

# Density Evaluation Strategies for the Mt. Vesuvius Great Cone

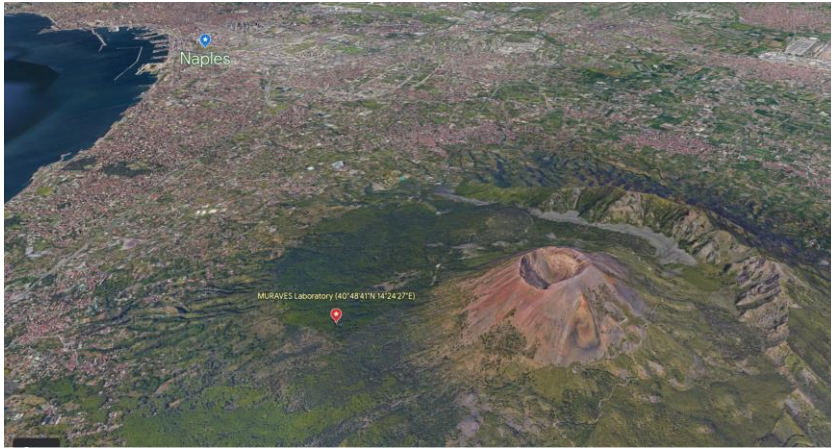
4 June, 2026

*MUOGRAPHERS26 Workshop, Budapest*

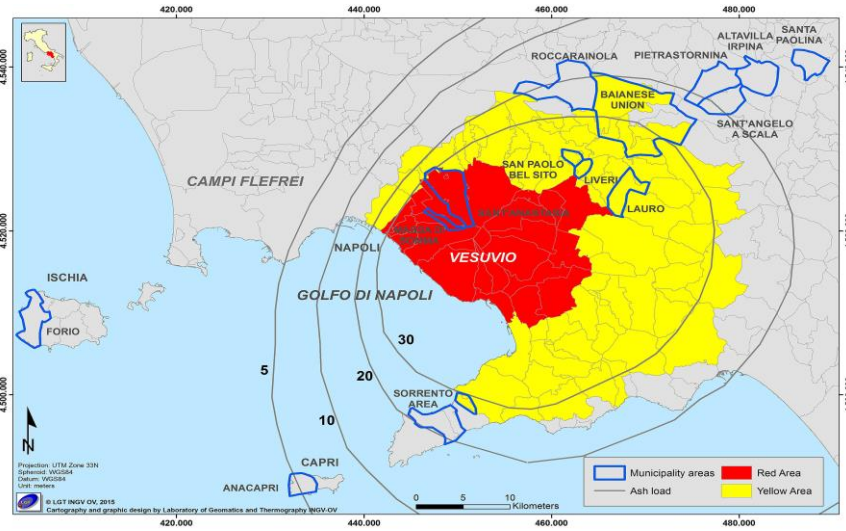
*Adithyan Rajan on behalf of MURAVES collaboration*

Pic

# Mount Vesuvius



The MURAVES observatory location (red marker) on Google Earth, with the city of Naples (blue marker) also indicated.



The red and yellow zones of Vesuvius Emergency Plan. Central circle indicates the limit of  $300\text{kg}/\text{m}^2$  of ash fallout load [1].

## LOCATION

Naples, Italy

Mt. Vesuvius is an active volcano on the Bay of Naples.

## NEARBY POPULATION

~0.6 million

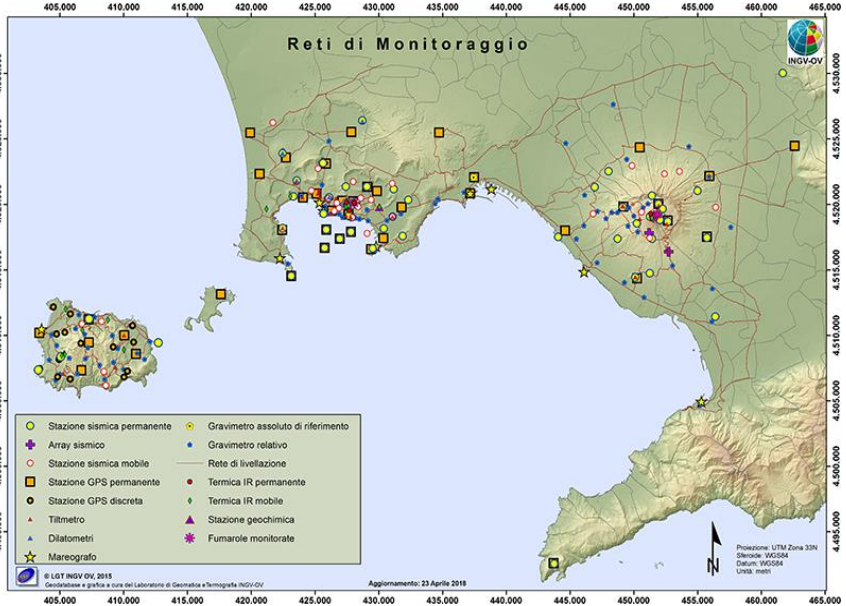
Residents living within the high-risk volcanic region.

# The MURAVES Experiment



Surveillance Room of the Vesuvius Observatory at INGV.

- Mt. Vesuvius is one of the world's most monitored volcanoes, with 24/7 surveillance by INGV (National Institute of Geophysics and Vulcanology).
- Monitored via seismic, GPS, thermal sensors and more.

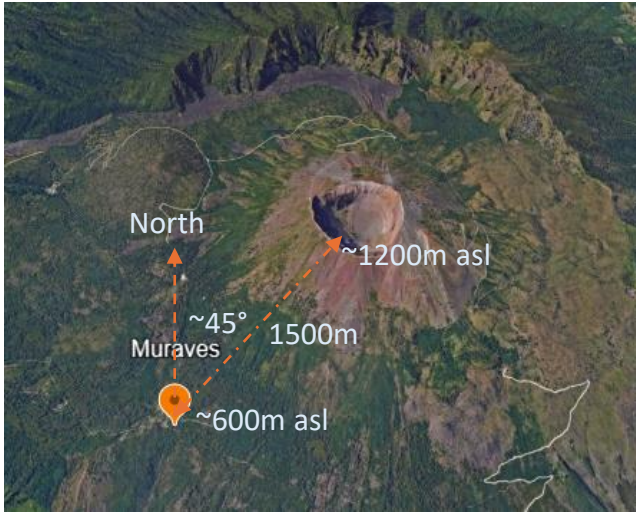


Map of monitoring networks of active volcanoes in Campania area: Vesuvius, Campi Flegrei, Ischia.

**Aim**

The MURAVES experiment aims to perform muographic imaging of the summital cone of Mt. Vesuvius.

# The MURAVES Detector



- MURAVES telescope is an array of three identical muon trackers.
- Muon trackers has 4 X Y planes of  $1\text{m}^2$  active area, each x and y layer composed of 64 triangular adjacent scintillator bars.
- scintillator light is collected via optical fiber and later read out by SiPM

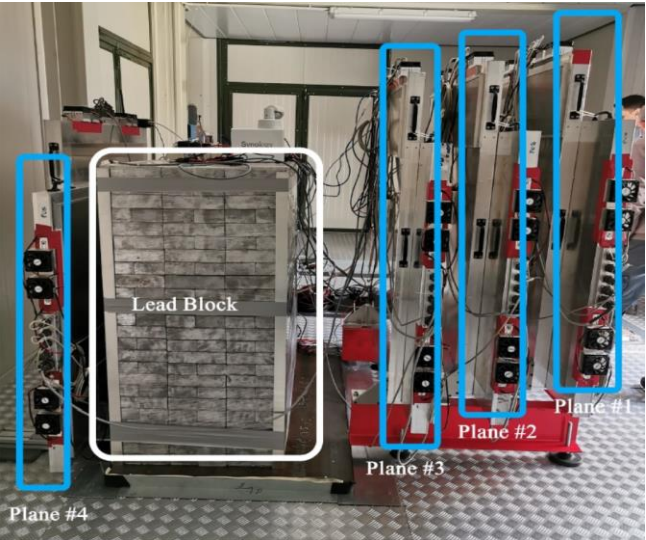


MURAVES hodoscope. Four scintillator station and the lead wall between 4<sup>th</sup> and 3<sup>rd</sup> plane is marked.

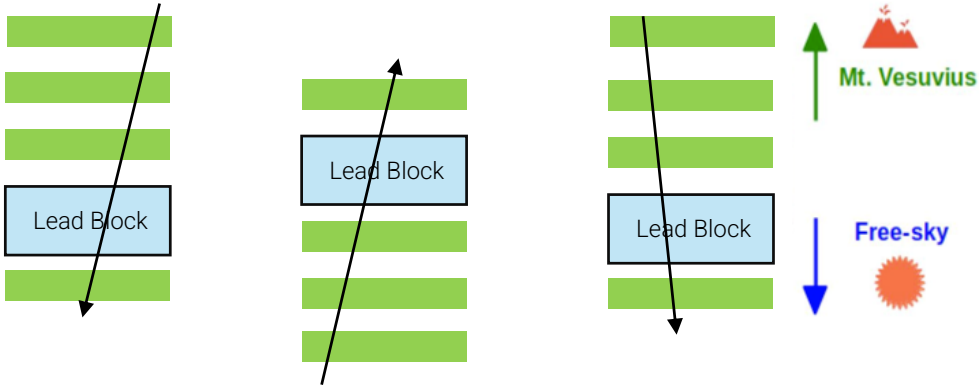
# The MURAVES Detector



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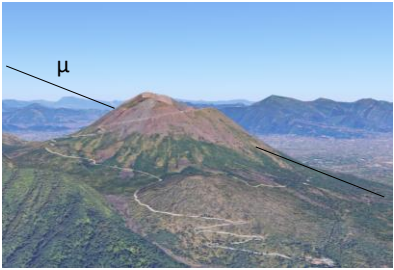
# Simulation Study

GOAL

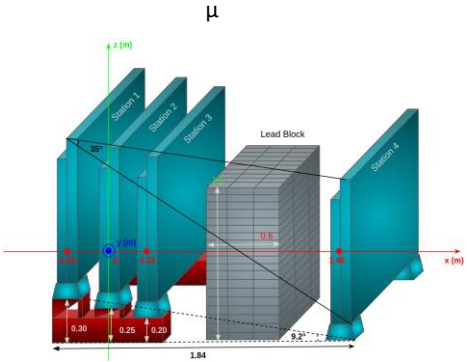
Muon Generation



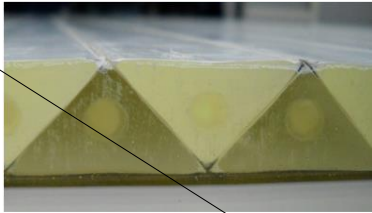
Transport through rock



Detector Simulation

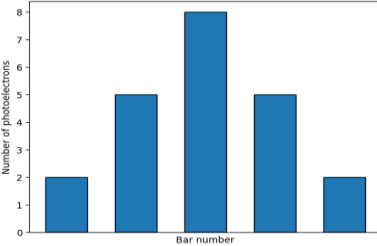


Digitization



Mulder (Pumas + Turtle)

Geant4

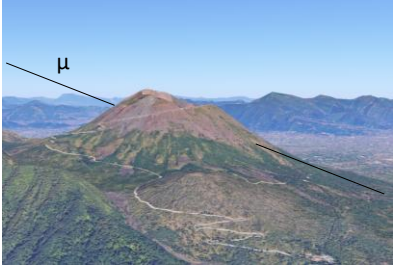


# Simulation Study

Muon Generation

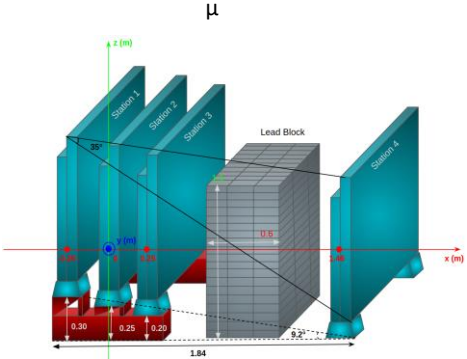


Transport through rock



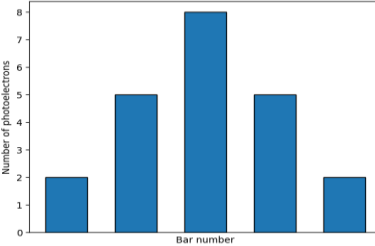
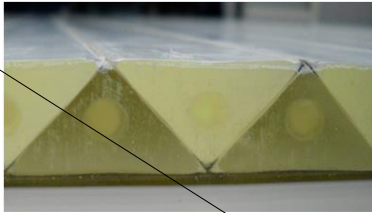
Mulder (Pumas + Turtle)

Detector Simulation



Geant4

Digitization



# Mulder (Pumas + Turtle)



## Ray Tracing

Computes rock thickness along each line of sight from the detector through the topography.



## PUMAS

## Muon Transport & Energy Loss

Computes muon transport and energy loss through volcanic rock.

## MULDER

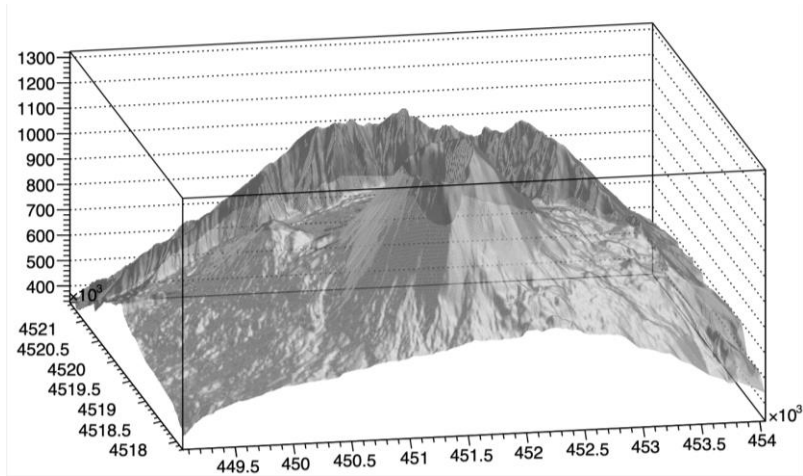
### Simplified Interface

Unified interface to Pumas and Turtle, providing the local flux of atmospheric muons at the detector.

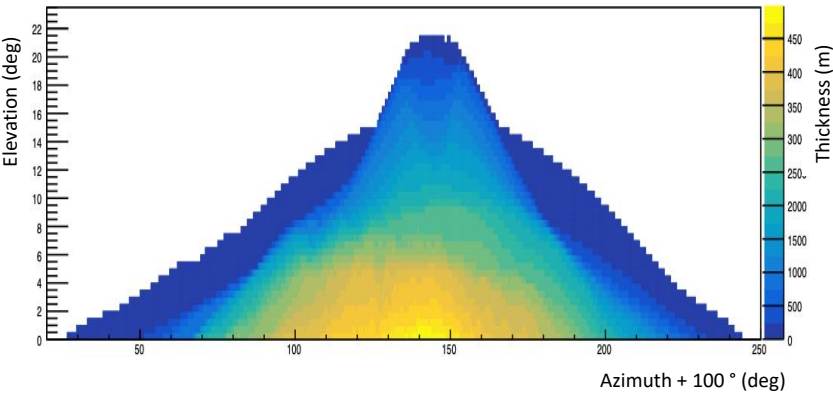
**OUTPUT**

Expected Muon flux at detector

# Turtle – Ray Tracing



DEM input: 5m precision terrain map, provided by INGV



Vesuvius thickness map — view from the detector position

DEM: 5m precision terrain map, provided by INGV

Azimuth  $\phi = 1^\circ$ , elevation  $\theta = 1^\circ$

**1° resolution**  $\rightarrow \sim 26.2$  m at the crater

$$(1500 \times \pi/180)$$

**TURTLE** 

**INPUT**

Digital elevation model and Detector location

# Energy loss modes in Mulder

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## **CONTINUOUS Slowing Down Approximation**

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- Straight deterministic trajectories
- Ignores hard loss fluctuations — fast

## **DISCRETE MODE**

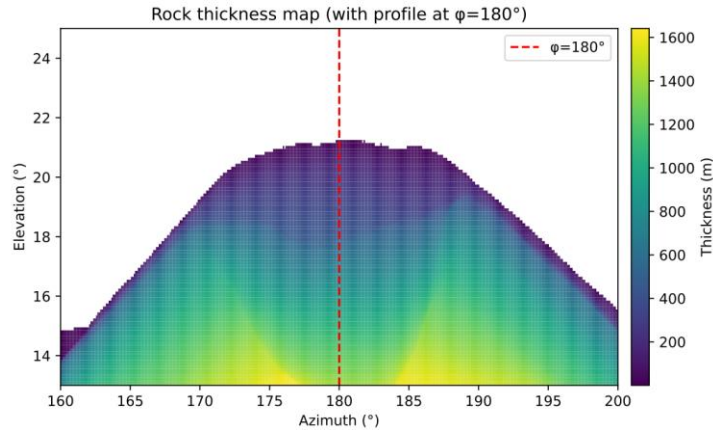
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- Multiple scattering + hard losses included
- Maximum realism — higher computational cost

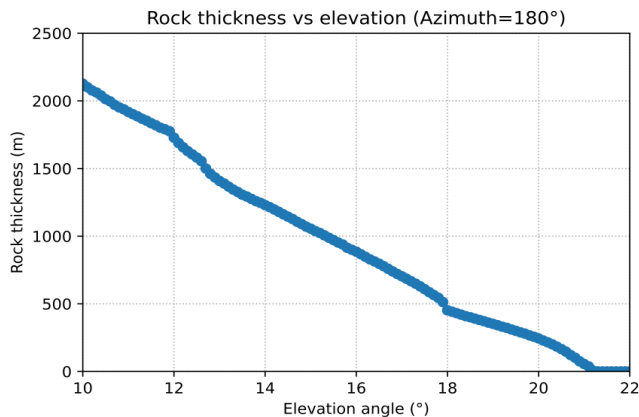
# Muon Flux – Mode Comparison

Credit: Yanwen Hong

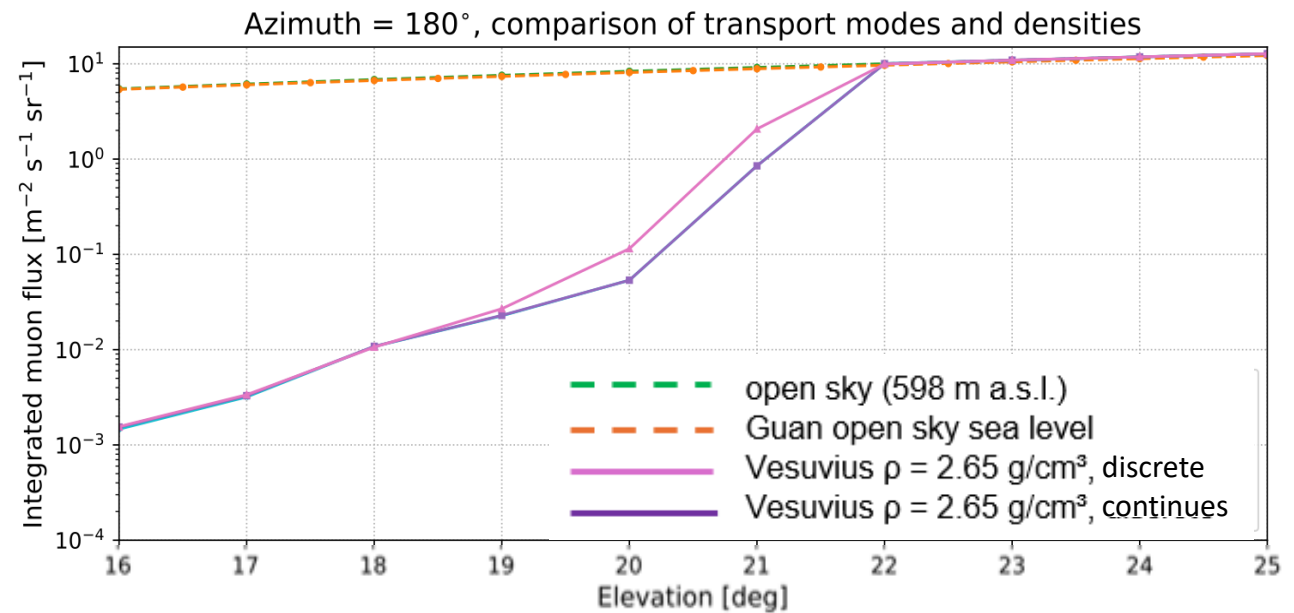
To determine which mode best, we compare muon flux along a slice at  $\varphi = 180^\circ$ .



Rock thickness map — red dashed line marks the  $\varphi = 180^\circ$  slice used for comparison.



Rock thickness vs elevation at  $\varphi = 180^\circ$  — input for the muon flux simulation.

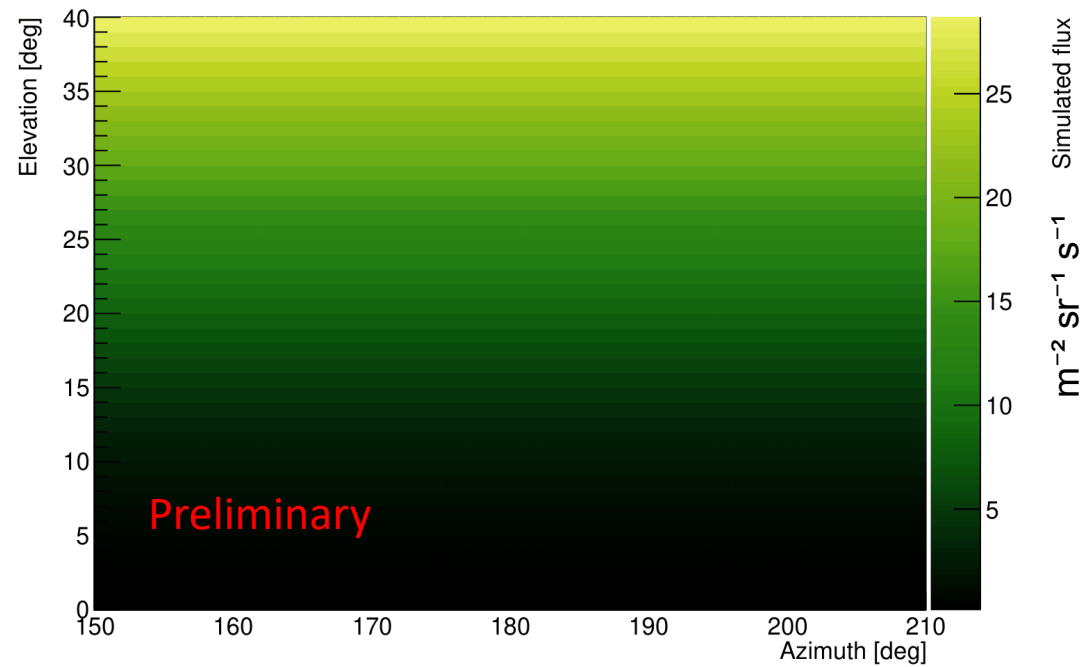


**Discrete mode** chosen for MURAVES simulation.

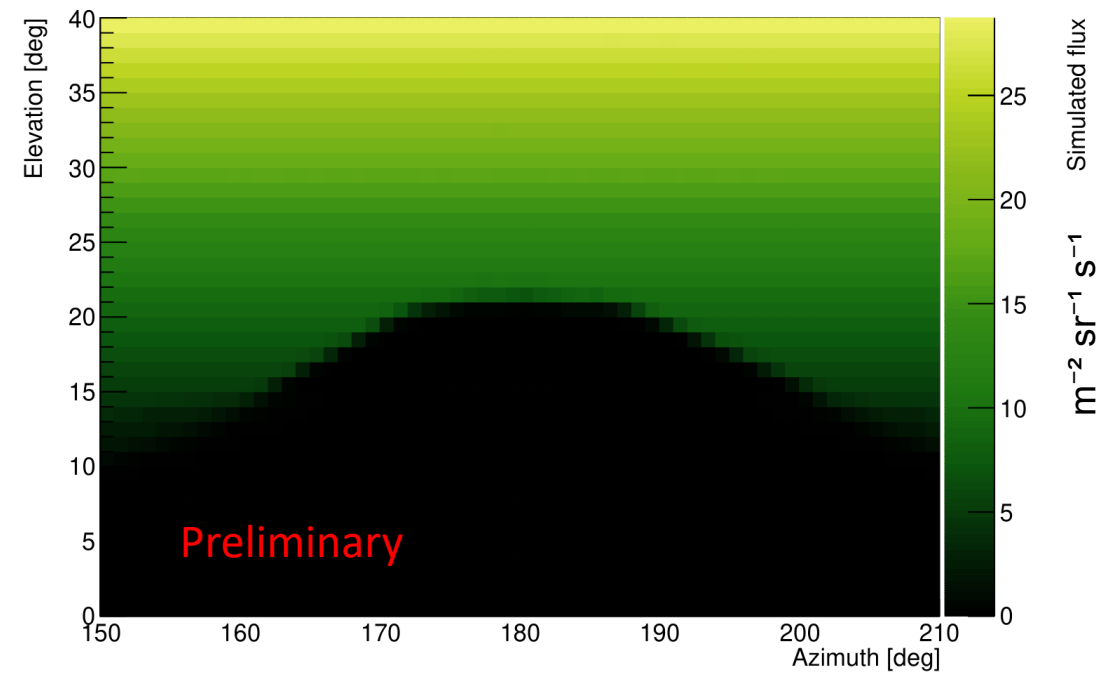
# Simulated Muon Flux

Credit: Yanwen Hong

## Free-sky muon flux



## Muon flux through Vesuvius

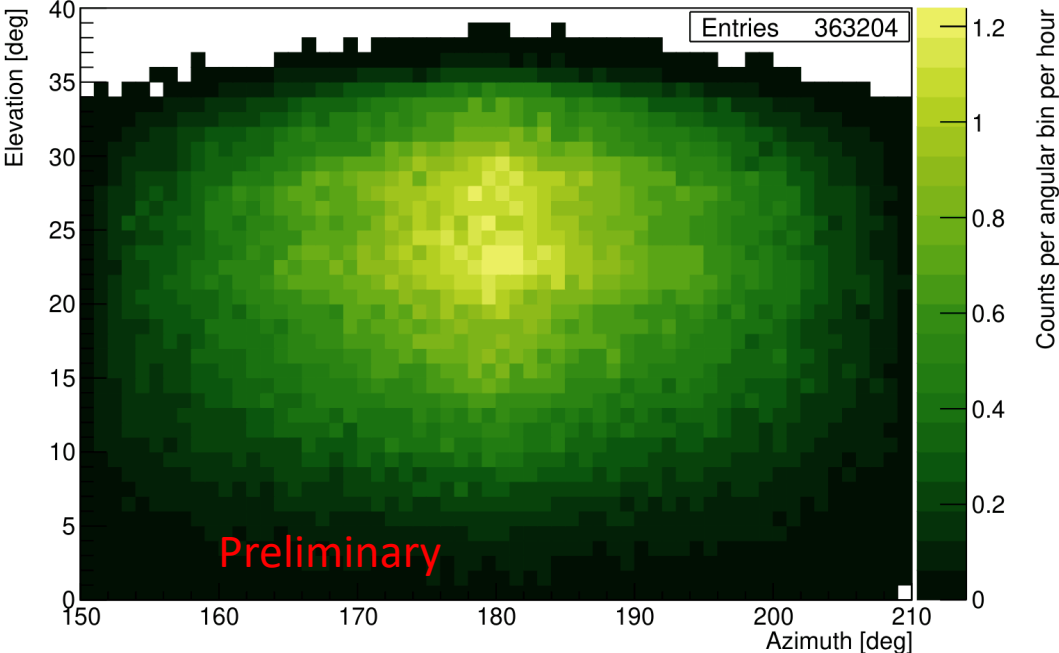


# Counts per hour per angular bin - Data

Credit: Yanwen Hong

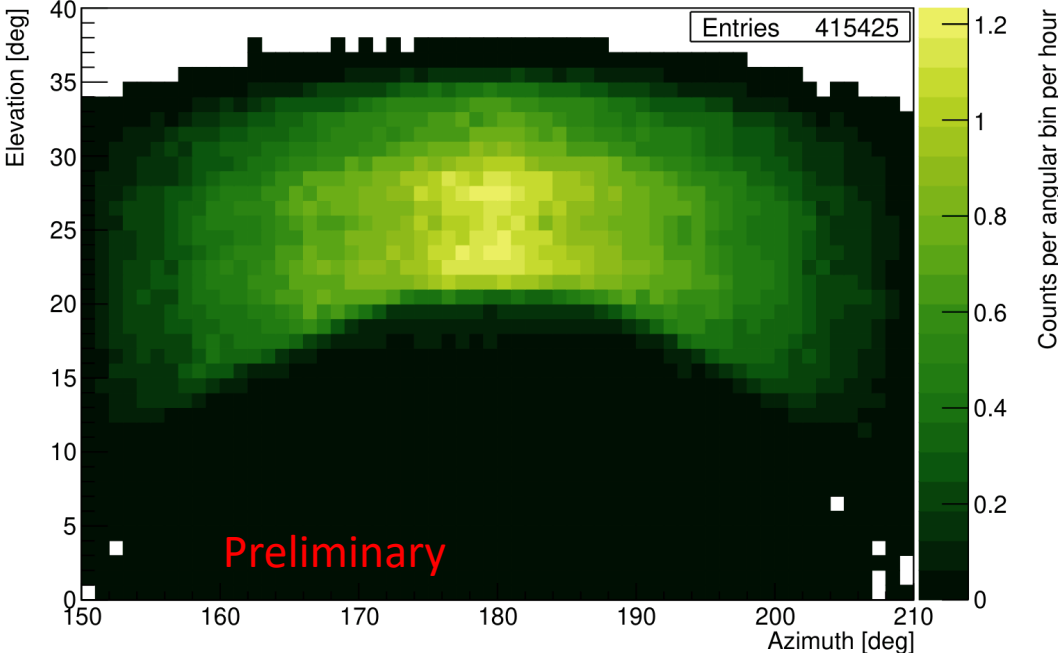
## Free-sky

NERO Freesky WP20



## Vesuvius

NERO Vesuvius WP20



Ref: talk by Alice Biolchini (Tuesday)

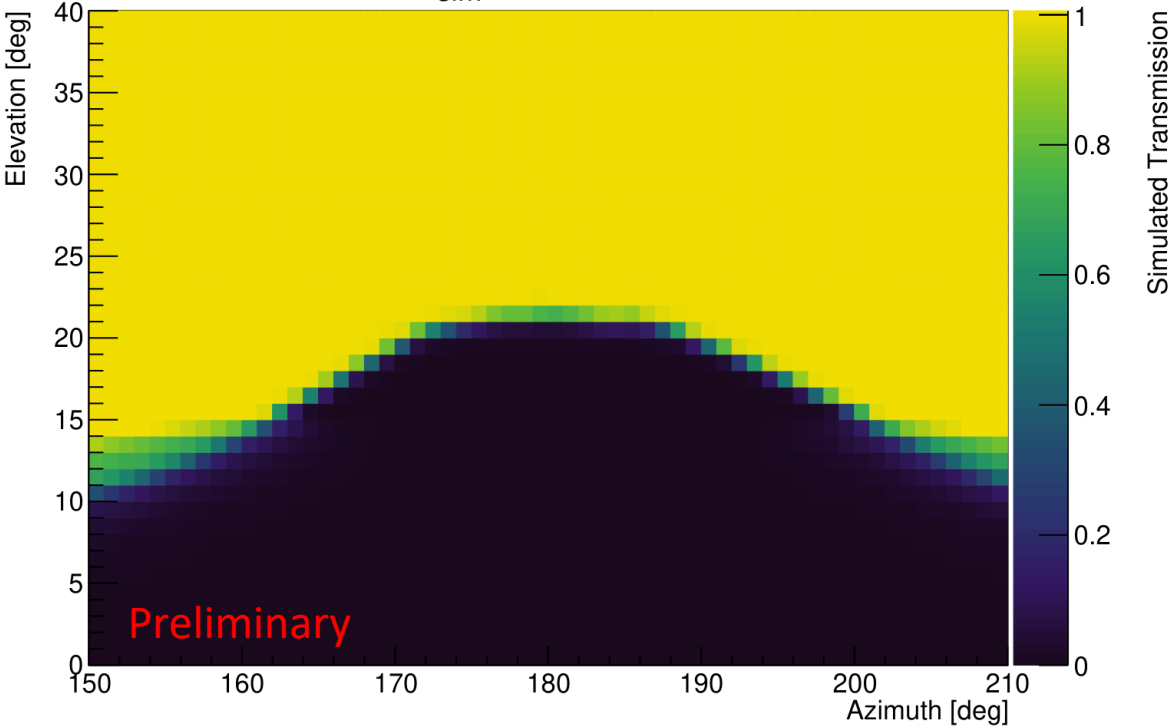
# Strategy for density measurement

Credit: Yanwen Hong

$$T_{\text{sim}} = \frac{\text{Simulated muon flux (Vesuvius)}}{\text{Simulated muon flux (freesky)}}$$

## Transmission Ratio – Simulation

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



# Strategy for density measurement

Credit: Yanwen Hong

$$N_{\mu}^{Ves}(\theta, \phi) = S_{eff} \cdot \varepsilon_{Det} \cdot \varepsilon_{tr} \cdot \varepsilon_{\chi^2}^{Ves} \cdot \Delta t^{Ves} \int_{E_{min}(\rho)}^{\infty} \Phi(\theta, \phi; E) dE + \delta N_{bkg}^{Ves}$$

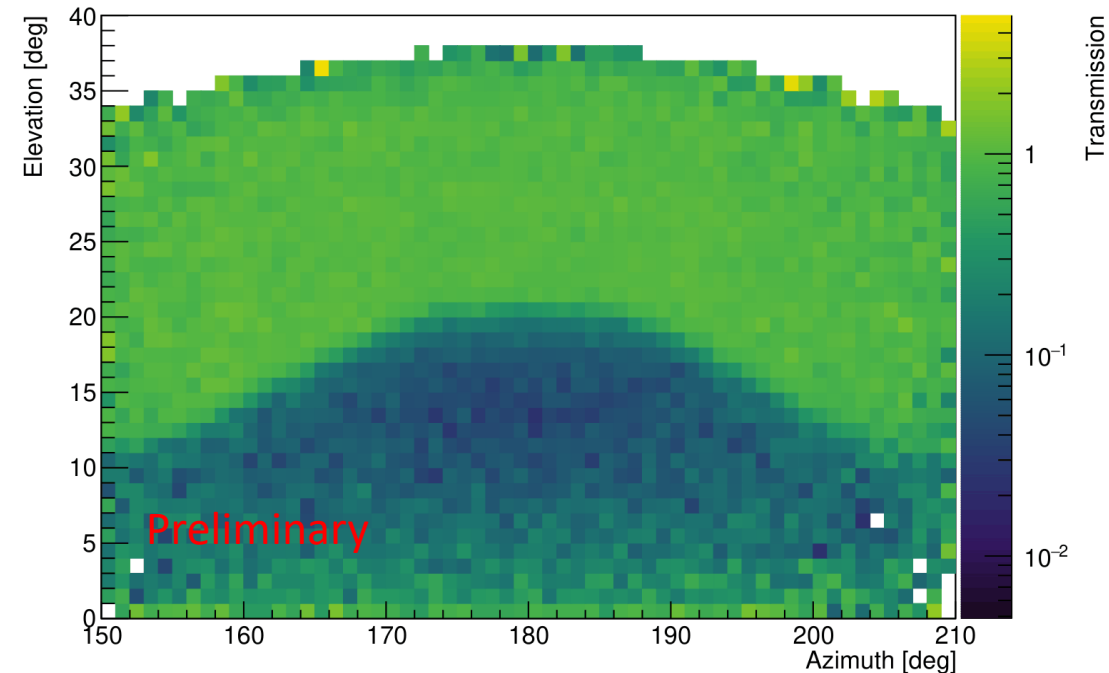
$$N_{\mu}^{FS}(\theta, \phi) = S_{eff} \cdot \varepsilon_{Det} \cdot \varepsilon_{tr} \cdot \varepsilon_{\chi^2}^{FS} \cdot \Delta t^{FS} \int_{E_0}^{\infty} \Phi(\theta, \phi; E) dE + \delta N_{bkg}^{FS}$$

Assumption : Noise is negligible

$$T_{data}(\theta, \phi) = \frac{N_{\mu}^{Ves} / \Delta t^{Ves}}{N_{\mu}^{FS} / \Delta t^{FS}} = \frac{\varepsilon_{\chi^2}^{Ves}}{\varepsilon_{\chi^2}^{FS}} \cdot \frac{\int_{E_{min}(\rho)}^{\infty} \Phi(\theta, \phi; E) dE}{\int_{E_0}^{\infty} \Phi(\theta, \phi; E) dE}$$
$$= C \cdot \frac{\int_{E_{min}(\rho)}^{\infty} \Phi(\theta, \phi; E) dE}{\int_{E_0}^{\infty} \Phi(\theta, \phi; E) dE}$$

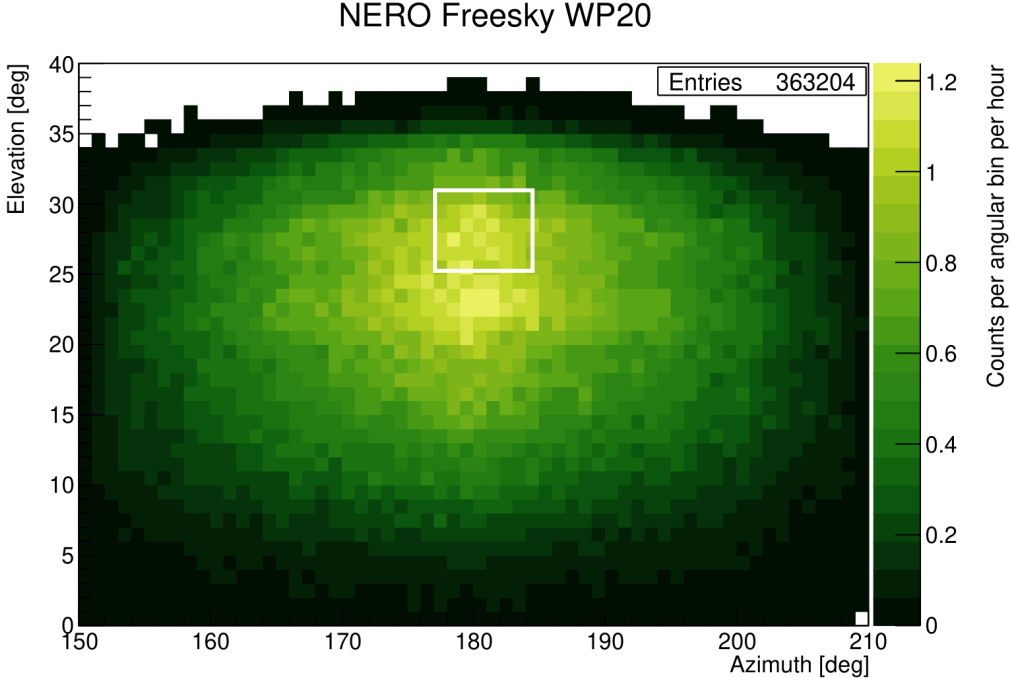
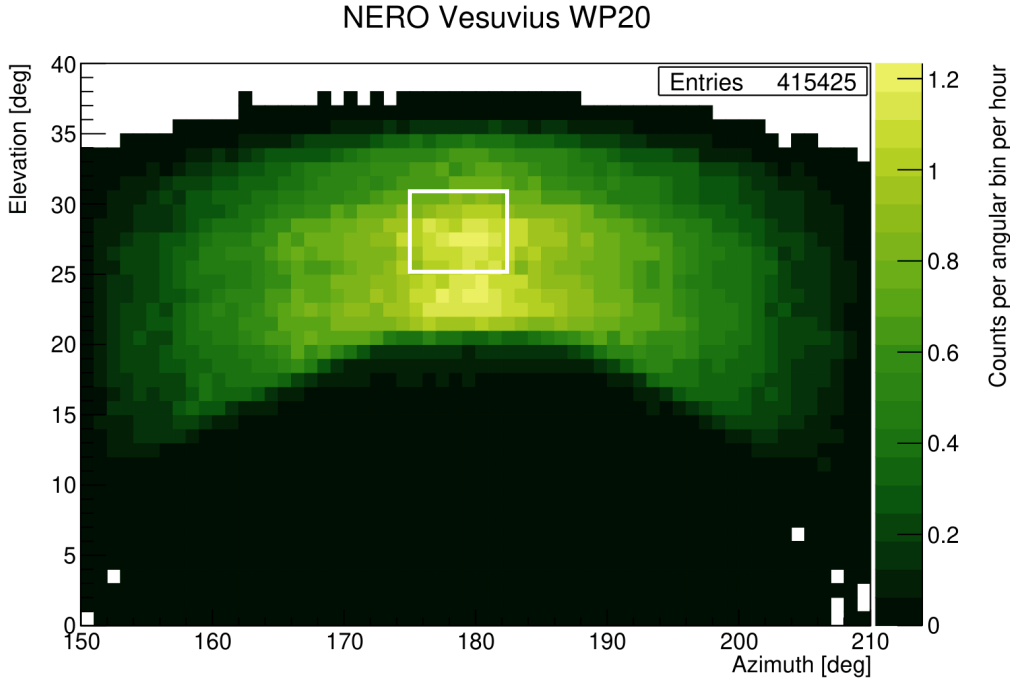
## Transmission Ratio – Data

NERO WP20 Transmission, selected tracks



# Strategy for density measurement

## Control Region:



# Strategy for density measurement

Choose  $\chi^2$  cuts in Vesuvius and free sky such that in control region  $(\theta_0, \phi_0)$ :

$$C = \frac{\varepsilon_{\chi^2}^{Ves}}{\varepsilon_{\chi^2}^{FS}}$$

$$\mathcal{D}(\phi, \theta; \rho) = \frac{\frac{N_{meas}^{Ves}/\Delta T_{Ves}}{N_{meas}^{FS}/\Delta T_{FS}}}{\frac{I_{sim}^{Ves}}{I_{sim}^{FS}}} = \frac{T_{data}(\phi, \theta)}{T_{sim}(\phi, \theta; \rho)}$$

$\mathcal{D} = 1 \rightarrow \rho$  correct

$\mathcal{D} > 1 \rightarrow$  density lower than  $\rho$

$\mathcal{D} < 1 \rightarrow$  density higher than  $\rho$

# Summary & Outlook

## Summary

- **Expected integrated muon flux** at the MURAVES location obtained from Mulder simulations using discrete mode
- **Simulated transmission maps** computed for  $\rho = 2.65 \text{ g/cm}^3$
- **Double ratio strategy established:**  $D = T^{\text{meas}} / T^{\text{sim}}$  to directly translate measured transmission into average density

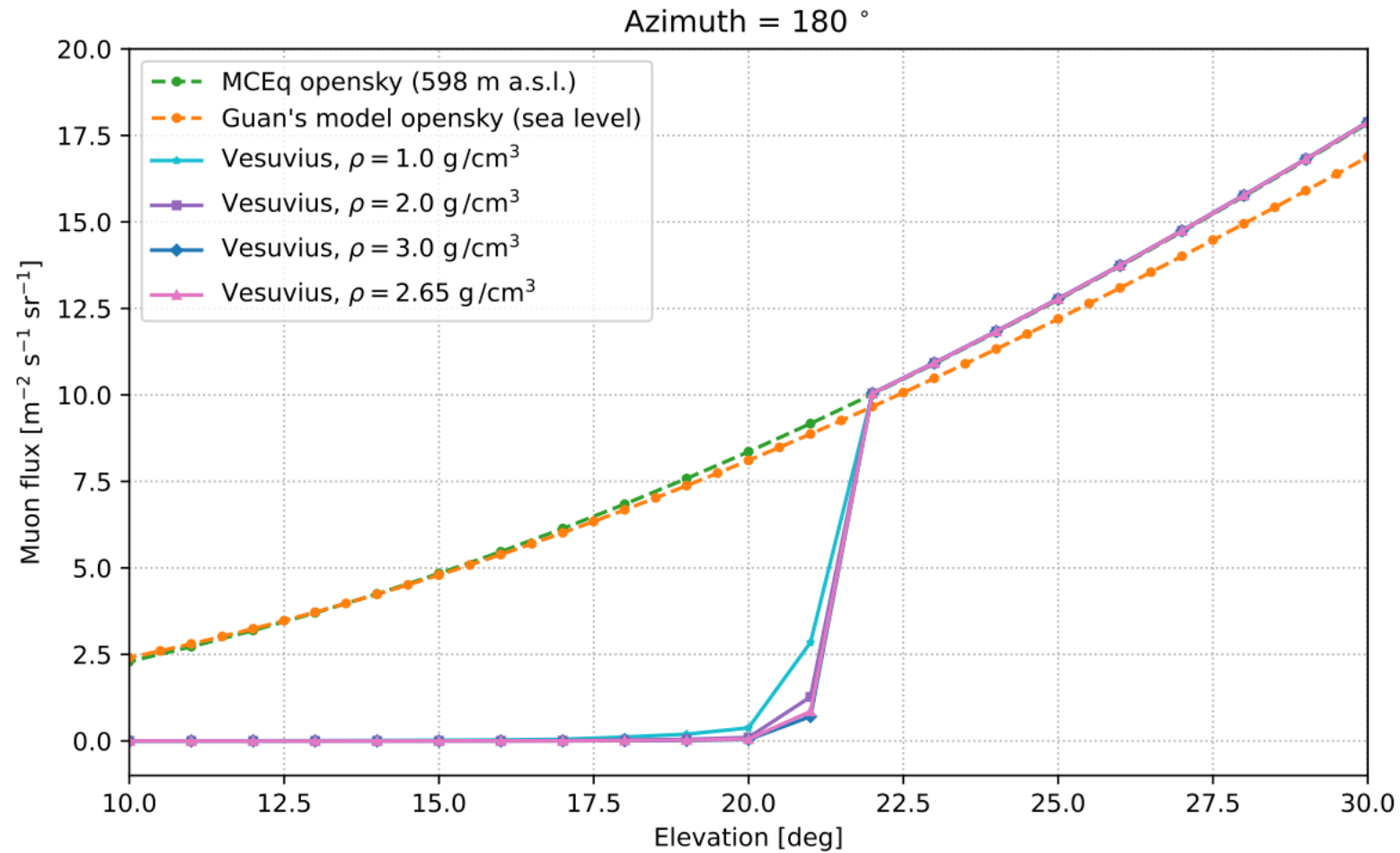
## Outlook

- **Geant4 detector simulation ongoing** — cosmic muon generation using EcoMug as input
- **Digitization in progress** — energy deposited by muons in simulation compared to number of photoelectrons in data using an effective cut
- **Data reconstruction update in progress** (ref: A. Biolchini, this conference)



**Thank you for your attention.**

# Muon Flux – Rock Thickness Comparison



# $\chi^2$ Selection Procedure

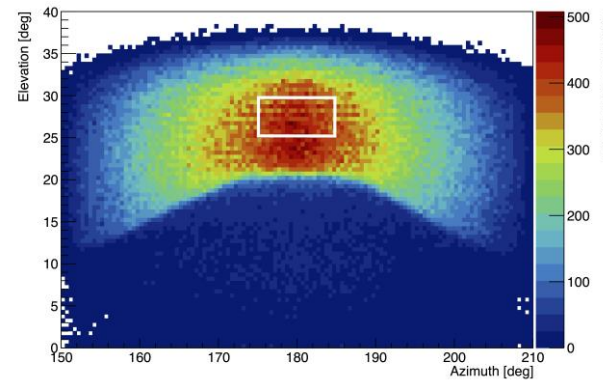
Control Region:  $\phi \in [175^\circ, 185^\circ]$  and  $\theta \in [25^\circ, 30^\circ]$ .

$$R(\chi_{Ves,cut}^2, \chi_{FS,cut}^2) = \frac{N_{Ves}(\chi_{Ves}^2 \leq \chi_{Ves,cut}^2)}{N_{FS}(\chi_{FS}^2 \leq \chi_{FS,cut}^2)}$$

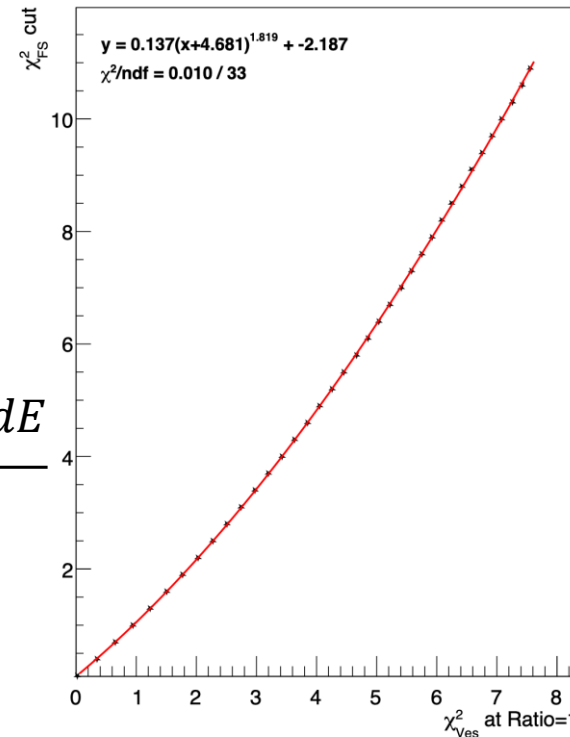
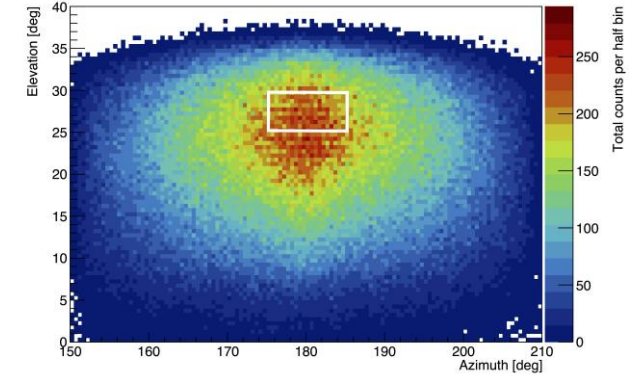
1. Fit the curves with exponential saturation model, find the pair value of

$Pair(\chi_{Ves,cut}^2, \chi_{FS,cut}^2)$  when  $R = 1$ .

$$T_{data}(\theta, \phi) = \frac{N_{\mu}^{Ves} / \Delta t^{Ves}}{N_{\mu}^{FS} / \Delta t^{FS}} = \frac{\varepsilon_{\chi^2}^{Ves}}{\varepsilon_{\chi^2}^{FS}} \cdot \frac{\int_{E_{min}(\rho)}^{\infty} \Phi(\theta, \phi; E) dE}{\int_{E_0}^{\infty} \Phi(\theta, \phi; E) dE}$$

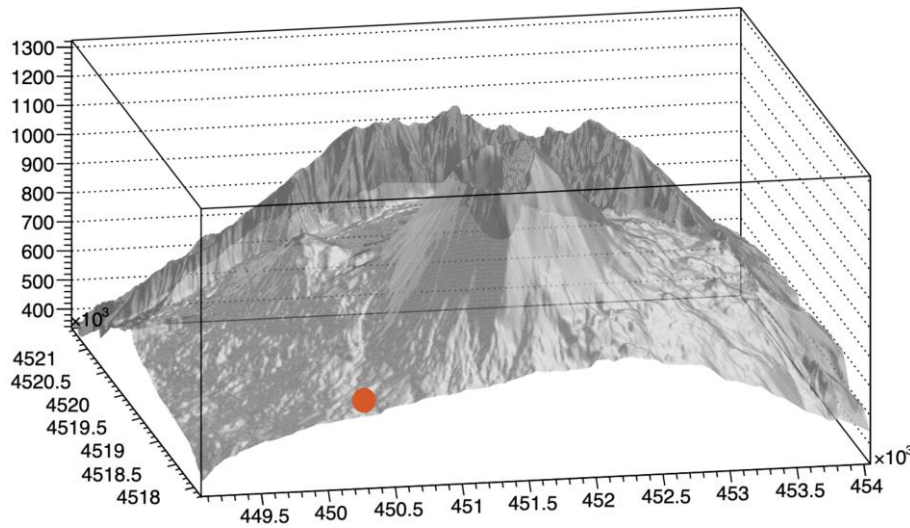


NERO WP20



# Five-meter DEM file

- Node x, node y = 1624, 1508
  - x range: 447,587.1875      455,702.1875      dx = 5.0
  - y range: 4,515,389.0      4,522,924.0      dy = 5.0
  - z range: 71.0      1274.0 m
- MURAVES detector: 450,382      4,517,860**



Rock Thickness Map seen from MURAVES Experiment

