Studying Mt. Vesuvius with the Muon Radiography Technique

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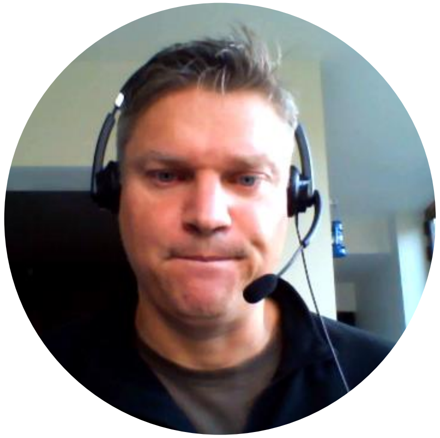
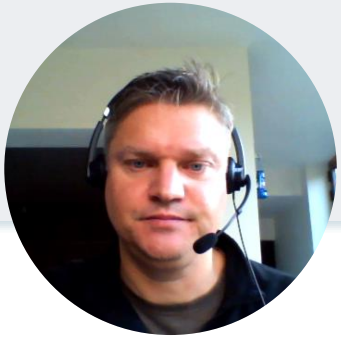


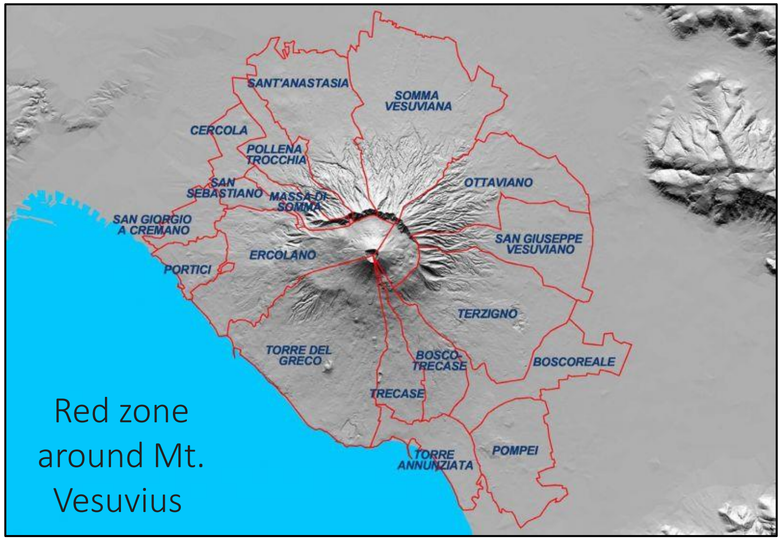
Motivation



Mt. Vesuvius

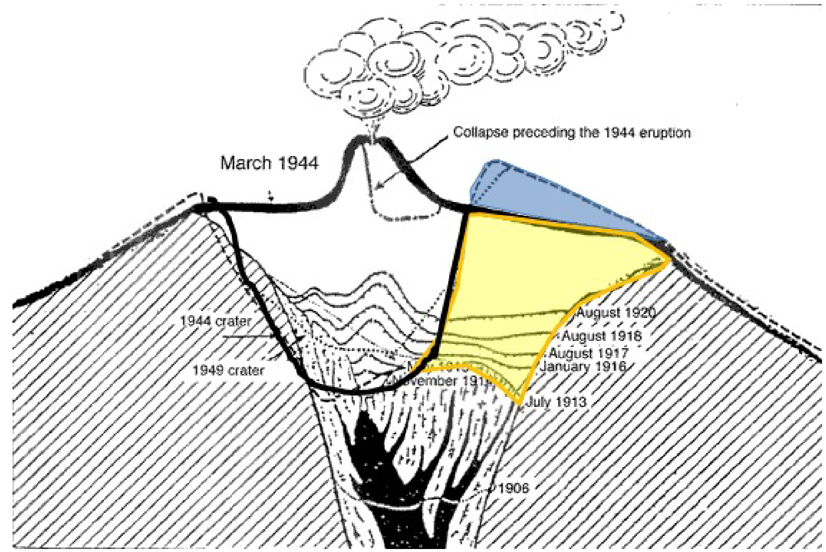
- On top of the subduction zone created by collision of African and Eurasian tectonic plates
- Volcano formed during caldera collapse of Mt. Somma ~25ka ago
- Quiescent since ~80 years, but still active and considered as one of most dangerous in the world:
  - Proximity to city of Naples
  - Tendency for explosive eruptions
- Long history of violent eruptions; most known one Plinian eruption in 79BC
- 27 significant eruptions between 79BC and last eruption in 1944
- Last few eruptions were effusive-explosive, i.e. combining flowing lava with violent expulsions of rock and ash

(Tatiana Mironenko iStock/Getty Images)



Motivation

- In course of history, Mt. Vesuvius morphology drastically changed due to its activity; subsequent eruptions in last period of activity caused collapse of caldera and formation of the present-day crater
- Interior of summit cone is thought to have a layered structure of materials with different densities
- Traditional measurement methods (e.g. gravimetry, seismology …) yield resolutions of order few 100m
- Muon radiography technique:
  - distribution of different densities along the body of volcano
  - high-resolution image (voxel size ~10m) of material layers



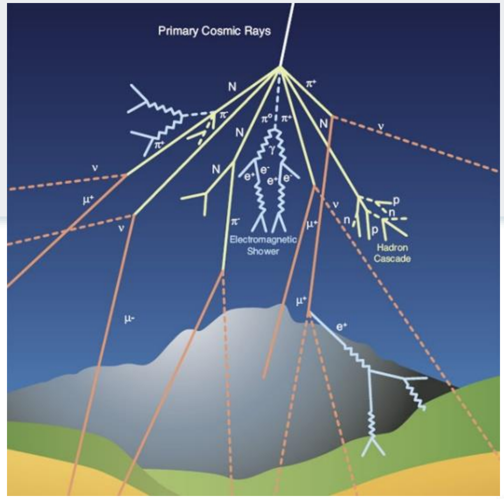
Width of the Vesuvius crater was reduced after 1944 eruption (yellow: lava, blue: pyroclasts); right part of the crater (filled with lava lake until 1944) is denser than rest of the cone (mostly incoherent material) [modified after Imbò (1949)]

Outline

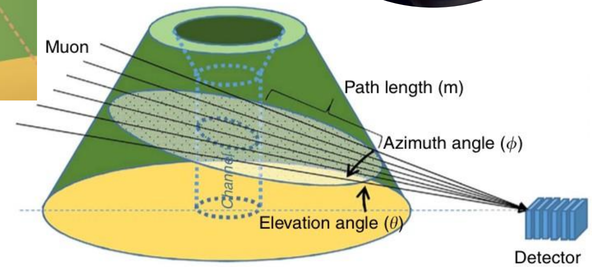
1. Muon Radiography
2. Measurement principle
3. The Muon Radiography of Mt. Vesuvius (MURAVES) project
4. Simulation studies
5. Initial results
6. Conclusions

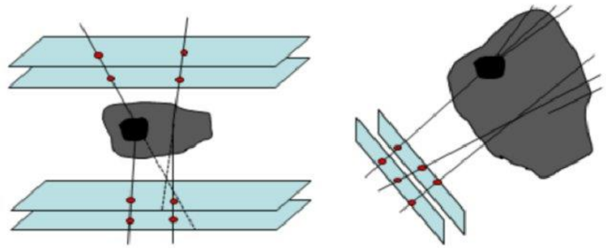
1. Muon Radiography

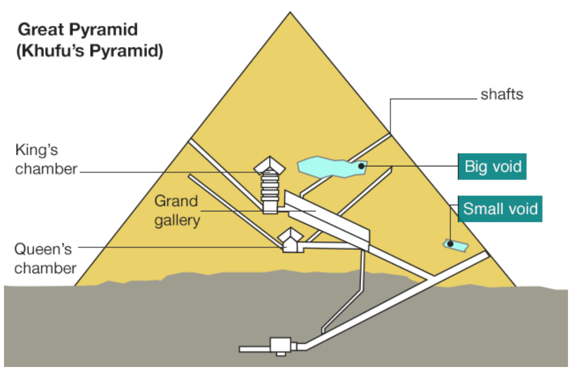
- Relatively new, non-destructive imaging technique similar to X-ray radiography, but based on cosmic-ray muons (high penetrative power), for large-scale objects
- Measurement of muon attenuation (or muon scattering angle) as muons pass through object
- 2D/3D density profile of target's internal structure
- Detection techniques and technology derived from Nuclear/Particle Physics
- Applications in many areas including archaeology, nuclear safety, geoscience …

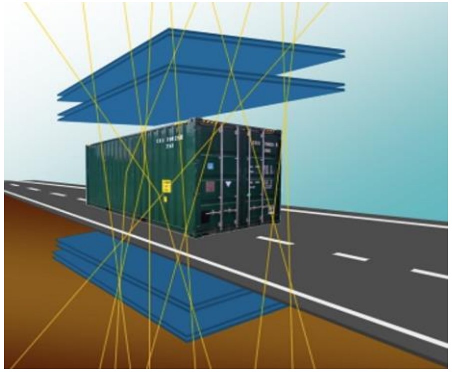


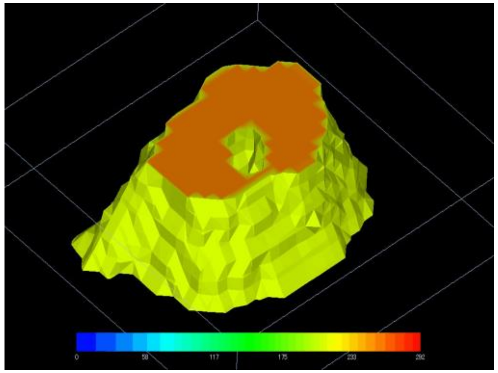
(Image: CERN)

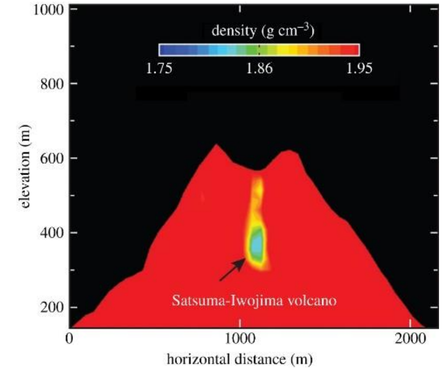




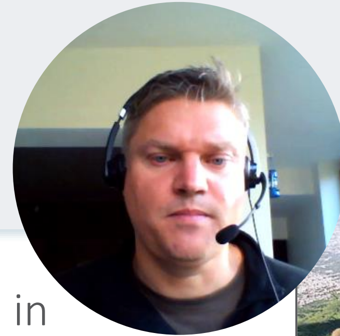




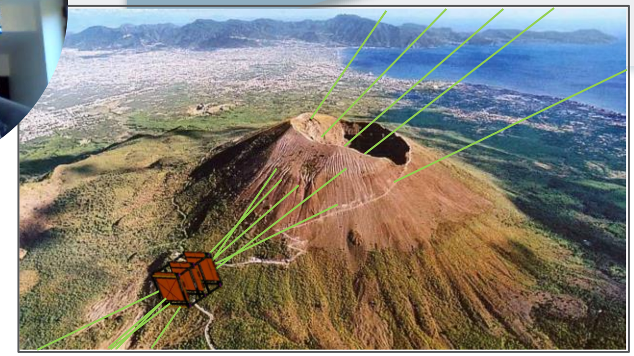


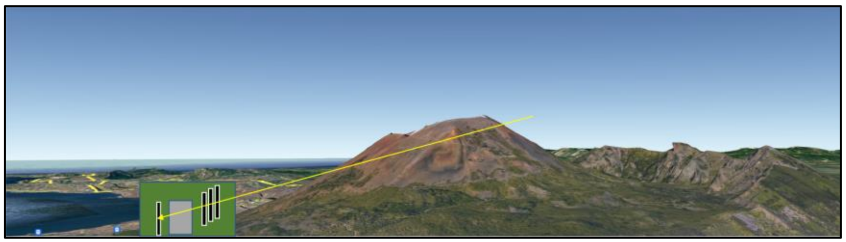


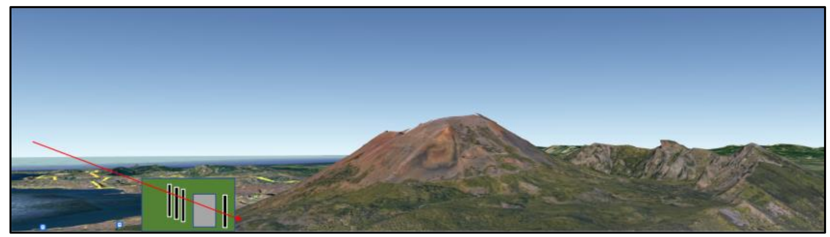
2. Measurement principle



Mapping of mean density of matter crossed by muons in the traversal of the volcano, through measurement of the muon flux reaching the telescope



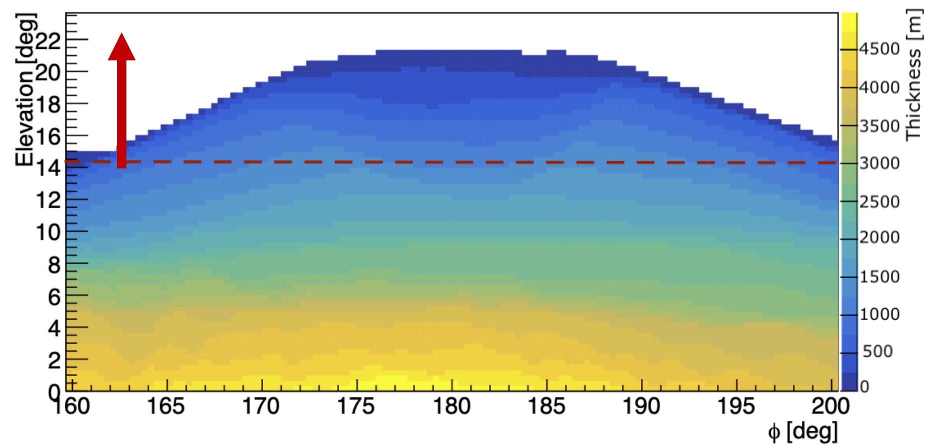




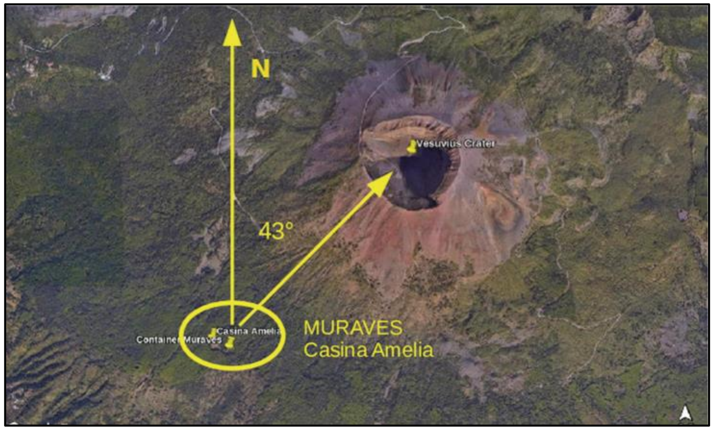
Muon transmission (ratio between the muon flux measured in acquisition runs and in calibration runs with the muon tracker pointing to open sky in the opposite direction)

$$T(\theta,\phi) = \frac{N_\mu^{v}(\theta,\phi)/\Delta t^{v}}{N_\mu^{fs}(\theta,\phi)/\Delta t^{fs}} = \frac{\epsilon^{v}\cdot S_{eff}(\theta,\phi)\int_{E_{min}(\rho)}^{\infty}\Phi(\theta,\phi;E)dE}{\epsilon^{fs}\cdot S_{eff}(\theta,\phi)\int_{E_0}^{\infty}\Phi(\theta,\phi;E)dE}$$

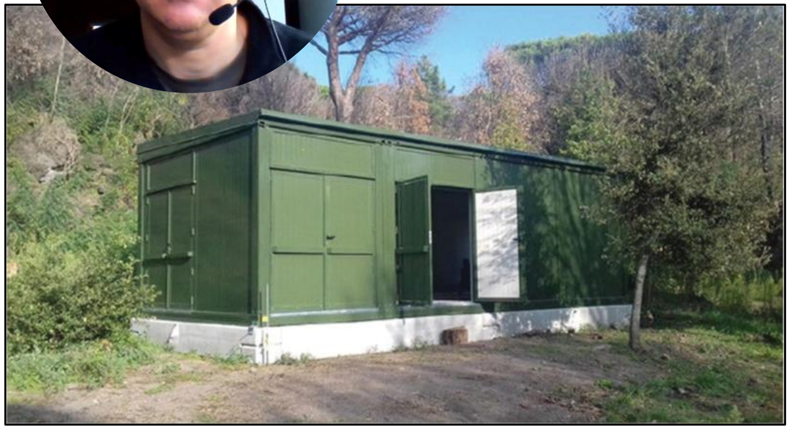
Rock thickness to be traversed by muons through Mt. Vesuvius as function of elevation and horizontal angles; horizontal line reflects the detector's geometrical acceptance (i.e. thicknesses up to ~1500m)



3. MURAVES @ Mt. Vesuvius



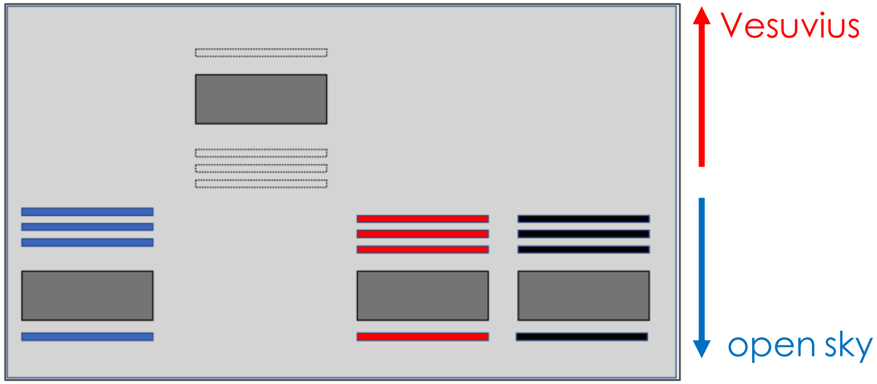
Muraves is located 1500m away from crater and ~640m asl, i.e. slightly below the bottom of the Vesuvius crater



Powered via solar panel system on the container roof connected to array of batteries

3 muon trackers inside the Muraves container

4 concrete platforms inside container, i.e. 3 pointing to Vesuvius and 1 open-sky calibration position



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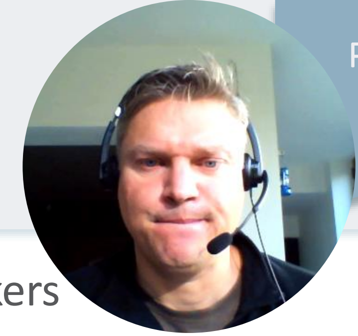
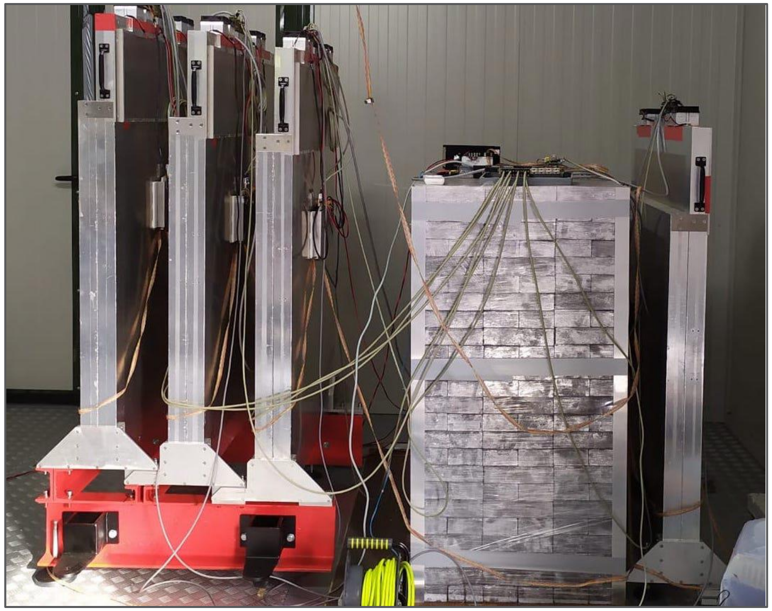
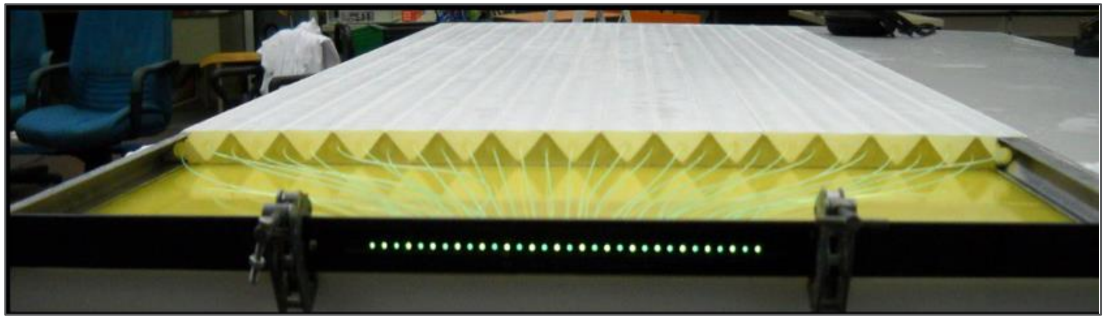
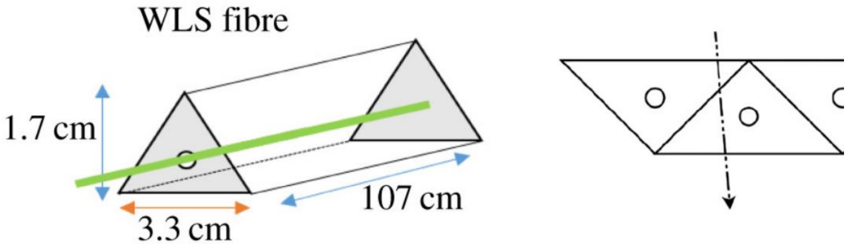




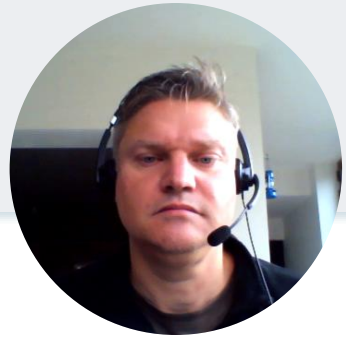
MURAVES Muon Trackers

- 3 equal muon trackers ("ROSSO, NERO and BLU") giving a 3m^2 muon telescope
- Each tracker has 4 tracking stations of 1m^2 active area, distributed over ~2m, with 60cm of lead (background rejection) in between the two downstream stations
- Each station consists of a pair of orthogonal (XY) planes, where each plane is made of 2 modules, composed of 32 triangular scintillator bars (produced at Fermilab) each (leading to ~3mm position resolution)
- Scintillation light collection via 1.2mm WLS fibers (Kuraray) inserted into each strip and coupled to SiPM (Advansid)



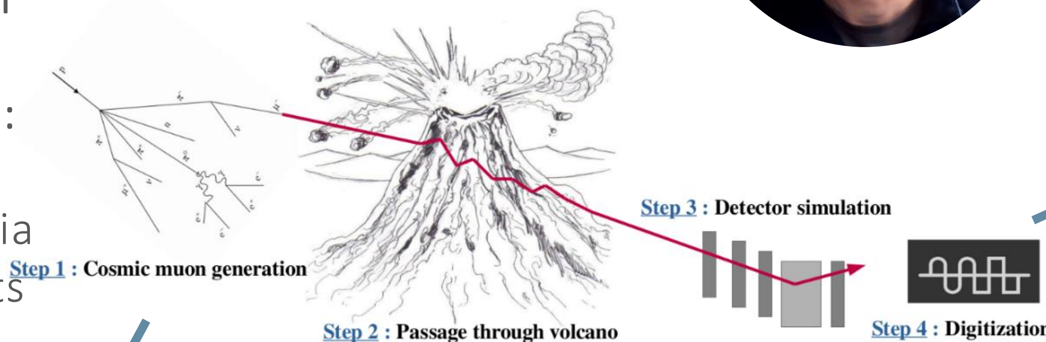


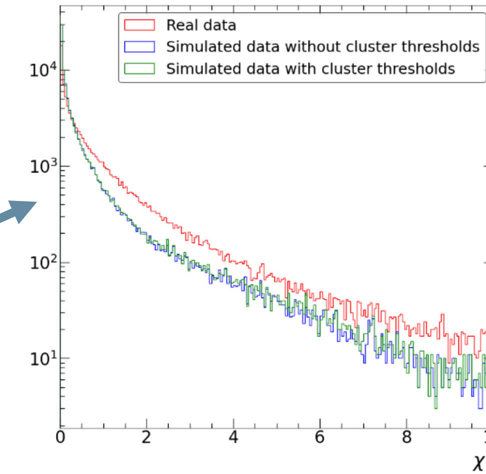
4. Simulation studies



Comparing data with Monte Carlo simulations is crucial:

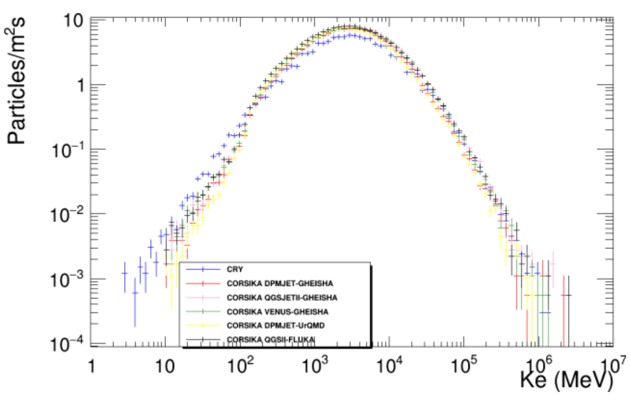
- Density image reconstruction via fit measurements
- Investigation of various effects of experimental constraints



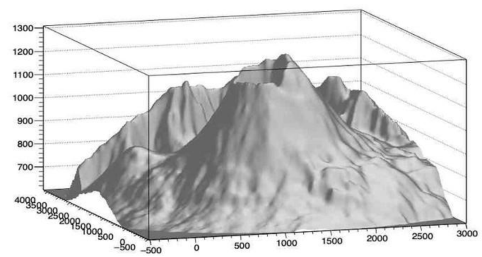


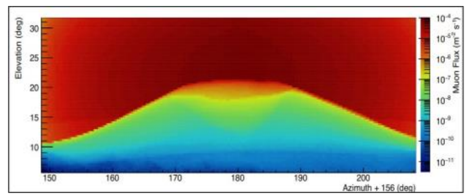
χ^2 comparison of muon tracks in real and simulated data

Cosmic-ray muon energy spectrum

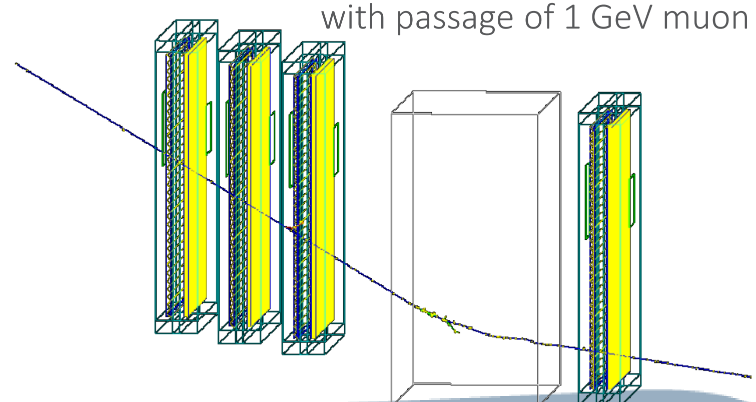


DTM with 1 m resolution [Vilardo *et al.*, Journal of maps 9(4):635 (2013)] and expected muon flux (PUMAS/TURTLE)

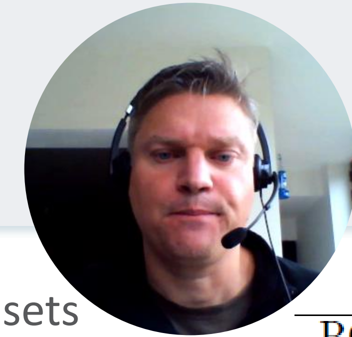




GEANT4 muon tracker model with passage of 1 GeV muon



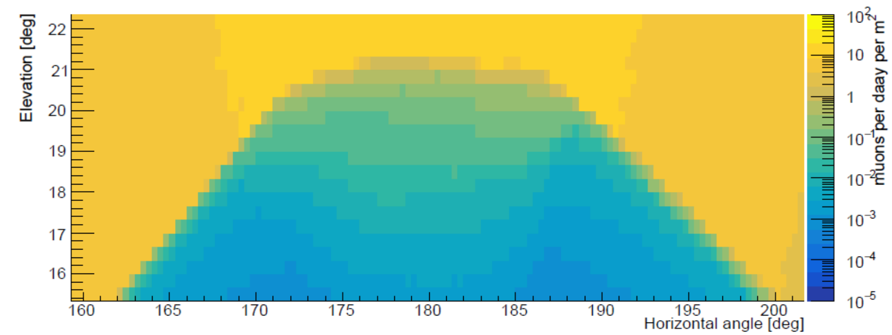
5. Initial results

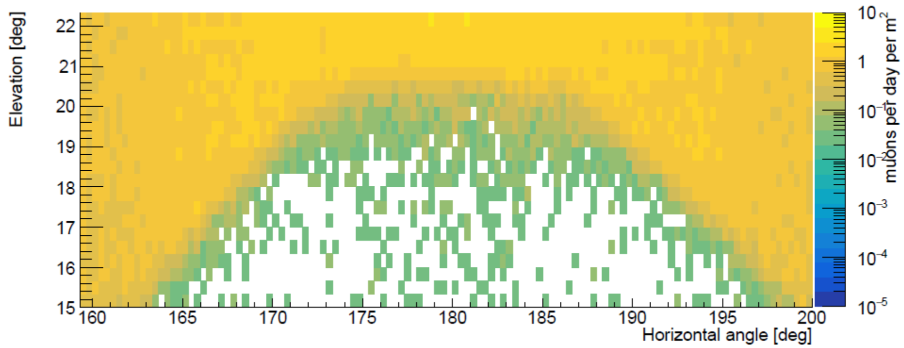


Preliminary analysis based on initial datasets from the Rosso and Nero trackers (both installed in 2019)

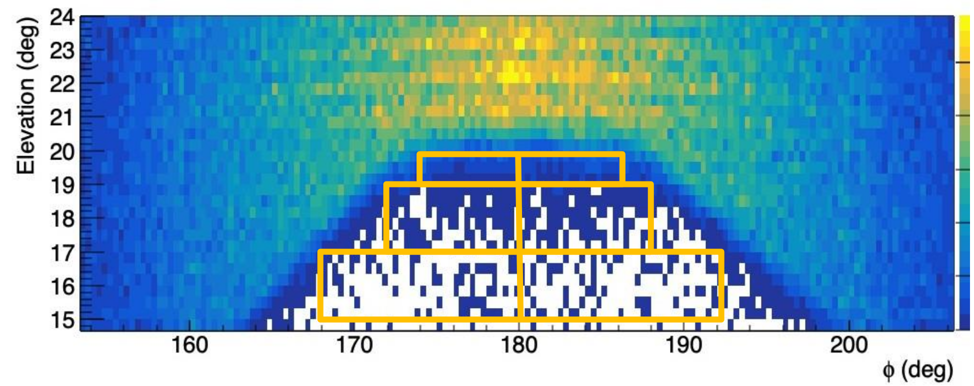
Dataset	Vesuvius	Free-sky
ROSSO wp 15°C	51 days	9.5 days
ROSSO wp 20°C	40 days	14.3 days
NERO wp 15°C	43 days	10 days
NERO wp 20°C	26 days	17 days

1-2 months of total exposure time, taken at 2 different working points corresponding to 2 SiPM temperature settings





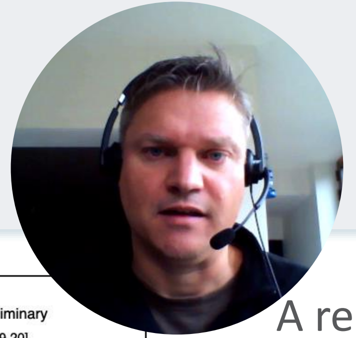
Expected muon flux (PUMAS, taking the lead wall energy threshold into account) and measured flux obtained from one of the datasets

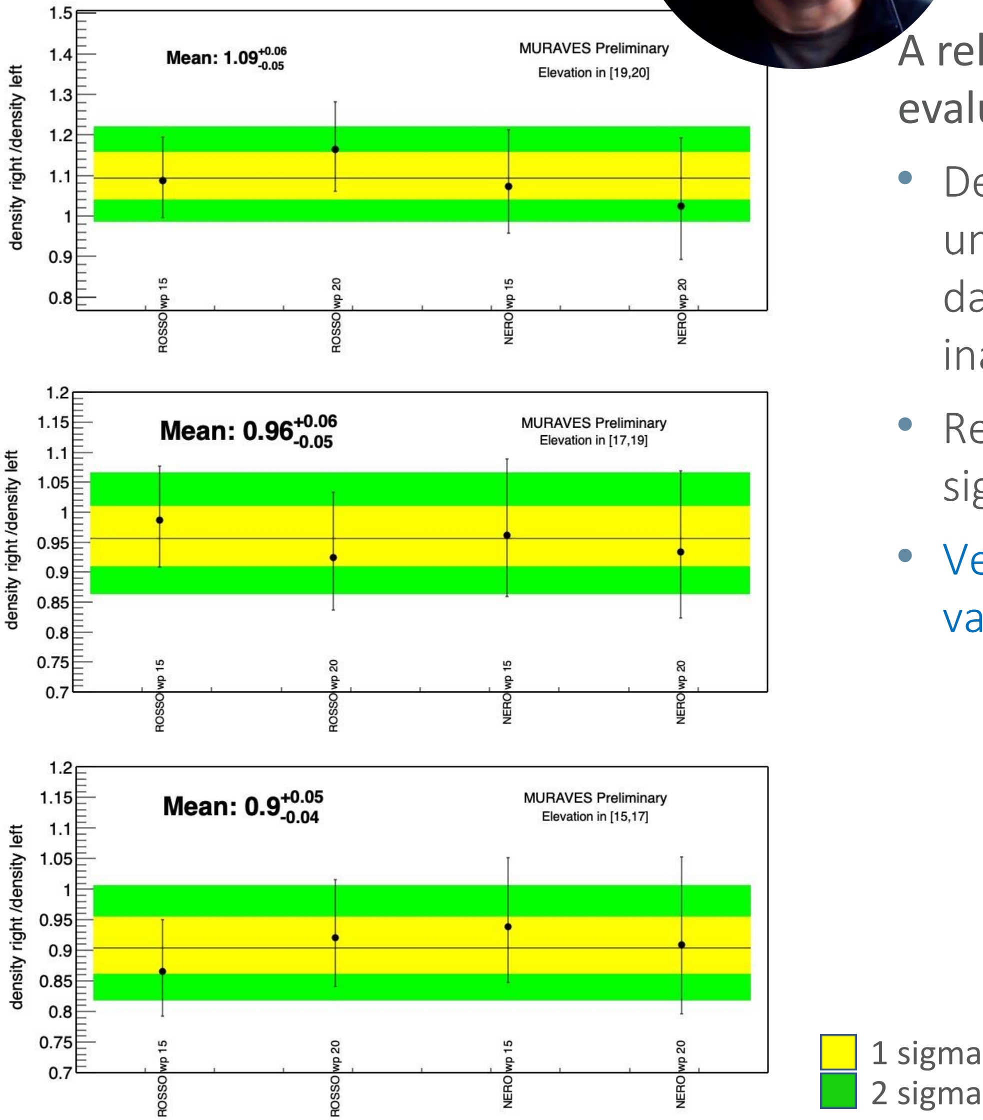


Upper part of the cone was divided into regions/layers large enough to contain a reasonable amount of events (Δx=180-315m; Δy=26-52m), to study expected layered structure

Further subdivision in left and right parts (from the point of view of the detector) in order to reveal possible asymmetries

5. Initial results





A relative horizontal asymmetry $\rho_{right}/\ \rho_{left}$ is evaluated

- Density ratio only, to reduce systematic uncertainties from e.g. differences between datasets, background subtraction, simulation inaccuracies …
- Results from different datasets agree within 1 sigma
- Very preliminary results seem to indicate density variations in different layers, i.e
  - Top layer shows right side more dense than left side
  - Middle layer shows left side more dense than right side
  - Bottom layer same as middle layer but stronger difference between right and left

6. Conclusions

- Muography is an imaging technique using cosmic-ray muons along with particle detectors to study the interior structure of large objects, including geological structures
- The MURAVES project is applying the muographic imaging technique to study the summit cone of the Mt. Vesuvius volcano
- Three identical plastic scintillator-based muon telescopes positioned at the slope of Mt. Vesuvius have been recording data since 2019
- Using the first data sets from the experiment, preliminary density projections have been obtained, revealing a possible density asymmetry in the cone of the volcano
- Data taking with the MURAVES setup is continuing over the coming years, which should yield much more precise, high-resolution results

Recent references

1. M. D'Errico et al., *The MURAVES experiment: study of the Vesuvius Great Cone with Muon Radiography*, Journal for Advanced Instrumentation in Science (2022) 273
2. M. Moussawi et al., *The simulations chain of the MURAVES experiment*, Journal for Advanced Instrumentation in Science (2022) 303

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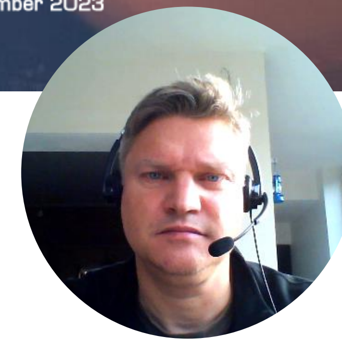

Thank you!

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