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

MUODIM

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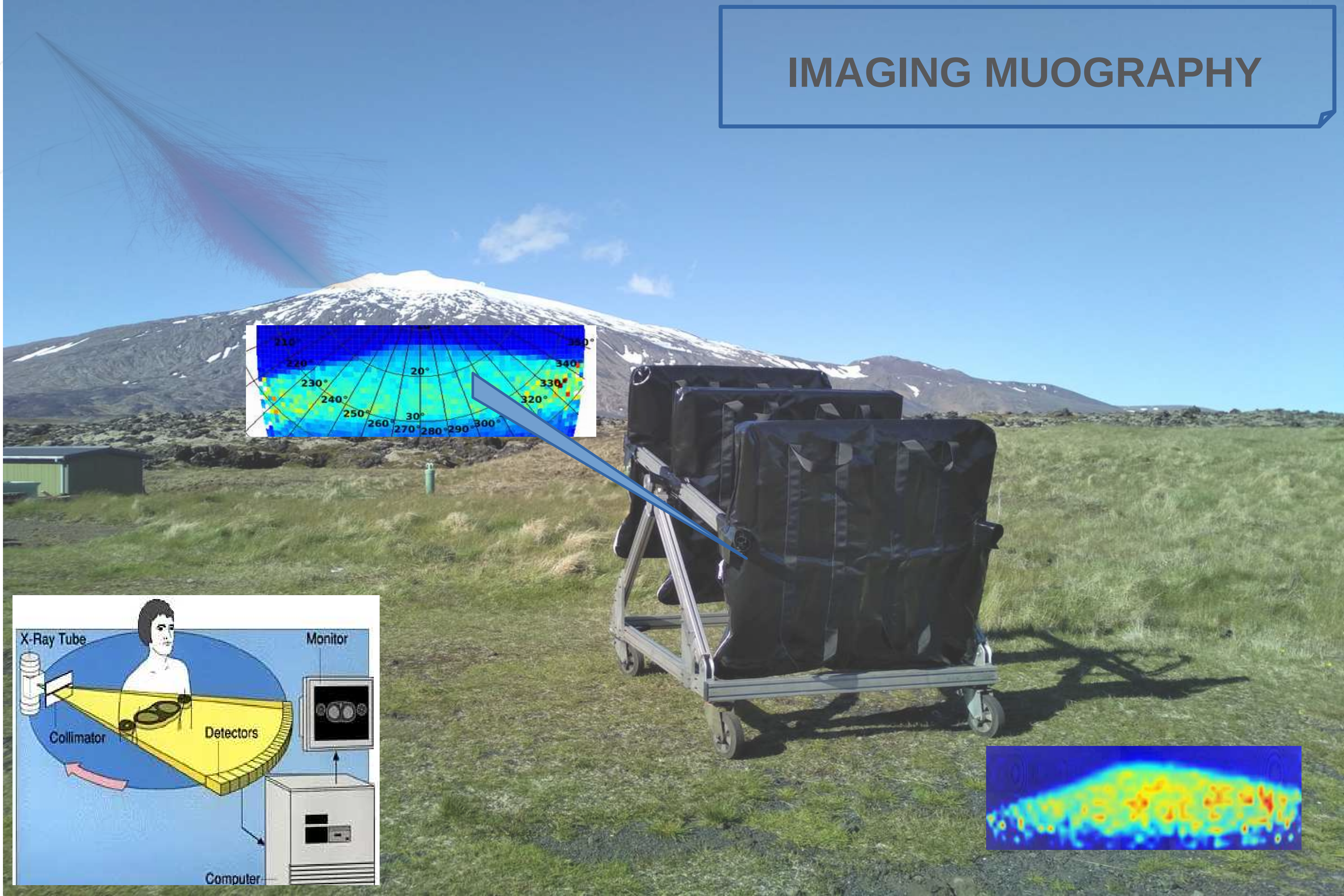
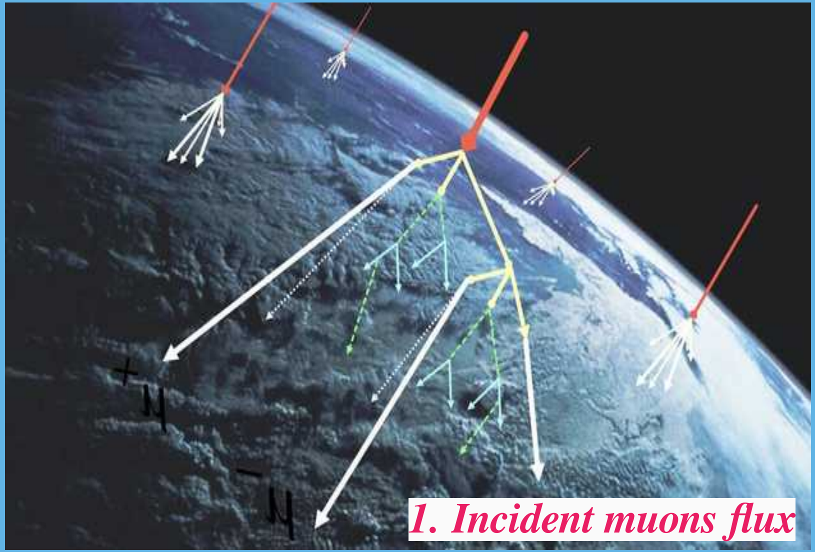
2 – MUODIM, 31 RUE SAINT-MAXIMIN, 69003 LYON

AHEAD workshop, March, 4-5th, 2024

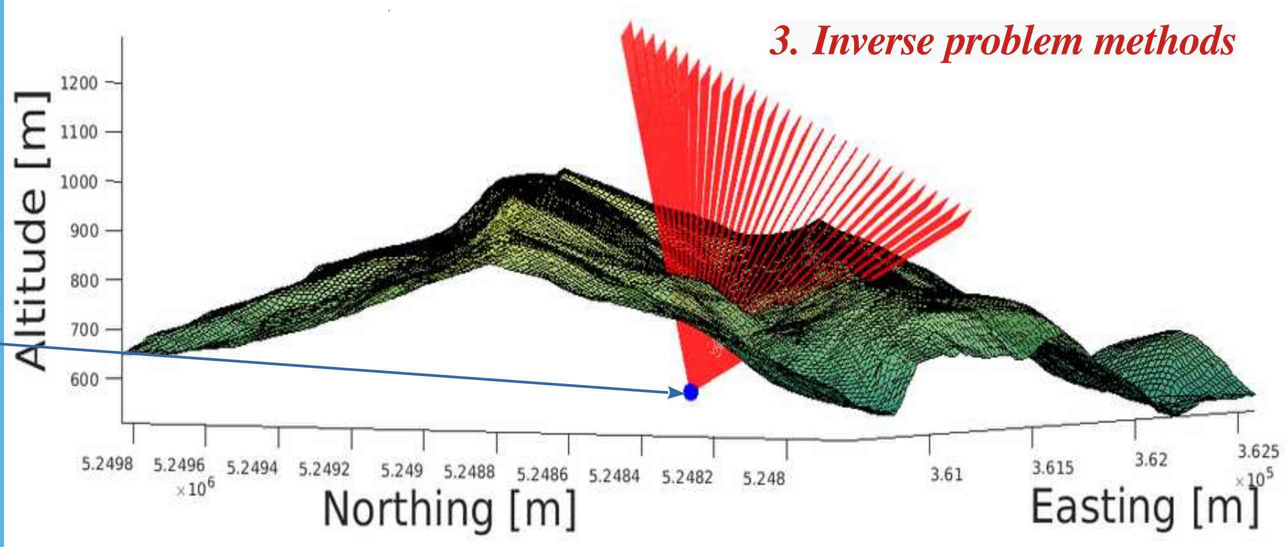

IMAGING MUOGRAPHY
210°
220°
20°
230°
240°
250°
30°
260°
270°
280°
290°
300°
320°
330°
340°
350°
X-Ray Tube
Monitor
Collimator
Detectors
Computer

Muography = absorption/scattering tomography

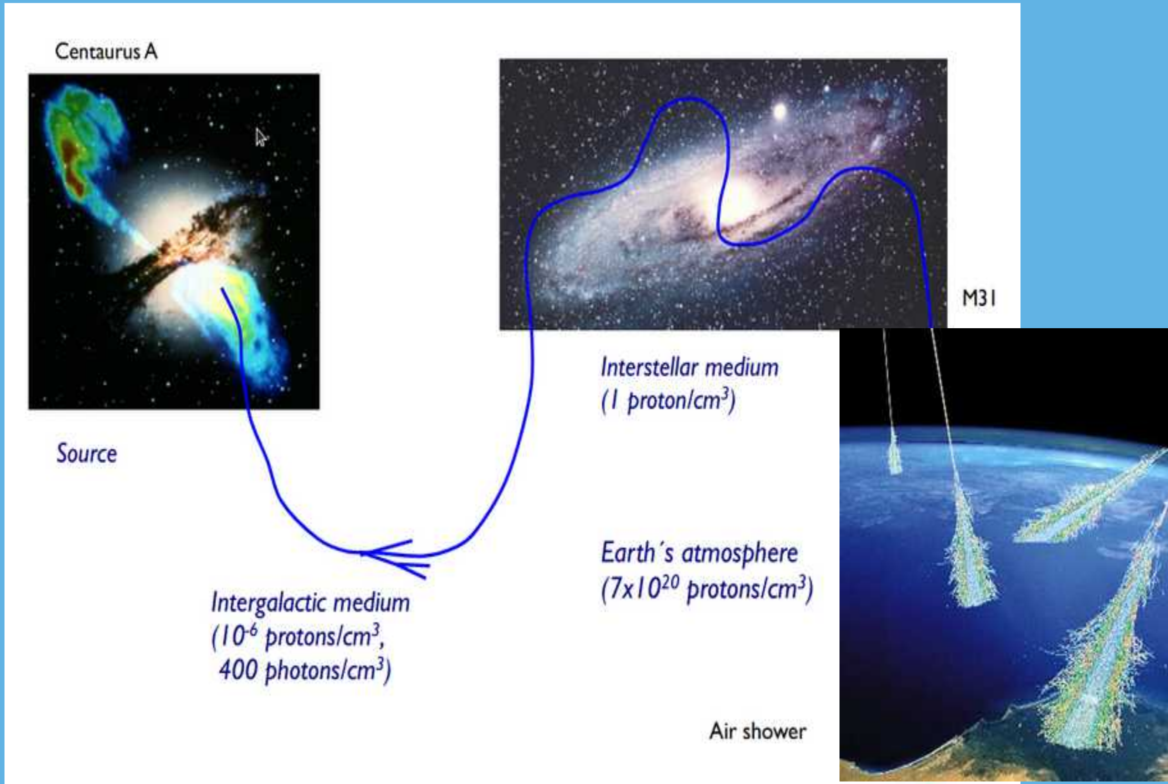
The particles (e.g. muons) generated in the atmosphere, lose energy and are scattered along their trajectories across matter (electromagnetic interactions with the charges inside the medium) according to the medium's density (ϱ) and chemical composition (Z/A).



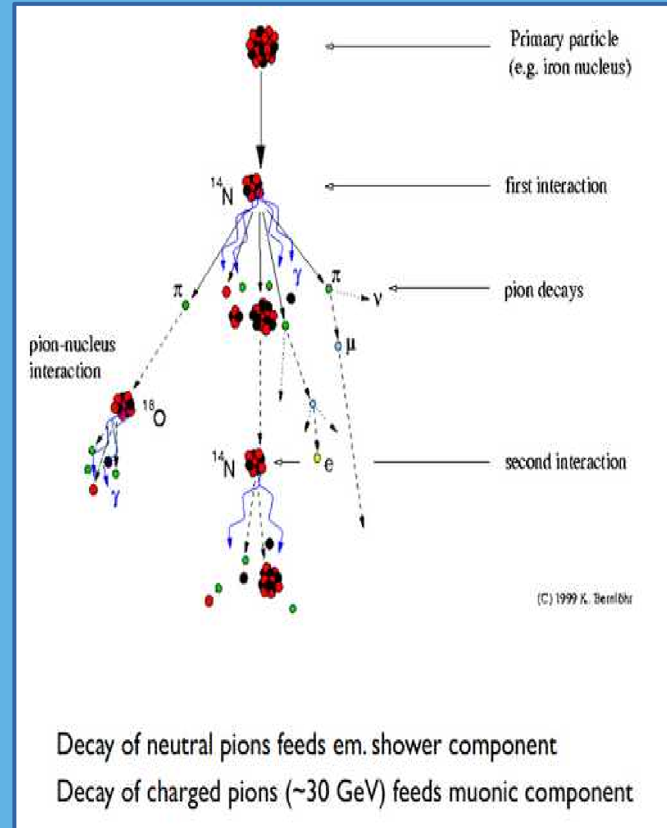
2. Tracking detector



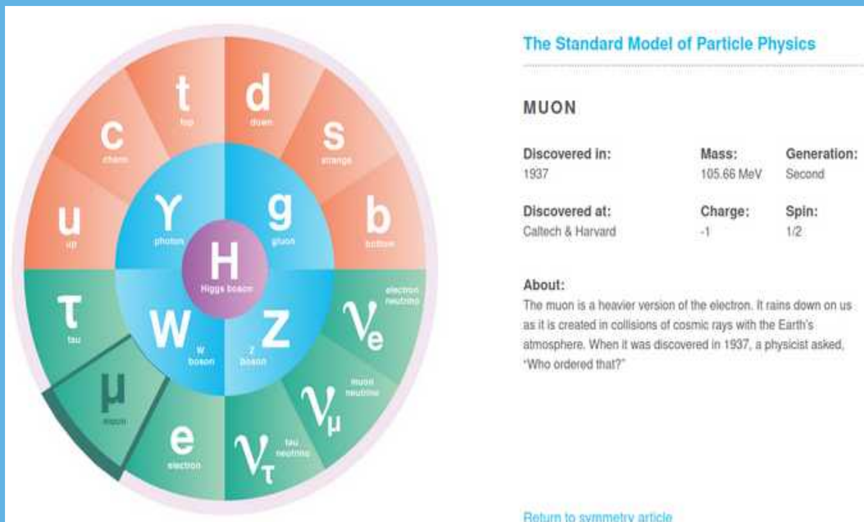
1. THE PROBES



Centaurus A
M31
Source
Interstellar medium
(1 proton/cm³)
Earth´s atmosphere
(7x10²⁰ protons/cm³)
Intergalactic medium
(10⁻⁶ protons/cm³,
400 photons/cm³)
Air shower

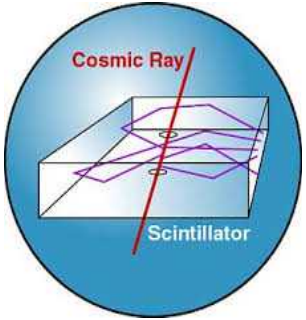


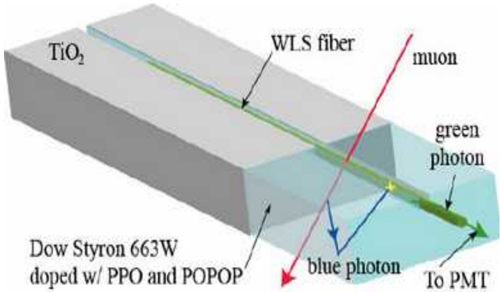
Primary particle
(e.g. iron nucleus)
first interaction
pion decays
pion-nucleus
interaction
second interaction
(C) 1999 K. Bernlöhr
Decay of neutral pions feeds em. shower component
Decay of charged pions (~30 GeV) feeds muonic component

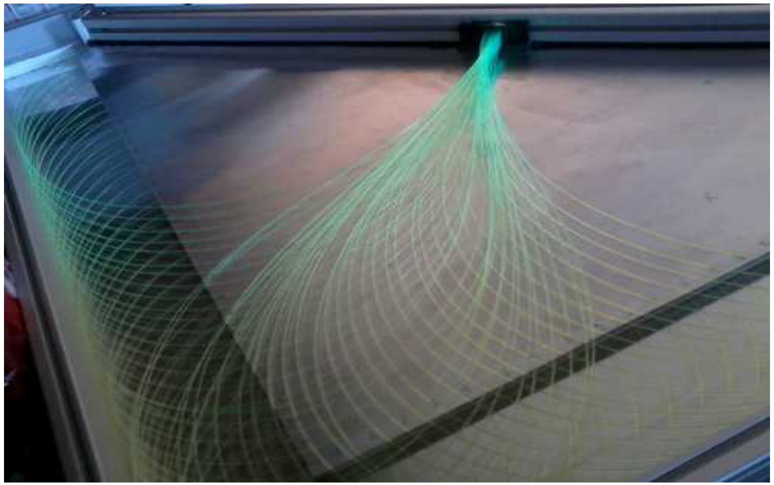


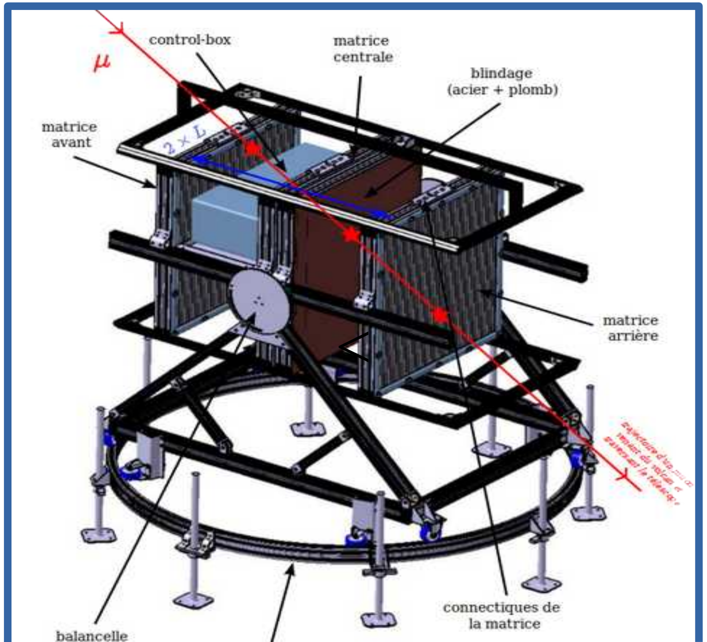
The Standard Model of Particle Physics
MUON
Discovered in:
1937
Mass:
105.66 MeV
Generation:
Second
Discovered at:
Caltech & Harvard
Charge:
-1
Spin:
1/2
About:
The muon is a heavier version of the electron. It rains down on us as it is created in collisions of cosmic rays with the Earth's atmosphere. When it was discovered in 1937, a physicist asked, "Who ordered that?"
Return to symmetry article

2. THE TRACKERS





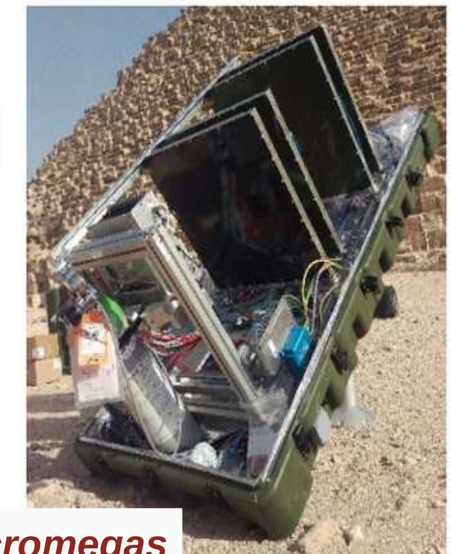




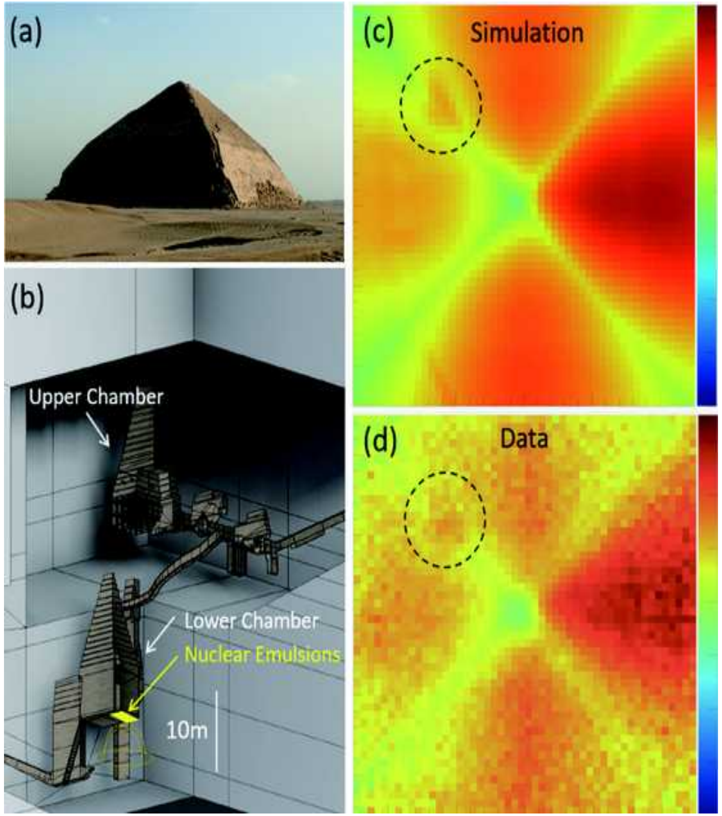
Scintillators

Emulsions

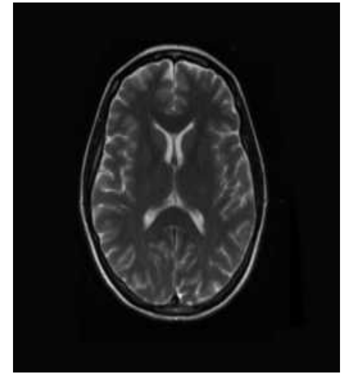
RPC



Micromegas



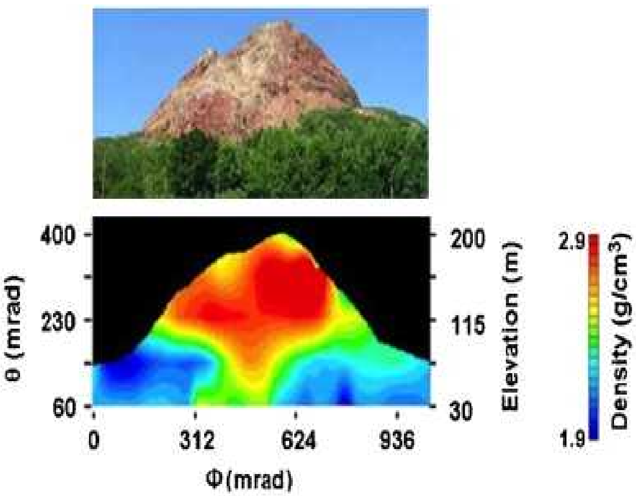
3a. IMAGING METHODS

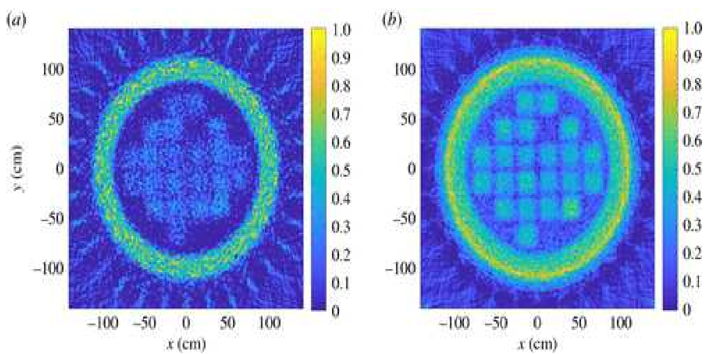


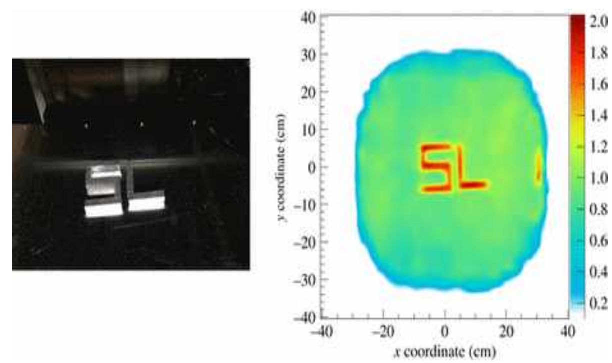
Détecteur

Reconstruction

Images

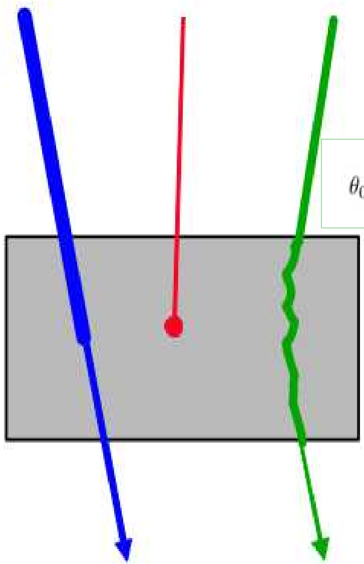






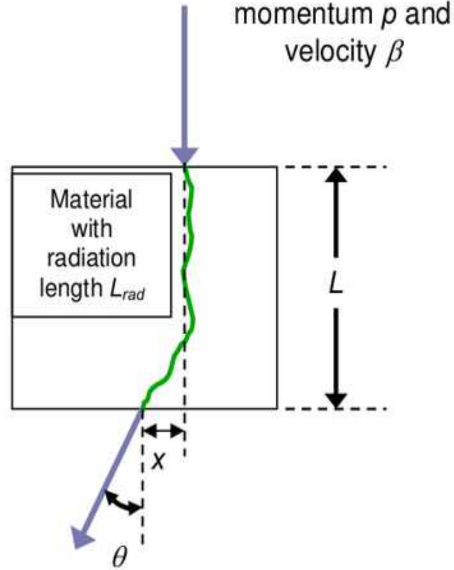
PHYSICS-CONSTRAINT INVERSE METHODS

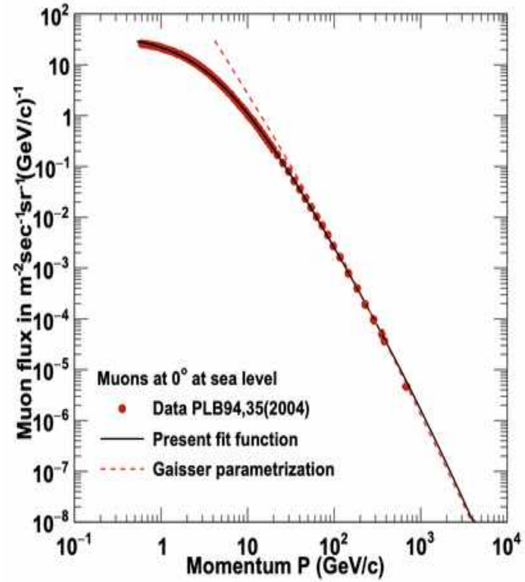
$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



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

Different types of interaction between muons and matter: trajectories with and without scattering (green and blue lines), stopping trajectories (red line).





POCA 3D: Point of Closest-Approach

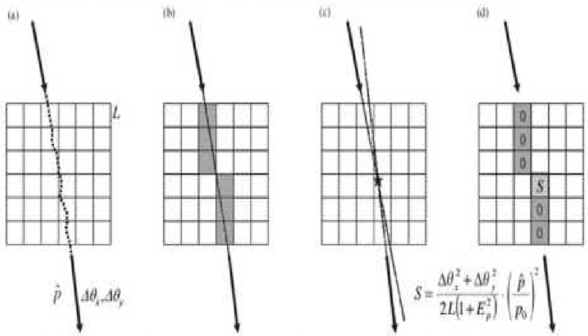


Fig. 4. PoCA reconstruction algorithm, shown in 2D for simplicity. A muon's stochastic path through an object volume (a). We measure scattering in two planes, and estimate particle momentum. Estimate muon path and identify voxels through which ray passed (b). Localize scattering signal to voxel containing PoCA (c). Define scattering signal as shown, and assign signal to the PoCA voxel, 0 to other candidate voxels (d). Take mean signal in each voxel over all muons to establish reconstructed scattering strength.

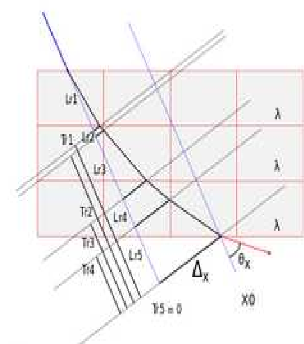
Pour chaque muon

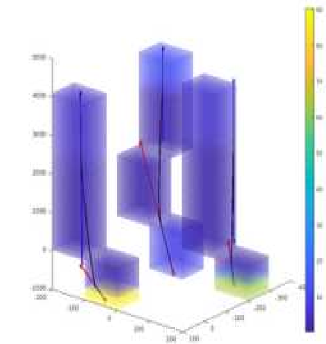
I : Nombre de muons par cellule : Pour toute cellule collorée : ajoute 1

S : Scattering Influence : Pour toute cellule colorée : ajoute Score S

λ : Densité de Scattering : $\lambda(j) = S(j)/I(j)/L$

MLEM: Maximum Likelihood Expectation Maximisation





x

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

y

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

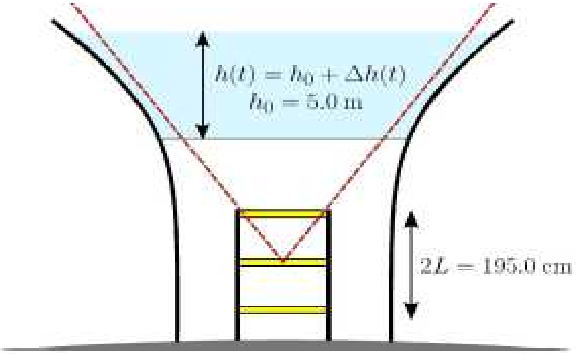
$$\frac{1}{|\Sigma_i|}\left(\Delta\theta_i^2 v_{x,i} - 2\Delta\theta_i w_i s_{\theta x,i} + \Delta w_i^2 v_{\theta,i}\right)$$

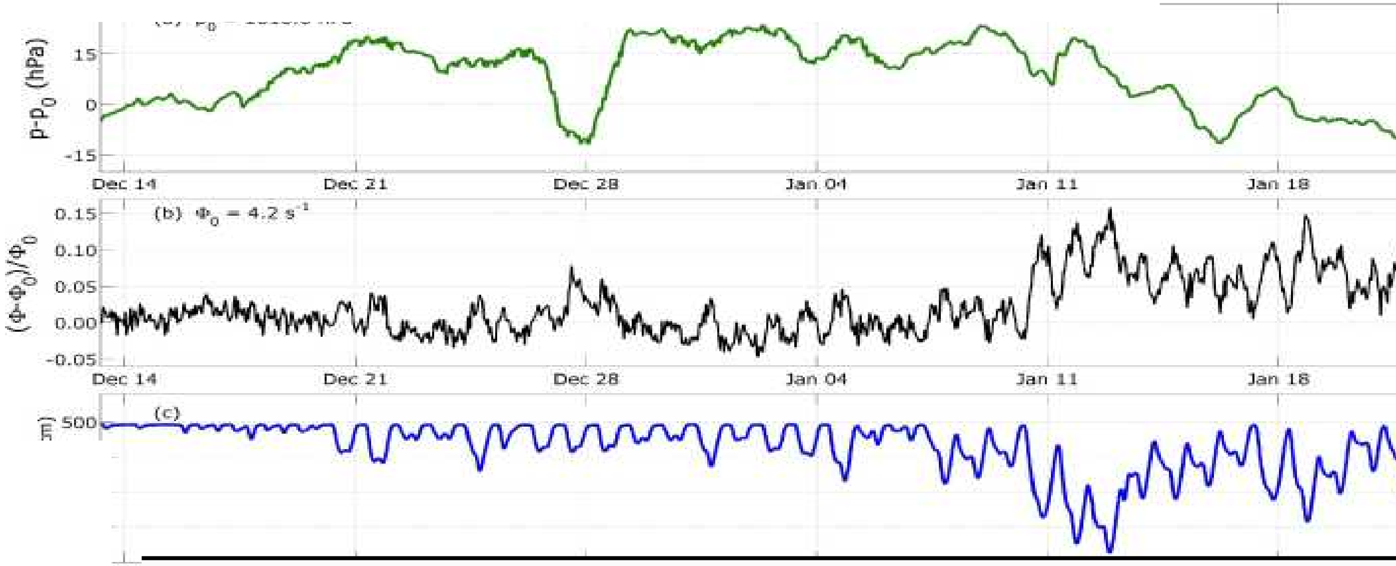
$$\Sigma_i = p_{r,i}^2 \sum_{j \le N} \lambda_j W_{ij},$$

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

P (D/λ) Vraisemblance :
Probabilité que l'observable (Angle de diffusion + Déplacement) existe sachant la distribution de densité proposée

3b. MONITORING METHODS

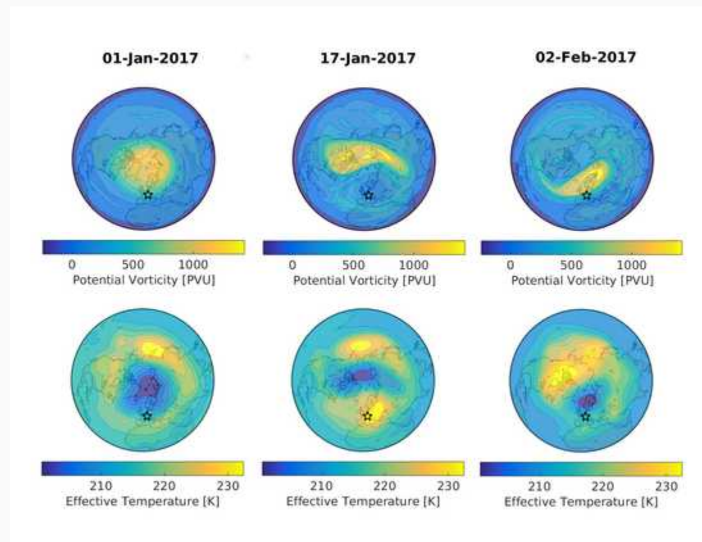


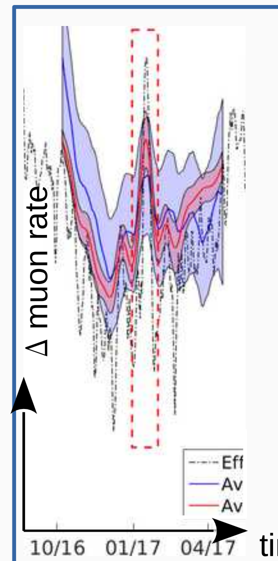


- Proof of concept
- Water tank level monitoring
- Barometric effects corrections

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

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

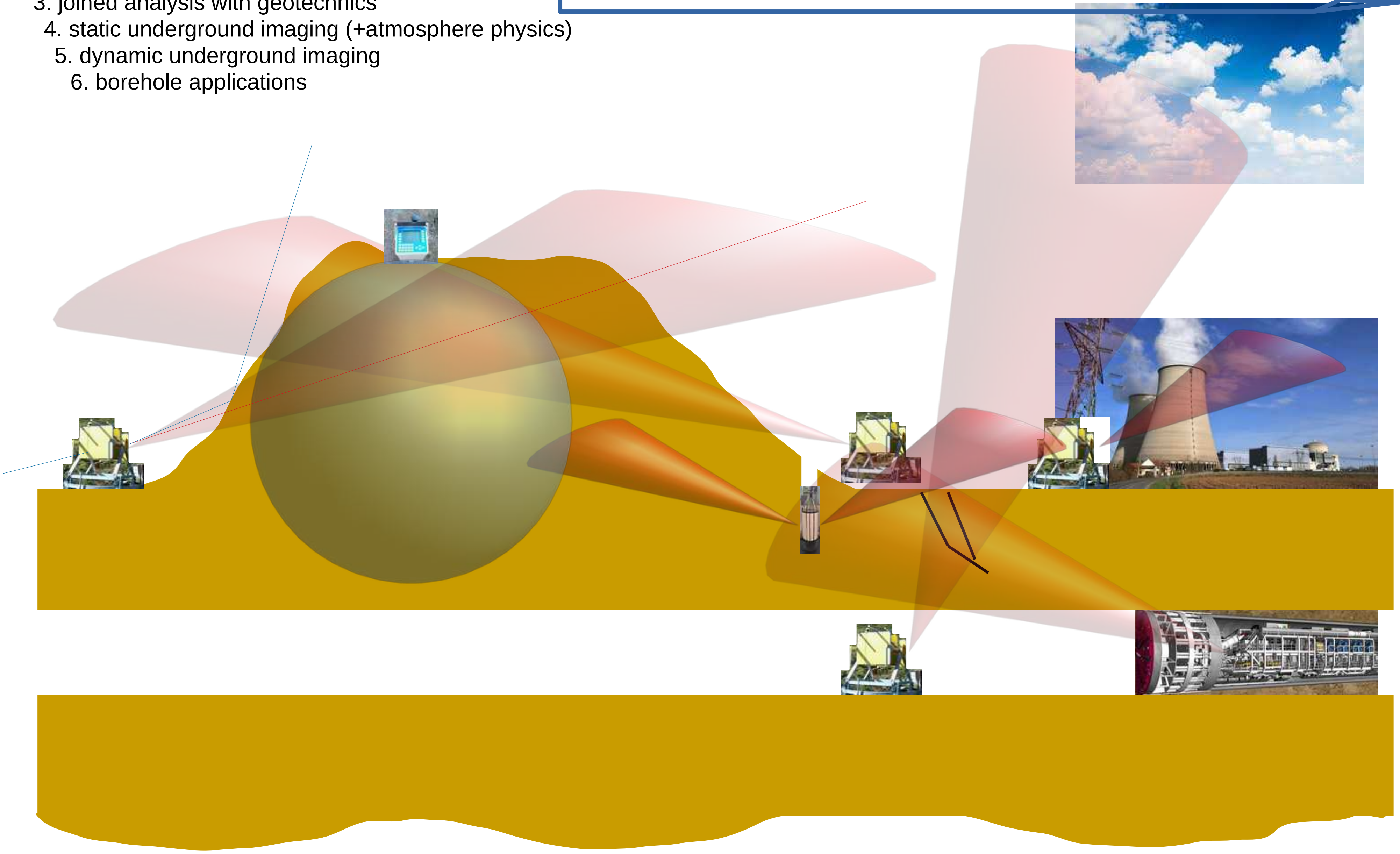




(Tramontini et al., 2019)

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
- ...

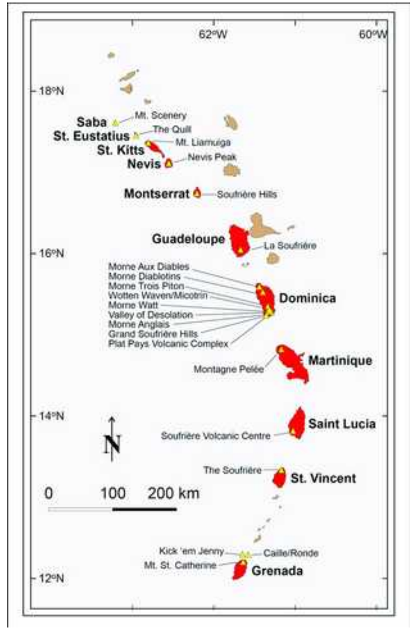
Archaelogy

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

Industrial controls

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

La Soufrière de Guadeloupe



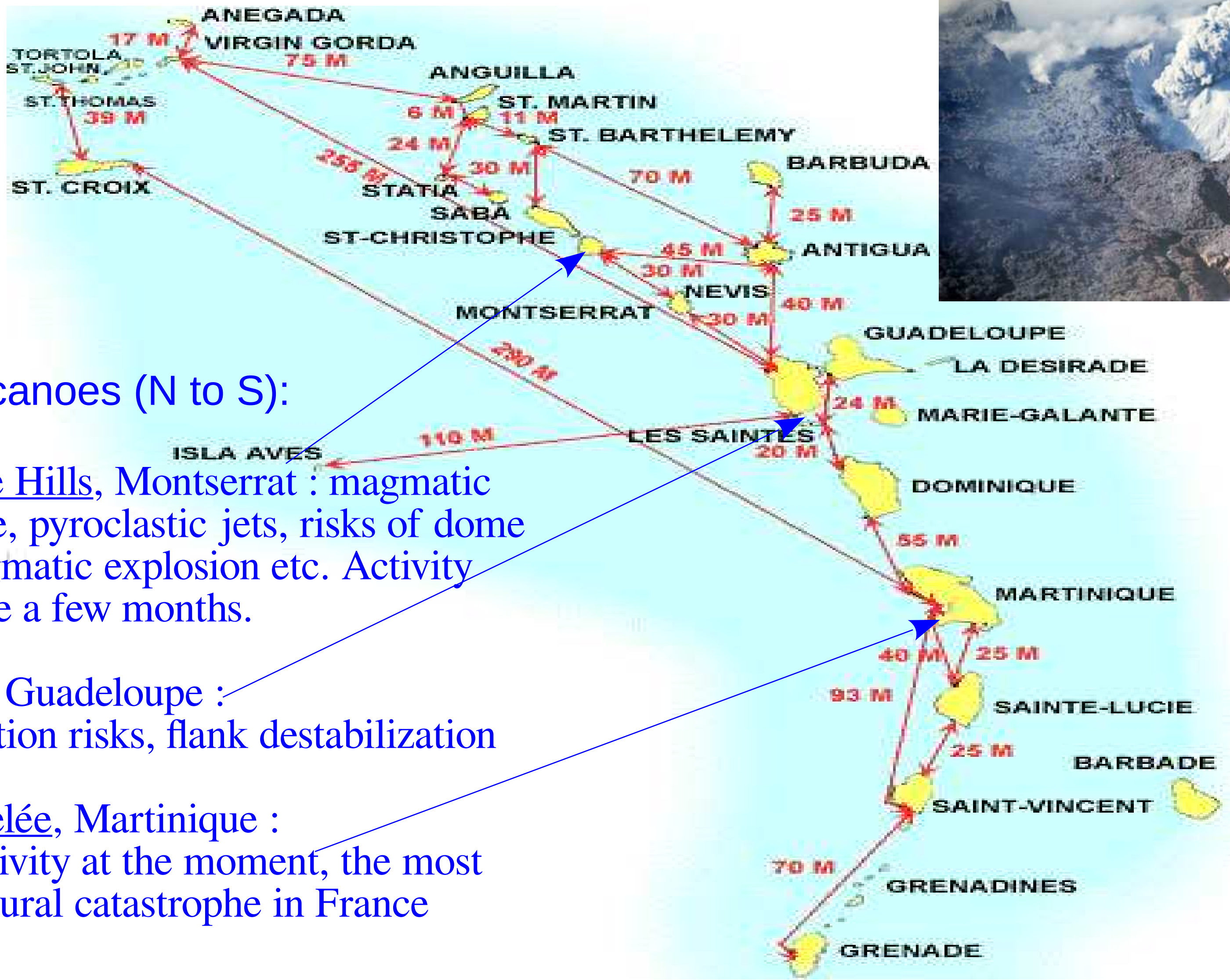
Etna

Volcanoes

Snaefellsjökull

Mayon

The Lesser Antilles



3 active volcanoes (N to S):

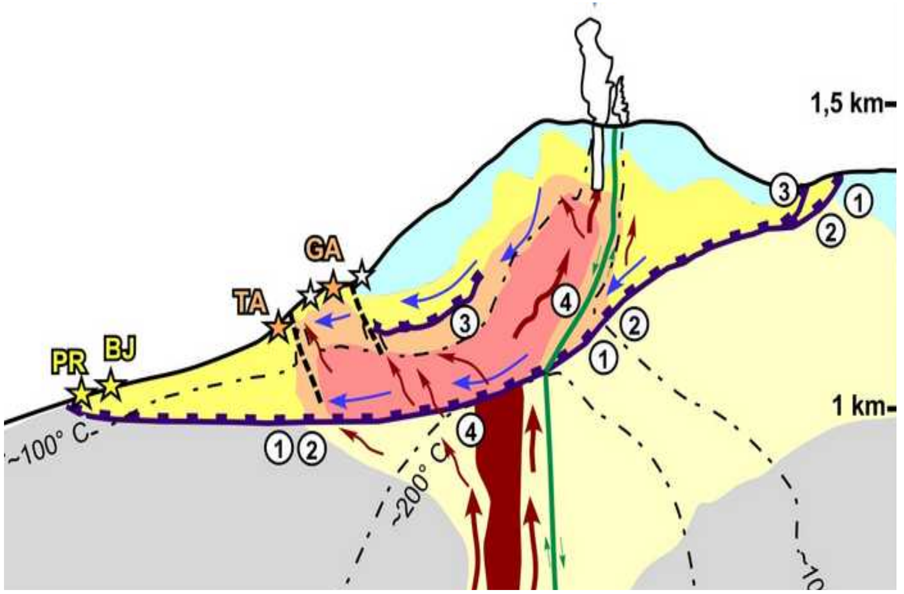
The Soufrière Hills, Montserrat : magmatic eruption since, pyroclastic jets, risks of dome collapse, magmatic explosion etc. Activity decrease since a few months.

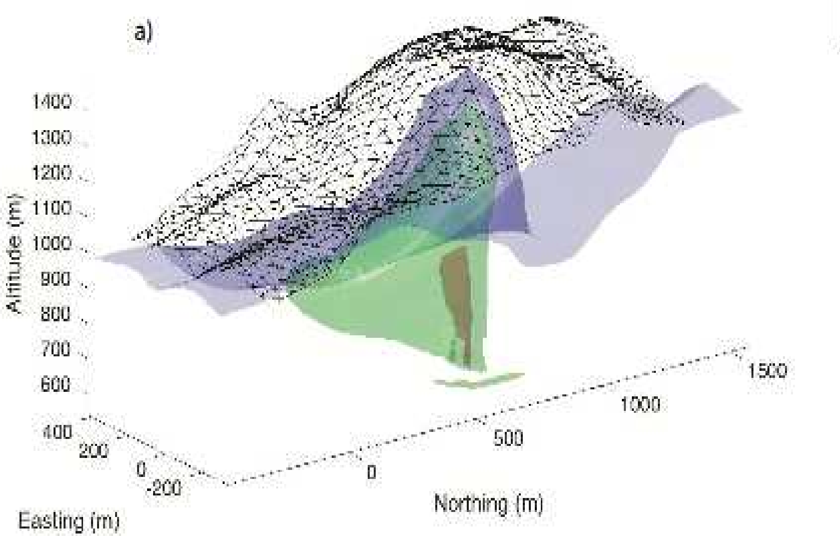
La Soufrière, Guadeloupe : phreatic eruption risks, flank destabilization

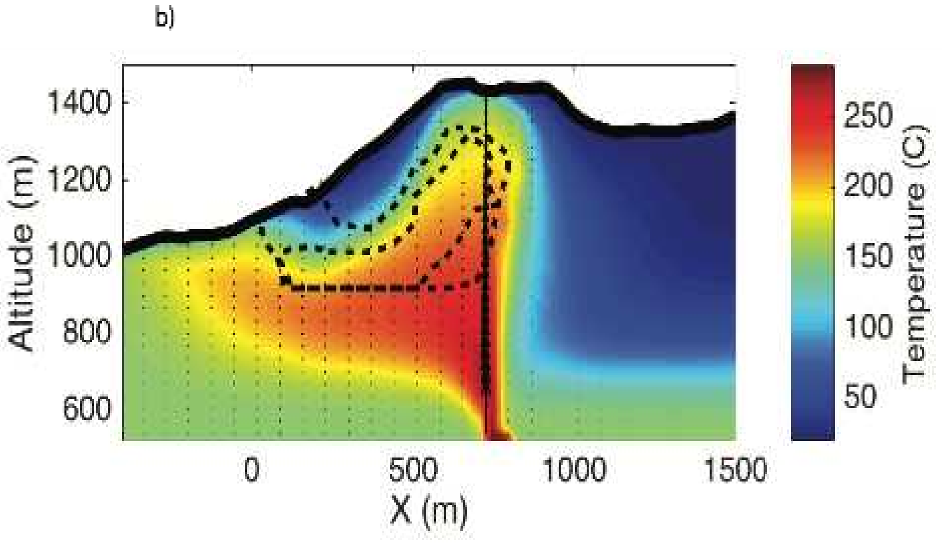
Montagne Pelée, Martinique : no sign of activity at the moment, the most important natural catastrophe in France (1910)

La Soufrière hydrothermal systems

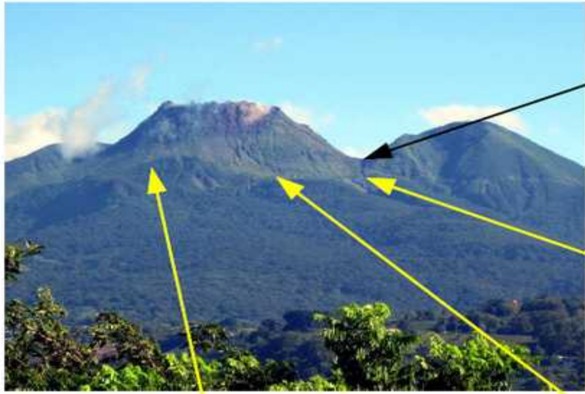
- Volcano hydrothermal systems are at the core of unpredictable volcanic hazards
- Complex interplay between internal and external forcing
- Classical geophysics provide limited information on spatio-temporal dynamics
- Need for techniques that can track in space and time the internal state of the system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

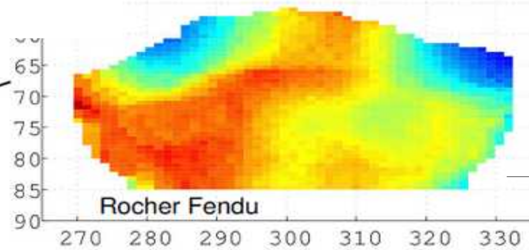


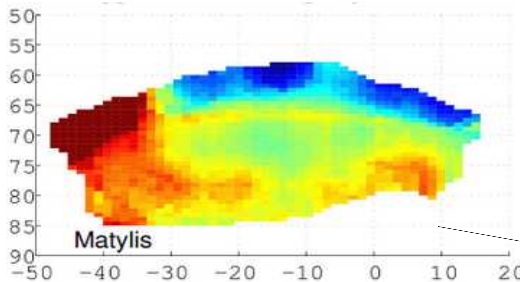


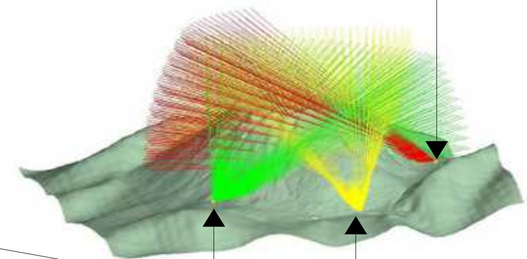


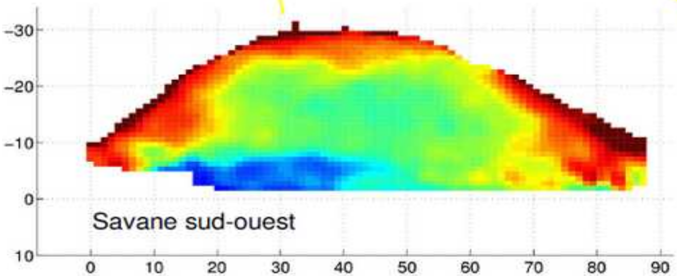
Imaging & monitoring

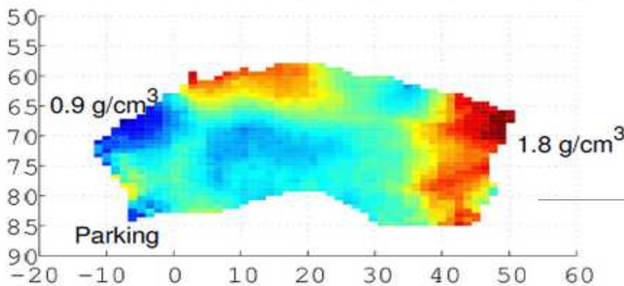






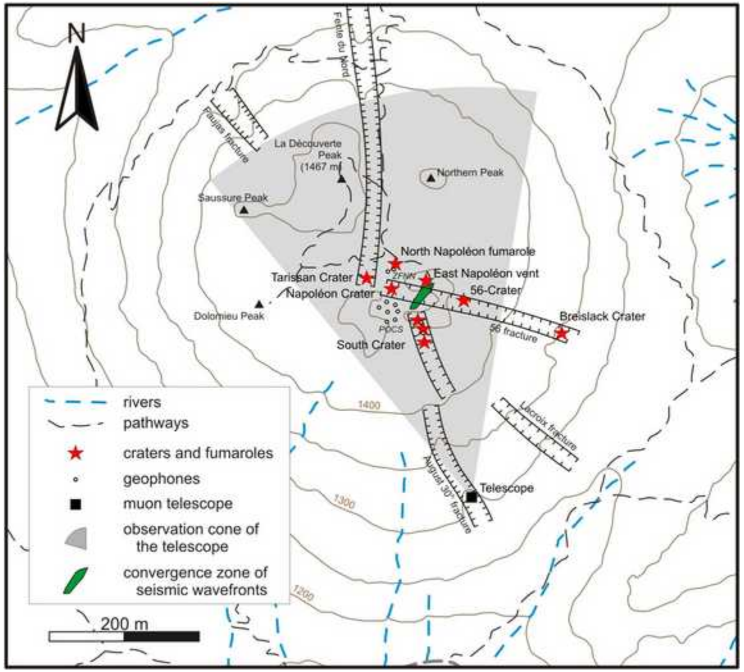


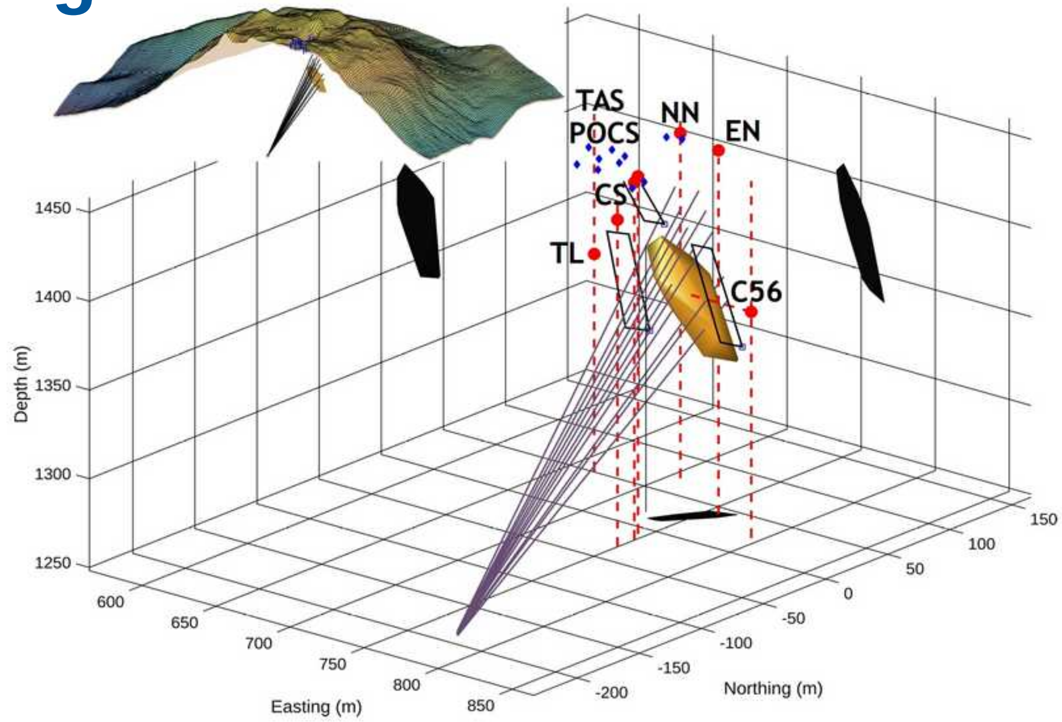




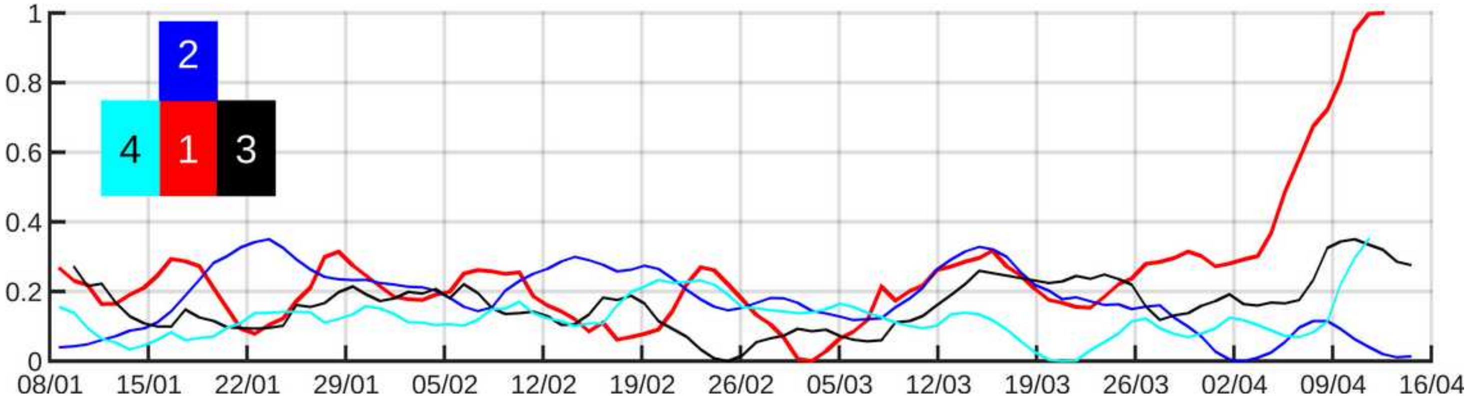
The largest muons station in the world (6 detectors running)

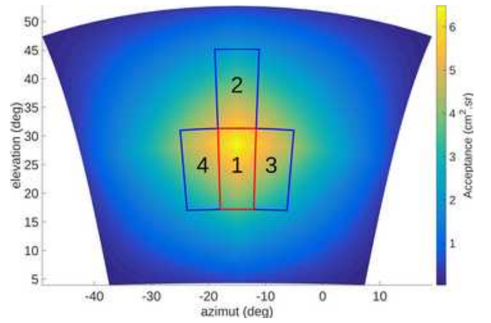
Sismo-muon joint monitoring





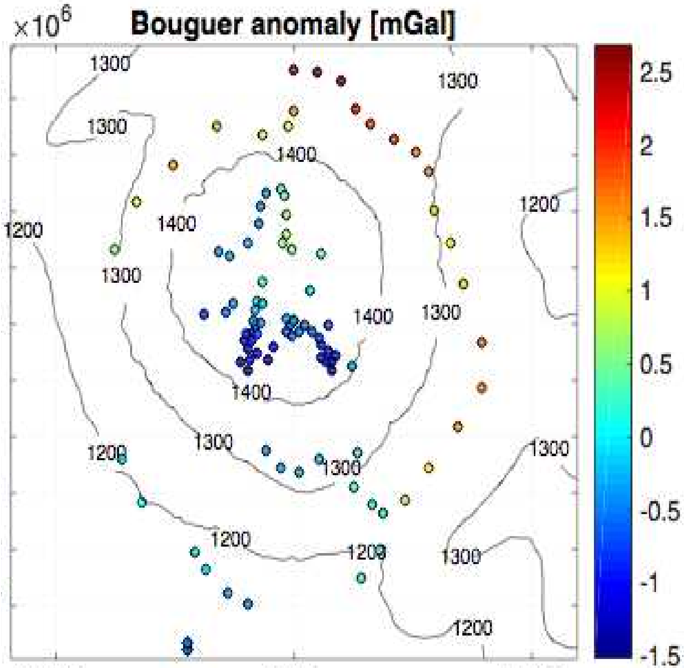
Global analysis of muon and seismic monitoring

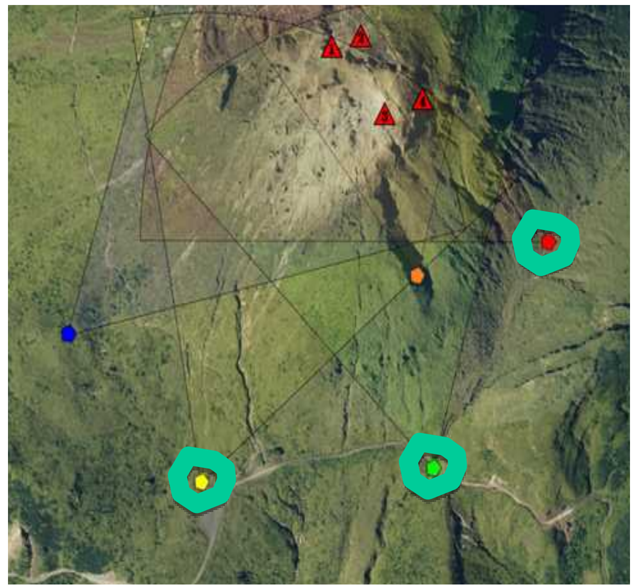




Abrupt changes of hydrothermal activity in a lava dome detected by combined seismic and muon monitoring : *Le Gonidec, J.-Y. et al. Scientific Reports 2019*

3-D gravi-muon joint inversion





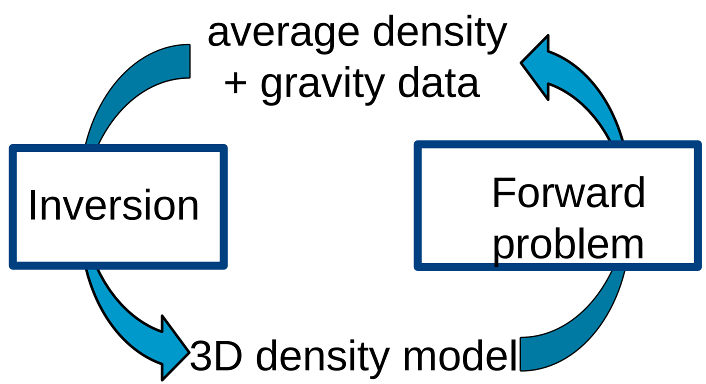
$$G\begin{bmatrix}\boldsymbol{\rho}_\mu\\ \Delta\rho\end{bmatrix} = \begin{bmatrix}G_g\\ G_\mu\end{bmatrix}\begin{bmatrix}\boldsymbol{\rho}_\mu\\ \Delta\rho\end{bmatrix} = \begin{bmatrix}\mathbf{d}_g\\ \mathbf{d}_\mu\end{bmatrix} = \mathbf{d}$$

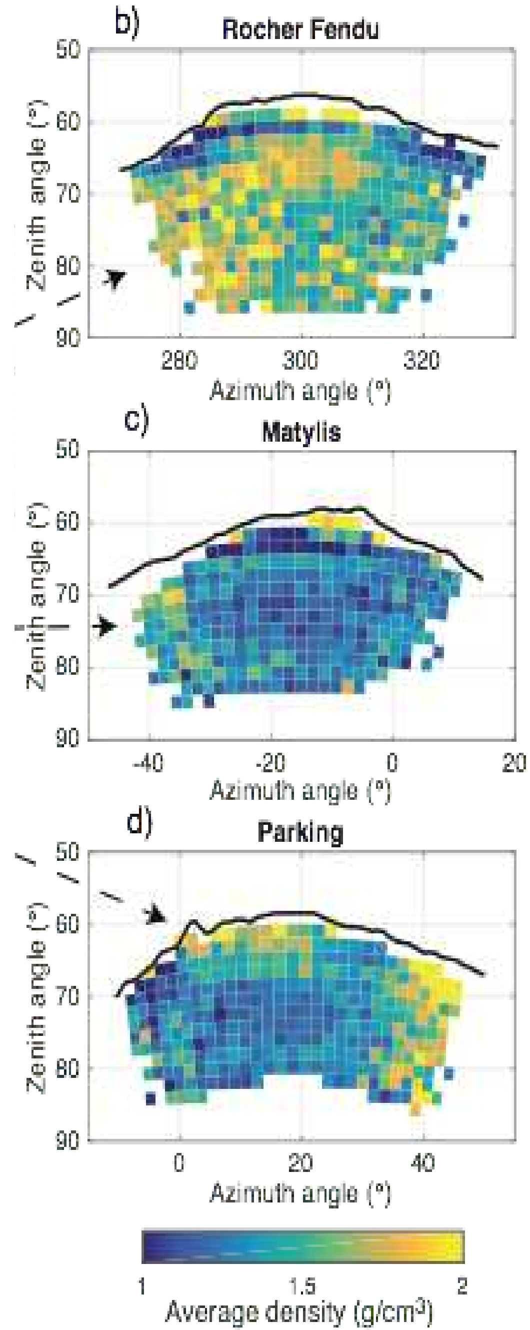
$$\phi(\mathbf{m}) = (\mathbf{d}-\mathrm{G}\mathbf{m})^{\mathrm{T}}\mathrm{C}_{\mathrm{d}}^{-1}(\mathbf{d}-\mathrm{G}\mathbf{m}) + \epsilon^2(\mathbf{m}-\mathbf{m}_{\mathrm{prior}})^{\mathrm{T}}\mathrm{C}_\rho^{-1}(\mathbf{m}-\mathbf{m}_{\mathrm{prior}}),$$

Smoothing

Damping

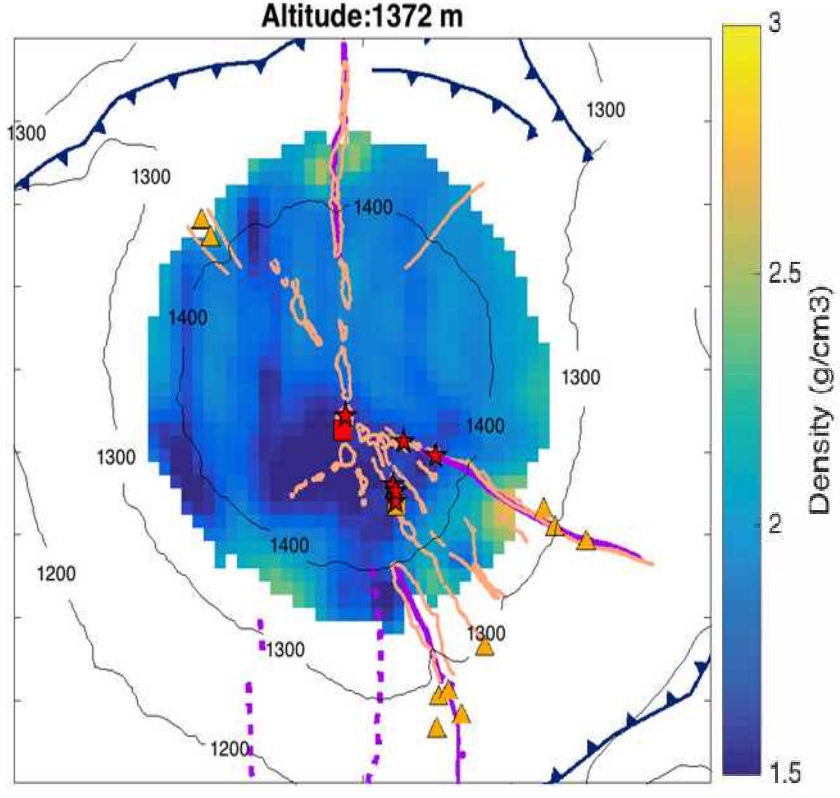
Matrix scaling

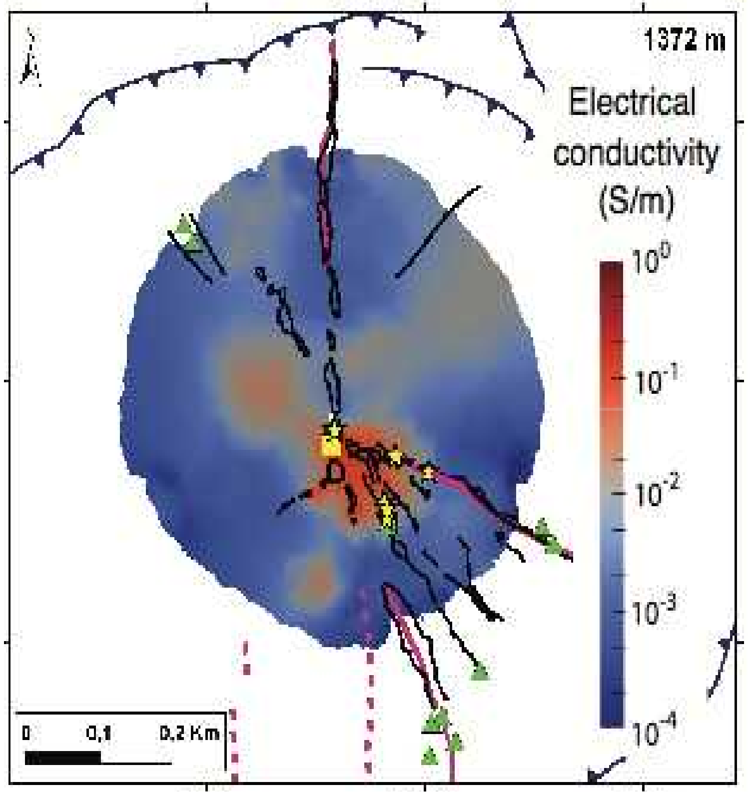




(Rosas-Carbajal et al., 2017)

Horizontal slices of density and electrical conductivity models





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

LIDENBROCK & SNAEFELLSJOKULL

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5 – SNAEFELLS NATIONAL PARK
6 – HTTPS://CAROLMULLER.FR/

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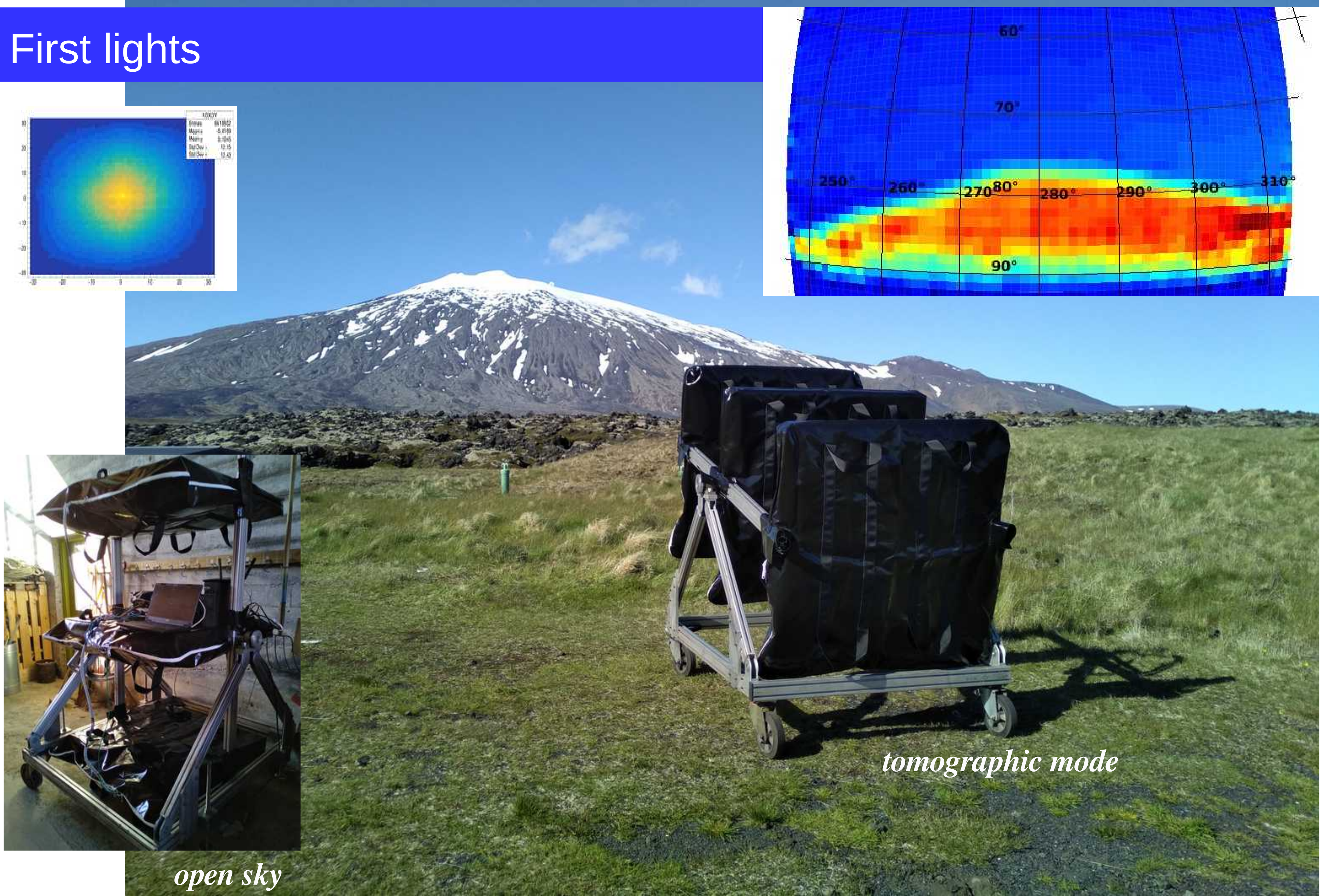
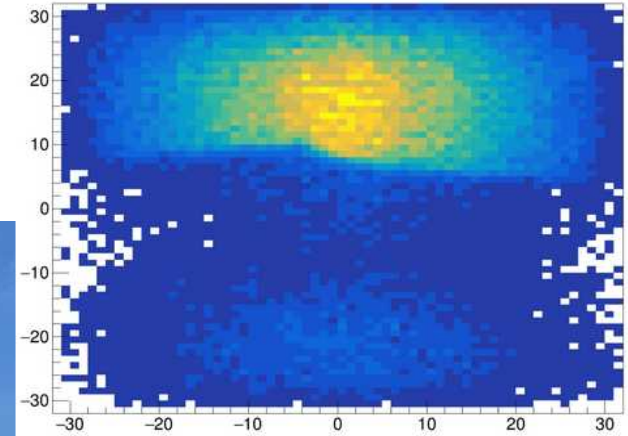
First lights



open sky

tomographic mode

Second run



Geotechnics

Nuclear evaporator

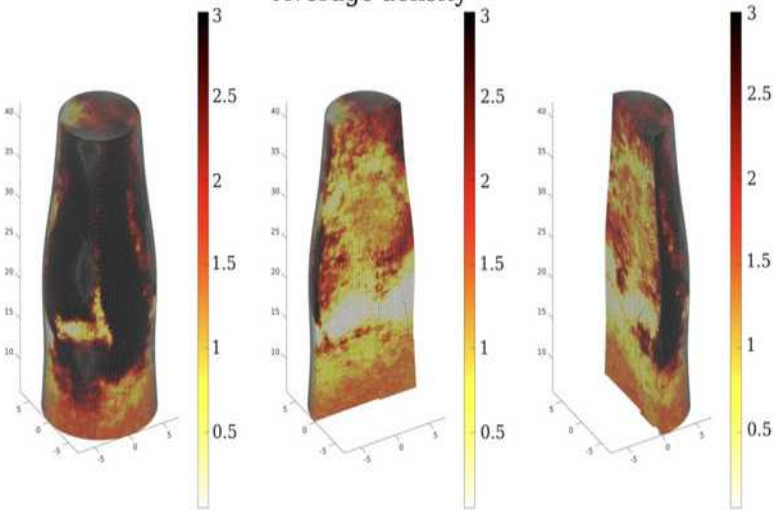
TBM

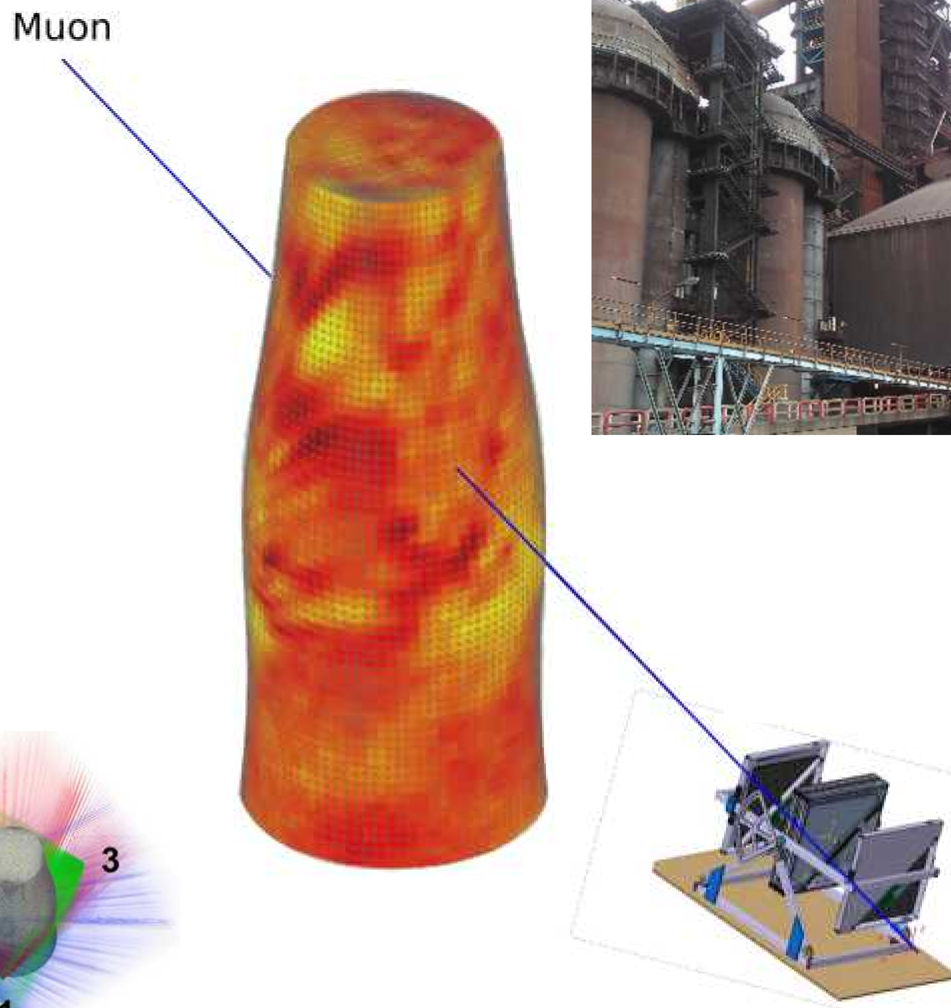
Blast furnace

Silos

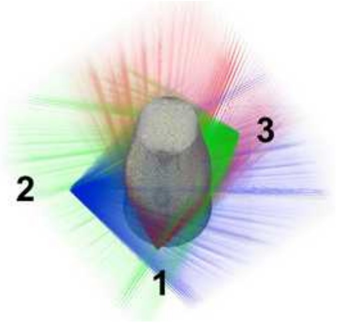
Application to Blast Furnaces

Average density

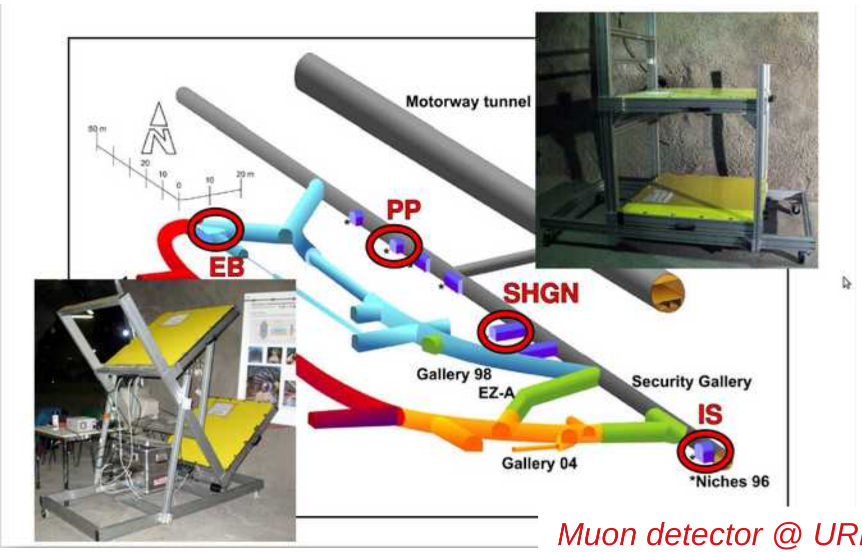




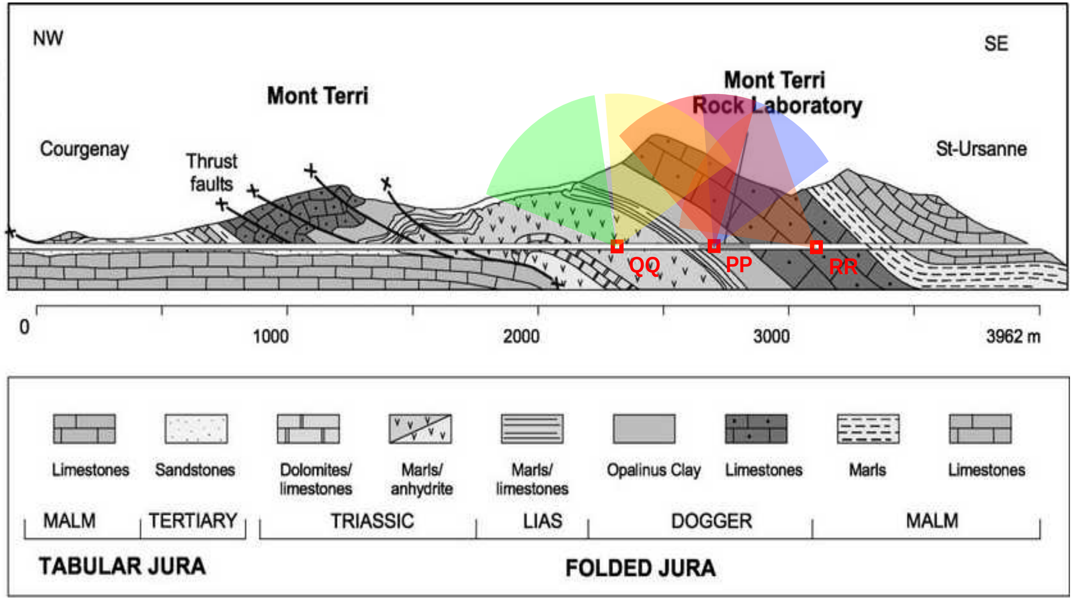
https://arxiv.org/abs/2301.04354



Confidentiel



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

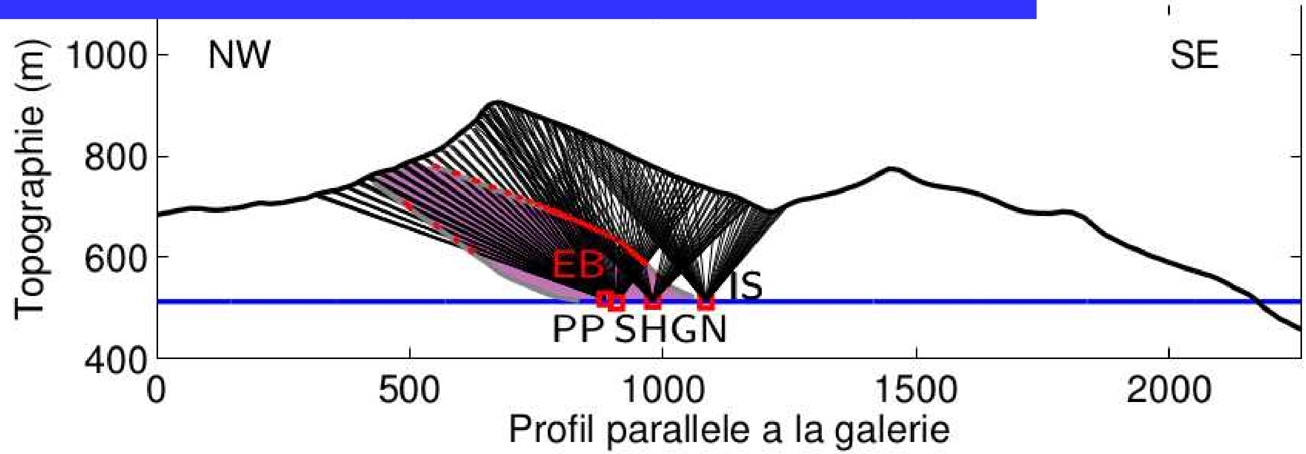
List of the 2012-2015 runs

Underground labs

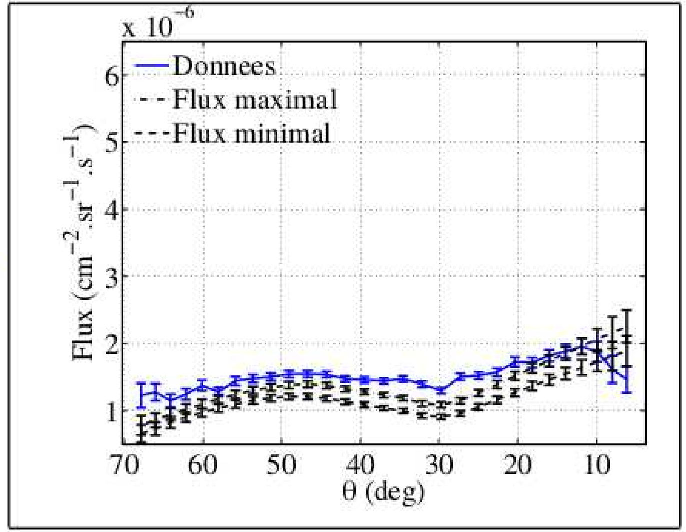
Muon – gravimetry joined analysis

Muon detector @ LSBB

The Mont-Terri lab

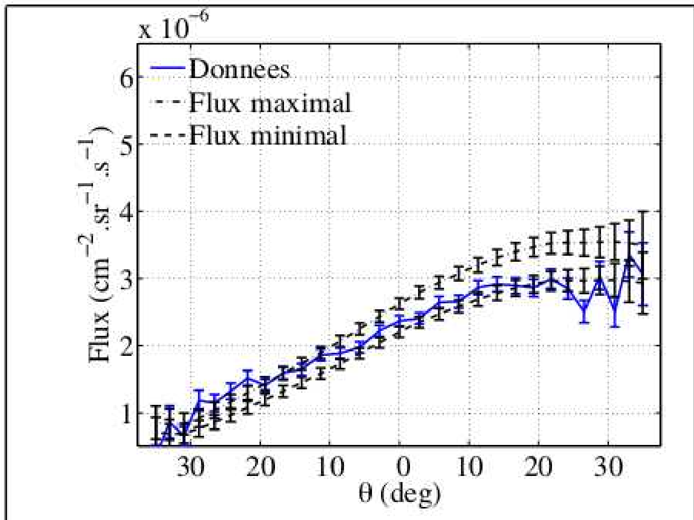


EB (177 jours)

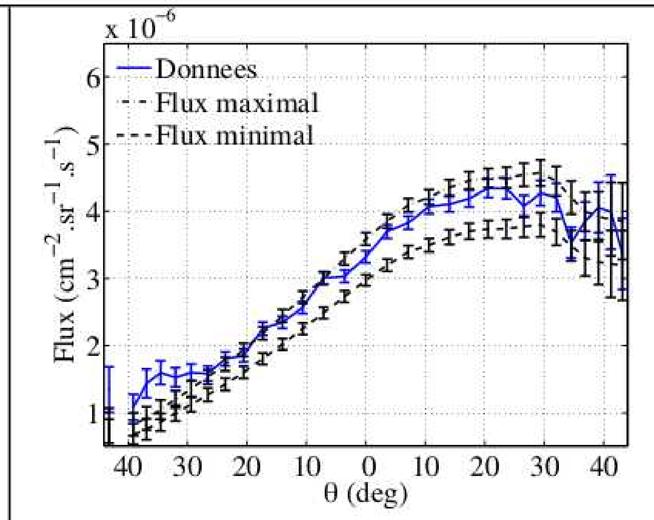


Bruit de fond décorrélé dans la niche PP : 1.7×10^{-7}/s

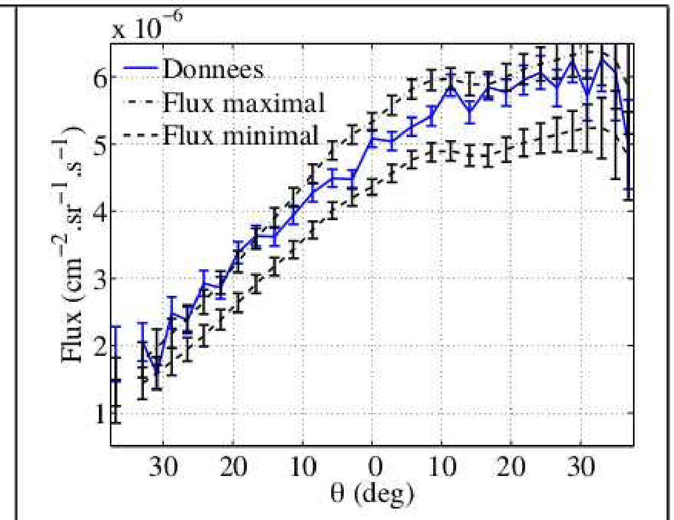
PP (56 jours)



SHGN (42 jours)

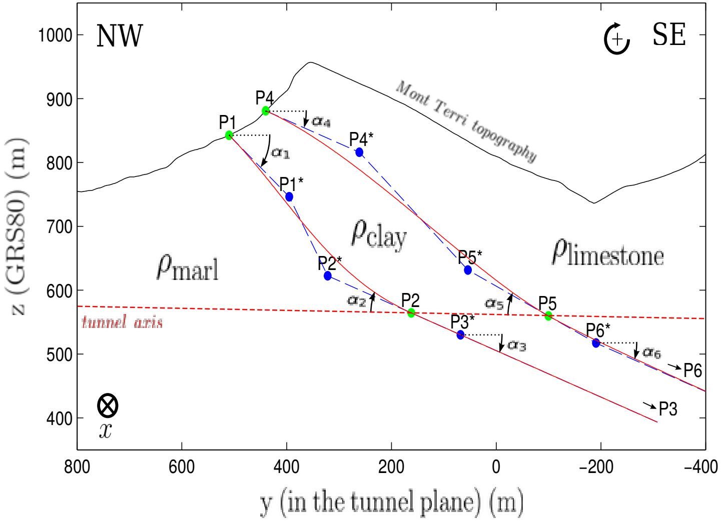


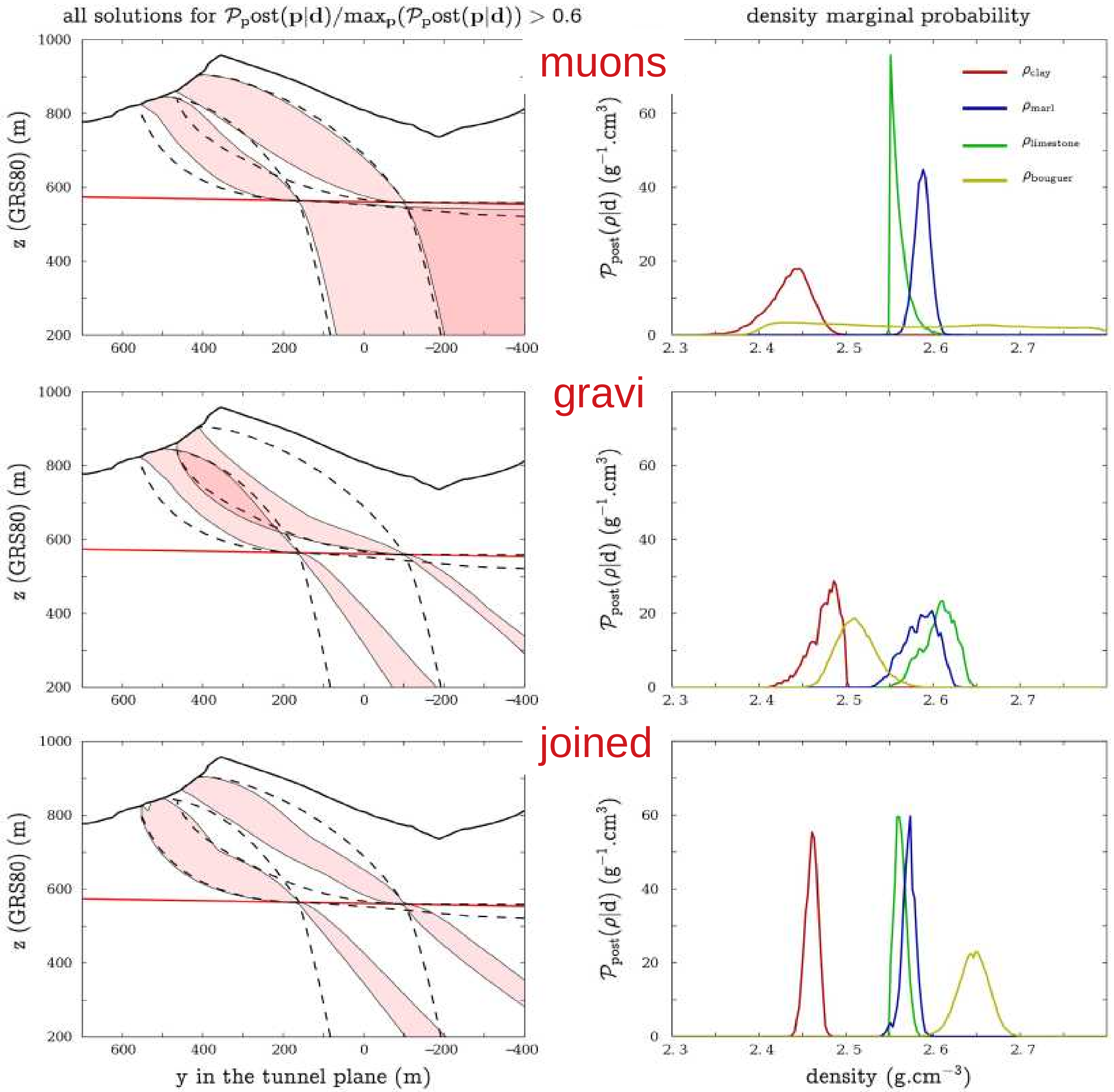
IS (47 jours)



Joint gravi-muon analysis

Opalinus layer parametrization

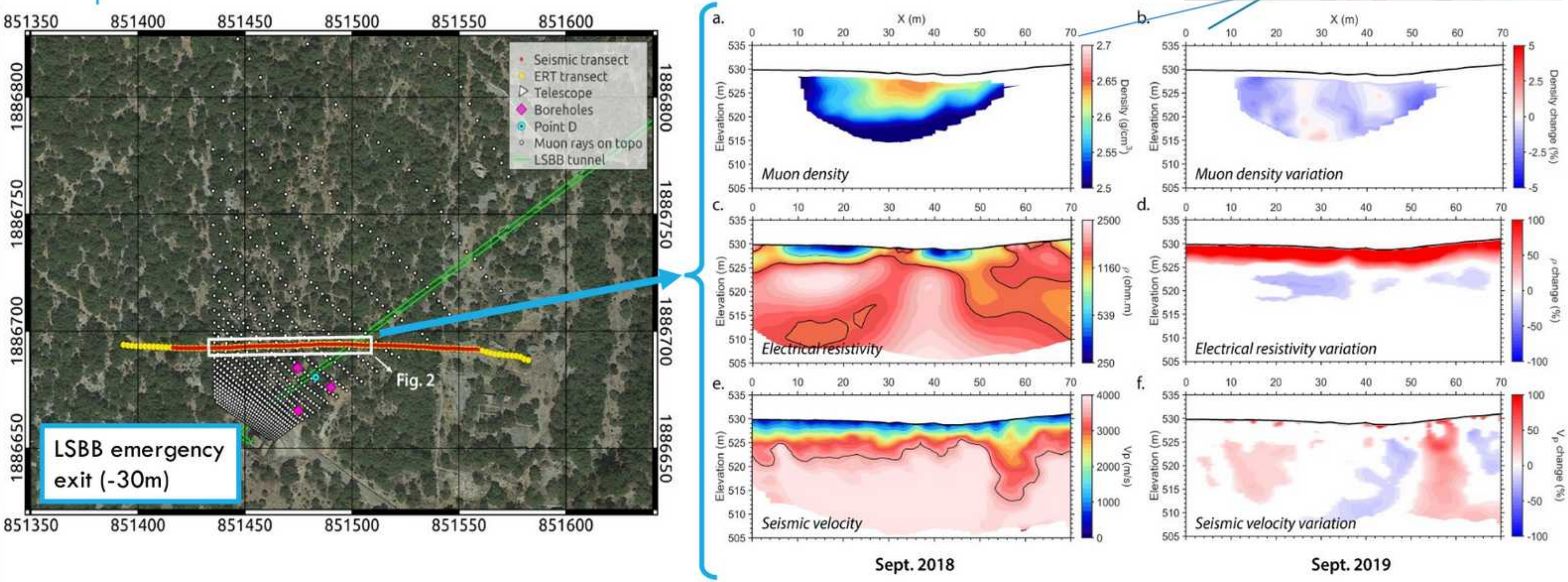




The LSBB facility

LSBB
Laboratoire Souterrain à Bas Bruit
Low Noise Inter Disciplinary Underground Science & Technology

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; Olah, L., Tanaka, H., Varga, D., Eds. American Geophysical Union , USA. DOI:10.1002/9781119722748.ch10

Archaeology

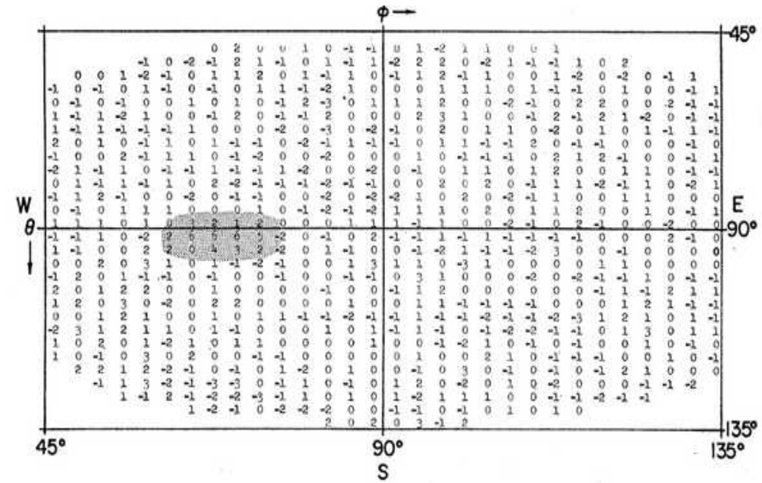
Great pyramids

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

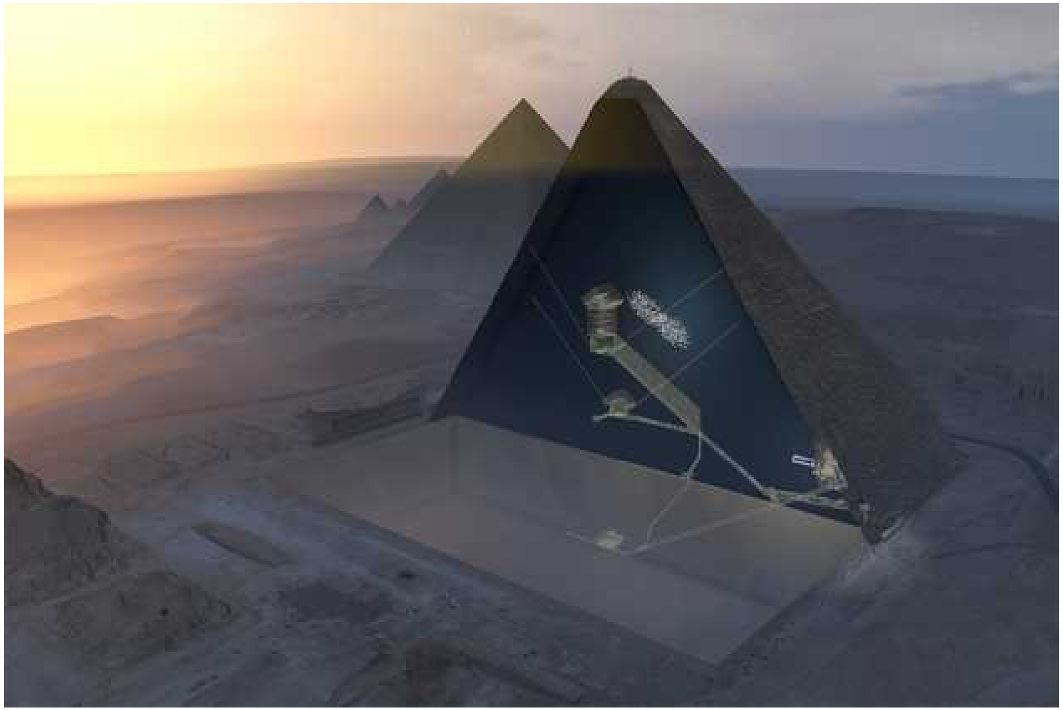


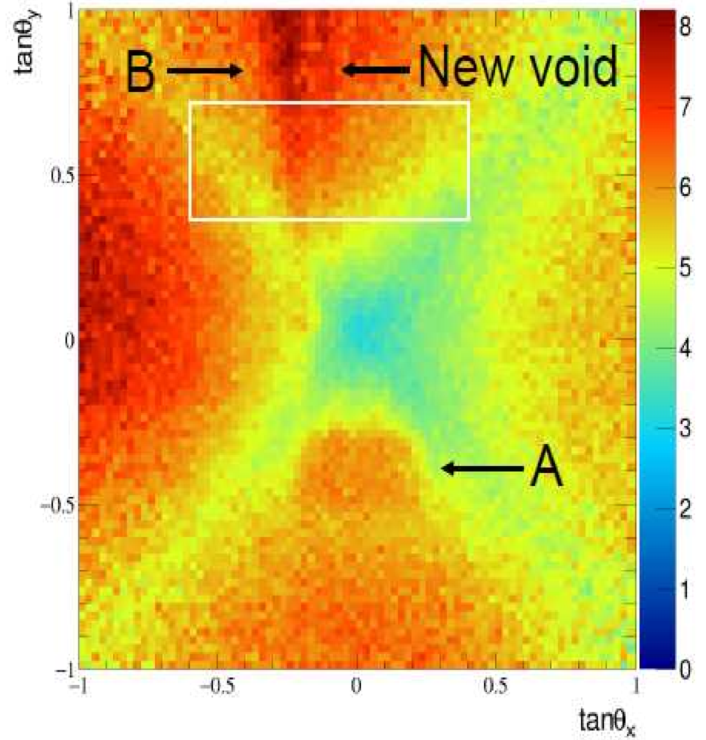
Greek tumulus

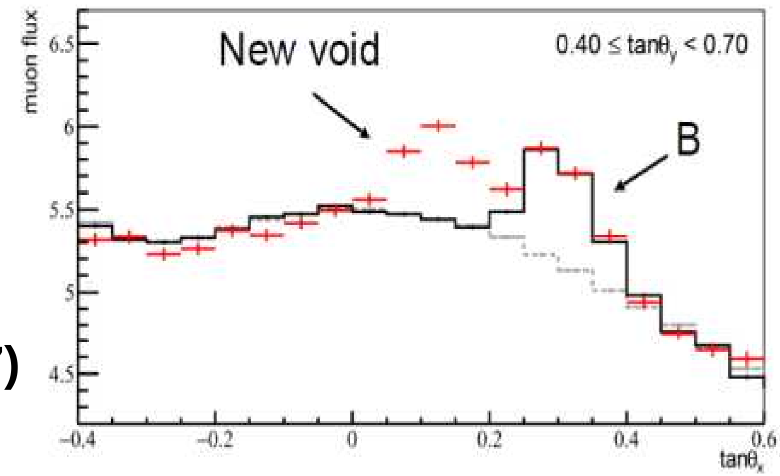
ArchéMuons

The ScanPyramids project

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



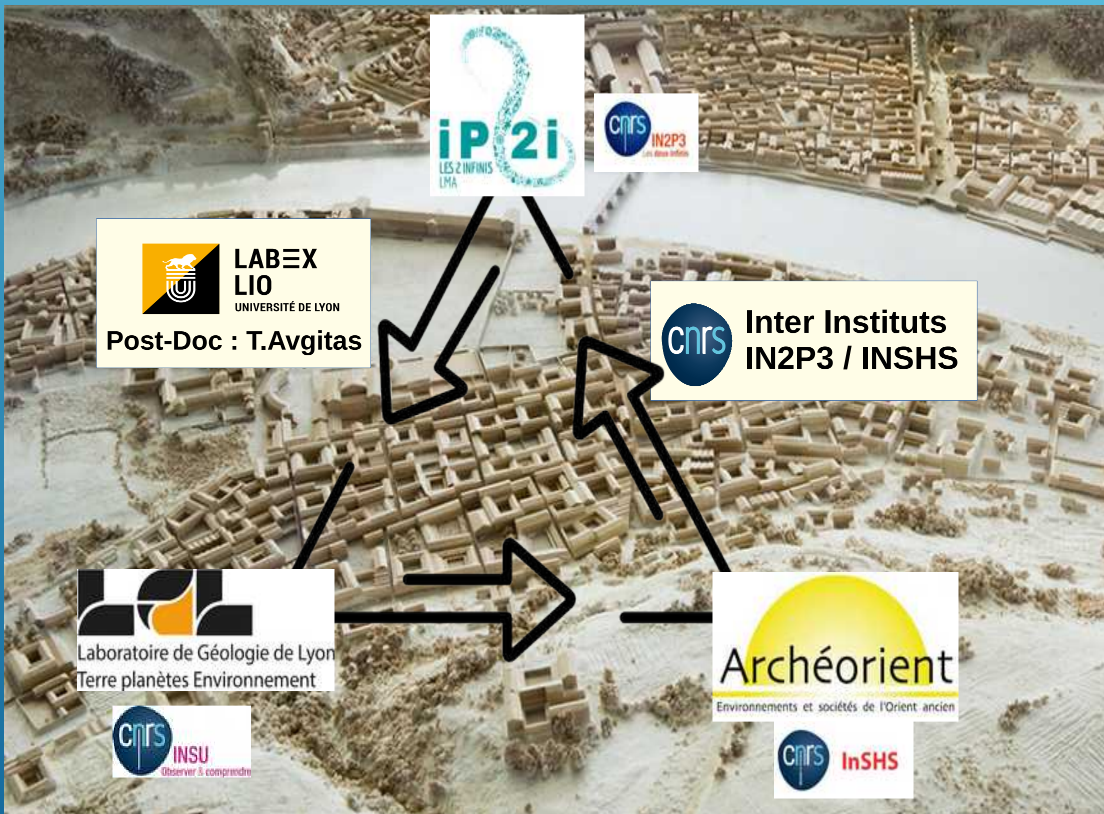




(388 | Nature | VOL 552 | 21/28 DECEMBER 2017)

MUon Tomography AND Innovative Investigation Solutions MUTANDIIS

T.Avgitas, J.-C.Ianigro, J.Marteau, B.Tauzin, S.Durand, J.Rodet
marteau@in2p3.fr

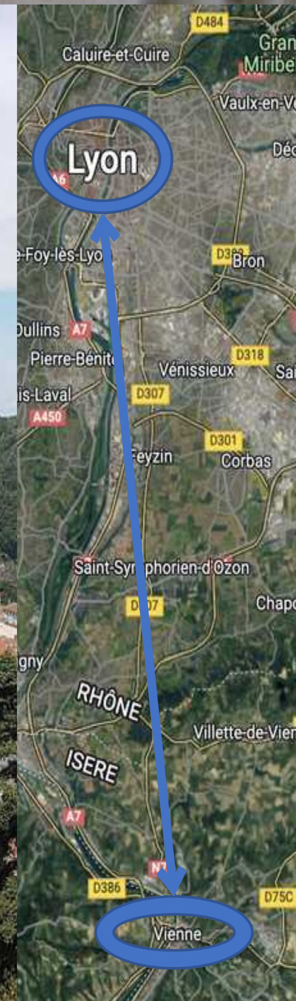


Palais du Miroir, Musée Gallo-Romain, Rhône, France

Joined analysis of an archaelogical site with Innovative investigation techniques :
- **Distributed Acoustic Sensing (DAS)**
- **Muography**

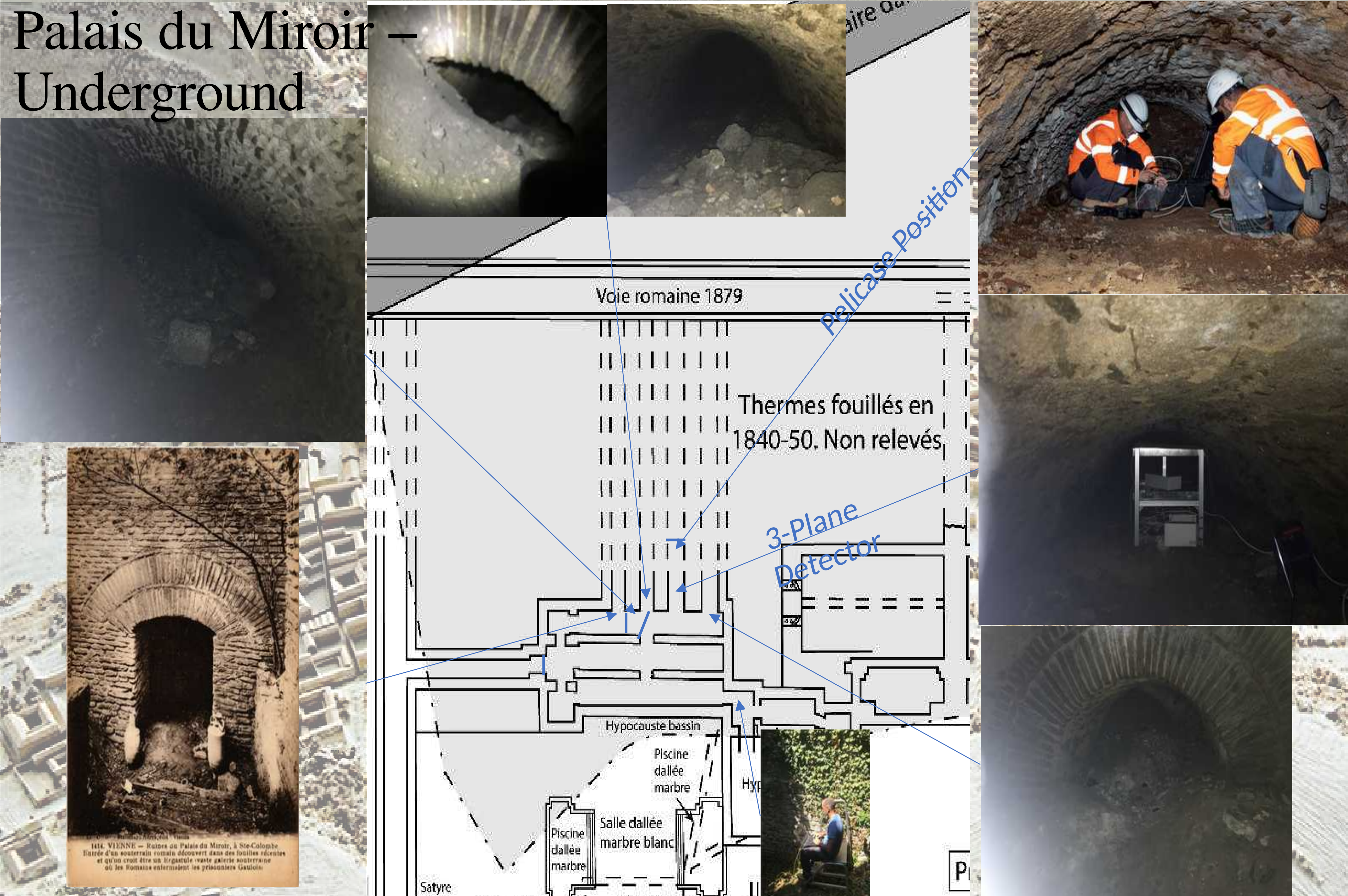
Characterization of the near surface zone :
- **archaelogical structures**
- **hydrology dynamics**

Vienne & St-Romain en Gal

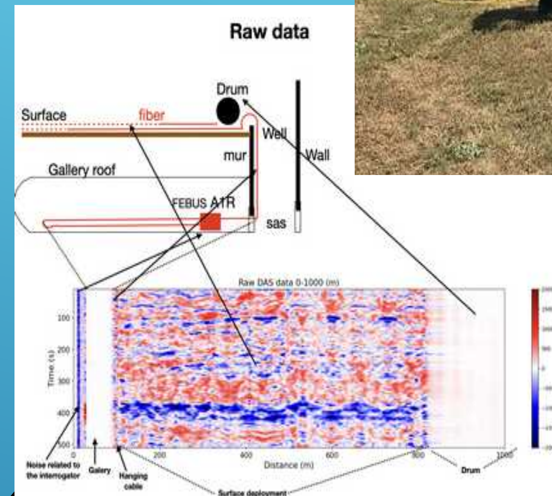


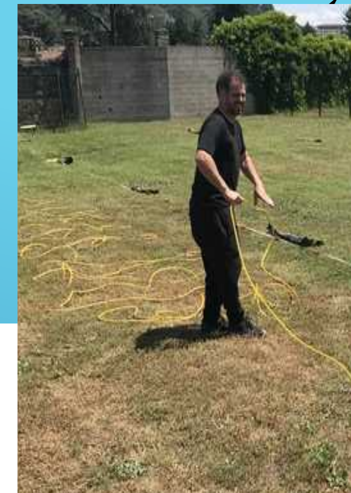
Palais du Miroir – Overground

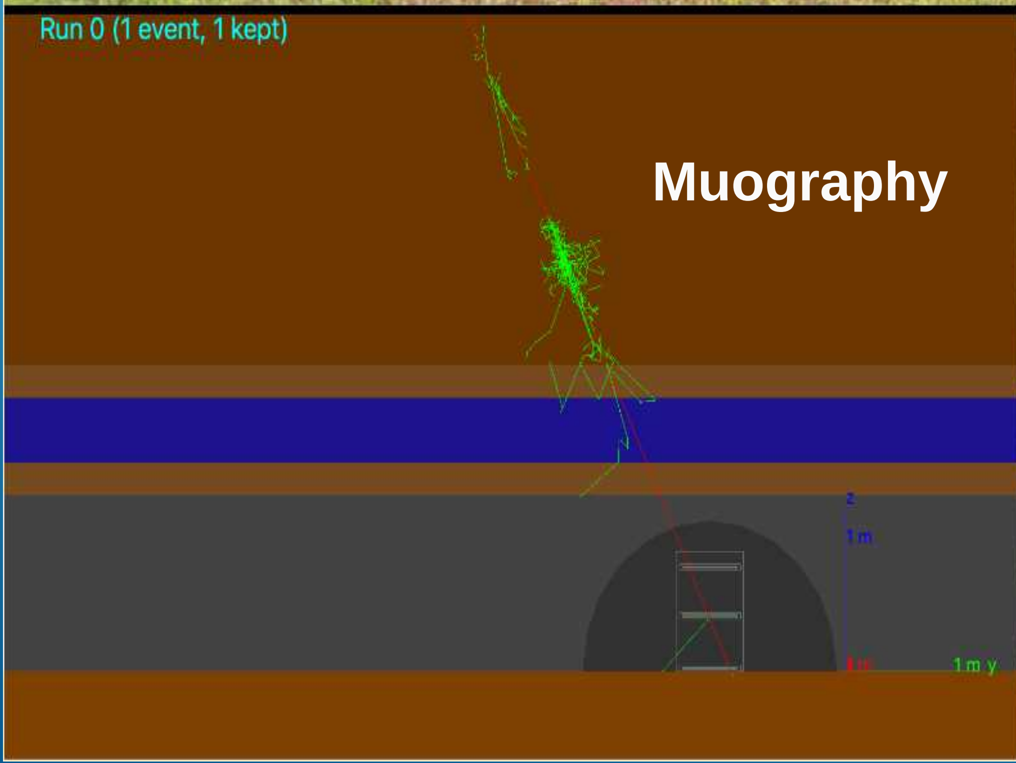
Palais du Miroir – Underground

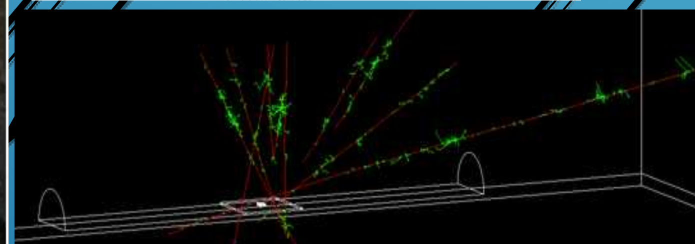


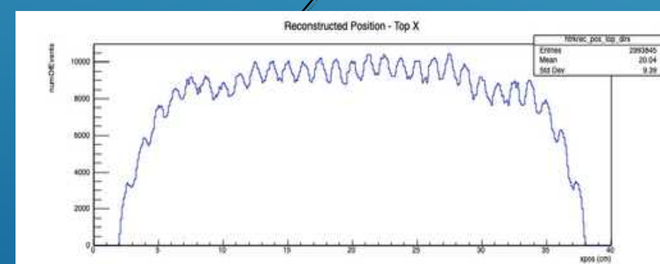

DAS


Raw data
Drum
Surface
fiber
Well
Wall
mur
Gallery roof
FEBUS A1R
sas
Raw DAS data 0-1000 (m)
Distance (m)
Noise related to the interrogator
Galery
Hanging cable
Surface deployment
Drum



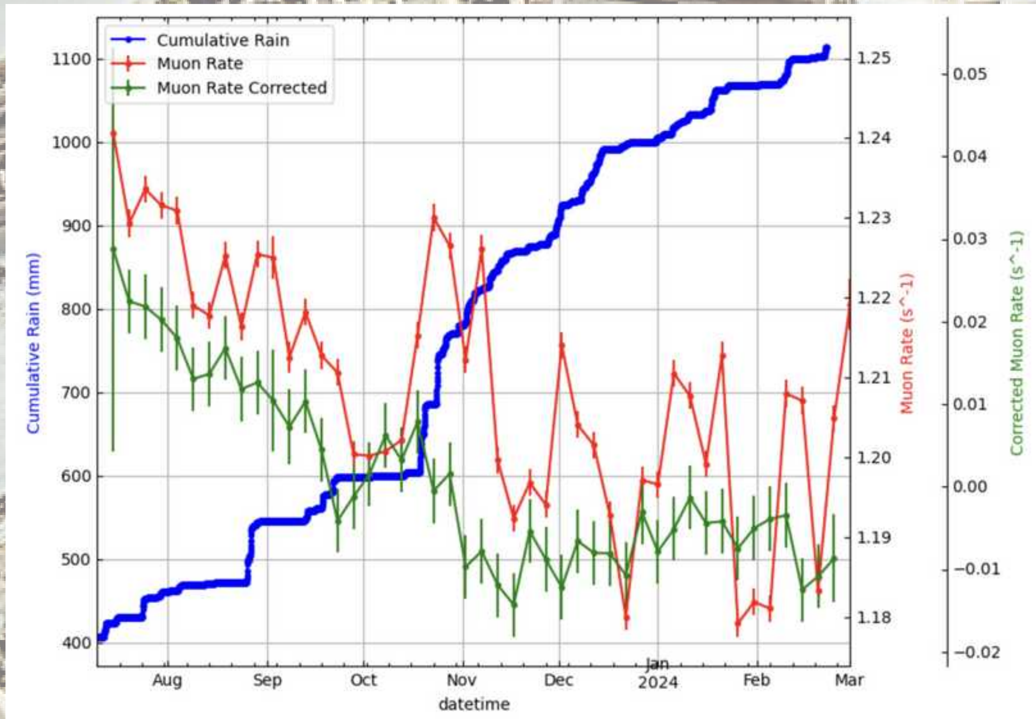

Run 0 (1 event, 1 kept)
Muography
1 m
1 m y




Reconstructed Position - Top X

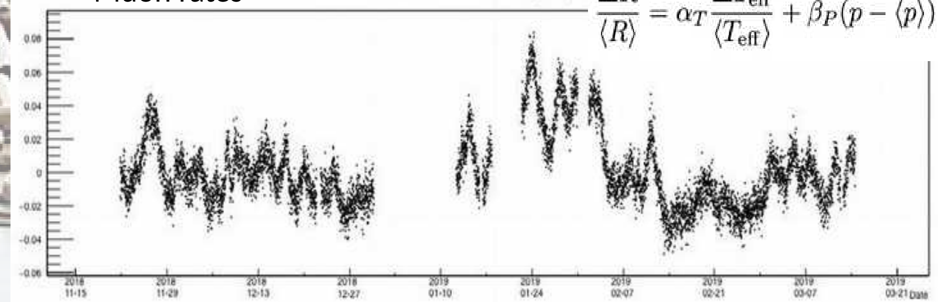
Atmospheric & hydrogeological effects

How soil water retention affects the measurement

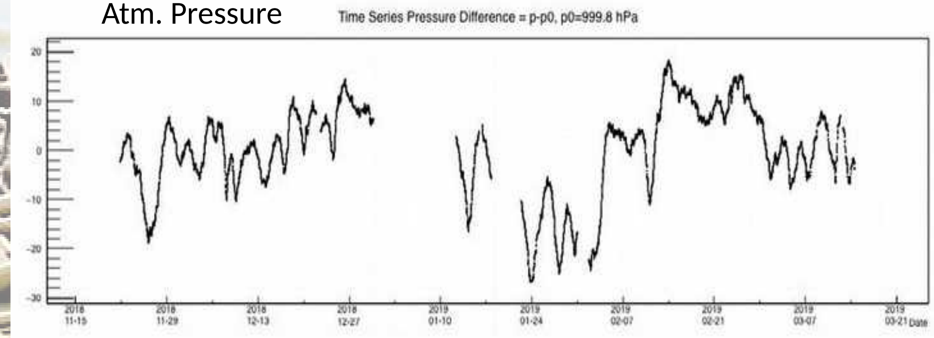


$$\frac{\Delta R}{\langle R \rangle} = \alpha_T \frac{\Delta T_{\text{eff}}}{\langle T_{\text{eff}} \rangle} + \beta_P (p - \langle p \rangle)$$

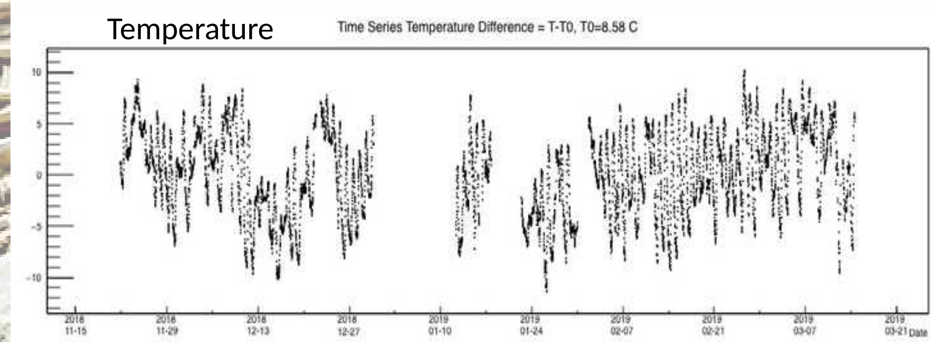
Muon rates

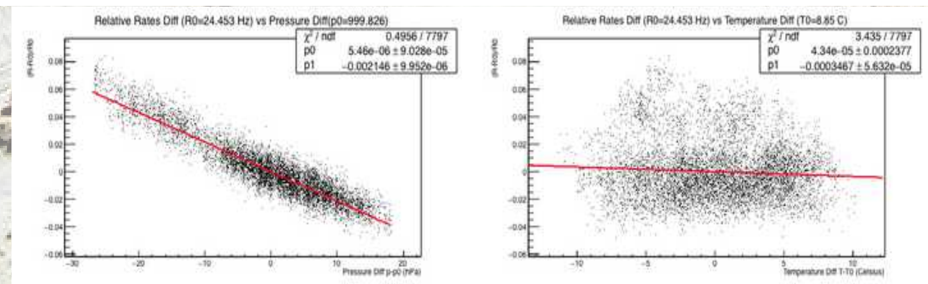


Atm. Pressure

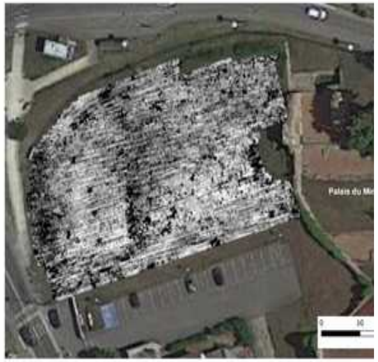


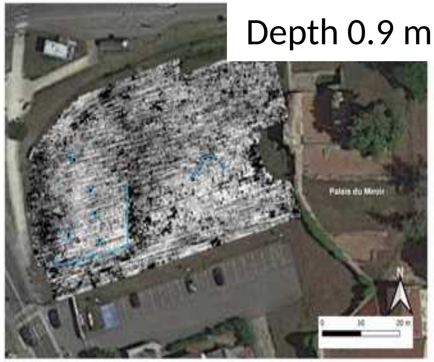
Temperature

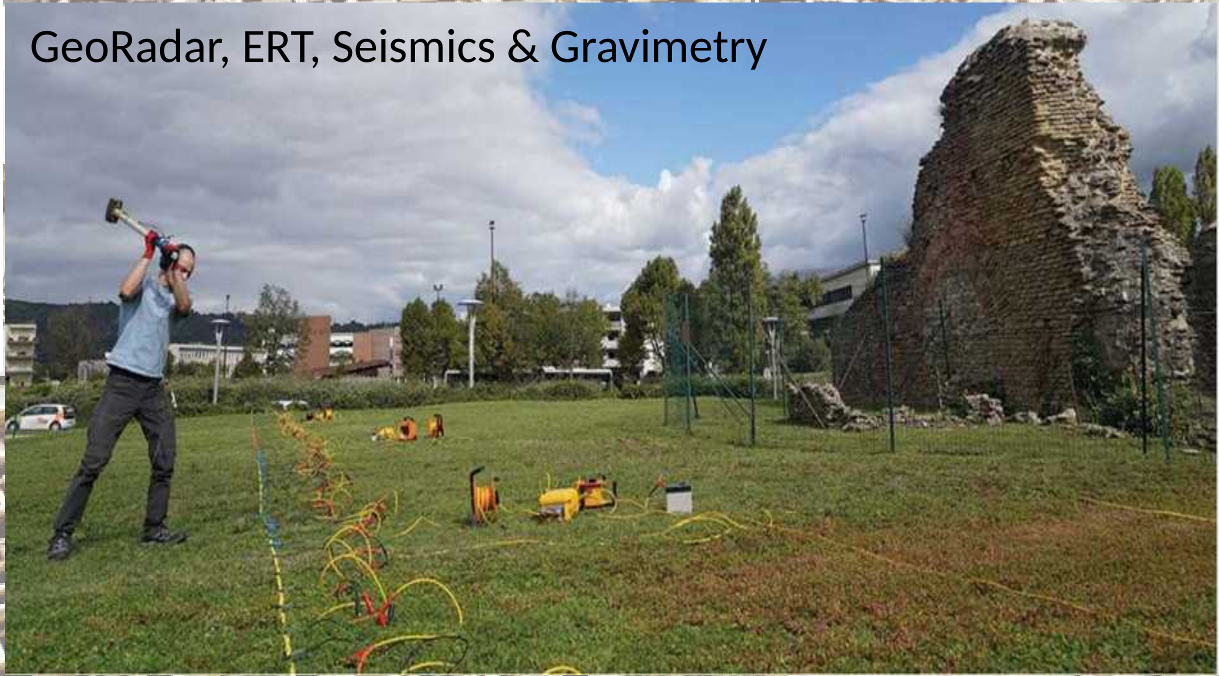


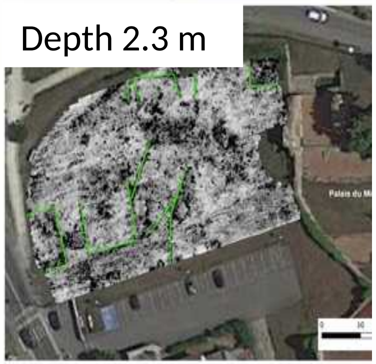


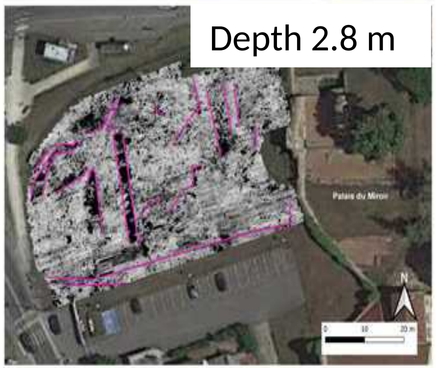
GeoRadar & ERT

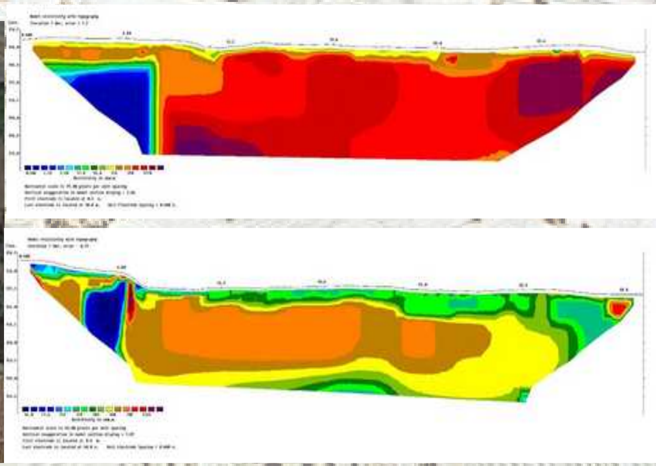


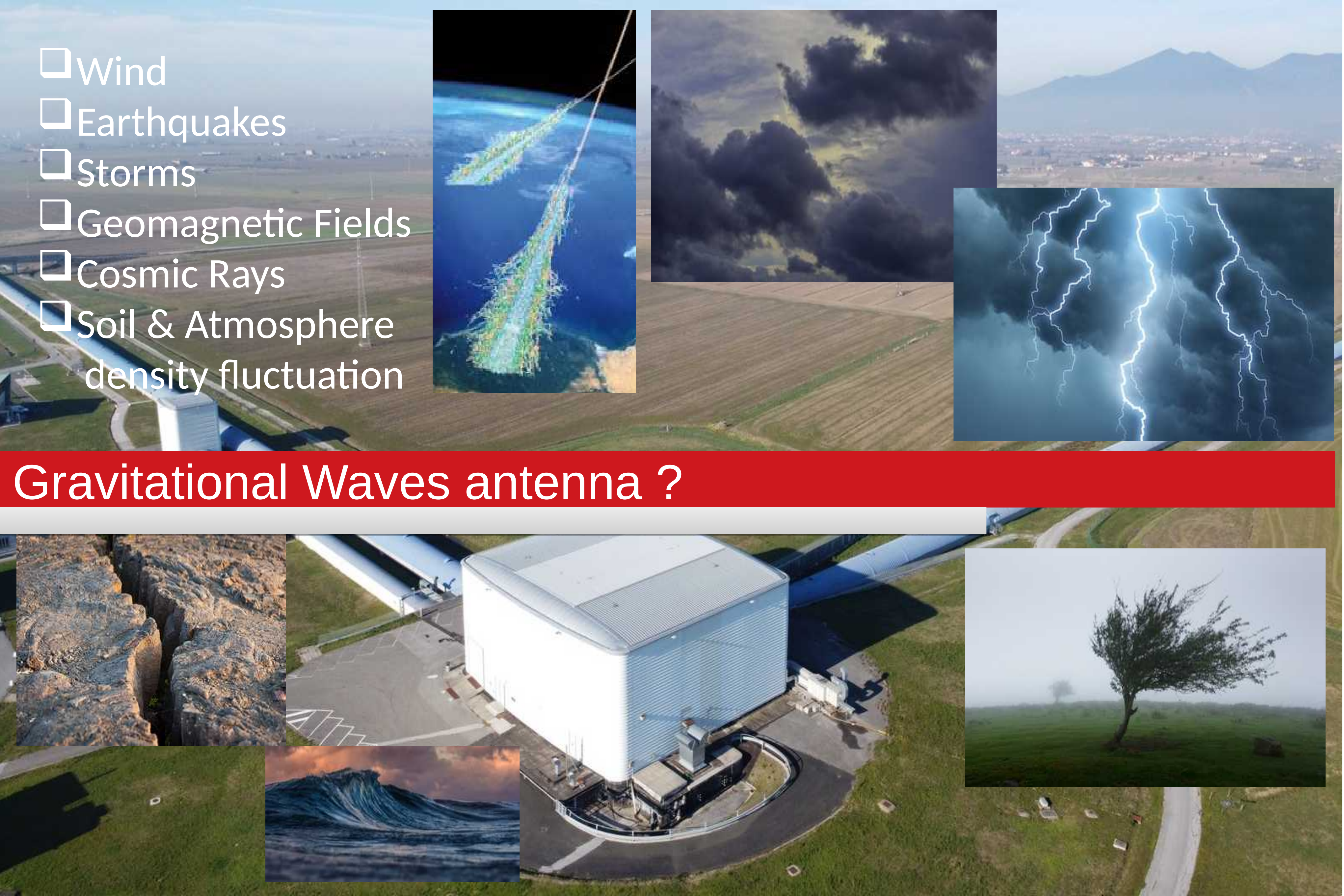






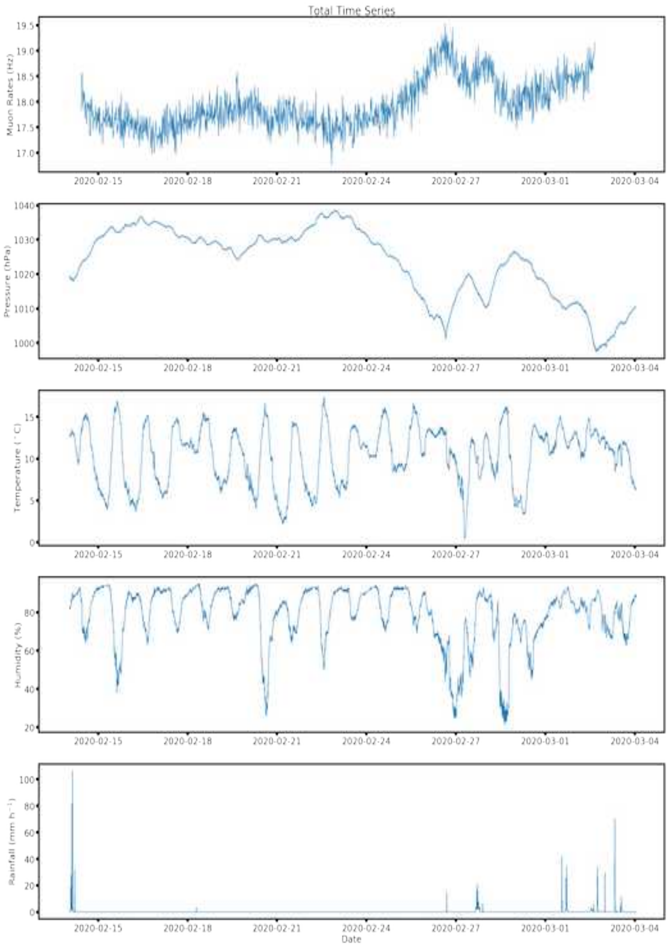


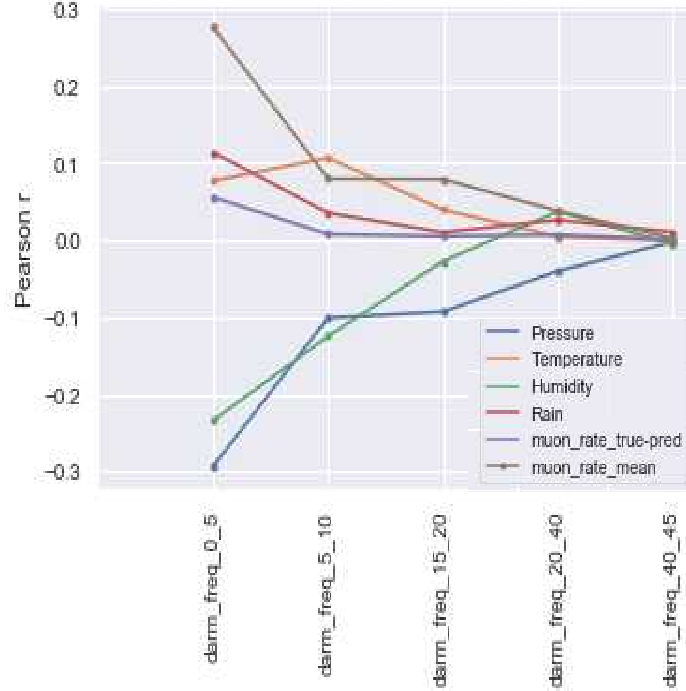



❑Wind
❑Earthquakes
❑Storms
❑Geomagnetic Fields
❑Cosmic Rays
❑Soil & Atmosphere density fluctuation
Gravitational Waves antenna ?

POC experiment during Virgo O3 run

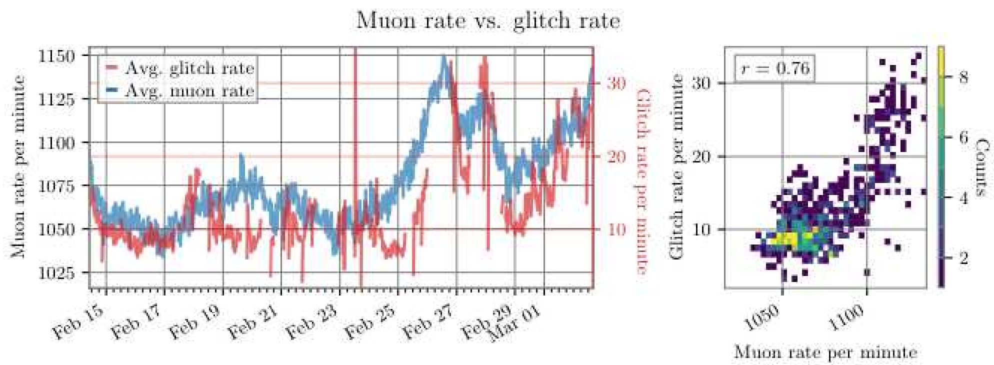
Investigate correlations: muon rates vs interferometer sensitivity (DAQ : 19 days)





Results:

- Correlation between muon rates and GW detector,
- Muons monitor atmospheric phenomena,
- Atmosphere impacts sensitivity



Cosmic Rays – Direct Interaction with Mirrors

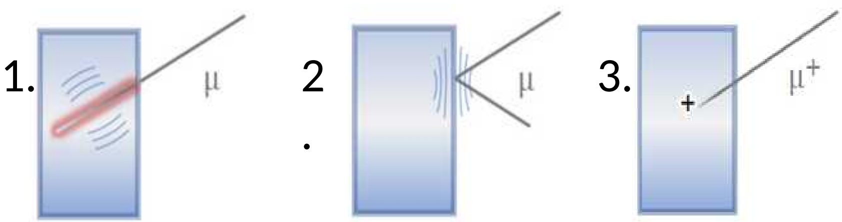
Notes about Noise in Gravitational Wave Antennae

Created by Cosmic Rays

V.B. Braginsky[1], O.G. Ryazhskaya[2], S.P. Vyatchanin[1]

We limit ourselves by only three possible mechanical "actions" on the rest masses (mirrors):

1. **Direct transfer of mechanical momentum** from cascade to the LIGO mirror.
2. **Distortion of mirror's surface due to the heating by the cascade** and subsequent thermal expansion — thermoelastic effect.
3. **Fluctuating component of the Coulomb force** between electrically charged mirror and grounded metal elements located near the mirror's surface.



Visualization for muons: can be extended to hadrons (pions, protons, neutrons), electrons/positrons

Parameters of High Energy Cascades

$\mathcal{E}$ is cascade energy, J_μ, J_h, J_e are the fluxes of cascades produced by muons, hadrons and by soft component, consequently, at the sea level; $N_{e,\,max}$ is a number of electrons in the cascade maximum; $\Delta\mathcal{E}$ is energy lost by cascade in the 20 cm of SiO_2; N_{ev} is the expected number per year of events with energy losses higher than $\Delta\mathcal{E}$.

$\mathcal{E}$, TeV	0.5	1	2
J_μ 1/cm^{2}s	1.8×10^{-9}	2.8×10^{-10}	4.3×10^{-11}
J_h 1/cm^{2}s	2.5×10^{-9}	4.0×10^{-10}	7.2×10^{-11}
J_e 1/cm^{2}s	3×10^{-10}	8×10^{-11}	1.7×10^{-11}
$N_{e,\,max}$	1000	2000	4000
$\Delta\mathcal{E}$, GeV	60	120	230
N_{ev}	~ 110	20	$3 \div 4$

GW signals are of the present class of sensitivities are 10^{-18}, 10^{-19} m

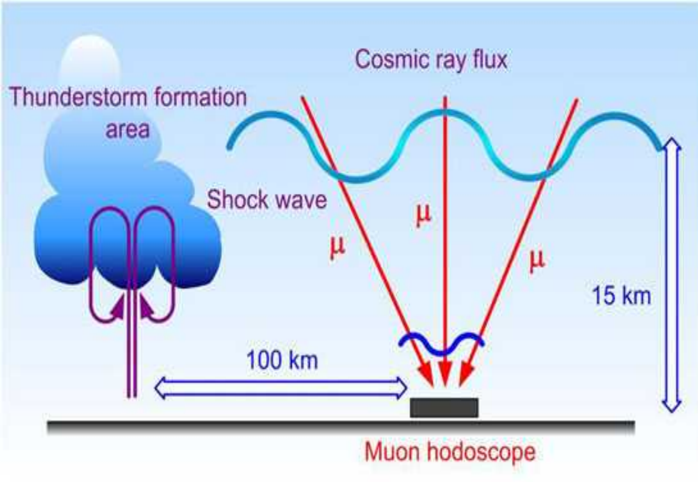
2 TeV perpendicular on a 20 cm mirror

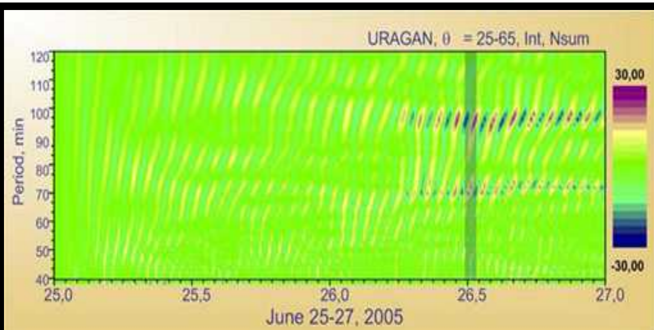
1. $\Delta L = 2 \times 10^{-19}$ m
2. $\Delta H = 8 \times 10^{-19}$ m

Difficulties:
- Rare events
- The detector needs to be placed beneath the mirror (we were barely let inside the building)

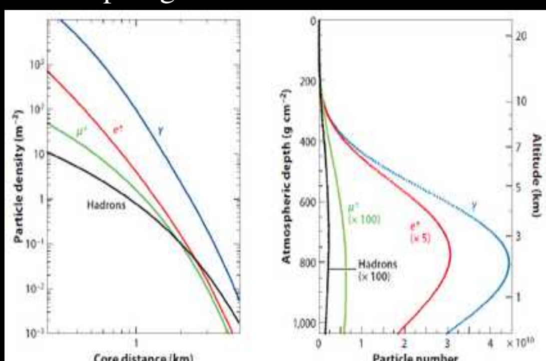
Solution: Long term study between Extensive Air Showers (EAS) and interferometer response

Interacting with particles ?





Hodoscope signal from Hurricane 100 km far from Uragan



Average lateral and longitudinal shower profiles for vertical, proton-induced showers at 10^{19} eV.

- The question of particles interacting with the mirror still open...
- Cosmic muons may be a powerful tool for atmospheric phenomena monitoring which provide remote access to atmospheric changes at large distances.
- Muon hodoscopes can be used as monitoring tools of large-scale atmospheric mass movements like thunderstorms and other important Newtonian Noise sources.
- Large surface particle detectors (~10-100 m^2) useful to :
  - ✓ VETO the Extensive Air Showers
  - ✓ Constrain the atmospheric models in a global approach
  - ✓ “Muography” the geology and its dynamics
- Robust, simple and low-cost technology required : large-scale scintillator detectors are easy to produce and operate.

MUODIM

The New York Times

TRILOBITES

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.

iP2i
LES 2 INFINIS
LYON