Muon Radiography: Imaging Large-Scale Structures with Cosmic Muons

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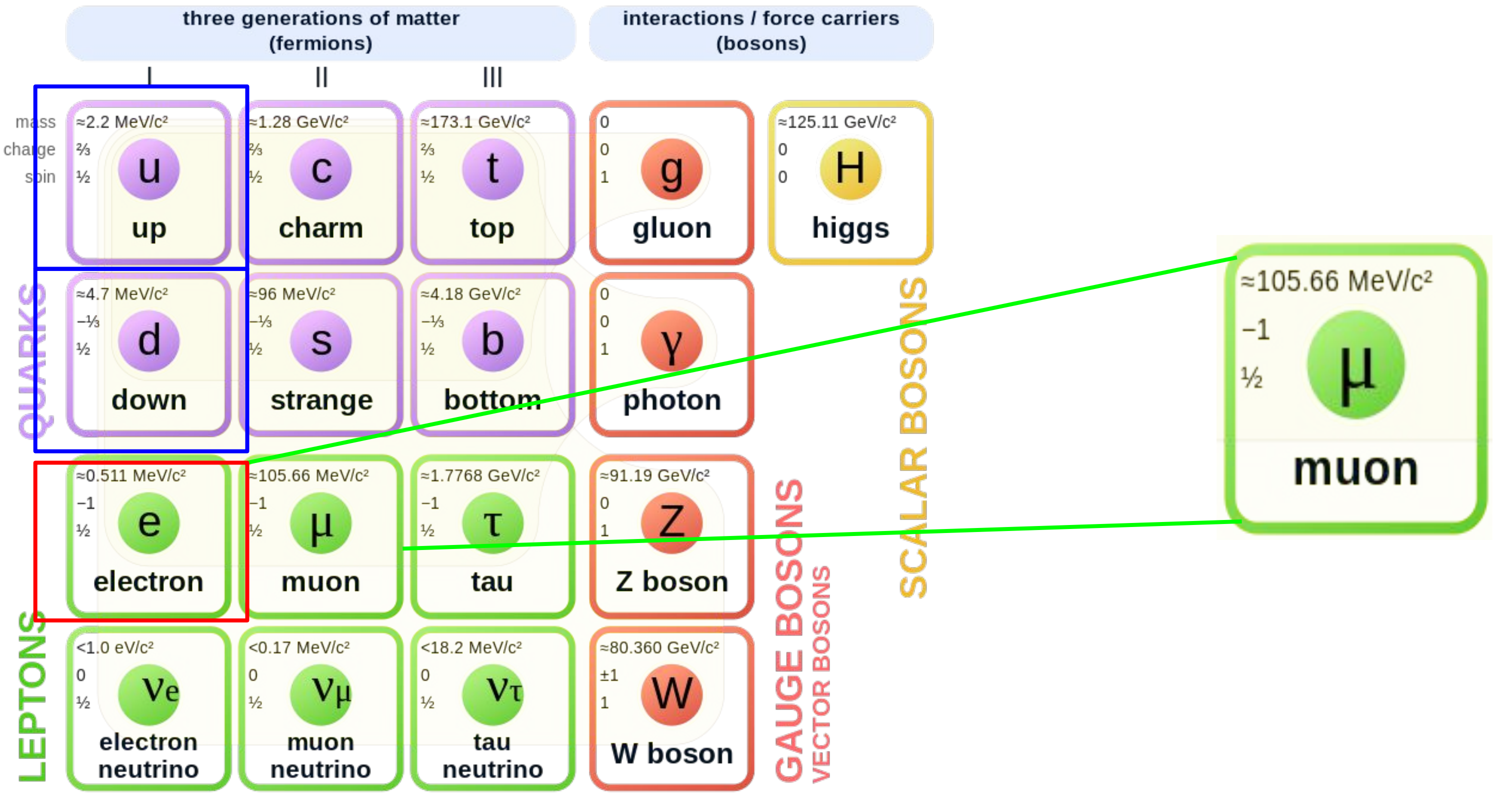
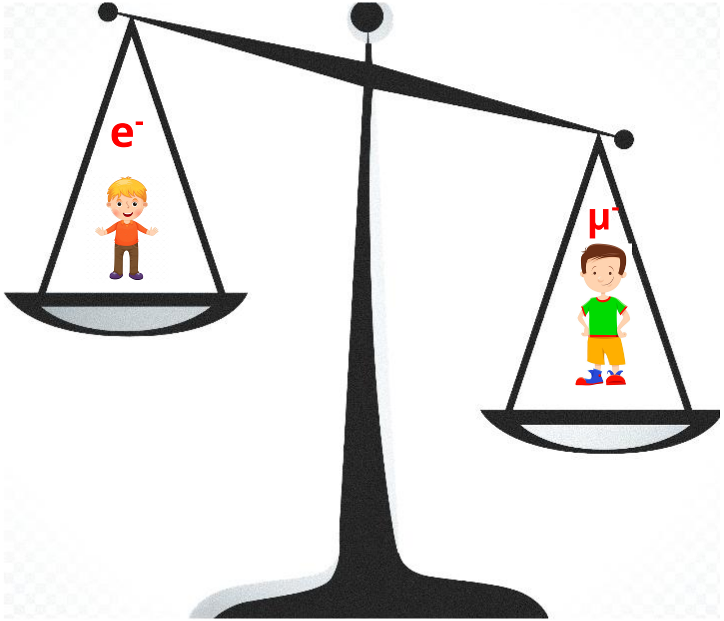
Standard Model of Elementary Particles



The Muon Particle



200 times heavier than electrons (105.7 MeV)

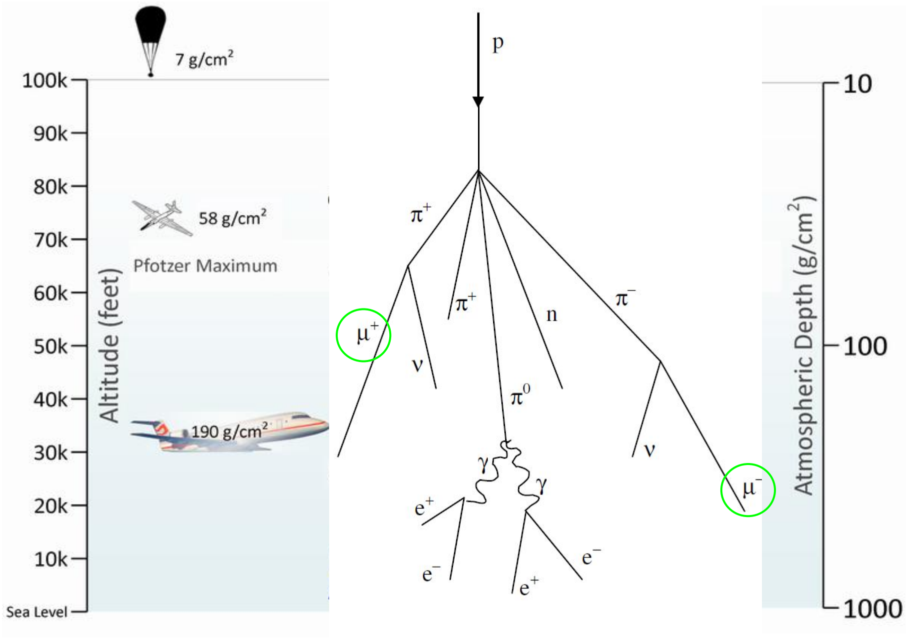
Relatively long life time (2.2 μs)

Muons are unstable particles and they further decay into electrons, and electron and muon neutrinos

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Cosmic Ray Muons

Cosmic rays are the natural source of muons



Primary cosmic rays interacts with atoms in the atmosphere

↓

Cascade of secondary particles
(protons, neutrons, pions, kaons, etc.)

↓

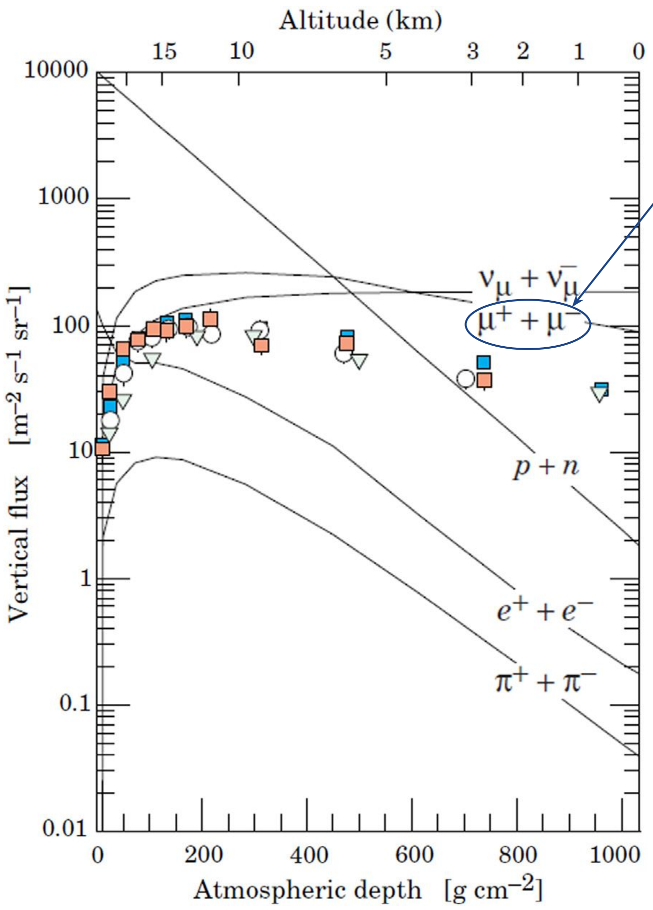
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\overline{\nu}_{\mu}$$

Short lived particles (τ ~26 ns)

Penetrates through the atmosphere (τ ~2.2 μs)

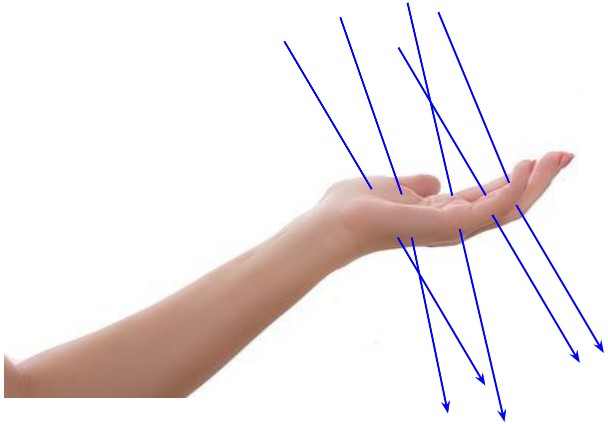
Sea level

Muons at Sea Level



Most abundant flux at sea level after Neutrinos
(1 muon/cm^2/min)

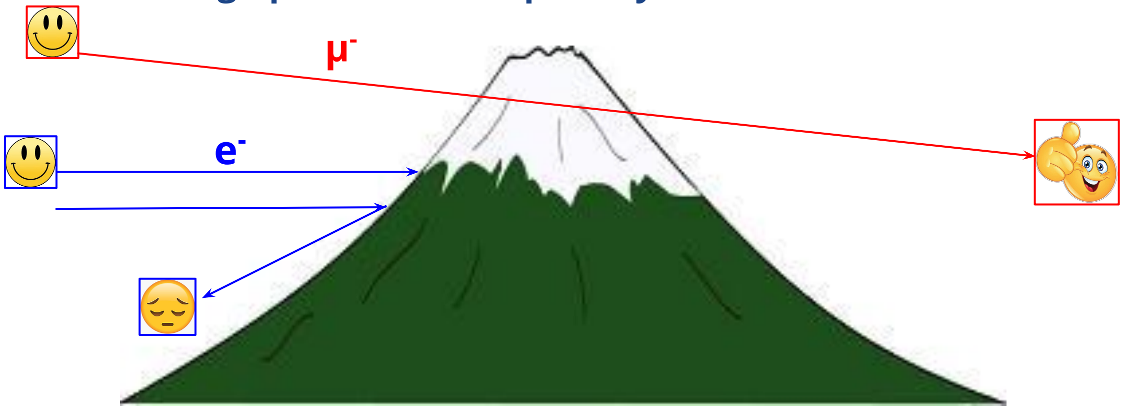
~150 muons/minute

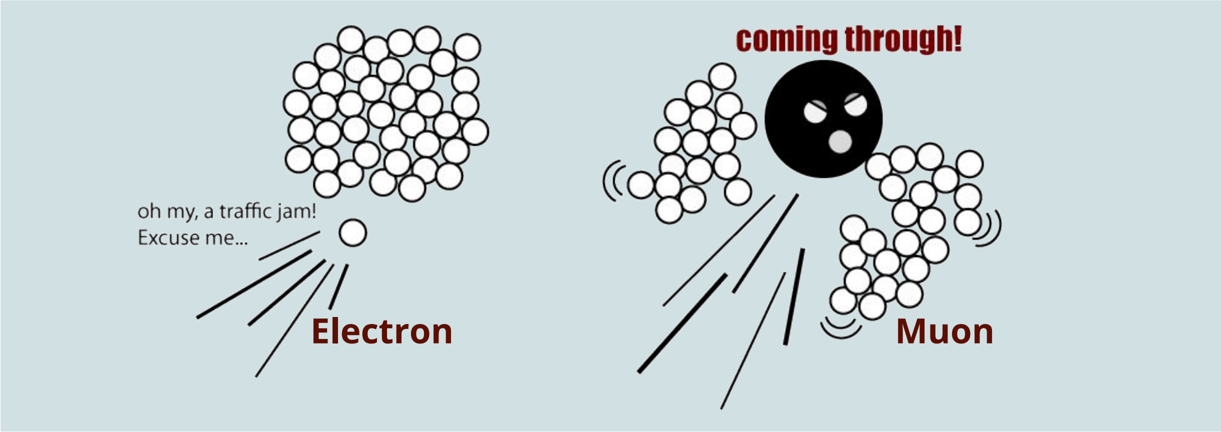


Altitude
Muon flux

What’s Special about Muons?

Higher mass and longer life time-> high penetration capability





Muons for Imaging

Muons are widely being used for studying the internal structure of large, thick and high density objects -> Muon Radiography

Applications:

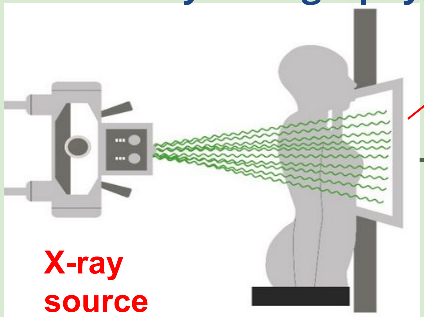
- **Volcanology**
- **Archaeology**
- **Civil Engineering**
- **Industry**

…



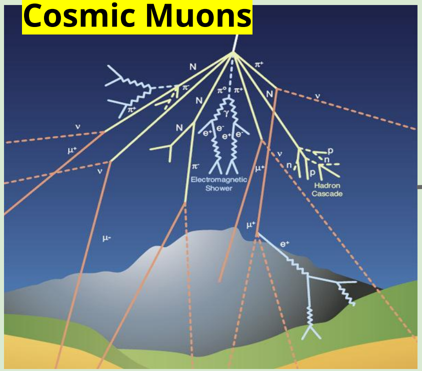

Muons Radiography

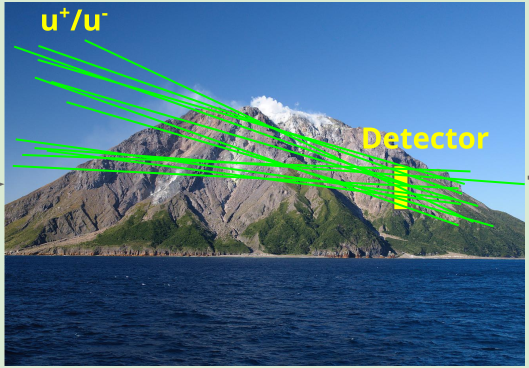
Similar to X-ray radiography, except penetrating muons in place of X rays

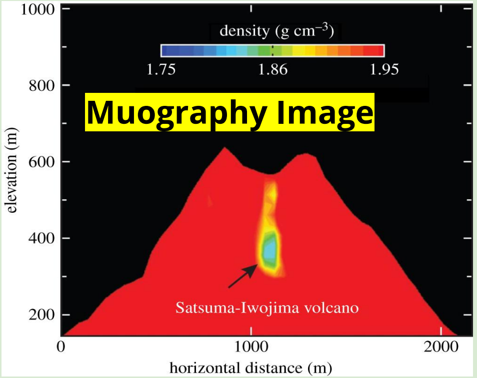


X-ray Image

Cosmic Muons







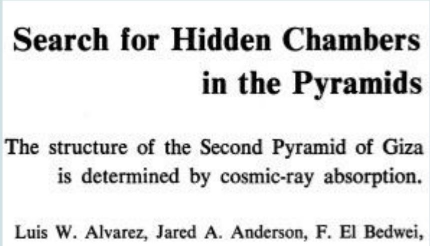
Measuring the outcoming muon flux we can indirectly measure the mean density of the object

Detector Technologies for Muons Radiography

Type	Surface	Resolution	Construction	Readout	Cost
Plastic scintillators					
Square bars	1-4 m^2	>10 mrad	Simple	Simple	Low
Triangular bars	1-2 m^2	<10 mrad	Simple	Medium	Medium
Scintillating fibers	1-2 m^2	0.1 mrad	Medium	Complex	High
Gaseous detectors					
Proportional tubes	1-4 m^2	10 mrad	Simple	Simple	Low
Multi-wire chambers	>4 m^2	<1 mrad	Medium	Simple	Medium
Drift chambers	>4 m^2	0.1 mrad	Complex	Complex	High
Resistive plate chambers	>10 m^2	0.1 mrad	Simple	Medium	Low
Nuclear emulsion detectors	>4 m^2	0.1 mrad	Simple	Complex	Low

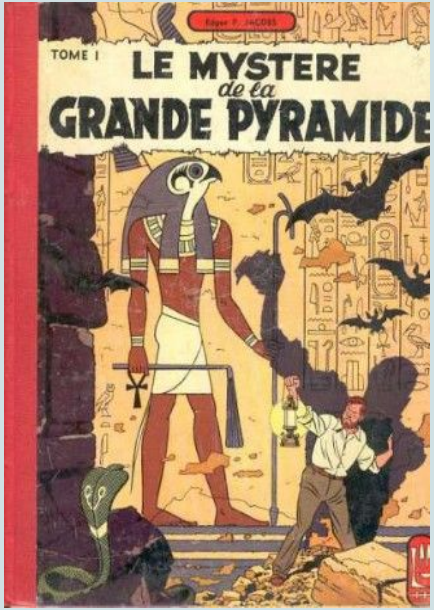
Bonechi, Lorenzo, Raffaello D’Alessandro, and Andrea Giammanco. "Atmospheric muons as an imaging tool." *Reviews in Physics* 5 (2020): 100038.

Muography of the Grand Pyramid

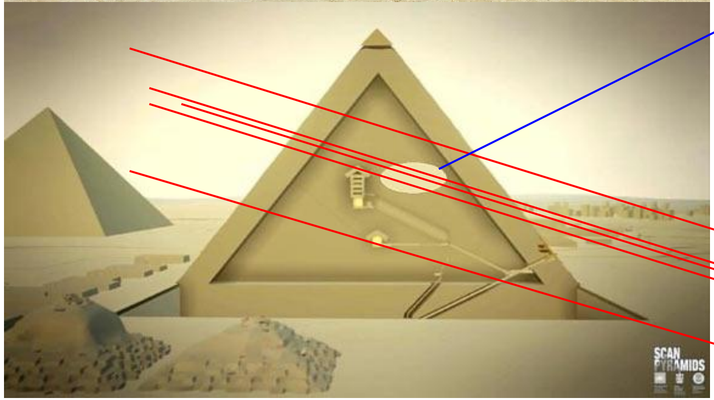

Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei,



Khufu's Pyramid is one of the largest archaeological monument all over the world

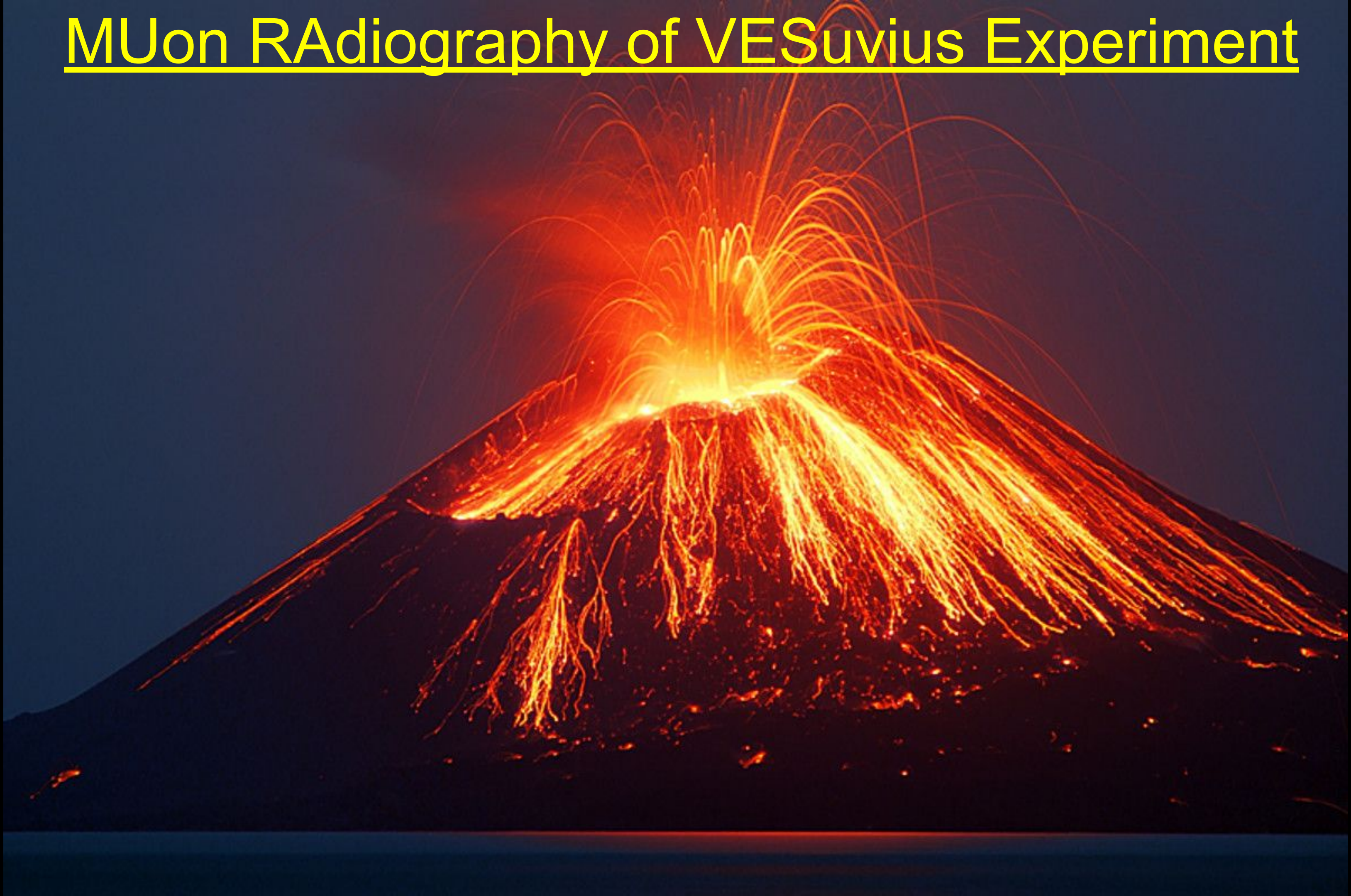


ScanPyramids project (2016-2017)

- **Detectors: Nuclear Emulsion Plates, Plastic Scintillator Detectors and Micromegas**
- **9-meter-long corridor about 2 meters wide by 2 meters tall, close to the pyramid's north face**

Increased muon flux from the direction of the hidden cavity

MUon RAdiography of VESuvius Experiment



Mt. Vesuvius

- Active volcano located in southern Italy (Naples)
- As per studies, Mt. Vesuvius originated less than 200,000 years ago (relatively young volcano)
- Quiescent since ~80 years, but still active!

Sleeping giant!

Mt. Vesuvius History

Illustration of eruption of Mt. Vesuvius in 79 AD

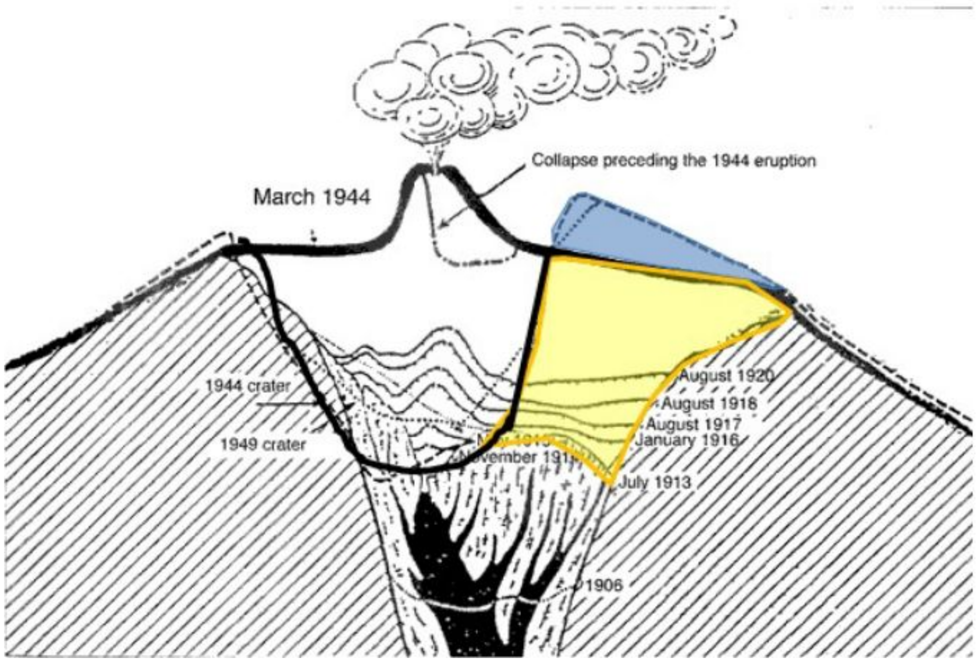
Remains of victims at Pompeii

March 17, 1944: The most recent eruption of Mt. Vesuvius

Mt. Vesuvius crater now

Between 79 AD and the last eruption in 1944: 27 significant eruptions

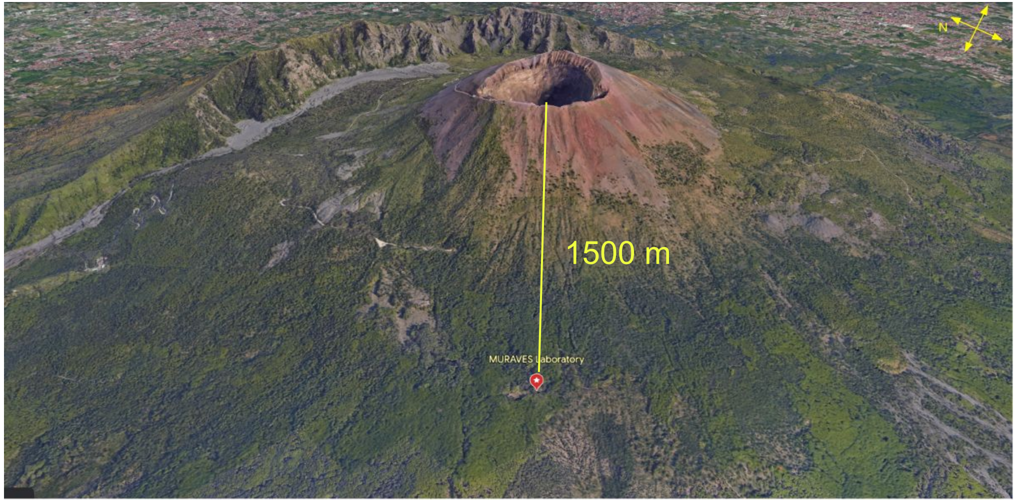
Interior Structure



Interior of summit cone is thought to have a layered structure of materials with different densities
Measurement of density distributions->Details of the internal dynamics of the volcano

MURAVES Experiment

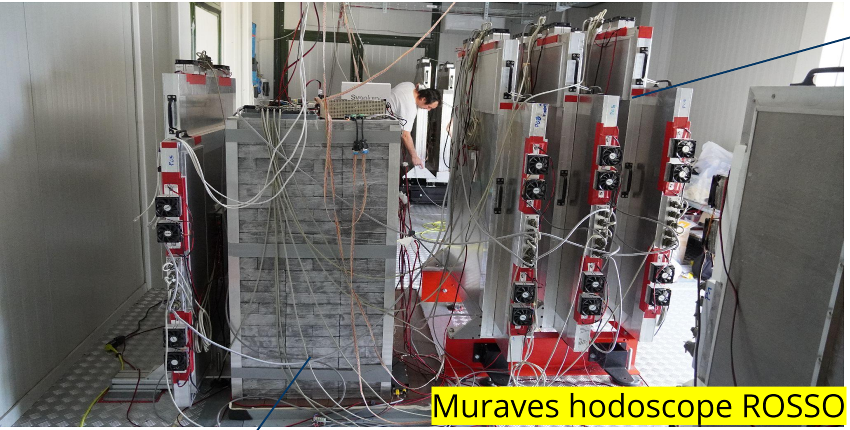
Aim: Study the density distribution of the summital cone of Mt. Vesuvius



- **Muon flux ∝ Density of the material**
- **By measuring the muon flux, we can get an idea of the density of the material through which the muons passed**

- **Container of the MURAVES experiment -> three scintillator based muon trackers**
- **Whole setup is powered with solar panels mounted on the roof connected to an array of batteries**

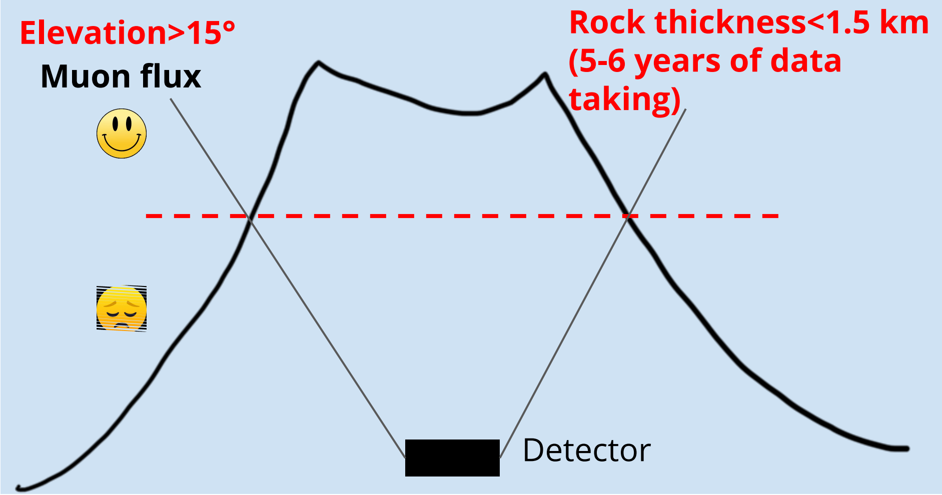
MURAVES Detector



Detection planes
(Only particles that passes through all the four layers are selected)

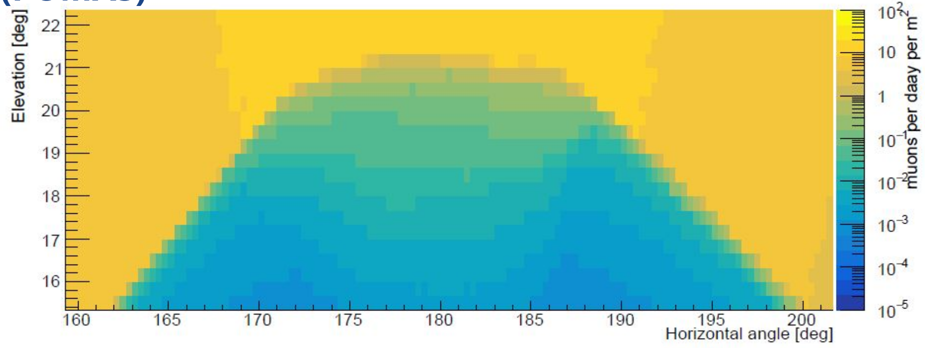
Three muon trackers: NERO, ROSSO and BLU pointing to the same direction -> To collect more data at the same time

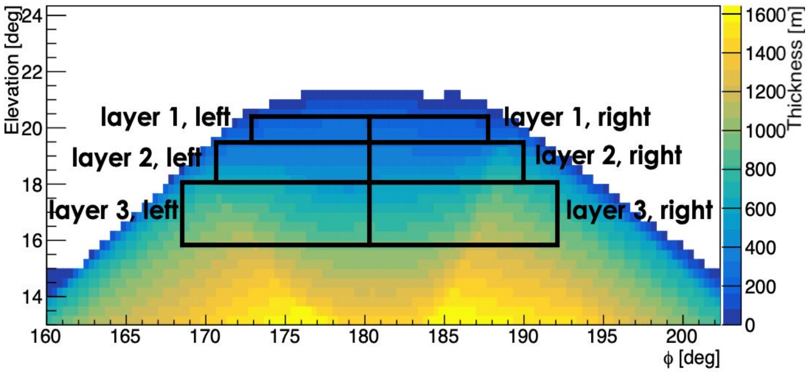
Lead wall to stop particle like electrons and filter out muons



Muon flux

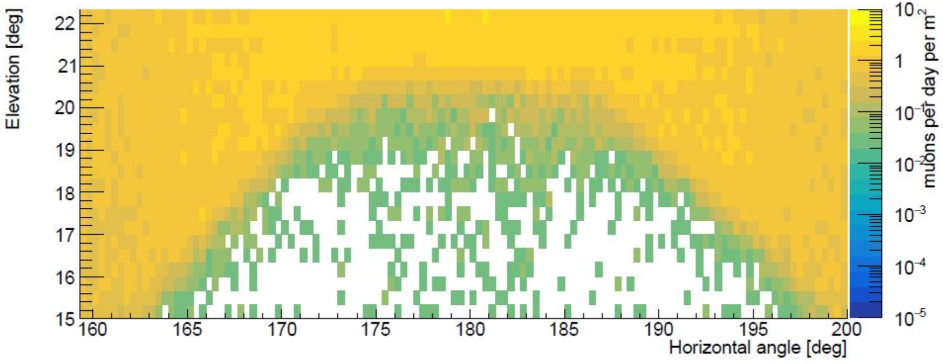
Expected muon flux measured using Monte Carlo simulation (PUMAS)





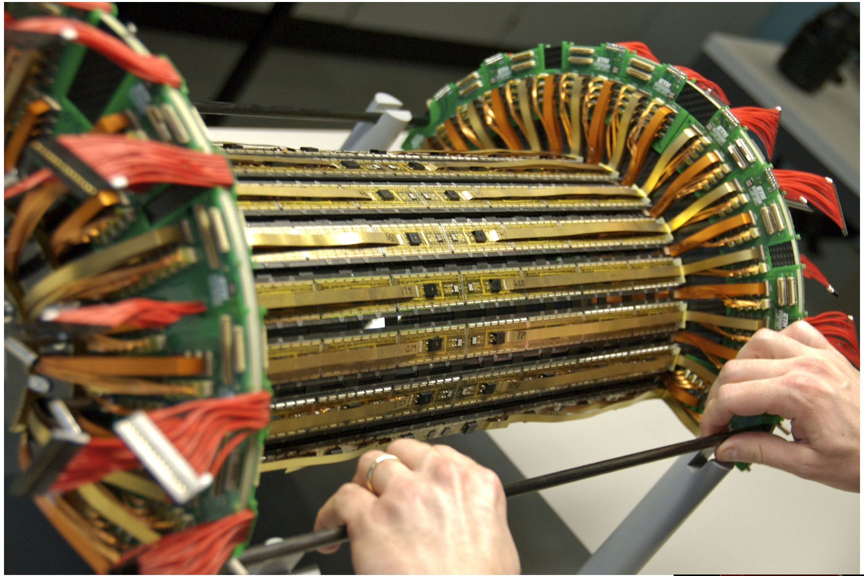
Angular regions defined for evaluation of the average density

Measured flux obtained from 50-days of data taking with one of the muon detectors

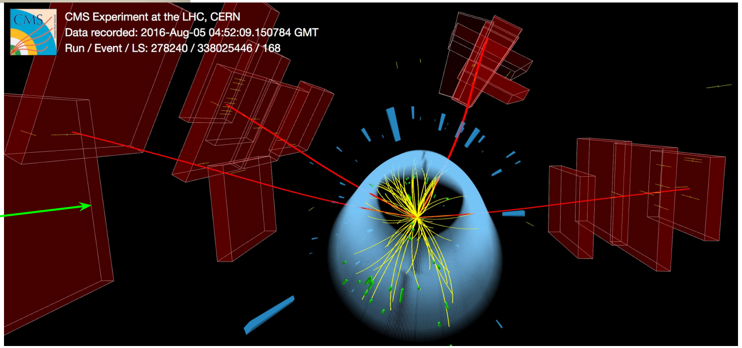


Preliminary results suggest notable density variations between the left and right side regions, with the right side appearing denser than the left.

Efforts at PSI

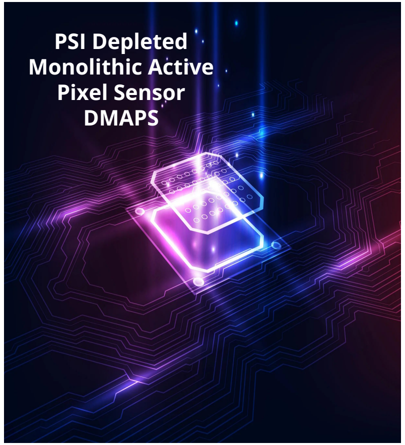


- For High Energy Physics Experiments at CERN and PSI
- More than a 100 million pixels
- 40 million images per second



DMAP Detectors for Muography

- Low production cost
- Low power consumption
- Integrated electronics
- Low production complexity
- Low operation complexity
- Very high-resolution
- Robust
- Portable
- Modular
- Mass producible



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Conclusions

- Muons can penetrate through hundreds of meters of rock, providing valuable information about the internal density variations and structures (presence of the magma chambers, magma pathways, etc.) without any drilling, excavation, or physically accessing the hazardous areas unlike the conventional methods.
- With cosmic-ray muons being a continuous source, muography enables ongoing and continuous monitoring of objects under study.
- As it is non-intrusive, it has a minimal environmental impact, making it particularly suitable for protected or ecologically sensitive areas.
- Muography is being widely applied to various interdisciplinary fields, and the different detector technologies used in fundamental physics are being utilized for muography.

Thank You