From cosmos to the center of the earth : muography basics and applications

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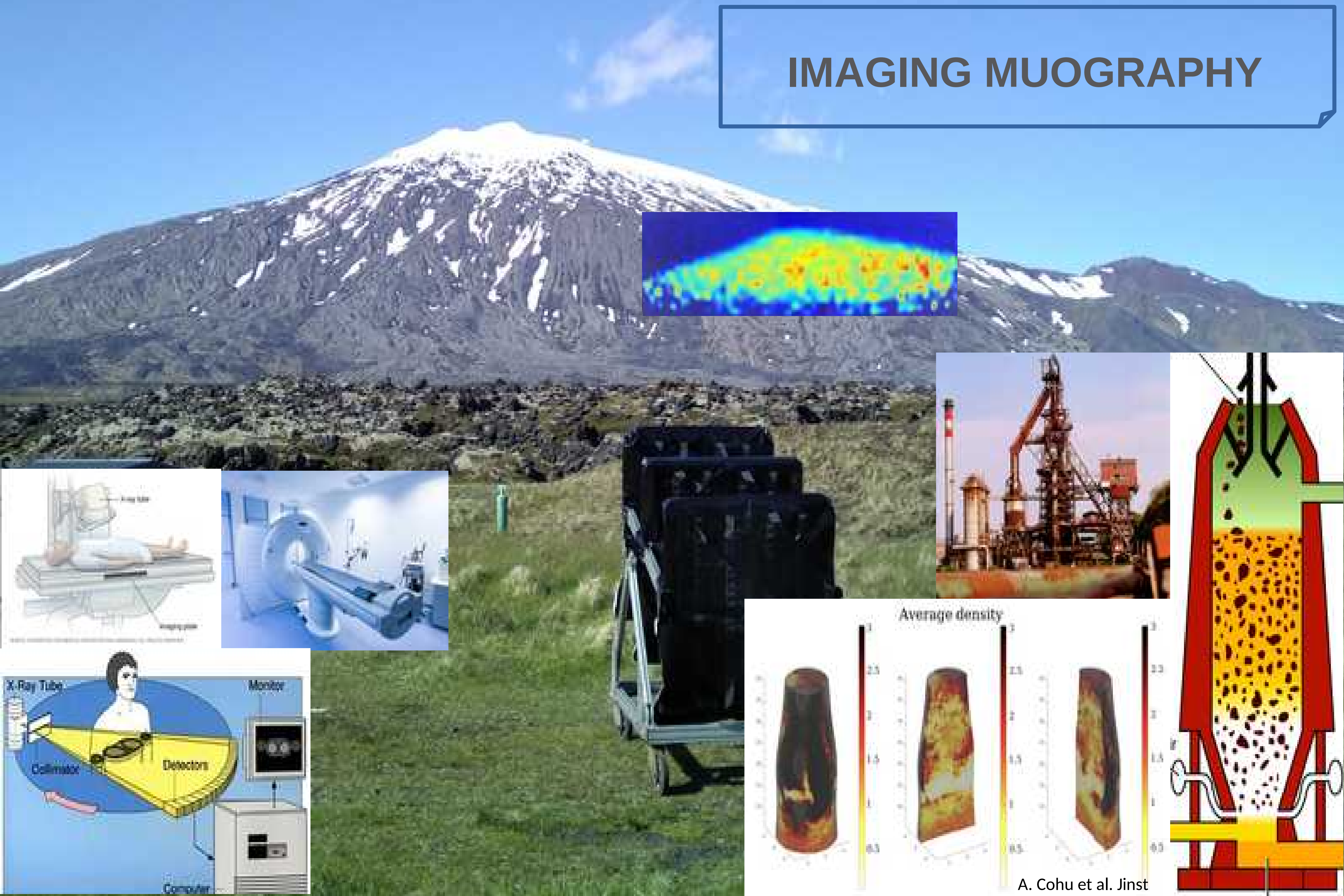
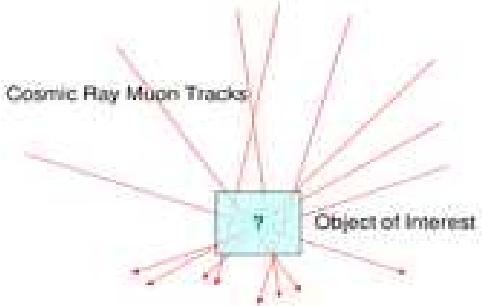
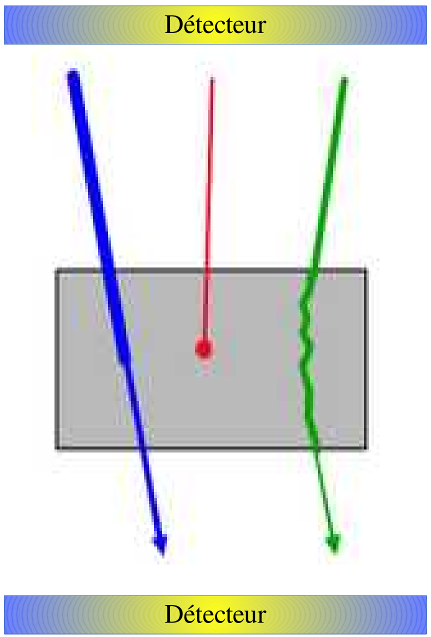
IMAGING MUOGRAPHY



A. Cohu et al. Jinst

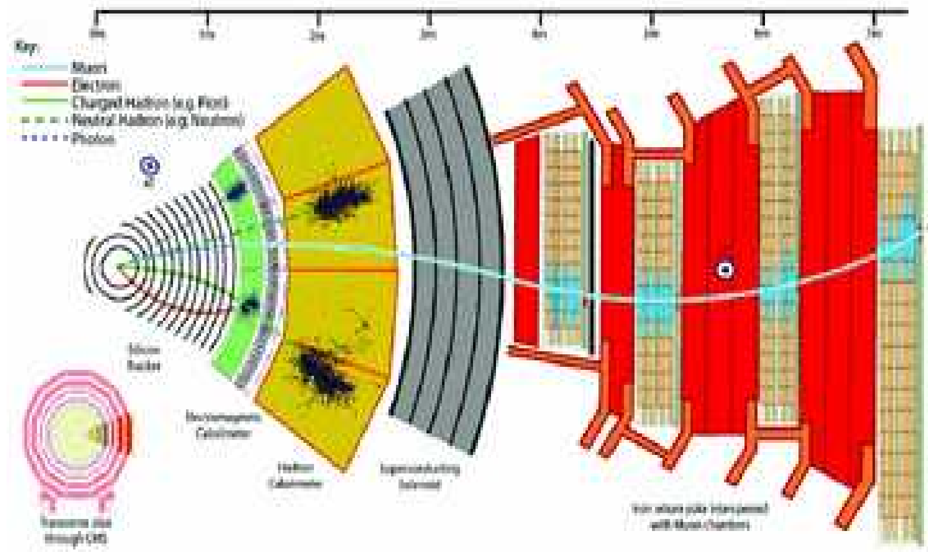
PARTICLES-MATTER INTERACTIONS





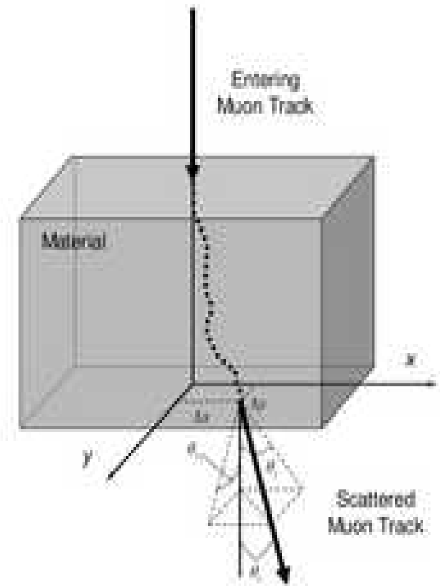
$$\varrho(L) \equiv \int_L \rho(\xi)\mathrm{d}\xi$$

ϱ = opacity ρ = density



$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

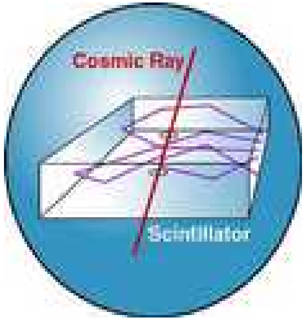
absorption

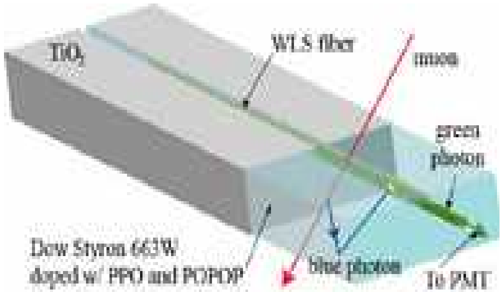


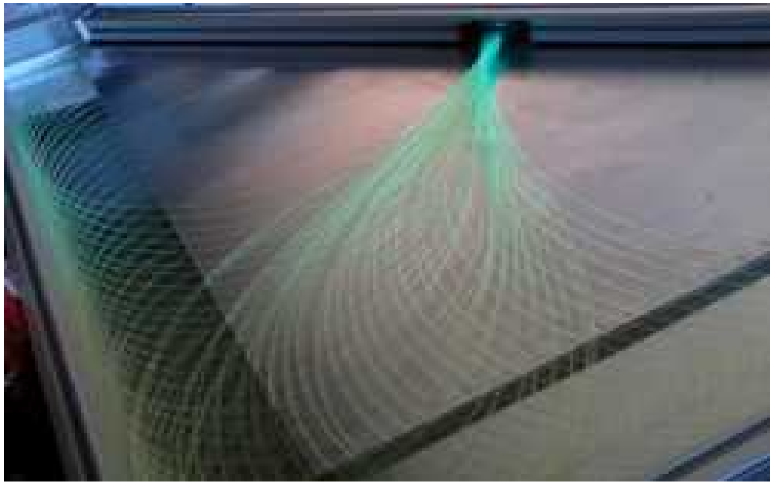
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}} \left[1 + 0.088 \log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right) \right]$$

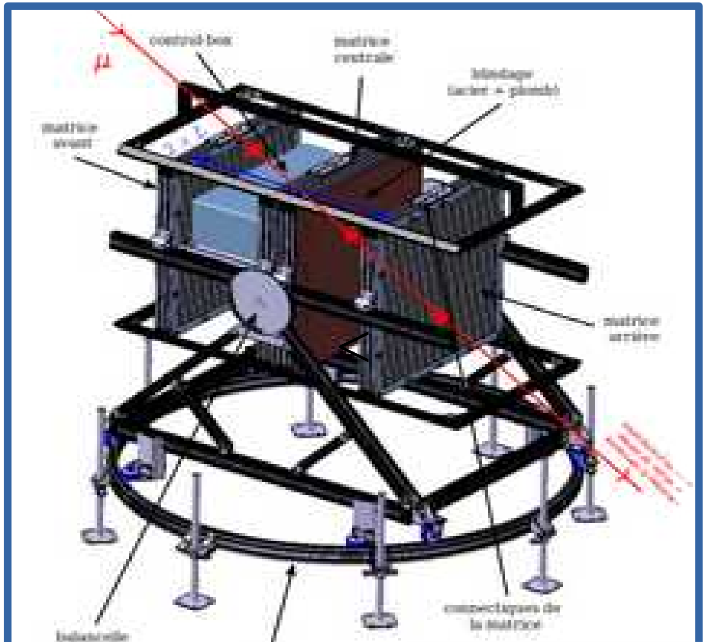
scattering

TRACKERS







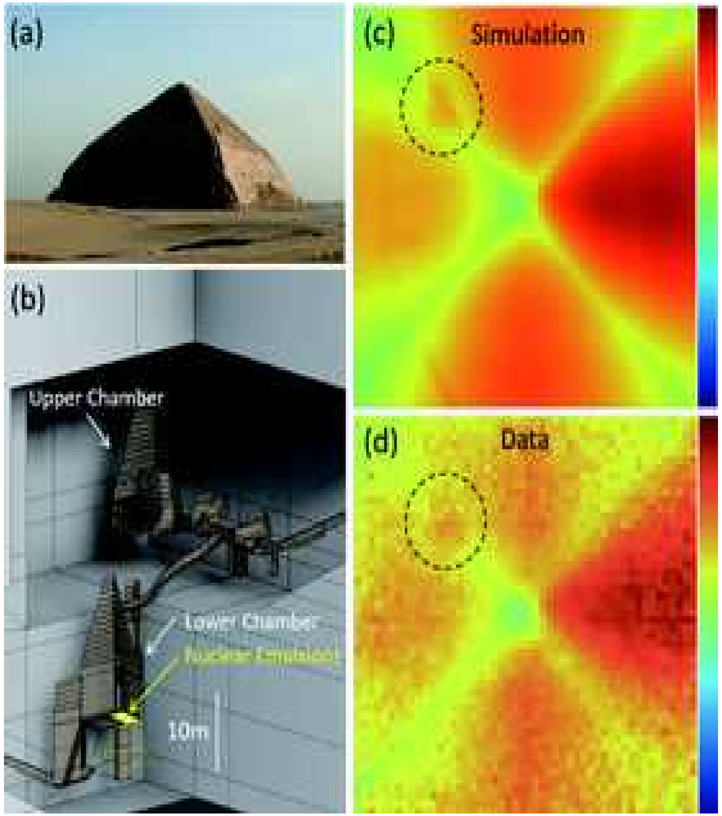


Scintillators

Emulsions

RPC

Micromegas

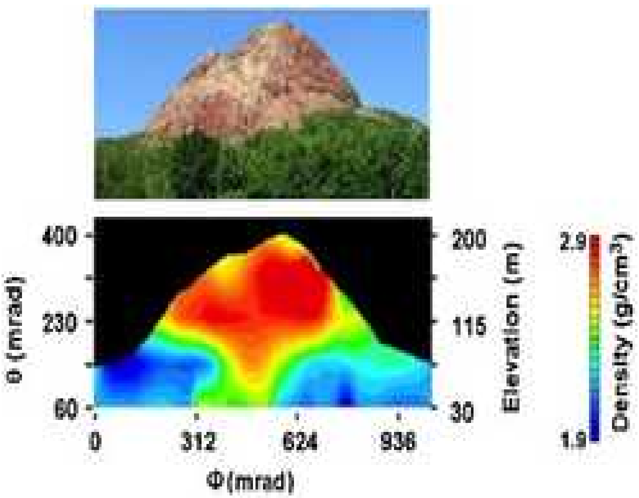


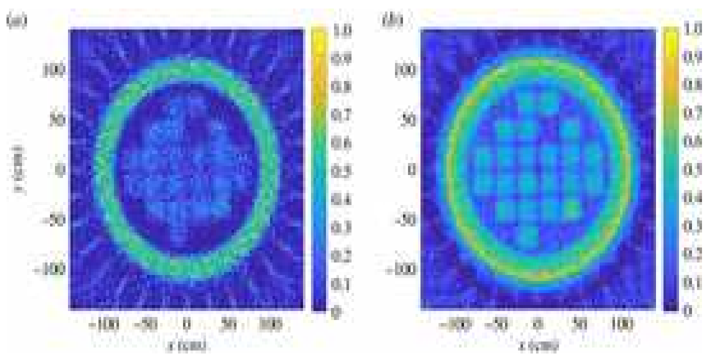
IMAGING METHODS

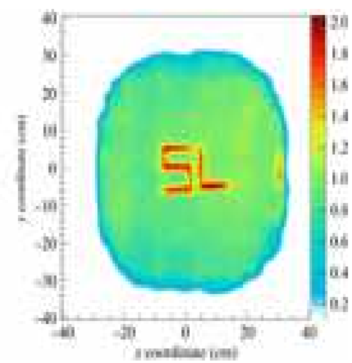
Détecteur

Reconstruction

Images

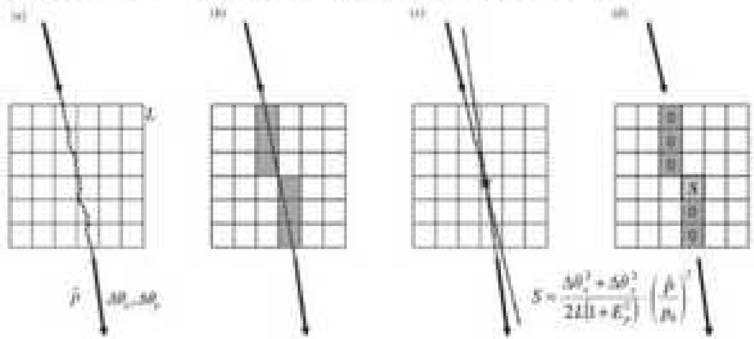




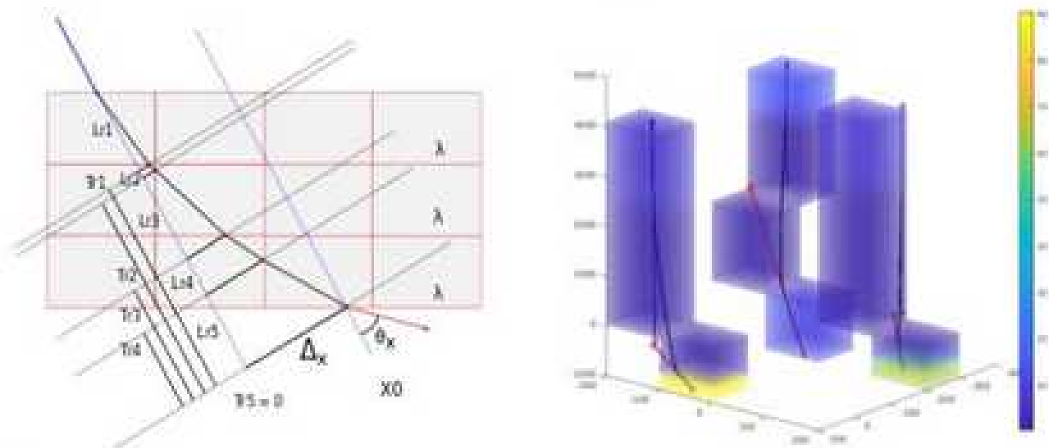


INVERSE PROBLEMS

POCA 3D: Point of Closest-Approach



MLEM: Maximum Likelihood Expectation Maximisation



x

$$P(D_i|\lambda) = \frac{1}{2\pi|\Sigma_i|^{1/2}} \exp\left(-\frac{1}{2} D_i^T \Sigma_i^{-1} D_i\right),$$

X

y

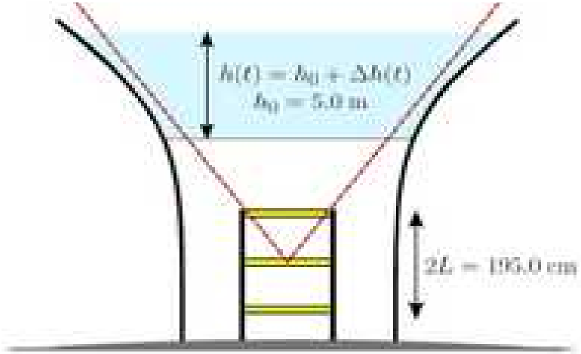
$$P(D_i|\lambda) = \frac{1}{2\pi|\Sigma_i|^{1/2}} \exp\left(-\frac{1}{2} D_i^T \Sigma_i^{-1} D_i\right),$$

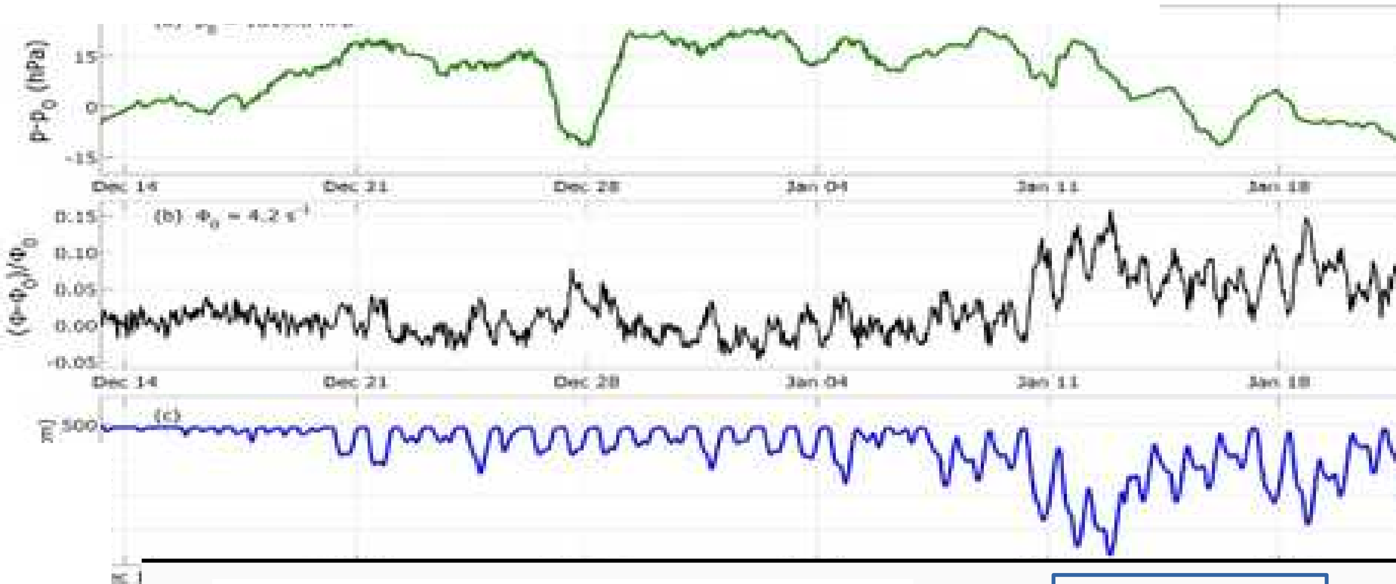
$$\frac{1}{|\Sigma_i|}\left(\Delta\theta_i^2 v_{x,i} - 2\Delta\theta_i x_i x_{\theta x,i} + \Delta x_i^2 v_{\theta,i}\right)$$

$$\Sigma_i = p_{r,i}^2 \sum_{j \le N} \lambda_j W_{ij},$$

$$W_{ij} = \begin{bmatrix} L_{ij} & L_{ij}^2/2 + L_{ij}T_{ij} \\ L_{ij}^2/2 + L_{ij}T_{ij} & L_{ij}^3/3 + L_{ij}^2 T_{ij} + L_{ij} T_{ij}^2 \end{bmatrix}$$

MONITORING METHODS

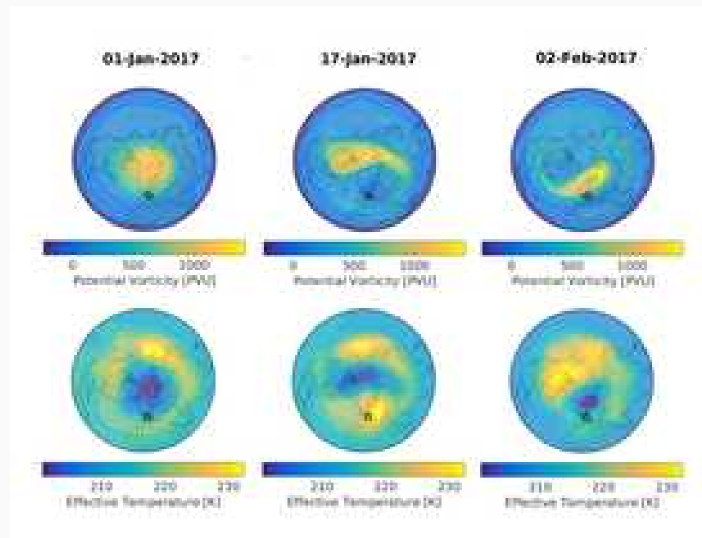


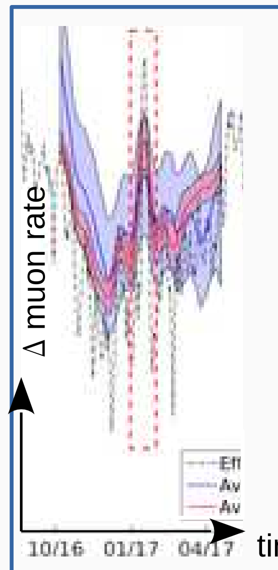


- Proof of concept
- Water tank level monitoring
- Barometric effects corrections

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

- Geomagnetic effects etc
- Application to the Sudden Stratospheric Warming (SSW) observation

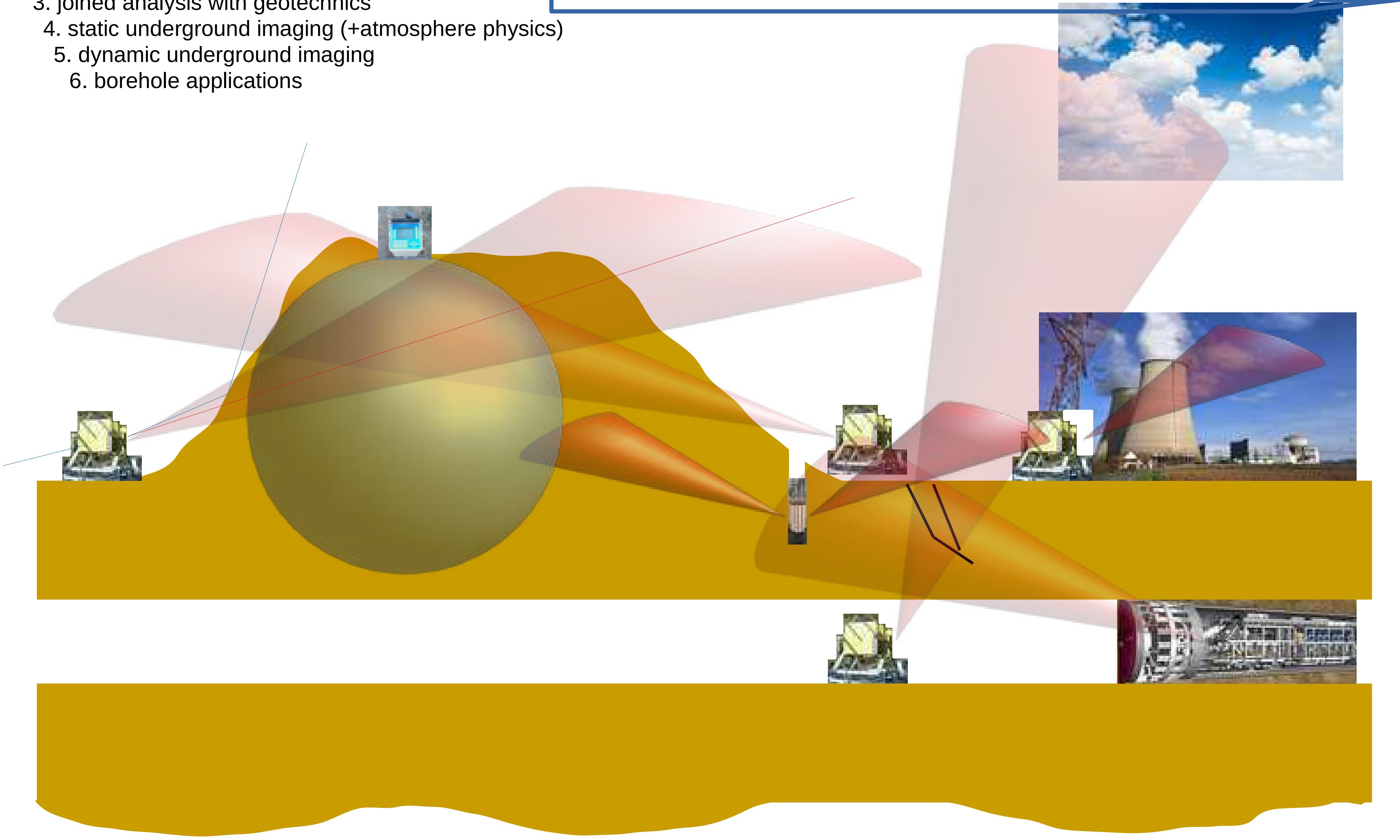




(Tramontini et al., 2019)

Field muography use cases

1. “radio”-like structural imaging & monitoring
2. “scanner”-like structural imaging & monitoring
3. joined analysis with geotechnics
4. static underground imaging (+atmosphere physics)
5. dynamic underground imaging
6. borehole applications



Muography use cases overview

Muography = transmission/scattering imaging technique → sensitive to (scattering) density + Z/A

Geosciences

- Volcanology
- Geology
- Hydrology
- Atmosphere physics
- CR physics
- ...

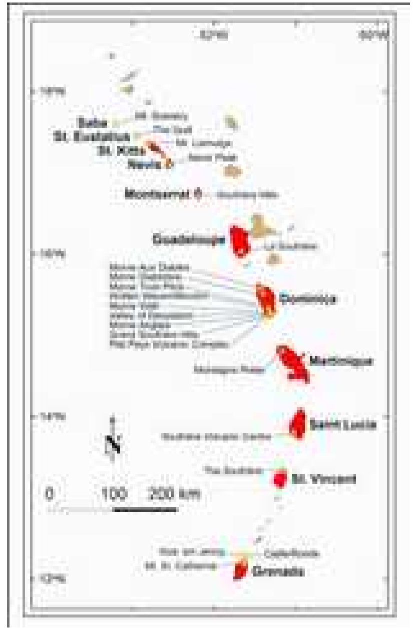
Archaelogy

- Pyramids
- Tumulus
- Anthropic structures
- Ruins
- ...

Industrial controls

- Non invasive controls
- Nuclear cycle production
- Civil engineering
- Tunnel boring machines
- Prospection & mining
- ...

La Soufrière de Guadeloupe



Etna

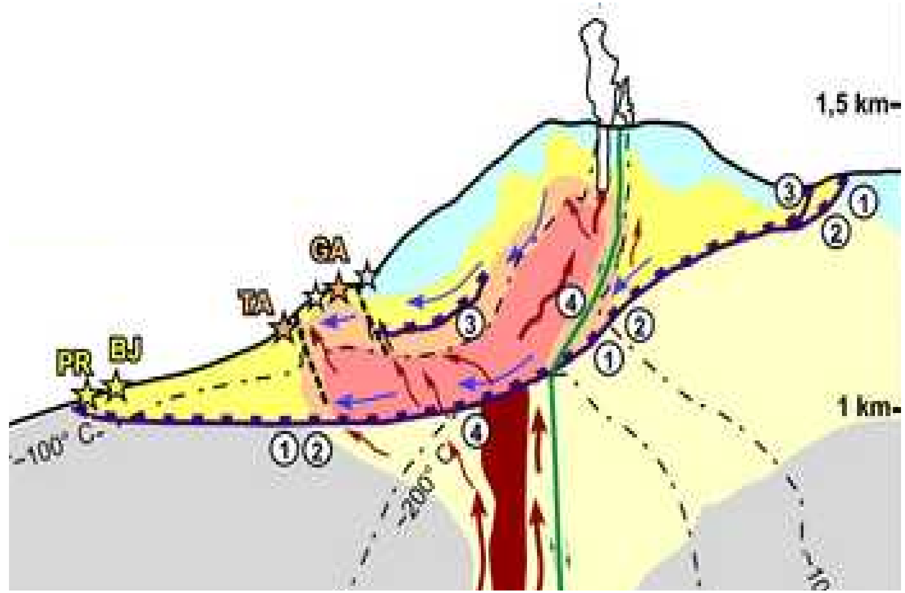
Volcanoes

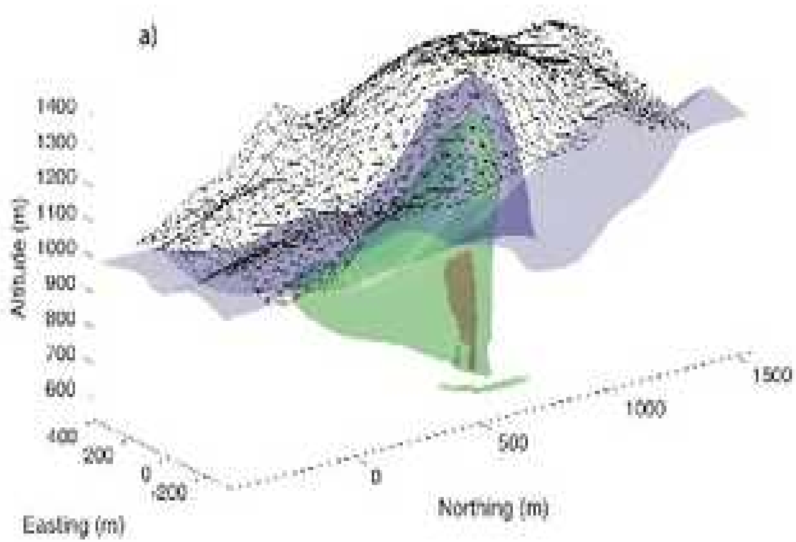
Snaefellsjökull

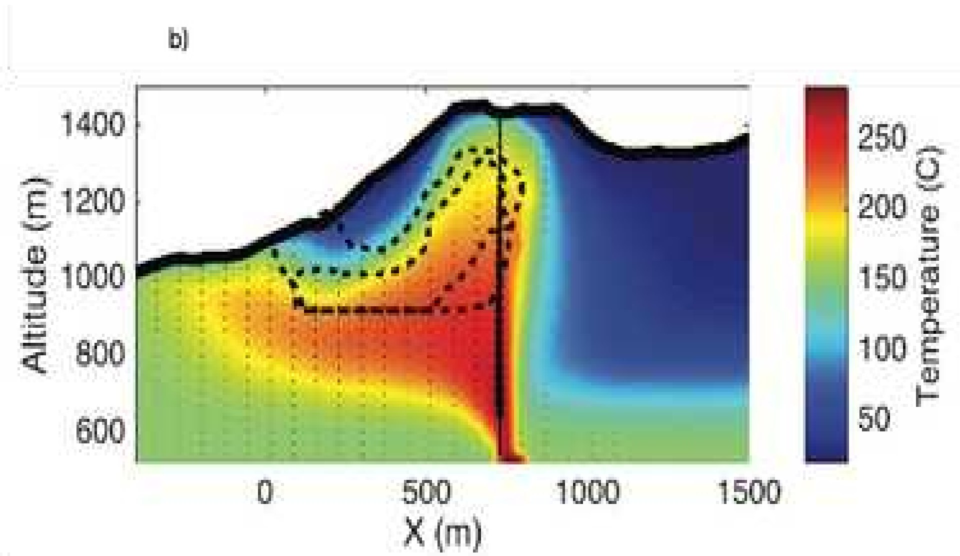
Mayon

La Soufrière hydrothermal systems

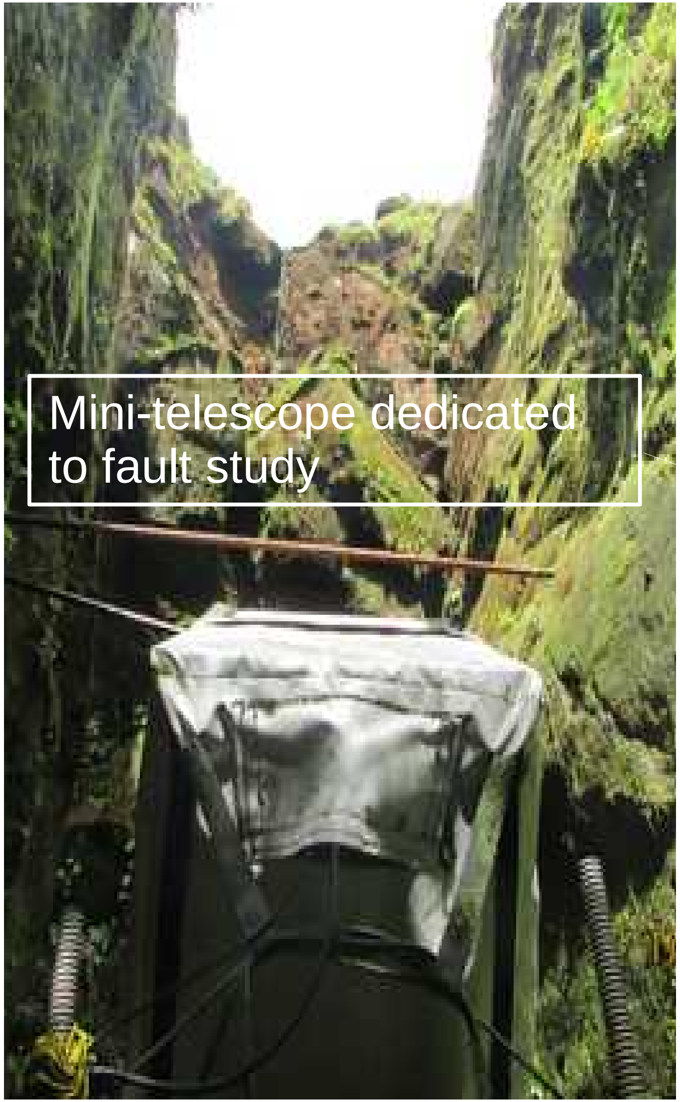
- Volcano hydrothermal systems are at the core of unpredictable volcanic hazards
- Complex interplay between internal and external forcing
- Classical geophysics provide limited information on spatio-temporal dynamics
- Need for techniques that can track in space and time the internal state of the system to constrain numerical models

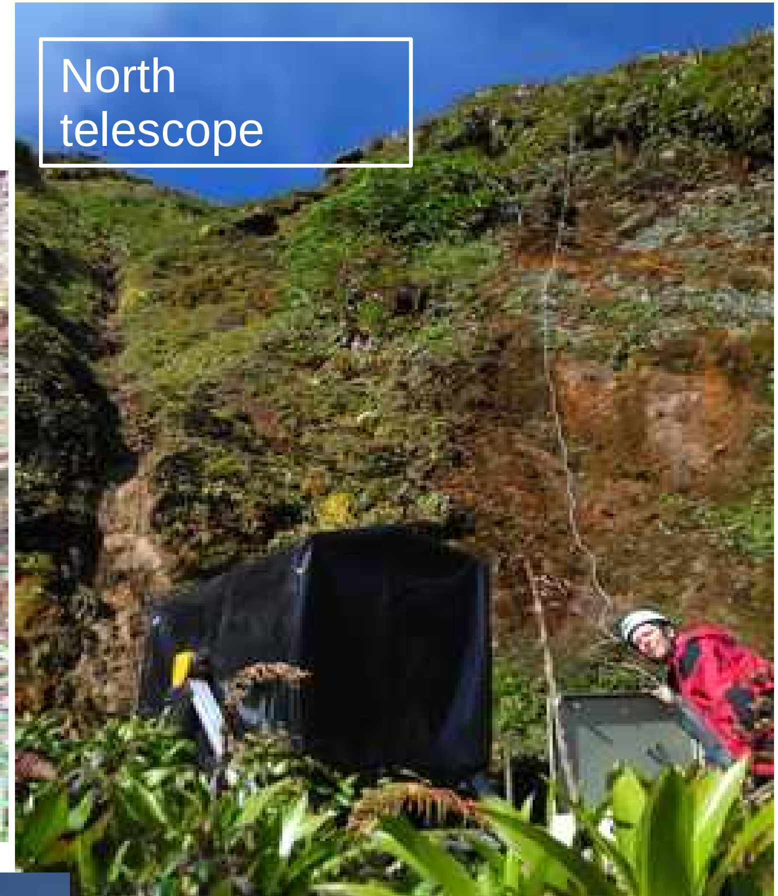




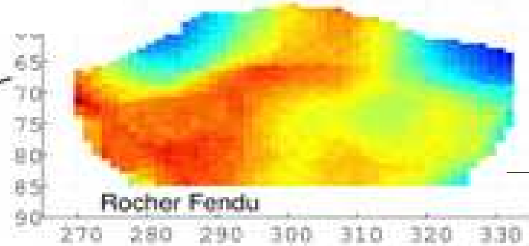


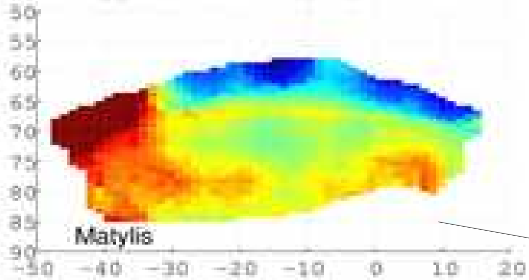
La Soufrière “muon station”

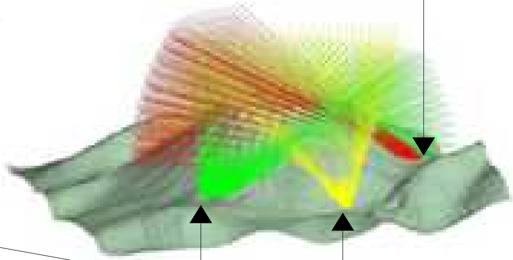


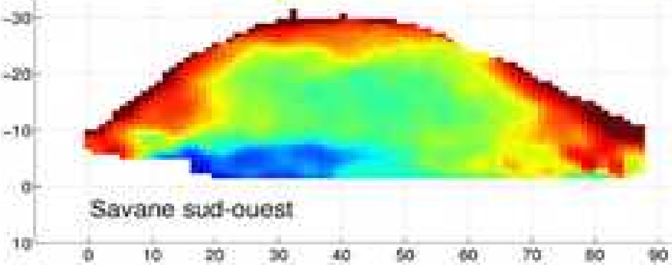


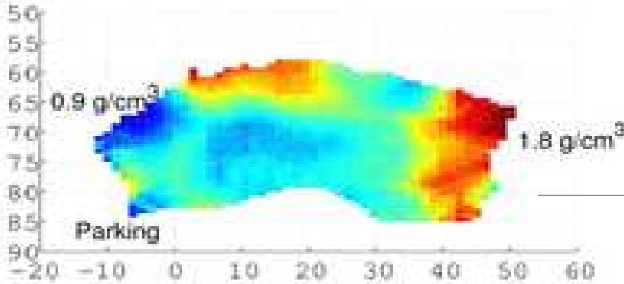
Imaging & monitoring





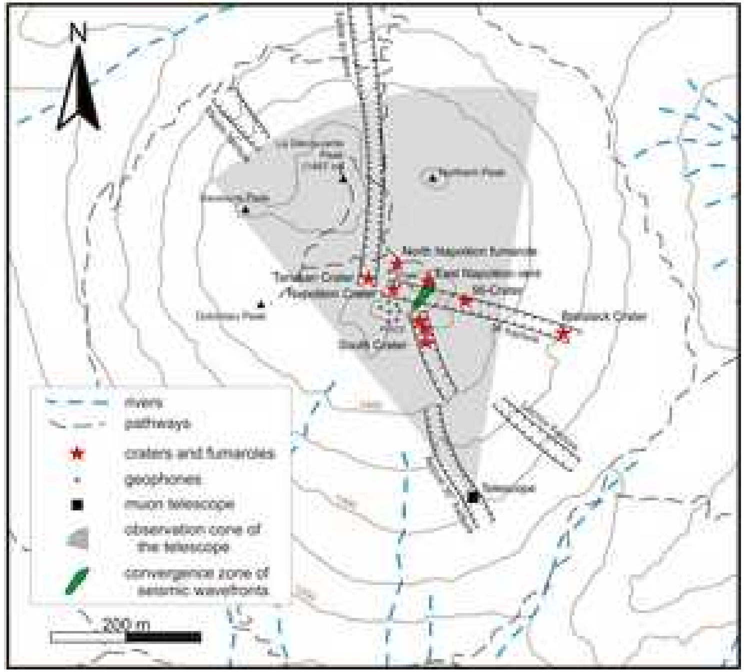


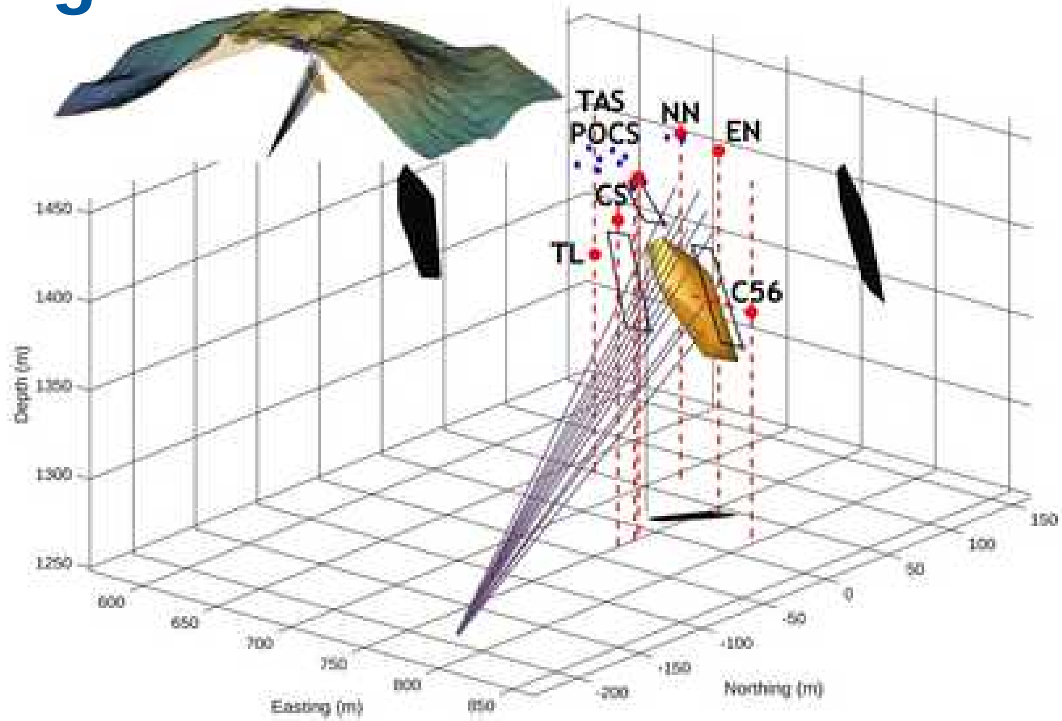




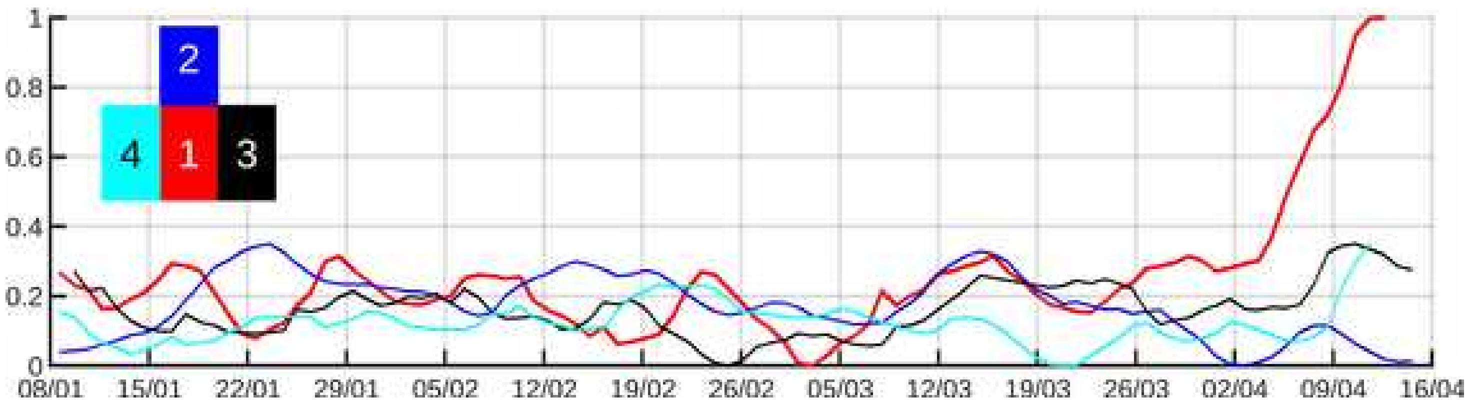
The largest muons station in the world (6 detectors running)

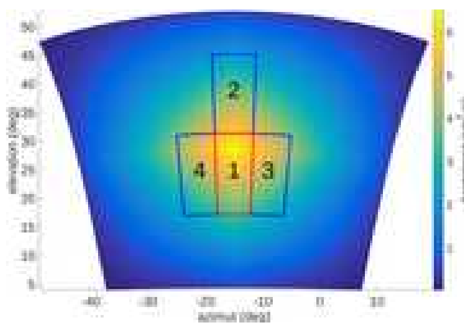
Sismo-muon joint monitoring





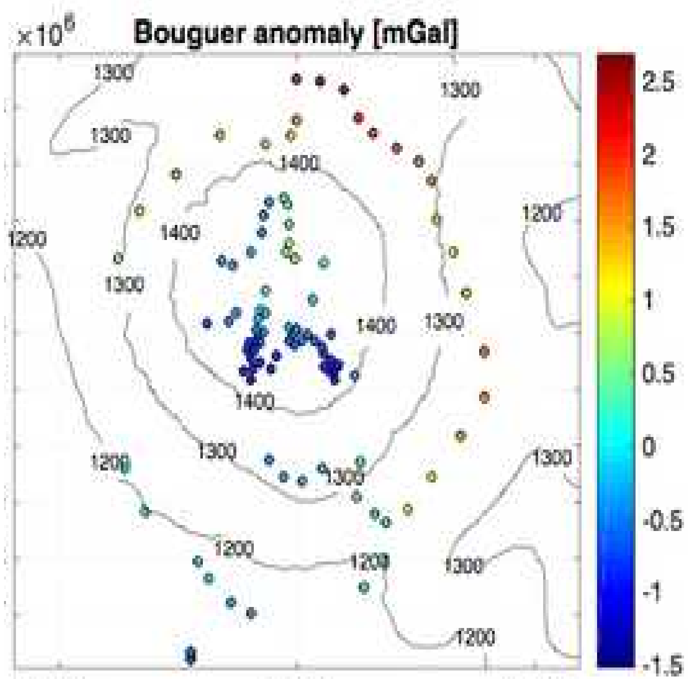
Global analysis of muon and seismic monitoring

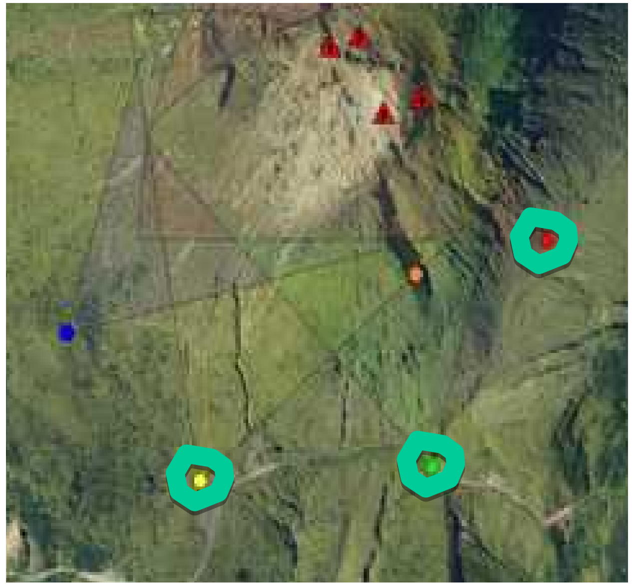




Abrupt changes of hydrothermal activity in a lava dome detected by combined seismic and muon monitoring : *Le Gonidec, J.-Y. et al. Scientific Reports 2019*

3-D gravi-muon joint inversion





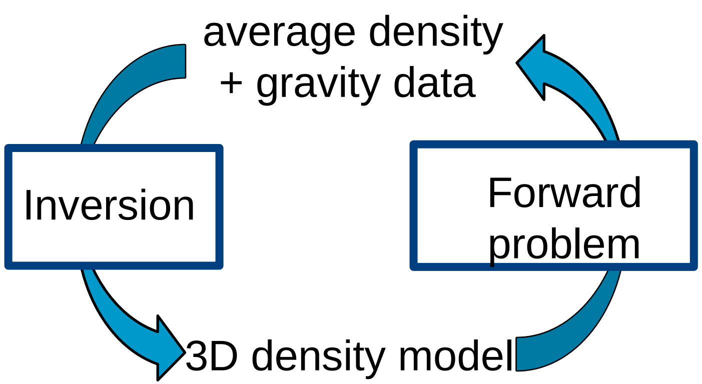
$$G\begin{bmatrix}\rho_\mu\\ \Delta\rho\end{bmatrix} = \begin{bmatrix}G_g\\ G_\mu\end{bmatrix}\begin{bmatrix}\rho_\mu\\ \Delta\rho\end{bmatrix} = \begin{bmatrix}d_g\\ d_\mu\end{bmatrix} = d$$

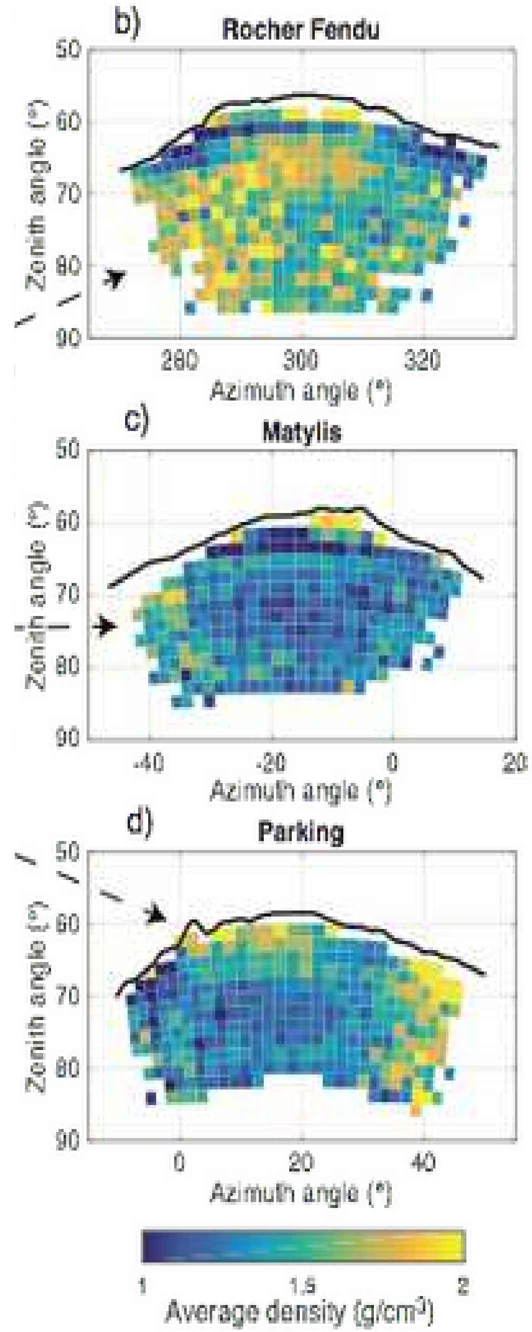
$$\phi(\mathbf{m}) = (\mathbf{d}-\mathbf{G}\mathbf{m})^T C_d^{-1}(\mathbf{d}-\mathbf{G}\mathbf{m}) + \epsilon^2(\mathbf{m}-\mathbf{m}_{prior})^T C_\rho^{-1}(\mathbf{m}-\mathbf{m}_{prior}),$$

Smoothing

Damping

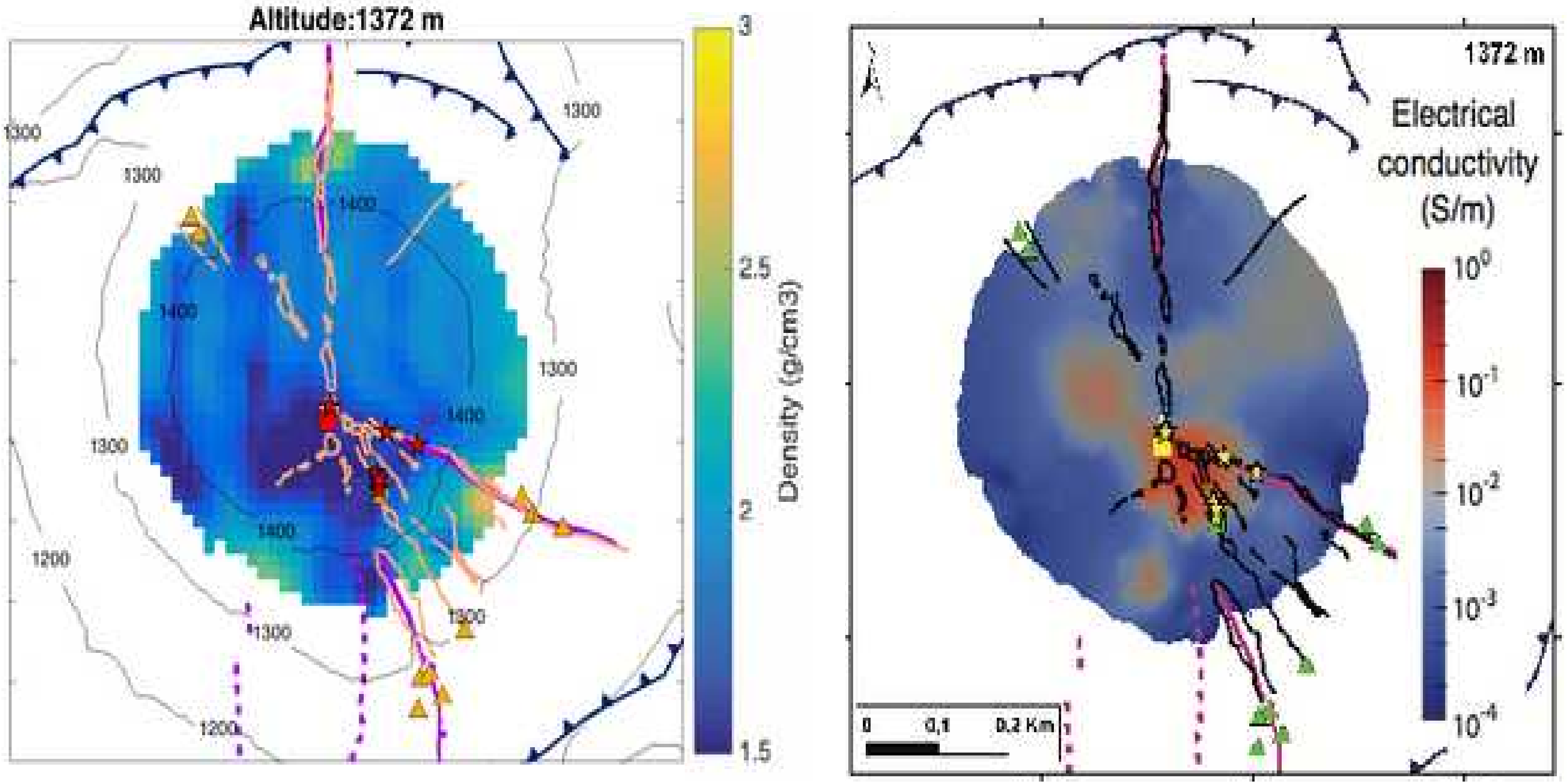
Matrix scaling





(Rosas-Carbajal et al., 2017)

Horizontal slices of density and electrical conductivity models



(Rosas-Carbajal et al., 2016, 2017)

LIDENBROCK & SNAEFELLSJOKULL

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4 – WARM ARCTIC, SKJOLBRAUT 22, IS-200 KOPAVOGUR, ICELAND
5 – SNAEFELLS NATIONAL PARK
6 – HTTPS://CAROLMULLER.FR/

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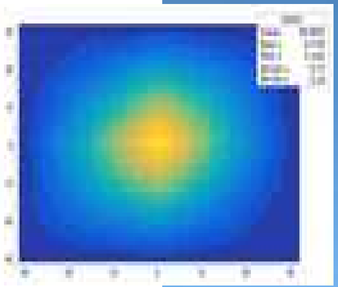
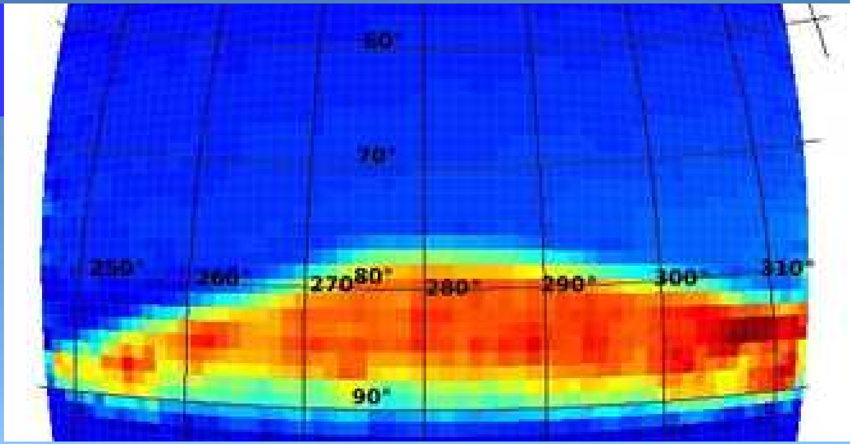
Detector mounting and assembly

First lights

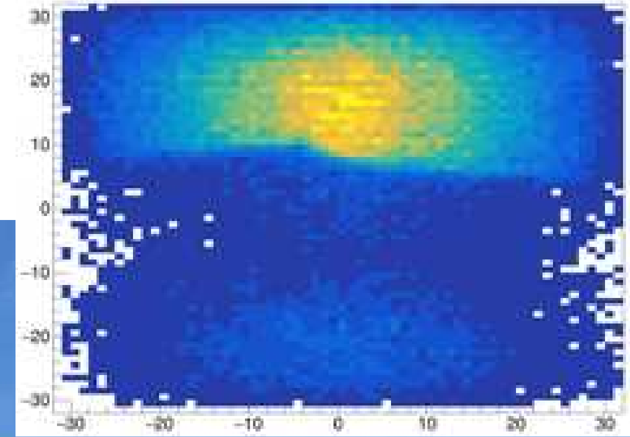


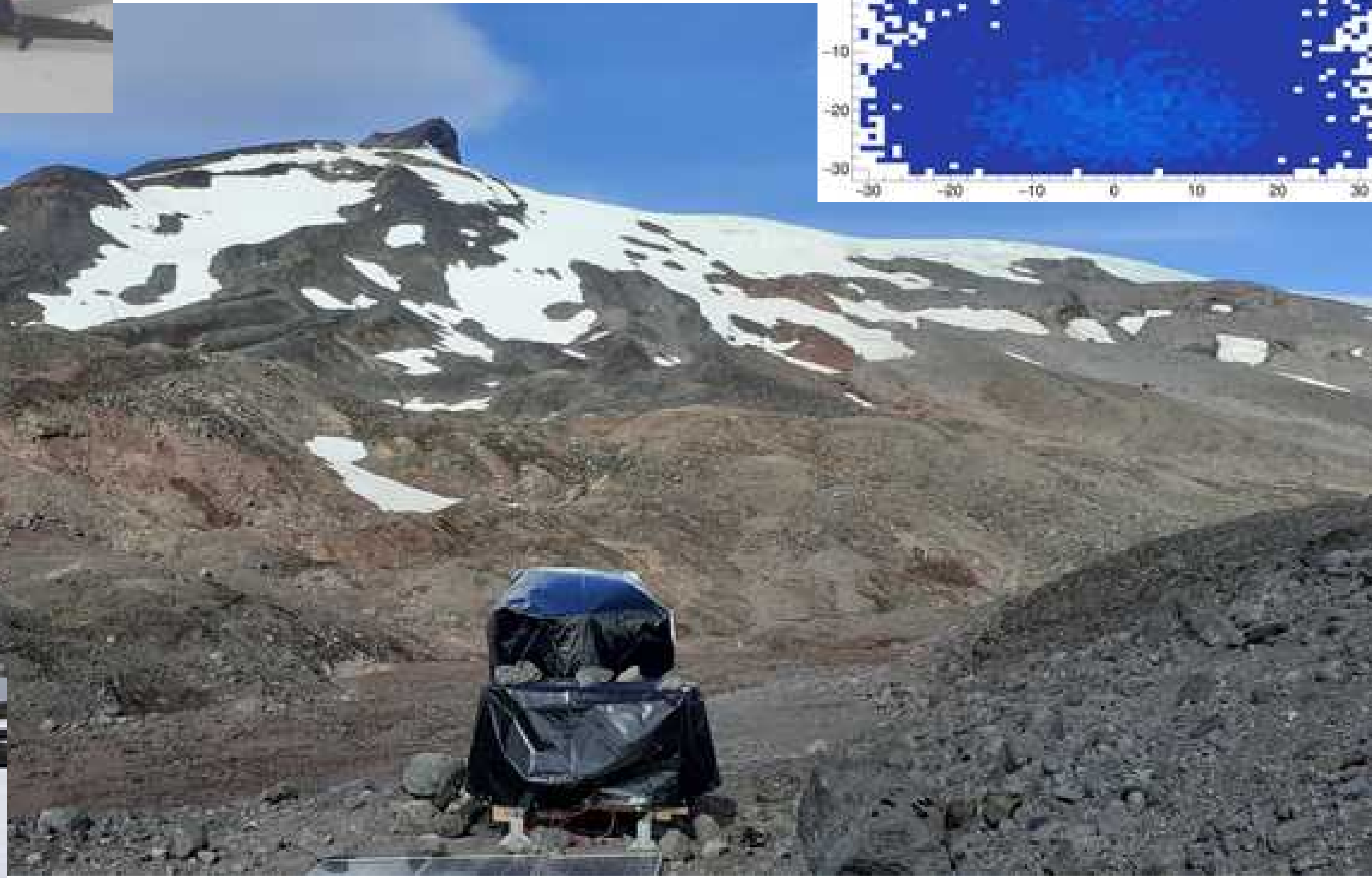


tomographic mode

open sky

Second run





Nuclear evaporator

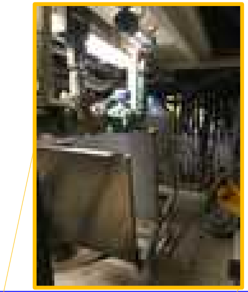
TBM

Geotechnics

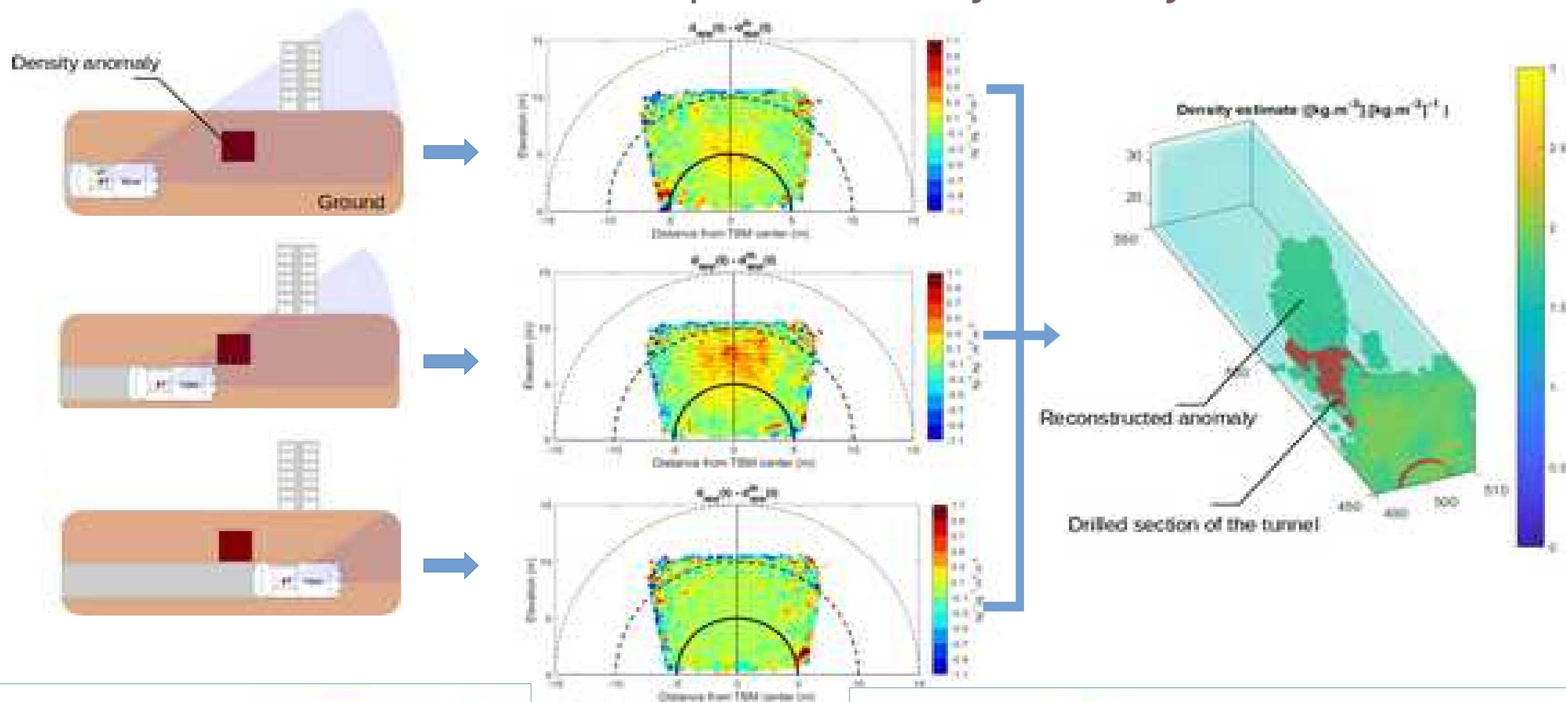
Silos

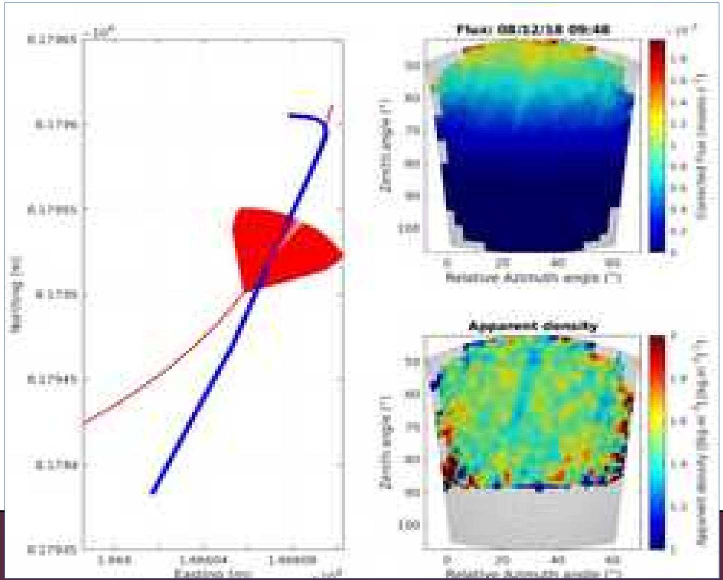
Blast furnace

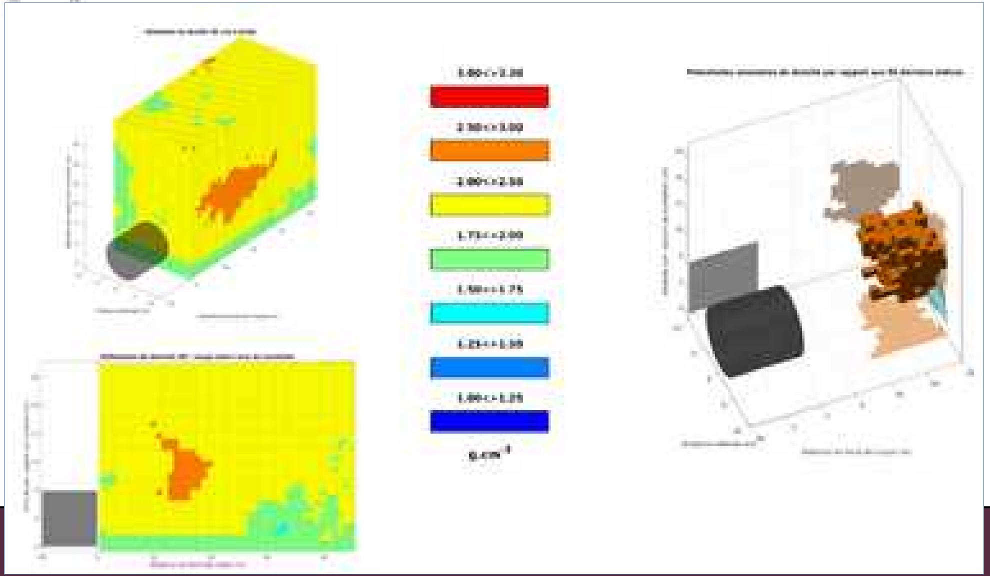
Application to Tunnel Boring machines



Measurements Principles & Density anomaly detection

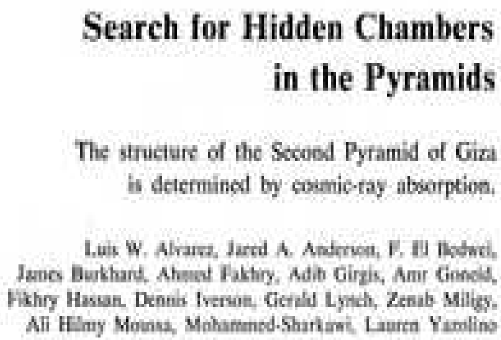






Archaeology

Great pyramids

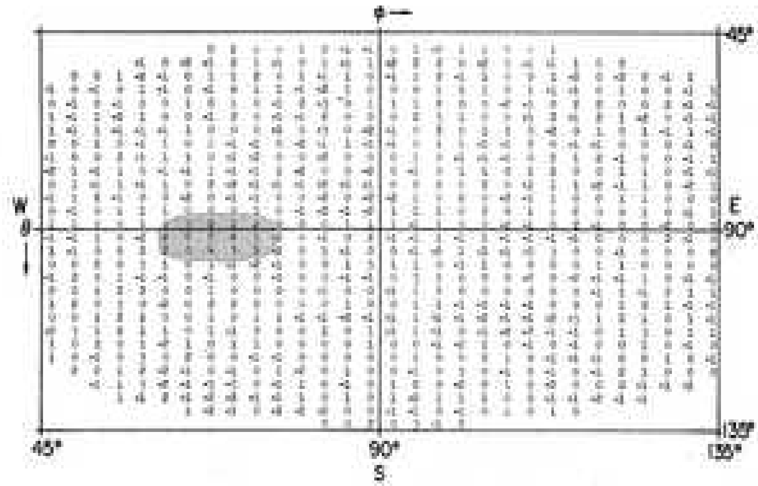


Search for Hidden Chambers in the Pyramids

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.Alvarez paper

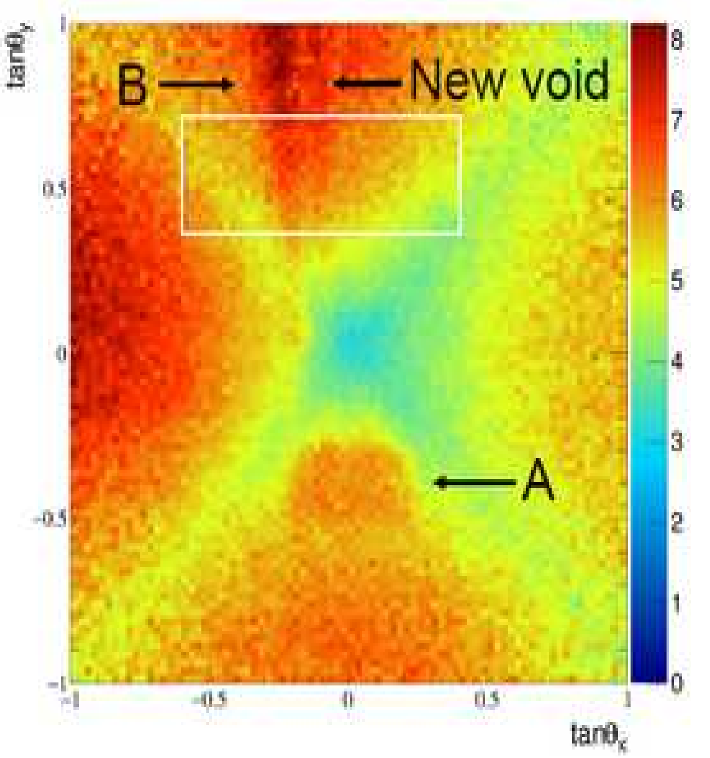


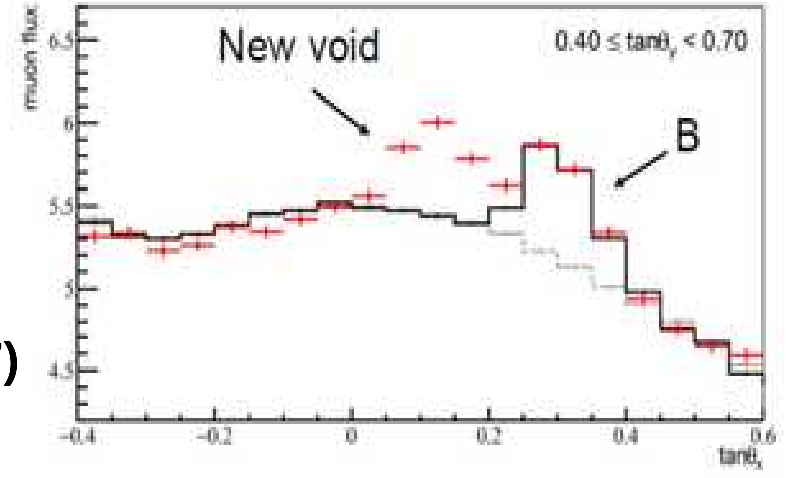
Greek tumulus

ArchéMuons

The ScanPyramids project

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



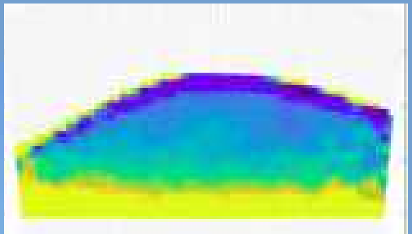


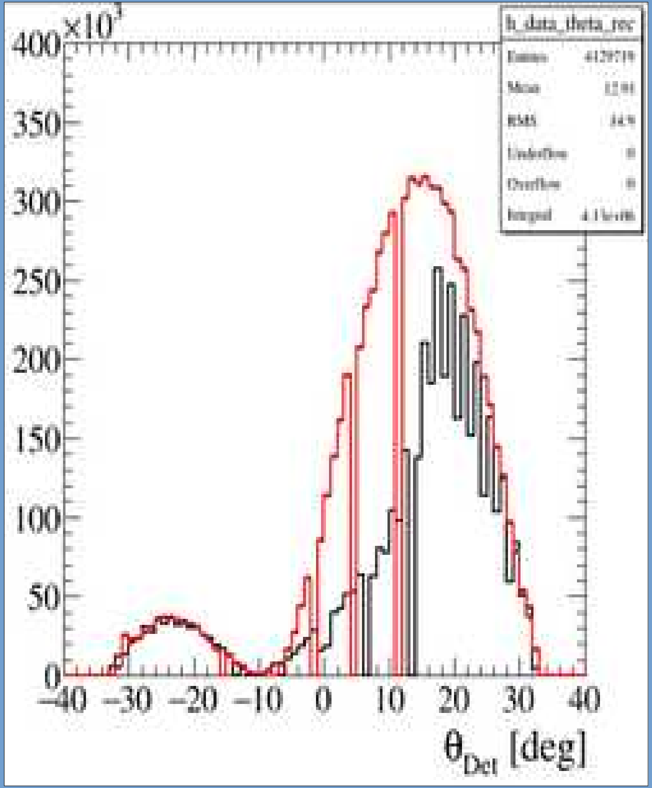
(388 | Nature | VOL 552 | 21/28 DECEMBER 2017)

The Apollonia tumulus

Challenges :

- Looking for an object with similar density as the surrounding materials r~2.3 gr/cm³ for dirt and 2.5 gr/cm³ 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 !





https://www.univearths.fr/fr/2018/07/18/excursion-experimentale-des-geoparticules-a-apollonia/

ArchéMuons

- Muon Tomography in controlled/confined environment

- Combine/Compare results with geophysical surveys:
  - ✔ ERT
  - ✔ Gravimetry
  - ✔ Seismometry

- Prospect of archaeological discovery in the “Palais du Miroir”

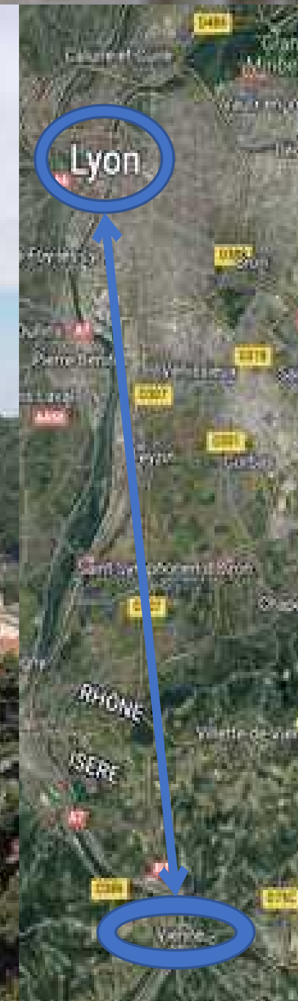
MUSÉE GALLO-ROMAIN SAINT-ROMAIN-EN-GAL

Archéorient

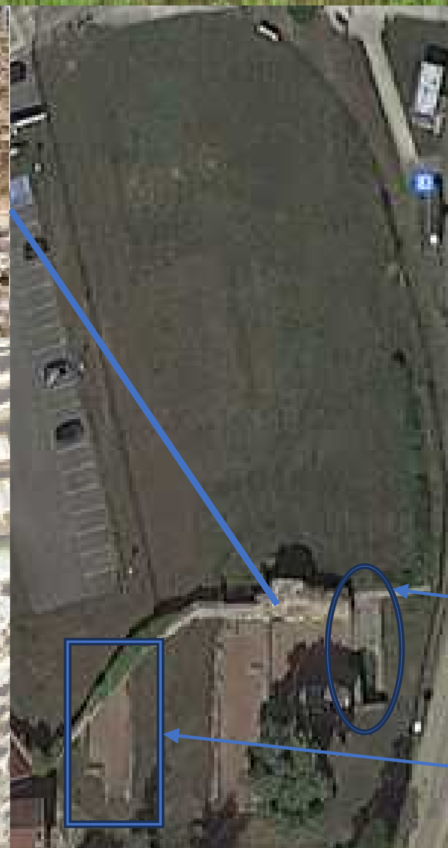
Laboratoire de Géologie de Lyon Terre planètes Environnement

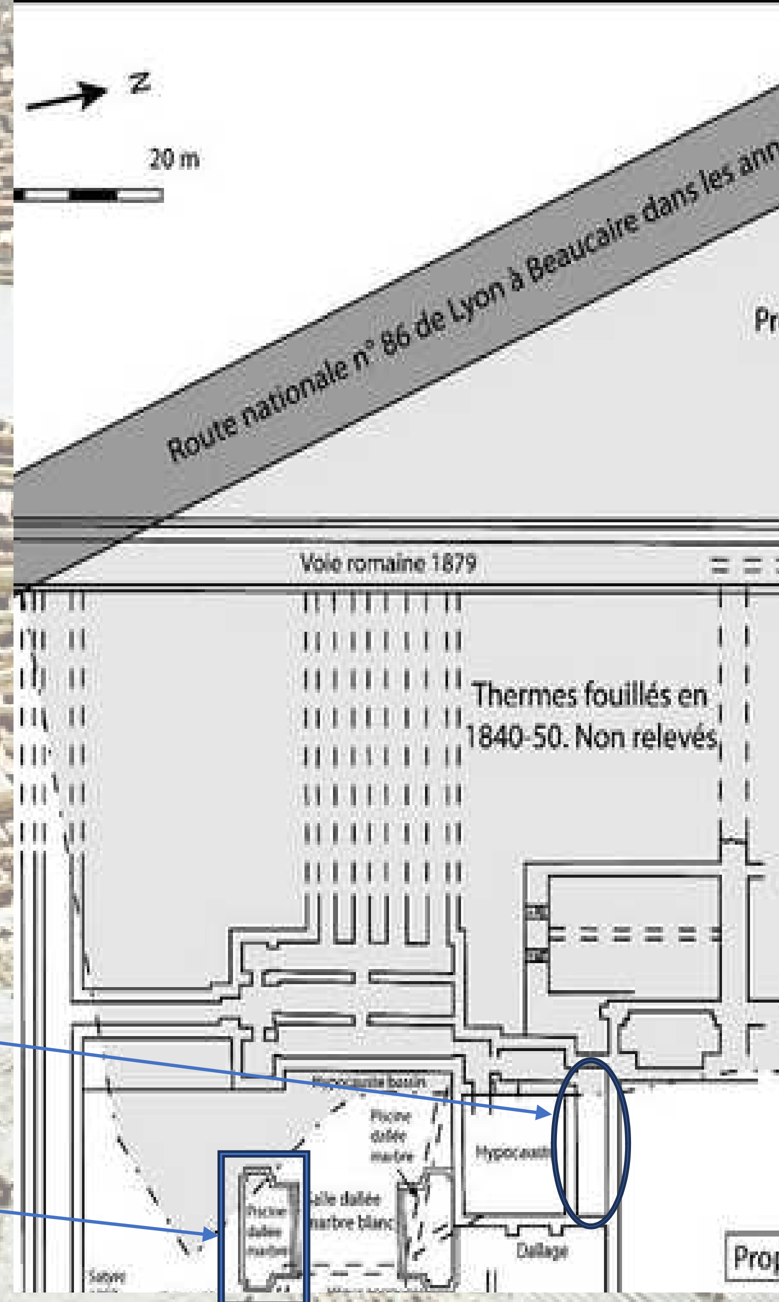
LABEX LIO UNIVERSITÉ DE LYON

Vienne & St-Romain en Gal

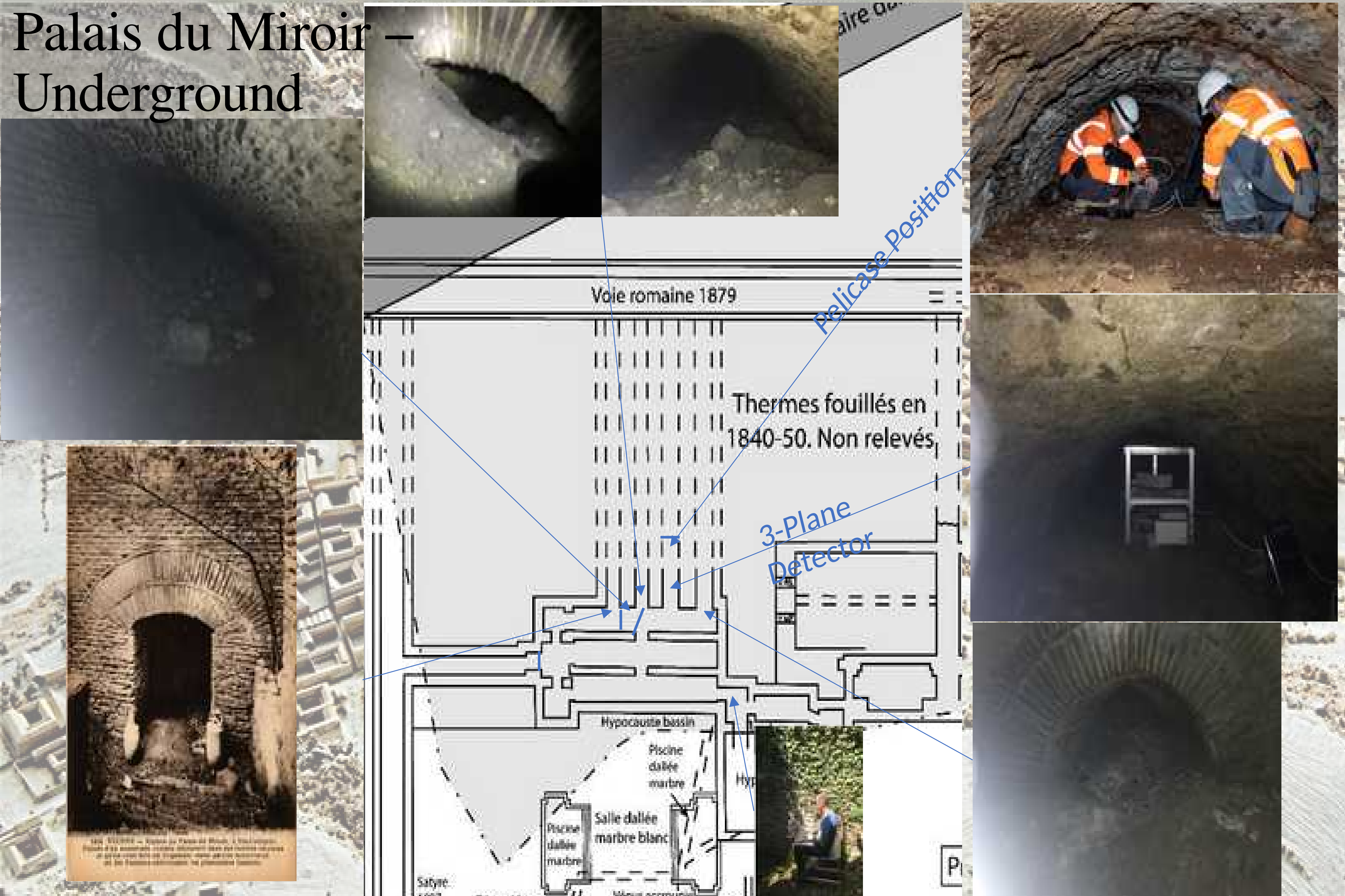


Palais du Miroir – Overground

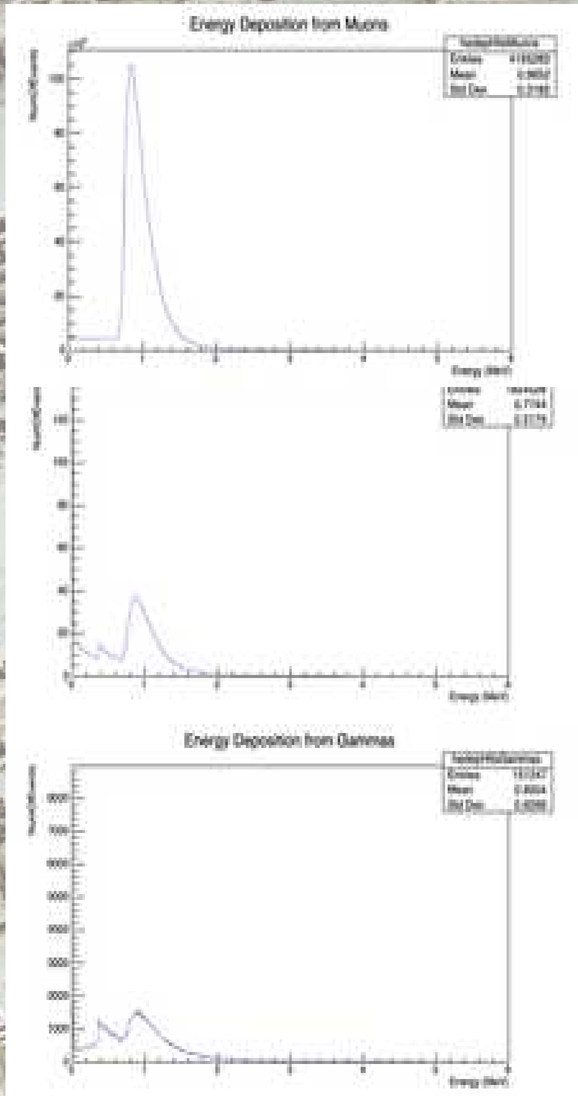




Palais du Miroir – Underground



MC simulation



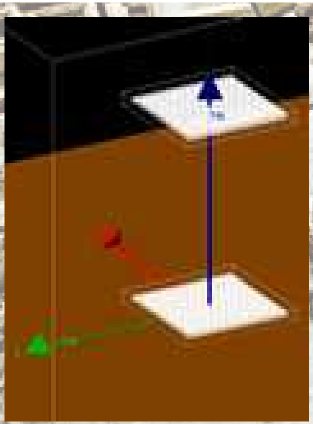
No Cuts

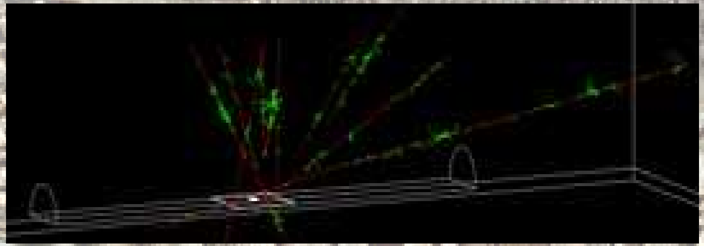
```
events with hits: 1993708
Events with 2 fold Coincidences: 351286
2-fold Coincidences with muon: 323597
2-fold Coincidences From Muons: 182544
```

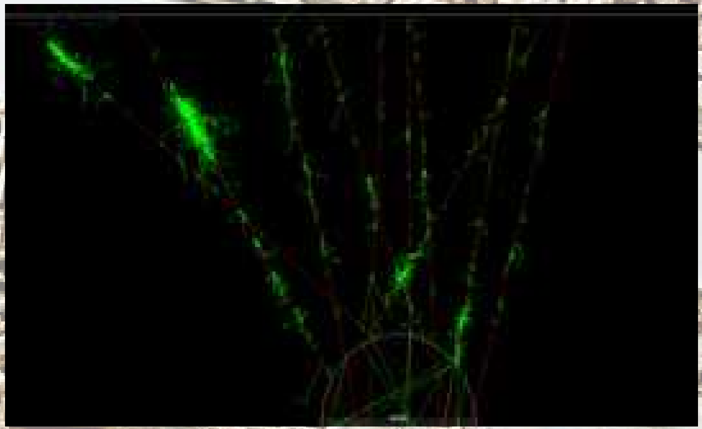
Energy Depostition>0.6 MeV

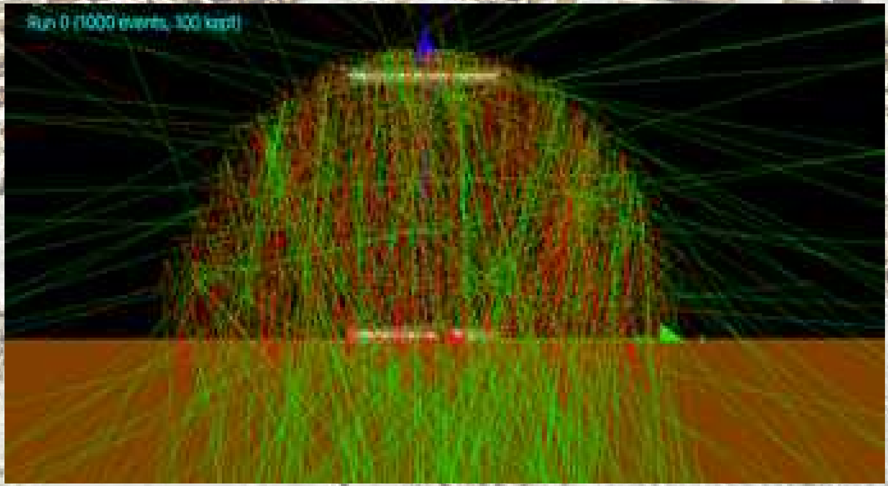
```
events with hits: 1526250
Events with 2 fold Coincidences: 273770
2-fold Coincidences with muon: 272918
2-fold Coincidences From Muons: 173913
```

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

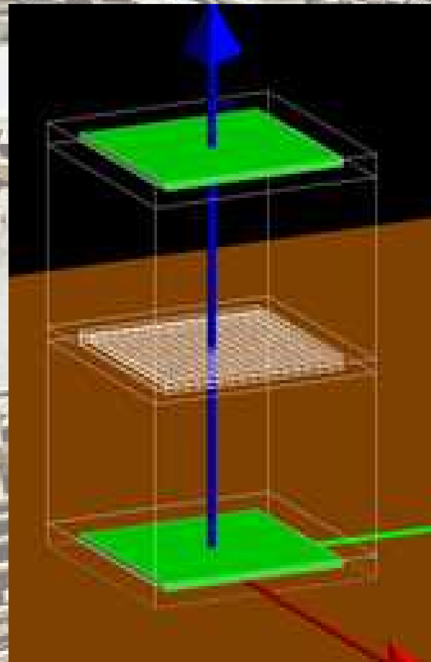


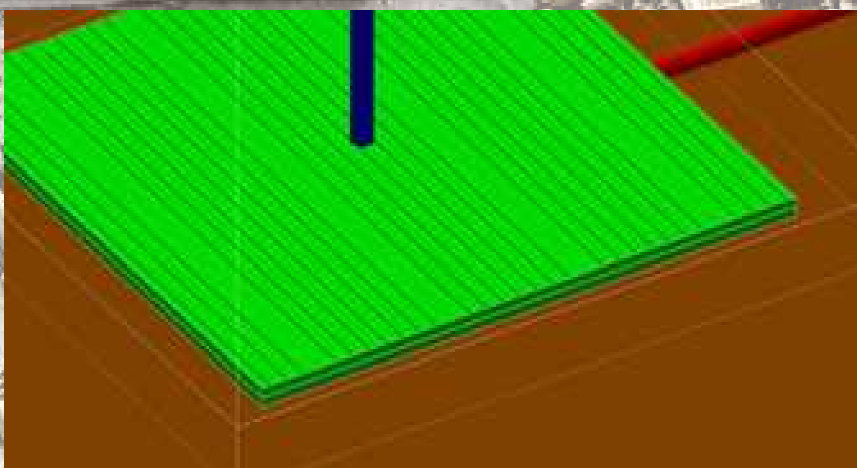






Detector development





Saint-Gobain

ref. Luxium Solutions

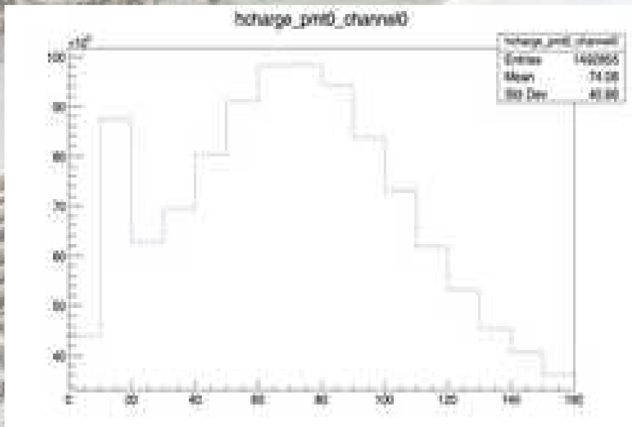
BC-416
203 cm X 63 cm X 5 mm

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

Large Area & Economy

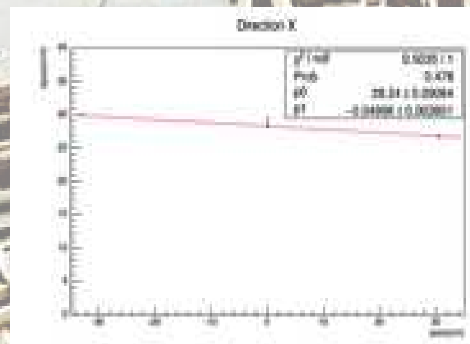
Track Reconstruction from charge deposit

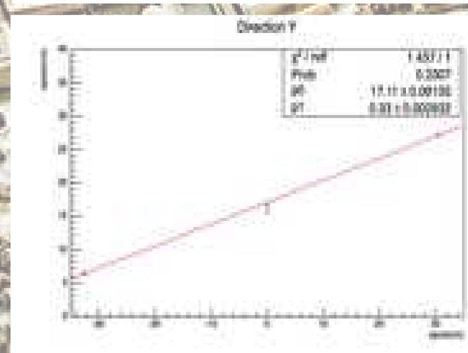
Gold Event Rates:
(1) 12.8 * 10^-3 Hz
(2) 8.1 * 10^-3 Hz
(3) 4.5 * 10^-3 Hz
(4) 8.4 * 10^-3 Hz

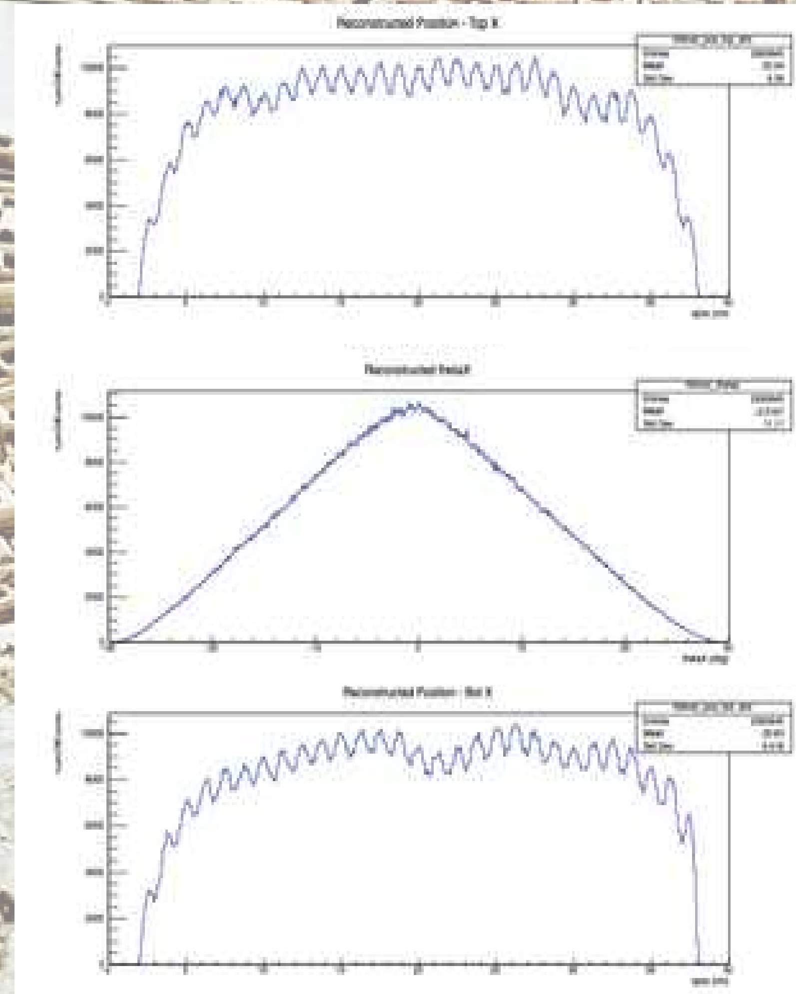


Charge cut:
Extreme plane channels: 30 ADC
Middle plane channels: 25 ADC

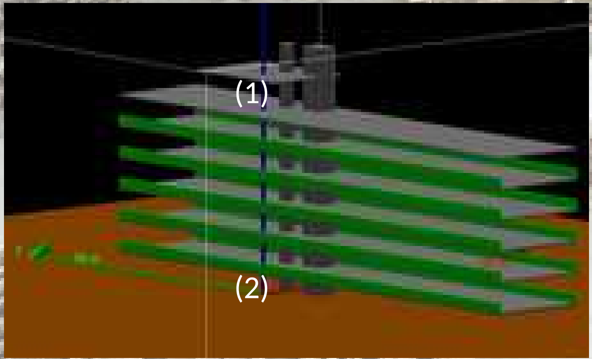
- Events that did not give charge on the fibers that are closest to the borders for the extreme panels.
- Events that gave one pair of (x,y) hits for the middle detector
- Exclude events that have position error = 0. This means that the multiplicity for the extreme panels is above 1.

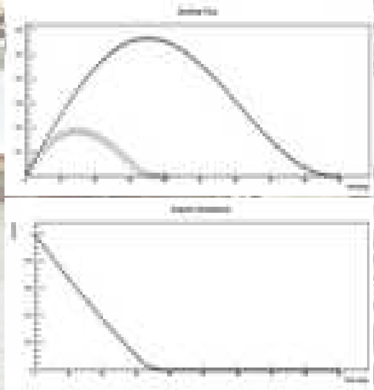


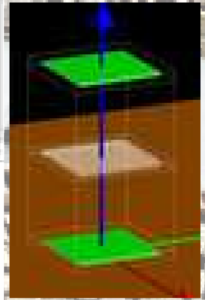


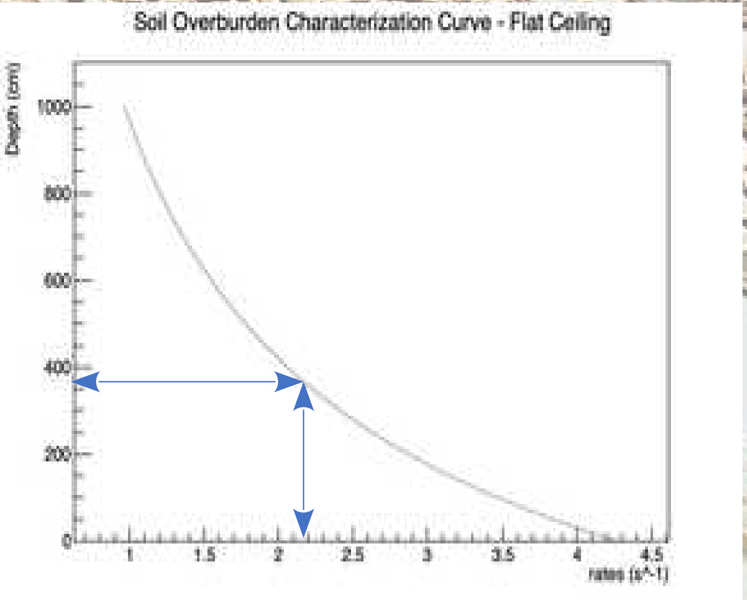


Overburden Thickness Calculation









<u>Detector Efficiency Calculation</u>

Theoretical Rates:

(1) - 4.120 s^-1

(2) - 3.175 s^-1

Experimental Rates:

(1) – 0.637 ± 0.0021 s^-1

(2) – 0.480 ± 0.0027 s^-1

Efficiency:

(3) - 0.1546 ± 0.0005

(4) - 0.1512 ± 0.0009

<Efficiency>: 0.1524 ± 0.0004

<u>Experimental rate inside the Cavity</u>

1st Run: 0.3381 ± 0.0007 s^-1

2nd Run: 0.3384 ± 0.0009 s^-1

3rd Run: 0.3209 ± 0.0008 s^-1

<Rate> = 0.3326 ± 0.0005 s^-1

Divide by efficiency

Rate = 2.182 ± 0.003 s^-1

<u>Overburden Characterization Curves</u>

Two Geometries for the overburden.

(a) Rectangular &

(b) Rectangular with Semispherical Cavity

The material is Standard Rock

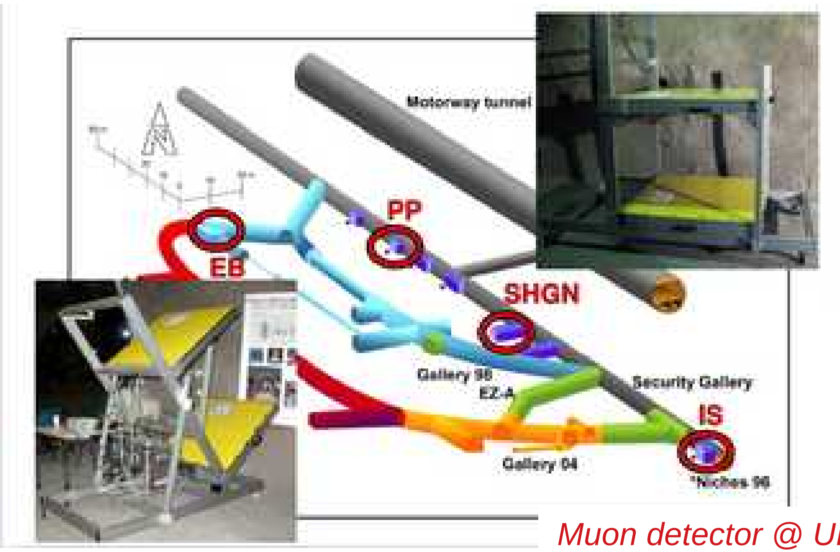
The step for the curve points is 10 cm

Height (a) = 362.9 ± 0.9 cm

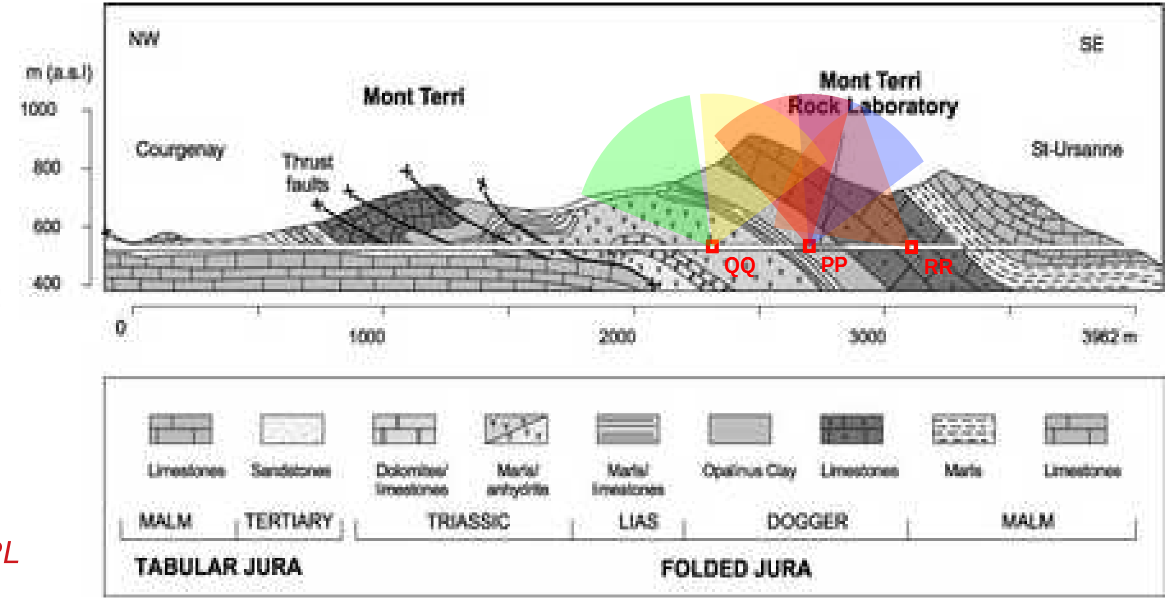
Height (b) = 358.4 ± 0.9 cm

<Height> = 360.7 ± 0.6 cm

Underground labs



Muon detector @ URL



MUON TOMOGRAPHY ACQUISITIONS :

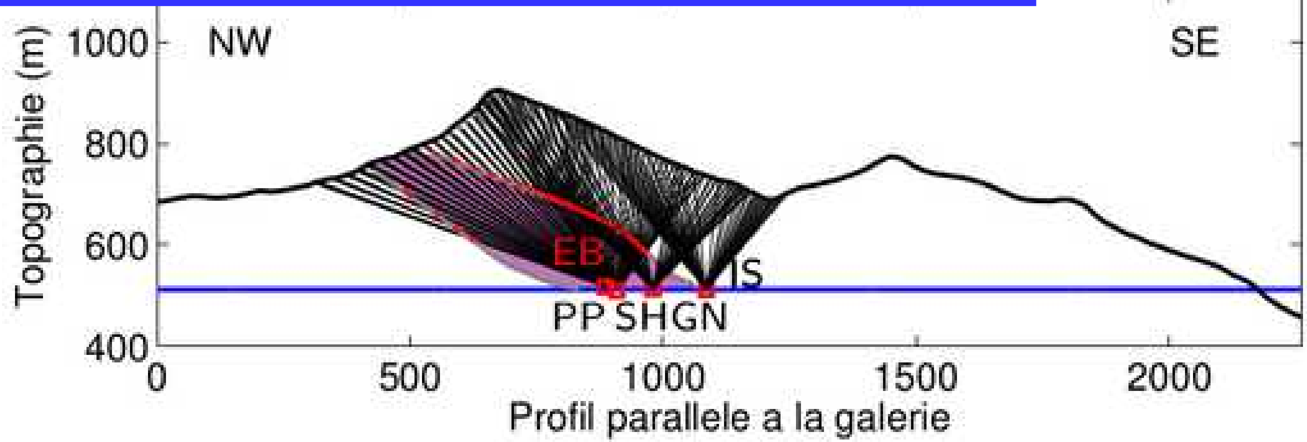
niche PP - run 1 | niche PP - run 2 | niche QQ - run 3
niche QQ - run 4 | niche RR - run 5

List of the 2012-2015 runs

Muon – gravimetry
joined analysis

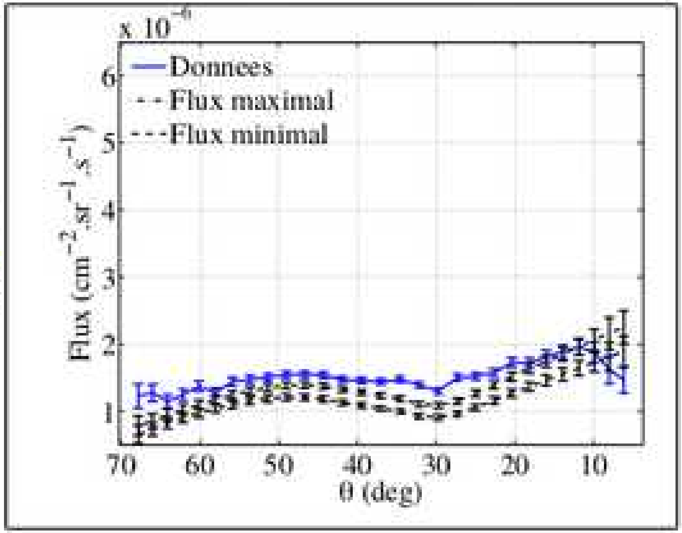
Muon detector @ LSBB

The Mont-Terri lab

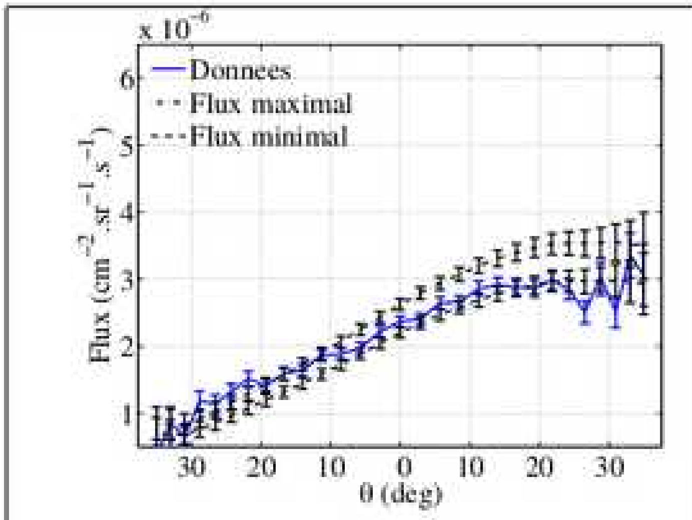


Bruit de fond décorrélé dans la niche PP : $1.7 \times 10^{-7}/s$

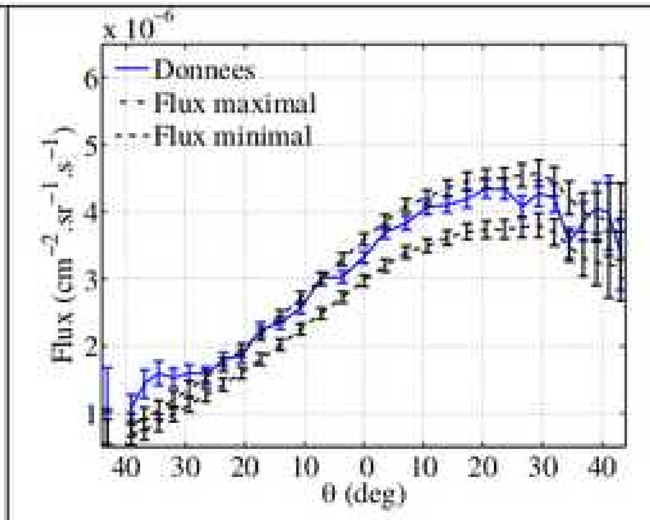
EB (177 jours)



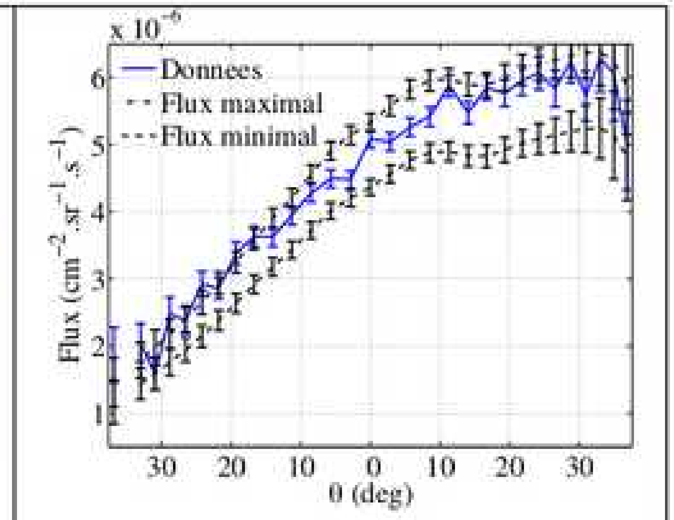
PP (56 jours)



SHGN (42 jours)

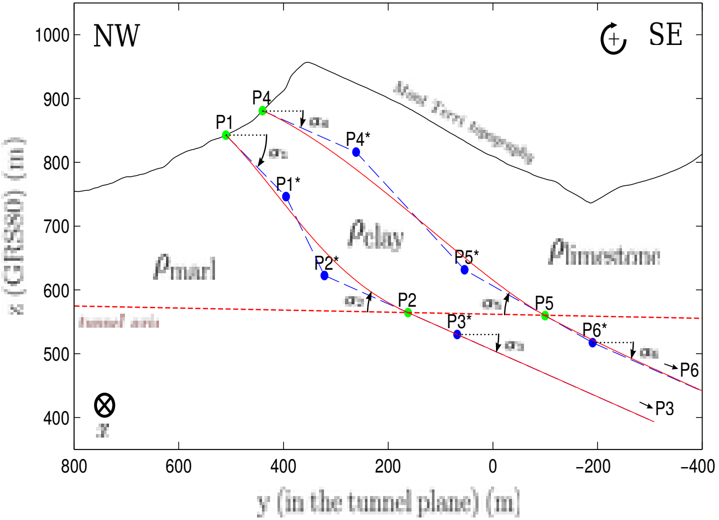


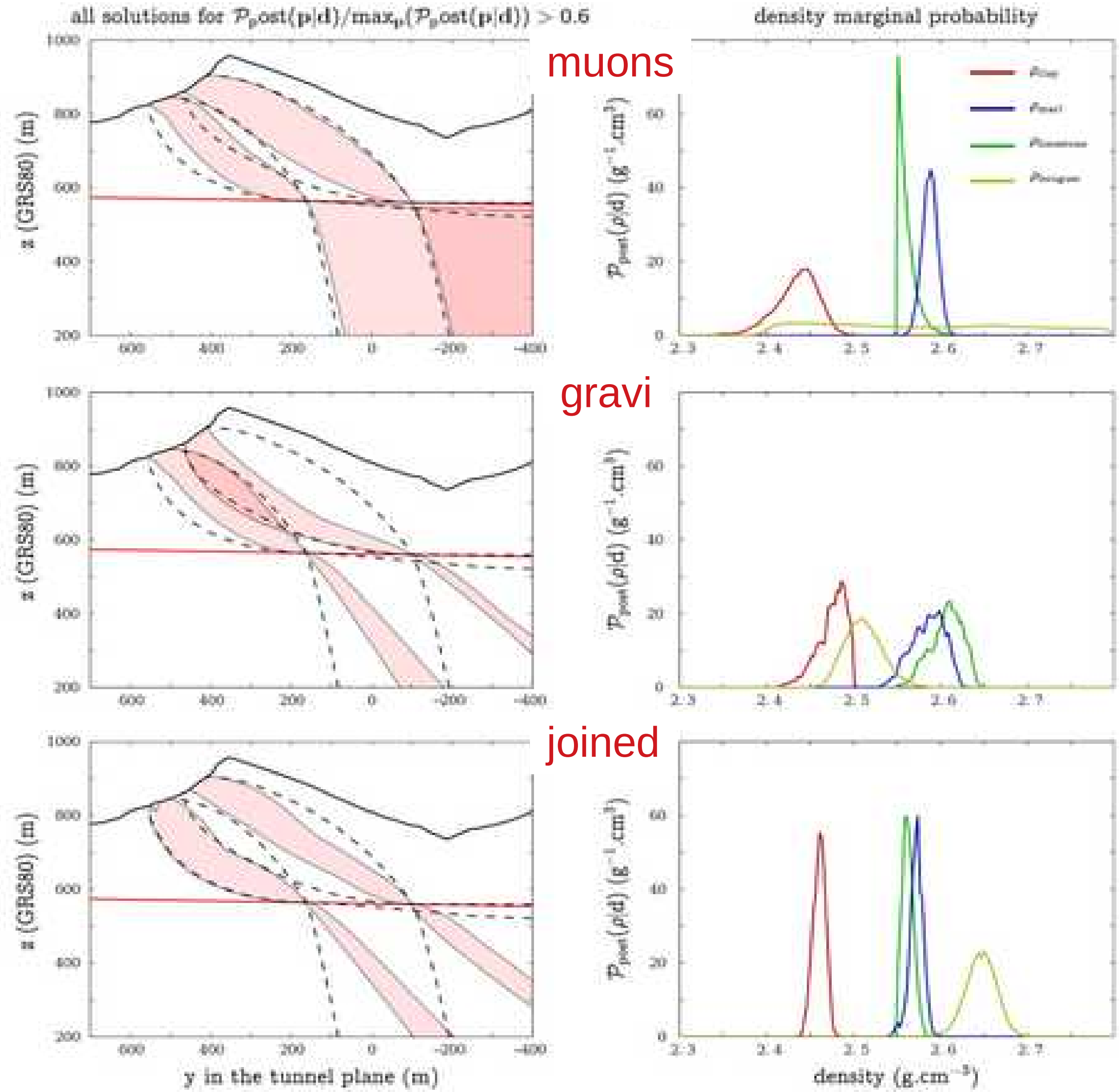
IS (47 jours)



Joint gravi-muon analysis

Opalinus layer parametrization

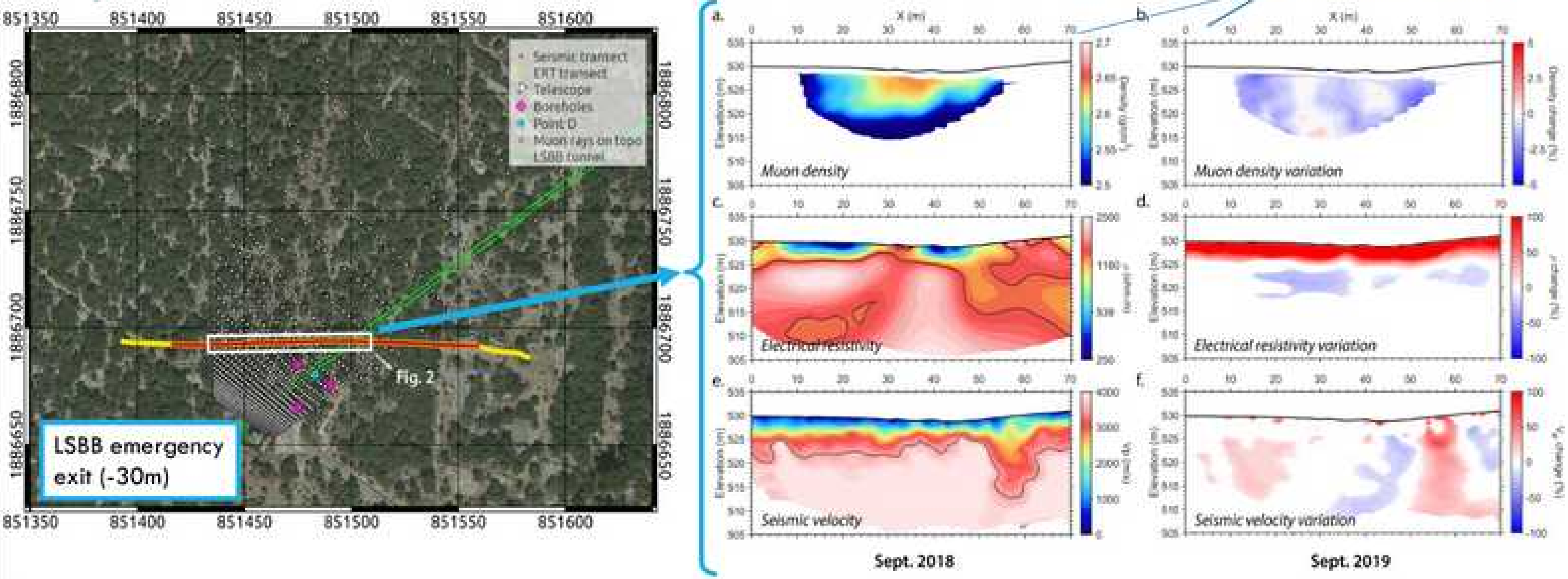




The LSBB facility

LSBB
Laboratoire Souterrain à Bas Bruit

A GOOD EXAMPLE: THE BUISSONIÈRE EXPERIMENT



Ref: Lázaro Roche, I.; Pasquet, S.; Chalikakis, K.; Mazzilli, N.; Rosas-Carbajal, M.; Decitre, J.B.; Batiot-Guilhe, C.; Emblanch, C.; Marteau, J.; et al.
Water resource management: The multi-technique approach of the Low Background Noise Underground Research Laboratory of Rustrel, France, and its muon detection projects.
In Muography: Exploring Earth's Subsurface with Elementary Particles. **2021**, Geophysical Monograph Series; Oláh, L., Tanaka, H., Varga, D., Eds. American Geophysical Union , USA. DOI:10.1002/9781119722748.ch10

MUODIM

The New York Times

iP2i LES 2 INFINIS LYON

How Do You See Inside a Volcano? Try a Storm of Cosmic Particles.

Muography, a technique used to peer inside nuclear reactors and Egyptian pyramids, could help map the innards of the world's most hazardous volcanoes.