XIII International Conference on New Frontiers in Physics
26 Aug – 4 Sep 2024
OAC, Kolymbari, Crete (Greece)

The transmission muography technique for locating potential Radon gas conduits at the Temperino mine (Tuscany - Italy)

Diletta Borselli[1,2], Tommaso Beni[3], Lorenzo Bonechi[1,2], Debora Brocchini[4], Roberto Ciaranfi[2], Vitaliano Ciulli[1,2], Raffaello D'Alessandro[1,2], Andrea Dini[5], Catalin Frosin[1,2], Giovanni Gigli[3], Sandro Gonzi[1,2], Silvia Guideri[4], Luca Lombardi[3], Andrea Paccagnella[1,2] and Simone Vezzoni[5]

[1]University of Florence, Department of Physics and Astronomy, Florence, Italy, [2]INFN-FI, Florence, Italy (borsellid@fi.infn.it),
[3]University of Florence, Department of Earth Sciences, Florence, Italy,
[4]Parchi Val di Cornia SpA, Livorno, Italy [5]CNR, Institute of Geosciences and Georesources, Pisa, Italy

INFN FI

UNIVERSITÀ DEGLI STUDI FIRENZE

PARCHI della VAL di CORNIA

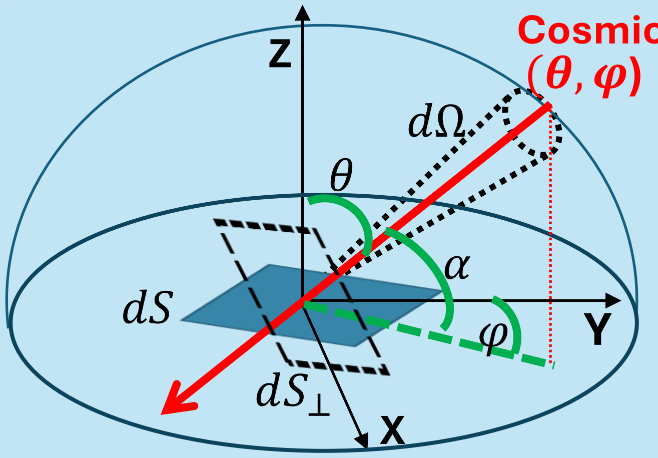
Index

- Introduction to the Transmission Muography technique
- The MIMA detector used for the measurements at the Temperino mine
- The Temperino mine case study: objectives of the study and installation points
- Preliminary two-dimensional muon imaging results and identification of possible cavities signal
- Conclusions and preliminary considerations on the 3D reconstruction of possible cavities

The MIMA detector in measurement at the Temperino mine

Atmospheric muons

Some definitions:



θ =zenith
φ=azimuth
$\alpha = 90 - \theta$=elevation

$dS_\perp$ is the infinitesimal detector surface that looks in the direction (θ, φ)

- Differential flux of cosmic rays:

$$\phi(\theta, \varphi, E, t, \Omega) = \frac{dN(\theta,\varphi)}{dS_\perp d\Omega\, dt\, dE} \; [\mathrm{m^{-2}\,GeV^{-1}sr^{-1}s^{-1}}]$$

- Integral flux of cosmic rays:

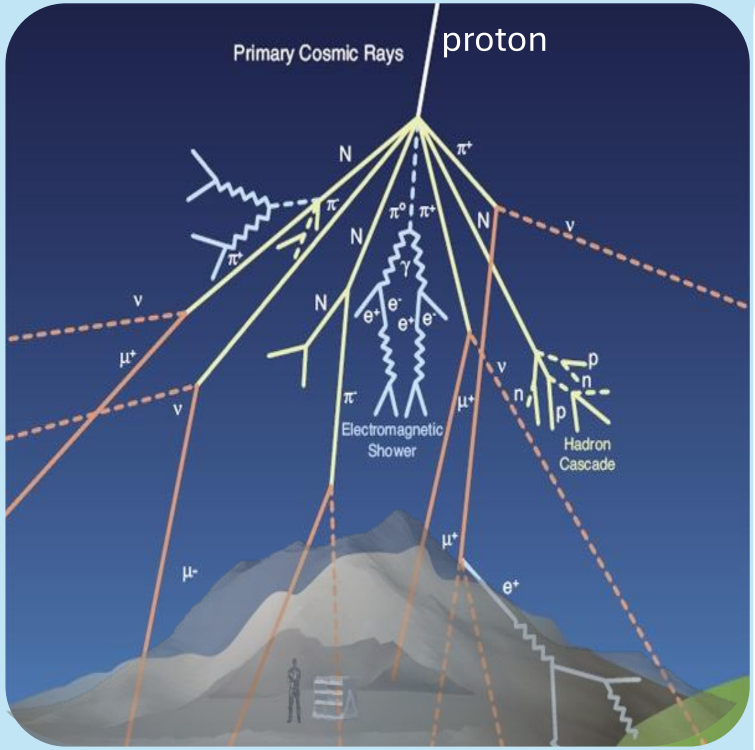
$$\Phi_I(\theta, \varphi, t, \Omega) = \int_{E_0}^{\infty} \phi(\theta, \varphi, E, t, \Omega)\, dE \; [\mathrm{m^{-2}\,sr^{-1}s^{-1}}]$$

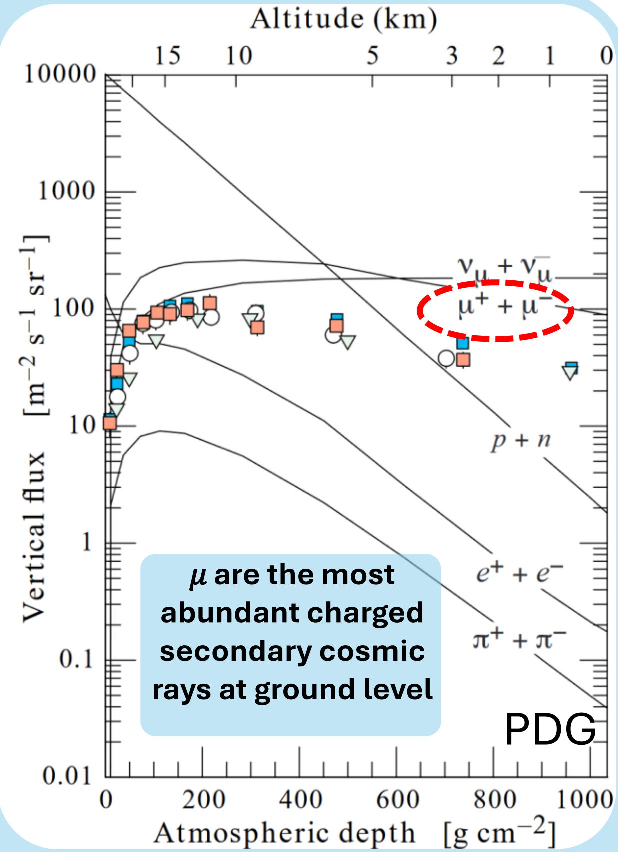
- Number of particles detected in the time dt:

$$N = \underbrace{\int_S dS \int_{\Omega_{dS}} d\Omega \cos(\theta)}_{\mathbf{G}} \int_{dt} dt\, \Phi_I = \boldsymbol{\Phi_I} \mathbf{G} \boldsymbol{\Delta t}$$

G detector geometric factor

Secondary cosmic rays:





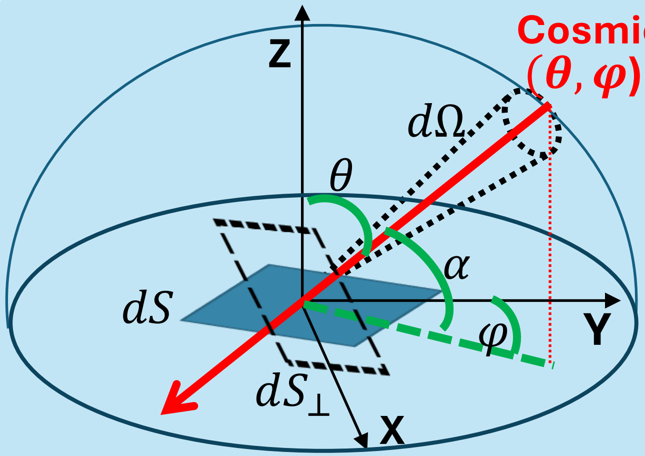
Muons:

About 70 muons s^{-1} m^{-2} sr^{-1} reach the sea level in the vertical direction (E>1GeV). The integral flux of cosmic rays depends on:

- zenith(θ) angle: $\Phi_I \;\alpha\; cos^2(\theta)$ for $E_\mu \cong 3\; GeV$
- on azimuth angle (φ) (East-West asymmetry)
- on geographical position and atmospheric conditions

Atmospheric muons

Some definitions:



θ =zenith
φ=azimuth
$\alpha = 90 - \theta$=elevation

$dS_\perp$ is the infinitesimal detector surface that looks in the direction (θ, φ)

- Differential flux of cosmic rays:

$$\phi(\theta,\varphi,E,t,\Omega) = \frac{dN(\theta,\varphi)}{dS_\perp d\Omega\, dt\, dE} \ [\mathrm{m^{-2}\,GeV^{-1}sr^{-1}s^{-1}}]$$

- Integral flux of cosmic rays:

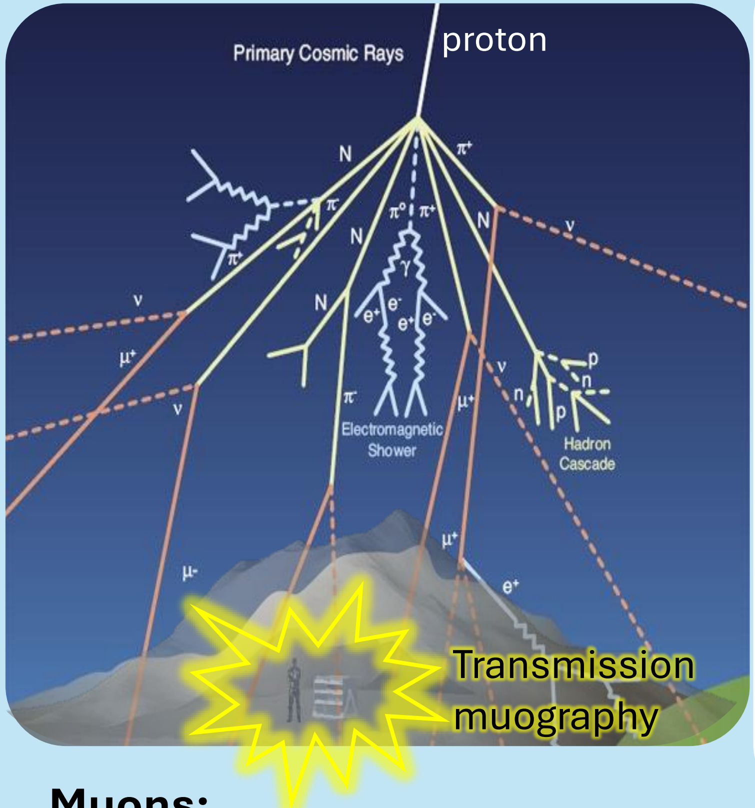
$$\Phi_I(\theta,\varphi,t,\Omega) = \int_{E_0}^{\infty} \phi(\theta,\varphi,E,t,\Omega)\, dE \ [\mathrm{m^{-2}\,sr^{-1}s^{-1}}]$$

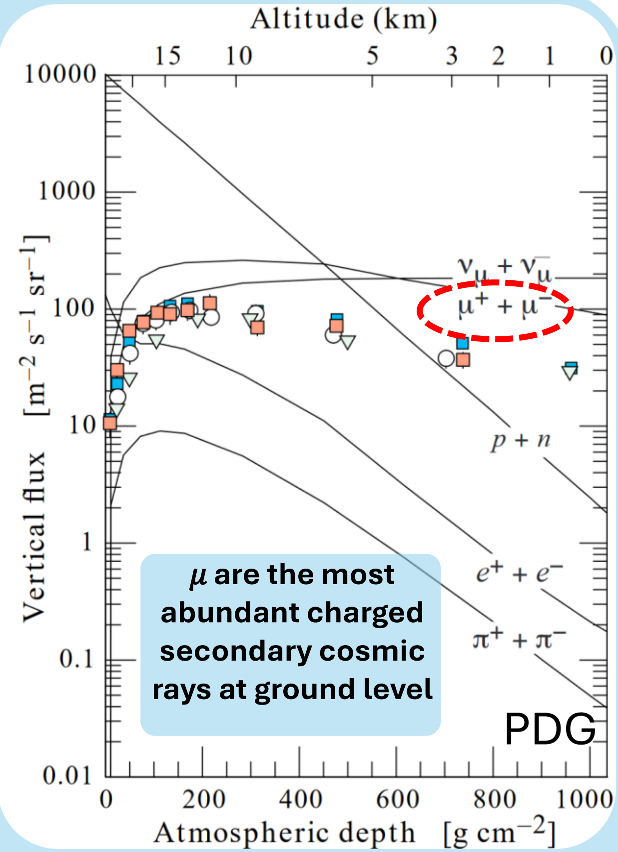
- Number of particles detected in the time dt:

$$N = \underbrace{\int_S dS \int_{\Omega_{dS}} d\Omega \, \cos(\theta) \int_{dt} dt}_{\mathbf{G}} \, \Phi_I = \boldsymbol{\Phi_I G \Delta t}$$

G detector geometric factor

Secondary cosmic rays:





Muons:

About 70 muons s^{-1} m^{-2} sr^{-1} reach the sea level in the vertical direction (E>1GeV). The integral flux of cosmic rays depends on:

- zenith(θ) angle: $\Phi_I \ \alpha \ cos^2(\theta)$ for $E_\mu \cong 3\ GeV$
- on azimuth angle (φ) (East-West asymmetry)
- on geographical position and atmospheric conditions

Muons interaction with matter and Transmission muography technique

Muons are the most penetrating charge particles in the matter

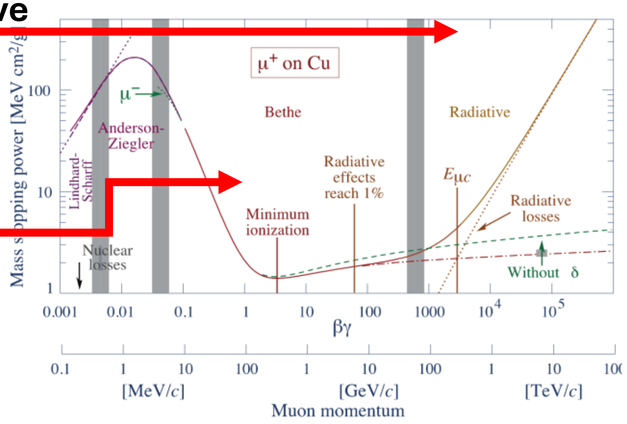
- **Loss of energy**

$$E > 10\text{MeV}$$

$$-\left(\frac{dE}{dX}\right) = a(E) + b(E)\,E$$

radiative

ionization



$X = \rho \cdot x$ Opacity [g cm^{-2}]

ρ: density x: depth

Range in the matter:

At high energy a and b are approximately constant and we can obtain:

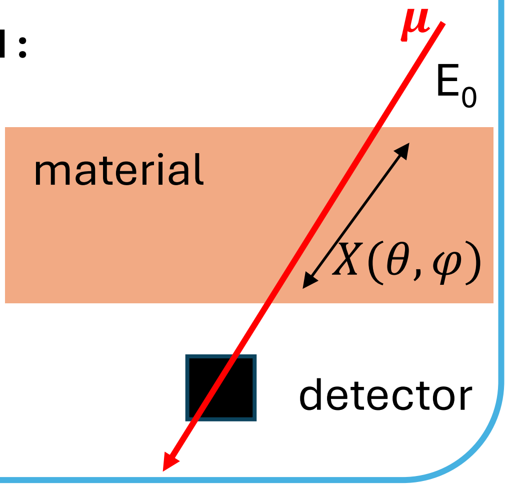
$$R(E_0) = \int_0^{E_0} \frac{dX}{dE}\,dE = \frac{1}{b}\ln\left(\frac{a + bE_0}{a}\right)$$

E_0 initial energy of the muon

Vertical integral flux of muons underground :

$$I(X) = A\left[\frac{a}{b}\left(e^{bX} - 1\right)\right]^{-\gamma}$$

γ spectral index



From a measurement of underground flux it is possible to calculate the opacity that depends from the material density

Muons interaction with matter and Transmission muography technique

Muons are the most penetrating charge particles in the matter

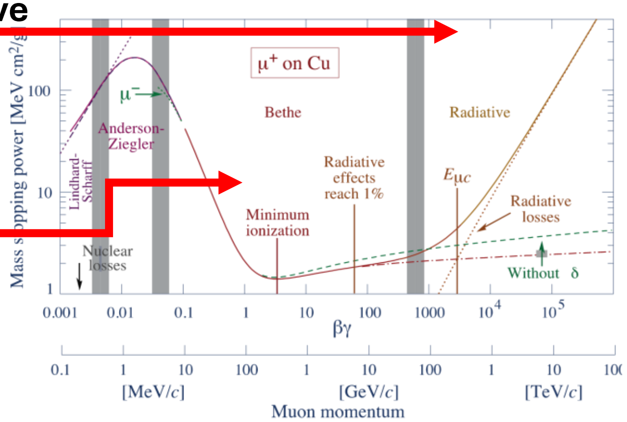
- **Loss of energy**

$E > 10\text{MeV}$

$$-\left(\frac{dE}{dX}\right) = a(E) + b(E)\,E$$

radiative

ionization



$X = \rho \cdot x$ Opacity [g cm^{-2}]

ρ: density x: depth

Range in the matter:

At high energy a and b are approximately constant and we can obtain:

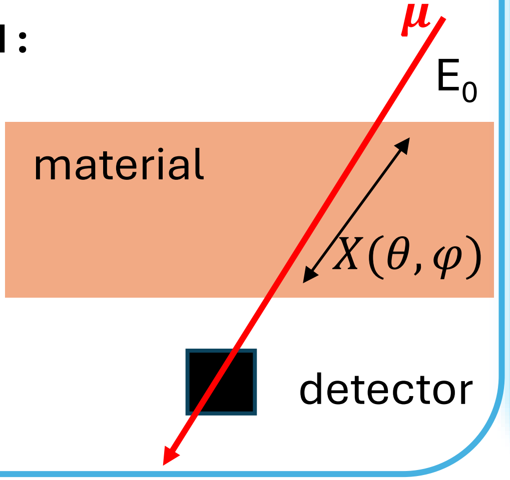
$$R(E_0) = \int_0^{E_0} \frac{dX}{dE}\, dE = \frac{1}{b} \ln\left(\frac{a + bE_0}{a}\right)$$

E_0 initial energy of the muon

Vertical integral flux of muons underground :

$$I(X) = A\left[\frac{a}{b}\left(e^{bX} - 1\right)\right]^{-\gamma}$$

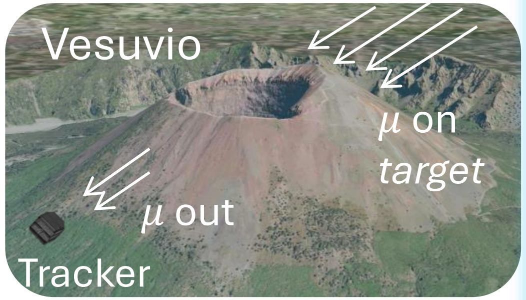
γ spectral index



From a measurement of underground flux it is possible to calculate the opacity that depends from the material density

Transmission muon radiography is an ***imaging technique*** that allows to create 2D or 3D images of the internal density distribution of the target through *Transmission measurements of atmospheric muons*. The detectors used are charged particle **trackers.**

- ✓ Non-invasive technique
- ✓ Mapping of anomalies as cavities in the areas or ore bodies



- ✓ It can monitor large structures
- ✓ Various fields of application: archaeological, geological, civil engineering and nuclear safety, industrial field, monitoring of large structures
- ✗ The acquisition times are linked to the flux of cosmic rays and the type of structure to be studied

Detectors

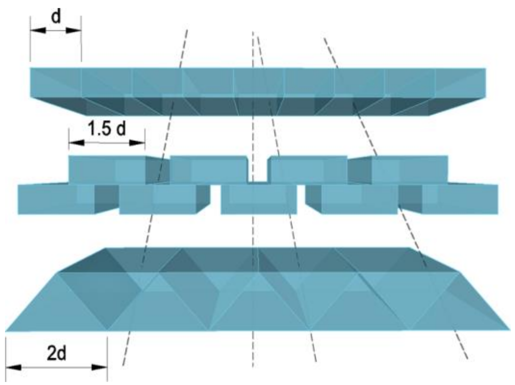
The detectors used for muon radiography measurements are trackers and must satisfy some requirements due to the type of application:

- easily transportable,
- with low energy consumption,
- robust and light,
- with the possibility of remote monitoring,
- low need for maintenance

The most used detector technologies are:

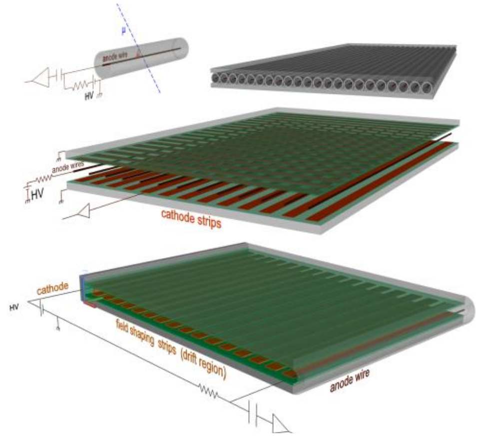
The planes are assembled as a telescope:

Scintillators Ref[1]



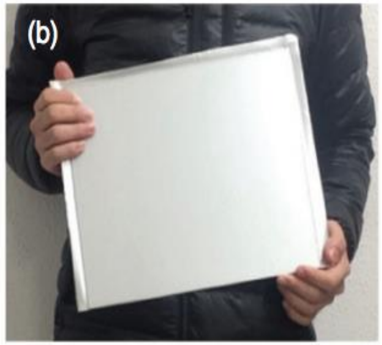
Resolutions of a few mm

Gas detectors Ref[1]

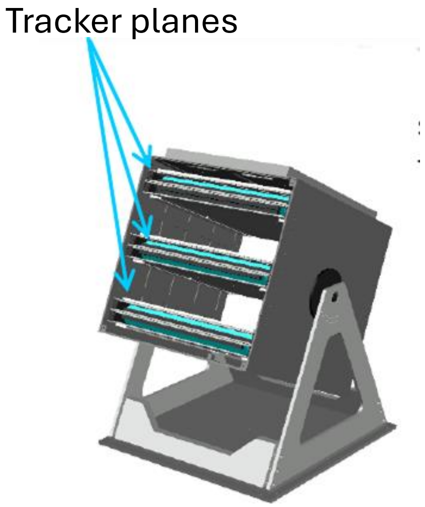


Resolutions of the order of 100 μm

Nuclear emulsions Ref[2]

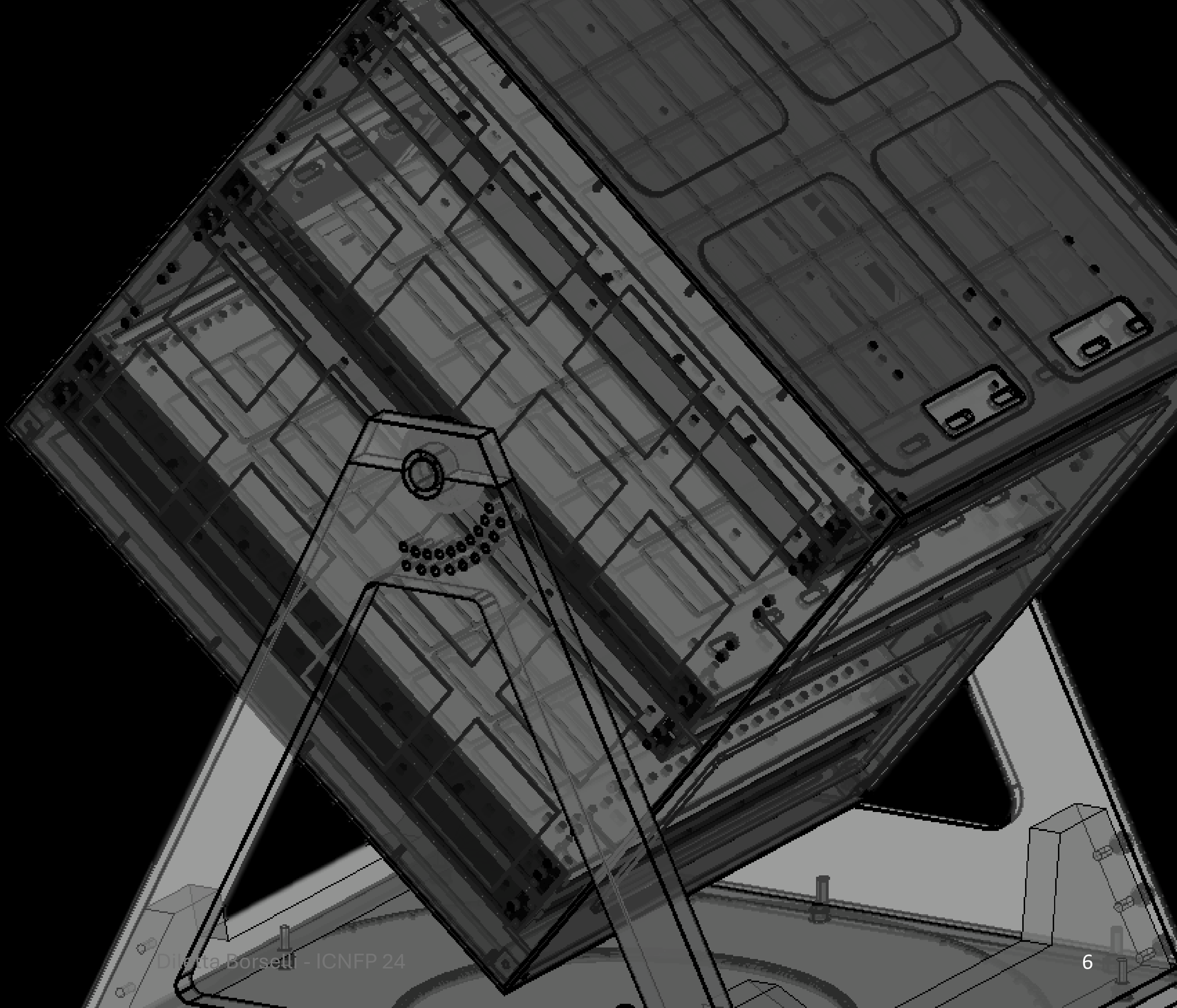


Resolutions of the order of μm
Data can only be analyzed in some laboratories in the world



[1] Bonechi, L., *et al.*, *Atmospheric muons as an imaging tool*, *Reviews in Physics* **5** (2020) 100038, DOI: 10.1016/j.revip.2020.100038
[2] Morishima, K., *et al.*, *Development of Nuclear Emulsions for Muography*, in in Muography, eds L. Oláh, H.K.M. Tanaka and D. Varga (2022), DOI: 10.1002/9781119722748.ch21

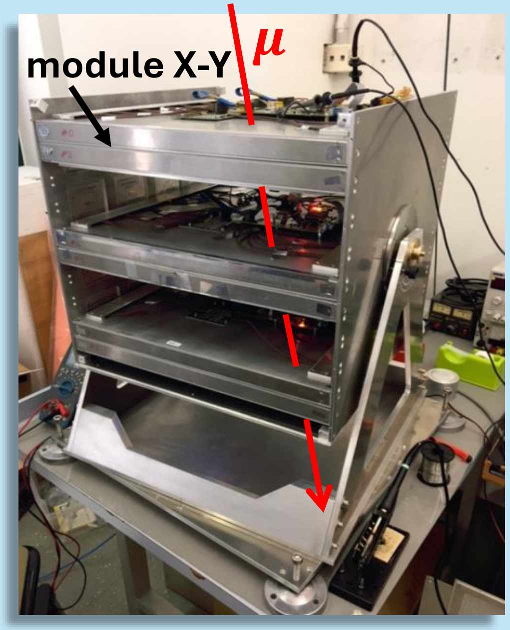
The detector



The MIMA tracker: detector for muography in mines

MIMA (**M**uon **I**maging for **M**ining and **A**rchaeology)
Developed at INFN FI and Physics Department UNIFI

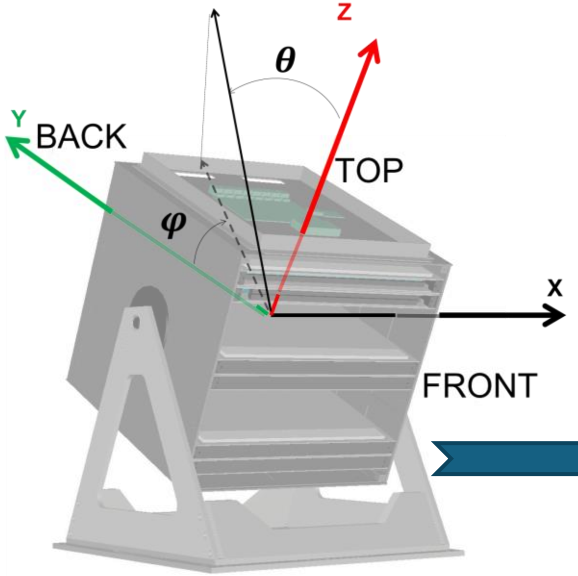
It is composed by plastic scintillators



Cubic dimension (50x50x50) cm^3 based on a rotating platform.

- Acceptance: about $\pm 65°$;
- Light sensor: SiPM;
- Spatial resolution 1.5 mm, angular resolution 5.6 mrad ($\sim 0.3°$);
- Weight about 70 kg;
- Power consumption 30 W

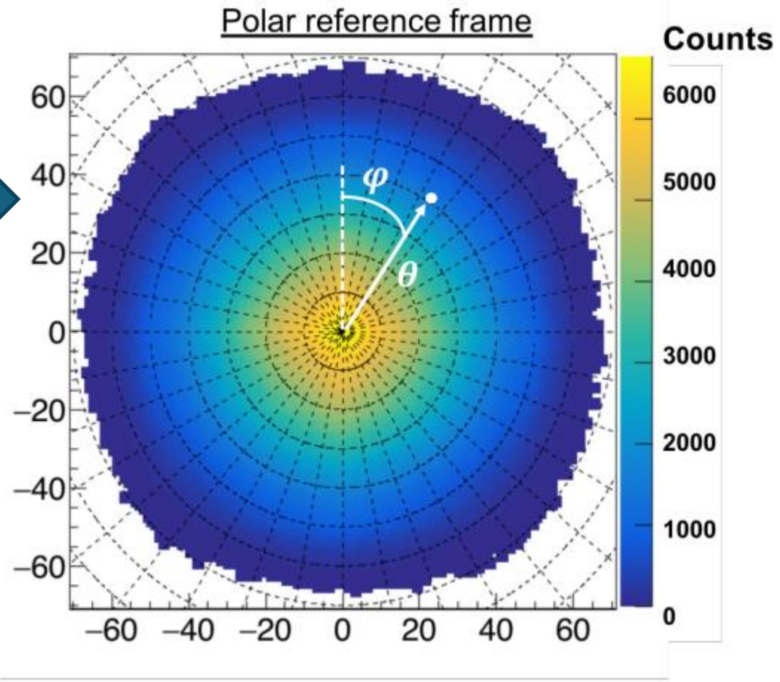
Detector reference system:



θ *zenith angle*
φ *azimuth angle*

It measures the number $N(\theta, \varphi)$ of particles arriving from every direction of view that falls within its acceptance range.

Angular distribution of muons measured in a free-sky configuration in the vertical direction

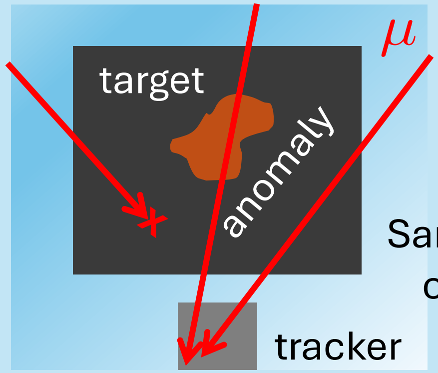


Imaging methodology (2D e 3D)

Imaging 2D: target density distribution

1. Target Measurement

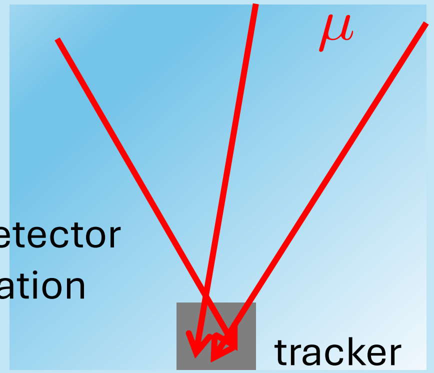
$N_{\mu_{target}}(\theta,\varphi)$



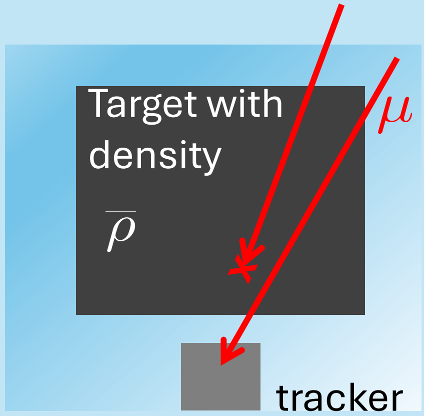
2. Free-sky Measurement

$N_{\mu_{freesky}}(\theta,\varphi)$

Same detector orientation



3. Simulation in the homogeneous case



Muon measured transmission

$$T_{misu}(\theta,\varphi) = \frac{N_{\mu\_target}}{N_{\mu\_freesky}} \cdot \frac{t_{freesky}}{t_{target}} \frac{\epsilon_{freesky}}{\epsilon_{target}}$$

ϵ:efficiency

Muon simulated transmission

$T_{simu}(\theta,\varphi,\bar{\rho})$

Anomaly identification

$$T_{rel}(\theta,\varphi,\rho) = T_{misu}(\theta,\varphi)/T_{simu}(\theta,\varphi,\rho)$$

>1 low density or <1 high density

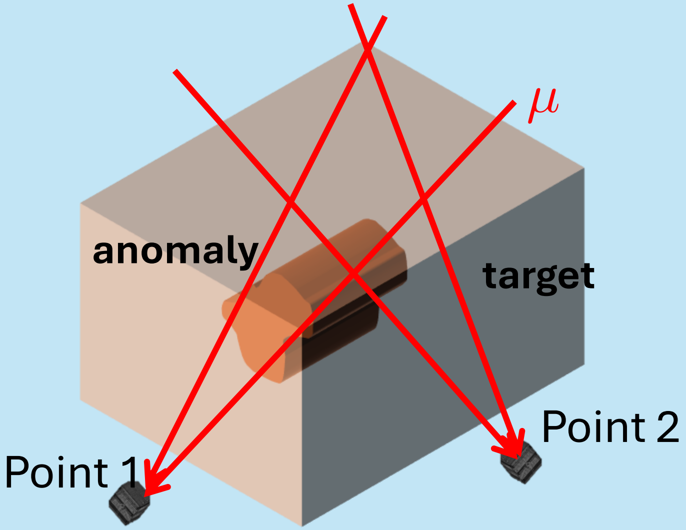
Varying $\bar{\rho}(\theta,\varphi)$:

$$T_{misu}(\theta,\varphi) = T_{simu}(\theta,\varphi,\bar{\rho})$$

⟶ **2D angular density distribution $\bar{\rho}_{target}(\theta,\varphi)$**

3D target density map

- Triangulation technique
- Tomographic algoritms



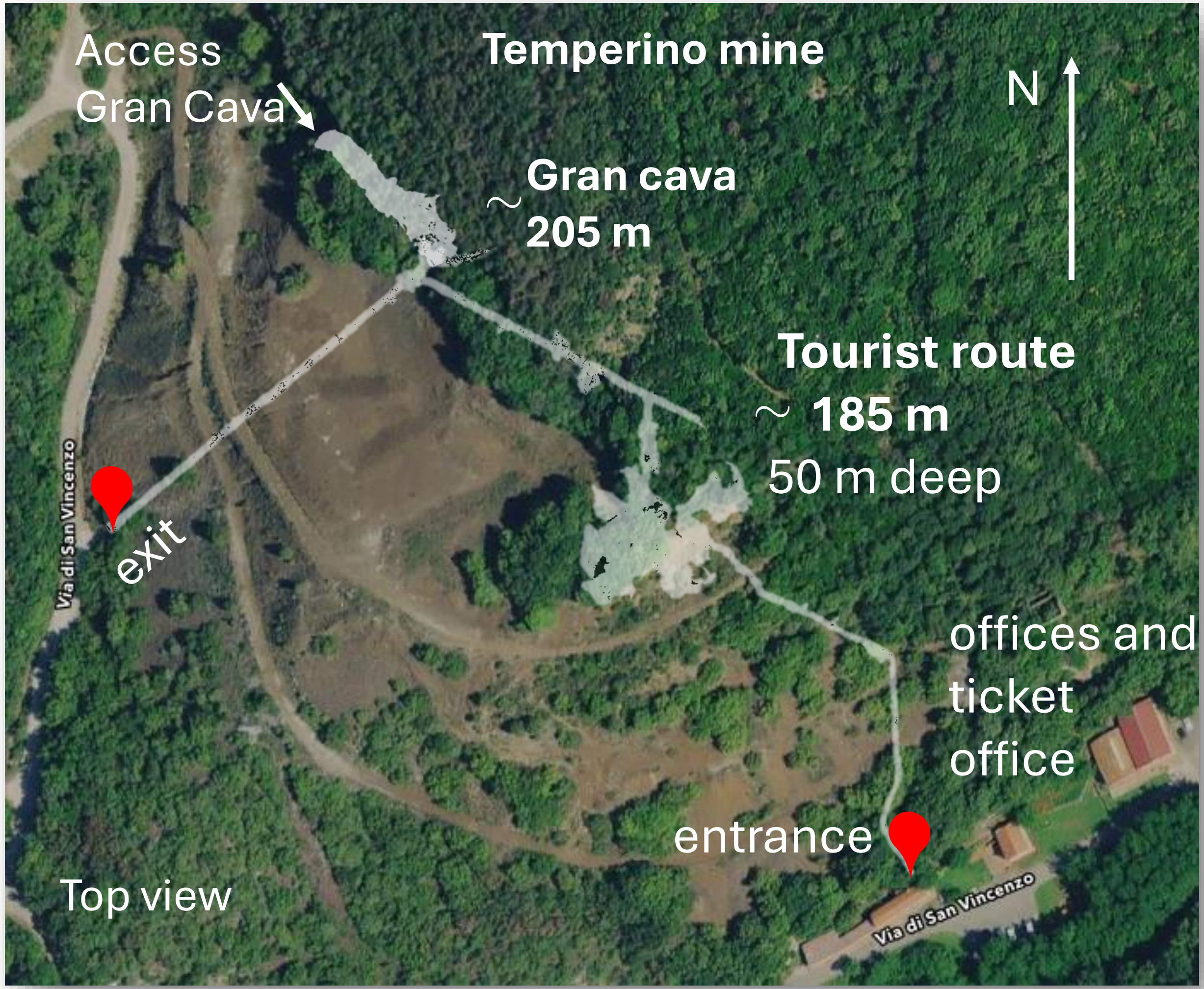
- Back-projection technique

Ref [3]: Bonechi L., et al, *A projective reconstruction method of underground or hidden structures using atmospheric muon absorption data*. Journal of Instrumentation, 10:P02003, 2015. DOI: 10.1088/1748- 0221/10/02/p02003.

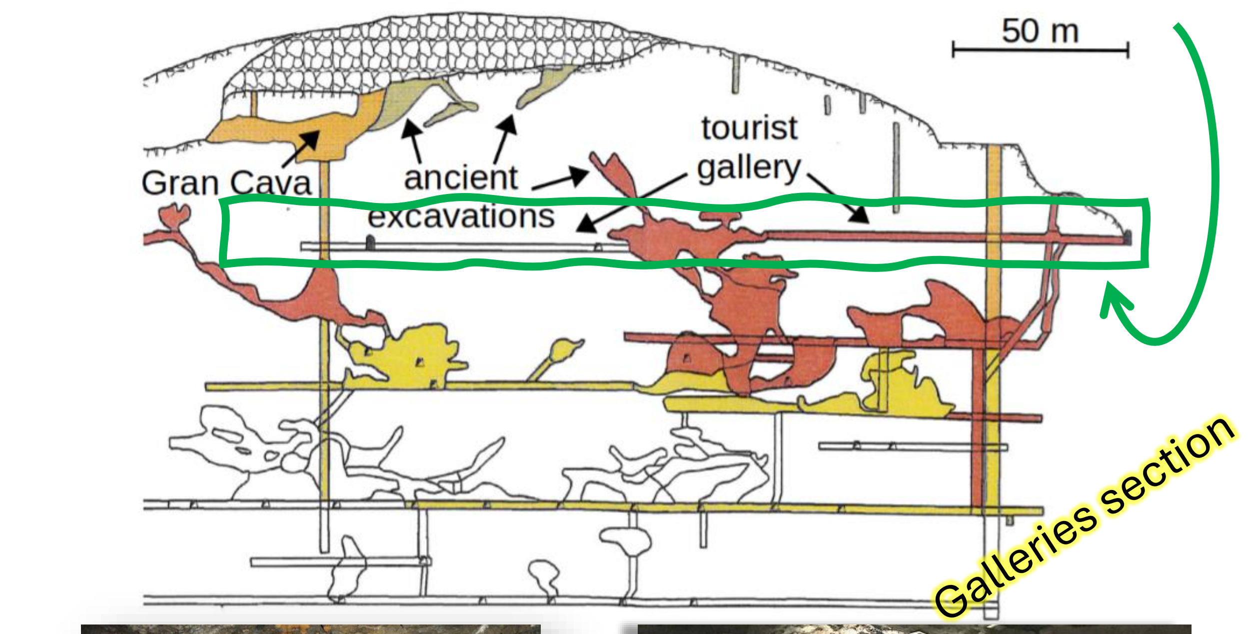
Muographic measurement at the Temperino mine

The Temperino mine – S. Silvestro Archaeological Mining Park (Tuscany -Italy)

<u>Mine of Etruscan origins</u>, re-exploited in the medieval period until its closure in 1980. **It is open to visitors today.**
<u>Extraction materials</u>: «skarn» rock rich in Cu, Ag, Pb, Zn, Fe.



Galleries up to 200 m deep. The tourist gallery is the first level

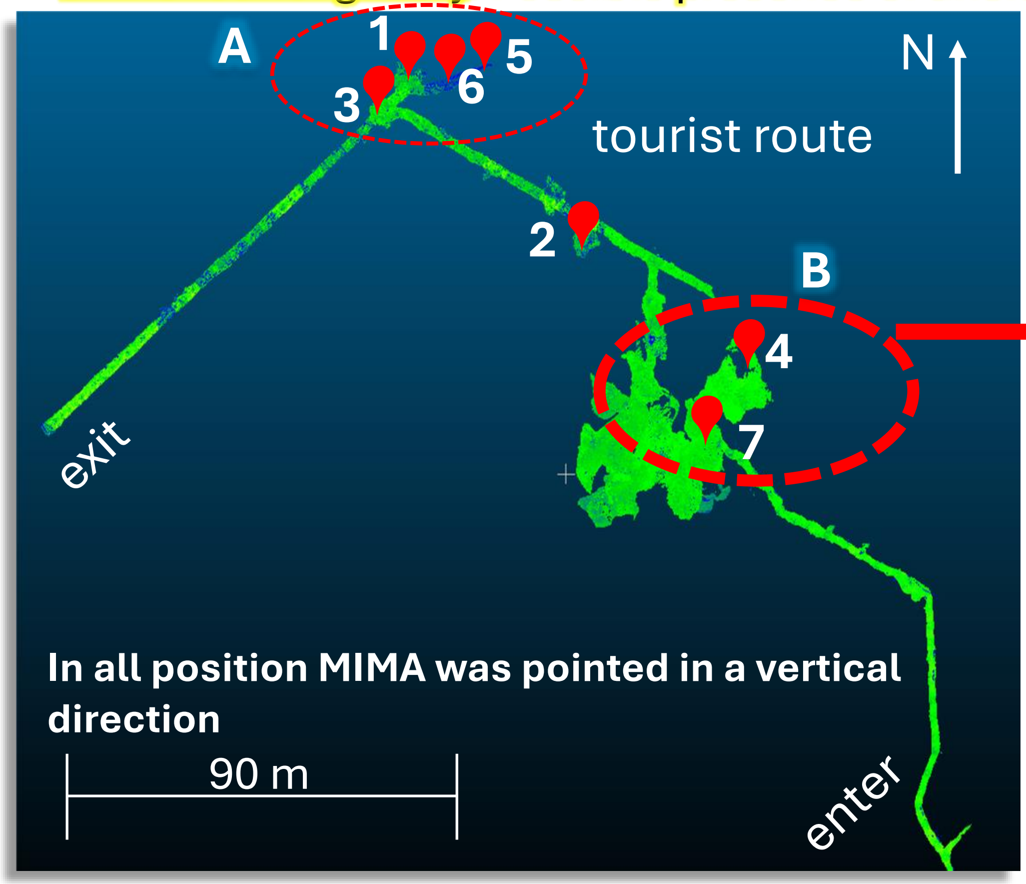


Some photos inside the tourist gallery

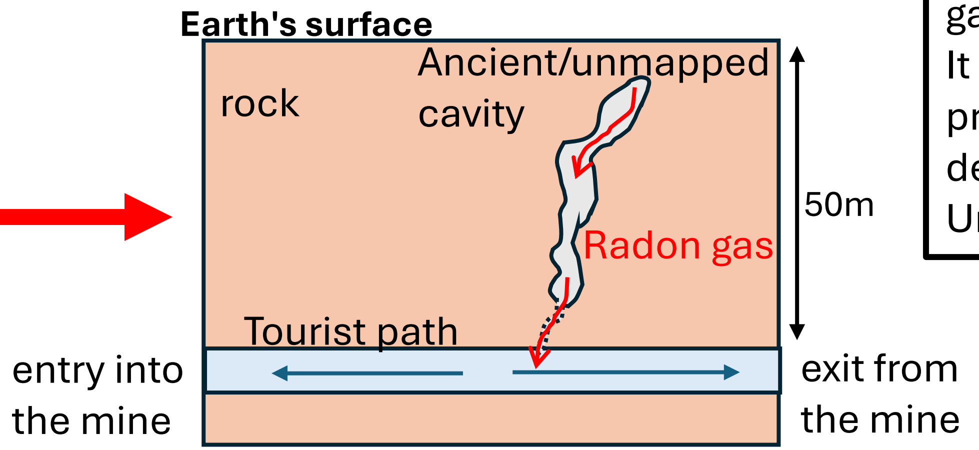
The Temperino mine – Installation points

Installation points (the numbers indicate the chronological order) from 2018 to 2023:

- **Area A**: area to test the transmission muography technique under a known cavity (Ref[4] [5])
- **Area B**: area where Radon gas was detected (in higher concentrations) during the annual measurement campaign at the tourist gallery. Possible presence of ancient unmapped cavities.



Possible scenario:



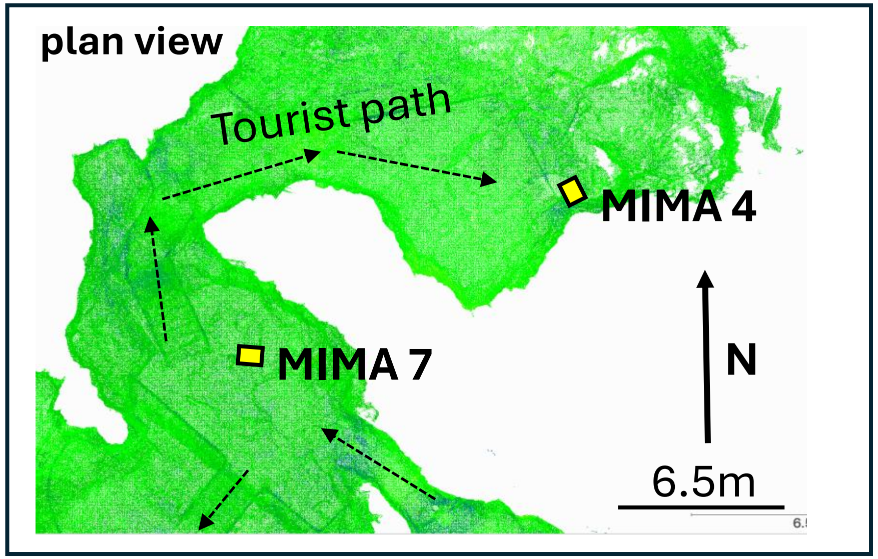
Radon (Rn) is an inert, radioactive gas of natural origin. It is one of the products of the decay sequence of Uranium.

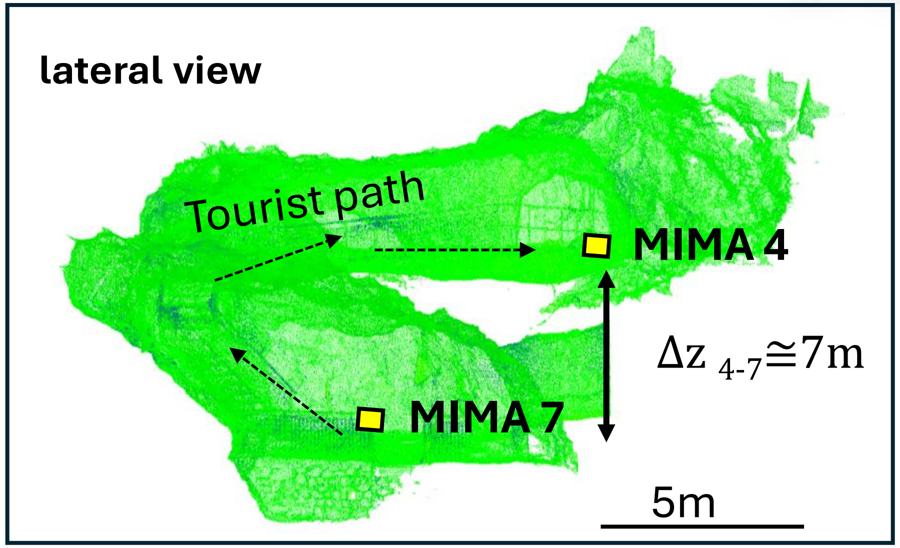
Knowing about the presence of a cavity can be useful for making the tourist route safer.

[4]: Borselli, D., *et al. Three-dimensional muon imaging of cavities inside the Temperino mine (Italy), Sci Rep* 12 (2022), 22329, DOI: 10.1038/s41598-022-26393-7
[5]: Beni, T. , *et al.*, *Transmission-Based Muography for Ore Bodies Prospecting: A Case Study from a Skarn Complex in Italy*, Nat. Resour. Res. **32** (2023) 1529. DOI: 10.1007/s11053-023-10201-8

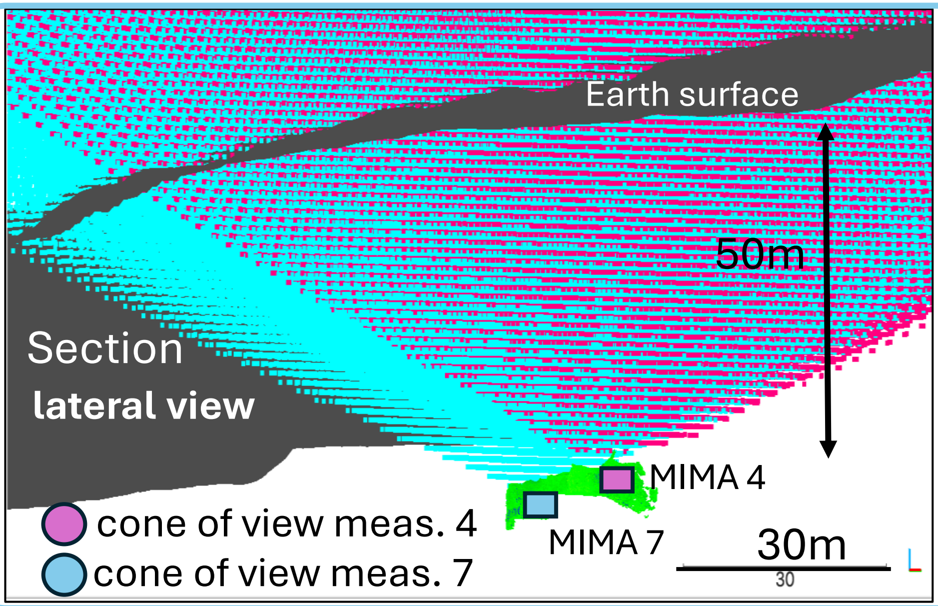
The Temperino mine – Installation points 4 and 7

Installation points 4 and 7:





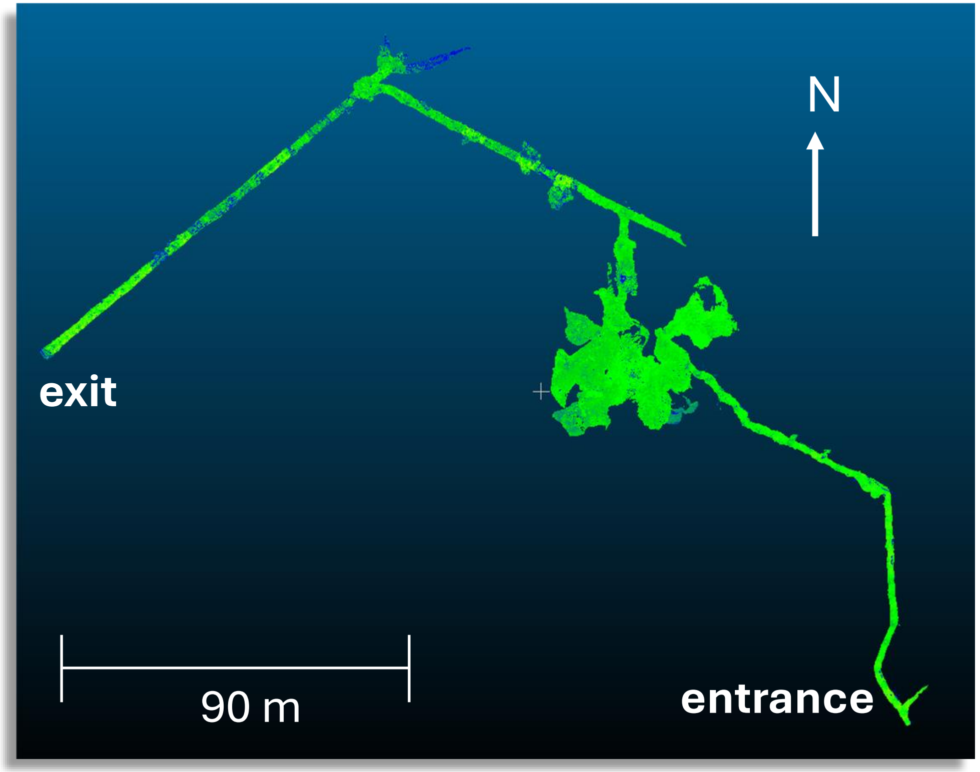
Schematic representation of the two acceptance cones from the measurements:



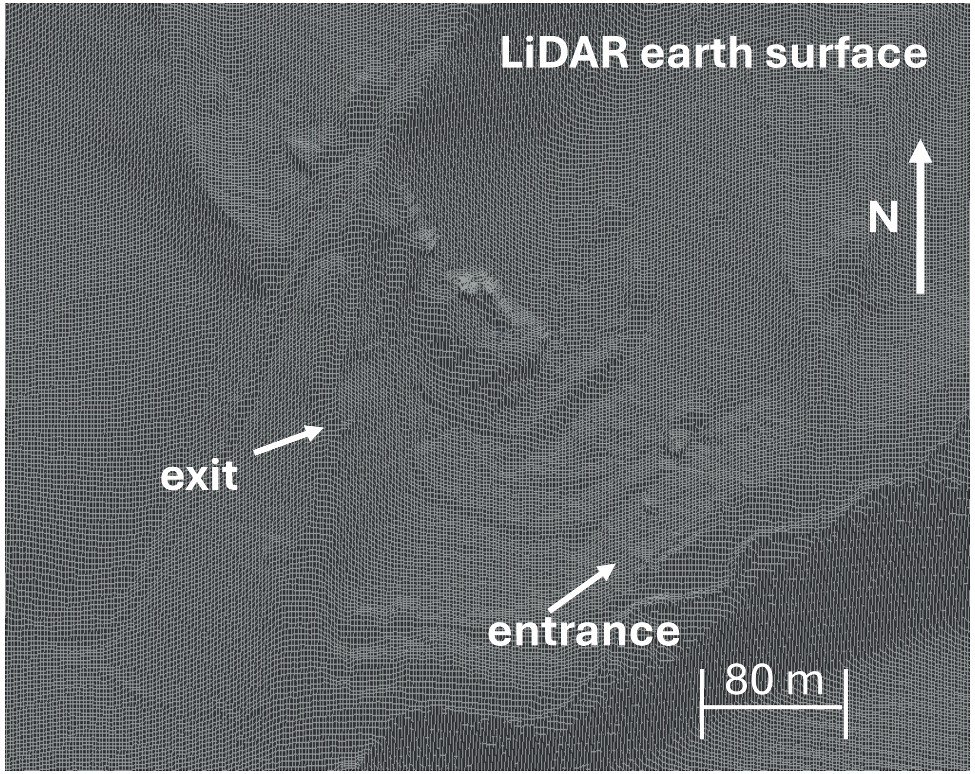
LiDAR, laser scanner, drone, GPS surveys

It is important to acquire the known geometry of the target for the construction of the geometry to be inserted in the simulation → collaboration with geologists from the University of Florence

laser scanner point clouds of the known cavity inside the mine



Digital Terrain Model (without vegetation) above the Temperino mine

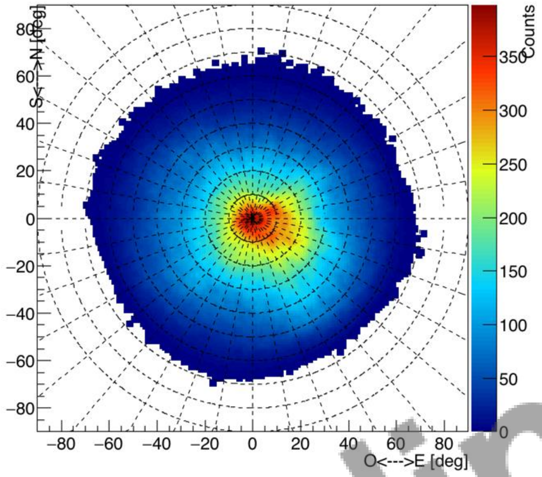


Muon imaging at the Temperino mine

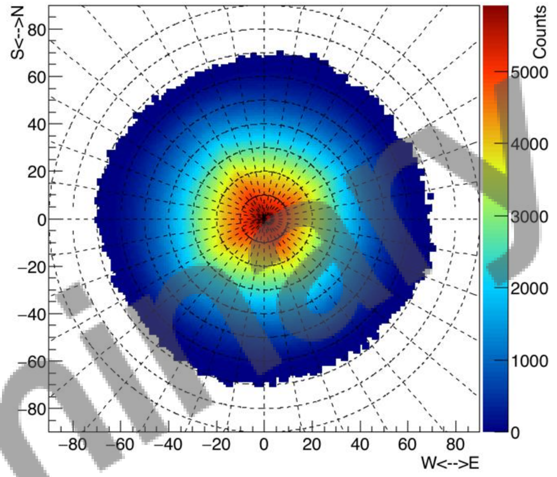
Two-dimensional distributions of muon counts and transmissions

Measurement 4 (target 25 days, 0.5 Hz)

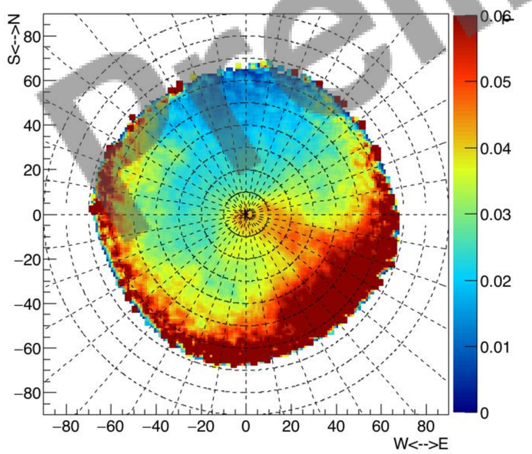
Target Muon Counts



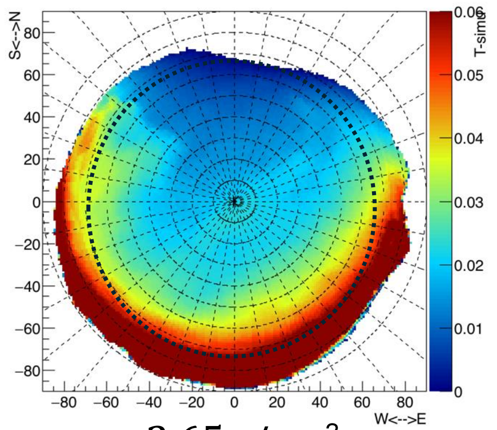
Freesky Muon Counts



Measured Transmission



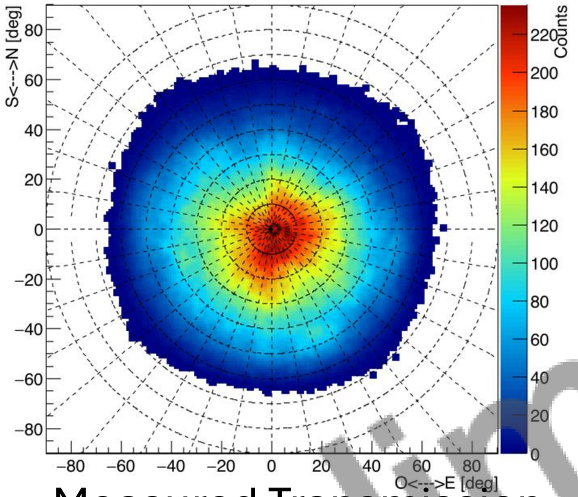
Simulated Transmission



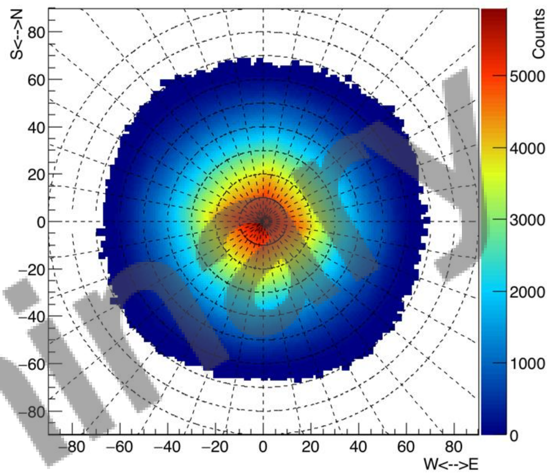
$\rho = 2.65 \text{ g/cm}^3$

Measurement 7 (target 33 days, 0.5 Hz)

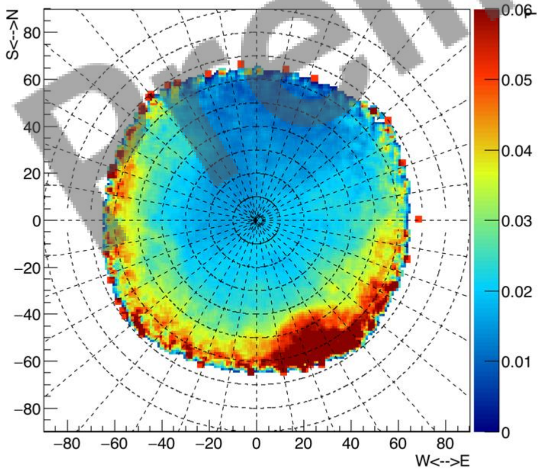
Target Muon Counts



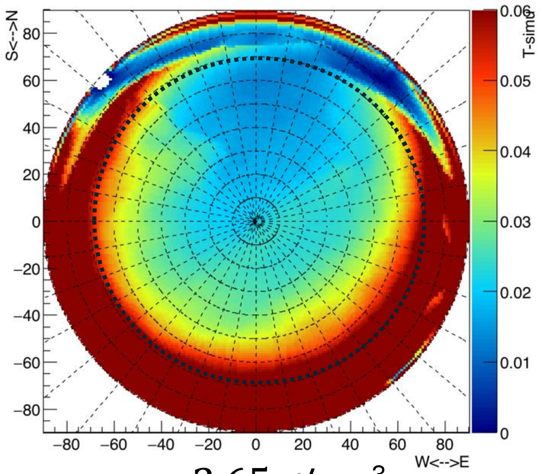
Freesky Muon Counts



Measured Transmission



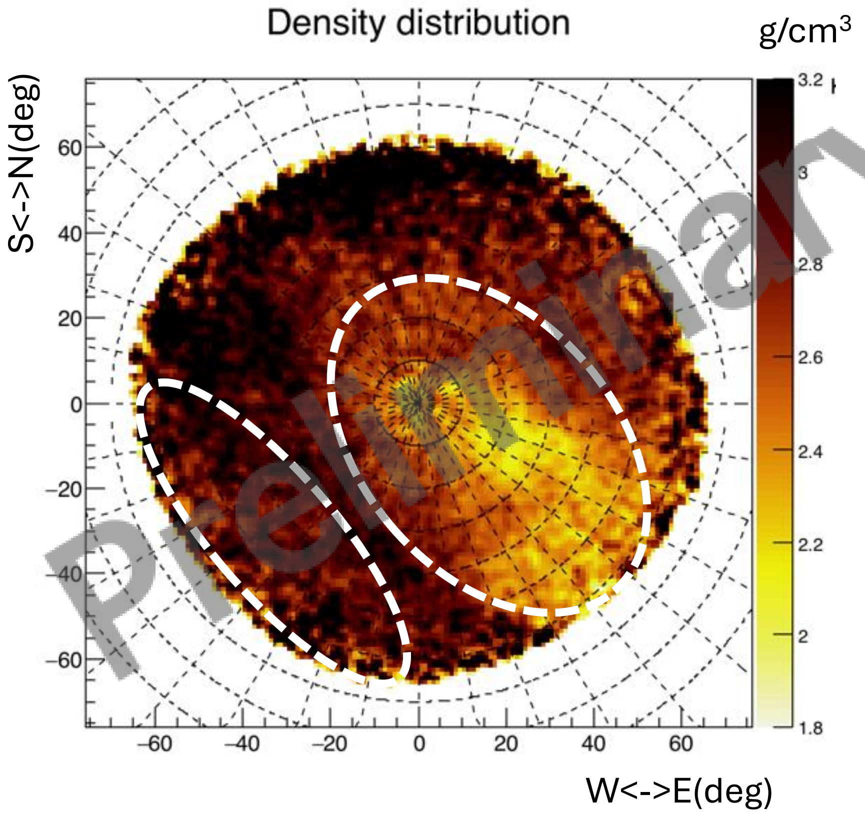
Simulated Transmission



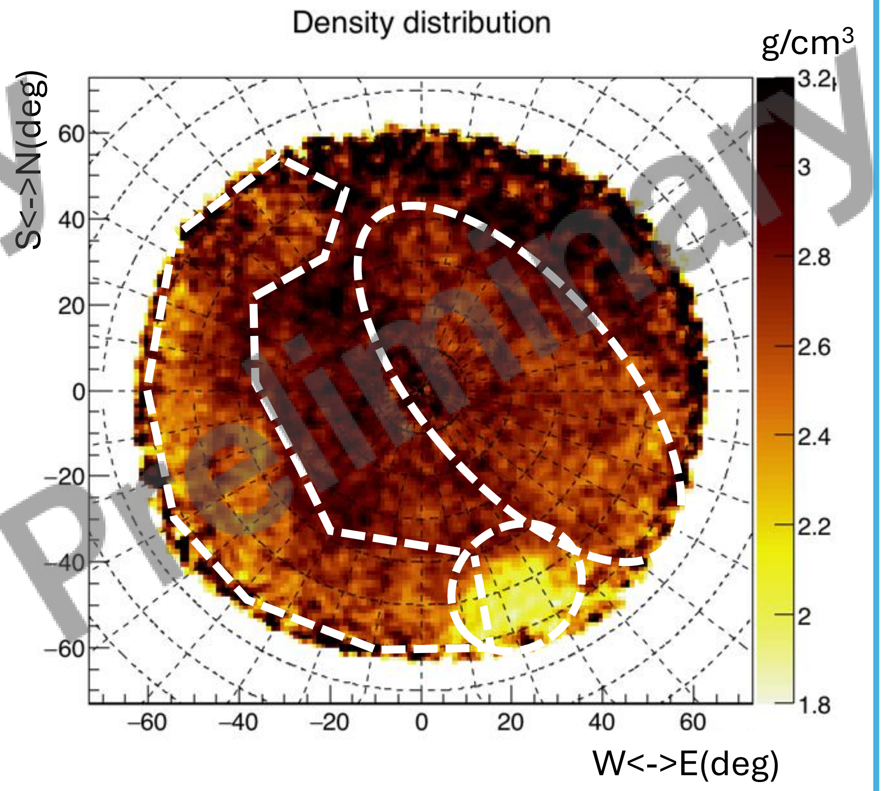
$\rho = 2.65 \text{ g/cm}^3$

Two-dimensional density distribution from the two point of view

Measurement 4



Measurement 7



Low density areas emerge compared to the rocks typically found in the mine

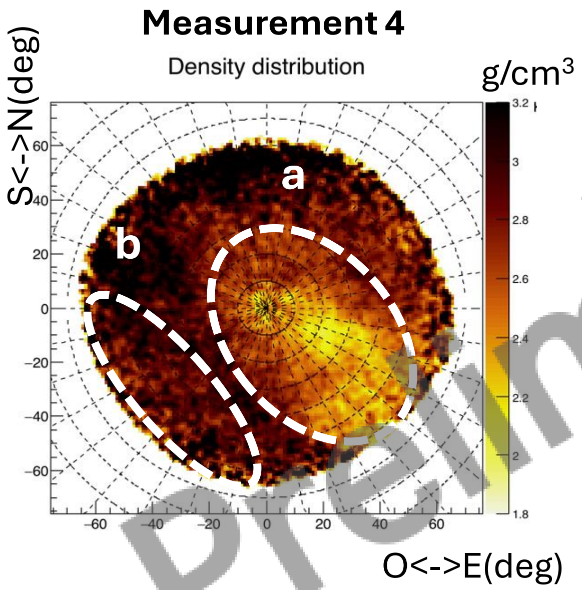
From Geological studies:

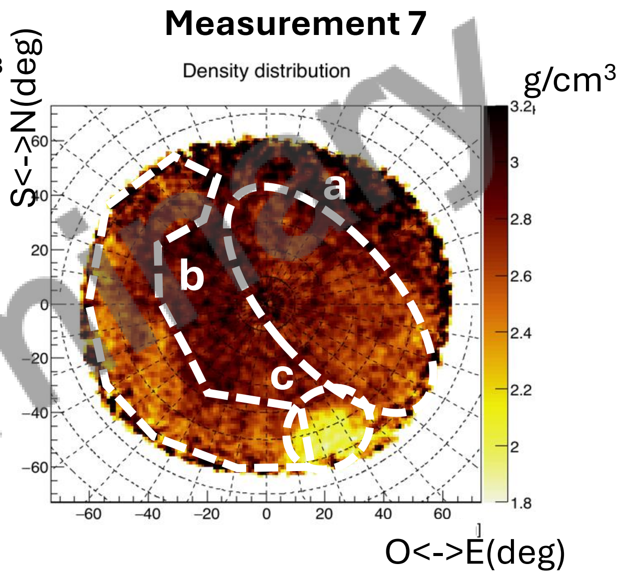
The rocks present in the Temperino mine have densities in the range 2.4 g/cm³ - 3.5 g/cm³

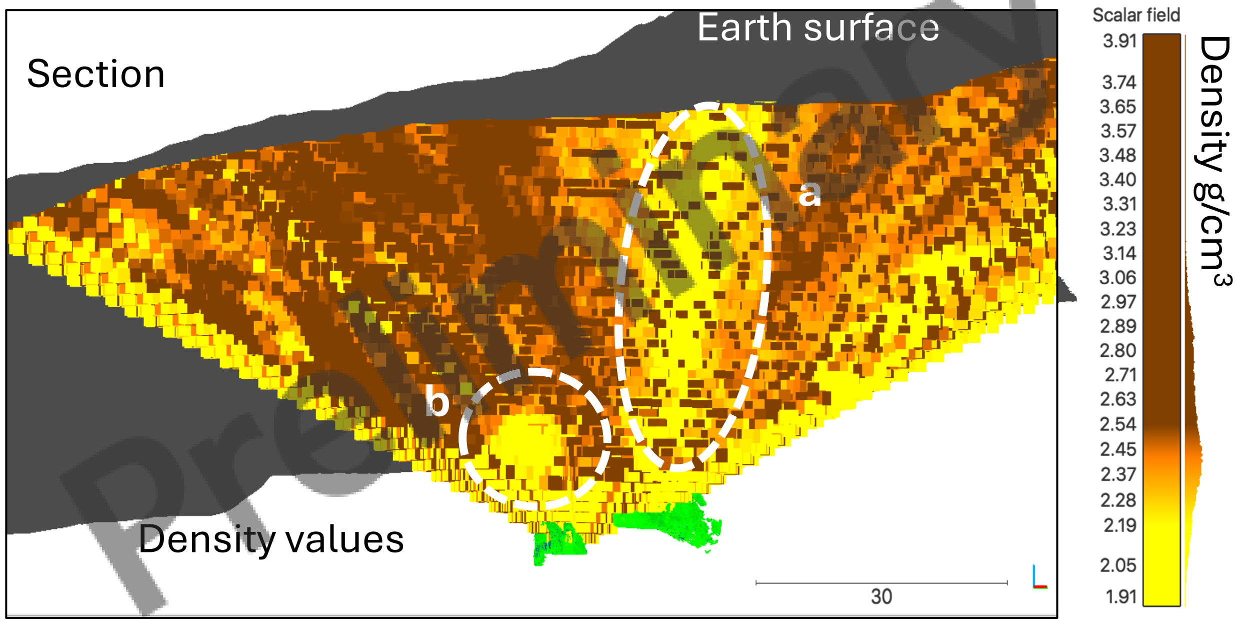
Three-dimensional density distribution – preliminary study

Through triangulation we look for volumes that, when observed by both measurements, have a density lower than a certain threshold.

From the first studies on triangulation it emerged that:







- Only two low-density signals (a and b) are seen by both measurements. Signal c does not fall within the acceptance of measurement 4.
- Signal a starts on the ceiling of the tourist gallery and has an elongated shape up to the surface. The measurement points may be too close to resolve the signal in 3D with the triangulation technique. Further studies might be needed.
- Signal b is located at a height of about 15 m from the tourist gallery

Conclusions and future developments

The rock area between the tourist gallery of the Temperino mine and the Earth's surface has been almost entirely surveyed with the transmission muography to search for unmapped cavities:

- in the presentation, measurements 4 and 7 were described. They are carried out in the area of the tourist gallery where a higher percentage of radon gas is detected (in the security range values). The presence of ancient etruscan unknown cavities above could explain the phenomenon;
- two-dimensional images of average density reveal the presence of three cavities above the tourist corridor;
- studies are underway for the three-dimensional reconstruction of cavities and their localization using different techniques (tomographic techniques and back-projections). Other muographic measures could be taken at different points.

INFN FI

UNIVERSITÀ DEGLI STUDI FIRENZE

PARCHI della VAL di CORNIA

The measures described are part of the Tuscany Region Project called MIMA-SITES which includes studies on the safety of the tourist route to the Temperino mine.

Some members of the Muography Group of Florence and the MIMA-SITES project:

From left: Andrea Paccagnella (UNIFI), Raffaello D’Alessandro (UNIFI), Andrea Dini (CNR-PI), Lorenzo Bonechi (INFN-FI), Debora Brocchini (Parchi Val di Cornia), Diletta Borselli (INFN-FI, UNIFI), Tommaso Beni (UNIFI), Catalin Frosin (UNIFI), the MIMA detector!