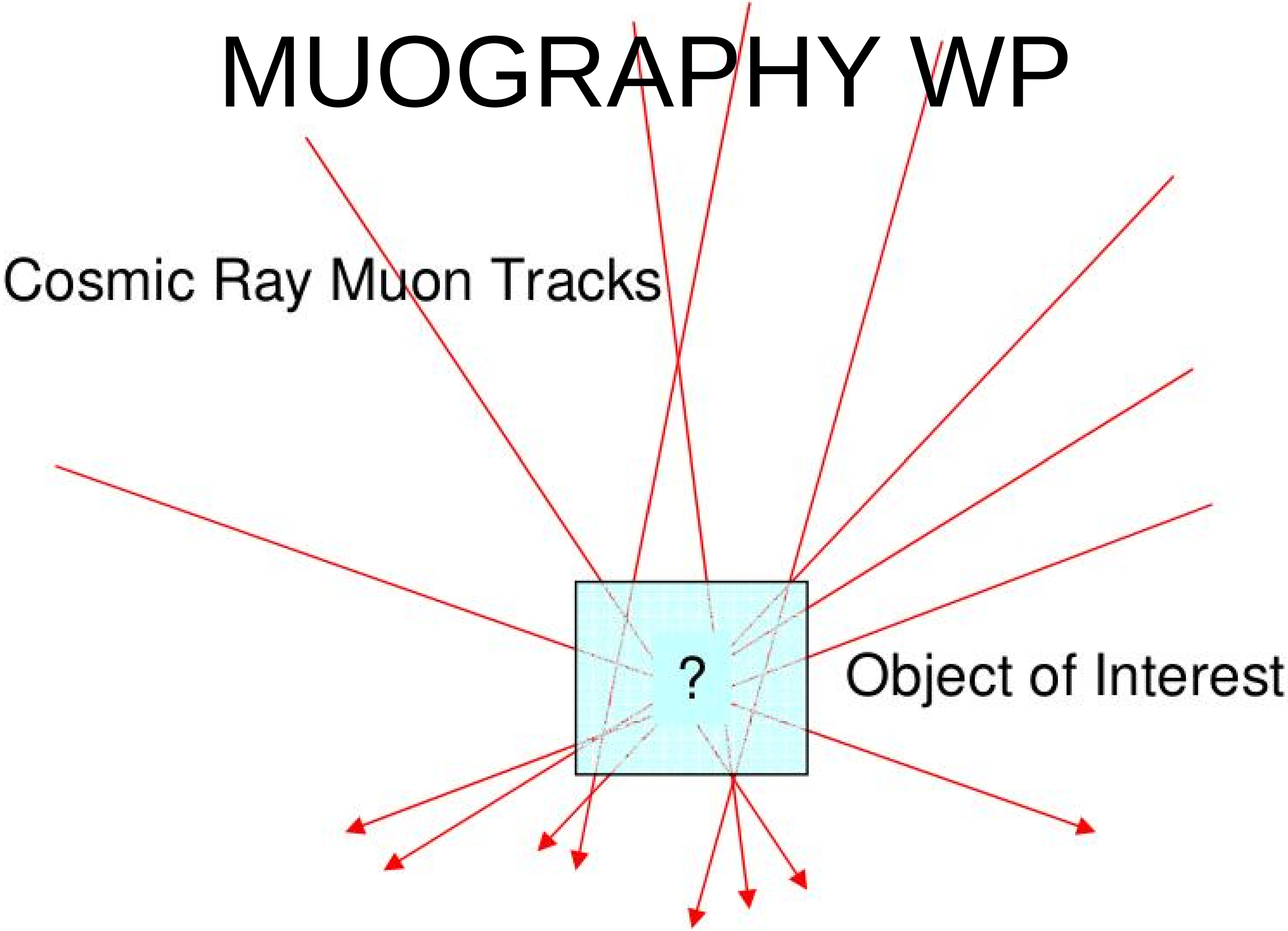
MUOGRAPHY WP



MUOGRAPHY WP

Schedule :

- Muography general presentation (30') J.Marteau
- Muography applications in Wigner RCP (10') D.Varga
- PROMOTEO and MONRAD proposals (10') D.LoPresti
- MURAVES proposals (10') G.Saracino
- NEUTRINO tomography (10') V.VanElewyck
- Space weather ad Atmosphere (10') Y. Sphrits
- CEA ideas (10') H. Gomez Maluenda
- LSBB ideas (10') I. Lazzaro
- General Discussion

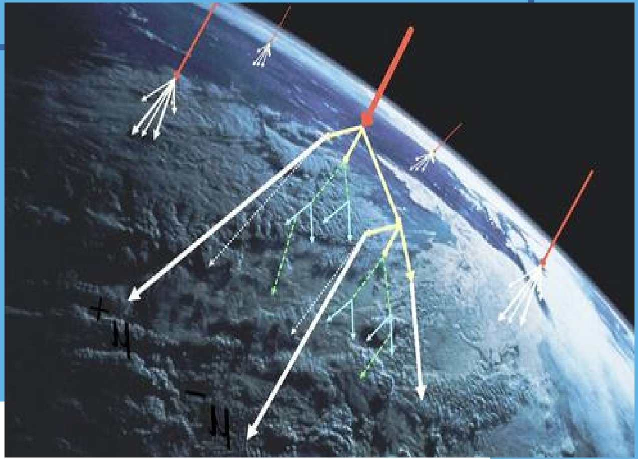
APOGEIA

The New York Times

How Do You See Inside a Volcano? Try a Storm of Cosmic Particles.

Muography, a technique used to peer inside nuclear reactors and Egyptian pyramids, could help map the innards of the world's most hazardous volcanoes.

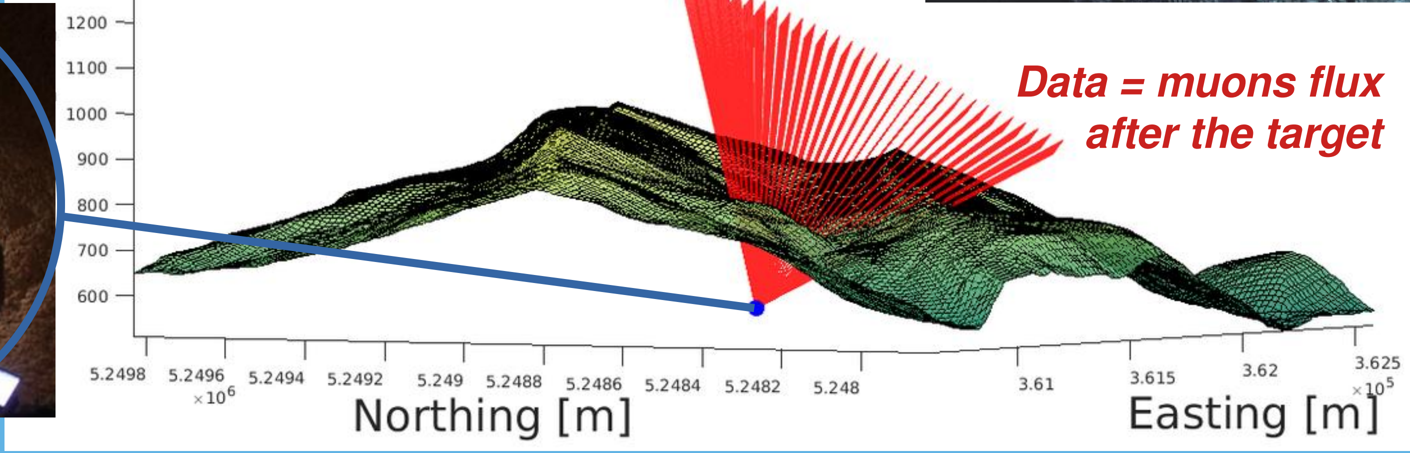
$$\textbf{Muography} = \left\{ \begin{array}{c} \textbf{absorption} \\ \\ \textbf{scattering} \end{array} \right\} \textbf{tomography}$$



The particles (muons) lose energy and are scattered along their trajectories because of interactions with the charges inside the medium (electrons & nuclei).

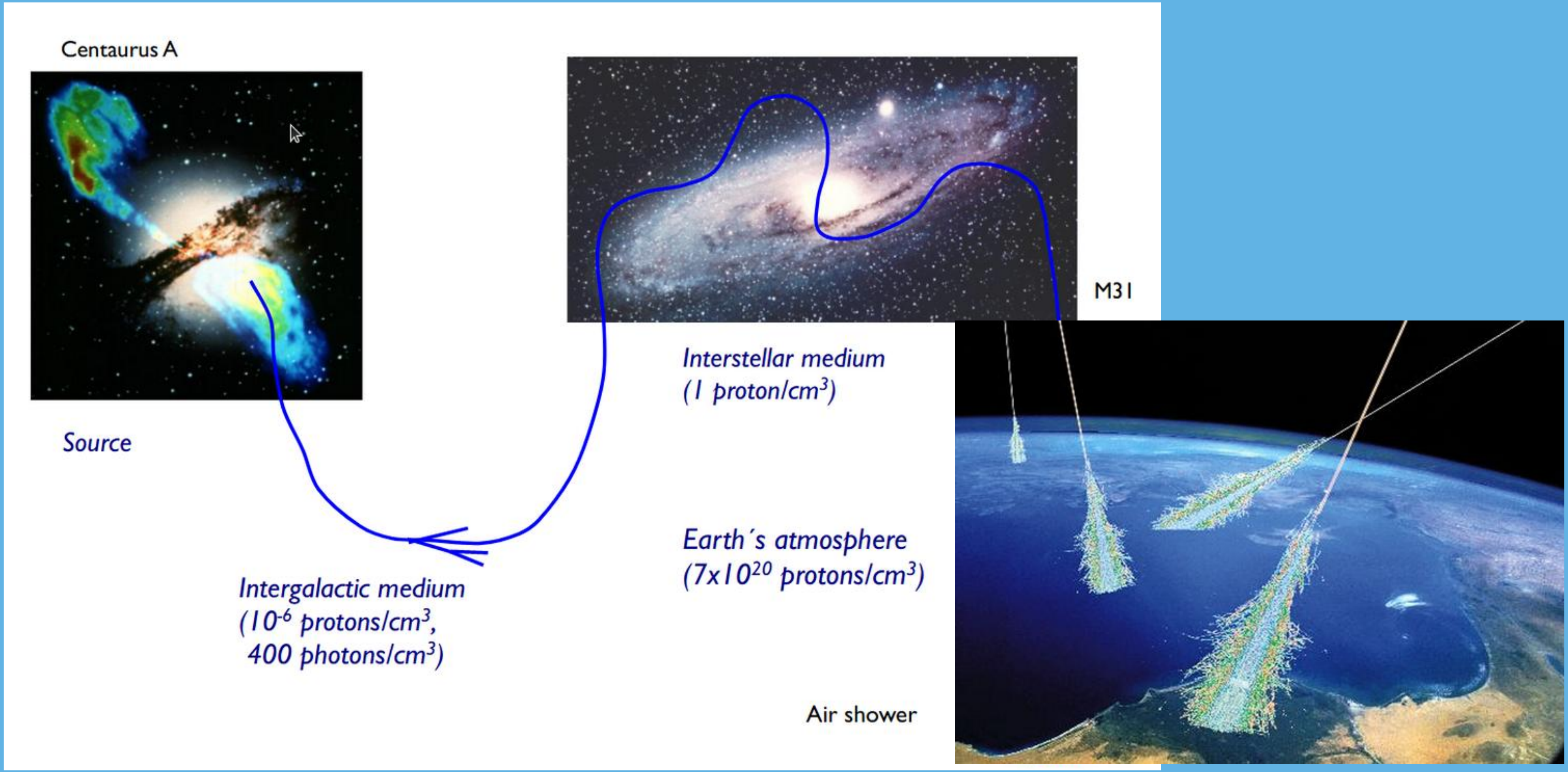
Incident muons flux

Detector

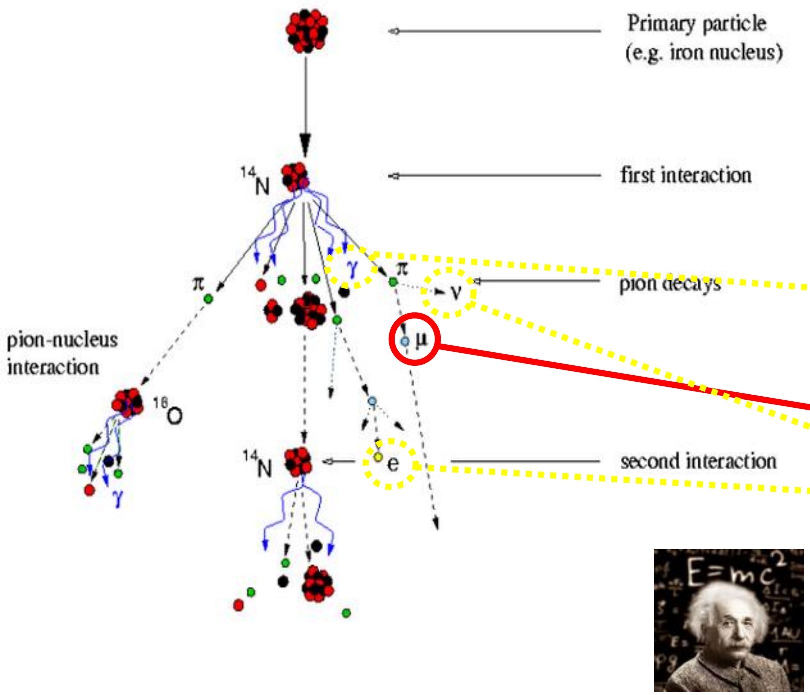


Data = muons flux after the target

Processing chain (1) : the probe(s) parents

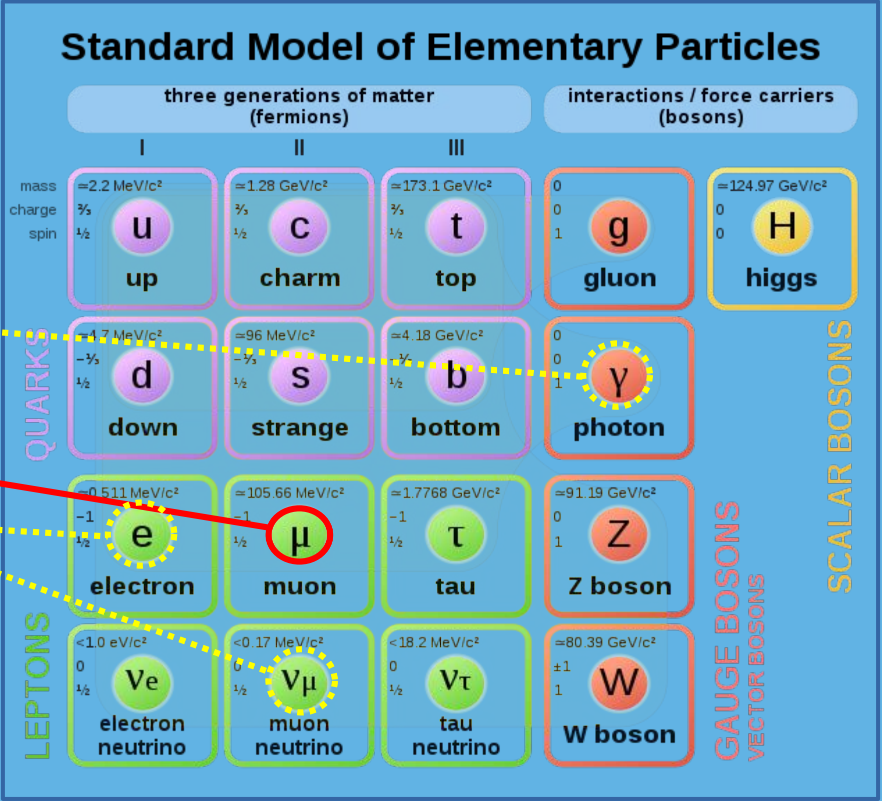


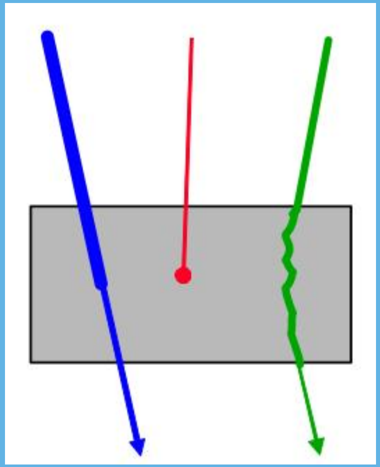
Processing chain (2) : the probe(s)



Decay of neutral pions feeds em. shower component

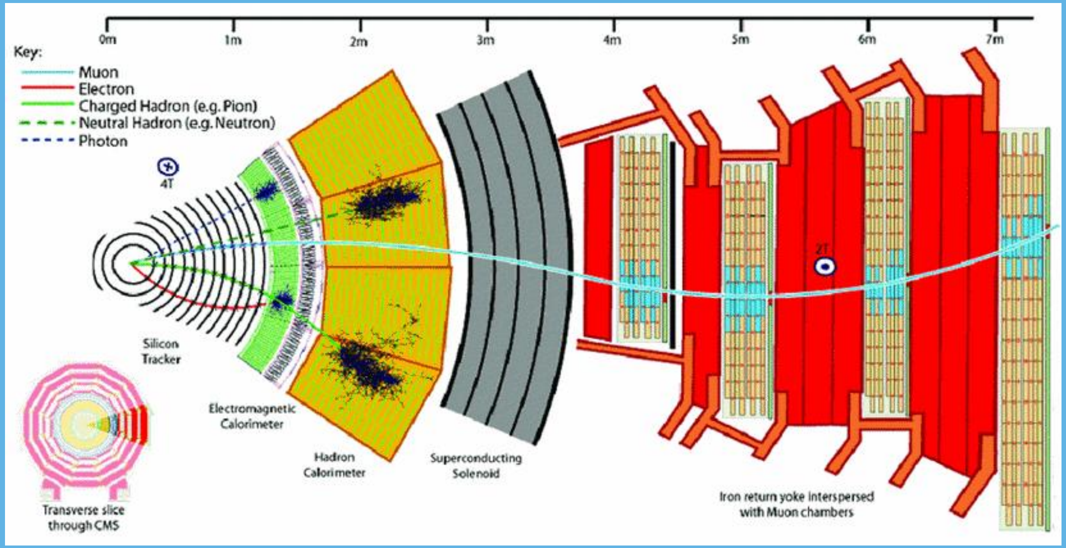
Decay of charged pions (~30 GeV) feeds muonic component

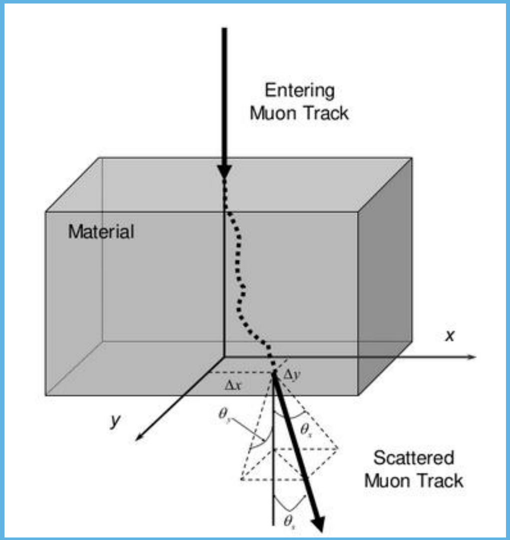




Schematically

Muons interaction with matter





$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\rm max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

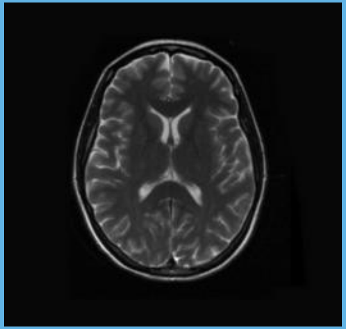
$$\theta_0 = \frac{13.6\ {\rm MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}} \left[1 + 0.088 \log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right) \right]$$

absorption

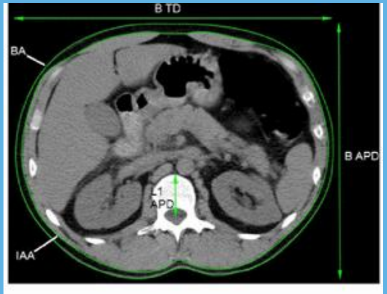
scattering

Medical imaging techniques

2 known examples :



MRI
(Magnetic Resonance Imaging)
→ observable = proton density
→ measurement = magnetic moment relaxation times
→ sensitive for soft tissues details

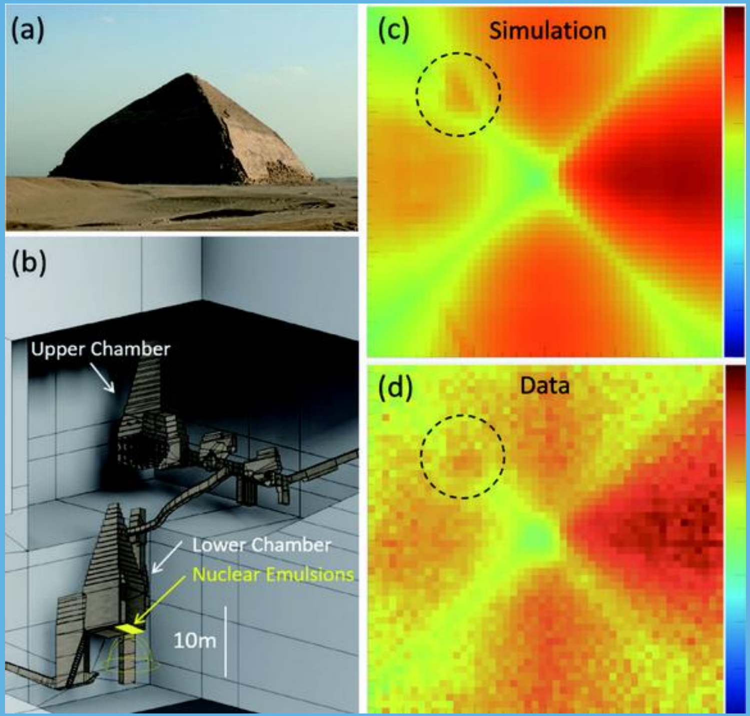


CT-scan
(Computed Tomography)
→ observable = density
→ measurement = X-ray absorption
→ sensitive to dense parts
(e.g. bones)

Detector
→ data measurement

Reconstruction
→ inverse problem

Images



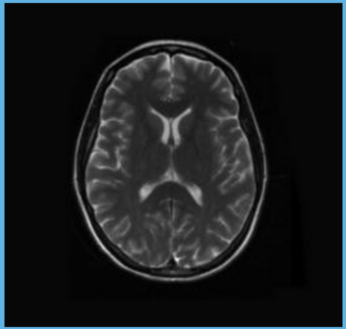
Inverse problem

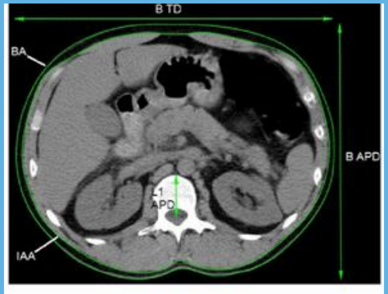
observable

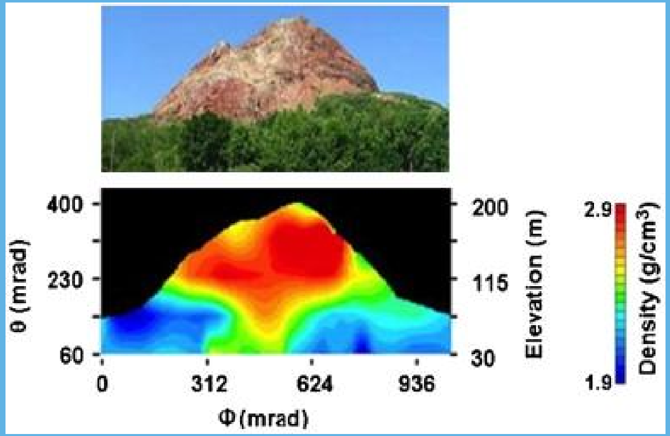
$$m = A(f)$$

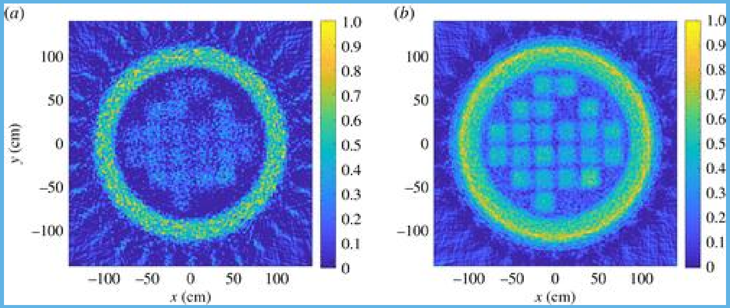
measurement

model

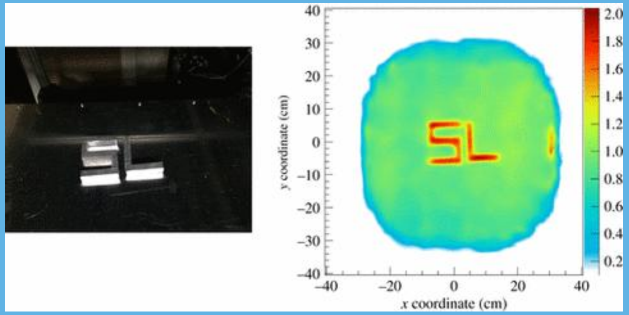








Images



Muography use cases overview

Muography = transmission/scattering imaging technique → sensitive to (scattering) density + Z/A

Geosciences

- Volcanology
- Geology
- Hydrology
- Atmosphere physics
- CR physics
- ...

Archaelogy

- Pyramids
- Tumulus
- Anthropic structures
- Ruins
- ...

Industrial controls

- Non invasive controls
- Nuclear cycle production
- Civil engineering
- Tunnel boring machines
- Prospection & mining
- ...

PROPOSALS – *Dezso Varga (Wigner RCP)*

- **Proposed work: Volcanology at Sakurajima and Etna**
  - Collaborators: UniTokyo, UniCatania + others (?)
  - Deliverables: Benchmark sites characterization? Common understanding of hardware?
  - Company: (Japanese companies but probably not as partners...)
  - Funds: 36 kEUR Person month: 12

- **Proposed work: Surface-based structural imaging (archeology, geoscience)**
  - Collaborators: UniTokyo, UniCatania
  - Deliverables: Structural imaging of medieval castle (Buda in Hungary and/or Mussomelli in Sicily); of ice-age remnant "tor" formations
  - Company: Muon Solutions (Finland)
  - Funds: 18 kEUR Person month: 6

- **Proposed work: Underground structural imaging (geosciences)**
  - Collaborators: UniTokyo, + others
  - Deliverables: Structural imaging for mining applications (ore prospecting, granite / formation contact)
  - Company: Muon Solutions (Finland)
  - Funds: 54 kEUR Person month: 18

- **Proposed work: Underground dynamical/temporal imaging (mining, hydrothermal)**
  - Collaborators: UniTokyo
  - Deliverables: Mine recultivation / tunnel stability monitoring demonstration, ground water dynamics
  - Company: Muon Solutions (Finland)
  - Funds: 36 kEUR Person month: 1

PROPOSALS – *Domenico Lo Presti (INGV Catania)*

PROMETEO Proposal:

- Partners: UNICT, INGV-Catania, WIGNER RCP (+ Etna Park Authority support)
- Duration: 3-4 years
- Objectives: Construction of an Etna Muography Observatory in the summit crater complex. Correlation of muography results with data from the sensor network, mainly deformation and seismic sensors, already installed by INGV.
- Deliverables: Etna South-East crater muography and deformation sensors joint monitoring and report.
- Funding requests:
  - Materials and instrumentation: 240 k€
  - Cost of contracts of non-employees, specifically to recruit:
    - Three-year research contract (RTD-A) 153: k€
    - Ph.D. 60 k€:
- Overheads: 70 k€

MONRAD Proposal:

- Partners: UNICT, WIGNER RCP, Civil and Software Engineering Companies
- Duration: 2 years
- Objectives: Non-invasive buildings' stability monitoring by muons tracking.
- Deliverables: Stability report and modeling on a historical building (+civil buildings or infrastructures and hydrogeological surveys)
- Funding request:
  - Materials and instrumentation: 200 k€
  - Cost of contracts of non-employees, specifically to recruit a Two-year post-doc grant: 72k€
- Overheads: 50 k€

PROPOSALS – *Giulio Saracino (for INFN/INGV)*

- **Proposed work: study of the Vesuvius**
  - Collaborators: INGV (Osservatorio Vesuviano section) and INFN (Florence and Naples sections)
  - Deliverables: provide muographic images of the Vesuvius, increase sensitivity and noise rejection, gravimetric and muographic joint inversion
  - Eventual companies: none
  - Funds needed:
    - person months: we need at least 36 months of post doc/contract for data analysis and 36 months for hardware construction and detector maintenance.
    - Hardware: design and construction of Cherenkov detectors for background rejection. New sensors and electronic boards for the up-grade of the actual apparatus at the Vesuvius.

- **Proposed work : Site and infrastructure characterization and monitoring**
  - Collaborators: INFN (Florence and Naples sections)
  - Deliverables: Geophysical characterization of sites
  - Eventual companies: TECNO-IN
  - Funds needed:
    - person months: 24 months of post doc/contract for data analysis and 24 months for hardware construction and detector
    - Hardware: design and construction of detectors.

PROPOSALS – *Jacques Marteau (for CNRS+IPGP)*

- **ARCHEMUON proposal :**
  - Underground dynamical/temporal imaging (archaelogy, hydrogeology)
  - Collaborators: CNRS (IP2I, LGL-TPE), ENS Lyon
  - Deliverables: Archaelogical survey. Ground water dynamics
  - Company: IRIS (instruments)
  - Funds: 120 kEUR Person month: 24

- **SOUFRIERE proposal :**
  - Volcanology in Lesser Antilles
  - Collaborators: CNRS, IPGP (?)
  - Deliverables: joined analysis methods (seismic + muons)
  - Funds: 30 kEUR Person month: 12

- **LINDENBROCK proposal :**
  - Volcanology in Iceland
  - Collaborators: CNRS, Université de Lyon, IMO, Carol Müller
  - Deliverables: Snaëffelsjökull + satellites volcanoes internal structure imaging
  - Company: MUODIM (consulting)
  - Funds: 100 kEUR Person month: 12

PROPOSALS – *Michael Tytgat (Ghent)*

- **Proposed work/interests:**
  - Development of reference tool set for volcano muography : full simulation chain (muon transport, detector ...), data reconstruction, image reconstruction (2D-3D)
  - Development of light-weight, low power muography hardware, possibly including Cherenkov technology
  - Studying the use of ML in image reconstruction, especially 3D imaging of volcanoes, but also interest in archaeological sites

- Collaborators:
  - Volcano related studies within Muraves collaboration
  - Hardware development in collaboration with UCLouvain, Belgium and INFN

- Deliverables:
  - Abovementioned reference tool set;
  - ML study deliverable to be discussed (e.g. publication, comparative study between different image reconstruction techniques ?);
  - Prototype of light-weight detector hardware & feasibility (simulation) study of additional Cherenkov technology

- Funds:
  - person months: 24 months for standard tool development & ML based image reconstruction; 24 months for hardware development
  - hardware: 50-100kEuro detector prototyping

PROPOSALS – *Jakub Ciazela*

(Institute of Geological Sciences, Polish Academy of Sciences)

- **Proposed work : volcano activity monitoring and ore formation (high-temperature geological processes)**
  - Concerning the volcano activity monitoring, we will investigate ascents and descents of magma in two active Italian volcanoes, one explosive (Stromboli) and one effusive (Etna). First studies of this kind have been recently published on Japanese volcanoes (e.g., Hiroyuki et al. 2014: Satsuma-Iwojima, Olah et al. 2019: Mt. Sakurajima) and are based on density differences between gas-saturated magmas (<2 g/cm^3) and country rocks (2.5–3.0 g/cm^3). The more volatiles in the magma and the more explosive is volcanism the higher is the density contrast with the country rocks.
  - Ore deposits have not yet been prospected using muon radiography but this should be feasible in mountainous areas. Metalliferous ore minerals such as pyrite, chalcopyrite, or pyrrhotite exhibit densities of 4.0–5.5 g/cm^3, which are considerably more than densities of the host rocks (2.5–3.0 g/cm^3). Large ore deposits such as Rio Tinto in the Iberian Pyrite Belt (Spain) are massive (homogenous) on a hundred-meter scale (Martin-Izard et al., 2015), which makes them detectable by muon radiography and suitable for our pioneer study.
  - In addition, detection of underground targets such as caves and lava tubes in planetary field analogues such as those on Iceland may be of contextual importance for future human missions to Moon or Mars. Caves and lava tubes provide best protection against solar wind and cosmic rays.
  - Potential collaborators: INGV (IT), CAMK (PL)
  - Deliverables: 2 or 3 articles in international geosciences journal
  - Funds needed: 24 or 36 personmonths and no hardware

PROPOSALS – *Andrea Gianmanco (UCL)*

- **Proposed work : volcanology, methods & simulation developments, detectors tests**

- Volcano task 7.1 :
  1) Continuation of MURAVES collaborative work.
  2) Potential start of a collaboration on Etna with Domenico Lo Presti's team in MC developments.

- Underground lab sub-WP task 7.3 : Whatever site is selected, LSBB or other, it can be interesting to test our portable RPC detector.

- Ressources needed : 2 years post-doc

- Collaborators : MIMA in Florence, natural sinergy with companies (IRIS Instruments, Muon Solutions Ltd, etc.)

PROPOSALS – *Andreas Haungs (KIT)*

- **Proposed work : Cosmic-Ray Detectors at adv.Virgo, as part of a future monitoring system at Einstein Telescope**

- Objectives :
  - Part of environmental control and noise mitigation
  - Study of disturbances by cosmic rays on mirrors and interferometer
  - Develop network of scintillator based monitoring detectors
  - Install and test at Virgo
  - Integrate concept in monitoring system of ET

- Milestones :
  - Tests of muon telescope at IP2I
  - Installation of muon and air shower monitoring system at Virgo
  - Data integration and conceptual design for ET

- Partners : IP2I, but also EGO and probably some more
- Contribution : mainly building large-size SiPM-scintillator or Cherenkov detectors for telescopes
- Companies : could include developments on monolithic SiPMs
- Funds needed 1 Postdoc, Hardware could be mainly own contribution

PROPOSALS – *Hector Gomez (CEA)*

- **Activity 1 : POC & industrialization of muon tomography compact instrument for geoscience applications**
  - Irfu is working since 4 years in a compact Time Projection Chamber capable to fit in boreholes in order to perform 360o muography measurements specially for geoscience applications.
  - Nowadays the concept has been proved in a laboratory test-bech, but the prototype must be upgraded to be capable to operate on-site, for example developing a more compact readout system.
- Collaborators : CEA / Irfu
- Deliverables :
  - First TPC-based muography instrument prototype capable to operate on-site
  - Proof-of-concept measurements
- Companies : IRIS Instruments for the conception of the final version, choose of the proof-of-concept measurement site and potential industrialization.

- **Activity 2 : New analysis techniques for 2D muography and 3D muon tomography**
  - Considering the wideness of the muography applications, new analysis techniques based on Artificial Intelligence, Machine Learning and Digital Image Processing needs to be developed to improve the performance of the technique, the quality of data exploitation and the analysis time, both for 2D and 3D reolution
- Collaborators : CEA / Irfu, ...
- Deliverables :
  - Analysis tools based on Digital Image Processing for 2D muography
  - Algorithm for 3D muon tomography of objects from single muography measurements

- **Funding (for both activities) : 510k€**
- Personnel : 1 ETP during 2 years to coordinate and develop Activity 1 and 2
- Hardware : TPC Prototype, DAQ development) + 50 kEuros (Computing resources, Software, ...)

PROPOSALS – *Sofia Andringa (LIP)*

- **Proposed work : muography around Lousal mine**
- **1- Development of an RPC-based telescope** capable of stable outdoor autonomous operation with low power and gas consumption. The number of detector planes is such that it provides redundancy and novel technologies under development at the lab can be tested and incorporated.
- **2- the development of data simulation and reconstruction procedures that allow to produce:**
  2.1- full GEANT4 simulations of the geological target interfaced to different state-of-the-art geophysical models;
  2.2- Fast simulations based on simplified step-by-step models of the geological target;
  2.3- an independent muography reconstruction image;
  2.4- a global image combining the muon information with the information obtained from gravimetry and other standard geophysics techniques.
  The goals of the project are:
  A- To produce the best possible map of the ground above the mine gallery and perform a detailed comparison with all forms of already existing information.
  B- To establish muography as a new technique for geophysical surveys, ready to be used in a standard and current way by geophysicists

- + data analysis and machine learning

- + education, outreach and citizen engagement

PROPOSALS – *Ignacio Lazaro (LSBB)*

Proposed work: LSBB offers its facilities and equipment to become benchmarking site for borehole, underground and infrastructure muographic characterization. Partners from all working packages of APOGEIA, with particular emphasis muographers, are welcome to perform multi-technique/multi-technology joint campaigns in a well-known, convenient environment.

Interest: Infrastructure: over 4,3km of easily accessible and fully equipped galleries dedicated exclusively to science (14.000m^2). Depths ranging from 0 to 518m. Low background noise conditions (including radon) and outstanding thermal stability. Versatile facilities; access to bare rock, concrete walls, electromagnetically shielded vaults, wells, surface and underground boreholes, electronics and optics clean room for detection assembly and servicing, data server…

Scientific: Local network of 20 autonomous muon trackers for the study of water transfer at the critical zone and infrastructure monitoring (T2DM2 project). Over 20 years of environmental data with several technologies. Access to a karstic environment (analogue to middle East oil fields). Located over the biggest aquifer of France. All the communities included in APOGEIA are currently and actively working in the LSBB, fostering and strengthening the transversal connection of the different work packages.

Logistics: convenient accommodation and less than 1h from bullet train and 1,5h from main airports.

Potential onsite collaborators: CEA and Febus Optics for optic fiber (thermic, seismic…), Institut d'Optique Graduate School and MIGA consortium for Grav. Waves, U. Strasbourg for gravimetry, U. Avignon for groundwater and multiphysics

Deliverables: Full access to the different facilities for 3 years. 1 fully dedicated engineer for local support and assistance during remote operation. Access to mult-- technique environmental data and local data server.

Funds needed: 36 person.months of an engineer in situ fully dedicated to ensuring the assistance in deployment, maintenance, servicing, data management and transfer, dismantling and shipping for all the equipment from the different partners.

XXXX€ as entry fee to cover the use of the facilities and the cost overrun so generated (these amounts can be distributed between the different impacted work packages proportionally).

PROPOSALS – *Aldo Ianni, Nicola D'Ambrosio (LNGS)*

LNGS interested in WP7 : Volcanology & Geosciences – Underground Target and site characterization

1) Proposal : use of the Nuclear Emulsion detector as muons detector
Volcano muography (e.g. Stromboli, ….), study of underground cavities and archaeological sites characterization

2) The LNGS Electronic Workshop is interested in a collaboration for development and test of proposed electronic muon detectors.
Our Electronic Workshop has a huge experience in this field.

At LNGS is operative the Emulsion scanning facility and emulsion development laboratory used for emulsion analysis of the OPERA experiment, analysis of the emulsion used as a detector in the study of Stromboli volcano in collaboration with INFN-NA and Japanese groups.
Part of this facility is actually used for NEWSdm R&D project, the other part of the facility can be used for WP7 proposal with a proper upgrade.

Recently we started also a new collaboration with INFN-NA group the use the emulsion for of underground cavities and archaeological sites characterization

Preliminary funding requests: 184 k€
1) 60 k€ for hardware upgrade, 30 k€ for materials, emulsion, chemicals.
1 contract for 3 years post-doc, 94 k€

2) Funding request for collaboration in electronic detector development ……to be defined

Proposal Inputs

APOGEIA – MUOGRAPHY

Tasks	7.1 Volcanoes Observatory : **Italy**	7.3 Atmosphere & GW detectors : **Virgo**	7.2 Undergound Facilities : **LSBB**	← Key Infrastructures
R&D	Soufrière, Iceland, Sakurajima	MIGA	Lousal mine, Finland ...	← Satellite infrastructures
Integrated & Smart Detectors	X		X	
Multi-Detection Techniques	X	X		
Analysis Methodes Including ML	X	X	X	
Simulation & Image Processing	X		X	

APOGEIA – MUOGRAPHY

Tasks	7.1 Volcanoes Observatory : **Italy**	7.3 Atmosphere & GW detectors : **Virgo**	7.2 Undergound Facilities : **LSBB**	← Key Infrastructures
Participants	Soufrière, Iceland, Sakurajima	MIGA	Lousal mine, Finland ...	← Satellite infrastructures
CNRS + universities	X	X	X	
IPGP	X	X		
LSBB		X	X	
CEA	X		X	
UCL	X			
U.Ghent	X			
INFN	X		X	
INGV	X		X	
KIT		X		
Wigner RCP	X		X	
IGS	X		X	
LIP			X	

APOGEIA – MUOGRAPHY

Requests	Budget (k€)	HR (men.months)	TOTAL = 2.8M€ (k€)	*APOGEIA 1.0 = 2.3M€*
CNRS + universities	250	84	460	*320*
IPGP				*340*
LSBB	XXX	36	90	*60*
CEA		(incl. 24)	510	*X*
UCL	X	24	60	*50*
U.Ghent	100	24	160	*60*
INFN	624	240	1224	*1000*
INGV				
KIT	0	1 post-doc	90	*280*
Wigner RCP	144	36	180	*120*
IGS	0	24-36	60-90	*60*
LIP		X		*X*

Hyp. 12 months post-doc = 30k€

APOGEIA – MUOGRAPHY

1. It concerns : **a) geosciences, b) geotechnics, c) industrial applications, d) hardware solutions, e) computing & methods; f) extensions (e.g. to neutrino tomography)**

2. Volcanology & Geosciences. There are well established collaborations for muon imaging of volcanoes, which led to huge progress in the understanding of the internal structure and magma dynamics. One of these is the DIAPHANE, combining continuous muon measurements with seismic noise acquisitions and continuous gravity data to characterize the hydrothermal activity of La Soufrière de Guadeloupe volcano in France. The other is MURAVES, aiming at the imaging of Mt. Vesuvius in Italy, one of the most dangerous and scientifically interesting volcanoes in Europe. Italian volcanoes are well known key targets for muography, but they are not the only one.
Secondary targets are the Soufrière of Guadeloupe (Lesser Antilles, France) and Sakurajima volcano in Japan. Although the distance of those volcanoes impedes the deployment of detectors by other teams, the teams already working on them will share their data such that they may be used for data analysis and methodology development.

3. **Underground targets and site characterization**. This task will perform cosmic muon imaging for several objectives: 1. to extract density distribution from underground targets with an array of muon sensors in order to characterize underground dynamics; 2. to monitor underground civil works and also archaeology; 3. to understand the impact of cosmic rays (e.g. via extended air showers effects on the mirrors) in the next generation buried gravitational wave telescope Einstein.

4. **Muon radiography and Machine Learning**. Analyse the data from the MURAVES experiment, applying for the first time ML to a muon radiography problem involving the imaging of a large target.

TO BE RE-WRITTEN

APOGEIA – CR PHYSICS

1. Use CR frequencies as an atmospheric probe (in association with portable lidars and other environmental sensors), including the monitoring of Ozone with CR.

2. GEO3BCN-CSIC (Jordi Diaz) Monitoring solar magnetic storms using permanent and portable broad-band seismometers. Last years were published some contributions on that subject (3 new publications added).

3. GFZ (Yuri Shprits) Development of the infrastructure for monitoring and now-casting particle environment in the near-Earth space. This effort is also directly relevant to climate and we can add the development of the infrastructure related to the precipitation of particles into the atmosphere where they affect the Ozone and climate. Installing a neutral monitor on a ship. That could help track GCRs and how they propagate through the atmosphere. We can of course look at other particles such as inner
magnetospheric electrons, ions, etc.

4. Offer by Evgenides Foundation to provide globe navigating ships for deployment of CR detectors and other atmospheric instruments

Potential common dev.

Minutes of meeting

- 2021, Nov, 9th
- 2022, Jan, 11th
- 2022, Jan, 20th-21st

APOGEIA – Meeting

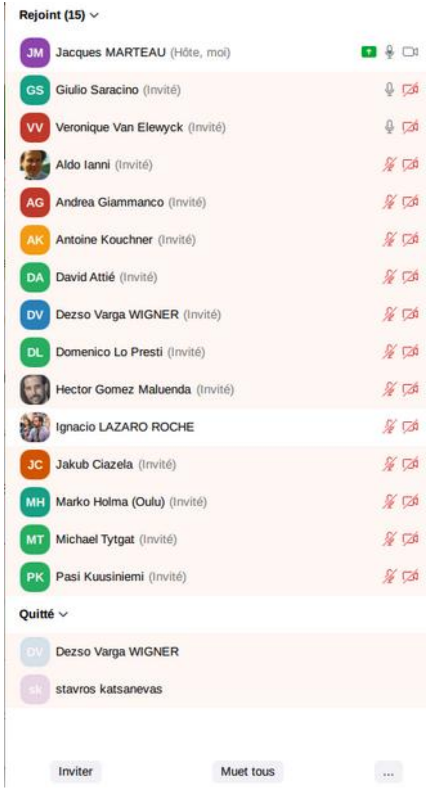
- **20 January**
- 9:30-10:00 The EU call (S. Katsanevas + F. Spagnuolo)
- 10:00-11:00 Fiber discusssion I (P. jousset) WP6
- 11:00-11:30 coffee break
- 11:30-12:30 Fiber discussion II (P. Jousset)
- 12:30:14:00 Lunch
- 14:00-16:00 CR Discussion (J. Marteau) WP7
- 16:00-16:30 Coffee
- 16:30-18:30 Underground science discussion (A. Ianni) WP8

- **21 January**
- 9:30-10:30 Data analysis and Machine Learning (E. Cuoco) WP9
- 10:30-11:30 Timing + Synchronisation (JE. Pottiie)   WP10
- 11:30-12:00 coffee break
- 12:00-13:00 Quantum and other sensors (F. Sorrentino) WP11
- 13:00:14:30 Lunch
- 14:30-15:30 The Art and Science part T. Saraceno WP3
- 15:30-16:30 Other Engagement actions WP3
- 16:30-17:00 Coffee
- 17:00-18:30 Discussion of workpages WP1, WP2, WP4, WP5
- 18/30-19:00 Final Discussion

APOGEIA – WP7

- **Minutes of the WP7 meeting : Jan, 11th :**

- Presentation of slides (JM)
- New proposal : LSBB (Ignazio Lazaro)
- New synergy identified : neutrino tomography (V.Van Elewyck)
- Global strategy : identify potential large synergies on tasks 1, 2, 3 to allocate ressources (→ to be discussed)
- Warning raised on access to dangerous sites (volcanoes)
- Warning raised on sharing of ressources
  → those warnings to be turned as a force in the proposal
- Open questions : format of the particpation of private companies ?



APOGEIA – WP7

- **Minutes of the WP-mu meeting : Nov, 9th :**
- Presentation of slides 3–15 (JM) followed by general discussion
- General introductory remark : the INFRA dimension to be included within the WP, with emphasis on the interdisciplinarity.
- Overlap between a large number of proposals → possible synergies and selection of some key infrastructures (adv.VIRGO, Etna, Vesuvius) as joint objectives.
- Importance of industrial partners in their advisory rôle and their guidance on practical developments. Of course may be associated as contractors.
- Deliverable of the WP on the form of a reference document for good practice and « certification » by the community of experts. Use benchmarks for comparative studies.
- Difficulties in setting up certified monitoring activities for volcanoes → this proposal may be a good opportunity to convince the communities (physicists and geophysicists) that the discipline reached the good level of maturity
- Presentation of underground facility in Finland as a benchmark for near-surface to deep applications.

- **Proposal for organization :**
  - Split the WP into **3 main target areas** (key infrastructure) :
    - Volcanoes Observatory (Italy, perhaps Iceland)
    - Near-surface and Environmental Characterization for GW detectors
    - Underground Characterization
  - Within those 3 sub-WPs share **4 tasks** on methods developments :
    - Integrated & Smart detectors
    - Multi-Detection Techniques (Cerenkov + Trackers + TPC etc)
    - Analysis Methods including ML (Joined analysis etc)
    - Simulation and Image Processing Techniques including ML (Digital Image Processing etc)

    → Deliverables as products of each tasks (detector prototypes, reference methods) to be benchmarked on local infrastructures and deployed on key infrastructures
  - As general deliverables → reference muography document / reference tools + outreach (cf LIP's proposal)