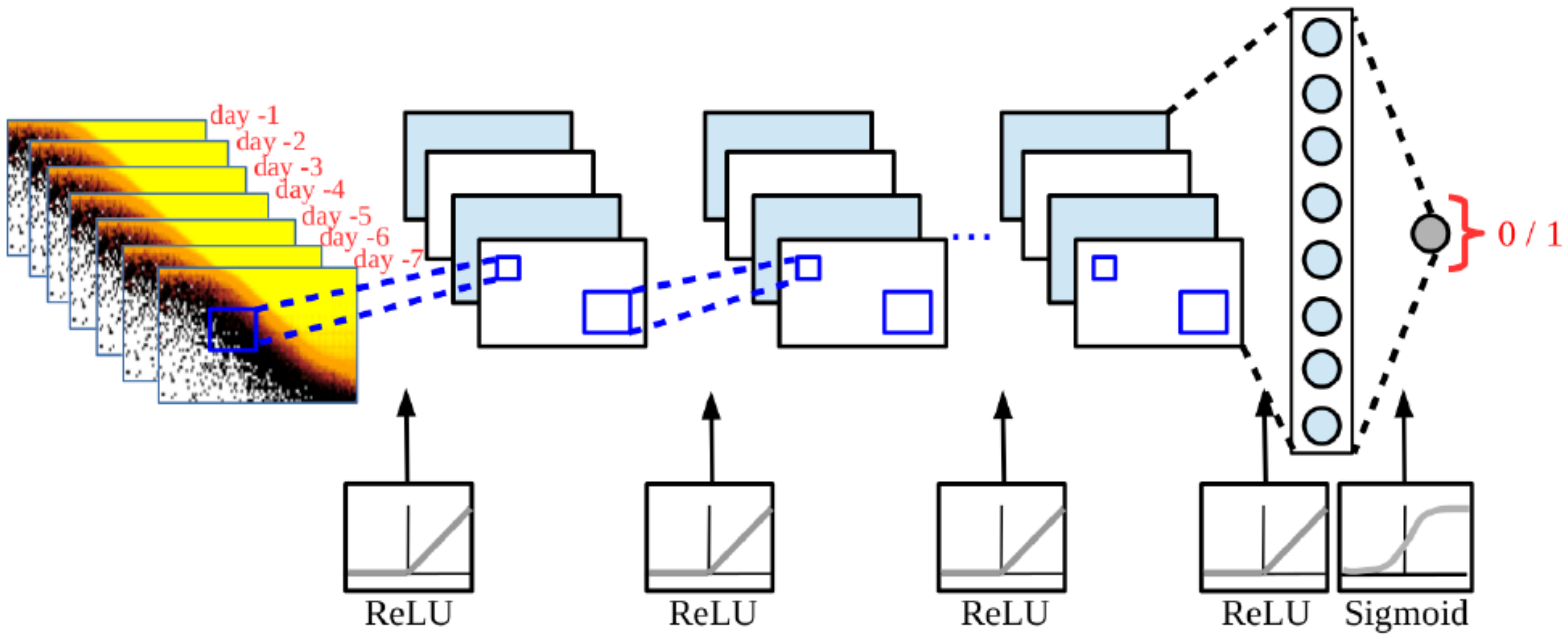


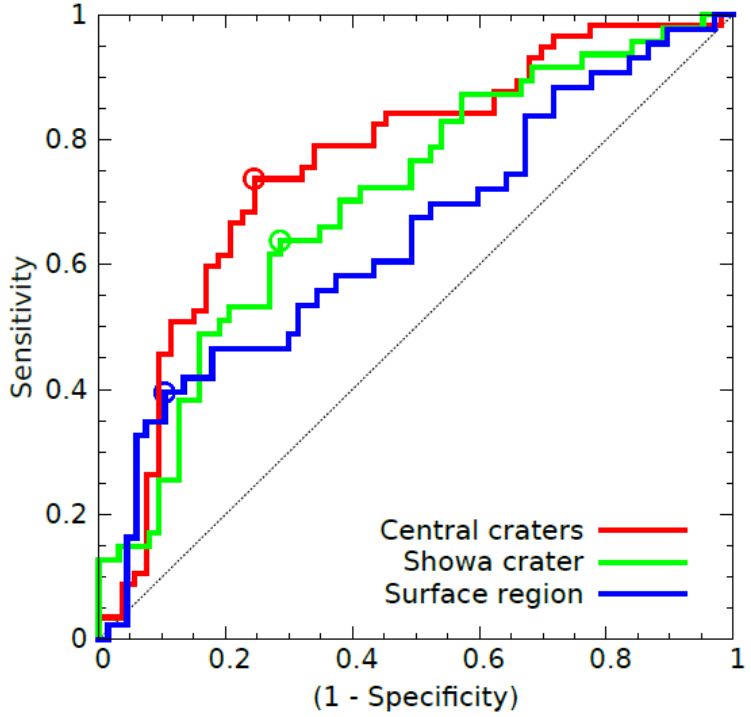
Morishima et al, *Nature* **552,** 386 (2017)



Satsuma-Iwojima Volcano
Tanaka et al, *GRL* **36,** 1 (2009)

Sakurajima Results: AI Forcasting

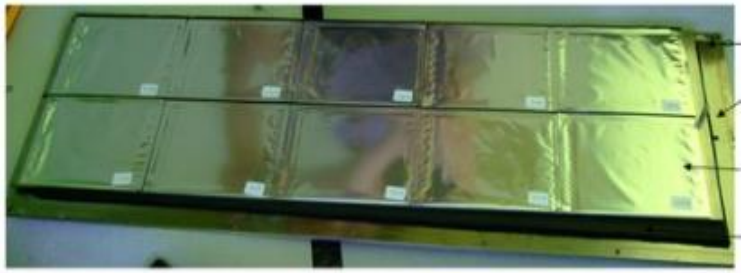




Muography detectors

Detector technologies

Emulsion detectors



Tioukov et al, *Sci Rep* **9,** 6695 (2019)

- Nuclear emulsion layer
- Submicroscopic track when muon passes
- Readout: development, scanning
- PRO: high resolution, no consumption
- CONTRA: no monitoring, complex readout

Scintillator detectors

Lo Presti et al, *NIMA* **904,** 195 (2018)

- Scintillator rods
- Light flash when muon passes
- Readout: photo-electron conversion, HV multiplier
- PRO: easy construction or good resolution
- CONTRA: weight, high cost vs. resolution tradeoff

Gaseous detectors

Nyitrai et al, JAP **129**, 244901 (2021)

- Gaseous chambers
- Electron ionization when muon passes
- Readout: HV, electron avalanche, amplification
- PRO: large area, low weight, good cost-resolution tradeoff
- CONTRA: complex construction, gas usage

Flux calculations

$$I(\rho,\Theta) = \int_{E_{min}(\rho)}^{\infty} \Phi(E_0,\Theta)dE_0 \ \ [\mathrm{m}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}]$$

- 1990 Gaisser

$$\Phi_G(E_0,\Theta) = A_G E_0^{-\gamma}\left(\frac{1}{1+\hat{E}_0\cos\Theta/E_{0,\pi}^{cr}} + \frac{B_G}{1+\hat{E}_0\cos\Theta/E_{0,\pi}^{cr}} + r_c\right)$$

- **2006 Tang**: modified Gaisser
- **2015 Guan**: modified Gaisser

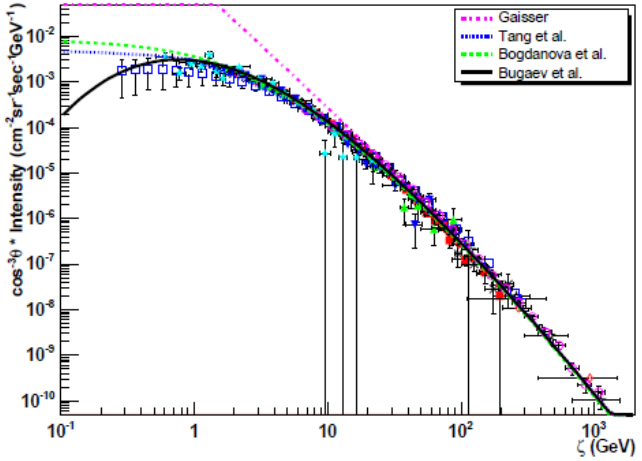
- 1998 Bugaev paraméterezés

$$\Phi_B(p) = A_B p^{-(\alpha_3 y^3+\alpha_2 y^2+\alpha y+\alpha_0)}$$

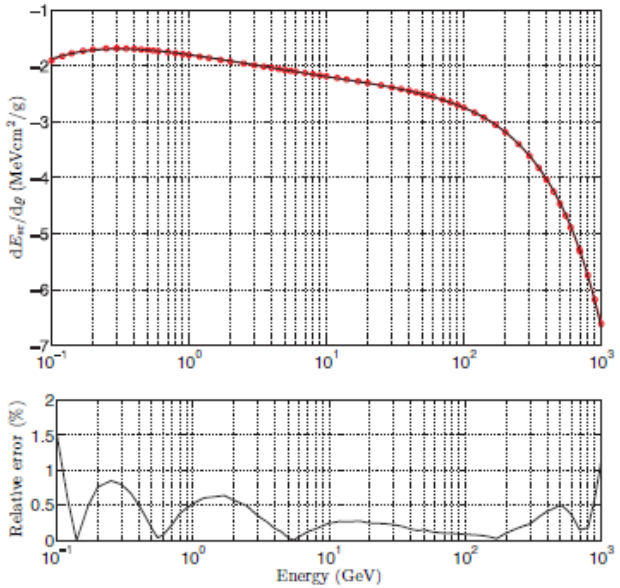
- **2006 Reyna**: Bugaev + angle dependence

$$\Phi_R(p,\Theta) = \cos^3(\Theta)\,\Phi_B(p\cos\Theta)$$

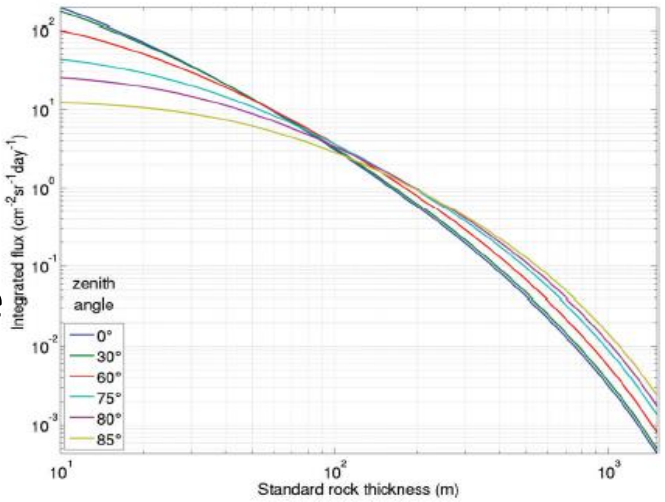
- MC simulations



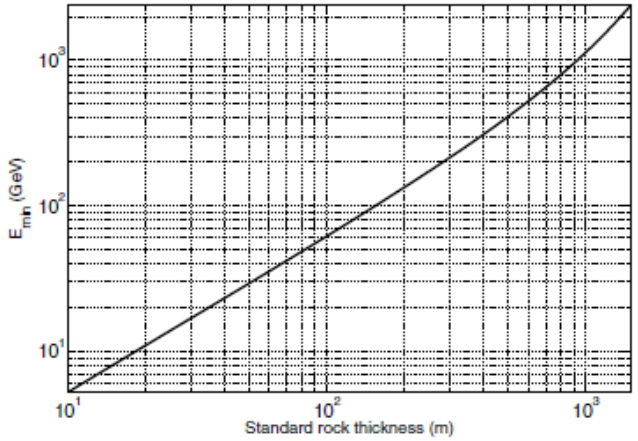
$\Phi(E_0,\Theta)$ Muon spectrum [2006 Reyna]



dE/dρ [PDG]



$I(\rho,\Theta)$ Flux [2012 Lesparre]



$E_{min}(\rho)$ [2010 Lesparre]

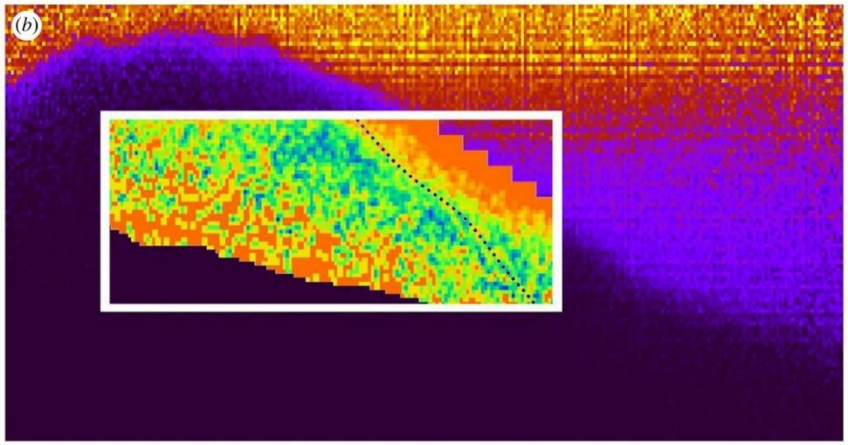
Fields of applications

Muon absorption

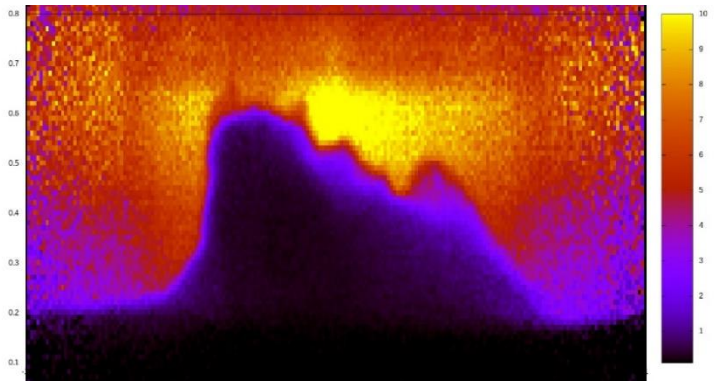
- Volcanology
- Mining
- Archaeology
- Civil engineering
- Others: speleology, glaciology, groundwater, atmosphare monitoring, nuclear reactor, etc…

Muon scattering

- Nuclear waste/fuel cargo tomography



Sakurajima volcano.
Tanaka and Olah,
Phil. Trans. R. Soc. A.
377 20180143 (2019)



Castle of Mussomeli, archaeology, preliminary. Collab with Univesity of Catania, University of Tokyo, and City of Mussomeli.

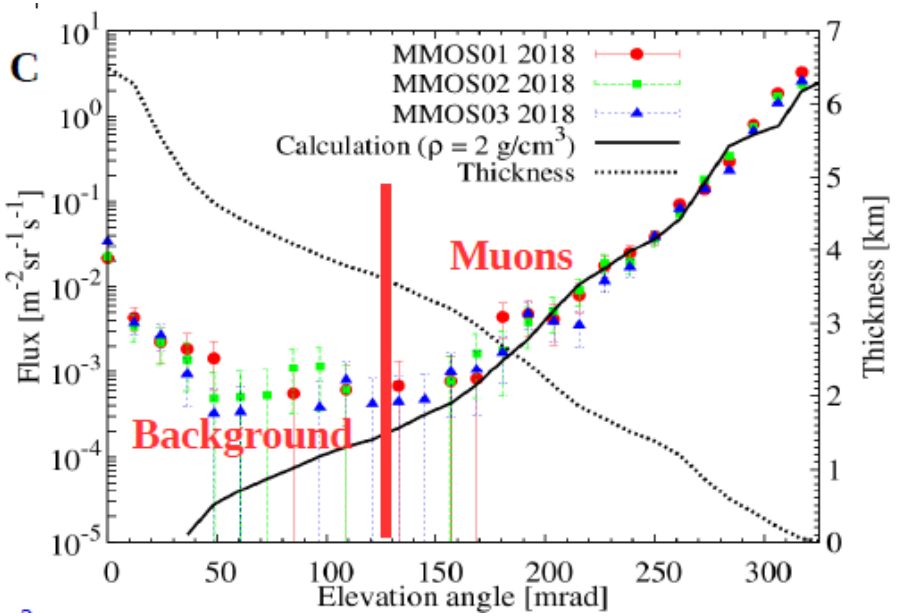
Further reading:
2022 L. Olah et al „Muography: Exploring Earth's Subsurface with Elementary Particles”
Geophysical Monograph **270**, ISBN 9781119723028

Background suppression

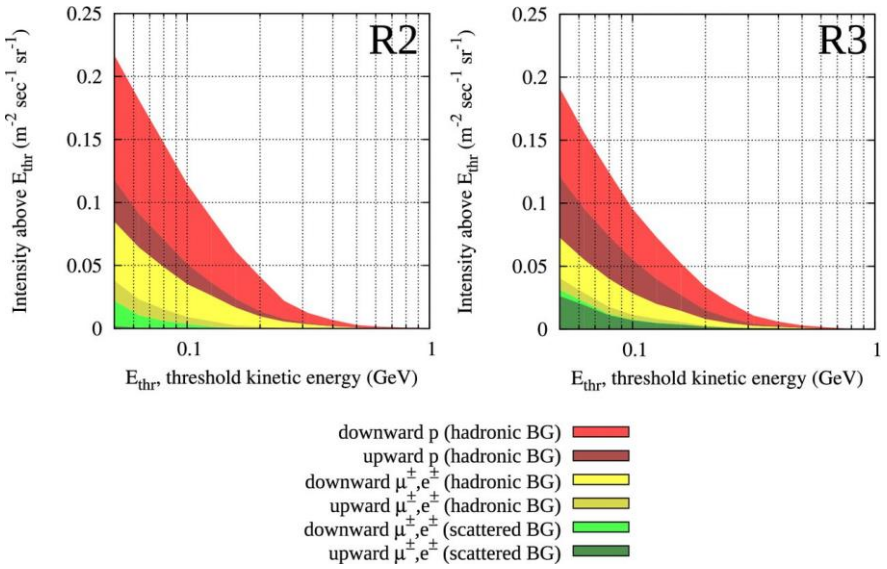
A review of background sources in:
L. Bonechi *Rev. Phys* **5**, 100038 (2020)

Practices to assort low energy particles

- Scattering lead wall for 0.1—1 GeV cut-off
  [L. Oláh *Sci. Rep.* **8**, 3207 (2018)]
  Background as low as 10^{-3} 1/m^2/s/sr with 5—10 cm lead
- Cherenkov detector and/or ToF measurement against backscattering
  [J. Peña-Rodríguez, PoS ICRC2021, 395 (2021)]



L.Oláh, Pisa Meeting (2018).



R. Nishiyama, *GJI* **206**, 2 (2016)

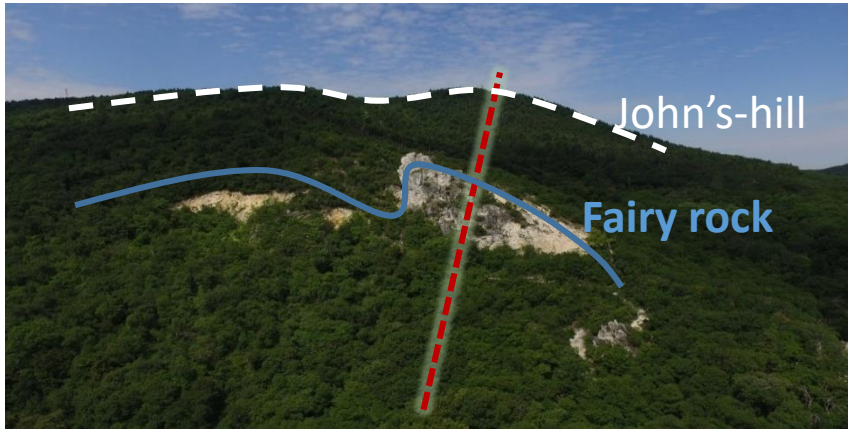
Surface muography projects:

Budapest Fairy Rock

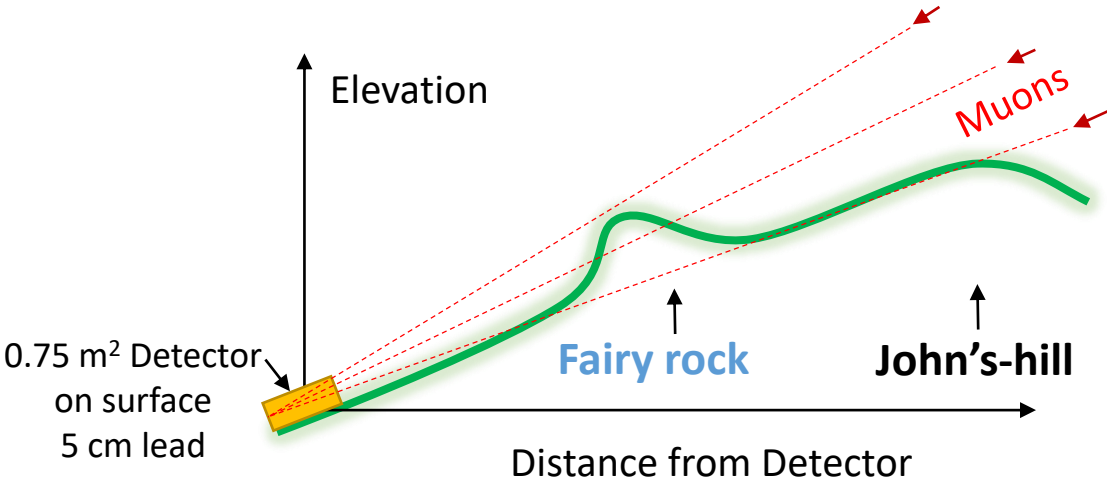
- Motivation:
  - Demonstration of looking through a mountain
  - Measuring the effect of multiple scattering
  - Measuring the imaging resolution of muography
- Idea:
  finding a geographical place where there is a high gradinet of density-length behind a hill
- Setup:
  Fairy Rock (50—100 m rock length) in front of the detector
  Contour of John’s hill behind the Fairy Rock is a high gradient region

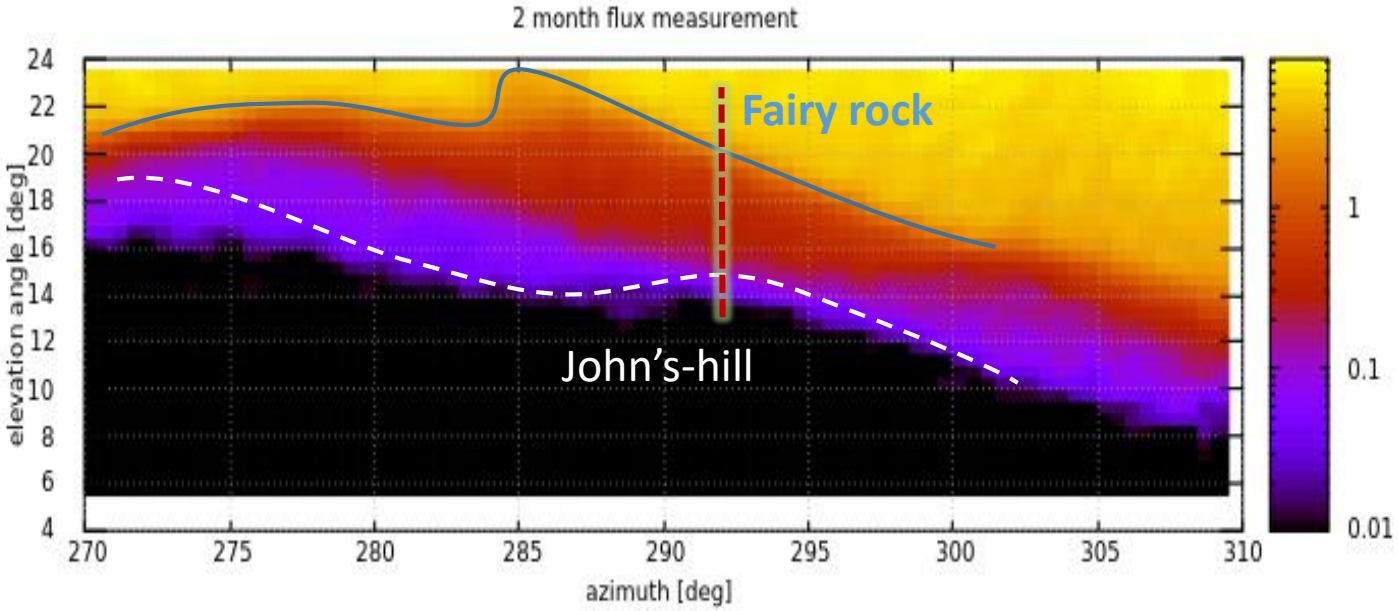
Resolution of muography

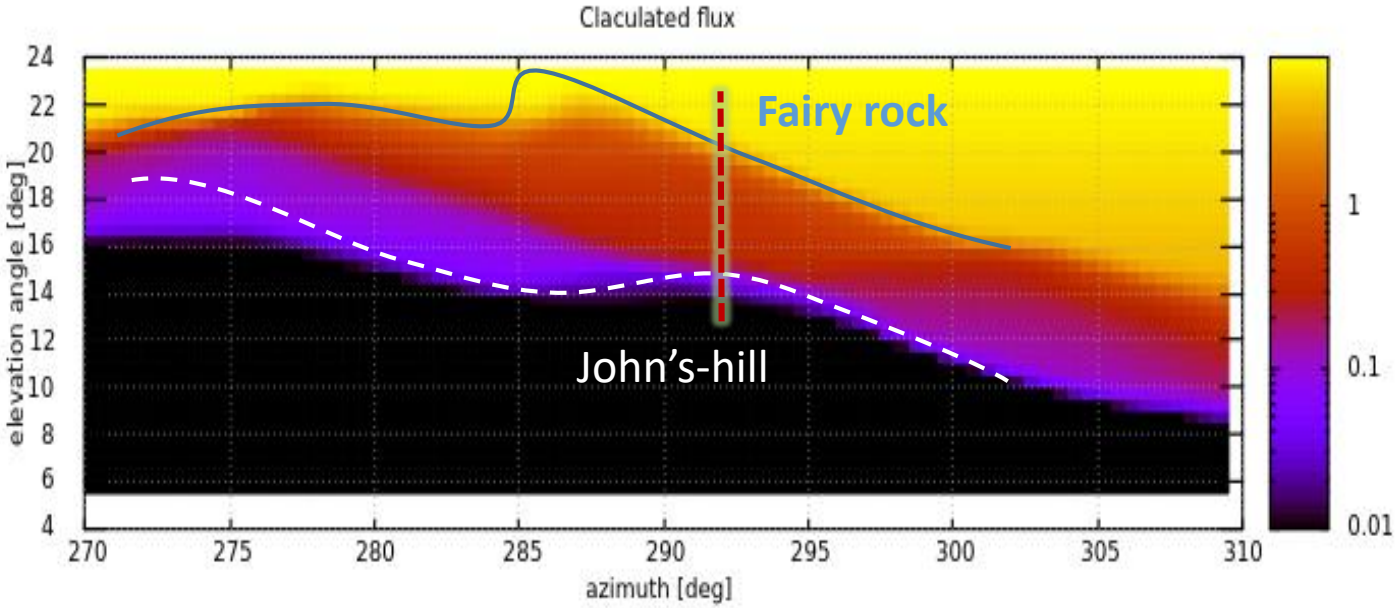
Budapest Fairy Rock



Drone photo 50 m above the detector







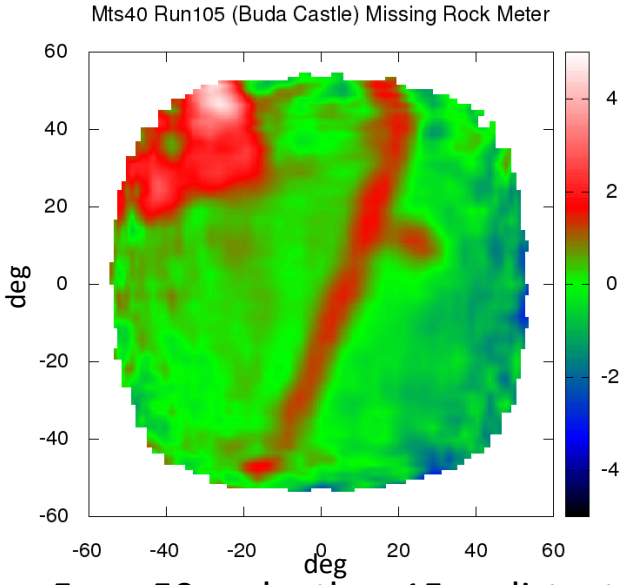
Underground

Detector requirements in practice…

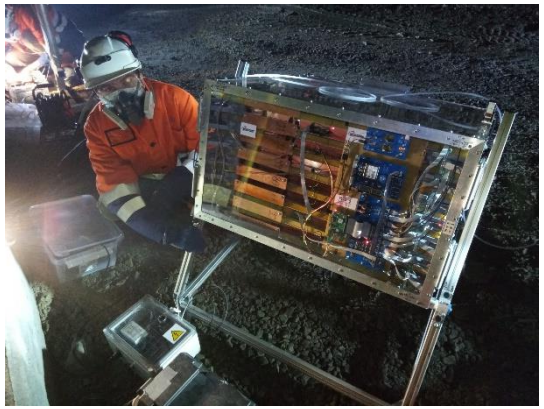
- Size (available space)
- Robustness (movement, vibrations, water, dust, temperature, humidity, pressure)
- Mobility (weight)
- Autonomy
  - low power consumption for battery
  - low gas consumption for gaseous detectors
  - remote data collection
- Resolution (10-50 mrad)

An old mine in Hungary.

A natural cave near Budapest.



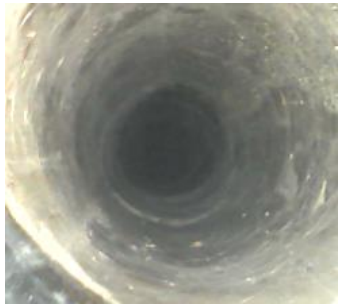
From 50 m depth, a 15 m distant ⌀ 1.5 m tunnel in the Buda Castle.

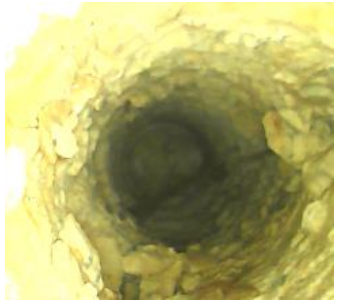


An active mine in Finland.

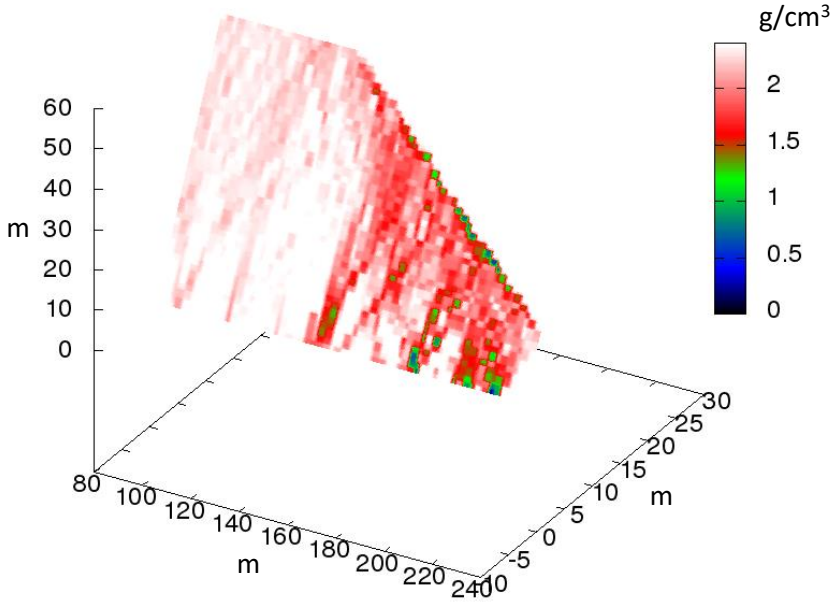
3D tomography

- Királylak (Budapest), speleology
- Measurements in a line
- 2+1D inversion on tilted slices
- Erosion zones found

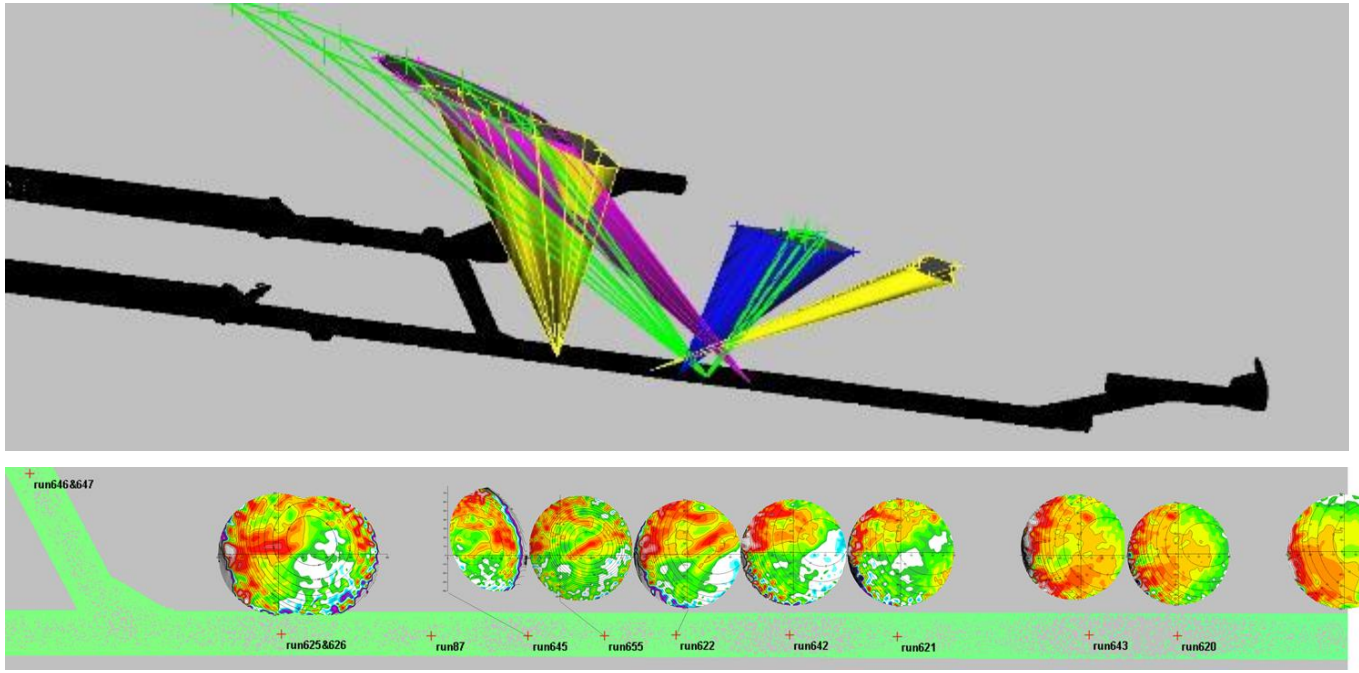




Validation by drilling.

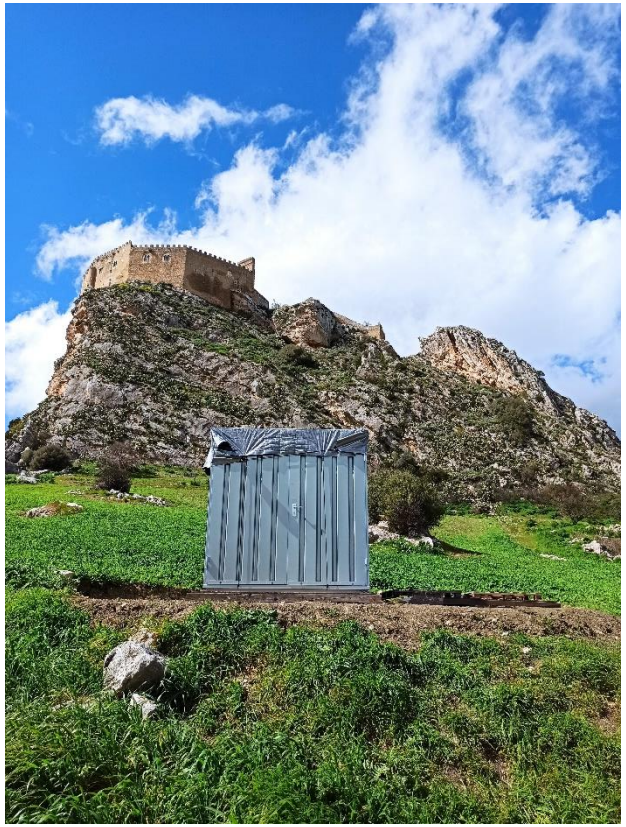


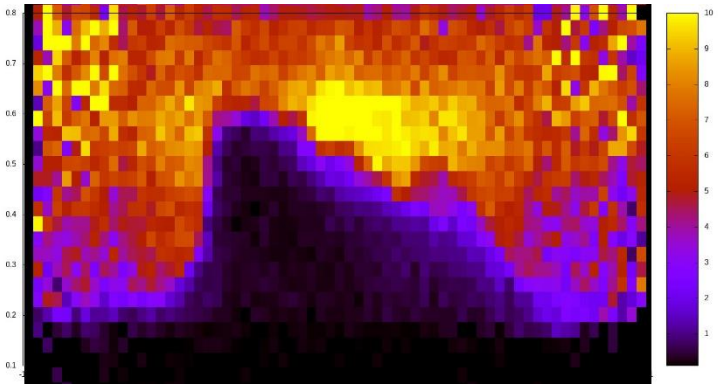
Inversion result with a weighted least square method.

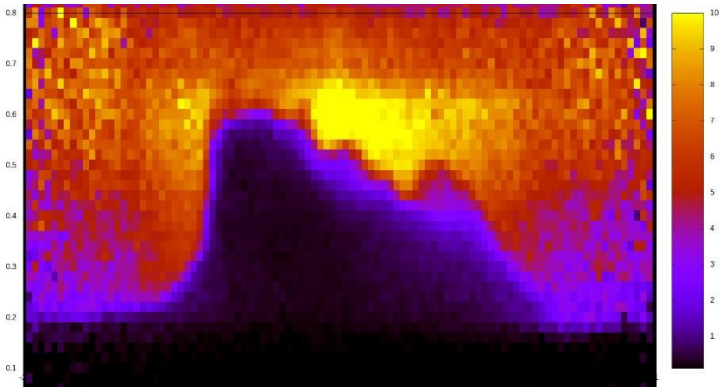


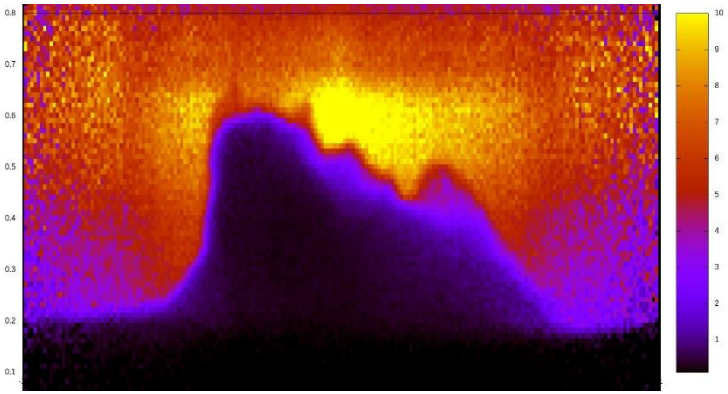
Multiple muograph image along a straight tunnel.

Mussomeli



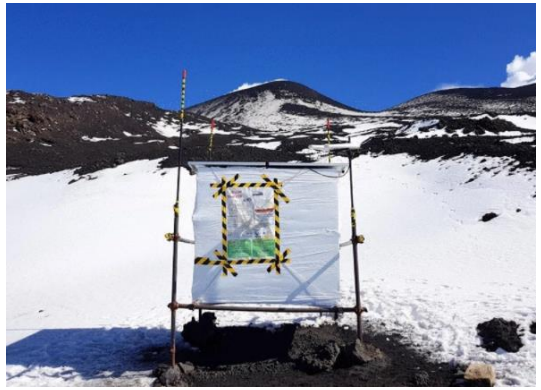


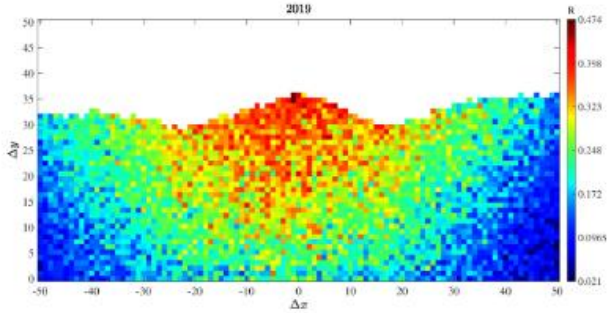




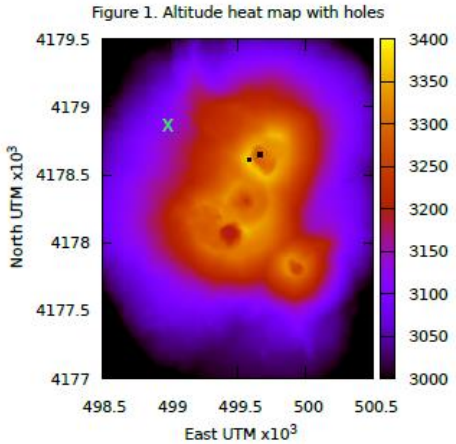
Surface muography projects:
Etna volcano

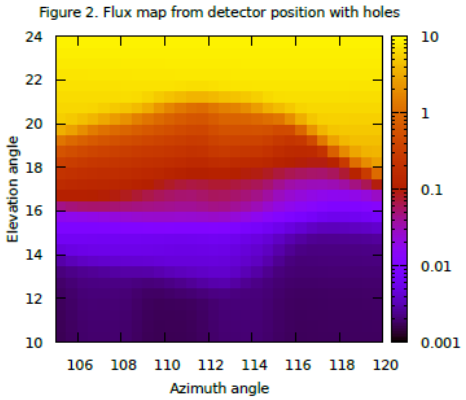
- New collaboration will be with the University of Catania
- For observation and tomography of the Etna
- Combination of scintillator and gaseous detector
- Challenges: 3000 m altitude, several m snow in winter, regular large eruptions (area closed)

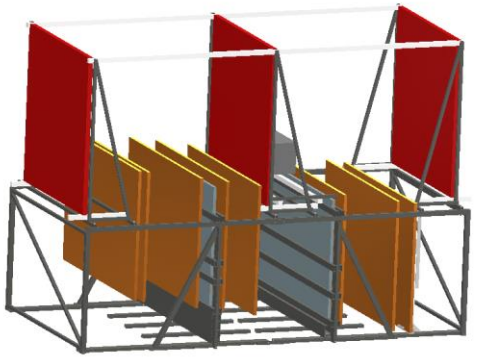




[Lo Presti, *SciRep* **10**, 11351 (2020)]







Systematic errors

- Different flux calculation methods
- Altitude-correction
  [2002 Hebbeker & Timmermans]
  $$\Phi(h) = \Phi(h = 0) \cdot \exp(-h/h_0)$$
- Geomagnetic effect
  [2000 Cecchini]
- Solar wind
  [1978 Bhattacharyya]
- Temperature/Pressure
  [1997 Ambrosio, 2009 Tilav]
- Rock composition
  [2018 Lechmann]

- Energy minimum calculation
- Multiple scattering
  [2018 Oláh]
- Detection errors
  (resolution, efficiency, acceptance, etc.)
- Density-length errors
  (detector position/angle, surface map accuracy, etc.)
- The angle dependence of the errors

+ Statistical errors..
(number of muons)