Muography for geophysical survey at the Lousal mine

Muography 2023
June, Naples

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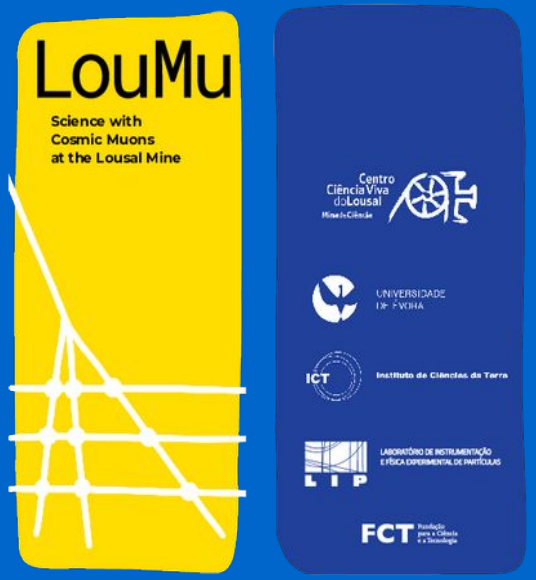
for the LouMu collaboration



LIP: Instrumentation and Experimental Particle Physics

ICT: Earth Sciences @UÉvora

Mina de Ciências: Public Science Center

LNEG: Energy & Geology

https://pages.lip.pt/LouMu

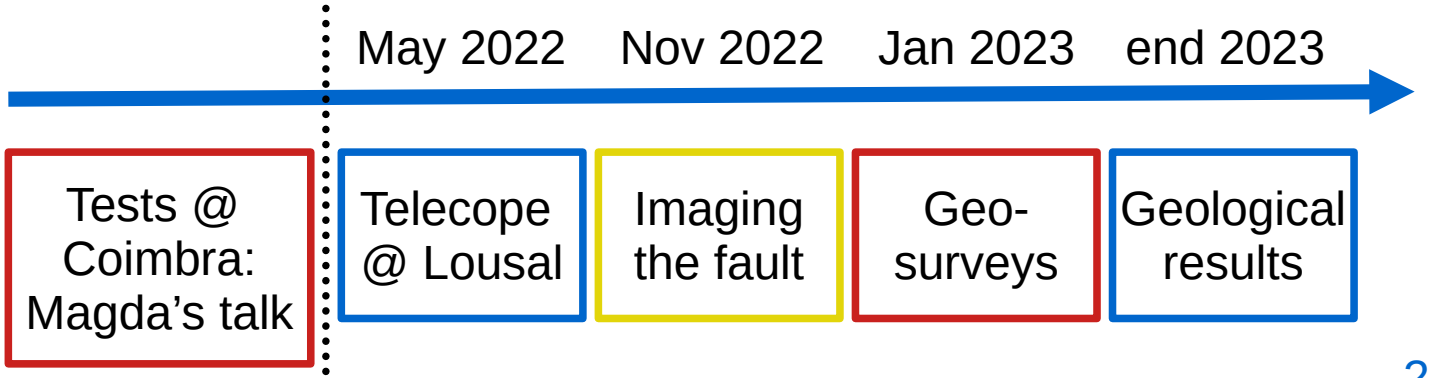
LouMu project: the team, goals and timeline

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*

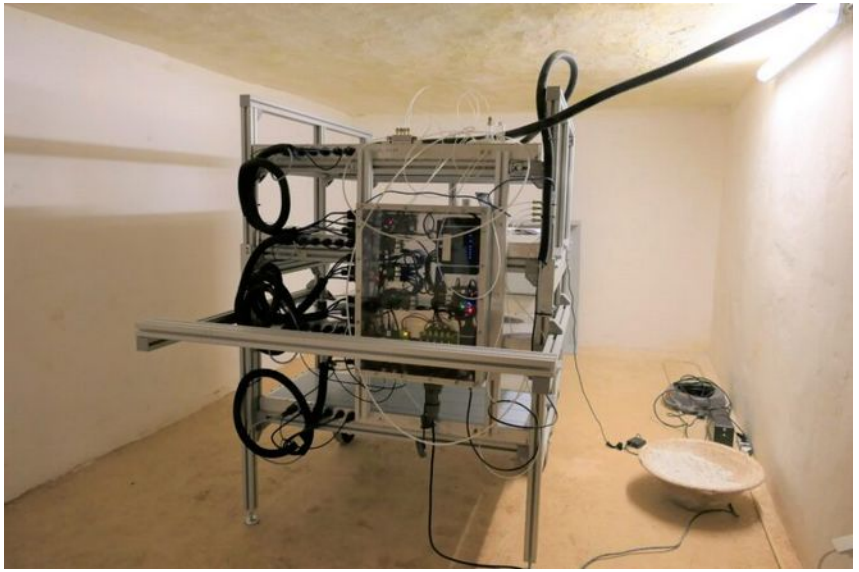
the LouMu telescope

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)



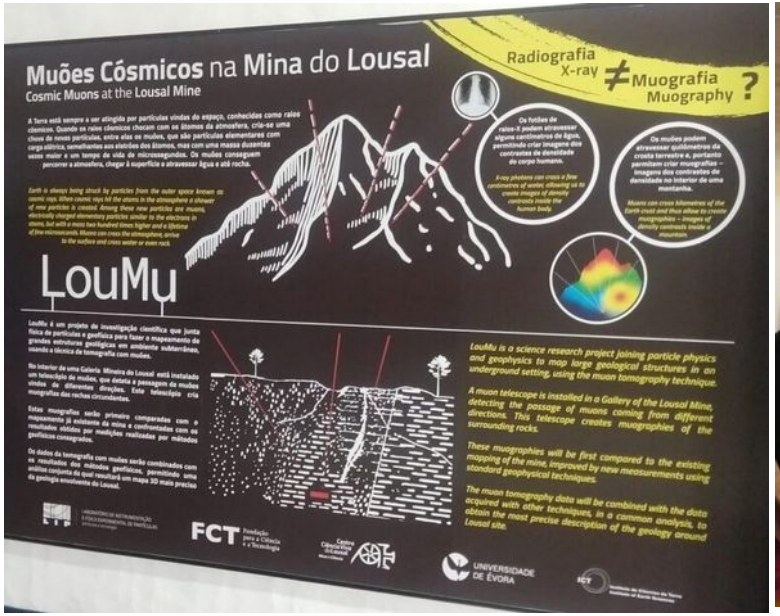
communication and gas flow from outside the gallery (~100 m)

in the Museum

Mine of Science
part of Ciência Viva
National Network

@Lousal devoted to mining
and underground sciences

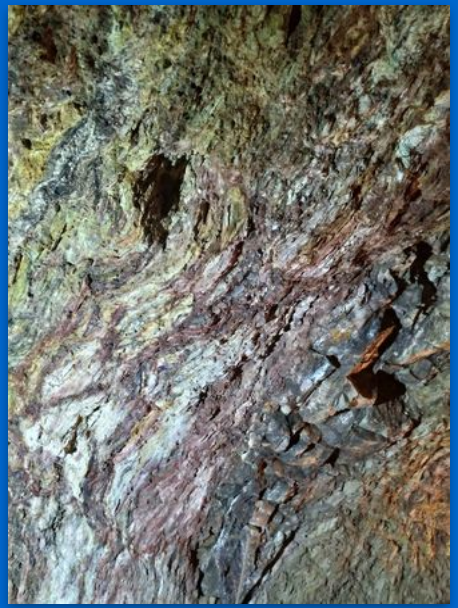
https://lousal.cienciaviva.pt/
https://pages.lip.pt/LouMu

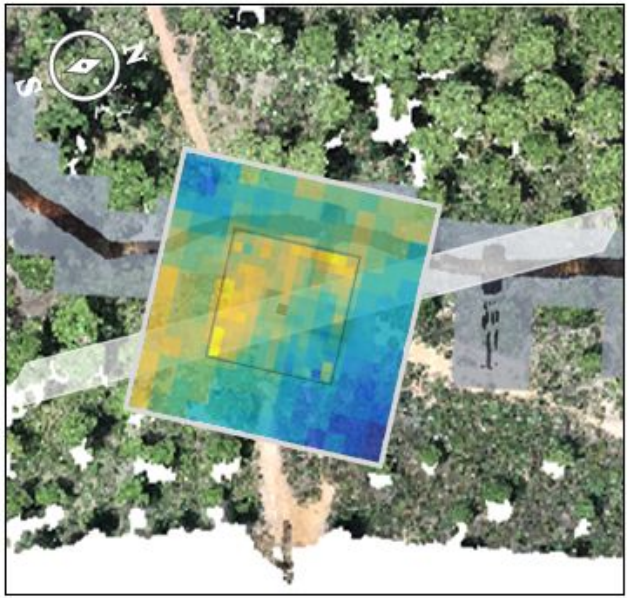


setting the target

telescope under 18 m rock inside a regional fault

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

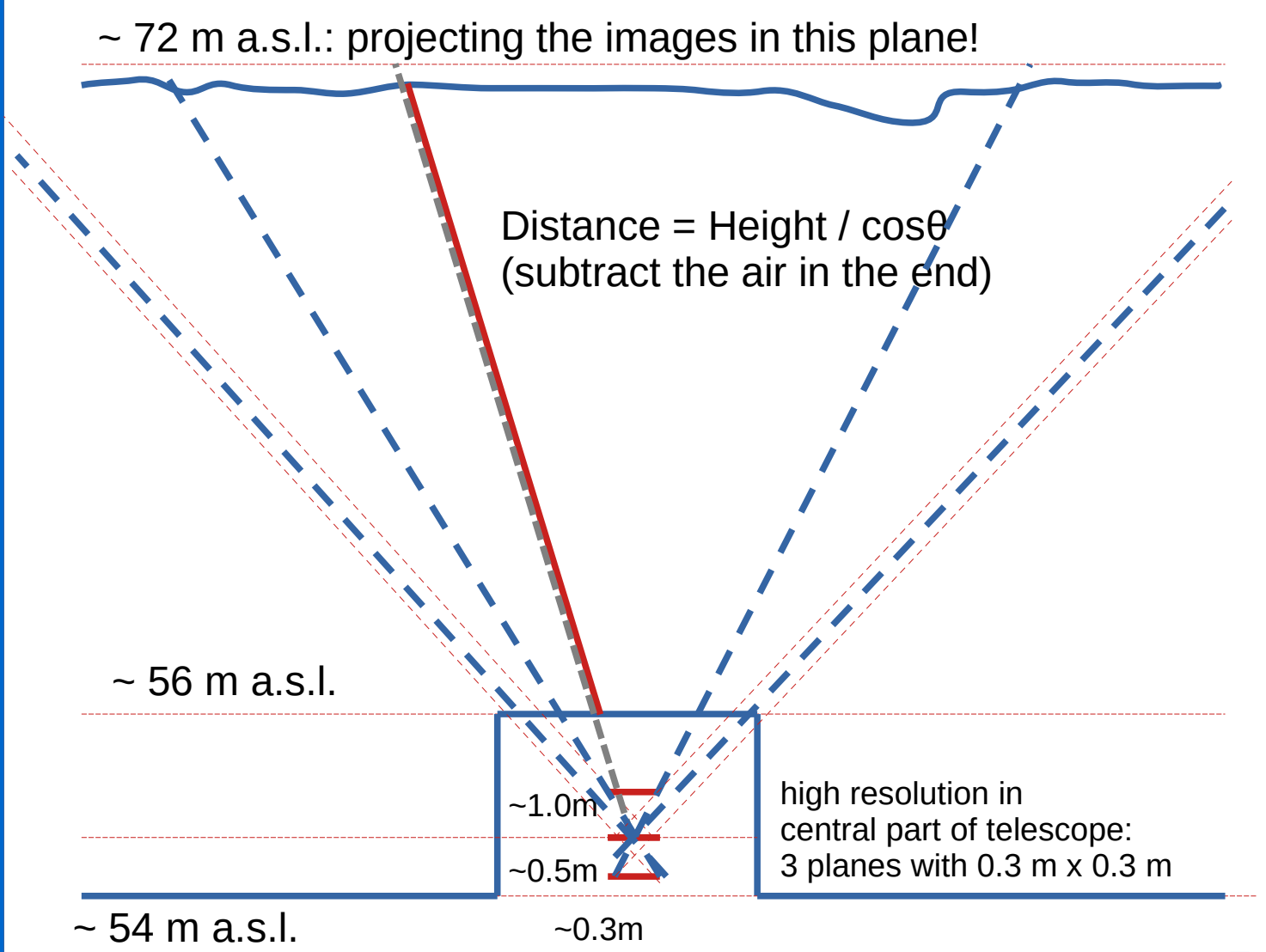




our setup

telescope under 18 m rock inside a regional fault

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



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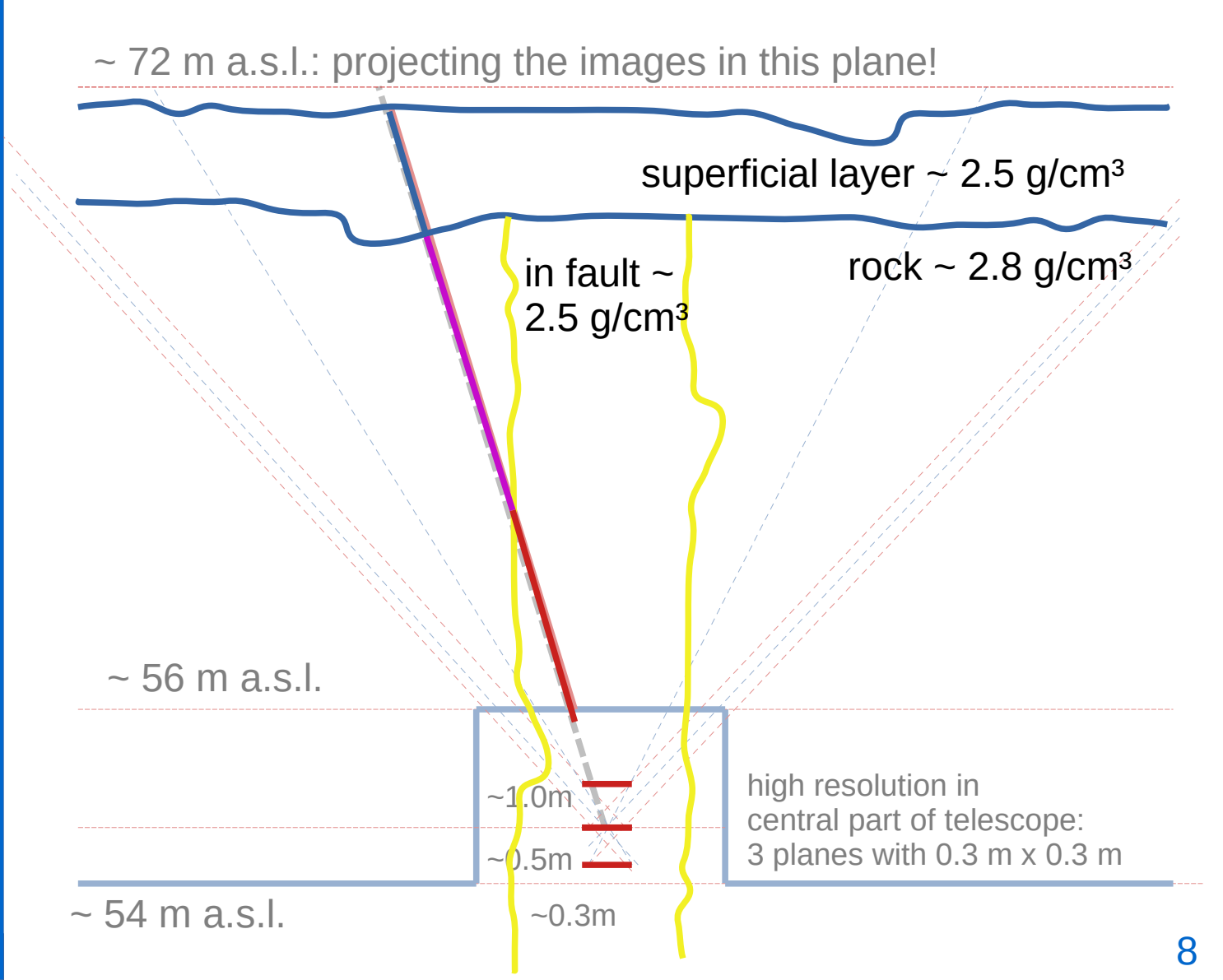
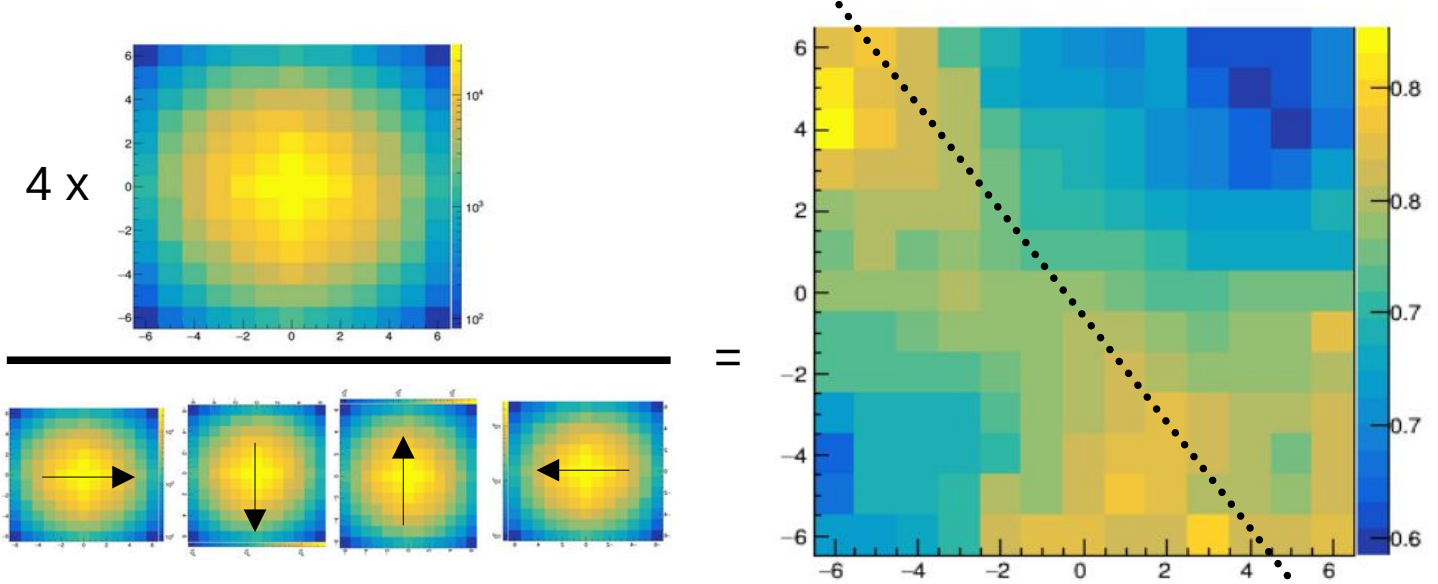


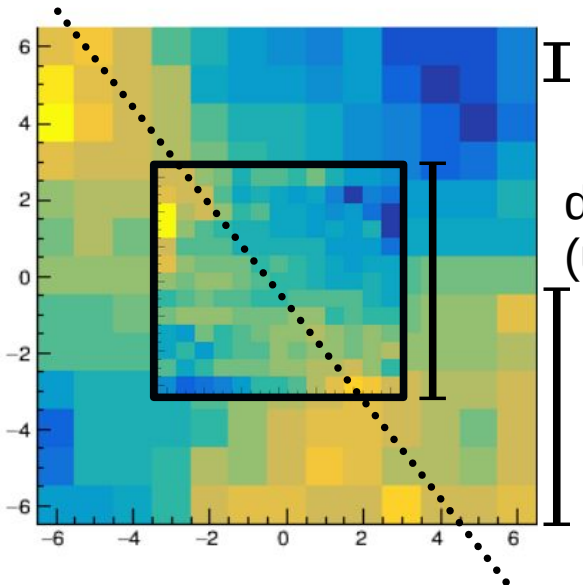
imaging the fault

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

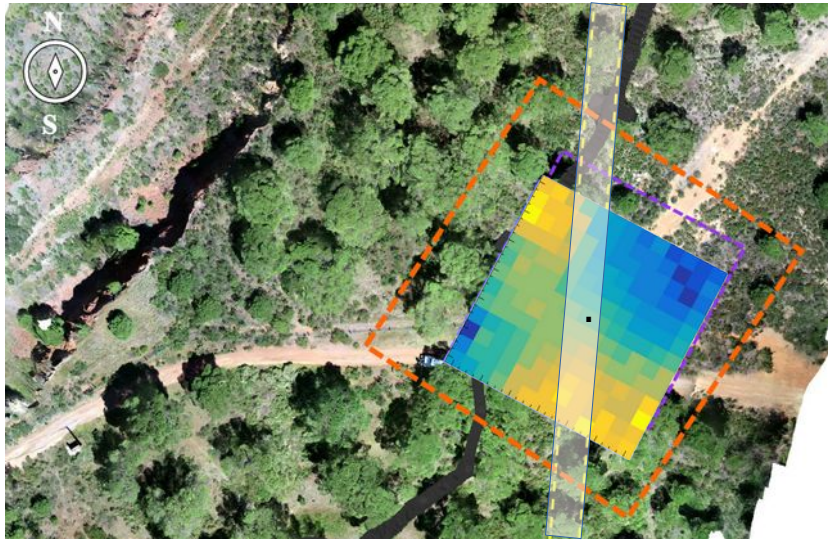
doubled resolution at image center
(using the upper and lower planes)

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

Corona geological fault

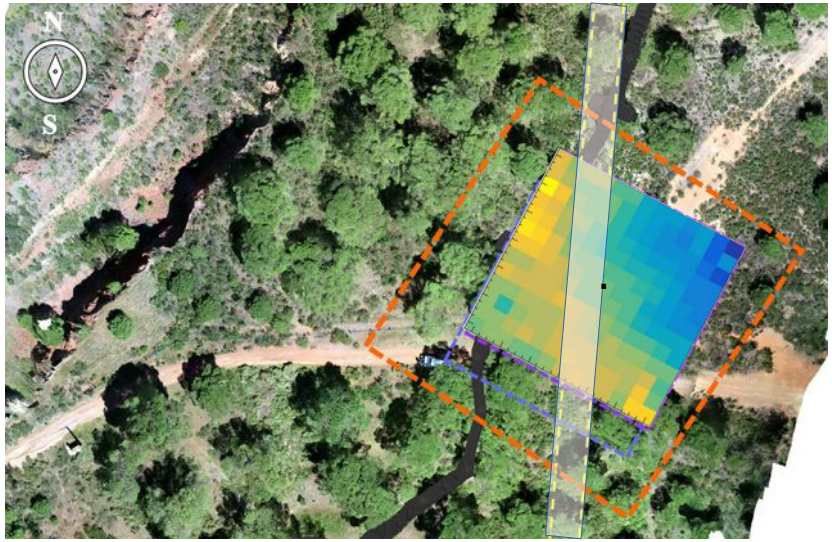
two telescope positions
giving consistent results

**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

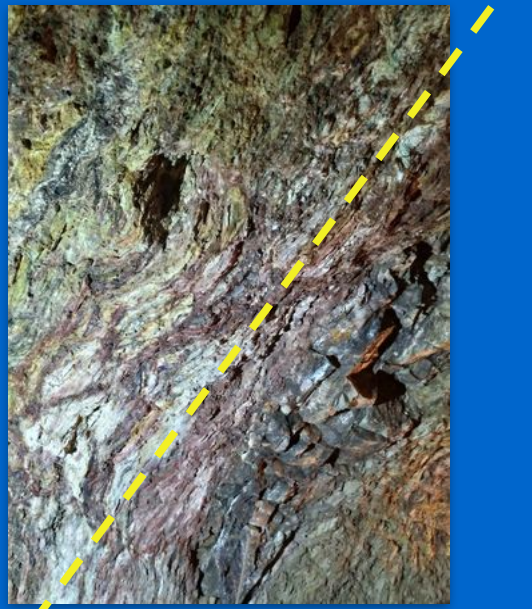
(telescope moved
5 m to the front,
1 m to the side)

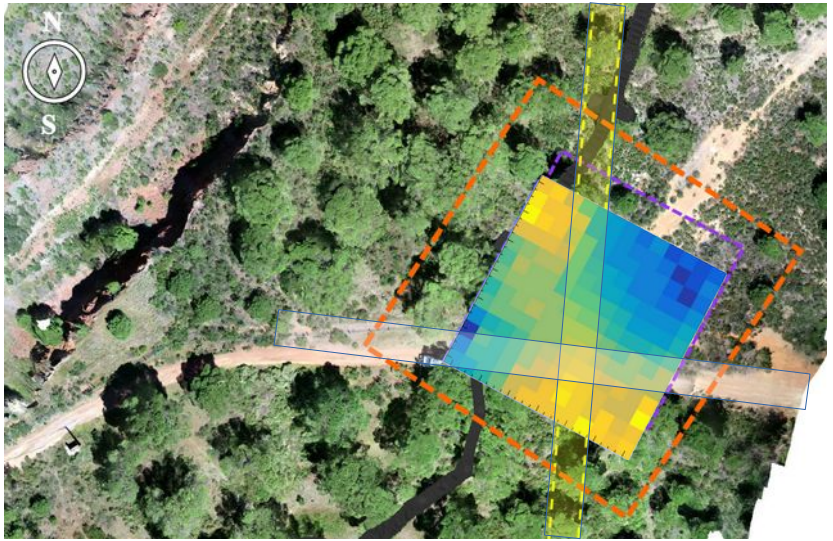
Corona geological fault

seen in the gallery

seen in muon asymmetry

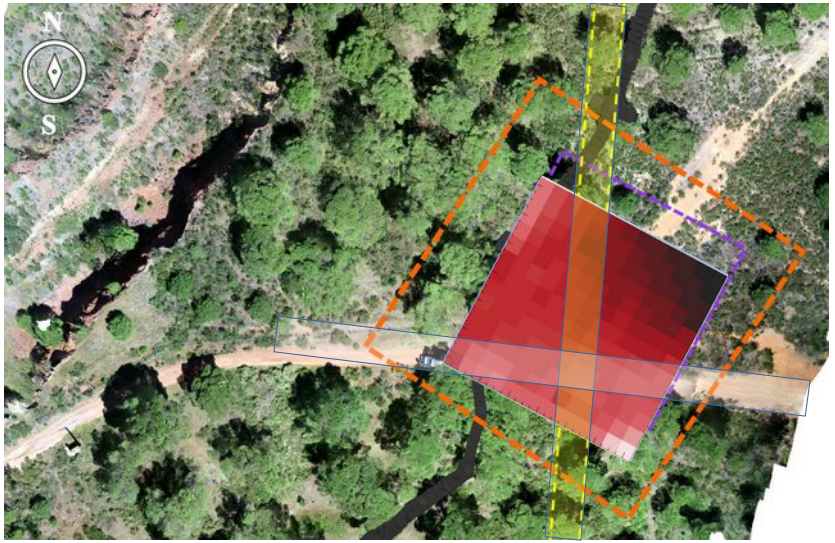
seen at the surface





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,θ) . A(tX) . A(tY)
select from geology
E > *mip*.X = *mip*.ρ.H/cosθ

- 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):

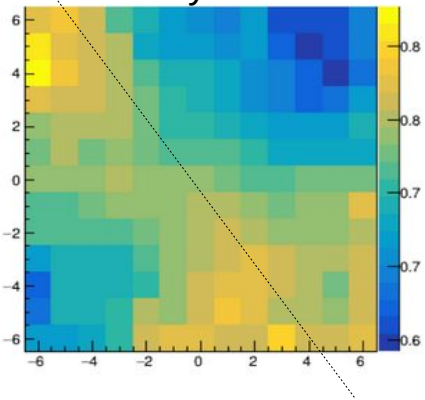
$$F(E,\theta) = F(\mathbf{E'=E.cos\theta},\theta) = f_0(E',0).\ \frac{E'.f_{1.7}(\theta)+5.f_{2.7}(\theta)}{E'+5}$$

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

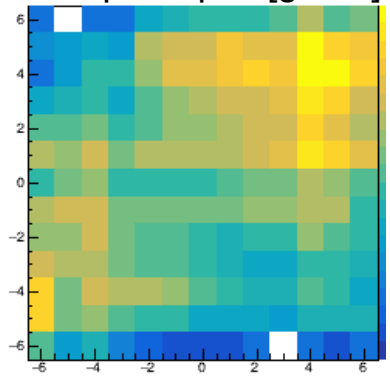
$$\int F(E'>mip.\rho.H)\,dE' = M_1 \int E'/(E'+5).f_0(E',0).dE' + M_2 \int 5/(E'+5).f_0(E',0).dE'$$

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

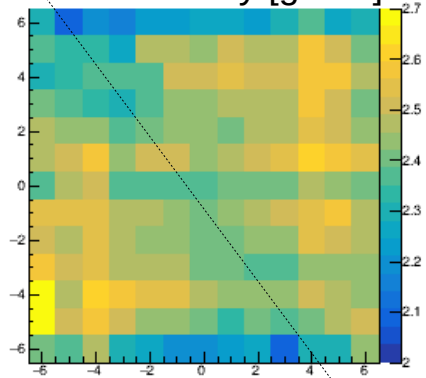
Muons/Symmetrized



VDepth = ρ.H [g/cm²]



Rock Density [g/cm³]



- 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

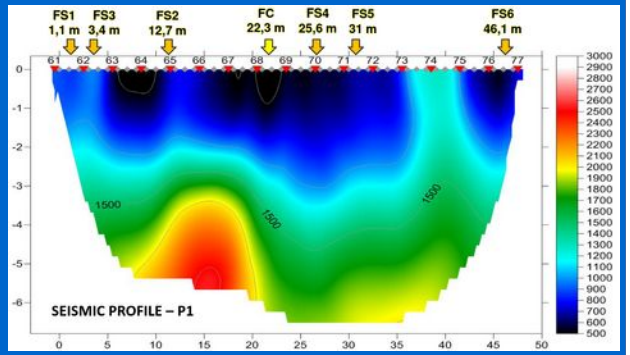
2. seismic refraction linear surveys from surface

seismic refraction

compactness and
homogeneity
of different rock layers

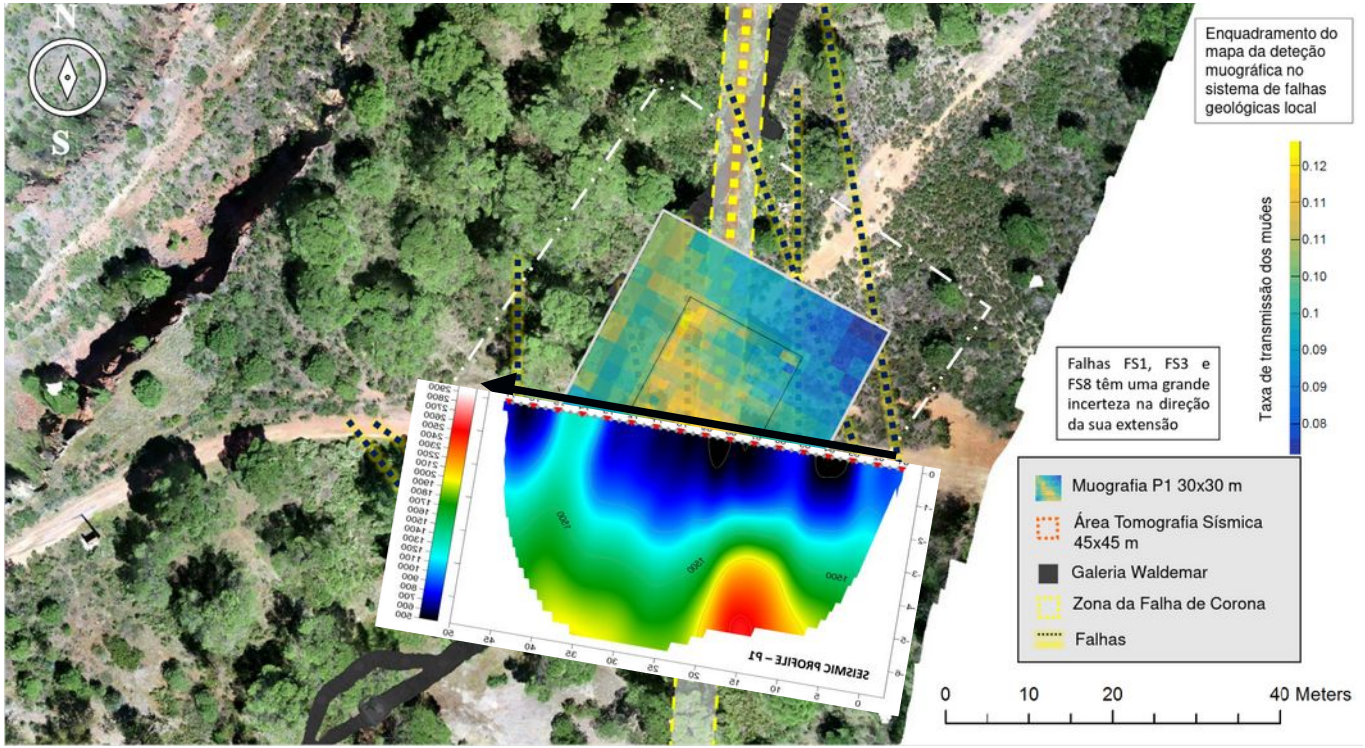
not just one fault?

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

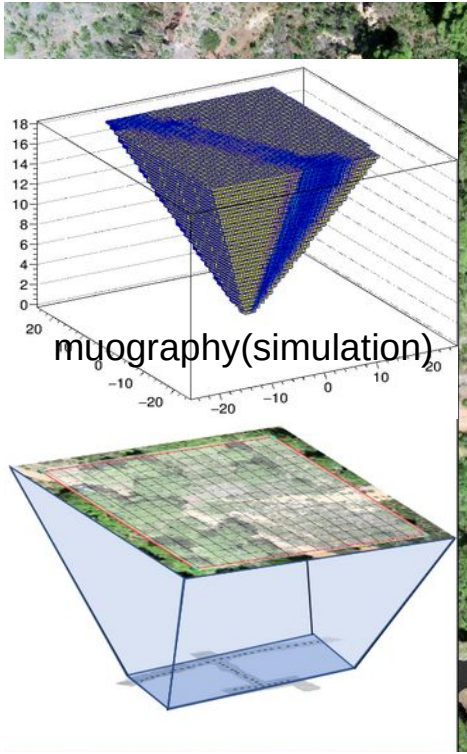


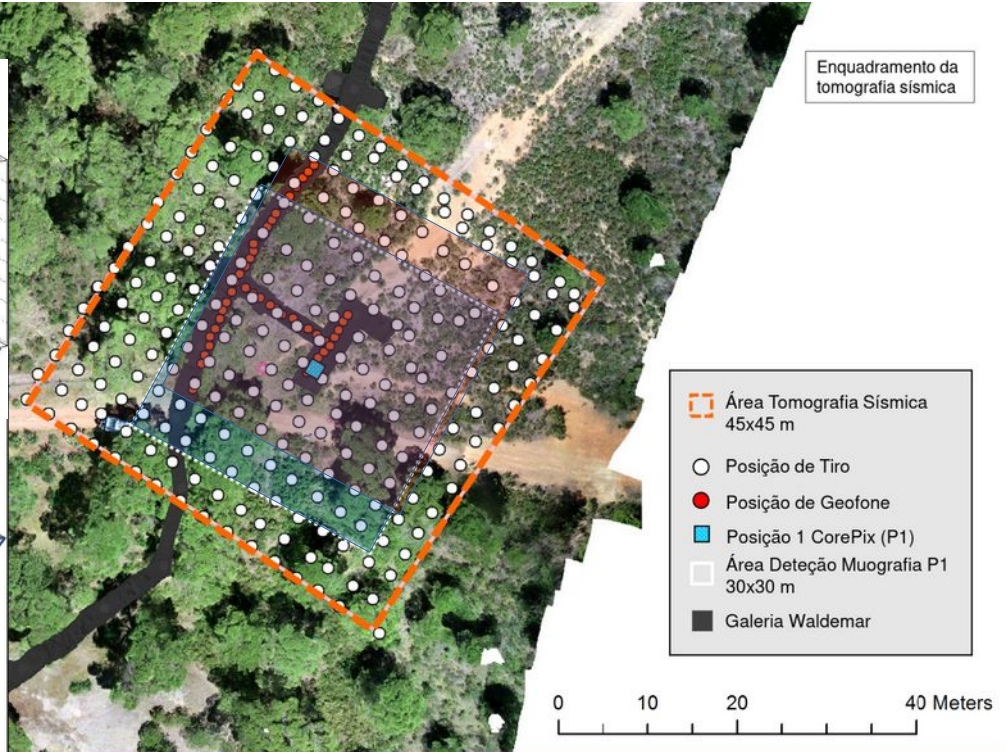
1. ground penetrating radar linear surveys
2. seismic refraction linear surveys from surface

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

LouMu prospects and future work

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

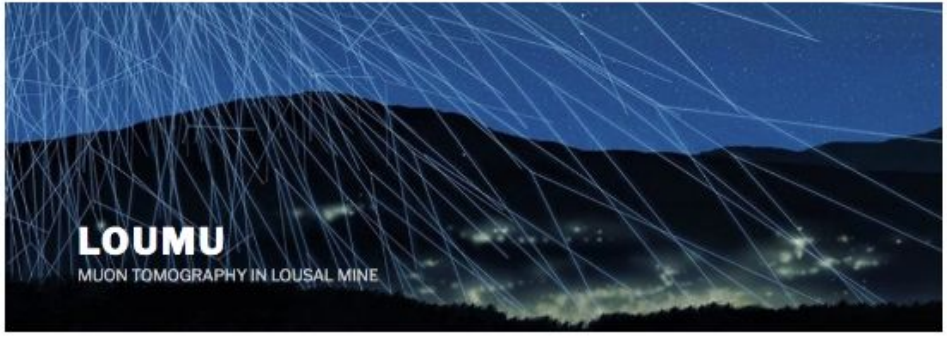
FCT Fundação para a Ciência e a Tecnologia

Cofinanciado por: COMPETE 2020

Lisb@20[20] REPÚBLICA PORTUGUESA UNIÃO EUROPEIA Fundo Europeu de Desenvolvimento Regional

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

Webpage



https://pages.lip.pt/loumu

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João Costa, Vanessa Pais

+ many short term internship students:
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