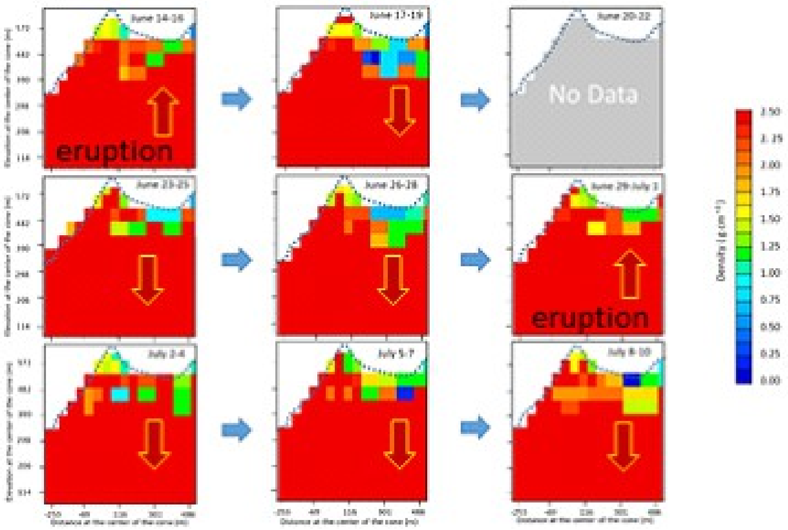
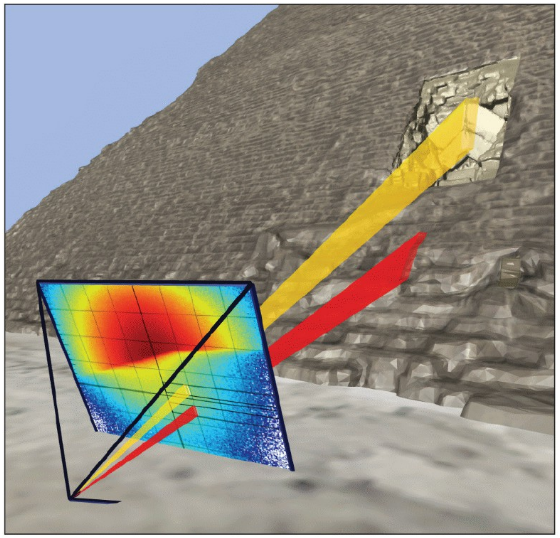
Cosmic-ray muons as practical tools





Andrea Giammanco

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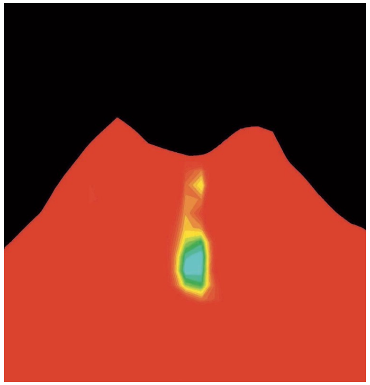
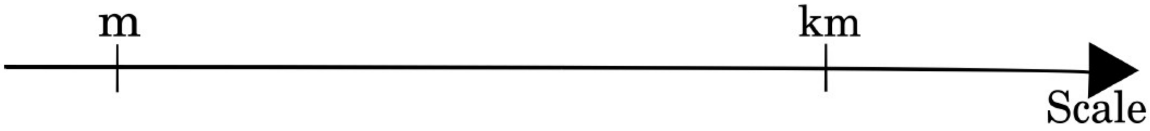
UCLouvain, Louvain-la-Neuve, Belgium

NISER, Oct. 14, 2022

Radiography vs Muography





Outline

1. Some physics
2. How-to
3. A few selected applications

Disclaimer:

- Choice of sub-topics is very biased, not representative at all of the variety of activities in this area

1. Some physics

What is a muon (μ)?

- One of the 3 charged leptons
- Unstable but long-lived
- ~200x heavier than the electron
- Leptons don't feel the strong nuclear force → no destructive interaction with the nuclei in matter
- Electromagnetic interactions depend inversely on the mass → muons in matter ionize less, are deflected less, and shower less than electrons

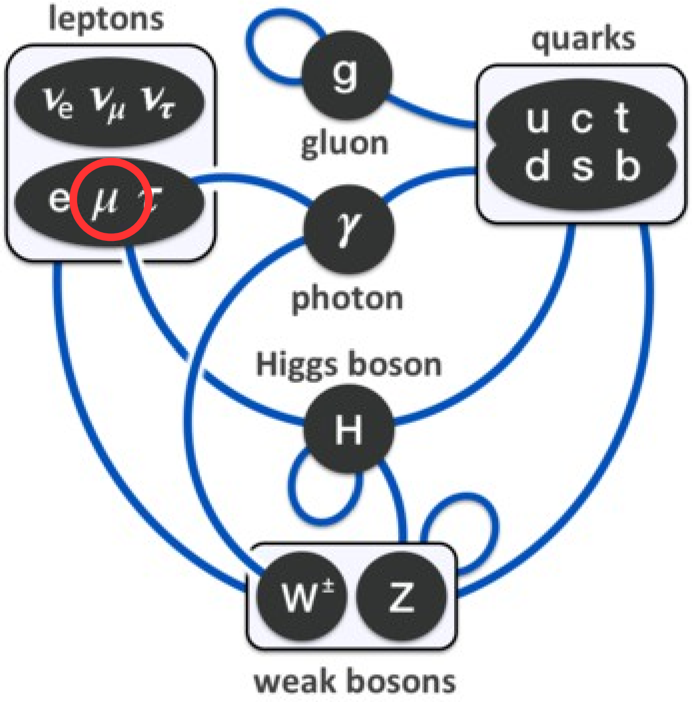


Image source: wikipedia

An old mystery

S.Neddemeyer & C.Anderson, Phys.Rev. 51 (1937) 884

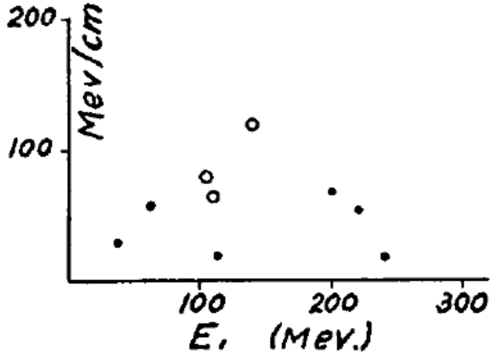


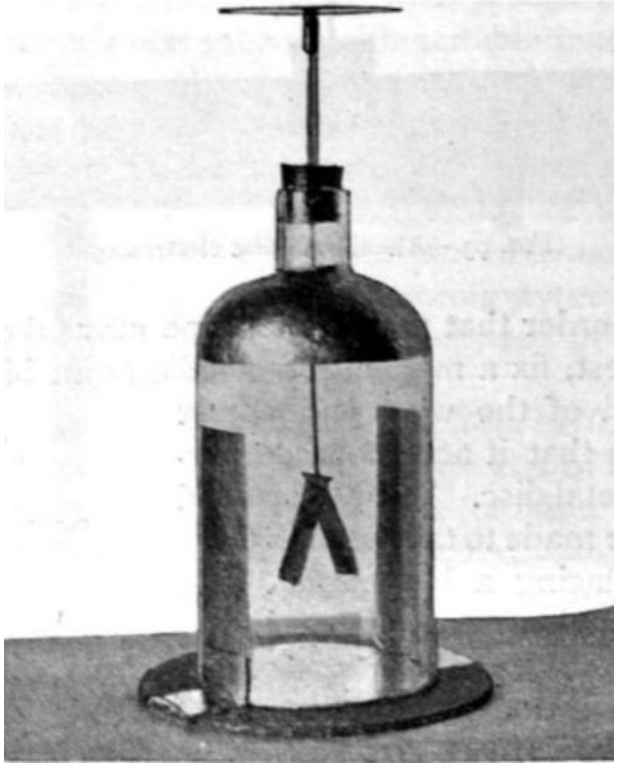
Figure 4: Early measurements of energy loss in 0.7-1.5 cm of Pb. Dots indicate single particles; circles, shower particles.

„Who ordered that?“ (I. Rabi)

Cosmic rays: how it all began

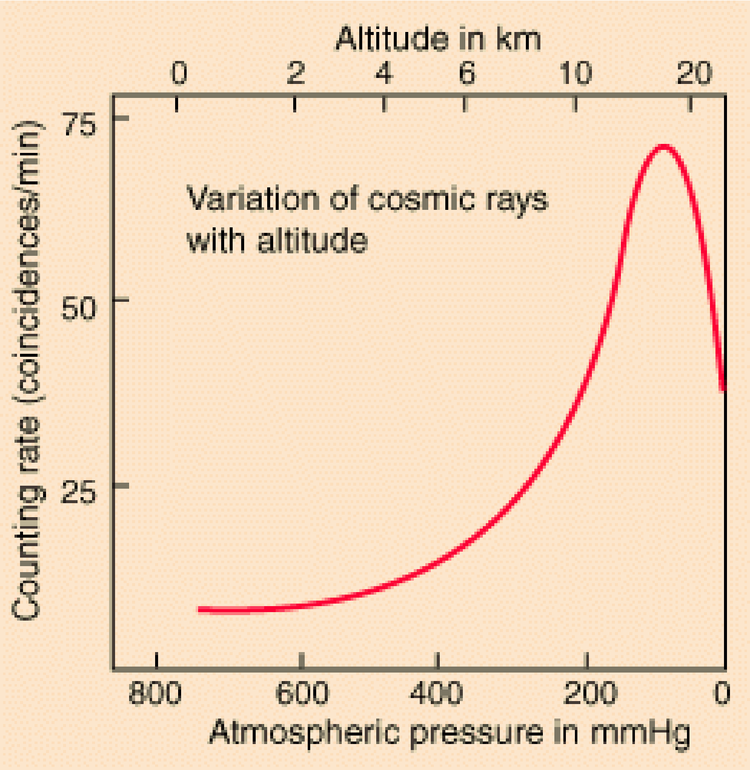
- Early 1900s: hypothesis that there is a natural background of ionizing radiation that discharges all the electroscopes
- People believed it was mostly due to radioactive rocks
- 1909: Theodor Wulf used Tour Eiffel to measure this background at different heights; surprisingly, he reported that it increases with the altitude, but measurements were not so precise and he was met with skepticism
- 1911-12: Victor Hess improved the instrument and used a balloon to study the phenomenon between 1000 and 5000 m over sea level

When the device is charged, the sheets move apart. Ionization of the gas leads to a discharge, and the sheets move towards each other.

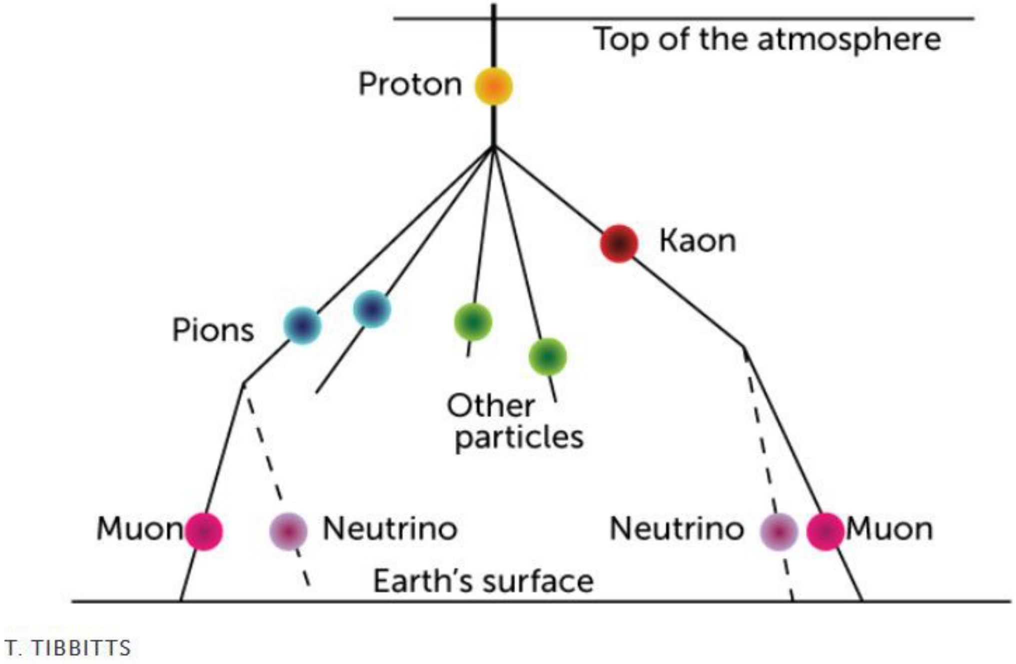


Source: http://cds.cern.ch/journal/CERNBulletin/2012/32/News%20Articles/1471207

Primary and secondary cosmic rays



Picture from here

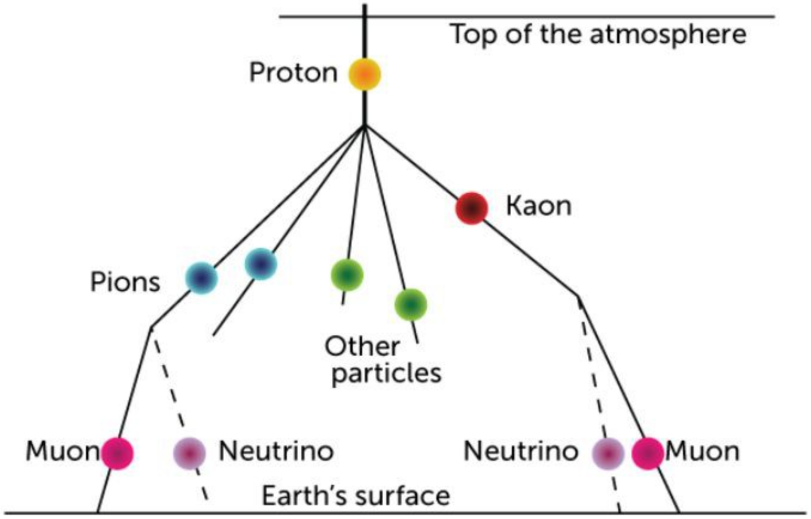


Picture from Science News

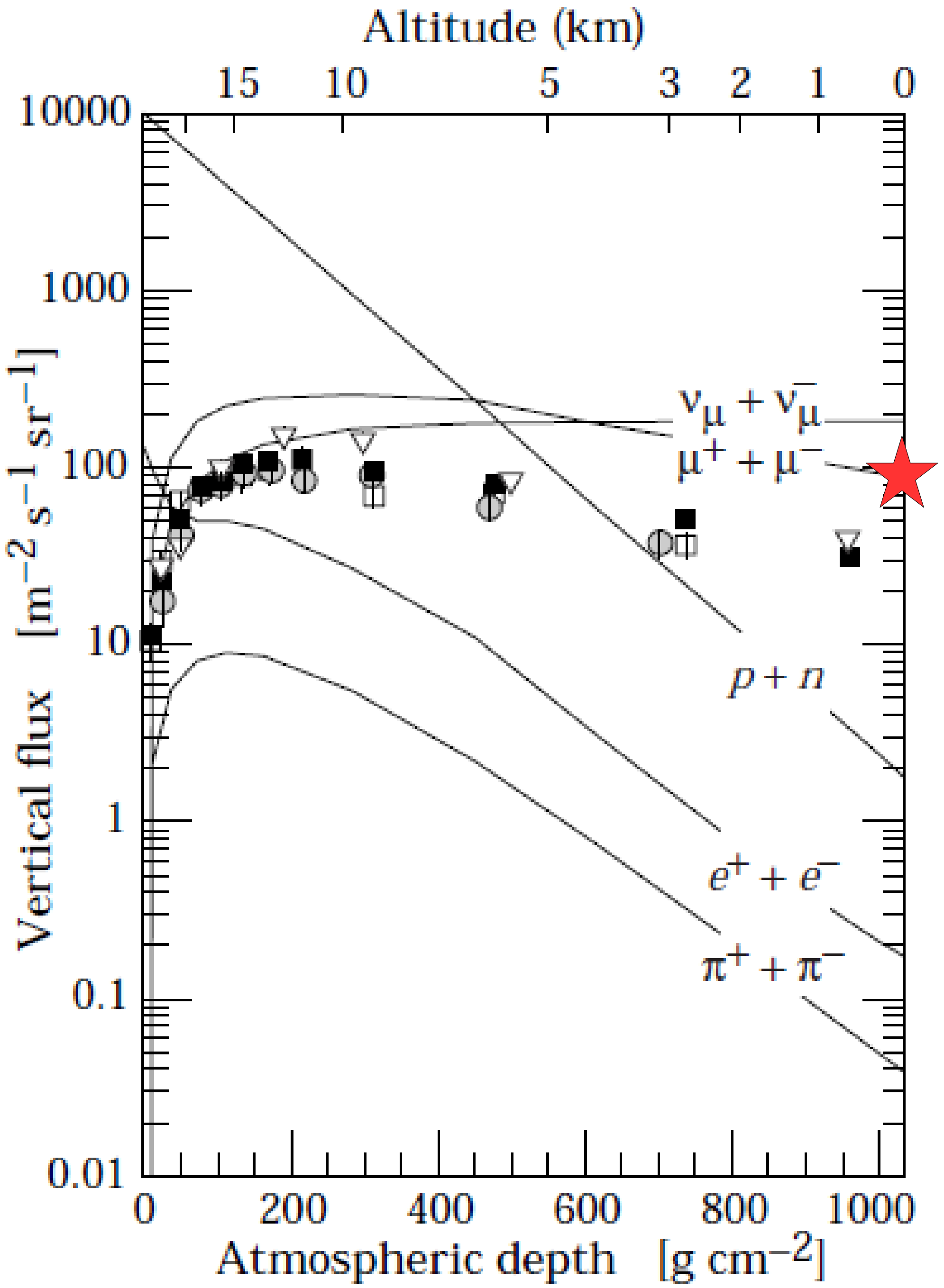
The number of charged particles increases as the cascade progresses, but eventually most of them are absorbed

Secondary cosmic rays in the atmosphere

- Primary CRs (mostly protons) entering the atmosphere collide mostly with Oxygen and Nitrogen, producing a shower of particles
- Most CR collisions happen between 15 and 16 km above sea level; the rest of the atmosphere absorbs most of the secondaries through nuclear or EM interactions; most muons pass through
- Rate at sea level: ~100 Hz/m^2 (~1 μ/second through your thumb)



T. TIBBITTS

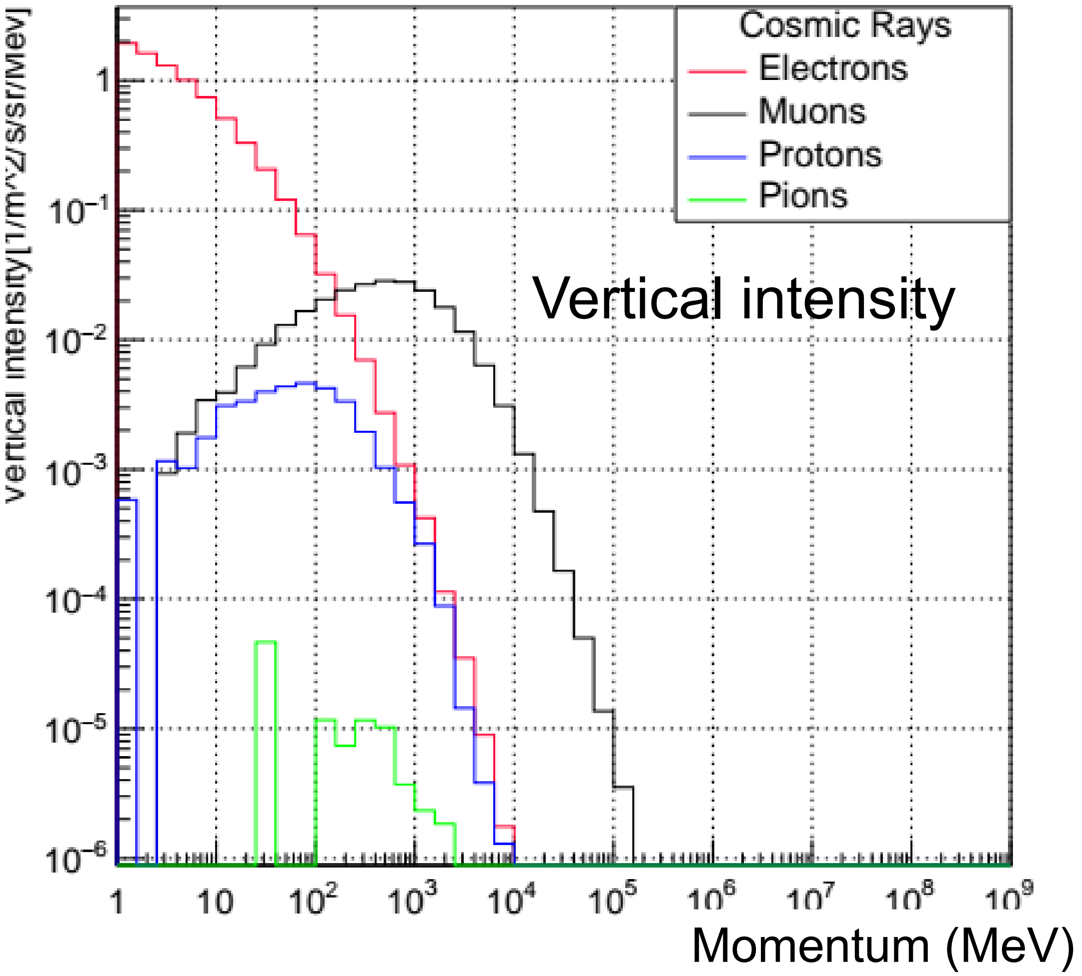


At ground level, the visible flux is dominated by muons

Source: Particle Data Group

All curves are for E>1 GeV; points are experimental measurements for negative muons

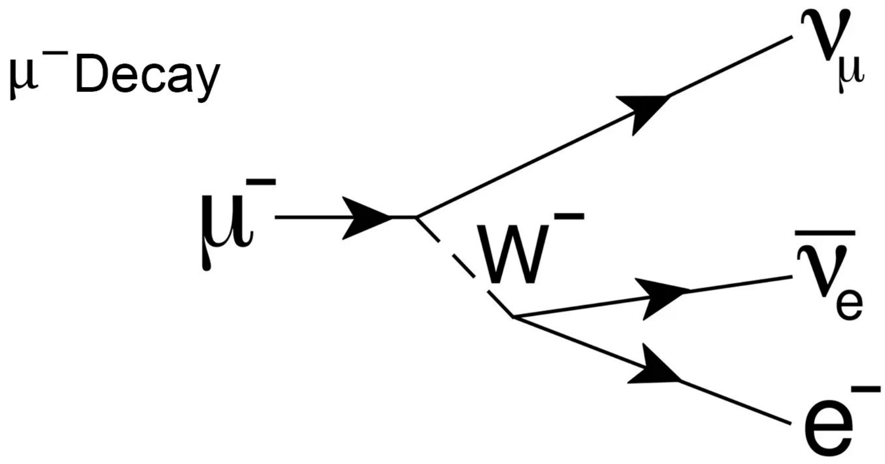
Spectrum at sea level



Plot by Marwa Al Moussawi, using the CRY cosmic-ray generator

Unstable but long-lived

- Muons decay into electrons and neutrinos; process mediated by the *weak* interaction, hence relatively slow
- Lifetime *at rest*: τ_0=2.2 μs
- But from the point of view of an observer in a different rest frame, *time dilates*: $\tau = \gamma\tau_0 \sim (P/mc)\tau_0$
- Mass is 105 MeV/c^2, and most muons from cosmic rays have momenta of several GeV/c
- $L = v\tau = \beta c\gamma\tau_0$
- The average pathlength is thus longer than the thickness of the atmosphere



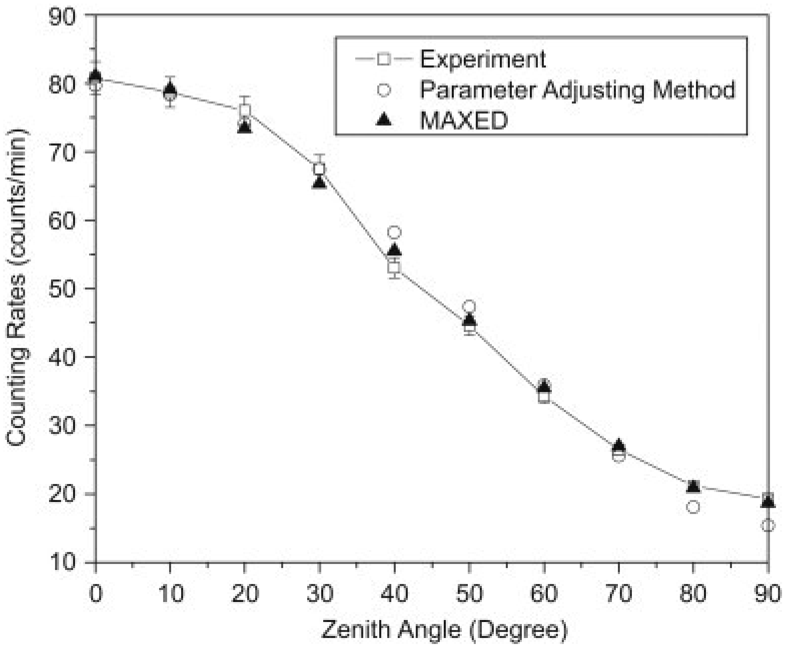
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Figure from https://digitash.com/science/physics/how-neutrinos-are-formed-and-detected-quantum-mechanics/

Angular distribution

$$\boxed{I_\theta = I_0 \cos^n \theta}$$

This is an approximation, and n~2 works pretty well; but it depends on energy, latitude, altitude, depth, …



From J.-W. Lin et al., *Measurement of angular distribution of cosmic-ray muon fluence rate*, NIM A 619 (2010) 24

⇒ Large difference in statistics between vertical and horizontal telescopes

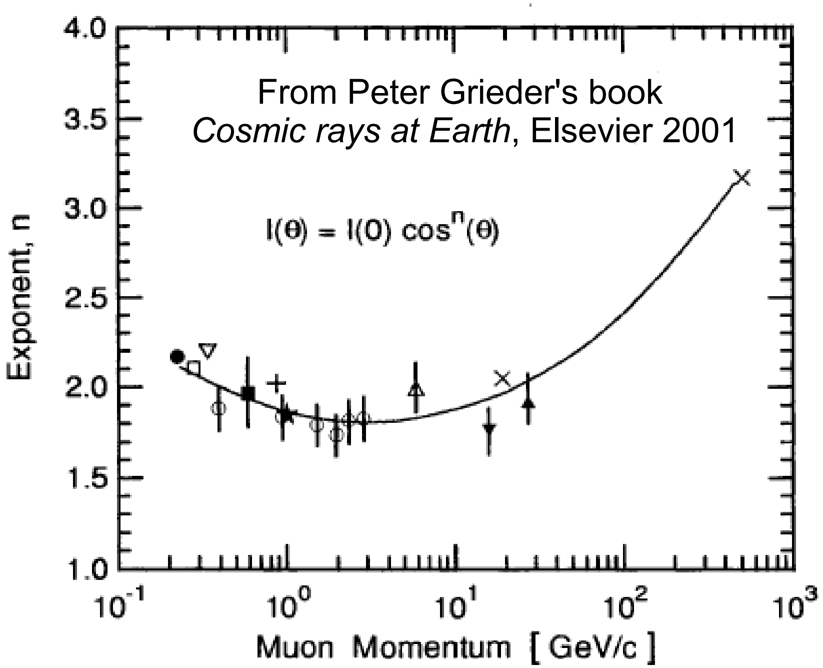
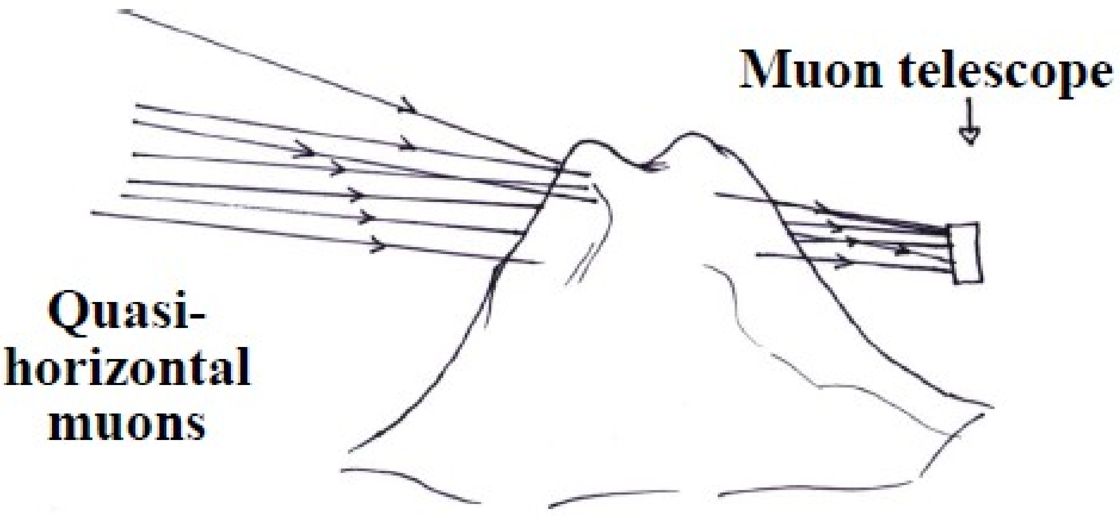

From Peter Grieder's book
Cosmic rays at Earth, Elsevier 2001

Figure 3.60: Momentum dependence of the exponent, n, of the zenith angular distribution of muons, $I(\theta, > p) = I(0°, \geq p)\cos^n(\theta)$ at sea level (Bhattacharyya, 1974b).

2. How-to

Absorption method

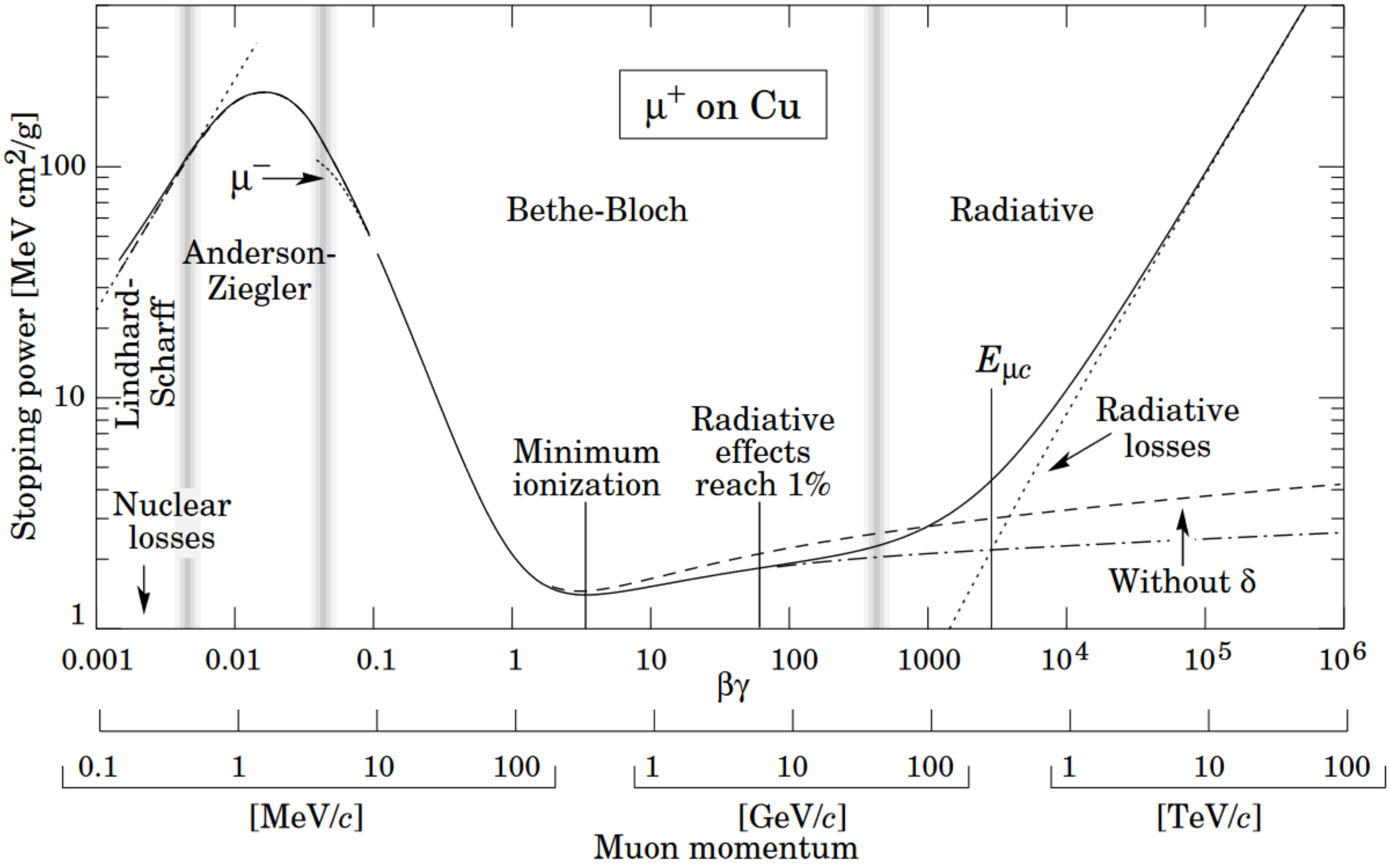


Picture from P. Strolin

- Just like normal radiography, with μ instead of X-rays
- Absorption is almost entirely due to energy loss by ionization
- We can see the 2D shadow of a large object, with denser regions absorbing larger fractions of the muon flux
- Observable: **opacity**, i.e. integral of the density along a line of sight, measured as ratio of the flux with respect to free sky

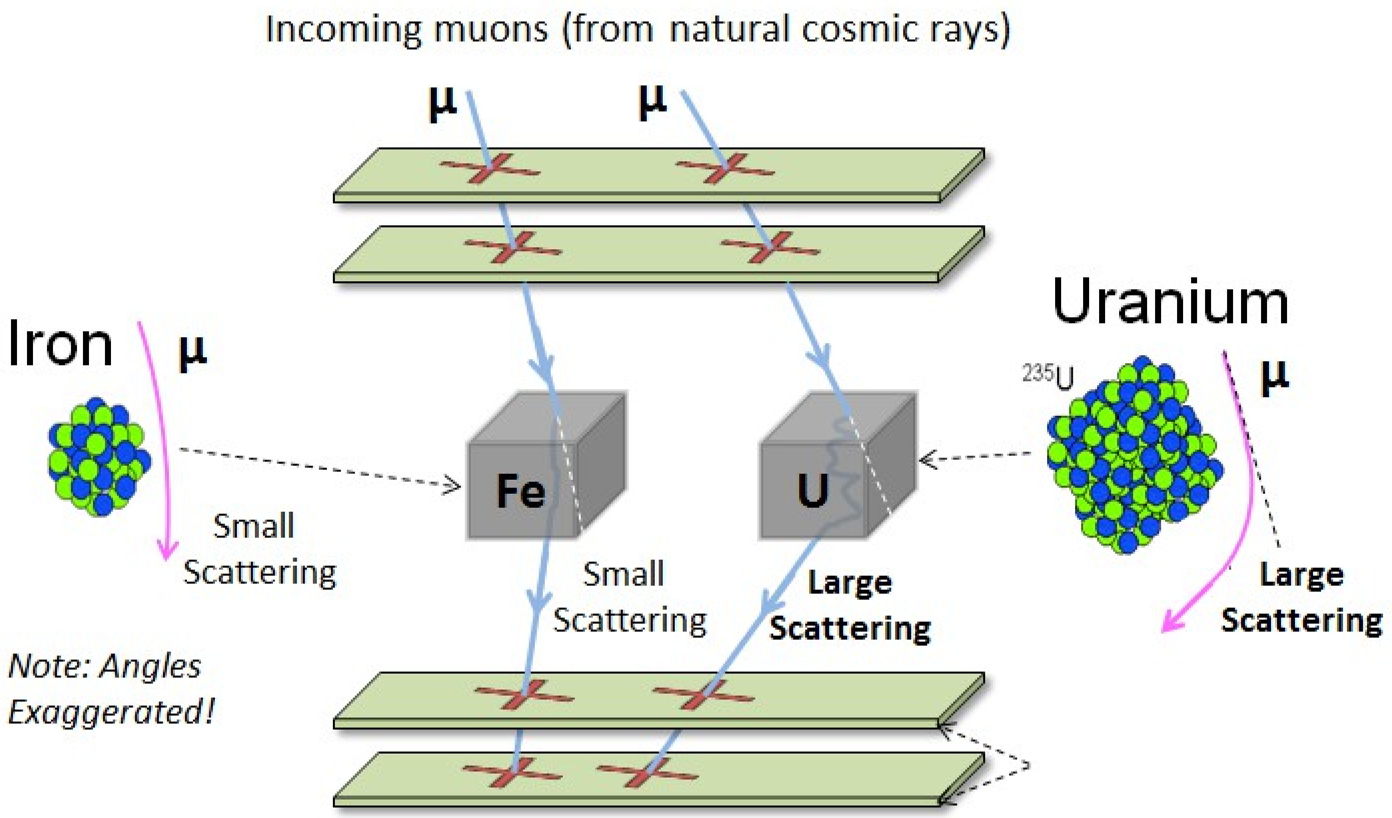
Stopping power

Source: Particle Data Group



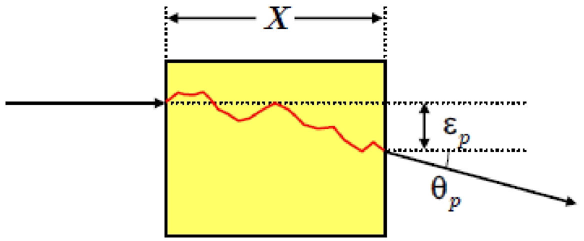
At typical cosmic energies, muons loose ~2 MeV/cm in water (ρ=1 g/cm^3)

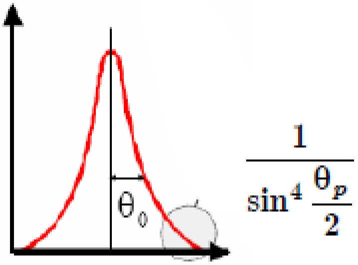
Scattering method



From http://cms.cern/content/homeland-security

Figures from here





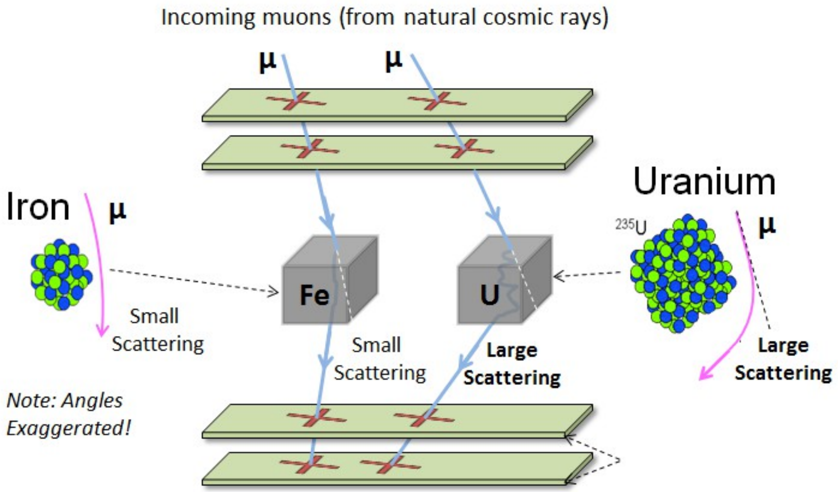
$$P(\theta_p) = \frac{1}{\sqrt{2\pi \langle \theta_p^2 \rangle}} \exp\left[-\frac{1}{2\langle \theta_p^2 \rangle} \theta_p^2 \right]$$

- Deflection distribution follows Rutherford's law in the tails (single hard scattering) and is ~ Gaussian in the bulk (multiple scattering)

$$\langle \theta_p^2 \rangle = K \frac{X}{X_0}$$

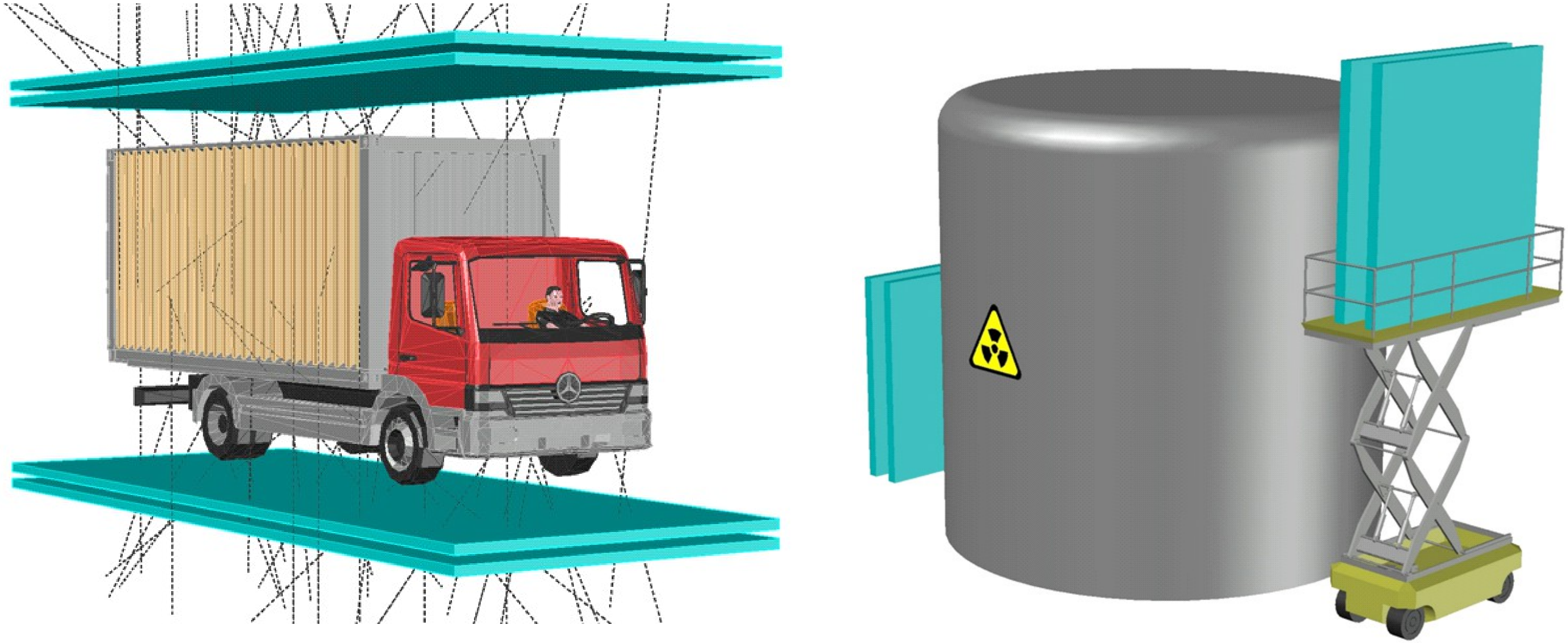
$$K = z^2 \left(\frac{0.0136}{p\beta} \right)^2$$

- X_0 is the radiation length, and it depends on the atomic number



$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 \left[L_{\rm rad} - f(Z) \right] + Z\, L'_{\rm rad} \right\}$$

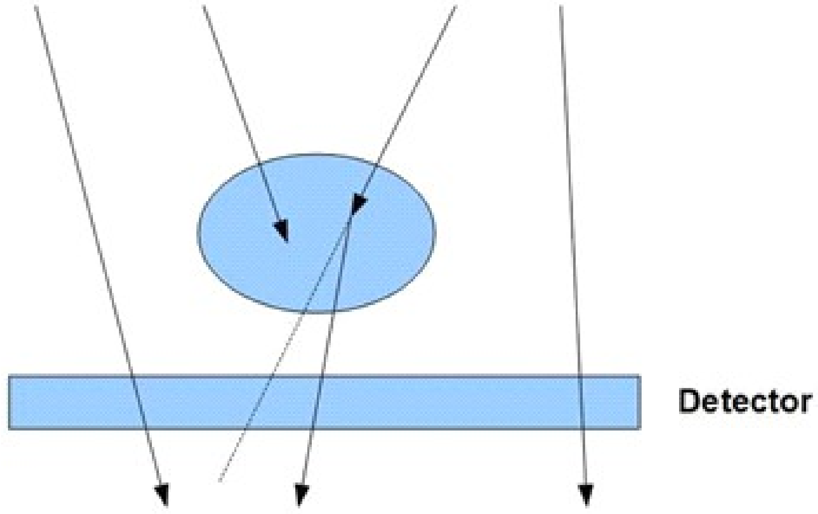
Typical use cases for scattering

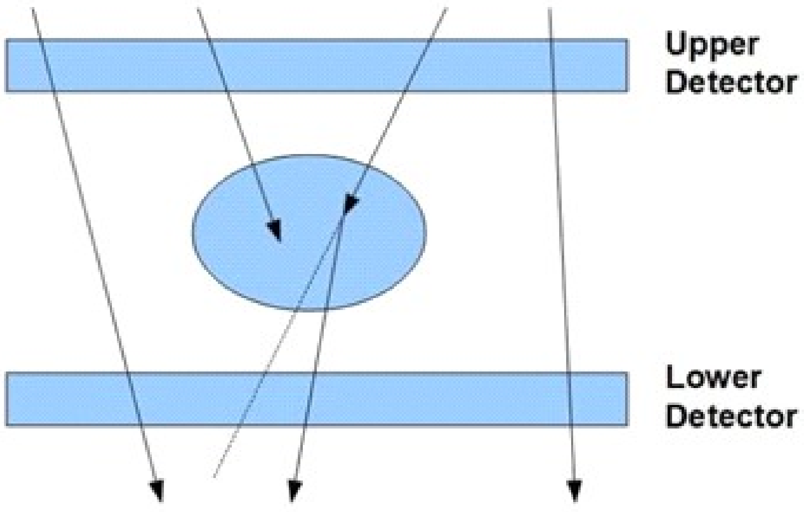


From L. Bonechi, R. D'Alessandro, A.G., arXiv:1906.03934, Rev. Phys. 5 (2020) 100038

- Most use cases are related to identification of high-Z materials (e.g., spent nuclear reactor fuel, smuggled fissile material, etc.)
- Invented in 2003, already attracted interest of the private sector and of the IAEA (see upcoming IAEA-TECDOC-2012)

Absorption vs scattering

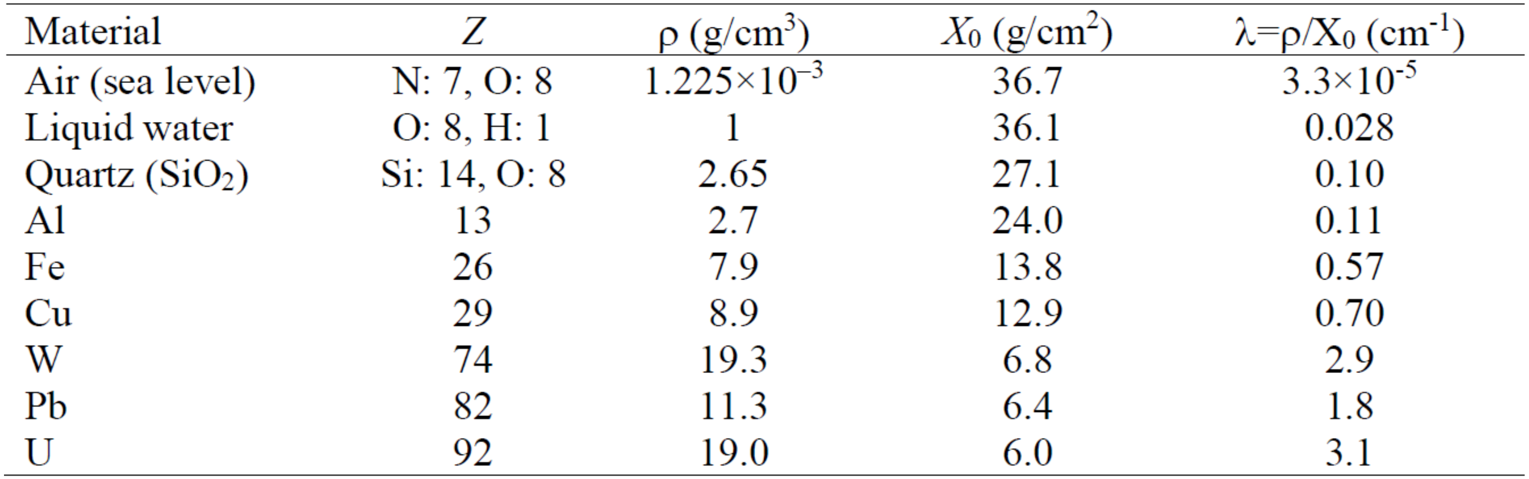




- Opacity measurement
- Sensitive to ρ
- Observable: deficit with respect to free sky
- Intrinsically 2D, can get 3D by using multiple points of view
- No limit on size of target

- Deflection measurement
- Sensitive to Z and ρ
- Observable: RMS of deflection
- (can be combined with absorption)
- Intrinsically 3D
- Size of target limited: must fit between the two detectors

What to use for what



Material	Z	ρ (g/cm^3)	X_0 (g/cm^2)	$\lambda=\rho/X_0$ (cm^{-1})
Air (sea level)	N: 7, O: 8	1.225×10^{-3}	36.7	3.3×10^{-5}
Liquid water	O: 8, H: 1	1	36.1	0.028
Quartz (SiO_2)	Si: 14, O: 8	2.65	27.1	0.10
Al	13	2.7	24.0	0.11
Fe	26	7.9	13.8	0.57
Cu	29	8.9	12.9	0.70
W	74	19.3	6.8	2.9
Pb	82	11.3	6.4	1.8
U	92	19.0	6.0	3.1

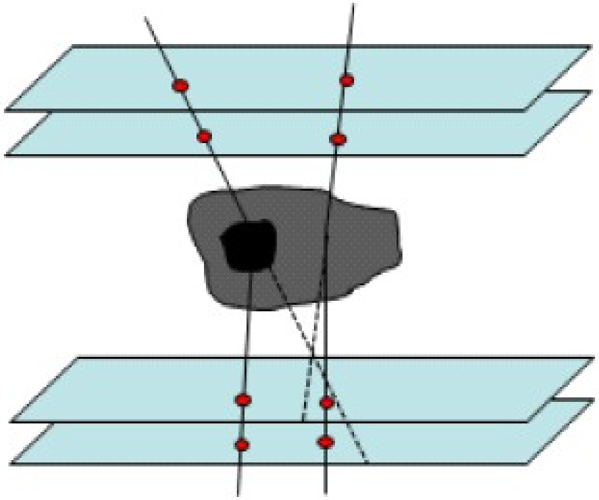
Absorption is sensitive to differences in ρ,
scattering is sensitive to differences in $\lambda=\rho/X_0$

(Table to appear in IAEA-TECDOC-2012)

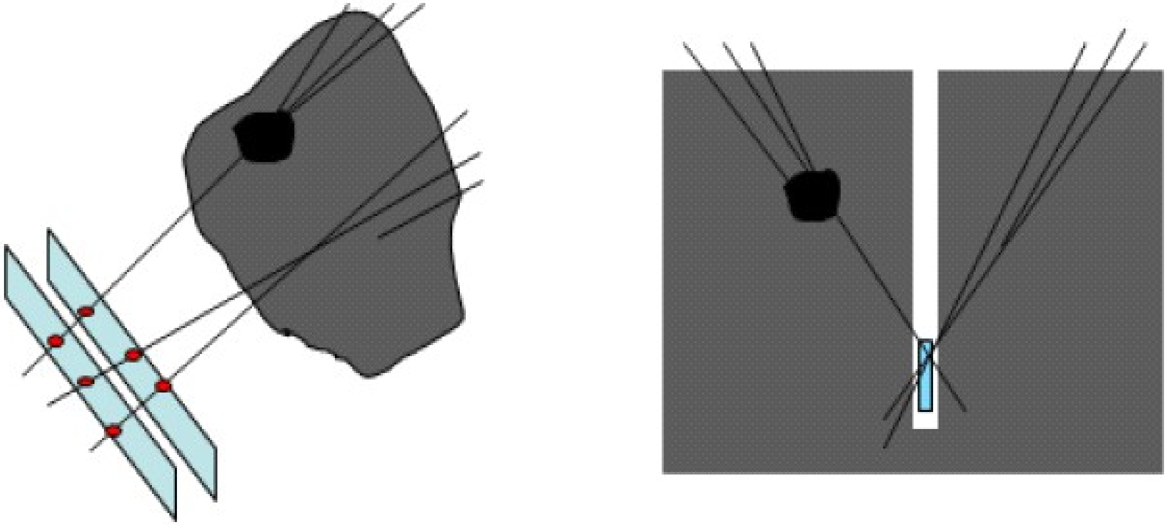
What to use for what

Material	Thickness	θ (°)	$P_{absorption}$
Air	100 m	0.094	0.78%
Lead	10 cm	1.01	2.9%
Water	1 m	0.35	4.2%
Ground	100 m		99%

Figures and table from S.Procureur



Scattering



Absorption

Scintillators

- Solid plastic scintillators, coupled to photomultipliers
- Strengths:
  - ✓ Cheap
  - ✓ Robust
  - ✓ Quick signal → can use time-of-flight to reject backgrounds
- Weaknesses:
  - ✗ Poor space resolution
  - ✗ Photomultipliers response may depend on temperature (issue if operating outdoors for months)

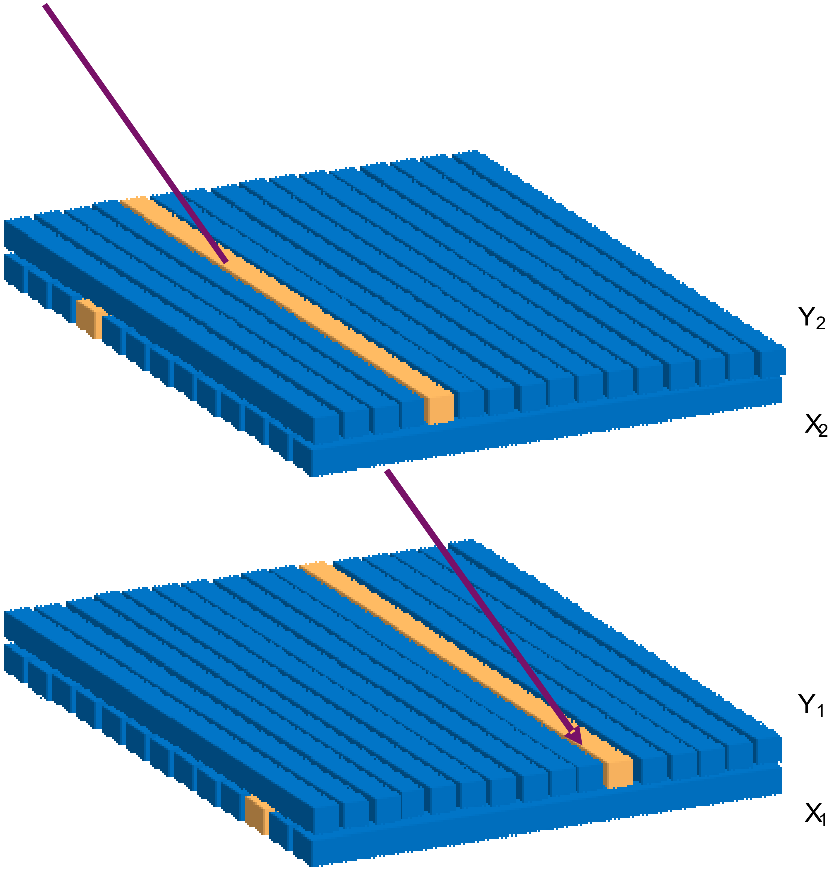
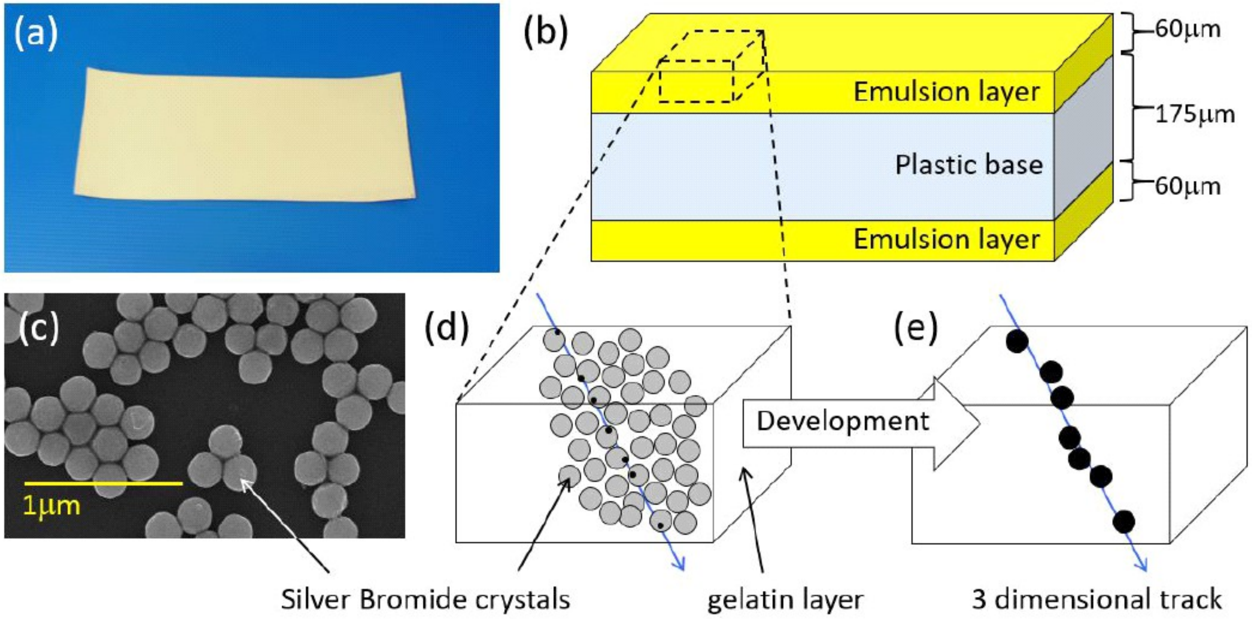
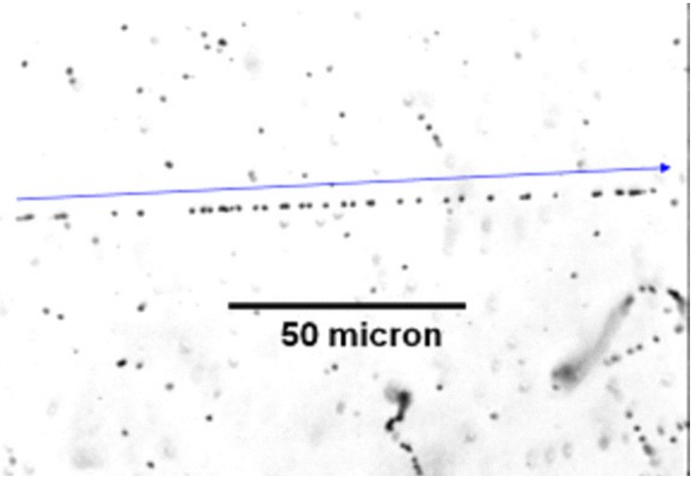


Illustration by S.Procureur

Nuclear emulsions

- Photographic plates
- Strengths:
  - ✔ Excellent resolution
  - ✔ No need for power supply
- Weaknesses:
  - ✗ Fragile
  - ✗ No real-time information
  - ✗ No background rejection
  - ✗ Dedicated analysis infrastructure (scanners)

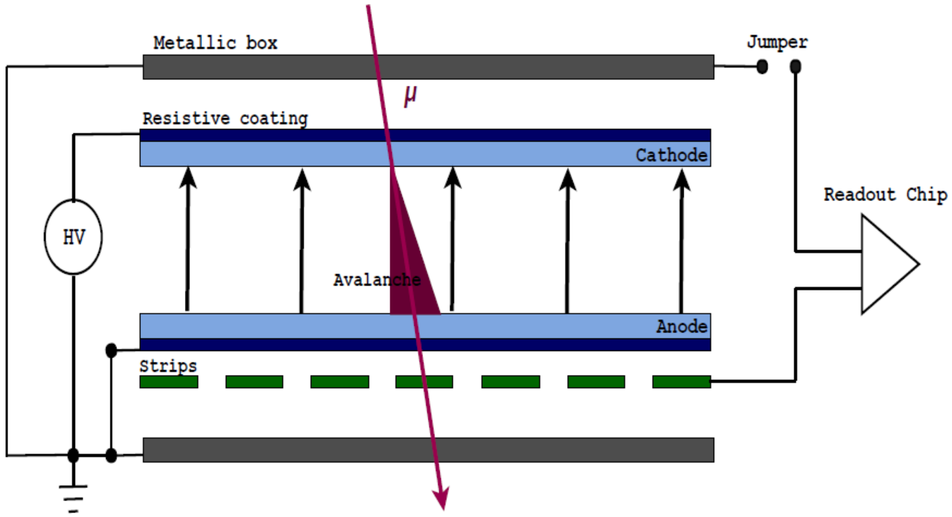




Some very impactful muography teams (e.g.: Bern, Salerno/Naples, Nagoya) previously belonged to the OPERA ν experiment, based on this technique

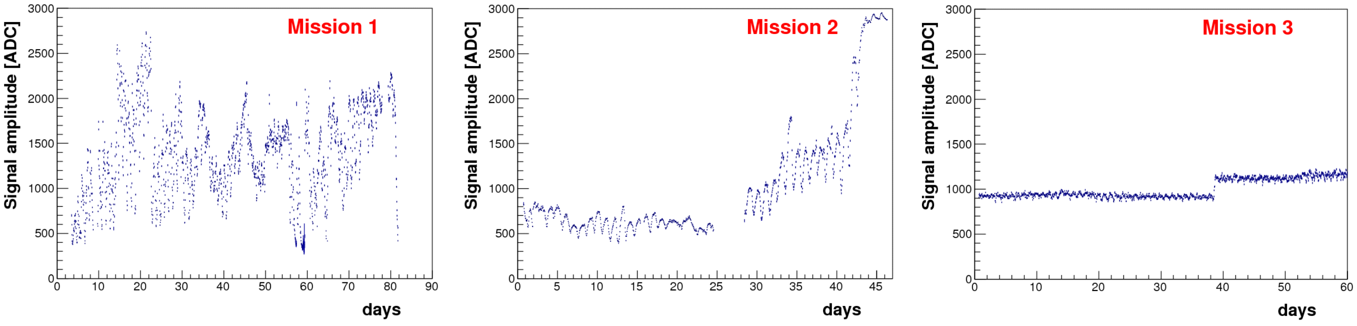
Gaseous detectors

- Huge variety of techniques are in use in muography (drift tubes, RPC, MWPC, MicroMegas, …), with very different complexity, cost, robustness
- General strengths:
  - ✔ Very good space resolution
  - ✔ Quick signal → can use time-of-flight to reject backgrounds
- General weaknesses:
  - ✗ Logistics (gas bottles), leakages, security issues
  - ✗ Stability



Example: RPC, illustration by Sophie Wuyckens

Gain variations of CEA/ScanPyramid MicroMegas detector, with increasingly complex gain corrections:

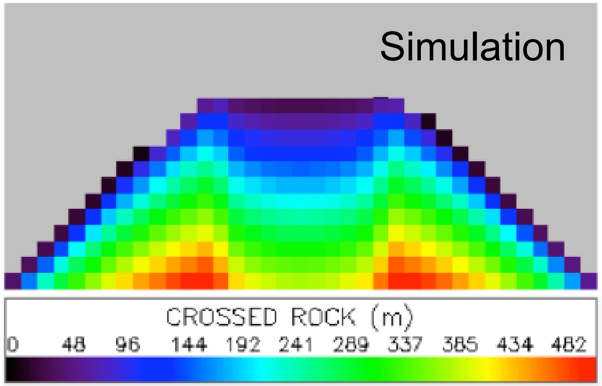


More exotic choices

- Silicon detectors
  - Lot of expertise in HEP with Si pixel and microstrip detectors; <100 μm resolution
  - A Fermilab team used CMS microstrip modules in a demonstrator for cargo scanners
  - Excellent option for extraterrestrial applications (compact payload, and rad-hard)
  - Problem: very expensive (CMS microstrips: ~1000 euros per module)
- Cherenkov light in air
  - ASTRI-Horn, a prototype for the CTA, located on Mt. Etna's slopes (Italy)
  - "Parasitic" usage for muography; but location not optimal (5 km from target), and not portable
  - Momentum threshold (20 GeV) limits statistics
  - On the other hand, practically 0 background
  - Movable/cheaper version has been proposed

CMS Si strip module

Image credit: INAF



O.Catalano, M.Del Santo, T.Mineo, G.Cusumano, M.C.Maccarrone, G.Pareschi, NIM A 807 (2016) 5

3. applications

First known application of muography (1955)

Commonwealth Engineer, July 1, 1955 455

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.

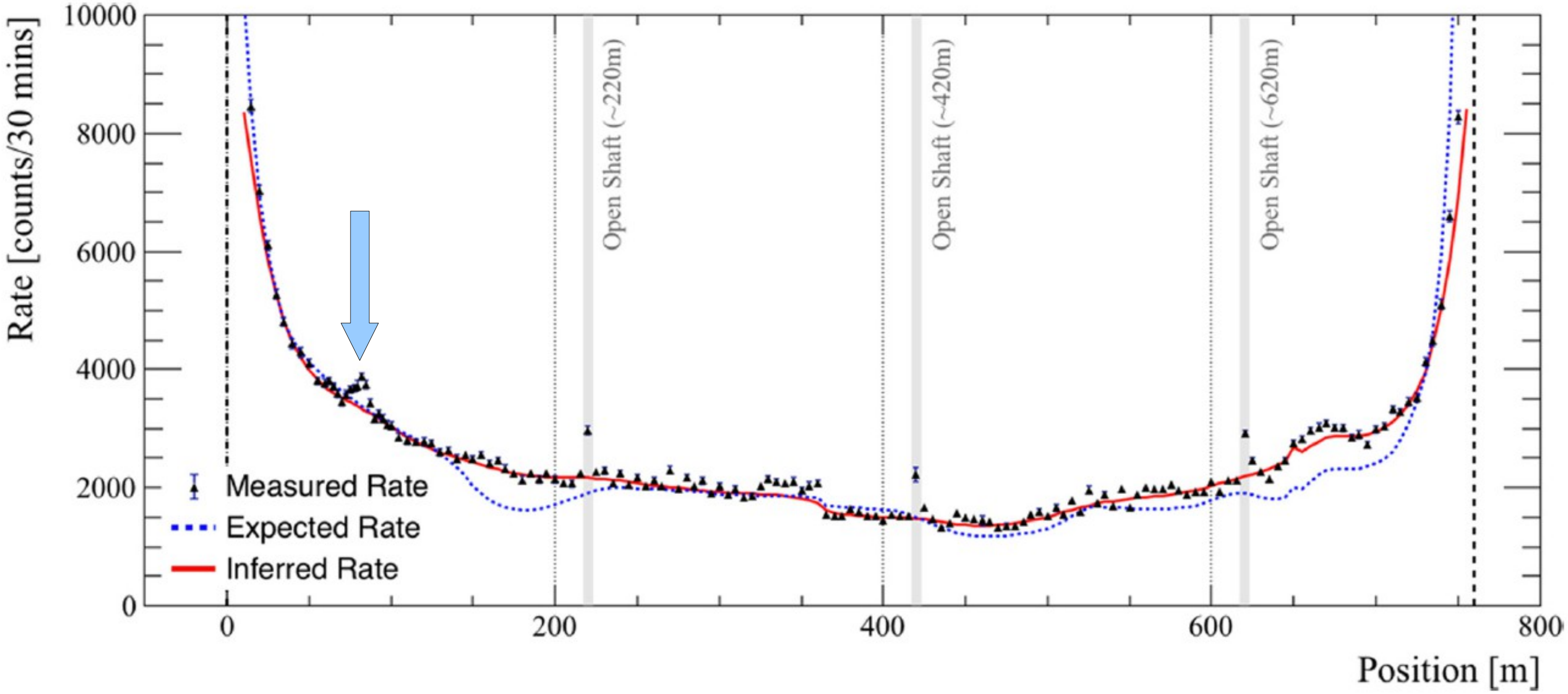
Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described

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

Image source: https://www.hep.ucl.ac.uk/creamtea/

- Used to measure ice thickness above a tunnel in Australia
- No directional information, just a Geiger counter on rails

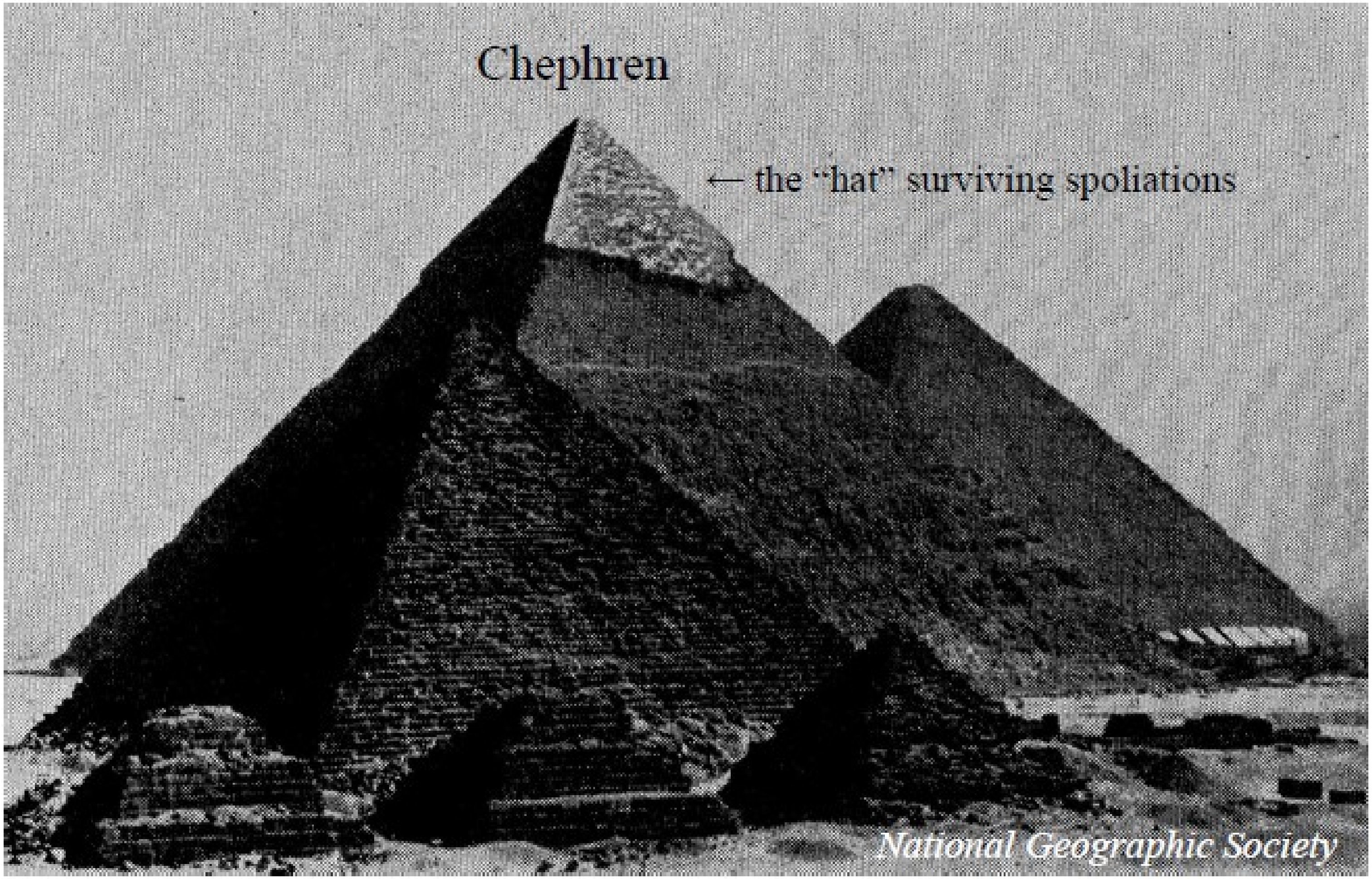
Fast-forward by 65 years



L. Thompson et al, Phys. Rev. Research 2, 023017 (2020)

- Recent incarnation of the same idea was used recently to survey a railway tunnel built in 1862 in the UK
- Movable detector on a rail, 30' at each detector position
- Found an unknown void (see arrow), interpreted as a long-forgotten shaft. Railway authorities then disclosed their pre-existing concerns of a hidden void in that area

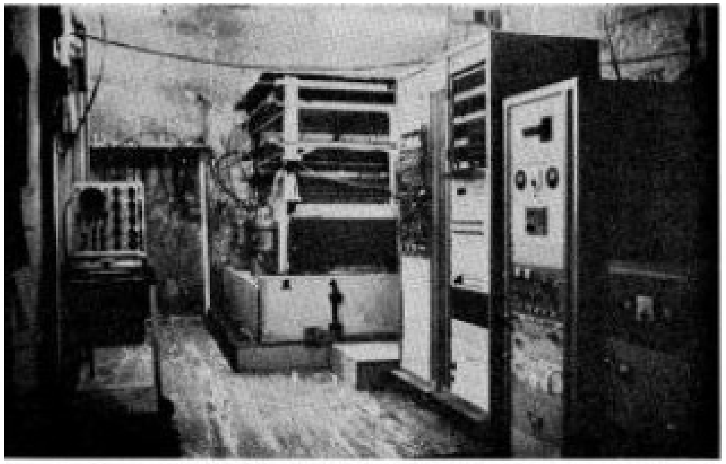
First application of muography to archaeology



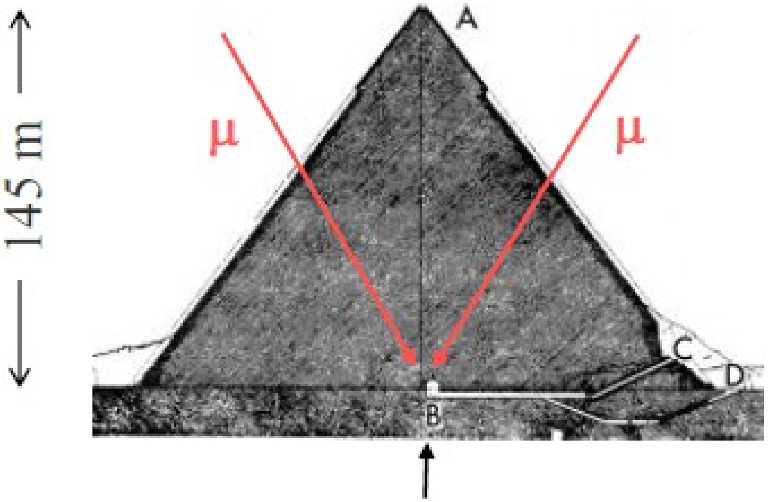
Search for hidden chambers in the Chephren's Pyramid

L.W. Alvarez et al. Science 167 (1970) 832

Alvarez's result: no hidden chamber

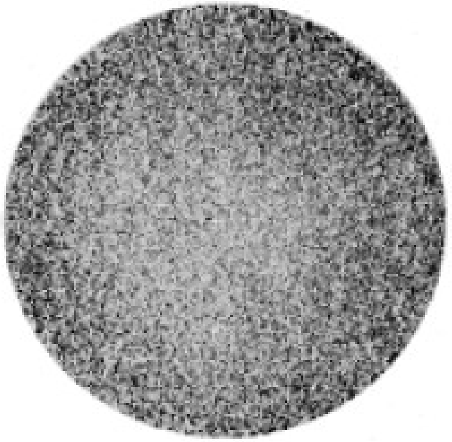


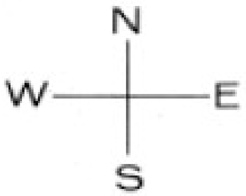
Spark chamber “muon telescope”



Telescope in Belzoni chamber

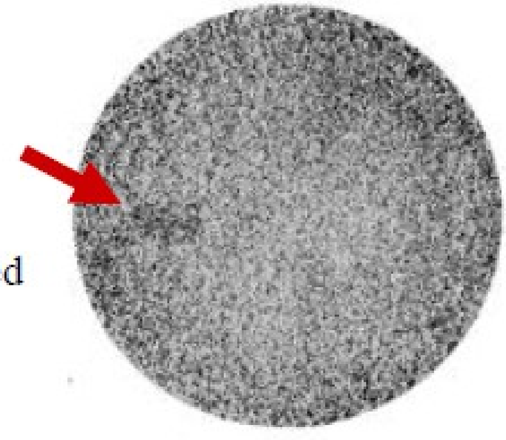
Data



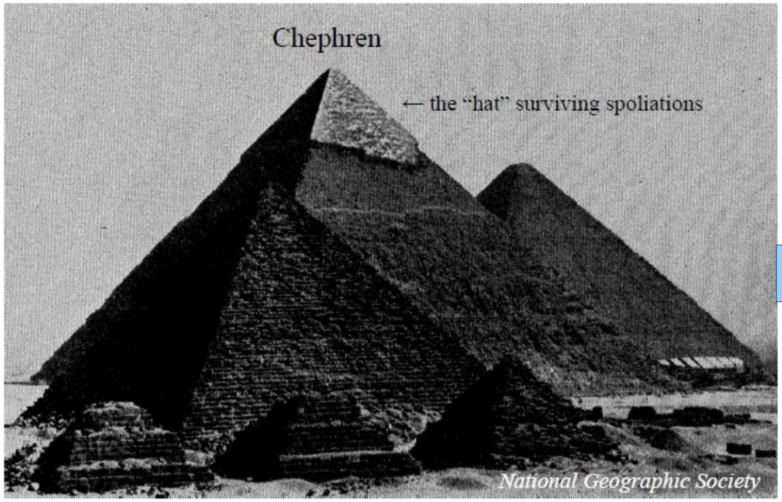


Data and simulation are corrected for pyramid structure and telescope acceptance

Simulation with hidden chamber

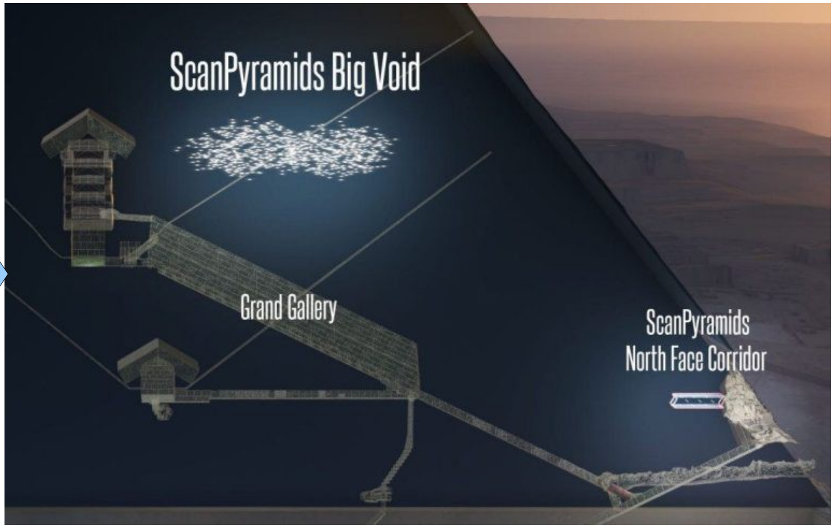


Fast-forward by 50 years



Search for hidden chambers in the Chephren’s Pyramid

L.W. Alvarez et al. Science 167 (1970) 832



Discovery of a big void in Khufu’s Pyramid by observation of cosmic-ray muons
Morishima et al., Nature 552 (2017) 386

Alvarez chose the wrong pyramid...

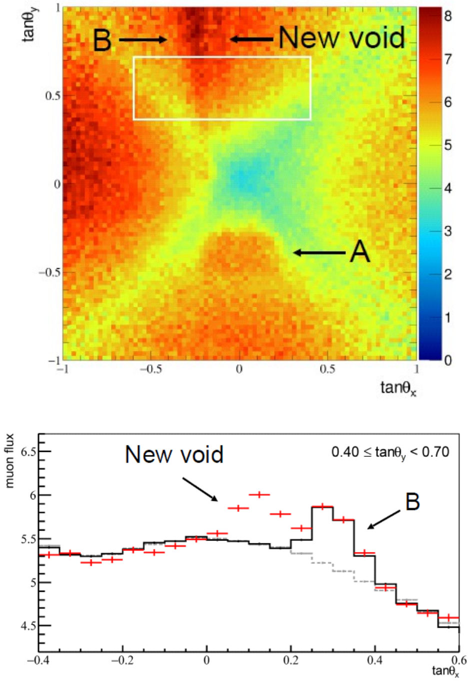
(But would have he been able to spot this void?)

Khufu's Great Pyramid

(ScanPyramids mission)

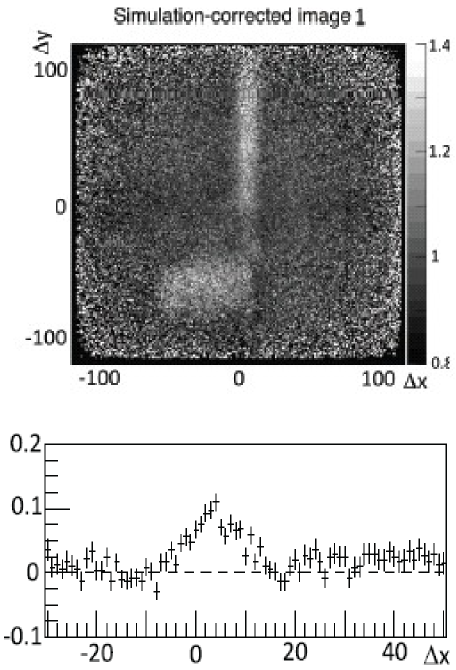
Nagoya

(emulsions,
indoors)



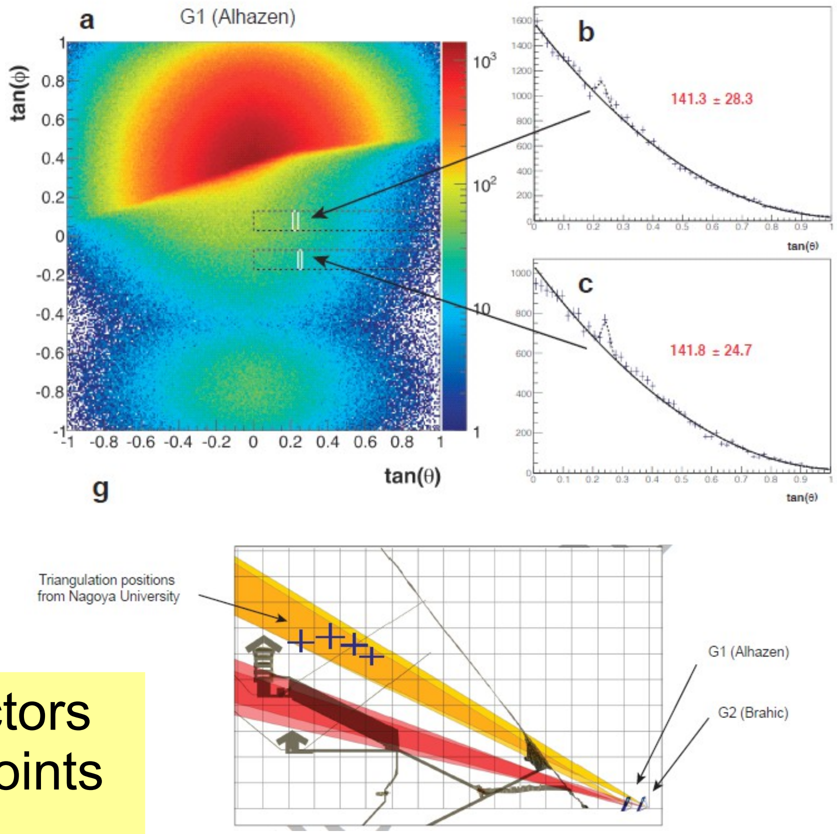
KEK

(scintillators,
indoors)



CEA

(MicroMegas,
outdoors)



Coherent results from 3 very different detectors (independent analysis) and from different points of view; position from triangulation

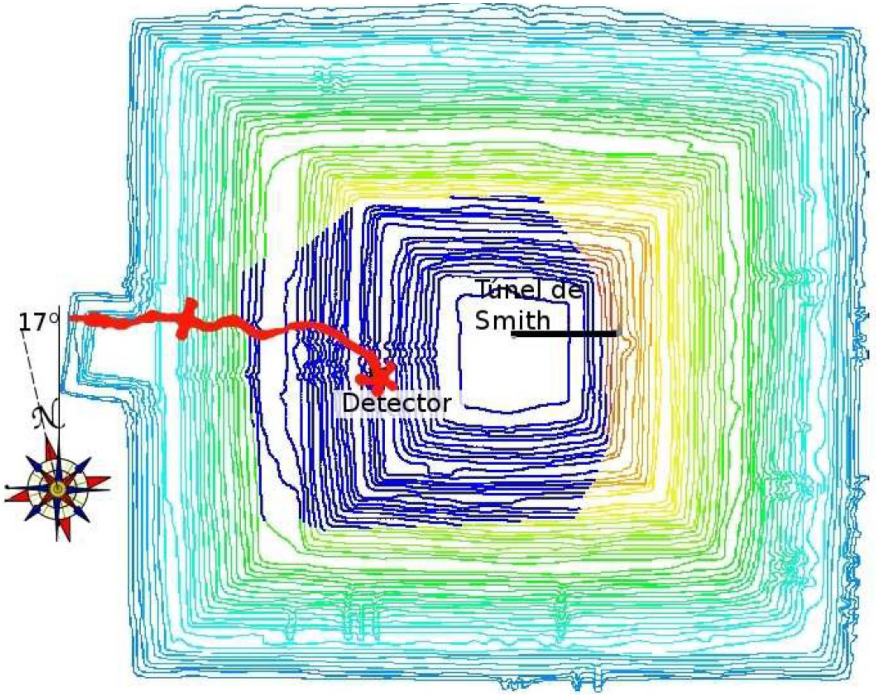
Morishima et al., Nature 552 (2017) 386

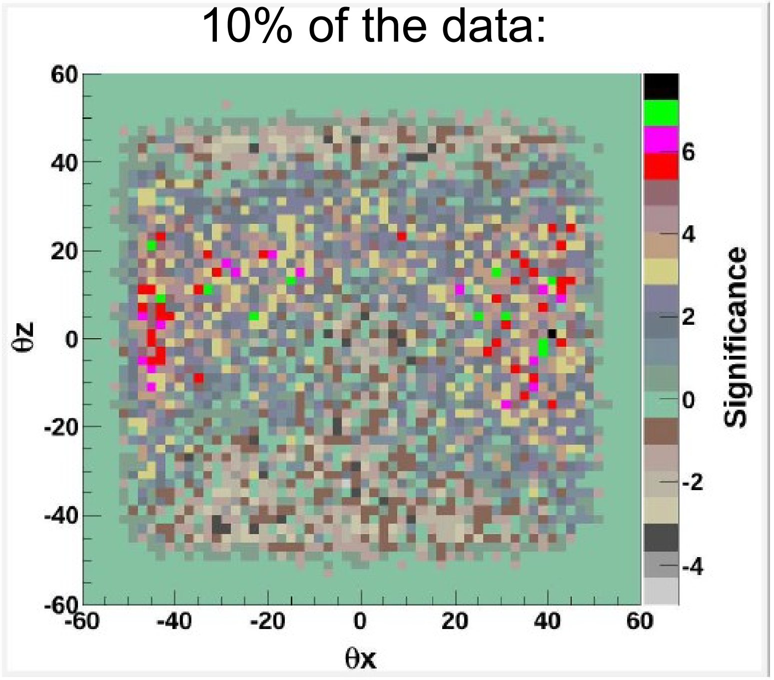
Another pyramid

Pyramid of the Sun at Teotihuacan, Mexico
3rd largest in the world, built 1800 years ago by the Aztecs

Picture from: L. Melesio, The pyramid detectives, Phys. World, 27 (12) (2014), p. 24

Pyramid of the Sun



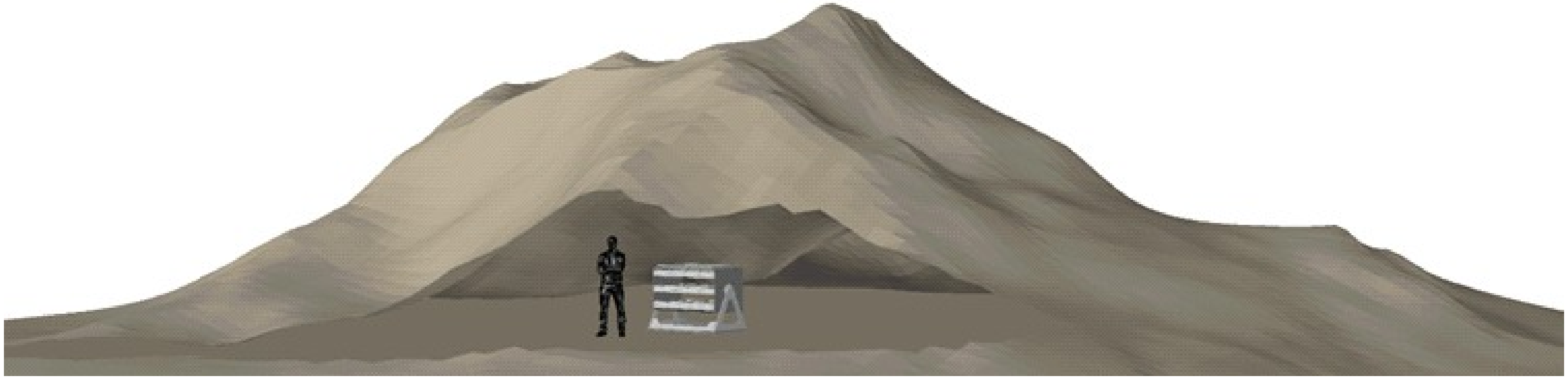

10% of the data:

- Had to use a deep underground chamber, crawling through a tunnel so narrow that the detector (1.5 m^3, six layers of multi-wire chambers) had to be dismantled and then reassembled inside!
- >10 years of data taking, yet unpublished (apart from proceedings)
- Preliminary analysis found 20% density difference between North and South faces; perhaps hinting at risk of collapse on the southern side

A. Menchaca-Rochas, proceedings of 10th Latin American Symposium on Nuclear Physics and Applications (2014)

Portable detectors

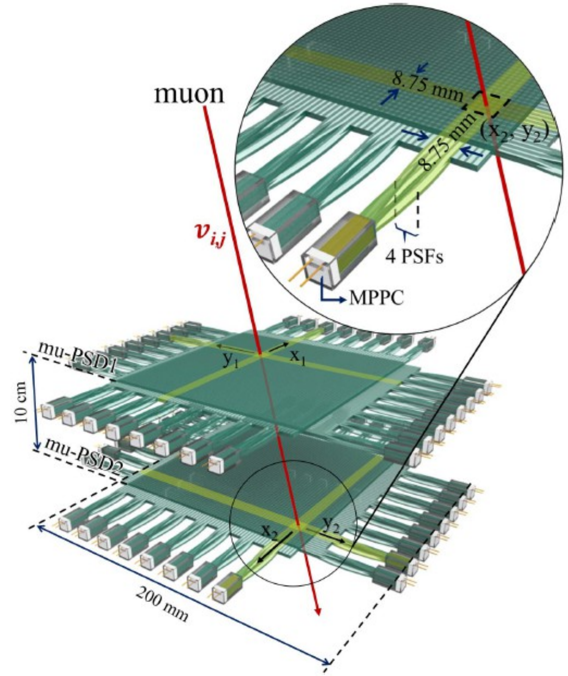
- Previous example is just one of many archaeology or geoscience use cases where the optimal location of the detector is hard to access and in a confined space
- A few groups are developing portable muon telescopes whose key design considerations include compact size, light weight and autonomous operation



From L. Bonechi, R. D'Alessandro, *A.G.*, arXiv:1906.03934, Rev. Phys. 5 (2020) 100038

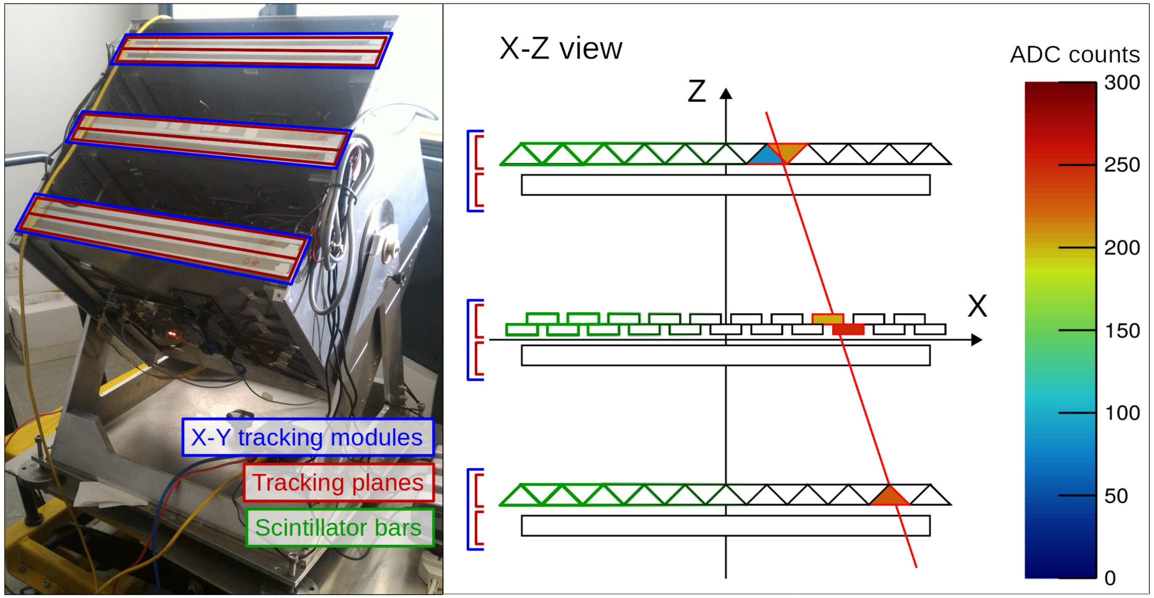
Examples

Kyushu detector:



Scintillating fibers (bundled)

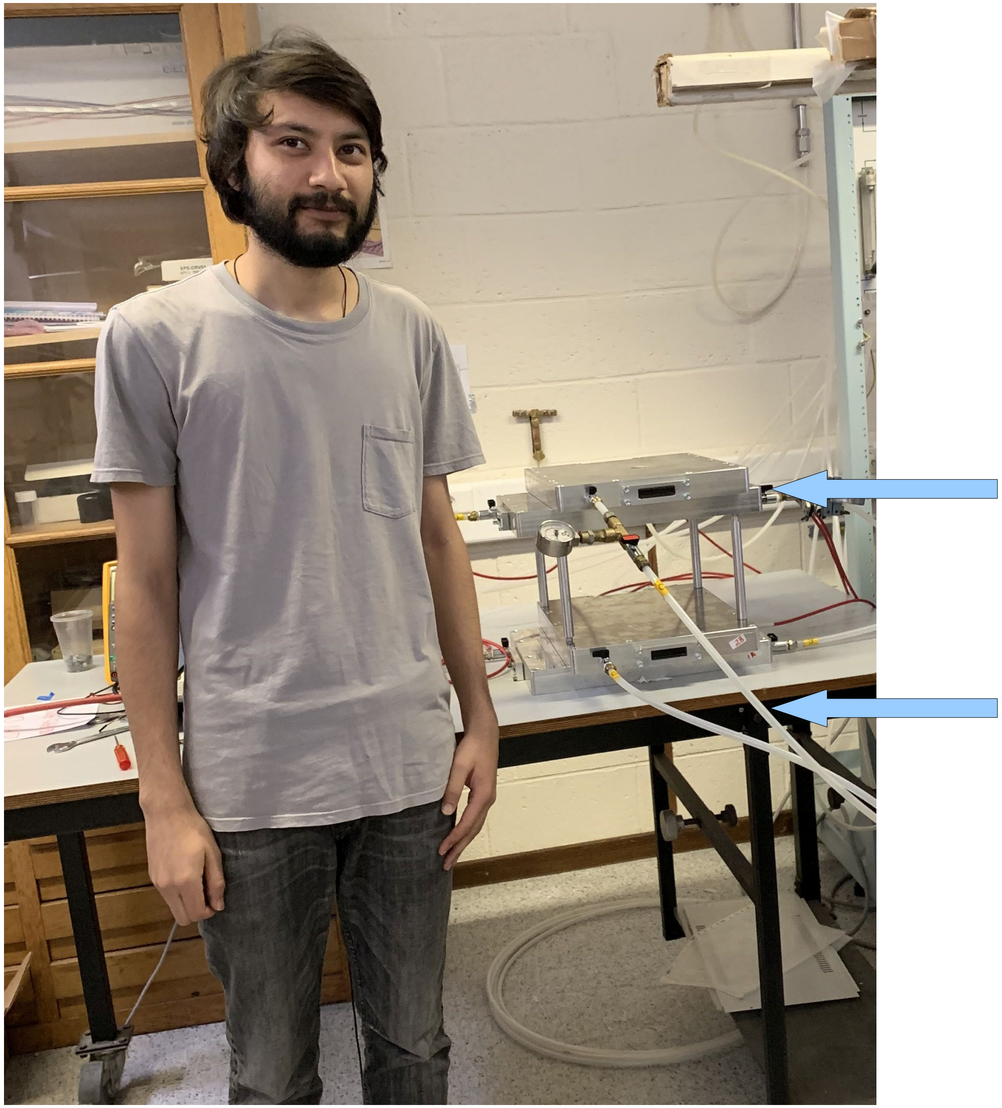
MIMA detector (Florence):



Scintillating bars

Left: from K. Chaiwongkhot et al., IEEE Trans. Nucl. Sci., 65 (2018), p. 2316
Right: from G. Baccani et al., Universe 5(1) (2019), p. 34

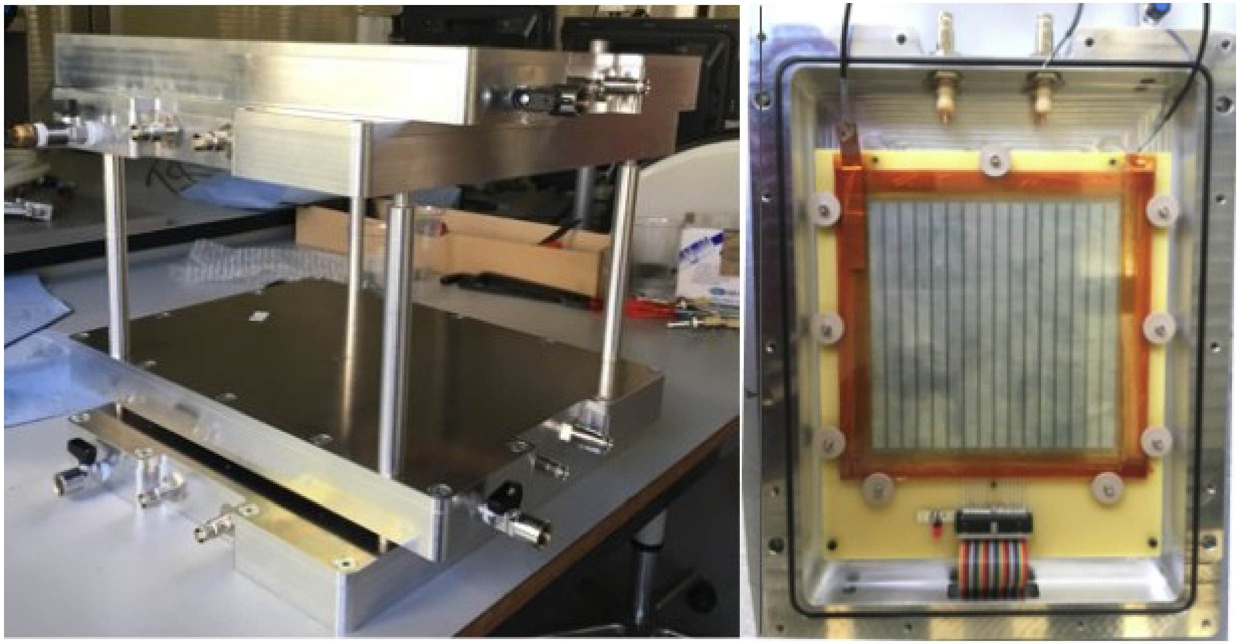
The CP3 mini-RPC muoscope



Superimposed detector layers, at 90° of each other

Tubes for gas filling; only needed once, then the muoscope is ready to go

First prototype

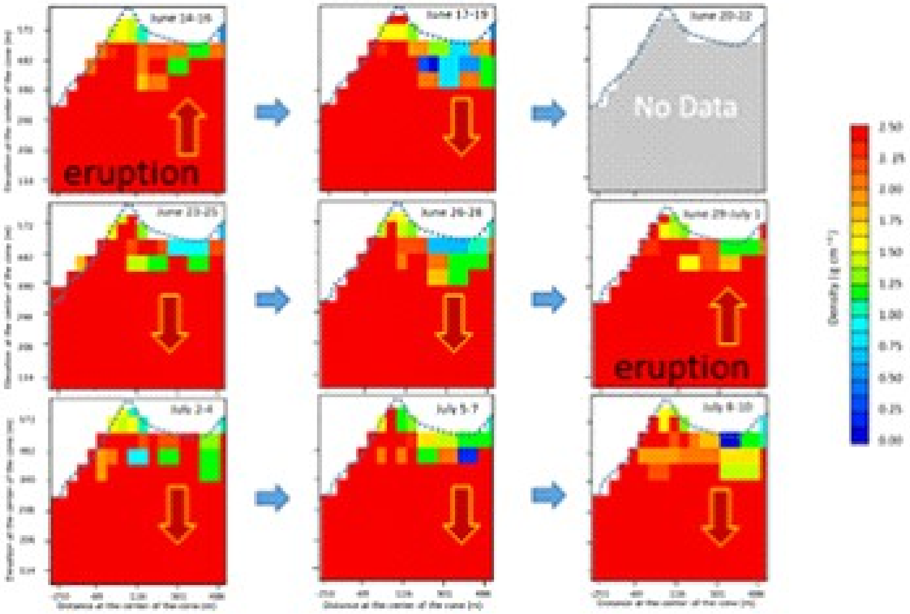


- Portability
  - Sealed; particular care in making gas-tight boxes (10^{-9} mbar l/s)
  - Small (active area: 16x16 cm^2)
  - Light, robust

- Versatile: modular geometry
- Cheap and easy to assemble
- First full prototype built entirely @ CP3 with UGent's support
  - 4 planes (x-y, x-y)
  - Eventually we intend to increase number of channels

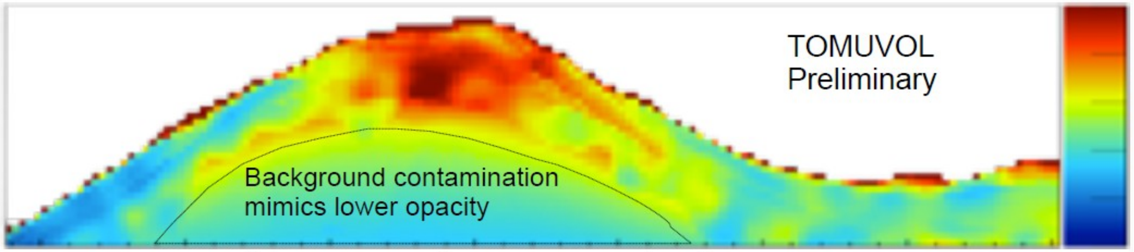
Mountains and volcanoes

- Pioneered since the 90's by Nagamine's team in Japan, intense activity in recent years in Japan, Italy, France, Colombia
- Both "static" and "time-series" studies are potentially useful for volcanology, the latter also for civil protection



Satsuma-Iwojima volcano, Japan, 2013 eruption
H.Tanaka, T.Kusagaya, H.Shinohara, Nature Comm.5 (2014) 3381

A "standard candle": Puy de Dôme



Linear opacity to atmospheric muons

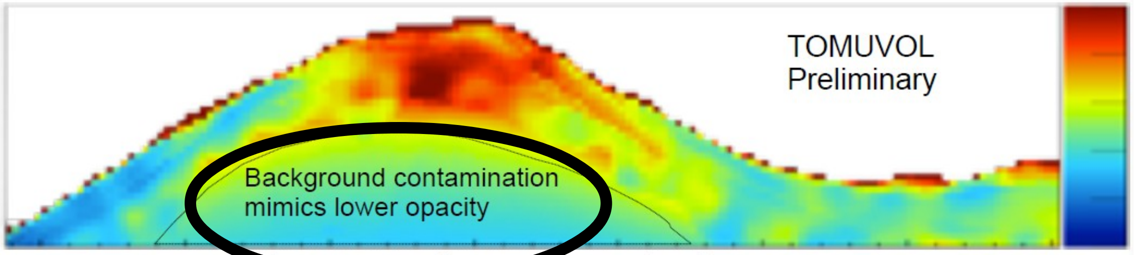
TOMUVOL telescope
(RPC detectors)

Dormant volcano in France, inner composition very well known by other means.

Here shown: two months of muon data

From: Carloganu & Saracino, Physics Today dec.2012

A "standard candle": Puy de Dôme



Background contamination mimics lower opacity

Linear opacity to atmospheric muons

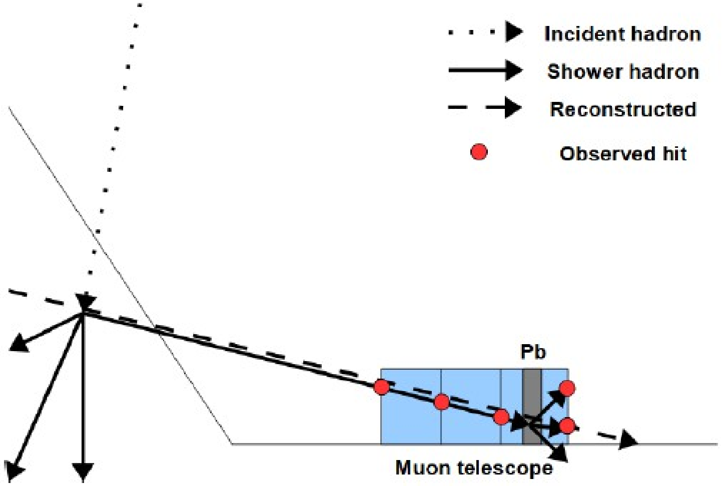
Nota bene!

The deepest (and most interesting) part of the volcano looks like it's glowing in muons...

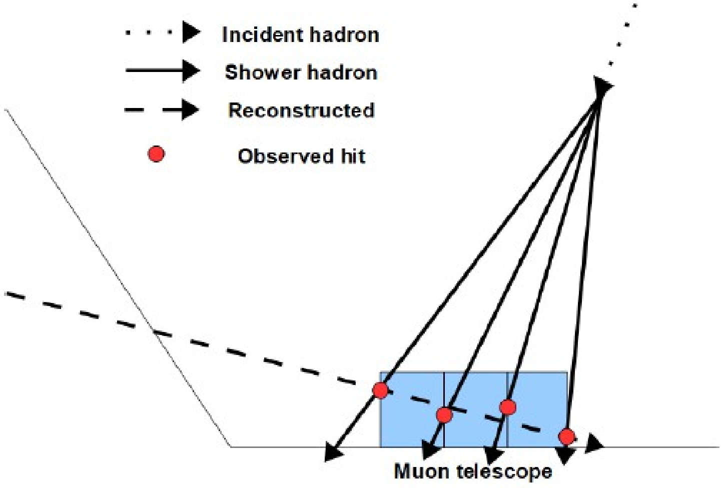
TOMUVOL telescope
(RPC detectors)

What are those backgrounds?

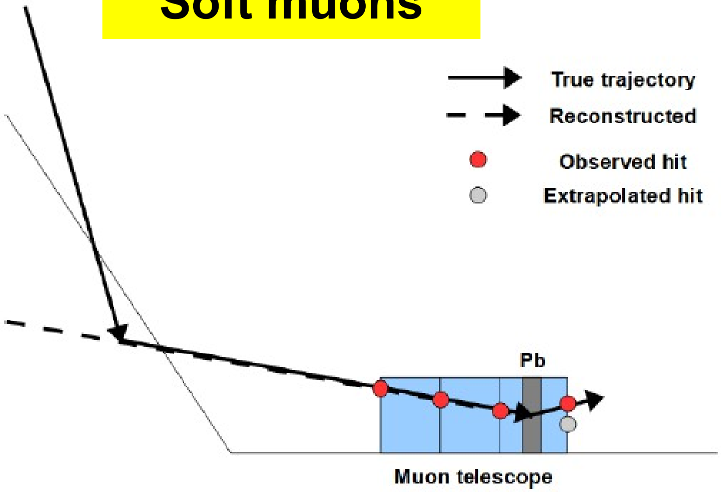
Fakes



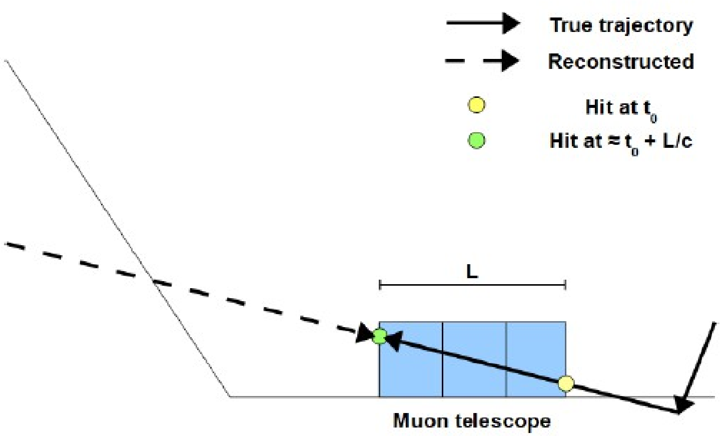
Combinatorial



Soft muons



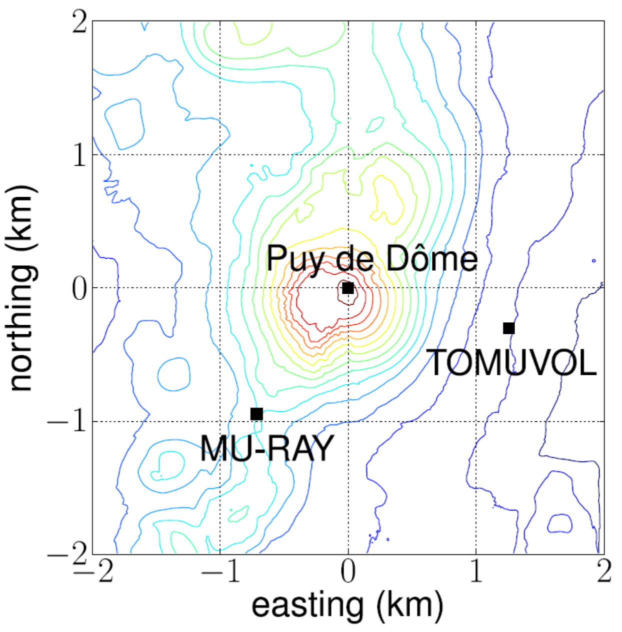
Backward muons

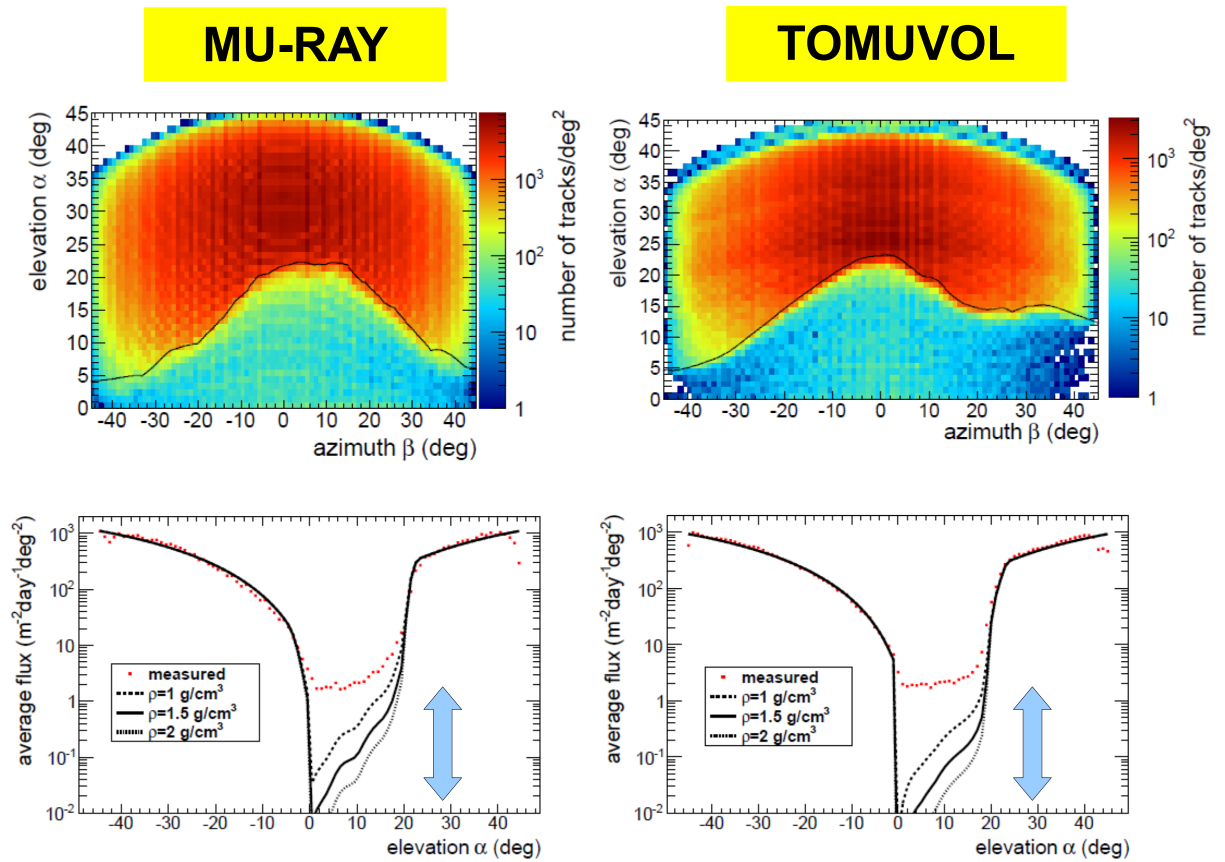


From L. Bonechi, R. D'Alessandro, *A.G.*, arXiv:1906.03934, Rev. Phys. 5 (2020) 100038

A joint experiment

Ambrosino et al. (TOMUVOL+MU-RAY coll.), J.Geophys.Res.Solid Earth 120 (2015), 7290



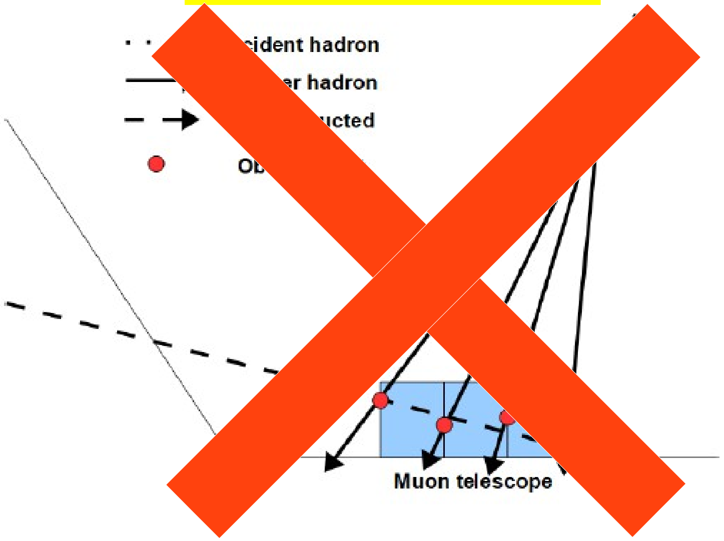


- Simultaneous measurement with two detectors in two different places
- MU-RAY: 3 x-y layers of scintillating bars; 3 cm steel plate (muon P threshold: 70 MeV) as absorber for **fakes**
- TOMUVOL: 4 x-y layers of RPC (less **combinatorics**); no absorber
- Compatible results ⇒ most background is **actually muons**

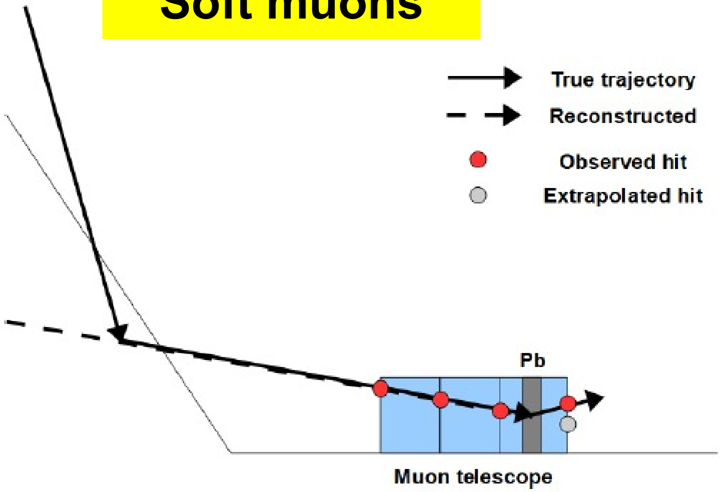
What are those backgrounds?

Fakes

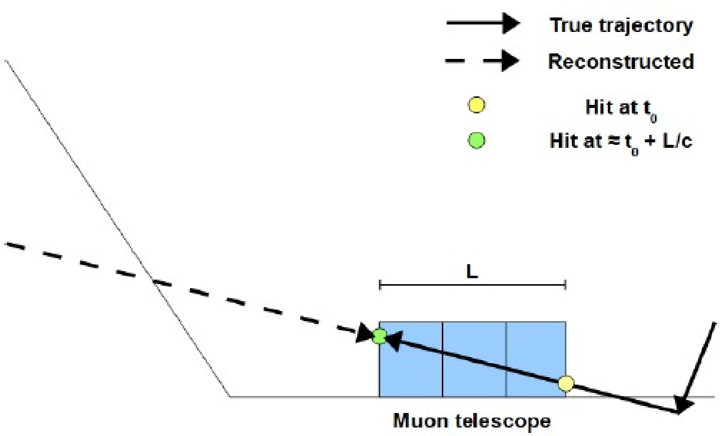
Combinatorial



Soft muons



Backward muons



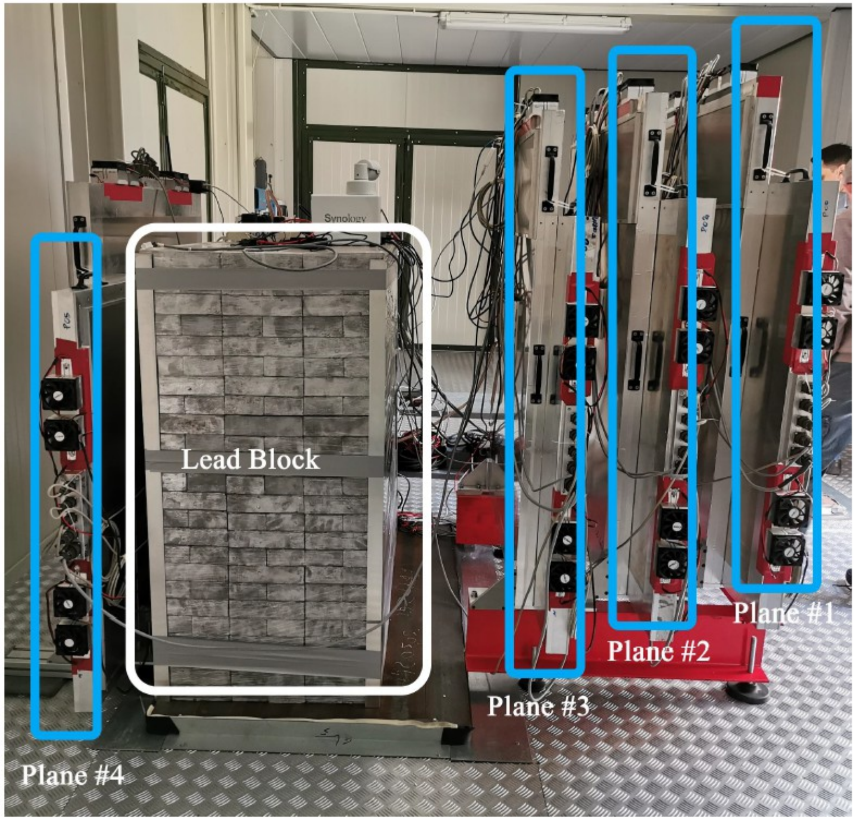
From L. Bonechi, R. D'Alessandro, *A.G.*, arXiv:1906.03934, Rev. Phys. 5 (2020) 100038

The MURAVES experiment

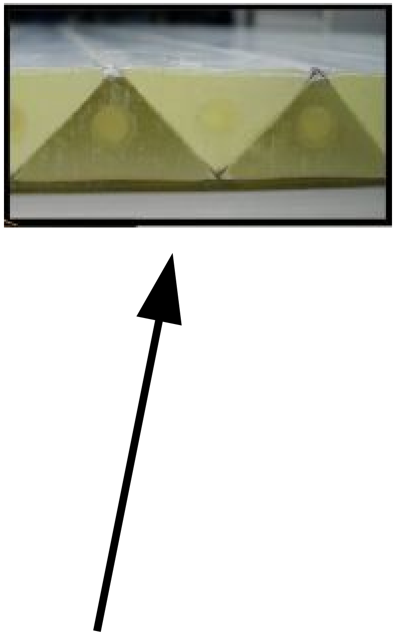
- MU(on)RA(diography) of VES(uvius)
- Vesuvius: active volcano near Naples (Italy)
- Eruptions are infrequent (last one in 1944) but potentially very dangerous
- Wiped out Pompeii and Hercolaneum in 79 AD
- Today, > 0.5M people live in its "red zone", i.e., need to be evacuated in case of eruption

- MURAVES: successor of MU-RAY project
- Consortium of INGV, INFN, Naples, Florence, and since 2019 also CP3 and UGent

One of the MURAVES telescopes

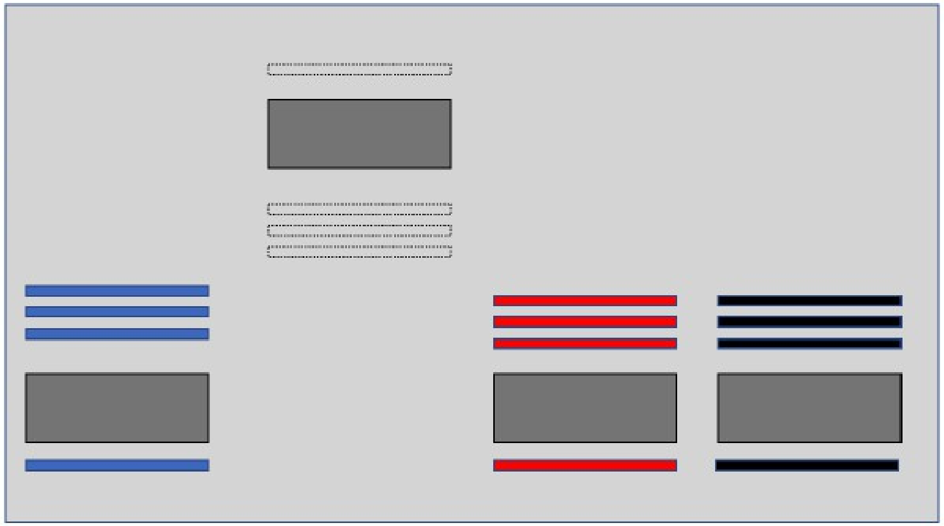


Picture by S.Wuyckens, July 2019



- 3 telescopes (was 1 in MU-RAY)
- 4 x-y layers (3 in MU-RAY) of scintillating bars with triangular section, coupled to SiPM
- Lead wall, 60 cm thick (recycled from OPERA experiment), corresponding to a ~1 GeV cut-off
- Also emphasis on Time-of-Flight against backward muons

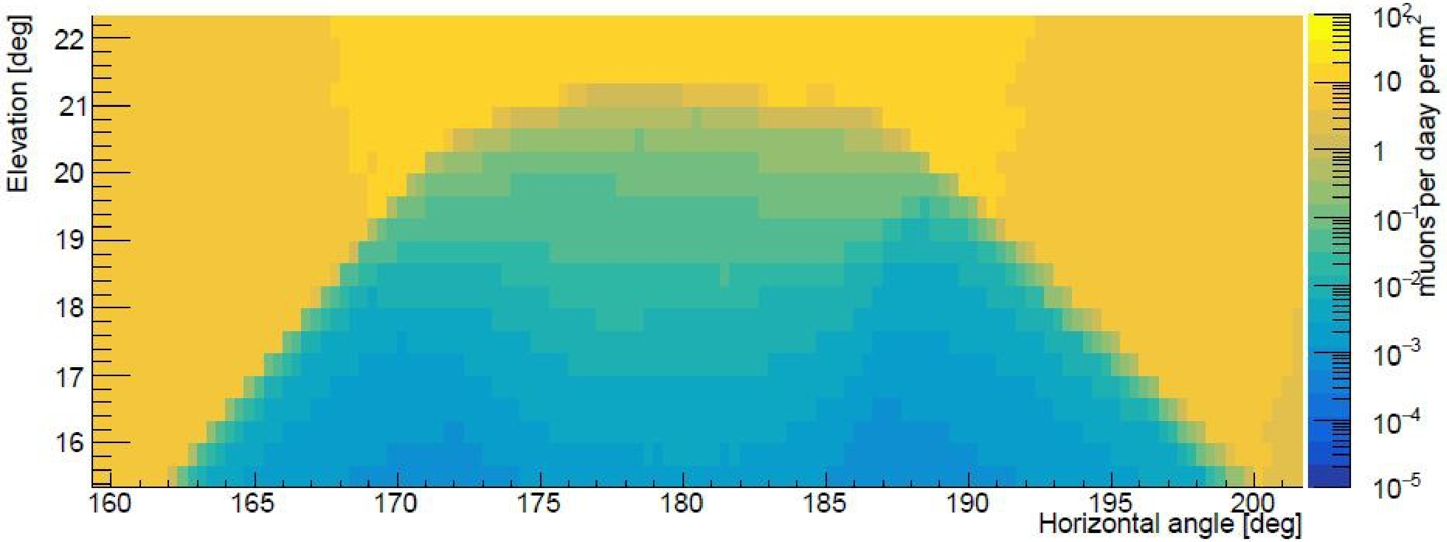
The MURAVES experiment



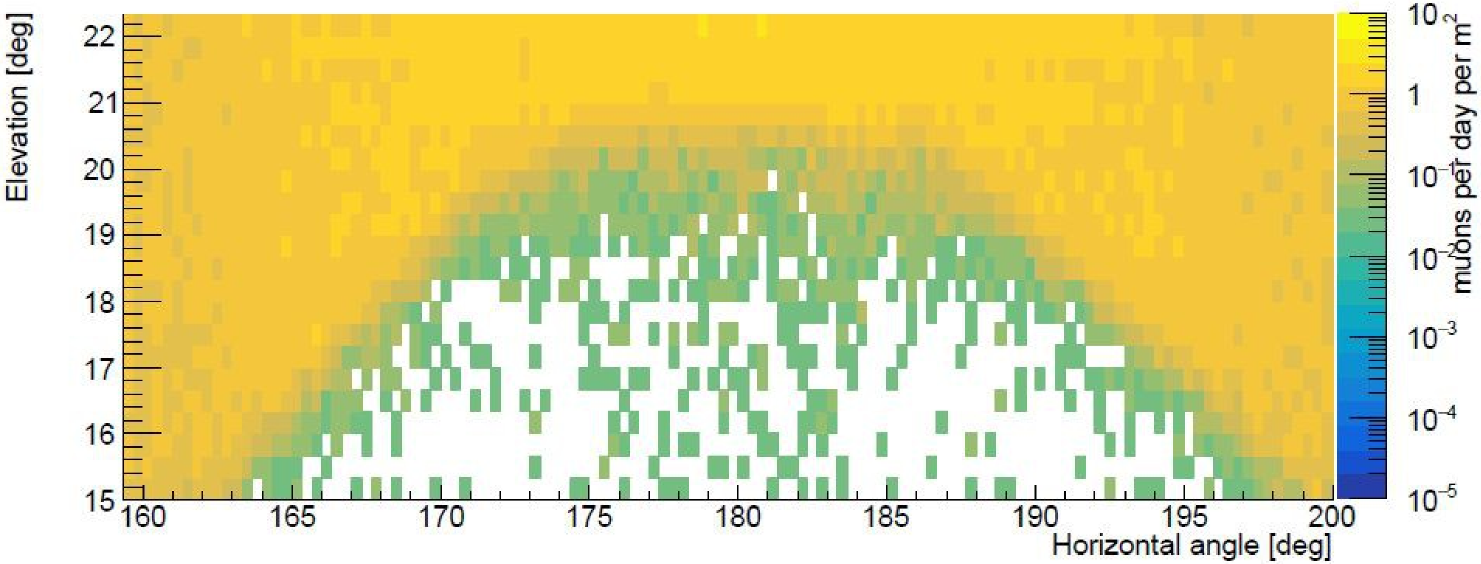
- Of the 3 telescopes, at any point in time 2 will point towards Vesuvius and one in the opposite direction
- Transmission probability (vs θ,ϕ) is defined with respect to the free-sky flux; measured with the backward-pointing telescope
- The 3 telescopes alternate in occupying the backward position, such that detector systematics cancel out

MURAVES Collaboration, arXiv:2202.12000 [physics.ins-det],
J. Adv, Instr. Sci., vol. 2022, no. 1, Sep. 2022.

First public data



Simulation

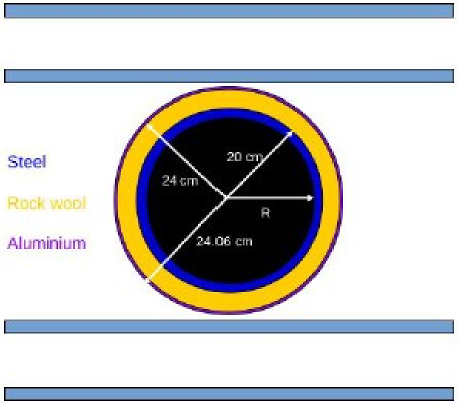


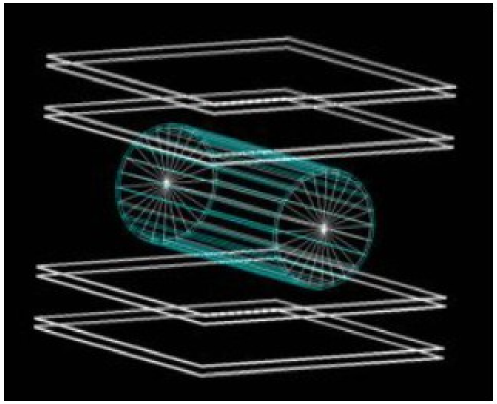
51 days of real data

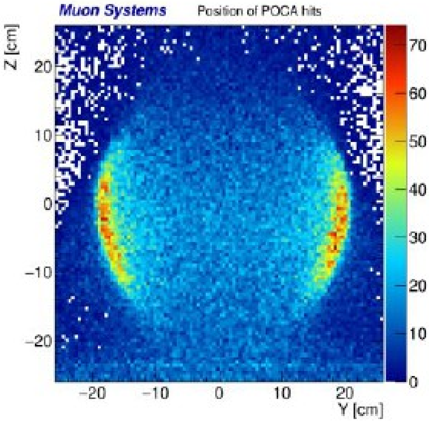
MURAVES Collaboration, arXiv:2202.12000 [physics.ins-det],
J. Adv, Instr. Sci., vol. 2022, no. 1, Sep. 2022.

Industrial applications

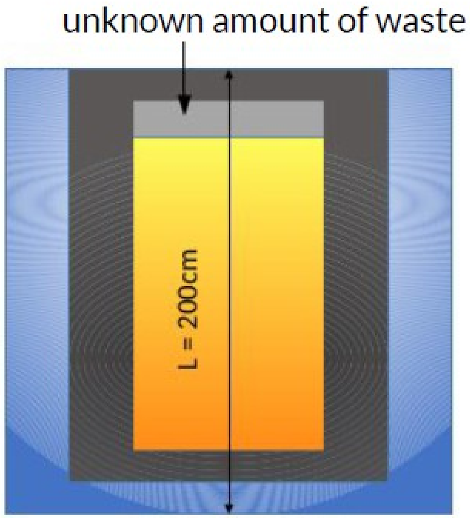
1 - Measurement of the width of an insulated pipe

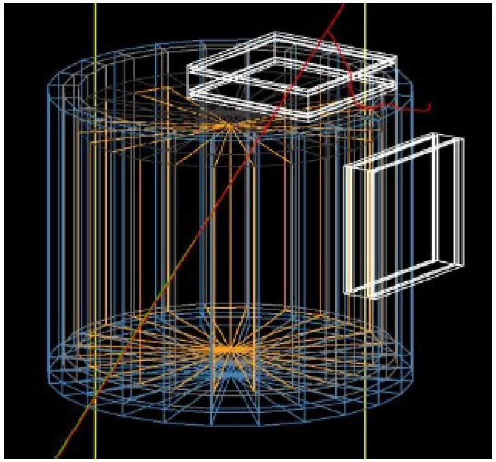


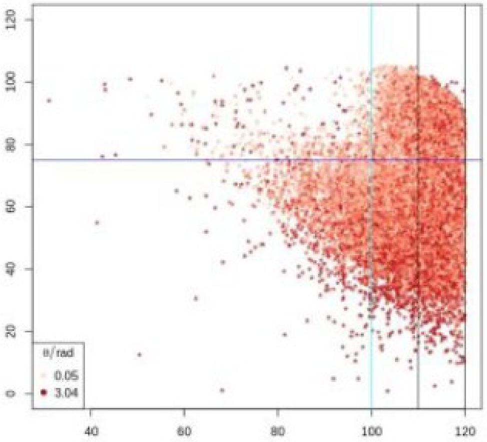




2 - Estimation of slag on a furnace laddle







Slide by M. Lagrange with material from P. Martinez et al., Phil. Trans. R. Soc. A.377 (2018) 0054

Conclusion

- Muography is a booming research direction, with several potential applications
- Some applications are more mature than others (e.g. volcanology, archaeology)
- Large potential for new teams to join (volcanoes and cultural heritage sites are ubiquitous...)
- Plenty of room for new ideas

Some reading material

- "Atmospheric muons as an imaging tool" / Bonechi, D'Alessandro, Giammanco, Reviews in Physics 5 (2020) 100038 [link]
- "Muon tomography in geoscientific research – a guide to best practice" / Lechmann et al., Earth-Science Reviews 222 (2021) 103842 [link]
- "Muography: Exploring Earth's Subsurface with Elementary Particles" / Wiley Geophysical Monograph Series (2022) [link]
- "Non-Destructive Testing using Muon Imaging" / IAEA-TECDOC-2012 (2022) [link]

Thanks for your attention!

Detector comparison

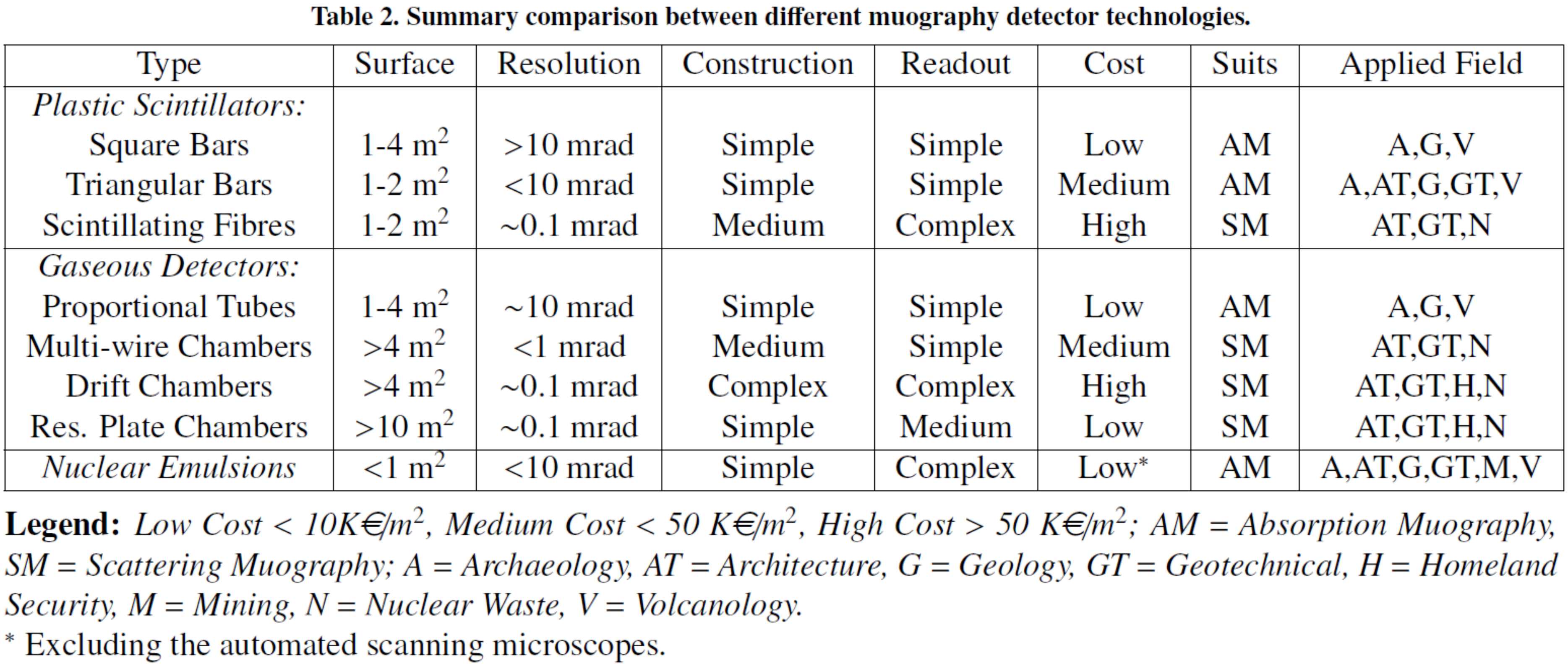


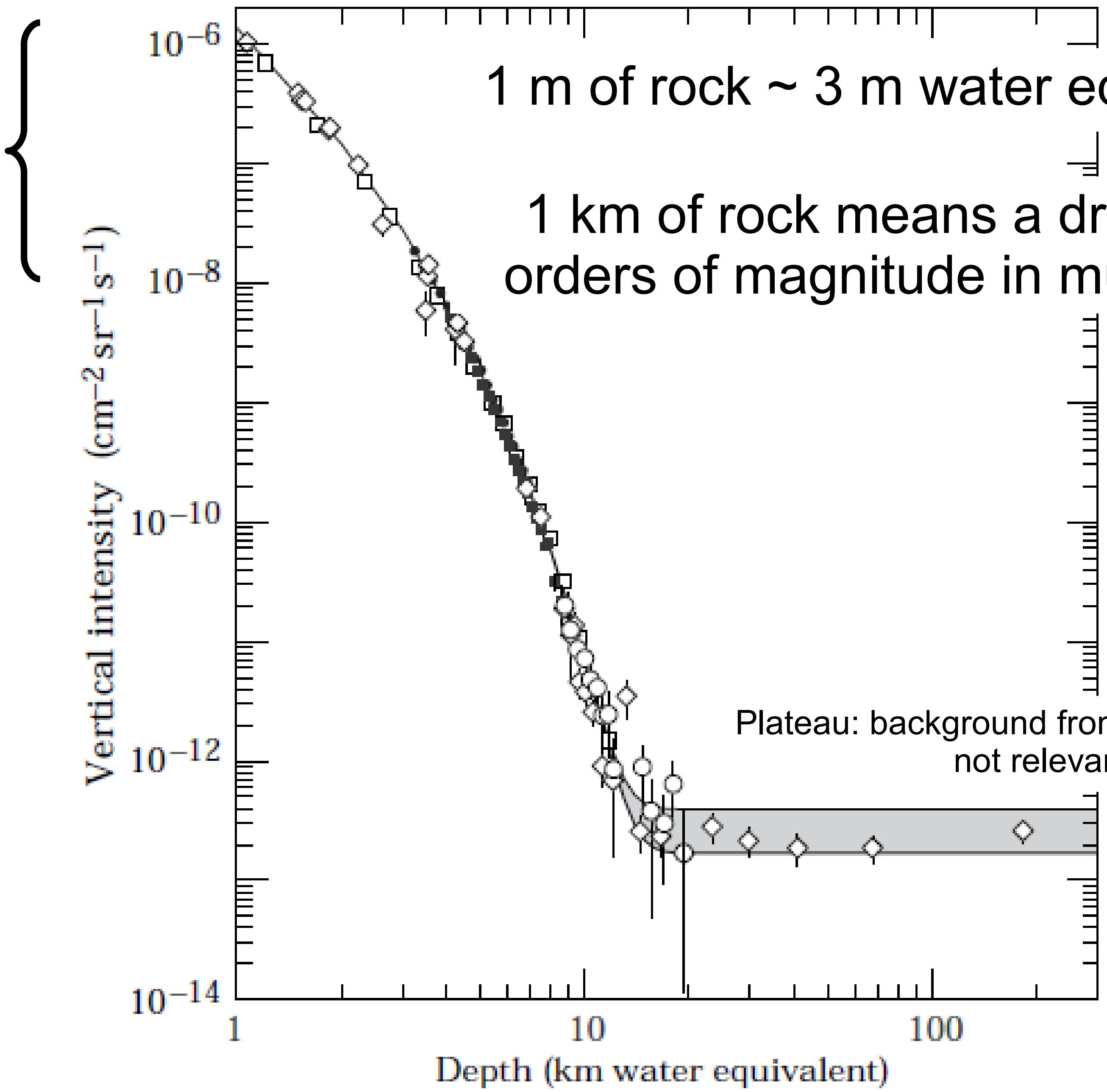
Table 2. Summary comparison between different muography detector technologies.

Type	Surface	Resolution	Construction	Readout	Cost	Suits	Applied Field
Plastic Scintillators:							
Square Bars	1-4 m^2	>10 mrad	Simple	Simple	Low	AM	A,G,V
Triangular Bars	1-2 m^2	<10 mrad	Simple	Simple	Medium	AM	A,AT,G,GT,V
Scintillating Fibres	1-2 m^2	~0.1 mrad	Medium	Complex	High	SM	AT,GT,N
Gaseous Detectors:							
Proportional Tubes	1-4 m^2	~10 mrad	Simple	Simple	Low	AM	A,G,V
Multi-wire Chambers	>4 m^2	<1 mrad	Medium	Simple	Medium	SM	AT,GT,N
Drift Chambers	>4 m^2	~0.1 mrad	Complex	Complex	High	SM	AT,GT,H,N
Res. Plate Chambers	>10 m^2	~0.1 mrad	Simple	Medium	Low	SM	AT,GT,H,N
Nuclear Emulsions	<1 m^2	<10 mrad	Simple	Complex	Low*	AM	A,AT,G,GT,M,V

Legend: *Low Cost < 10K€/m^2, Medium Cost < 50 K€/m^2, High Cost > 50 K€/m^2; AM = Absorption Muography, SM = Scattering Muography; A = Archaeology, AT = Architecture, G = Geology, GT = Geotechnical, H = Homeland Security, M = Mining, N = Nuclear Waste, V = Volcanology.*

* Excluding the automated scanning microscopes.

From L. Bonechi, R. D'Alessandro, *A.G.*, arXiv:1906.03934, Rev. Phys. 5 (2020) 100038



1 m of rock ~ 3 m water equivalent

1 km of rock means a drop of 2 orders of magnitude in muon flux

Plateau: background from up-going neutrinos; not relevant here

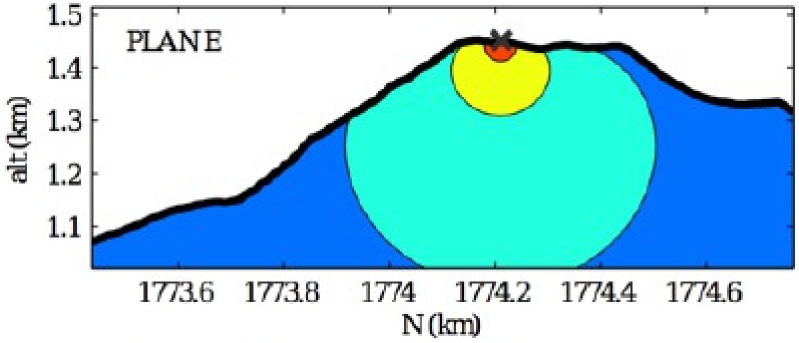
Source: Particle Data Group

Combination with "standard methods"

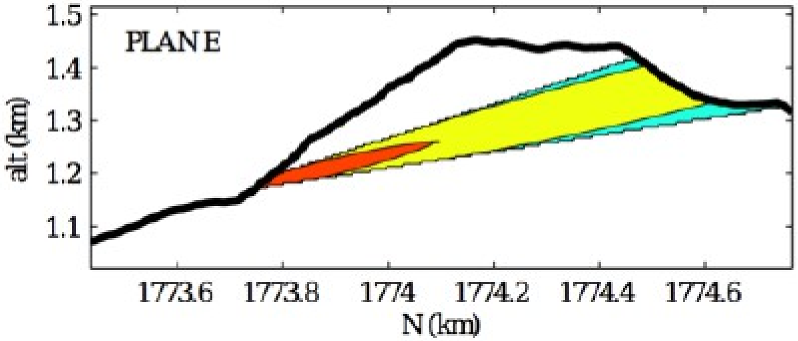
$$\mathbf{A} \quad \boldsymbol{\rho} = \boldsymbol{d}$$

$$\begin{bmatrix} \mathbf{G} \\ \mathbf{M} \end{bmatrix} \begin{bmatrix} \boldsymbol{\rho} \end{bmatrix} = \begin{bmatrix} \boldsymbol{g} \\ \boldsymbol{\varrho} \end{bmatrix}$$

Jourde *et al.* 2015



(1) gravimetry acquisition kernel, $\mathcal{G}$



(2) tomography acquisition kernel, $\mathcal{M}$

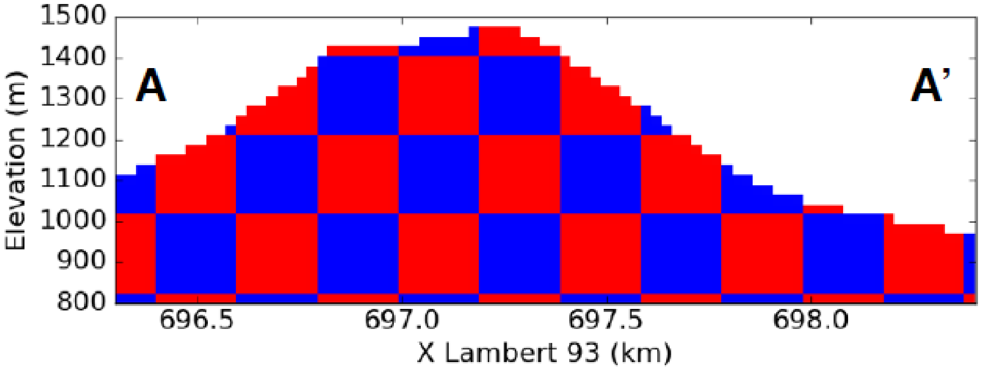
Most geoprospecting methods are non-linear inversion problems: solutions wildly degenerate, need strong constraints to converge, different assumptions lead to qualitatively different results

Muography: highly directional, breaks degeneracy of the other methods

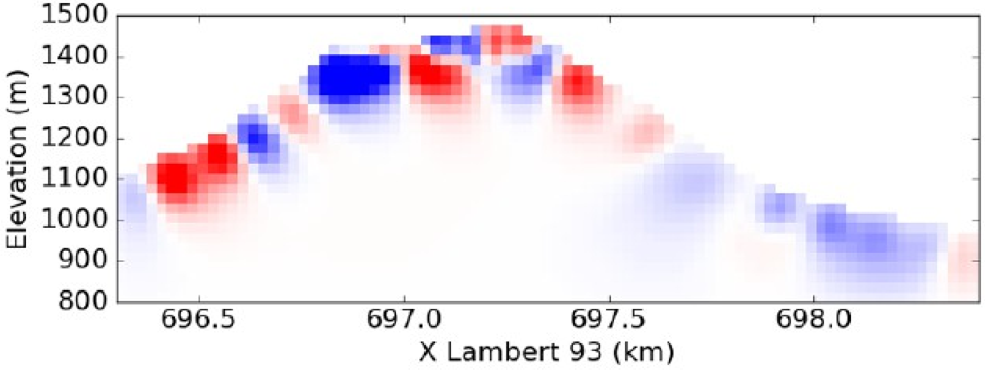
Formula from Anne Barnoud

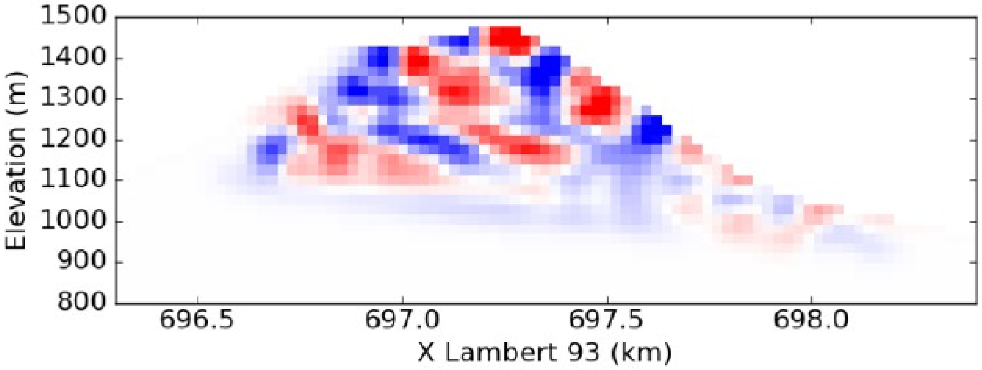
Checkerboard test

Simulated density pattern:



Red: high density
Blue: low density





Seen from gravimetric inversion

Seen from muographic inversion

Study from Anne Barnoud