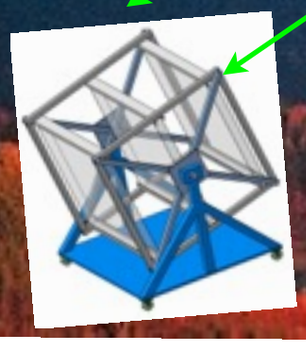
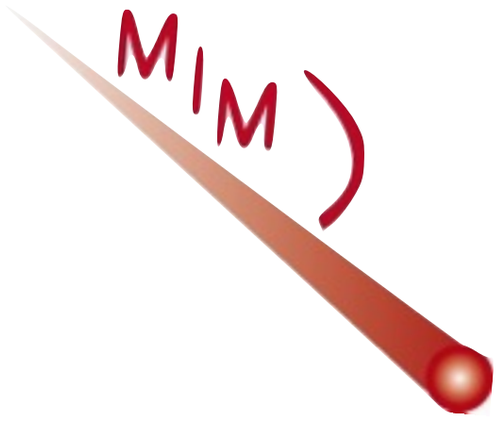
Looking to the volcanoes from far away



Cristina Cârloganu 31.03.2011



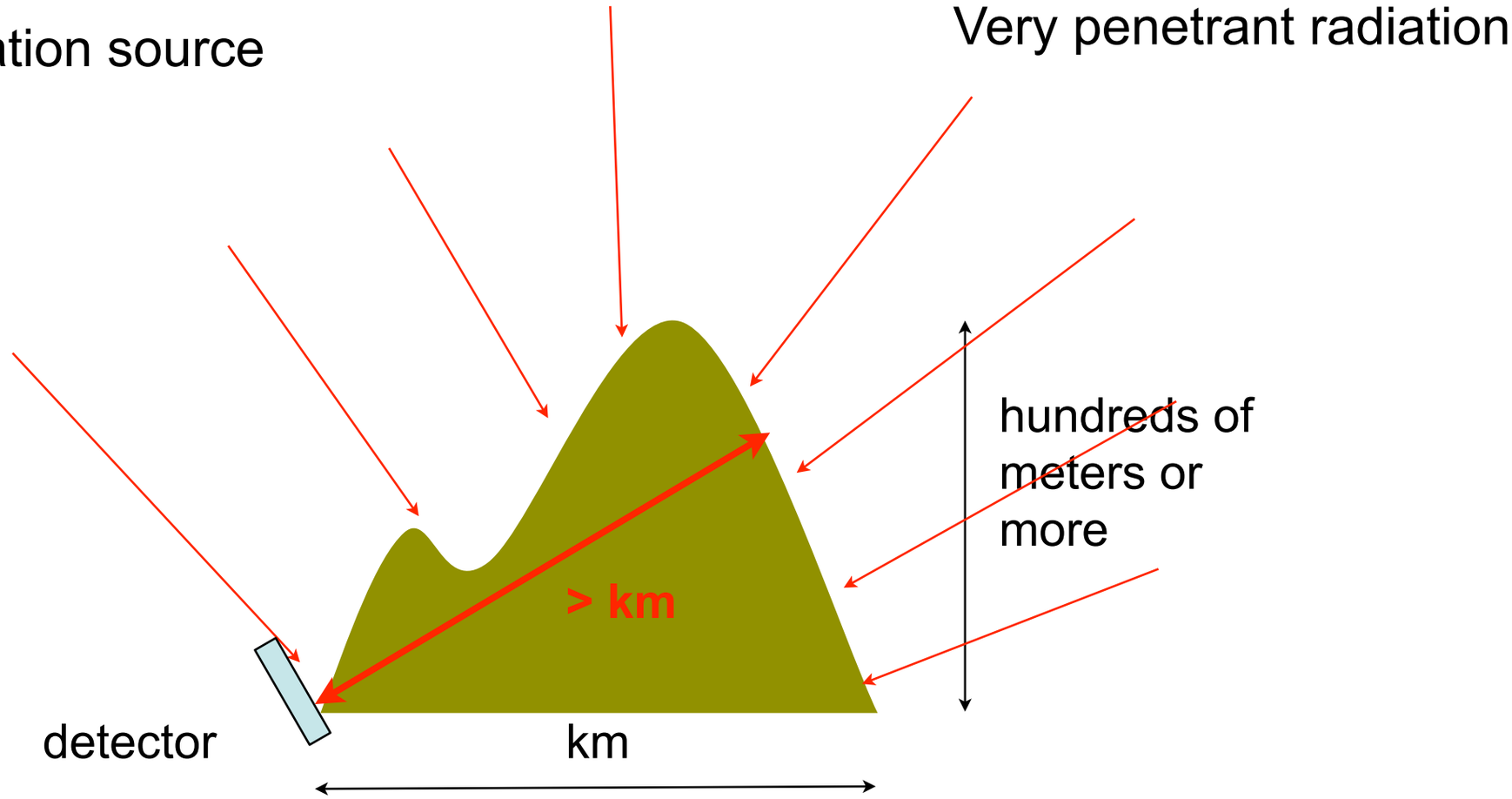
Muography: from dreams to reality

Cristina Cârloganu

Atmospheric muons

Very broad radiation source

Very penetrant radiation



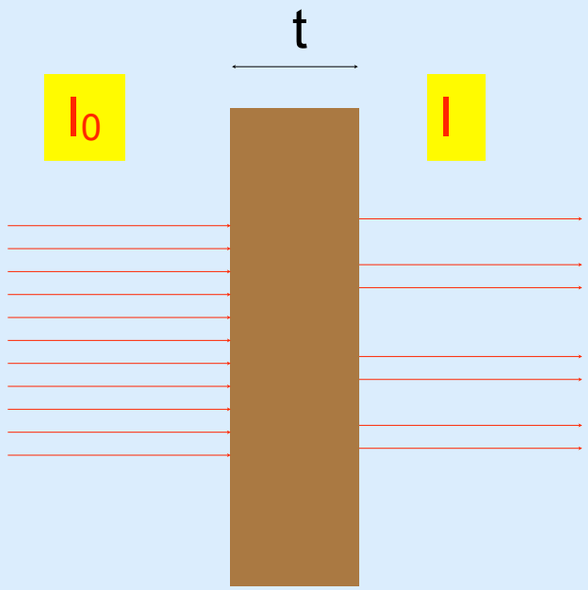
$$\langle R_\mu(E_\mu)\rangle = \int_0^{E\mu} dE_\mu / \langle \Delta E/dx\rangle \sim \beta^{-1} \ln(1+\beta/\alpha\, E_\mu)$$

standard rock:
A=22, Z=11,
ρ=2.65 gcm^{-3}

E_μ	10 GeV	100 GeV	1 TeV	10 TeV
R_μ	19m	155m	0.9km	2.3km

Two exploitable interactions

TRANSMISSION

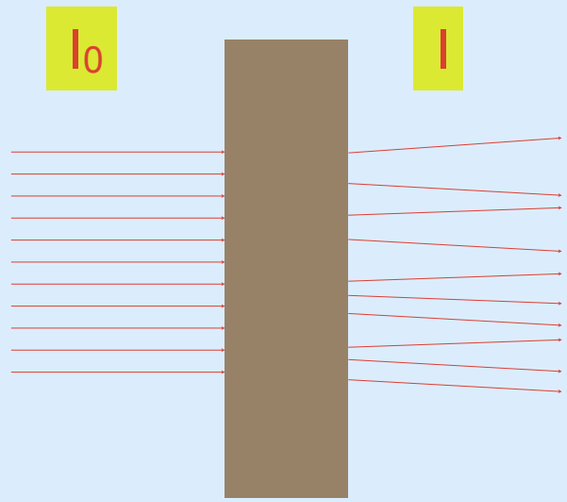


$I = I_0 f(\rho)$

DENSITY

- 2D image
- relies on incident flux knowledge
- applicable to very large targets

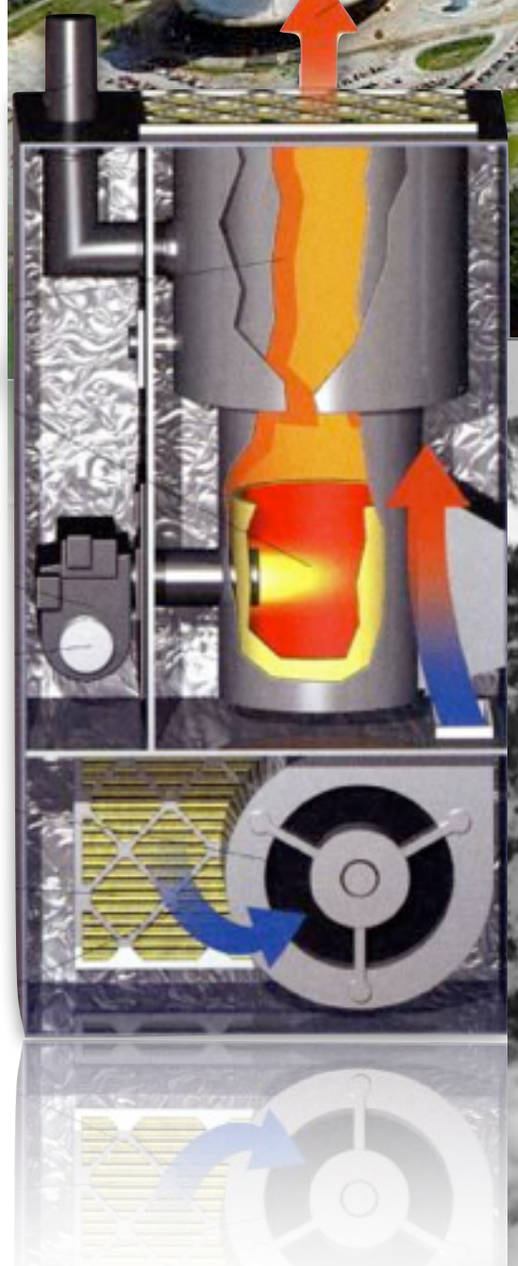
SCATTERING



$\delta = f(Z)$

ATOMIC NUMBER

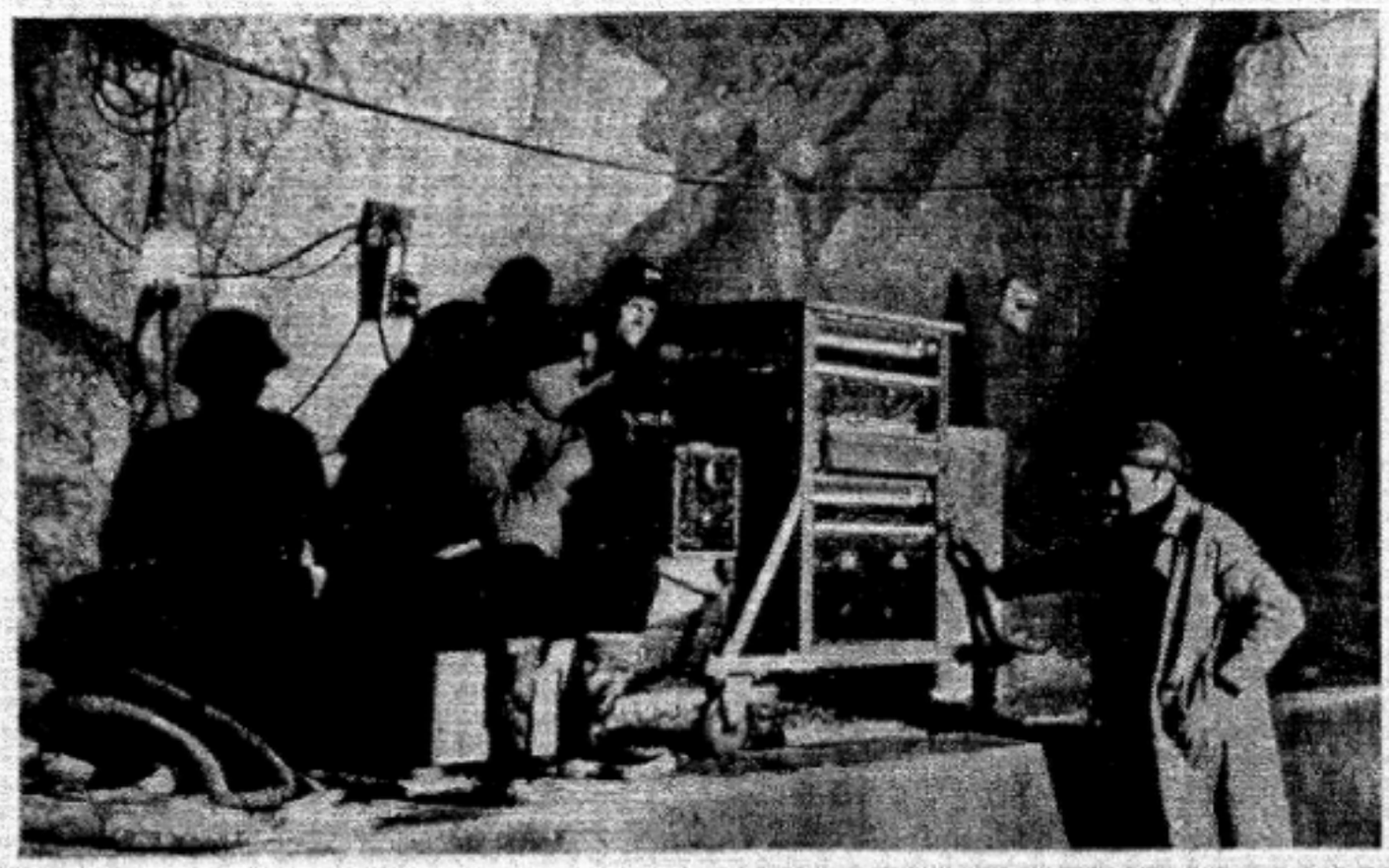
- 3D image
- necessary to measure each individual track before and after the target
- high position resolution, large area detectors
- small to medium targets




Eiger
Eiger glacier

Early muographic attempts: George, 1955

Cosmic Rays Measure Overburden of Tunnel

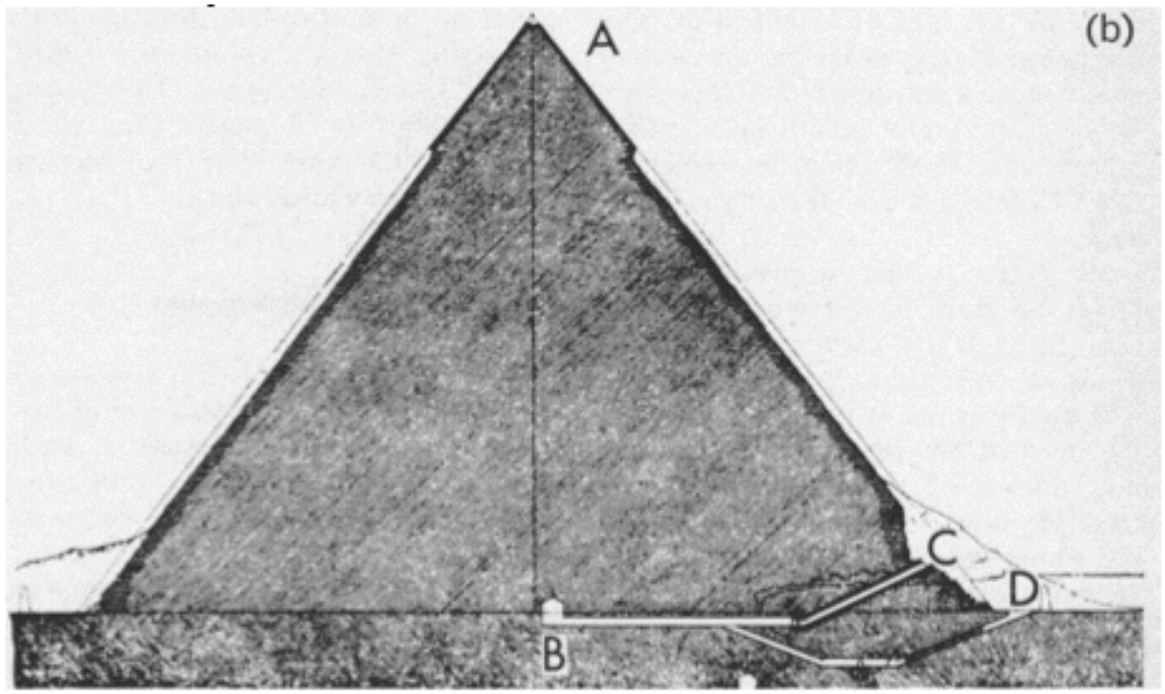


● Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehane and Mr. O'Neill.

Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described

By Dr. E. P. George*
University of Sydney, N.S.W.

Early muographic attempts: Alvarez 1970



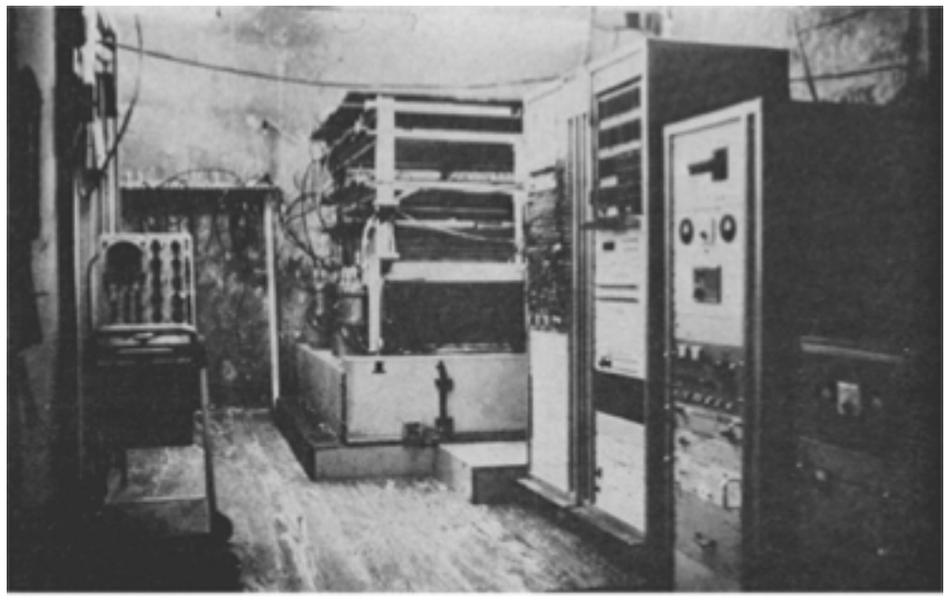


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.
Fig. 7 (right). The detection apparatus containing the spark chambers.

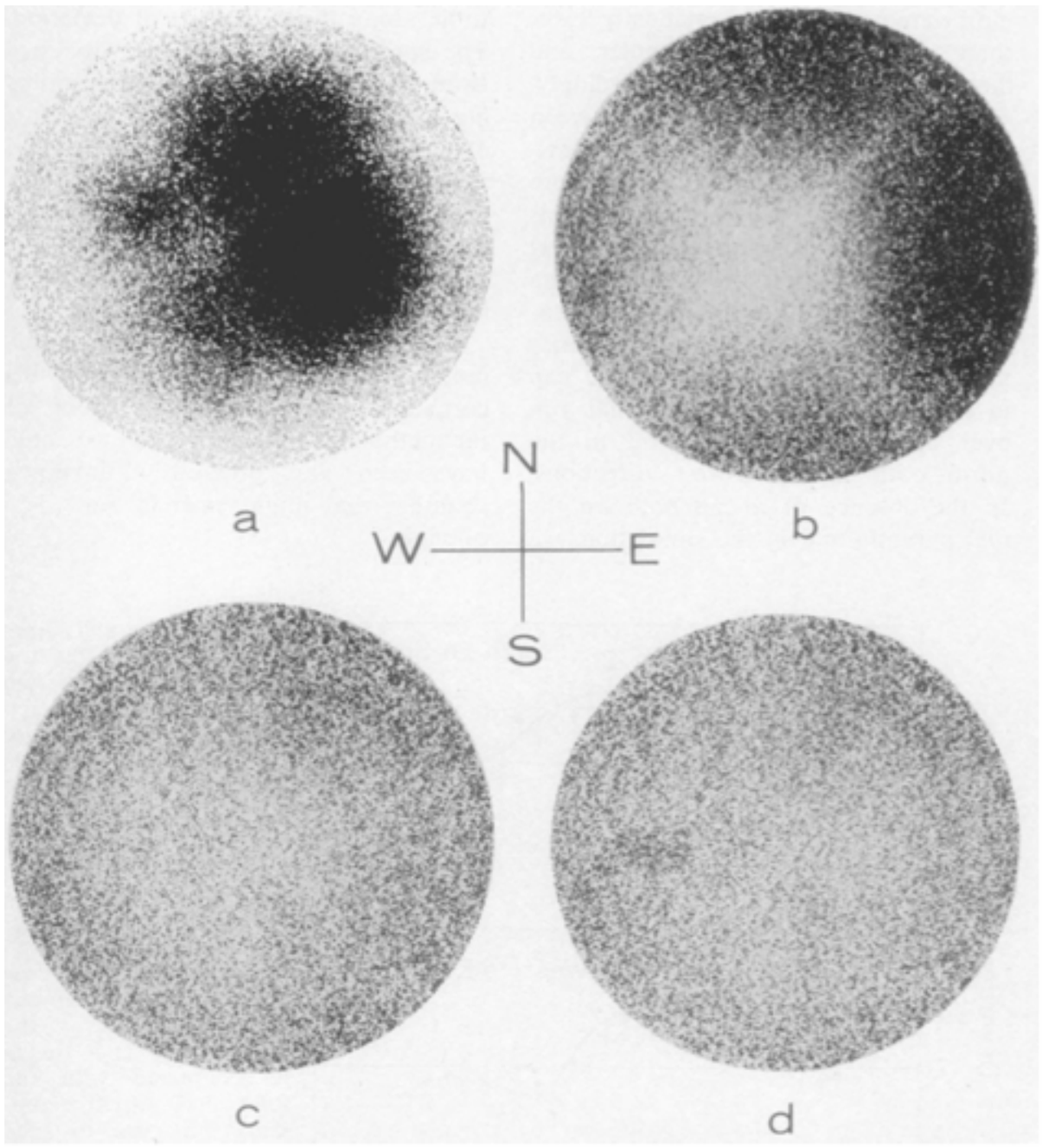


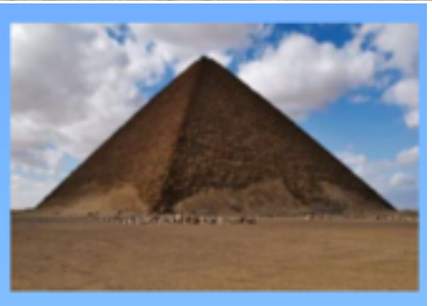
Fig. 13. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber. (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure as well as geometrical acceptance. (d) Same as (c) but with simulated chamber, as in Fig. 12.

http://www.scanpyramids.org

Pyramide rhomboïdale

Pyramide rouge

Dashour

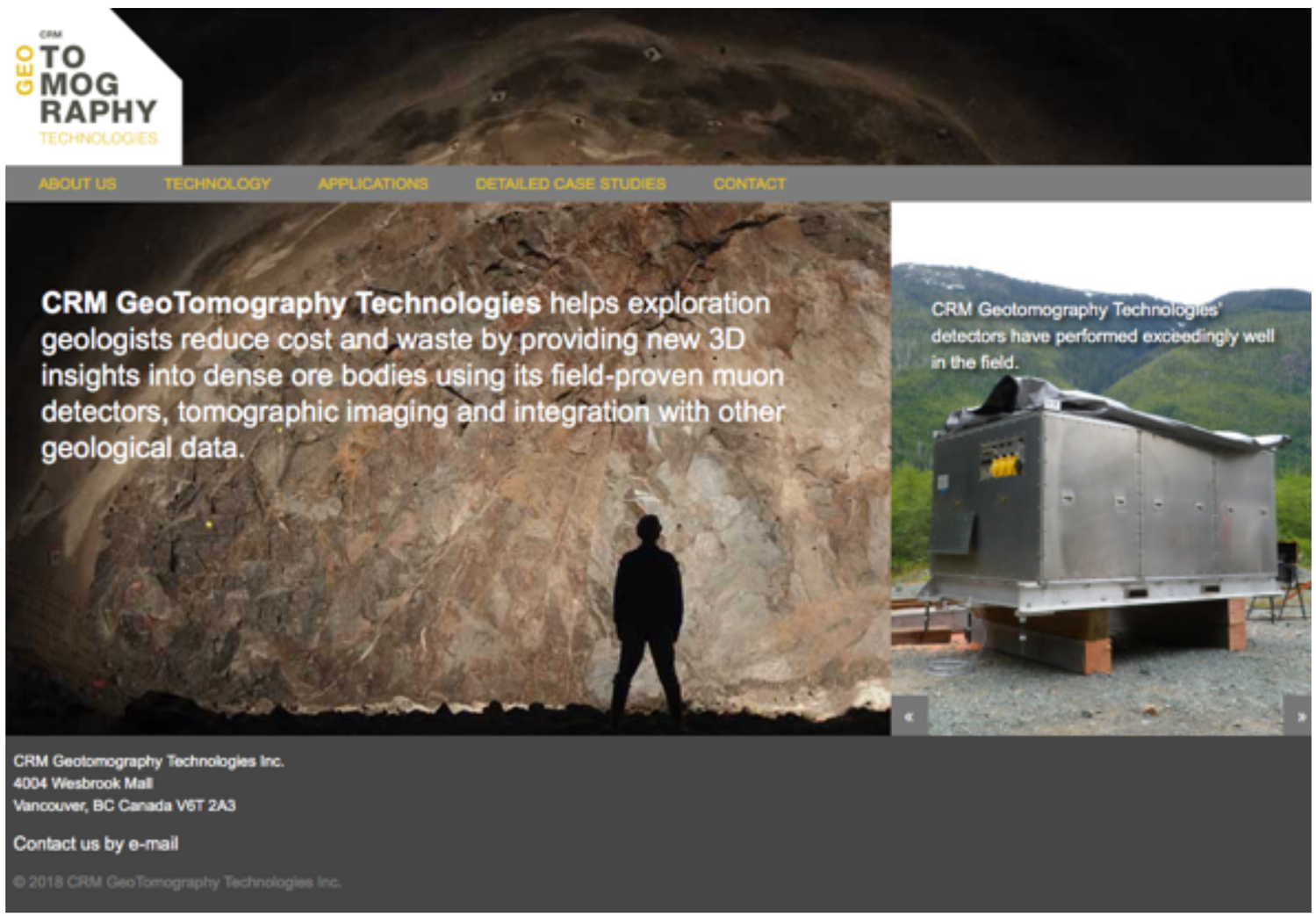


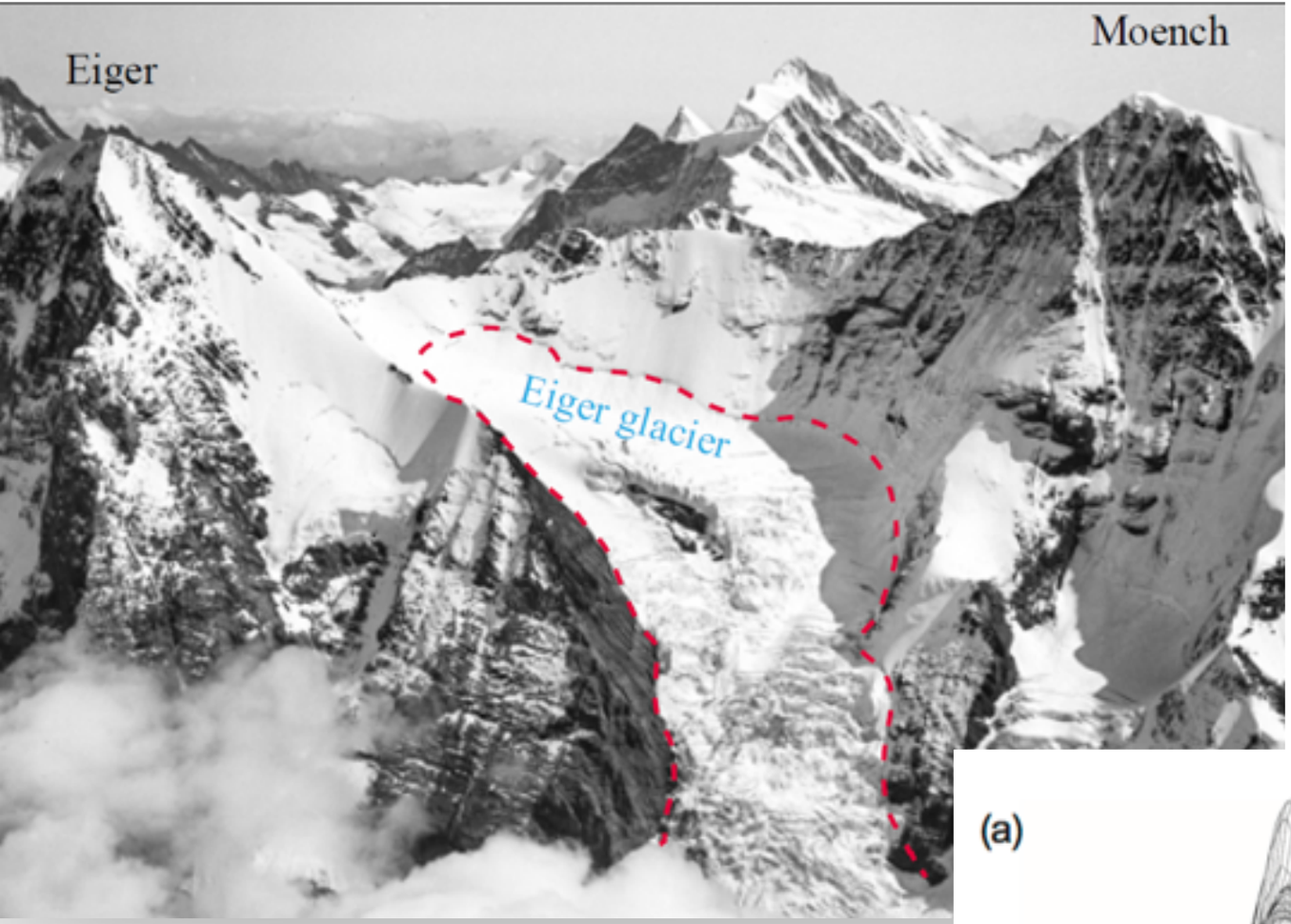
Pyramide de Kheops

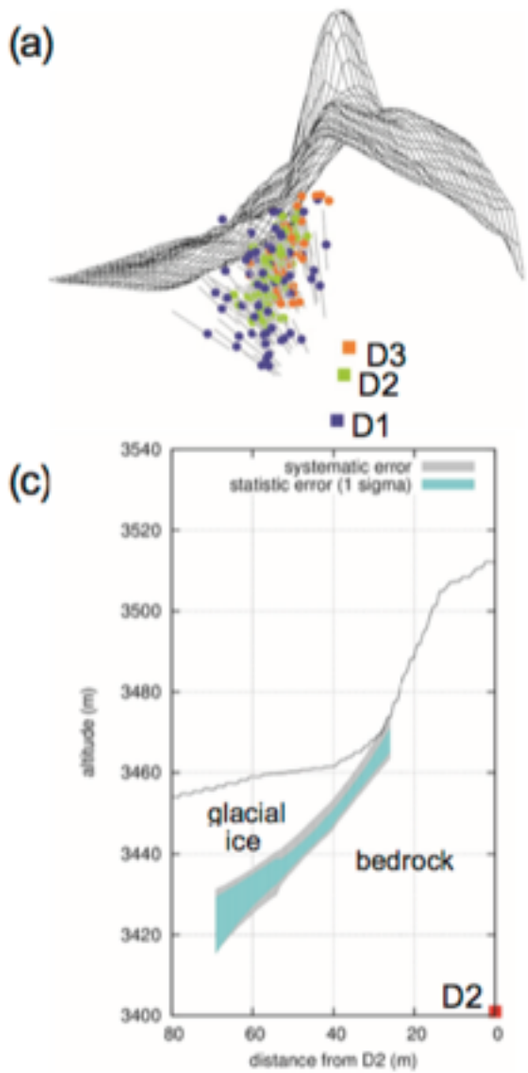
Pyramide de Khephren

Gizeh

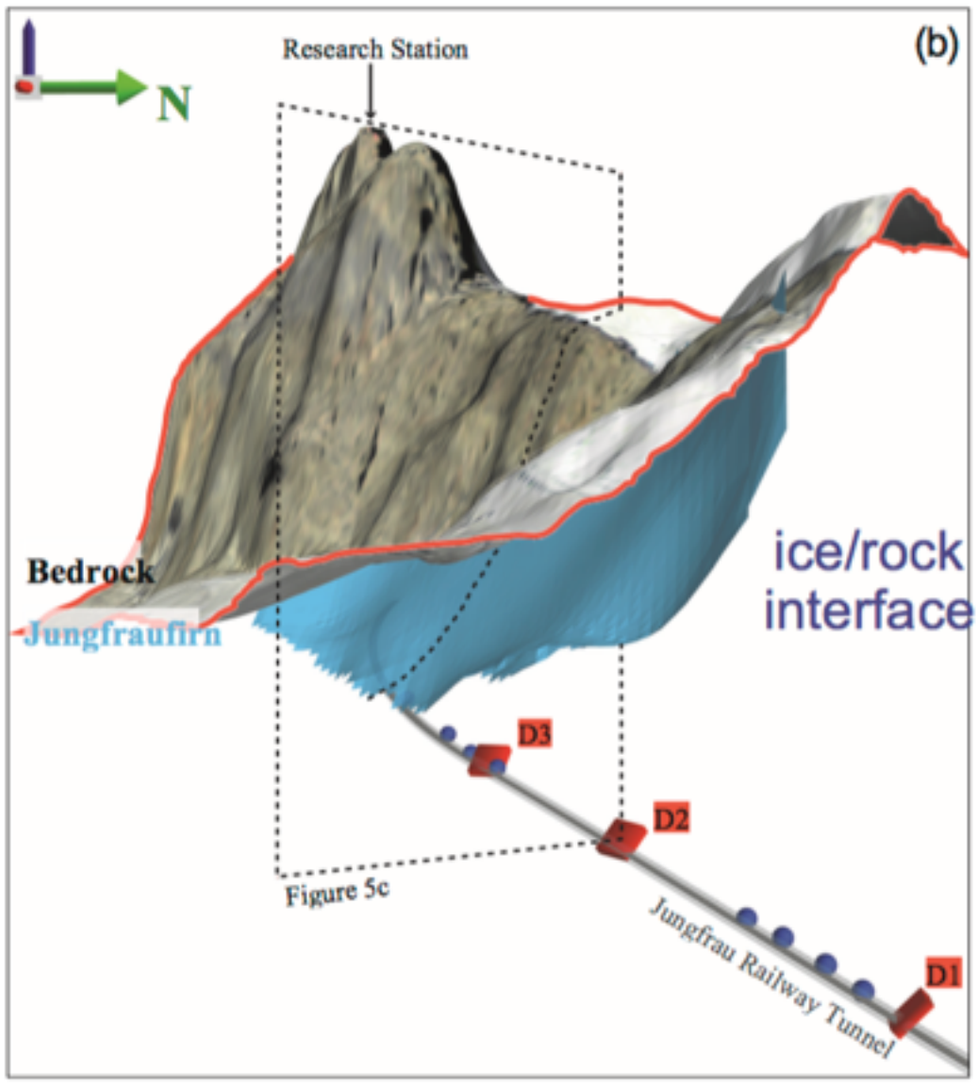
McArthur River Uranium mine



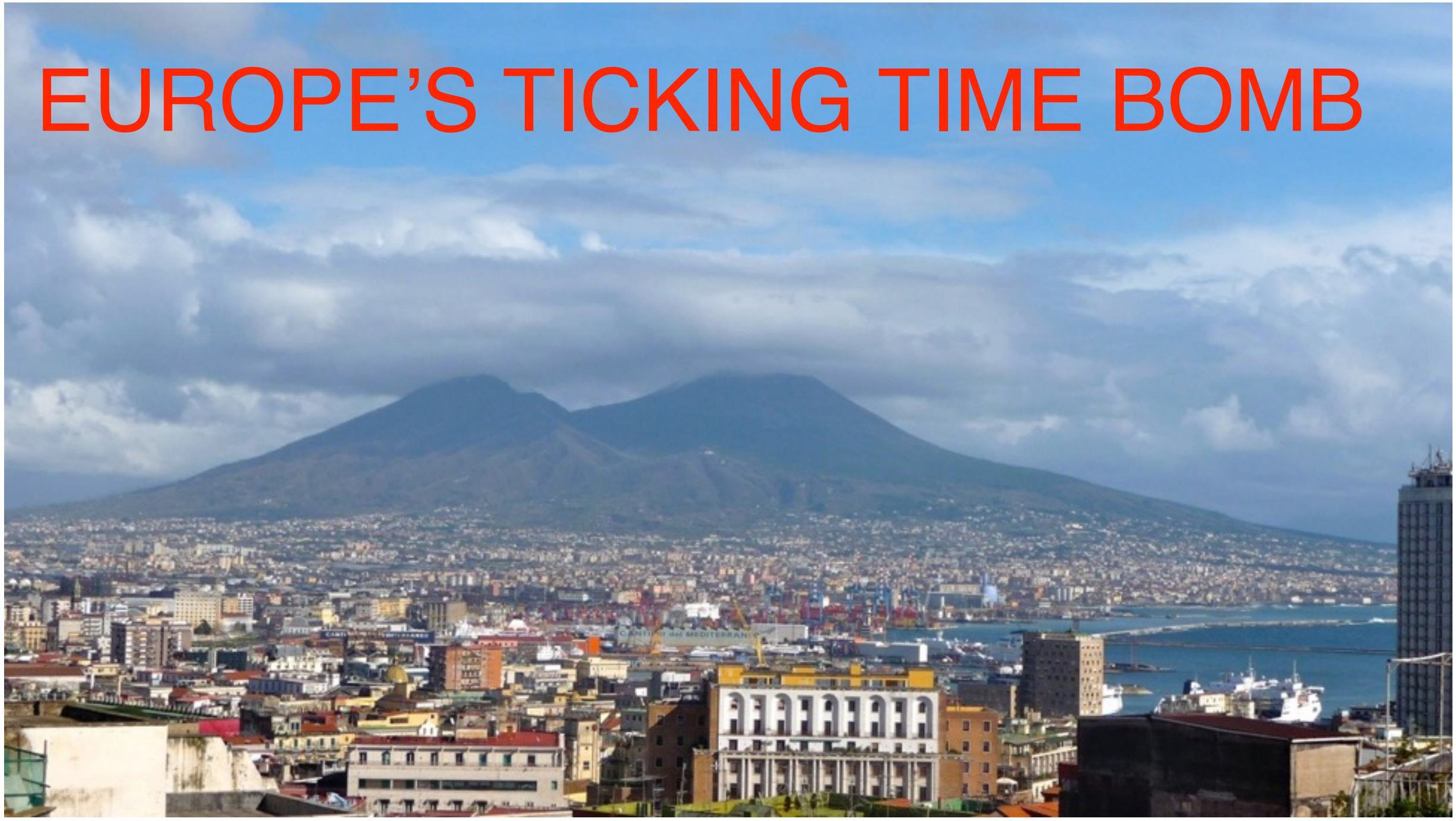




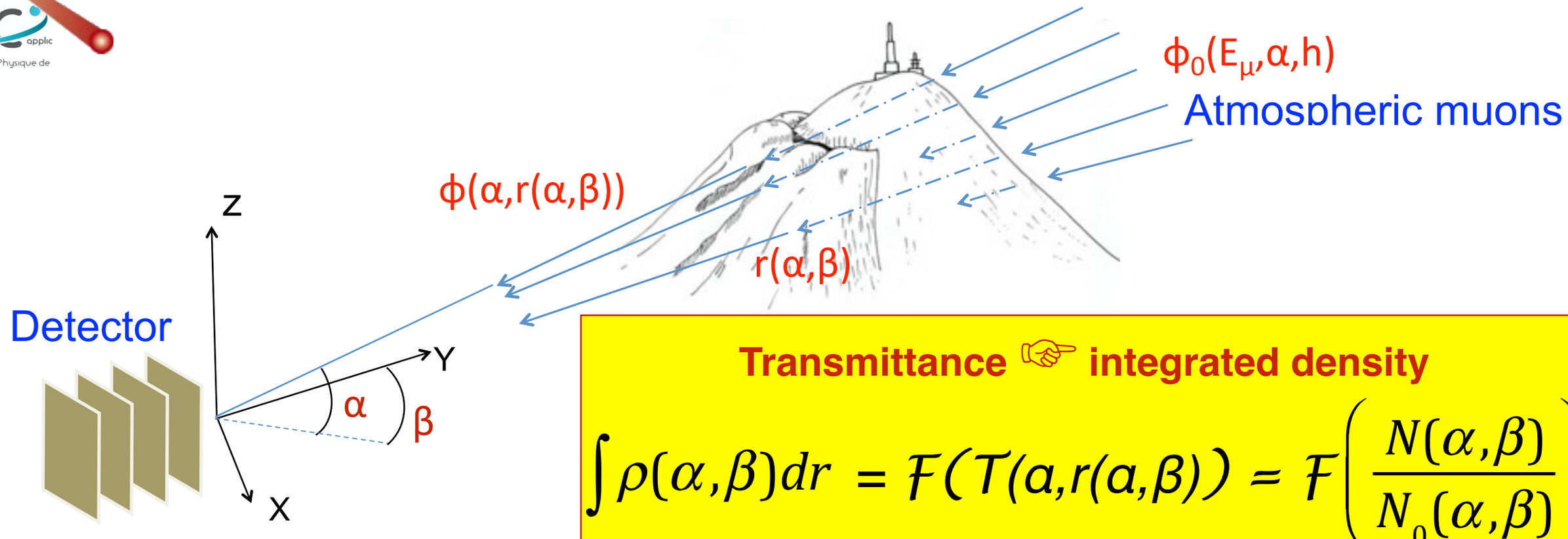
First measurement of ice-bedrock interface of alpine glaciers by cosmic muon radiography
Geophys Res Lett, doi:10.1002/2017GL073599



EUROPE'S TICKING TIME BOMB



Transmission muography: muons ☞ integrated density



Transmittance ☞ integrated density

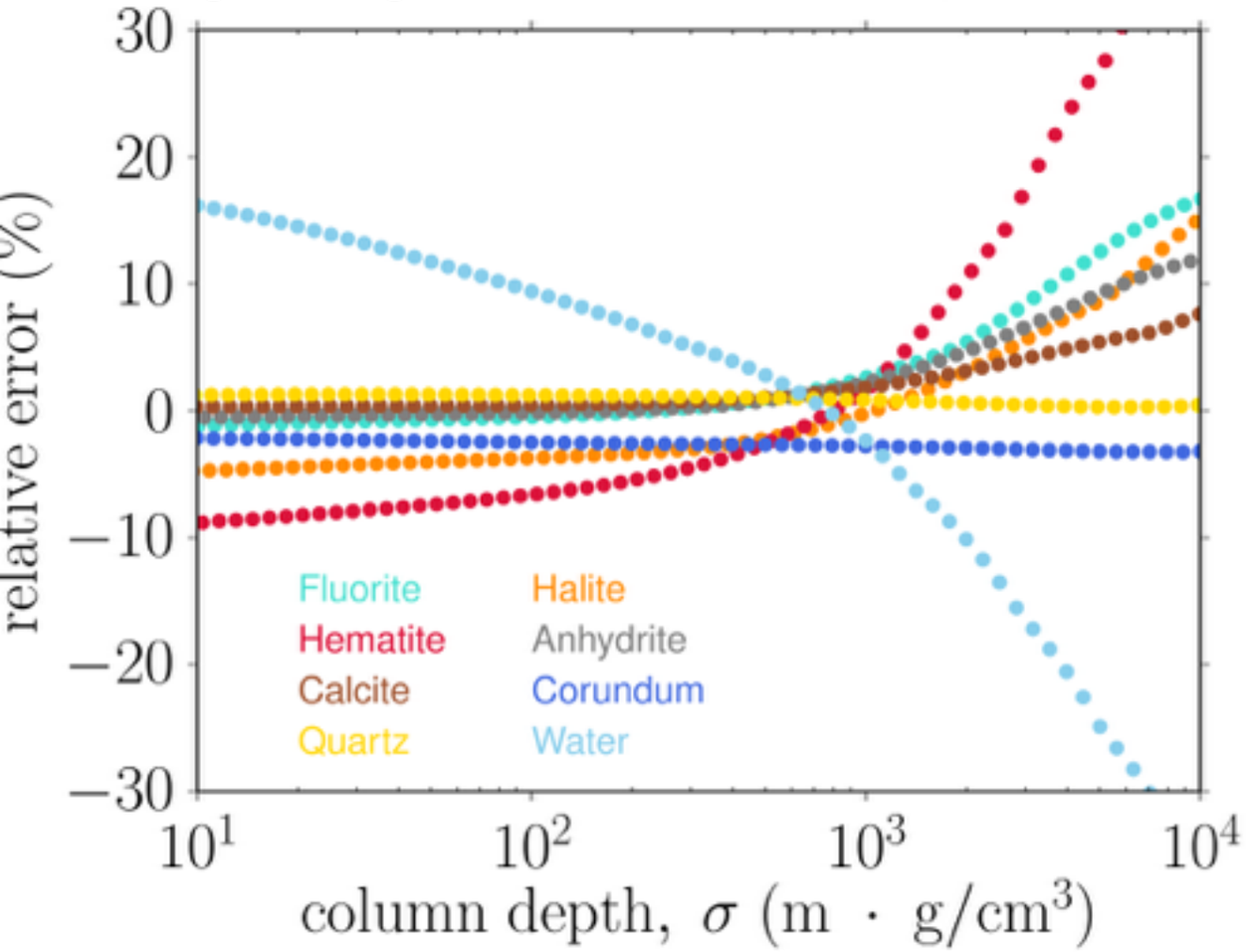
$$\int \rho(\alpha,\beta)dr = F(T(\alpha,r(\alpha,\beta)) = F\left(\frac{N(\alpha,\beta)}{N_0(\alpha,\beta)}\right)$$

1. model and monitor the (double differential) atmospheric flux
2. select the ballistic muons
3. know and calibrate continuously the detector
4. solve (efficiently and accurately) the direct problem

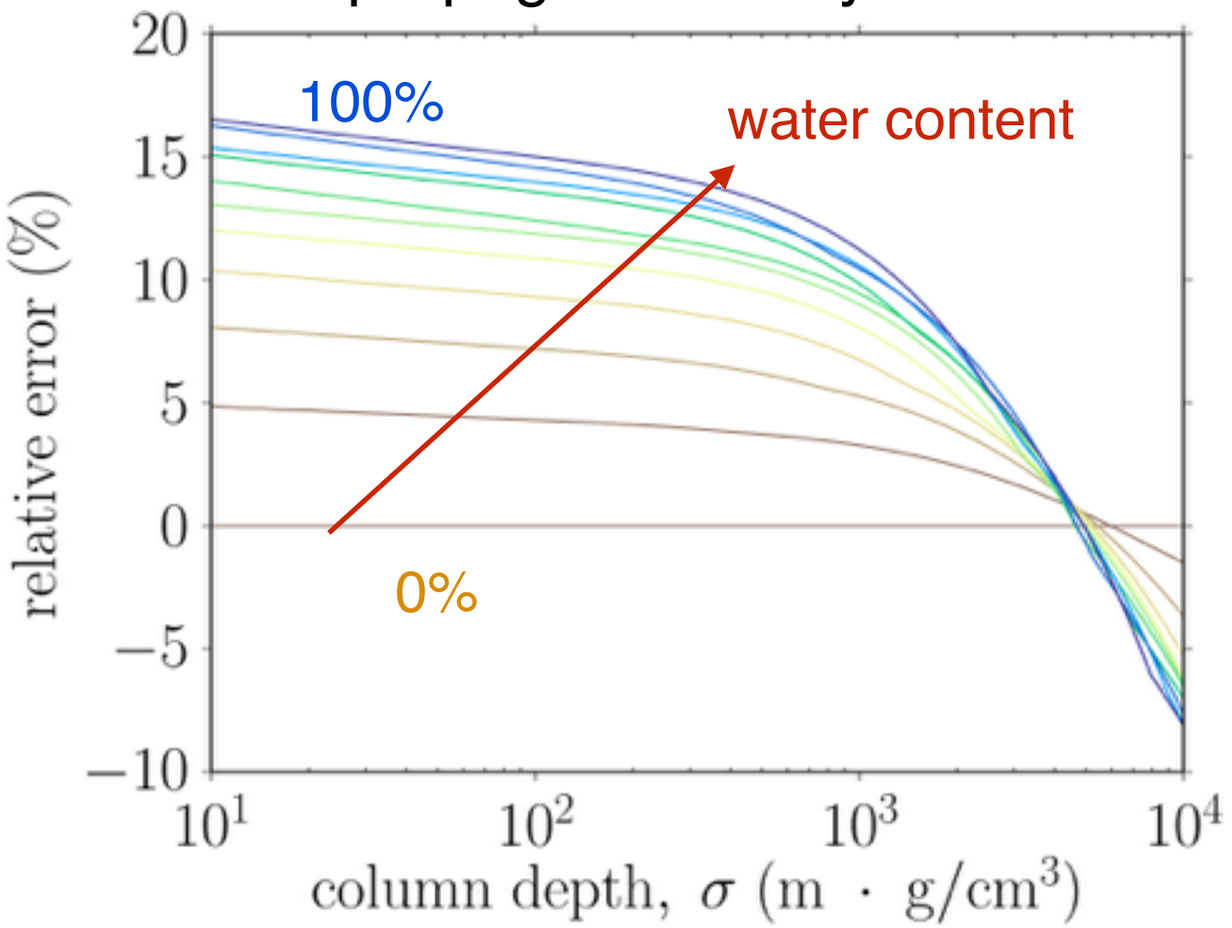
Build a minimisation procedure that tests a full range of integrated densities / rock structural models and selects the one compatible with the measurement

Standard rock approximation & systematic biases

Relative error on integrated density when assuming propagation in standard rock and ignoring the chemical composition



Relative error on integrated density when assuming propagation in dry rock



Clermont Ferrand ...

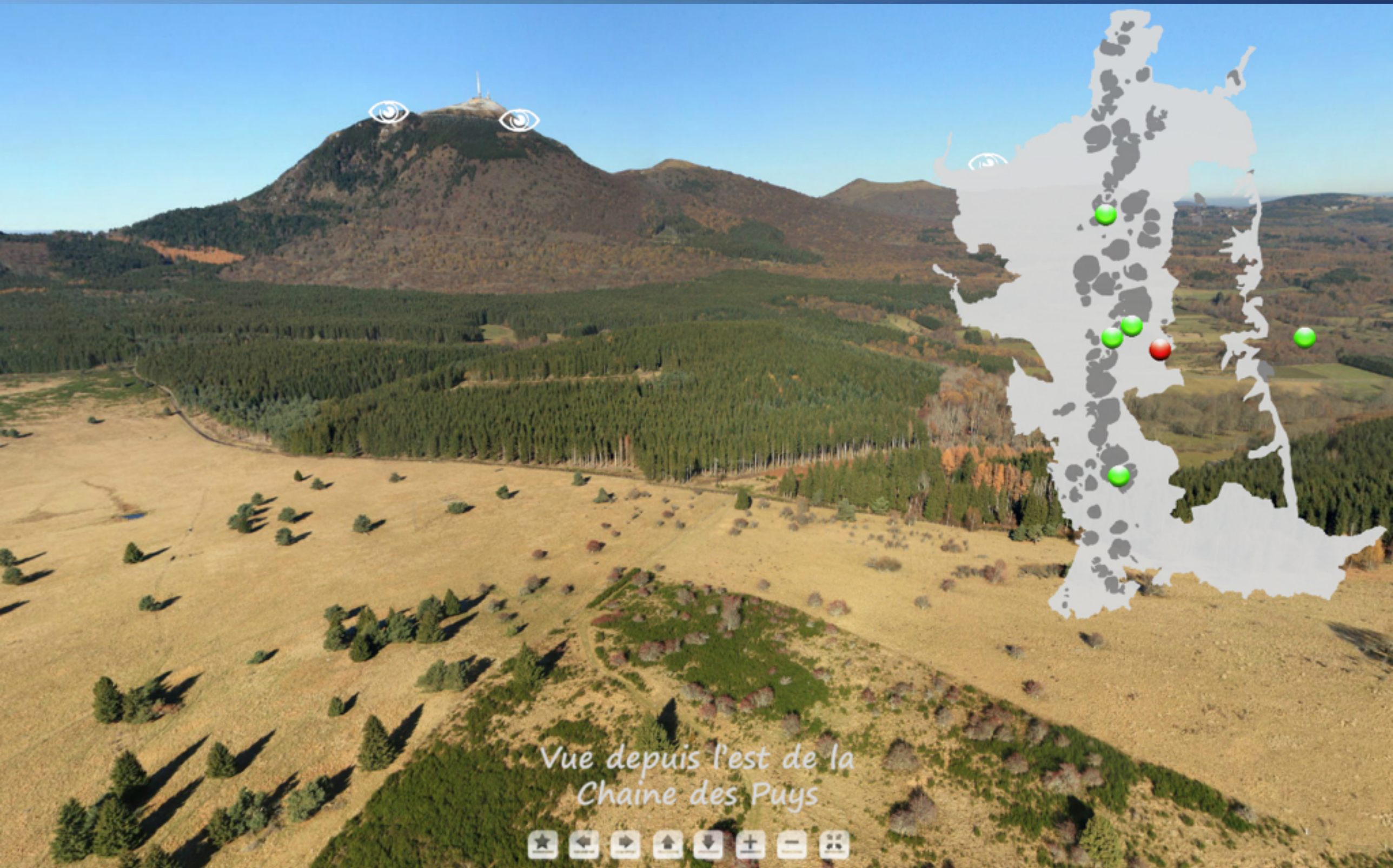
Tectonic arena
Chaîne des Puys and Limagne fault UNESCO WORLD HERITAGE

J'♥ Chaîne des Puys faille de Limagne

40262

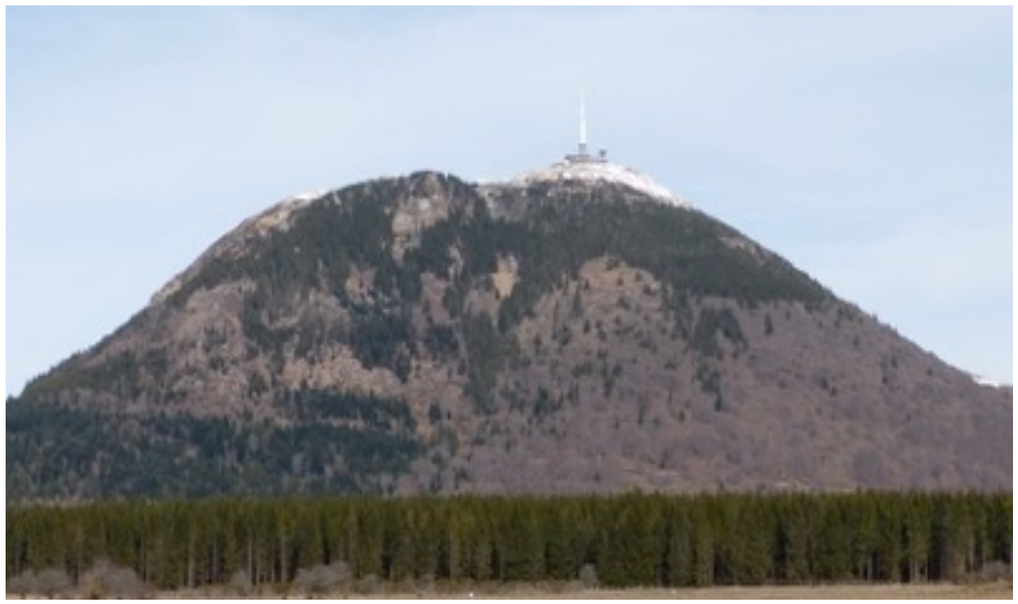
Surname * | First Name * | Postal code *

Email | I support

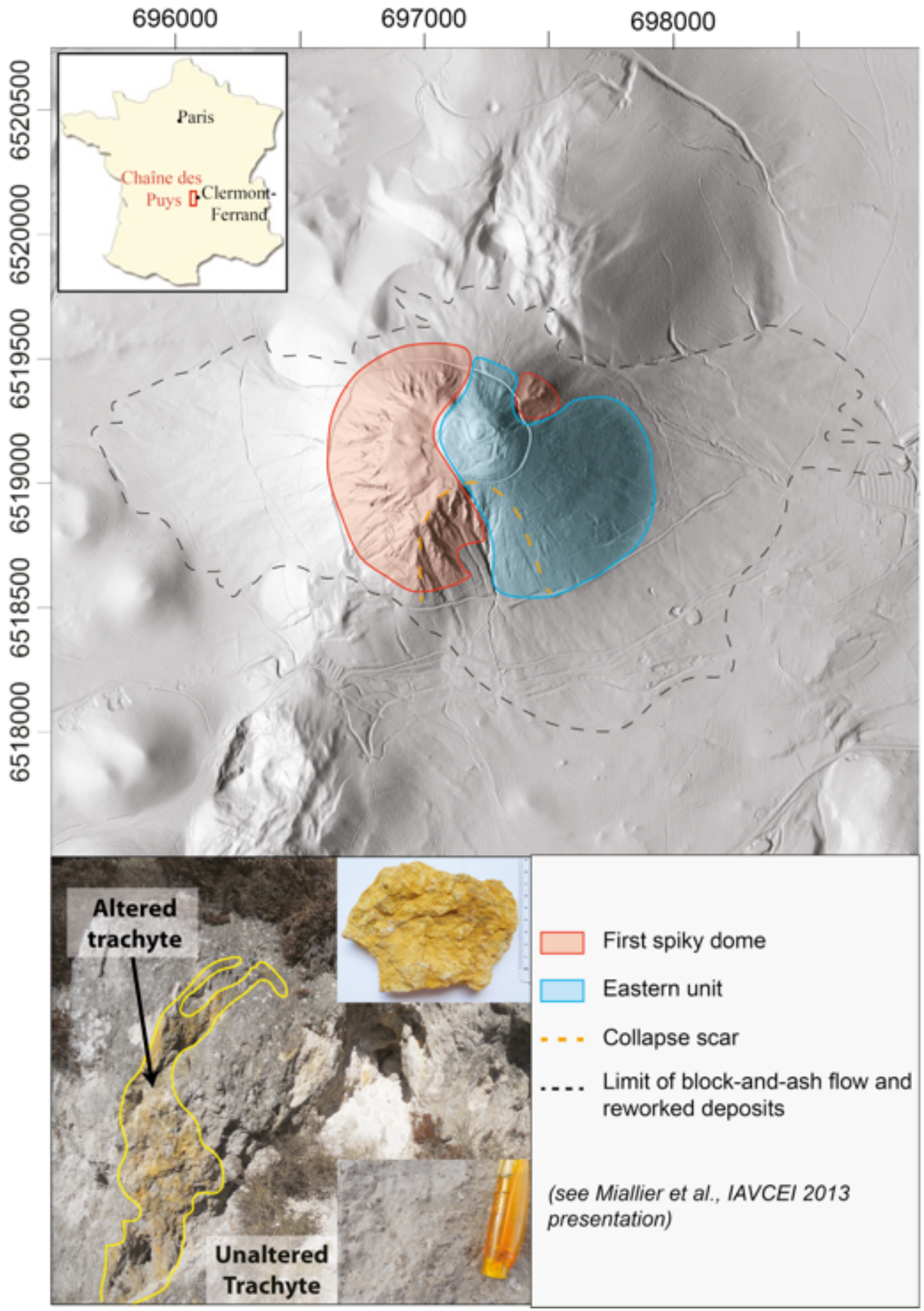


Puy de Dôme Volcano

- 11,000 years old composite dome in the Chaîne des Puys
- Dome characteristics: ~400m high, 1.8 km wide at its base
- Two distinct units:
  - × two lava pulses
  - × partial destruction of the first construction
- Important hydrothermal alteration

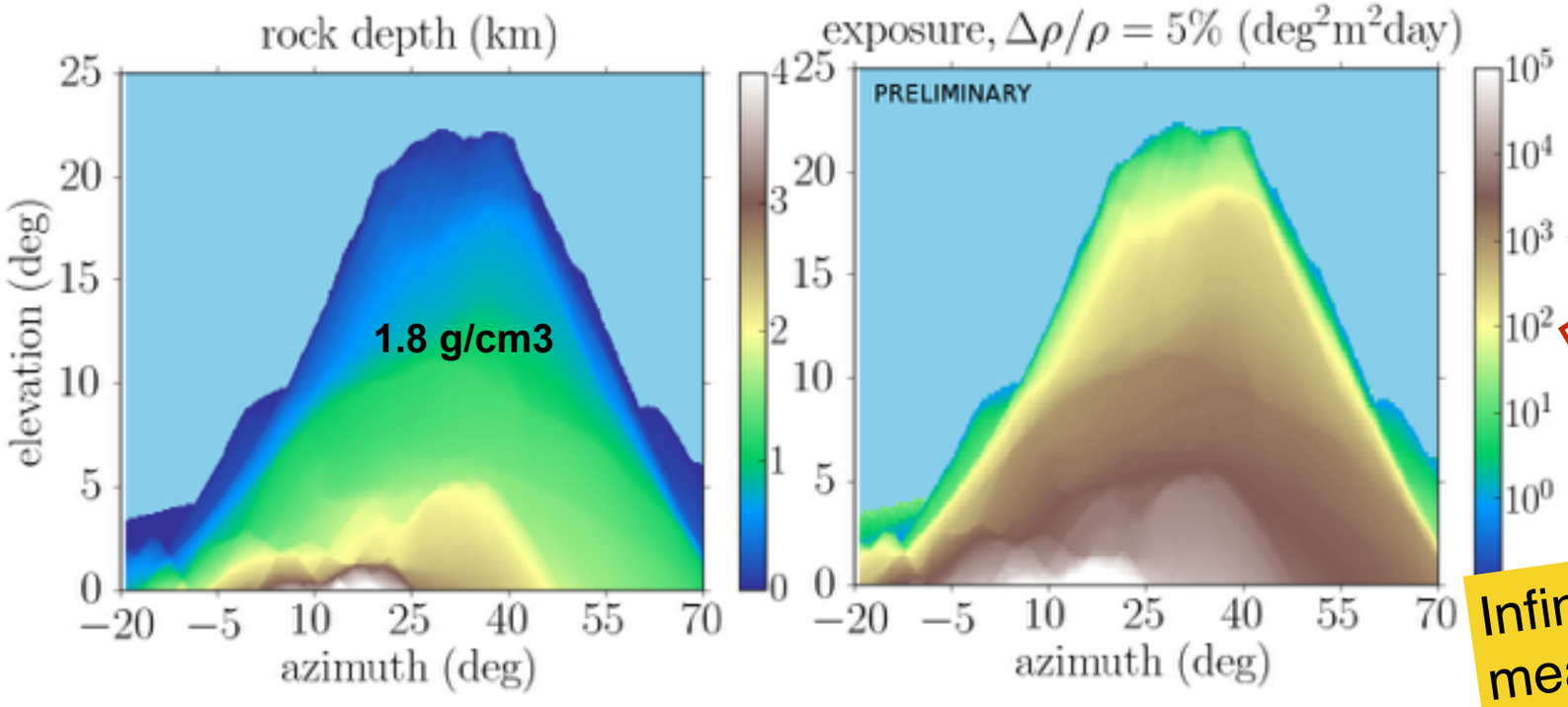


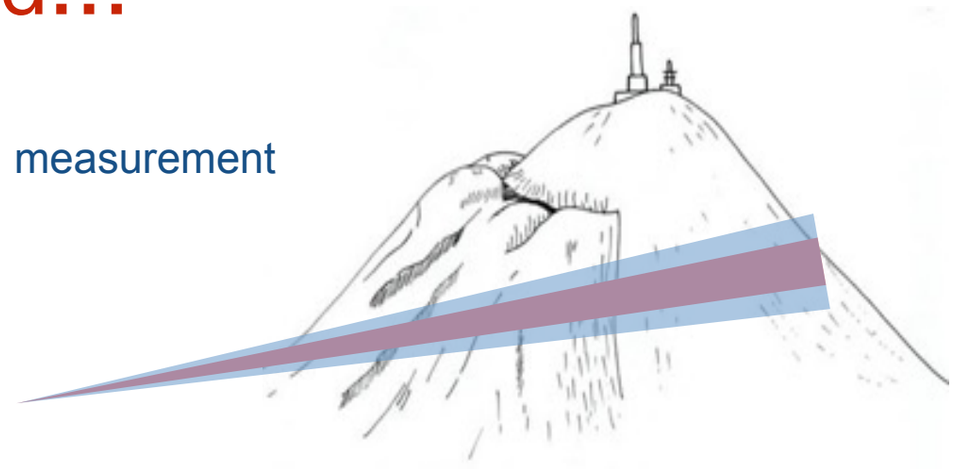
South flank of the Puy de Dôme



What can be theoretically measured...

Exposure ≡ time needed to reach a certain precision on the density measurement
for a given angular resolution and detector size



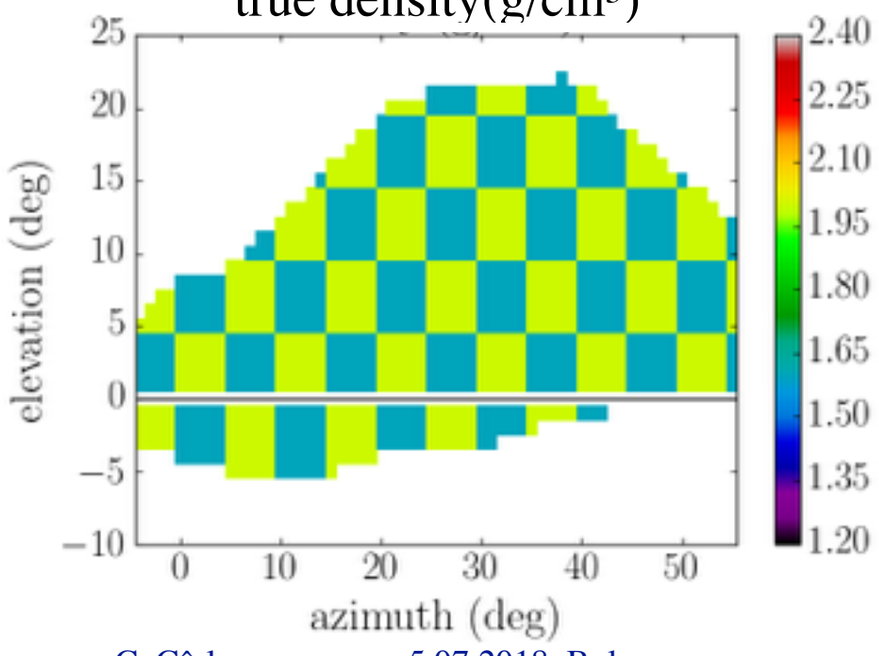


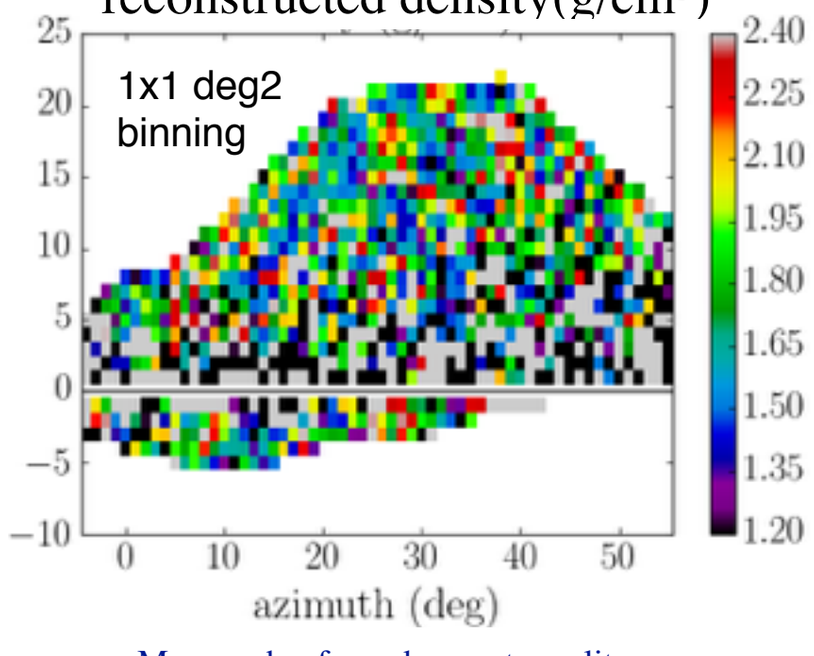
⇦ 10 days (10m² detector, 3ºx3º)

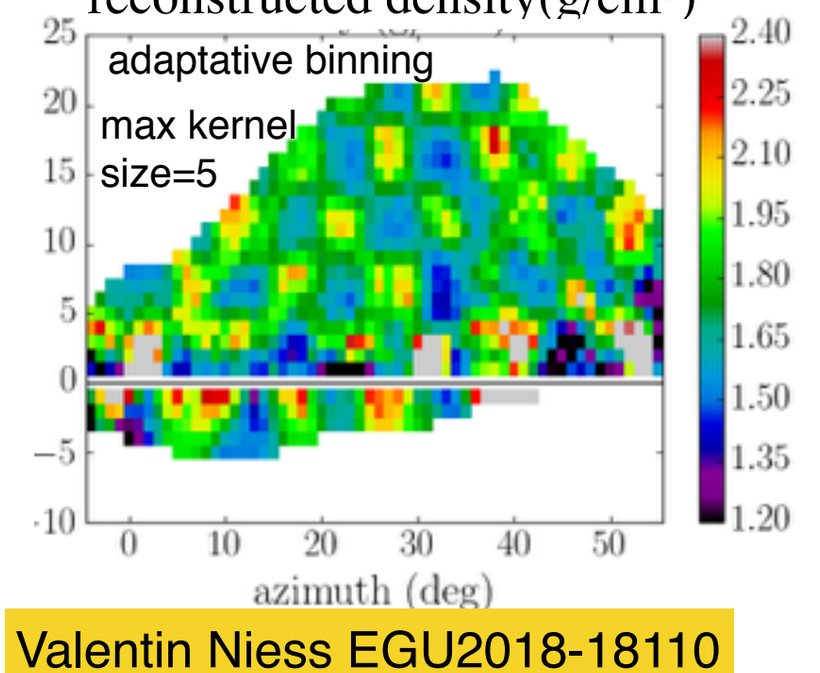
⇦ 10 days (1m² detector, 3ºx3º)

Infinite ways of statistically optimising the measurements and the model testing

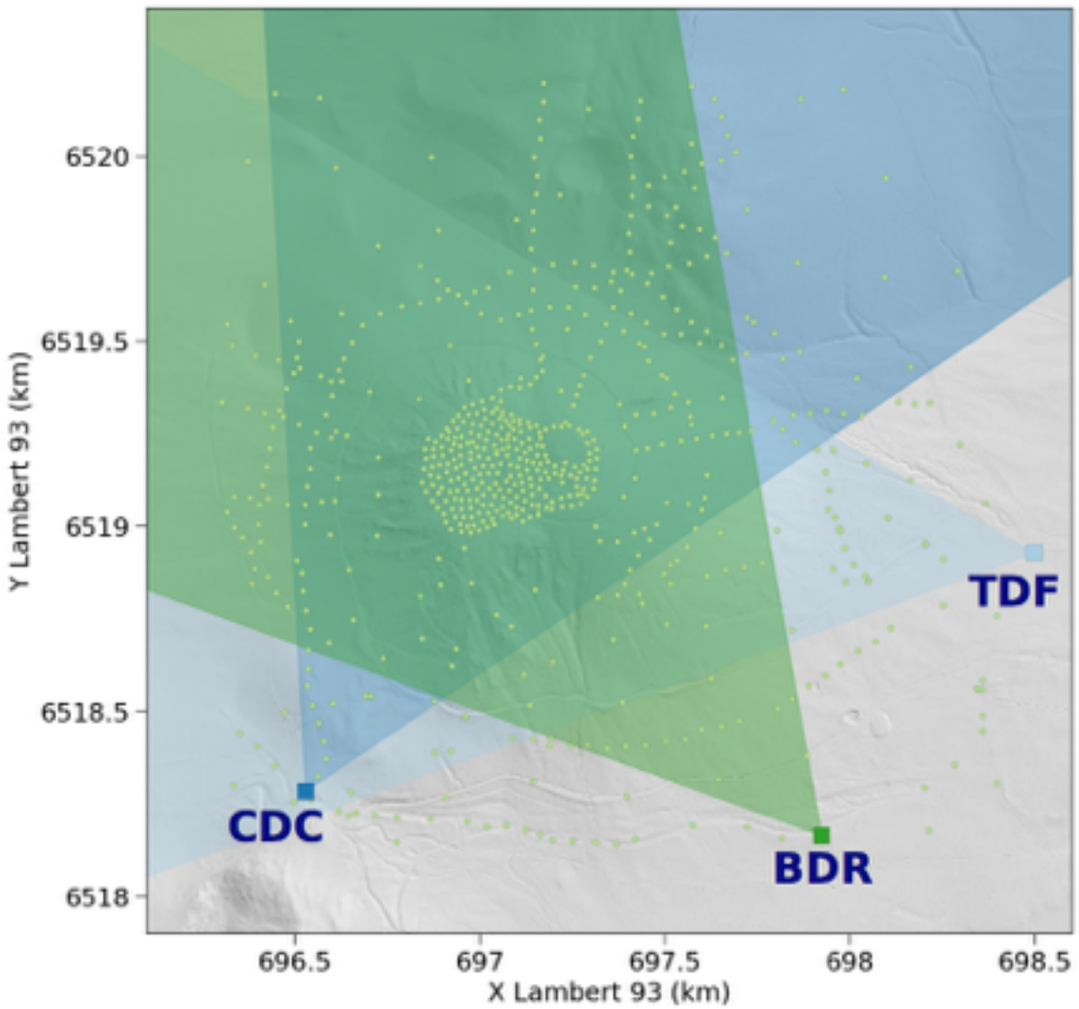
Synthetic model for Puy de Dome and 1 year data with TOMUVOL detector

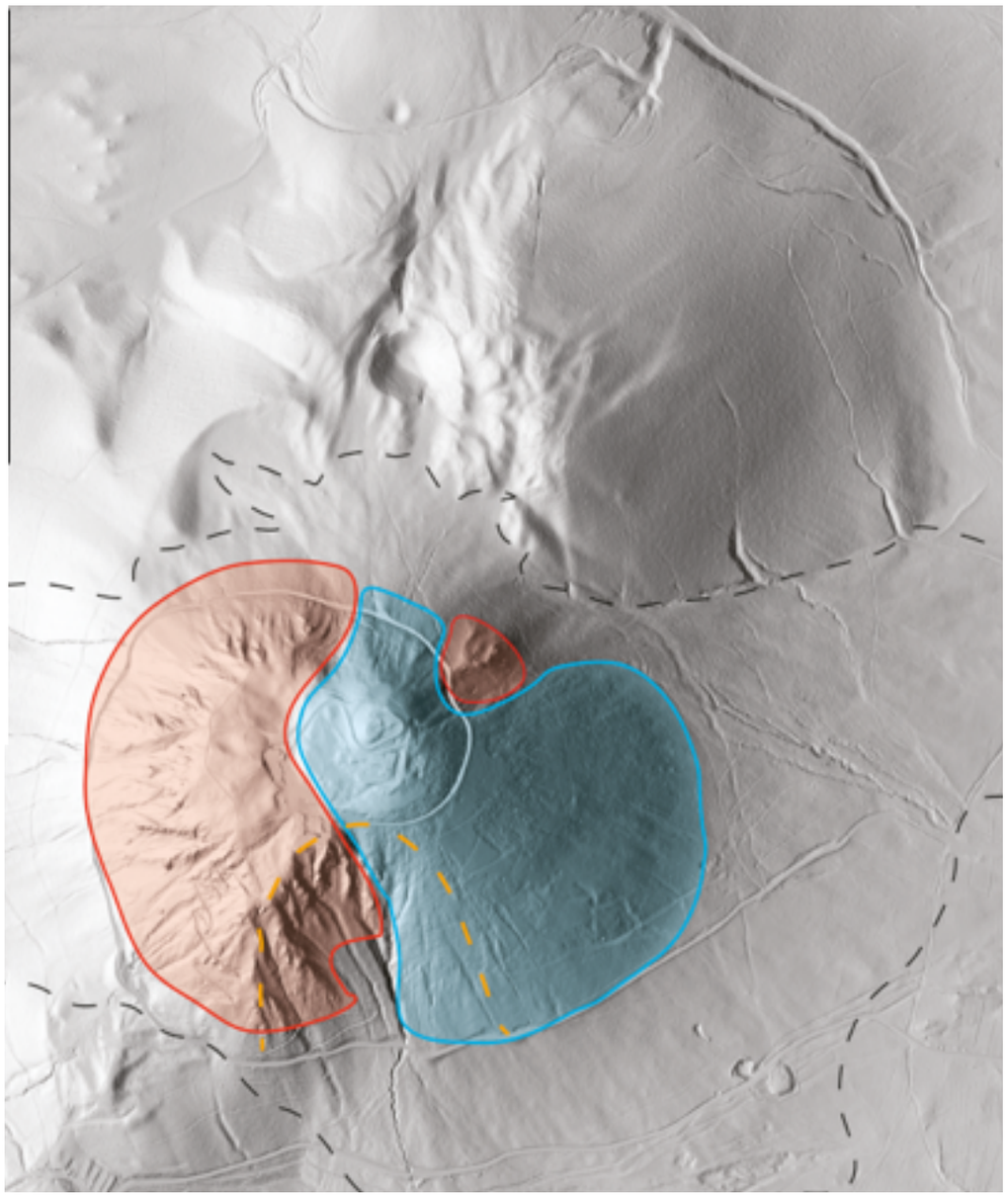




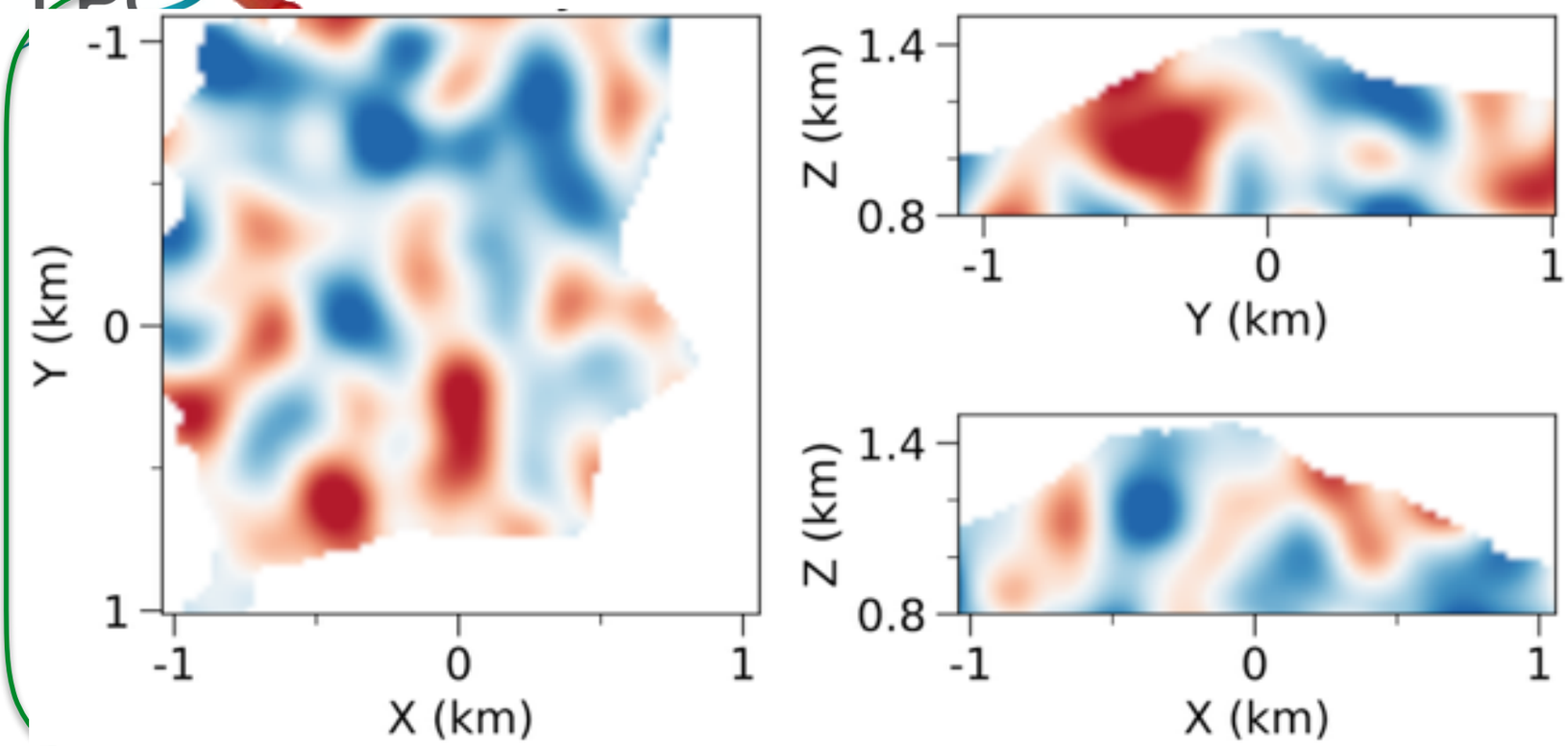


Valentin Niess EGU2018-18110


6520
6519.5
6519
6518.5
6518
Y Lambert 93 (km)
696.5
697
697.5
698
698.5
X Lambert 93 (km)
CDC
TDF
BDR



3D Information from tomographic inversion



Synthetic model of Puy de Dôme

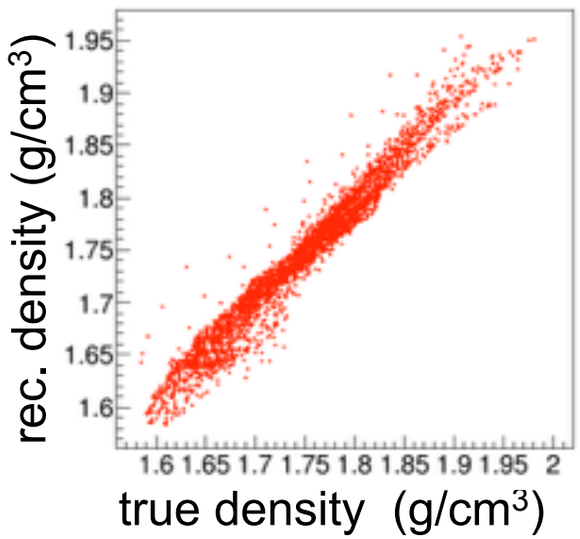
0.5 x 0.5 x 0.5 m^3 voxels

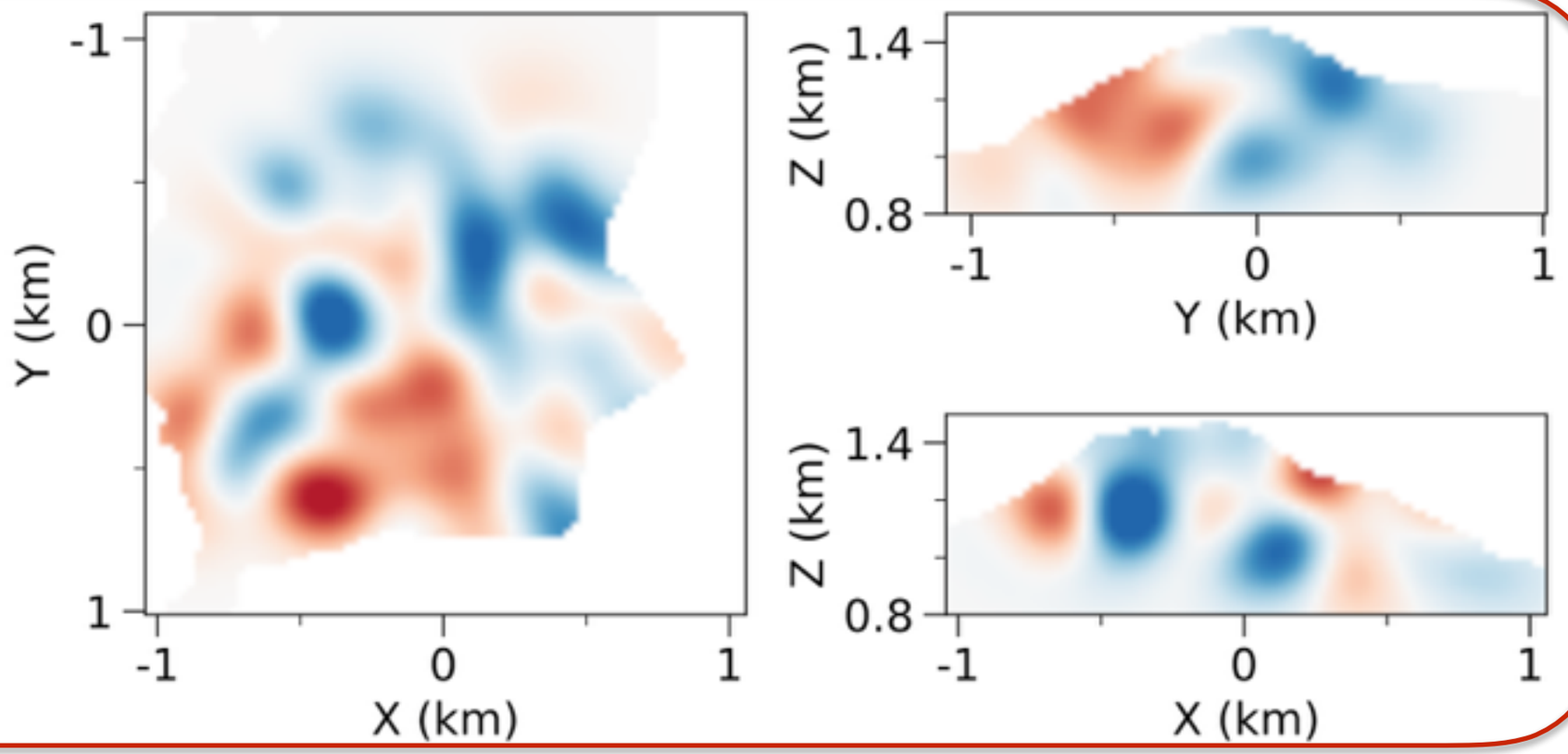
Gaussian random field for densities:

σ_ρ= 100 kg/m^3

Λ = 200 m

One particular choice of inversion with three muographic viewpoints



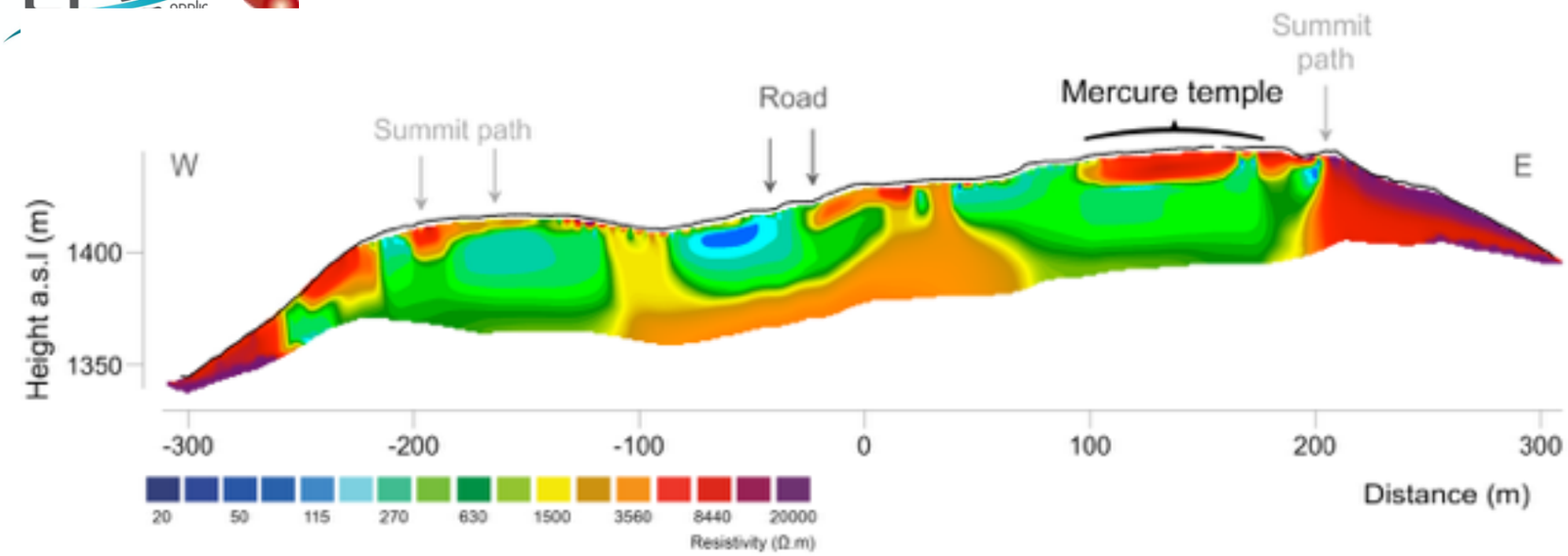


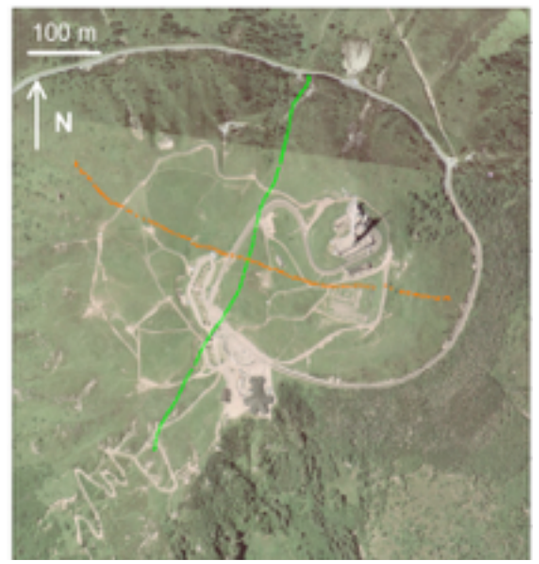
Geophys. methods for volcano imaging: electrical resistivity

Vulcano, Stromboli (Iles Eoliennes; Italie)

Finizola et al., GRL (2006, 2009); Revil et al., JGR (2008)

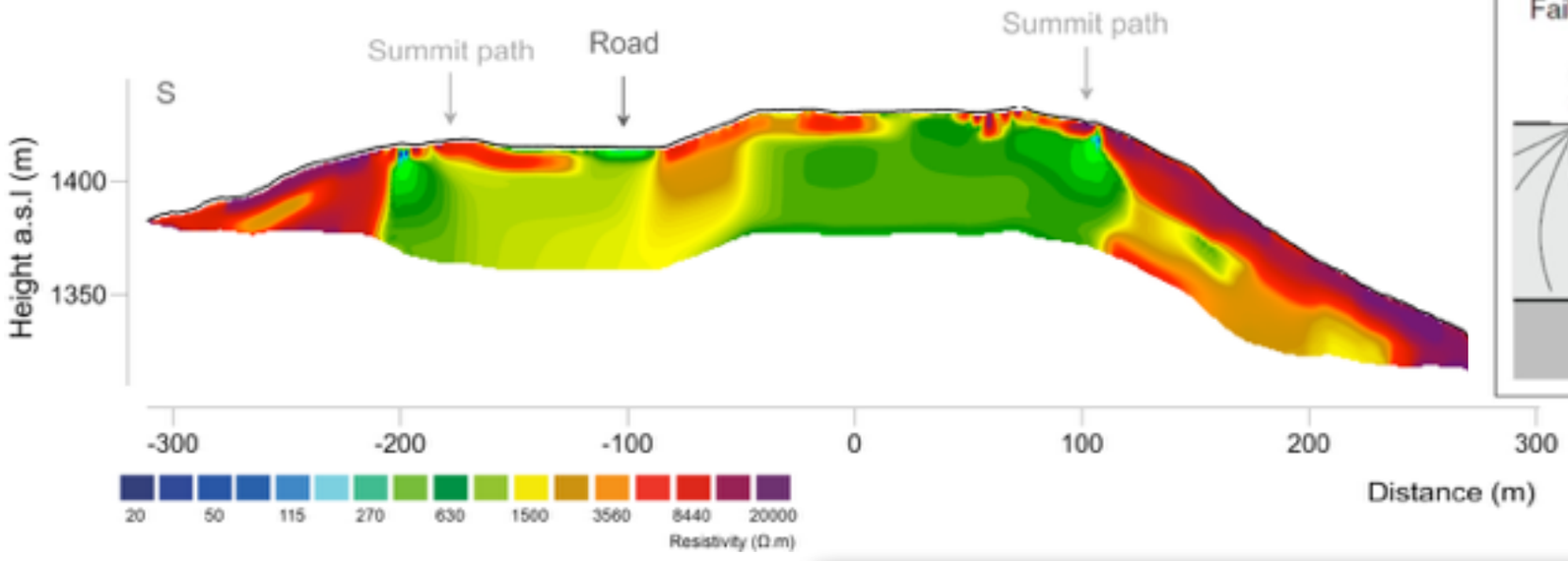
Electrical resistivity of Puy de Dôme

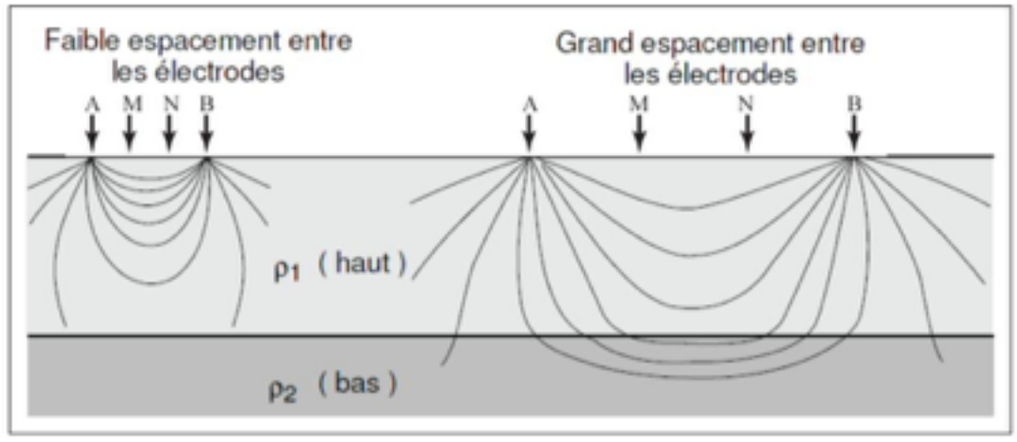




Anthropic structures

Erreur rms 7.3%





Erreur rms 6.8%

Computed with Res2DInv *(Loke, 2011)*

Seismic and electrical tomography rely on curved paths

⇓

non-linear inverse problem

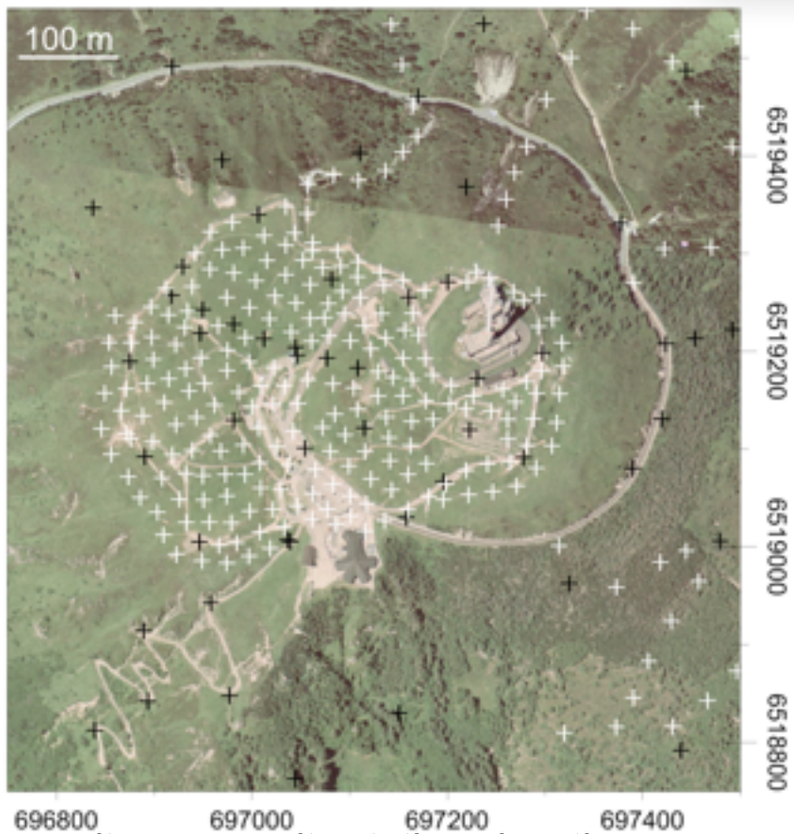
Geophys. methods for volcano imaging: micro-gravimetry

- 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

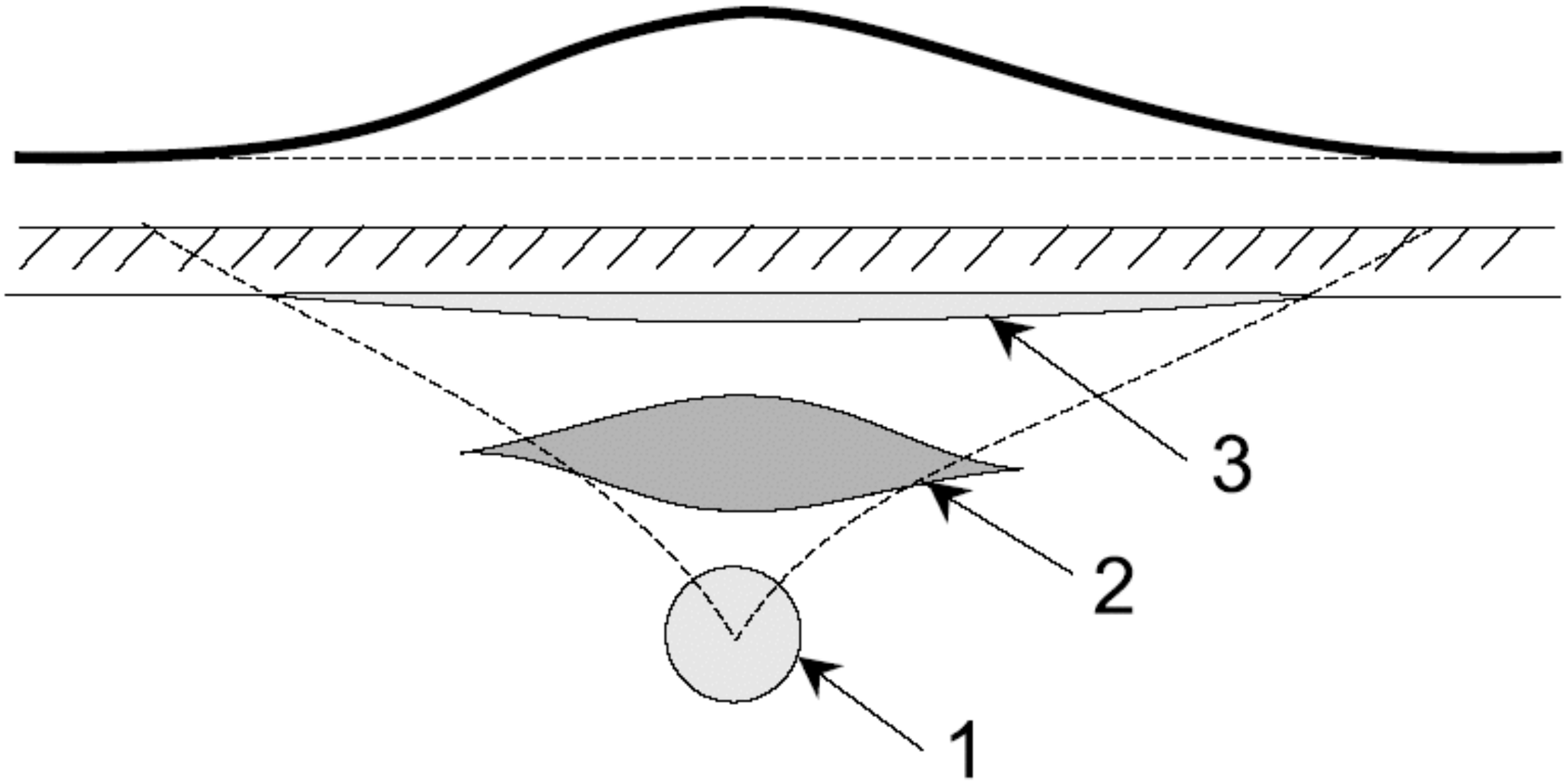
GPS and Scintrex CG5 gravimeter

Gravity stations location for the total survey



Summit area gravity stations location

Inverse problem in gravimetry



Micro-gravimetry 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

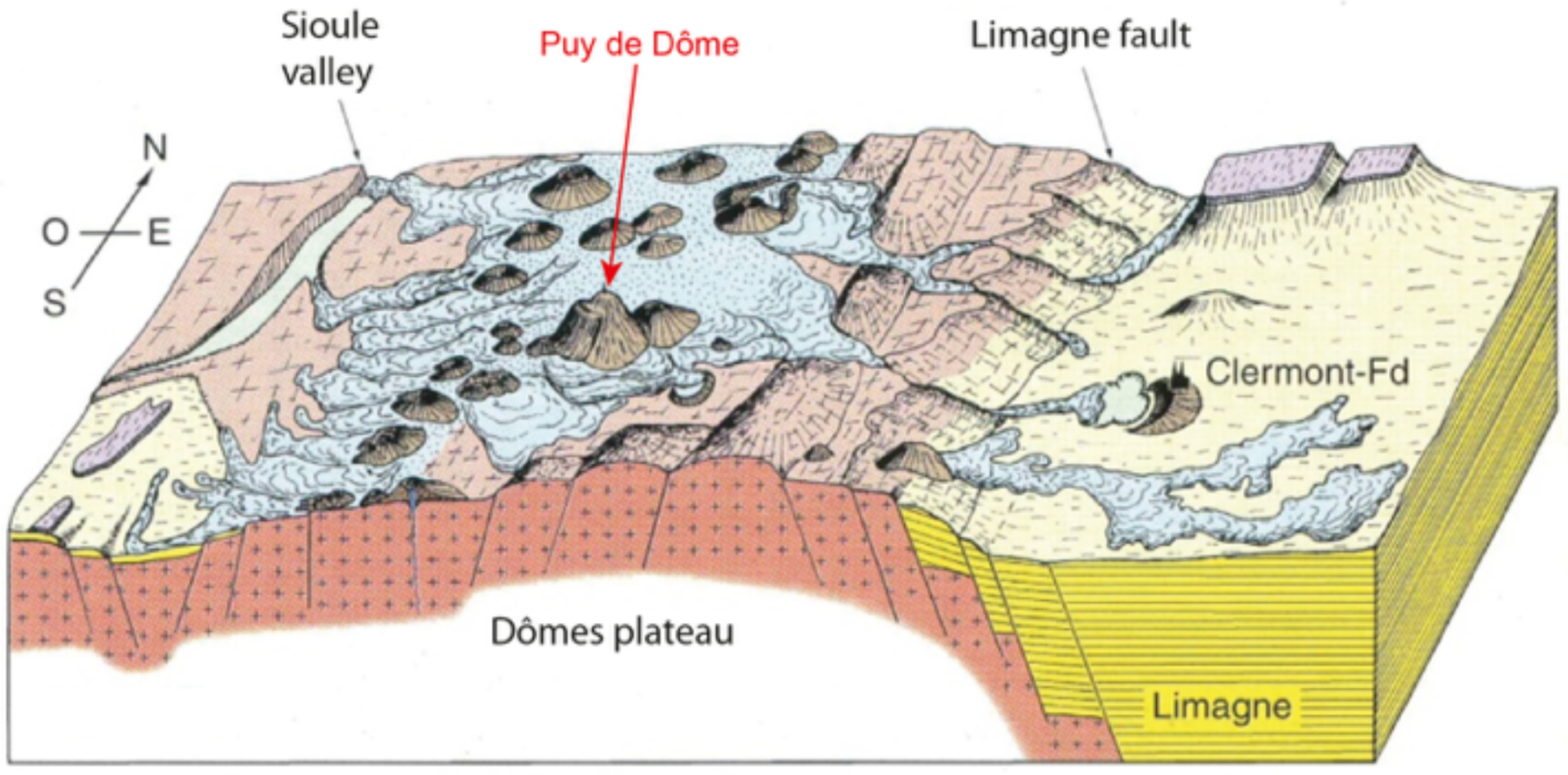


Figure Boivin and al., 2004

… and the real life complexity

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

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

Measurement = $_{\text{Signal}}$ + **Background**

Only known after dedicated measurements and detailed Monte Carlo simulations

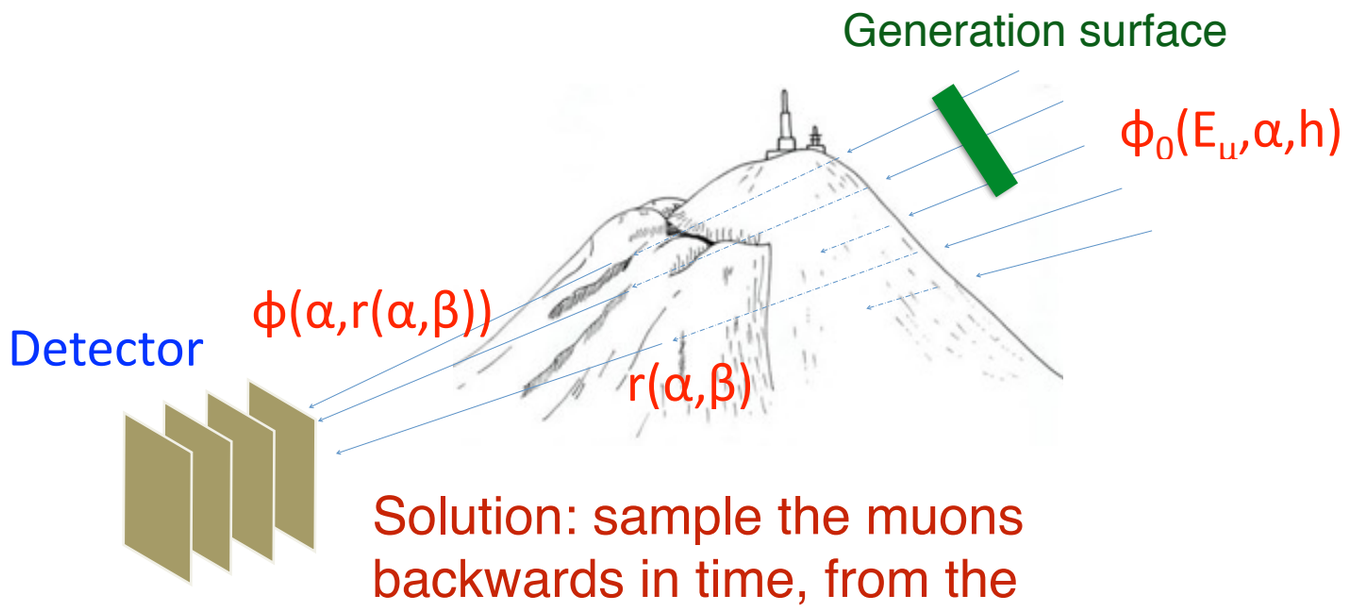
Can be calculated beforehand analytically (approximatelly)

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

Ambrosino, F., et al. (2015), Joint measurement of the atmospheric muon flux through the Puy de Dôme volcano with plastic scintillators and Resistive Plate Chambers detectors, J. Geophys. Res. Solid Earth, 120

Backward Monte Carlo



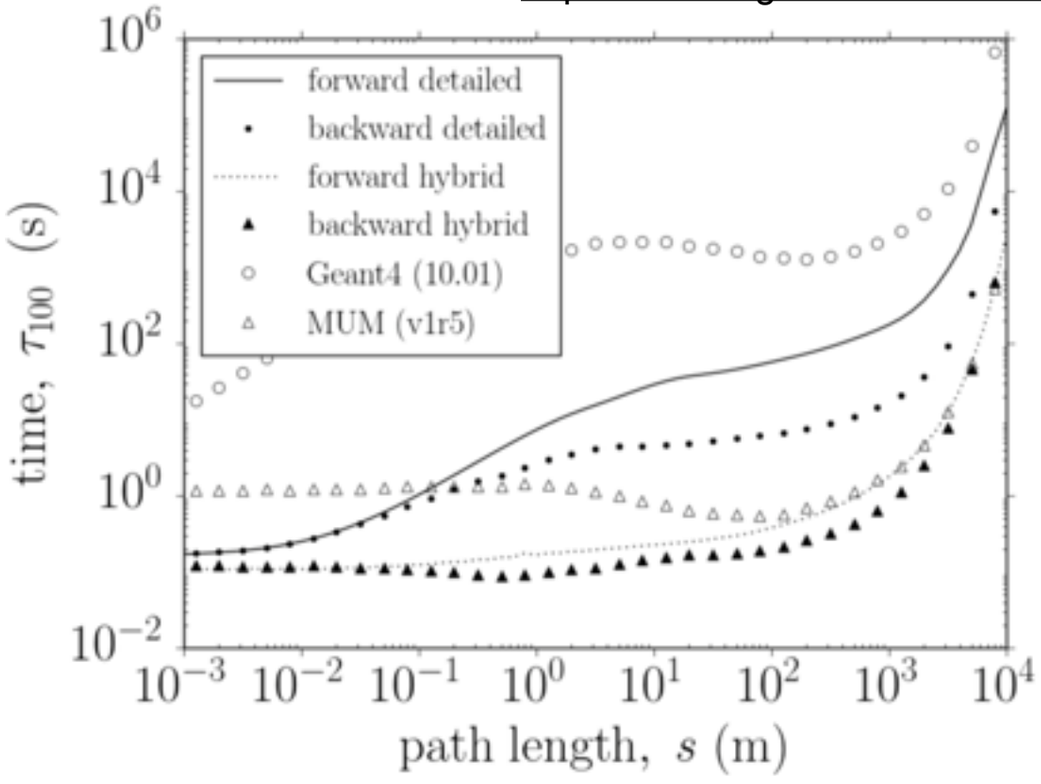
Solution: sample the muons backwards in time, from the detector to the atmosphere

Backward Monte Carlo applied to muon transport, CPC, https://arxiv.org/abs/1705.05636

https://authors.elsevier.com/c/1X8CY2OInW2z5

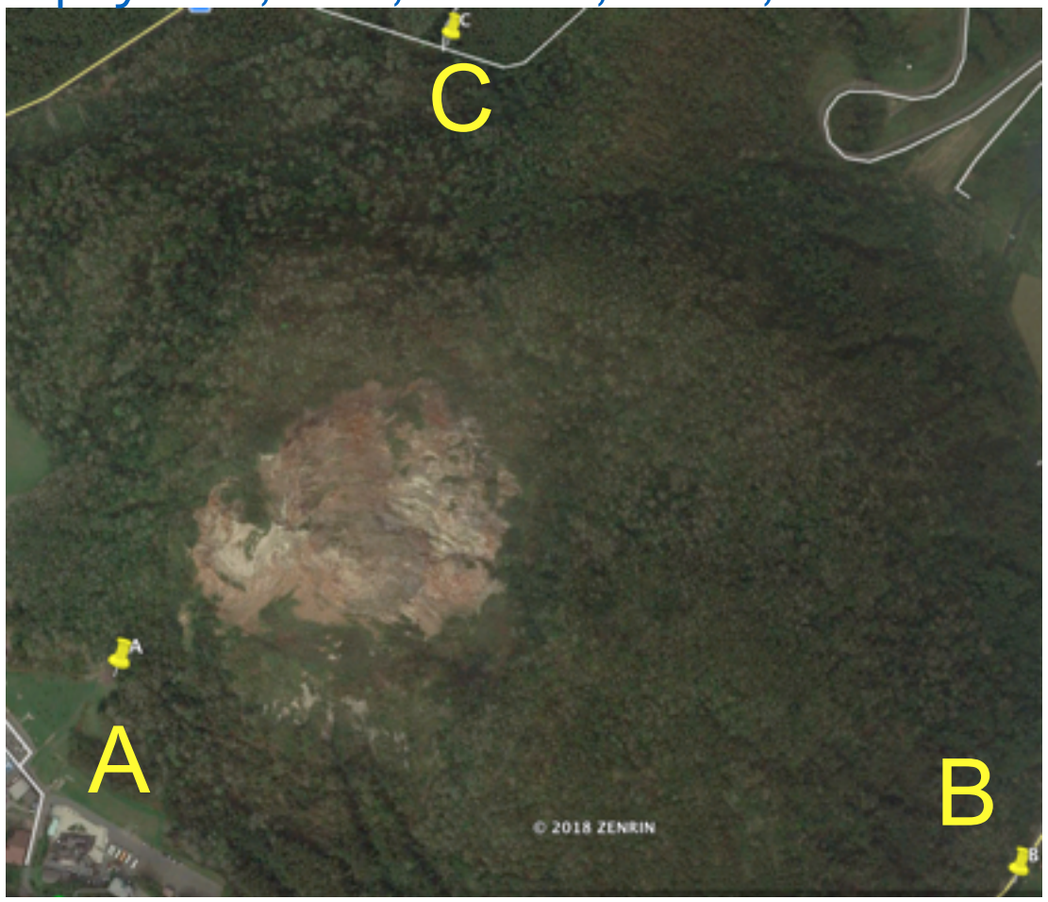
CPU time needed to simulate the transmitted flux with 1% accuracy

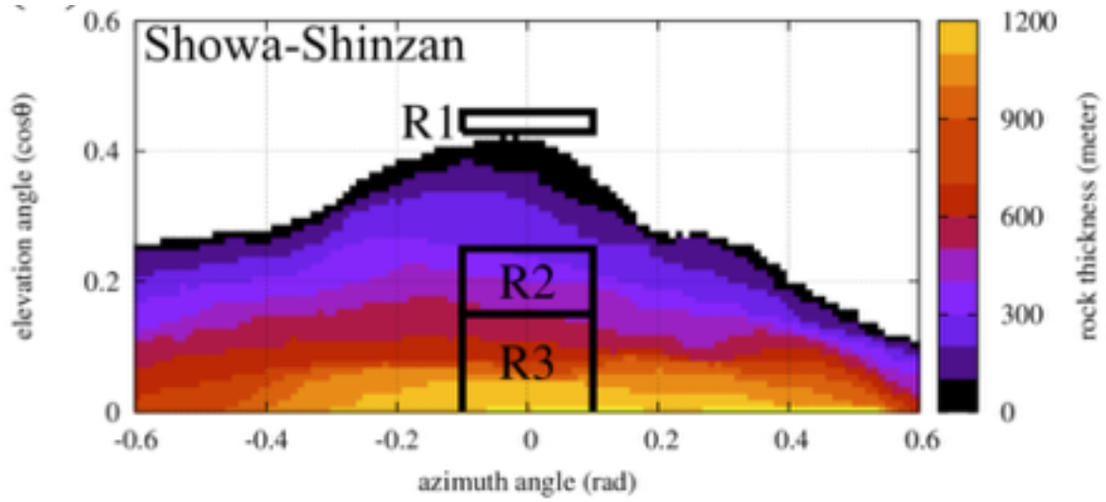
https://arxiv.org/abs/1705.05636

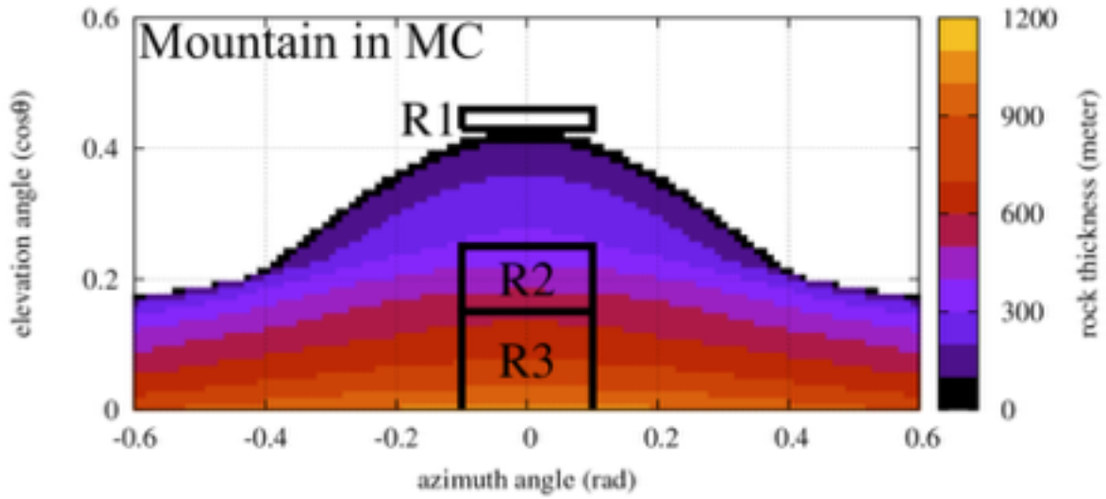


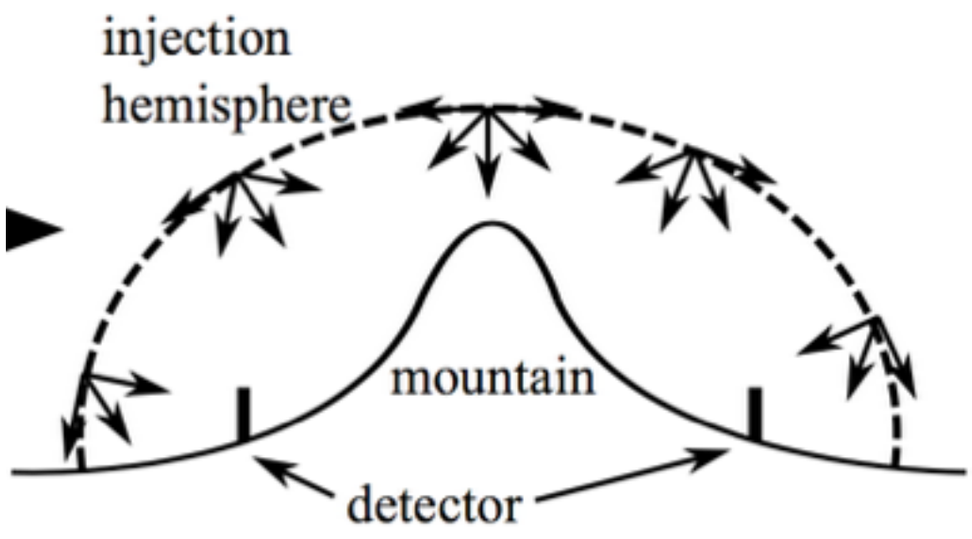
Showa Shinzan Volcano

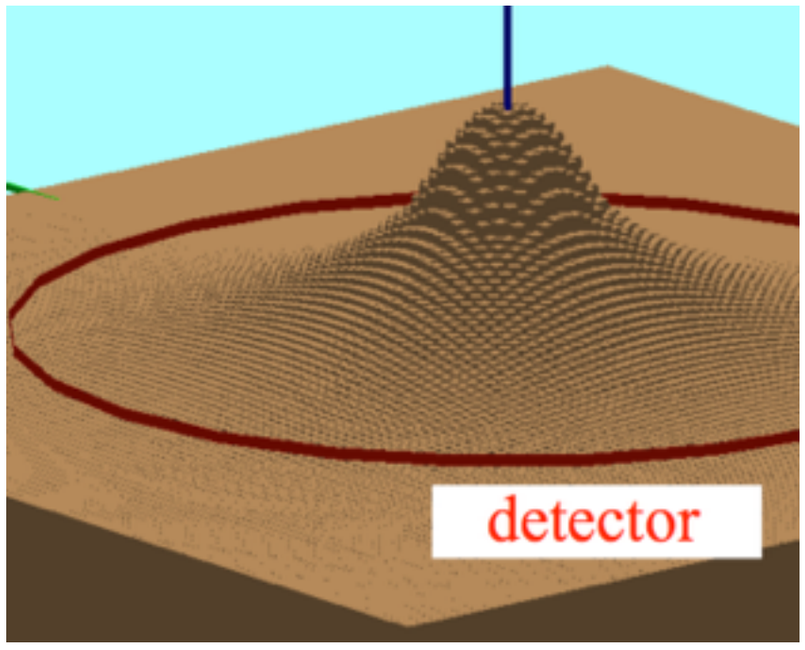
Nishiyama et al,
GeophysJInt, 206, Issue 2, 2016, 1039–1050,



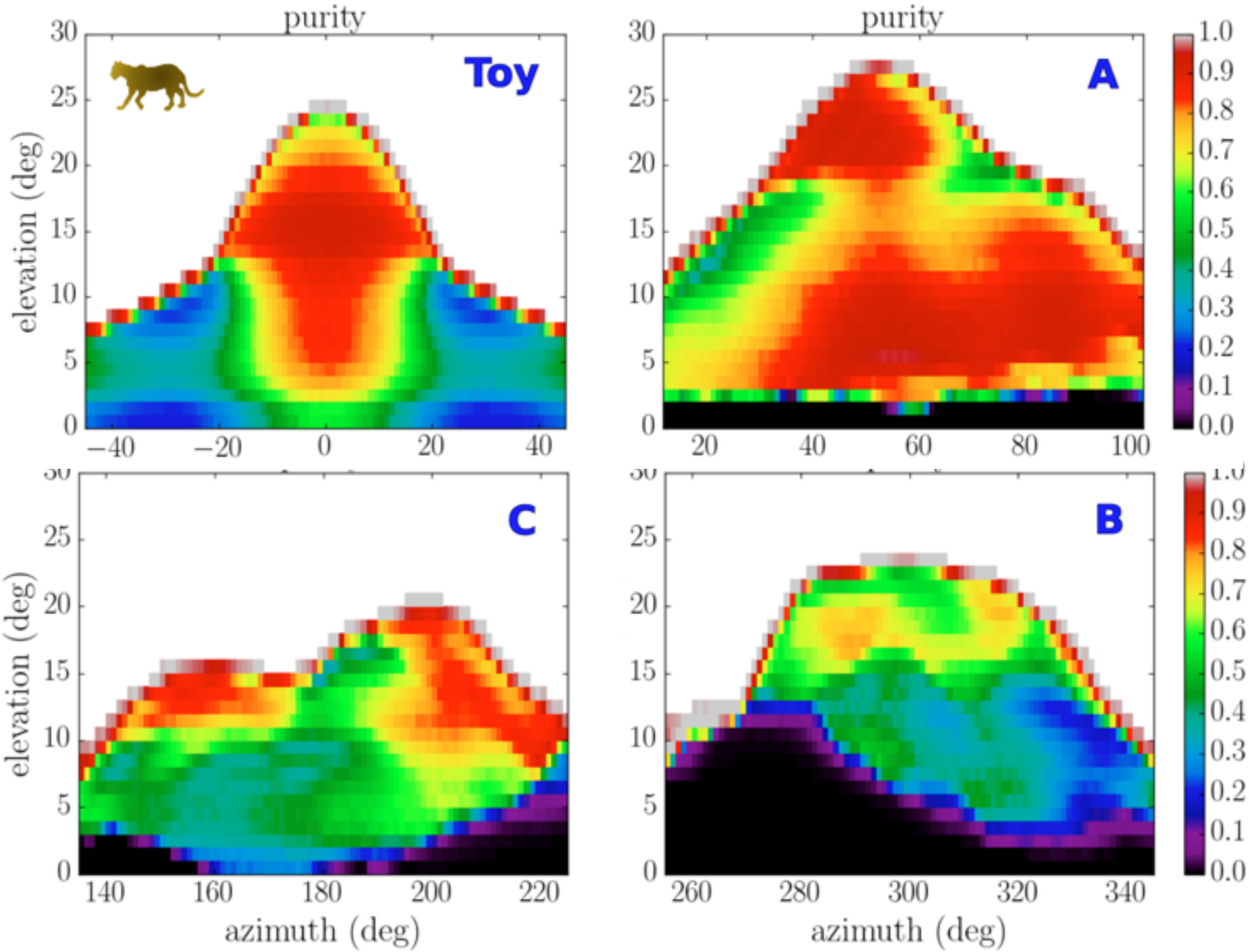




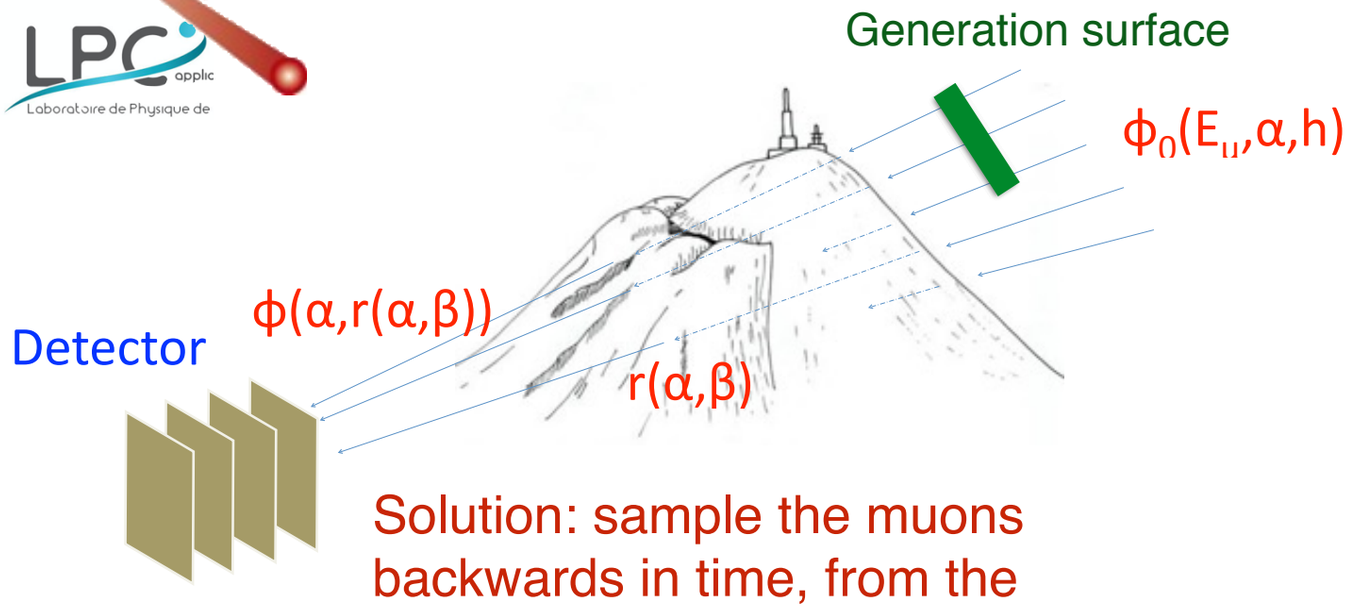




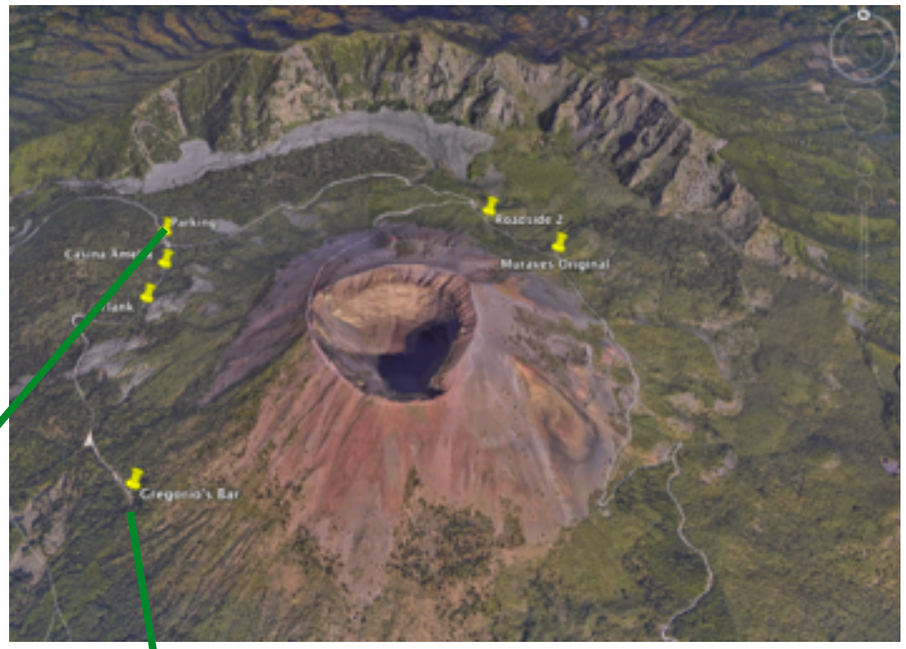
Showa Shinzan Volcano

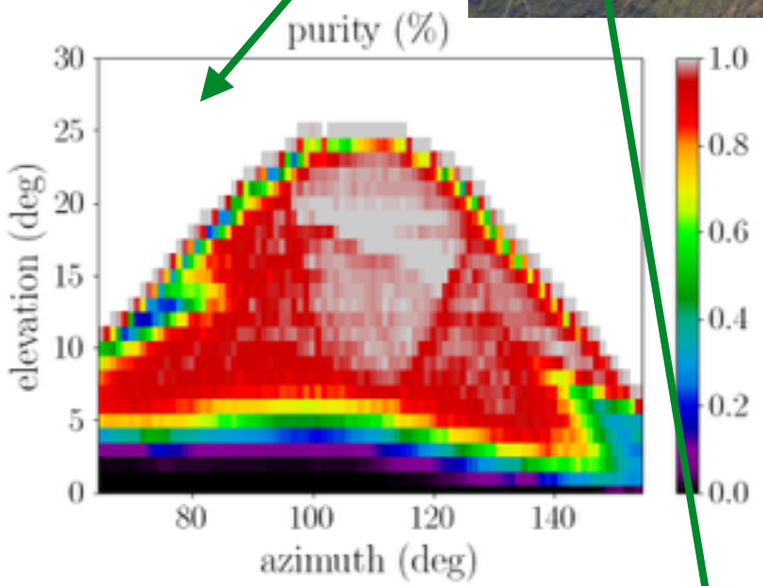


Backward Monte Carlo



Solution: sample the muons backwards in time, from the detector to the atmosphere

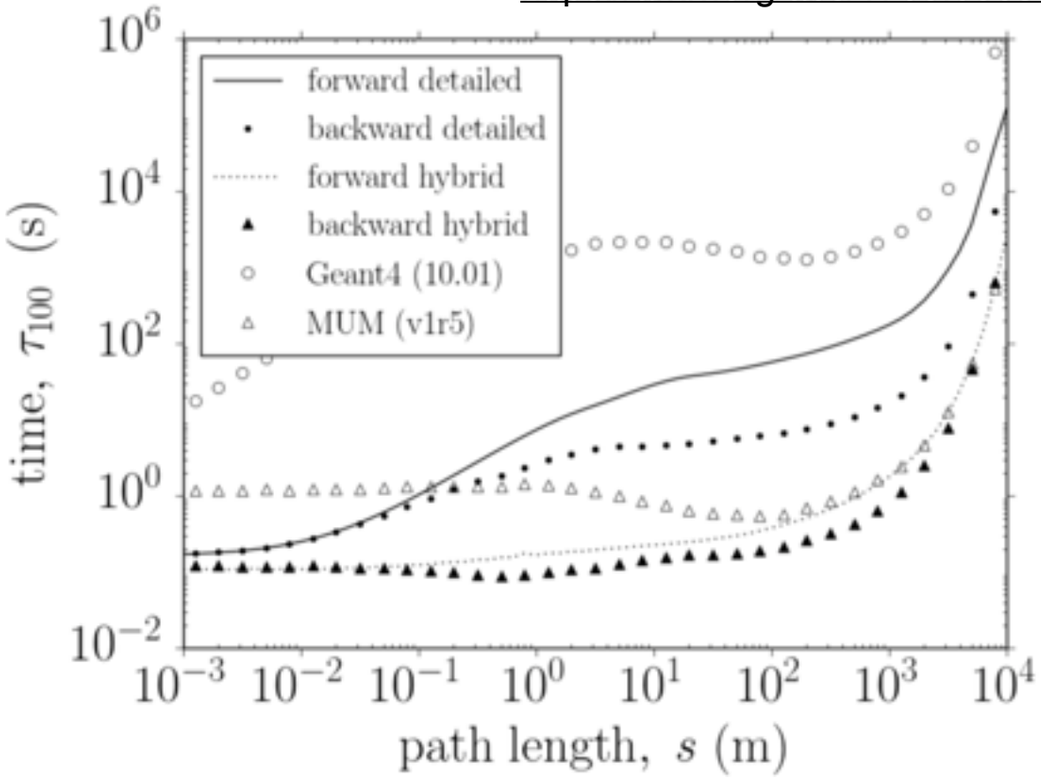


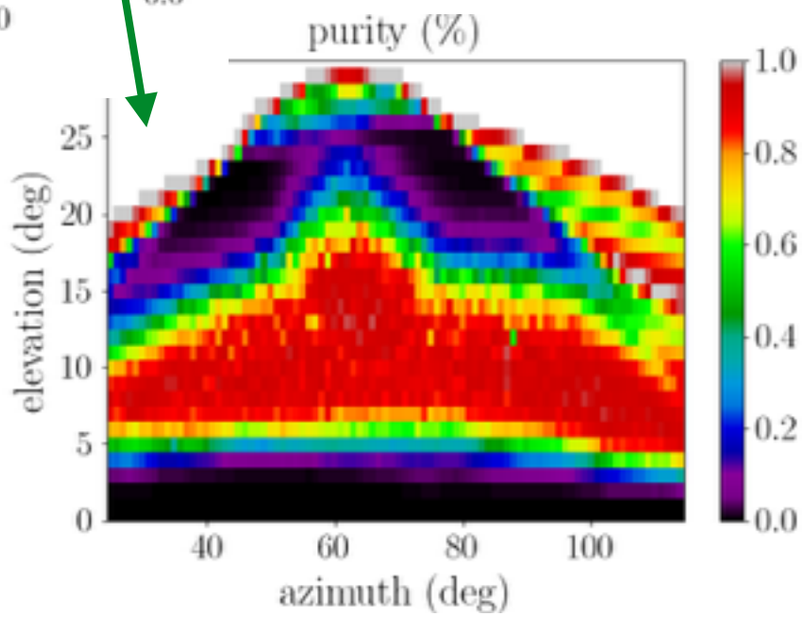


1 GeV/c threshold for detecting the muons

CPU time needed to simulate the transmitted flux with 1% accuracy

https://arxiv.org/abs/1705.05636





TOMUVOL Collaboration

Laboratoire de Physique de Clermont

Observatoire de Physique du Globe de Clermont-Ferrand

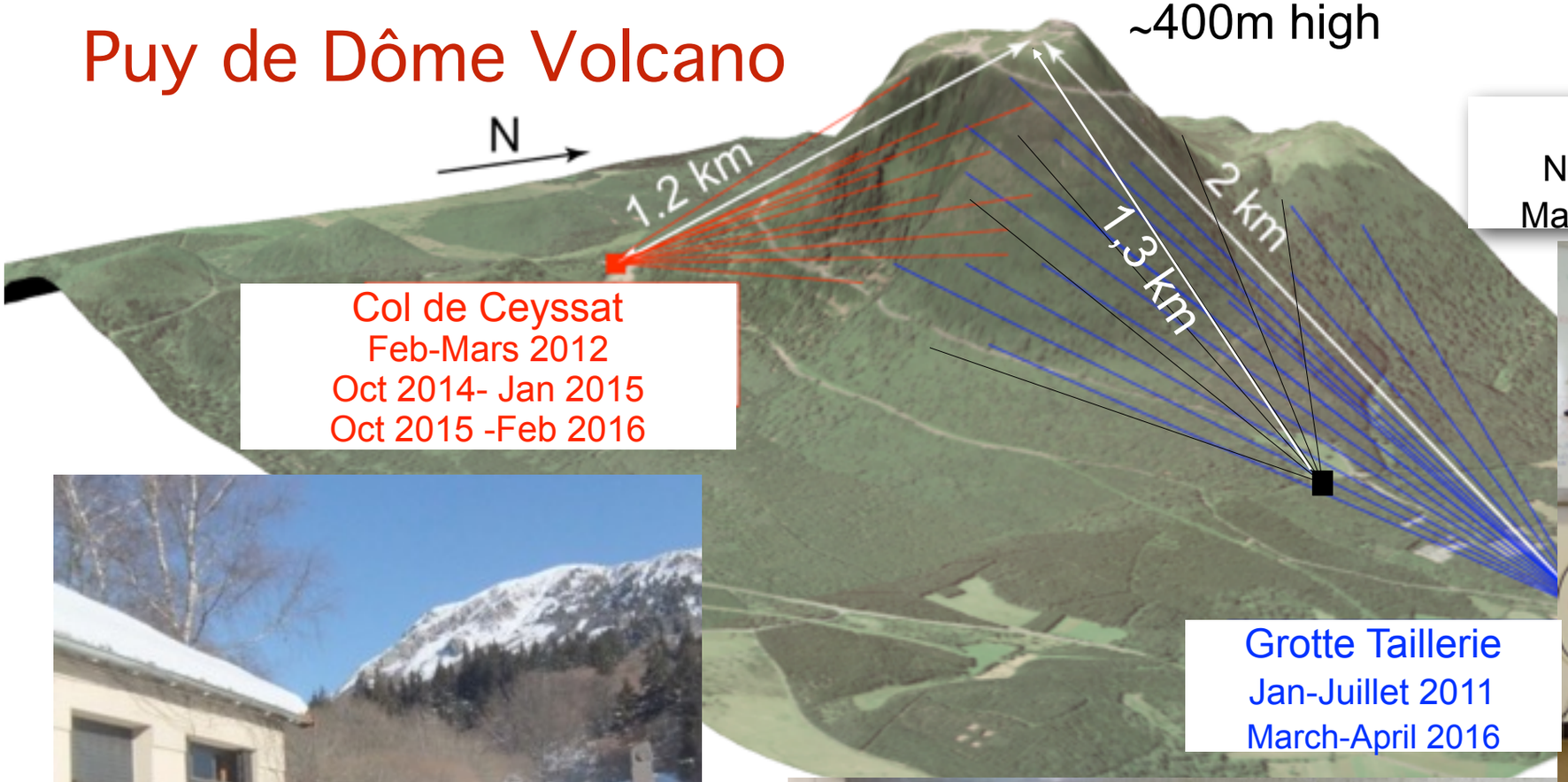
Laboratoire Magmas et Volcans

Institute of Nuclear Physics of Lyon

Proof of Principle for Muographic Imaging of Volcanoes

Puy de Dôme Volcano

~400m high

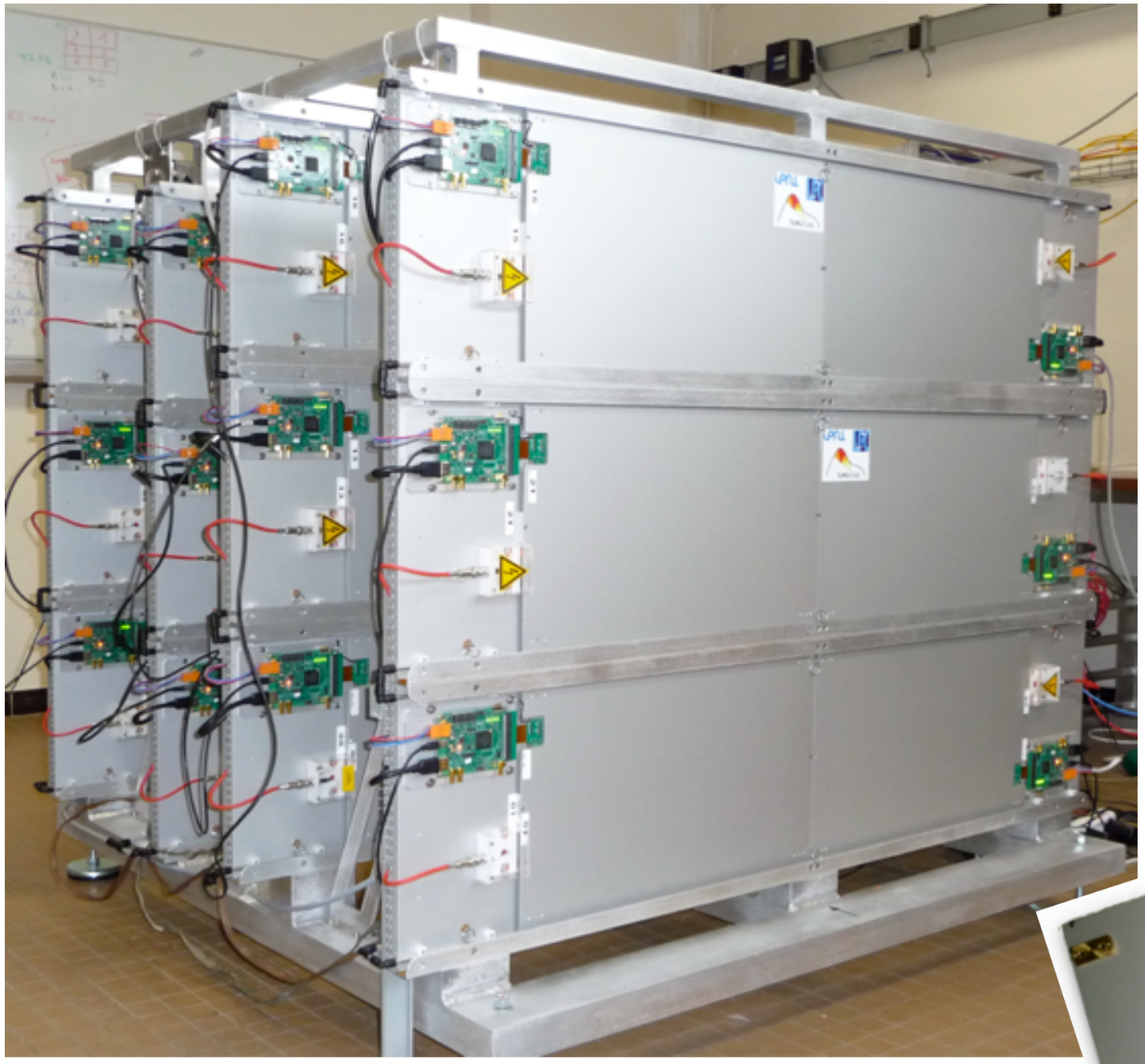


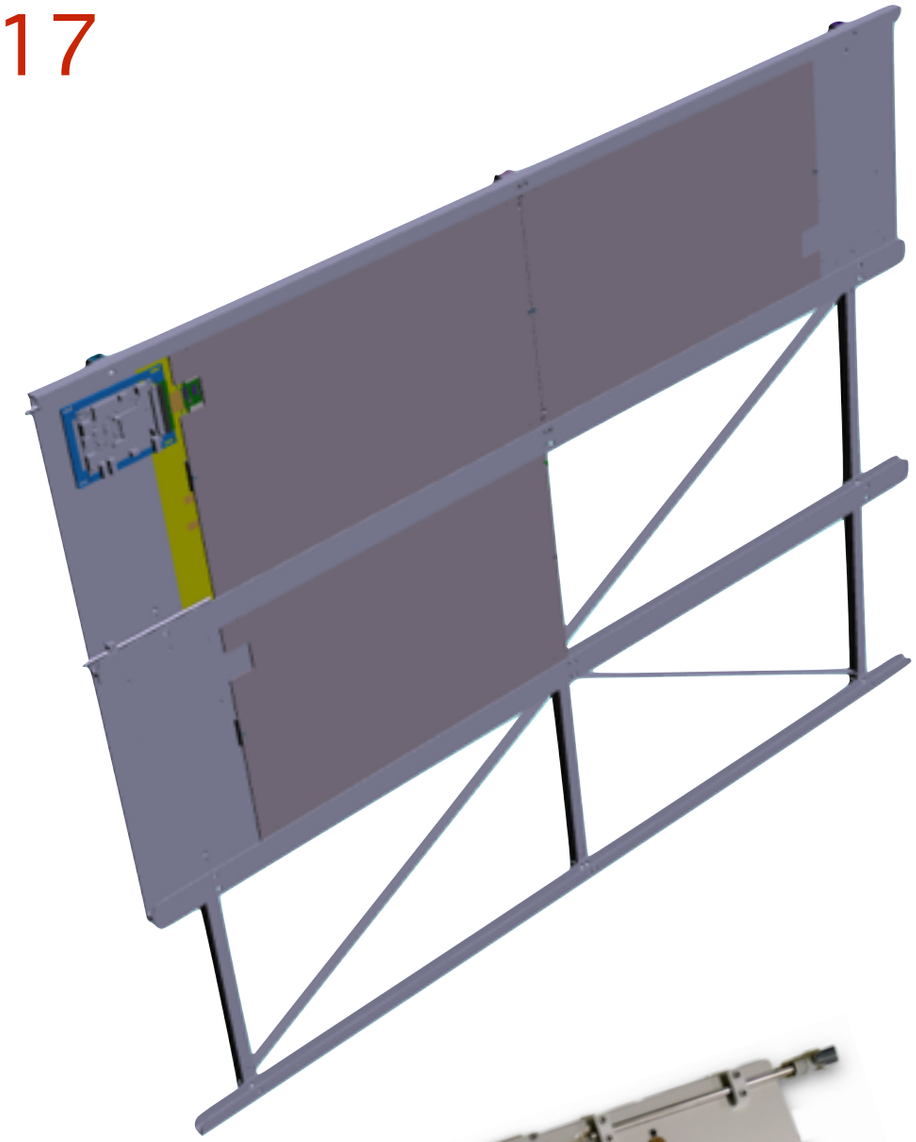
Col de Ceyssat
Feb-Mars 2012
Oct 2014- Jan 2015
Oct 2015 -Feb 2016

Site TDF
Nov-Dec 2013
March-April 2013

Grotte Taillerie
Jan-Juillet 2011
March-April 2016

TOMUVOL Telescope @ 2013-2017

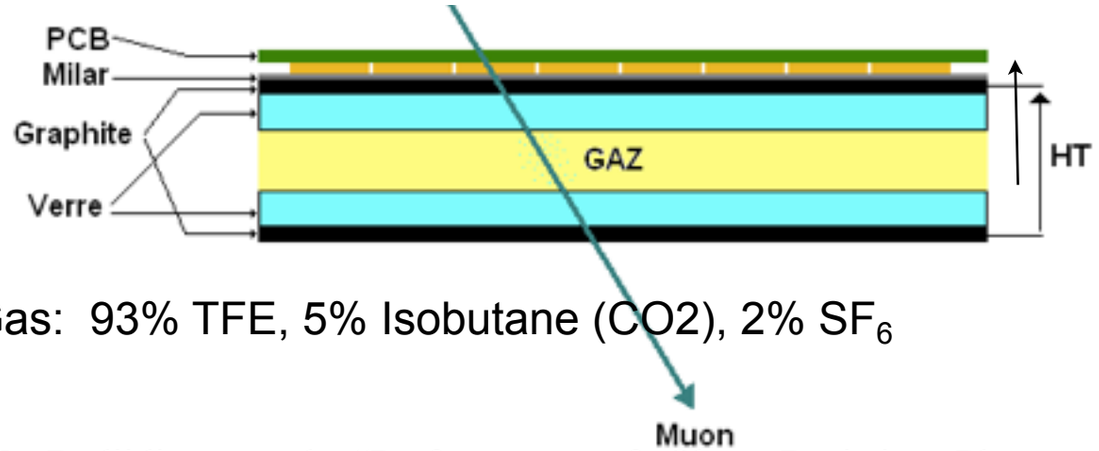





DUSTER
DK-366-FZ

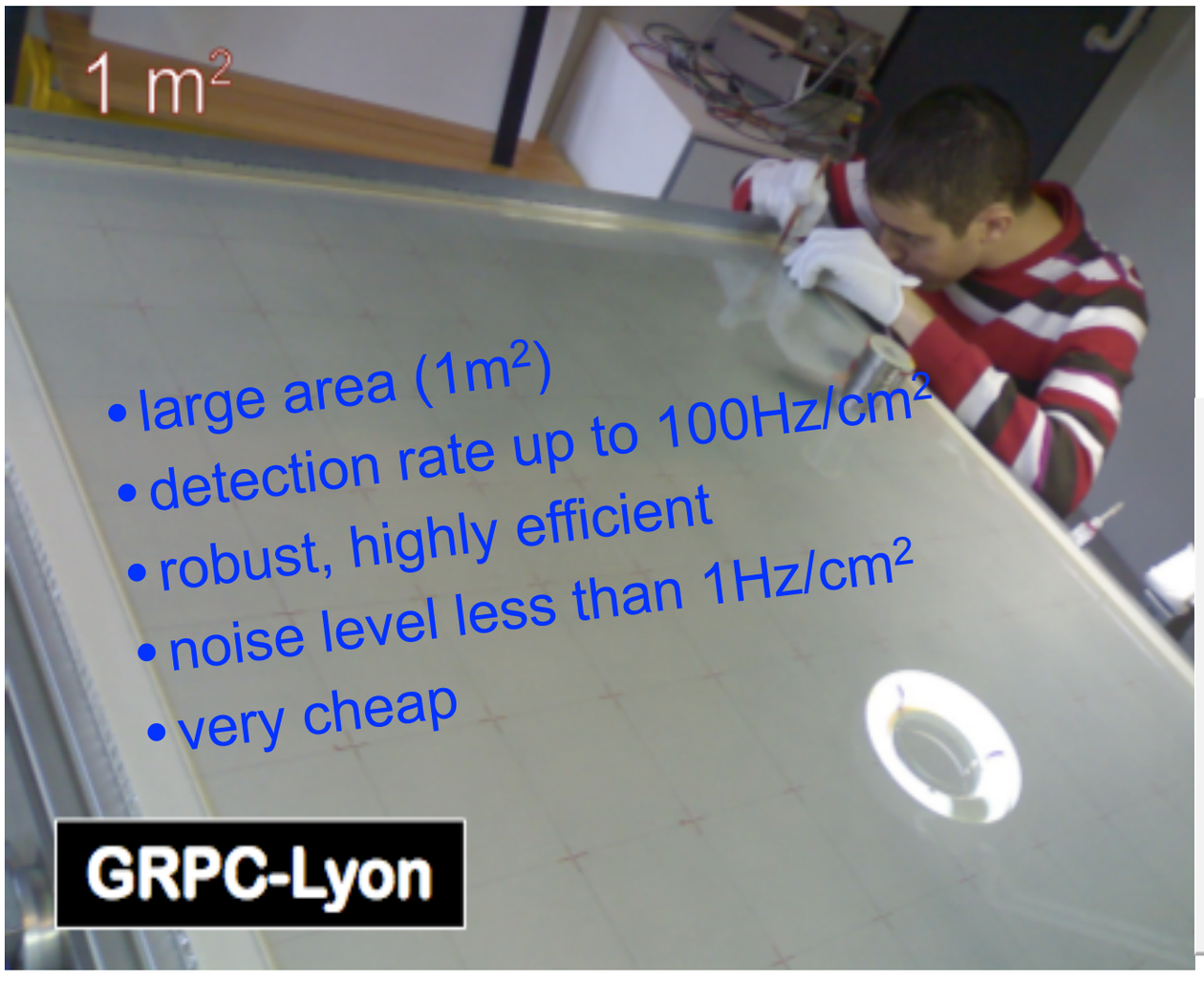
CALICE GRPC's

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

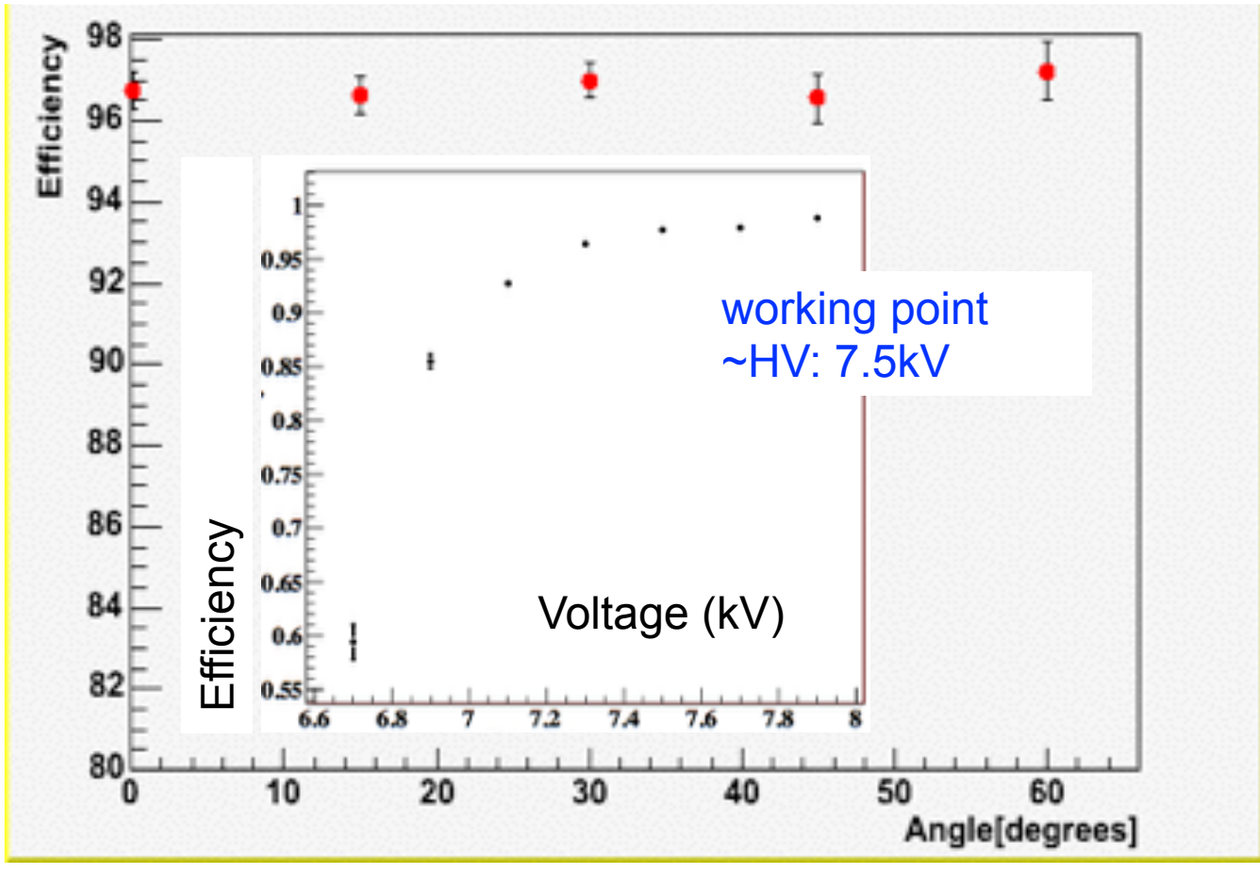


Gas: 93% TFE, 5% Isobutane (CO_2), 2% SF_6

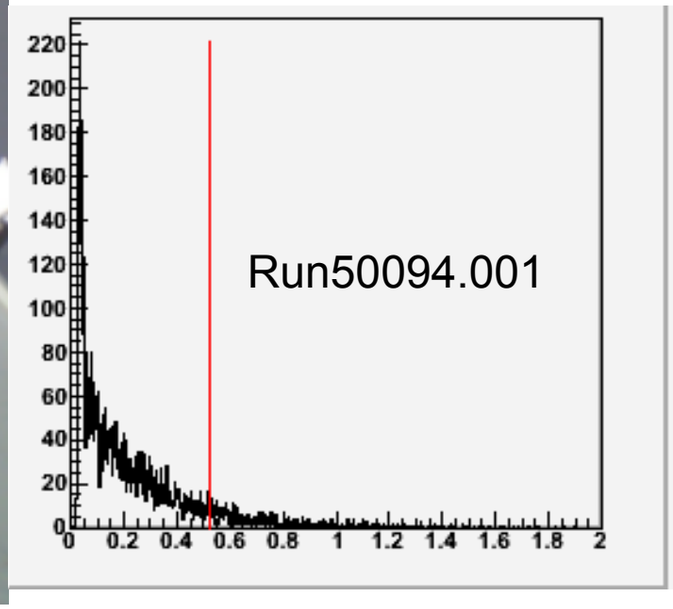
M. Bedjidian et al, "Performance of Glass Resistive Plate Chambers for a high granularity semi-digital calorimeter", JINST 6:P02001,2011

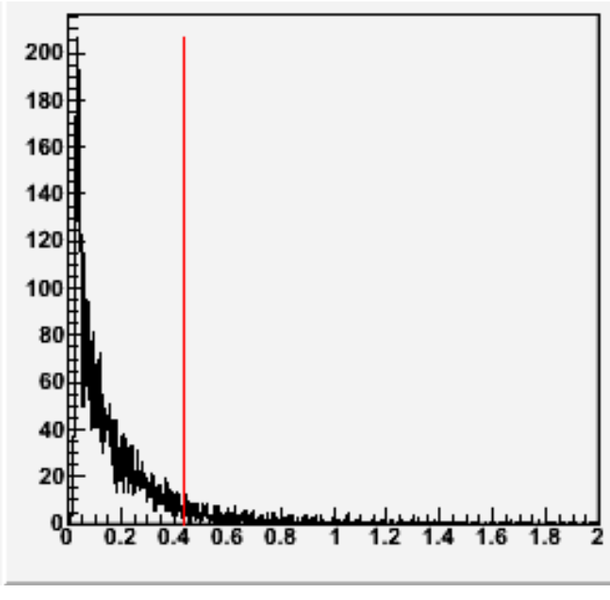


Efficiency vs. HV & track incident angle

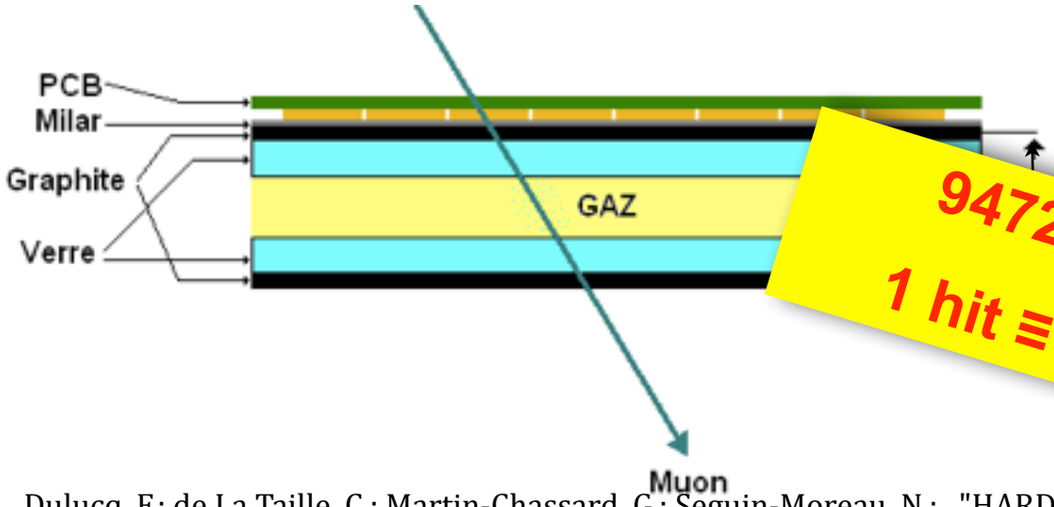


Noise rate (Hz)



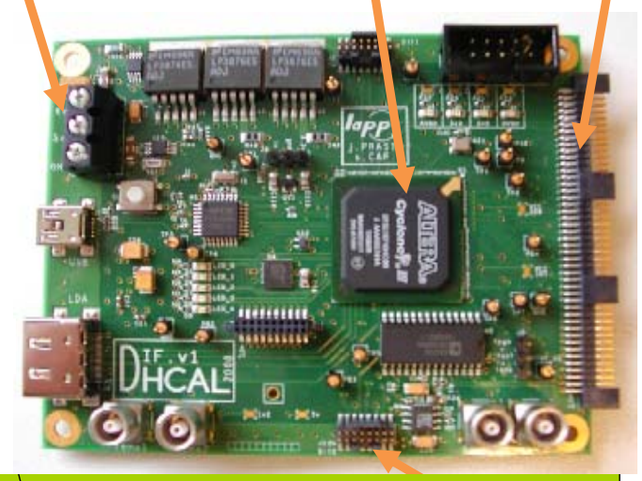


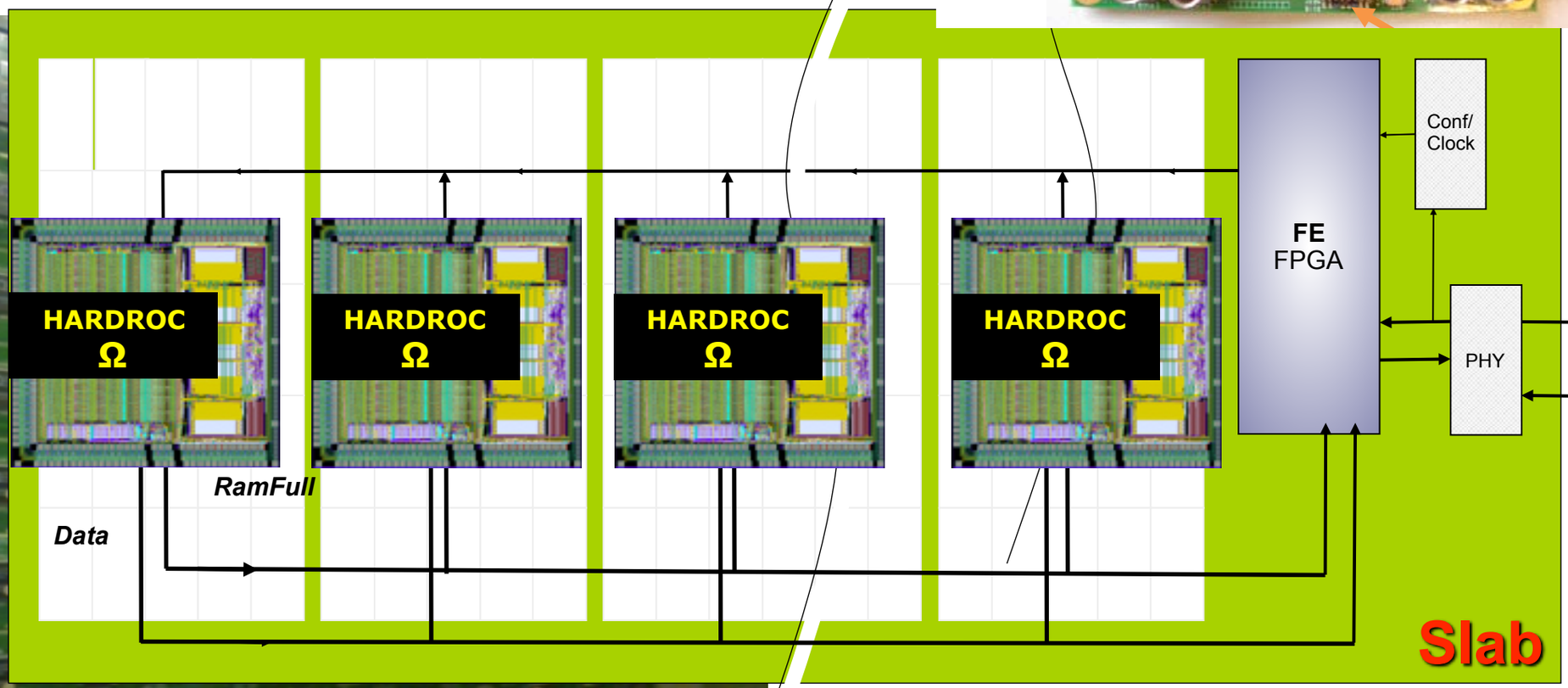
Muon Tracker : CALICE Electronics



9472 channels/m2
1 hit ≡ time + thresh

Dulucq, F.; de La Taille, C.; Martin-Chassard, G.; Seguin-Moreau, N.; , "HARDROC: Readout chip for CALICE/EUDET Digital Hadronic Calorimeter," *Nuclear Science Symposium Conference Record (NSS/MIC), 2010 IEEE*

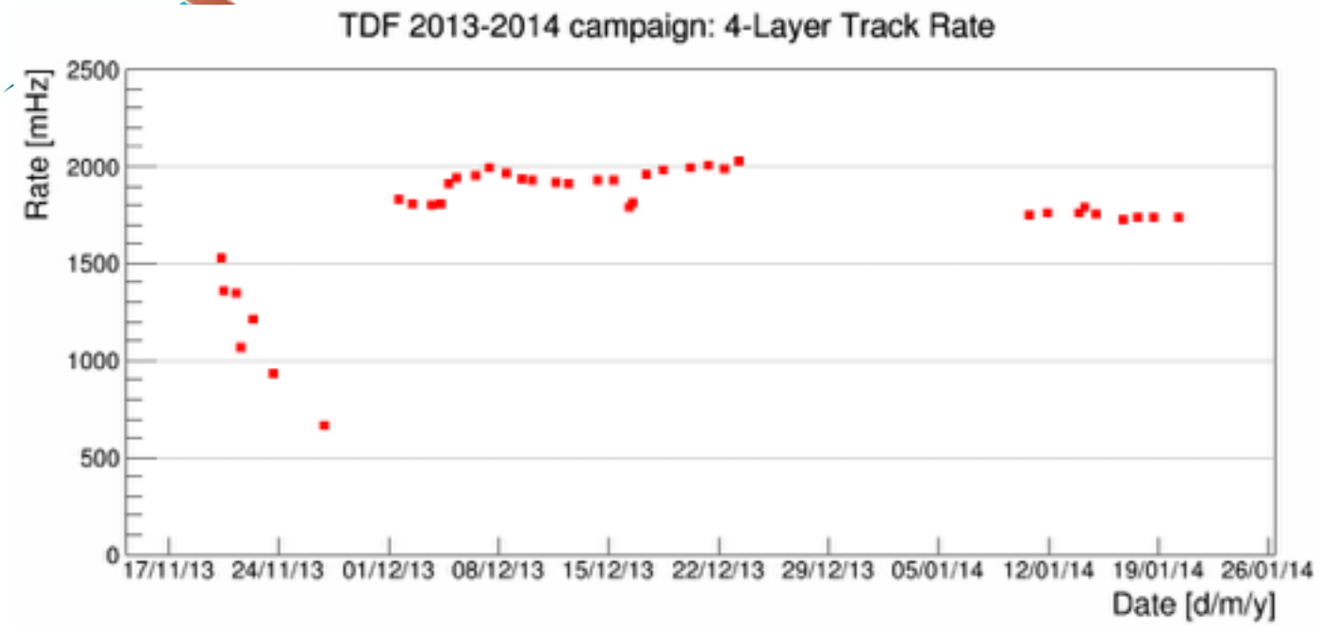


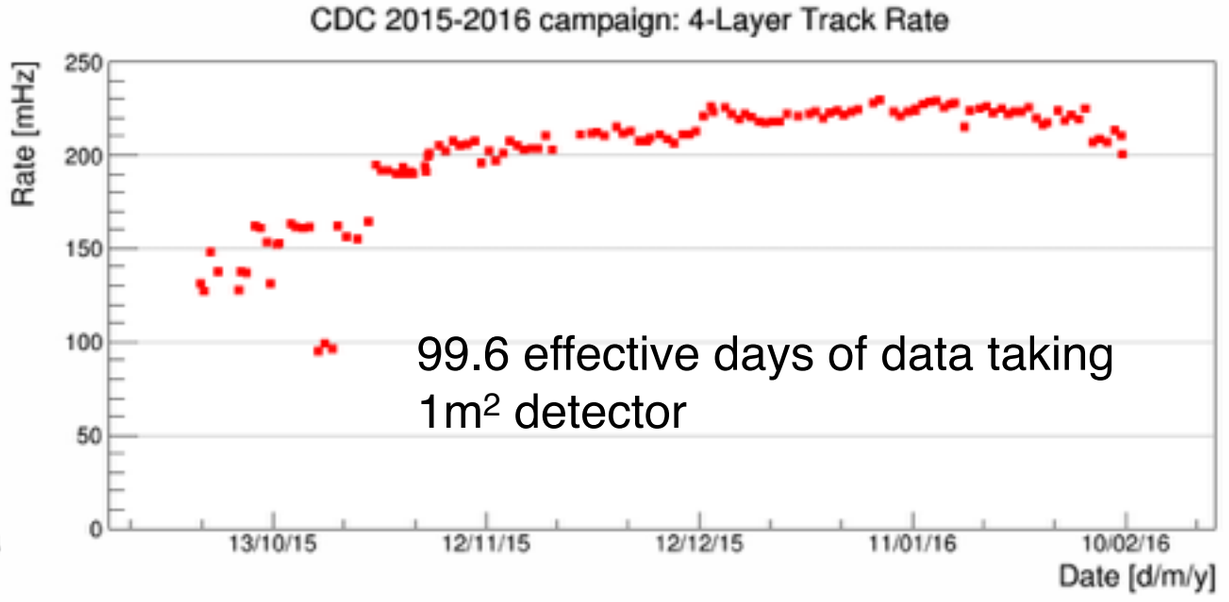


- 8 layers PCB, 800µm thick.
- readout by induction (1 cm² pads)

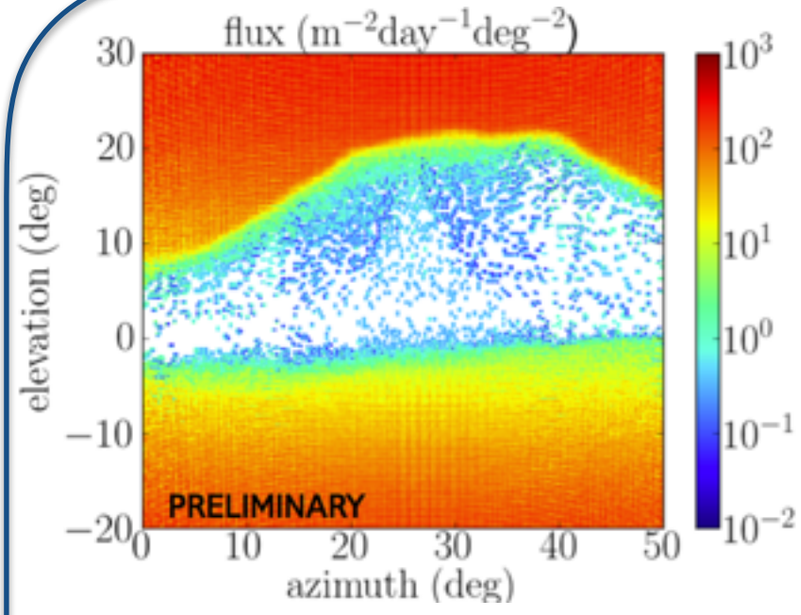
- 64 channels, 16 mm²
- digital output (3 adjustable thrs)
- low power consumption (1.5 mW/ch)
- large gain range
- xtalk <2%
- ajustable gain for each channel

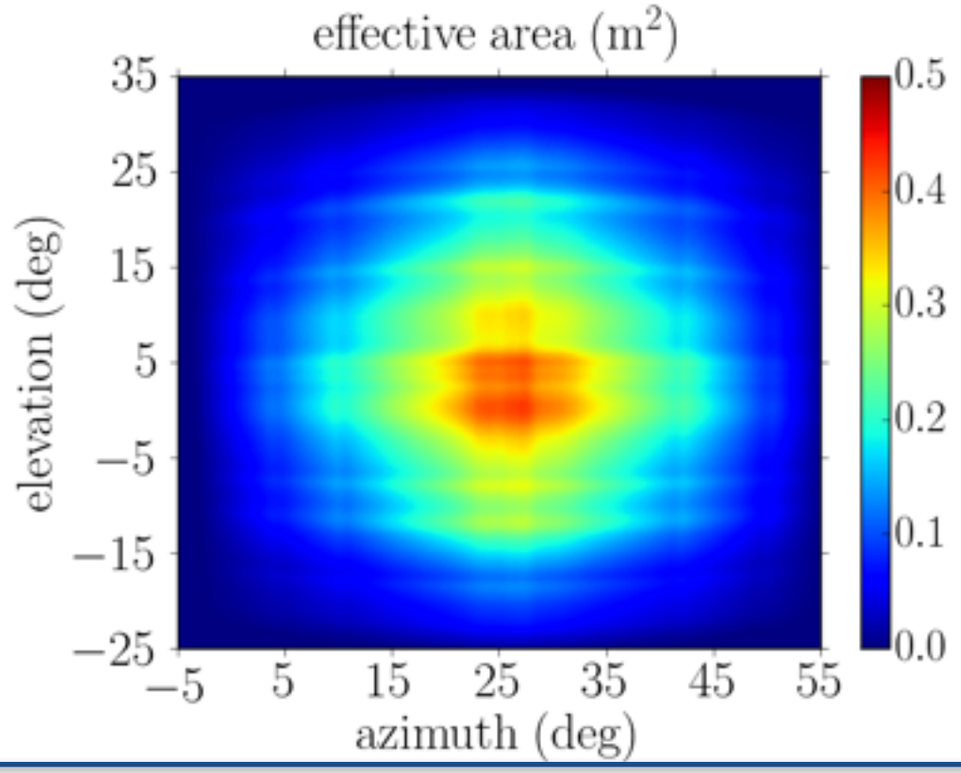
TOMUVOL 2013 - 2015

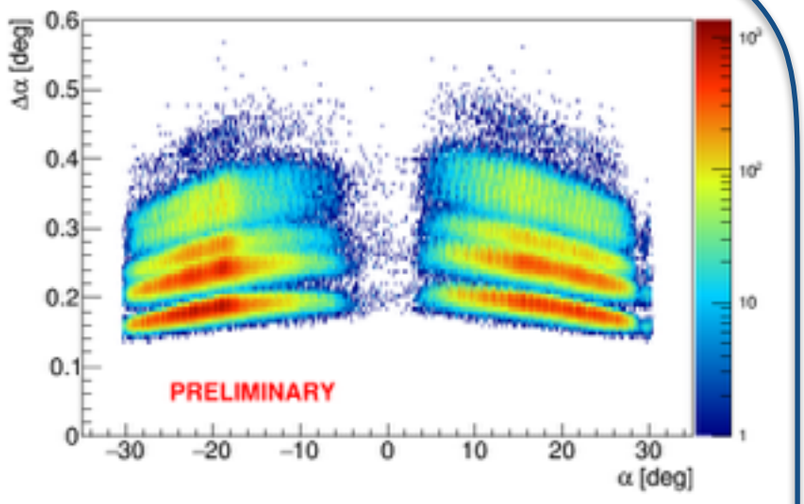


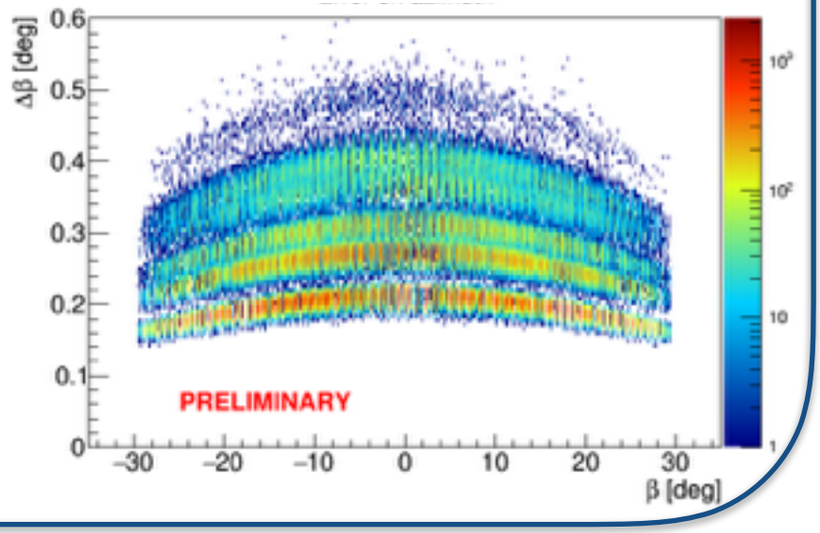


Col de Ceyssat 2015

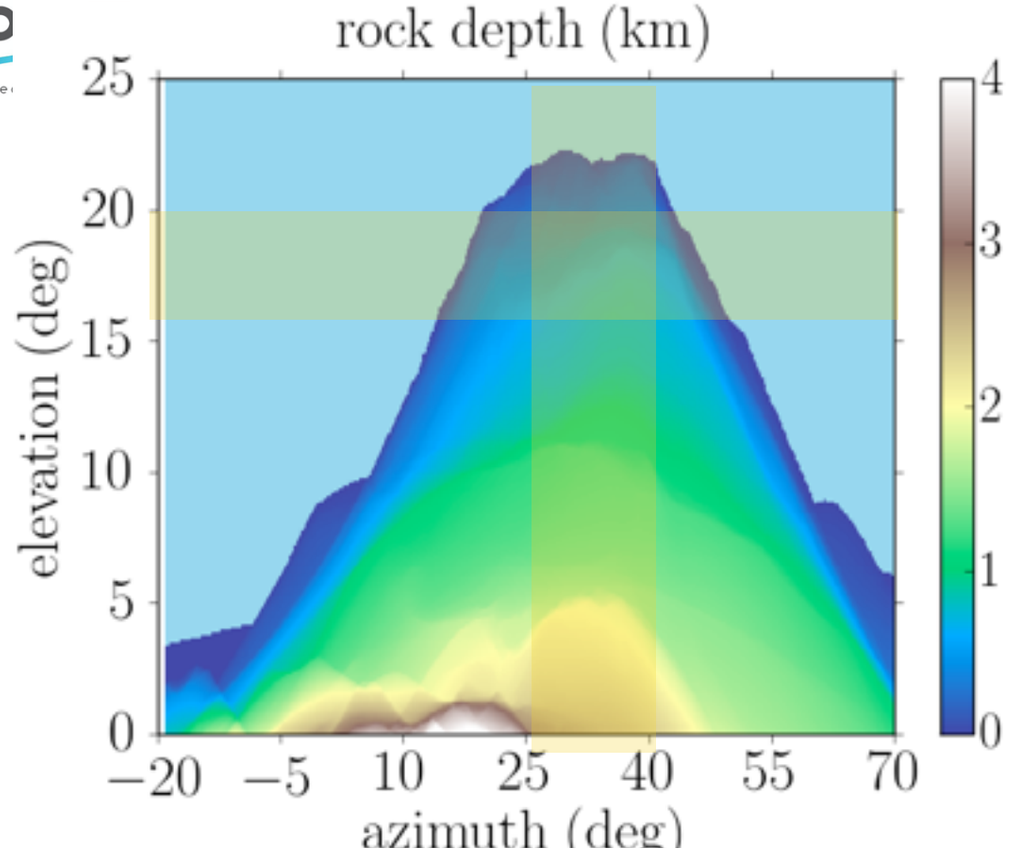


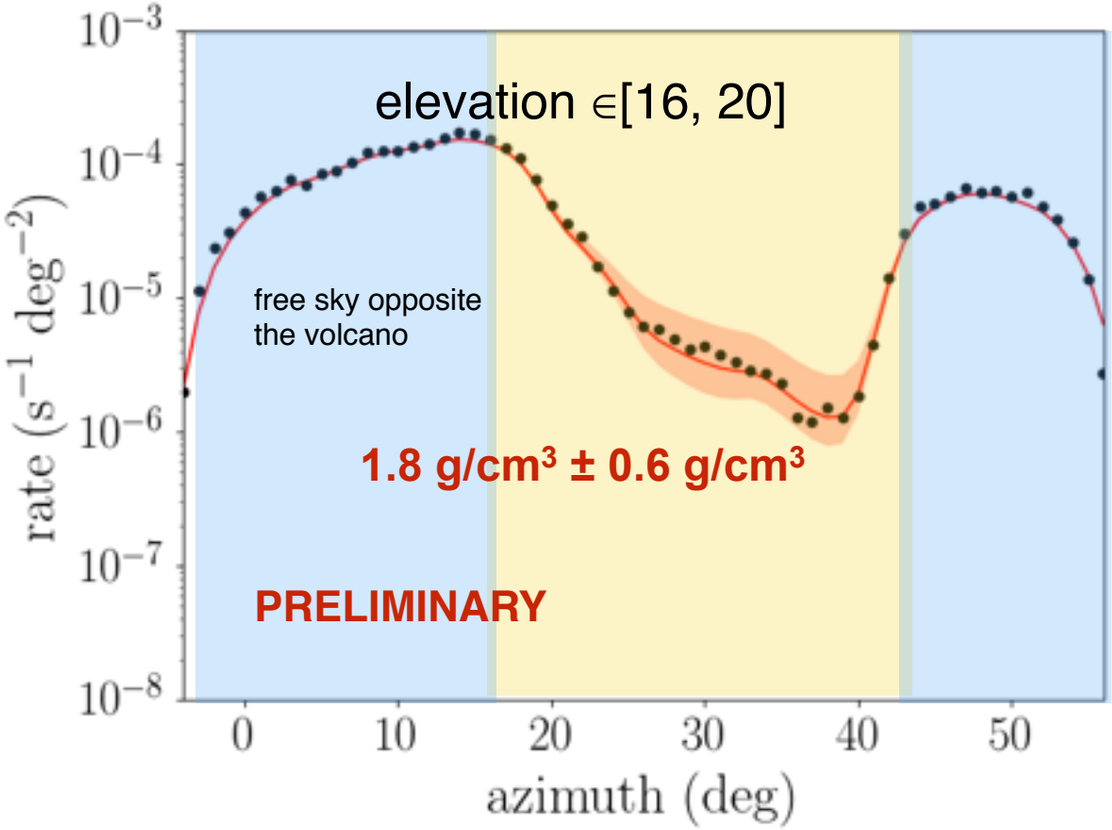


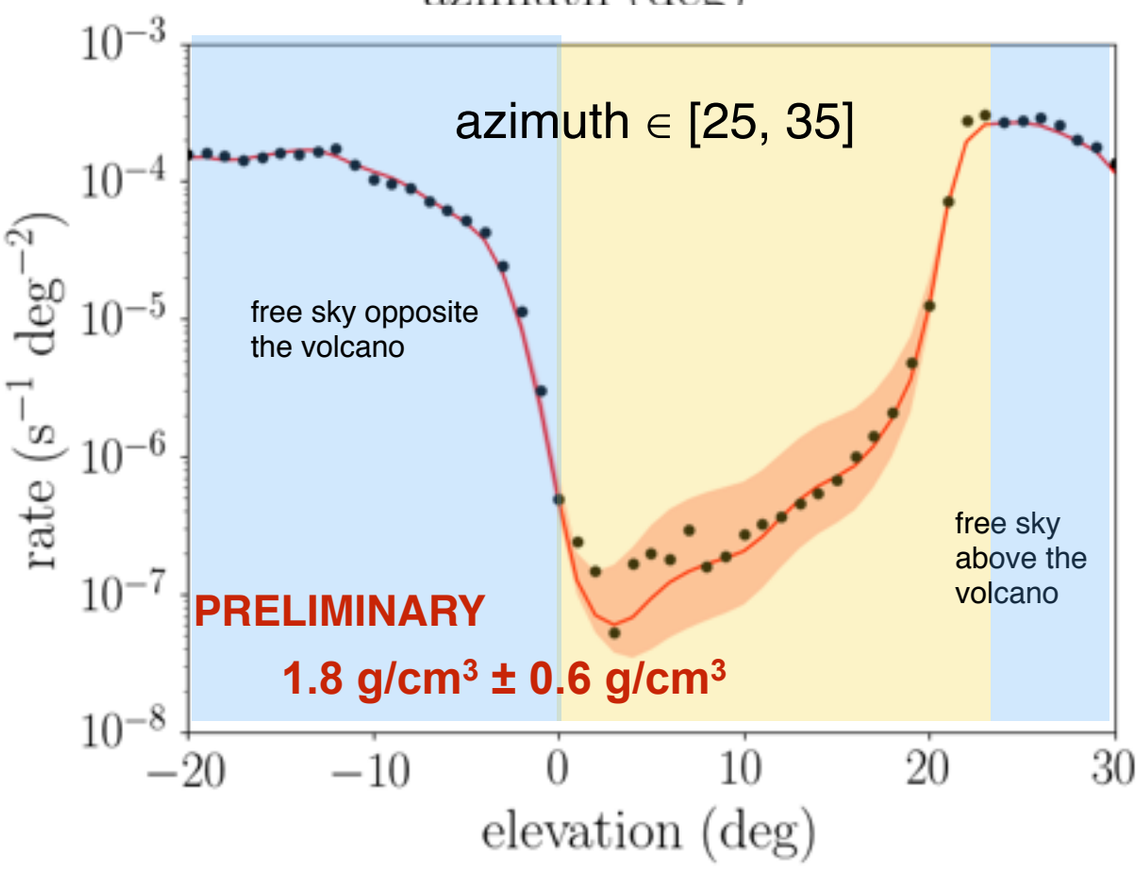




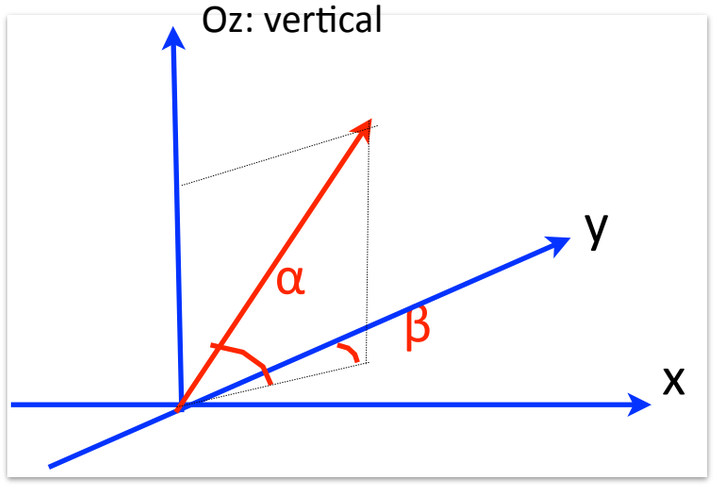
CDC 2015 Campaign



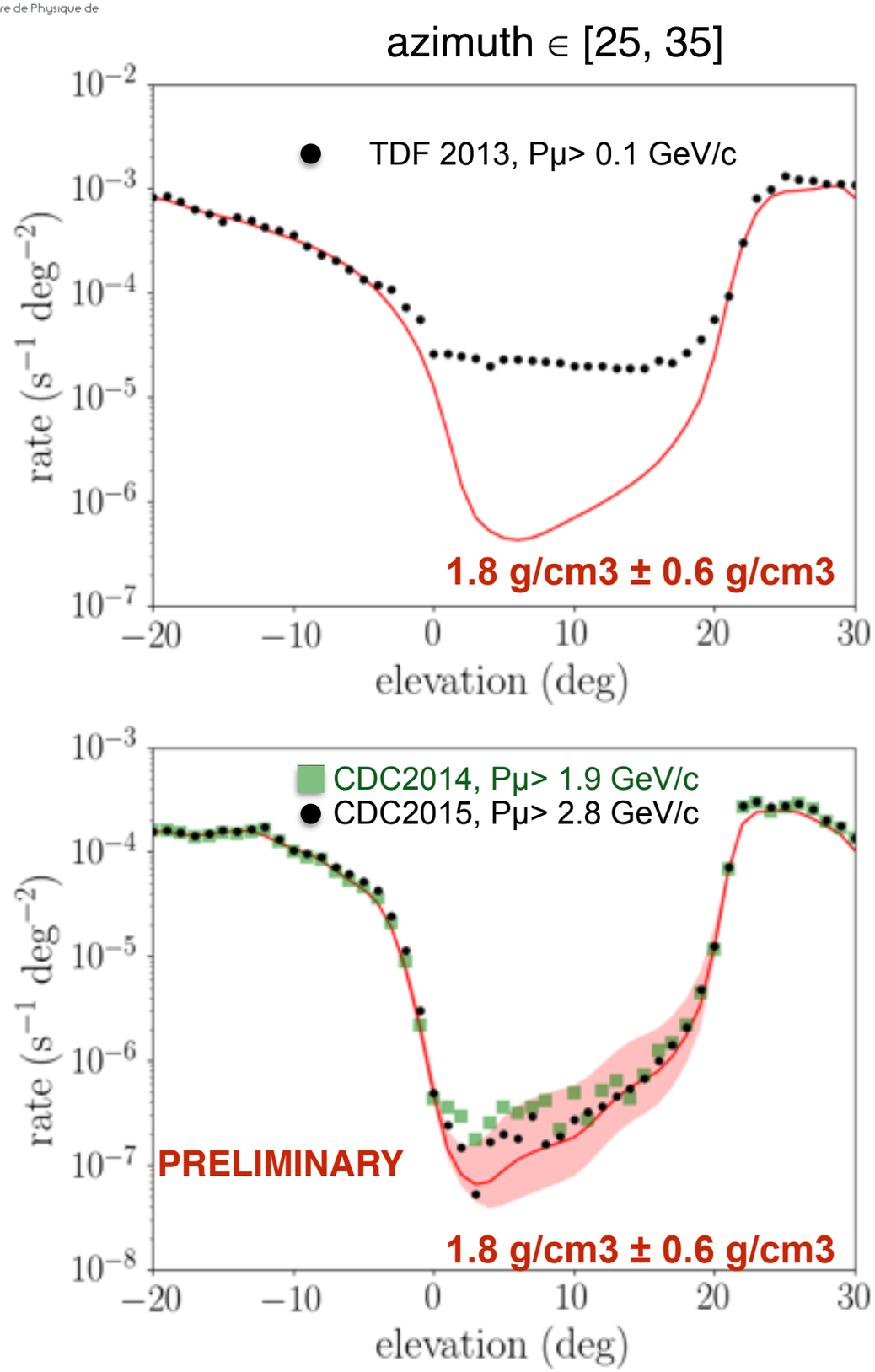


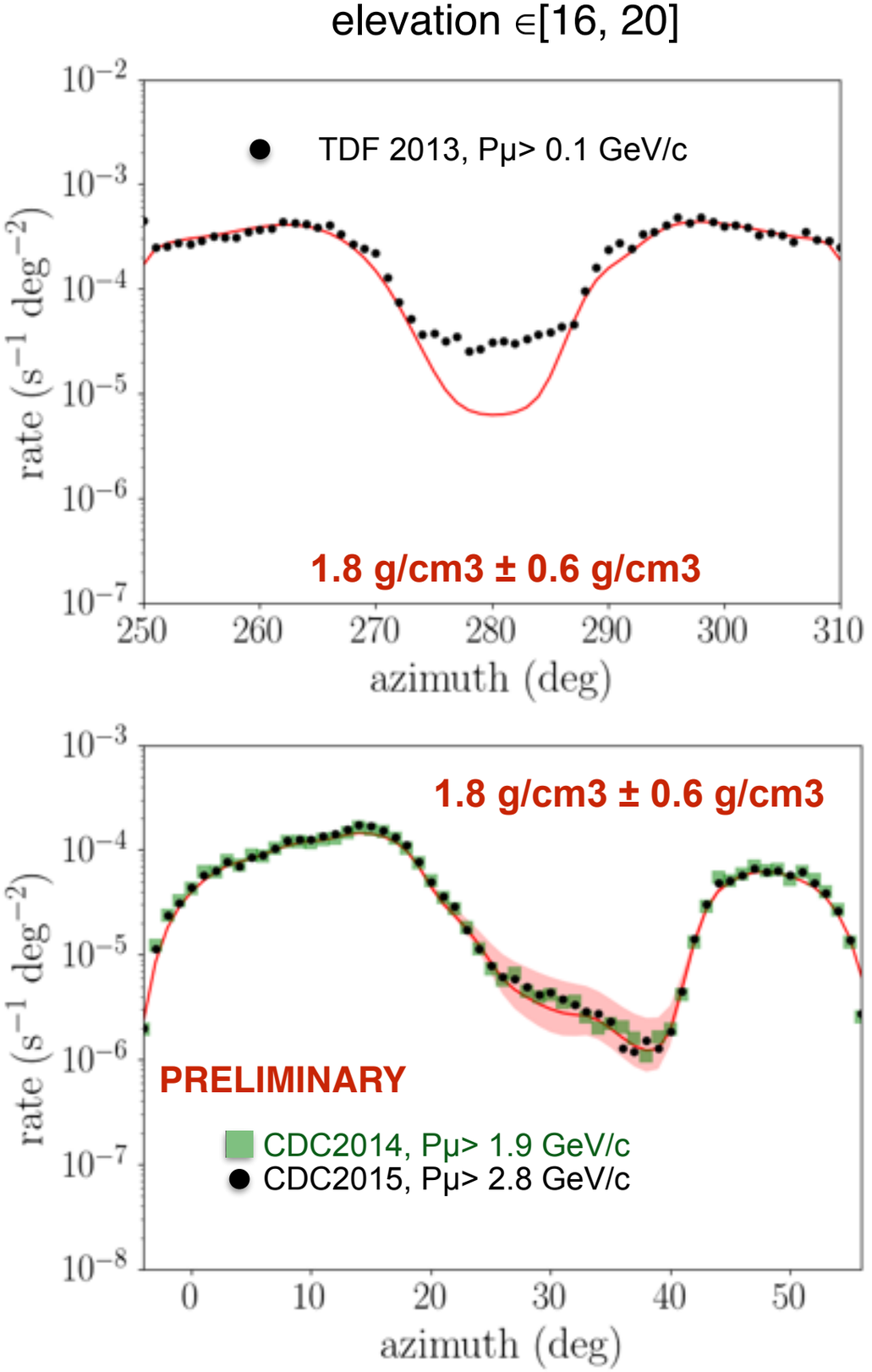


Data/flux model agreement:
~5% for free sky

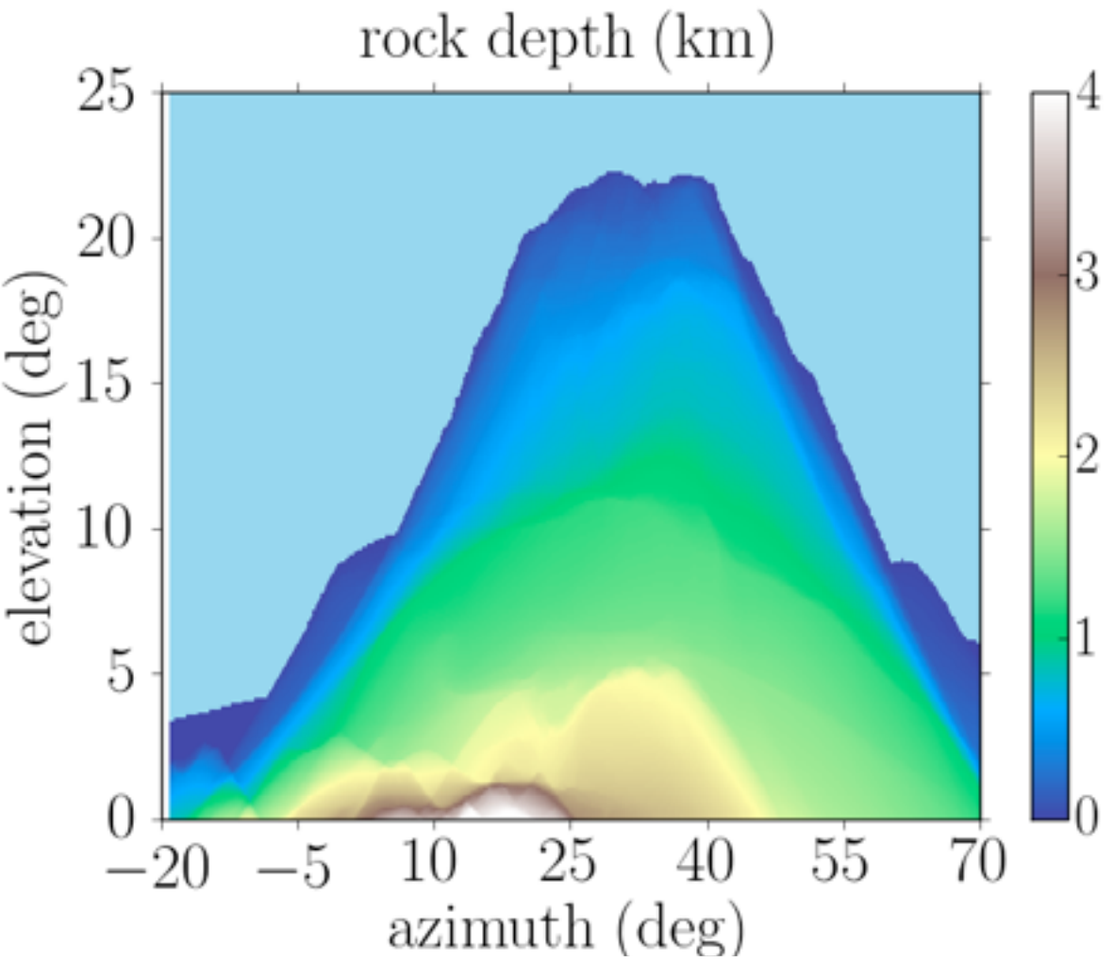


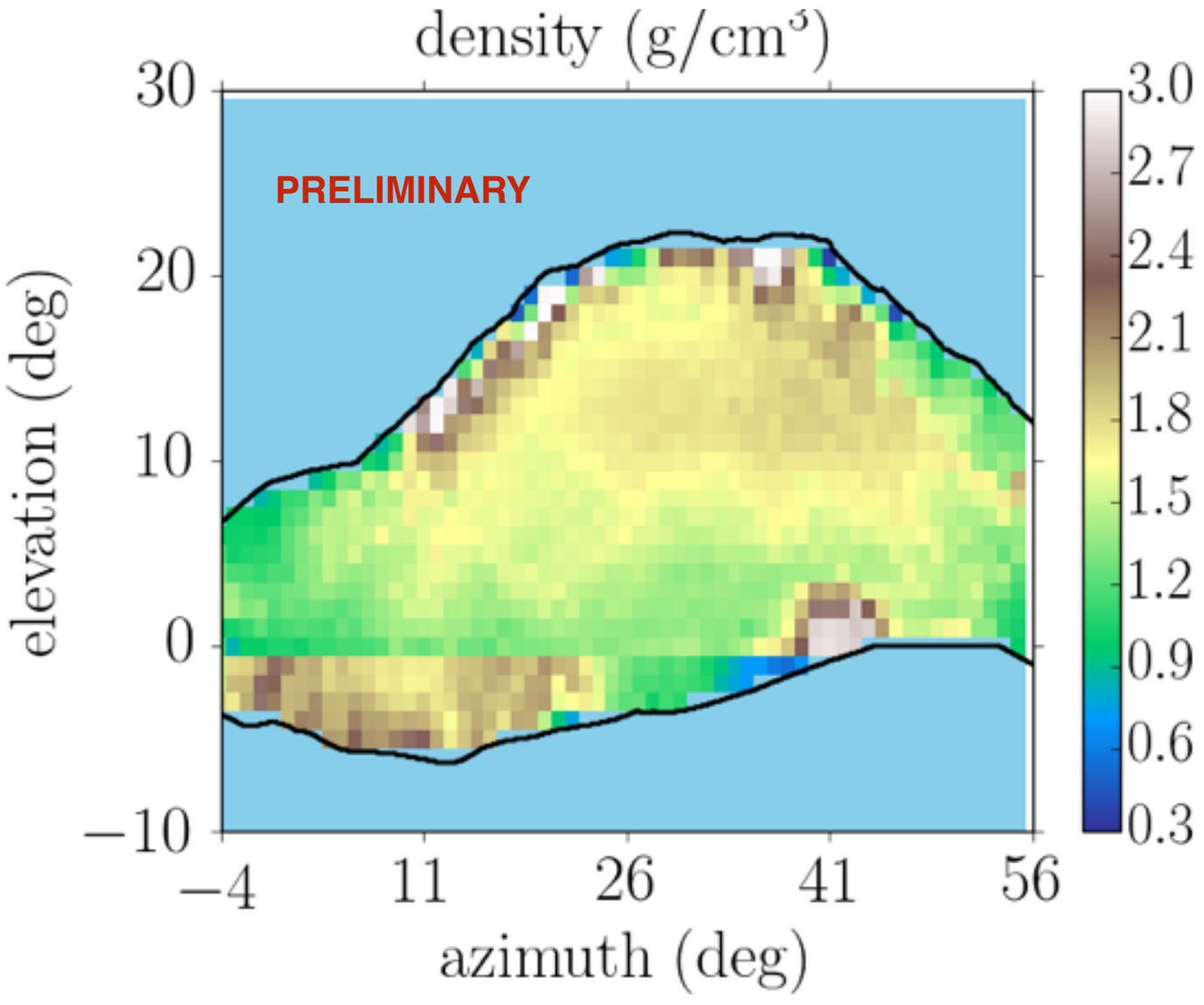
Impact of the muon-momentum detection threshold





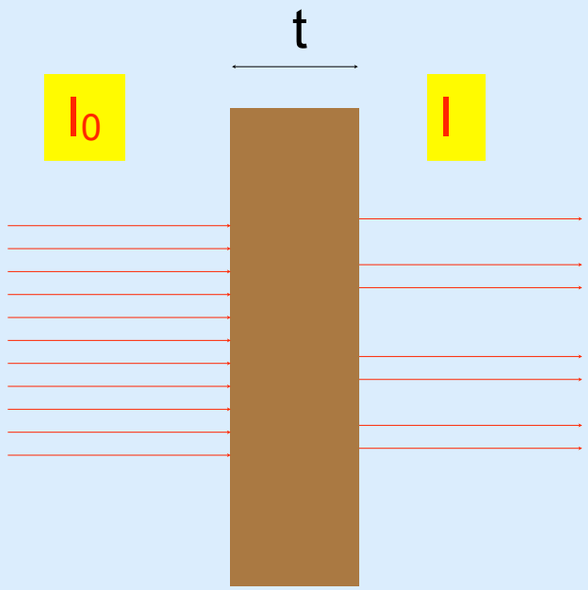
CDC 2015 Campaign





Two exploitable interactions

TRANSMISSION

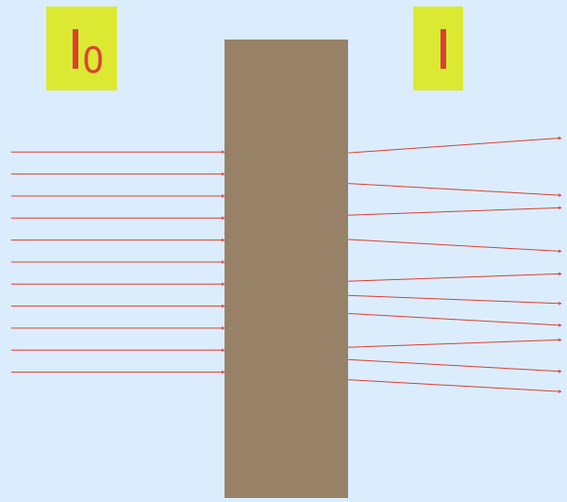


$I = I_0 f(\rho)$

DENSITY

- 2D image
- relies on incident flux knowledge
- applicable to very large targets

SCATTERING

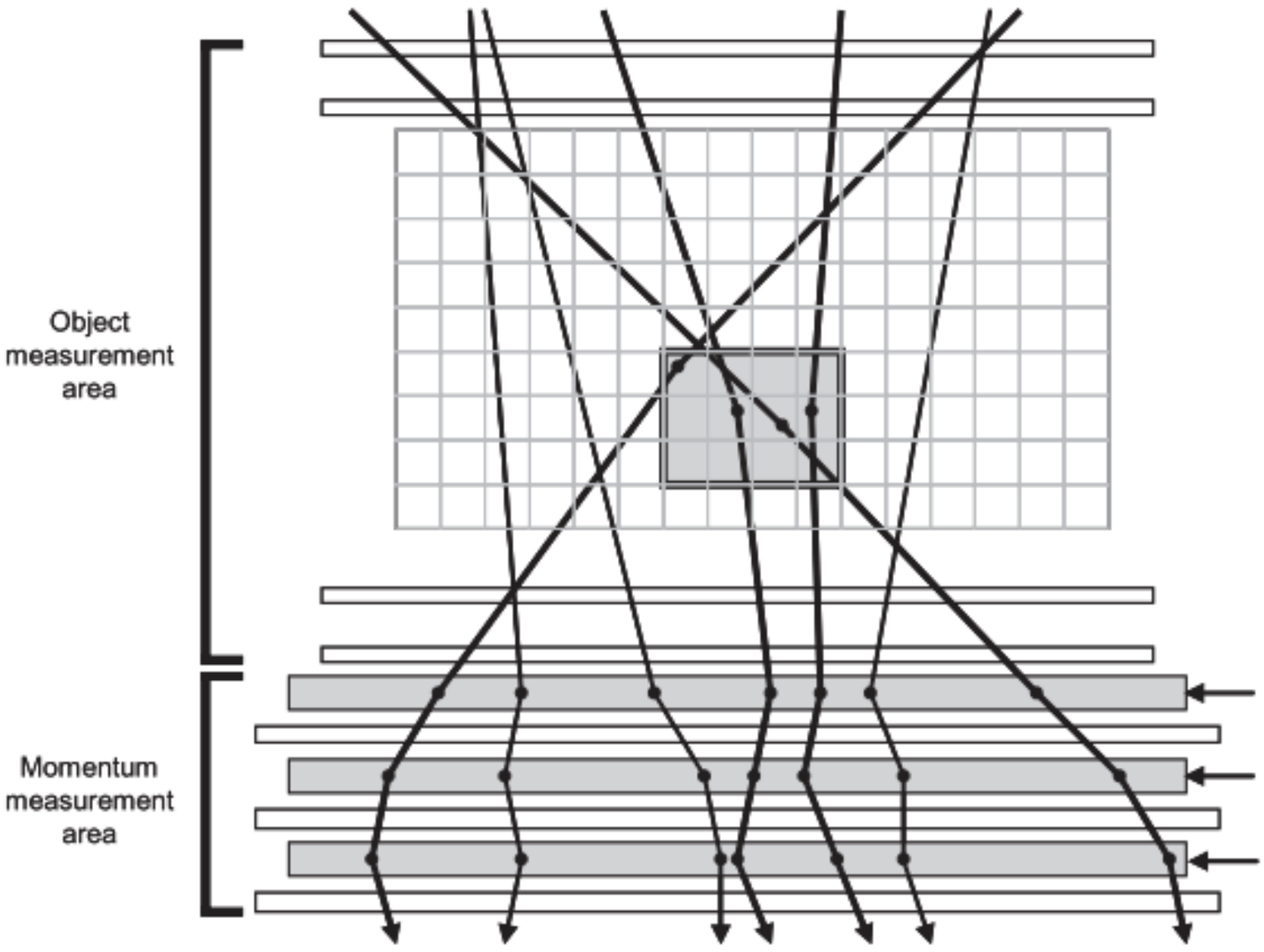


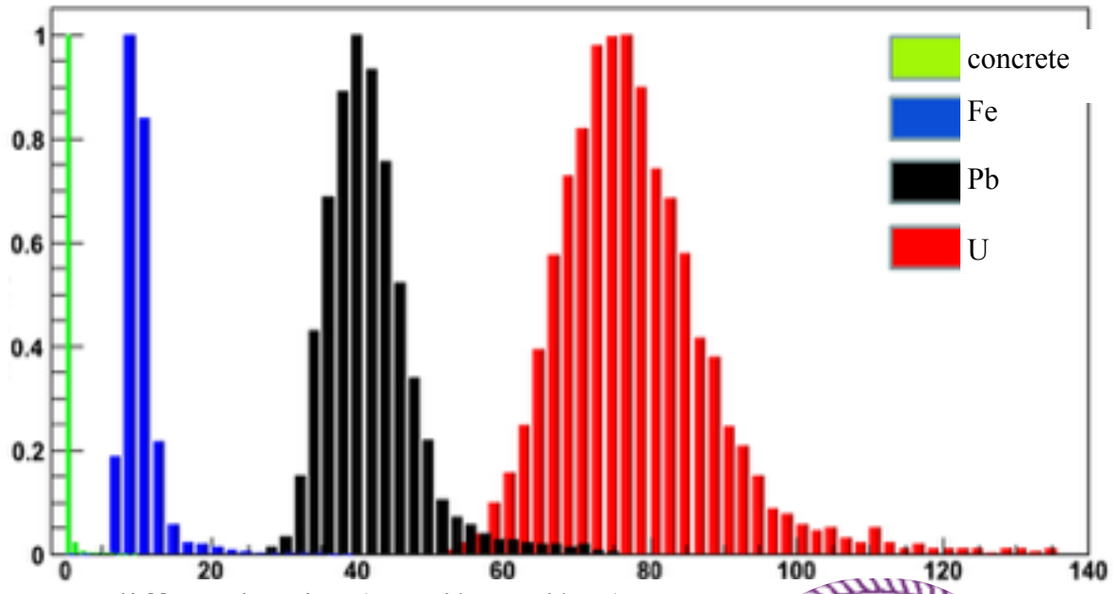
$\delta = f(Z)$

ATOMIC NUMBER

- 3D image
- necessary to measure each individual track before and after the target
- high position resolution, large area detectors
- small to medium targets

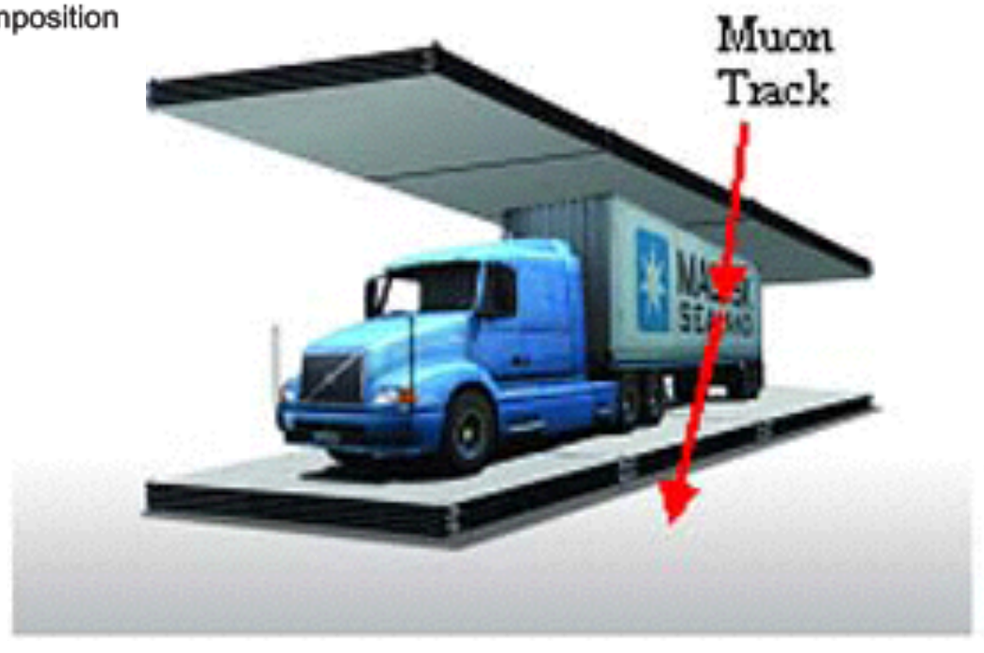
Scattering muography





diffuse density (mrad*mrad/cm)

K.N. Borozdin, G.E. Hogan, Ch. Morris, W.C. Priedhorsky, A. Saunders, L.J. Schultz, M.E. Teasdale, "Surveillance: Radiographic imaging with cosmic-ray muons", Nature 422, 277 (20 March 2003) , doi:10.1038/422277a



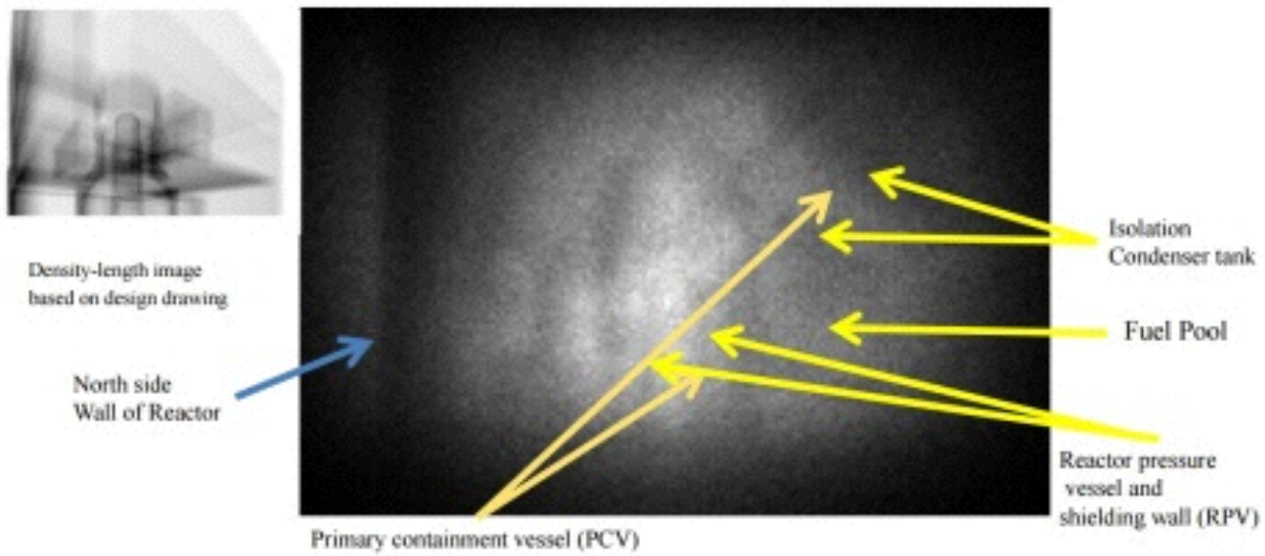
Scattering muography

Energy & Environment | New Nuclear | Regulation & Safety | Nuclear Policies | Corporate | Uranium &

Muon data confirms fuel melt at Fukushima Daiichi 1

23 March 2015

Initial results from using a muon detection system at the damaged Fukushima Daiichi unit 1 in Japan appear to confirm that most of the fuel has melted and dropped from its original position within the core, Tokyo Electric Power Company (Tepco) announced.



Results obtained from the muon detector on the northwest side of the reactor building (Image: Tepco)

The company completed installation of the muon detection system on 12 February. Two detectors were installed: one on the northwest side of the reactor building and the other on the north side. Since then, data collection continued until 10 March (a period of 26 days). The initial results have now been analysed.

The detector system was developed by Japan's High Energy Accelerator Research Organization (KEK). The system uses the so-called permeation method to measure the muon data.

Related Stories

- Looking inside Fukushima Daiichi unit 1
- Cosmic rays to pinpoint Fukushima cores
- Fukushima fuel melt confirmed

WNA Links

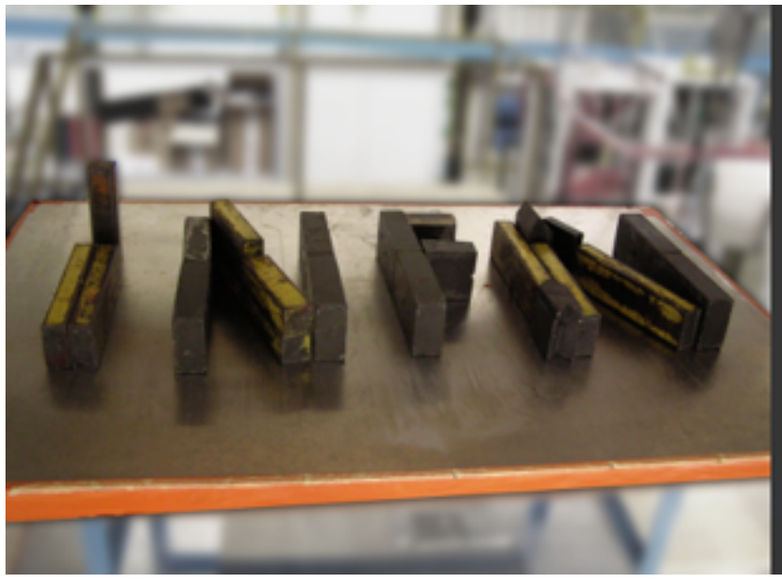
- Fukushima Daiichi 1
- The Situation at Fukushima

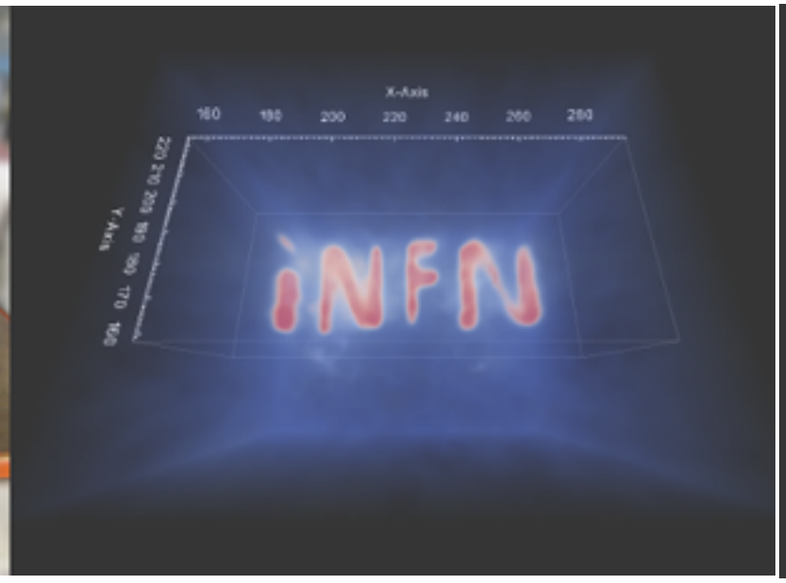
Related Links

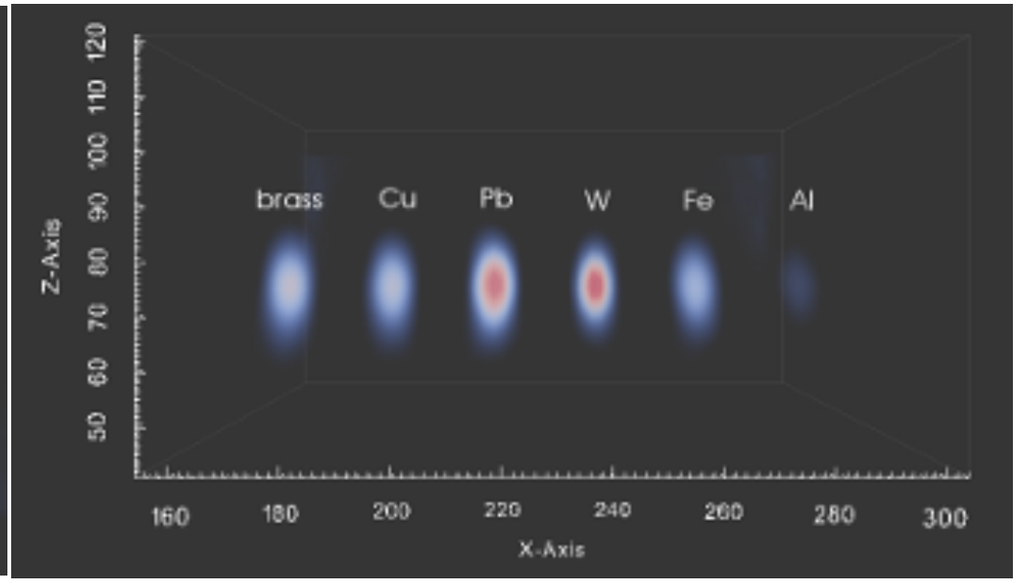
- Tokyo Electric Power Co. (Tepco)

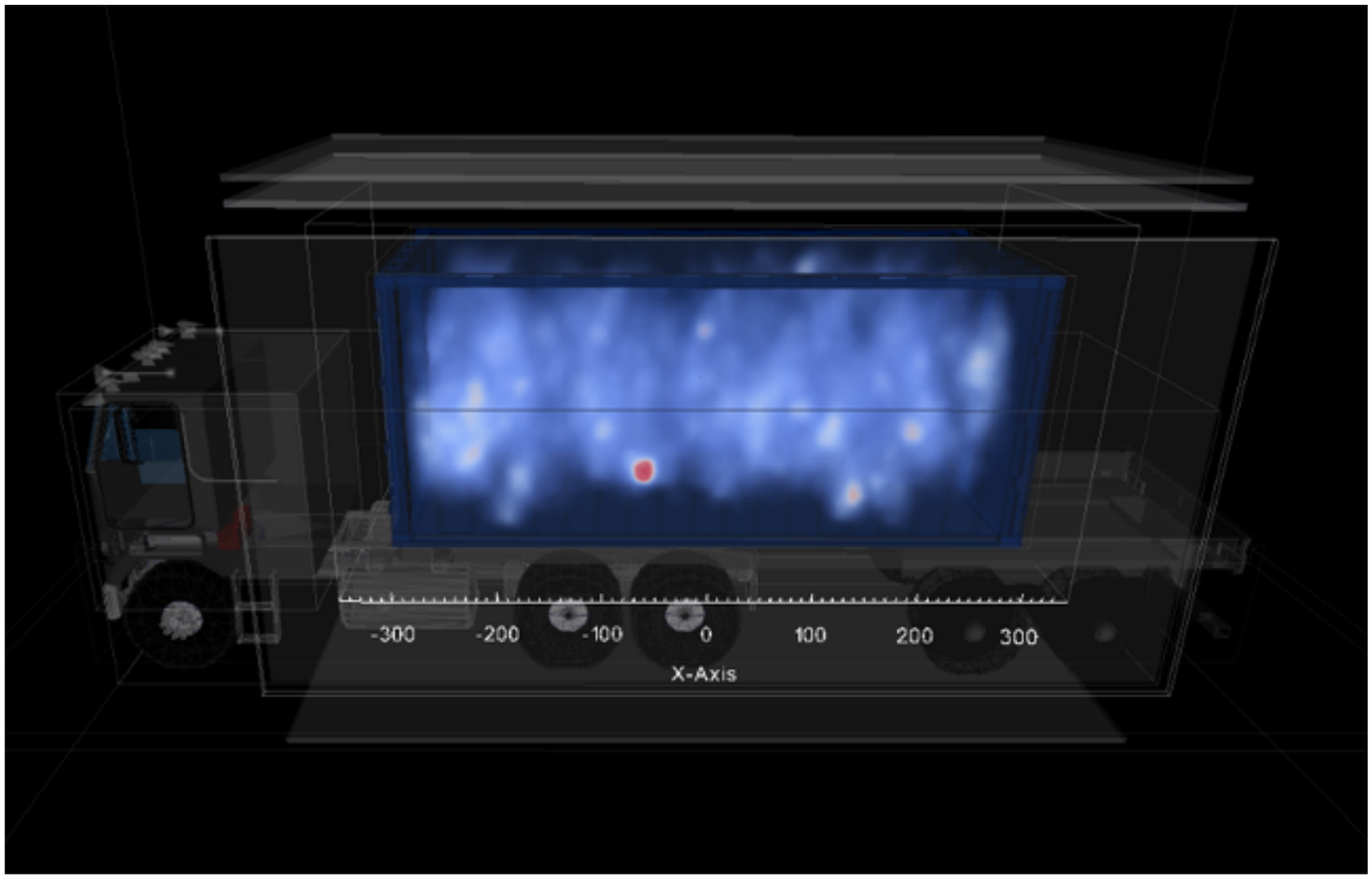
CMT(p) Cosmic Muon Tomography (project)

http://mutomweb.pd.infn.it:5210/?page_id=258



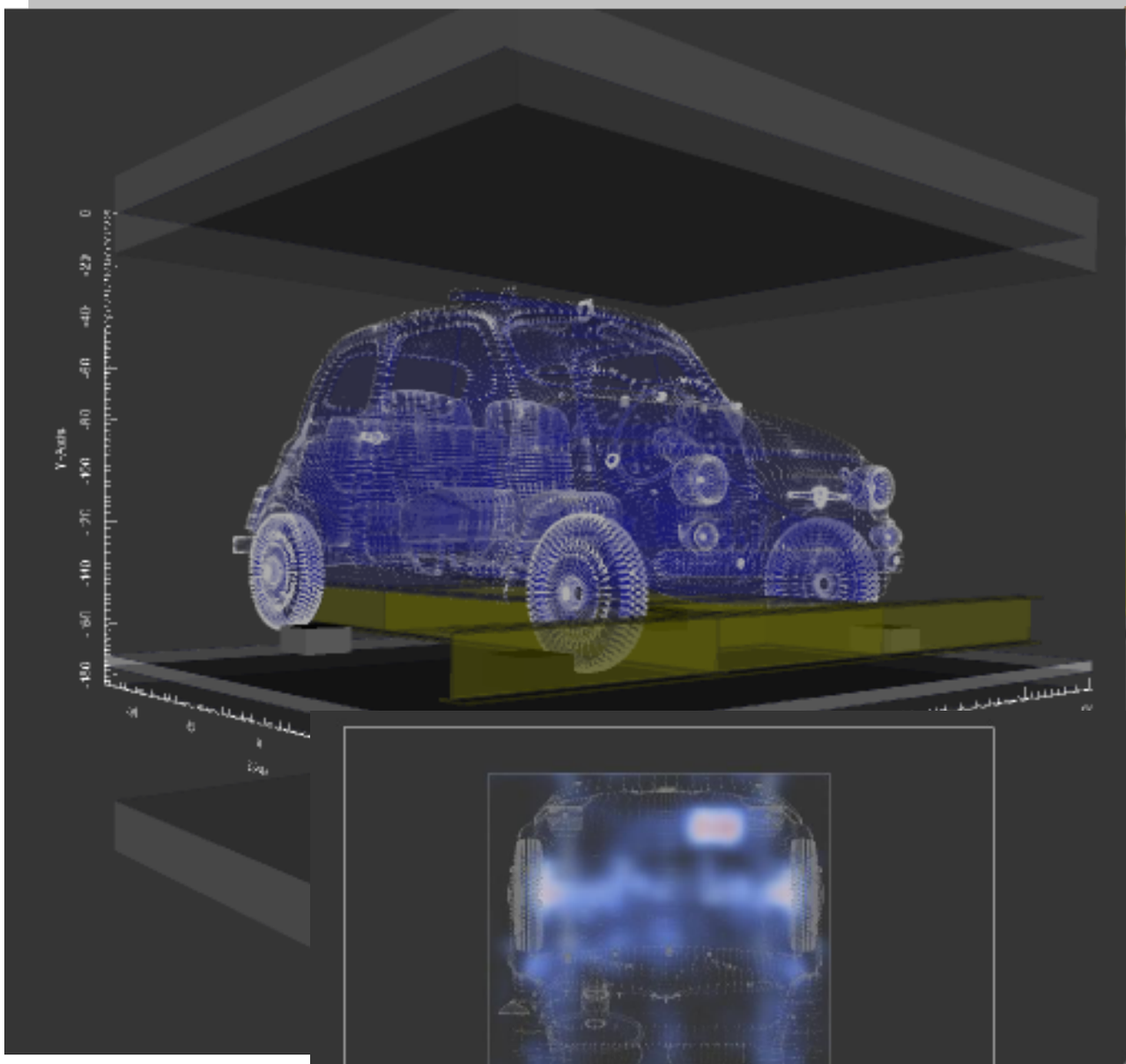


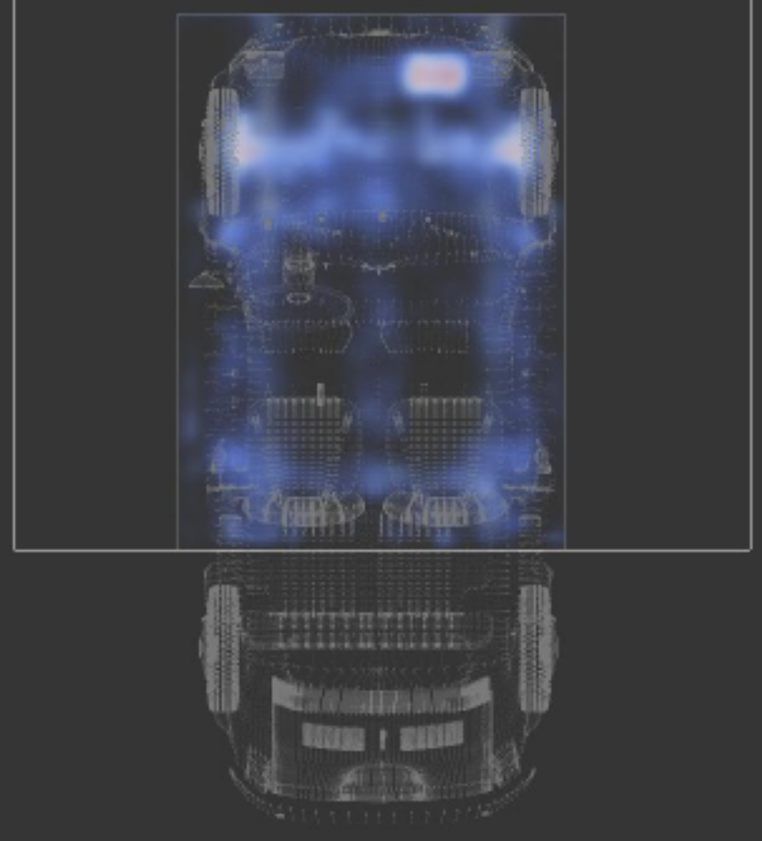


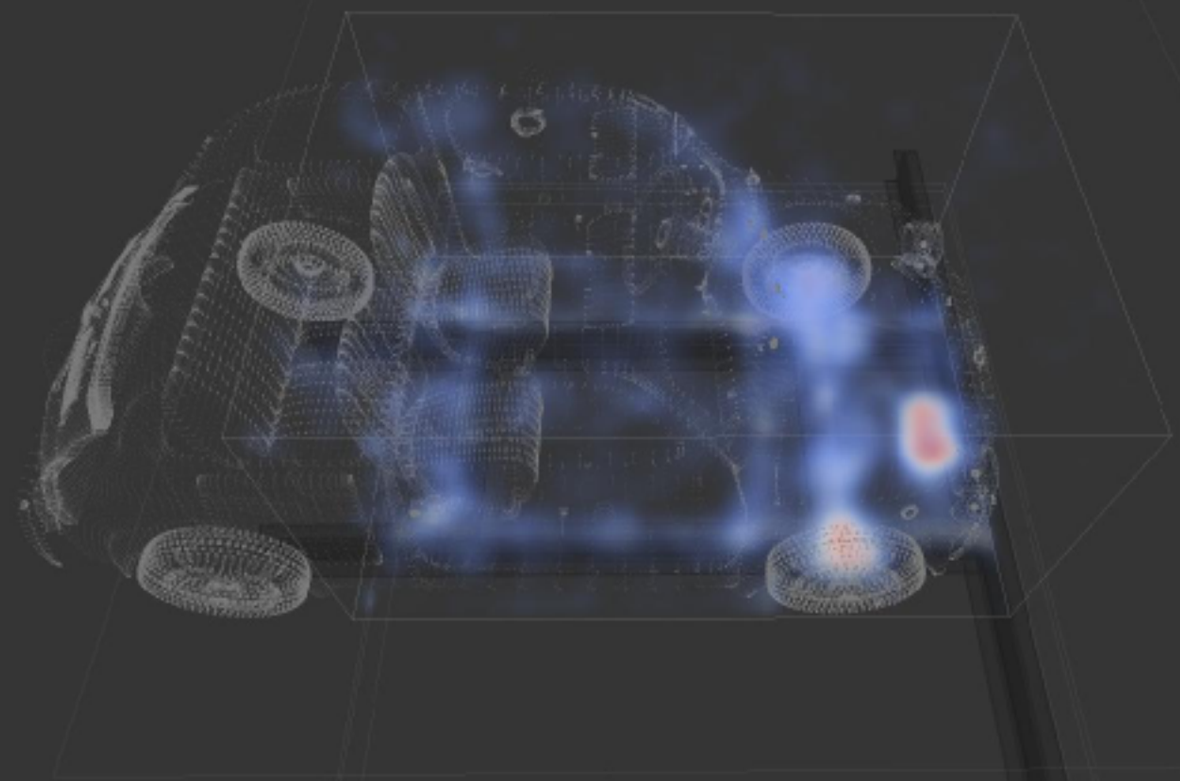


CMT(p)

Cosmic Muon Tomography (project)







https://ww

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NATURAL SOLUTIONS TO MANMADE PROBLEMS

USING MUON TOMOGRAPHY

High-energy cosmic rays create showers of particles (Muons) in the upper atmosphere.

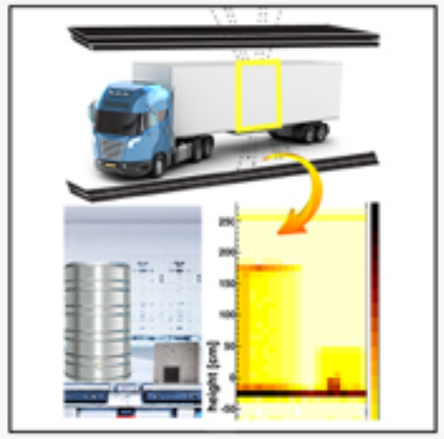
Using the **Lynkeos Muon Imaging System** we are able to noninvasively scan objects and differentiate between different materials.

The system is ideal for scanning Intermediate Level Nuclear Waste.

MORE

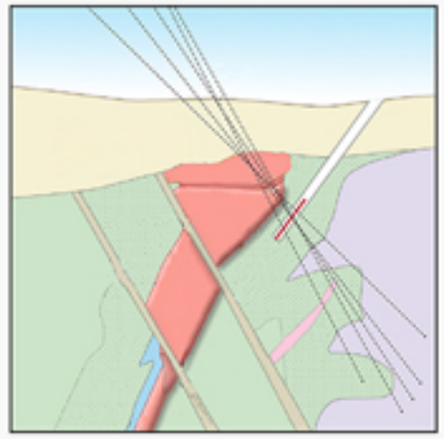
Lingacom Muon Detection Solutions

Solutions



Inspection of Containers & Vehicles

solutions for seaports, airports, cross border points



Mineral Mapping for Mining Exploration

solution for minerals exploration

Imaging of Large Geological Objects

solutions for map geological and civil objects

Muography::groups & applications