Inter-Disciplinary Underground Science and Technology

ArchéMuon: A Gallo-Roman archaeological site as a "sandbox" for testing muography and geophysical imaging techniques

B. Tauzin[1], C. Benech[2], J. Marteau[3], T. Avgitas[3]

[1]LGL-TPE UCB Lyon1, [2]UMR Archéorient, [3]UCBL – IP2I Lyon

iP2i LES 2 INFINIS LYON

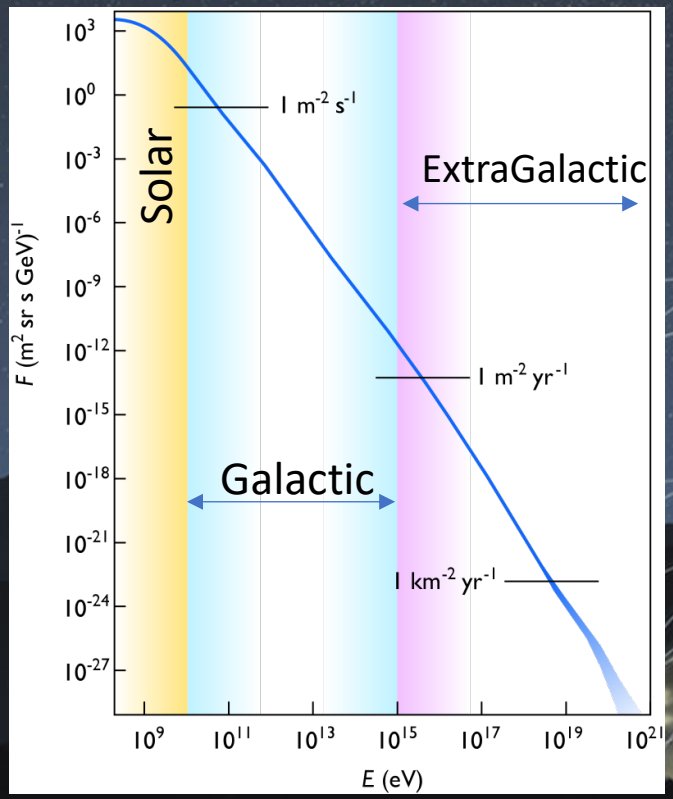
Archéorient
Environnements et sociétés de l'Orient ancien

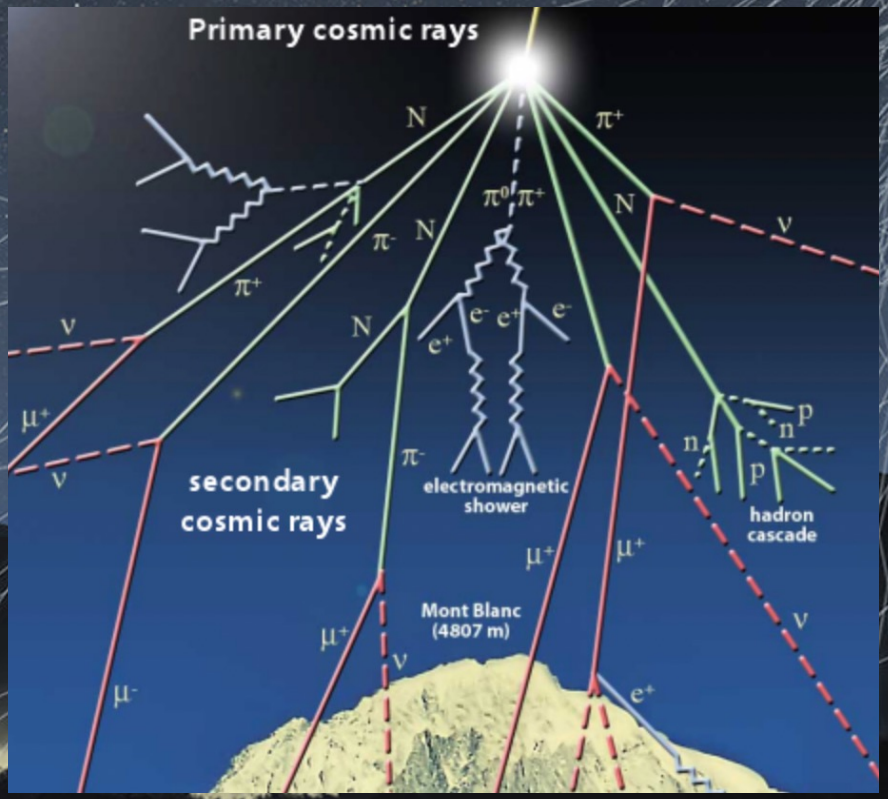
MUSÉE GALLO-ROMAIN
SAINT-ROMAIN-EN-GAL

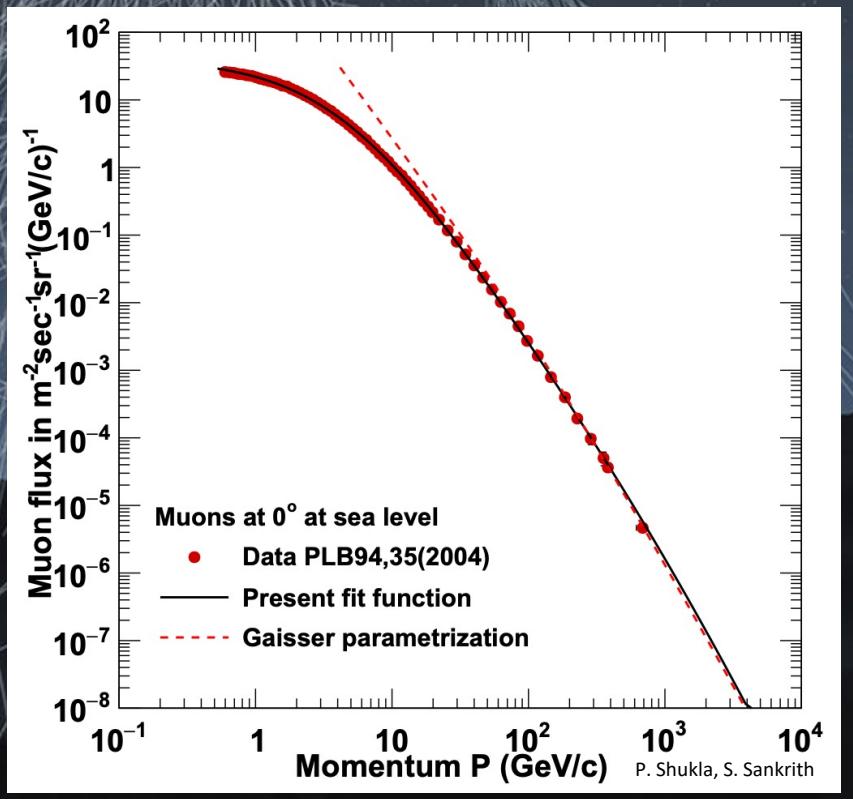
Laboratoire de Géologie de Lyon
Terre, Planètes, Environnement

Cosmic Rays

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



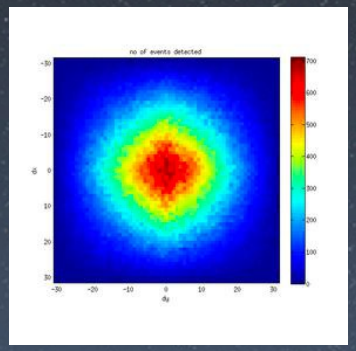


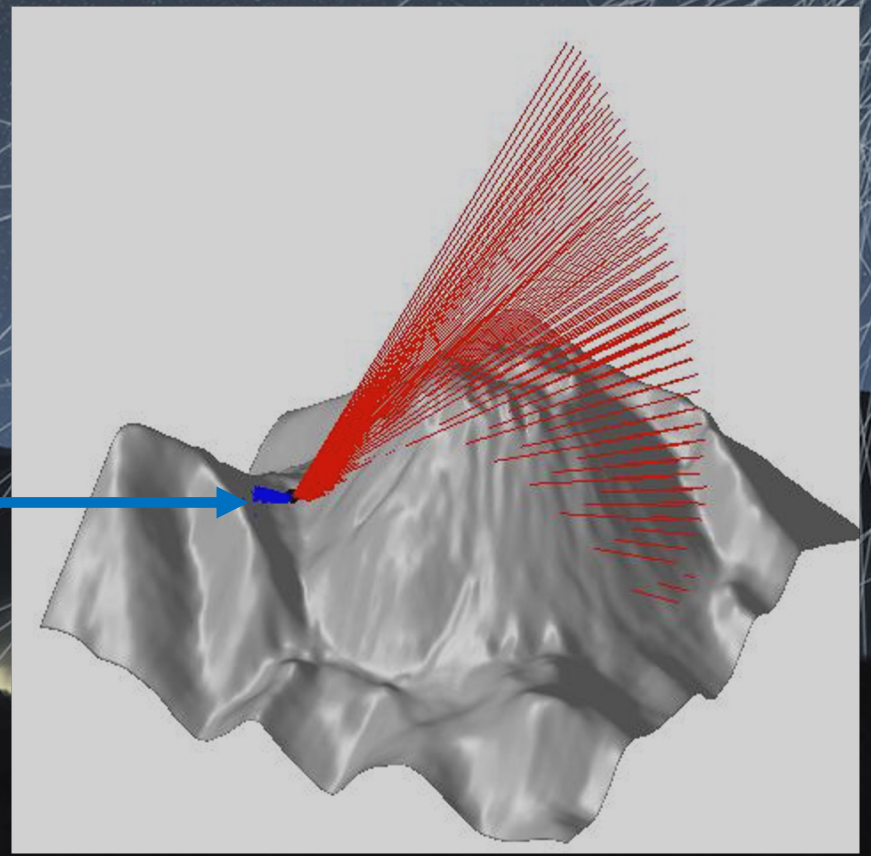


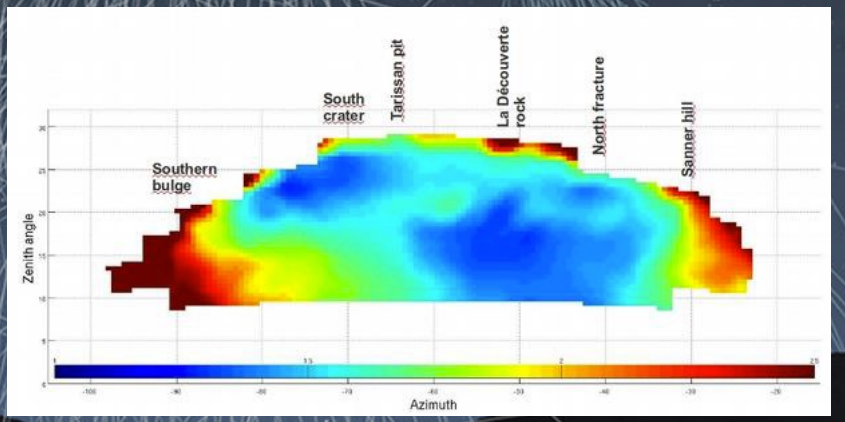
Muon Tomography

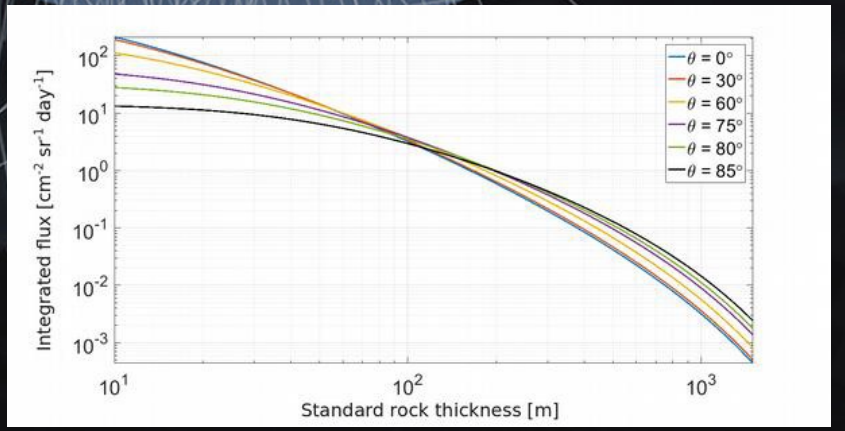
$$\varrho(L) \equiv \int_L \rho(\xi)\mathrm{d}\xi$$

ϱ = opacity ρ = density









Volcano Imaging

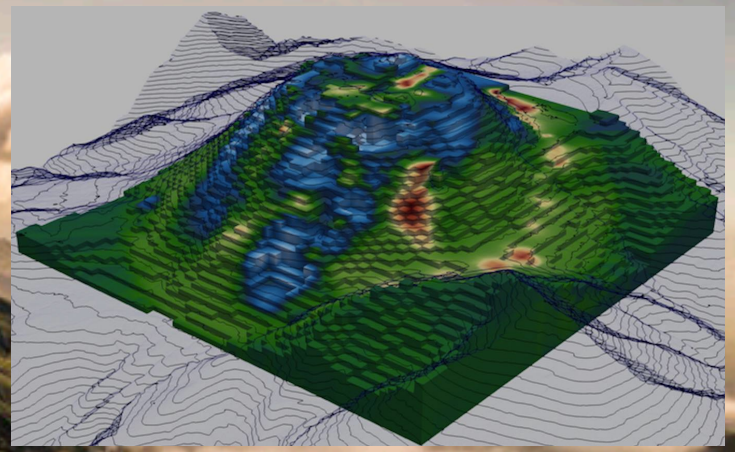
Muography benefits:

- Remote sensing
- Total structure imaging (+ 3D)
- Monitoring

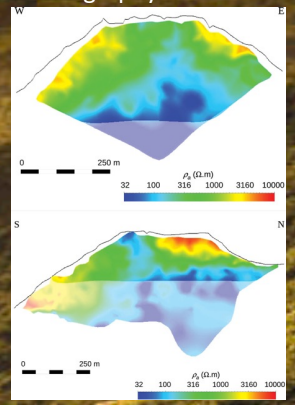
Important Questions:
1)What happens inside a volcano during unrest
2) Links between observations and internal activity
3) Which types of unrest are precursors to which eruptions

Multimessenger Geophysics

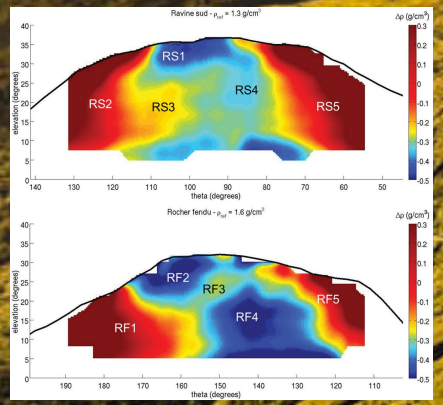
Combining Exploration Geophysics
with Muon Tomography
at the active volcano “La Soufrière” in Guadeloupe

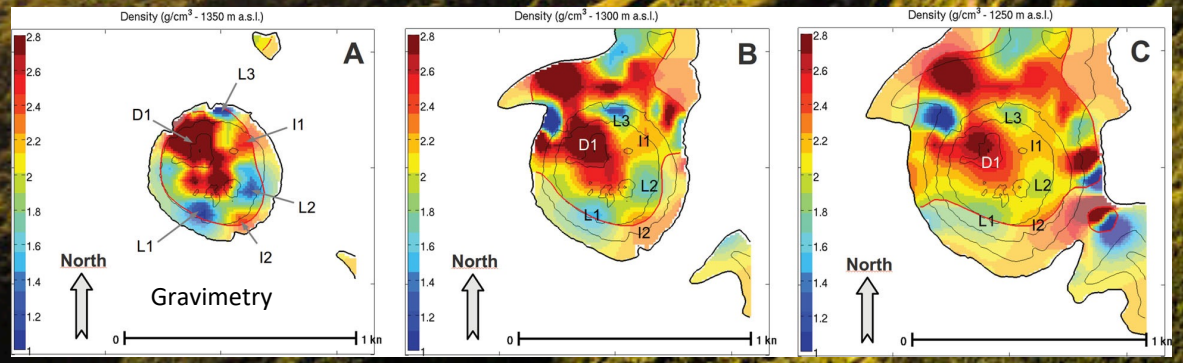


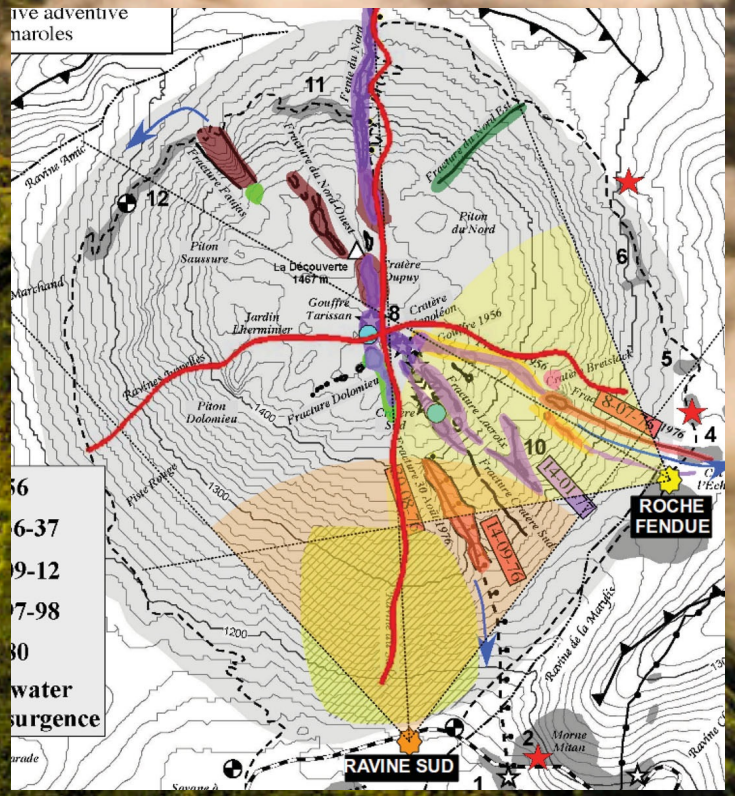
Electric Resistivity Tomography



Muon Tomography



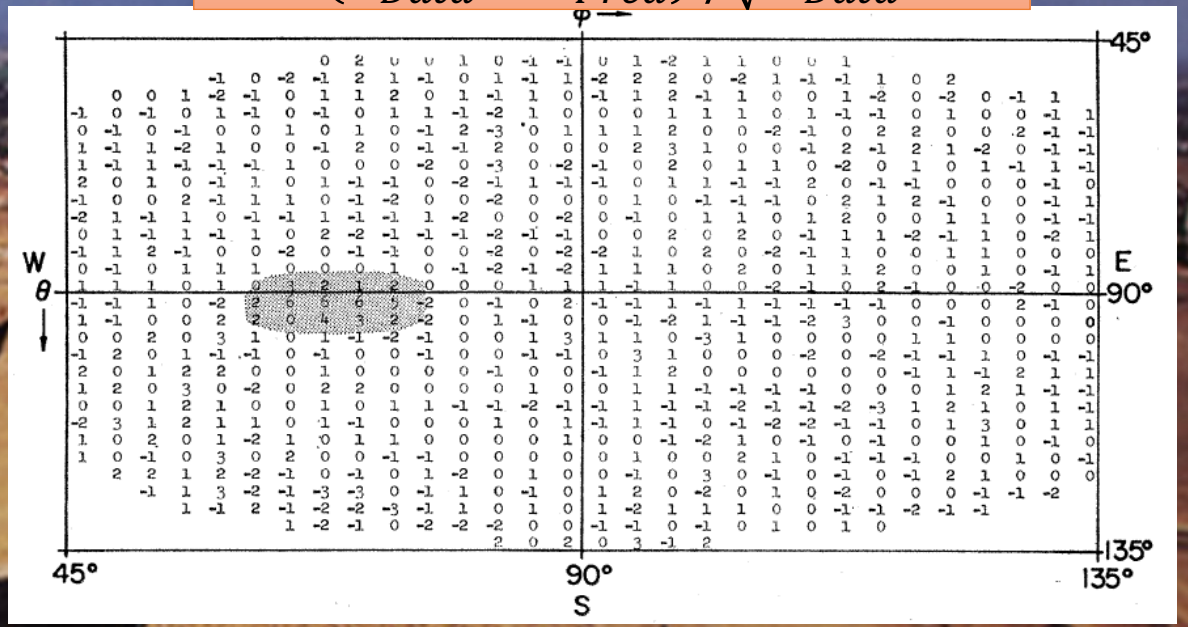




Giza Plateau: Birthplace of Muon Tomography

Luis Alvarez invented muon tomography in 1960's to study the 2nd 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.

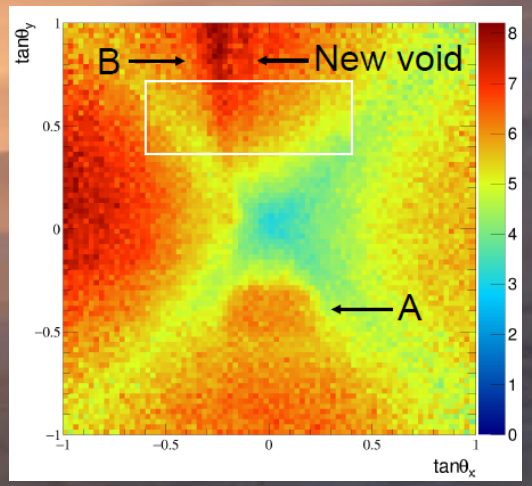
Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

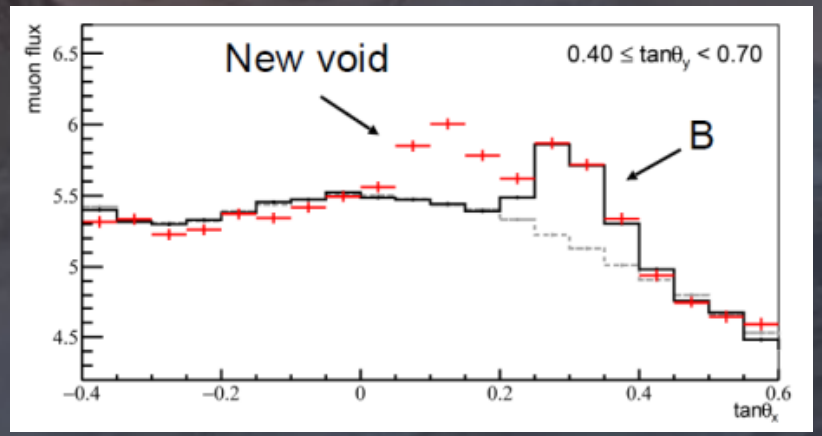
L.W. Alvarez, *et al*, *Search for Hidden Chambers in the Pyramids Using Cosmic Rays*, Science **167**, 832-839, 1970.

Return to the roots

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

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





New Void

A: King's Chamber

B: Grand Gallery

A more difficult case : Tumuli

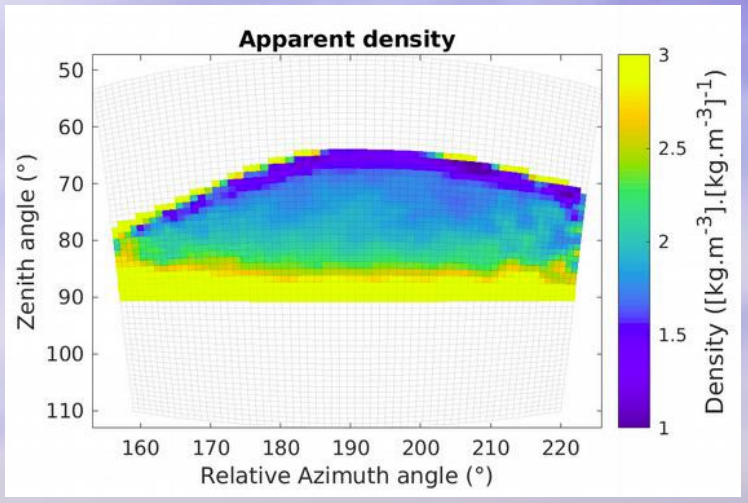
The Apollonia tumulus as a benchmark for the method

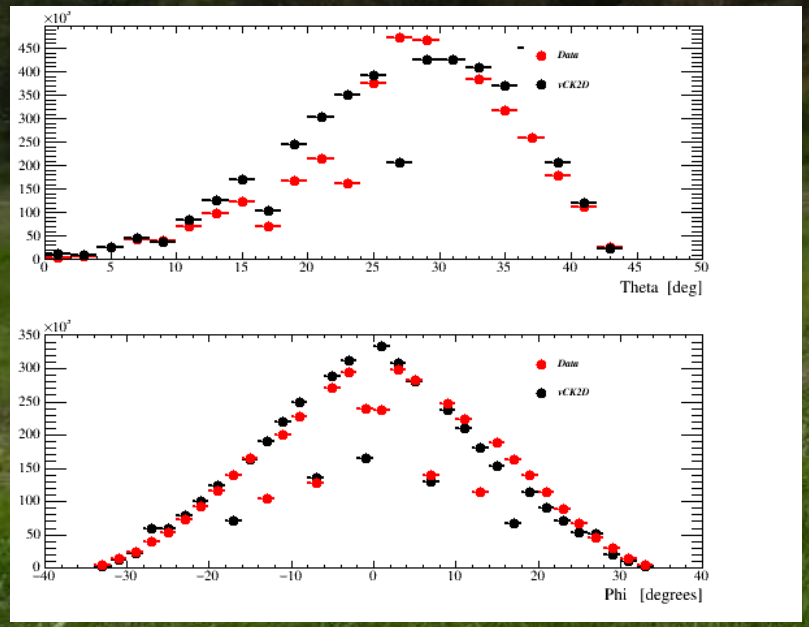
- Existing monument
- Density anomalies detected by other methods

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





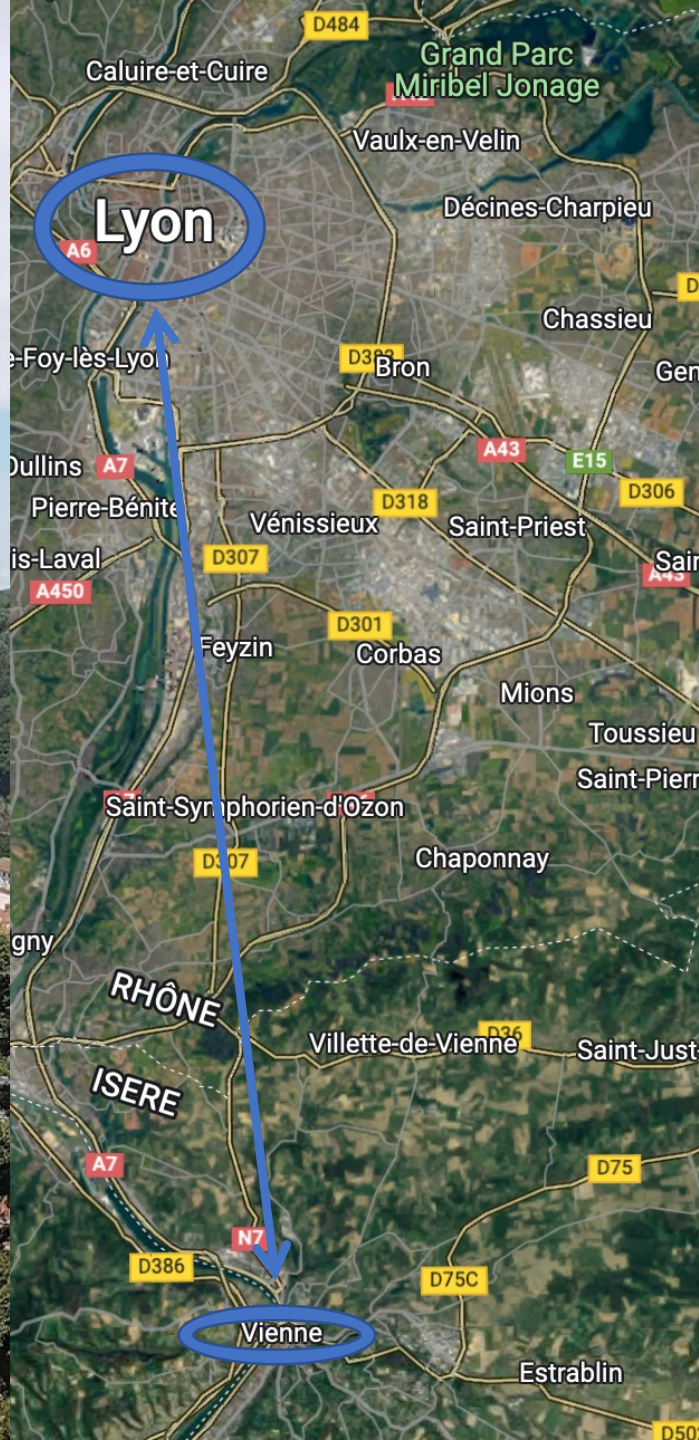
- Level of agreement ~10 to 20% between observed muon fluxes and simulation
- Precision experiment looking for tiny effects
- Limitations:
  - The precise knowledge of the muon spectrum and muon statistics
  - A more accurate geometrical description of the tumulus and the density of soil

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



MUSÉE GALLO-ROMAIN

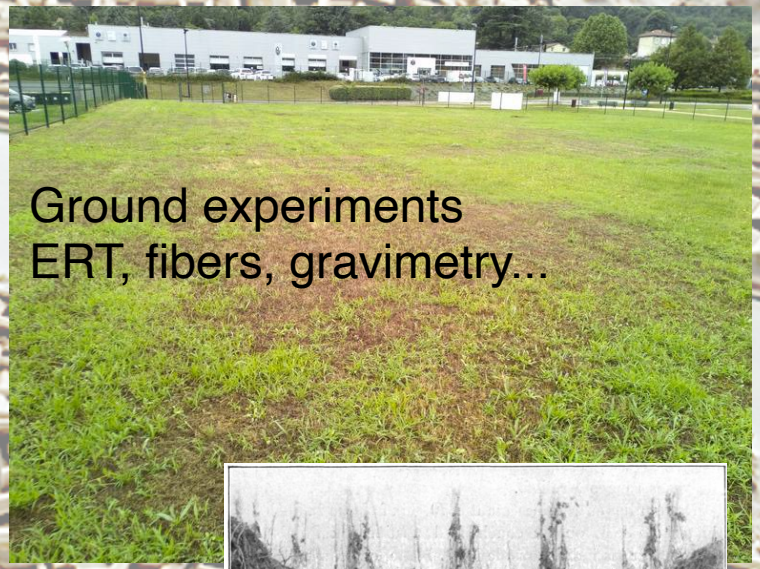
SAINT-ROMAIN-EN-GAL

Palais du Miroir

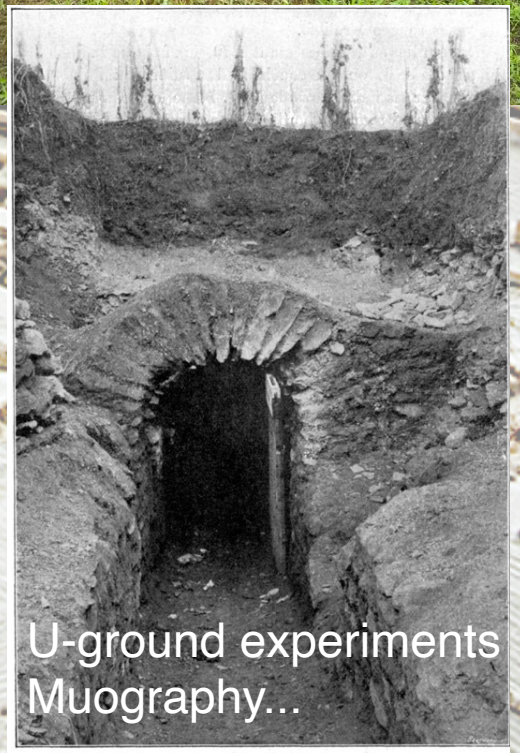
Cl. C. D. - Blanchard frères, édit. - Vienne

1414. VIENNE — Ruines du Palais du Miroir, à Ste-Colombe
Entrée d'un souterrain romain découvert dans des fouilles récentes
et qu'on croit être un Ergastule (vaste galerie souterraine
où les Romains enfermaient les prisonniers Gaulois)

Physics Case



Ground experiments
ERT, fibers, gravimetry...



U-ground experiments
Muography...

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

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

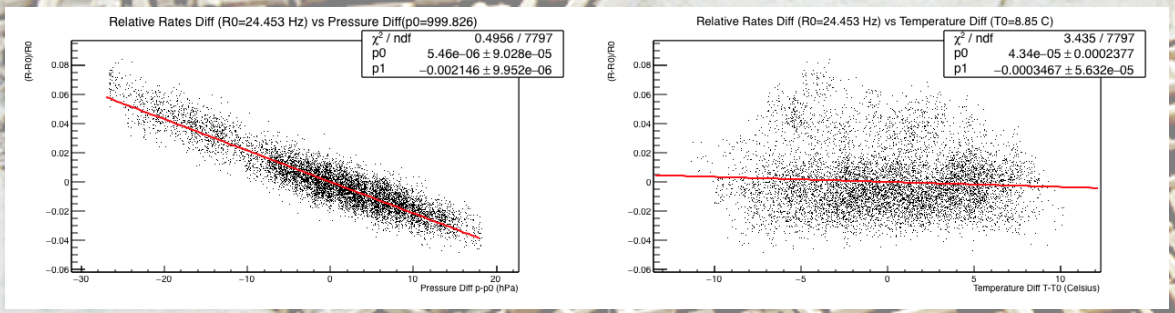
<u>Prospects</u>

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

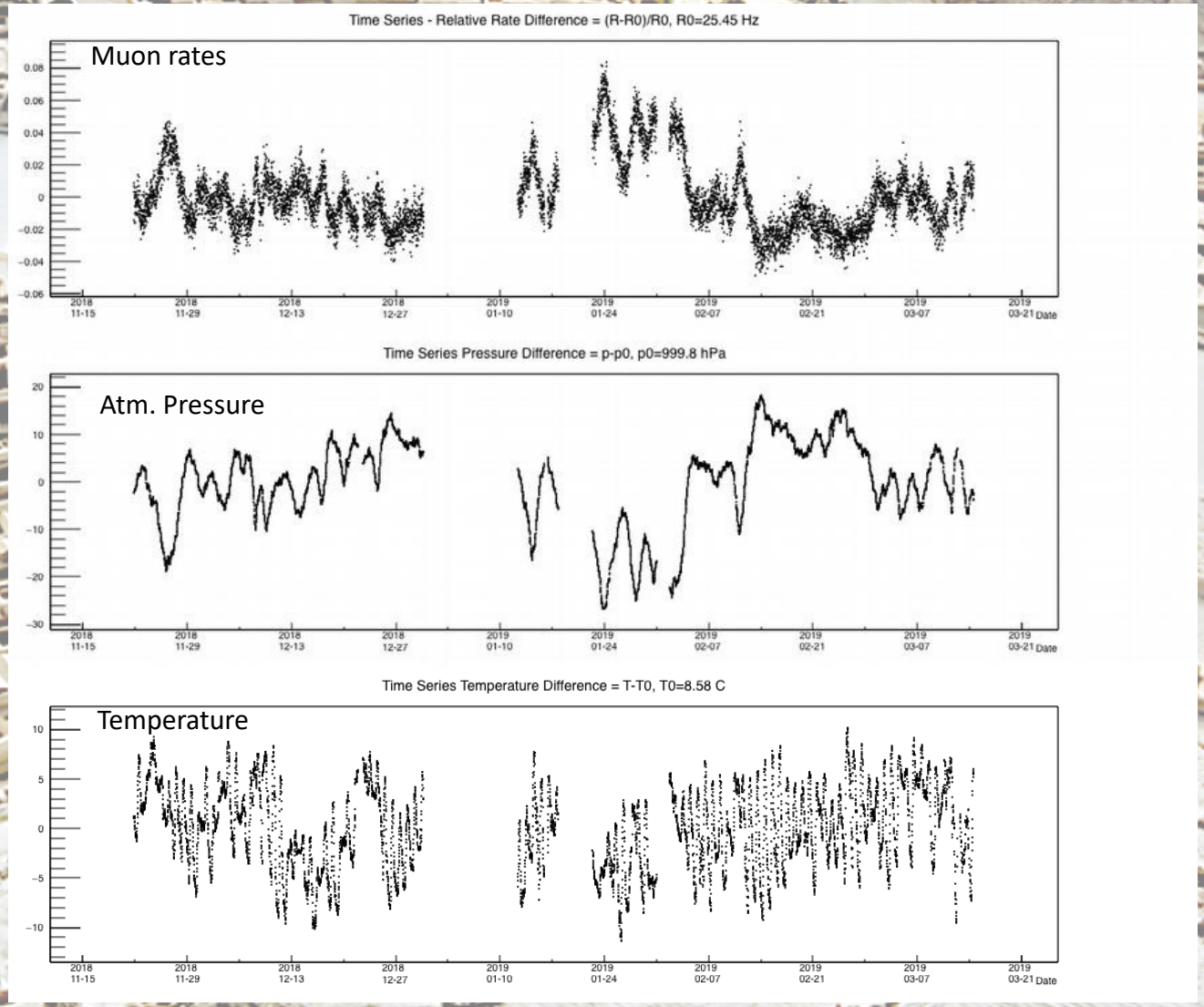
Atmosperic effects

Weather affects muon rates
Correction for precision experiments

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



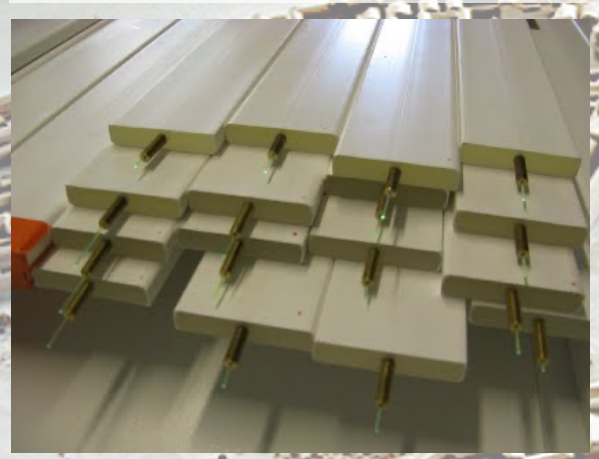
How soil water retention affects the measurement

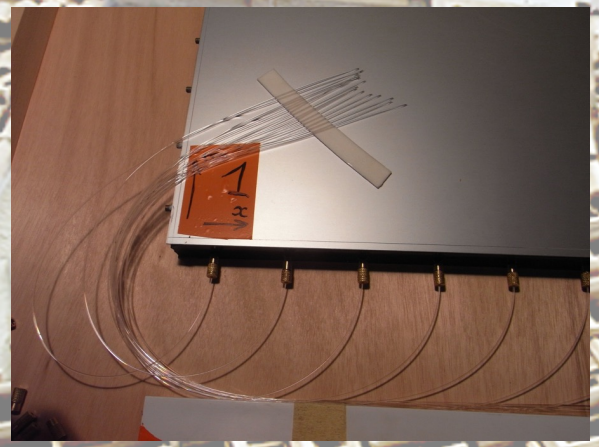


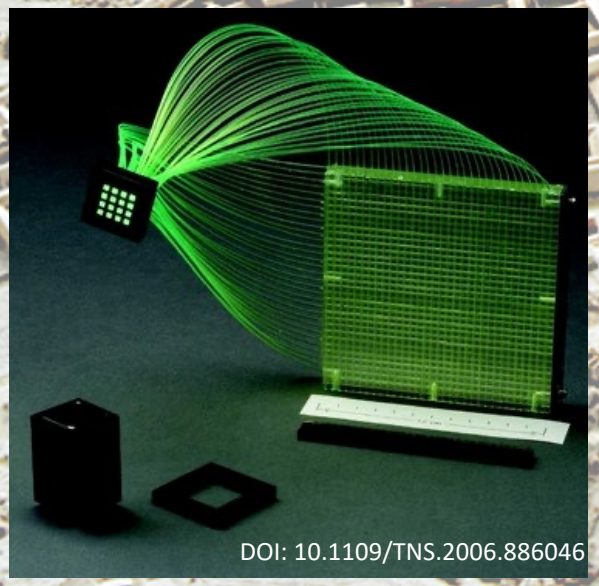
EGO-Virgo CR monitoring

Instrumentation

New detector R&D
Field performance evaluation

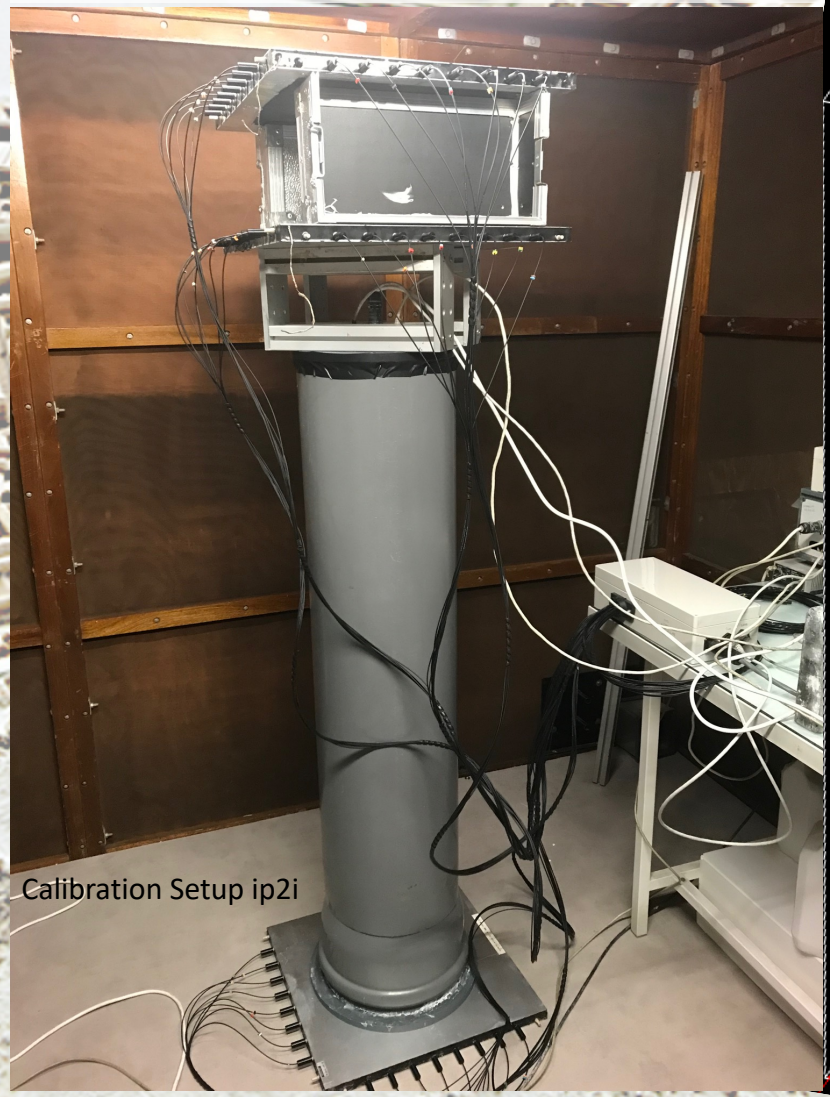






DOI: 10.1109/TNS.2006.886046

+ portable Cherenkov Detector
μ/e discrimination
low/high energy discrimination



Calibration Setup ip2i