Muography, aka Muon Imaging

29.06.2021

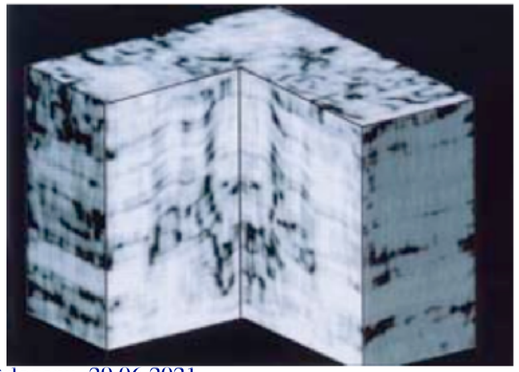
C Cârloganu

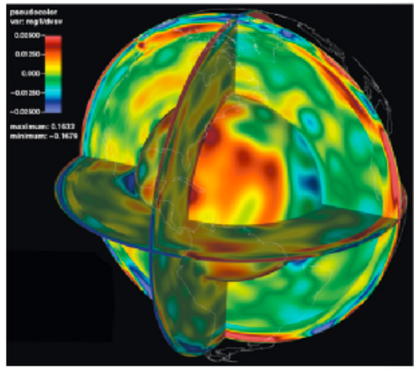
Imaging Nowadays

Medical

Security

Geophysical





Muography :: based on naturally present atmospheric muons

The precursors

Commonwealth Engineer, July 1, 1955 453

Cosmic Rays Measure Overburden of Tunnel

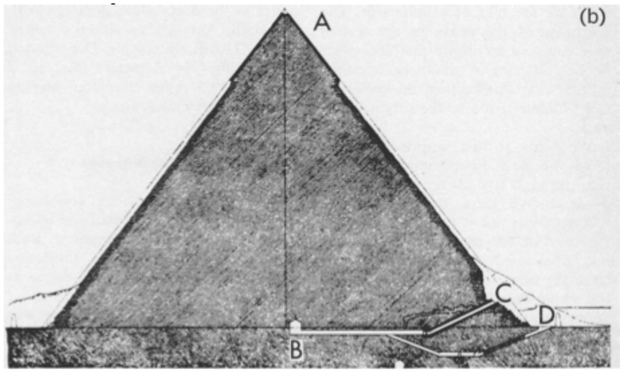
• Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehane and Mr. O'Neill.

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.

George 1955

Alvarez 1970



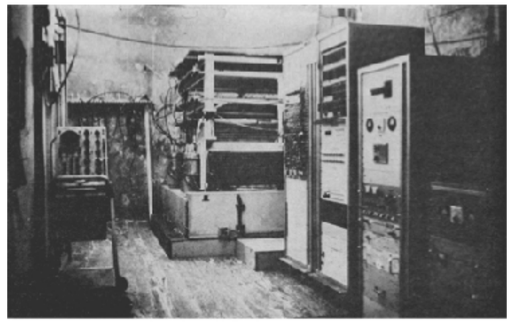


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.
Fig. 7 (right). The detection apparatus containing the spark chambers.

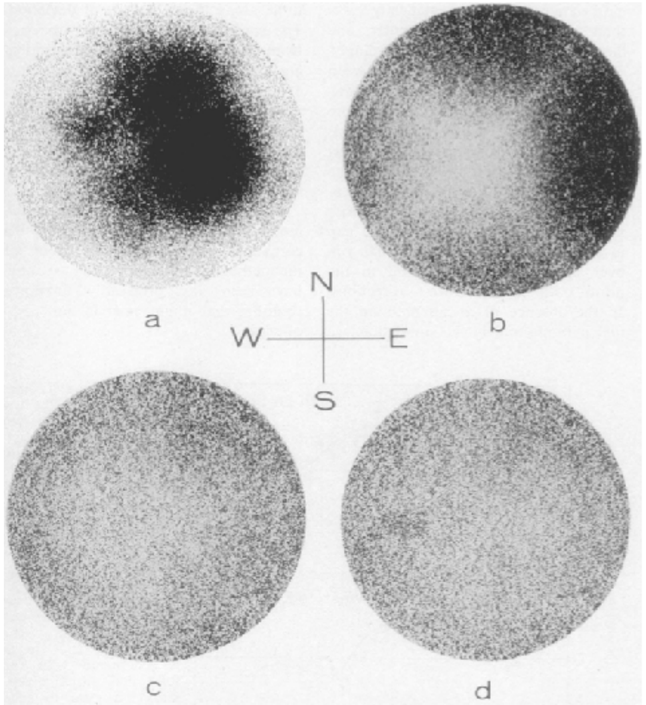
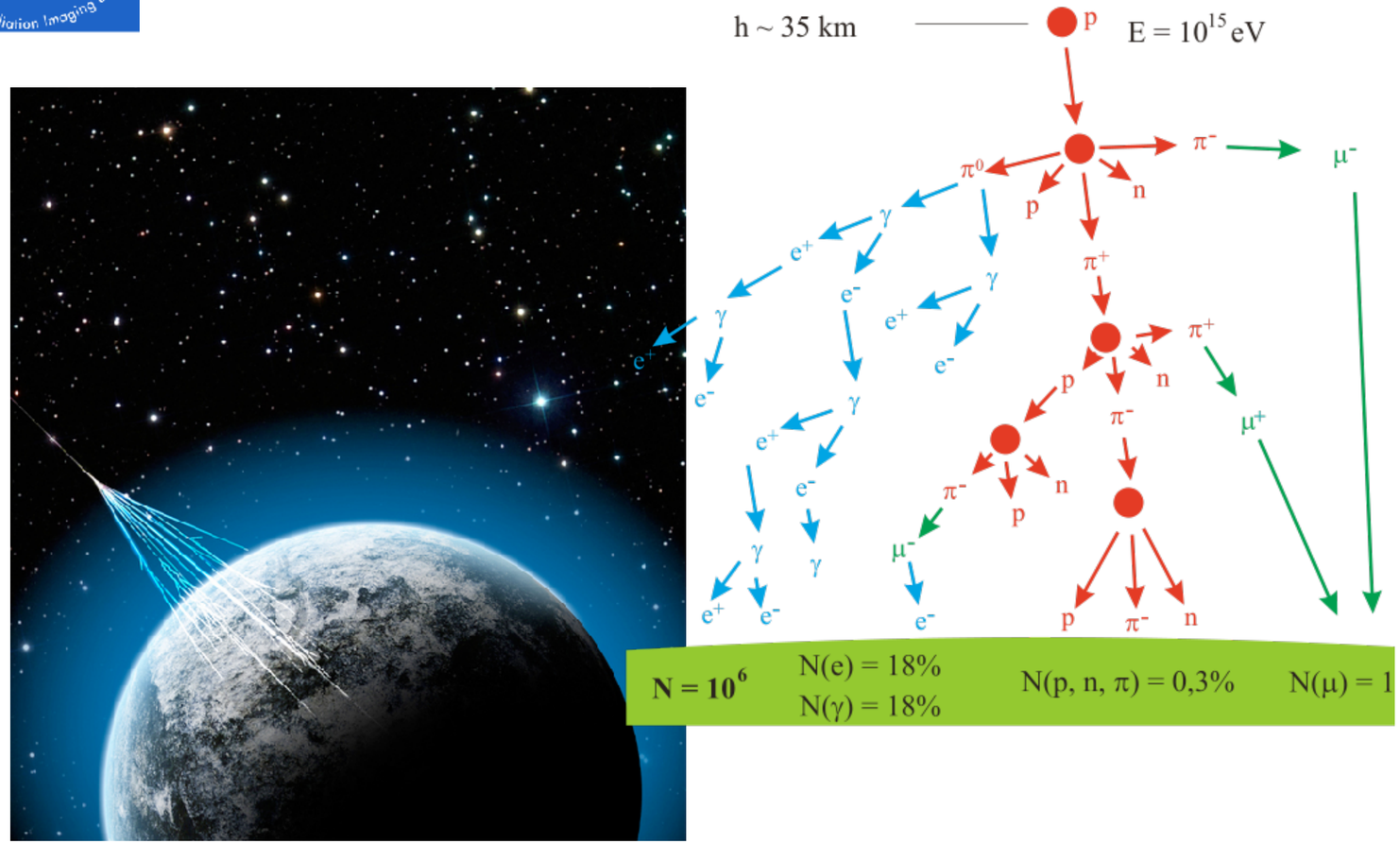
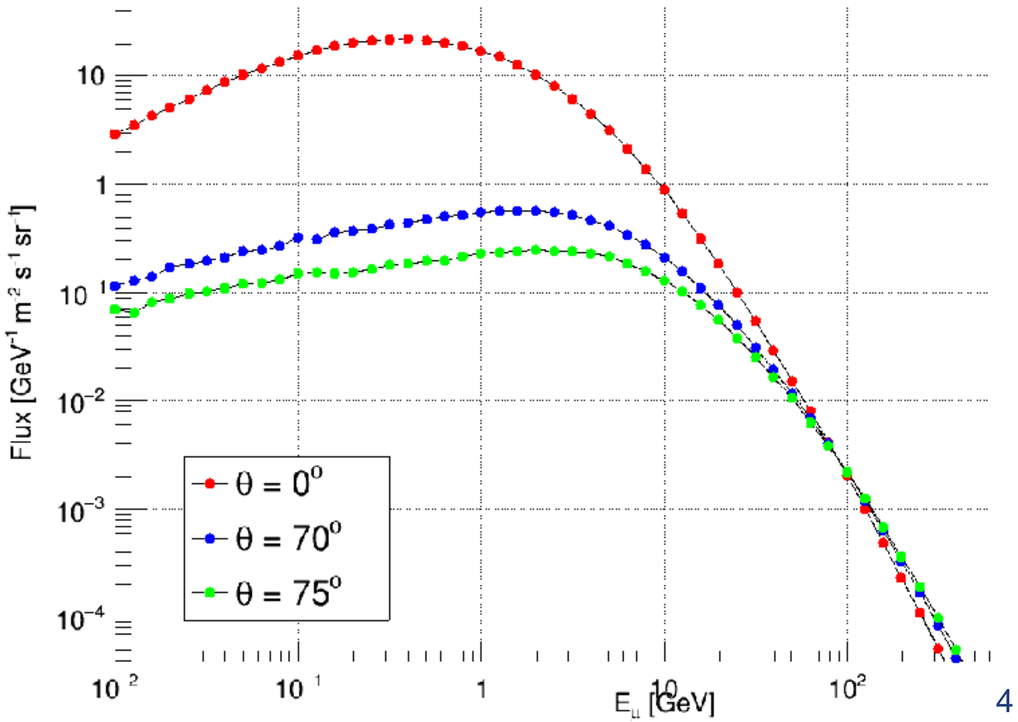


Fig. 13. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber. (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure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

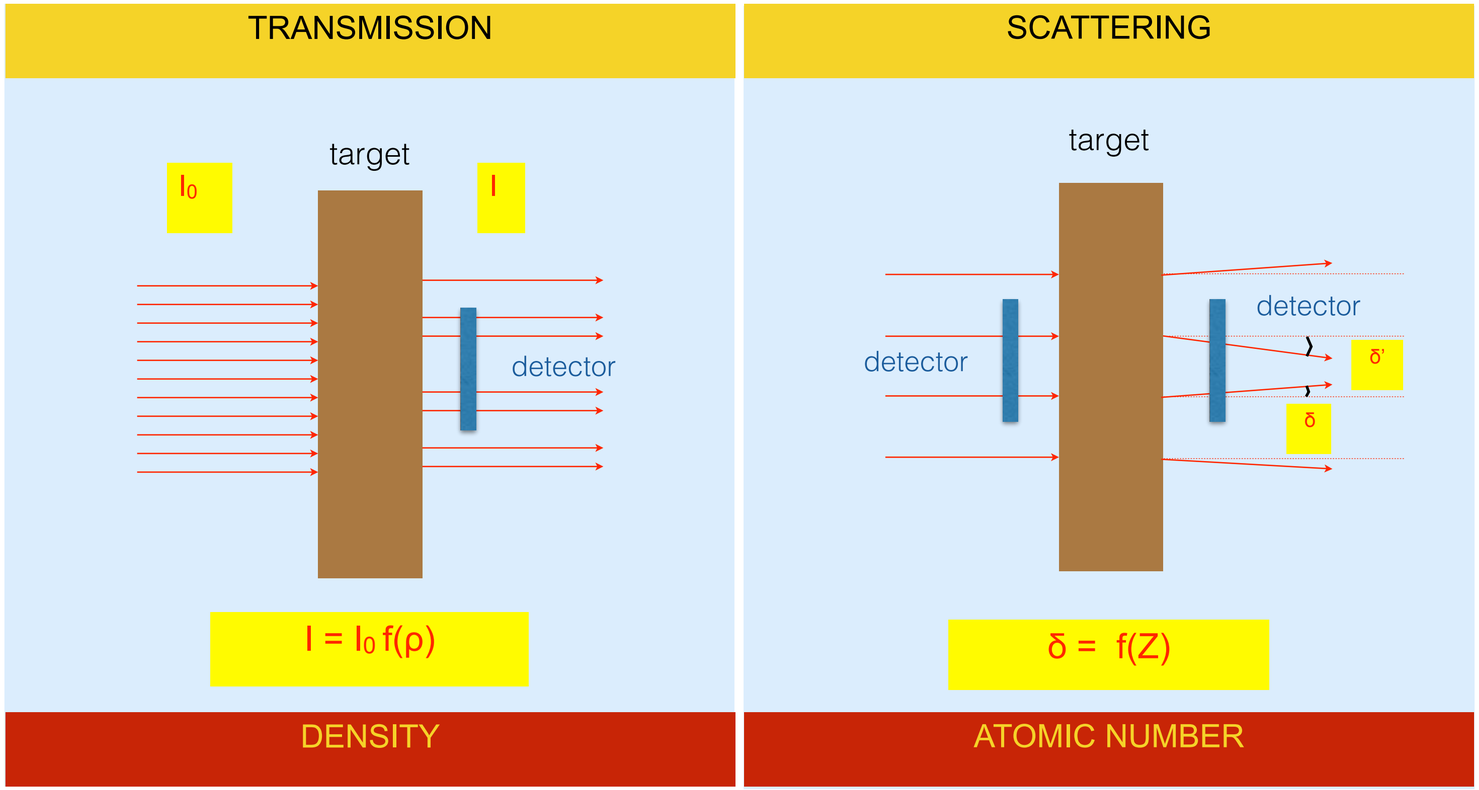
Muons from Atmospheric Showers



At sea level:
~1 muon/cm2/min i.e. ~1 muon/s crosses one's hand



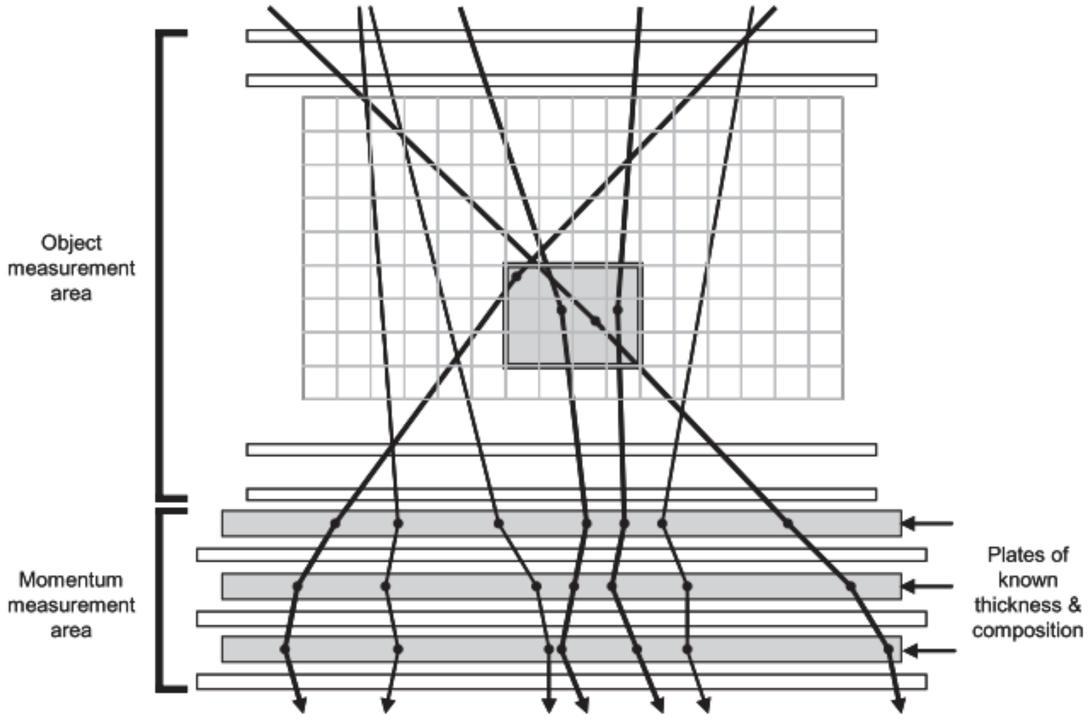
Two Interactions Useful for Imaging



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

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

Scattering muography



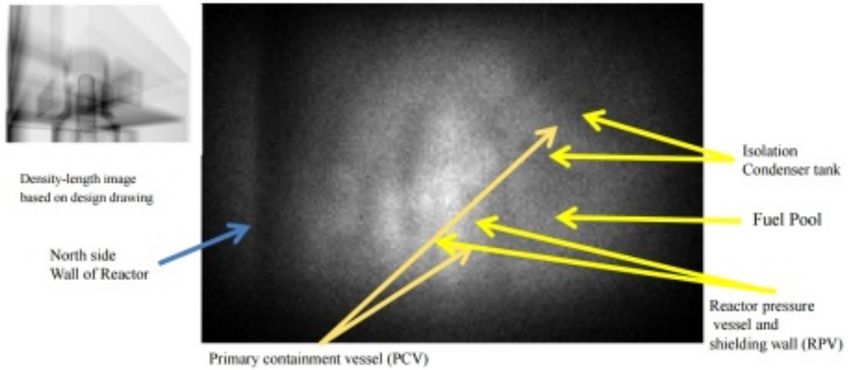
K.N. Borozdin, G.E. Hogan, Ch. Morris, W.C. Priedhorsky, A. Saunders, L.J. Schultz, M.E. Teasdale, "Surveillance: Radiographic imaging with cosmic-ray muons", Nature 422, 277 (20 March 2003) , doi:10.1038/422277a

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

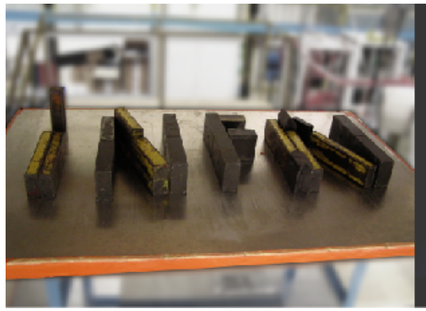
- Fukushima Daiichi 1
- The Situation at Fukushima

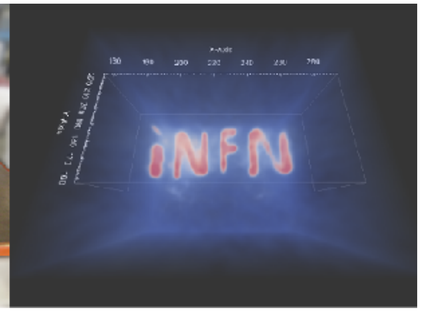
Related Links

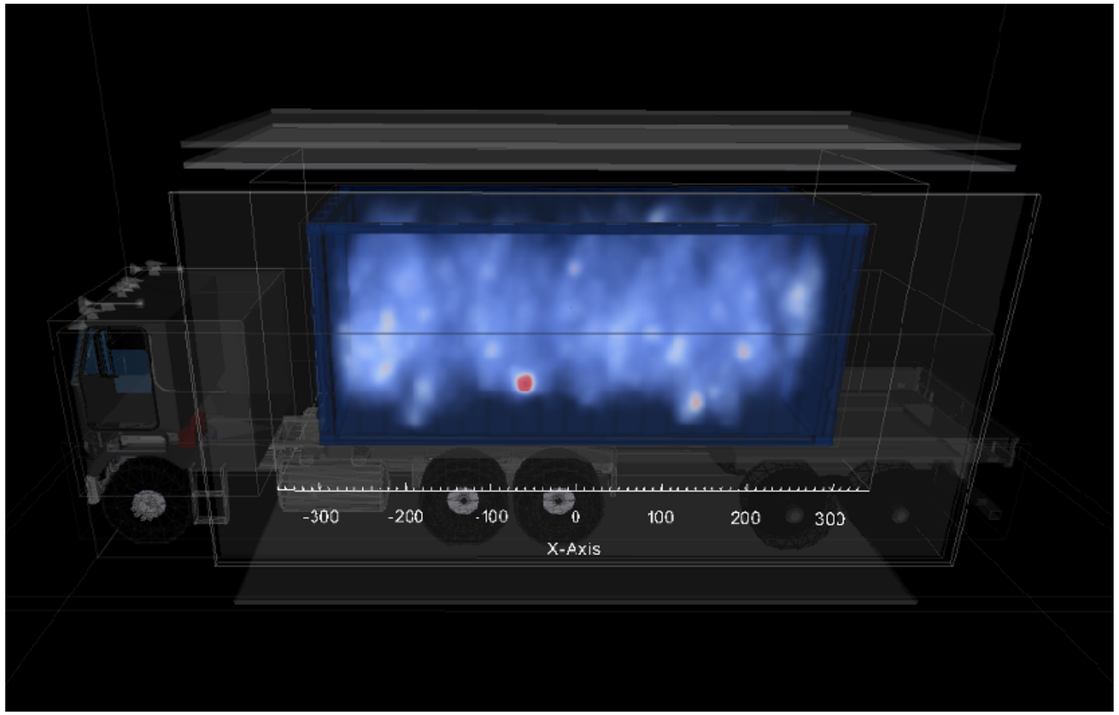
- Tokyo Electric Power Co. (Tepco)

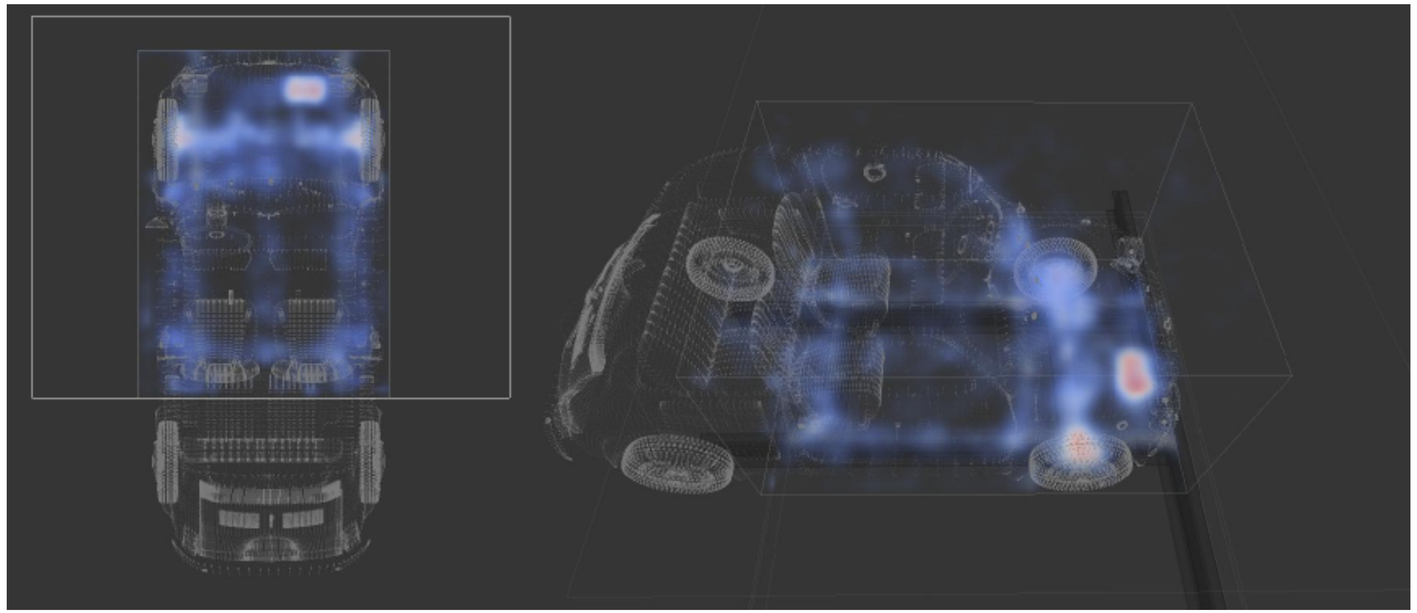
CMT(p) Cosmic Muon Tomography (project)

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





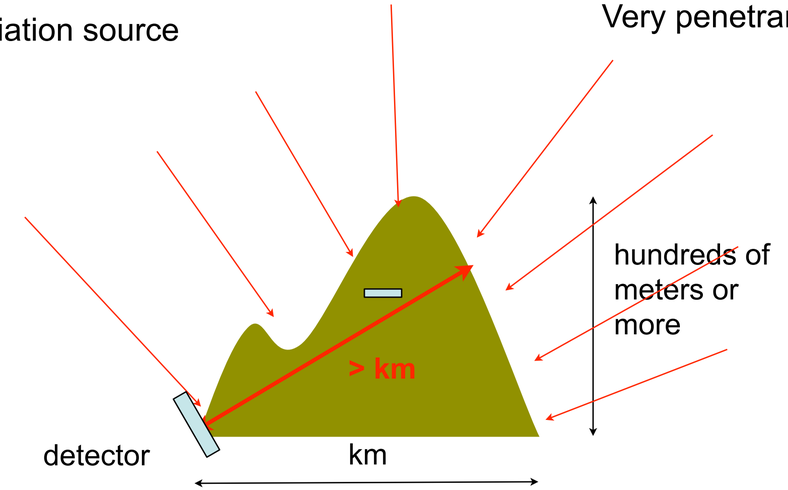


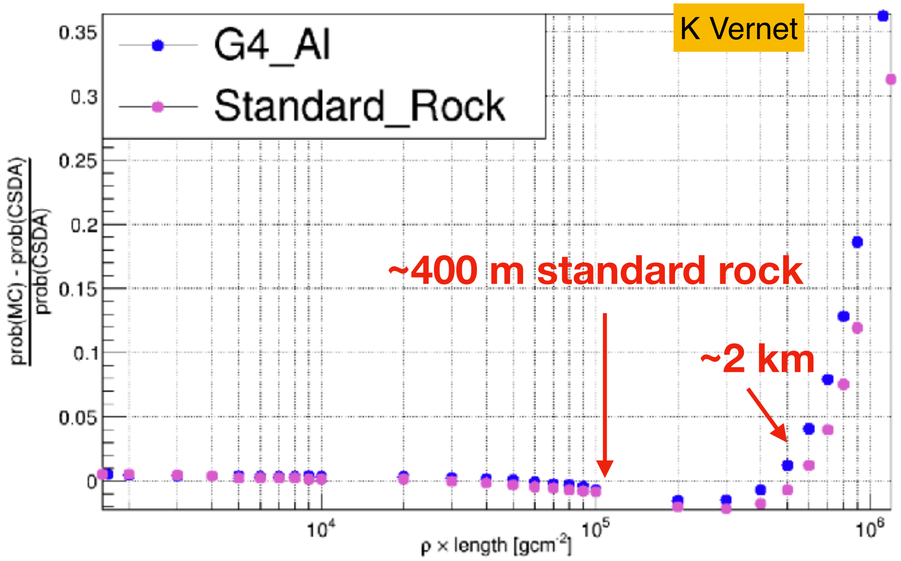


Transmission muography

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}

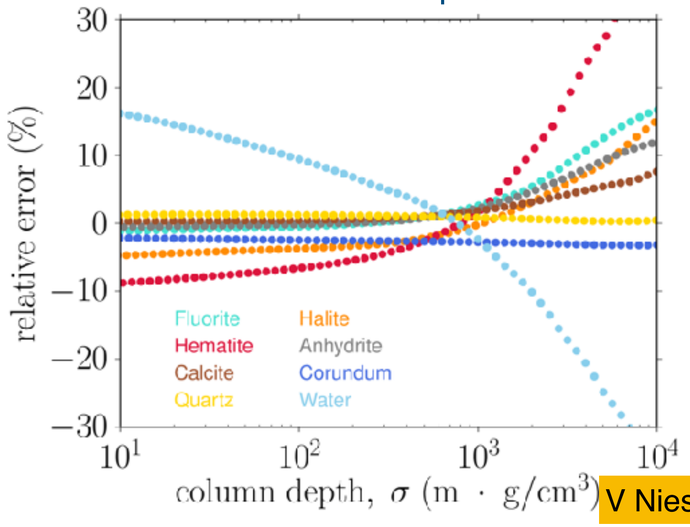
E_μ	10 GeV	100 GeV	1 TeV	10 TeV
R_μ	19m	155m	0.9km	2.3km

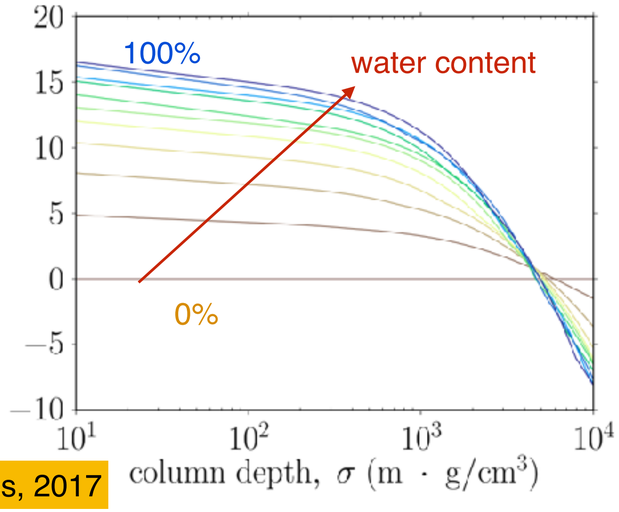
Transmittance ☞ integrated density

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

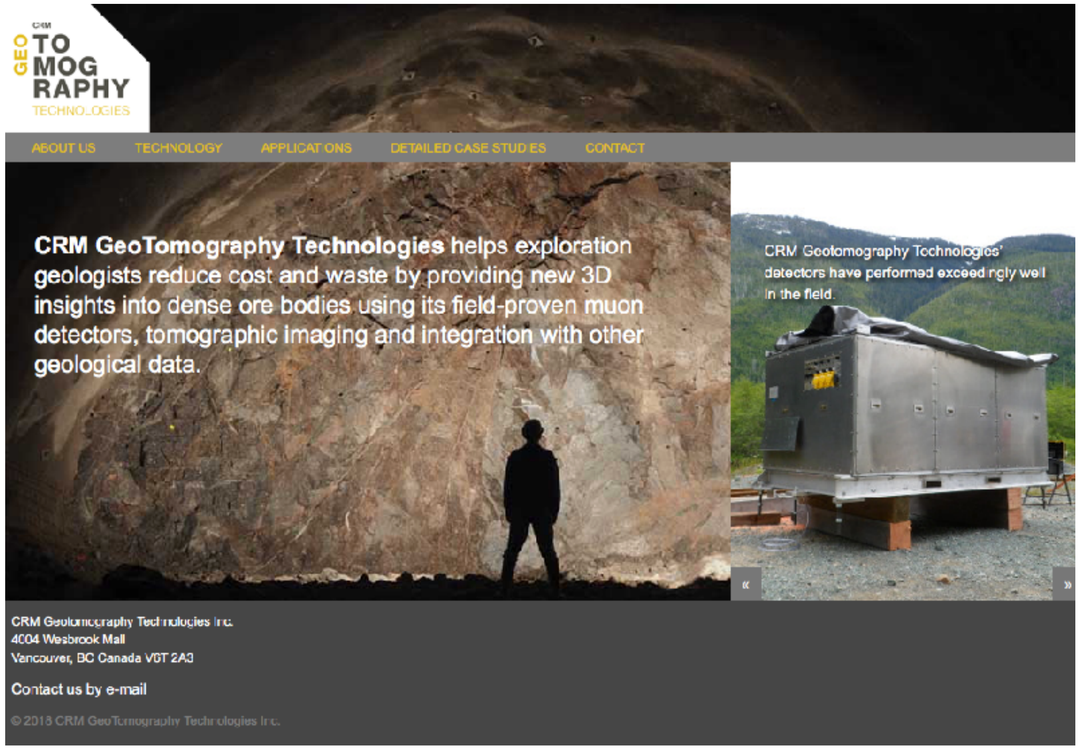
Relative error on integrated density

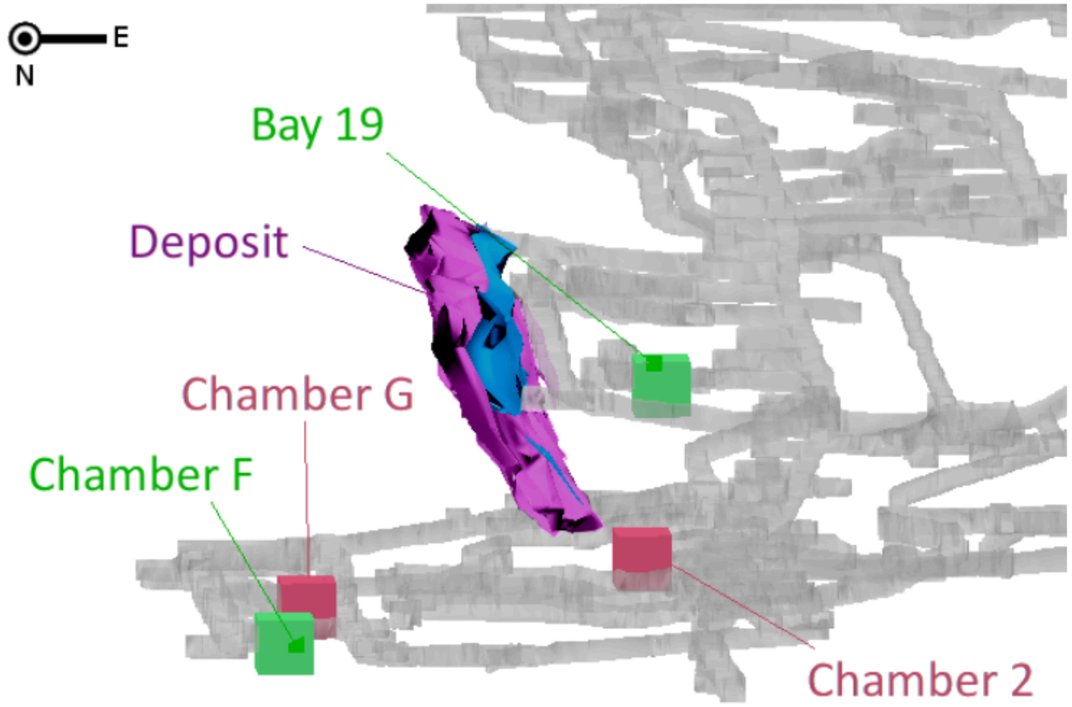
- when assuming propagation in standard rock and ignoring the chemical composition
- when assuming propagation in dry rock





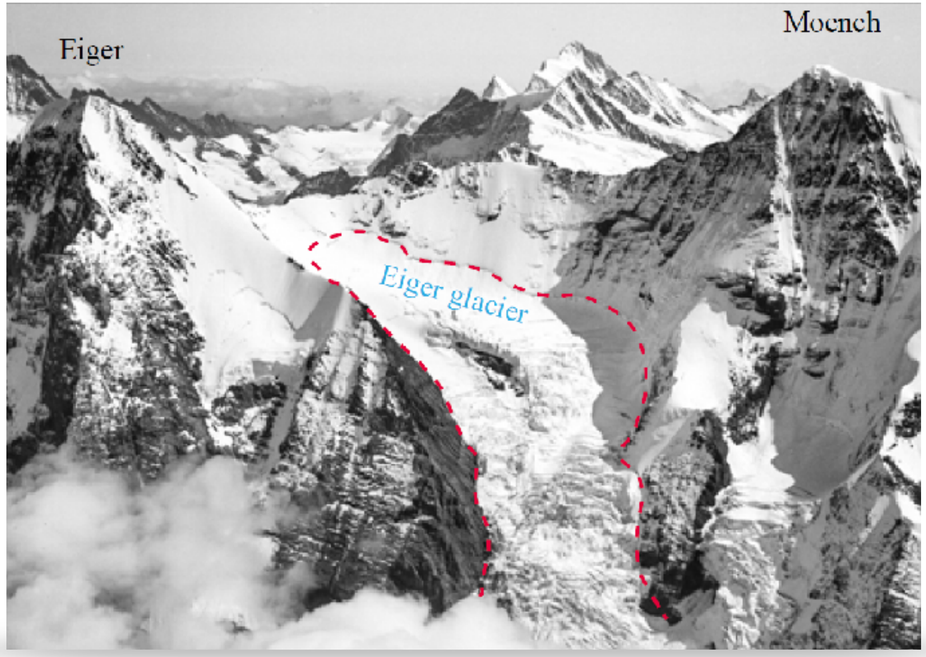
Transmission muography from "inside" : mining





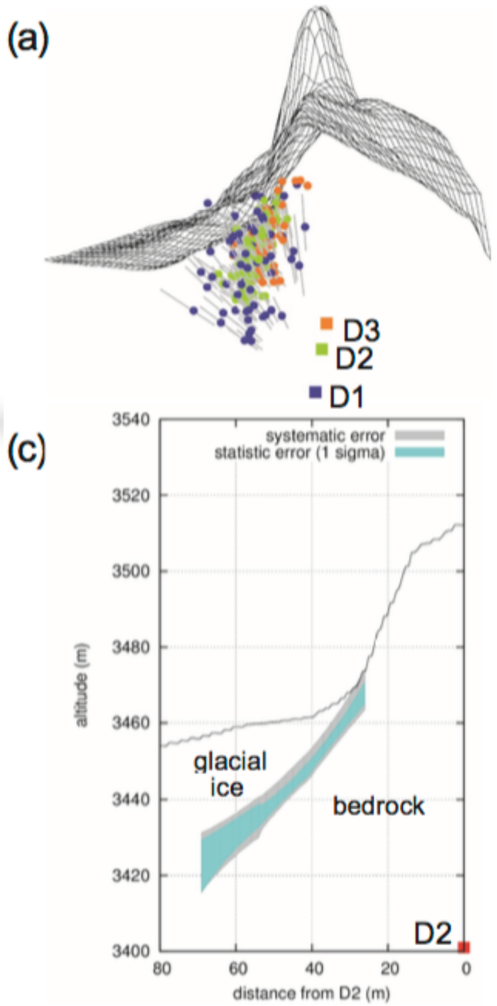
McArthur River Uranium Mine, 500 m underground

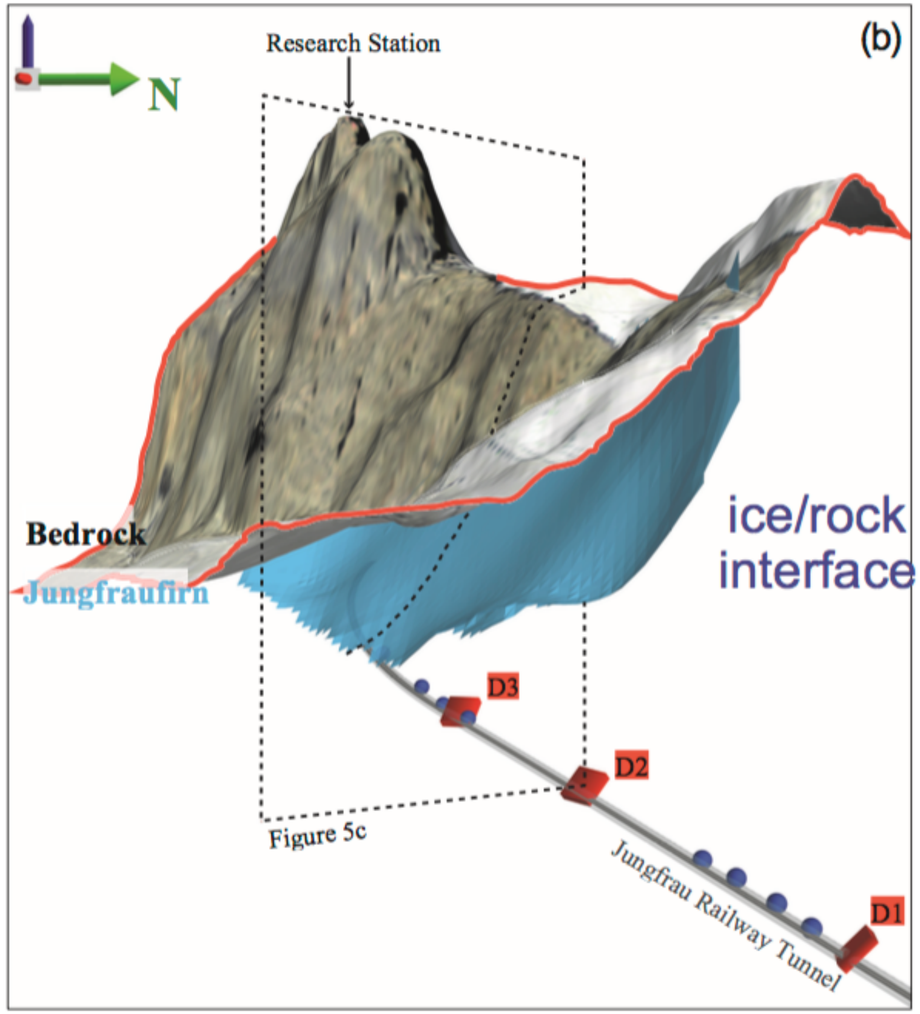
Transmission muography from "inside" : glacier stability



First measurement of ice-bedrock interface of alpine glaciers by cosmic muon radiography

Geophys Res Lett, doi:10.1002/2017GL073599





Obvious industrial & Military Applications

USING MUON TOMOGRAPHY

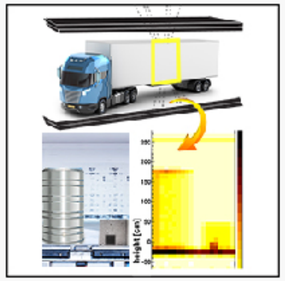
High-energy cosmic rays create showers of particles (Muons) in the upper atmosphere.

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.

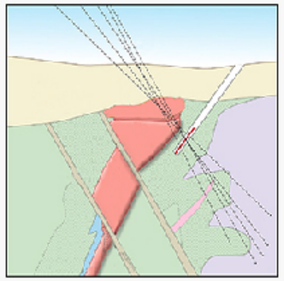
MORE

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

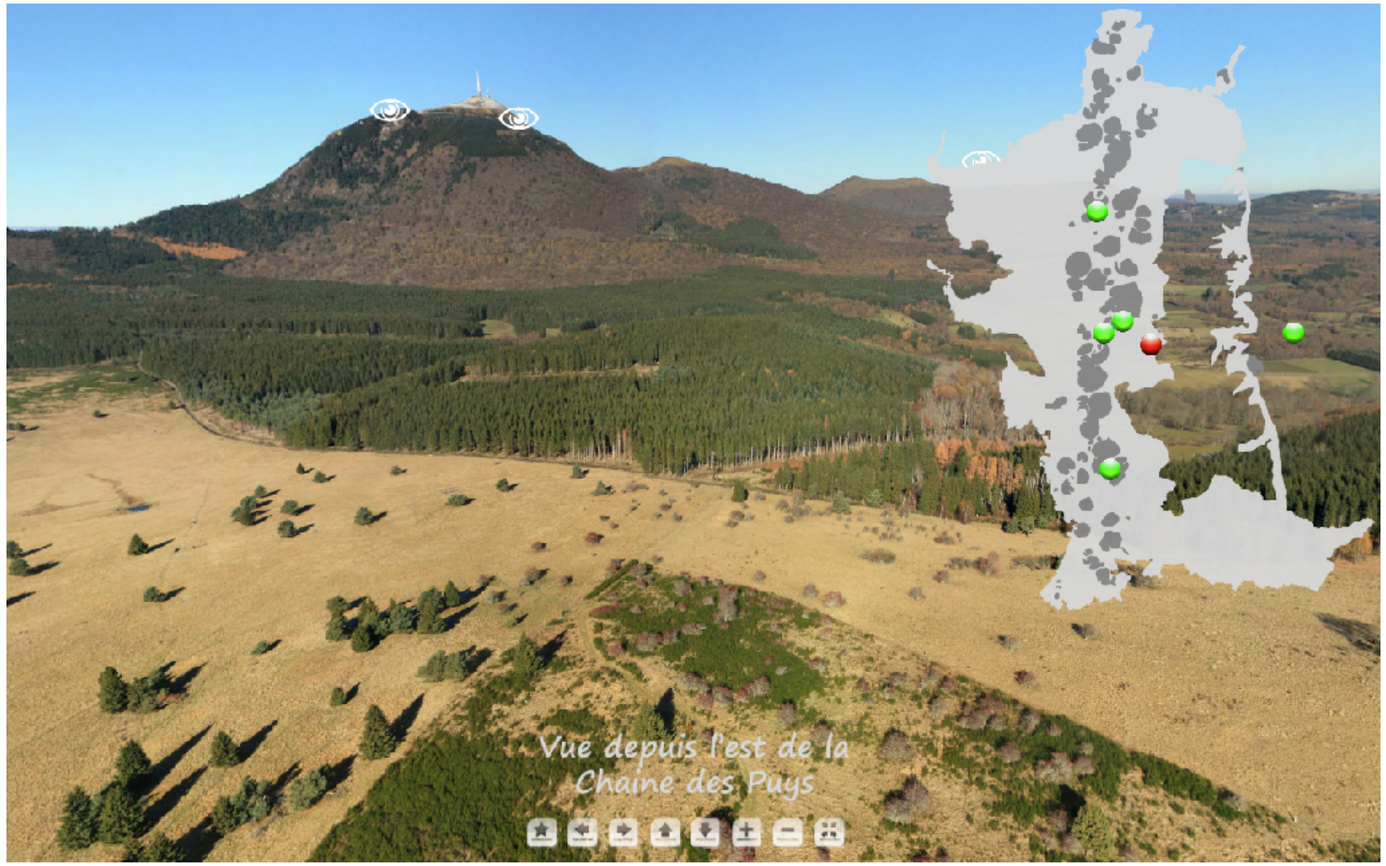
Transmission muography from "outside" : volcanology

- 11,000 years old composite dome in the Chaîne des Puys

- Dome characteristics:
  - ~400m high,
  - 1.8 km wide at its base

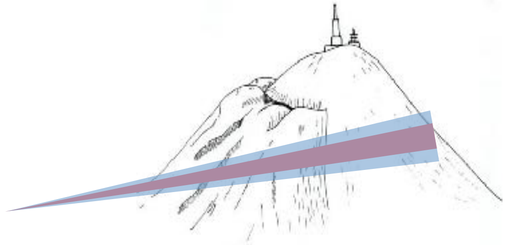
- Two distinct units:
  - × two lava pulses
  - × partial destruction of the first construction

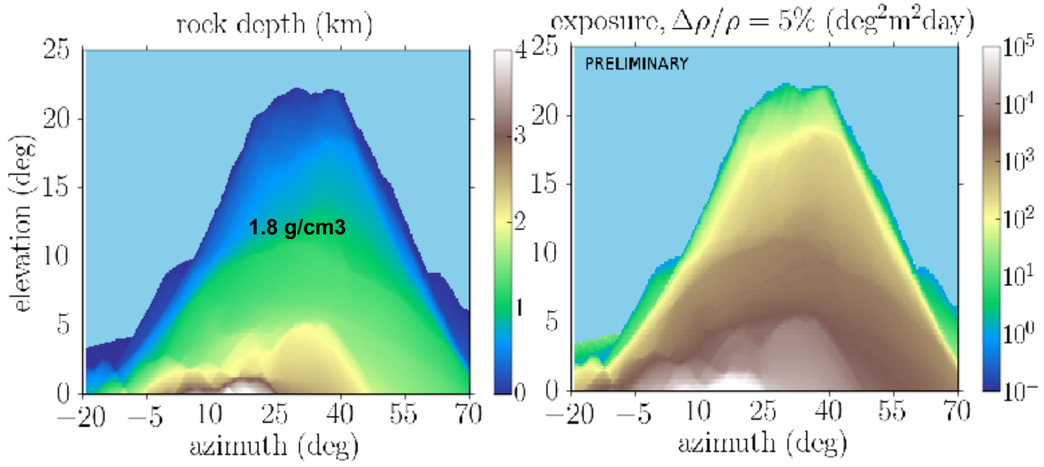
- Important hydrothermal alteration



Volcano Imaging with Ballistic Muons

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



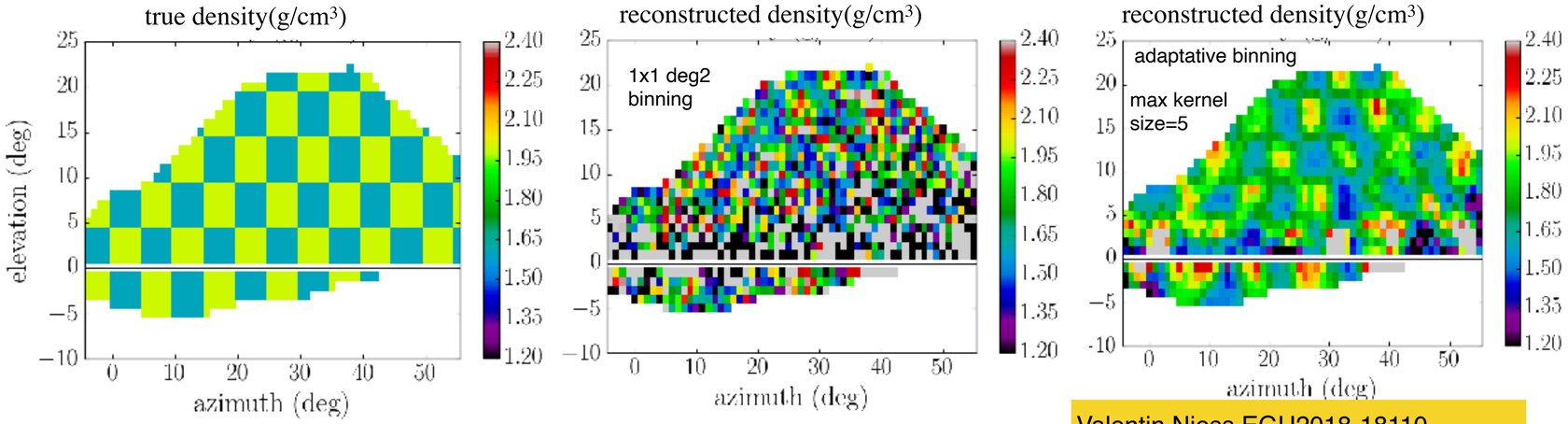


⇦ 10 days (10m² detector, 3°x3°)

⇦ 10 days (1m² detector, 3°x3°)

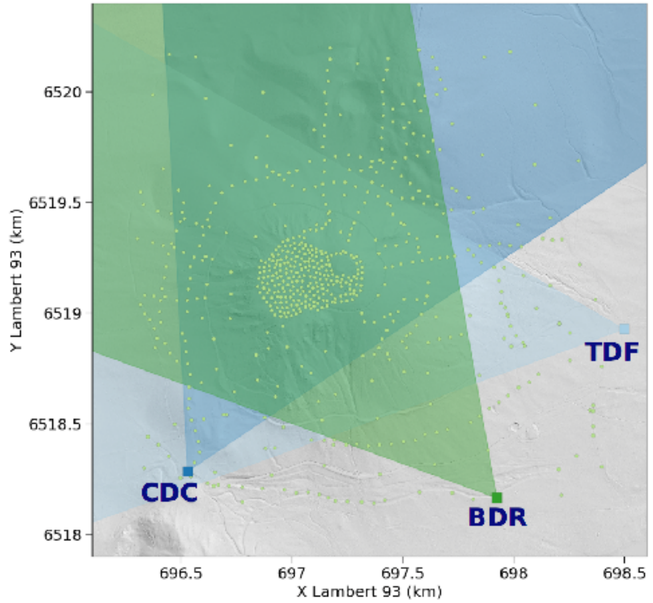
Infinite ways of statistically optimising the measurements and the model testing

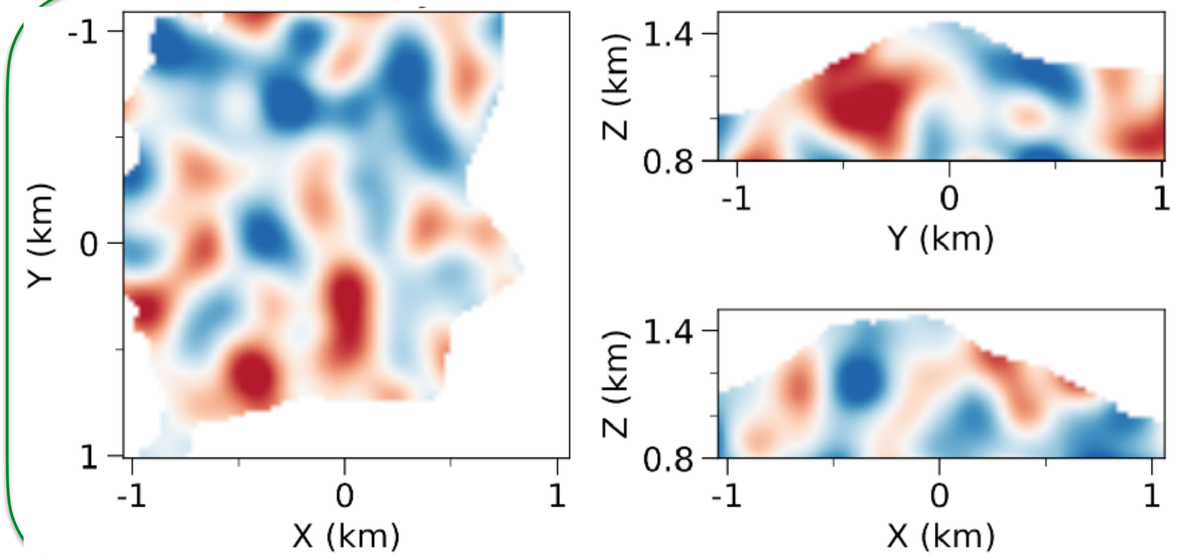
Synthetic model for Puy de Dome and 1 year data with TOMUVOL detector (~0.5 m2)



Valentin Niess EGU2018-18110

Tomographic Imaging with Ballistic Muons





Synthetic model of Puy de Dôme

0.5 x 0.5 x 0.5 m³ voxels

Gaussian random field for densities:

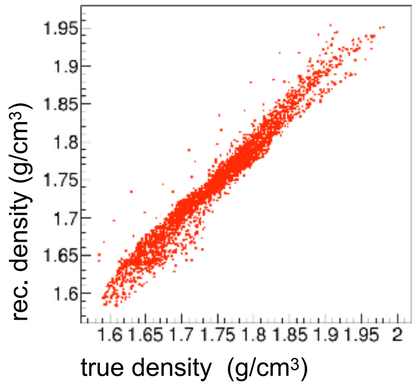
σ_ρ= 100 kg/m³

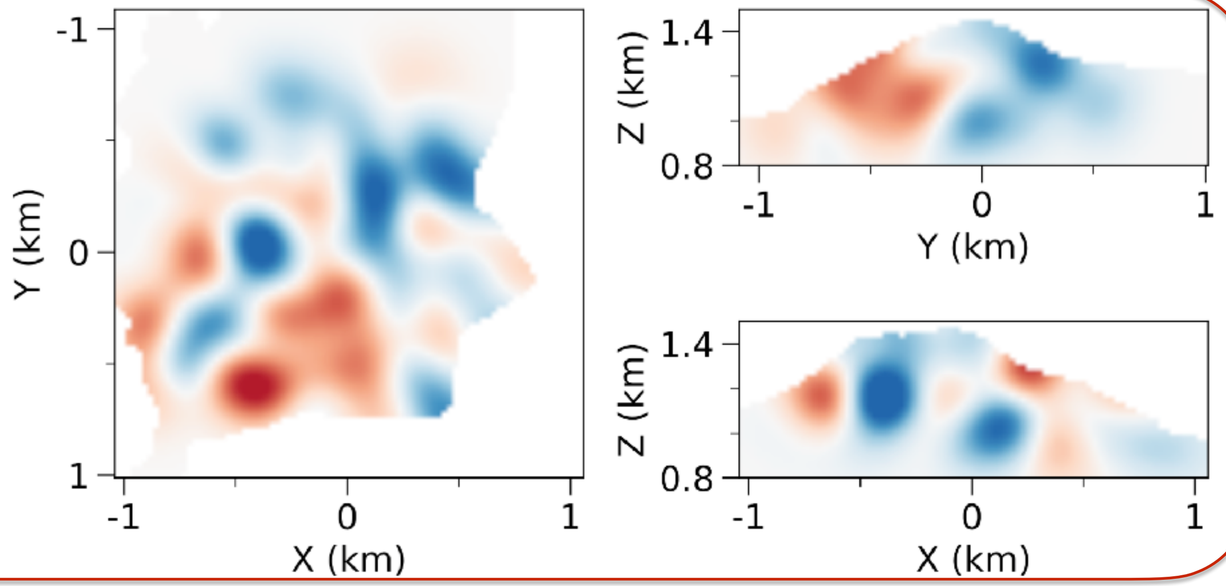
Λ = 200 m

A Barnoud et al, ``Bayesian joint muographic and gravimetric inversion applied to volcanoes"

Geophys J Int (2019)

One particular choice of inversion with three muographic viewpoints





Volcano Imaging with Atmospheric Muons

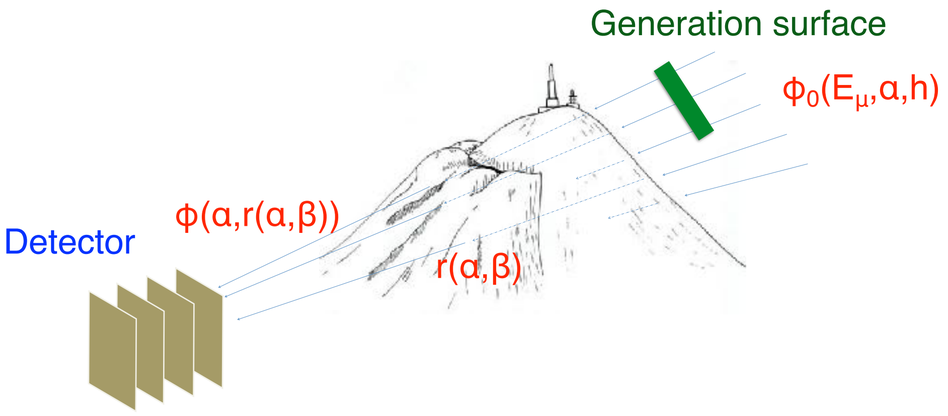
$$\frac{N}{N_0}(\alpha,\beta) \rightarrow \int \rho(r,\alpha,\beta)dr$$

calculated from an measured number of muons in a given direction

Measurement = Signal + **Background**

Can be calculated beforehand analytically (approximatelly)

Only known after dedicated measurements and detailed Monte Carlo simulations



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

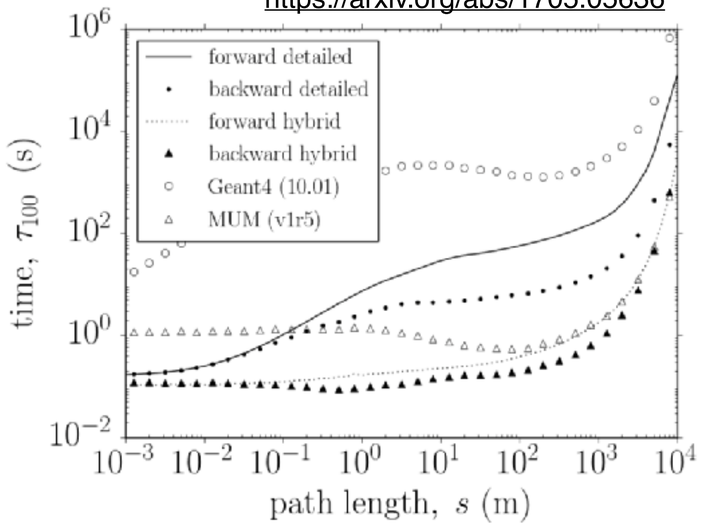
Table 1. Transmitted Flux of Ballistic Atmospheric-Muons Behind Different Rock Thicknesses and the Inverted Density Through a Muographic Measurement Affected by a Background Flux of 1.94 $m^{-2}\ d^{-1}\ deg^{-2}$ (the Quadratic Mean of the MU-RAY and TOMUVOL Measurements Given in Equations (4) and (5))

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

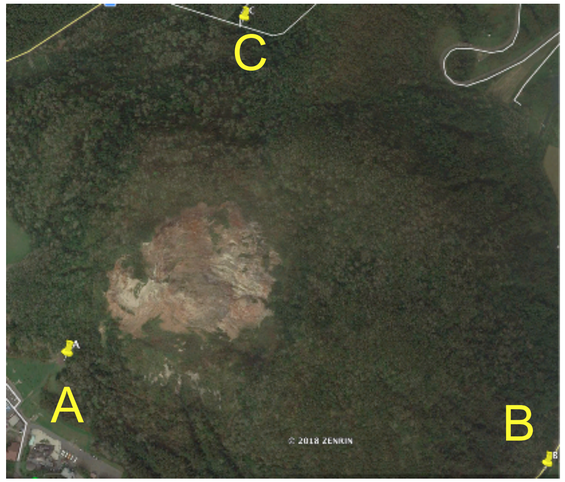
CPU time needed to simulate the transmitted flux with 1% accuracy

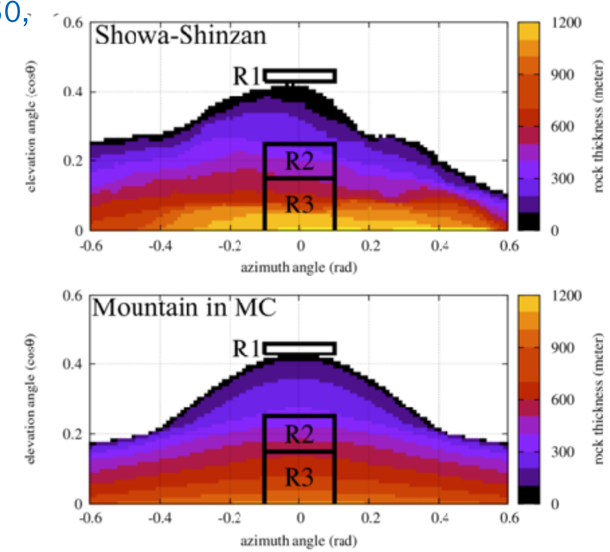
https://arxiv.org/abs/1705.05636

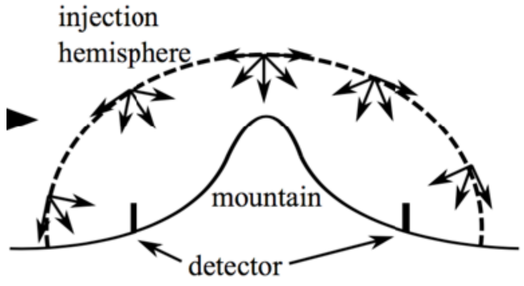


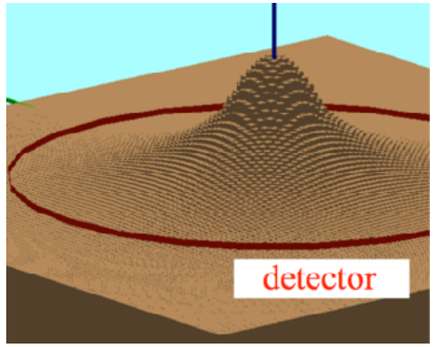
Showa Shinzan Volcano

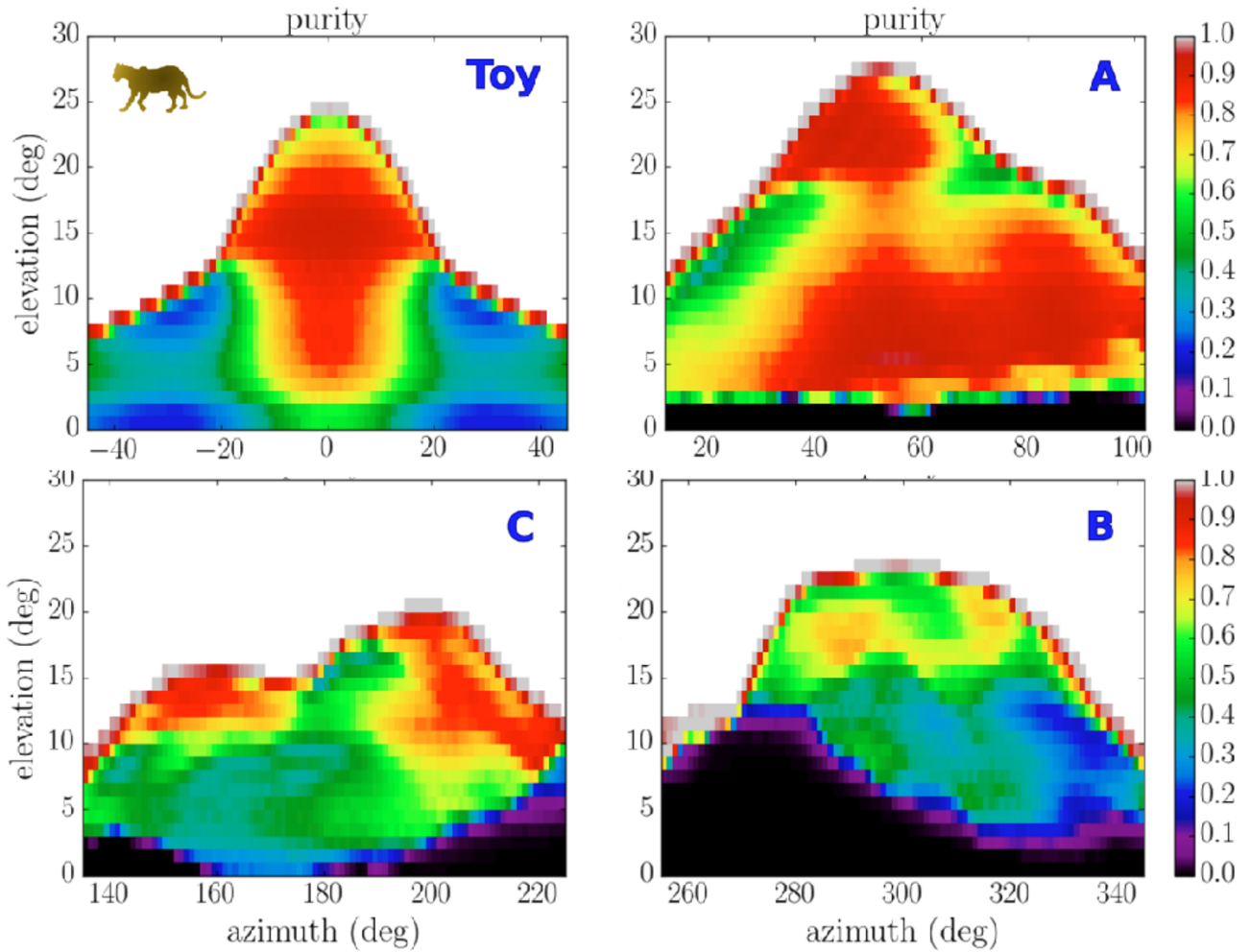
Nishiyama et al,
GeophysJInt, 206, Issue 2, 2016, 1039–1050,



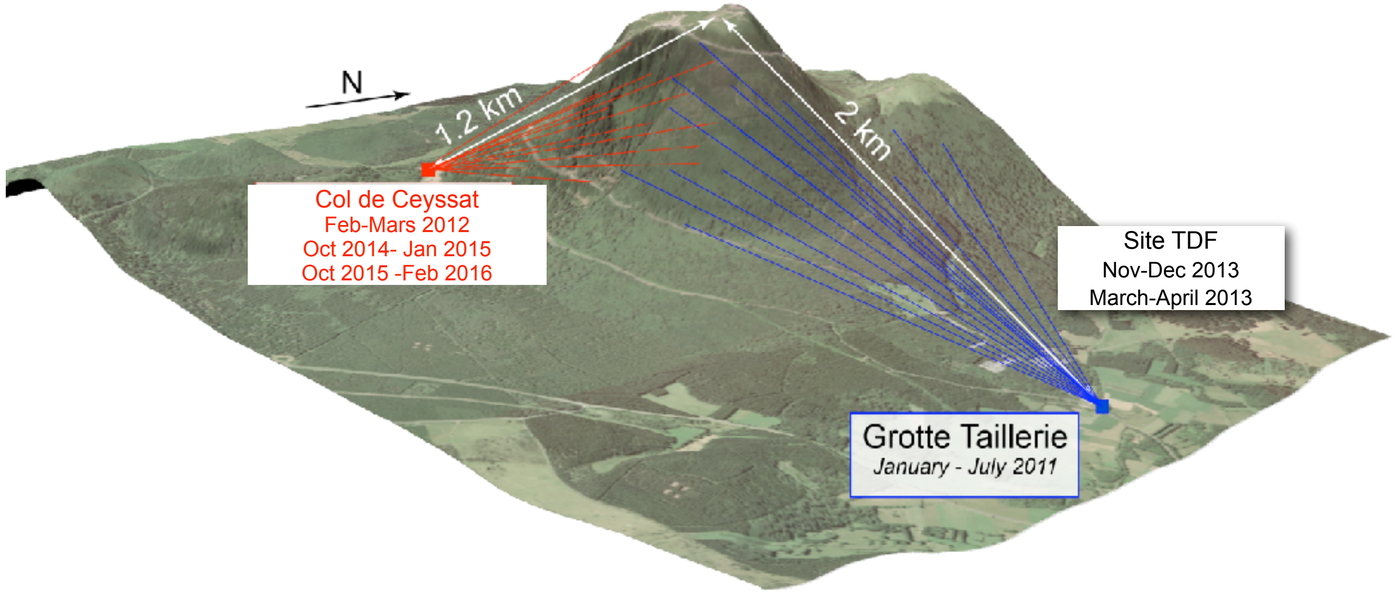


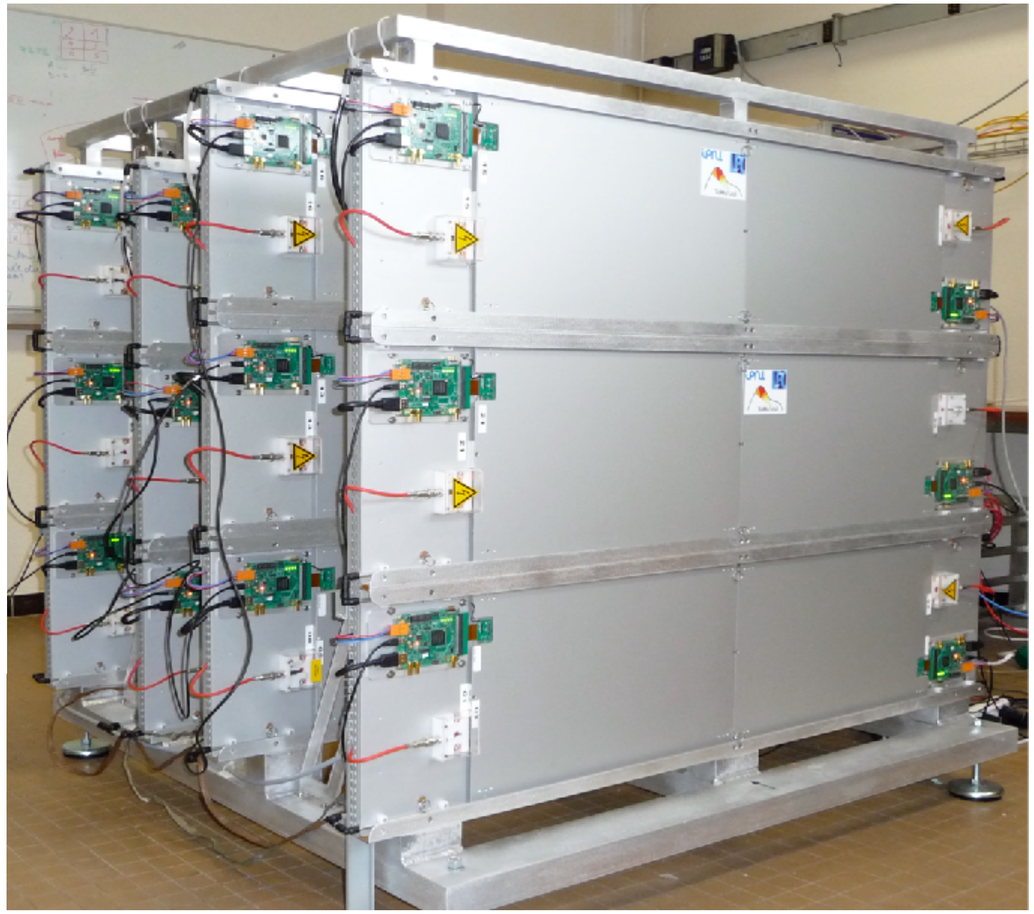






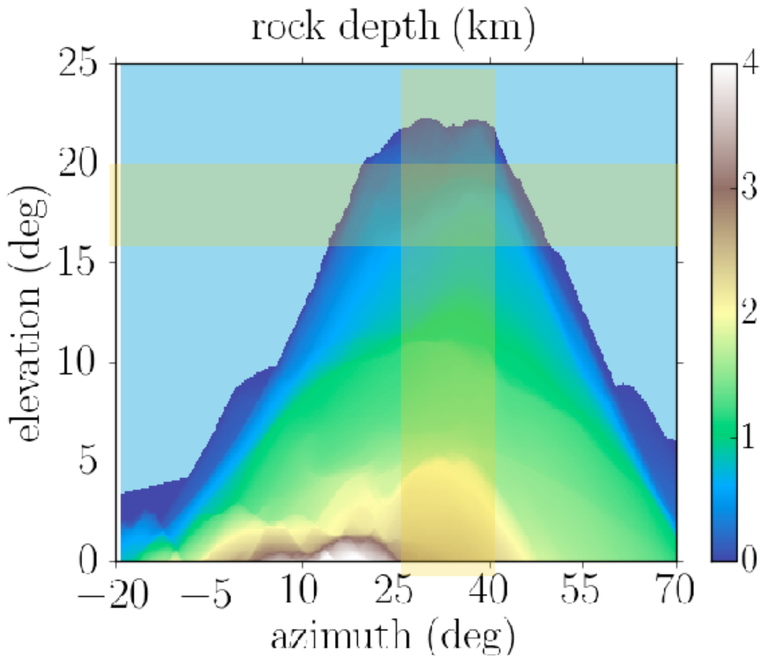
TOMUVOL project (2012-2018)

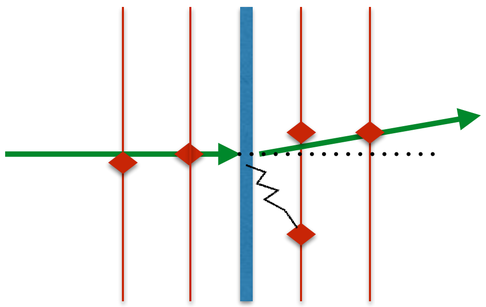




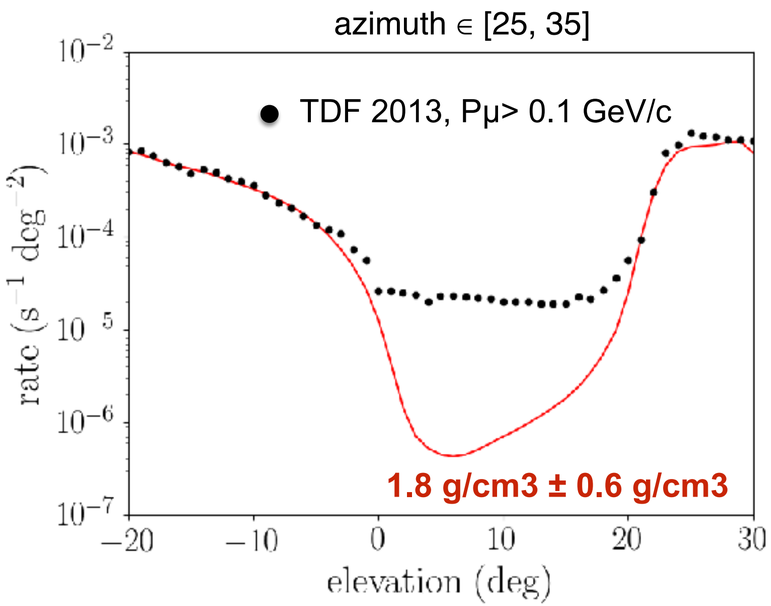
- 4 layers of 6 Glass Resistive Plate Chambers (GRPC)
- GRPC: gaseous detector with glass electrodes
- Applied voltage: 7.5 kV
- 1.2 mm gap filled by a gas mixture chosen for its ionisations properties
- 1layer:~1m^2
- Readout cells of 1 cm^2 (~ 40000 cells in total)
- Using a 5 MHz clock and auto-triggered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

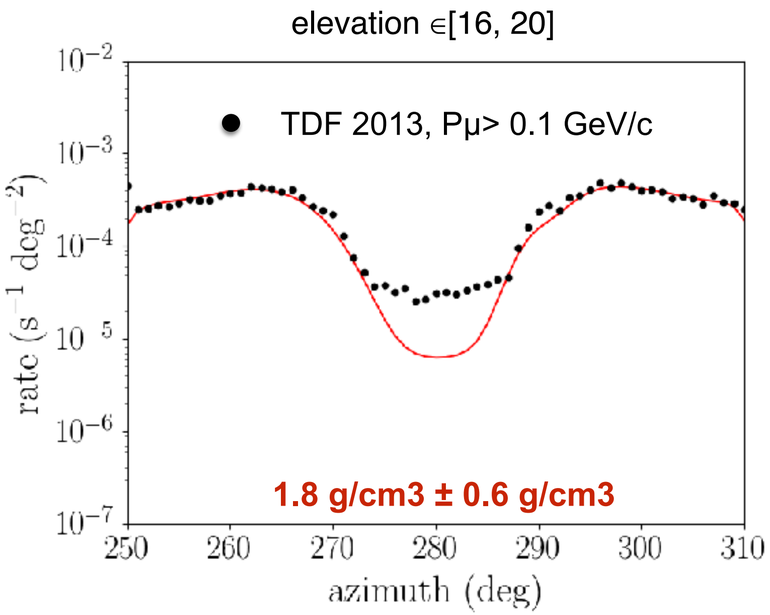
TOMUVOL :: Impact of the muon detection threshold

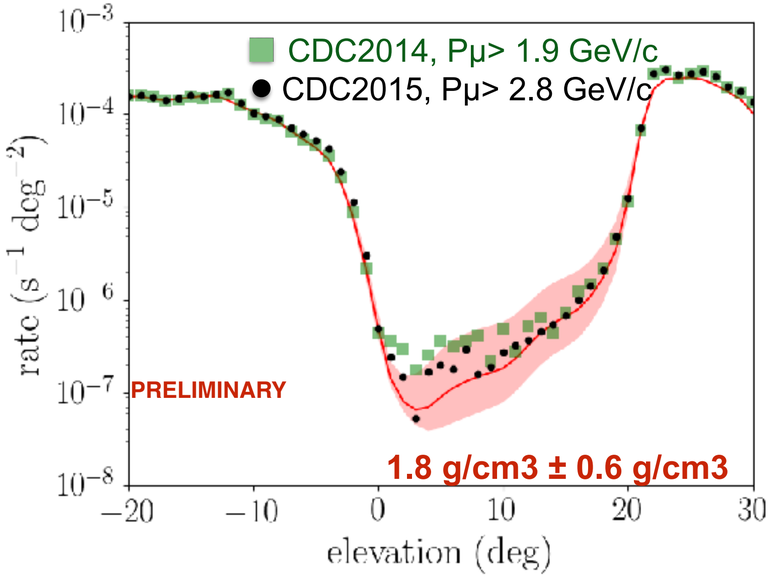


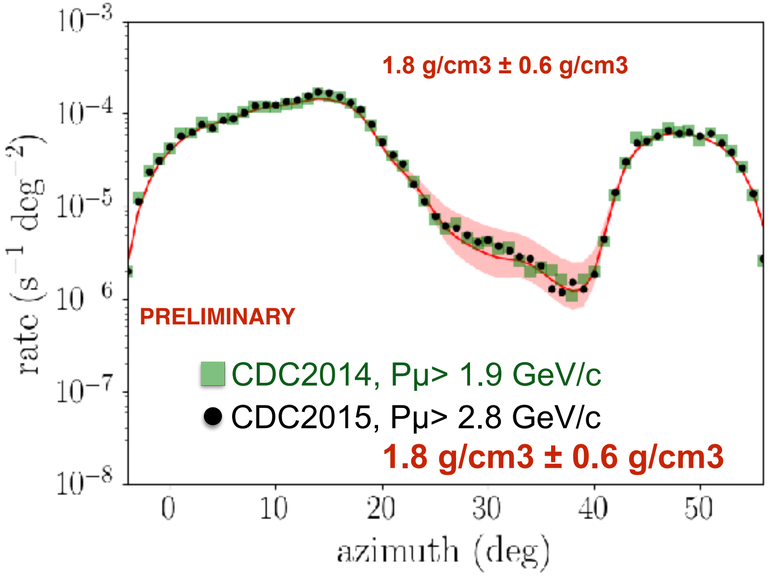


0 - 5 cm - 10 cm Pb

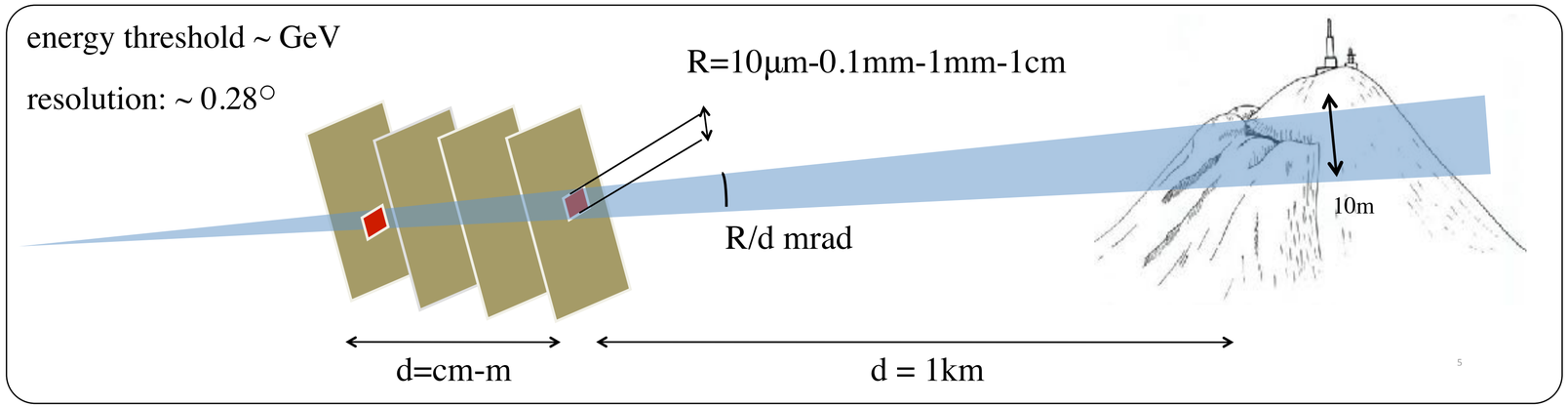


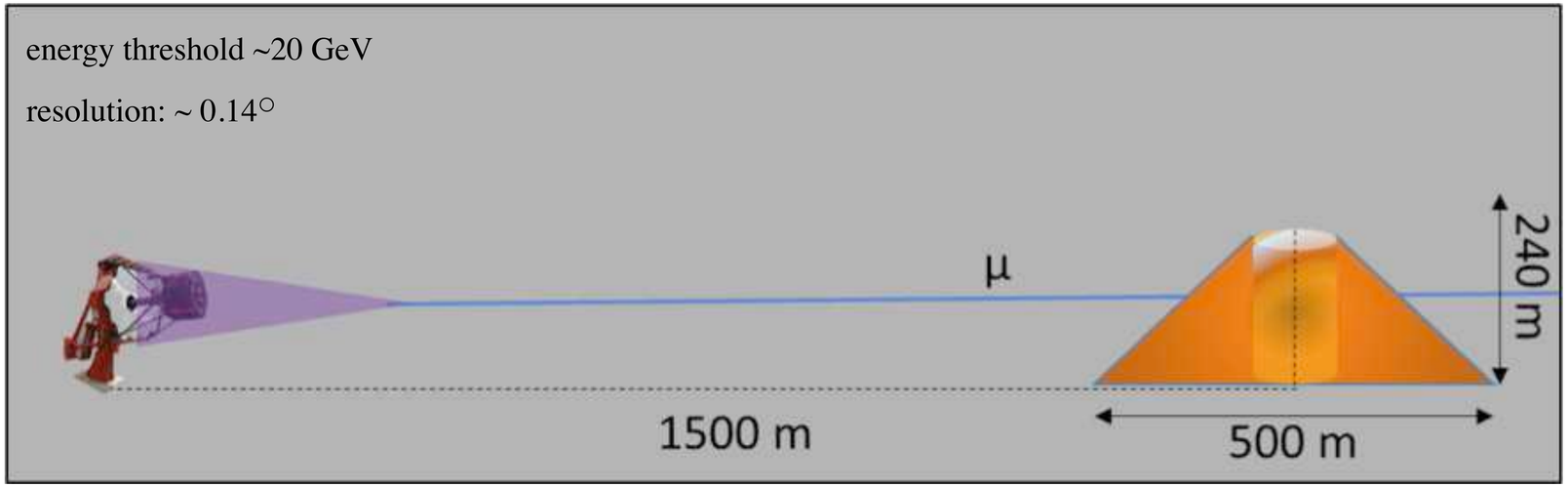


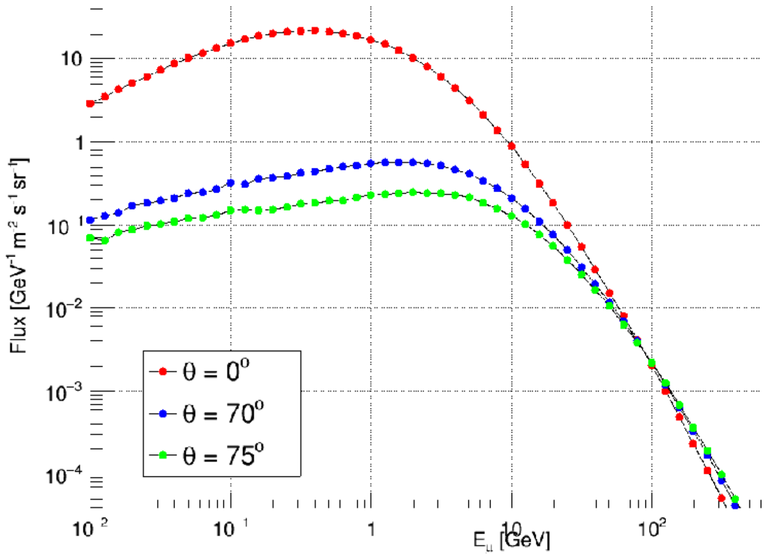




Different Types of Telescopes for Vulcano Imaging





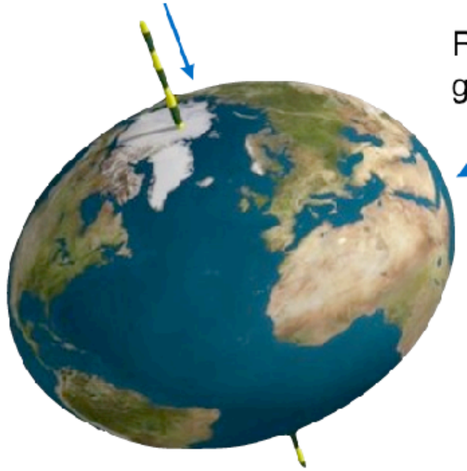


Osvaldo Catalano, Melania Del Santo, Teresa Mineo, Giancarlo Cusumano, Maria Concetta Maccarone, Giovanni Pareschi, arXiv:1511.01761

Muography vs Traditional Geophysical Methods for Volcano Imaging : Gravimetry

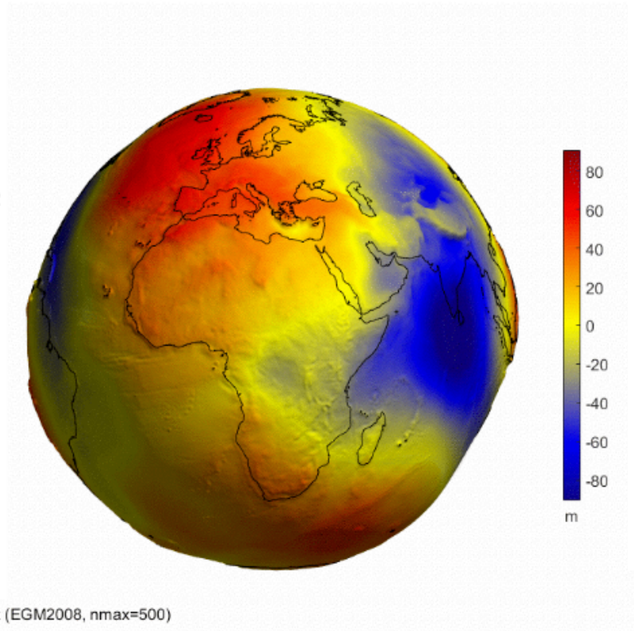
Ellipsoidal Earth

R_{poles} = 6357 km
g_{poles} = 9,832 m/s²



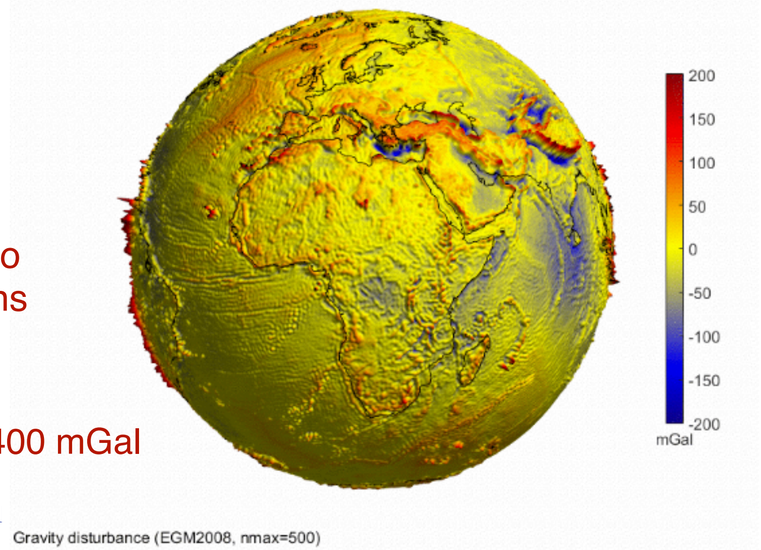
$R_{equator}$ = 6378 km
$g_{equator}$ = 9,780 m/s²

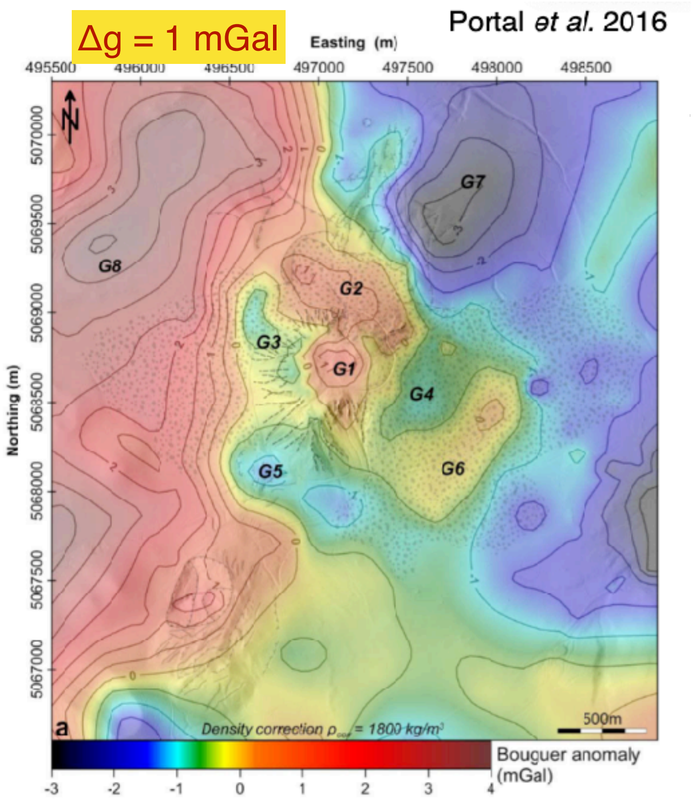
Geoid (equipotential surface following the averaged sea level)



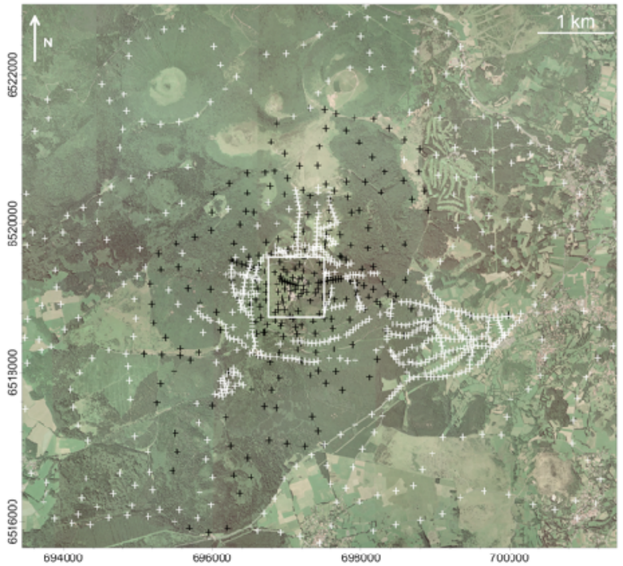
Gravity field variations due to density variations

Δg = 0,004 m/s2 = 400 mGal

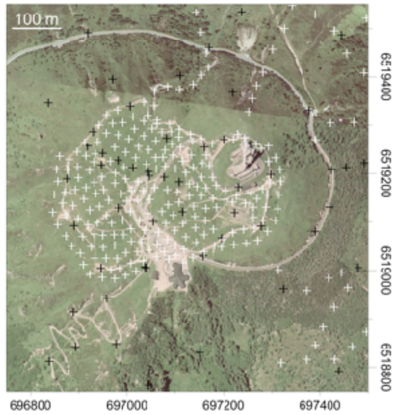




GPS and Scintrex CG5 gravimeter



Gravity stations location for the total survey

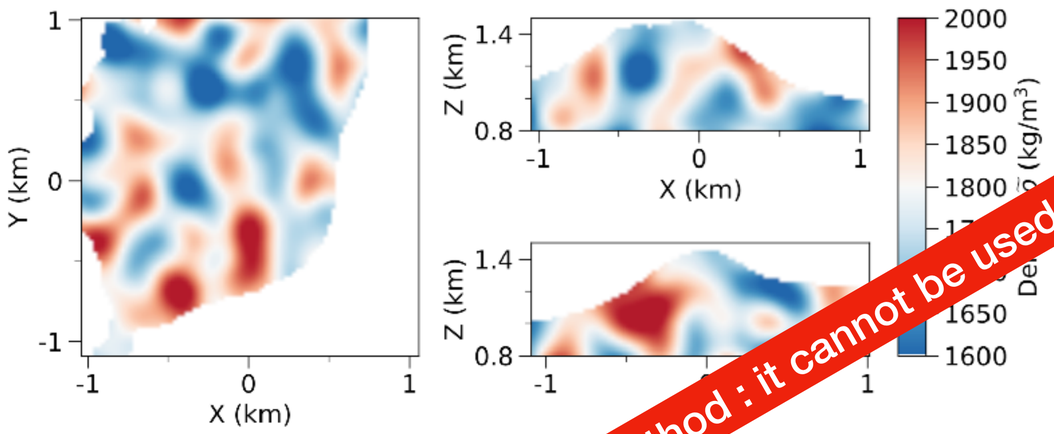


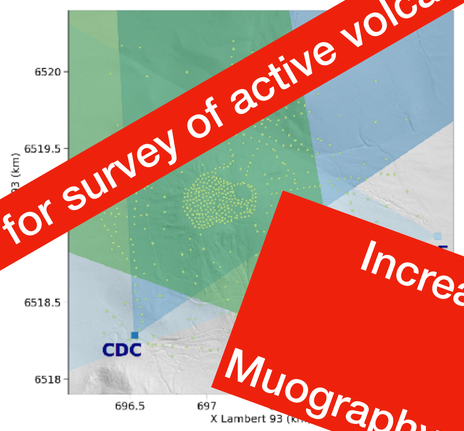
Summit area gravity stations

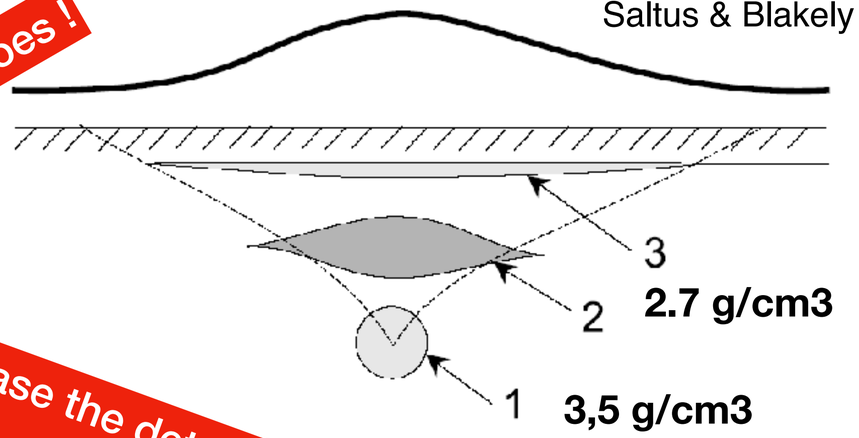
Muography vs Traditional Geophysical Methods for Volcano Imaging : Gravimetry

Saltus & Blakely 2011

Simulated model of the volcano

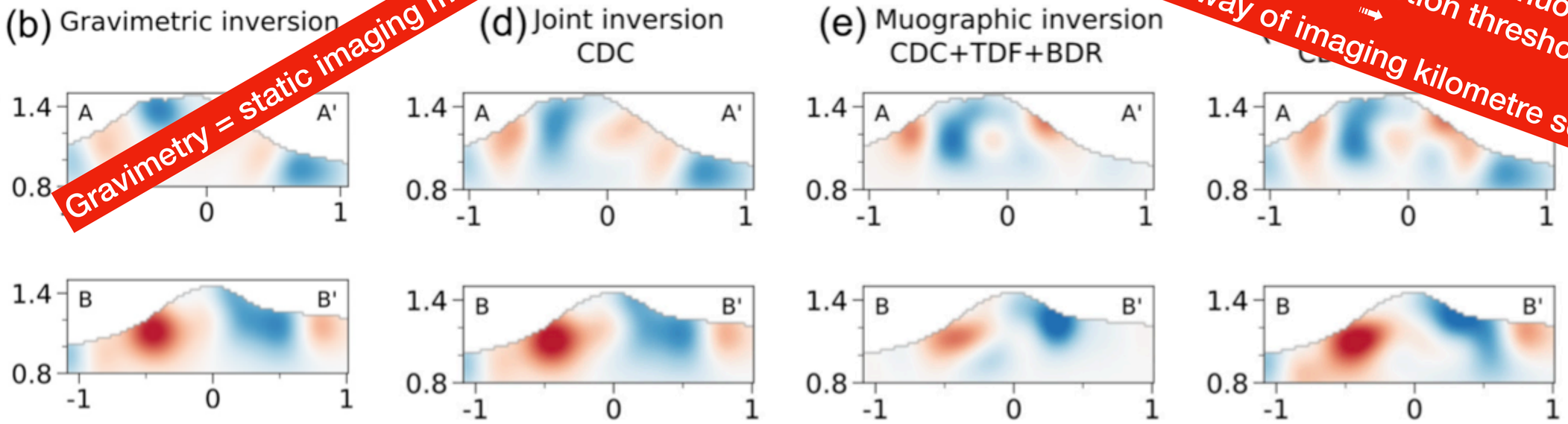






Gravimetry = static imaging method : it cannot be used for survey of active volcanoes !

Increase the detection surface of muon telescopes
Control the detection threshold
➡
Muography= best way of imaging kilometre scale vulcanoes



Conclusion

Muography - is a fast developping field with a lot of potential and a broad spectrum of applications:

- **inland security**
- **archeology**
- **mining**
- **volcanology**
- **....**

Further development will depend on the availability of

- **robust**
- **low cost**
- **large area**
- **high segmentation**

detectors and (in same cases) successful transfer of rather complex reconstruction algorithms towards the user community.