

# Muon Tomography

@ LIP

Sofia Andringa,

for the LouMu collaboration

4 LIP/IGFAE 2023



# imaging with muons

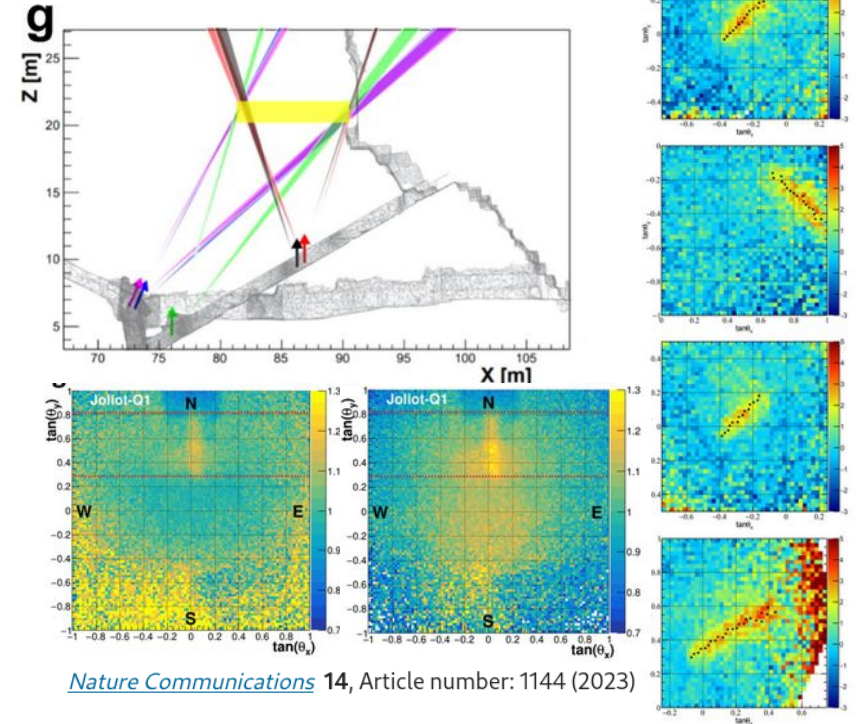
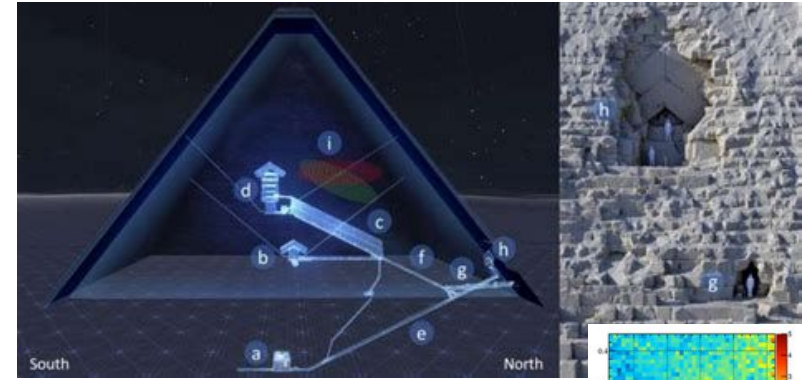
- muon scattering on high Z materials, measured with object within two telescopes (each muon contributes with one 3D point)
- flux attenuation by constant energy loss, measured with one telescope far from the object (statistical reduction in a direction map)

can be used for imaging large objects  
**but** can only see objects above horizon

need a reference model for muon flux  
**better** to confirm with our measurements

**3d** can be obtained by combining images

from ScanPyramid project – 3d imaging & tests



# the LouMu project

End-to-end test of muography for sub-surface geophysical surveys: how useful is it?

develop tools, methods and a team, and communicate the possibilities of muography

1st: telescope; 2nd: a building; 3rd: a mine; 4th: generalization

**LouMu**  
Ciência com  
Muões Cósmiticos  
na Mina do Lousal

LouMu é um projeto científico que combina física de partículas e geofísica para mapear grandes estruturas geológicas, usando a técnica de tomografia muônica.

São parceiros neste projeto o LIP, o Instituto de Ciências da Terra da Universidade de Évora e a Mina de Ciência – Centro Ciência Viva do Lousal.

Centro  
Ciência Viva  
do Lousal  
Mina de Ciência

UNIVERSIDADE  
DE EVORA

ICT  
Instituto de Ciências da Terra  
Universidade de Évora

LABORATÓRIO DE INSTRUMENTAÇÃO  
E FÍSICA EXPERIMENTAL DE PARTÍCULAS  
partículas e tecnologia

FCT  
Associação  
para a Ciência  
e a Tecnologia

O planeta Terra está constantemente a ser bombardeado por partículas vindas do Espaço, conhecidas como raios cósmiticos.

Quando chocam com os átomos da atmosfera criam uma chuva de novas partículas, entre elas, os muões que chegando à superfície da Terra atravessam as rochas.

Contando o número de muões que consegue chegar até nós, podemos determinar as diferentes densidades no interior das rochas atravessadas. Assim, o invisível torna-se visível. É isto a muografia: como uma radiografia, mas com muões.

Na mina do Lousal está instalado um detetor de muões que, em combinação com outras técnicas geofísicas, nos permitirá fazer a tomografia muônica com informação em três dimensões. Para melhor mapear o interior da mina e de outras estruturas geológicas.

Os muões são partículas semelhantes aos eletrões, mas com maior capacidade de atravessar matéria.

O telescópio de muões usado no LouMu é constituído por Câmaras de Placas Resistivas (RPC), detetores que contêm um gás que é ionizado pela passagem de partículas com carga elétrica, permitindo-nos saber com precisão o ponto de passagem de cada muão.

A Tomografia de Muões fornece imagens com a informação sobre o interior da estrutura atravessada pelos muões.

# the LouMu project



February, 2019  
MiniMu at Lousal



from March, 2020  
CorePix at Coimbra



April, 2022  
CorePix at Lousal

# our muon telescope

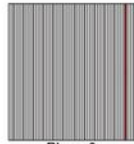
Ver os muões / Seeing the muons

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

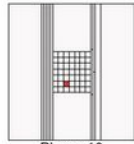


Data: 12/4/2023

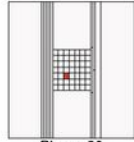
Hora: 5:48:30



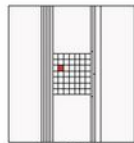
Plano 0



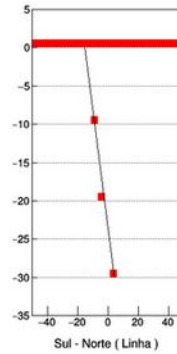
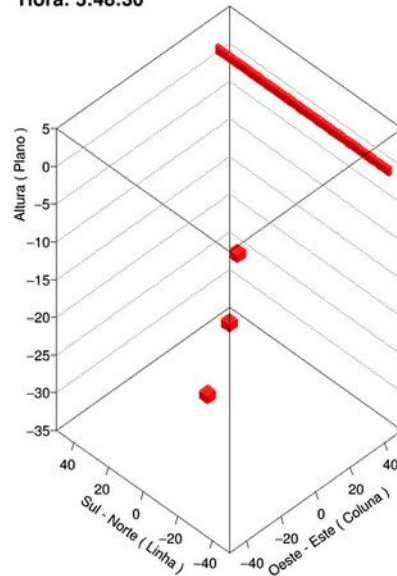
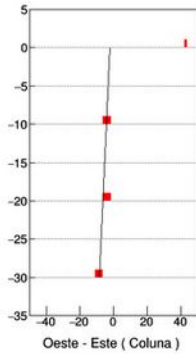
Plano -10



Plano -20



Plano -30



gas fed/recovered from 100 m away  
plane 2 with a window for outreach...

# our muon telescope

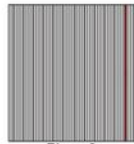
Ver os muões / Seeing the muons

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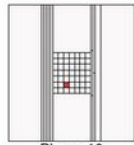


Data: 12/4/2023

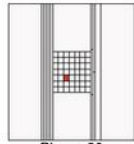
Hora: 5:48:30



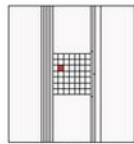
Plano 0



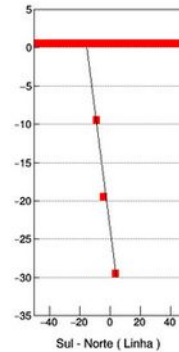
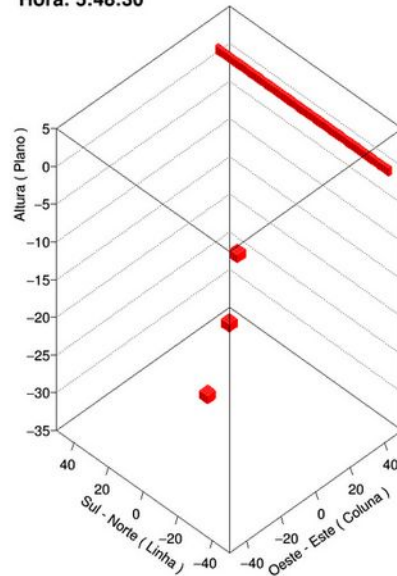
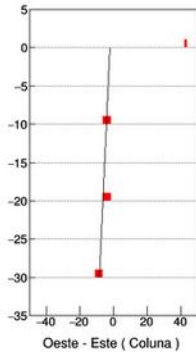
Plano -10



Plano -20



Plano -30



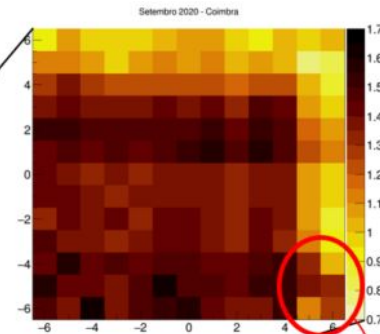
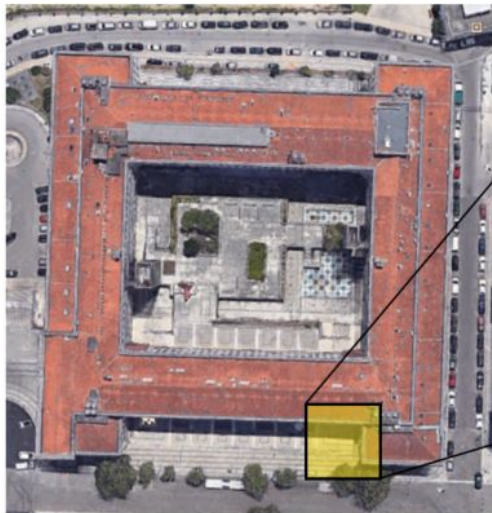
Trigger with 30 ns coincidence  
on high resolution CorePix

(3 planes, 7 x 7 pads of 4 x 4 cm<sup>2</sup>)

Map images in tanX, tanY:

- smaller FoV with high resolution  
(13 bins for  $-0.4 < \tan X < 0.4$ )
- larger FoV with lower resolution  
(13 bins for  $-0.8 < \tan X < 0.8$ )

# reading the first images



ENTRADA  
DO EDIFÍCIO

the same telescope in two positions  
a high contrast / uniform coverage

Canceling most systematics:

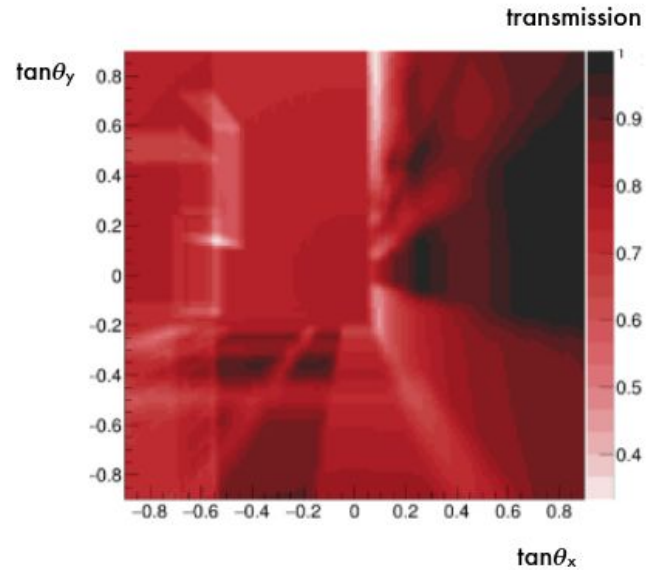
from the open-air muon flux  
from the detector response

# imaging the building

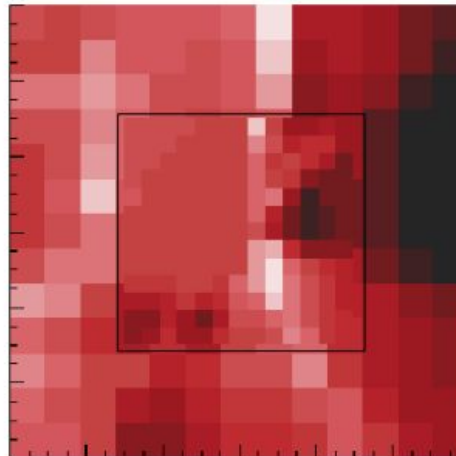
and modelling what we expect to see



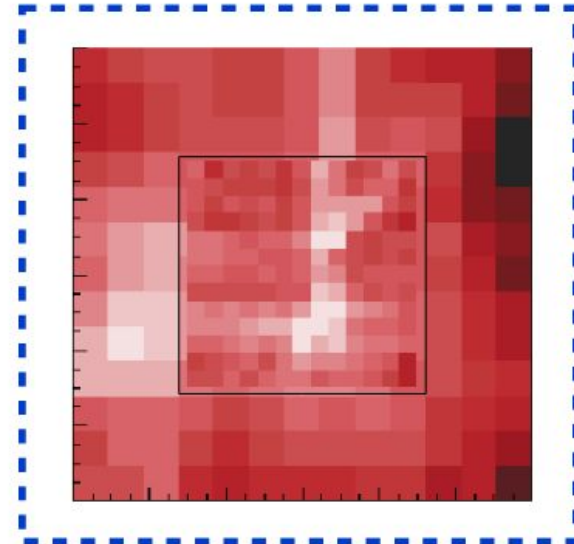
high resolution  
simulation



telescope resolution  
simulation



data





# from muons to images

Measured Flux

=

Open Air Flux

~ 130 muons / cm<sup>2</sup> / s / sr . cos<sup>3</sup>θ

confirmed after correcting other factors

x

Attenuation

exponential with some characteristic length

T=0.97 for each vertically crossed ceiling

x

Acceptance

simple geometrical model with details of each plane

inner structure of detector visible after gain equalization

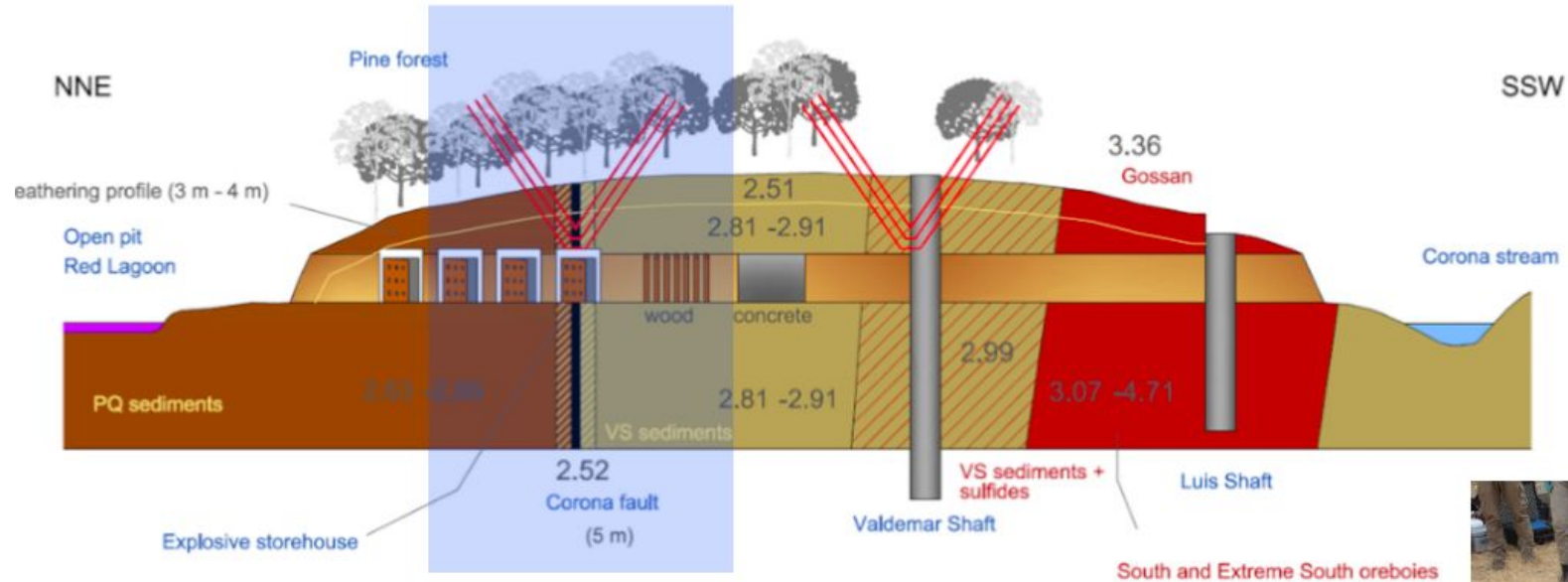
x

Efficiency

measured for each pad in each plane from the same data

reasonably constant as RPC compensates E/N for T,P,H

# geological imaging



geological samples



laser scans

On-going campaigns for seismic refraction tomography with grid of source / receiver



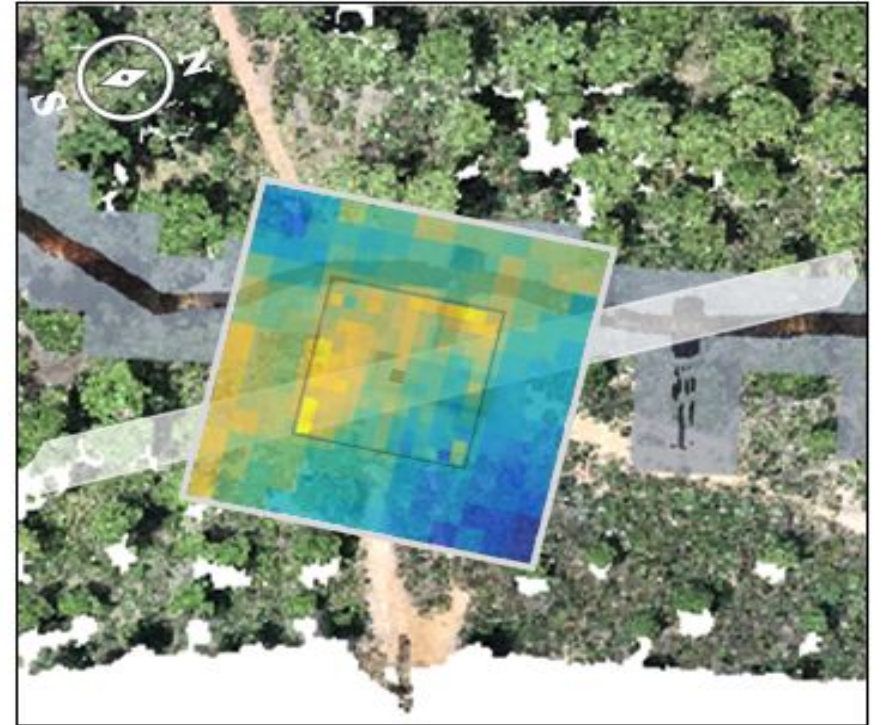
seismic refraction



ground penetrating radar

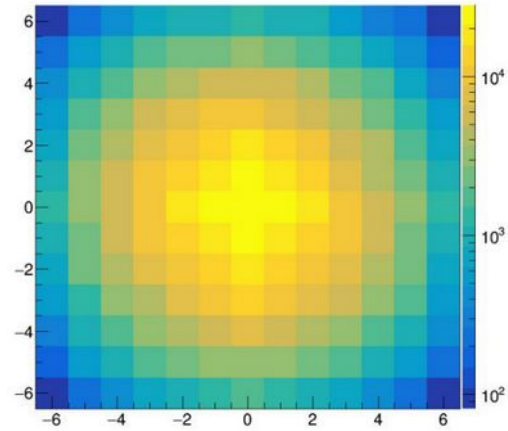
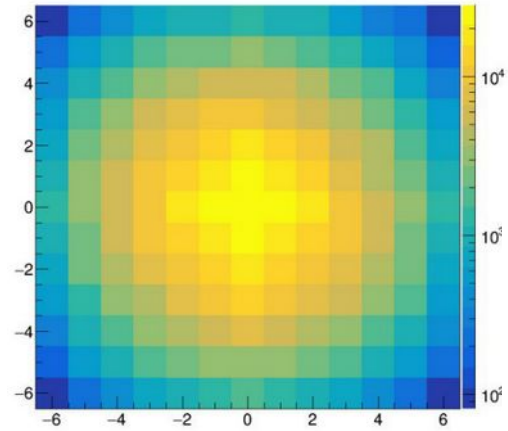
# geological imaging

## ENQUADRAMENTO DA OBSERVAÇÃO DO COREPIX NO LOUSAL

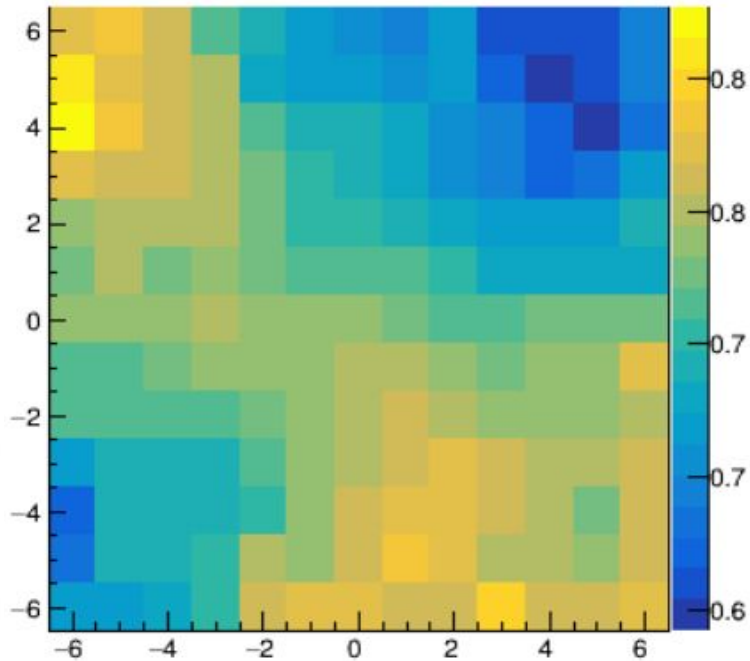


# looking again from two positions

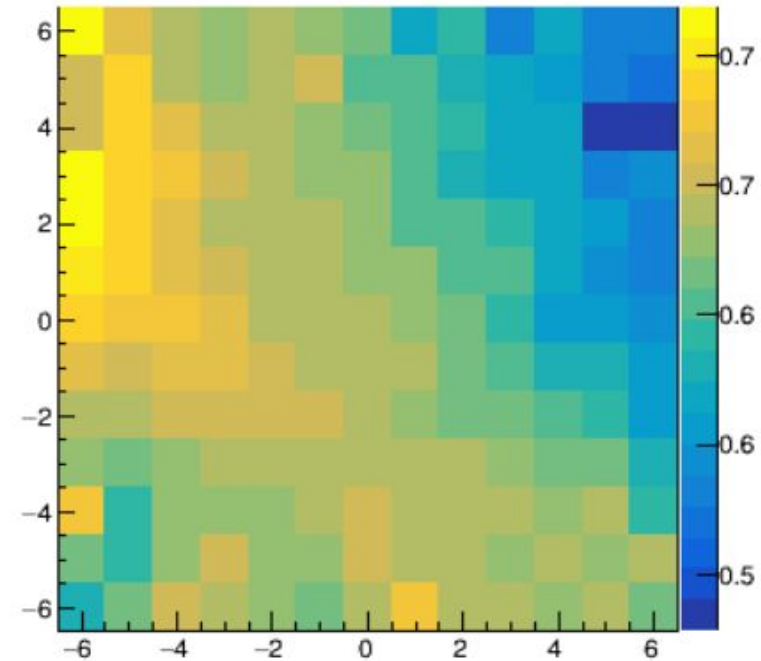
raw data is symmetric, dominated by flux and detector acceptance  
averaging over the four quadrants we can obtain a “flat” reference



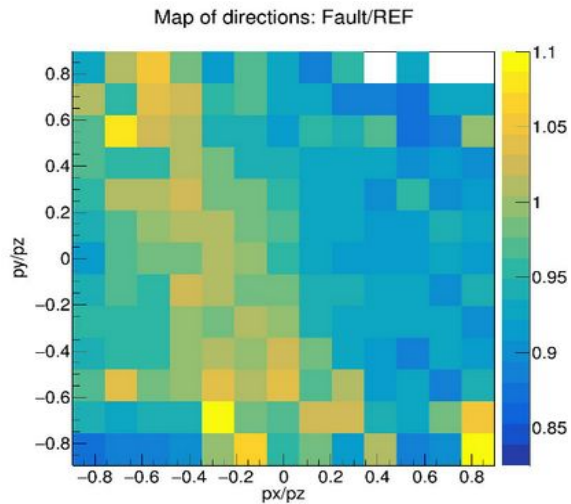
D1 /aver



D2 /aver



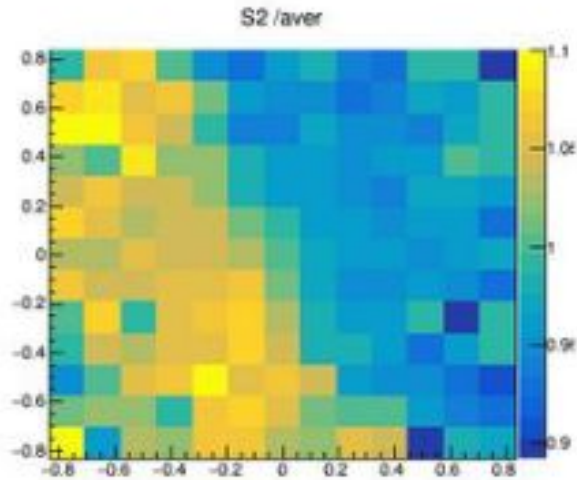
# testing the models



Geant 4 (30 days) /  
Geant 4 (30 days)

Compatible energy and  
angular spectra:  $E \cdot \cos Q$

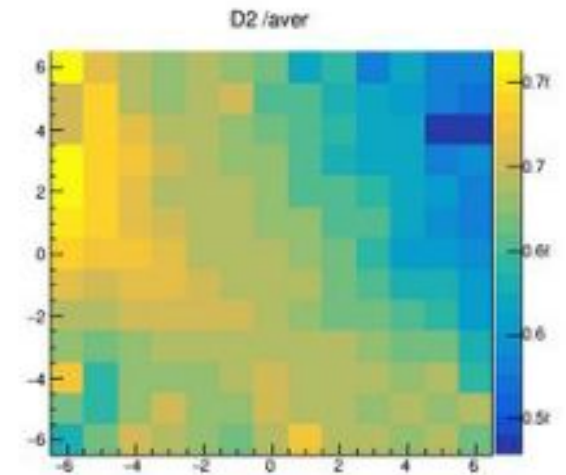
Scattering can be ignored



Fast sim. (30 days) /  
constant density model

No energy, angular distribution  
validated in symmetrized data

Normalization more uncertain



Data (60 days) /  
symmetrized data

# translation to density

Measured Flux

=

Open Air Flux

$F(E, \cos\theta) = f_0(E'=E \cdot \cos\theta) \cdot (E' \cos\theta^{1.7} + 5 \cos\theta^{2.7}) / (E'+5)$   
almost  $\cos\theta^3$  at  $E' \sim 0$ , as we used in Coimbra

x

Attenuation

Integrate  $F(E, \cos\theta)$  for  $E > X$  [g/cm<sup>2</sup>] . mip [MeV/(g/cm<sup>2</sup>)]  
height is constant in Lousal  $\Rightarrow E \cdot \cos\theta > H \cdot \text{mip} \cdot \rho$  [g/cm<sup>3</sup>]

x

Acceptance

another  $\cos\theta^3$  for reaching two detector planes  
partial superposition between adjacent direction pixels

x

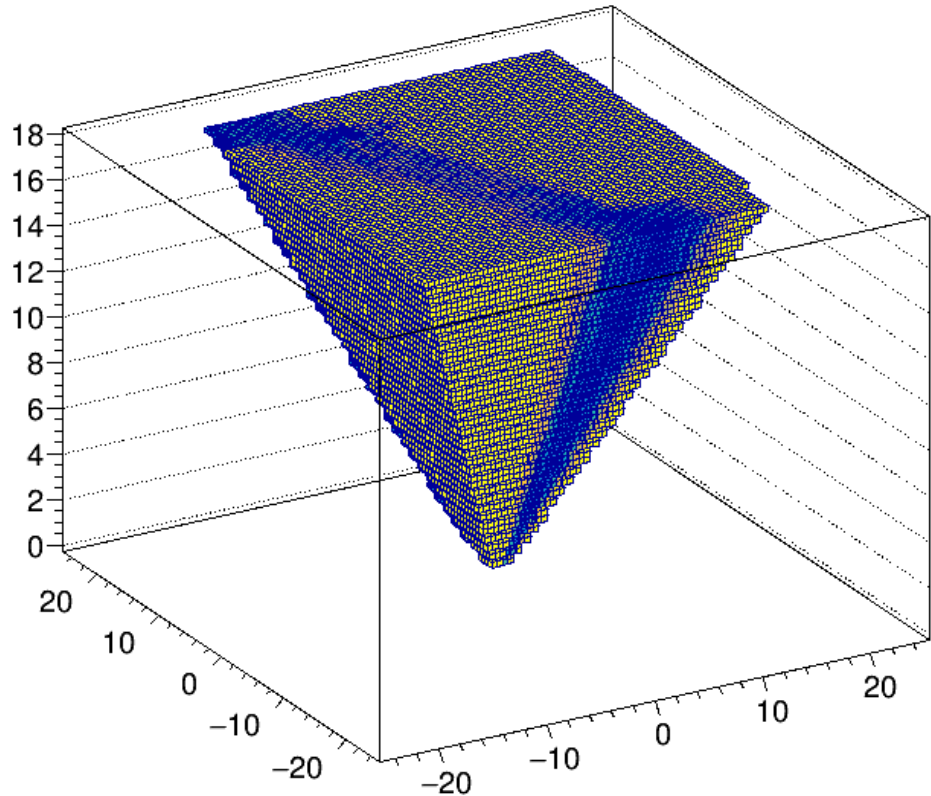
Efficiency

Telescope status, more variations than anticipated at Lousal  
a few lessons learned about the detector, analysis underway

*This works well in simulation !*

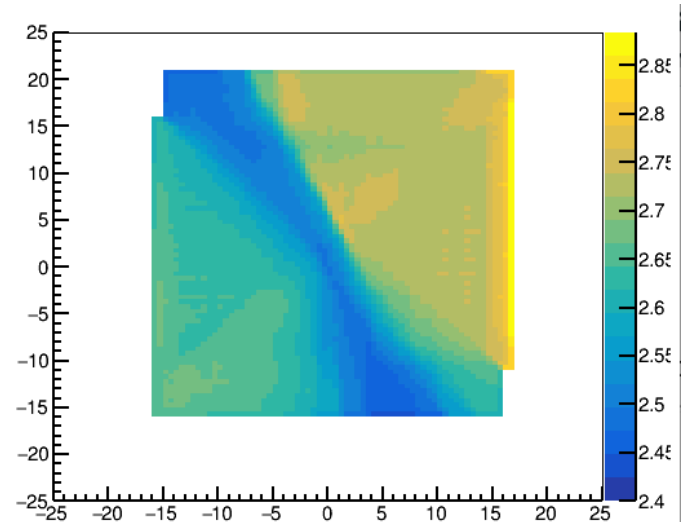
# going to 3D

Having two positions, we can recover the fault geometry and density more precisely!



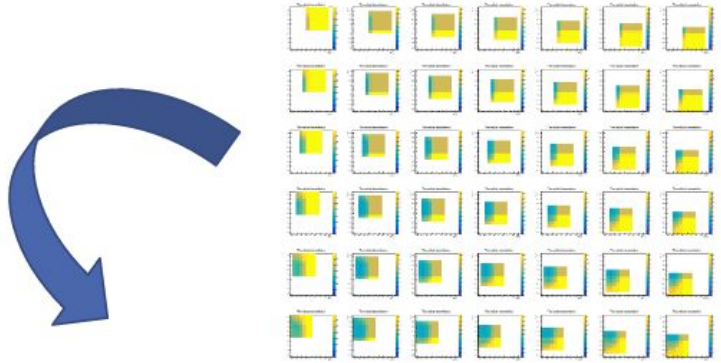
Testing in simulation an iterative method (SART, used in medicine and muography)

Will cross-check with constrained inversion, as used for the other geophysical analyses



# going to 3D

Testing also using the full detector information, for resolution improvement in the building



Each position gives 3 maps x 49 sub-maps!

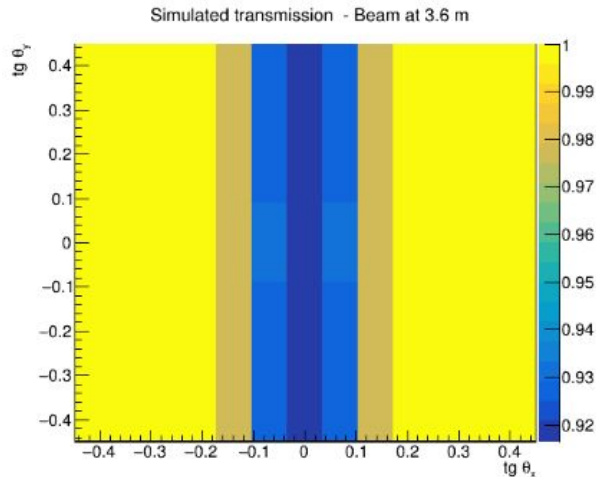
All compatible in 2D for far-away objects

- a way to check for systematics
- a way to improve 2D resolution

All providing 3D info for close-by objects

- search for the best 3D model, ie, that minimizes the residuals (taking into account uncertainties)

Catching up with recent work in muography!





# going further

Seeing the geological fault was our first target, we will soon have its 3D density map

Will then compare & combine muon tomography with seismic refraction tomography

Using the Coimbra building to test more precise target analyses, to repeat at Lousal

Using the Lousal geophysical analyses to better understand the usual requirements

Simulating other scenarios, with different depths, shortened exposures, movement

The team is looking forward to new applications of the developed tools and methods



# Acknowledgments

## Funding



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## 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 Sarmento

### Equipa de Geofísica

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LNEG:

João Matos

## Webpage



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

+ many internship students: André, Zhou, João, Catarina, Daniel, Inês, Rodrigo, Luis, Diogo, Gonçalo, Joana, Henrique