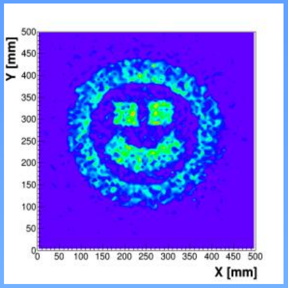
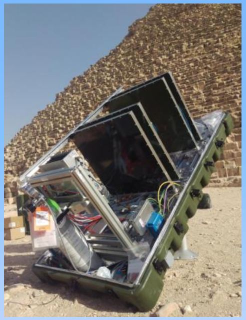
DE LA RECHERCHE À L'INDUSTRIE

Muography: principle & applications



The ScanPyramids project



S. Procureur
CEA Paris-Saclay

Ecole Joliot-Curie, Seminar, 24/09/2017

Content

Muography: principle & applications

- Cosmic muons
  - Cosmic rays
  - Showers
  - Muon and muon flux
- Muography principles
  - Muon absorption & transmission
  - Muon deviation (or scattering)
  - Muon metrology
- Muon imaging technologies
  - Specificities
  - Detection techniques
- Selected Applications
  - Volcanology
  - Archeology
  - Nuclear waste and reactor
  - Homeland security

The ScanPyramids project

- Instrumentation
  - Irfu technology
  - Miniaturization
- Telescope prototype
  - Water tower experiment
  - Performance: static & dynamic
- 1st mission on Khufu
  - Preparation & tests
  - Installation
  - Performance
  - Results
- 2nd mission
- Perspectives

COSMIC RAYS - HISTORY

→ Mystery for a very long time

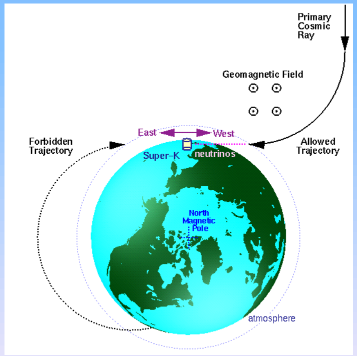
- *Effects known since 18th century (electroscope discharges)*
- *Question of the source (from Earth or extra-terrestrial)*
- *Wulf experiment on Eiffel Tower (1910)*

→ 2 decisive sets of experiments in 1912

- *Hess with balloons to measure electroscope discharges*
- *Pacini with sea measurements (above and under)*

→ Still many years to understand its composition

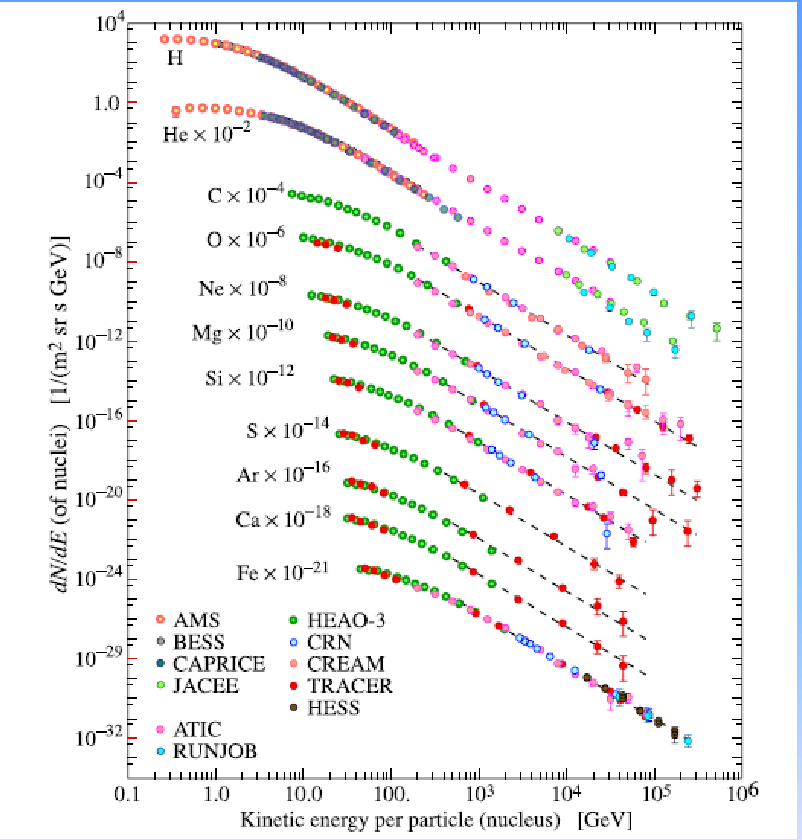
- *« Birth cry of atoms » theory of Millikan (cosmic « rays »)*
- *Latitude effect measured by Compton (1933)*
- *East-West effect measured by Alvarez, Compton and Rossi (1933)*



COSMIC RAYS - COMPOSITION

⟶ High energy particles produced in the Universe

- *Solar flares (lowest energy)*
- *Supernovae*
- *AGN*
- *…*



$$I_N(E) \approx 1.8\times 10^4 \left(\frac{E}{\text{GeV}}\right)^{\alpha} \frac{\text{nucleons}}{\text{m}^2\ \text{s sr GeV}}$$

⟶ ~90% of protons and ~9% of He

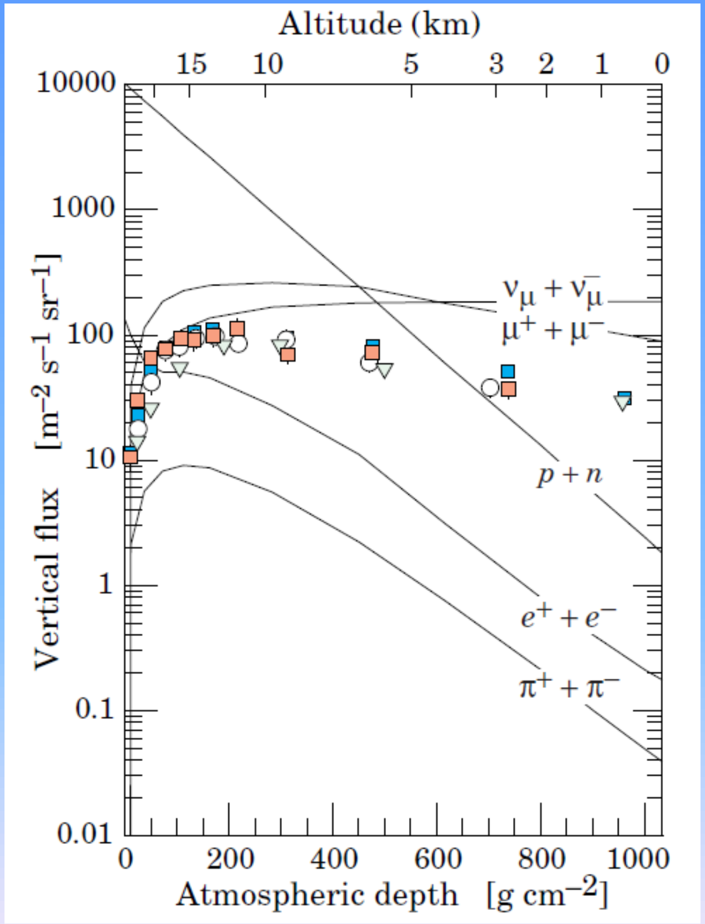
⟶ Measured up to 3.10^8 TeV

⇔ *tennis ball at 150 km/h*

⟶ Flux anti-correlated with solar activities

⟶ Produce a cascade of reactions when entering the Earth's atmosphere

- *« cosmic showers »*
- *Pions, kaons, electrons, muons,…*



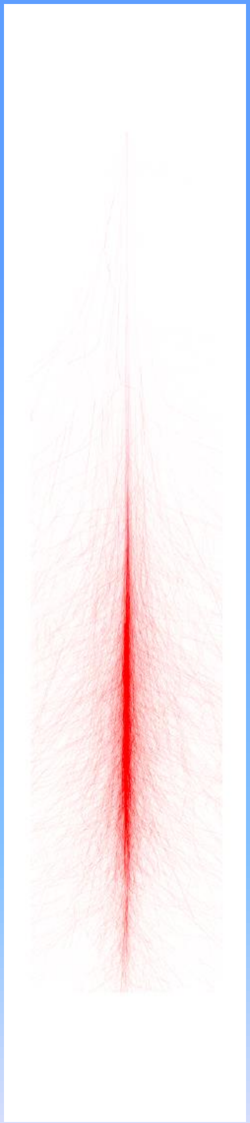
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

BR: 99.99%

$$K^- \rightarrow \mu^- + \bar{\nu}_\mu$$

BR: 63.5%

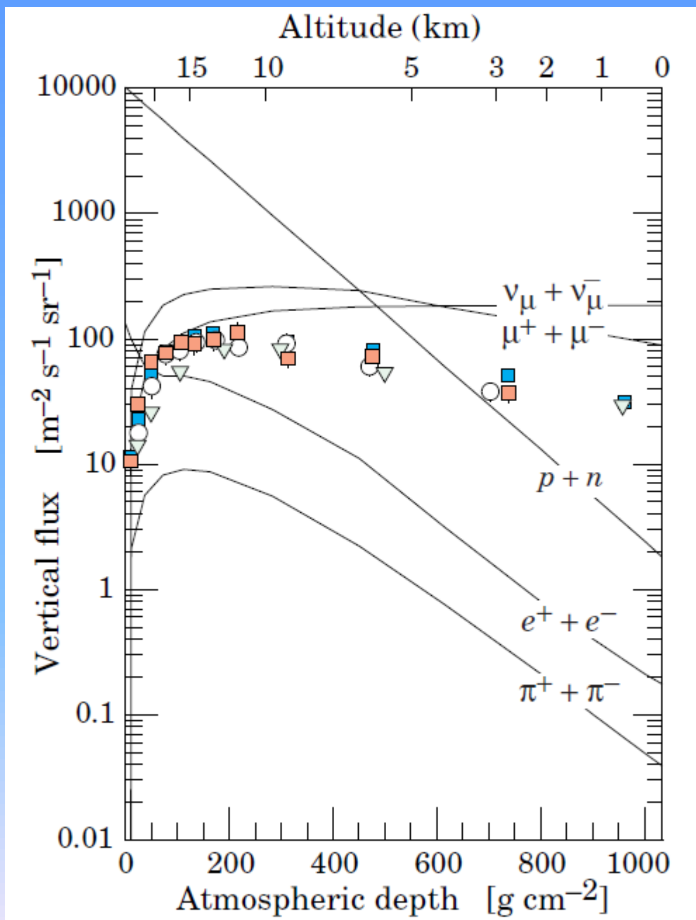
⟶ why no decay into electrons (lighter)??



COSMIC RAYS - SHOWERS

→ Produce a cascade of reactions when entering the Earth's atmosphere

- *« cosmic showers »*
- *Pions, kaons, electrons, muons,…*



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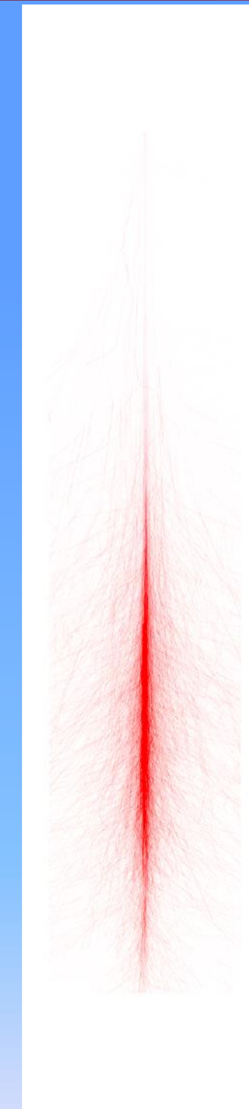
→ why no decay into electrons (lighter)??

$$R_\pi = (m_e/m_\mu)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2} \right)^2 = 1.283 \times 10^{-4}$$

→ helicity effect!



MUONS

⟶ Muon is an unstable particle $\tau = 2{,}2\mu s$

- *At speed of light, decay after* $c\tau \cong$*660 m…?*

Muons

→ Muon is an unstable particle $\tau = 2{,}2 \mu s$

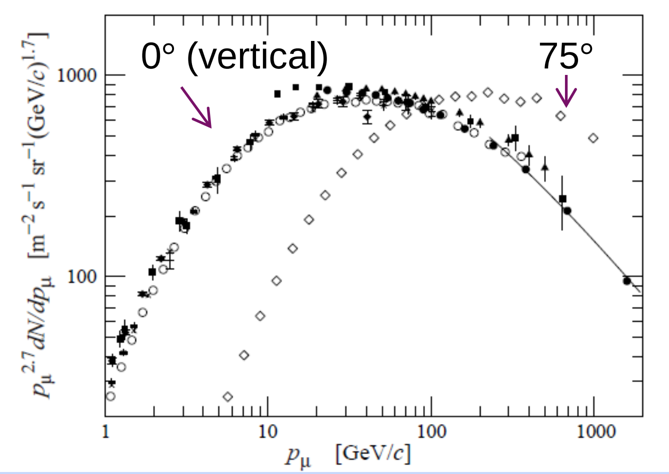
- *At speed of light, decay after $c\tau \cong 660$ m…?*
- *… but time dilatation allows it to travel along much longer distances*

→ Muons combine 3 advantages compared to other particles produced in cosmic showers

- *Larger lifetime vs other unstable particles*
- *Larger mass compared to electrons*
- *No hadronic interactions (like p, n)*

→ Mean muon flux

$$\frac{dN}{dE\,d\Omega} = \frac{0.14E^{-2.7}}{\text{cm}^2 \text{ s sr GeV}} \times \left(\frac{1}{1 + \frac{1.1 \times E\cos\theta}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{1.1 \times E\cos\theta}{850 \text{ GeV}}} \right)$$

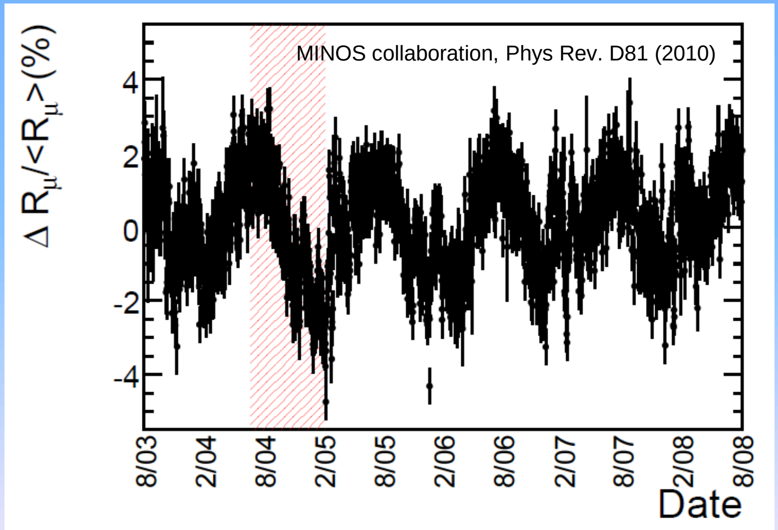


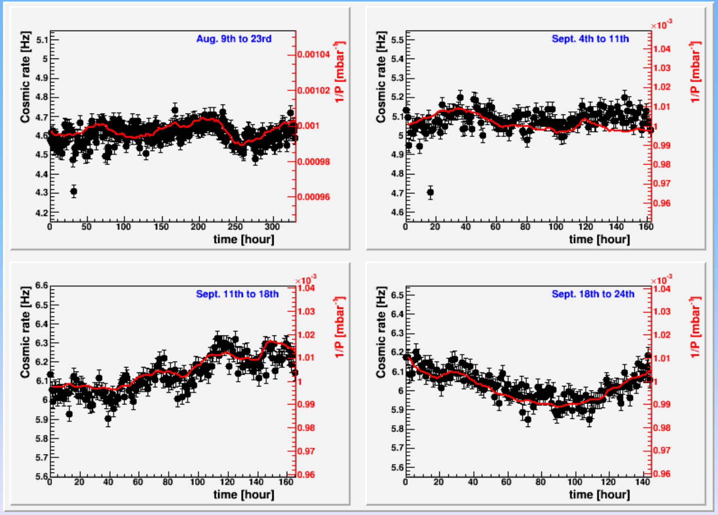
- *Typically 1 / min / cm²*
- *Mean energy 4 GeV*
- *Angular distribution close to cos²θ*

Muons rate variations

→ Several factors influence the muon rate

- *Latitude effect (more muons close to the poles)*
- *East-West effect (more muons in the West direction)*
- *Solar activity (less muons during high activity, 11 year cycle)*
- *High atmosphere temperature (more muons during summer)*
- *Atmospheric pressure (more muons if low pressure)*



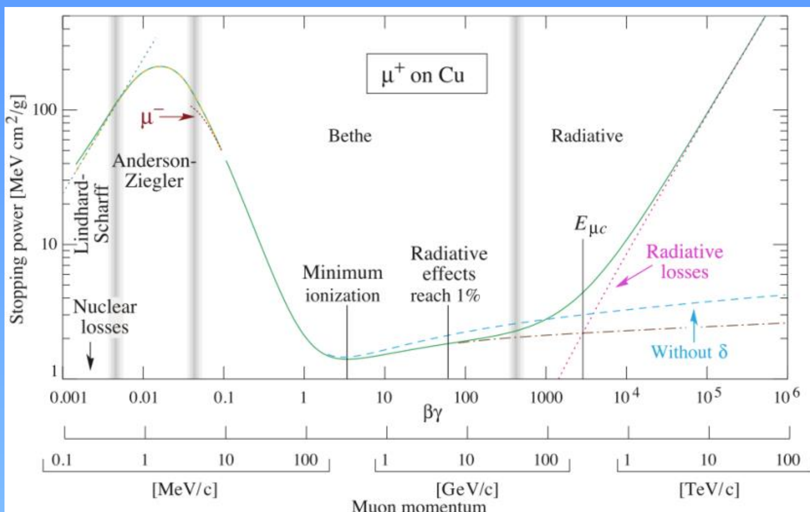


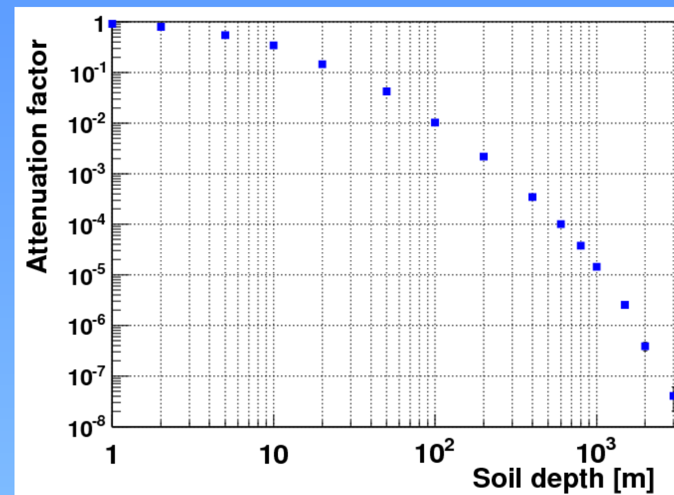
Muon interactions with matter

⟶ Electromagnetic interactions

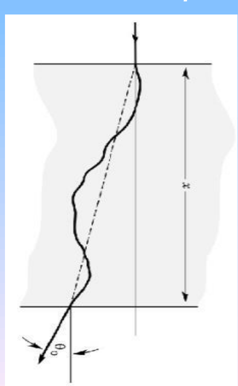
- *Energy loss*

$$-\frac{dE}{dX} = 4\pi N_0 r_e^2 m_e c^2 {Z_a}^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2} ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2}\right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C}{Z}\right]$$





- *Multiple scattering*

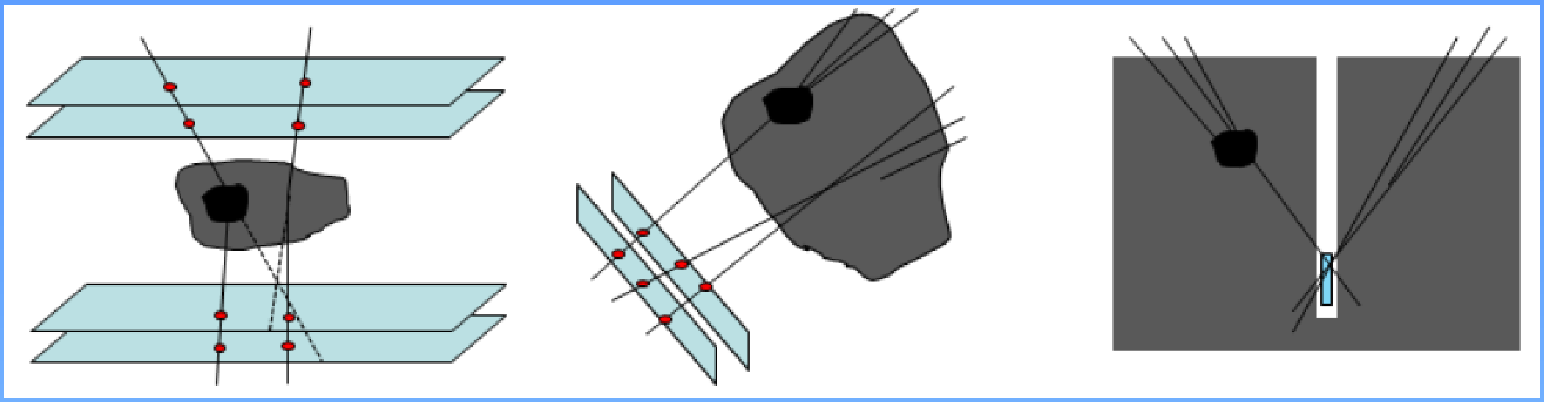


$$\sigma = \frac{13.6\,\mathrm{MeV}}{\beta pc}\sqrt{\frac{x}{X_0}}\left[1 + 0.038\,\log(x/X_0)\right] \approx \frac{13.6\,\mathrm{MeV}/c}{p}\sqrt{\frac{x}{X_0}}$$

$$X_0 = \frac{716.4\,(\mathrm{g/cm^2})}{\rho}\frac{A}{Z(Z+1)\,\log(287/\sqrt{Z})}$$

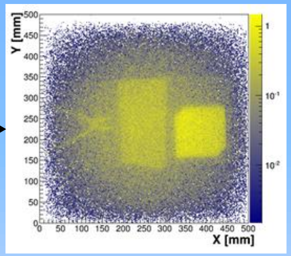
Material	Thickness	θ (deg)	$P_{absorption}$
Air	100 m	0.094	0.78%
Lead	10 cm	1.01	2.9%
Water	1 m	0.35	4.2%
Soil	100 m		99%

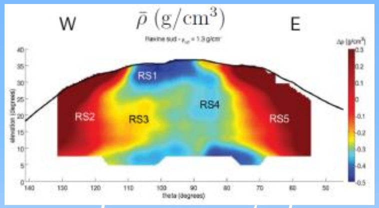
⟶ These effects can be used to probe/image matter



Deviation

Transmission (& Absorption)





Lesparre et al.

- *3D imaging (diffusion point)*
- *ρ and Z measurement (deviation angle)*
- *« Fast » (from minutes to days)*

- *2D imaging (muon flux)*
- *Opacity measurement*
- *Slow (from days to months)*

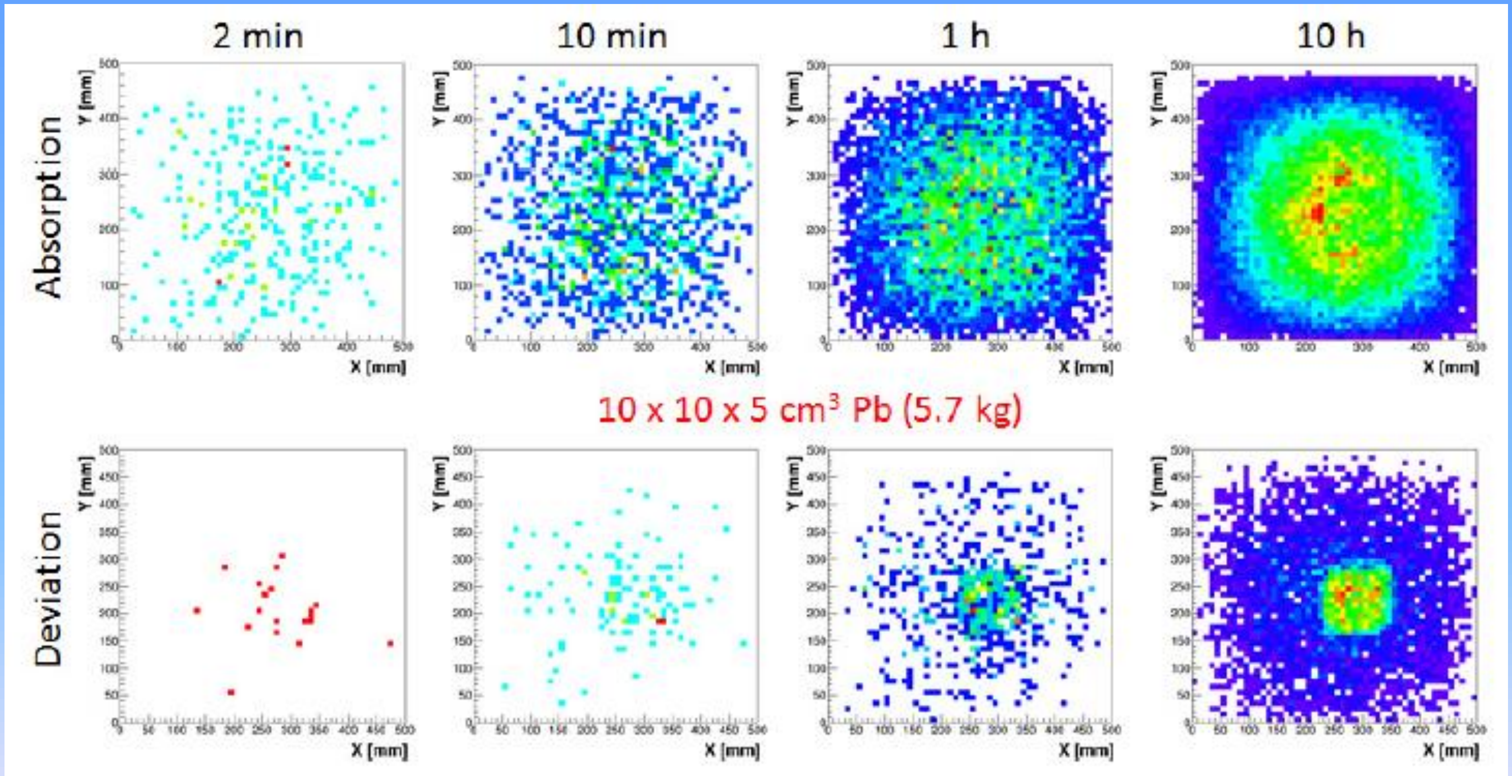
⟶ Many applications: volcanology, archeology, civil engineering, nuclear reactor monitoring

Muography

⟶ Deviation adapted to small objects / Transmission to large ones

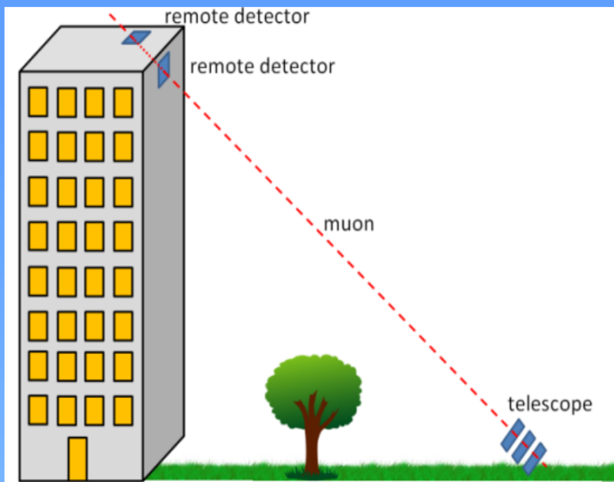
⟶ Deviation adapted to thin objects / Transmission to thick ones

- *Transition between the 2 methods around 0.5-2 m*
- *Absorption can be competitive in this region*

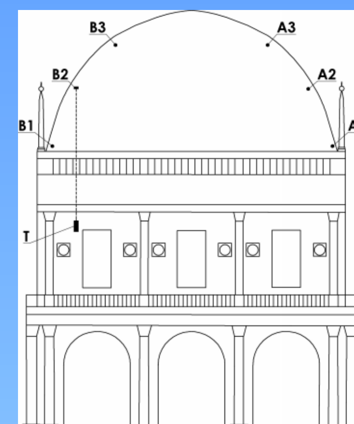


MUON METROLOGY

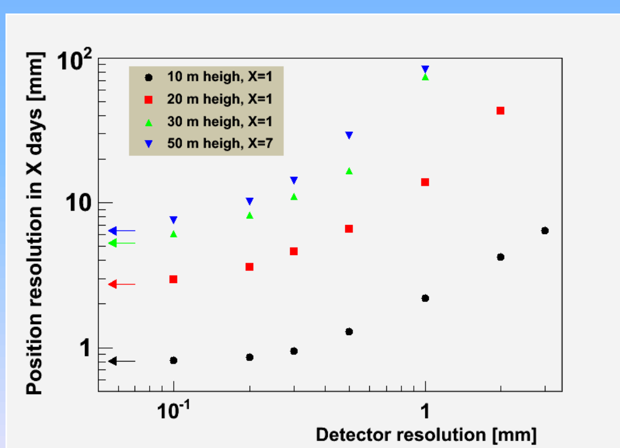
⟶ Muons travel <u>in average</u> along straight lines



- *Can act as a free, autonomous laser*
- *Works even in case of obstacles (roof, wall, tree, ground, etc.)*



Zenoni et al.



⟶ Requires extremely good spatial resolution

- *Practically infinite resolution for long term monitoring*

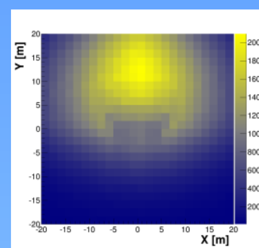
MUON IMAGING TECHNOLOGIES

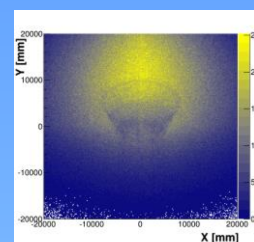
⟶ Muons are charged particles, means easy to detect…

⟶ … but muography usually imposes specific, contradictory requirements

- *Large area*

- *Angular resolution*





- *Large acceptance*

  e.g. large structures, underground

- *Robustness*

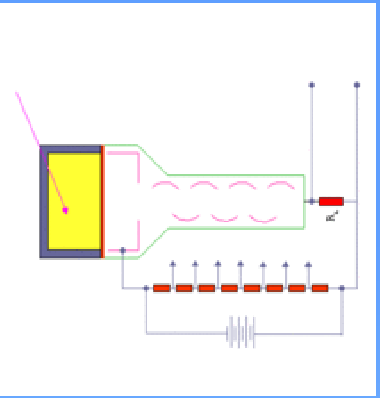
- *Autonomy*

- *Cost!*

⟶ historically 3 different technologies:

- **Scintillators**
- **Emulsions**
- **Gaseous detectors**

MUON IMAGING TECHNOLOGIES: SCINTILLATORS



⟶ perhaps the most robust detector in particle physics

⟶ Spatial resolution

- *Limited (~ 1 cm), determined by scintillator size*

⟶ Direct imaging

- *Online (electronics), dynamics possible*

⟶ Sensitivity to environmental conditions

- *~ none*

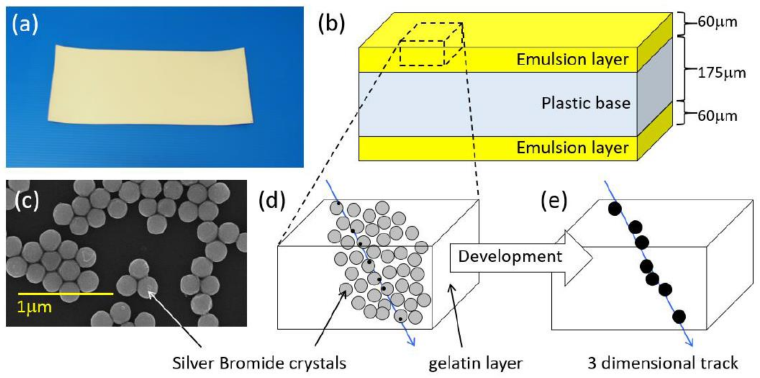
⟶ Electric consumption

- *Electric: low (a few (tens of) W)*

⟶ Most common use in muography

- *Volcanology*
- *Homeland security (!)*

Muon imaging technologies: emulsions



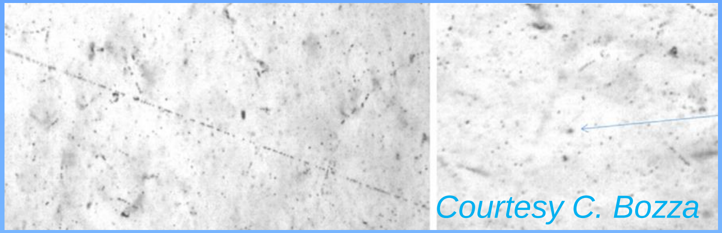
⟶ perhaps the most precise detector in particle physics

⟶ Spatial resolution

- *Outstanding (<1 micron)*

⟶ Direct imaging

- *Not possible (no dynamic)*

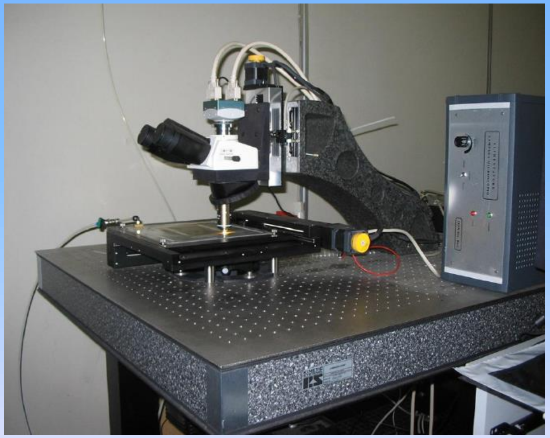


⟶ Sensitivity to environmental conditions

- *Emulsions degrade at high temperature (~>25℃)*

⟶ Electric consumption

- *None (passive system)*



⟶ Most common use in muography

- *Volcanology*
- *Archeology*

MUON IMAGING TECHNOLOGIES: GAS DETECTORS

⟶ perhaps the most versatile detector in particle physics

⟶ Spatial resolution

- *Good(~ 0.1 – 1 mm)*

⟶ Direct imaging

- *Online (electronics), dynamics possible*

⟶ Sensitivity to environmental conditions

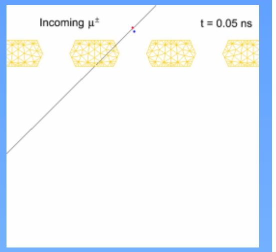
- *Gain variations with T and P*

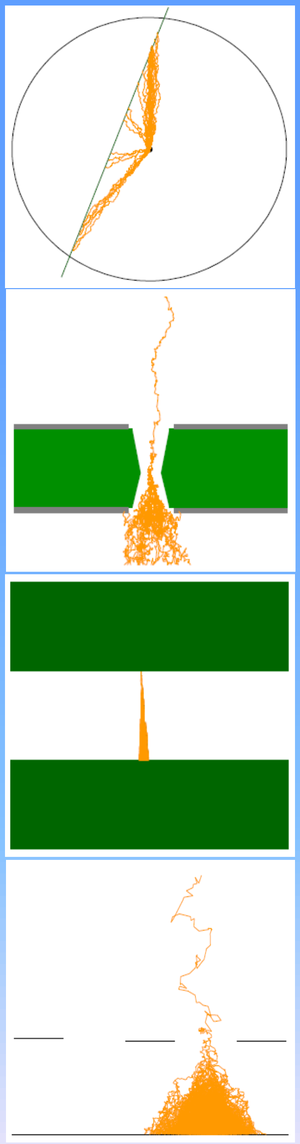
⟶ Consumption

- *Electric: low (a few tens of W) + gas*

⟶ Most common use in muography

- *Homeland security*
- *Volcanology*
- *Archeology*

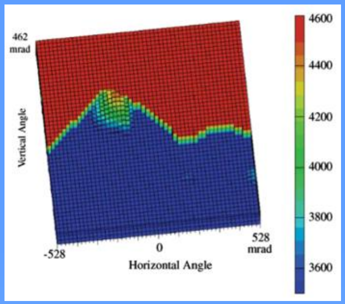


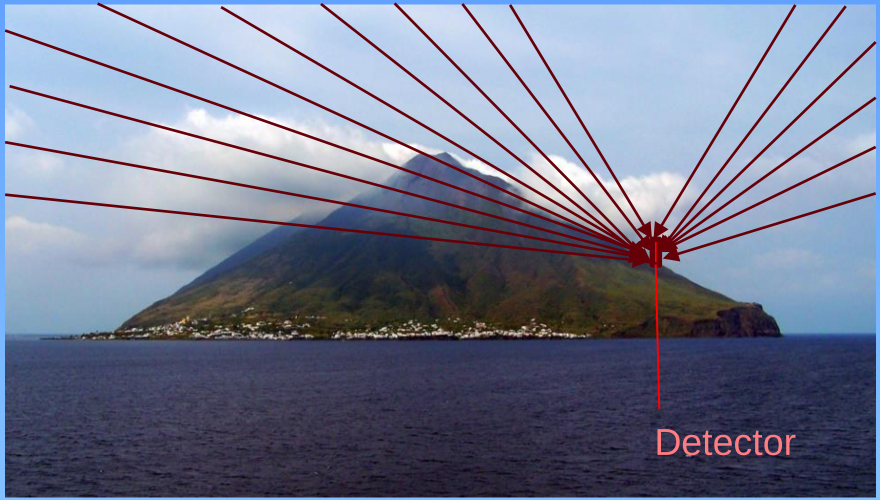


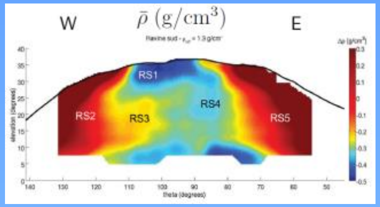
Selected applications: Volcanology

⟶ drove the muography renaissance at the end of the 1990s

- *First in Japan (Tanaka & Nagamine)*
- *Later in France (Diaphane, TomuVol), Italy (Mu-Ray), etc.*





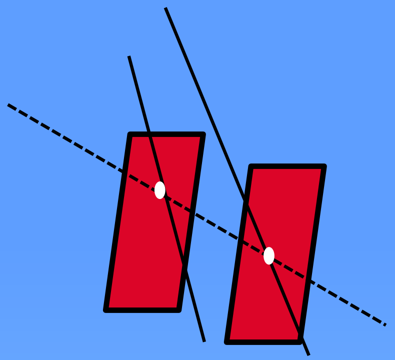


⟶ main goal: better understand the inner structure of volcanoes, and study their dynamics

- *Complementary to other techniques (resistivity, micro-gravimmetry)*
- *Harsh conditions*
- *Requires very long acquisitions*

SELECTED APPLICATIONS: VOLCANOLOGY

→ many difficulties were identified during the early years

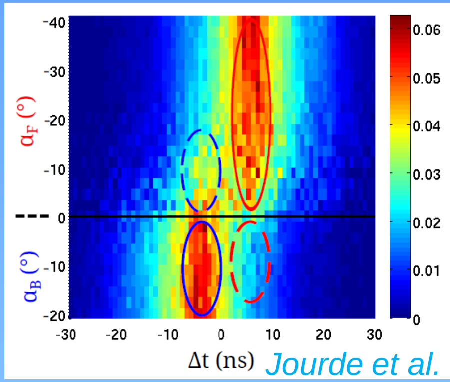


- *Accidental coincidence from 2 muons of a single shower*

  - **Requires at least 3 planes of detection**

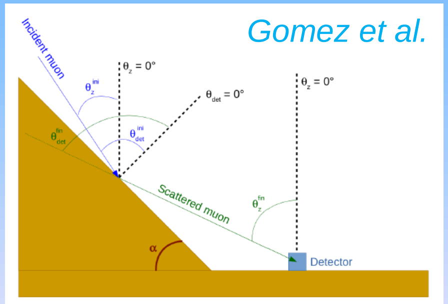
- *Upward muon flux in some configurations*

  - **Excellent timing required…**
  - **… or precise simulation**



- *Contamination from low energy particles and scattering on the surface*

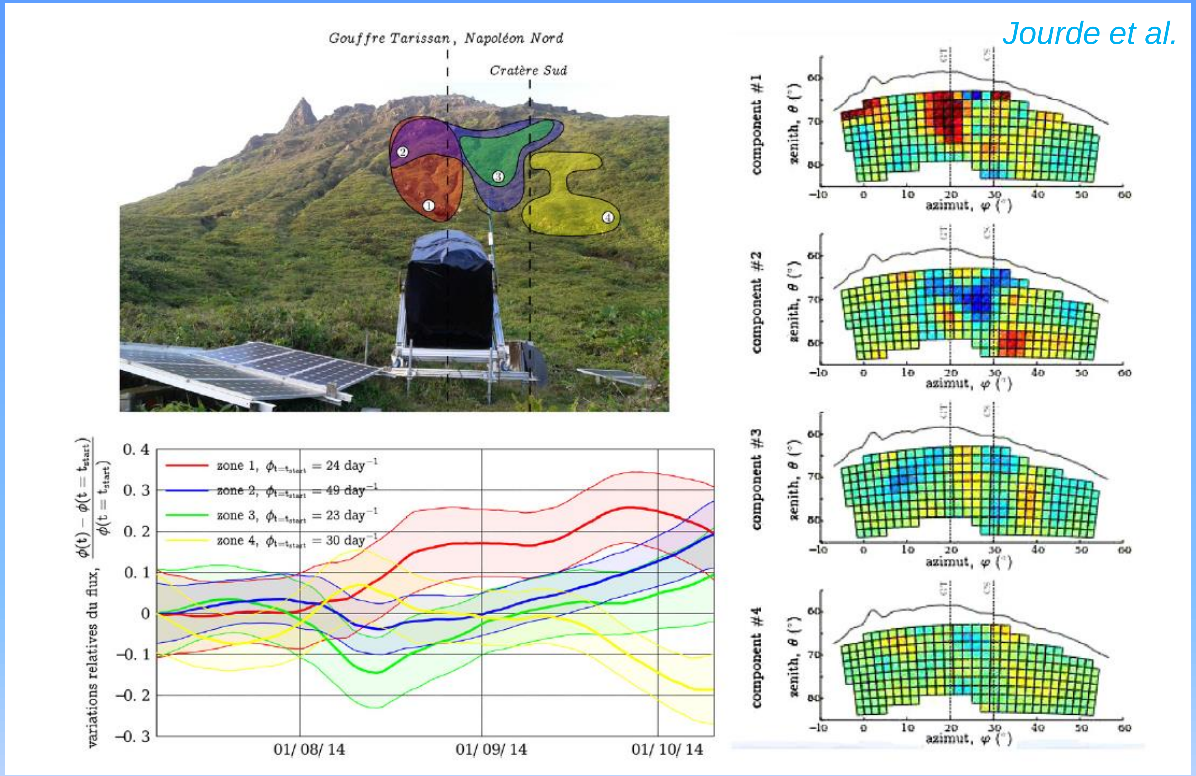
  - **Can be lowered with e.g. Lead layer…**
  - **… or estimated by simulation (very recent!)**



SELECTED APPLICATIONS: VOLCANOLOGY

⟶ Dynamics possible

- *Density variations measured, correlated with external activity (fumerolle)*



- *~ 10 volcanoes studied, some being continuously monitored*
- ***Graal: anticipate big activities of volcanoes***

SELECTED APPLICATIONS: ARCHEOLOGY

→ Pyramids

- *Historic experiment by Alvarez on Khafre pyramid (1967!)*
- *Experiment in Sun pyramid at Teotihuacan (2011-2013)*

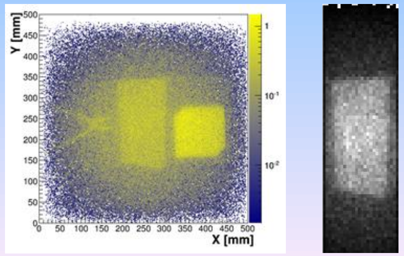
→ Tumuli and necropols

- *Complementarity with other measurements (resistivity)*
- *Main difficulty: close to the horizon, very few muons*

→ Cavern findings

- *Lascaux, Qumran, etc.*

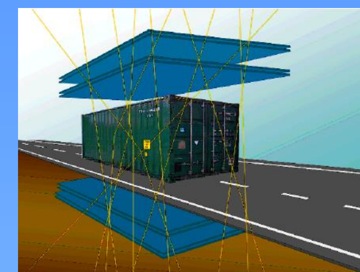
→ Preservation



Selected applications: Homeland security

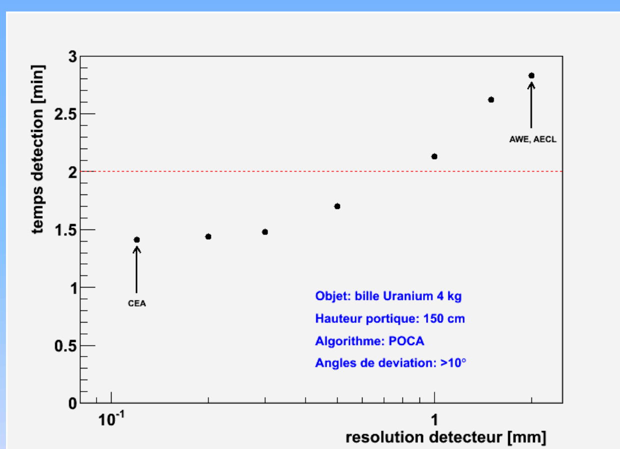
→ Detect contraband nuclear material (nuclear activity or « dirty » bombs)

- *Initiated by Los Alamos group in 2003*
- *Very first commercial muon portal in 2012 (Decision Science)*
- *… but no more scanners so far (industrialization issue)*

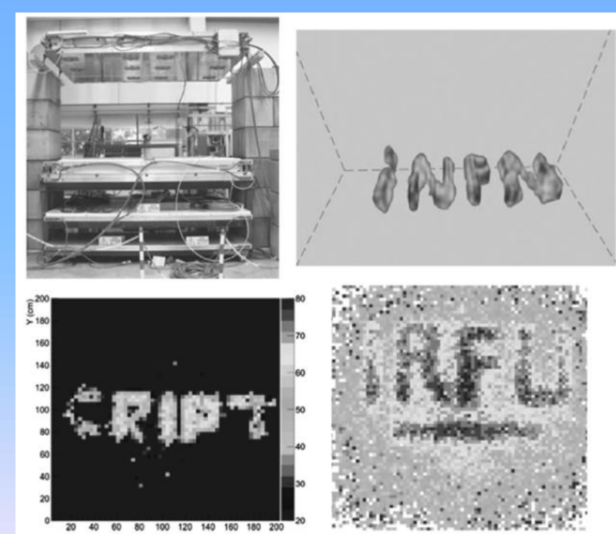


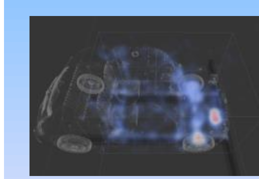
→ Spatial resolution & large area are curcial

- *DNDO criteria: 4 kg of U in <2 min!*



→ Many projects in the world





→ momentum measurements help!

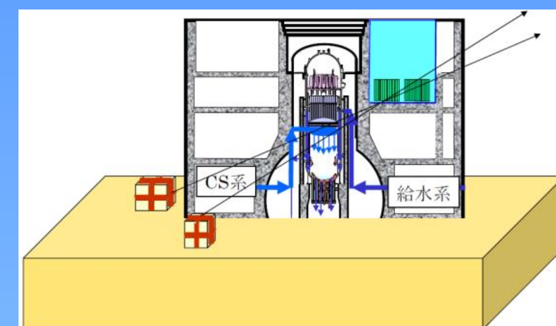
SELECTED APPLICATIONS: NUCLEAR REACTOR

⟶ Interest either after catastrophic event or prior to reactor dismantling

- *Probe areas inaccessible otherwise*
- *Want to check integrity of structures before dismantling (and check old plans!)*

⟶ Tests started with TEPCO company after Fukushima accident

- *So far only in transmission*
- *Limited communication…*



But this is only a simulation!

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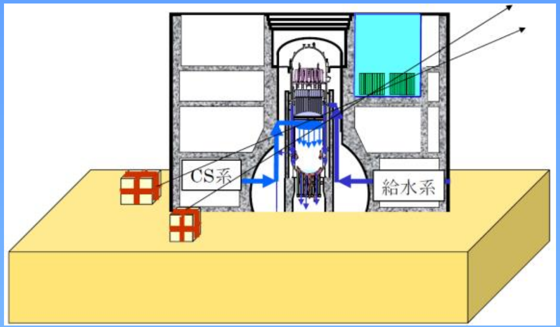
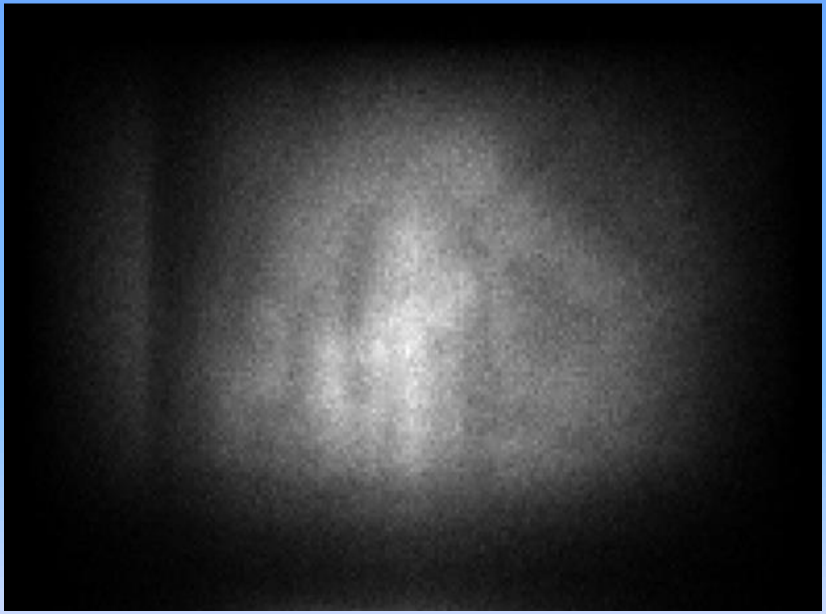




Real data

⟶ Suggests that nuclear fuel has leaked

⟶ Deviation measurements should start soon

Selected applications: Nuclear waste

⟶ Characterization of (old) storage containers with spent fuel

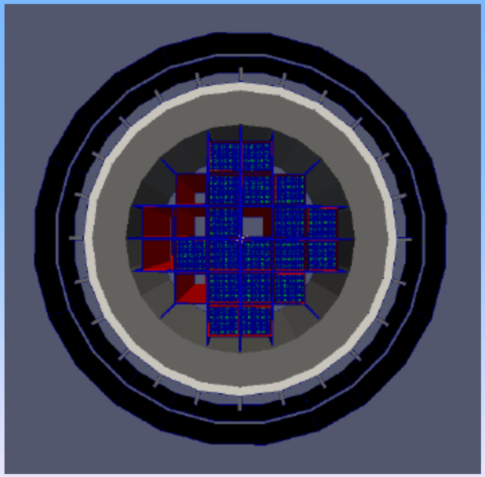
- *Not always precisely documented*
- *Heavily shielded (neutron or gamma probing difficult)*

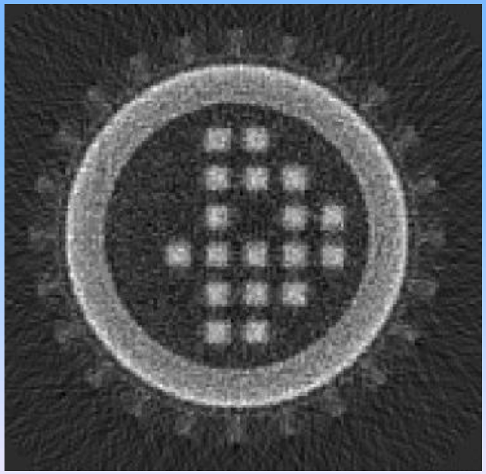
⟶ Typical configuration for deviation muography

⟶ Still prospective, essentially simulations so far

- *Data with just 2 planes, difficult localization of the compartments*

⟶ Can use medical imaging algorithms with surrounding detectors

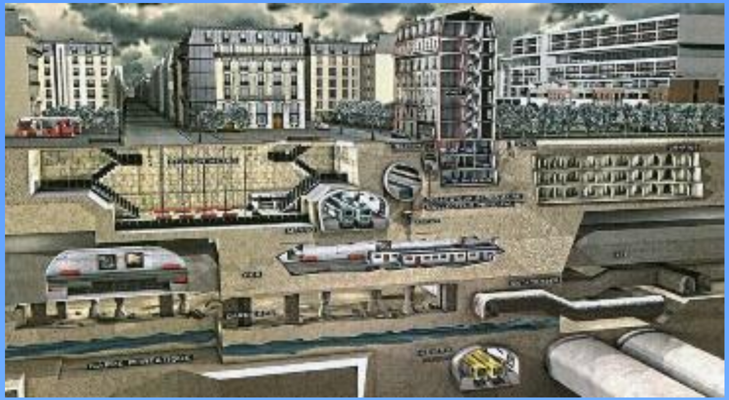




Perspectives (1/2)

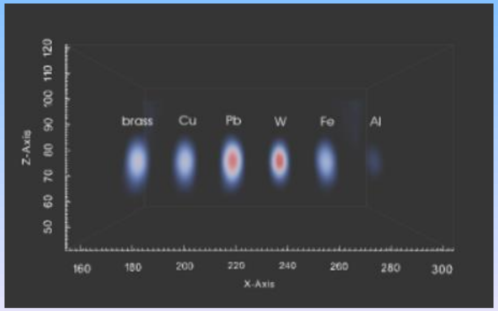
→ Many more fields of applications… known and unknown

- *Underground exploration (soil geology, mining, borehole)*

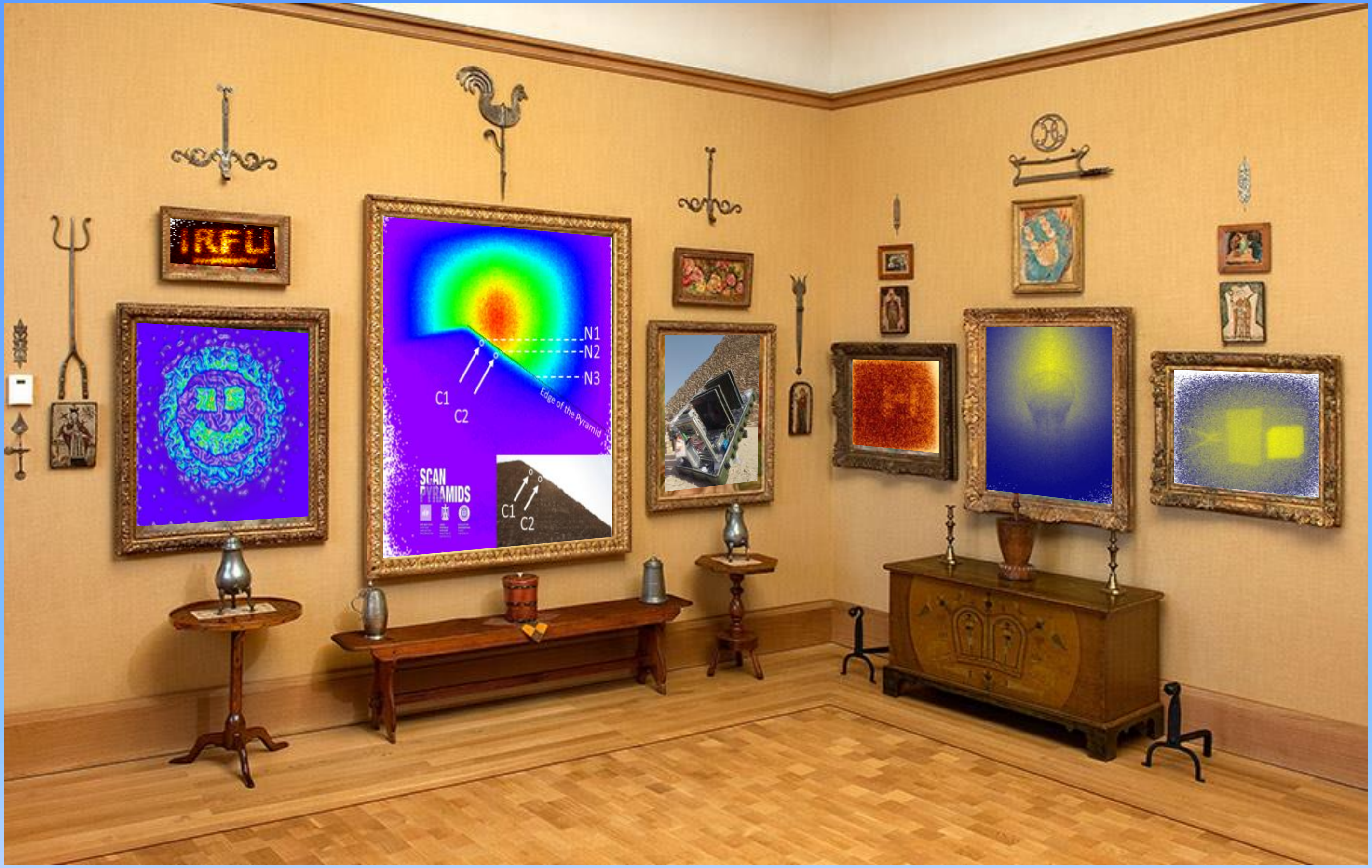


- *CO2/fuel geological storage & monitoring*

- *Civil engineering*



Perspectives (2/2)



ScanPyramids

International collaboration

→ coordinated by HIP Institute (M. Tayoubi) and Cairo Engineering Faculty (H. Helal)

→ Under the authority of Ministry of Egyptian Antiquities

Goal: scan 4 big pyramids of the IVth dynasty

→ Bent pyramid
→ Red pyramid
} *Dashour*

→ Khufu pyramid
→ Khafre pyramid
} *Giza*




THE SCANPYRAMIDS PROJECT

SCAN PYRAMIDS

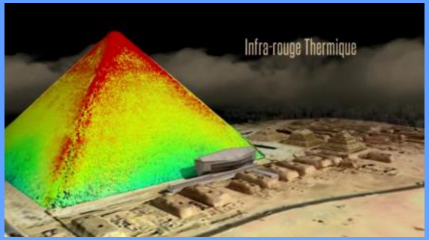
HIP.INSTITUTE HERITAGE INNOVATION PRESERVATION

ARAB REPUBLIC OF EGYPT MINISTRY OF ANTIQUITIES

FACULTY OF ENGINEERING CAIRO UNIVERSITY

Several innovating technologies:

⟶ thermography (weakly penetrating): Laval University

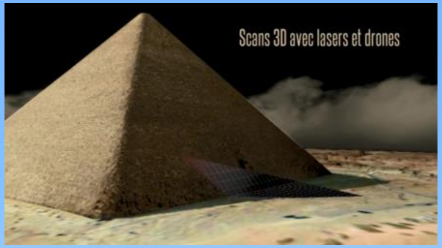


⟶ Muography (deeply penetrating): Nagoya University, KEK, CEA

Nagoya & KEK inside, ***CEA-Irfu outside***

⇒ **Extreme conditions!**

⟶ Drones (surface reconstitution): Cairo University



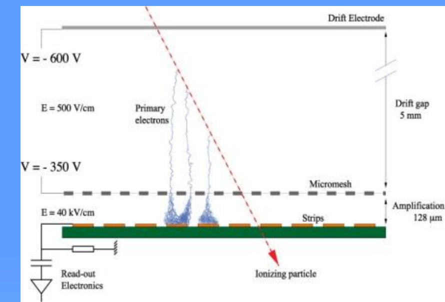
⟶ Photogrammetry & 3D models: Emissive

⟶ + real time simulation

IRFU TECHNOLOGY (1/2)

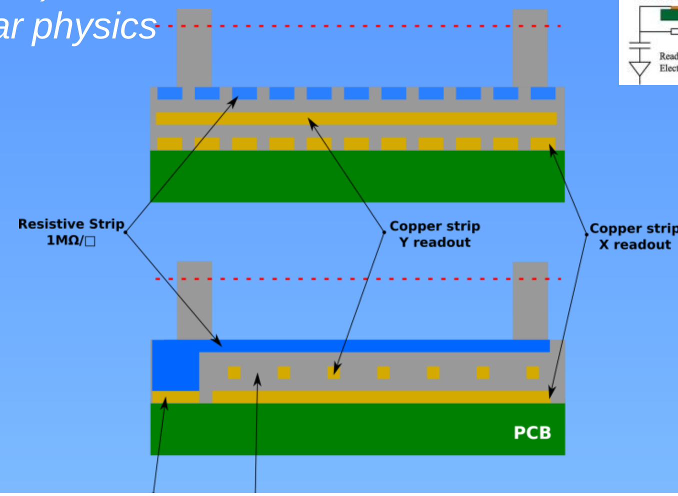
→ relies on Micromegas detector (1996)

- *Micro Pattern Gaseous Detector (MPGD)*
- *Good spatial resolution (~ 100 microns)*
- *Extensively used in particle & nuclear physics*



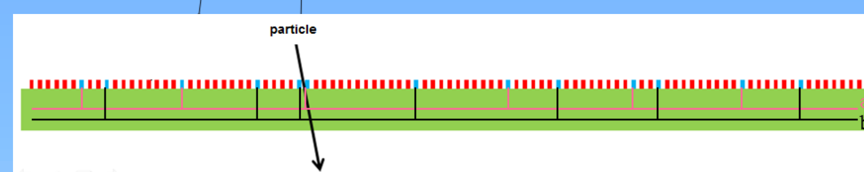
→ with resistive technology (2010)

- *Suppression of discharges*
- *Higher gain*
- *Better stability / robustness*



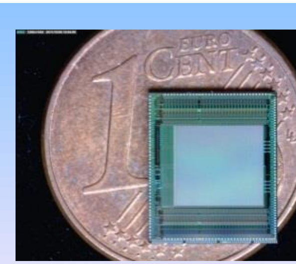
→ and genetic multiplexing (2012)

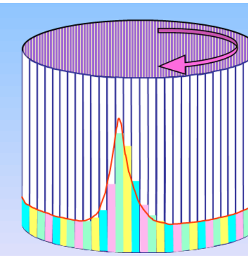
- *Use redundancy of signal*
- *Much less electronics channels*



→ and DREAM electronics (2013)

- *Deadtime less asic, continuous reading*
- *Adapted to large capacitance detectors*

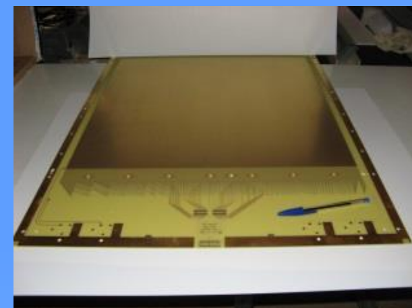


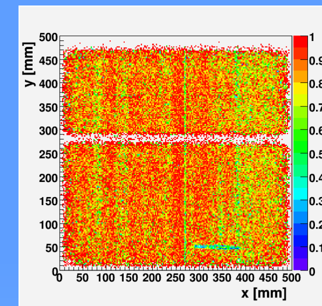


IRFU TECHNOLOGY (2/2)

→ 2013: 1st 1D multiplexed prototype

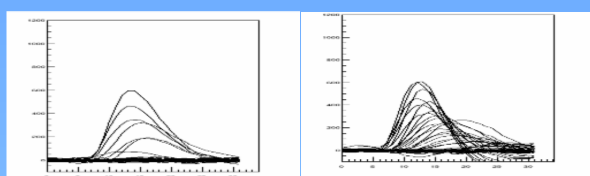
- *61 channels for 1024 strips*
- *~90% 1D efficiency*

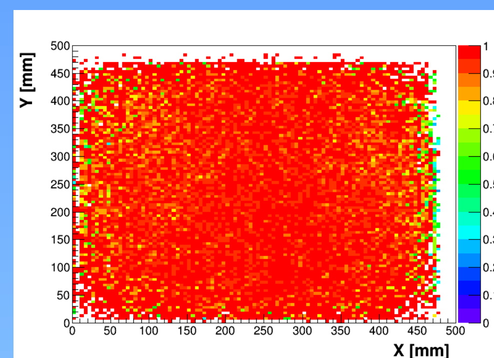


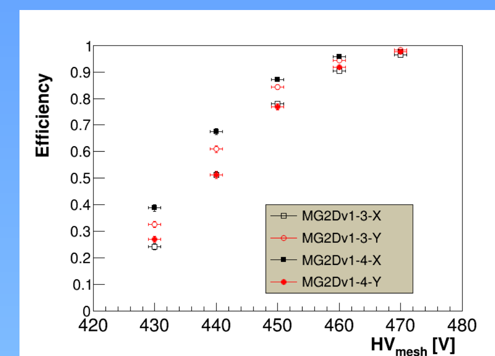


→ 2014: 2D resistive detectors (MG2D-v1)

- *~95% 2D efficiency*

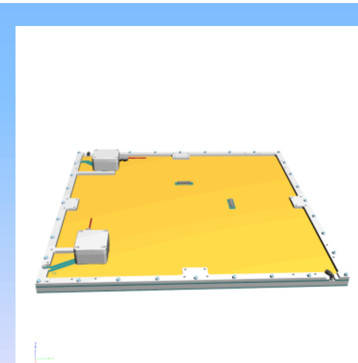


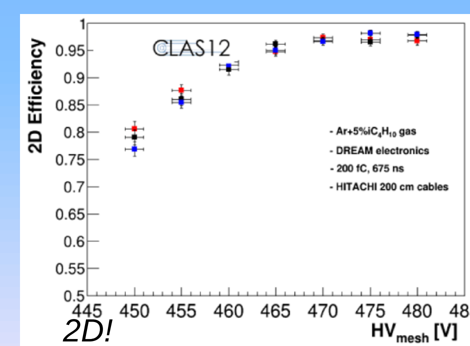




→ 2015: improved version (MG2D-v2)

- *Better shielding (N~2600 e-, S/N~60-100)*
- *61x17=1037 strips*
- *1.5 cm drift gap (μ-TPC)*
- *~97% 2D efficiency*
- *Extended plateau*



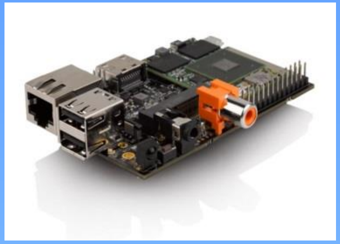


TOWARD MINIATURIZATION, SAFETY & AUTONOMY

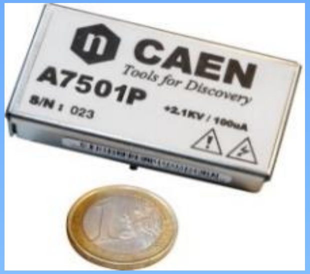
→ Front end electronics: 1 card (FEU) for 4 detectors

- *Self triggering option*
- *Connected to detectors via long, coaxial Hitachi cables (2m)*

→ Nano-PC: 1 Hummingboard



- *ARM technology (smartphone)*
- *Linux*
- *Acquisition software & monitoring*

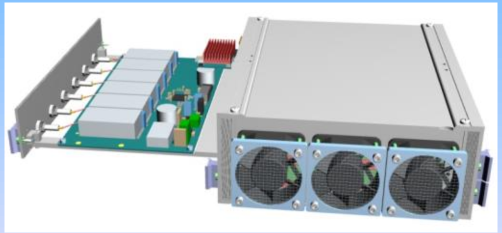


→ High voltage power supply

- *CAEN miniature modules (12V, <0.5 W)*
- *Implemented in a ad hoc card controlled by the nano-PC*

→ General power supply

- *35 W of overall consumption!*
- *220 V or solar panels with battery*



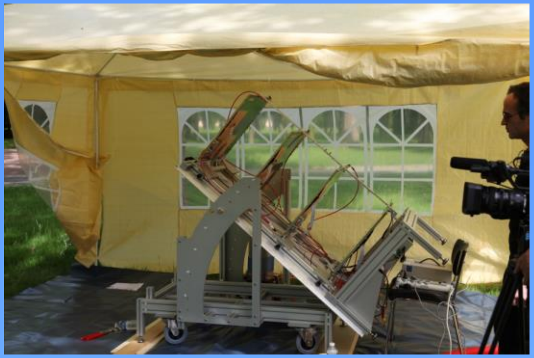
→ 3G connexion

→ non flamable gas

- *Ar-Iso-CF4 (95-2-3)*

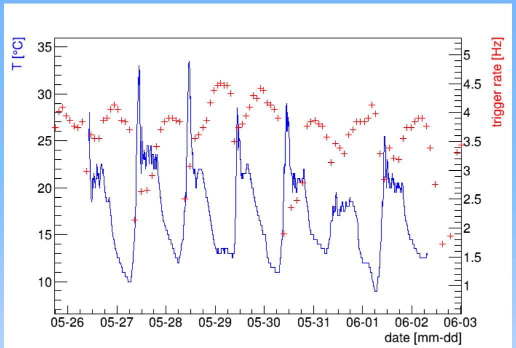
TEST OF THE FIRST TELESCOPE PROTOTYPE

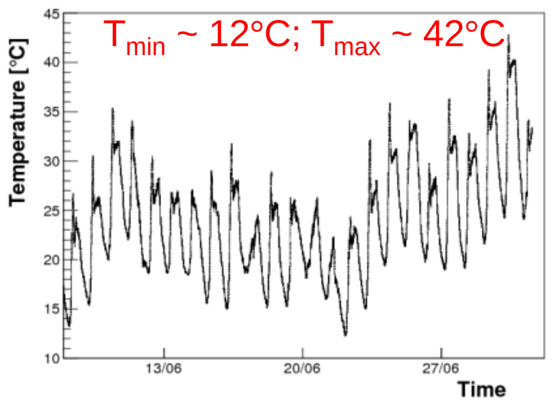
⟶ Test @ Saclay on water tower in 2015



⟶ Many lessons learnt…

- *Have to adjust the high voltage with T and P variations*
- *Issues with noise & grounding*
- *Solar panels require sun!!*



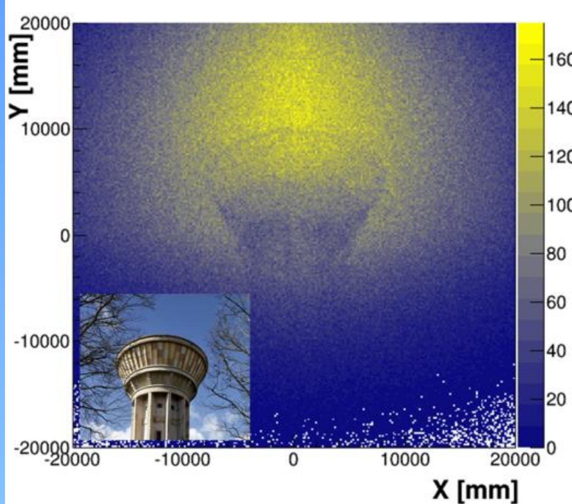


⟶ But it works!

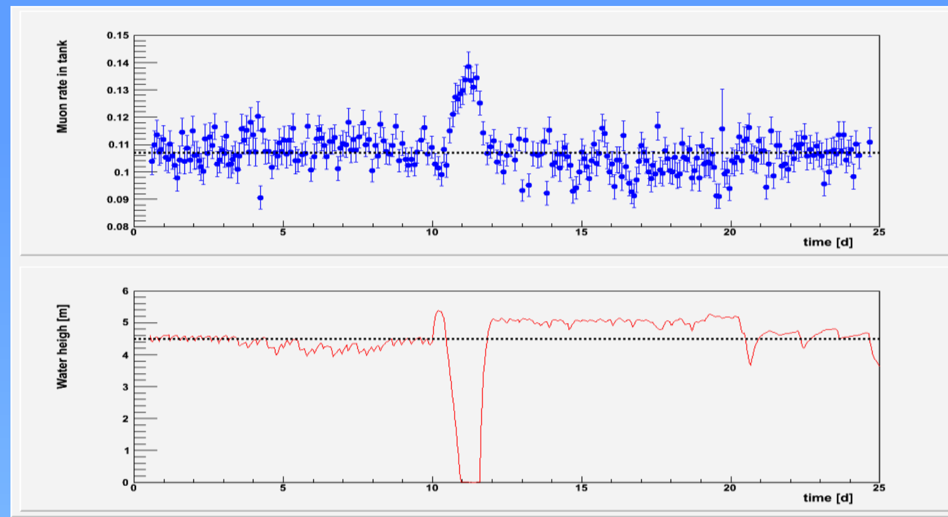
TEST OF THE FIRST TELESCOPE PROTOTYPE

→ Static imaging

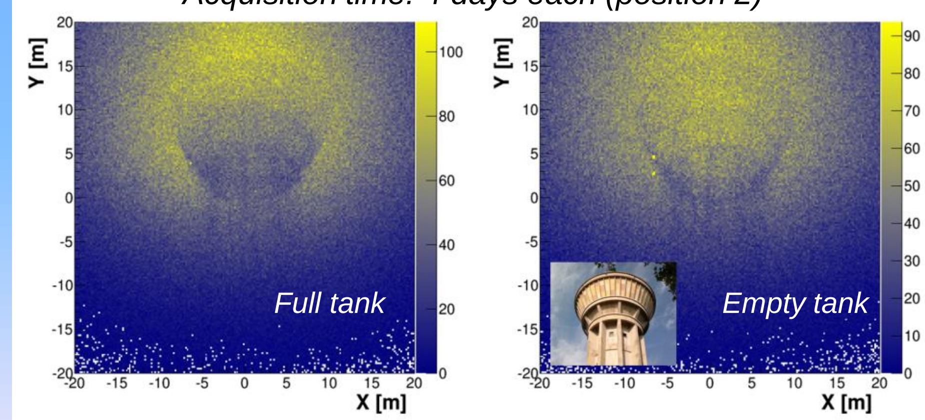
Acquisition time: 4 weeks (position 1)



→ Dynamic imaging

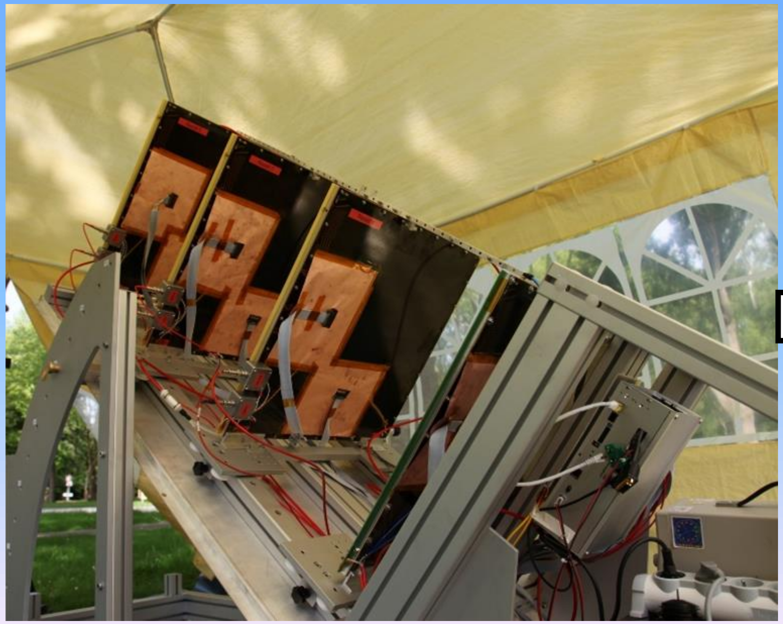


Acquisition time: 4 days each (position 2)



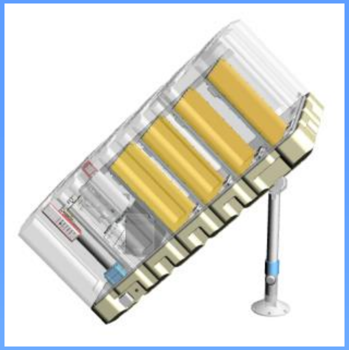
From Water tower to Khufu

- Telescopes : 1 → 3
- Chassis → fly-case
- Detectors: prototype (Cern) → serial (Industrial)
- Construction time: 9 months → 3 months
- Weight: ~ 200 kg → ~ 130 kg
- Data: raw → processed



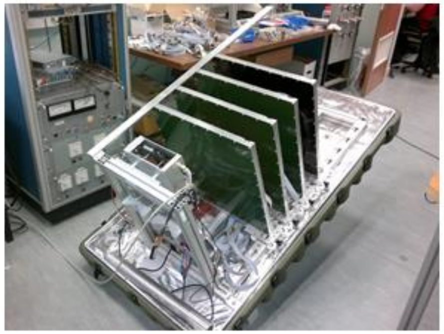
Preparation @ Saclay

→ Design, construction, integration, tests

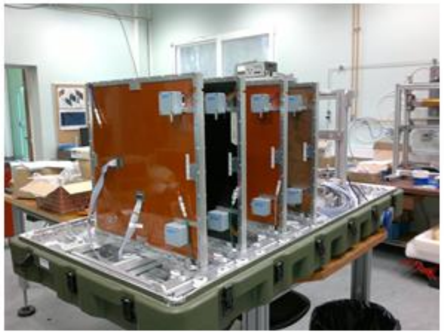


Alhazen (n°1)

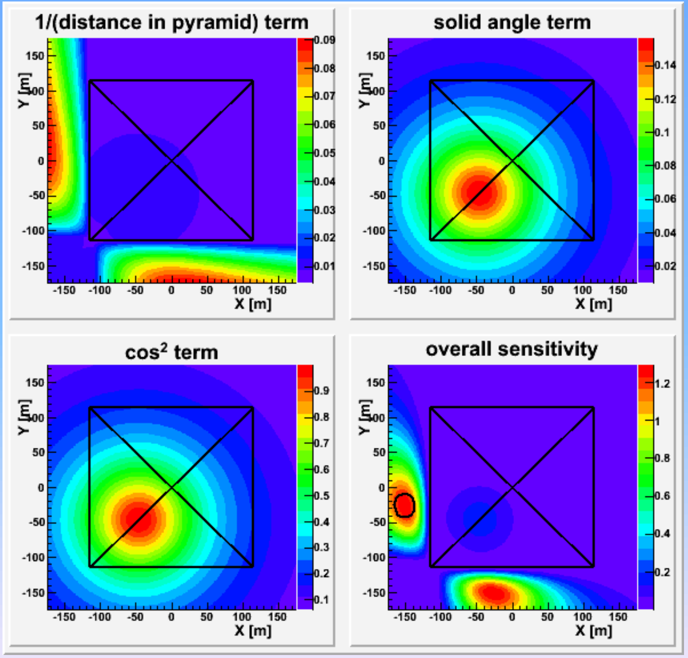
Alvarez (n°2)

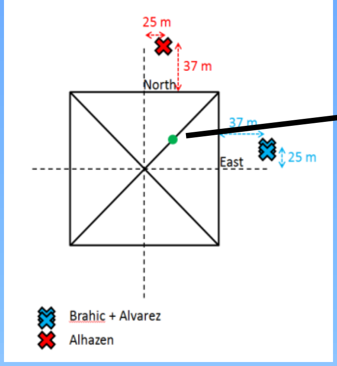


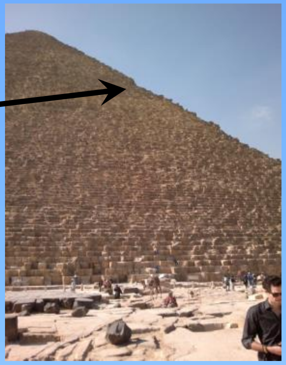
Brahic (n°3)



→ Simulation







Challenge: prove the performance of telescopes by detecting a 3m cavity in 20 m of limestone… at a distance of 150 m!

TELESCOPE TRANSPORTATION

Alhazen

Saclay, April 19th 2016

Khufu pyramid, May 19th 2016

Brahic & Alvarez

Saclay, May 19th 2016

University→Giza, May 30th 2016

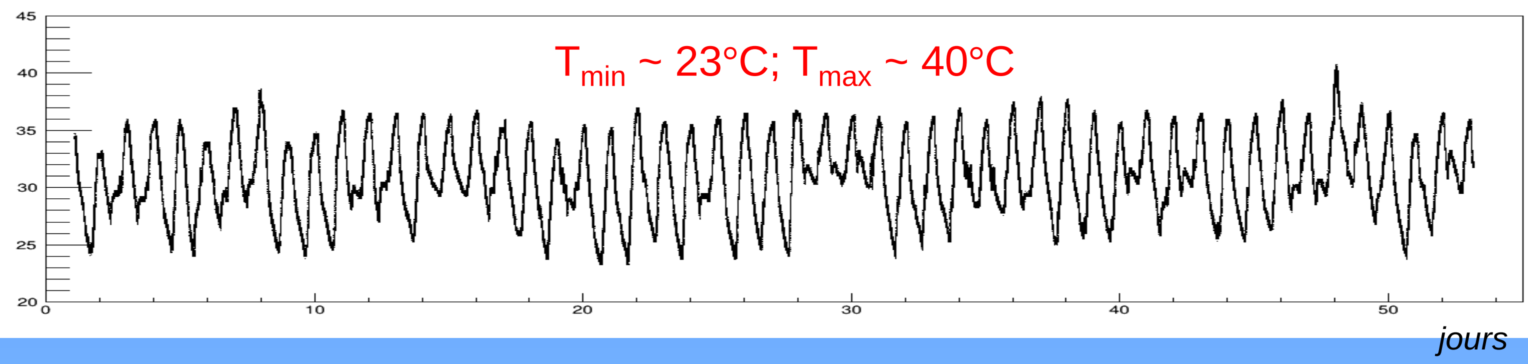
Cairo University, May 30th 2016

INSTALLATION @ GIZA

MEASUREMENTS

→ Each telescope ran for 2-3 months (depending on gas autonomy)

- *Temperature evolution*



→ Stable acquisition, thanks to local team (3G, gas, maintenance)

→ Excellent spatial resolution => ≤ 1 m accuracy at 150 m

→ Integrated statistics:

- *Alhazen (North): 30.8 million triggers (4.5 Hz)*
- *Brahic (East): 24.6 millions (4.2 Hz)*
- *Alvarez (East): 18.7 millions (3.3 Hz)*

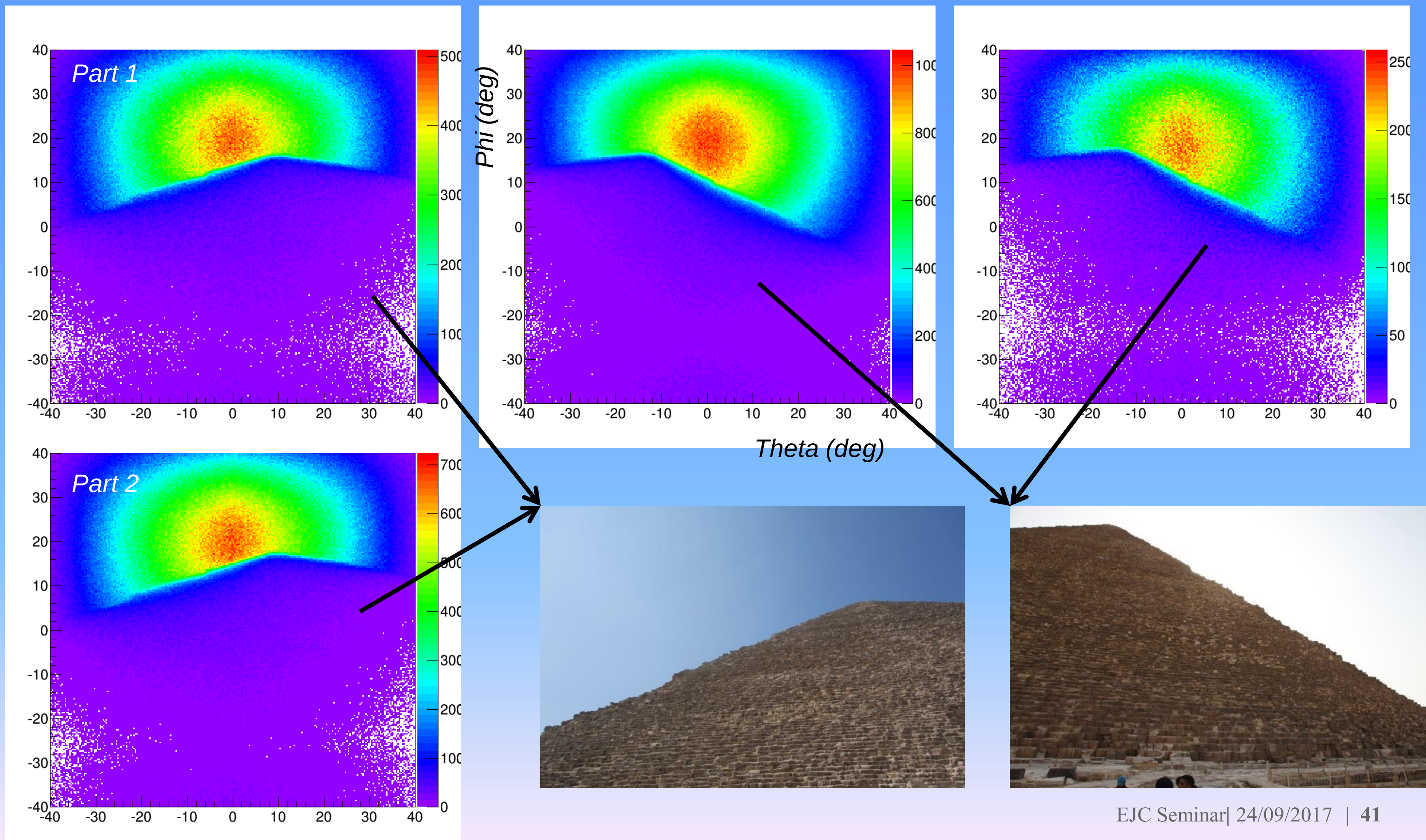
~70% are « good » muons

→ Issues with Alvarez telescope (degraded data because of a faulty detector)

Image reconstruction

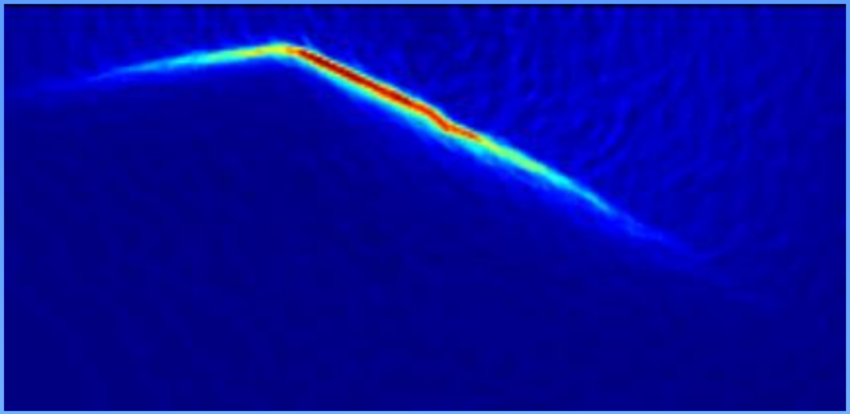
→ Muography obtained from angular parameters of each muon

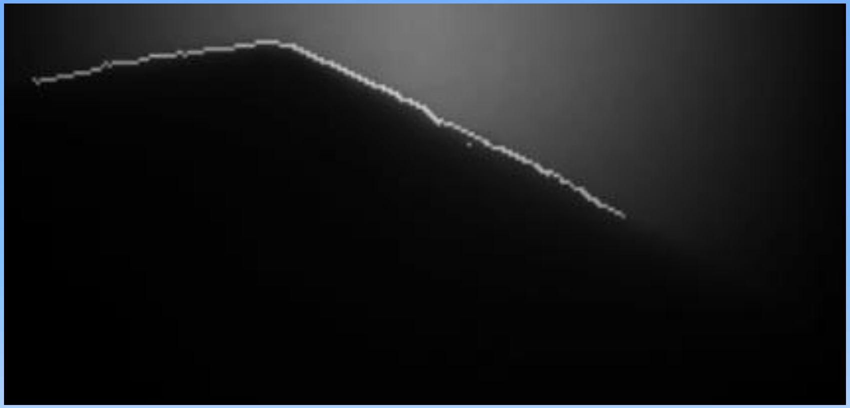
Alhazen *Brahic* *Alvarez (partial)*



ANALYSIS

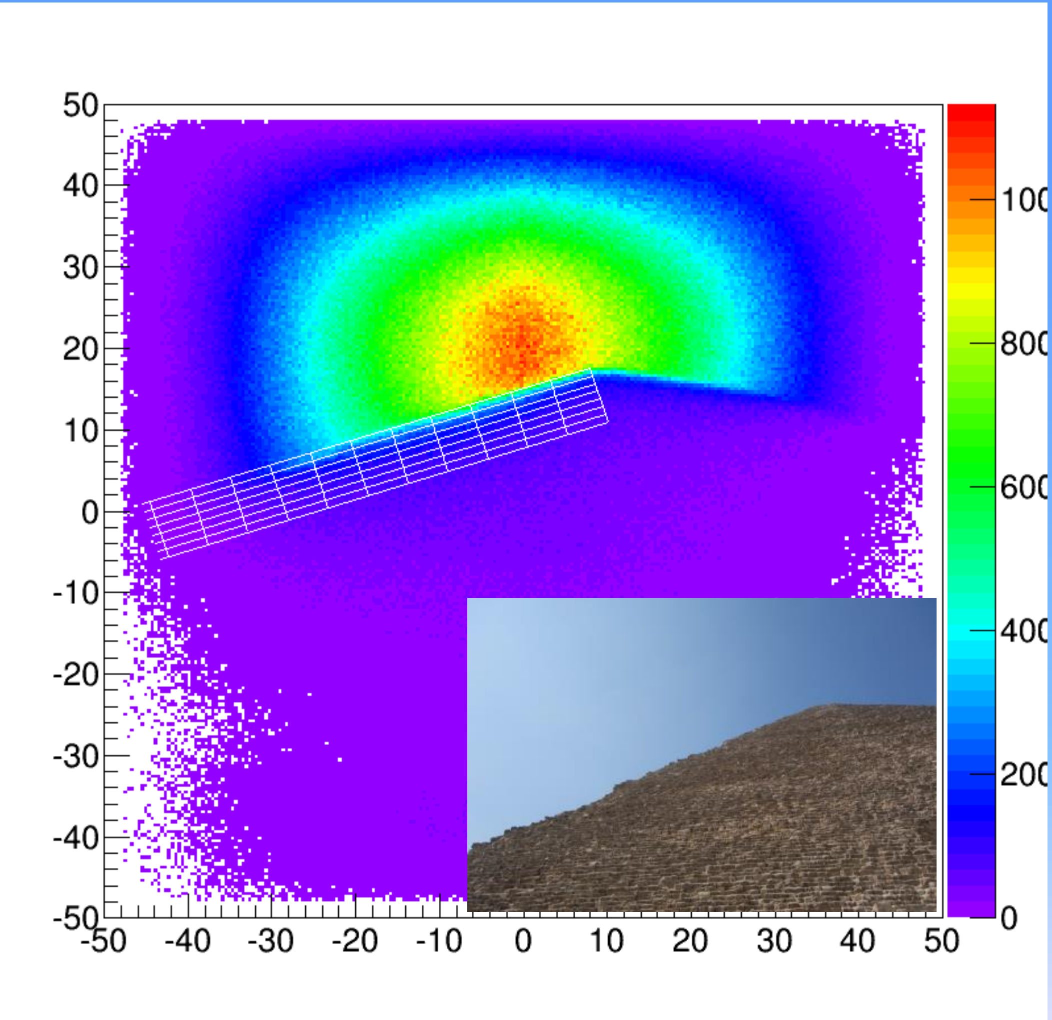
⟶ Option 1: try to look at local variation of opacities through gradient images





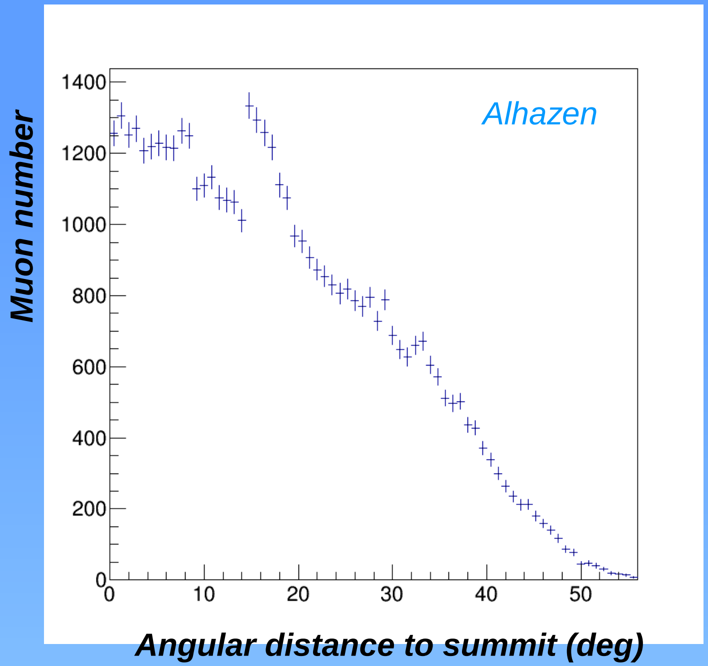
⟶ can reconstruct the pyramid profile, but not very sensitive technique

→ Option 2: look for muon excesses within slices parallel to the edge

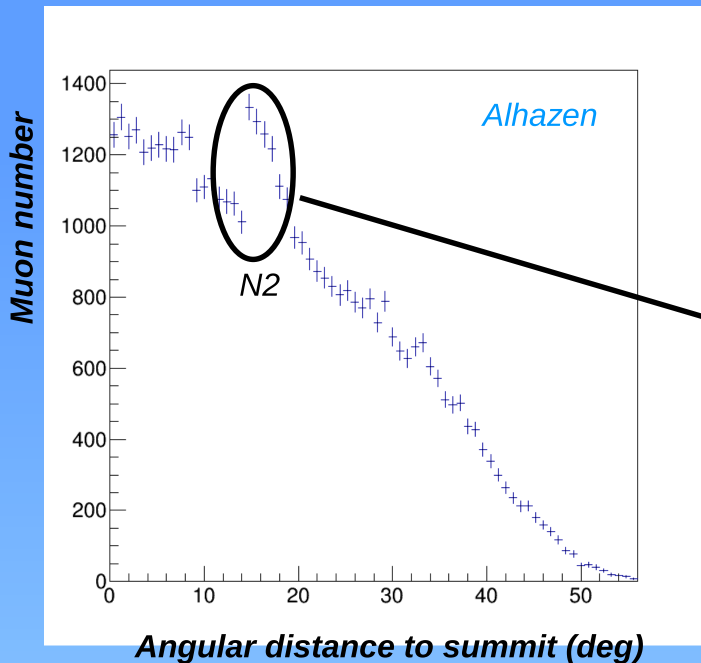


Analysis

→ First, superficial slices show various notches along the edge

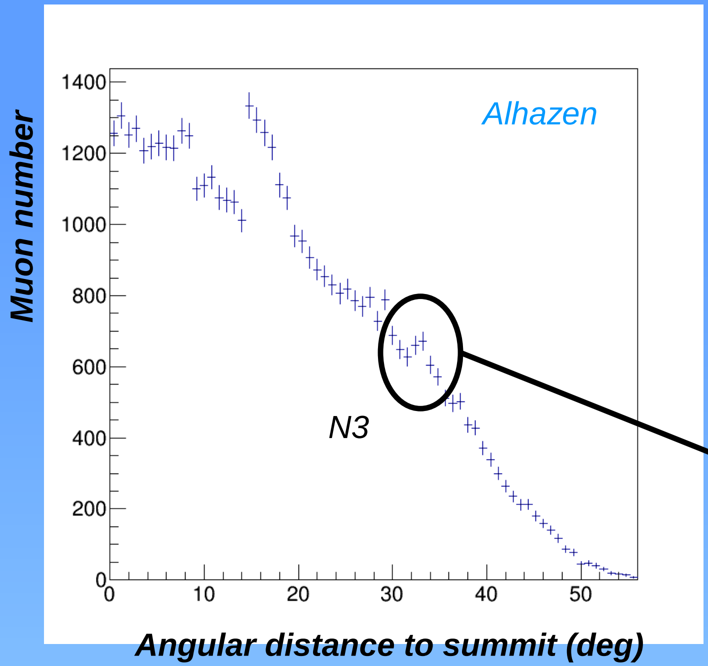


→ First, superficial slices show various notches along the edge



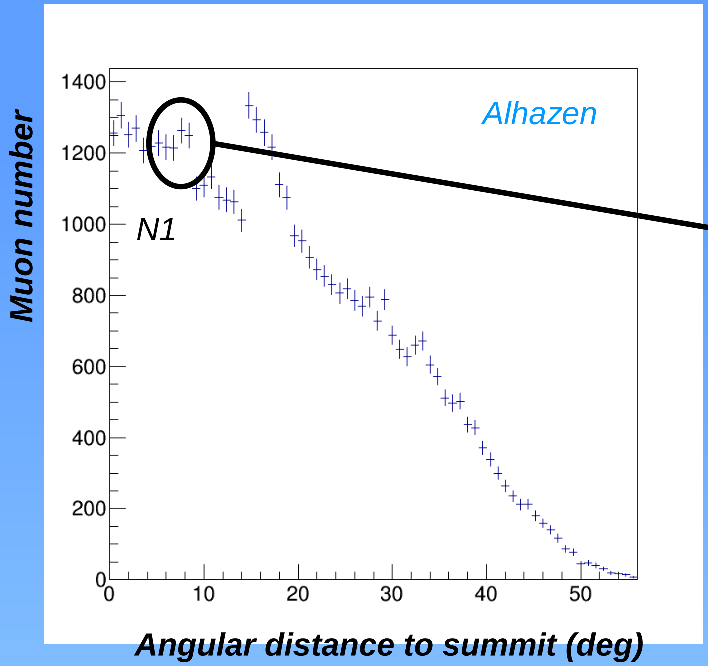
ANALYSIS

→ First, superficial slices show various notches along the edge



ANALYSIS

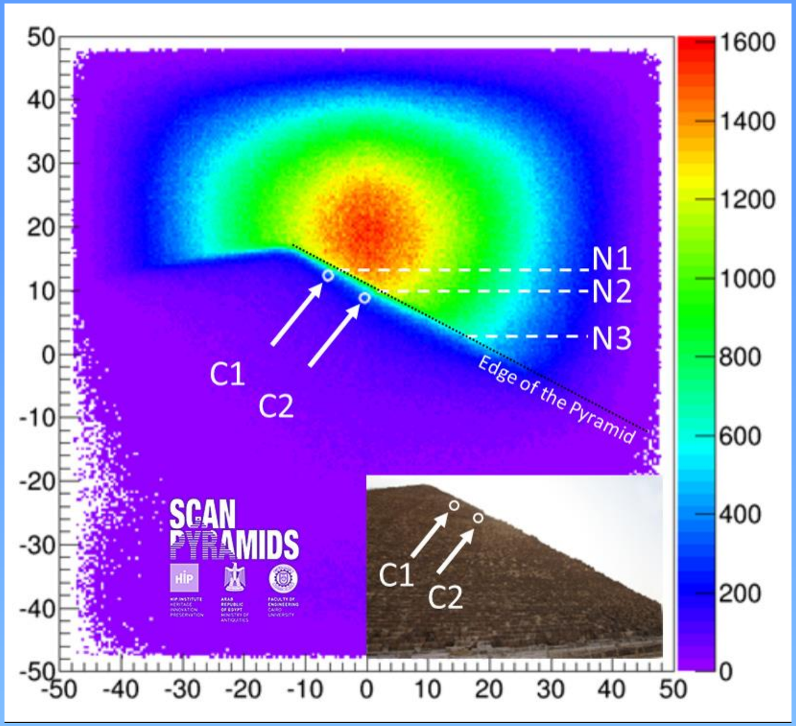
→ First, superficial slices show various notches along the edge



1st validation: N1 not visible from the ground (and not known from the team…)

→ Brahic & Alvarez see the same, 3 notch structure

RESULTS (RELEASED ON OCT. 15TH, 2016)



- *Validated performance on N1 and C2*
- *Discovery of C1*

⇒ *Next question: what was the purpose of these cavities?*

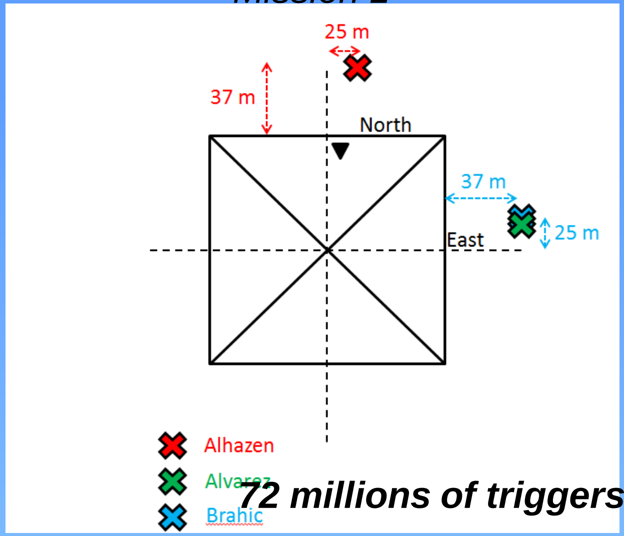
Probably linked to the construction of the pyramid

⟶ Discovery of another cavity by Nagoya University behind the North face chevrons

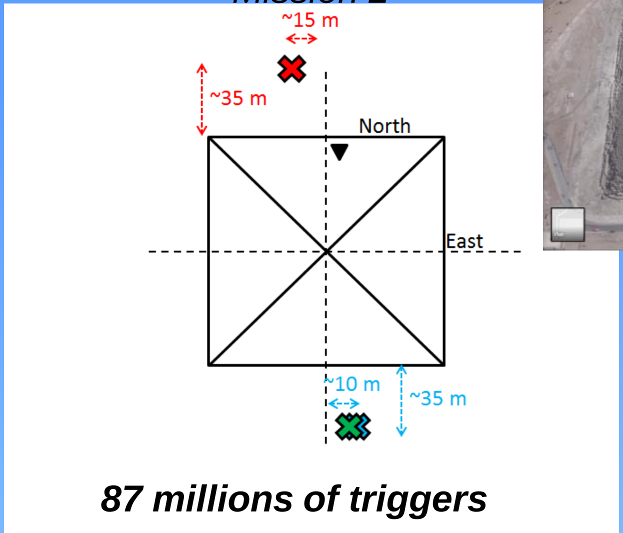
2ND MISSION (JAN-AVR 2017)

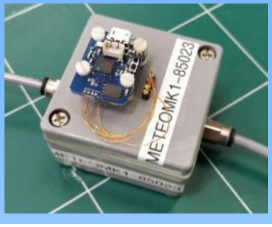
→ should be other cavities close to the other edges…?

Mission 1

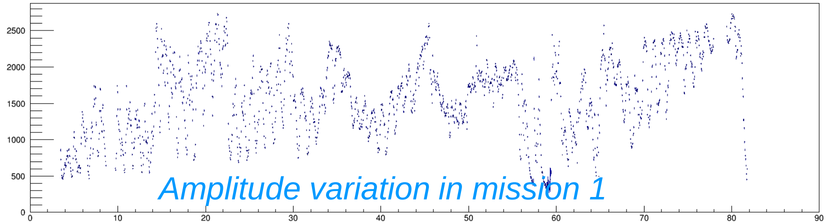


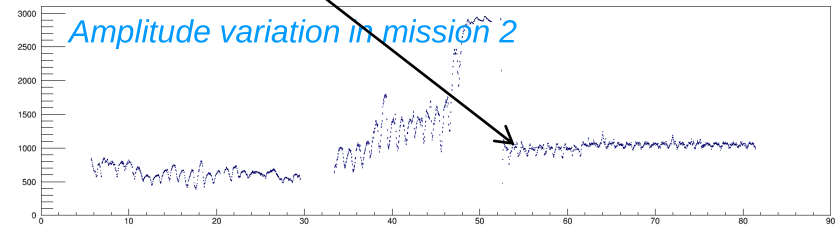
Mission 2





- Internal probes (T,P,H from Yoctopuce) in mission 2 for better HV feedback…
- …then direct feedback on the amplitude of the signal
- Better gas tightness





2^{ND} MISSION (JAN-AVR 2017)

⟶ automatic amplitude feedback integrated in the SlowControl

- Amplitude feedback
  - **Voltage dependence on signal amplitude itself**
  - $U(t+\Delta t) = U(t) - \alpha(S(t) - S_T)$
  - Use online tracking to filter computed amplitude

```
commands | u : update HV | r : reset HV | {t,p,a} : toggle {T,P,ampl} feedback | f : toggle FEU power
last update : 2017-05-11 15:12:26
Temperature feedback disabled | Pressure feedback disabled | Amplitude feedback enabled
HB T : +34.469°C | Time until next feedback : 37s
board monitoring :
    T : +32.133°C | 3.3V : +3.308V | 5V : +4.789V | 12V : +11.878V
environmental sensors :
    METEOMK1-7B9F9 (id : 0) :
        T : +34.660°C | P : 1009.480hPa | H : 10.300g/m3
    METEOMK1-7BB8A (id : 1) :
        T : +34.800°C | P : 1008.640hPa | H : 10.230g/m3
Drift :
    V   : -491.353V (set : -497.710V ; max : -800.000V)
    I   : 0.623µA (max : 3.487µA)
    OVC : 0 | sensor : 0
    ampl : 0.000ADC (at : 1970-01-01 01:00:00 ; target : 0.000)
Rstrip1 :
    V   : +489.300V (set : +495.140V ; max : +600.000V)
    I   : 2.055µA (max : 3.985µA)
    OVC : 0 | sensor : 0
    ampl : 1151.580ADC (at : 2017-05-11 15:10:12 ; target : 1000.000)
Rstrip2 :
    V   : +487.246V (set : +493.083V ; max : +600.000V)
    I   : 1.308µA (max : 3.985µA)
    OVC : 0 | sensor : 0
    ampl : 952.986ADC (at : 2017-05-11 15:10:12 ; target : 1000.000)
Rstrip3 :
    V   : +491.867V (set : +497.196V ; max : +600.000V)
    I   : 5.106µA (max : 14.976µA)
    OVC : 0 | sensor : 1
    ampl : 977.175ADC (at : 2017-05-11 15:10:12 ; target : 1000.000)
Rstrip4 :
    V   : +496.488V (set : +502.852V ; max : +600.000V)
    I   : 0.560µA (max : 3.985µA)
    OVC : 0 | sensor : 1
    ampl : 1160.120ADC (at : 2017-05-11 15:10:12 ; target : 1000.000)

FEU current state :
    power           : on    over temperature : false (0/10)
```

⟶ relatively smooth data taking, but Spring not better than Summer…

PERSPECTIVES

SCAN PYRAMIDS

HIP.INSTITUTE HERITAGE INNOVATION PRESERVATION

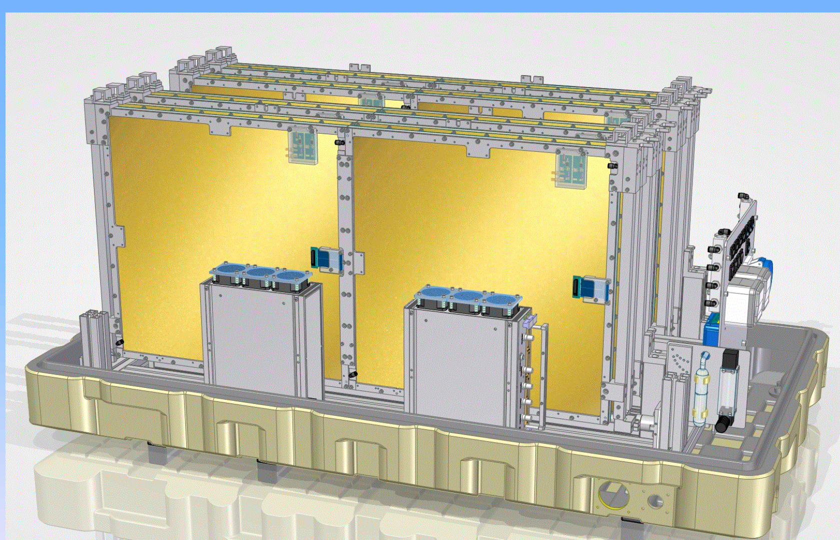
ARAB REPUBLIC OF EGYPT MINISTRY OF ANTIQUITIES

FACULTY OF ENGINEERING CAIRO UNIVERSITY

→ Investigate 2 major upgrades for potential future missions

- *Sealed or semi-sealed detectors (no gas consumption)*

- *Larger telescopes (0.25 -> 1m²)*



Workshops

→ TomoMu setup

- *Can work both in deviation, transmission & absorption*

→ Will see how to operate it

- *Settings of HV, self-trigger parameters (multiplicity, thresholds)*
- *Effects of environmental conditions, feedback*
- *Signal characteristics (amplitude, TOT, timing, etc), clustering*
- *Track reconstruction*
- *Imaging in various modes*

→ You are encouraged to propose experiments!