Status and first results of the Muon Radiography of Vesuvius (MURAVES) campaign

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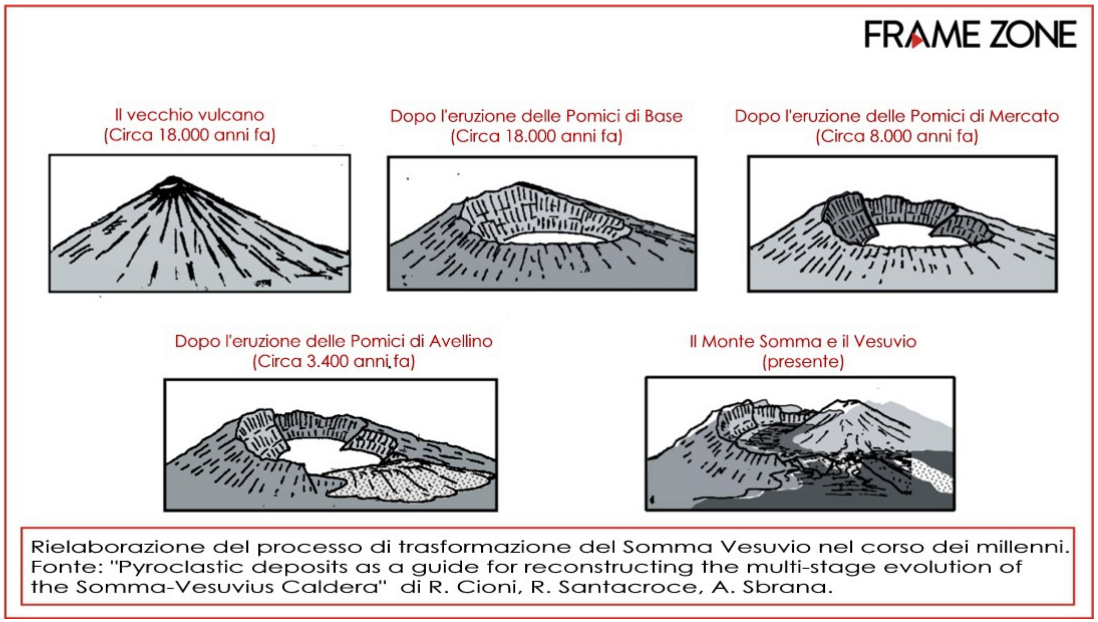
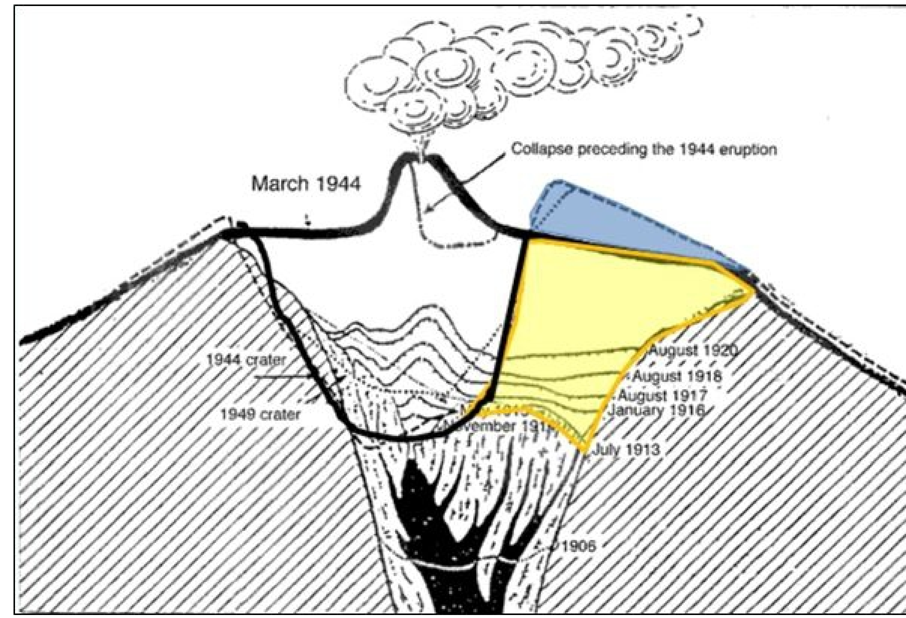
Mount Vesuvius

Vesuvius seen from Pompeii's
ruins (from wikipedia)

- Understanding its composition is very important for volcanology and civil protection
- One the most dangerous volcanoes in the world
  - Famous for the eruption that buried Pompeii and Herculaneum in 79 C.E.
  - >0.5 M residents in its surrounding *Red Zone*, defined as being at high risk of pyroclastic fallout in case of a new Sub-Plinian eruption

A complex history

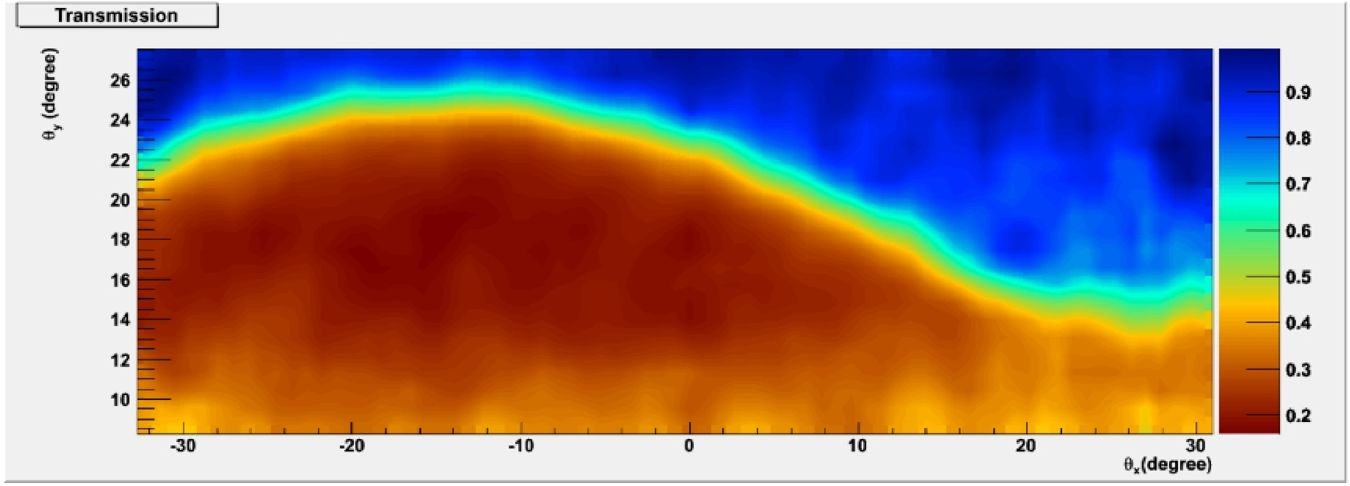




Picture source: www.framezone.it

Latest major structural modification during the eruption of 1944

Pilot study in 2014: MU-RAY project



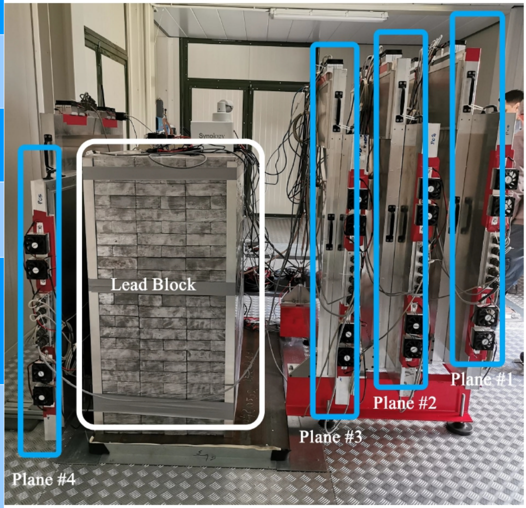
One week of data; from:
F. Ambrosino, et al.,
JINST, 9 (2014), p. C02029

From MU-RAY to MURAVES

MU-RAY

	MU-RAY	MURAVES
Telescopes	1	3
X-Y layers	3	4
Length	~1 m	~2 m
Area of a layer	1 m^2	1 m^2
Scintillating bars / layer	64	64
Passive bkg rejection	3 cm steel plate	Lead wall (60 cm thick)
Momentum cut-off	70 MeV	~1 GeV

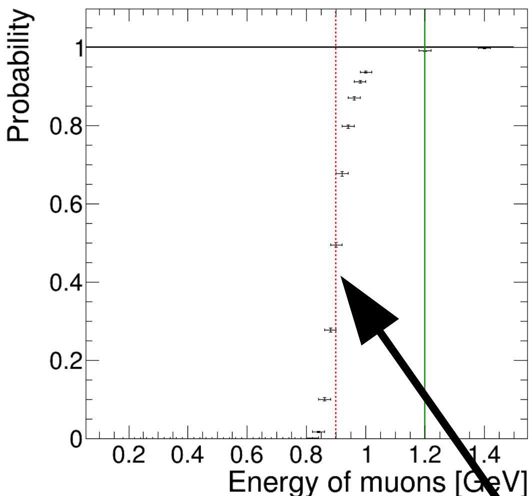
MURAVES

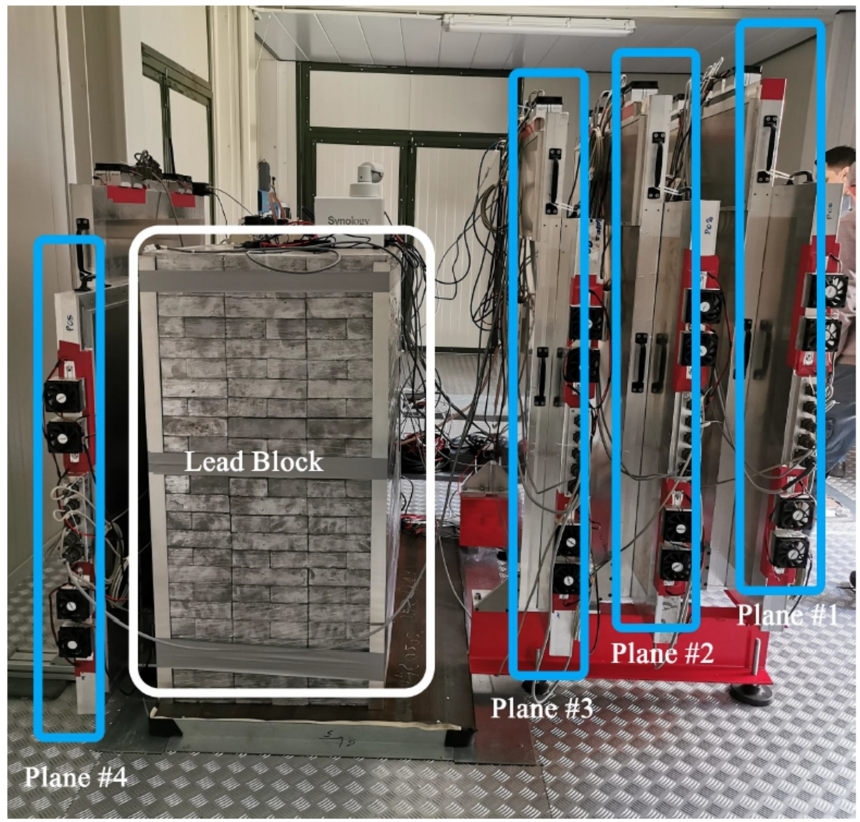


The MURAVES collaboration

- Naples (Università Federico II and INFN)
  - F. Ambrosino, L. Cimmino, M. D'Errico, V. Masone, G. Passeggio, G. Saracino, P. Strolin
- Florence (Università di Firenze and INFN)
  - L. Bonechi, M. Bongi, R. Ciaranfi, C. Ciulli, R. D'Alessandro, S. Gonzi, N. Mori, L. Viliani
- Fermilab
  - A. Bross, A. Pla-Dalman
- INGV (Osservatorio Vesuviano)
  - A. Caputo, F. Giudicepietro, G. Macedonio, M. Orazi, R. Peluso, G. Scarpato, E. Vertechi
- UCLouvain
  - S. Basnet, A. Giammanco, S. Ikram, R. Karnam, M. Moussawi
- Universiteit Gent
  - Y. Hong, C. Rendon, A. Samalan, M. Tytgat (also at VUB)

MURAVES telescope

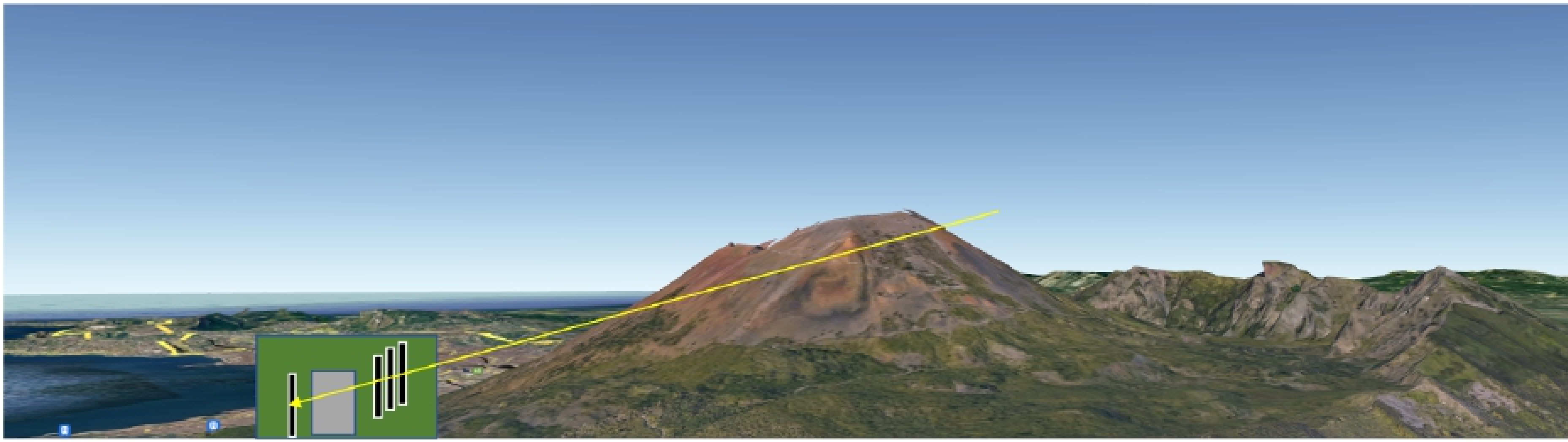




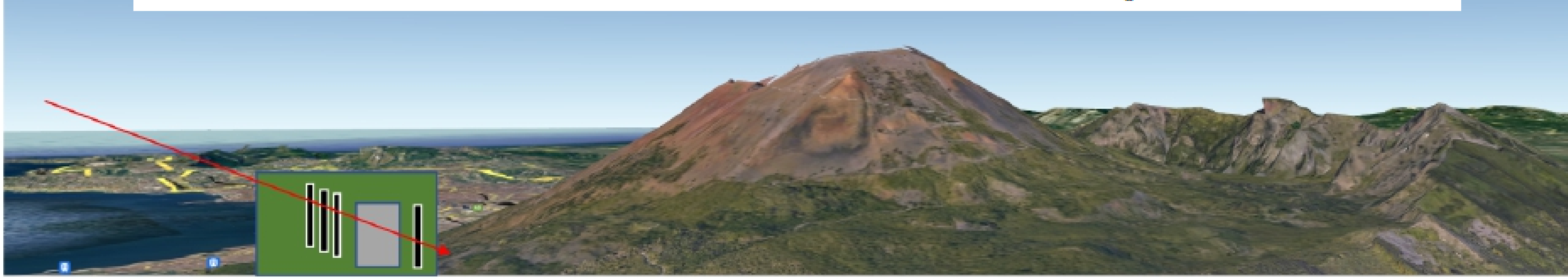
Picture by S.Wuyckens, July 2019

- 3 telescopes, each with 4 x-y layers of scintillating bars with triangular section, coupled to SiPM
- Lead wall, 60 cm thick (recycled from OPERA ν experiment), corresponding to a ~1 GeV cut-off
- Trigger logic: AND of all x and y layers of the 3 stations before lead; for each layer, OR of all 64 channels

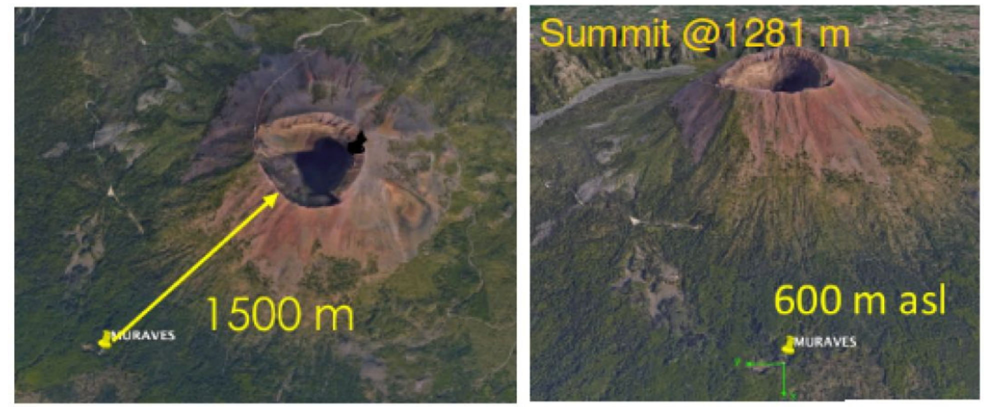
Measurement strategy



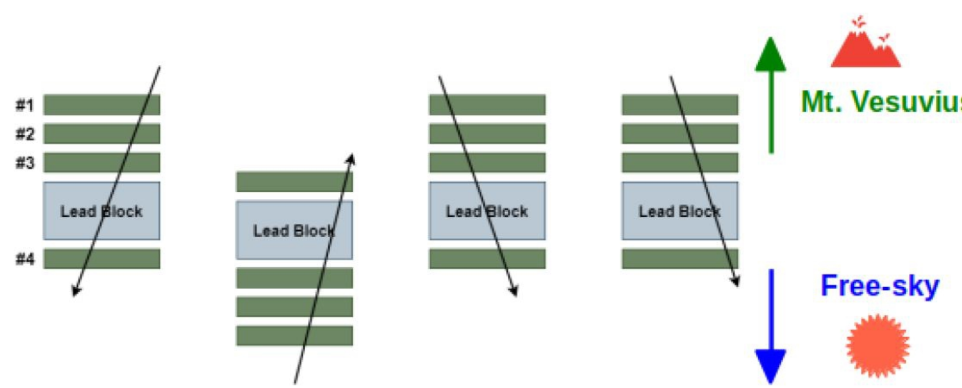
$$T(\theta,\phi) = \frac{N_\mu^{v}(\theta,\phi)/\Delta t^{v}}{N_\mu^{fs}(\theta,\phi)/\Delta t^{fs}} = \frac{\epsilon^{v}\cdot S_{eff}(\theta,\phi)\int_{E_{min(\rho)}}^{\infty}\Phi(\theta,\phi;E)dE}{\epsilon^{fs}\cdot S_{eff}(\theta,\phi)\int_{E_0}^{\infty}\Phi(\theta,\phi;E)dE}$$



MURAVES installation

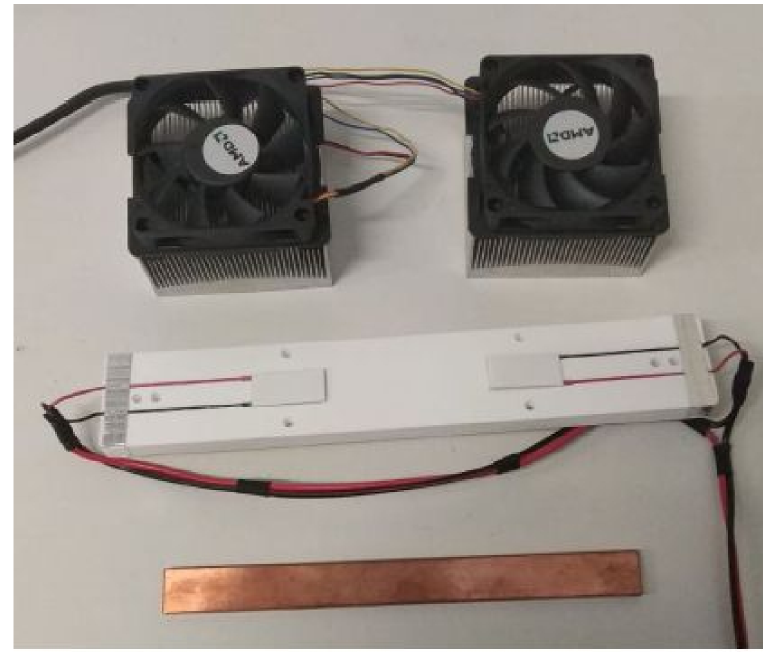


Four lead walls at fixed positions; the telescopes alternate in occupying the free-sky position, such that detector systematics cancel out ($\varepsilon^{v} \sim \varepsilon^{fs}$)



Temperature control

- SiPM gain has a strong dependence on ambient temperature (T)
- Custom designed T control system based on thermoelectric cooling
- Keep constant SiPM overvoltage by adjusting bias voltage as function of T; two main working points: 15º & 20º



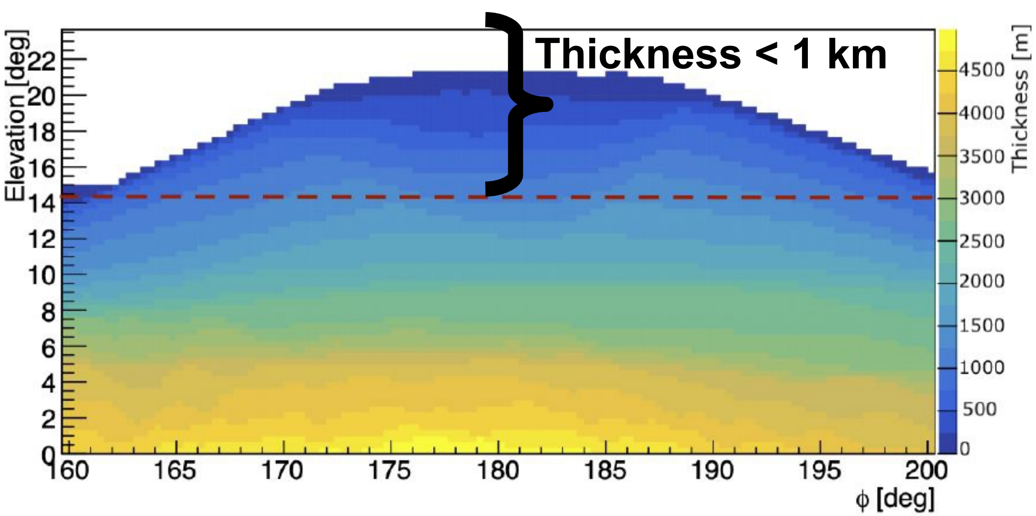
- Two Peltier cells every 32 SiPMs
- From bottom to top:
  - Copper strip for thermal conduction
  - Peltier cells
  - Fans for heat dissipation

Prospects for resolution vs time

Δy	Δx	$\bar{L}$ = 500 m	$\bar{L}$ = 1000 m	$\bar{L}$ = 3000 m
9 m	9 m	8 months	3 years	100 years
9 m	26 m	3 months	1 year	33 years
9 m	130 m	15 days	2.5 months	6 years
26 m	130 m	5 days	1 month	2 years
52 m	260 m	2 days	6 days	16 months

Table 1: Exposure times expected to be required to measure the mean density with a 10 % statistical uncertainty for a set of values of the muon path length in the rock and of horizontal and vertical space resolutions Δx and Δy.

Elevation (deg)	Mean Thickness (m)
20-21	90
19-20	290
18-19	490
17-18	720
16-17	920
15-16	1100
10-15	1500
5-10	2700
0-5	4050



First data

- The three telescopes (**NERO**, ROSSO and BLU) have been deployed between Fall 2019 and Summer 2020
- Earliest fully-validated and well-understood datasets from **NERO** and ROSSO, at two T working points:

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

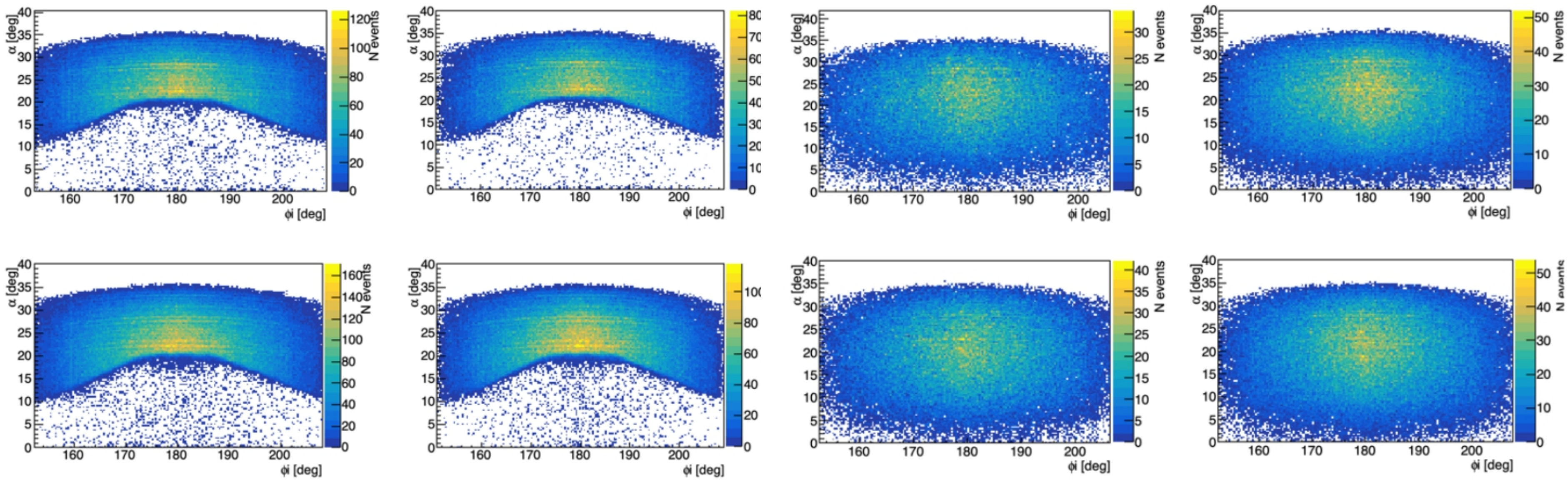
Given that Φ(free sky) >> Φ (Vesuvius), even short free-sky runs give very large statistics ; uncertainty in the trasmission map $T(\theta,\phi)$ is dominated by stat. uncertainty in the numerator (Vesuvius)

First data

Vesuvius: **Free sky:**

NERO

ROSSO

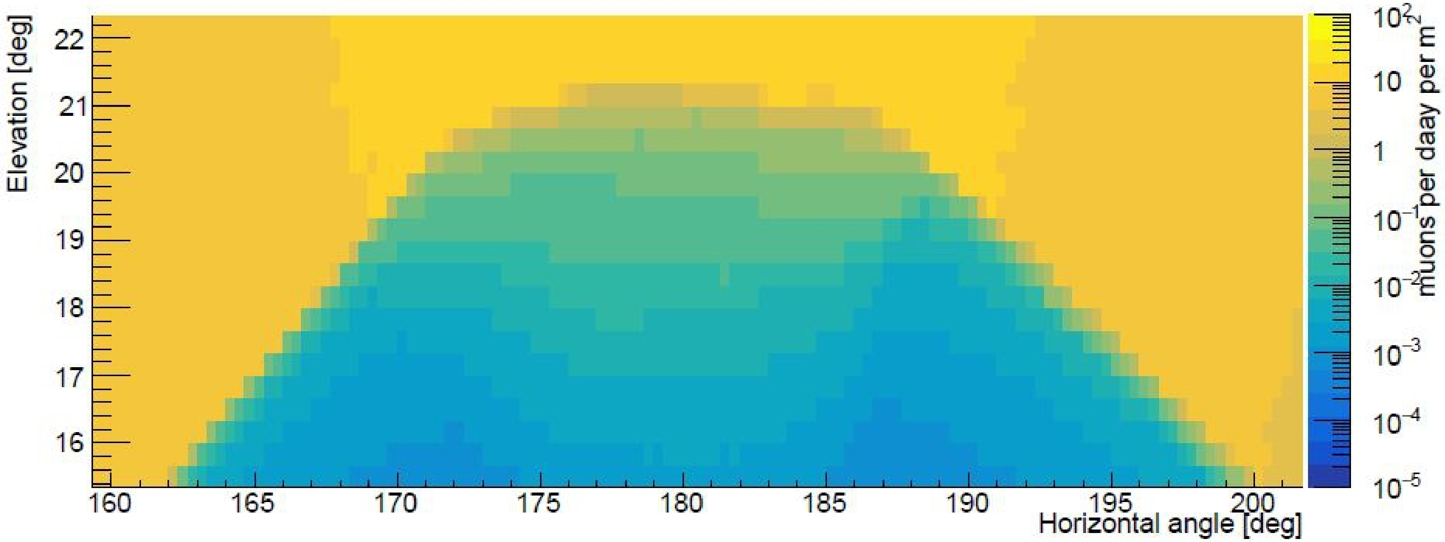


WP 15° **WP 20°** **WP 15°** **WP 20°**

Dataset	maximum χ^2
ROSSO wp 15°C	5
ROSSO wp 20° C	4.4
NERO wp 15°C	5.1
NERO wp 20°C	5.1

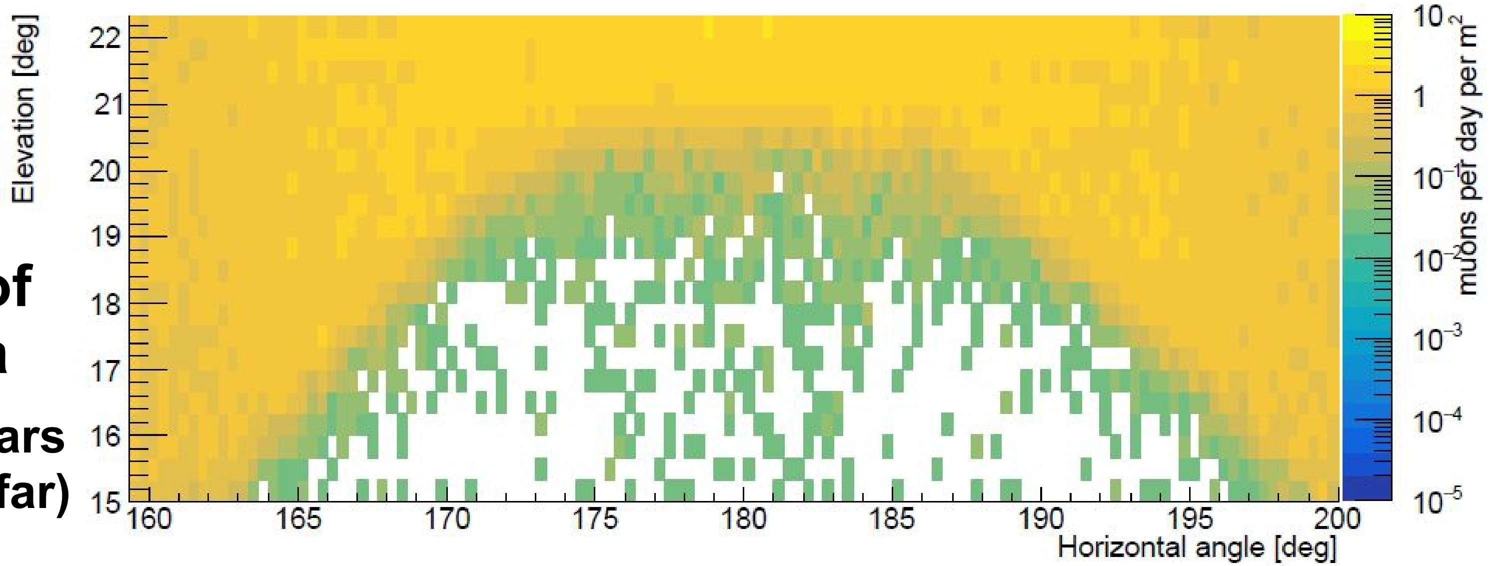
First transmission map from MURAVES

Simulation (PUMAS)



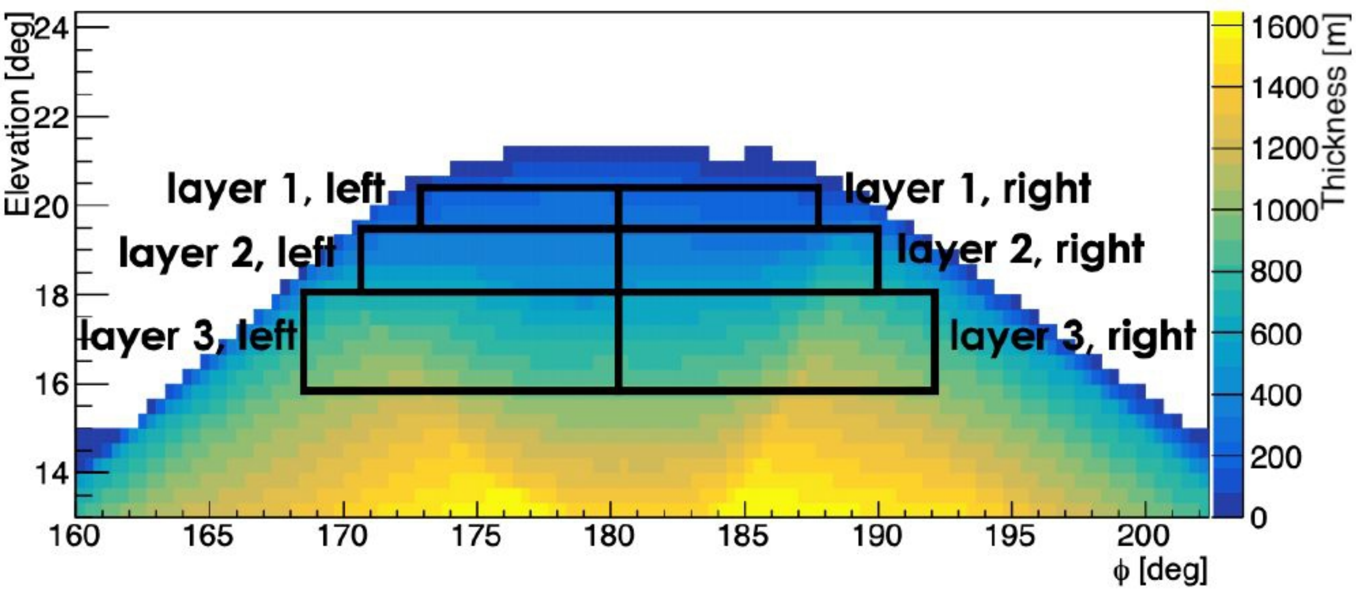
51 days of real data

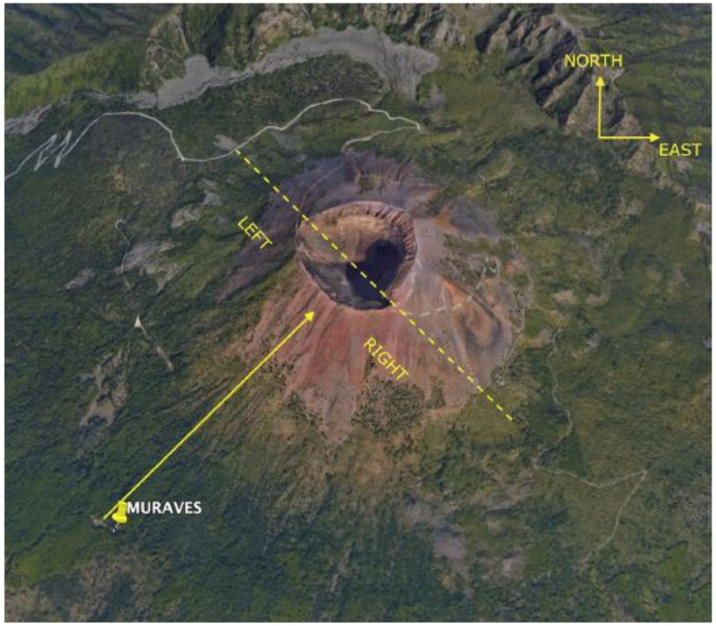
(out of ~3 years recorded so far)



Right/left density asymmetry

- Even with such small statistics, we can do a first measurement of actual interest for volcanologists
- Focusing on the summit (< 1 km thickness)
- Most modeling uncertainties cancel out in the ratio



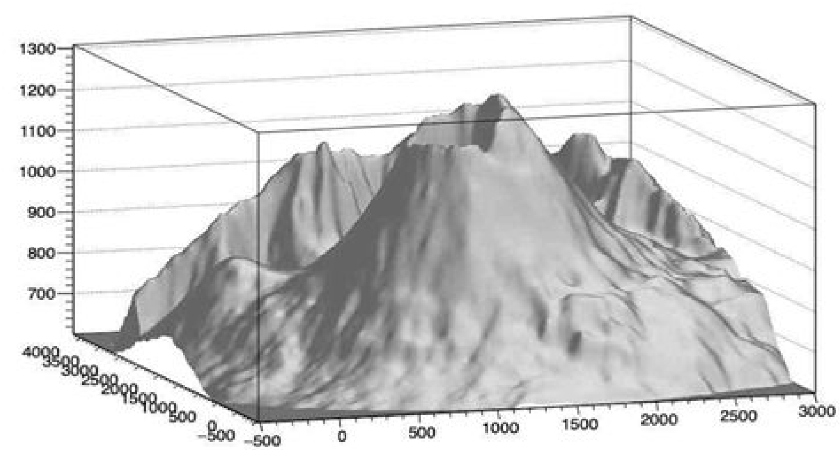


Results (raw)

	N events		Stat. unc. (%)	
Dataset	left	right	left	right
Layer 1				
ROSSO wp 15°C	428	439	0.05	0.05
ROSSO wp 20°C	346	323	0.05	0.05
NERO wp 15°C	231	258	0.05	0.05
NERO wp 20°C	128	258	0.07	0.06
Layer 2				
ROSSO wp 15°C	164	140	0.08	0.08
ROSSO wp 20°C	106	109	0.10	0.10
NERO wp 15°C	78	79	0.11	0.11
NERO wp 20°C	61	63	0.13	0.13
Layer 3				
ROSSO wp 15°C	61	76	0.12	0.11
ROSSO wp 20°C	58	63	0.13	0.13
NERO wp 15°C	47	47	0.14	0.15
NERO wp 20°C	27	30	0.19	0.18

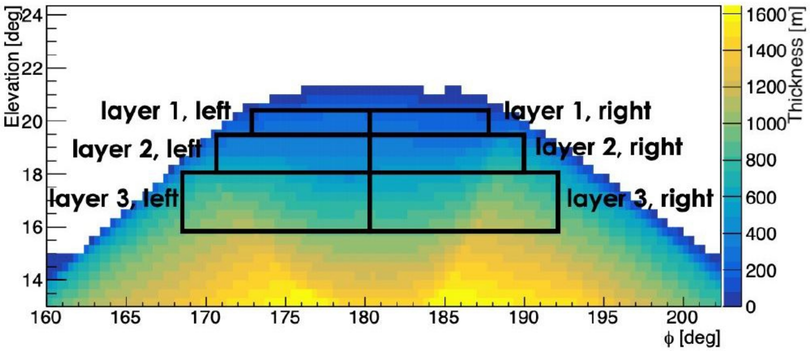
These raw numbers are then normalized by ***run duration*** and by ***thickness of rock*** traversed.

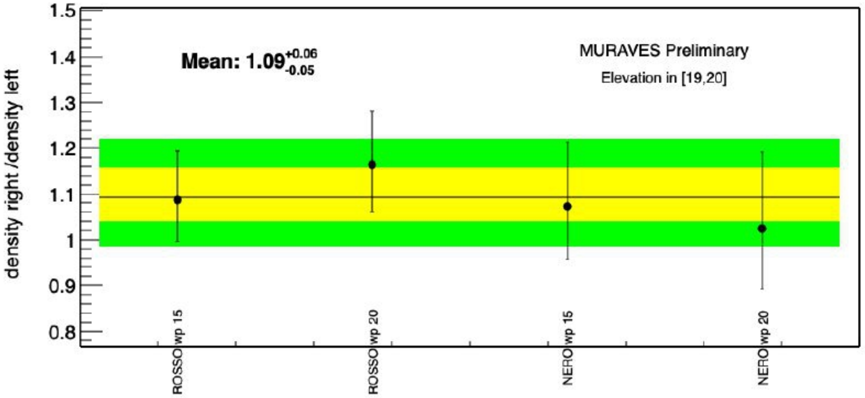
For the latter, we used a Digital Terrain Model provided by INGV (data from Vilardo et al., Journal of maps, 9(4):635–640, 2013)

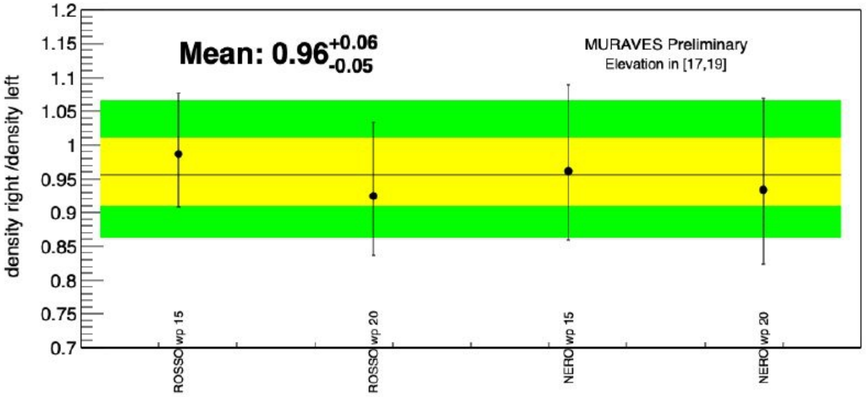


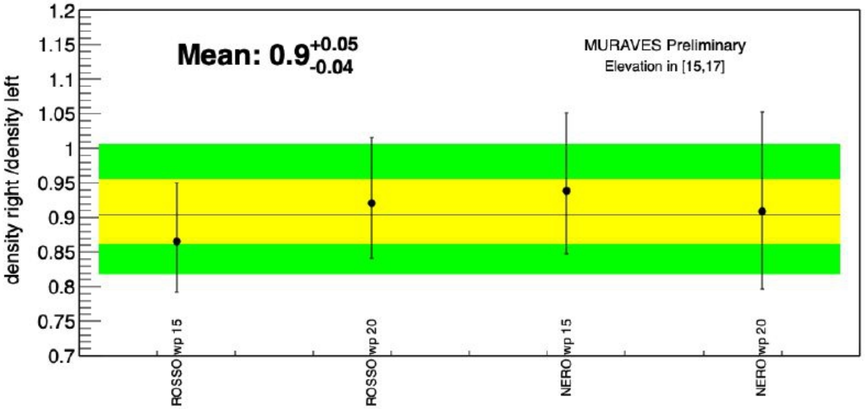
Right/left density asymmetry results

- These four independent samples agree within 1σ
- We combine them under assumption of statistical independence
- Indication (1.5σ) of density larger on the right than on the left at high quota
- But relationship inverts at lower quota



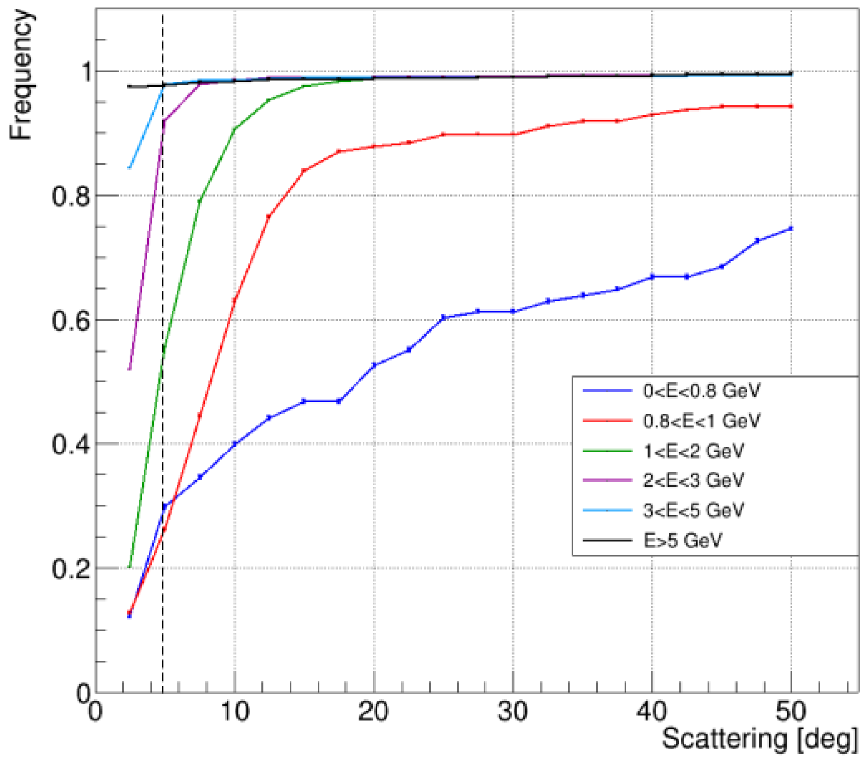






Future perspectives

- Analysis of three years of data with all three detectors is ongoing
- Thorough estimation of the detector systematics (particularly important for absolute ρ measurement)
- Estimation of modeling systematics via Monte Carlo (see Yanwen Hong's talk): muon spectrum, time dependent effects, passage through rock, etc.
- Improvements in μ selection and fitting
- Introduction of new cuts to reduce the low-momentum component (e.g. scattering, time-of-flight); optimization based on achievable resolution



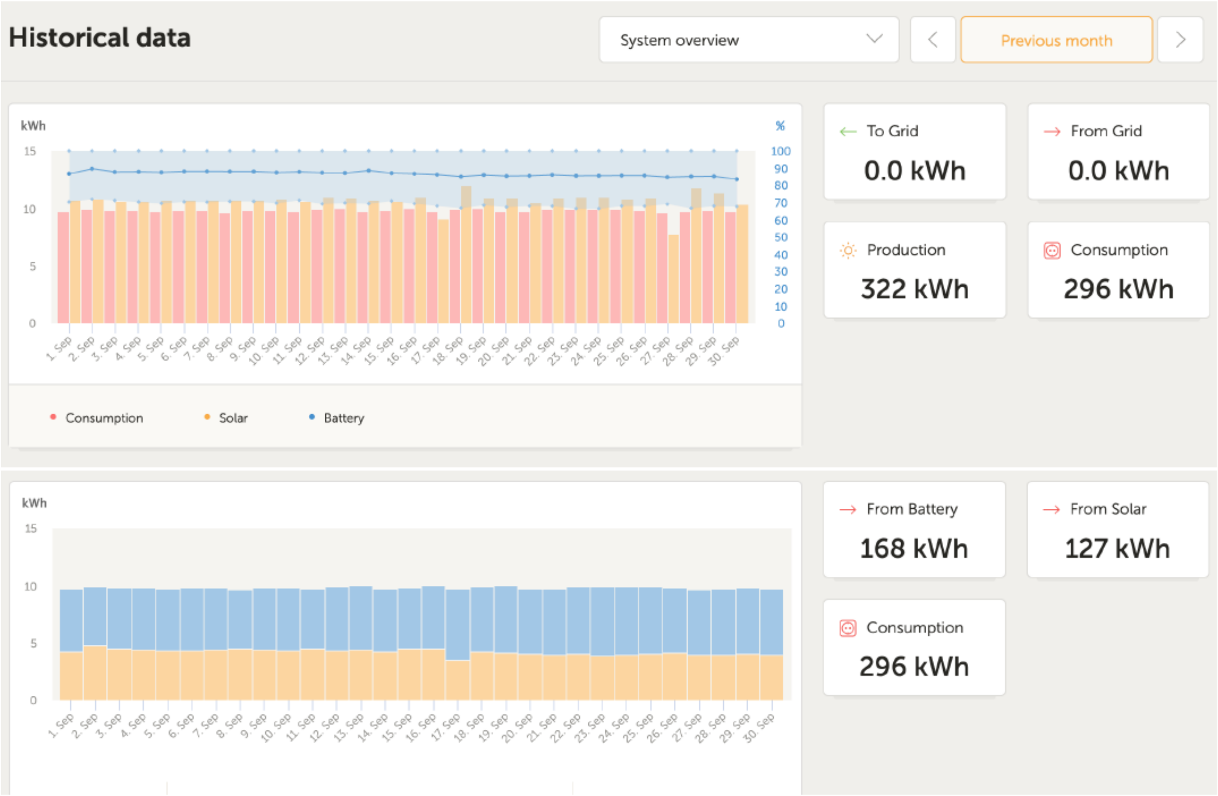
Upper cut on angle of scattering within the lead wall, as a way to select ballistic muons and improve angular resolution

Summary

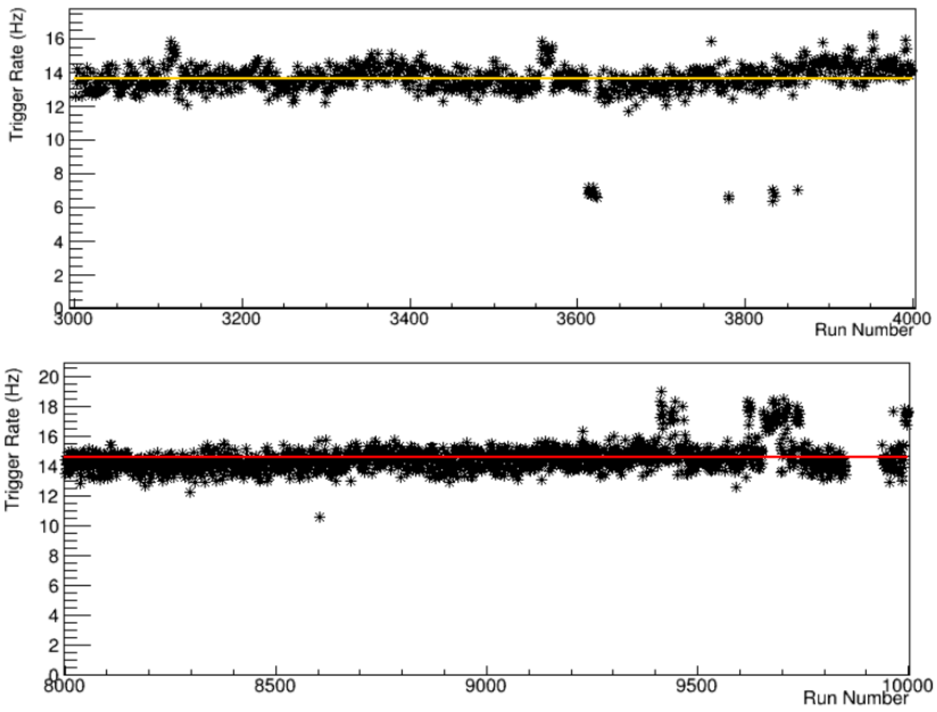
- MURAVES is currently taking data smoothly
- Very early data, based on only two detectors, have been thoroughly validated and used for :
  - First rough transmission map (ratio to free sky)
  - Right/left density asymmetry
- Three years of data already on disk, with all three detectors
- Systematics will soon be the limit; but we have several ideas to estimate and reduce them

Thanks for your attention!

Power consumption

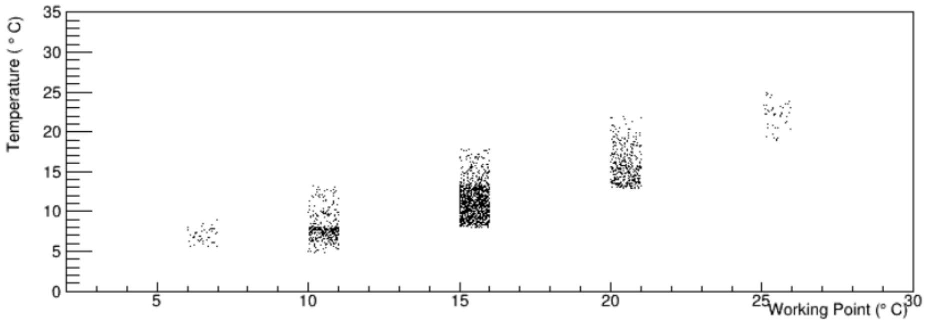


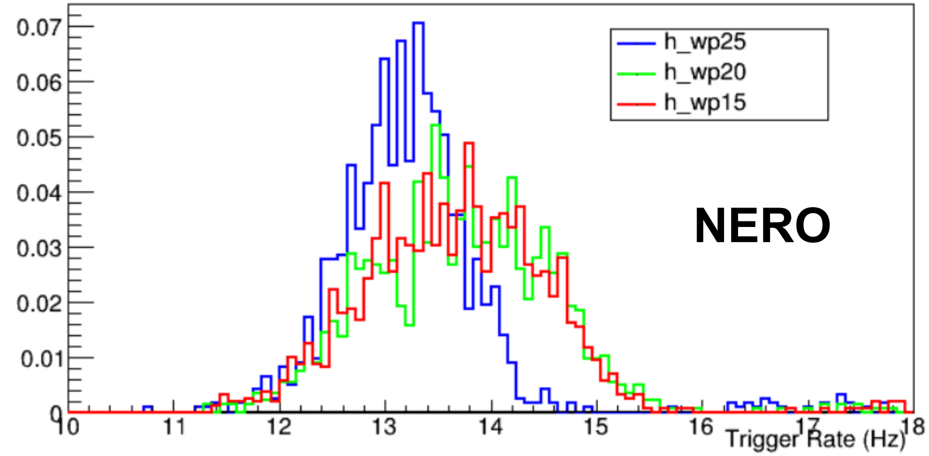
Rate stability

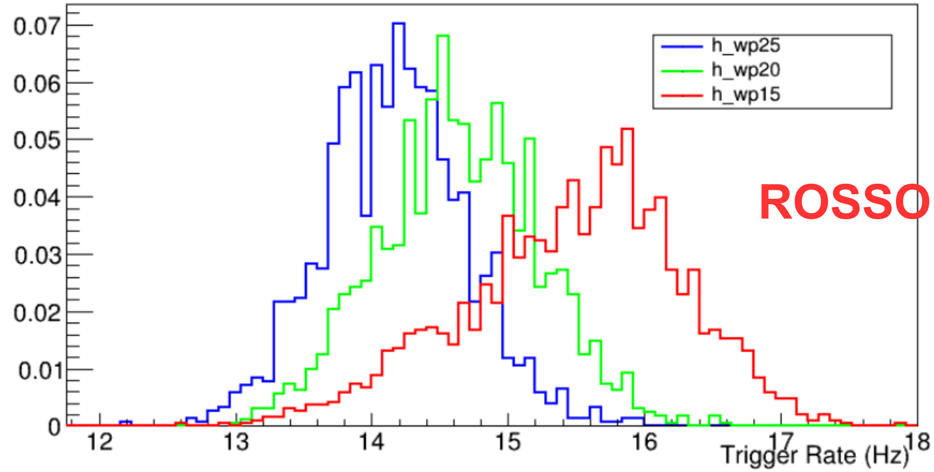


Trigger rate vs run number for NERO (top) and ROSSO (bottom)

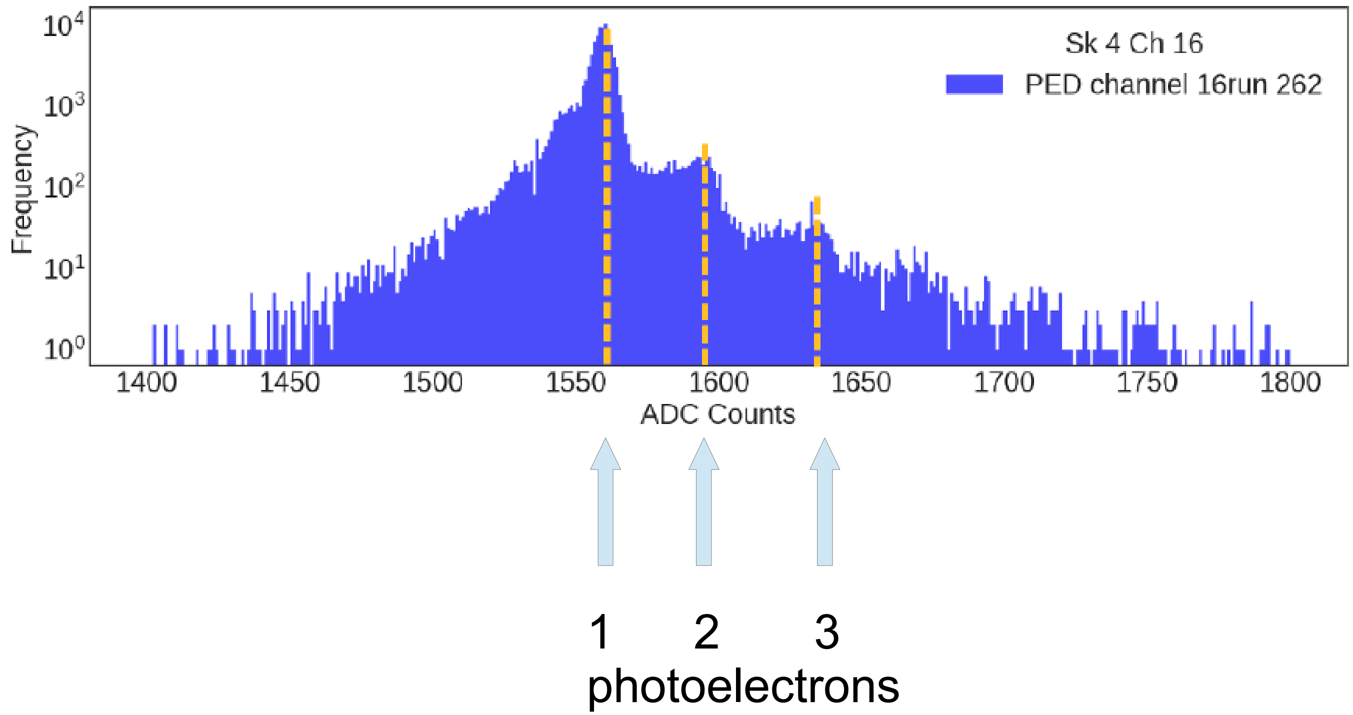
Temperature working points







Signal distribution

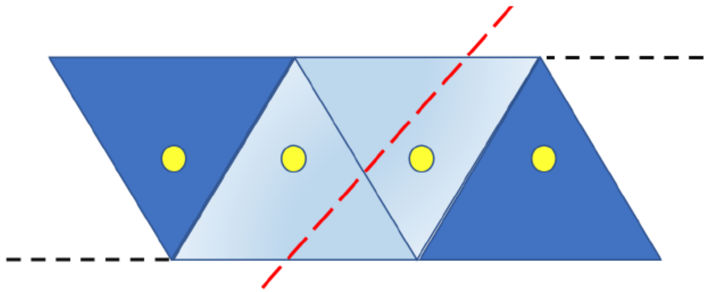


Conversion ADC counts -> number of photoelectrons (phe) -> energy deposited

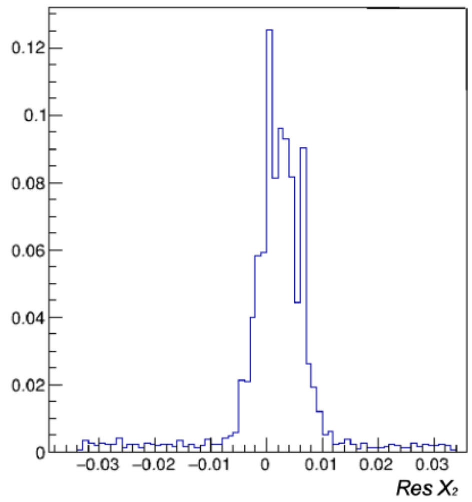
$$E_{phe} = \frac{N_{ADC}^{signal} - N_{ADC}^{ped}}{N_{ADC}^{1phe}}$$

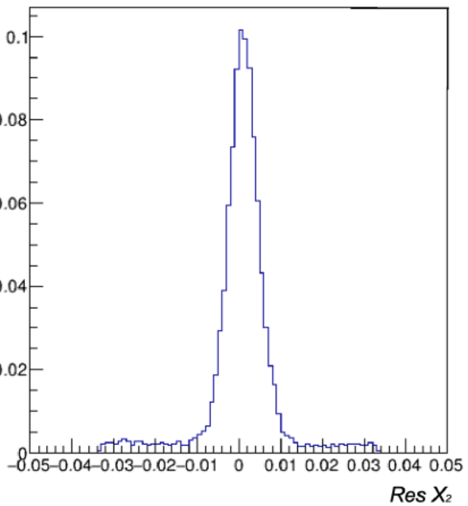
Clustering

$$x_{cluster} = \frac{\sum_{strips} x_i E_i}{\sum_{strips} E_i}$$

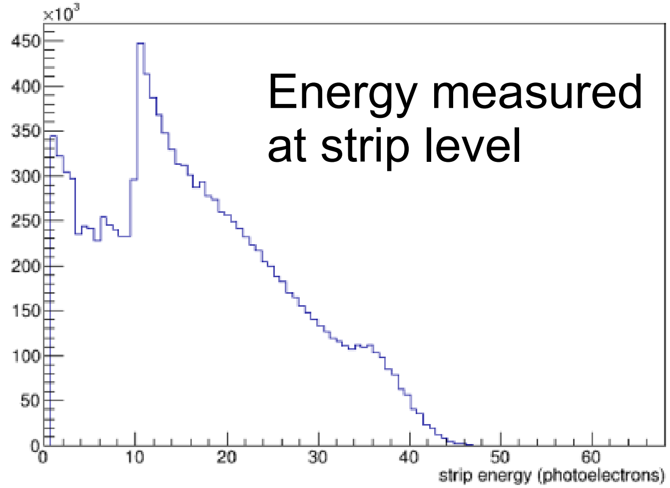


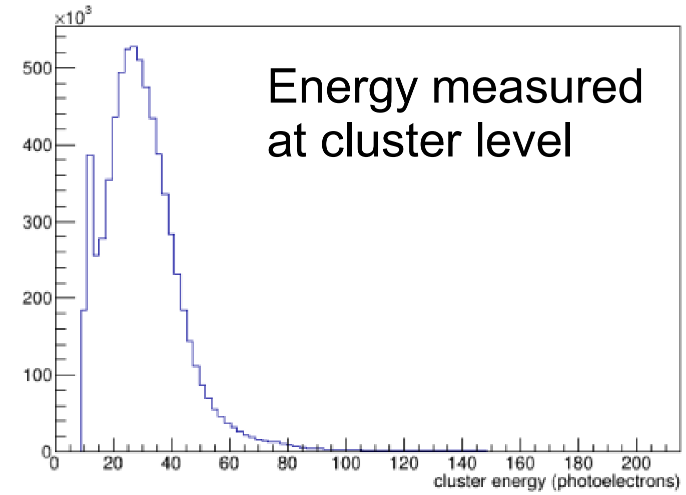
- Consider strips for clustering if phe > 6
- If strip is isolated, retain it as cluster only if phe > 10
- To improve resolution, additional strips are attached to single-strip clusters if their phe > 1
  - Figure below : residuals for 2nd-layer clusters before (left) and after (right) this refinement





Clusters

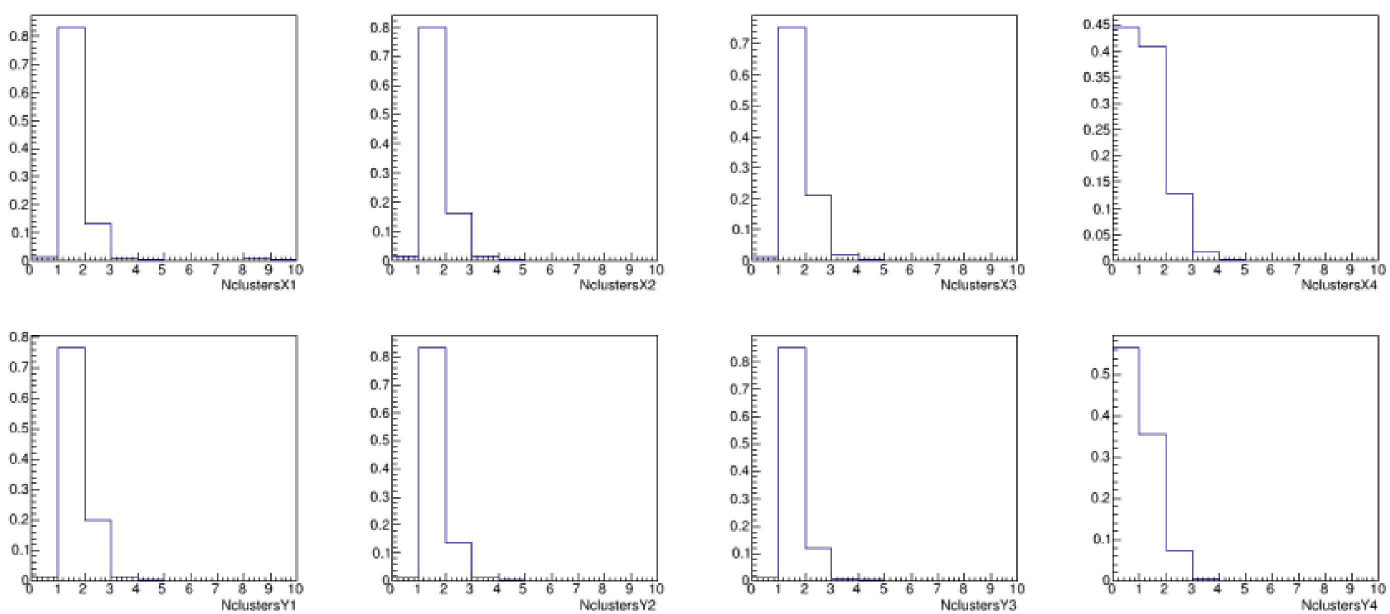




Number of clusters per layer :

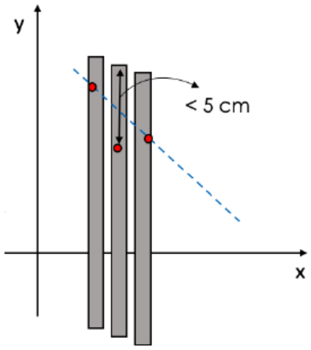
X views :

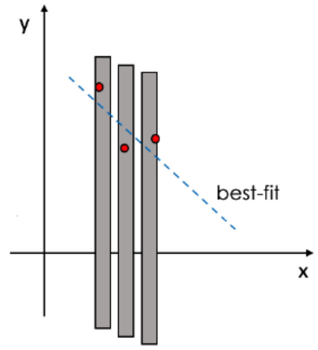
Y views :

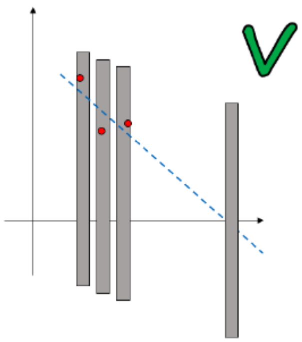


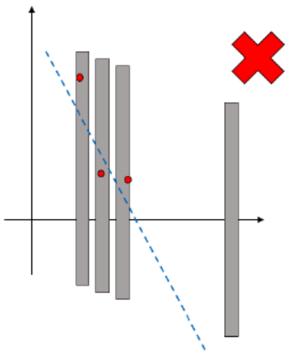
Layer 1 Layer 2 Layer 3 Layer 4

Tracking



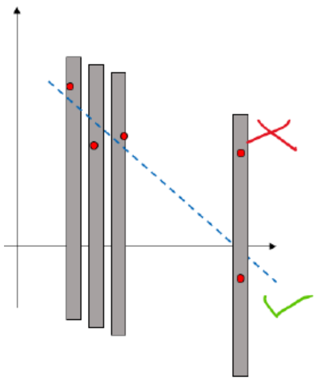


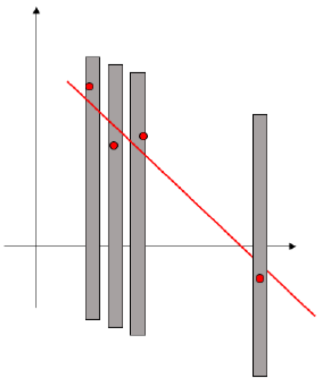




$$\chi^2 = \sum_i^n \frac{(x_i^{model} - x_i^{data})^2}{\sigma_x^2}$$

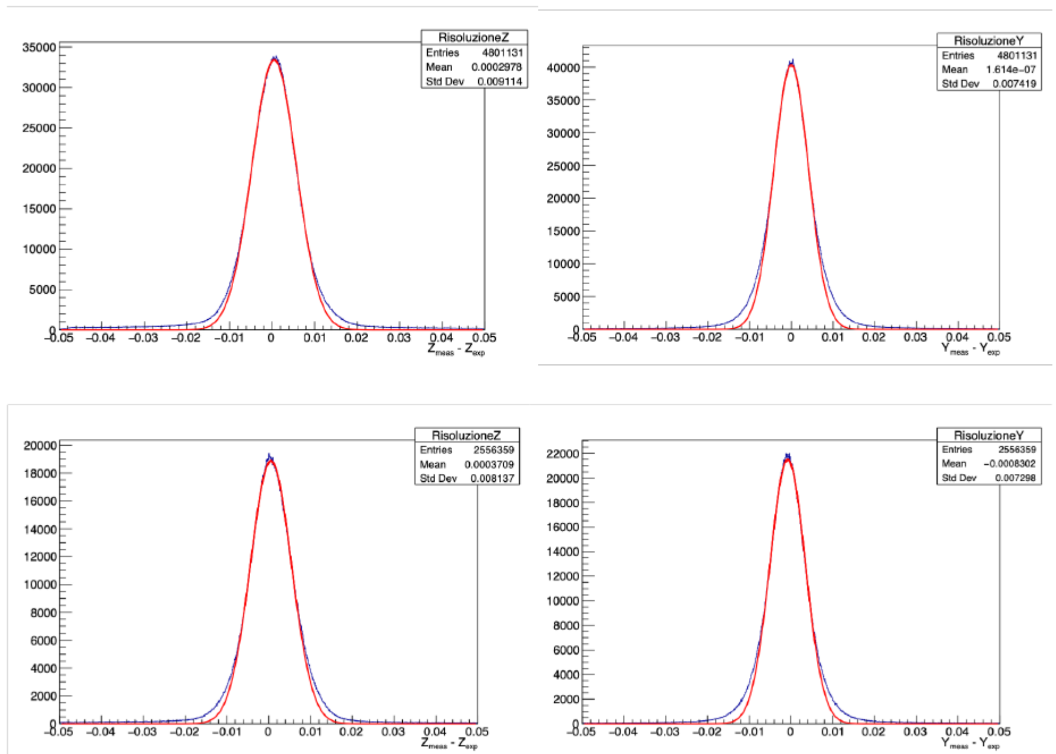
$$\chi^2_{3planes} \cdot |x_4^{model} - x_4^{data}|$$





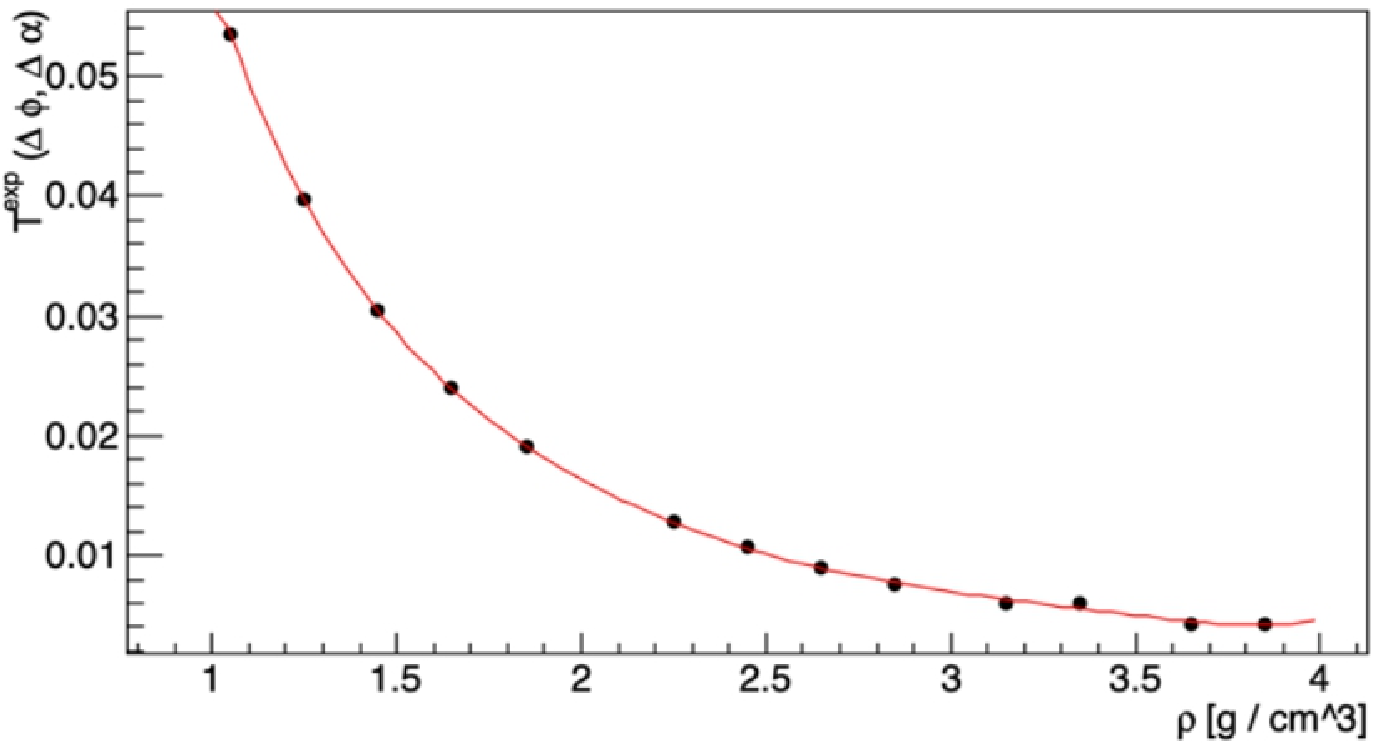
$$\chi^2 = \sum_i^n \frac{(x_i^{model} - x_i^{data})^2}{\sigma_x^2}$$

Spatial resolution



detector	z resolution (mm)	y resolution (mm)
ROSSO	4.3	3.4
NERO	4.0	3.5

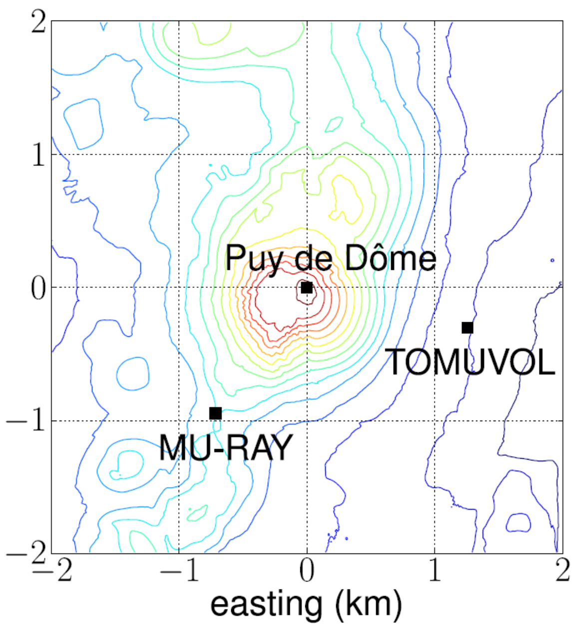
Transmission – density relationship



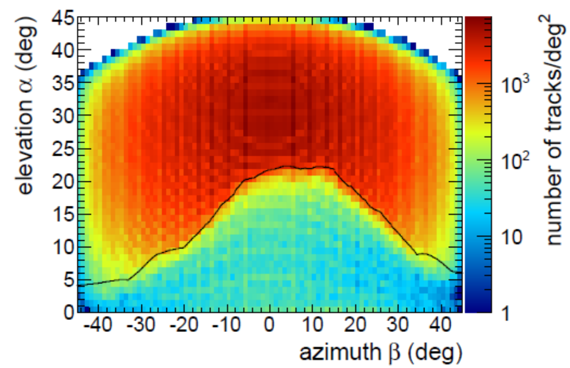
Obtained from PUMAS
(https://github.com/niess/pumas)

MU-RAY TOMUVOL joint experiment (2014)

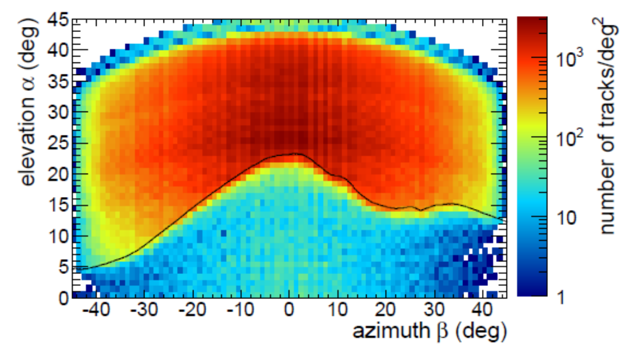
Ambrosino et al. (TOMUVOL+MU-RAY coll.), J.Geophys.Res.Solid Earth 120 (2015), 7290

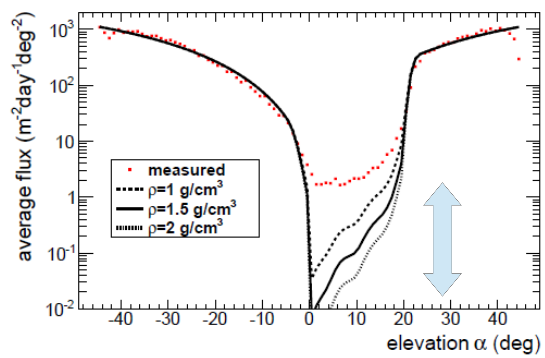


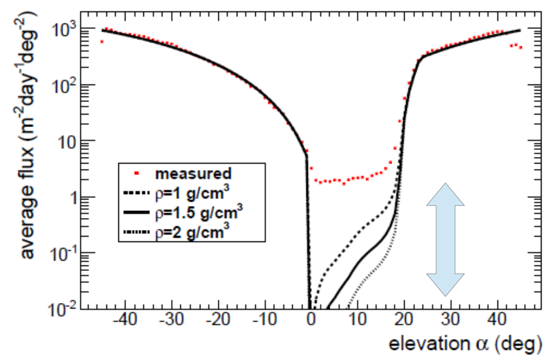
MU-RAY



TOMUVOL



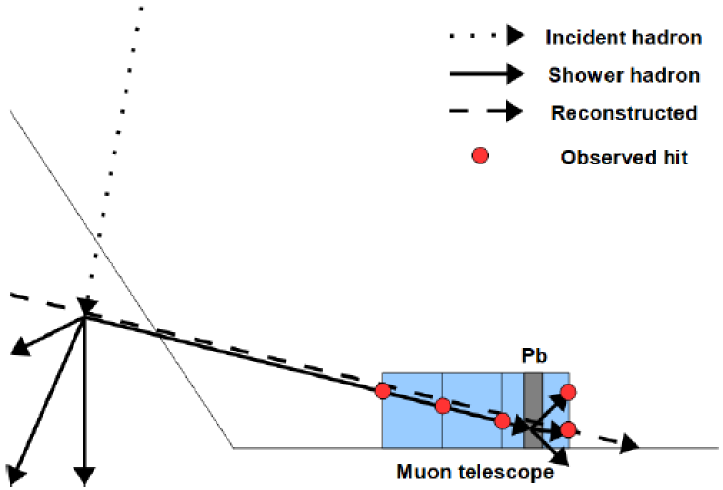




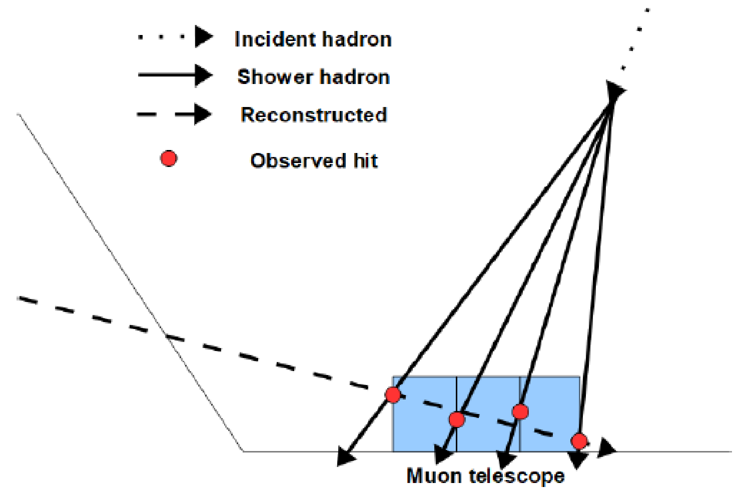
- Simultaneous measurement with two detectors in two different places
- MU-RAY: 3 x-y layers of scintillating bars; 3 cm steel plate (muon P threshold: 70 MeV) as absorber for **fakes**
- TOMUVOL: 4 x-y layers of RPC (less **combinatorics**); no absorber
- Compatible results $\Rightarrow$ most background is **actually muons**

What are those backgrounds?

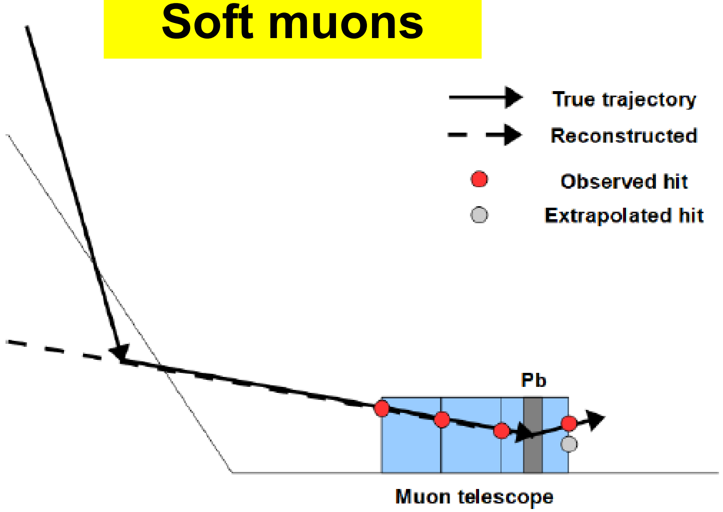
Fakes



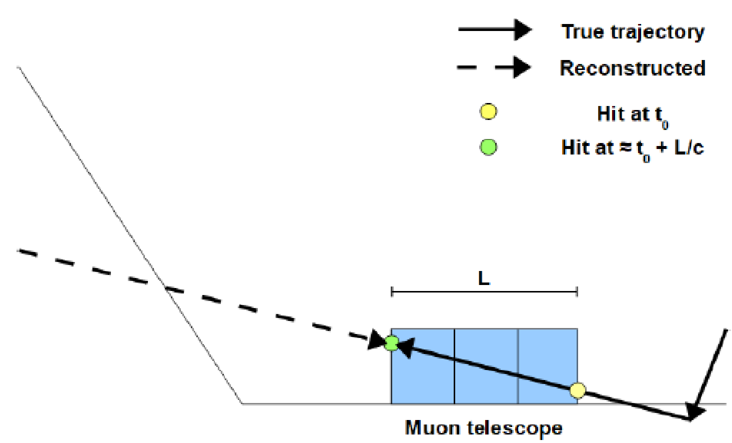
Combinatorial



Soft muons



Backward muons



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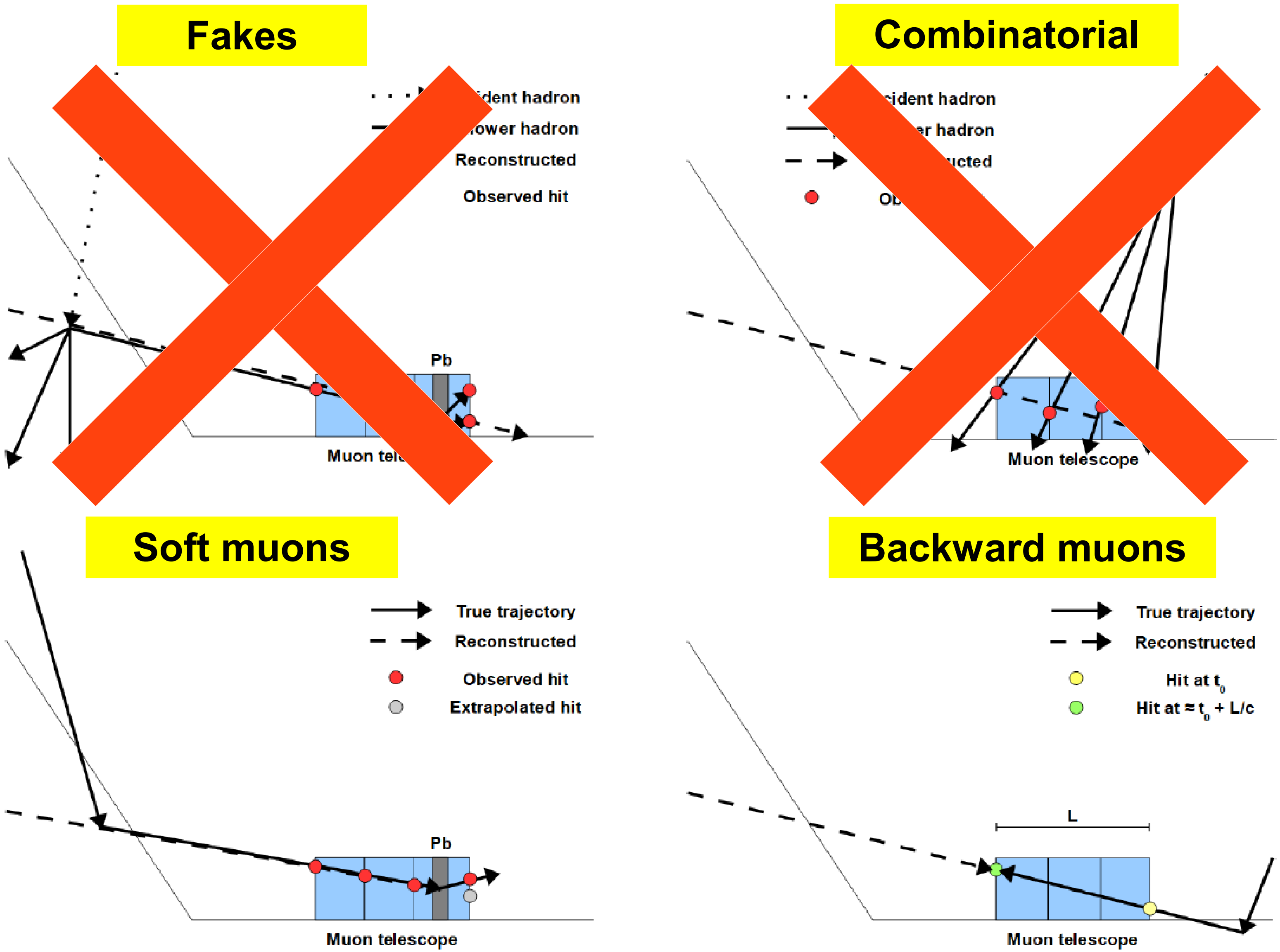
What are those backgrounds?



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