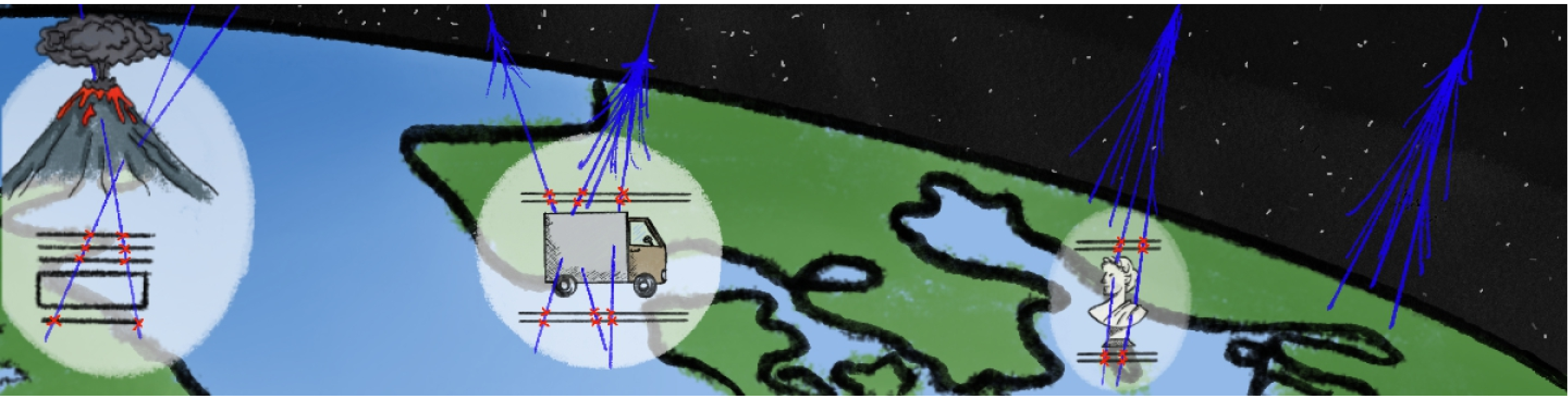
Shadows of Cosmic Rays

Imaging the Macroscopic World with *Muography*



Picture from Alice Biolchini

Andrea Giammanco
Centre for Cosmology, Particle Physics and Phenomenology
UCLouvain, Louvain-la-Neuve, Belgium

INPP Demokritos, Online Seminar, 26 May 2026

The muon

- One of the 3 charged leptons
- Unstable but long-lived (2.2 μs)
- ~200x heavier than electron (105 MeV)
- 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

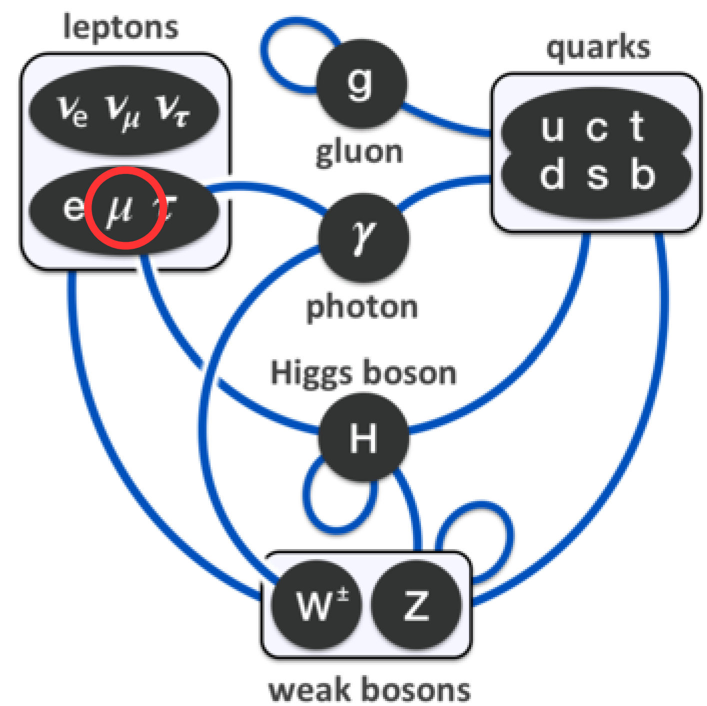
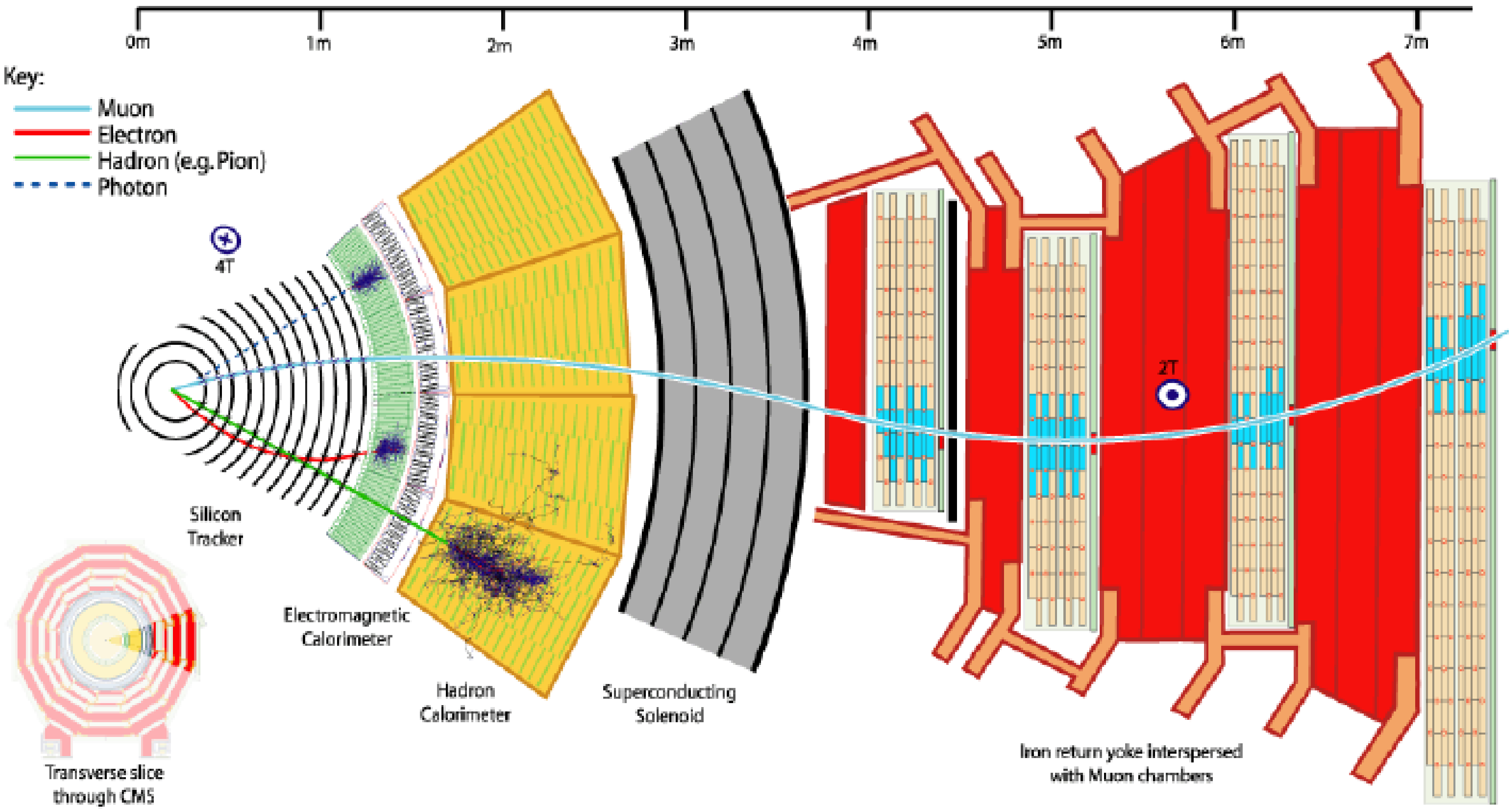


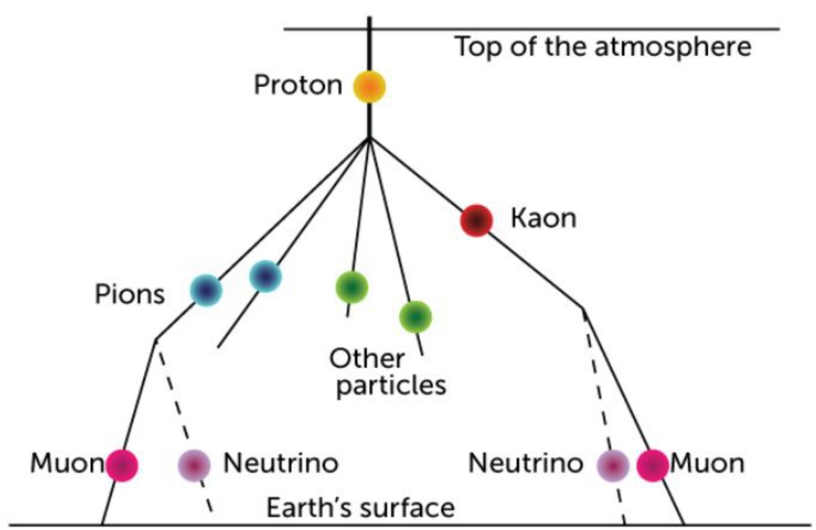
Image source: wikipedia

The most penetrating elementary charged particle



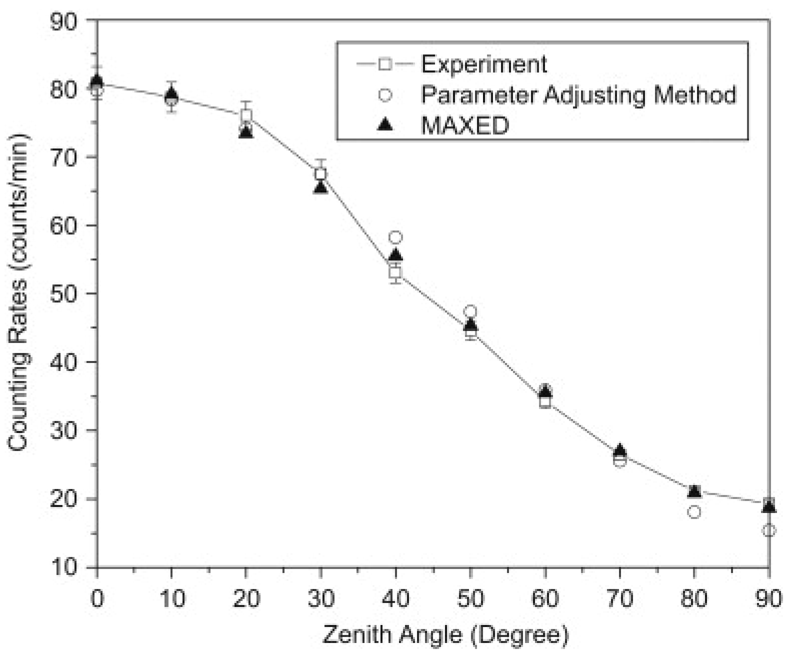
Natural muon source

- Primary cosmic rays (mostly protons) collide with nuclei in the Earth's atmosphere, producing showers of particles
- Most collisions happen at ~15 km above sea level; atmosphere absorbs most of the secondaries via nuclear or EM interactions
- Most flux of charged secondaries at sea level is muons
- Bulk of spectrum O(GeV) $\rightarrow$ time dilation makes μ long-lived
- Rate at sea level: ~100 Hz/m^2 (~1 μ/second through your thumb)



T. TIBBITTS

Angular distribution



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

$$I_\theta = I_0 \cos^n \theta$$

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

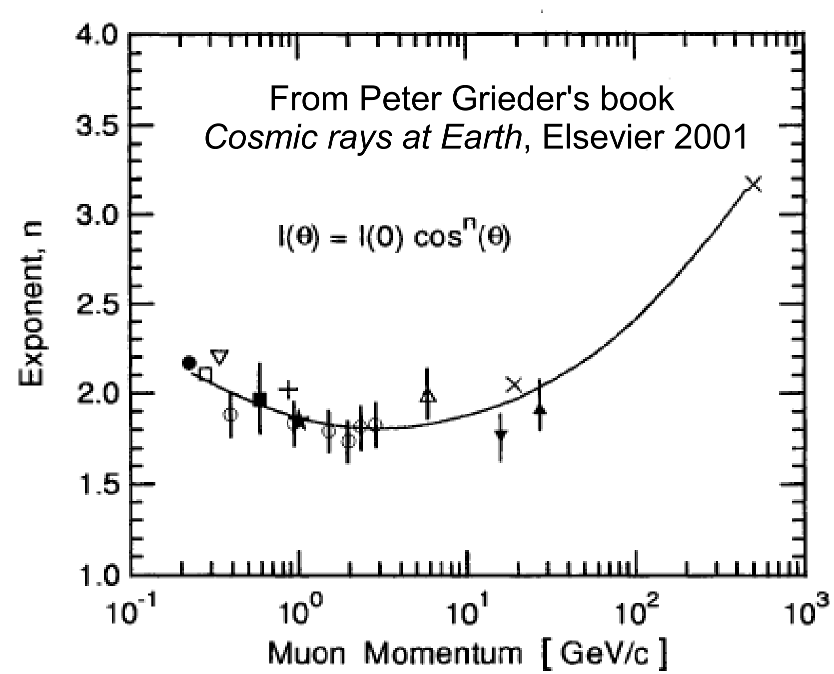
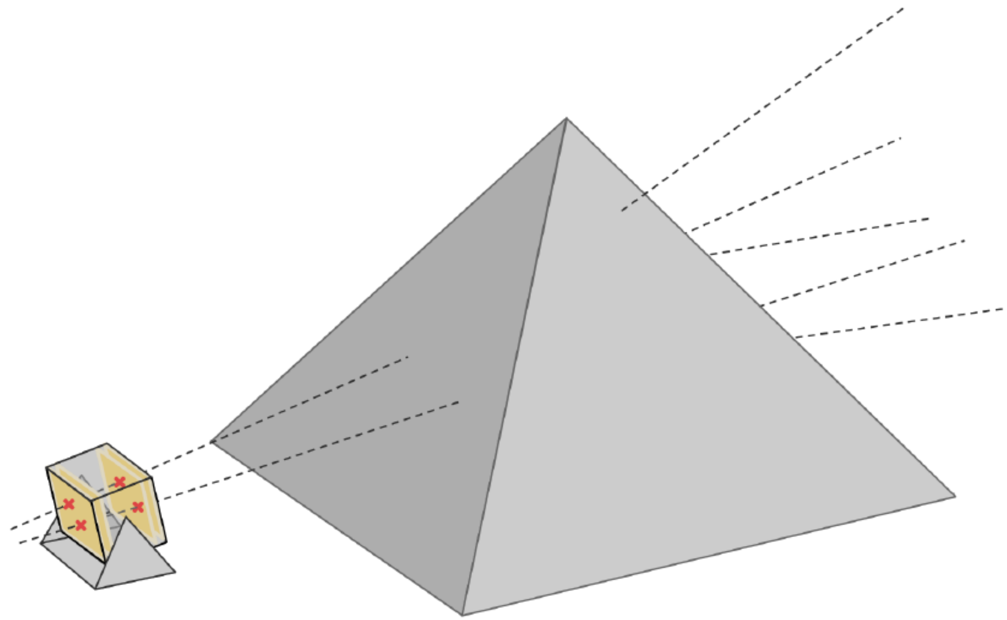


Figure 3.60: Momentum dependence of the exponent, n, of the zenith angular distribution of muons, $I(\theta, > p) = I(0°, \geq p) \cos^n(\theta)$ at sea level (Bhattacharyya, 1974b).

⇒ Large difference in statistics between vertical and horizontal telescopes

Absorption (or transmission) method

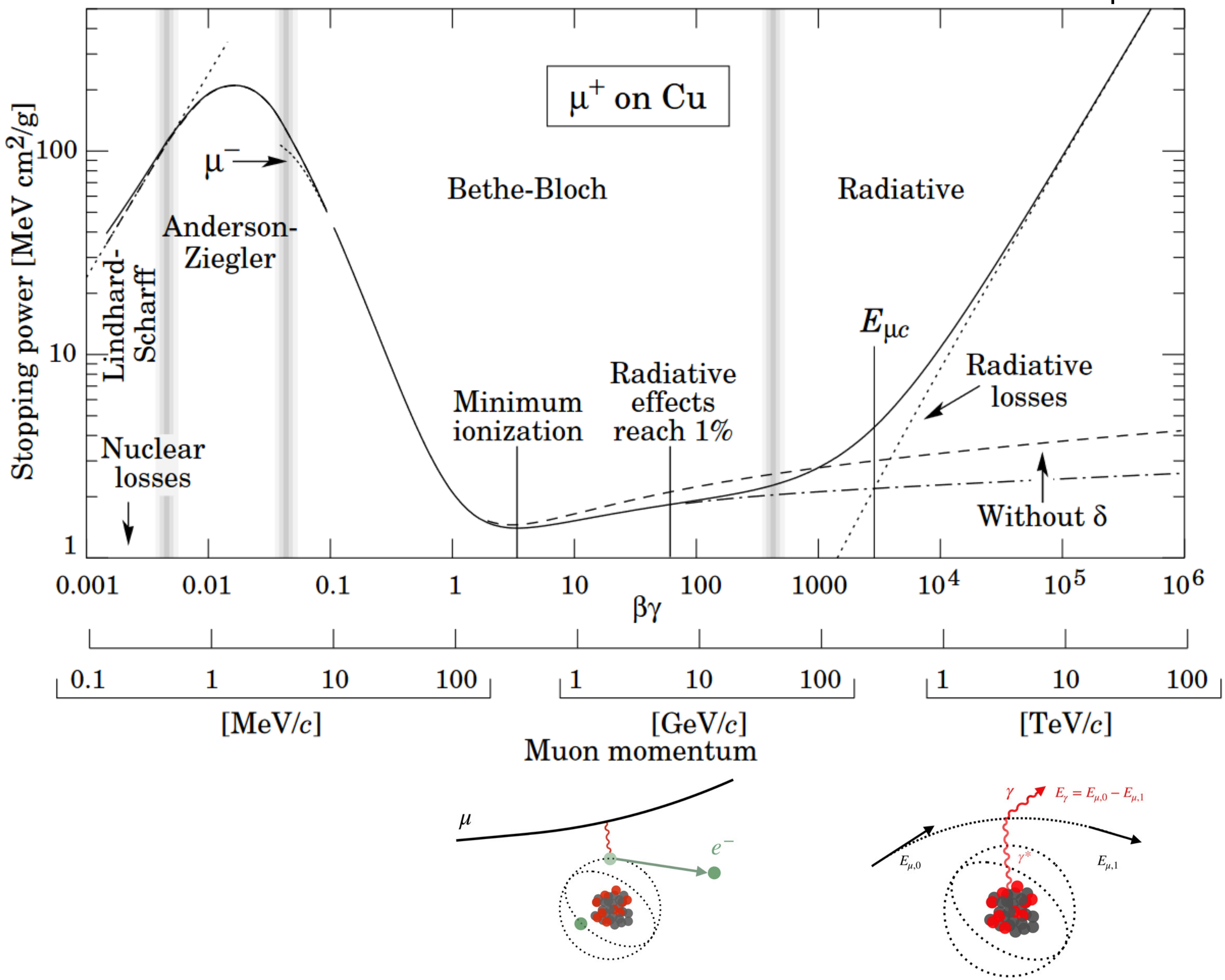
Picture from Maxime Lagrange



- 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**

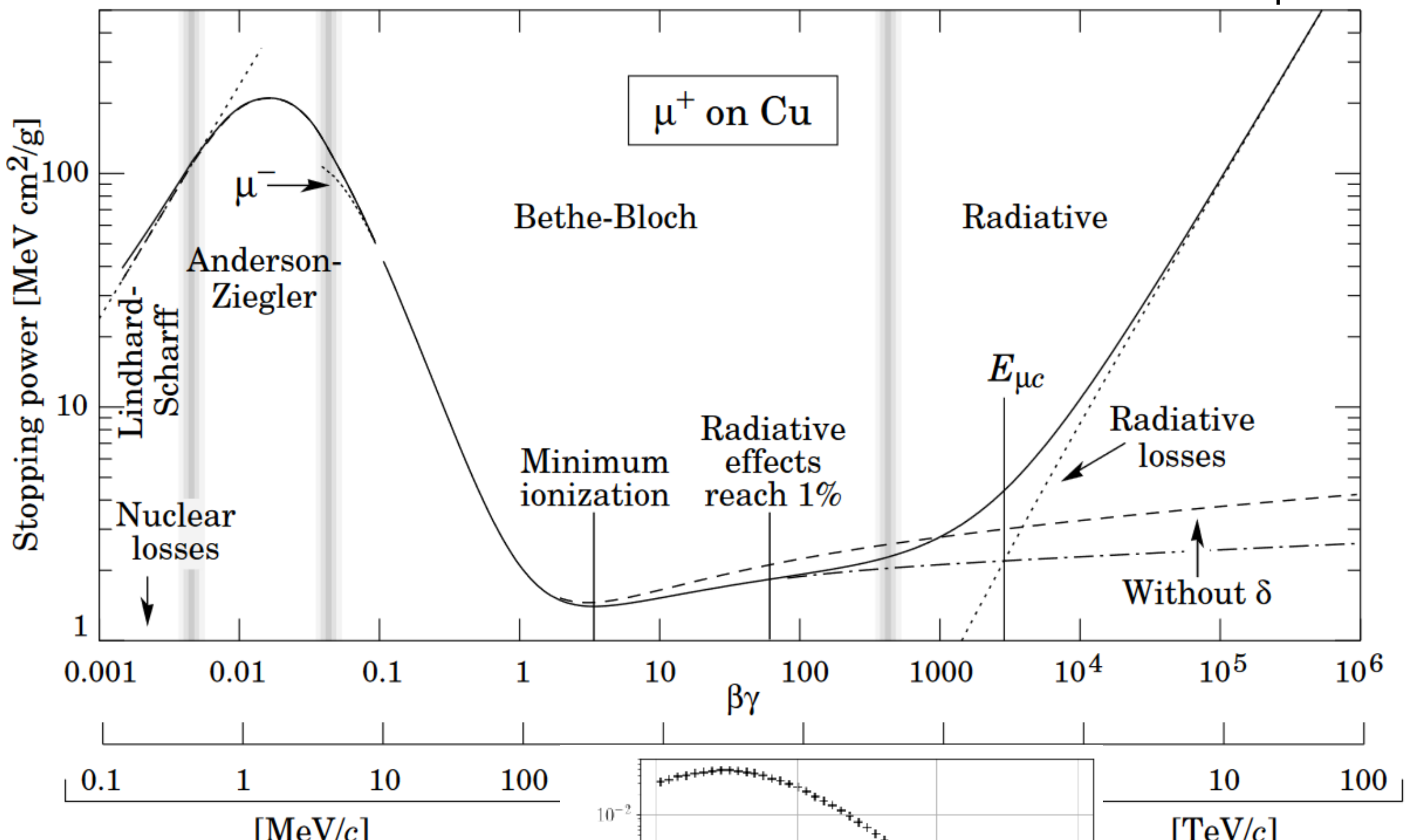
The underlying process

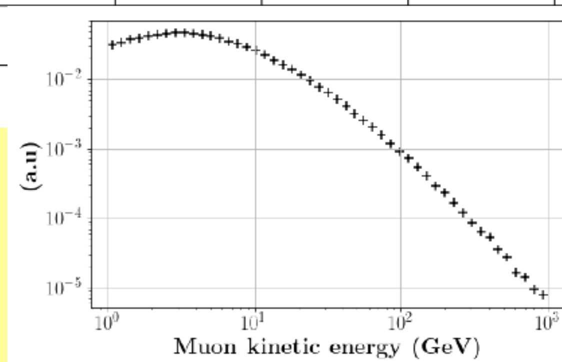
Source: Particle Data Group



The underlying process

Source: Particle Data Group



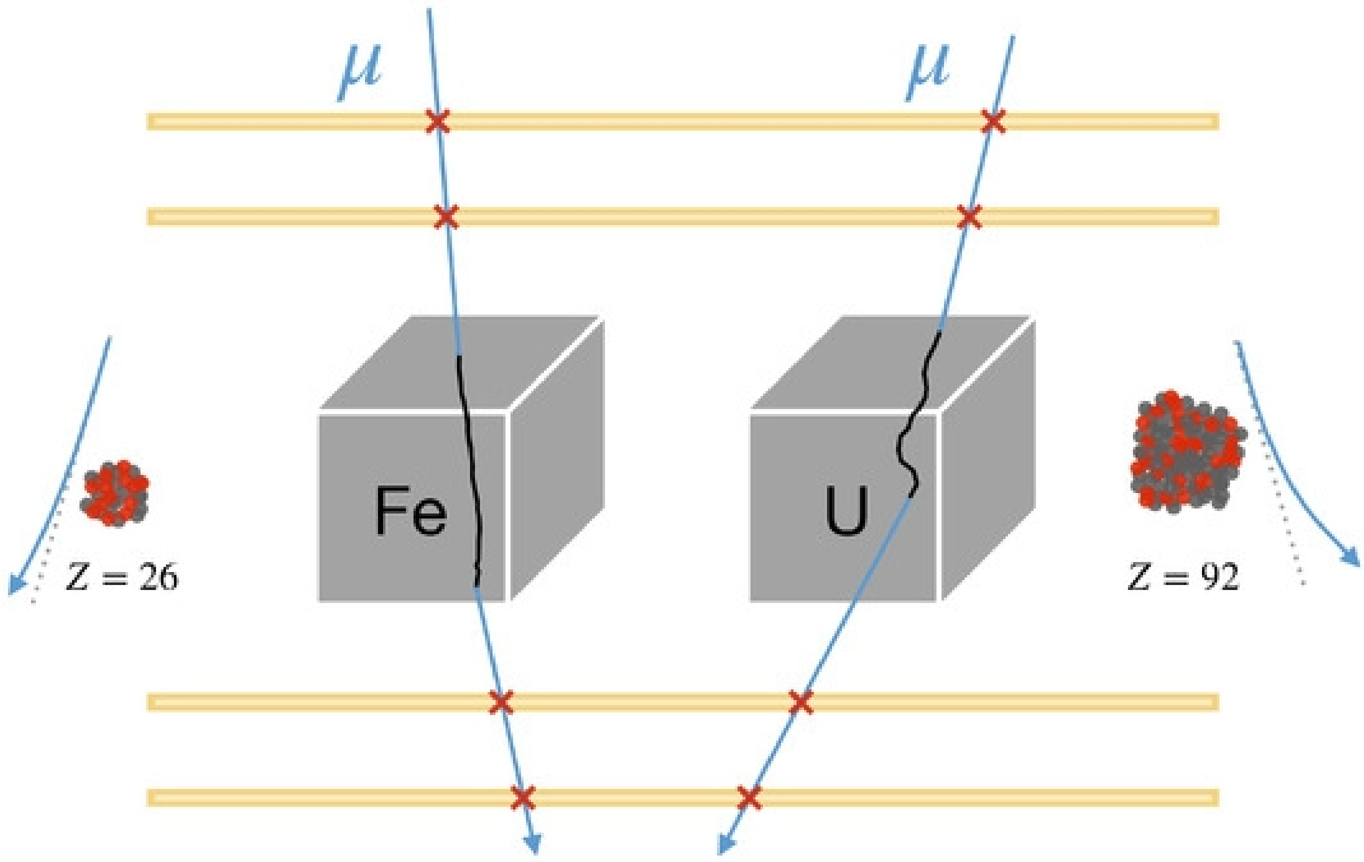


Plot from M. Lagrange, using CRY Monte Carlo

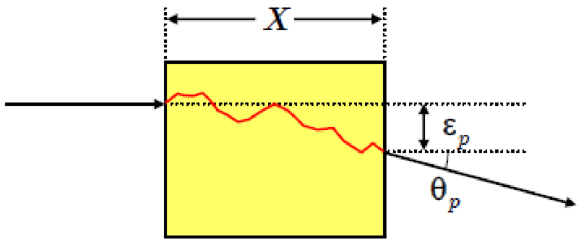
At typical cosmic energies, muons loose ~2 MeV/cm in water (ρ=1 g/cm^3)

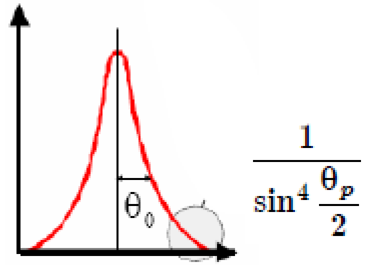
Scattering method

From: S. Barnes et al., Instruments 7 (2023) 13



Figures from here





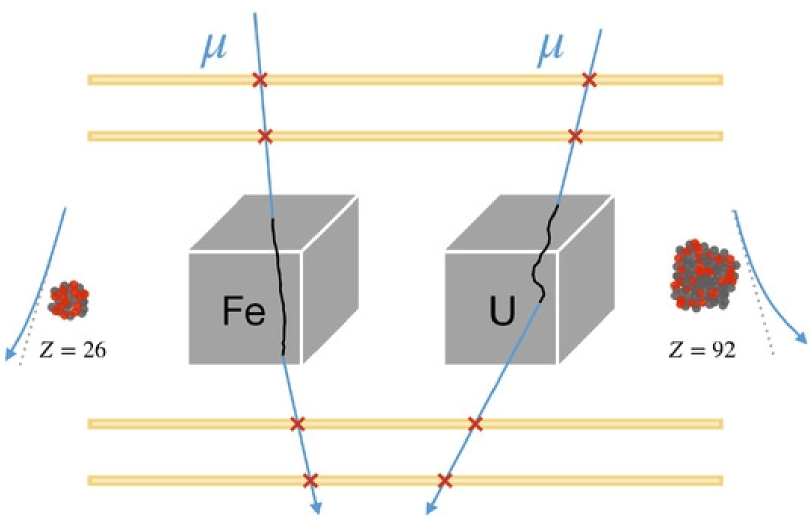
$$P(\theta_p) = \frac{1}{\sqrt{2\pi\langle\theta_p^2\rangle}} \exp\left[-\frac{1}{2\langle\theta_p^2\rangle}\theta_p^2\right]$$

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

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

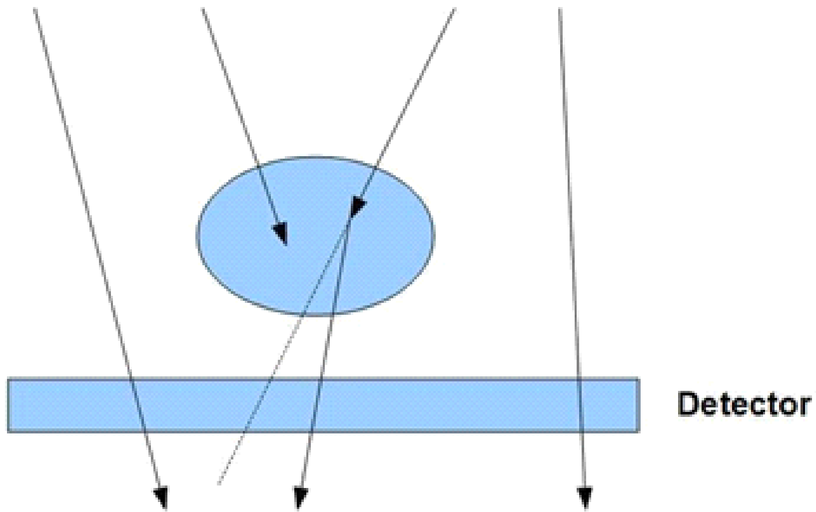
$$K = z^2\left(\frac{0.0136}{p\beta}\right)^2$$

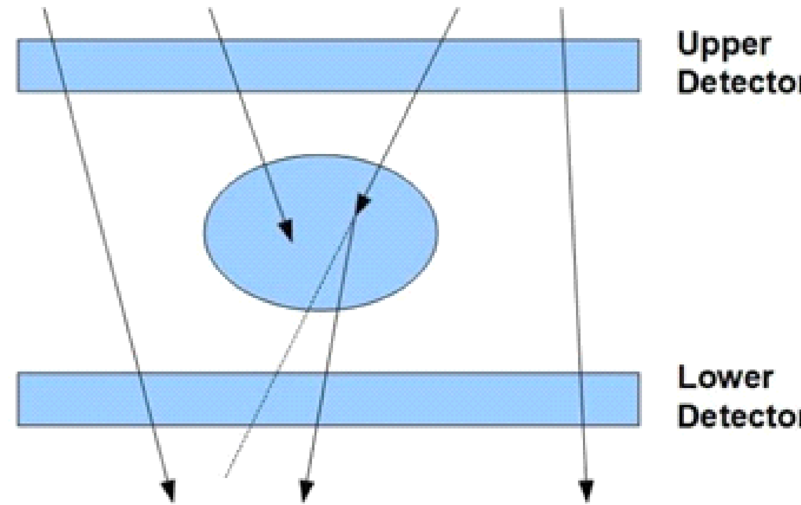
- X_0 is the radiation length, and it depends on the atomic number



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

Absorption vs scattering





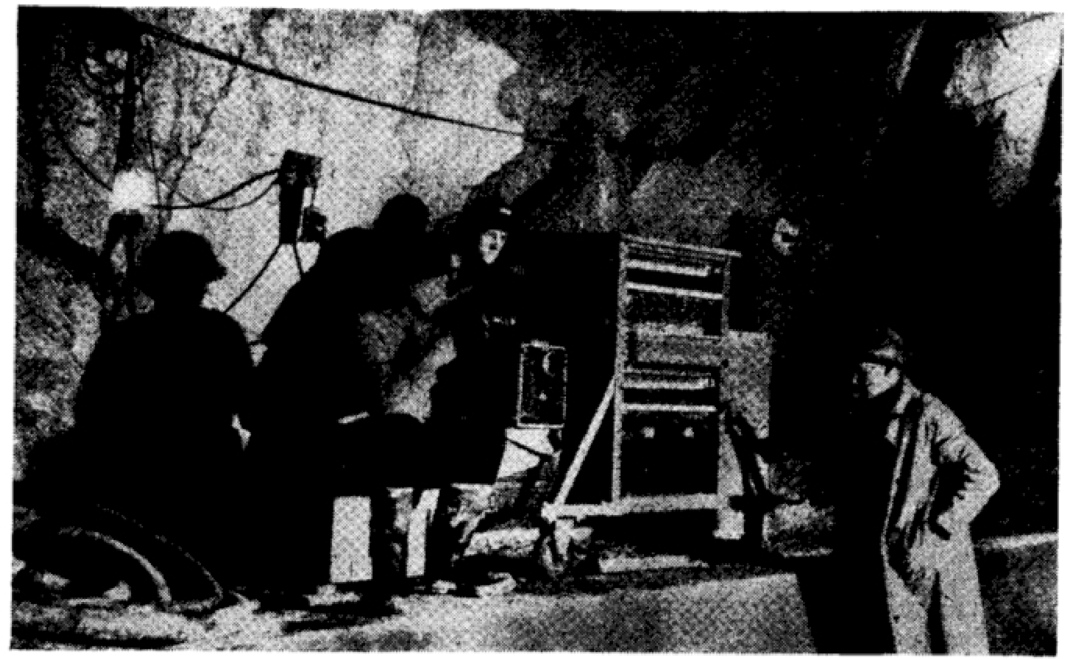
- Opacity measurement
- Sensitive to density (ρ)
- Observable: deficit with respect to free sky
- Intrinsically 2D, can get 3D by using multiple points of view
- No limit on size of target

- 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

The birth 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.

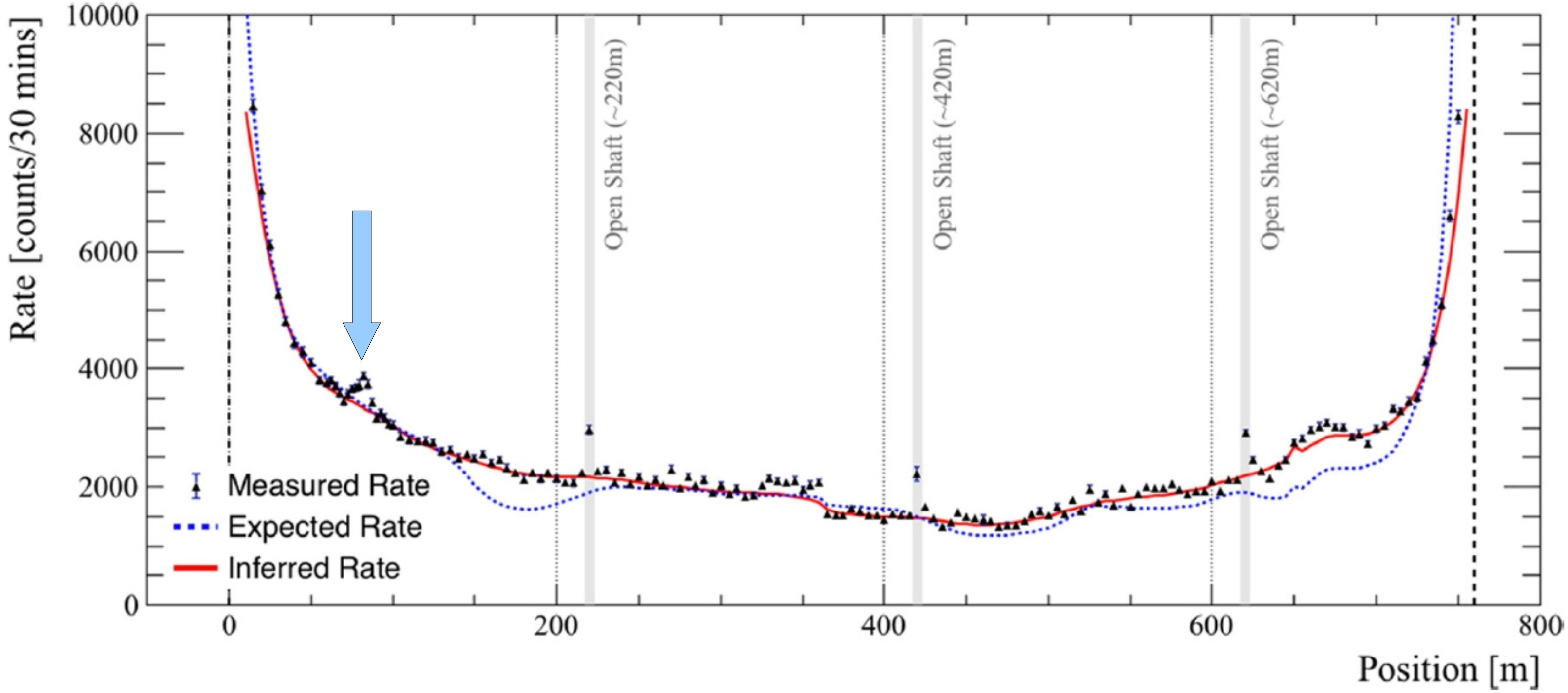
Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described

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

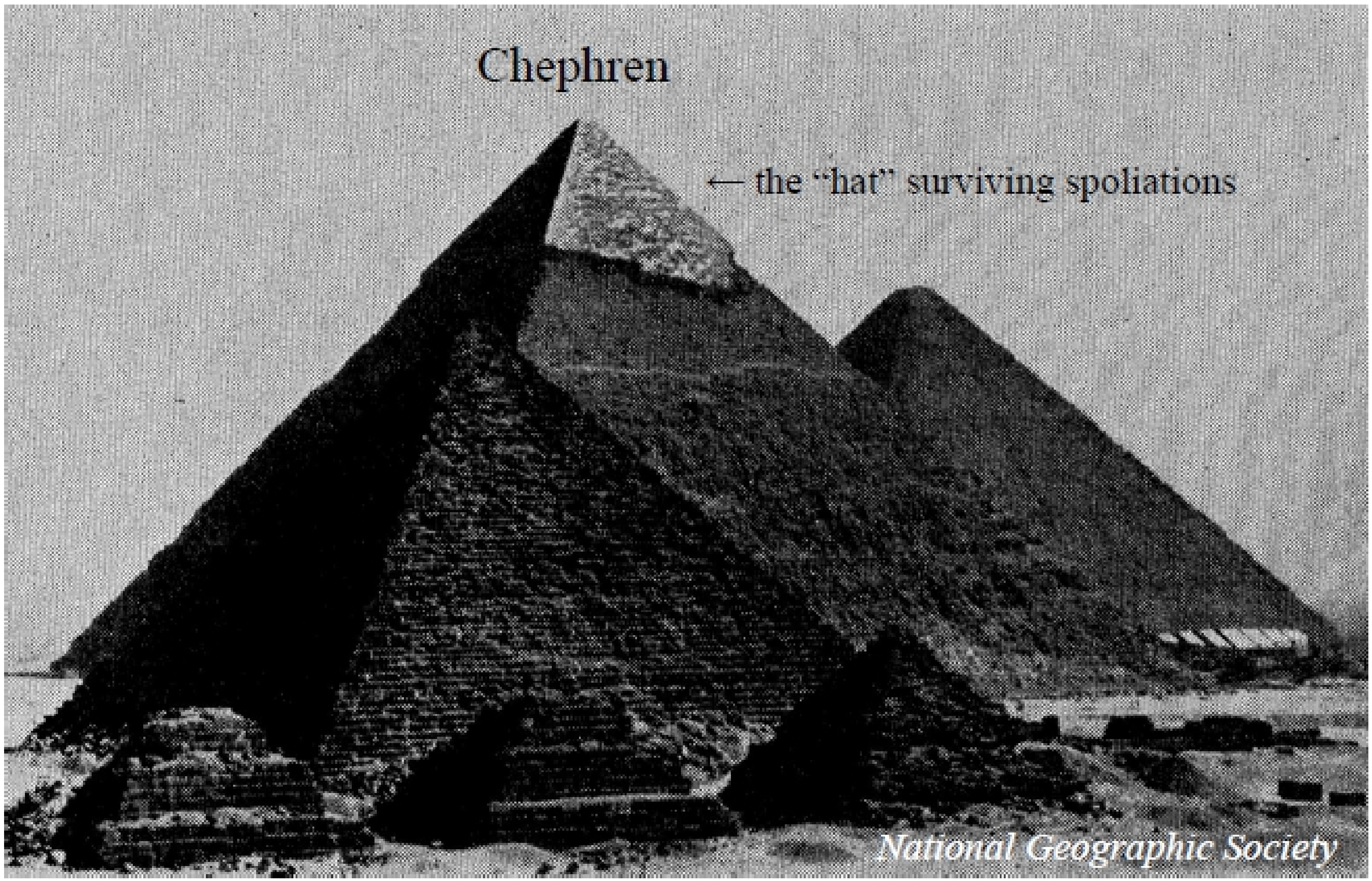
Fast-forward to present



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

- Survey of a railway tunnel built in 1862 in the UK
- Movable tracker 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

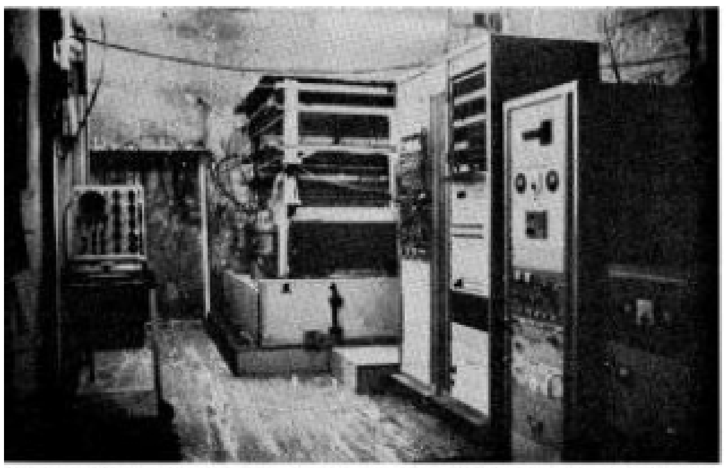
First application of muography to archaeology



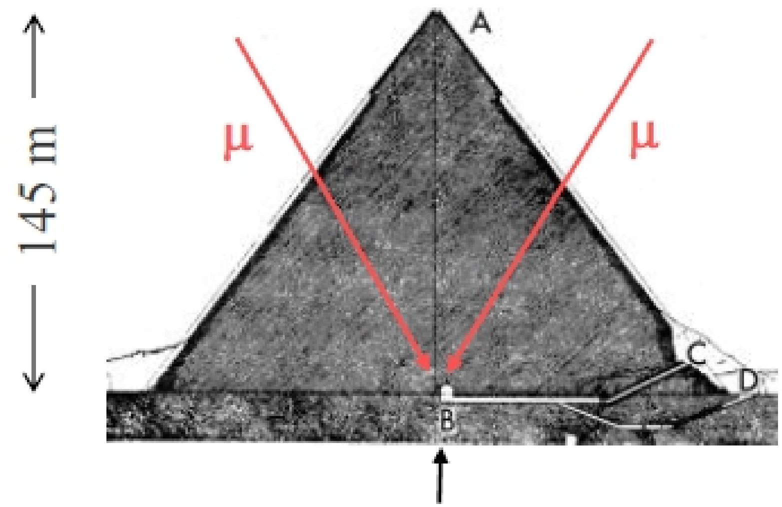
Search for hidden chambers in the Chephren's Pyramid

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

Alvarez's result: no hidden chamber

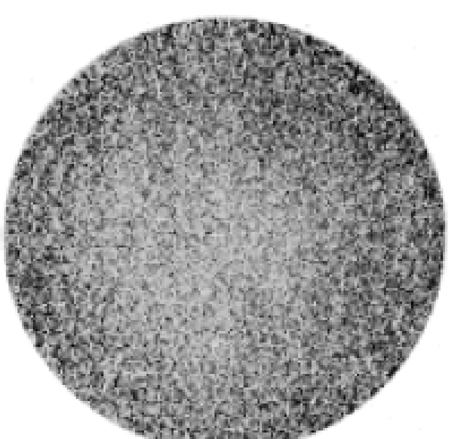


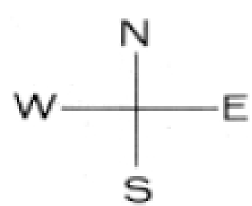
Spark chamber "muon telescope"



Telescope in Belzoni chamber

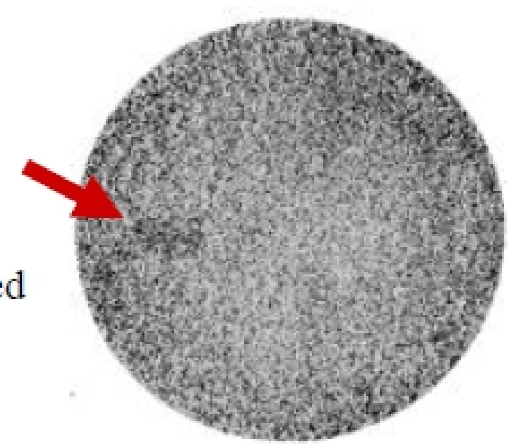
Data



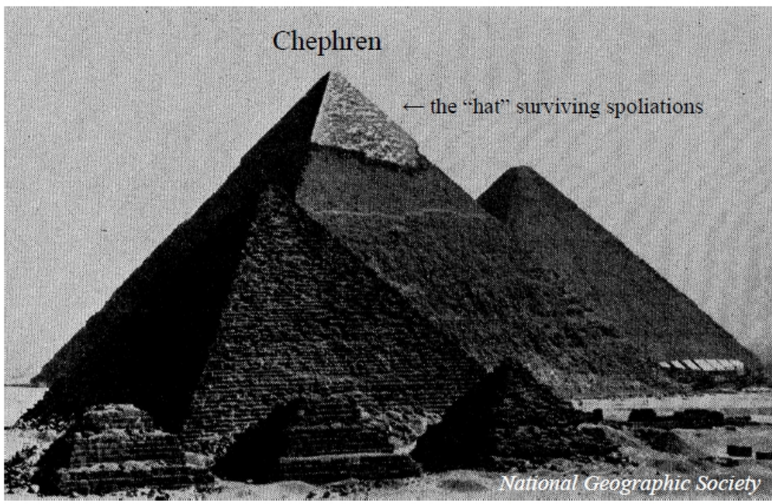


Data and simulation are corrected for pyramid structure and telescope acceptance

Simulation with hidden chamber

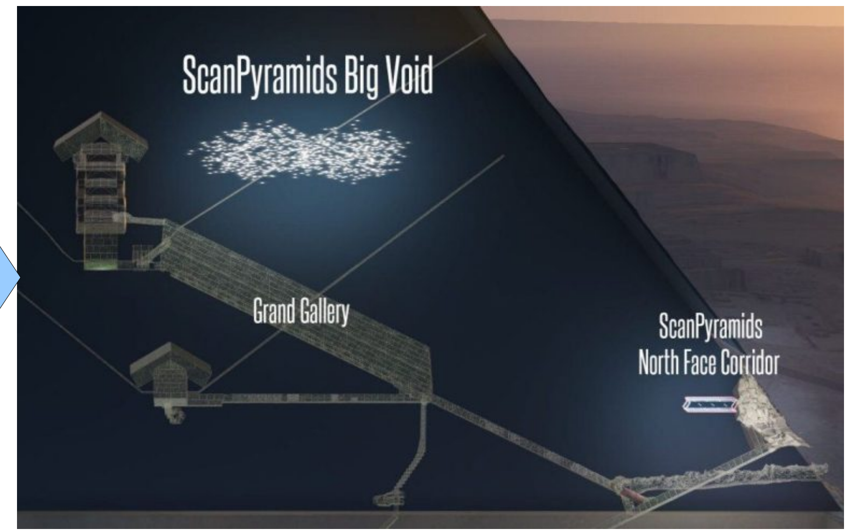


Fast-forward to present



Search for hidden chambers in the Chephren's Pyramid

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



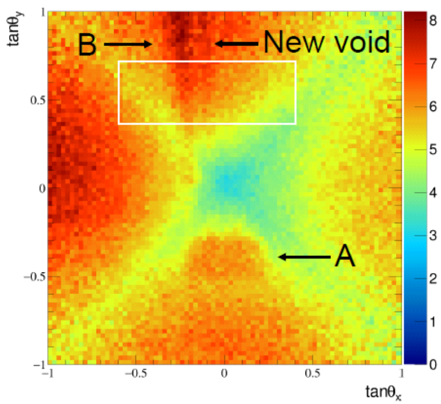
Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons
Morishima et al., Nature 552 (2017) 386

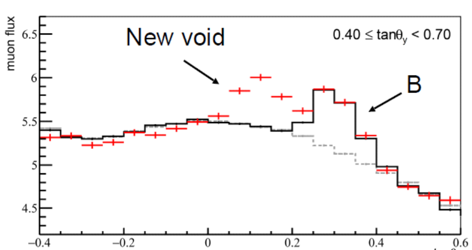
Alvarez chose the wrong pyramid...

Khufu's Great Pyramid
(ScanPyramids, 2017)

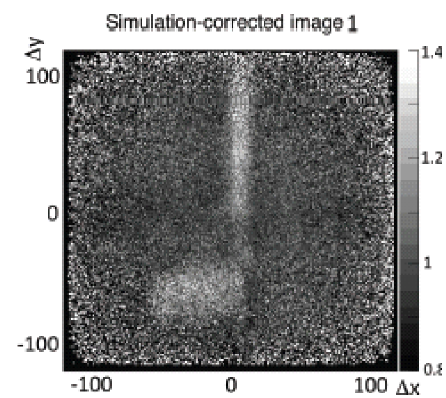
Morishima et al., Nature 552 (2017) 386

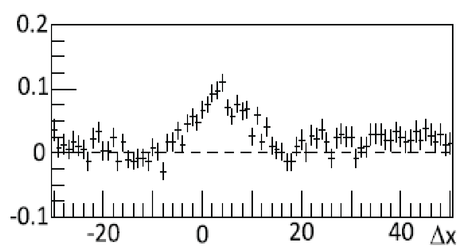
Nagoya
(emulsions, indoors)



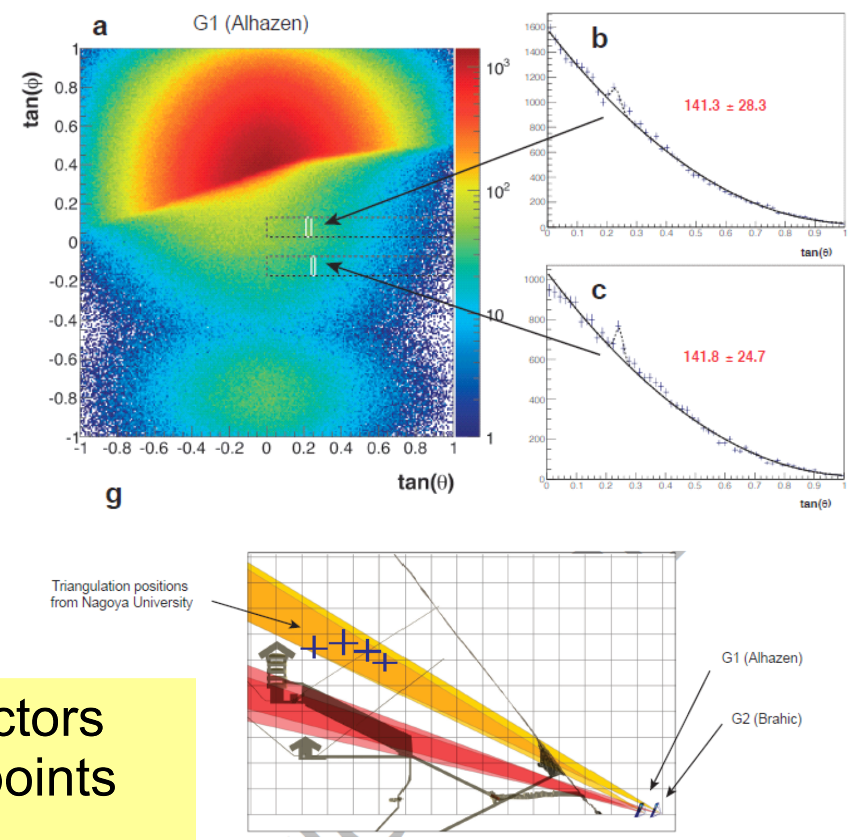


KEK
(scintillators, indoors)





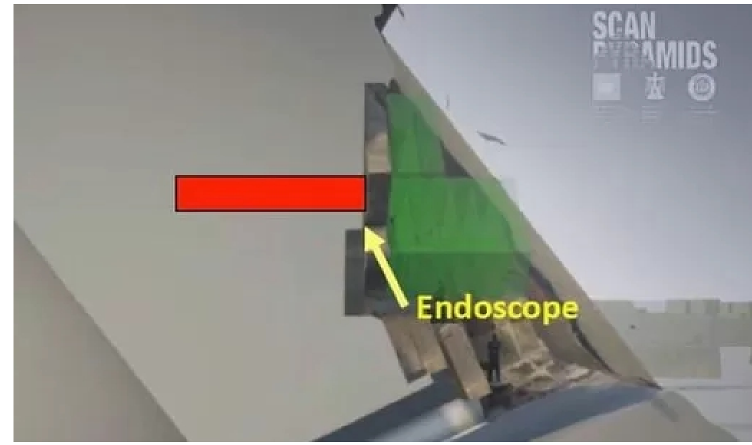
CEA
(MicroMegas, outdoors)



Coherent results from 3 very different detectors (independent analysis) and from different points of view; position from triangulation.
Evidence for low-ρ volume, size ~ 30 x 10 x 3 m^3

Khufu's Great Pyramid
(ScanPyramids, 2023)

- Additional data have been collected since then to characterise that and other anomalies in the same pyramid
- Announcement in 2023 of a corridor-like cavity, 2x2x9 m^3
- Cross-check measurements: GPR and ultrasounds
- Final confirmation: visual inspection via an endoscope



Discovery by Muography: S. Procureur et al., “Precise characterization of a corridor-shaped structure in Khufu’s Pyramid by observation of cosmic-ray muons”, Nature Communications 14 (2023) 1144

Confirmation by standard methods: M. Elkarmoty et al., “Localization and shape determination of a hidden corridor in the Great Pyramid of Giza using non-destructive testing”, NDT & E International (2023) 102809

The scattering revolution: 2003

brief communications

Radiographic imaging with cosmic-ray muons

Natural background particles could be exploited to detect concealed nuclear materials.

Despite its enormous success, X-ray radiography[1] has its limitations: an inability to penetrate dense objects, the need for multiple projections to resolve three-dimensional structure, and health risks from radiation. Here we show that natural background muons, which are generated by cosmic rays and are highly penetrating, can be used for radiographic imaging of medium-to-large, dense objects, without these limitations and with a reasonably short exposure time. This inexpensive and harmless technique may offer a useful alternative for detecting dense materials — for example, a block of uranium concealed inside a truck full of sheep.

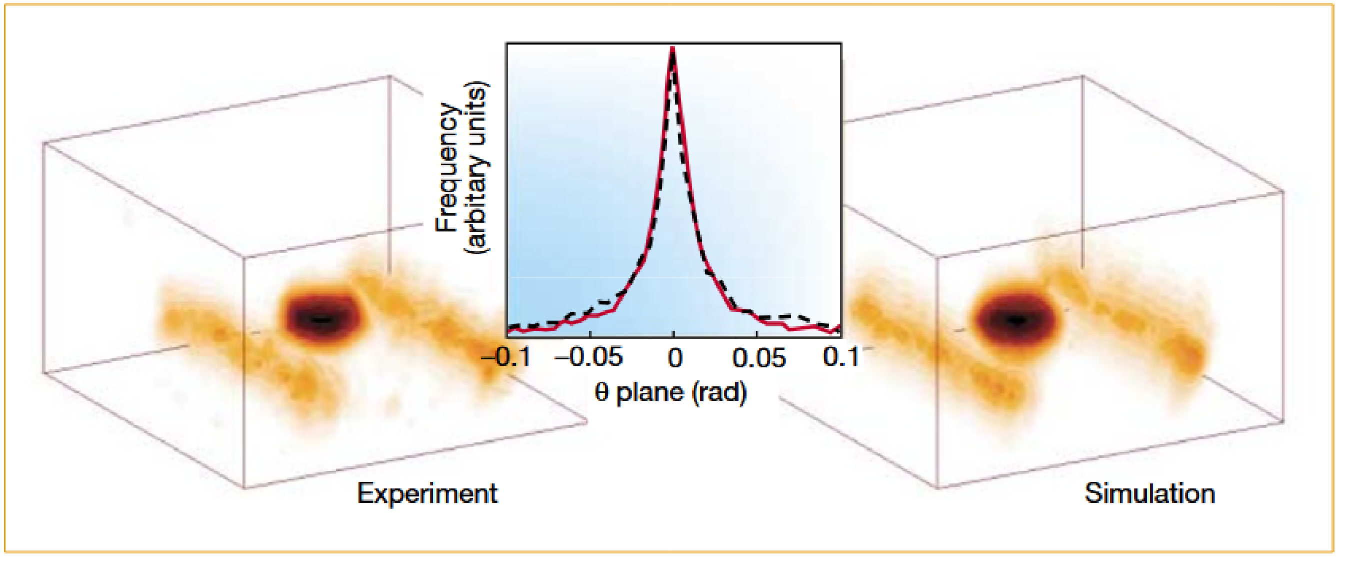
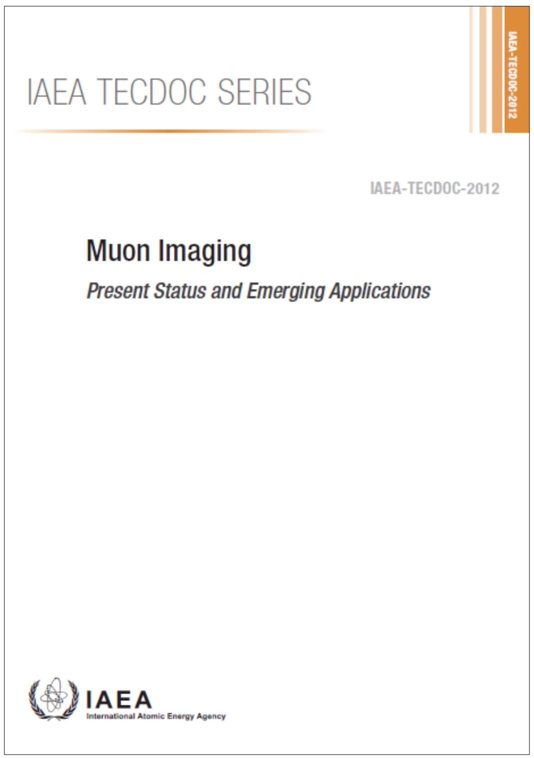
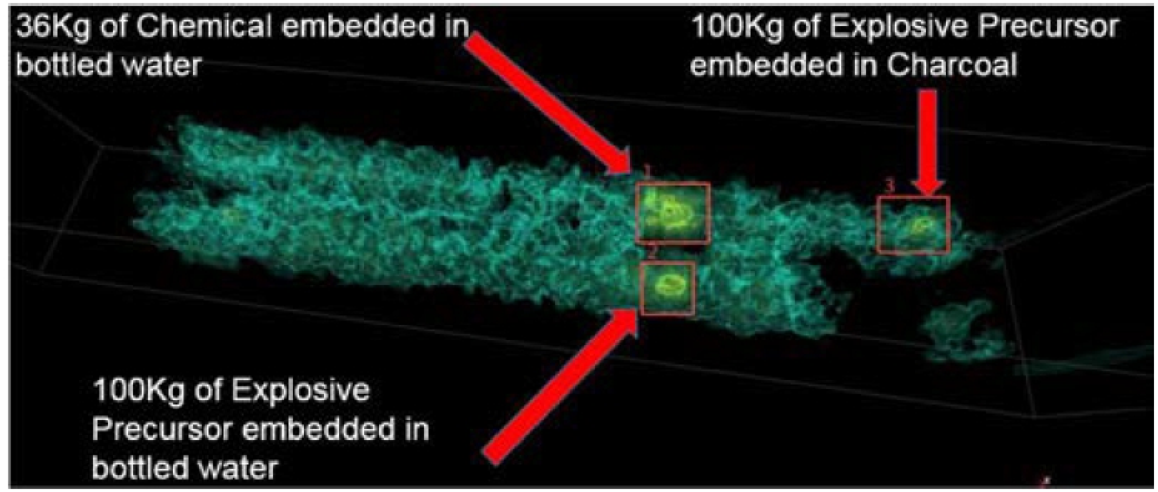


Figure 1 Radiographic imaging with muons of a test object (left) and the reconstructed image of its Monte Carlo simulation (right). The test object is a tungsten cylinder (radius, 5.5 cm; height, 5.7 cm) on a plastic ($35 \times 60 \times 1$ cm^3) plate with two steel support rails.

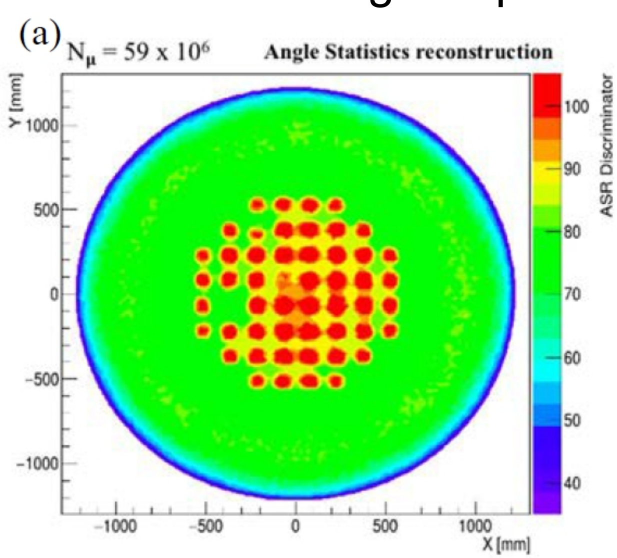
1-page communication on Nature:
K. Borozdin et al., Nature 422 (2003) 277

Fast-forward to present

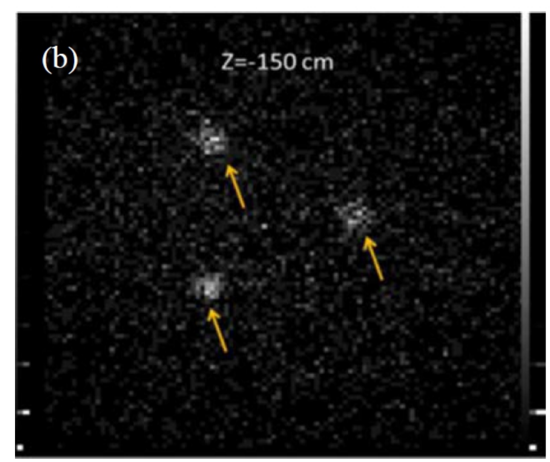




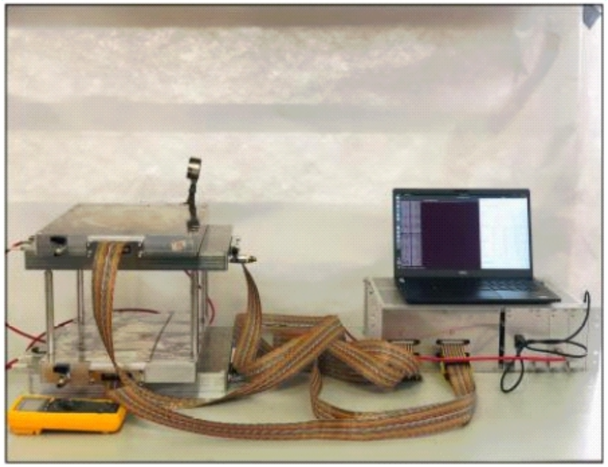
Cargo inspection at borders

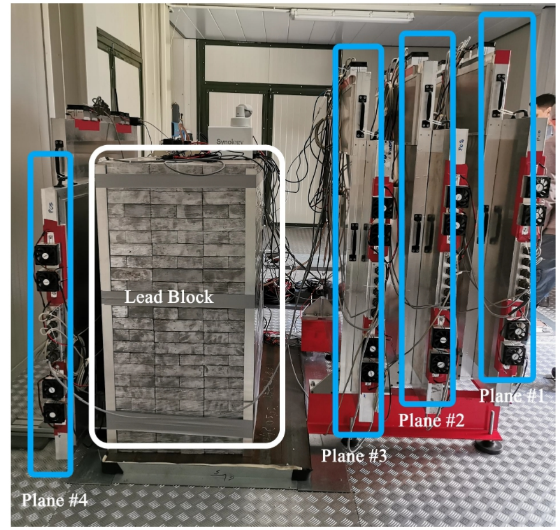


Nuclear waste monitoring

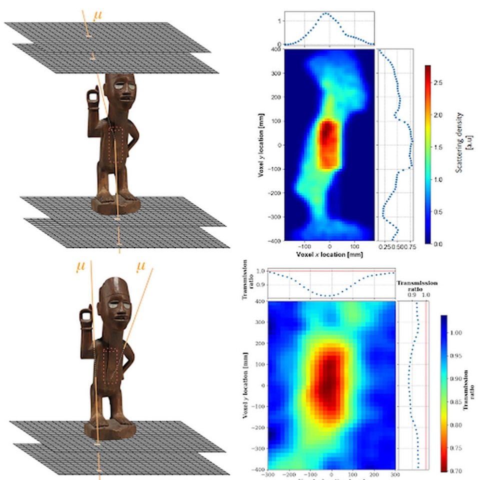


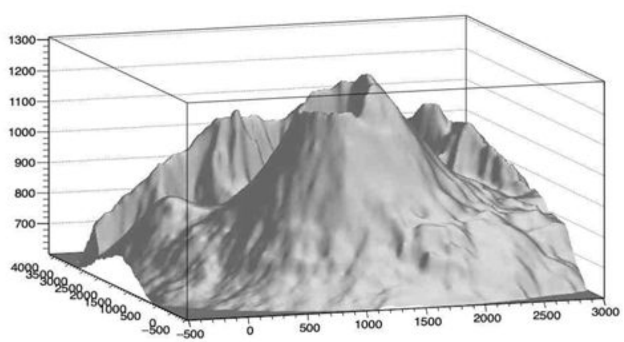
Nuclear warheads verification

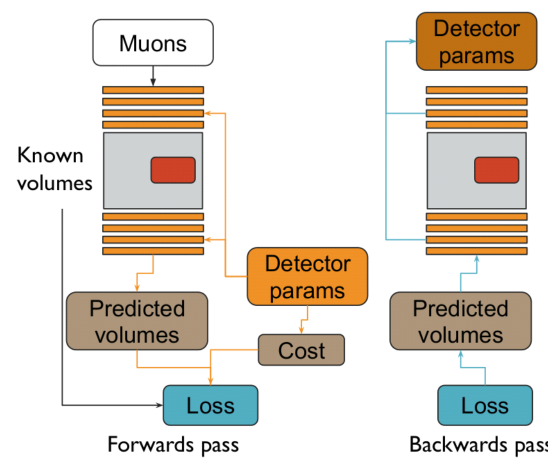




Ongoing activities at CP3



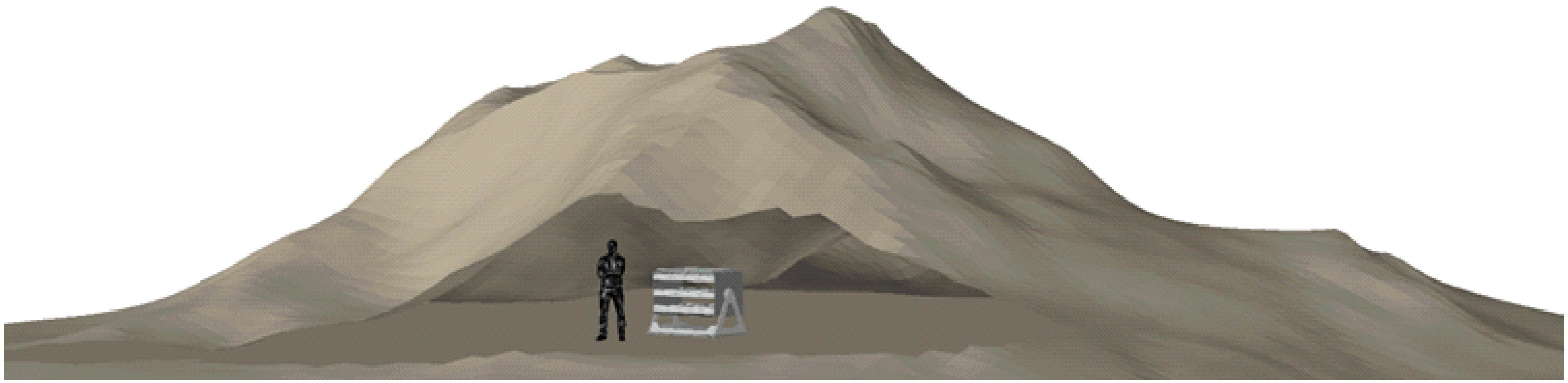




Portable detectors

- 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

Image from L. Bonechi, R. D'Alessandro, *A.G.*, Rev. Phys. 5 (2020) 100038



Portable detectors

- 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

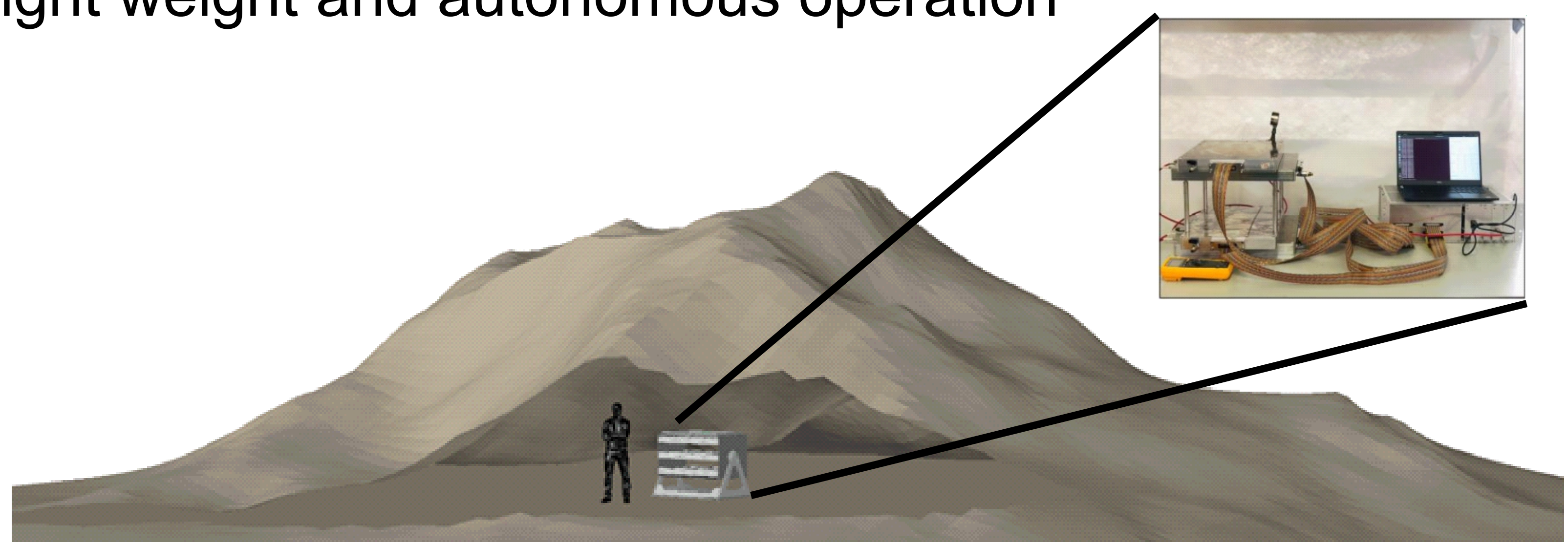
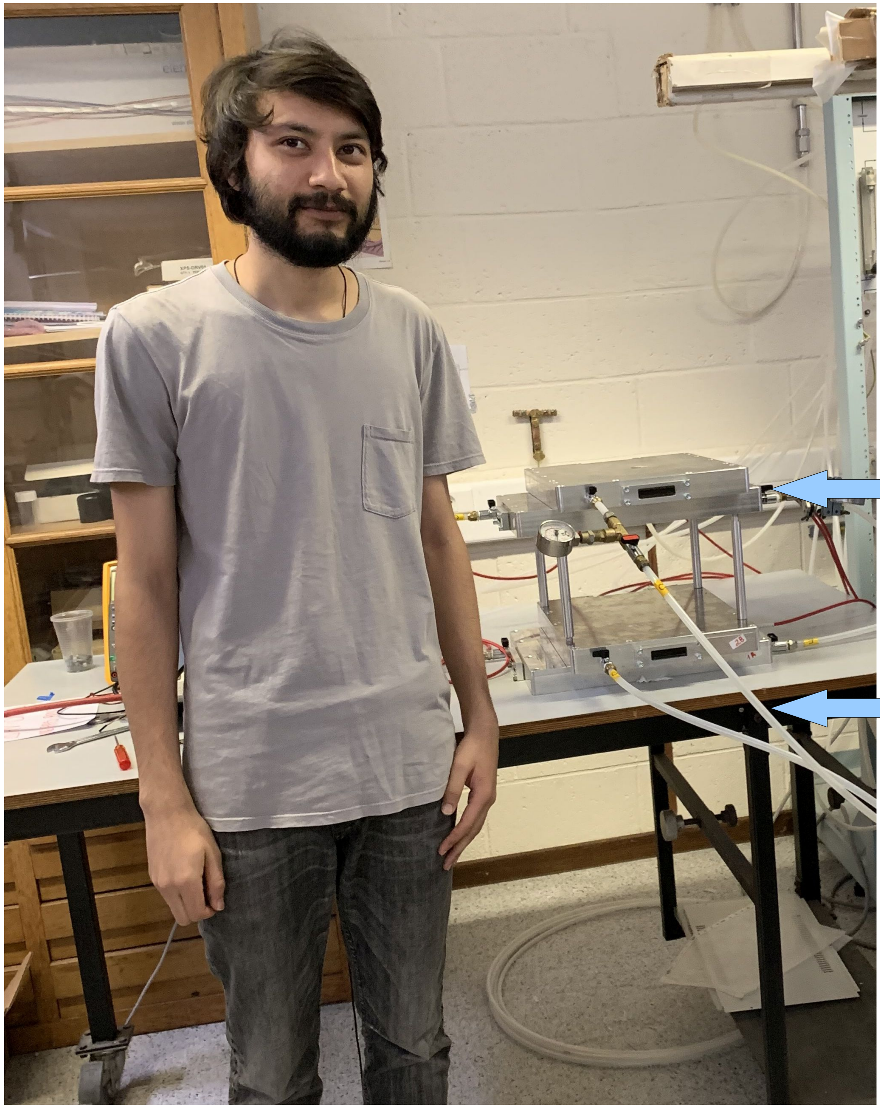


Image from L. Bonechi, R. D'Alessandro, *A.G.*, Rev. Phys. 5 (2020) 100038

Portable glass-RPC muoscope

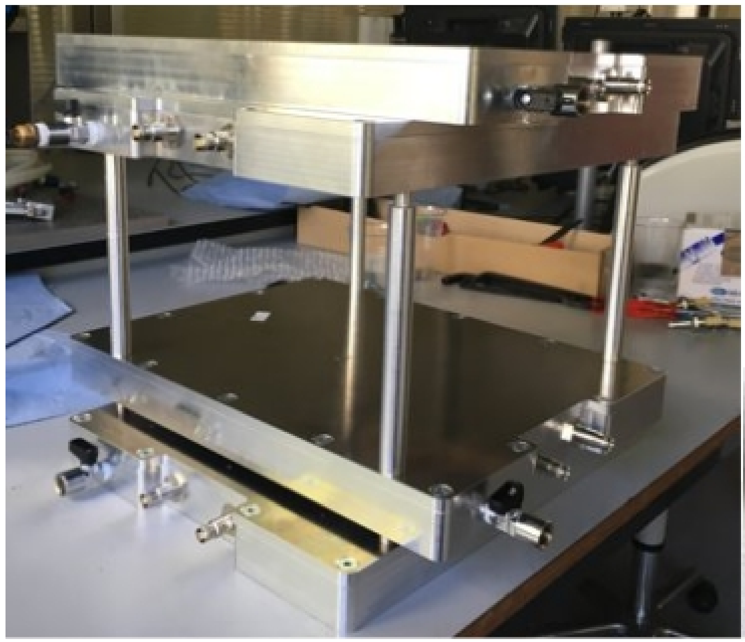
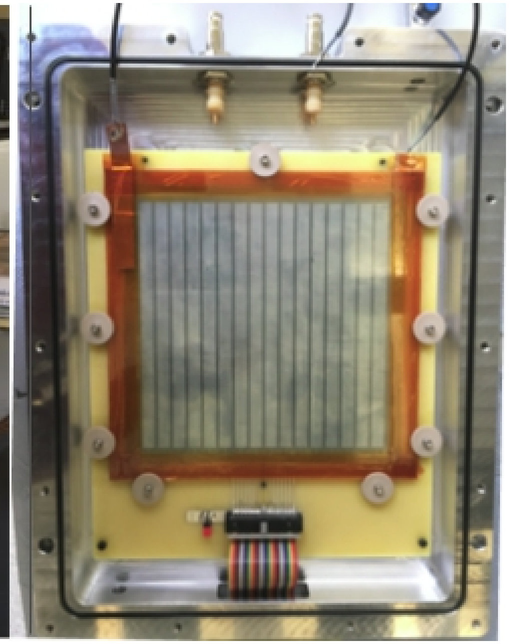
Picture from Samip Basnet



Superimposed detector layers, at 90° of each other

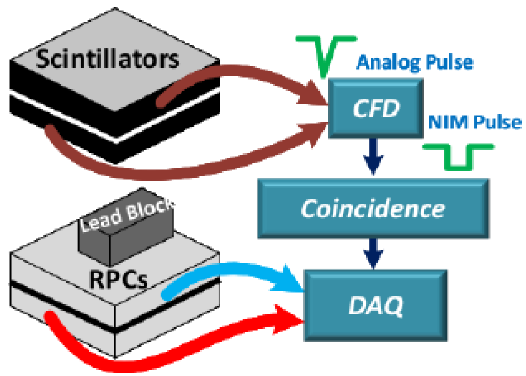
Tubes for gas filling; only needed once, then the muoscope is ready to go

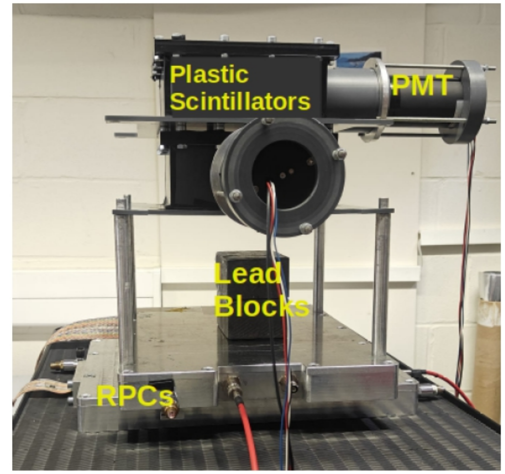
Portable glass-RPC muoscope

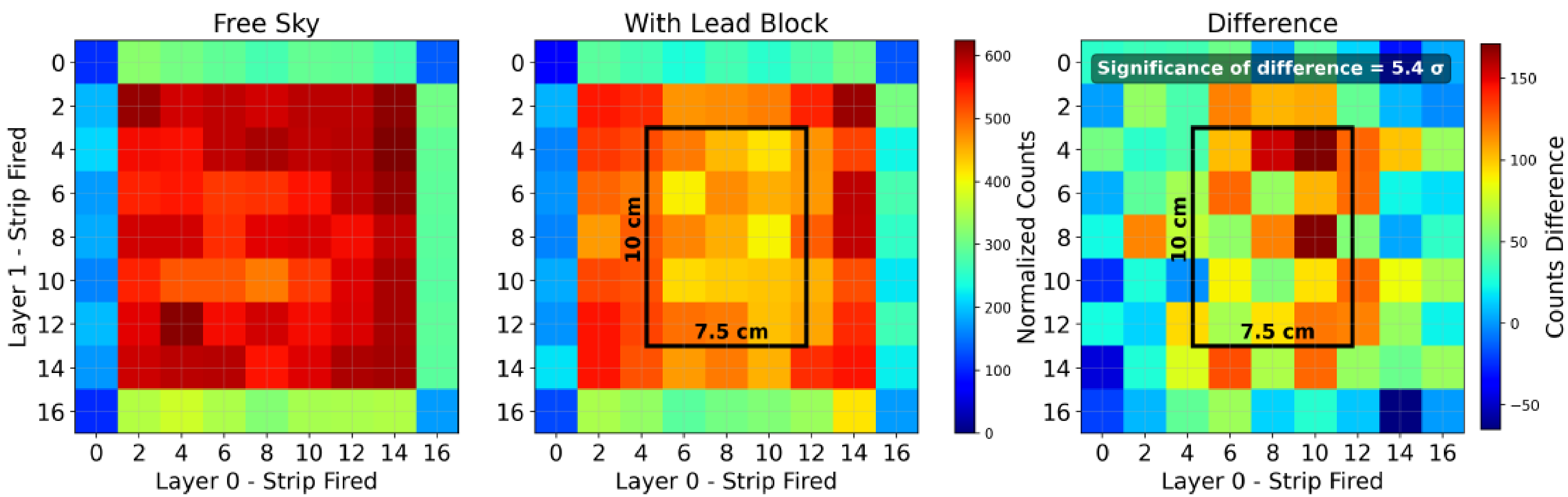



- Portability
  - Sealed; particular care in making gas-tight boxes (10^{-9} mbar l/s)
  - Small (active area: 16x16 cm^2)
  - Light, robust
- Versatile: modular geometry
- Cheap

- 1st prototype to test feasibility
  - Read-out recycled from CMS
  - 16 channels/layer → 1 cm strip width
  - Bulky aluminum casing
- 2nd prototype under development
  - Modern read-out chip (MAROC)
  - 128 channels/layer
  - Very light plastic frame (3D-printed)

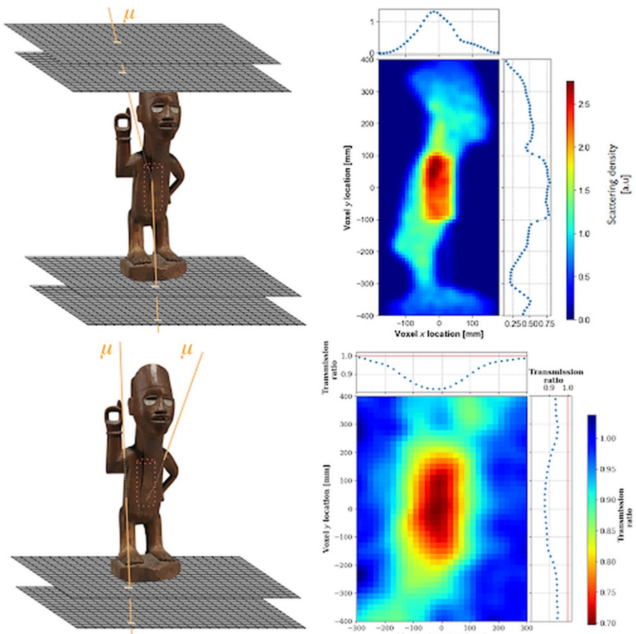






> 5σ difference in (normalized) counts observed by each RPC
(31 hours of free-sky data, 20 hours with lead blocks)

Ideas for application in cultural heritage preservation



Church of Riches Claires

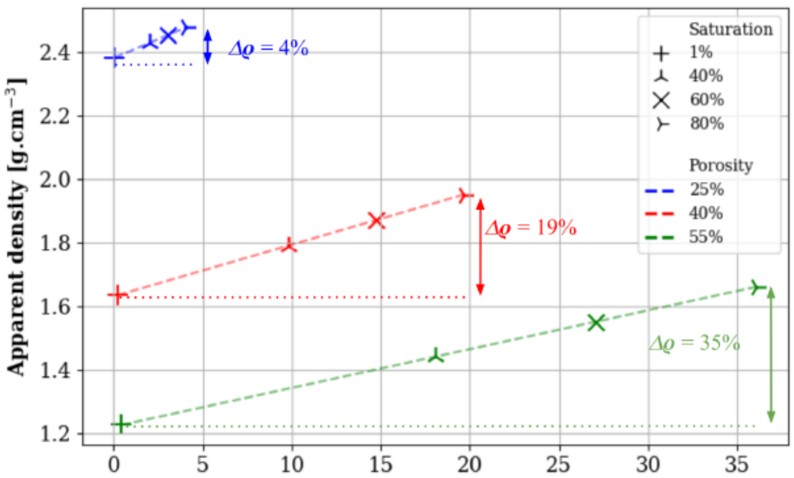
Fountain of the Three Graces

Collaboration with KIK-IRPA, VUB and UAntwerp; identified some interesting future targets; started with exploratory *simulation* study: AG et al., iScience 28 (2025) 112094

Objective	Absolute ρ	ρ vs position	ρ vs time	Material id.
Moisture	Important	Low resolution	High frequency	Not needed
Bulk features	May be useful	Medium resolution	Not needed	May be useful
Inner cracks	Not needed	High resolution	Low frequency	Not needed

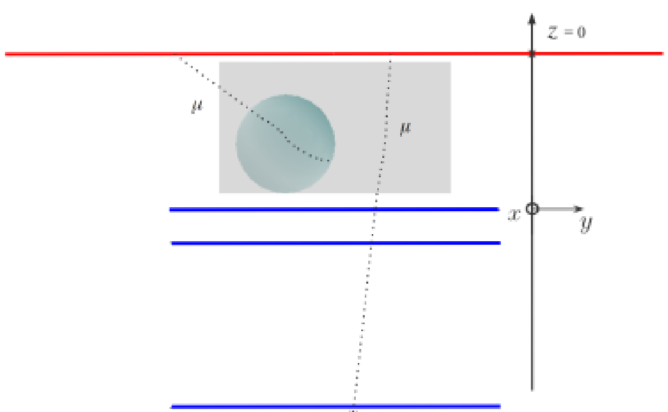
Water content in monuments

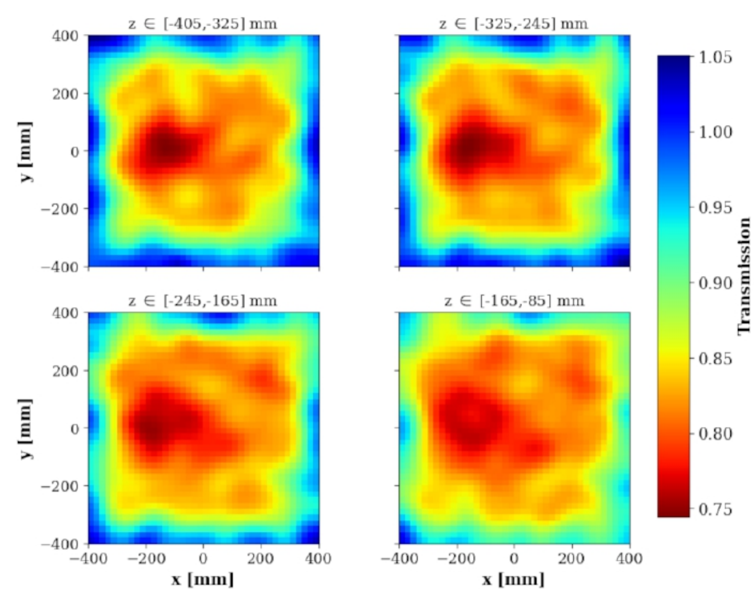
From AG et al., iScience 28 (2025) 112094



Something that we learned through this study: monitoring moisture (water %) in monuments seems quite promising for muography. It is very important for preservation. **Standard methods are either destructive or unreliable →** opportunity to make a difference!

$$\rho' = \rho_{dry} \times (1 + \mathrm{MC})\,, \quad \mathrm{MC} = \frac{\rho_{water}}{\rho_{dry}} \times porosity \times saturation$$





Using a custom backprojection algorithm for coarse 3D imaging

Mount Vesuvius

Vesuvius seen from Pompeii's ruins (from wikipedia)

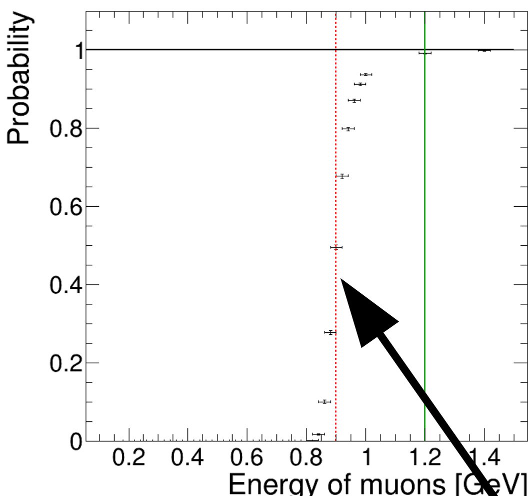
- Understanding its composition is very important for volcanology and civil protection
- One the most dangerous volcanoes in the world
  - Famous for the eruption that buried Pompeii and Herculaneum in 79 C.E.
  - >0.5 M residents in its surrounding *Red Zone*, defined as being at high risk of pyroclastic fallout in case of a Sub-Plinian eruption

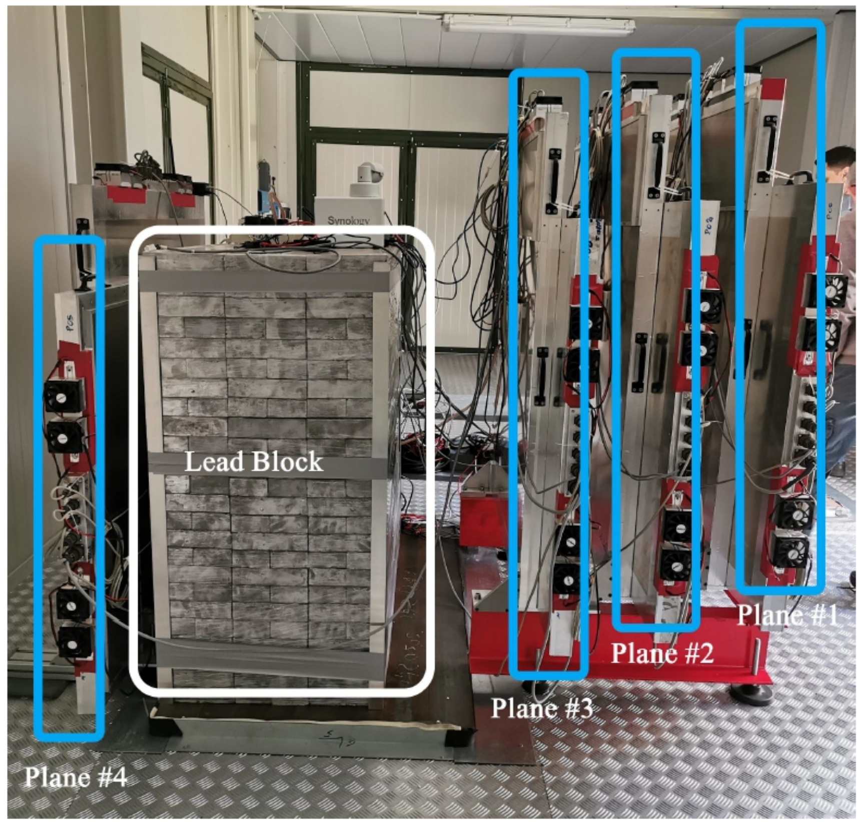
The MURAVES project

- MURAVES: MU(on) RA(diography) of VES(uvius)
- Successor of MU-RAY project (INFN+INGV, Italy)
- Consortium of INGV, INFN, Naples, Florence, FNAL, UCLouvain and VUB

MURAVES telescopes

Plot by Marwa Moussawi

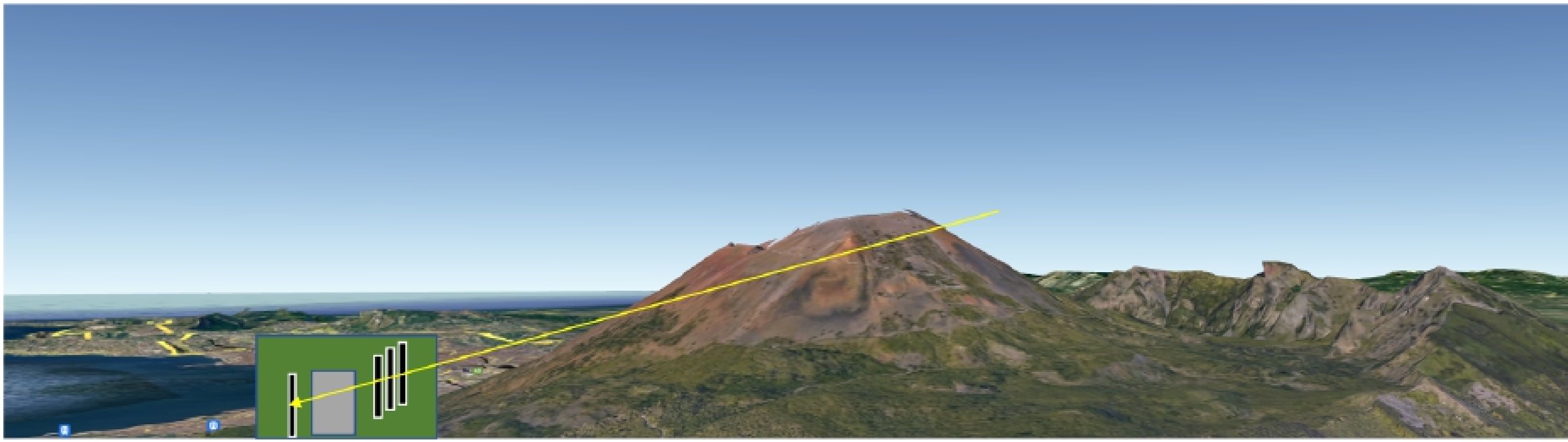




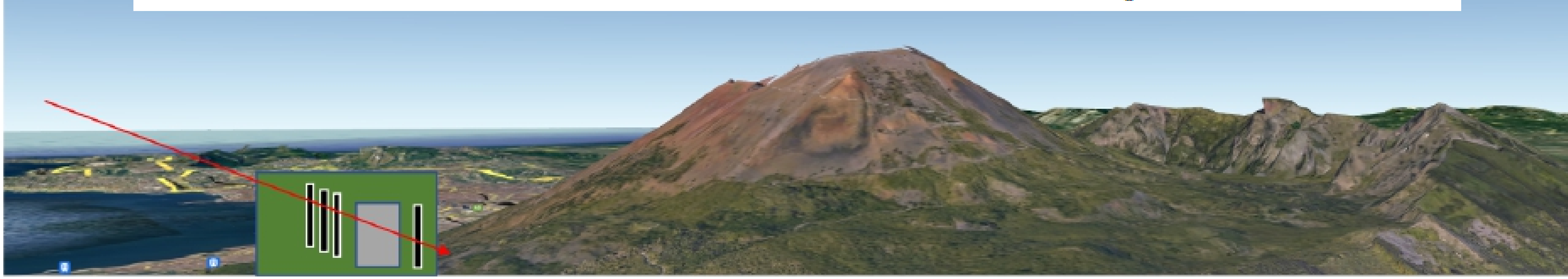
Picture by S.Wuyckens

- 3 telescopes, each with 4 x-y layers of scintillating bars with triangular section, coupled to SiPM
- Lead wall, 60 cm thick (recycled from OPERA ν experiment), corresponding to a ~1 GeV cut-off

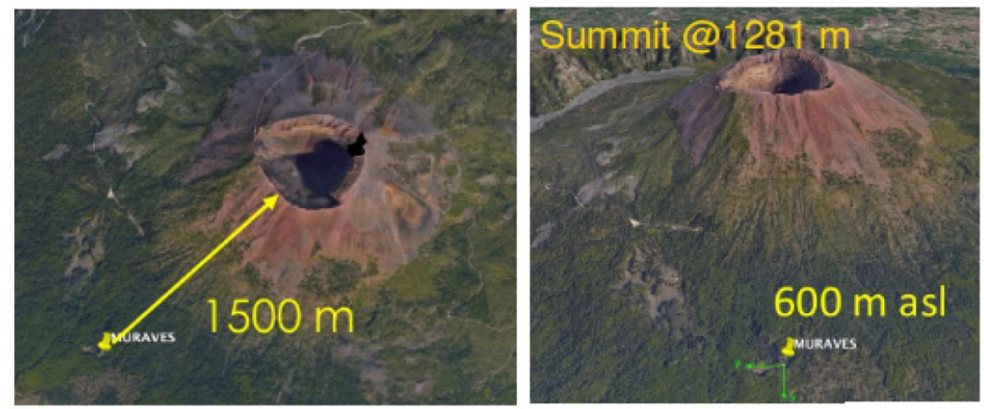
Measurement strategy



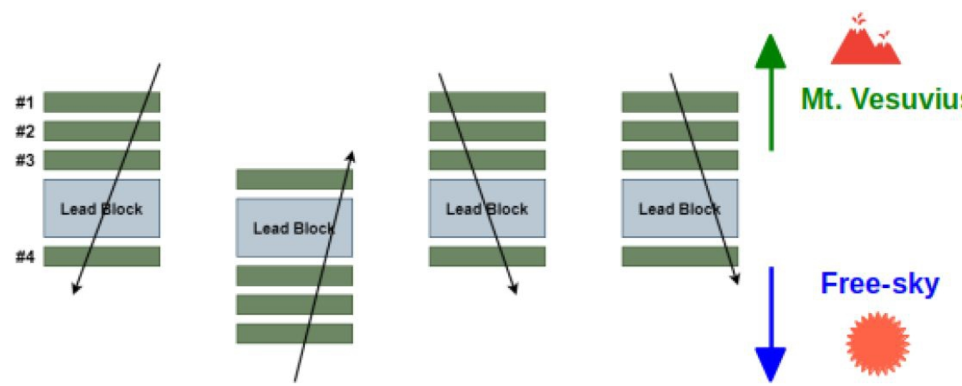
$$T(\theta,\phi) = \frac{N_{\mu}^{v}(\theta,\phi)/\Delta t^{v}}{N_{\mu}^{fs}(\theta,\phi)/\Delta t^{fs}} = \frac{\epsilon^{v} \cdot S_{eff}(\theta,\phi) \int_{E_{min(\rho)}}^{\infty} \Phi(\theta,\phi;E)dE}{\epsilon^{fs} \cdot S_{eff}(\theta,\phi) \int_{E_{0}}^{\infty} \Phi(\theta,\phi;E)dE}$$



MURAVES installation

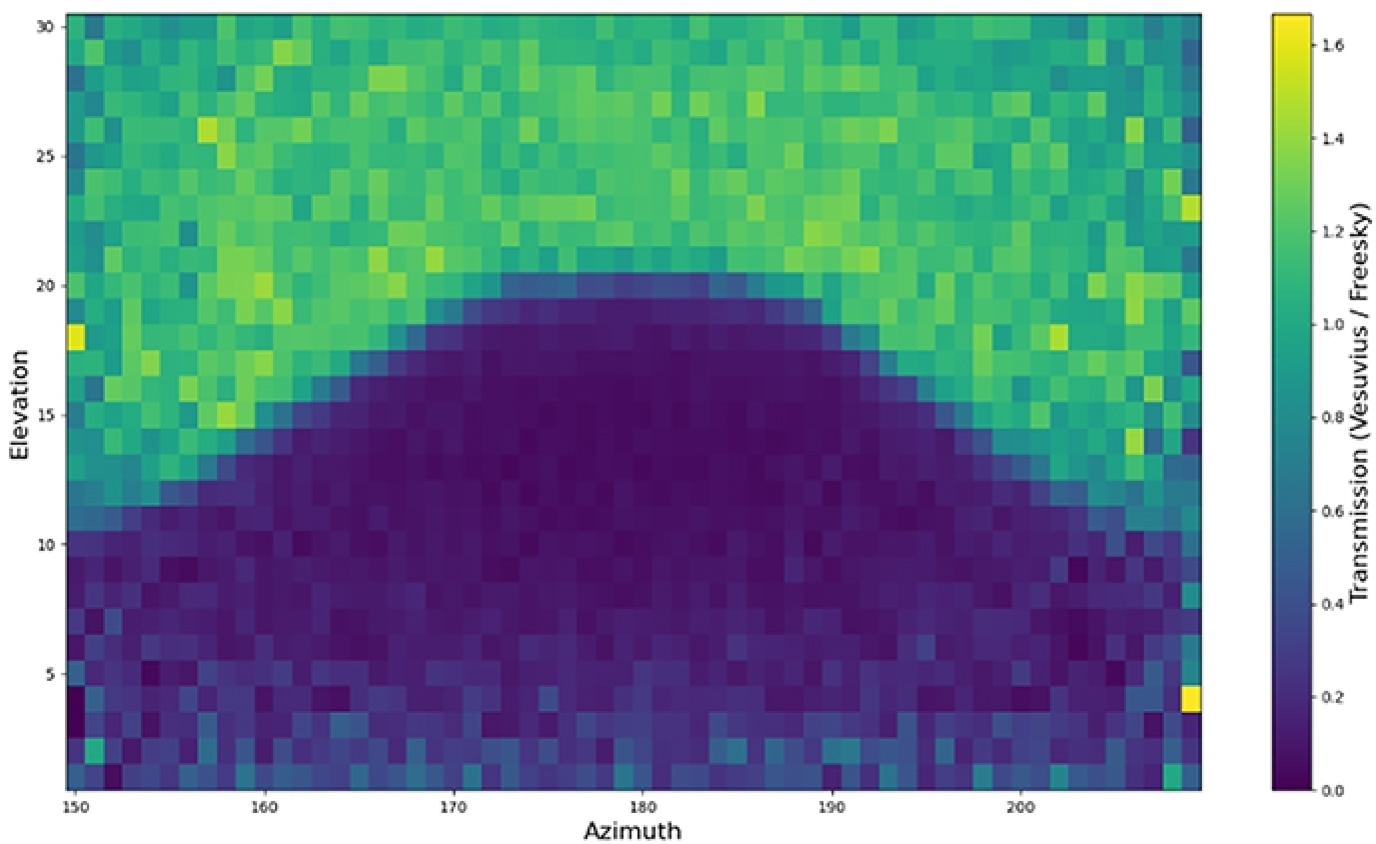


Four lead walls at fixed positions; the telescopes alternate in occupying the free-sky position, such that detector systematics cancel out ($\varepsilon^{v} \sim \varepsilon^{fs}$)



First transmission map from MURAVES

From: Y. Hong et al. (MURAVES),
J. Appl. Phys. 138, 064906 (2025)

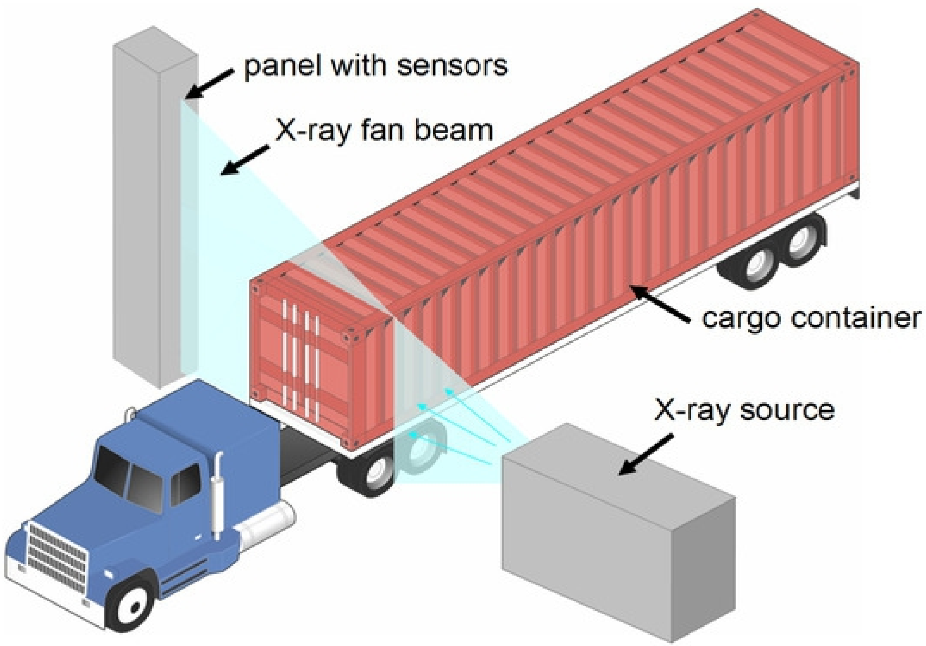


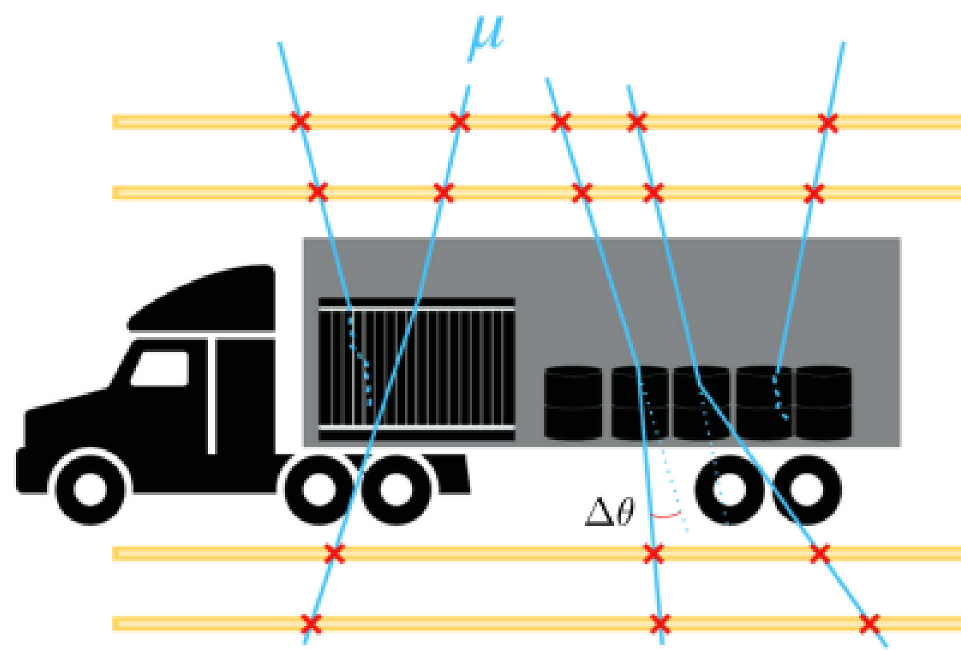
Measured transmission map from one of the telescopes, with 51 days of Vesuvius data and 9.5 days of free sky data

We took ~2 years of data, now in the process of analysing

Cargo inspections

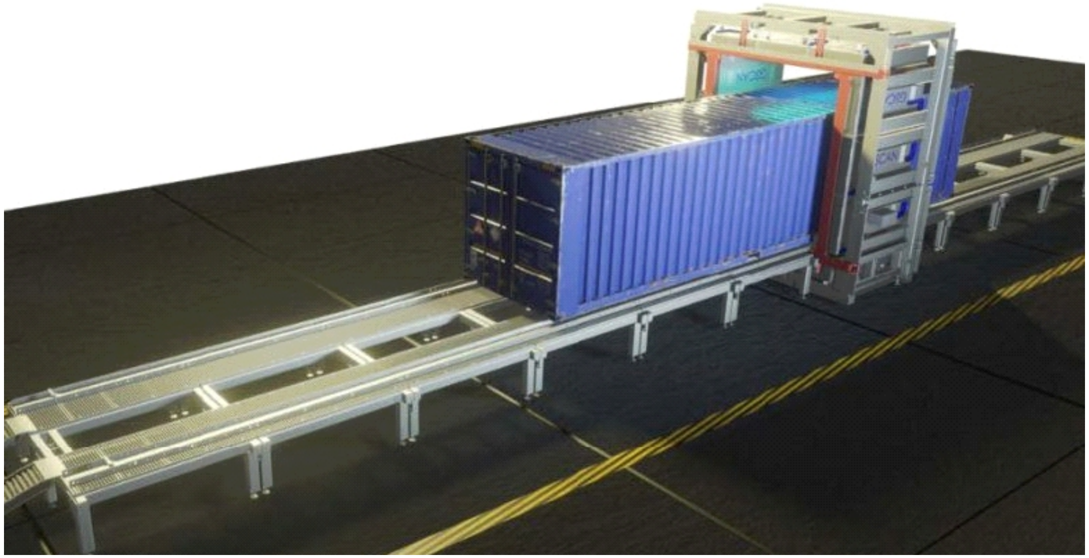
Pictures from: S. Barnes et al., Instruments 7 (2023) 13





- Radiation portals (X and γ rays) increasingly used for cargos
- Very fast; very detailed images; but easy to shield
- Ionizing radiation implies complications and concerns
- Cosmic muons pass through thick shielding, while posing no radiological hazard

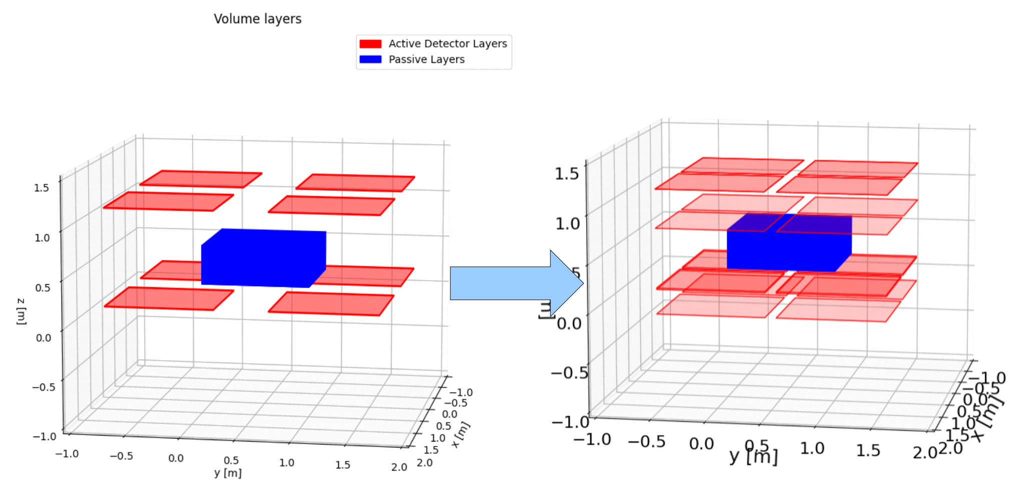
SilentBorder project



- EU project, 2021 to 2025, led by a private company (GScan, in Estonia) and including 3 national EU border control authorities
- Main goal: a working **muon portal** prototype (demonstration took place in June 2025)
- But also methodological studies using MC, towards the next generation portals
- Our task in CP3: optimization studies
- Follow-up: SilentBorder2 (2026-2030)

TomOpt

- Framework for end-to-end detector optimisation
- Loops over entire pipeline: simulation, reconstruction, material ID, anomaly search
- Enables task- and constraint-aware design of particle detectors
- Enables **co-design** studies (hardware and data analysis parameters optimized at once)
- Case studies so far: estimating **fill levels in furnace ladles**, and cargo scanning scenarios within SilentBorder (which funded M. Lagrange and Z. Daher)

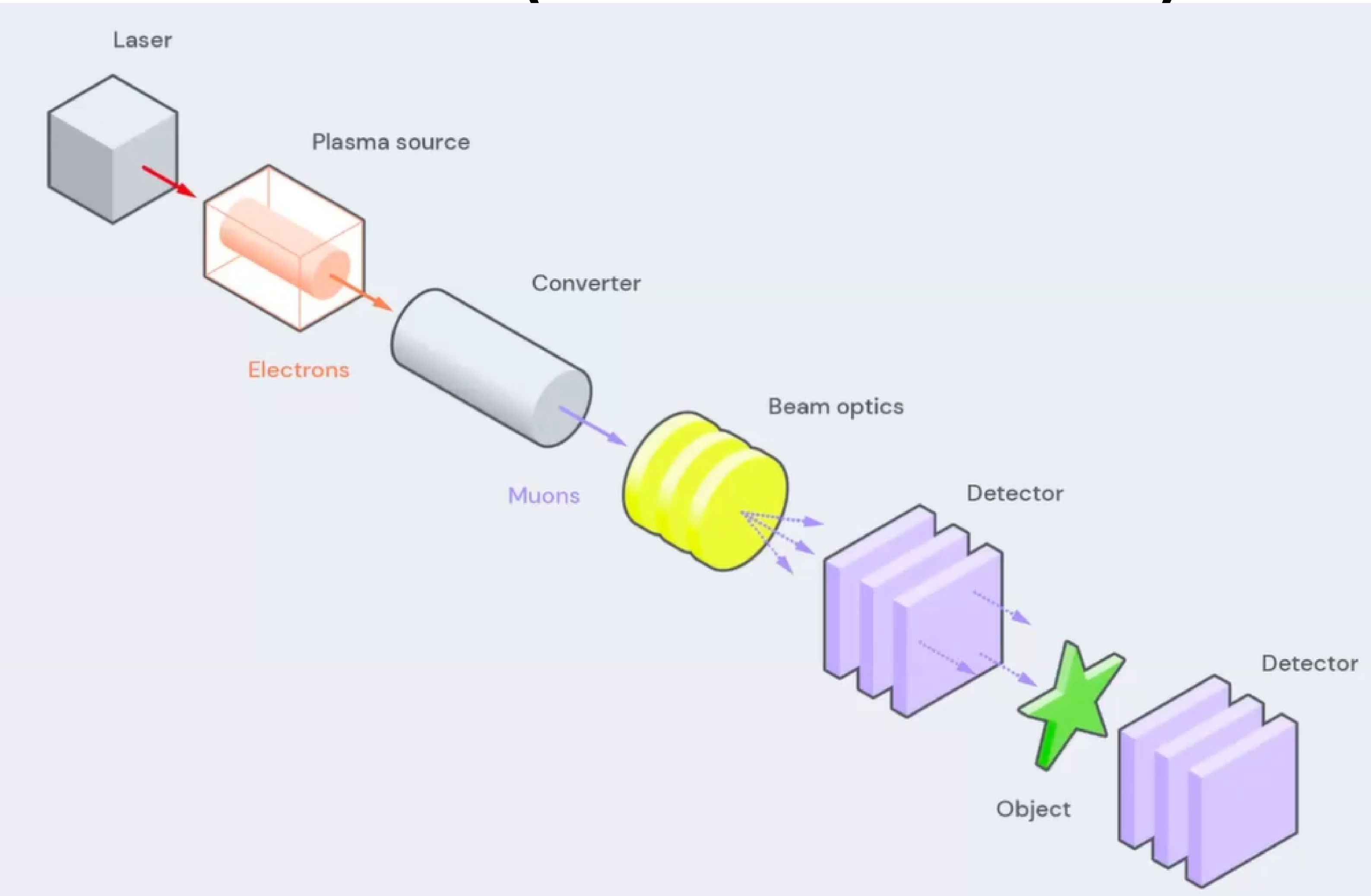


G.C. Strong et al., Mach. Learn.: Sci. Technol. 5 (2024) 035002
Z. Daher et al., arXiv:2507.10253 [physics.ins-det]

All nice and well, but what are the limitations?

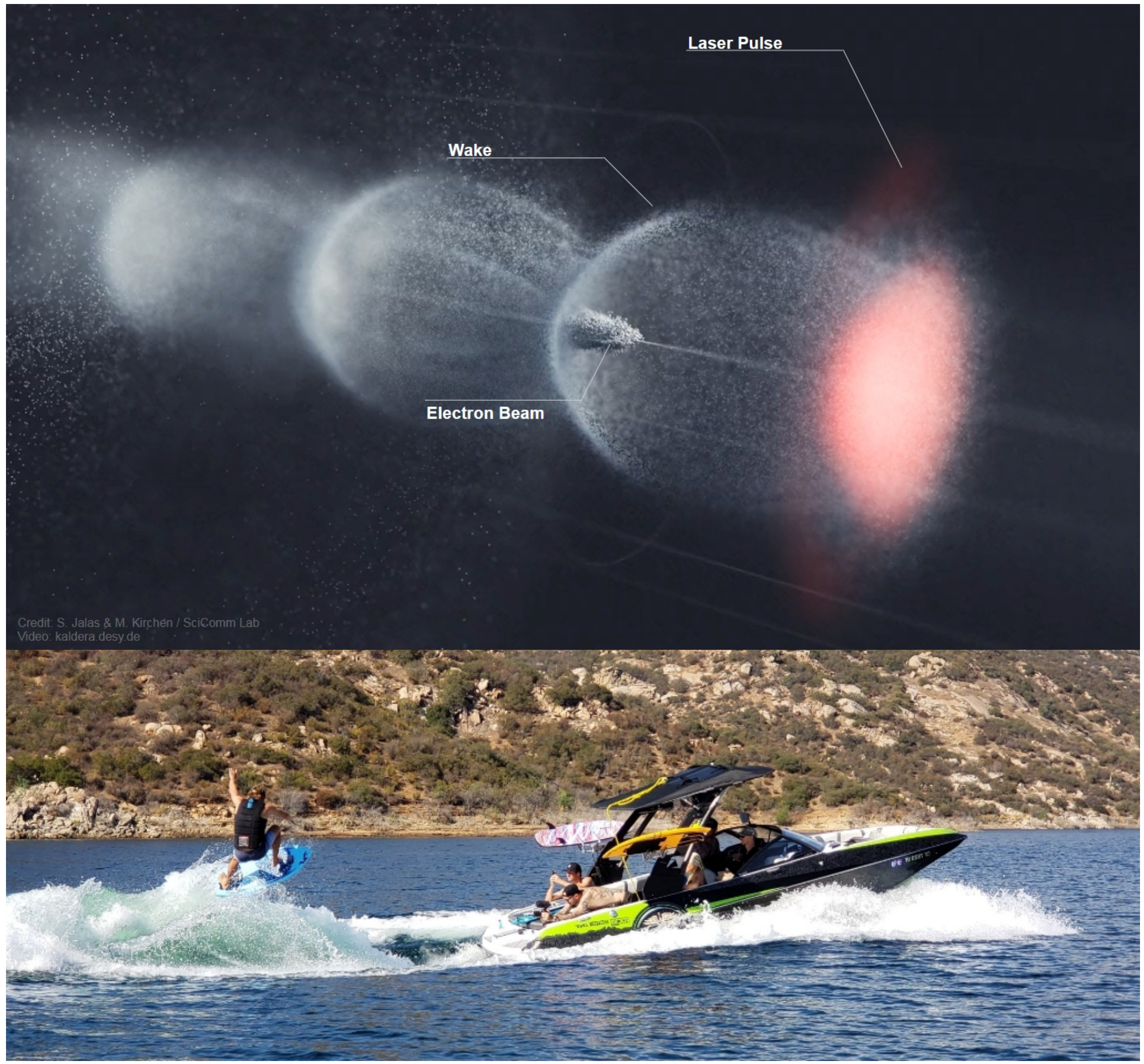
- Very long data-taking is needed
  - Natural flux is low (~1 μ per cm^2 per minute)
  - In most use cases, traditional methods exist that are faster
  - Muography makes sense only if it beats them in some other aspect (e.g., probes deeper, or less assumption-dependent)
- Even with ∞ statistics, blurring by multiple scattering
  - Which you can partially correct if you know energy μ by μ...
  - ... but to know it precisely you would need magnets ($$$)
  - **Very broad energy spectrum**, and affected by various systematics (depends on time, location, temperature, ...)
- Cannot control direction
  - In particular, often unpractical to put detectors underneath!

Another way to do imaging with muons (human-made)



From Andi Hektor (Mu-Ray Tech), Wigner RCP Seminar, 2025

Laser plasma acceleration



Analogy stolen from Kristjan Põder (DESY)

Dream on!

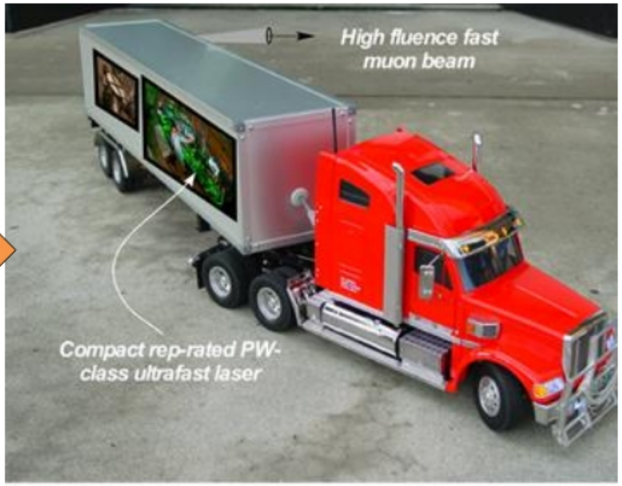
Slide stolen from Todd Ditmire, ELI workshop 2025

The technology challenge is to shrink and make cost effective standard accelerator production of muons

Because of the large mass of muons, accelerators capable of producing GeV particles are needed to produce muons

Existing facilities are typically large

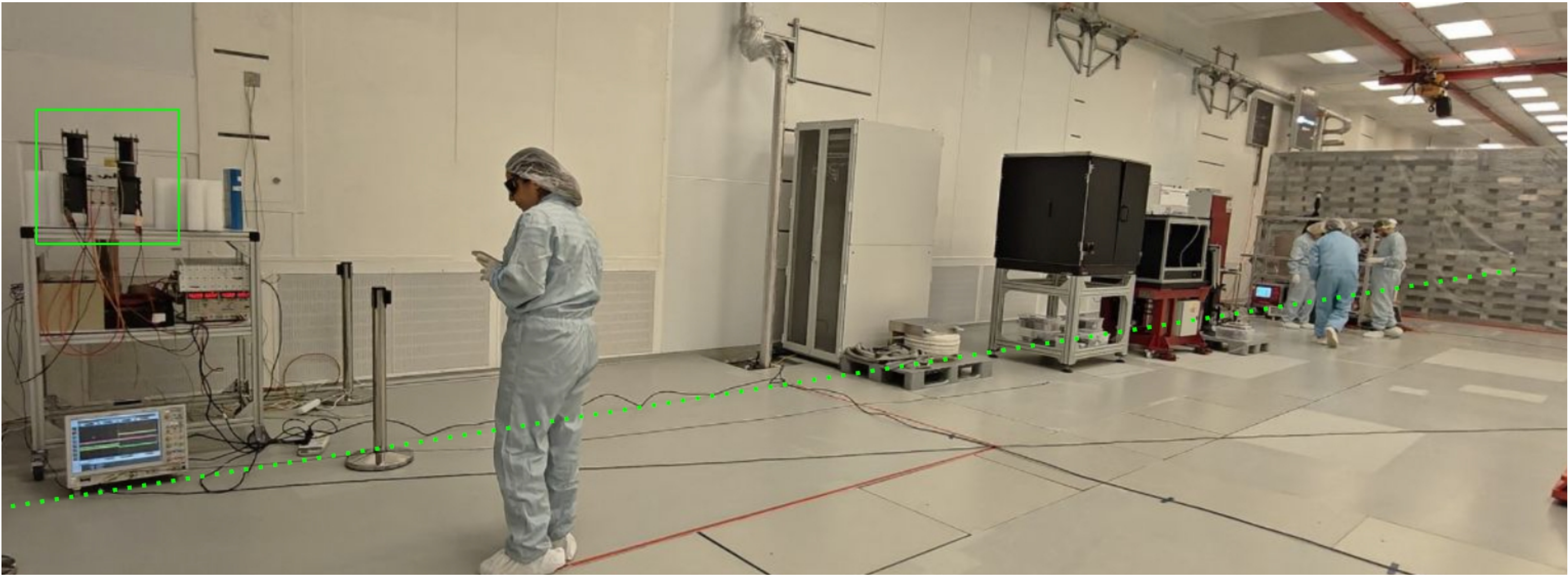
Proposed technology is compact and mobile



Established accelerator technology for producing muons is very large, costly and NOT mobile, however laser technology offers a path forward

12

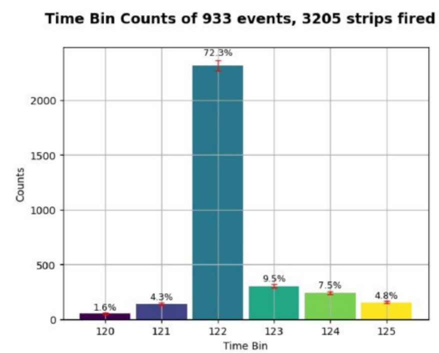
Our tests at ELI, Prague



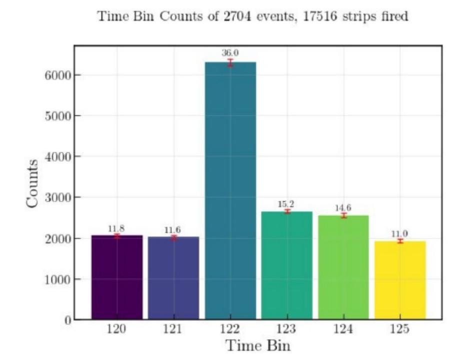
At ELI Beamlines in August 2025,
with our portable RPCs
(the same that I showed earlier)

Our tests at ELI, Prague

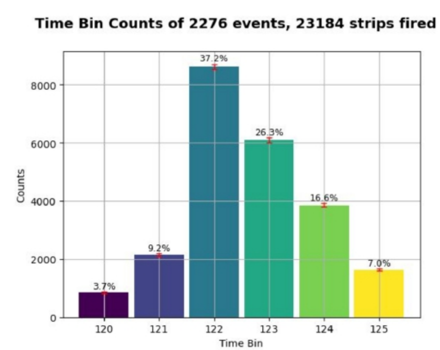
- Participated parasitically to two test beams in 2025
- Demonstrated that our portable RPCs are able to operate properly (and do tracking) in spite of the very unfriendly environment: significant **neutron background**, EM pulses, stray magnetic fields, etc.
- Next data taking in September 2026: we expect drastic bkg reduction by **triggering on laser beam coincidence**
- We aim at measuring muon production and learning optimal operating configuration



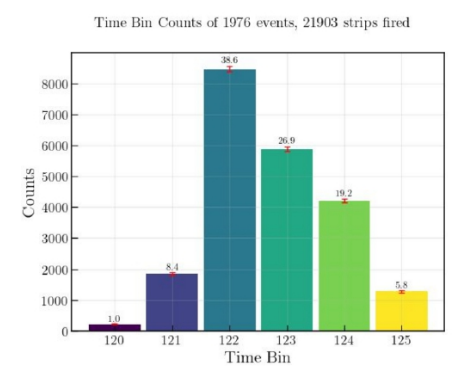
No beam (cosmics)



Beam on, no shielding



Beam on, lead shielding



Beam on, lead + polyethilene

S. Ikram et al., arXiv:2605.13118

Conclusion

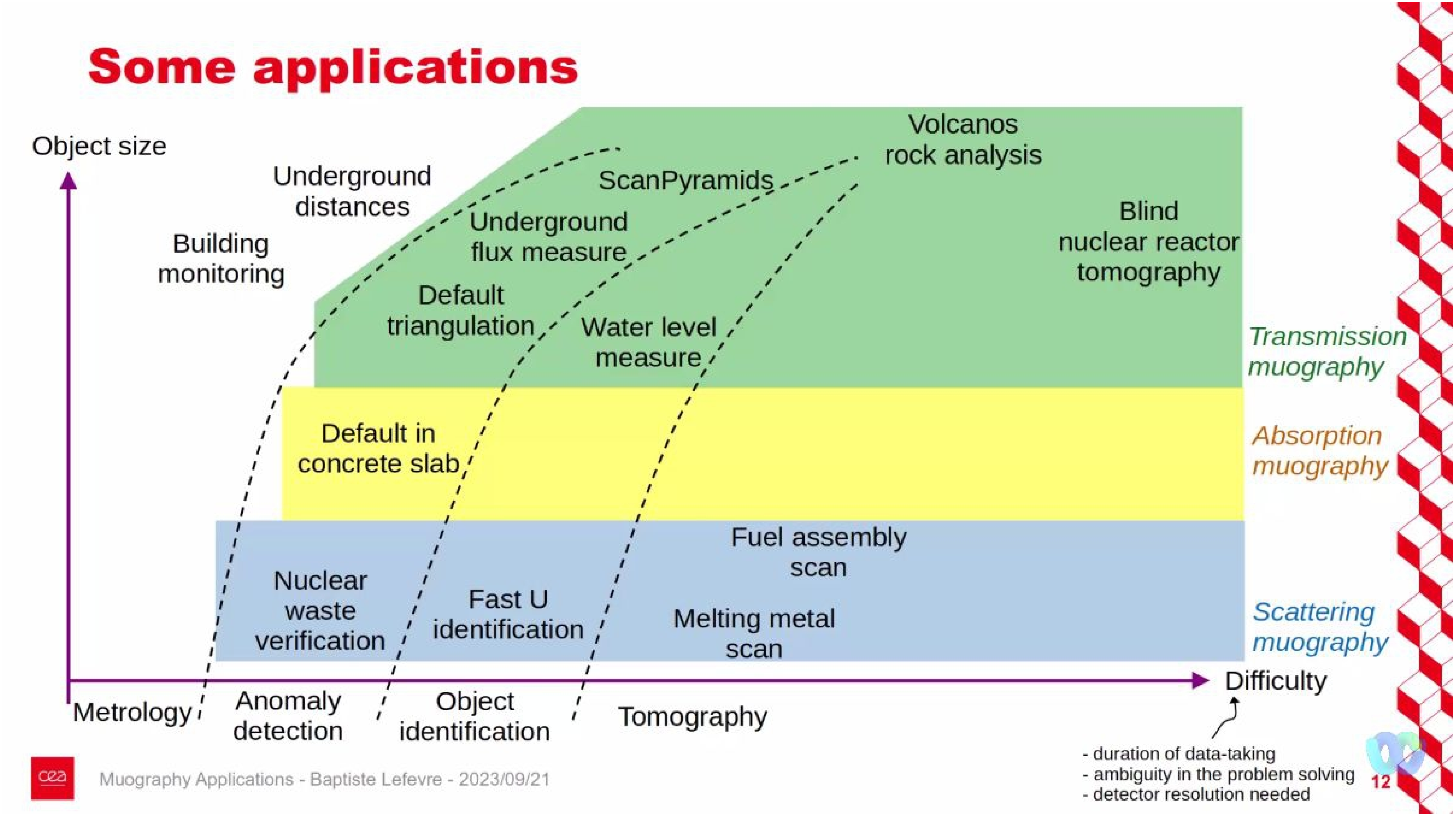
- Muography is booming
- Nice spin-off from fundamental research to societal impact
- Large potential for new teams to find some niche where to have impact
- Plenty of room for new ideas
- One has to be careful, though, to avoid the "*when one has a hammer everything looks like a nail*" effect
- Laser-driven μ sources are likely to be the next revolution in this area

Thanks!

- To you for your attention
- To *past* and **present** members of CP3-μ team:
  - **Eduardo Cortina, Pavel Demin**, *Sophie Wuyckens, Ishan Darshana, Samip Basnet, Marwa Moussawi, Raveendrababu Karnam, Vishal Kumar*, *Maxime Lagrange,* **Zahraa Daher, Sumaira Ikram, Alice Biolchini, Hamid Basiri, Gábor Nyitrai, Aitor Orio**

Backup slides

...and many more applications

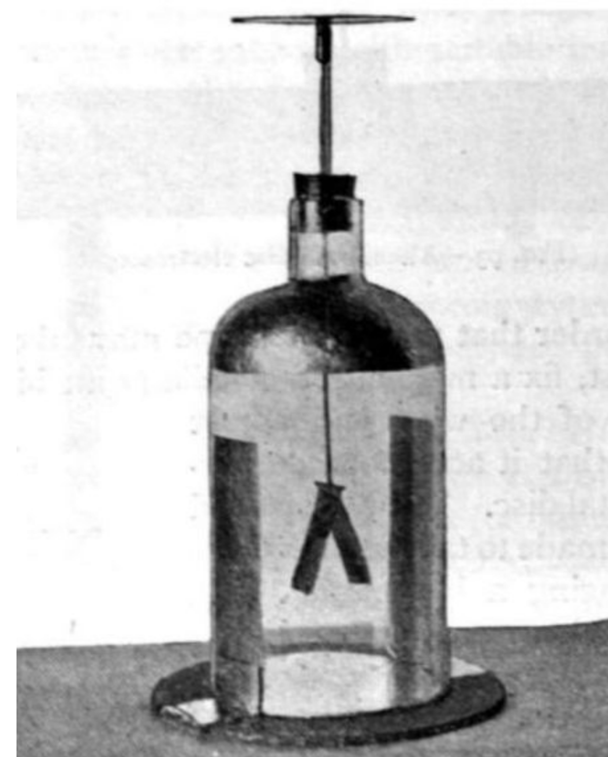


Slide stolen from B. Lefevre, CEA webinar, 2023

More than a century of cosmic rays

- Early 1900s: hypothesis that there is a natural background of ionizing radiation that discharges all the electroscopes
- General belief: mostly 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 very imprecise
- 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

...and almost a century of muons

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

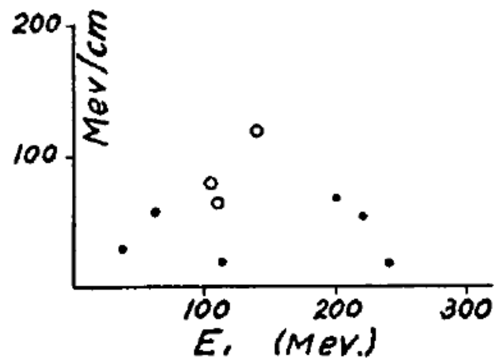
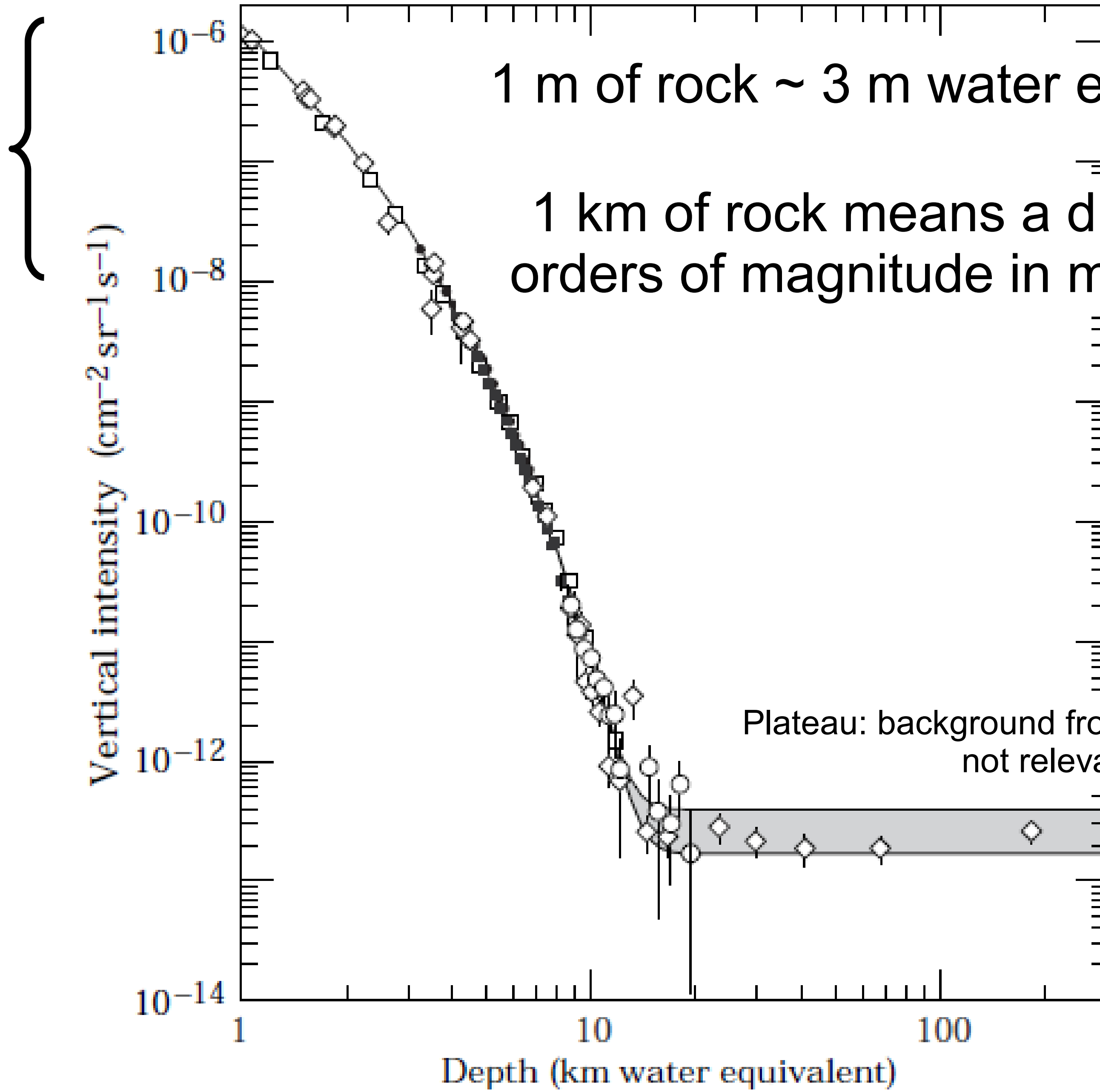


Figure 4: Early measurements of energy loss in 0.7-1.5 cm of Pb. Dots indicate single particles; circles, shower particles.

(And by the way, *who ordered that?*)



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

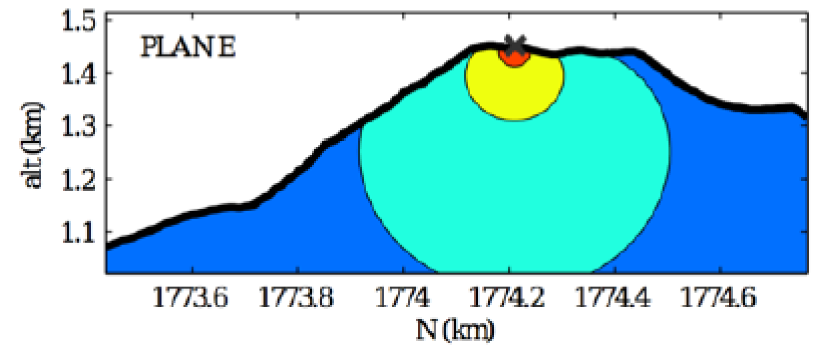
Source: Particle Data Group

Combination with "standard methods"

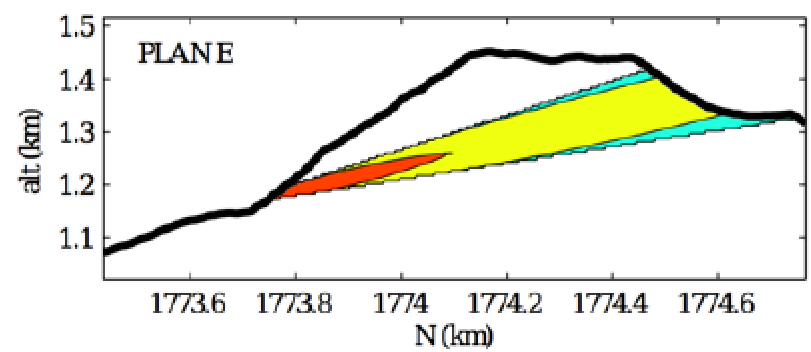
$$\mathbf{A} \quad \boldsymbol{\rho} \quad = \quad \boldsymbol{d}$$

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

Jourde *et al.* 2015



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



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

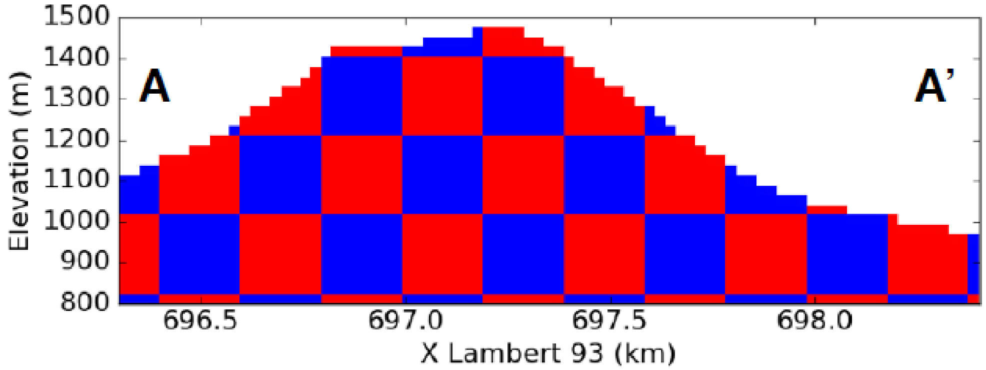
Most geoprospecting methods are non-linear inversion problems: solutions wildly degenerate, need strong constraints to converge, different assumptions lead to qualitatively different results

Muography: highly directional, breaks degeneracy of the other methods

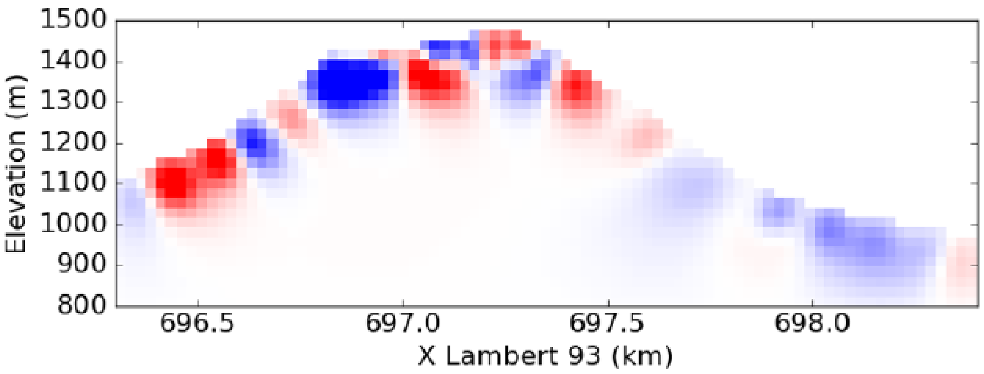
Formula from Anne Barnoud

Checkerboard test

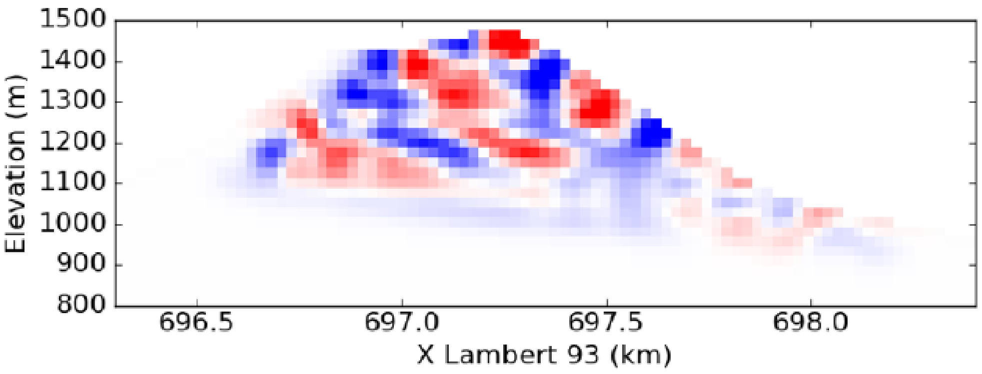
Simulated density pattern:



Red: high density
Blue: low density



Seen from gravimetric inversion



Seen from muographic inversion

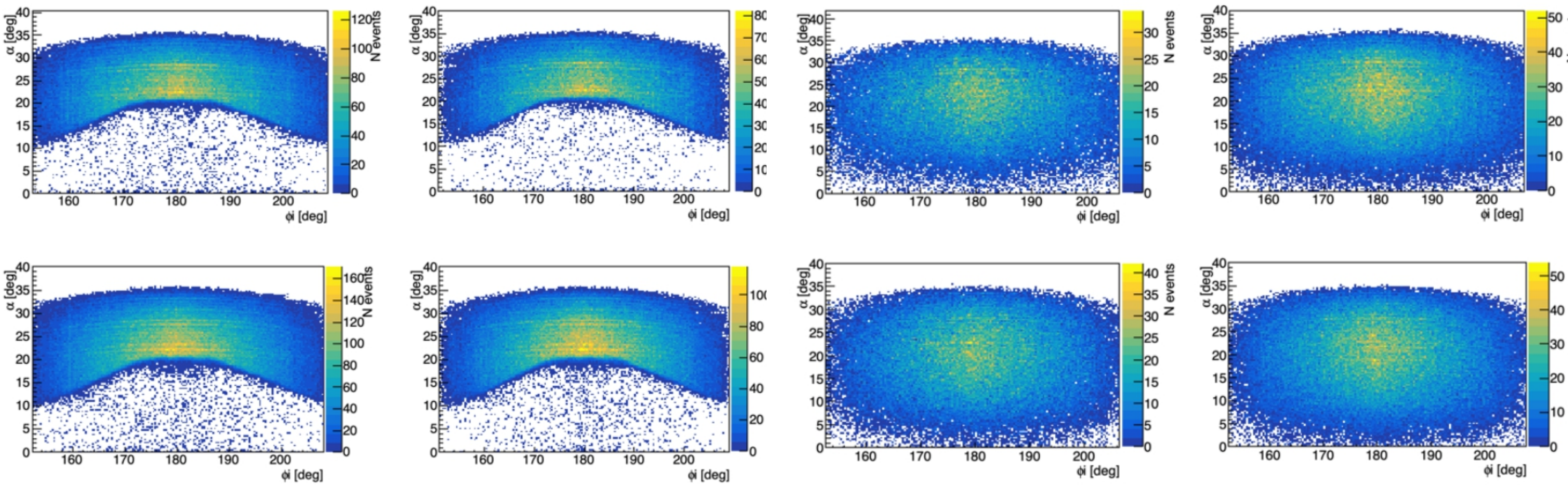
Study from Anne Barnoud

First MURAVES data

Vesuvius: **Free sky:**

NERO

ROSSO



WP 15° **WP 20°** **WP 15°** **WP 20°**

From Mariaelena D'Errico's PhD thesis, 2023

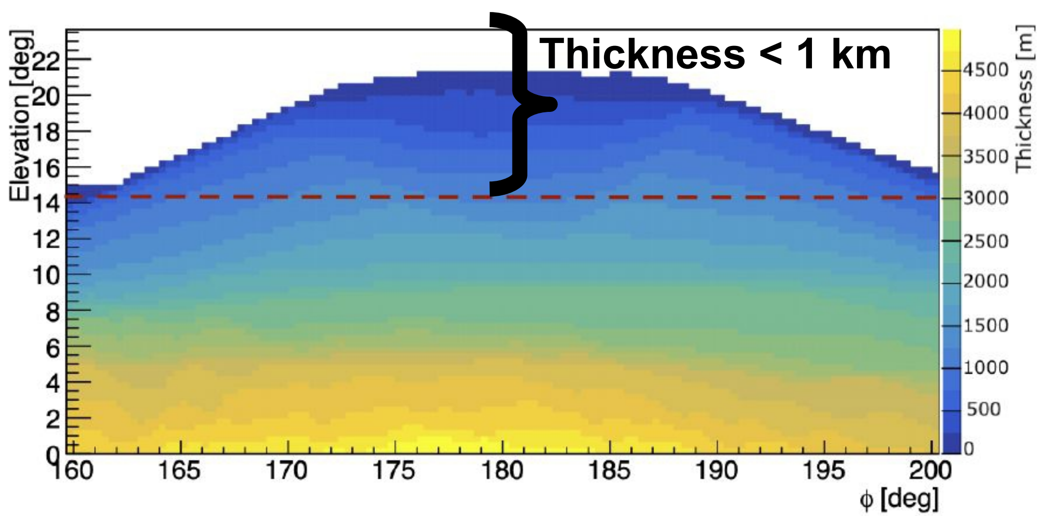
Dataset	Vesuvius	Free-sky
ROSSO wp 15°C	51 days	9.5 days
ROSSO wp 20°C	40 days	14.3 days
NERO wp 15°C	43 days	10 days
NERO wp 20°C	26 days	17 days

Prospects for resolution vs time

Δy	Δx	$\bar{L}$ = 500 m	$\bar{L}$ = 1000 m	$\bar{L}$ = 3000 m
9 m	9 m	8 months	3 years	100 years
9 m	26 m	3 months	1 year	33 years
9 m	130 m	15 days	2.5 months	6 years
26 m	130 m	5 days	1 month	2 years
52 m	260 m	2 days	6 days	16 months

Table 1: Exposure times expected to be required to measure the mean density with a 10 % statistical uncertainty for a set of values of the muon path length in the rock and of horizontal and vertical space resolutions Δx and Δy.

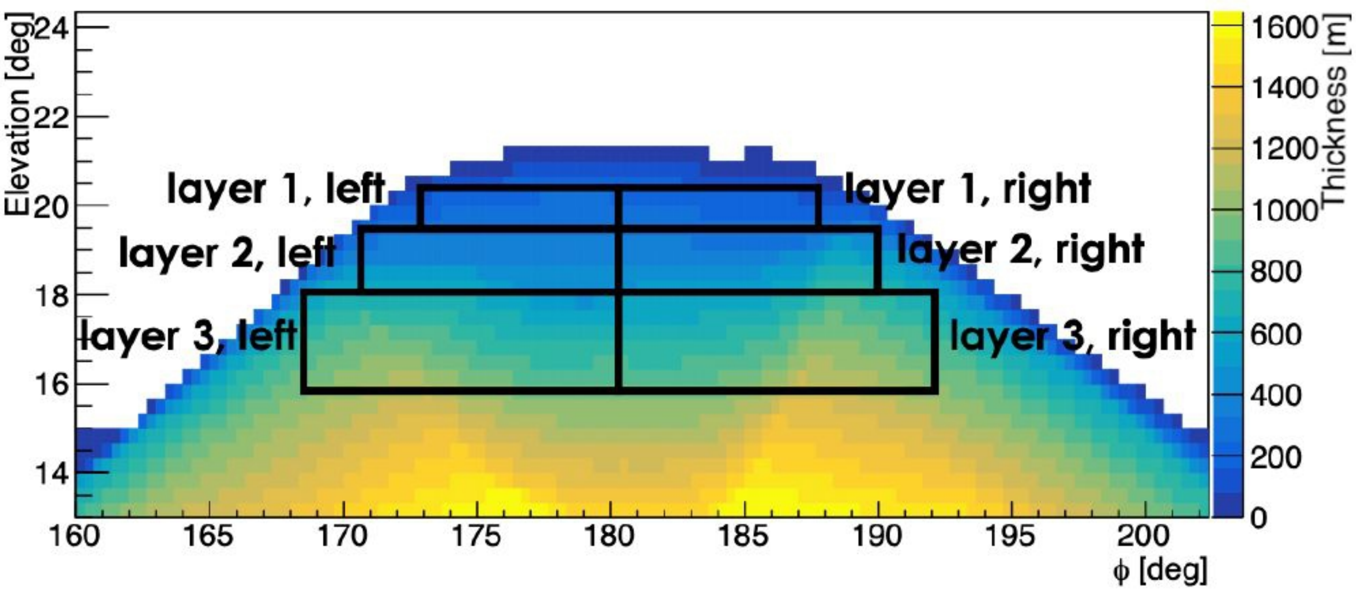
Elevation (deg)	Mean Thickness (m)
20-21	90
19-20	290
18-19	490
17-18	720
16-17	920
15-16	1100
10-15	1500
5-10	2700
0-5	4050

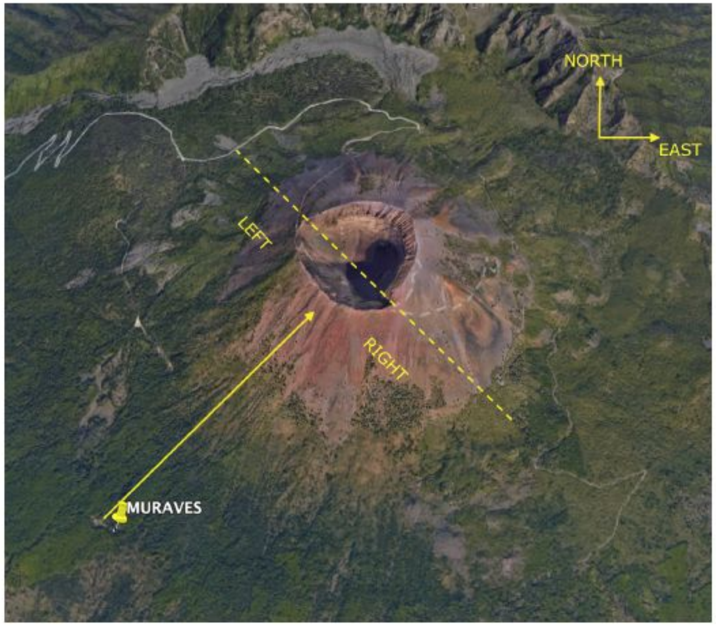


From: M. D'Errico et al. (MURAVES), J. Adv. Ins. Sci. 1, 273 (2022)

Right/left density asymmetry

- Even with such small statistics, we can do a first measurement of actual interest for volcanologists
- Focusing on the summit (< 1 km thickness)
- Most modeling uncertainties cancel out in the ratio



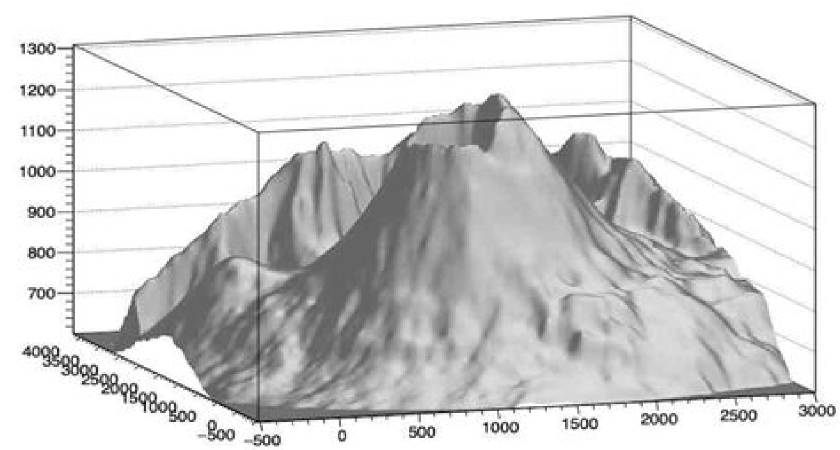


Results (raw)

	N events		Stat. unc. (%)	
Dataset	left	right	left	right
Layer 1				
ROSSO wp 15°C	428	439	0.05	0.05
ROSSO wp 20°C	346	323	0.05	0.05
NERO wp 15°C	231	258	0.05	0.05
NERO wp 20°C	128	258	0.07	0.06
Layer 2				
ROSSO wp 15°C	164	140	0.08	0.08
ROSSO wp 20°C	106	109	0.10	0.10
NERO wp 15°C	78	79	0.11	0.11
NERO wp 20°C	61	63	0.13	0.13
Layer 3				
ROSSO wp 15°C	61	76	0.12	0.11
ROSSO wp 20°C	58	63	0.13	0.13
NERO wp 15°C	47	47	0.14	0.15
NERO wp 20°C	27	30	0.19	0.18

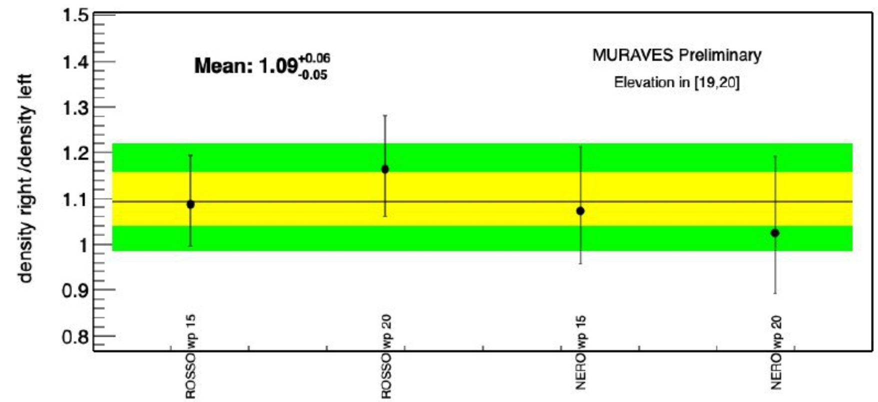
These raw numbers are then normalized by ***run duration*** and by ***thickness of rock*** traversed.

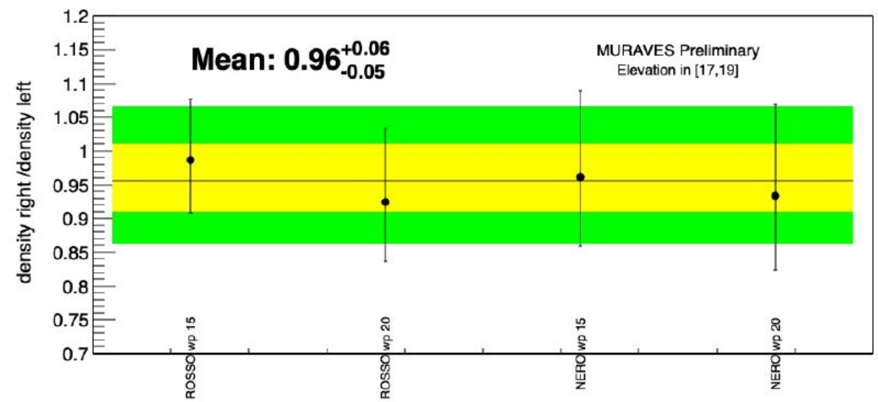
For the latter, we used a Digital Terrain Model provided by INGV (data from Vilardo et al., Journal of maps, 9(4):635–640, 2013)

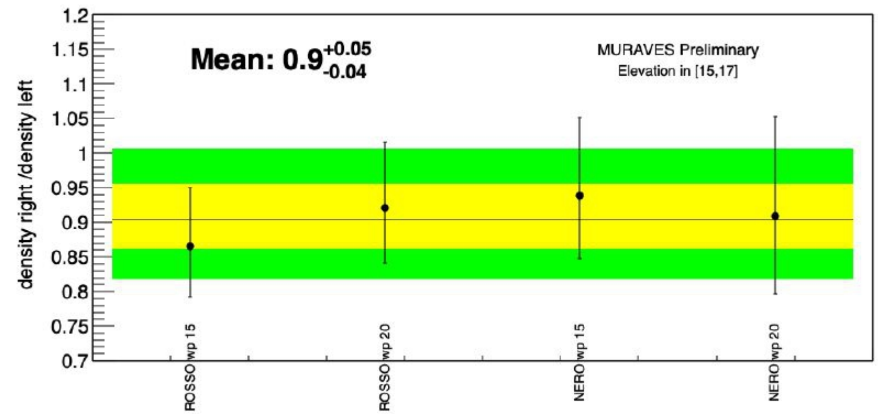


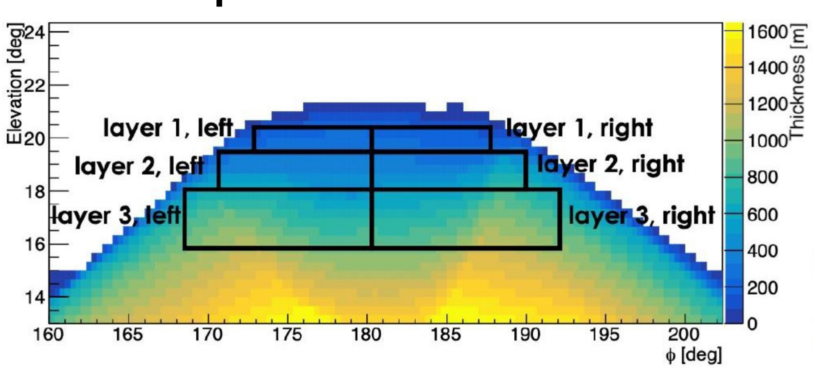
Right/left density asymmetry results

- These four independent samples agree within 1σ
- We combine them under assumption of statistical independence
- Indication (1.5σ) of density larger on the right than on the left at high quota
- But relationship inverts at lower quota

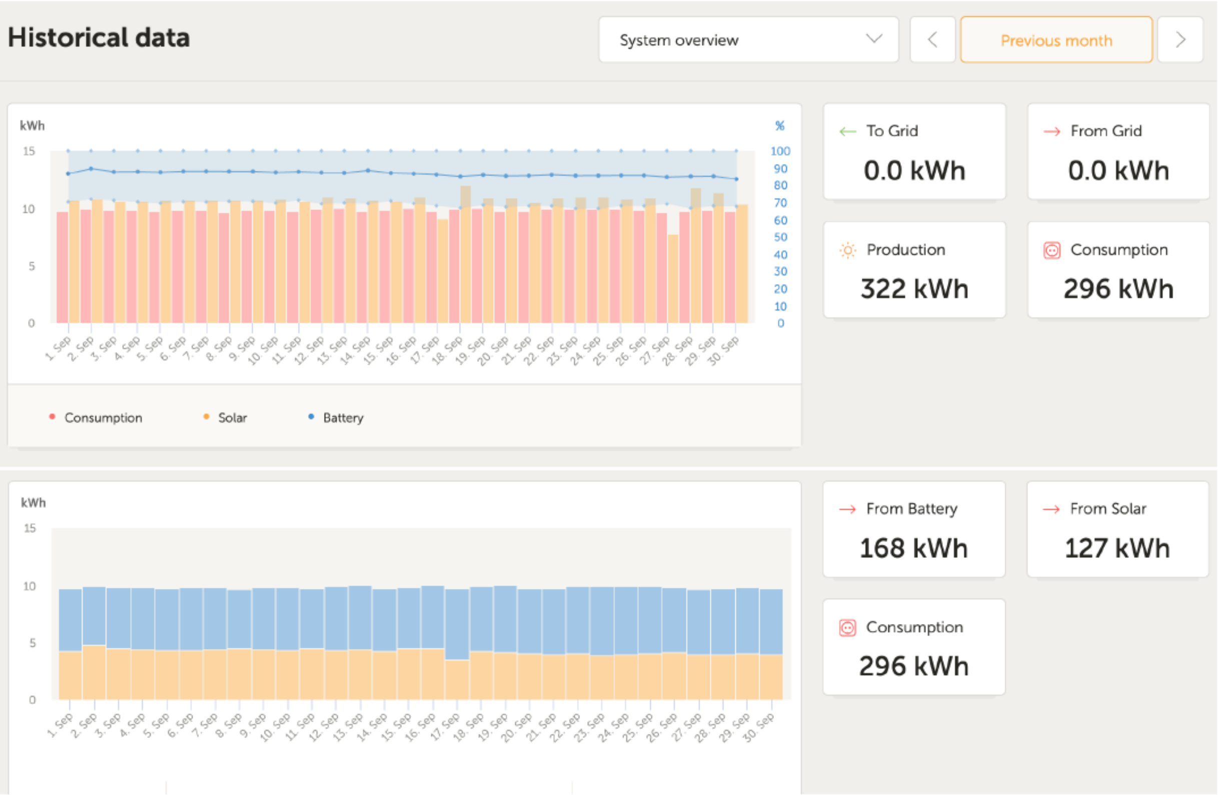




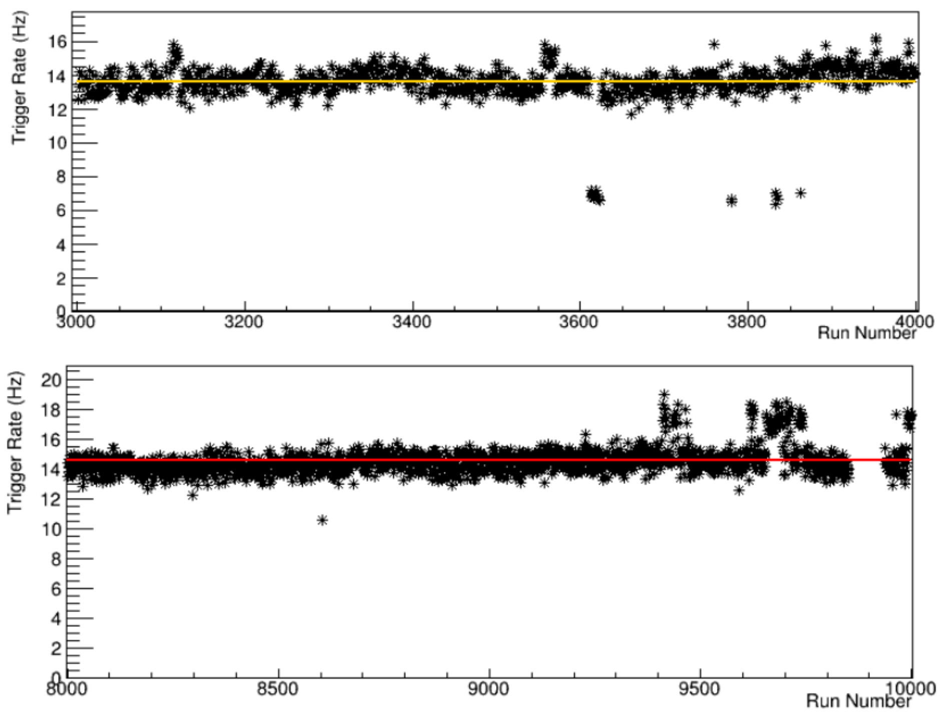




Power consumption

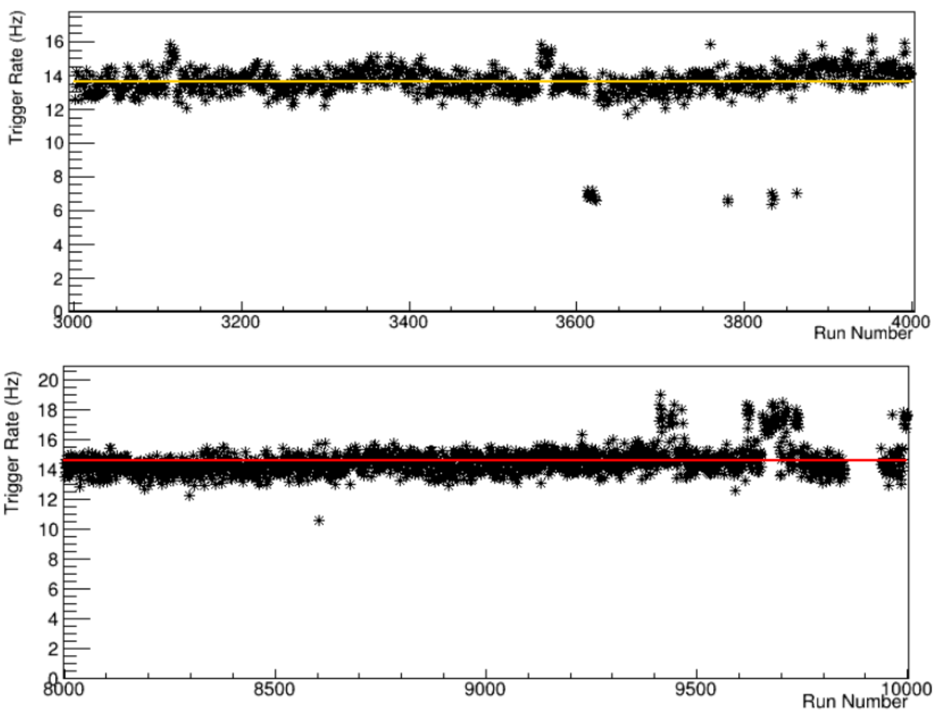


Rate stability



Trigger rate vs run number for NERO (top) and ROSSO (bottom)

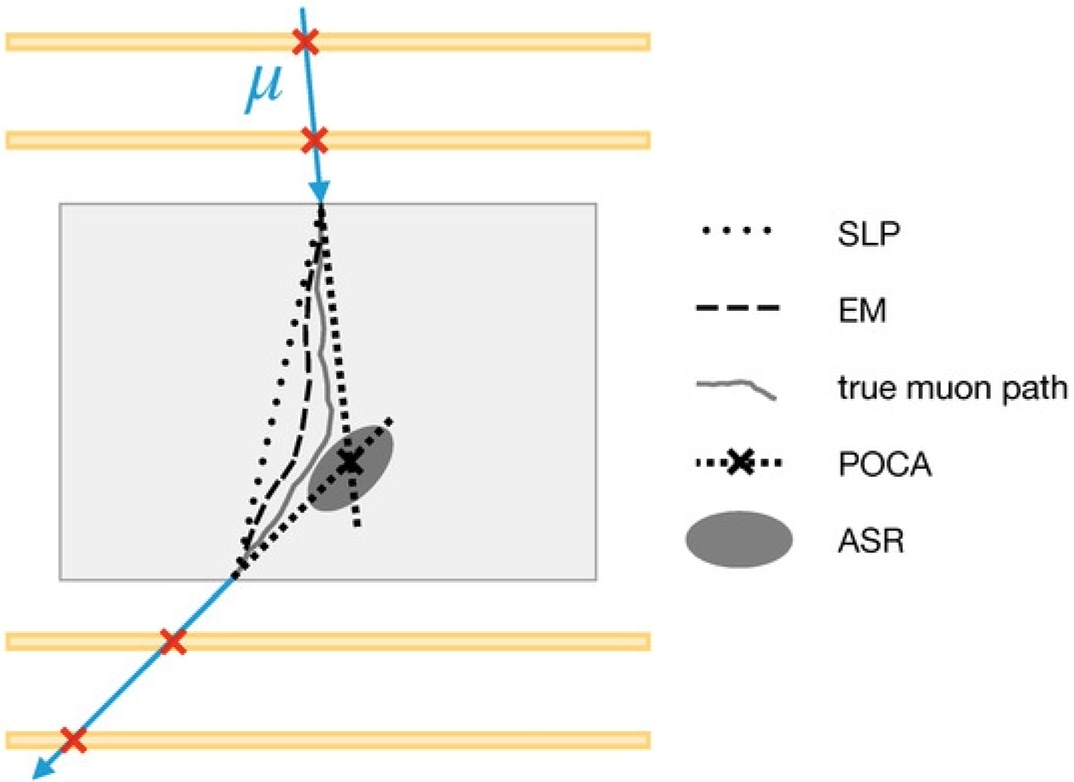
Rate stability



Trigger rate vs run number for NERO (top) and ROSSO (bottom)

Where did the muon scatter?

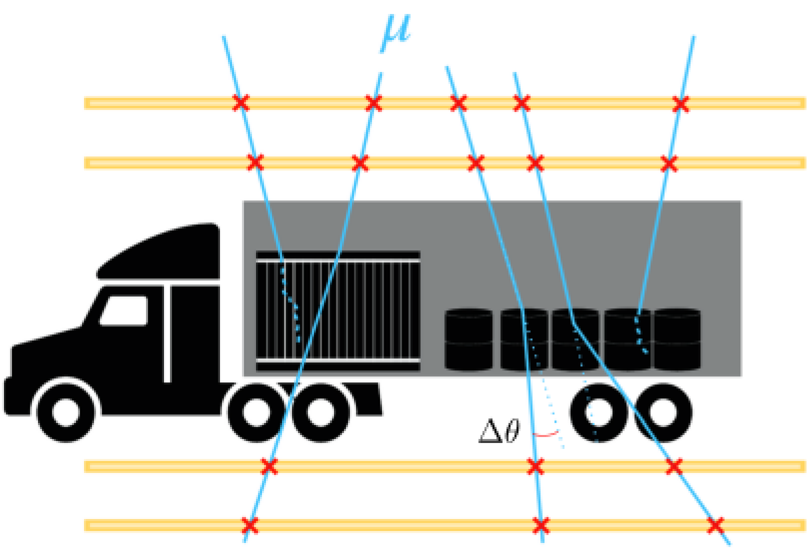
From: S. Barnes et al., Instruments 7 (2023) 13

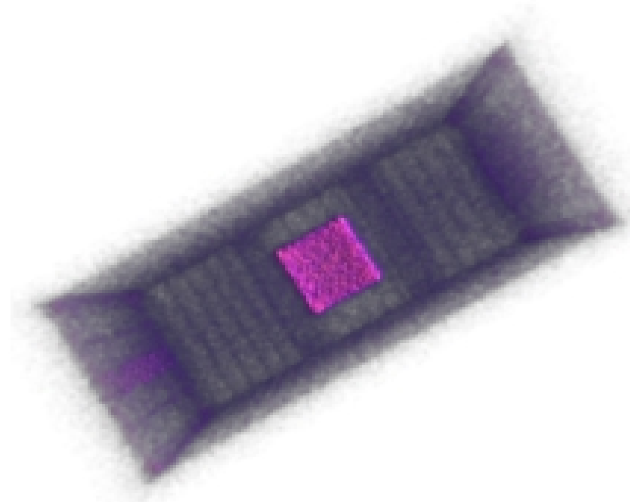


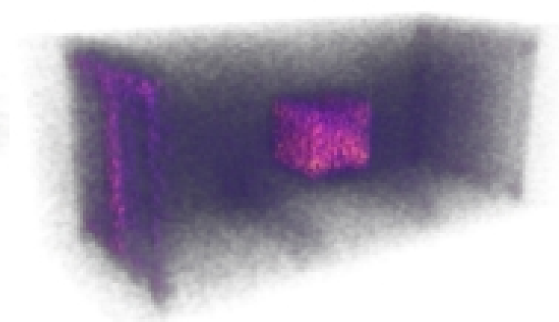
- Most popular method: point of closest approach (POCA)
- It implicitly assumes there is only one scattering per muon
- But this approximation only holds for thin targets
- Variants include: straight line path (SLP), angle statistic reconstruction (ASR), expectation maximisation (EM)

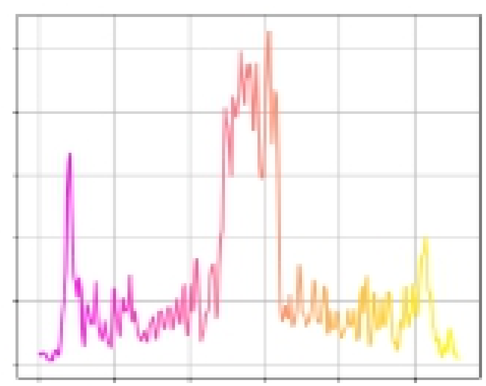
Coulomb scattering and cargo inspections

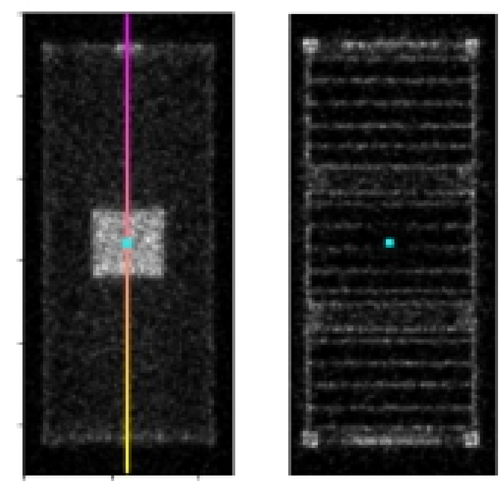
From M. Lagrange's PhD thesis





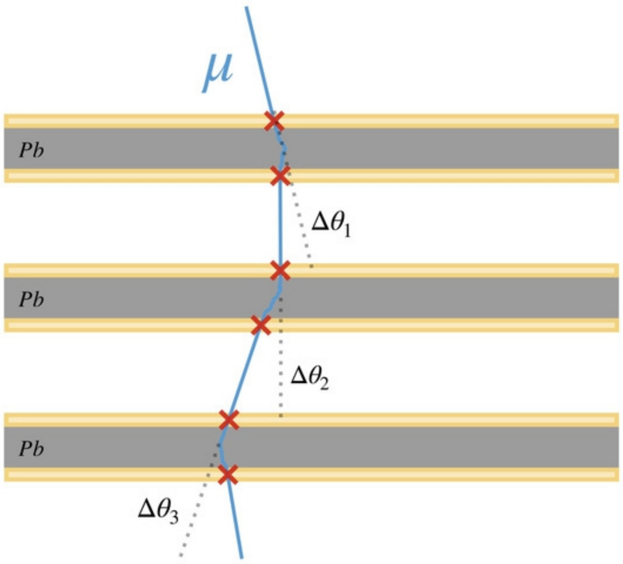




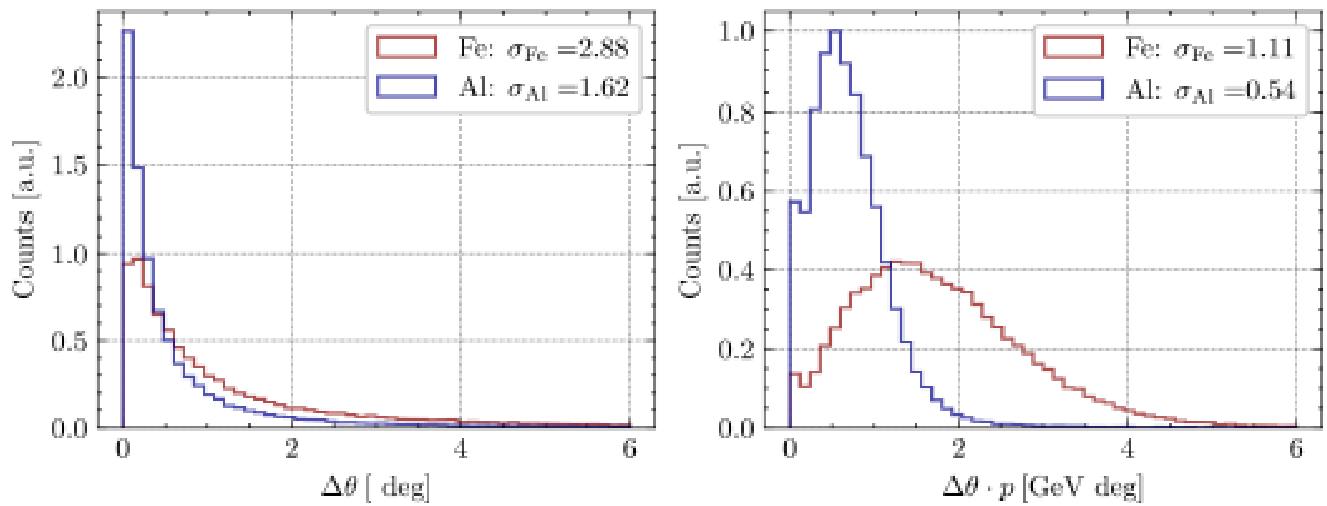


- Simulated example: 1 m³ iron cube in a container
- POCA reconstruction
- 30' data acquisition with a muon portal

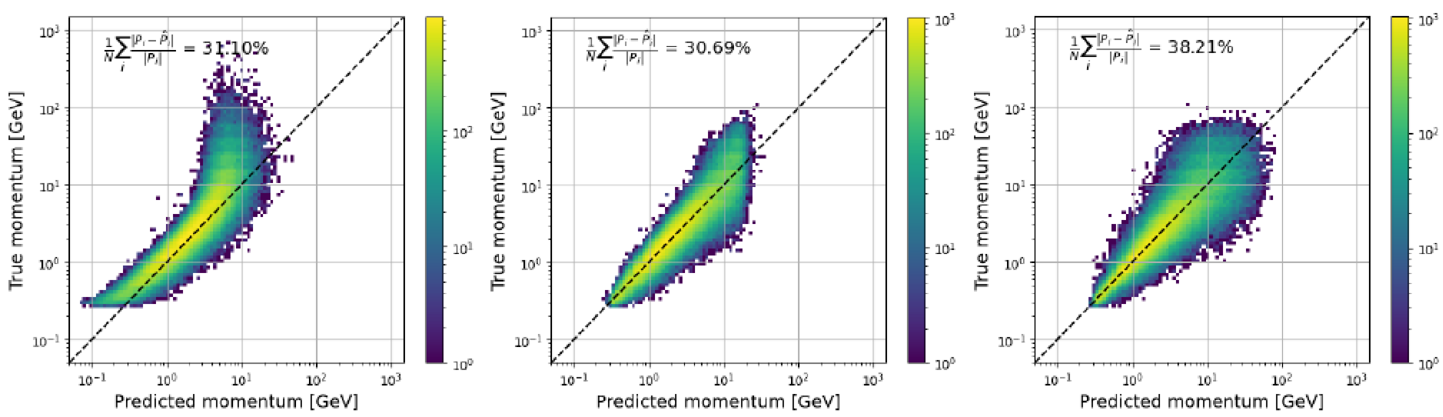
Measuring momentum (at low cost)



Plot from M. Lagrange's thesis



Simulation study, 1mm hit resolution, in: M. Lagrange & F. Bury, Particles 8 (2025) 43

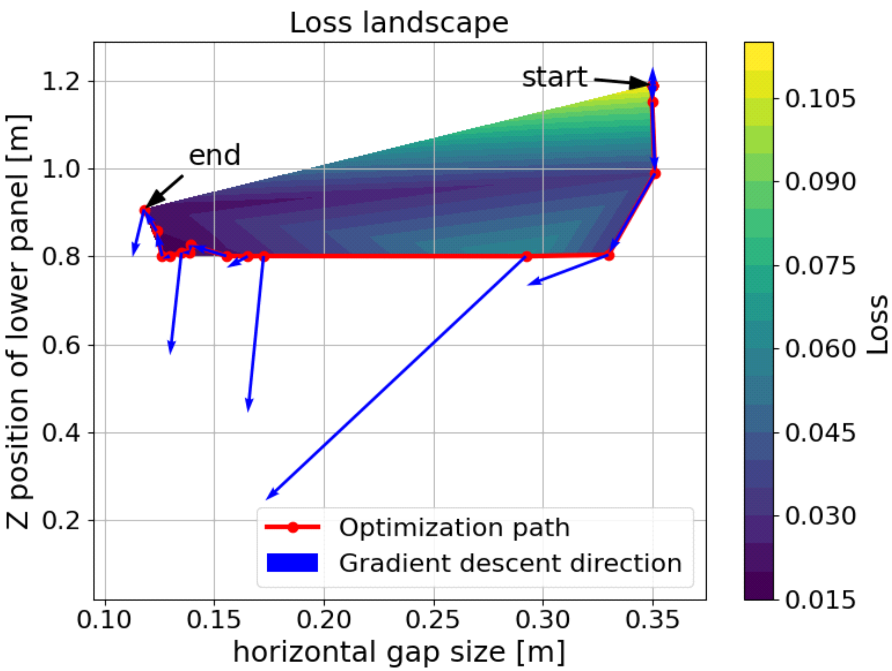


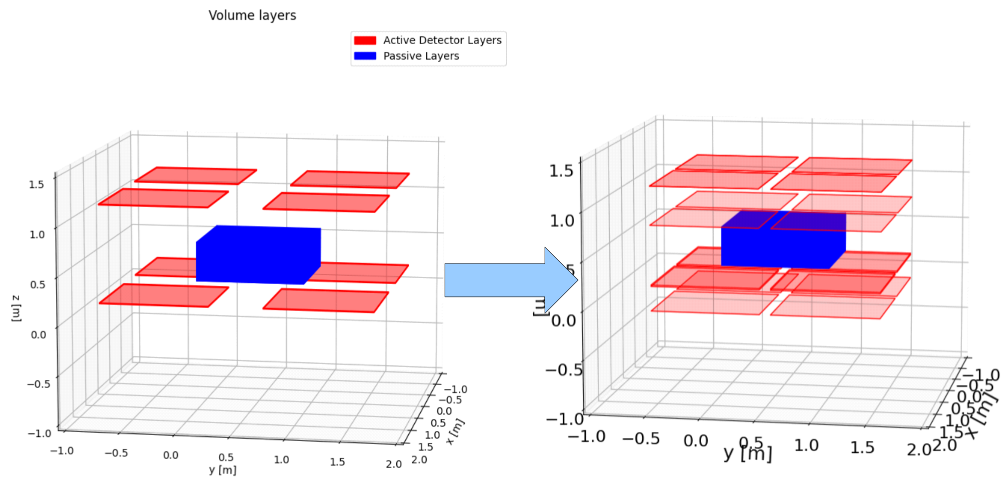
Just using scattering angle

DNN

Transformer

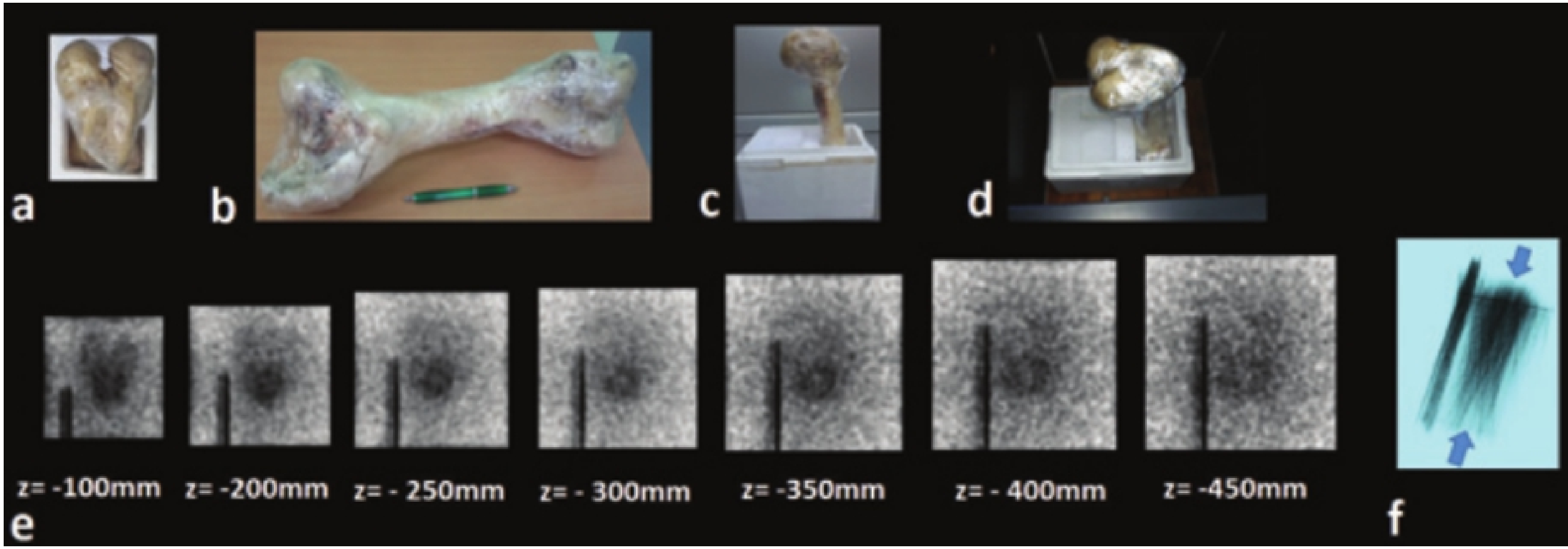
TomOpt optimization loop

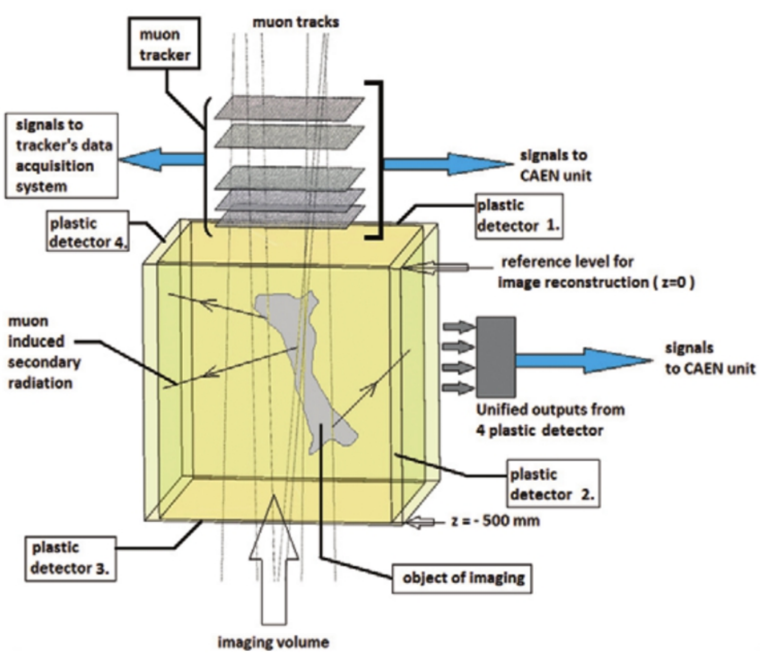




$$a_{n+1} = a_n - \gamma \nabla \mathcal{L}(a_n)$$

From:
G.C. Strong et al., Mach. Learn.: Sci. Technol. 5 (2024) 035002
Z. Daher et al., arXiv:2507.10253 [physics.ins-det]





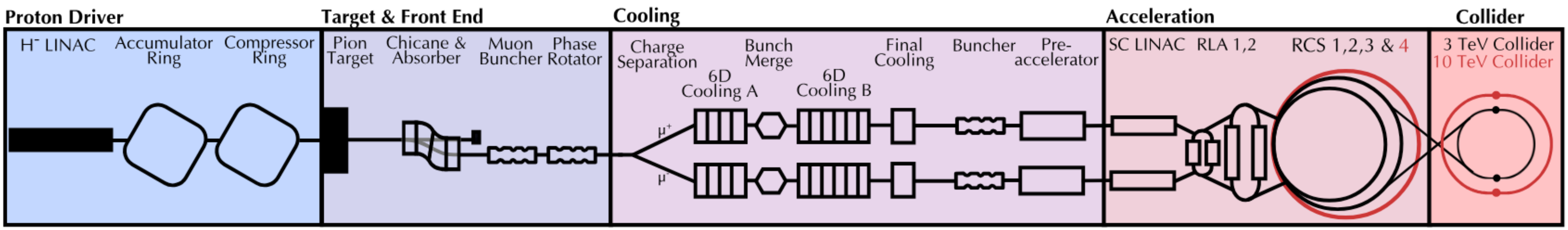
Someone actually thought about applications to organic material:
D. Mrdja et al., EPL, 116 (2016) 48003
G. Galgóczi et al., JINST 15 (2020) C06014

A cow's femur has been successfully imaged by muography (complemented with analysis of secondary gammas and electrons) with ~4 days of data.

But it is difficult to find use cases, for organic material, where no other method can give sharper images in less time!
(Laura Longo's suggestion: **paleophorensics**)

How to make muons

- Typical way: $p + A \rightarrow X + \pi^{\pm}$, followed by $\pi \rightarrow \mu\nu$



From: Accettura et al., arXiv:2504.21417 [physics.acc-ph] (ESPP 2025)

- Low energy, high rate:
  - Single pion production (E_p>280 MeV): $p+p(n) \rightarrow p+n(p)+\pi^{+(-)}$
  - Double pion production (E_p>600 MeV): $p+p \rightarrow p+p+\pi^{+}+\pi^{-}$


ISIS, Oxfordshire, UK


Paul Scherrer Institute, Zurich, Switzerland

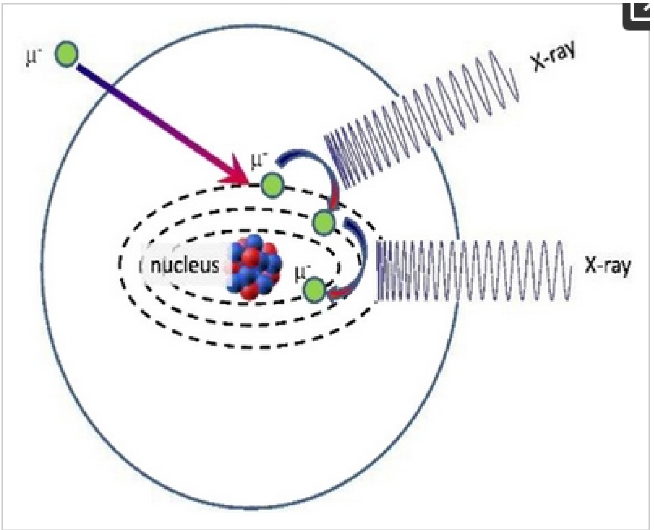

MuSIC, Osaka, Japan

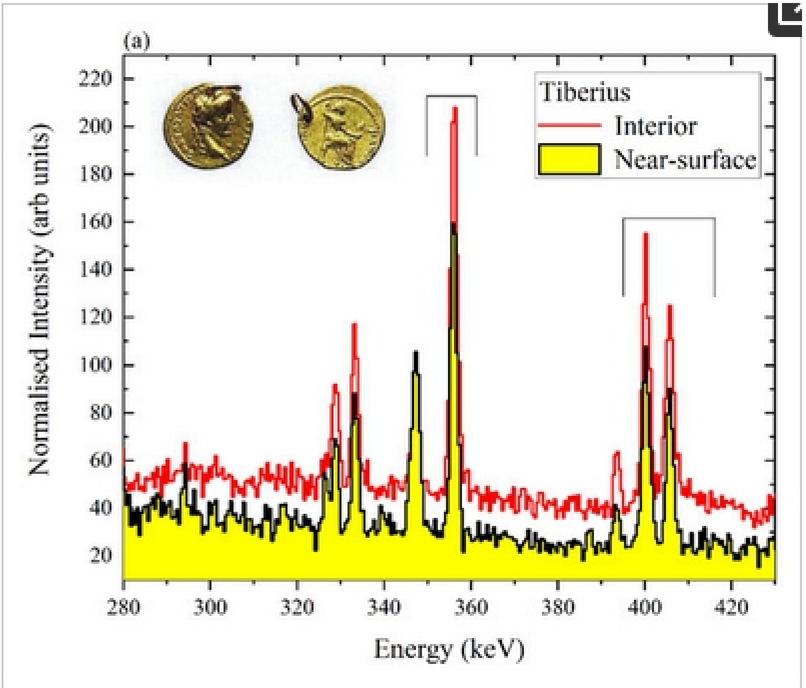

TRIUMF, Vancouver, Canada

J-PARC, Ibaraki, Japan

Another way to (≈)image with muons

- Muonic Atom X-ray Emission Spectroscopy (μ-XES) or Muon Induced X-ray Emission (MIXE)
- Conceptually similar to XRF (photons), PIXE and PIGE (protons), but MIXE probes deeper in the material
- Recently used in archaeology (coins, arrows, etc.)
- **Not appropriate for bulky objects**, because of X-ray absorption





From: M. Cataldo et al., Appl. Sci. 12 (2022) 4237

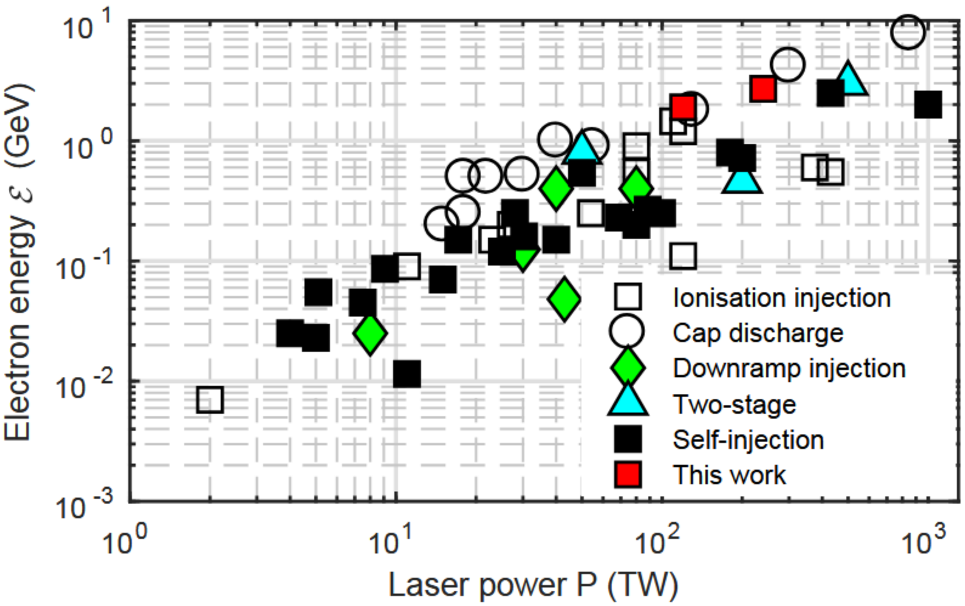
Collaboration with ELI

- Extreme Light Infrastructure (ELI): high-power laser infrastructure in 3 Eastern EU countries
- ELI Beamlines, near Prague, specialises in high-energy femtosecond / petawatt-class lasers with high repetition
- Also interested in compact (eventually portable) muon sources for imaging or other purposes

State-of-the-art LPAs

Depending on driver laser, very different beam parameters can be generated

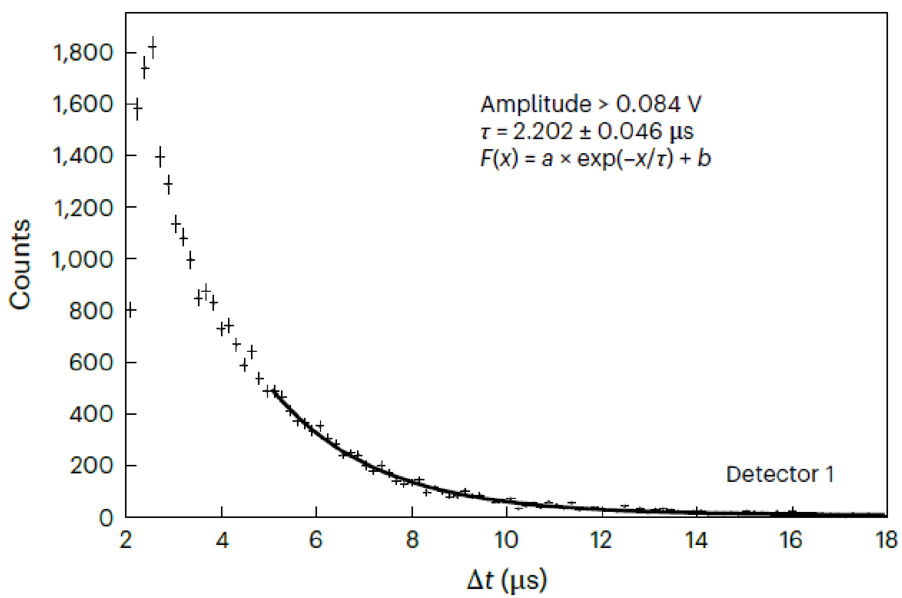
- Rep rate: ~1 Hz to 1 kHz
  - Small laser can fire more often!
- Laser peak power: ~1 TW to 10 PW
- Single stage energy gain: few MeV to 8.6 GeV
- Relative energy spread: down to 0.5%
- Peak current: up to few kA
- Normalised emittance: sub-micron
- Plasma length: from 0.1mm to 30 cm
- Stability: down to a few percent
- Efficiency: up to 30% laser-to-electrons

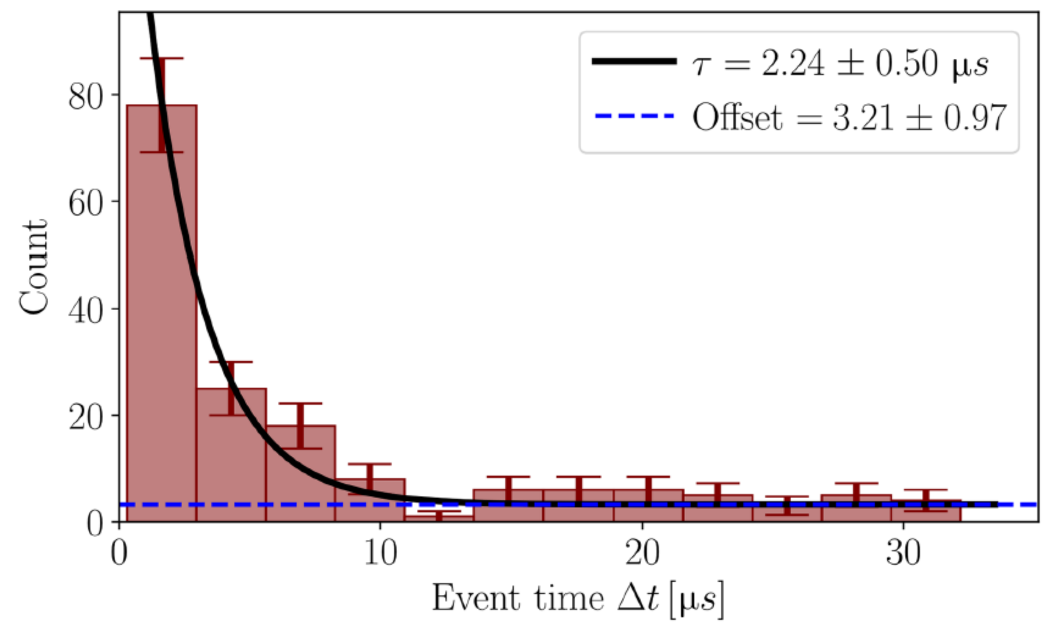


Slide stolen from Kristjan Põder (DESY), link

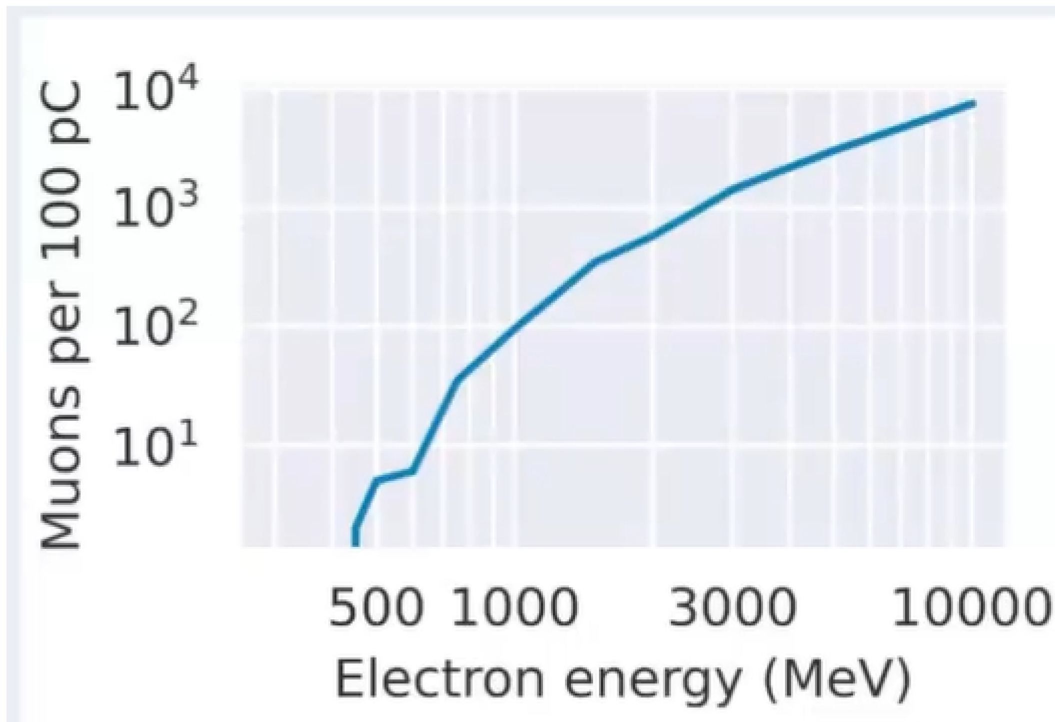
How to make muons at LPAs

- Bethe-Heitler: $e+A \rightarrow e+\gamma^{(*)}+A \rightarrow e+A+\mu^+\mu^-$



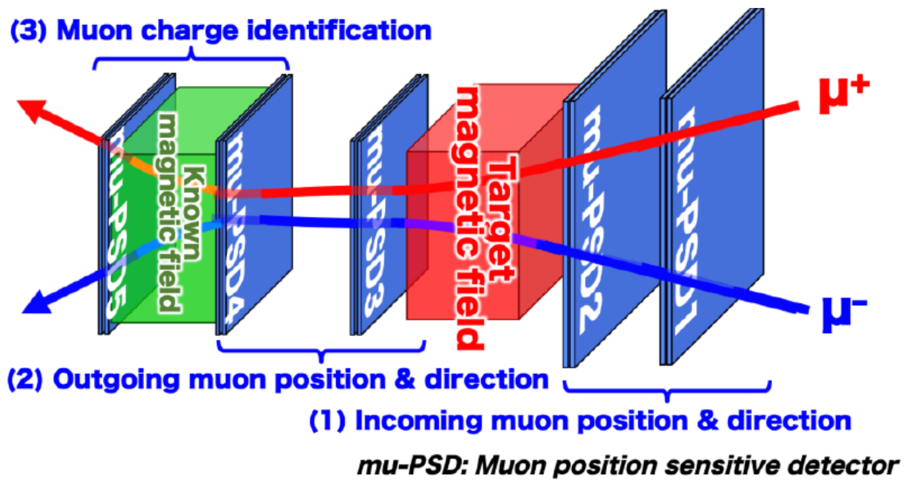


Recently demonstrated at LPAs in China and USA:
F. Zhang et al., Nature Physics volume 21, pages 1050–1056 (2025)
D. Terzani et al., DOI: Phys. Rev. Accel. Beams 28, 103401 (2025)
(Both teams used the lifetime plot to argue that they see actual muons)

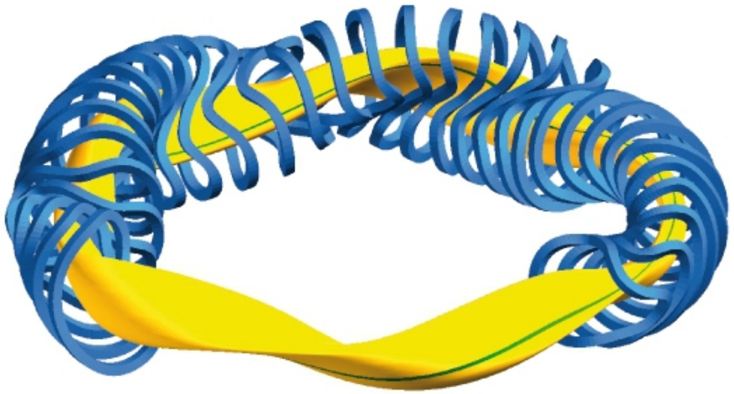


From Andi Hektor

Magnetic fields



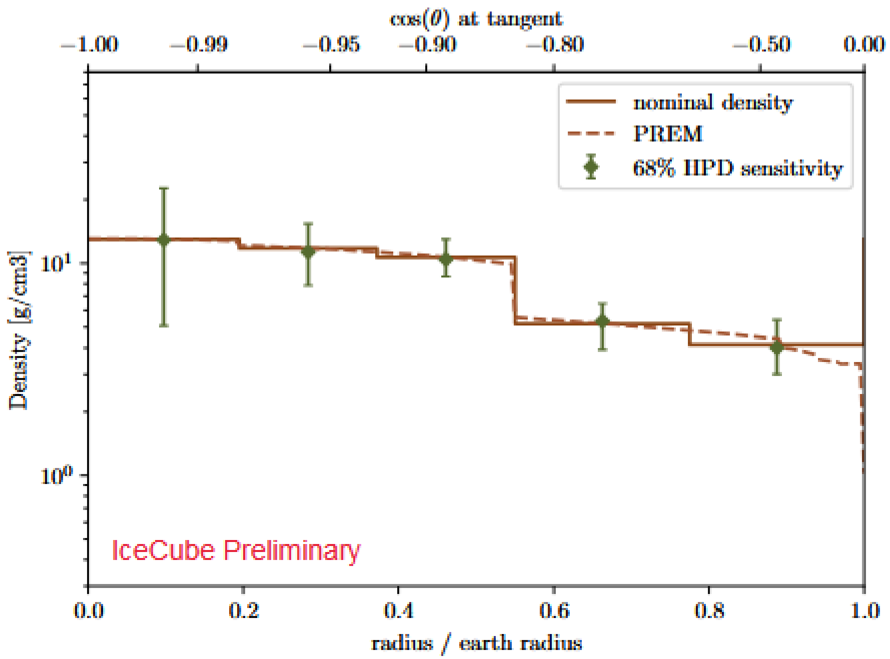
Stellarator field, from wikipedia:

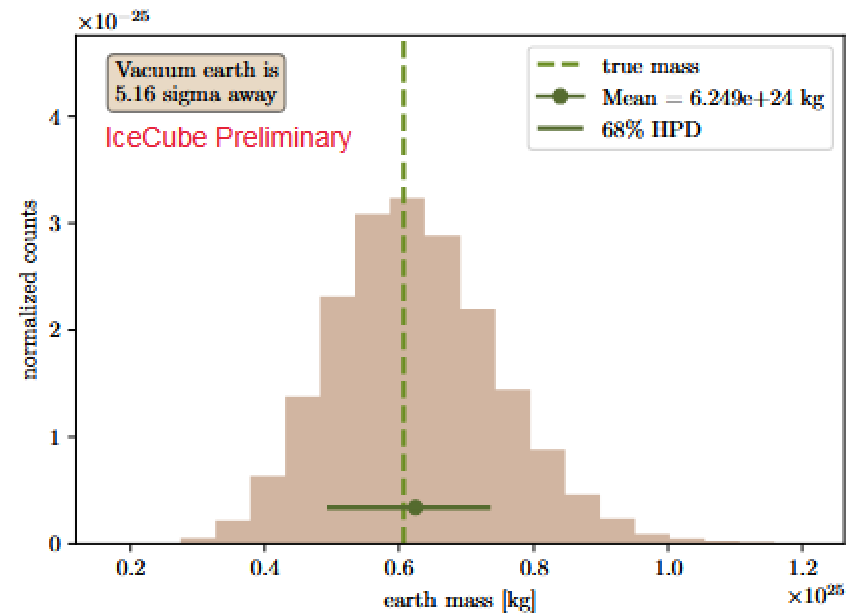


- Deterministic deflection, not stochastic diffusion (still, complex inversion problem)
- Promising use case: *in situ* monitoring of magnetic field in **nuclear fusion reactors**
- Particularly *stellarators* (which are having a resurgence lately)
- Standard methods (based on Hall probes) rely on model-dependent extrapolations
- They become less and less sustainable as EM fields and neutron backgrounds grow
- Particle-based method: small accelerator shooting heavy ions through the plasma
- When fusion reactors will be a reality, **simple methods will not work, and the best methods will not be simple**
- This method is of intermediate complexity, and complementary to standard ones

H. Basiri et al., J. Adv. Inst. Sci., 1 (2022) 277
T. Kin et al., J. Adv. Inst. Sci., 1 (2023) 297
T. Kin, E. Cortina Gil, A. Giammanco. **International Patent** Number WO/2023/031265

Neutrinography





From: Alex Wen (IceCube), PoS-ICRC2025-1211, arXiv:2507.09763 [astro-ph.HE]