Exploration des tombes de rois :

archéologie et tomographie par muons

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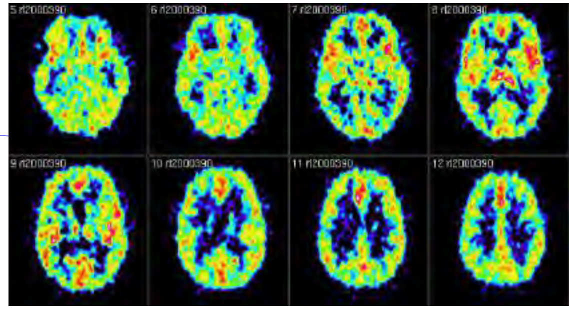
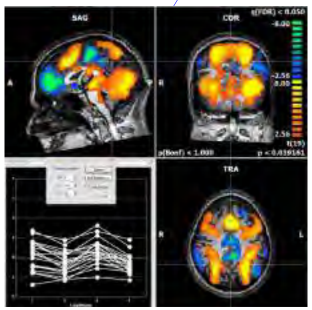
Tomography

- Study of an object by processing images by cuts or slices

Radiography → X – Rays

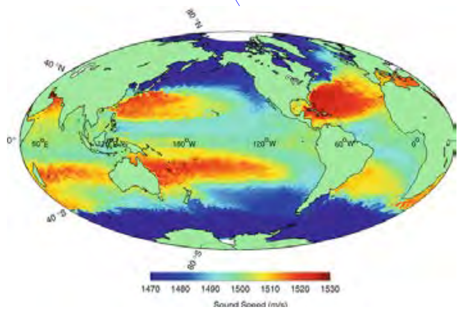


PET → Positrons

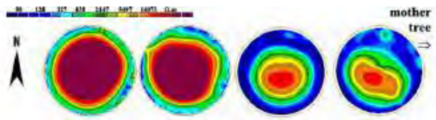


SPET → Photons

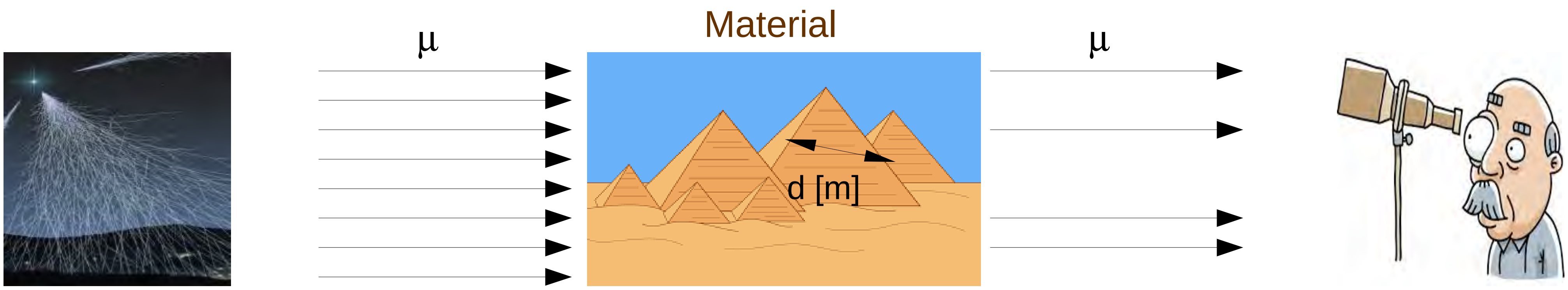
- ✔ Non – invasive technique
- ✔ Multiple applications
- ✔ Different approaches depending on the goal
- ✖ Handling of Radiation



AT → Sound speed



ERT → Electric Resistivity



Initial flux ϕ_i

Basically dependant on the μ energy and zenith angle (E, θ)

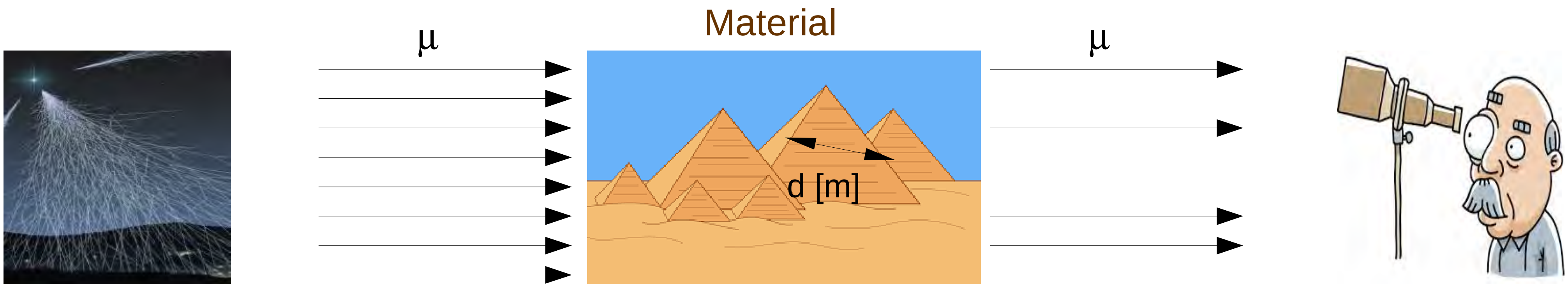
Density: ρ [g/cm3]

Linear Density: **δ [g/cm²]** = ρ d

Final flux ϕ_f

Detected muons for a given direction

- Ratio between initial and final fluxes is directly related with Linear Density
- Differences in final flux for different directions also points to Linear Density differences



Initial flux ϕ_i

Density: ρ [g/cm3]

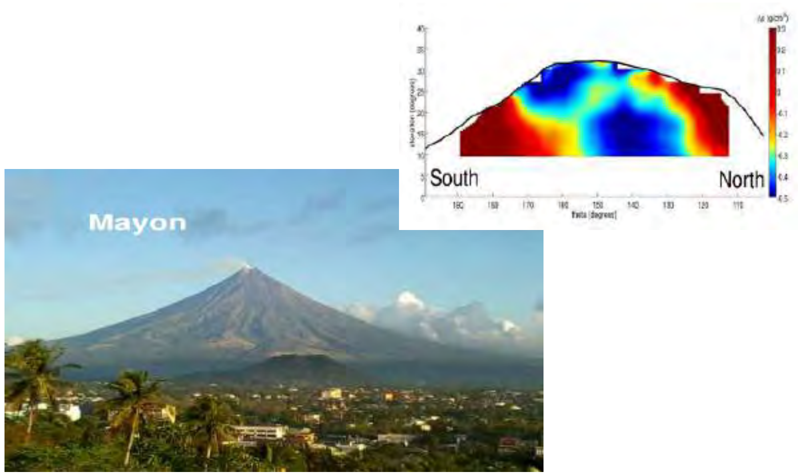
Final flux ϕ_f

Basically dependant on the μ energy and zenith angle (E, θ)

Linear Density: **δ [g/cm²]** = ρ d

Detected muons for a given direction

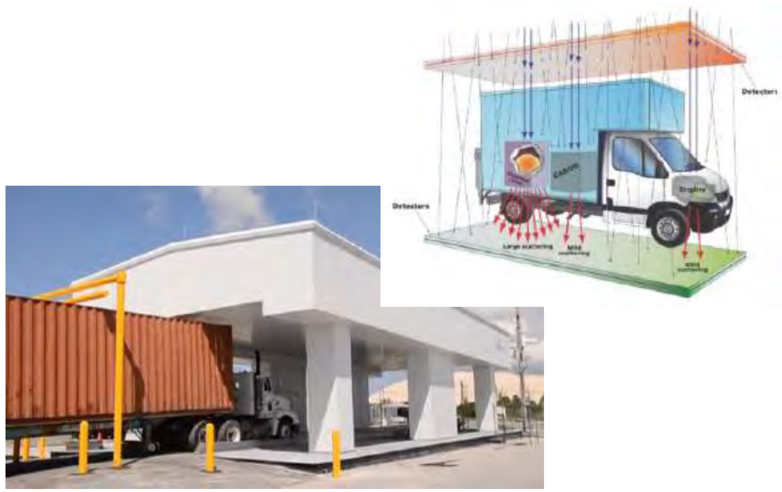
- It has all the general advantages of tomography techniques (mainly that it is non - invasive)
- But in addition → It uses an “Advantageous” radiation source
  - ✔ Natural → Cosmic rays
  - ✔ Healthy non-risky → based on muons that are traversing us right now
  - ✔ Extended and deeper penetrating → ***Large structures***



Volcano Tomography

Nuclear control and safety

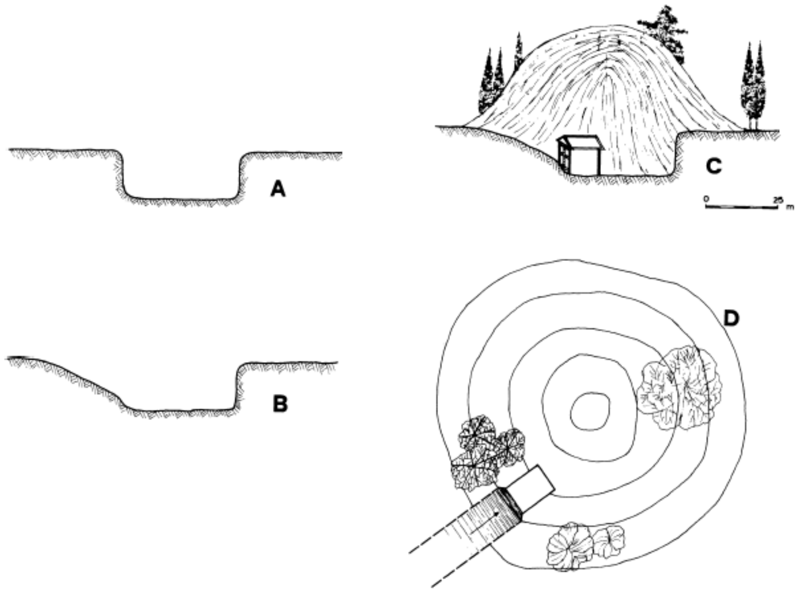
Archaeology



Merchandise scanning

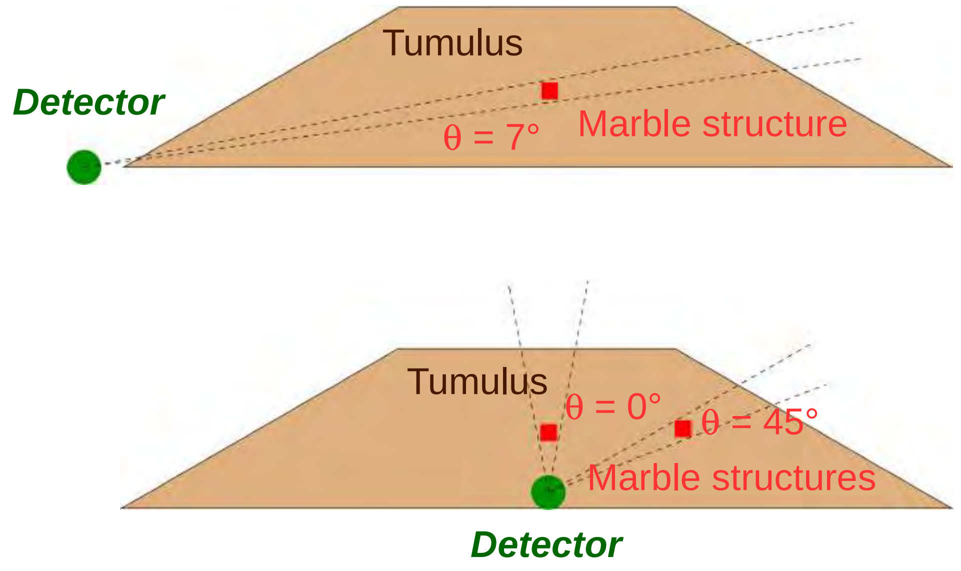
- Macedonian tumulus: Burial structures
  - They can contain hidden tombs, corridors, vaults...
  - A non – invasive way to explore them can be really useful
    - Other tomography techniques already used

Tomb of King Phillip II (Imathia, Greece)



- Explore the feasibility to apply muon tomography to archaeological studies
    - First step: ***Simulations***
        - Estimation of the differences in the detected muon rate for different directions
        - Interpretation of the results after analysis

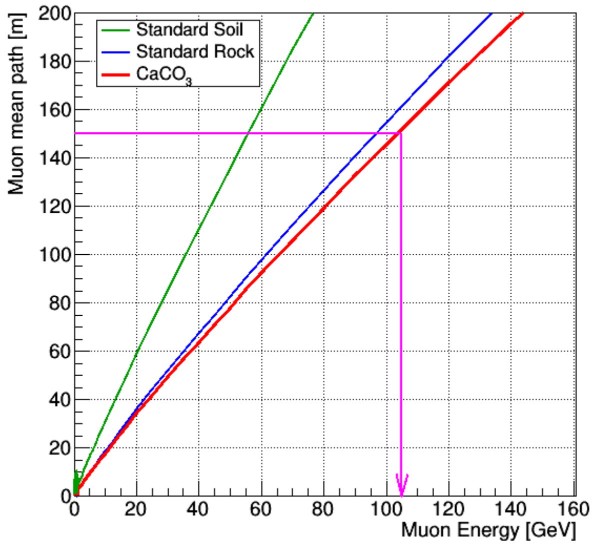
- For a given, tumulus different questions can be addressed:
    - Best detector position (for those possible)
    - Sensitivity vs structure anomaly size



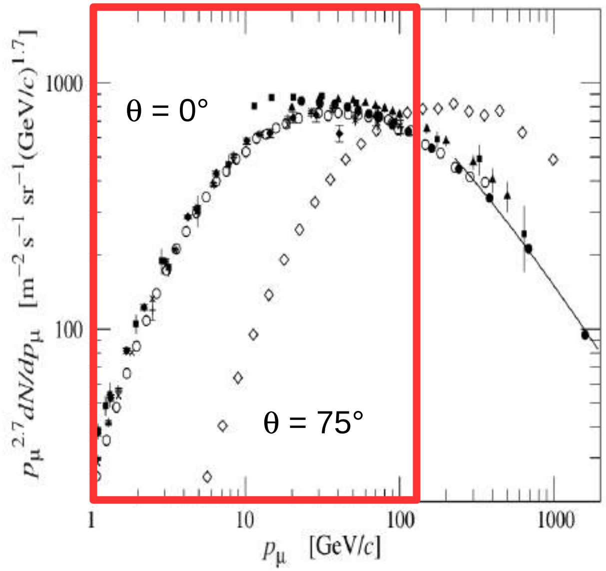
Schemes of the configurations considered for the simulations

- Explore the feasibility to apply muon tomography to archaeological studies
  - First step: ***Simulations***
    - Estimation of the differences in the detected muon rate for different directions
    - Interpretation of the results after analysis

- For typical tumulus dimensions, low energy muons are those that can produce differences on the detected muon rate
- Different models have more uncertainties for these low energy muons

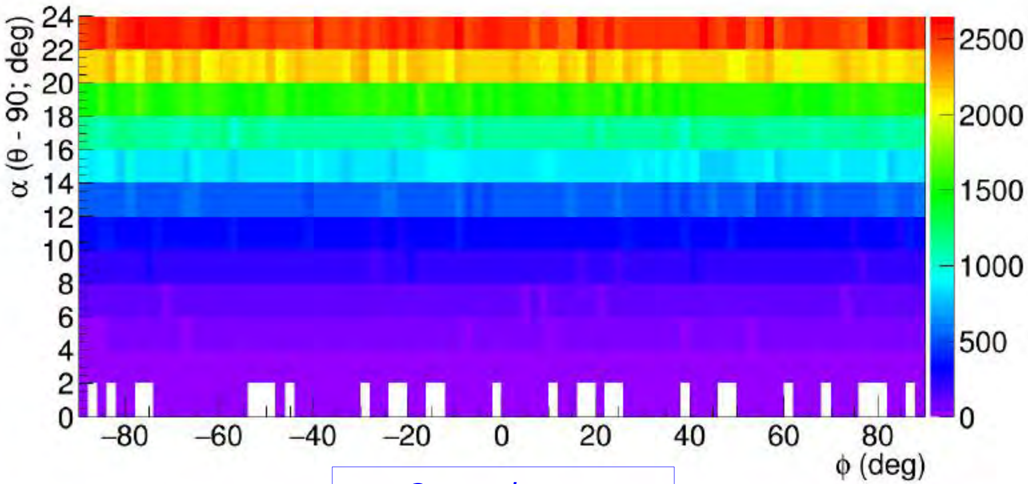


Muon mean path vs Energy for different materials

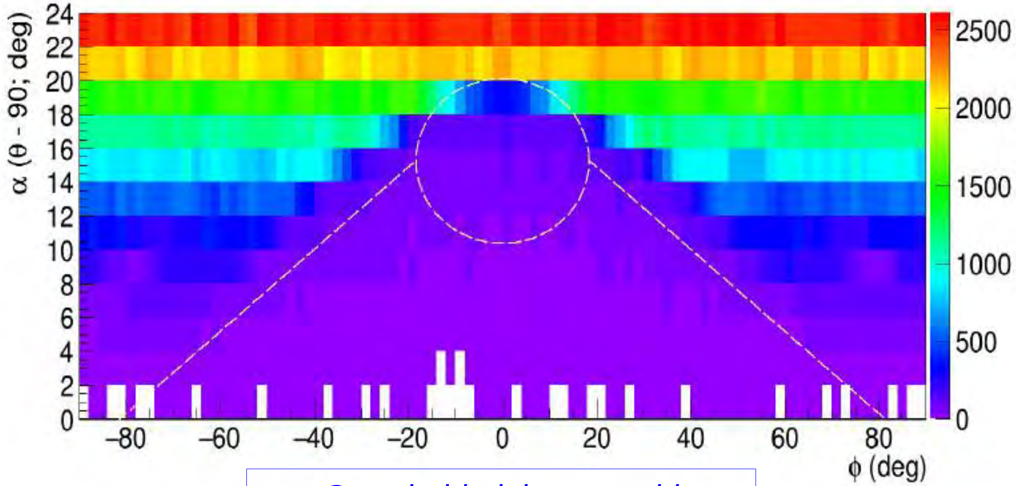


Muon momentum spectra from different measurements PDG. Phys. Rev. D 86 (2012) 010001

- Explore the feasibility to apply muon tomography to archaeological studies
    - First step: ***Simulations***



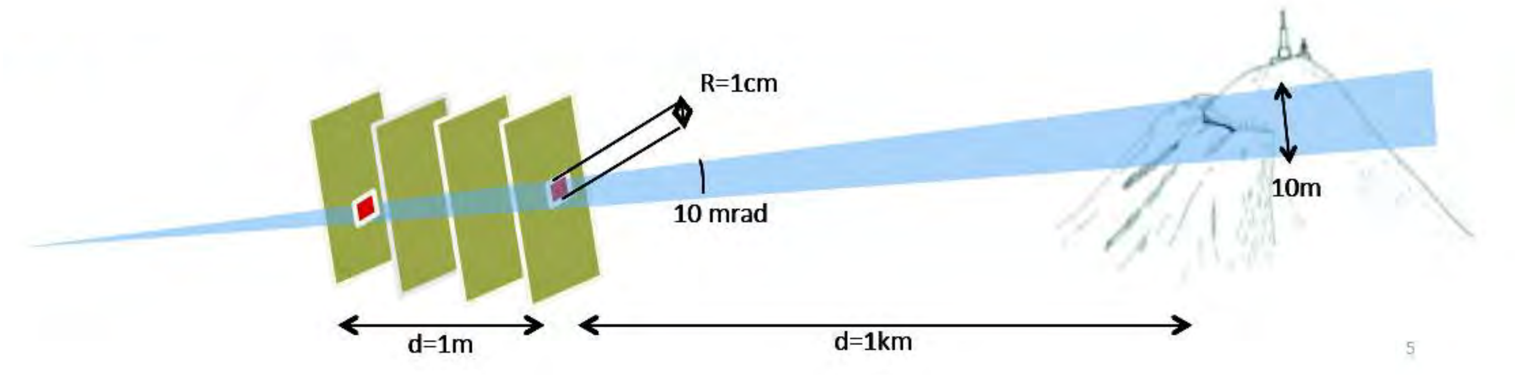
Open air scan



Scan behind the pyramid

- In general, ***shape of the pyramid*** is clearly identifiable
- Difference on the detected muon rate strongly depends on:
    - Muon zenith incident angle
    - Muon path across the tumulus (more traversed → smaller differences in the linear density)
    - Muon model selected for simulations
- Identification of a marble structure (2x2x2 m^3): $\alpha \sim 45° \rightarrow \delta\mu \sim [260 – 280]\ day^{-1}$
  $\alpha \sim 5° \rightarrow \delta\mu \sim [0.02 – 0.10]\ day^{-1}$

- Explore the feasibility to apply muon tomography to archaeological studies
    - ***The detector***



- Since the muon tomography is based on the ***number of detected muons for a given direction*** and not in their energy. It is needed a detector capable to reconstruct the muon trajectories

- Most of the times it will be needed to install it at open air during long periods of time:
    - Robust
    - Autonomous (Batteries, Solar panels)
    - Light and portable

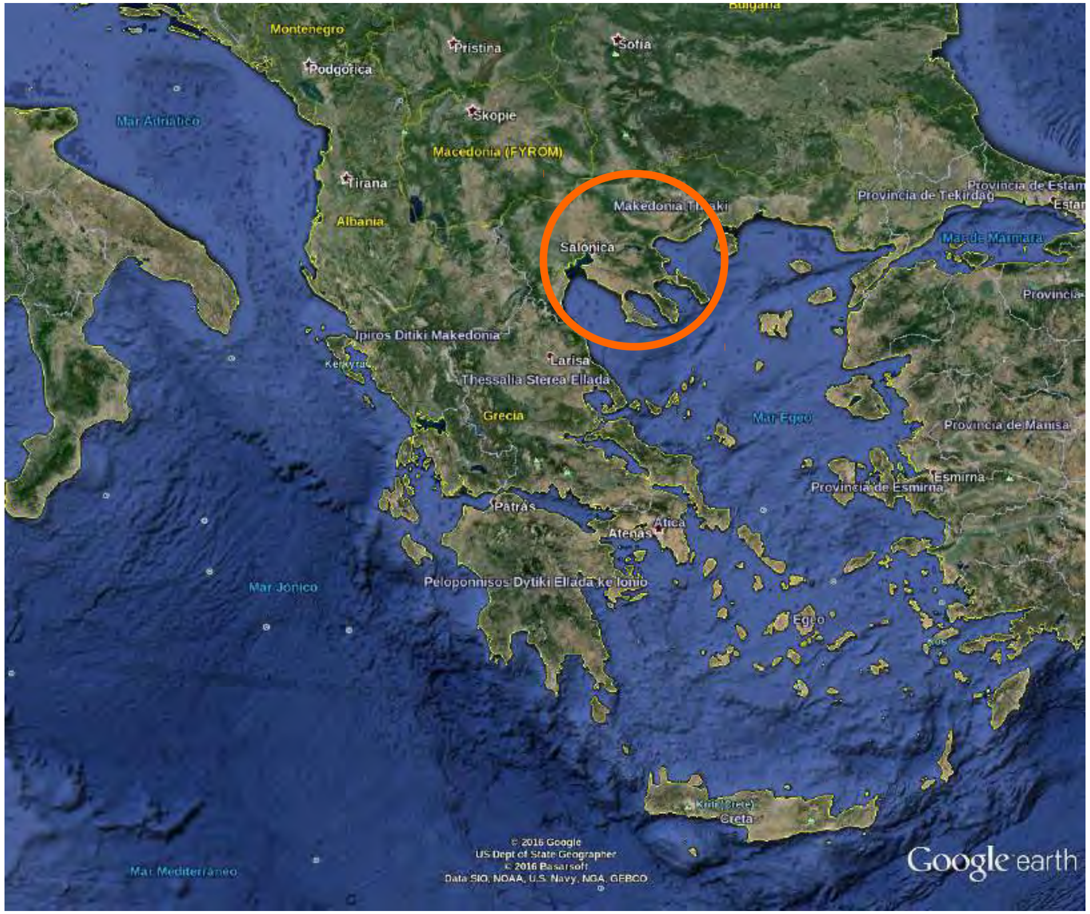
Plastic scintillators + PMTs

Plastic scintillators + SiPMs

Resistive Plate Chambers (RPCs)

Micromegas

- Make an *in situ* measurement to check the feasibility of the technique
  - ***Where?*** Apollonia Tumulus (near Thessaloniki - Greece)



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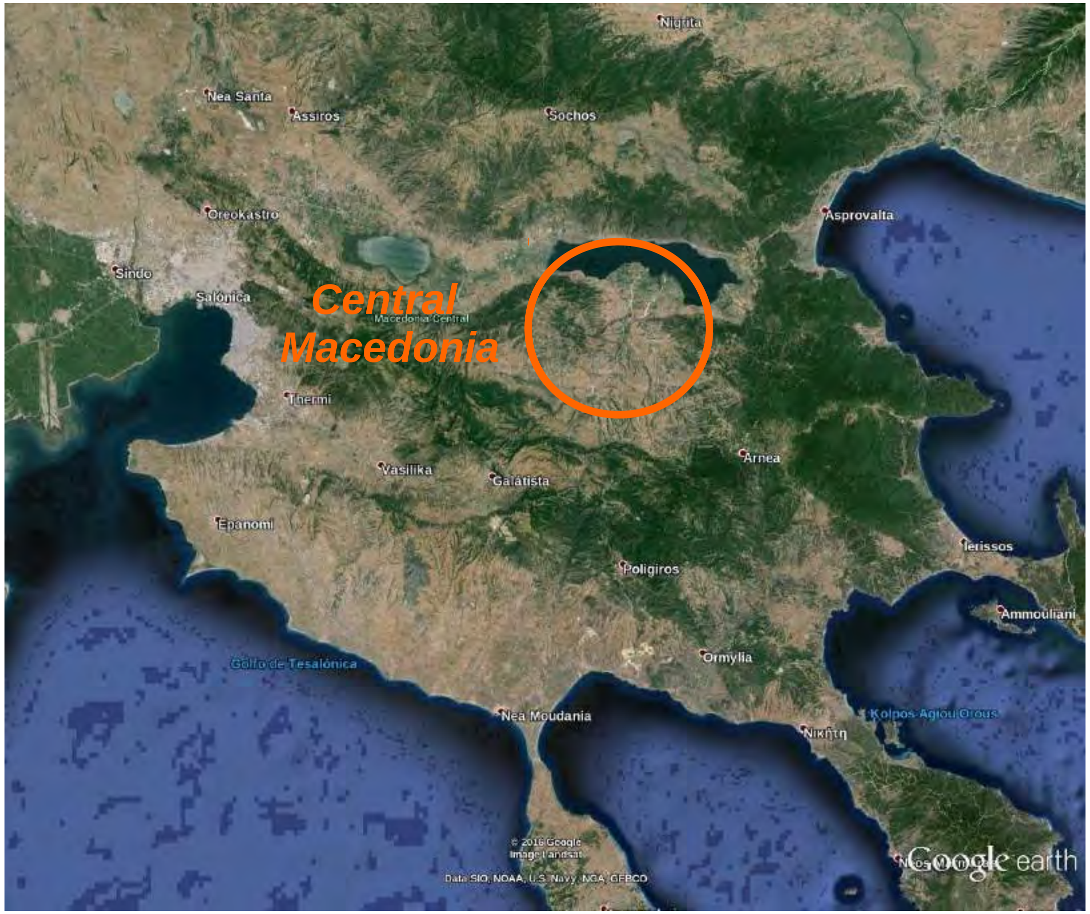

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Truncated cone geometry

Bottom Ø ~ 93 m

Top Ø ~ 21 m

Height ~ 17 m

Summary

- ***Muon tomography*** could represent a valuable technique for ***big objects scanning***
  - Already several applications are being considered
- Use it for ***archaeology*** arises as an interesting option
  - Non – invasive
  - Complementary to other exploration techniques
- ***Monte Carlo simulations*** could shed light to the ***feasibility*** of the technique
  - They also help on further data analysis
  - ***First studies*** point to muon tomography as ***valid technique***
- ***First measurement*** of a tumulus project is ***ongoing*** (APC, IPNL, LAPP, AUTH)
  - Dedicated simulations and data analysis
  - ***Installation*** of the detector around ***May***
  - Keep tuned for results ...

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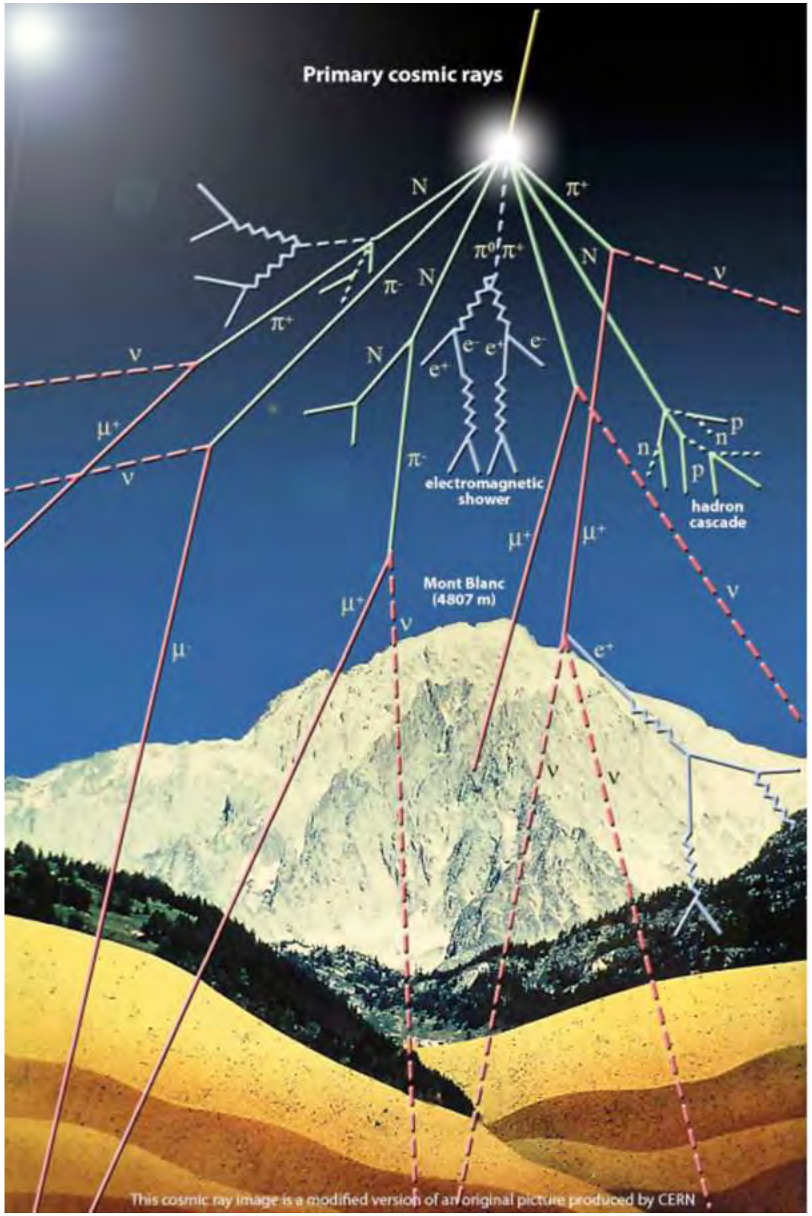
- Fundamental particle, discovered by C.D. Anderson (1936) while he studied the Cosmic Radiation

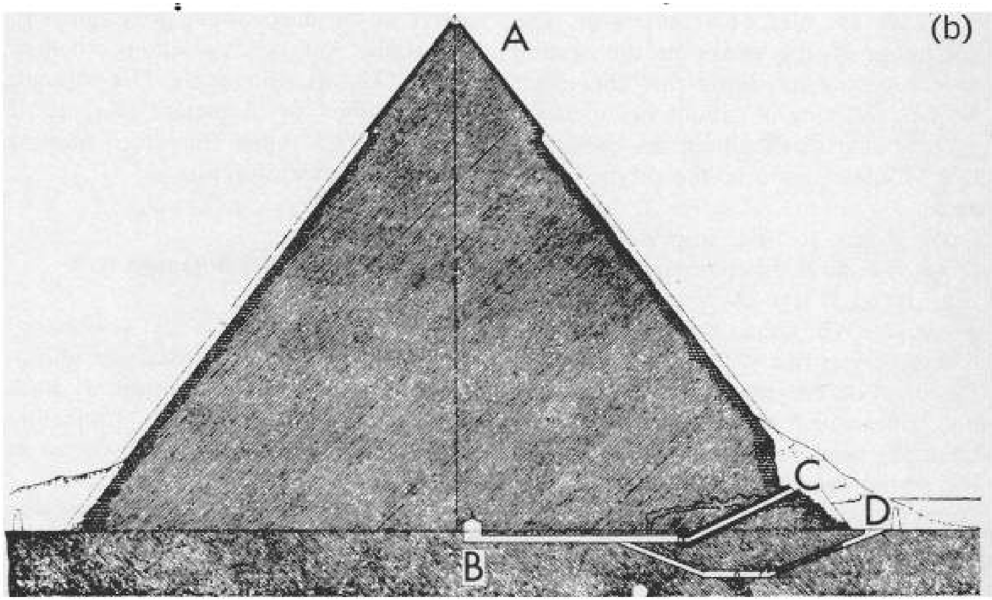


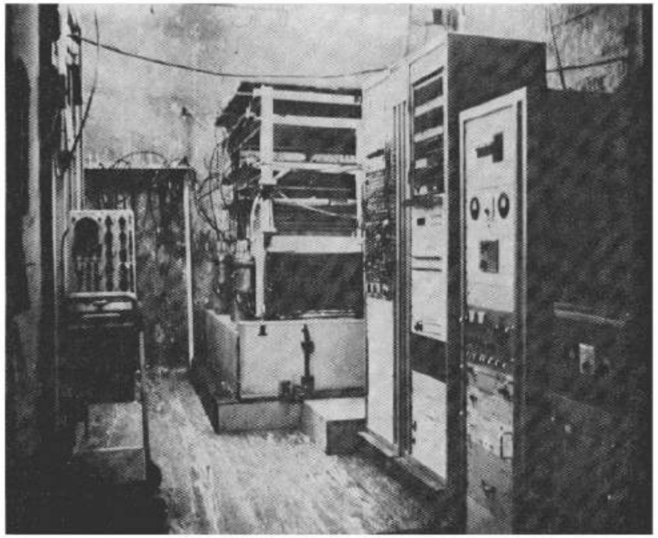
Muon Flux at Earth's Surface ~ 130 muons/m²/s

- Natural and relatively active radiation source
  - A problem for low background experiments:
    - Placement underground
    - Event rejection techniques
  - But and advantage for other objectives...

- ***1955: E.P. George***
  - First application of muon tomography for large structures
  - Rock overburden over an underground tunnel in Australia was measured
  - George, E.P. (July 1, 1955). "Cosmic rays measure overburden of tunnel". Commonwealth Engineer: 455.

- ***1970: L.W. Alvarez (1968 Physics Nobel Prize)***
  - Scanning of Chefren Pyramid looking for internal vaults
  - No conclusive results
  - Alvarez, L.W. (1970). "Search for hidden chambers in the pyramids using cosmic rays". Science 167: 832





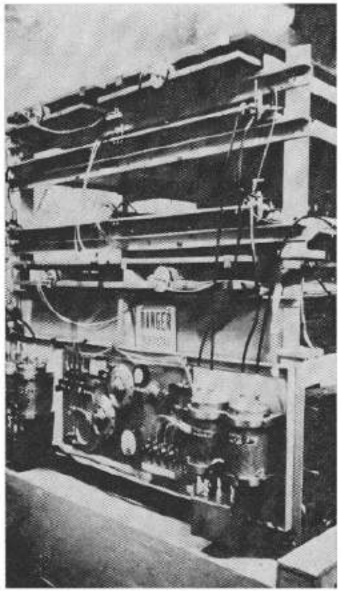


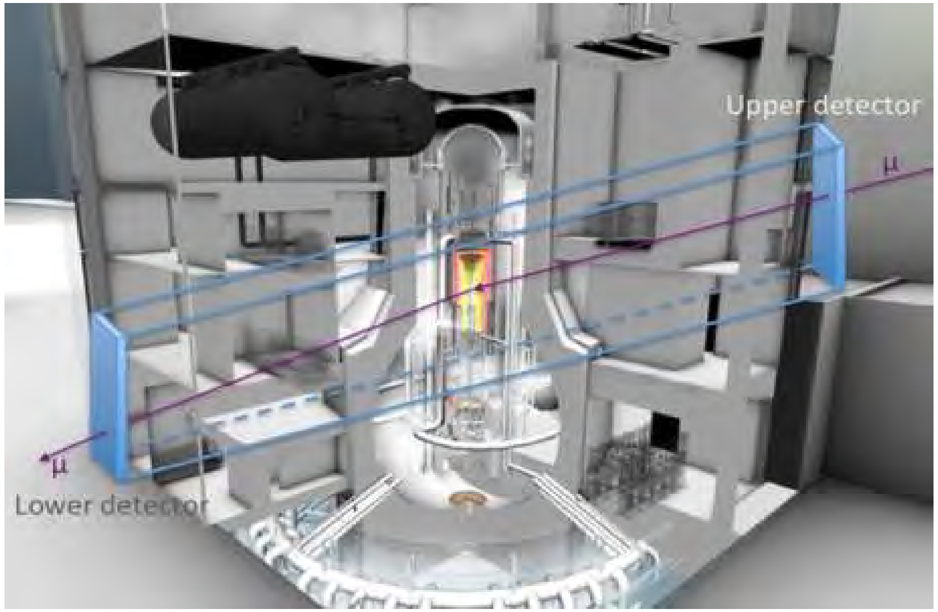
Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid. Fig. 7 (right). The detection apparatus containing the spark chambers.

- After the accident (11/03/2011) it was necessary to know the state of the cores...

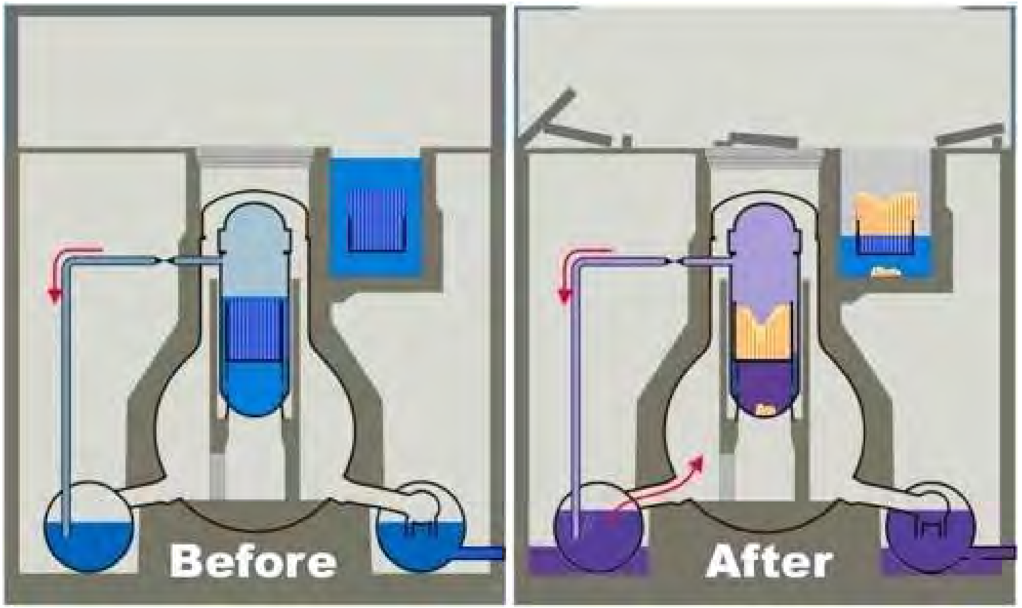
- But it was impossible (and still quite dangerous) to approach to the core

Solution?

- Muon tomography could help us to:

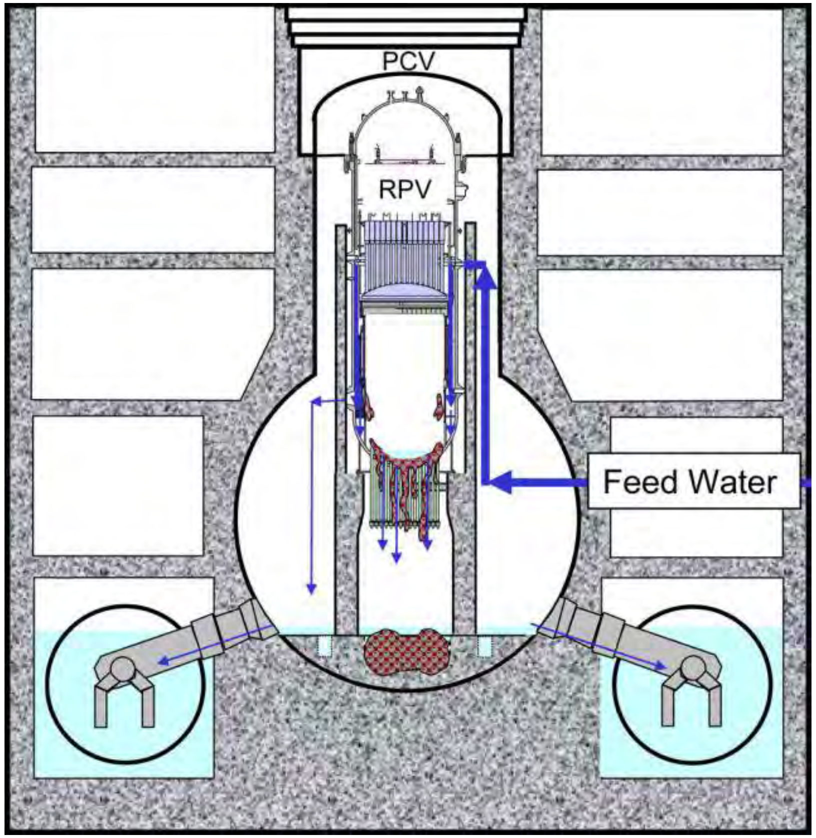


- Detect holes in the core:
  - Lower density → Higher muon flux
- Locate the the nuclear/radioactive fuel
  - Higher density → Lower muon flux

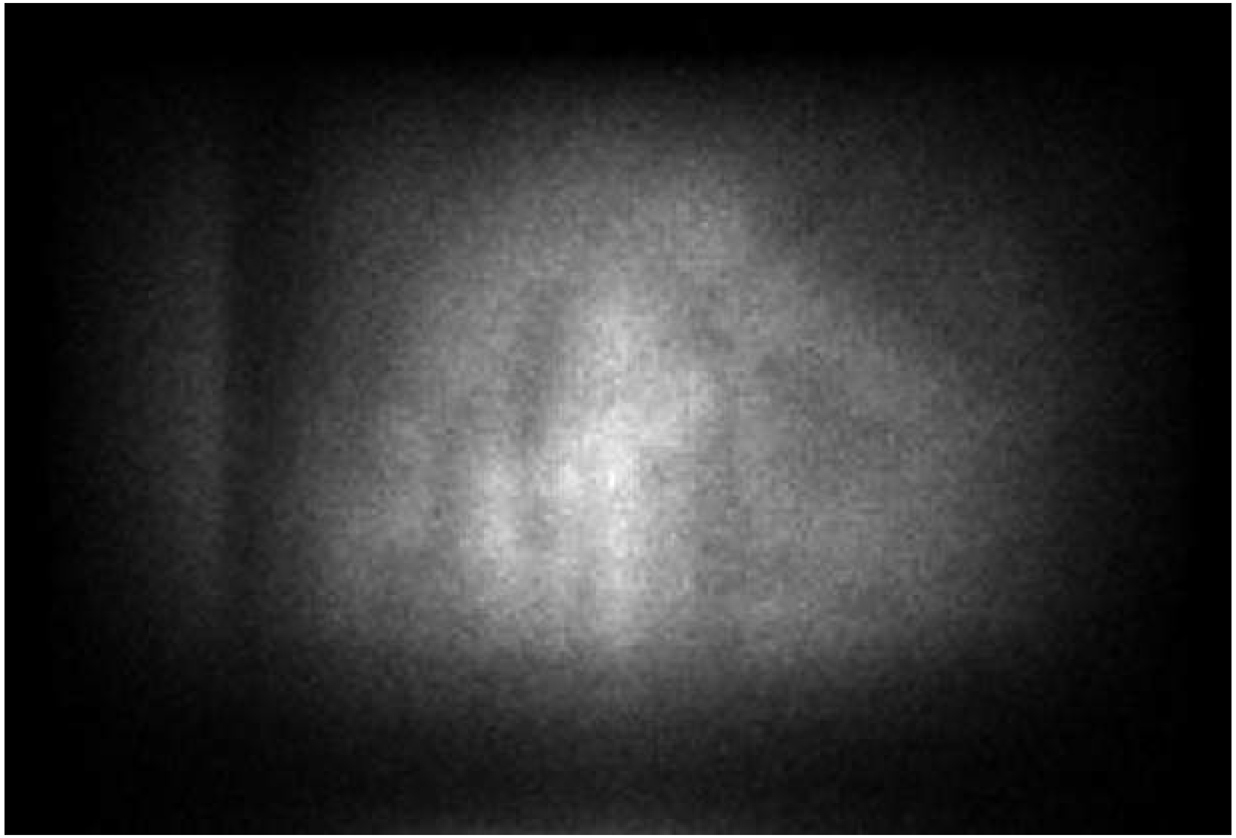


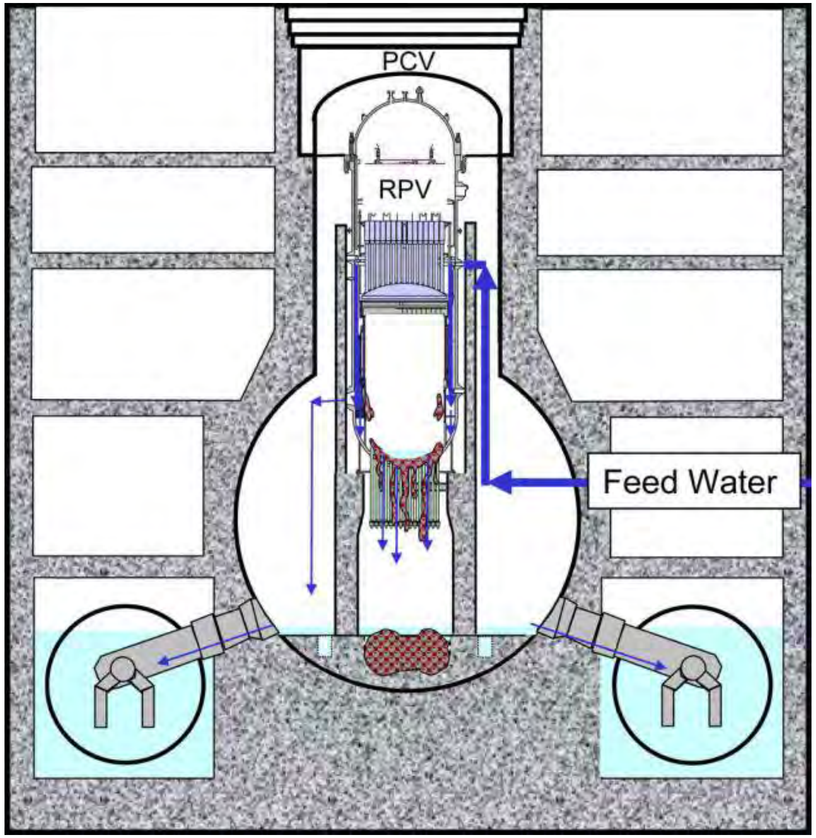
- Results (and their interpretation):

Density model based on reactor design

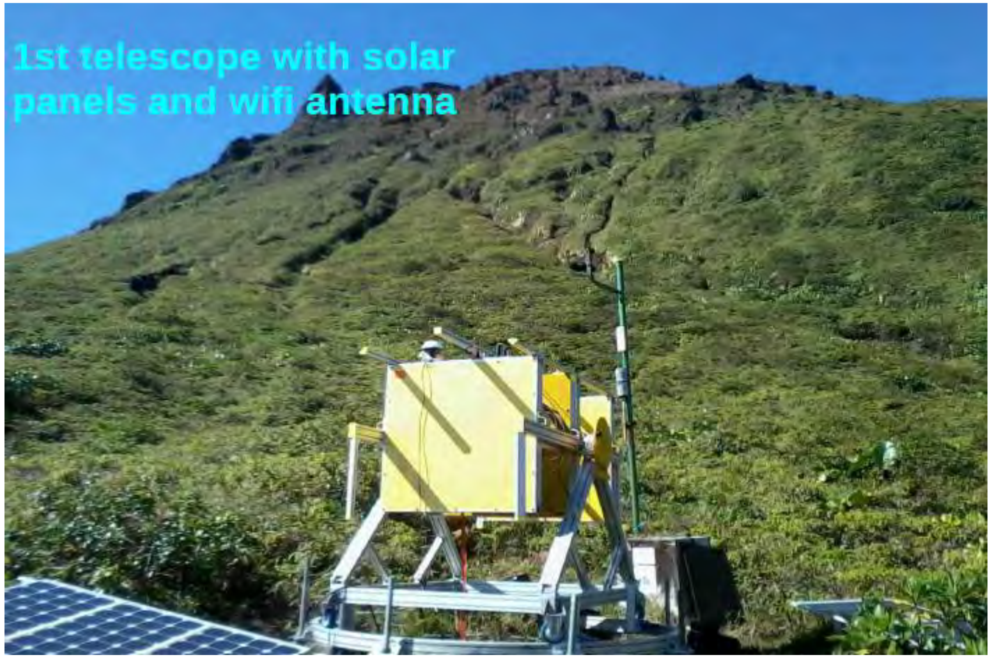


- Results (and their interpretation):





- Survey of the internal composition to eventually detect changes (eruption, activities...)

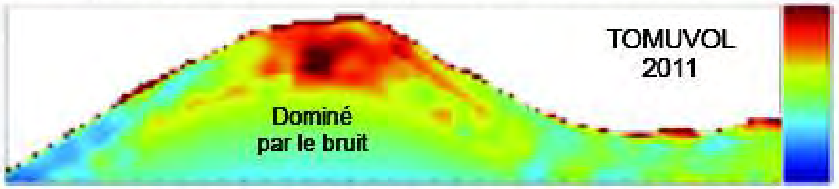


The Soufrière of Guadeloupe

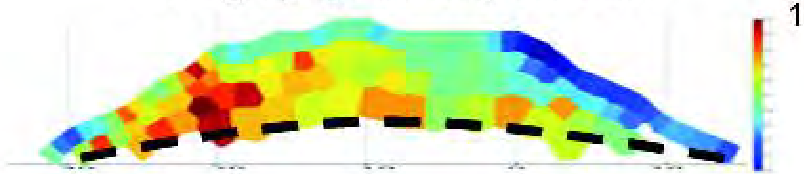
- Survey of the internal composition to eventually detect changes (eruption, activities...)

The Puy de Dome

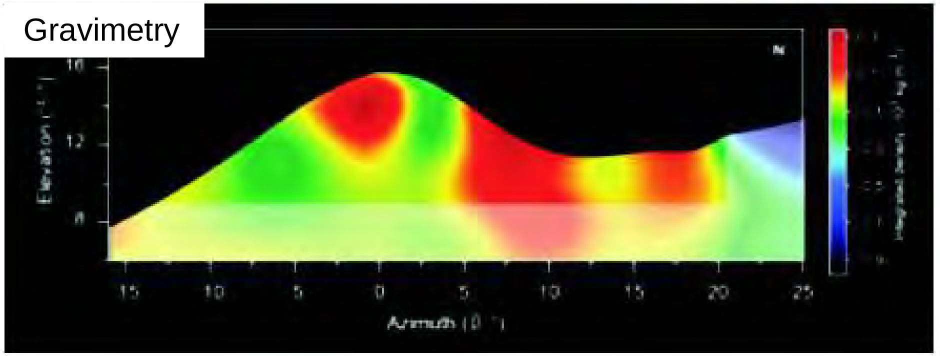
Muography: relative opacity (~density)

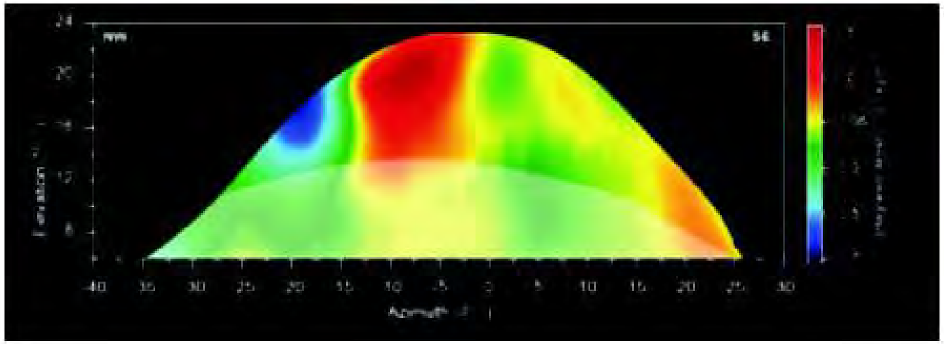


Muography: density contrast



Gravimetry





- Survey of the internal composition to eventually detect changes (eruption, activities...)

The Soufrière of Guadeloupe

Last eruption (1976)

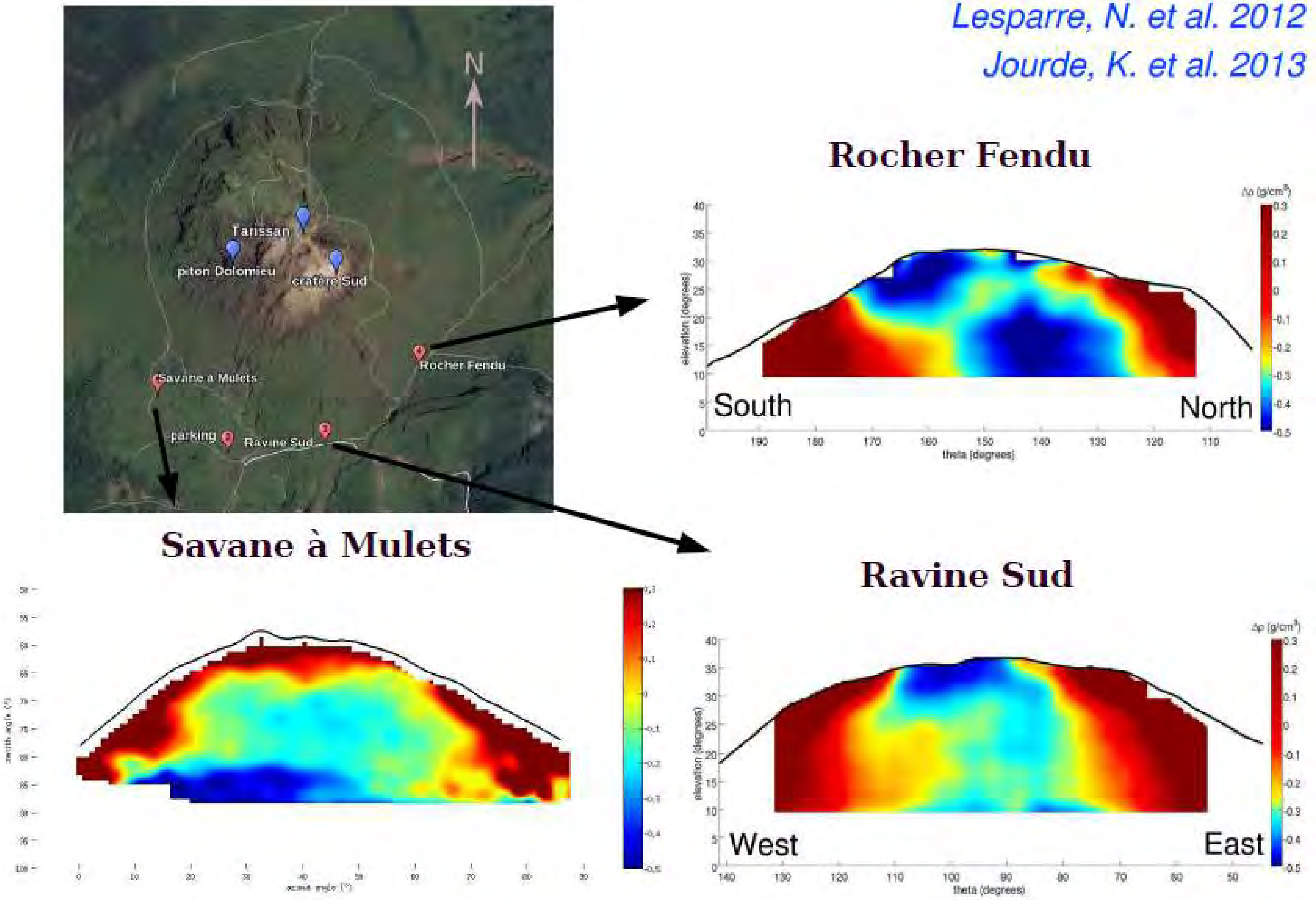
Same picture at 2010

- Survey of the internal composition to eventually detect changes (eruption, activities...)

The Soufrière of Guadeloupe

Measurements from 2010

Lesparre, N. et al. 2012
Jourde, K. et al. 2013



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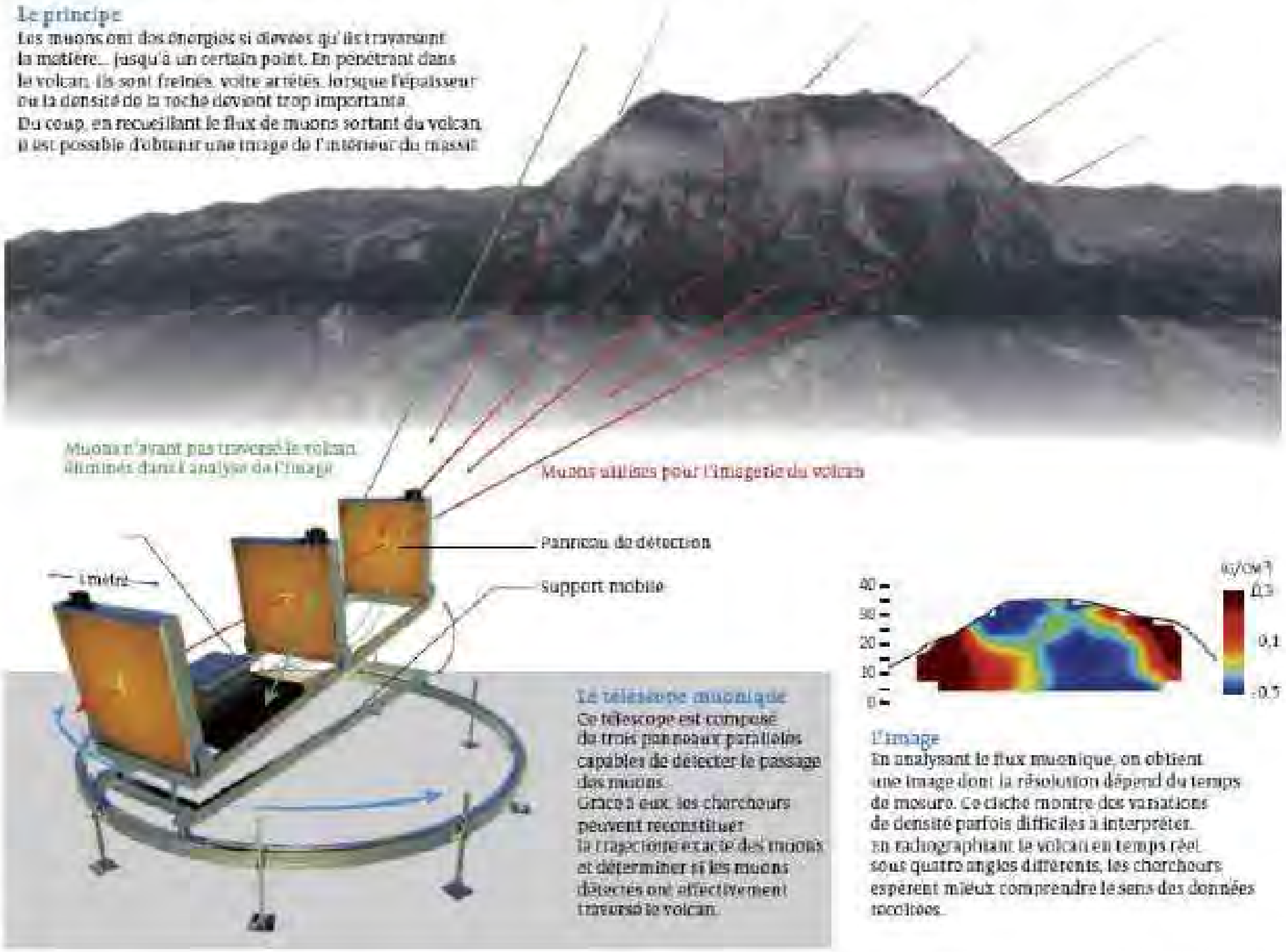
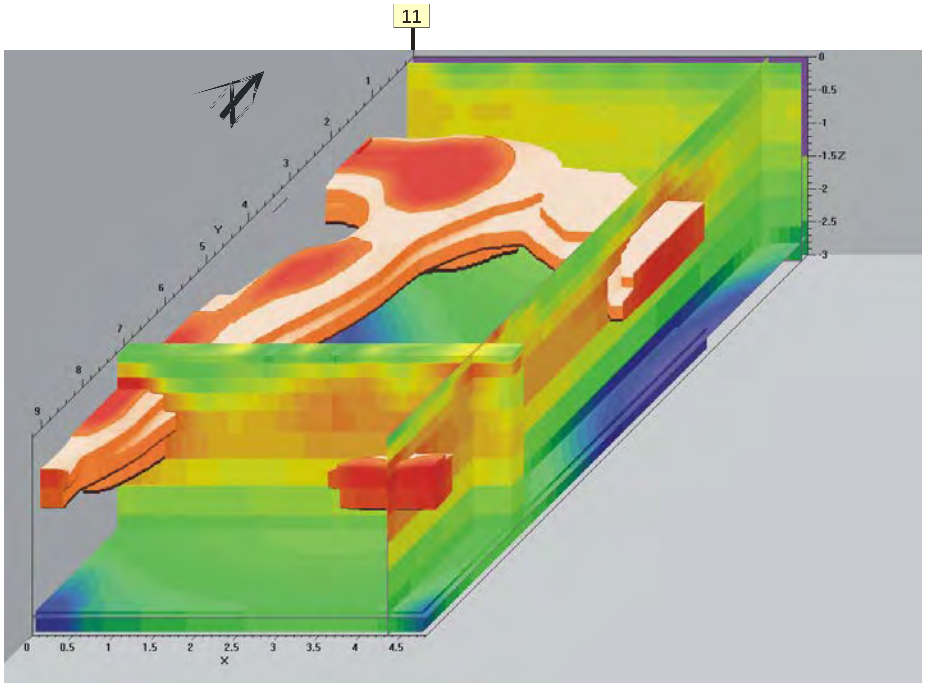
Les muons, explorateurs des entrailles de la Soufrière

En avril, quatre télescopes d'un genre particulier vont être installés en Guadeloupe, autour de la Soufrière. Ils n'auront d'yeux que pour le « petit » volcan et pour des particules qui se forment dans la haute atmosphère, les muons. « *Depuis 2008, nous développons une méthode utilisant ce flux de muons pour radiographier les entrailles des volcans* », explique Dominique Gibert, de l'Observatoire des sciences de l'université de Rennes. Les muons peuvent tout à la fois traverser la matière et être absorbés quand cette dernière devient trop dense ou trop épaisse. Ils peuvent donc être utilisés pour visualiser les variations de densité au cœur d'un volcan et ce de façon très directe : les muons parcourent la matière en ligne droite là où les ondes sismiques, signaux très souvent utilisés pour surveiller les entrailles des volcans, sont déviées chaque fois que le milieu change de nature. « *Nous testions les performances de notre méthode lorsque, en 2014, de nouvelles fumerolles sont apparues au sommet de la Soufrière. Or, peu avant cette nouvelle activité, notre télescope a détecté ce qui semble être de petites poches de vapeur en formation.* » Ce qu'aucune autre méthode n'aurait pu déceler. C'est la raison pour laquelle les chercheurs ont décidé d'installer des télescopes tout autour du volcan en vue d'effectuer un suivi en temps réel des humeurs du volcan. Une première. ■

VIVIANE THIVENT



- Resistivity tomography:
  - Tested in some archaeological founds which has been possible to dig up



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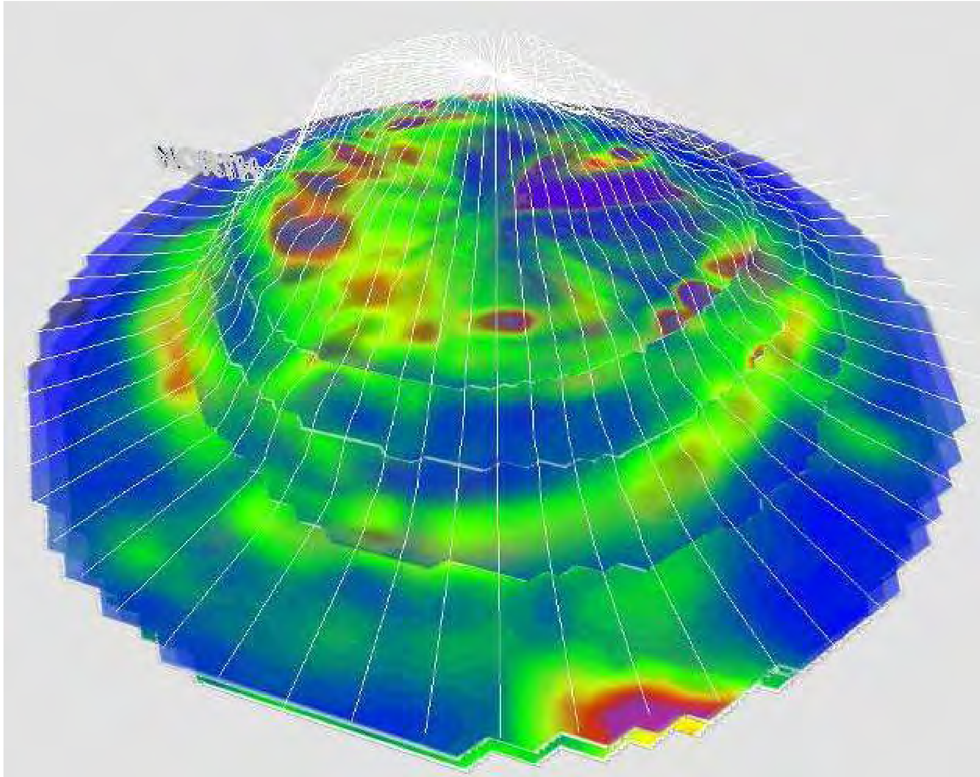
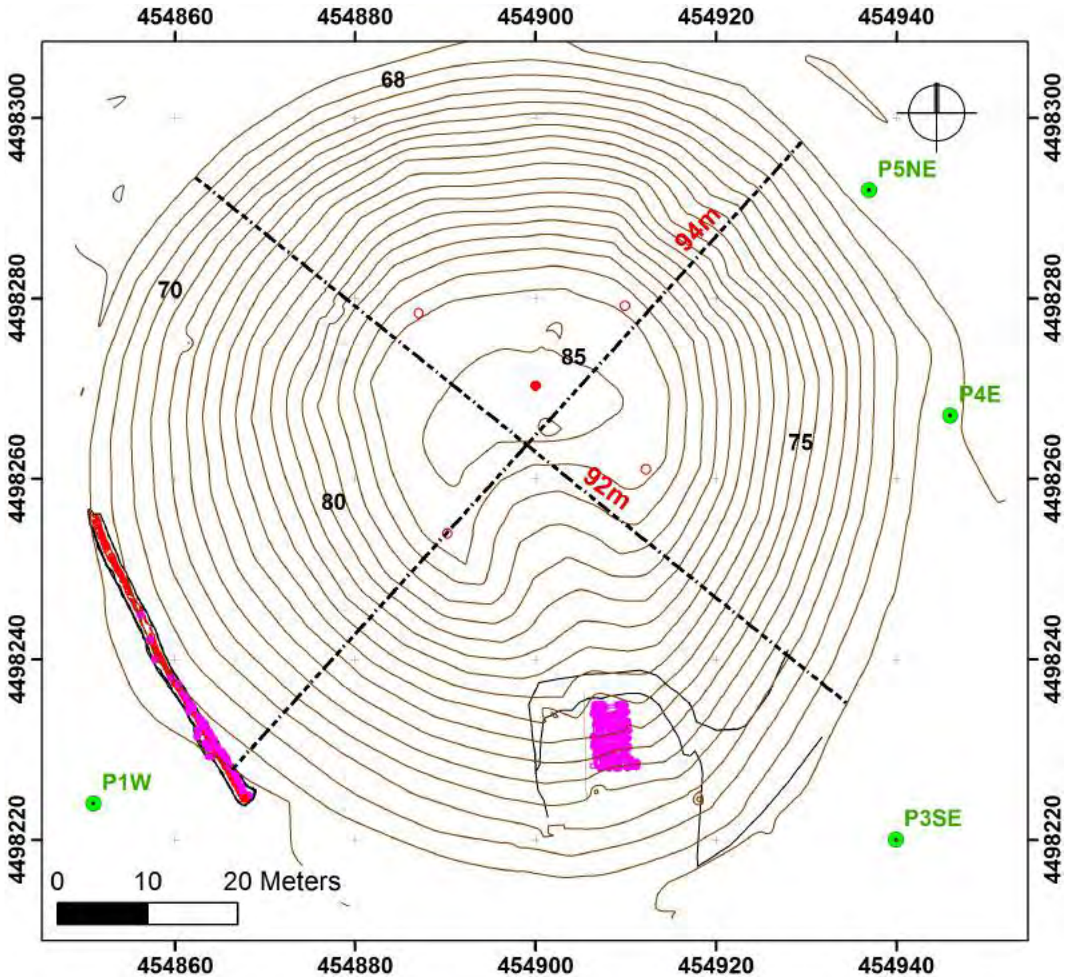


- But the method is slow and heavy to carry out:
    - Several measurements are needed


P5-N
P4-E
P1W
P3-SE
P2-S
Google earth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68
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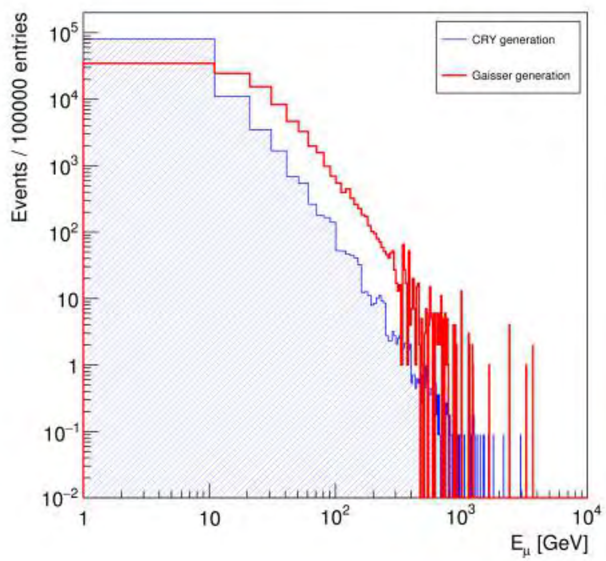
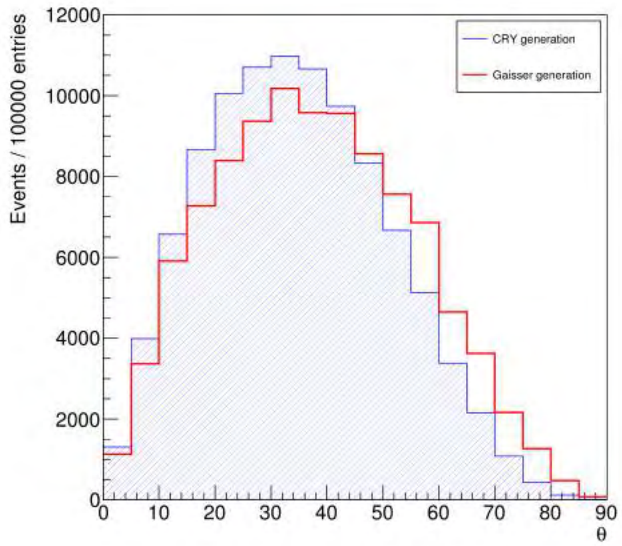
92m
P5NE
P4E
P1W
P3SE
0
10
20 Meters

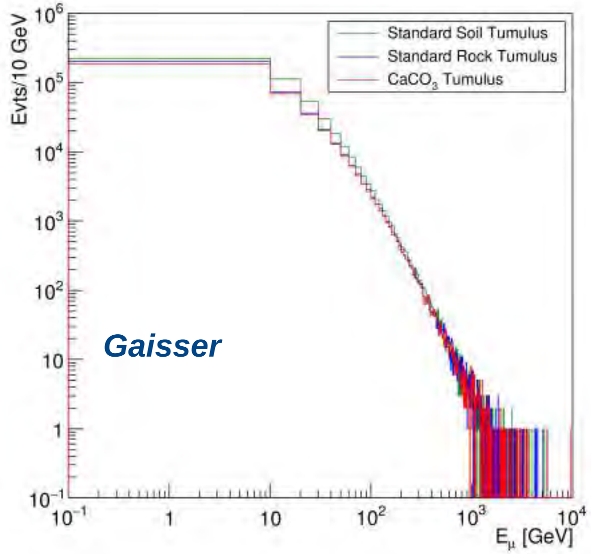
Muon Energy spectrum at surface



Muon incident zenith angle distribution at surface



Centred Detector



Side Detector