Volcanoes Tomography With Atmospheric Muons

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on behalf of the **TOMUVOL** collaboration

[1]**Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC**
[2] **Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPNL**

The Tomuvol collaboration

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

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

Phase 1 : 2010-2014

- Validate the muon imaging of the Puy-de-Dôme against standard geophysical techniques.

Phase 2 : 2014-2016

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

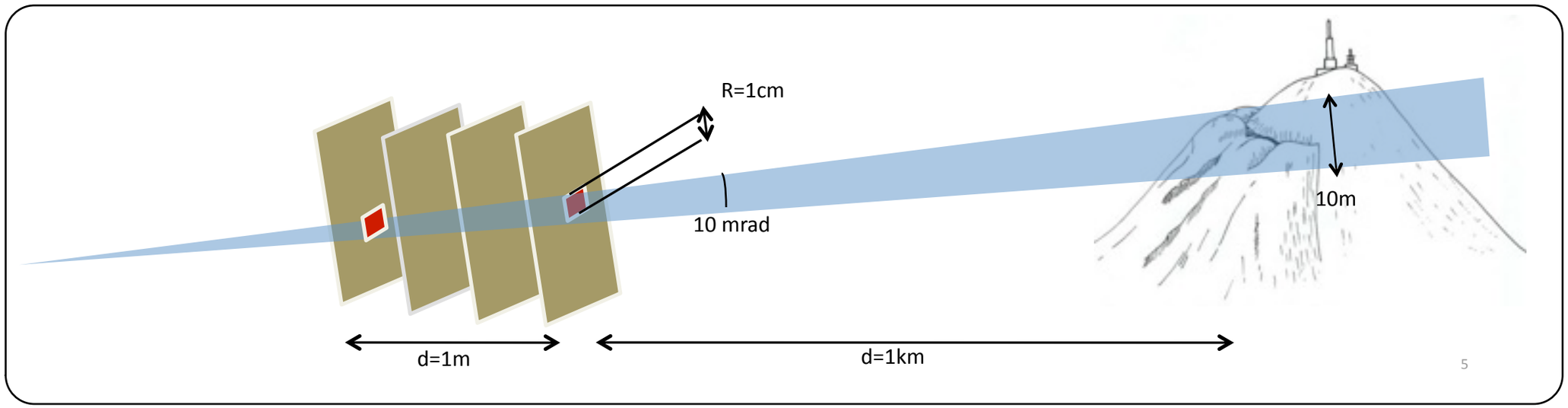
Ultimate phase:

- Monitoring active volcanoes.

Base design of the detector :

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

The muography in a nutshell …



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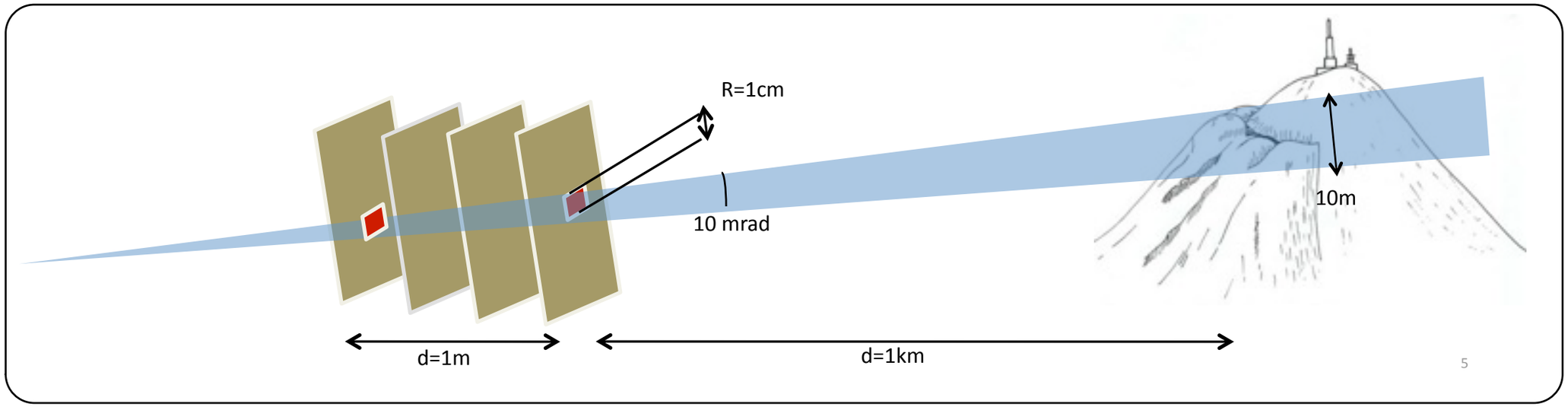

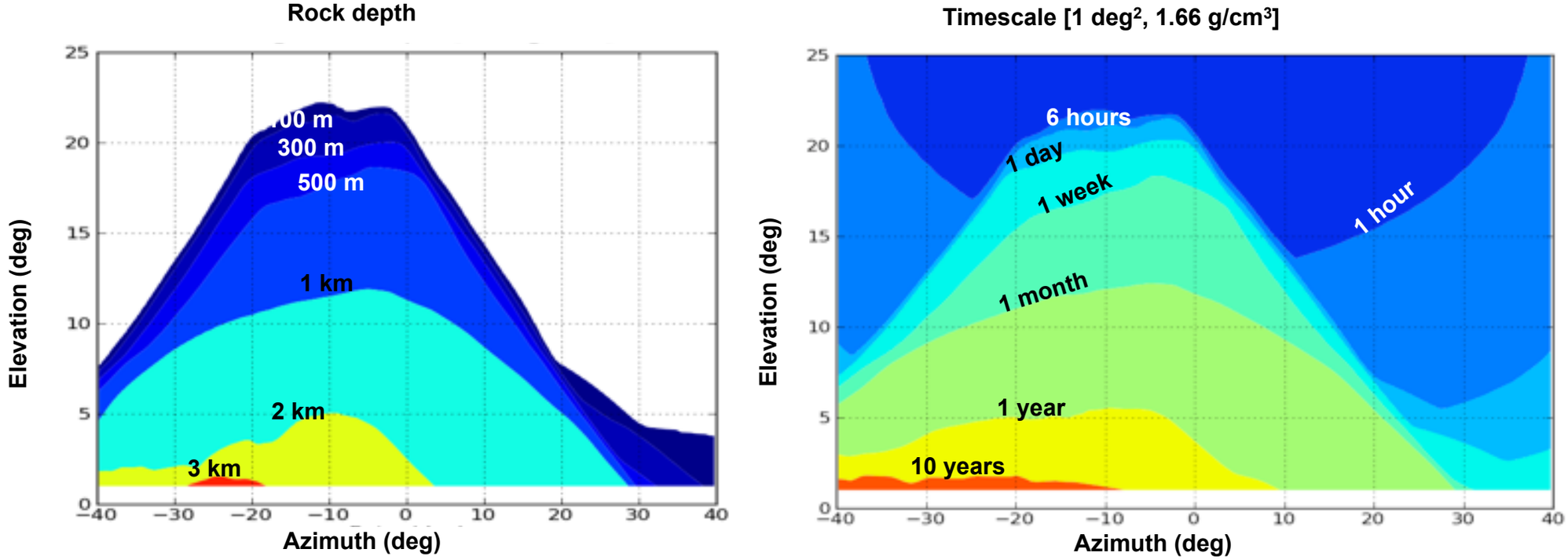

Computation for a uniform target with ρ=1.66g/cm^3 and a **0.67 m^2** ideal detector

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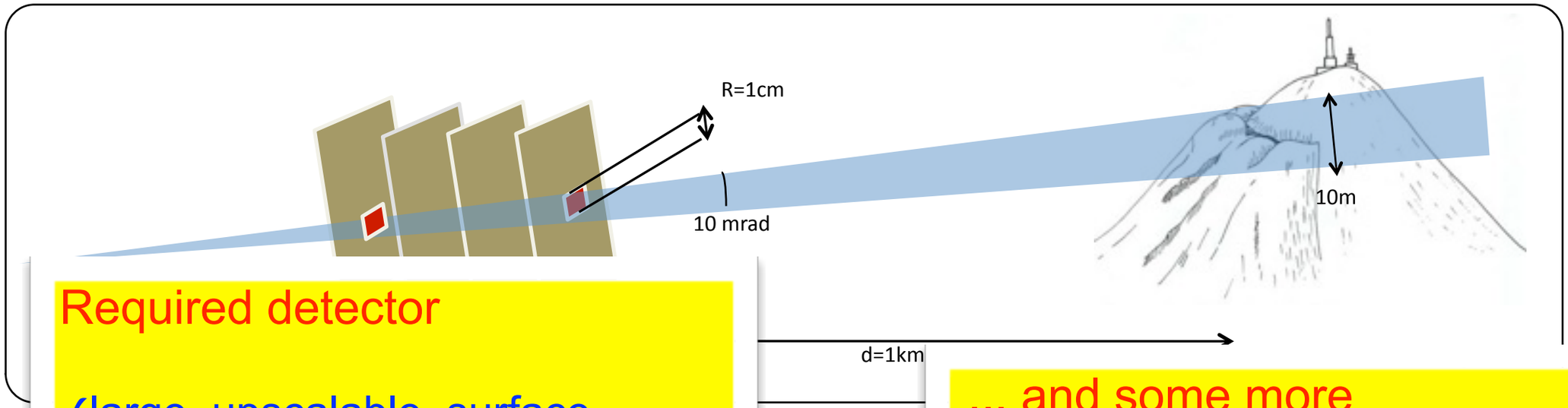
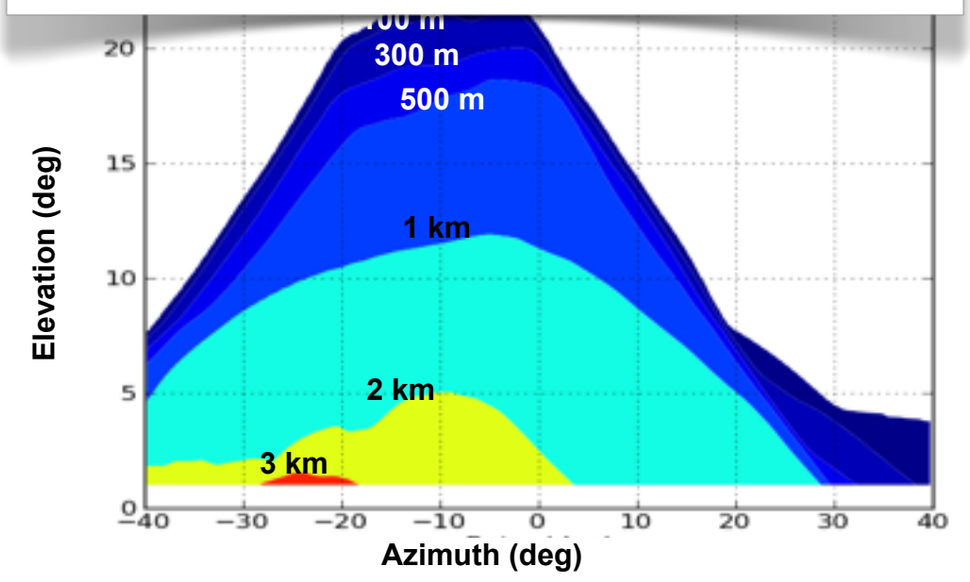


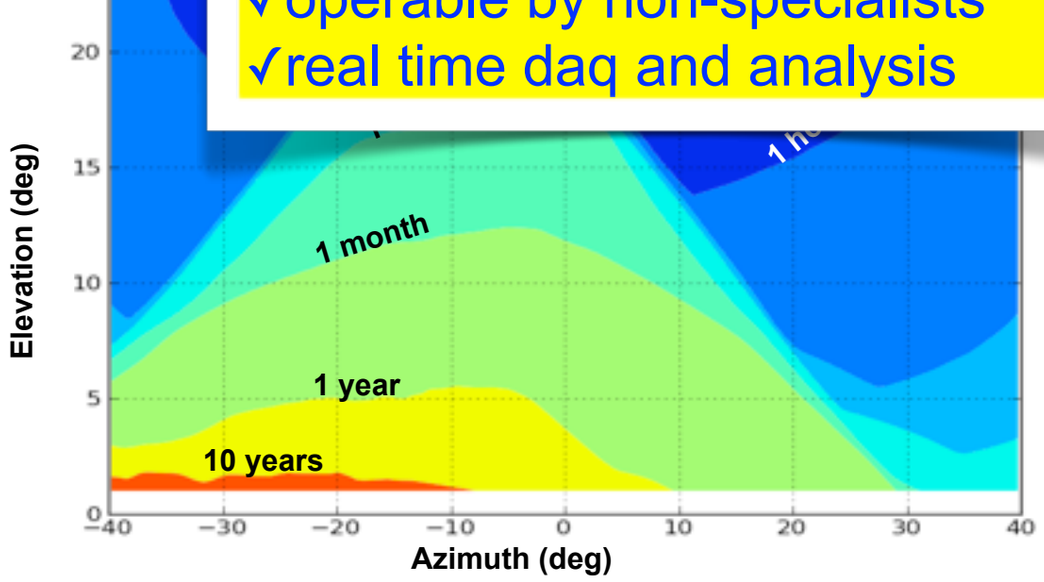
Required detector

✓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



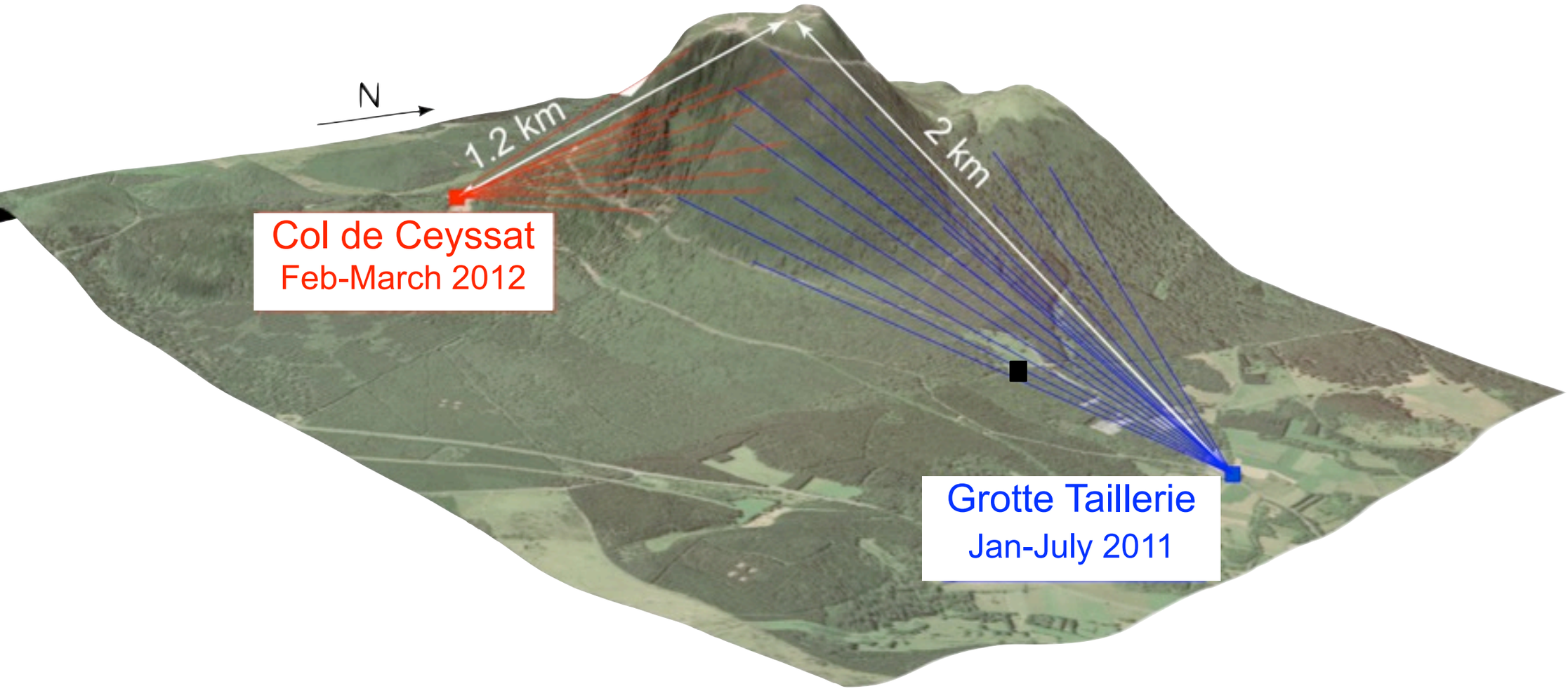


Computation for a uniform target with ρ=1.66g/cm^3 and a **0.67 m^2** ideal detector

Puy de Dôme as reference site for muon imaging

Aim: infere the volcano history from its present structure for prediction future behaviour

⇨ Proof of principle on a large volcano (~2km at the base)



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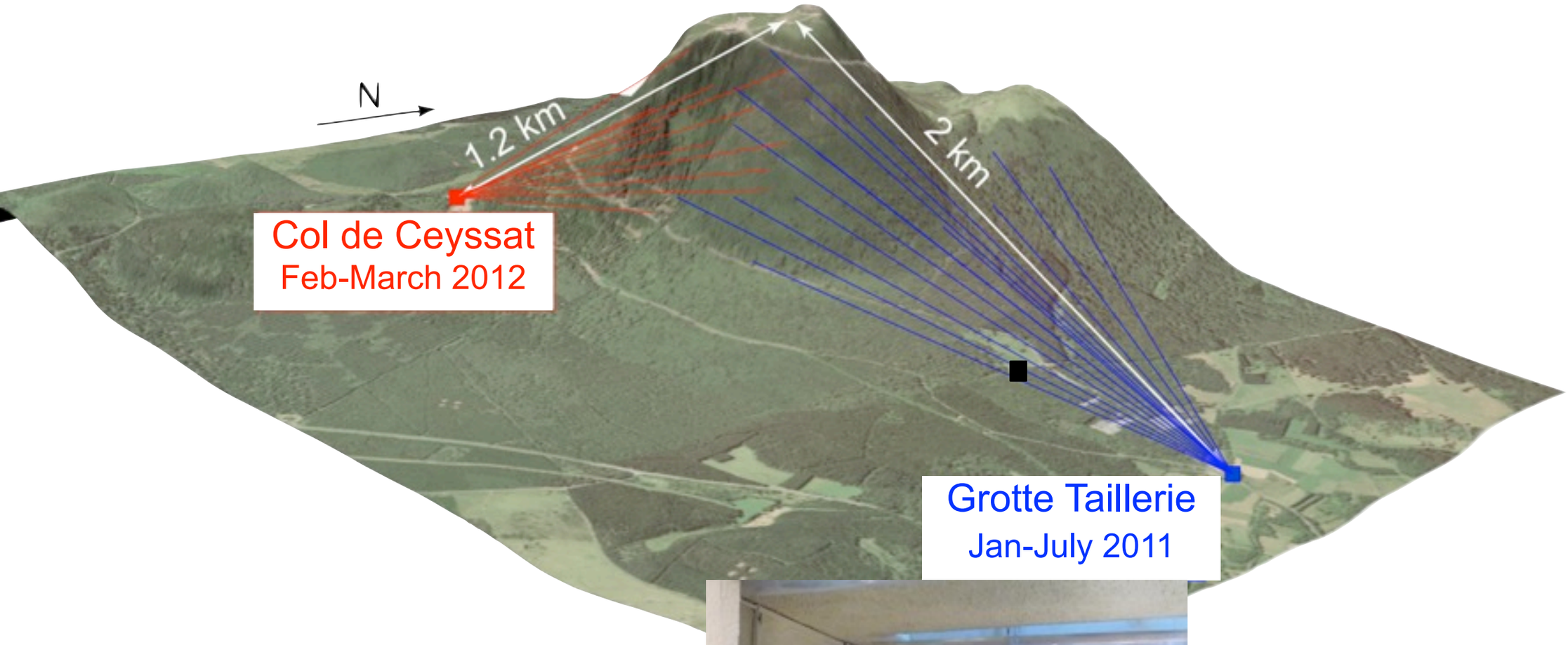

Setup:

- 3 layers of 1m² x 1m² x 0.16 m².
- outer spacing : 0.5 m / 1 m.
- underground site.

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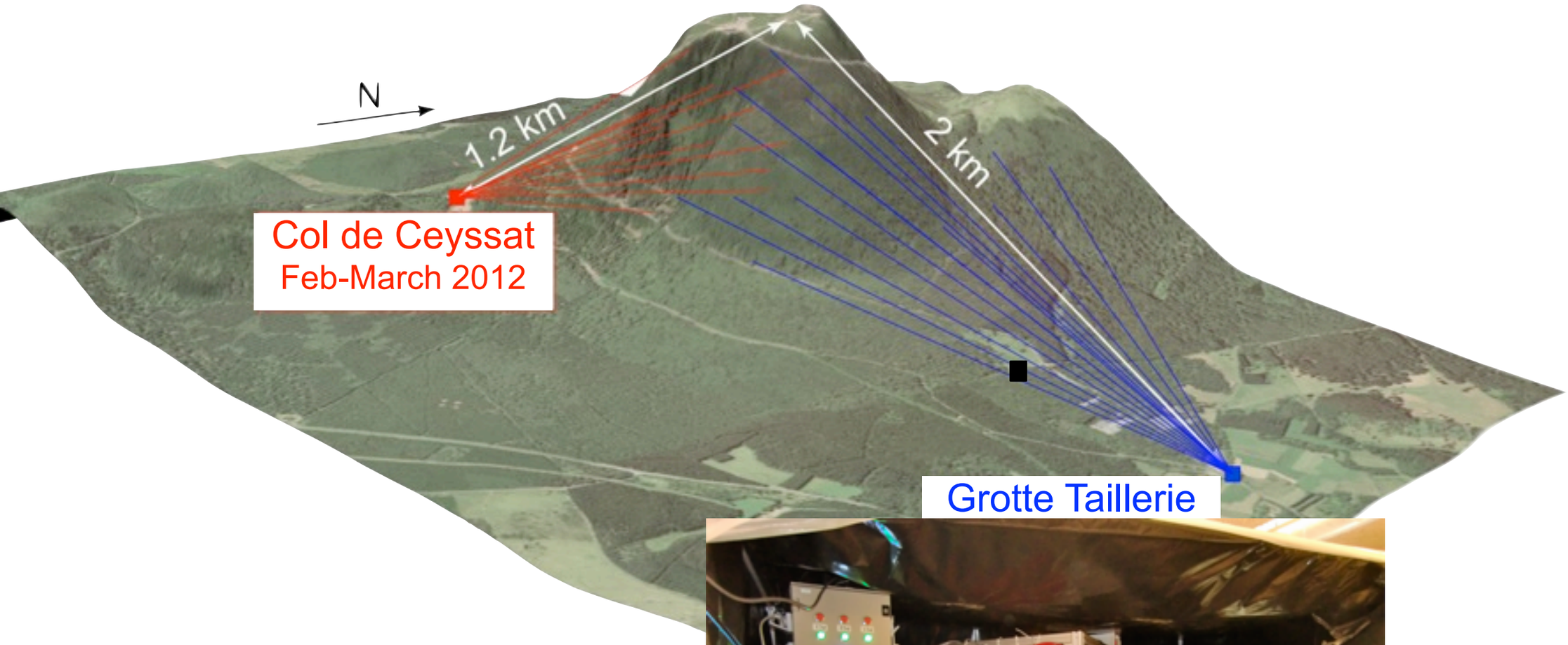

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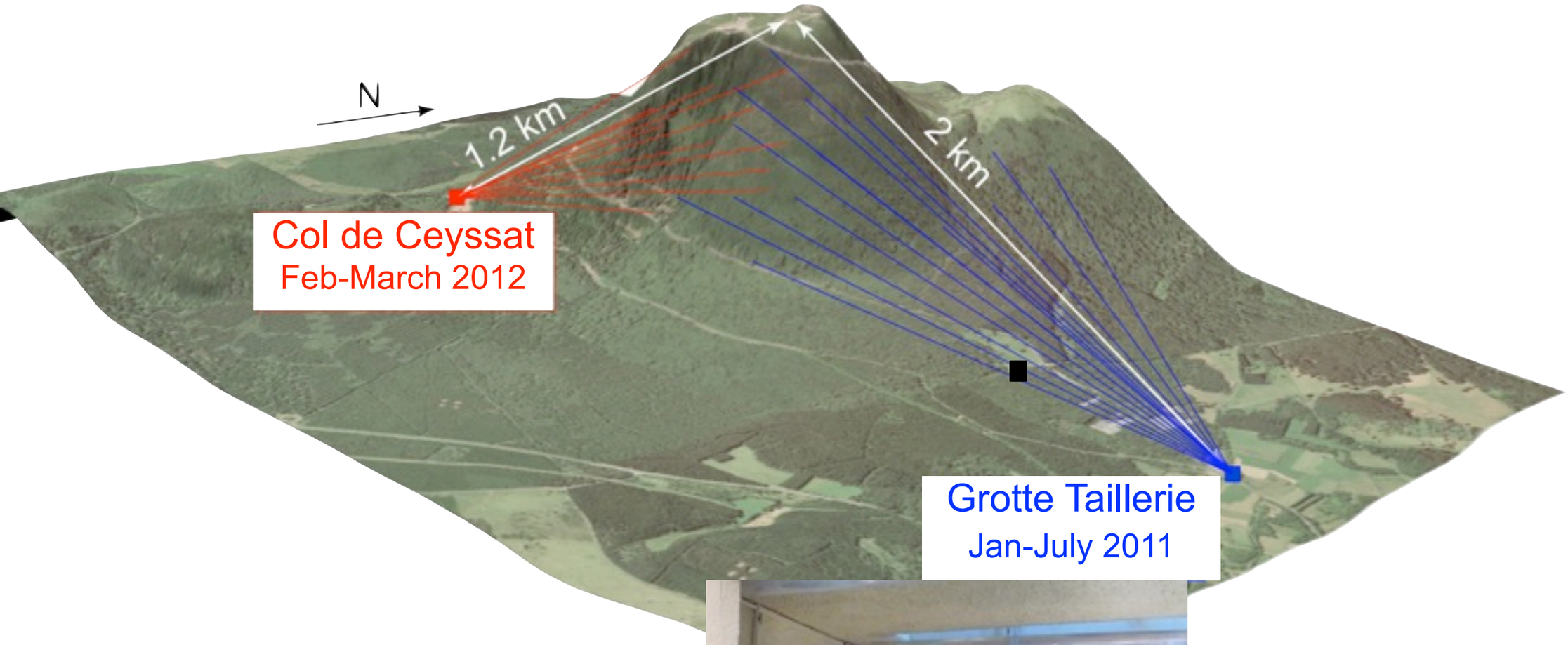

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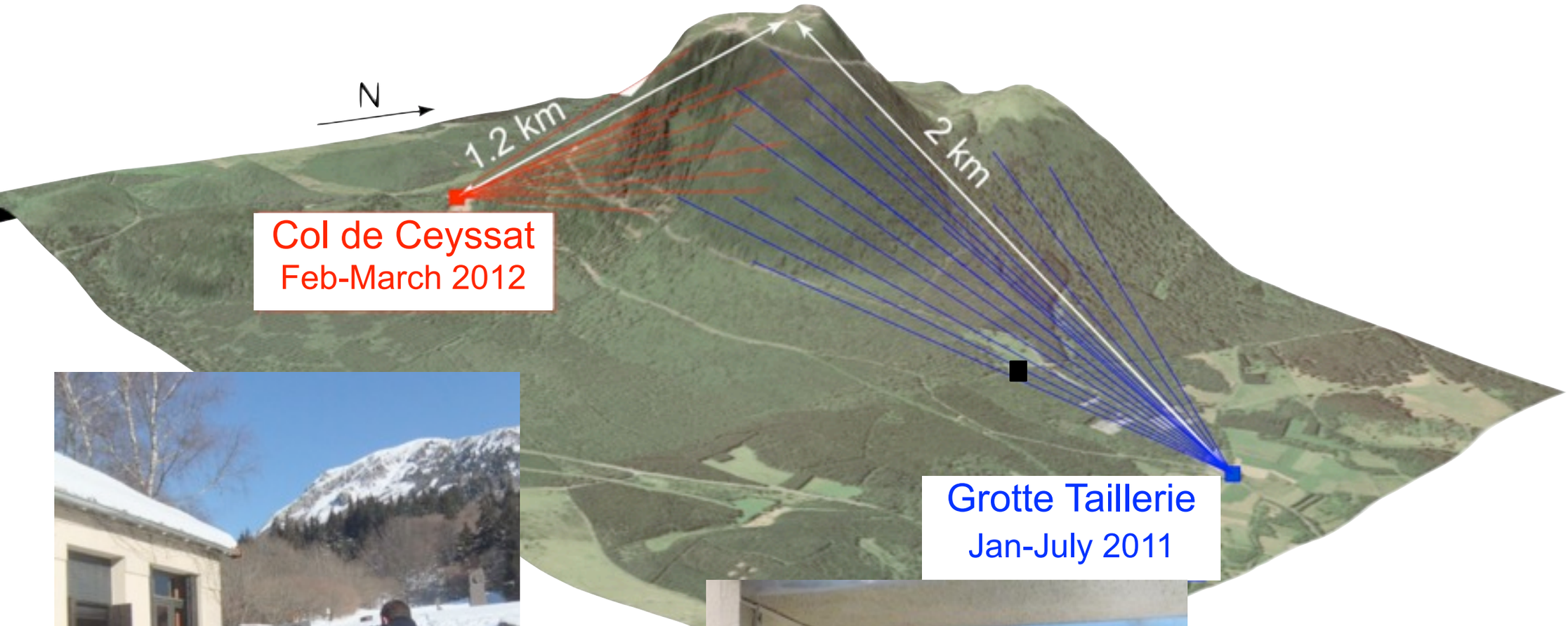

Setup:
- 4 layers of 1m² x 1m² x 1m² x 0.66 m².
- outer spacing : 1 m.
- surface site, but detector partially shielded by buildings around

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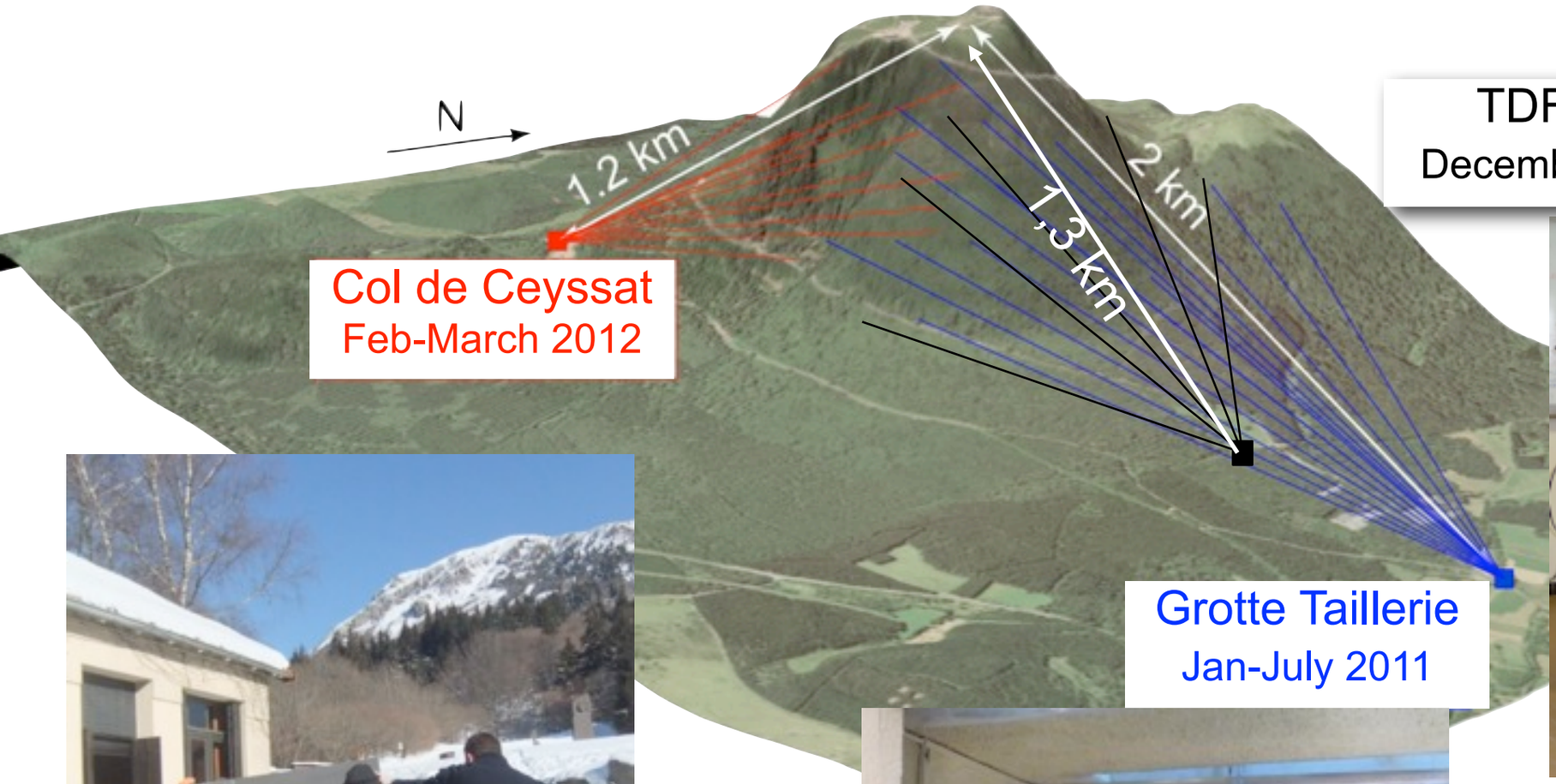


Col de Ceyssat
Feb-March 2012

Setup:
- 4 layers of 1m² x 1m² x 1m² x 0.66 m².
- outer spacing : 1 m.
- surface site, but detector partially shielded by buildings around

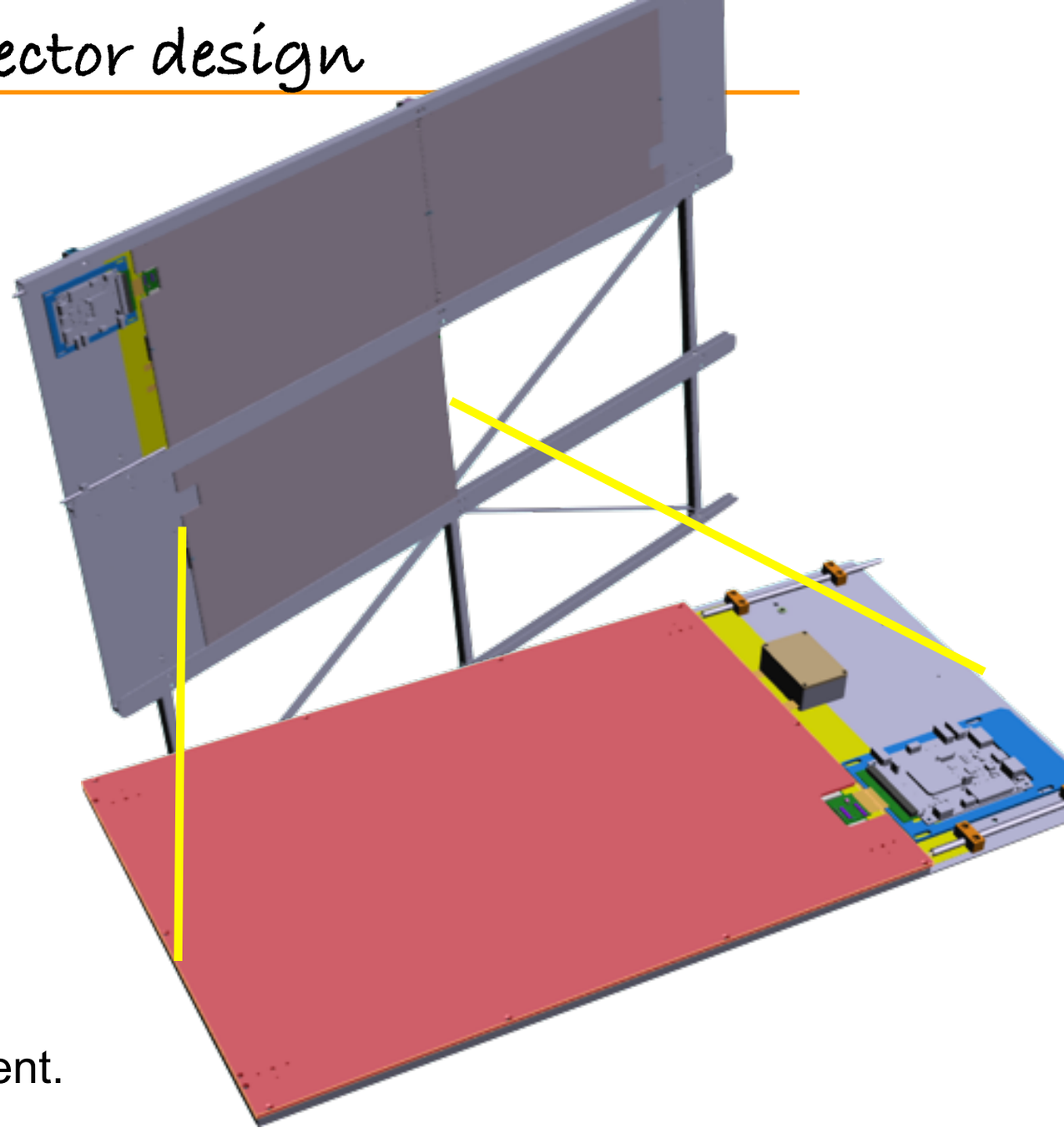
Grotte Taillerie
Jan-July 2011

Setup:
- 3 layers of 1m² x 1m² x 0.16 m².
- outer spacing : 0.5 m / 1 m.
- underground site.

TDF site
December 2013

- 4 layers of 1m² x 1m² x 1m² x 1m².
- outer spacing : 1 m .
- surface site, no shielding at all.

The Tomuvol detector design



- $1m^2$ chambers not really suited for field deployment.
- Difficult to transport (heavy, fragile).

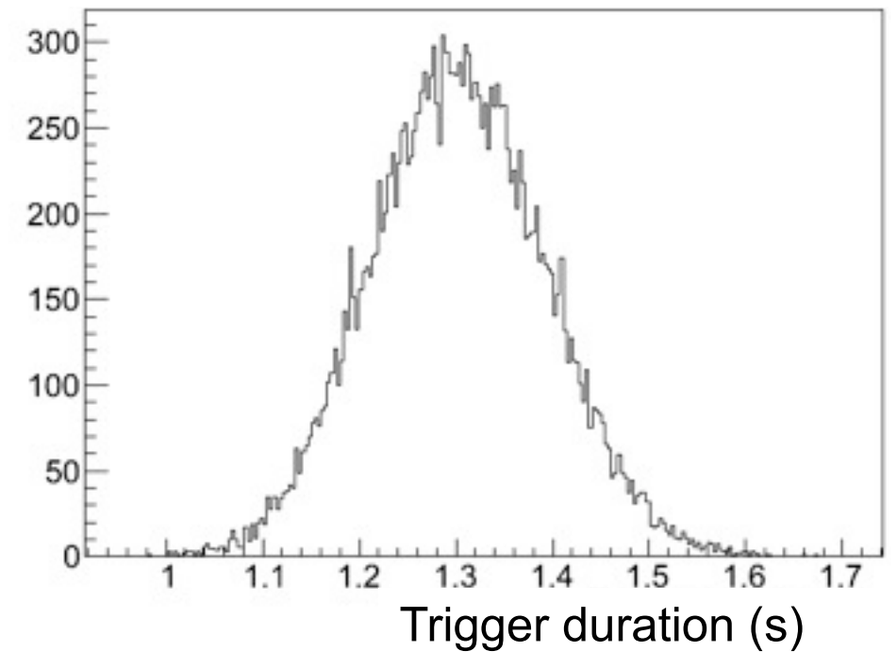
➥

$1m^2$ made out of 6 chambers $50x33\ cm^2$

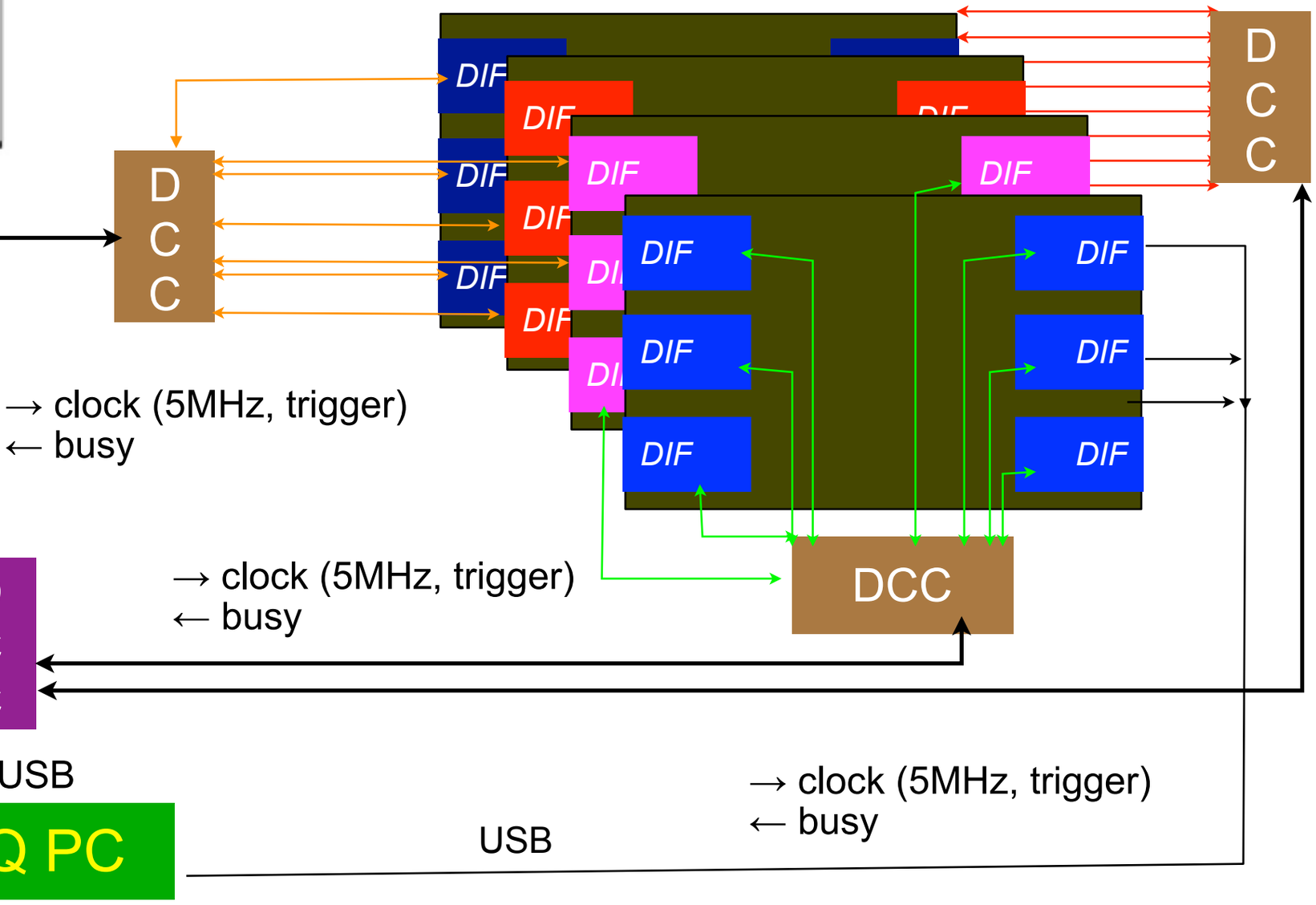
- easy to transport
- price/unit compatible with spare production
- special care in designing the structure for precise alignment

(Present) TOMUVOL detector

Tomuvol Clock & DAQ Synopsis



- system operated synchronously @ 5 MHz
- each DIF reads/controls 24 HARDROC2 ASICS (autotrigged and with internal RAM holding 128 consecutive events)
- first full RAM triggers the readout of the whole detector
- Oracle database for ASIC configurations and slow control
- XDAQ-based DAQ



Remote control and data taking

Network :

- La Taillerie & TDF site : using wifi antenna, relayed by the Puy-de-Dôme.
- Col de Ceyssat : “regular” Internet Service Provider.

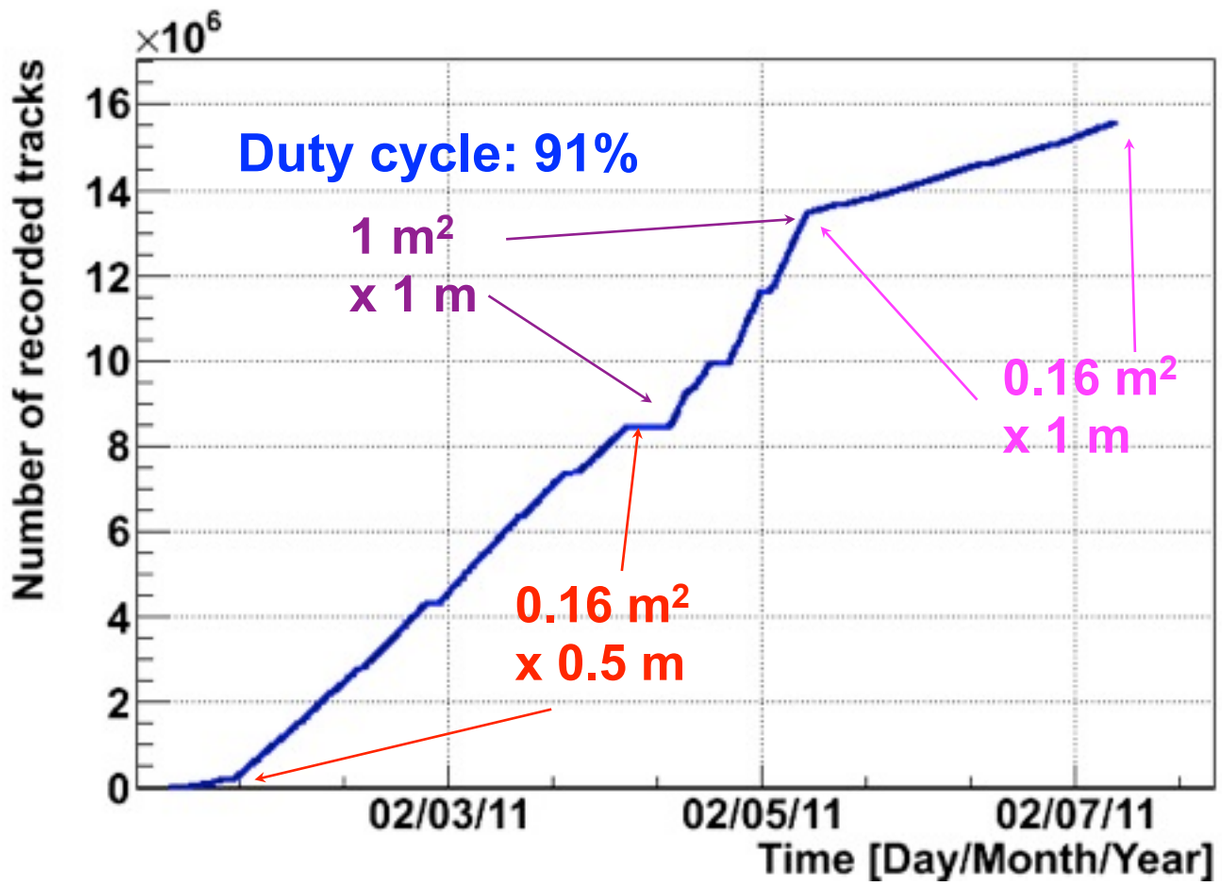



17 M μ candidates @ Grotte Taillerie,

11 M μ candidates @ Col de Ceyssat

(w/o any selection)

Thanks to daily shifts + very dedicated experts.



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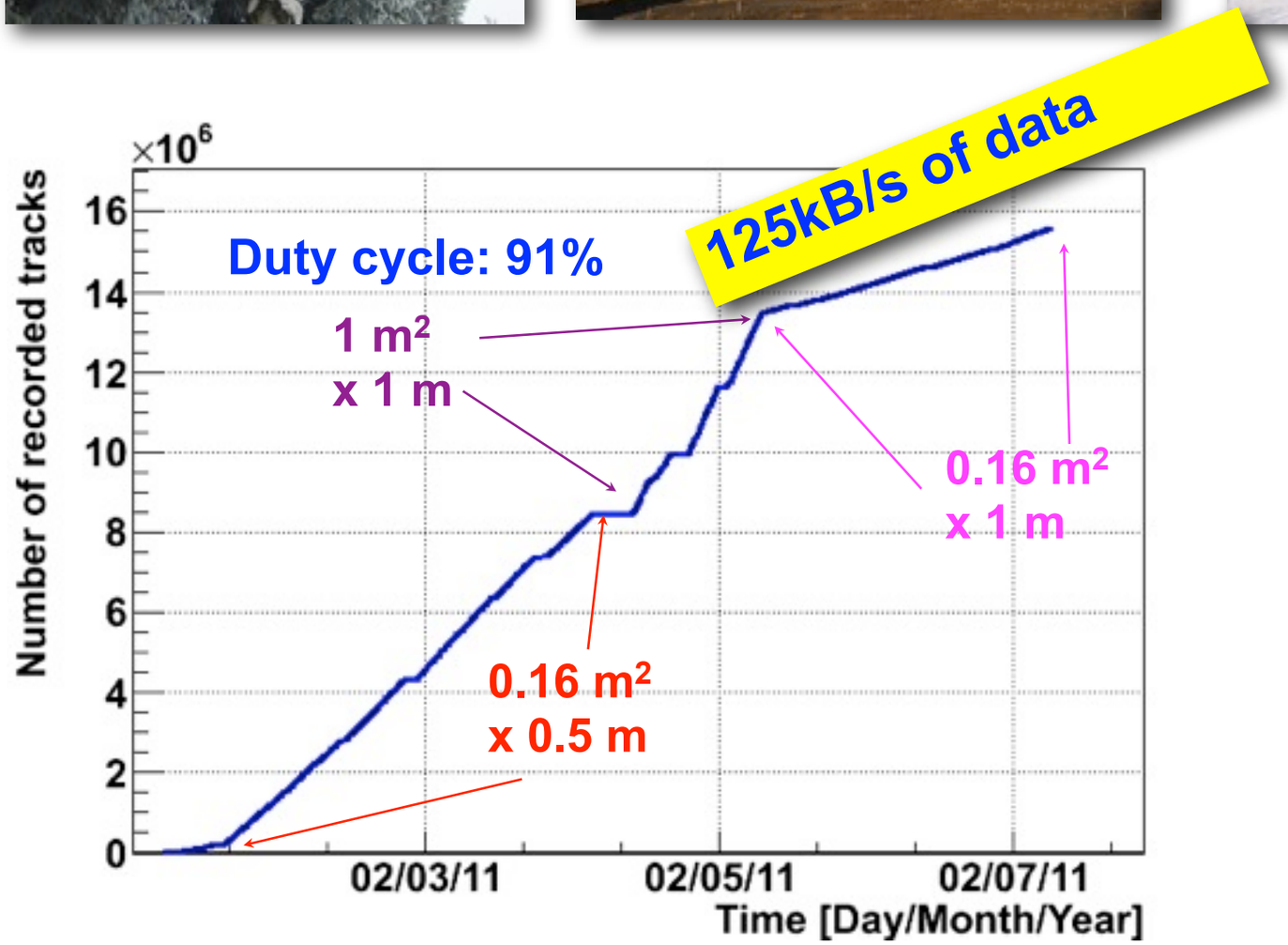

TDF Site - October 13- Jan 14

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Detector remotely controlled

Accueil Alarmes Détecteur Châssis Gaz SMS Configuration Historique Mon compte Déconnexion

Cristina Carloganu, administrateur

Liaison avec la carte contrôleur OK
Liaison avec le mélangeur gaz OK
Liaison avec le châssis OK

#1 châssis HV LV

#2 système gaz

#3 PC, USB et Webcam

#4 réseau

#5 châssis SDCC

#6 USB détecteur

24V on

220V on

Paramètre	Valeur	Unité
Humidité	45	%
Pression 0	88.8	kPa
Pression 1	89.8	kPa
Température	18	°C
Inclinomètre 1	1544.40	mrd
Inclinomètre 2	475.80	mrd
Forane	37.70	ml/mn
Isobutane	2.00	ml/mn
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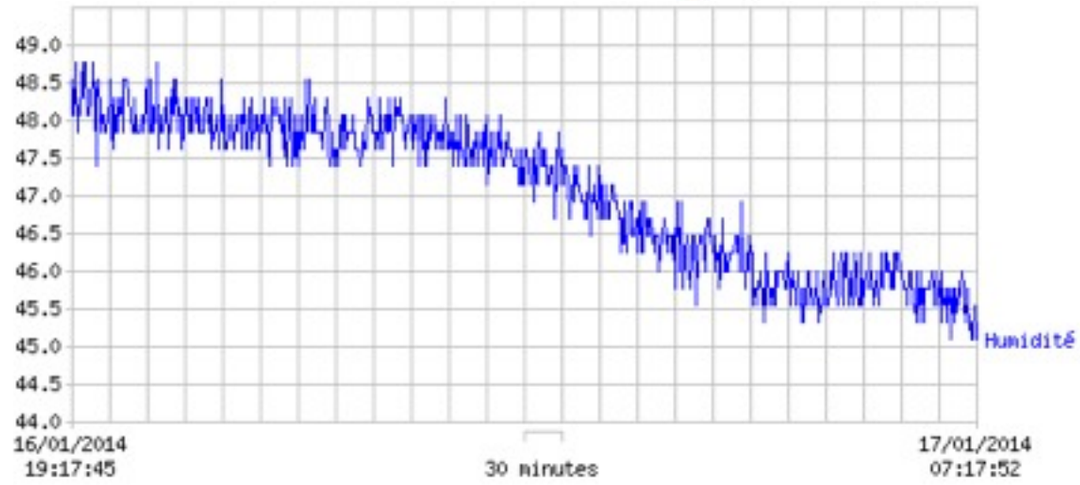

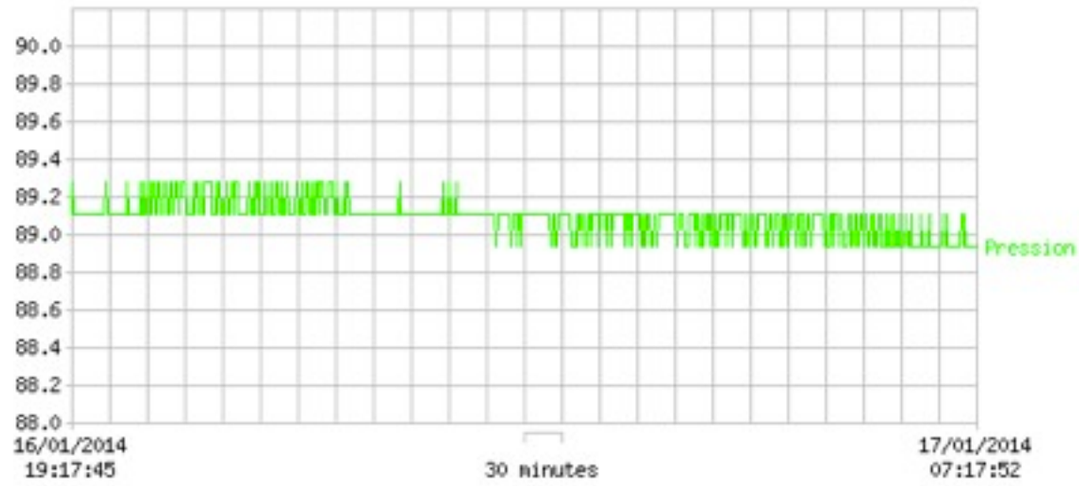

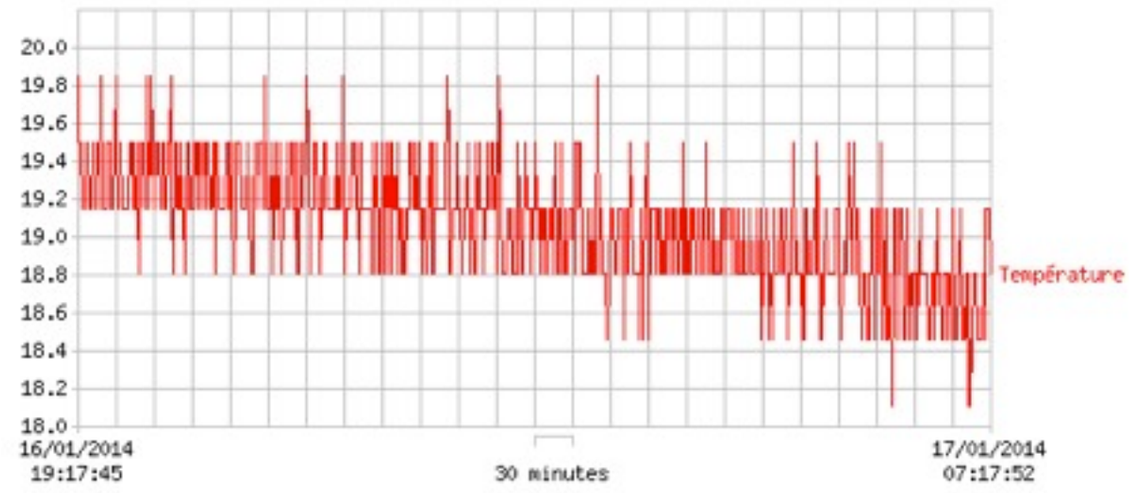

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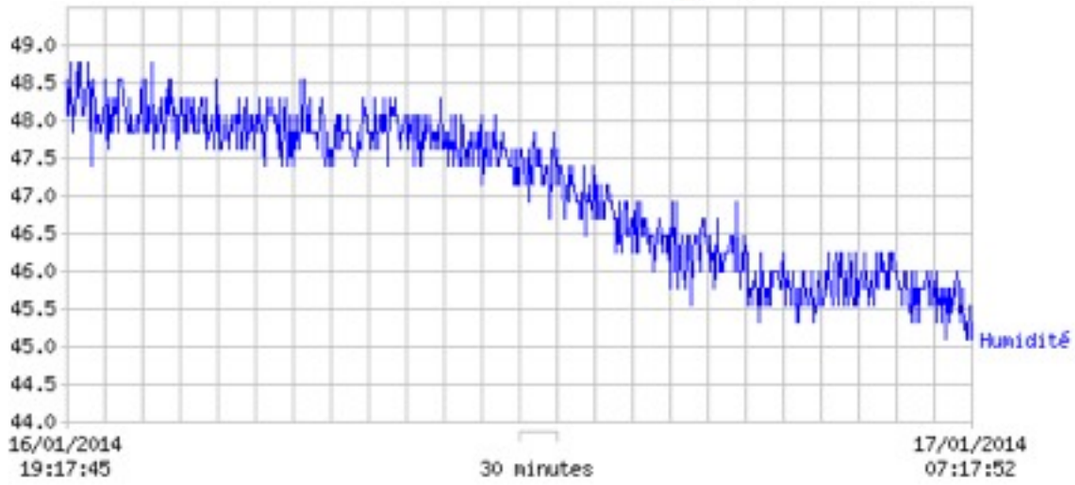

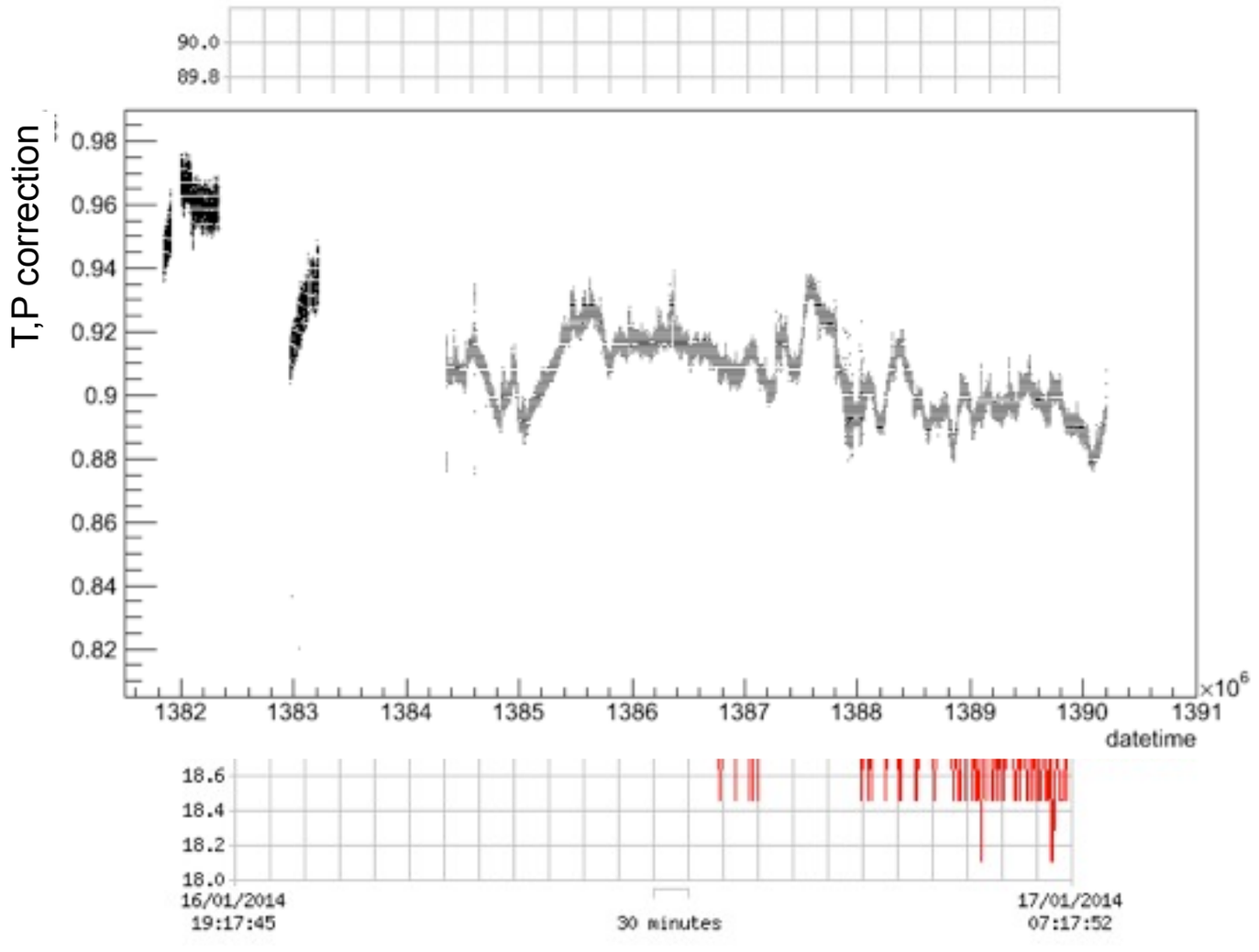

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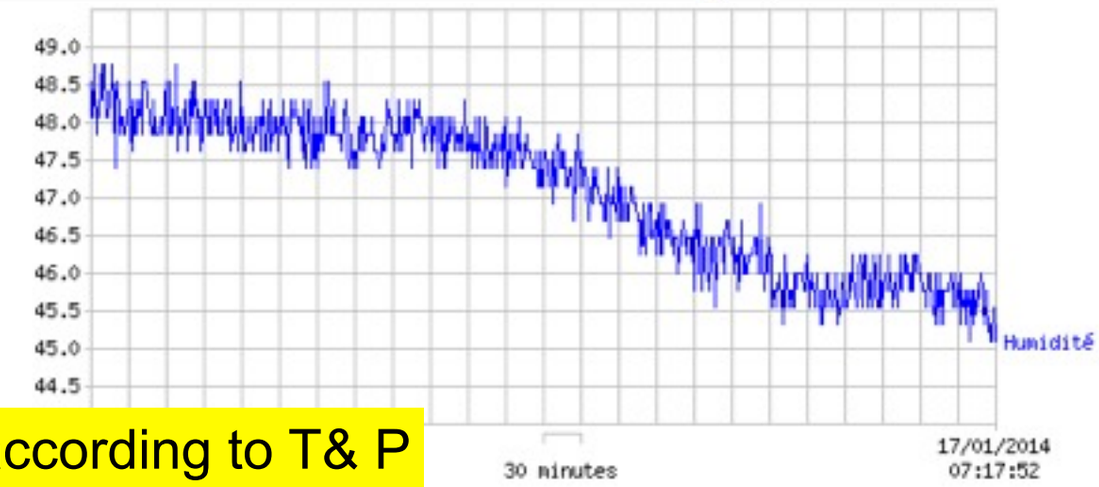
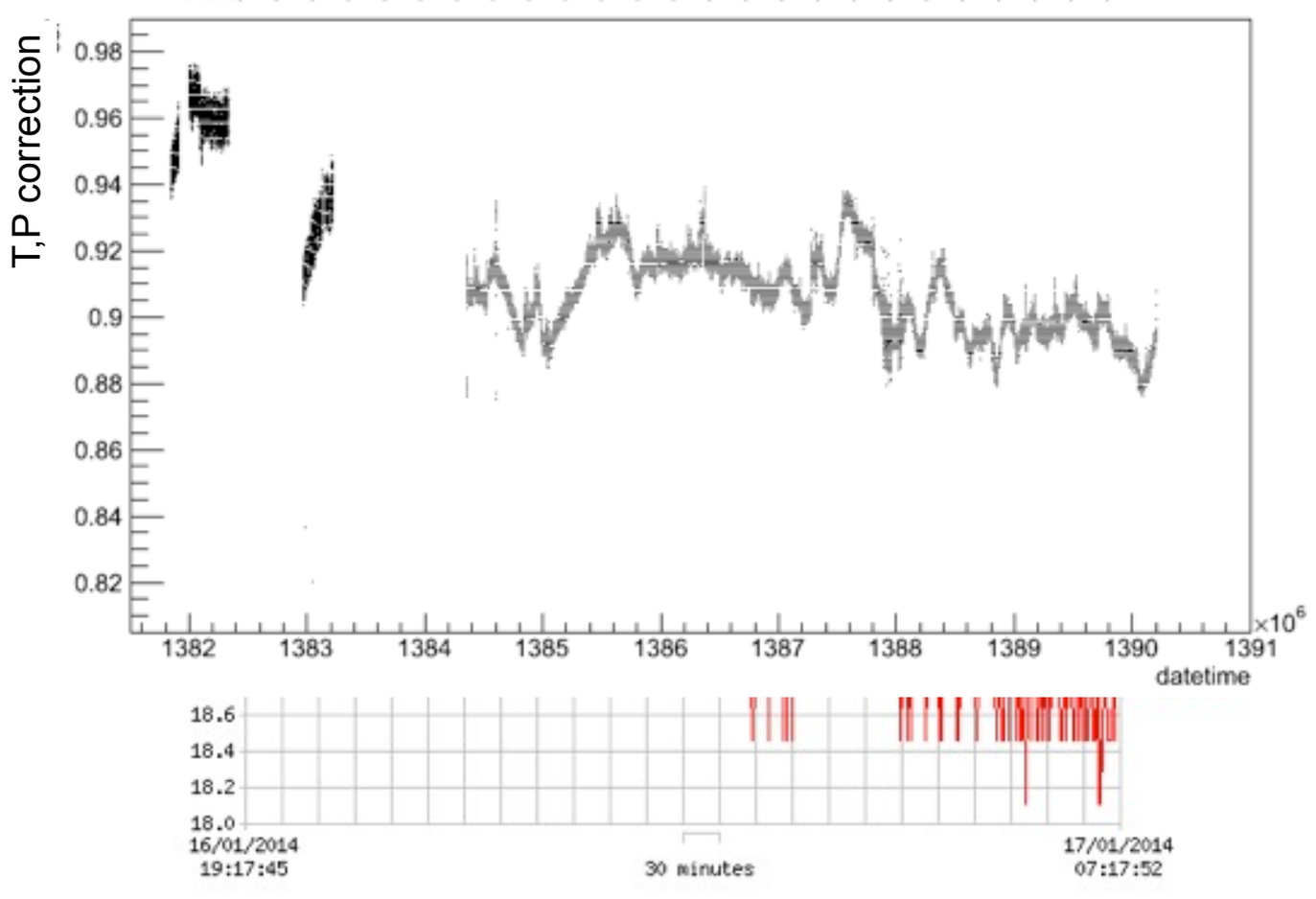


HV adjusted every 20 min according to T& P
~ 600 V of offset from sea leve/ 20º

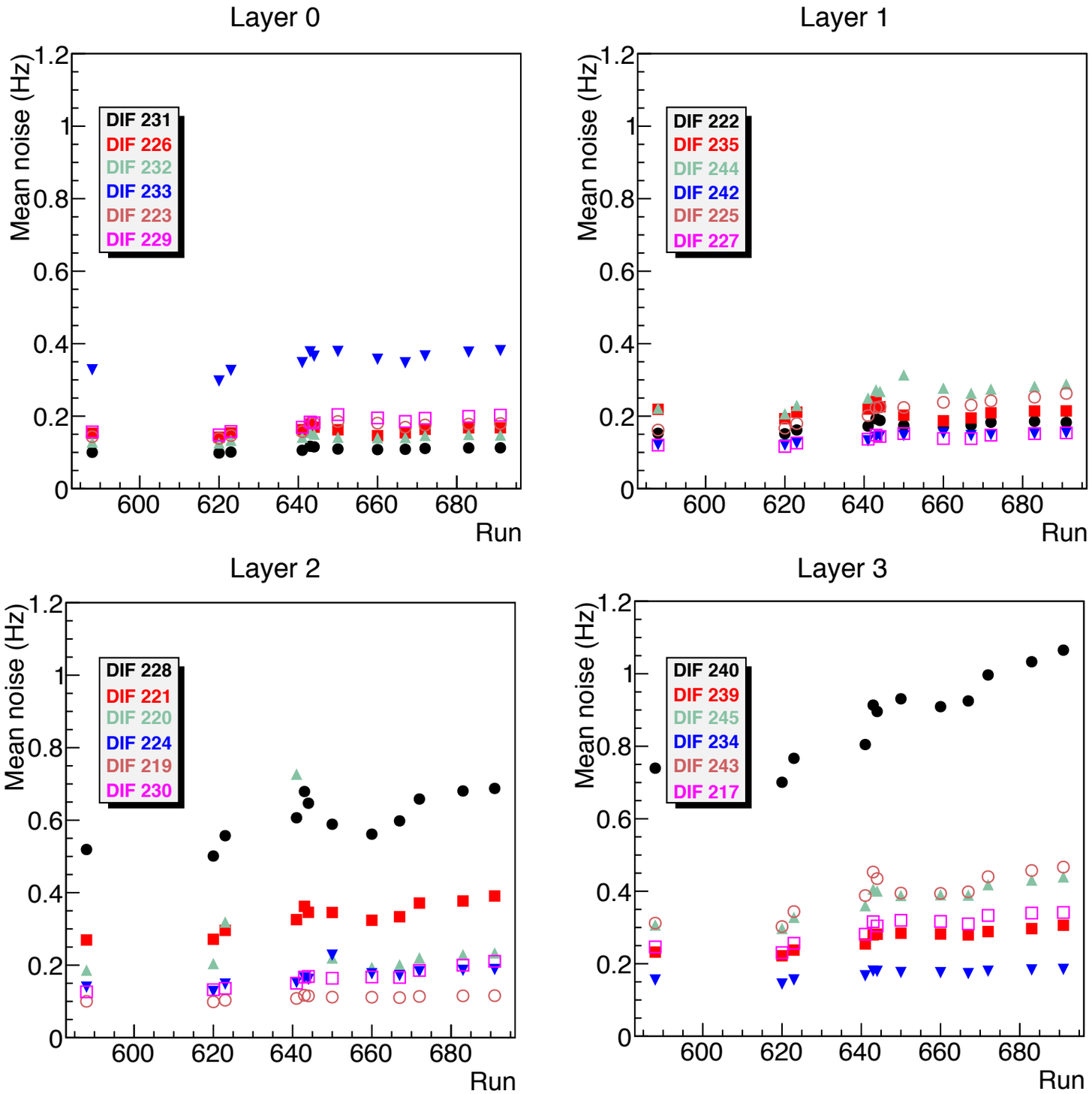


Uniform noise functioning

The USB DAQ does not support high rates ...

➪ agressive gain correction for every single noisy pad

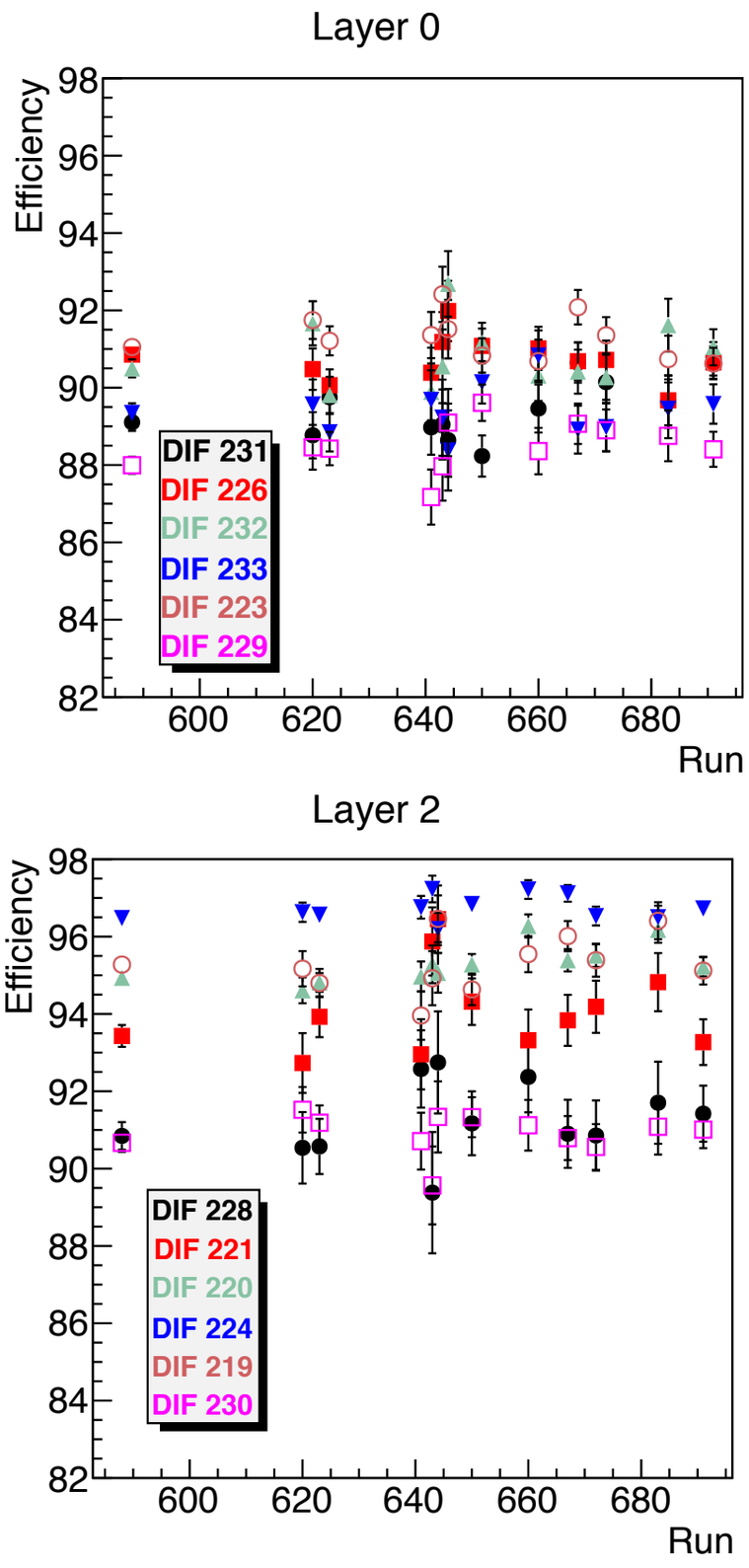
➪ choose a working point such that mean noise ~< 0.5Hz/cm2

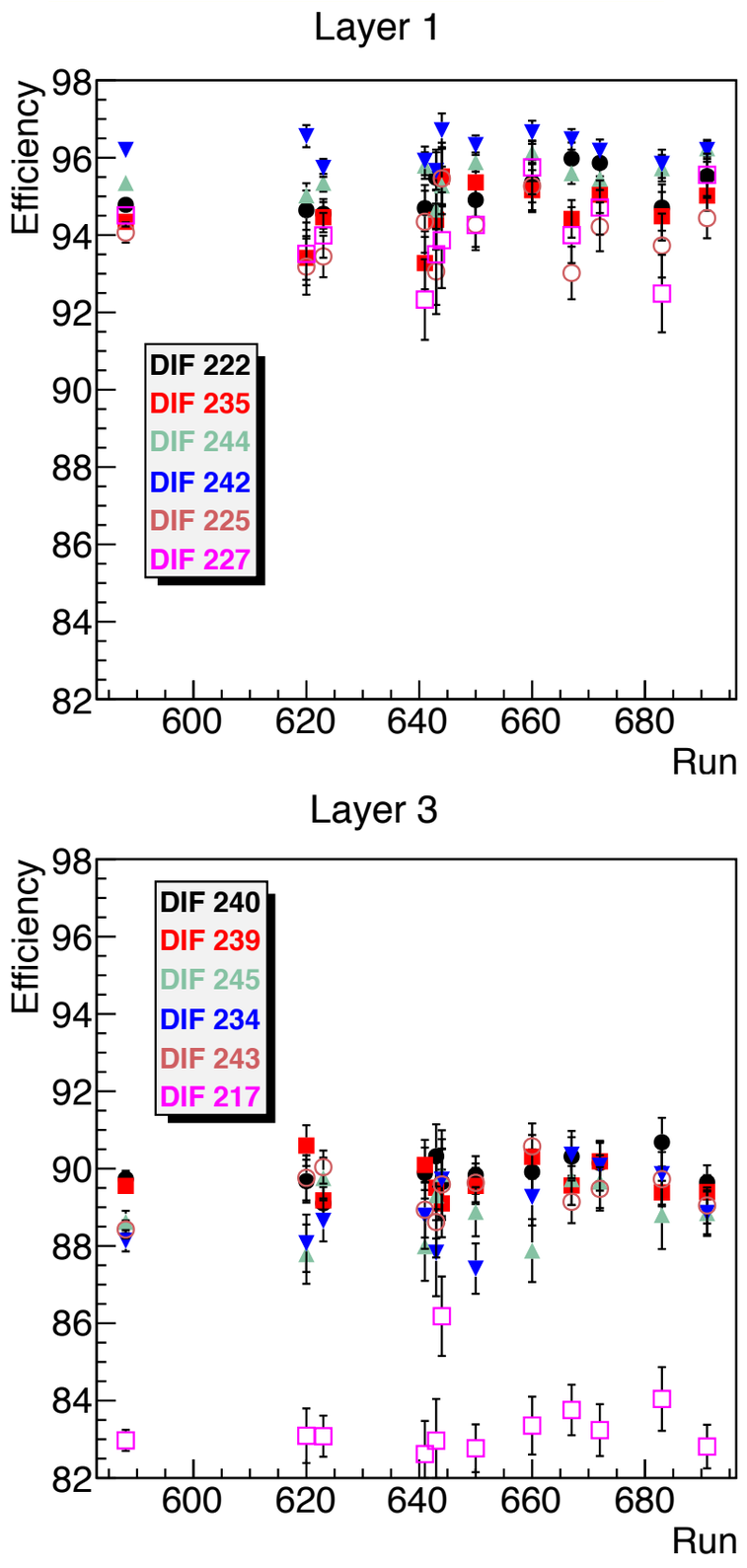


Detector working very satisfactorily

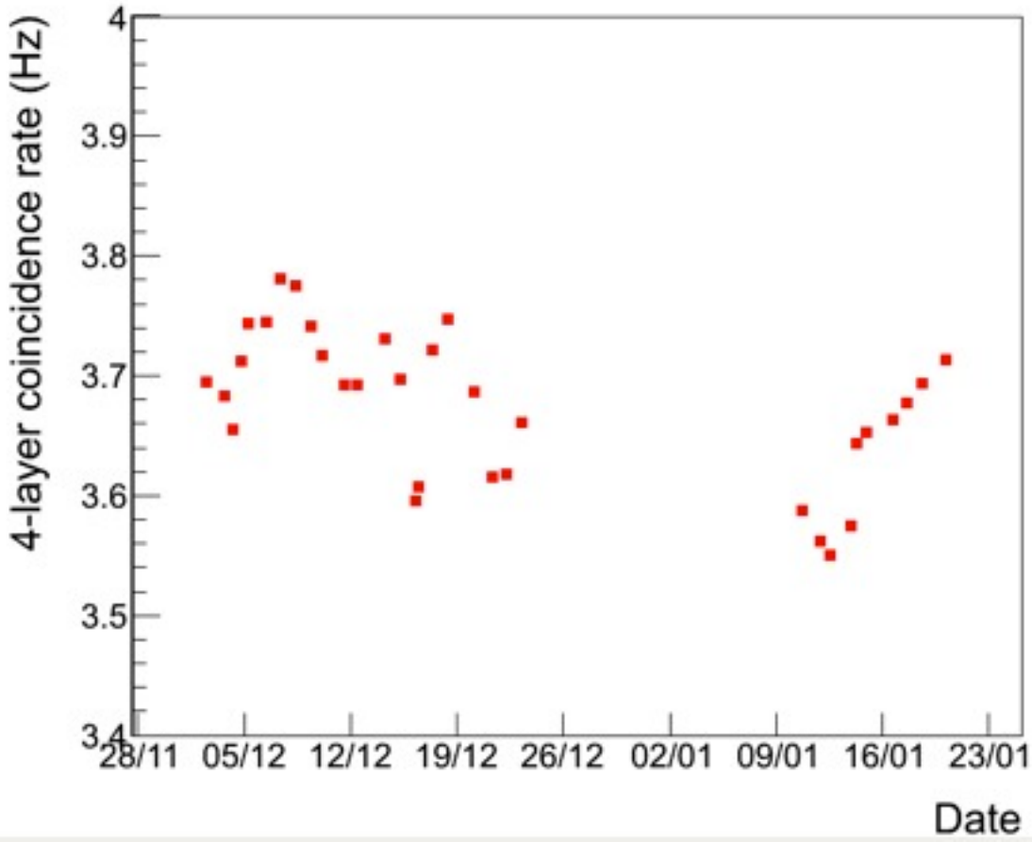
Efficiencies well above 90%

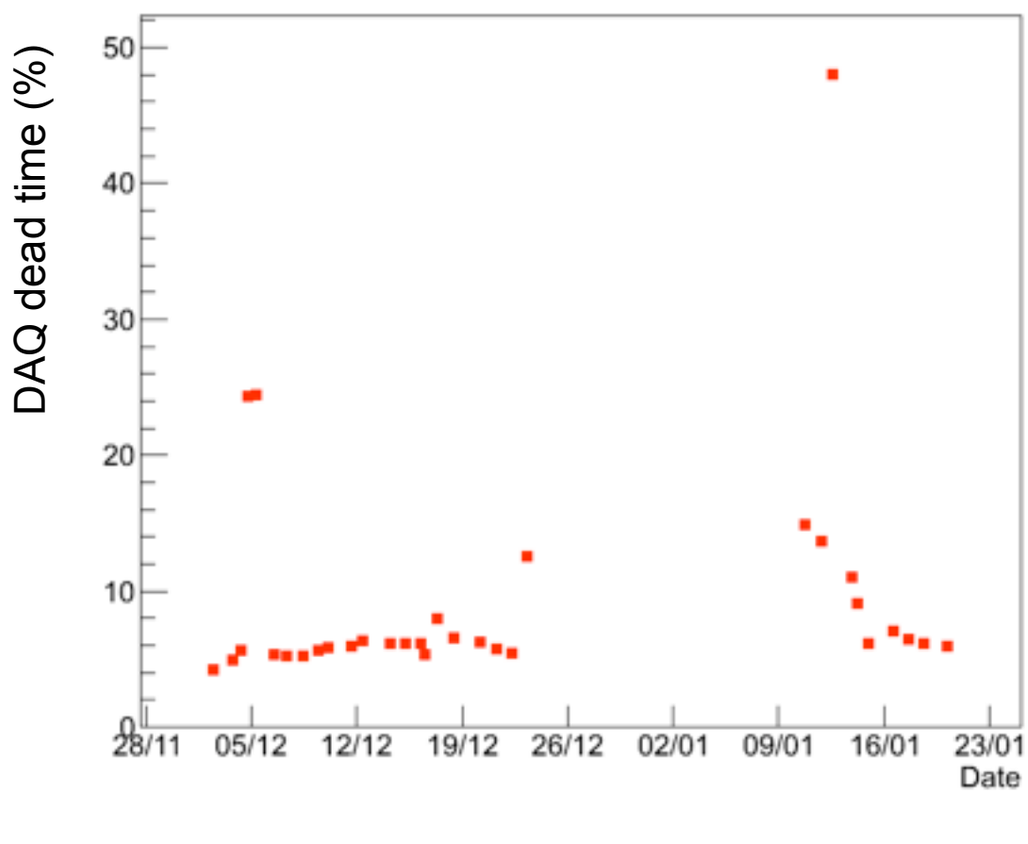
and ~ 6% of deadtime

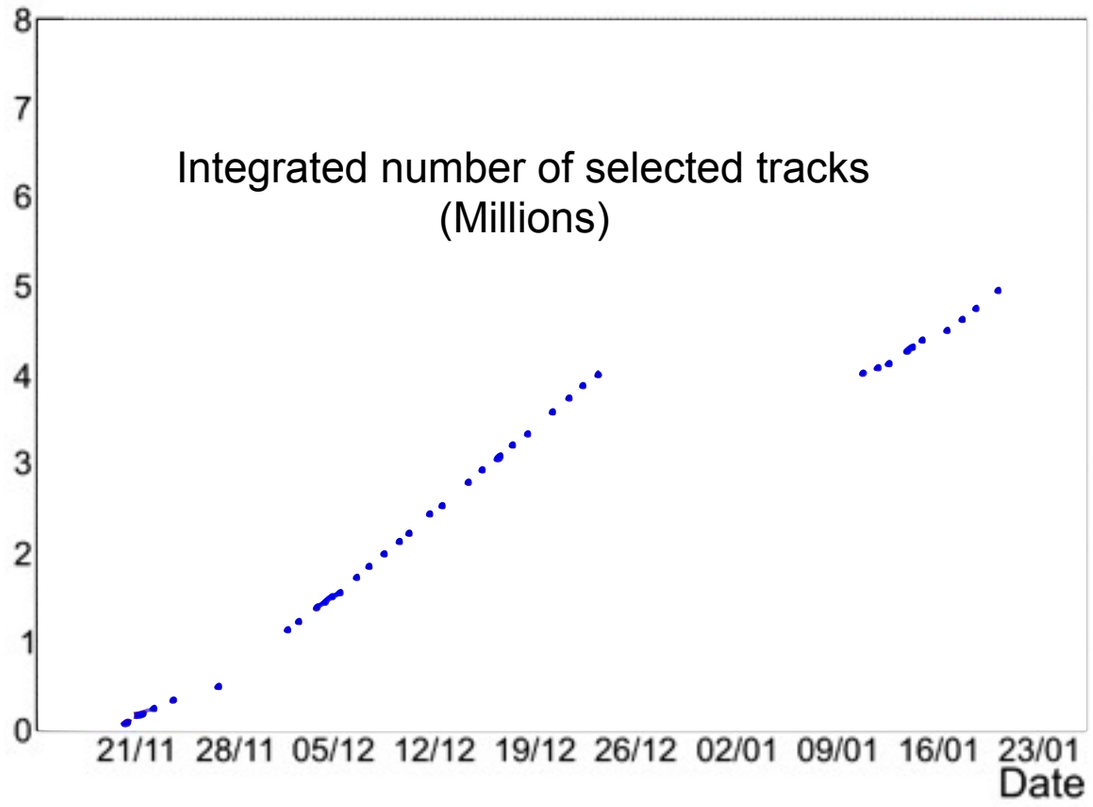




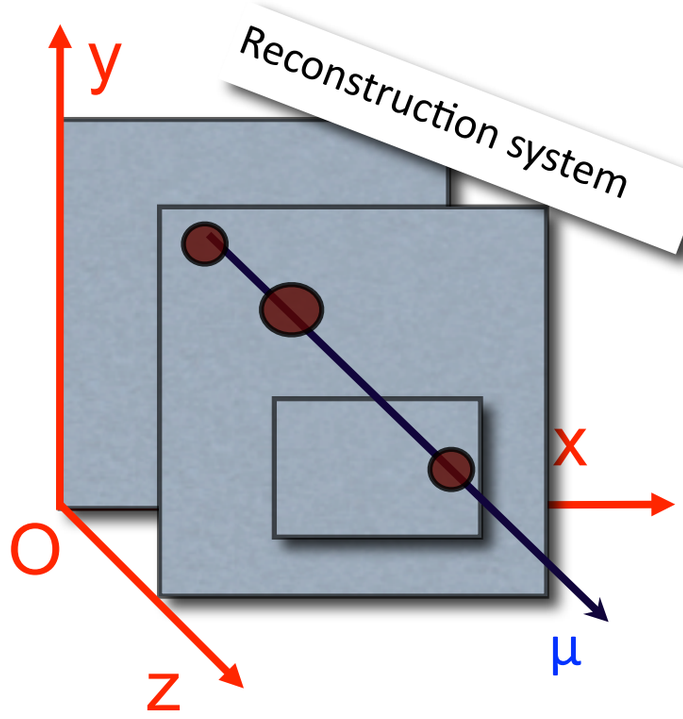
Detector working very satisfactorily… when not water contaminated







Track fit and Chambers Inter-alignment



⇒ Detector inter-alignment

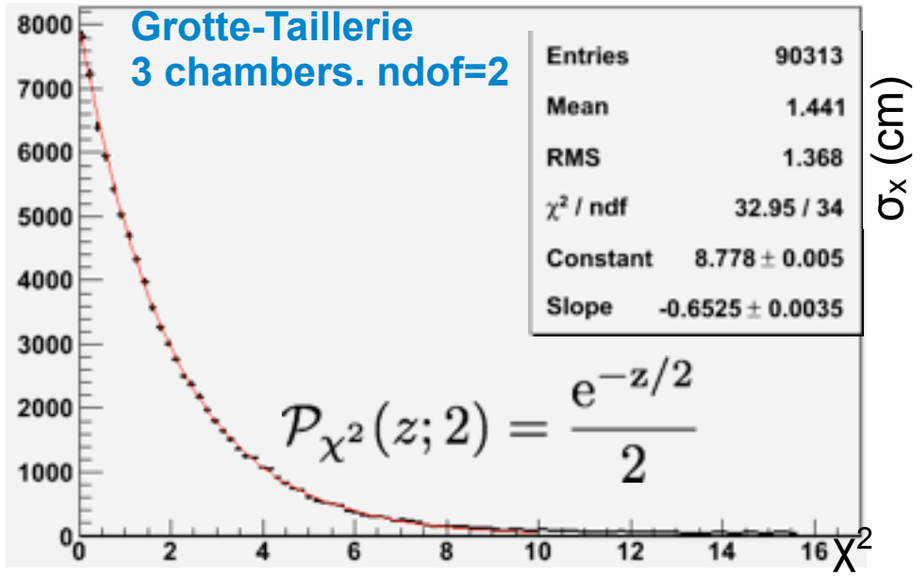
Detector inter-alignment from 4-layers tracks. Likelihood fit with in-house program & **MillePede** algorithm (http://www.desy.de/~blobel/mptalks.html).

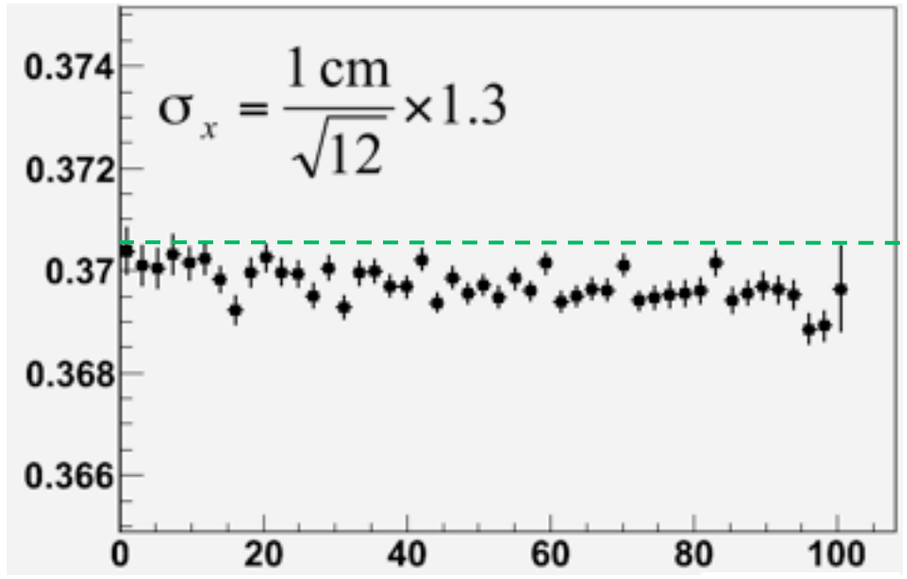
Track reconstruction

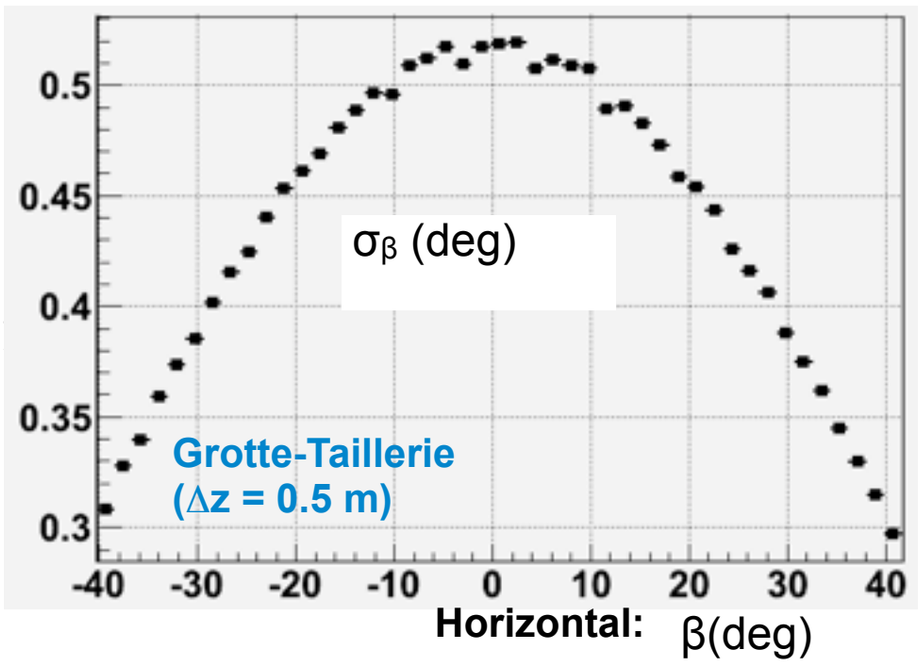
-Select hits if they occur in time window of less than 400 ns in the three chambers.

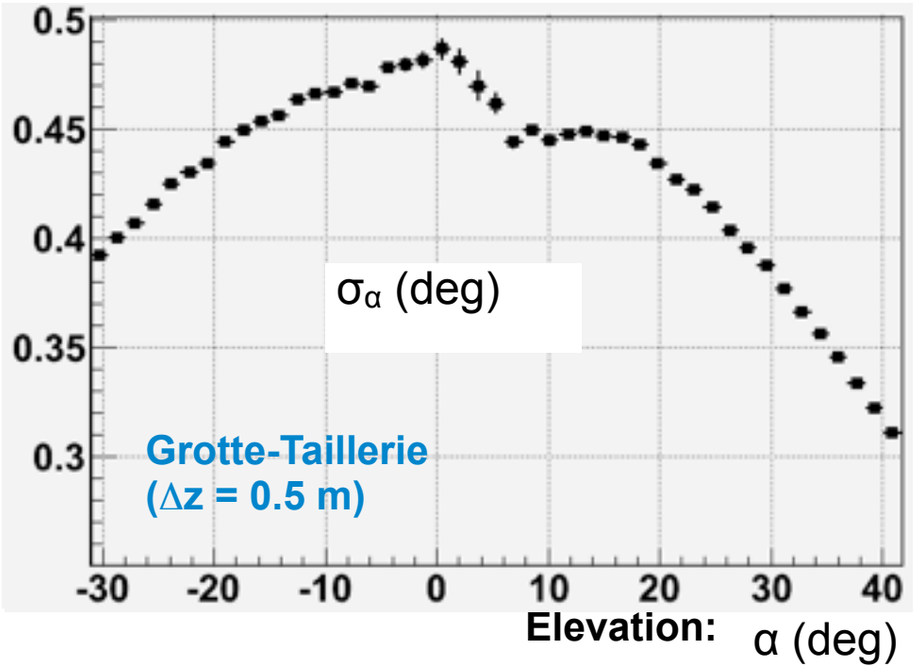
-Clusterise the hits in the chambers. Only tracks with one cluster per chamber are kept.

Analytically minimise χ^2 w.r.t. 4 track parameters using the cluster barycentres in each chamber. N.B.: the **average cluster** size is **1.3 cell**.

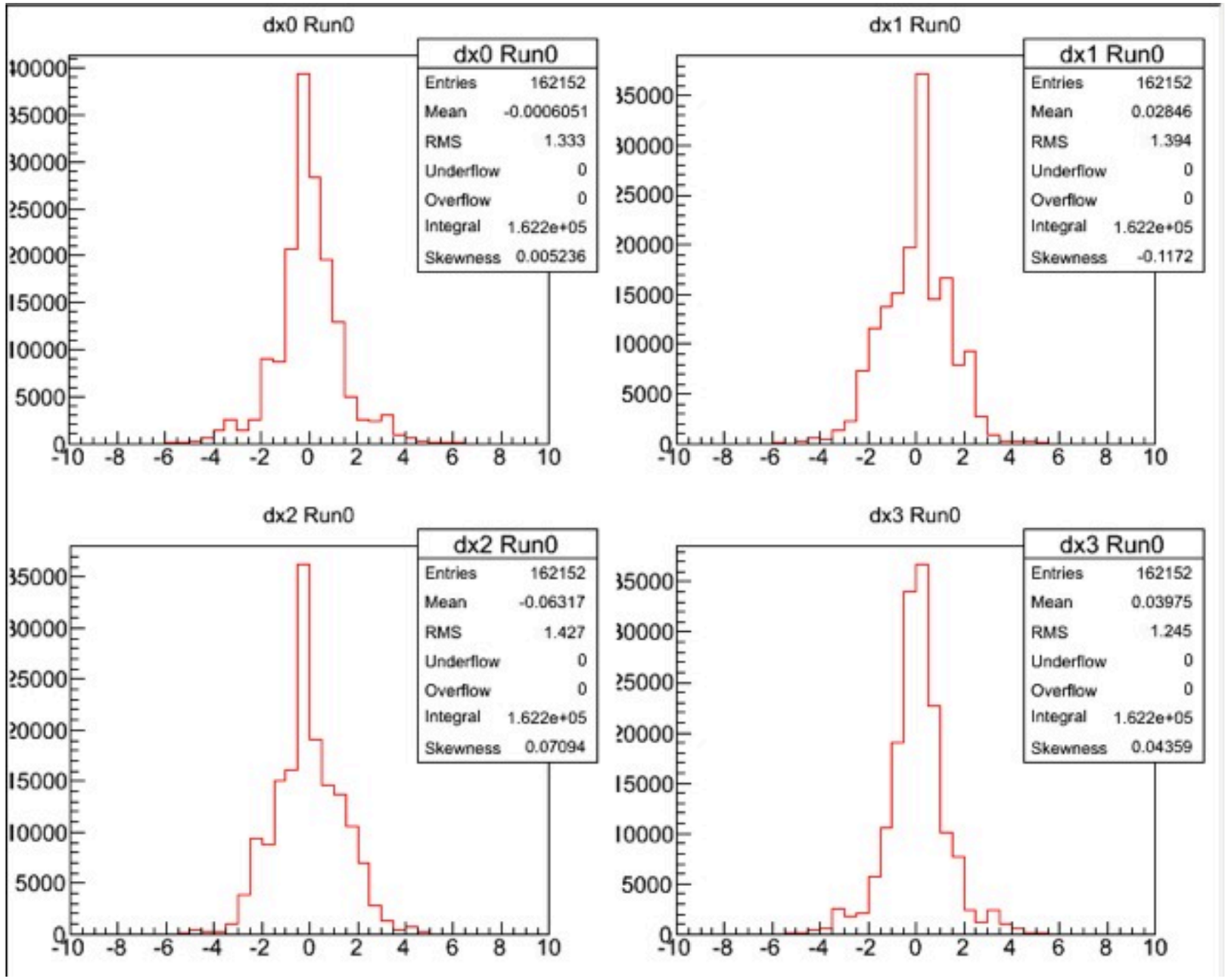








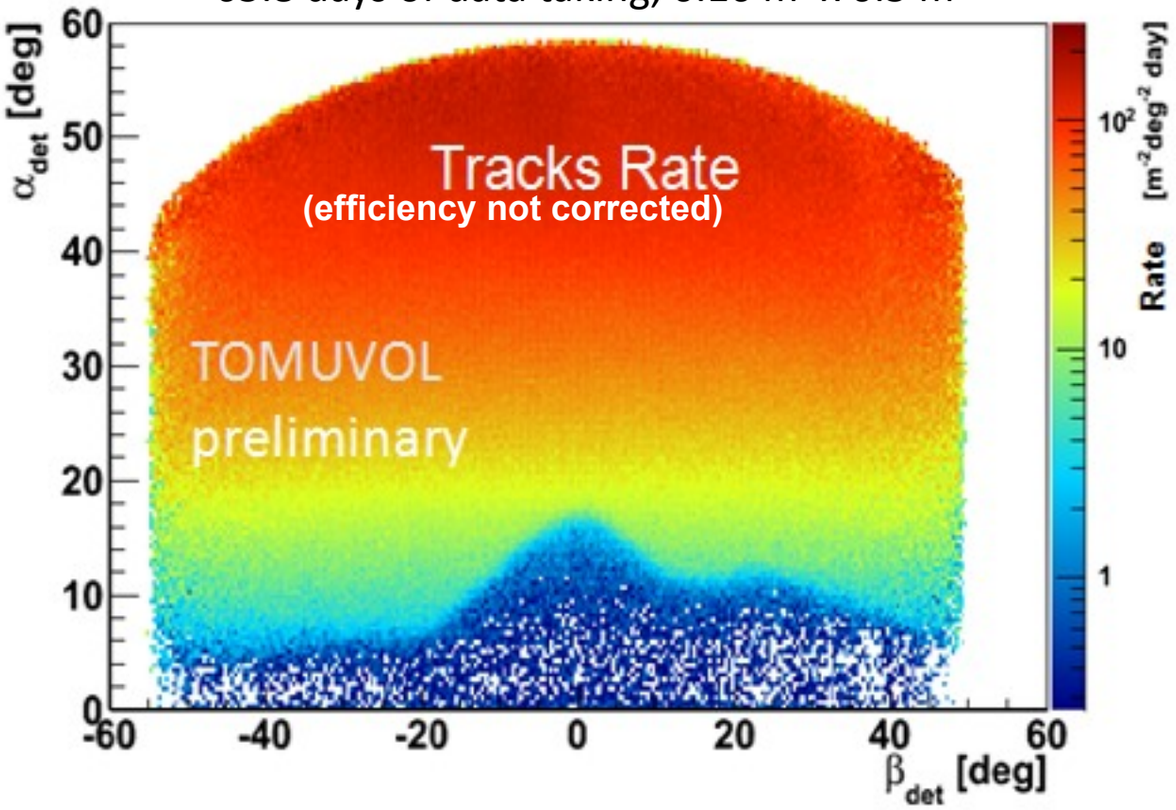
Track resididuals (mm) @ TDF



Grotte Taillerie data

21/01/2011 - 06/04/2011

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



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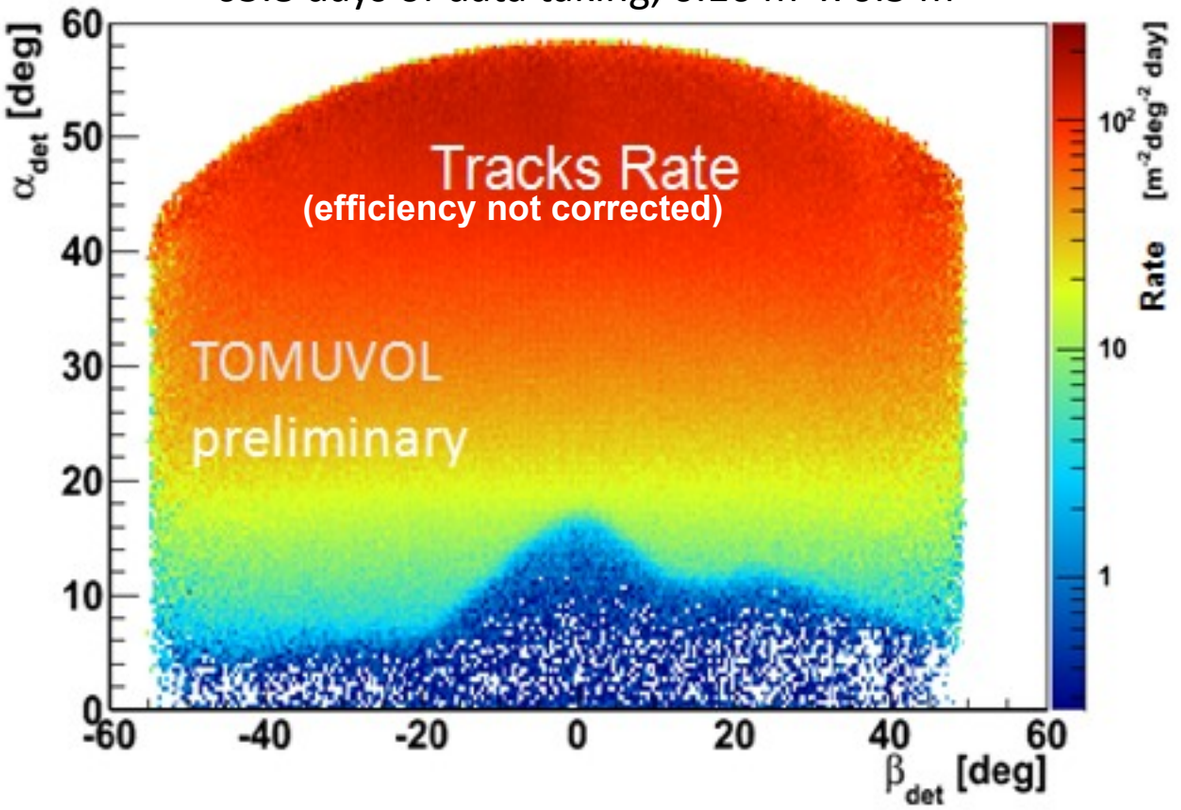
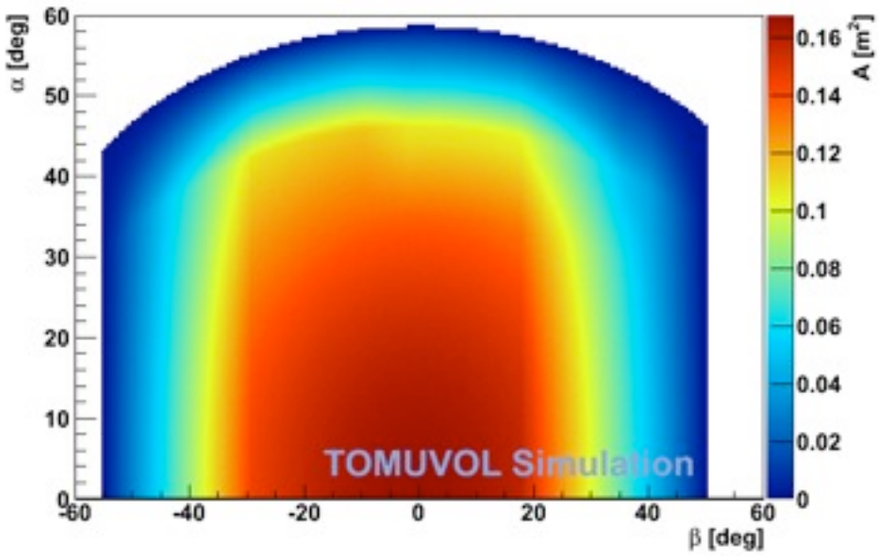


Detector acceptance

from ray-tracing simulation

takes masked cells into account



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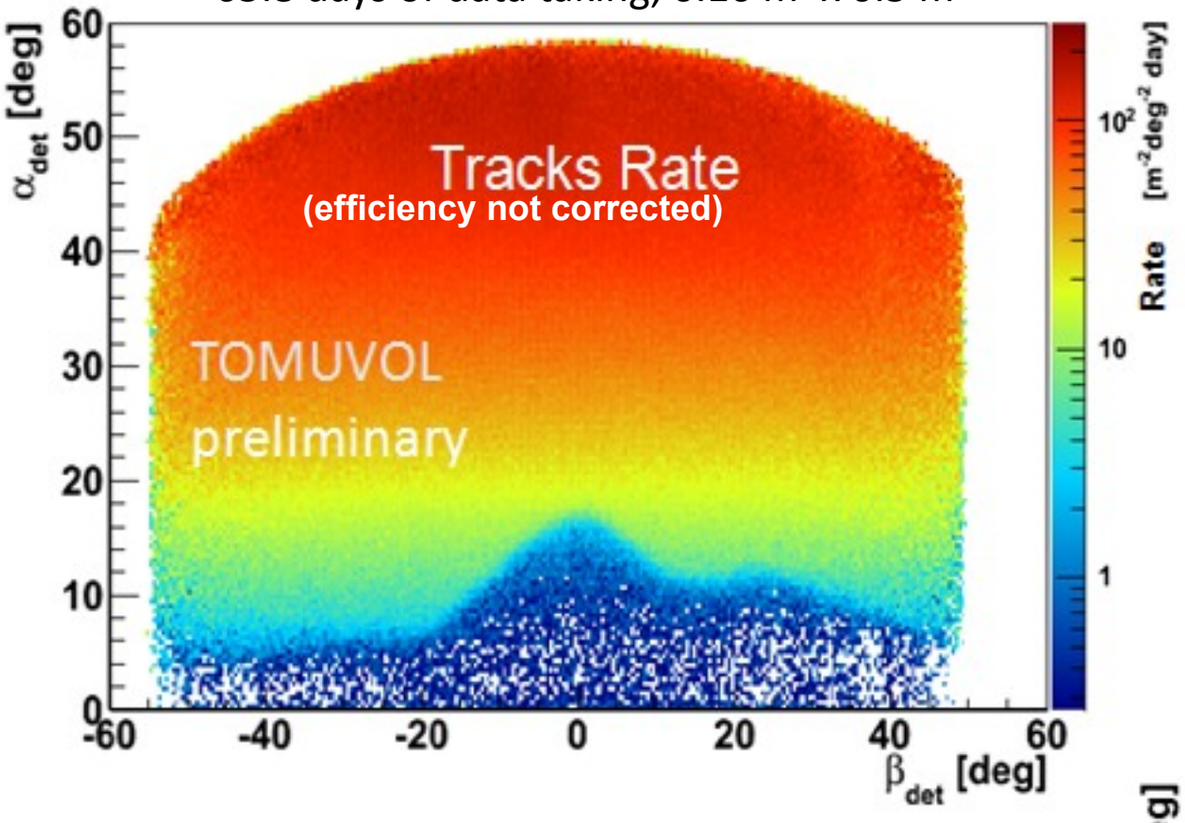

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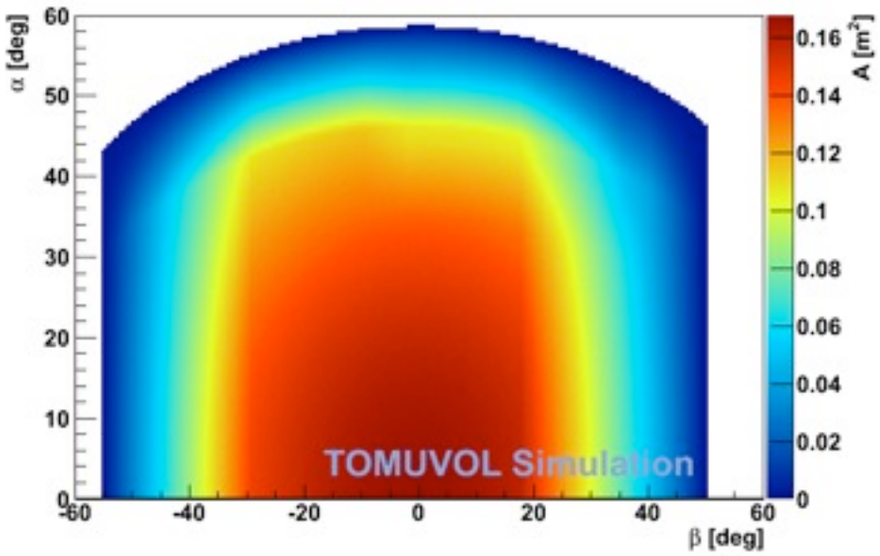
from ray-tracing simulation

takes masked cells into account



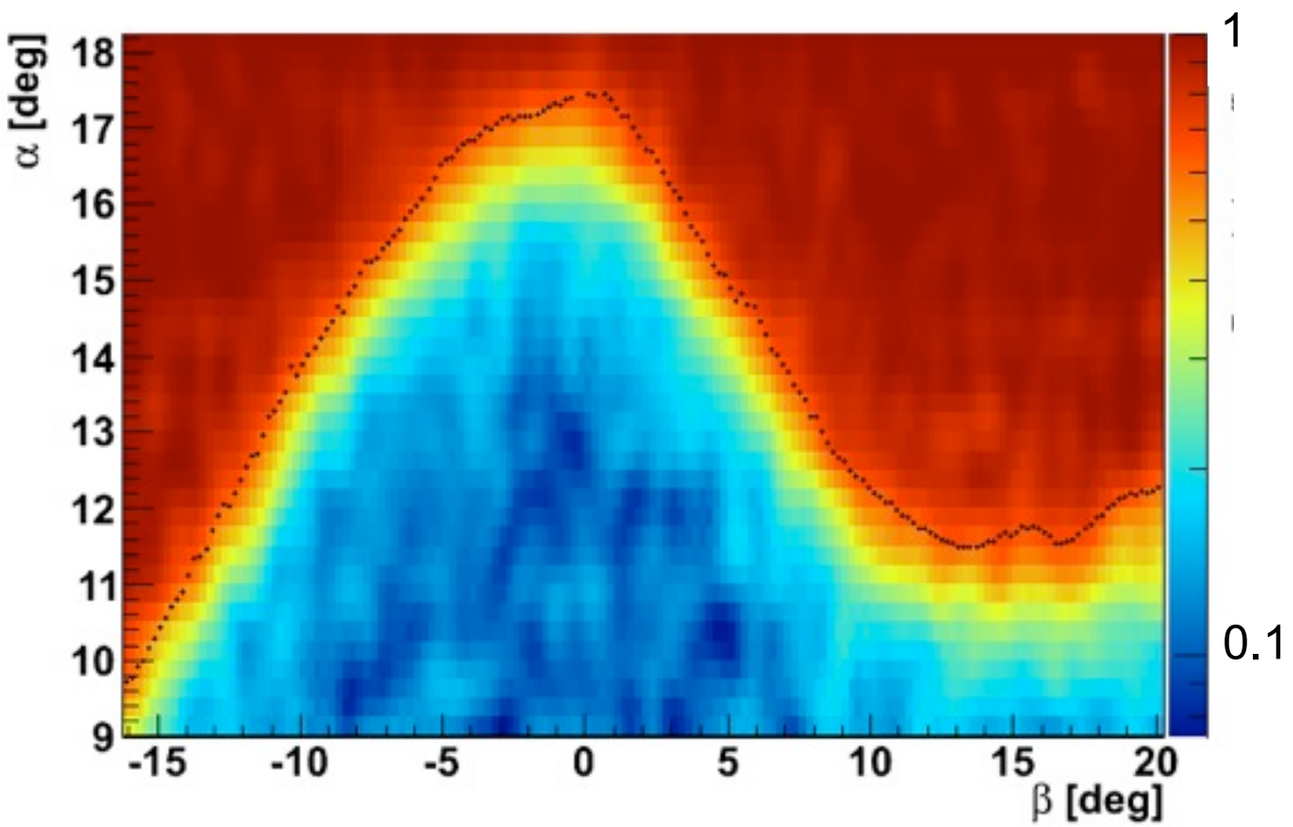
Transmission coefficient

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

measured flux through volcano

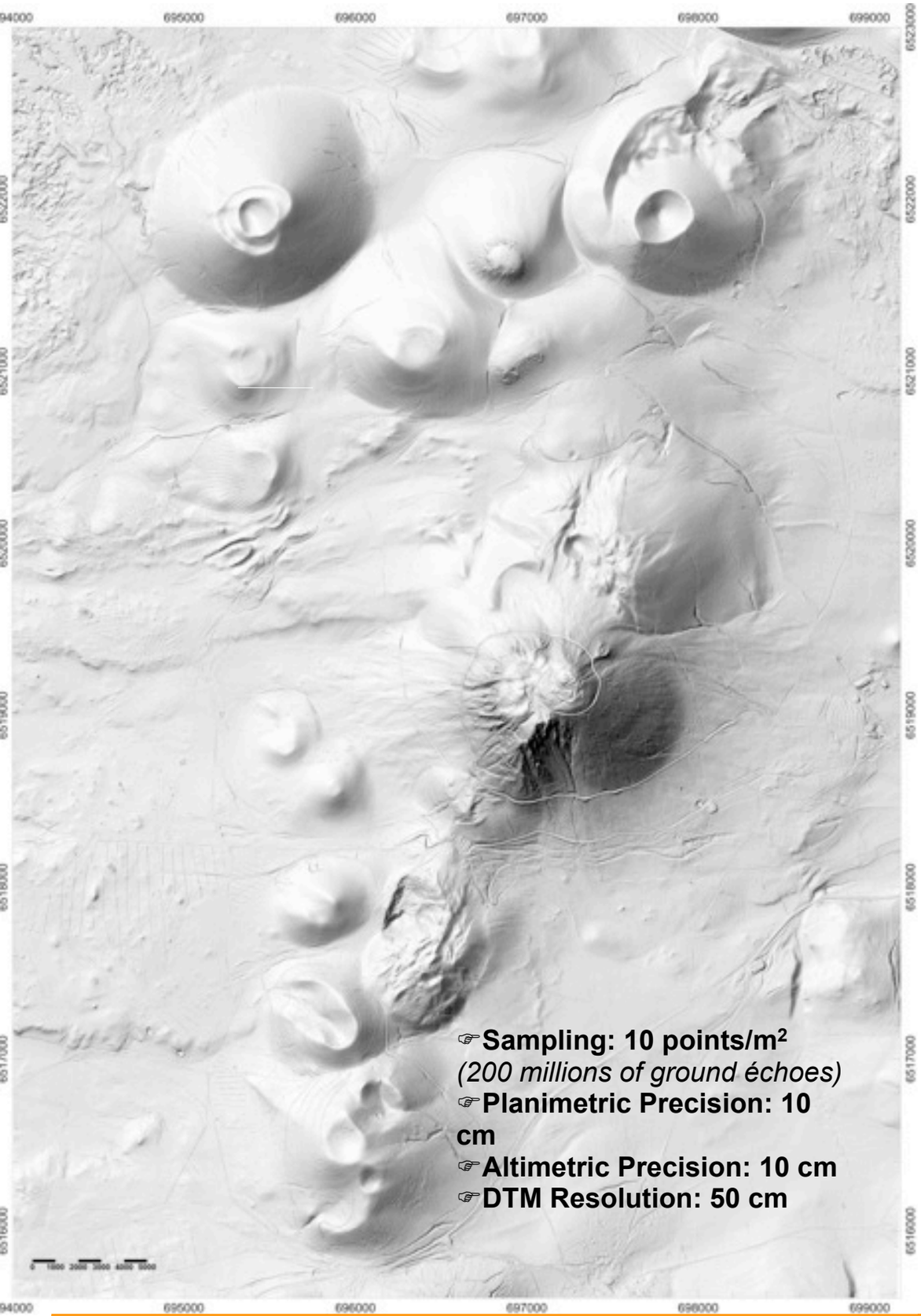
open sky flux

unknown density!



High Resolution Airborne LiDAR Survey

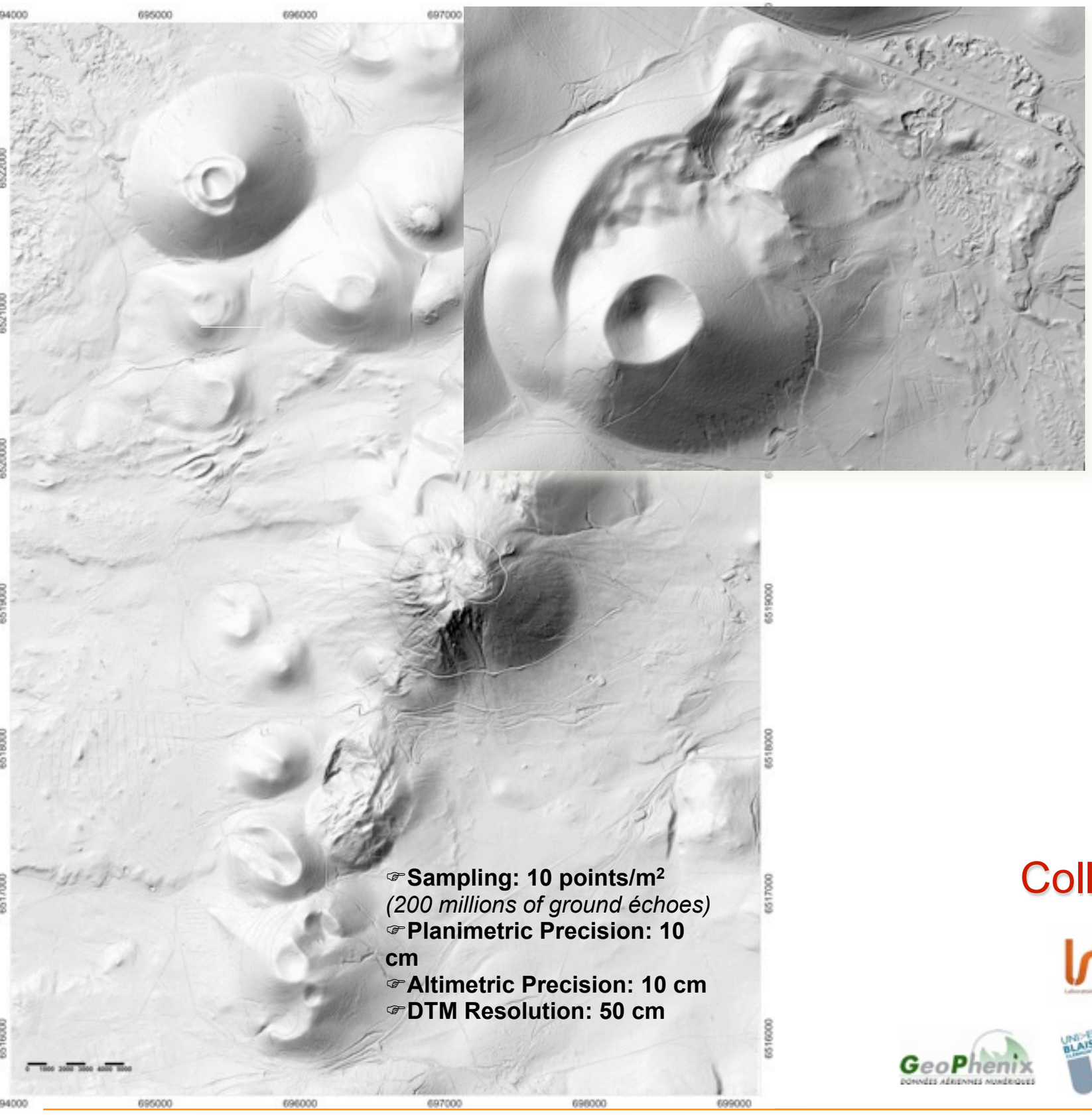
(Puy de Dôme and central part of the Chaîne des Puys)



Collaboration LiDARverne (2011)

High Resolution Airborne LiDAR Survey

(Puy de Dôme and central part of the Chaîne des Puys)

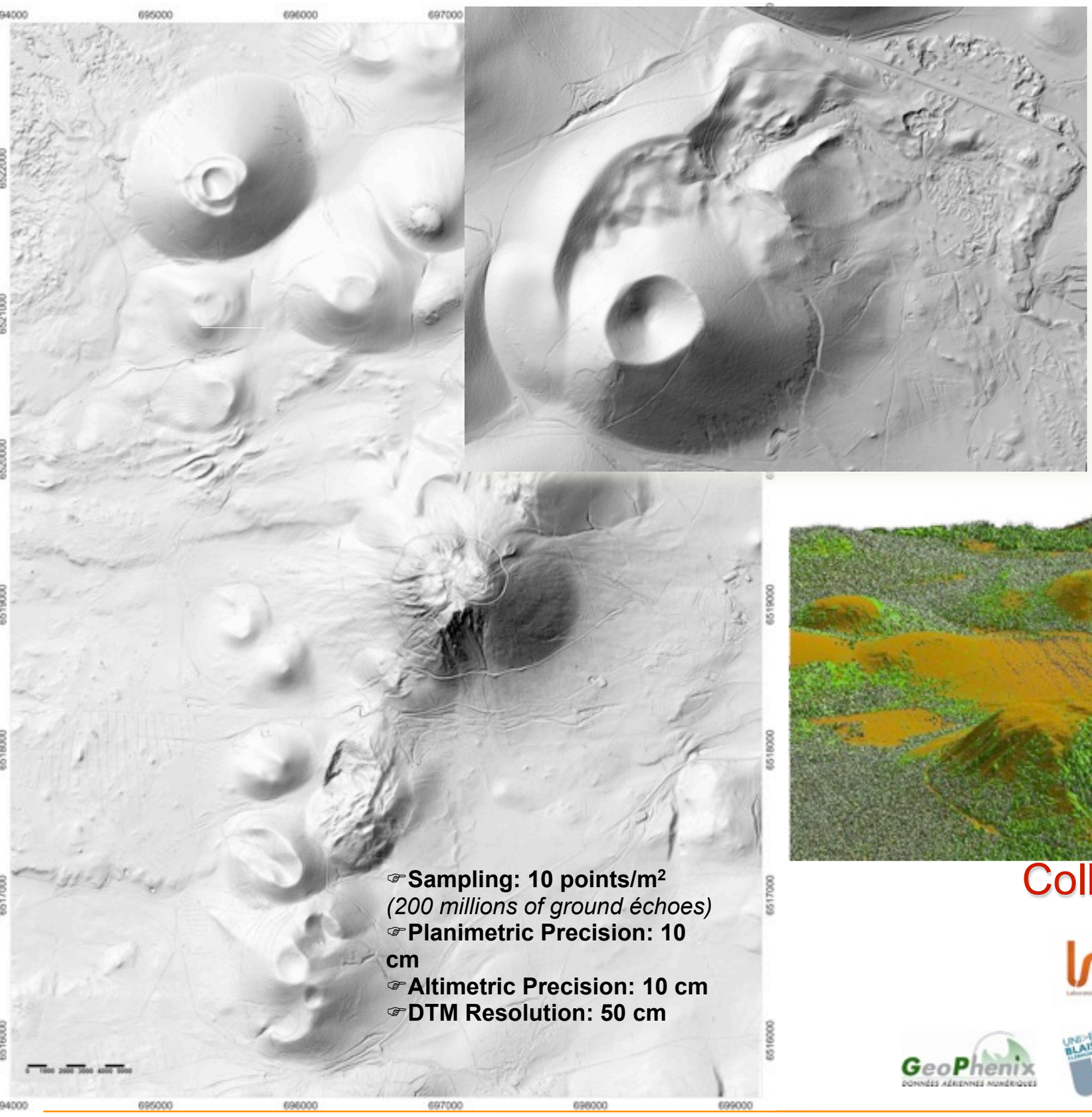


- **Sampling: 10 points/m²**
  (200 millions of ground échoes)
- **Planimetric Precision: 10 cm**
- **Altimetric Precision: 10 cm**
- **DTM Resolution: 50 cm**

Collaboration LiDARverne (2011)

High Resolution Airborne LiDAR Survey

(Puy de Dôme and central part of the Chaîne des Puys)



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High Resolution Airborne LiDAR Survey

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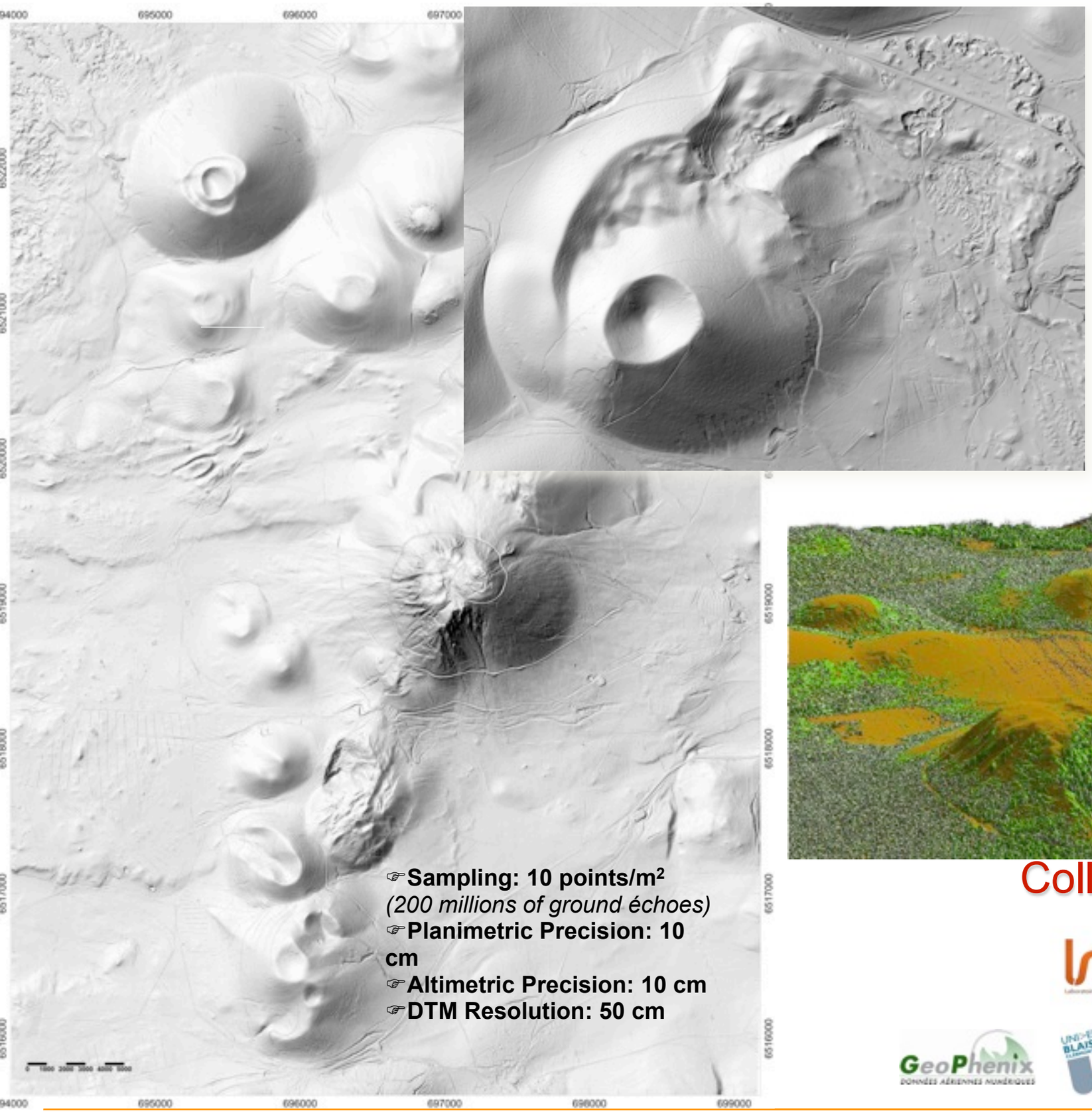

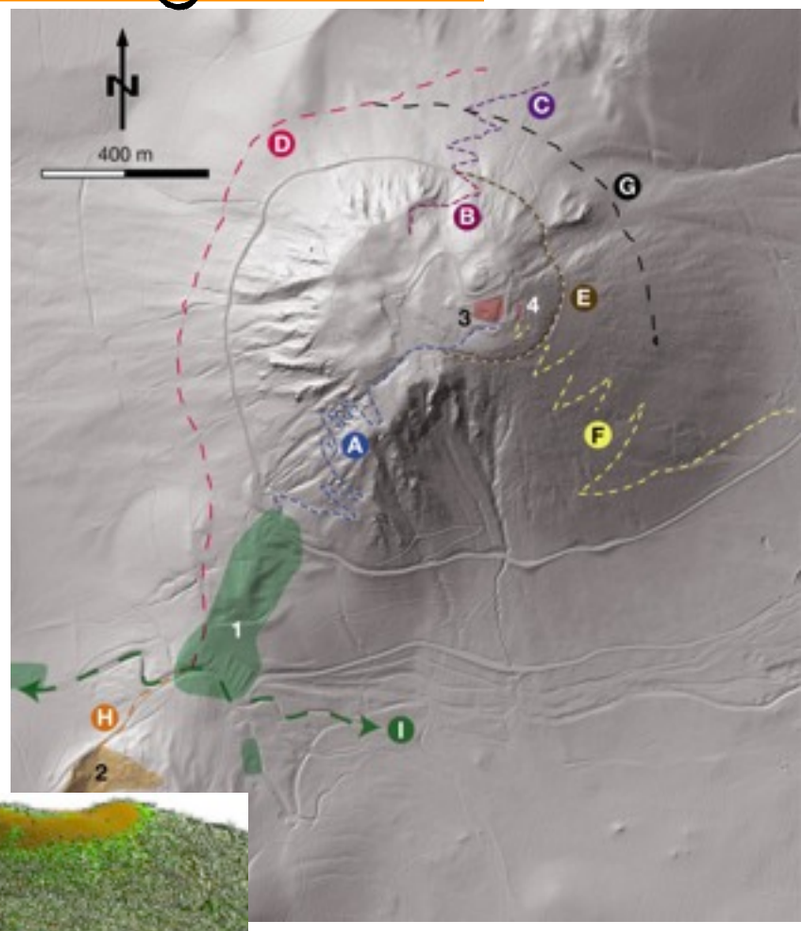

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- **Planimetric Precision: 10 cm**
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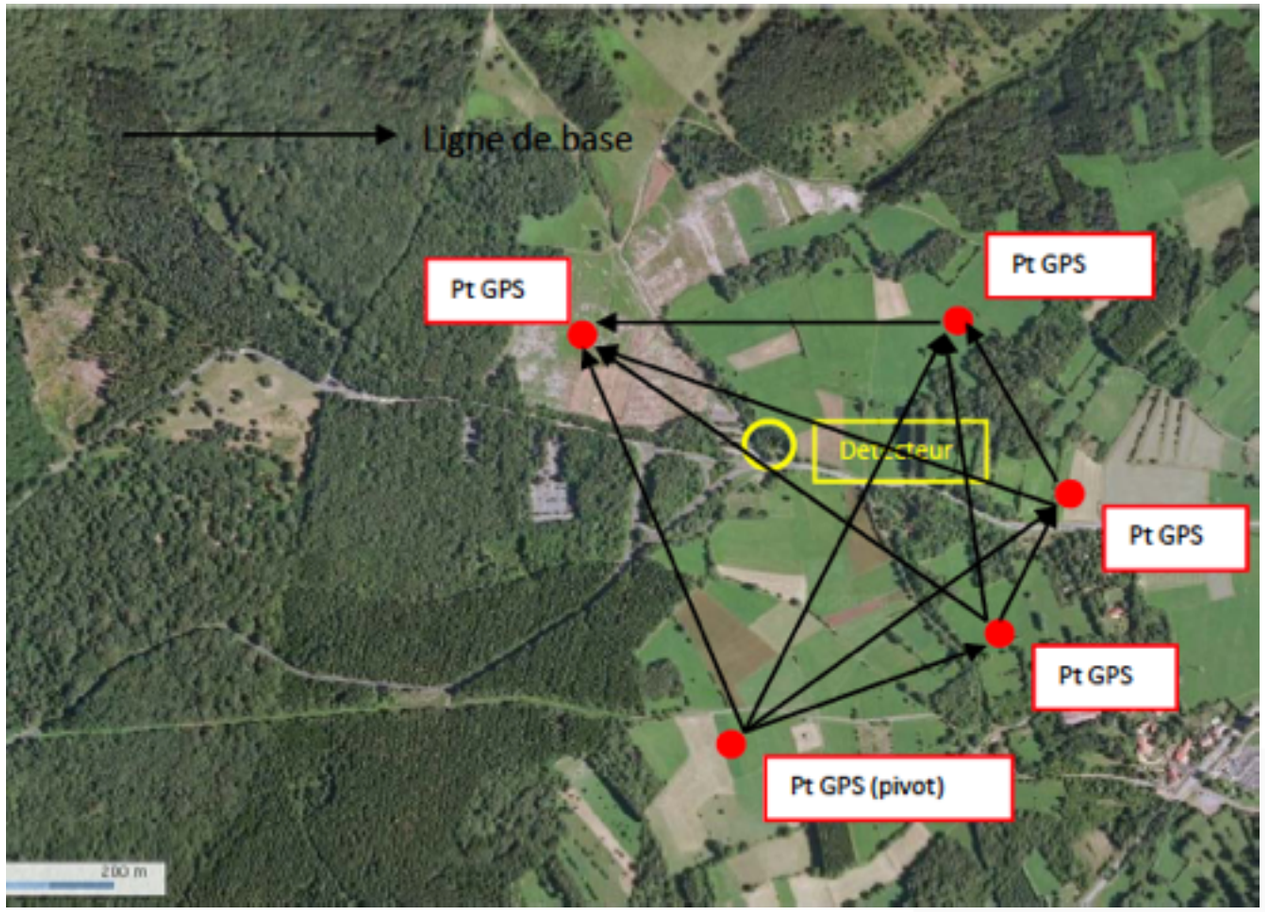
Collaboration LiDARverne (2011)

Detector positioning



Detector alignment w.r.t target

- GNSS and tacheometric measurements on surface and on detector with the help of ESGT Le Mans

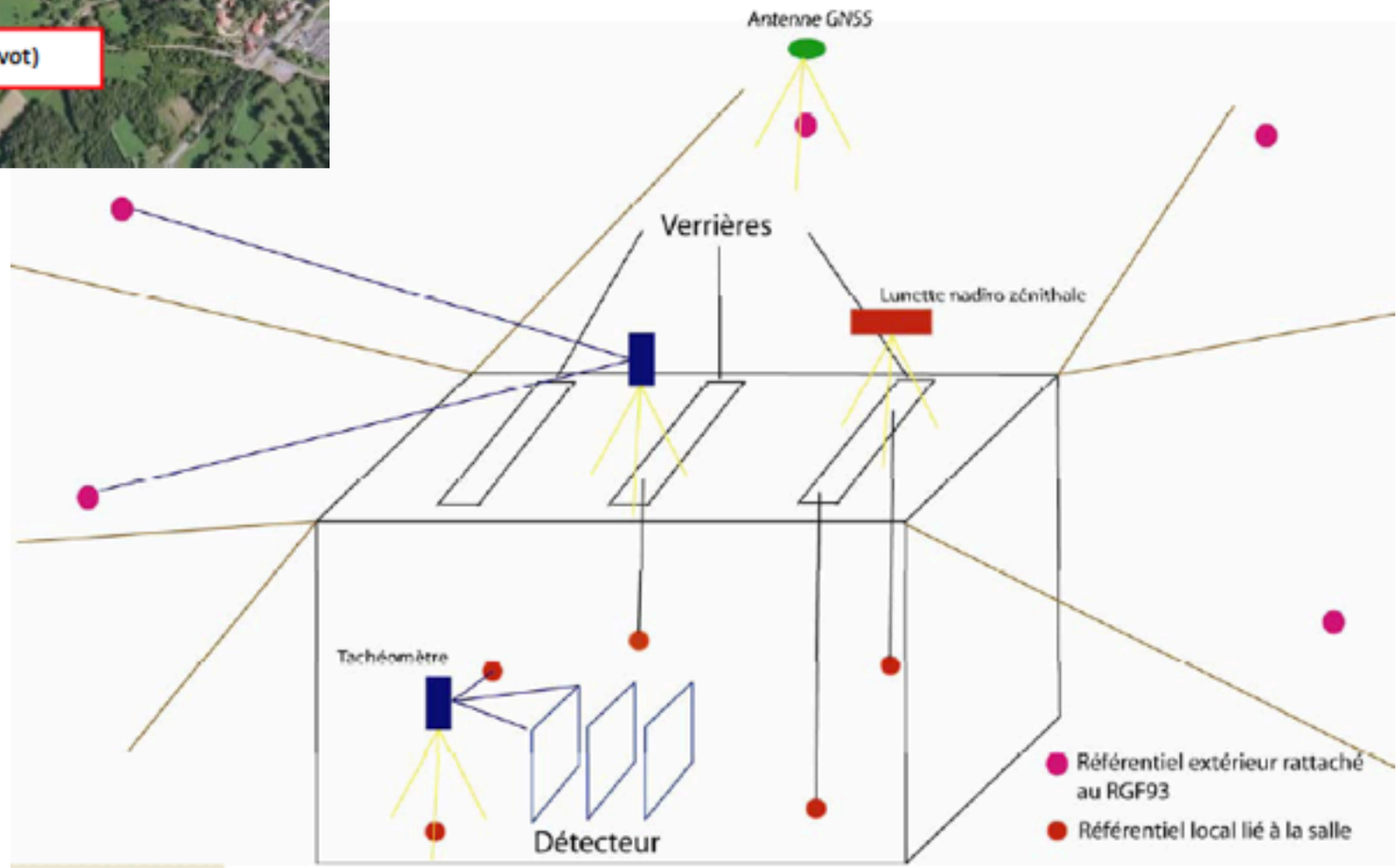
Grotte Taillerie :

accuracy better than 5 mm

Col de Ceyssat :

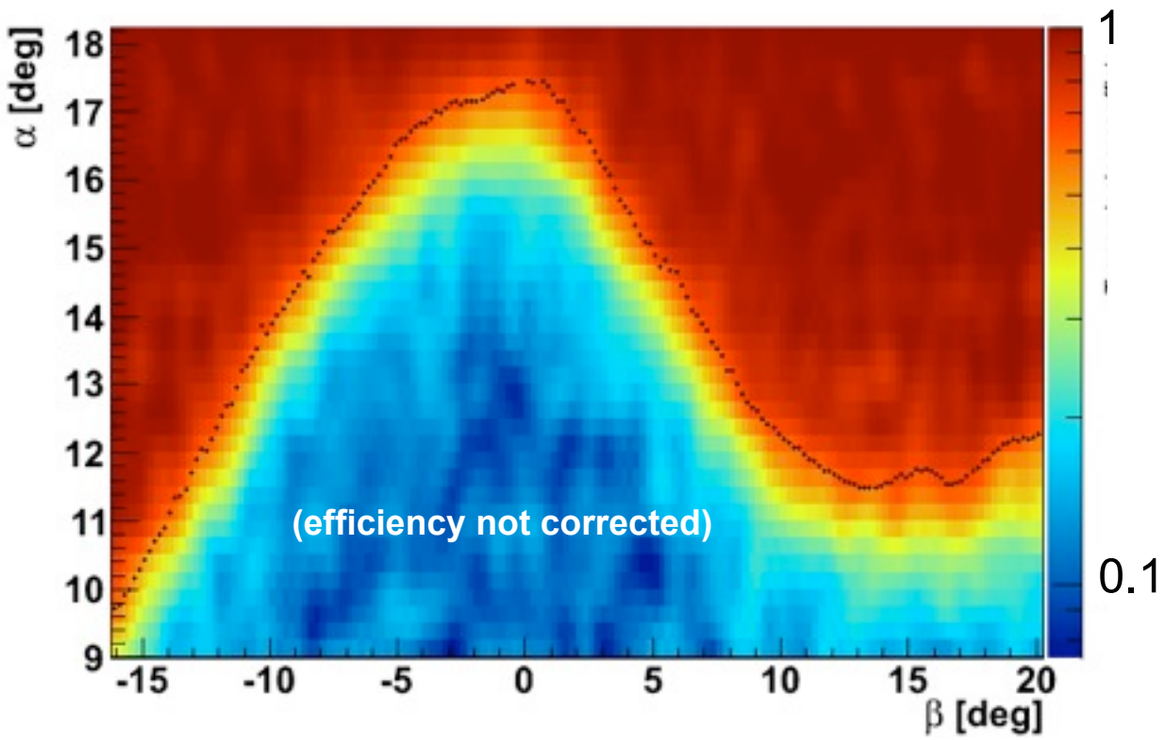
accuracy ~ 10 mm

Local measurements difficult due to the detector location within a small room with little to no openings …



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

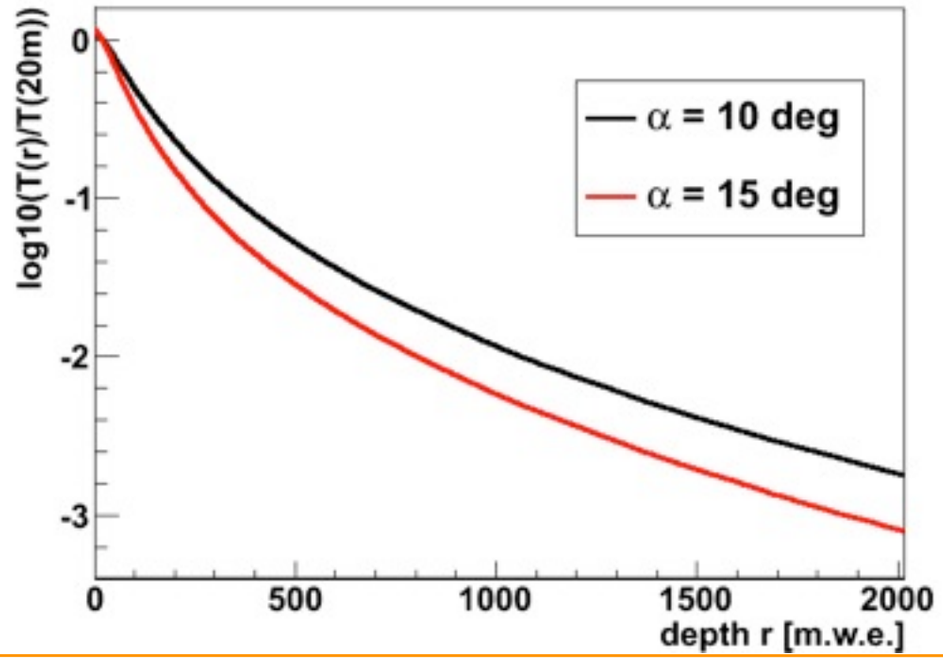
Transmission coefficient



Measured **transmission** coefficient depends on unknown density averaged along a given direction.

The transmission curve as function of depth (in m.w.e.) can be extracted from simulation.

⟹ Detailed simulation needed to measure the density.



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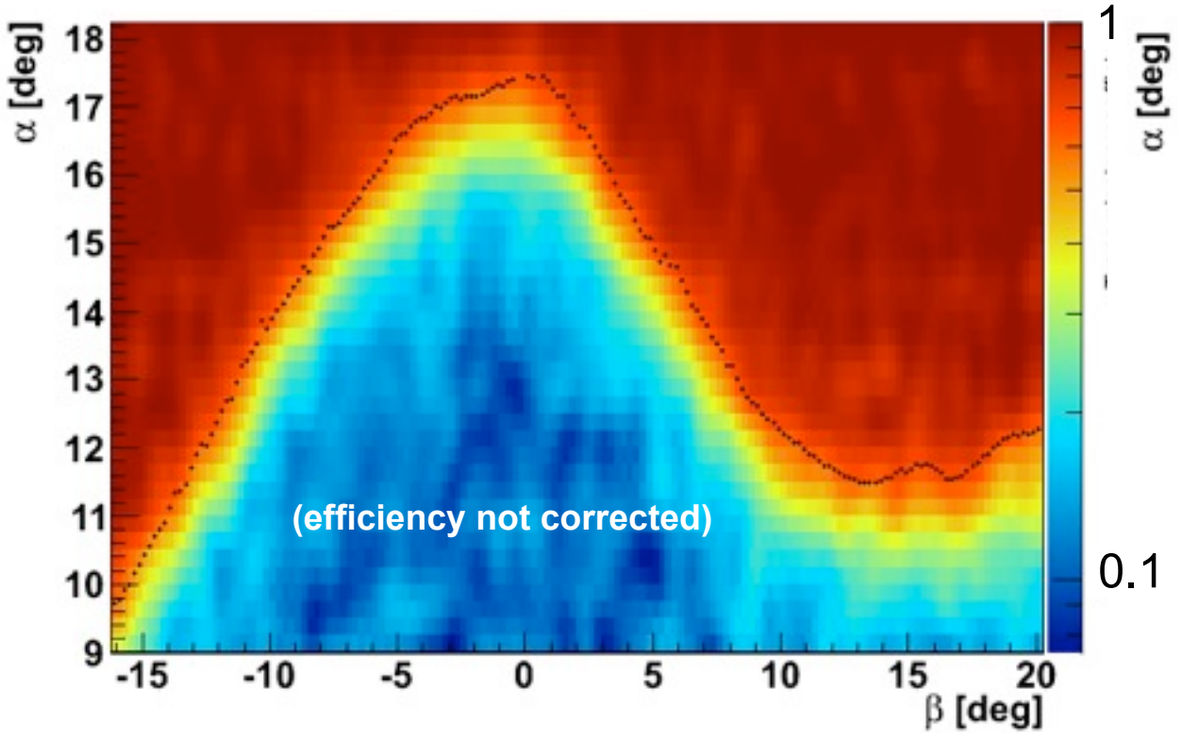
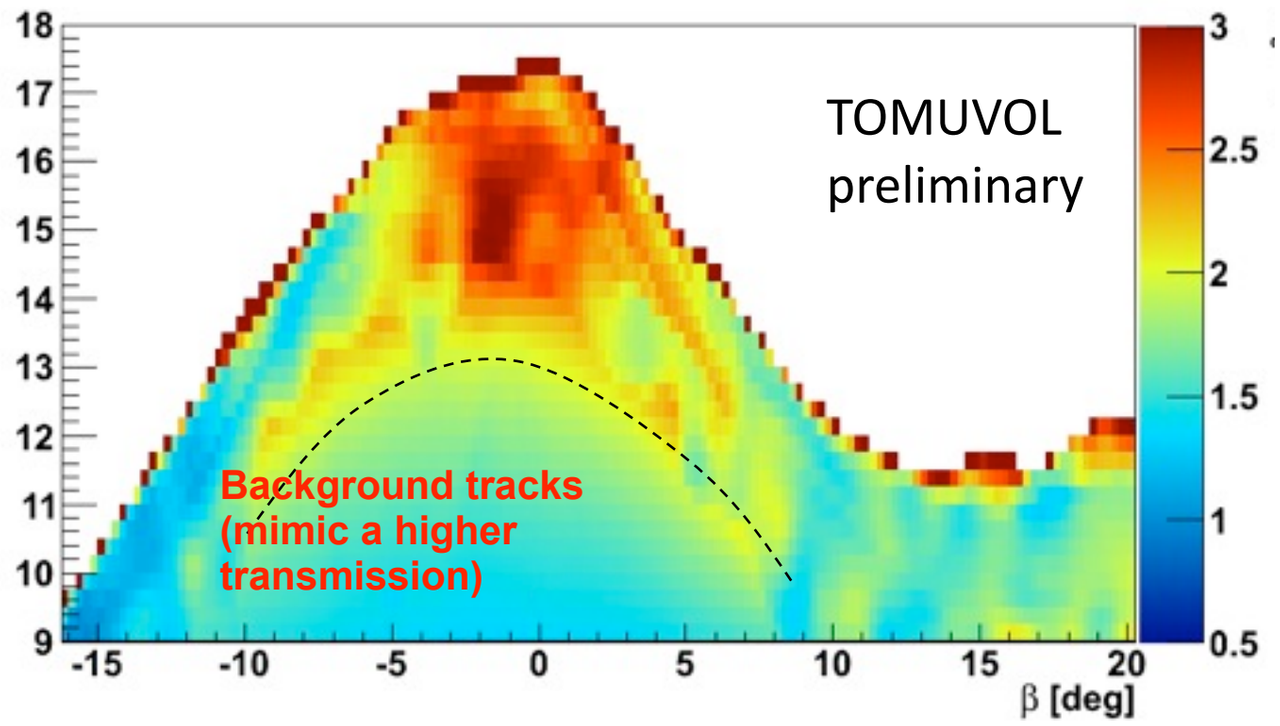
Transmission coefficient



Opacity coefficient



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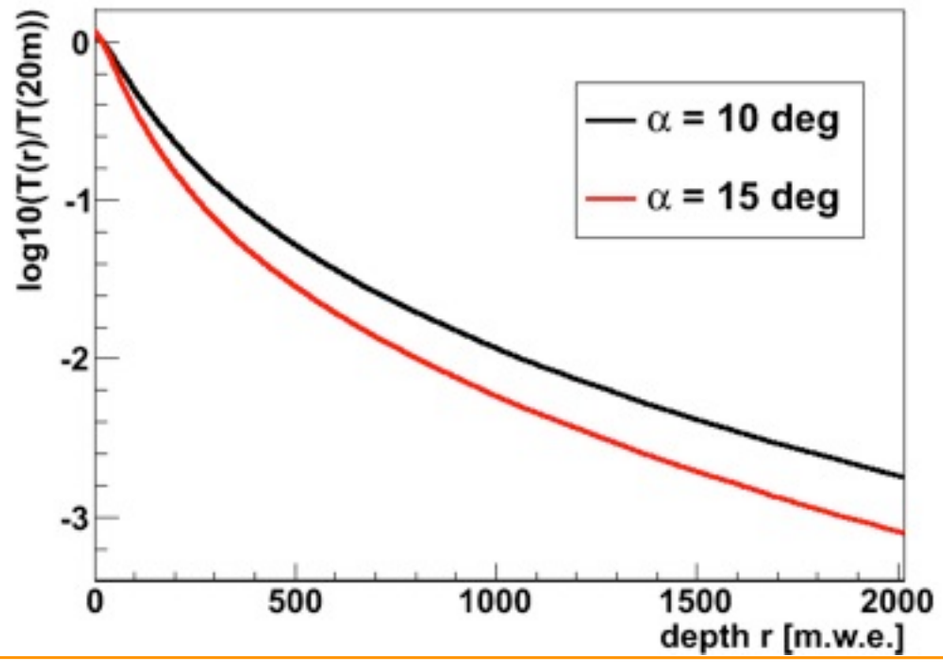
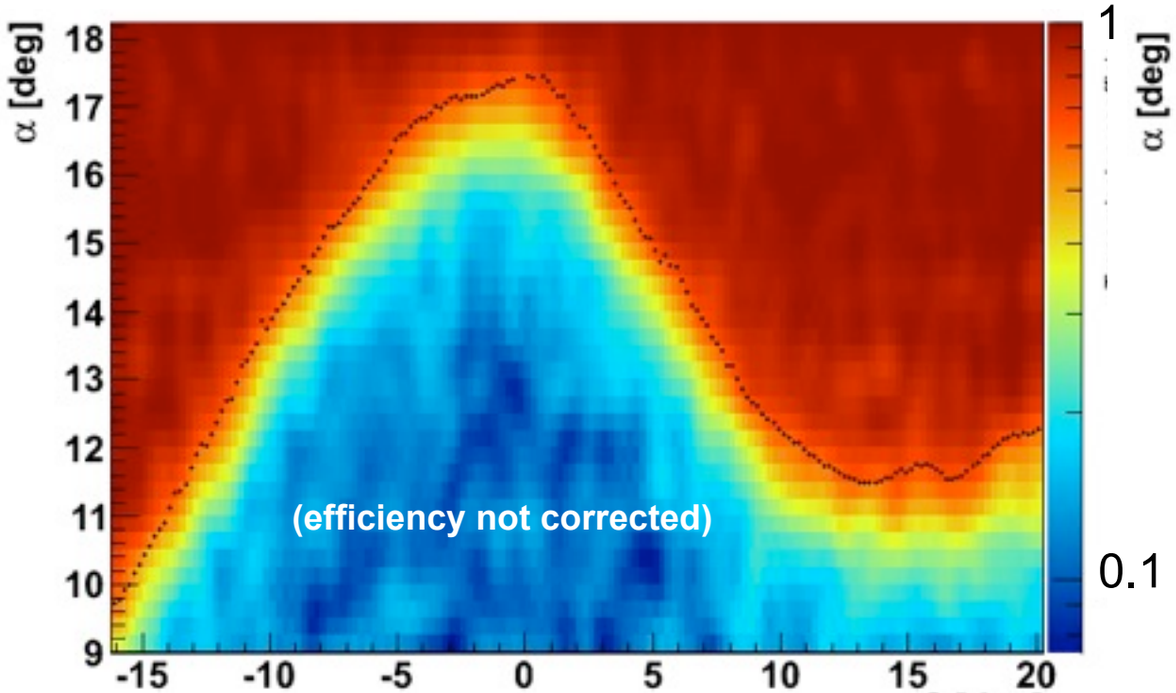
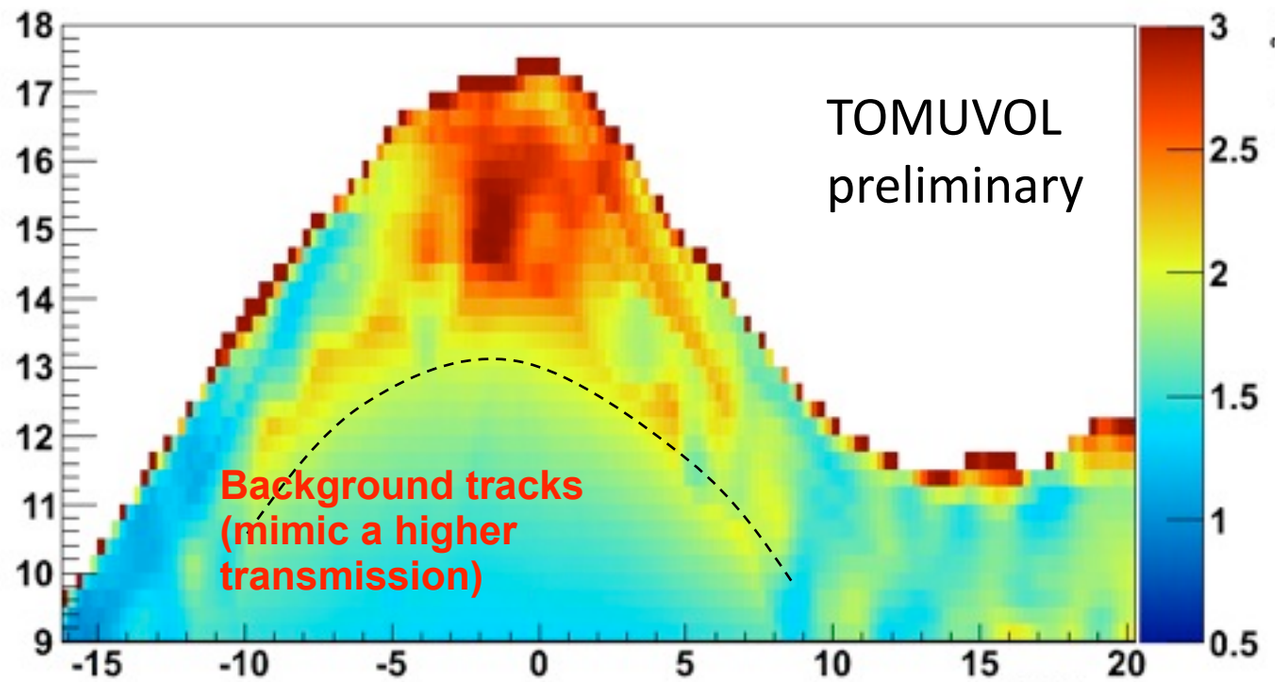


65.8 days of data taking, 0.16 m^2 x 0.5 m

Transmission coefficient



Opacity coefficient

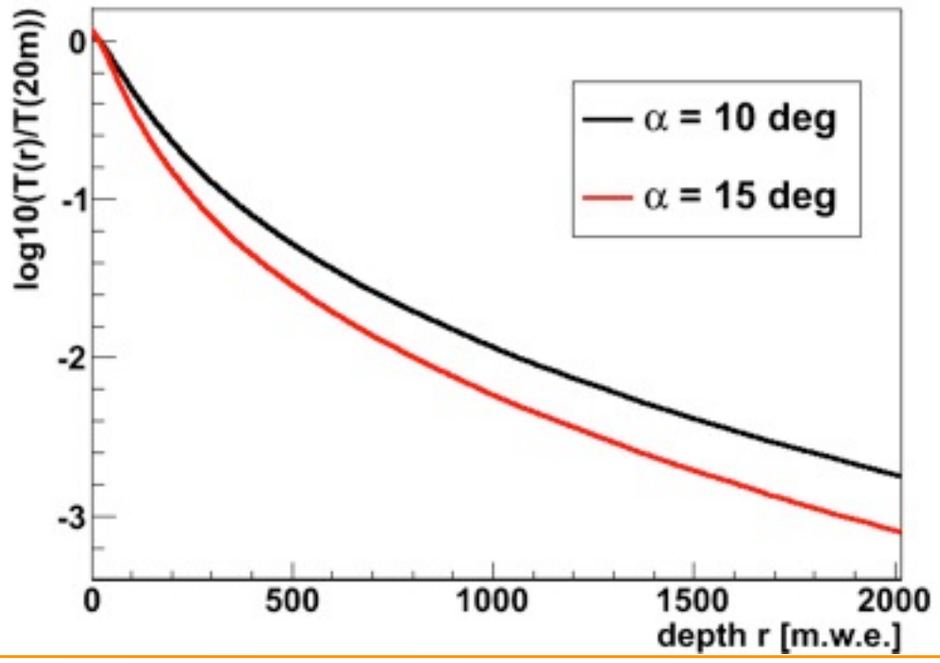


Hints of a structural contrast in the summit area. At the base, background mimics a higher transmission.

Measured **transmission** coefficient depends on unknown density averaged along a given direction.

The transmission curve as function of depth (in m.w.e.) can be extracted from simulation.

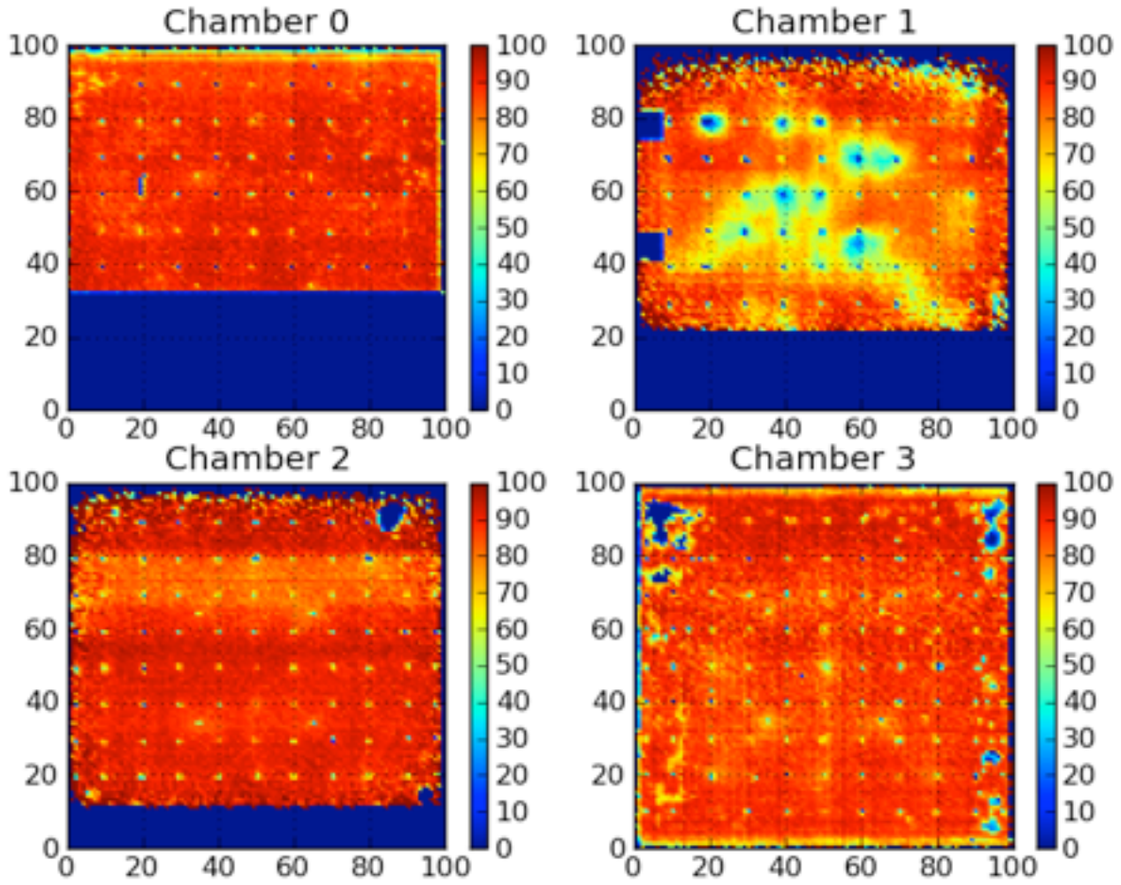
⟹ Detailed simulation needed to measure the density.

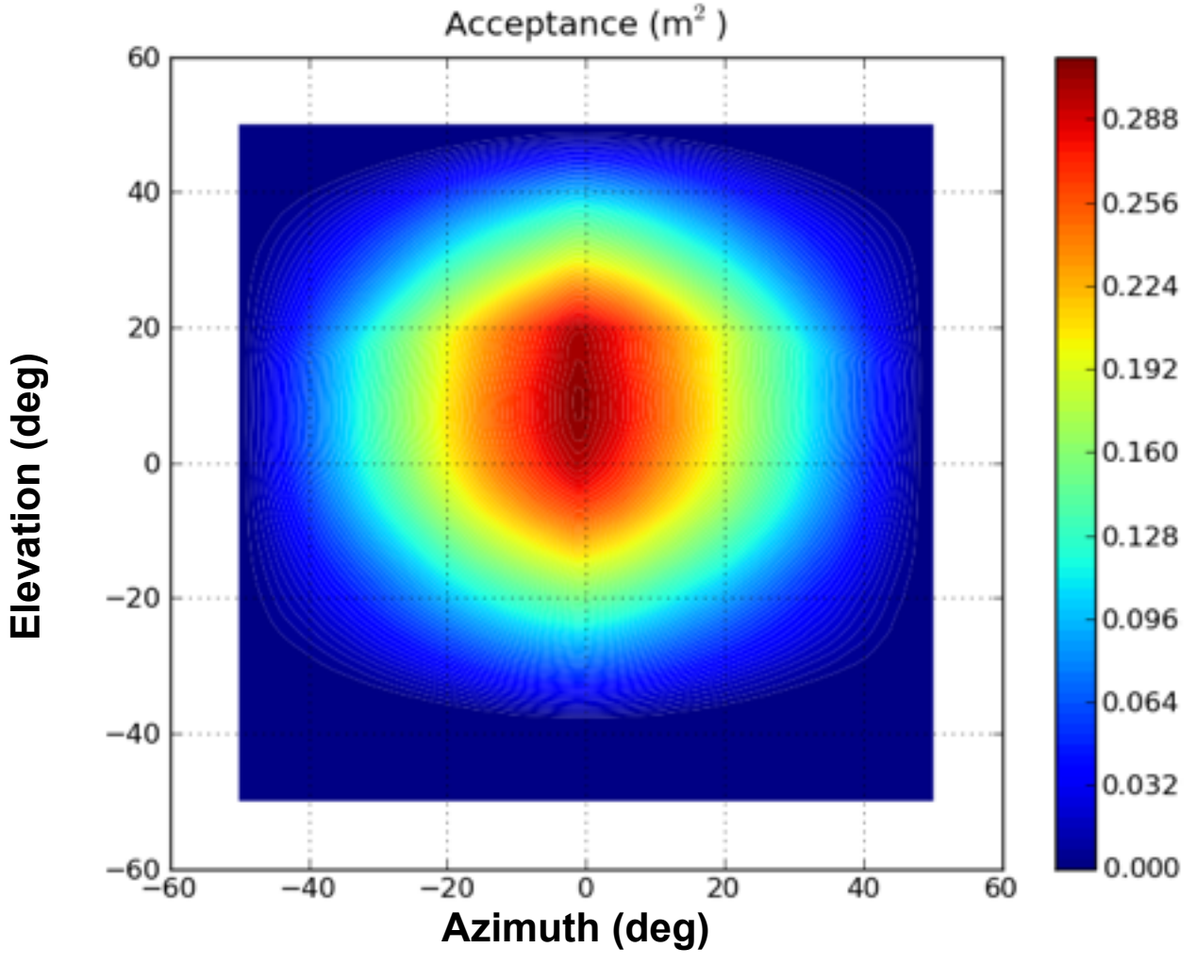


Col de Ceyssat Data

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

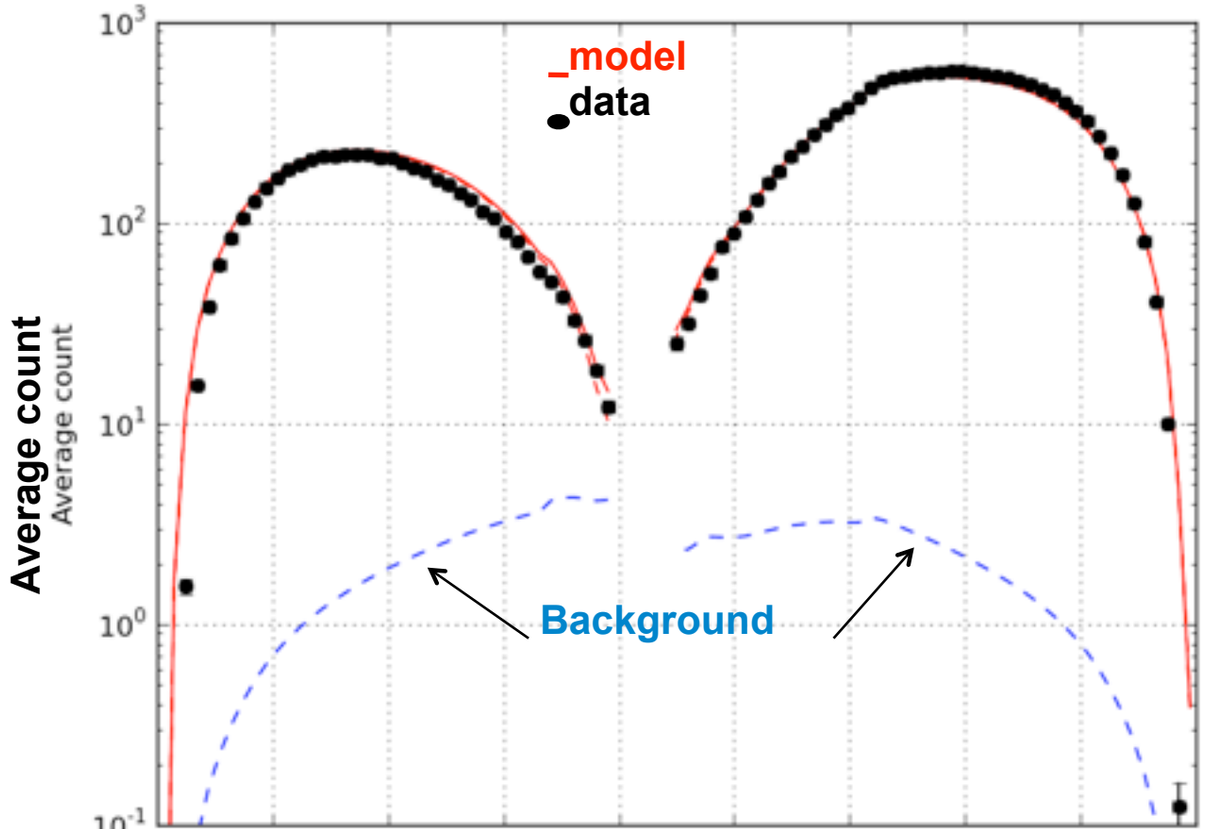
Average **dead time** fraction was **22 % (unstable prototype electronics & DAQ)**

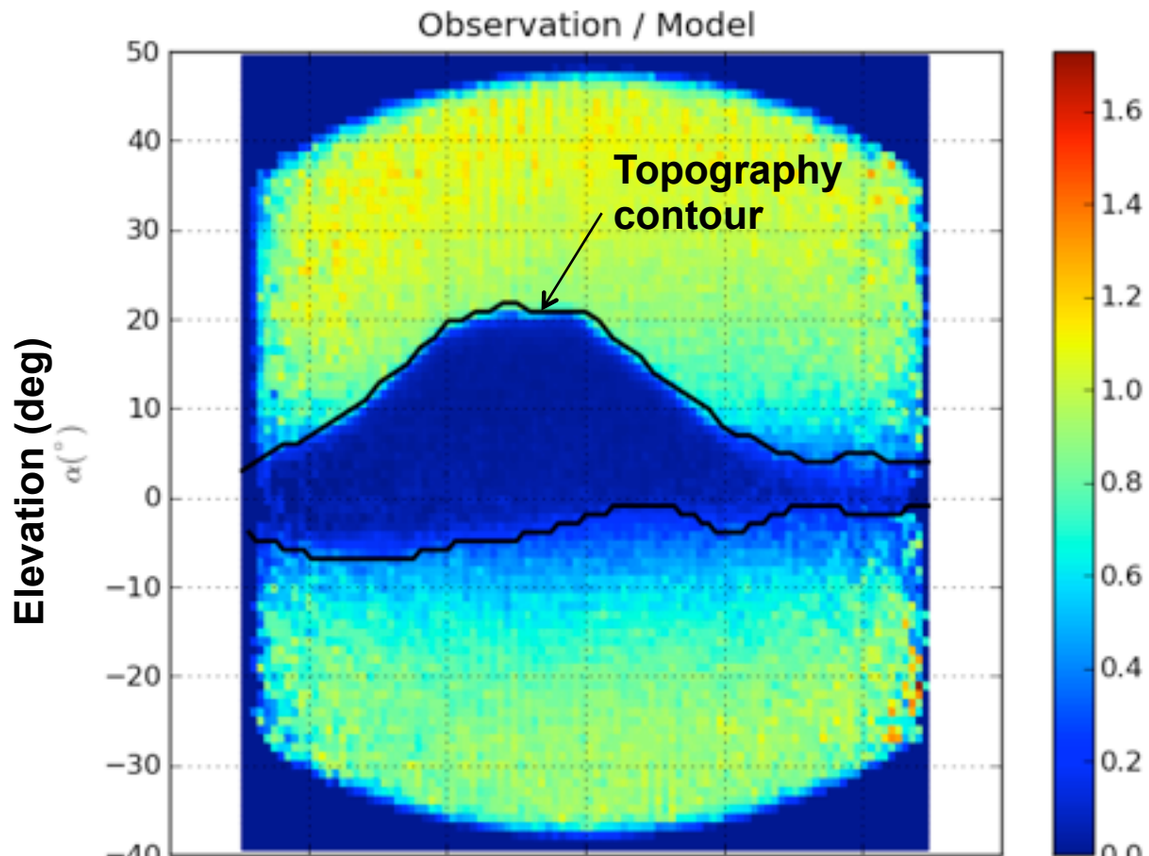




- **Relative cell efficiencies estimated in-situ** using >= 3 chambers isolated tracks within the 4 chambers acceptance. Typically ~90%.
- **Acceptance** computed by Monte-Carlo **including efficiencies** and in-situ alignment.
- **Selection** of **isolated tracks** (90 % of the overall number of events) giving coincident signals within 400 ns in the **4 chambers**.

Fit of the Open Sky Flux





❑ The **measured atmospheric μ flux**, substracted from background, **is fitted to Chirkin's parametric model** (arXiv:hep-ph/0407078) (modified Gaisser's parametrisation, fitted to CORSIKA simulations with primaries according to Hoerandel's poli-gonato model).

⇒ **Two free parameters**: the **lifetime**, and the detection momentum **threshold**.

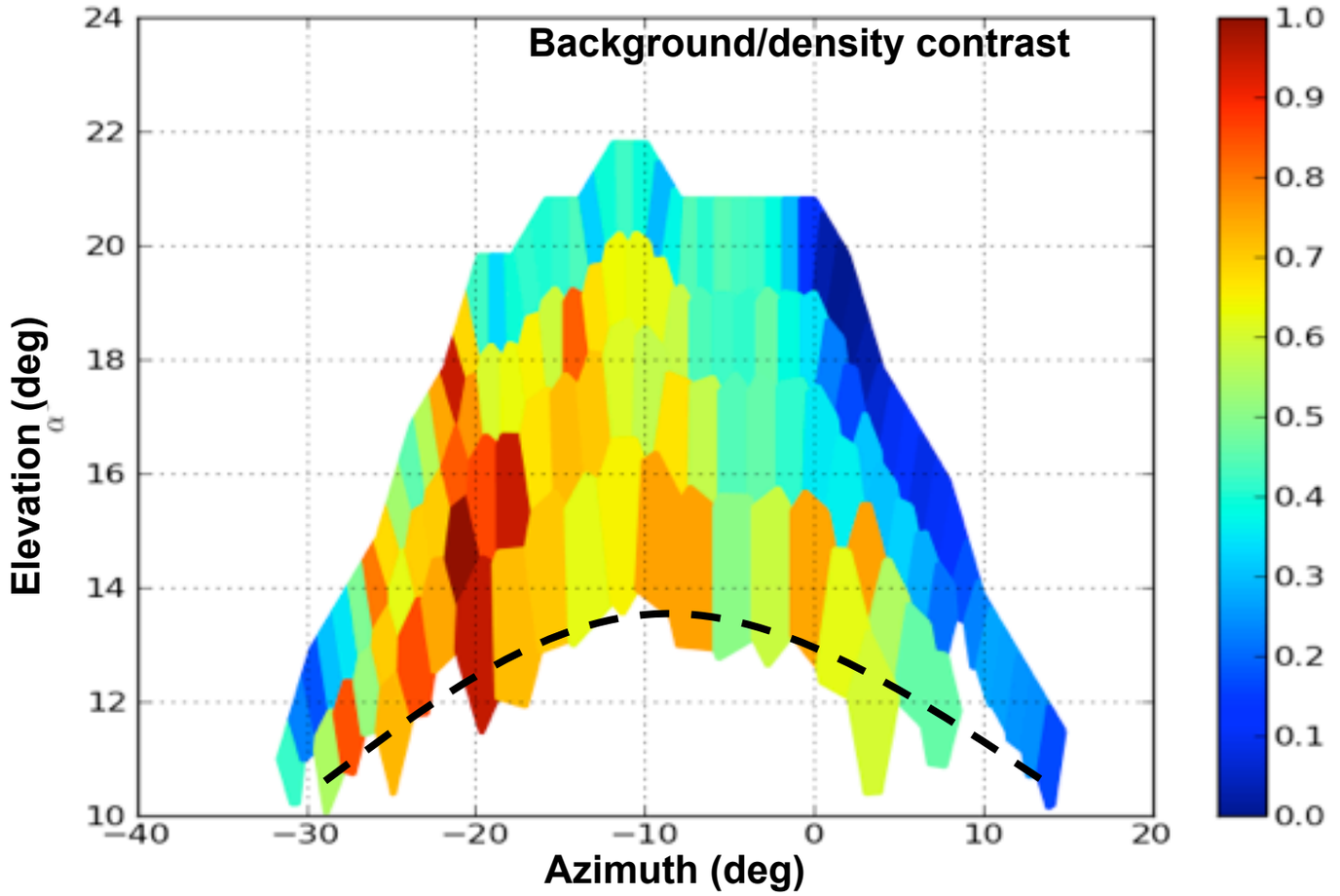
❑ **Agreement within 5 %** with data above 10 degrees elevation (summit part of the Puy de Dome).

Fitted values:

⇒ Lifetime = 14.3 day, versus 13.7±0.7 as estimated from data, taking selections and dead time into account.

⇒ Threshold: 200-300 MeV/c (loose dependency in the sub GeV range)

Tentative Contrast Map

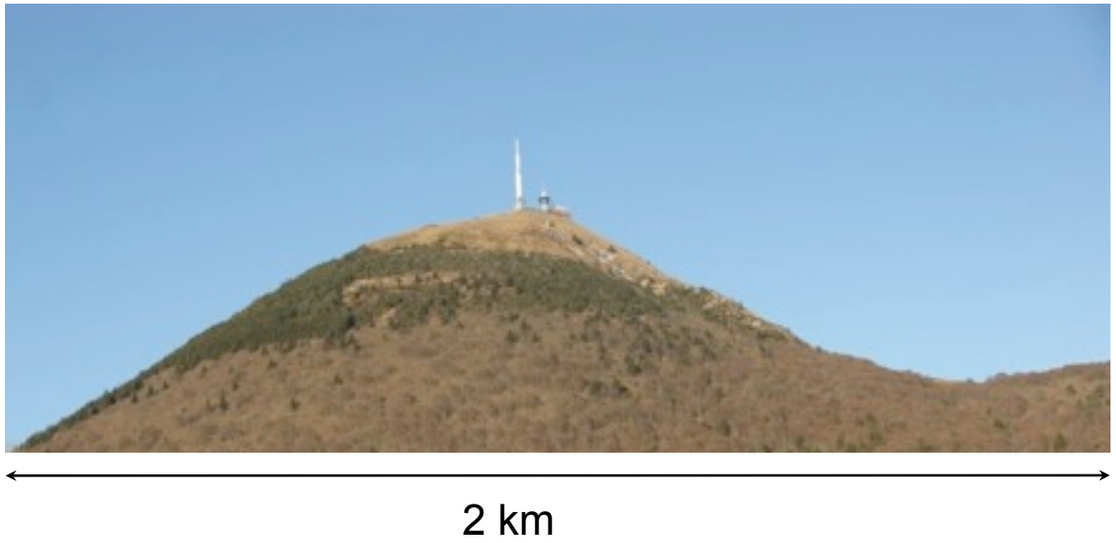


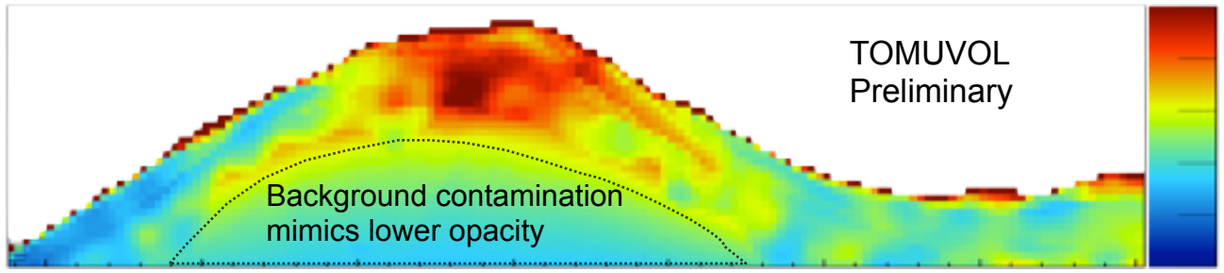
❑ **Integrated density** along line of sights was **estimated** using the fitted atmospheric spectrum and Particle Data Group CSDA (Continuously Slowing Down Approximation) μ range in rocks
However, **results yield an obviously too low average density, < 1 g/cm^3**
⇒ Points toward a **contamination from background tracks** that is not correctly accounted .

❑ **Contrast map** (unit less) of the reconstructed density. Data suggest an over density (or lower background ?) on the West side of the Puy de Dome.

2011-2012 Campaigns

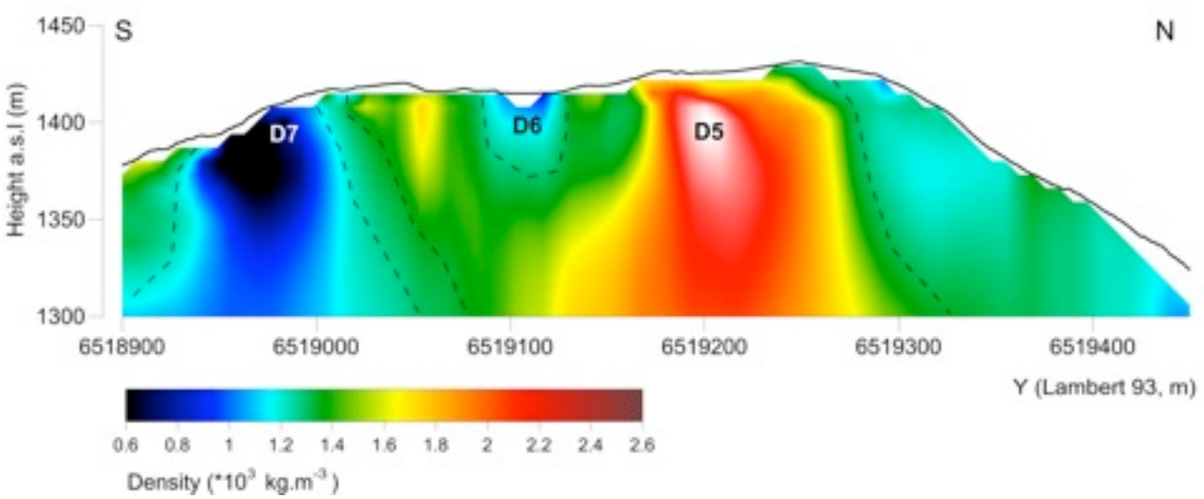
2011-2012 Campaigns



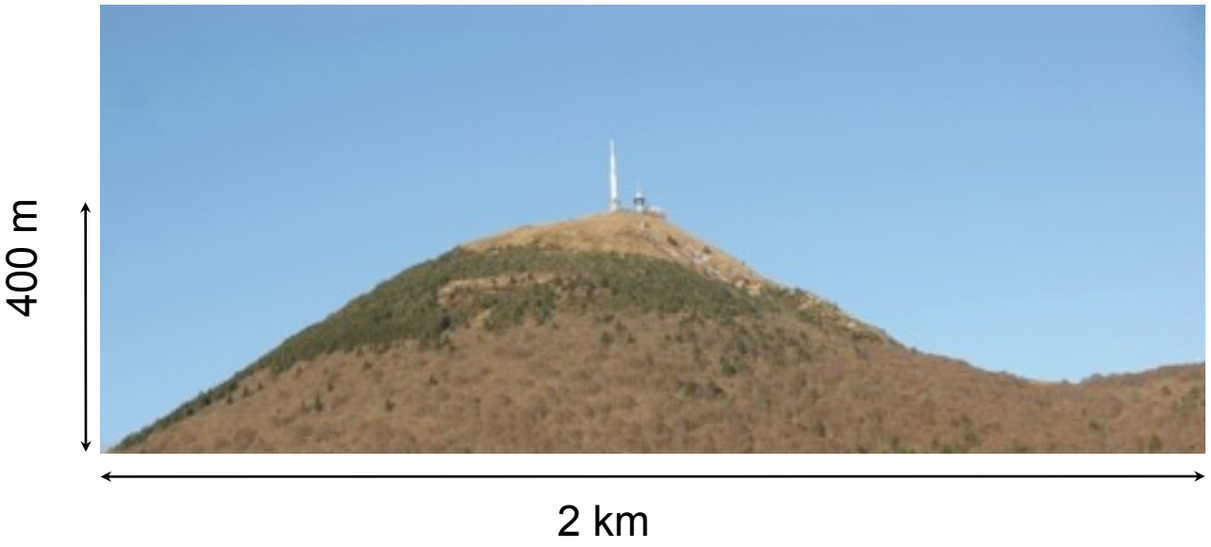


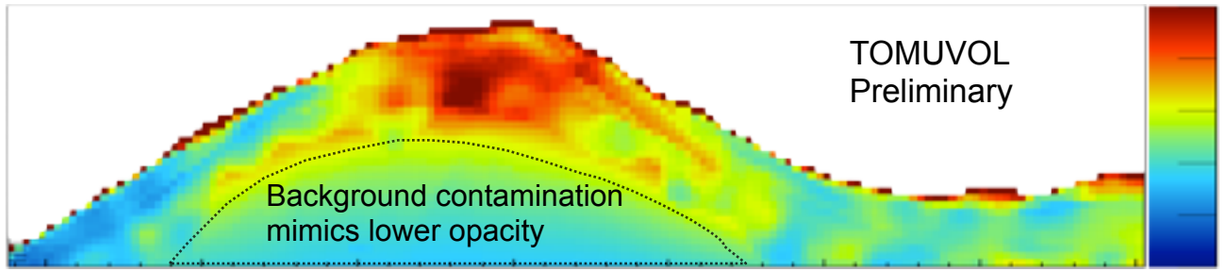
Linear opacity to atmospheric muons

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



2011-2012 Campaigns





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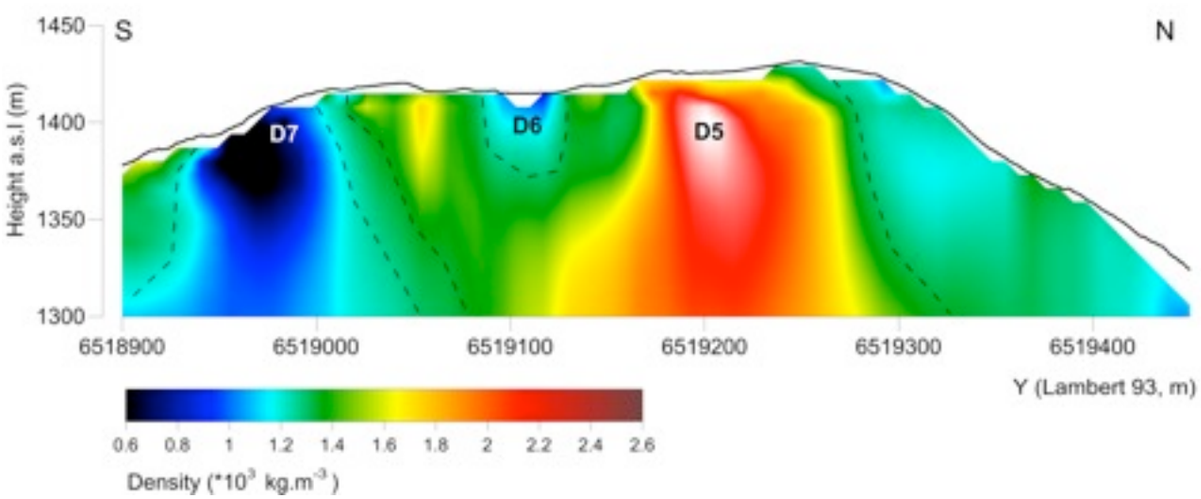
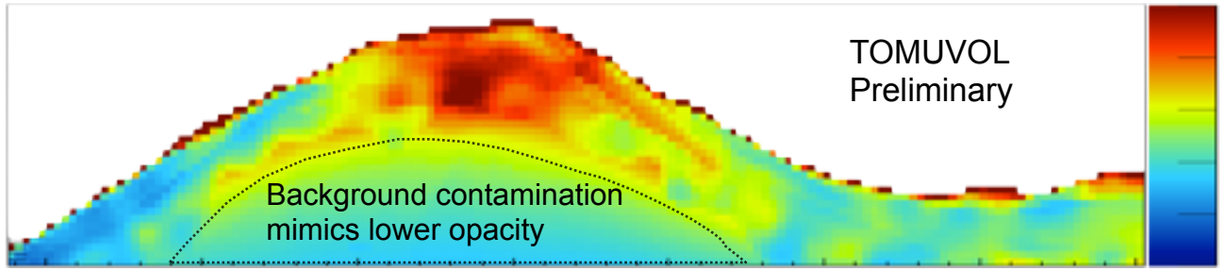


2011-2012 Campaigns



Linear opacity to atmospheric muons

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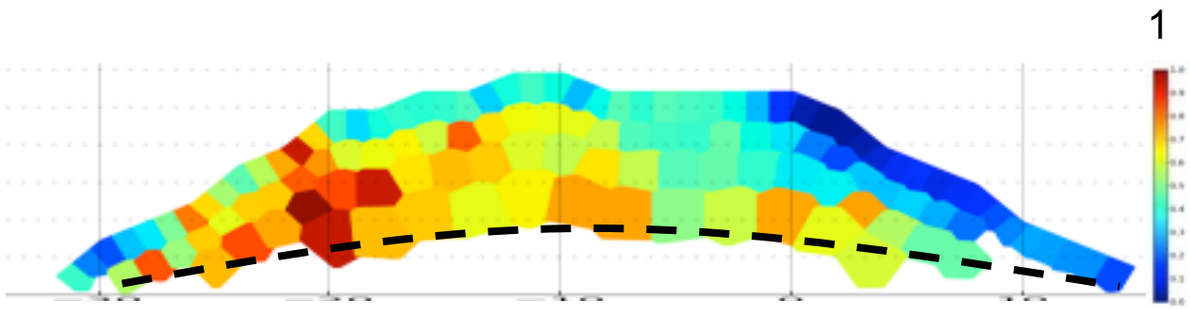
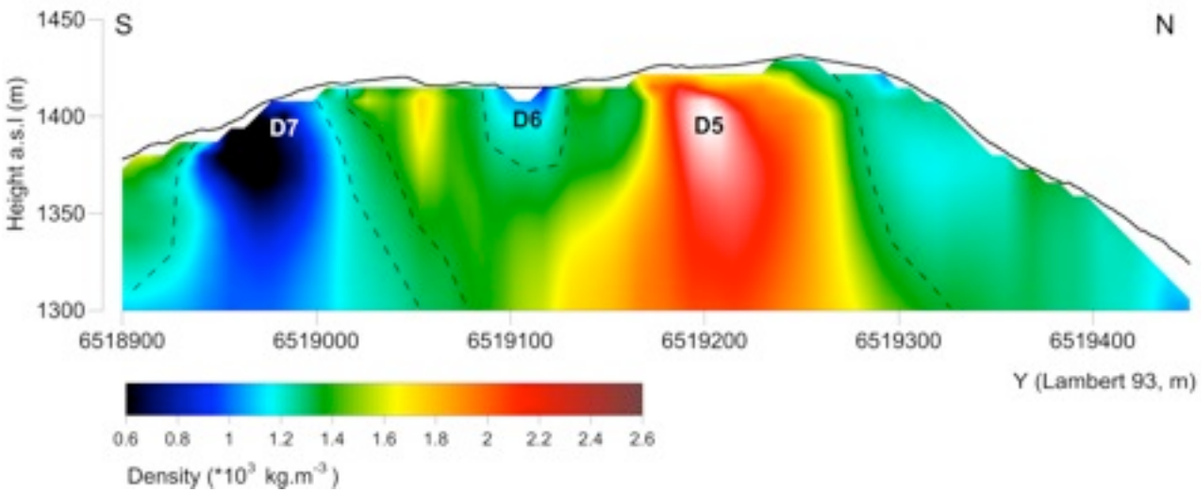
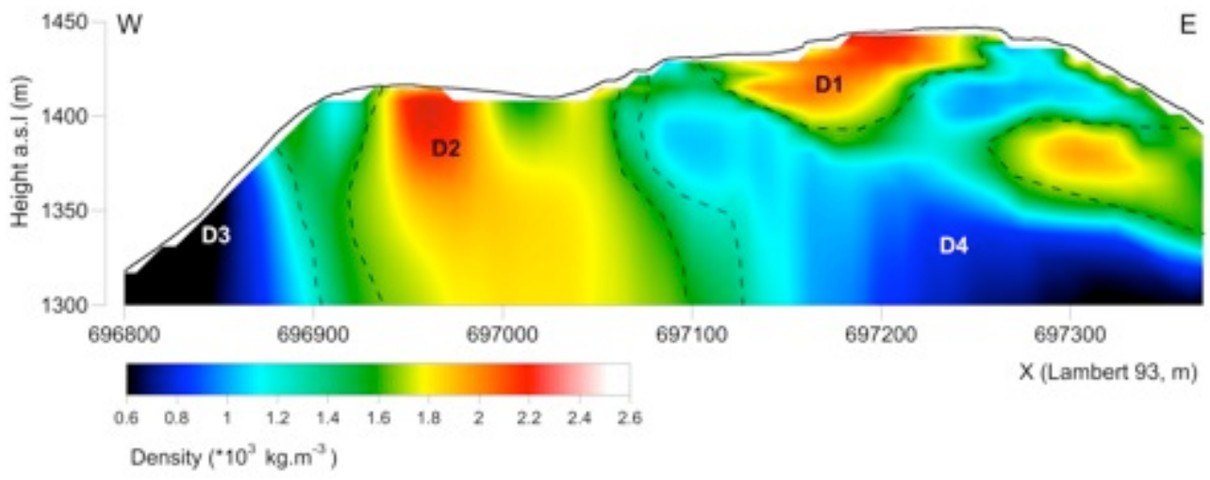


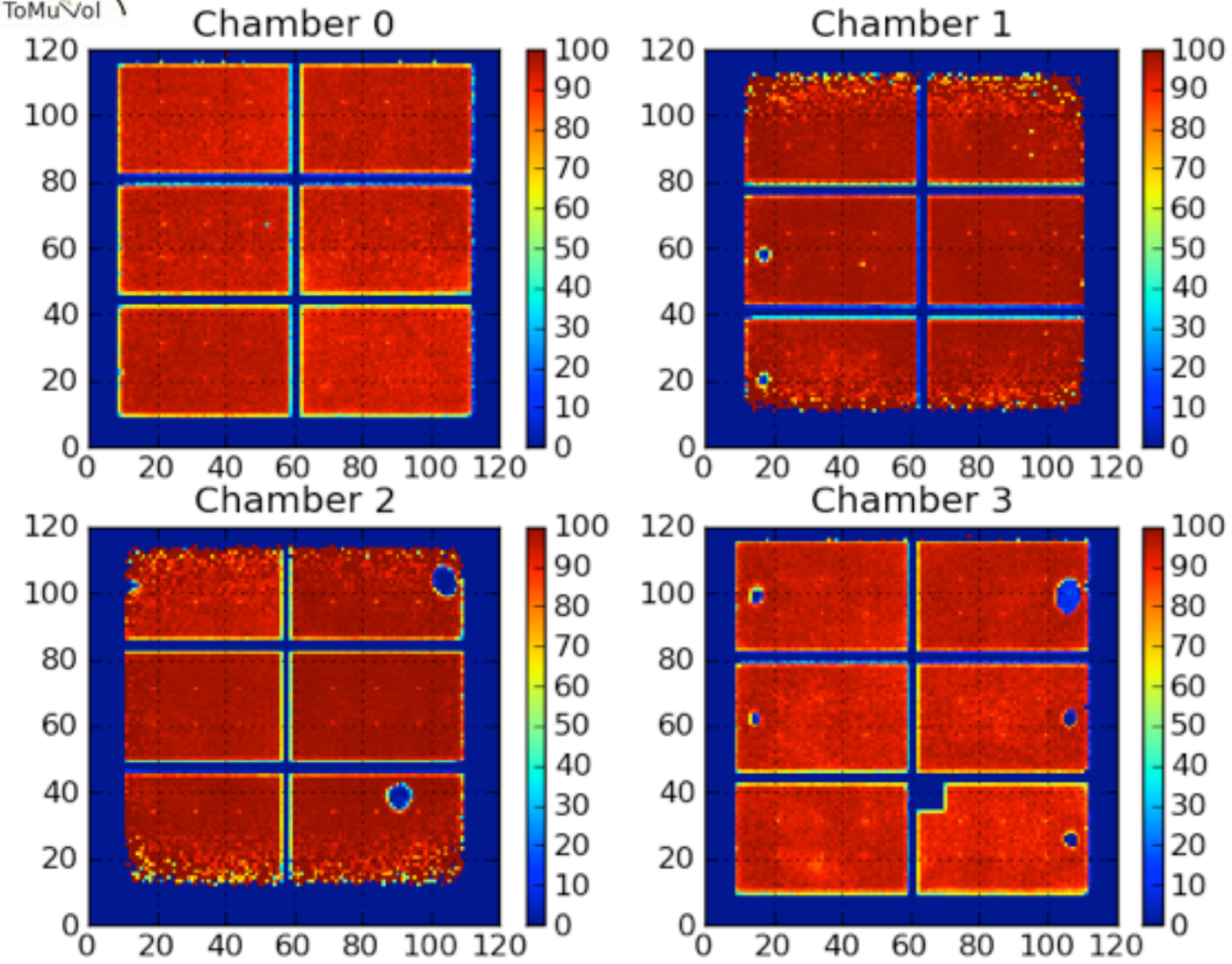
Density contrast

14 days of data taking, 0.66 m^2 x 1 m

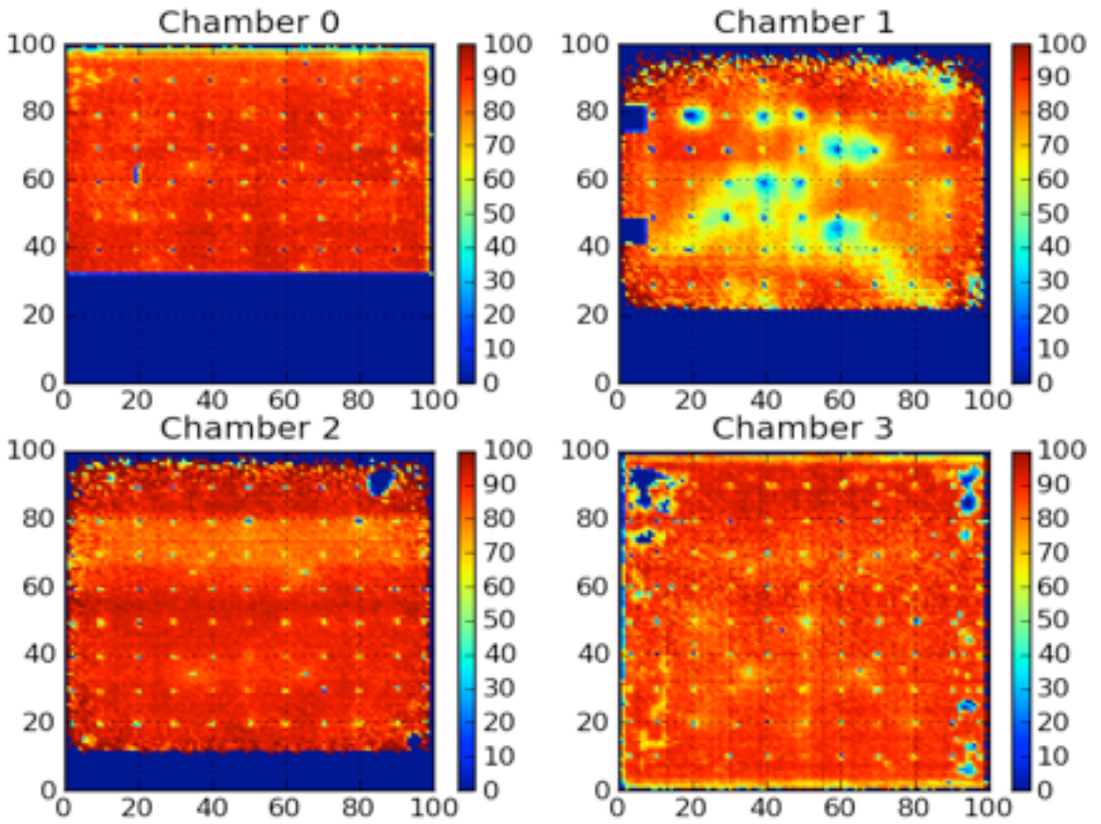




TDF Data



Reminder - 2012 data



TOMUVOL Summary

Borrowed detectors working as prototypes allowed us to define a good muon telescope (the CALICE GRPC chambers slightly optimised for field deployment)

The data acquired in 2011 / beginning 2012 fully demonstrate the potential of the method

The TOMUVOL detector was completed in 2013. Excellent quality tracks were collected in a short period of time. New data taking campaign will start soon.

Turn Puy de Dôme is really becoming a reference site:

Muon tomography (several detectors, several technologies, several groups)
Electrical resistivity measurements
Gravimetry measurements

Develop a coherent and robust multi-probe analysis of the volcano structure

Volcano Imaging Overview:: Volcanic Hazards

Various hazards with different physical causes and magnitudes

- phreato-magmatic explosion
- phreatic explosion (release of thermal energy contained in the hydrothermal reservoirs)
- landslide and flank collapse (may be triggered by internal overpressure, earthquake)

Hazard level depends on present-day state of the volcano

- Degree of alteration (mechanical integrity)
- Volume of reservoirs (stored energy)
- Internal changes (liquid/vapor transition)
- Channels and conduits

Structure imaging plays a leading role in hazard prediction

- Electrical conductivity : resistivity
- Seismic waves velocity + coda waves : elasticity
- Gravimetry and muography : density

Volcano Imaging Overview::Muography

- restricted to the top part of volcanoes
- depending on the volcano size and the budget, it may be “slow” monitoring (weekly, monthly...)
- low signal rates impose large area detectors and strong control of the background.
- may be systematics prone ...

- wide angle remote imaging (km).
- 10 mrad resolution seems achievable, with few percent contrast. Trade to play between exposure and resolution
- simple inverse Radon transform (density determination via straight-ray geometry)