Overview of muography in geoscientific research

EGU General Assembly 2022

Vienna

[1,2,3]Gábor Nyitrai, [1]G. Surányi, [1,2]G. Hamar
[1]Wigner RCP, Budapest, Hungary
[2]International Virtual Muography Institute, Global
[3]Budapest University of Technology and Economics, Hungary

nyitrai.gabor@wigner.hu

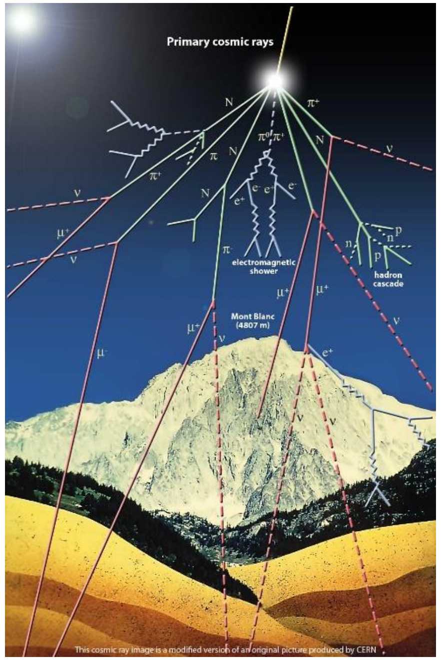
Outline

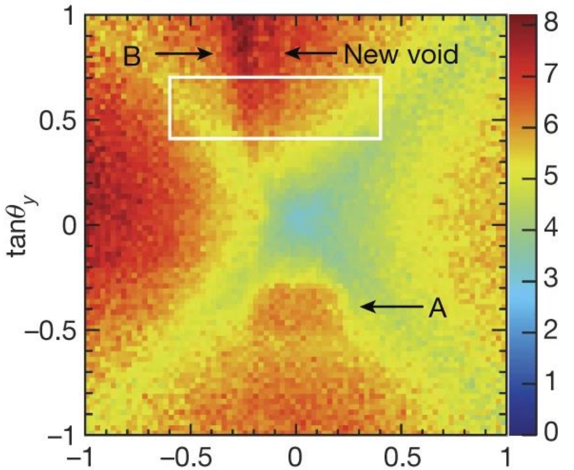
- Muography principles
- Fields of application
- Detector technologies
- Characteristics of muography
- Examples

Muography principles

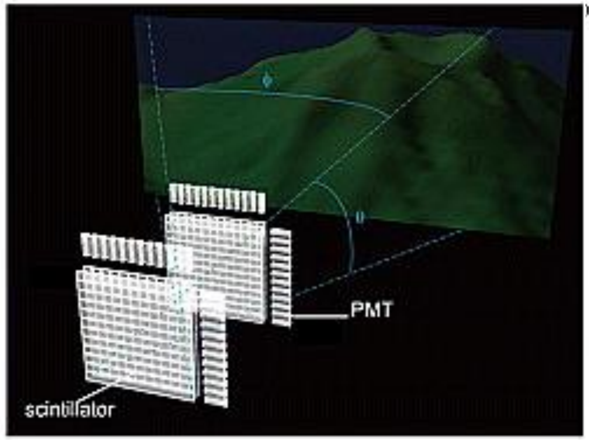
Imaging with cosmic muons

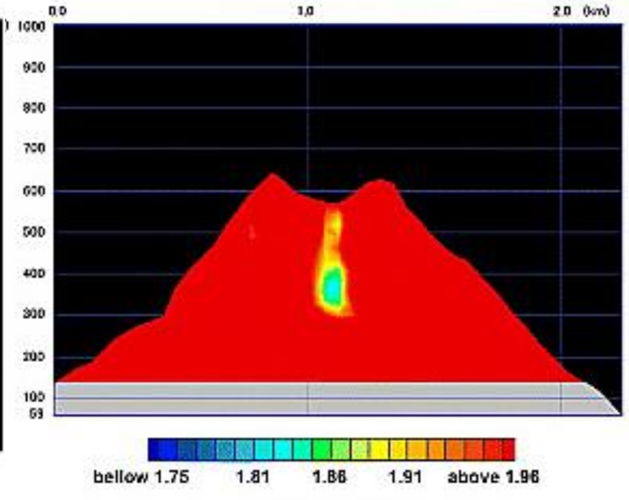
- High energy cosmic particle collisions in the upper atmosphere
  → **Muons**
- Muon flux can be measured in a direction by tracking
  → **Detectors**
- Flux is proportional to the integrated density-length (absorption)
  → **X-ray-like images**
- Imaging static **density anomalies** or
  dynamic **density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





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





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

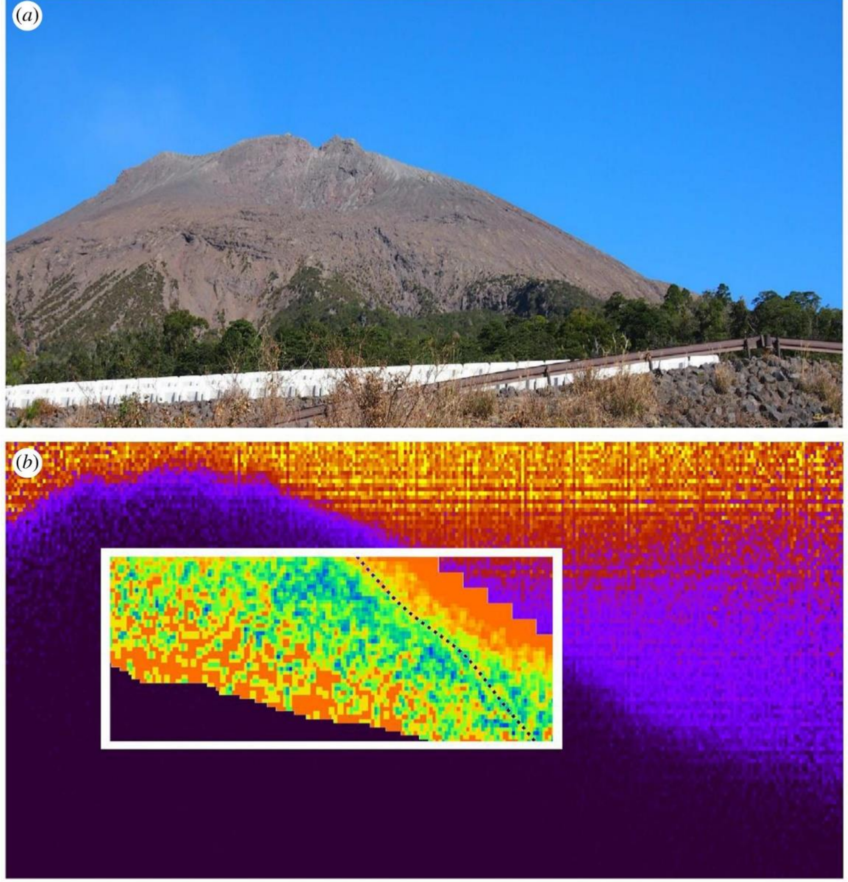
Fields of applications

Muon absorption

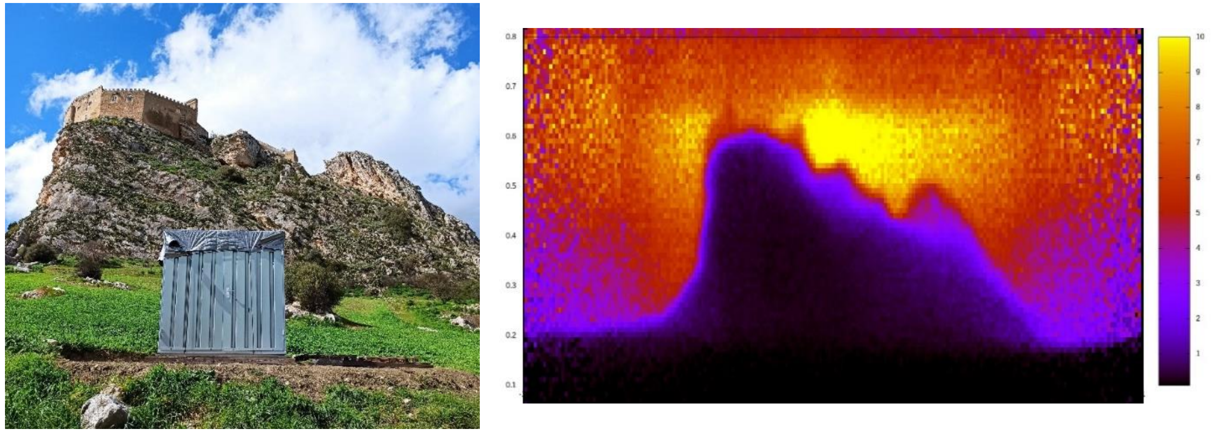
- Volcanology
- Mining
- Archaeology
- Civil engineering
- Others: speleology, glaciology, groundwater, atmosphare monitoring, nuclear reactor, etc…

Muon scattering

- Nuclear waste/fuel cargo tomography



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

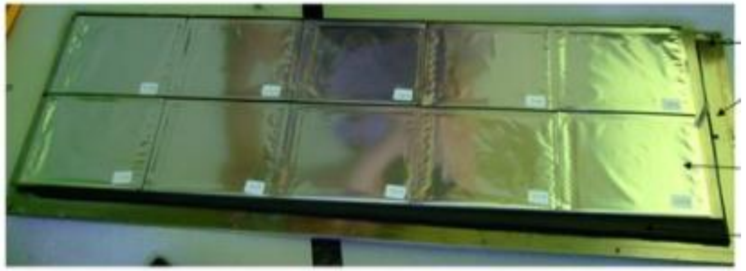


Castle of Mussomeli, archaeology, preliminary. Collab with Univesity of Catania, University of Tokyo, and City of Mussomeli.

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

Detector technologies

Emulsion detectors



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

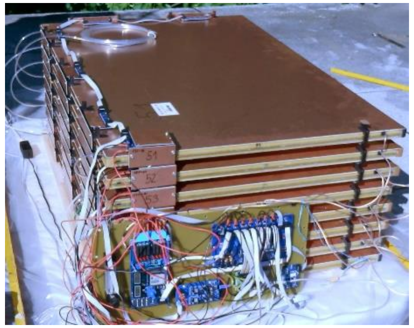
- Nuclear emulsion layer
- Submicroscopic track when muon passes
- Readout: development, scanning
- PRO: high resolution, no consumption
- CONTRA: no monitoring, complex readout

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

Characteristics of muography

Measurement preparation:

- 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

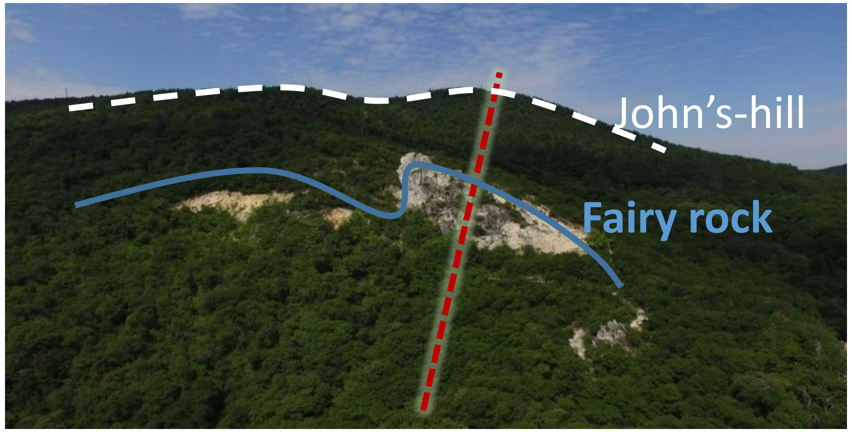
Requirements for detector design:

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

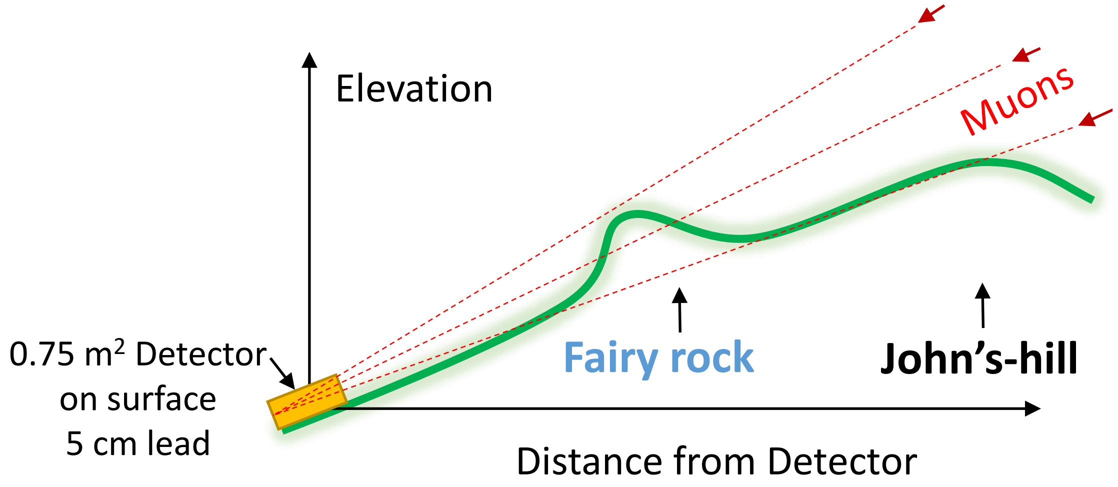
Reviews:
2021 A. Lechmann et al „Muon tomography in geoscientific research – A guide to best practice"
Earth-Science Reviews **222**, 103842
2020 L. Bonechi et al „Atmospheric muons as an imaging tool"
Reviews in Physics **5**, 100038

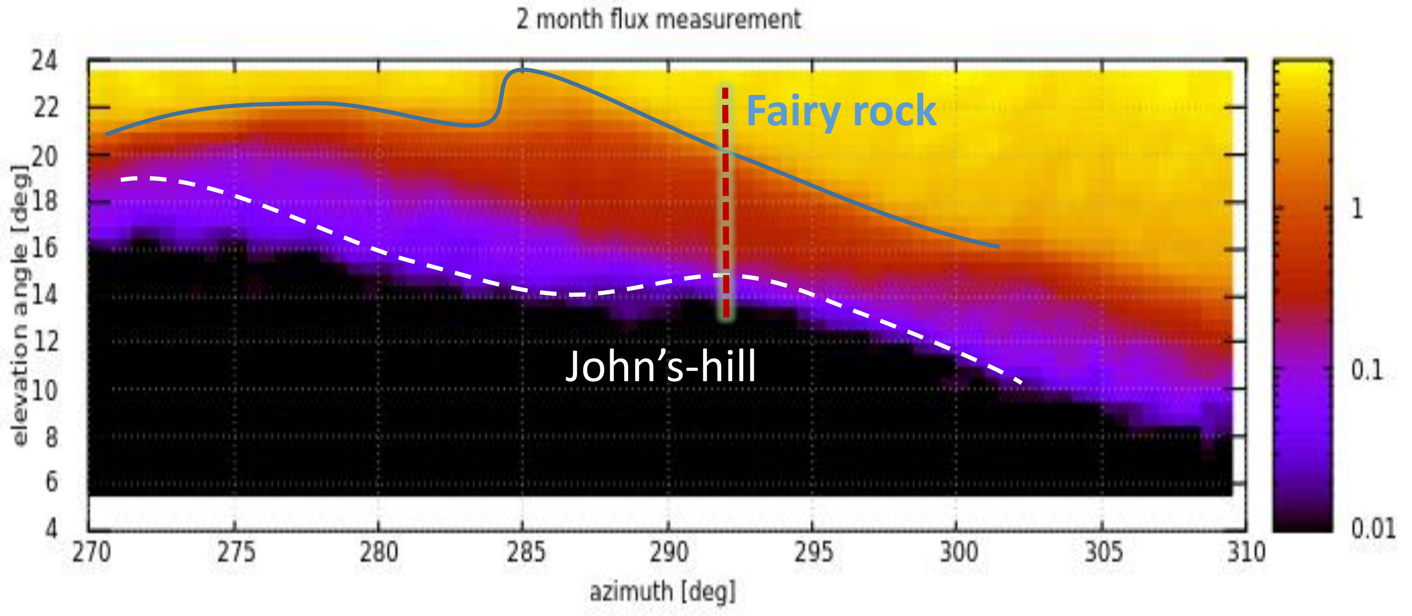
Resolution of muography

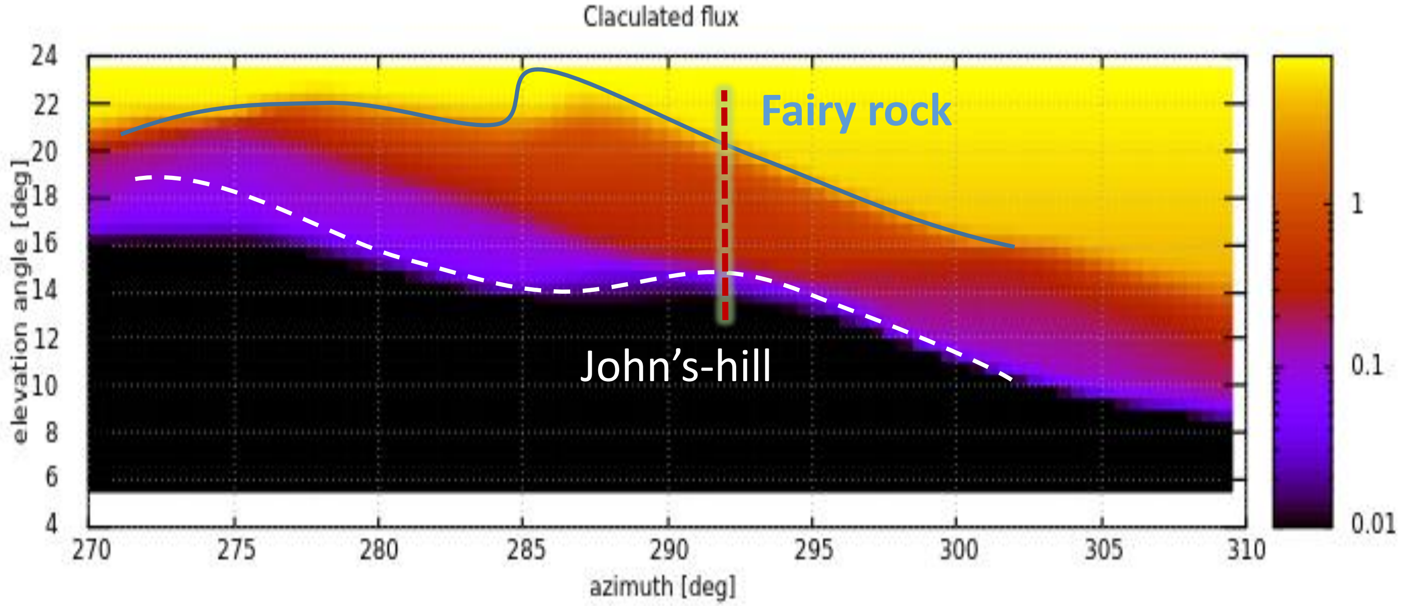
Budapest Fairy Rock



Drone photo 50 m above the detector







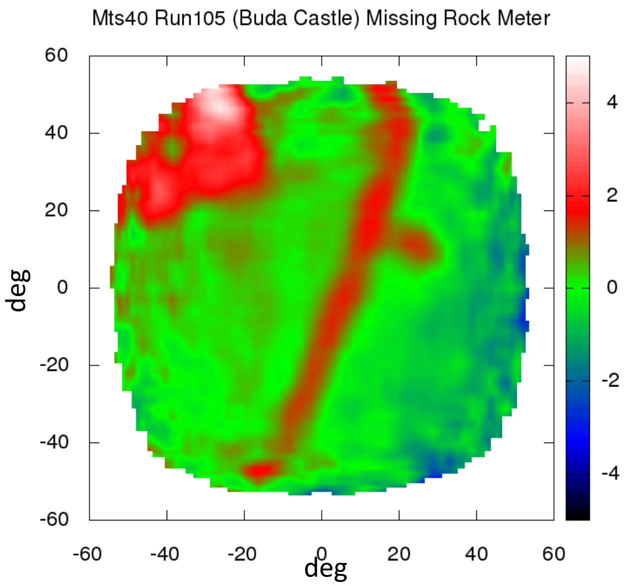
Underground

Detector requirements in practice…

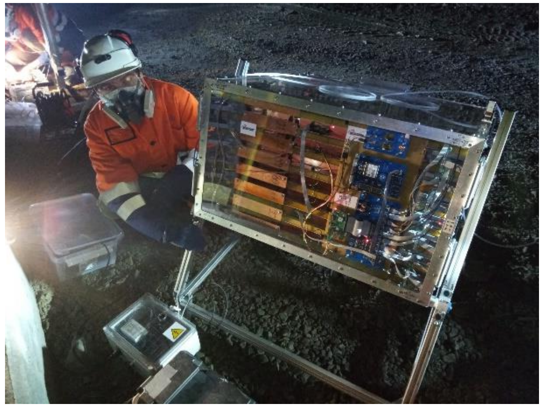
- Size (available space)
- Robustness (movement, vibrations, water, dust, temperature, humidity, pressure)
- Mobility (weight)
- Autonomy
  - low power consumption for battery
  - low gas consumption for gaseous detectors
  - remote data collection
- Resolution (10-50 mrad)

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.

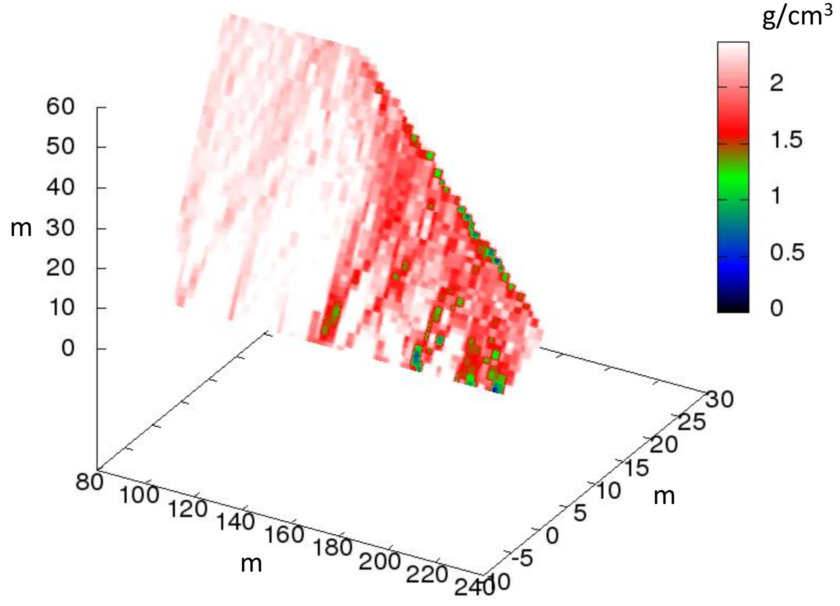


An active mine in Finland.

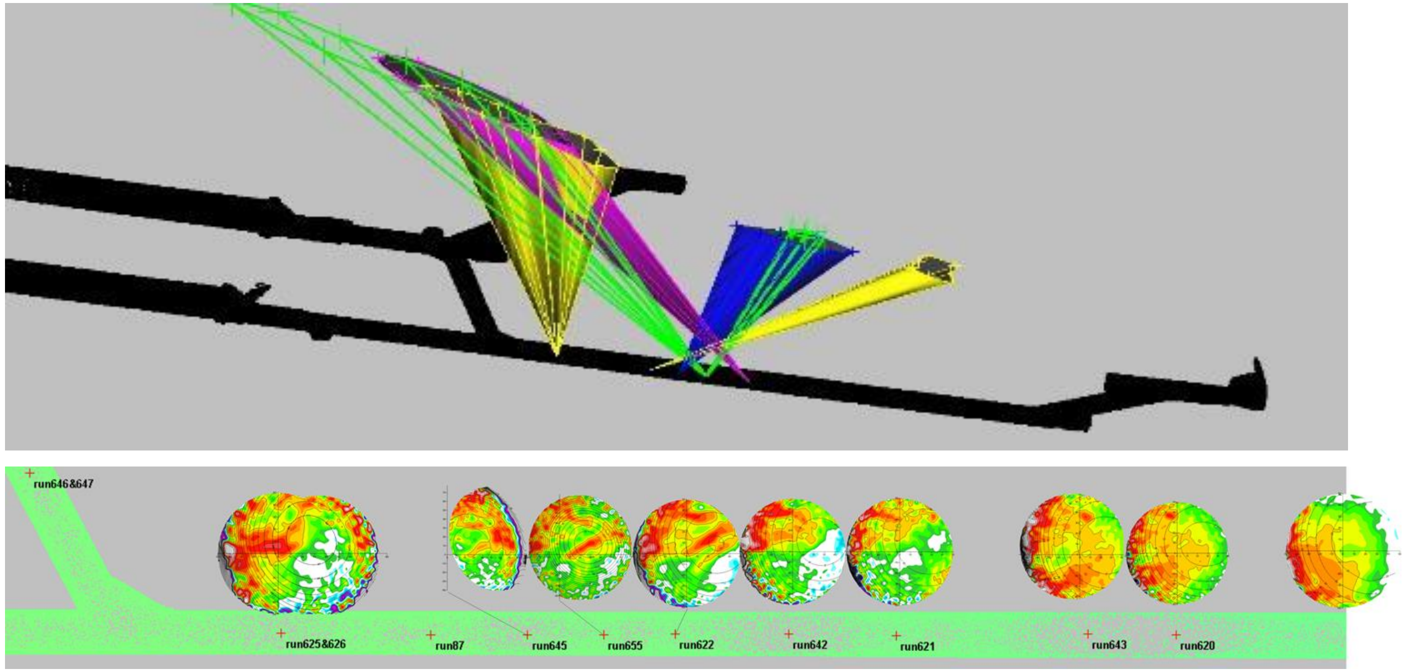
3D tomography

- 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.



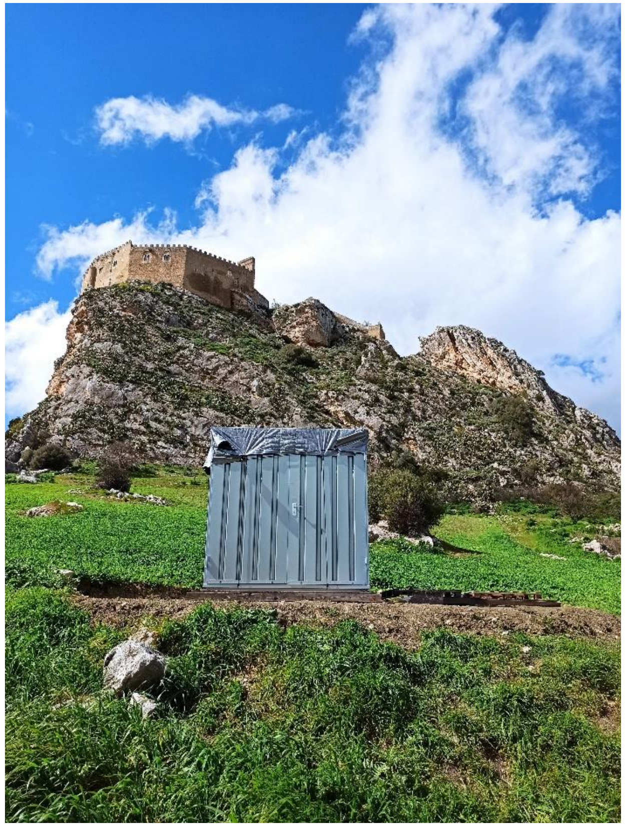
Multiple muograph image along a straight tunnel.

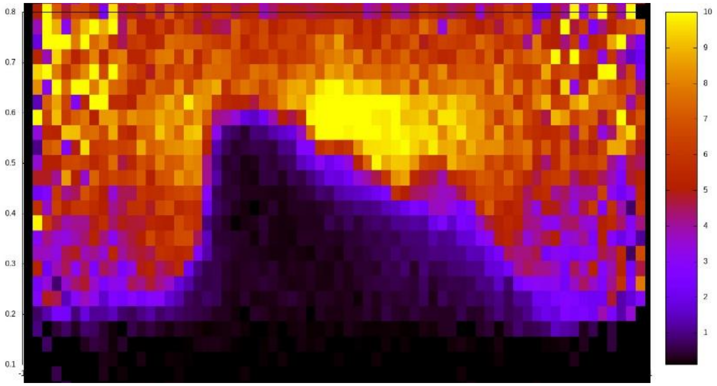
Thank you for your attention!

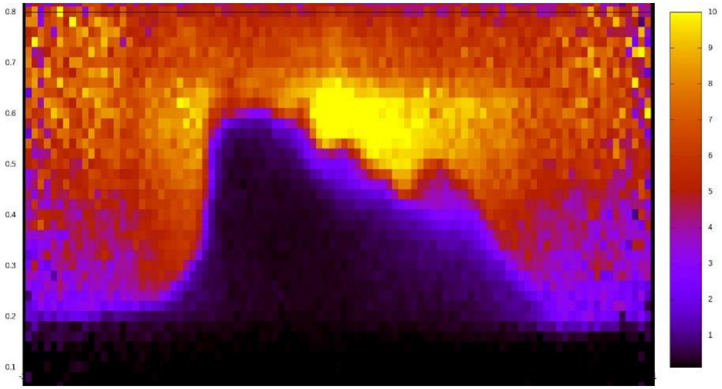
Backup slides

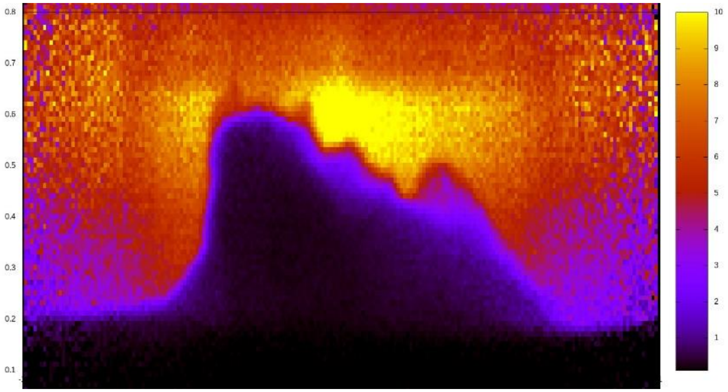
Mussomeli

- Measurement preparation in practice…



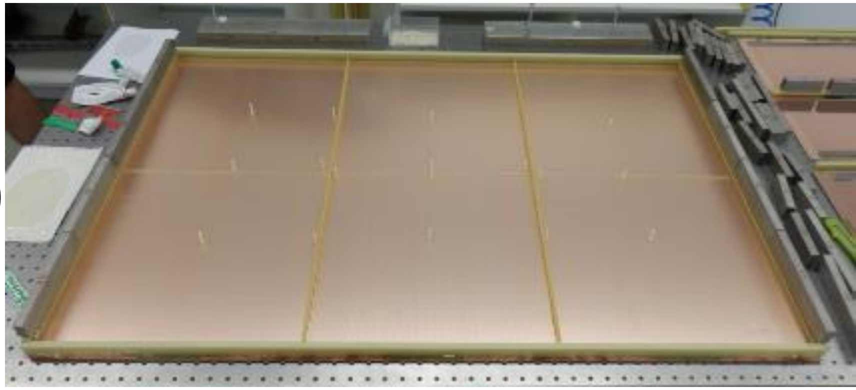


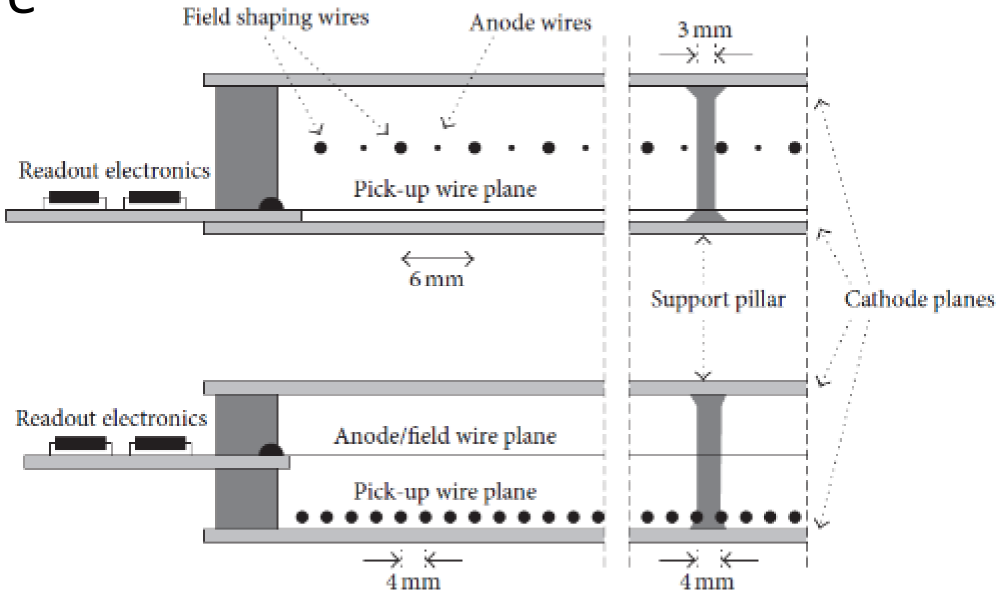




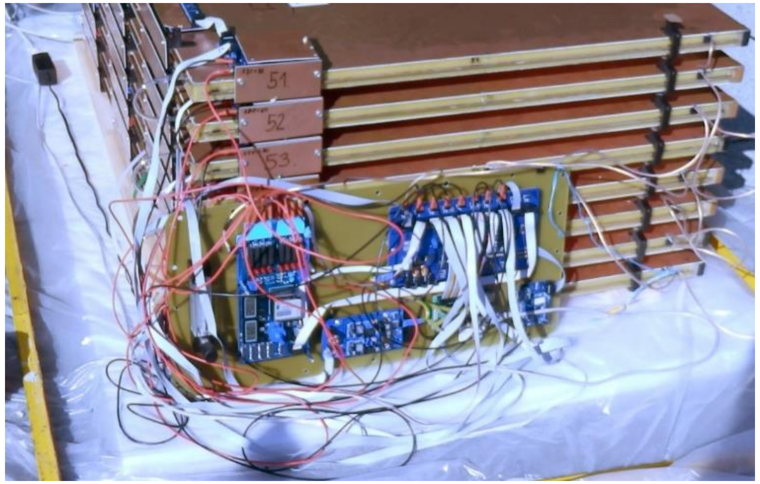
Detector technology
developed at Wigner RCP

- Gaseous detector (MultiWire Proportional Chamber, MWPC)
- >98% tracking efficiency, 4 mm RMS position resolution
- Gas: commercial, nontoxic, non-flammable (Ar:CO_2 82:18)
- Robust, lightweight, cost-efficient mechanical structure
- Wide range of sizes (40x40 – 120x80 cm^2)
- Custom designed DAQ and electronics (5—10 W)





D.Varga, *AHEP* **2016,** 1962317 (2016).



Low gas consumption

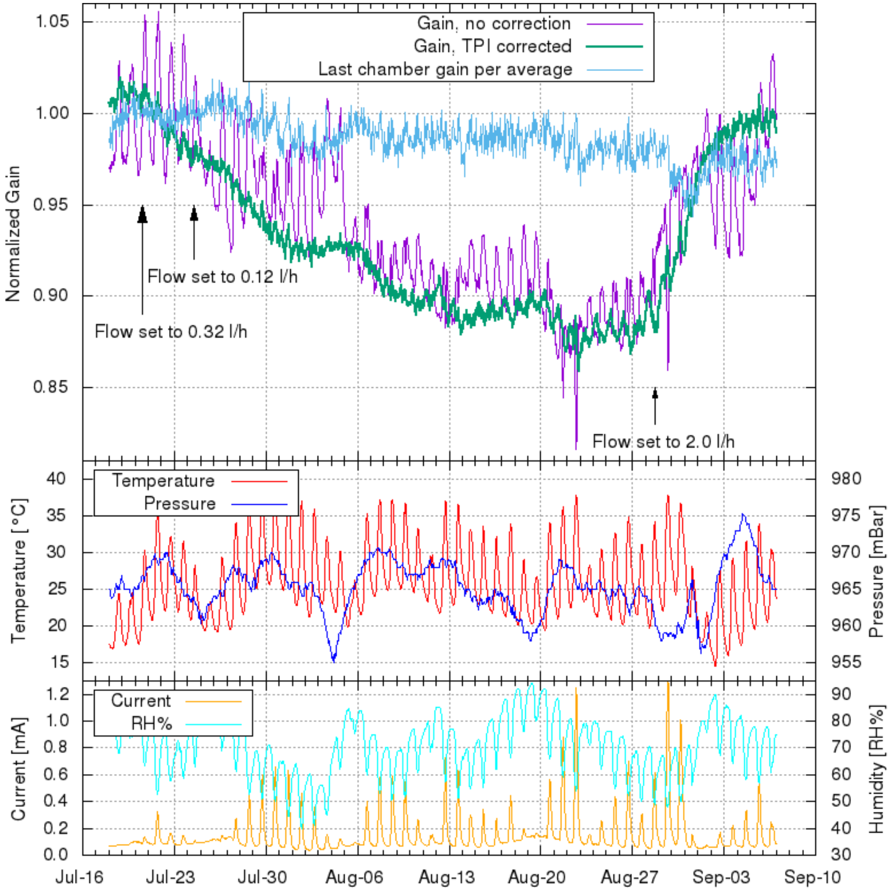
G.Nyitrai TIPP (2021)

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



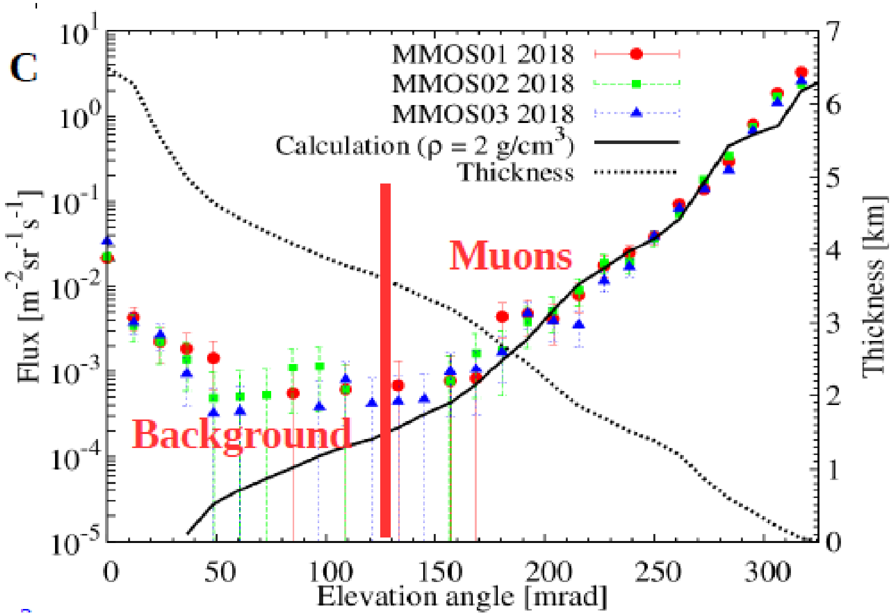
G.Nyitrai, *JAP* **129,** 244901 (2021).

Background suppression

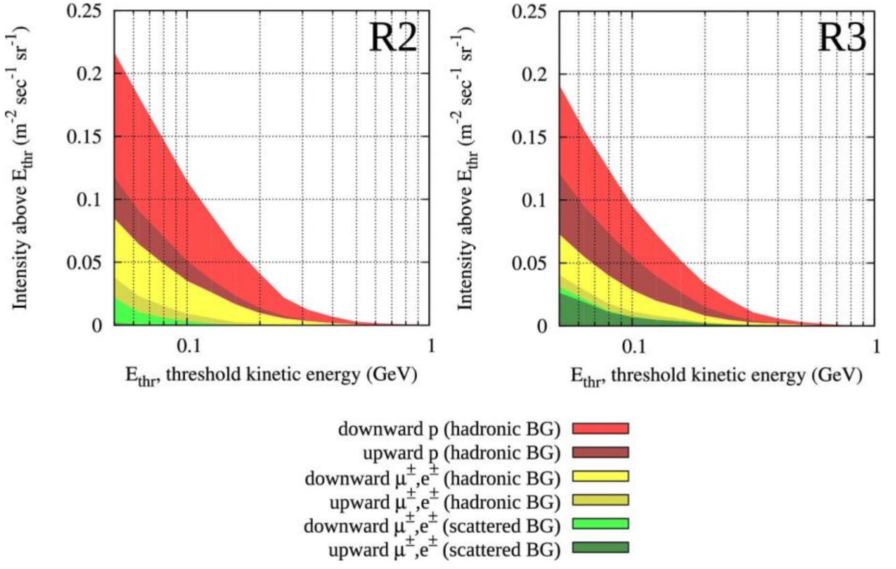
A review of background sources in:
L. Bonechi *Rev. Phys* **5**, 100038 (2020)

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/m²/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)

Flux calculations

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

- 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

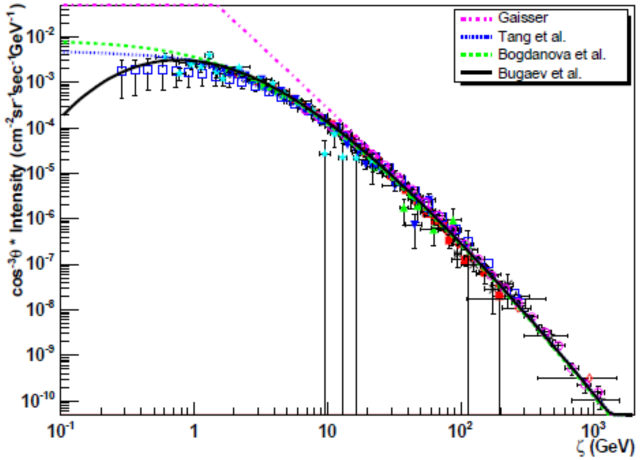
- 1998 Bugaev paraméterezés

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

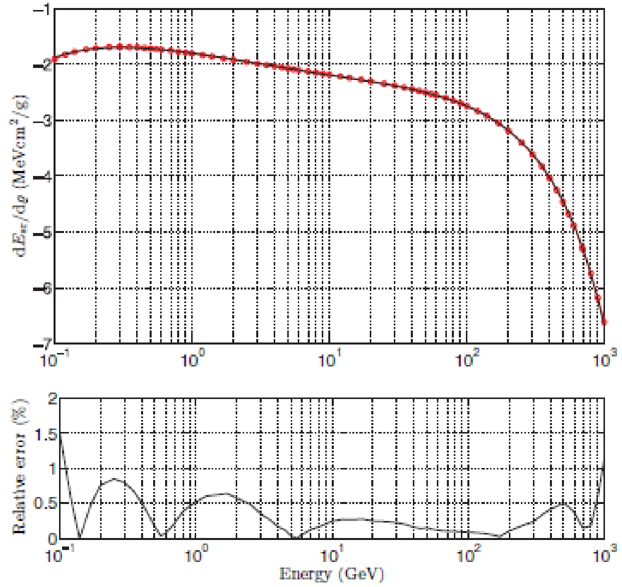
- **2006 Reyna**: Bugaev + angle dependence

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

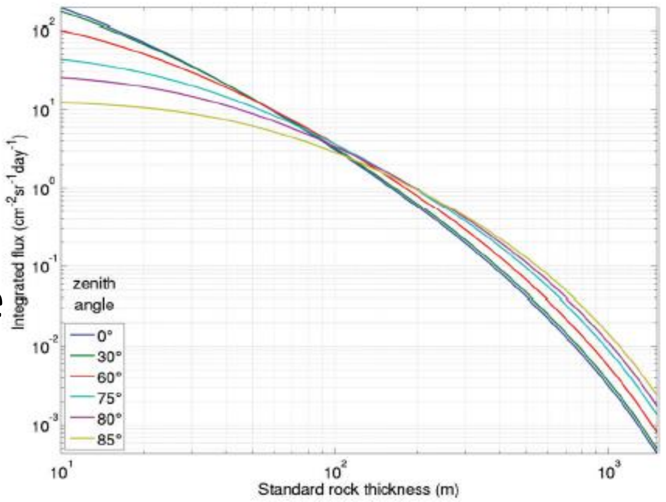
- MC simulations



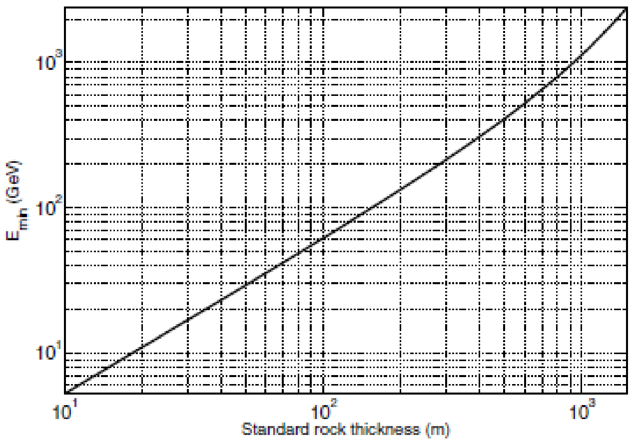
$\Phi(E_0,\Theta)$ Muon spectrum
[2006 Reyna]



dE/dρ [PDG]



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



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

16

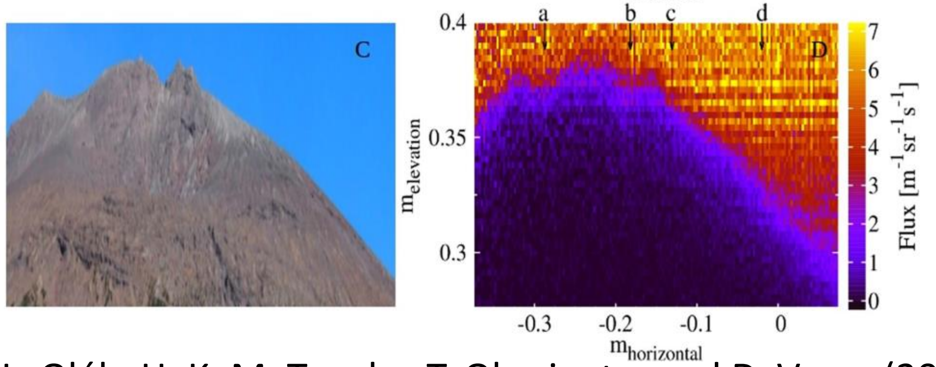
Systematic errors

- 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)

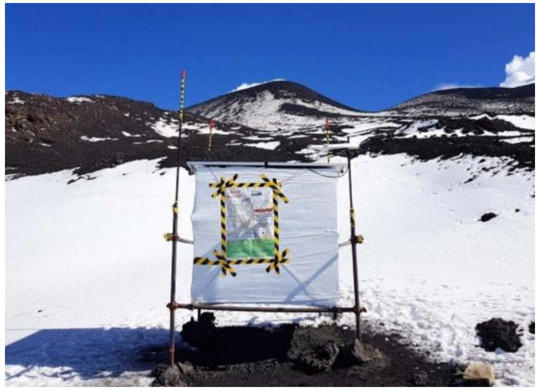
Surface muography projects:
Sakurajima volcano

- Collaboration and patent with the University of Tokyo since 2016
- Continuous development of SMO (Sakurajima Muography Observatory)
- 8.7 m^2, 11 detector module, 6-8 chamber/module
- See more in the presentation of L. Oláh

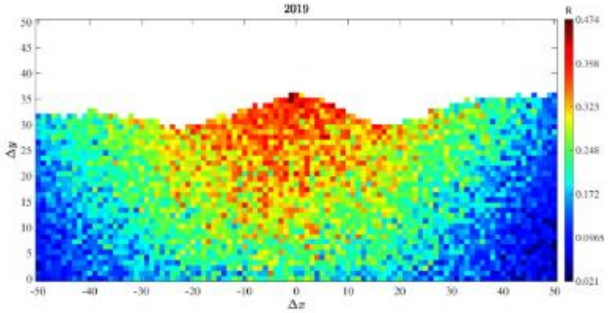


L. Oláh, H. K. M. Tanaka, T. Ohminato, and D. Varga (2018). Scientific reports, 8(1), 1-13.

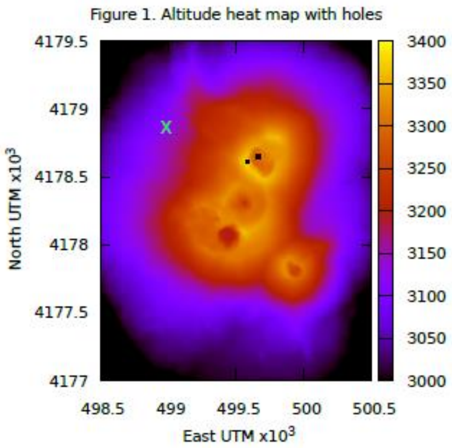
Surface muography projects:
Etna volcano

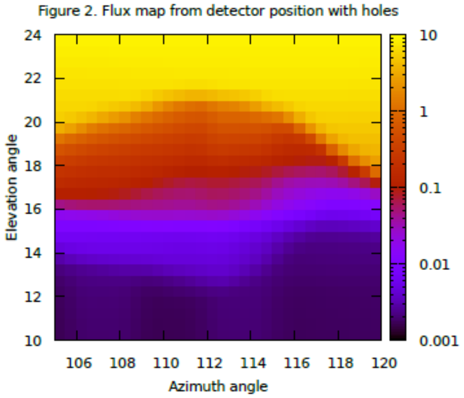


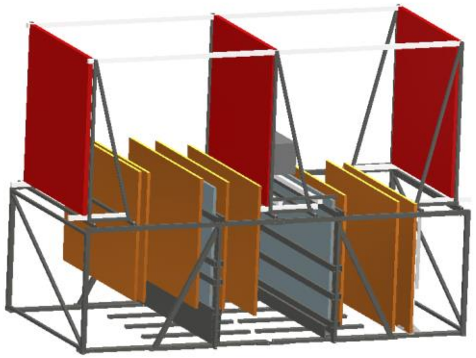
- New collaboration will be with the University of Catania
- For observation and tomography of the Etna
- Combination of scintillator and gaseous detector
- Challenges: 3000 m altitude, several m snow in winter, regular large eruptions (area closed)



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







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

Summary

- On-surface muography has a lot of technical challenges
- The MWPC detector in Wigner has been developed to meet these challenges
- A common question about on-surface muography is the background suppression
- Further issues are the different flux calculation methods and systematic errors
- Some of our on-surface projects presented:
  - Japan Sakurajima volcano observation (collab. with the University of Tokyo)
  - Italian Etna volcano observation (new collab. with University of Catania)
  - Budapest Fairy Rock for measuring the imaging capabilities of muography