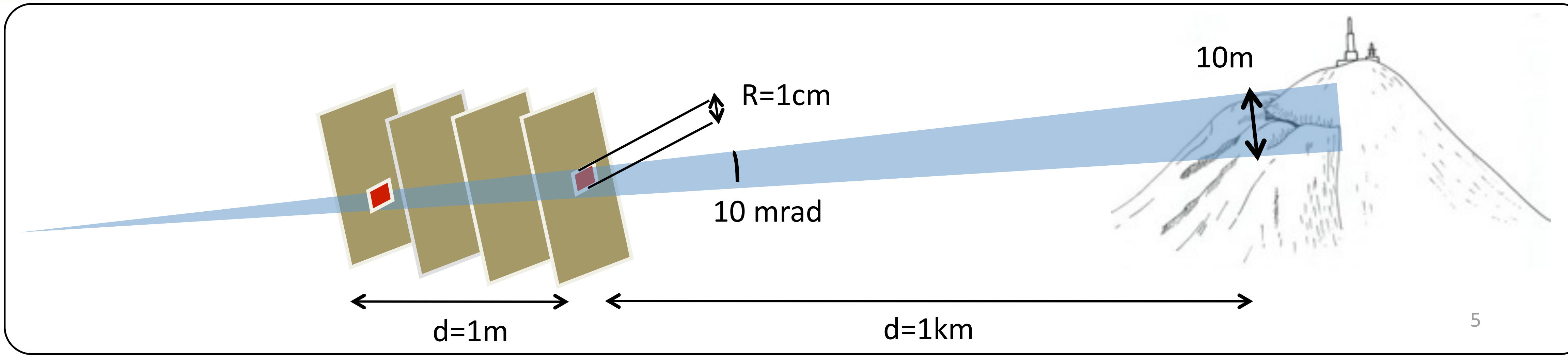
# *Muography in France*

# The muography in a nutshell …



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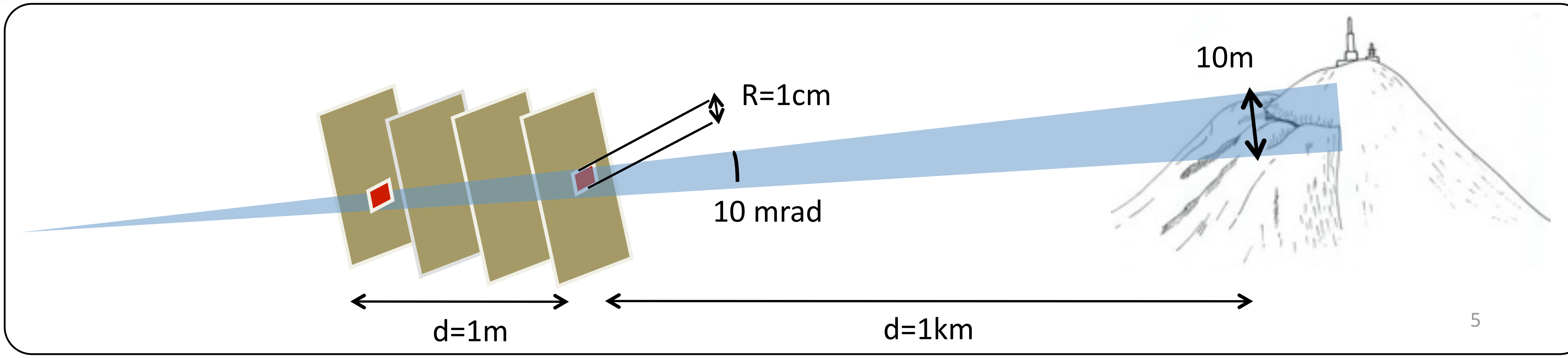


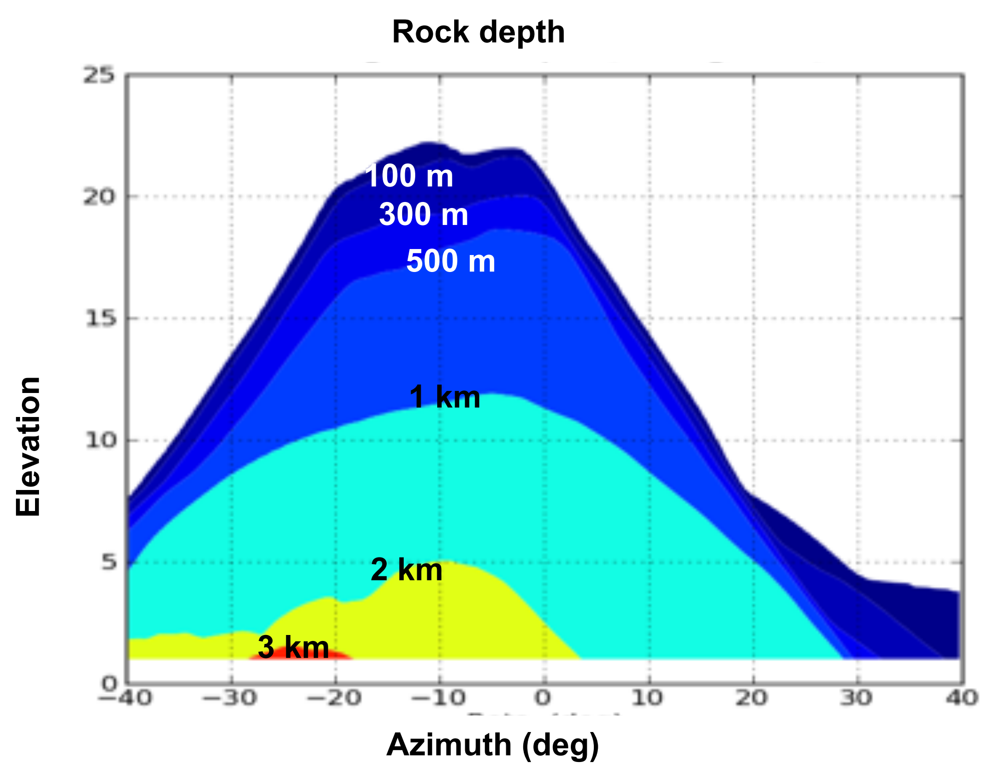


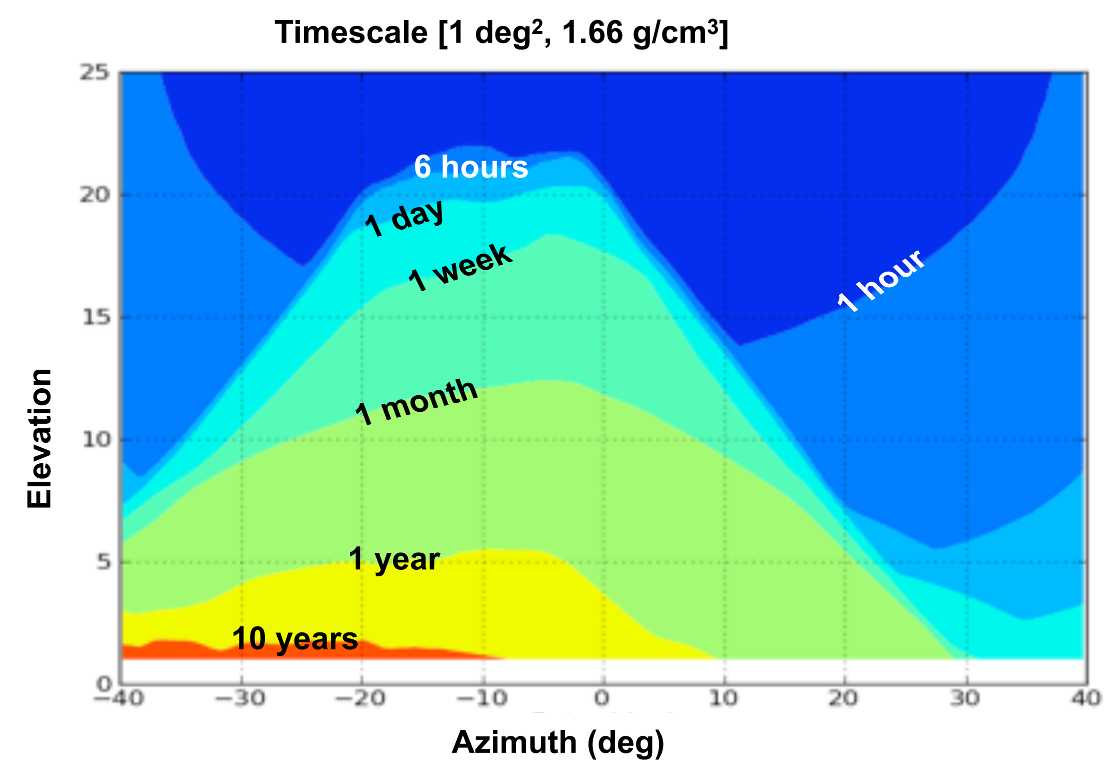


Computation for a uniform target with $\rho$=1.66g/cm$^3$ and a **0.67 m$^2$** ideal detector

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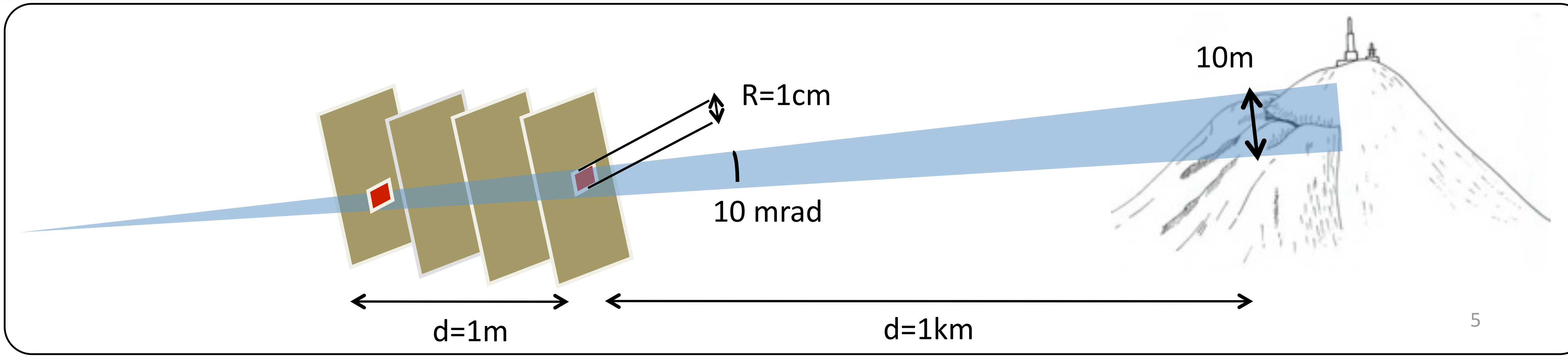


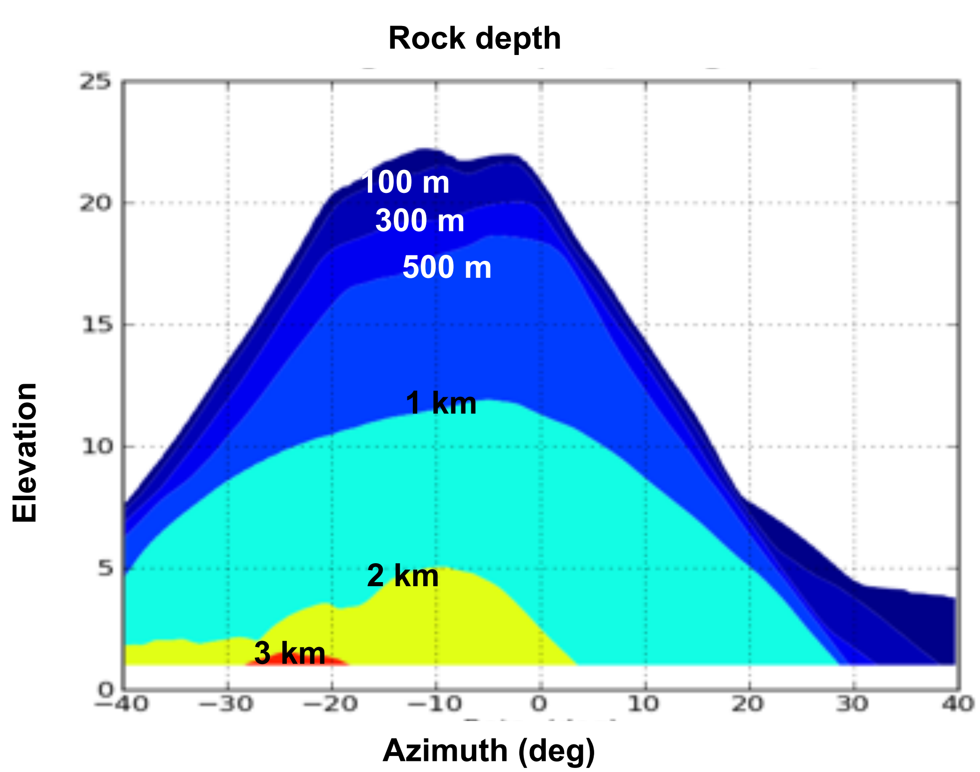


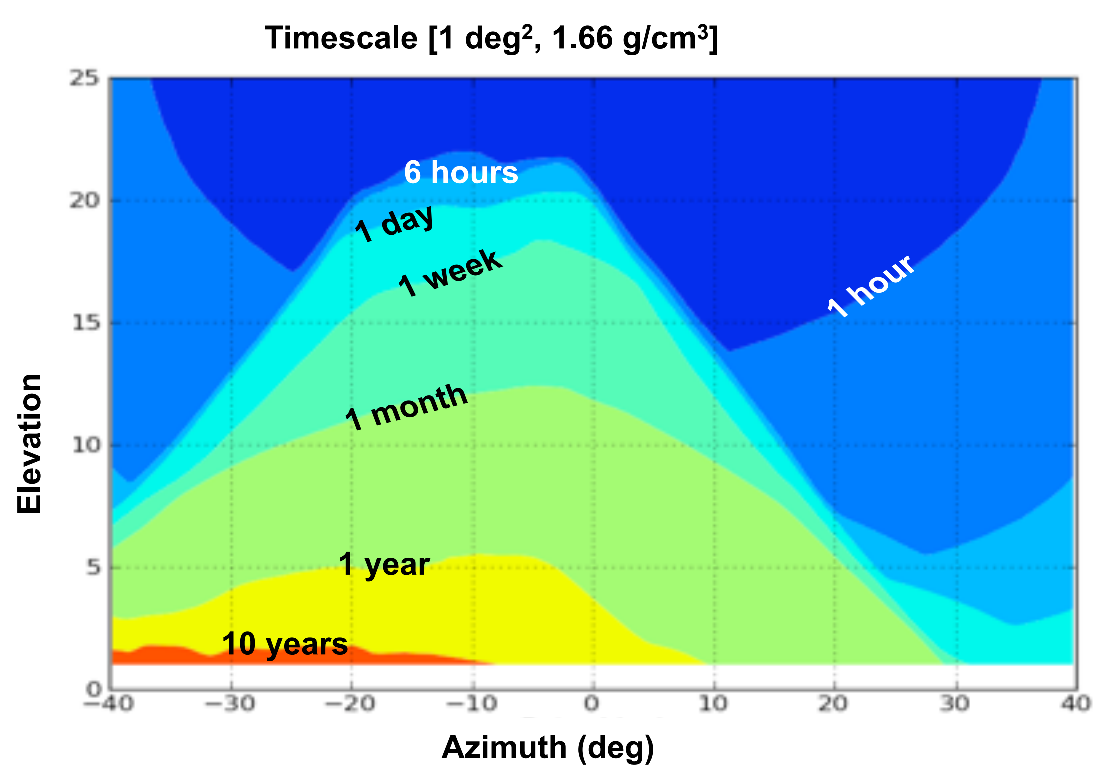


Computation for a uniform target with ρ=1.66g/cm³ and a **0.67 m²** ideal detector

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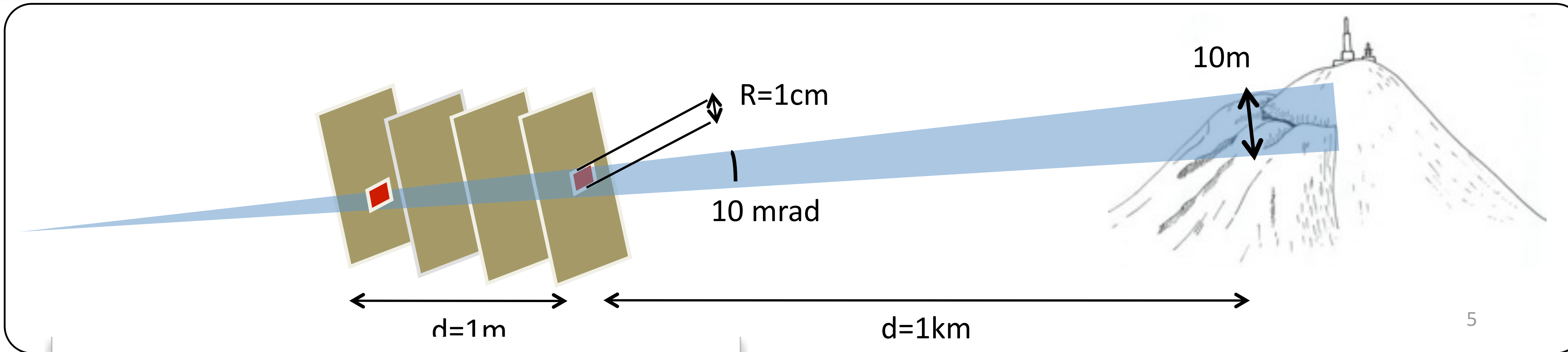
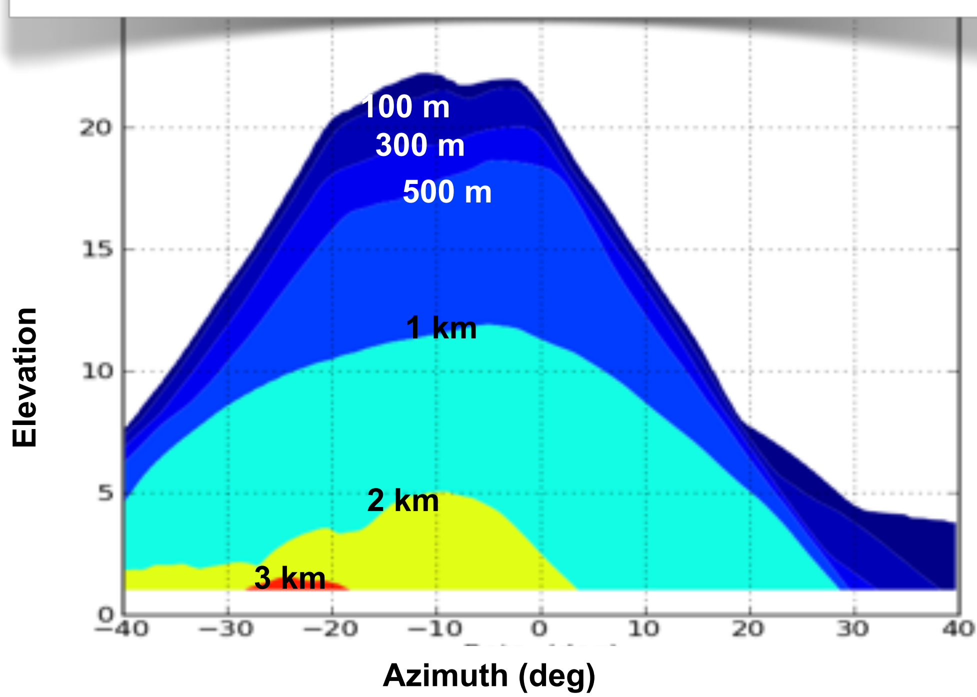


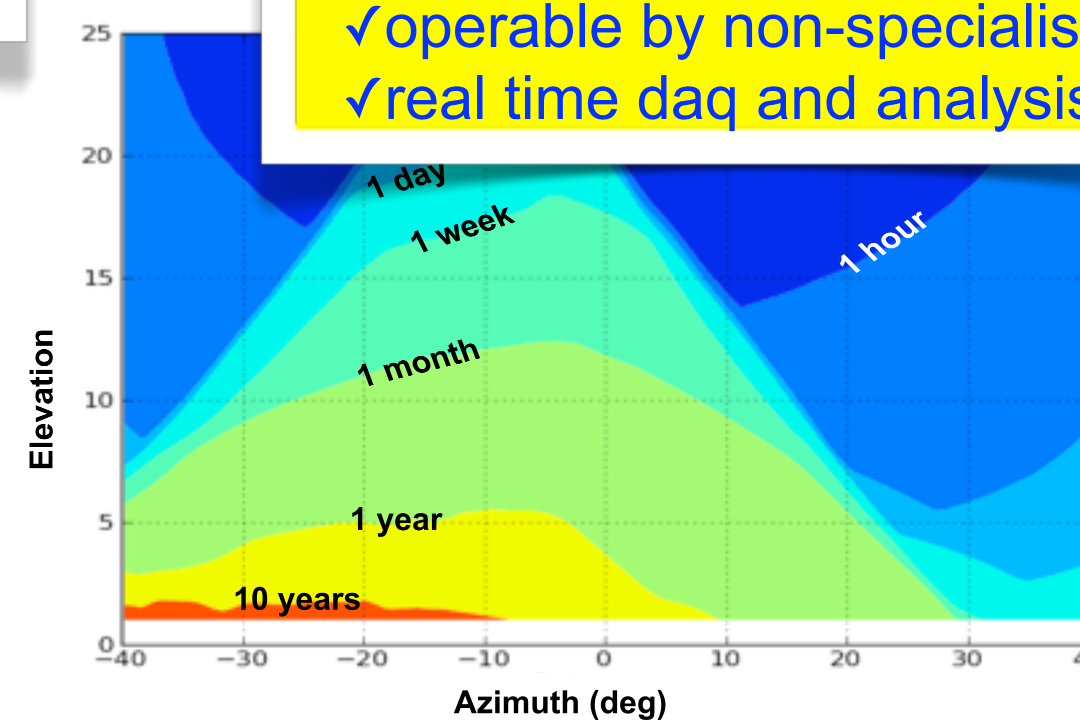

Required detector

- ✓large, upscalable surface
- ✓(very) good angular resolution
- ✓high efficiency
- ✓low noise

… and some more

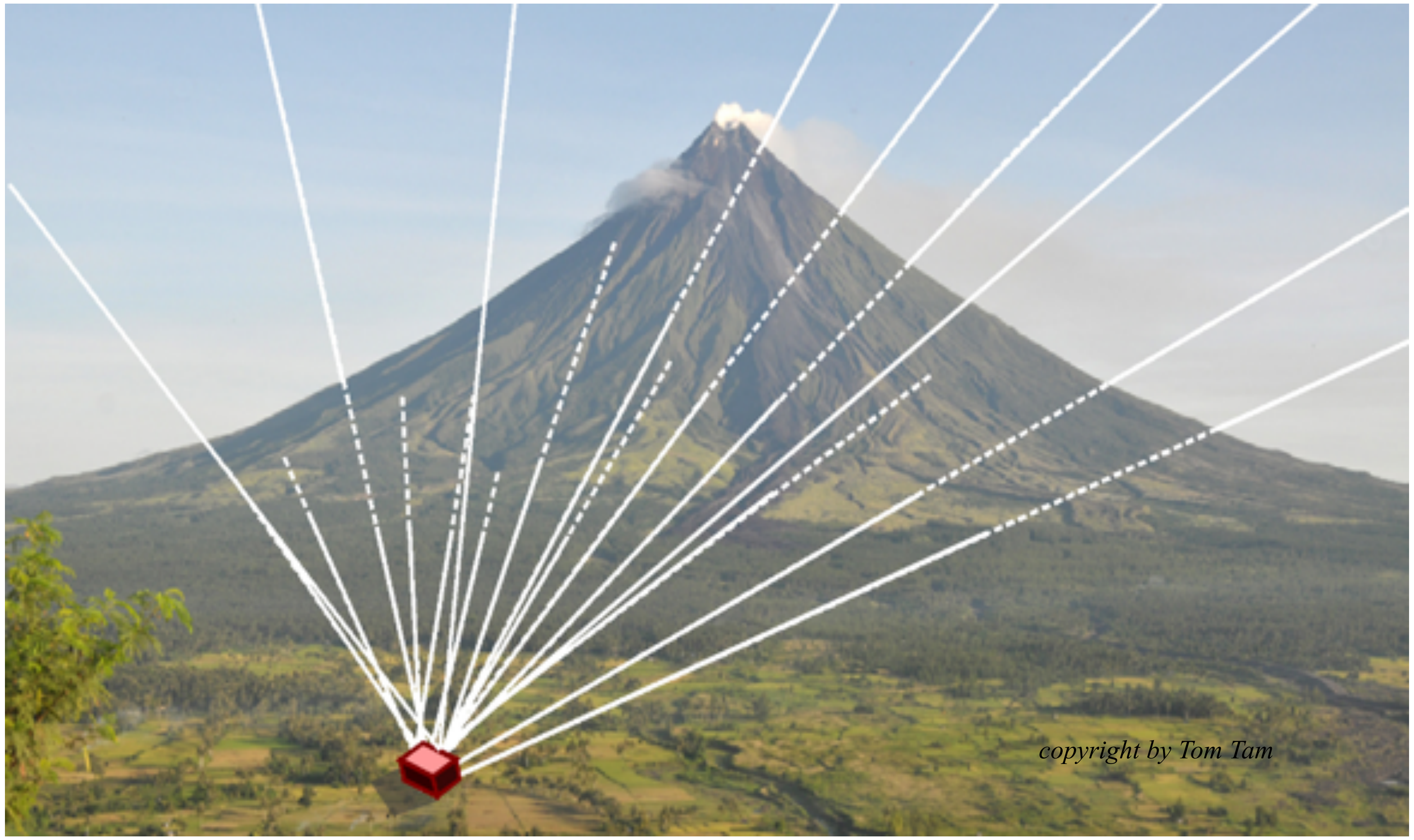
- ✓low power consumption
- ✓robust and stable
- ✓operable by non-specialists
- ✓real time daq and analysis



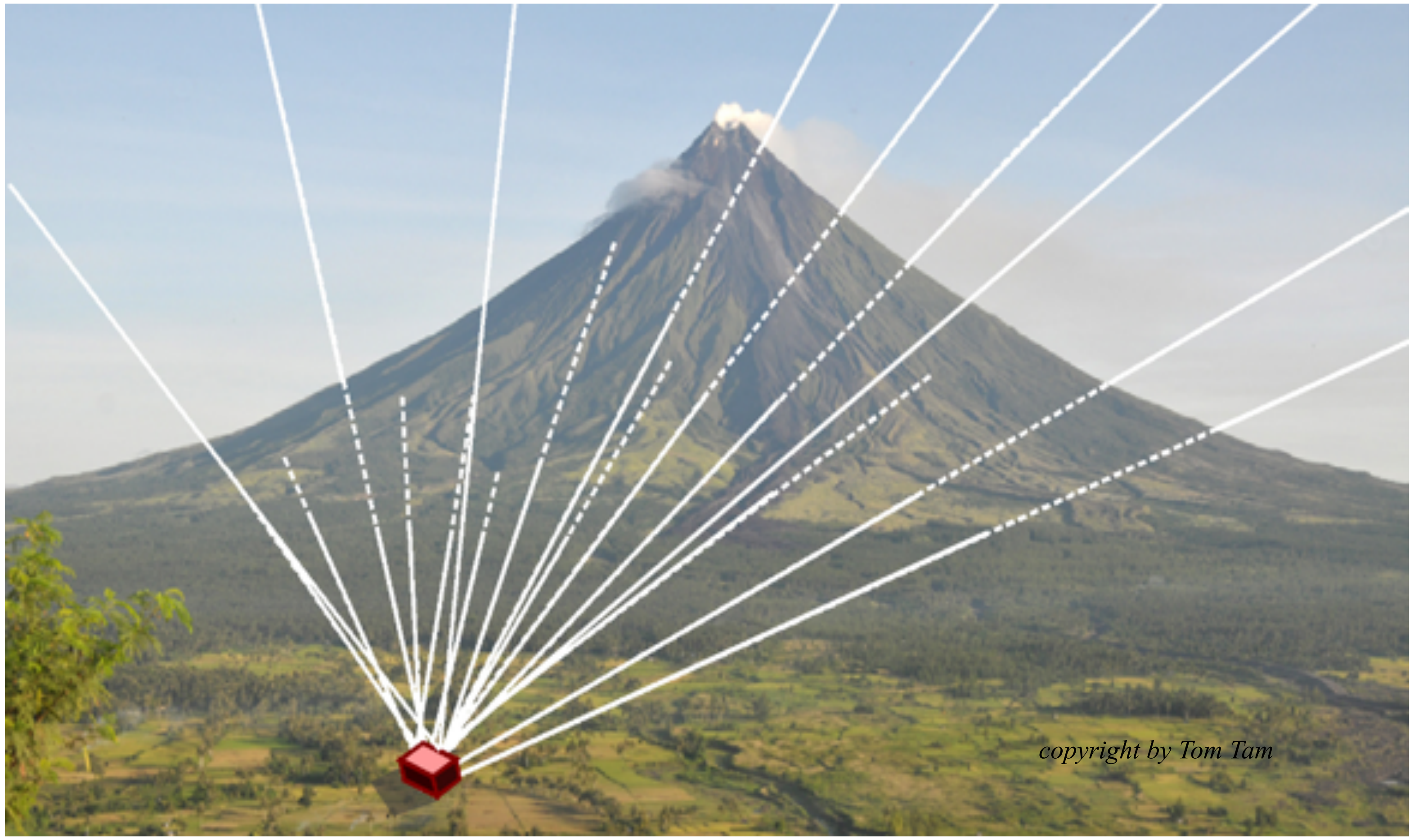




Computation for a uniform target with ρ=1.66g/cm³ and a **0.67 m²** ideal detector

## Study the target from outside



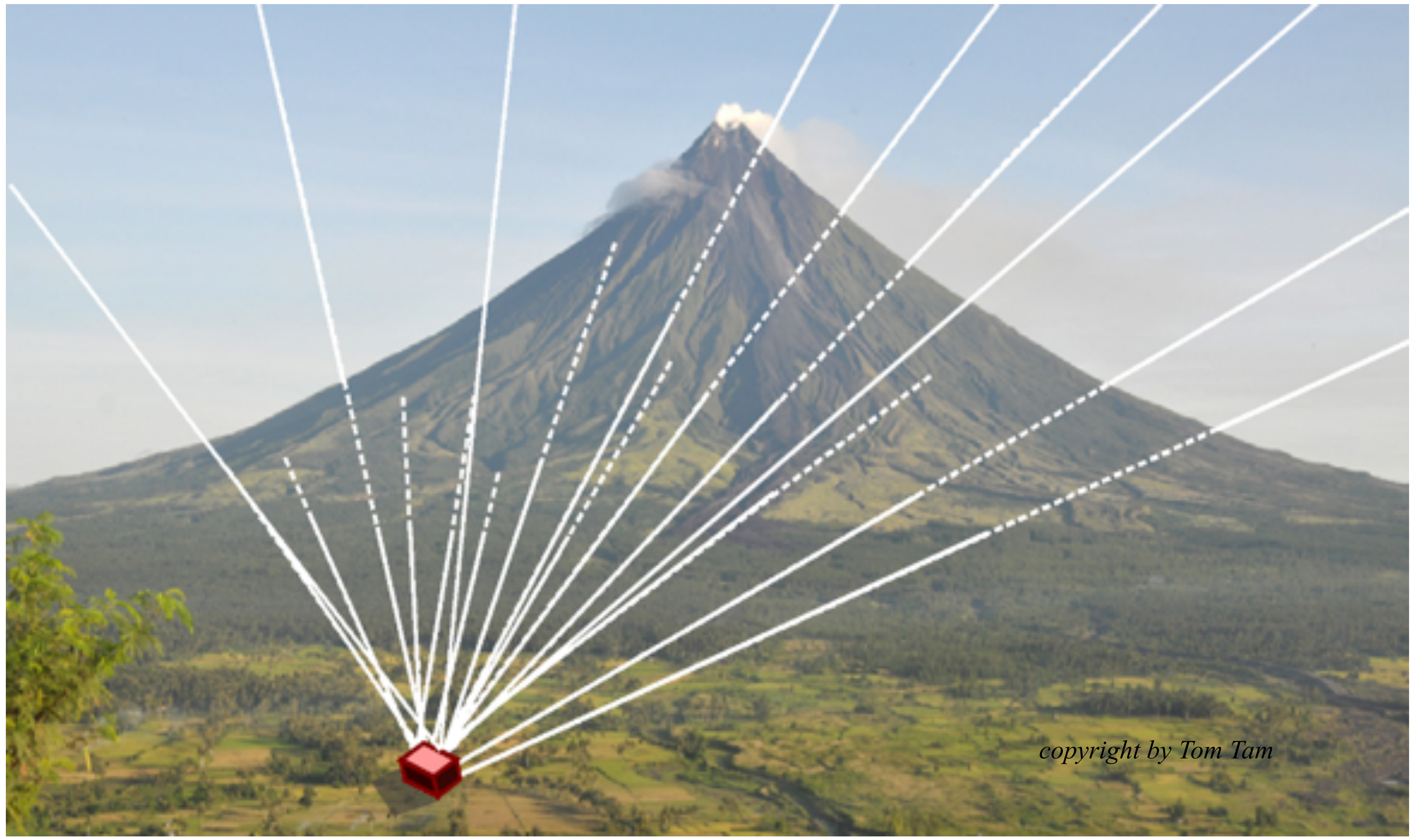
Study the target from outside




When a tunnel / borehole / cavity available use it to host your detector and look above your heads

- for metal deposits (@ Triumph)
- for water infiltration or rock structure alterations (T2DM2)

Study the target from outside




When a tunnel / borehole / cavity available use it to host your detector and look above your heads

- for metal deposits (@ Triumph)
- for water infiltration or rock structure alterations (T2DM2)

➥ No background problem (shielded by the target) ☺

➥ Generally little space available and sometimes demanding environment ☹

# T2DM2 PROJECT

## TOMOGRAPHY OF TIME VARYING ROCK DENSITY USING MUONS FLUX MEASUREMENTS

LSBB URL - *http://www.lsbb.eu*

*UMS 3538 University of Nice, University of Avignon, CNRS, Aix-Marseille University, OCA*

**F. HIVERT[1,2,3], S. GAFFET[1,2], J. BUSTO[3], P. SALIN[4], I.L. ROCHE [2]**

(1) GEOAZUR; (2) LSBB; (3) CPPM ; (4) C3IS

PARTNERSHIP

GEOAZUR, CPPM, CERN/RD51, CEA/IRFU, GÉOSCIENCES Montpellier, EMMAH (University of Avignon)

INTERDISCIPLINARITY

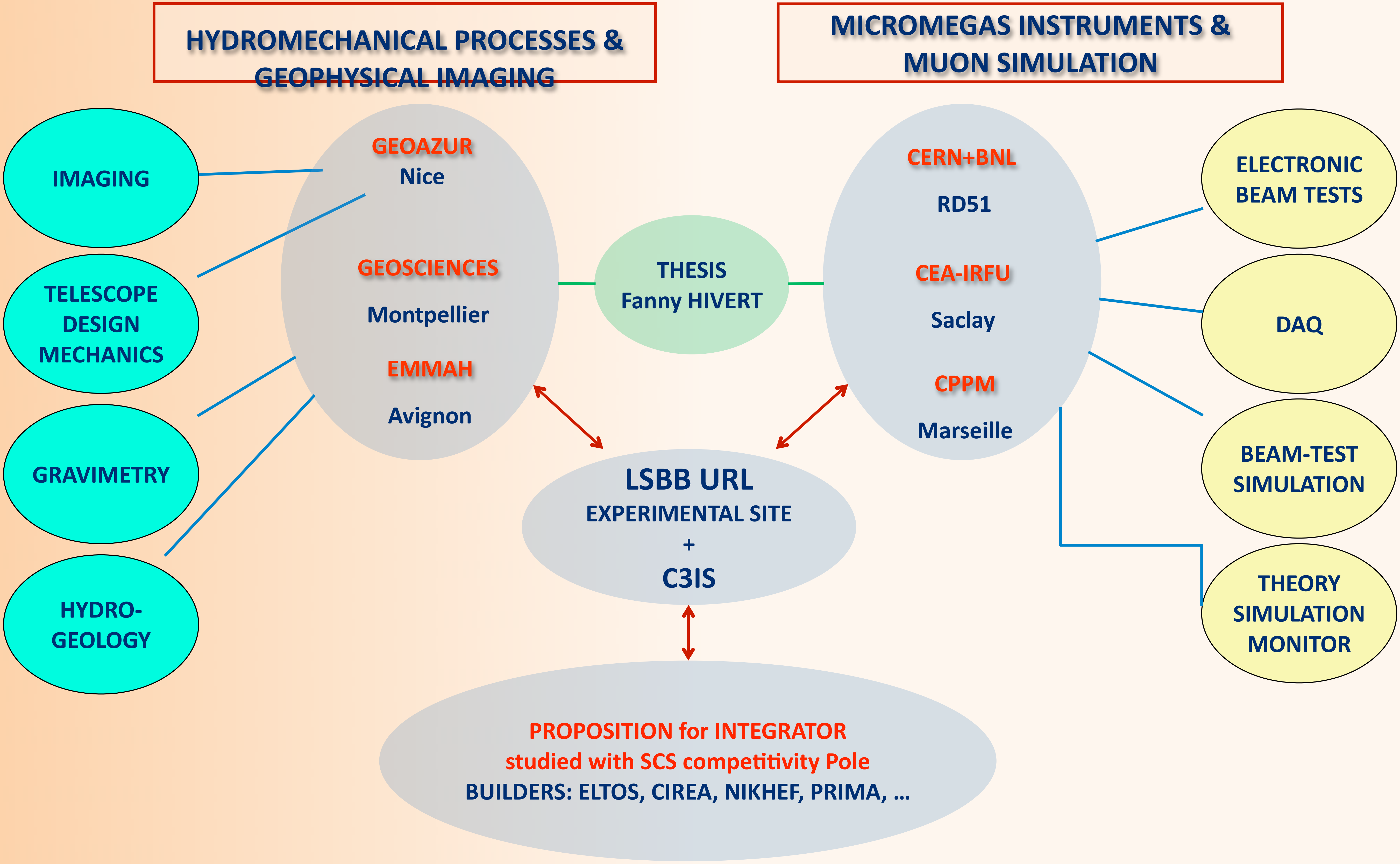
ASTROPARTICULES – SEISMOLOGY– GRAVIMETRY - HYDROGEOLOGY - ROCK MECHANICS - EM IMAGERY

FUNDED BY

l'Europe s'engage en Provence-Alpes-Côte d'Azur avec le FEDER

MAIF FONDATION Soutenir la recherche pour prévenir les risques

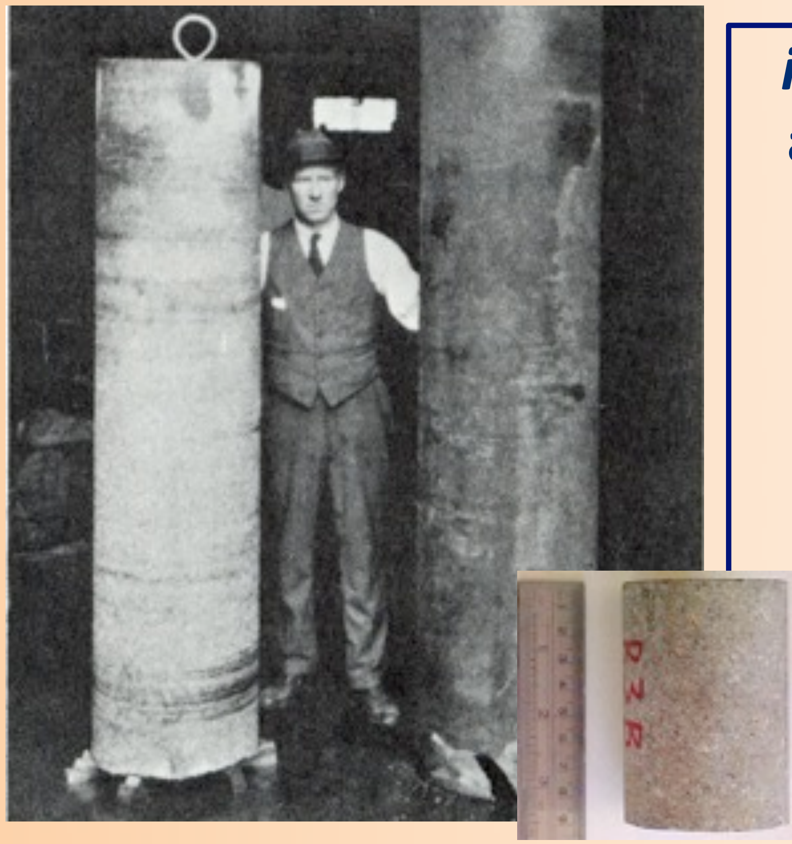
# T2DM2 PROJECT - STRUCTURE OF COLLABORATION



# T2DM2 PROJECT: FUNDAMENTAL QUESTION ADDRESSED

## What are the sub-surface mechanical parameters of rock in situ ?

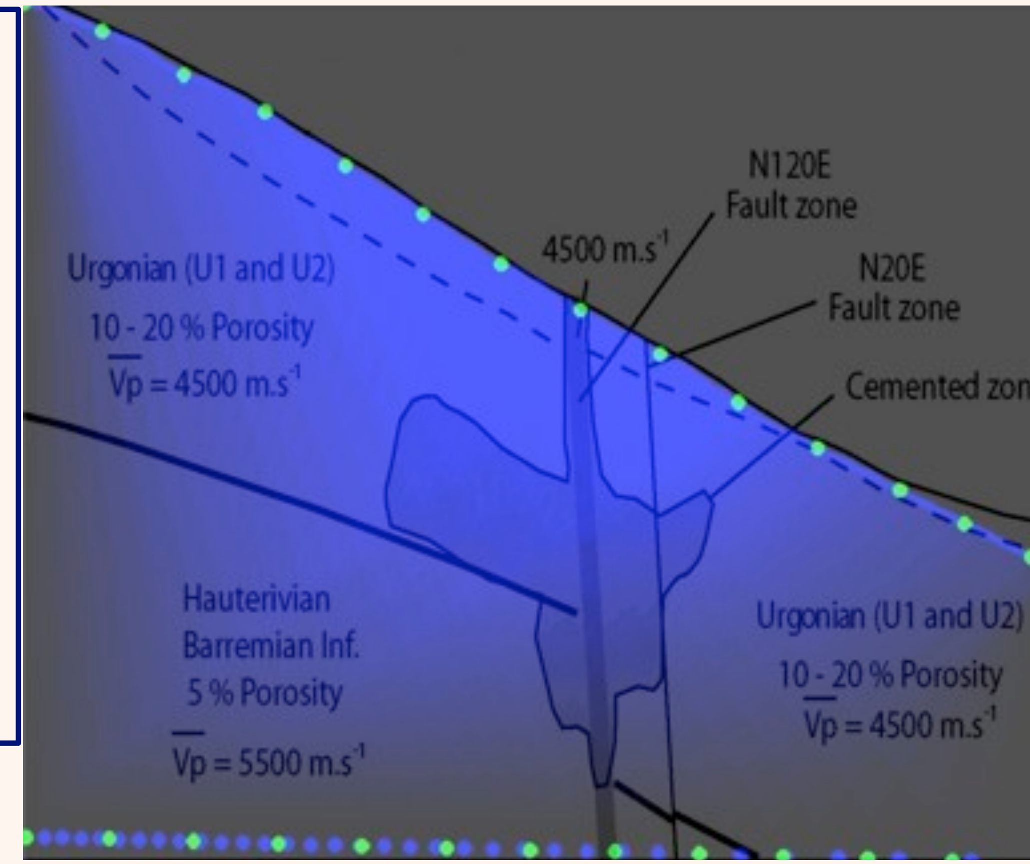
- **MEASUREMENTS ON SAMPLES OF SMALL SCALES ALTHOUGH THEY APPEAR OF LARGE SIZES**



**_in situ_ mechanical parameters are unknown at the scale of a multi hectometric subsurface rock mass**

**Effective stress ?**
**Rock damage ?**

**⇒ Coupling**
**eismic imaging & densitometry**



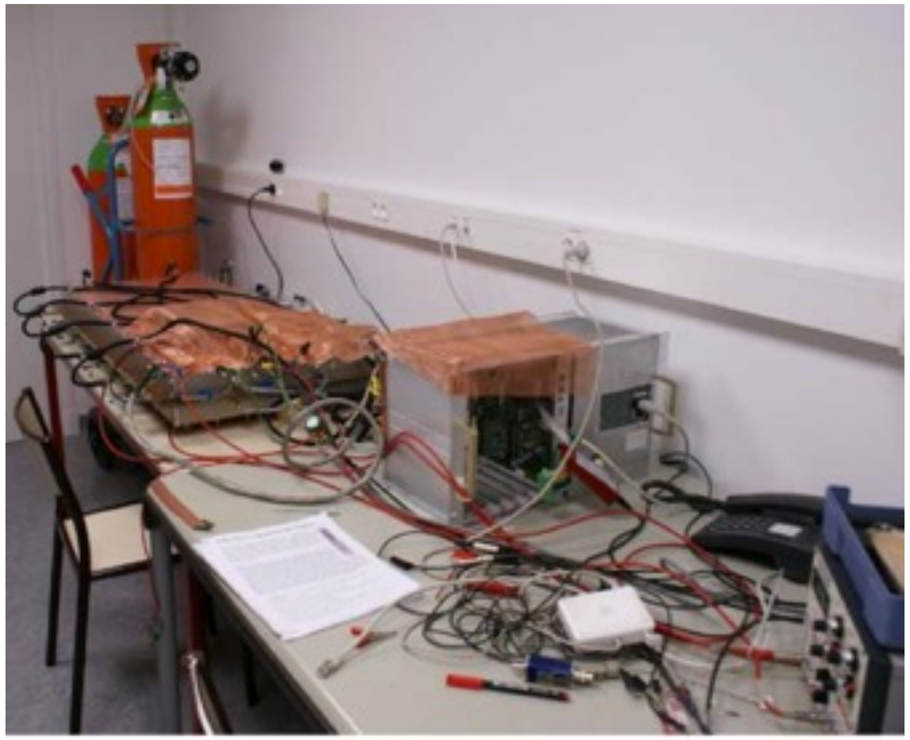

- **EMPIRICAL METHOD**

| **Measurement**<br>Mechanical parameters at small scale | → | Qualitative description of rock mass (scale, fracturation, hydraulic alteration, …) | → | **Estimation**<br>Mechanical parameters at large scale |
|---|---|---|---|---|

*Bieniawski (1976), Hoek & Brown (1980)*

## Micromegas

*T2DM2*



position res: 0.22 mm
angular res(@10 cm) : 2 mrad
time resolution : 25 ns

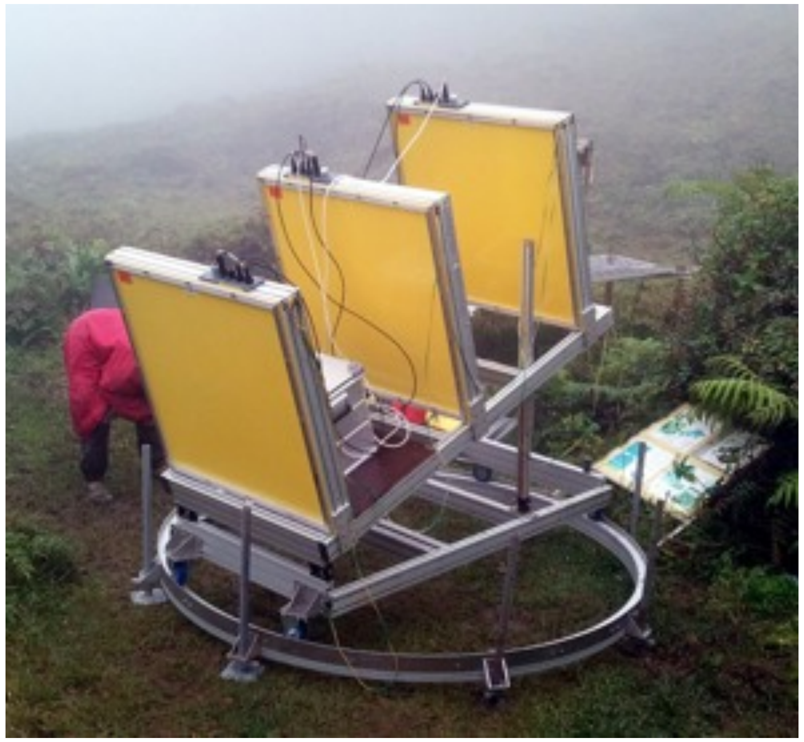
# Different detector technologies for the French projects

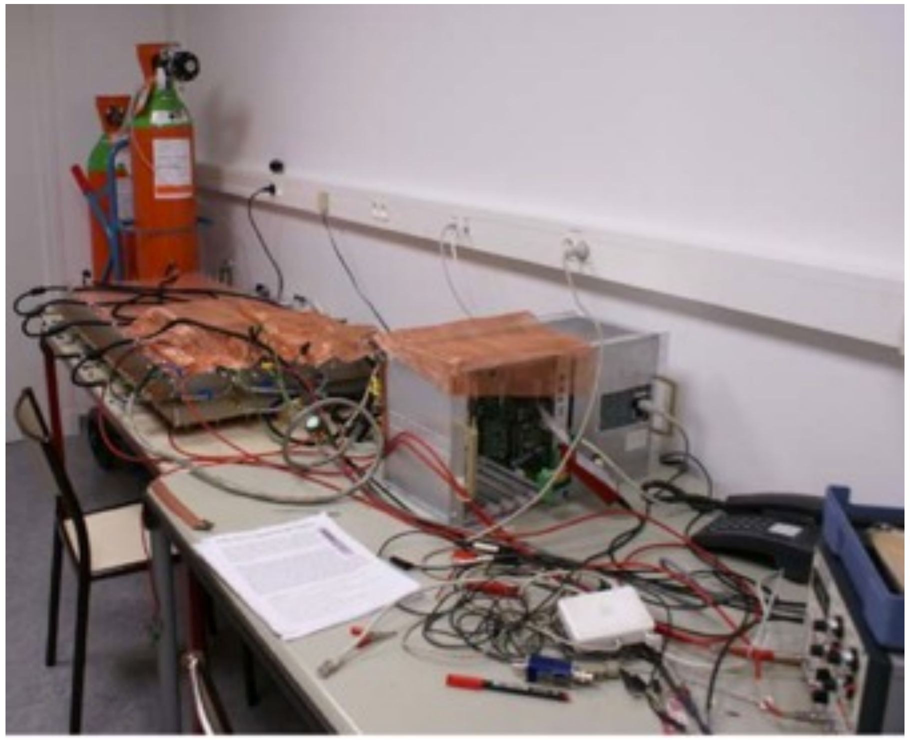
Scintillators

*DIAPHANE*

Micromegas

*T2DM2*



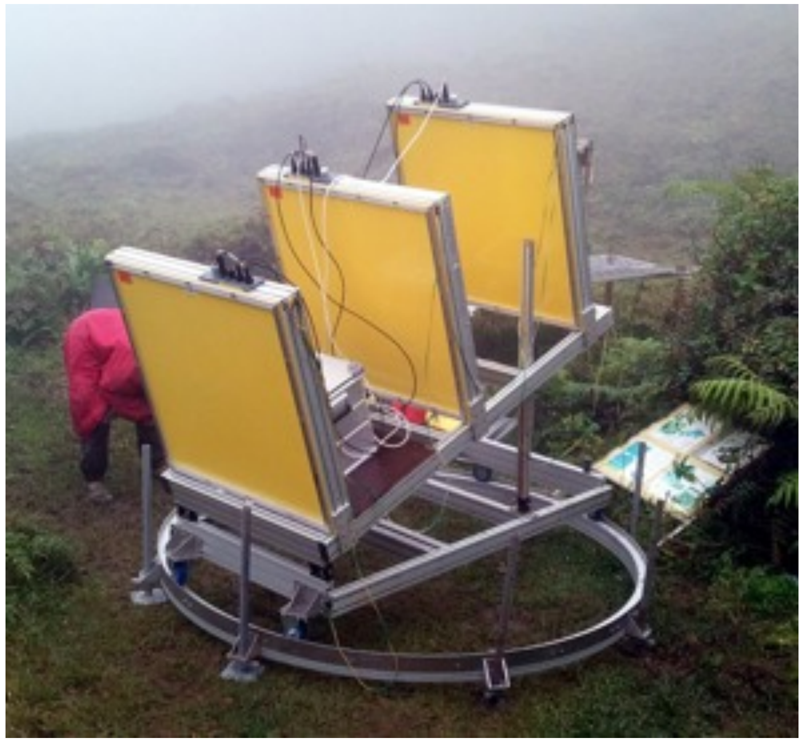


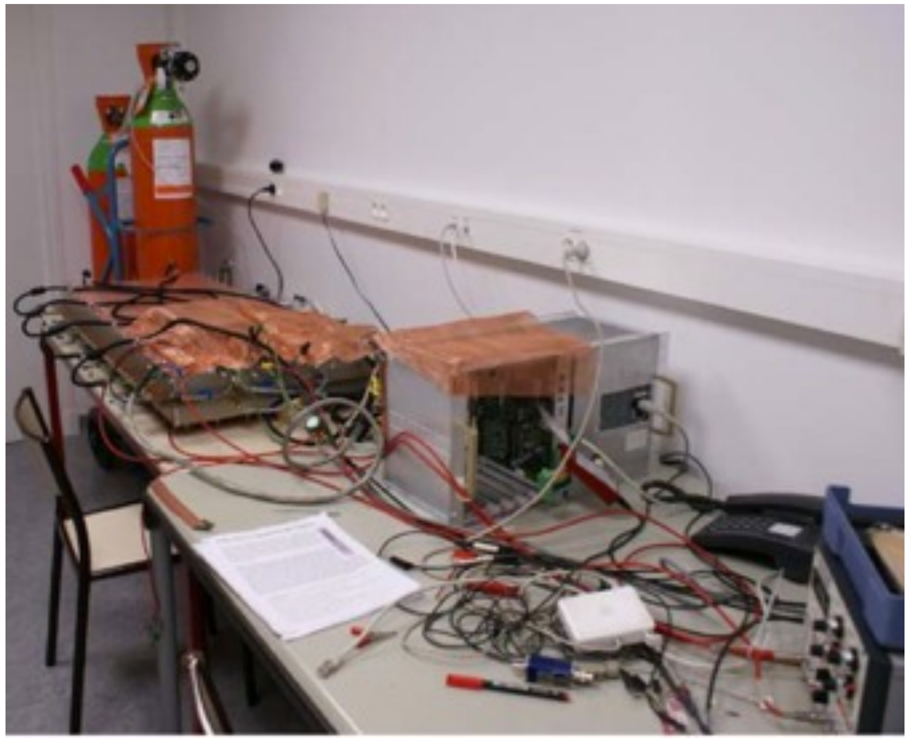
position res: 35 mm
angular res(@1m) : 35 mrad
time resolution : 1 ns
surface: 0.64 $m^2$

position res: 0.22 mm
angular res(@10 cm) : 2 mrad
time resolution : 25 ns

# Different detector technologies for the French projects

| Scintillators | Micromegas | GRPCs |
| --- | --- | --- |
| *DIAPHANE* | *T2DM2* | *TOMUVOL* |





position res: 35 mm
angular res(@1m) : 35 mrad
time resolution : 1 ns
surface: 0.64 $m^2$

position res: 0.22 mm
angular res(@10 cm) : 2 mrad
time resolution : 25 ns

position res: 4 mm
angular res(@1m) : 4 mrad
time resolution : 200 ns
surface: 1 $m^2$

# Different by-targets and measurement strategies

- ➥ shallow targets (< hundreds of meters)
  small detectors, easy to deploy and operate
- ➥ large targets (> kilometers)
  large detectors
  tight control of the background needed

# Different by-targets and measurement strategies

➥ shallow targets (< hundreds of meters)
small detectors, easy to deploy and operate

➥ large targets (> kilometers)
large detectors
tight control of the background needed

➥ close to the target
- statistics optimised
- can generally isolate the target from neighboring relief
- no need for extraordinary resolution
- deployment difficulties
- tropicalisation / safety issues

➥ safely away from the target (~ kilometers)
- deployment/safety issues minimised
- larger detectors needed
- very good resolution required, helps with background rejection

# DIAPHANE PROJECT

# Structural imaging and monitoring of volcanoes with cosmic muons

P.I. Dominique Gibert[1] & Jacques Marteau[2]
1: IPG Paris and Géosciences Rennes
2: IPN Lyon and Univ. Claude Bernard
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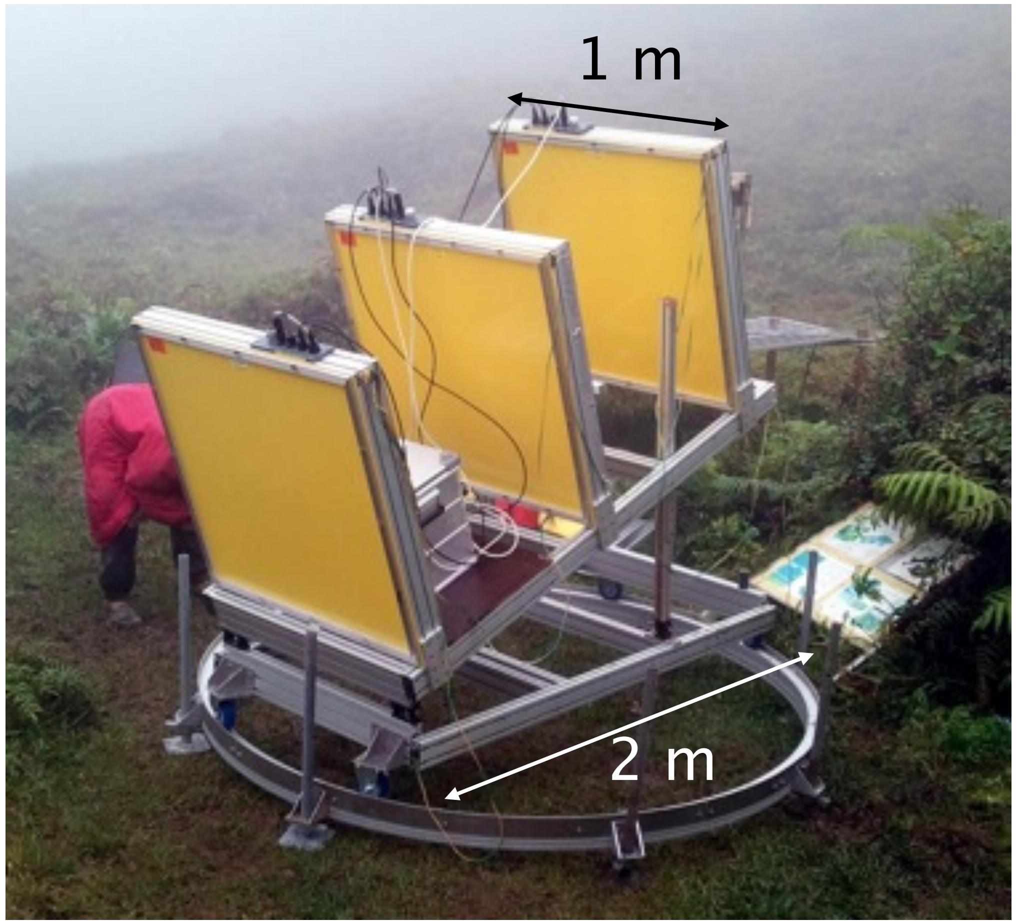
Main partners: IPG Paris, IPN Lyon, Geosciences Rennes, APC
Collaborations: INGV Catania, CEA/IRFU, Earth Obs. Singapour, Swisstopo, IRSN

We acknowledge financial supports from: the UnivEarthS Labex program of Sorbonne Paris Cité (ANR-10-LABX-0023 and ANR-11-IDEX-0005-02), the DomoScan ANR project, Swisstopo, IRSN, Earth Observatory of Singapour, IPGP BQR, IN2P3 programs.

# Field telescopes: 5 instruments in operation

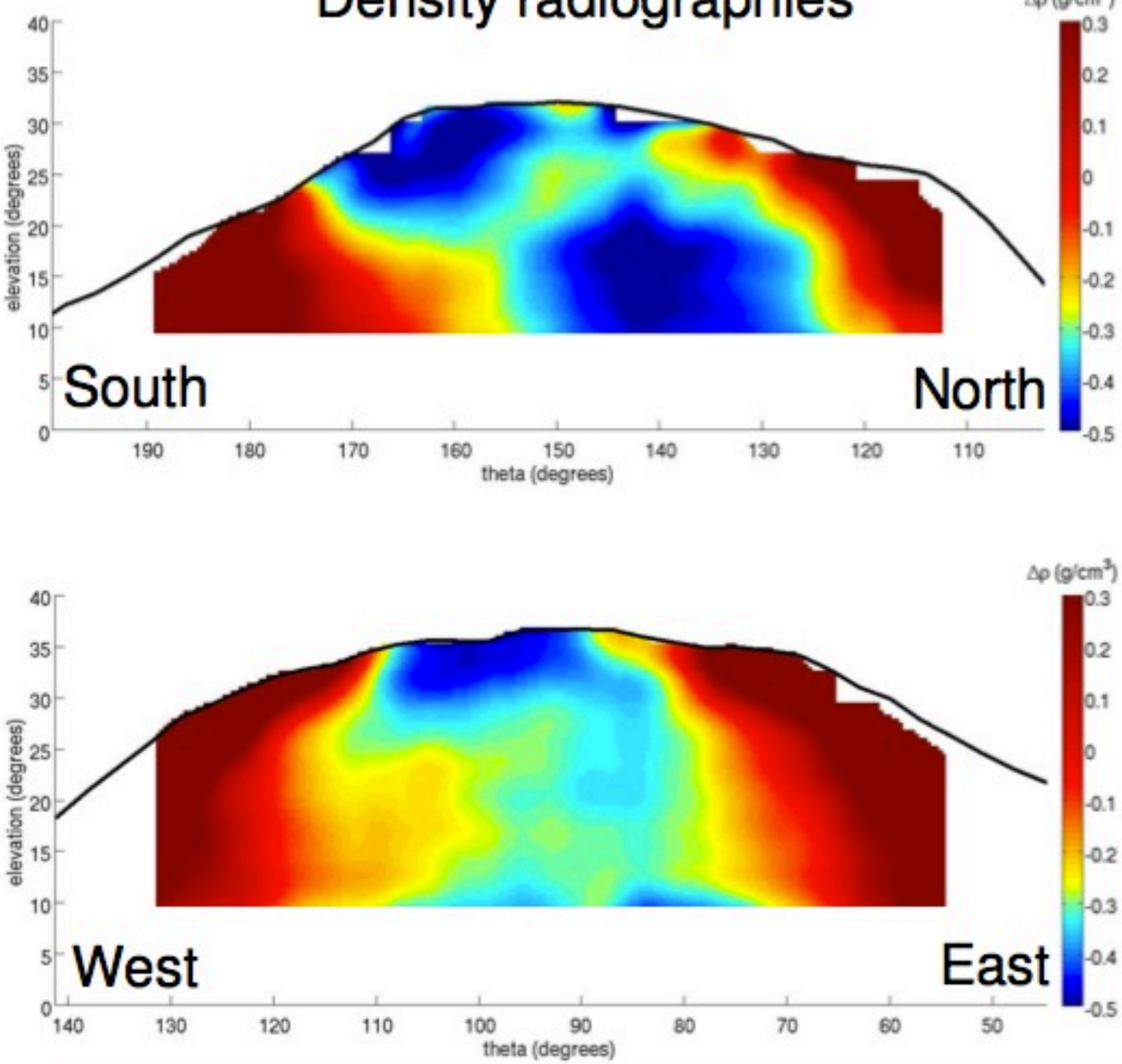



Matrices made with scintillator strips (256 pixels)
Total power consumption < 50W @ 10-30V
Power units: photovoltaic, wind turbine, fuel cells
Remote control and environmental sensors
Total mass: 200 to 600 kg depending on options used
Modular design for easy installation and moving
Rugged design for harsh weather conditions
Angular aperture 30°- 60°Angular resolution 1° - 2°
Typical acceptance: 10 - 25 $cm^2$.sr
Field experiments: Soufrière of Guadeloupe, Soufrière Hills Montserrat, Mayon, Etna, Mont-Terri and Tournemire underground laboratories

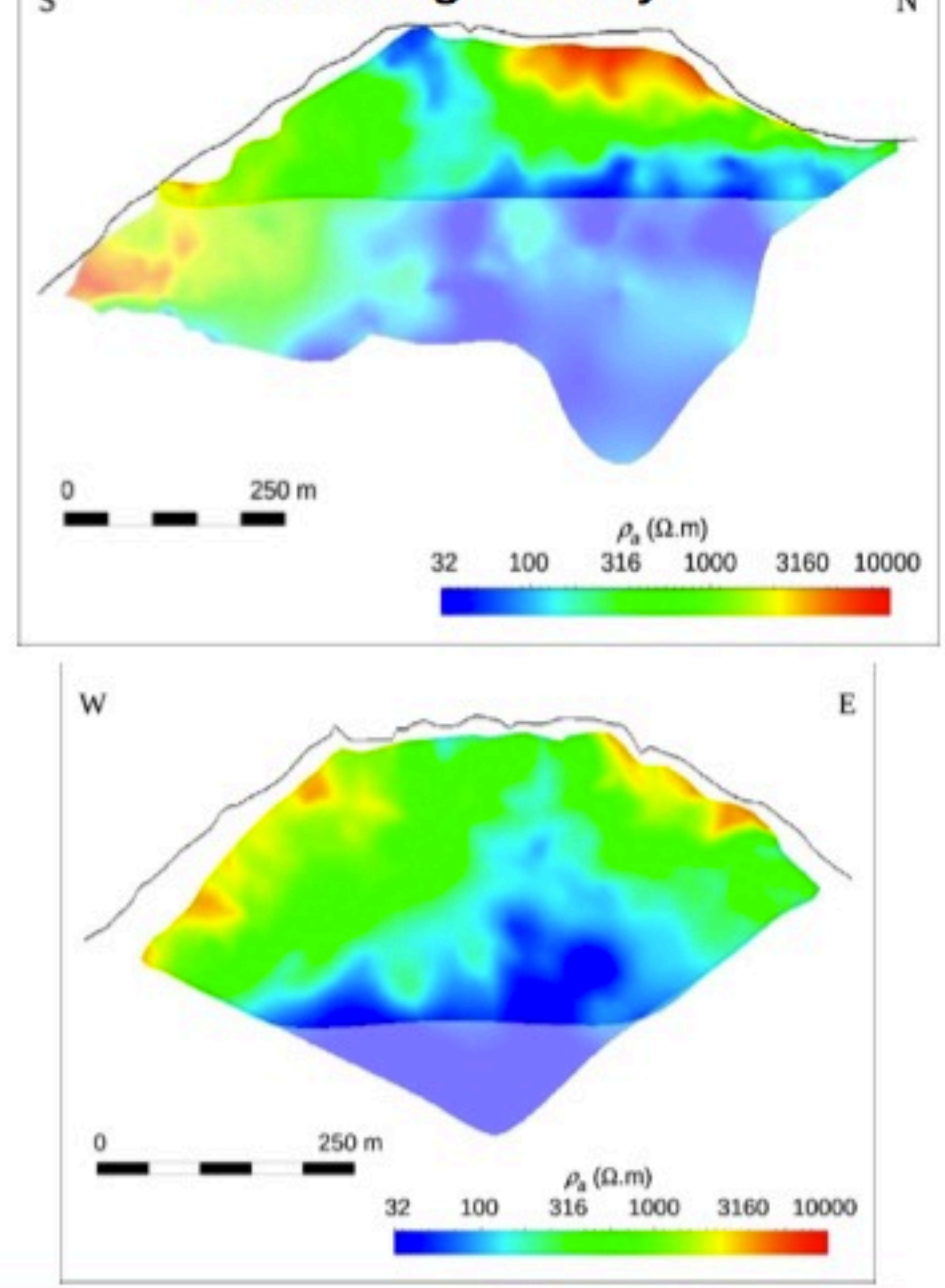


# La Soufrière structural imaging

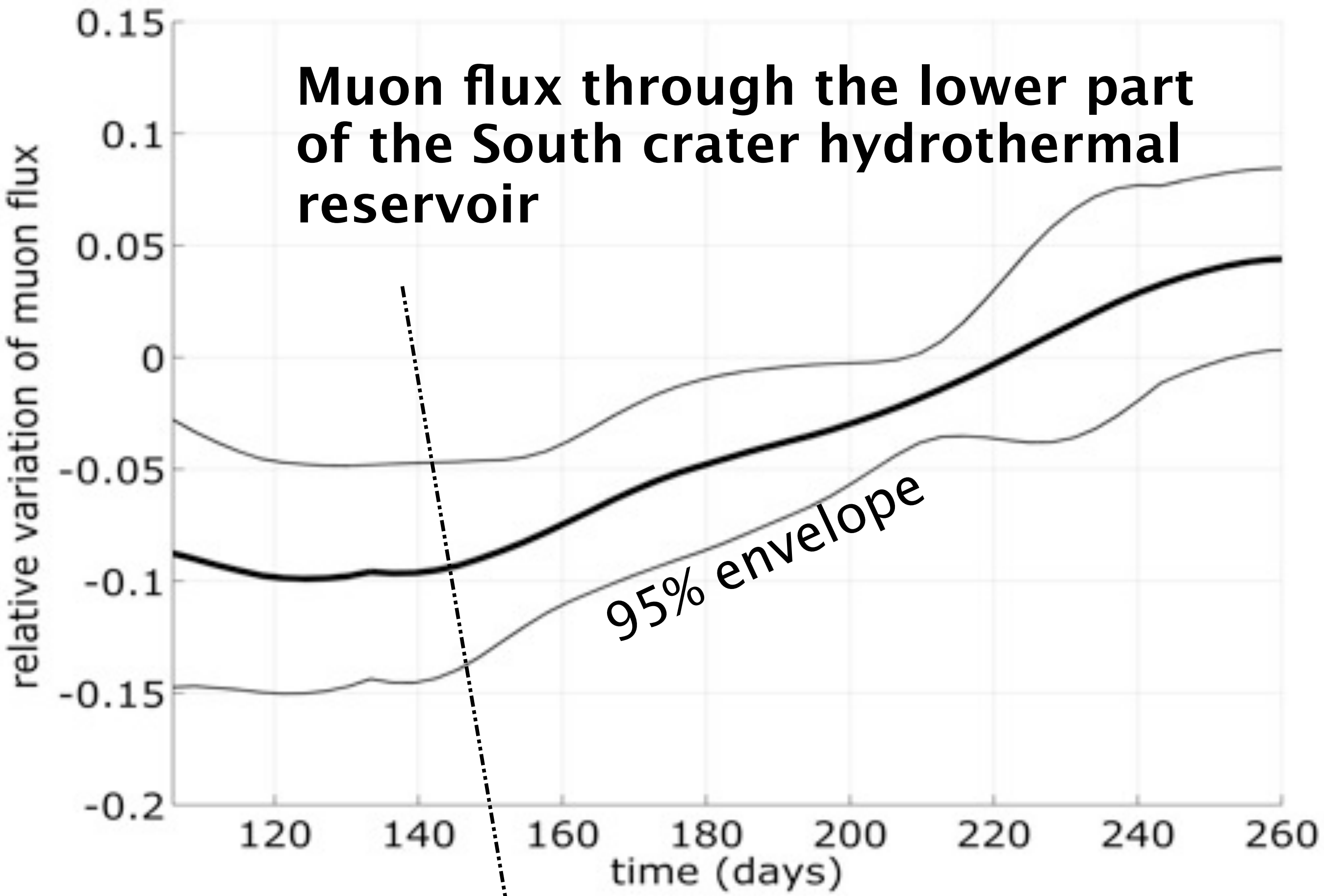
## Density radiographies




## Electrical resistivity
*Distorted geometry*



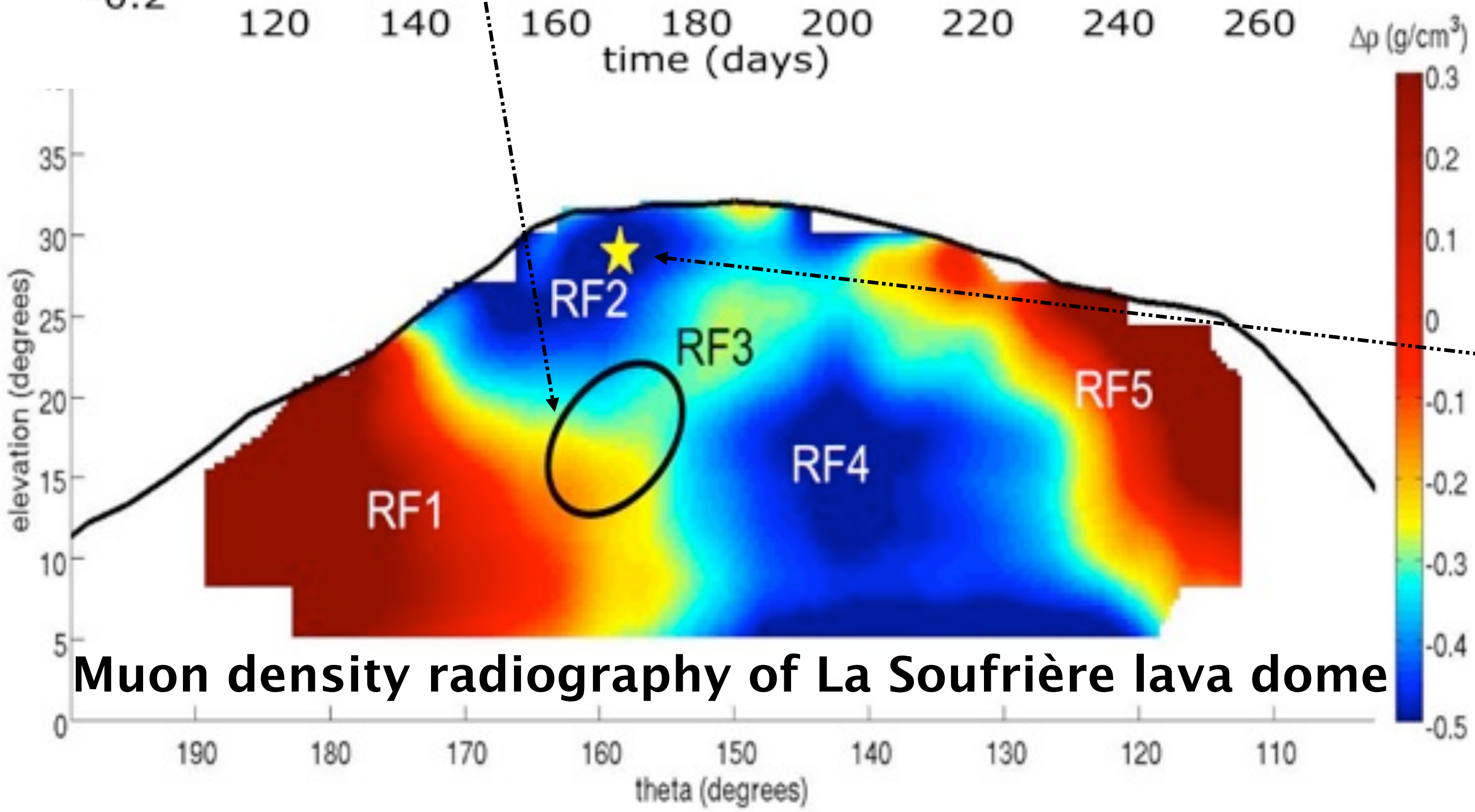
# Example of results: La Soufrière monitoring




Monitoring of La Soufrière of Guadeloupe lava dome performed during the first semester of 2012 revealed an increase of the flux of muons (i.e. decreasing density) in the bottom part of the South crater hydrothermal reservoir.

This phenomenon preceded the activation of new vents at the summit.

Publications: www.ipgp.fr/~gibert/




Muon density radiography of La Soufrière lava dome

# The Tomuvol collaboration

*Proof of principle for the "**To**mographie with **Mu**ons of the **Vol**canoes"*

Interdisciplinary collaboration, emerged in 2010: particle physicists (IPNL, LPC) and volcanologists (LMV, OPGC).

**Phase 1 : 2010-2014**

- Extensive studies of the Puy-de-Dôme.
- Comparison to geophysical techniques.

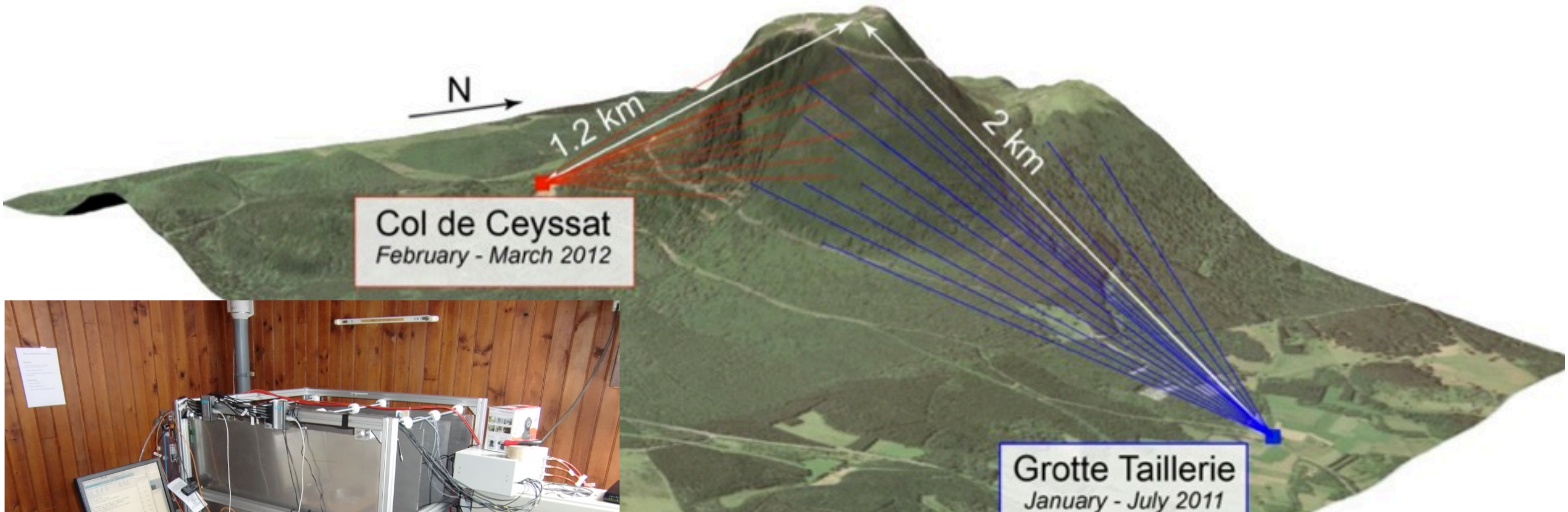
**Phase 2 : 2014➟**

- Design, construction and validation of an autonomous and easily transportable radiographic device.

**Base design of the detector :**

Muon tracker composed of four layers made of Glass Resistive Plate Chambers.

# Two data taking campaigns with prototype detectors



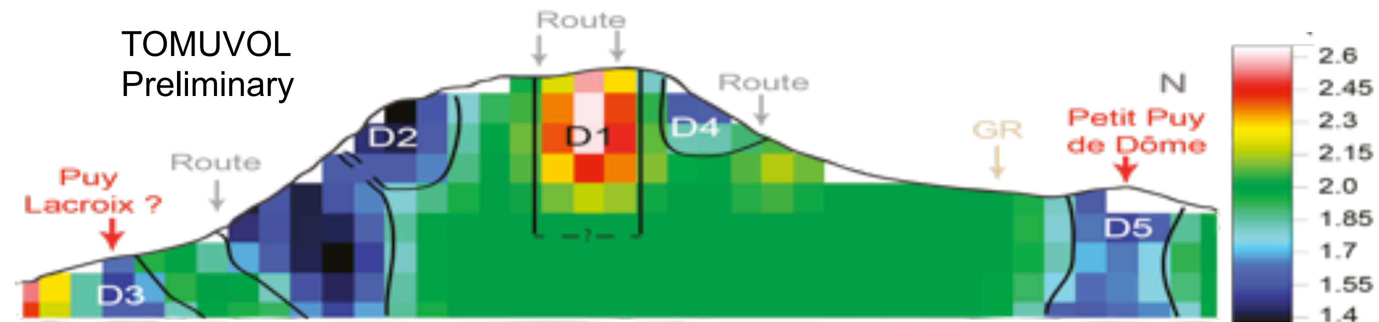

**Setup:**
- 4 layers of $1m^2 \times 1m^2 \times 1m^2 \times 0.66\ m^2$.
- outer spacing : 1 m.
- surface site.

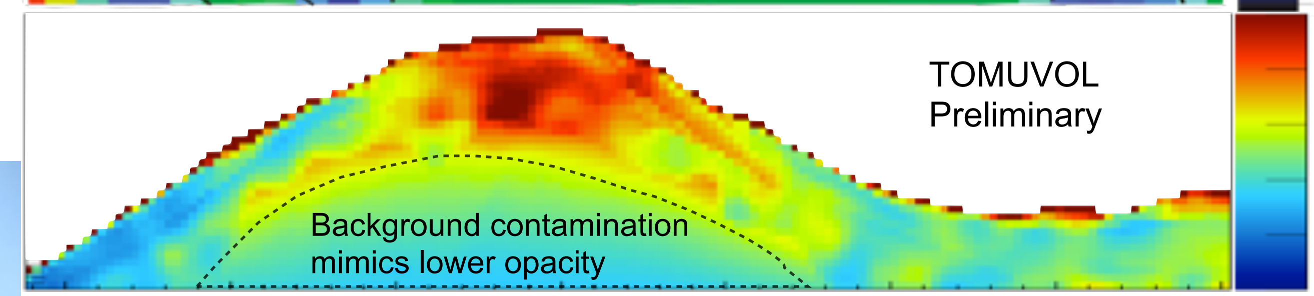
**Setup:**
- 3 layers of $1m^2 \times 1m^2 \times 0.16\ m^2$.
- outer spacing : 0.5 m / 1 m.
- underground site.

# Grotte Taillerie Campaign

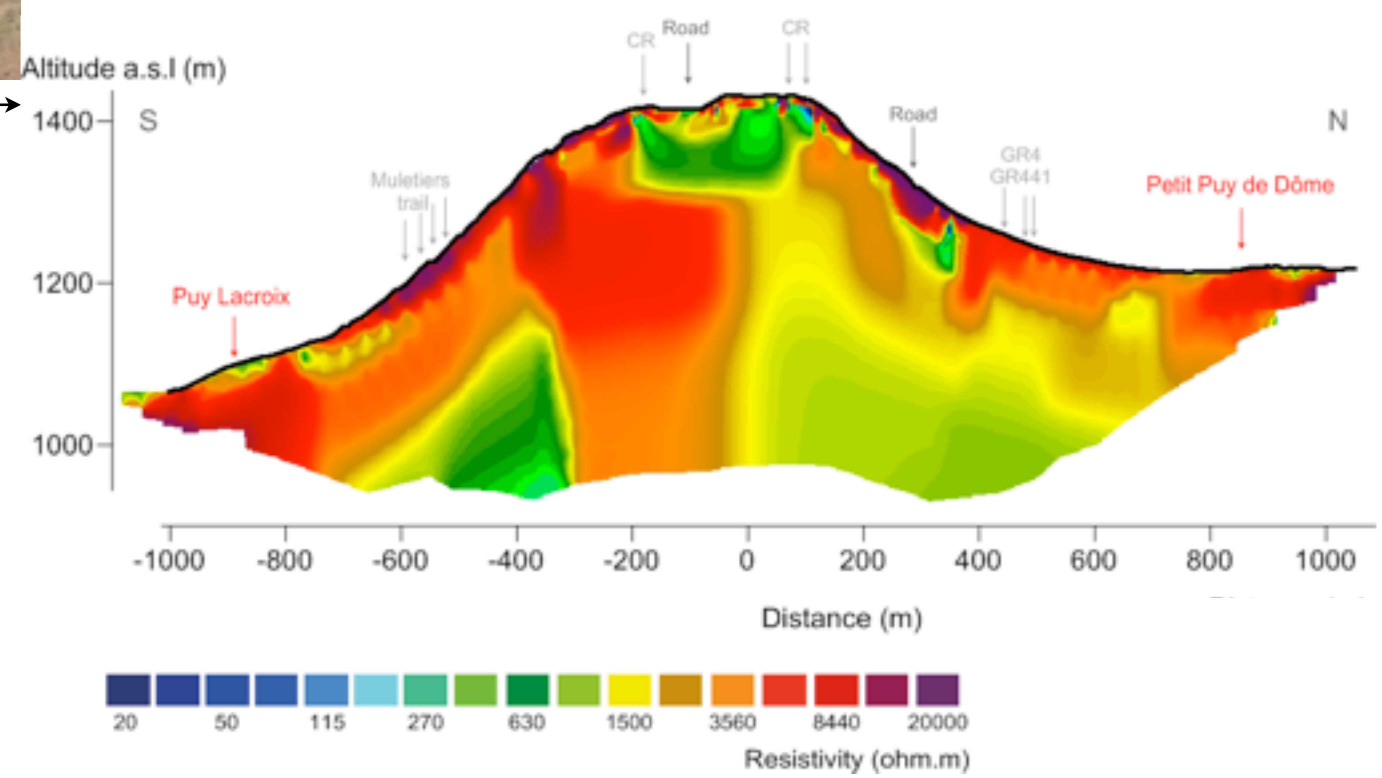
Puy de Dôme Inner Structure, imaged through gravimetric tomography, with atmospheric muons and by electrical restivity

Density ($10^3 kg/m^3$)

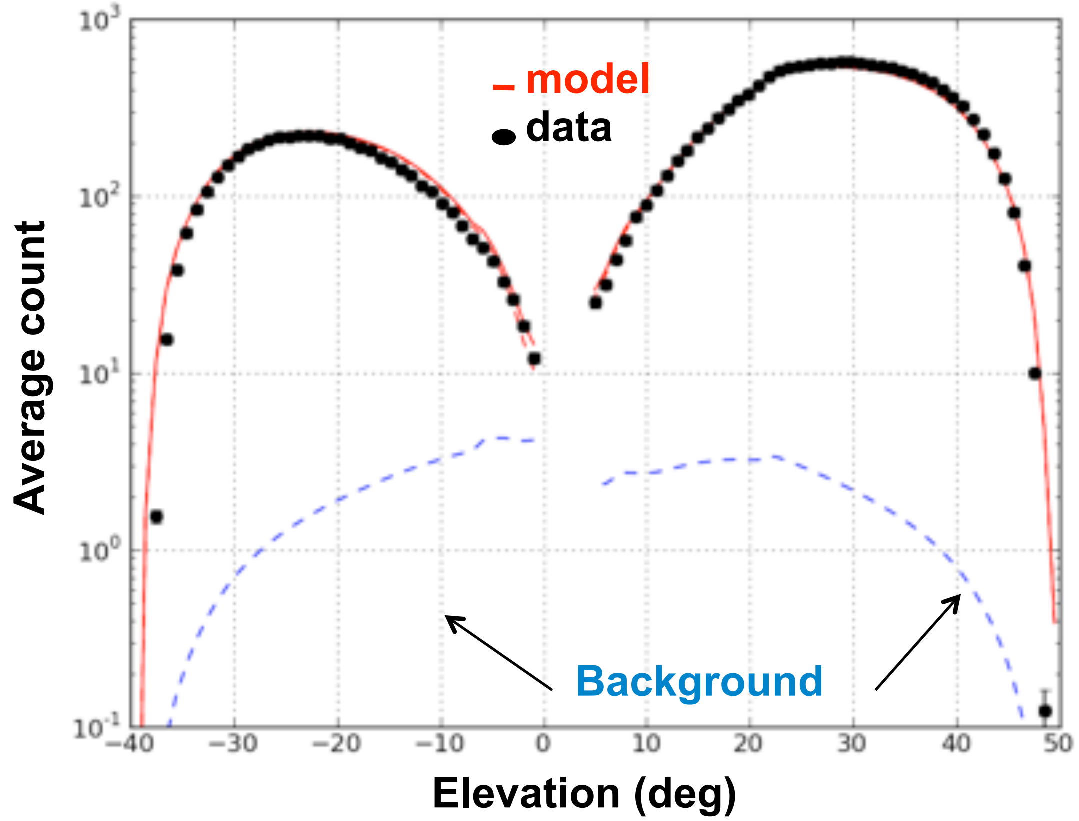



Linear opacity to atmospheric muons
65.8 days of data taking, 0.16 $m^2$ x 0.5 m

# Col de Ceyssat Campaign

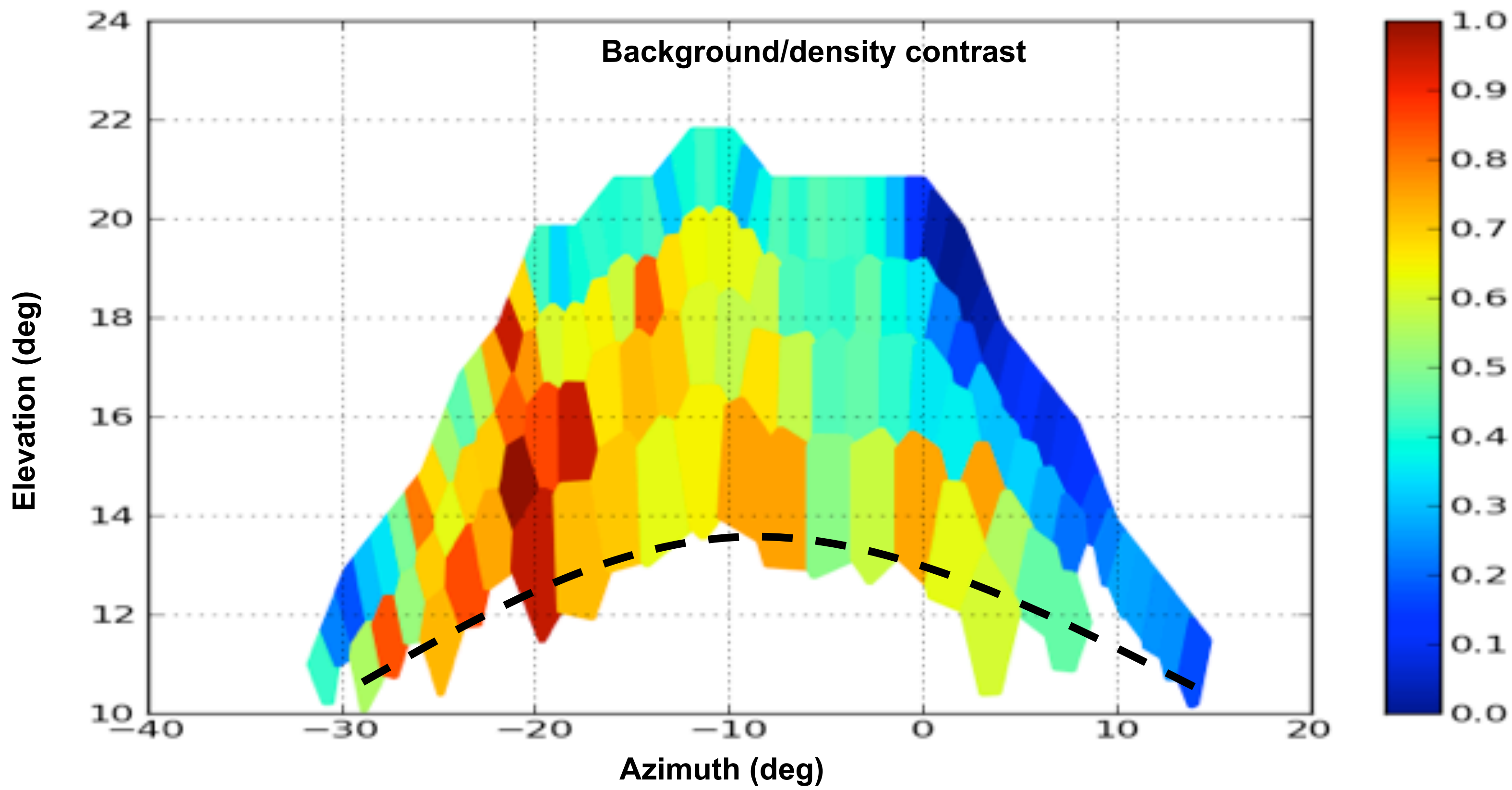



18.9 days of data taking
with 4 chambers: 0.67 $m^2$ x 0.8 m

Data/free sky expectation agree within 5 % above 10 deg elevation

⇒ Livetime = 14.3 day, versus 13.7±0.7 (direct computation)

⇒ Threshold: 200-300 MeV/c




# … and right now

TOMUVOL detector currently being commissioned: 4 layers of 1 $m^2$ each with modular transportable design and improved timing.


- **MURAY** detector (scintillators and SiPMTs) currently taking data at Col de Ceyssat(~**2 months data taking expected**).
- **Bristol group (**GRPCs**)** expected to join soon for a common campaign of measurements with TOMUVOL.

# Conclusion

**Muography in France == a rich research field**

- three different groups.
- three different detector technologies.
- three different research approaches.

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**... as always, much more work necessary to actually reach those goals ...**