Active volcanoes muon tomography

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Soufrière, Guadeloupe

Collaboration DIAPHANE (ANR, 2014-2018):

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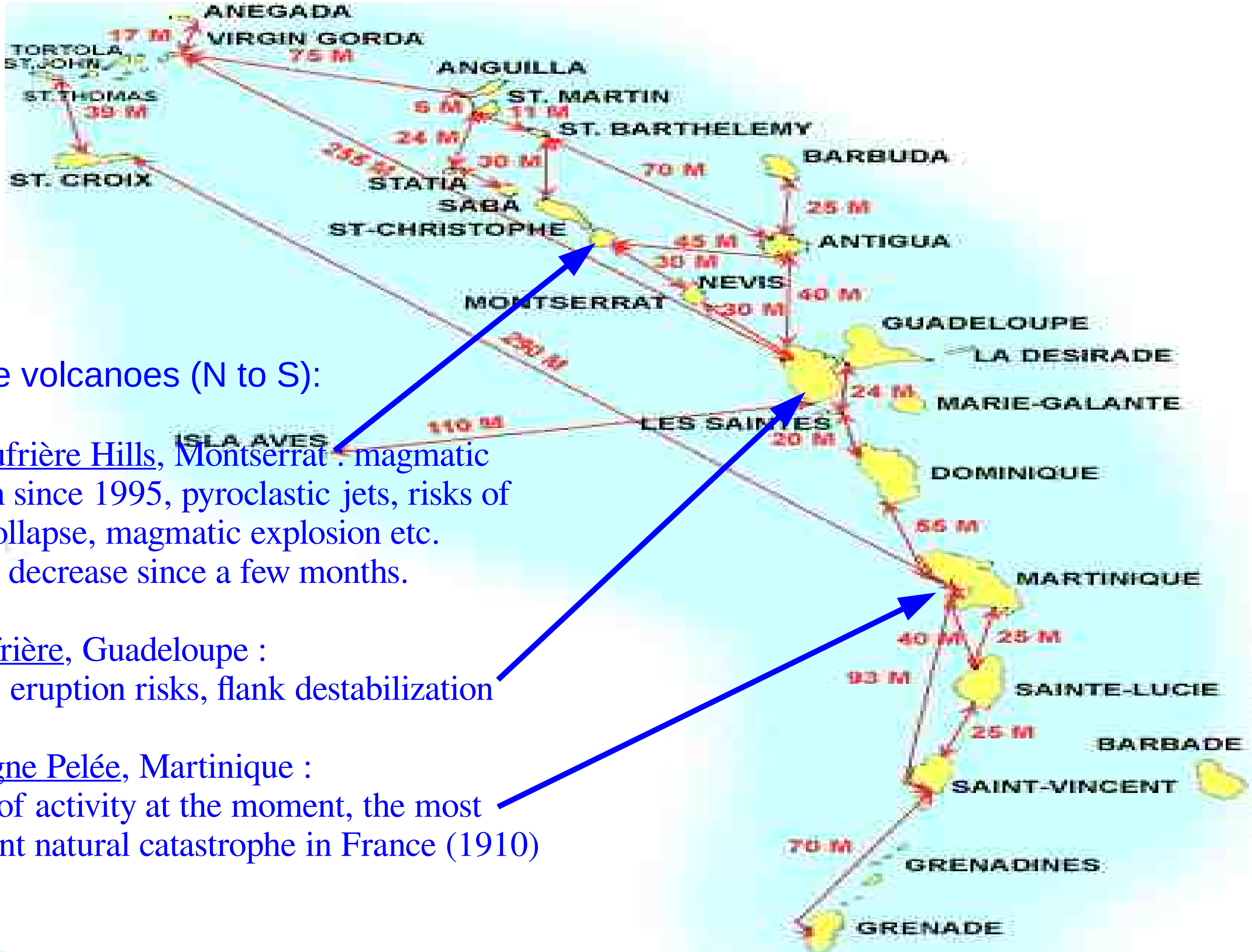
Géosciences Rennes: Dominique Gibert (co-PI), Jean de Bremond d'Ars, Bruno Kergosien, Yves Legonidec, Florence Nicollin, Pascal Rolland
IPG Paris: Sébastien Deroussi, Céline Dessert, Michel Diament, Jean-Christophe Komorowski, Jean-Jacques Sibilla, Olivier Sirol
Labex UnivEarthS (IPGP-APC)
Observatoires: OVSG (Guadeloupe), EOS (Singapour), Phivolcs (Philippines), Laboratoire du Mont-Terri (Swisstopo), Laboratoire de Tournemire (IRSN)
Other collaborators : Daniele Carbone (INVG Catane), Fabrice & Christel Dufour, Aurélie Talard-Breton, Quentin Gibert, Benoît Taisne (EOS Singapour), Nolwenn Lesparre (IRSN)

Photo: Xavier Béguin

ISAPP, GSSI, July 19th 2016

Extended monitoring: the 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 :
phreatic eruption risks, flank destabilization

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

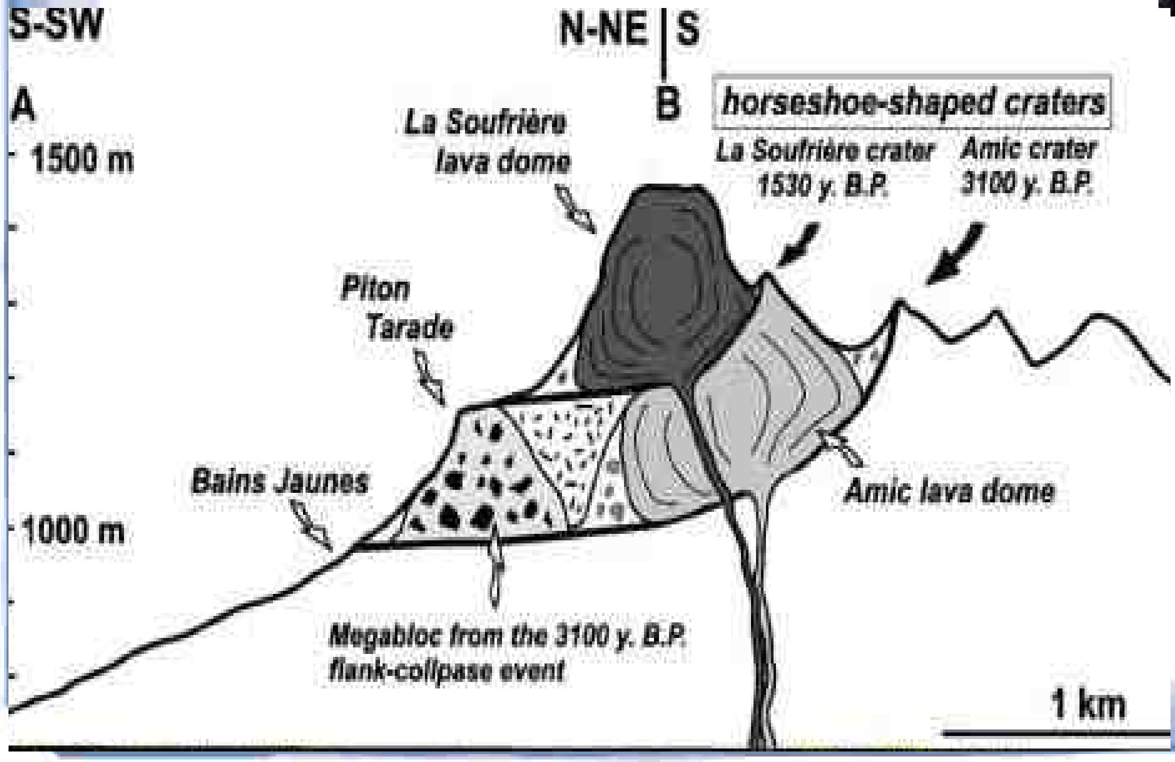
The Soufrière of Guadeloupe

The Soufrière of Guadeloupe is an **active volcano** which last important manifestation was a **phreatic eruption in 1976-1977**.

The present dome is young (~500 y.). Its dimensions are typically ~500m (height, radius).

A new phreatic eruption or a flank collapse are the most likely hazards for la Soufrière today.

Active vent during 1976 eruption



... the same in 2010

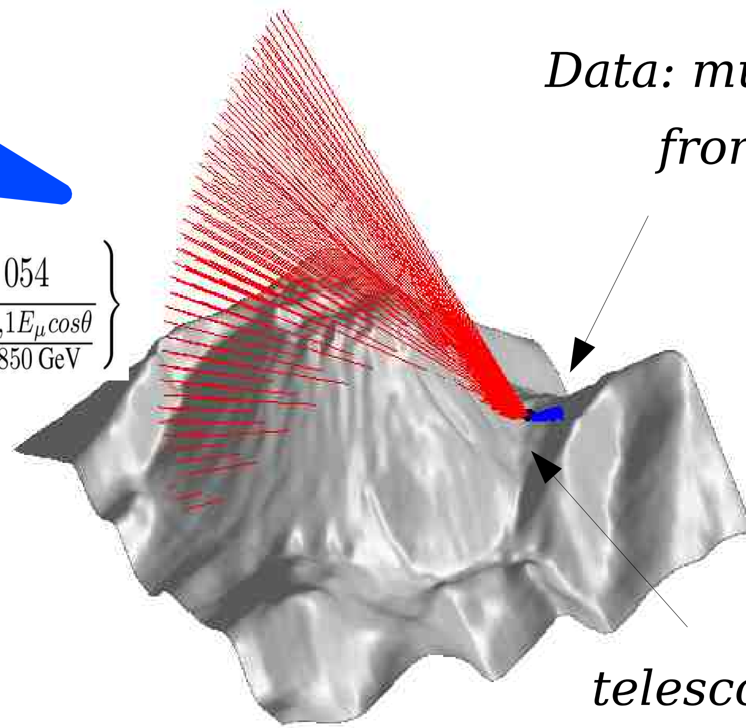
The volcano is under cautious surveillance as a **regain of activity** has been noticed in the fumes (Allard et al. 2014) and in the sources (Villemant et al. 2014).

Measurement of the muon flux emerging from the volcano to determine its opacity (amount of matter):

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

ϱ = opacity
ρ = density

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



Alvarez, L.W. et al., 1970

Nagamine, K. et al., 1995

Röntgen, 22 déc. 1895.

Diaphane 2008-2014

- 2007: BQR D.Gibert (Université Paris / IPGP) to start a technical evaluation

- 2008 : ANR Domoscan (INSU) including a small muon tomography part
- 2008 : collaboration started between IPNL-IPGP-GR (IN2P3/INSU) on technical aspects (Opera opto-electronics chain recycled)

- 2009: first installation in Mont-Terri (funding: Swisstopo) for methodological developments in a known geology

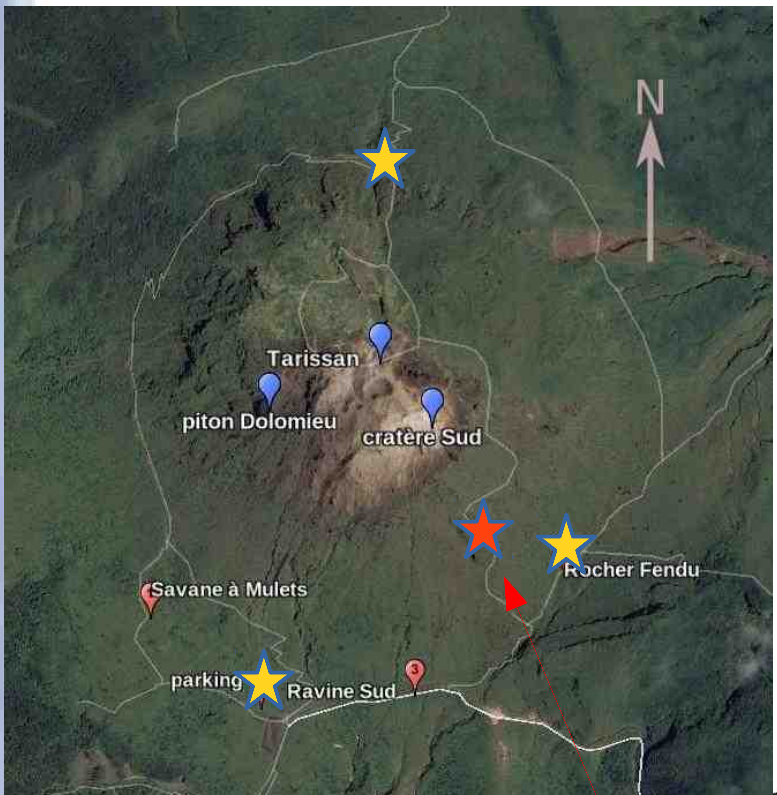
- 2010 (and 2012): exploration of Etna South crater (funding: INSU & IN2P3 AAP : P & U, Instrumentation aux limites)

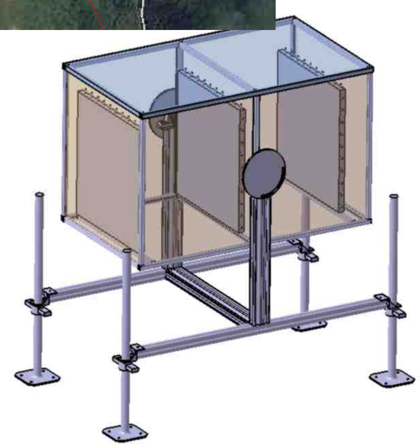
- 2010: first installation of a detector on the Soufrière de Guadeloupe (Ravine Sud site)
- 2011-2014: upgrades of the local telescope on the Soufrière and other sites explored (Roche Fendue, Savane à Mulets)

- 2013: collaboration started with IRSN for methodological developments in Tournemire (funding: IRSN)

- 2014: installation of a detector on the Mayon volcano (funding: E.O.Singapore, PHIVOLCS)

Diaphane 2014-2018





- ANR Diaphane retained in 2014
- Solved: technical choices (opto-electronics, computing, power supply, network) and adaptation to harsh field conditions (transport, dust, rains, acids, hurricanes, large T variations etc)
- From the R&D phase to the active volcano monitoring (integration as a standard geophysical instrument)
- Just done: installation of 4 telescopes around Soufrière (April 2015)
- One reduced telescope in a fault to monitor the activity of the South crater
- Muons-gravimetry coupling to improve the overall resolution

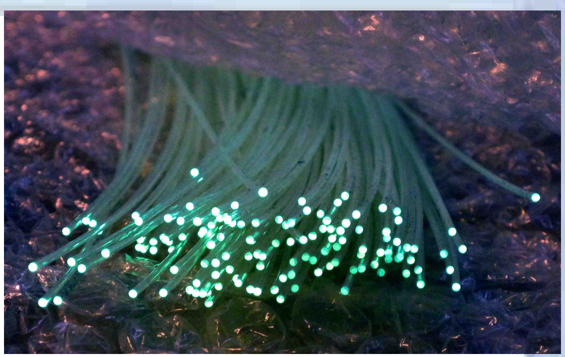
A field instrument

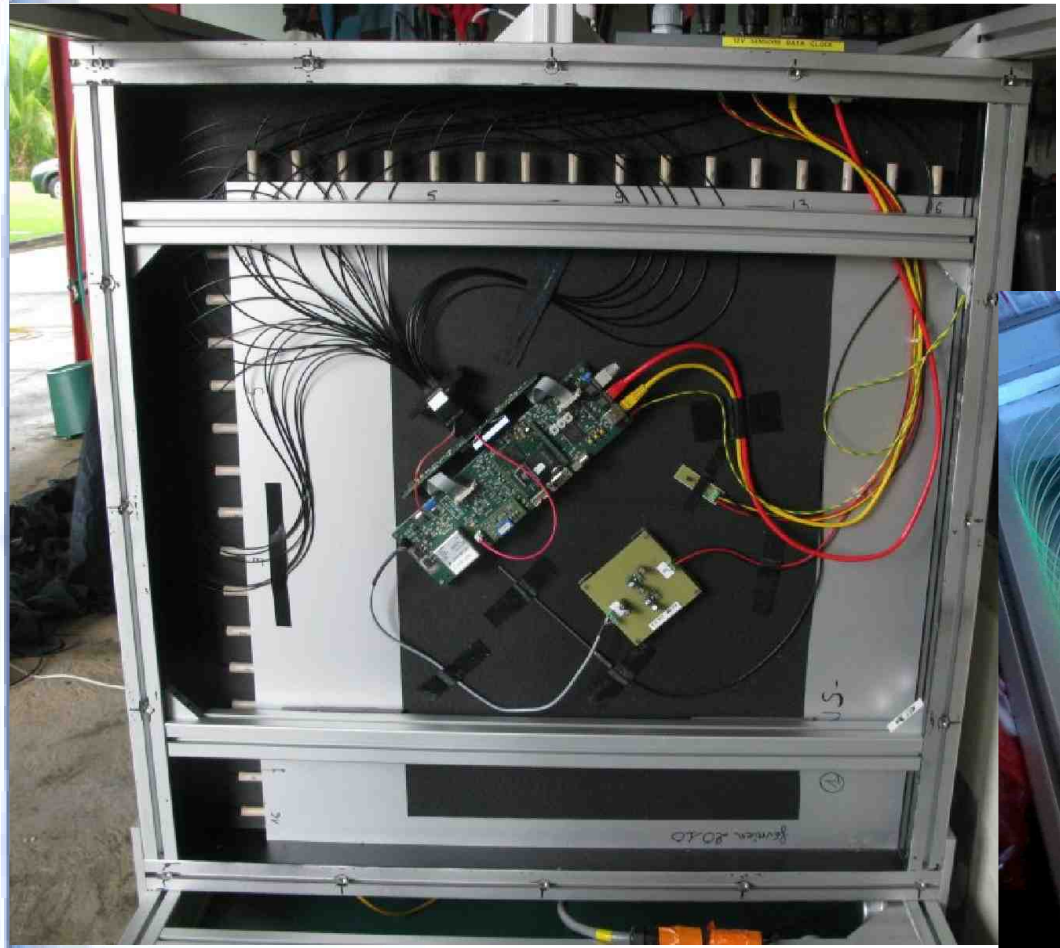
Methodology of data taking

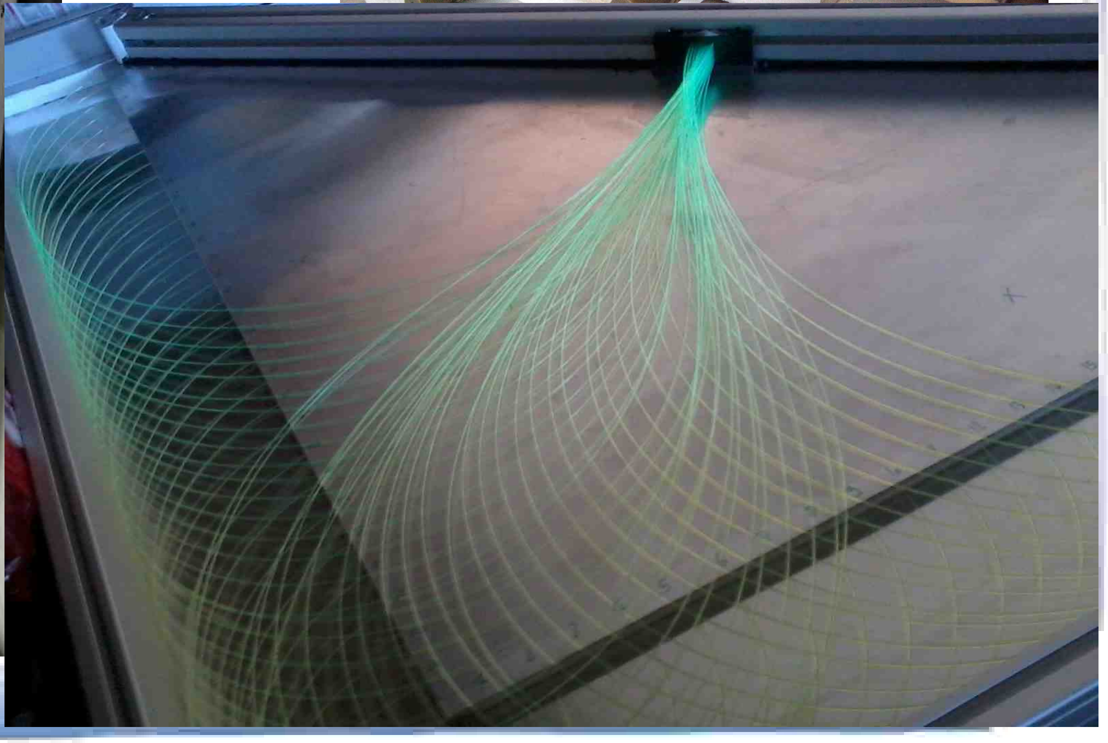
Photographie Dominique Gibert

Detection planes

- 256 = 16 x 16 or 1024 = 32x 32 pixels.
- Scintillators + WLS + MaPMT/SiPM
- Same électronics for all types of matrices / photosensors (OPERA T.T.)
- Common Clock locked on GPS
- TDC embedded in the FPGA (100ps vernier) for tof measurements

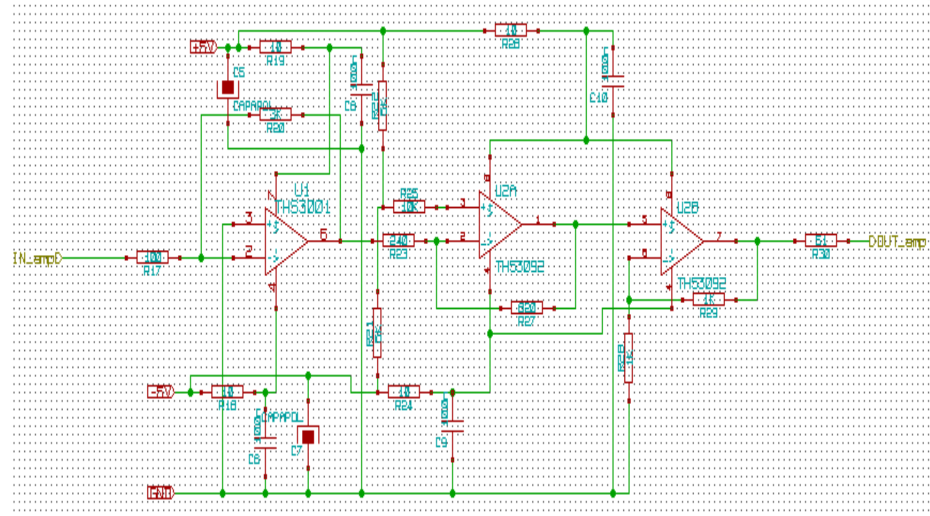






SiPM readout system

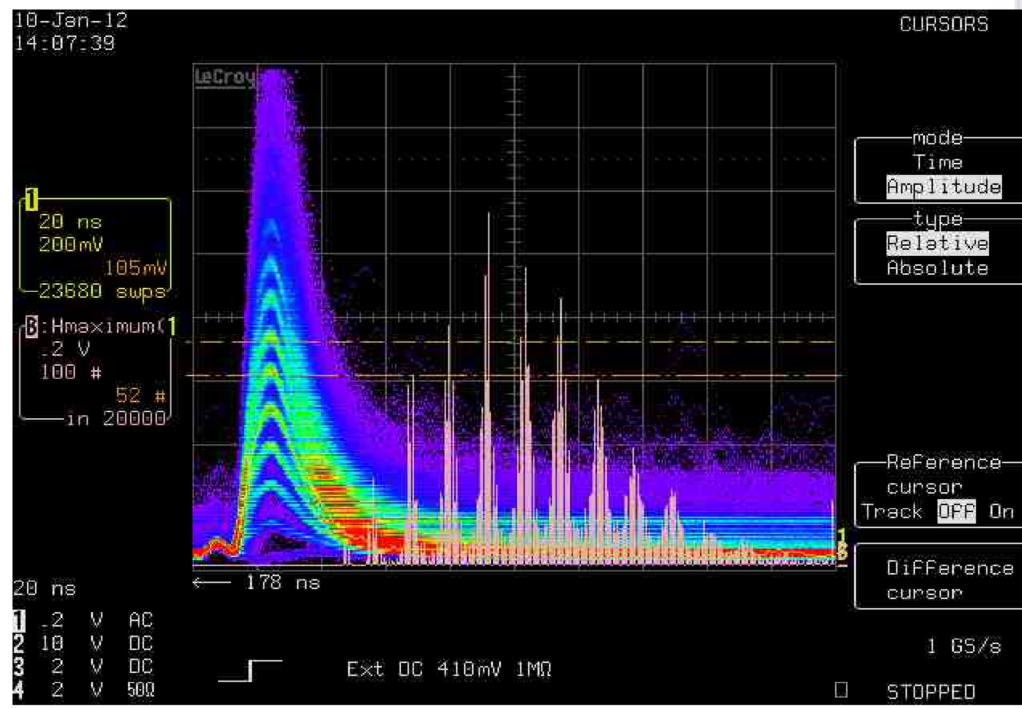
Front-end stage design based on a simplified chain (P.E. counter) with a robust, high gain amplifier.

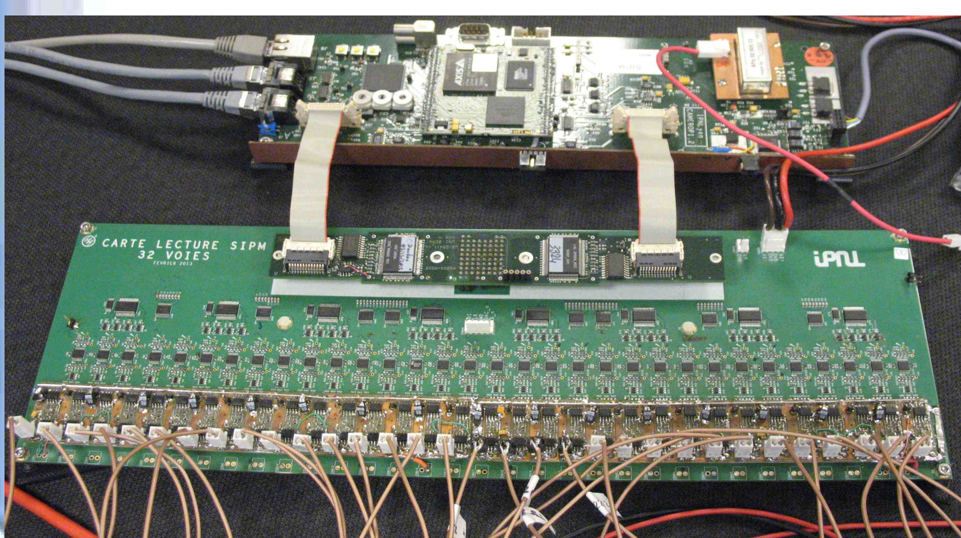


Successful operation in auto-trigger mode (full telescope running in Lyon)

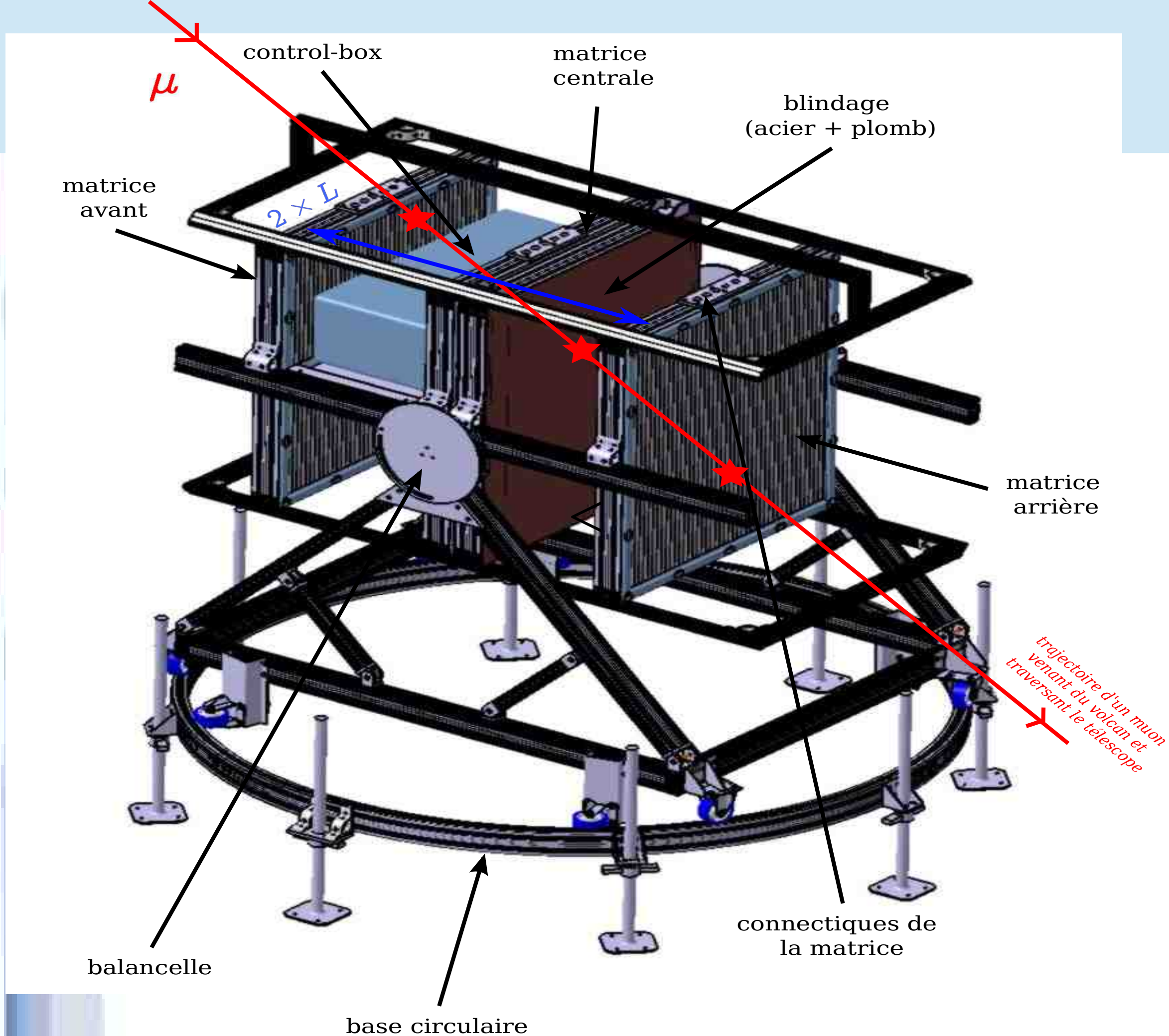
Benefits from the excellent P.E. counting capabilities

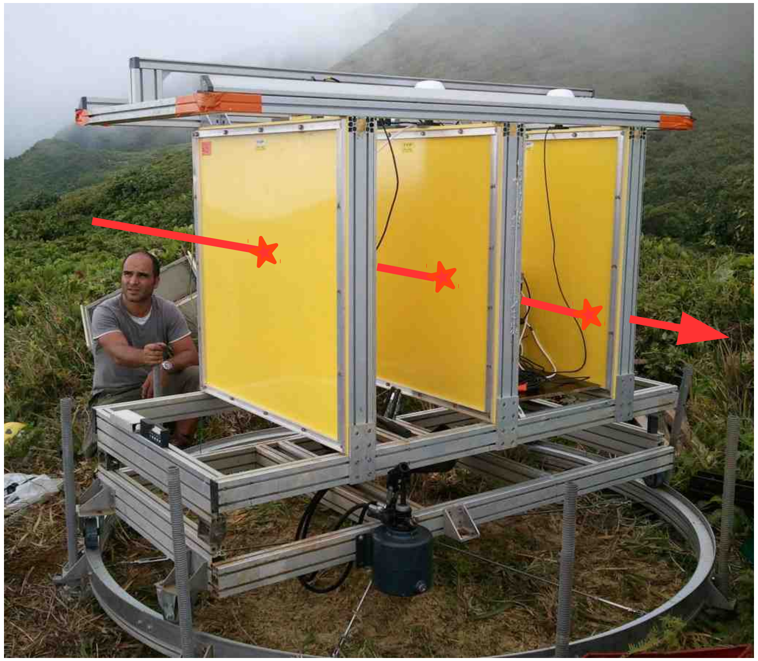
Integrated in the same DAQ chain as for the PMT's option





Muon telescope





Power: photovoltaic panels, wind turbine, fuel cells

Total mass: 200 to 600 kg (lead/iron shielding)

Angular aperture: 30° - 60°

Angular resolution: 1° - 2°

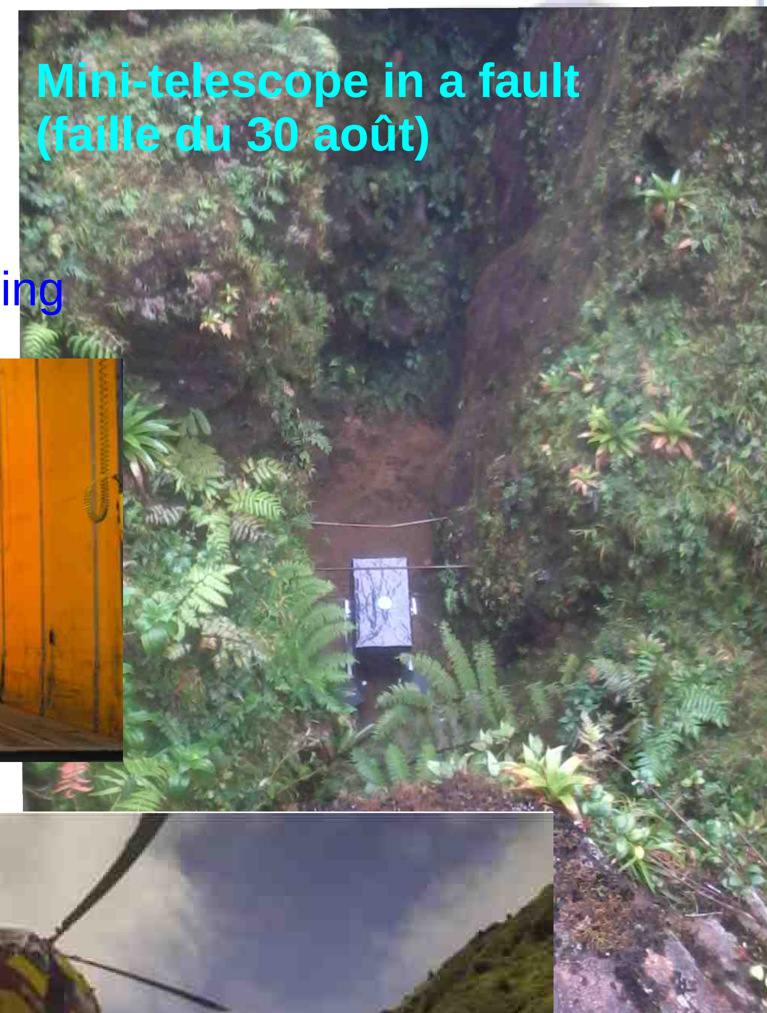
Consumption: ~50W

Remote Ethernet control

Diaphane '15: installation

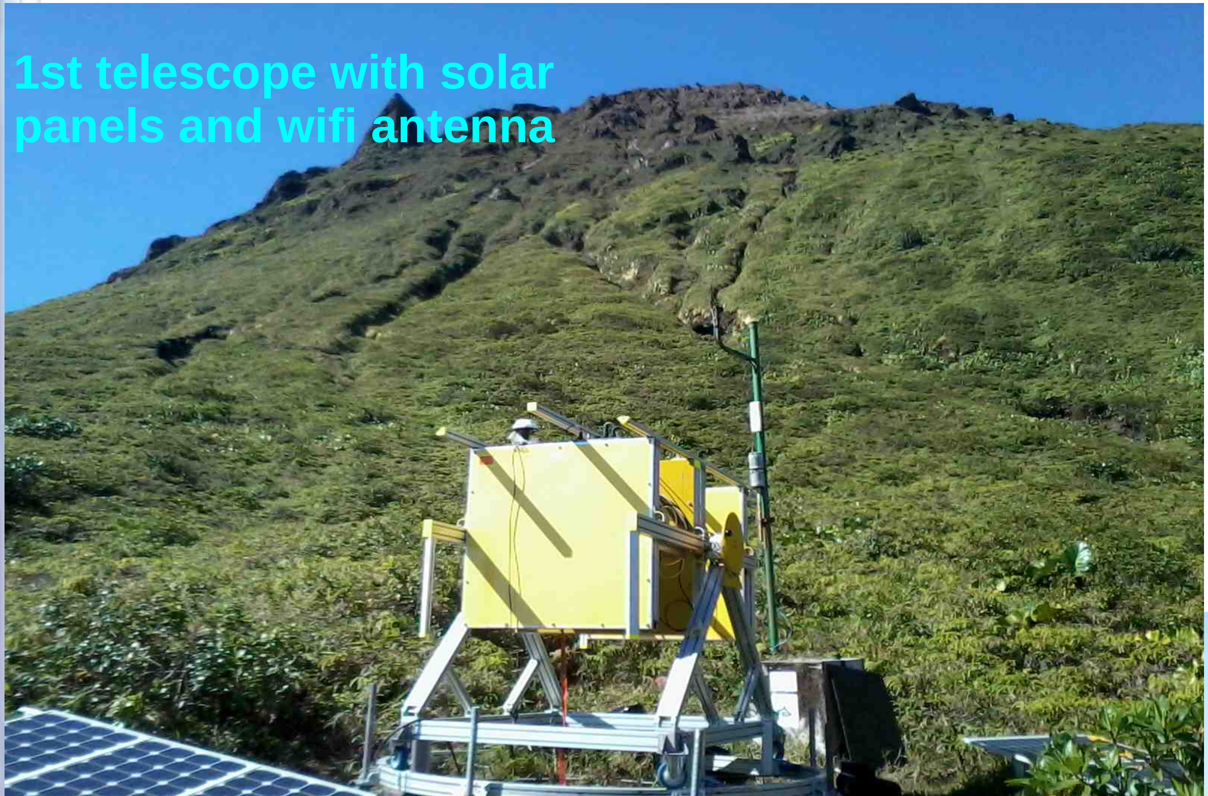
Helicopter transfer of a premounted structure

4 telescopes installed
and operated on site
in 2 weeks. 3 tons of
material including shielding



Mini-telescope in a fault
(faille du 30 août)

Diaphane '15: installation



Telescope acceptance

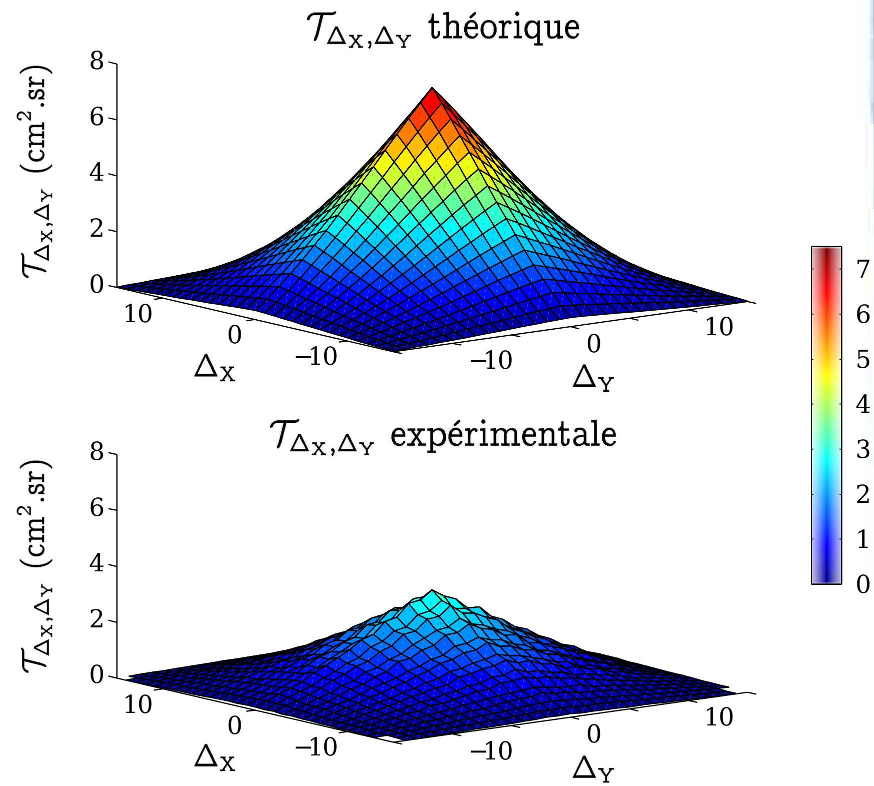
Instrumental transfer function

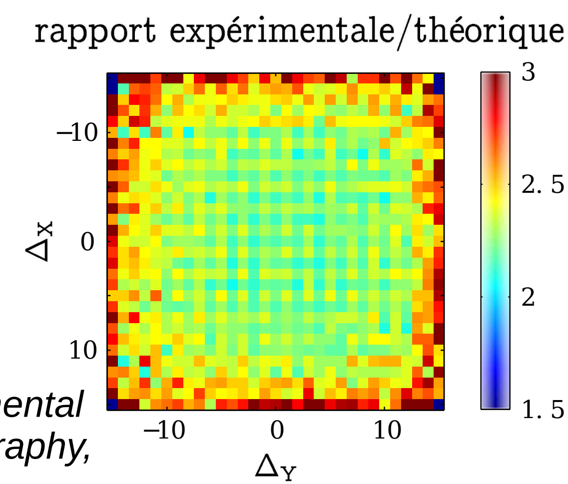
Each detection axis (Δ_X, Δ_Y) is charaterized by its acceptance $\mathcal{T}_{\Delta_X,\Delta_Y}$.

$$\phi_{\Delta_X,\Delta_Y} = \mathcal{T}_{\Delta_X,\Delta_Y} \times \partial\phi_{\Delta_X,\Delta_Y}$$

The acceptance depends on geometrical, instrumental and numerical factors.

It is measured via open-sky calibrations and modellized by a bayesian inversion process.

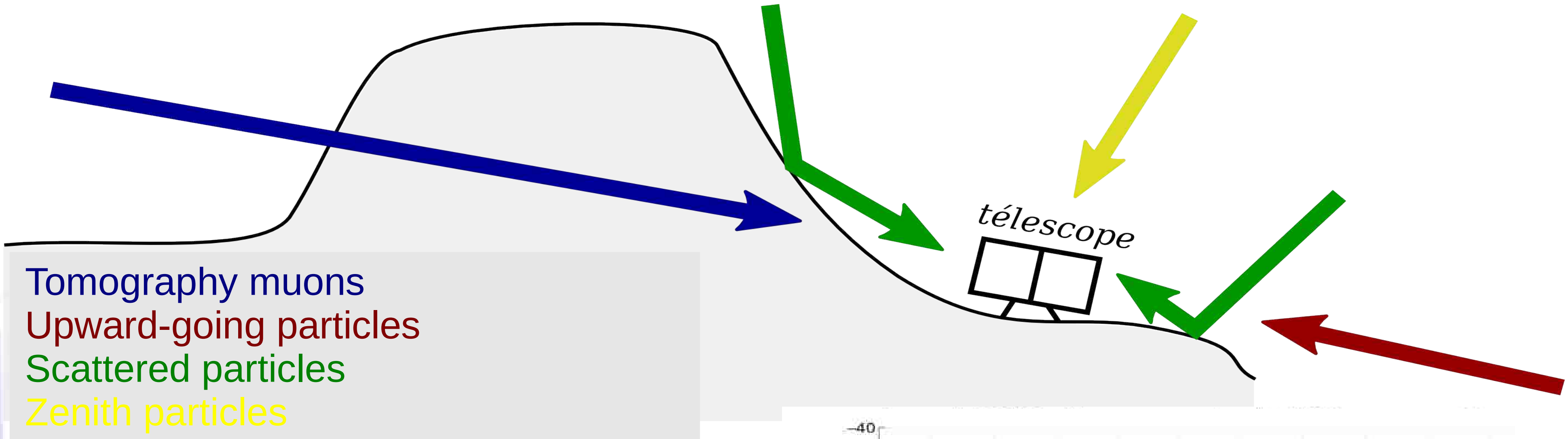




Lesparre, N., D. Gibert & J. Marteau, Bayesian Dual Inversion of Experimental Telescope Acceptance and Integrated Flux for Geophysical Muon Tomography, Geophysical Journal International, Vol. 188, 490-497, 2012.

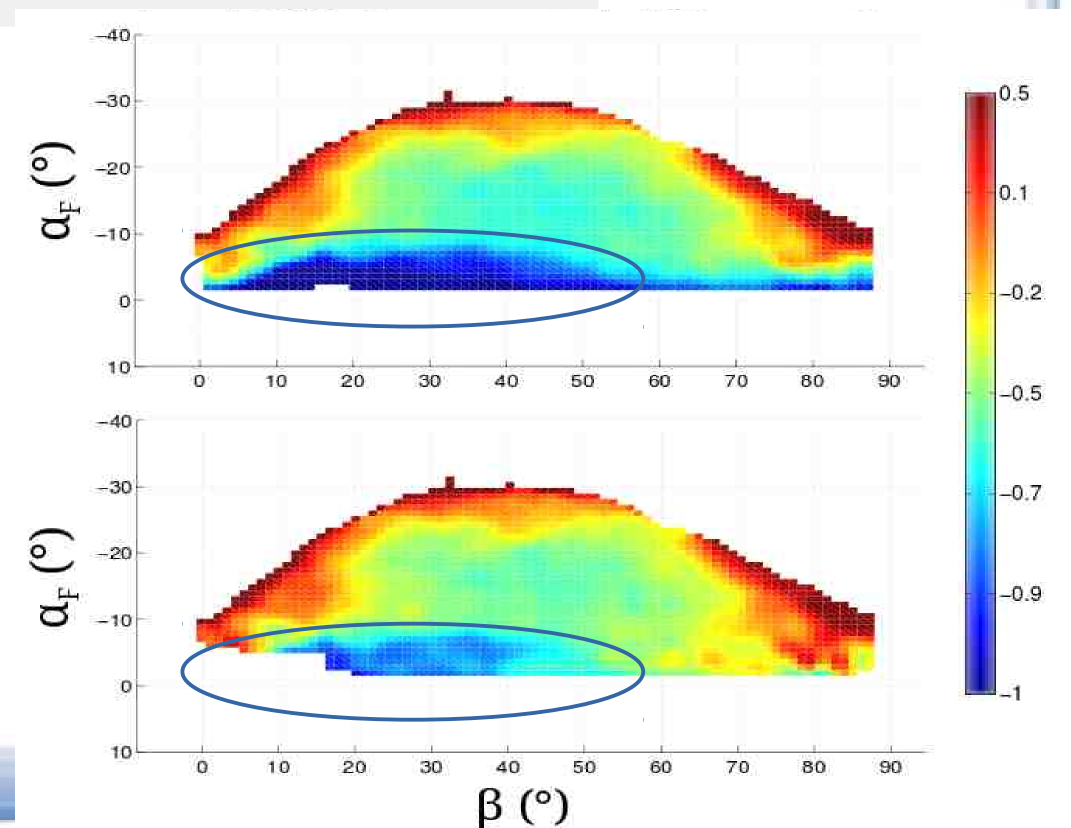
Upward-going particles background reduction

Many sources of background in the open-sky conditions



A **high precision clock** TDC technique allows a TOF analysis to disentangle particles coming either from **the front or the rear** of the telescope

A particle upward-flux was enhanced on the Savane à Mulets site permitting to **correct the low density region** above the horizon.

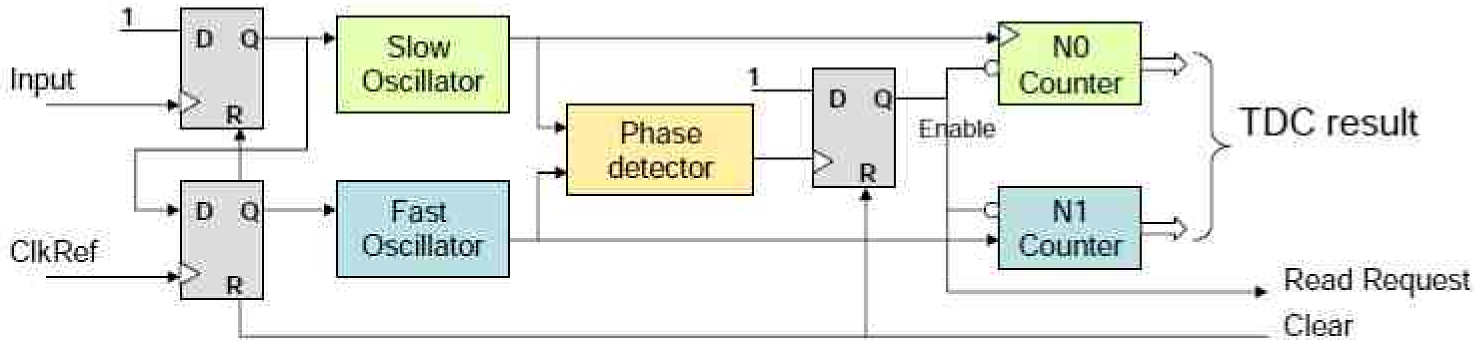


Jourde, K. et al. GRL 2013

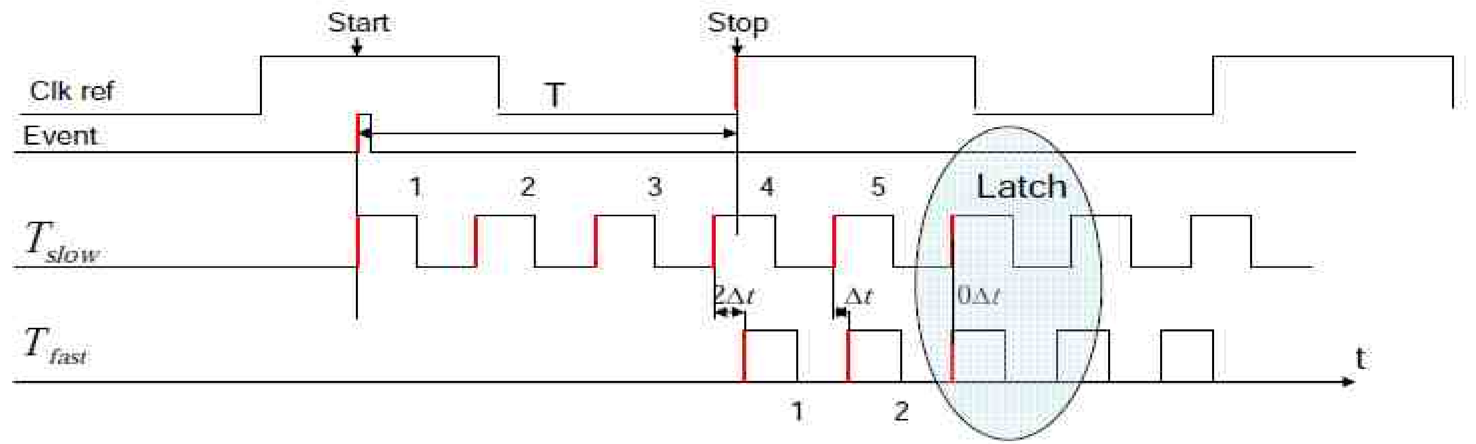
Upward-going particles : TDC techniques

Marteau, J. et al. MST 2013

Ring-oscillator TDC technique implemented in FPGA allowed, without any extra hardware, to improve the timing resolution of the electronics down to a few tens of picoseconds.



Low area, low power consumption, no extra fast clock.



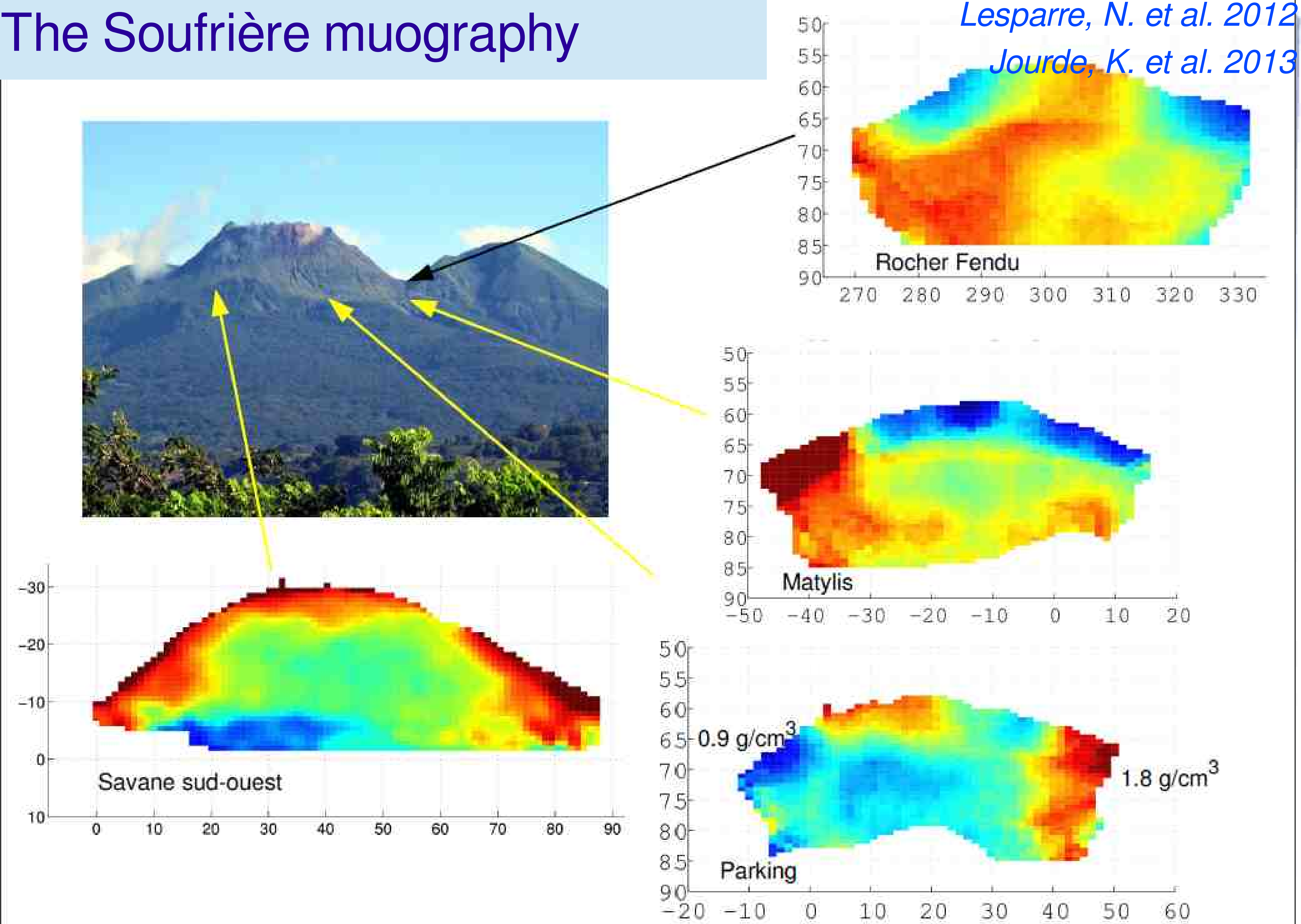
Direct implementation inside FPGA. Different design = optimal timing resolution

Active volcano structural imaging

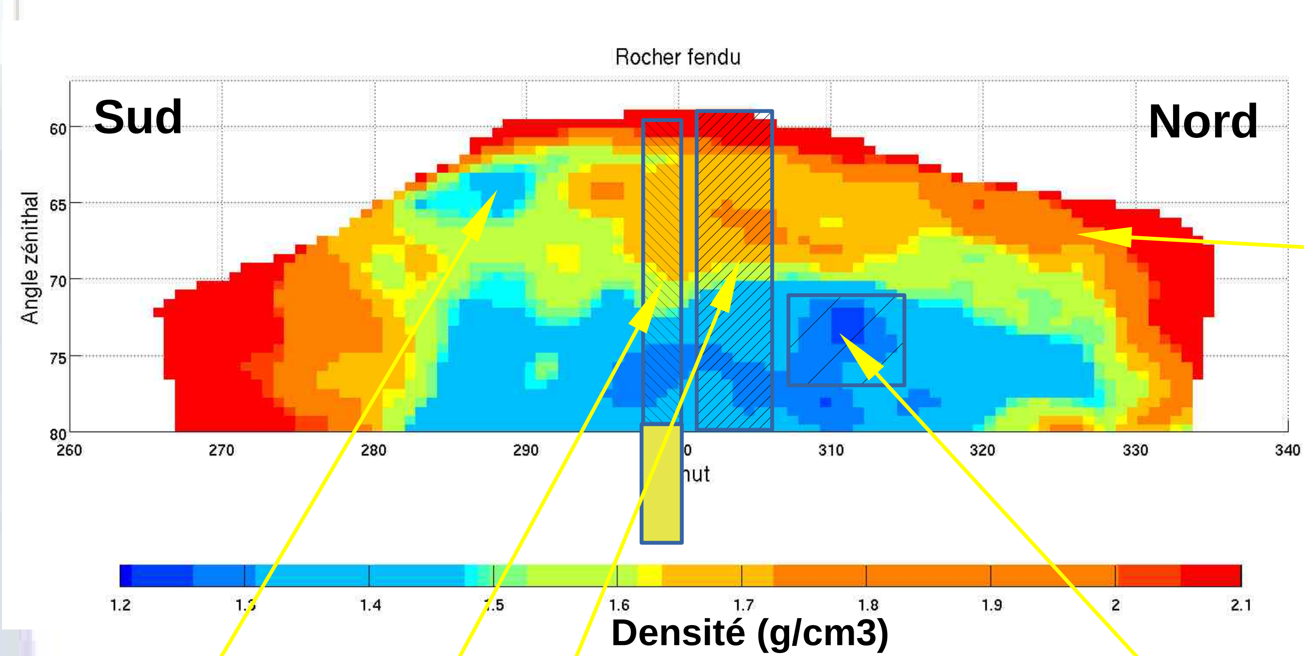
Soufrière of Guadeloupe

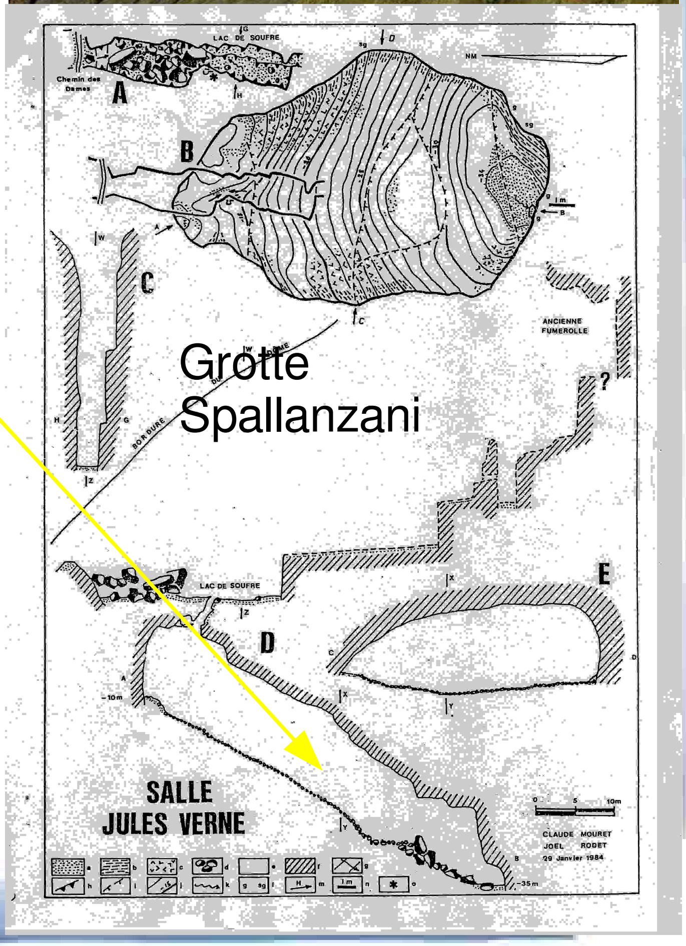
The Soufrière muography

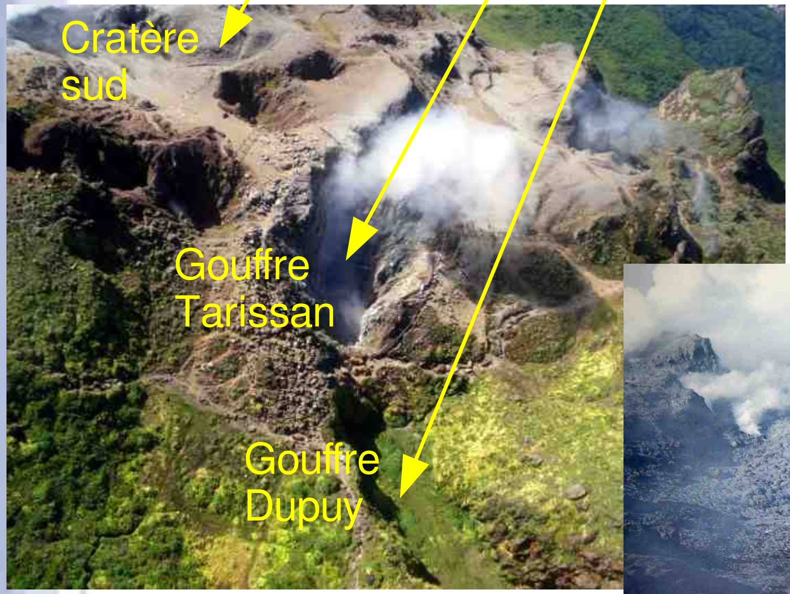
Lesparre, N. et al. 2012
Jourde, K. et al. 2013



The Volcano of La Soufrière de Guadeloupe

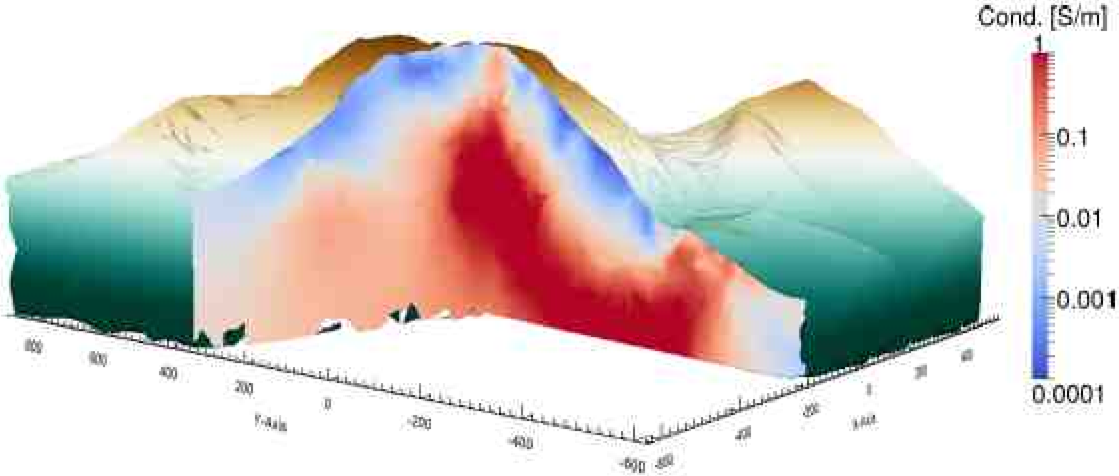


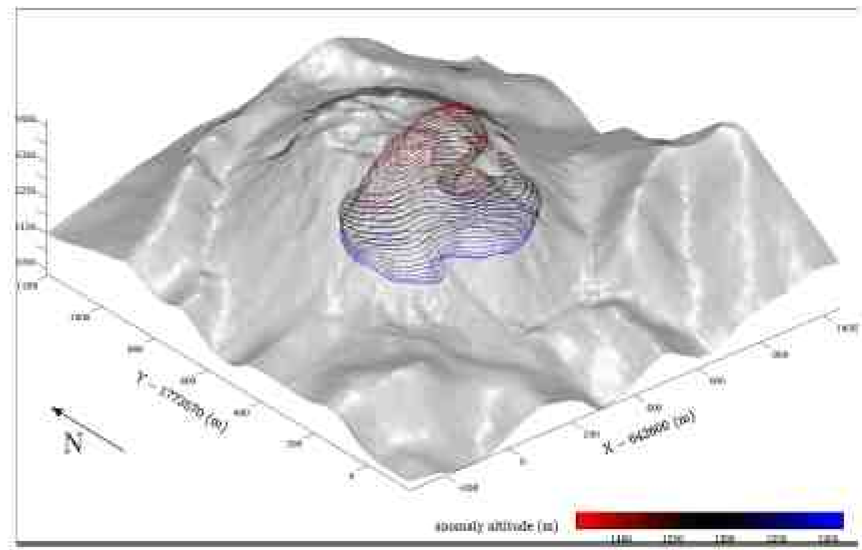


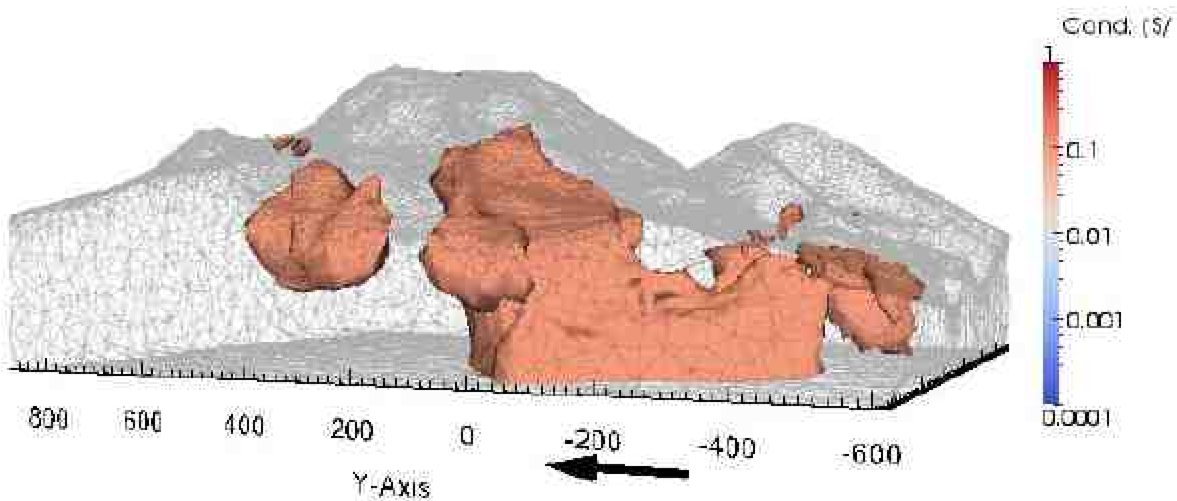


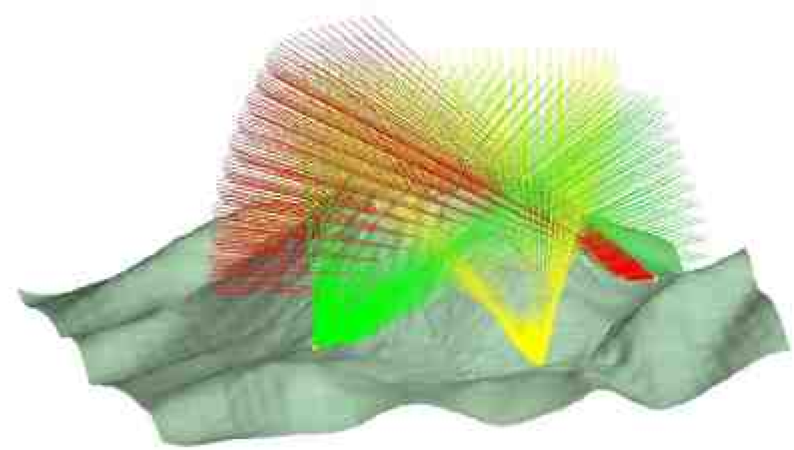
Integration of other methods

Electrical tomography – Gravimetry – Cosmic muons tomography









Active volcano monitoring

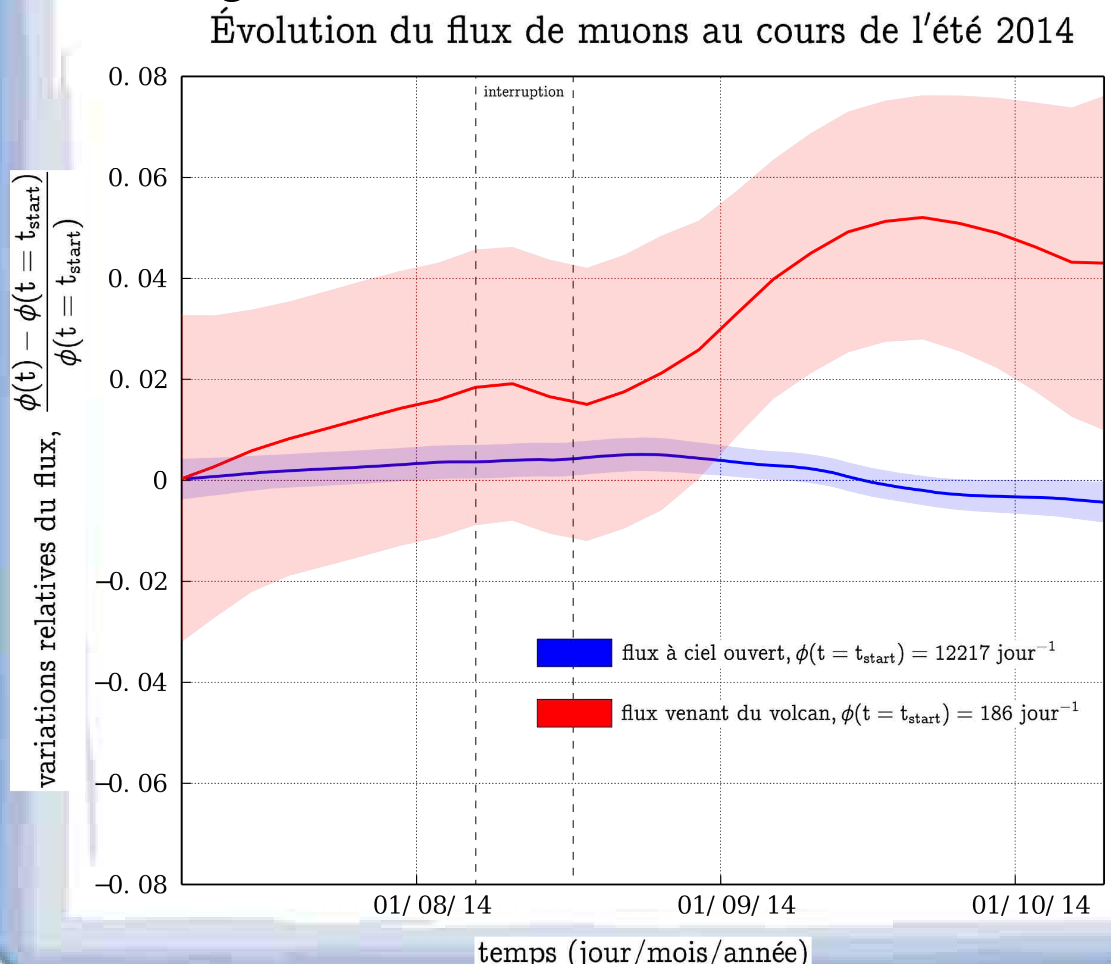
Soufrière of Guadeloupe

Photographie Dominique Gibert

Volcano activity monitoring

Long data taking series with a stable telescope allows to monitor the activity of the phreatic system.

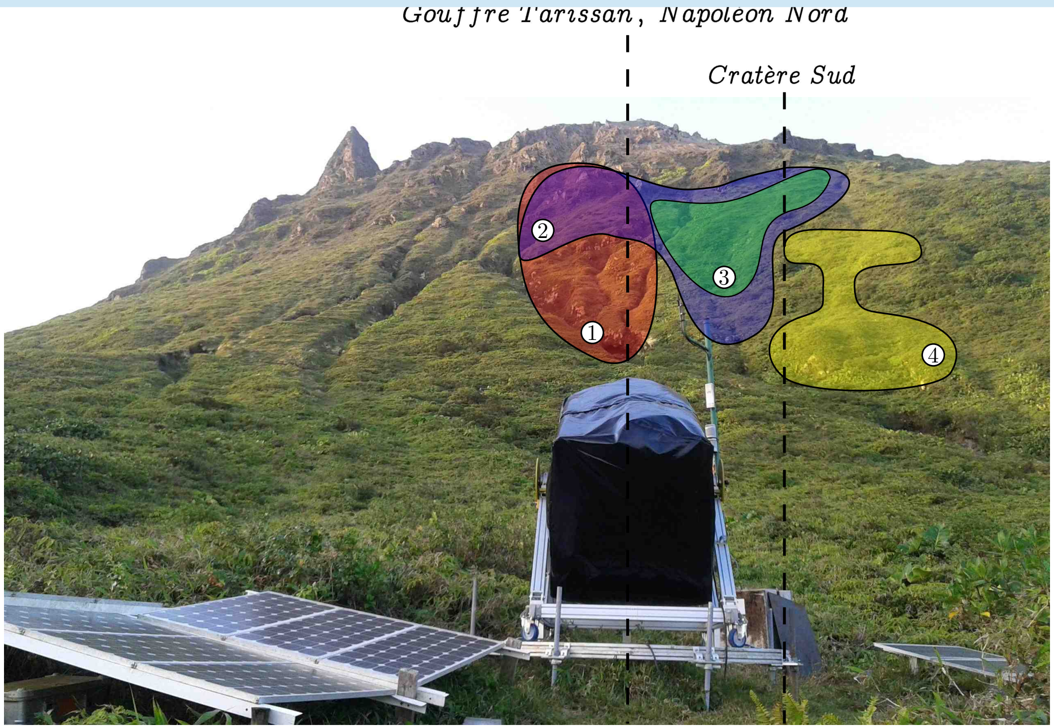
In July 2014, a new vent appears at the summit of the volcano (“Nord Napoléon” vent). The muons telescope records large and significant changes in the muons flux.

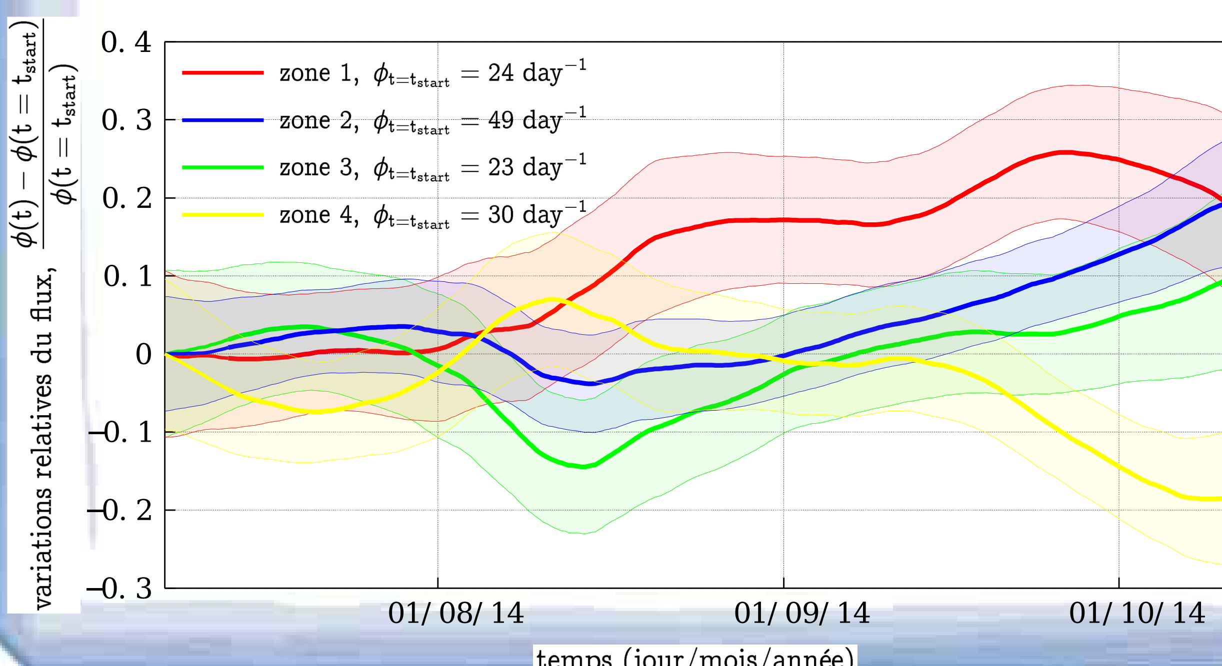


Muons telescope in acquisition

Potential, external sources of variations are totally negligible w.r.t. the activity of the volcano itself.

Volcano activity monitoring





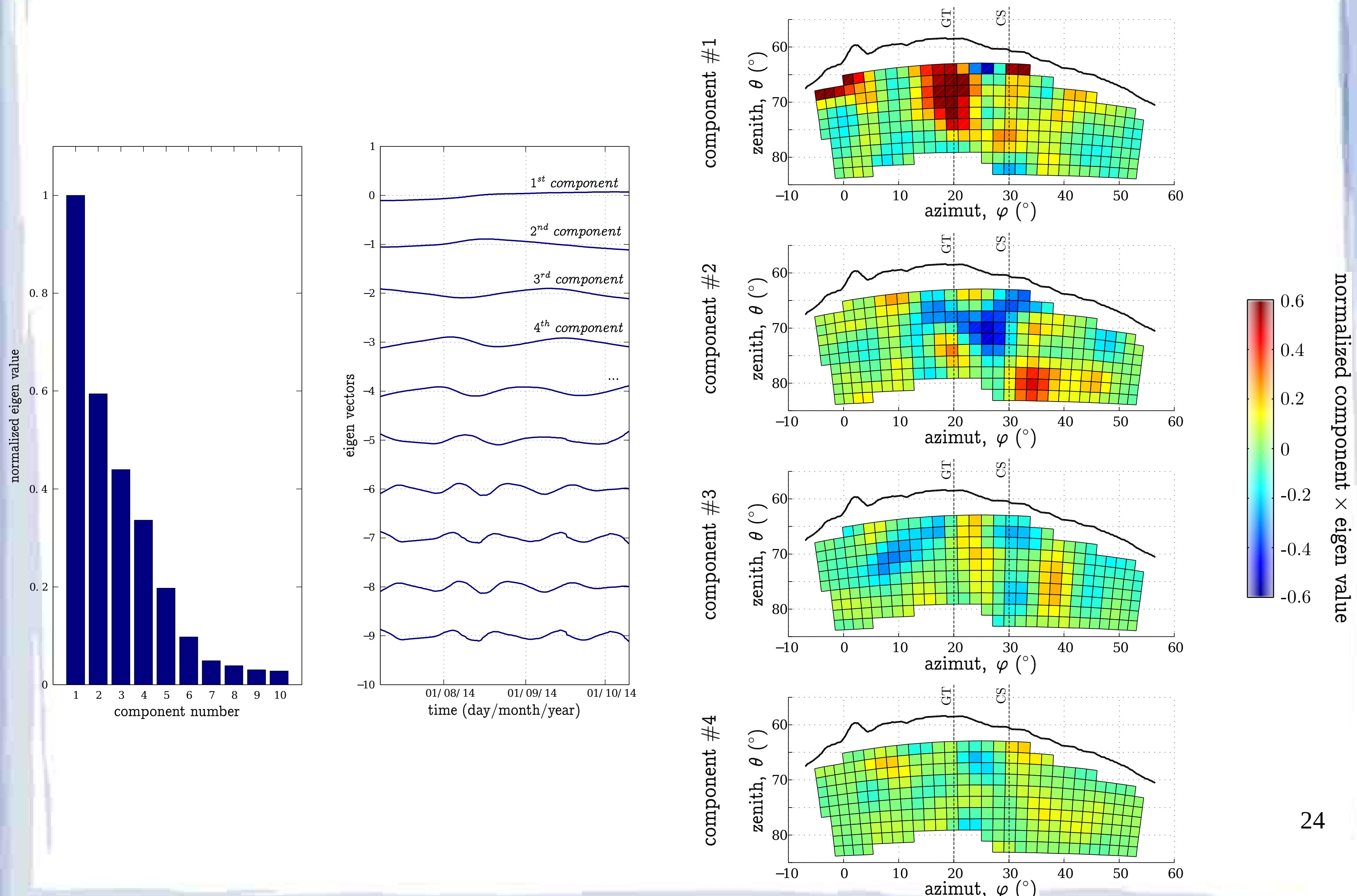
Principal vector analysis allows to isolate regions in the volcano with similar time behaviours.

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.

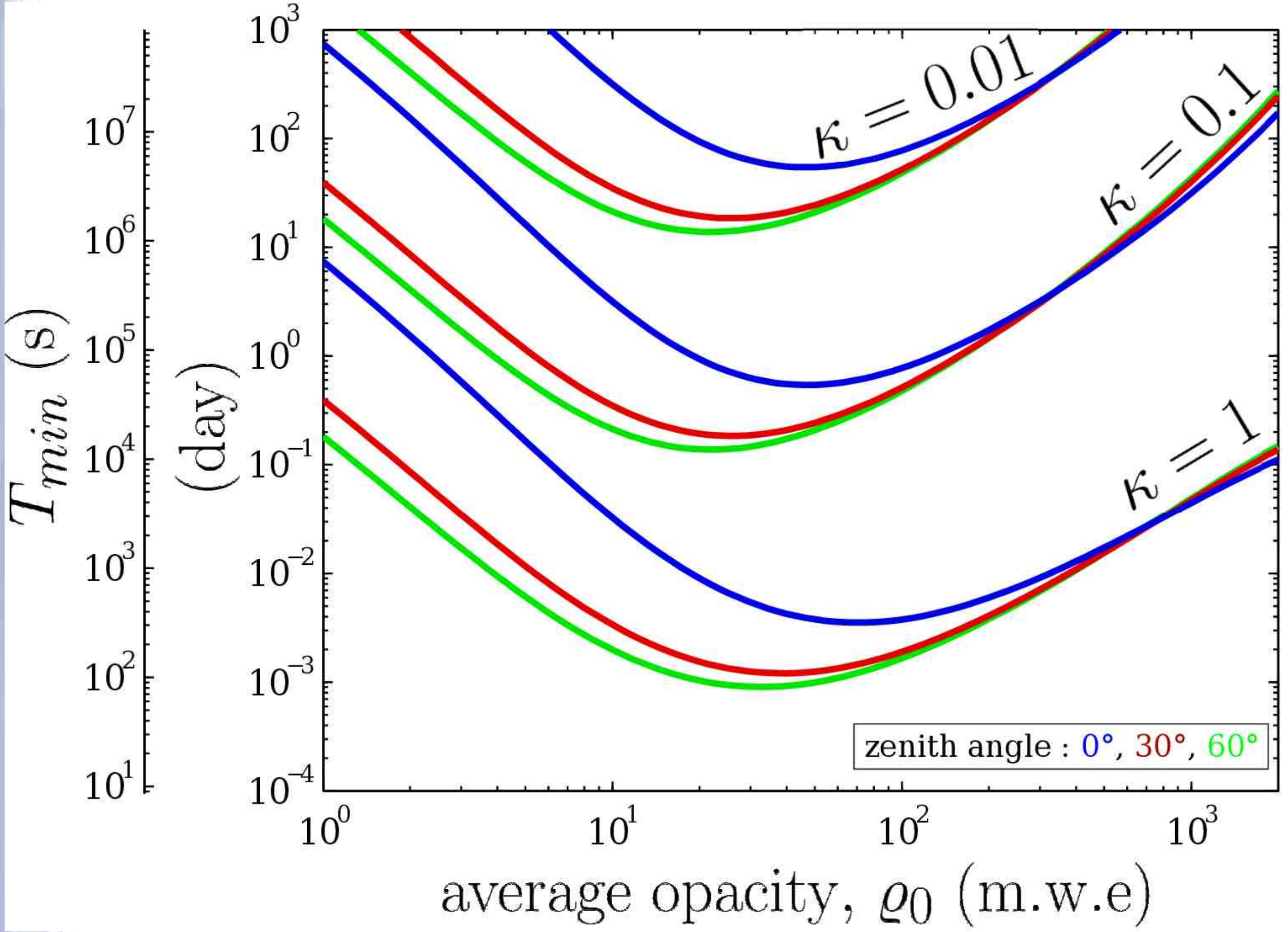
The observed fluctuations in zone 1 correspond to vaporization of 40 mwe in only 3 months.

Volcano activity monitoring




Methodology developments
Shadow, gravimetry etc
Photographie Dominique Gibert

Muon tomography monitoring statistical feasibility

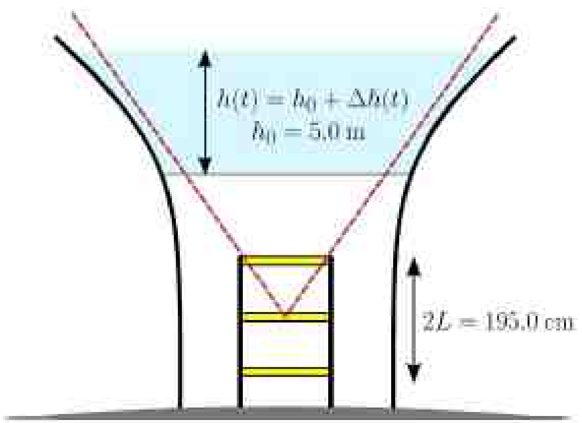


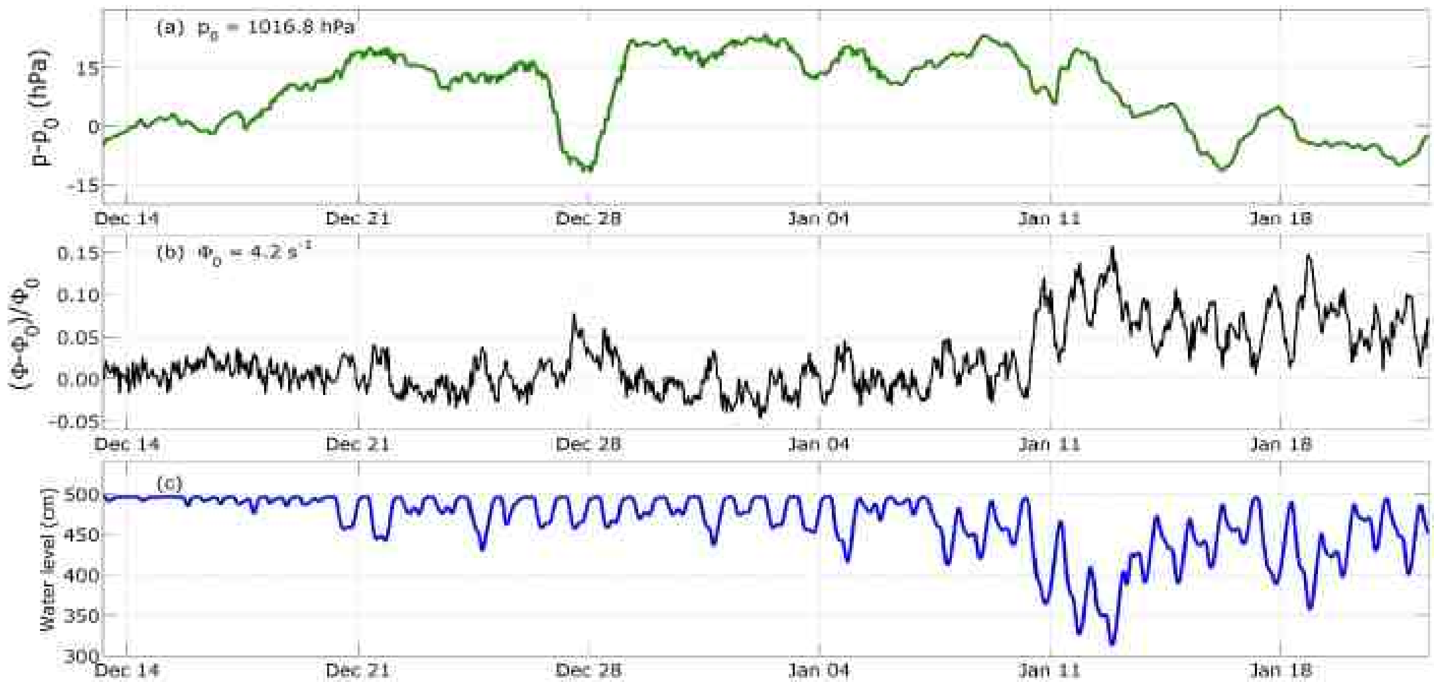
Computed with an acceptance of 10 cm2.sr and using the modified Gaisser model from Tang et al. 2006.

For example : at a zenith angle of **60°**, a **10%** opacity fluctuation around an average opacity of **600 mwe** needs about **30 days** to be detected.

Muon tomography monitoring: SHADOW experiment

Water level monitoring of a water tower tank



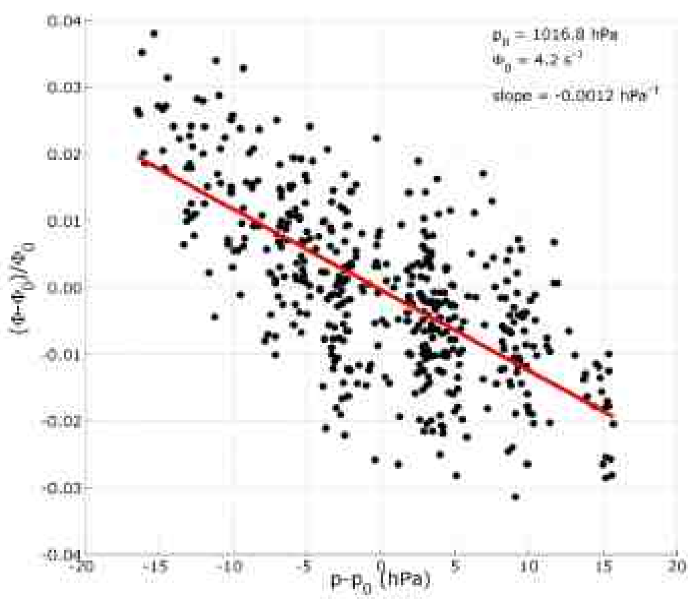


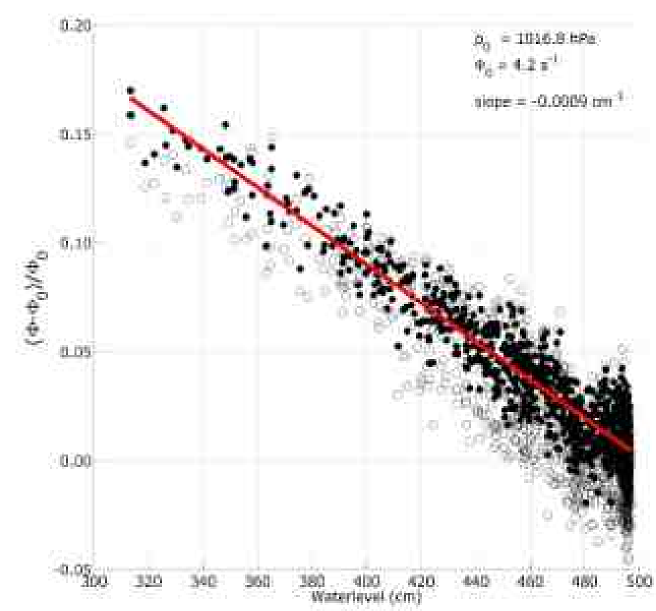
Low energy cut ~1.5 GeV:

=> barometric effects

=> geomagnetic effects

=> Solar activity effects



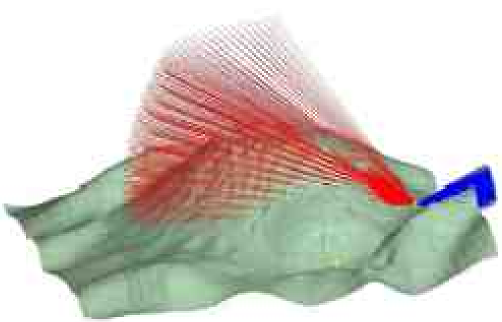


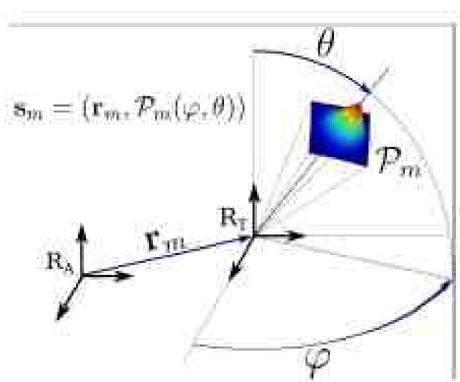
Joined gravimetry – muography inversion

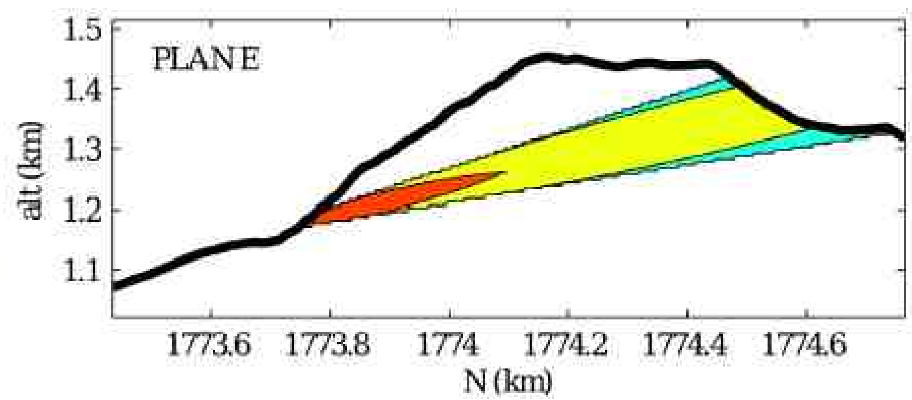
Motivations:

* Muons => limited in depth (no data under the horizon)
* Muons => high resolution and easy linear inversion
* Muons => compact support integration (=> existence of “holes”)

* Gravimetry => integration over full space
* Gravimetry => low resolution and difficult inversion (non uniqueness etc)

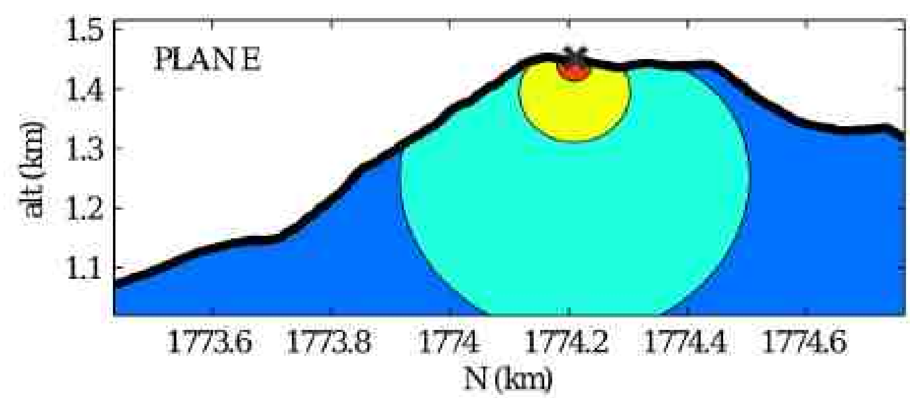






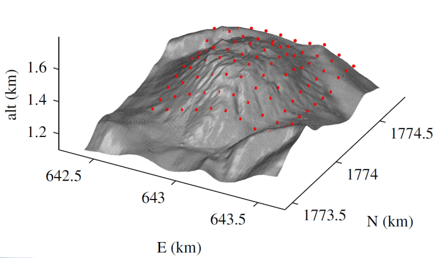
$$\tilde{\phi}_m = \langle \mathcal{M}_m, \rho - \rho_0 \rangle_X, \quad m = 1, \cdots, M$$
$$\tilde{g}_n = \langle \mathcal{G}_n, \rho - \rho_0 \rangle_X, \quad n = 1, \cdots, N,$$

$$\mathcal{M}_m(\mathbf{r}) = \frac{\mathcal{P}_m(\varphi, \theta)}{\mathcal{T}_m} \times \frac{\alpha_t}{C_{\phi,m}\, \xi^2},$$
$$\mathcal{G}_n(\mathbf{r}) = \frac{G}{C_{g,n}} \times \frac{(\mathbf{r}_n - \mathbf{r})}{\|\mathbf{r}_n - \mathbf{r}\|^3} \cdot \mathbf{e}_z.$$

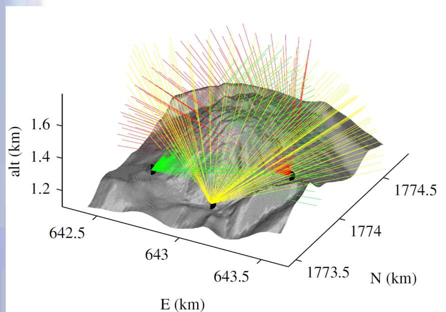


Joined gravimetry – muography inversion (1)

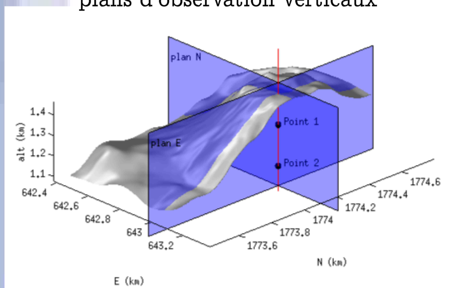
points de gravimétrie



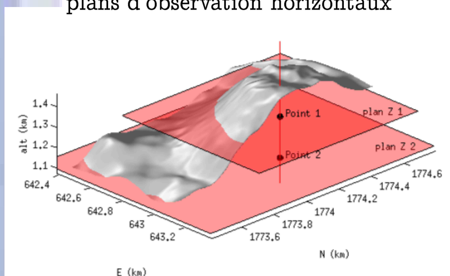
acquisitions de tomographie



plans d'observation verticaux



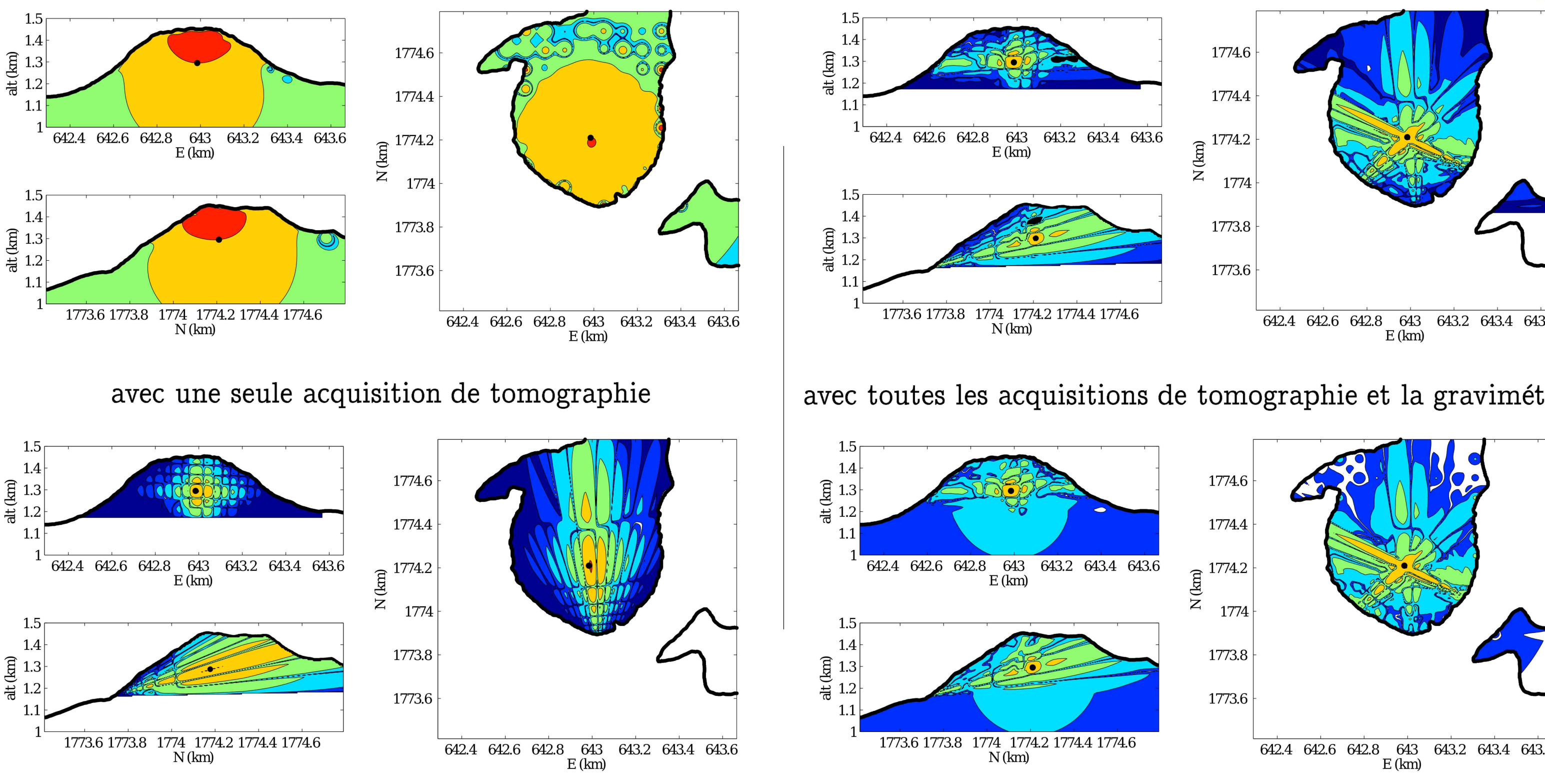
plans d'observation horizontaux



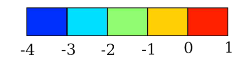
Resolving kernels, individual and joined, point 1 (in the dome)

avec uniquement la gravimétrie — avec toutes les acquisitions de tomographie

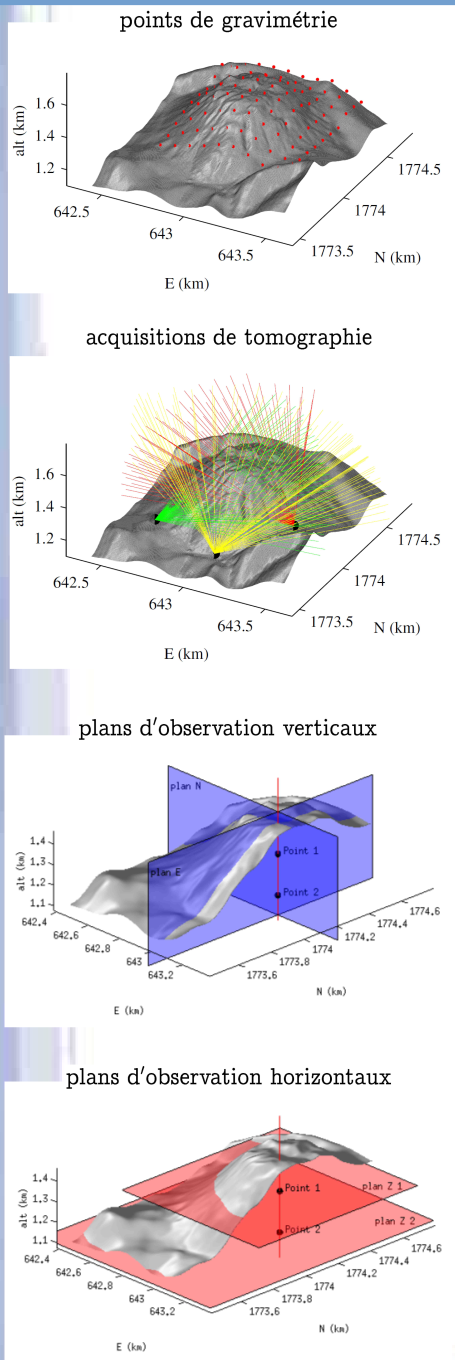
avec une seule acquisition de tomographie — avec toutes les acquisitions de tomographie et la gravimétrie



noyau résolvant normalisé au point 1 (échelle log)

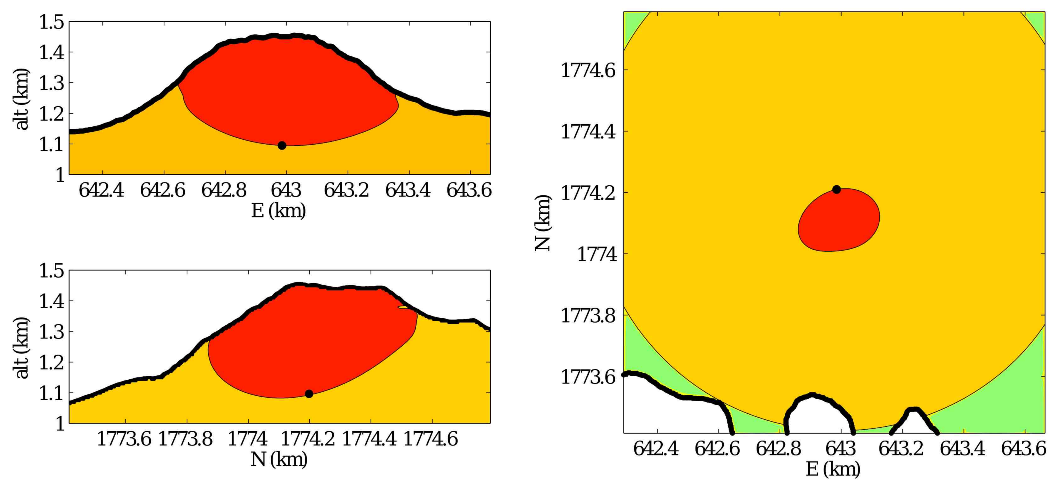


Joined gravimetry – muography inversion (2)

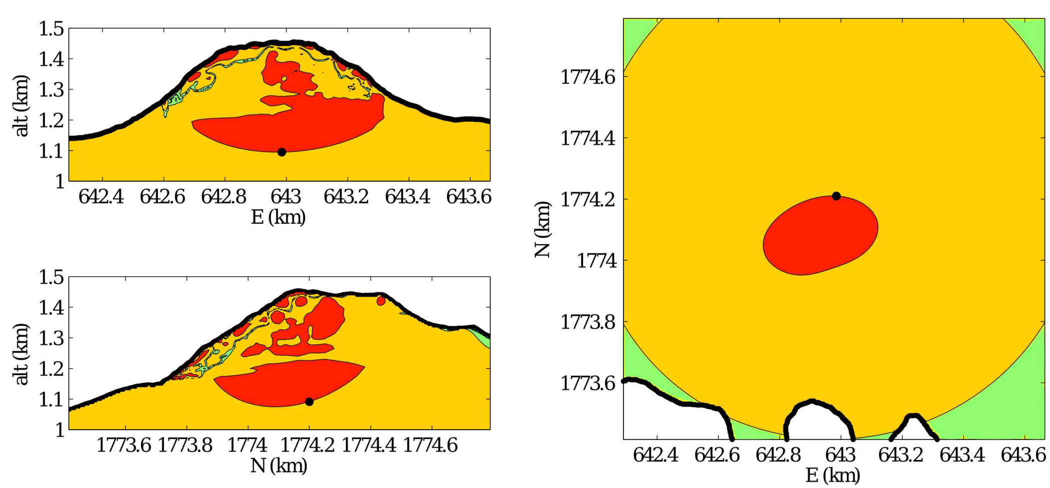


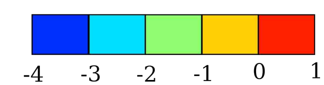
Resolving kernels, individual and joined, point 2 (under the dome)

avec uniquement la gravimétrie



avec toutes les acquisitions de tomographie et la gravimétrie



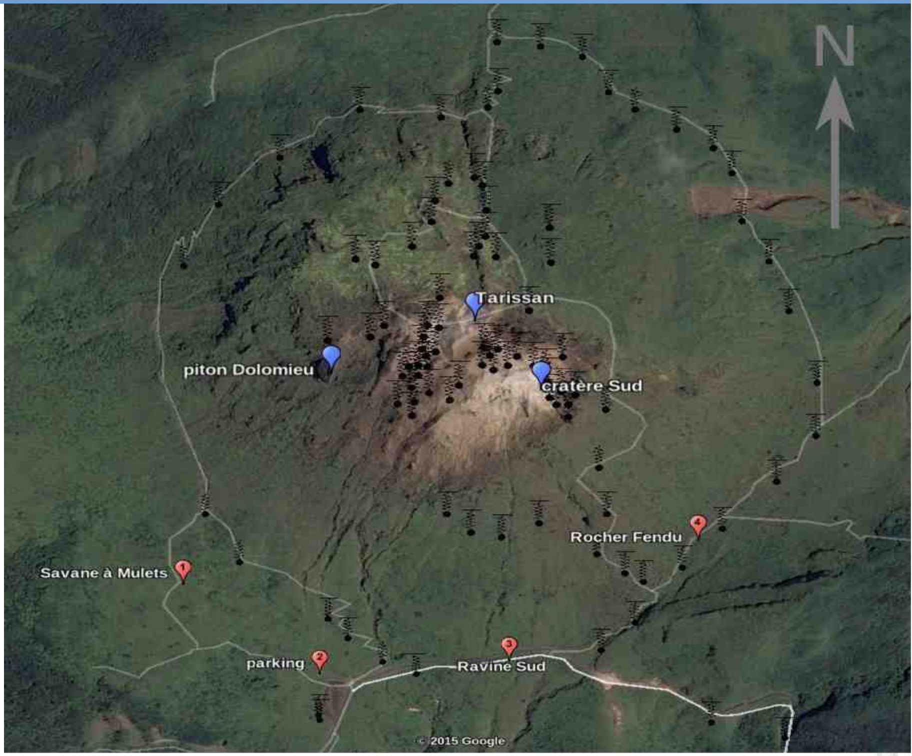


noyau résolvant normalisé au point 2 (échelle log)

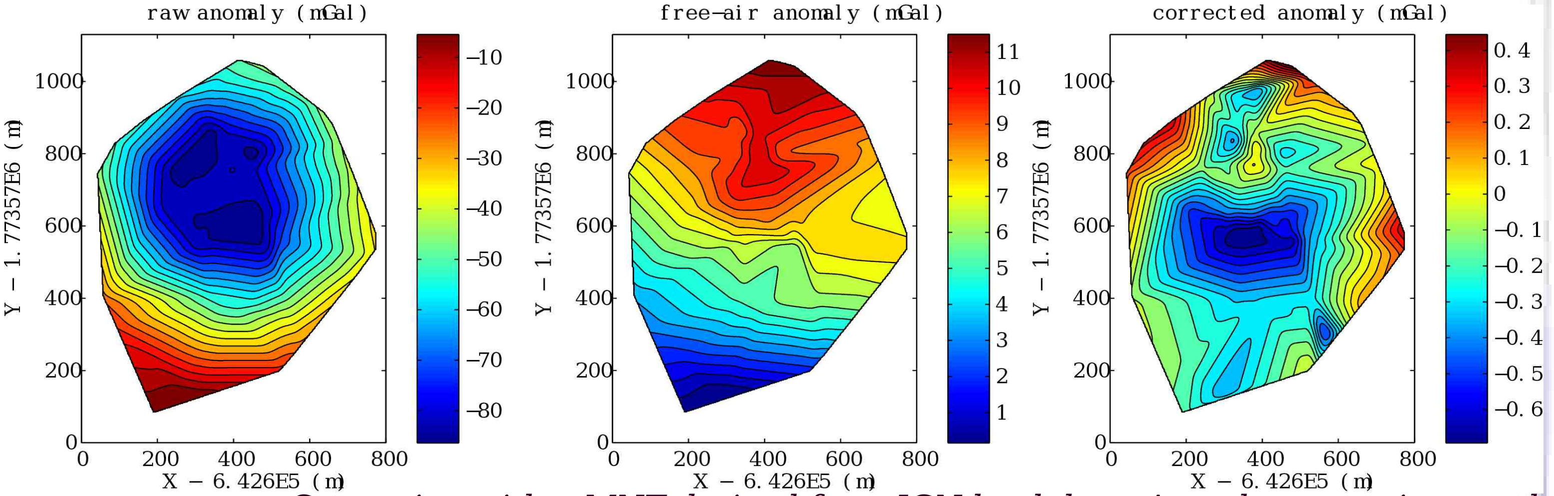
Real data joined inversion underway

La Soufrière gravimetry survey

2014/2015 Soufrière gravimetry survey:
- 146 measurements
- 2 CG5 gravimeters during 1 year
- 1.5km large, 500m height difference survey
- on an island
- 40 µGal precision
- 1 absolute measurement



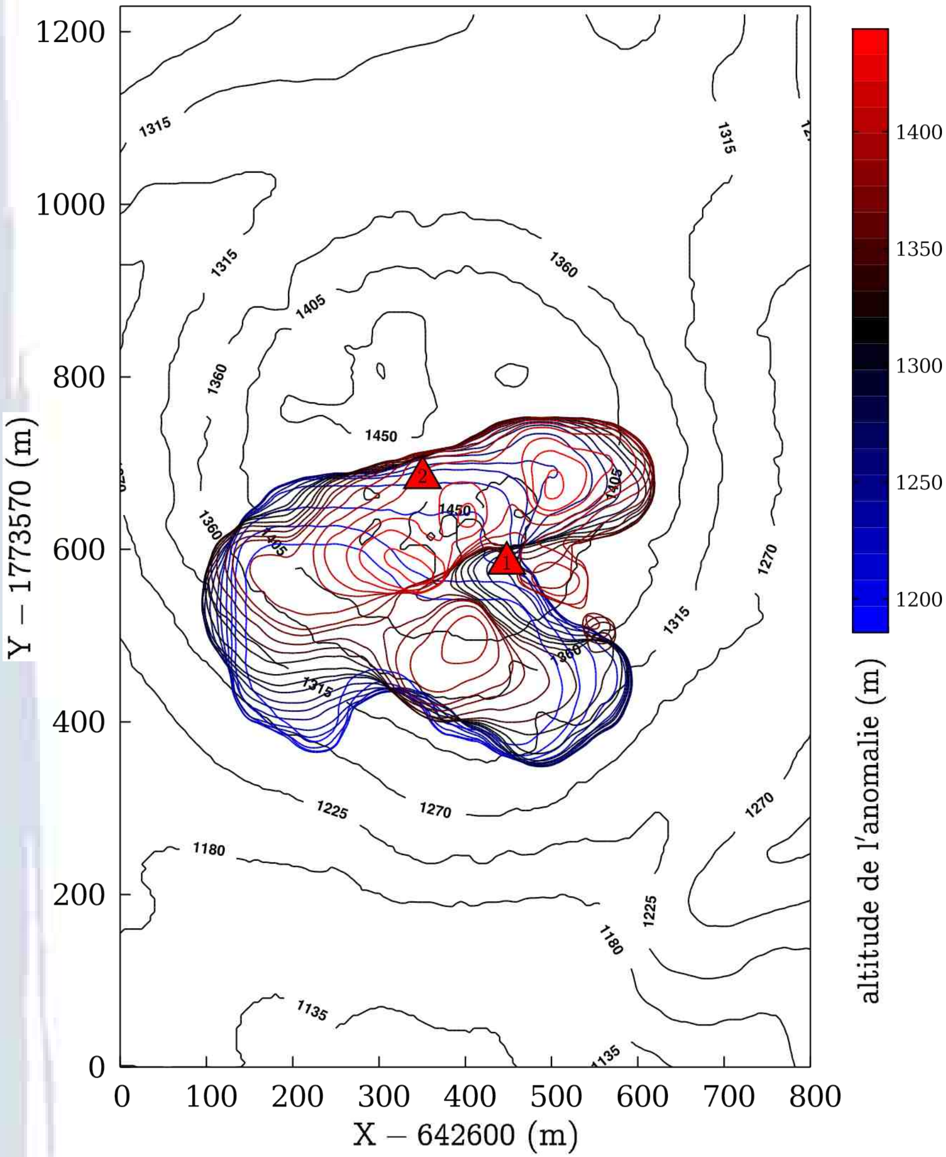
Imply complex corrections:
- geoid oscillations
- earth and sea tides
- atmosphere weight
- earth curvature
- precise Bouguer correction



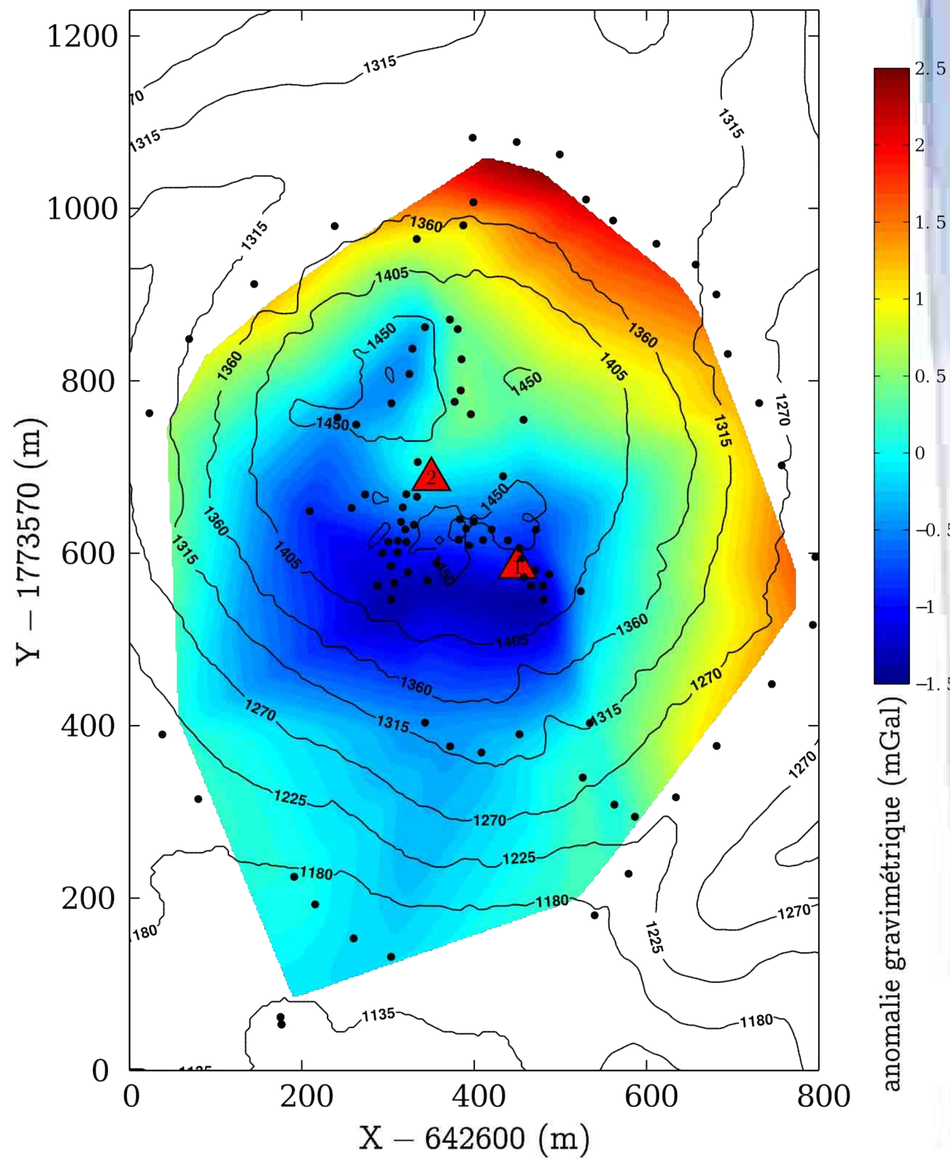
Correction with a MNT derived from IGN land data, Aguadomar cruise swath bathymetry and SRTM model (provided by C. Deplus and N. Feuillet)

La Soufrière gravimetry survey

3D inversion using muon tomography



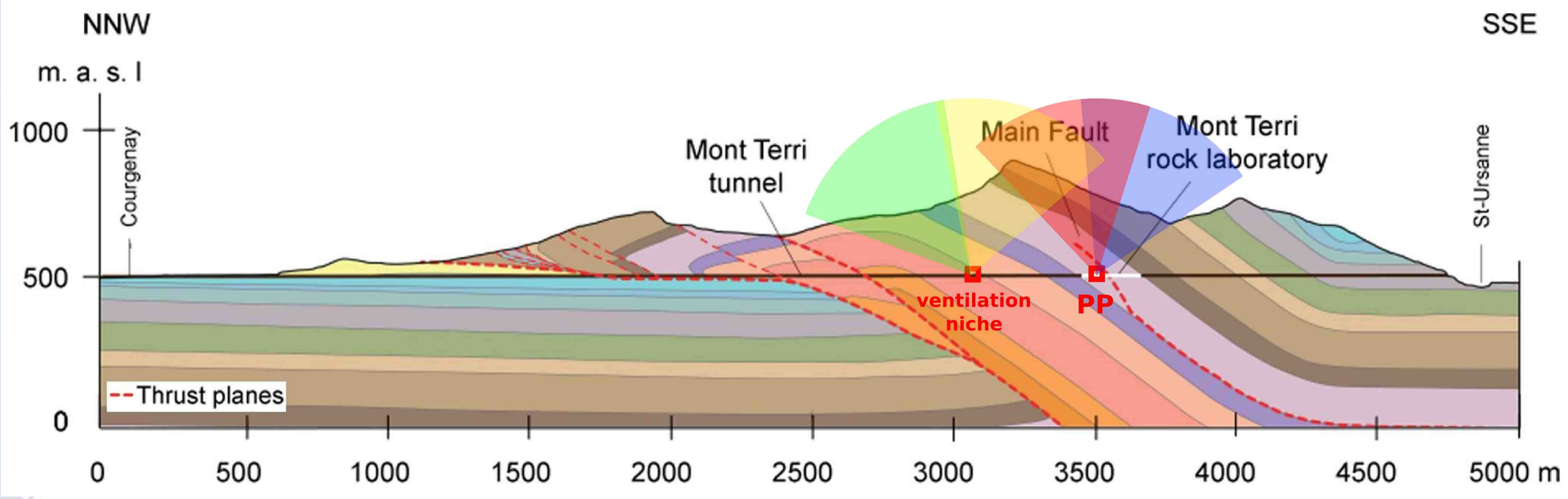
Bouguer anomaly




Underground activity
Mont-Terri, Tournemire etc
Photographie Dominique Gibert

Between 2012 and 2015 :

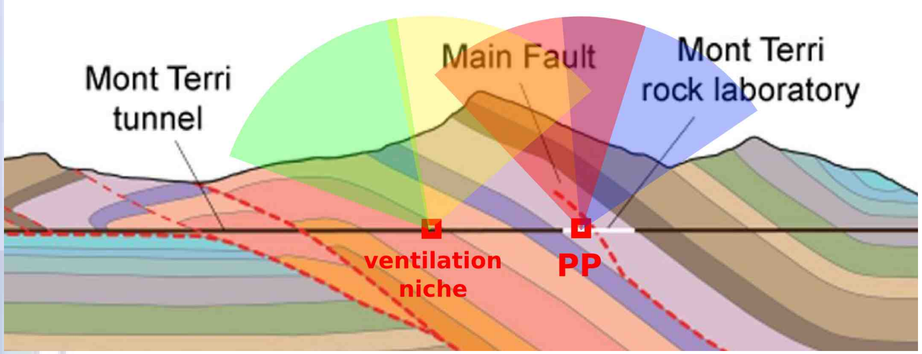
- 5 muography acquisitions from 3 different places.
- 2 calibration acquisitions at the entrance of the lab.

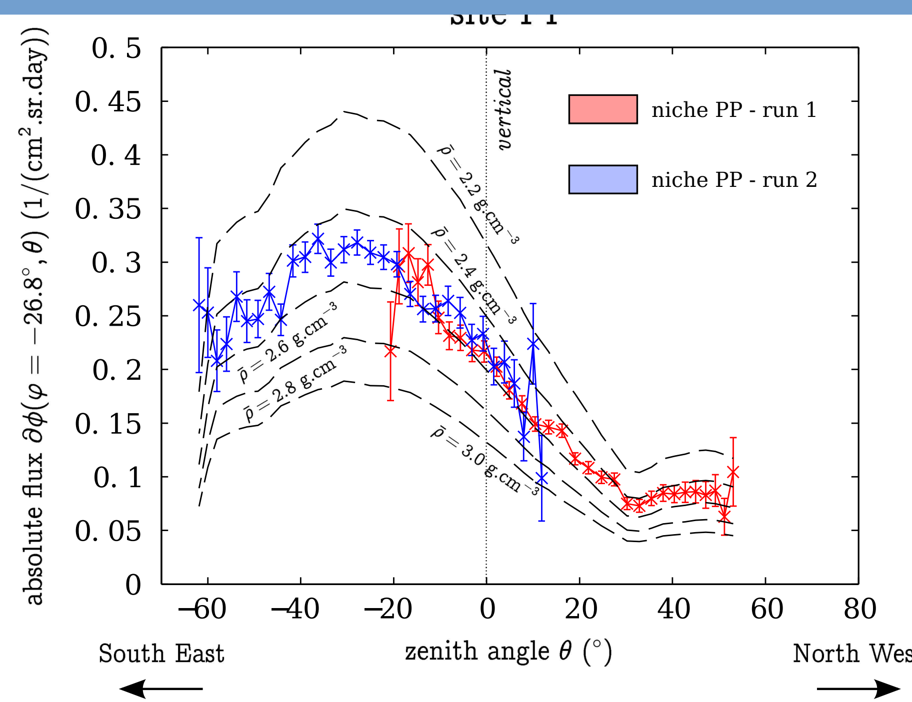


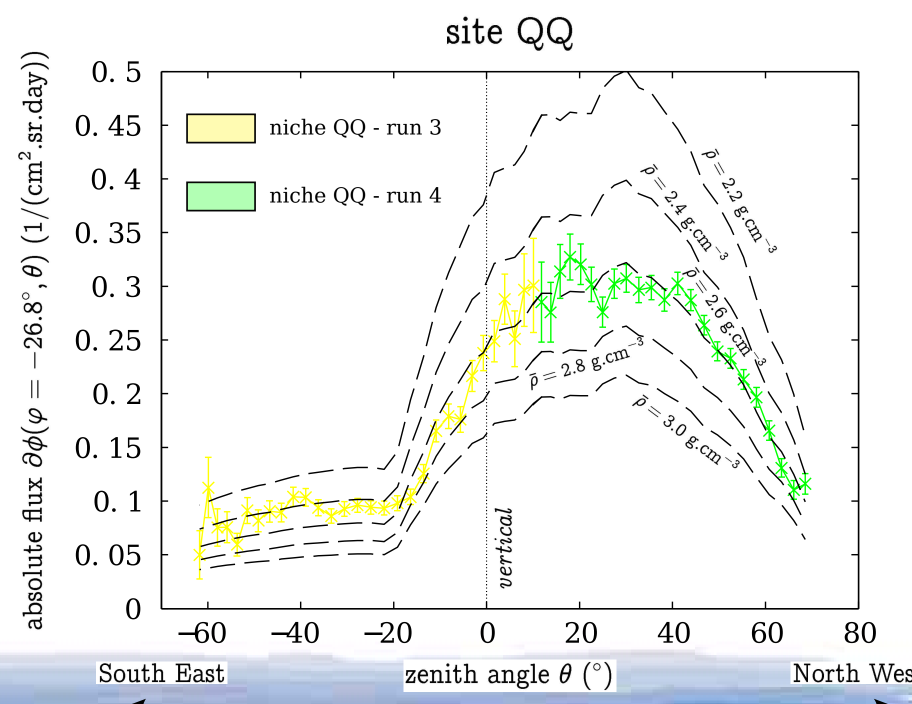
MUON TOMOGRAPHY ACQUISITIONS

niche PP - run 1	niche PP - run 2
ventilation niche - run 3	ventilation niche - run 4

Mont Terri muography



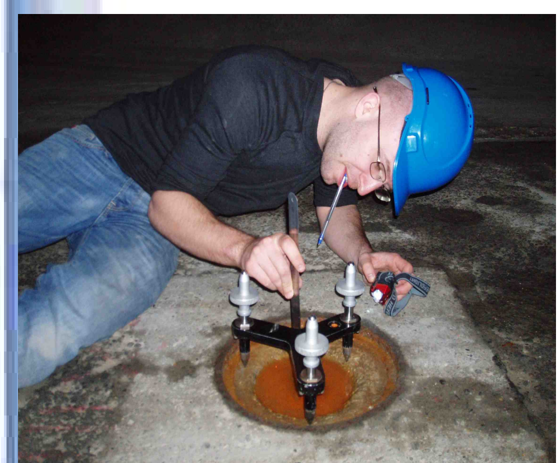


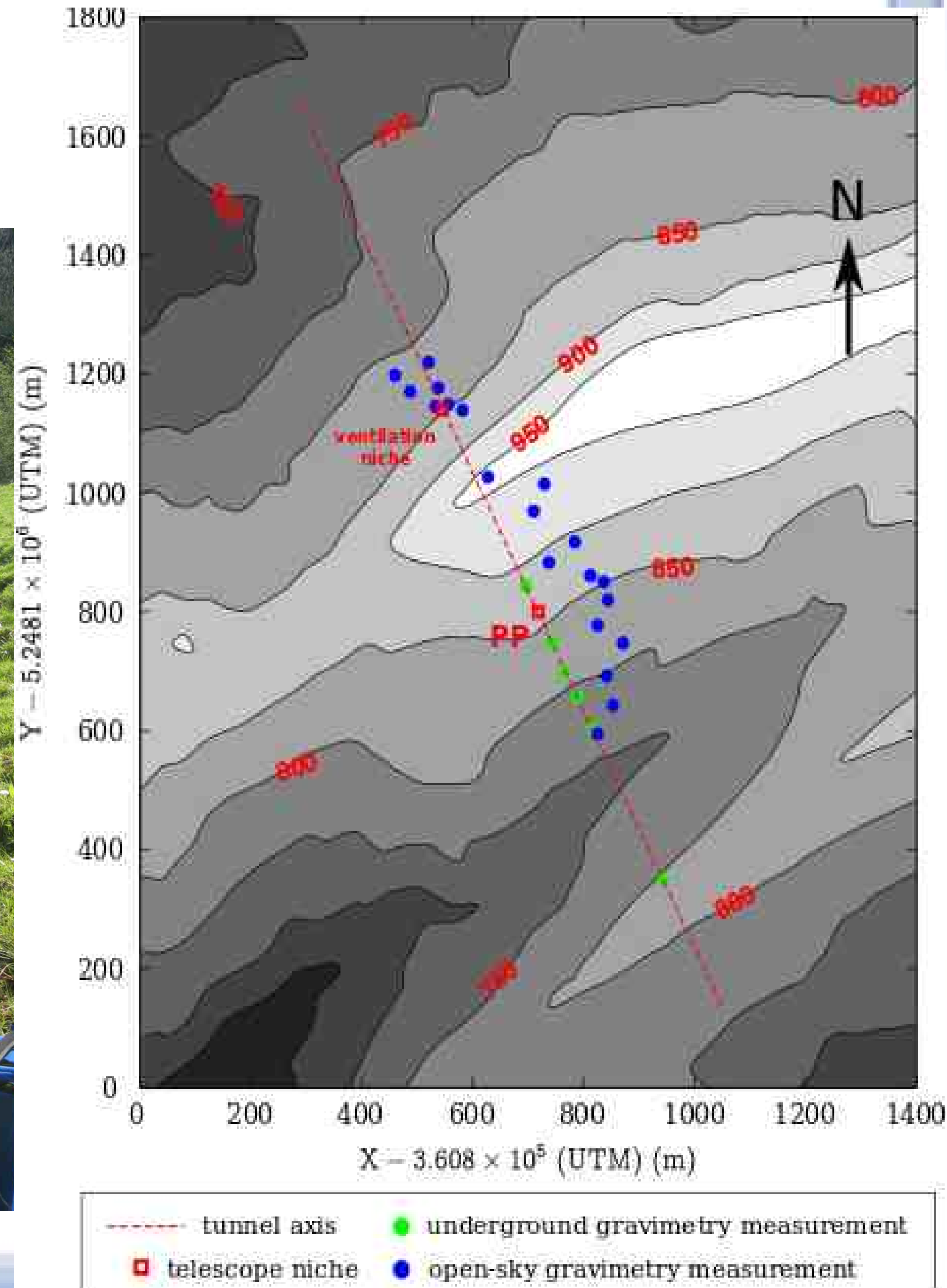


Mont Terri gravimetry

In Spring 2014 :

- 26 gravimetric points in the underground lab.
- 31 gravimetric points on surface.

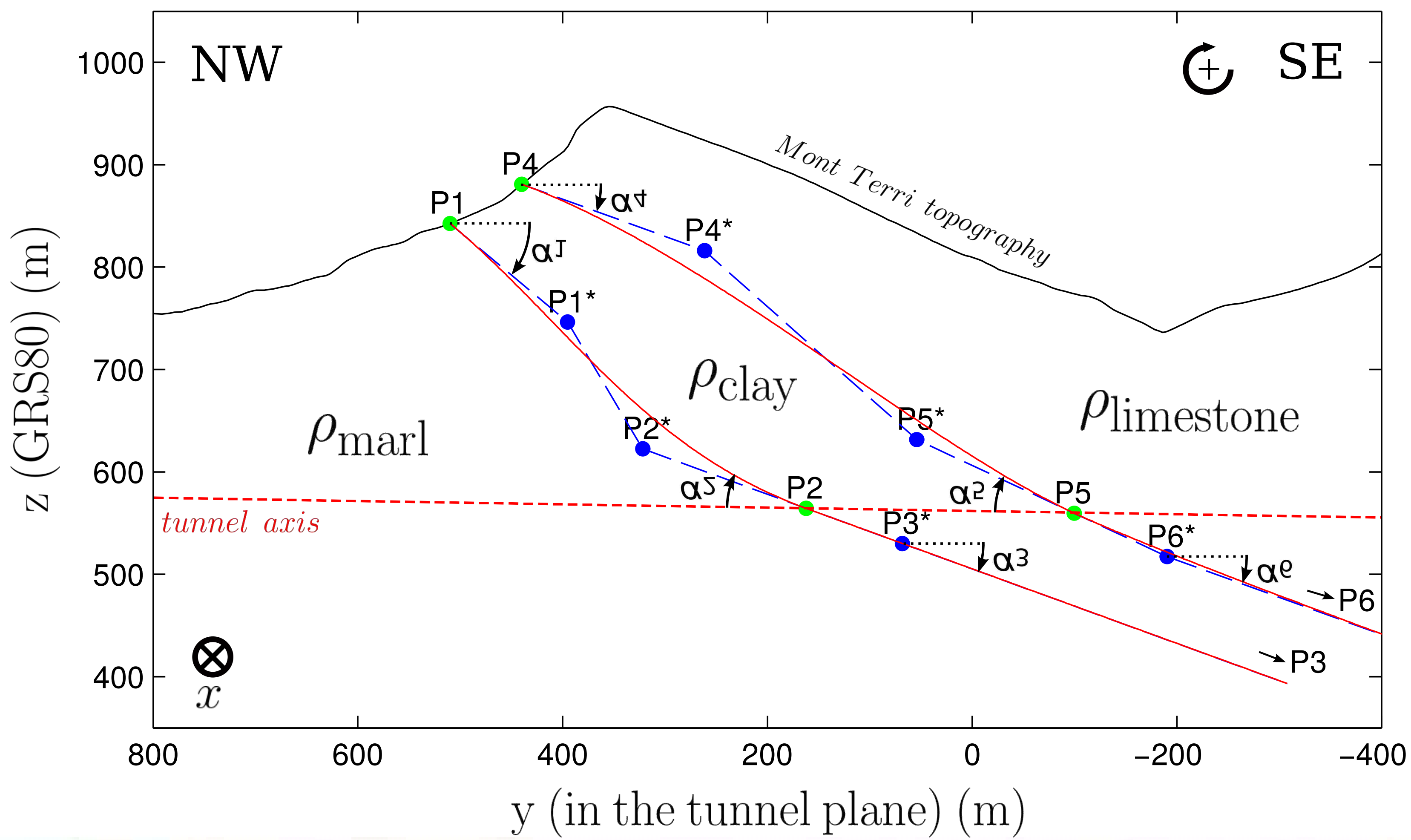




Mont Terri joined gravimetry – muography

The form of the interfaces is modellized using Bezier curves. The data are inverted to optimize the fit to the interfaces.

Opalinus layer parametrization

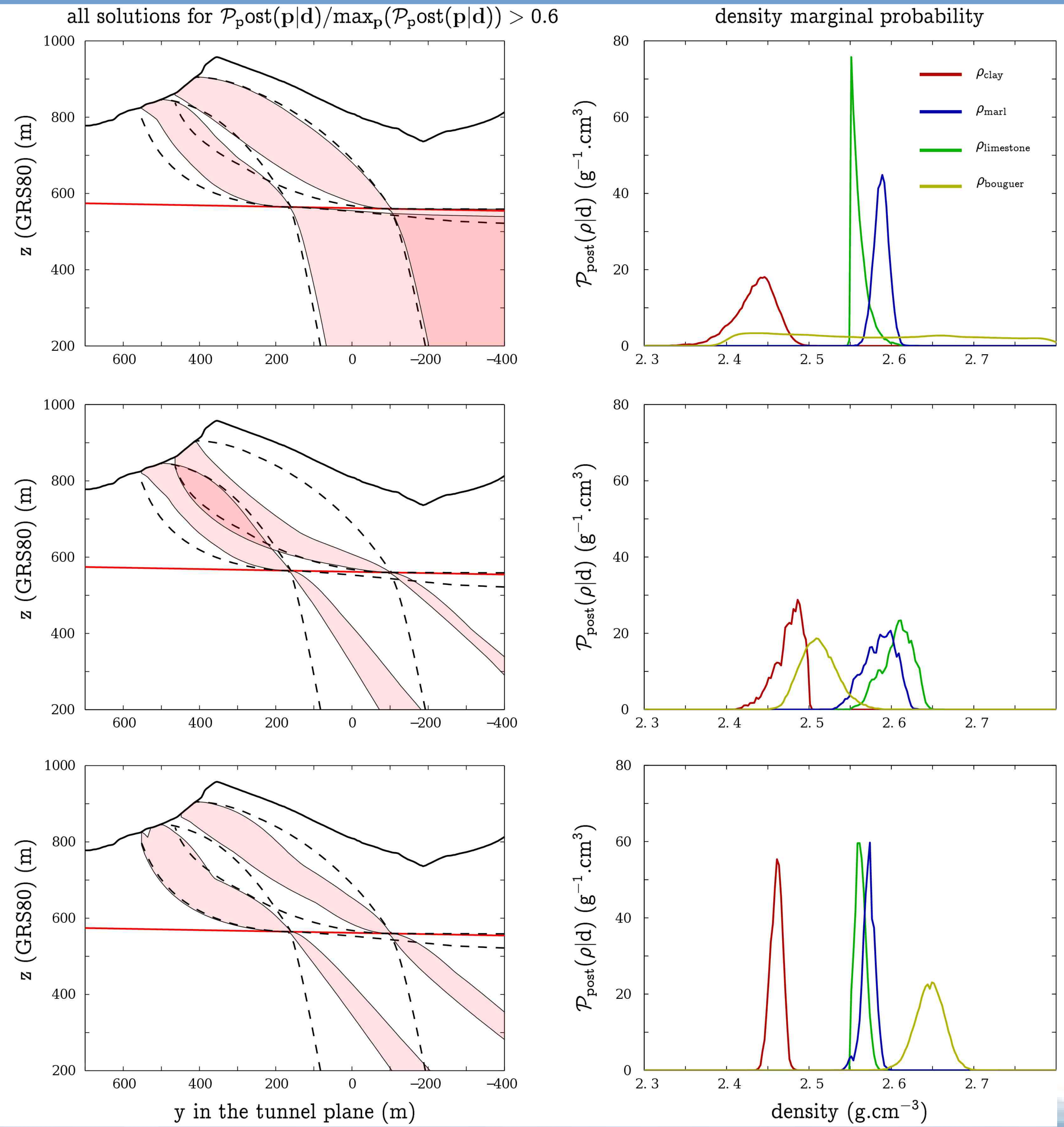


Mont Terri joined gravimetry – muography

tomography

gravimetry

tomography + gravimetry



Structural imaging of an urban tunnel (Lyon)

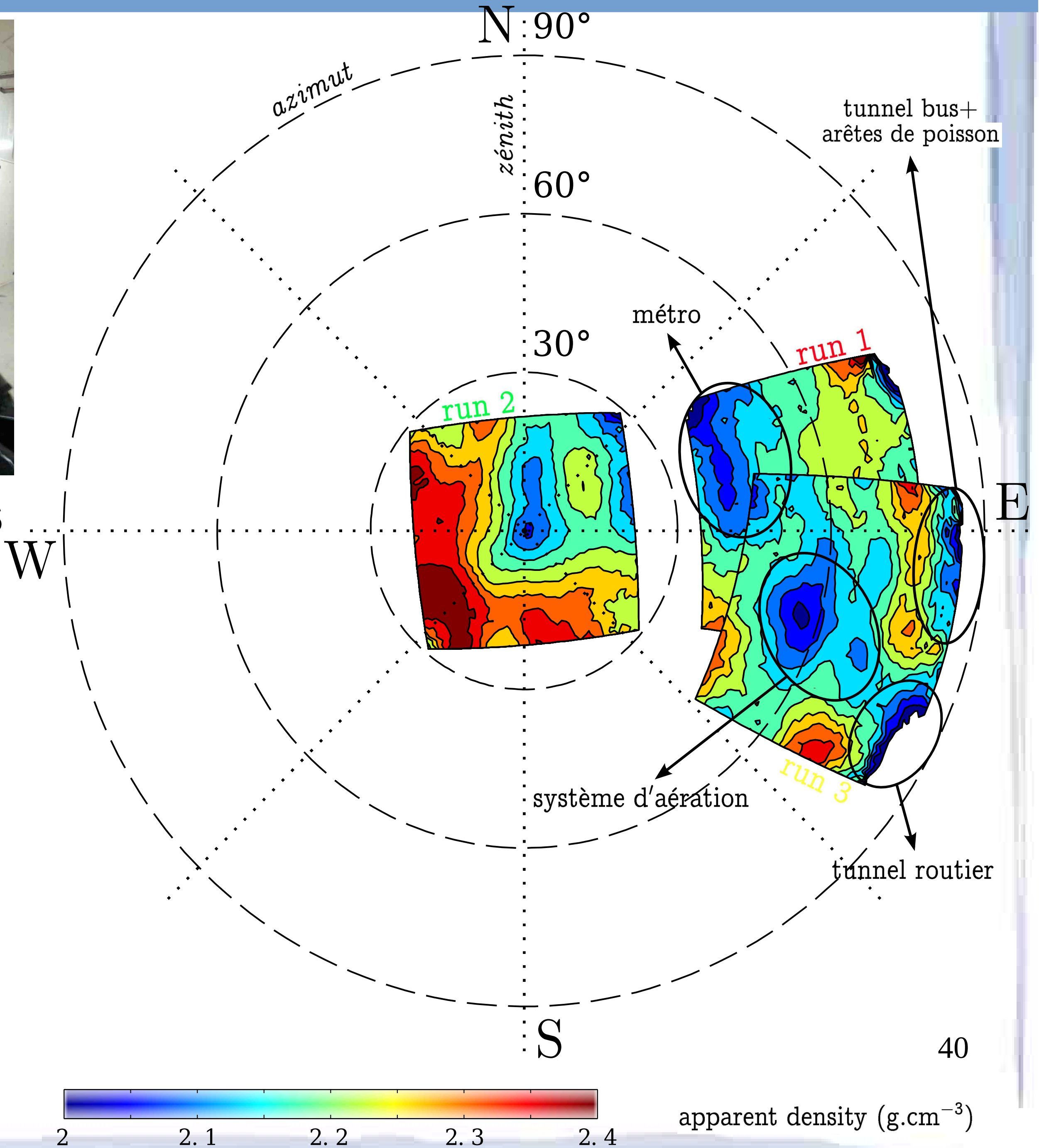
Structural imaging of an urban tunnel (Lyon)

Collaboration IPNL – CETU – PDS (private-public partnership).

Measurements in Croix Rousse tunnel (Lyon) to validate potential applications in civil engineering.

Geological cover of ~80m (20 m granite & 60 m clay, approx. 170 mwe).

Anthropic structures clearly visible on the images obtained after the 3 runs.



Conclusions

- DIAPHANE group is operating **scintillator-based** detectors, adapted to the harsh environmental conditions of active volcanoes since 2007.
- Muon tomography is providing new kind of measurements on la Soufrière de Guadeloupe, and is now part of the **permanent monitoring and survey** system of the volcano
- Besides the “standard” structural imaging, we demonstrated the feasibility of a **real-time monitoring** of the dome activity, related to the hydrothermal system.
- The coincidence of a larger number of detectors allows to perform 3D analysis, remove fake effects and improve the sensitivity.
- At this moment we are monitoring the regain of activity of la Soufrière
- Muon tomography finds various applications beyond active volcanoes studies: urban civil engineering, archaelogy, mining, etc. But getting muons flux maps is not the end of the job...

WEB*:* http://www.diaphane-muons.com/

MOVIE*:* https://vimeo.com/139232294

Mails*:* gibert@univ-rennes1.fr / marteau@ipnl.in2p3.fr