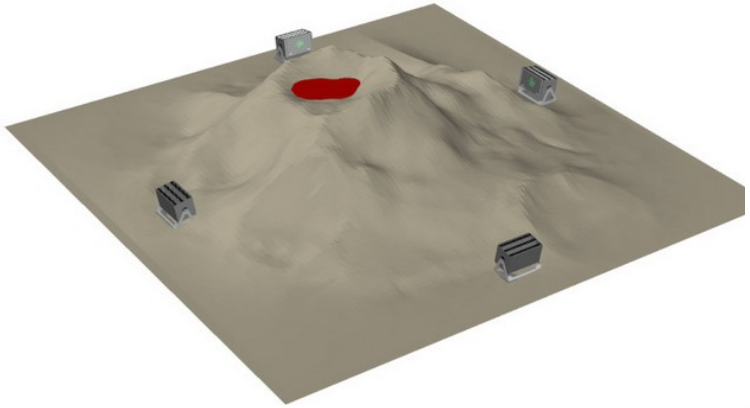
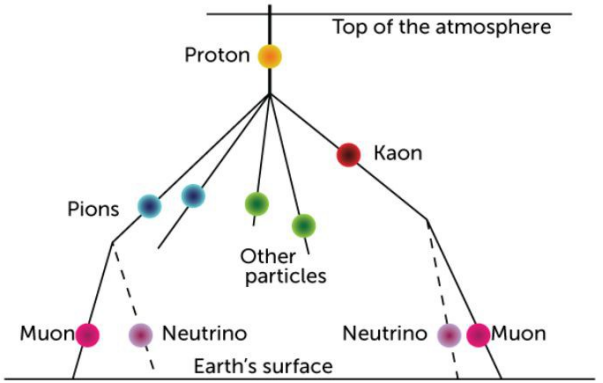
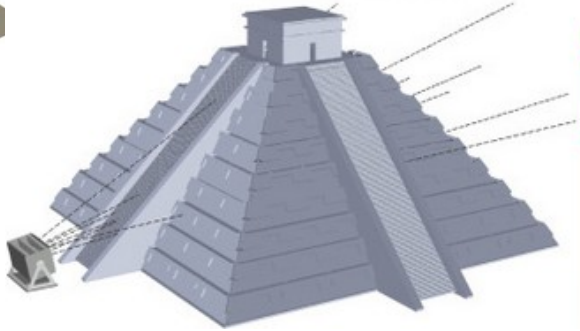
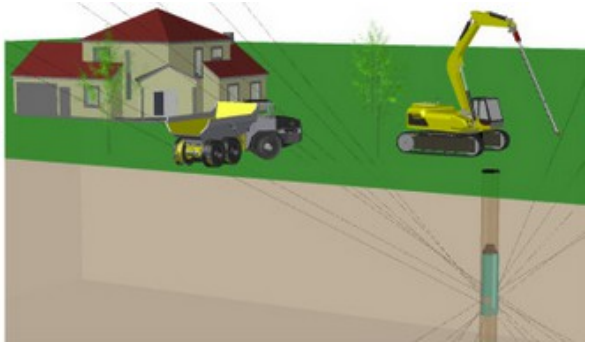
Work Package 5: Muography









Andrea Giammanco

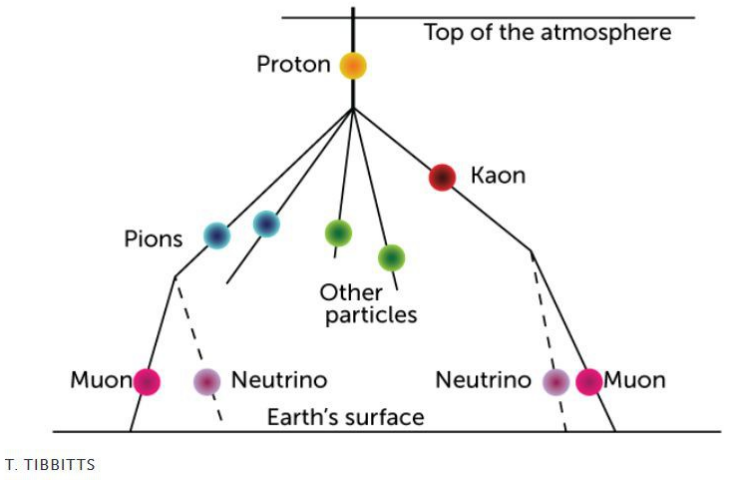
Centre for Cosmology, Particle Physics and Phenomenology

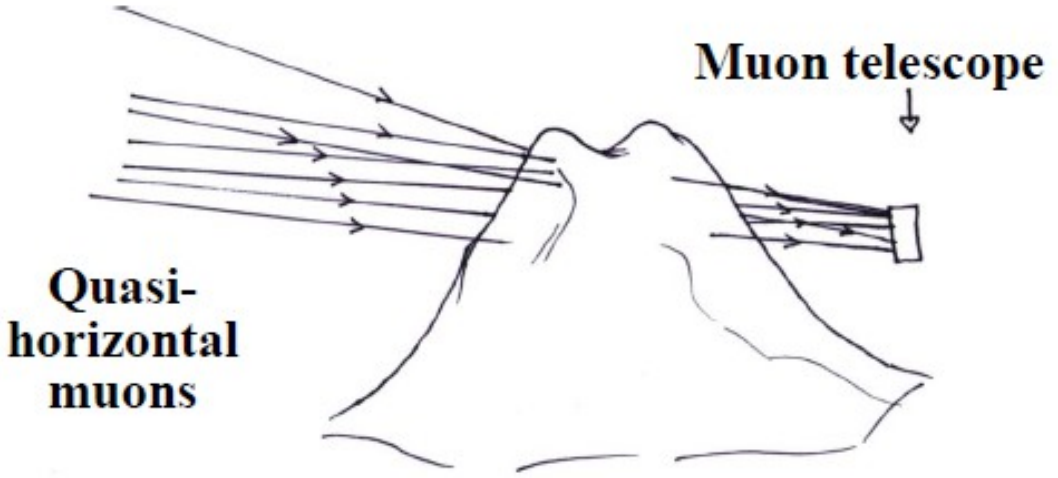
UCLouvain, Louvain-la-Neuve, Belgium

INTENSE mid-term meeting, 2022

Muography in a nutshell

Pictures from T. Tibbits for Science News (left) and P. Strolin (right)





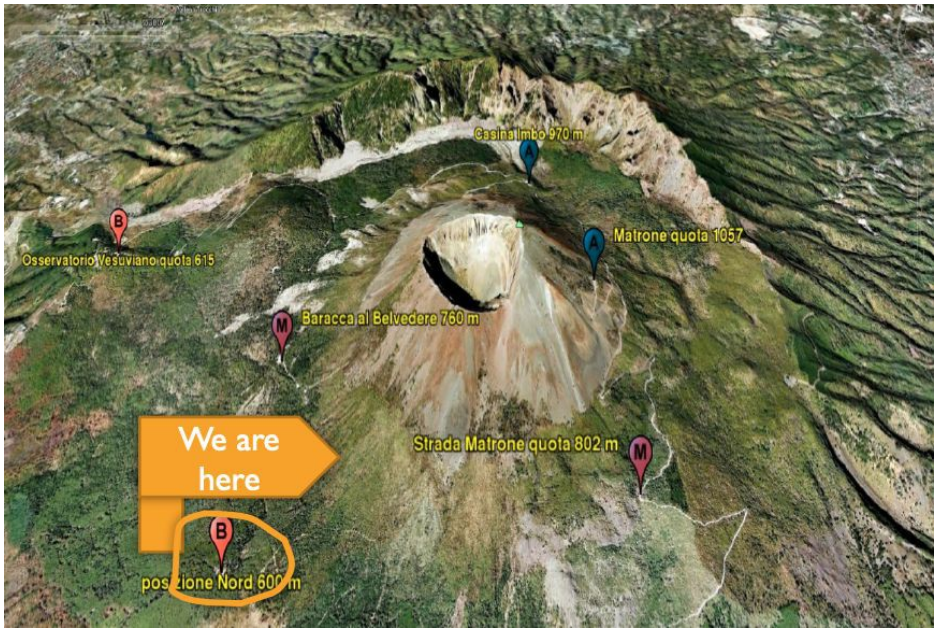
- Just like normal radiography, but instead of X rays we use cosmogenic muons arriving at a rate of ~100 Hz/m^2 at sea level
- Absorption is almost entirely due to energy loss by ionization
- We can see the 2D shadow of any large object, with denser regions absorbing larger fractions of the muon flux

Main research ongoing in WP5

- Applications to volcanology:
  - MURAVES (Muon Radiography of Vesuvius)
    - INFN, INGV (Italy), UCL, Gent (Belgium)
  - SMO (Sakurajima Muography Observatory)
    - Wigner (Hungary), Tokyo (Japan)
- Novel instruments for geophysics, archaeology, civil eng.:
  - Portable gaseous detectors for underground exploration
    - UCL, Gent (Belgium); Wigner (Hungary)
  - Cylindrical scintillator detector for boreholes
    - INFN, TECNO-IN (Italy)
- Auxiliary measurement of muon differential spectrum:
  - NEWCUT
    - Wigner (Hungary), Tokyo (Japan)

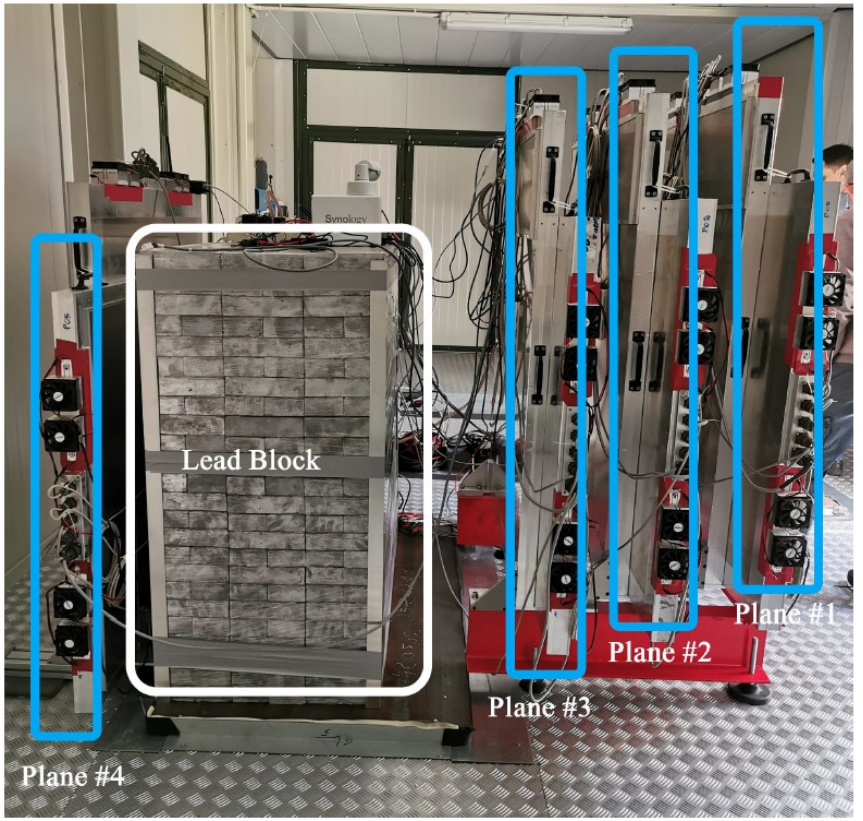
The MURAVES experiment

- MU(on)RA(diography) of VES(uvius)
- Vesuvius: active volcano near Naples (Italy)
- Eruptions are infrequent (last one in 1944) but potentially very dangerous
- Wiped out Pompeii and Hercolaneum in 79 AD
- Today, > 0.5M people live in its "red zone", i.e., need to be evacuated in case of eruption

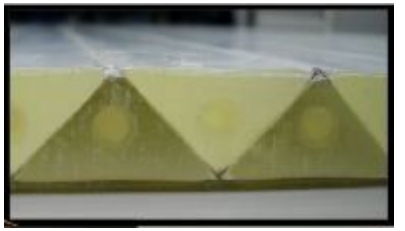


- MURAVES: successor of MU-RAY project
- Consortium of INFN, INGV, Naples, Florence, and since 2019 also UCL and Ghent

MURAVES



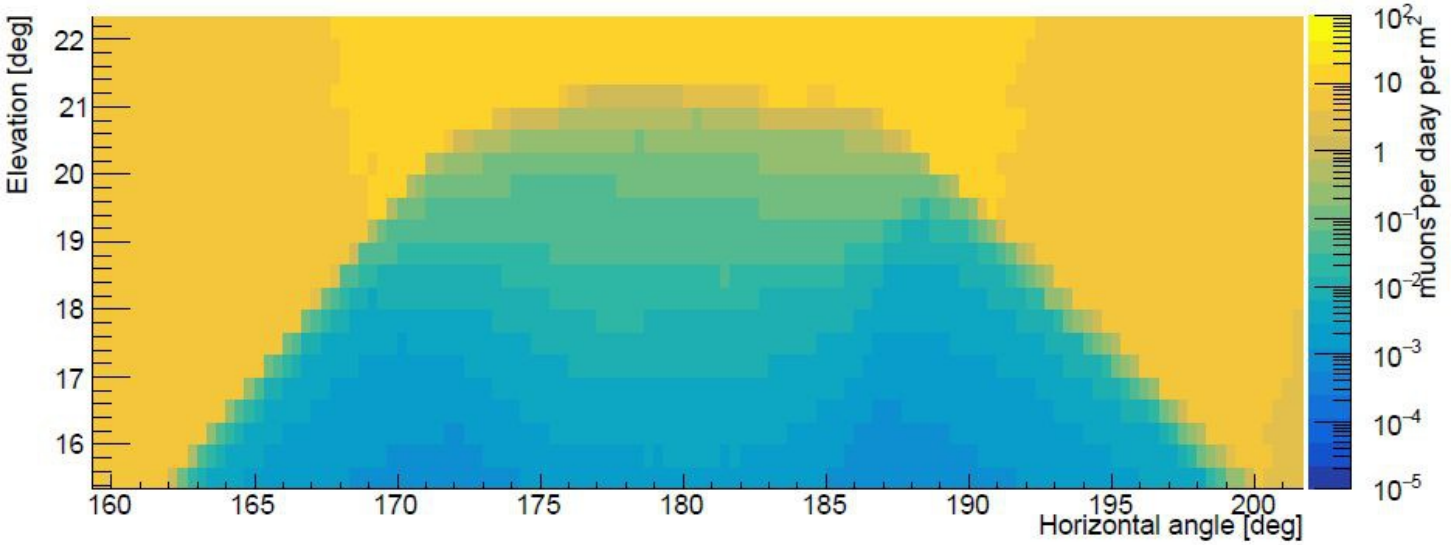
Picture by S.Wuyckens, July 2019



- 3 telescopes, each with 4 x-y layers of scintillating bars with triangular section, coupled to SiPM
- Lead wall, 60 cm thick (recycled from OPERA ν experiment), corresponding to a ~1 GeV cut-off
- UCL and Ghent contributing to Monte Carlo simulations and Time-of-Flight calibration (+ other analysis tasks)

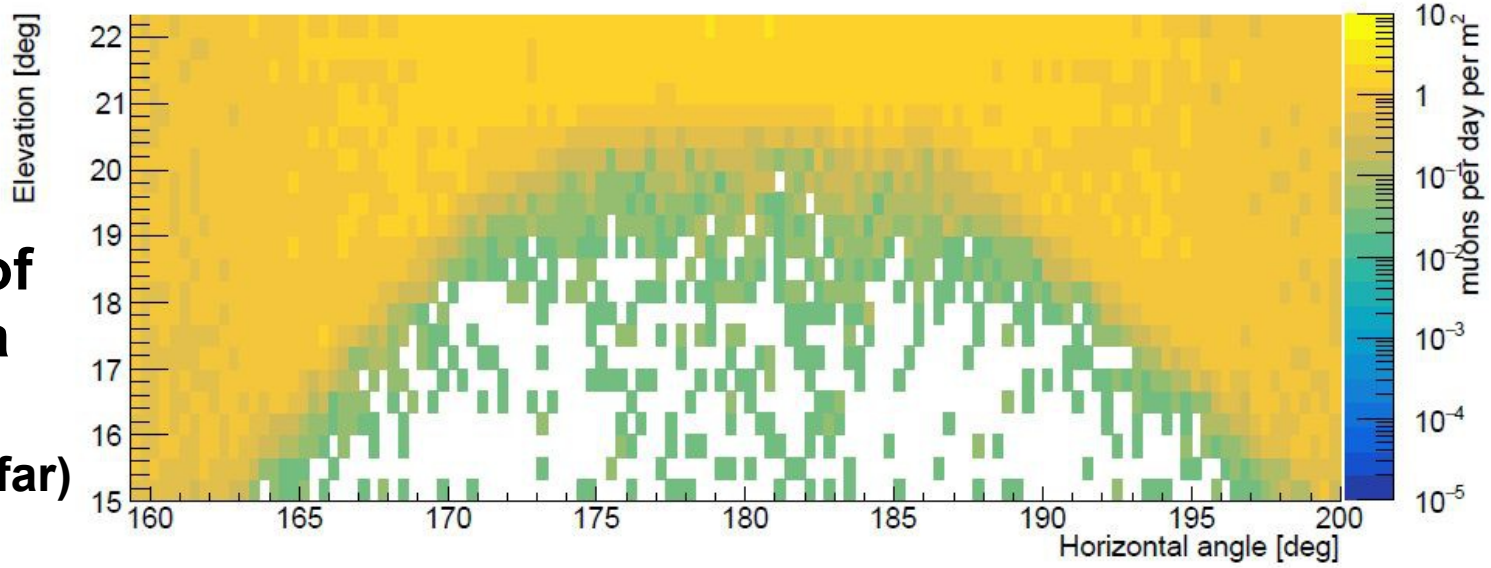
First MURAVES public data

Simulation



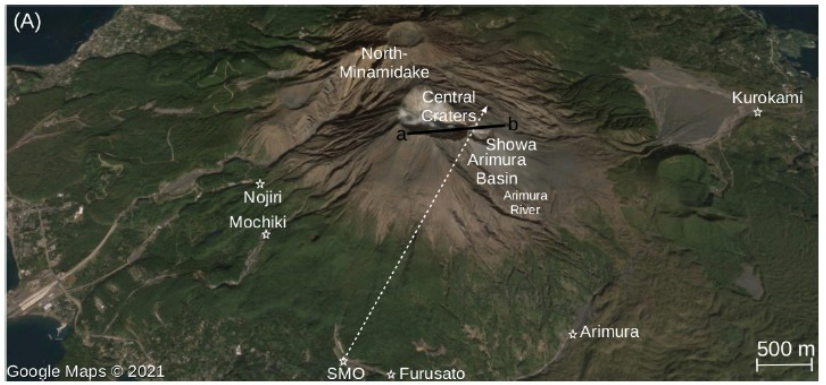
51 days of real data

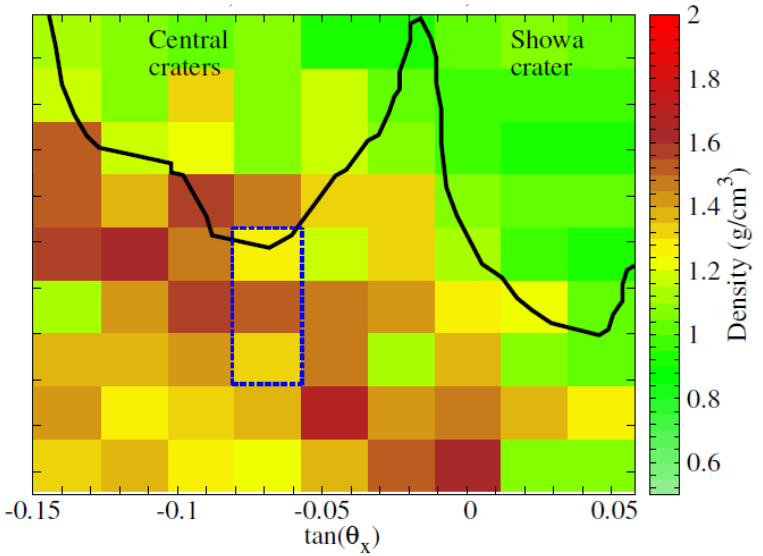
(~2 years recorded so far)



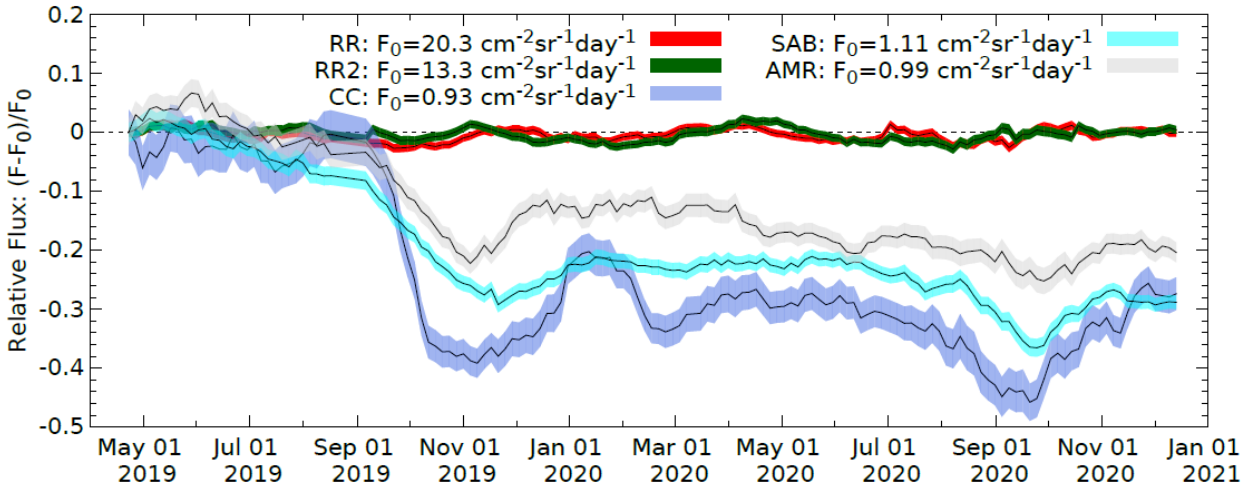
MURAVES Collaboration, arXiv:2202.12000 [physics.ins-det],
J. Adv, Instr. Sci., vol. 2022, no. 1, 273

Sakurajima Muography Observatory





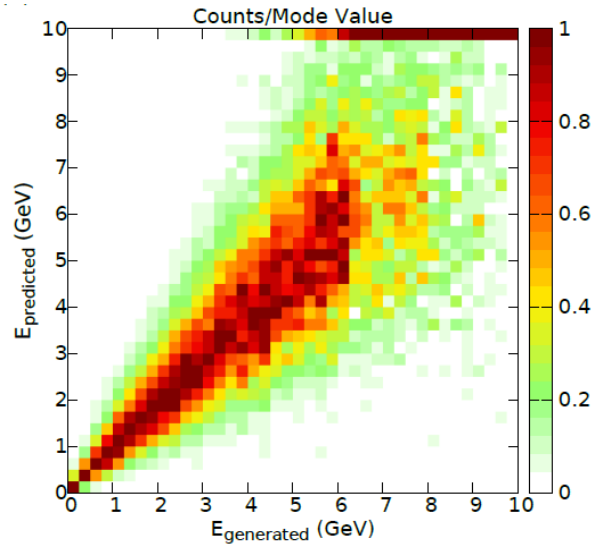
- Sakurajima is one of the most active volcanoes in the world
- Wigner-Tokyo partnership, installing MWPC detectors for eruption monitoring
- Continuous extension of the laboratory; currently 11 MWPC modules, totalling 8.7 m² area

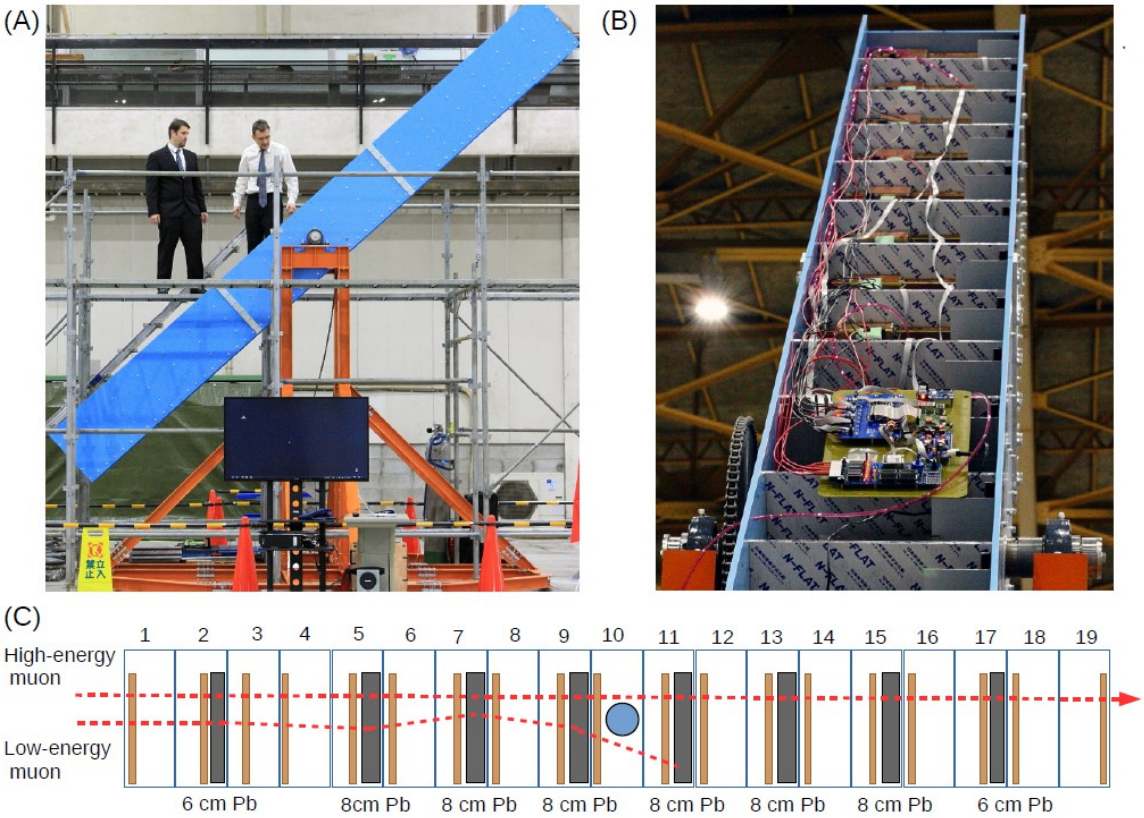


Olah et al., J. Adv, Instr. Sci., vol. 2022, no. 1, 285

NEWCUT

- Goal: differential measurement of muon flux at low momentum
- Important input for muography
- 19 MWPC detectors alternating with lead slabs, acting as absorbers and scatterers



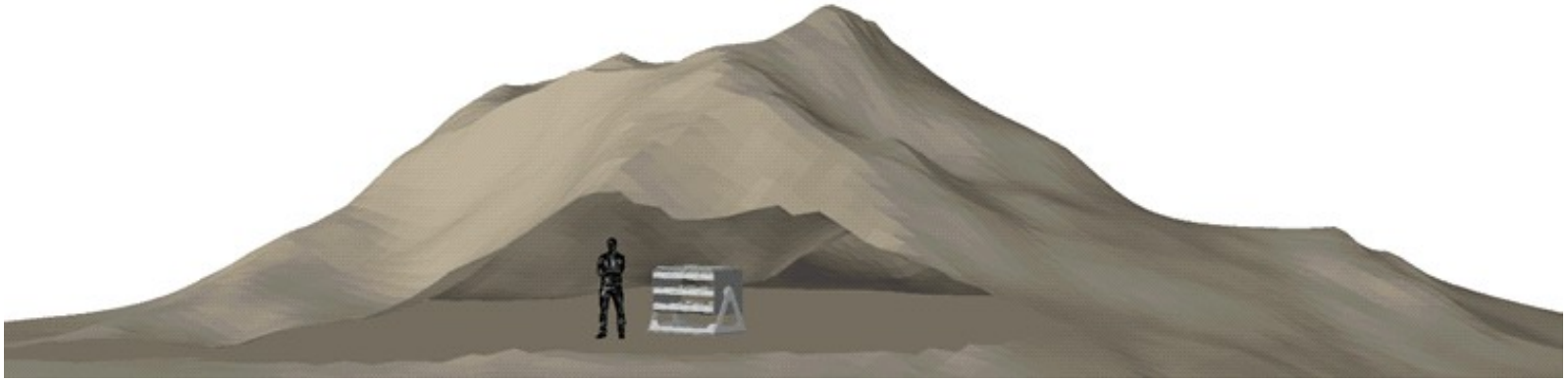


- Scattering and energy loss are combined in a Neural Network
- Very good linearity observed up to 5 GeV

Olah et al., J. Adv, Instr. Sci., vol. 2022, no. 1, 264

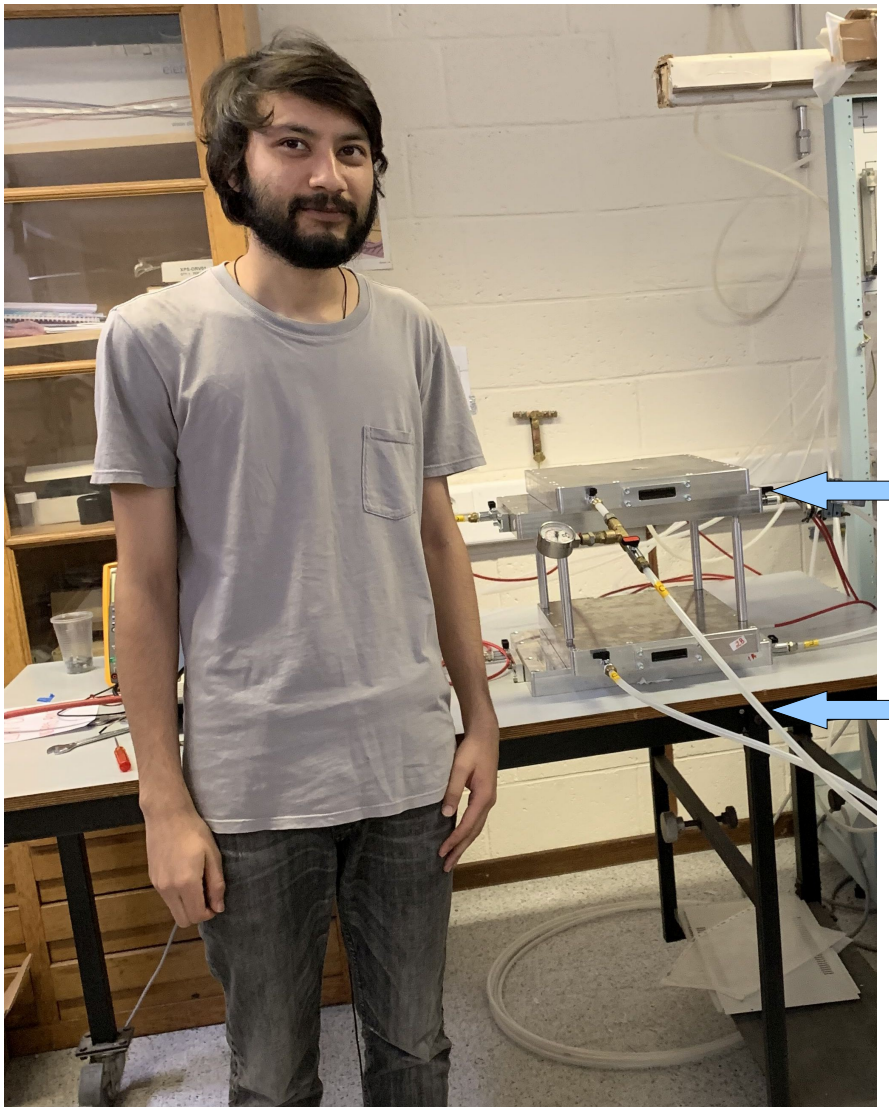
Portable gaseous detectors

- Many archaeology or geoscience use cases where optimal detector location is hard to access and in a confined space
- Large interest in portable muon telescopes whose key design considerations include compact size, light weight and autonomous operation
- *Gaseous detectors* pose specific challenges (gas autonomy; hazards due to flammability, toxicity, anoxia) but can achieve excellent position resolution
- Dedicated R&D by UCL+Ghent and Wigner+Tokyo teams



From L. Bonechi, R. D'Alessandro, *A.G.*, arXiv:1906.03934, Rev. Phys. 5 (2020) 100038

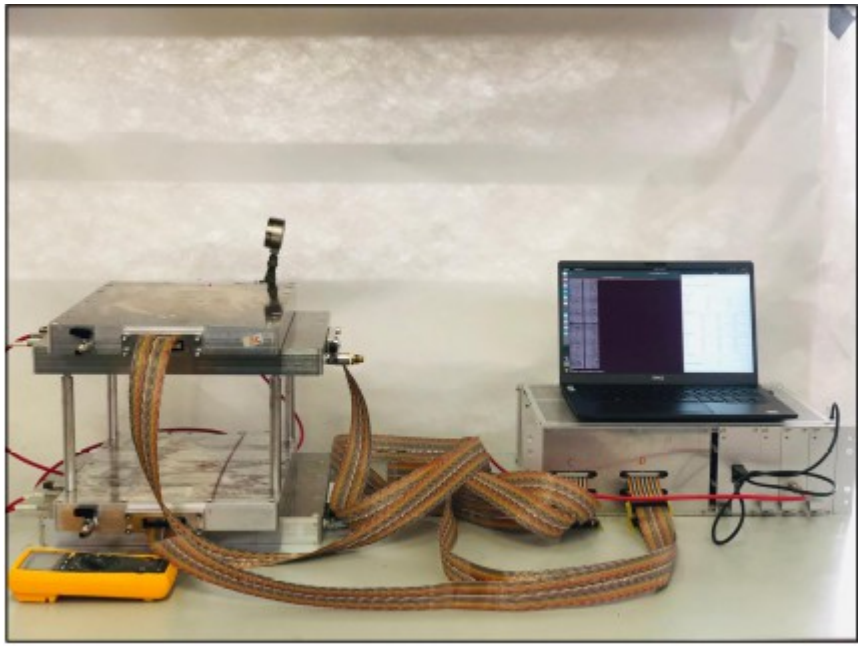
UCL & Ghent: mini-RPC muoscope

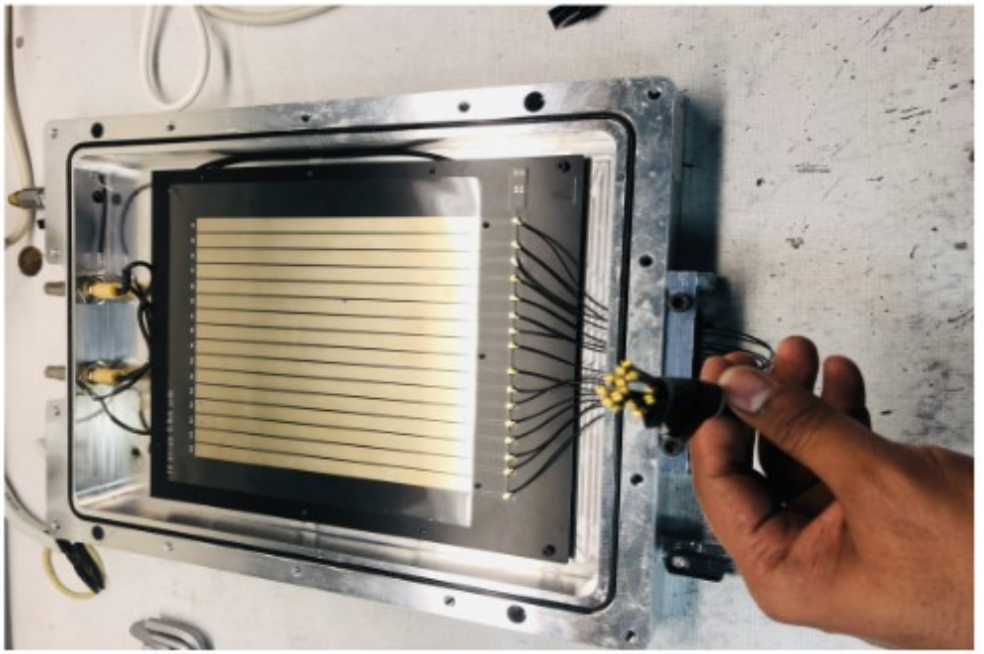


Superimposed detector layers, at 90° of each other

Tubes for gas filling; only needed once, then the muoscope is ready to go

UCL & Ghent: mini-RPC muoscope

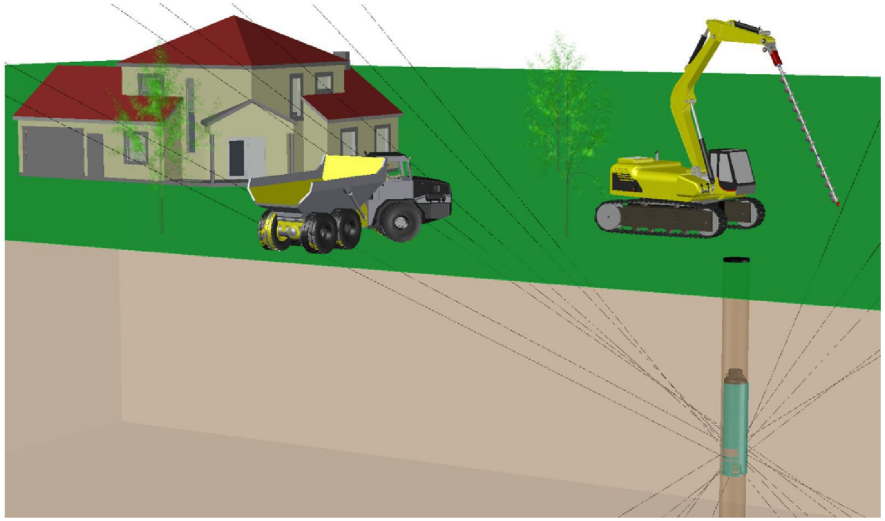


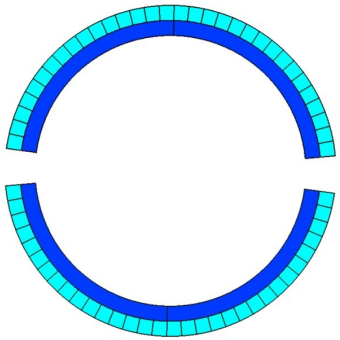


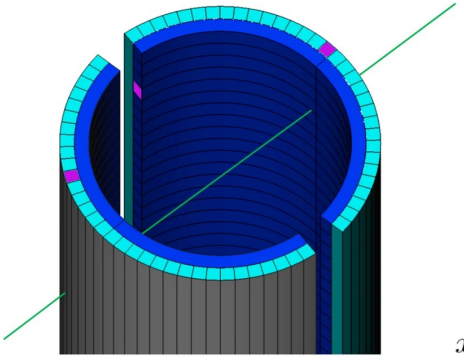
- Versatile: modular geometry
- Cheap and easy to assemble
- Portability
  - Small: active area 16x16 cm² (UCL), 28x28 cm² (Ghent)
  - Light, robust
  - Sealed

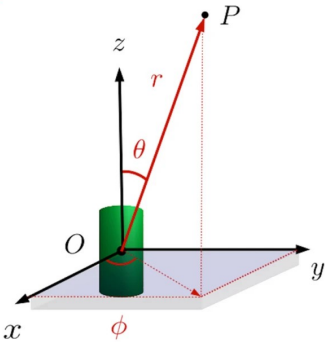
- First prototypes built and tested at UCL and Ghent
  - Slightly different design choices, to compare
  - Joint data takings & data analysis
  - A patent has been submitted

INFN & TECNO-IN: cylindrical borehole detector









- Use cases in civil engineering, archaeology, geosciences
- Unusual geometry needed to fit a muon detector in a borehole
- Scintillators are shaped as bars and arcs; each muon crosses 2 bars and 2 arcs, giving theta-phi information that can be translated in density maps
- A patent resulted from this work

Figures from (left) L. Bonechi, R. D'Alessandro, *A.G.*, arXiv:1906.03934, Rev. Phys. 5 (2020) 100038 and (right) Cimmino et al., Sci Rep 11 (2021) 17425

Secondments

- UCL->TECNO IN:
  - Sophie Wuyckens, 1 month in 2019
  - Samip Basnet, 1.25 months from 2019 to now
  - **2023**: 1 month Marwa Al Moussawi, 0.75 months Samip Basnet
- Ghent->TECNO IN:
  - Amrutha Samalan, 0.5 months in 2022
  - Yanwen Hong, 0.5 months in 2022
  - **2023**: tbd for Amrutha, Yanwen and Michael Tytgat
- Wigner->Tokyo
  - Gábor Nyitrai, 2 months in 2019-2020
  - Gábor Galgóczi, 1.5 months in 2019-2020 (cut short by pandemics)
  - **2023**: 2 months Gergo Hamar, 0.5 months Gabor Galgoczi **+ if possible** 1 month Gabor Nyitrai, 1 month Gabor Galgoczi

See talks this afternoon by Gabor Nyitrai, Samip Basnet and Yanwen Hong

Secondments

Beneficiary	Months foreseen	Used so far	Planned in 2023
UCL	8	2.25	1.75
Ghent	9	1	> 1
Wigner	6	3.5	2.5
TECNO IN	2	0	?
INGV	3	0	0
Total	28	6.75	> 5.25

Overall underused due to some changes in research realities, but Ghent ramping up, and Wigner is close to full usage of their quota.

INTENSE has been rather instrumental to ramp-up Wigner-Tokyo cooperation, and SMO activities are expanding.

Can we consider an amendment to transfer months from some other institutes to Wigner?

Publications (1)

- General muography
  - Muon Imaging: Present Status and Emerging Applications / International Atomic Energy Agency (IAEA); various authors **(including INTENSE members from INFN, INGV, UCL)**. IAEA-TECDOC-2012. Published in Oct. 2022
  - Muography: Exploring Earth's Subsurface with Elementary Particles / Various authors **(including INTENSE members from Bern, Gent, INFN, INGV, UCL, TECNO-IN, Tokyo, Wigner)**, published by Wiley and the American Geophysical Union (AGU) in Feb. 2022
  - Atmospheric muons as an imaging tool / L. Bonechi, R. D'Alessandro, **A. Giammanco**. Reviews in Physics 5 (2020) 100038

Publications (2)

- MURAVES
  - The MURAVES experiment: study of the Vesuvius Great Cone with Muon Radiography / MURAVES collaboration **(including Gent, INFN, INGV, UCL)**. Journal for Advanced Instrumentation in Science 1 (2022) 273
  - The simulations chain of the MURAVES experiment / MURAVES simulations team **(including Gent, INFN, INGV, UCL)**. Journal for Advanced Instrumentation in Science 1 (2022) 303
  - End-to-end simulations of the MUon RAdiography of VESuvius experiment / MURAVES simulations team **(including Gent, INFN, INGV, UCL)**; JINST 17 (2022) C01015

Publications (3)

- SMO
  - Muography of the active Sakurajima volcano: recent results and future perspectives of hazard assessment / **Wigner+Tokyo**; J.Adv.Instr.Sci. 1 (2022) 285
  - Muographic monitoring of hydrogeomorphic changes induced by post-eruptive lahars and erosion of Sakurajima volcano / **Wigner+Tokyo**; Scientific Reports 11 (2021) 17729
- NEWCUT
  - Development of Machine Learning Assisted Spectra Analyzer for the NEWCUT Muon Spectrometer / **Wigner+Tokyo**; J.Adv.Instr.Sci. 1 (2022) 264

Publications (4)

- Portable gaseous detectors
  - Portable Resistive Plate Chambers for Muography in confined environments / **UCL+Ghent**, E3S Web of Conf. 357 (2022) 01001
  - Towards a portable high-resolution muon detector based on Resistive Plate Chambers / **UCL+Ghent**, Journal for Advanced Instrumentation in Science 1 (2022) 299
  - A portable muon telescope for multidisciplinary applications / **UCL+Ghent**; JINST 17 (2022) C01051
  - Towards portable muography with small-area, gas-tight glass Resistive Plate Chambers / **UCL+Ghent**; JINST 15 (2020) C10032
  - Construction and readout system for gaseous muography detectors / **Wigner+Tokyo**; J.Adv.Instr.Sci. 1 (2022), 307
  - Toward low gas consumption of muographic tracking detectors in field applications / **Wigner+Tokyo**; J. of Applied Physics 129 (2021) 244901

Publications (5)

- Borehole detector
  - A new cylindrical borehole detector for radiographic imaging with muons / **INFN**; Sci Rep 11, 17425 (2021)
  - A Borehole Muon Telescope for Underground Muography / **INFN**; J. Adv. Ins. Sci. 1 (2022) 279
  - Borehole cylindrical detector: A compact muon telescope for muon radiography applications / **INFN**; NIM A 1045 (2023) 167619

Patents

- Muographic Observation Instrument/ **Tokyo + Wigner**, Japanese Patent JP2016-087436
- Sistema e metodo per la prospezione del sottosuolo mediante rilevamento di muoni / **INFN + TECNO IN**, Italian Patent 102017000138317
- Radiographic imaging based on detection of ionizing particles / **UCL**, European patent application EP21201857.6
- Magnetic field structure imaging apparatus and method using muons / **Kyushu U. + UCL**, Japanese patent application JP2021-141234

Events organized by WP5 members

- 1st International Workshop on Cosmic-ray Muography (Muographers 2021), Ghent (Belgium), 24-26 Nov. 2021, https://indico.cern.ch/event/1033631/
- Plenary session on Muography at the 22nd International Workshops on Radiation Imaging Detectors (iWoRID 2021), Ghent (Belgium) - virtual, 27 June - 1 July 2021, https://indico.cern.ch/event/820476/
- Open session on Muography at the General Assembly of the European Geophysical Union (EGU 2022), Vienna (Austria), 23-27 May 2022, https://meetingorganizer.copernicus.org/EGU22/session/41950
- **Forthcoming**: Muographers 2023 in Naples, and a new muography session at EGU 2023
- ***More details in Michael Tytgat's talk***

Outreach

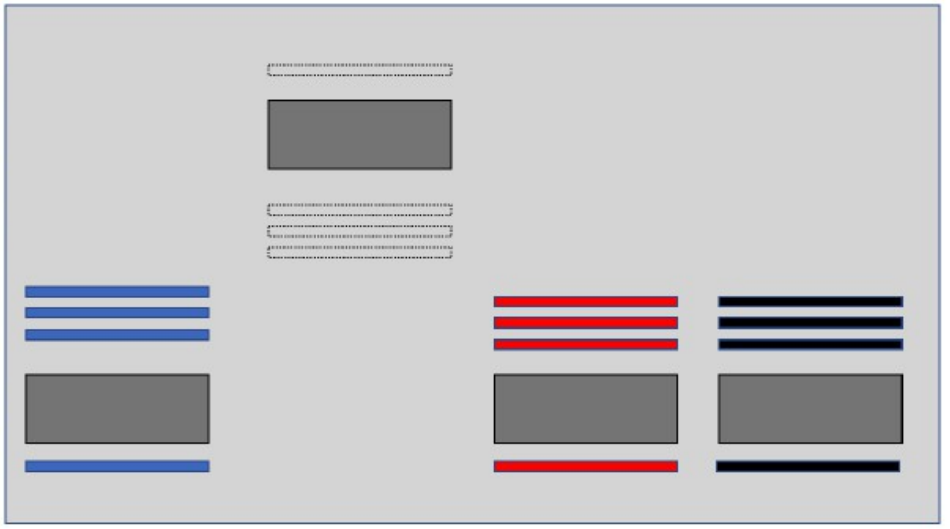
- Science Agora series, Tokyo, 2022: "Talks on the universe, subatomic particles, disasters, natural resources and archaeology through international dialogue"
- Several members of INTENSE have been interviewed on topics related to WP5:
  - "Physics Particles Fly as Practical Tools", in Scientific American
  - "Muons spill secrets about Earth’s hidden structures" and "Muons Open Doors", in Science News
  - "Seeing deeper with atmospheric muons: From archaeology to geology", in "Reviews in Physics - Highlighted article"; same article also on Phys.org
  - "Les muons sondent les entrailles du Vésuve", in “Daily Science” (in French)

Conclusion

- Muography is a booming research direction, with several potential applications
- Some collaborative activities in WP5 of INTENSE are at the forefront of this research
- INTENSE secondments have significantly helped transfer of knowledge between different muography teams
- Particularly benefical to teams that are relatively new

Thanks for your attention!

The MURAVES experiment



- Of the 3 telescopes, at any point in time 2 will point towards Vesuvius and one in the opposite direction
- Transmission probability (vs θ,ϕ) is defined with respect to the free-sky flux; measured with the backward-pointing telescope
- The 3 telescopes alternate in occupying the backward position, such that detector systematics cancel out

MURAVES Collaboration, arXiv:2202.12000 [physics.ins-det],
J. Adv, Instr. Sci., vol. 2022, no. 1, 273