16TH Topical Seminar on Innovative Particle and Radiation Detectors (IPRD23)
Siena, 25 - 29 September 2023

ArchéMuons: Near surface muography studies for targets of archaelogical interest

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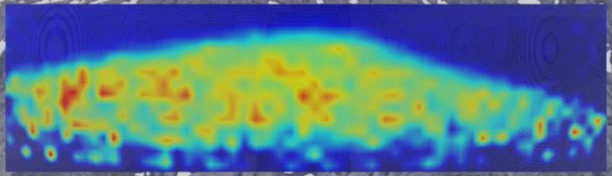
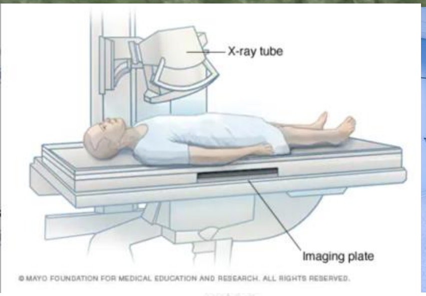
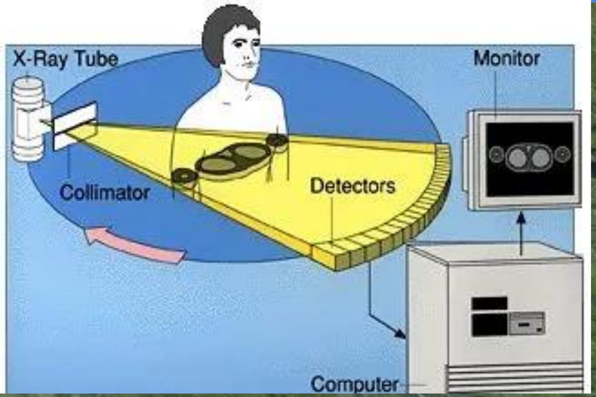
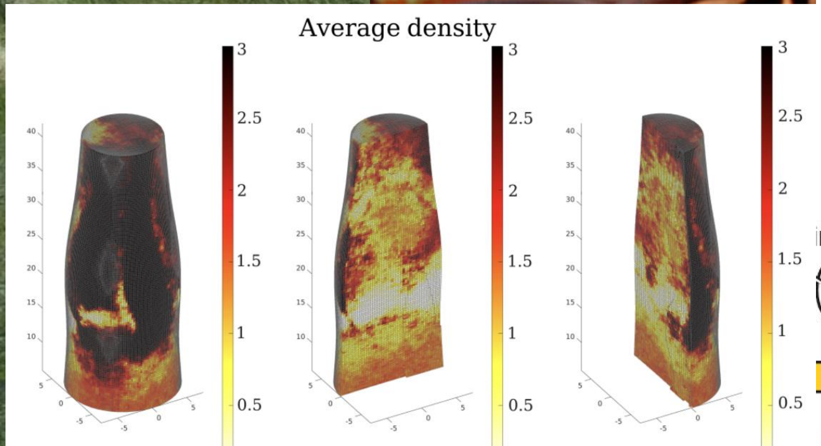
Introduction
Medical X-rays & Muography
Parallels

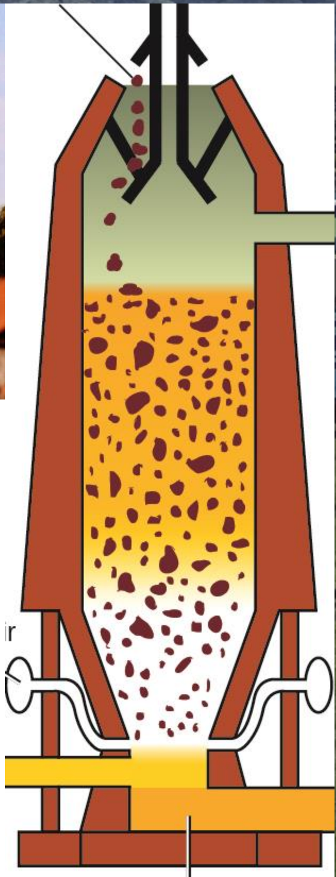








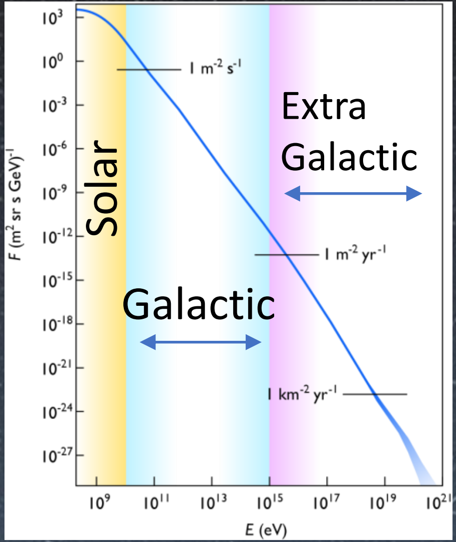
A. Cohu et al. Jinst

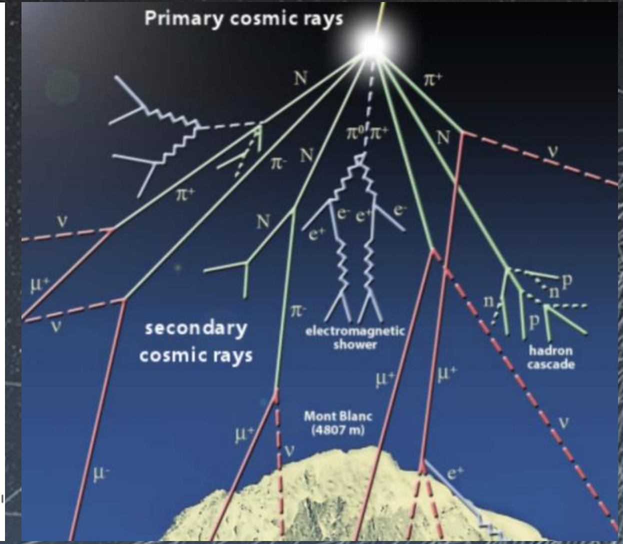


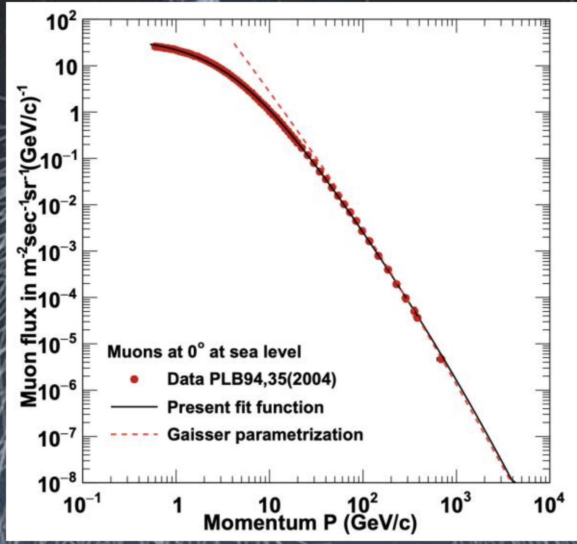
Muon Tomography

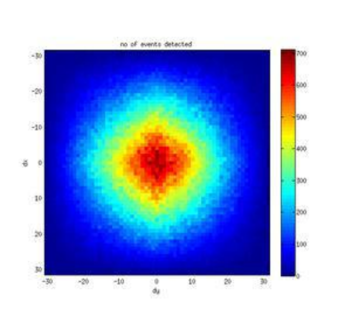
Cosmic Rays

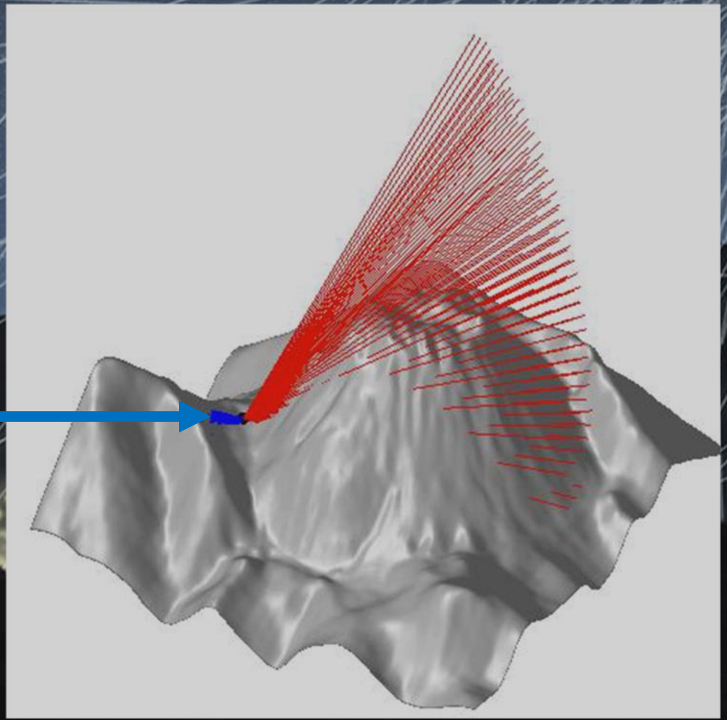
- High Energy Particles
- Atmospheric Cascades
- Extensive Air Showers
- “Steady” Muon Stream

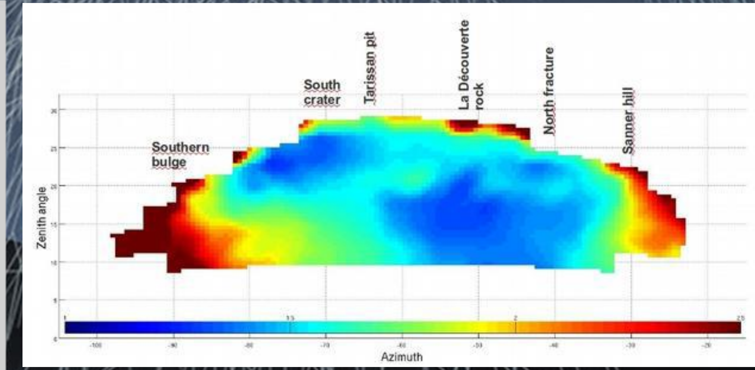


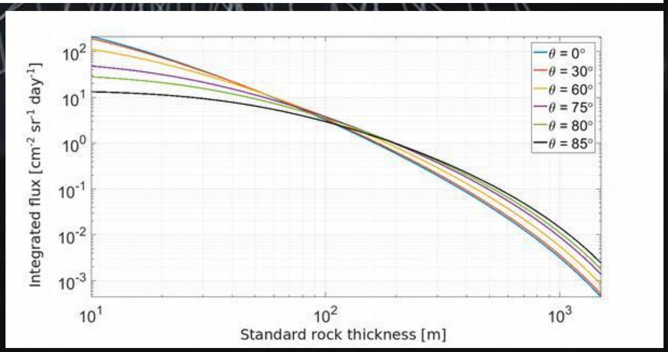








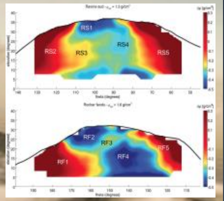




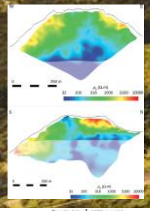
IP2I Lyon – Activities

Volcanology: Guadeloupe – La Soufriere

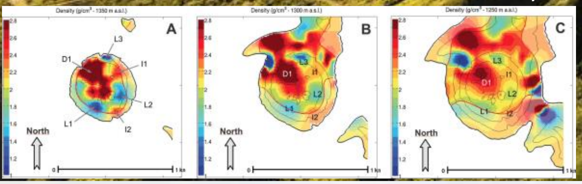
Muon Tomography

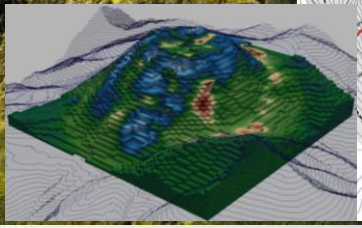


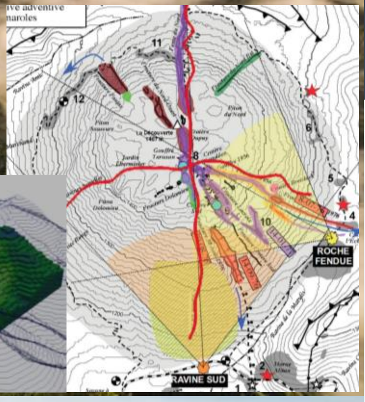
Electric Resistivity Tomography



Gravimetry

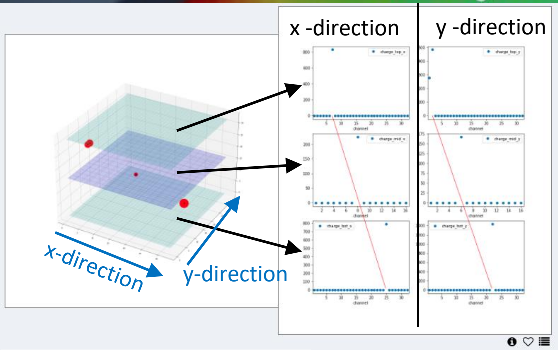




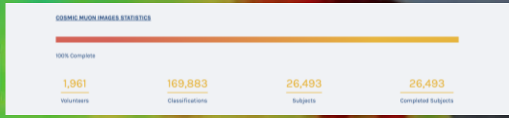


Citizen Science: REINFORCE – Zooniverse

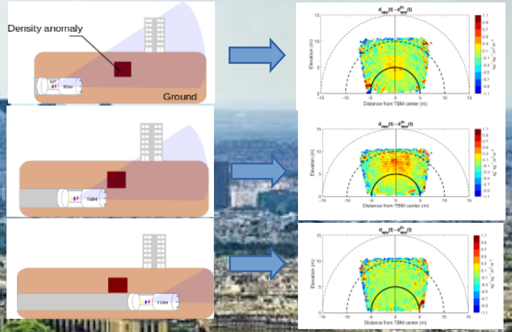
Using Muon Tomography we can probe the internal structure of massive objects, like volcanoes, with particles from stars and galaxies far far away... help us identify these particles inside our detectors

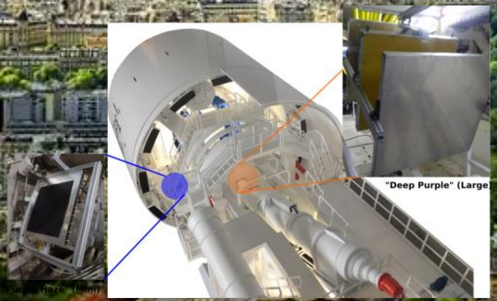


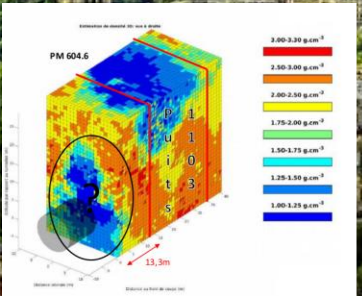
Learn more



Civil Engineering: Paris Metro Line







Outreach

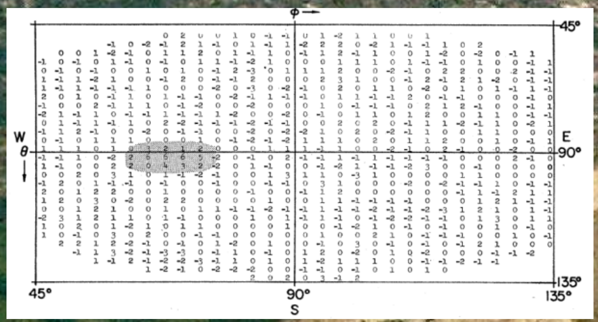
Jules Vernes Museum Nantes

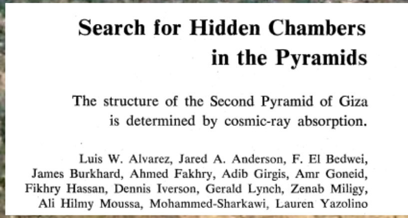
Museo se la Grafica Pisa

Muon Tomography - Archaelogy

Luis Alvarez invented muon tomography in 1960’s to study the Pyramid of Chephren

$$(N_{Data} - N_{Pred}) / \sqrt{N_{Data}}$$




Search for Hidden Chambers in the Pyramids

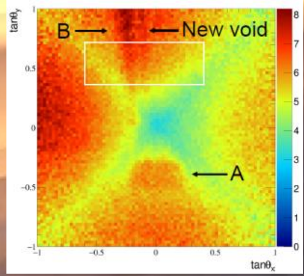
The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

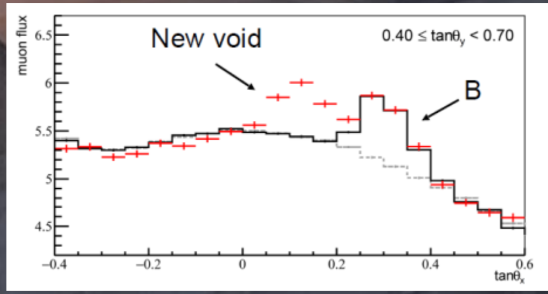
Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

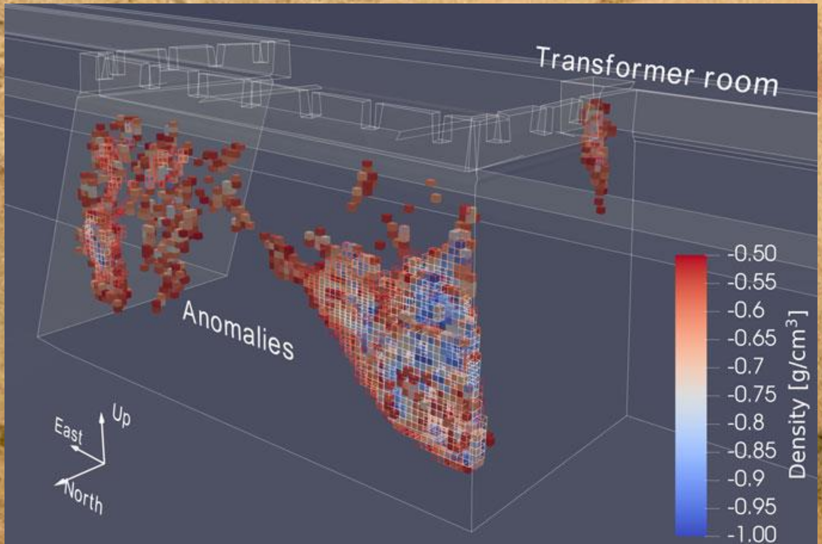
L.W. Alvarez, *et al, Search for Hidden Chambers in the Pyramids Using Cosmic Rays*, Science **167**, 832-839, 1970.

Discovery of a big void in Khufu’s Pyramid by observation of cosmic-ray muons

388 | Nature | VOL 552 | 21/28 DECEMBER 2017







High-precision muography in archaeogeology: A case study on Xi’an defensive walls.

L. Guorui et al. J. Appl. Phys 133, 014901 (2023)

A more difficult case : Tumuli

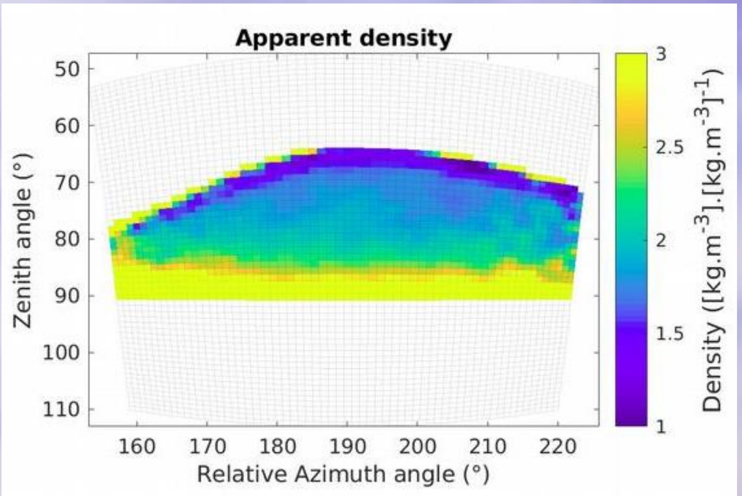
The Apollonia tumulus as a benchmark for the method

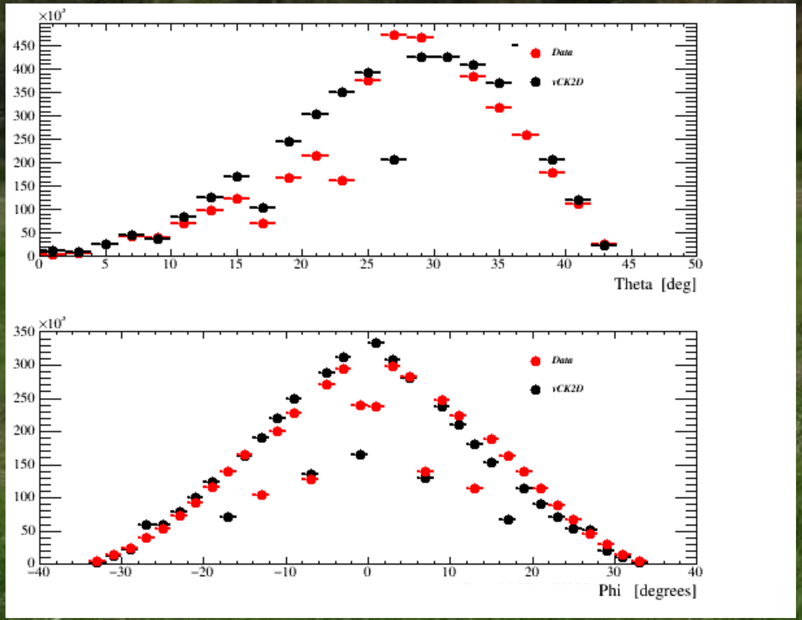
- Existing monument
- Density anomalies detected by other methods

Difficulties :

- Looking for an object with similar density as the surrounding materials $\rho \sim 2.3\ gr/cm^3$ for dirt and $2.5\ gr/cm^3$ for marble !
- If any monument, it must be at the horizon level. Very low number of muons, wait a LONG time !
- Muons must cross a lot of dirt. Need high energy muons, their number is even less !

Apollonia Tumulus





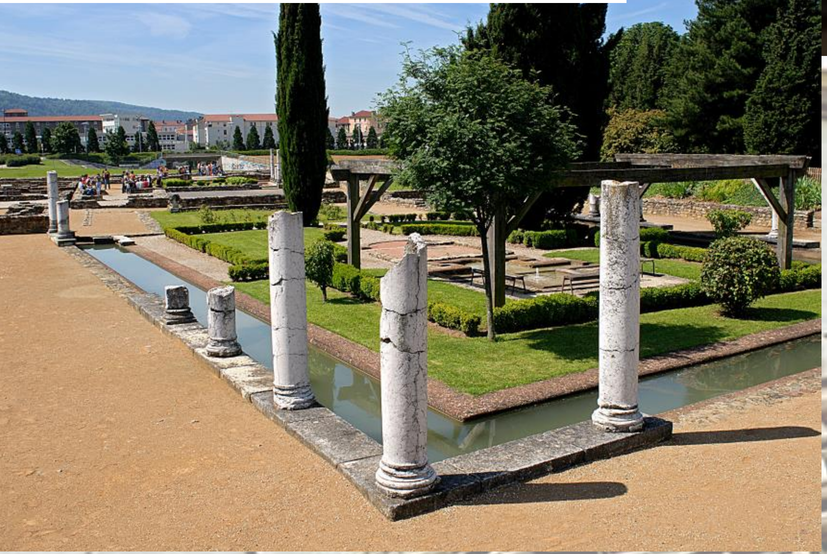
- Level of agreement ~10 to 20% between observed muon fluxes and simulation
- Precision experiment looking for tiny effects
- Limitations:
  - The precise knowledge of the muon spectrum and muon statistics
  - A more accurate geometrical description of the tumulus and the density of soil

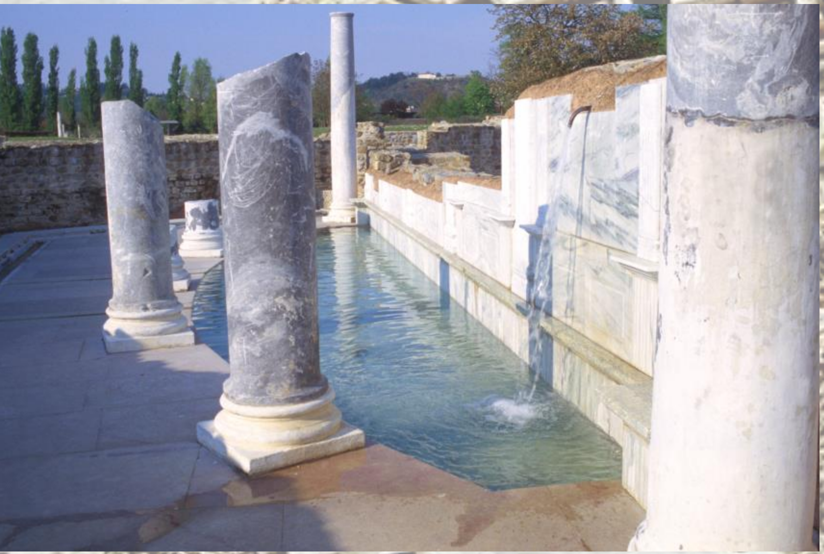
ArchéMuons

A miniature implementation of the “La Soufrière” experience

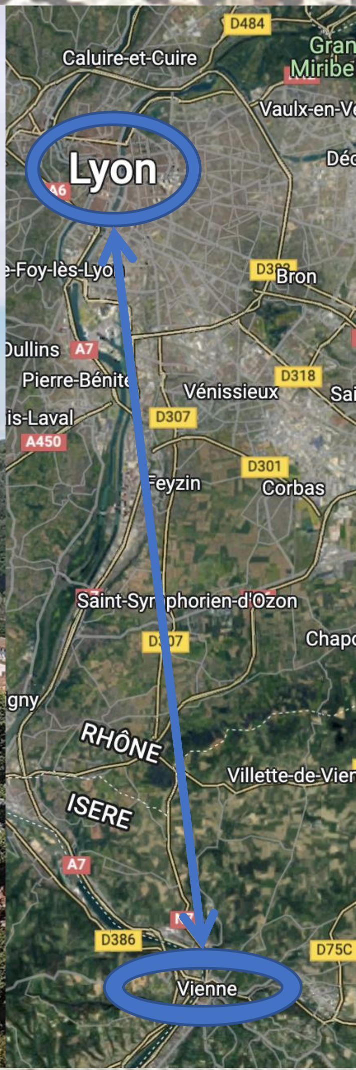
- Muon Tomography in controlled/confined environment
- Combine/Compare results with Geophysical Surveys: ERT
  Gravimetry
  Seismometry
- Prospect of archaeological discovery

MUSÉE GALLO-ROMAIN
SAINT-ROMAIN-EN-GAL



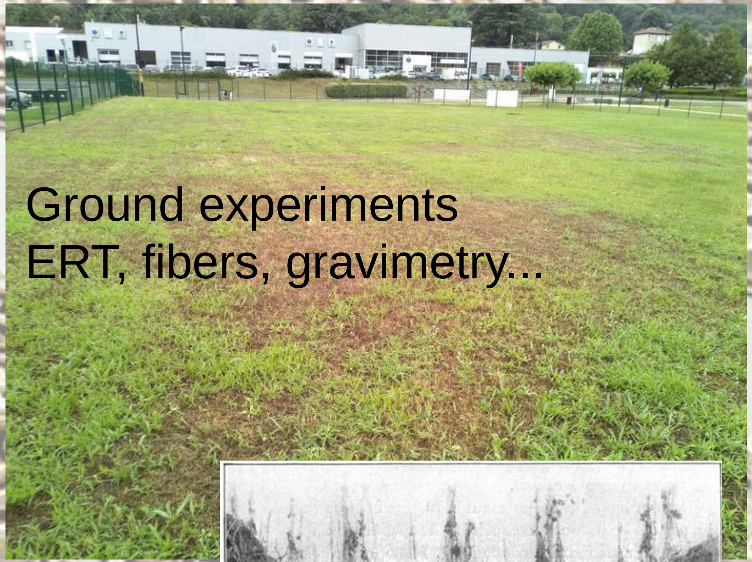


The town of Vienne



Palais du Miroir

Physics Case



Underground Network Of Galleries
Unknown Size and Pattern (estimated ~9000 m^2)

<u>Prospects</u>

Better understand the limitations of the method
Evaluate the thickness of the collapsed parts
Possibly mapping nearby unexplored tunnel parts

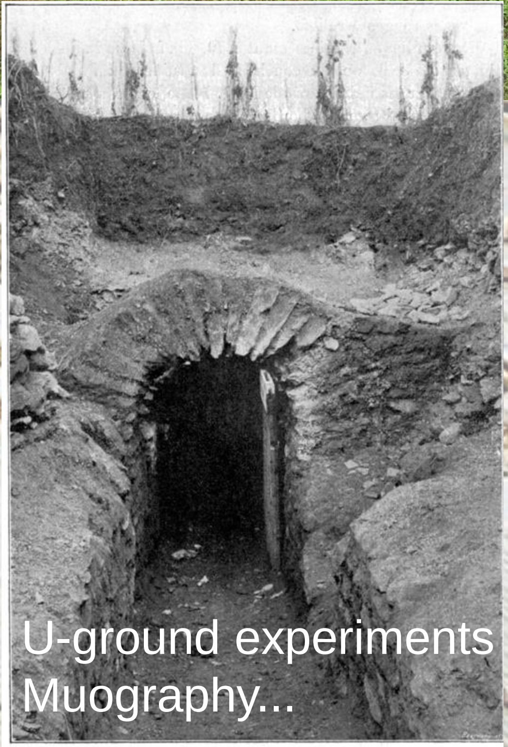
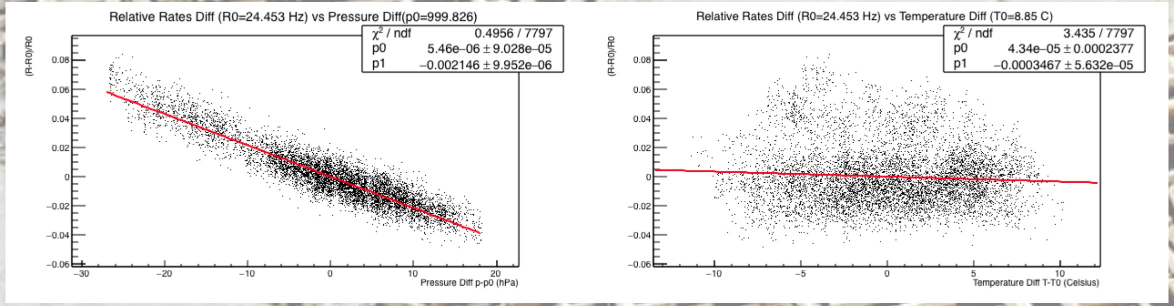


Fig. 8. — Entrée des aqueducs du Palais du Miroir.

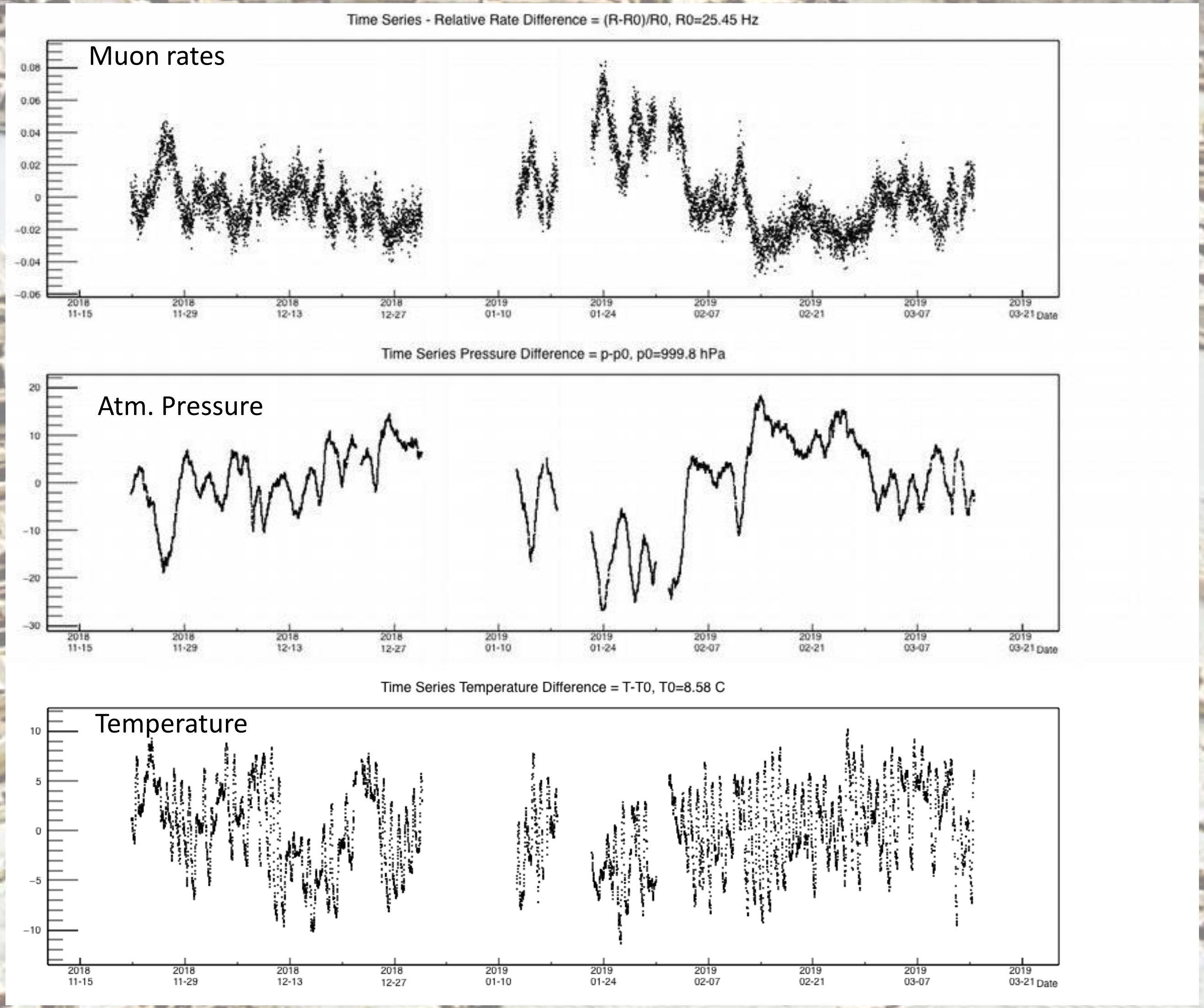
Atmosperic effects

Weather affects muon rates
Correction for precision experiments

$$\frac{\Delta R}{\langle R\rangle} = \alpha_T \frac{\Delta T_{\mathrm{eff}}}{\langle T_{\mathrm{eff}}\rangle} + \beta_P (p - \langle p\rangle)$$

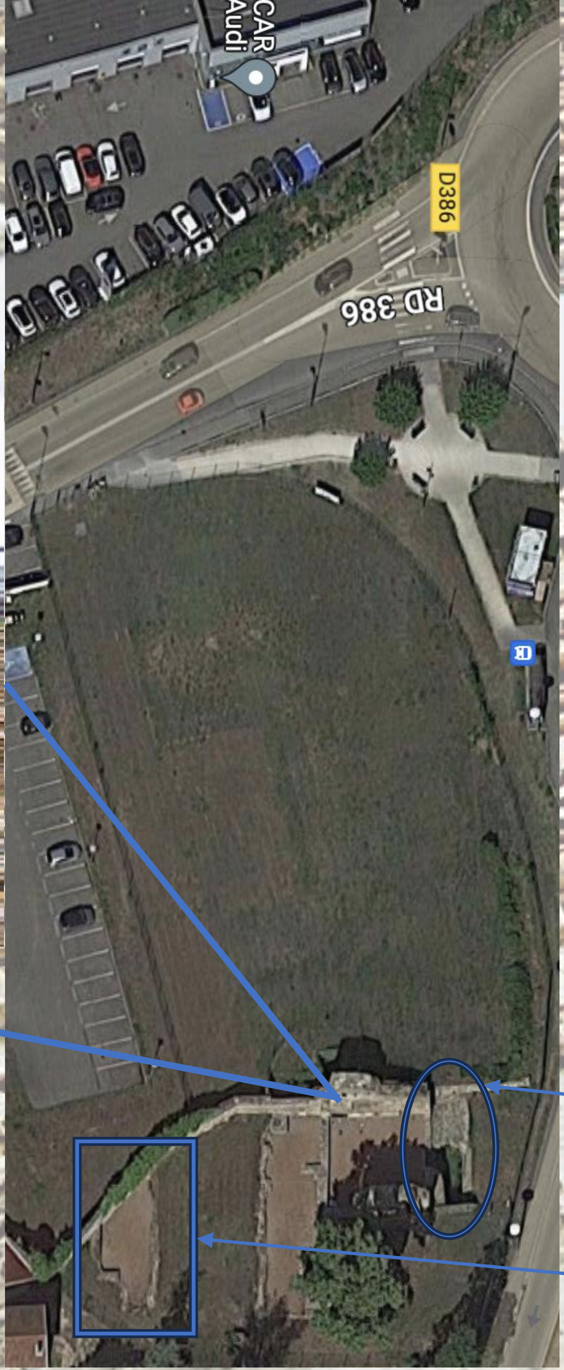


How soil water retention affects the measurement



EGO-Virgo CR monitoring

OverGround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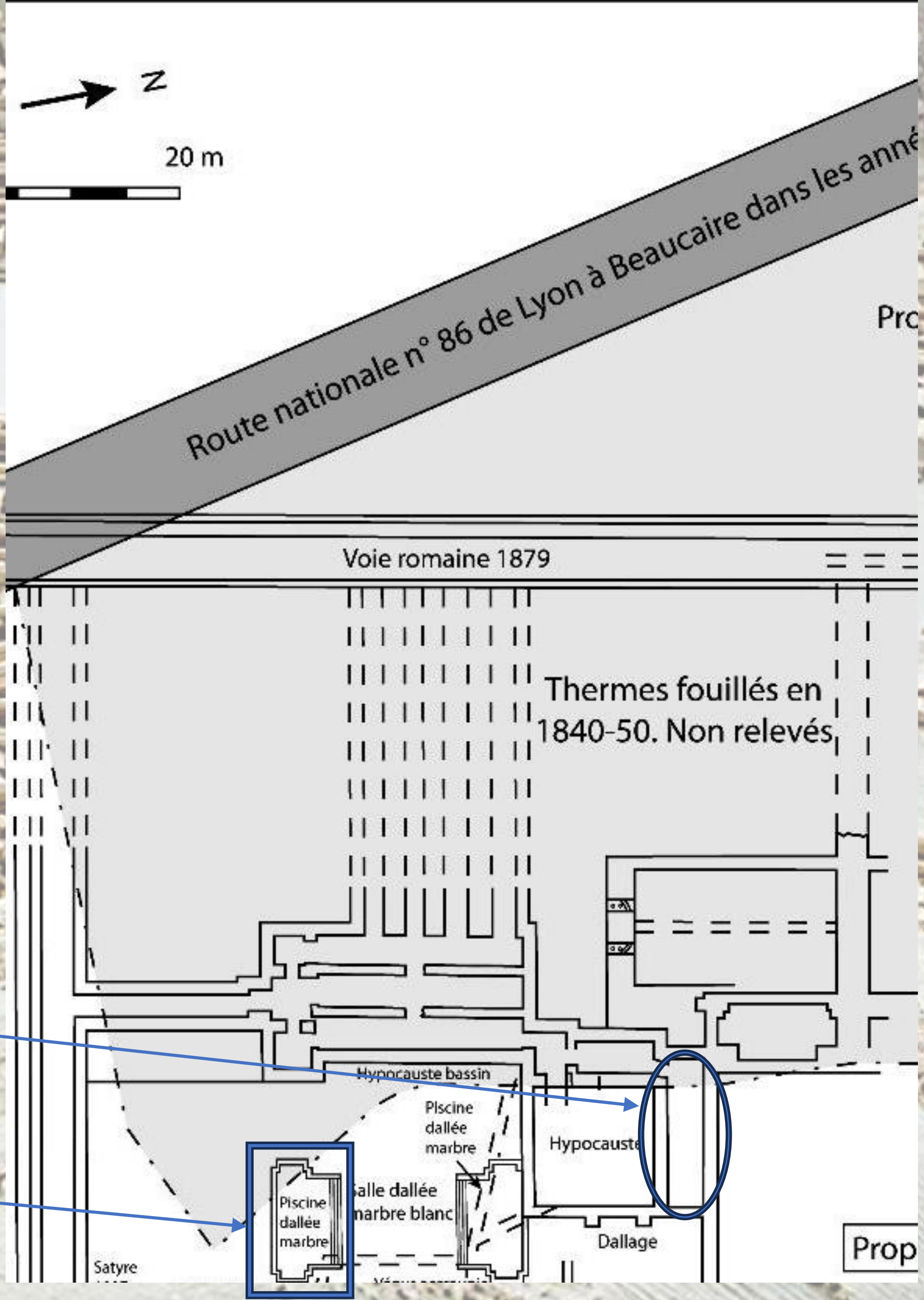
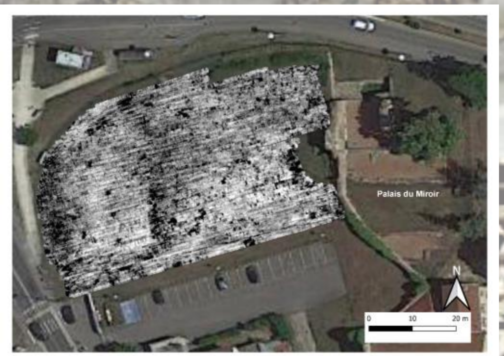
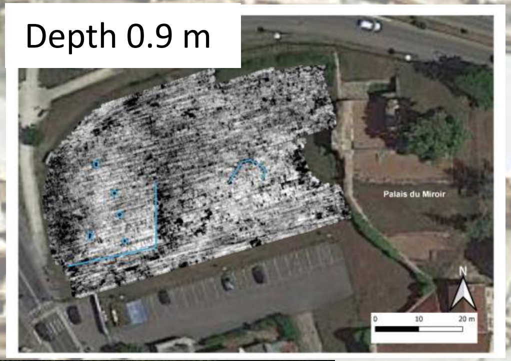
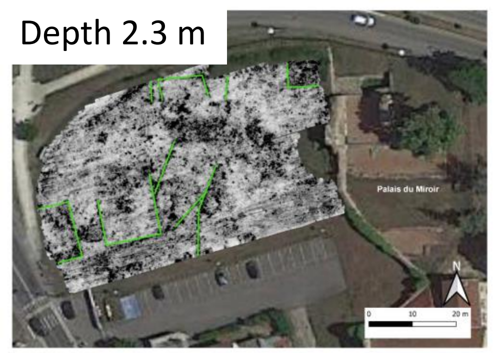
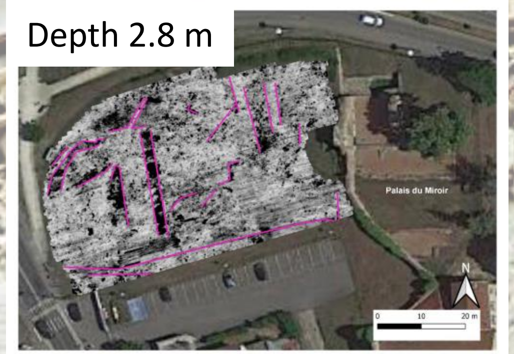

N
20 m
Route nationale n° 86 de Lyon à Beaucaire dans les anné
Pro
Voie romaine 1879
Thermes fouillés en 1840-50. Non relevés
Hypocauste bassin
Piscine dallée marbre
Hypocauste
Piscine dallée marbre
Salle dallée marbre blanc
Dallage
Satyre
Prop

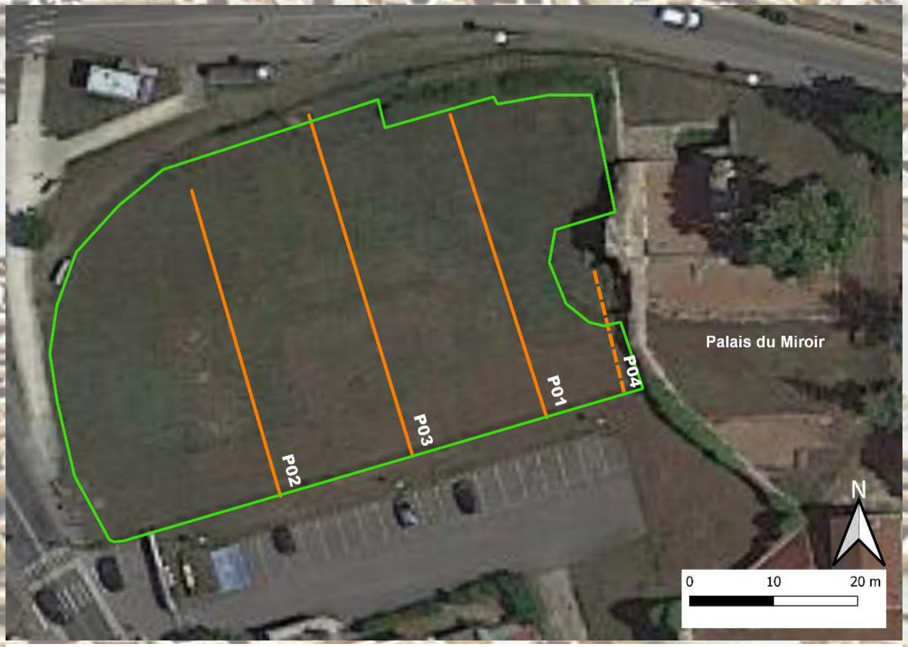
GeoRadar & Electric Resistivity Tomography

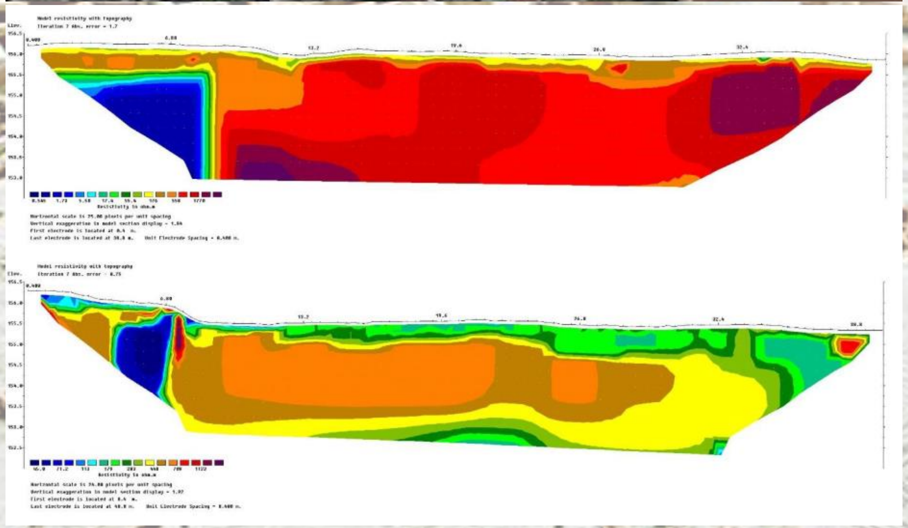




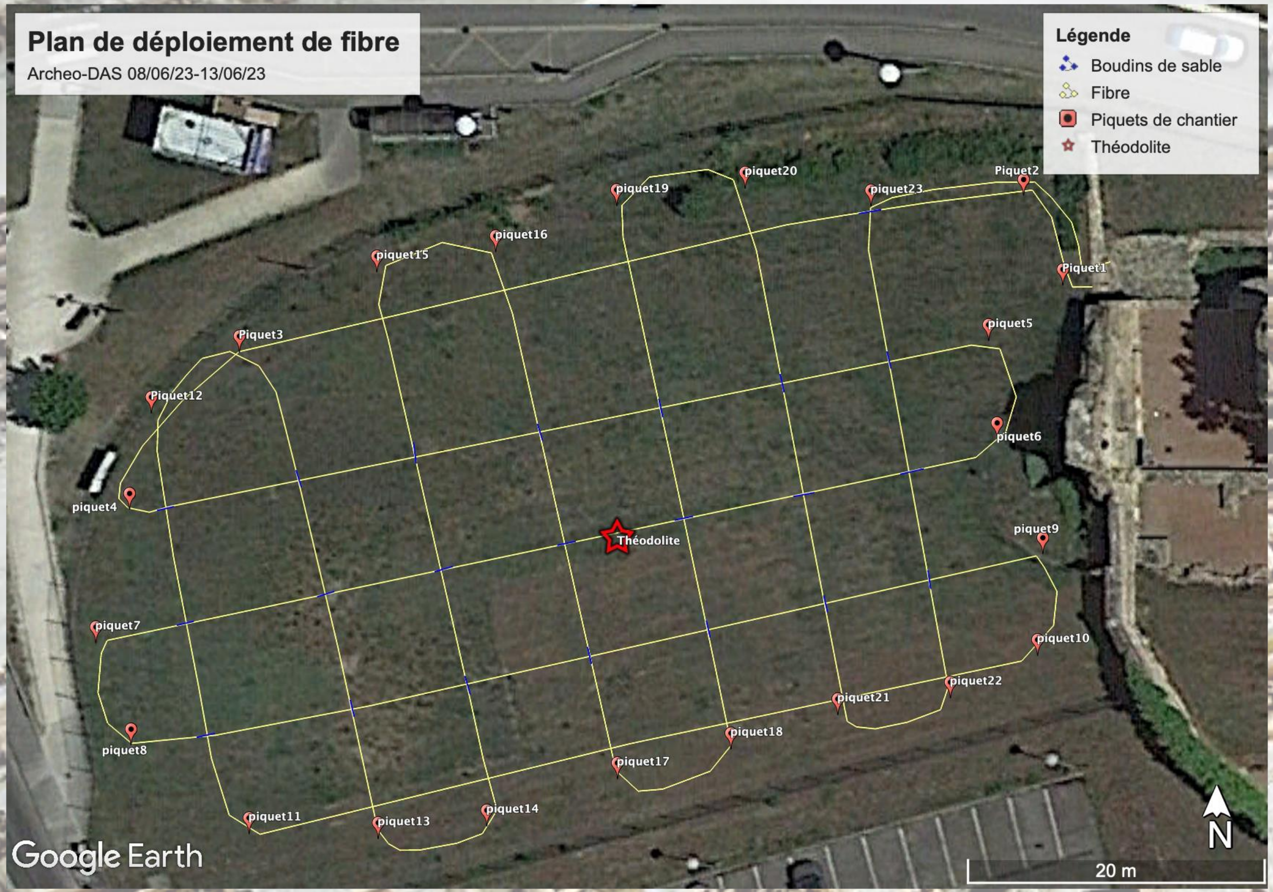


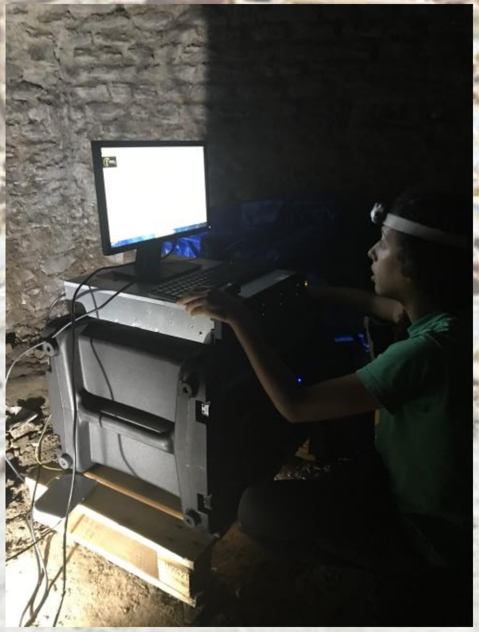


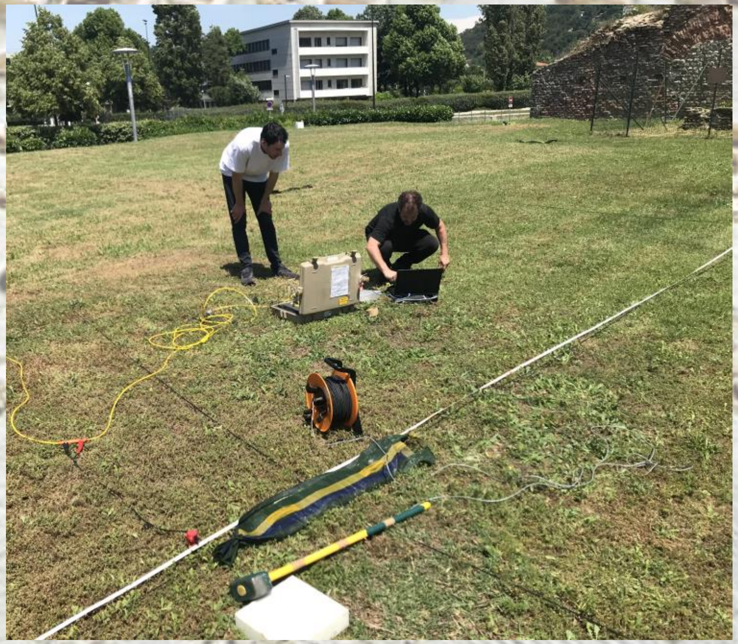




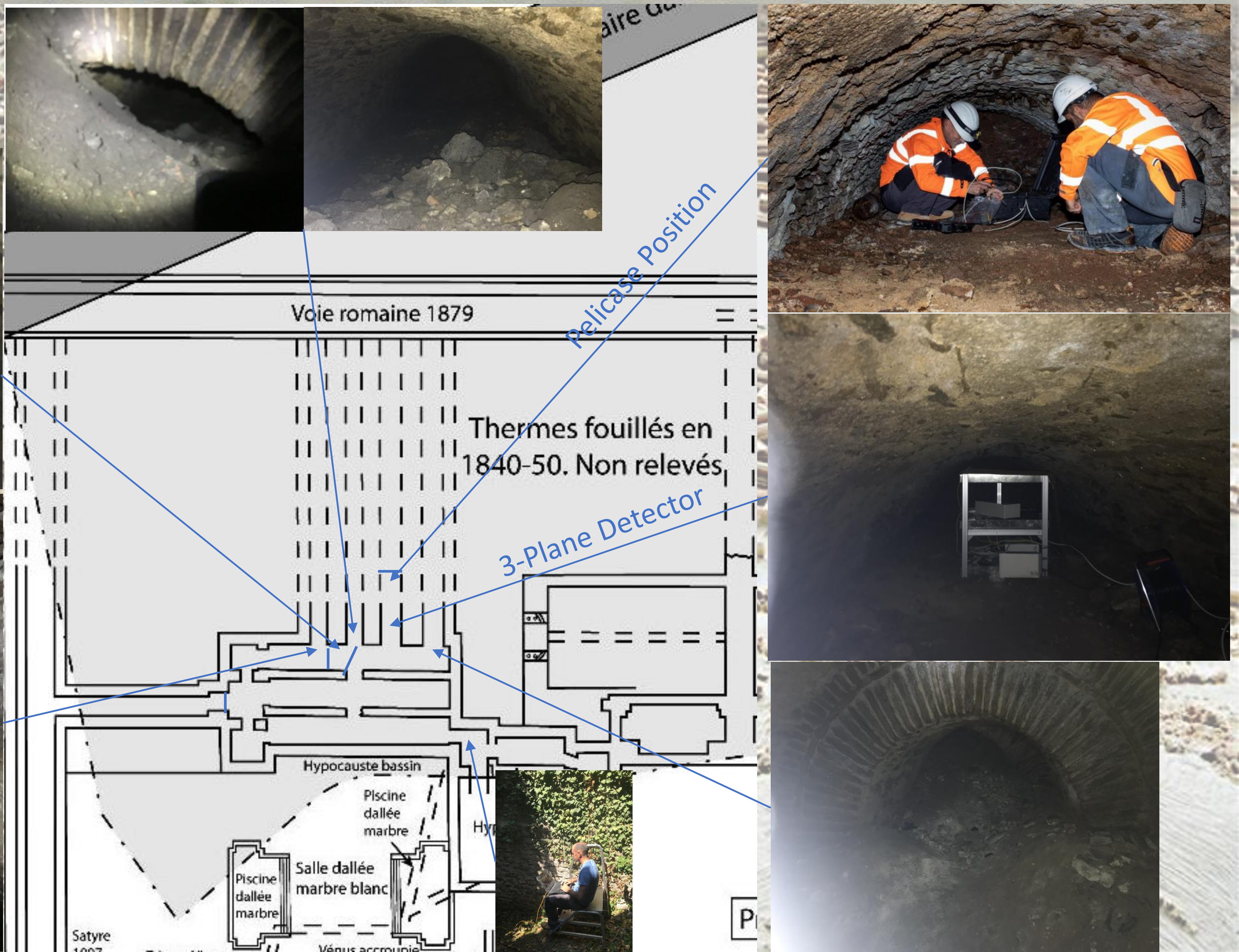
Distributed Acoustic Sensing & Seismometry



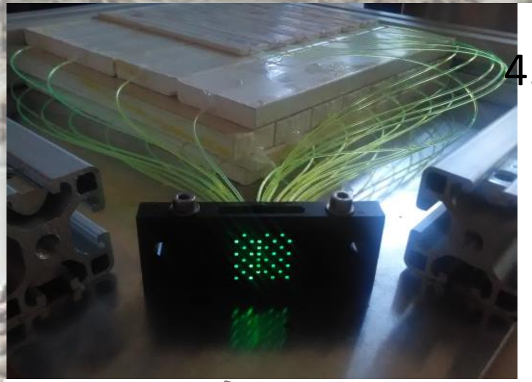


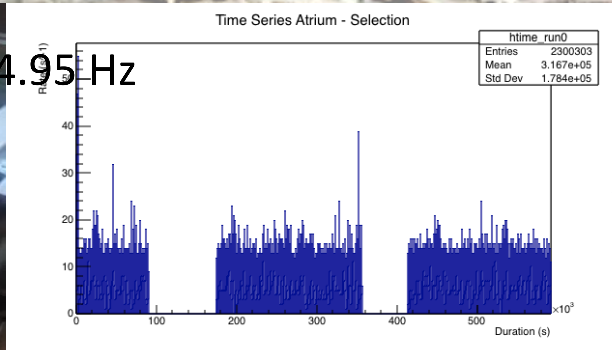


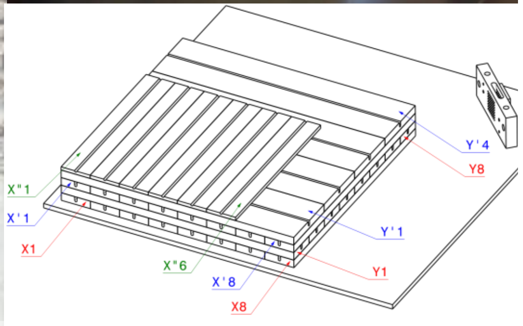
Underground

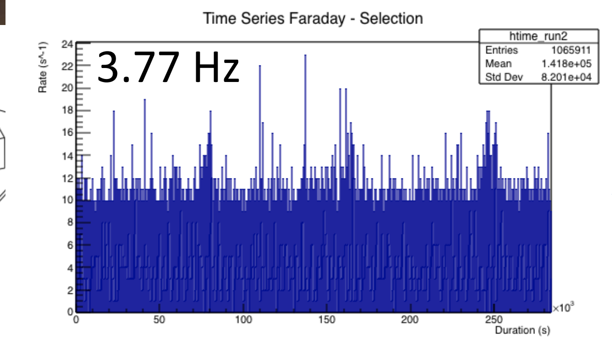


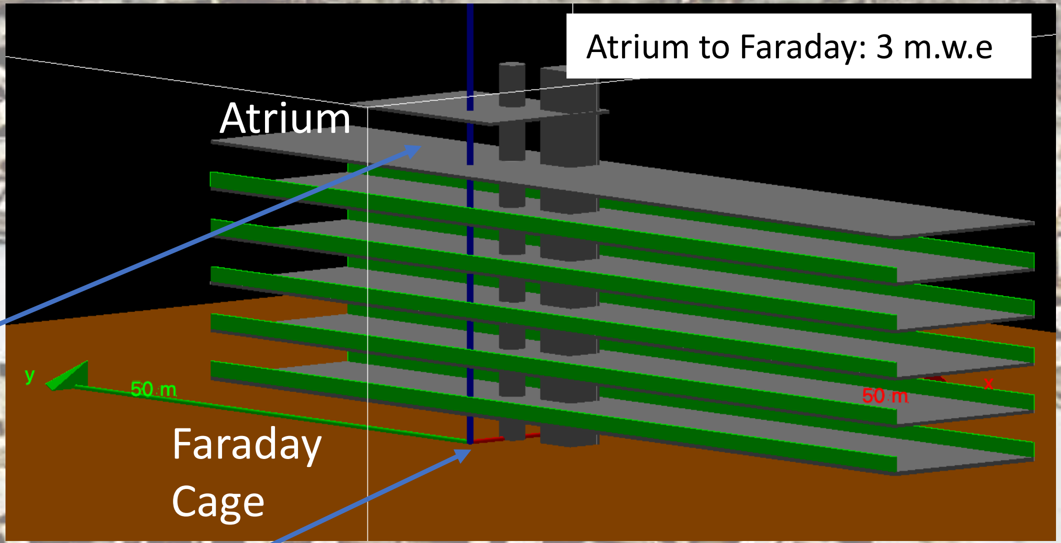
Pelicase detector







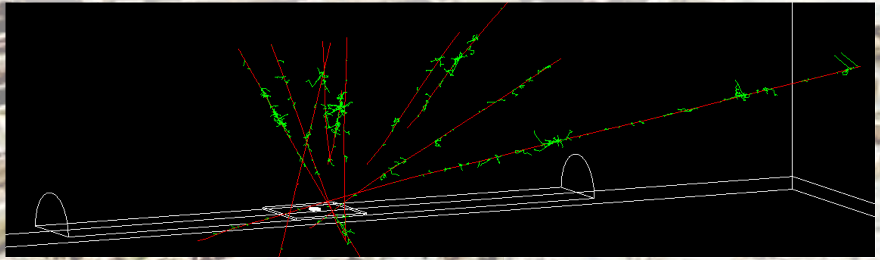




Theoretical Rates (calc. Shukla et al):

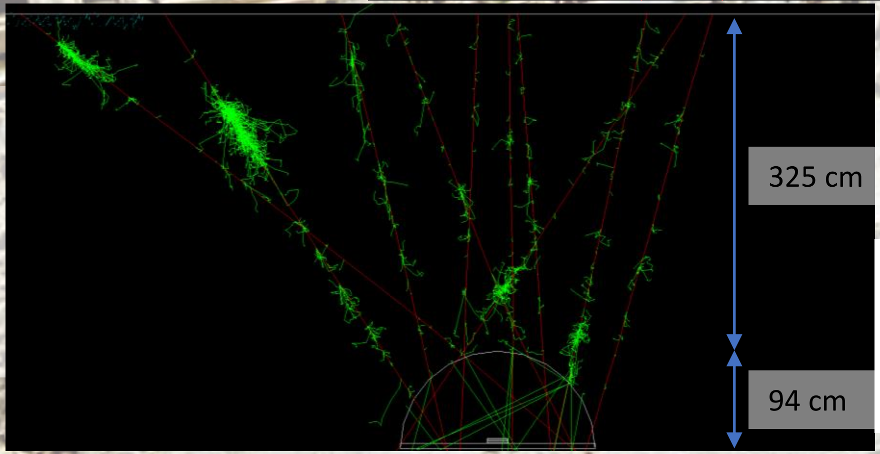
$Rate(0\ GeV) = 7.335 \times sec^{-1}$ (Atrium – No Overburden, Eth = 0 GeV)

$Rate(0.598\ GeV) = 5.702 \times sec^{-1}$ (Faraday – 3 m.w.e, Eth = 0.598



(A. Begneu)

Selection: 4–fold Coincidenses between lower planes



<u>Experiment @ Tunnel</u>

Rate = Selection Rate / Det Eff = 4.090 Hz

Eth = 1.455 GeV

OverBurden: 730 cm water eq. or

325 cm Standard Rock

<u>Pelicase Calibratio @ Laboratory</u>

Det. Efficiency (DE): Selection Rate / Theoretical Rate

Atrium: 0.6743±0.0004

Faraday: 0.6587±0.0007

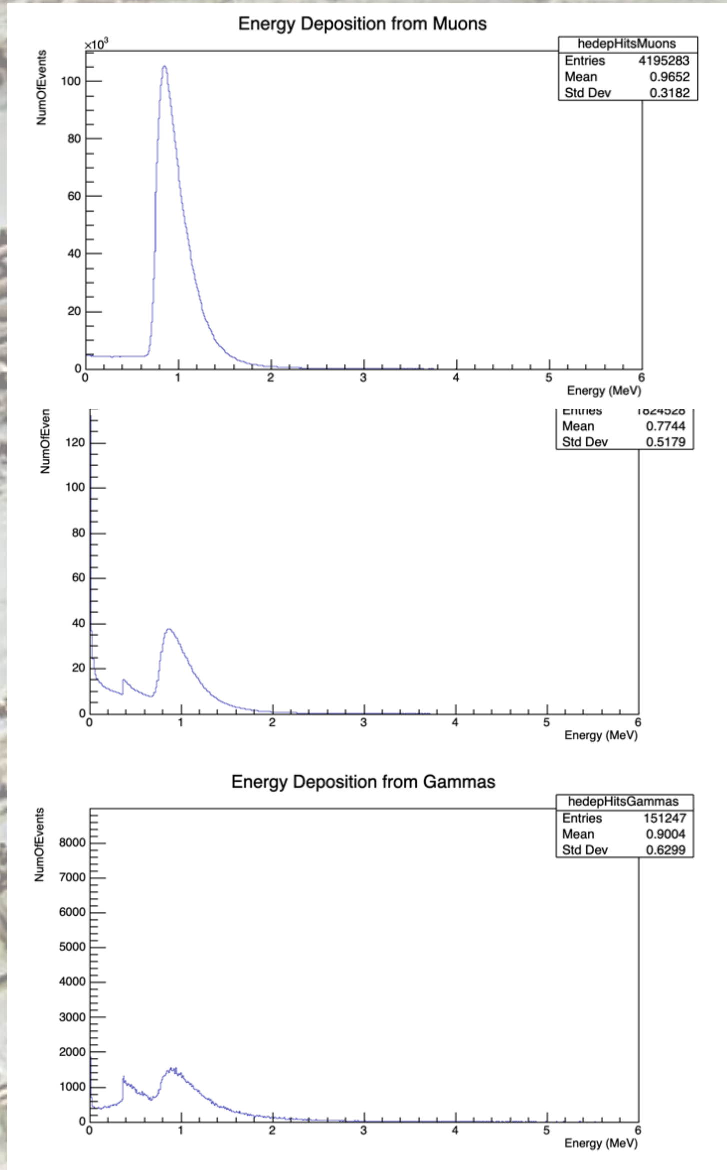
Mean value: 0.6665

Very noisy environment

Noise ~ muon rates

Pelicase is insufficient for this study

2 Plane Detector - Simulation



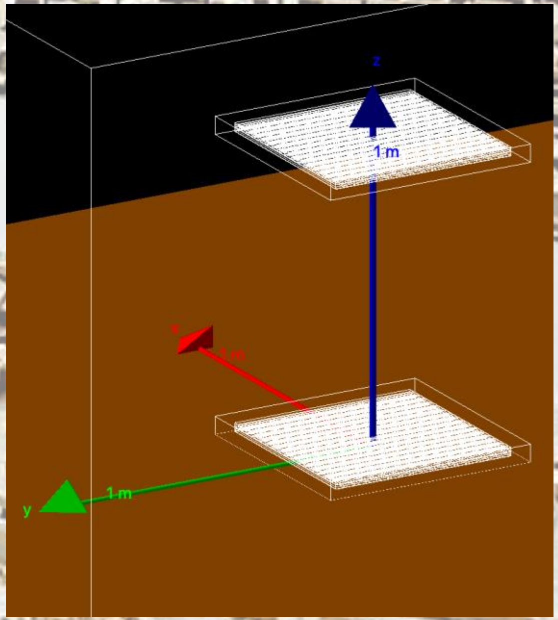
No Cuts

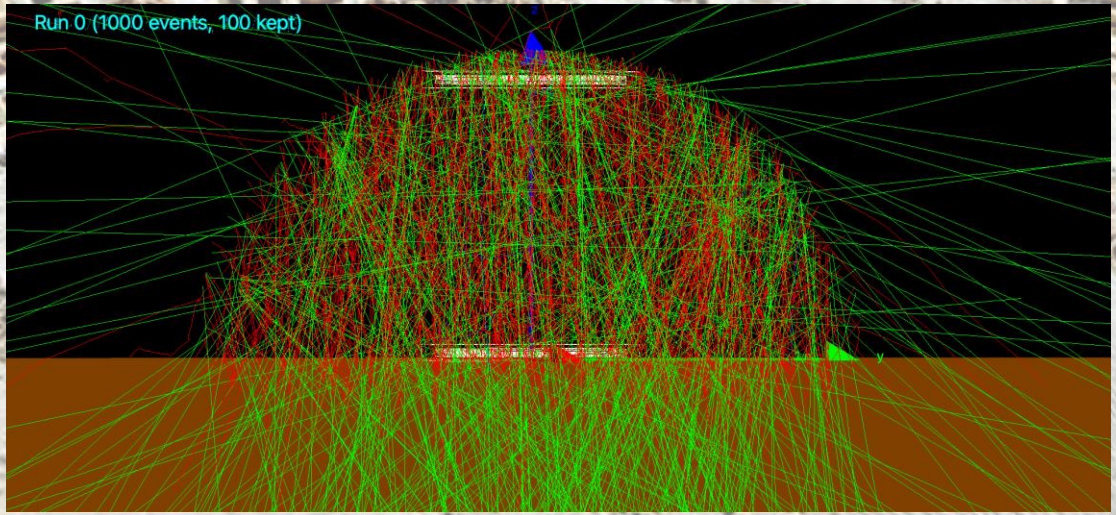
```
events with hits: 1993708
Events with 2 fold Coincidences: 351286
2-fold Coincidences with muon: 323597
2-fold Coincidences From Muons: 182544
```

Energy Depostition>0.6 MeV

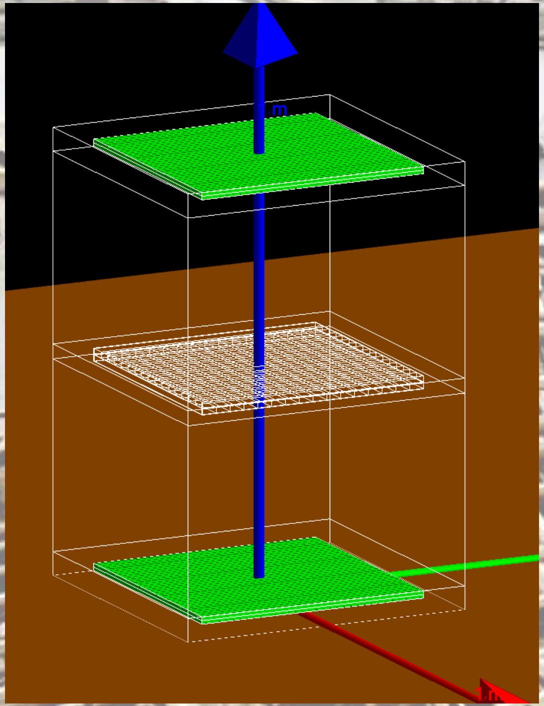
```
events with hits: 1526250
Events with 2 fold Coincidences: 273770
2-fold Coincidences with muon: 272918
2-fold Coincidences From Muons: 173913
```

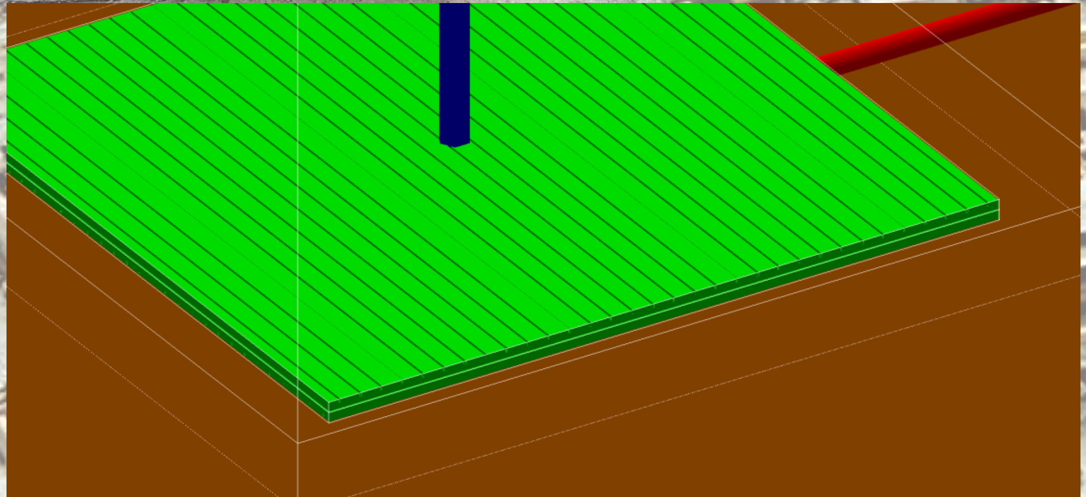
Preliminary Finding Shows
2-fold Coincidence are
64% actual muons
36% Muon + other particle



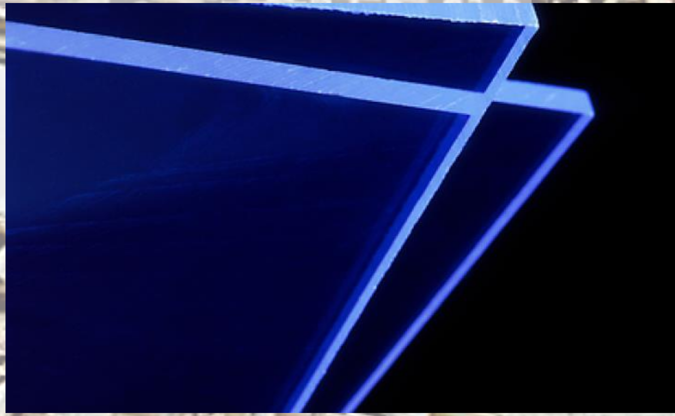


Current Detector – Palais de Mirroir





Saint-Gobain Crystals



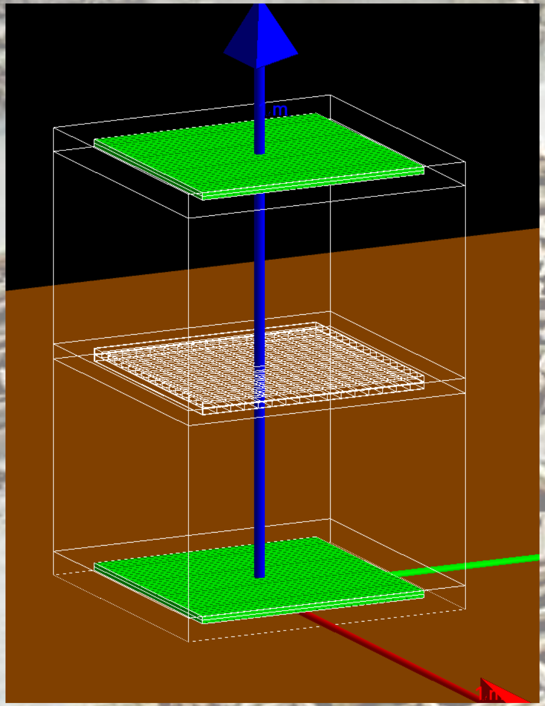
ref. Luxium Solutions

BC-416
203 cm X 63 cm X 5 mm

Detection: Alphas, betas, charged particles, cosmic rays, Muons, protons

Large Area & Economy

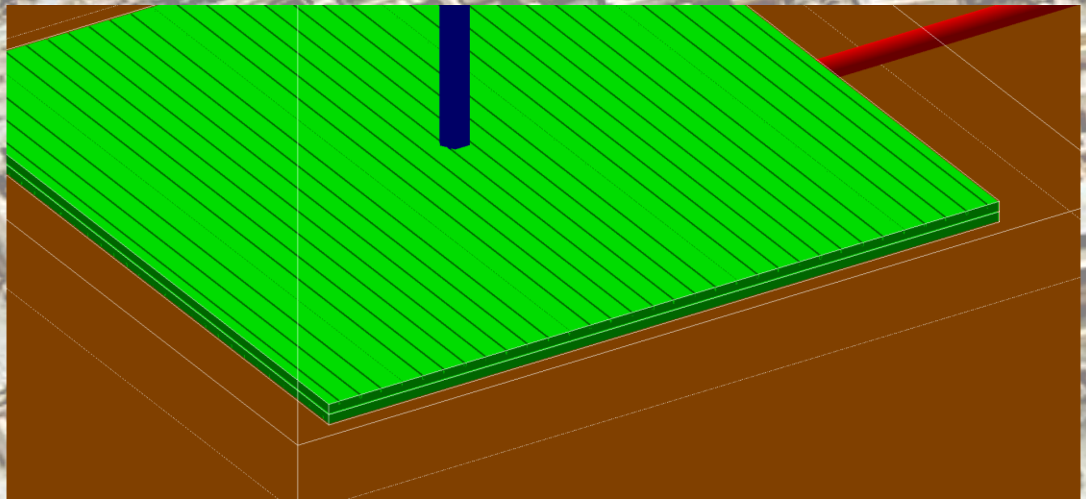
Current Detector – Gold Events



2 Hits per PMT -> 1 per direction x & y

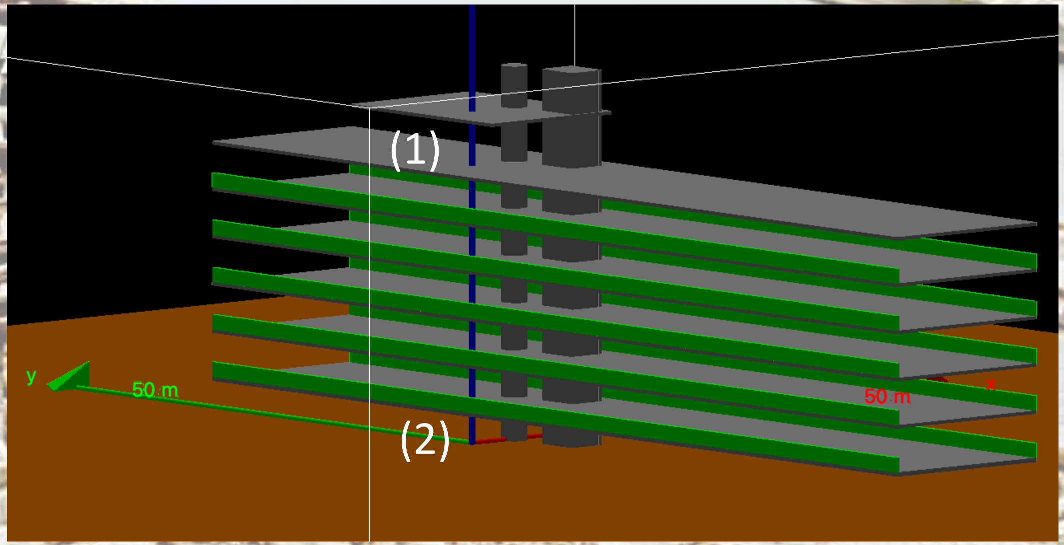
Middle Detection Plane => 1 scint Bar per direction

Rear Detection planes => Consecutive fibers per direction



4 Set of measurements

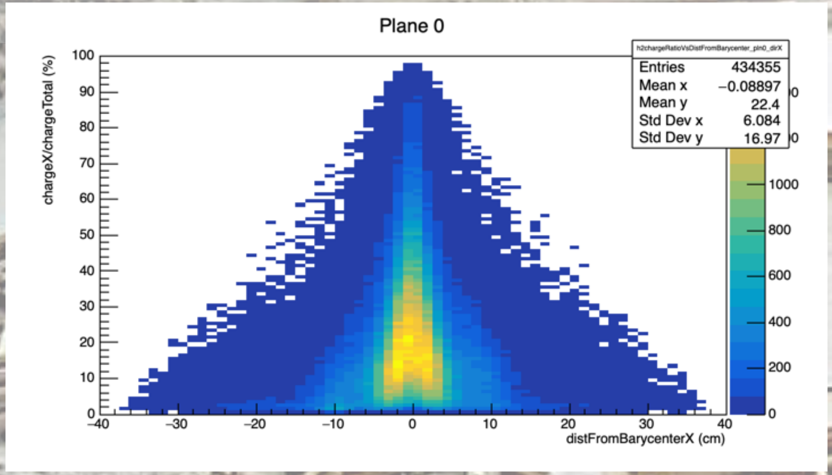
(1) Atrium
(2) Faraday
(3) Vienne – 3 Planes
(4) Vienne – 2 (rear) Planes

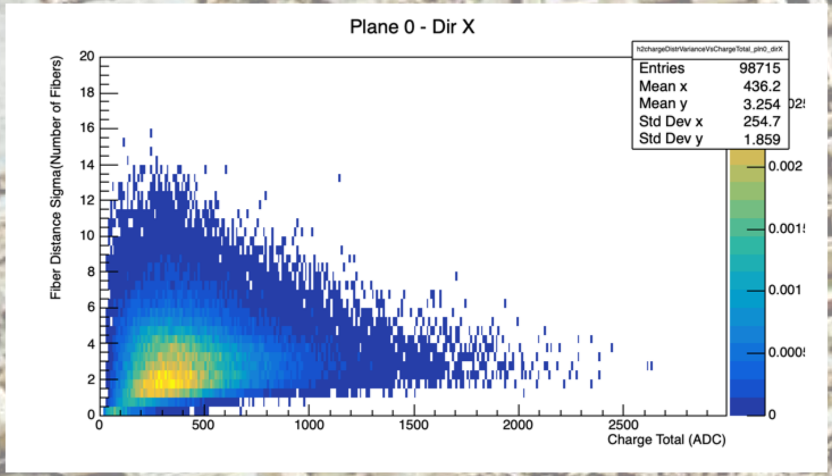


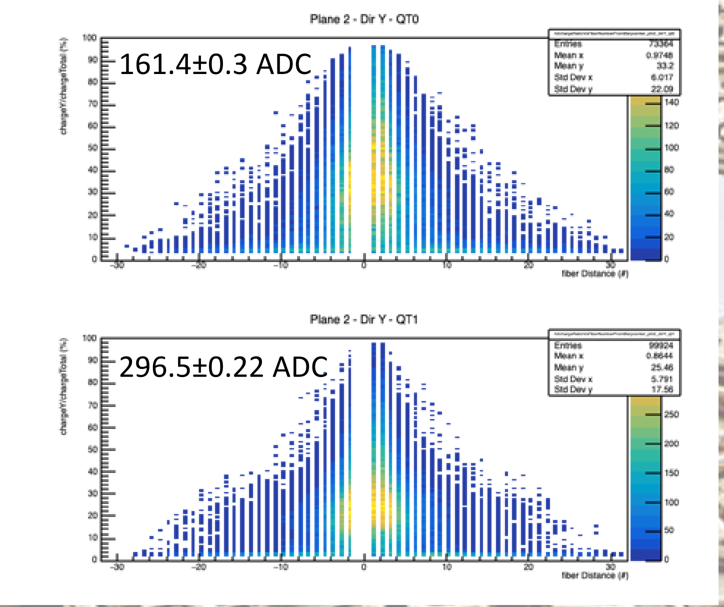
Gold Event Rates:

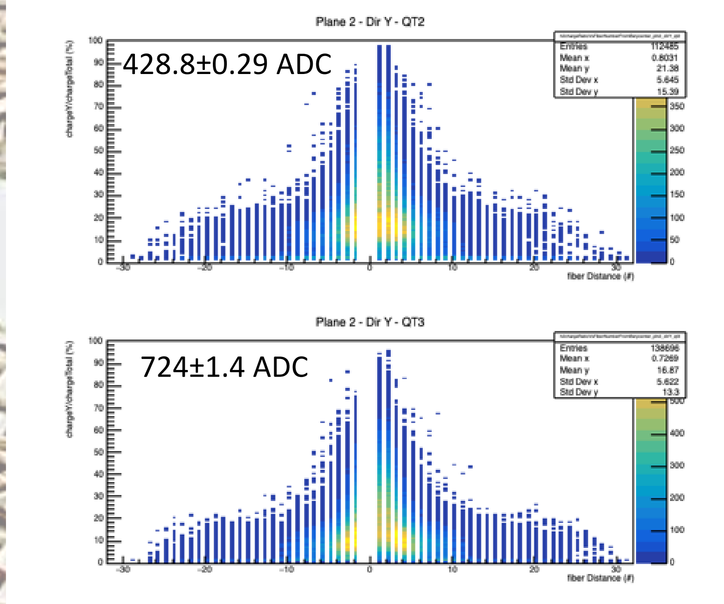
(1) 12.8 * 10^-3 Hz
(2) 8.1 * 10^-3 Hz
(3) 4.5 * 10^-3 Hz
(4) 8.4 * 10^-3 Hz -> A substantial contribution from noise

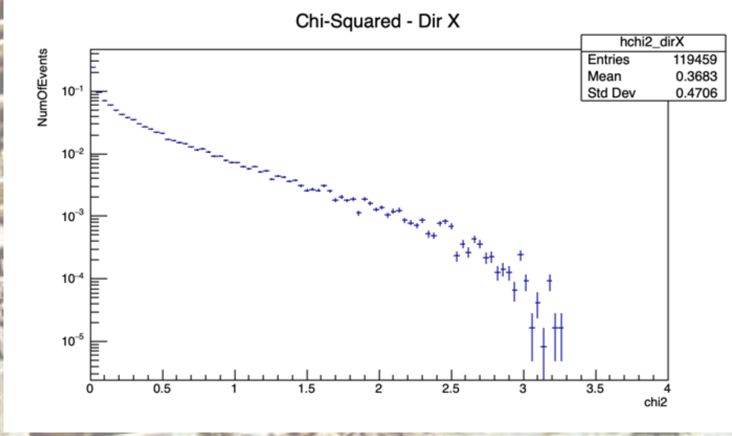
Track Selection - cuts

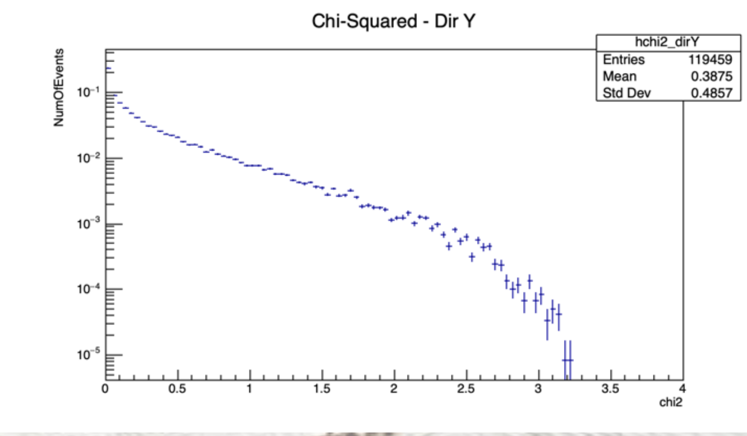




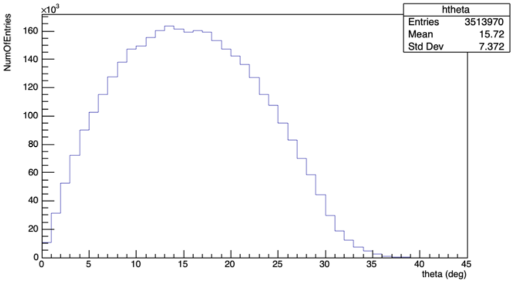


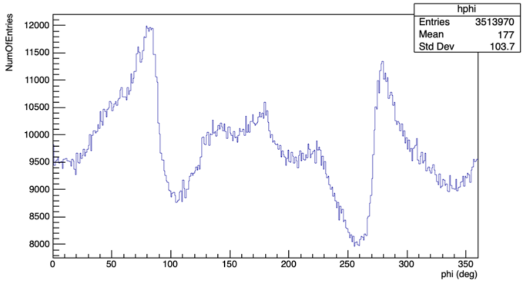


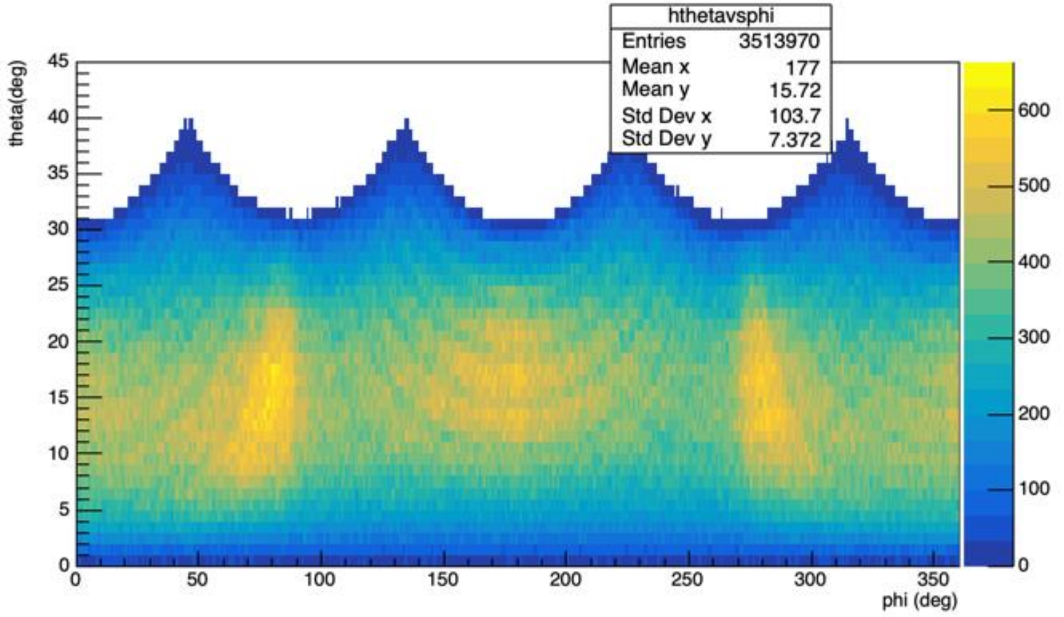


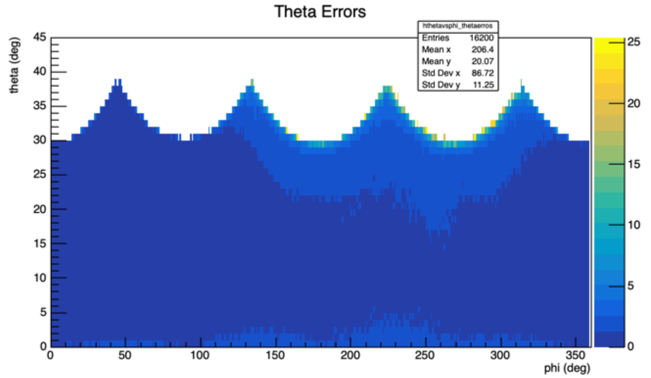


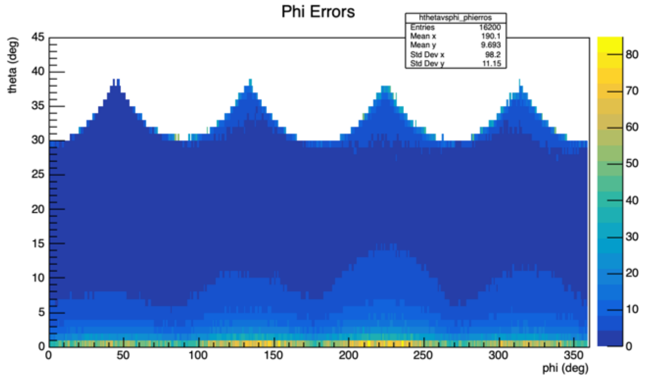
Track Angular Distribution & Errors

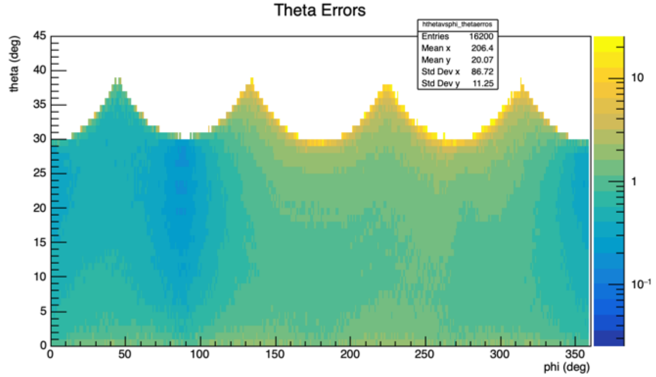


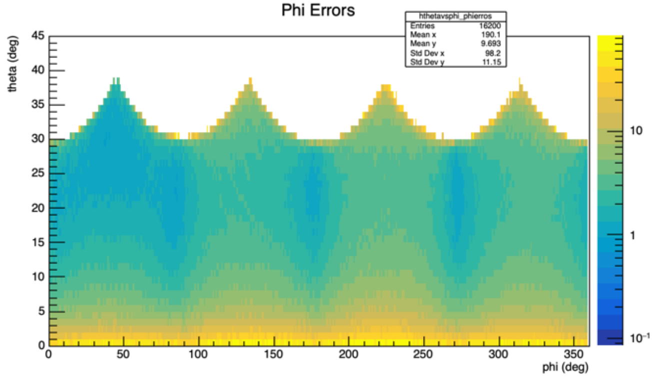




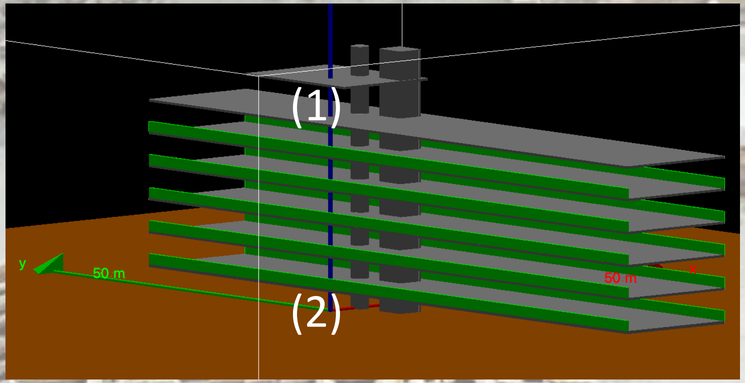


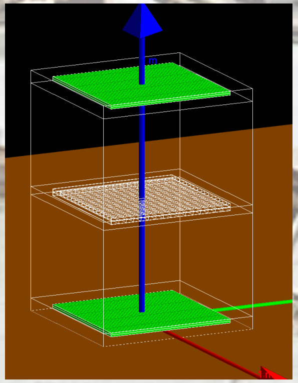


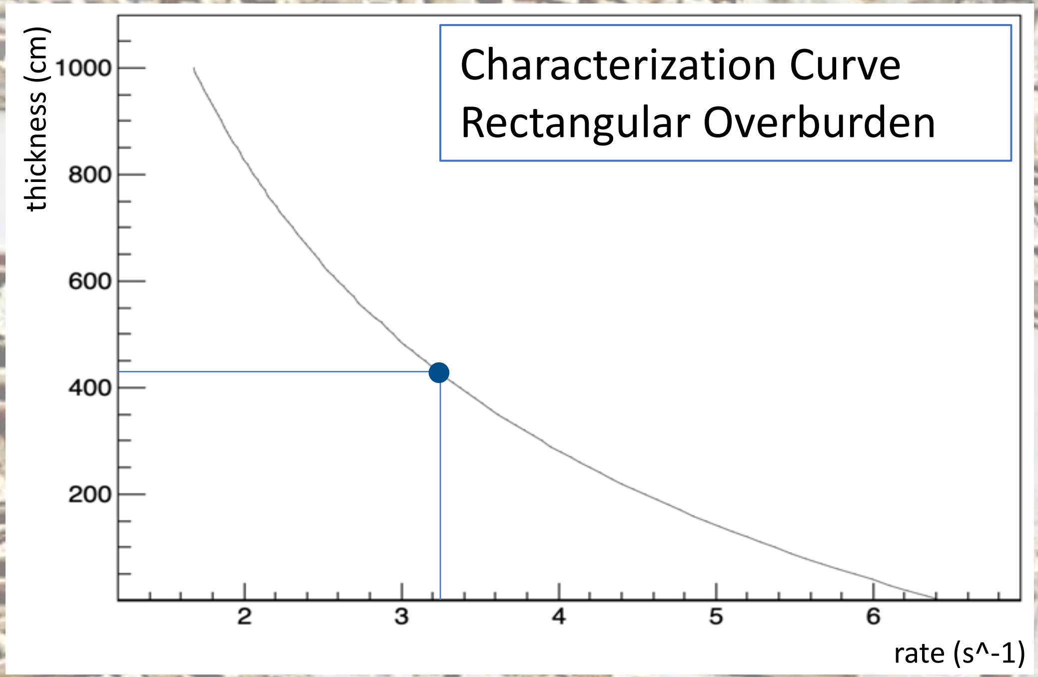




Overburden Thickness Calculation







Detector Efficiency Calculation

Theoretical Rates:

(1) - 6.27852 s^-1

(2) - 4.8298 s^-1

Experimental Rates:

(1) - 1.417 ± 0.003 s^-1

(2) - 1.045 ± 0.004 s^-1

Efficiency:

(1) - 0.2257 ± 0.0005

(2) - 0.2164 ± 0.0008

<Efficiency>: 0.22308 ± 0.00013

Experimental rate inside the Cavity

(Meassured Rate/Efficiency)

1st Run: 0.721 ± 0.007 s^-1

2nd Run: 0.727 ± 0.006

<Rate> = 3.246 ± 0.020 s^-1

Overburden Characterization Curves

Two Geometries for the overburden.

(a) Rectangular &

(b) Rectangular with Semishperical Cavity

The material is soil with dE/dx for Standard Rock

The step for the curve points is 10 cm

Height (a) = 433 ± 5 cm

Height (b) = 427 ± 5 cm

<Height> = 430 ± 5 cm

Conclusions

- ❖ Noisy Environment: High Muon rates
  Surrounding materials proximity to detectors
- ❖ Long DAQ time duration for investigating the surrounding galleries
- ❖ Good opportunity to study new detectors in a confined/controlled environment

Outlook

- ➢ Develop the Simulation, implement the surrounding structures
- ➢ Acquire Open sky data to better estimate the result
- ➢ Implement the Inverse Problem workframe
- ➢ <u>Study the behavior of water retention by the overburden by taking into account the atmospheric condition variabilty.</u>
- ➢ Evaluate the performance of the new detector in the case of Volcanoes


Jacques Marteau


Benoit Tauzin


Julie Rodet