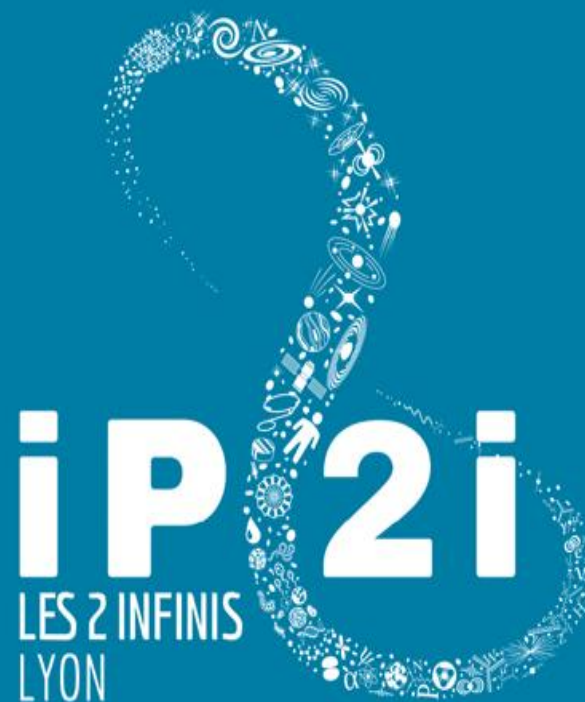


Tomographie Muonique



Muography = μ -ray imaging technique : absorption / scattering → sensitive to ρ (opacity)

Geosciences



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

Archaeology



- Tumulus
- Anthropic structures
- Ruins
- ...

Industrial controls



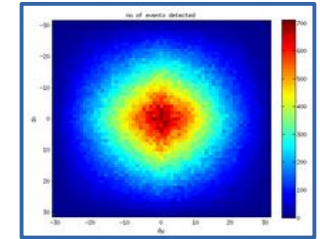
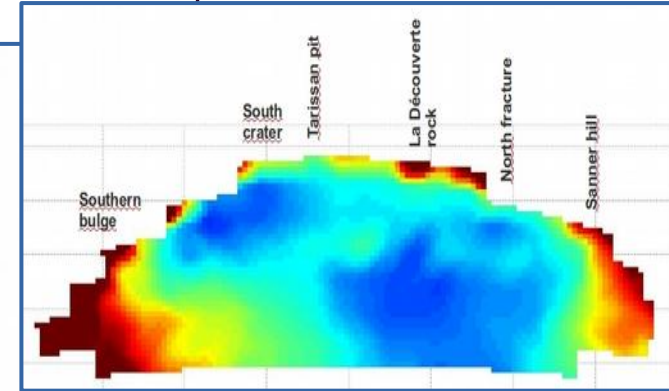
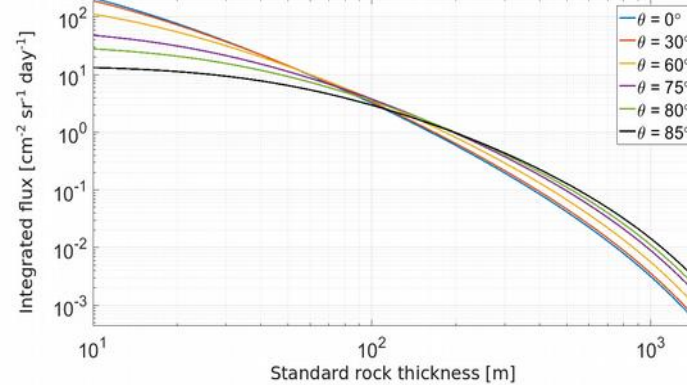
- Non invasive controls
- Nuclear cycle production
- Civil engineering
- Tunnel boring machines
- Prospection & mining
- ...

Absorption Muon Tomography

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

$$\varrho(L) \equiv \int_L \rho(\xi) d\xi$$

ϱ = opacity ρ = density



Incident muon flux

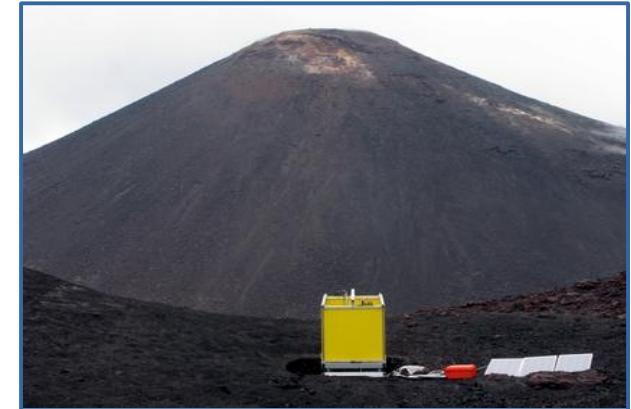
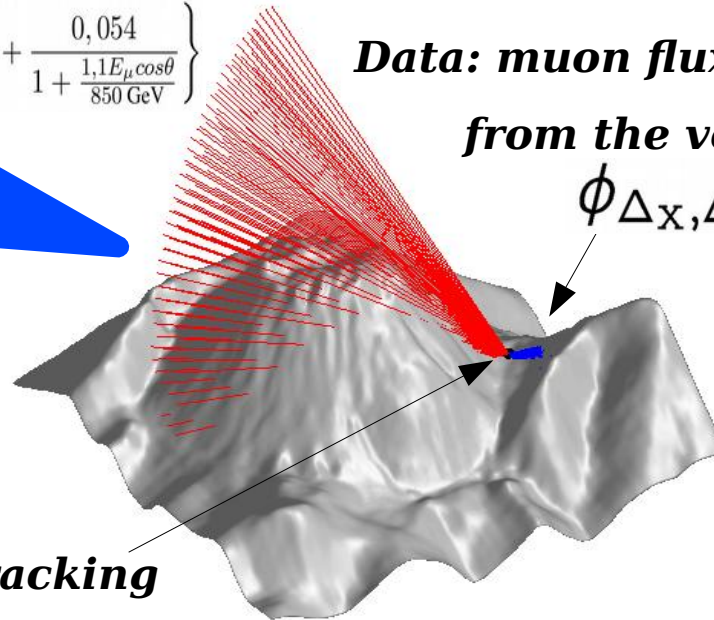
$$\frac{dN_\mu}{dE_\mu d\Omega} \approx \frac{0,14 E_\mu^{-2,7}}{\text{cm}^2 \text{ s sr GeV}} \times \left\{ \frac{1}{1 + \frac{1,1 E_\mu \cos\theta}{115 \text{ GeV}}} + \frac{0,054}{1 + \frac{1,1 E_\mu \cos\theta}{850 \text{ GeV}}} \right\}$$

Data: muon flux emerging from the volcano

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

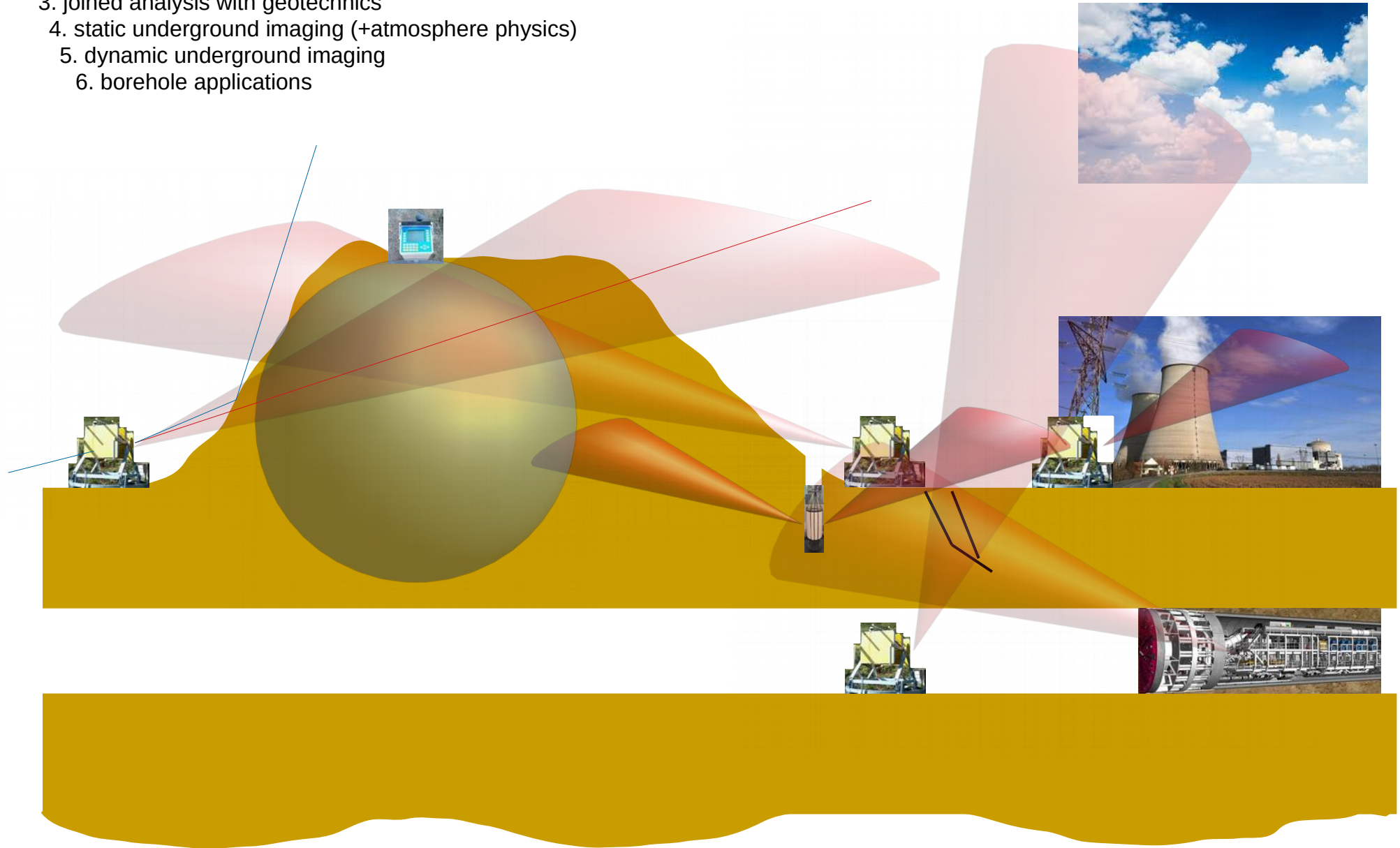


Tracking detector



Muon Tomography use cases

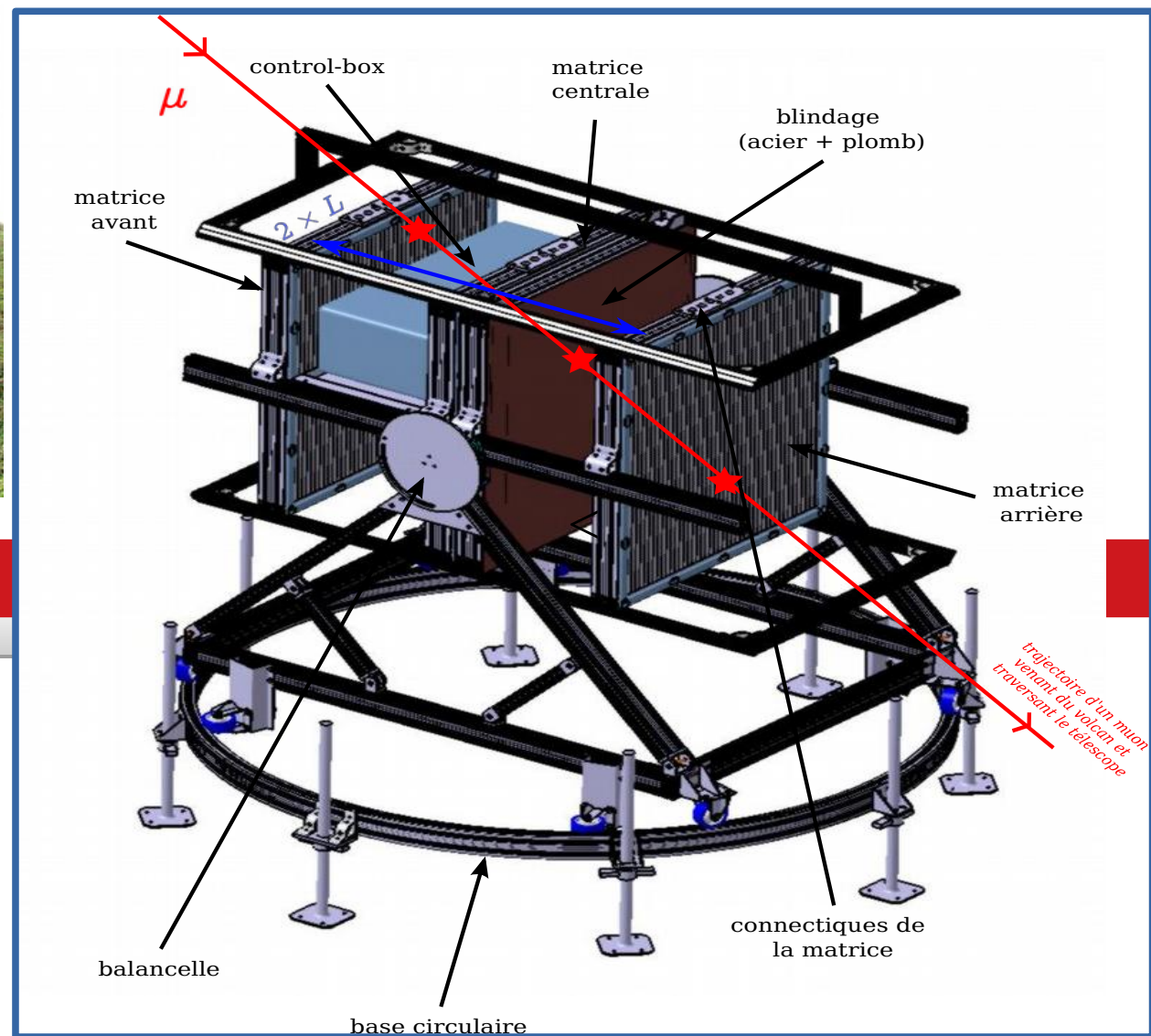
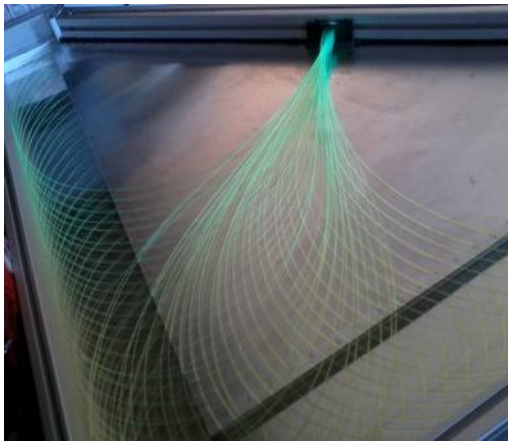
1. “radio”-like structural imaging & monitoring
2. “scanner”-like structural imaging & monitoring
3. joined analysis with geotechnics
4. static underground imaging (+atmosphere physics)
5. dynamic underground imaging
6. borehole applications





Muon detector @ Soufrière

A field detector



Detector scheme

A simple **tracking++** device using scintillators, emulsions, micro-megas, RPC's...⁵

DIAPHANE projects : 10++ years



Mayon
(Philippines)



Etna
(Italy)

- **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 ...** : from R&D to volcano monitoring (risks analysis)
 - ✓ 1 detector installed on the **Mayon** volcano (Philippines)
 - ✓ ANR **Diaphane** retained in 2014
 - ✓ 6 muon detectors installed (May '15, Aug. '16, March 17)
 - ✓ muon-gravimetry coupling,
 - ✓ 3D imaging
 - ✓ hydrothermal system continuous monitoring
 - ✓ ANR **Megamu** funded in 2020

- **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 ...** : “industrialization” process initiated
 - ✓ ORANO nuclear plant monitoring
 - ✓ ArcelorMittal funding for **blast furnace** study
 - ✓ LSBB hydro-thermal monitoring

- **2018** : TBM first round completed

- **2019** : startup launched : www.muonsight.eu

Borehole



Croix-Rousse



Soufrière

μ -gravimetry coupling



LSBB



Water tank monitoring



Tunnel Boring Machine



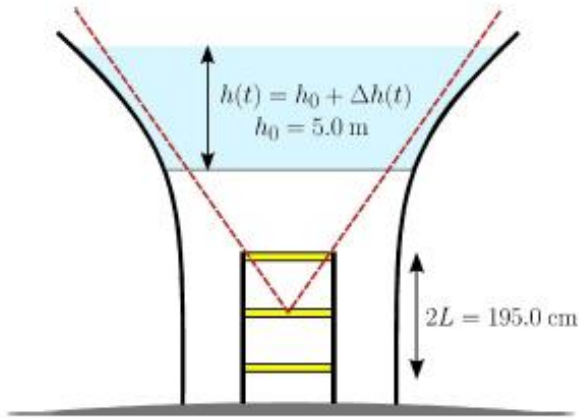
Blast furnace



Mont-Terri
(Switzerland)

Monitoring capabilities – P & T sensitivity

Water level monitoring of a water tower tank

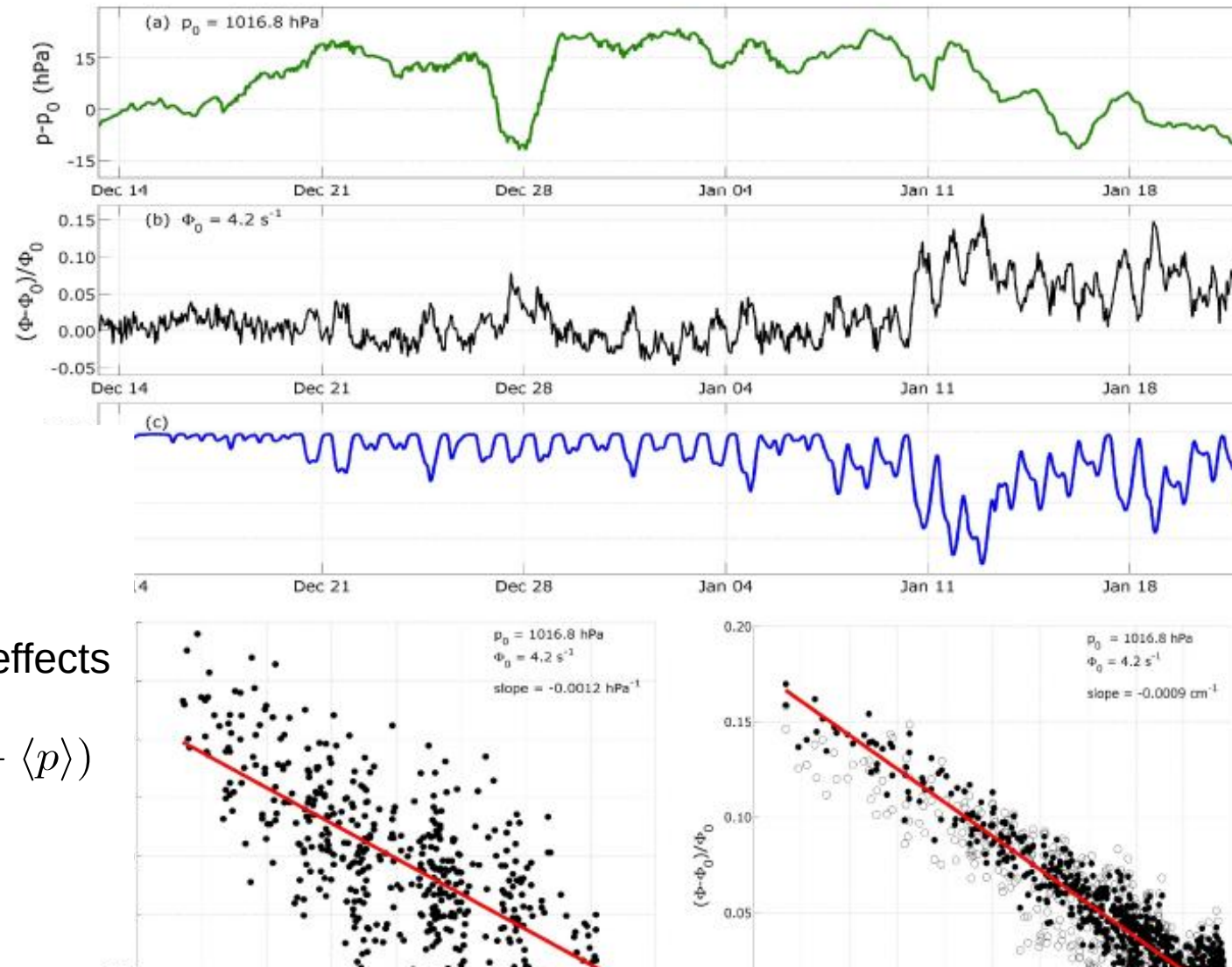


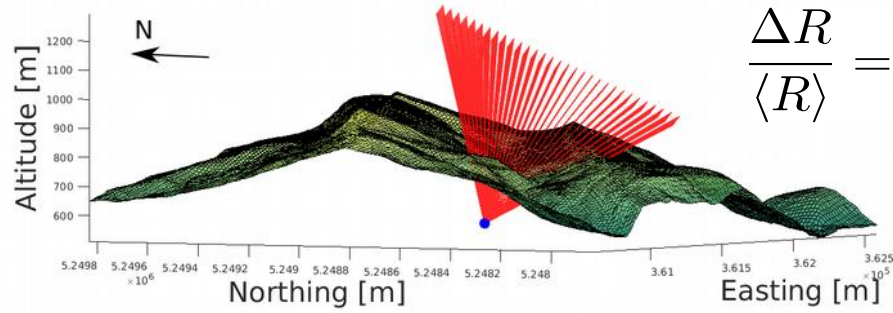
Low energy cut $\sim 1.5 \text{ GeV}$:

- ▶ high statistics
- ▶ time resolution
- ▶ E-dependent barometric effects

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

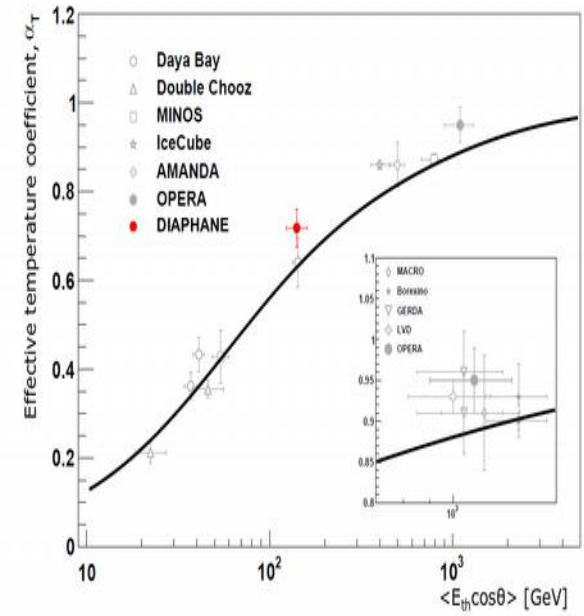
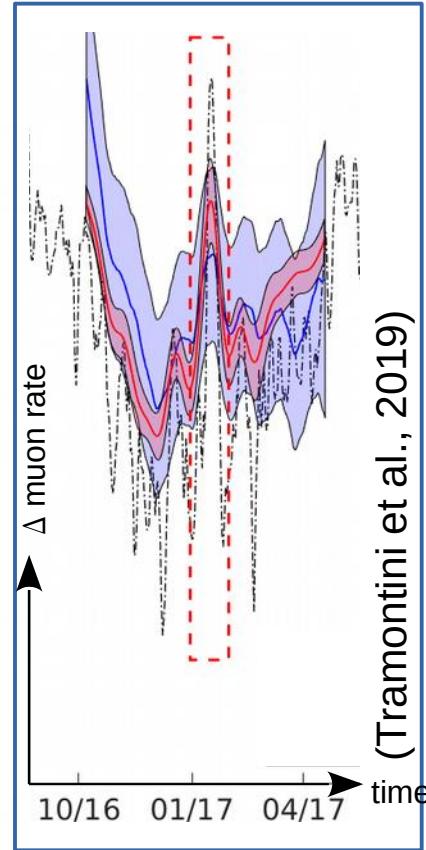
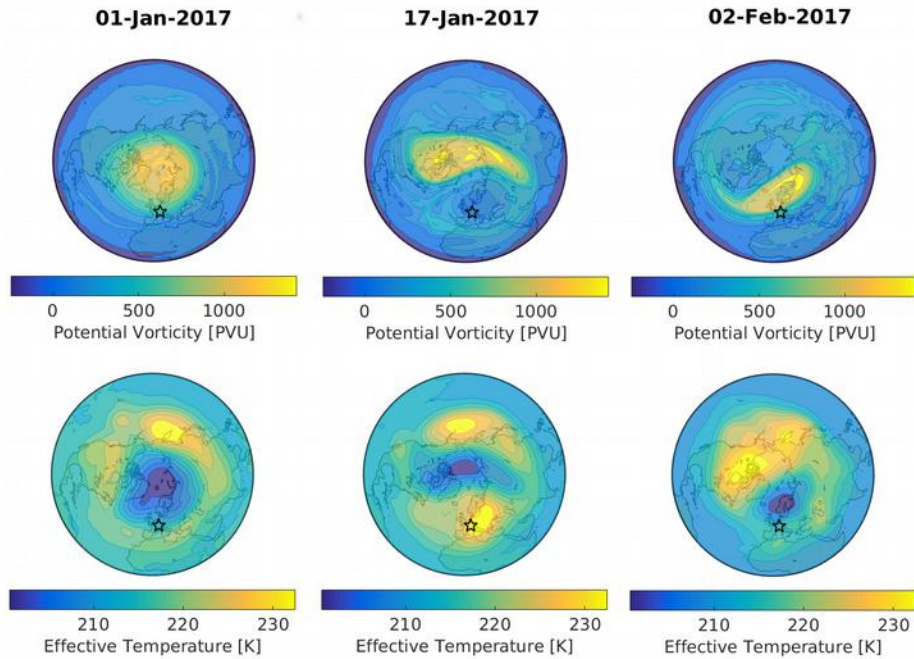
- ▶ geomagnetic effects
- ▶ solar activity effects





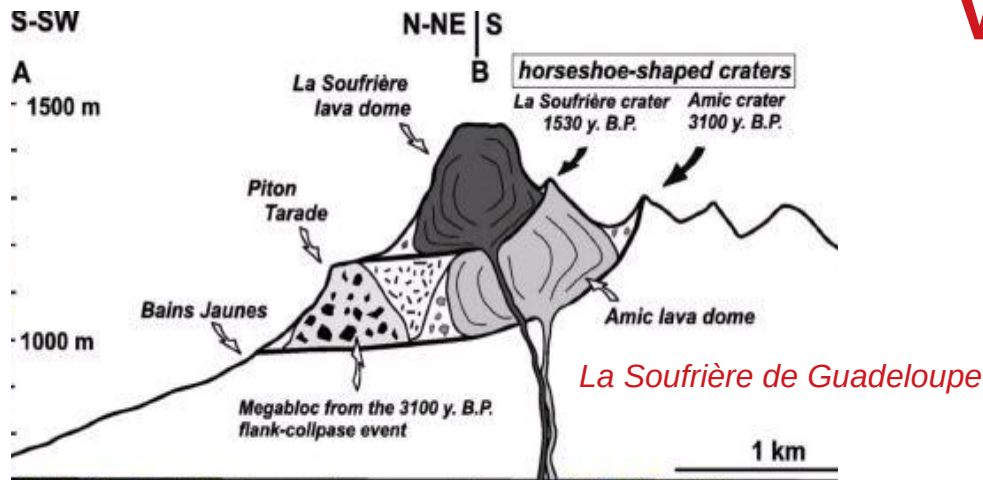
$$\frac{\Delta R}{\langle R \rangle} = \alpha_T \frac{\Delta T_{\text{eff}}}{\langle T_{\text{eff}} \rangle} + \beta_P (p - \langle p \rangle)$$

P & T sensitivity



Sudden Stratospheric Warming + hydro-geological global analysis

Volcanology : Lesser Antilles

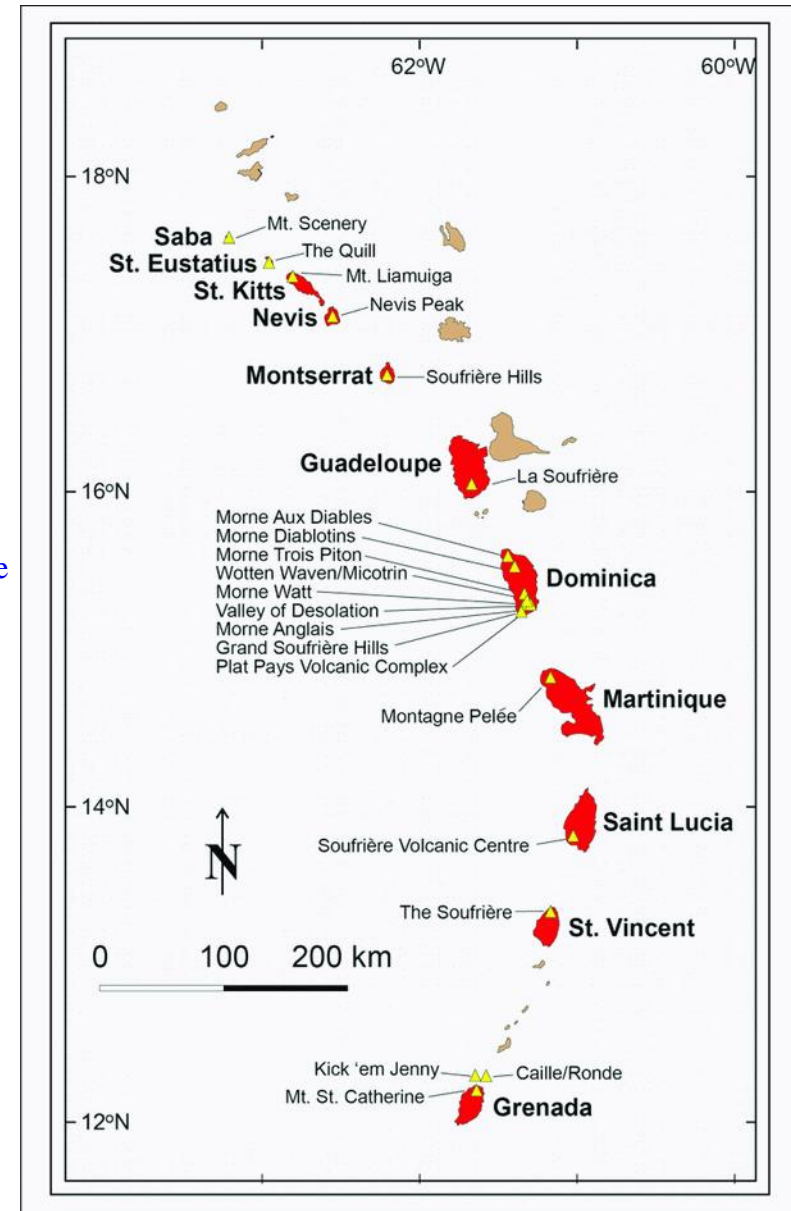
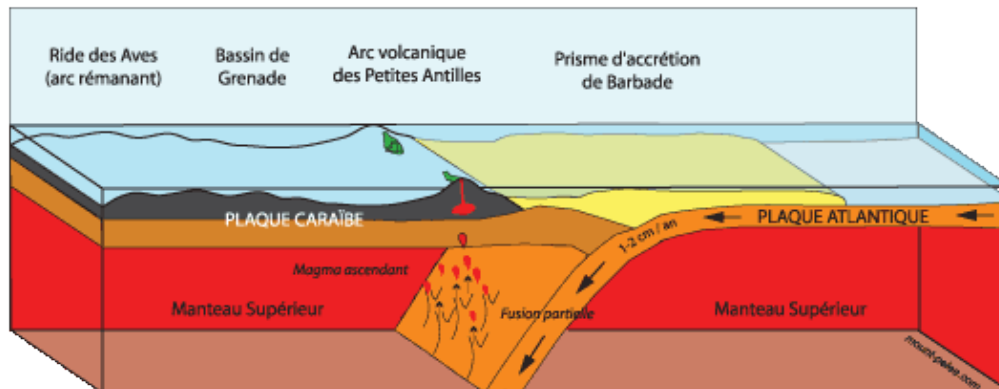


3 active volcanoes (N to S):

The Soufrière Hills, Montserrat : magmatic eruption since 1995, pyroclastic jets, risks of dome collapse, magmatic explosion etc. Activity decrease since a few months.

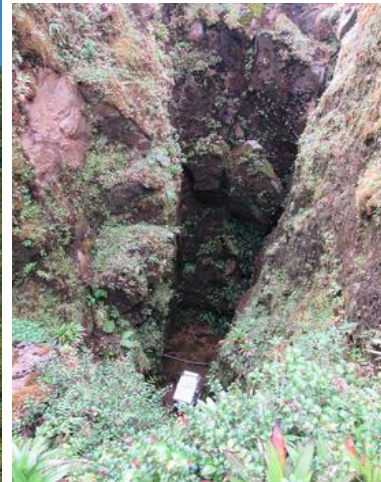
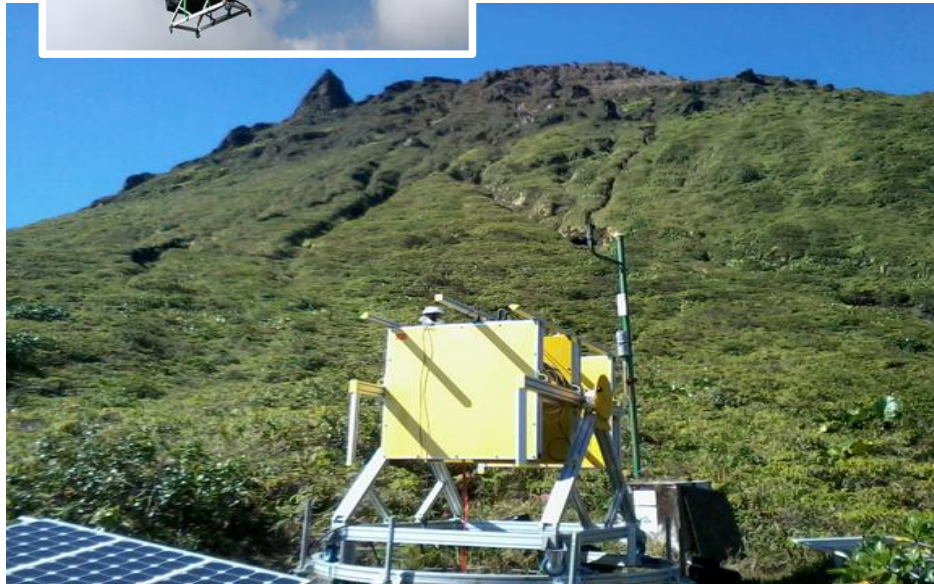
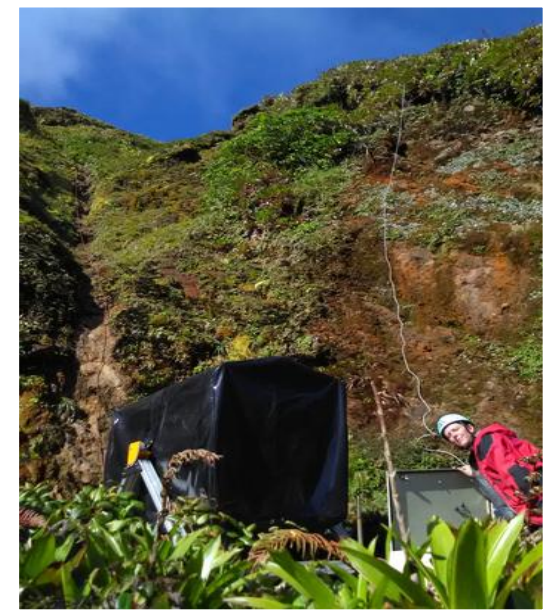
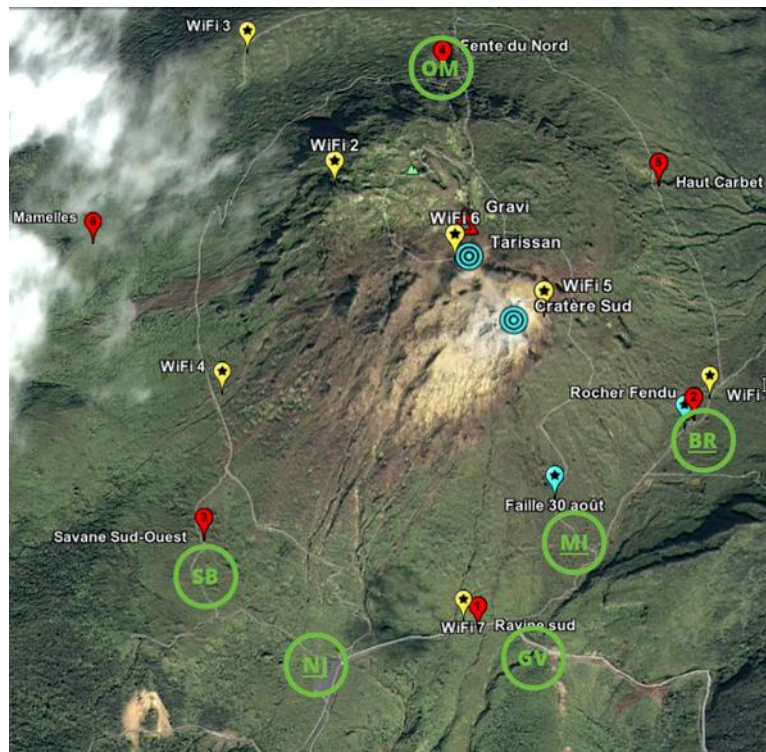
La Soufrière, Guadeloupe : active, young dome (~500y), phreatic eruption risks, flank destabilization

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

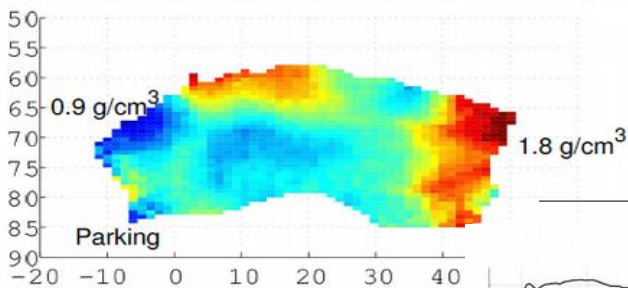
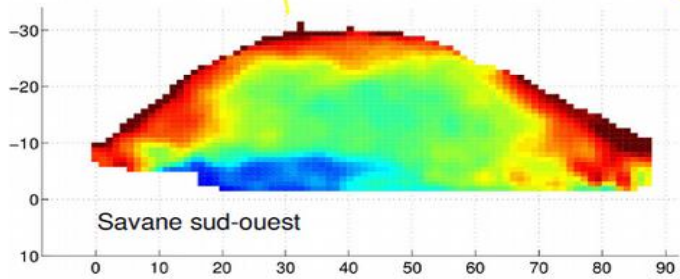
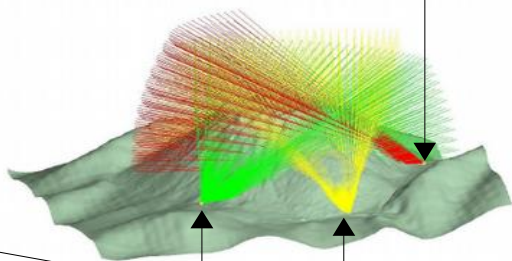
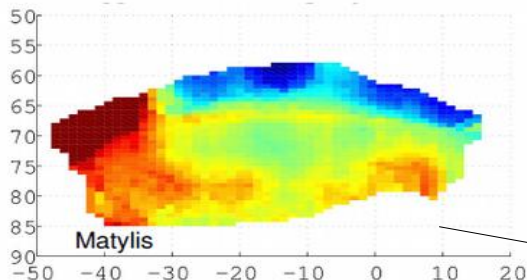
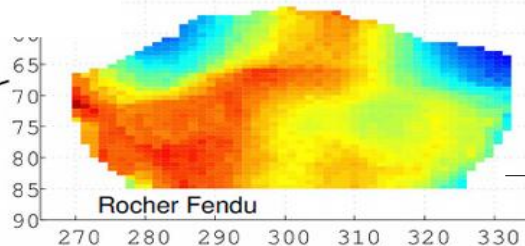


Muons @ Soufrière

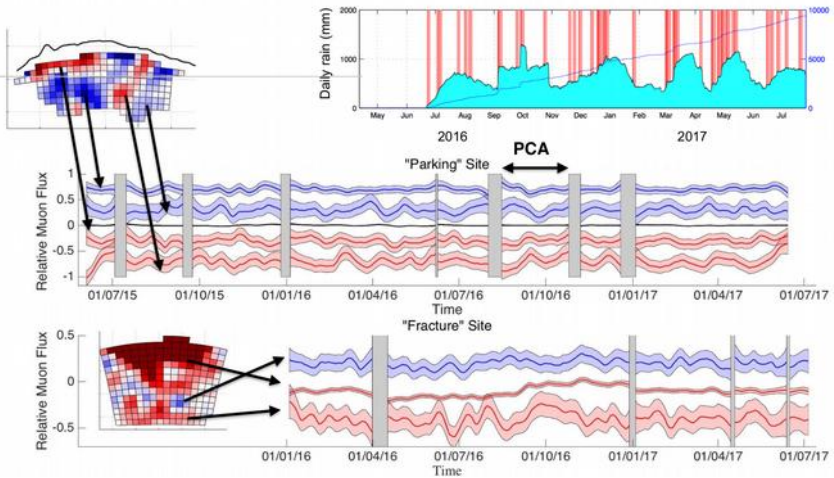
5 + 1 detectors
around the
dome



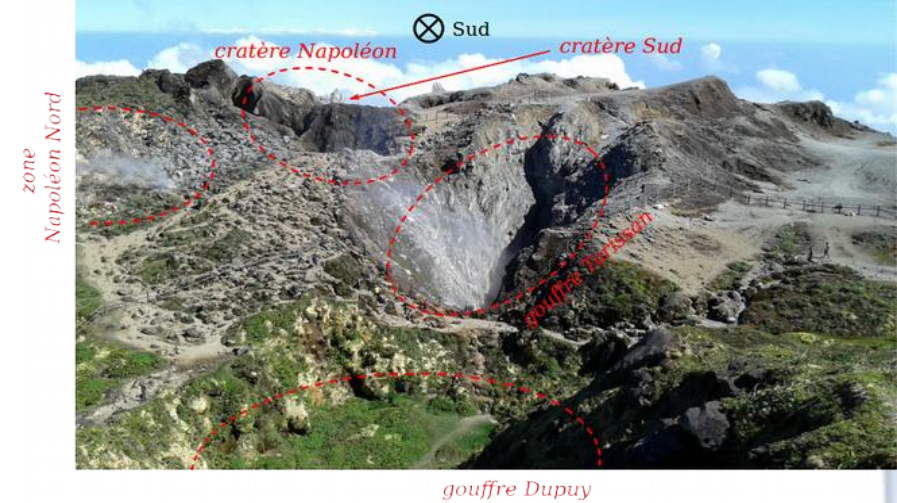
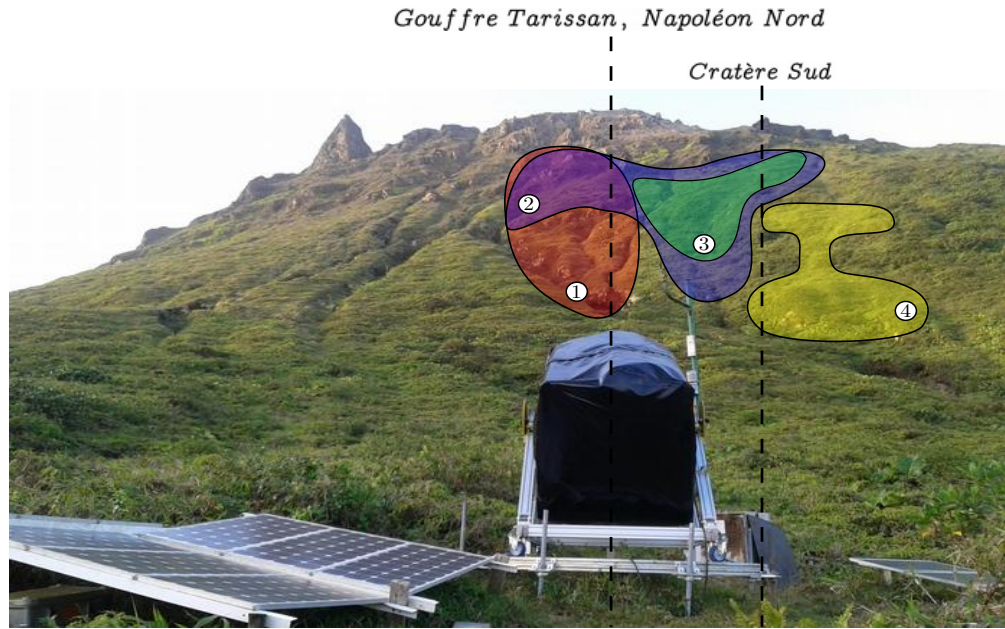
Imaging & monitoring



World's largest
muon station



Imaging & monitoring

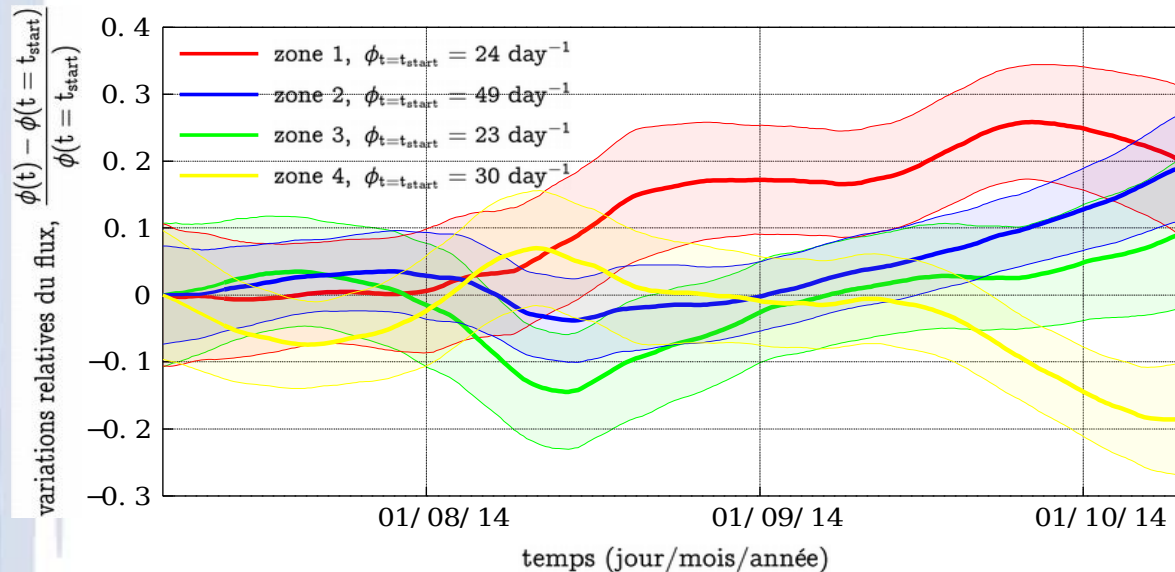


The volcano is under cautious surveillance as a **regain of activity** has been noticed in the fumes (Allard et al. 2014) and in the sources (Villemant et al. 2014).

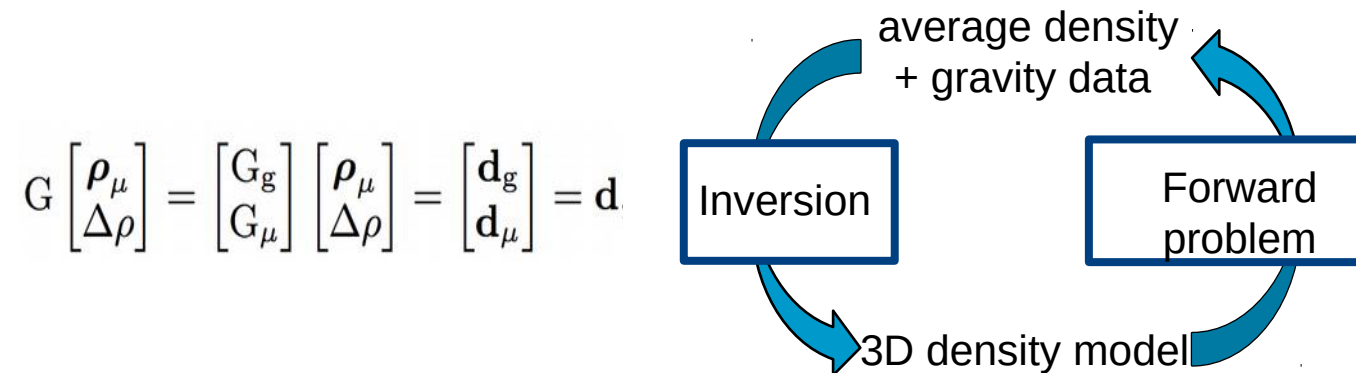
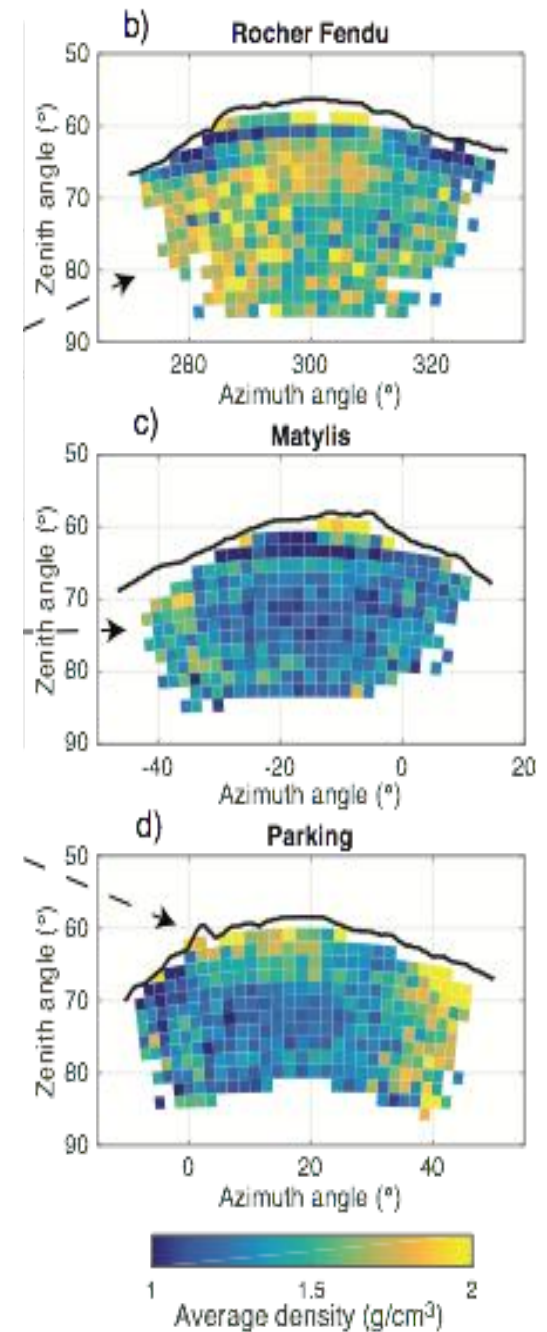
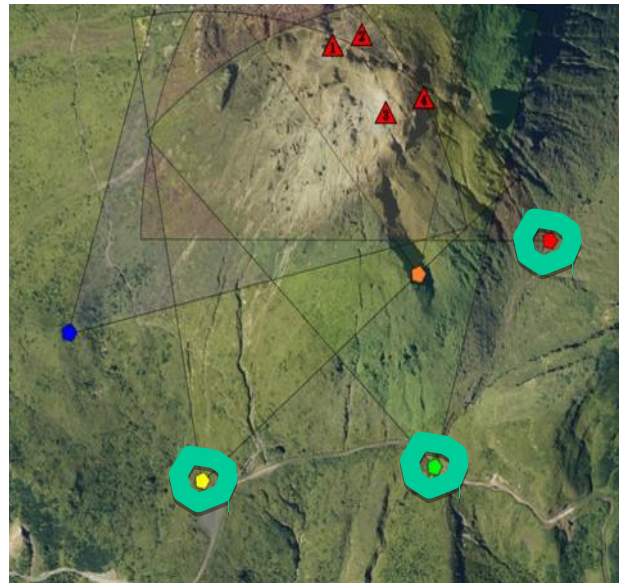
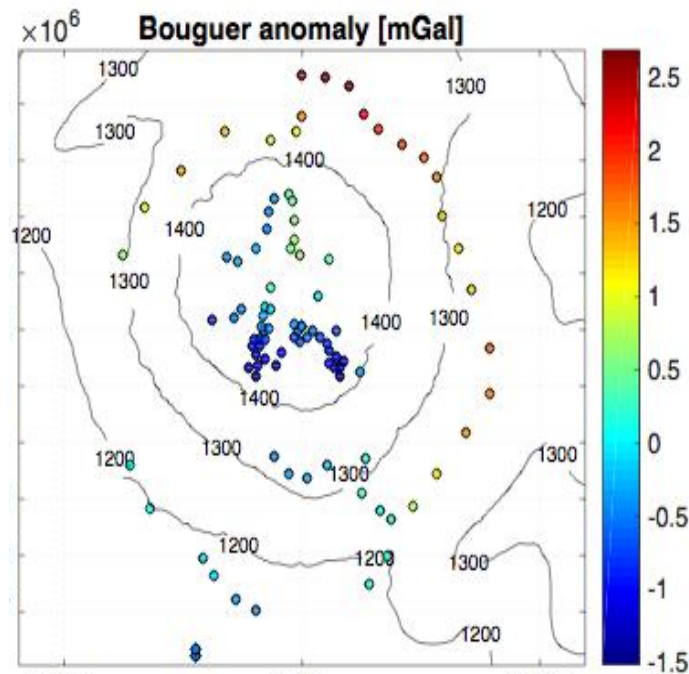
Principal component analysis allows to isolate regions in the volcano with similar time behaviors.

The various active zones are clearly correlated with the observations on the surface. They are correlated in time with the appearance of the new vent at the summit.

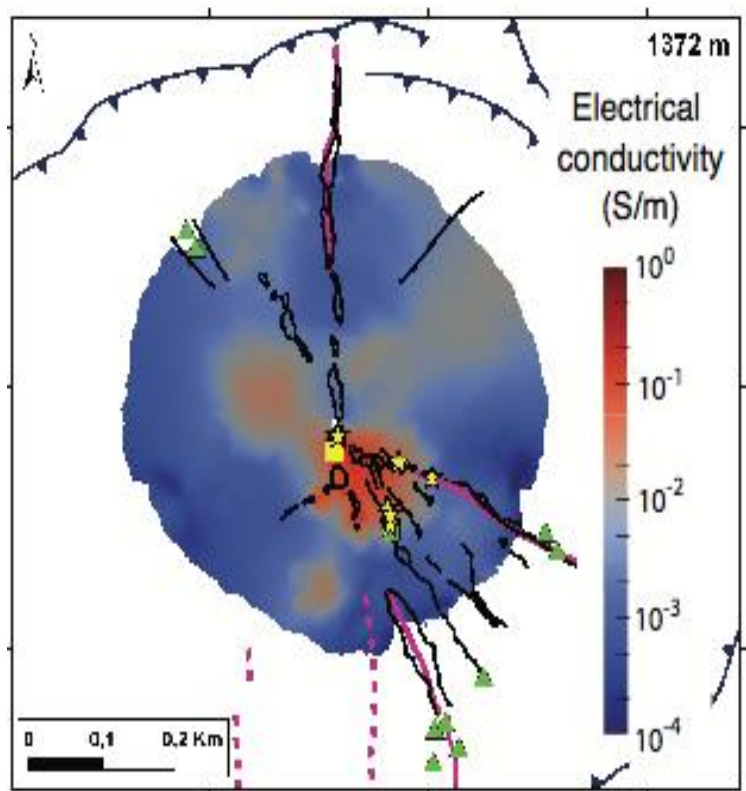
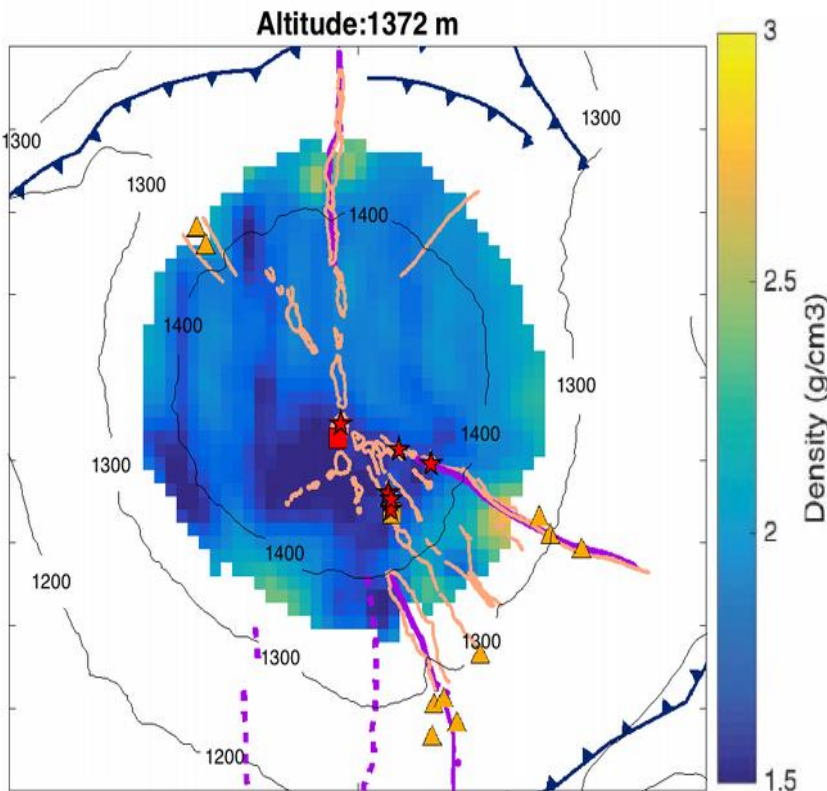
The observed fluctuations in zone 1 correspond to vaporization of 40 mwe in only 3 months.



3-D joined inversion of muon & gravity data



Horizontal slices of density and electrical conductivity models

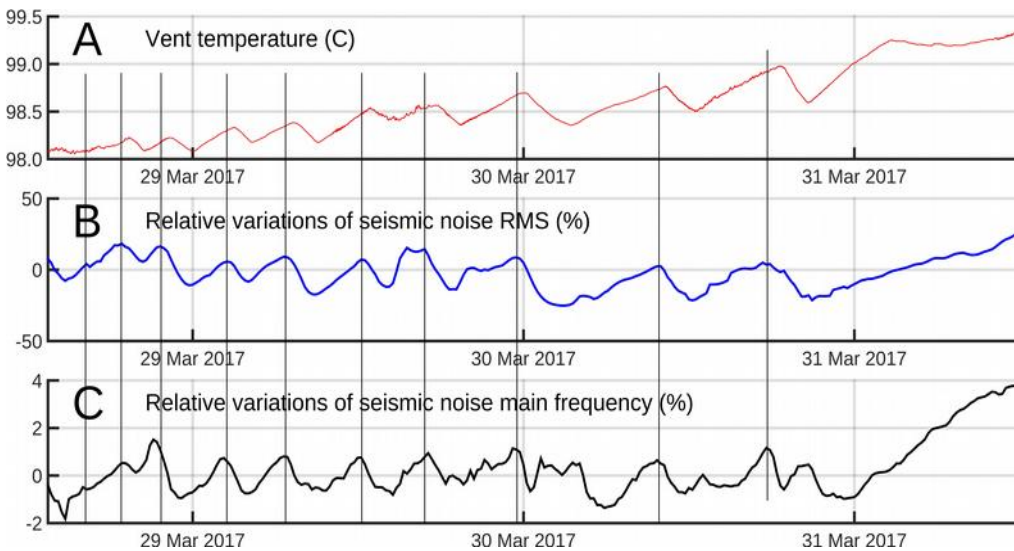


(Rosas-Carbajal et al., 2016, 2017)

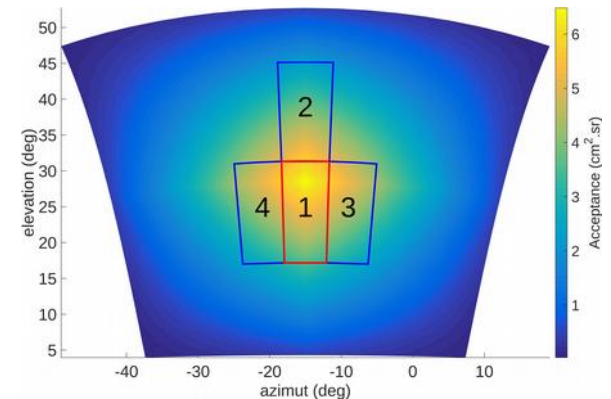
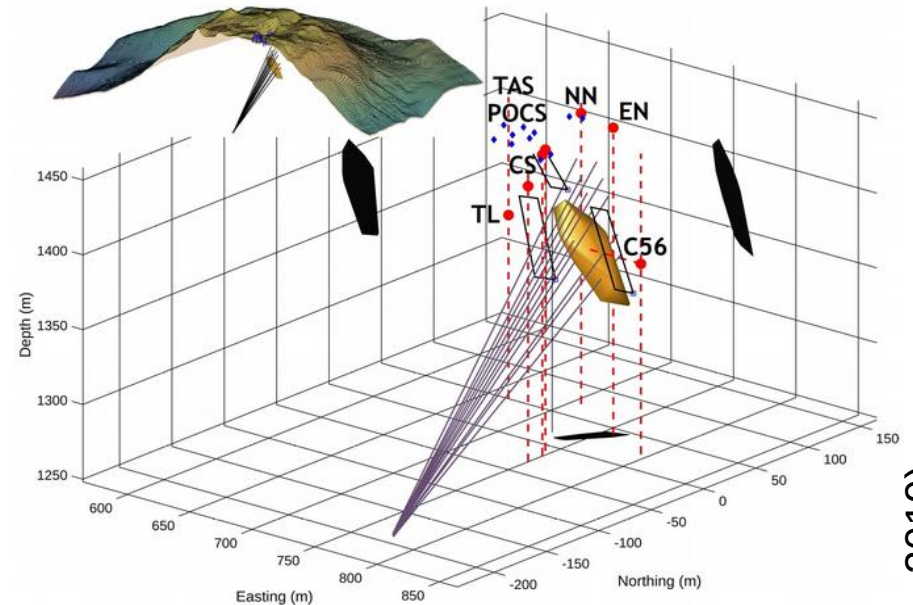
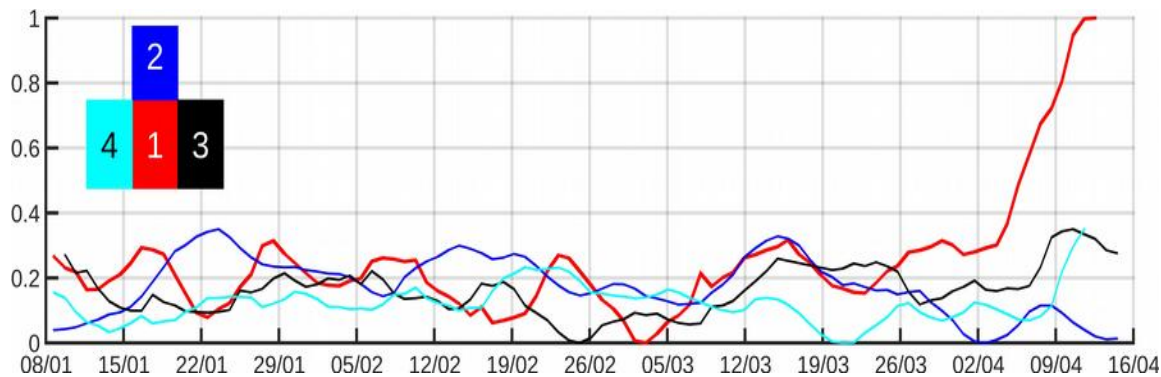
Joined monitoring :

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

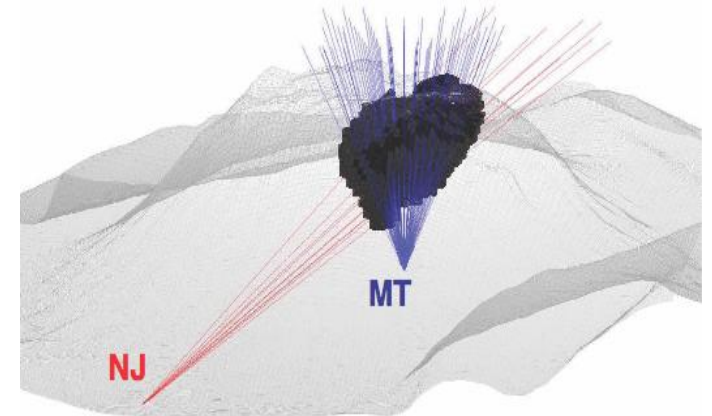
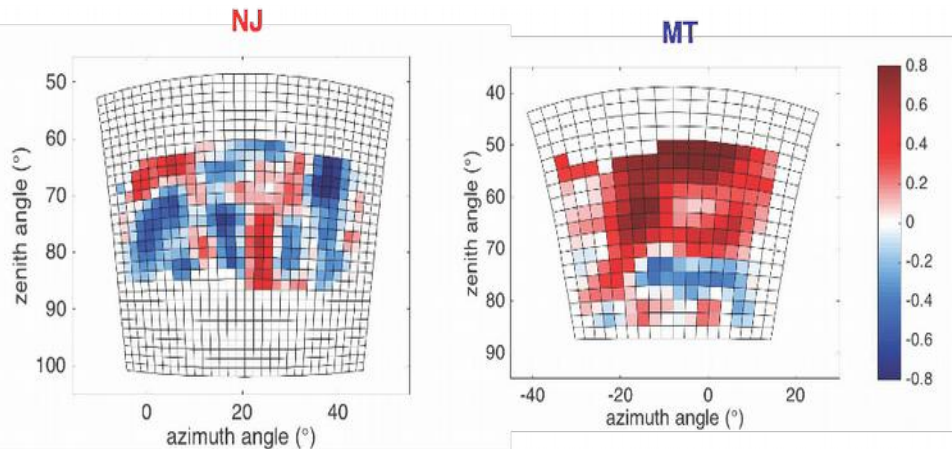
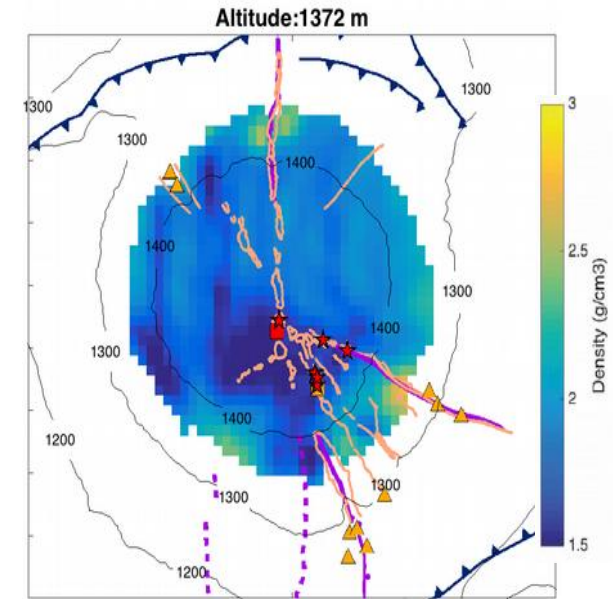
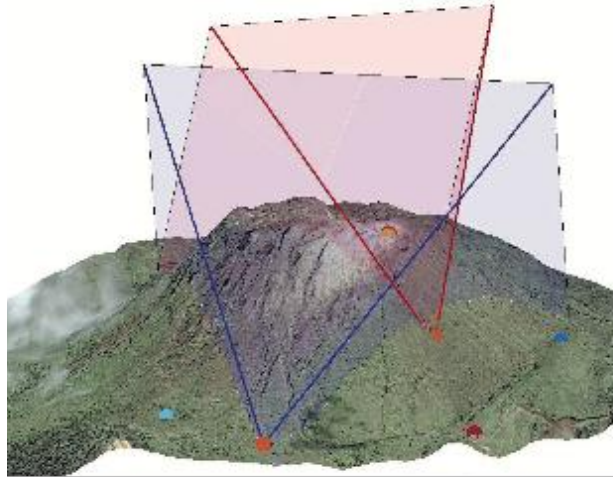


Relative muon flux variations



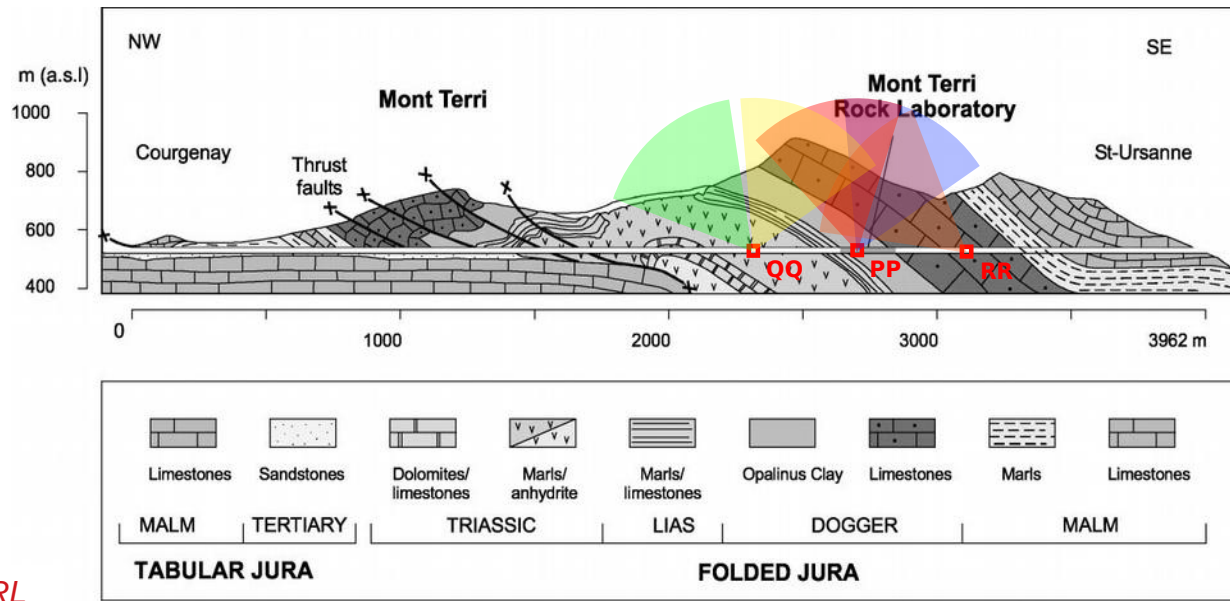
Long-term density variations from continuous muon measurements

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










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

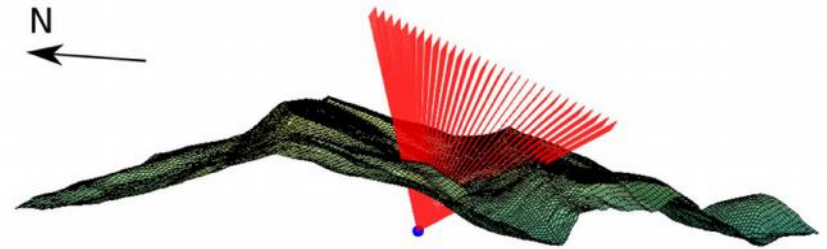
DIAPHANE @ Mont-Terri



*Muon – gravimetry
joined analysis*



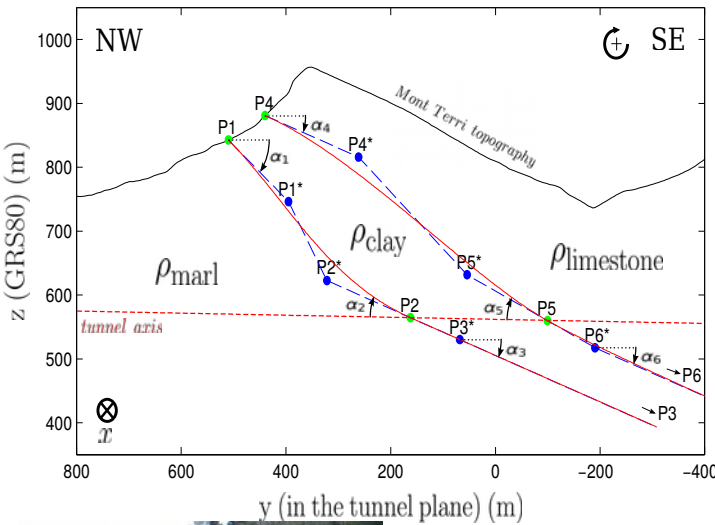
b)



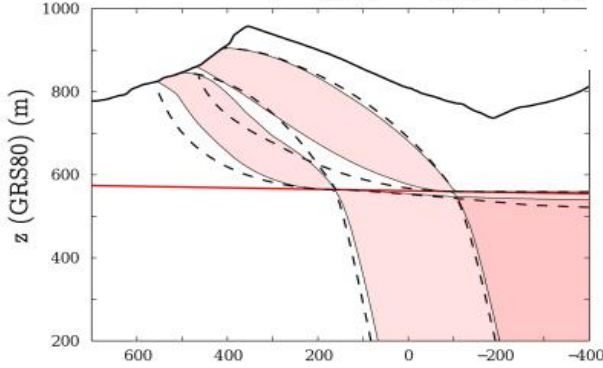
2016-2018 niche IS measurements

Geological layers studies

Opalinus layer parametrization

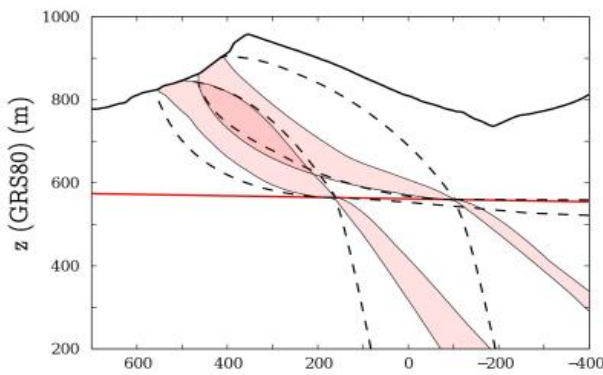
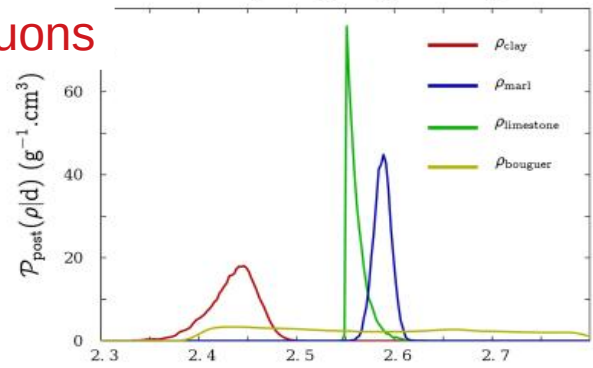


all solutions for $\mathcal{P}_{\text{post}}(\mathbf{p}|\mathbf{d})/\max_{\mathbf{p}}(\mathcal{P}_{\text{post}}(\mathbf{p}|\mathbf{d})) > 0.6$

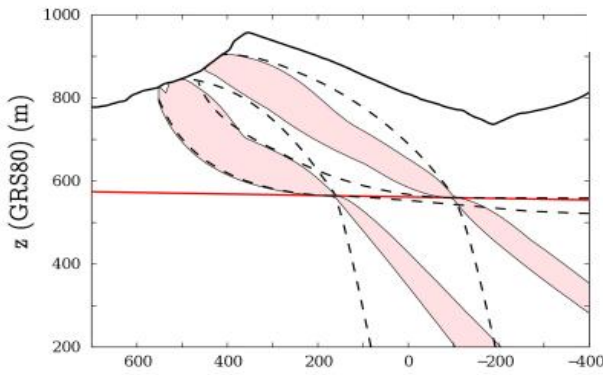
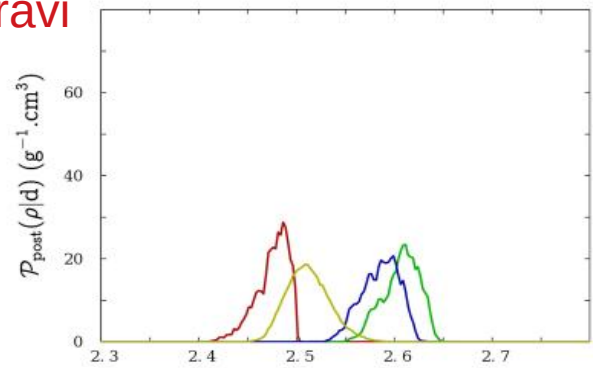


muons

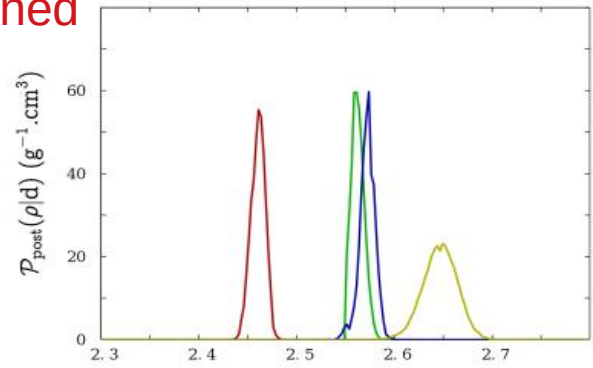
density marginal probability



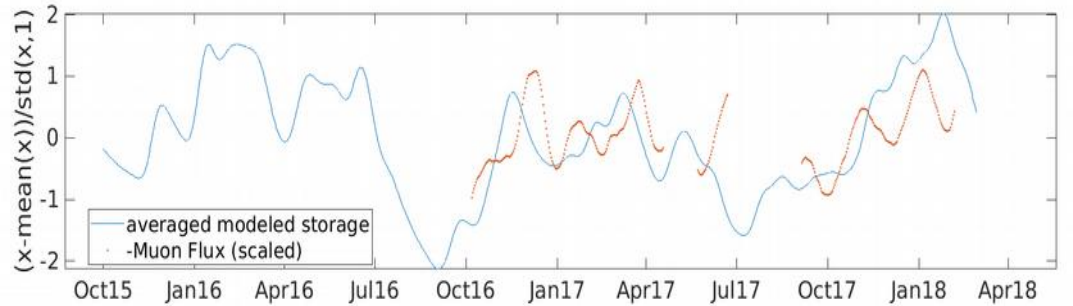
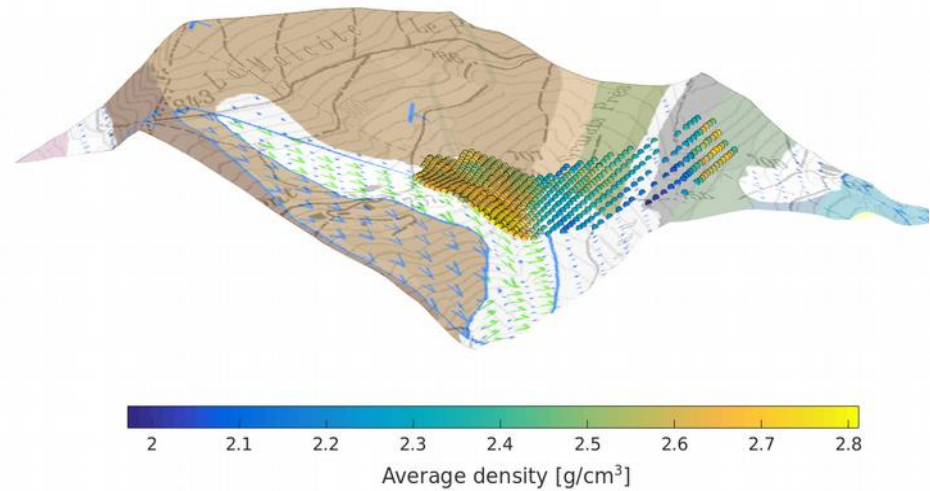
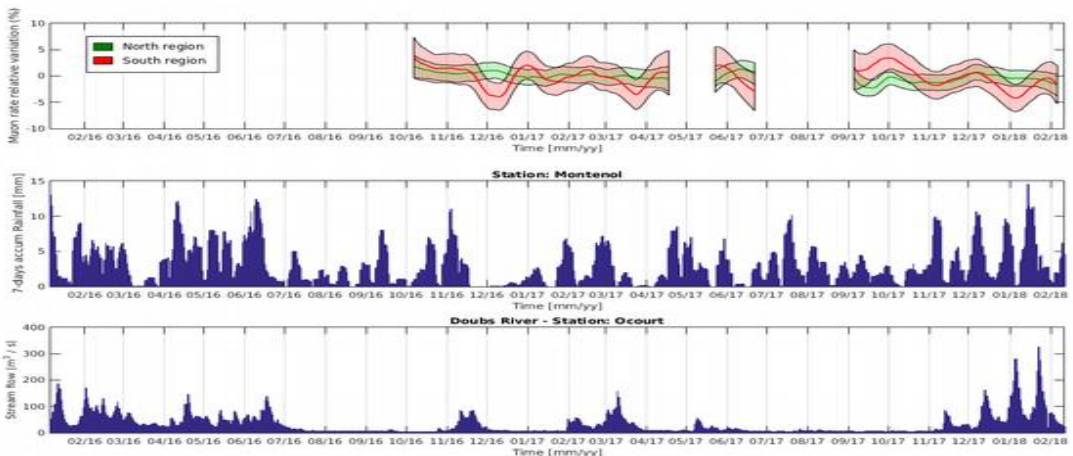
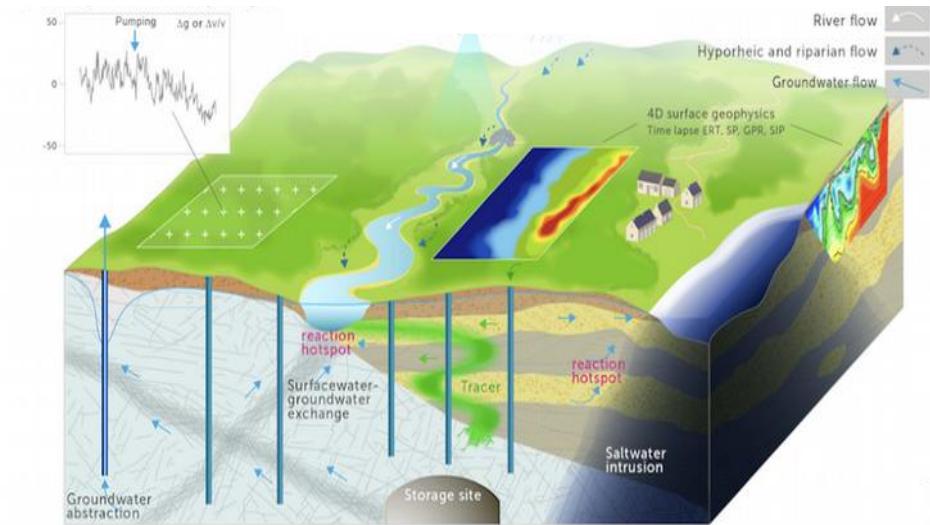
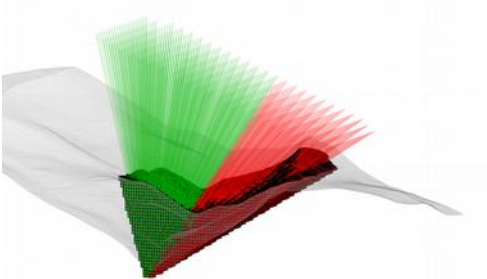
gravi



joined



Near surface geophysics





Blast furnace

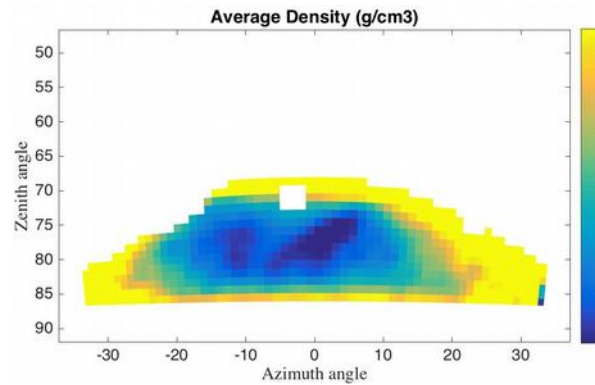


TBM

Geotechnics & archaeology

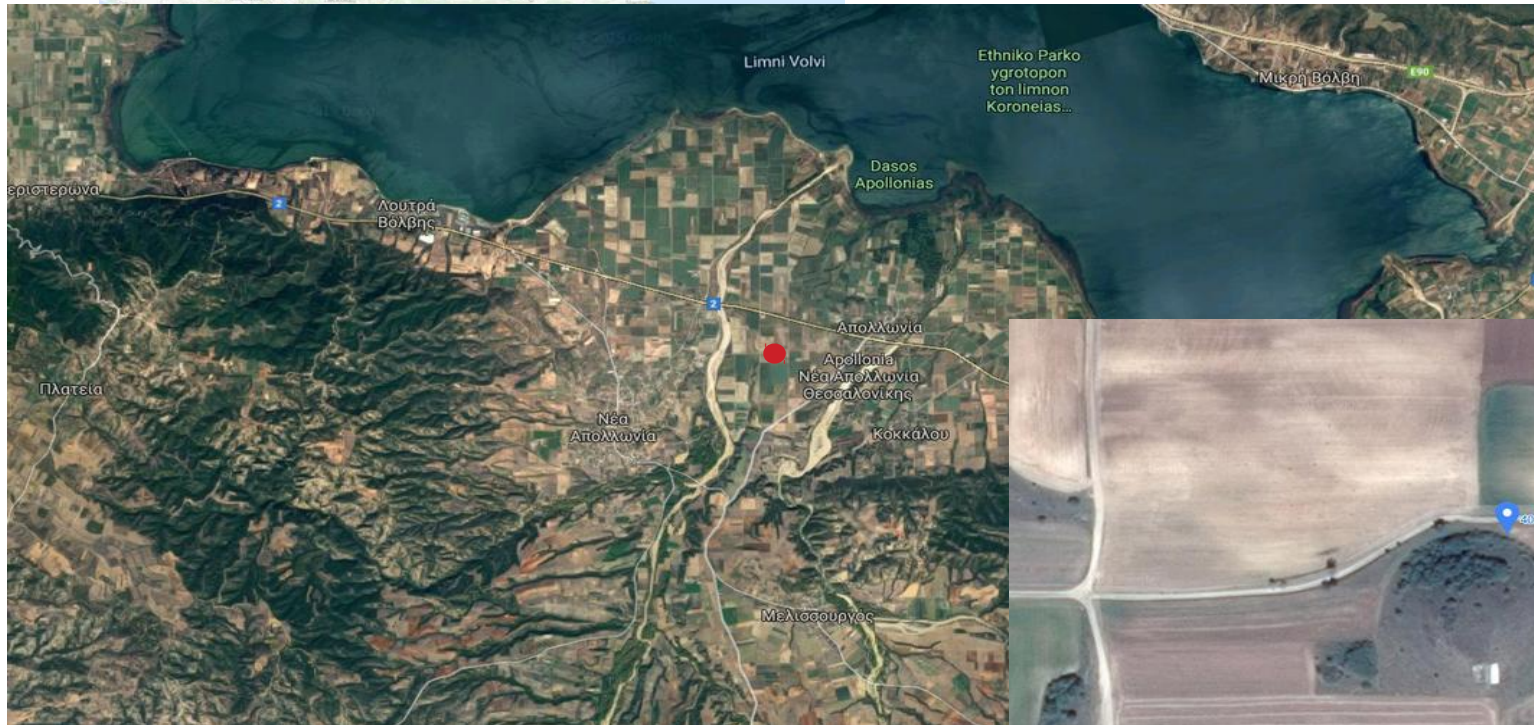


Greek tumulus



Nuclear evaporator

Archaeology : Apollonia tumulus (IP2I, APC, LAPP, labex UnivEarth, AUTH)

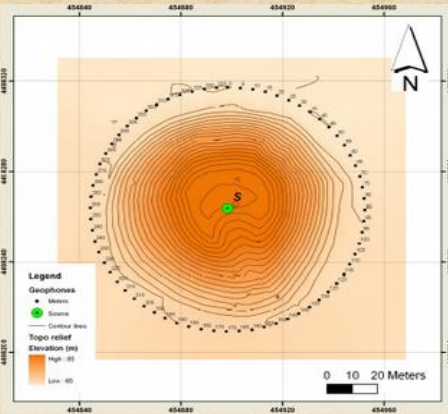


Tumulus & muon-mobile



A massive “Macedonian-type” tumulus

Tumulus in Apollonia North Greece
Diameter 100 m; Height 24 m. The biggest in Greece?



CHALLENGES OF THE GEOPHYSICAL SURVEYS ON TUMULI

The material of the tumulus might be highly inhomogeneous (a fact that renders difficult the data interpretation). In some cases, stratification of the tumulus infill material has been observed.

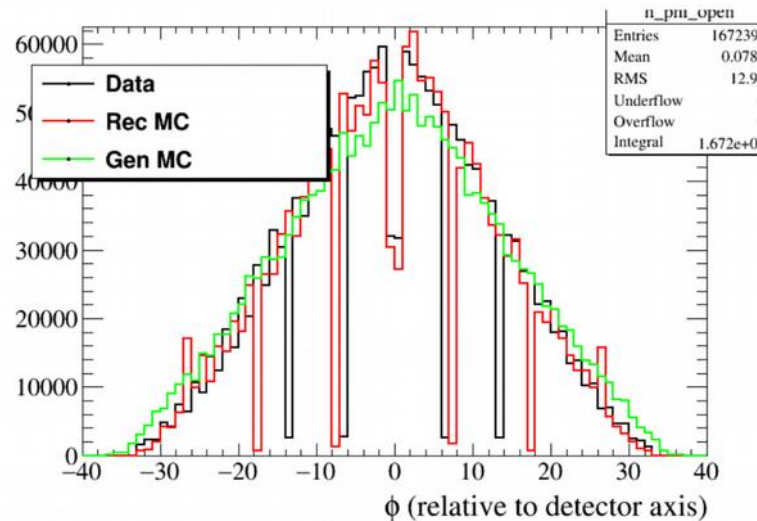
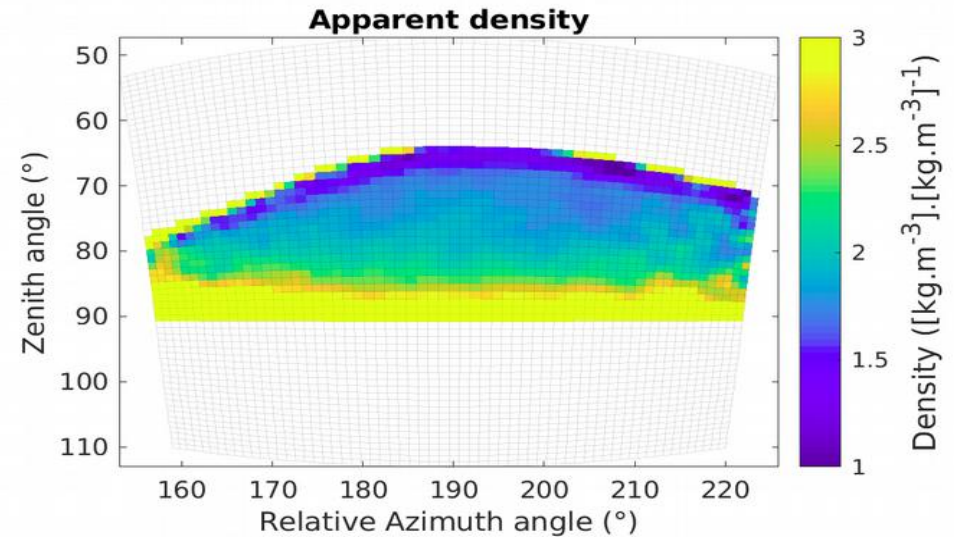
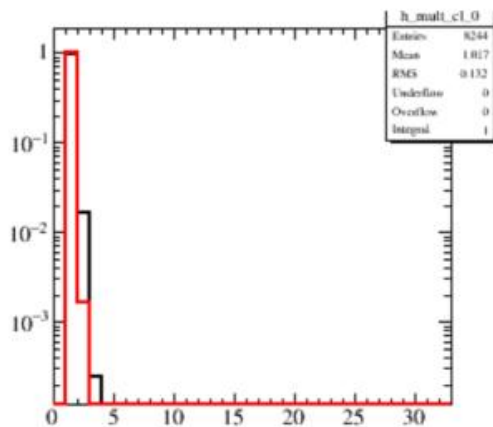
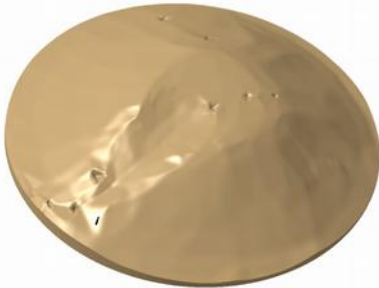


G. Tsokas et al. (2015)

- What kind of information can the Muon tomography provide to non-destructive tumulus survey ?

Analysis and simulation

- Data / MC comparison (LAPP + T.Avgitas)
 - Electrons
 - Acceptance effects
 - Role of the CR generators
 - fwd/bkw tracks comparisons etc



Muography = a perfect field for collaborative interdisciplinary projects :

HEP / AGU / EGU conferences
 AEIA interest
 “Muographers” network
 European Muon Network (ITN)
 ANR funds
 MITI projects
 ...

Geosciences



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

Archaeology



- Tumulus
- Anthropic structures
- Ruins
- ...

Industrial controls



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