MUOGRAPHY FOR UNDERGROUND GEOLOGICAL SURVEYS

ONGOING APPLICATION AT THE LOUSAL MINE (PORTUGAL)

PEDRO TEIXEIRA

FOR THE LOUMU COLLABORATION

ICT
Instituto de Ciências da Terra
Institute of Earth Sciences

UNIVERSIDADE DE ÉVORA

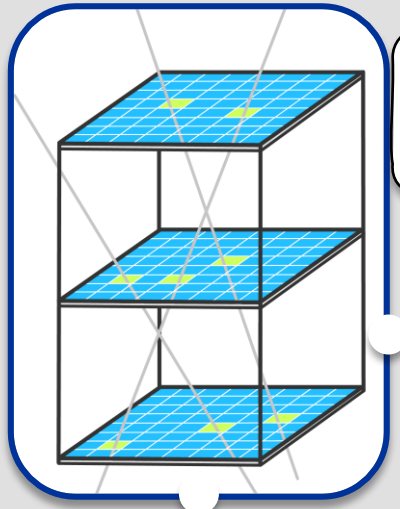
Centro Ciência Viva do Lousal
Mina de Ciência

LIP
LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

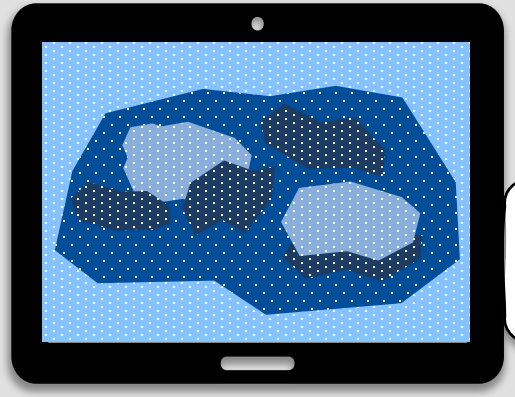
FCT Fundação para a Ciência e a Tecnologia

MUOGRAPHY OVERVIEW

MUOGRAPHY OVERVIEW



Muon detectors assembled in a structure called a **MUON TELESCOPE**

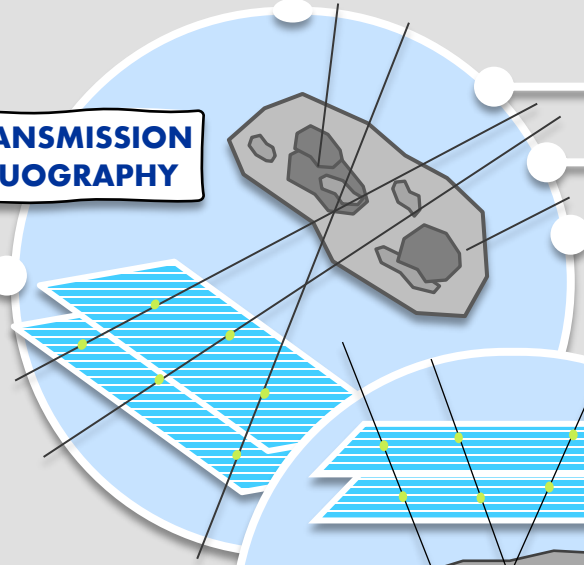


The observation produces images called **MUOGRAPHS**

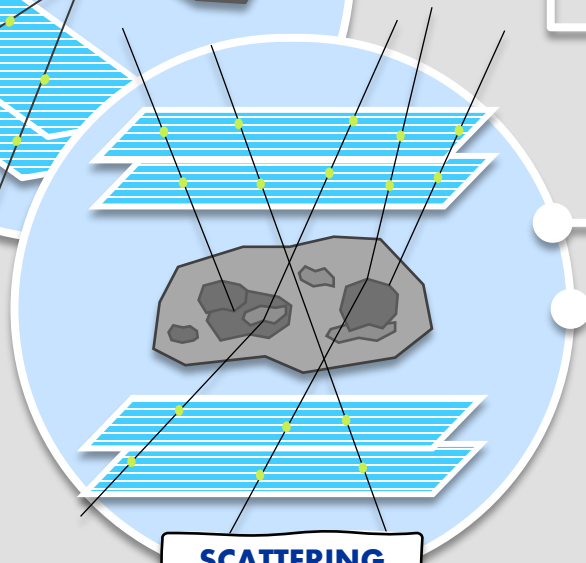
COSMIC RAYS

PARTICLE SHOWERS

ATMOSPHERIC MUONS

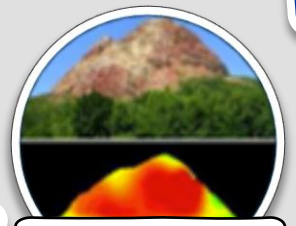


TRANSMISSION MUOGRAPHY



SCATTERING MUOGRAPHY

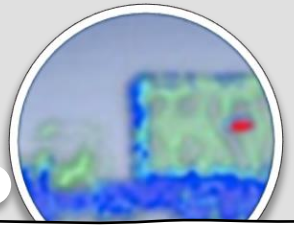
APPLICATIONS IN DIFFERENT FIELDS



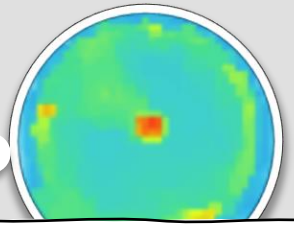
GEOSCIENCES

ARCHAEOLOGY

CIVIL ENGINEERING



CARGO SURVEILLANCE



NUCLEAR REACTOR AND WASTE CONTROL

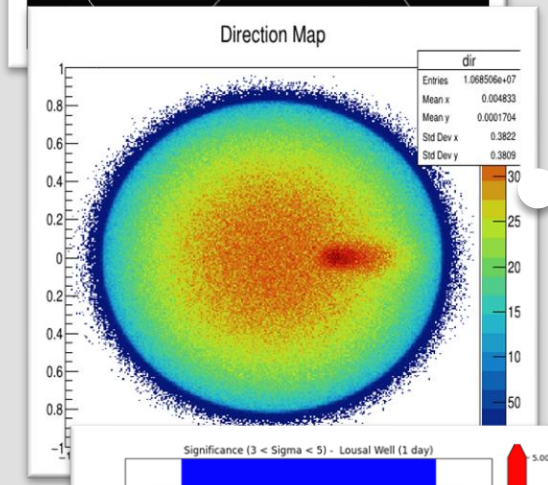
LOUMU PROJECT

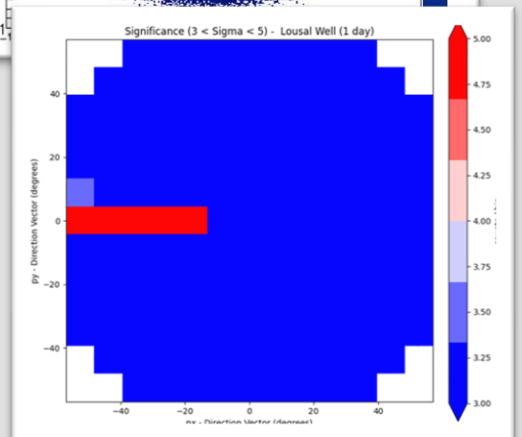
LOUMU PROJECT

LouMu

SCIENCE WITH COSMIC MUONS AT THE LOUSAL MINE

SIMULATIONS AND ANALYSIS TOOLS





LIP

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

partículas e tecnologia

Laboratory of Instrumentation and Experimental Particle Physics (LIP)

PURPOSE: to develop and make muography available in Portugal for applications in geophysics

ICT

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Institute of Earth Sciences of the University of Évora

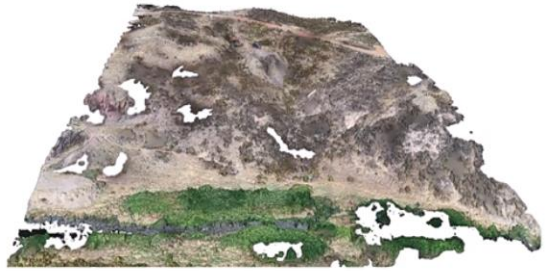
Centro Ciência Viva do Lousal

Mina de Ciência

Lousal Living Science Center

MUOGRAPHY AND TELESCOPES

GEOPHYSICAL WORK



LOUMU TEAM

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Particle Physics and Instrumentation Group

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Bernardo Tomé
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Lorenzo Cazon
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Mário Pimenta
Luis Afonso
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Bento Caldeira
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Centro Ciência Viva do Lousal
MinadeCiência

Outreach Only Group (Science Museum)

João Costa
Vanessa Pais

Sofia Andringa
Particle Physicist
(Principal Investigator of the LouMu)

Pedro Teixeira
Geophysicist
(PhD thesis about LouMu)

TALK
"Muography in the university and in the museum"
Thursday, Nov 25, 2:20 PM

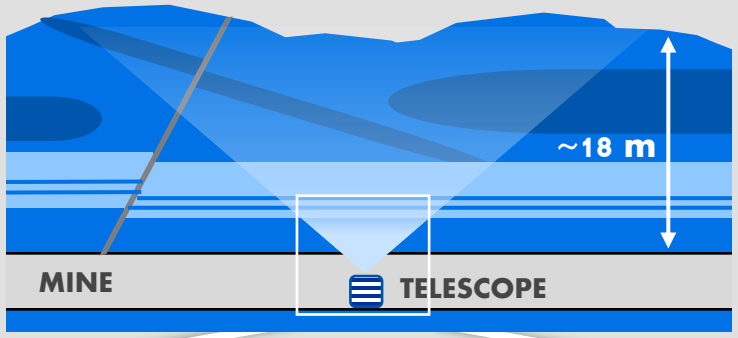
OUTREACH ACTIVITIES

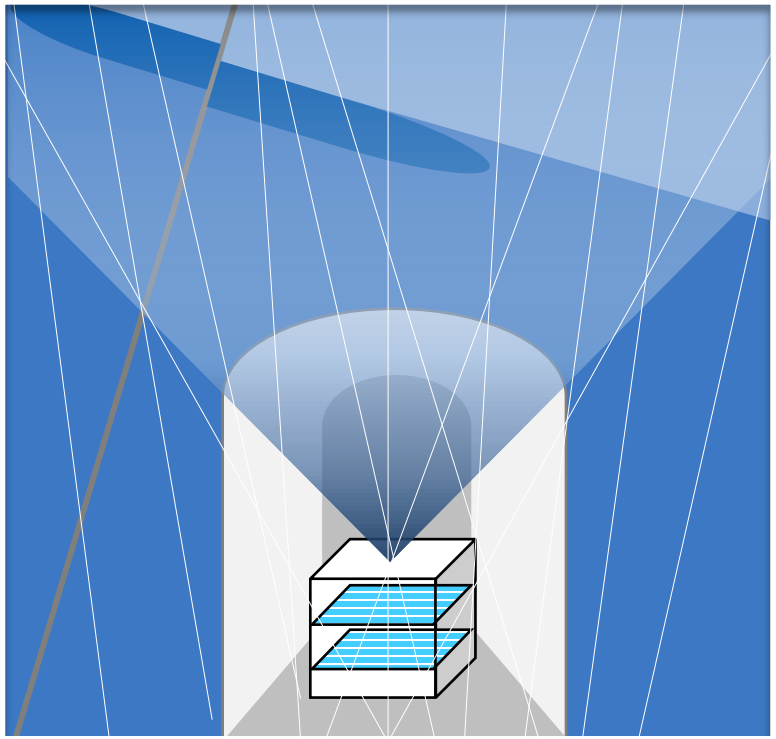
LOUSAL MINE

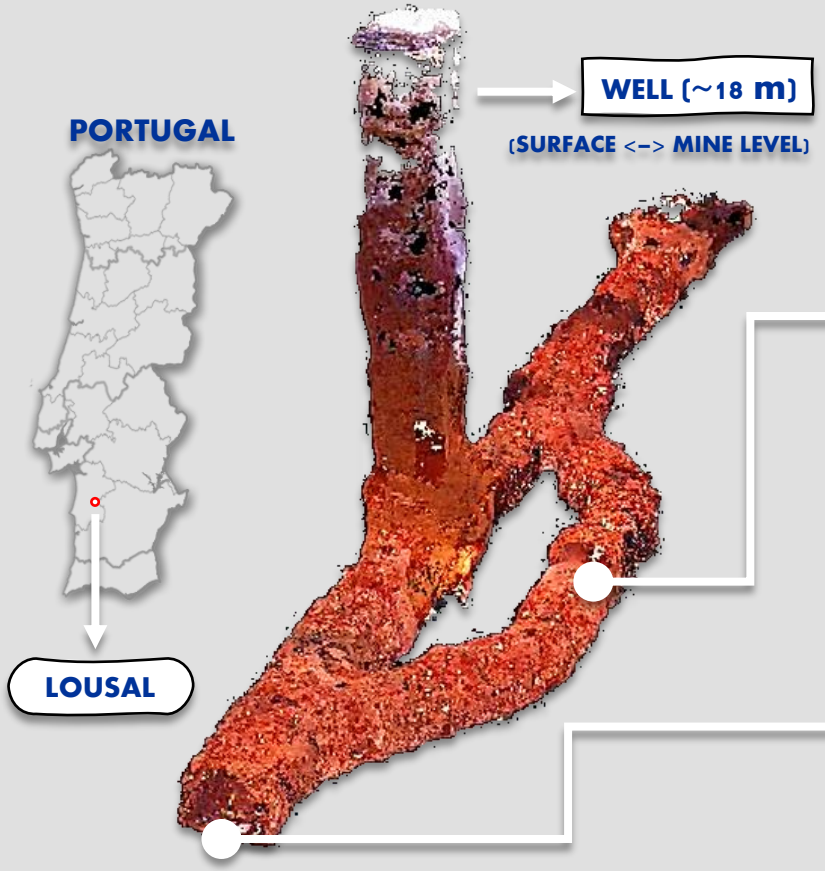
SCANNED SEGMENT OF THE LOUSAL MINE - WALDEMAR GALLERY

PROVIDED BY LIVING SCIENCE CENTER OF LOUSAL

LOUSAL MINE

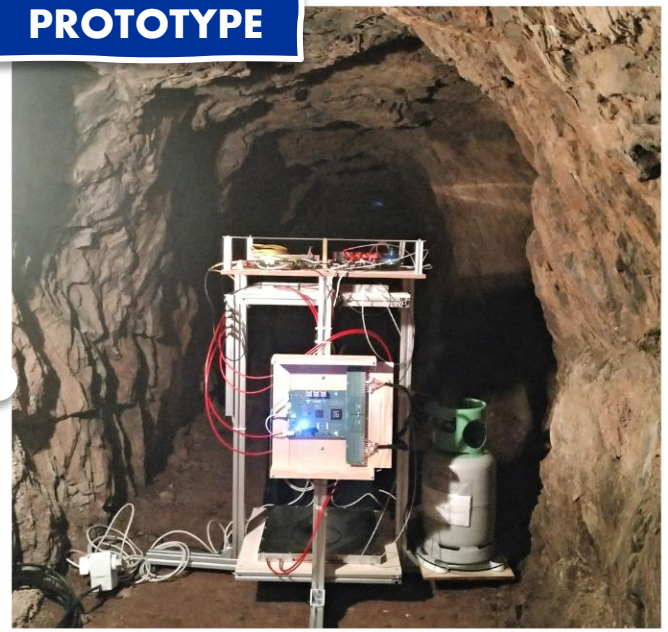




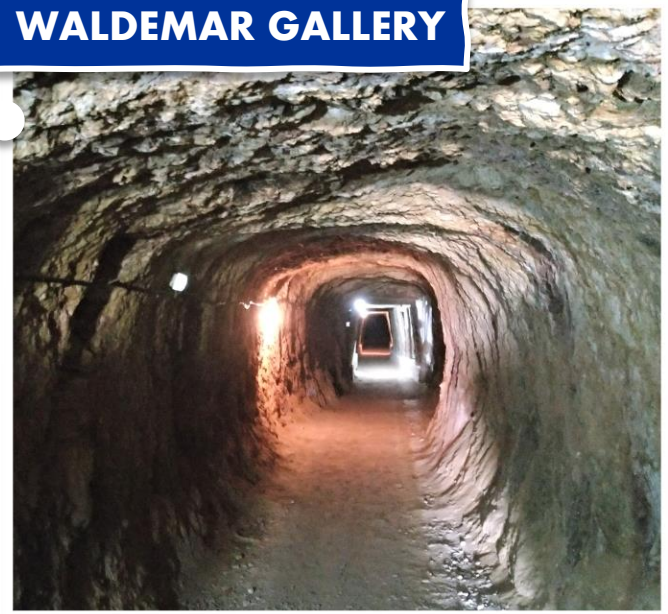


GOAL: to do a geological survey with muography of the terrain between the telescope and the surface and improve the existing information with new data while evaluating the performance of the telescope and the muography analysis.

PROTOTYPE



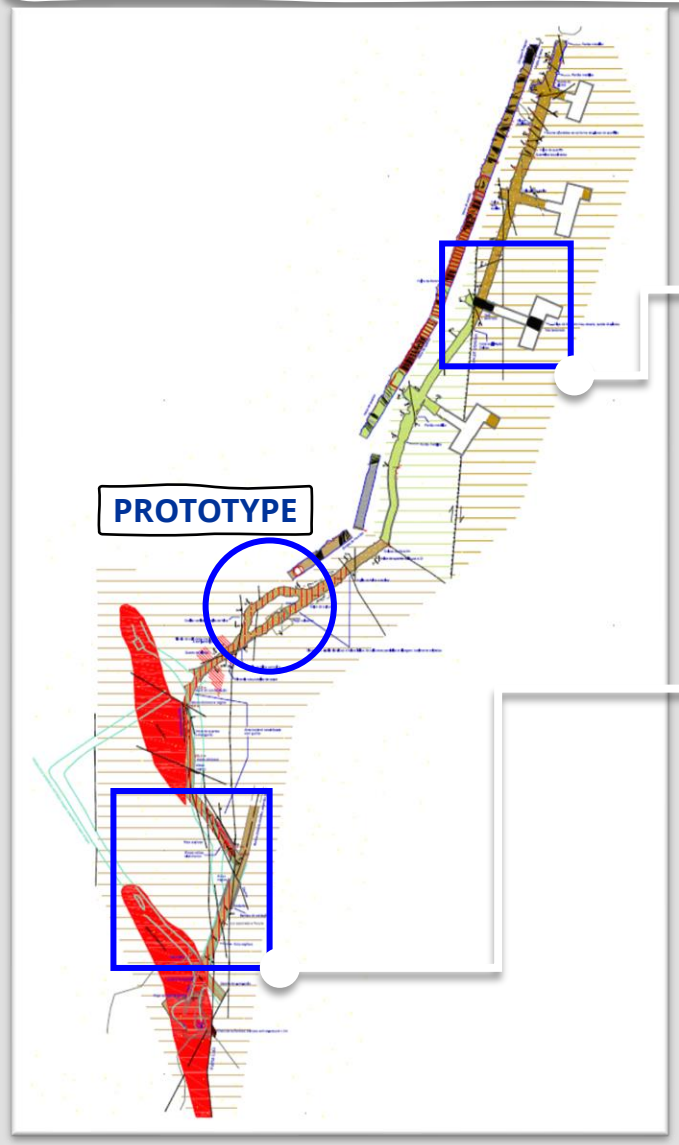
WALDEMAR GALLERY

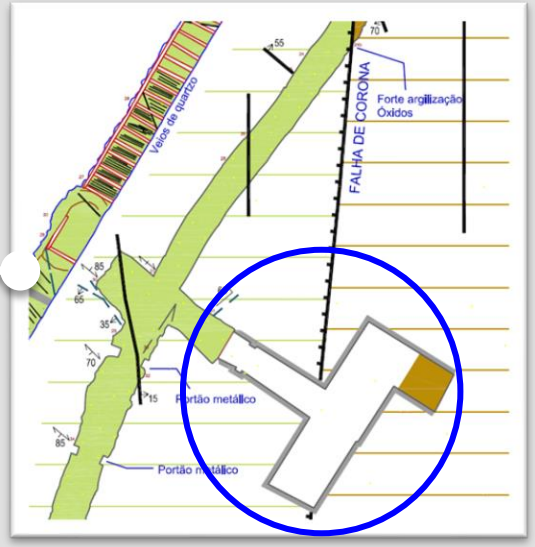


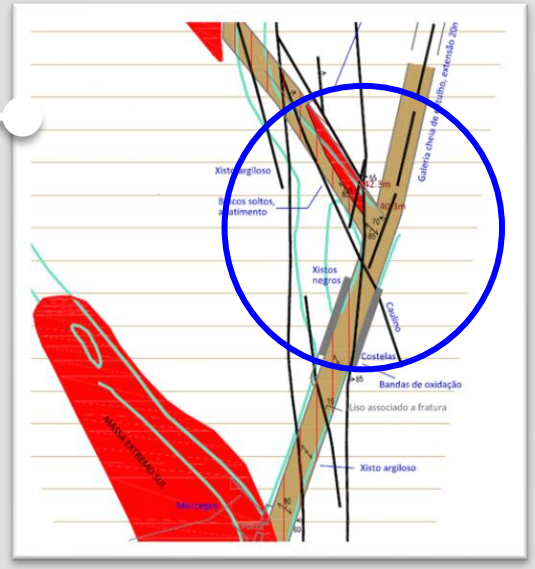
OBSERVATION MAIN TARGETS

We expect these targets to offer density contrasts that make them able to be identified with muography.

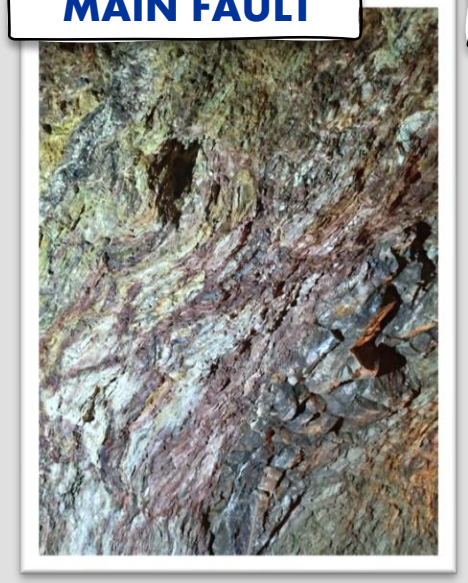
WALDEMAR GALLERY MAP – OBSERVATION LOCATIONS



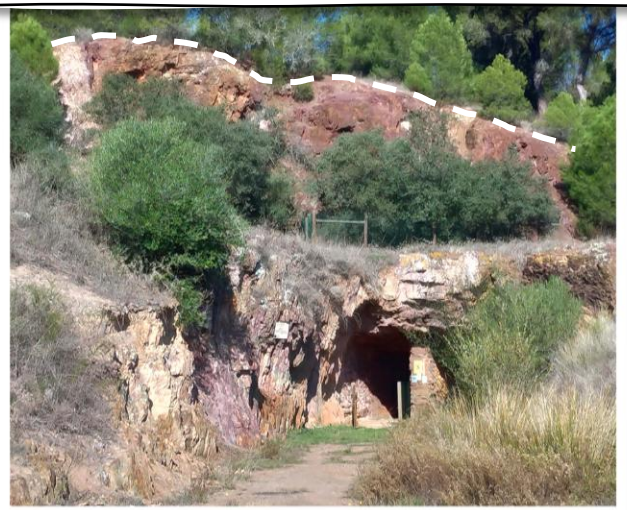


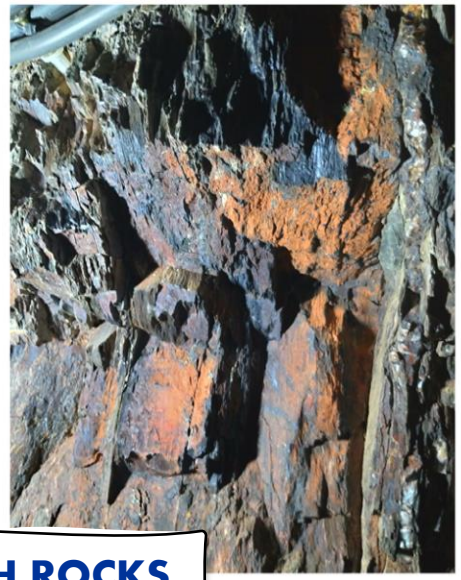


MAIN FAULT



IRON CAPROCK ABOVE GALLERY



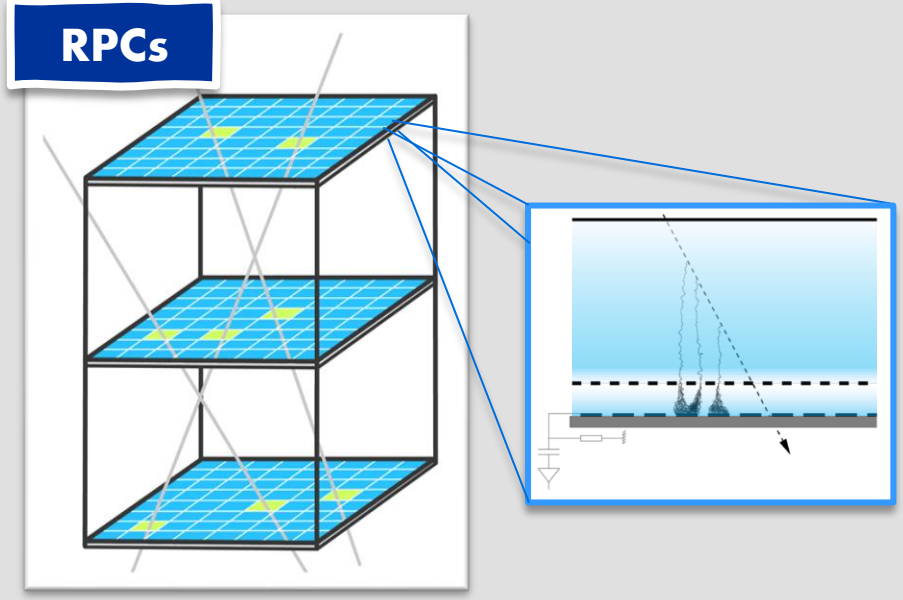


IRON-RICH ROCKS

DETECTORS AND TELESCOPE

MUON DETECTORS / RPCs

RPCs



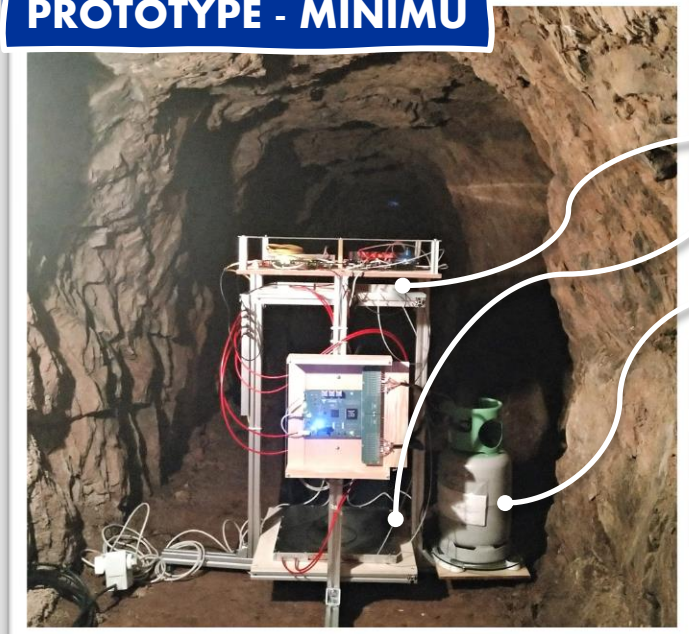
WHAT TYPE OF DETECTORS OUR TELESCOPES USE ?

- RPCs (Resistive Plate Chambers) are particle detectors that contain a mixture of an ionizing gas.
- The passage of muons ionize the gas and causes an avalanche of electrons, which produce an electrical signal.
- The gas is sent to the RPCs and collected with a low flux, from a container outside the mine, without leakage to the environment.

WHY WE USE RPCs ?

- LIP developed these detectors autonomously for the Pierre Auger laboratory, so they are an “house acquisition”.
- The characteristics of its operation can be adapted according to the temperature and humidity of the environment.
- RPC detectors are an ideal choice for good angular resolution and for tracking the detection in real time.
- They have a low gas and electricity consumption and low maintenance needs. Ideal for remote and outdoor environments.

PROTOTYPE - MINIMU



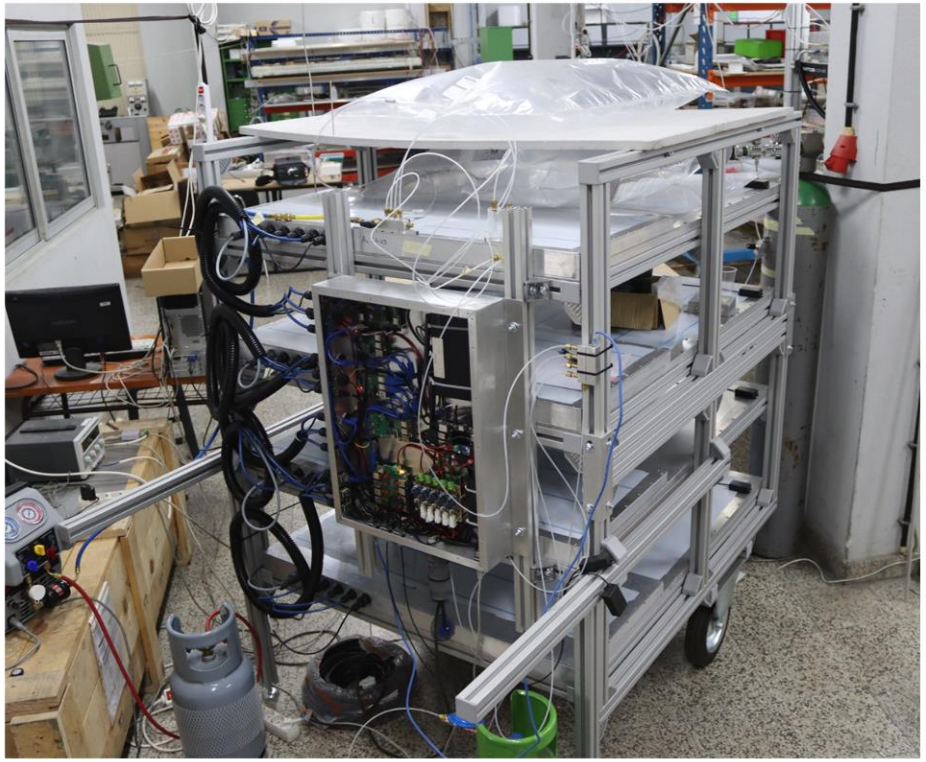
MINIMU

- 2 RPC planes
- Each RPC is 30 cm x 30 cm square shaped and 3x3 pixels
- The gas container now sits outside the gallery

MUON TELESCOPE / COREPIX

- Our muon telescope, nicknamed "**CorePix**", is currently in the LIP laboratory collecting data for calibration purposes, before being moved to the Lousal Mine.

RPCs AND ELETRONICS ASSEMBLED



4 RPC DETECTORS

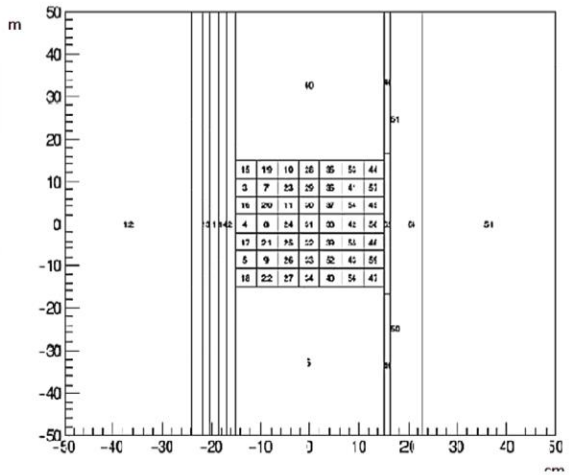
1

2

3

4

RPC MAIN CONFIGURATION

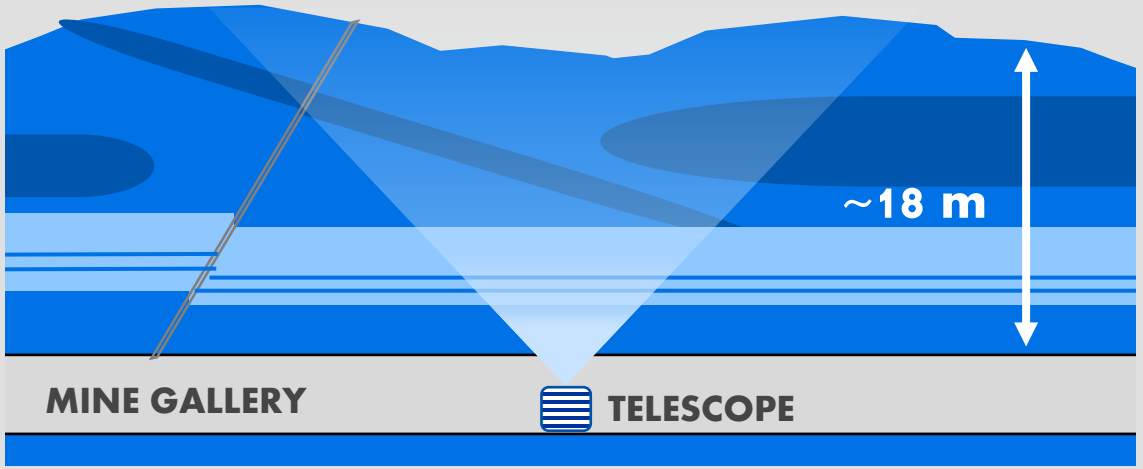


COREPIX

- 4 RPC detectors
- 64 channels (pixels) each
- Each RPC is 1 m x 1 m square shaped
- Detection pads configured in different shapes
- Higher resolution in the center (CorePix)

SIMULATIONS AND ANALISYS TOOLS

UNDERGROUNG MUON FLUX / Φ



THEORETICAL MUON FLUX VALUES *

$$\Phi = \frac{dN_\mu}{dA\ dt}$$

*Total muon flux integrated in energy and angle

	$h = 0\ m$	$h = 20\ m$
$\Phi_{TOTAL}/m^{-2} \cdot s^{-1}$	$\approx 250\ \mu$	$\approx 30\ \mu$

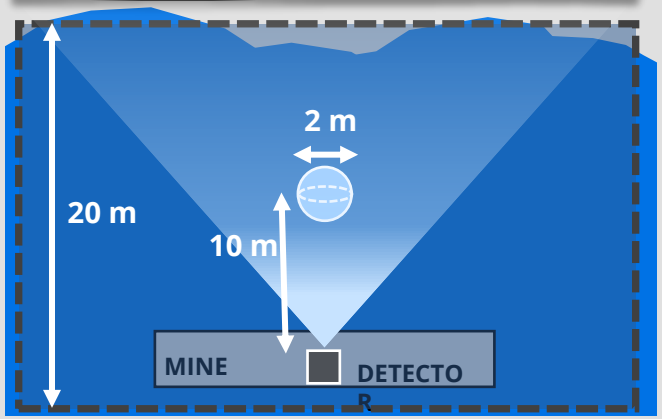
- Around the mine level, only 12% of the surface muon flux has the probability to reach the detectors

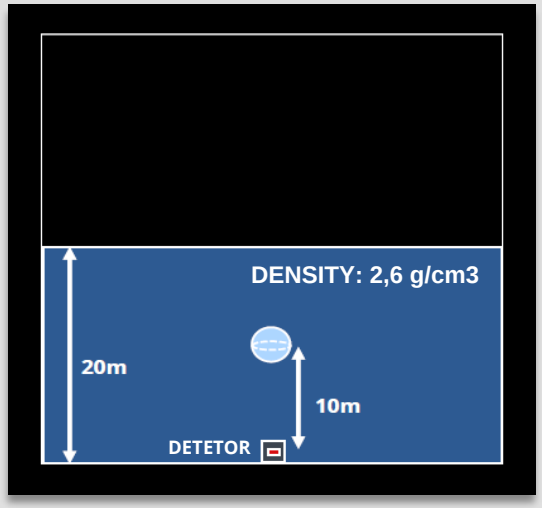
UNDERGROUND MUOGRAPHY

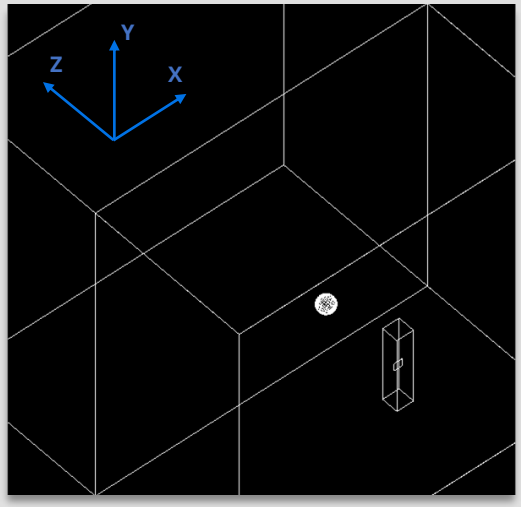
- Muography with muon telescopes in an underground setting has an easy side due to the absence of the background radiation.
- On the other hand, the muon flux is much lower compared to what is measured on the surface.
- It is a matter of geological and underground conditions, suitable muon detectors and the necessary exposure time to carry out the observation.

GEANT SIMULATIONS

BUILDING A SIMPLE GEOMETRY







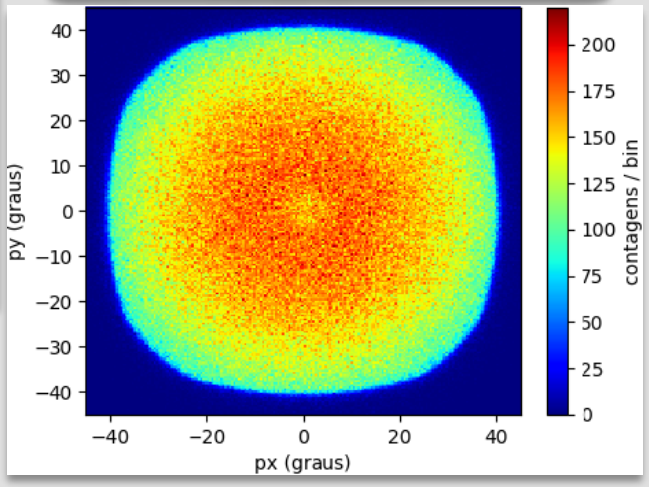
ORE SPHERE SIMULATIONS

- Our first approach was a simple geometry of an ideal scenario, where a sphere was used to study the exposure time needed to distinguish different ore minerals in the simulations muographs.

SOME MINERAL ORES TESTED IN THE SPHERE – TIME NEEDED TO DISTINGUISH

Ore	Metal	Density (g/cm3)	Density Difference	1 hour	3 hours	6 hours	12 hours	1 day	2 days	4 days	8 days	16 days	32 days	64 days
---	GROUND	2,6		o	o	o	o	o	o	o	o	o	o	o
Al(OH)3	Aluminium	2,35	-0,25							X	V	O	O	O
LiAlSi4O10	Lithium	2,4	-0,2	h	h	h	h	h	h	X	X	X	Y	Y
ZnS	Zinc	3,85	1,25	X	X	X	X	X	X	Y	Y	O		
Cu5FeS4	Copper	5,07	2,47					V	V	O				
Fe3O4	Iron	5,175	2,575					V	V	O				
Fe2O3	Iron	5,3	2,7						V	O				
Cu2S	Copper	5,65	3,05					Y	V	O				
CaWO4	Tungsten	6	3,4					V	O					
SnO2	Tin	7,04	4,44			Y	V	O	O					
0,2 x FeWO4 + 0,8 x MnWO4	Tungsten	7,25	4,65			Y	V	O						
PbS	Lead	8,9	6,3			O	O	O						

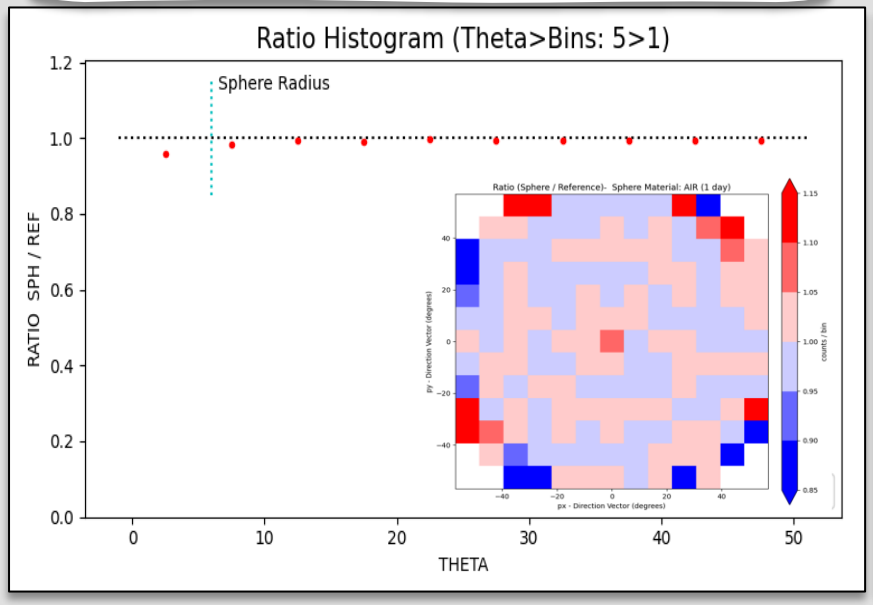
WITH SPHERE OF Fe_2O_3 – 2 DAYS



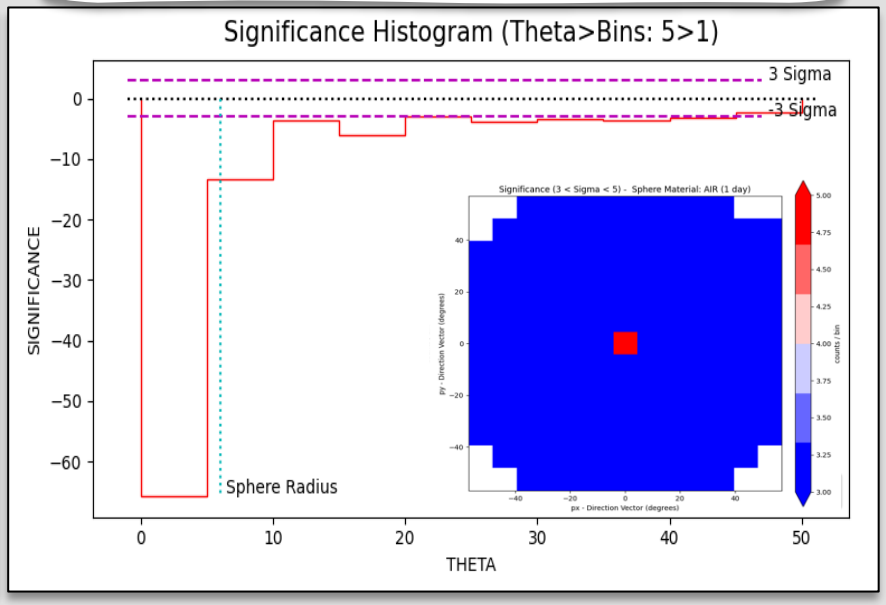
- This geometry is a simplification of the mine scenario. The ground is made of a homogeneous chemical compound equivalent to shale, as observed in the mine. The sphere has 1 m radius and is located in the middle and above the detector.

QUANTITATIVE ANALYSIS PARAMETERS

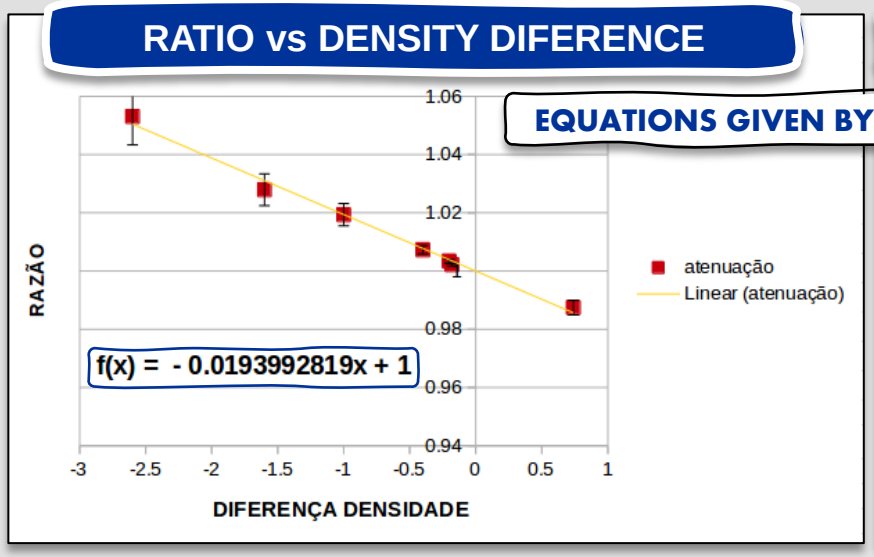
RATIO



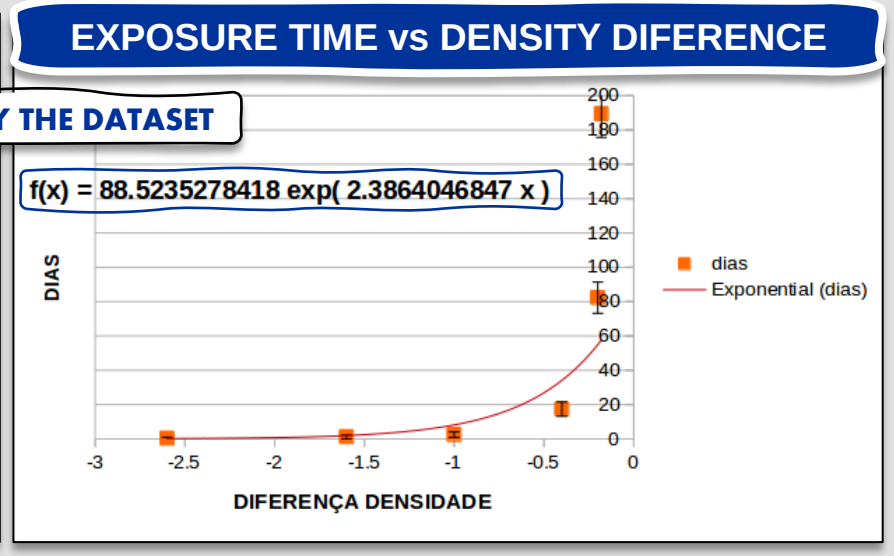
SIGNIFICANCE



RATIO vs DENSITY DIFERENCE



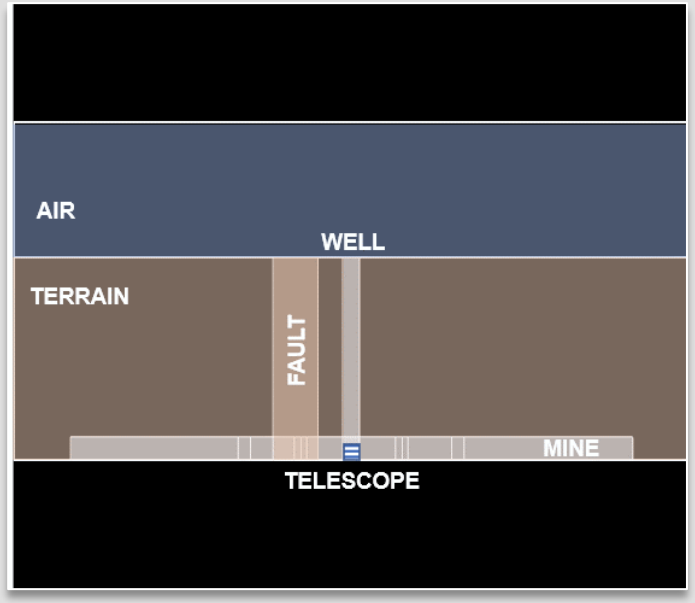
EXPOSURE TIME vs DENSITY DIFERENCE



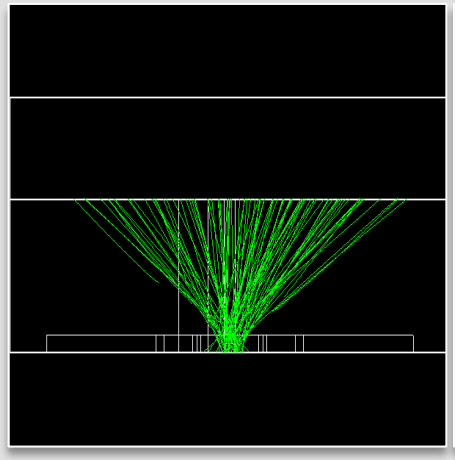
- In the simulation analysis, the Ratio and the Significance are the quantitative parameters that are used.
- By applying them, the probabilistic fluctuations of the muon counts are attenuated, and the density contrasts become clear. The results can be viewed in 1D or 2D histograms.
- By plotting the dataset values given by the simulations, for fixed conditions, we obtain the general equations that can be used to extrapolate the Ratio and the Exposure Time needed for most minerals in function of the density difference with the ground medium mean density.

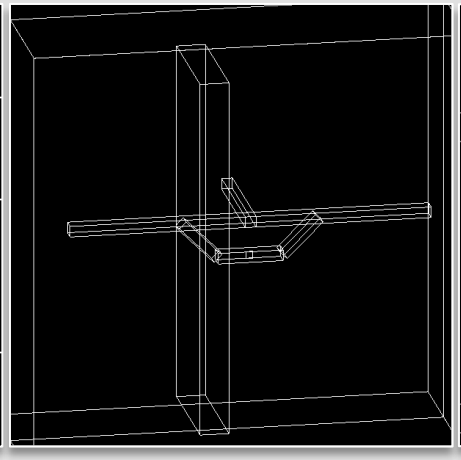
A MORE REALISTIC SCENARIO

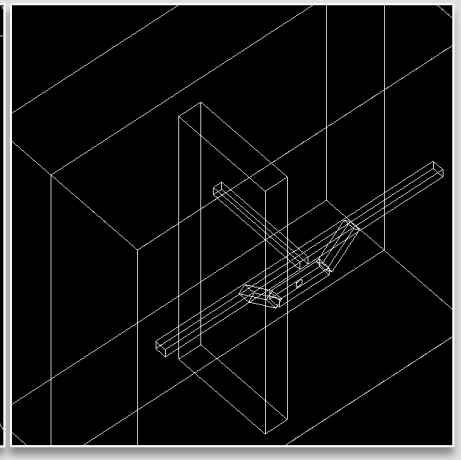
WALDMAR GALLERY CROSSED BY A FAULT ZONE



- Our latest approach uses a more realistic geometry of the Waldemar Gallery, that is crossed by a fault zone that has a mean density lower than the terrain.

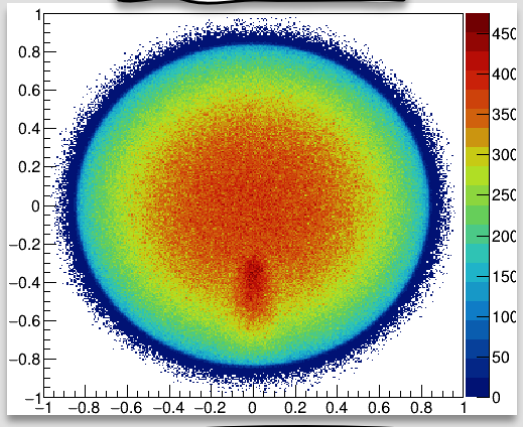




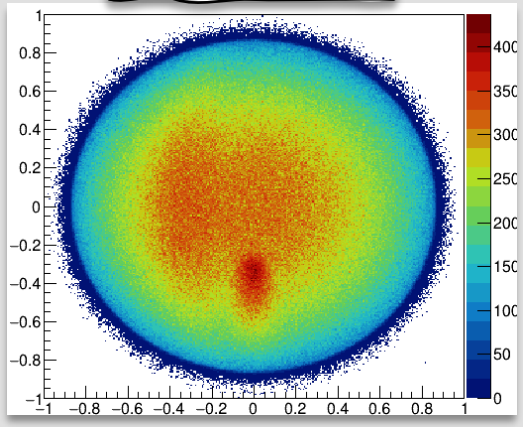


MUOGRAPHS

WITHOUT FAULT

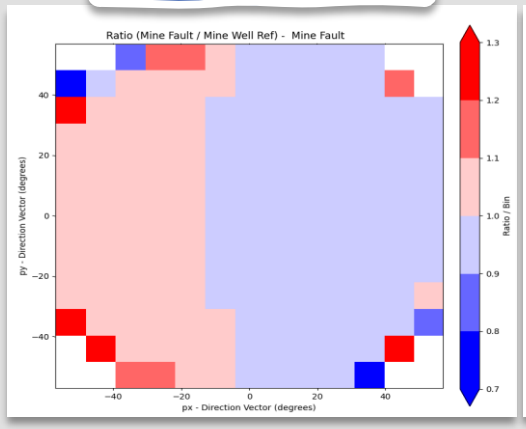


WITH FAULT

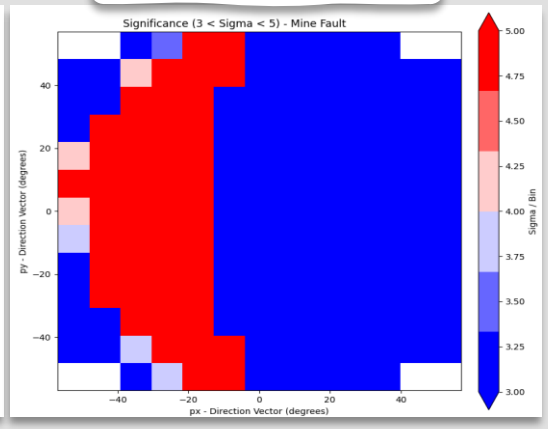


- The presence of the fault zone changes the symmetry of the muon counts, when compared to the muograph without the fault, with only the well visible (red spot).
- Applying the analysis parameters to both muographs, the well is subtracted and only the fault stands out, because it's the difference between the two.

RATIO



SIGNIFICANCE



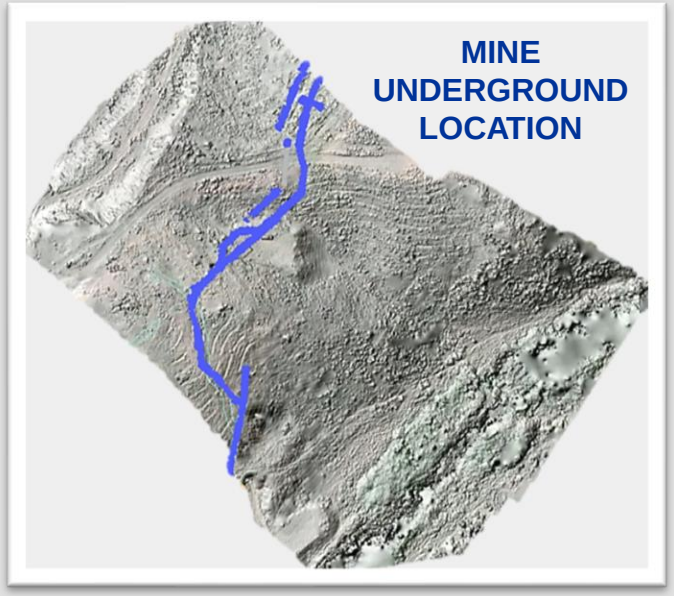
GEOPHYSICAL WORK

DIGITAL ELEVATION MODEL

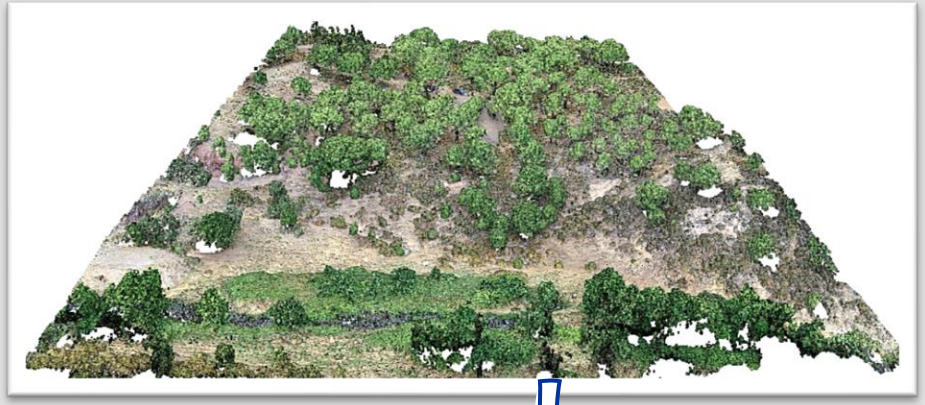
PHOTOGRAMMETRY

DRONE

- Through some steps, the digital elevation model, or DEM, can be converted in a Geant geometry for simulation.
- A detailed characterization of the topography is needed to compare the observed information with the expected results, so that the attenuation caused by topographic differences can be normalized.

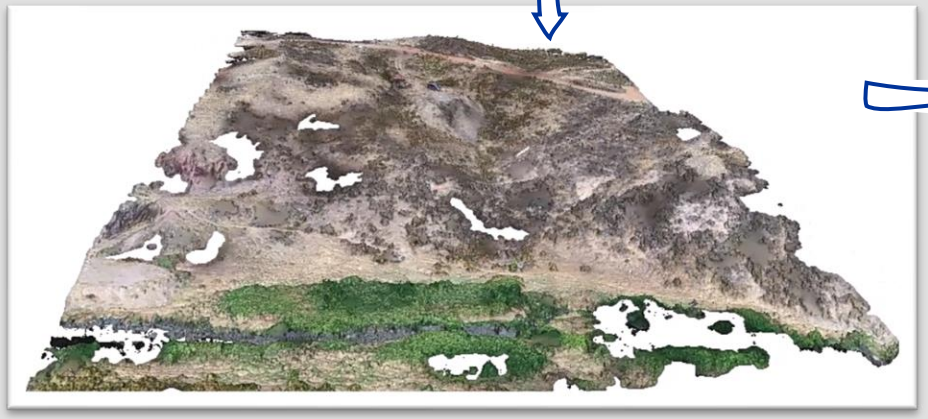


DIGITAL SURFACE MODEL

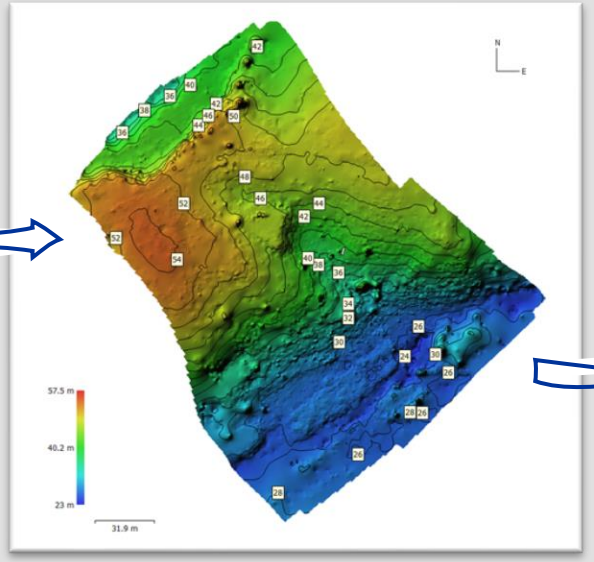


- The computational feasibility of using this detailed geometry in big simulations is still in study.

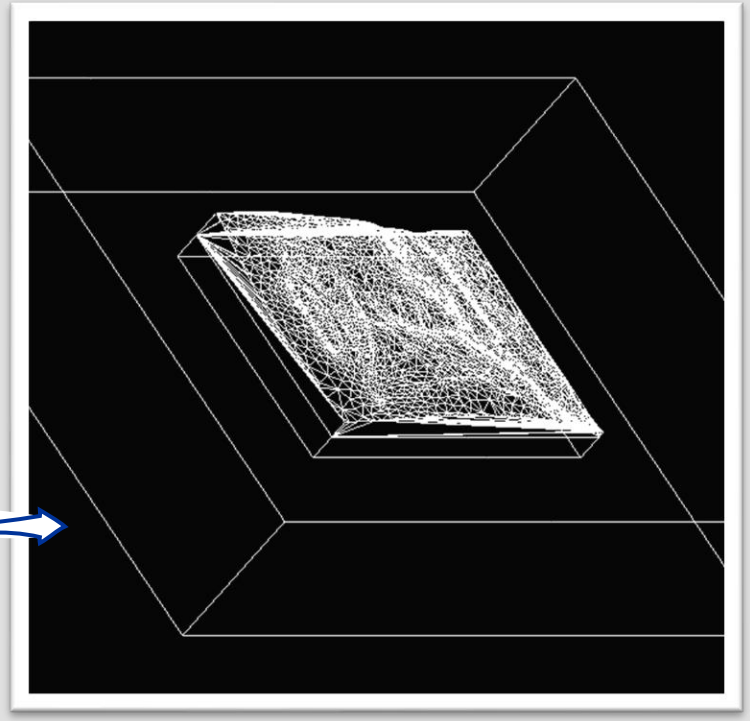
DIGITAL ELEVATION MODEL



DEM WITH COUNTOUR LINES



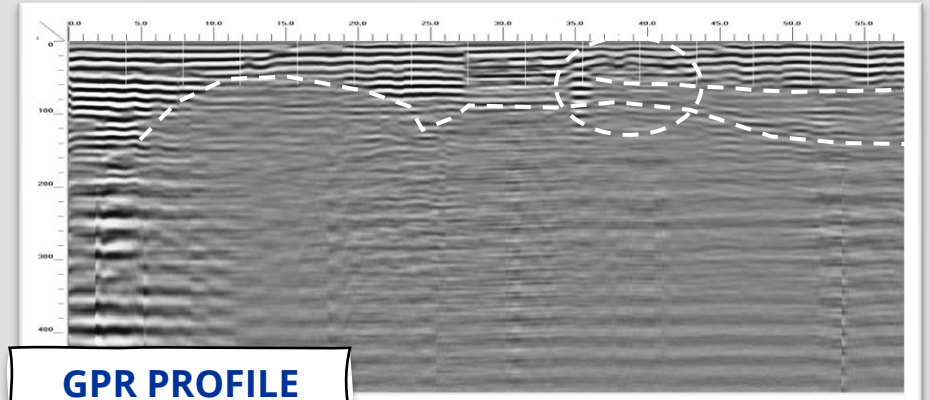
DIGITAL MESH IN GEANT4



GROUND PENETRATING RADAR

GPR ANTENNA

- The GPR antenna emits electromagnetic pulses through the ground and measures the dielectric constant of the materials.

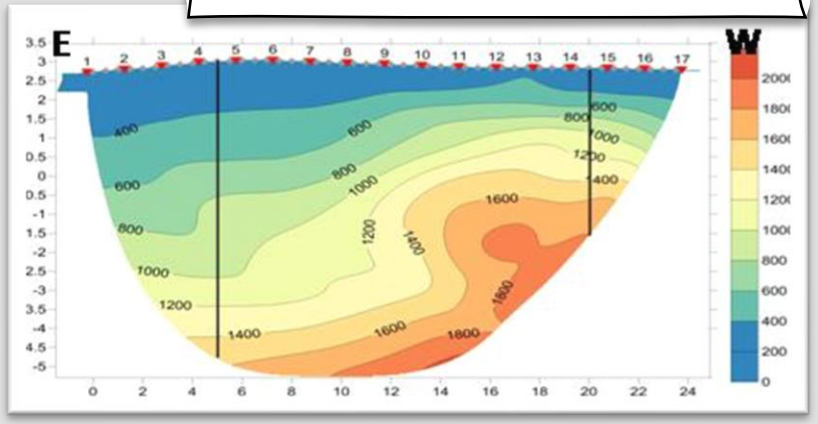


GPR PROFILE

SEISMIC REFRACTION

GEOPHONES

2D VELOCITY MODEL



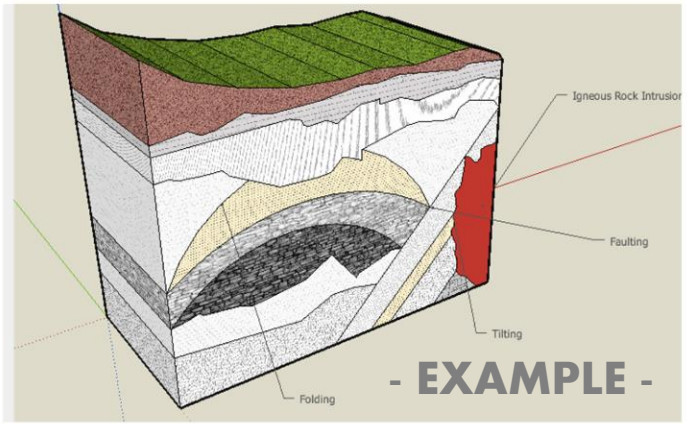
- The geophones detect the vibration waves induced on the ground with hammer strokes and measure the propagation speed of these waves through the ground.

WORK PROGRESSION

STANDARD TECHNIQUES

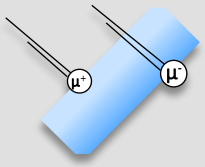
PHOTOGRAMMETRY + **GPR** + **SEISMIC REFRACTION** =

REFERENCE GEOLOGICAL MODEL



FOCUS TECHNIQUE

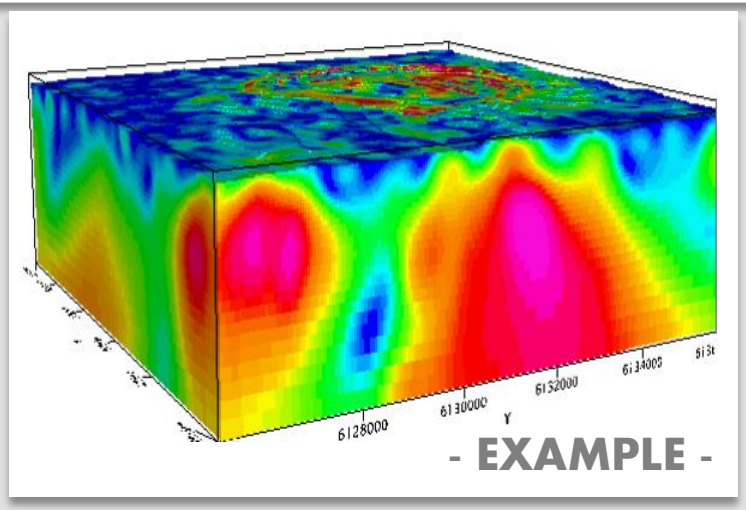
MUOGRAPHY → **SIMULATIONS** / **ANALYSIS TOOLS** → **TELESCOPE**



$$\phi \propto \frac{1}{\rho}$$

$$g \propto \rho$$

RECONSTRUCTED 3D DENSITY MODEL



JOINT INVERSION (FUTURE)

MUOGRAPHY + **GRAVIMETRY**

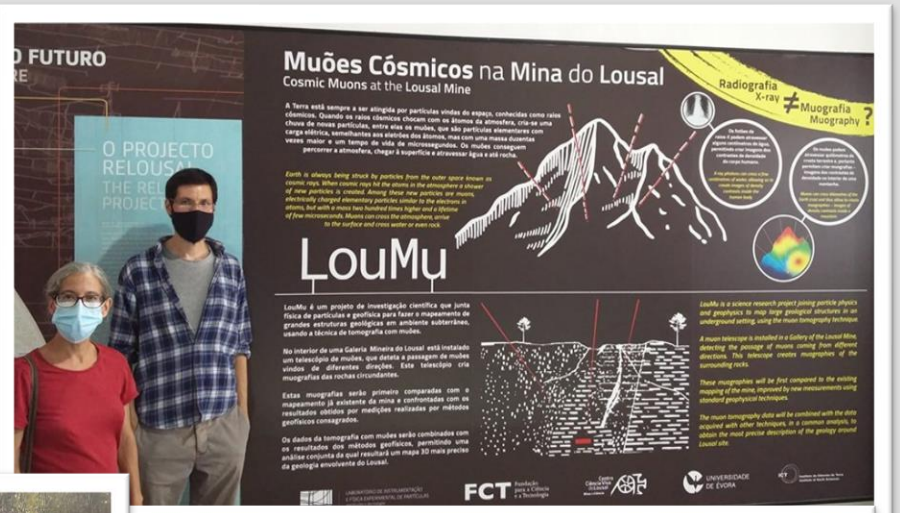
MUOGRAPHY	GRAVIMETRY
obtains the density through the attenuation of the muon flux	obtains the density through the strength of the gravitational field

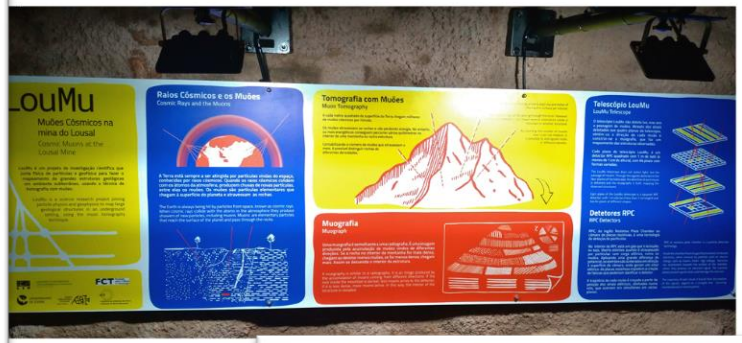
PROJECT OUTPUT AMBITIONS

- LouMu is a local project where the muography technique is being developed independently.
- We are confident that one of our strengths are the opportunities that arise and are created from having a multidisciplinary team and the capacity for education and outreach.

OUTPUTS

- To add geological information about Lousal to the national heritage.
- To make available functional and stand-alone telescopes for the geophysical community.
- Generalized muography methods to apply in other scenarios.
- A trained multidisciplinary team with comprehensive knowledge that can transfer it to other communities.
- Educate local academic and general publics about muography.





THANK YOU!

EMAIL

mutom-info@lip.pt

WEBPAGE

https://pages.lip.pt/loumu/en/

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

UNIVERSIDADE DE ÉVORA

ICT
Instituto de Ciências da Terra
Institute of Earth Sciences

Centro Ciência Viva do Lousal
Mina de Ciência

FCT Fundação para a Ciência e a Tecnologia

IDPASC-FCT: PD/BD/150490/2019
I&D: EXPL/FIS-OUT/1185/2021

LOUSAL MINE