MUOGRAPHERS '23
Naples, 19-22 June
International workshop on Muography

Near Surface Muography Studies and Application to Archaeology

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MUSÉE GALLO-ROMAIN SAINT-ROMAIN-EN-GAL

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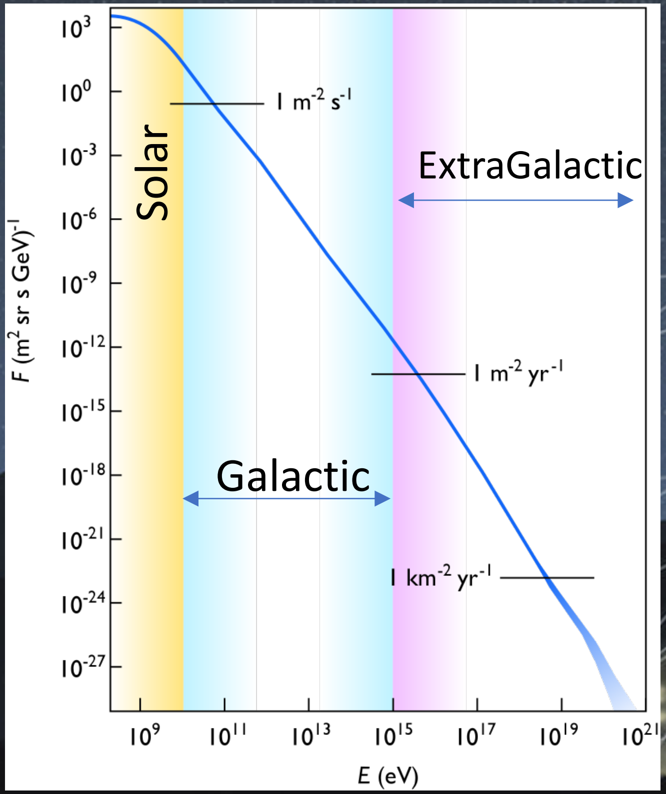
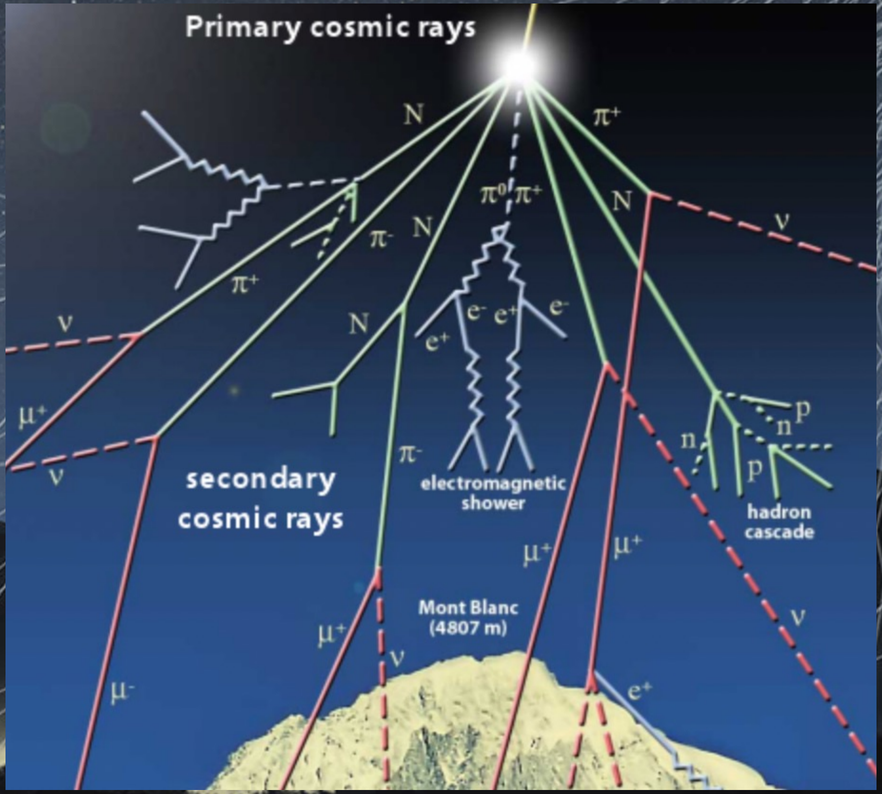
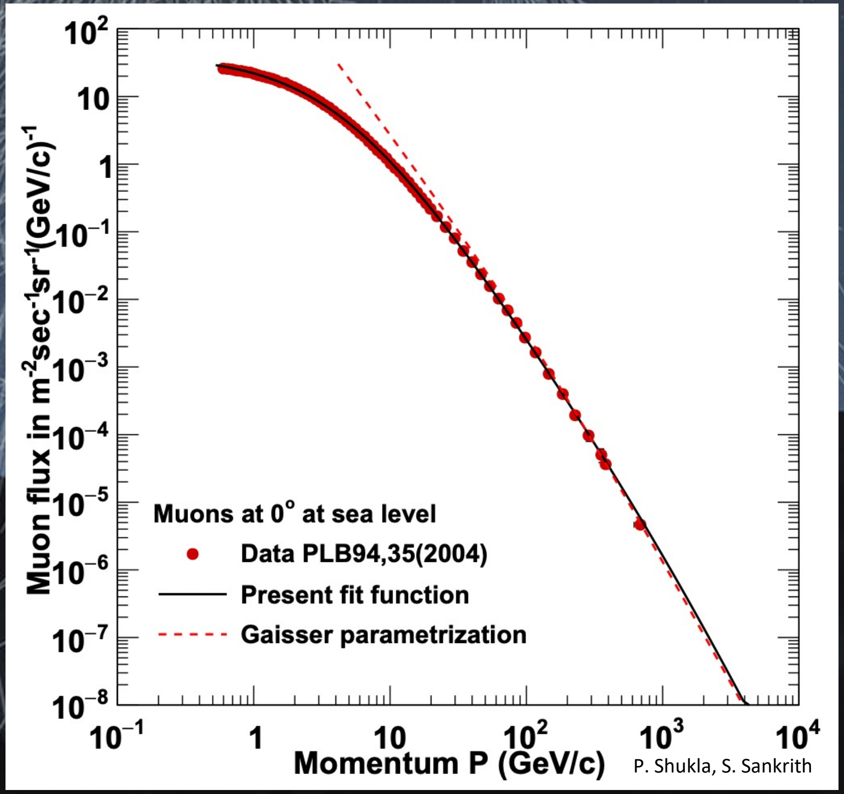
Cosmic Rays

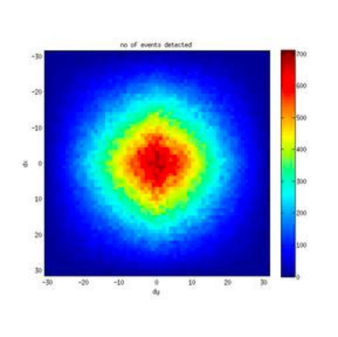
- High Energy Particles
- Atmospheric Cascades
- Extensive Air Showers
- “Steady” Muon Stream





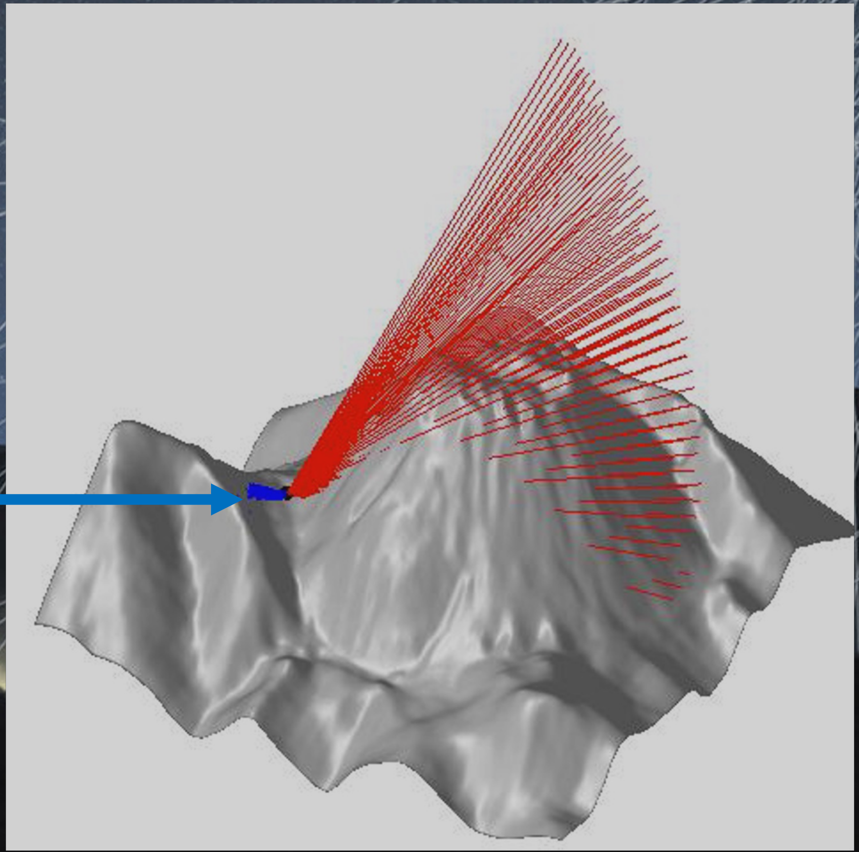


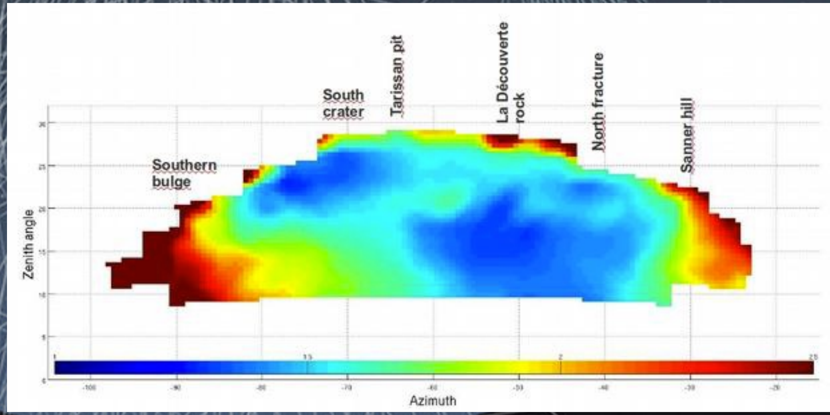
Muon Tomography

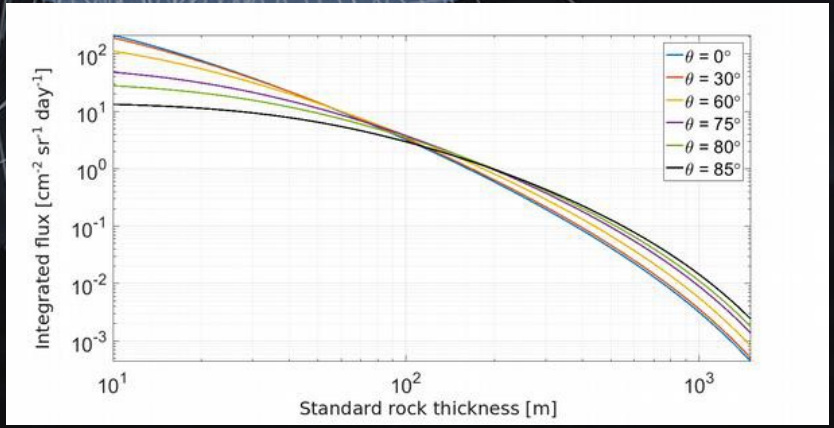


$$\varrho(L) \equiv \int_L \rho(\xi)\mathrm{d}\xi$$

ϱ = opacity ρ = density

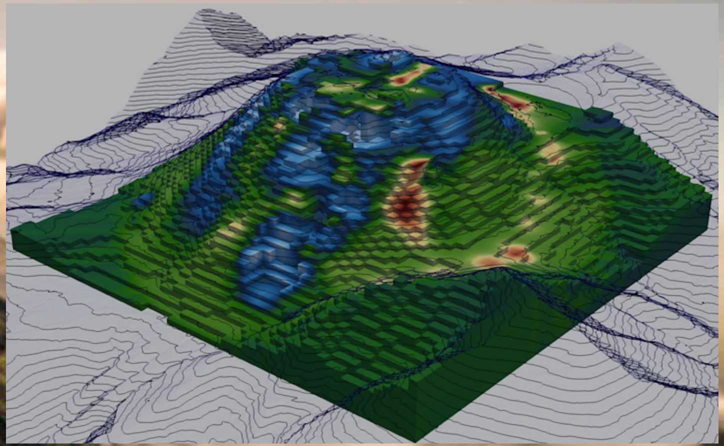




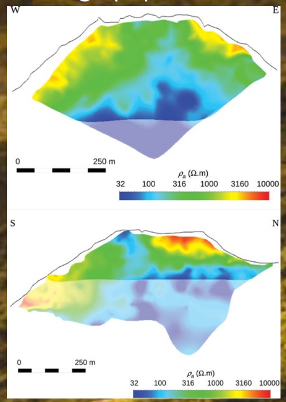


Multimessenger Geophysics

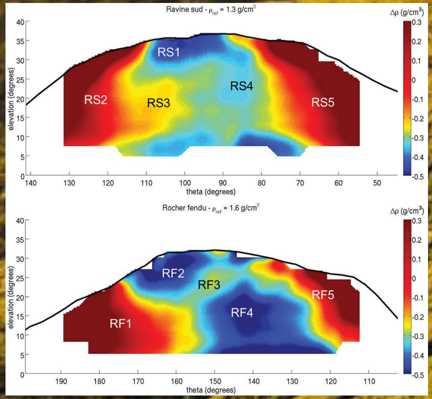
Combining Exploration Geophysics
with Muon Tomography
at the active volcano “La Soufrière” in Guadeloupe

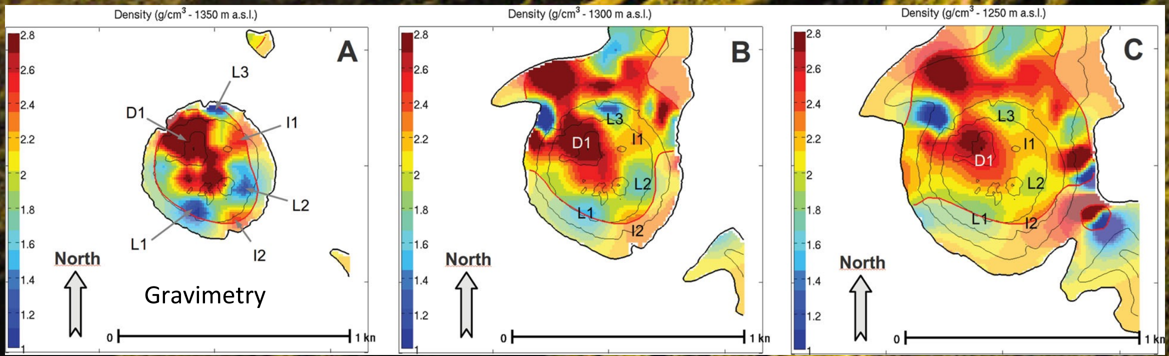


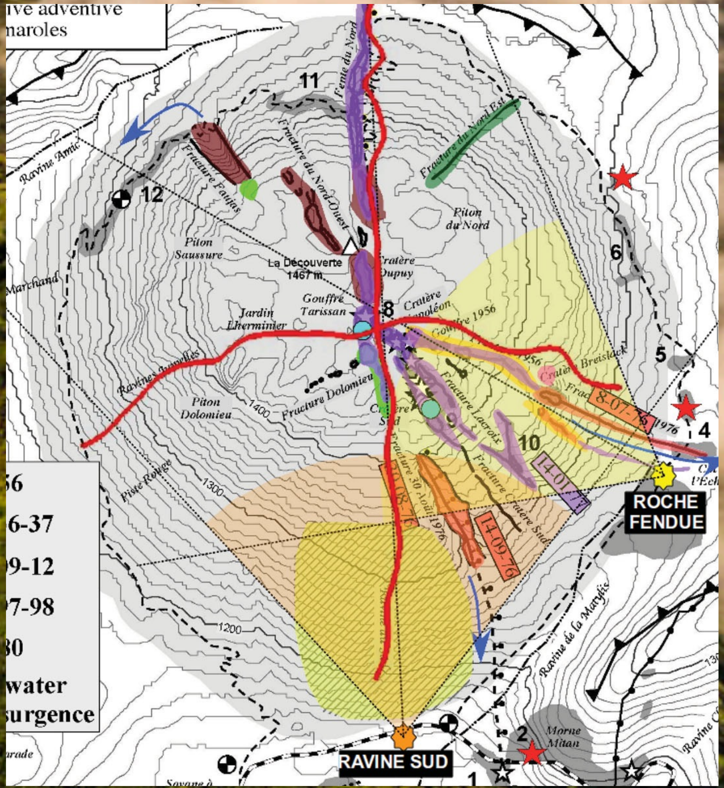
Electric Resistivity Tomography



Muon Tomography







A more difficult case : Tumuli

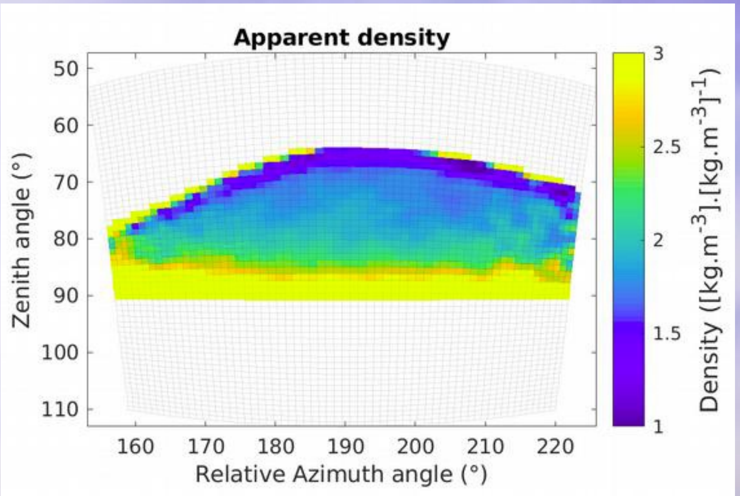
The Apollonia tumulus as a benchmark for the method

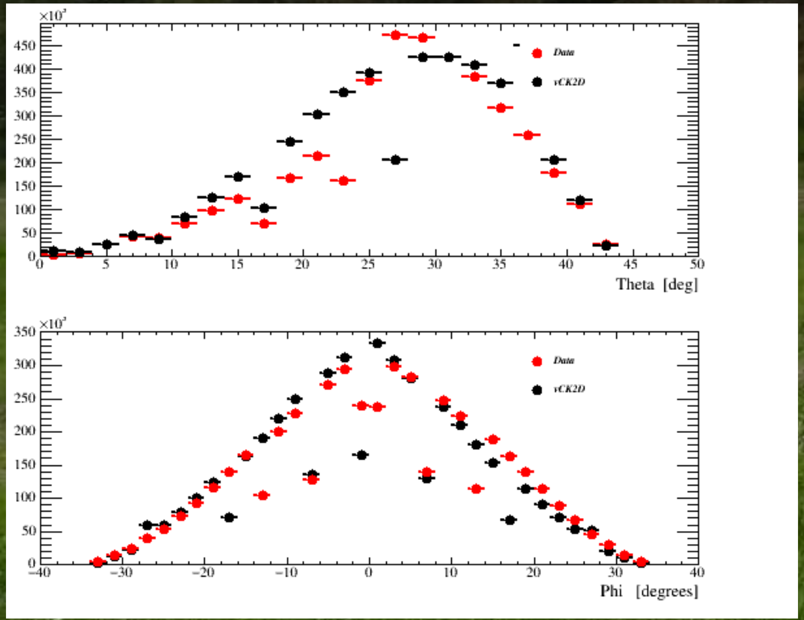
- Existing monument
- Density anomalies detected by other methods

Difficulties :

- Looking for an object with similar density as the surrounding materials ρ~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





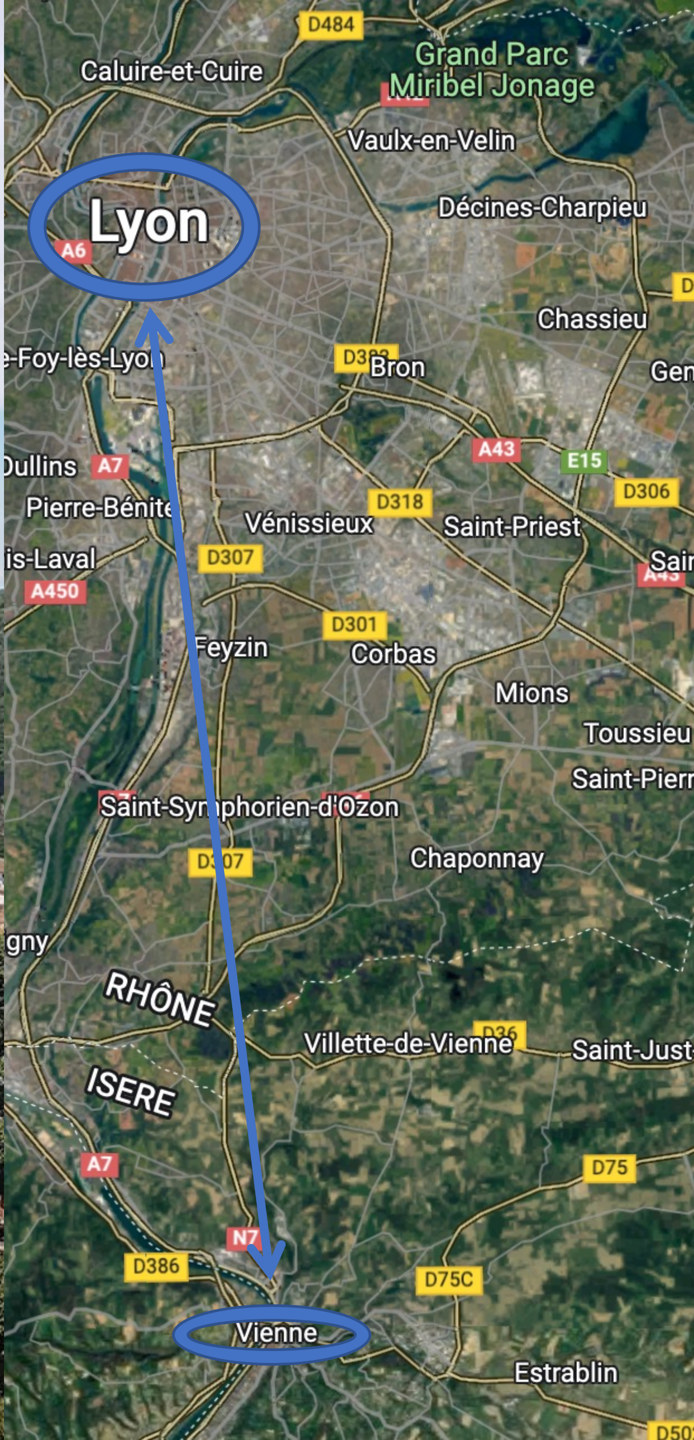
- Level of agreement ~10 to 20% between observed muon fluxes and simulation
- Precision experiment looking for tiny effects
- Limitations:
  - The precise knowledge of the muon spectrum and muon statistics
  - A more accurate geometrical description of the tumulus and the density of soil

ArchéMuon

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

The town of Vienne



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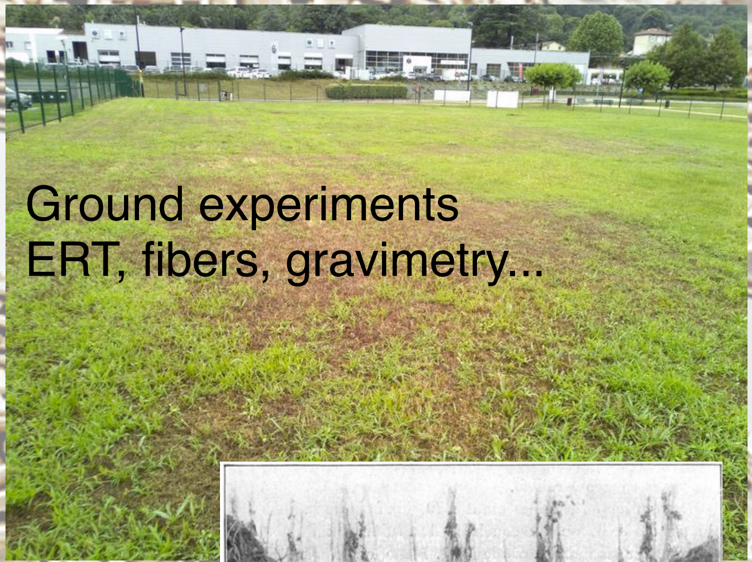
Palais du Miroir

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

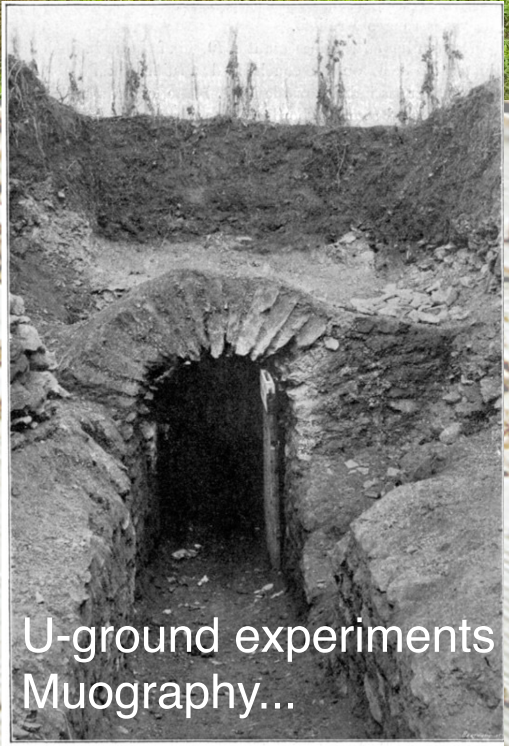
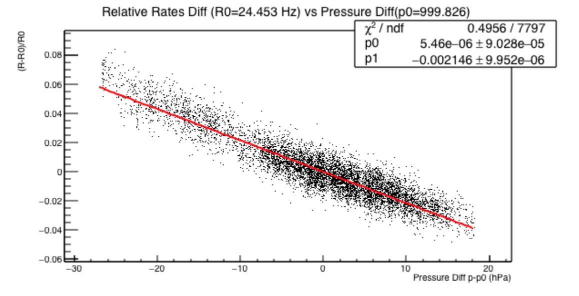


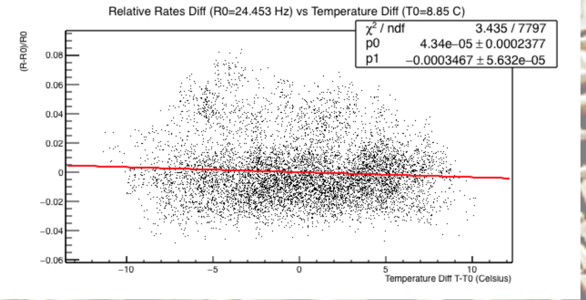
Fig. 8. — Entrée des aqueducs du Palais du Miroir.

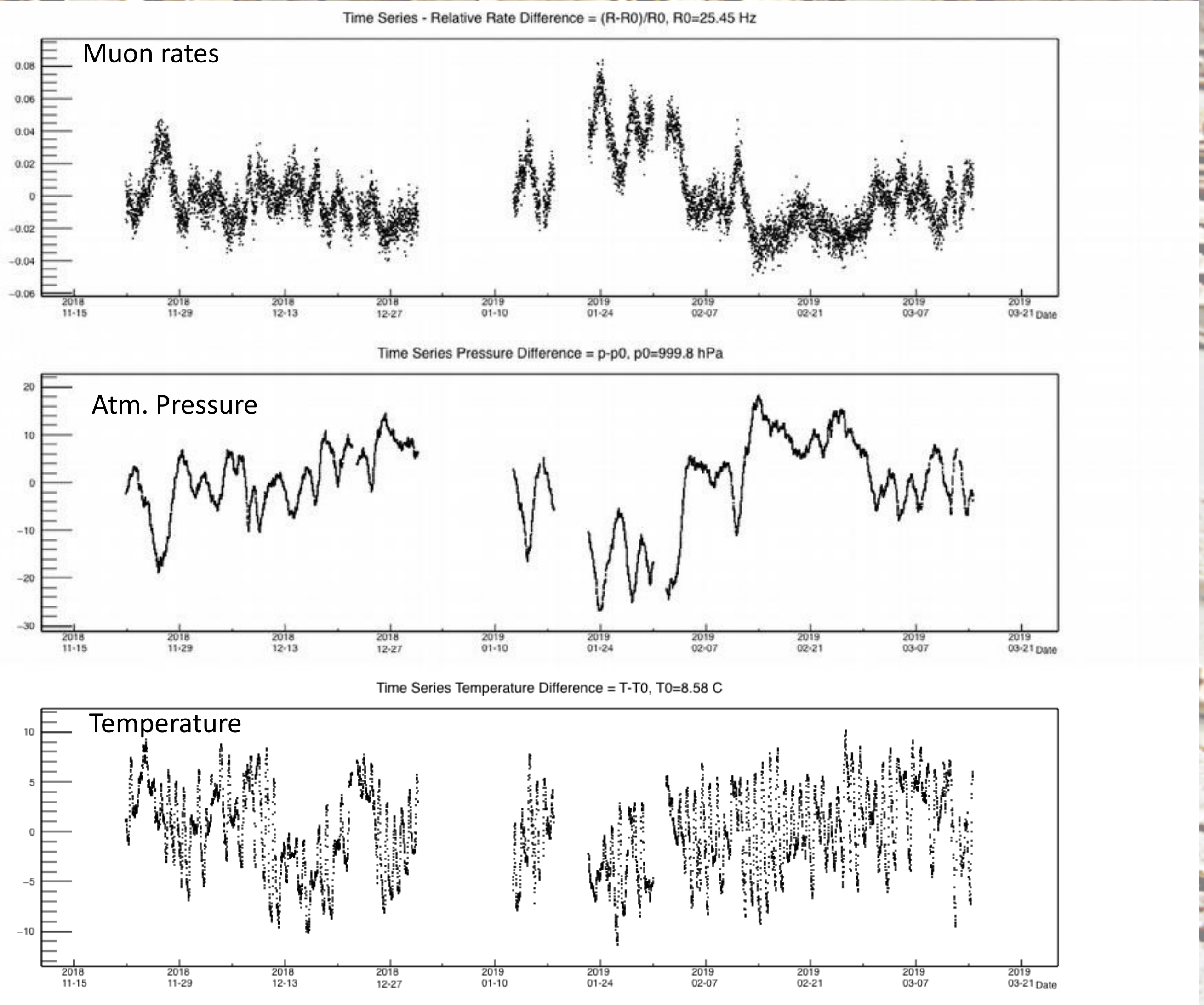
Atmosperic effects

Weather affects muon rates
Correction for precision experiments

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



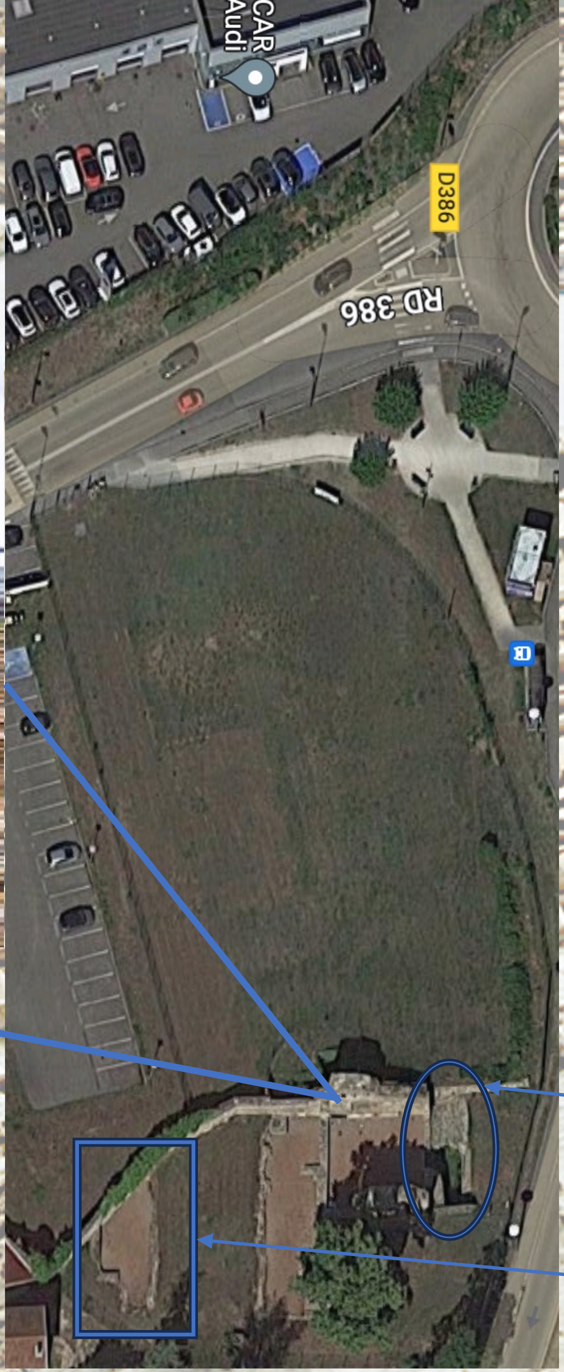




How soil water retention affects the measurement

EGO-Virgo CR monitoring

OverGround


CAR
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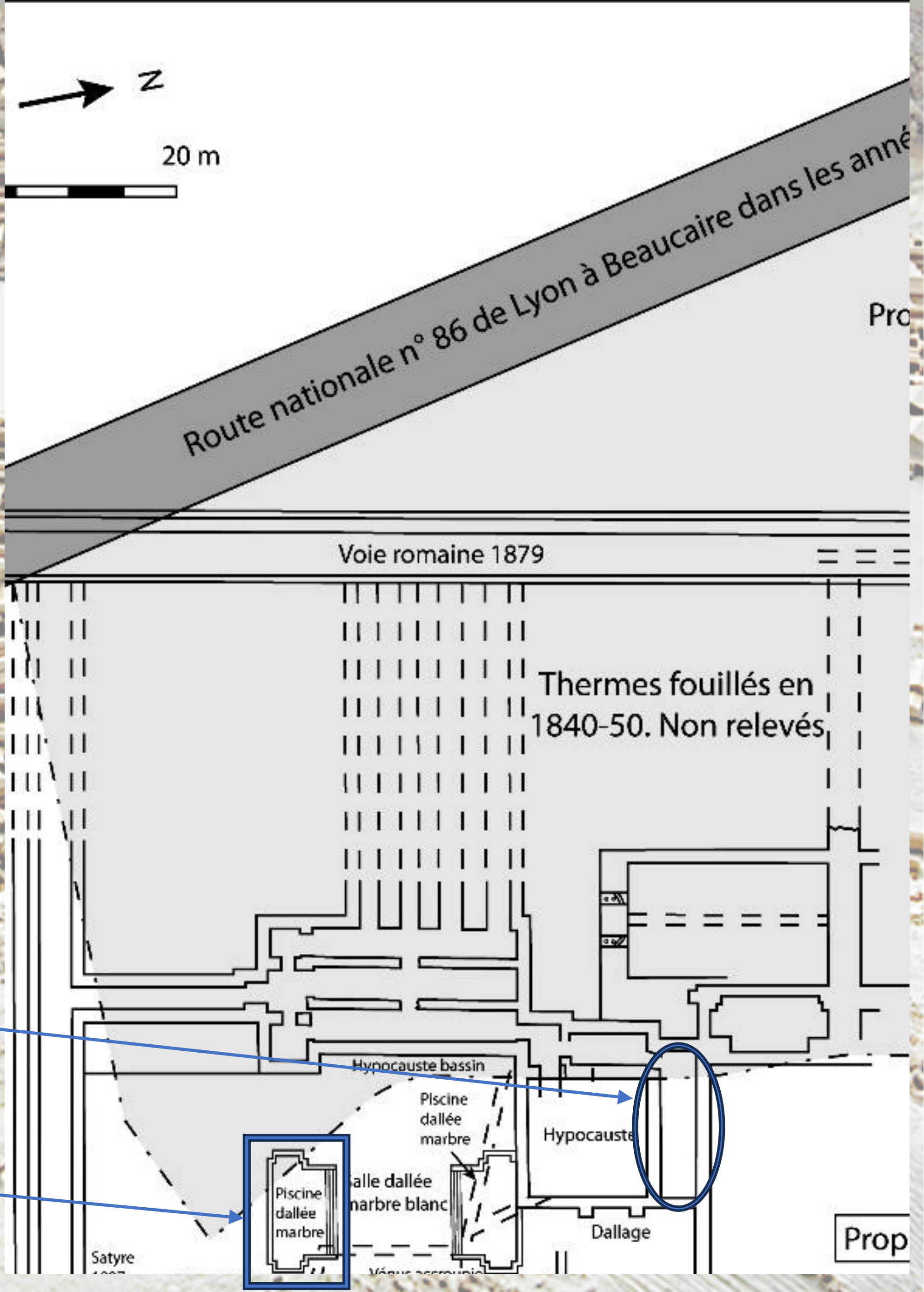
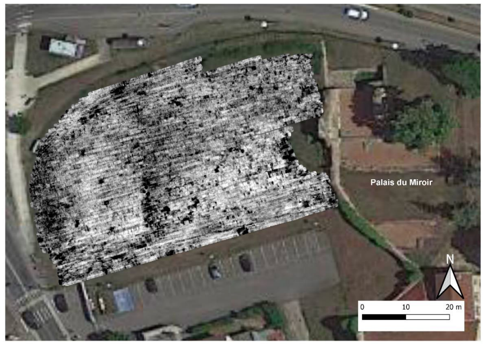
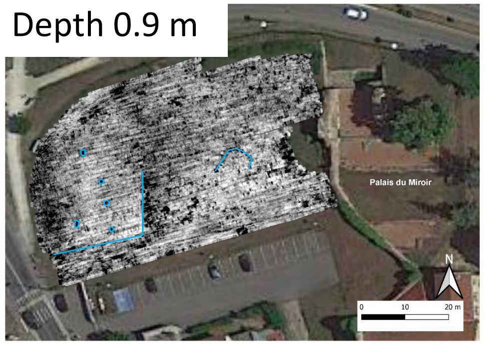
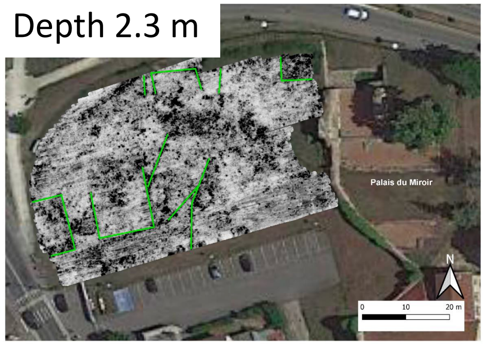
D386
RD 386

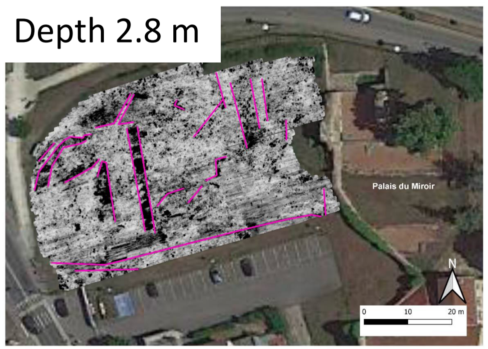

N
20 m
Route nationale n° 86 de Lyon à Beaucaire dans les anné
Pro
Voie romaine 1879
Thermes fouillés en 1840-50. Non relevés
Hypocauste bassin
Piscine dallée marbre
Hypocauste
alle dallée narbre blanc
Piscine dallée marbre
Dallage
Satyre
Prop

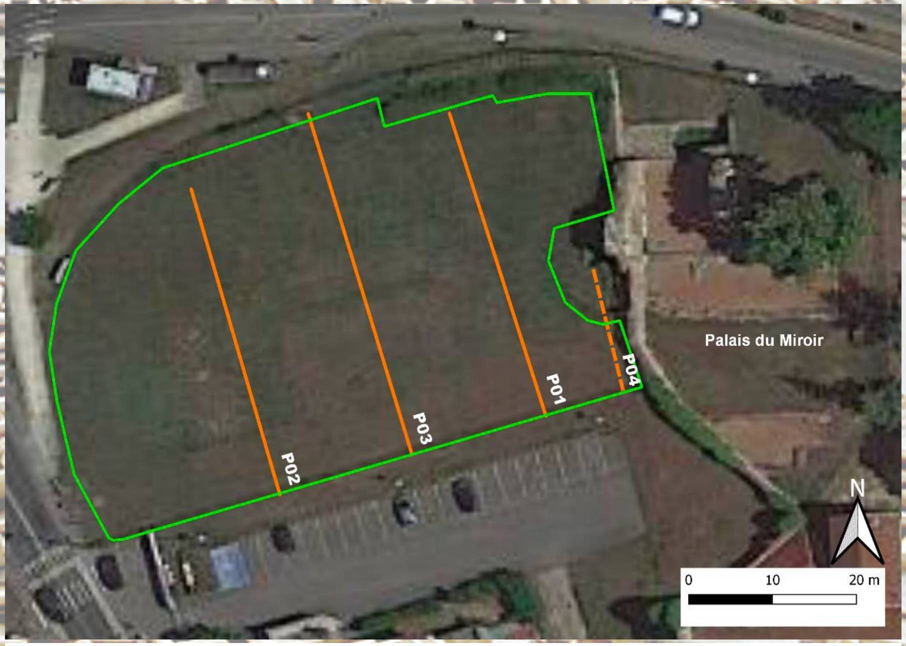
GeoRadar & Electric Resistivity Tomography

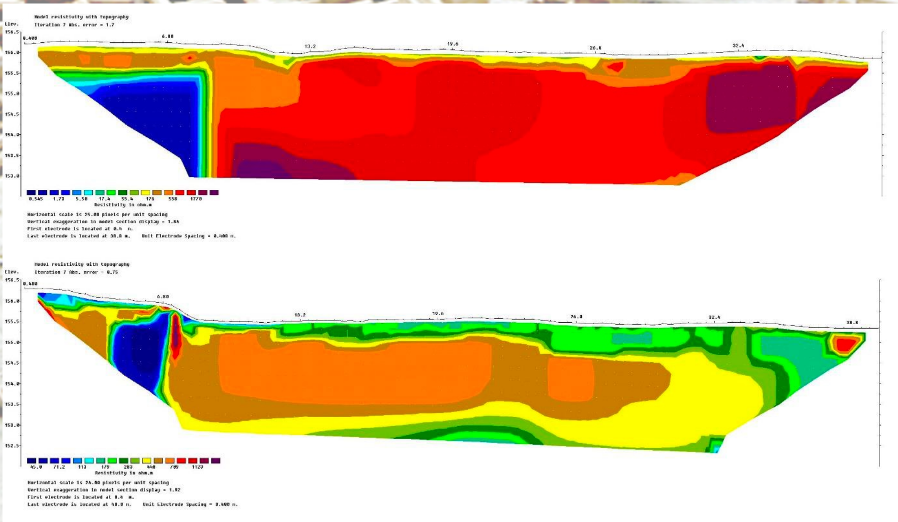




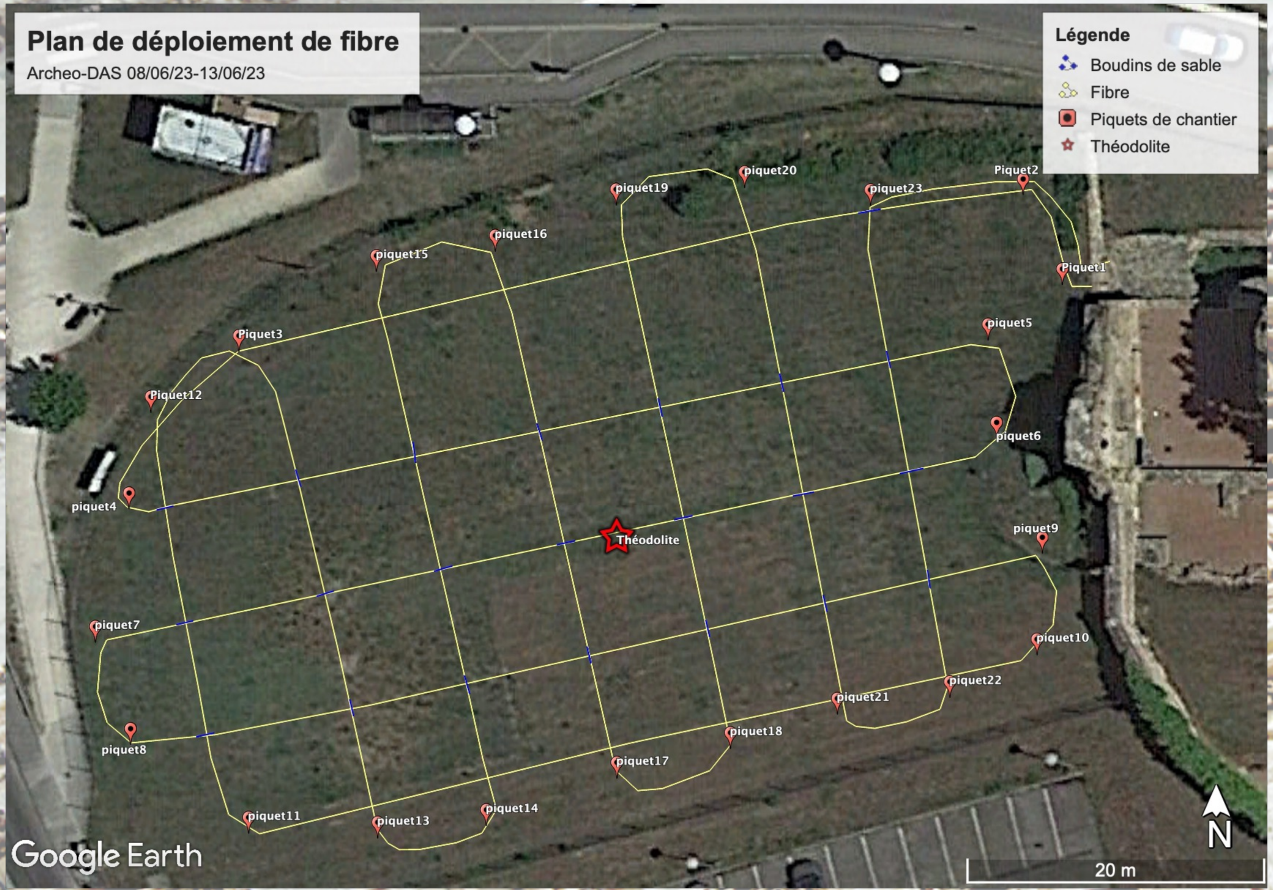


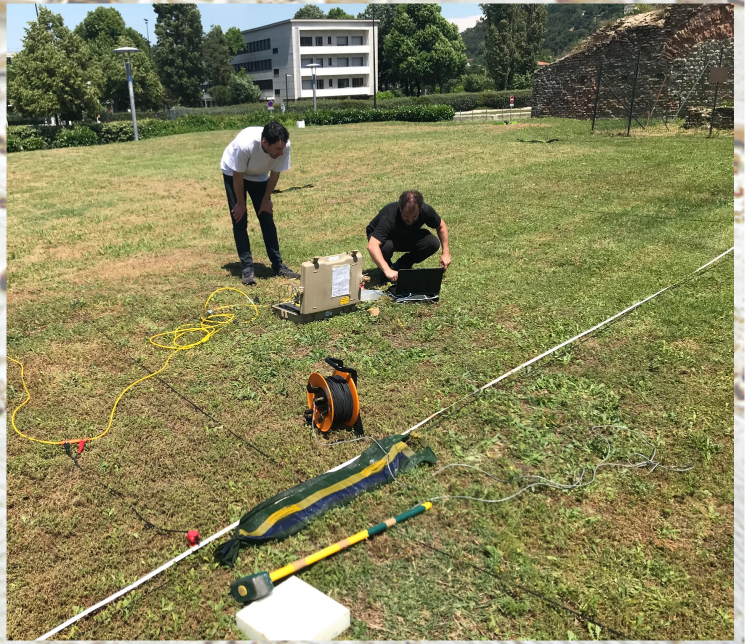




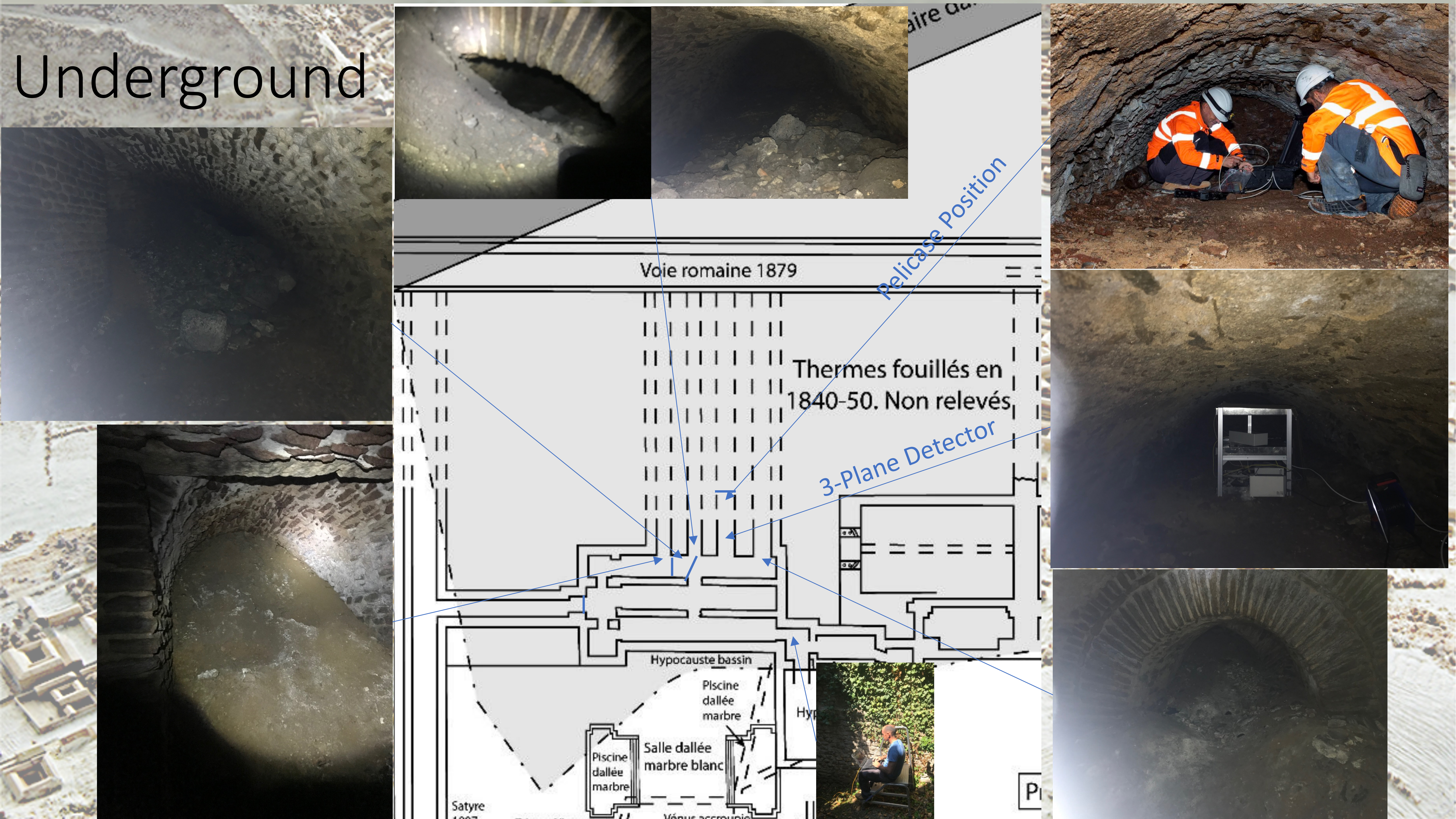


Distributed Accoustic Sensing & Seismometry

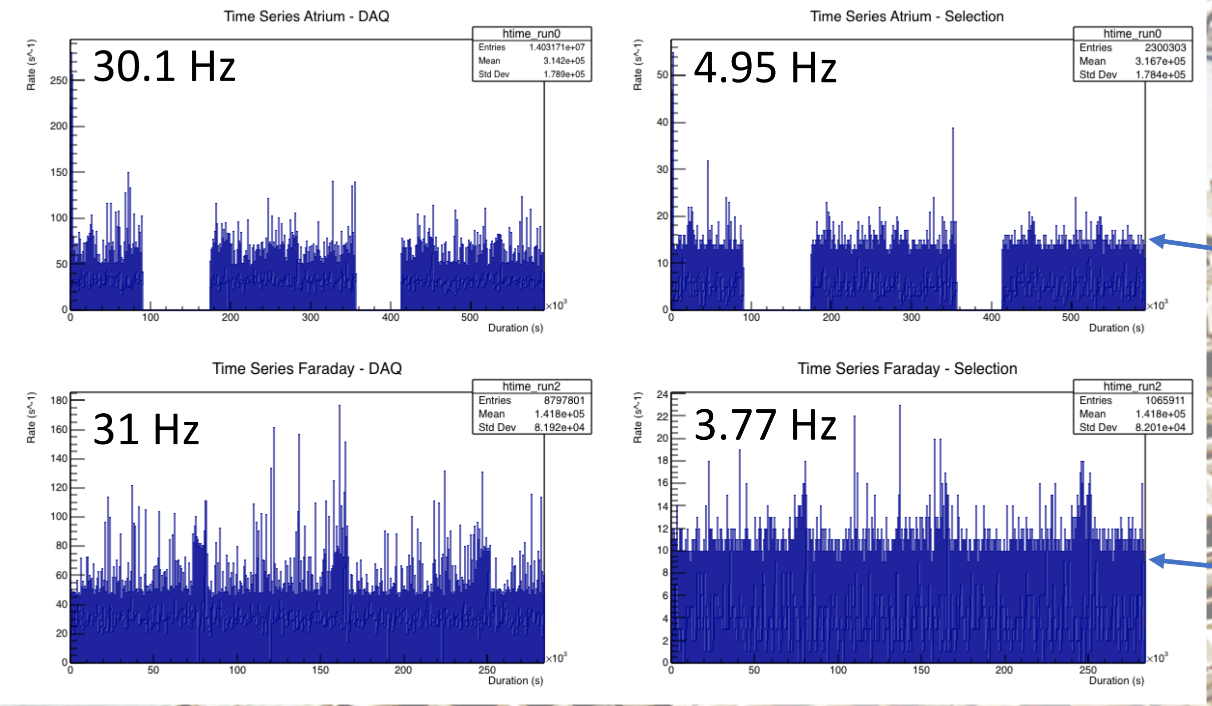


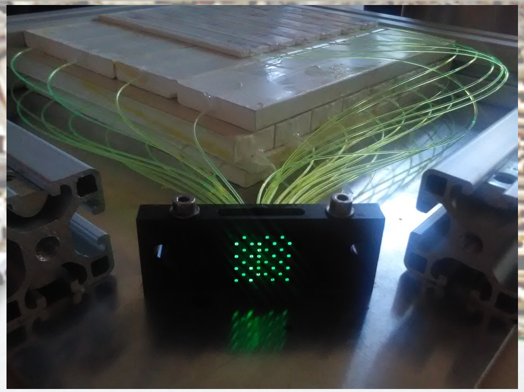


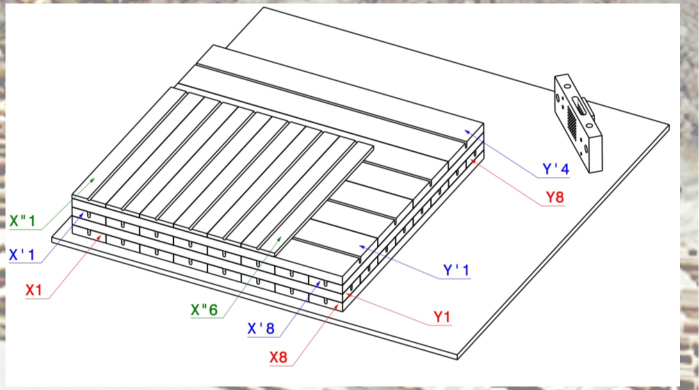
Underground

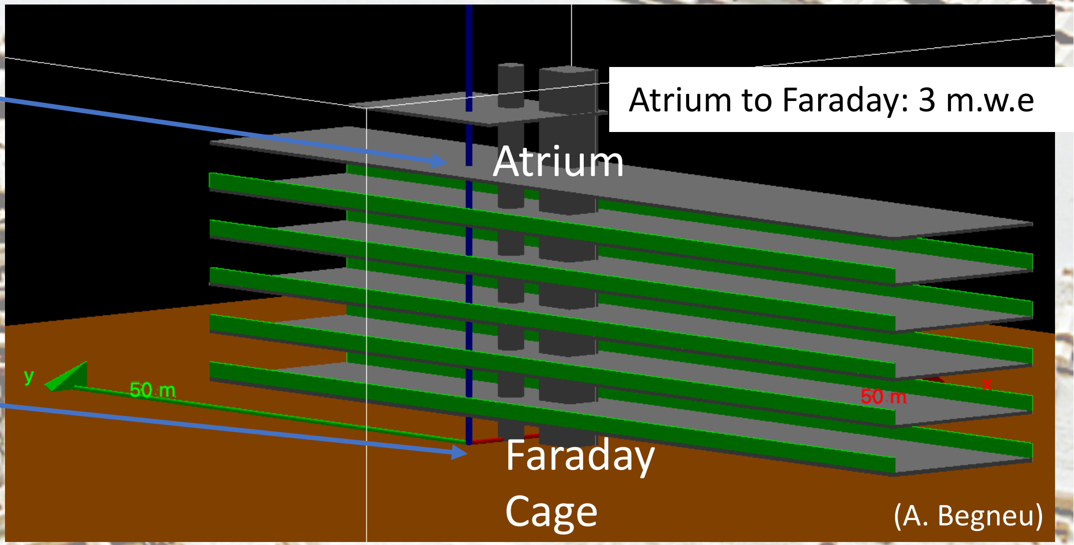


Pelicase detector @ IP2I









Selection: 4–fold Coincidenses between lower planes

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 GeV)

Pelicase

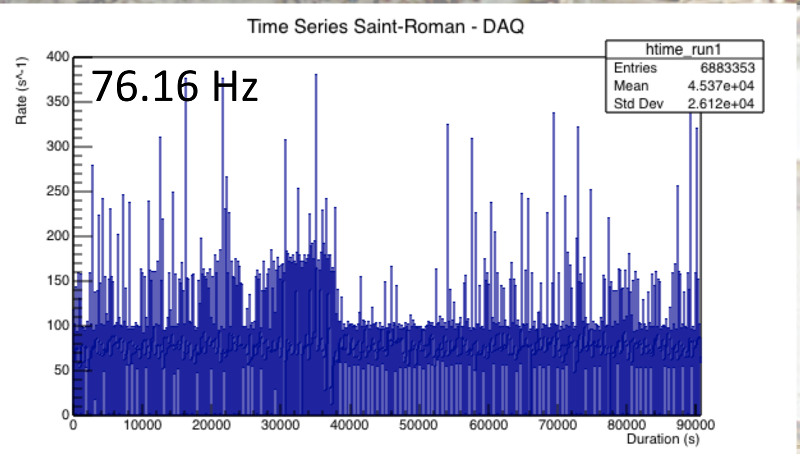
Detection Efficiency (DE): Selection Rate / Theoretical Rate

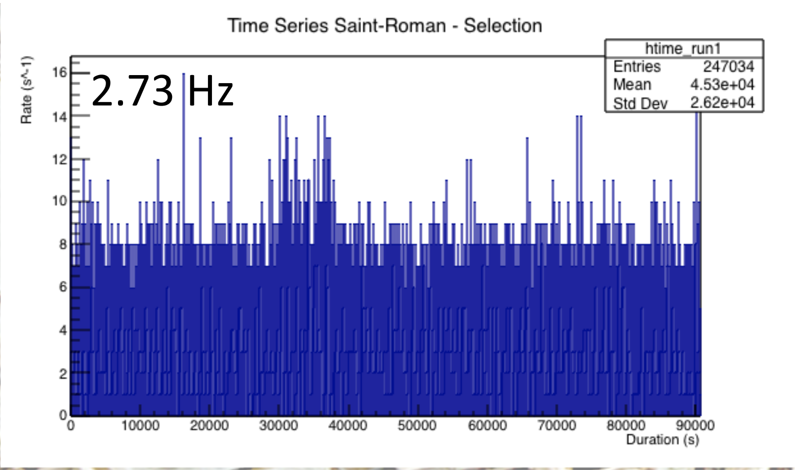
Atrium: 0.6743±0.0004

Faraday: 0.6587±0.0007

Mean value: 0.6665

Pelicase detector @ Palais de Miroir

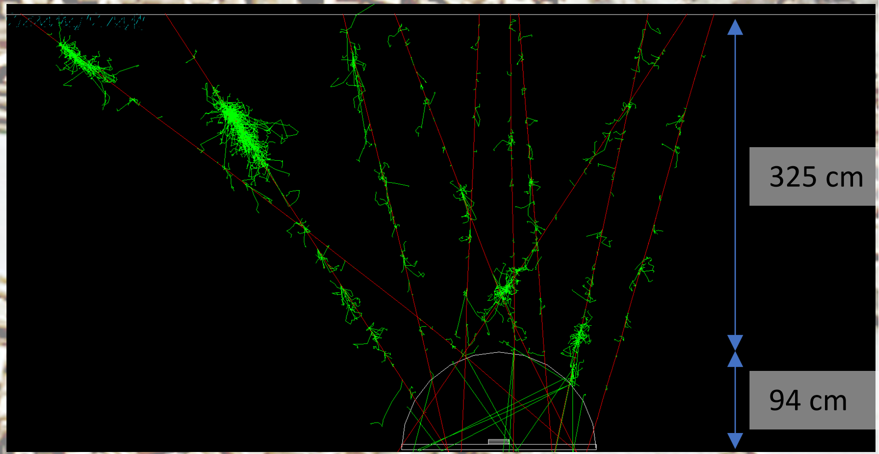




Experiment

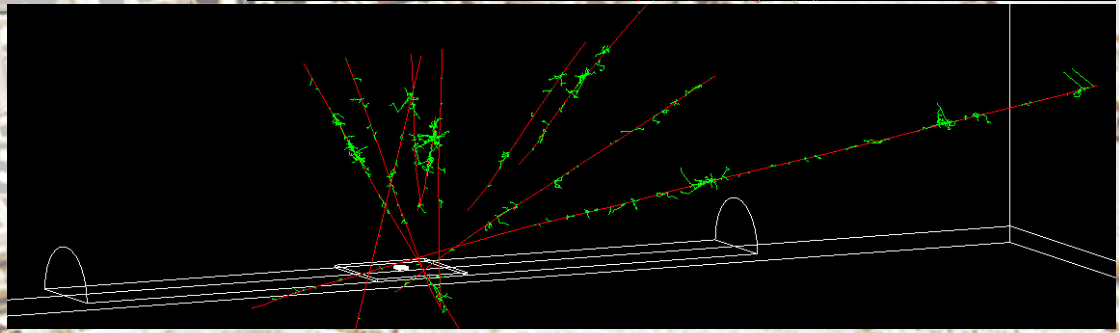
Rate = Selection Rate / Det Eff = 4.090 Hz
Eth = 1.455 GeV
OverBurden: 730 cm water eq. or
325 cm Standard Rock

Surface (pelicase) 20 cm x 20 cm
Expected muons on ±94 cm x ±94 cm = 32M



Simulation

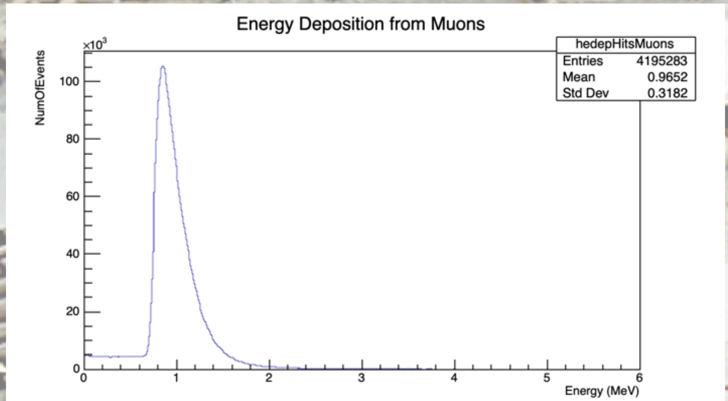
14M Muon Tracks over
±94 cm x ±94 cm surface
Reweight param: 32M/14M = 2.286

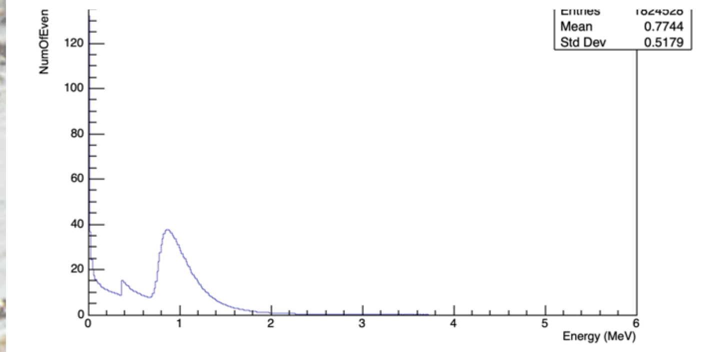


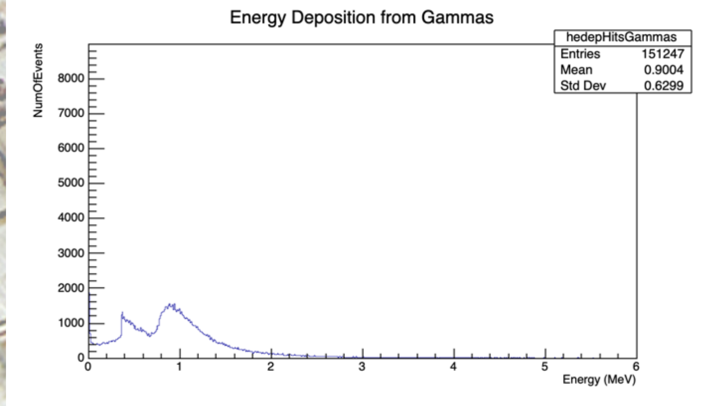
Total 4-fold Coincidences:	114843	x 2.286 =	262531
Muon 4-fold Coincidences:	1767		4039
4-folds with at least 1 Muon:	18314		41865
4-folds WITHOUT Muons:	96529		220665

Very noisy environment
Noise ~ muon rates
Pelicase is insufficient for this study

2 Plane Detector - Simulation







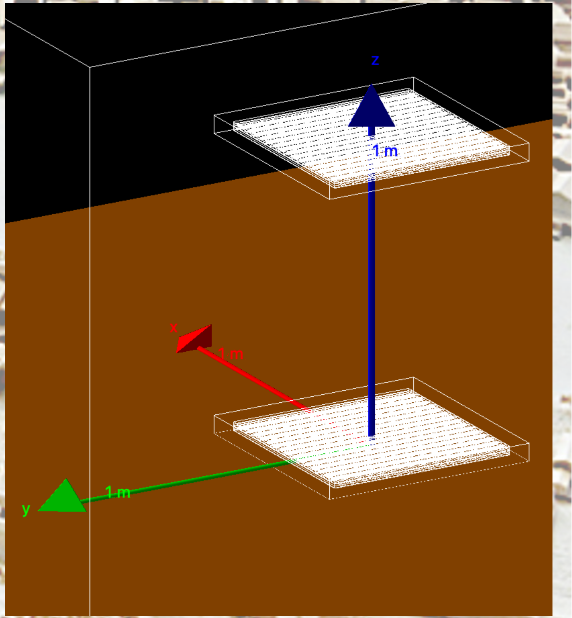
No Cuts

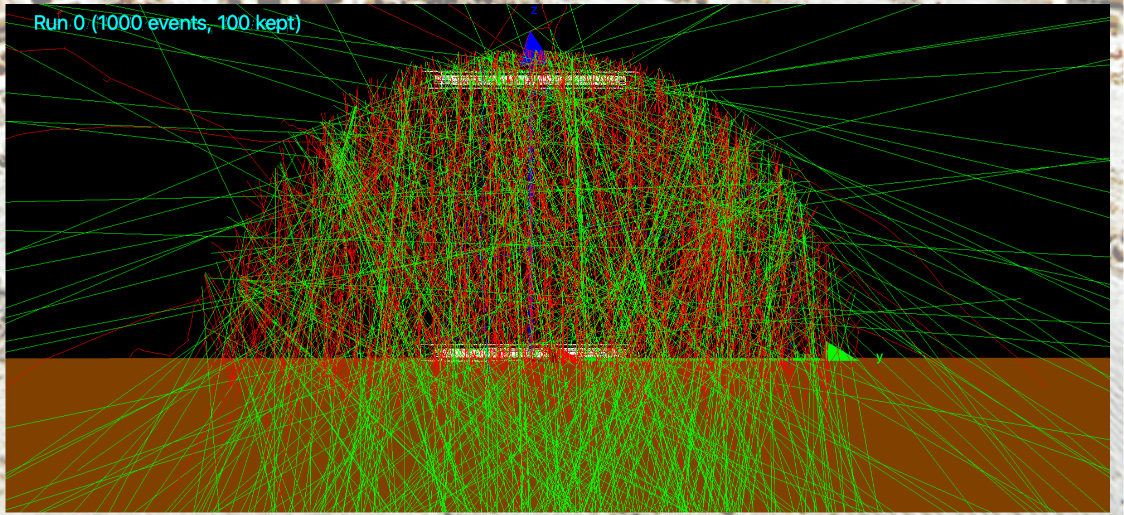
```
events with hits: 1993708
Events with 2 fold Coincidences: 351286
2-fold Coincidences with muon: 323597
2-fold Coincidences From Muons: 182544
```

Energy Depostition>0.6 MeV

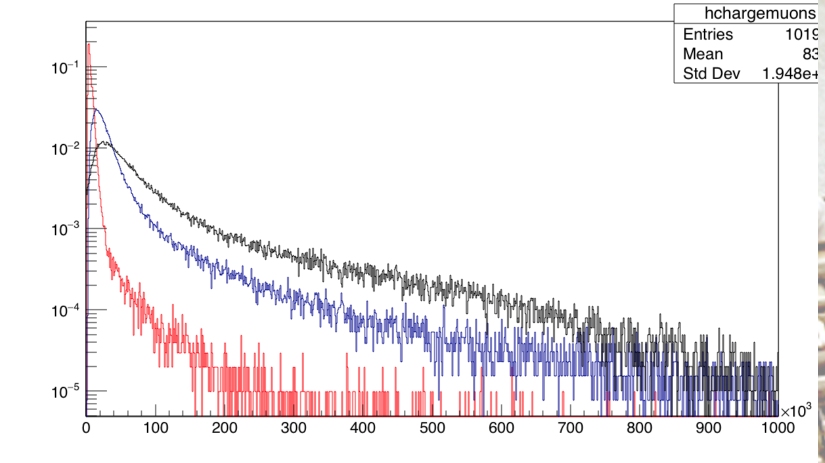
```
events with hits: 1526250
Events with 2 fold Coincidences: 273770
2-fold Coincidences with muon: 272918
2-fold Coincidences From Muons: 173913
```

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

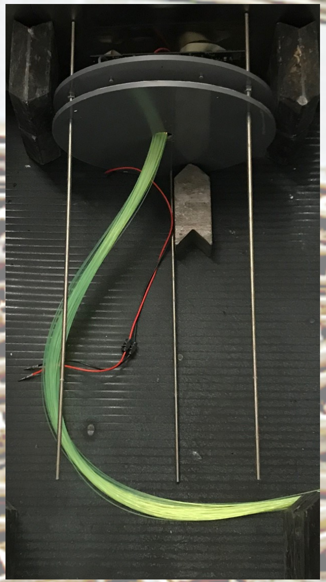


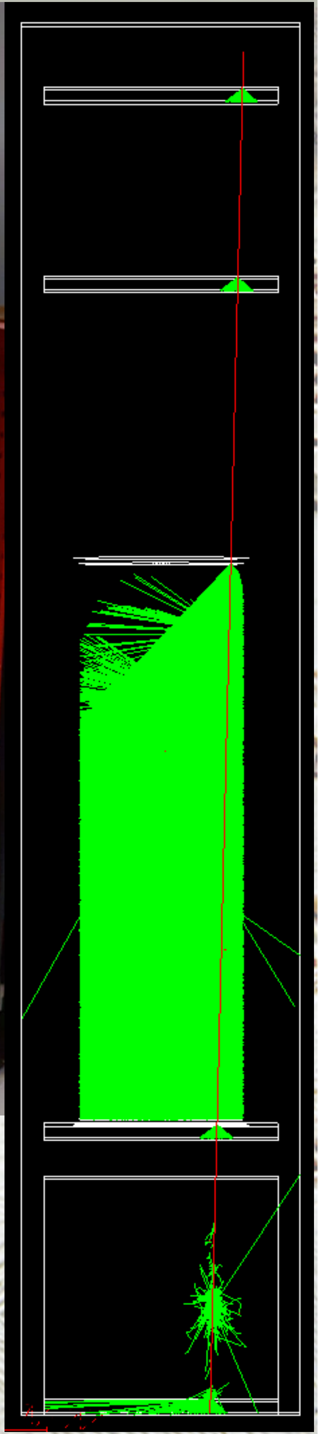


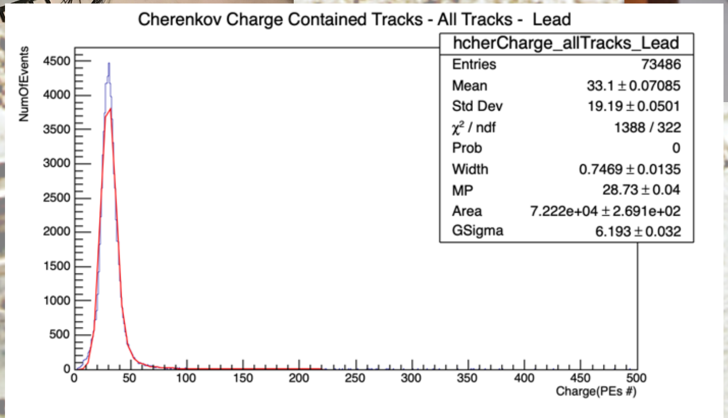
Portable Cherenkov detector (ongoing work)



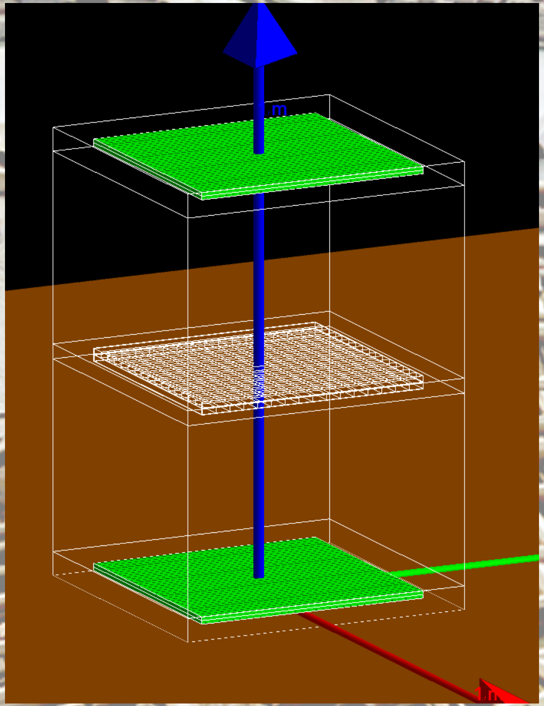
- Energy < 10GeV
- Particles Crossing the entire Cherenkov Detector
- Red – Muons (Peak@4K photons)
- Blue – Electrons (Peak@15K photons)
- Black - Electrons that may exit the Cherenkov detector or get absorbed inside it

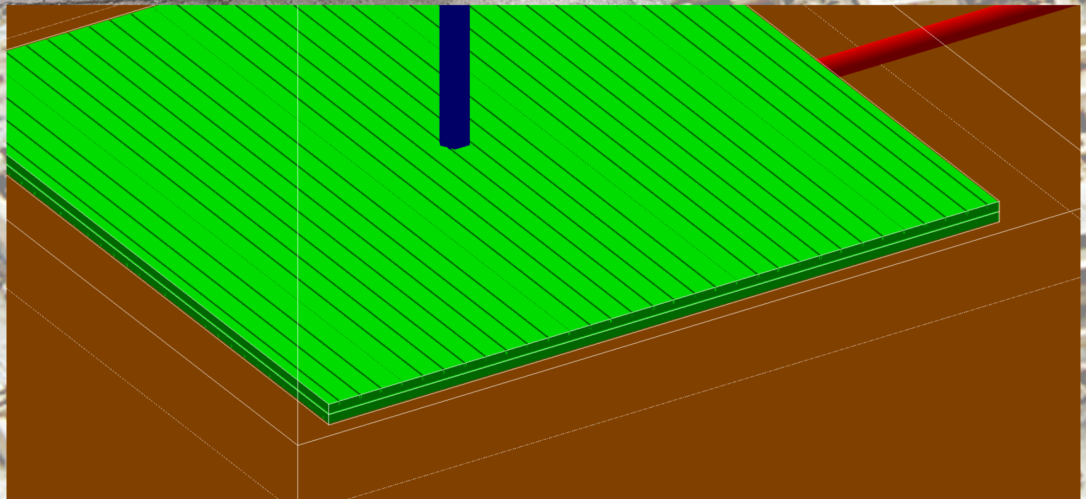




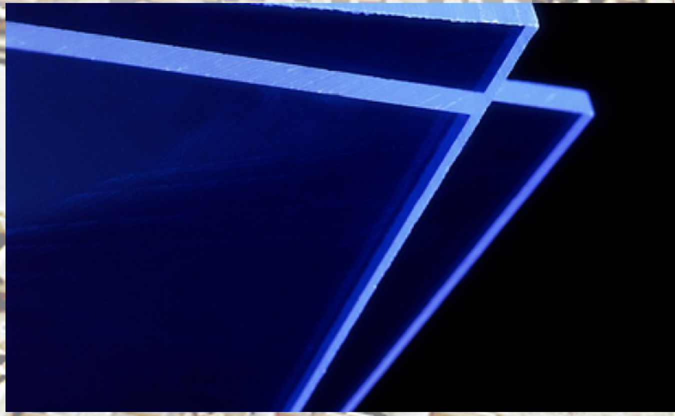


Current Detector – Palais de Mirroir





Saint-Gobain Crystals



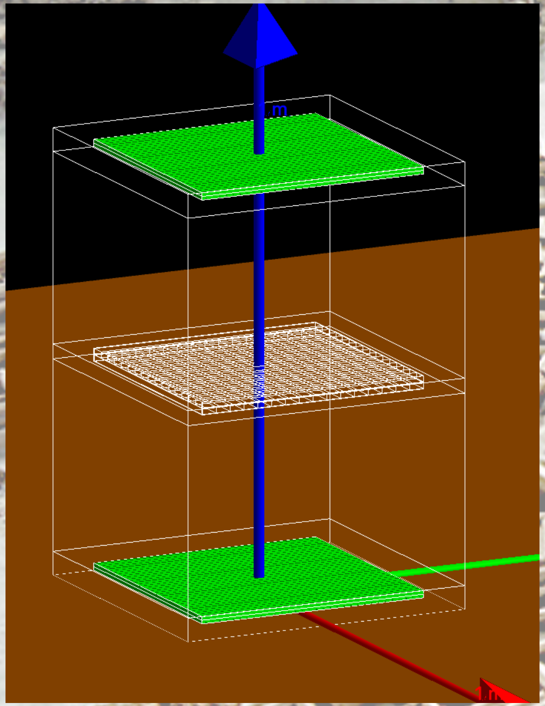
ref. Luxium Solutions

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

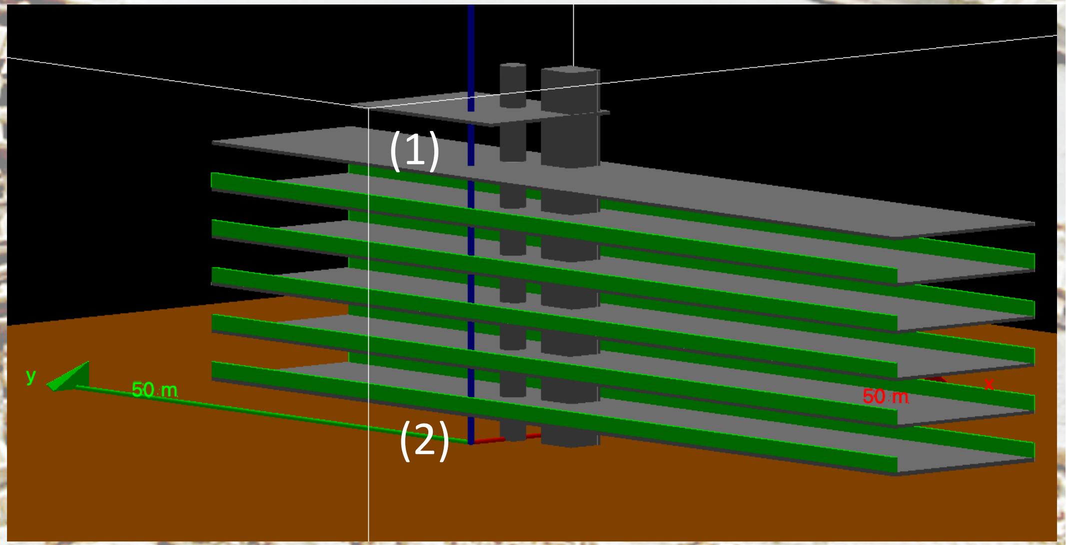


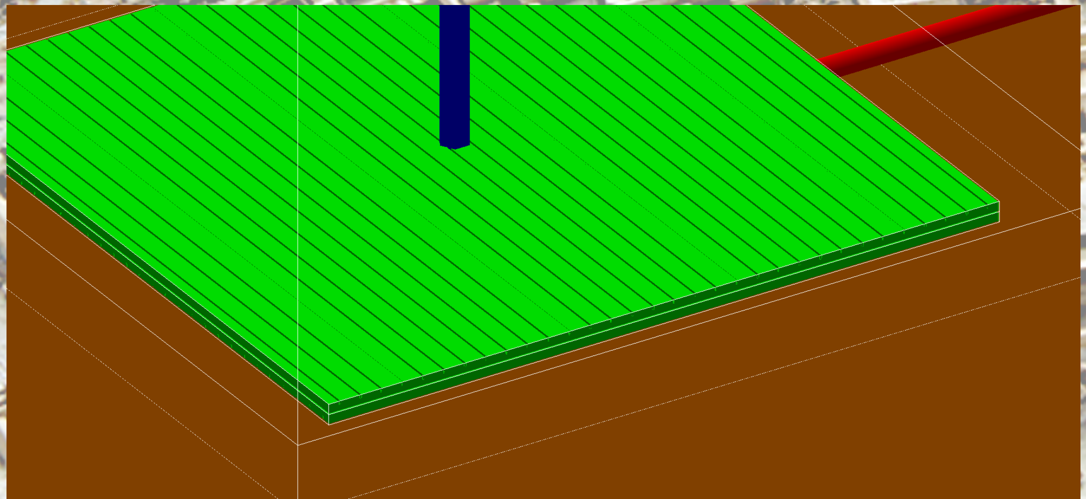
2 Hits per PMT -> 1 per direction x & y

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

Conclusions

- Noisy Environment: High Muon rates
  Surounding materials proximity to detectors
- Long Data Acquisition time to retrieve results for the overburden
- Even longer DAQ time duration for investigating the surrounding galleries
- Good oportunity to study new detectors in a confined/controlled environment
- Especially on the noise rejection front

Outlook

- Develop the Simulation, implement the surrounding structures
- Finalize the portable Muon Cherenkov prototype
- Evaluate its capabilities in comparison to the 3-plane detector