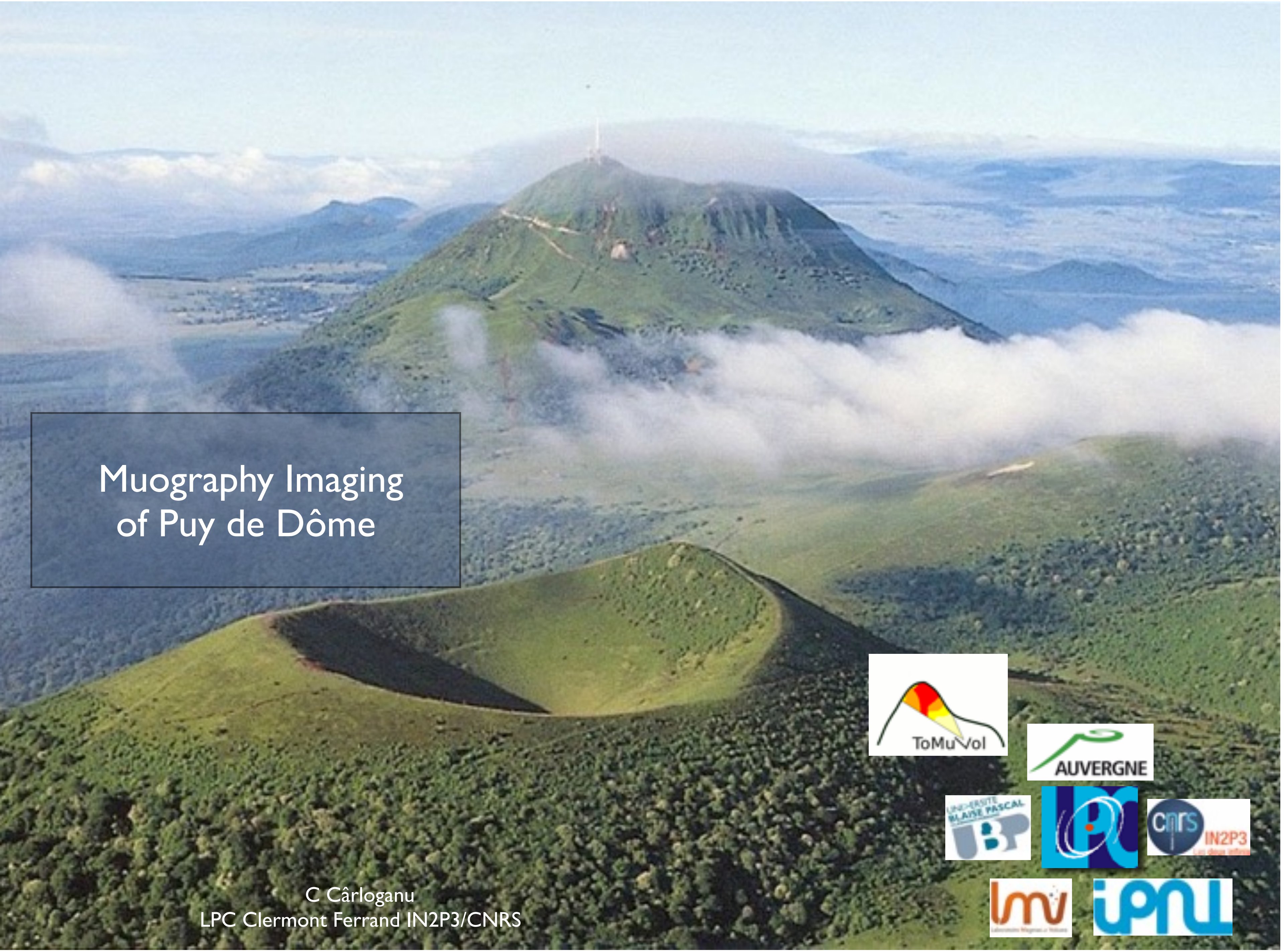
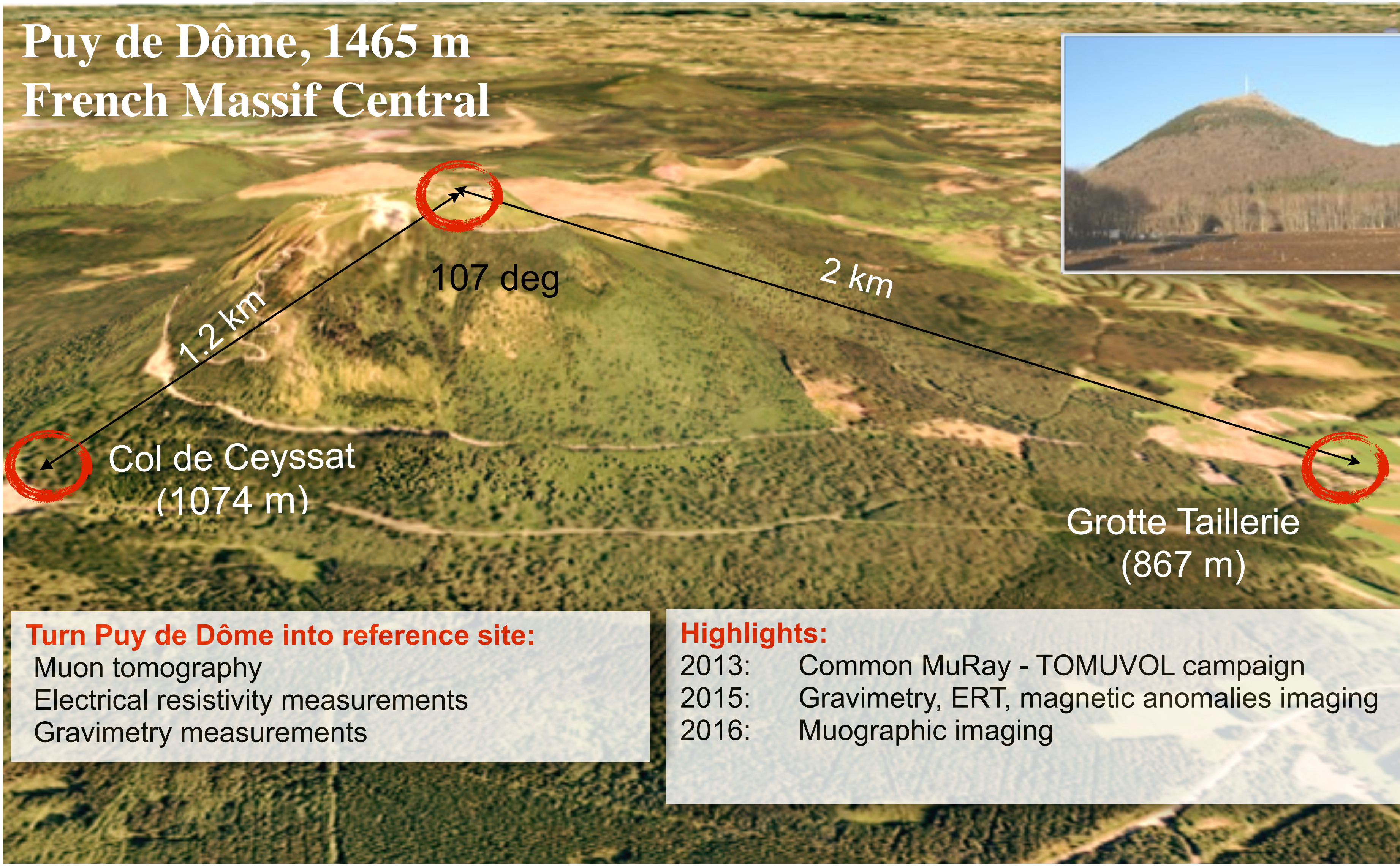


Muography Imaging of Puy de Dôme

C Cârloganu
LPC Clermont Ferrand IN2P3/CNRS

Proof of principle for **muon tomography** of volcanoes



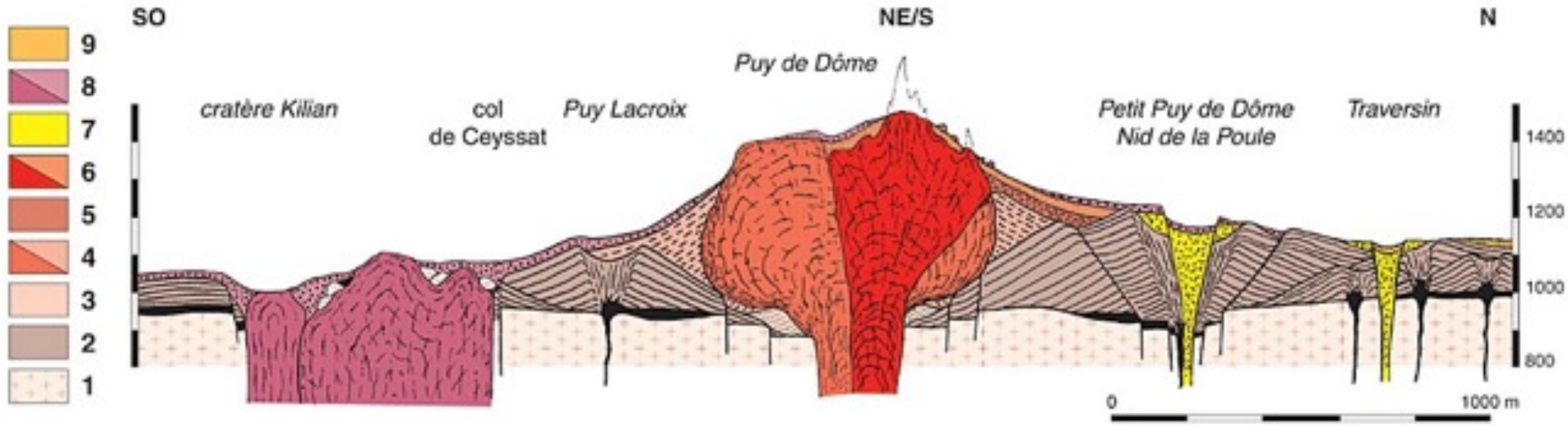
Turn Puy de Dôme into reference site:

Muon tomography
Electrical resistivity measurements
Gravimetry measurements

Highlights:

2013: Common MuRay - TOMUVOL campaign
2015: Gravimetry, ERT, magnetic anomalies imaging
2016: Muographic imaging

Puy de Dôme

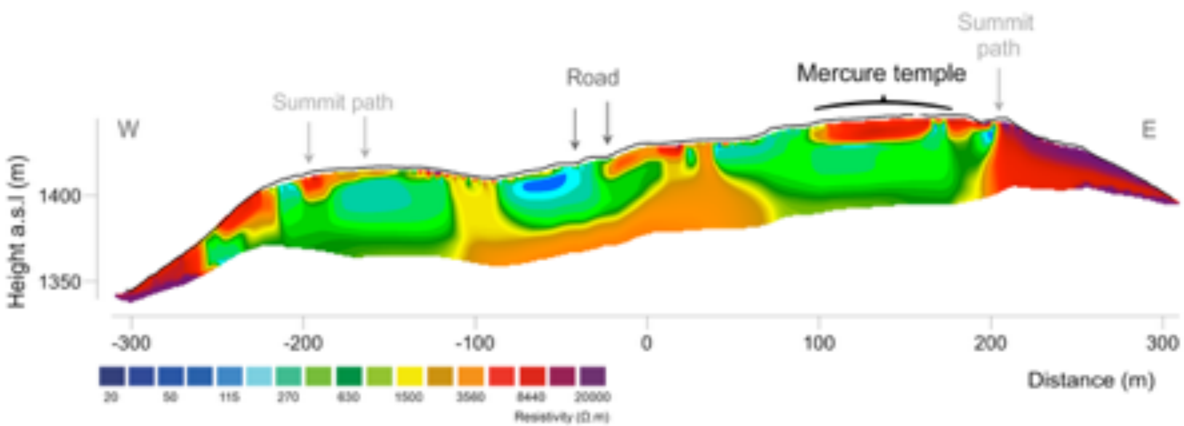


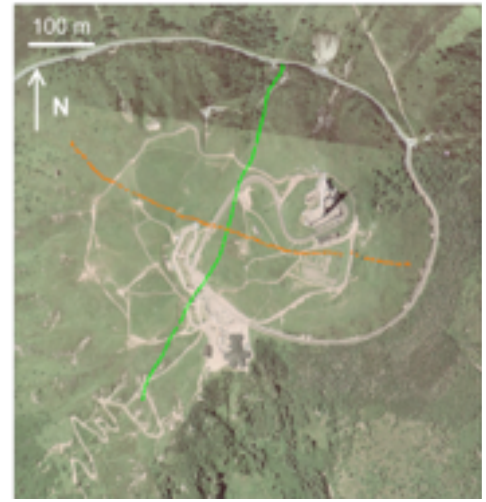
- Dome: ~400m high, 1.8 km wide at its base
- Two distinct units:
  - two lava pulses
  - partial destruction of the first construction
- Important hydrothermal alteration

- Expected to be highly contrasted
- Isolated, averaged sizes volcano
- Close to labs, easy to access, power and network facilities

Ideal choice for testing an imaging technique !

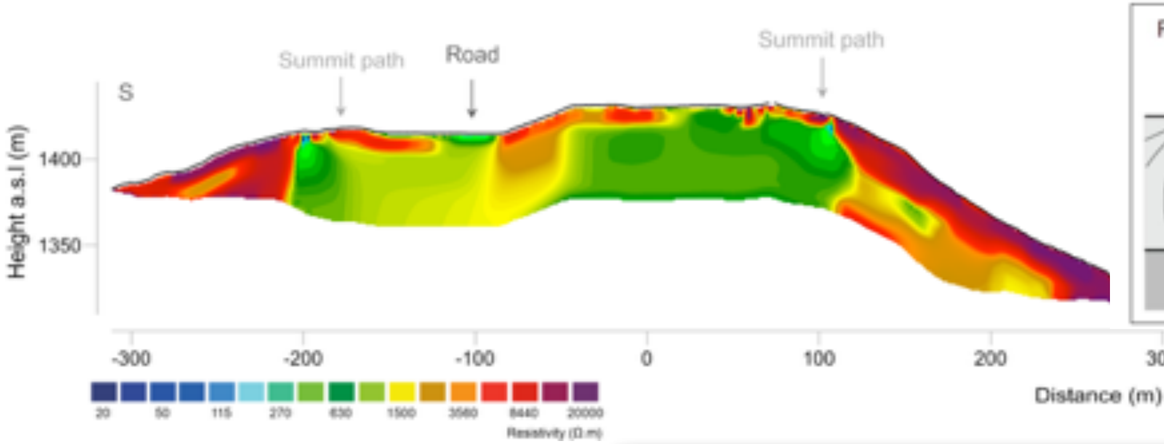
Resistivity models of th summit area

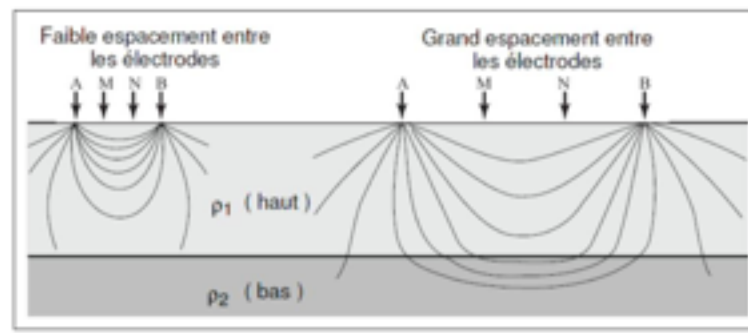




Erreur rms 7.3%

Anthropogenic structures





Erreur rms 6.8%

Computed with Res2DInv *(Loke, 2011)*

Seismic and electrical tomography rely on curved paths

⇓

non-linear inverse problem

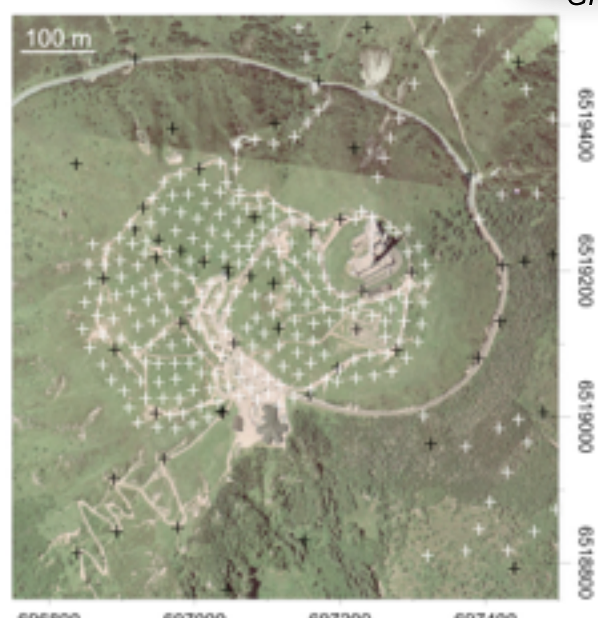
Gravity survey

- Relative gravimeter (February-March, 2012, May, 2012 and March-June, 2013)
- 610 gravity stations, around 2500 gravity measurements
- High resolution differential GPS positioning at the gravimeter tripod center

  average accuracy: **1.6 cm** in planimetry and **2.3 cm** in altimetry

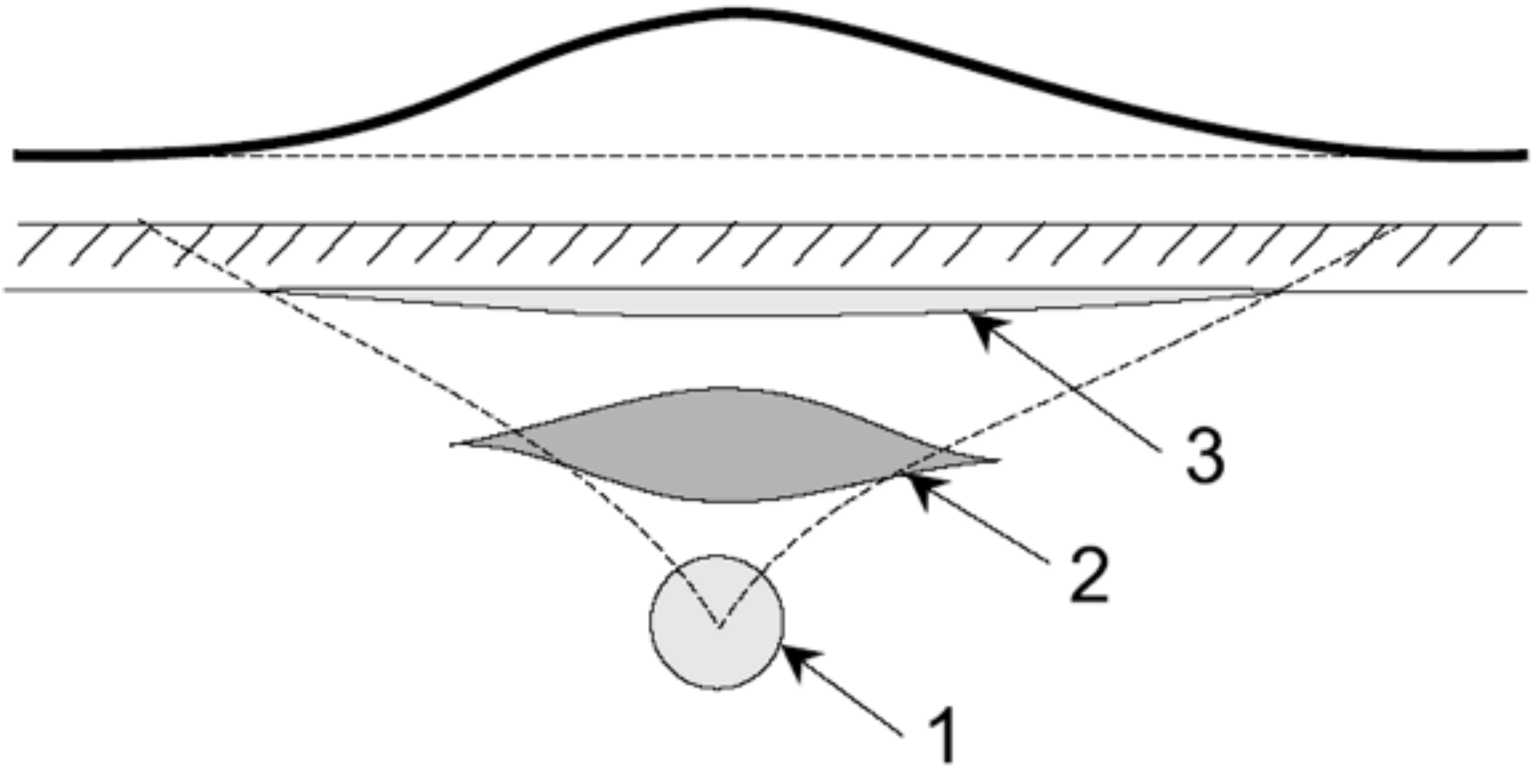
GPS and Scintrex CG5 gravimeter

Gravity stations location for the total survey



Summit area gravity stations location

Non-unique inverse solution



Geological setting of Puy de Dôme

The Chaîne des Puys volcanic field

- The latest active zone of the French "Massif Central" volcanism
- Important rifting episode -> hemi-graben formation (*Michon and Merle, 2001; Boivin and al., 2004*)
- Volcanoes emplaced on a Hercynian granitic basement along a N-10° direction

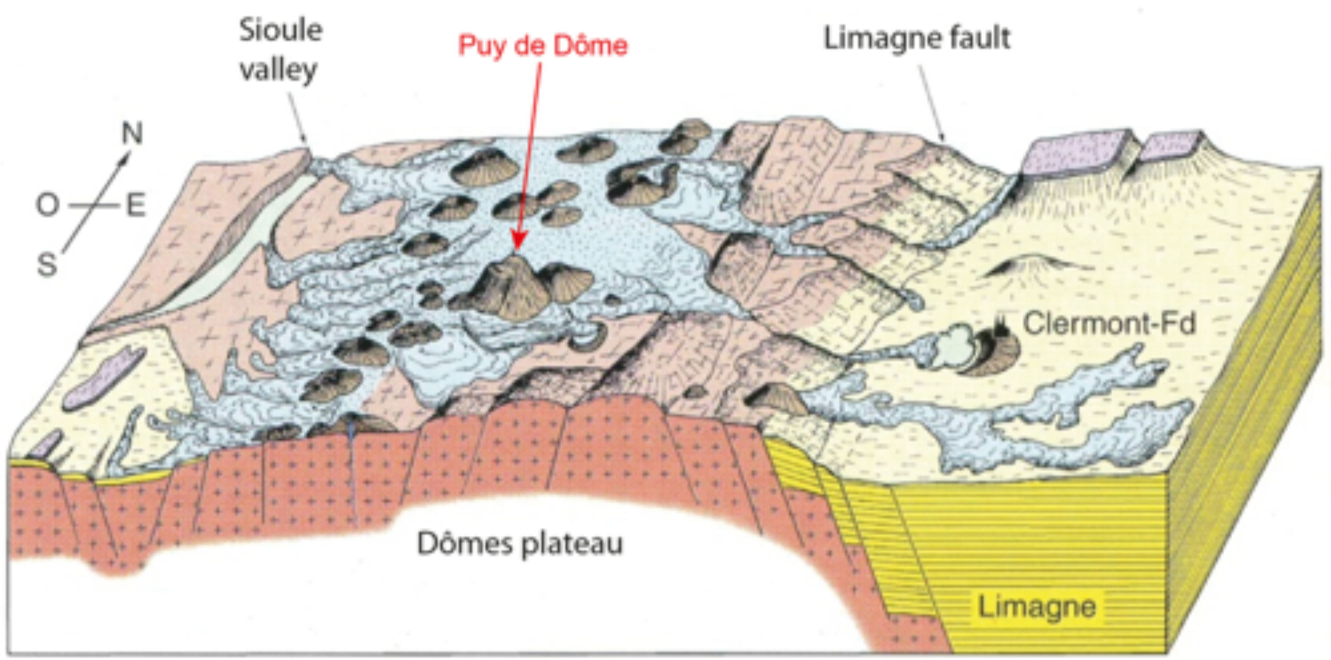
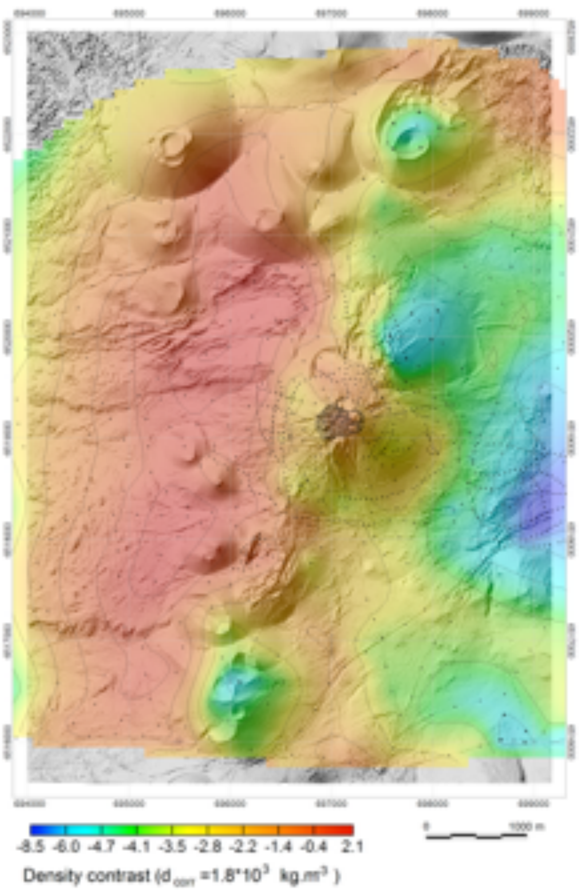


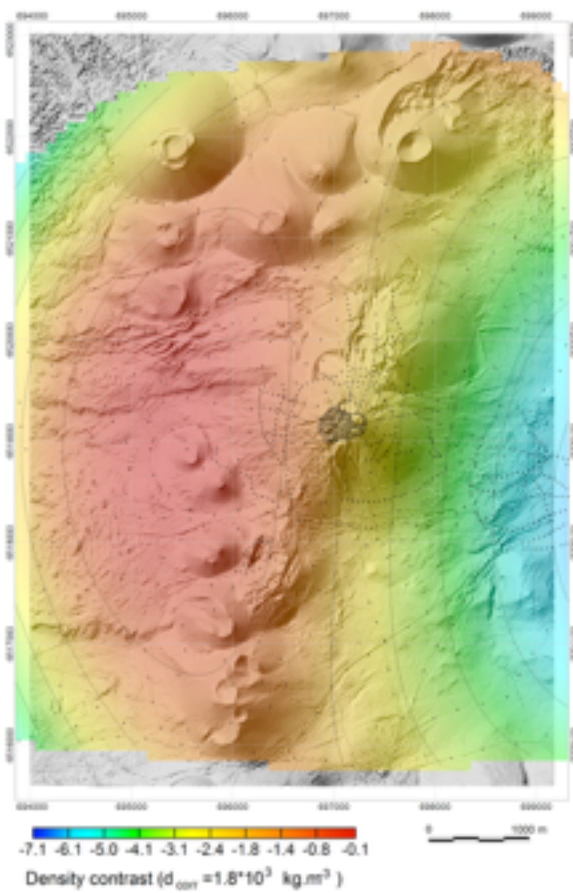
Figure Boivin and al., 2004

Gravity map of Puy de Dôme and its surroundings

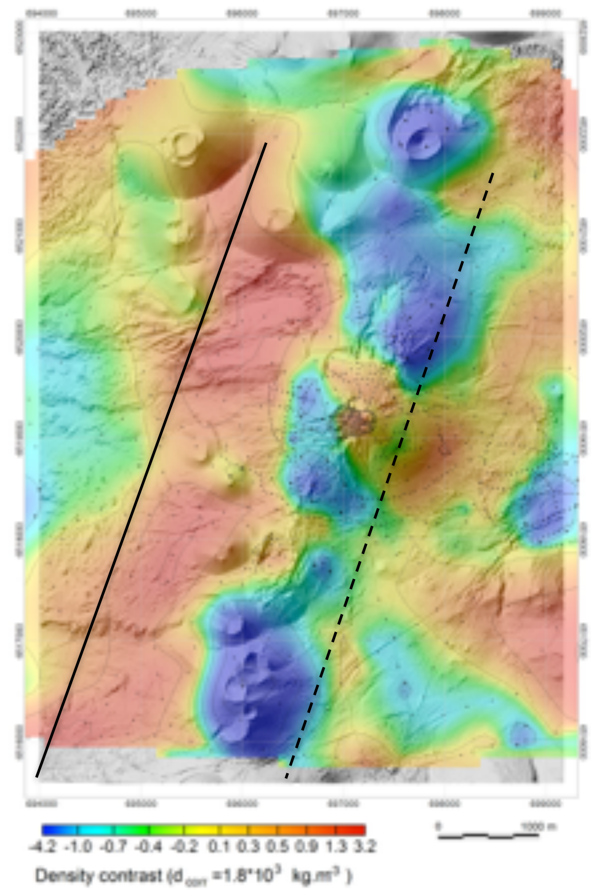
- Volcanic constructions have negative signature (lower density than the correction density)
- Complex construction of the Puy de Dôme (heterogeneous signal)
- Clear positive anomaly to the West of the volcanic chain, possibly masked by negative signal beneath the volcanic constructions.
- Complex construction of the Puy de Dôme (heterogeneous signal)



Total Bouguer anomaly

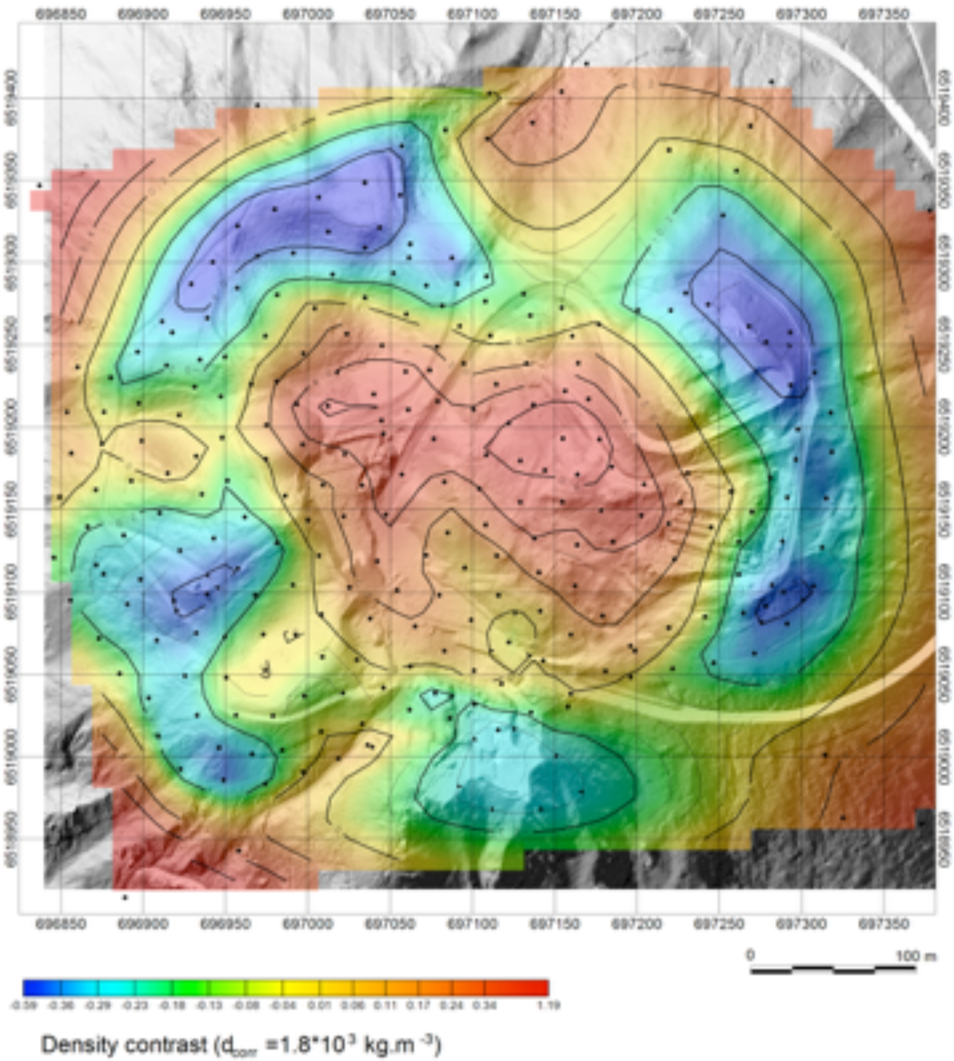


Regional trend
(using 3rd order surface)



Residual anomaly

Gravity map of the summit area



Positive anomaly in the central part of the summit area

→ dense structure (massive extrusion?)

Negative signal at the periphery

→ pyroclastic deposits ?

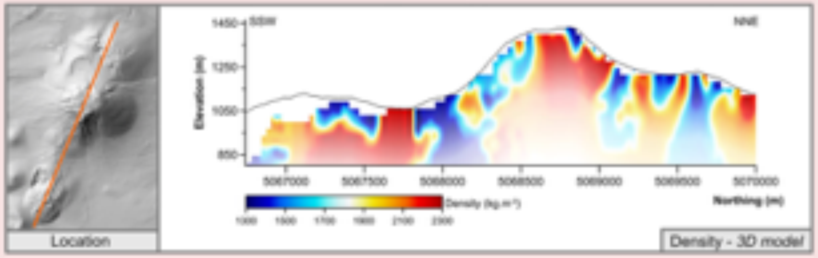
Gravity measurements are volume integrals !

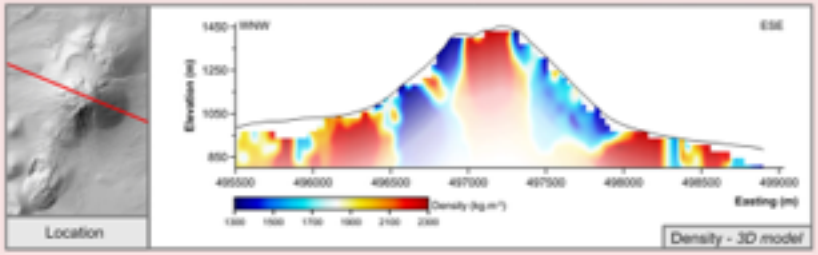
Standard geophysical inversions on Puy de Dôme

- Electrical Resistivity Tomography measurements: Portal et al., EGU2016-8549 (poster)
- Gravimetry and magnetism surveys: Portal et al., 2015, JVGR, accepted

Density model derived from gravimetric data

Inversion performed via GROWTH2.0 (Camacho et al., 2011)
Bulk density between 1.4 and 2.2 g/cm^3 while density measurements on rock samples range between 1.2 and 2.15 g/cm^3

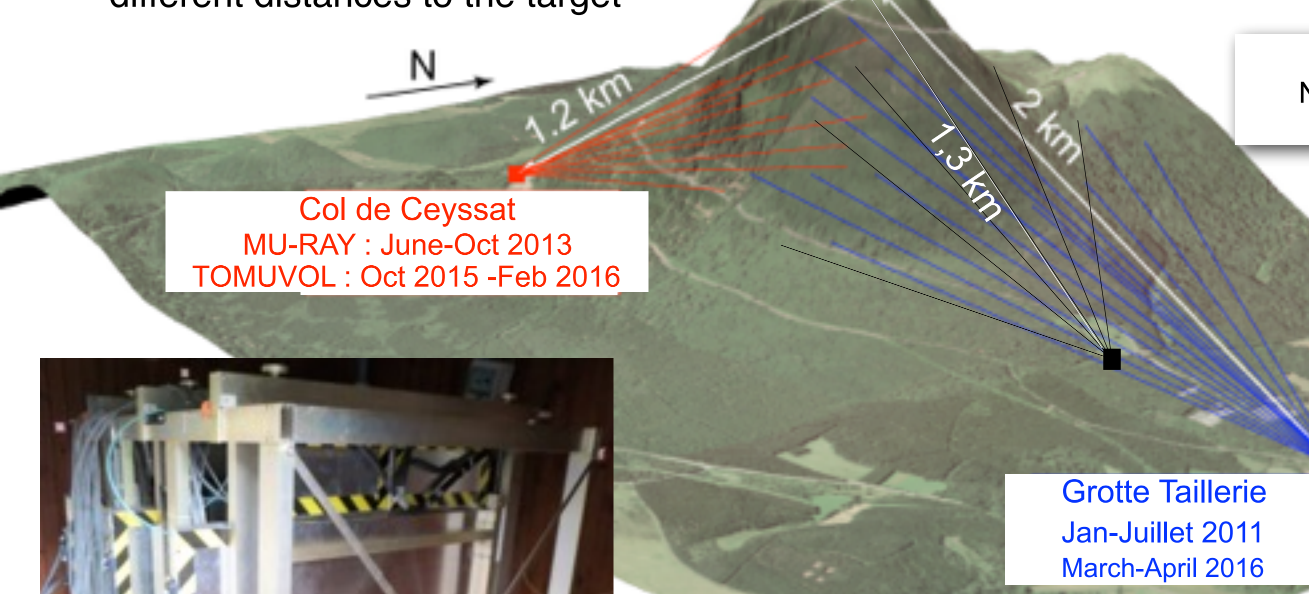




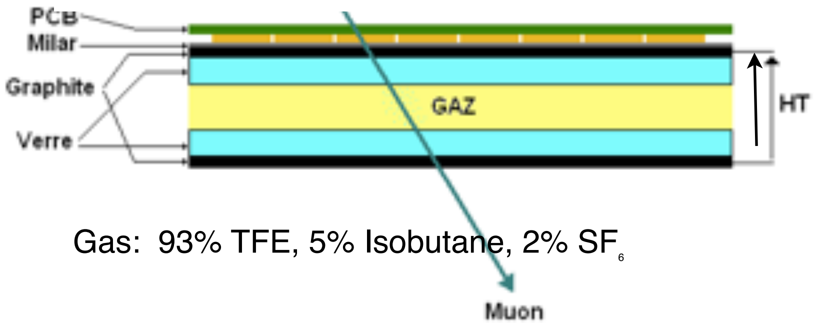
Ref: Portal et al., 2015, JVGR, accepted

Long Range Muography

- underground and surface deployment sites
- different distances to the target

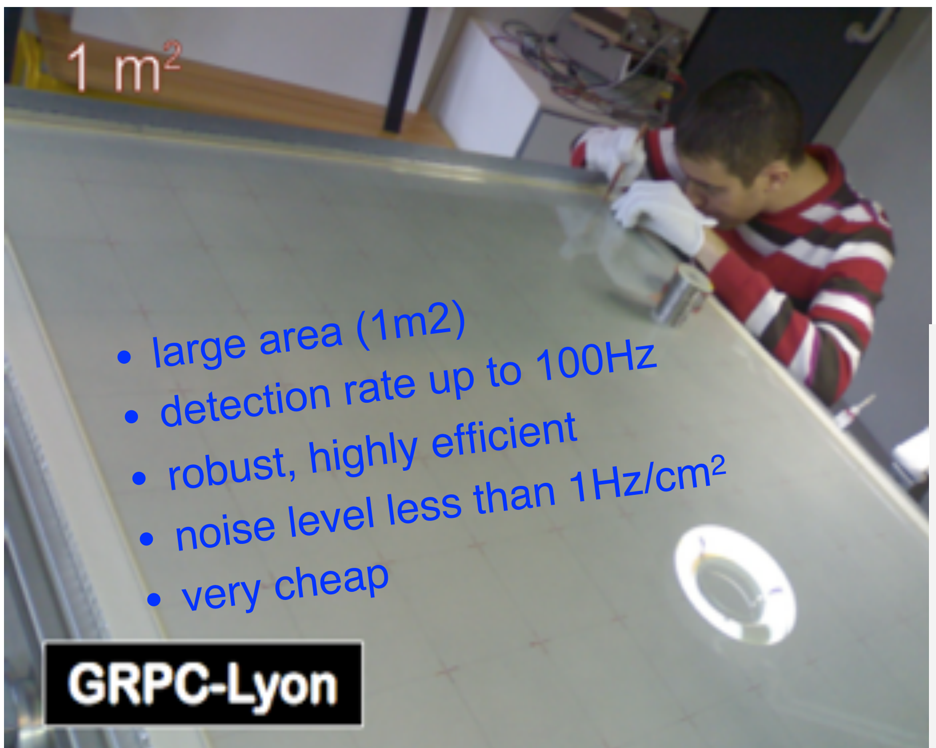


Avalanche mode: mean MIP charge 2.6pC, RMS: 1.6pC

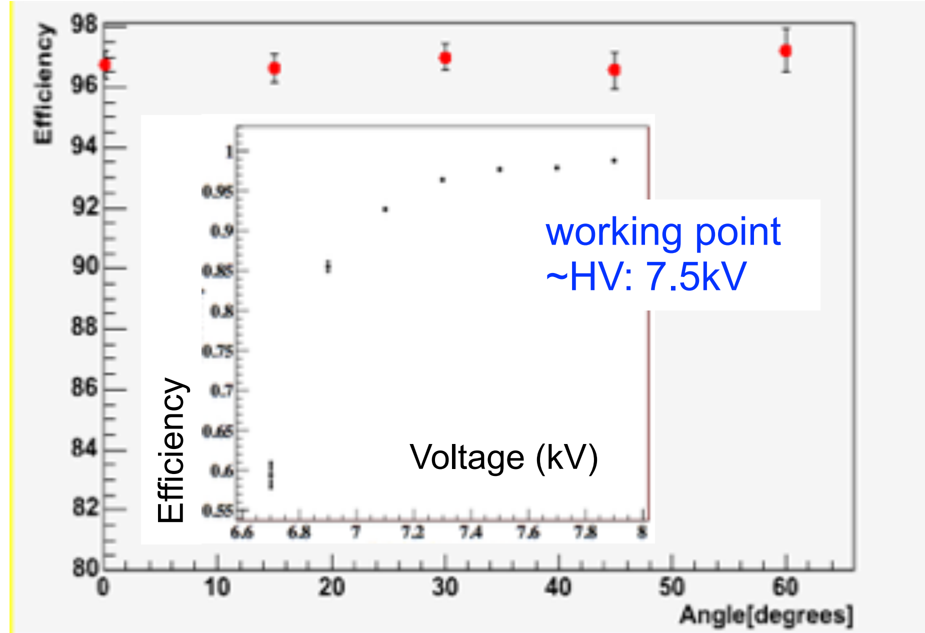


Gas: 93% TFE, 5% Isobutane, 2% SF_6

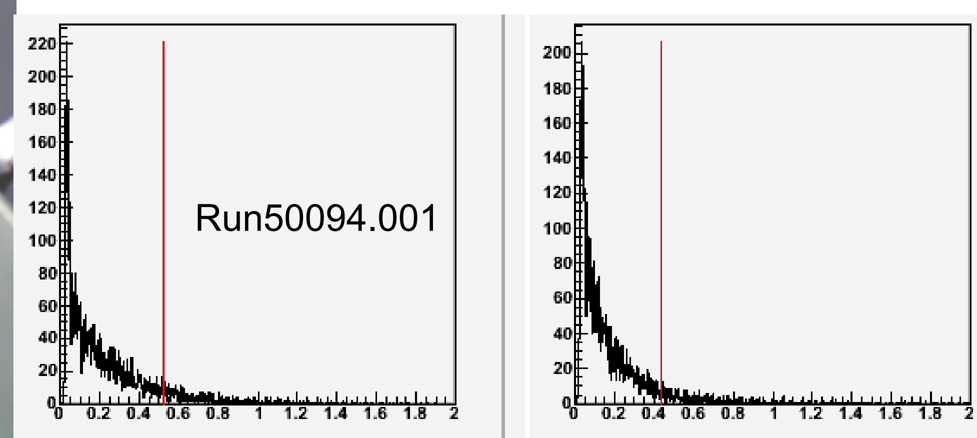
M. Bedjidian et al, "Performance of Glass Resistive Plate Chambers for a high granularity semi-digital calorimeter", JINST 6:P02001,2011



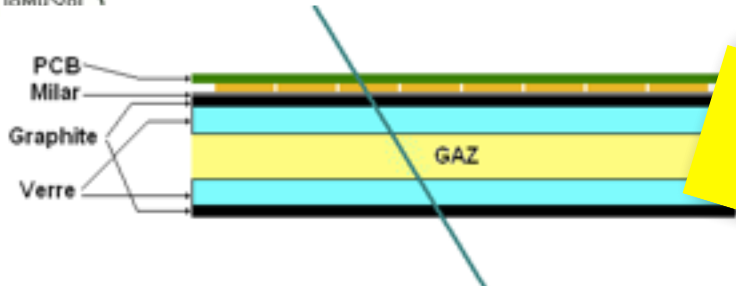
Efficiency vs. HV & track incident angle



Noise rate (Hz)



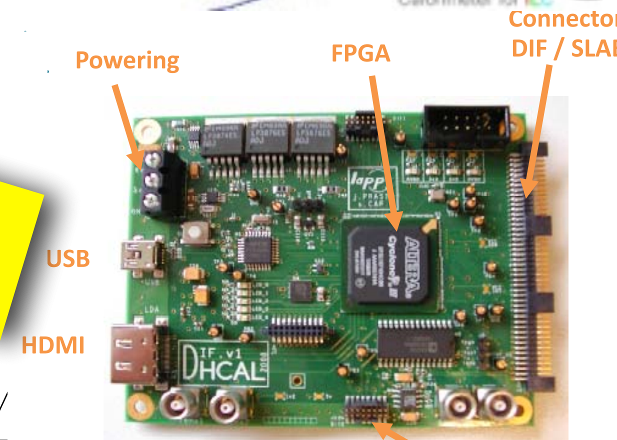
Muon Tracker : CALICE Electronics

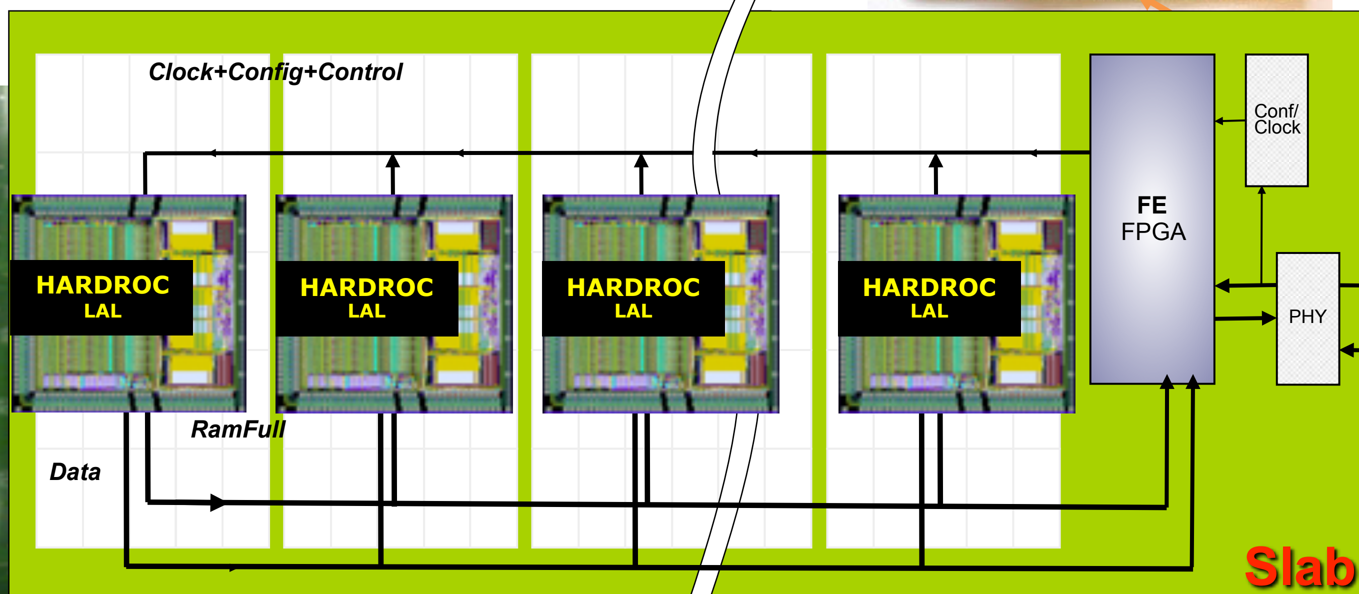


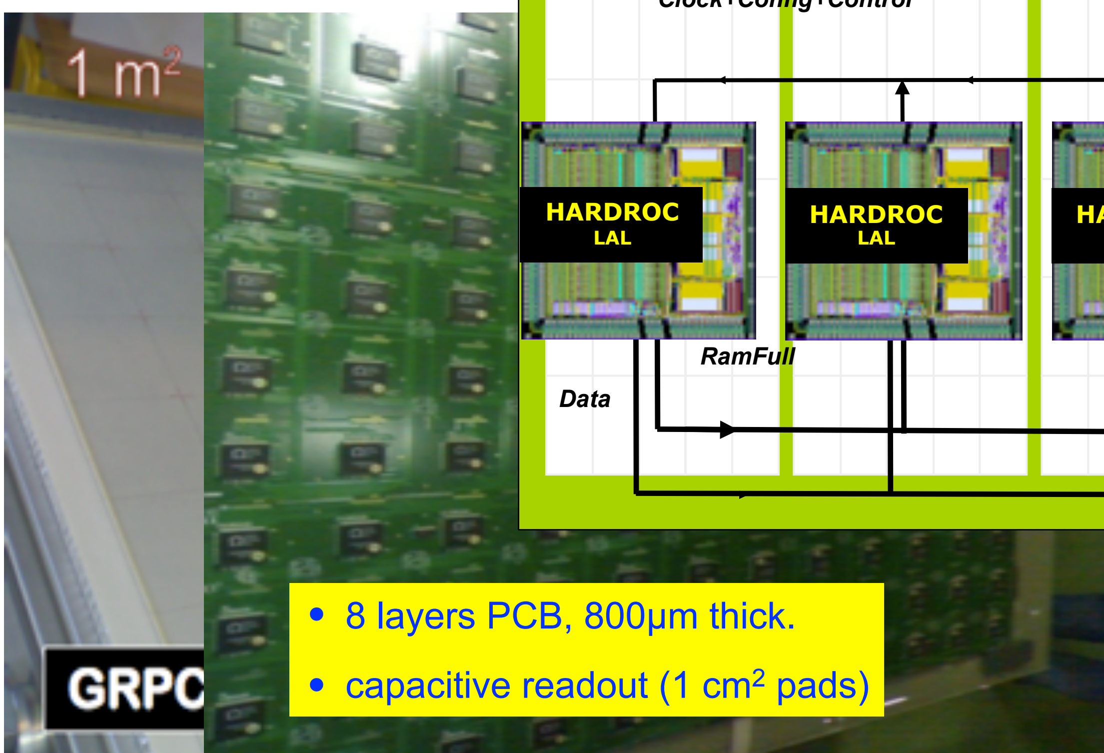
N.Seguin-Moreau, Proc.ofTWEPPPrague(2007) and IEEE Hawei (2007)

9472 channels/m2

1 hit ≡ time + thresh



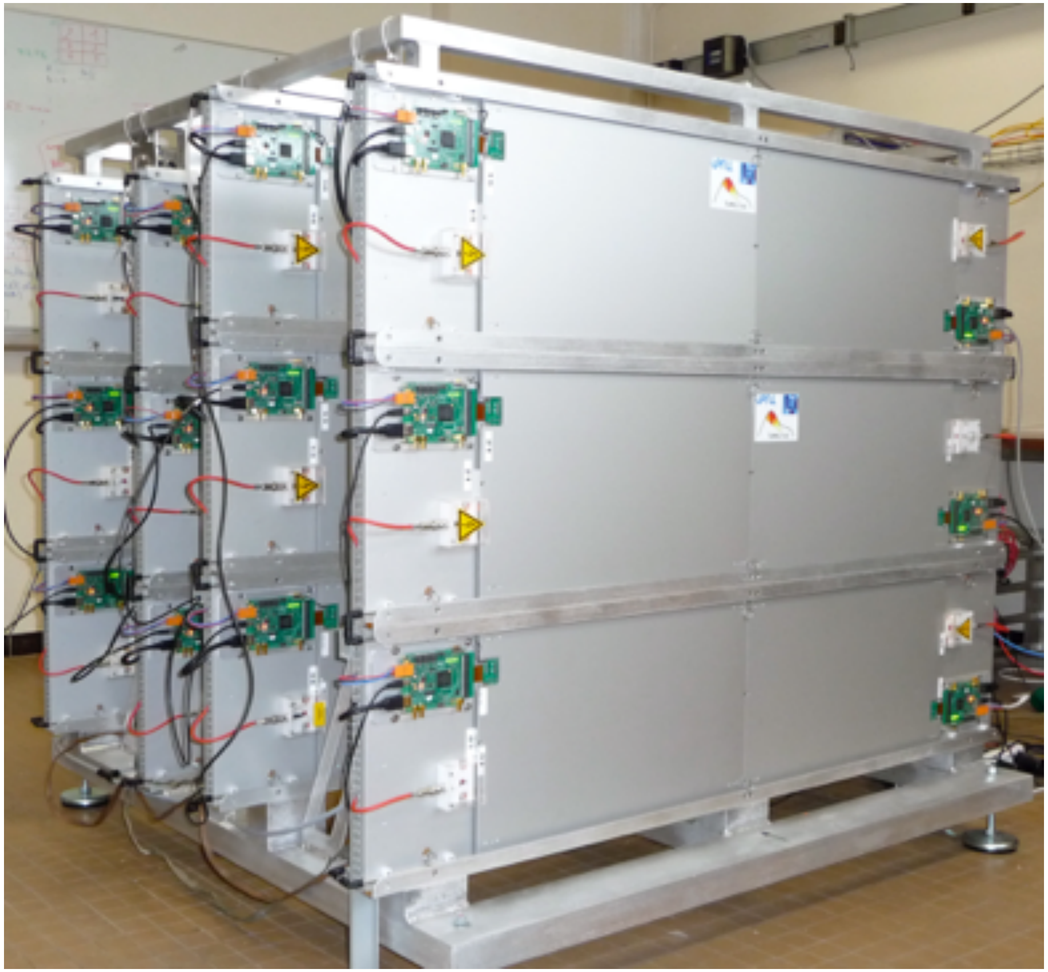




- 8 layers PCB, 800µm thick.
- capacitive readout (1 cm² pads)

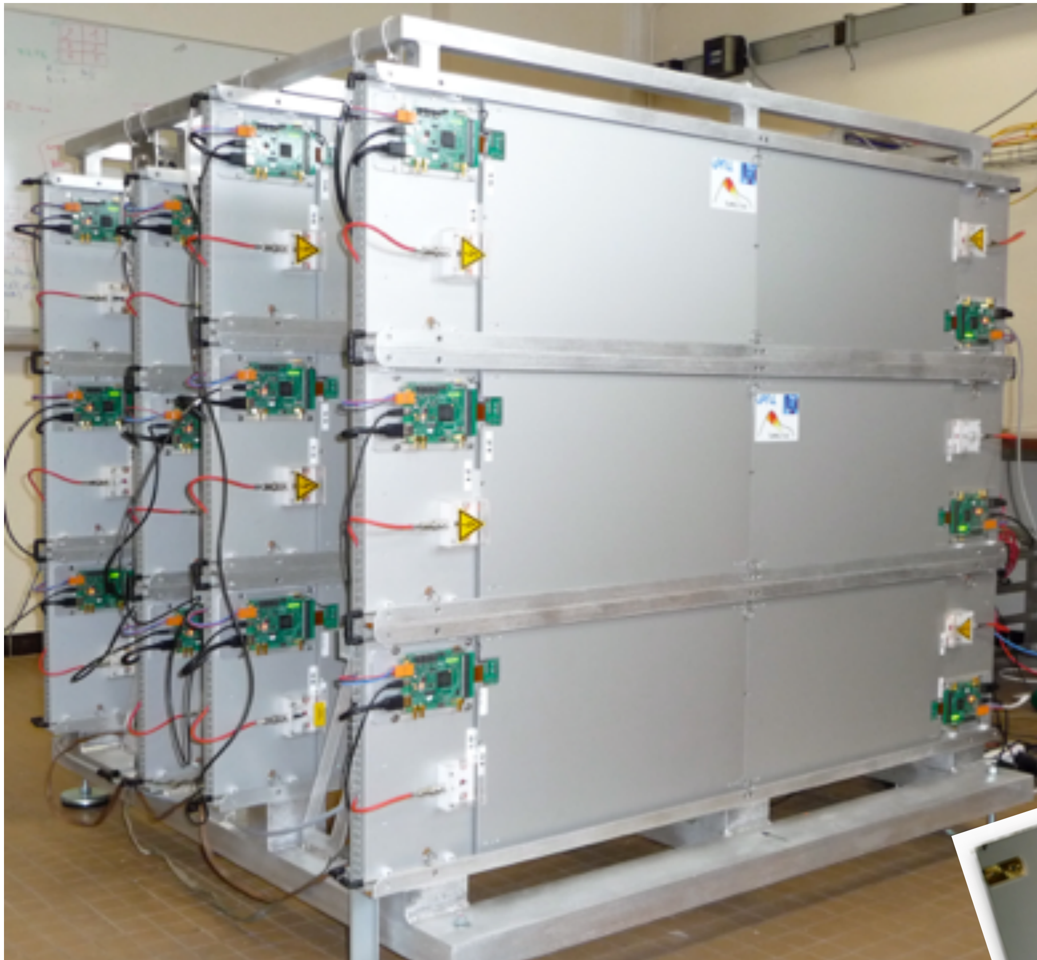
- 64 channels, 16 mm²
- digital output (2 adjustable thrs)
- low power consumption
- large gain range
- xtalk <2%
- ajustable gain for each channel

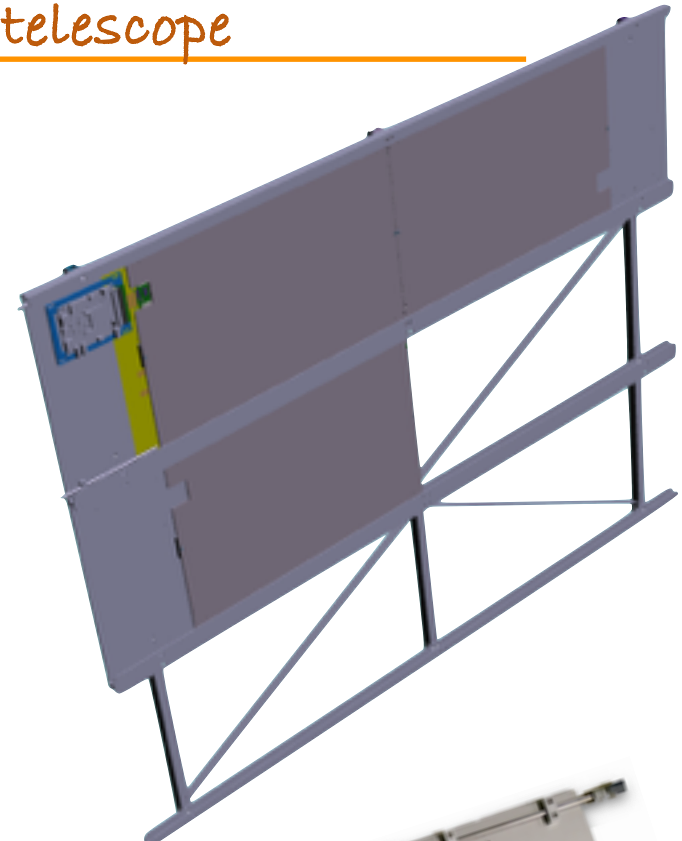
Tomuvol: a 4-layer muon telescope



- 4 layers of 6 Glass Resistive Plate Chambers (GRPC)
- GRPC: gaseous detector with glass electrodes
- Applied voltage: 7.5 kV
- 1.2 mm gap filled by a gas mixture chosen for its ionizations properties
- 1layer:~1m^2
- Readout cells of 1 cm^2 (~ 40000 cells in total)
- Using a 5 MHz clock and auto-triggered
- Remotely monitored from web interface

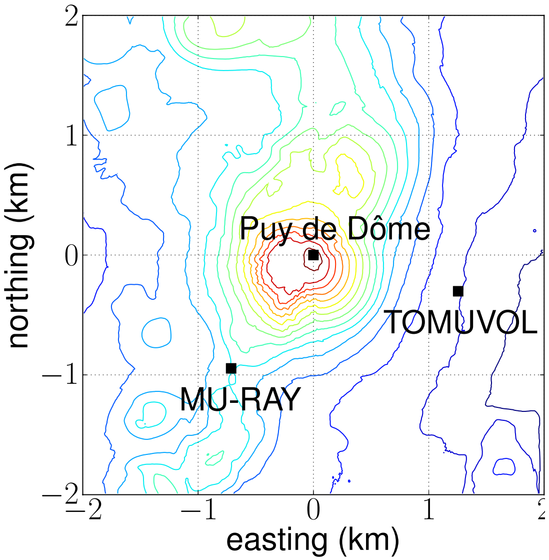
Tomuvol: a 4-layer muon telescope

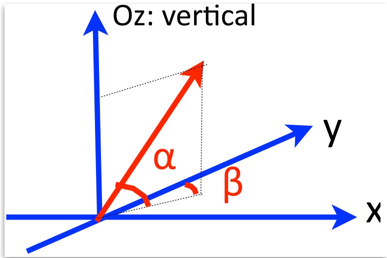


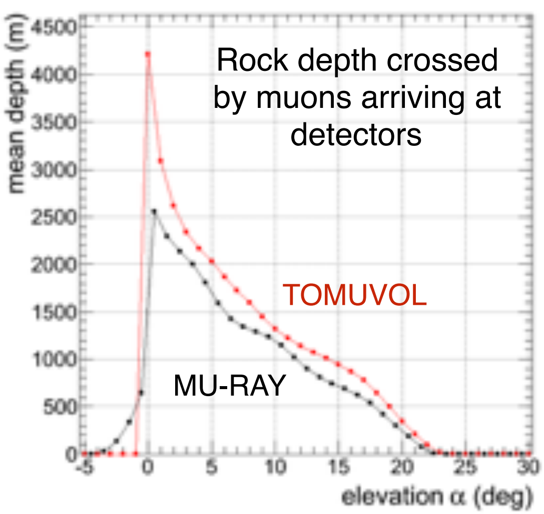


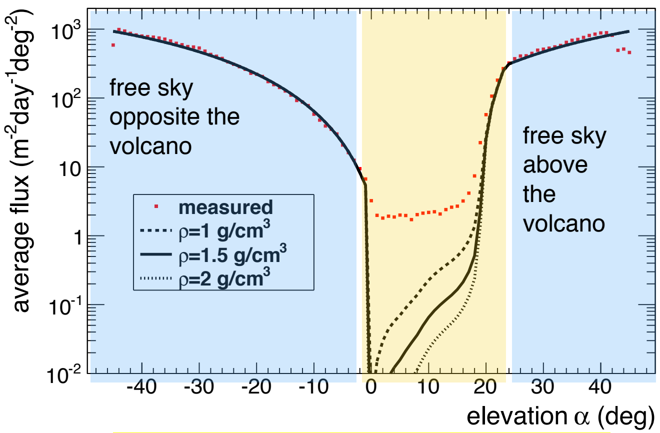
MURAY detector (scintillators and SiPMTs) took data on Puy de Dôme from July to November 2013

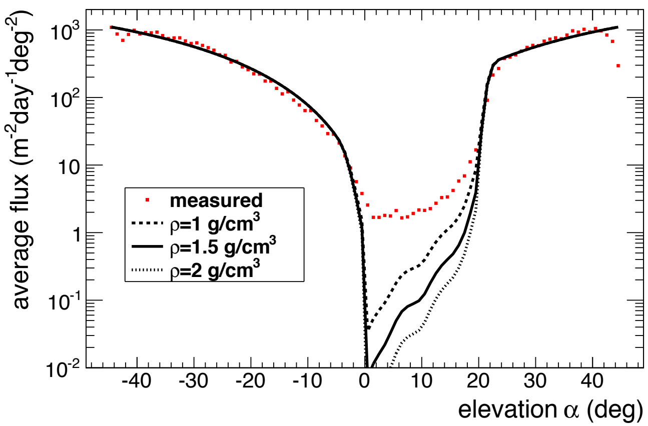
MURAY-TOMUVOL 2013 campaign on Puy de Dôme











Data/flux model agreement:
~5% for free sky

J. Geophys. Res. Solid Earth, 120,
doi:10.1002/2015JB011969

Background impact on muographic imaging

$N/N_0\ (\alpha,\beta)$ ⇒ $\int \rho(r,\alpha,\beta)\, dr \,/ \int dr$

$\mathcal{T}_\rho$ is calculated from an measured number of muons in a given direction

Measurement = Signal + Background

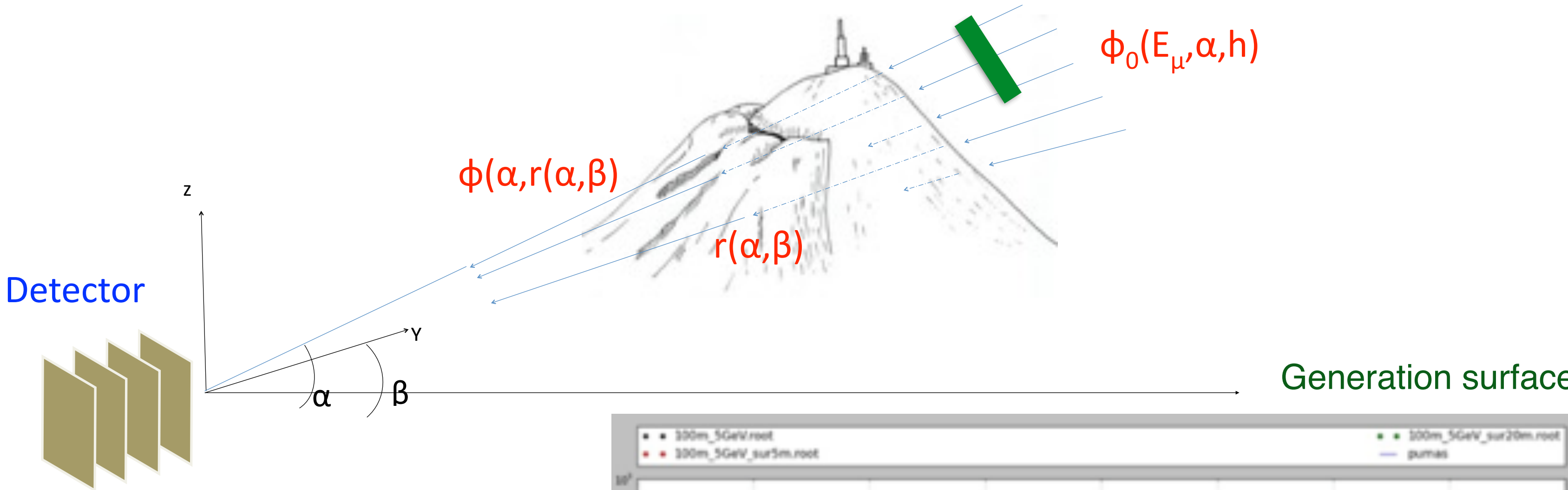
Only known after measurements and detailed Monte Carlo simulations

Can be calculated beforehand analytically

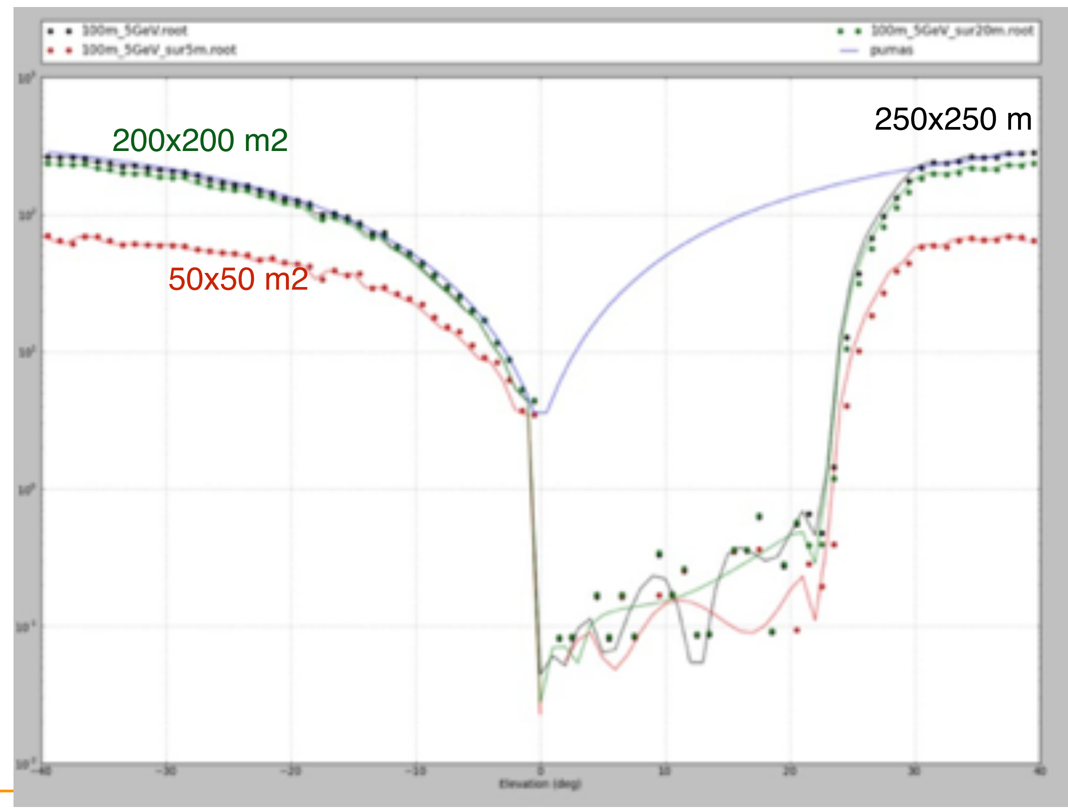
Table 1. Transmitted Flux of Ballistic Atmospheric-Muons Behind Different Rock Thicknesses and the Inverted Density Through a Muographic Measurement Affected by a Background Flux of 1.94 $m^{-2}\ d^{-1}\ deg^{-2}$ (the Quadratic Mean of the MU-RAY and TOMUVOL Measurements Given in Equations (4) and (5))

Integrated Density (True, mwe)	Elevation Angle (deg)	Transmitted Flux ($m^{-2}\ d^{-1}\ deg^{-2}$)	Integrated Density (measured, mwe)	Bias (%)
500	18	3.18	389.7	−22
1000	11	0.83	539.6	−46
2000	3	0.19	498.3	−75

A methodological development: tracking simulations



right now :
20 computing days
(IN2P3 computing centre)
for
1 day of data



Standard vs Backward MC

Through the implementation of our proposals, we were able to optimise one of the Monte Carlo simulations, permitting us to achieve a 400X speedup, once optimised and parallelised on a computing node with 32 physical cores.


LPC

LIMOS

UMR 6158 CNRS

UNIVERSITÉ BLAISE PASCAL

Université Blaise Pascal

École Doctorale des Sciences pour l'Ingénieur

N° d'ordre : XXX

Thèse

pour l'obtention du grade de

DOCTEUR D'UNIVERSITÉ

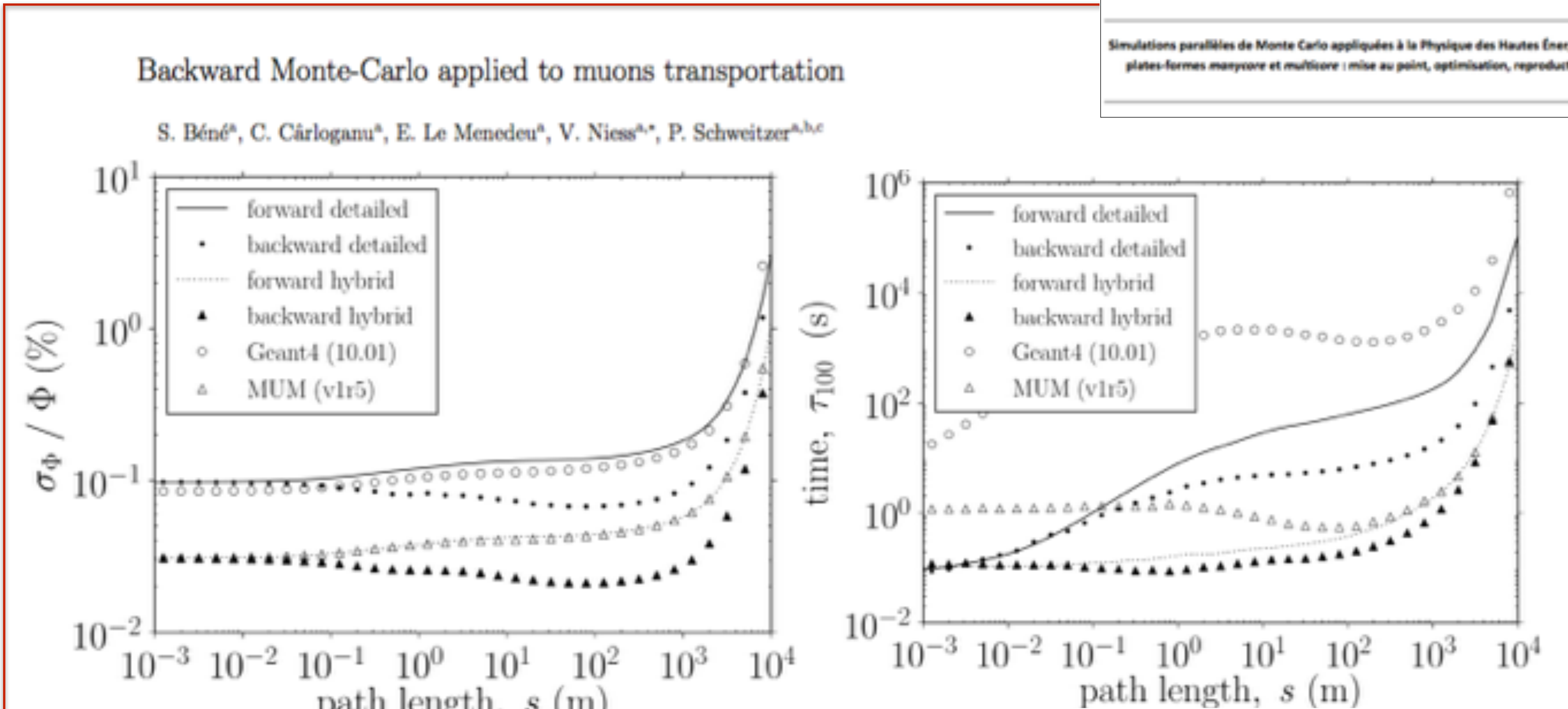
Discipline : Informatique

Présentée par

Pierre SCHWEITZER

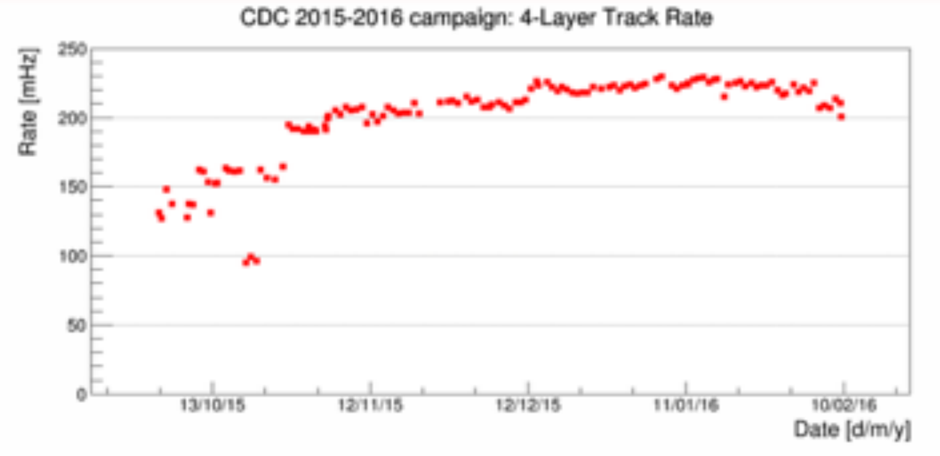
le 19/10/2015

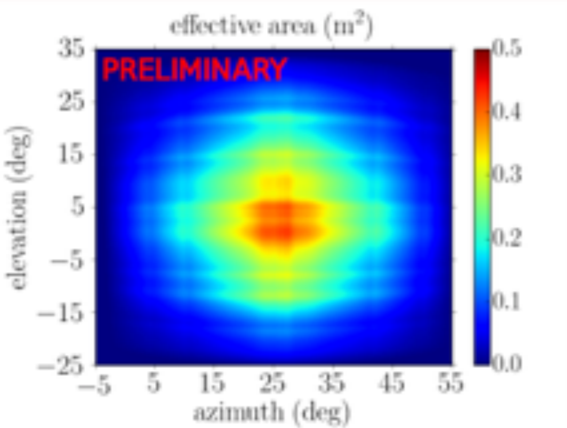
Simulations parallèles de Monte Carlo appliquées à la Physique des Hautes Énergies pour plates-formes manycore et multicore : mise au point, optimisation, reproductibilité

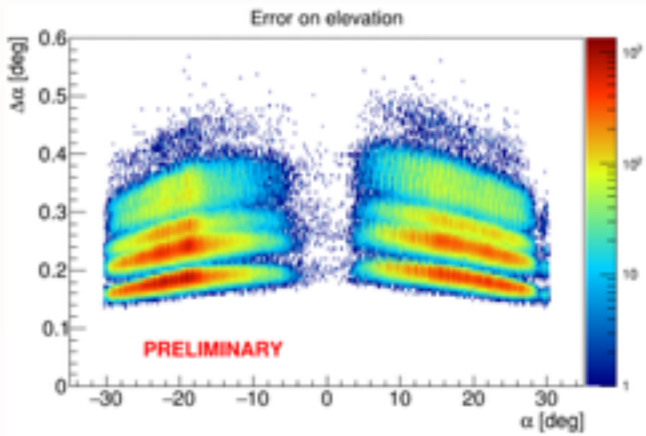


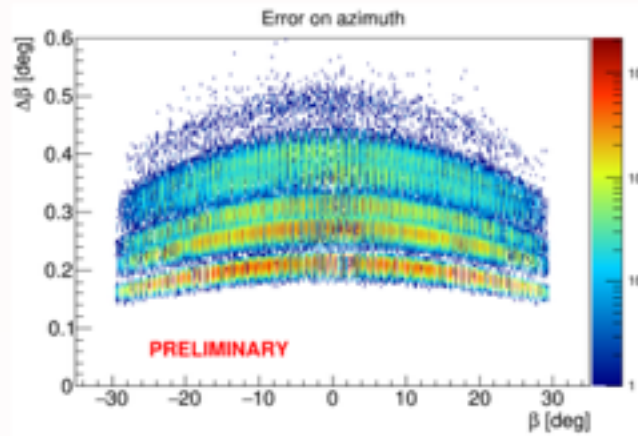
TOMUVOL 2015 campaign on Puy de Dôme

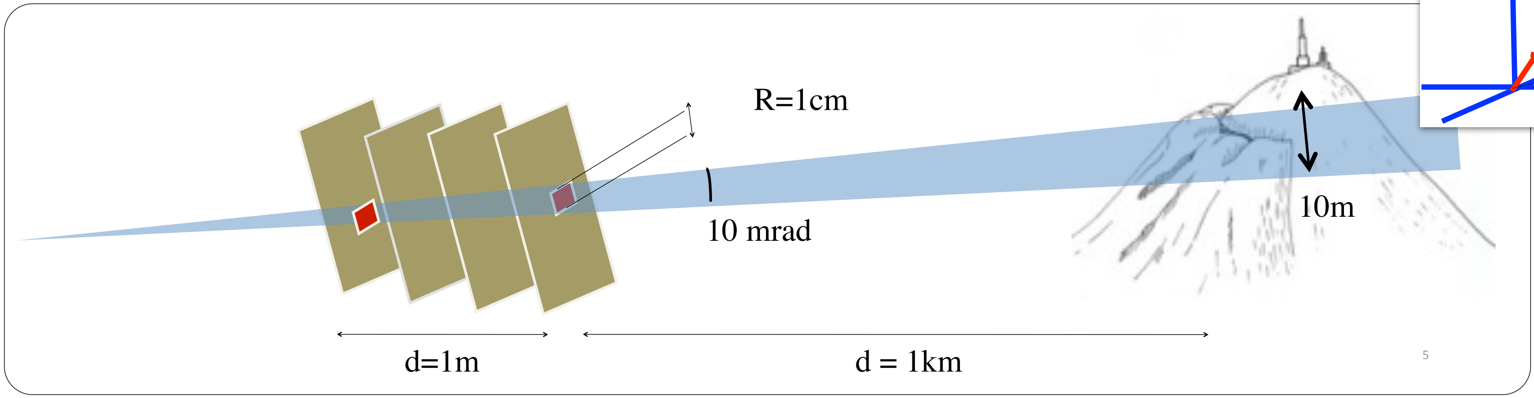
- Very preliminary results on the CDC 2015-2016 campaign
- 99.6 effective days of data taking
- 1 m^2 detector

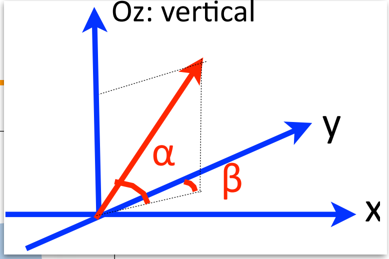










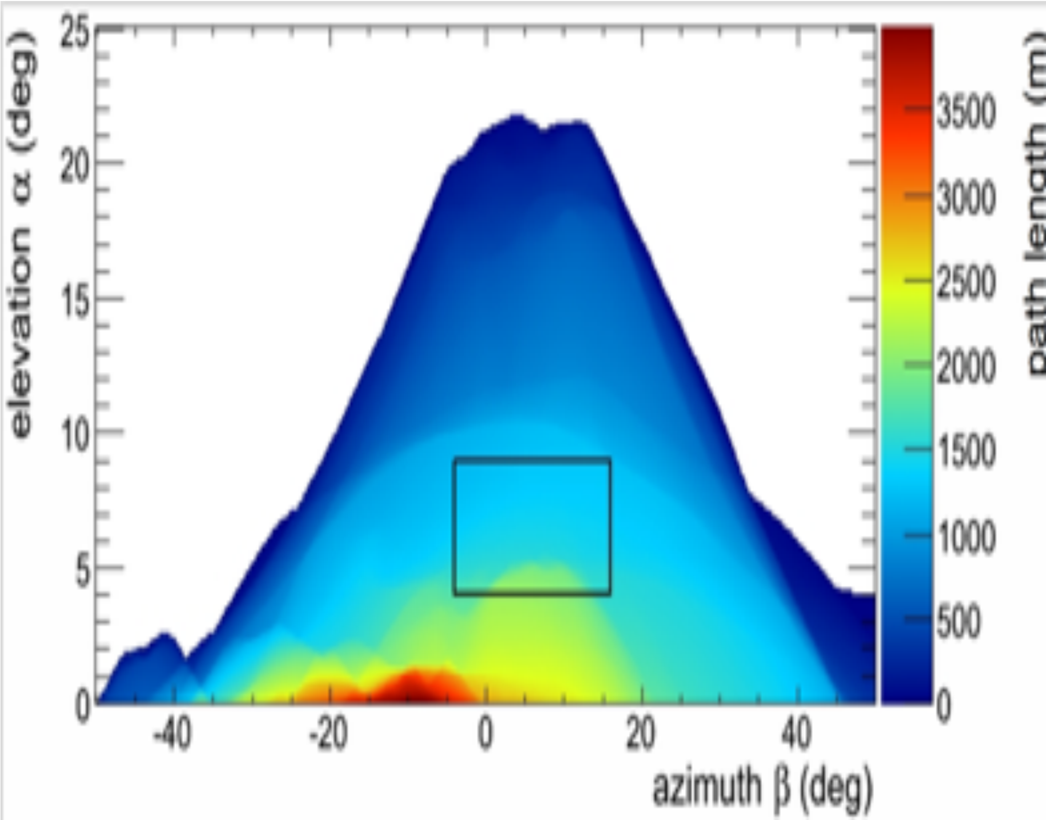


$$\mathcal{T}_{\rho}(\alpha, r(\alpha,\beta)) = \frac{\Phi(\alpha, r(\alpha,\beta))}{\Phi_0(\alpha)}$$

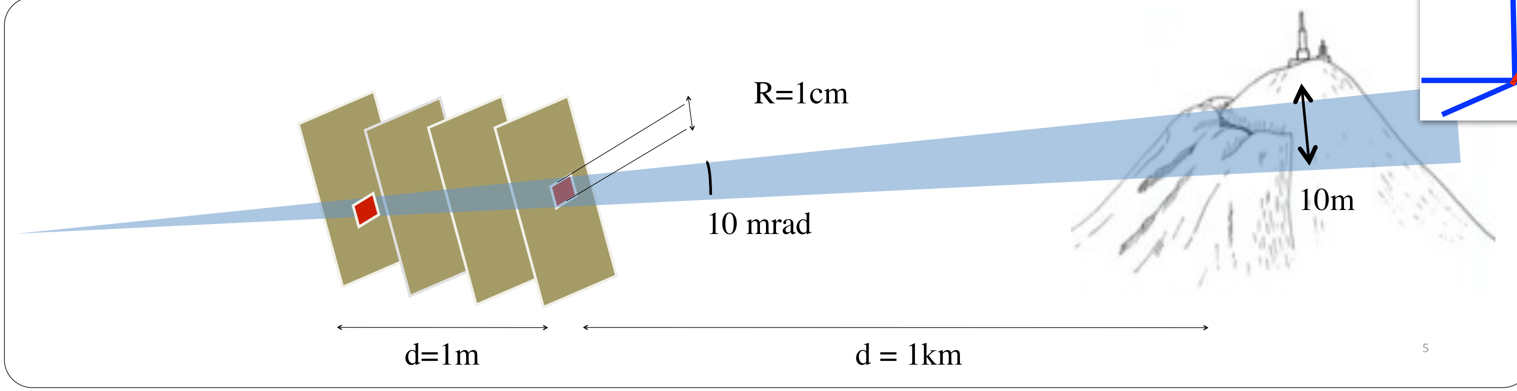
$$\int \rho(\alpha,\beta)dr = \mathcal{F}(\mathcal{T}(\alpha,\beta))$$

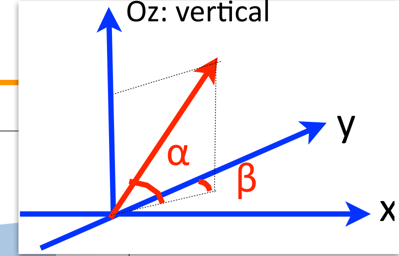
$$\Phi(\alpha,\beta) = \frac{N(\alpha,\beta)}{Seff(\alpha,\beta)\Delta T \Delta\Omega}$$

$$S_{eff} = S_{det}\varepsilon_{det}\varepsilon_{geom}\varepsilon_{illum}$$



Transmission muography in a nutshell …





$$\mathcal{T}_\rho(\alpha, r(\alpha,\beta)) = \frac{\Phi(\alpha, r(\alpha,\beta))}{\Phi_0(\alpha)}$$

$$\int \rho(\alpha,\beta)dr = \mathcal{F}(\mathcal{T}(\alpha,\beta))$$

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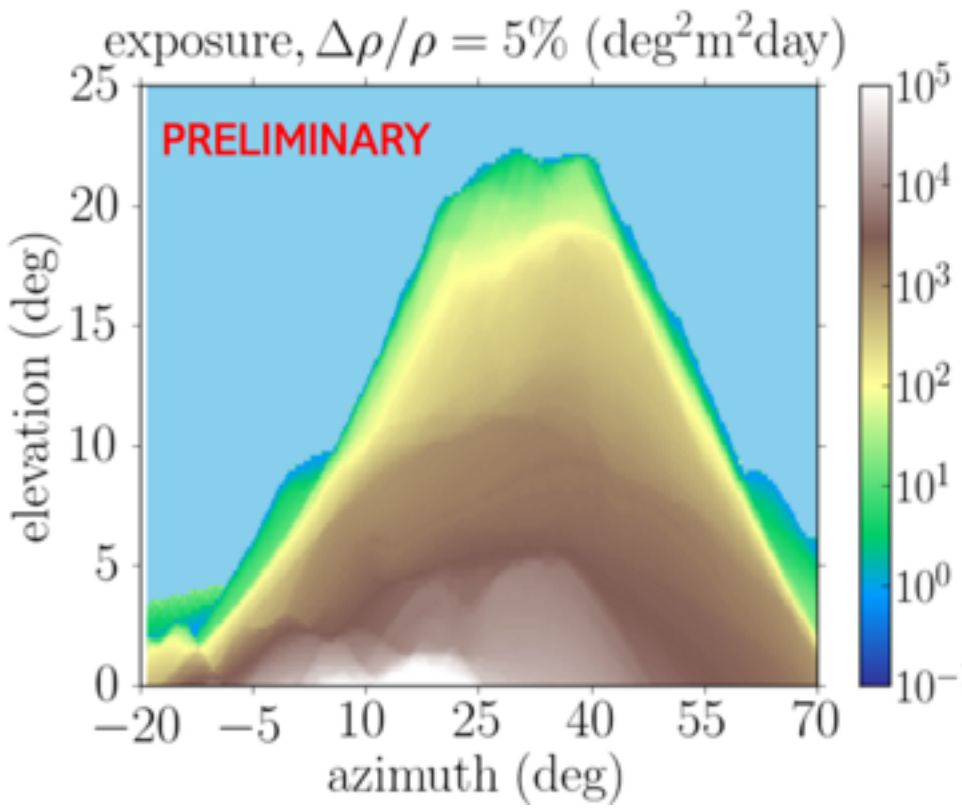
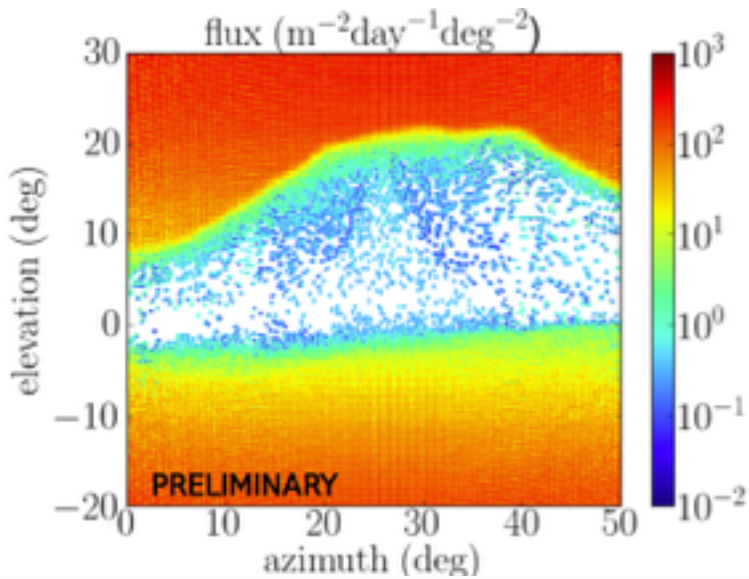
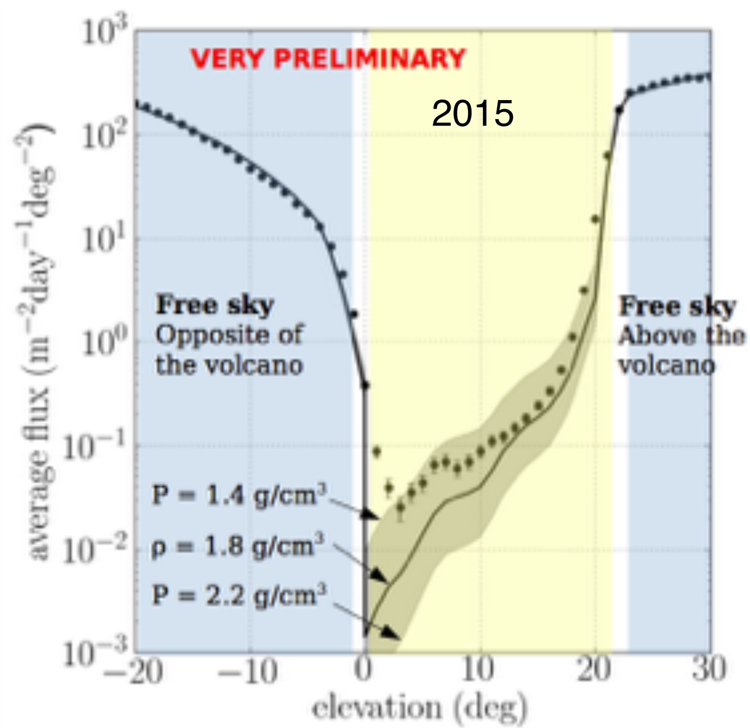
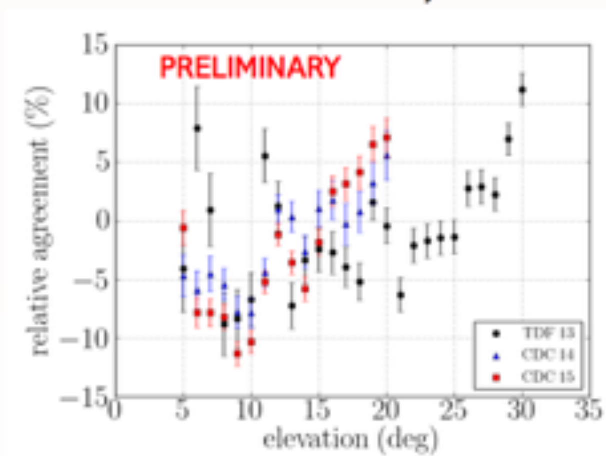


Transmission muography in a nutshell …

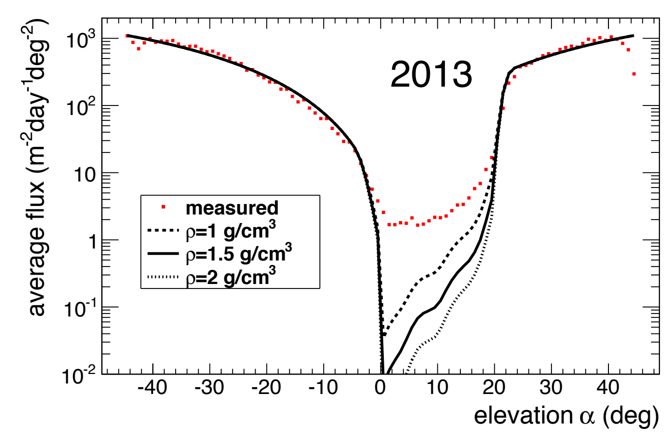




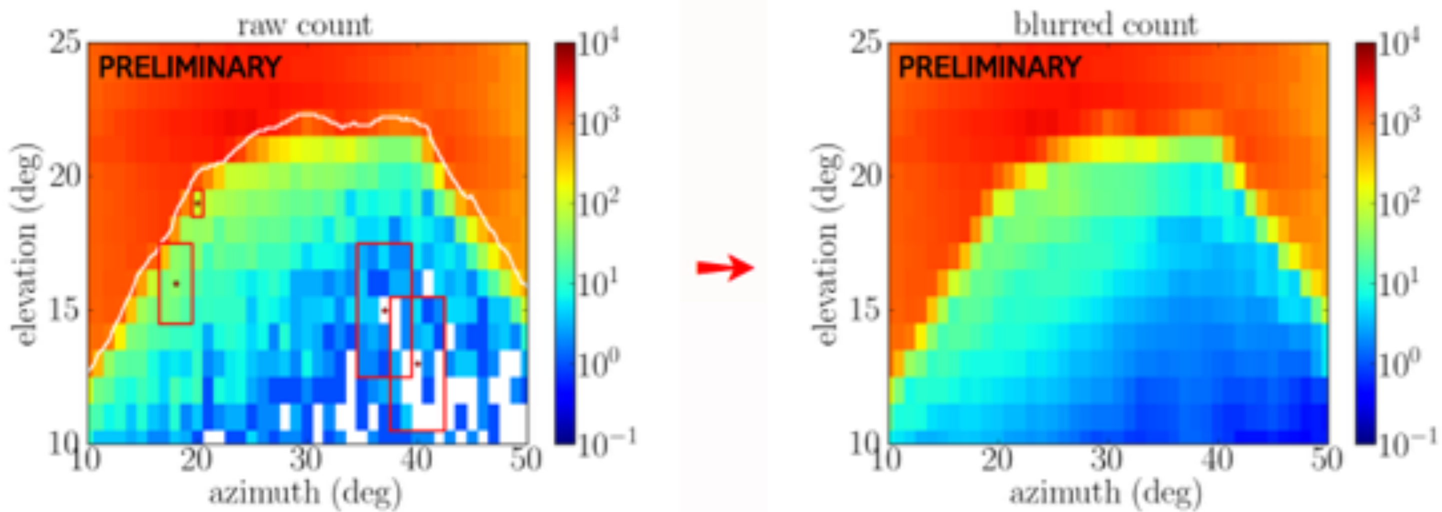
For the moment, systematic uncertainty estimated from comparison between data and model in the free sky



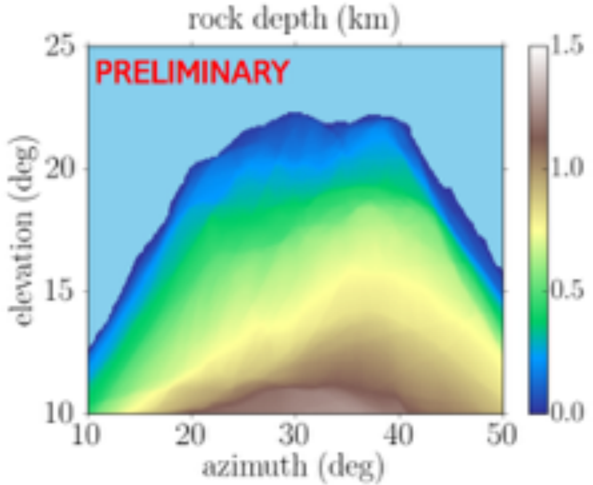
$$rel.\ agreement = 100 \times \left(\frac{data}{pred} - 1\right)$$



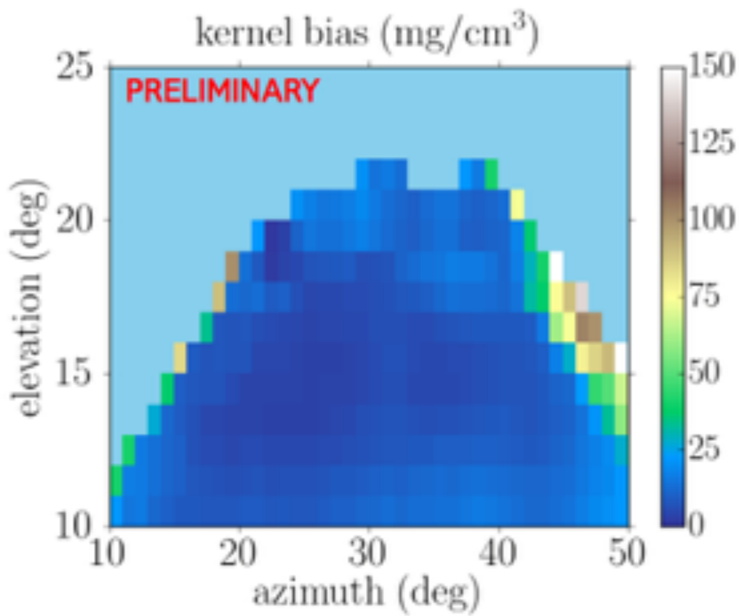
- Density estimation is limited by the statistics: low rate of transmitted muons, i.e. larger the rock depth the lower the muon rate is
  - → Use a kernel like method with a variable/tuned kernel size: balance bias vs statistical uncertainty
- Consider the binned muon count as classical image and apply image processing methods
  1. Start from a map of the muons count in angular bins of 1×1 deg^2
  2. In the rocky area, apply a Gaussian blurring with pencil size increasing as the distance to the rock border from 1×1 deg^2 to a maximum of 7×7 deg^2.
  3. For each bin, compute the expectation for the blurred image for a uniform density hypothesis. Assign the density value that best matches the observation.

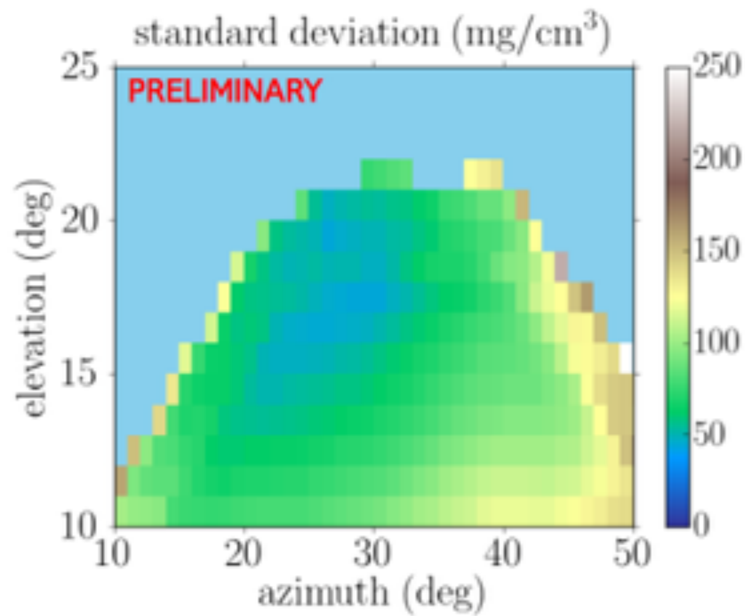


Crosscheck for a uniform volcano with ρ=1.8g/cm3

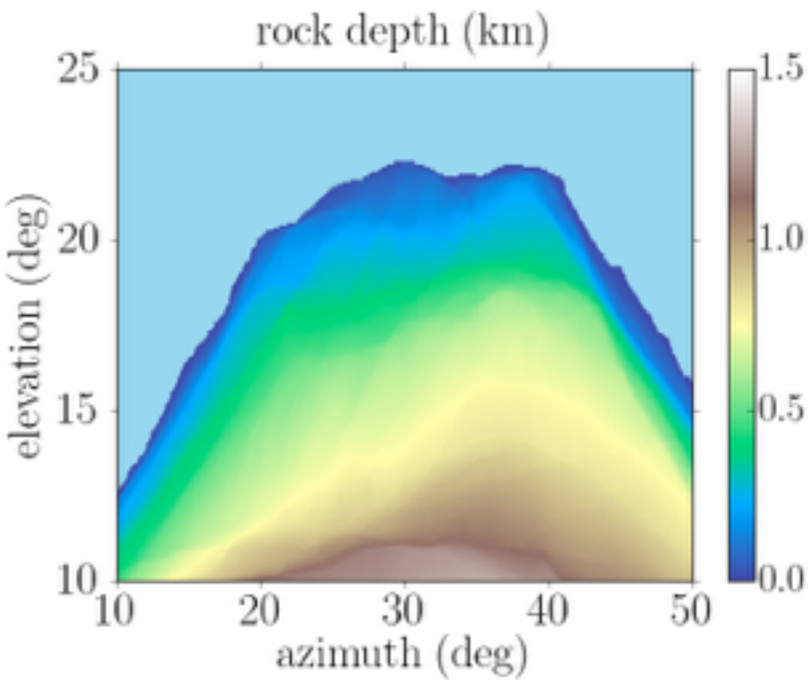


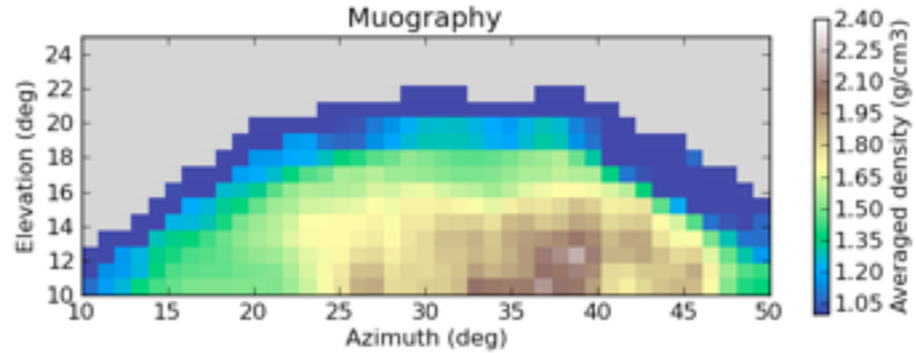
- The bias is negligible, ~ 10-20 mg/cm^3, except close to the rock border, where the transmitted and free sky flux mix.
- Few degrees farther from the border the statistical uncertainties are below ~ 100 mg/cm^3.

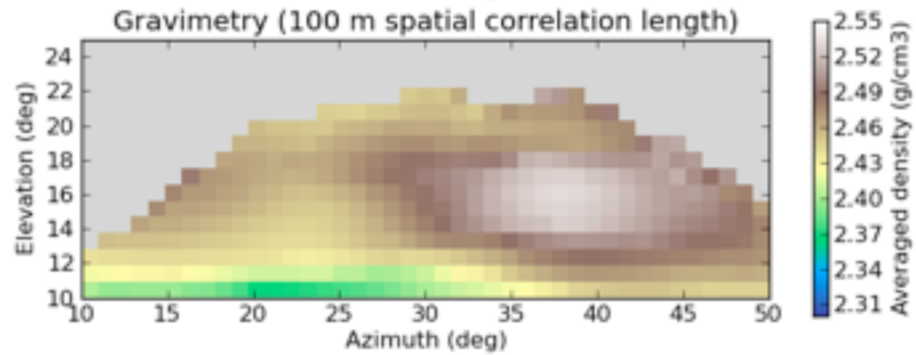


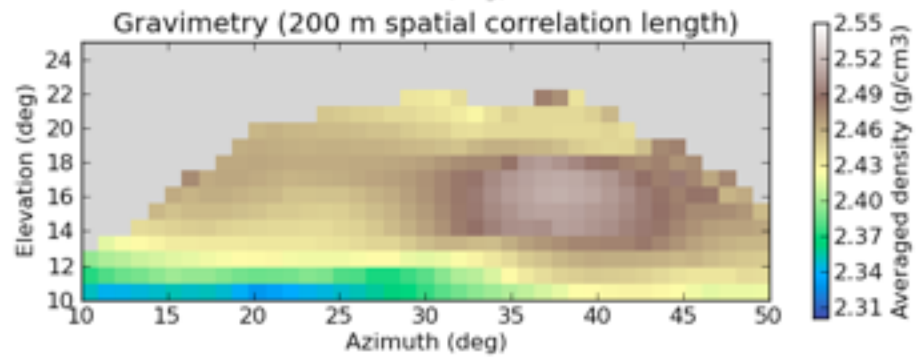


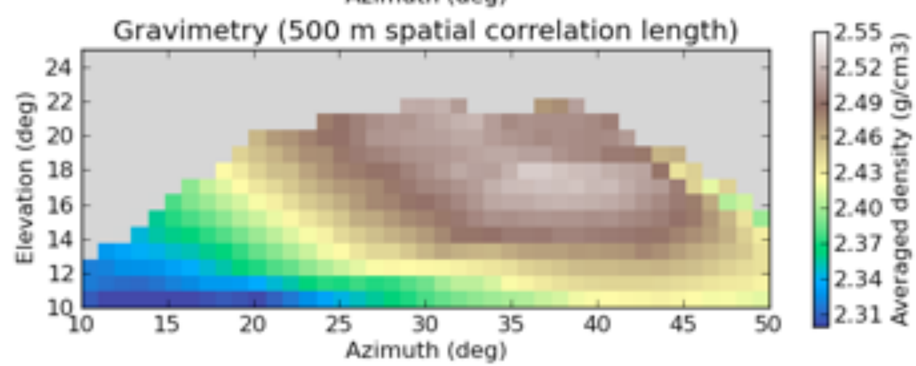
Puy de Dôme
Inner structure

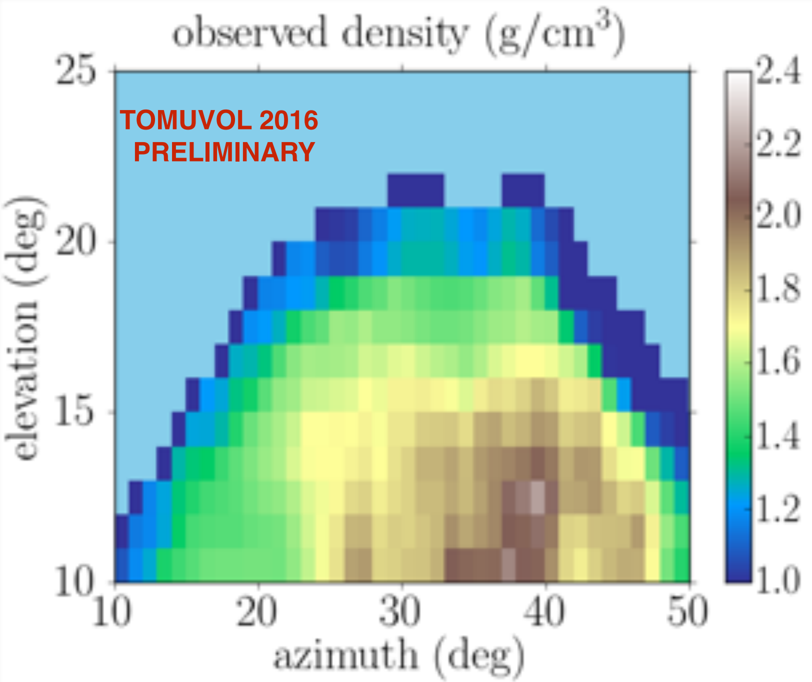








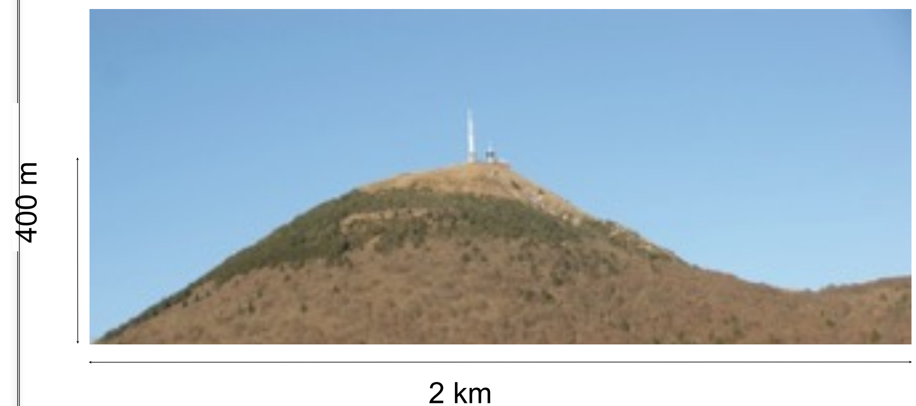




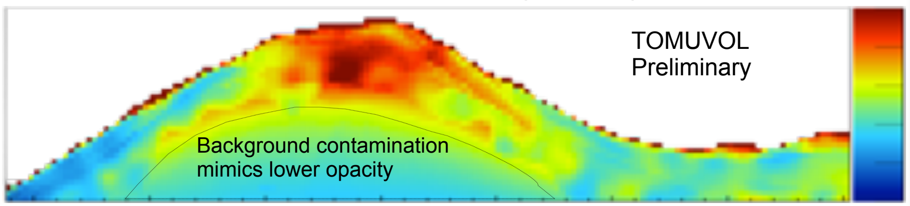
Measurement (the image binning follows strictly the uncertainties, no filtering, smoothing, etc)

If additional image treatment & geophysical hypothesis considered the image greatly improved

Puy de Dôme as seen from the muon telescope site



Internal structure observed through muography



Linear opacity to atmospheric muons

65.8 days of data taking, 0.16 m^2 x 0.5 m

Physics Today, decembre 2012

Conclusion

Proof of principle on Puy de Dôme done, common inversion of muographic and gravimetry data expected very soon.

... time to image some active volcanoes with increased area and improved telescopes!