Muon tomography of the La Soufrière de Guadeloupe hydrothermal system : 3D structure and dynamics

Jacques MARTEAU
Institut de Physique Nucléaire de Lyon –
Laboratoire des Matériaux Avancés (IPNL – LMA)
UMR 5822 – Université de Lyon / CNRS-IN2P3
marteau@ipnl.in2p3.fr

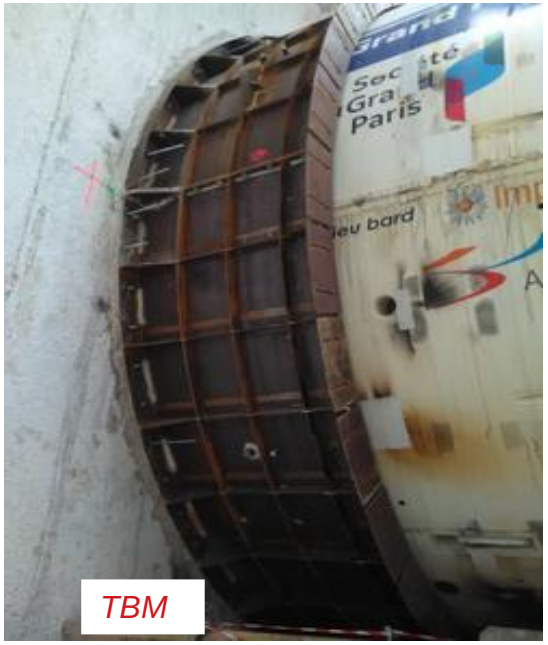
Marina ROSAS-CARBAJAL
Institut de Physique du Globe de Paris (IPGP)
UMR 7154 – Université de Paris / CNRS-INSU
rosas@ipgp.fr

IPN Lyon: J.Marteau, B.Carlus, J.-C.Ianigro, J.-L.Montorio, A.Chevalier, A.Cohu, C.Dufour (ext.)
OSU Rennes: D.Gibert, J. de Bremond d'Ars, B.Kergosien, Y. Legonidec, P.Rolland
IPG Paris – OVSG – UnivEarthS : S.Deroussi, M.Diament, M.Rosas-Carbajal

ANR DIAPHANE (2014 – 2019) www.diaphane-muons.com
External fundings : ArcelorMittal, Alliance / Implenia / Société du Grand Paris, ORANO (ex-AREVA), PDS consulting

Blast furnace

VIRGO



TBM

General features & use cases

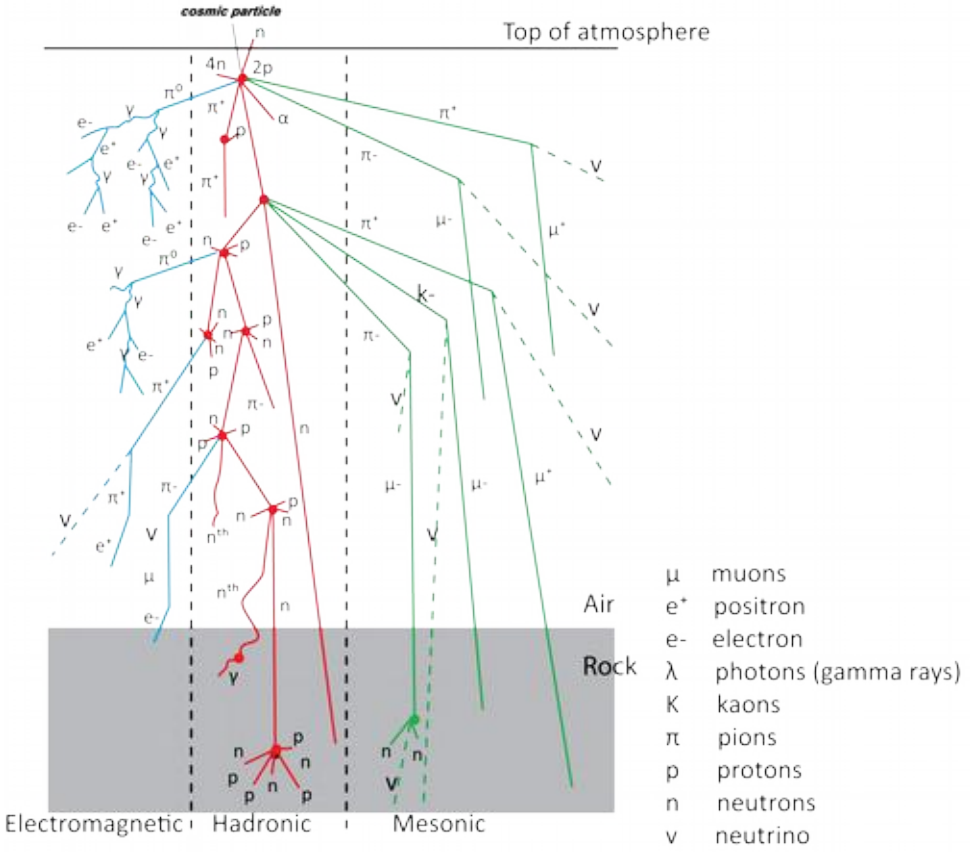
Greek tumulus

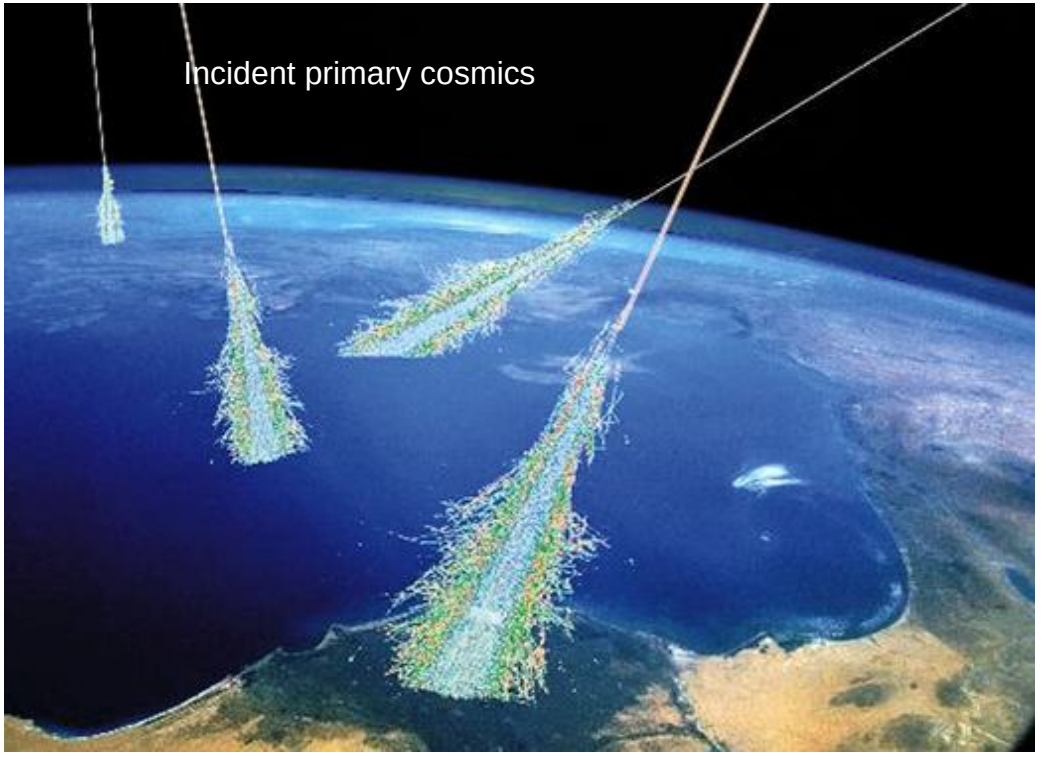
Active volcano

Nuclear evaporator

Basic cosmic Muon Features

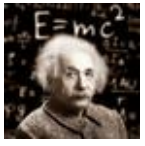
Muons are produced in pions/kaons decay chains





Production : $\pi / K \longrightarrow \mu + \nu_\mu$

Decay : $\mu \longrightarrow e + \nu_\mu + \nu_e$ &



Alvarez, L.W. et al., 1970 / Nagamine, K. et al., 1995

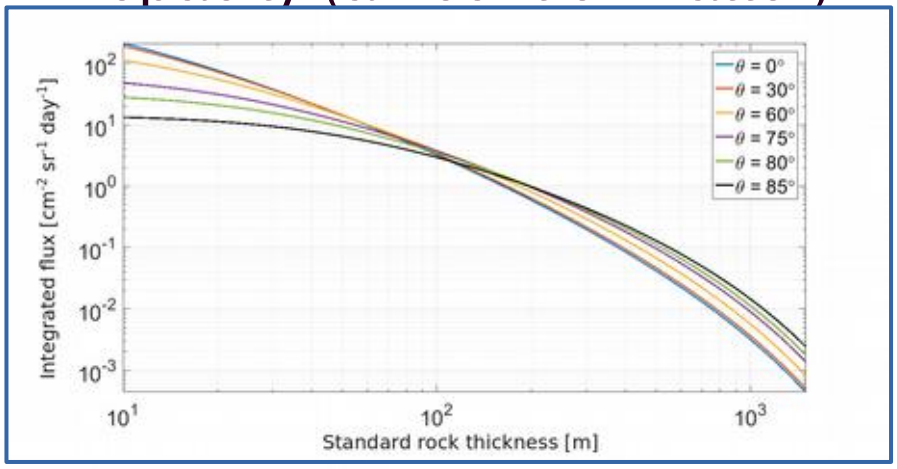
Absorption Muon Tomography

Muon flux emerging from the target ↔ opacity (amount of matter)

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

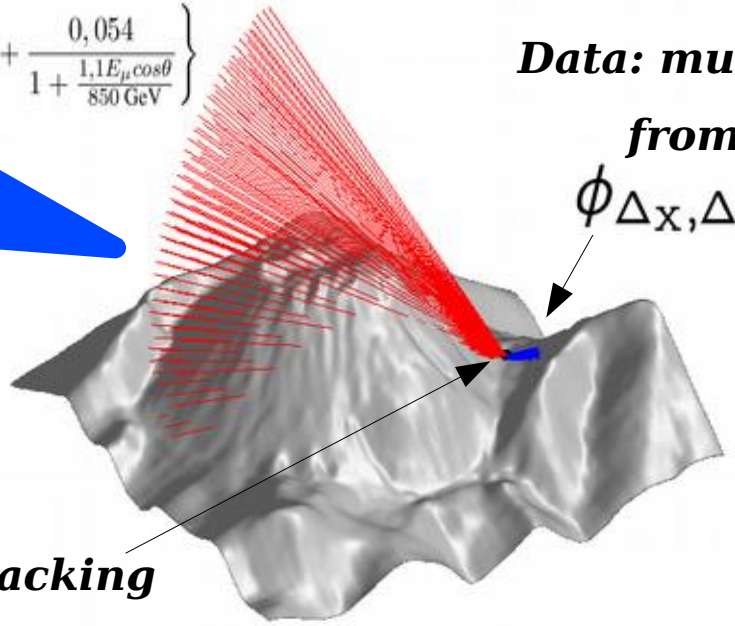
ϱ = opacity

ρ = density



Incident muon flux

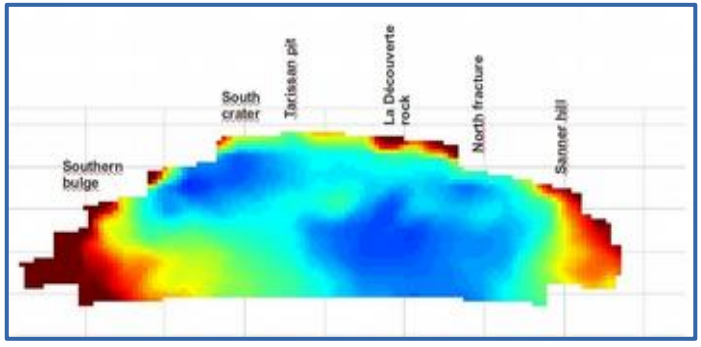
$$\frac{dN_\mu}{dE_\mu d\Omega} \approx \frac{0,14E_\mu^{-2,7}}{\mathrm{cm^2\ s\ sr\ GeV}} \times \left\{ \frac{1}{1+\frac{1,1E_\mu cos\theta}{115\ \mathrm{GeV}}} + \frac{0,054}{1+\frac{1,1E_\mu cos\theta}{850\ \mathrm{GeV}}} \right\}$$



Tracking detector

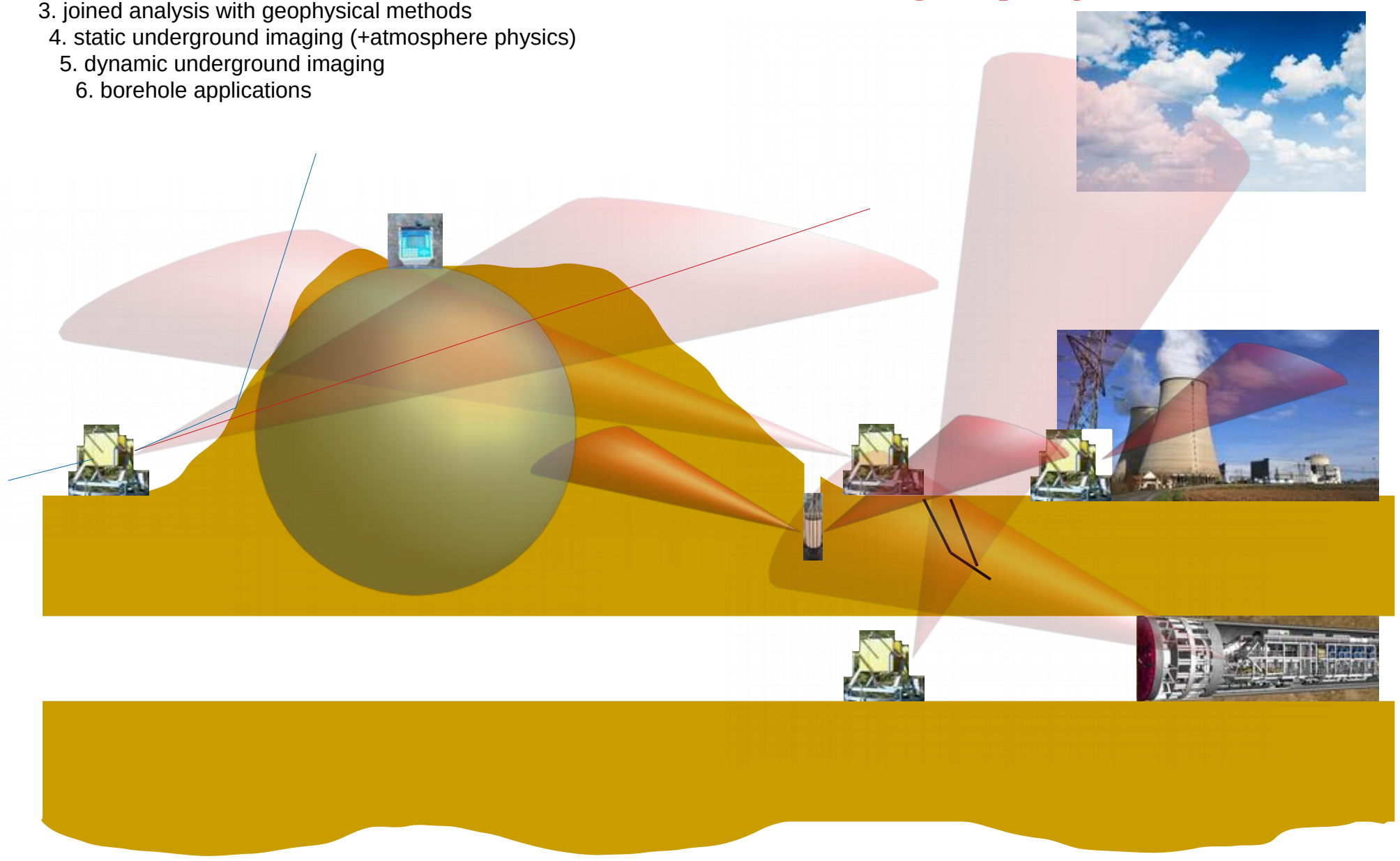
Data: muon flux emerging from the volcano

$$\phi_{\Delta X,\Delta Y} = \mathcal{T}_{\Delta X,\Delta Y} \times \partial\phi_{\Delta X,\Delta Y}$$

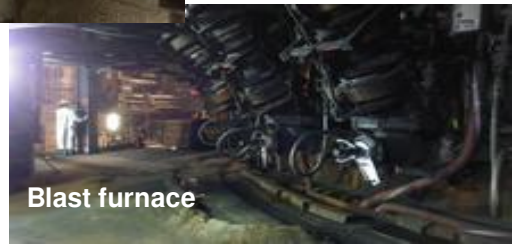


Muon Tomography use cases

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



DIAPHANE projects : 10++ years



- **2007** : technical evaluation started (BQR Univ.Paris / IPGP)

- **2008** : first collaborations
  - ✔ **ANR Domoscan** (INSU) including a small muography part
  - ✔ IPNL-IPGP-OSUR (IN2P3/INSU) collaboration started

- **2009** : first installation in **Mont-Terri** underground lab

- **2010** (and 2012): exploration of **Etna** South crater

- **2010 – 2014**: 1st experiments on the **Soufrière de Guadeloupe**
  - ✔1 telescope / 3 different sites explored
  - ✔ t.o.f. background subtraction (TDC vernier in FPGA)

- **2013** : experiment in **Tournemire** underground lab (IRSN)

- **2014** :
  - ✔ 1 detector installed on the **Mayon** volcano (Philippines)
  - ✔ **ANR Diaphane** retained in 2014

- **2014 – 2019** : R&D → volcano monitoring (risks analysis)
  - ✔ 6 muon detectors installed (May '15, Aug. '16, March 17)
  - ✔ muon-gravimetry coupling,
  - ✔ 3D imaging
  - ✔ hydrothermal system continuous monitoring

- **2015** : underground tunnel scanned in Lyon (**Cx-Rousse**)

- **2016** : **archaeology** and industrial applications:
  - ✔ ARCHé project for greek tumulus scanning
  - ✔ AREVA-NEEDS funding : borehole applications

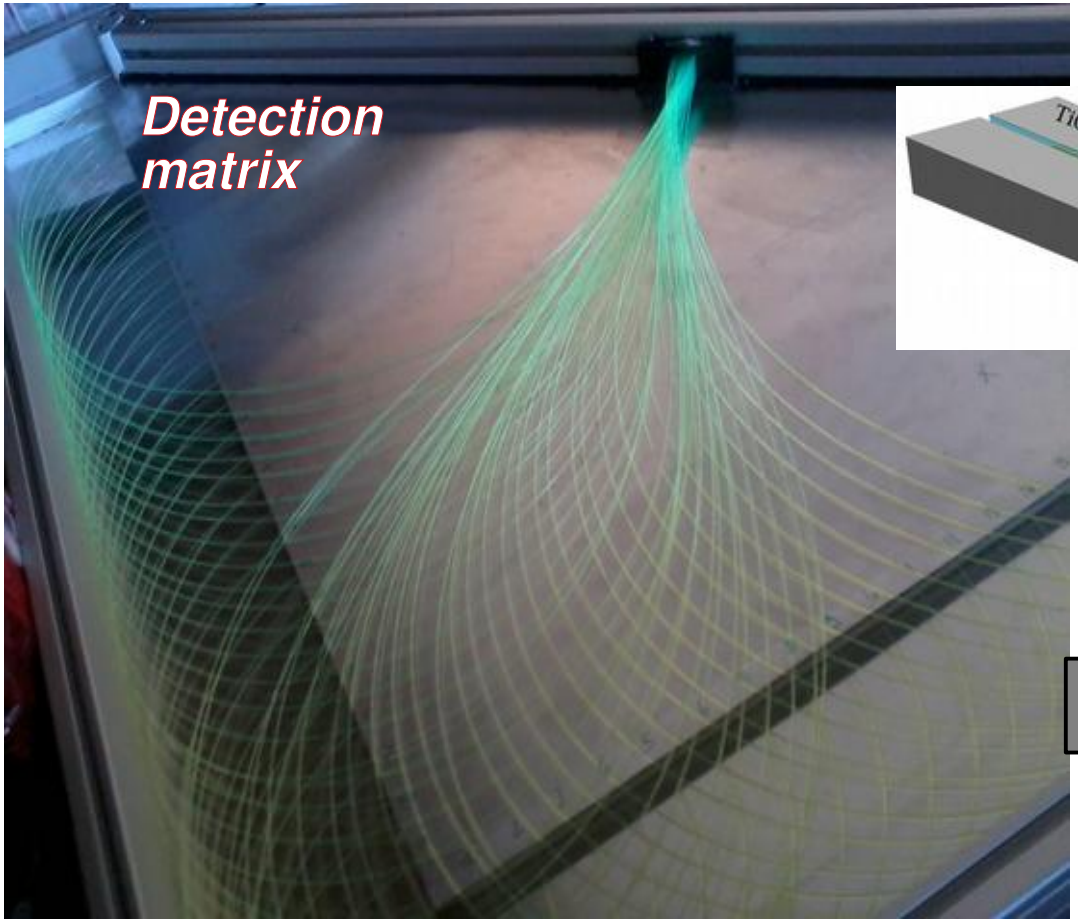
- **2017 & 2019** :
  ArcelorMittal funding for **blast furnace** study

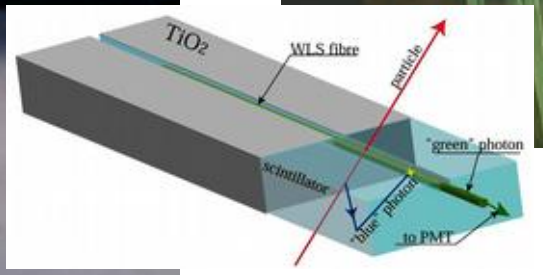
- **2018** : “industrialization” process initiated
  - ✔ ORANO nuclear plant monitoring
  - ✔ LSBB hydro-thermal monitoring

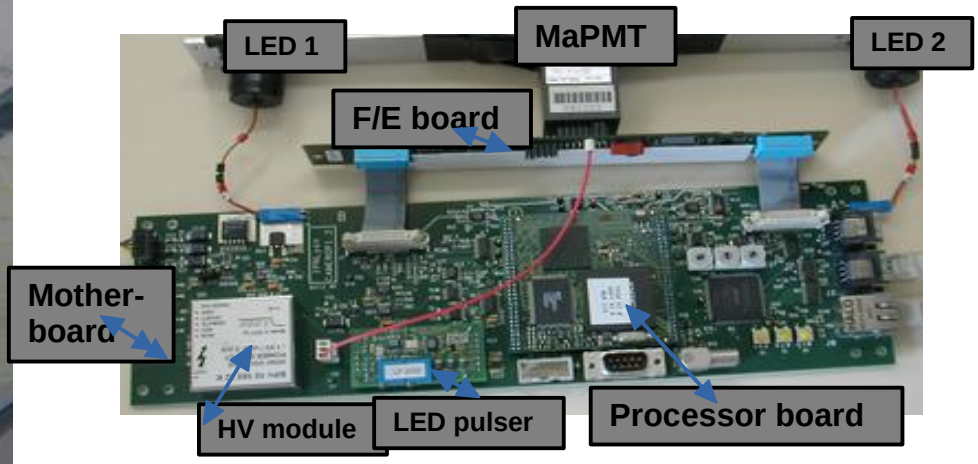
Detection planes : scintillator + WLS + opto-electronics

- Scintillator technology :
  → (JINR): 2.5 x 0.7 x 80 cm^3 → 32x32 matrix (20kg)
  → (FermiLab): 5.0 x 1.0 x 80 cm^3 → 16x16 matrix (45kg)
- WLS technology : BC91A or Kuraray Y11
- PhotoSensors : MaPMT or MPPT

- Same electronics for all types of matrices : IPNL design
- Common Clock locked on GPS (10ns timestamps)
- TDC embedded in the FPGA (100ps vernier) for t.o.f.
- Smart sensor fully Ethernet capable, raspberry PI backend

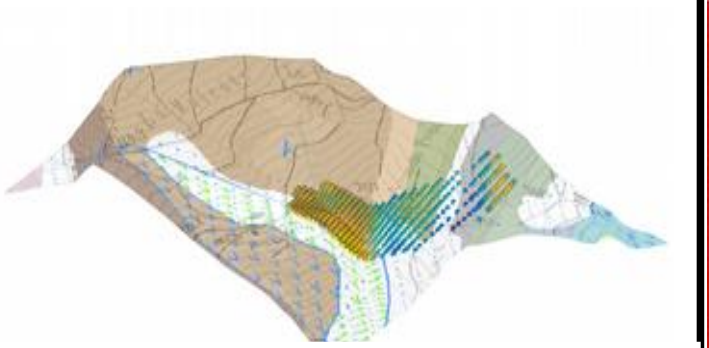




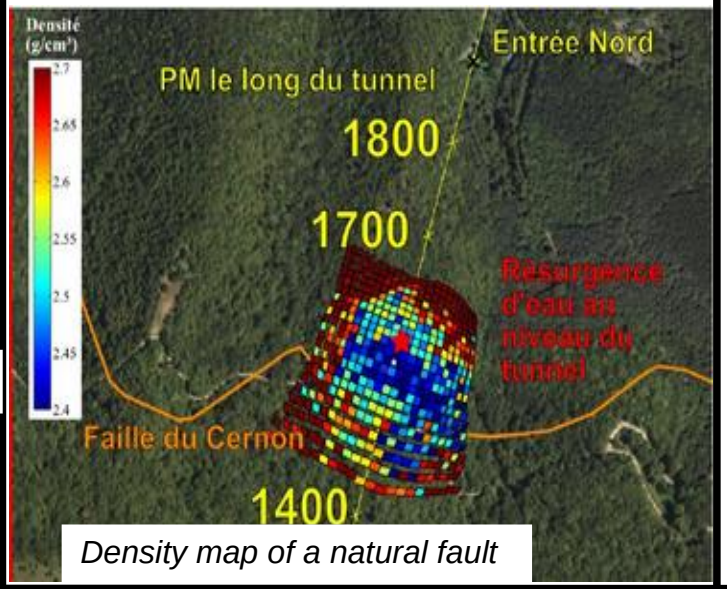


Ethernet-capable R/O electronics

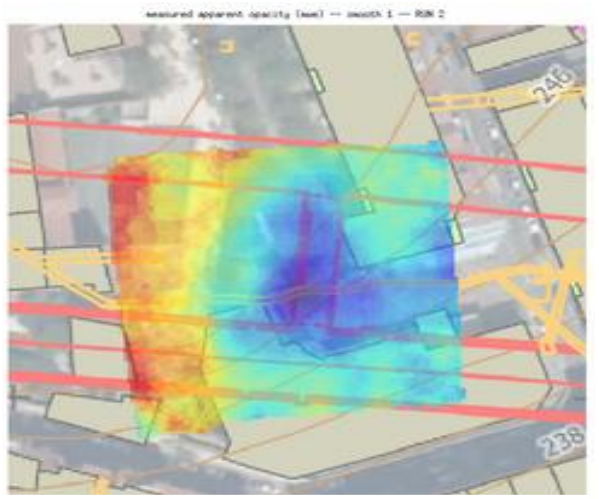
Imaging capabilities underground



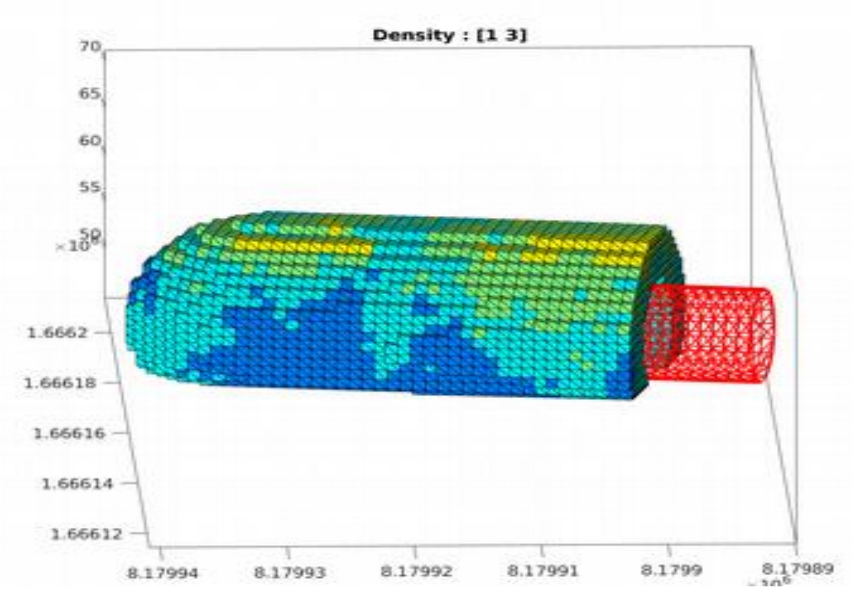
Density map of geological layers



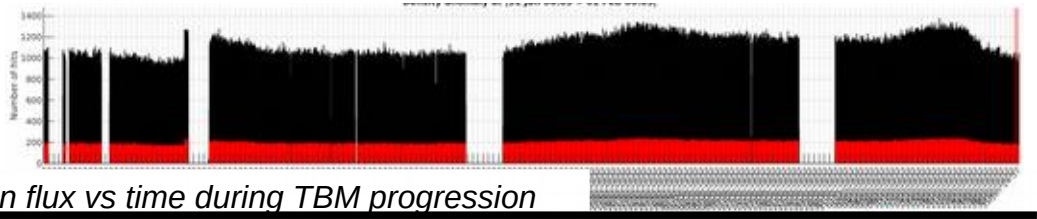
Density map of a natural fault



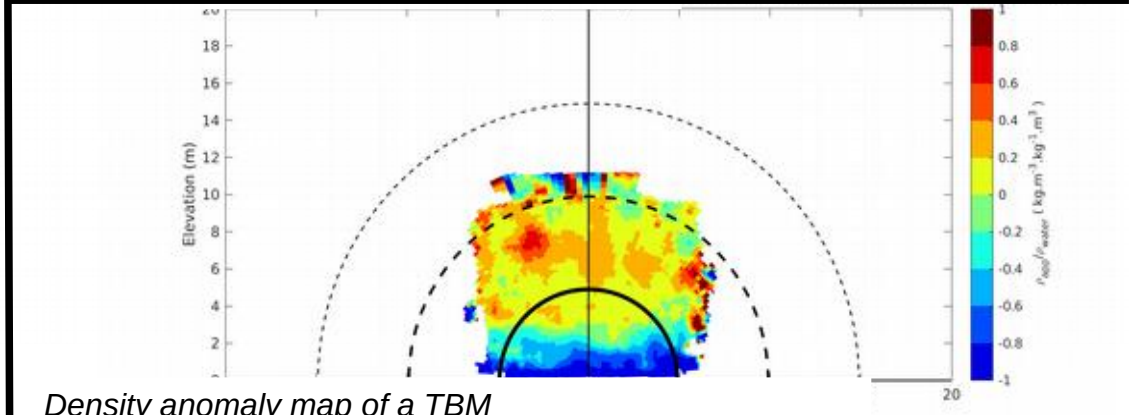
Urban surface from Cx-Rousse tunnel



3D density map around a TBM path



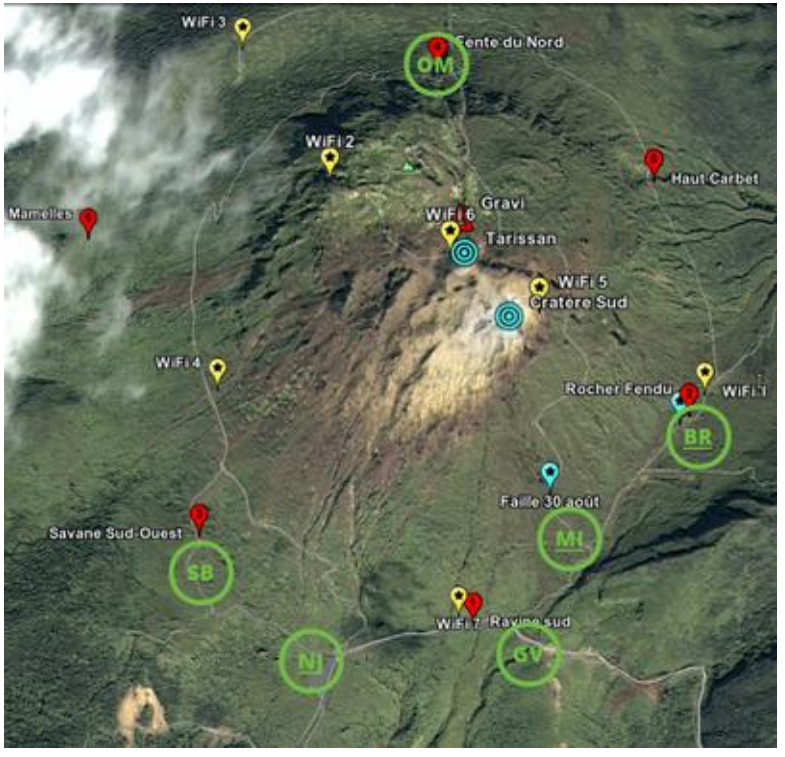
Muon flux vs time during TBM progression

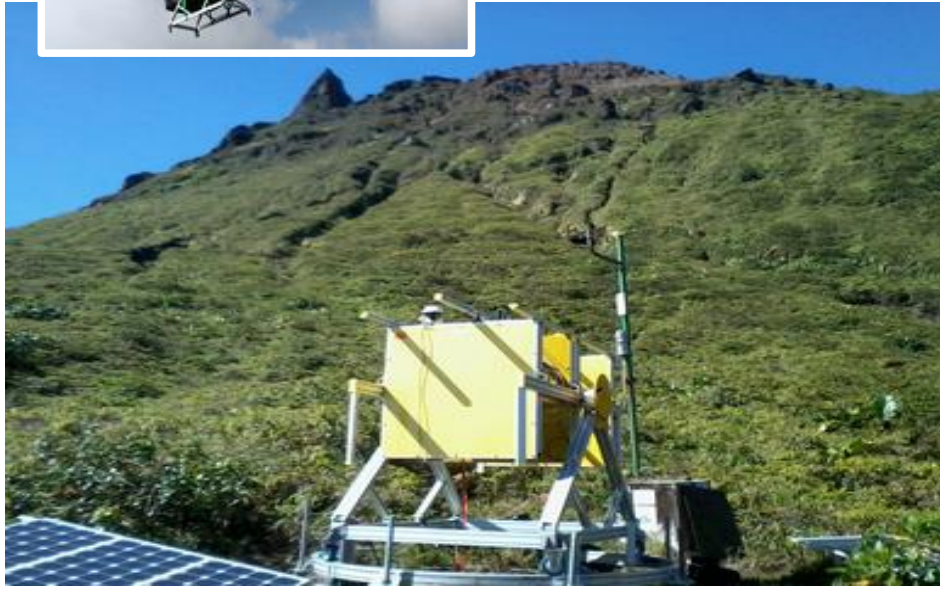


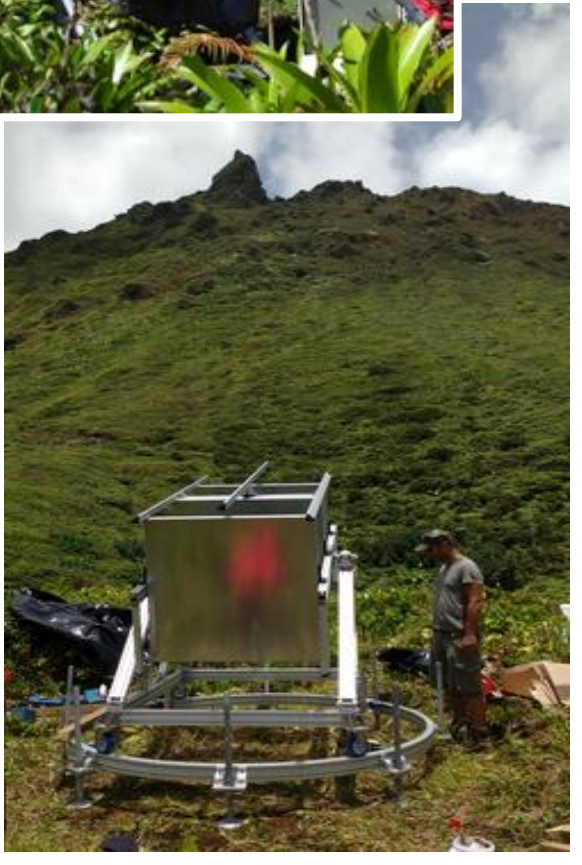
Density anomaly map of a TBM

Muons @ Soufrière

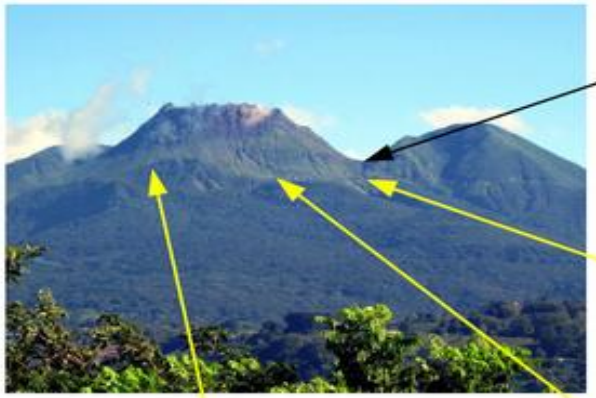
5 + 1 detectors **around the dome**

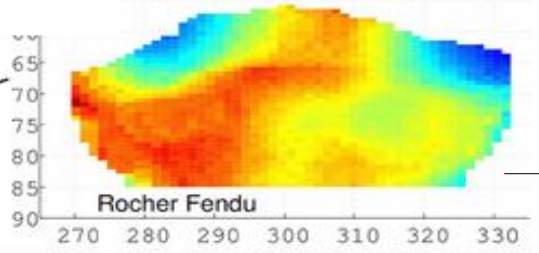


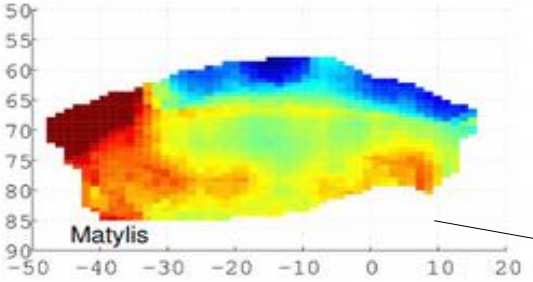


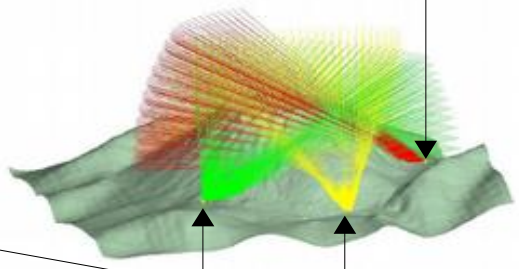


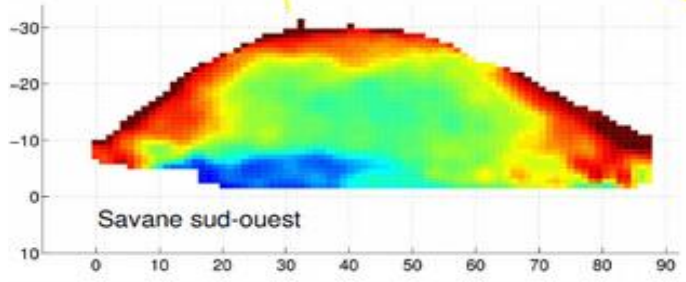
Imaging & monitoring

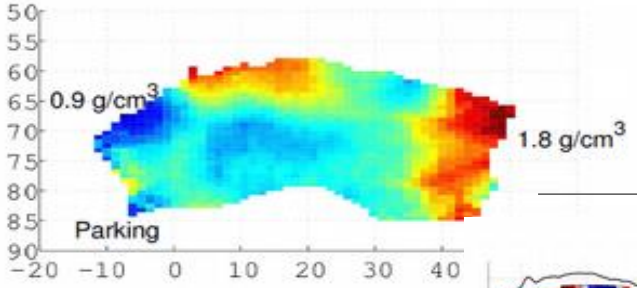




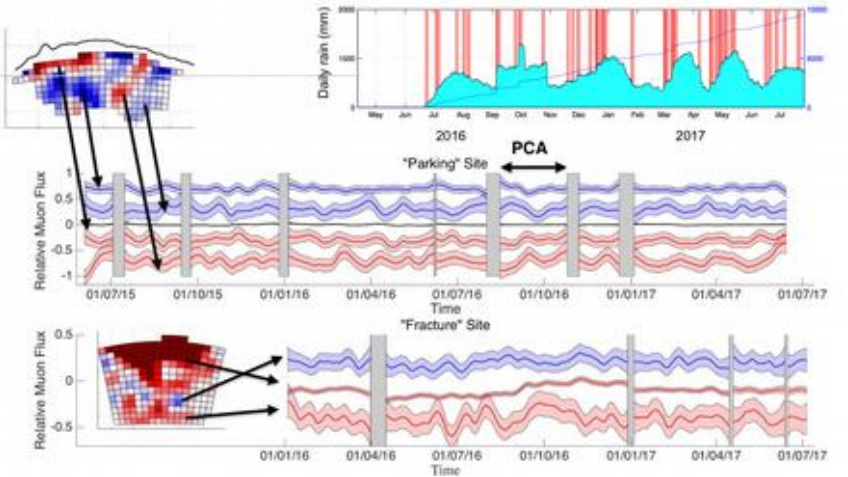








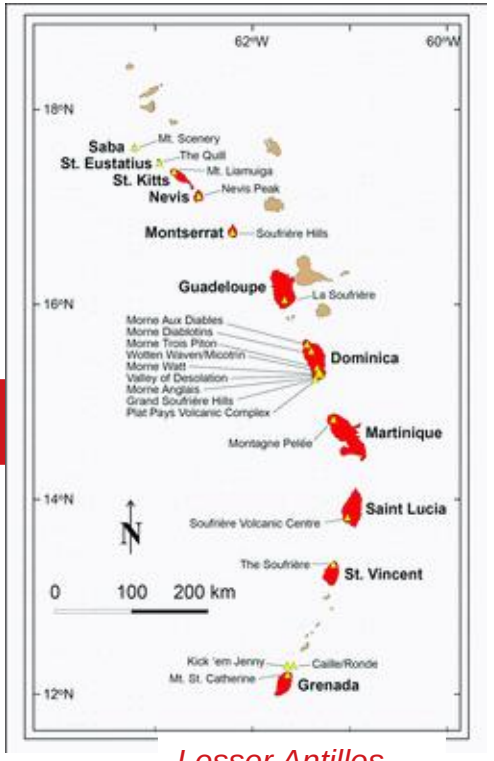
World's largest muon station



La Soufrière de Guadeloupe

Inverse problem & continous monitoring

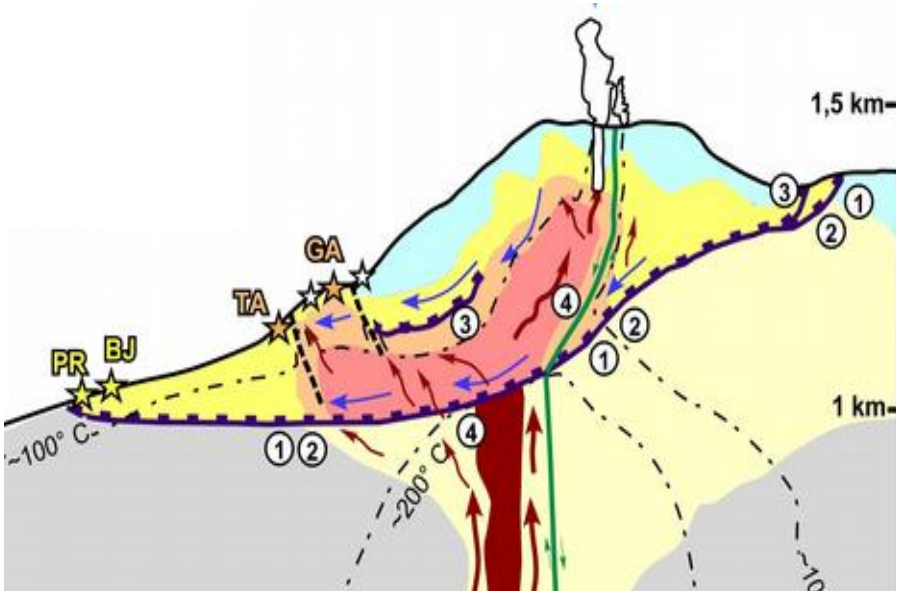
Muon detector @ FDN

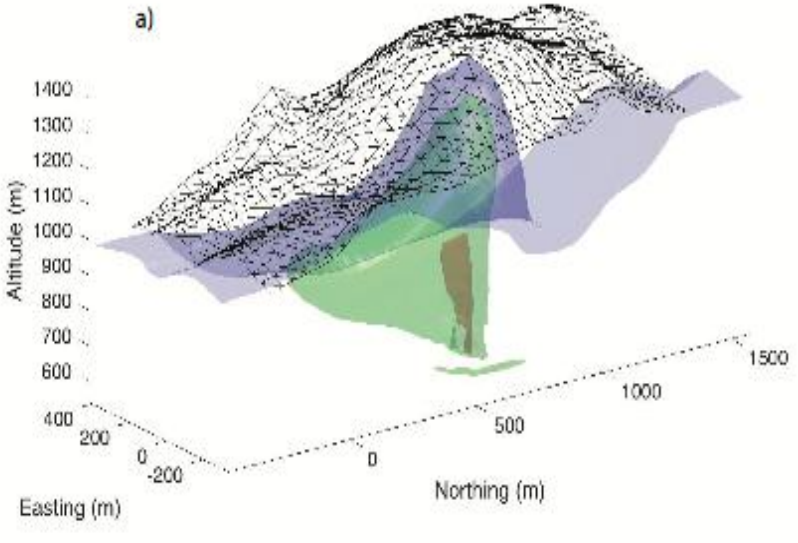


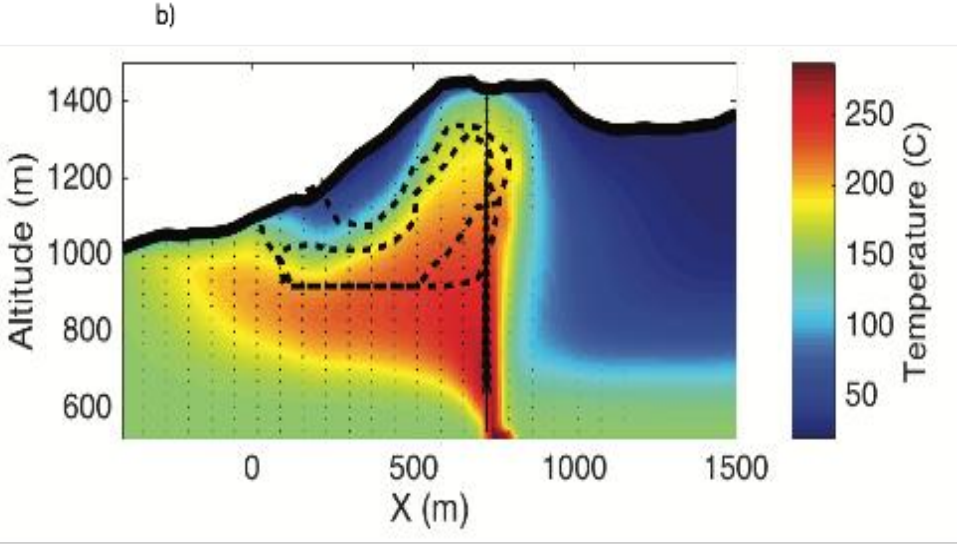
Lesser Antilles

Application(s) to La Soufrière

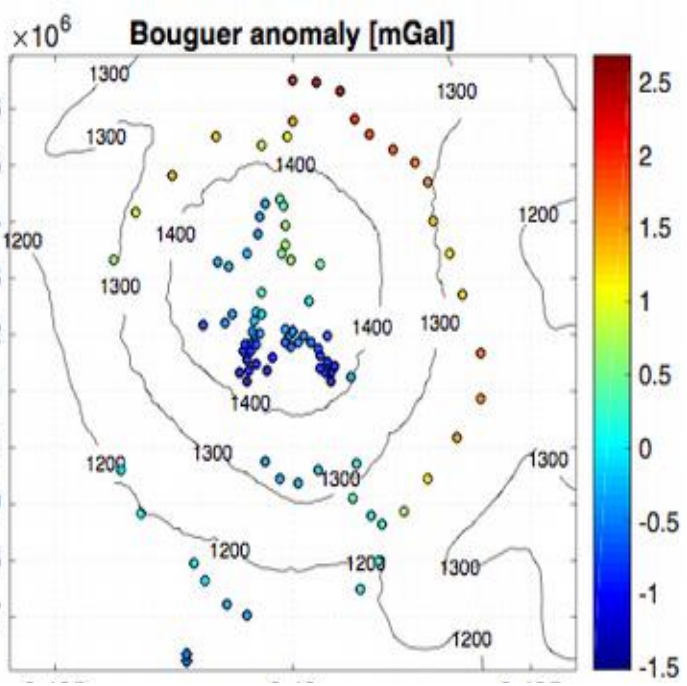
- Volcano hydrothermal systems are at the core of unpredictable volcanic hazards
- Complex interplay between internal and external forcing
- Classical geophysics provide limited information on spatio-temporal dynamics
- Need for techniques that can track in space and time the internal state of the system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

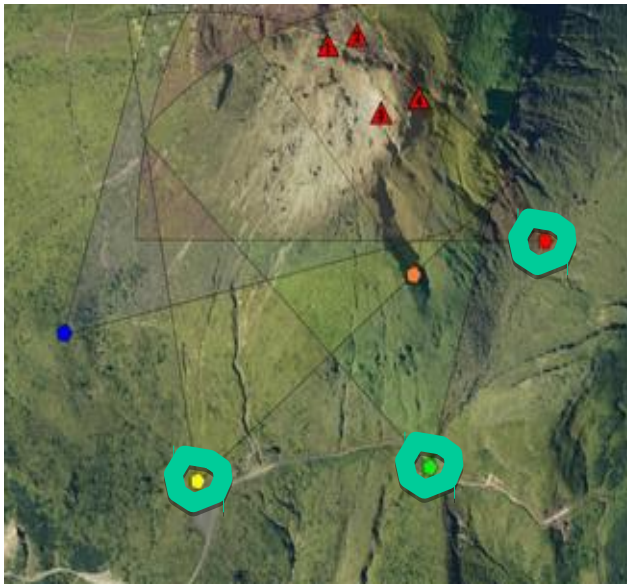




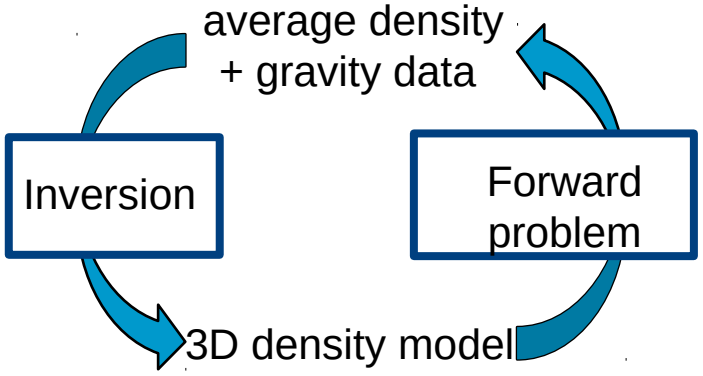


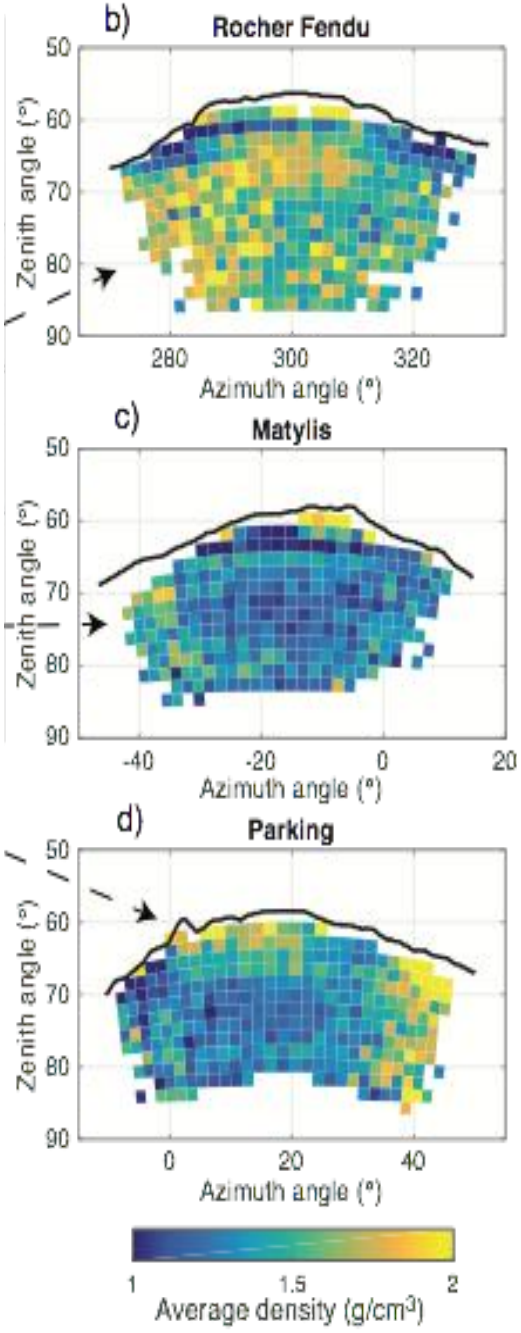
3-D joint inversion of muon and gravity data





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





(Rosas-Carbajal et al., 2017)

3-D joint inversion of muon and gravity data

- Linear, deterministic inversion with model regularization

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

Smoothing

Damping

Matrix scaling

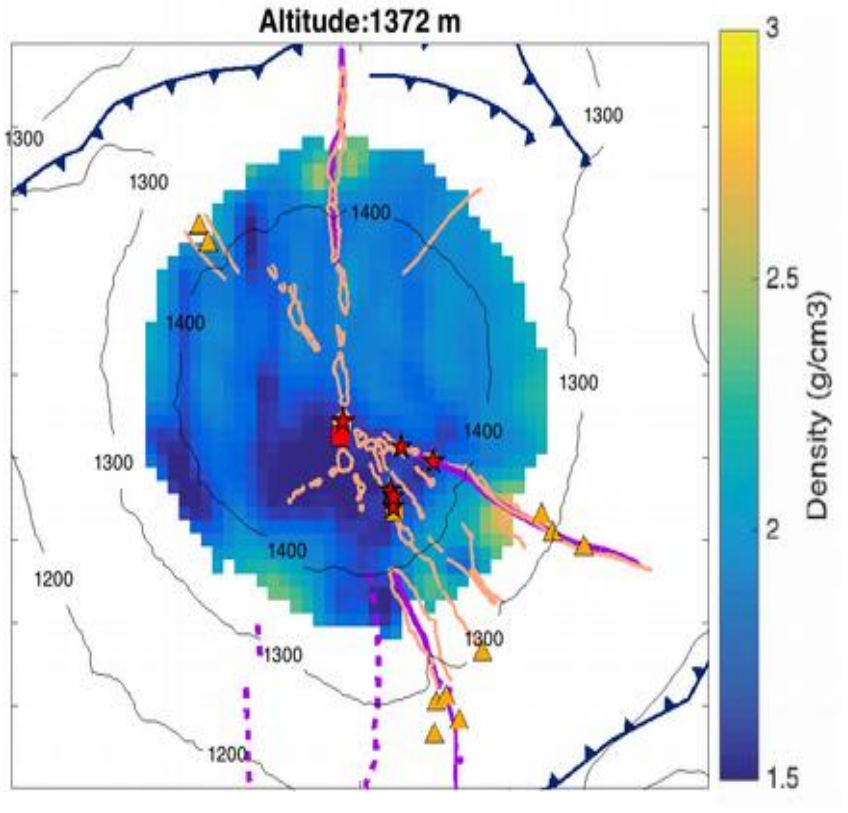
- Matrix scaling (depth weighting in the regularization matrix to counteract the natural decay of the kernels)

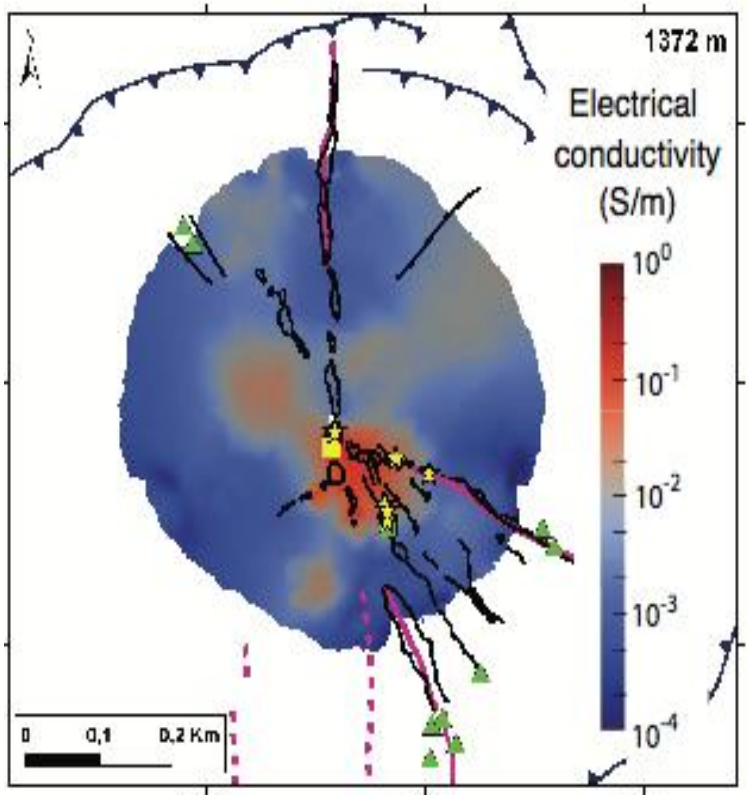
$$\mathrm{W}_i = \frac{1}{\min\left\{(z_{\min,i} + z_0)^2, r_{\min,i}^{1.5}\right\}}$$

- Parameterization based on cubes of 8x8x8 m^3

(Rosas-Carbajal et al., 2017)

Horizontal slices of density and electrical conductivity models

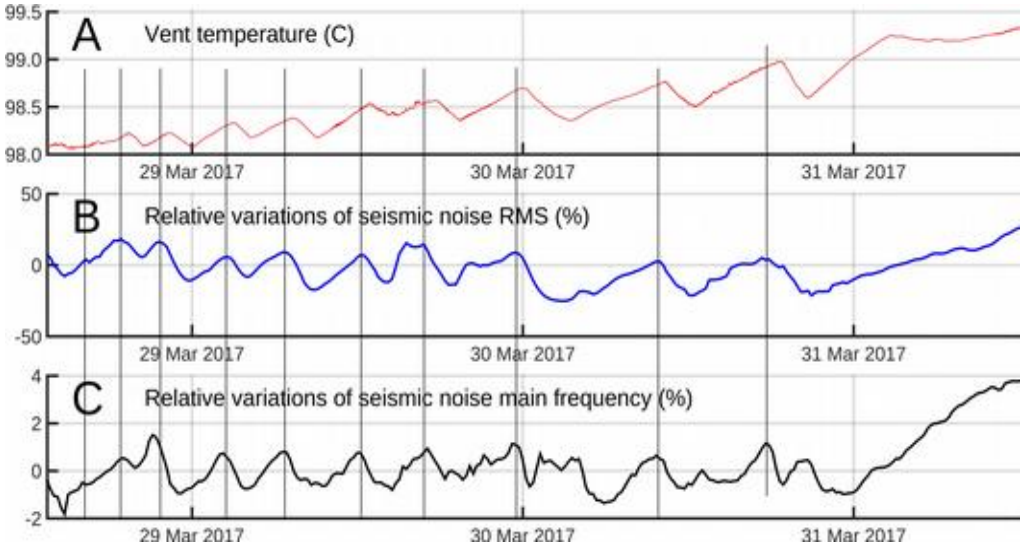


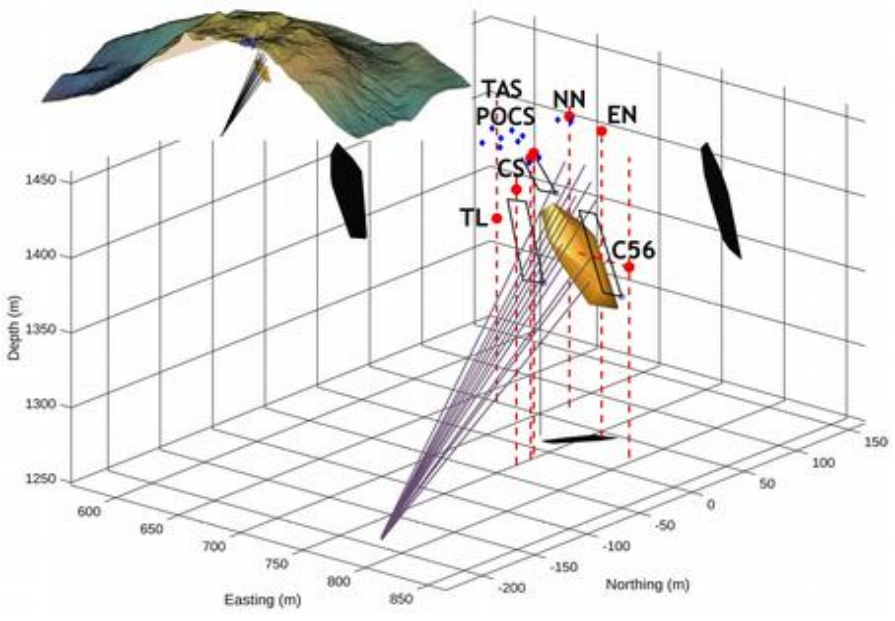


(Rosas-Carbajal et al., 2016, 2017)

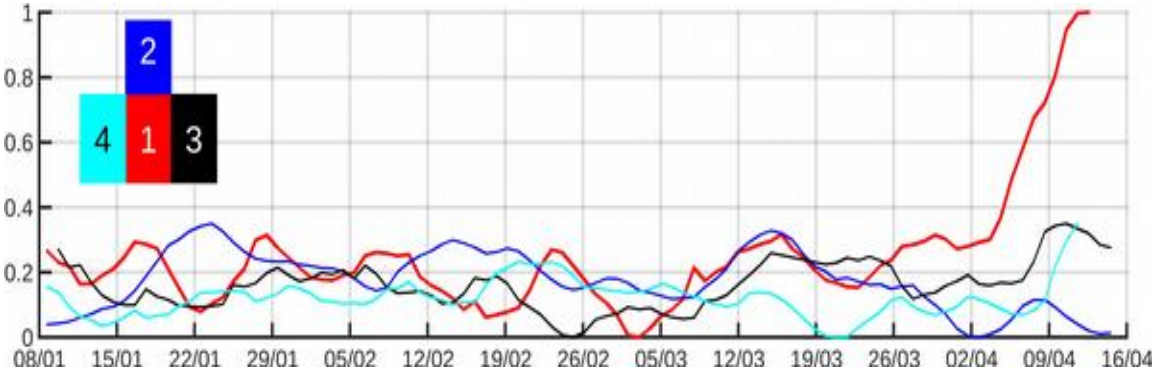
Joined monitoring :
muon flux variations in region determined by seismic noise

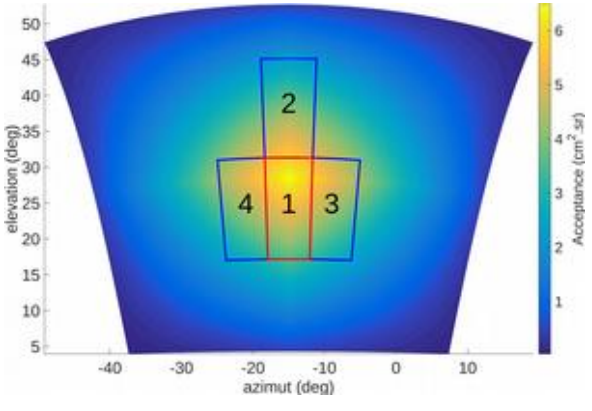
- Density changes are expected as a result of fluid content variations
- These variations are related to meteoric and magmatic mass input, and/or phase transitions





Relative muon flux variations

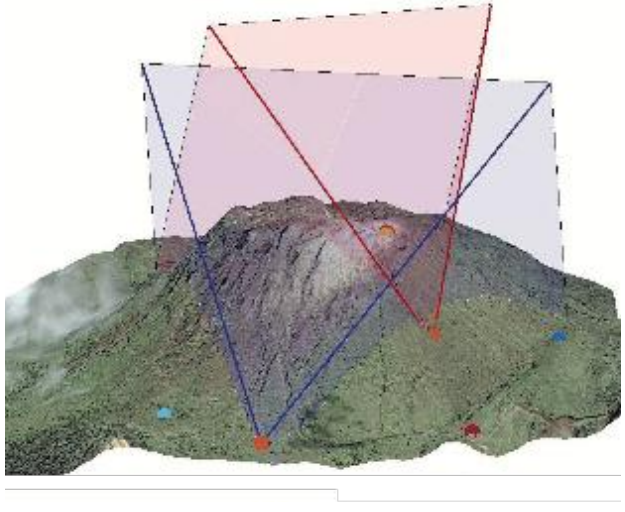


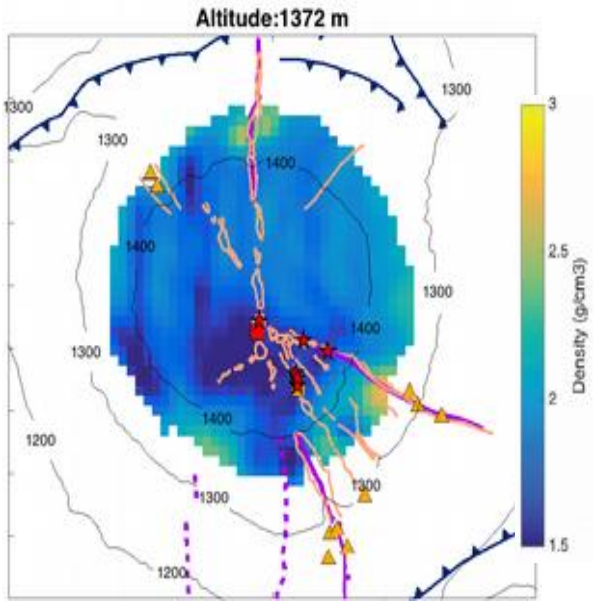


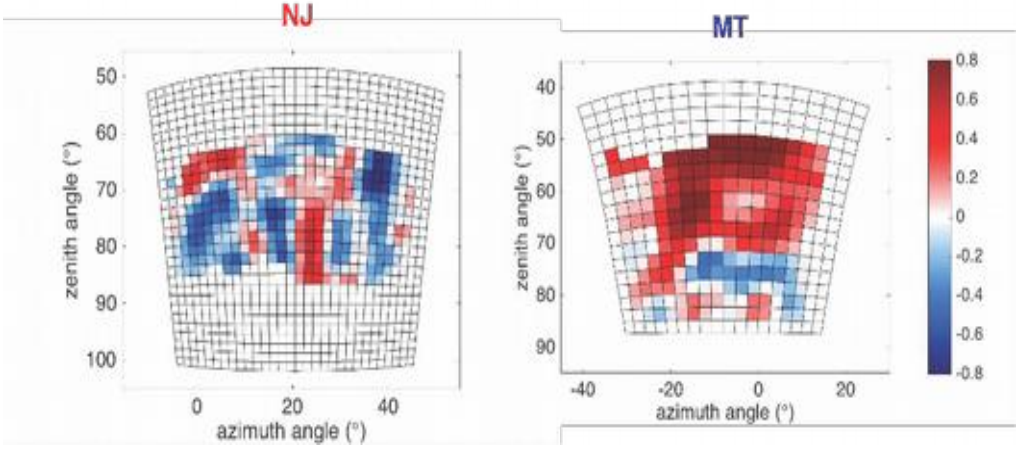
(Le Gonidec et al., accepted)

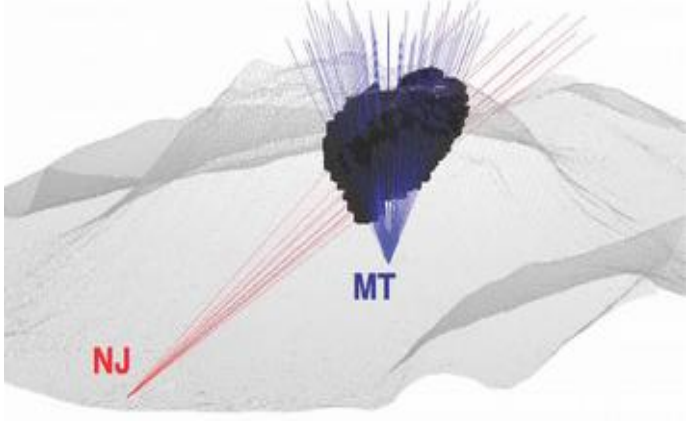
Long-term density variations from continuous muon measurements

- Continuous muon measurements with 2 muon detectors
- Common regions scanned include fumarolic zone
- Coherent variations found with PCA analysis



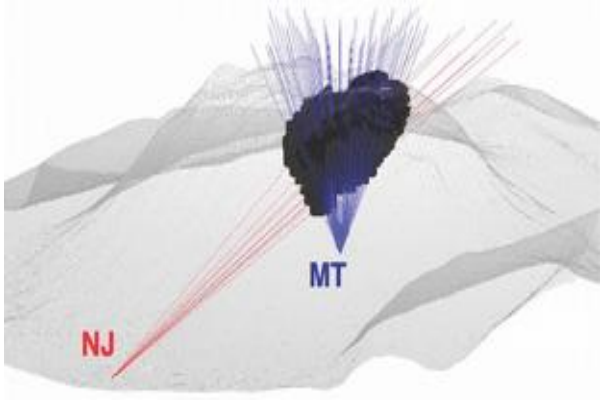


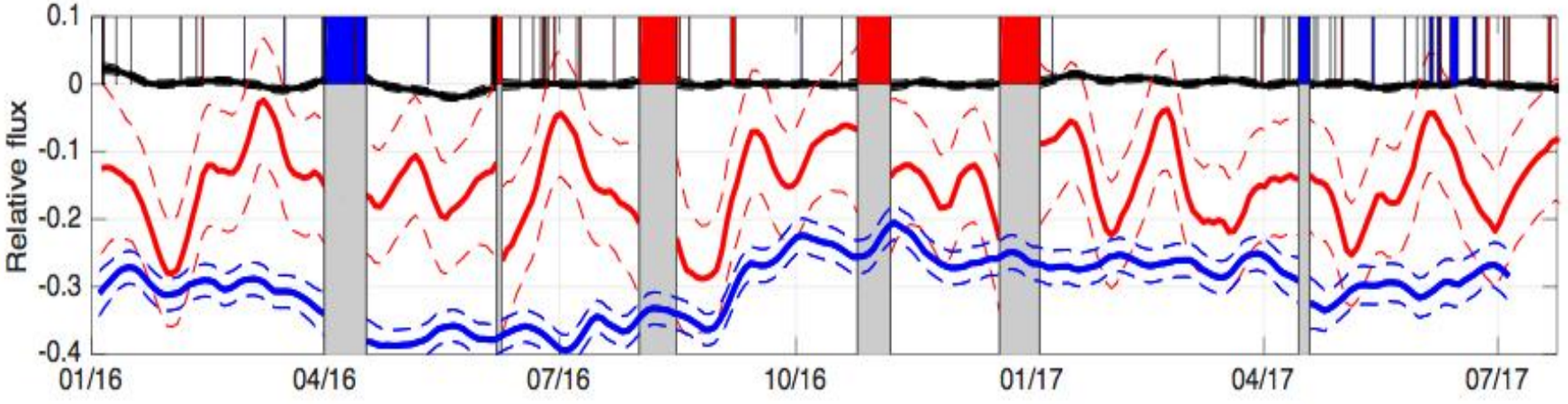




Flux variations measured by each detector in selected zone

PCA joined analysis





Coherent increase in the muon flux with a 4 % decrease in average density.

Conclusions

• **Muon tomography** has been developed since the last decade to increase its **robustness** and **sensitivity.**

• It is applied world-wide, in various use cases, in particular for studying density structures of large geological bodies.

• Coupling of muography with standard geophysical methods in **joined analysis** has been established to improve the resolution and the sensitivity to the internal processes.

• **Continuous muon measurements** provide insights into the internal processes for a real geophysical **monitoring**.

• **Simultaneous measurements** from different detectors validate the observations and better estimate the region where changes are happening.

• The **world's largest muon observation system** is deployed and running at **La Soufrière**, and provides measurements to constrain the internal dynamics.

• The present configuration of the hydrothermal system can be explained by a simple **numerical model**. Calibrating this model with multiple observables will help to evaluate future scenarios and study transient behavior.

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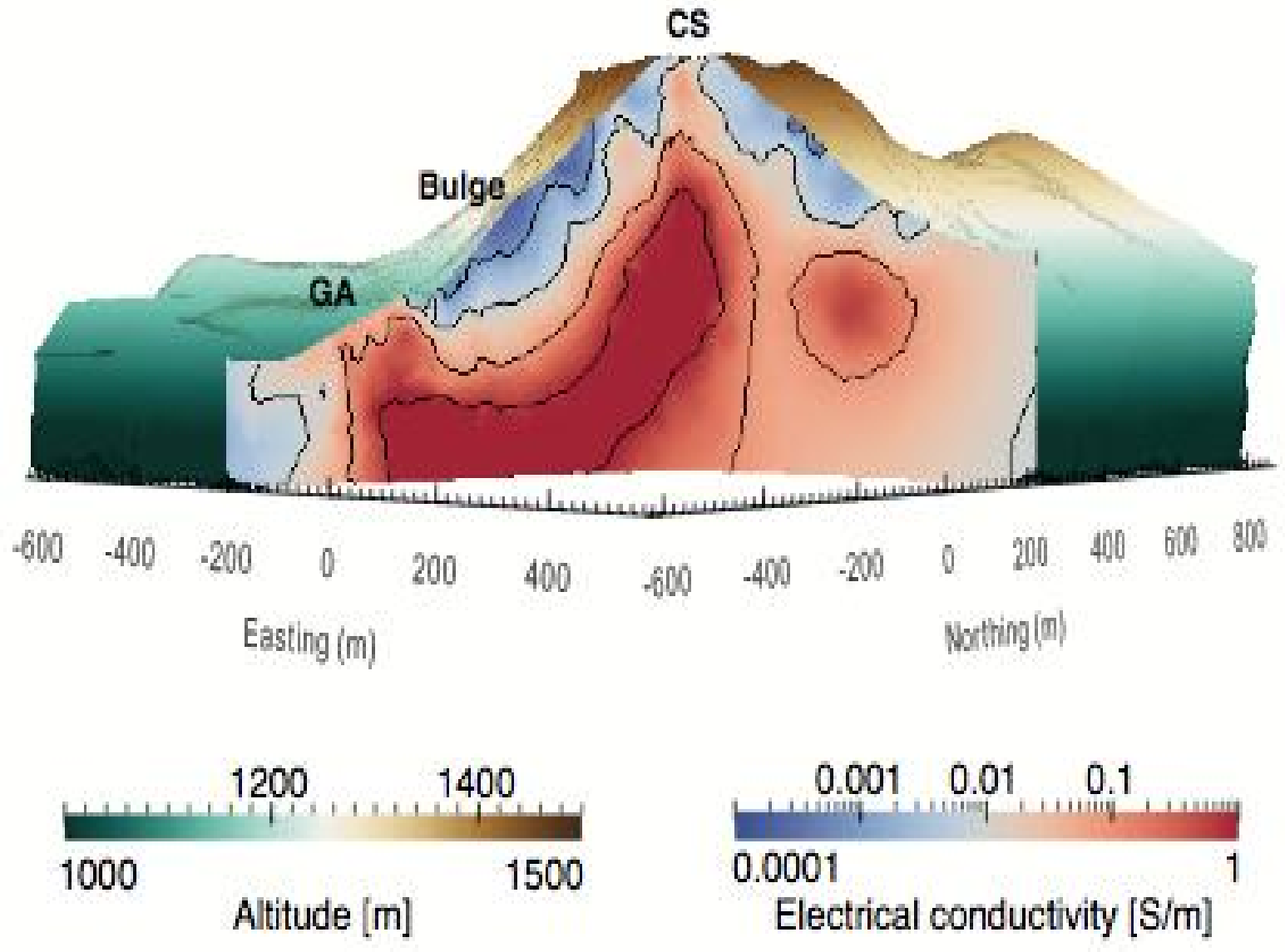
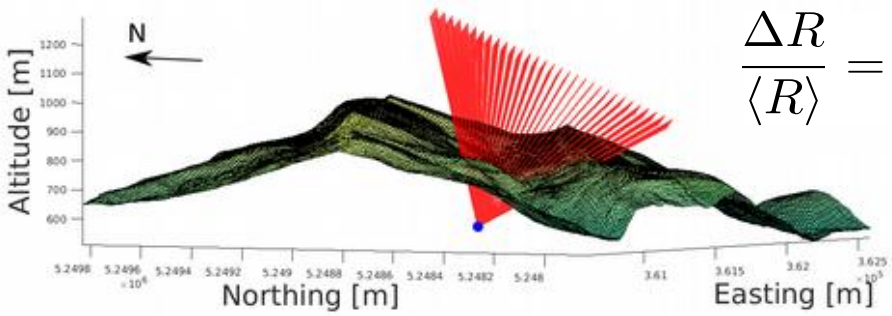
3-D conductivity model of La Soufrière

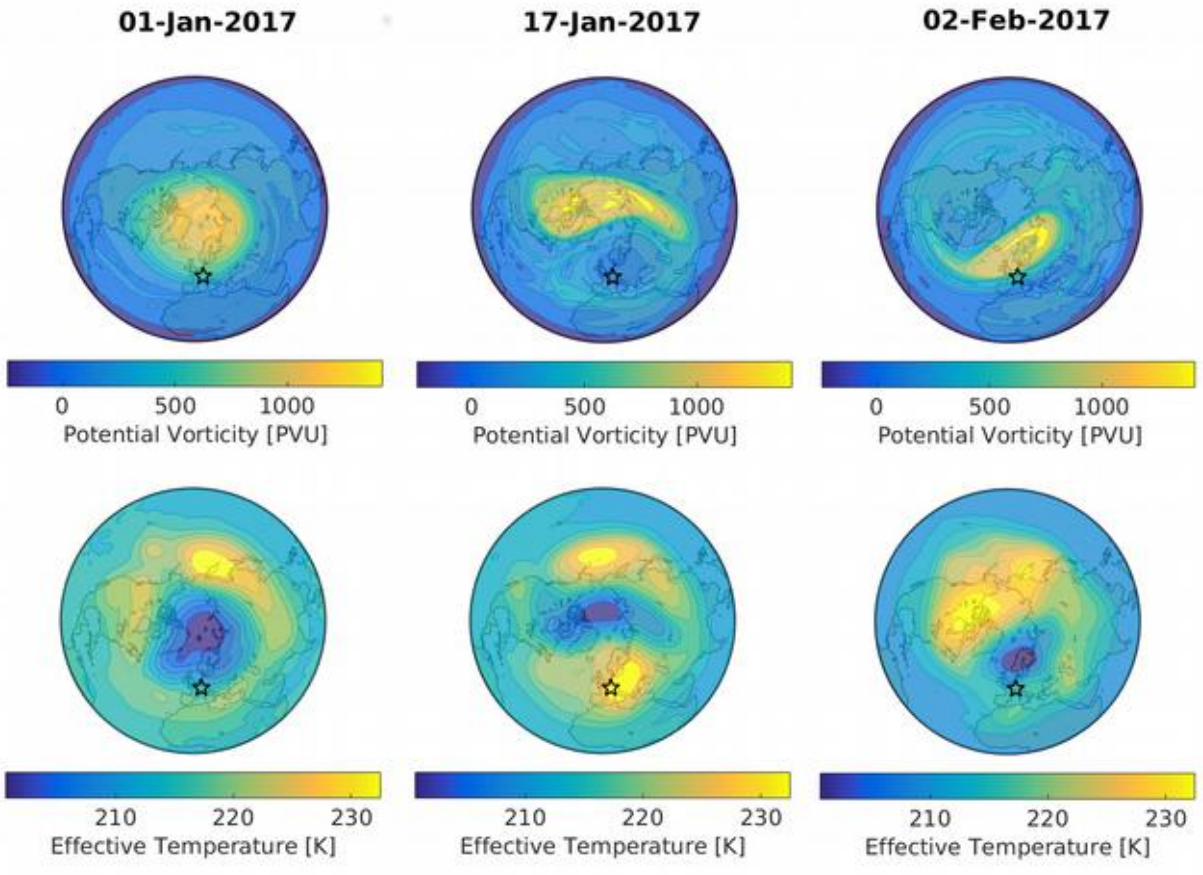


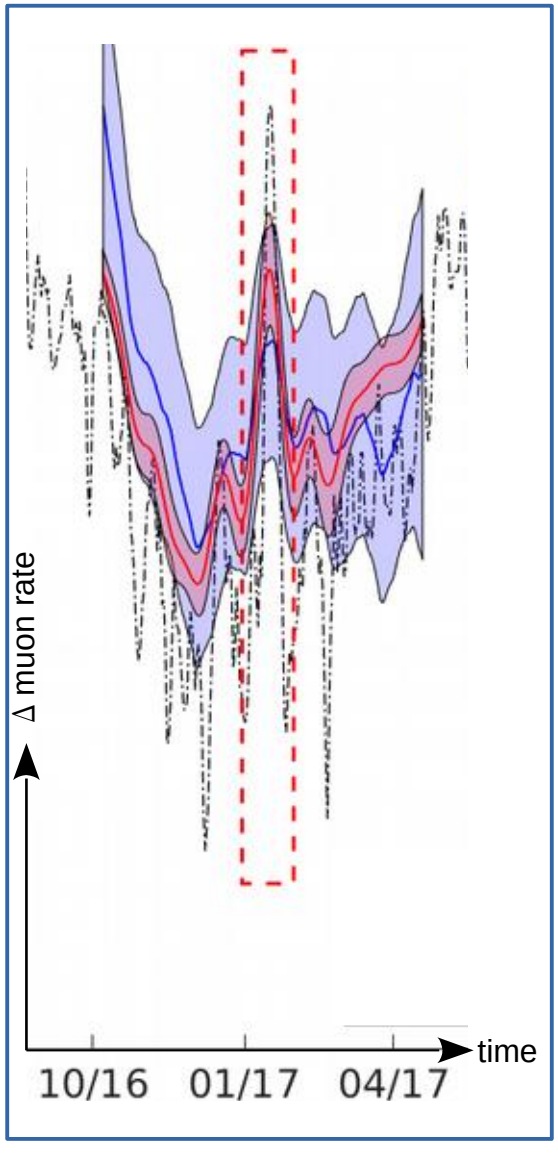
(Rosas-Carbajal et al., 2016)

P & T sensitivity

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







Sudden Stratospheric Warming + hydro-geological global analysis :

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