Muography:
overview, applications and future developments

Giulio Saracino
Università degli studi di Napoli Federico II
INFN sezione di Napoli
MuonX SPA

Summary

- Introduction to muography
- Some applications
  - Nuclear safety and safeguarding
  - Volcanoes
  - Archeology
  - Cavities detection
- Conclusions and perspectives

Muons and muon radiography

Cosmic muons are produced in the upper part of earth atmosphere by the primary cosmic radiation reaching the earth's surface

They have an incredible ability to penetrate matter and, at the same time, are easily detectable

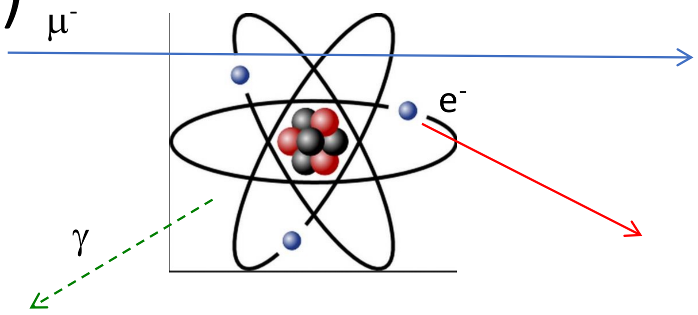
Two different physics process at the base of muon radiography techniques

Energy Loss -> M.R. by transmission

Coulombian Multiple Scattering -> Muon tomography by scattering

Sometime a mix of the two techniques, called absorption, is used

Muon radiography by transmission (I)

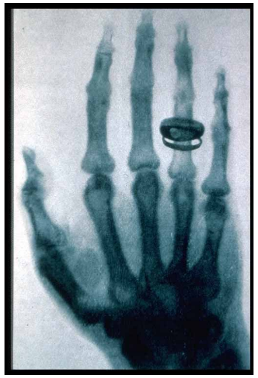


Muons lose energy by interacting with atoms.
The energy loss depends mainly on the density of the material and less on its atomic number.

Material opacity $x = \rho d$ Product of density and distance

$dE/dx \simeq A + B \ln(E)$

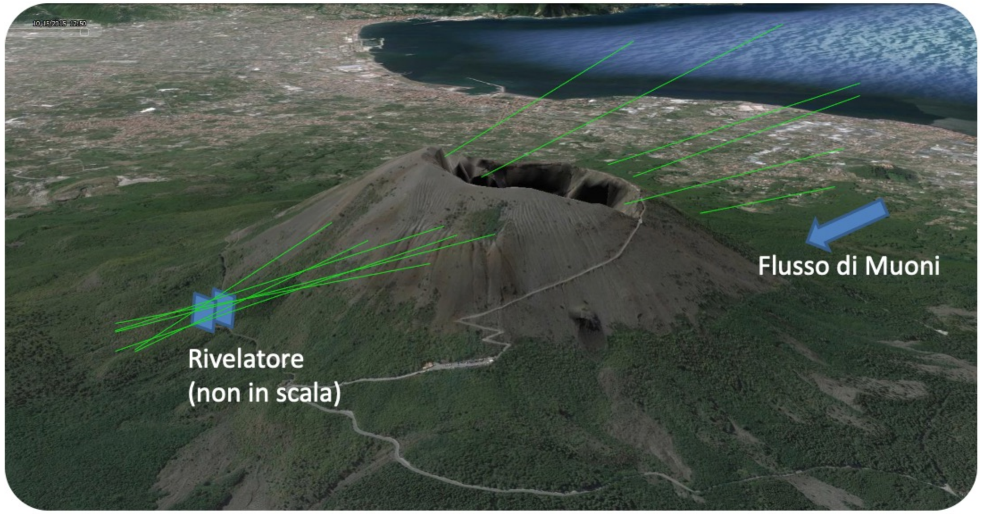
The range of a muon of fixed energy depends on the opacity
Since the muon energy spectrum is continuous, the measured flux is related to opacity



Similar to x-ray radiography:
the intensity of radiation measured in a certain direction depends on opacity passed through

M.R. by transmission (II)

Transmission is measured using a muon tracker positioned downstream with respect to the investigated volume
The measured flux is compared with the expected one, computed by simulation models.
Large volume can be investigated
Measurement from a single observation point provides a 2D image of the average density distribution.
Combining more measurements from different points 3D information can be provided



Suitable for the determination of density distribution
and for the detection of cavities in large volumes

M.R. by multiple scattering (muon tomography)

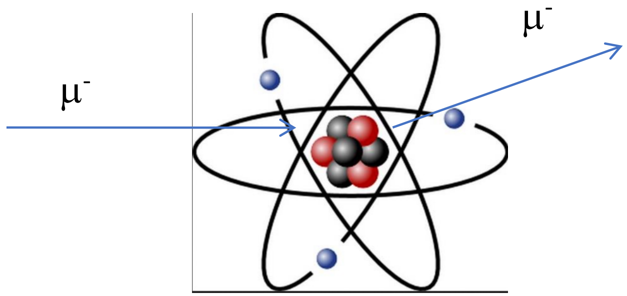
Interactions with the atomic nuclei deflect the muon trajectory

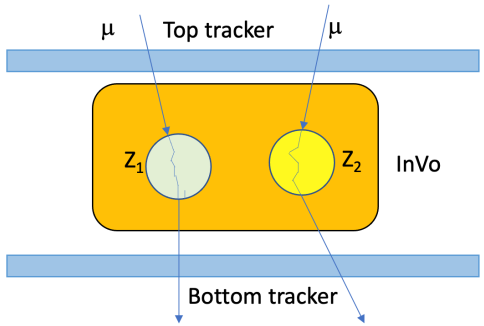
The amount of scattering depends on opacity and atomic number Z

Two muon trackers measure the direction of the incoming and outcoming muons.

Realistic detector sizes limit the volume investigated

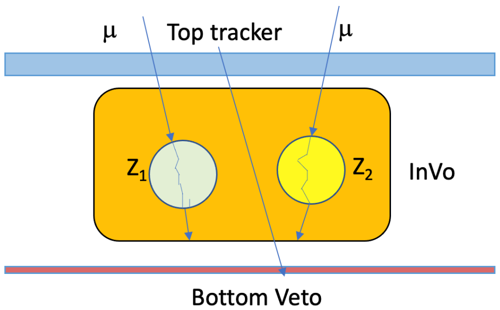
3D native





$$\theta^2 \propto xZ$$

Suitable for the determination of high Z material



absorption method measures the incoming muons that are stopped by the material using a simple veto detector downstream

Examples of applications

SCATTERING:

- Nuclear material imaging
  - Container scanning for illegal transport and security
  - Nuclear waste drums scanning
  - Inspection of basket of exhausted bars
  - Nuclear reactor
- Industrial application
  - Reinforced concrete
  - Pipelines imaging
  - Blast furnace (density distribution and deterioration of the walls)
- Medical applications (?)

ABSORPTION

- Geophysical survey
  - Volcanoes
  - Cavity or density anomalies (safety, safeguarding, and archeology)
  - mineral deposit exploration
  - Underwater bradyseism
- Industrial application
  - Blast furnace
  - Dam inspection
  - Reinforced concrete
  - pipelines
  - Buildings stability monitoring
- Environmental survey
  - Glacier thickness
  - Stratosphere temperature dynamics

Muon radiography tracking detectors

Actual characteristics depend on the specific application.
As example:

Detector Characteristic	Scattering	Transmission
Surface area	$\gtrsim 1\ m^2$ X 2	$\lesssim 1\ m^2$
Spatial resolution	$\lesssim$ 1 mm	$\gtrsim$ 1 mm
Volume to be investigated	$\lesssim 100\ m^3$	$>> 100\ m^3$
Dimension of the object to be resolved	$\lesssim$ 10 cm	$\gtrsim$ 1 m
3D imaging	yes	possible
Acquisition time	$\gtrsim$ 1 min	$\gtrsim$ 1 day

Transportability, robustness and low power consumption are also required for applications outdoors

Muon radiography detectors technologies

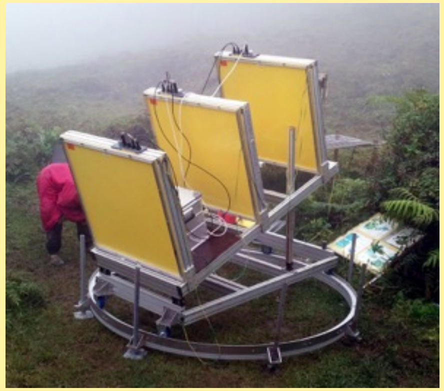
- SCINTILLATOR BASED
  - Plastic bars with or without WLS fiber, PMT or SiPM
  - Fibers with MA-PMT or SiPM
- GAS BASED
  - Drift Tubes (5 cm in diameter)
  - RPC
  - Micromegas
  - multi-wire proportional chamber
- Nuclear emulsion
- Air Cherenkov telescope

Examples of technologies in use in muon absorption

Plastic scintillators with Photomultiplier tubes or Silicon photomultiplier (PMT o SiPM)

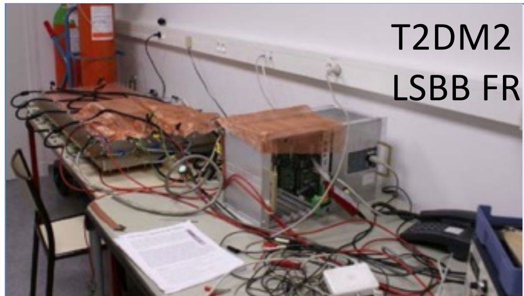
MU-RAY - INFN

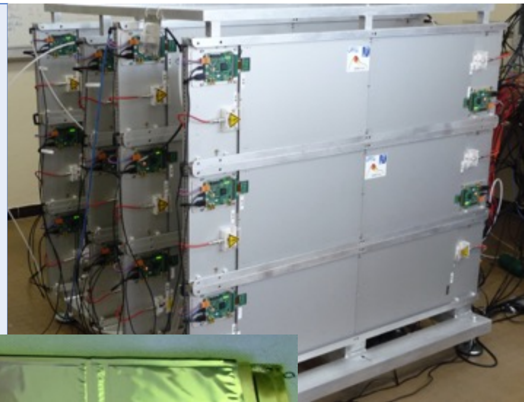
TANAKA -ERI



DIAPHANE IN2P3

Gas detectors RPC, wire chamber, micromegas





TOMUVOL - IN2P3

ASTRI-INAF

Nuclear emulsions and RICH

OPERA INFN, NAGOYA BERN

Which is the best technology ?

It depends on the specific application. Each technology has pros and cons

Scintillator and gas detectors are electronic devices : they gives results in real time but they need electricity and take up some space.

Nuclear emulsions are very compact , don't need electricity and have good spatial resolution. But they are complicated to analyze and results can be obtained some time after the exposure.

Gas detector are less stable than plastic scintillator, they need gas and high voltage. But they are less expensive (per square meter) and can provide better spatial resolution than scintillators at reasonable costs.

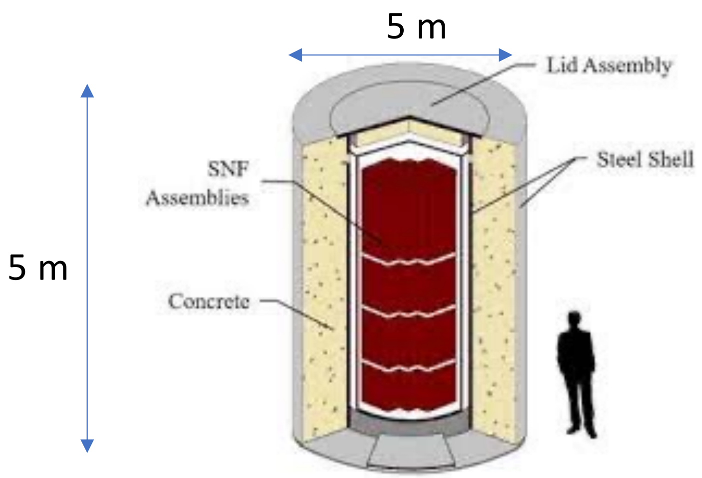
Case studies

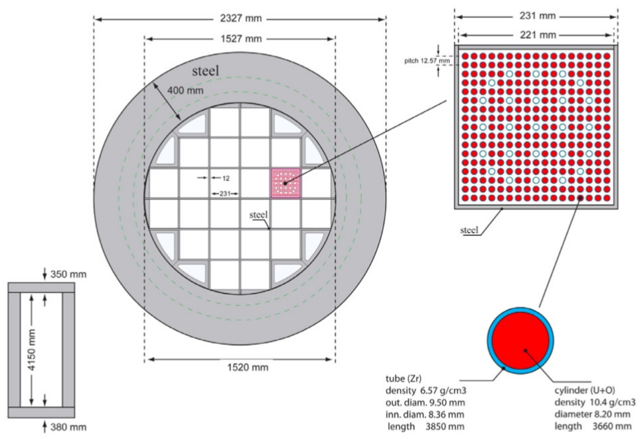
Monitoring nuclear reactor fuel in dry storage cask (DSC)

Verification of their content prior to permanent storage in a geological repository

Routine verifications or re- verifications in case of a *loss of continuity of knowledge*

Typical DSCs as CASTOR® V or Westinghouse MC-10 have height of about 5 m, an external diameter of 2.4 m and a mass of more than 120 tons
Concrete and steel shielding reduce the radioactivity but prevent the inspection with traditional procedures.
The presence of the other casks disturbs the methods based on radioactivity measurement
Visual inspection can be performed only in dedicated water pool



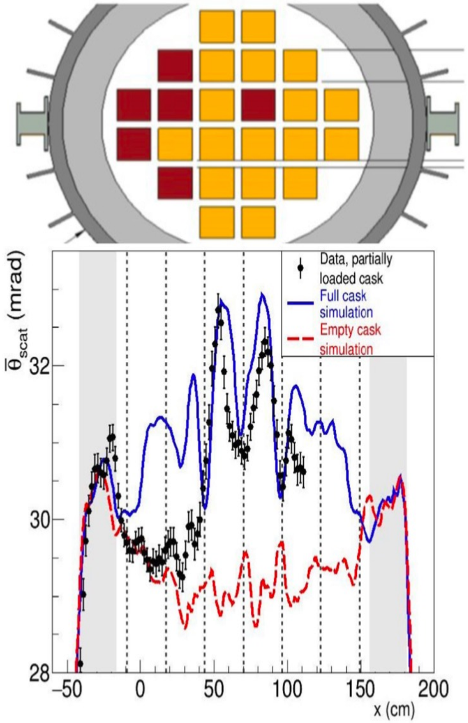


A test at the Idaho National Laboratory (USA)

A canister with some missing fuel assembly

Los Alamos National Laboratory)

1.2 m x 1.2 m drift tube gas trackers X-Y measurement



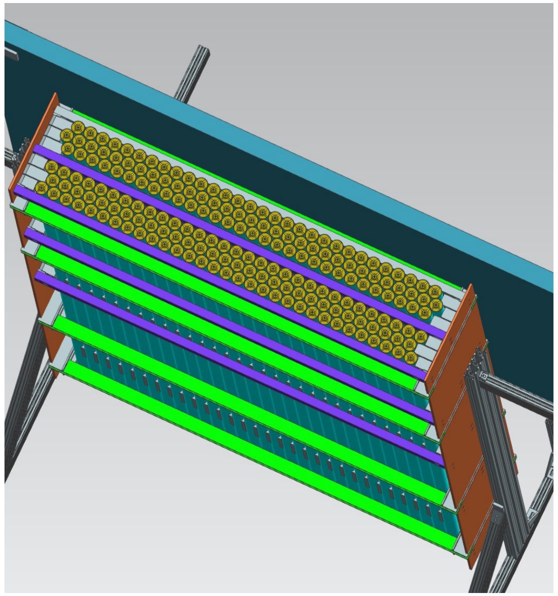
Comparison data and simulation

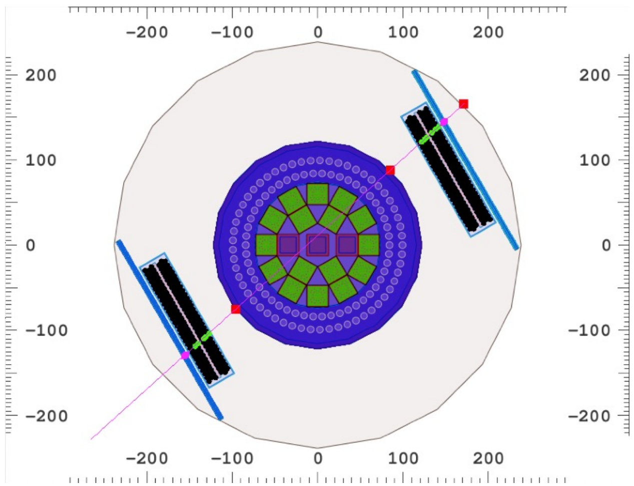
J.M. Durham, et al., Phys. Rev. Appl. 9 (2018) 044013.

The MUTOMCA project

INFN, FZJ (Germany), BGZ company (Germany), e European Commission, Directorate-General for Energy.

Two drift tubes based trackers that can be rotate around the cask





The detector measures with high precision the horizontal coordinate and with poor precision the vertical coordinate v.

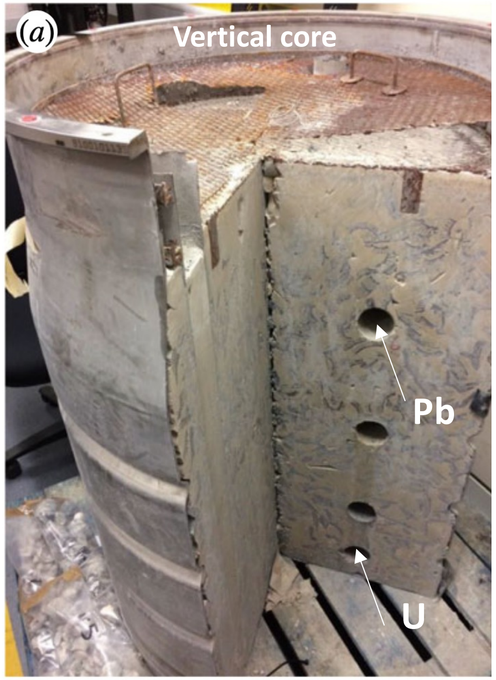
Safety application
Nuclear materials stored in legacy waste containers

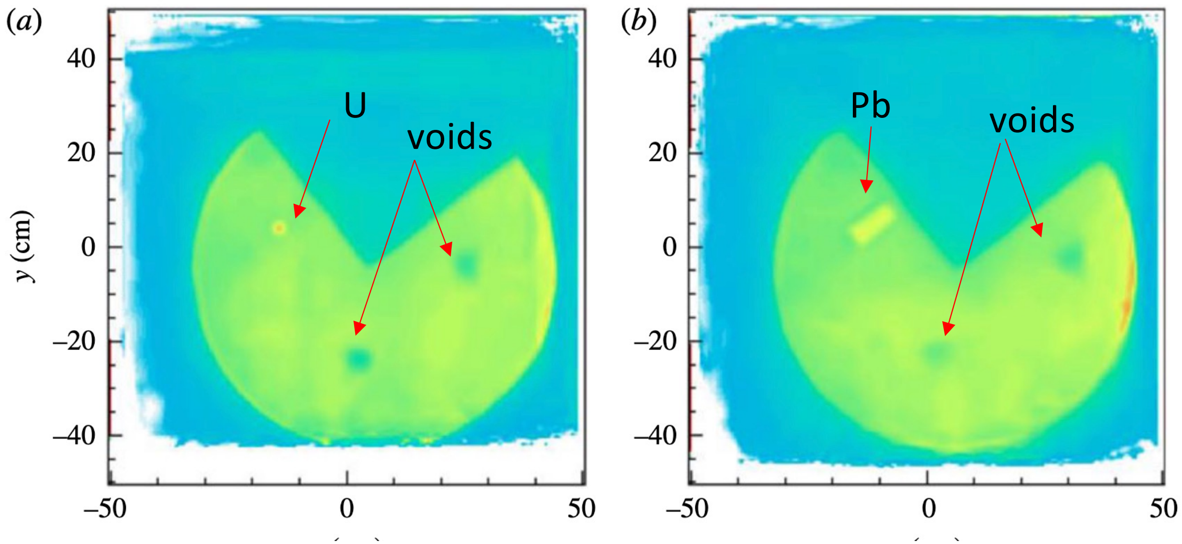
In 2009 UK Nuclear Decommissioning Authority (UK NDA) and Sellafield Ltd funded a project, now *Lynkeos* Technology LTD start-up.

imaging 500-litre stainless-steel intermediate level waste (ILW) drums containing cladding material stripped from uranium fuel rods encapsulated within concrete containing also unknown quantity of fuel fragments.

Full-scale demonstrator Muon Imaging System
installed at the National Nuclear Laboratory (Sellafield, UK).
1m^2 scintillating fiber trackers

Nuclear materials stored in legacy waste containers: experimental test





Horizontal slice (1 cm) in a region with Uranium and lead.
(24.7 million muons)

bottommost horizontal core: uranium sample cylinder 20x30 mm^2
uppermost horizontal lead core 90 mm×40 mm×20 mm.

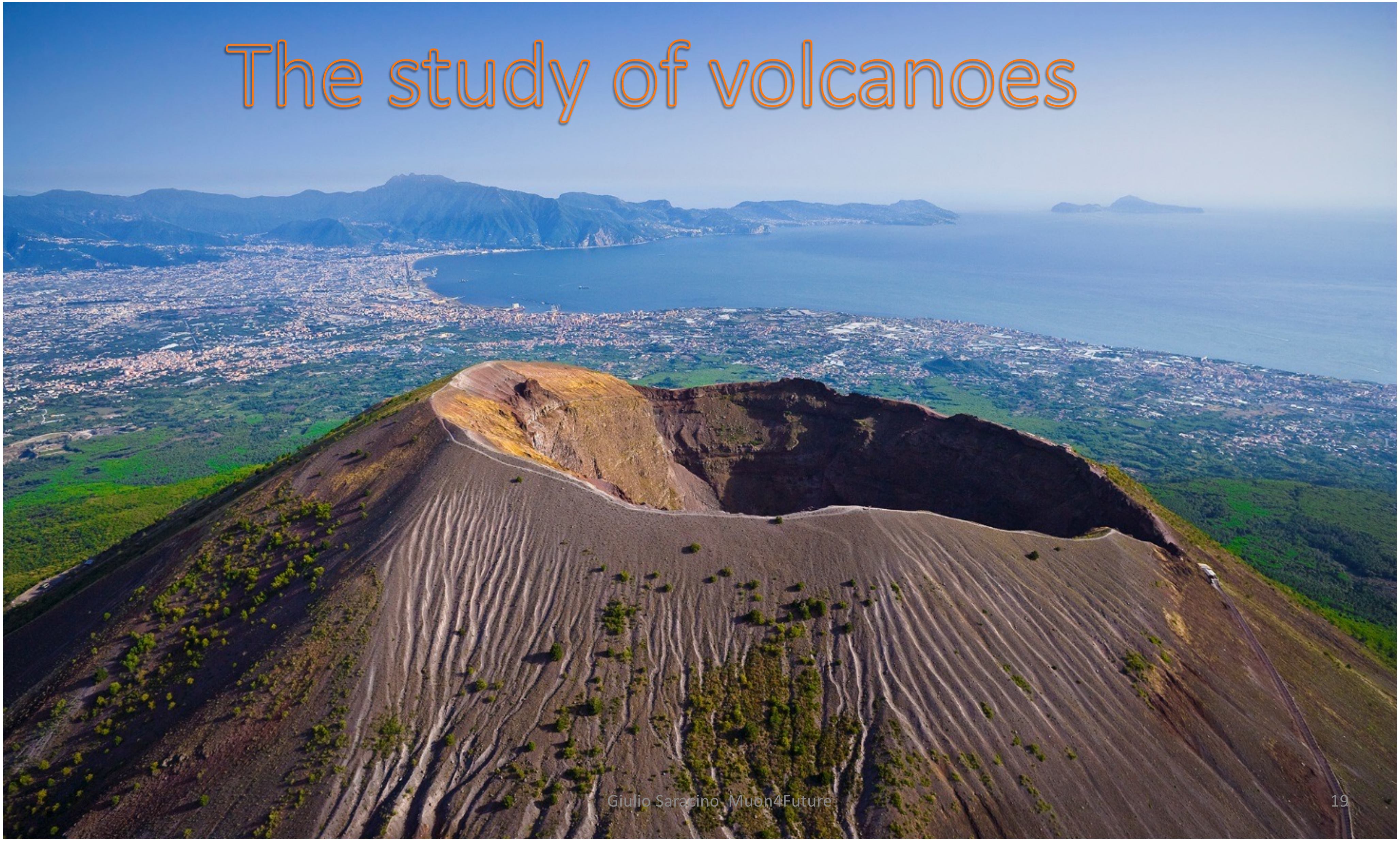
Mahon D. et al. 2019. Phil.Trans.R.Soc. A377

Muon radiography by transmission

Study of volcanoes

Cavity detection -> archaeology, safeguarding

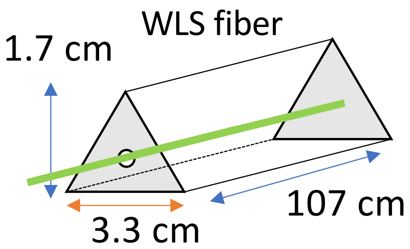
Industrial application: blast furnace


The study of volcanoes

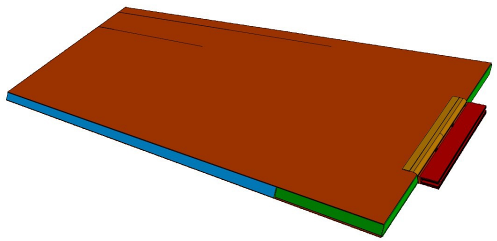
The study of volcanoes: the MU-RAY Project

- 2009-2012: MURAY funded by INFN
  - Electronic detector R&D dedicated to volcanic applications
  - Low power consumption
  - Robust
  - Transportable
  - Good angular resolution
  - TOF background rejection
- *Progetto Premiale* 2012 MURAVES Muon Radiography VESuvius
  - In collaboration with Vesuvian Observatory INGV (NA) (operational since March 2015)
  - laboratory at Vesuvius: 3 detectors with 4 X:Y traccking stations of $1m^2$

MU-RAY



12 x



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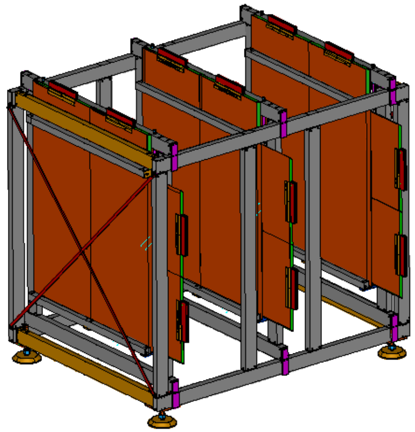
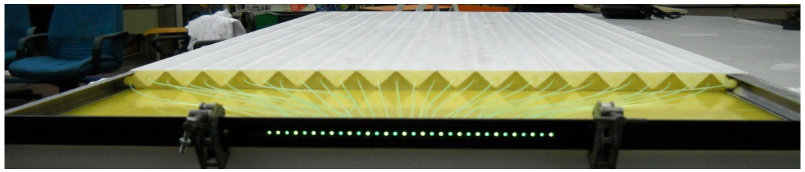
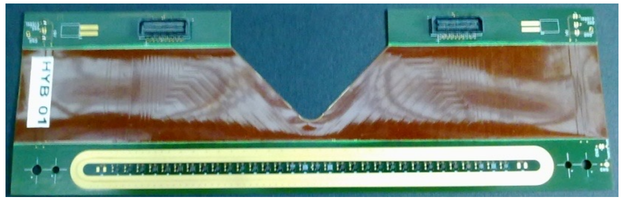


Tracker
3 piani X-Y 1mq

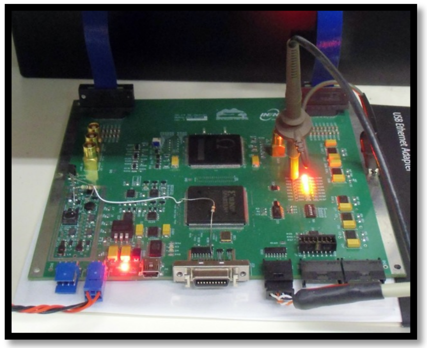
Single module 1m x 0.5m 20 kg



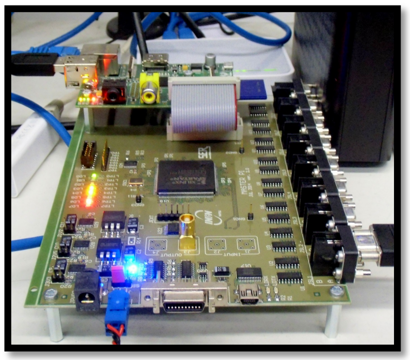
32 Plastic scintillators + WLS 2-3 mm resolution



PCB 32 SiPM termally controlled (FBK)



Elettronica front end
ASIC EASIROC (OMEGA)
FPGA
HV on board
32 Ch
2W power



DAQ board

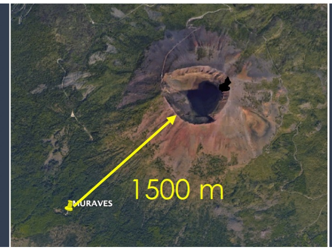
FPGA +
Raspberri-Pi
384 channels

30W/detector

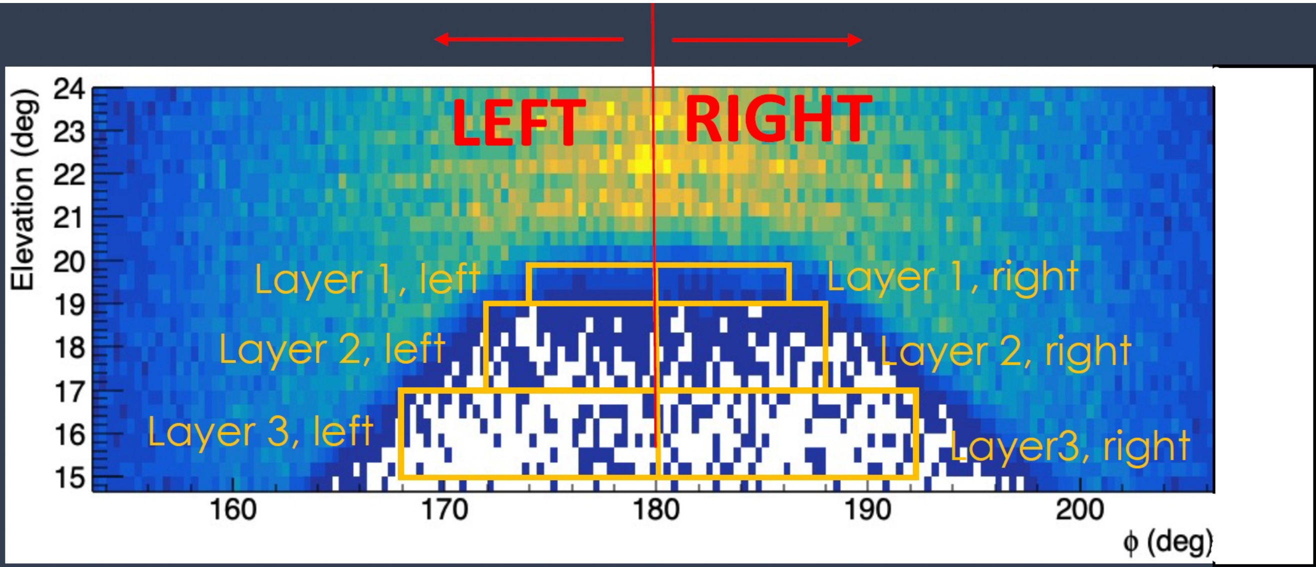
MURAVES

The laboratory 4.5m x 9.6m x 2.5m

The MURAVES experiment: the laboratory

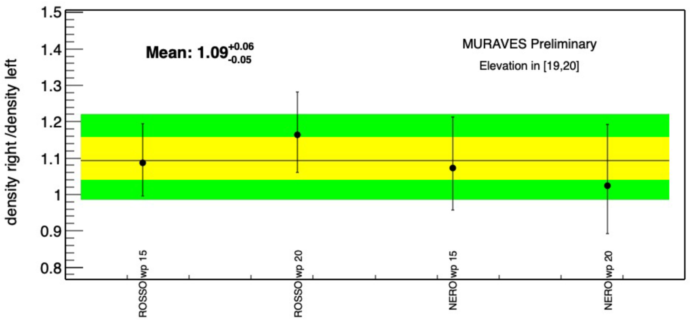


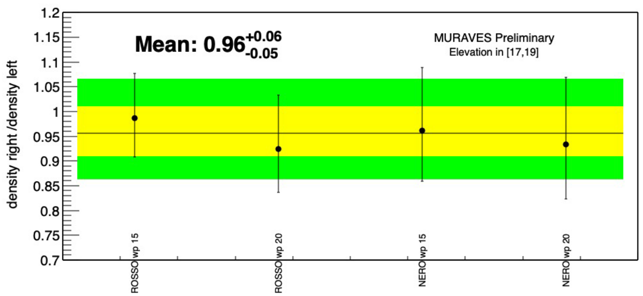
The MURAVES experiment: preliminary results on a reduced data sample

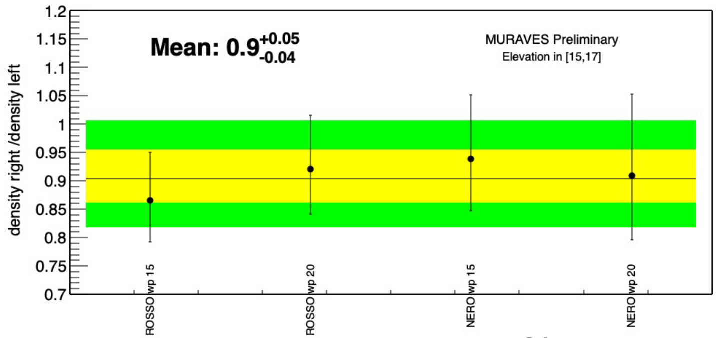


	SPATIAL RESOLUTION	
	Δx	Δy
LAYER 1	180 m	26 m
LAYER 2	210 m	52 m
LAYER 3	315 m	52 m

- Vertical resolution better than orizonthal resolution to highlight the expected layered structure
- layers are symmetrically divided in two parts to evaluate density right/left asymmetries







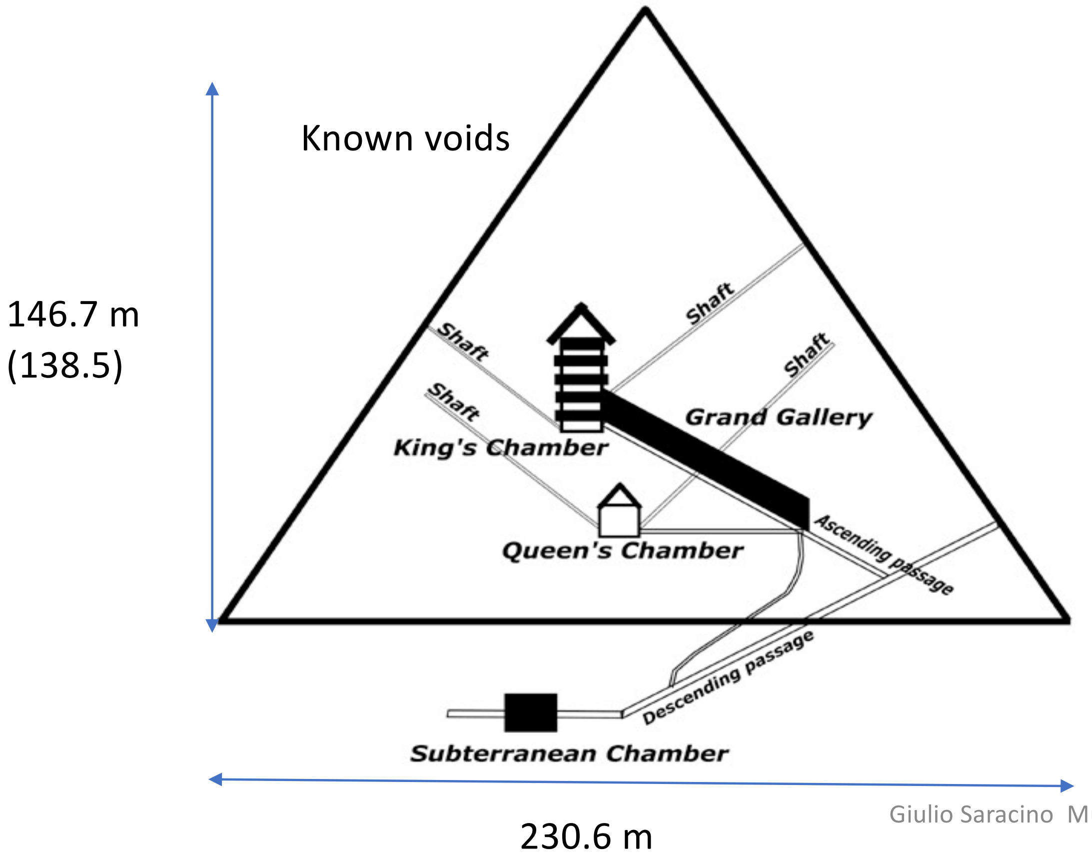
CAVITY DETECTION

Cavity detection: Giza pyramid complex

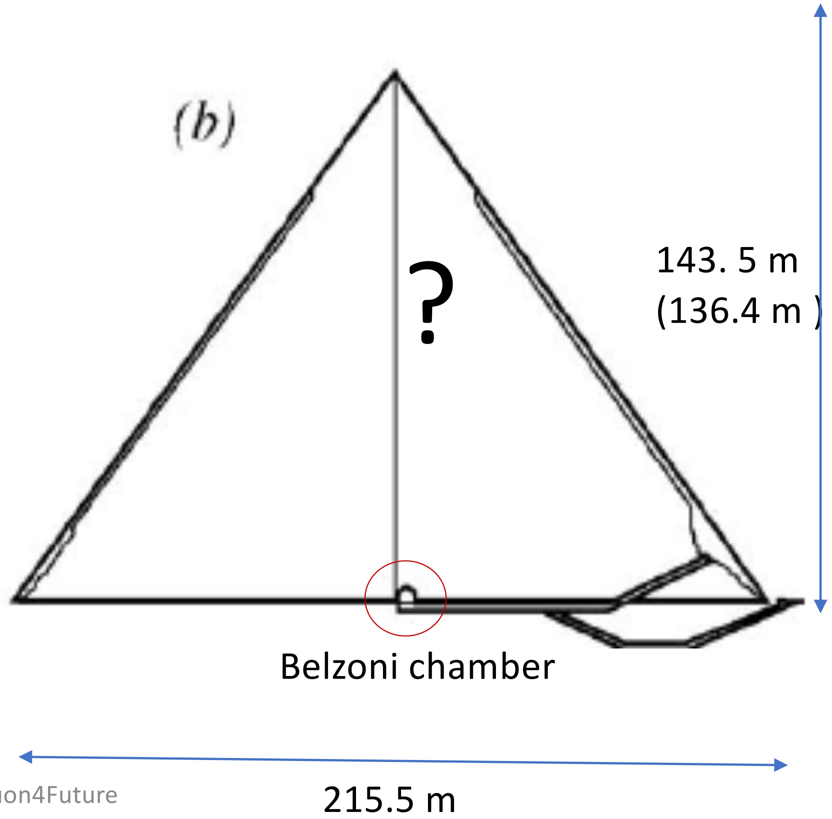
A comparison between Cheope and Chefren pyramids

externaly they are very similar, this is not the case with regard to known internal structures

Cheope (**Khufu)**



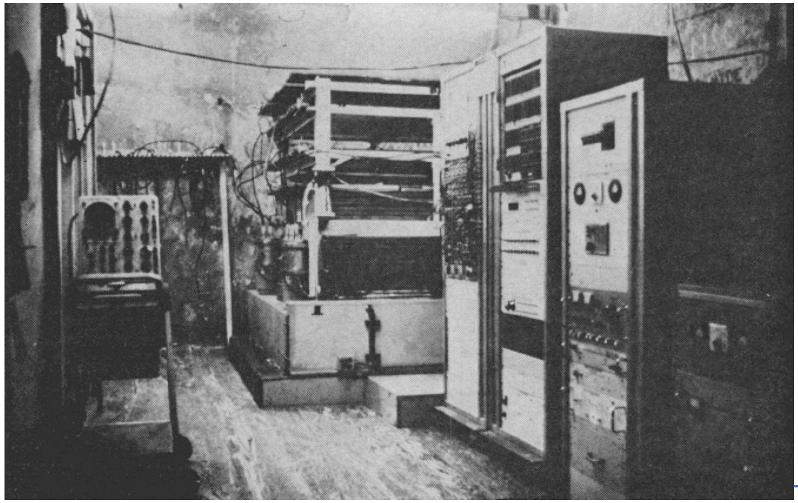
Chefren (Khafre)

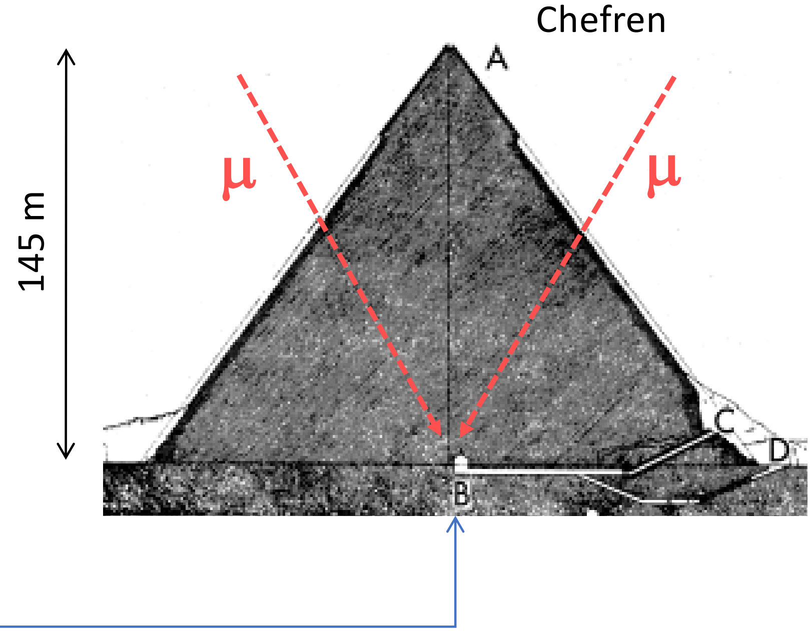


1969-70: Alvarez

looking for possible unknown cavities with muon radiography

He installed one of the most advanced detectors of the time in the Belzoni chamber

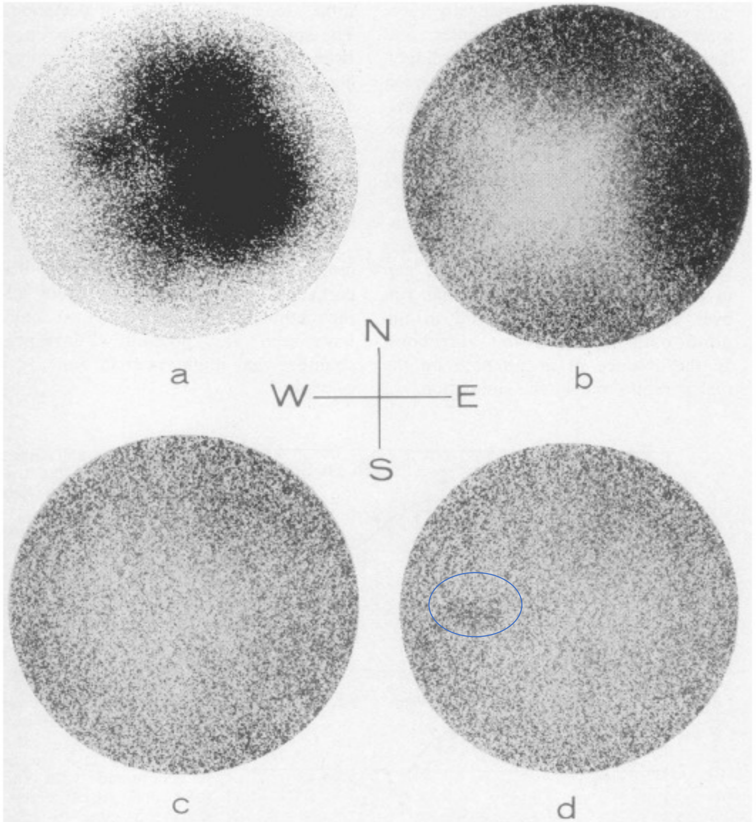




The first muon radiography image ever obtained

Raw data

First correction for the detector geometrical acceptance



Pyramid geometry correction

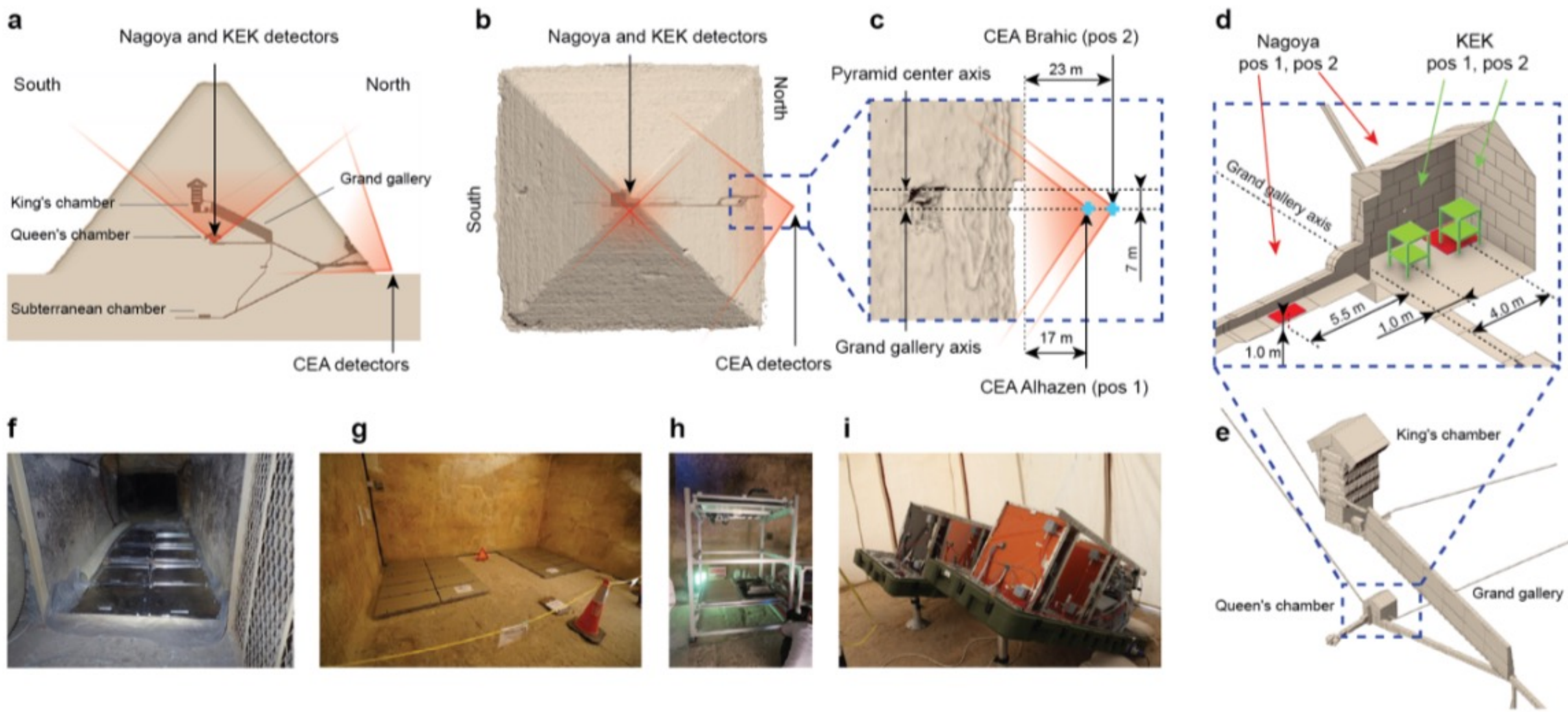
Simulated data with a void

No evidence of the presence of a unknown chamber
(but only the 19% of the volume was observable….)

The SCAN Pyramids project

The scan pyramids big-void discover in Khufu (Cheope)

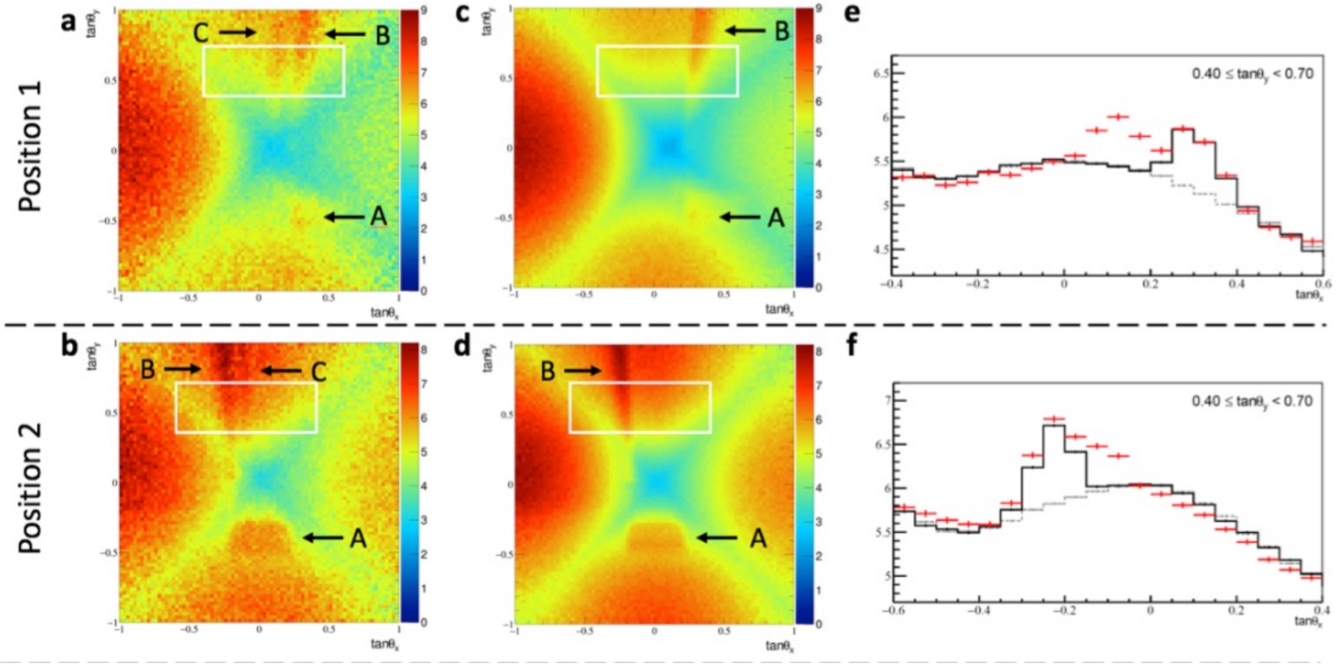
Three different technologies: nuclear emulsions, gas detector, plastic scintillator detector



The scan pyramids big-void discover 2016

Clear signal of an unknown void is seen with the emulsion detectors A

Real data Simulation Data in red

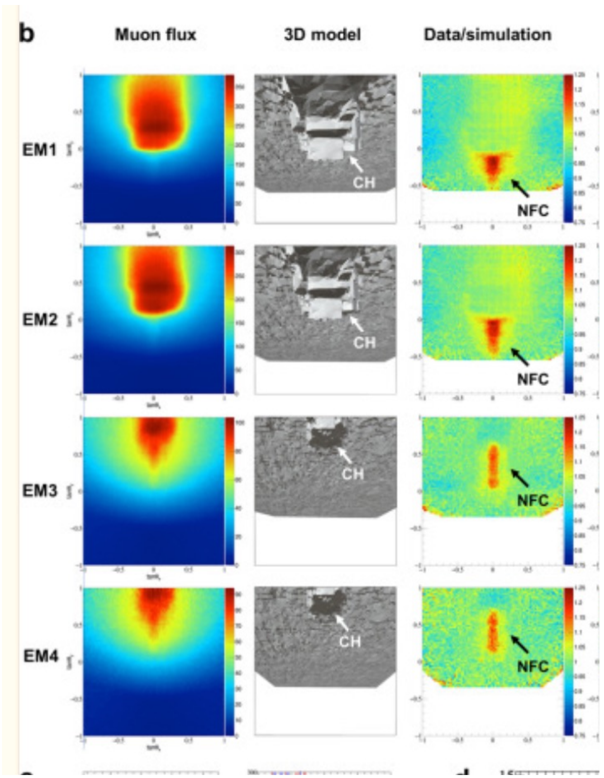


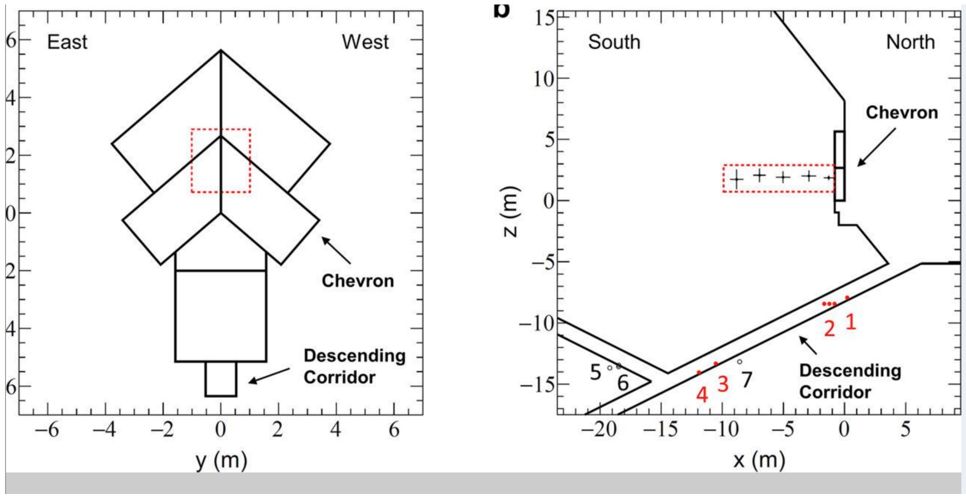
Observed Muon flux: Red means an excess of muons
Know voids: B great gallery ; A the king room
Unaxpected signal: C

K. Morishima et al.
N AT U R E VO L 5 5 2
2 1 / 2 8 D E C E M B E R 2 0 1 7
doi:10.1038/nature24647

2023: The Nord Face Corridor (NFC)

Evidence of a new structure of about 9 m length
with a transverse section of about 2.0 m by 2.0 m.





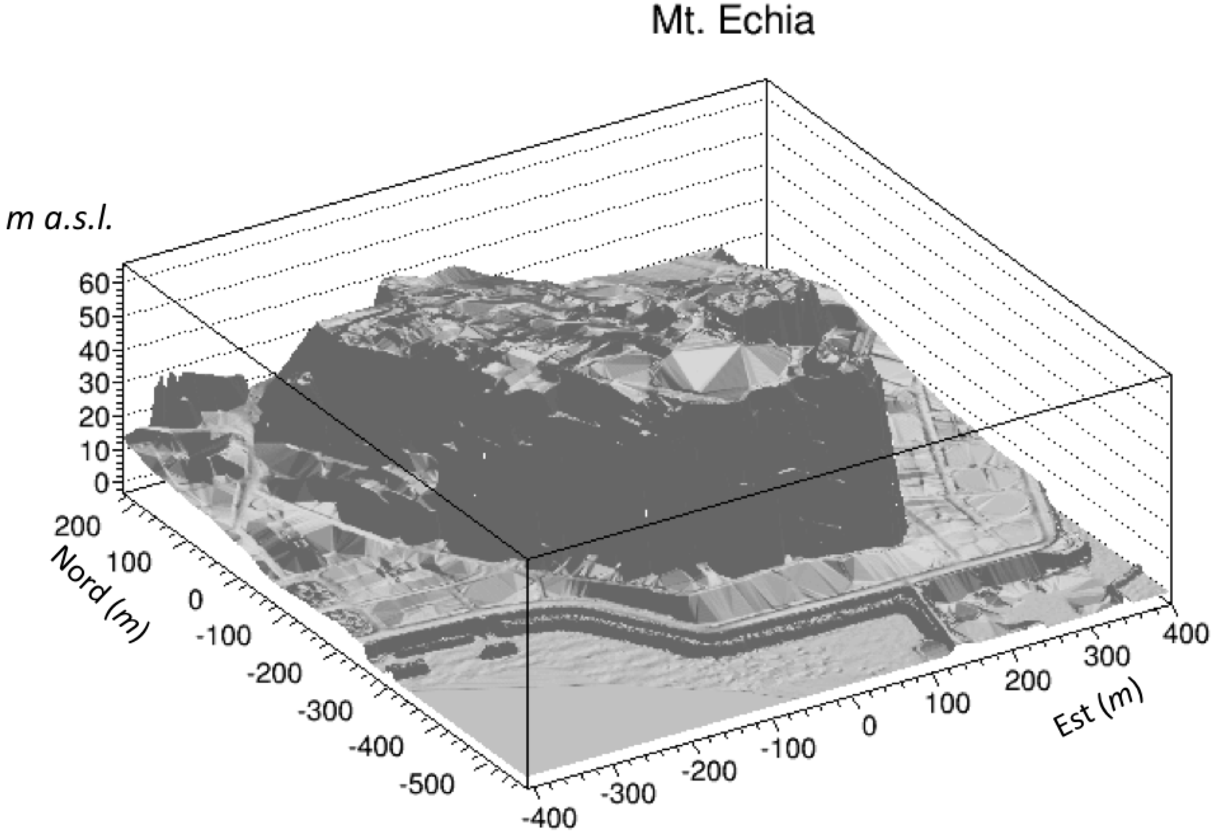
Nat Commun. 2023; 14: 1144.

Test of cavity detection in Naples

The test site: Mt. Echia

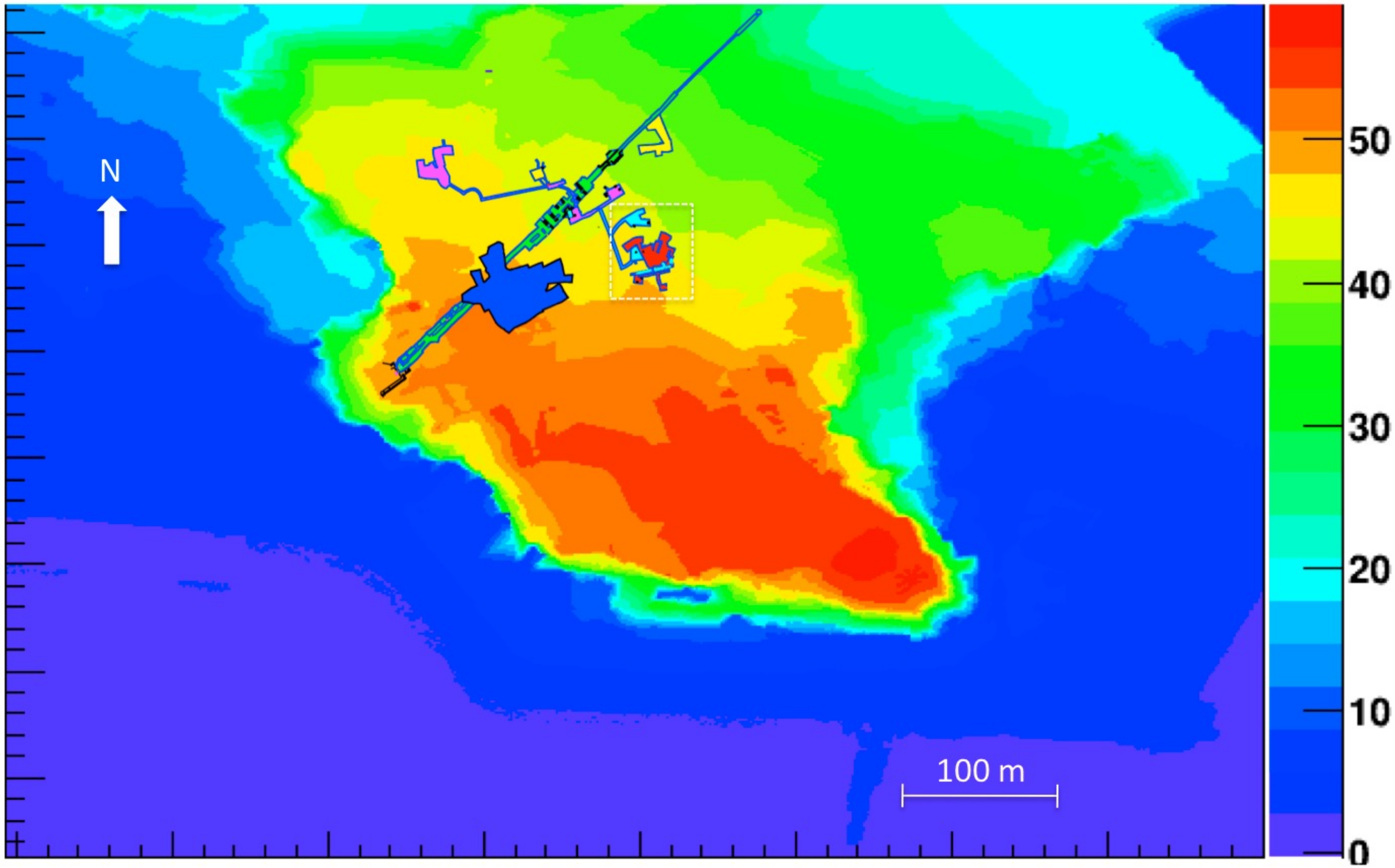
Bulk: Neapolitan yellow tuff
ρ 1.2 ÷ 1.4 g/cm^3

Maximum altitude: 60 m a.s.l.



Digital Elevation Model

Mt Echia: a complex system of cavities

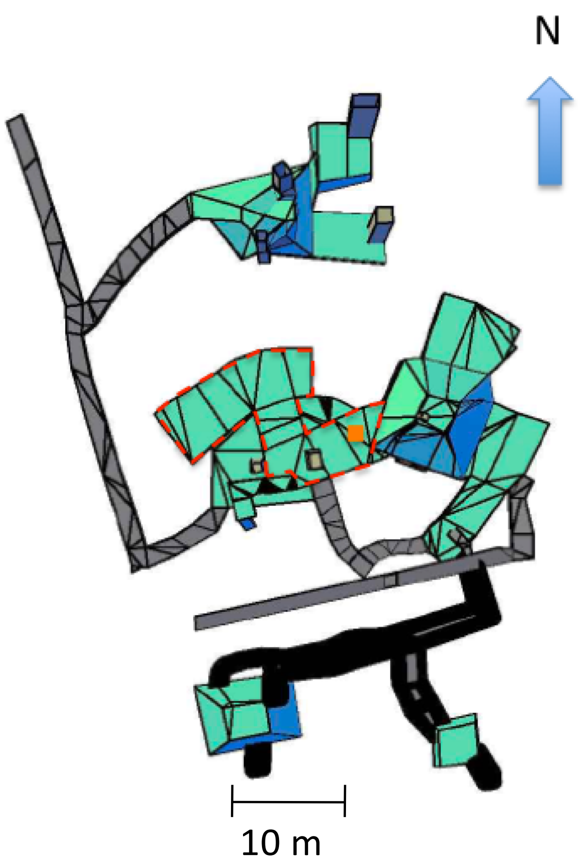


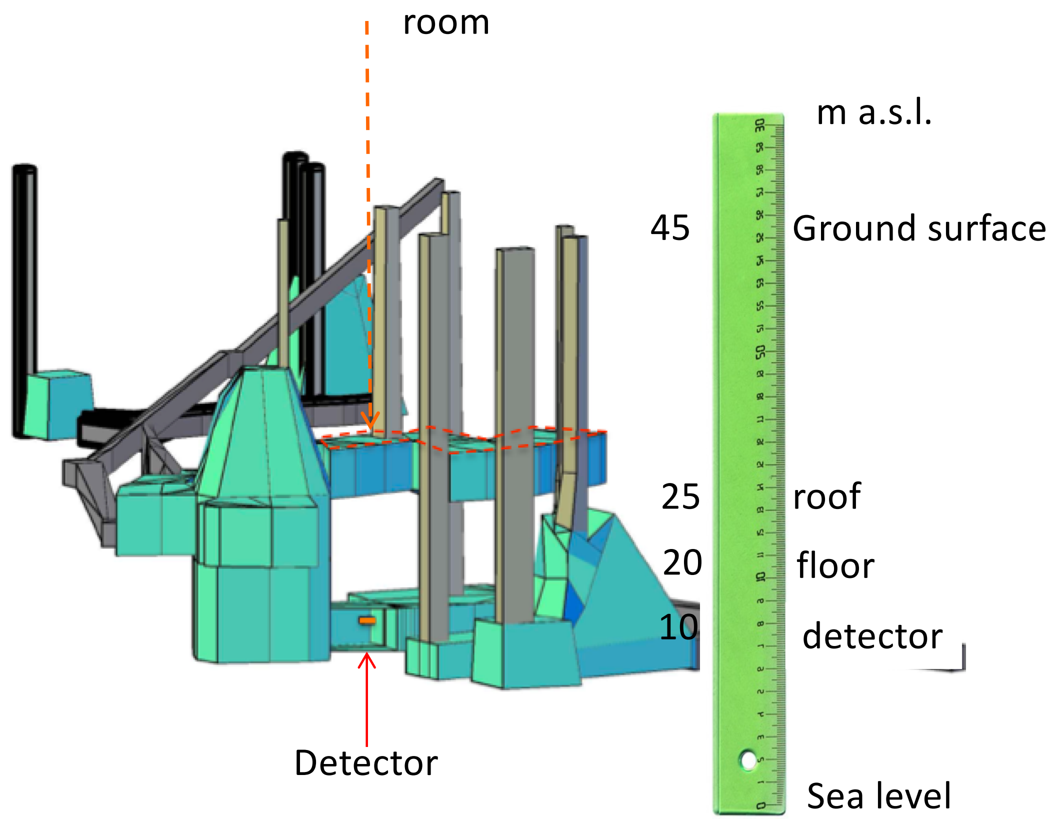
The observation position

12 m a.s.l

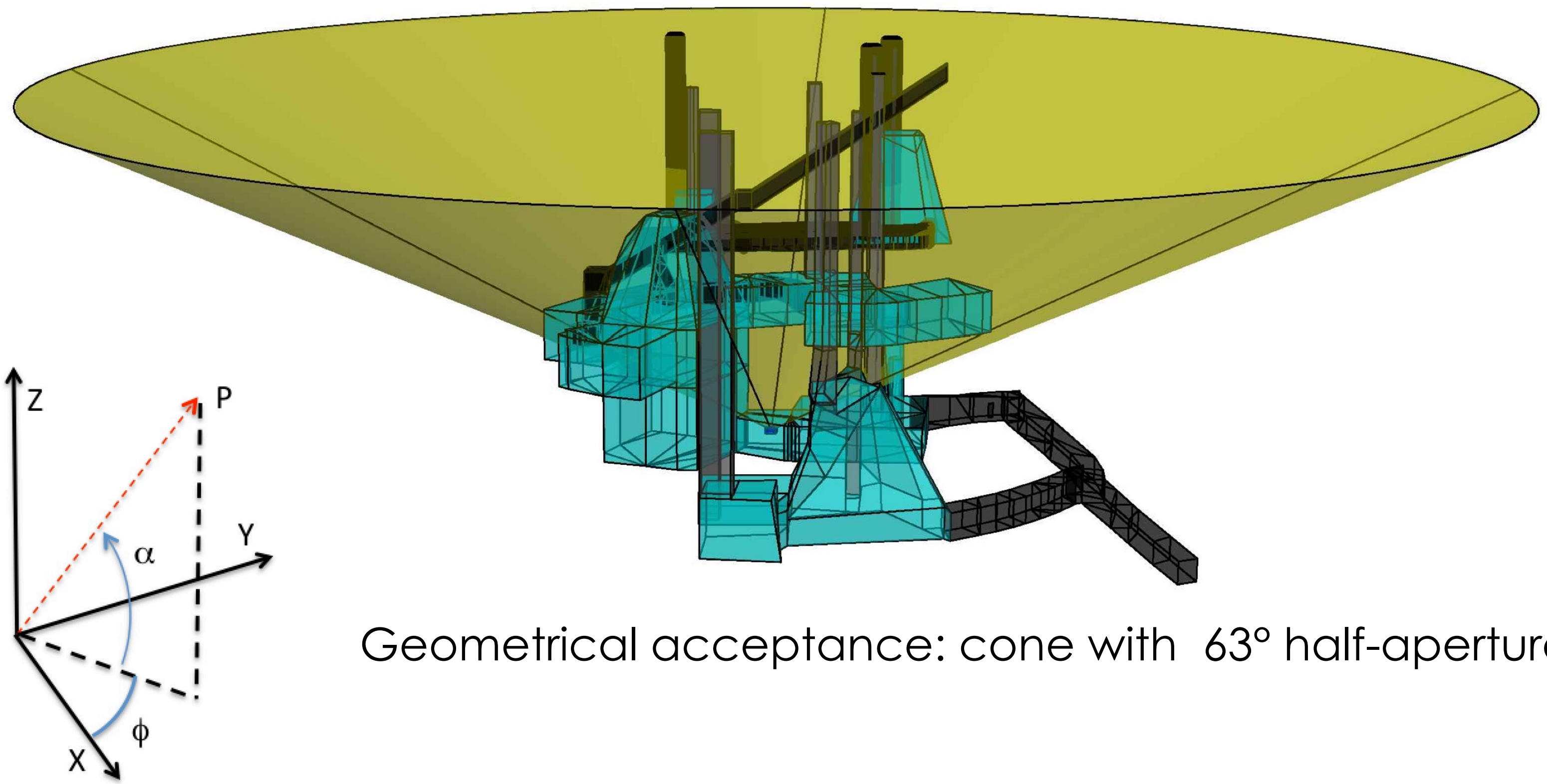
35 m deep

The Test: Detect a room on the top of the detector position





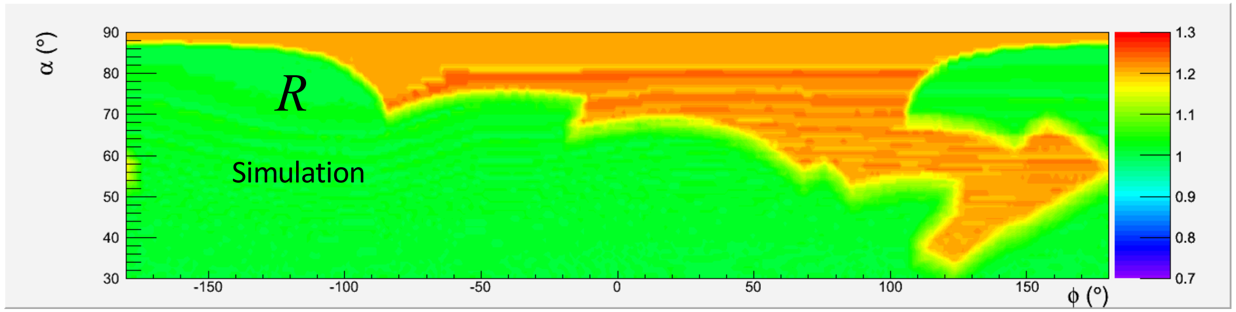
Other voids inside the detector acceptance

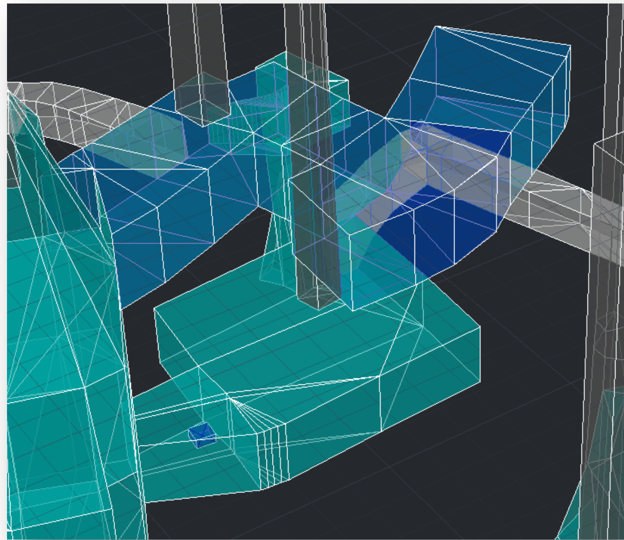


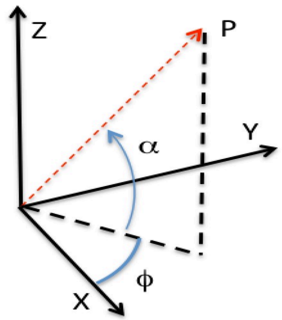
Geometrical acceptance: cone with 63° half-aperture

The expected signal from the test chamber

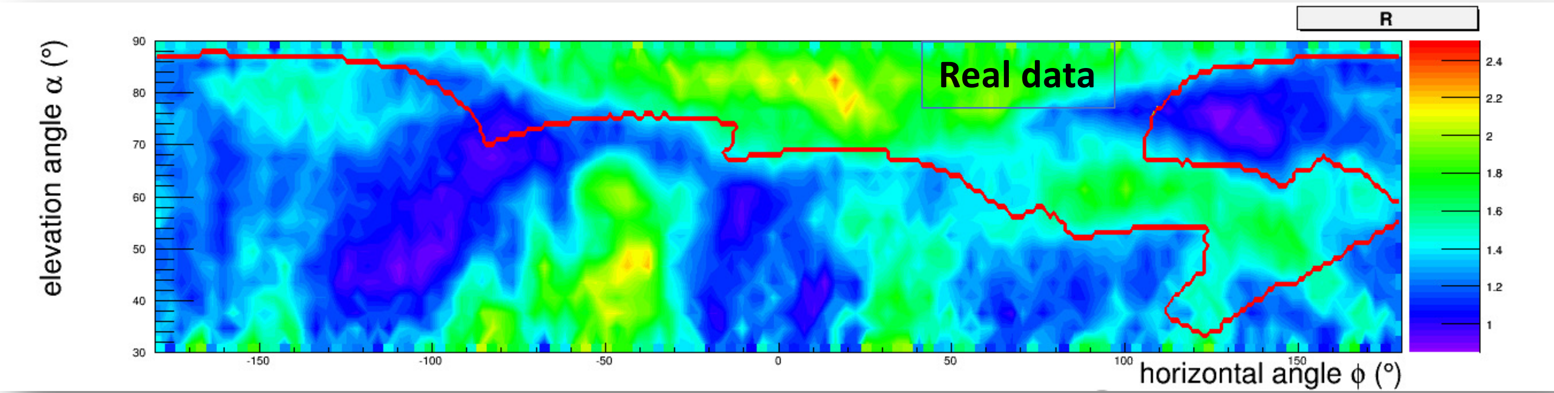
Since the test chamber is known, we can evaluate the expected shape

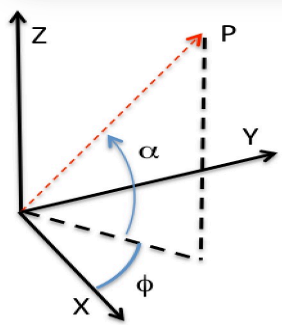


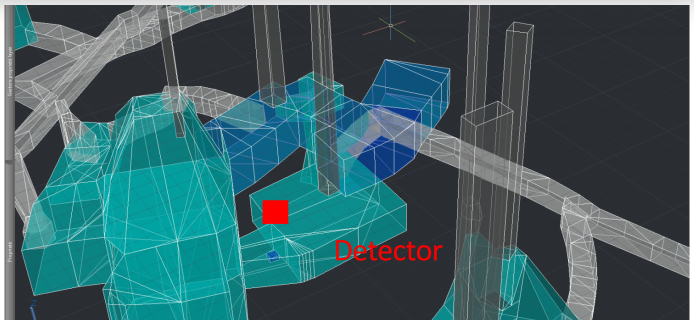




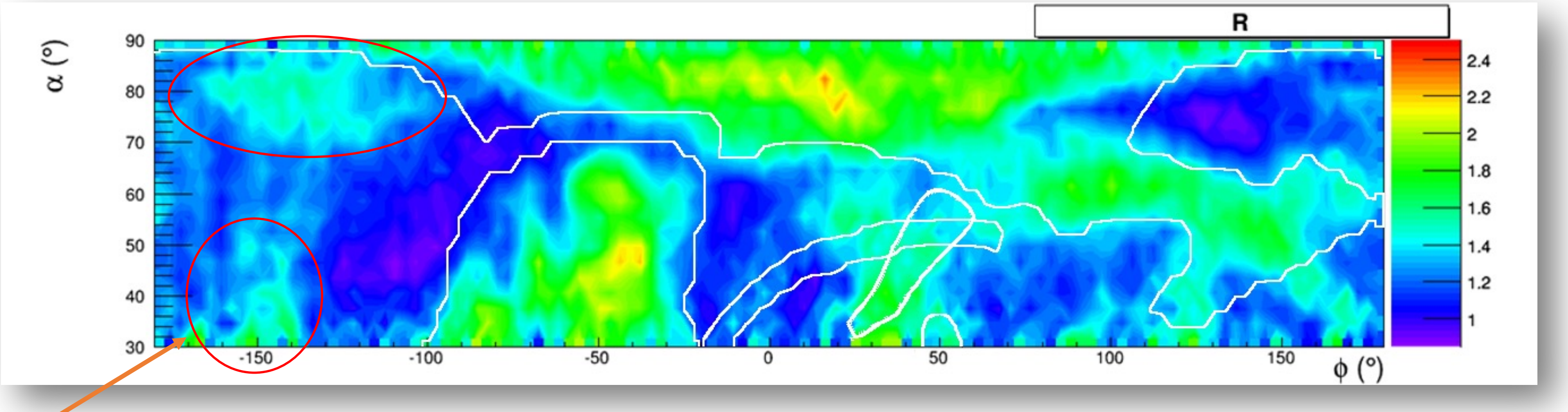
The muographic image







Comparison with known cavities



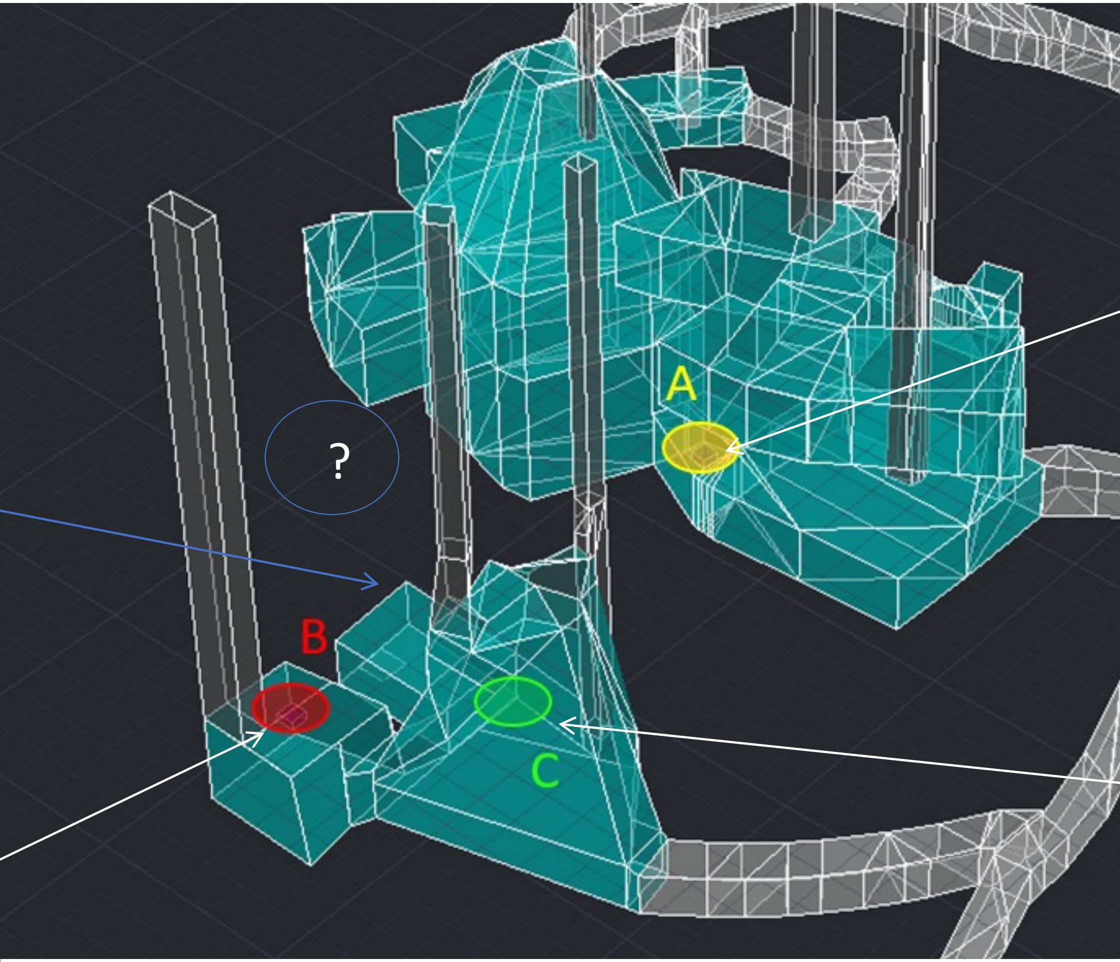
White contours correspond to known cavities

Red contours show signals of unknown structures

speleologists had indirect evidence of a possible cavity in this direction.
An obstructed corrridor did not allow a survey

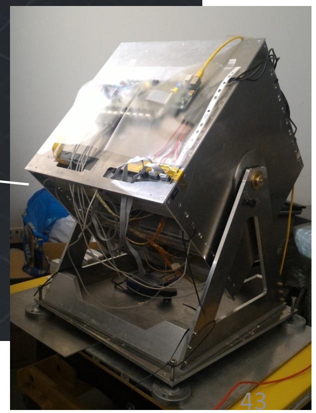
Three different measurements with two detectors

Here there is a corridor blocked by debris



MURAY

MIMA



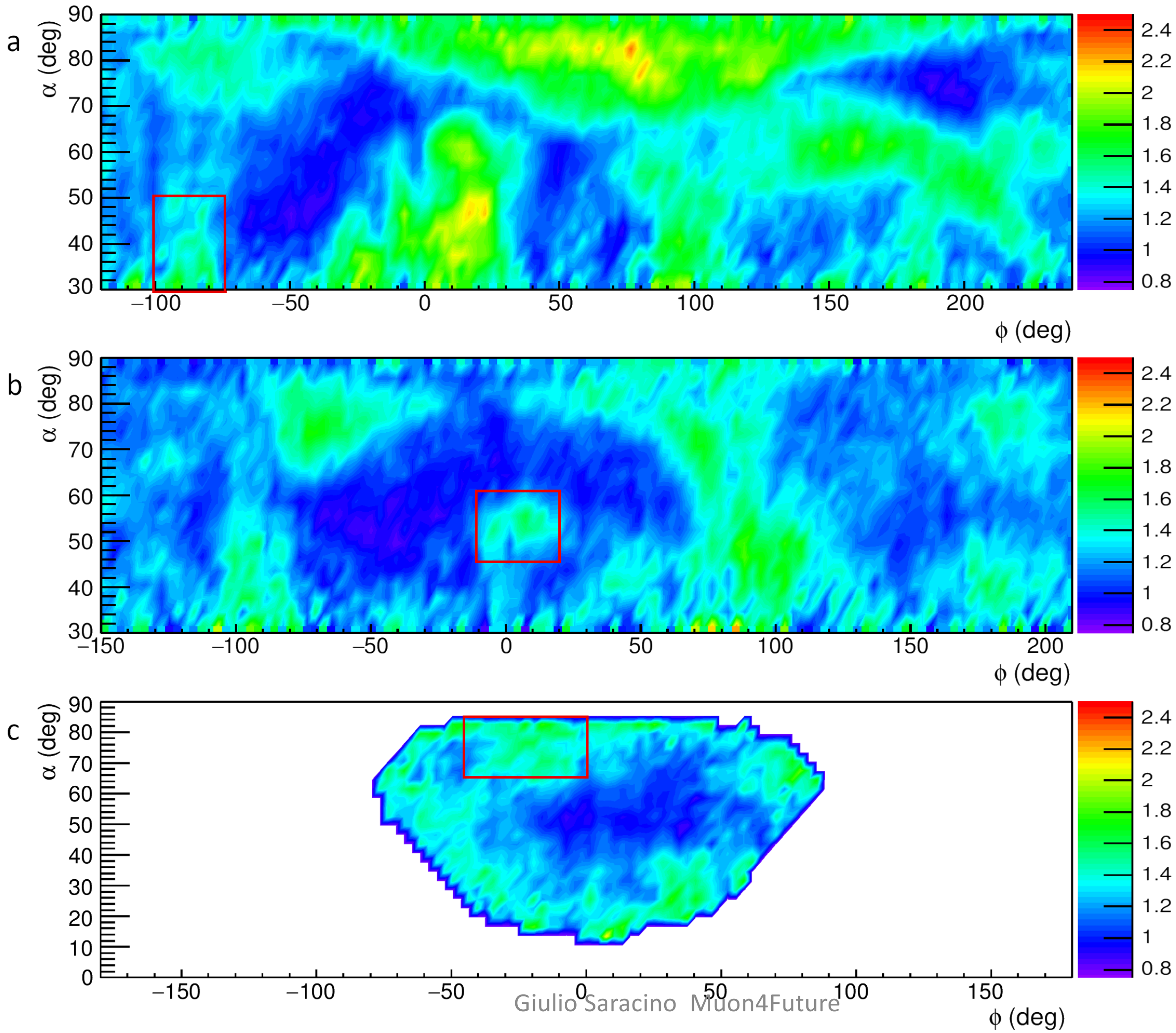
MURAY

The three muographies

A

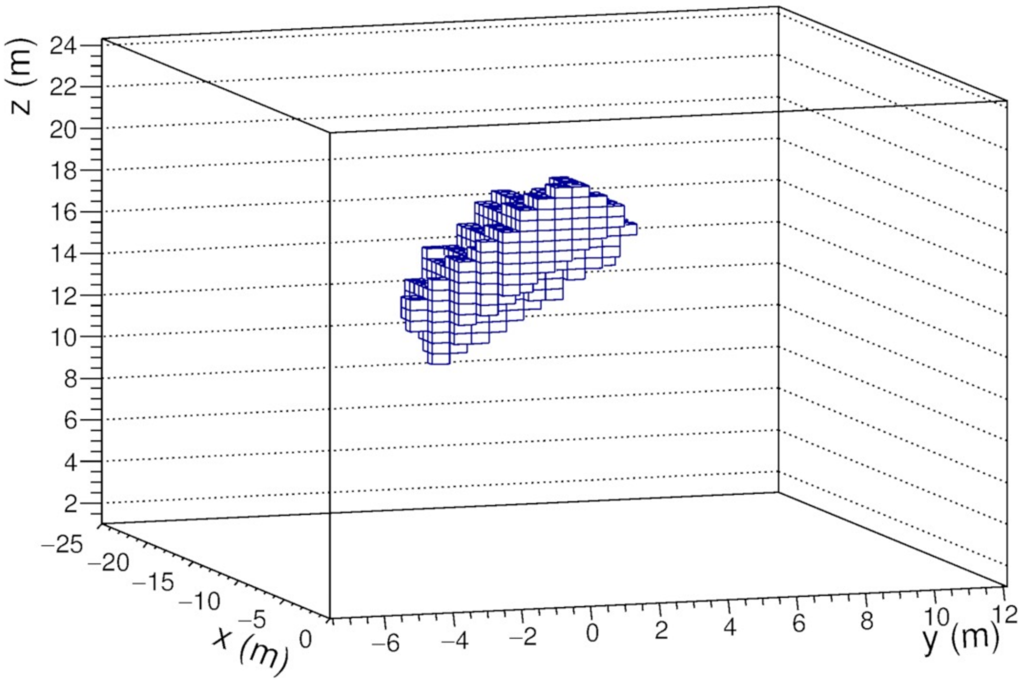
B

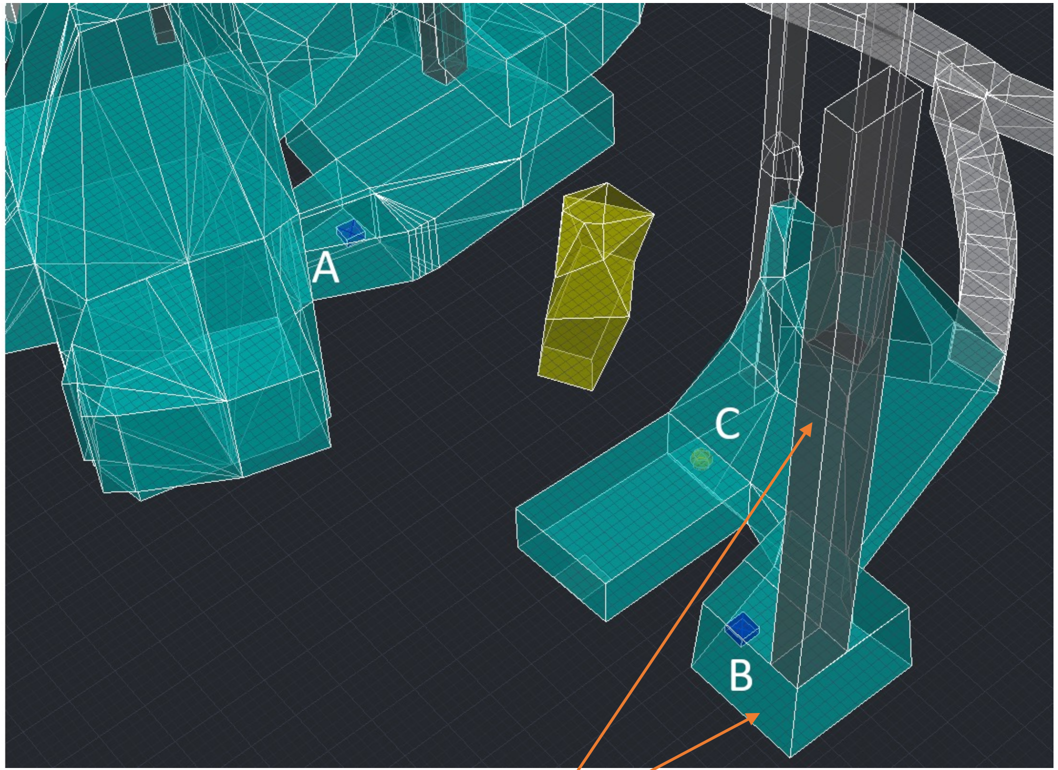
C



3D reconstruction algorithm

We reconstructed the possible shape and position of the void





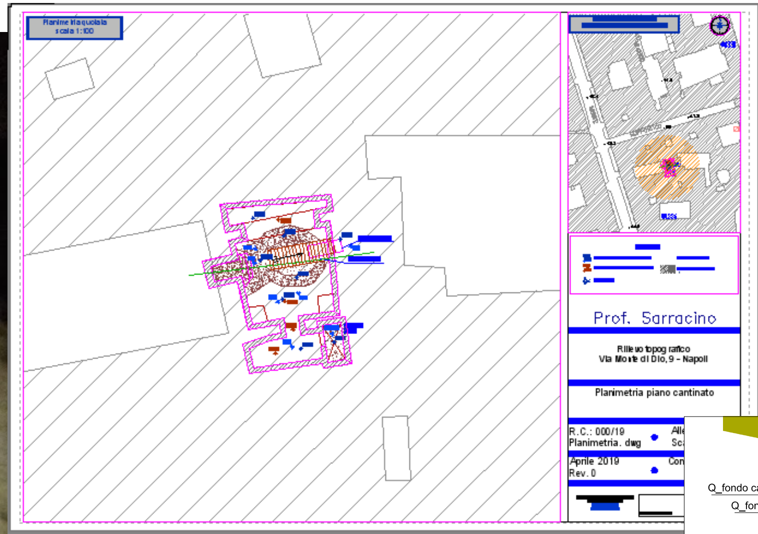
Typical voids are pools connected at the surface with a well

3D reconstruction algorithm

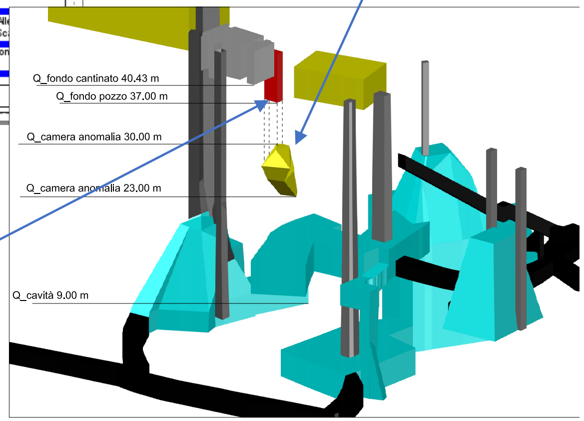
By reporting the points of the cavity on the surface,
the position where the well entrance could be found was located

Site inspection

Identified a trap door with underlying cellar and an obstructed well that could put the hidden chamber in communication with the surface



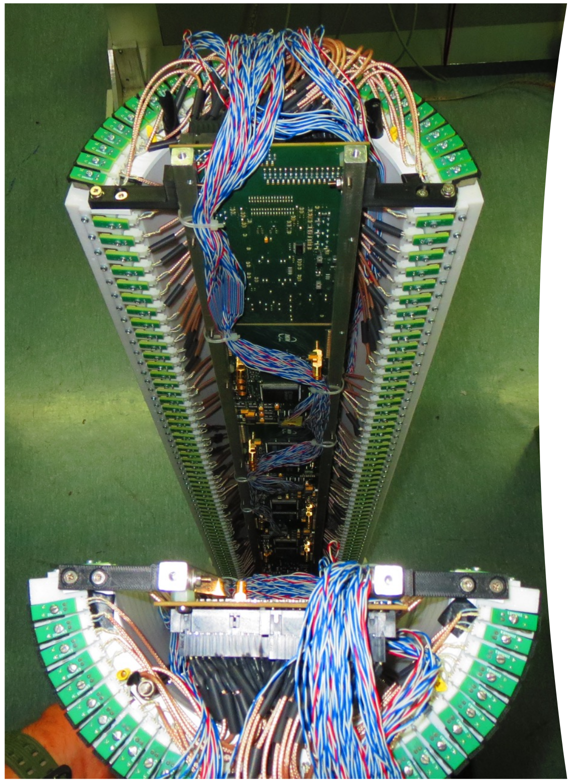
Expected position of the cavity

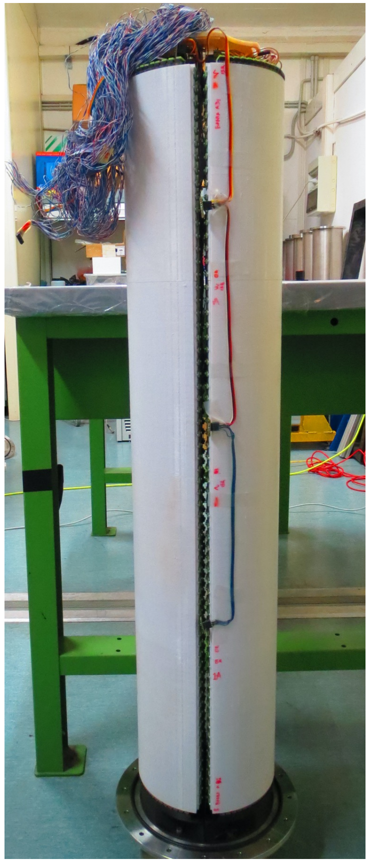


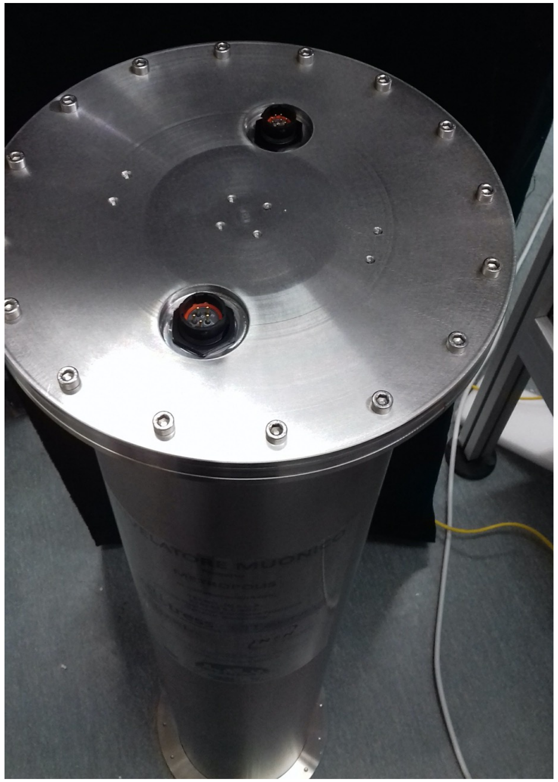
Geo-referenced position of the well after the inspection
Very good agreement !

Cimmino, L., et *al. Sci Rep* **9,** 2974 (2019). https://doi.org/10.1038/s41598-019-39682-5

A cylindrical detector for borehole muography



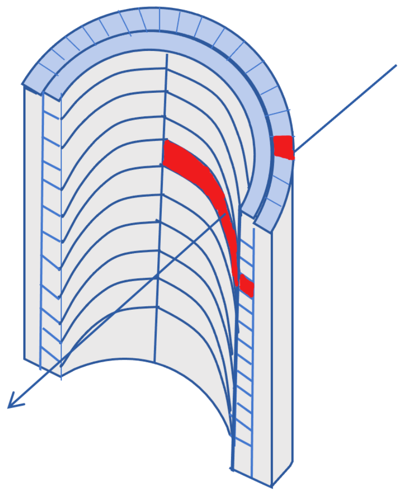


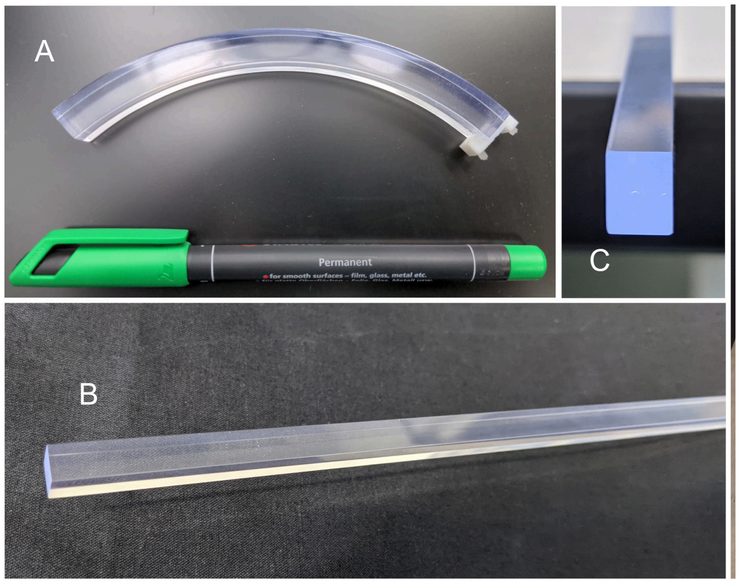


Cimmino, L. *Sci Rep* **11,** 17425 (2021)

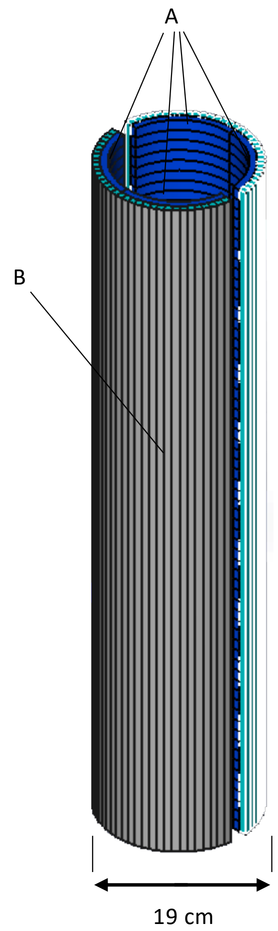
Design of a new detector with a cylindrical shape

Borehole muography opens to very interesting prospectives
The shape of the well suggest the use of a cylindrical geometry to maximize the sensitive surface



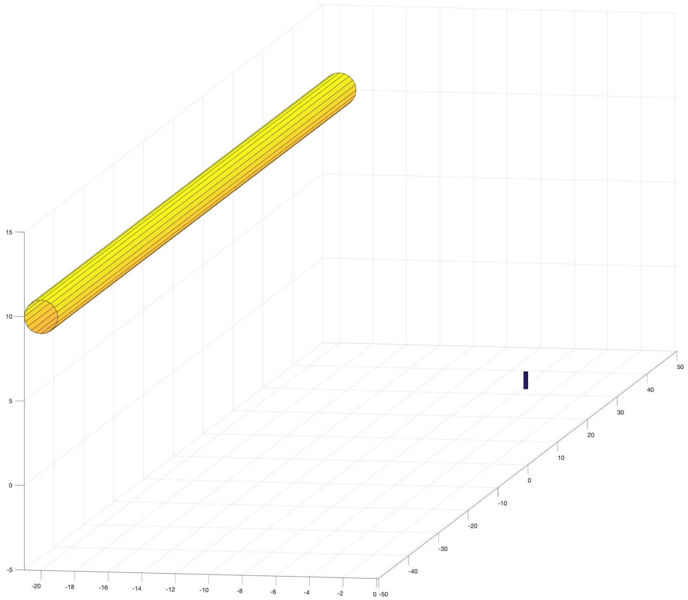


Based on arc shaped scintillators and SiPM (patented)

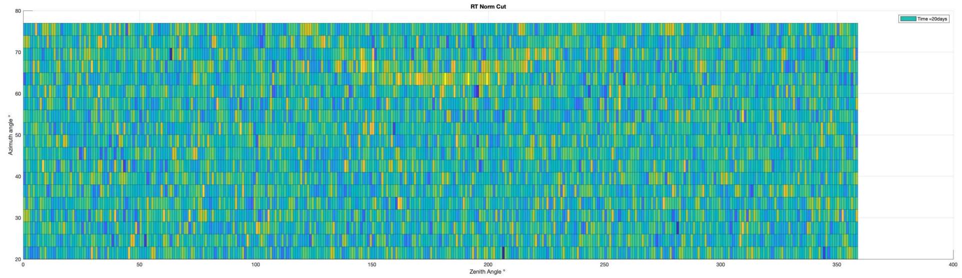


Tunnel's detection

Tunnel: 100 m long and 1 m radius at a depth of 5 m.



cylindrical detector at a depth of 15 m
and at a lateral distance of 20 m



Relative transmission (20 days)

Simulation

Conclusions

Muons: useful tools for the safety and safeguarding

Multiple scattering -> detection of nuclear material

Transmission -> cavity detection and geological survey

Many activities in progress in different fields

Start-up companies started commercial applications

Start-up in Muon Radiography

Company	**Founded**	**Country**	**Main application**	**Tecnolgy**
Decision Sciences	2001	USA	Cargo scanning, nuclear fuel cask monitoring	MS
Lingacom	2012	Israel	Cargo scanning, ground survey	MS, TR
CRM GeoTomography now *Ideon Technologies Inc.*	2013	Canada	Mining exploration -> oil and gas, infrastructure, national security	TR
Muon System	2015	Spain	Industrial application, cargo scanning	MS, TR
Lynkeos Technology	2016	UK	Nuclear	MS
Muon Solutions	2016	Finland	Mining exploration	TR
GSCAN	2018	Estonia	Nuclear safety	MS
GEOPTICS	2020	UK	Geological, industrial, nuclear	TR, MS
MUODIM	2021	FR	Geological	TR
MUONX	2022	IT	Geological. nuclear	TR, MS

A large community is connected all over the world. Every year we have an international meeting

Muographers2023 - International workshop on muography

Jun 19 – 22, 2023
Naples
Europe/Zurich timezone

Enter your search term

https://indico.cern.ch/e/muographers2023

THE END

Safety application: muon tomography within the PREDIS project

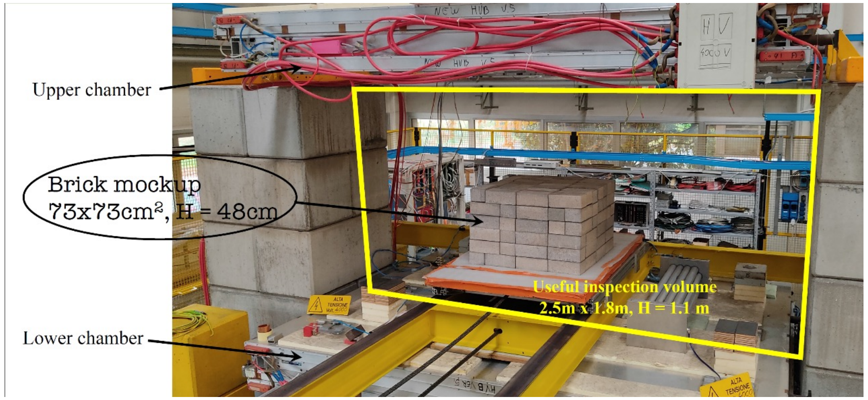
PREDIS = The Pre-Disposal Management of Radioactive Waste project (EURATOM NFRP-2019-2020-10 RIA call , started in 2020, 4 years duration)

The *PREDIS* project develops and increases the Technological Readiness Level of treatment and conditioning methodologies for wastes for which no adequate or industrially mature solutions are currently available, including metallic materials, liquid organic waste and solid organic waste

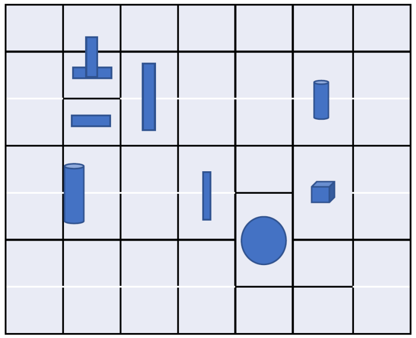
INFN muon tomography is in WP7: *Innovations in cemented waste handling and pre-disposal storage,* in particular subtasks:

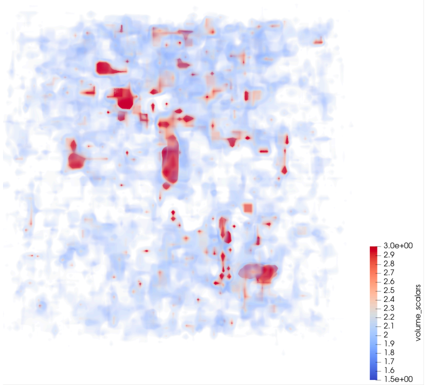
T7.3 Test and Monitoring

T7.6 Demonstration and implementation



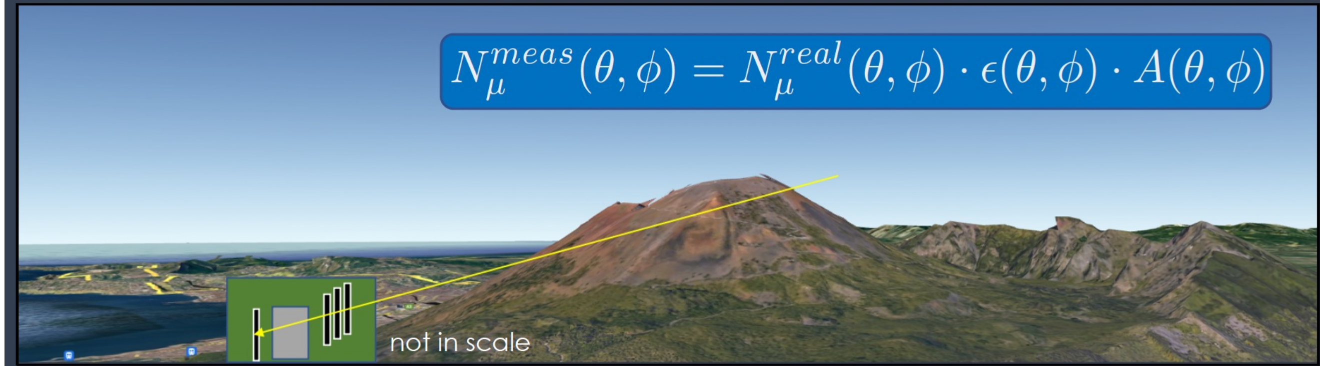
metallic (stainless steel – lead – tungsten) pieces of various shape and dimensions (order of 1-10 cm



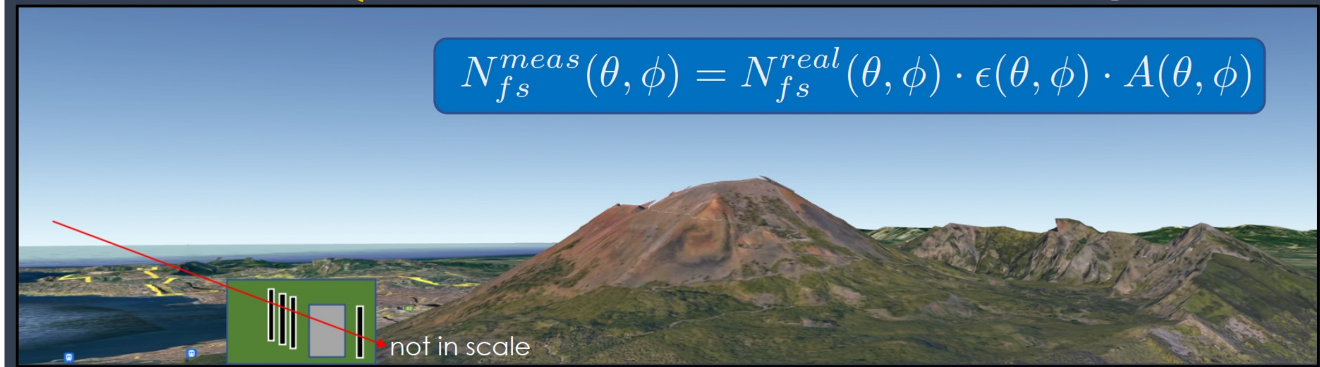


The MURAVES experiment: goal measurement

DATA ACQUISITION: muons are counted *below* the volcano



CALIBRATION ACQUISITION: muons are counted pointing to the *open-sky*



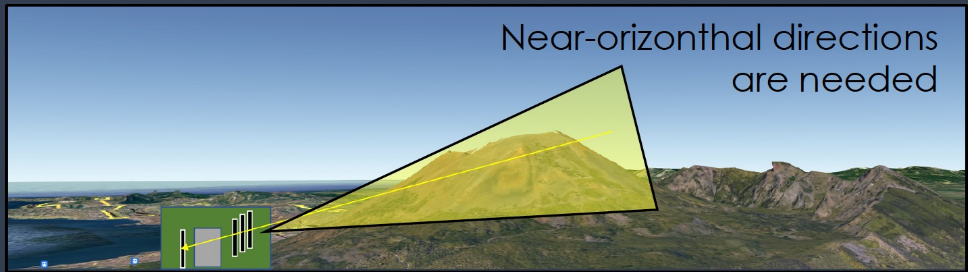
MEASURED TRANSMISSION

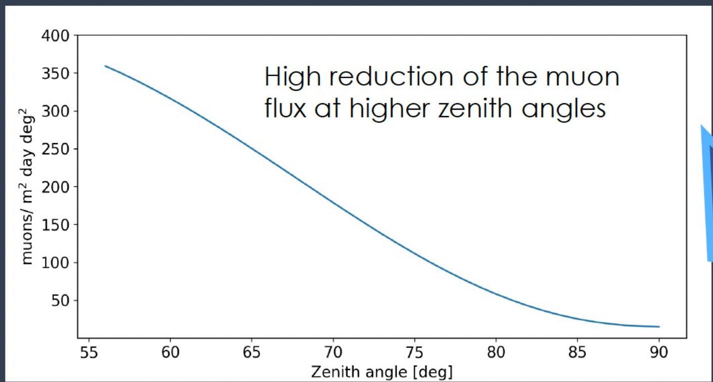
$$T = \frac{N_{\mu}^{meas}}{N_{fs}^{meas}} = \frac{N_{\mu}^{real}}{N_{fs}^{real}}$$

$$T = \frac{\int_{E_{min}(\rho)}^{\infty} N_{\mu}(E)dE}{\int_{E_0}^{\infty} N_{\mu}(E)dE}$$

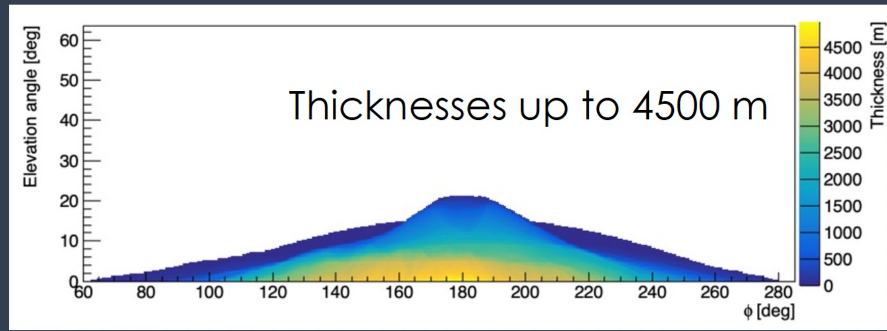
GOAL OF THE EXPERIMENT

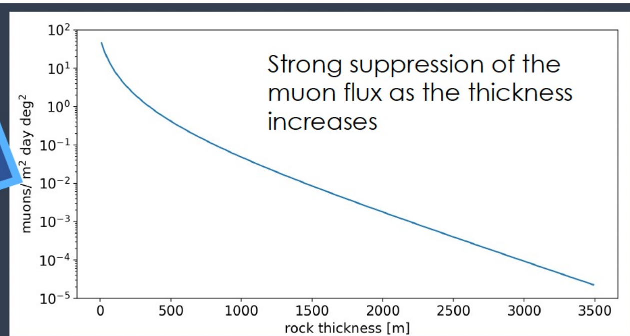
The MURAVES experiment: measurement feasibility





Long exposures to achieve acceptable resolutions





Δy	Δx	**500 m**	**1000 m**	**3000 m**
9 m	9 m	8 months	3 years	100 years
9 m	26 m	3 months	1 years	33 years
9 m	130 m	15 days	2.5 months	6 years
26 m	130 m	5 days	1 month	2 years
52 m	260 m	2 days	6 days	16 months

THICKNESS

$$\frac{\delta\rho}{\rho} = 0.1 \quad \rho = 2.65g/cm^2$$

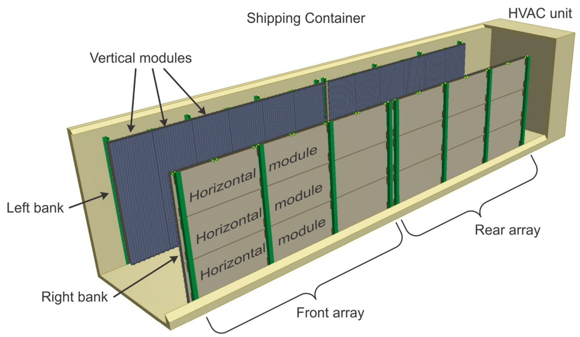
Sensitive area 3 m²
Not accounting for detector efficiencies, except geometrical acceptance

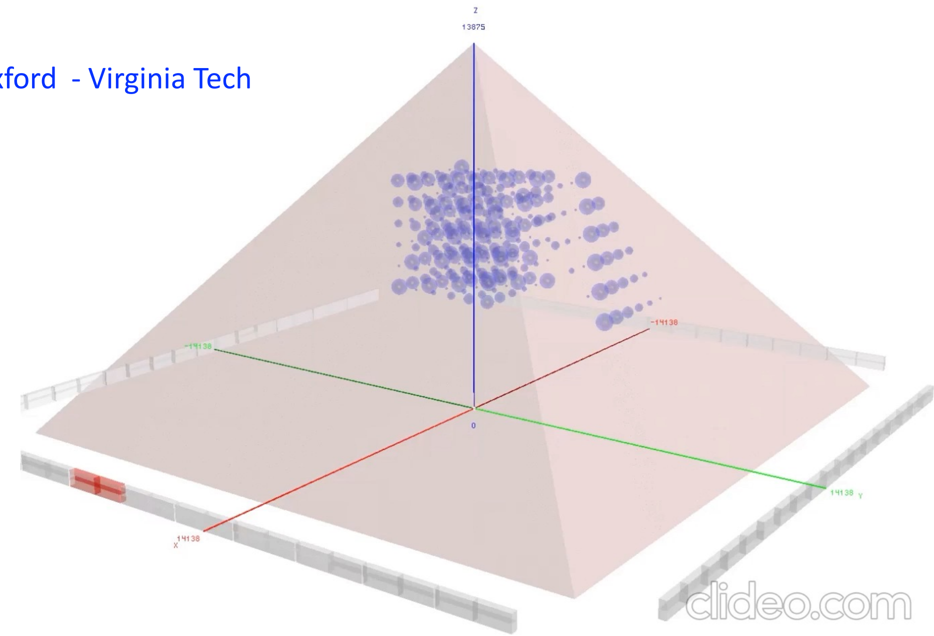
New measurements starting in 2022

The EGP project (Exploring the Great Pyramid) : tomographic imaging with muons

from outside the pyramid

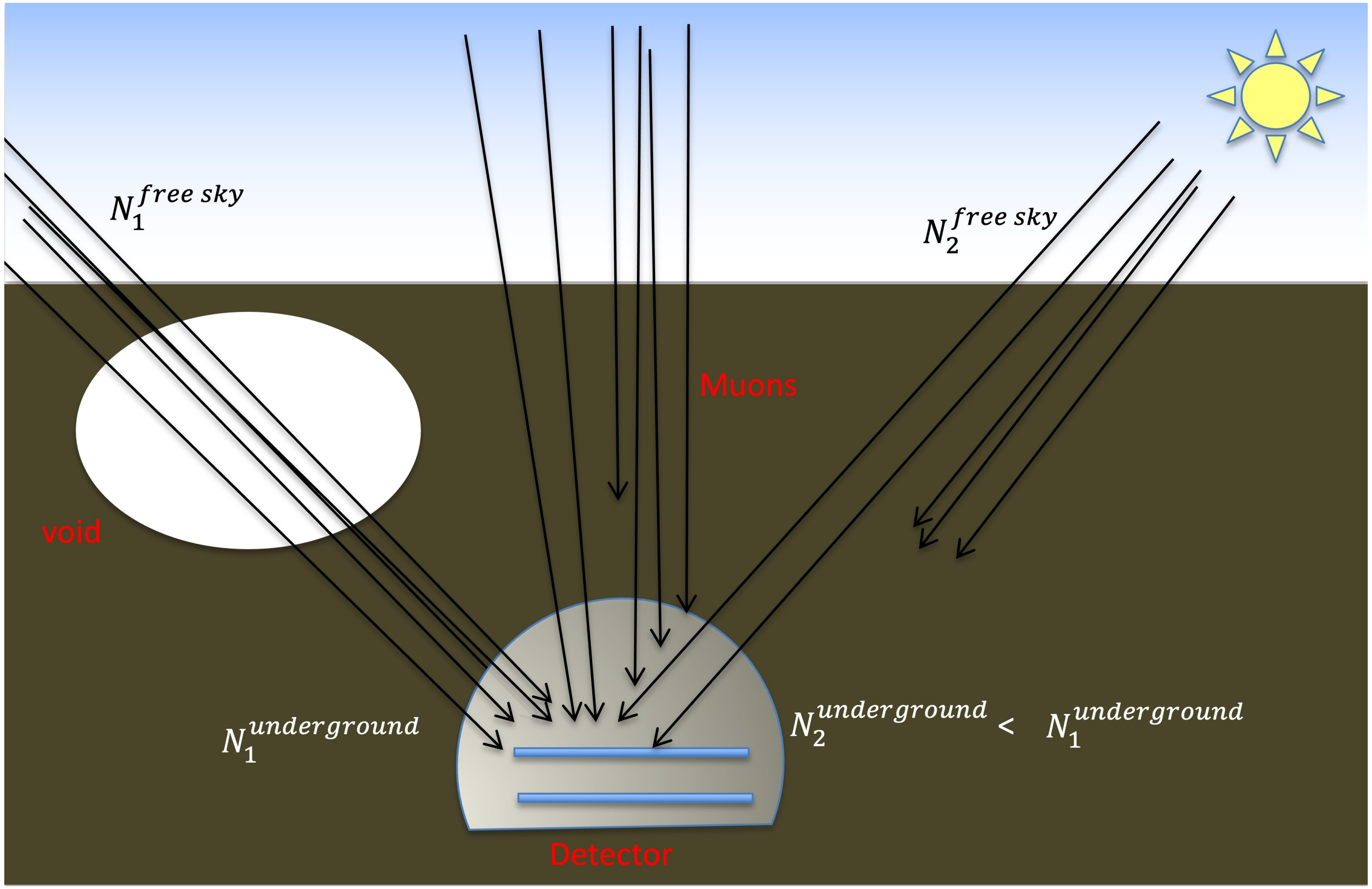
Cairo University – Fermilab - University of Chicago - University of Virginia - University of Oxford - Virginia Tech





Credits: Alan Bross; Muographers 2021 workshop , Ghent University

Principles of cavity detection



How to detect a cavity: the relative transmission *R*

The transmission T is the fraction of muons that arrive at the detector with respect to the number of muons at the surface

$$T(\alpha,\phi) = \frac{N^{detc.}(\alpha,\phi)}{N^{free\,sky}(\alpha,\phi)}$$

$T^{measured}$ is obtained positioning the detector at the surface (free sky sample) and then underground

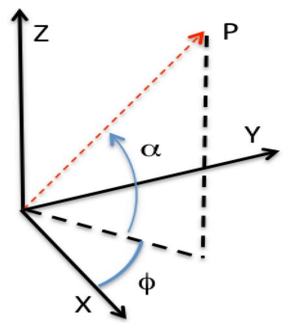
From the muon flux model, the energy loss formula and the thickness of rock crossed computed by the DEM we can evaluated the expected (*theoretical*) transmission $T^{expected}$

The relative transmission R is obtained dividing the measured transmission by the expected transmission

$$R(\alpha,\phi) = \frac{T^{measured}}{T^{expected}}$$

$R \cong 1$ without cavities

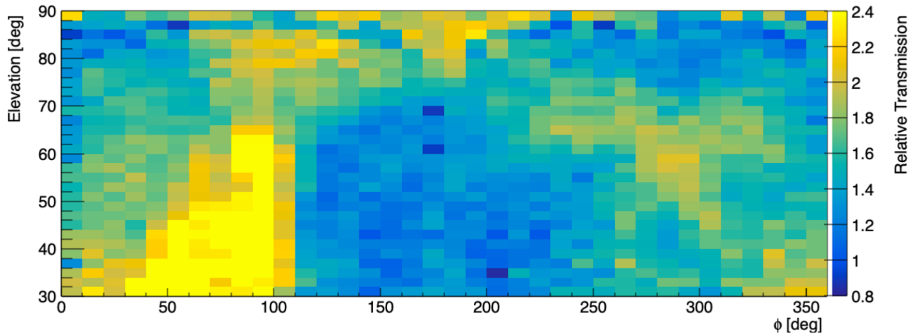
$R > 1$ with cavities

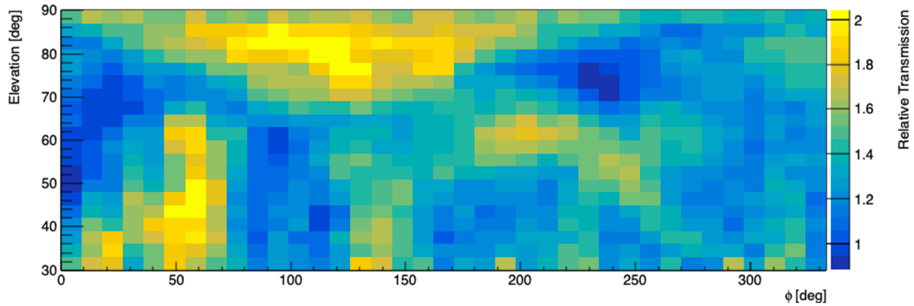


Some preliminary results at Mt Echia

Comparing the two technologies

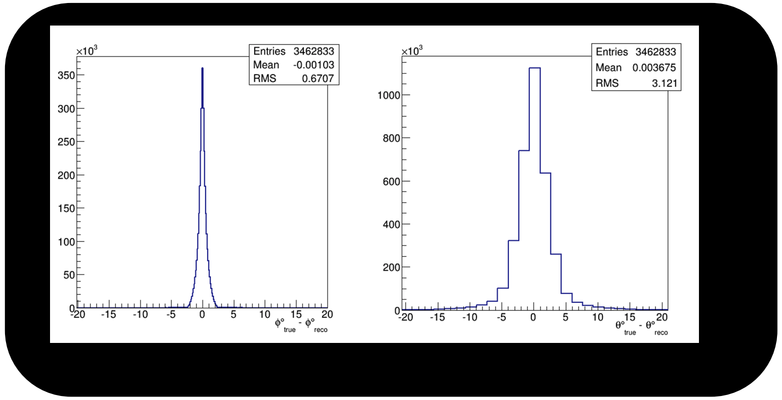
Cylinder





MURAY

Expected results



- 0.67° expected azimuth resolution
- 3.12° expected zenith anglular resolution