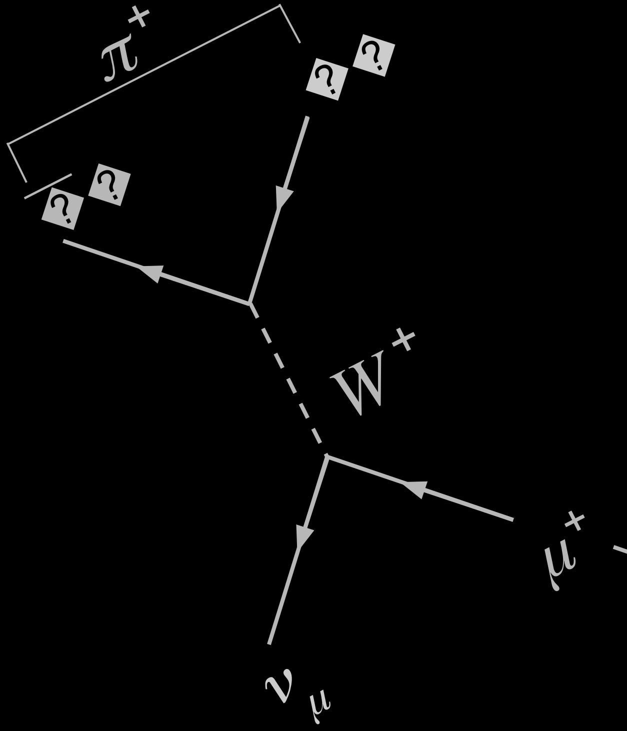


Introduction to muography

École Européenne Bruxelles III

Maxime Lagrange

Bruxelles III
SCHOLA EUROPAEA

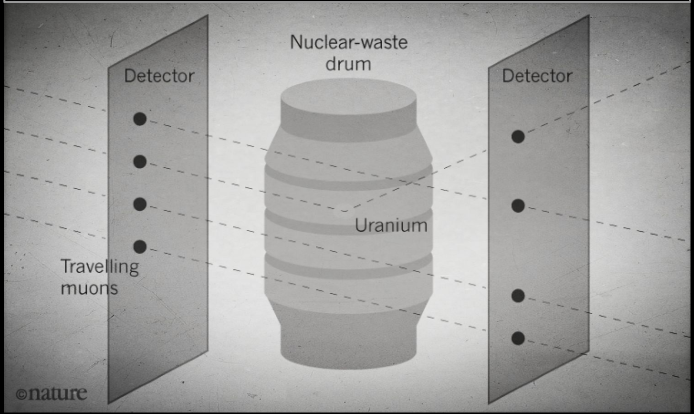
Structure

1. **Introduction to muography**
2. Cosmic rays
3. Muons through matter
4. Muon scattering tomography
5. Absorption muography
6. Conclusion

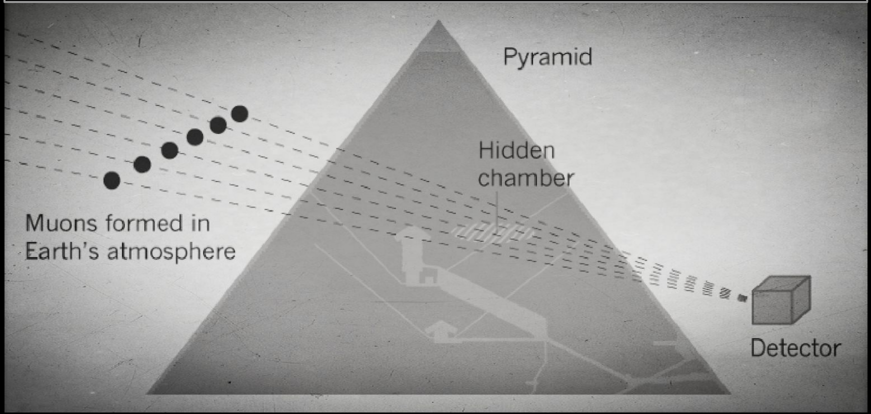
Introduction

Definition: **Radiographic imaging** with muons (**Muography**) based on the measurement of **absorption** or **scattering** of cosmic muons interacting with matter

Scattering muography



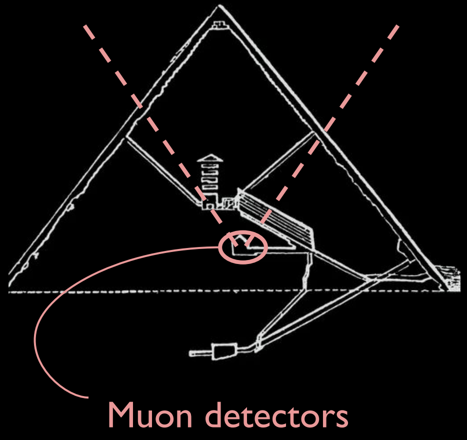
Absorption muography

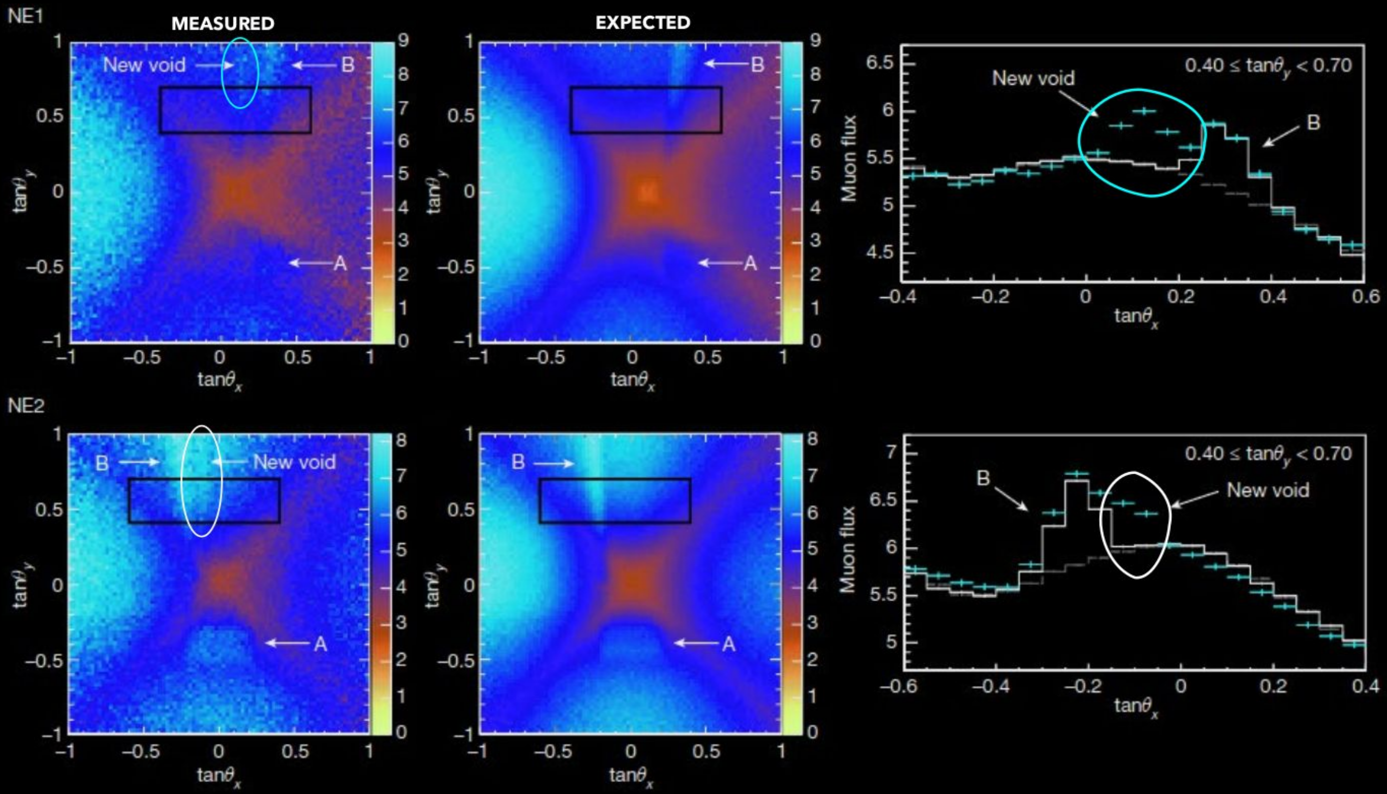


- **Muon** are elementary particles with **high penetration power**.
- Muons **interact** with matter by mean of **electromagnetic interaction**.
- Detectors **count** muons and **measure** their **direction**. **Measuring absorption rate** or **scattering distribution**, one can **infer** the mean **density** of the object.

Illustrations from *Muons: the little-known particles helping to probe the impenetrable*

Introduction





[Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons]

History: muon discovery

- Muons were discovered by **Carl D. Anderson** and Seth Neddermeyer in a **cloud chamber** experiment in 1936.
    - He had noticed particles in the **cosmic radiation** that **curved differently from** other **known particles** when they passed through magnetic field.
- It was then assumed that their **mass** was **greater than** that of an **electron** but **smaller** than that of a **proton**.
    - Later, it was named as "***mu-meson***" but due to its weak interactions and absence of quark composition (not truly qualify as meson but it behaves more like a heavier version of electrons) so the name change and became what we know as ***muon.***

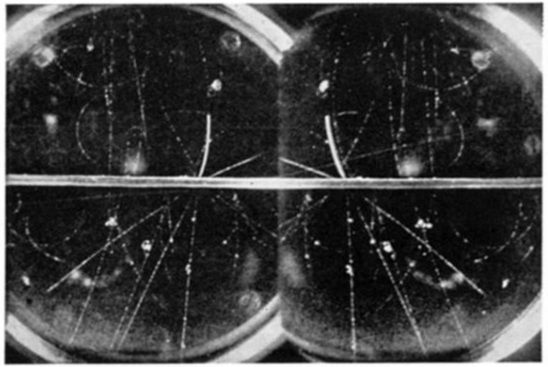
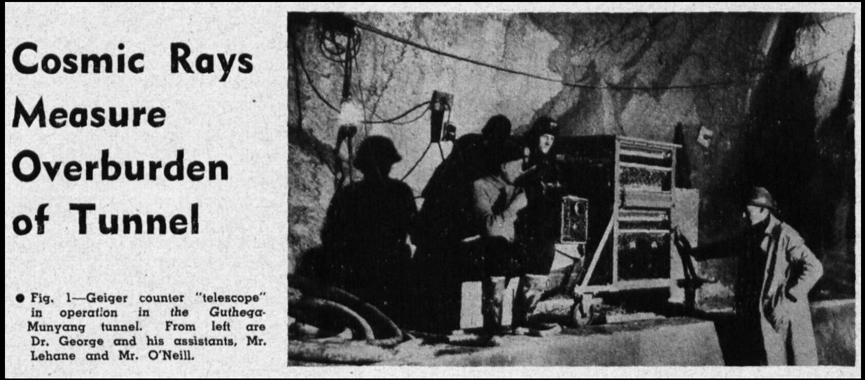


FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus.

https://journals.aps.org/pr/pdf/10.1103/PhysRev.50.263

History: muography

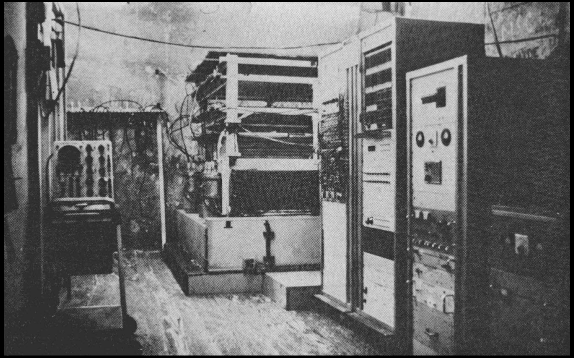
- The first cosmic rays muon application was done by Eric George to **measure** the **ice thickness** above a tunnel in Australia in 1955.
- The **measured count rate** was found to have clear **correspondence** with the **thickness** of the overburden.
- The next major attempt was made by the team of Luis Alvarez in 1969, to search the hidden chambers in the Pyramid of Khafre in Egypt, using spark chamber and scintillator counters.



Cosmic Rays Measure Overburden of Tunnel

● Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehane and Mr. O'Neill.

George EP. 1955 Cosmic rays measure overburden of tunnel. **Commonwealth Engineer 43**, 455–457.



Luiz W. Alvarez et al paper in Science 167 (3919)

Structure

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2. **Cosmic rays**
3. Muons through matter
4. Muon scattering tomography
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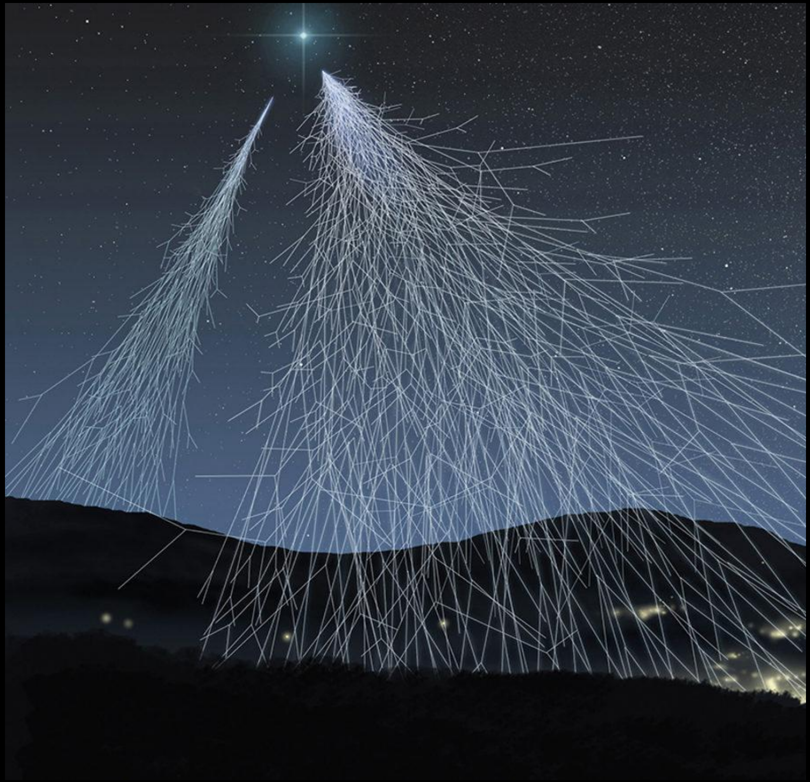


Muons

Particle	charge q	mean life τ	mass m
e	-e	> 6.6 x 10^{28} yr	0.511 MeV
μ	-e	2.2 x 10^{-6} s	105.7 MeV

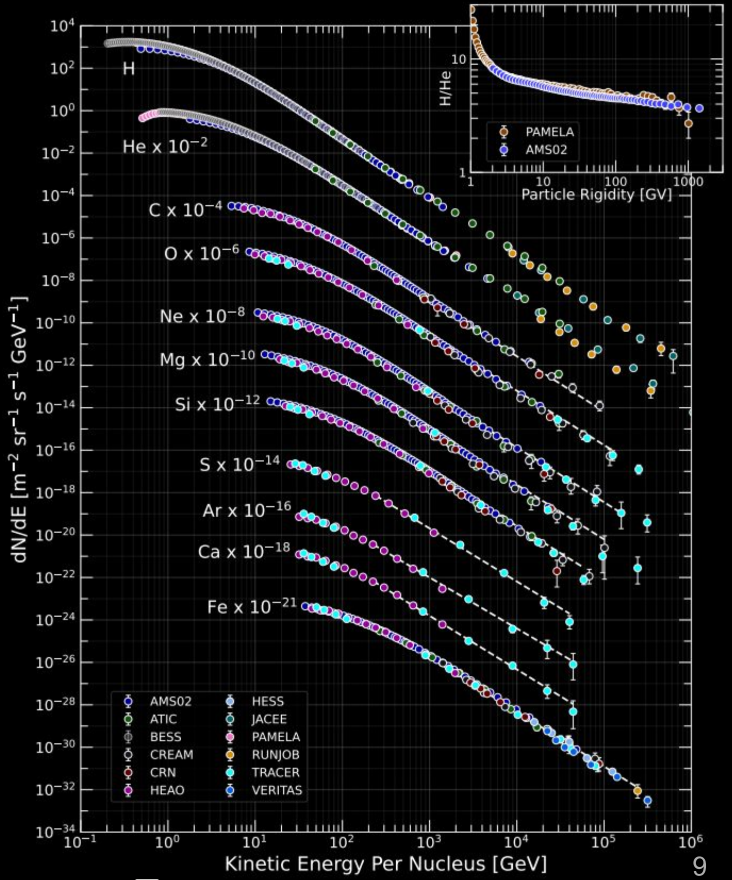
- **Muons** are elementary particles of the lepton family, like electrons.
- Muons have a "**long life-time**": at $v = 0.99c$ a muon travels a distance $L = 4.6\text{km}.$
- Muons have a **high penetration power**.
  - *Having a greater mass than electron, they decelerate slower than electrons in matter.*
- Muon decays systematically into an electron and 2 neutrinos. $\mu^- \longrightarrow e^- \bar{\nu}_e \nu_\mu \quad (\approx 100\%)$

Cosmic muons - a cosmic origin…

- Cosmic muons are the final **decay products** of nuclear interactions of **cosmic particles** with **atoms** of the **upper atmosphere**.

- **Cosmic** particles are **elementary particles** but also **nuclei**.
    - *The cosmic radiation incident at the top of the terrestrial atmosphere includes all stable charged particles and nuclei with lifetimes of order 10^6 years or older.*

- "**Primary**" cosmic rays are particles accelerated at astrophysical sources and "**secondaries**" are those produced in interaction of the primaries with interstellar gas.



Particle Data Group Cosmic Rays review

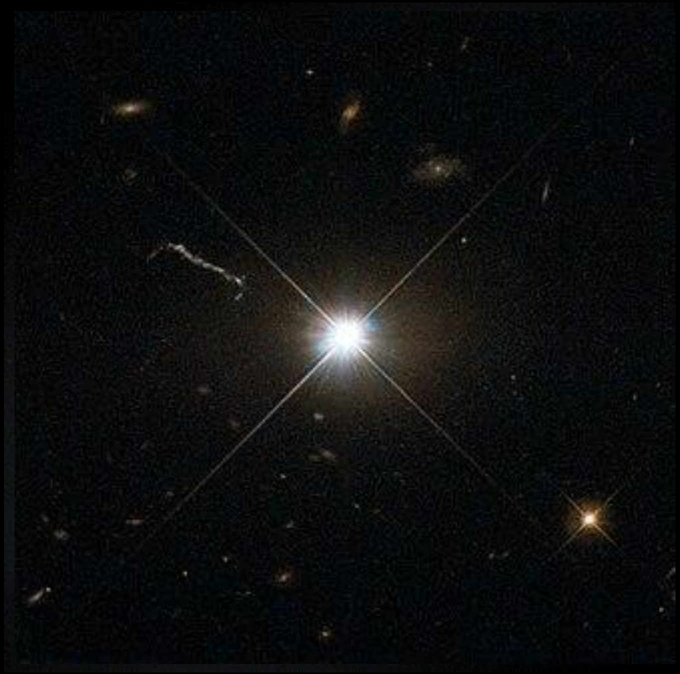
Cosmic muons - a cosmic origin…

- **Physicist** are **not sure** about the **sources** of the primary cosmic rays.

- There is a wide variety of **potential sources**:

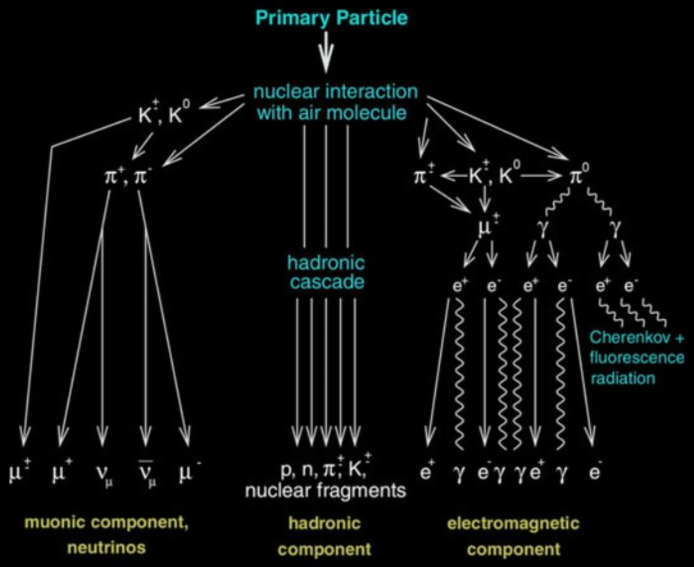
  - **Supernovae**: explosion of a dying star

  - **Active Galactic Nuclei (AGN)**: accretion of matter by a supermassive black hole at the center of its host galaxy emitting non-stellar radiation.



Cosmic muons - ...but produced on earth!

- Muons are **produced** high in the atmosphere (typically 15 km) and the result of a cascade of **nuclear interactions** between **cosmic rays** and **air molecules**.
  - *They typically lose 2 GeV of kinetic energy while passing through the atmosphere.*
- Muons (and neutrinos) are the **products** of **decay chain** of **charged mesons ($\pi^{\pm}$, $K^{\pm}$)**.
  - *The excess of free and bound protons over free and bound neutrons in the primary spectrum and the fact that they are more π^{+} and K^{+} than π^{-} and K^{-} in the forward fragmentation region of proton initiated interactions creates and asymmetry in the muon charge ratio.*
  - *Mean energy at sea level is about 4 GeV.*
- At sea level, muon flux is $\approx 1\,\mathrm{cm}^{-2}.\,\mathrm{min}^{-1}$



[Introduction to Cosmic Rays and Extensive Air Showers]

$$K^{\pm} \longrightarrow \pi^{\pm}\pi^{0} \quad (20.67\%) \qquad K^{\pm} \longrightarrow \mu^{\pm}\nu_{\mu} \quad (63.56\%)$$

$$\pi^{\pm} \longrightarrow \mu^{\pm}\nu_{\mu} \quad (99.99\%) \qquad R(\mu^{+}/\mu^{-}) = 1.27$$

Cosmic muons - …but produced on earth!

Artist view of a cosmic ray air shower, ASPERA/Novapix/L. Bret

Cosmic muons - …but produced on earth!

Structure

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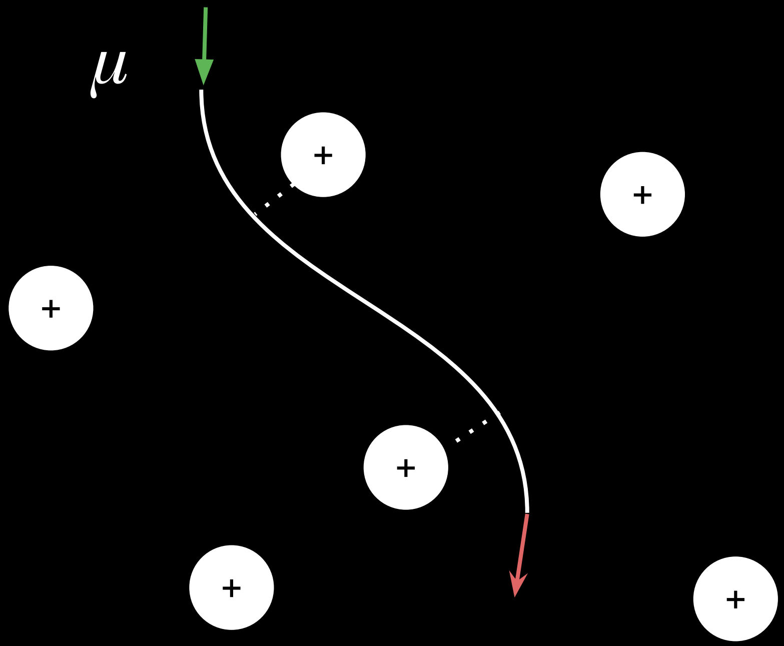
Muons through matter - Multiple Coulomb scattering

- A charged particle traversing a medium is **deflected** by many small-angle scatters. Most of this deflection is **due** to **Coulomb scattering** from **nuclei** (figure 1).



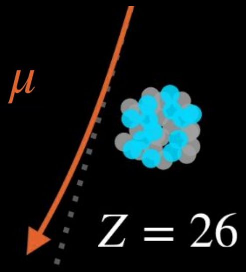


figure 1

Atoms nuclei (protons and neutrons)

Muon with negative electric charge

Attractive force due to electromagnetic interaction

Incoming and outgoing muon directions are different

Muons through matter - Multiple Coulomb scattering

- The **bigger** the **nucleus**, the **stronger** the **electromagnetic interaction** and the **larger the deflection is.**
- The **more nuclei** the muon meets along its path, the **more deflection** it will undergo.

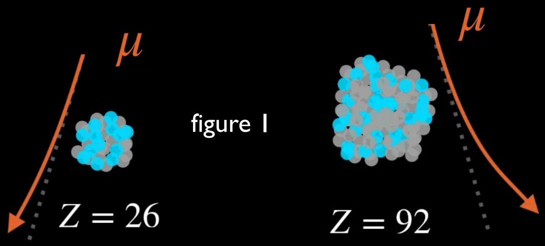


figure 1

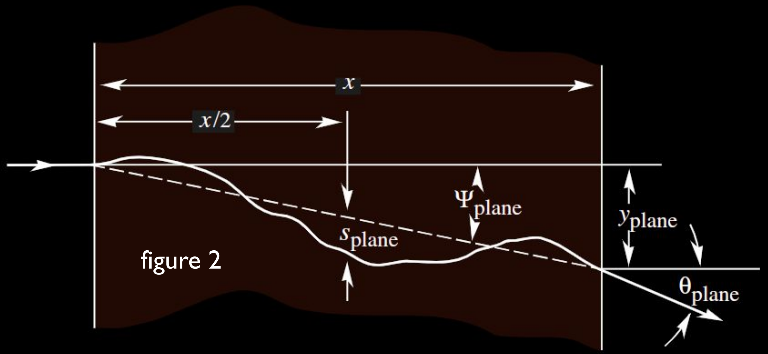
Scattering amplitude	**Material density** [g.cm^3] *(related to number of nuclei per unit of volume)*	**Atomic number Z** *(number of proton per nuclei)*
Large	Large	Large
Medium	Large	Low
Medium	Low	Large
Low	Low	Low

Muons through matter - Multiple Coulomb scattering

- At a macroscopic scale, it is a **random process** involving multiple small deviations (figure 2). After traversing a block of material will get both displaced y_{plane} and scattered θ_{plane}.

- **Scattering amplitude** is related to the muon momentum kinetic energy (the "speed of the particle").

- The **more kinetic energy** the muon has, the **smaller the scattering**.
    - *Why ?*



Particle Data Group, passage of particles through matter

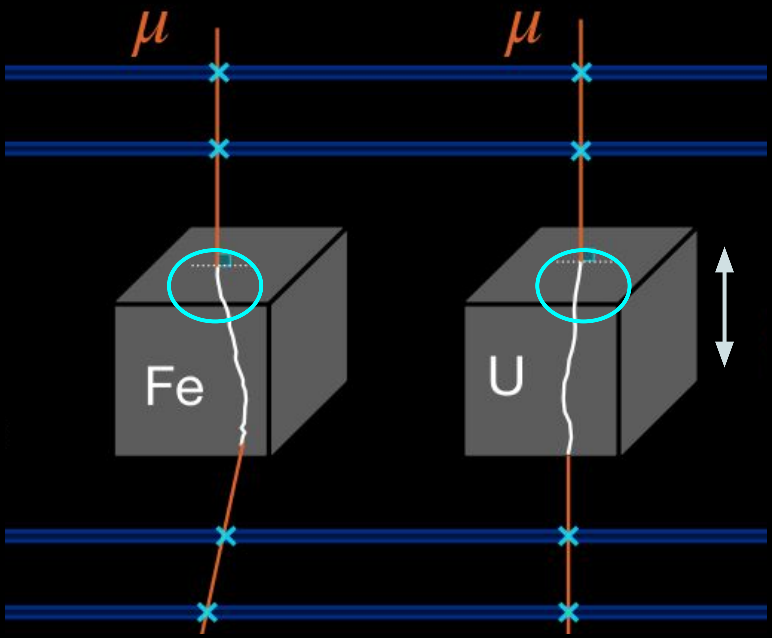
figure 2

Muons through matter - “Low energy muon”

Muons through matter - “High energy muon”

Muons through matter - Multiple Coulomb scattering

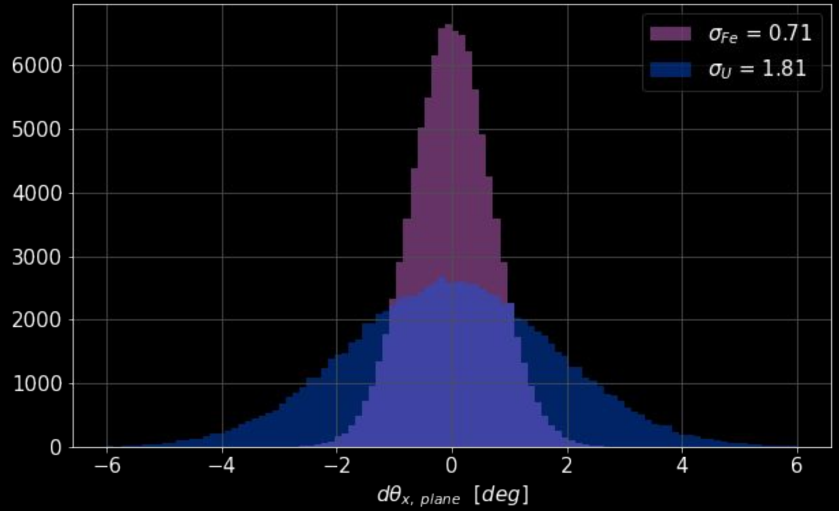
perpendicular muons with kinetic energy of 4GeV



U: **Uranium**, with atomic number **Z = 92**

Fe: **Iron**, with atomic number **Z = 26**

Projected (XZ plane) scattering angle of 4 GeV muons through 20cm material



$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}}\left[1 + 0.088 \log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right)\right]$$

$$X_0\ [\text{cm}] = \frac{X_0\ [g.cm^{-2}]}{\rho\ [g.cm^{-3}]}$$

Muons through matter - Energy loss

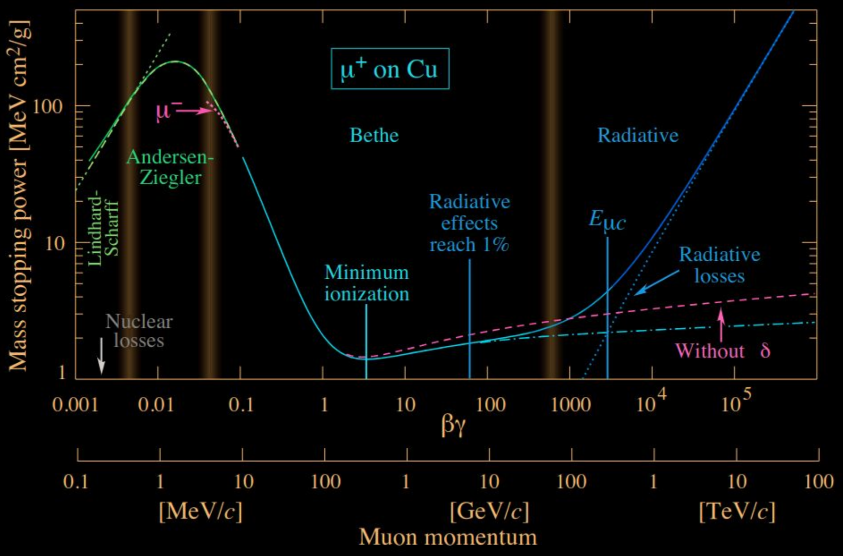
- **Charged particles** traversing matter **lose energy** via **electromagnetic interaction.**
- **The energy loss** described by the Bethe-Bloch formula.
- The amount of energy loss depends on the **material element** (number of protons and neutrons) and **density** (number of nuclei per unit of volume).

Bethe-Bloch

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

$$n = \frac{N_A \cdot Z \cdot \rho}{A \cdot M_u}$$

Particle Data Group, passage of particles through matter

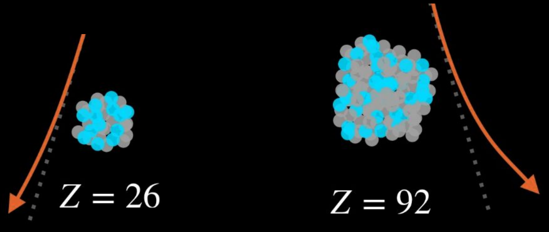


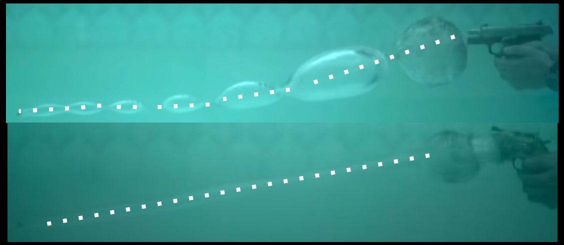
- When a **muon losses all of its kinetic energy** in matter, **it decays**.

Summary

Scattering

- **Muons** undergo **scattering** when passing **through matter.**
- The **higher** material **density,** the **larger** the **scattering.**
- The **larger atomic number,** the **larger** the **scattering.**
- The **higher** muon **kinetic energy,** the **smaller** the **scattering.**





Energy loss

- **Muons lose kinetic energy ("speed") when traversing matter.**
- **After losing most of its kinetic energy, the muon decays.**

Structure

1. Introduction to muography
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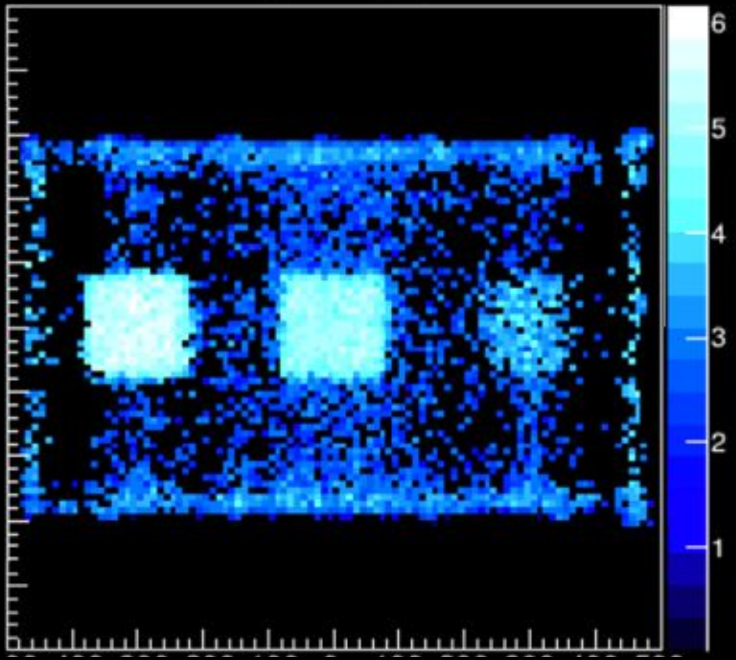
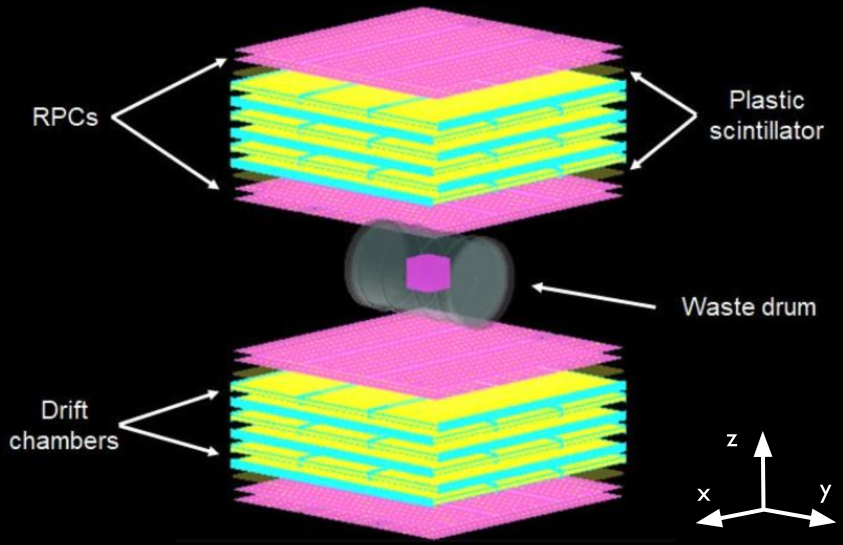


Muon Scattering Tomography (MST)

Muon Scattering Tomography (MST) is an **imaging technique** utilizing the **scattering** behaviour of **cosmic muons** within the object of interest in order to **estimate** its relative **density**.



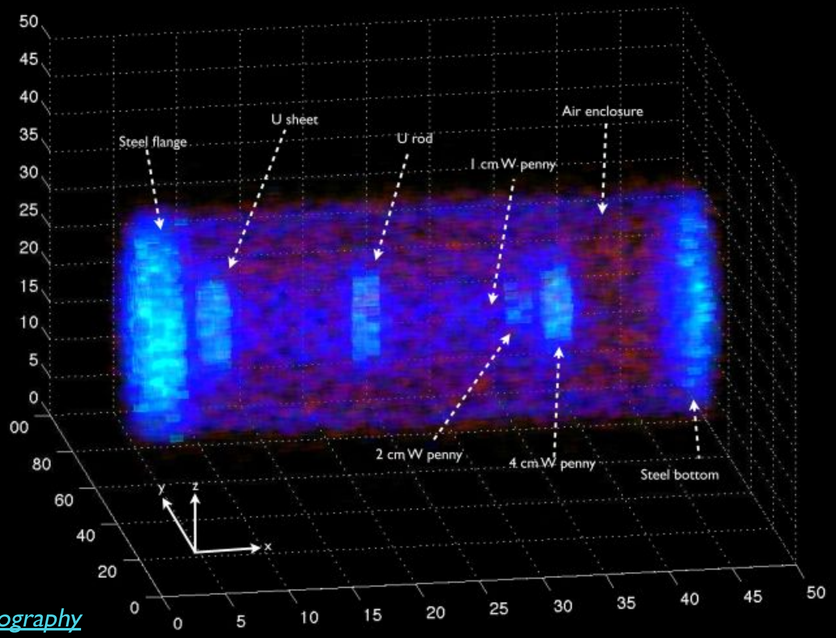
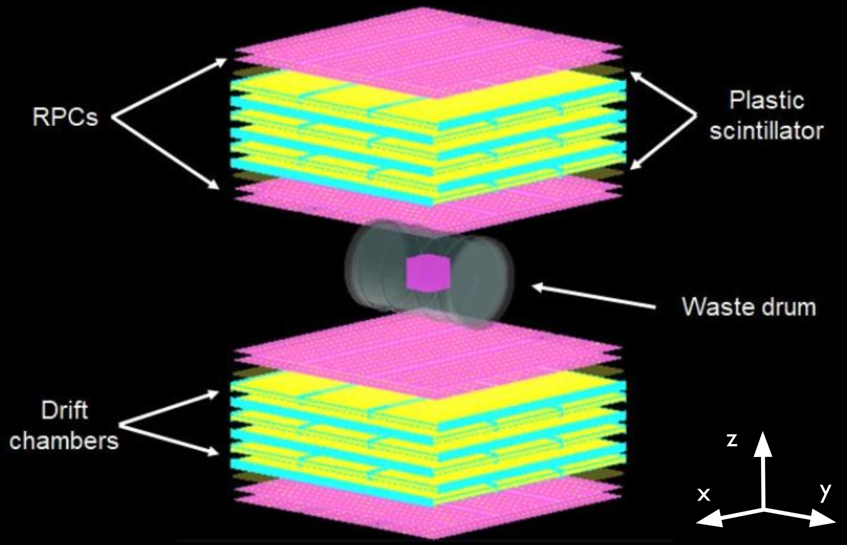
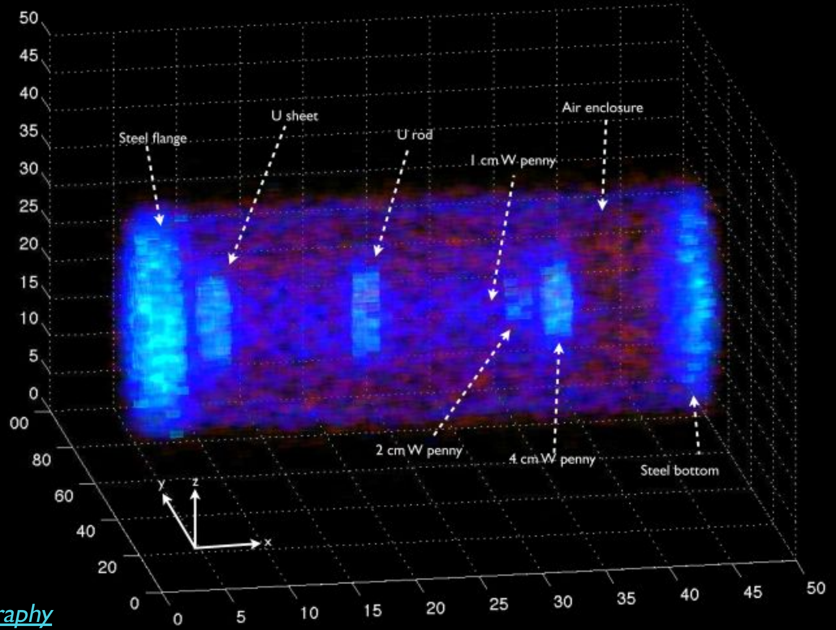


Illustration from *[Passive 3D imaging of nuclear waste containers with Muon Scattering Tomography]()*

Muon Scattering Tomography (MST)

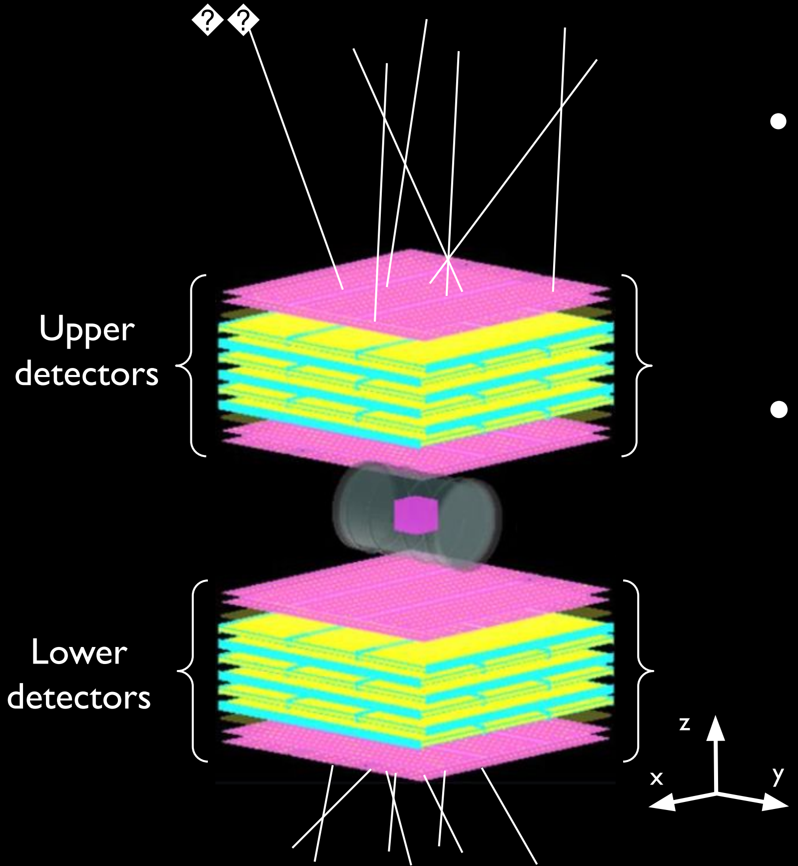
?





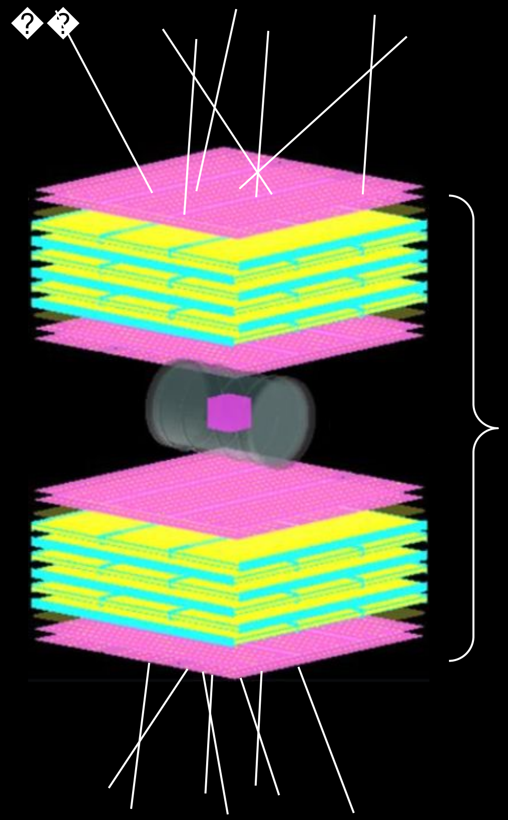
Pictures from *[Passive 3D imaging of nuclear waste containers with Muon Scattering Tomography]()*

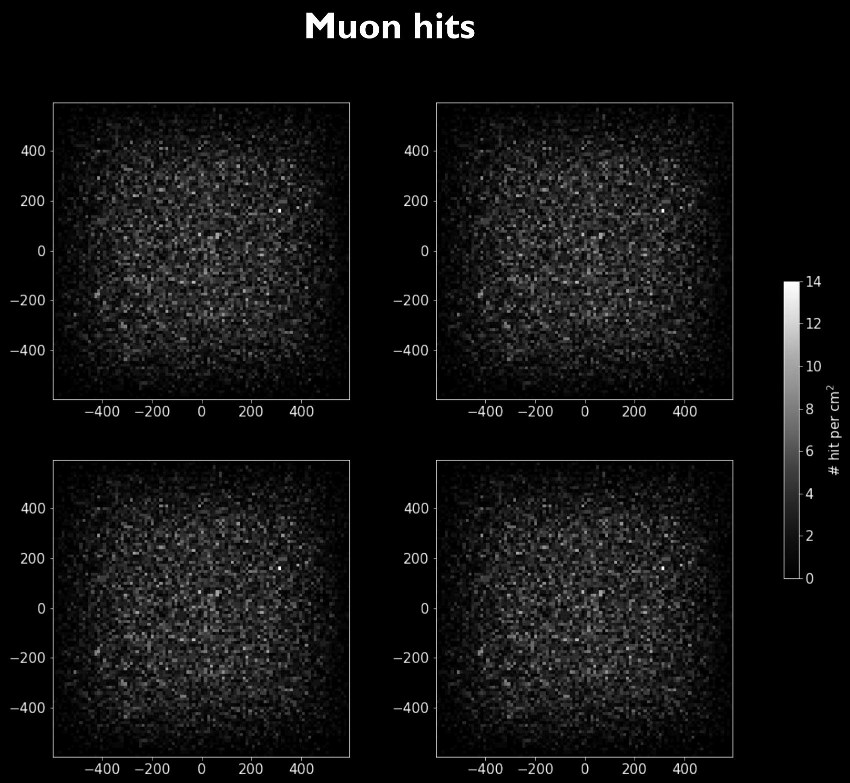
Step 1 - Data acquisition



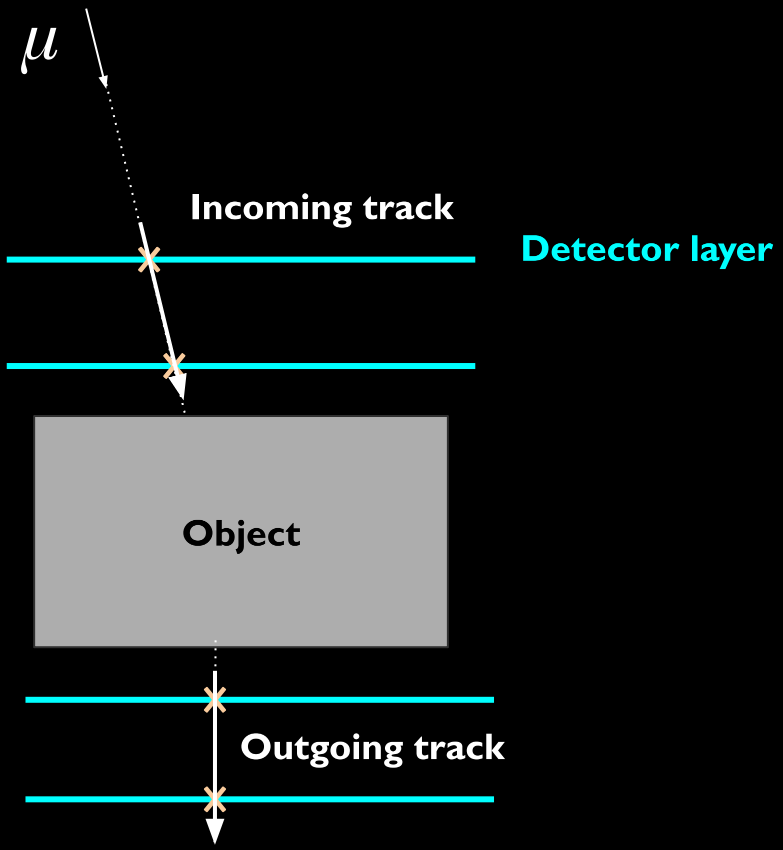
- Detector planes measure muon **X** and **Y position**.
  - *After detector alignement, the Z position of each plane is known.*
- Data acquisition time depends on the task, ranging from 10 min up to days.
  - *In the context of nuclear waste imaging you have no time constraint unlike for cargo scanning.*

Step 1 - Data acquisition



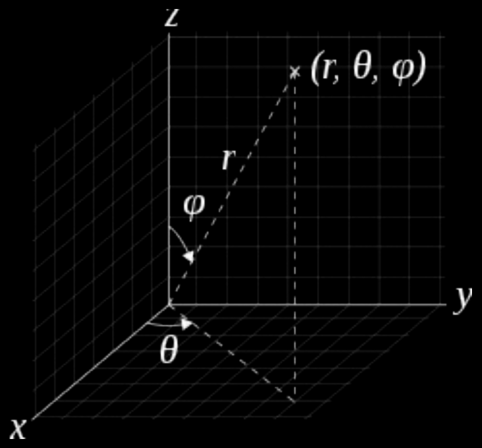


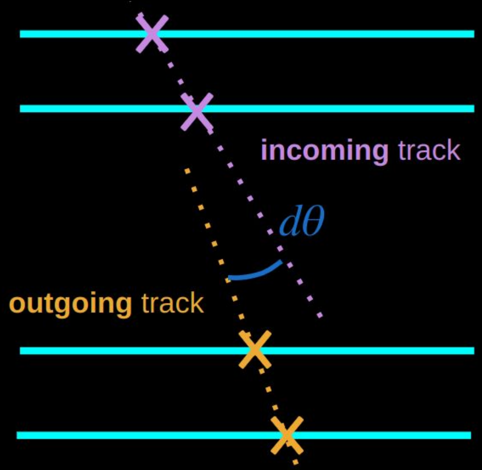
Step II - Tracking



- **Muons** traverse detector layers in **straight line**.
- **Detectors record** the muon **position** a.k.a "*Hit*"
- **Upper** and **lower** muon **hits** are **fitted independently** and will be **used** to **compute scattering angles**.

Step II - Tracking





After tracking, the following variables are computed:

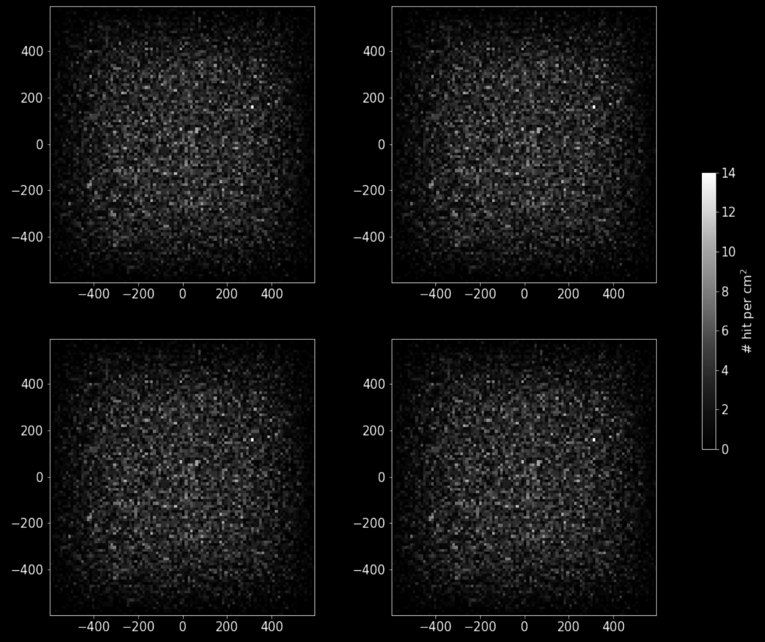
- $\theta_{\text{in}}, \theta_{\text{out}}$: Respectively the **zenith** angle of incoming and outgoing tracks
- $\phi_{\text{in}}, \phi_{\text{out}}$: Respectively the **azimuthal** angle of incoming and outgoing tracks
- $d\theta$:The **scattering angle** between incoming and outgoing tracks. Given the two tracks v_1 and v_2, it is computed as:

$$d\theta = \cos^{-1}\left(\frac{\vec{v_1} \cdot \vec{v_2}}{|\vec{v_1}| \times |\vec{v_2}|}\right)$$

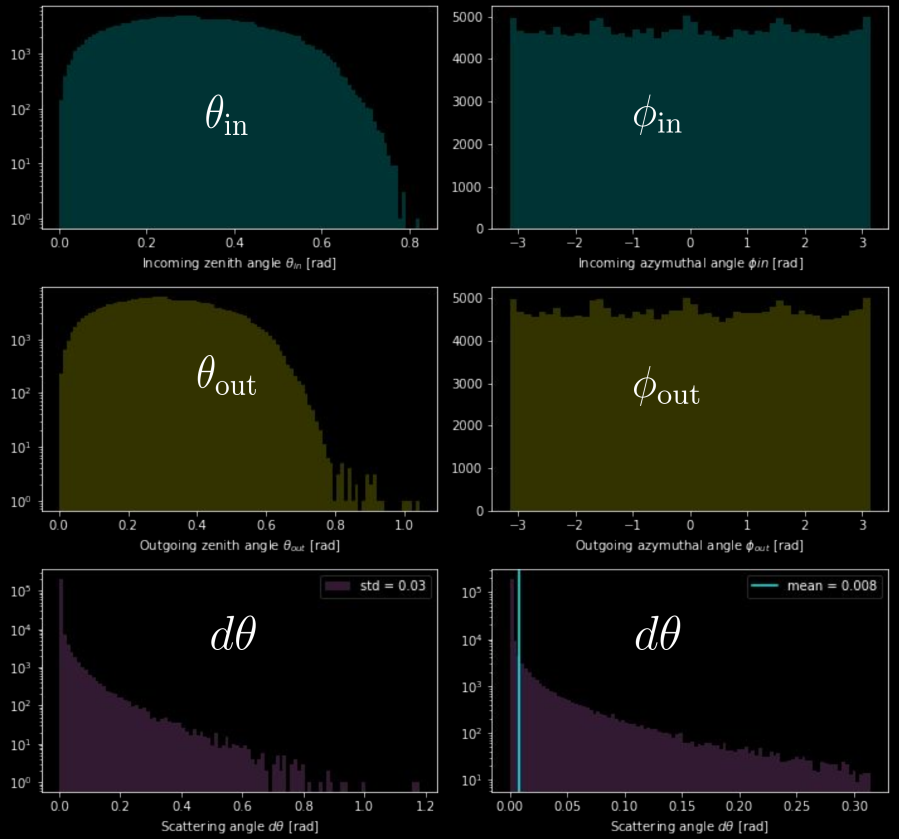
While $d\theta$ will be used by the reconstruction algorithms, θ_{in}, θ_{out}, ϕ_{in} and ϕ_{out} can be used for event filtering purposes.

Step II - Tracking

Muon hits

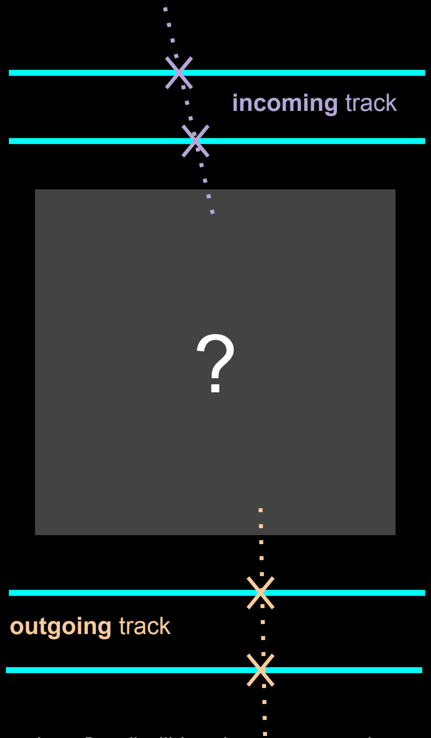


Muon angular distributions



Step III - Muon path reconstruction

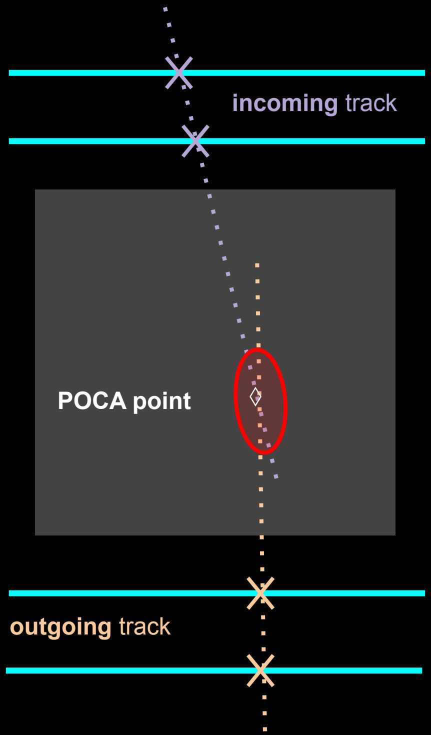
Path reconstruction: Uses information on muon position and tracks to **infer** the **muon path within** the **object**



- The **true muon path** within the object is **unknown.**
- Using **incoming** and **outgoing track**, path reconstruction algorithms **infer** the **muon path within** the **object**.

Step III - Muon path reconstruction

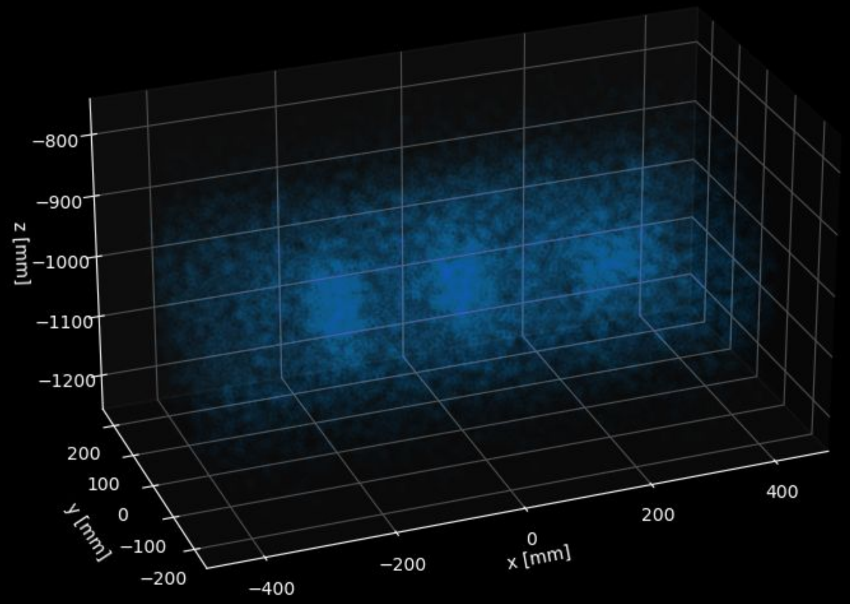
Path reconstruction: Uses information on muon position and tracks to **infer** the **muon path within** the **object**



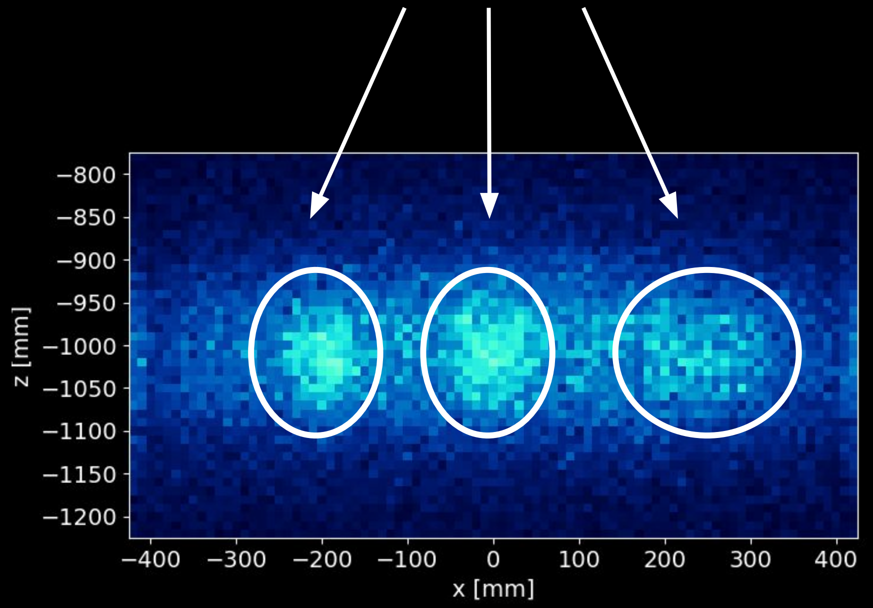
- The **true muon path** within the object is **unknown.**
- Using **incoming** and **outgoing track**, path reconstruction algorithms **infer** the **muon path within** the **object**.
- **Point Of Closest Approach** (POCA) is a commonly used algo. Assumes muon scatters **only once** at the closest point between incoming and outgoing track.
- The estimation of the **scattering location** and the scattering angle will then be used by the **image reconstruction algorithms**.

Step III - Muon path reconstruction

Scattering location provides **meaningful information** about the object density. **<u>Denser regions</u>** are more likely to **scatter muons**, and thus create a POCA point.



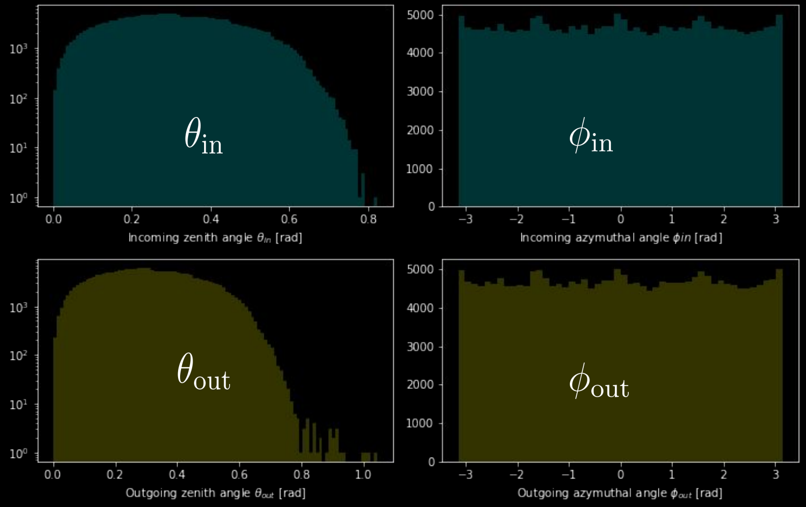
3D POCA points cloud



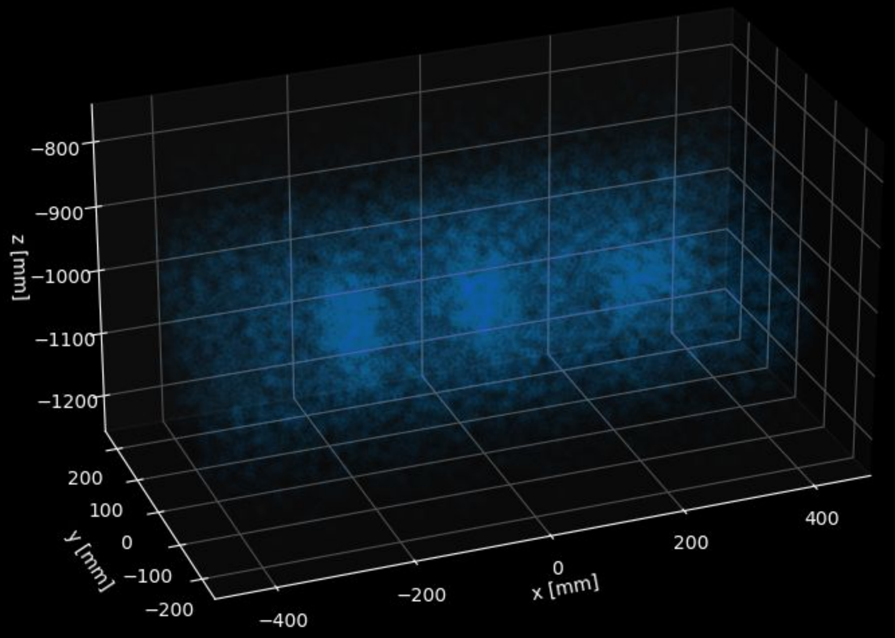
POCA points 2D histogram

Step III - Muon path reconstruction

Muon angular distributions



Scattering locations



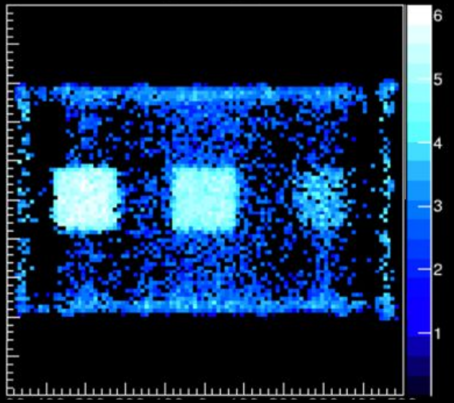
Step V - Post processing

MST reconstruction algorithm outputs (scattering locations, scattering angles, density maps) can be used as input of **Machine learning algorithms** for **segmentation**, **classification**, **clustering,** etc…

Clustering

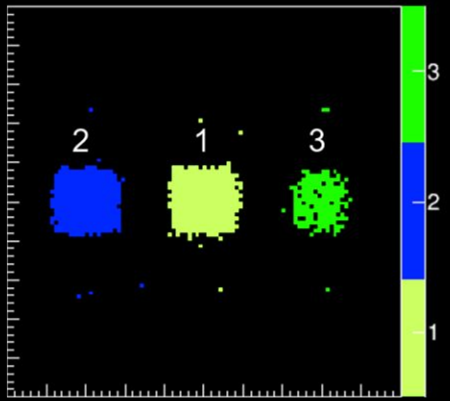
- **Clustering** can be applied to **scattering locations** (e.g POCA points) or **voxels scores** (S_{final}).
- Clustered object can the be classified

Voxel scores S_{final} map



INPUT

Clustered voxel score map through k-means++

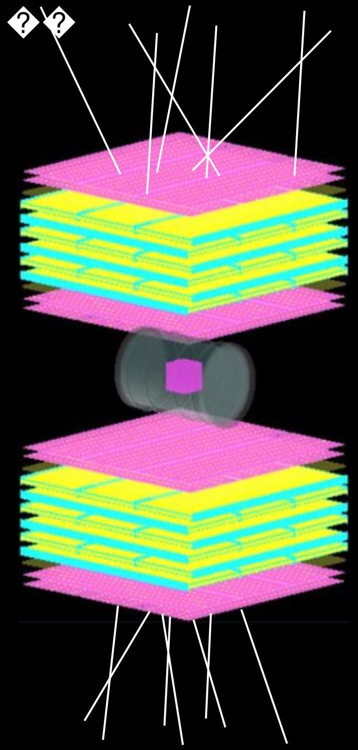


OUTPUT

Clustering and Example in [Material Identification in Nuclear Waste Drums using Muon Scattering and Multivariate Analysis]

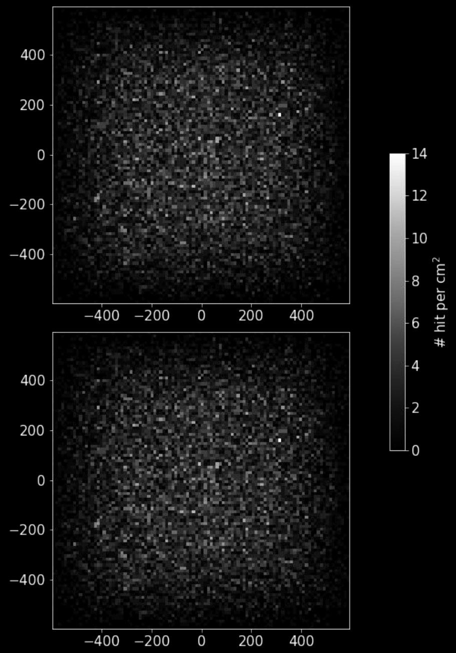
MST - Summary

INPUT



OUTPUT

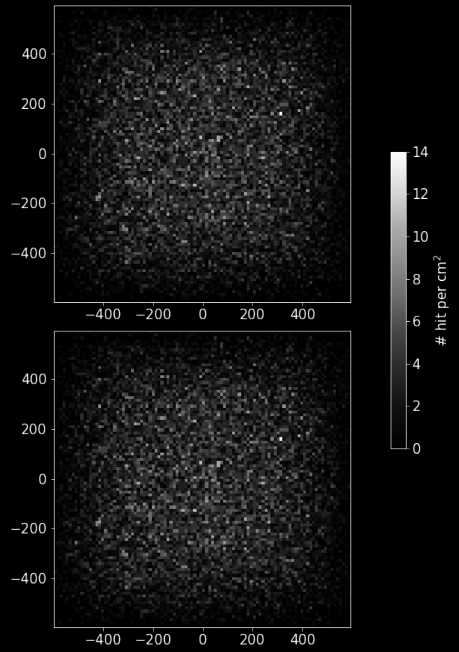
1. **Data acquisition**



Hits

MST - Summary

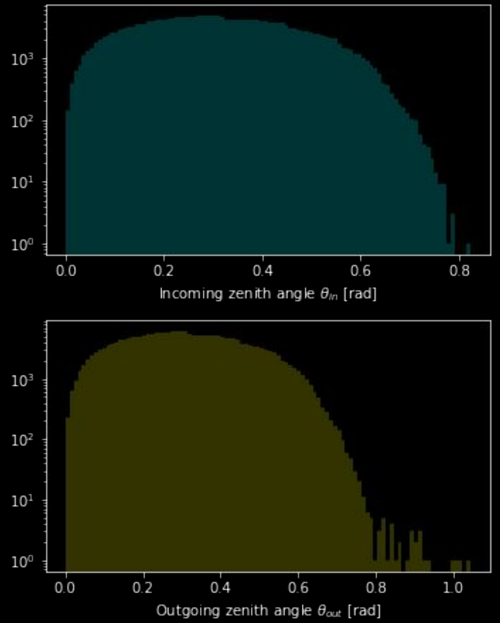
INPUT



Hits

1. Data acquisition
2. **Tracking**
   - From muon hits, computes incoming and outgoing muon tracks assuming straight line trajectory.
   - Reject background tracks based on hits timing, hit clusters, track χ^2, etc…
   - Compute scattering angles $d\theta$

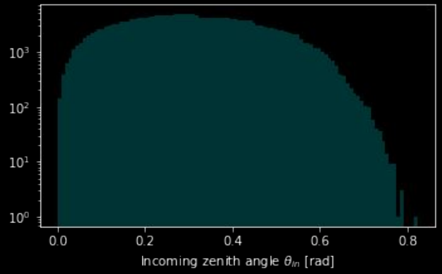
OUTPUT

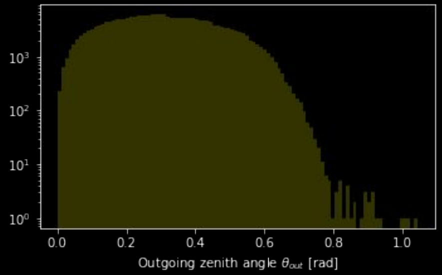


Tracks

MST - Summary

INPUT





Tracks

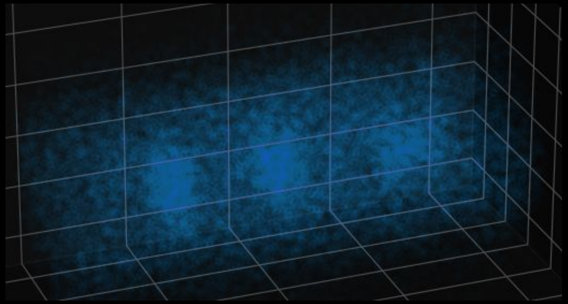
+

Hits

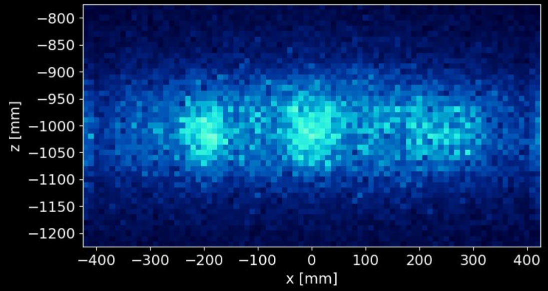
1. Data acquisition
2. Tracking
3. **Path reconstruction**

- Some algorithms handle both path and scattering density reconstruction
- Scattering location provide relevant information on material density

OUTPUT

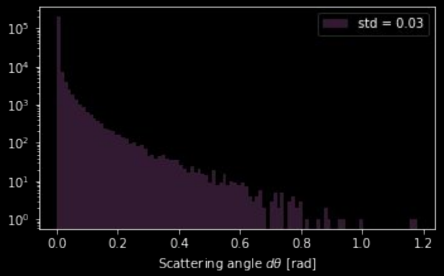


Scattering locations



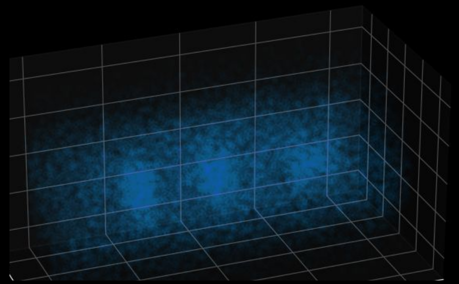
MST - Summary

INPUT



Scattering angles

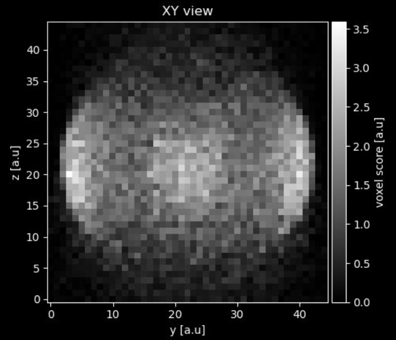
+

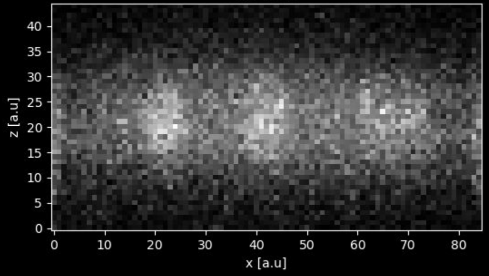


Scattering locations

1. Data acquisition
2. Tracking
3. Path reconstruction
4. **Scattering density reconstruction**
    - Associate a scattering density estimator to each region of the volume

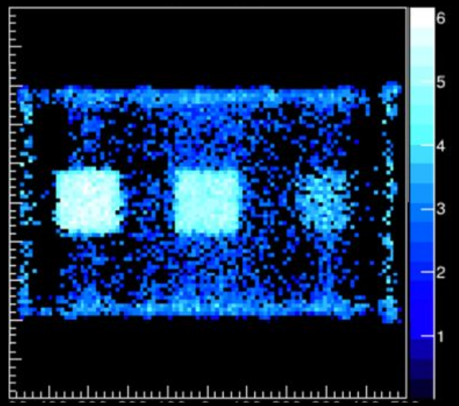
OUTPUT





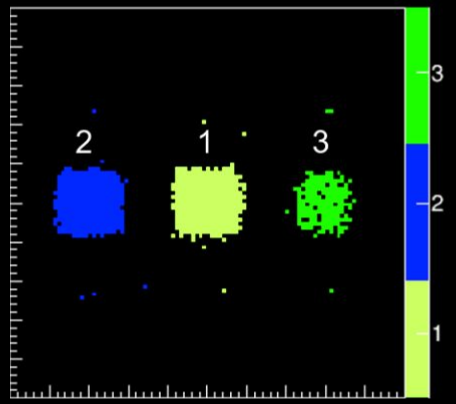
MST - Summary

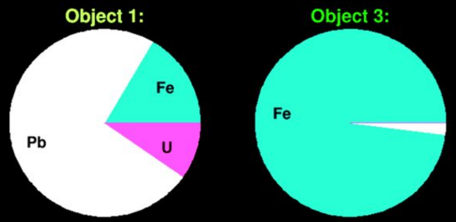
INPUT



1. Data acquisition
2. Tracking
3. Path reconstruction
4. Scattering density reconstruction
5. **Post processing**
   - *Post processing is not mandatory*
   - *ML brings new tools which are relevant!*
   - *Material classification, shape recognition, segmentation, clustering, anomaly detection, etc…*

OUTPUT



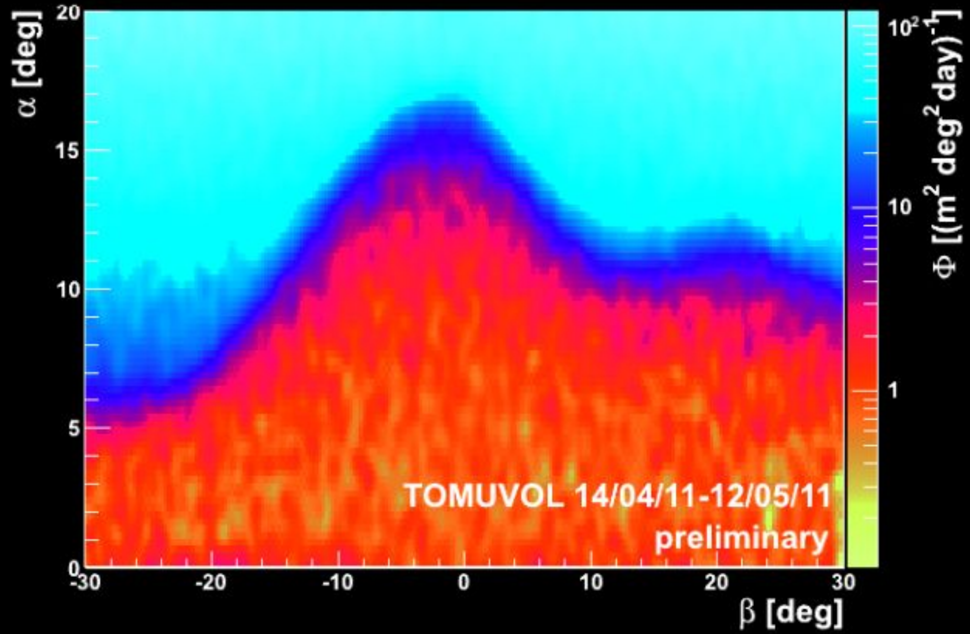


Ob 1: vol 2936.0 cm^3
Fe: 0.169 +/- 0.008,
Pb: 0.744 +/- 0.029,
U: 0.099 +/- 0.006

Ob 3: vol 1363.0 cm^3
Fe: 0.980 +/- 0.038,
Pb: 0.020 +/- 0.004,
U: 0.000 +/- 0.000

Structure

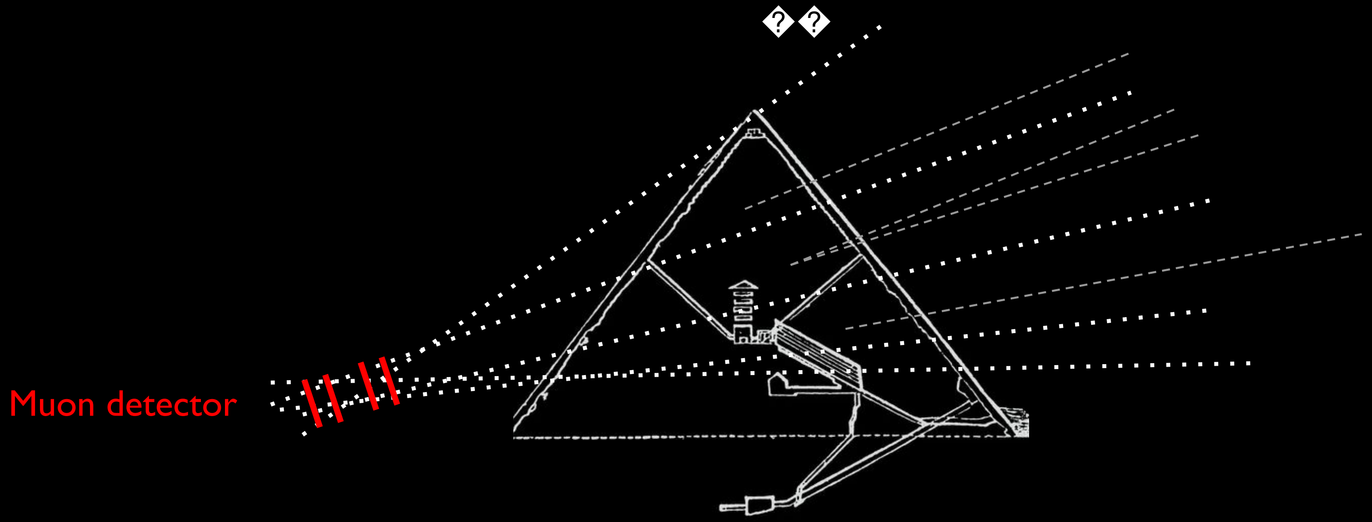
1. Introduction to muography
2. Cosmic rays
3. Muons through matter
4. Muon scattering tomography
5. **Absorption muography**
6. Conclusion



Absorption tomography - Object measurement

Absorption muography is a **counting experiment** utilizing the **absorption** of **muon** in **matter**.

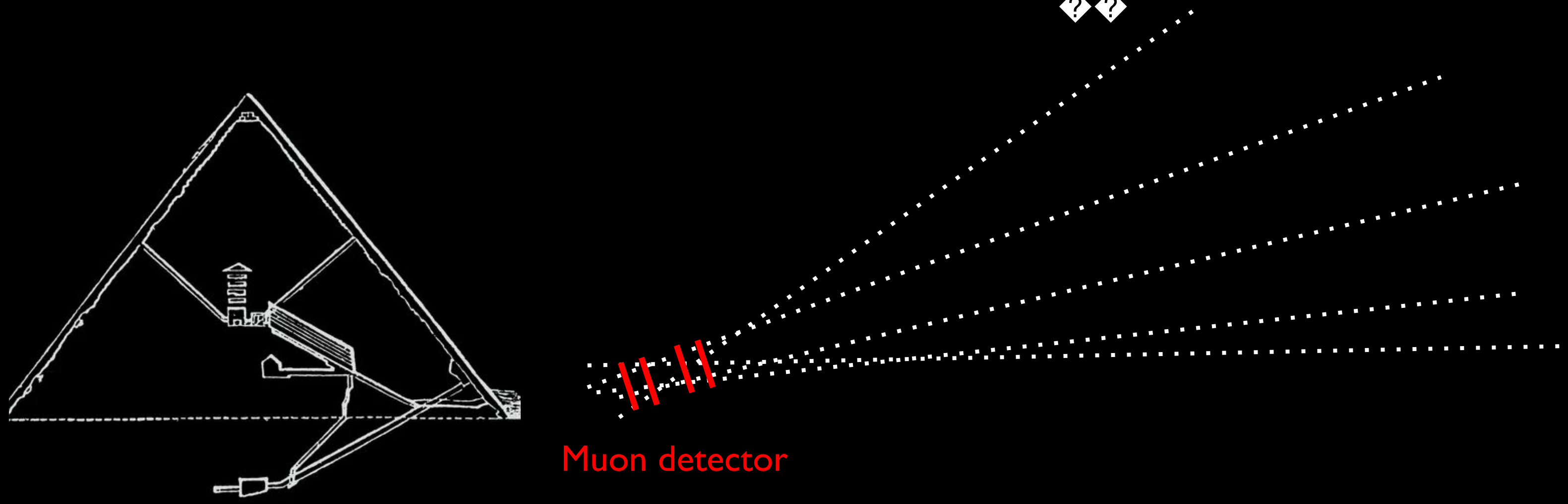
By **counting** the **number** of absorbed **muons** in a given region of the target volume, one can **infer** its **density**.

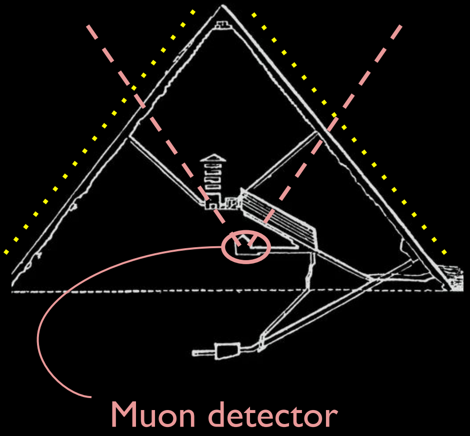


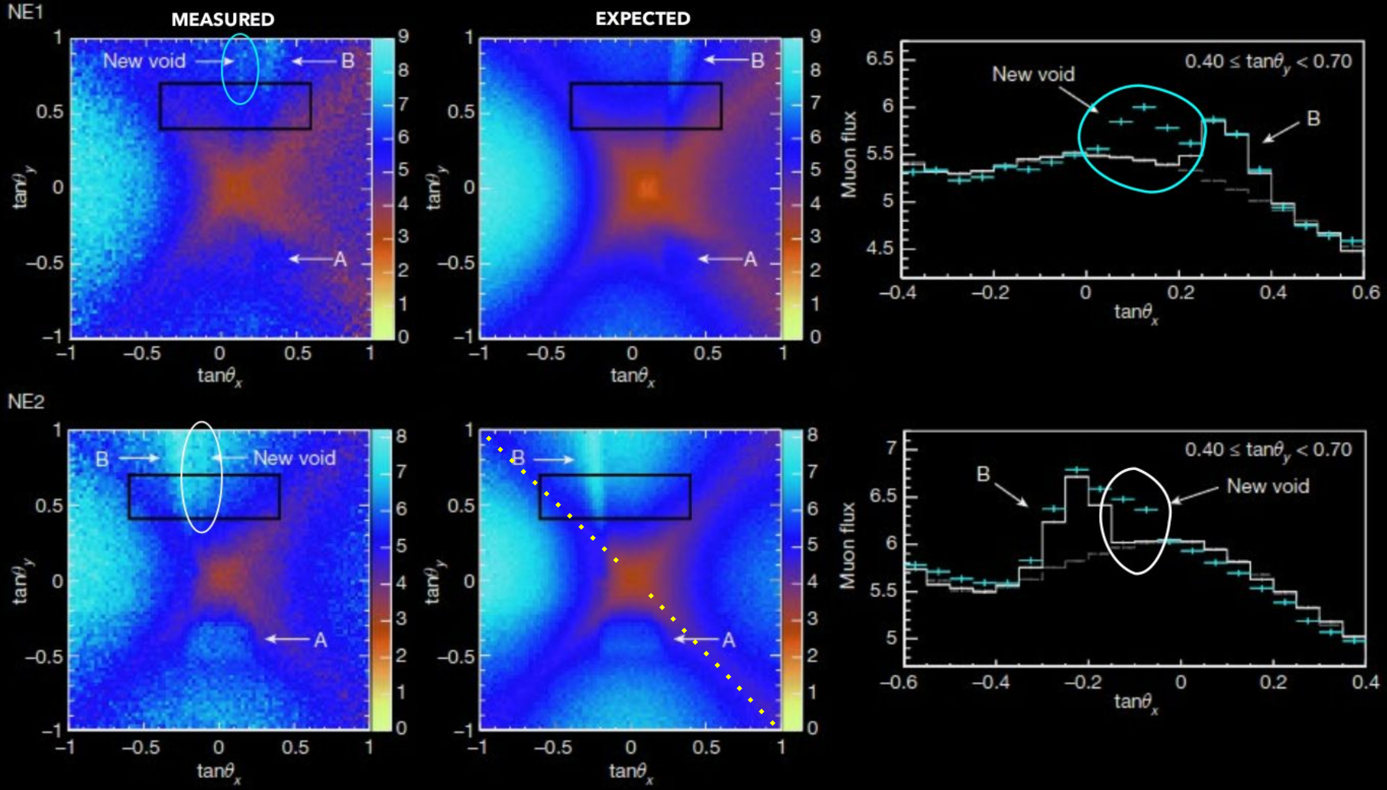
Absorption tomography - freesky measurement

The **measured flux** of muons **through** the **object** is then **compared** to the “**freesky**” **muon flux**.

The ratio between the two measured fluxes gives the transmission rate, which is related to the properties of the material.







MEASURED FLUX IN THE SQUARED REGION

[Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons]

IV - Detectors for muography application

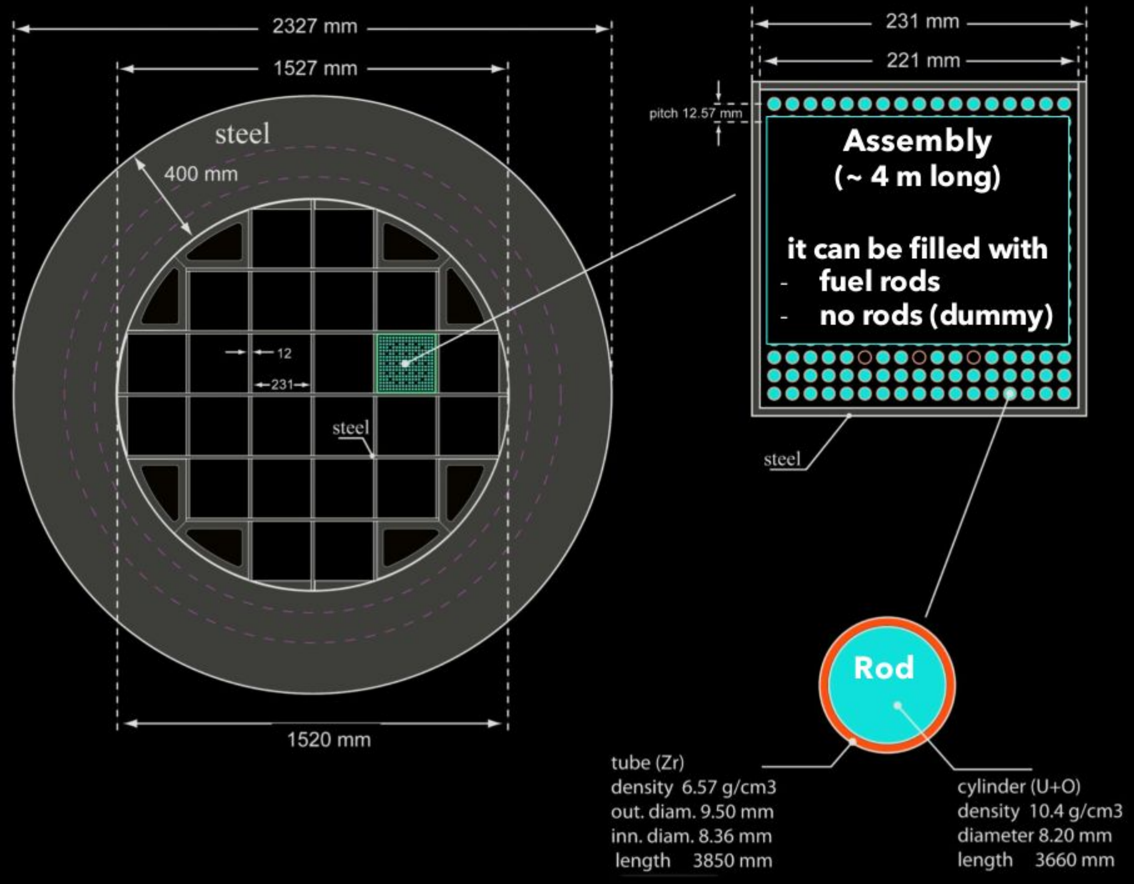
MUTOMCA

Picture from Muographers 2023

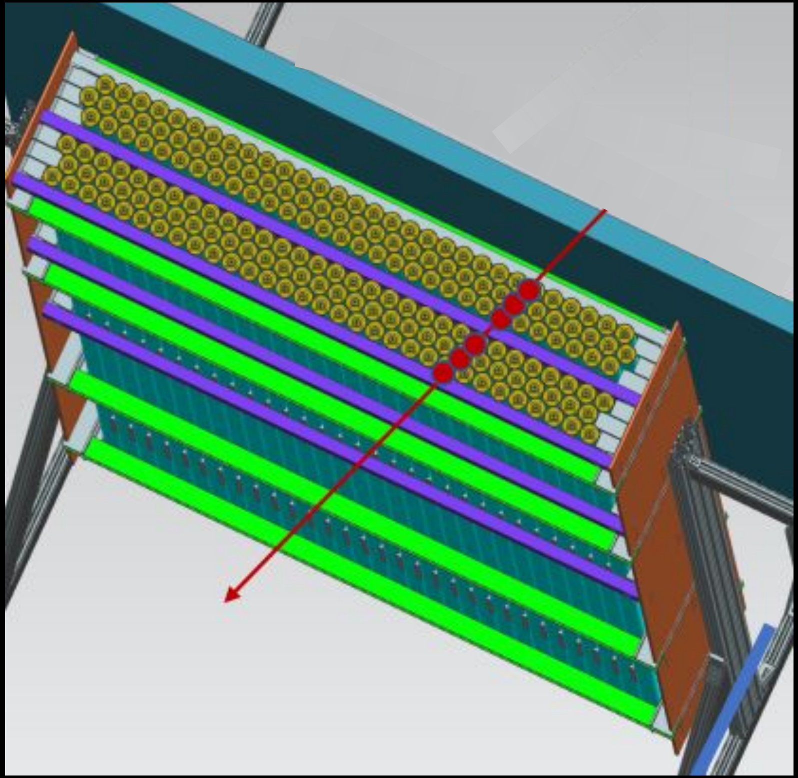
MUTOMCA: Muon tomography for shielded casks

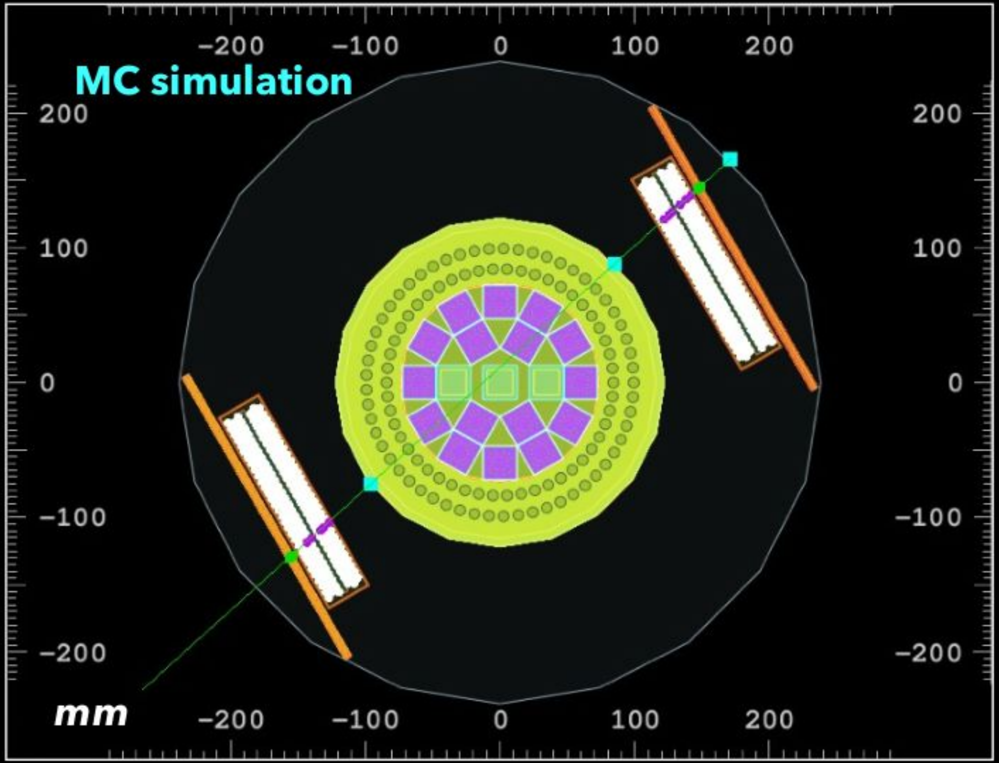
- **Shielded casks inspection** via muon scattering tomography, detect spent fuel assemblies, for re-verification purposes.
- **Only muography** can **achieve** such an **imaging task** (X rays get absorbed in dense materials)
- Drift tubes based detector leftovers from CMS muon chamber production.
- **Challenging** environment because of **material activity** and logistic **constraints**.
- Few days of **data taking** in 2023, **data** currently **being processed**

MUTOMCA: shielded casks

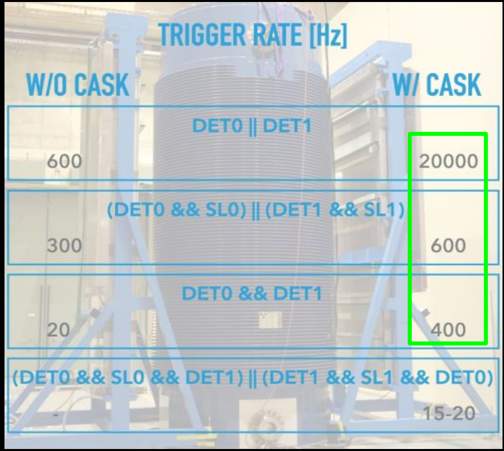


MUTOMCA: Muon tomography for shielded casks



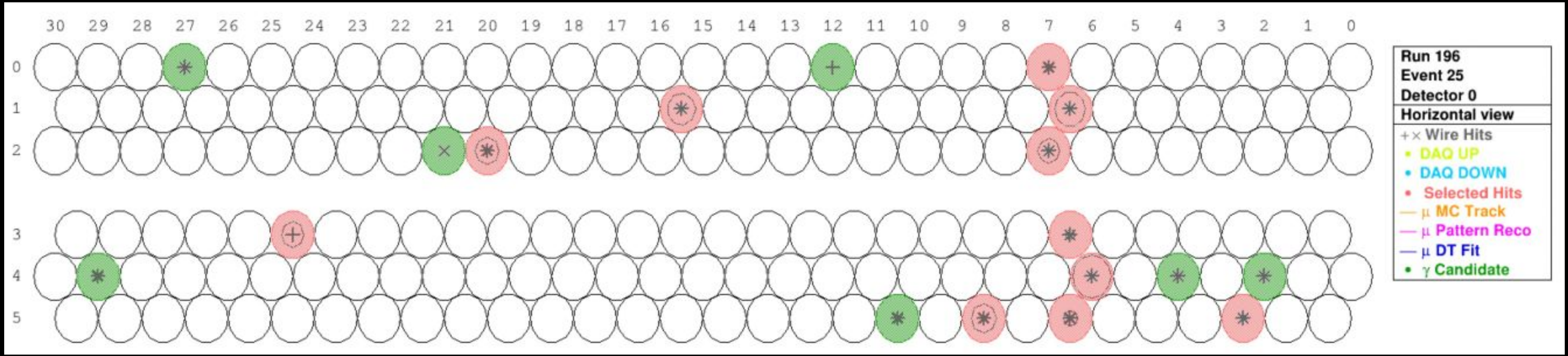


MUTOMCA: tracking strategy

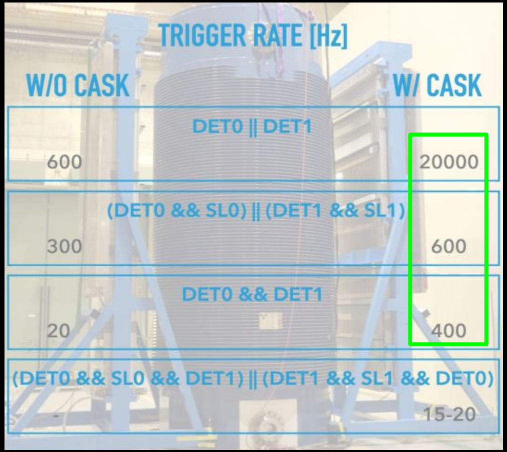


A robust **noise cancelling** strategy was **implemented** in the **track reconstruction software** to remove the random radioactivity hits recorded together with muon tracks:

1. **Time filter**: exploit the time correlation of muon hits (neutrons and gammas arrival time is uncorrelated).

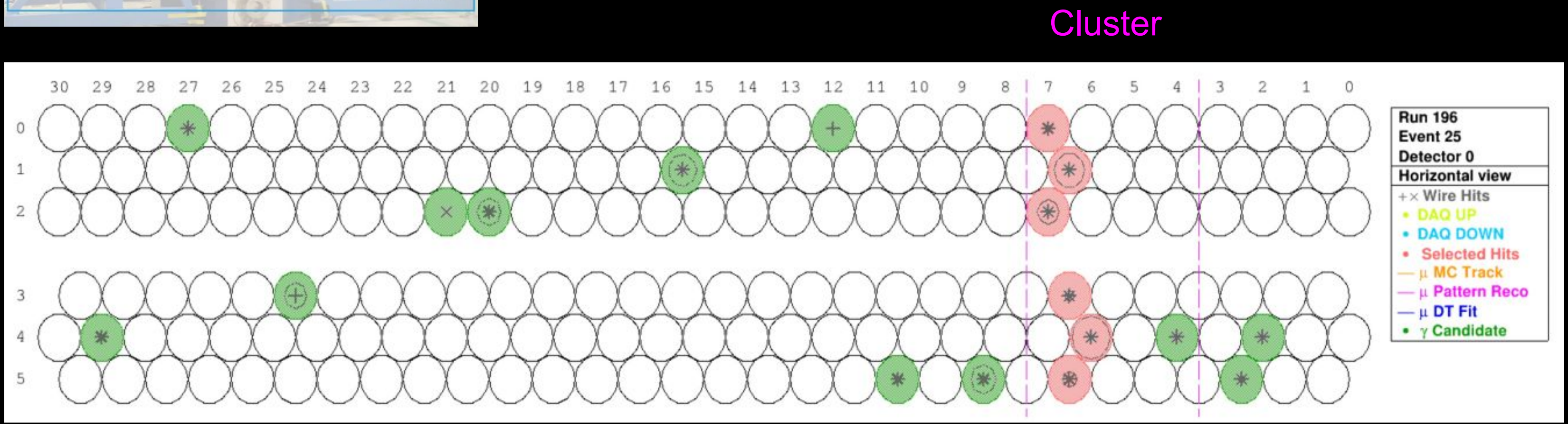


MUTOMCA: tracking strategy

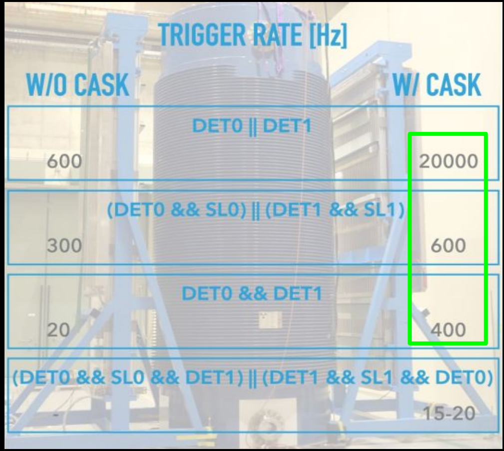


A robust **noise cancelling** strategy was **implemented** in the **track reconstruction software** to remove the random radioactivity hits recorded together with muon tracks:

1. Time filter
2. **Space filter and cluster filter:** while the muon hits forming a track are connected, noise hits are more likely to be isolated

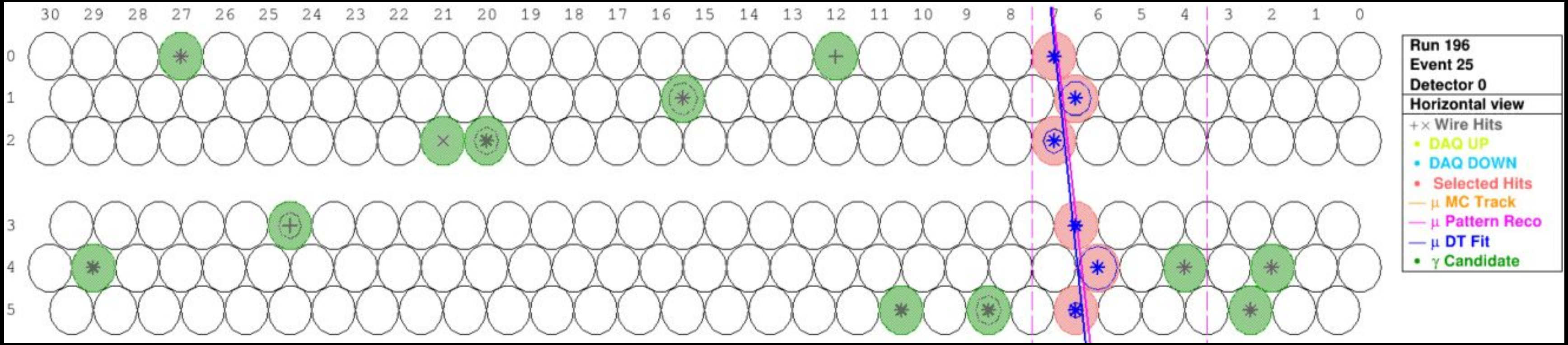


MUTOMCA: tracking strategy



A robust **noise cancelling** strategy was **implemented** in the **track reconstruction software** to remove the random radioactivity hits recorded together with muon tracks:

1. Time filter
2. Space filter and clustering
3. **Pattern Recognition**: It is linear regression of the wire coordinates of selected hits: it is useful to identify track candidates.

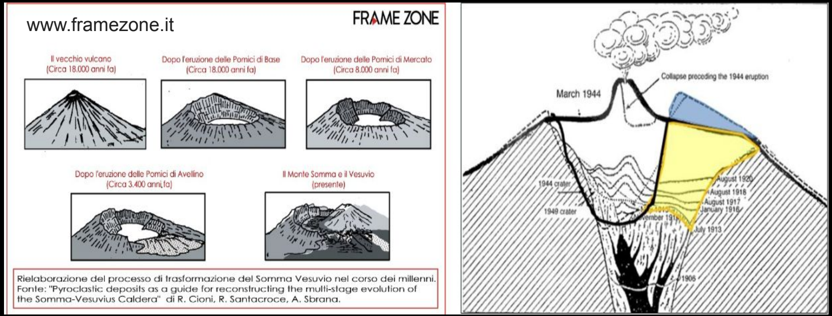


MURAVES: MUon RAdiography of VESuvius

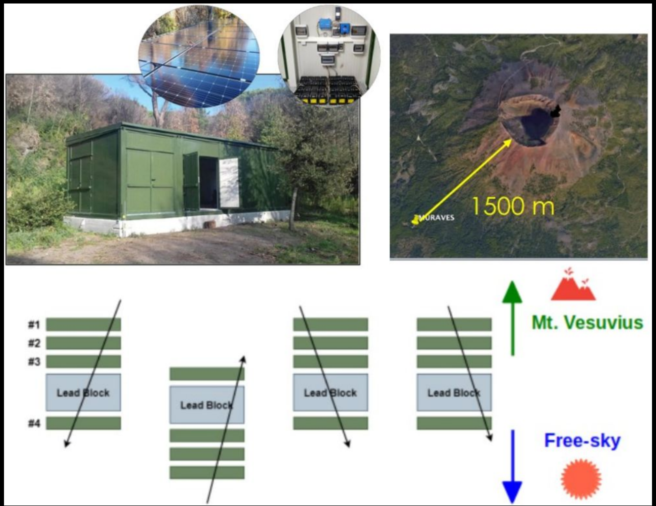
- **Target:**
  - **Mt. Vesuvius** located in the south of Italy near city of Naples.

  Why?
  - One of the **most dangerous** active volcanoes in the world with more than **half a million people** living in the **red zone**.
  - **Muography** can shed light on the **distribution** of **different densities** along the body of the volcano providing a direct image of the layers that form the structure of Vesuvius.

- **How?**
  - **4 MURAVES telescopes** housed inside a container located **@1500m from** the crater.
  - **3 detectors** point **towards Mt. Vesuvius** and **one collects freesky reference data**.



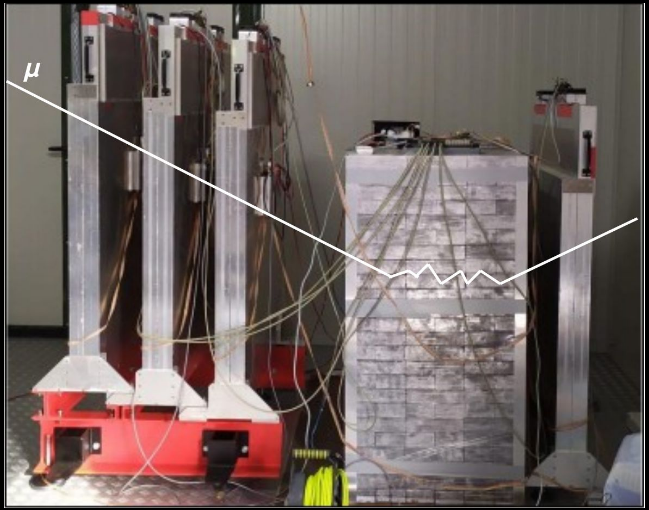
Latest structural modification during the eruption of 1944



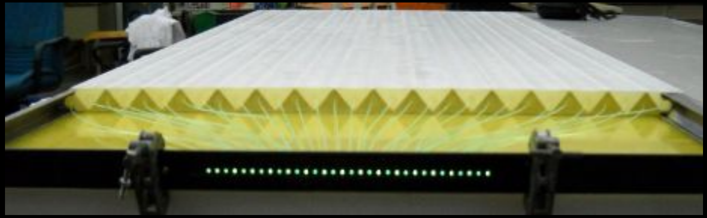
MURAVES @ Mt.Vesuvius

MURAVES: MUon RAdiography of VESuvius

- **The detection setup of MURAVES:**
  - 3 tracking hodoscopes (or "telescope") consisting of triangular scintillator bars coupled to SiPMs via a wave-length fiber embedded through the center of each bar.
  - Each tracker has 4 XY tracking stations of $1m^2$ active area, distributed along a length of ~ 2m, with 60cm-thick lead wall between 3rd and 4th station.
  - Each tracking station is made of 2 adjacent modules, where each module consisting of 32 triangularly shaped bars glued together in a roughly 50cm wide half-plane.



One of the MURAVES hodoscope



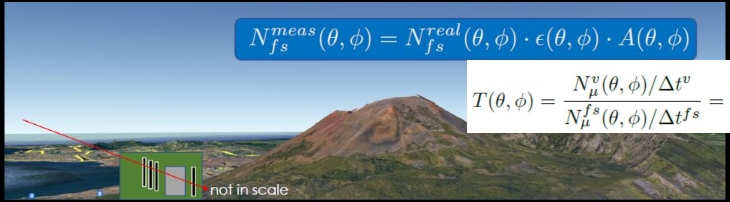
The 32 scintillator bars and WLS fibers assembled in a half of a planar array (1 module)

MURAVES: MUon RAdiography of VESuvius

- **Measurement principle and initial datasets:**

  - The experiment **maps** the **mean density** of the matter crossed by muons, through the **measurement** of the **muon flux** that **reach** the **detector** as a **function of θ and** φ.

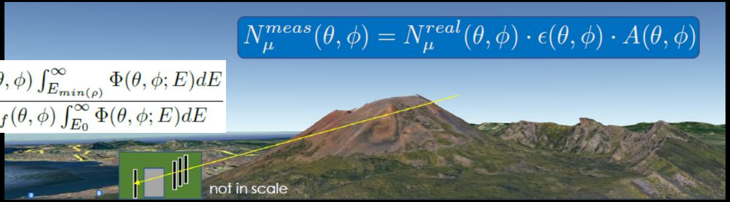
  - Its **ratio** with the muon flux measured in **freesky** gives a **muon transmission**

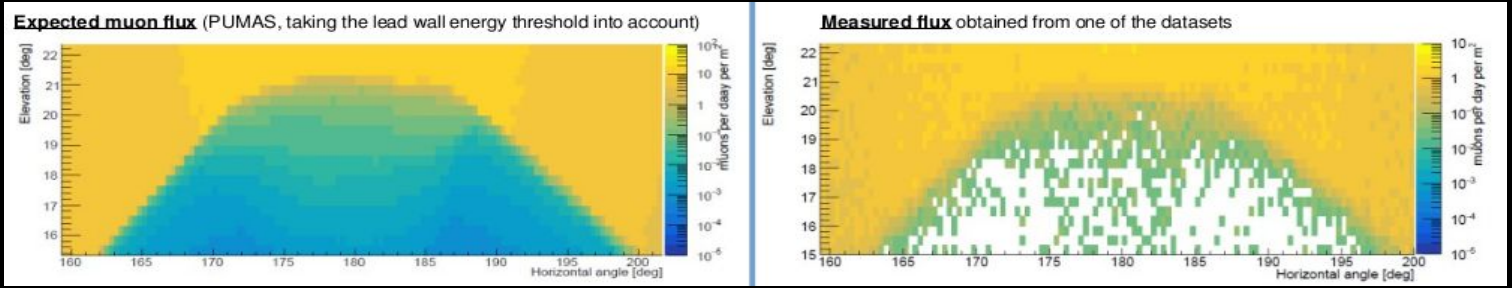


$$N_{fs}^{meas}(\theta,\phi) = N_{fs}^{real}(\theta,\phi)\cdot\epsilon(\theta,\phi)\cdot A(\theta,\phi)$$

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

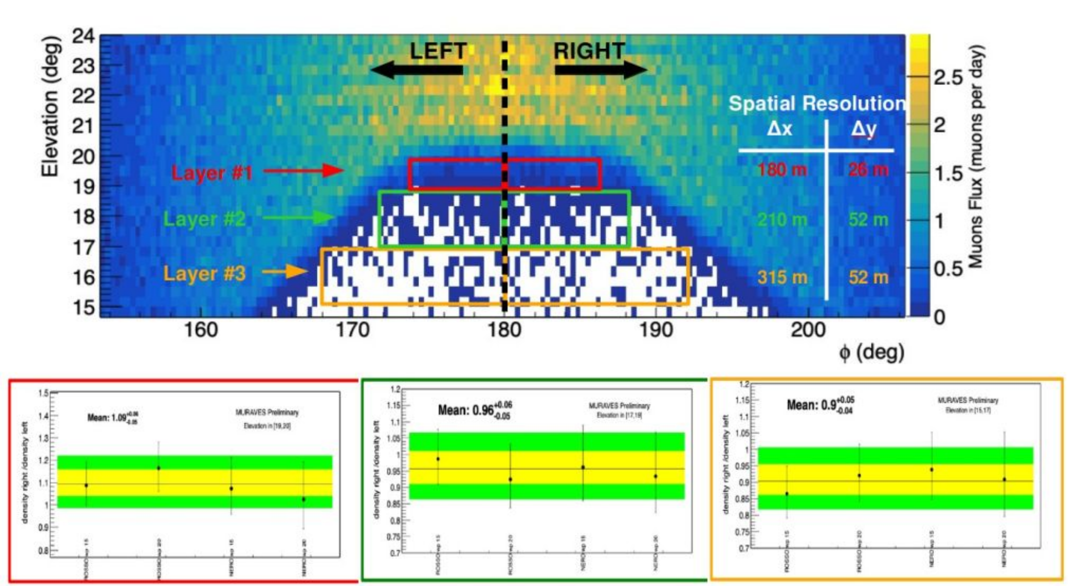
$$N_\mu^{meas}(\theta,\phi) = N_\mu^{real}(\theta,\phi)\cdot\epsilon(\theta,\phi)\cdot A(\theta,\phi)$$





MURAVES: MUon RAdiography of VESuvius

- **Preliminary results:**
  - The visible cone was divided into 3 regions, further subdivided in left and right parts in order to measure possible asymmetries between the slopes of the volcano.



Top layer shows right side more dense than left side

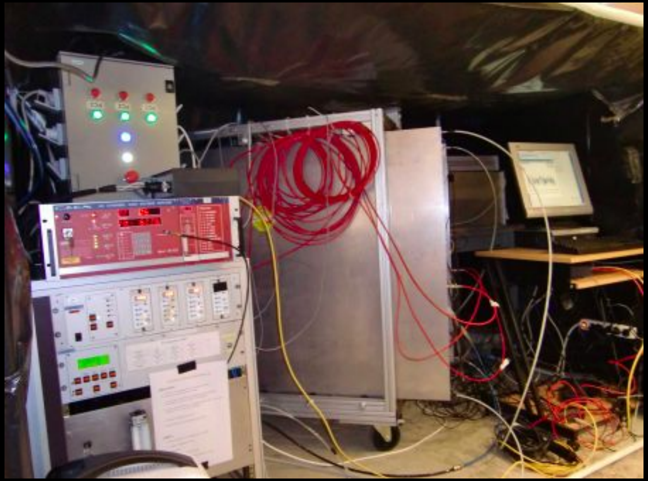
Middle layer shows left side more dense than right side

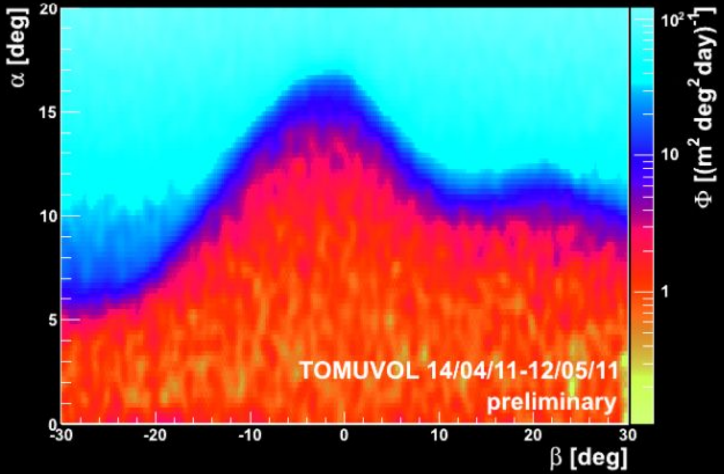
Bottom layer same as middle layer but stronger difference between right and left

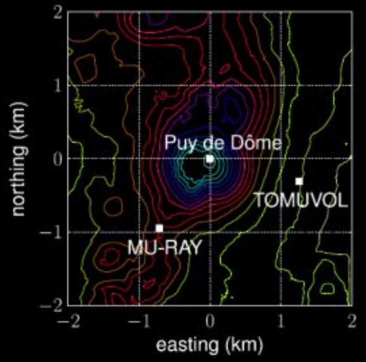
- A measurement of the density asymmetry $\frac{\rho_{\text{right}}}{\rho_{\text{left}}}$ is obtained indicating density asymmetry variations between different layers.

- More data are being accumulated and a thorough assessment of possible biases is going.

TOMUVOL




α [deg]
β [deg]
Φ [(m² deg² day)⁻¹]
TOMUVOL 14/04/11-12/05/11
preliminary


Puy de Dôme
TOMUVOL
MU-RAY
northing (km)
easting (km)

References

- "*Atmospheric muons as an imaging tool*", L. Bonechi and R. D'Alessandro and A. Giammanco, https://doi.org/10.1016/j.revip.2020.100038
- "*Figures of Merit for the Application of Muon Tomography to the Characterization of Nuclear Waste Drums-19253*", P. Stowell et al.
- "*Passive 3D imaging of nuclear waste containers with Muon Scattering Tomography*", C. Thomay *et al* 2016 *JINST* 11 P03008, https://dx.doi.org/10.1088/1748-0221/11/03/P03008
- *"First results on material identification and imaging with a large-volume muon tomography prototype", S. Pesente et al, https://doi.org/10.1016/j.nima.2009.03.017*
- *"Angle Statistics Reconstruction: a robust reconstruction algorithm for Muon Scattering Tomography",* M. Stapleton *et al* 2014 *JINST* 9 P11019, https://dx.doi.org/10.1088/1748-0221/9/11/P11019
- *"Image reconstruction and material Z discrimination via cosmic ray muon radiography",*

References

- "*Muon tomography for dual purpose casks (MUTOMICA) project*", D. Ancius et al.,
- Check presentations from Muographers Conferences (2021, 2022, 2023)