



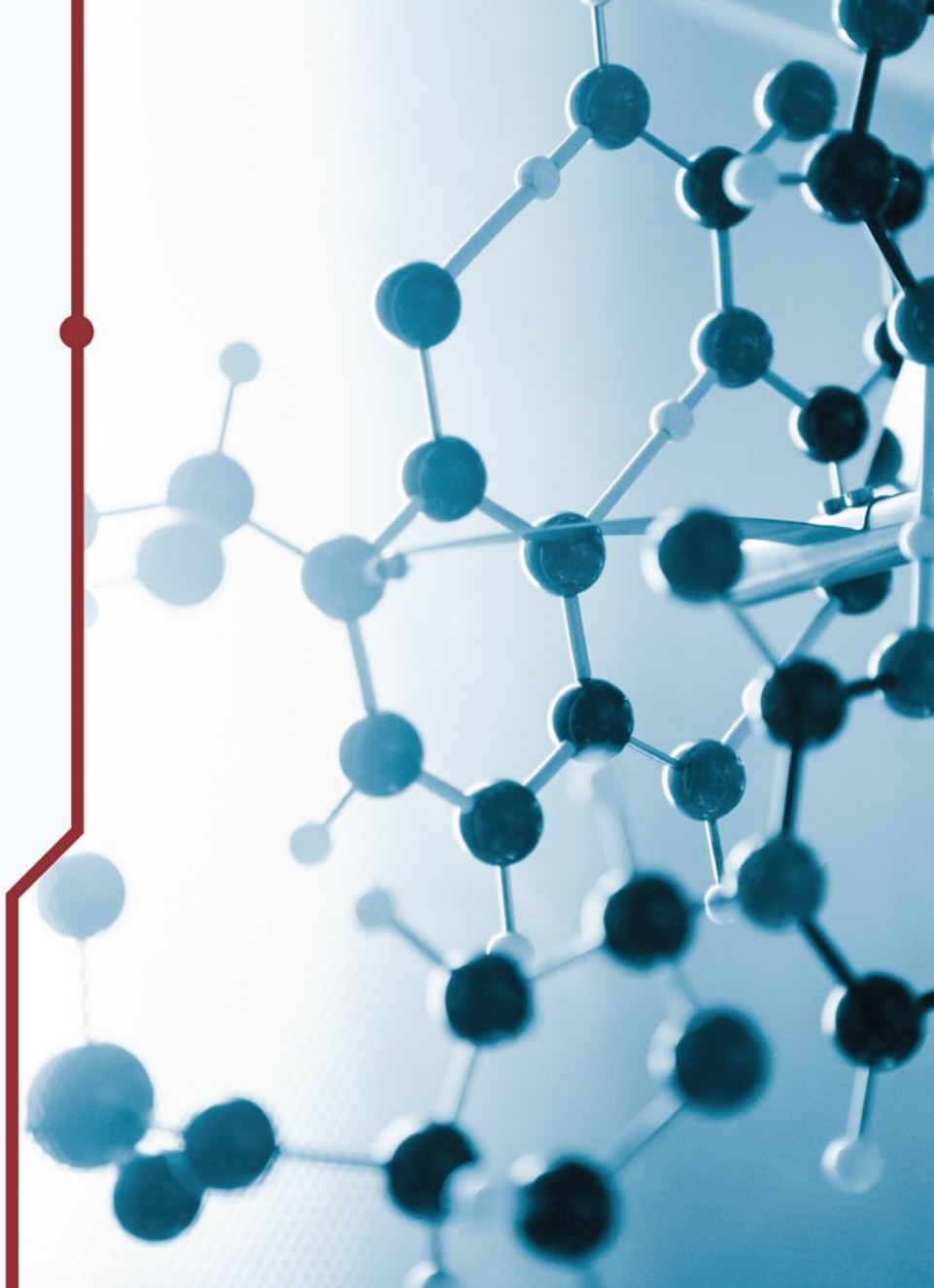
# REINFORCE

REsearch INfrastructures FOR Citizens in Europe

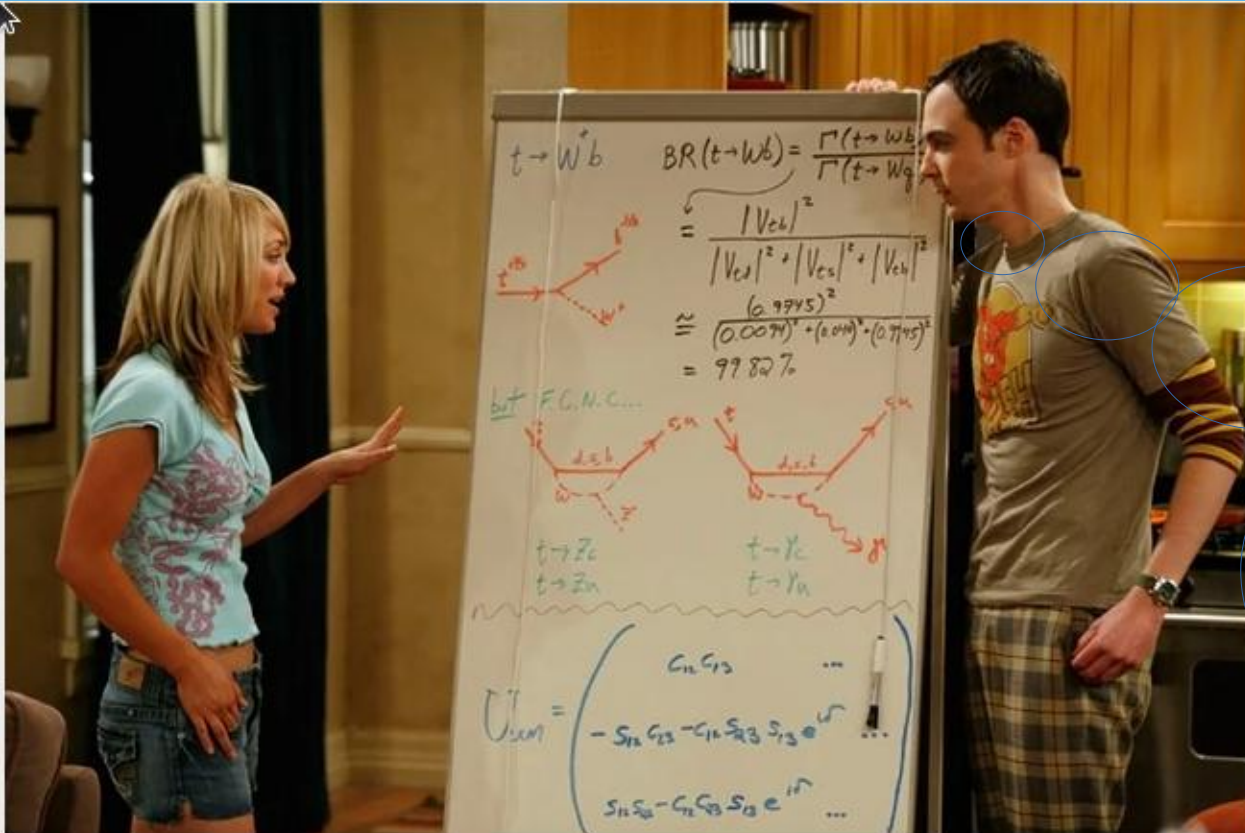
## How to use cosmic rays in the study of geosciences and archaeology

WEBINAR

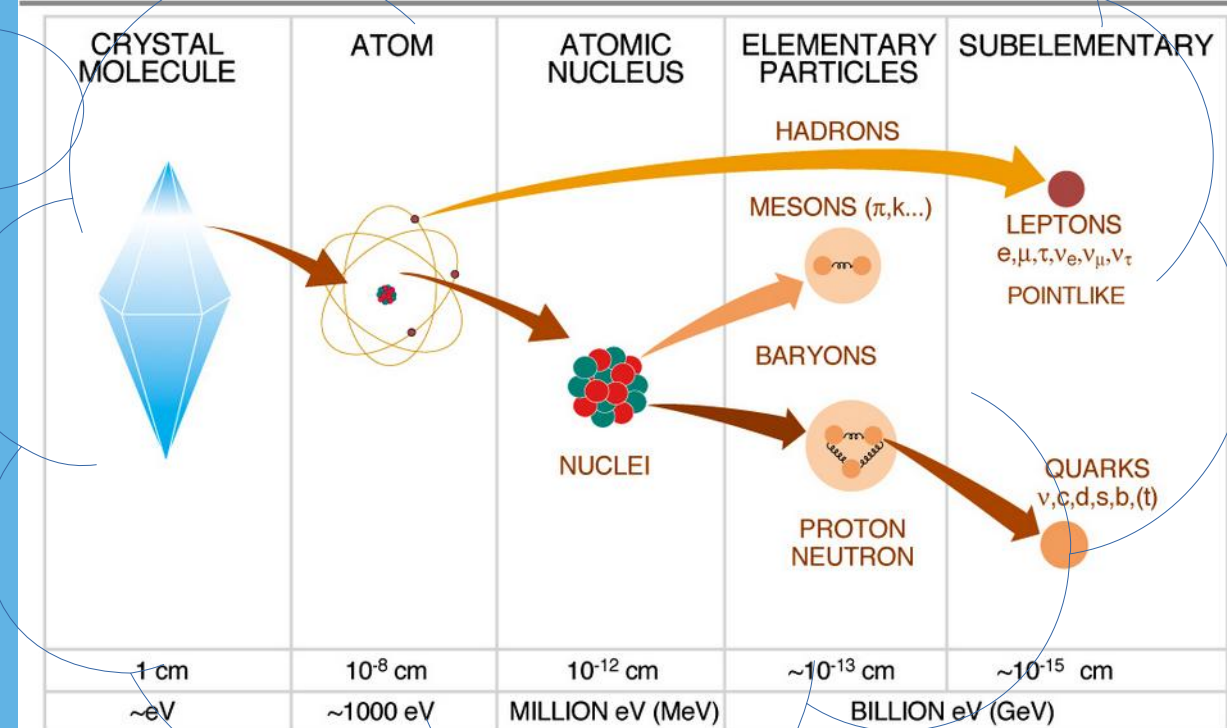
May 11, 2021, 15:00 CEST



# Big bang perspectives

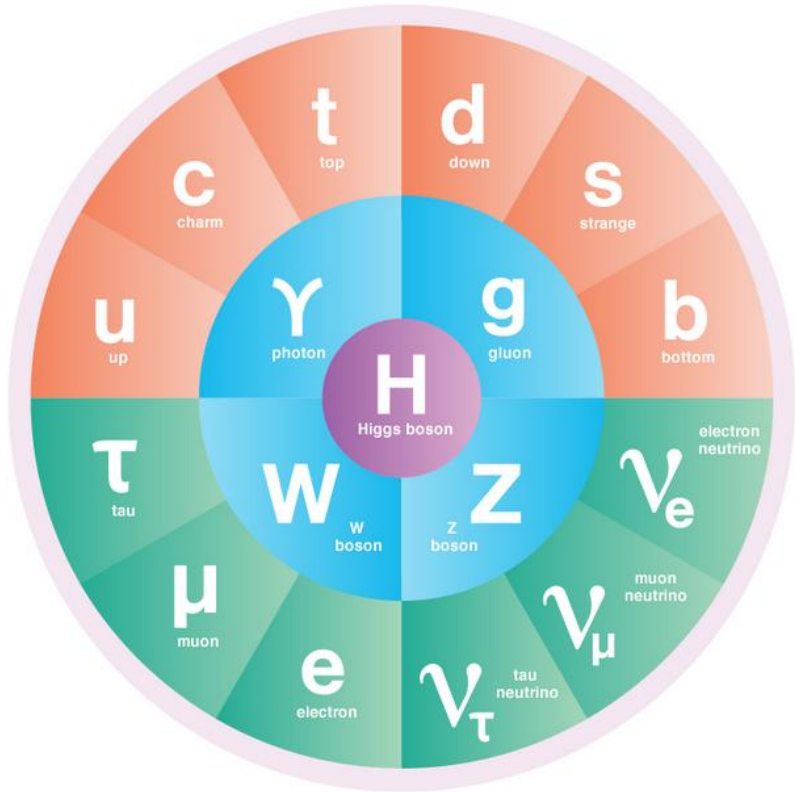


## DIFFERENT SCALING STRUCTURE OF MATTER



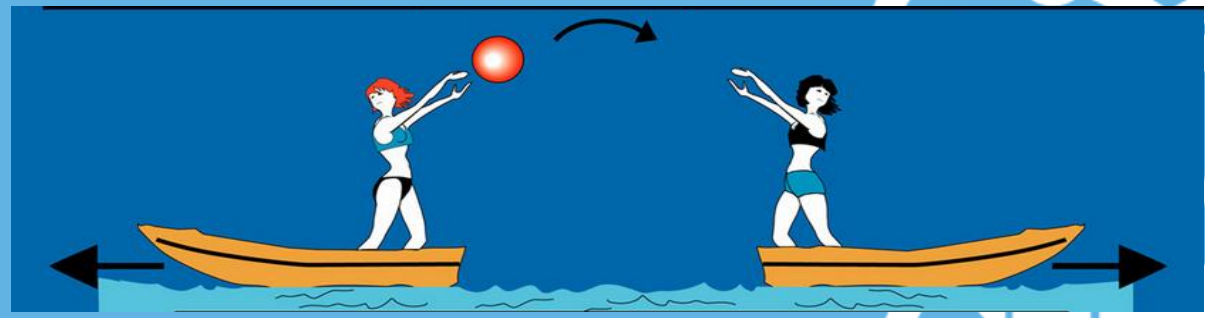
MICROSCOPE • VAN DE GRAAFF - GENERATOR • SYNCHROTRON • LARGE ACCELERATORS (CERN, FNAL)  
ELECTRON MICROSCOPE • CYCLOTRON • BETATRON • COLLIDERS (DORIS, PETRA, CERN LEP)

# Particles & Interactions

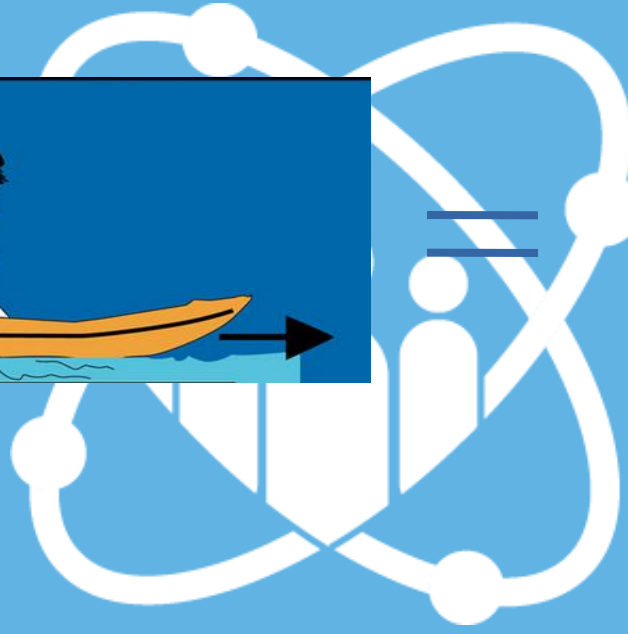


● QUARKS   
 ● LEPTONS   
 ● BOSONS   
 ● HIGGS BOSON

+



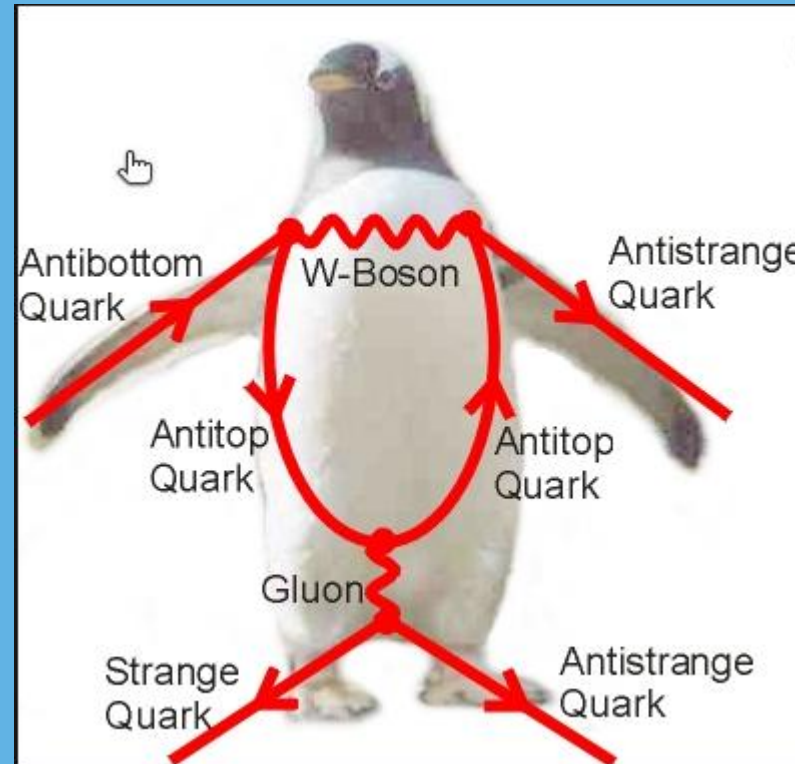
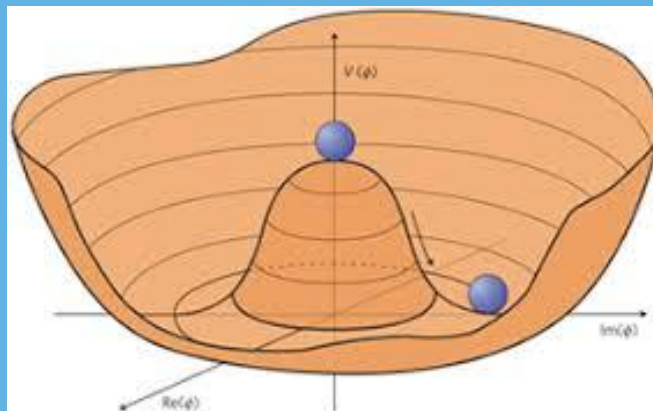
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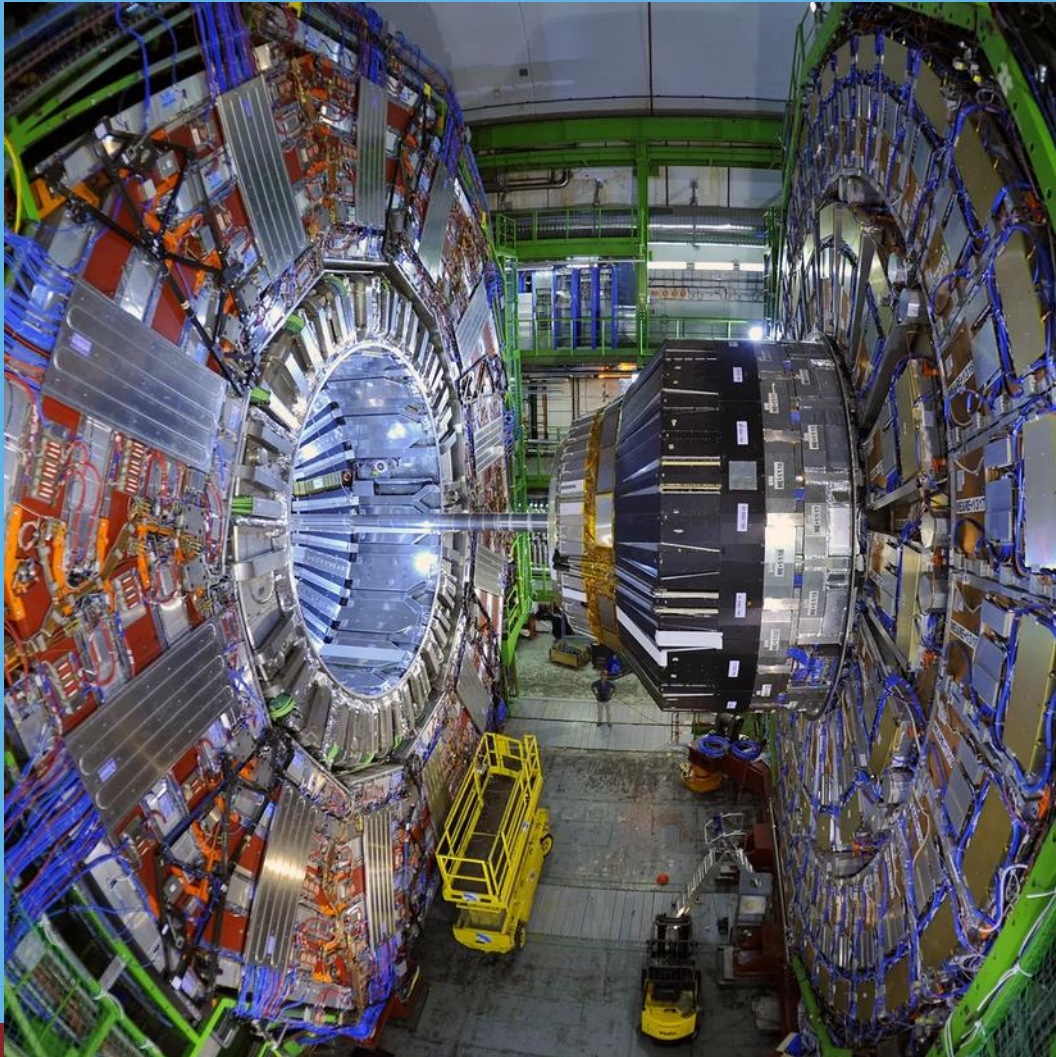


# A (standard) model

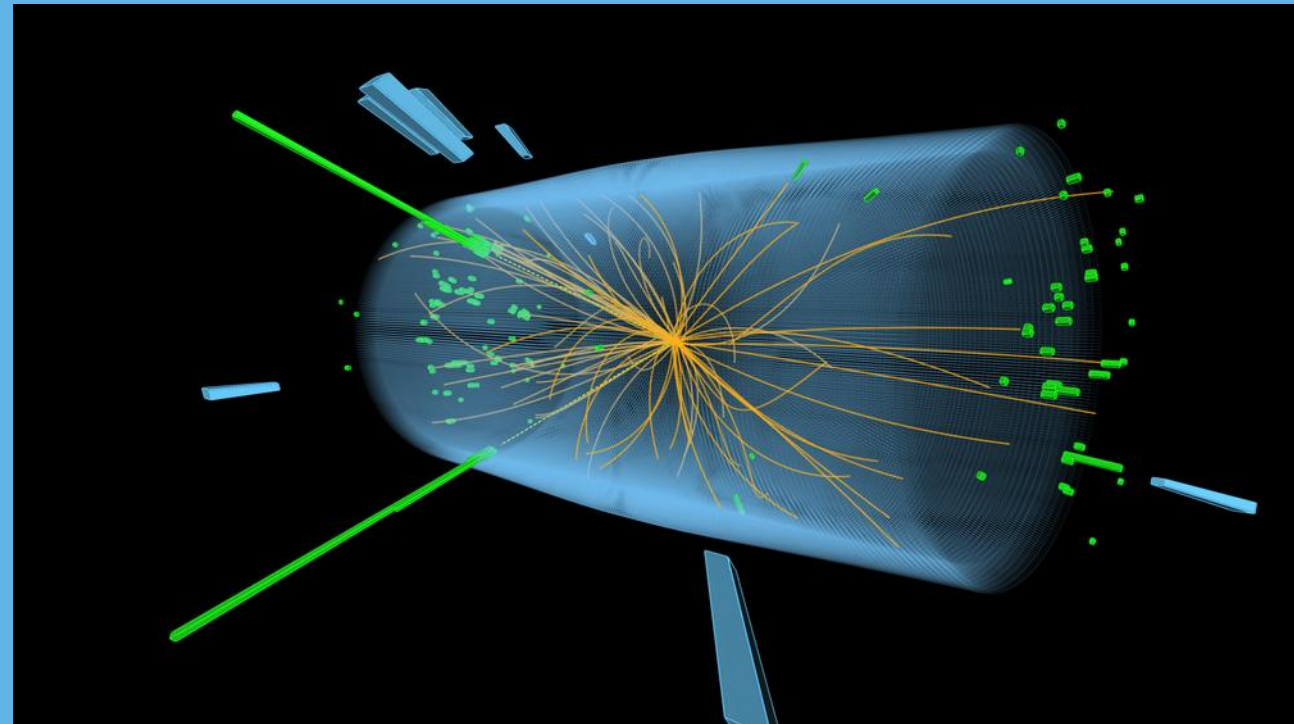
$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\nu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)) - \\
 & ig_s w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
 & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
 & \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\
 & g\alpha_h M (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\
 & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+)) - ig \frac{g_s}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig_s w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig_s w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{g_s^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{g_s^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{g_s}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_3^2 (\bar{q}^i \gamma^\mu q_j^i) g_\mu^a - \bar{e}^\lambda (\gamma^\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma^\partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma^\partial + \\
 & m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\partial + m_d^\lambda) d_j^\lambda + ig_s w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \\
 & \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep}{}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
 & \frac{g}{2M\sqrt{2}} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_e^2}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \nu_\kappa - \\
 & \frac{1}{4} \bar{e}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) e_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
 & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^+ X^0) + ig_s w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^0 X^+) + ig_s w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) + ig_s w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
 \end{aligned}$$



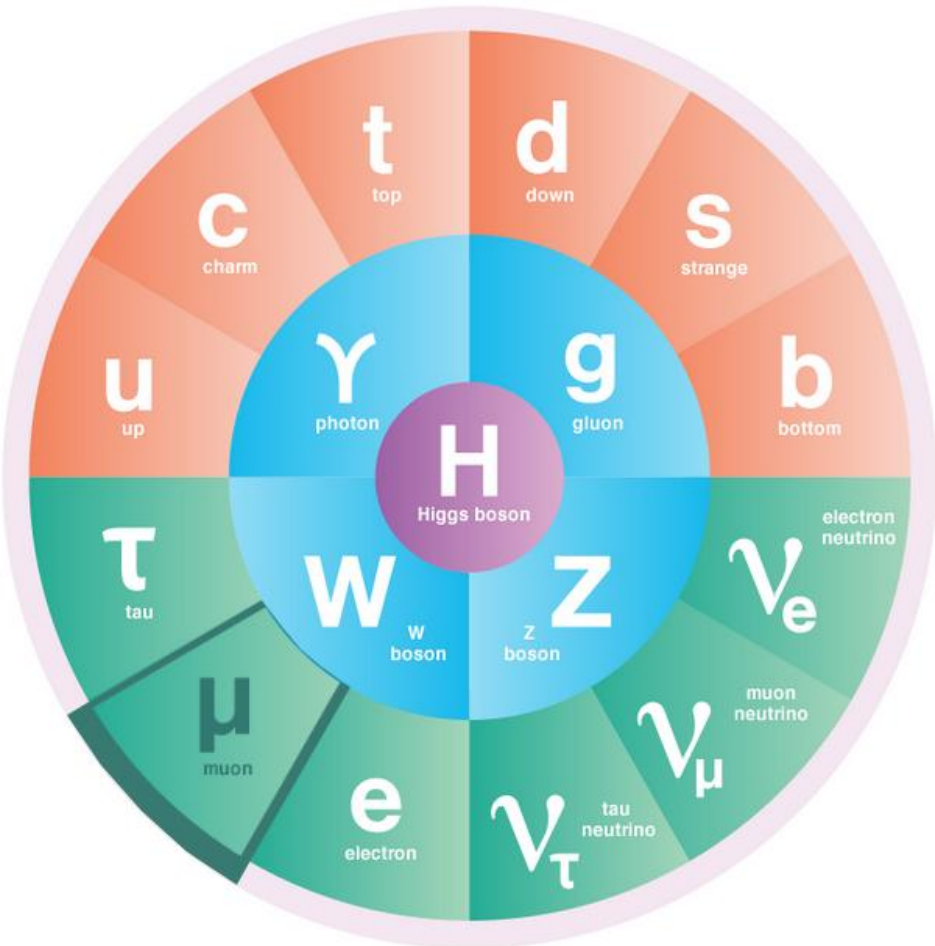
# (Non-Standard) experiments



CMS @ CERN



# The actors : a particle ...



## The Standard Model of Particle Physics

### MUON

**Discovered in:**  
1937

**Mass:**  
105.66 MeV

**Generation:**  
Second

**Discovered at:**  
Caltech & Harvard

**Charge:**  
-1

**Spin:**  
1/2

#### About:

The muon is a heavier version of the electron. It rains down on us as it is created in collisions of cosmic rays with the Earth's atmosphere. When it was discovered in 1937, a physicist asked, "Who ordered that?"

[Return to symmetry article](#)



# ... and some humans

**15:00 - 15:20:** Welcome and introduction - Muography: from basics to a new world of images - **Jacques Marteau** (Deputy director of IP2I, WP6 responsible)



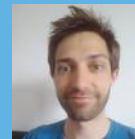
**15:20 - 15:30:** Cosmic rays: from heaven to underground - **Amélie Cohu** (PhD in IP2I) & **Matias Tramontini** (PhD in UNLP)



**15:30 - 15:40:** Interdisciplinarity at work: volcanology & risks assessment with muons - **Marina Rosas-Carbajal** (Researcher in IPGP)



**15:40 - 15:50:** Because boring is not boring: an application of muography in civil engineering - **Antoine Chevalier** (Member of PULSALYS)



**15:50 - 16:00:** Muons in the particles zoo - **Theodore Avgitas** (REINFORCE post-doc in IP2I)



**16:00 - 16:10:** Q&A and wrap-up





# REINFORCE

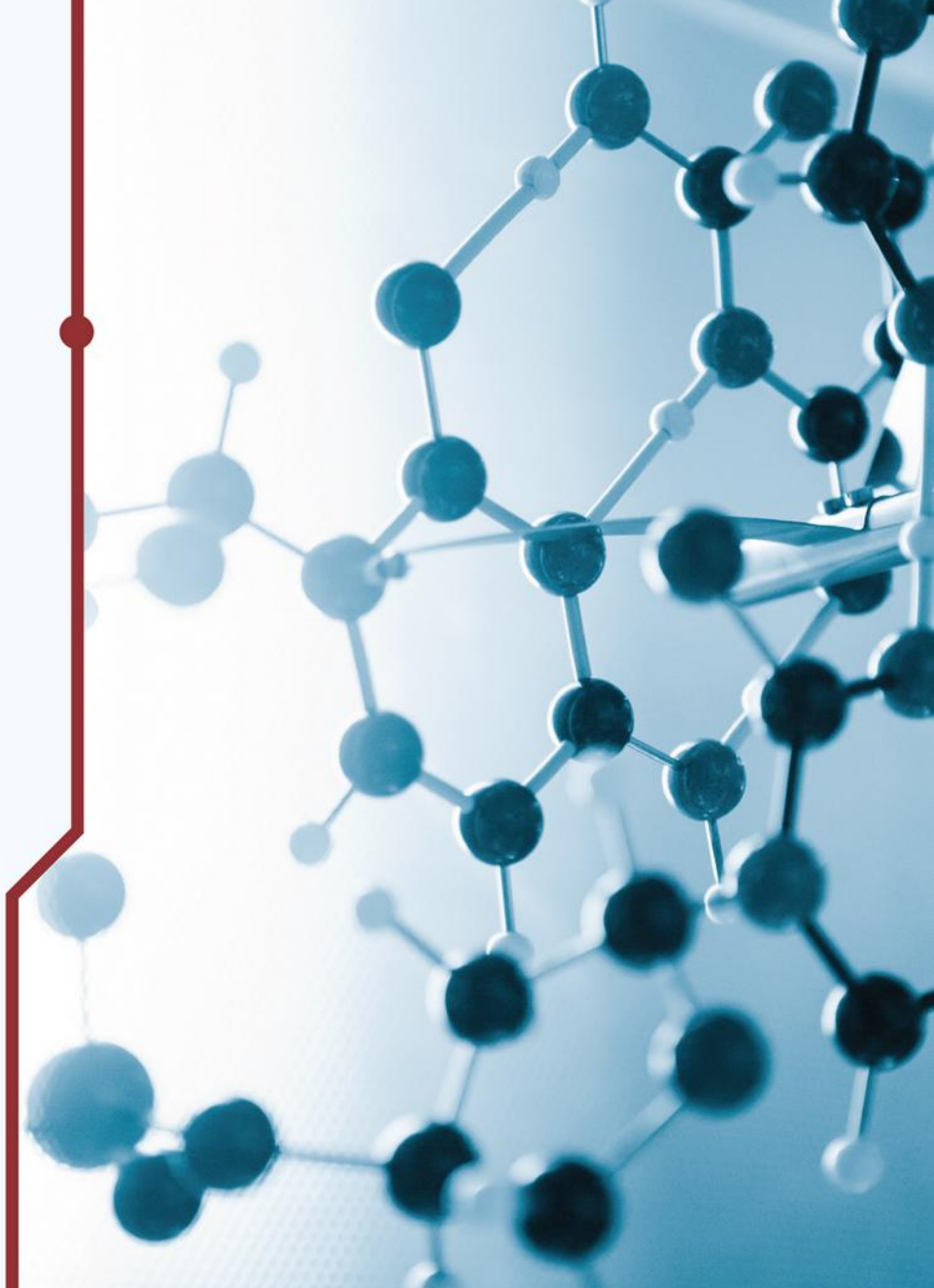
REsearch INfrastructures FOR Citizens in Europe

## Muography: from basics to a new world of images

by J.MARTEAU, IP2I, Univ.Lyon, CNRS/IN2P3

WEBINAR

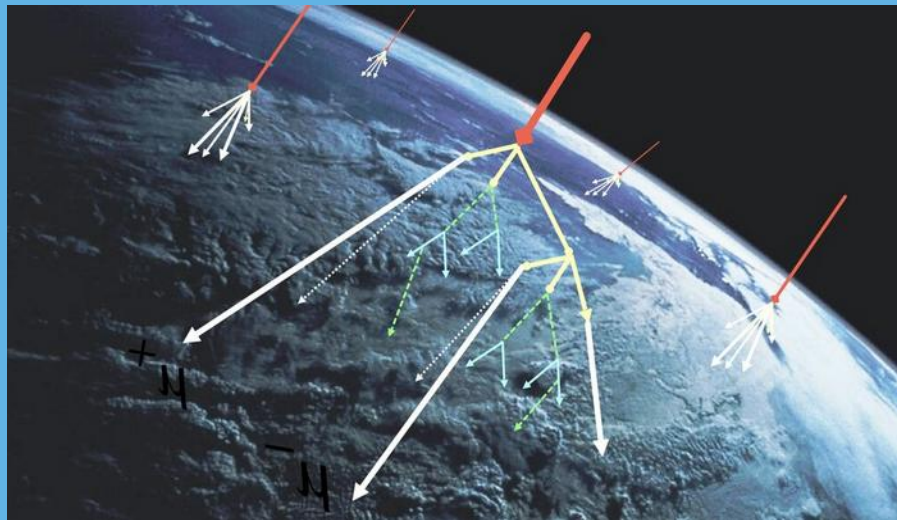
May 11, 2021, 15:00 CEST



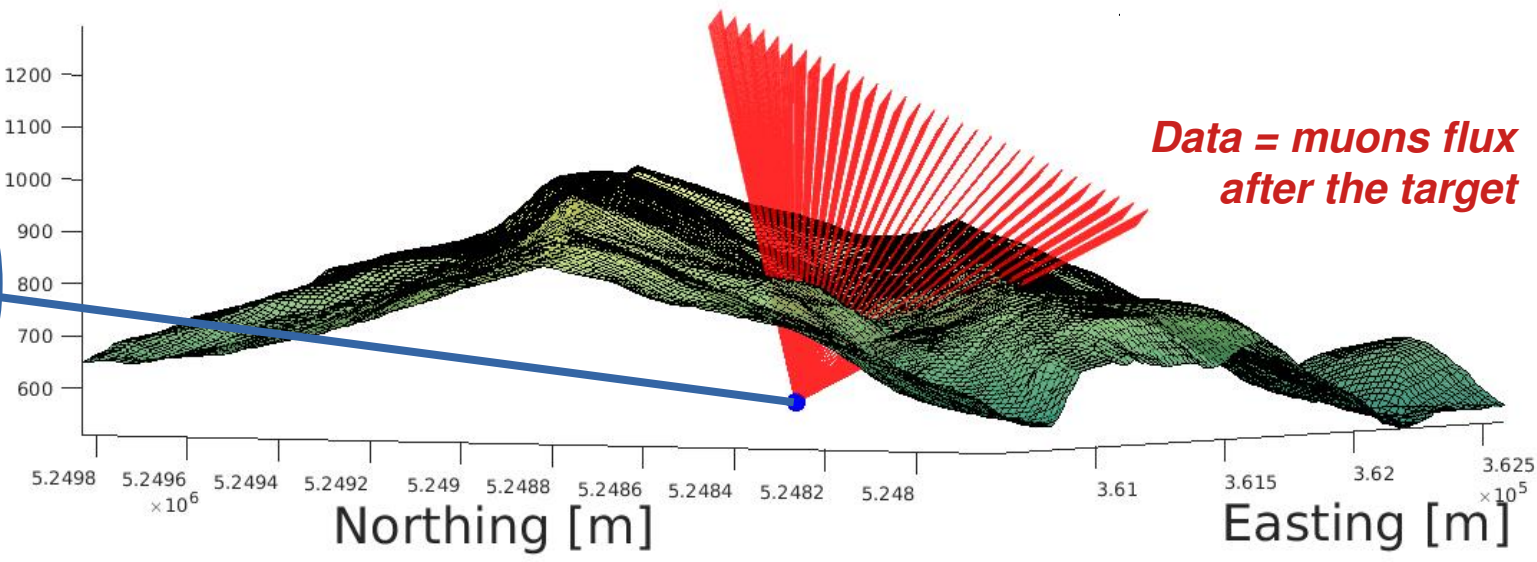


Muography = { absorption } tomography  
 { scattering }

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



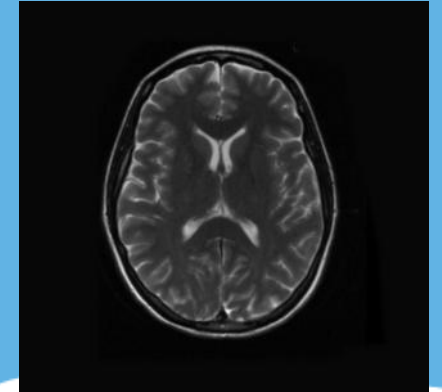
**Detector**



# Medical imaging techniques

2 known examples :

MRI  
(Magnetic Resonance Imaging)



CT-scan  
(Computed Tomography)



**Detector**  
→ *data measurement*

**Reconstruction**  
→ *inverse problem*

**Images**

# Inverse problem

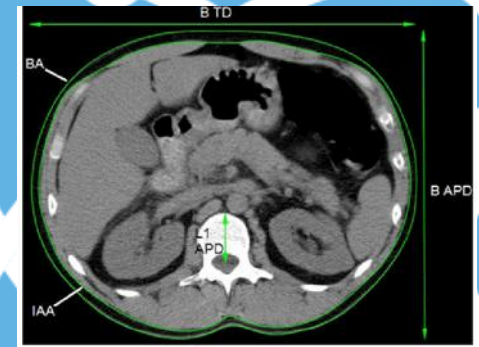
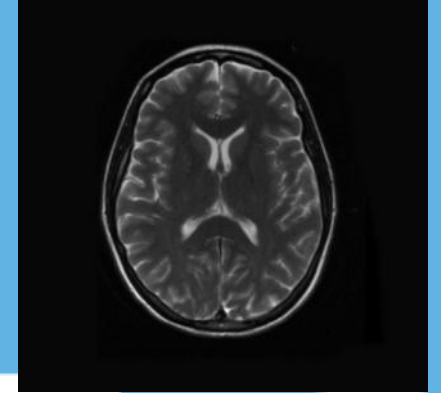
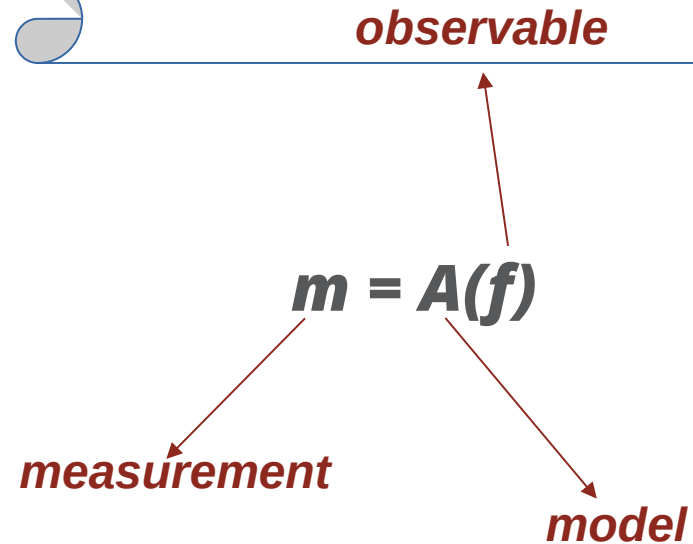
2 known examples :

MRI :

- observable = proton density
- measurement = magnetic moment relaxation times
- sensitive for soft tissues details

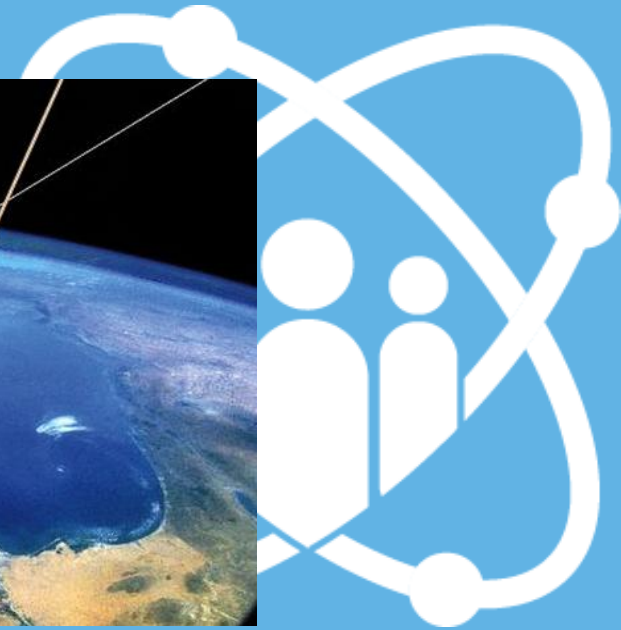
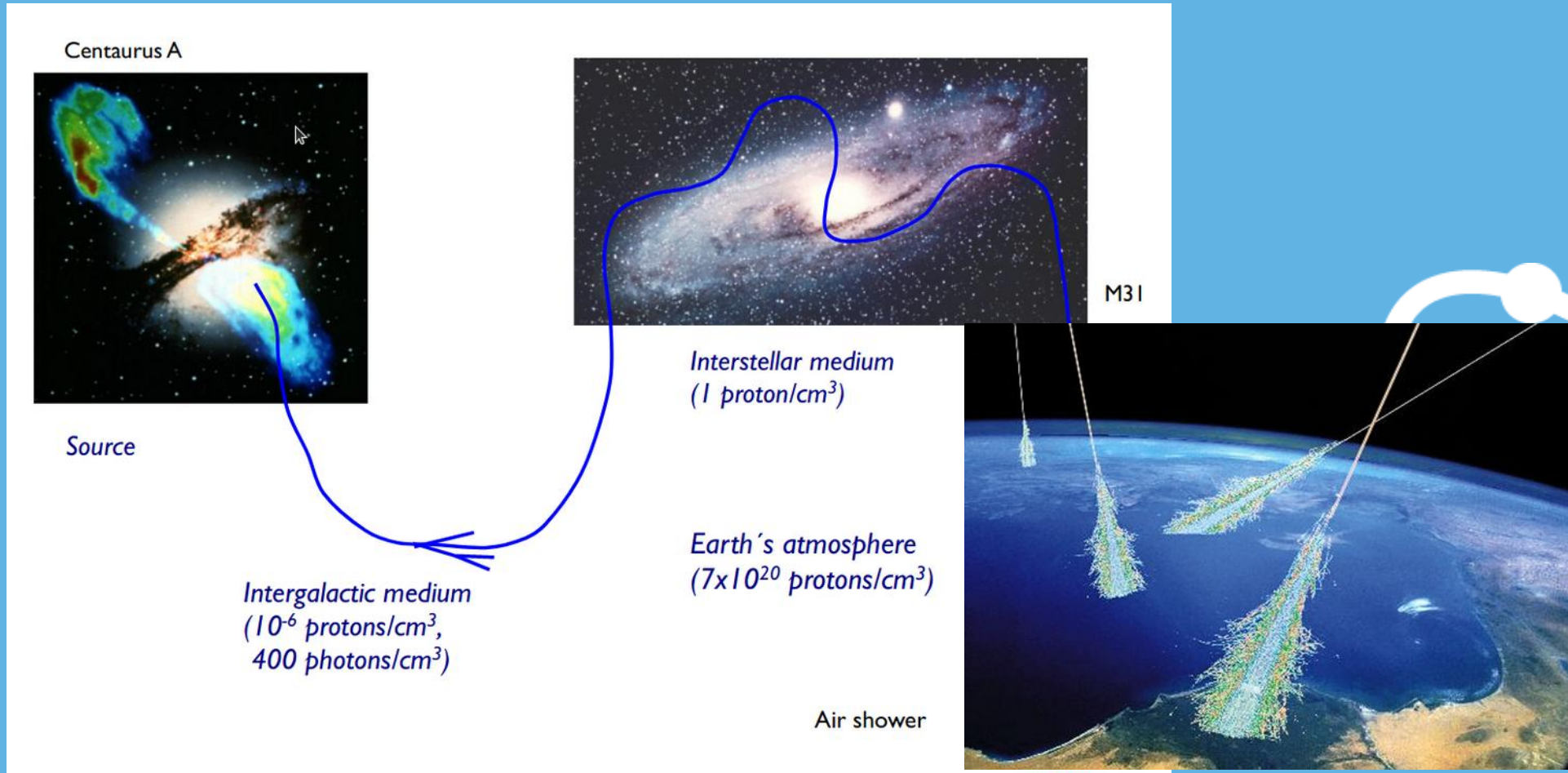
CT-scan :

- observable = density
- measurement = X-ray absorption
- sensitive to dense parts (e.g. bones)

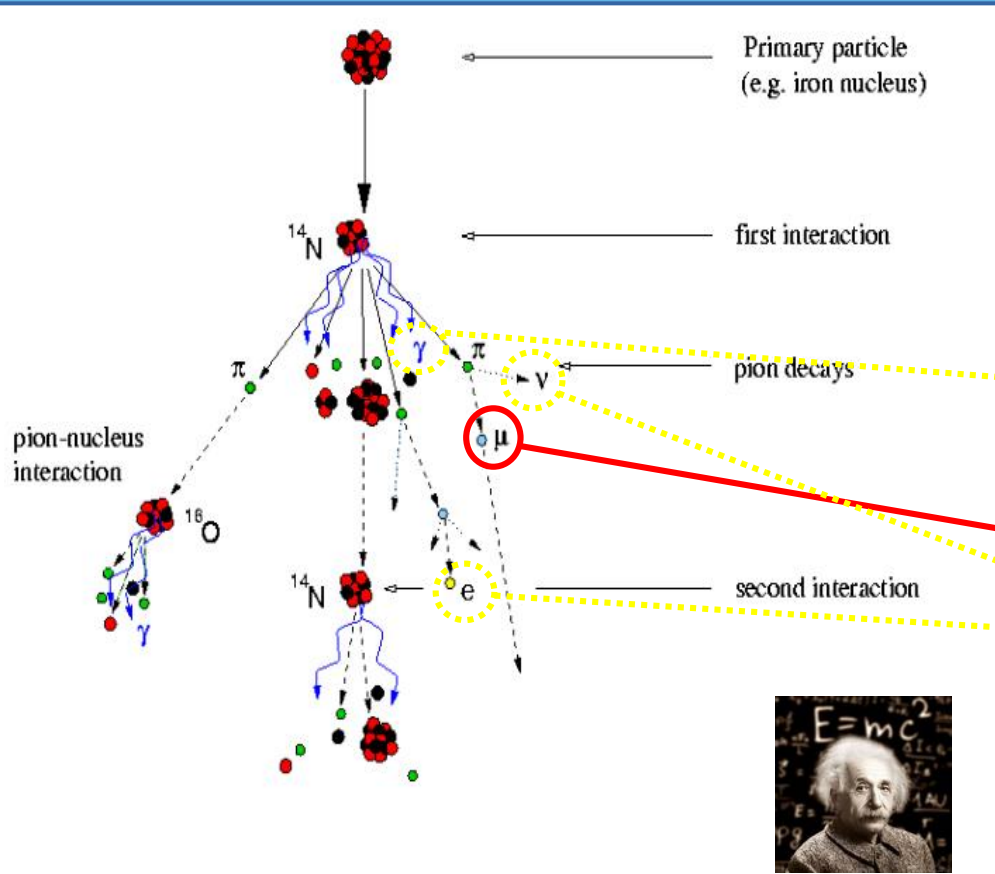


*Images*

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



# 2. Processing chain : the probe(s)



Decay of neutral pions feeds em. shower component  
 Decay of charged pions (~30 GeV) feeds muonic component

### Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	=2.2 MeV/c <sup>2</sup>	=1.28 GeV/c <sup>2</sup>	=173.1 GeV/c <sup>2</sup>	0	=124.97 GeV/c <sup>2</sup>
charge	2/3	2/3	2/3	0	0
spin	1/2	1/2	1/2	1	0
<b>QUARKS</b>	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
	=4.7 MeV/c <sup>2</sup>	=96 MeV/c <sup>2</sup>	=4.18 GeV/c <sup>2</sup>	0	0
	-1/3	-1/3	-1/3	0	0
	1/2	1/2	1/2	1	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon	
<b>LEPTONS</b>	=0.511 MeV/c <sup>2</sup>	=105.66 MeV/c <sup>2</sup>	=1.7768 GeV/c <sup>2</sup>	=91.19 GeV/c <sup>2</sup>	
	-1	-1	-1	0	1
	1/2	1/2	1/2	1	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson	
	<1.0 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<18.2 MeV/c <sup>2</sup>	=80.39 GeV/c <sup>2</sup>	
	0	0	0	+1	1
	1/2	1/2	1/2	1	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson	

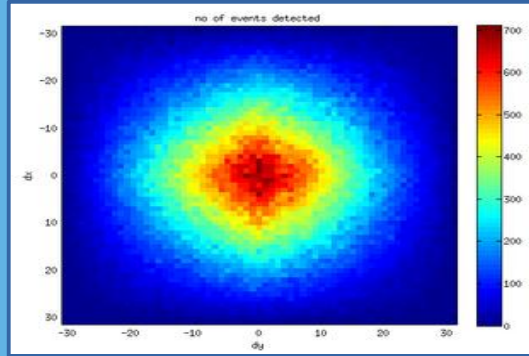
**Gauge Bosons Vector Bosons** (g, γ, Z, W)  
**Scalar Bosons** (H)

# 3. Processing chain : the target(s)

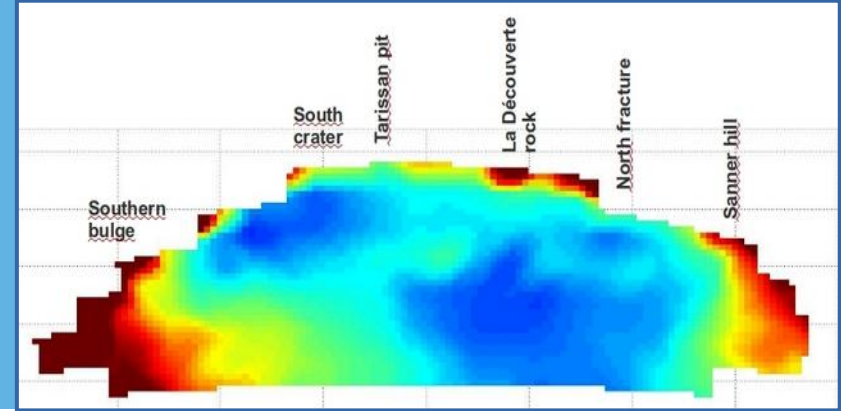
$$q(L) \equiv \int_L \rho(\xi) d\xi$$

$q = \text{opacity}$     $\rho = \text{density}$

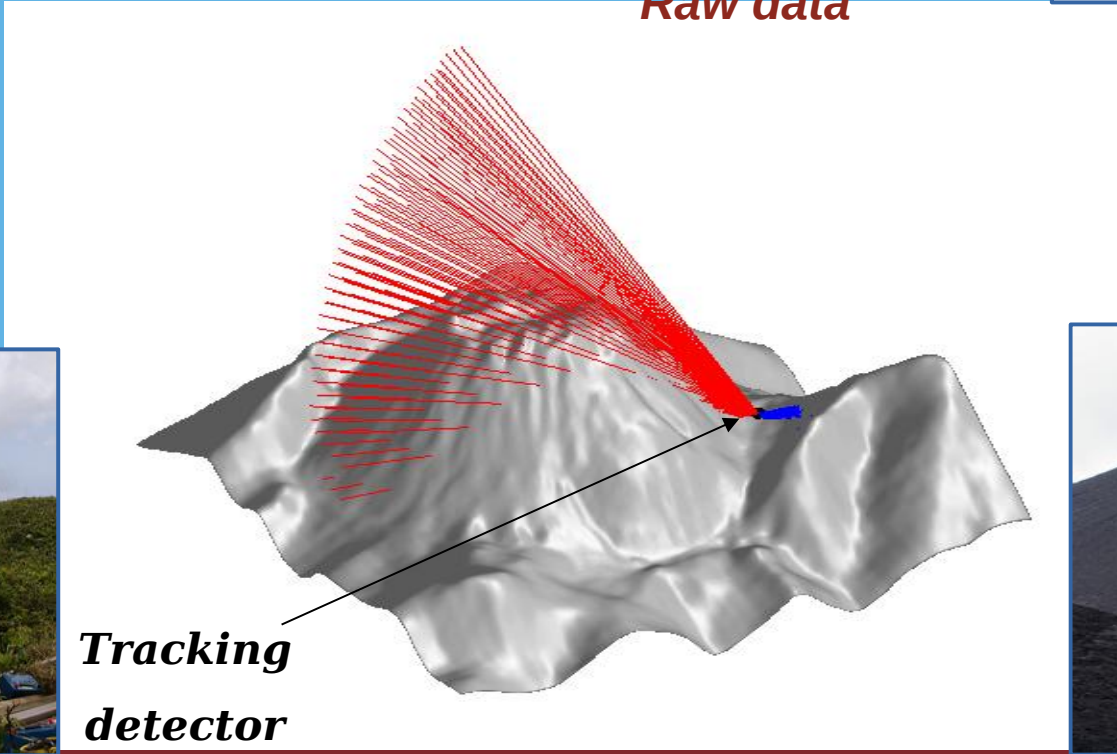
*Observable*



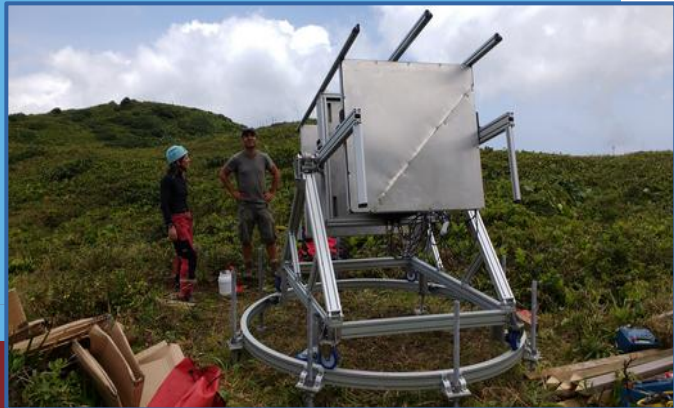
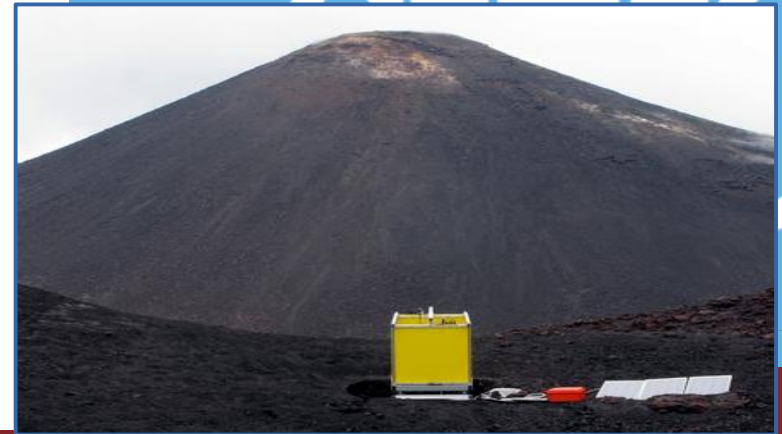
*Raw data*



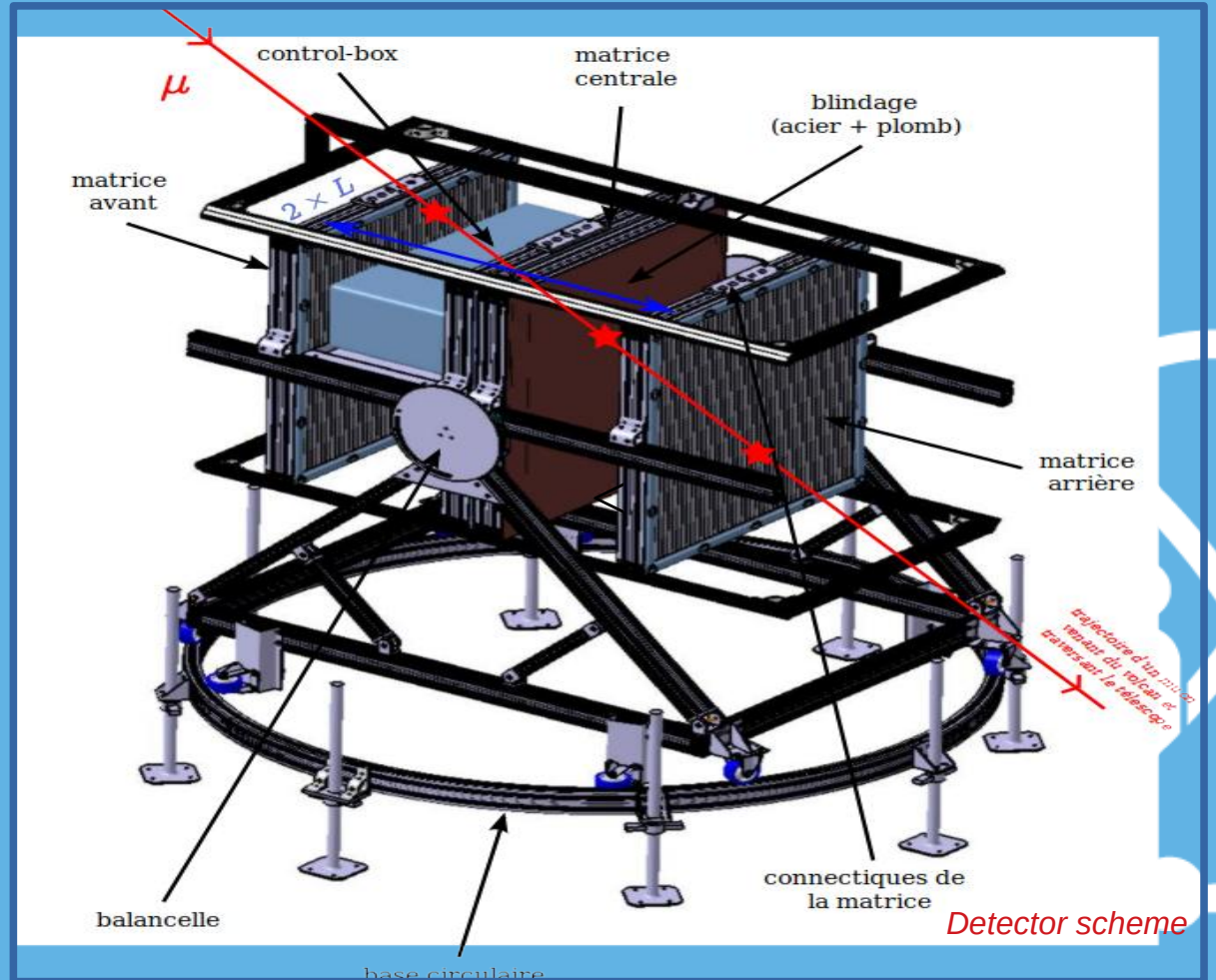
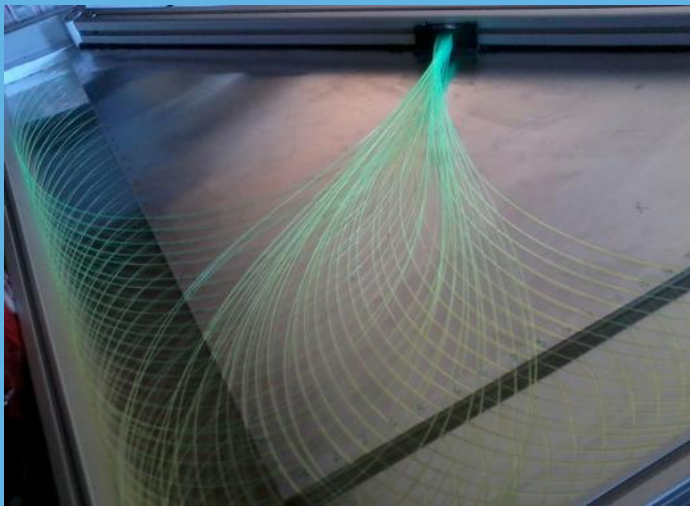
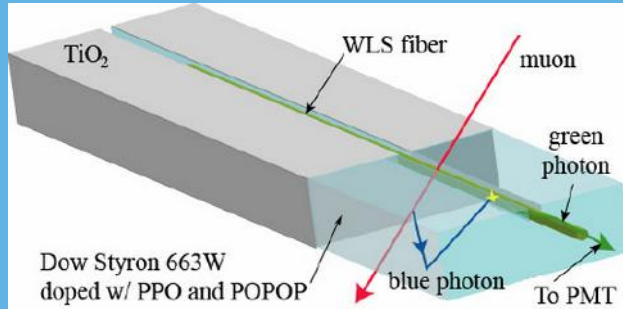
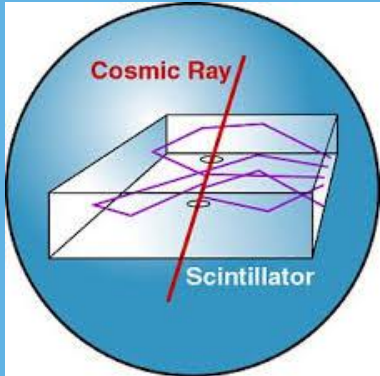
*Reconstructed image*



*Tracking detector*



# 4. Processing chain : the tracker



A simple **tracking++** device using scintillators, emulsions, micro-megas, RPC's...

# Muography use cases overview

**Muography =  $\mu$ -ray imaging technique : absorption / scattering  $\rightarrow$  sensitive to  $\rho$  (opacity)**

## Geosciences



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

## Archaeology



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

## Industrial controls



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



# Geosciences, Geotechnics, Archaeology



Mayon  
(Philippines)



Etna  
(Italy)



Blast furnace



Urban tunnel



Soufrière

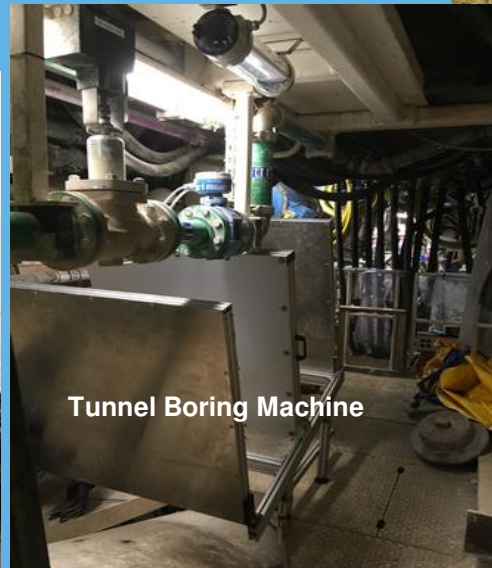
$\mu$ -gravimetry coupling



Mont-Terri Underground lab



Water tank monitoring



Tunnel Boring Machine



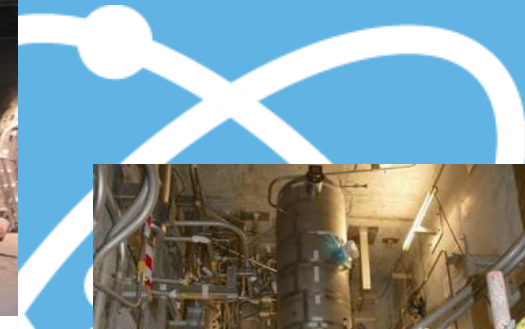
LSBB



Greek tumulus

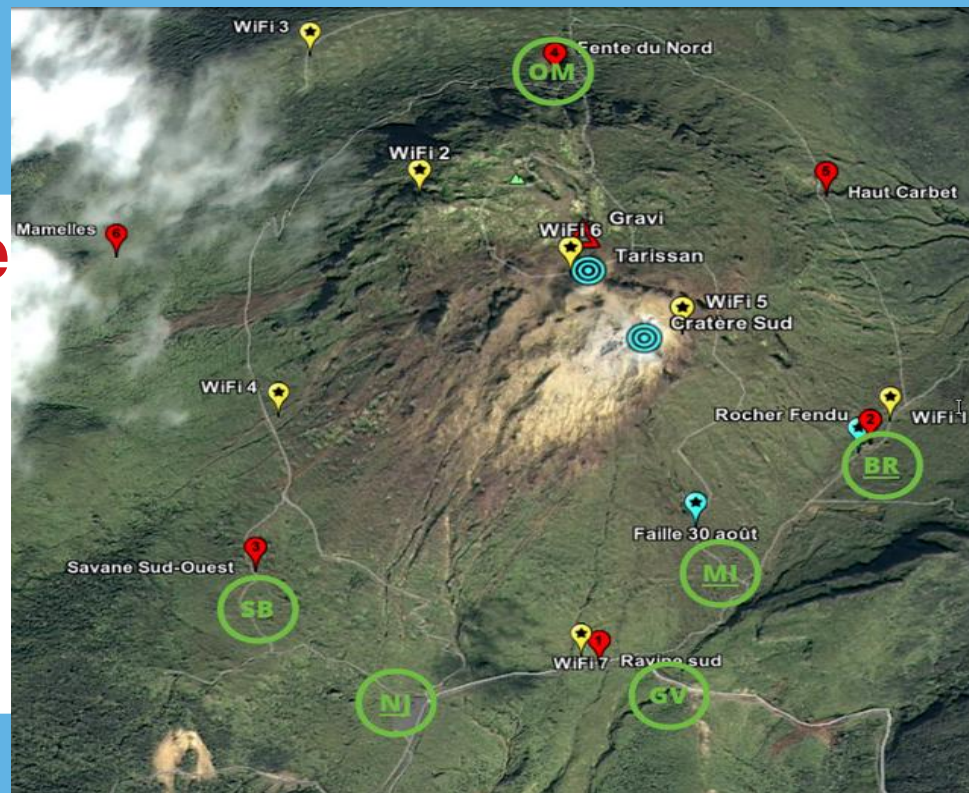


Nuclear evaporator



# Muons @ Soufrière

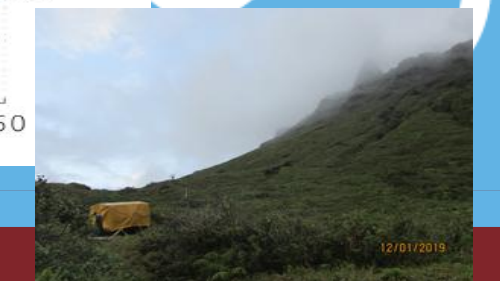
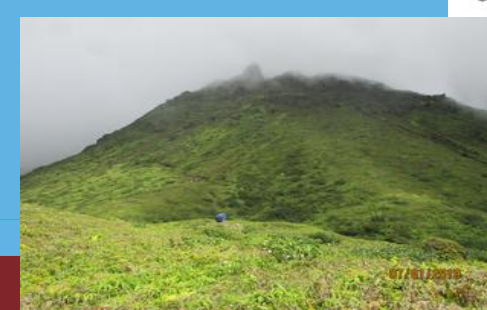
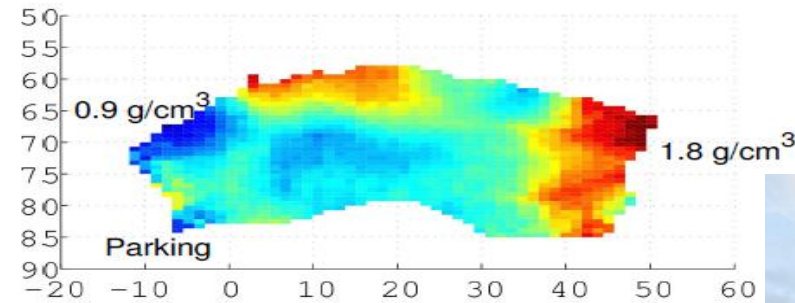
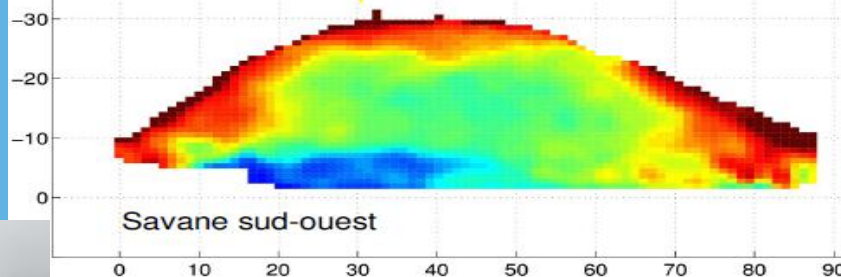
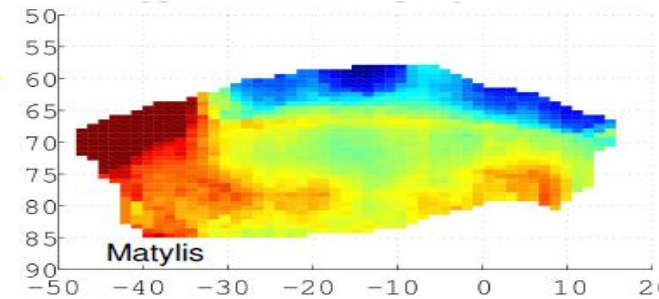
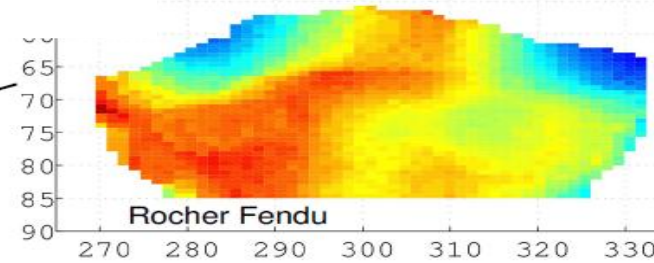
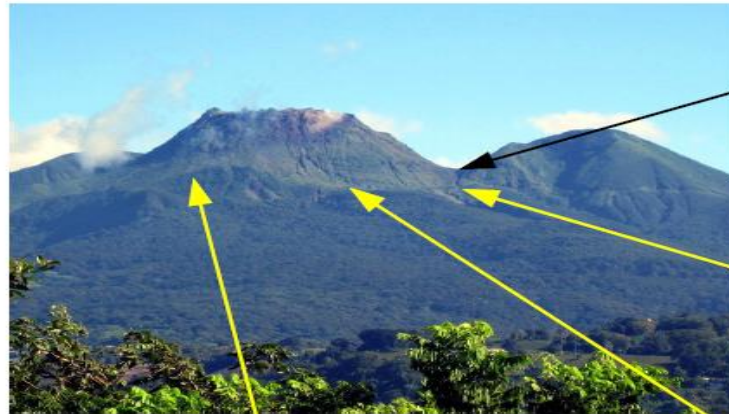
## 5 + 1 detectors *around the dome*

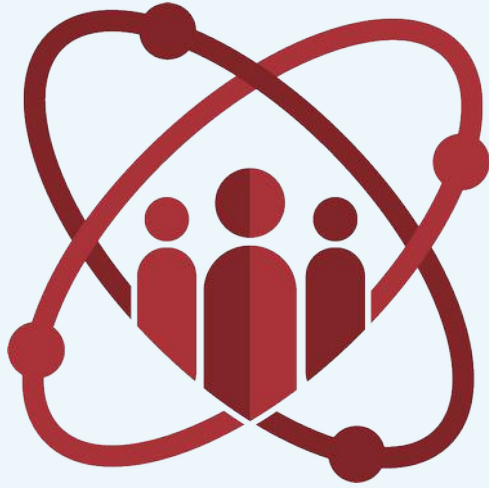


# Example of a muons system



## Imaging & monitoring





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