DE LA RECHERCHE À L'INDUSTRIE

High-definition muography

or how fundamental physics can help to see through a pyramid

S. Procureur, D. Attié, S. Bouteille, D. Calvet, H. Gomez,
P. Magnier, I. Mandjavidze, M. Riallot

PSI, 4th October 2018

SCAN PYRAMIDS

HIP INSTITUTE HERITAGE INNOVATION PRESERVATION

ARAB REPUBLIC OF EGYPT MINISTRY OF ANTIQUITIES

FACULTY OF ENGINEERING CAIRO UNIVERSITY

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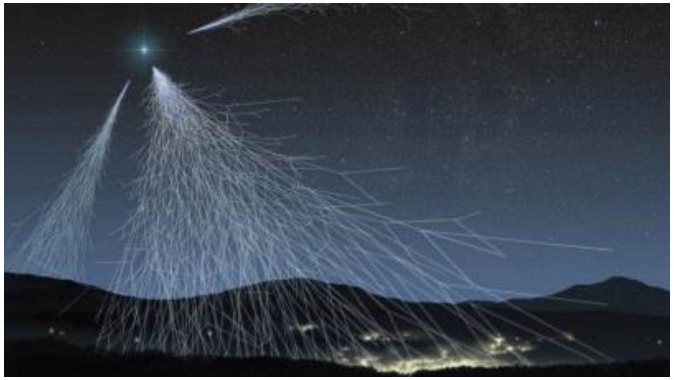
SUMMARY

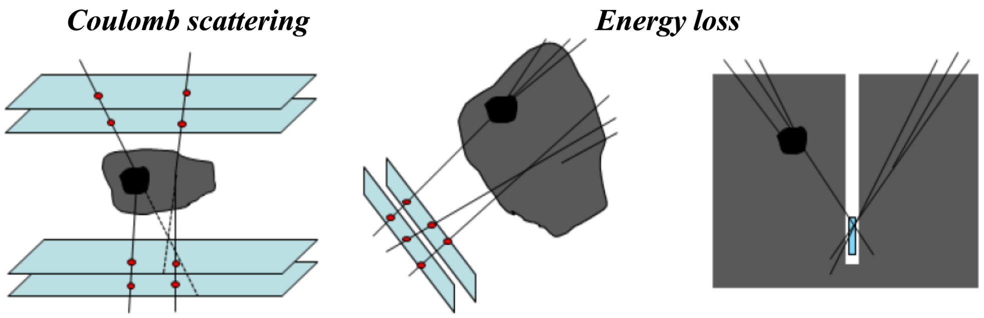
- Muography: principles & main technologies
- The WatTo experiment @ Saclay
- ScanPyramids: preparation and discoveries
- Perspectives

Muon Tomography / Muography

- Cosmic muons produced by cascade of reactions induced by cosmic rays in the upper atmosphere
  - Flux: ~150/m²/s ~ $\cos^2\theta$ (maximum in zenith direction)
  - Mean energy: 4 GeV
  - Life-time: 2 μs
  - Natural, free and harmless radiation
  - Straight propagation (in average)



- Electromagnetic interactions with matter

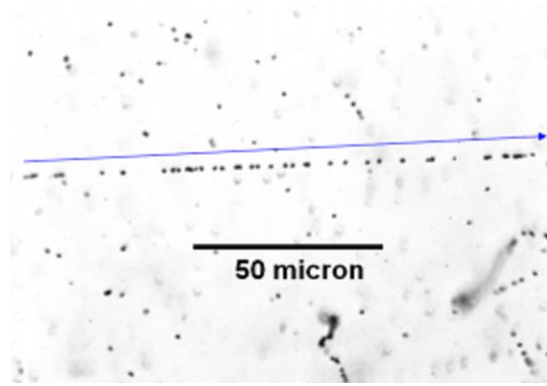


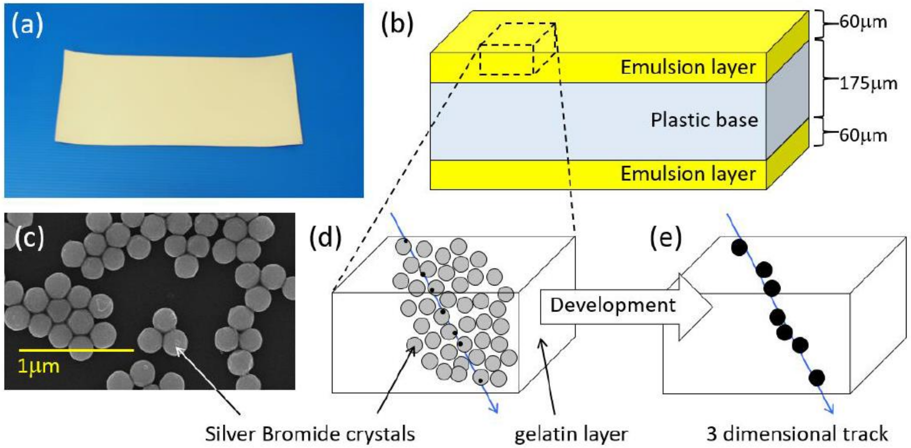
Deviation (3D) *Absorption/Transmission (2D)*

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

- Many potential applications

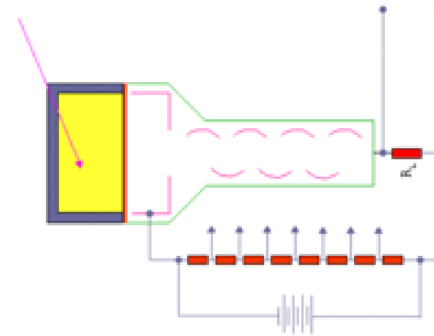
- Photographic plate to record tracks from charged particles
  - Excellent resolution
  - No need for power supply
  - Fragile
  - No real time

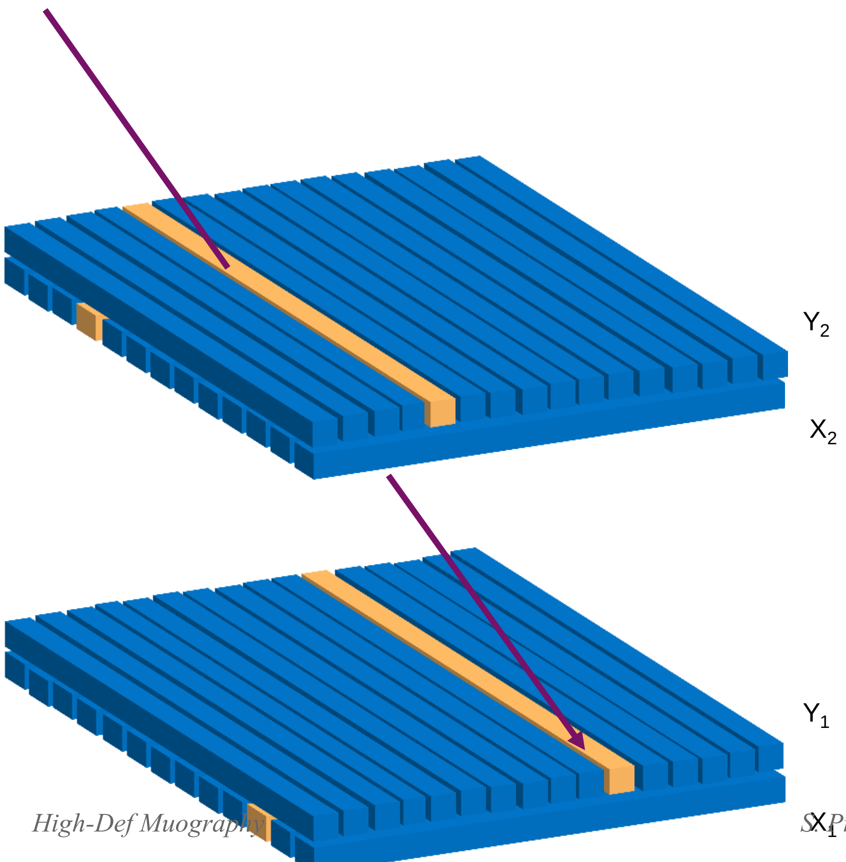




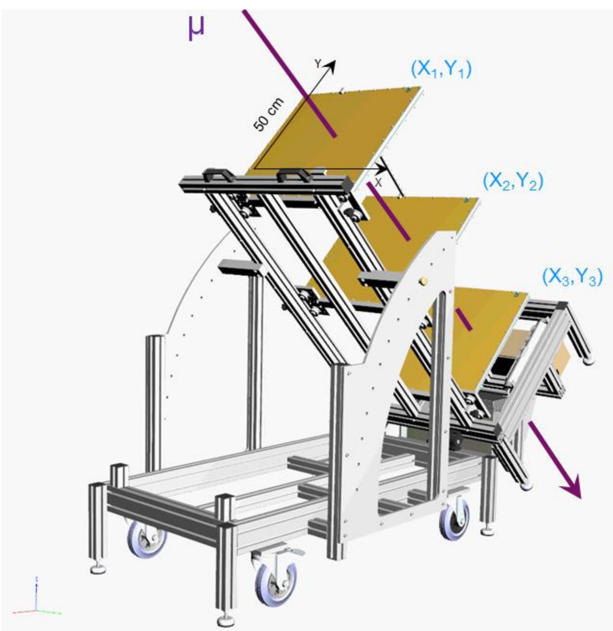
Muography technologies: scintillators

- Solid, plastic scintillators
  - Robust & well known technology
  - Real time imaging
  - Poor resolution





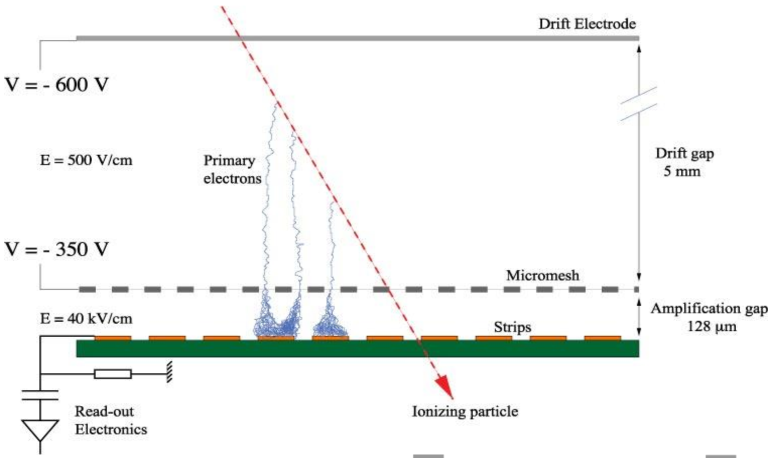
- Based on ionization of the gas by the charged particle
  - Robust
  - Very good resolution
  - Real time

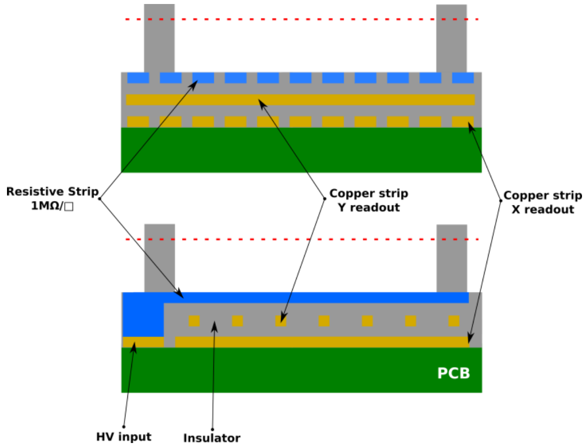


Micromegas Detector

- Gaseous detector invented at CEA-Saclay (1996)
- Excellent performance for detection in nuclear and particle physics
  - spatial resolution < 100 µm
  - time resolution < 10 ns
  - high rate capability

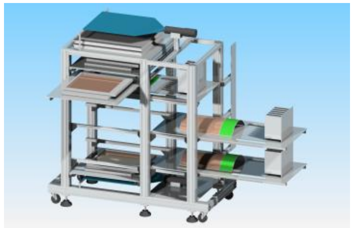
  - *Micromegas bulk* technology (2005) :
    - robust, high area possible
    - easily made in company (printed circuit board)
  - resistive strips for spark suppression and 2D readout

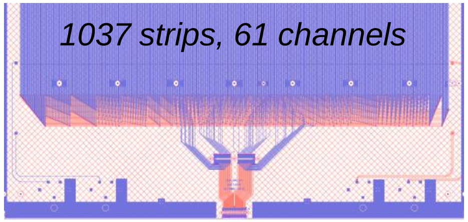




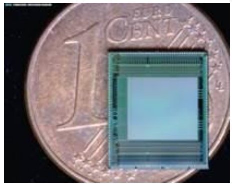
ORIGIN OF MUOGRAPHY @ SACLAY

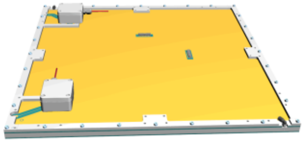
- Dvt of 50x50 cm² MM with genetic multiplexing (2012)
  - *Reduction of electronics (price, consumption) by factor of ~15*
  - *Use of resistive strips to increase S/N and efficiency*

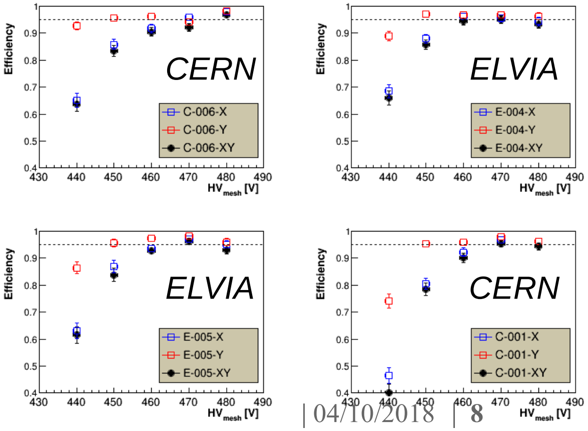




- First final prototypes available in 2015 (made @ CERN)
  - *N~2600 e-, S/N~60-100*
  - *1.5 cm drift gap*
  - *~97% efficiency in 2D*
  - *Ar-Iso-CF_4 (95-2-3) mixture (non flamable)*
  - *~300 micron resolution*



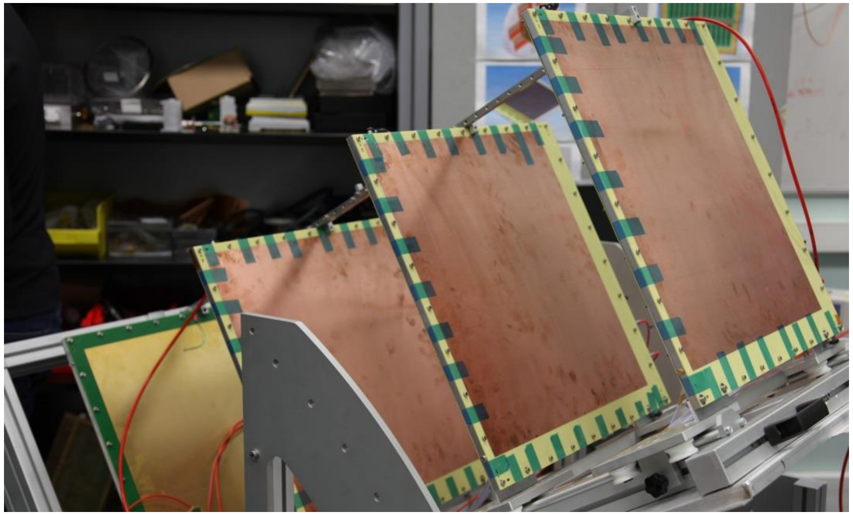


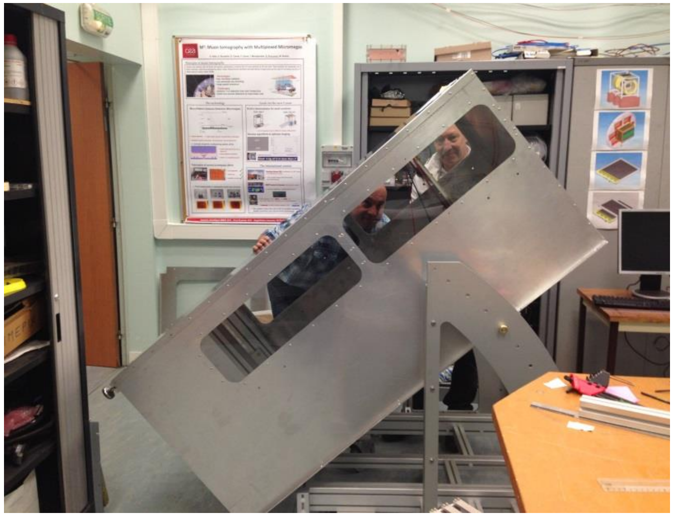


- Know-how transfer with PCB company in France

  ⇒ **2014: proposition of a Micromegas-based muon telescope (WatTo)**

WATTO: INTEGRATION

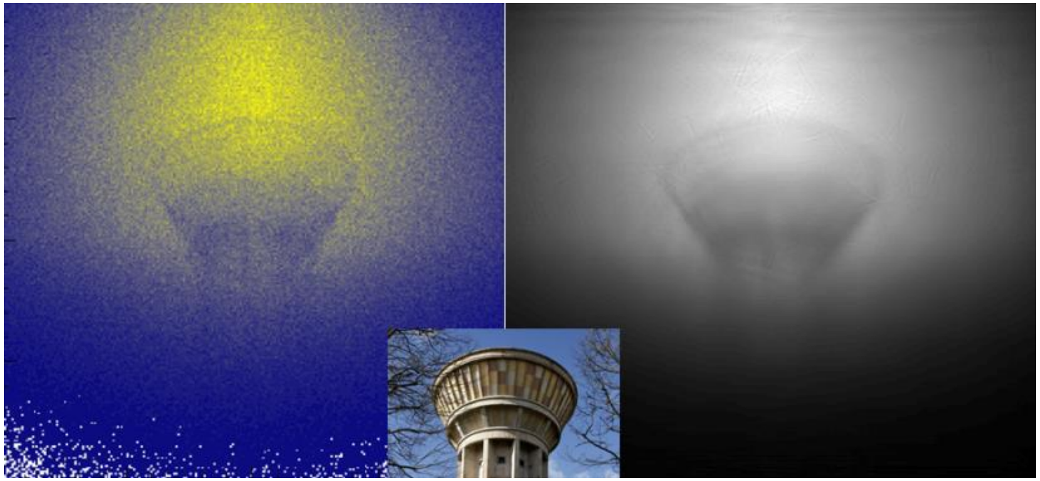




HV+ nano PC + Dream electronics (self-triggering)

- Static Muography:

Integration time: 4 weeks (position 1)



How to read a muography:

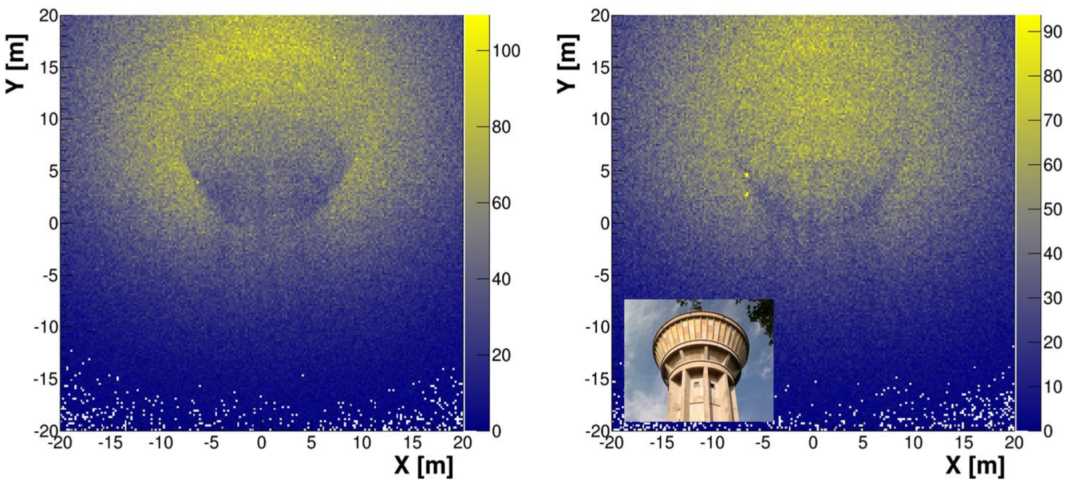
- *Each pixel is a number (or a flux) of reconstructed muons in the corresponding direction*
- *Light (yellow) colour → more muons → less absorption → less matter*
- *Dark (blue) colour → less muons → more absorption → more matter*

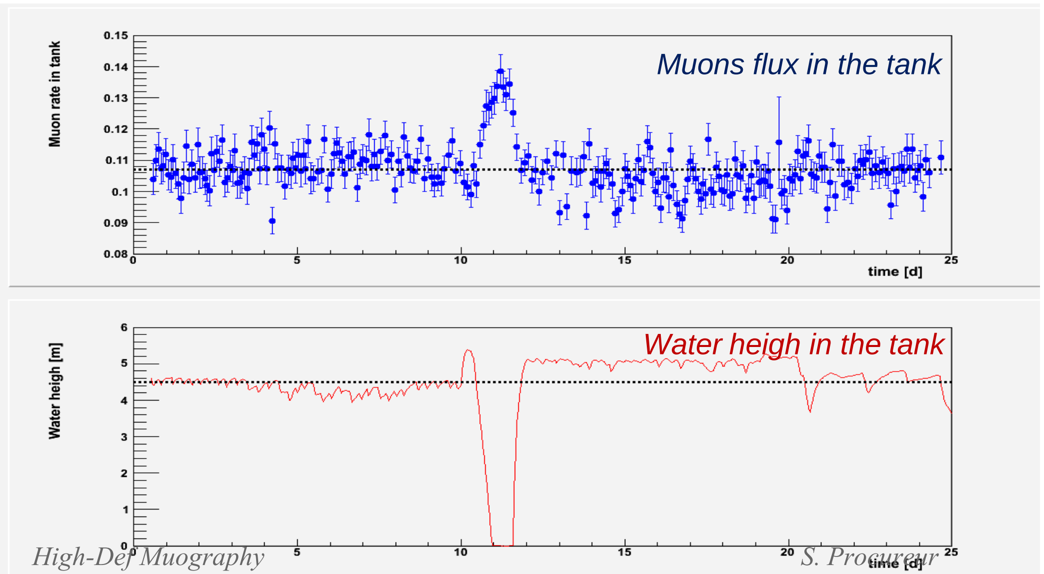
→ First recognizable muography of a structure

WATTO: RESULTS (2/2)

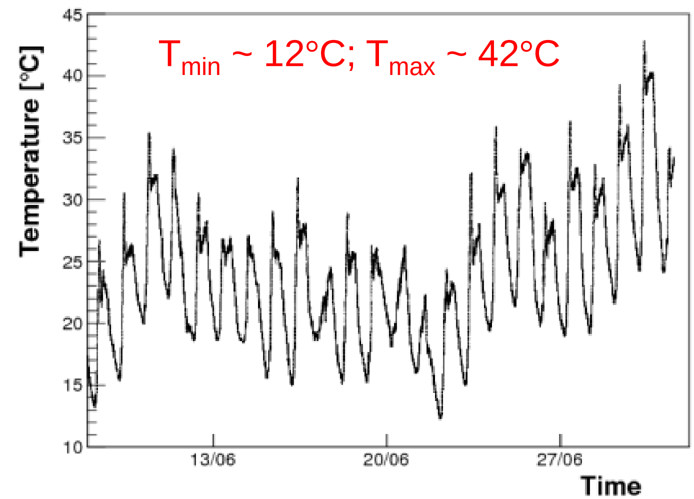
- Dynamic Muography:

Integration time: 4 days each (position 2)





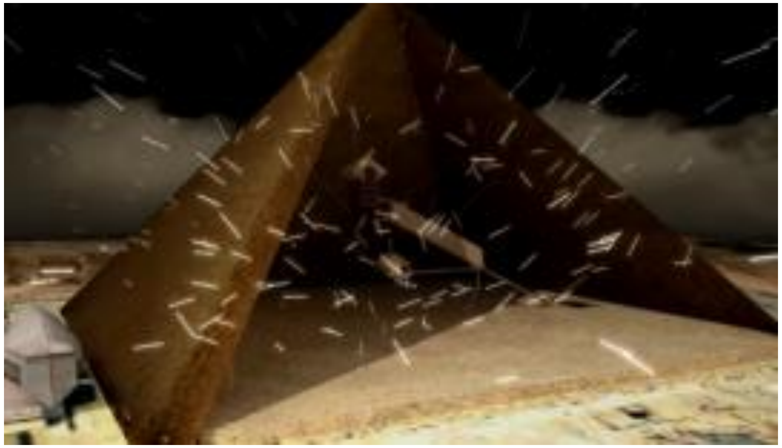
- *Environmental conditions (noise, T&P effects, etc.)*



- *30 W on solar panel*

WatTo→ScanPyramids

- September 2015: end of WatTo experiment …
- … announcement of ScanPyramids on October 25th



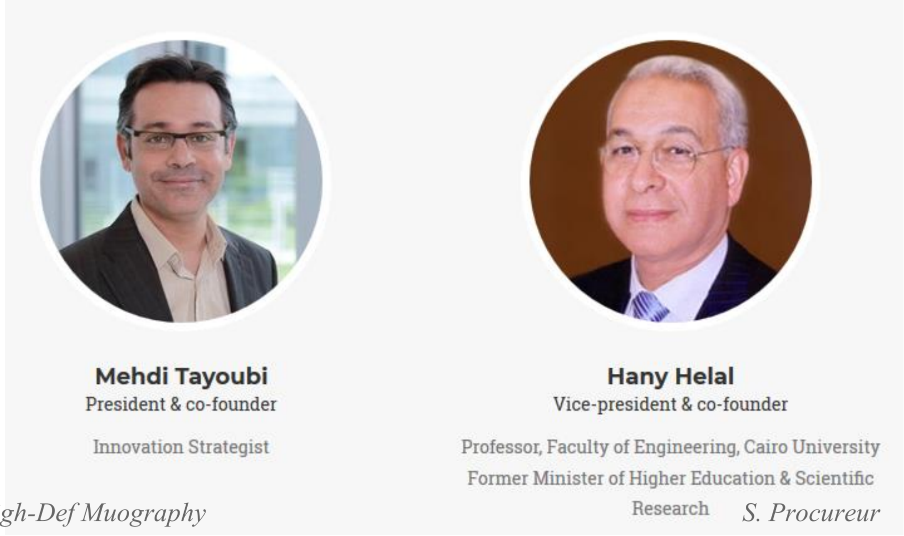
→ *Email to Mehdi Tayoubi on October 26th*

→ *1st meeting mid-December in Paris*

→ *Official announcement CEA participation April 2016*

→ *1st telescope installation in Egypt May 2016*

→ *2nd telescope installation in January 2017*



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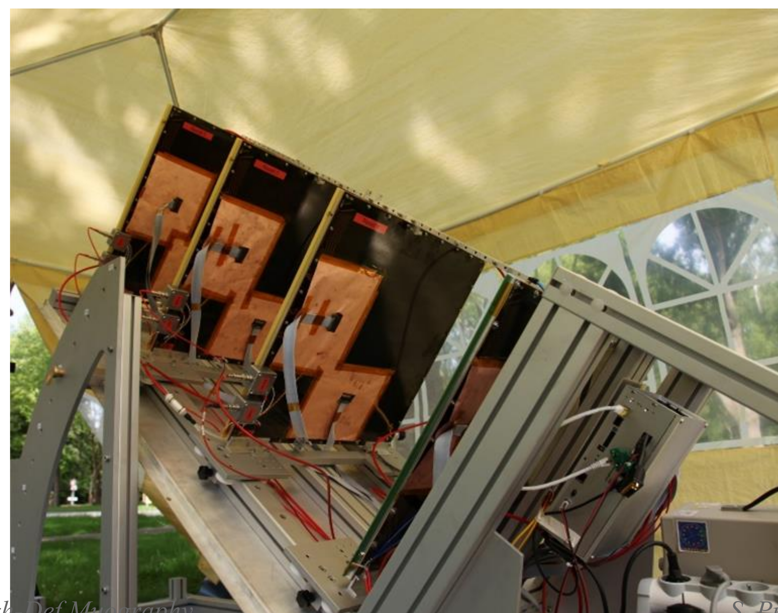
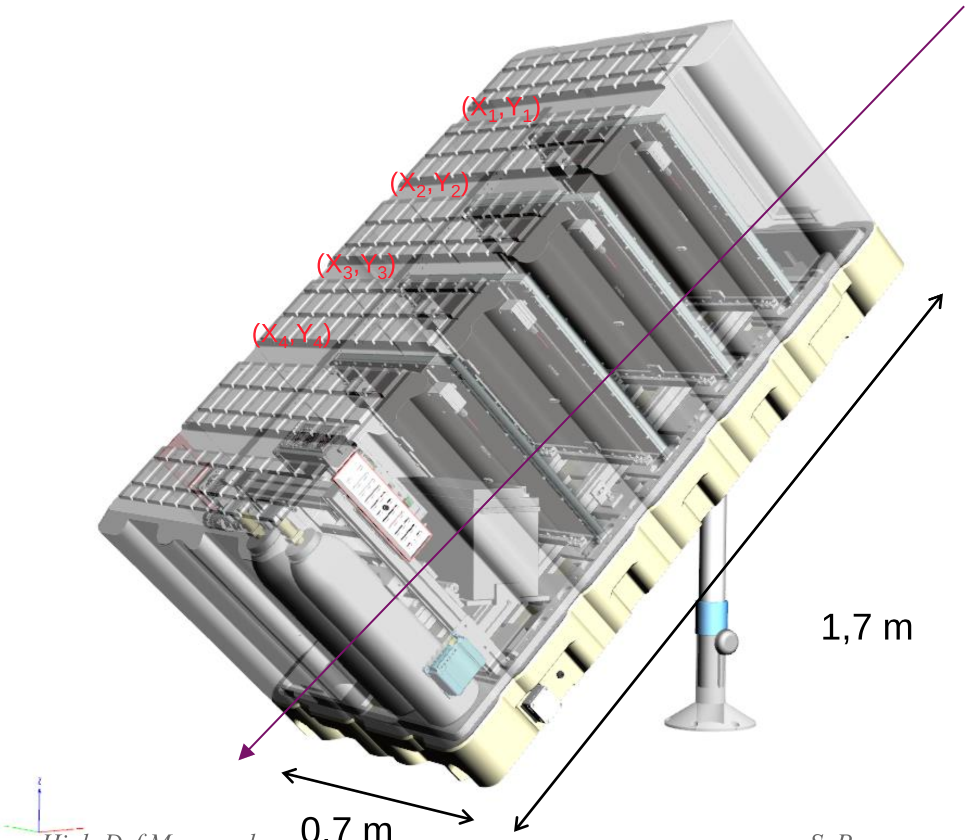
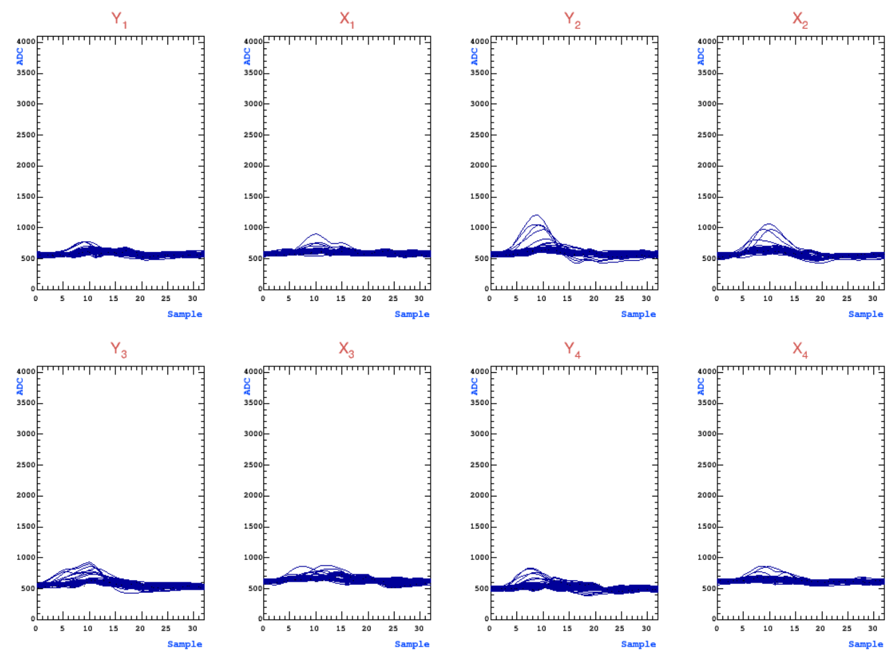
WATTO→SCANPYRAMIDS

- Telescopes : 1 → 3
- Chassis → valise
- Detection plane: prototype (Cern) → serial (Elvia-PCB company)
- Building period: 9 months → 3 months
- Weight : ~ 200 kg → ~ 130 kg
- Detector high voltage: independent of temperature → f(T)
- Data: raw → raw + pre-processing



- New telescope:
  - transportable and easily functional
  - 4 × 2D resistive Micromegas
  - 3G connection for operation, monitoring and transfer of processed data



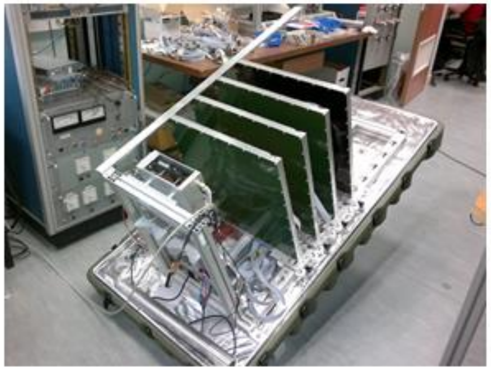


Telescope Integration and Construction

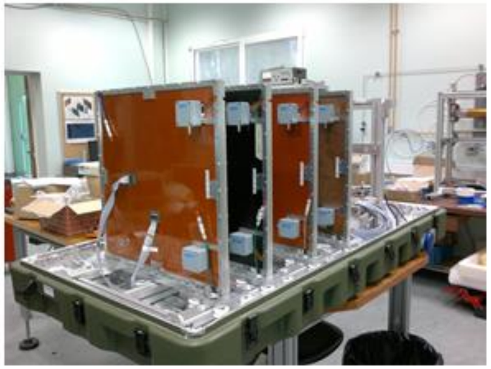
- Detection plane integration in clean room

- Tests in outdoor conditions

Alhazen (n°1)



Alvarez (n°2)



Brahic (n°3)

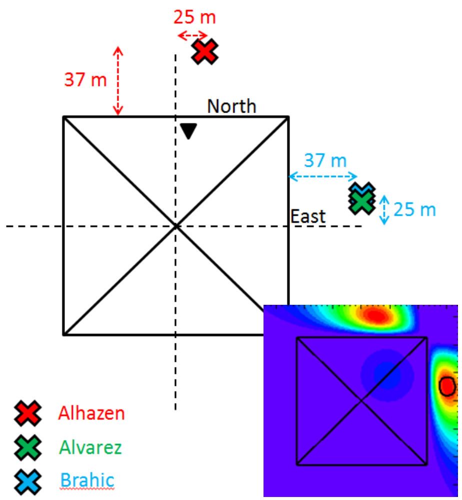
- 3 telescopes assembled and shipped to Egypt

GIZA PLATEAU INSTALLATION

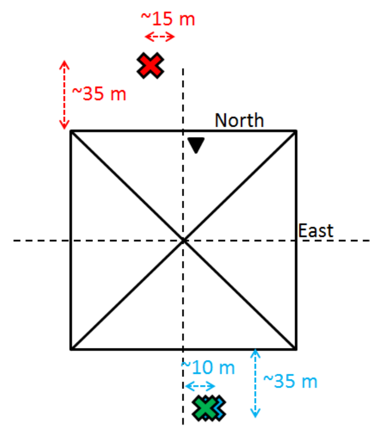
MEASUREMENT CAMPAIGNS

- 3 missions between 2016 & 2017

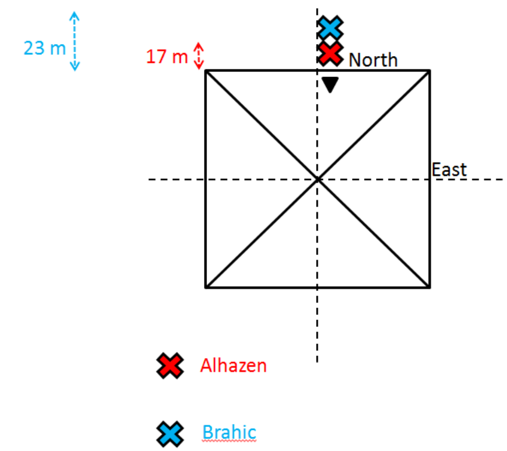
1st mission (jun-aug 2016)

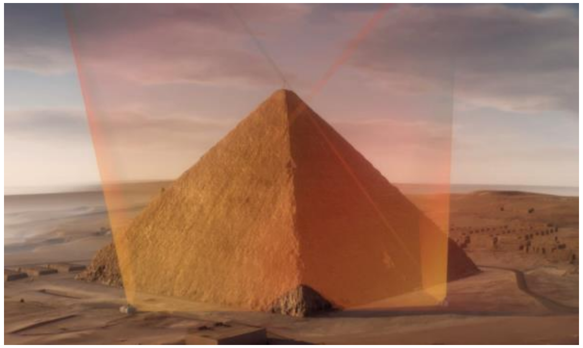


2nd mission (jan-april 2017)



3rd mission 3 (may-jul 2017)

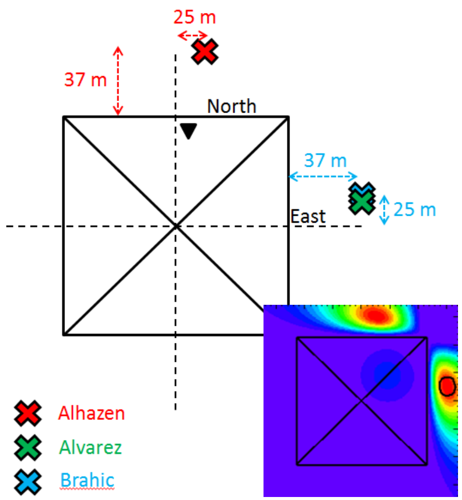




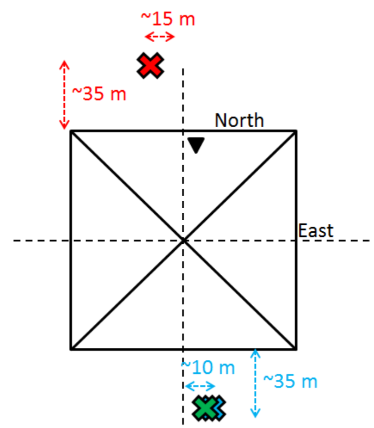
MEASUREMENT CAMPAIGNS

- 3 missions between 2016 & 2017

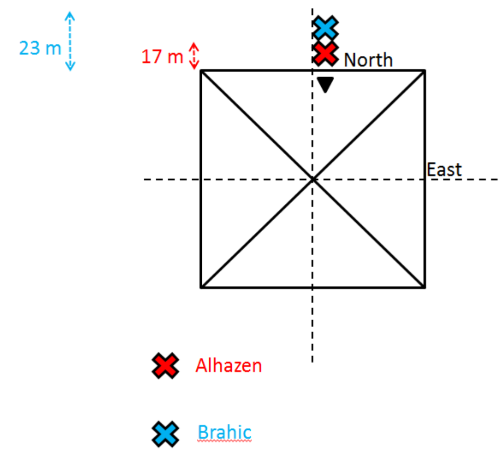
1st mission (jun-aug 2016)



2nd mission (jan-april 2017)



3rd mission 3 (may-jul 2017)



- Statistics: around 200 millions of muons!

Telescope	Mission1	Mission2	Mission3
Alhazen	29,0 millions	34,1 millions	16,6 millions
Brahic	24,6 millions	25,6 millions	16,9 millions
Alvarez	18,3 millions	28,0 millions	X
Total	71,9 millions	87,7 millions	33,5 millions

DATA TAKING

- Relatively smooth…

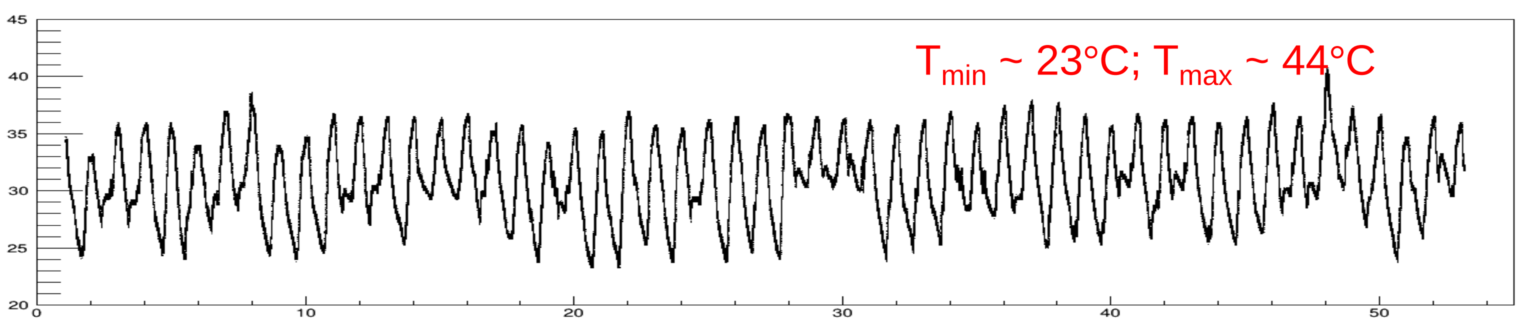
before

after

+ issues with 3G/4G

+ …

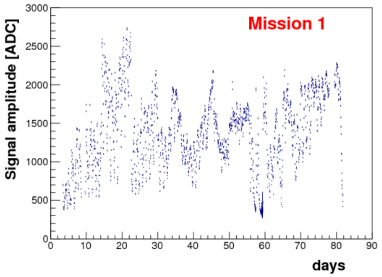
- Temperature variations (gas & electronics & mechanics)

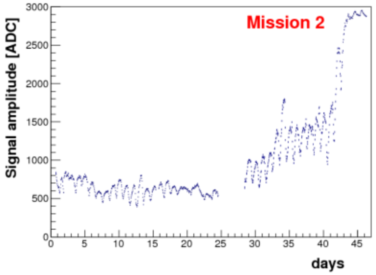


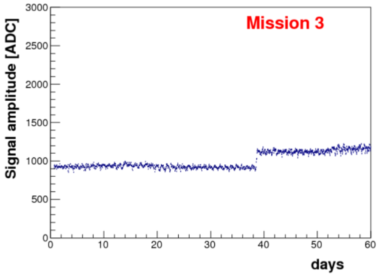
(instruments checked at Saclay between 2°C and 55°C)

- Successive improvements of the instruments

Signal stability







Monitoring of environmental conditions

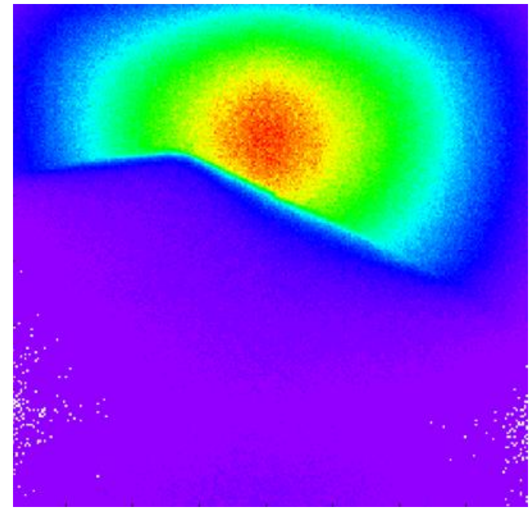
Full, online analysis on the nano-PC

ANALYSIS

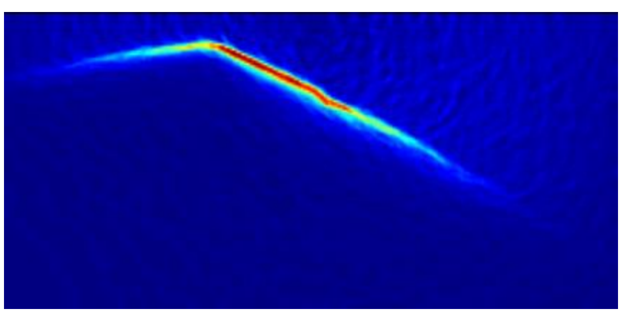
- Necessity to adjust photo and muo for comparison with 3D model

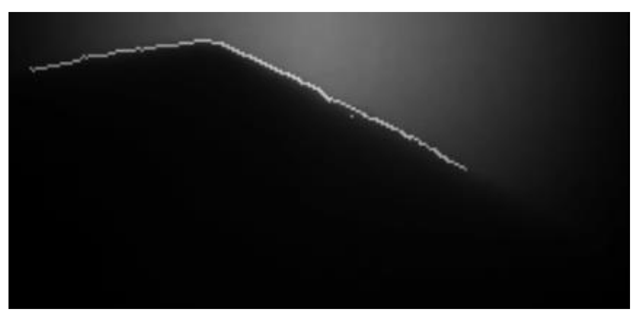
photo

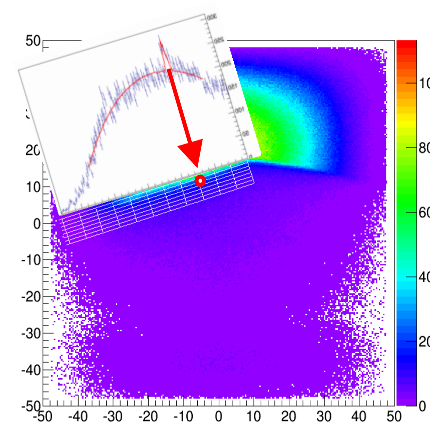
muo



- Requires edge detection (image filtering)

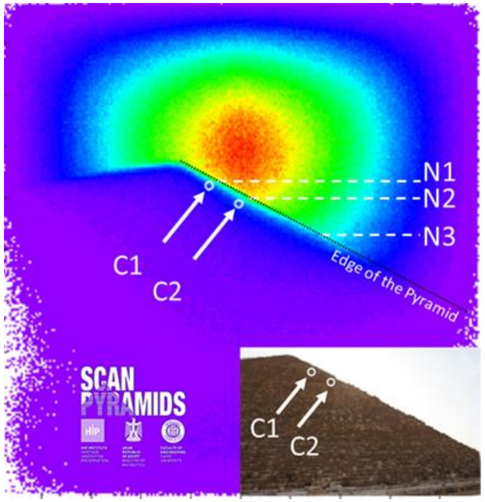


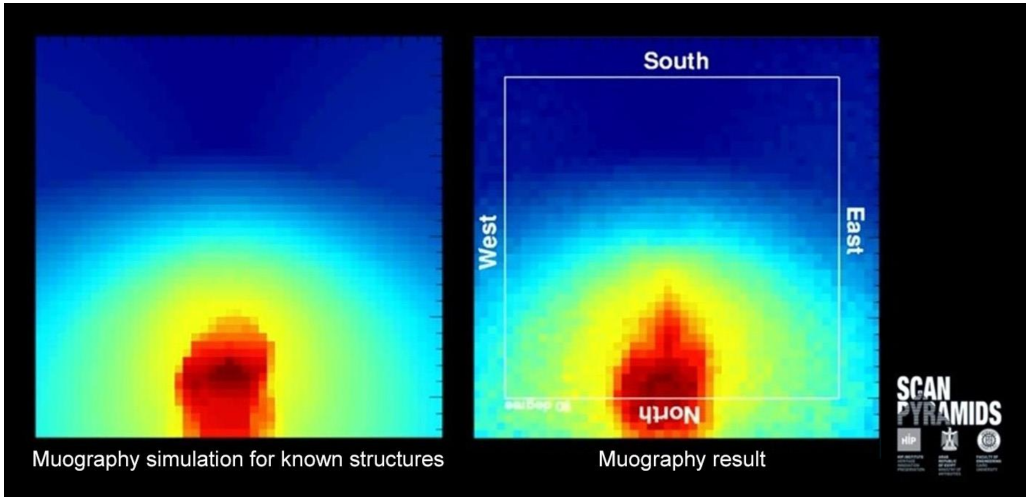


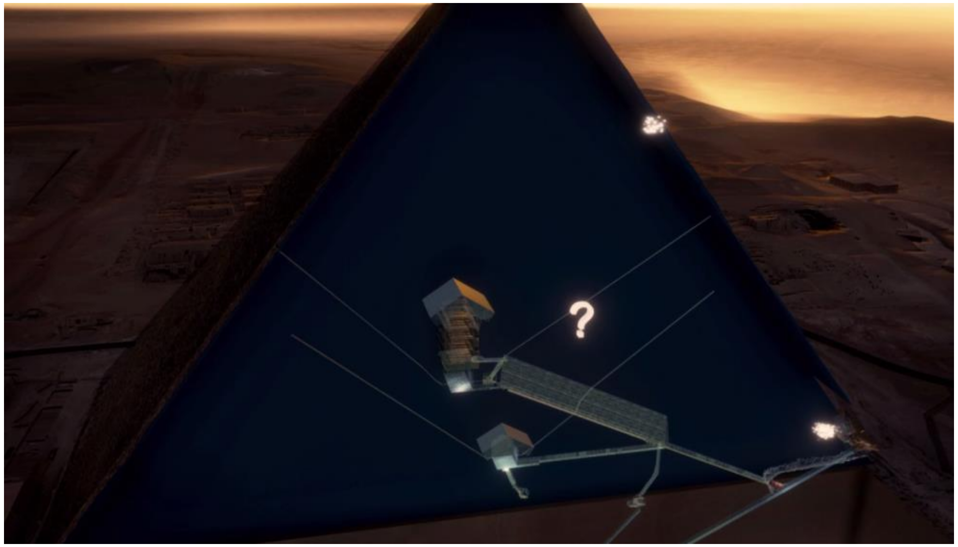


RESULTS - 2016

- October 2016: discoveries of 2 voids in the pyramid





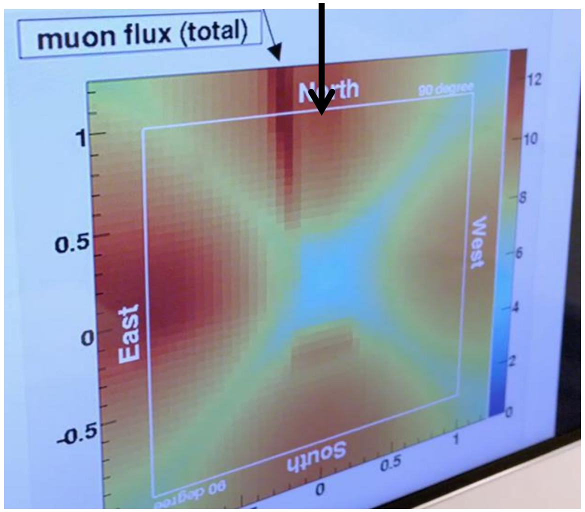


⇒ ***Question for egyptologists: what is the purpose of these voids?***

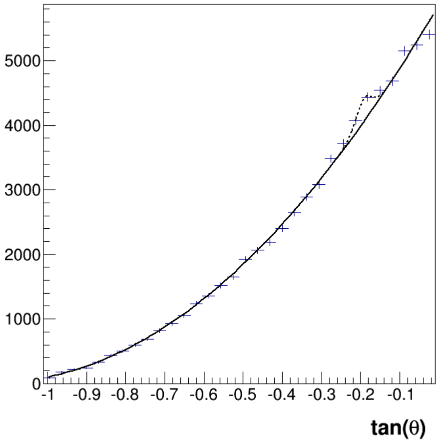
RESULTS

- Early 2017: 1st results from Nagoya emulsion in Queen's Chamber…

Significant muon excess close to the Grand Galery ⇒ **void**



Anomalies appearing also on KEK scintillator (Queen's Chamber), and on CEA telescope (North face)



- 3D model suggests that all these anomalies point to the same direction

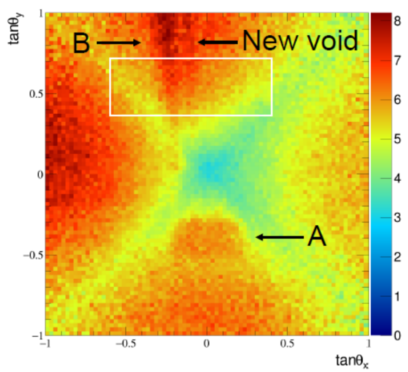
⇒ **Dedicated measurement campaign started**

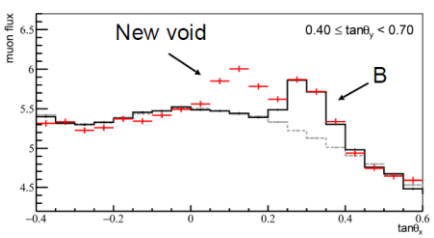
- *Queen's Chamber: new emulsion from Nagoya and move of the KEK scintillator*
- *Outside: move of 2 telescopes in front of the North face Chevrons*

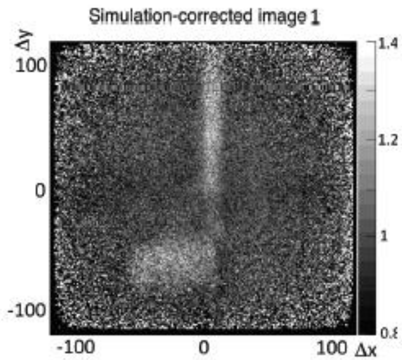
RESULTS (FROM NATURE PAPER)

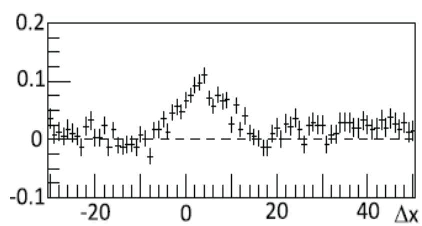
- All the measurements confirm a large void above the Grand Gallery

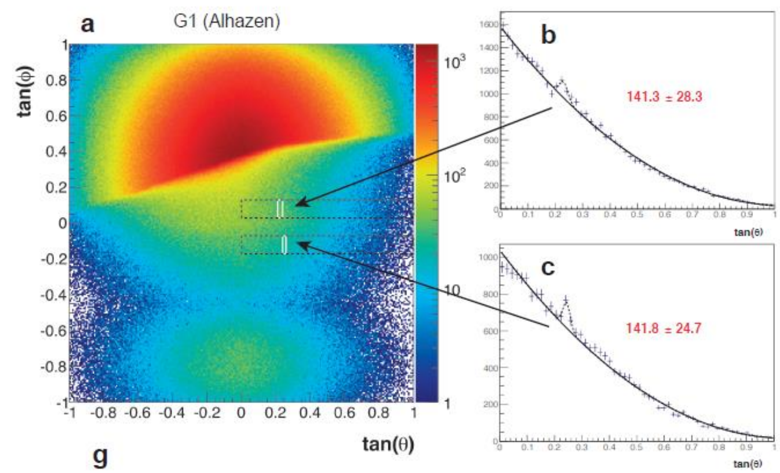
Nagoya | *KEK* | *CEA*





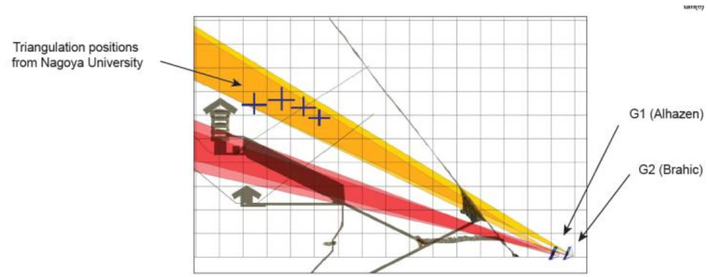


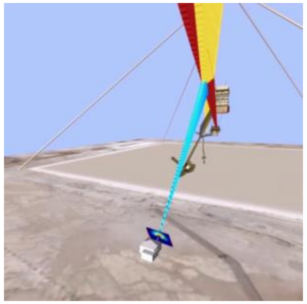




- *Only 2 such voids detected*
- *1st detection ever from outside of a deep structure*

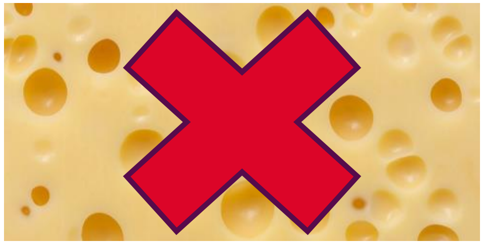
- Good triangulation with Nagoya and CEA instruments

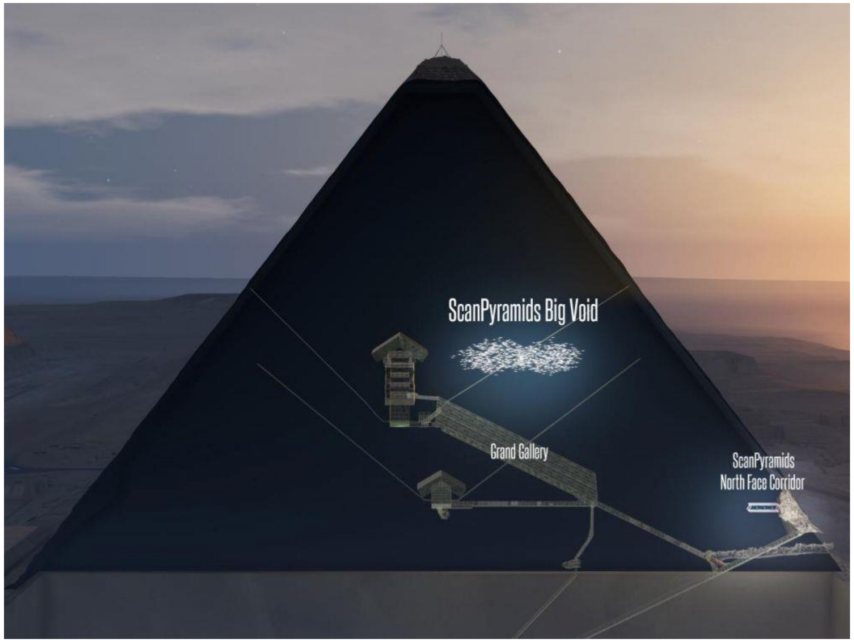


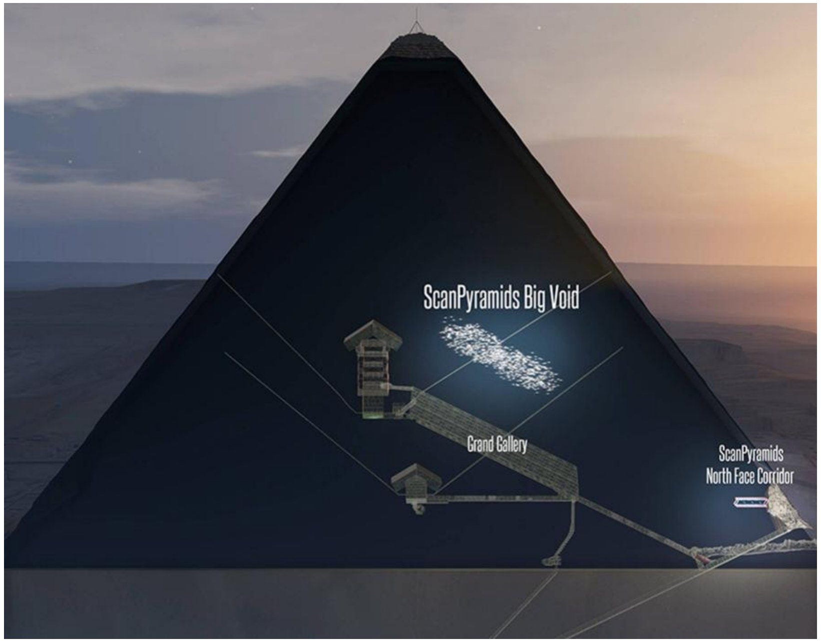


ScanPyramids Big Void

- Remarkable features of the ScanPyramids Big-Void:
  - *Within the same plane as all other known (big) structures*
  - *Large under-density, only at this place*



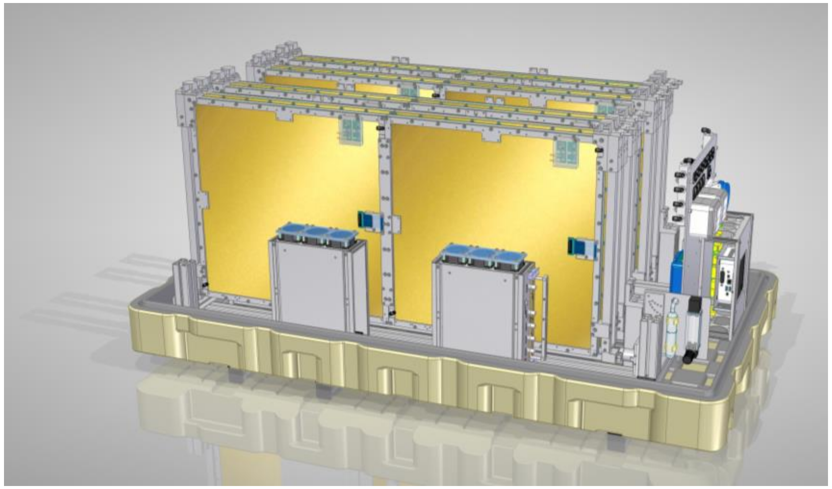


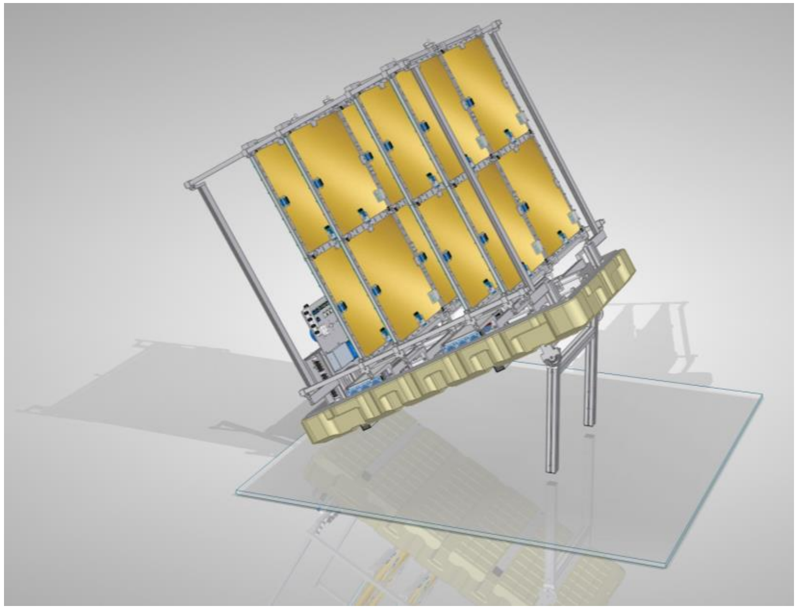


- *Volume estimate: several hundreds of m^3*
- *Length: ~ 30 m*
- *Inclined or horizontal…* ⇒ **More measurements needed!**

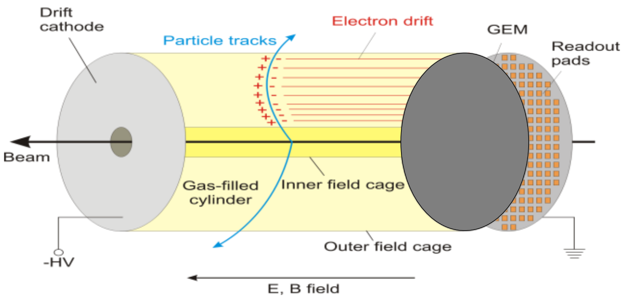
FUTURE INSTRUMENTS

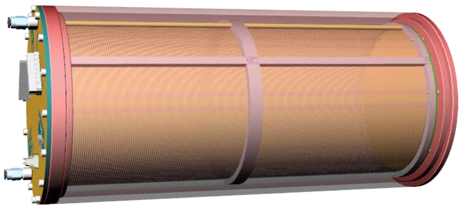
- Larger telescopes ($1m^2$)





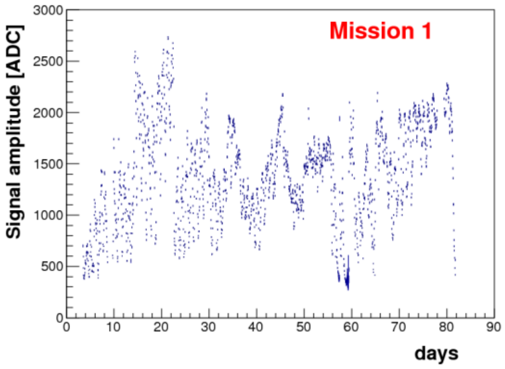
- Time Projection Chambers (isotropic) for underground measurements (borehole)

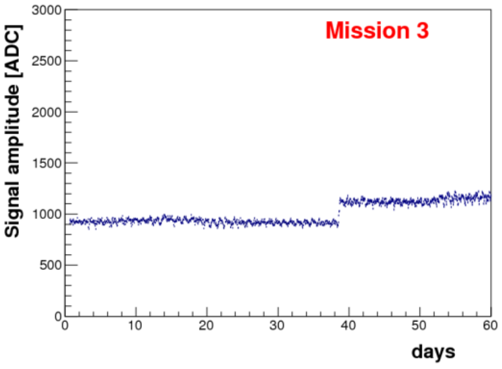




CONCLUSION (BEYOND BIG VOID…)

- MPGD robust enough for extreme applications in spite of gas





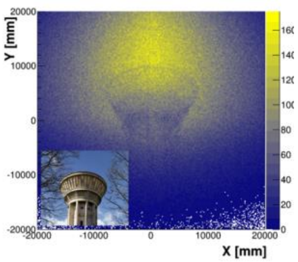
- Probably the best technology for precise muography

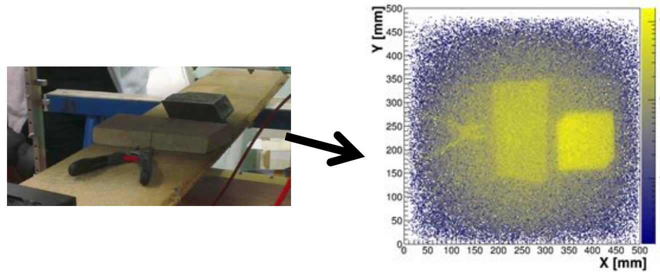
	Nuclear emulsion *Nagoya University*	Hodoscopes *KEK*	Gas detectors *CEA*
Angular Resolution	2-14 mrad	7-10 mrad	0.8 - 4 mrad
Angular Acceptance	45 degrees	34 - 45 degrees	45 degrees
Active area (for this analysis)	30 cm x 25 cm / unit: 0.75 m x 0.6 m (NE1) 0.9 m x 0.5 m (NE2)	1.2 m x 1.2 m	50 cm x 50 cm
Position Resolution	1 μm	10 mm	400 μm
Height	0.2 mm	1-1.5 m	60 cm
Power requirement	No	Yes (300W)	Yes (35W)
Data taking	Need development	Real time	Real time

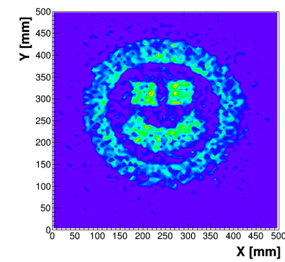
CONCLUSION (BEYOND PYRAMID…)

- Deep imaging: many more applications

« high def » muography: cano now recognize structures and even small objects



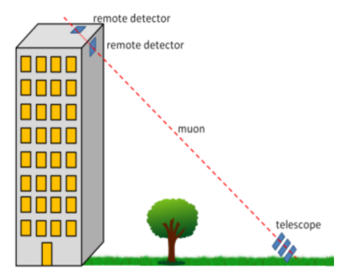




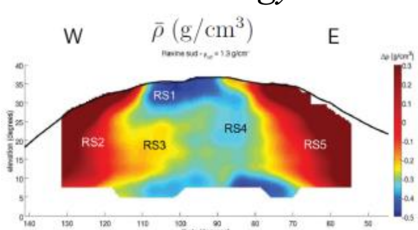
Civil engineering

Dismantling, nuclear waste

(muon) metrology



Volcanology



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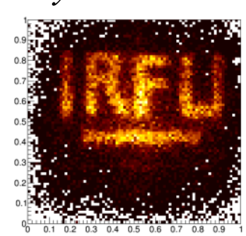
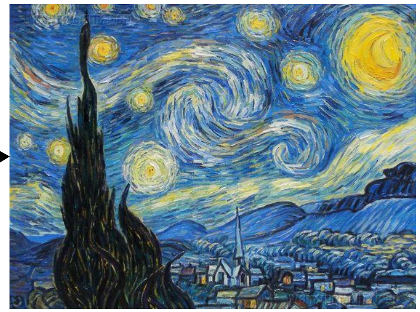
Homeland security



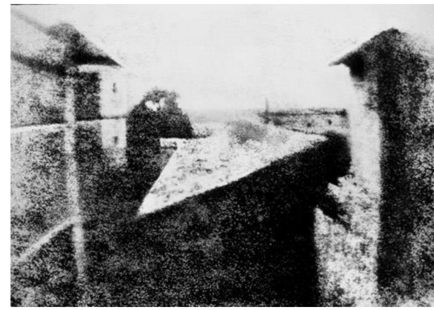
+…

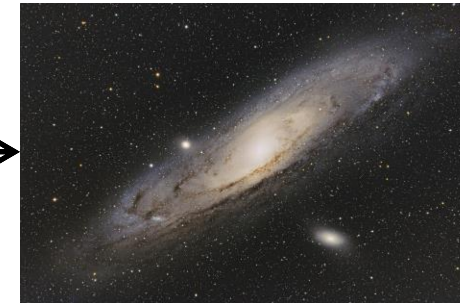
MUOGRAPHY (BEYOND IMAGINATION…)

- Painting



- Photography





- Muography?