Muography

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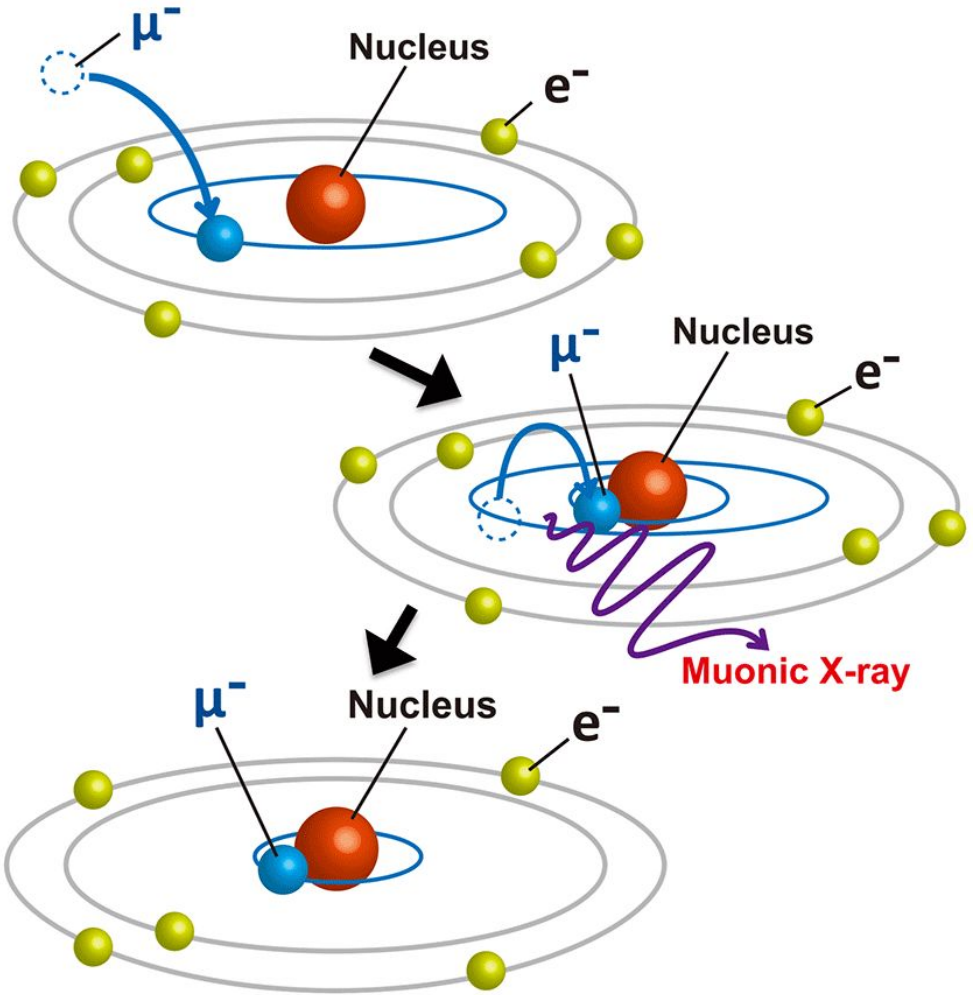
21.02.2022 13:00

Muons

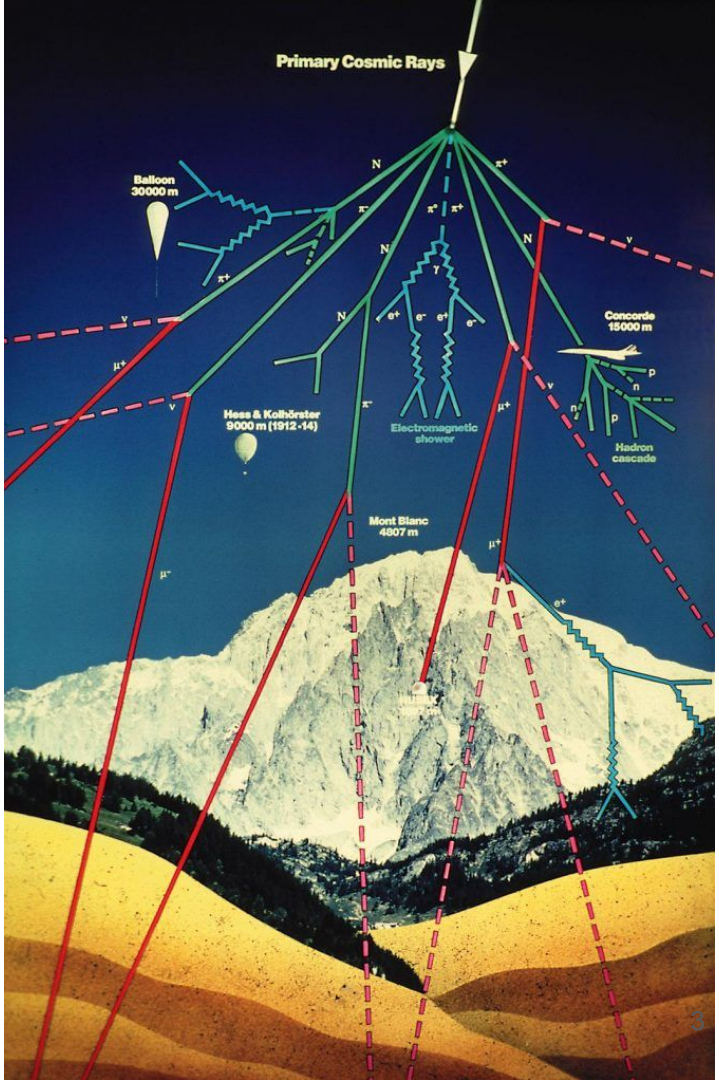
- Discovered in 1936, the muon is a heavier (~ 200 times) cousin of the electron.
- It has a lifetime of 2.2 μs and decays into an electron and electron neutrino.
- Due to this long (relatively) lifetime, it can reach the sea level before decaying.
- Muons penetrate much further than X-rays, and they are nondestructive.



Cosmic muons

Muons are unstable particles and they are continuously being created naturally when charged particles from outer space enter our atmosphere.

These muons appear at a rate of about one muon per minute per cm^2 at sea level.



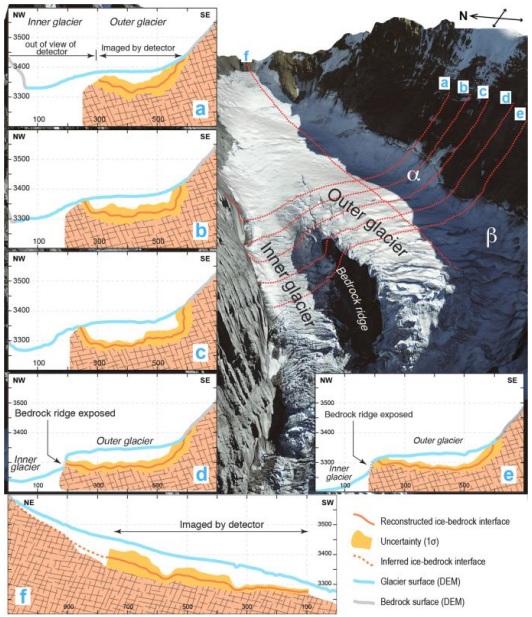
Disclaimer

Muography is a very broad topic.

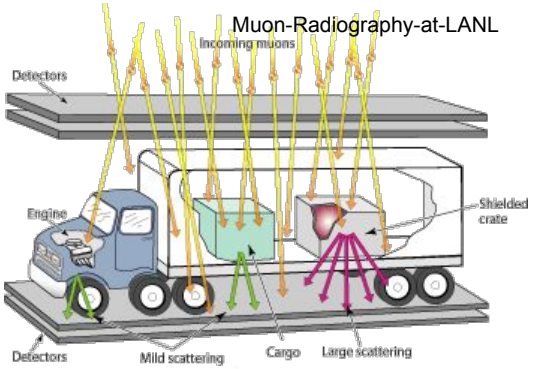
I can only provide an overview of my experience.

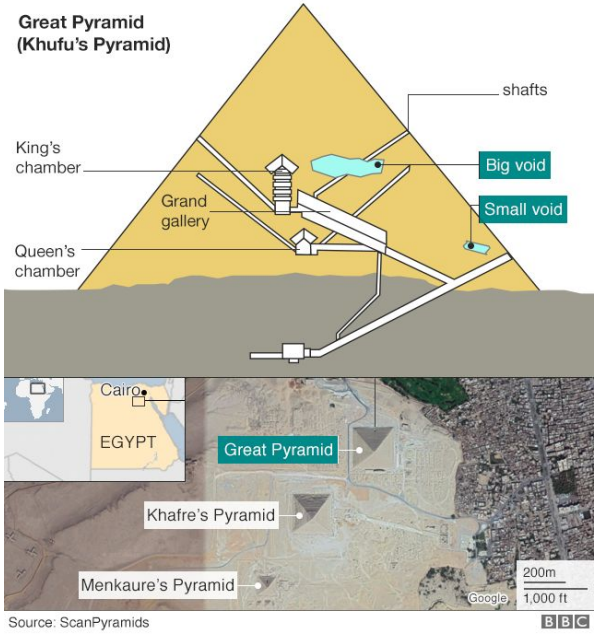
Only 2+ years working on instrumentation and DAQ for the GRPC detector (Tomuvol / MIM) in Clermont-Ferrand, France.

Muography targets



doi.org/10.1038/s41598-019-43527-6





bbc.com/news/science-environment-41845445

https://doi.org/10.1002/2015JB011969

Puy de Dôme

doi.org/10.1038/s41598-019-43131-8

Stromboli

Challenges with muography

- Offsite experiments in remote areas without infrastructure. (No electricity, high speed internet)
- Long travel time to fix problems or collect disk drives.
- Long (~ days to weeks) of stable detector operation (nothing disturbing the setup including people or animals)
- High background rate
- Portability, transportation issues.

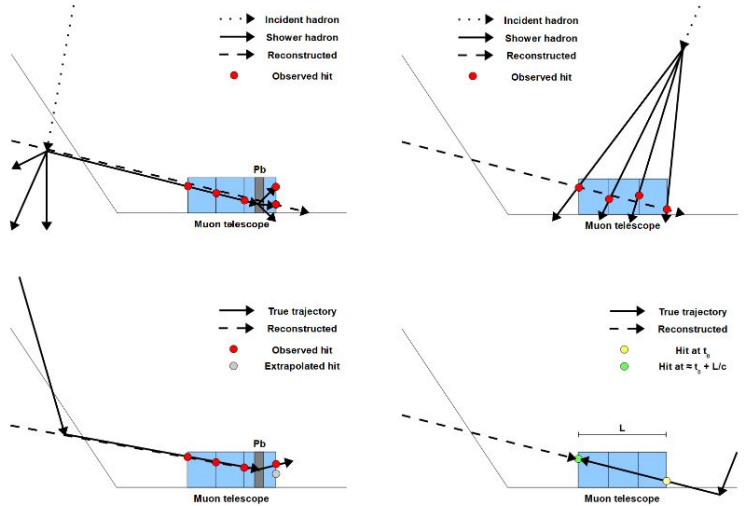
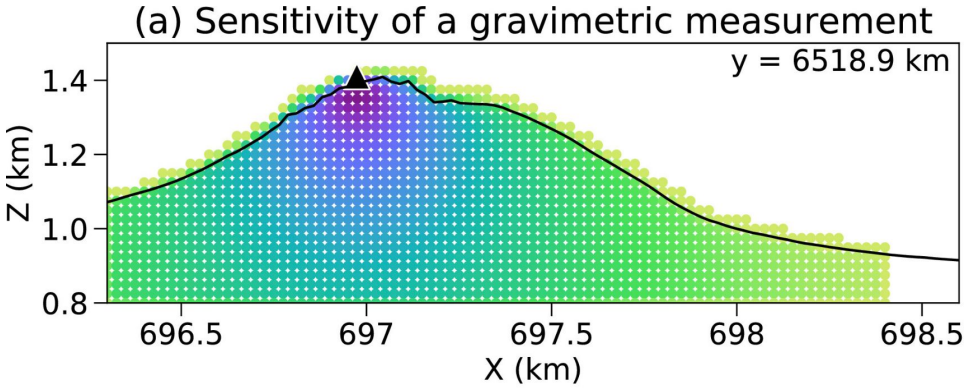


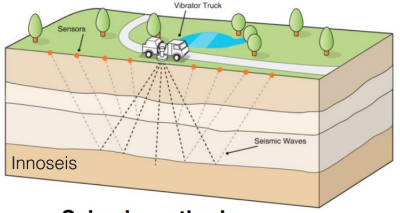
Figure 9: (Top left) Fake muon, e.g. a charged hadron. (Top right) Combinatorial background. (Bottom left) Soft muon. (Bottom right) Backward muon. Background mitigation includes the use of lead to cause further inelastic interactions (top left) or further elastic scattering (bottom left), strict selection on the quality of the reconstructed track (top right), and usage of hit-level timing information (bottom right).

arxiv:1906.03934

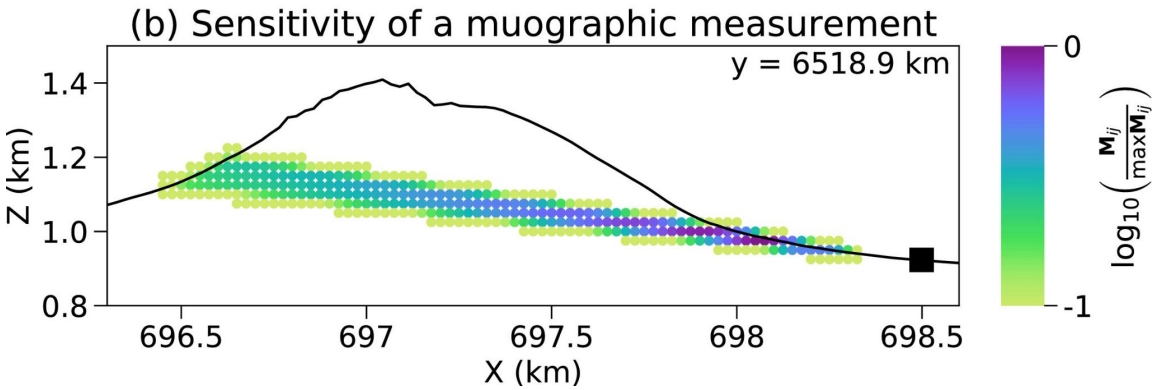
Other ways of ‘looking’ inside a volcano



Gravimetry

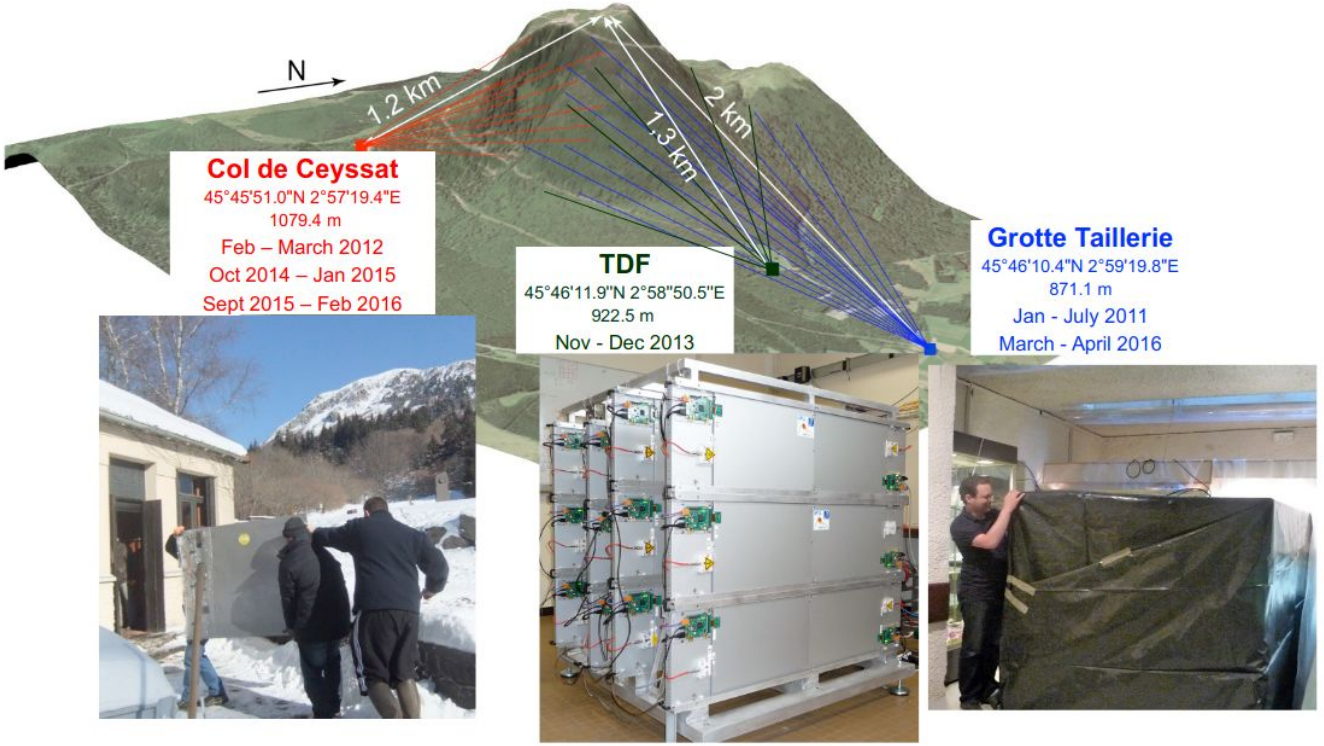


Seismic methods



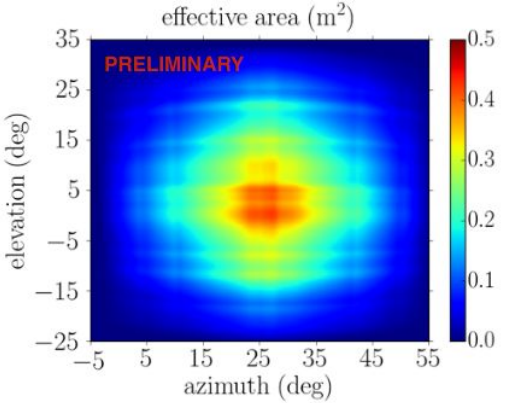
Data acquisition for Tomuvol

- Col de Ceyssat campaign 2015-2016: equivalent to **100 days of data**

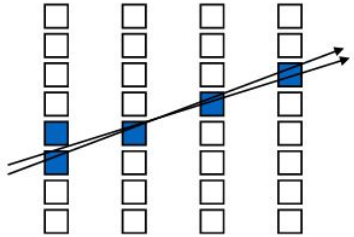


4 layers of gas resistive plate chambers (GRPCs)

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



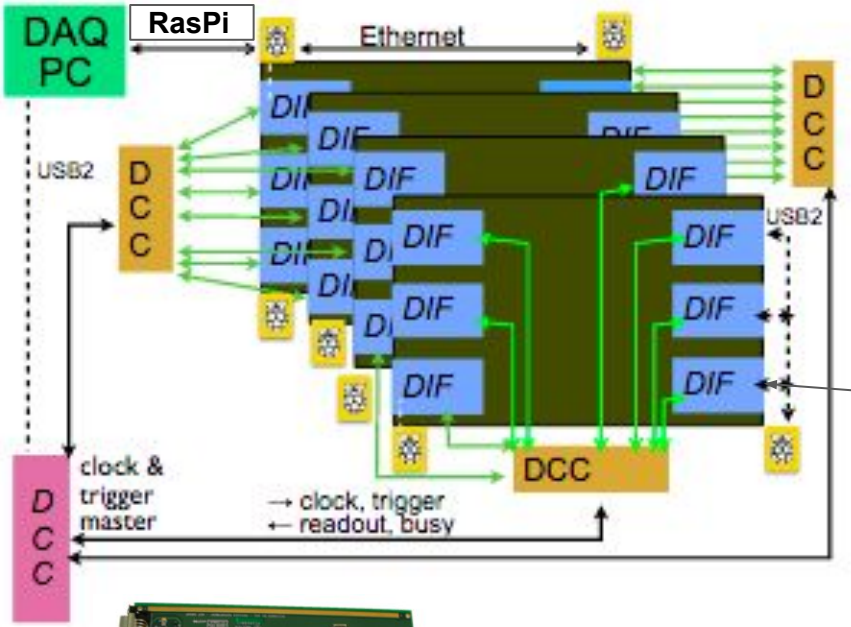
200 ns, 4 layer coinc

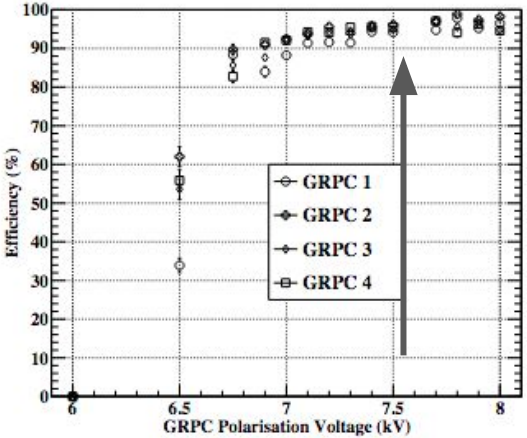


Track reconstruction with measurement uncertainties

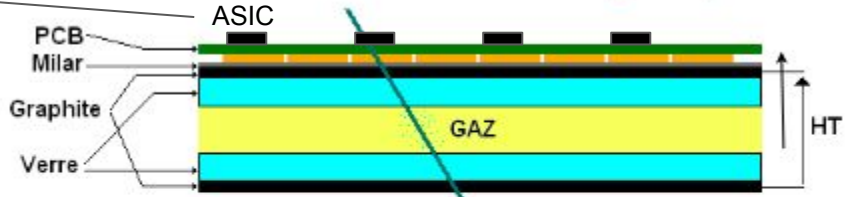
Tomuvol detector

Electronics and GRPC





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



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

Op. voltage:7.5 kV

Muon

DCC (distributes trigger and/or BUSY signals

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

Where is Puy de dôme?

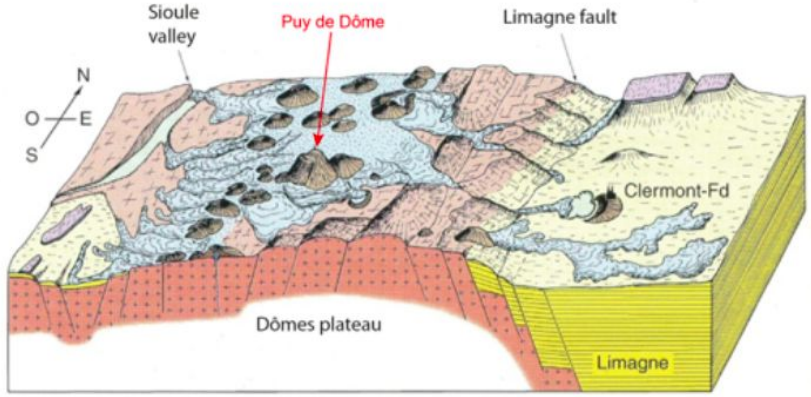


Figure Boivin and al., 2004

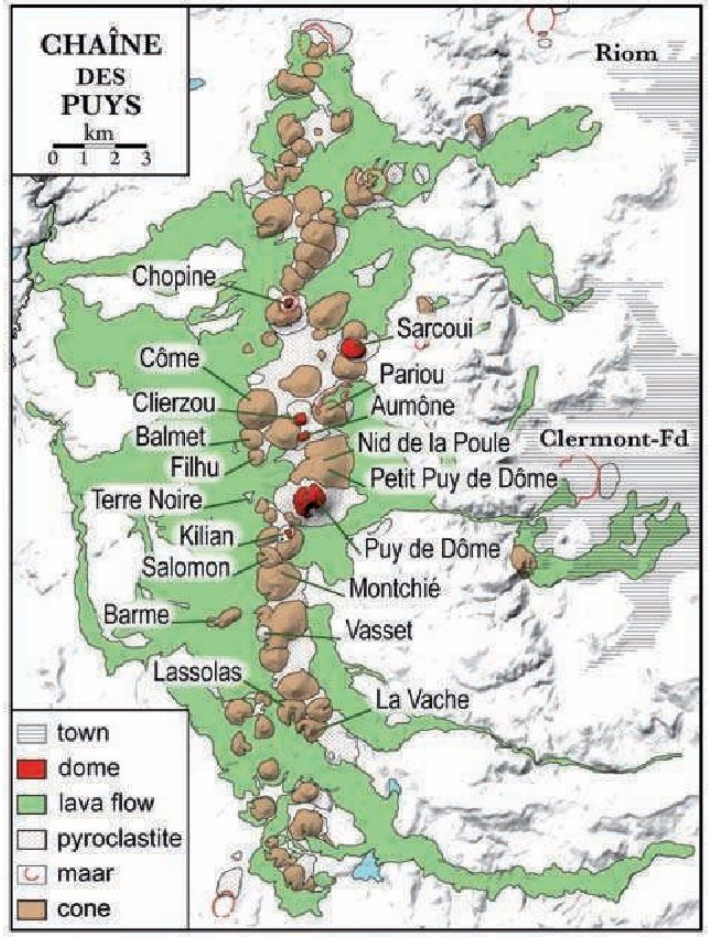
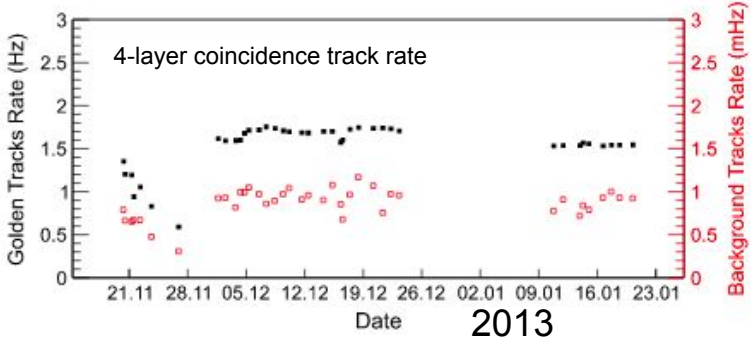
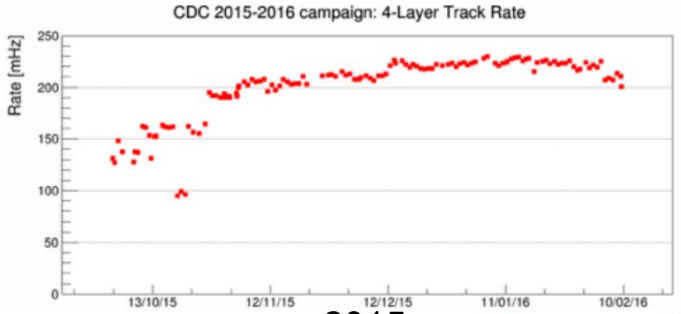


Fig. 1: General map of the Chaîne des Puys. For details, see Boivin

Transmission muography

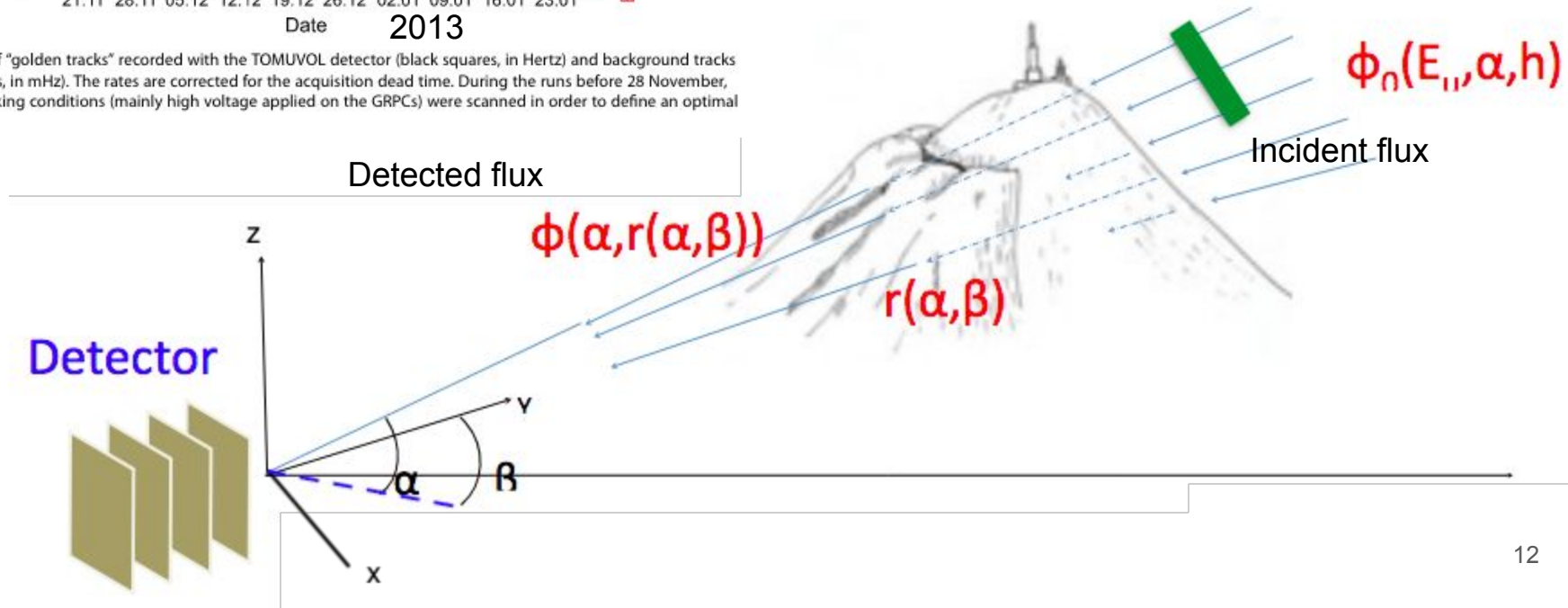


2013



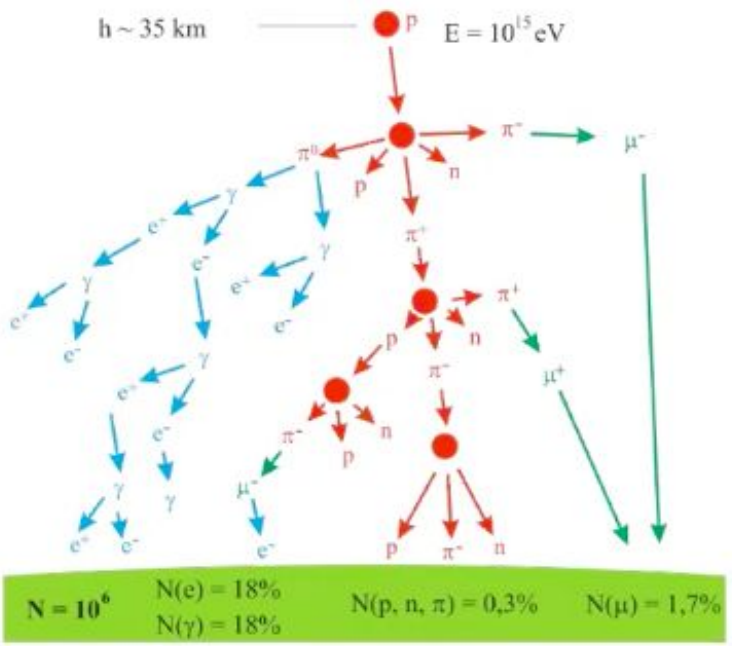
2015

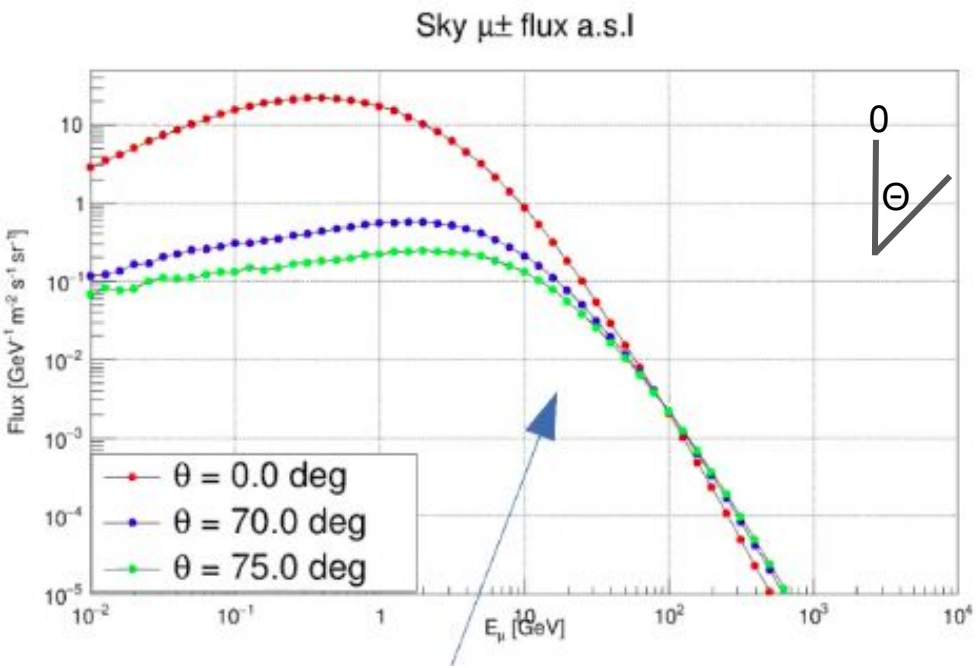
Figure 7. Rates of "golden tracks" recorded with the TOMUVOL detector (black squares, in Hertz) and background tracks (open red squares, in mHz). The rates are corrected for the acquisition dead time. During the runs before 28 November, the detector working conditions (mainly high voltage applied on the GRPCs) were scanned in order to define an optimal working point.



Atmospheric muon flux simulation with CORSIKA

- The flux of ballistic muons (E > 100 GeV) does not vary significantly with the direction. These are the horizontally travelling muons.
- This is good for transmission muography.

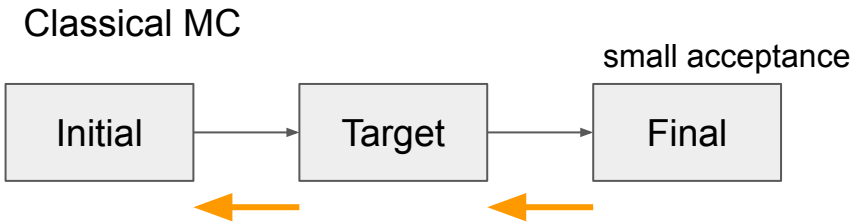




Backward Monte Carlo muon transport

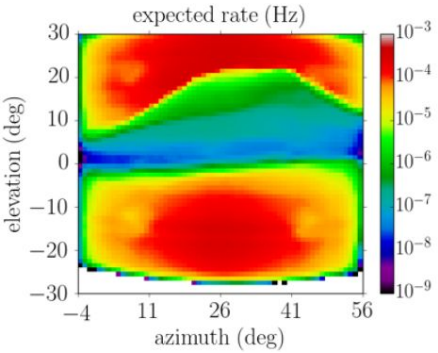
- A precise density measurement requires dedicated Monte-Carlo (MC) computations. This is **inefficient** since in a classical MC one has to sample muons produced **over the whole atmosphere but going through a tiny ≃ 1 m^2 detection plane**.
- **<u>Used to reject low energy muons</u>** that scatter away a lot from their initial directions.
- BMC guarantees to **sample only useful** events by starting from the detector and going backwards to the source.

arXiv:1705.05636



Observed muon flux through Puy de dôme

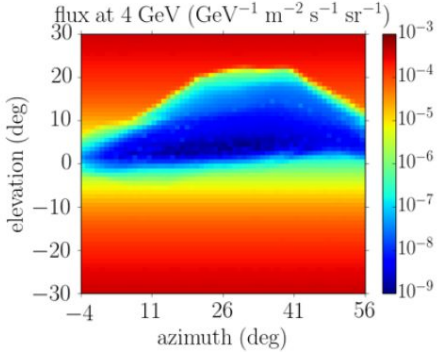
observed rate of muons



$=$

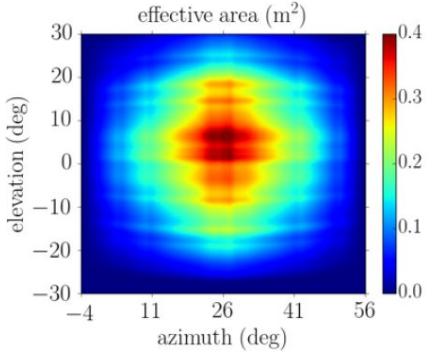
$\int$

transmitted flux



$\times$

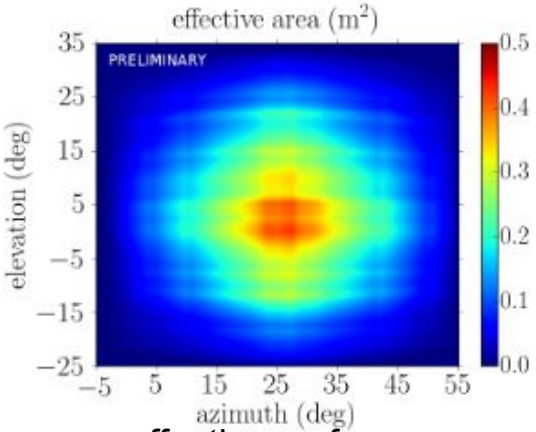
effective area of the detector



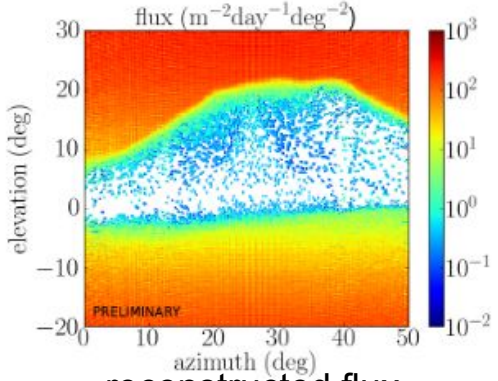
$\mathrm{d}E$

- Count the number of muons along line of sight
- Compute the transmitted flux (Averaged density).
- The observed rate is matched to the best density hypothesis.

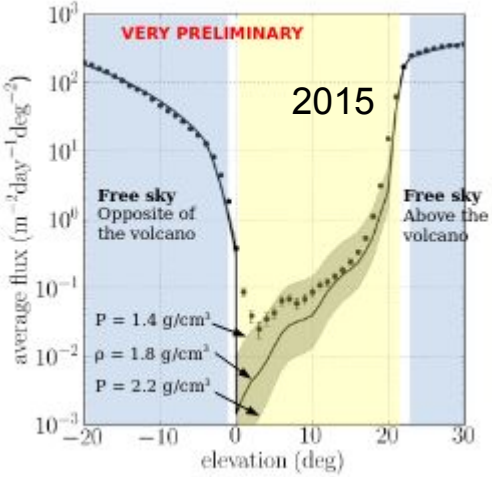
2013, 2015 Preliminary Results

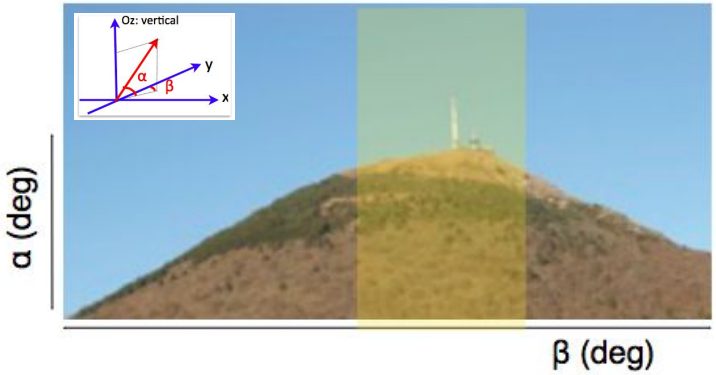


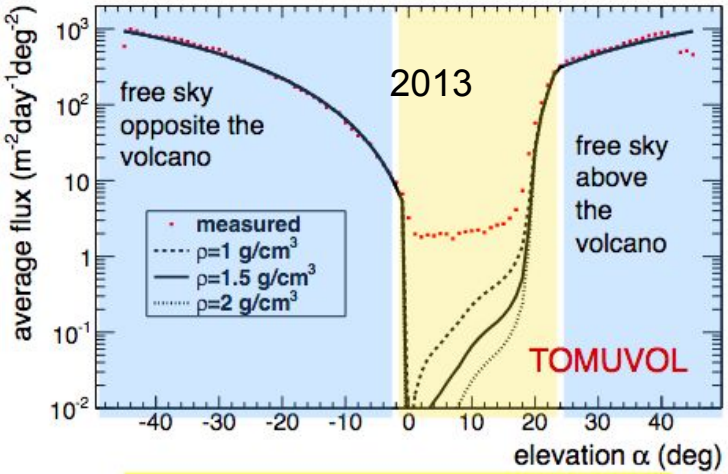
effective surface



reconstructed flux

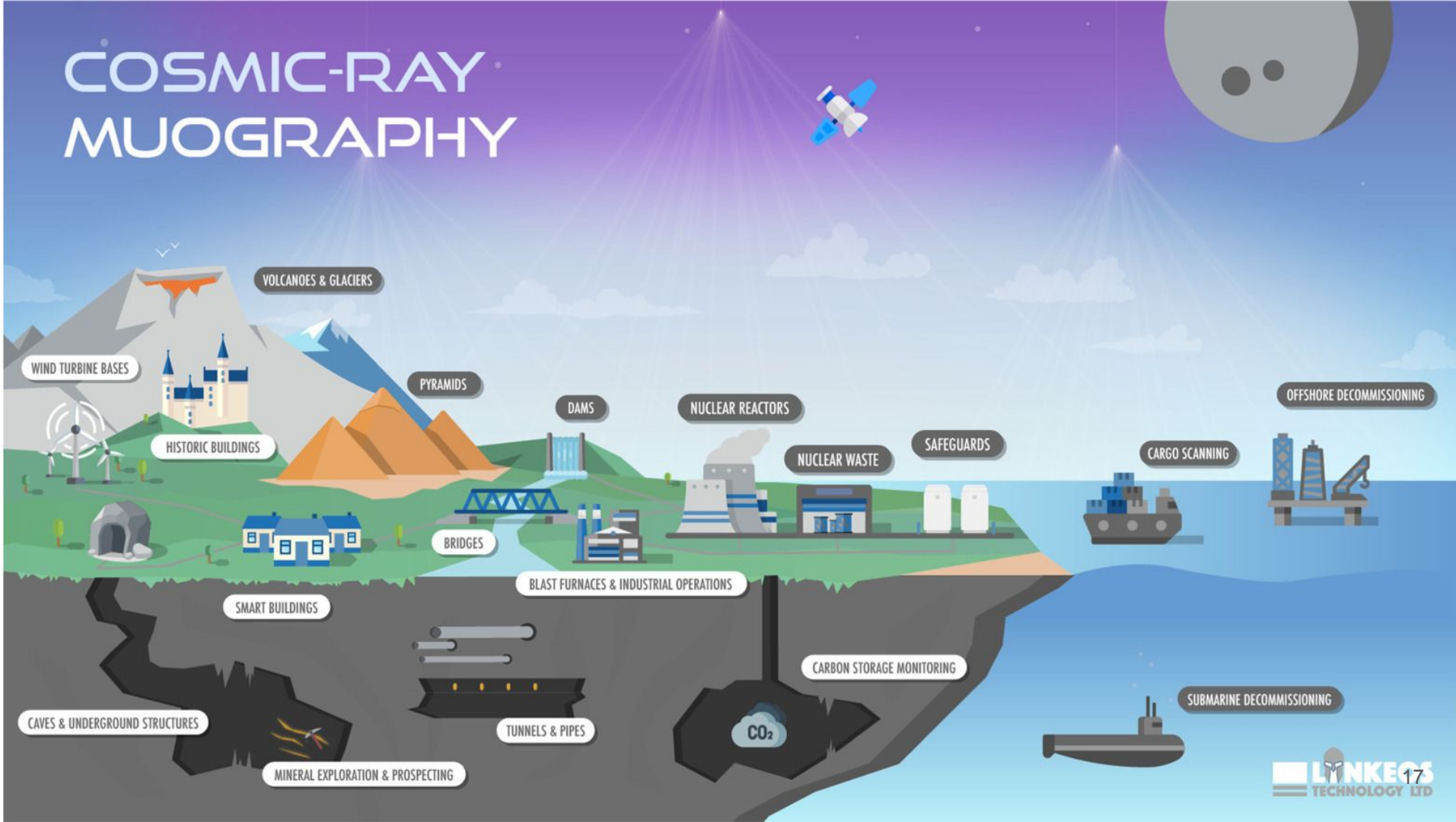






Considerable improvement in the technique

Data/flux model agreement:
~5% for free sky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WIND TURBINE BASES
PYRAMIDS
DAMS
NUCLEAR REACTORS
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HISTORIC BUILDINGS
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Some references

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Tanaka, H. K. M., Nakano, T., Takahashi, S., Yoshida, J. & Niwa, K. Development of an emulsion imaging system for cosmic-ray muon radiography to explore the internal structure of a volcano, Mt. Asama. *Nuclear Instruments and Methods A* **575**, 489–497 (2007), https://doi.org/10.1016/j.nima.2007.02.104

Morishima, K., Kuno, M., Nishio, A. *et al.* Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons. *Nature* **552,** 386–390 (2017). https://doi.org/10.1038/nature24647

C. Cârloganu et. al.,Towards a muon radiography of the Puy de Dôme, https://doi.org/10.5194/gi-2-55-2013

Eve Le Menedeu, RPC application in muography and specific developments, https://doi.org/10.48550/arXiv.1605.09218

Valentin Niess et. al., Backward Monte-Carlo applied to muon transport, https://doi.org/10.48550/arXiv.1705.05636

Atmospheric muons as an imaging tool, Lorenzo Bonechi et. al., https://doi.org/10.1016/j.revip.2020.100038