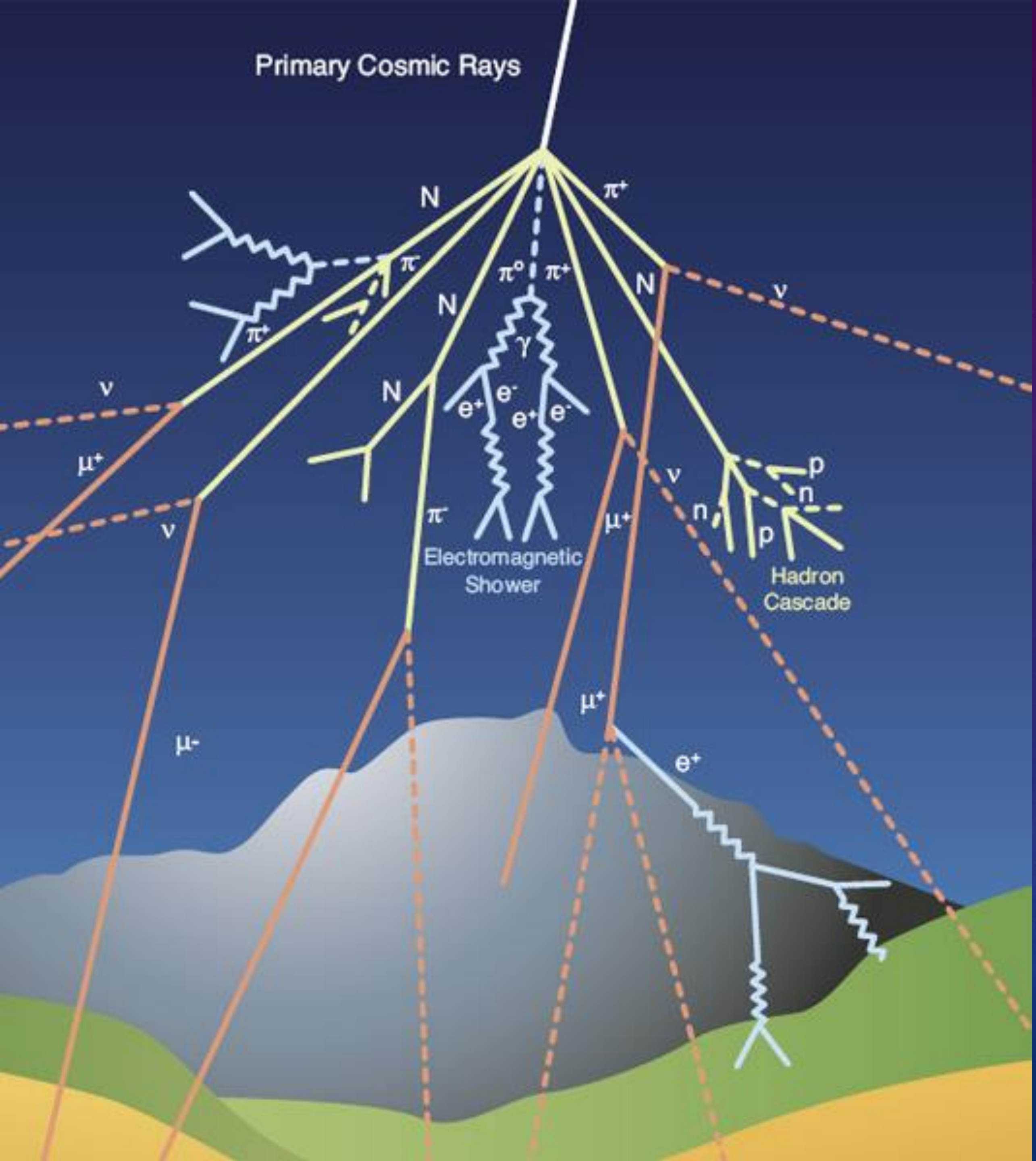
MUOGRAPHY

BENCE RÁBÓCZKI

EÖTVÖS LORÁND UNIVERSITY



ORIGINS AND BASIC PROPERTIES OF MUONS

- Muons are part of the secondary cosmic radiation

  $\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

- Their flux is roughly constant (galactic and extragalactic source, not solar!)
- They have the same charge as an electron, but ~200 times times it’s mass
- Their lifetime is 2.2 microseconds, allowing most of them to penetrate the surface
- Their mean energy is ~4 GeV

WHAT MAKES MUONS IDEAL FOR IMAGING?

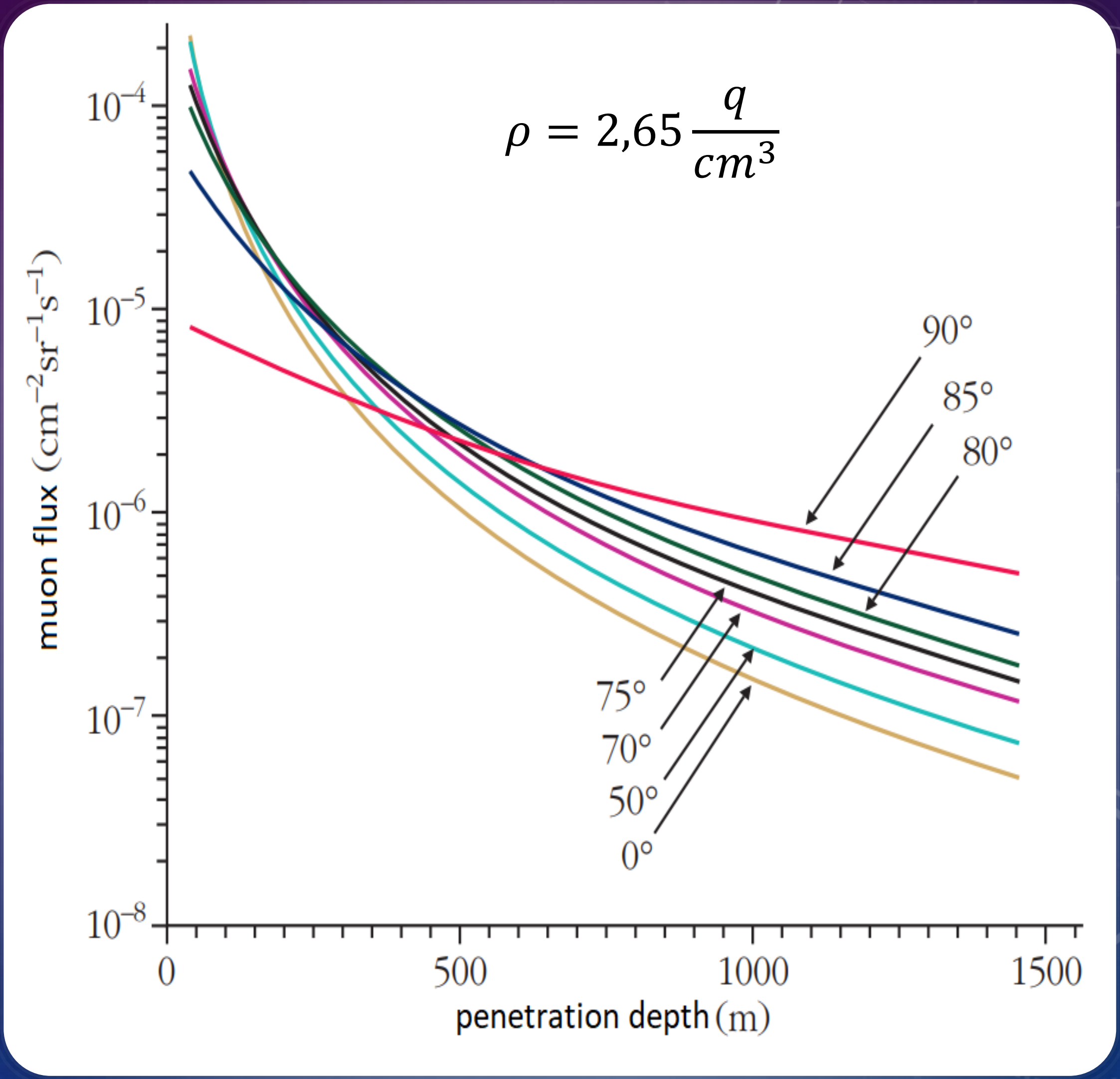
- When muons pass thorugh a medium they lose energy (Bethe-Bloch)

$$\left\langle -\frac{dE}{dx}\right\rangle = K\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2Q_{max}}{I^2} - \beta^2 - \frac{\delta}{2} + \frac{1}{8}\frac{Q_{max}^2}{(\gamma Mc^2)^2}\right] + \Delta\left|\frac{dE}{dx}\right|$$

- On large scale the amount of energy lost depends on the density and the thickness of medium

- They suffer little to no scattering even on heavier elements, such as lead

→ ideal candidates for an upscaled version of Roentgen tomography

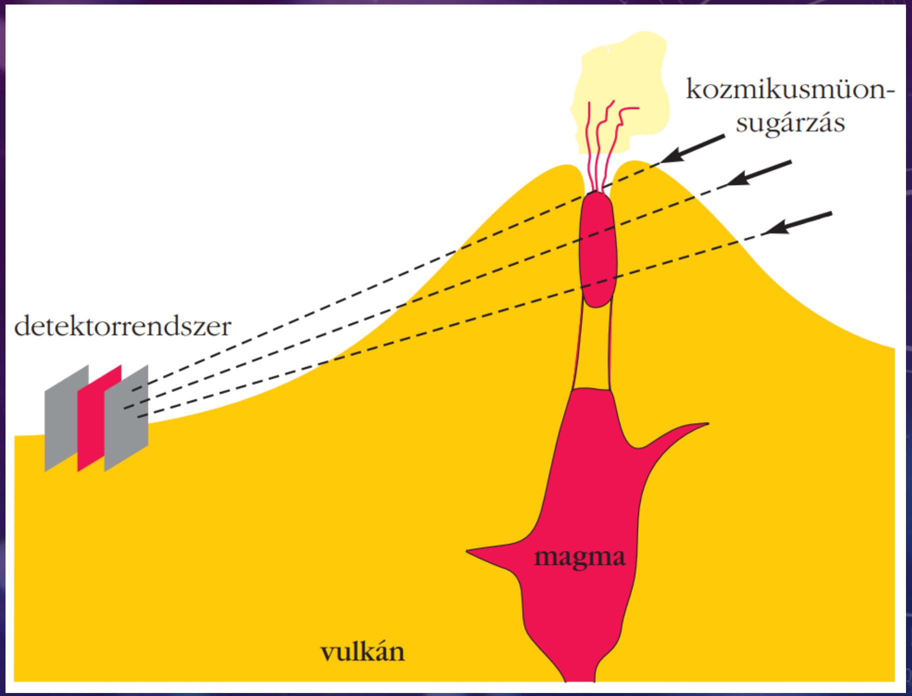


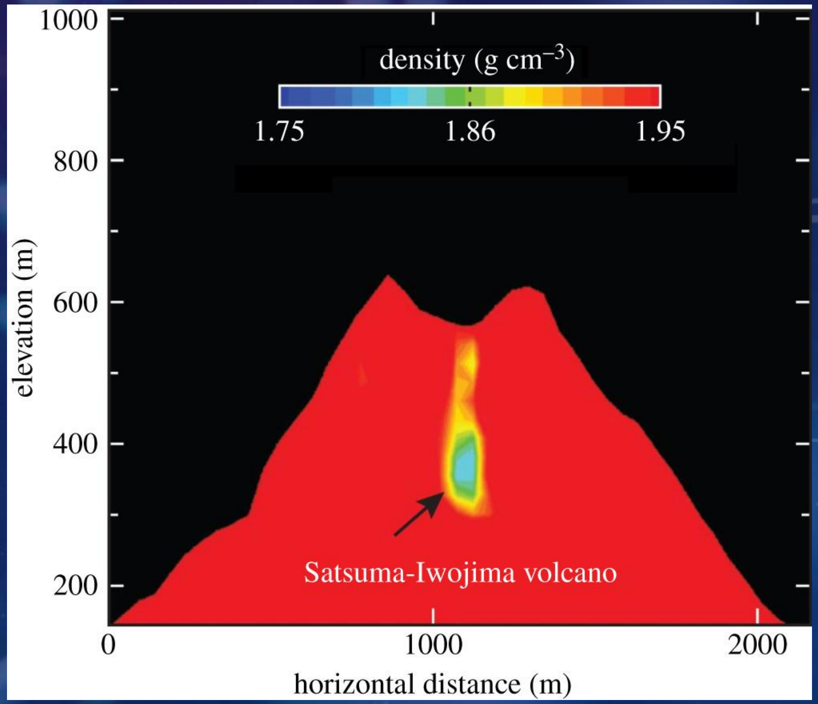
CREATING MUOGRAPHIC IMAGES

- We record the trajectory of muons that pass through the observed body in 3D
- We filter background effects from the data
- We calculate the muon flux for all angles

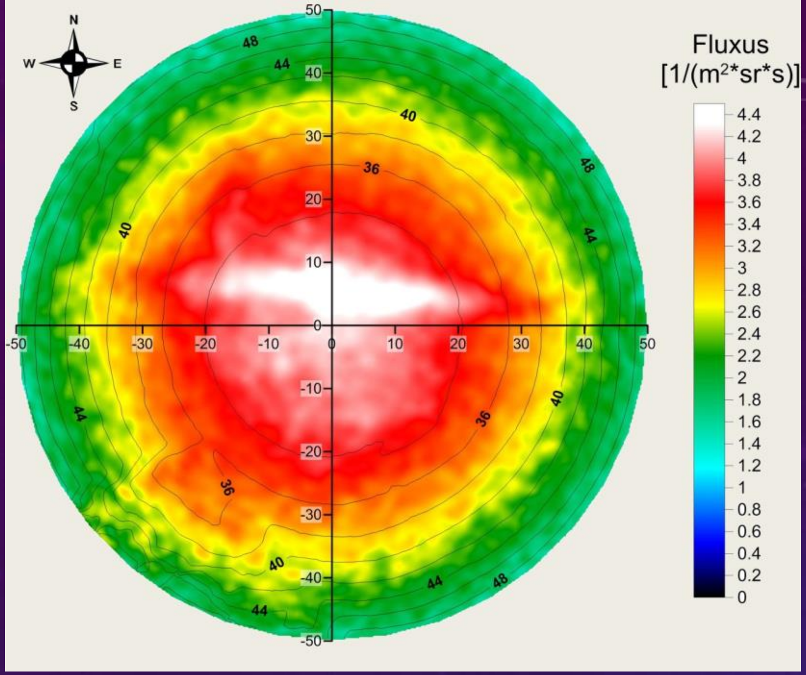
$$\Phi = \frac{N}{A \cdot \alpha \cdot \epsilon \cdot t}$$

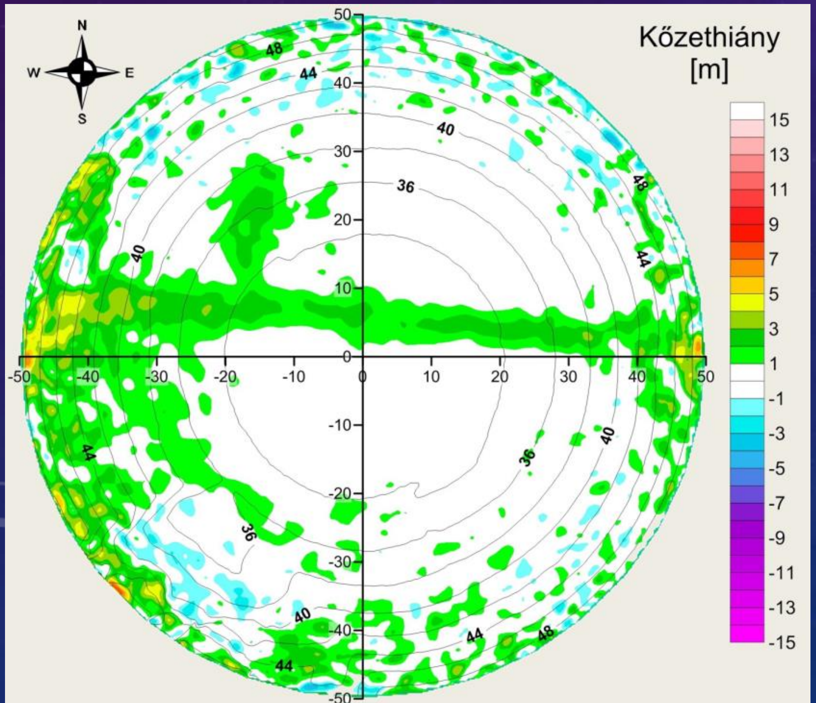
- Flux fluctuations inside the body indicate inhomogenities





DETECTING DENSITY ANOMALIES





Digital Surface Model

Average density of the object

→ Model

↓

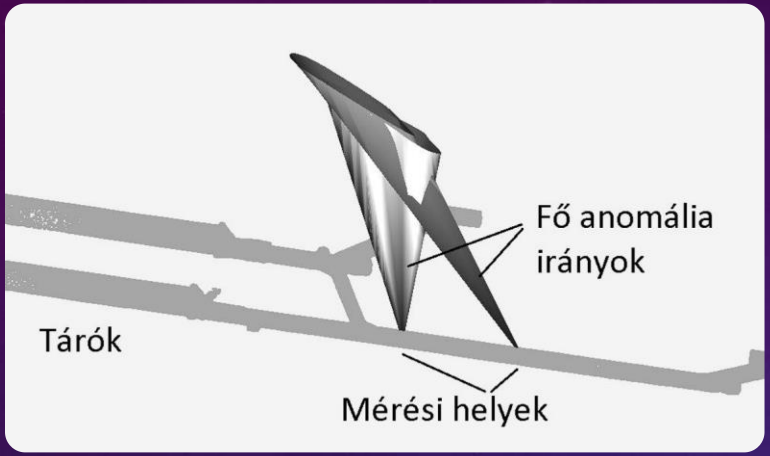
Differences are density anomalies

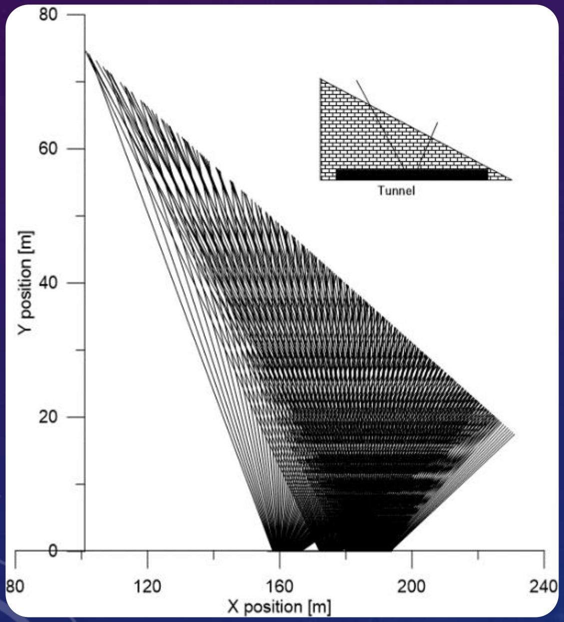
↑

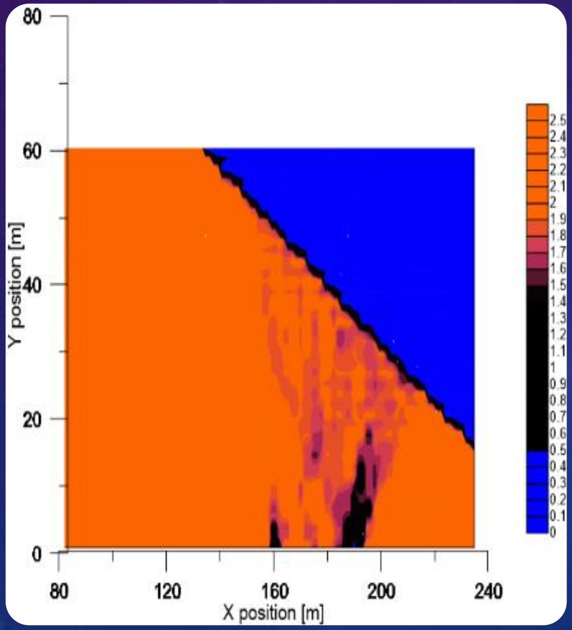
Digital Surface Model

Measurement

→ Muogram







GEOPHYSICAL INVERSION

- Inversion tries to fit the measured data on a previously defined model
- We can only measure density multiplied by lenght directly

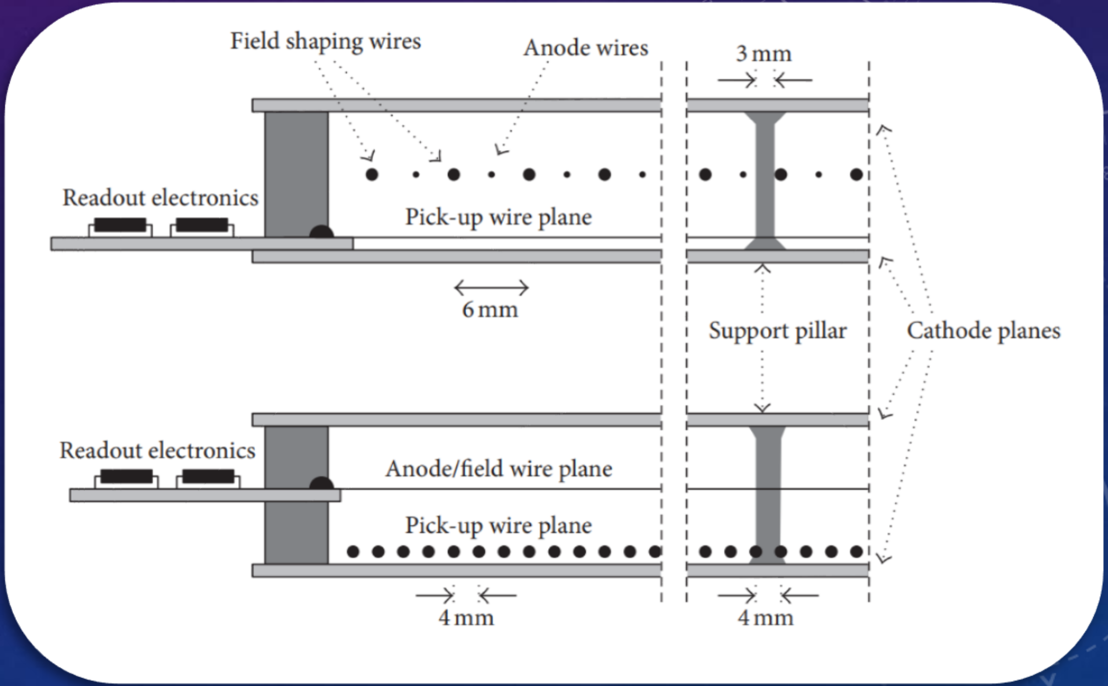
  → we must find a density model that results in the measured flux map

- Some points in the grid have many tracks passing through, but most have few or none

  → we solve this problem by using Bayesian inversion (heavily forces the results to be distributed around a predefinied value)

MUOGRAPHIC DETECTOR BASICS

- MWPC (multi-wire proportional chamber) technology, developed by the REGARD Research Group in Wigner RCP especially for in situ muography (multiple week or month long measurements with no human supervision)
- Main features include cheapness, easy accessibility and resistance to harsh conditions (temperature and humidity)
- X and Y dimensions are recorded by electron avalanches near the high-voltage wires, caused by charged particles ionising the gas-filled inside of the detector chamber
- Z dimension is recorded by stacking multiple chambers on top of each other



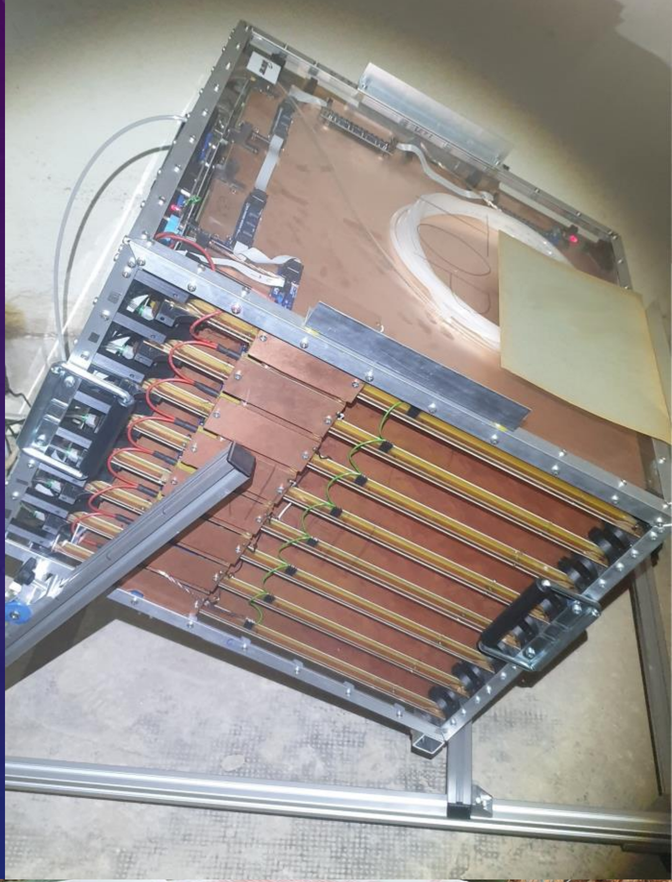
THE TWO MAIN TYPES OF DETECTORS

- Underground and surface muography have different focuses and require different detector designs (vertical vs horizontal muons)

- On the surface targets (volcanoes, buildings) are easily accesible → compactness isn't an issue → we can focus on better resolution by having more space between each chamber
  (the detector surface can be increased by using multiple detectors, for example: SMO in Japan)

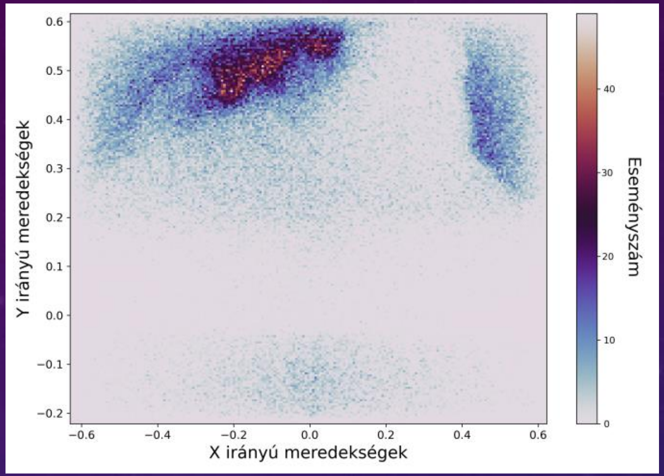
- Underground muography is used for archeology, mining and cave exploration. Here we must be under the target → narrow tunnels and caves → detector must be small and easy to carry

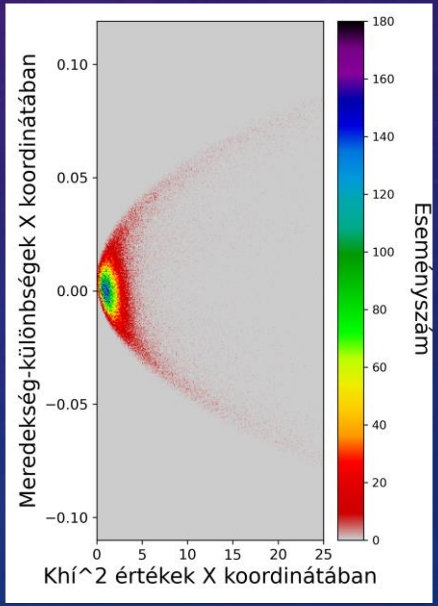
(alternative muographic methods are also in developement → borehole, national security, secondary particle analysis)



BACGROUND EFFECTS IN SURFACE MUOGRAPHY

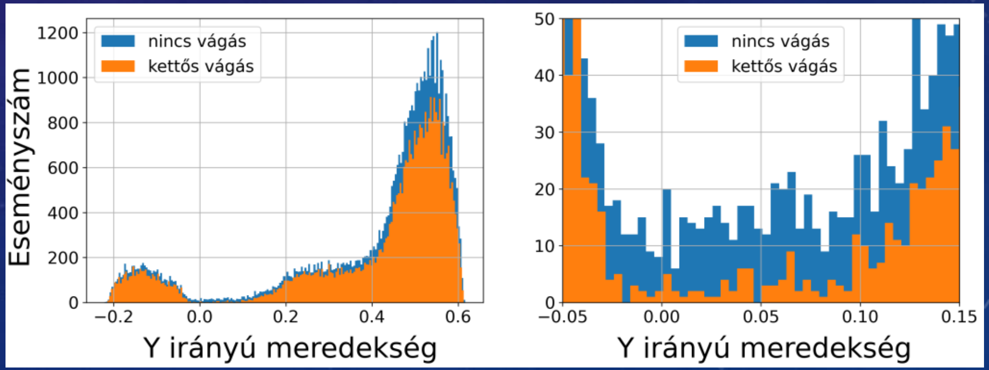
- Main problem: low-energy and scattered particles
- Detectors contain lead plates to scatter low-energy particles between chambers
- Two ways to filter the dataset: chi^2 test and fitting two small tracks and calculating the difference between their slopes → good correlation
- We can cut for a maximum value in both → we still have a few completely horizontal tracks that can't be muons → we assume that there are an equal number of these fake tracks in all directions (probable cause: radioactivity)



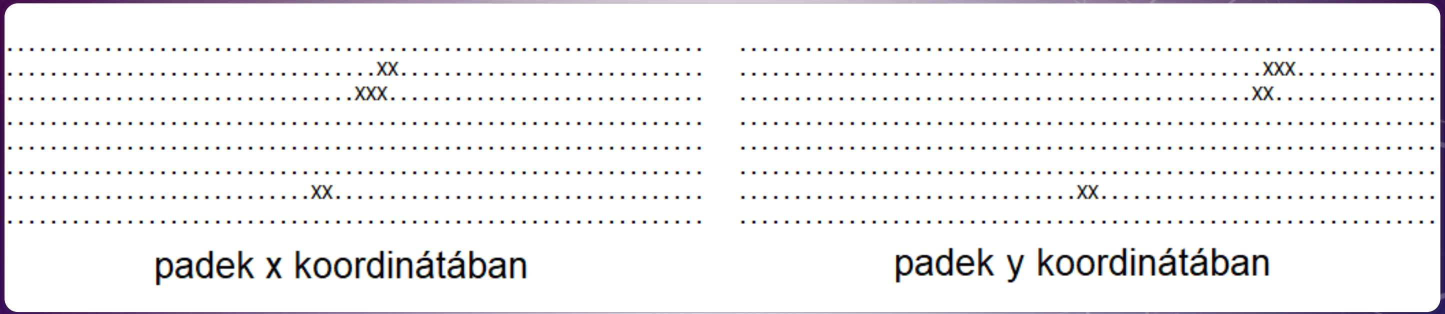


$$\chi^2 = \sum_{i=1}^{8} \frac{(E_i - O_i)^2}{\sigma^2}$$

$$f(x)_1 = m_1 \cdot x + b_1$$
$$f(x)_2 = m_2 \cdot x + b_2$$
$$D = |m_1 - m_2|$$



BACKGORUND EFFECTS IN UNDERGROUND MUOGRAPHY



- High radioactivity in some mines
- Through sheer coincidence fake tracks can form → their ratio can be calculated statistically using multiple detector layers
- The more chambers we have the less probable is the forming of a fake track
- At 5-6 chambers they become negligible (we use 7-8)

$$P_n = \binom{N}{n} p^n$$

Chance of a chamber triggering

$$\left[\binom{N}{n} / \binom{N}{n-1}\right] p = P_n / P_{n-1}$$

The value of p can be calculated using the total number of events recorded by two neighbouring chambers

$$P_{fake} = \binom{N}{n} p^n k^{n-2} = \binom{N}{n} p^n \left(\frac{3}{m}\right)^{n-2}$$

Chance for a track to be fake (3 of the m number of pads on each wire plane must be triggered and they must form a line)

SOURCES

- https://cds.cern.ch/images/CMS-PHO-GEN-2017-008-1/file?size=large
- L. Oláh, et al.: Képalkotás kozmikus részecskékkel - Fizikai Szemle 2017/3, 74-78.
- B. Rábóczki – BSc Thesis, ELTE 2022
- Hiroyuki K. M. Tanaka: Japanese volcanoes visualized with muography - Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, Vol. 377
- D. Varga, G. Nyitrai, G. Hamar, L. Oláh: High Efficiency Gaseous Tracking Detector for Cosmic Muon Radiography - Advances in High Energy Physics Volume 2016 (2016), 1962317
- G. Surányi *et al.:* Karsztfejlődés 21 (2016) pp. 205-218.
- https://media-cdn.tripadvisor.com/media/photo-s/0c/55/ae/d6/view-of-the-castle-and.jpg

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THANK YOU FOR YOUR ATTENTION