

# Muography for geophysical survey at the Lousal mine

Muography 2023  
June, Naples



Sofia Andringa, [sofia@lip.pt](mailto:sofia@lip.pt)  
for the LouMu collaboration



LIP: Instrumentation and Experimental Particle Physics

ICT: Earth Sciences @UÉvora

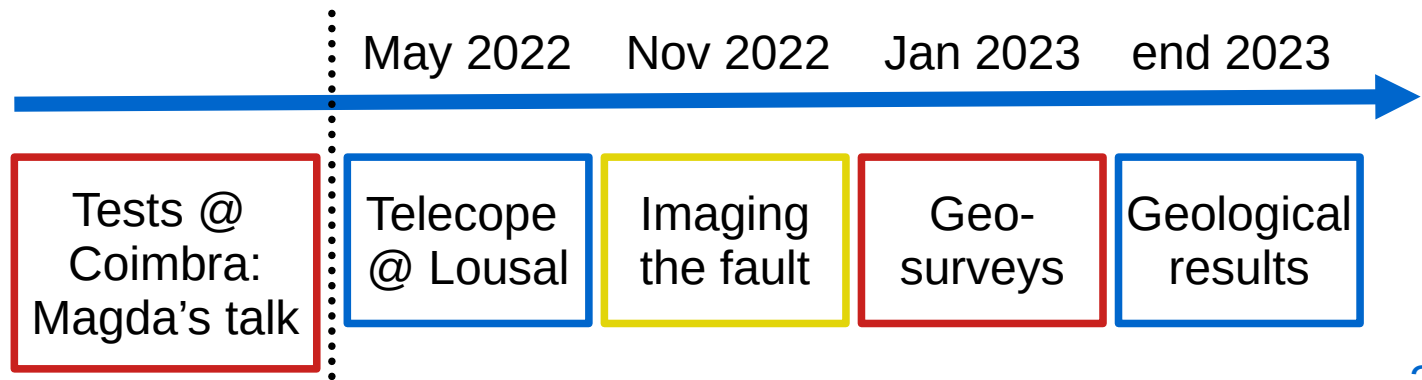
Mina de Ciências: Public Science Center

LNEG: Energy & Geology

<https://pages.lip.pt/LouMu>

# LouMu project: the team, goals and timeline

1. Test operation of an RPC muon telescope in a mine: gas flow constraints in confined (public) space
2. Test muography for geophysical subsurface imaging: target the regional Corona geological fault
3. Develop methods for geophysical muographic analysis: compare and combine with other surveys
4. Assess and communicate muography capability: for future users and the public at large



## the LouMu RPCs

spin-off from R&D for the  
Pierre Auger Observatory



## LIP R&D in RPCs for different applications

1. high resolution TOF trackers
2. high resolution PET imaging
3. epi-thermal neutron detection
4. **cosmic ray experiments**

- > automatic adjustment for environmental conditions
- > low maintenance & low consumption
  - fed by solar powered stations
  - 4 cc/min of R-124a gas
- > 64 channels read by FEE based on MAROC-3



*LouMu uses much smaller pads and guard rings*



*but the same basic RPC structure:*

- gas in 2 gaps of 1mm
- separated by 2mm of glass
- readout from the pads on the top

# the LouMu telescope

entering the Lousal Mine



it seems slightly too large!

4 x 1m x 1m planes, 64 channels each  
telescope can be moved, tilted and adjusted for focus

HV adjustment with environmental parameters  
(temperature and humidity very stable in the mine gallery)

Feeding gas bottle exchanged few times a year  
(used gas is re-compressed into bottles for recycling)



communication and gas flow from outside the gallery (~100 m)

in the Museum

Mine of Science  
part of Ciência Viva  
National Network

@Lousal devoted to mining  
and underground sciences



**Muões Cósricos na Mina do Lousal**  
Cosmic Muons at the Lousal Mine

A terra está sempre a ser atingida por partículas vindas do espaço, conhecidas como raios cósmicos. Quando de mais elevada densidade que as demais do planeta, criam-se uma classe de muões particulares, entre eles os muões, que são partículas abundantes com larga penetração através da crosta da Terra, cruzando com uma massa densa e pesada, nasce a um tempo de vida de microsegundos. Os muões carregam o momento e a matéria, chegam à superfície a atravessar água e até rochas.

*Earth is always being struck by particles from the outer space known as cosmic rays. When cosmic rays hit the atoms in the atmosphere a shower of new particles is created. Among these come muons, the most penetrating charged elementary particle on earth in the universe. Muons can cross the thickness of the Earth's crust and that allow them to penetrate through the crust of the planet. As they cross a dense and heavy material, muons are created and their lifetime is measured in microseconds.*

**LouMu**

LouMu é um projeto de investigação científica que junta física de partículas e geofísica para fazer o mapeamento de grandes estruturas geológicas em ambientes subterâneos, usando a técnica de tomografia com muões.

Na galeria de uma Galeria Minária da Lousal está instalado um telescópio de muões, que detecta a passagem de muões vindos de diferentes direções. Esta tecnologia cria muógrafias das rochas circundantes.

Estes muógrafias serão primeiro comparadas com o mapeamento já existente da mina a condições com os muógrafias criadas por muógrafias realizadas por técnicas geofísicas convencionais.

Os dados de tomografia com muões serão combinados com os mapeamentos das técnicas geofísicas. Isto permitirá obter uma imagem completa do que se encontra em uma mina 3D mais precisa e geológica semelhante da Lousal.

**Radiografia X-ray ≠ Muografía Muography?**

Os feixes de raios-X podem penetrar alguns centímetros de água, gerando uma imagem das estruturas de densidade do corpo humano.

*These particles can cross a few centimeters of water, allowing us to generate images of the human body.*

Os muões podem atravessar aproximadamente 100 metros de rocha terrestre e, portanto, permitem criar muógrafias – imagens das estruturas de densidade no interior de uma montanha.

*Muons can cross thousands of the Earth's crust and that allow them to generate muography – images of density structures inside a mountain.*

LouMu é um projeto científico que junta física de partículas e geofísica para fazer o mapeamento de grandes estruturas geológicas em ambientes subterâneos, usando a técnica de tomografia com muões.

*LouMu is a science research project joining particle physics and geophysics to map large geological structures in an underground setting, using the muon tomography technique.*

Um telescópio de muões é instalado numa galeria da Mina do Lousal, detectando a passagem de muões vindos de diferentes direções. Este telescópio cria muógrafias das rochas circundantes.

*A muon telescope is installed in a Gallery of the Lousal Mine, detecting the passage of muons coming from different directions. This telescope creates muographies of the surrounding rocks.*

Estes muógrafias serão primeiro comparadas com o mapeamento já existente da mina a condições com os muógrafias criadas por técnicas geofísicas convencionais.

*These muographies will be first compared to the existing mapping of the mine, improved by new measurements using standard geophysical techniques.*

Os dados de tomografia com muões serão combinados com os mapeamentos das técnicas geofísicas. Isto permitirá obter uma imagem completa do que se encontra em uma mina 3D mais precisa e geológica semelhante da Lousal.

*The muon tomography data will be combined with the data acquired with other techniques, in a common analysis, to obtain the most precise description of the geology around Lousal site.*

FCT, UNIVERSIDADE DE ÉVORA, ICT, IGP, CITEC

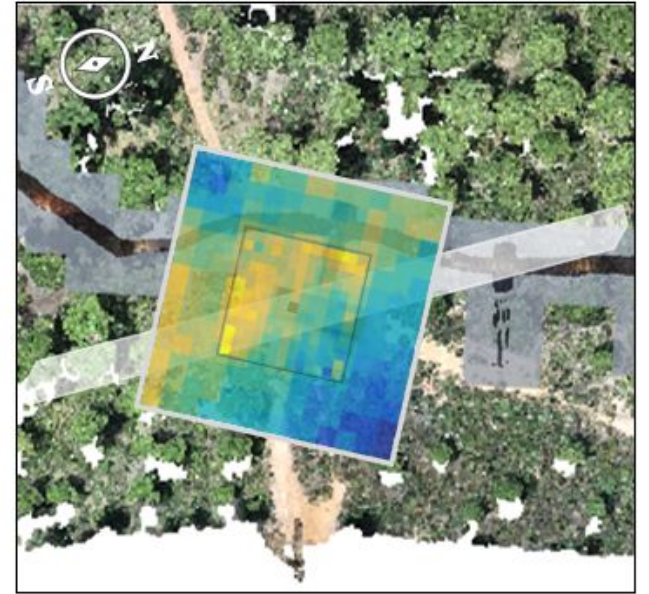
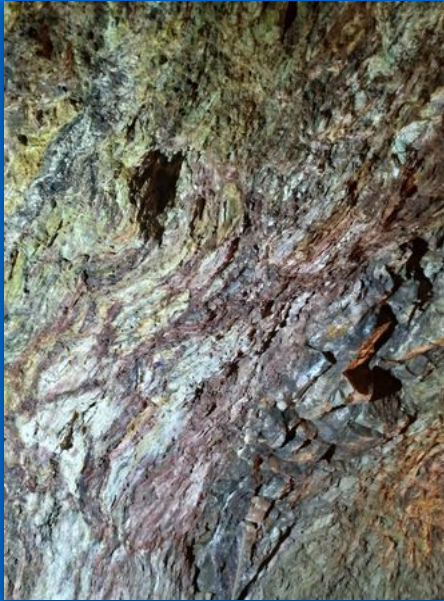


<https://lousal.cienciaviva.pt/>  
<https://pages.lip.pt/LouMu>

## setting the target

telescope under 18 m rock  
inside a regional fault

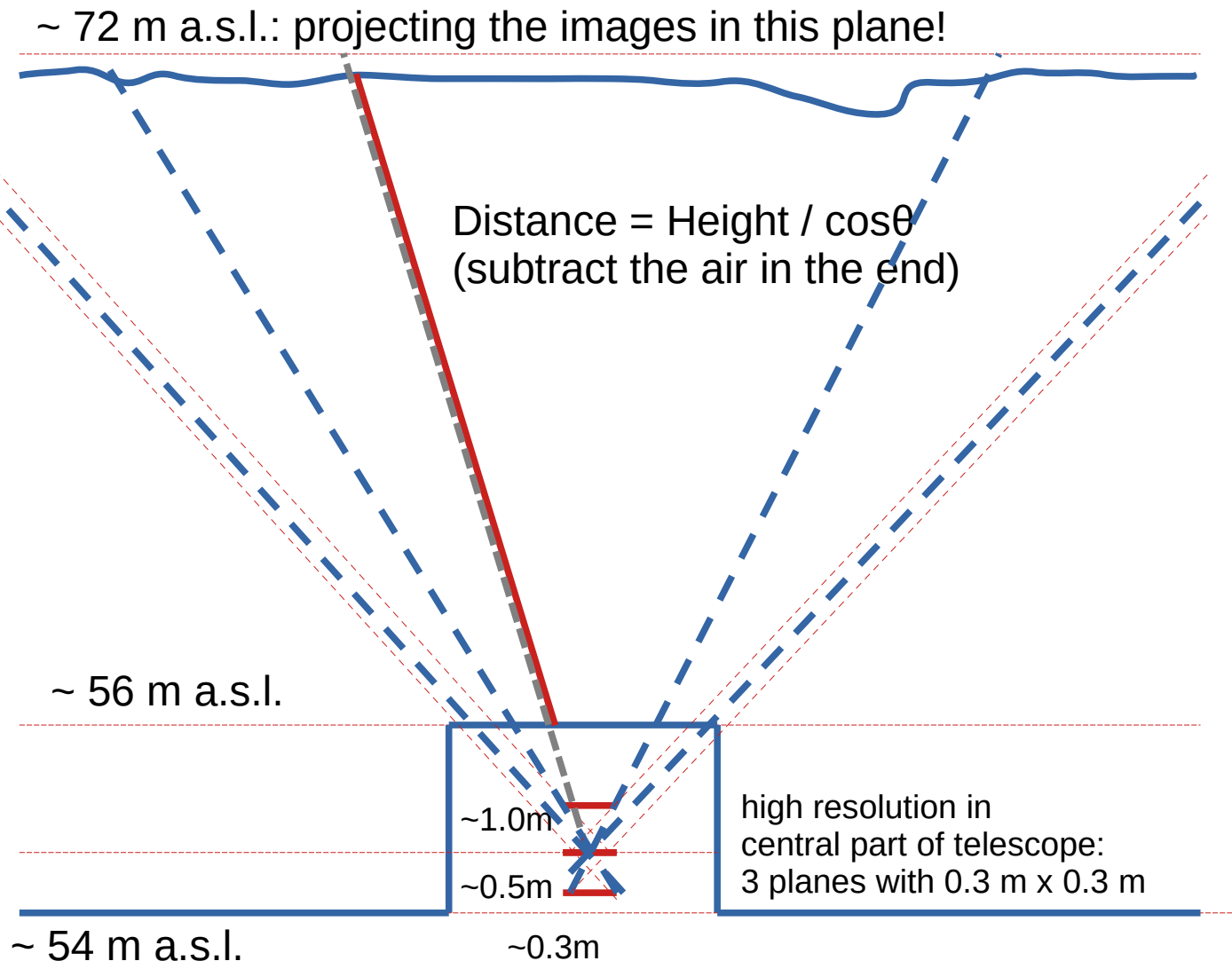
with a flat target region of  
30 m x 30 m at surface



## our setup

telescope under 18 m rock  
inside a regional fault

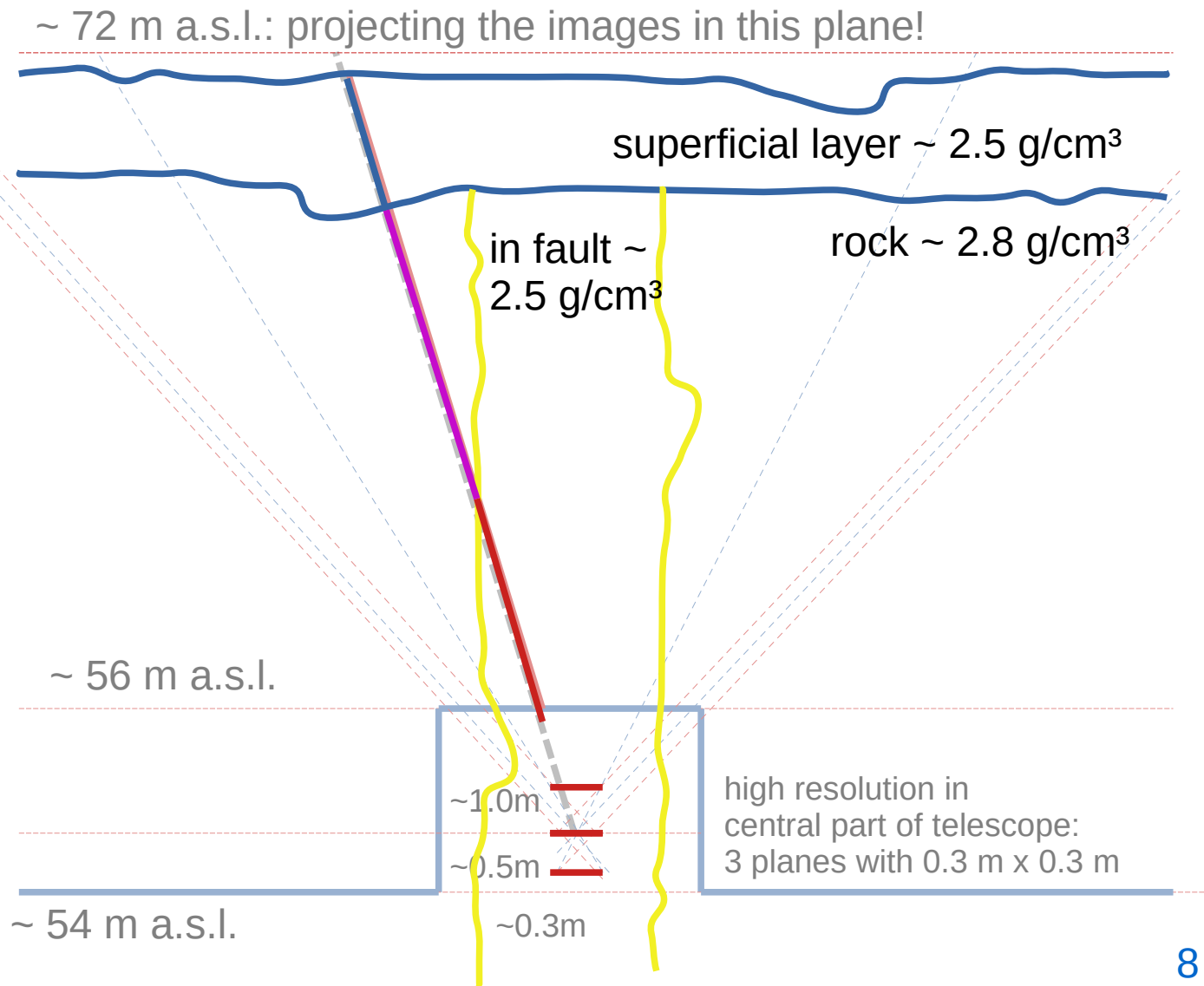
with a flat target region of  
30 m x 30 m at surface



## our setup

telescope under 18 m rock  
inside a regional fault

with a flat target region of  
30 m x 30 m at surface



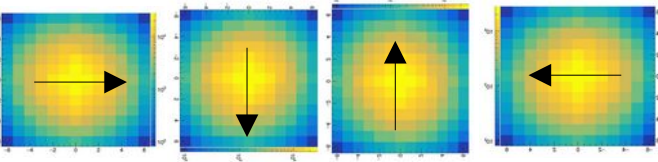
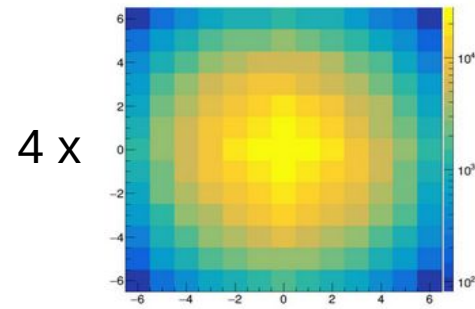


# imaging the fault

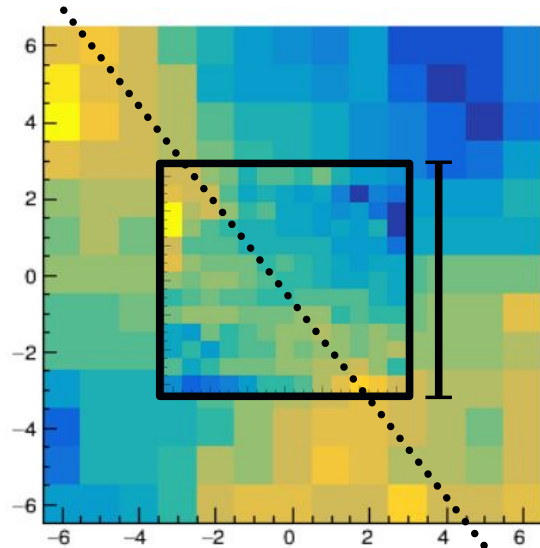
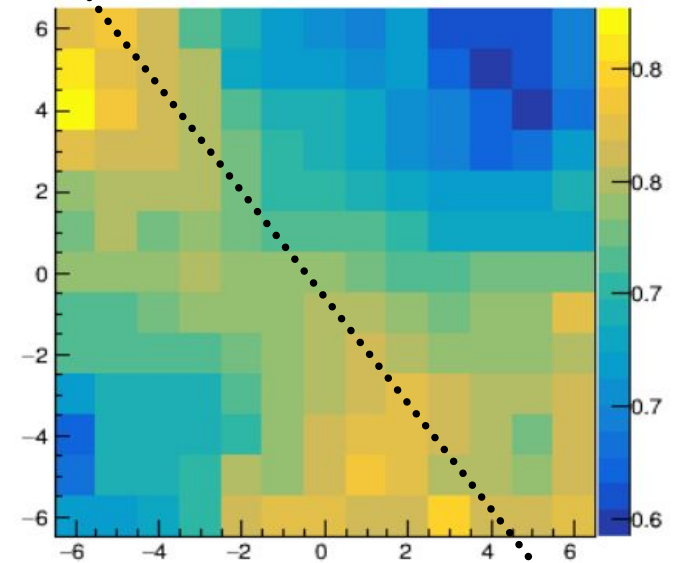
using just the muon data

- map muons in pad pairs
- correct for pad efficiency
- exploit symmetry of muon flux & detector

real data highlights the expected fault pattern !



=



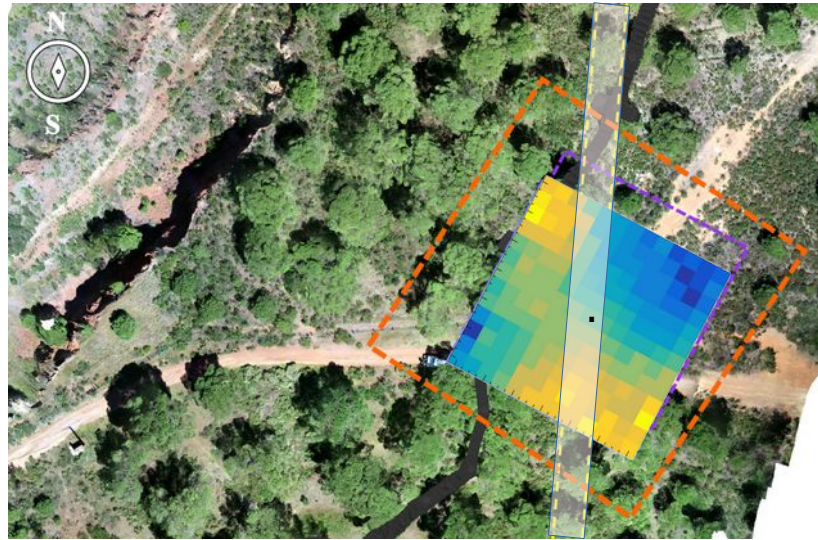
4.3 cm / 33.5 cm = tY:  
2.3 m at a surface 18 m above  
doubled resolution at image center  
(using the upper and lower planes)

more information within each pixel:  
resolution will be increased when  
combining several images  
using pad - pad acceptance tX, tY

## Corona geological fault

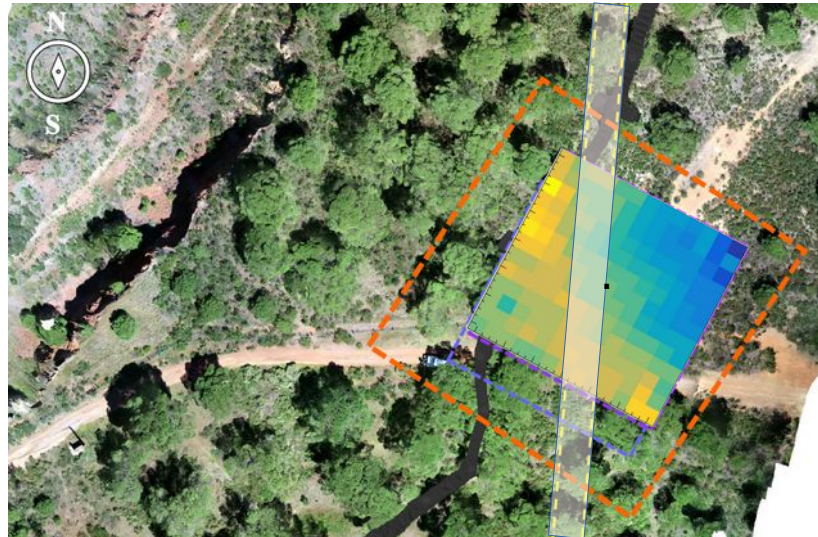
two telescope positions  
giving consistent results

for 3D reconstruction  
in muon tomography



**from within the fault**

all muons crossing  
the lower density region



**from next to the fault**

muons crossing more  
different densities  
depending on direction

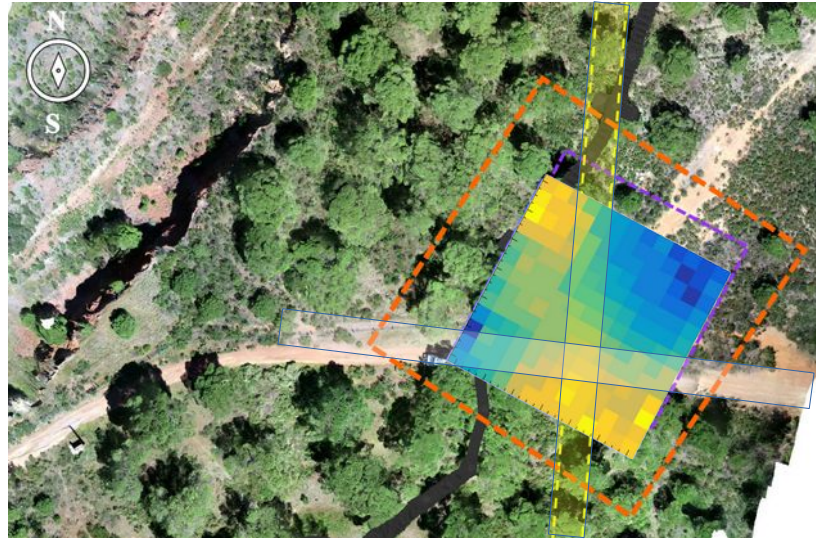
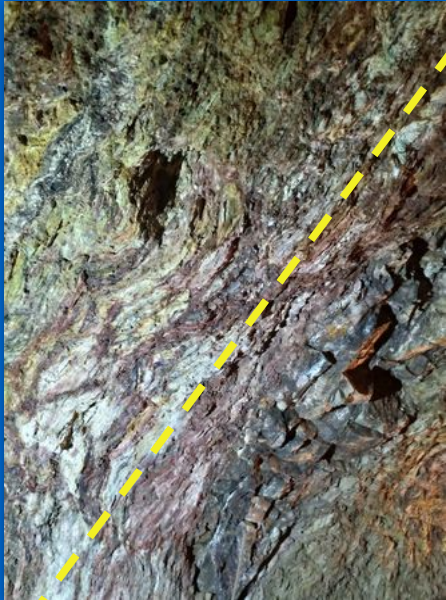
(telescope moved  
5 m to the front,  
1 m to the side)

# Corona geological fault

seen in the gallery

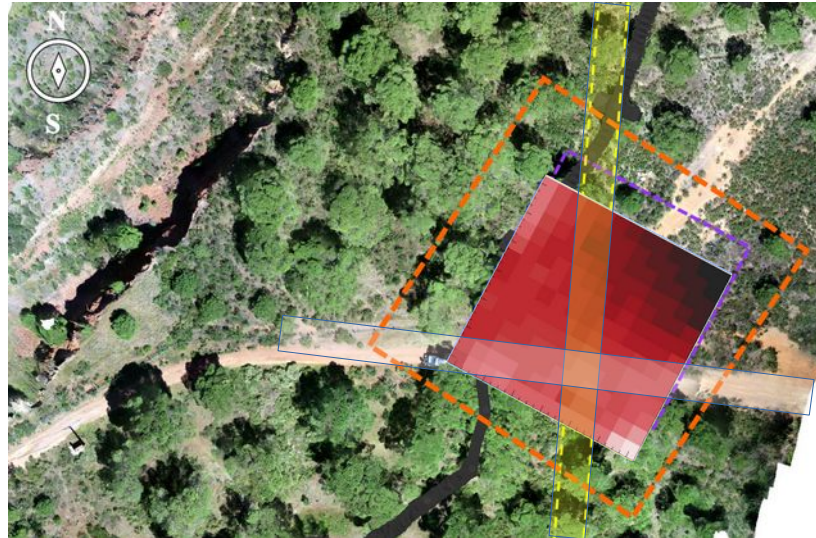
seen in muon asymmetry

seen at the surface



Muon flux contrast map:

expect muon transmission similar at all angles for constant density \* height



Topography map:  
*road and the Corona fault at slightly lower altitudes*

expect similar effects from densities and topography

# from muons to density

test with fast MC model:

sample muons from  
 $F(E, \theta) \cdot A(tX) \cdot A(tY)$

select from geology

$E > mip \cdot X = mip \cdot \rho \cdot H / \cos\theta$

- muon energy distribution
- muon angular distribution
- reconstructed raw maps

compatible with full Geant4:

**scattering effect negligible**

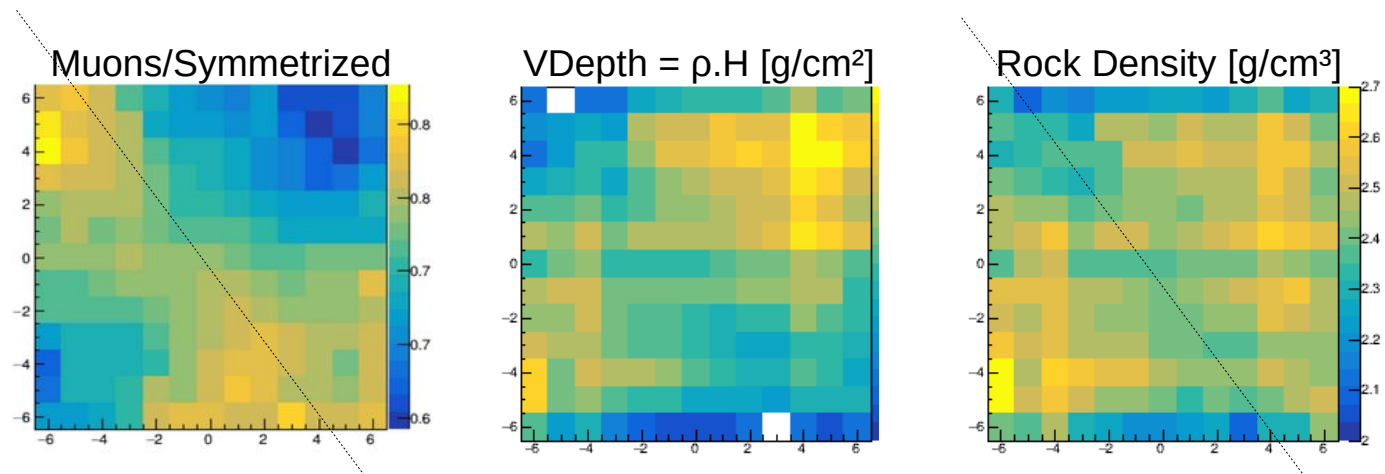
Muon open air flux (from L. Bogdanova *et al* Phys.Atom.Nucl. 69 (2006) 1293):

$$F(E, \theta) = F(E' = E \cdot \cos\theta, \theta) = f_0(E', 0) \cdot \frac{E' \cdot f_{1.7}(\theta) + 5 \cdot f_{2.7}(\theta)}{E' + 5}$$

similar threshold from any angle, expect around 8 GeV at Lousal

$$\int F(E' > mip \cdot \rho \cdot H) dE' = M_1 \int E' / (E' + 5) \cdot f_0(E', 0) \cdot dE' + M_2 \int 5 / (E' + 5) \cdot f_0(E', 0) \cdot dE'$$

with  $M_{1/2} = \iint dtX \cdot dtY A(tX) \cdot A(tY) \cdot f_{1.7/2.7}(\theta(tX, tY))$



- too low opacity top & bottom pixels: from detector dis-uniformity?
- correcting for topography reduces contrast: but highlights the fault?

*need better treatment of detector effects and higher resolution maps*

## superficial geology

adding information  
on top layer contrasts  
from independent  
measurements

### 1. ground penetrating radar linear surveys



ground penetrating radar

borders between regions with  
different dielectric constants

### 2. seismic refraction linear surveys from surface



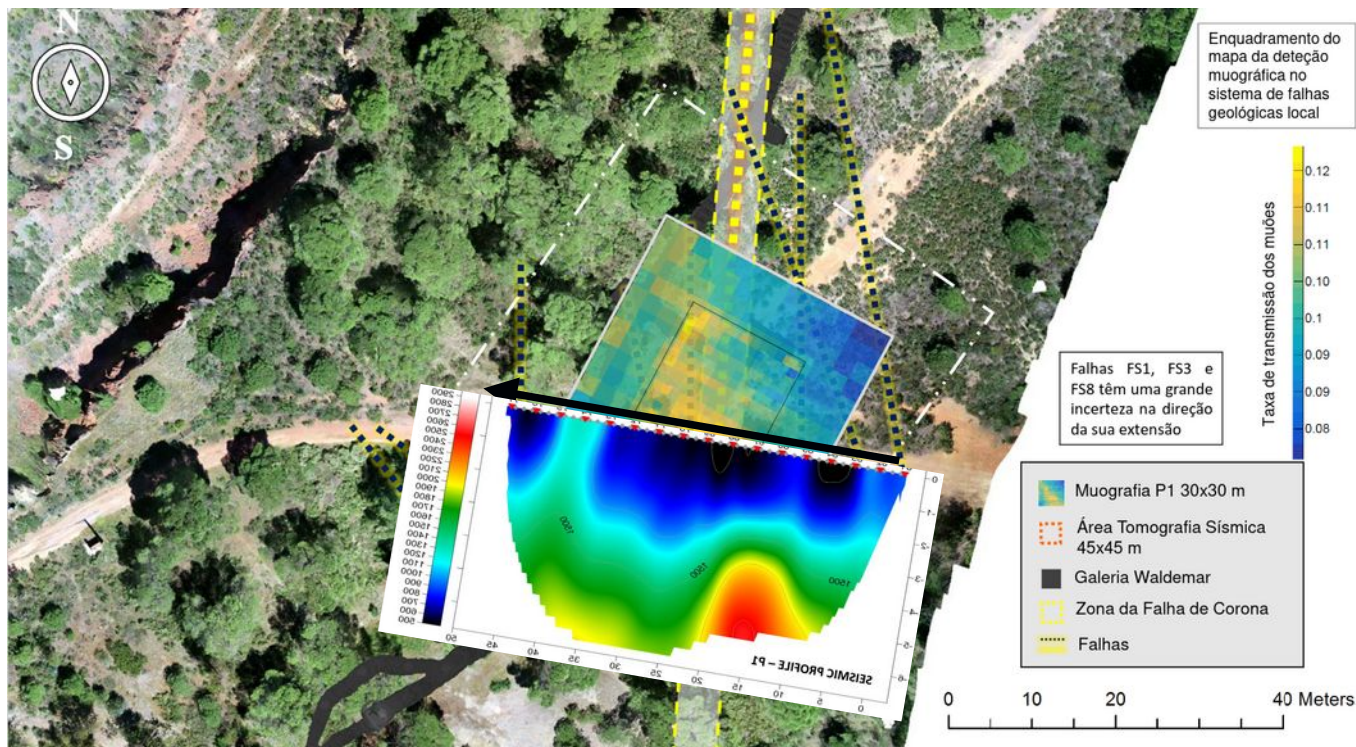
seismic refraction

compactness and  
homogeneity  
of different rock layers

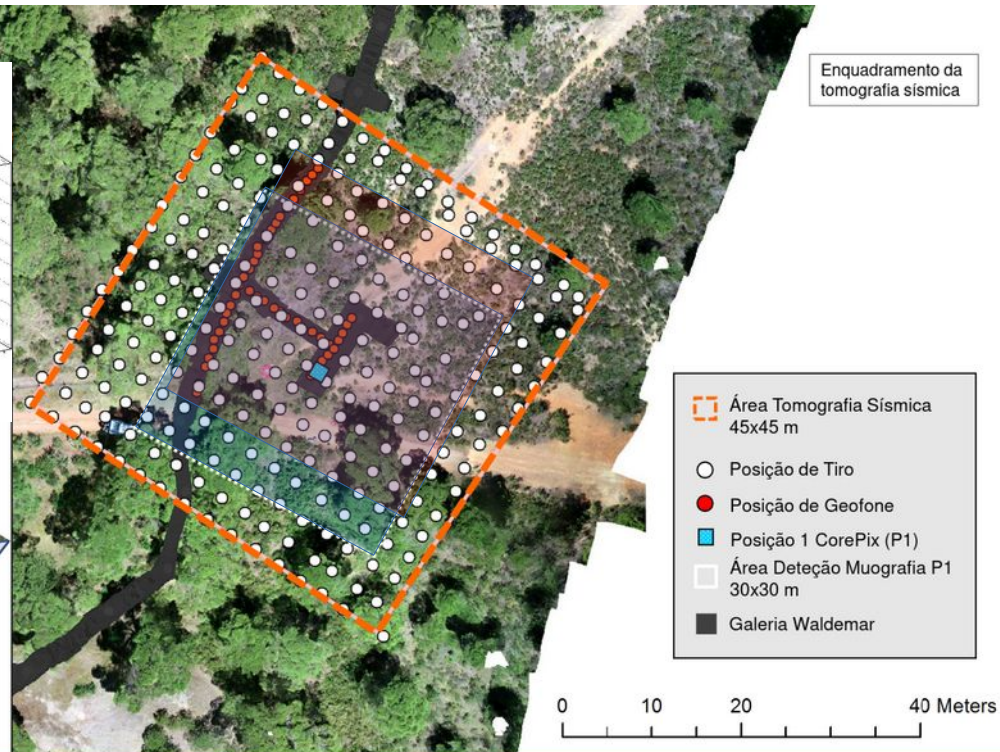
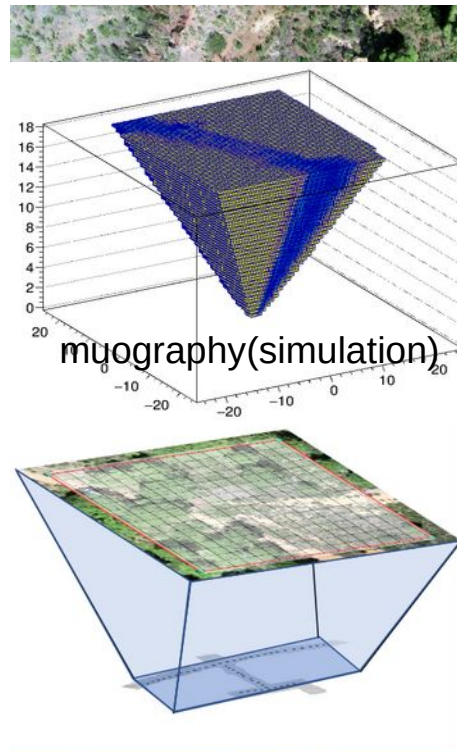
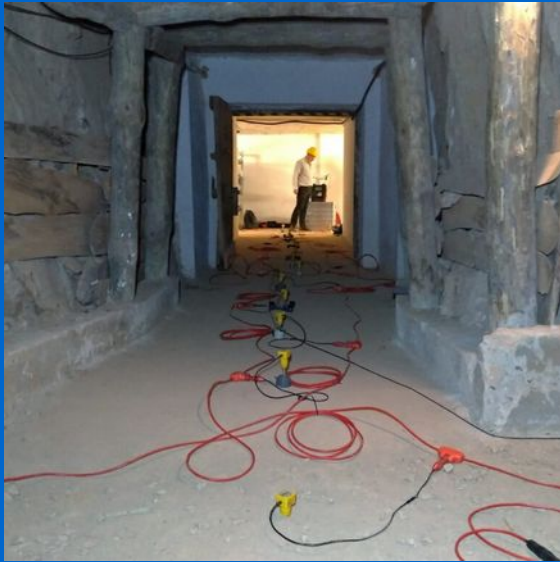
## not just one fault?

local secondary faults seem to intersect the regional Corona fault within our field of view

1. ground penetrating radar linear surveys
2. seismic refraction linear surveys from surface
3. both indicate consistent results on unexpected anomalies
4. back to the mine geological map to identify possible structures



# Seismic refraction tomography



geophones next to muon telescope and along the mine gallery  
receiving signals from a larger area grid at surface

signals propagating along the rock, as in the muography

ongoing analysis to directly cross-check muon tomography 15

## **1. Telescope**

- sealed RPC (no gas flux) tested standalone in lab for 1 year
- will replace one of the planes in the Lousal telescope soon!

## **2. Lousal analyses**

- had planned to study density distribution within Corona fault
- preliminary data indicates secondary faults to be measured
- will update the mine geological map with all our new data

## **3. Muographic methods**

- check description of flux and attenuation at different depths
- consolidate treatment of uncertainties in 2D maps
- consolidate the methods for 3D reconstruction

## **4. Geophysical muon tomography**

- compare standalone muography and seismic tomography
- develop the appropriate methods to combine both results



# Acknowledgments

## Funding



FCT project: EXPL/FIS-OUT/1185/2021  
+ CERN/FIS-PAR/0012/2021, CERN/FIS-PAR/0020/2021

## Team

### Equipa de Instrumentação e Física de Partículas (LIP)

Polo Lisboa:

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

Polo Coimbra:

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

Polo Minho:

Magda Duarte, Raul Sarmiento

### Equipa de Geofísica

ICT – UÉvora:

Bento Caldeira, Ines Hamak, José Borges, Josué Figueira, Mourad Bezzeghoud, Pedro Teixeira, Rui Oliveira

LNEG:

João Matos

### + many short term internship students:

André, Zhou, João, Catarina, Daniel, Inês, Rodrigo, Luis, Diogo, Gonçalo, Joana, Henrique, João

## Webpage



<https://pages.lip.pt/loumu>