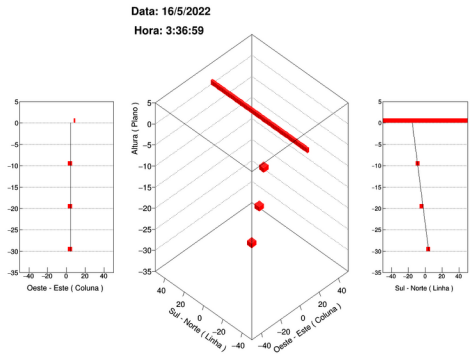
Muography

and the LouMu project

LIP, May 2022

Sofia Andringa, sofia@lip.pt

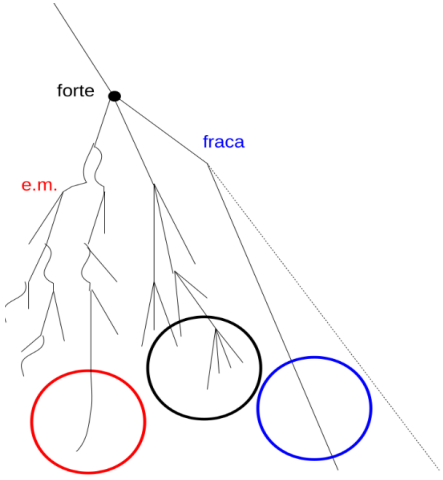


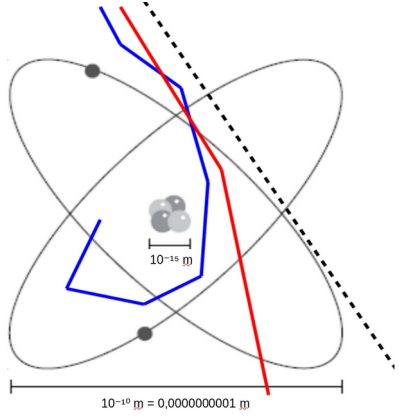
muography

using particles produced by cosmic rays showering in the atmosphere to make images

muons can easily reach the ground
- ~ 1 muon / cm² / minute, at sea level
- mostly vertical, falling with zenith angle
- spectra extending to very high energies

muons are charged and heavy (~200.m_e)
- travel large distances in mostly straight lines
- energy loss to ionization of 2.5 MeV/(g/cm²)
- until they stop and decay





scattering muography

Muons travel in straight lines,

but scatter of heavy nuclei

Identify hidden nuclear materials

using several detectors

around “small” objects

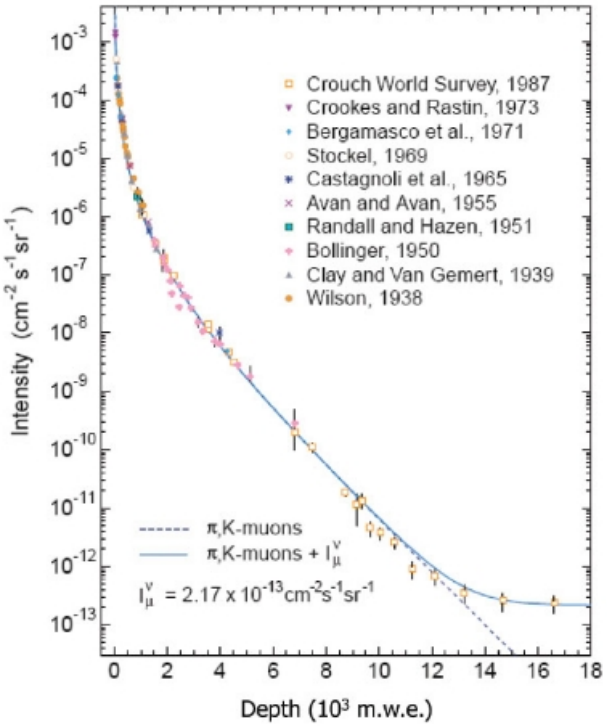
transmission muography

count surviving muons
after crossing large objects
using one single detector

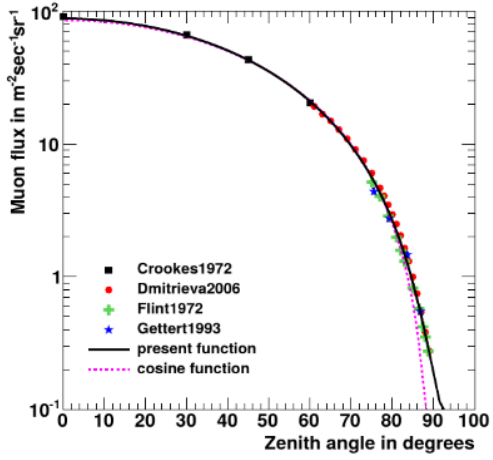
used in 1955 on a tunnel

or, better, a “telescope”
measuring different directions
and knowledge of open air flux

used in 1969 on a pyramid

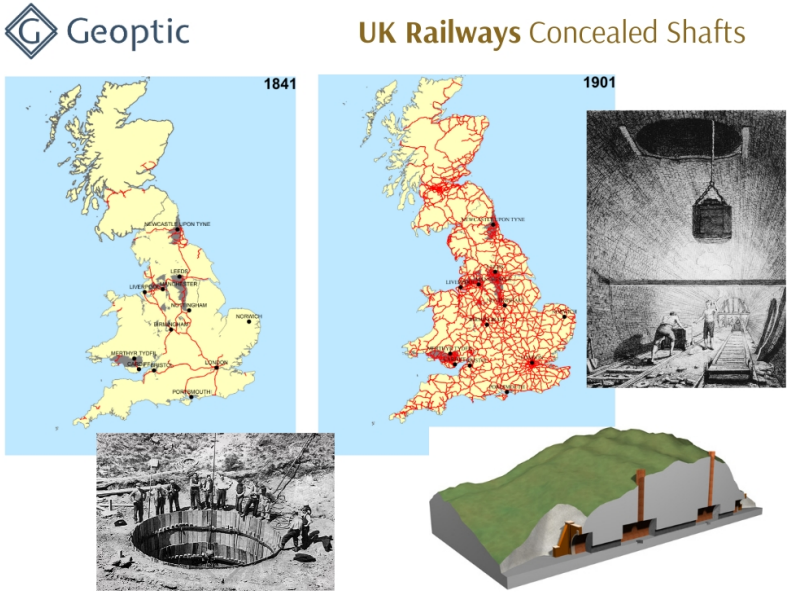


Bugaev et al. Physical Review D 58 (1998): 054001.



Shukla *et al. International Journal of Modern Physics A* 33, no. 30 (2018): 1850175.

the old train tunnels



Khufu’s Pyramid

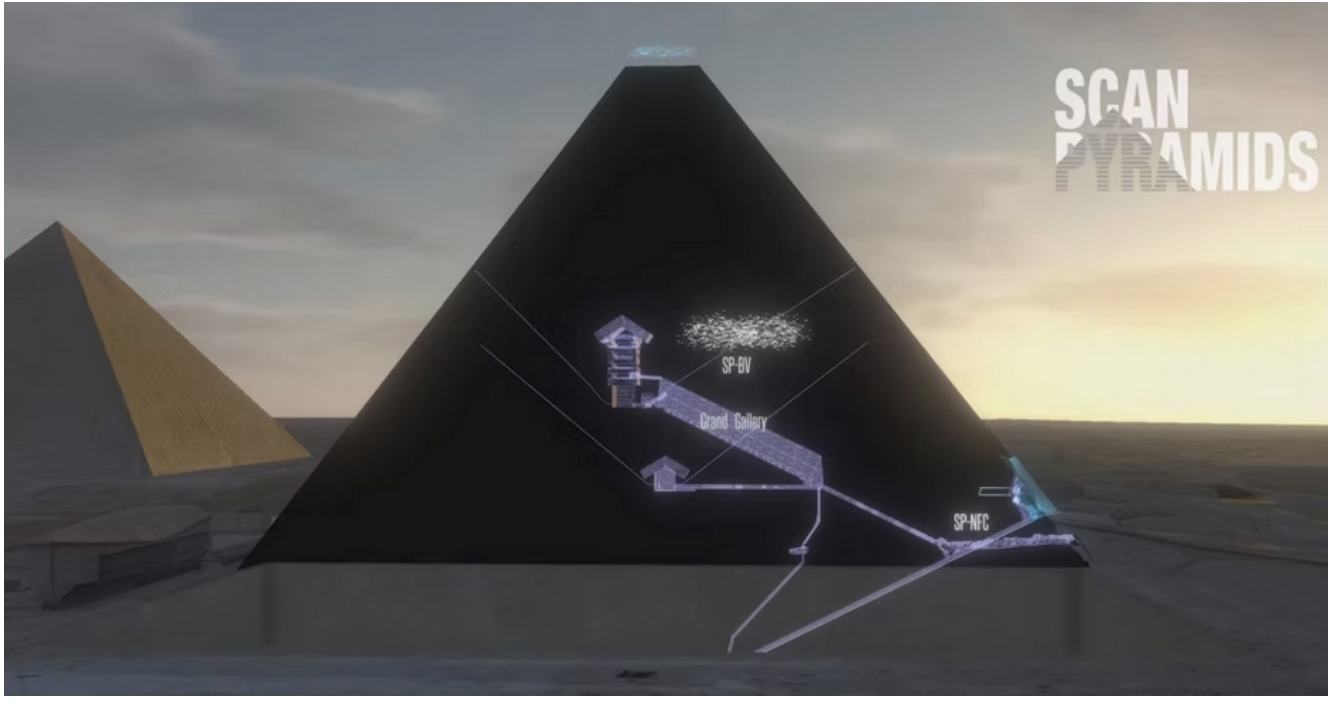
Discovery of a big void in Khufu’s Pyramid by observation of cosmic-ray muons
Nature 553, 386-390 (2017)

- different detector technologies

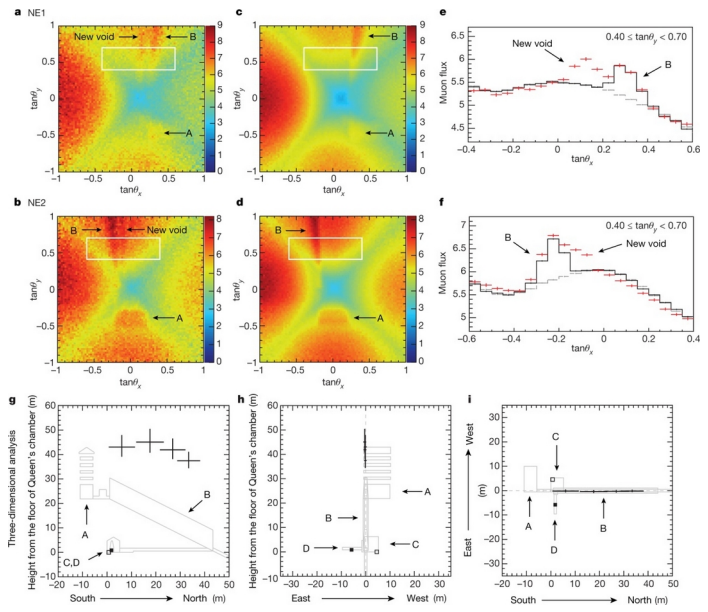
- different detector placing

- long term analyses

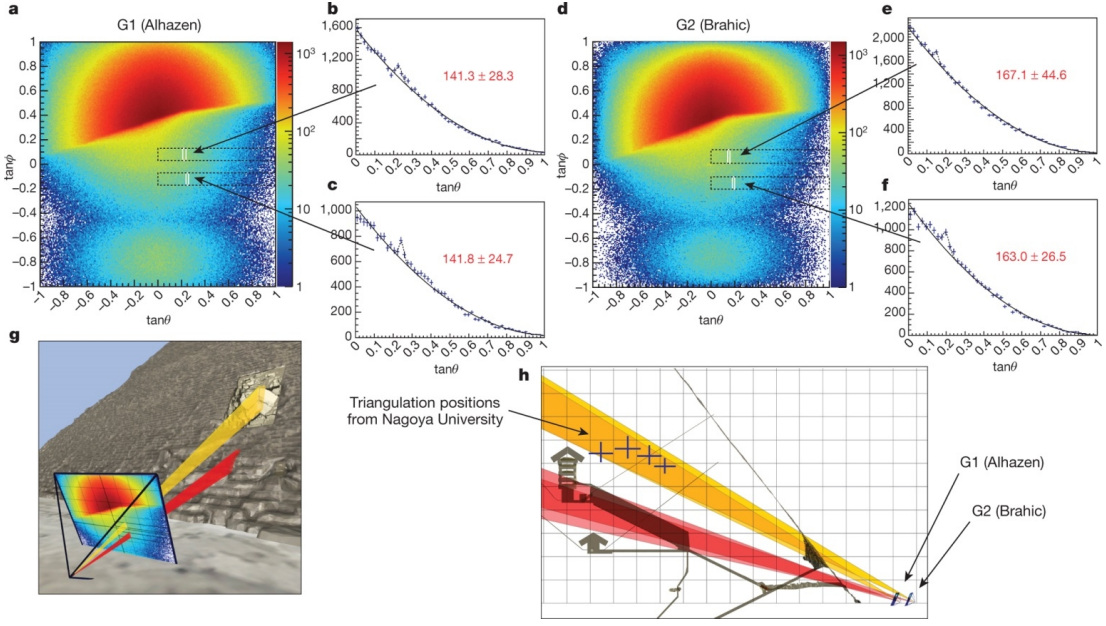
- future projects



Khufu's Pyramid



Muographing from 2 positions below
Using nuclear emulsion films
(data vs model with known chambers or not)



Muographing from 2 positions from outside
Using micromega gas detectors
(data excesses, also for known and unknown chambers)

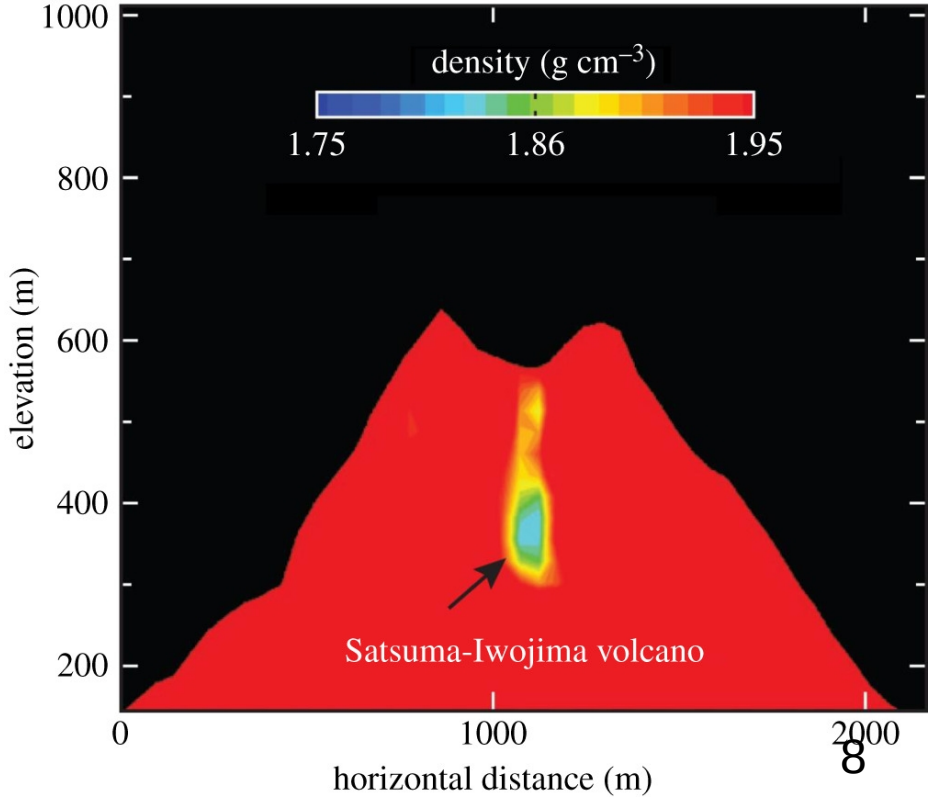
many volcanoes

Characterization and long term monitoring

Separate projects with common challenges
in Japan, Europe, South America,...

Very long distances and small transmission

- model of high energy muon fluxes
- model of low energy muon fluxes
- scattering and secondary particles
- inversion with other geological data
- …



the LouMu project

LouMu

Science with Cosmic Muons at the Lousal Mine

LouMu is a scientific research project combining particle physics and geophysics in order to map large geological structures, using the Muon Tomography technique.

The partners in the project are LIP — Laboratory for Instrumentation and Experimental Particle Physics, the Institute of Earth Sciences of the University of Évora, and the Mine of Science – Lousal Ciência Viva Science Centre.

Centro Ciência Viva do Lousal — Mina de Ciência

UNIVERSIDADE DE ÉVORA

ICT Instituto de Ciências da Terra Institute of Earth Sciences

LIP Laboratório de Instrumentação e Física Experimental de Partículas

FCT Fundação para a Ciência e a Tecnologia

- muon telescope
- muographic imaging
- usefulness for geophysics
- & a strong outreach component

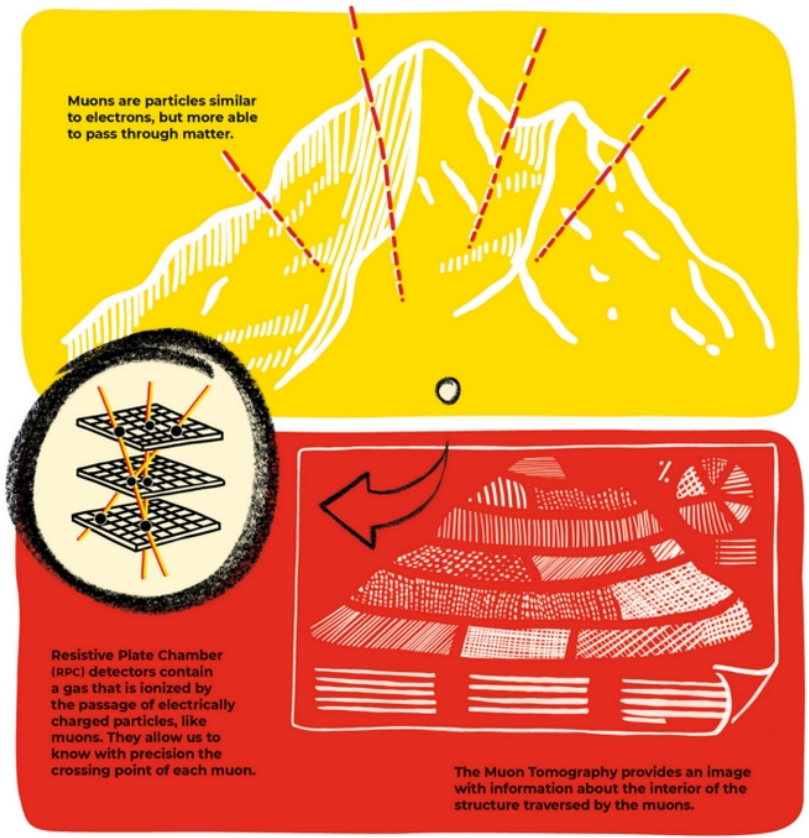
Planet Earth is constantly being struck by particles coming from space, known as cosmic rays.

As they collide with atoms in the atmosphere, a shower of new particles is created. Among them are muons, particles that can reach the surface of the Earth and pass through rocks.

Taking into account the number of muons that reach us, it is possible to figure out the different densities in the interior of rocks. In this way, the invisible becomes visible.

This is a Muography: like a radiography, but with muons.

In the Lousal Mine a muon detector is installed which, in combination with other geophysical techniques, will enable the Muon Tomography, three dimentional information, to let us better understand the interior of the mine and of other geological structures.



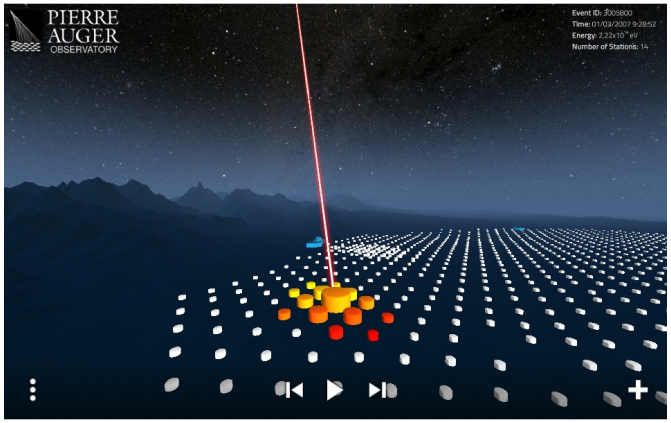
LIP R&D on RPCs
Resistive Plate Chambers

High resolution TOF trackers
High resolution PET imaging
Epi-thermal neutron detection
Cosmic Ray experiments

- Adjustment to environment
- Very low consumption (gas and power)
- Very low maintenance (once per year)

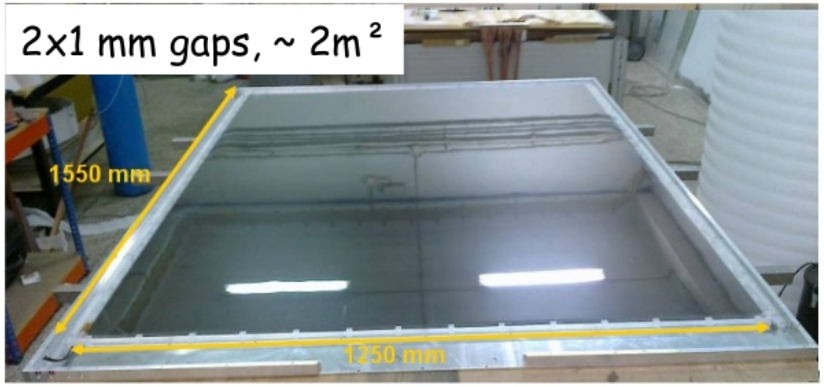
LouMu inherits R&D done for the Pierre Auger Observatory:
same RPC detectors now installed under water Cherenkov detectors*

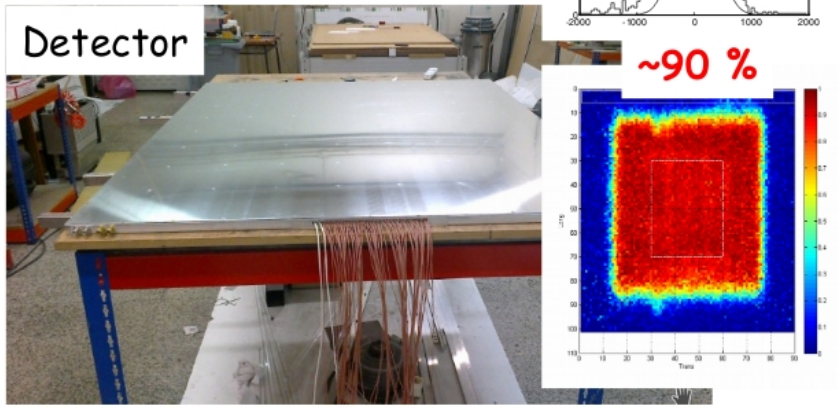
The Pierre Auger Observatory
and the MARTA project



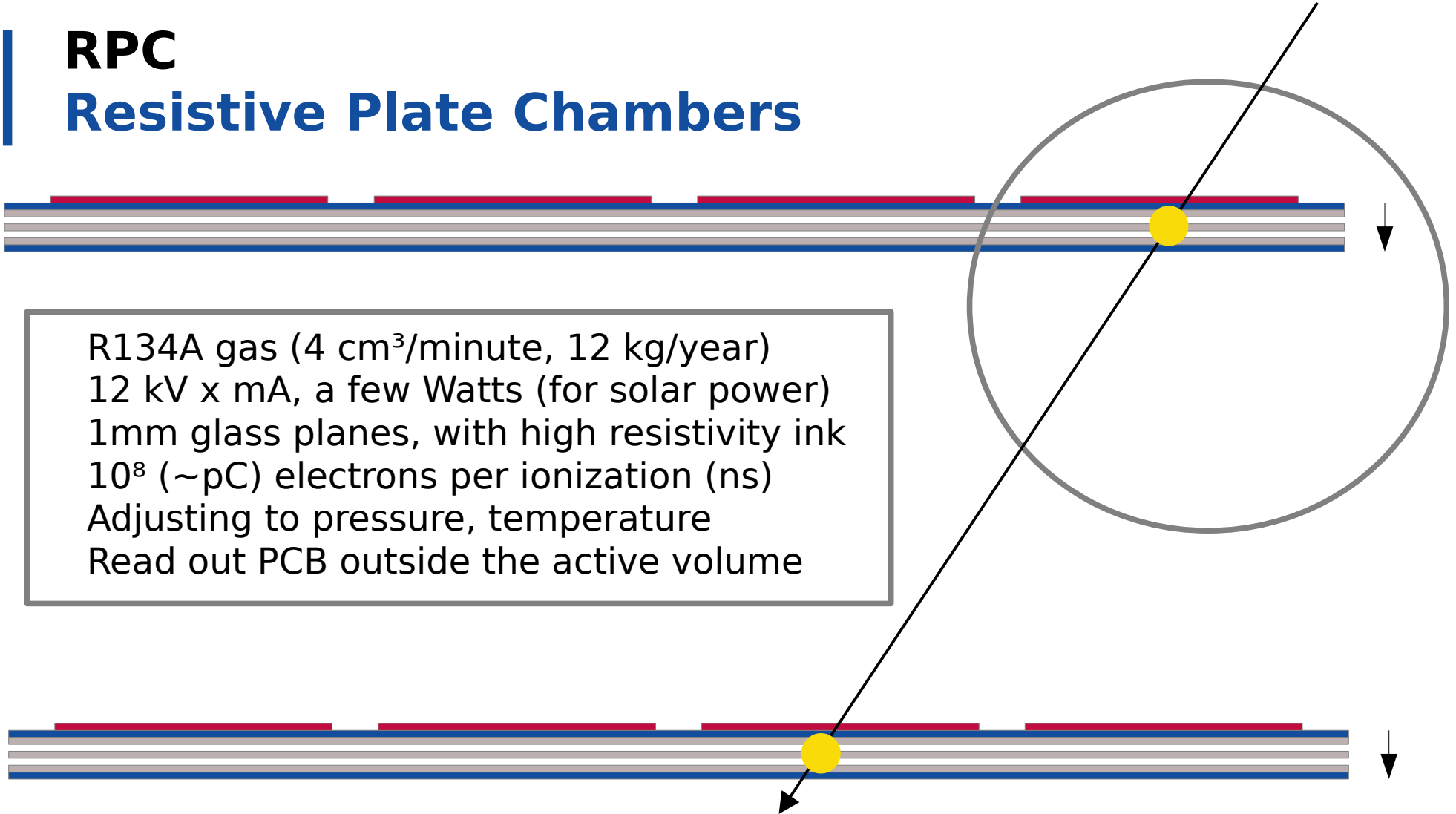
https://pages.lip.pt/auger/
and check our open data!

RPCs for cosmic rays
large areas and good resolution





RPC
Resistive Plate Chambers

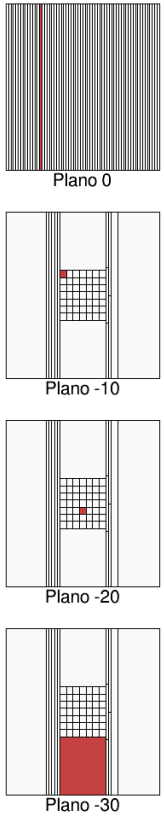


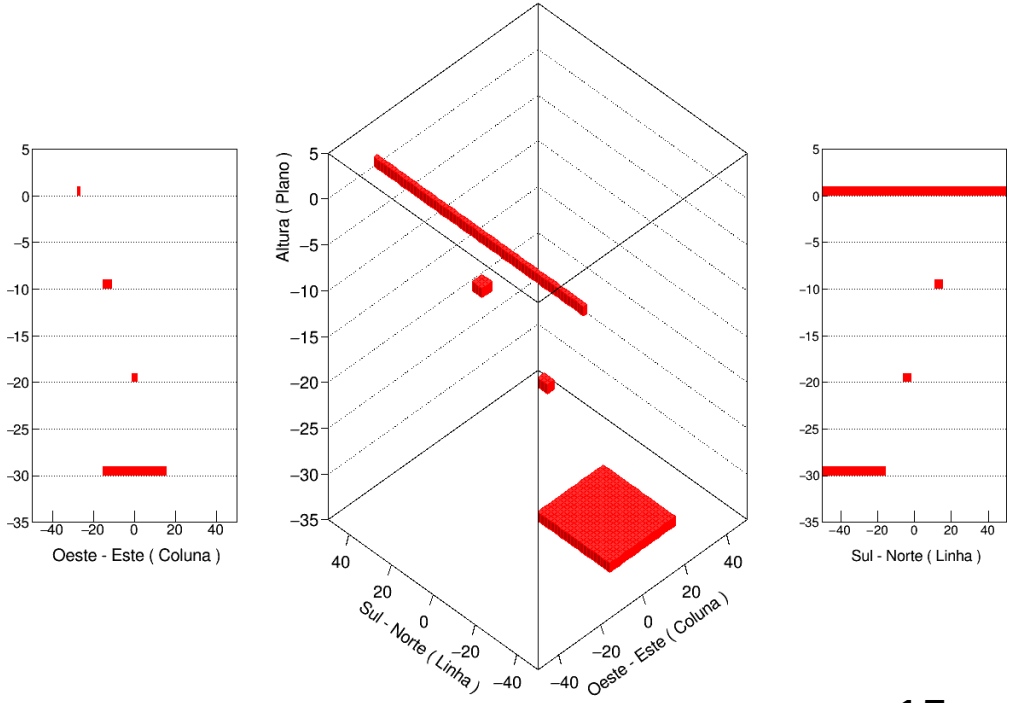
R134A gas (4 cm^3/minute, 12 kg/year)
12 kV x mA, a few Watts (for solar power)
1mm glass planes, with high resistivity ink
10^8 (~pC) electrons per ionization (ns)
Adjusting to pressure, temperature
Read out PCB outside the active volume

RPCs for muography
a movable muon telescope

- four 1m x 1m planes
- at adjustable heights
- can tilt up to 30º
- gas feeding & recovery
- different segmentation

the LouMu telescope
a layout for different tests





- same 64 channels per plane
- smaller pads & guard-rings
- strips of different widths

Planned to optimize readout
for future telescopes

the LouMu telescope
a layout for different tests

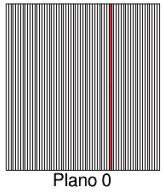
- same 64 channels per plane

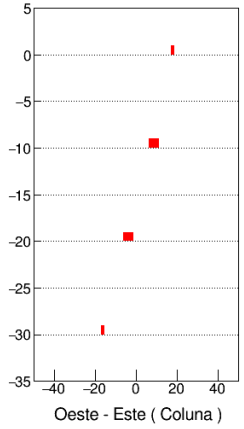
- smaller pads & guard-rings

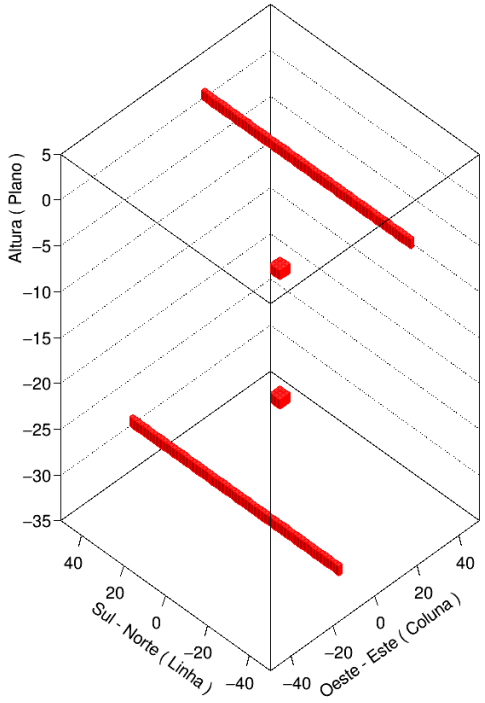
- strips of different widths

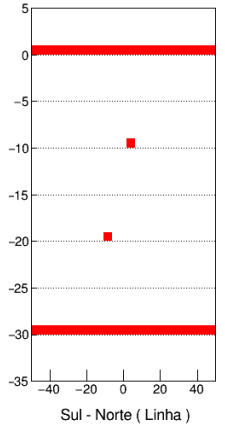
Optimize readout for upgrades

X vs Y strips??









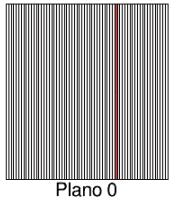
the LouMu telescope
a layout for different tests

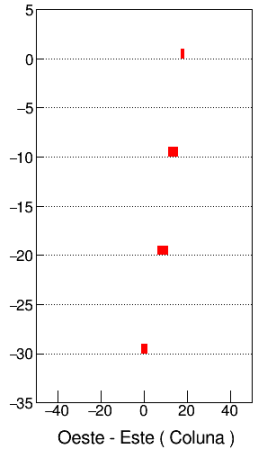
For muography now

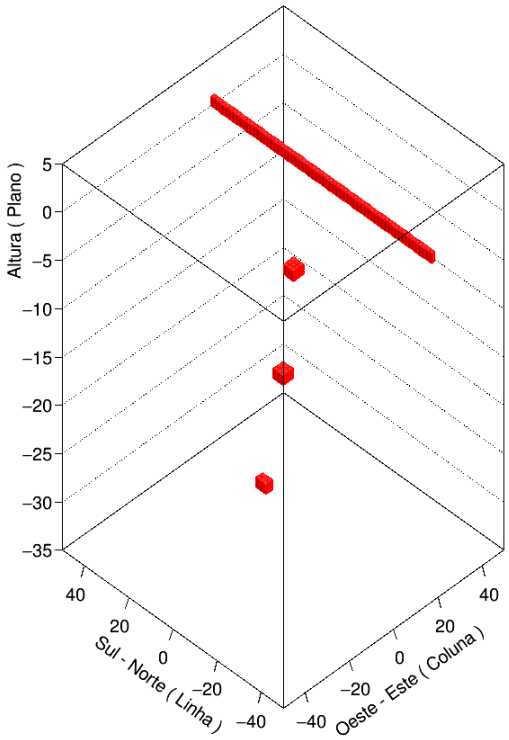
- use 7 x 7 inner pads

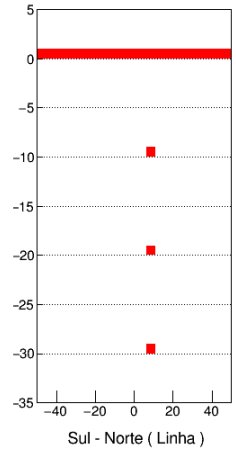
- 3 planes for redundancy

- strips for extra coverage







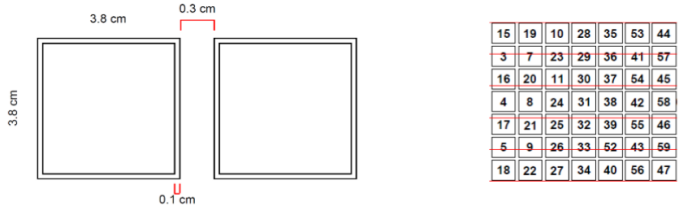


telescope response model
efficiency and uniformity

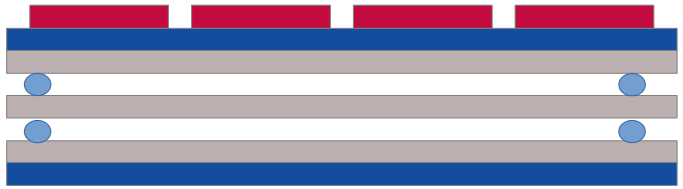
- measuring “vertical” counts uniformity

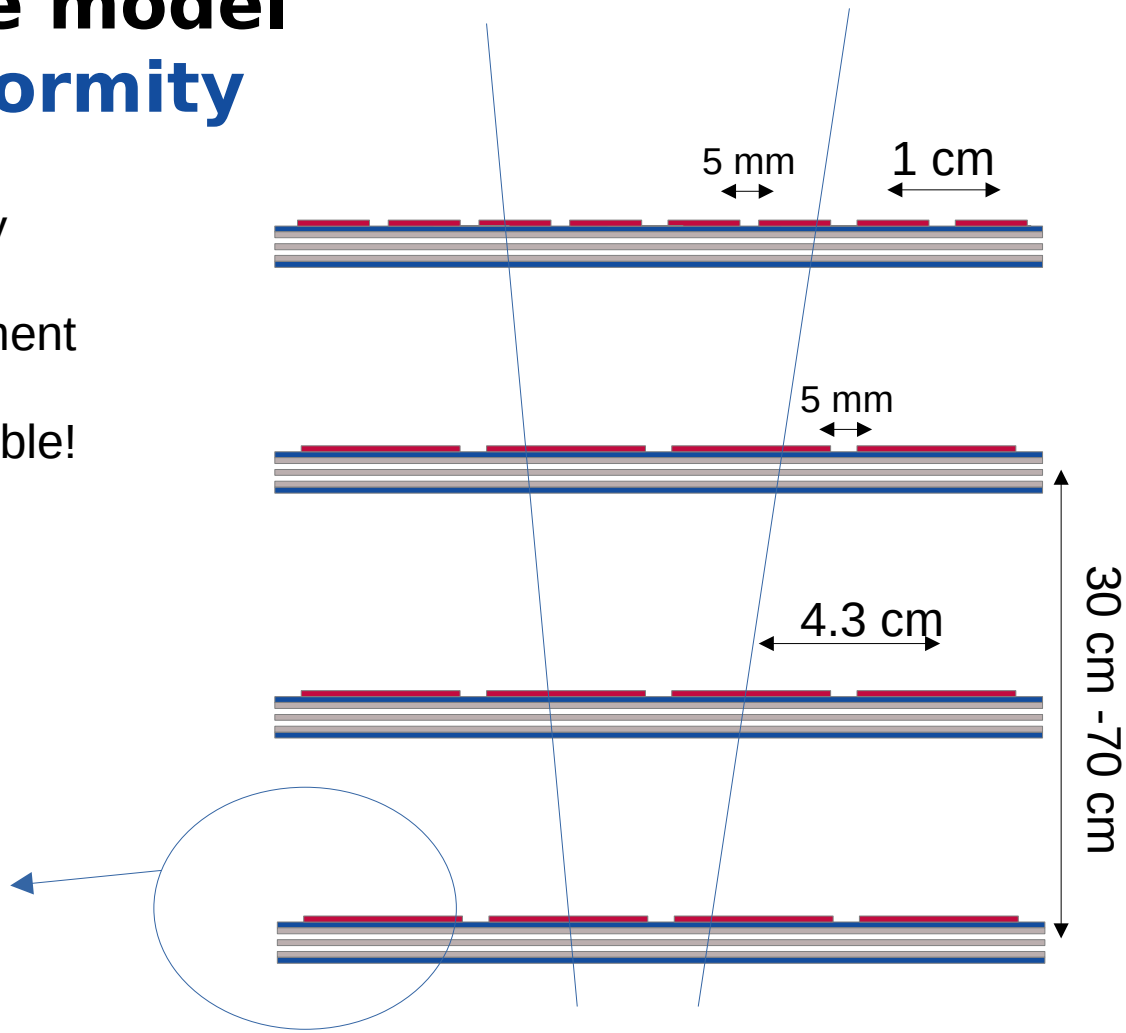
- improved with electronic gain adjustment

- inner structure of RPCs becomes visible!



15	19	10	28	35	53	44
3	7	23	29	36	41	57
16	20	11	30	37	54	45
4	8	24	31	38	42	58
17	21	25	32	39	55	46
5	9	26	33	52	43	59
18	22	27	34	40	56	47





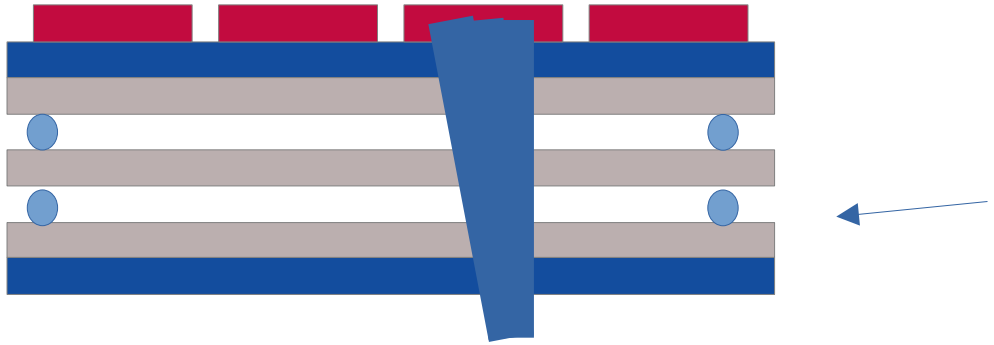
telescope response model
RPC detailed description

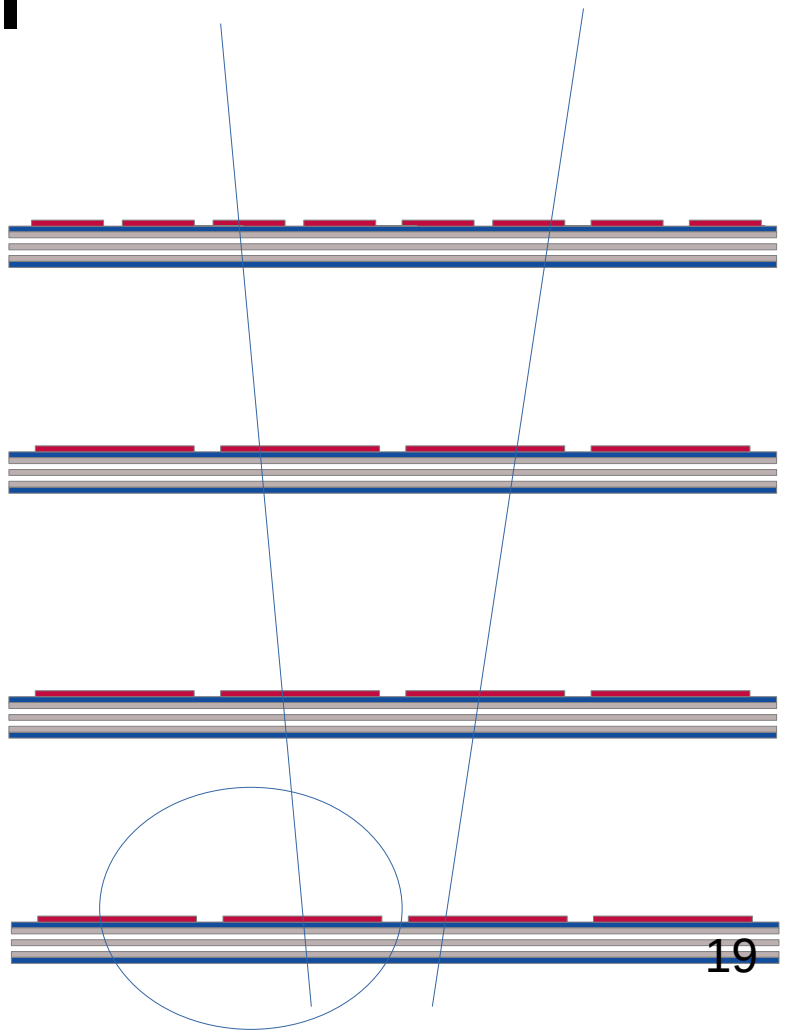
- Thin strips have many multiple hits

- CorePix pads have mostly single hits

- Active area larger than pad sizes?

- Use an effective size of avalanche?





the LouMu telescope
the first muographs

- counting muons in 13 x 13 directions

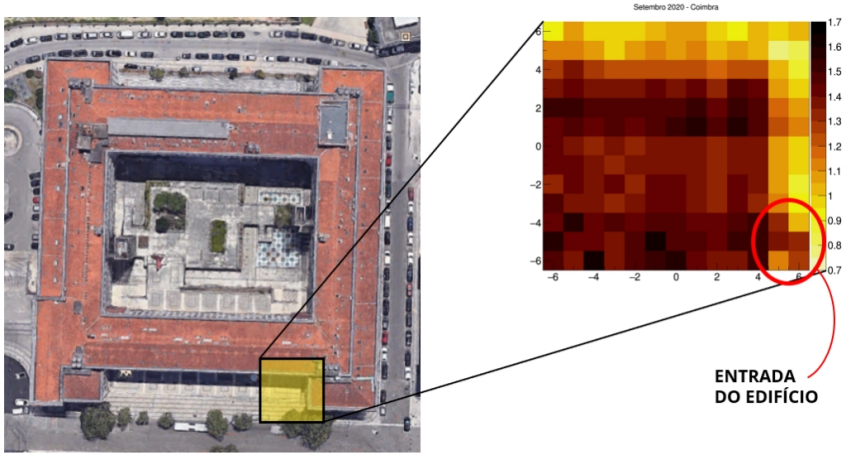
  using the CorePix region only

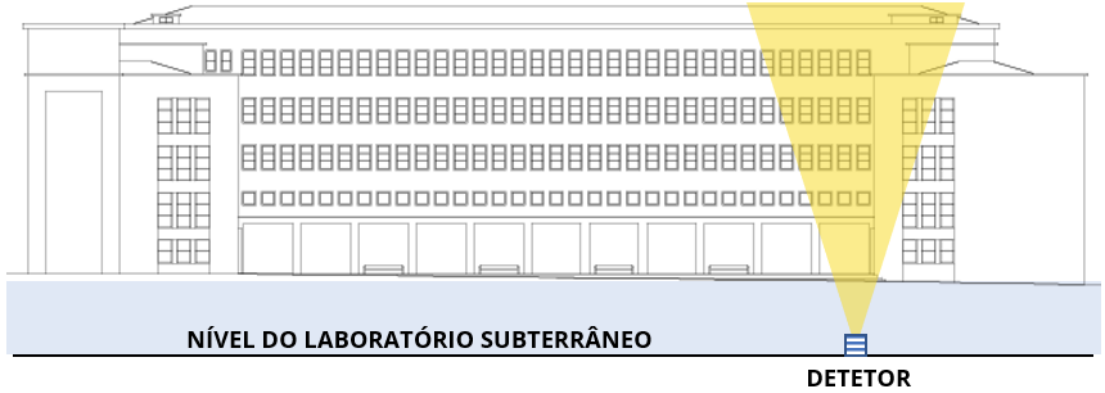
- projective images in squared pyramid

  X/Z vs Y/Z ie $\tan\theta_x$ vs $\tan\theta_y$

- divide map by a reference flux

  (here a totally covered location;
  usually the known open air flux)





the LouMu telescope
modeling the building

- starting from data, with just ceilings and walls

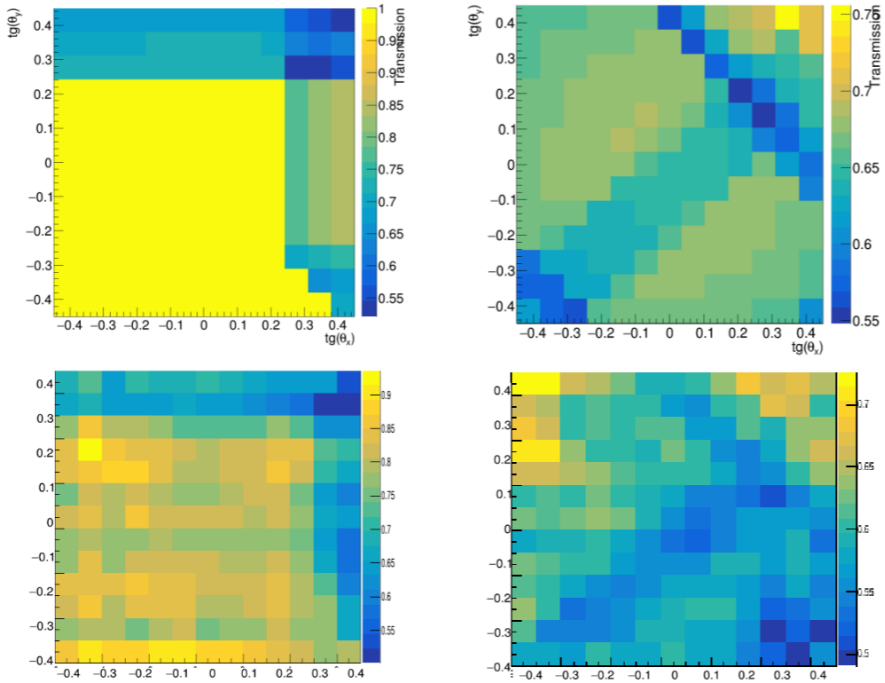
  Transmission in ceiling from vertical data compatible with model expectations

- developed a more detailed 3D lego model

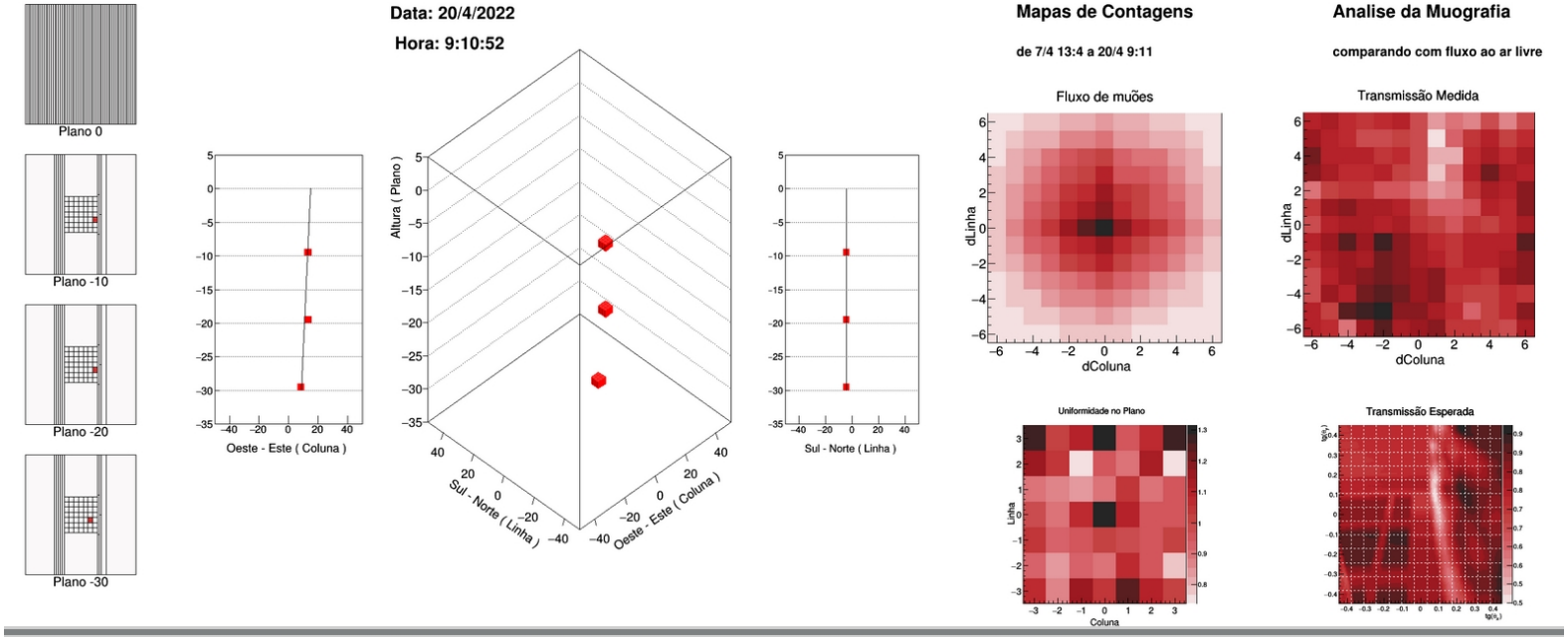
  Check for the beam above the detector and other features at lower contrasts

- uniformity must be considered in analysis

  Limitation for imaging and also sensing



muographying the building
at the door in Coimbra



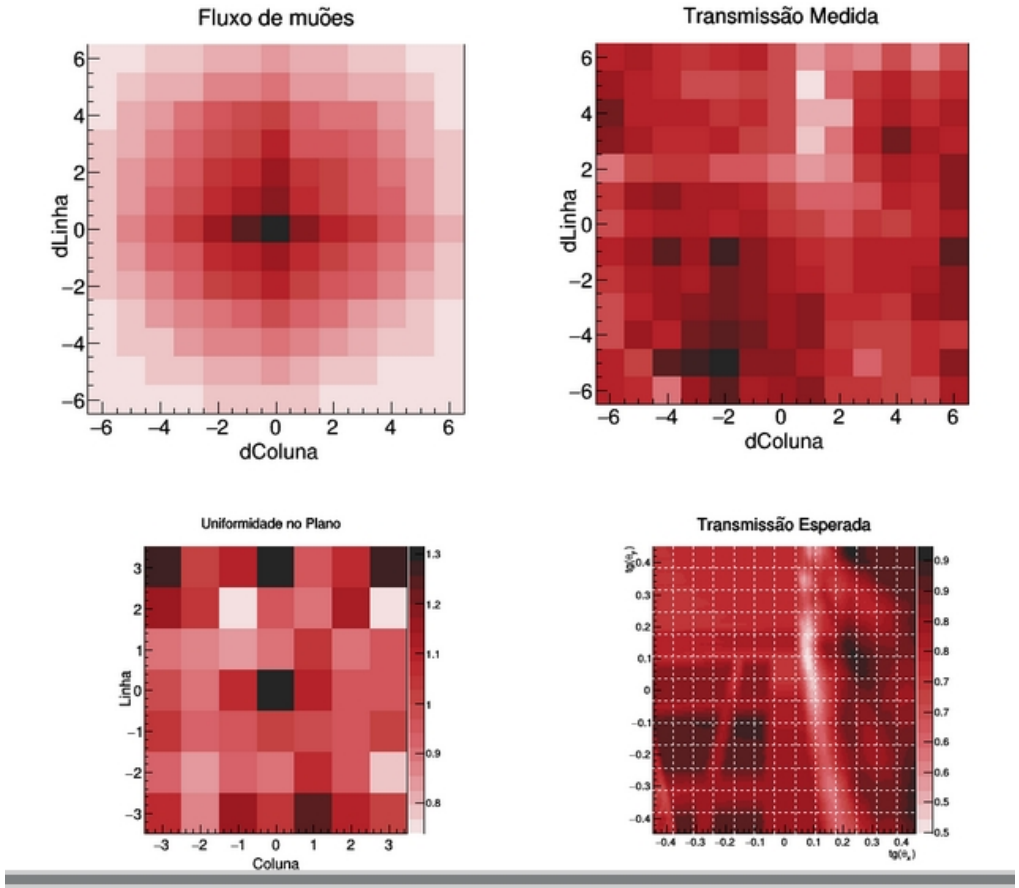
muographying the building
at the door in Coimbra

Open Air Rates

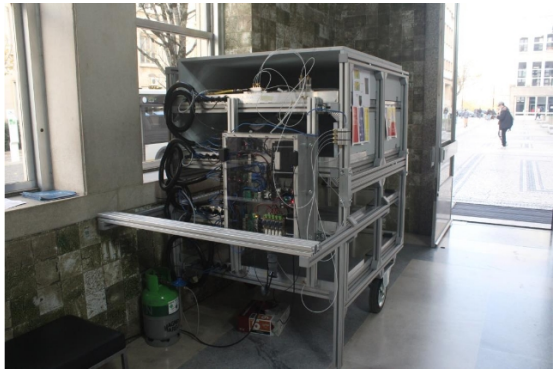
49 x 0.4 mHz
in center
1 x 0.2 mHz
in diagonal

Contrasts

0.5 in walls
0.9 in ceilings
(~0.1 uniformity)



muographying the building
at the door in Coimbra



muographying the building
end of a first phase

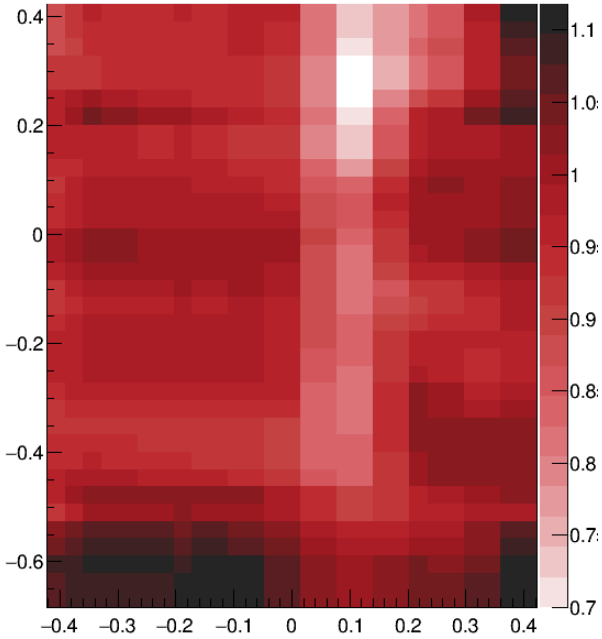
- LouMu telescope ready to produce “raw images” using average efficiency in detector modeling

- Muographys and detector effects analyzed together: depth of walls = ceilings? Hot days vs cold nights?

- Working on combination of muographys:
  - extended images from telescope rotation
  - 3-dimensional images from different positions

- Explore muon tomography capabilities of present telescope

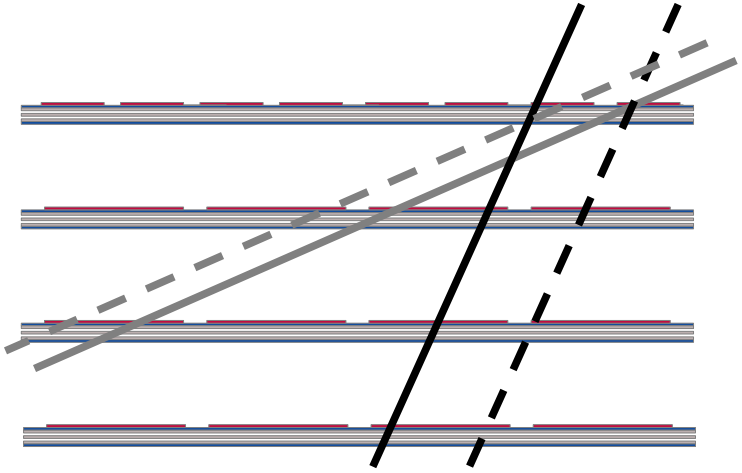
- Provide guidance for the design of an upgraded telescope

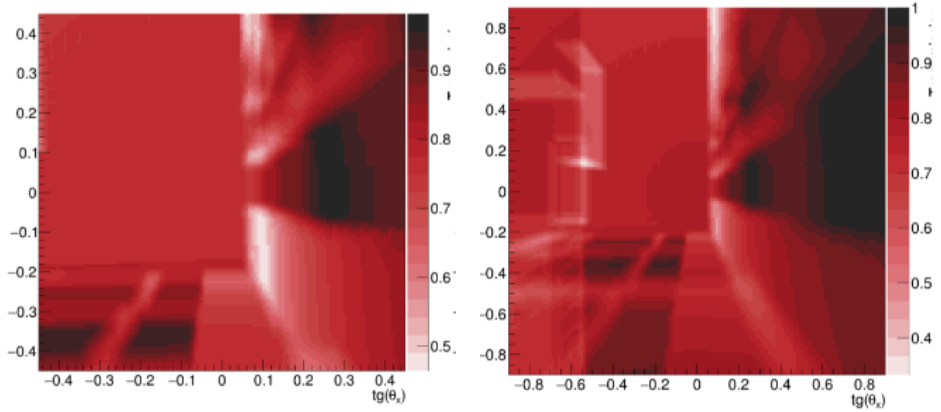


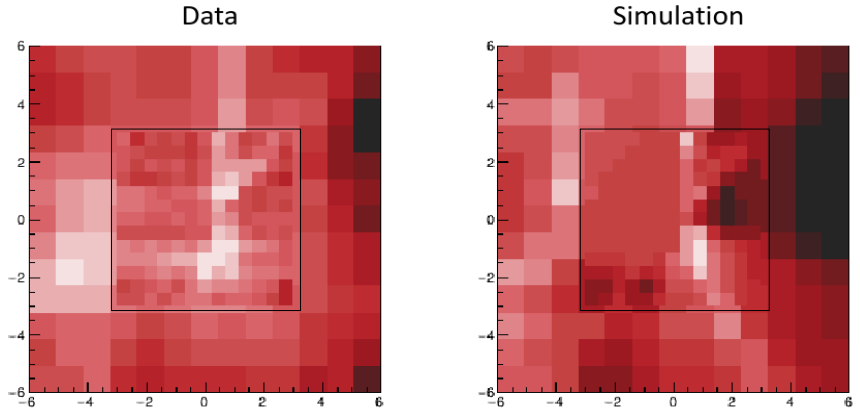
imaging with LouMu
combining simultaneous “raw maps”

- Another combination of planes:
  wider field of view; worse resolution

- Combination of both muographys:
  better resolution with same telescope







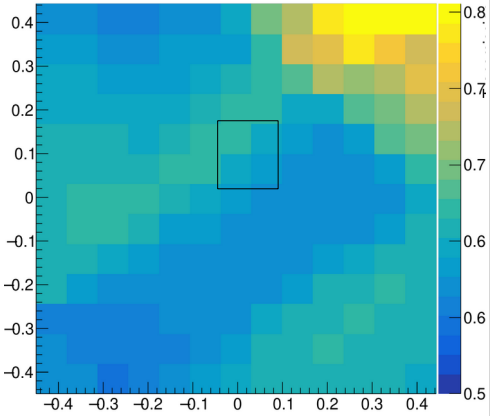
imaging with LouMu
towards single 3D images?

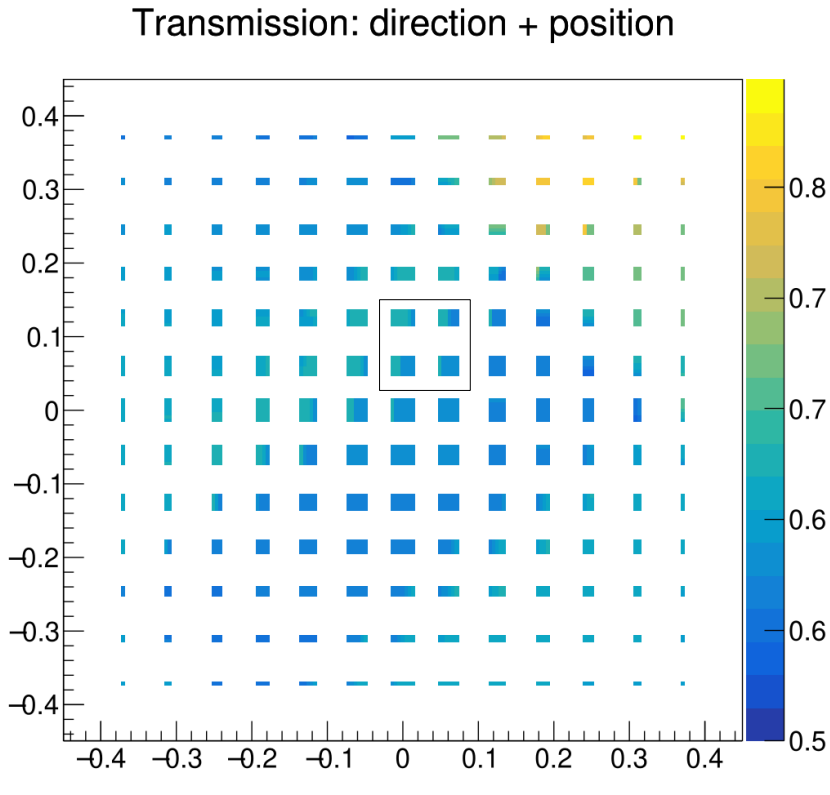
- only from far away is the telescope point-like

- two “raw maps” focused ~15 cm apart in height

- CorePix pads up to ~30 cm apart in x and y

- 3D reconstruction of nearby objects?



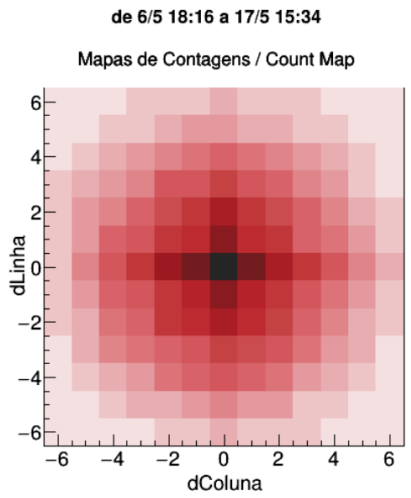


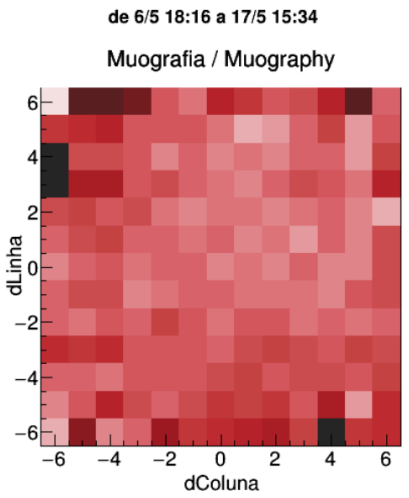
from Coimbra to Lousal
the next phase starts

Data taking at Lousal
creating the first maps

Mapas / Maps

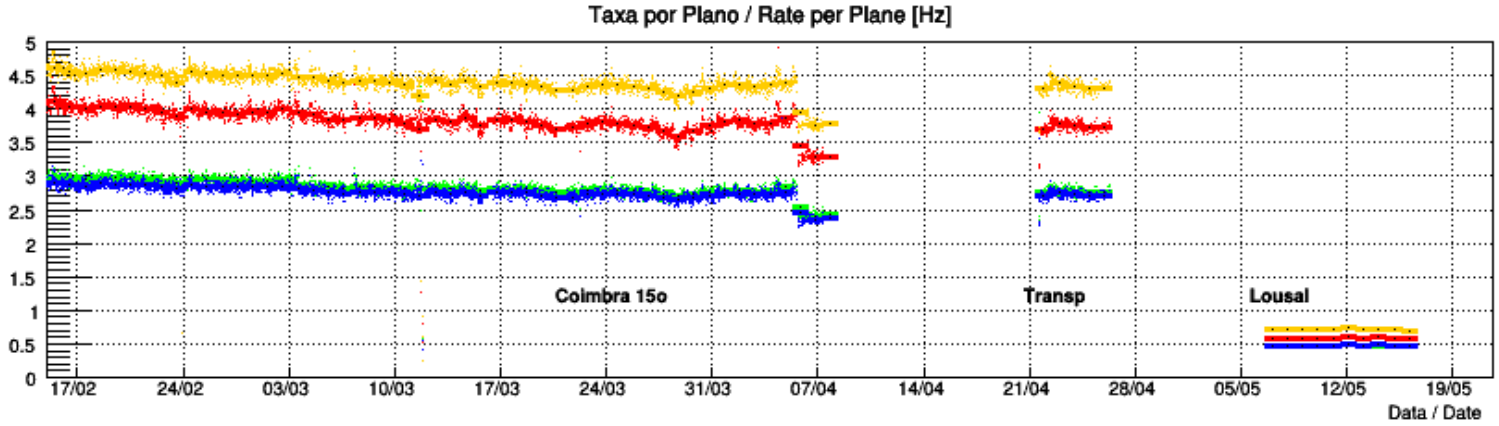
https://pages.lip.pt/loumu

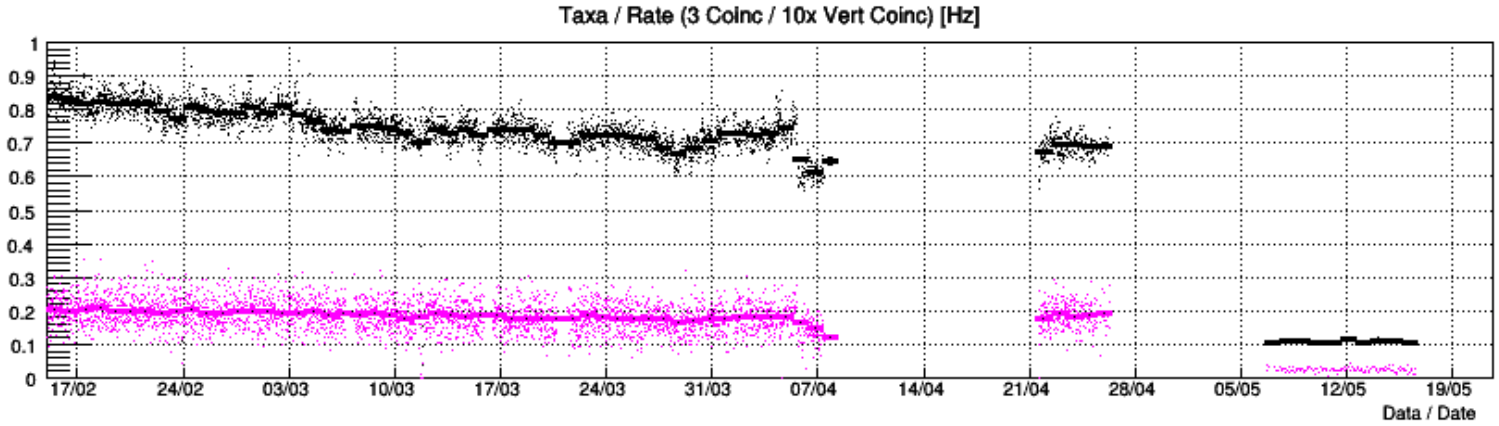




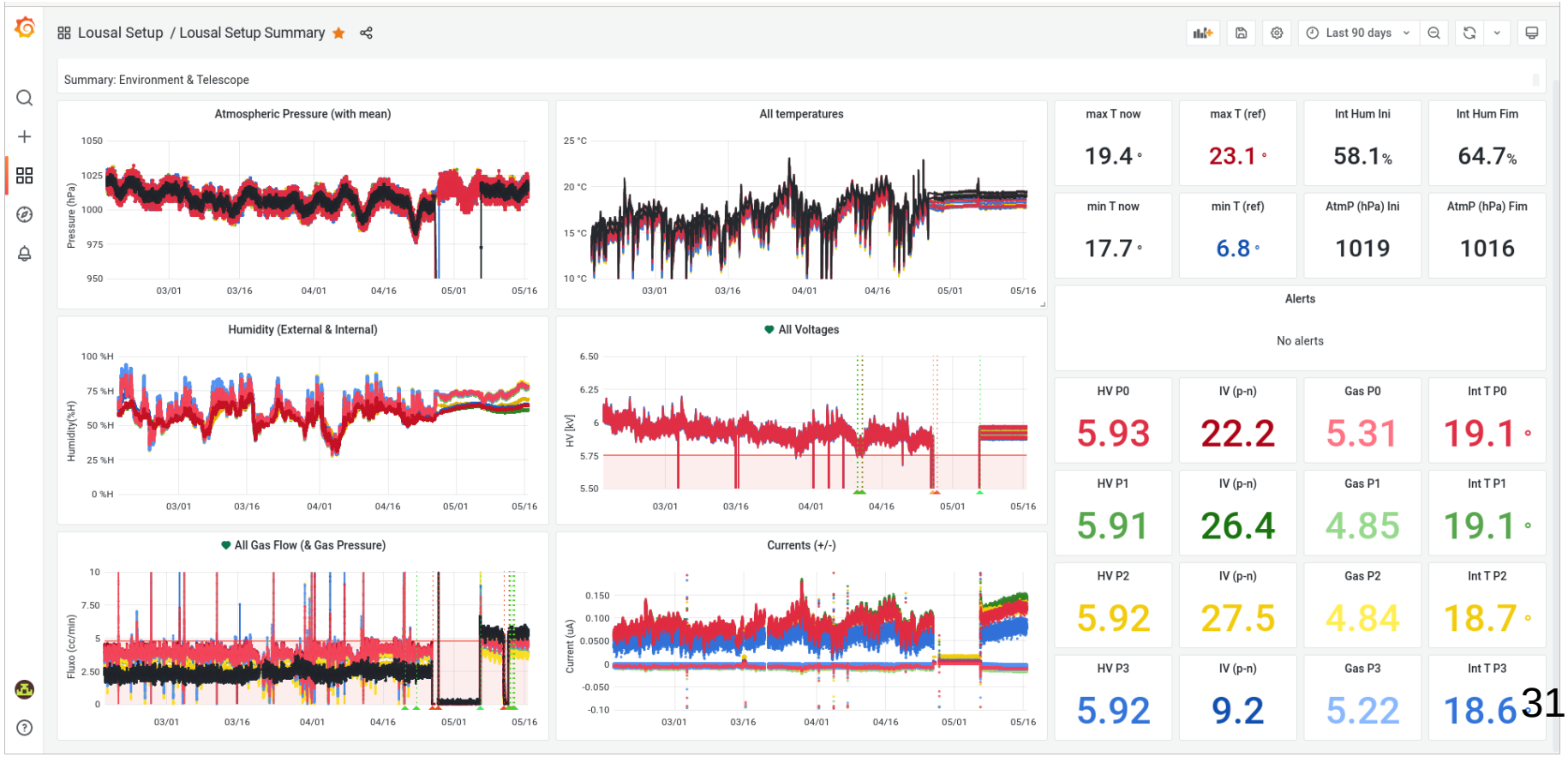
https://www.lip.pt/experiments/LouMu_/tablets

Muography at Lousal
muons and telescope

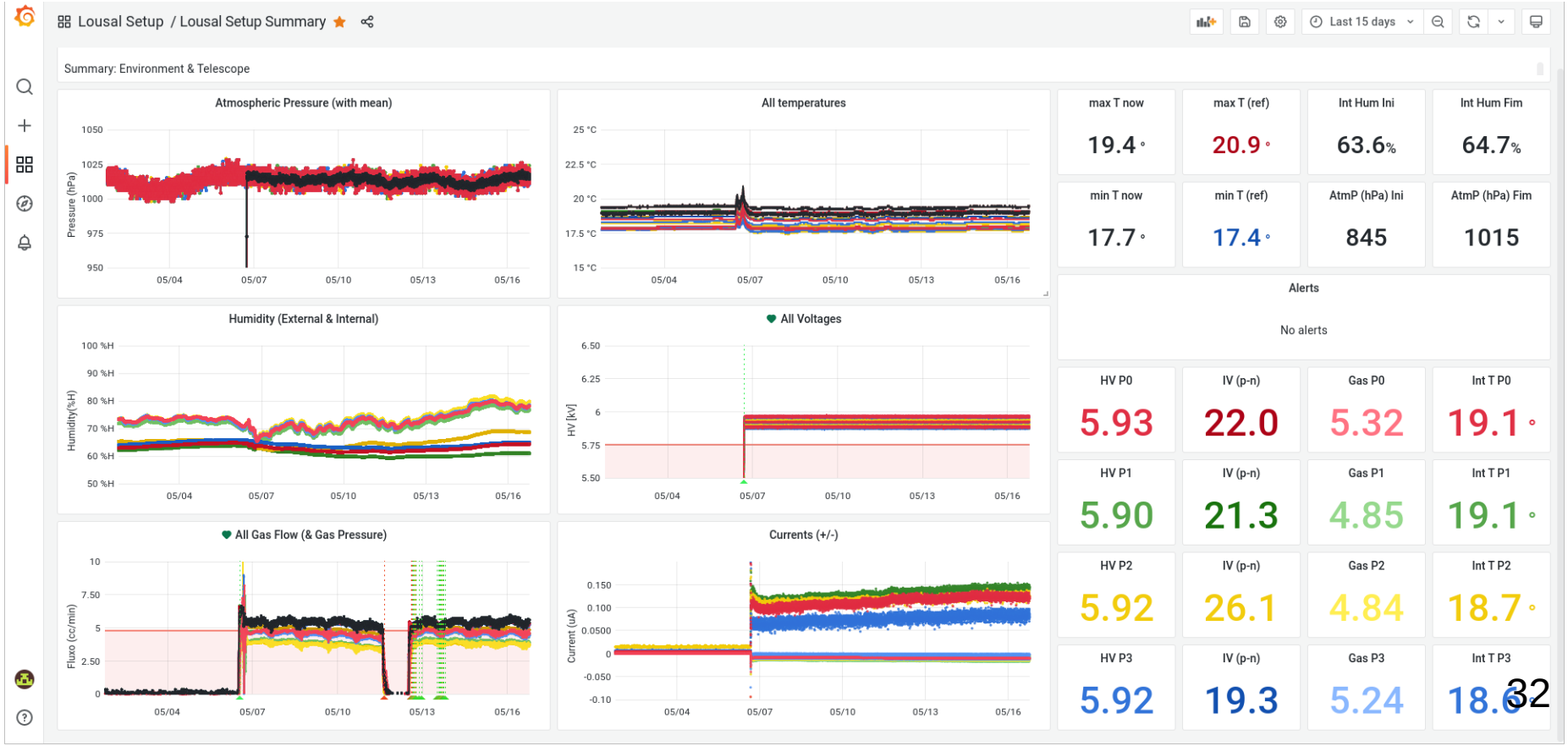




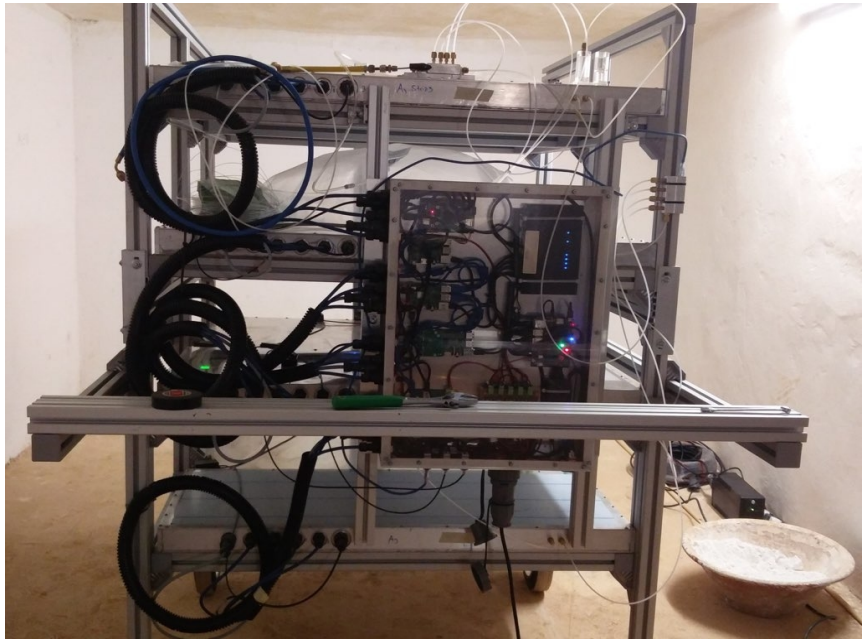
Muography at Lousal
muons and telescope



Muography at Lousal
muons and telescope



Muon telescopes at Lousal
the MiniMu and the LouMu



- MiniMu prototype was used to test logistics and stayed for outreach to visitors
- Main challenges for telescope are gas feeding and recovery from 100 m away

from Coimbra to Lousal
similar geometry?

- much less clear features

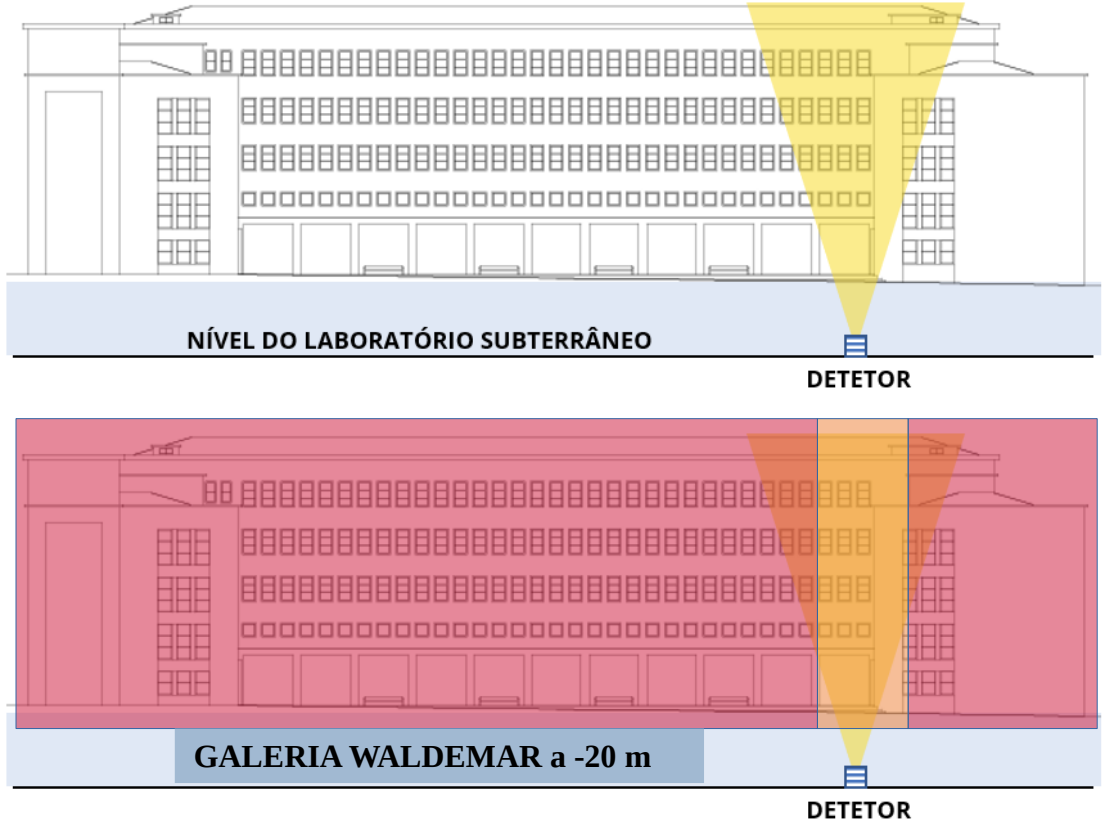
- less muon transmission

- effect of muon scattering ?

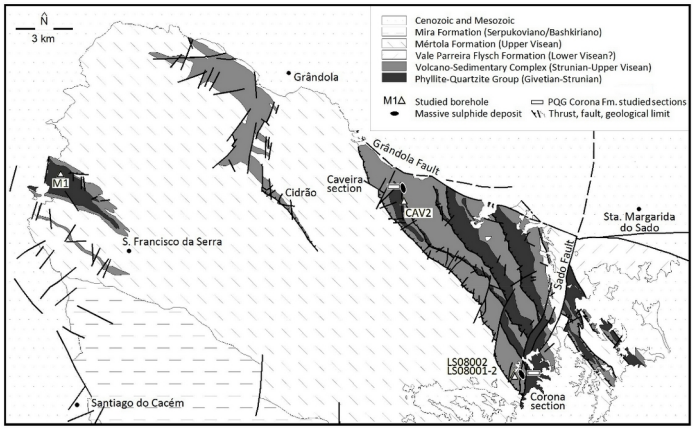
- even secondary particles ?

- full detailed simulation with of muon spectra and propagation (+ model detector response)

- for geological interpretation

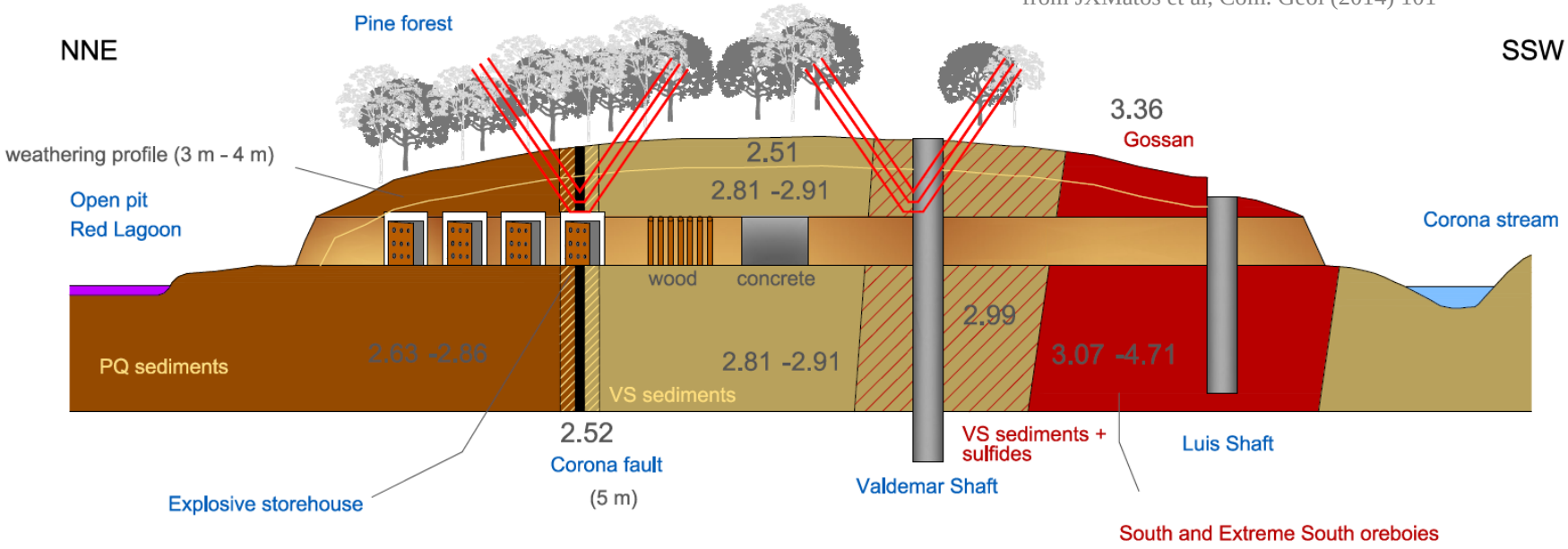


Reference model of Lousal
the Corona fault



from JXMatos et al, Com. Geol (2014) 101

Lousal Mine - Valdemar gallery



Reference model of Lousal
the geophysical campaigns

- Rock sampling along the gallery and along the access shaft

- Lidar scanning of the full gallery and photogrametry at surface

Reference model of Lousal
the geophysical campaigns

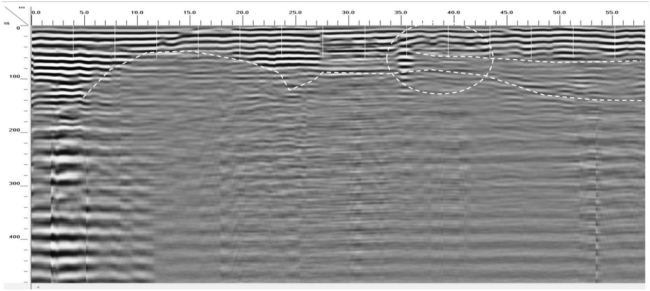
- Rock sampling along the gallery and along the access shaft

- Lidar scanning of the full gallery and photogrametry at surface

- Seismic refraction profiles

- EM absorption/reflection profiles

To extend the existing information and create a reference 3D model



Muography of Lousal
simulation tests and prospects

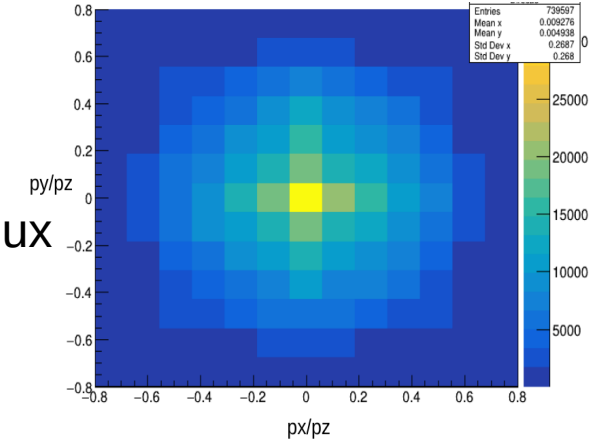
- Geological reference model implementation in Geant4

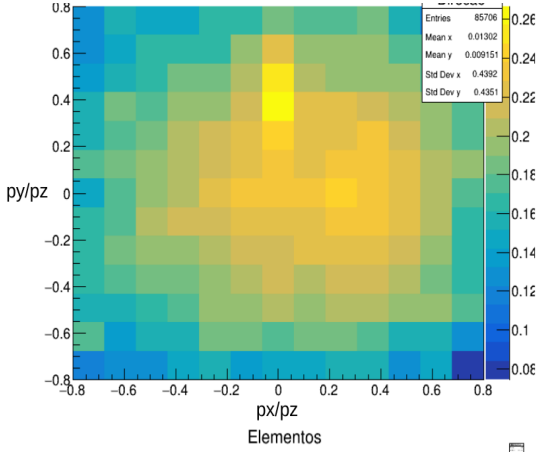
- Detailed atmospheric muon flux

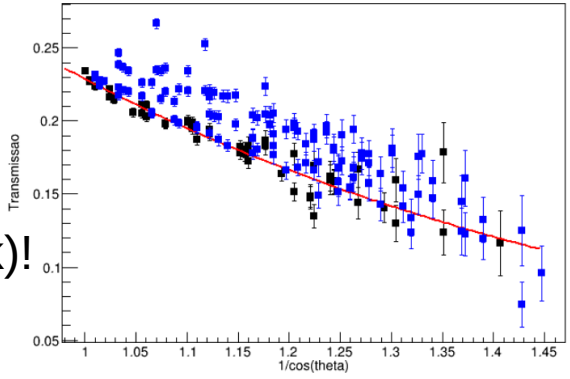
- Simulate all muons that can reach parts of the telescope, taking account scattering (then pass to detector model)

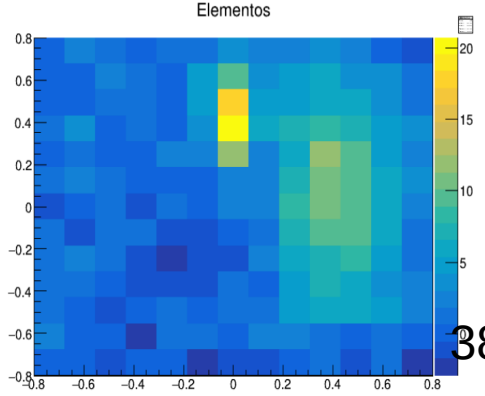
- Previous simple analysis can work for a simplified geometry (air / good rock / fractured rock)!

16 days, full efficiency









Shaft!

Fault!!

Muography of Lousal
viewing the Corona Fault

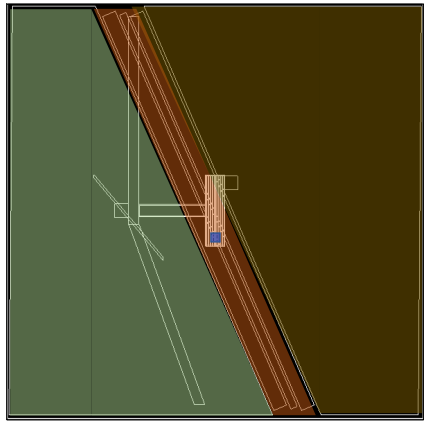
- Now inside the Corona fault!

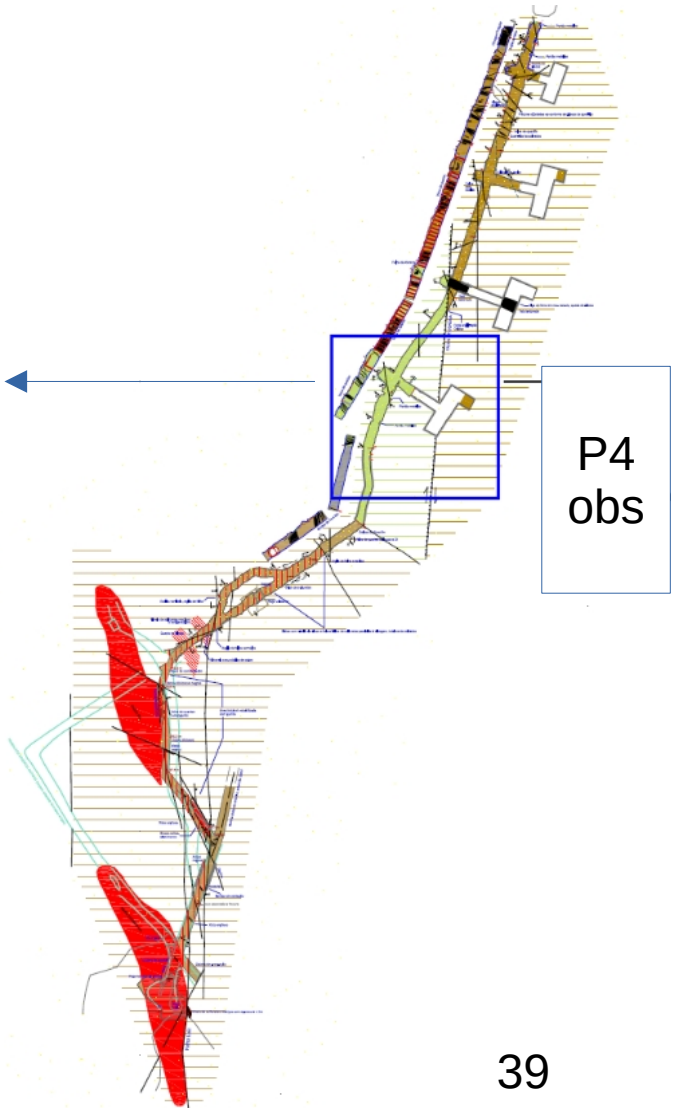
- Expecting small contrasts with seasonal density changes

- Unfragmented rock on the other side of the same room

  but... occupied by bats!

- Several locations to observe the Corona fault, for 3D characterization





Geological model of Lousal
putting together all data

- Check muography vs detailed 3D model to cross-check the new method's results

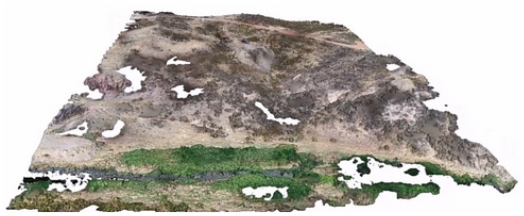
- Invert muography with other geo-data for an improved 3D model of Lousal

- Provide new data to geoscience community and Lousal CV center

- Evaluate muography vs gravimetry: is it useful for sub-surface surveys?

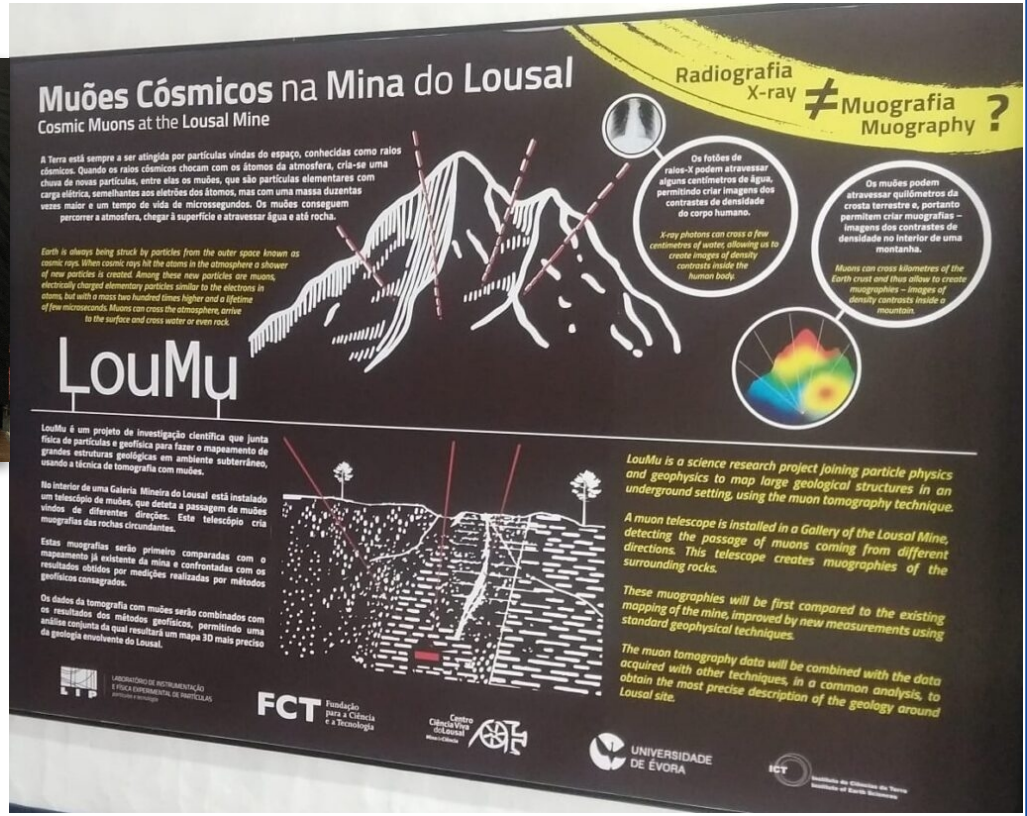
- Tools and methods for new projects!

Digital surface model



Digital elevation model

LouMu in
the “mine of science”



LouMu team
and thank you!

Instrumentation and Particle Physics Team (LIP)

Lisbon Pole:

Bernardo Tomé, Isabel Alexandre, Lorenzo Cazon, Marco Pinto, Mário Pimenta, Luis Afonso, Pedro Assis, Sofia Andringa

Coimbra Pole:

Alberto Blanco, João Saraiva, Jorge Francisco Silva, Luís Lopes, Paolo Dobrilla

Minho Pole:

Magda Duarte, Raul Sarmento

https://pages.lip.pt/loumu

Geophysics Team

ICT – UÉvora:

Bento Caldeira, José Borges, Mourad Bezzeghoud, Pedro Teixeira, Rui Oliveira

LNEG:

João Matos

Outreach Team

CCV do Lousal:

João Costa, Vanessa Pais

+ support from Auger, SWGO, RPC, Detector Lab & Workshops, ECRLab, ECO teams at LIP
+ funding by FCT: EXPL/FIS-OUT/1185/2021