DE LA RECHERCHE À L'INDUSTRIE

cea

SCAN PYRAMIDS

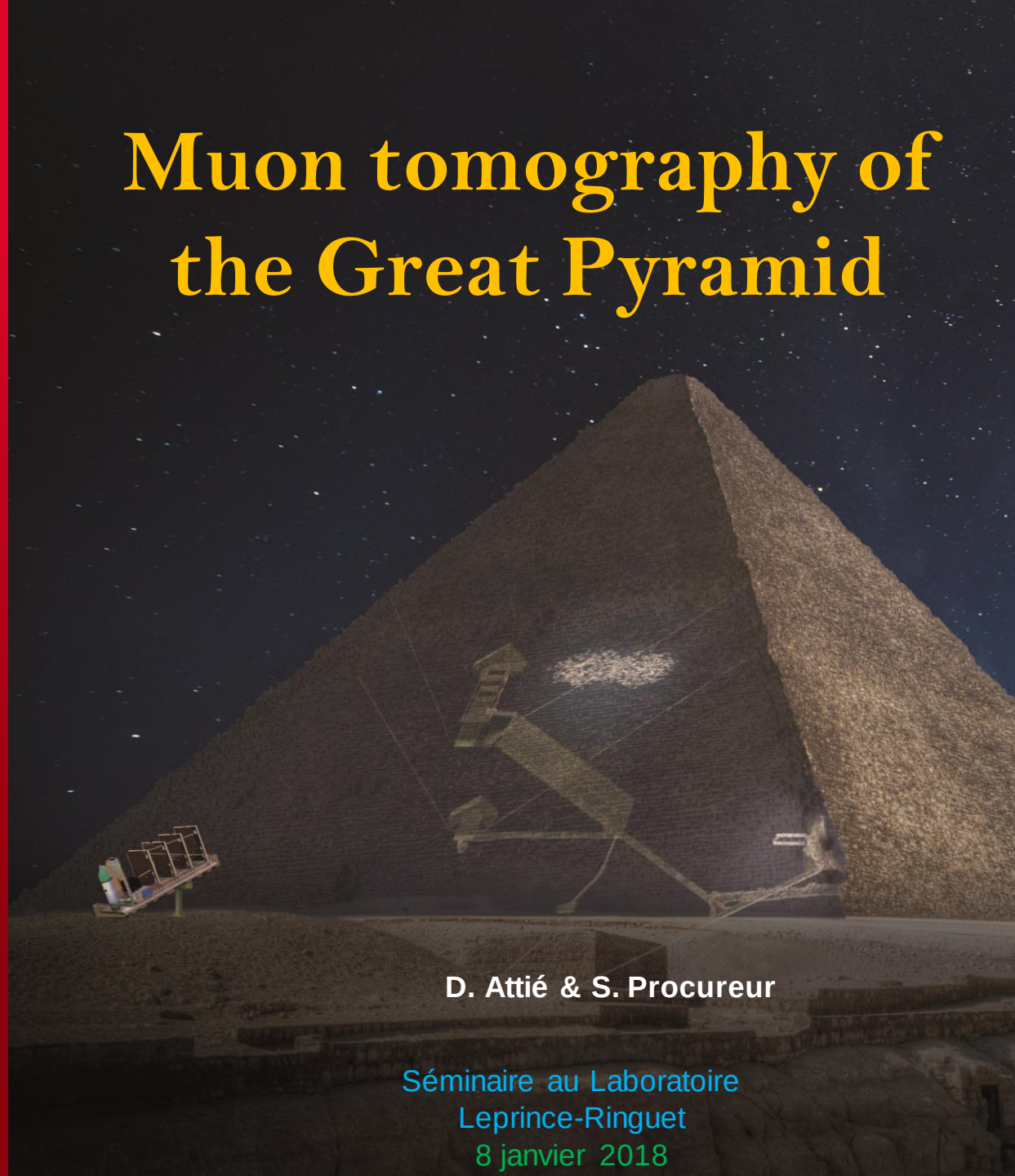
HIP INSTITUTE HERITAGE INNOVATION PRESERVATION

ARAB REPUBLIC OF EGYPT MINISTRY OF ANTIQUITIES

FACULTY OF ENGINEERING CAIRO UNIVERSITY

Irfu

Muon tomography of the Great Pyramid



D. Attié & S. Procureur

Séminaire au Laboratoire
Leprince-Ringuet
8 janvier 2018

SUMMARY

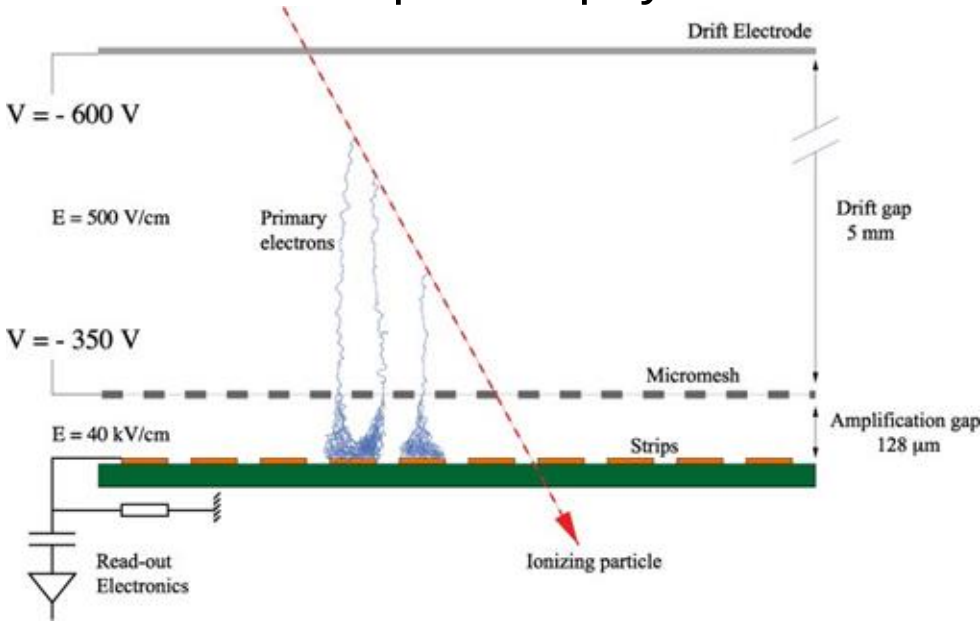
- Fundamental physics detectors
- Muon tomography
- WatTo, experiment for demonstration
- ScanPyramids: preparation and discoveries
- Other applications of the muon tomography

INTRODUCTION: MICROMEGAS DETECTOR

- Gas detector invented for physics experiments at Irfu (90's)
  - *Micromegas bulk* technology (2005) :
    - robust, high area possible
    - easily made in company (printed circuit board processes)
  - resistive strips: use for spark removal and 2D readout

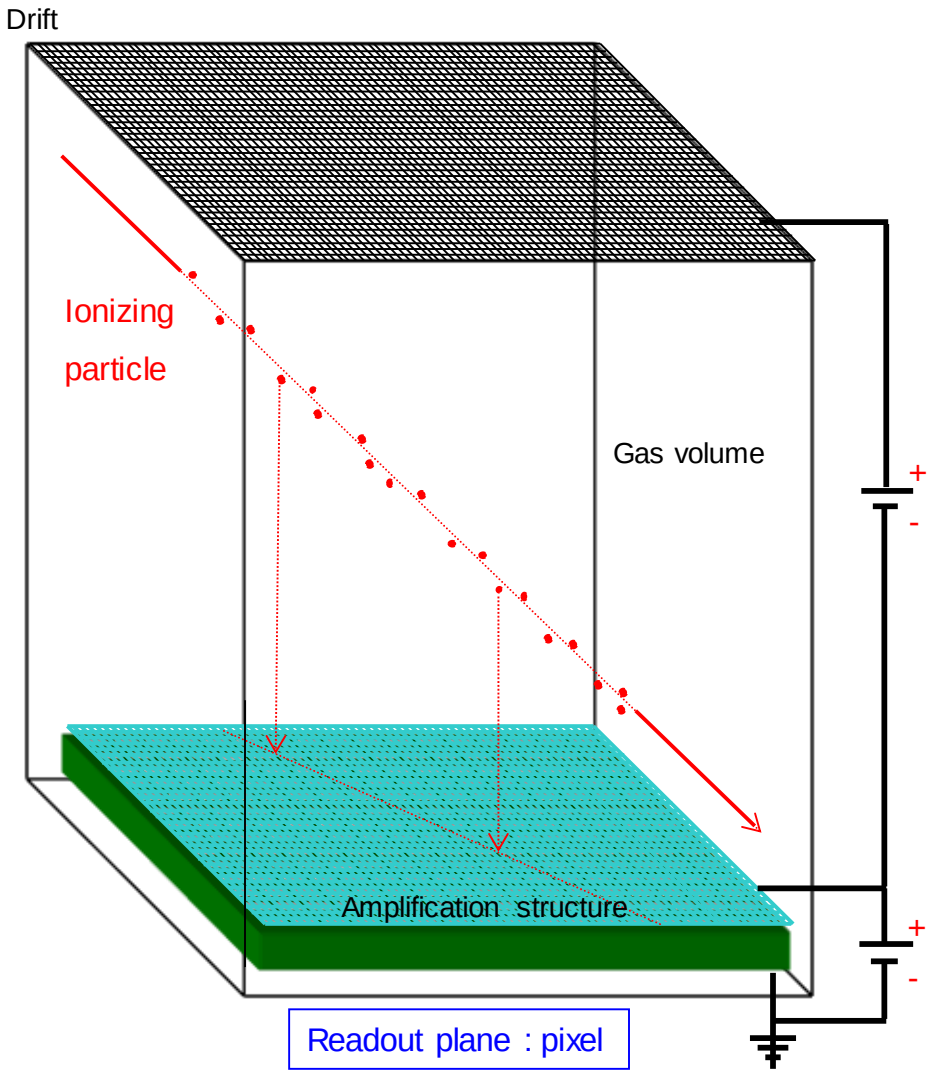
- Excellent performances for detection in nuclear and particle physics
  - spatial resolution < 100 µm
  - time resolution < 10 ns
  - High rate capability

- Interest for societal applications
  - technological transfer succeed
  - relatively low cost

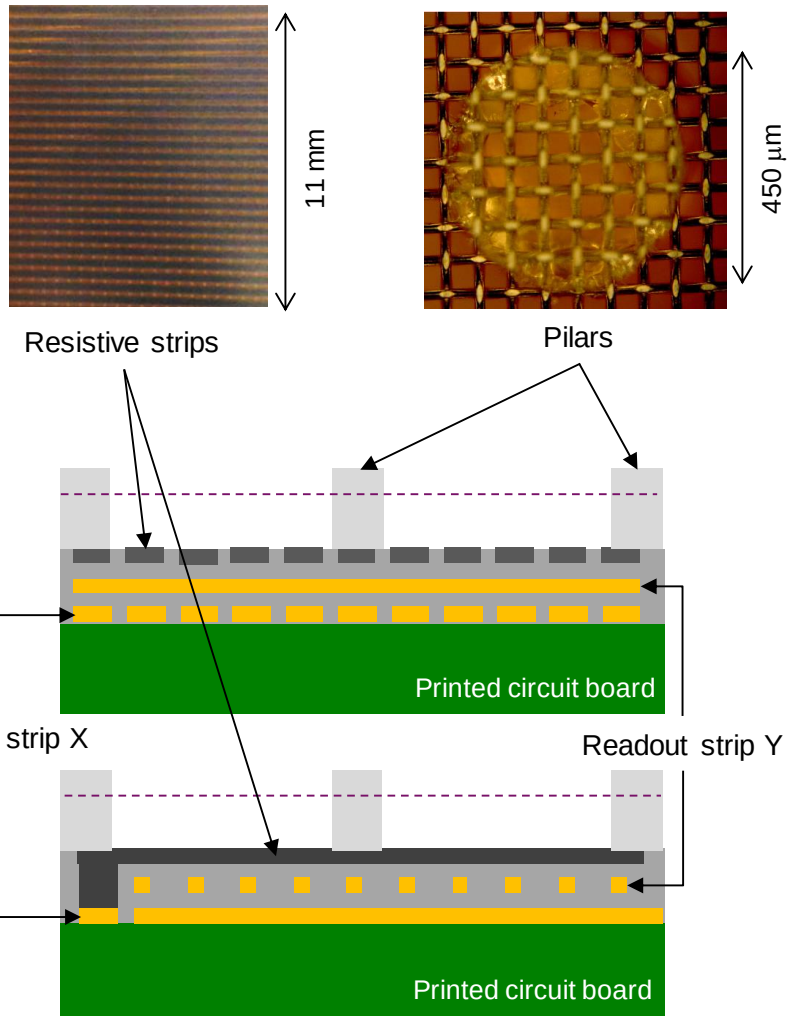


GASEOUS DETECTORS WITH 2D READOUT (CEA)

- Charged particle: x, y, t, Q(x, y)



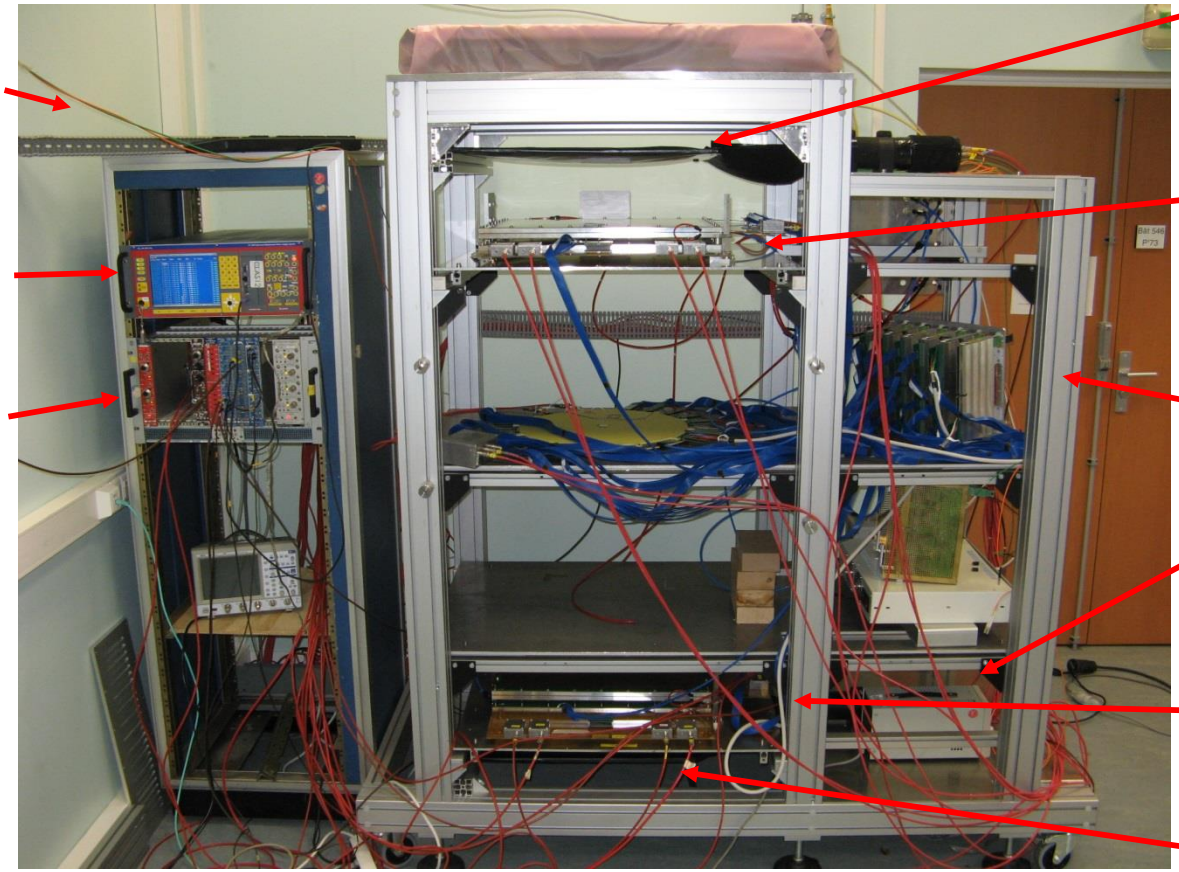
Readout plane : pixel



Readout plane : 2D strips

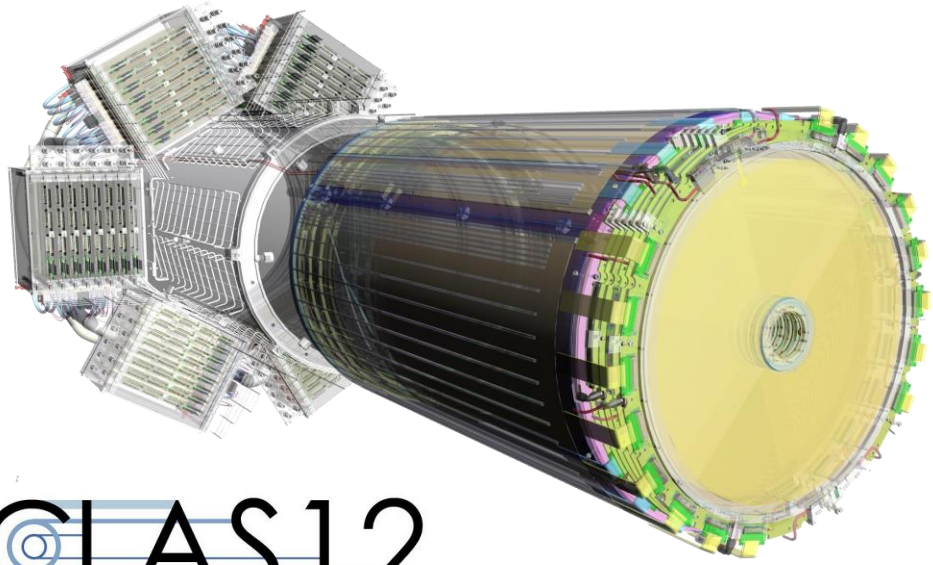
COSMIC BENCH FOR DETECTOR STUDY

- Cosmic bench used to characterize physics experiment detectors
- Free, in house and without beam schedule



EXAMPLE OF DETECTOR IN HADRONIC EXPERIMENT

- 4 m² of Micromegas detectors installed in 2017 (last month) in 5T magnet
  - *Forward* detectors:
    - 6×430 mm diameter dimension
    - high rate (30 MHz) supported by resistive strips divided in 2 zones inner/outer
  - cylindrical *Barrel* detectors
    - 3×6 layers in 10 cm space for low momentum particle (light detectors)



CLAS12

Micromegas Vertex Tracker

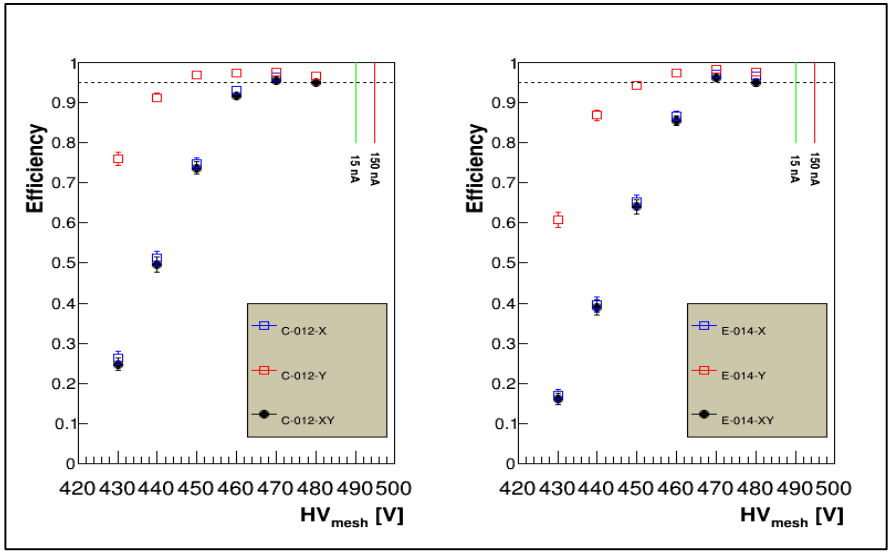
Jefferson Lab
Thomas Jefferson National Accelerator Facility

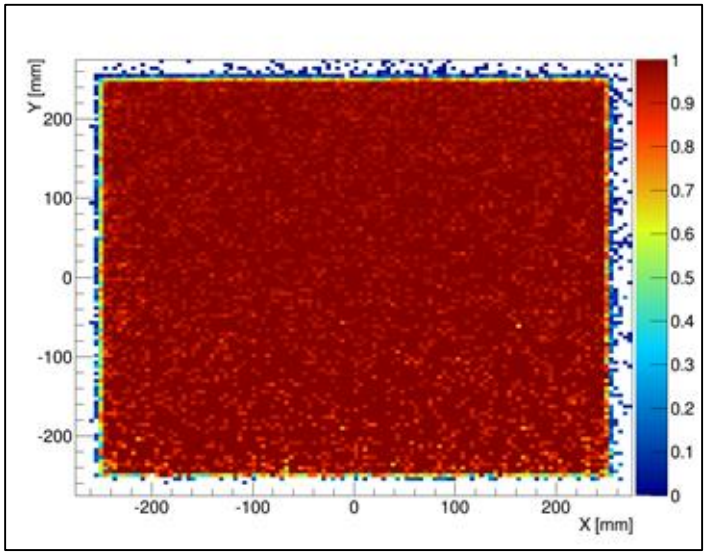
PHYSICS DETECTOR CHARACTERIZATION

Efficiency vs. HV

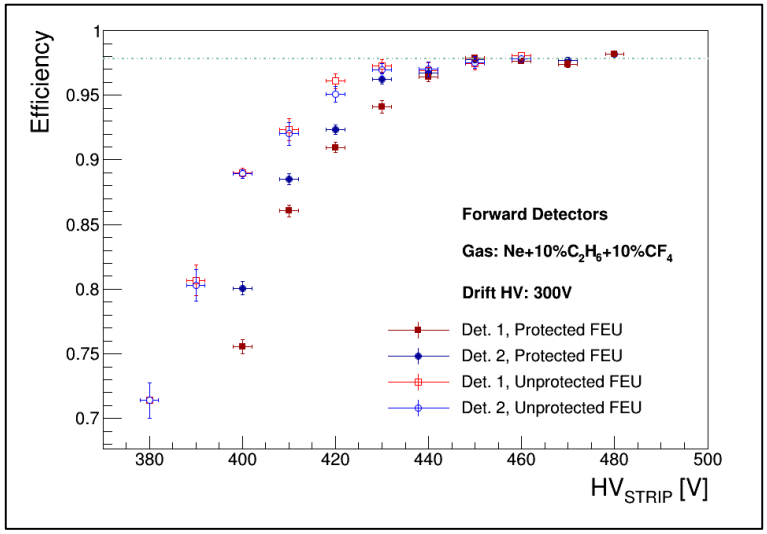
2D efficiency

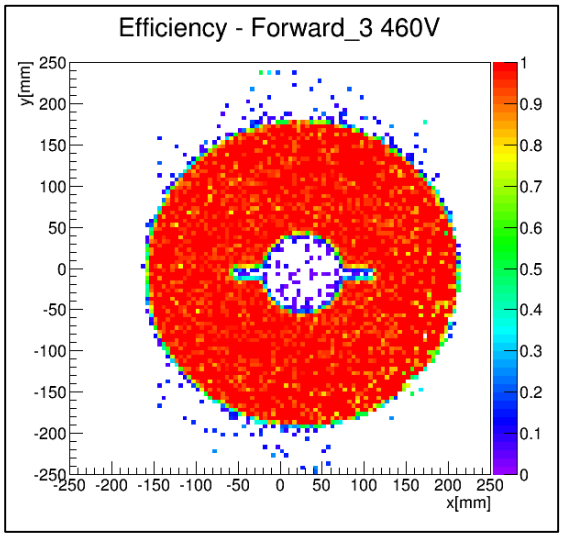
Barrel





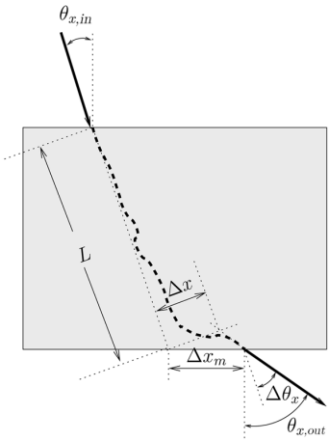
Forward

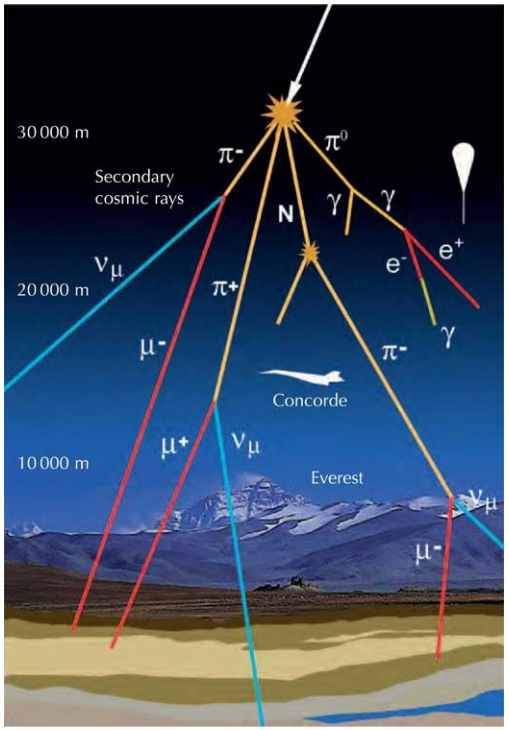




MUON TOMOGRAPHY

- 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 mean)





- Muon interaction with matter
  - Bethe-Bloch ionization stopping power

$$-\frac{dE}{ds} = \rho q^2 \frac{N_A e^4}{4\pi\epsilon_0^2 m_e c^2}\frac{Z}{A}\frac{1}{\beta^2}\left(\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta}{2}\right)$$

  - Standard deviation of the scattering angle

$$\sigma_\theta = \frac{19.2MeV}{\beta pc}\sqrt{\frac{\rho s}{X_0}}\left(1 + 0.038\ln\frac{\rho s}{X_0}\right)$$

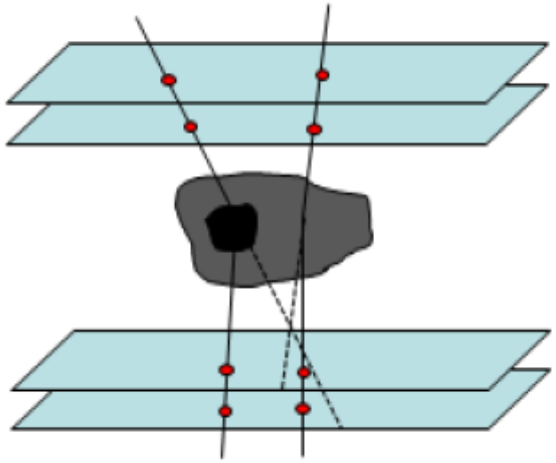
  - Radiation length

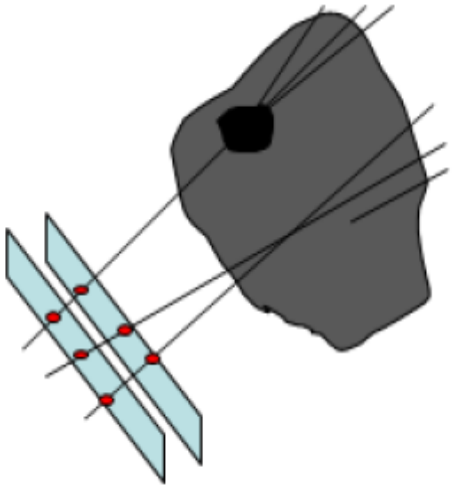
$$X_0 = 716.4 g cm^{-2}\frac{A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$

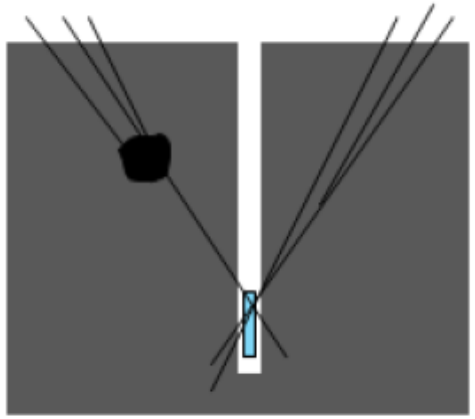
Material	Thickness	θ (°)	$P_{absorption}$
Air	100 m	0.094	0.78%
Lead	10 cm	1.01	2.9%
Water	1 m	0.35	4.2%
Ground	100 m		99%

MUON TOMOGRAPHY

- Muons can be stopped (decay) or their trajectory can be changed
- Two modes of muon tomography can be extracted from muon flux
  - Absorption muography
  - Deviation muography







- High potential of societal applications in many fields:
  - volcanology, archaeology
  - mineral exploration, civil engineering, …

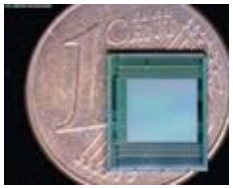
FIRST DEMONSTRATOR: WATTO (WATER TOWER)

October 13th, 2014

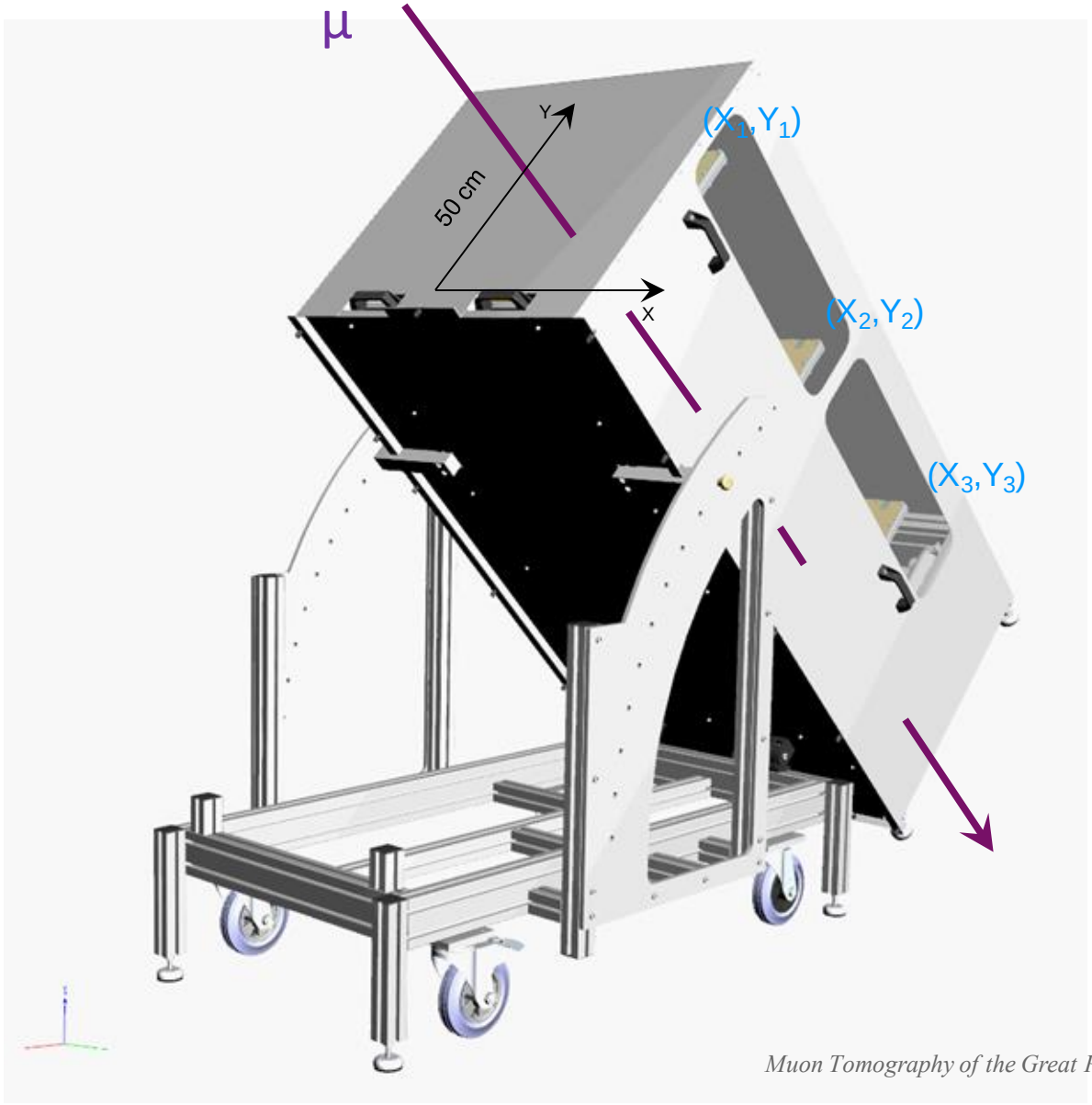
May 11th, 2015

TECHNOLOGIC CHOICES AND INNOVATION

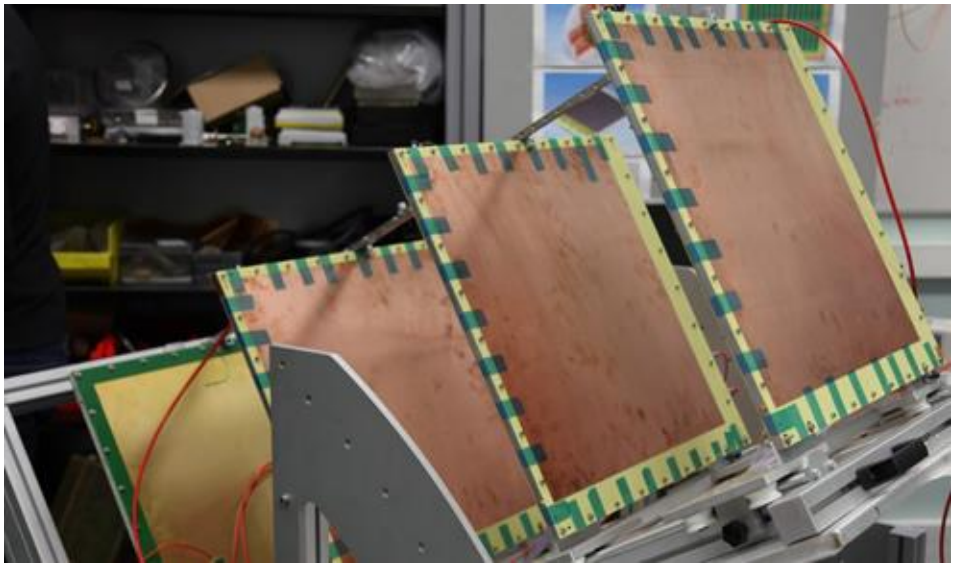
- **Unusual specifications** (outdoor, weight, power consumption, autonomy)
  - Non flammable gas (safety): Ar-Iso-CF4 (95:23)
  - Very low flow rate (~1L/h) → months of data taking
  - Dream-based electronics *made in Irfu:* 1 board FEU of 8 ASICS
    - 1 Dream per coordinate
      → Low capacitance micro-coax Hitachi cable (Clas12)
    - Design for large capacitance detector (MultiGen~1-2nF)
    - Self trigger mode, coincidence between 8 plans
  - Nano-PC (Hummingboard from Solid-Run)
    - 4-core ARM at 1GHz with Linux OS
    - Software to control and monitor HV, electronics
    - Transfer data to analysis PC
  - HV board *made in Irfu*
    - Running and monitoring
    - Using CAEN DC-DC LV-HV converter
  - Power supply & Network
    → Power in 230V and internet wired connection
    → Full autonomy tested
    - Power at 12V using battery and solar panels
    - 3G communication

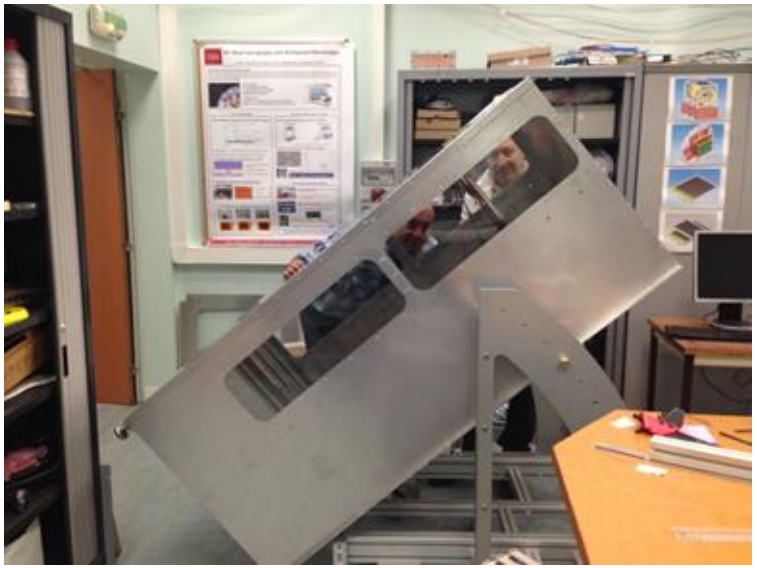


WATTO TELESCOPE



INTEGRATION AND TESTS IN LAB





HV+ nano PC + Clas12 electronics board in a box

TWO CONFIGURATIONS OF DATA TAKING

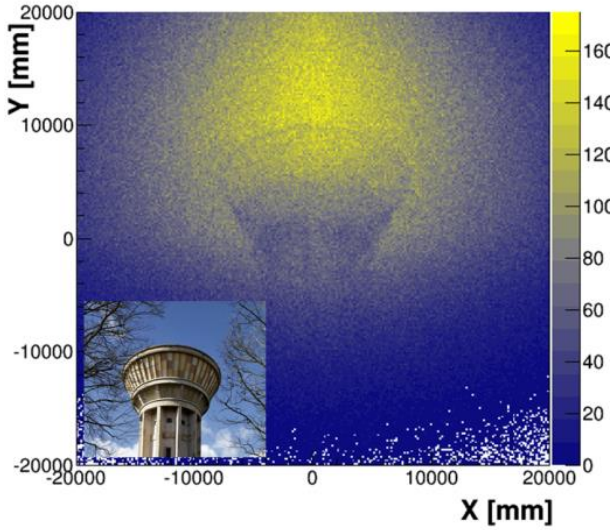
- Mid-May to Mid-July
- 230V, wire network

- Mid-July to beginning of September
- Solar panel/battery

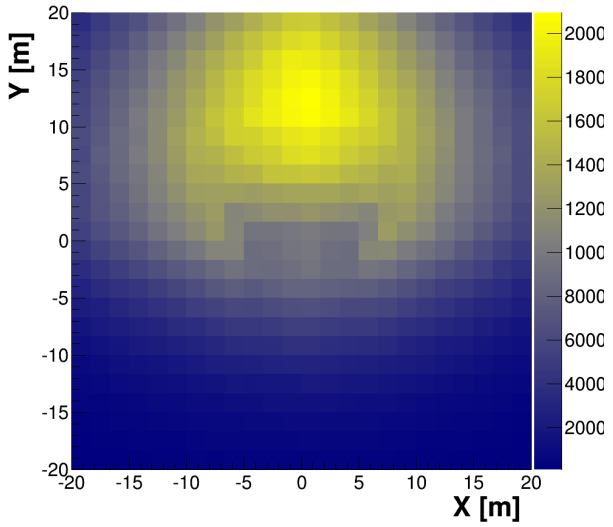
RESULTS (1/2)

- Static Muography:

Integration time: 4 weeks (position 1)

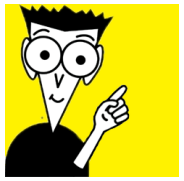


Same size of a scintillator telescope



How to read a muography:

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

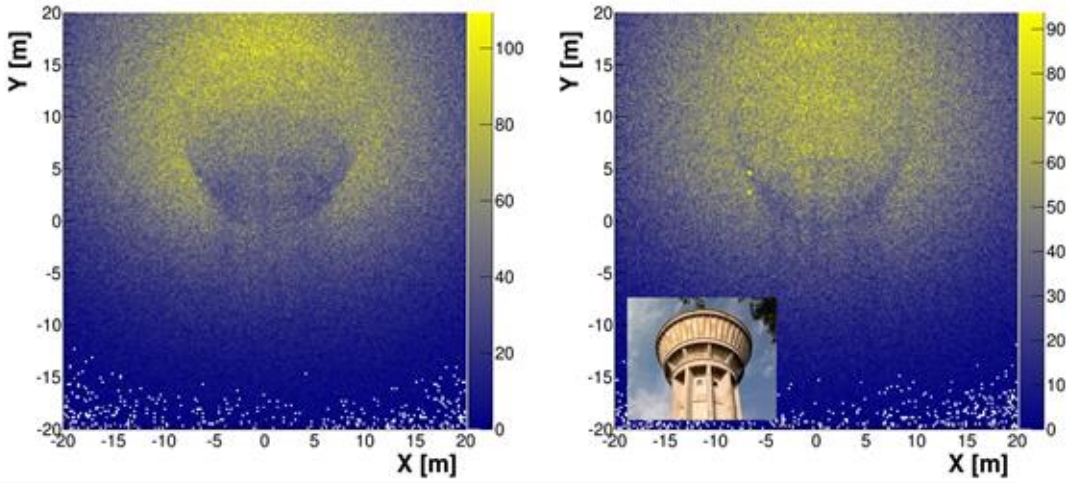


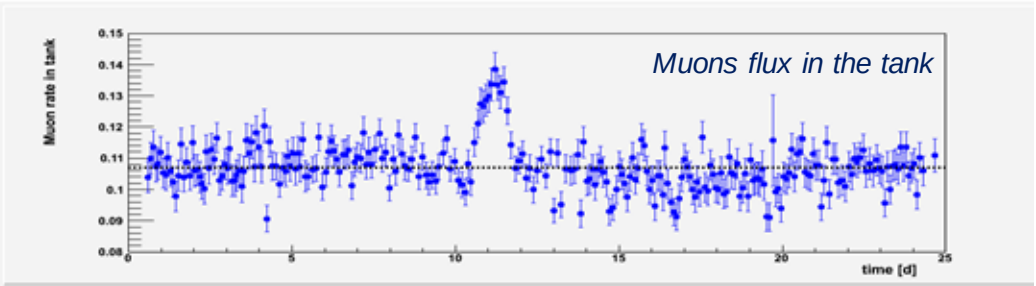
→ First muography of a recognizable building

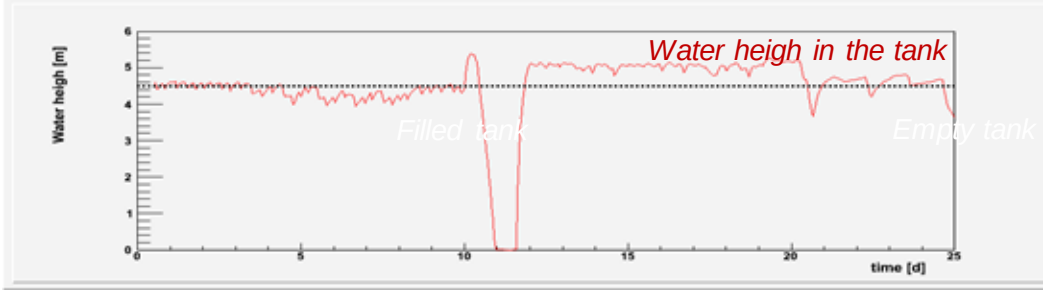
RESULTS (2/2)

- Dynamic Muography:

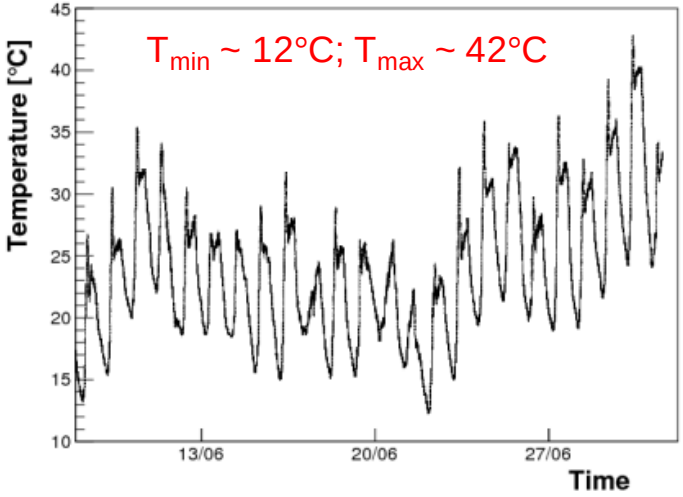
Integration time: 4 days each (position 2)







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



- *30 W on solar panel*

WATTO→MISSION SCANPYRAMIDS

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

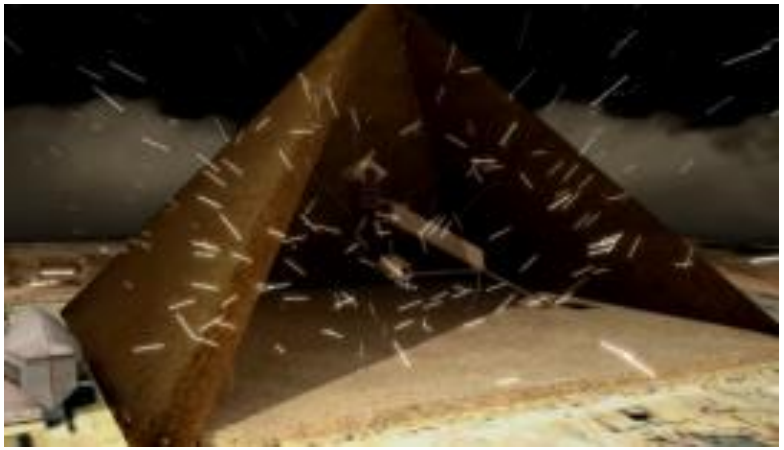
→ *Email to Mehdi Tayoubi on October 26th*

→ *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*



Mehdi Tayoubi
President & co-founder

Innovation Strategist

Hany Helal
Vice-president & co-founder

Professor, Faculty of Engineering, Cairo University
Former Minister of Higher Education & Scientific Research

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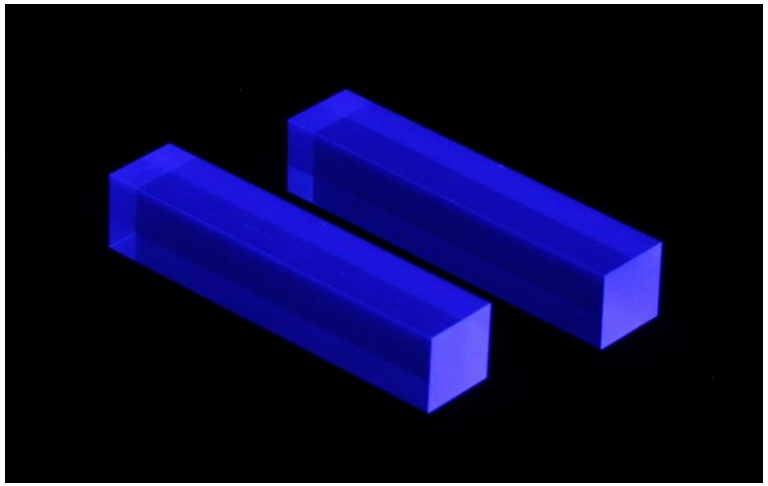
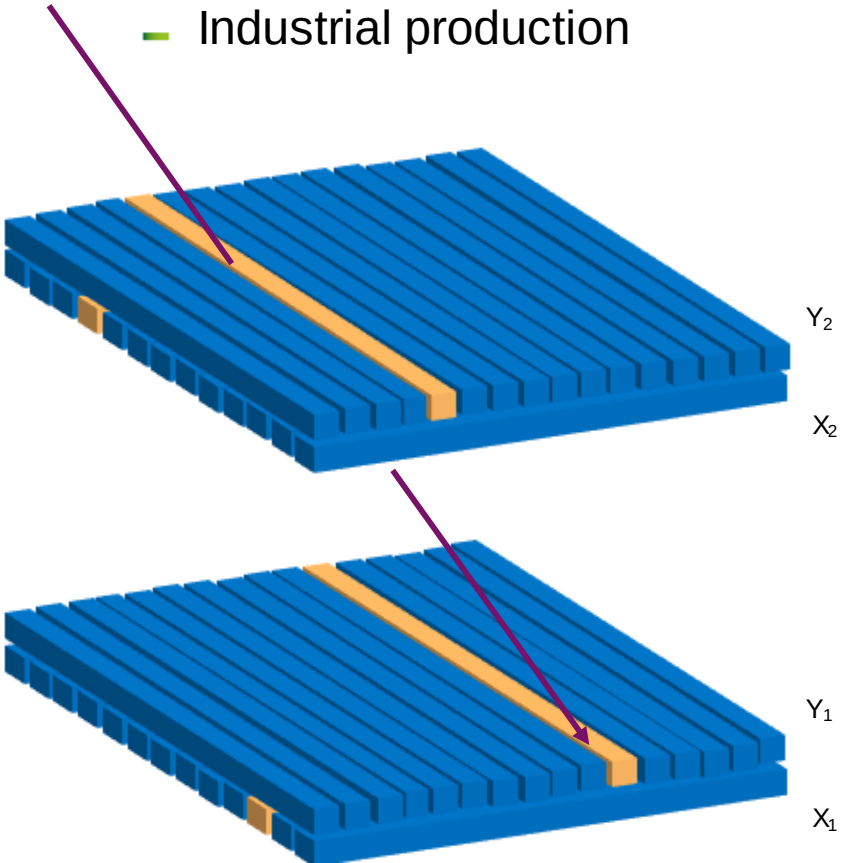
SCINTILLATION (KEK)

- Plastic Scintillators:
  - Well-known technology
    - robust
    - large area
  - Industrial production

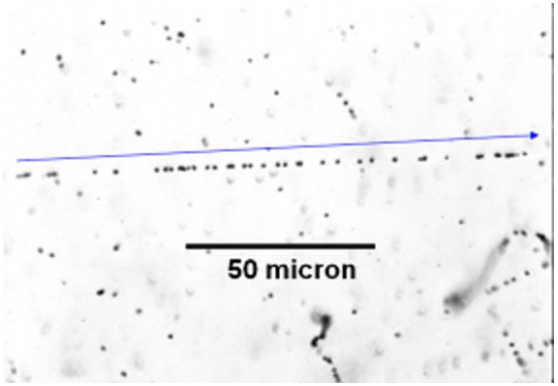


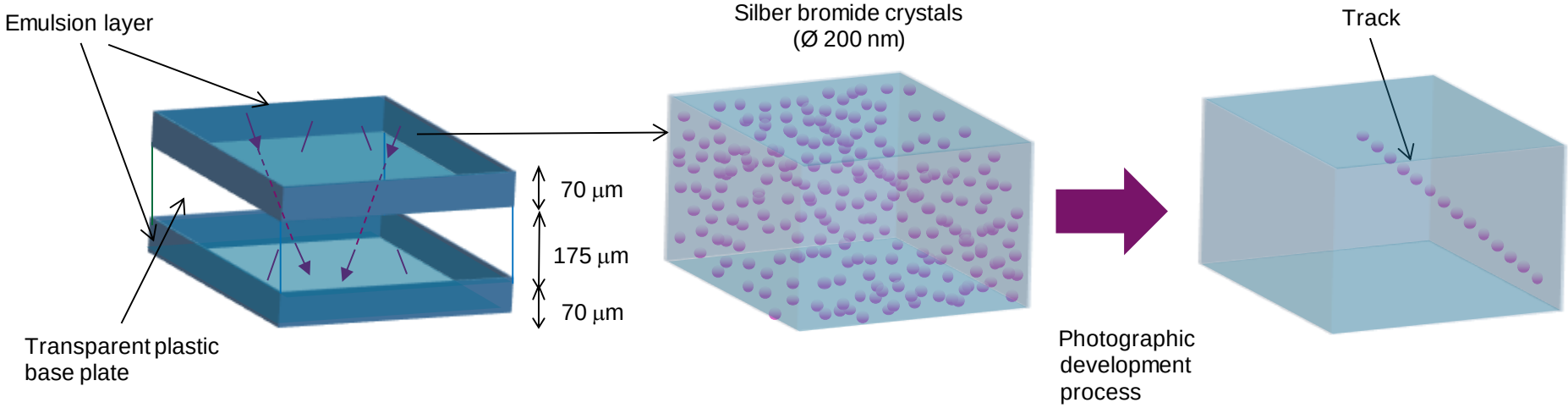


- Each coordinate: 120 bars of 120 cm x cm x 1cm
- Read by MPPC (Multi-Pixel Photon Counter)

NUCLEAR EMULSION (NOGOYA UNIV.)

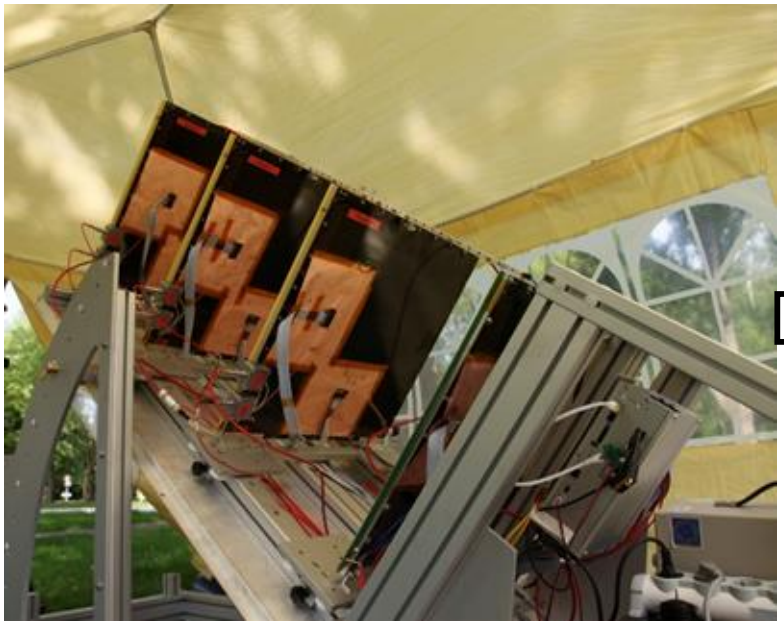
- Photographic plate to record tracks from charged particles (30's)
  - Easy to operate
    - Large area
    - No power
  - Micrometric spatial resolution





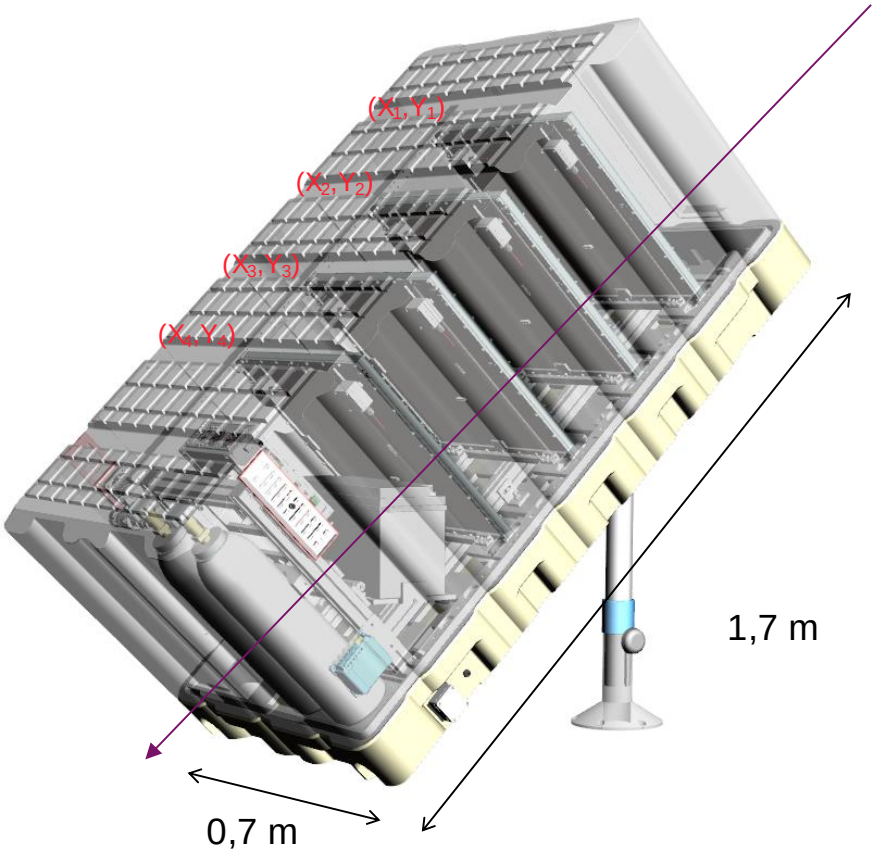
WATTO→MISSION SCANPYRAMIDS

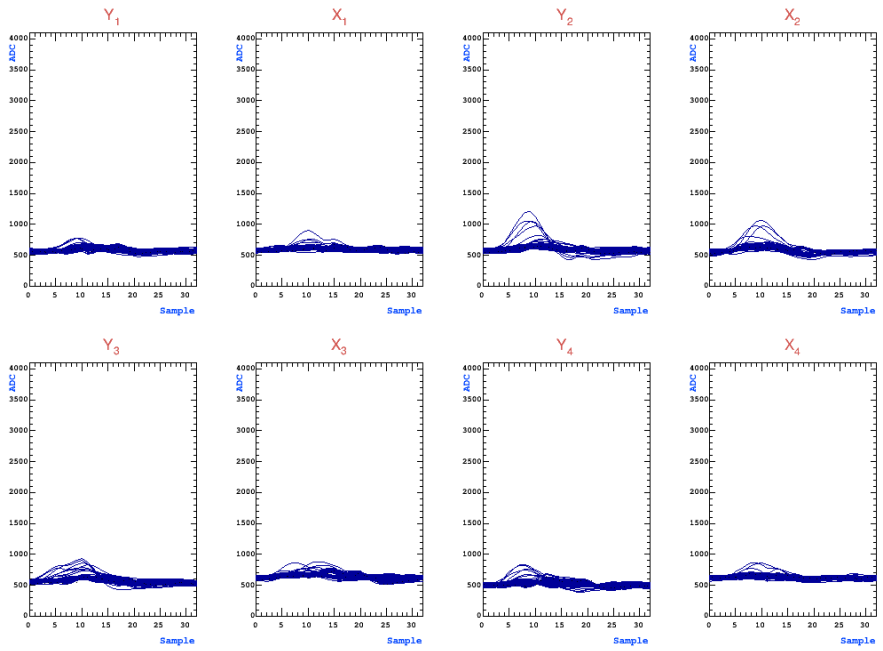
- Telescopes : 1 → 3
- Chassis → valise
- Detection plane: prototype (Cern) → serial (Elvia-PCB company)
- Building period: 9 months → 3 months
- Weight : ~ 200 kg → ~ 130 kg
- Detector high voltage: independent of temperature → f(T)
- Data: raw → raw + pre-processing



WATTO→MISSION SCANPYRAMIDS

- New telescope:
  - transportable and easily functional
  - 4 × 2D resistive Micromegas (version 2)
  - 3G connection for operation, monitoring and retrieve pre-processed data



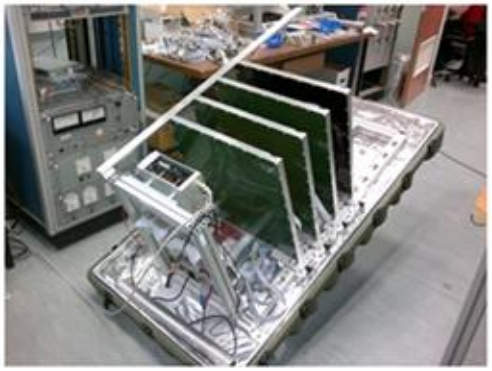


TELESCOPE INTEGRATION AND CONSTRUCTION

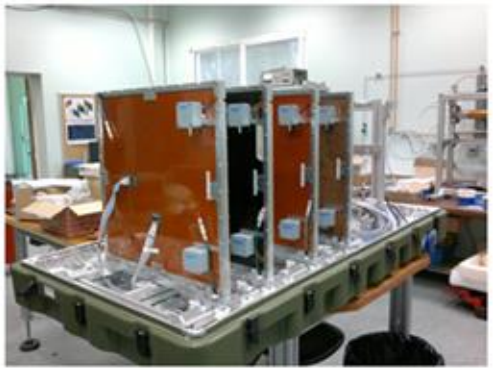
- Detection plane integration in clean room

- Tests in outdoor conditions

Alhazen (n°1)



Alvarez (n°2)



Brahic (n°3)

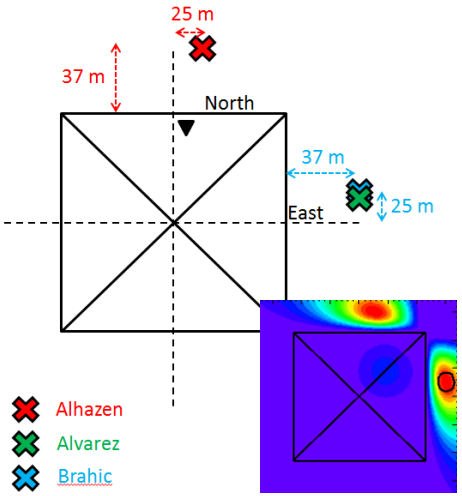
- 3 telescope assembled and shipped to Egypt measurement campaigns

GIZA PLATEAU INSTALLATION

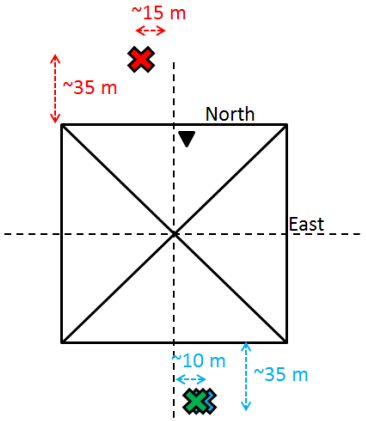
MEASUREMENT CAMPAIGNS

- 3 missions between 2016 & 2017

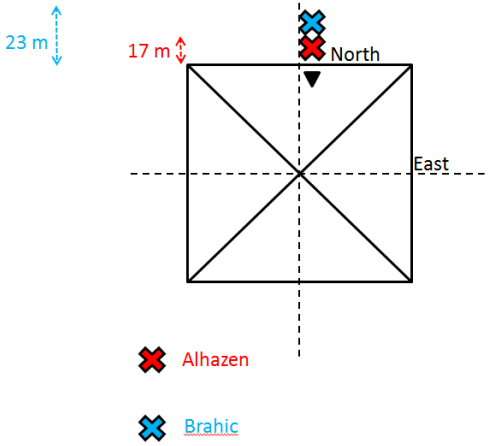
1st mission (jun-aug 2016)

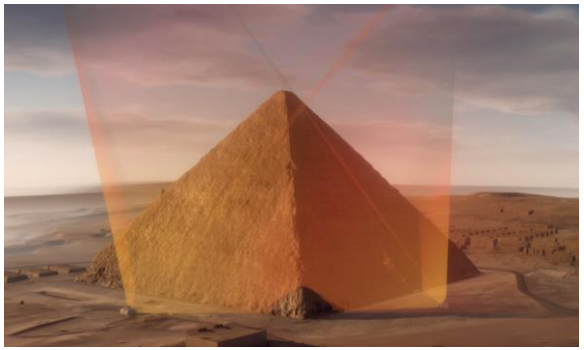


2nd mission (jan-april 2017)



3rd mission 3 (may-jul 2017)

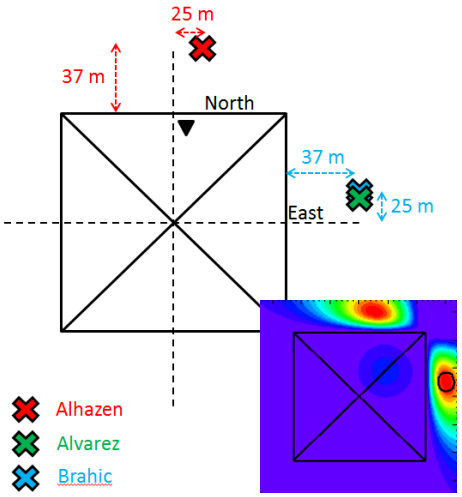




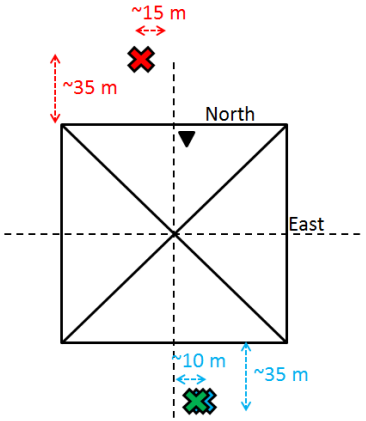
MEASUREMENT CAMPAIGNS

- 3 missions between 2016 & 2017

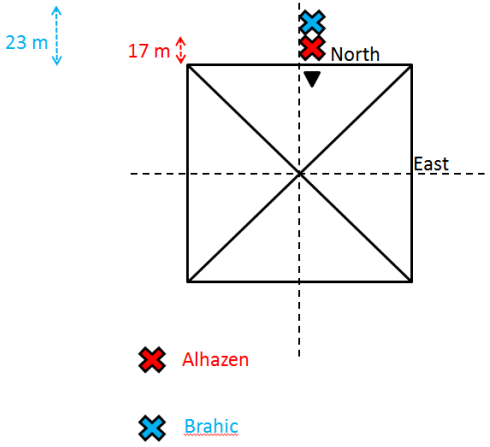
1st mission (jun-aug 2016)



2nd mission (jan-april 2017)



3rd mission 3 (may-jul 2017)



- Statistics: around 200 millions 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

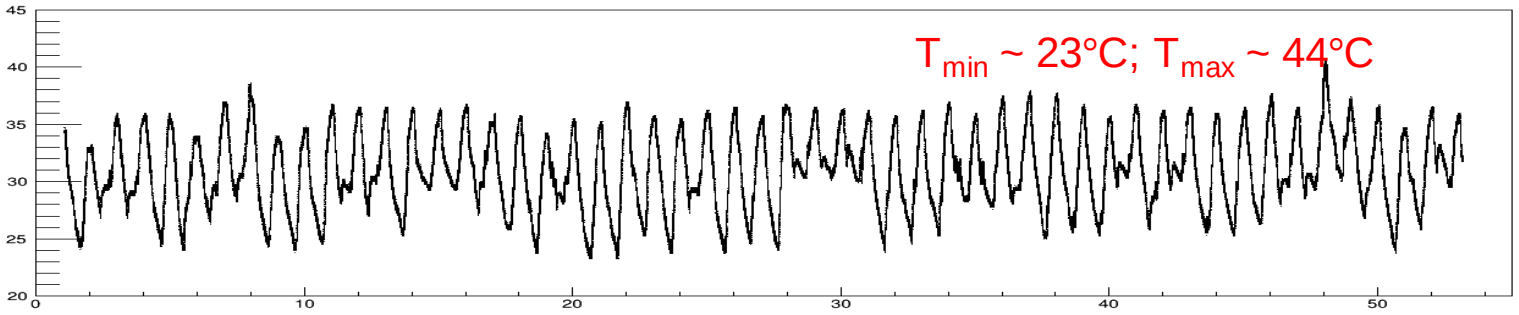
before

after

+ issues with 3G/4G

+ ...

- Temperature variations (gas & electronics & mechanics)

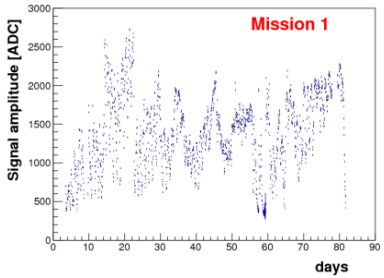


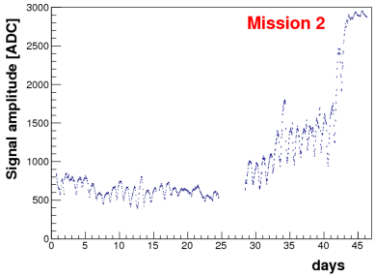
(instruments checked at Saclay between 2°C and 55°C)

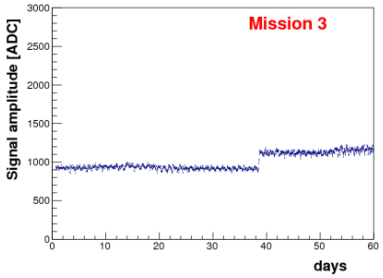
DATA TAKING

- Successive improvements of the instruments

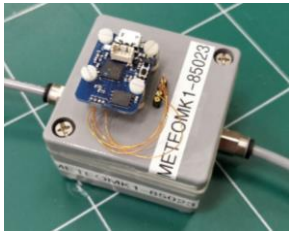
Signal stability





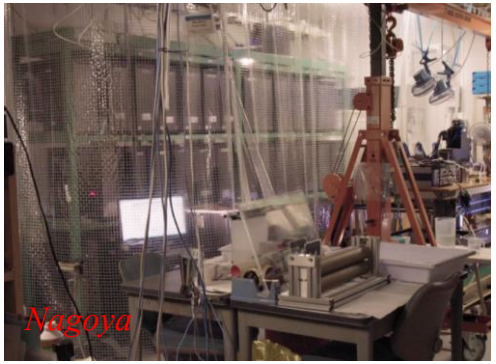


Monitoring of environmental condictions



Full, online analysis on the nano-PC

CEA



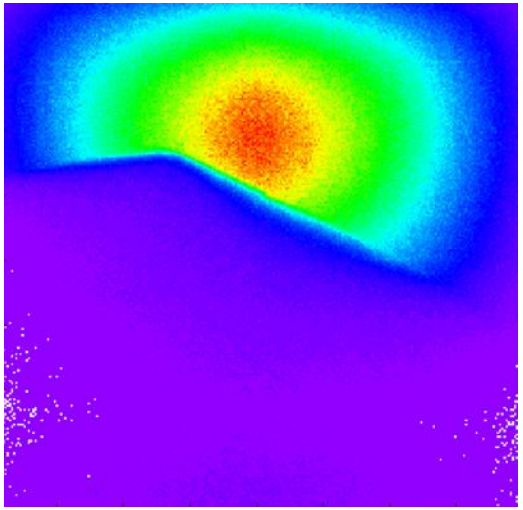
Nagoya

ANALYSIS

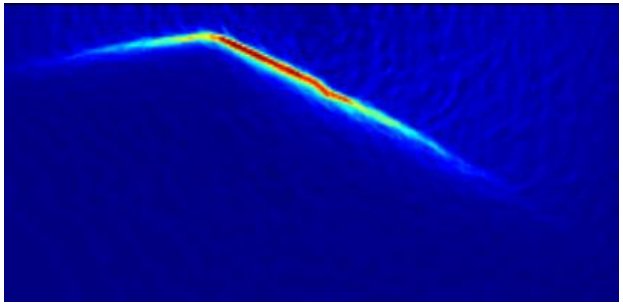
- Necessity to adjust photo and muo for comparison with 3D model

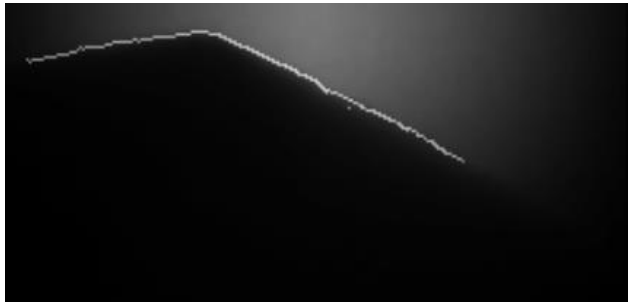
photo

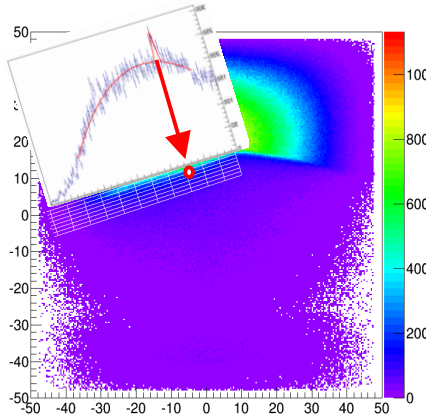
muo



- Requires edge detection (image filtering)

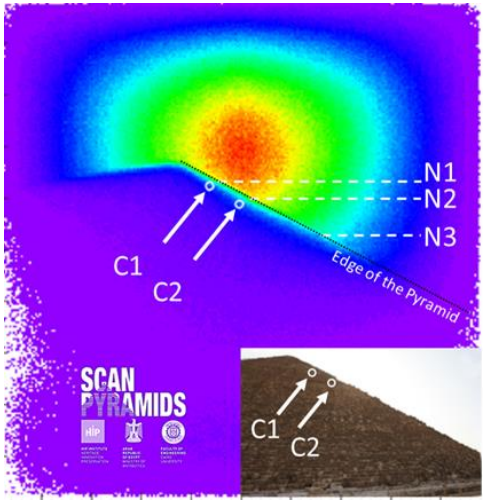


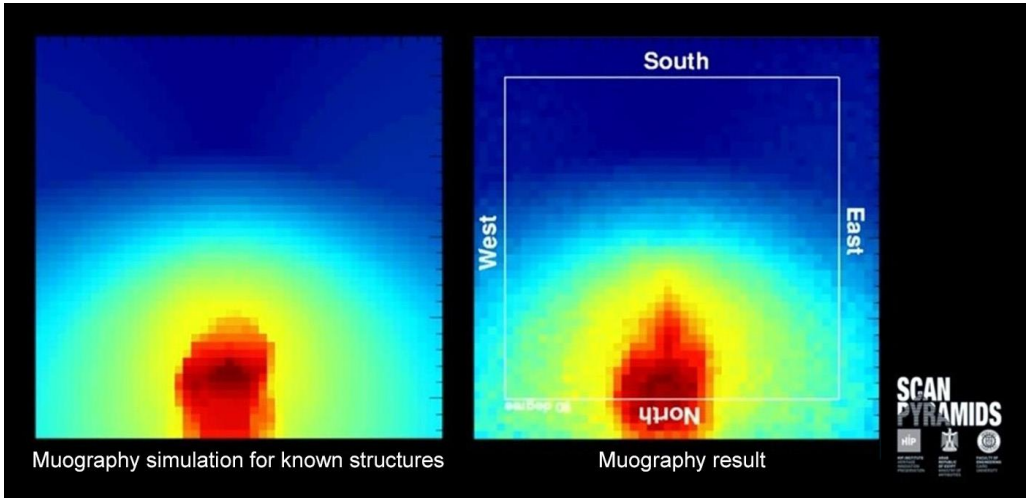




RESULTS - 2016

- October 2016: discoveries of 2 voids in the pyramid



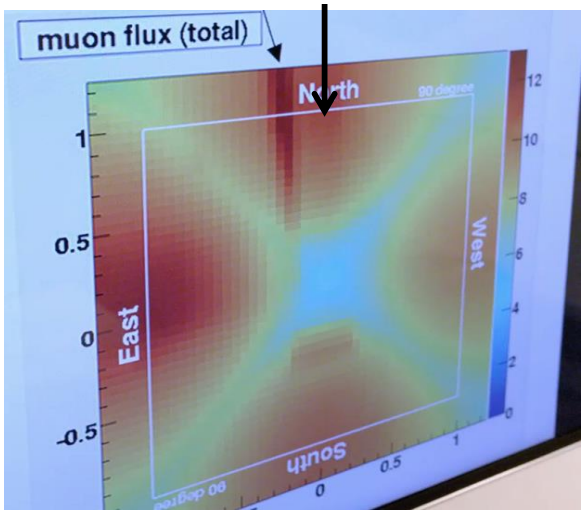


⇒ ***Question for egyptologists: what is the purpose of these voids?***

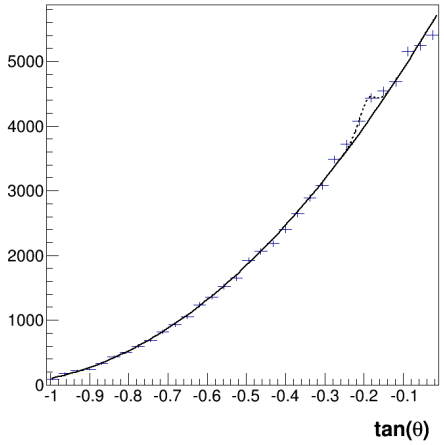
RESULTS

- 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

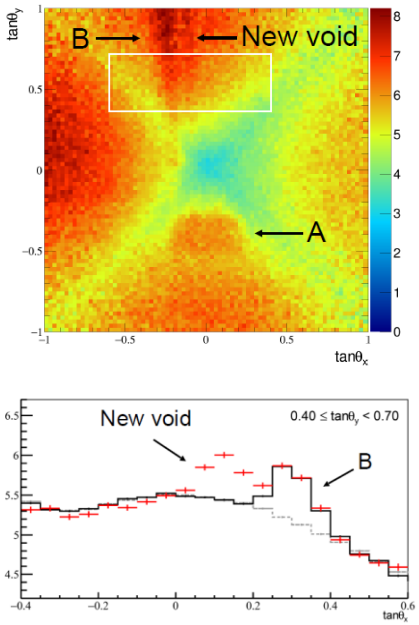
⇒ **Dedicated measurement campaign started**

- *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*

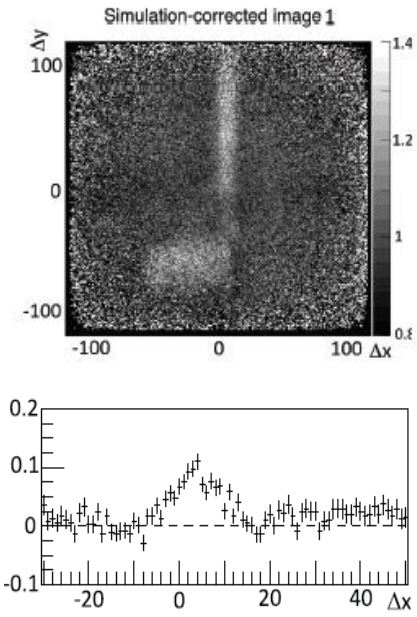
RESULTS (FROM NATURE PAPER)

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

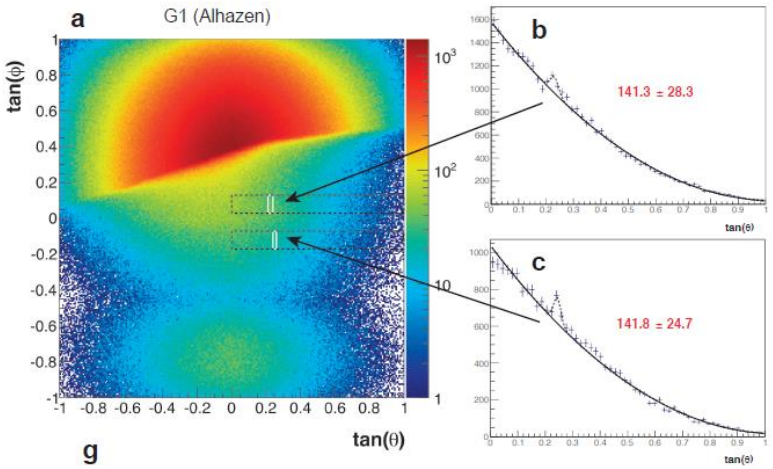
Nagoya



KEK

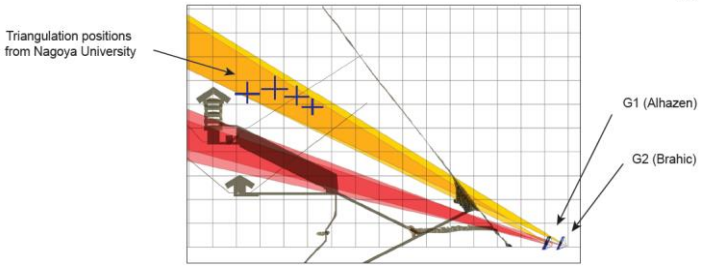


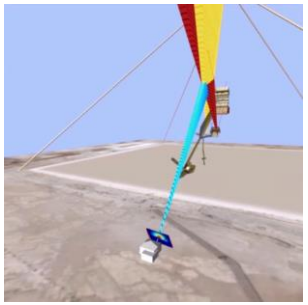
CEA



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

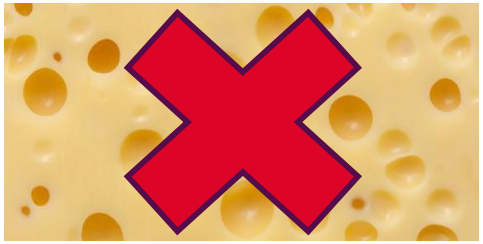
- Good triangulation with Nagoya and CEA instruments

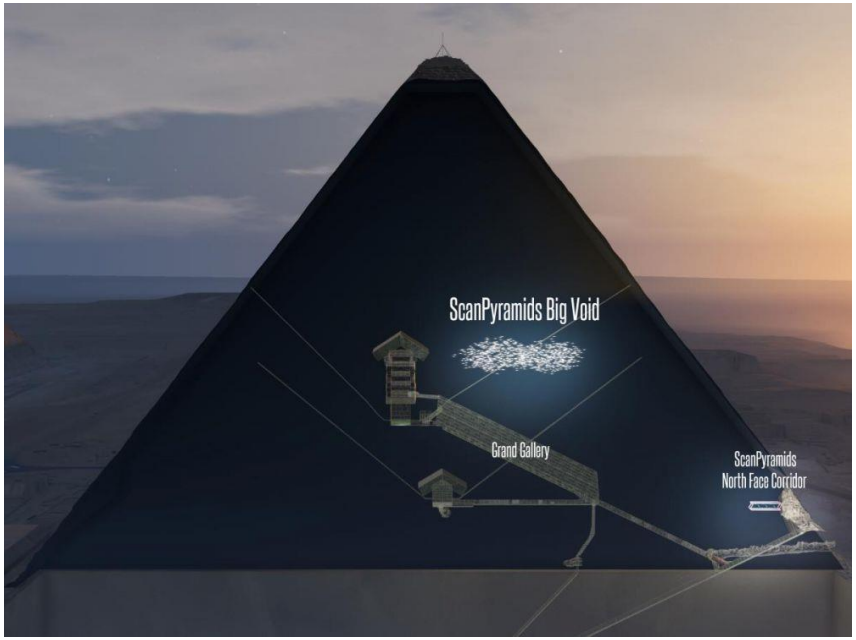


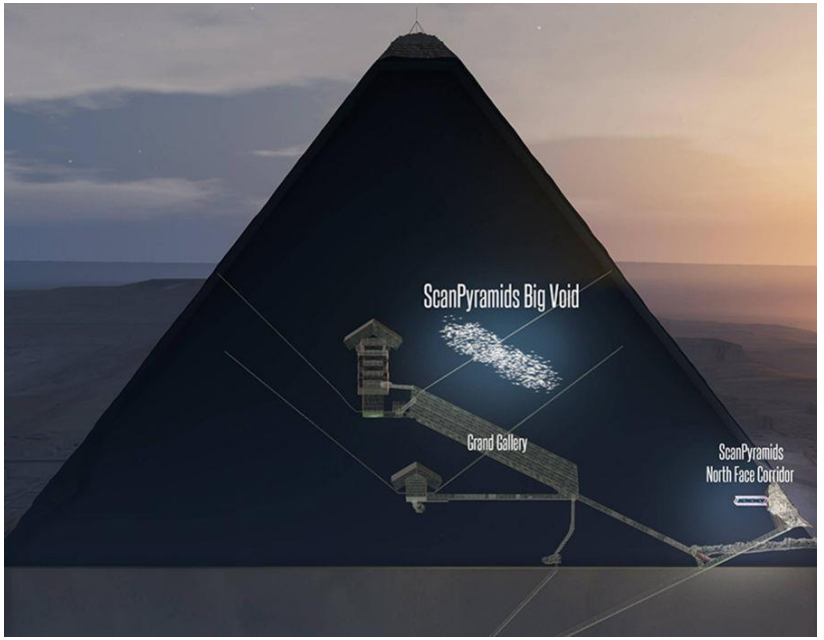


SCANPYRAMIDS BIG VOID

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





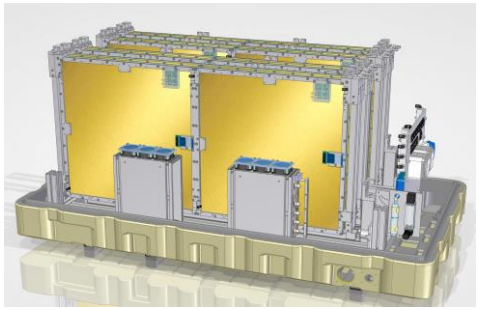


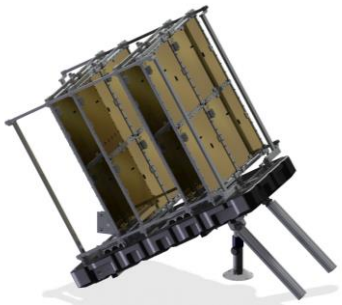
- *Volume estimate: several hundreds of m3*
- *Lenght: > 30 m*
- *Inclined or horizontal…* ⇒ **More measurements needed!**

NEXT STEP(S)

- Electronic management of the gas flow with new HVPS-v2 card
  - *Test in progress*

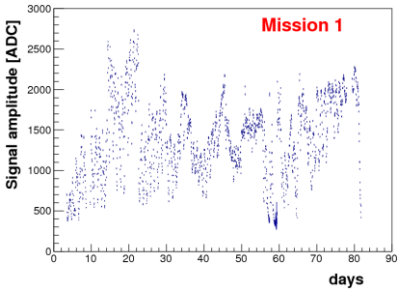
- Proposition of a mission inside the pyramid to better observe the Big Void
  - *Goal: < 1 m^3 in 4 months*
  - *Could take place in early Spring 2018*
- Longer term: sealed, bigger telescopes and TPC
  - *Vacuum chamber at Saclay, test started (a la Harpo!)*

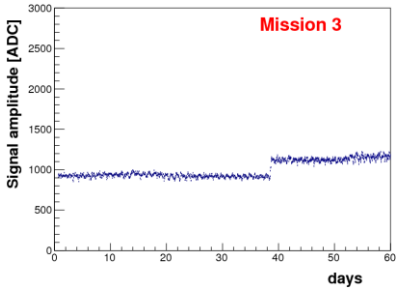




CONCLUSION (BEYOND BIG VOID…)

- MPGD robust enough for extreme condition 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	30 cm x 25 cm / unit:	1.2 m x 1.2 m	50 cm x 50 cm
(for this analysis)	0.75 m x 0.6 m (NE1) 0.9 m x 0.5 m (NE2)		
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

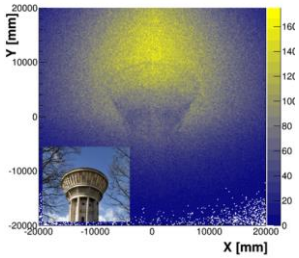
- Key ingredients for large scale, societal or industrial applications

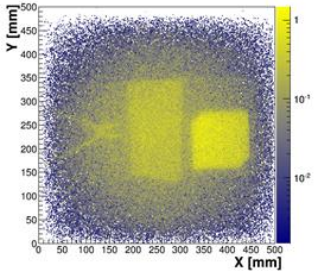
  - ***Manufacturer (ELVIA)***
  - ***Potential integrator (Iris Instruments)***
  - ***Media coverage (advertisement)***

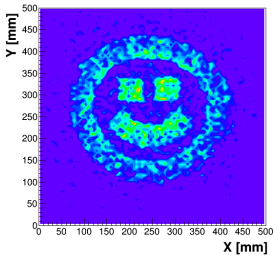
CONCLUSION (BEYOND PYRAMID…)

- Deep imaging: many more applications

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



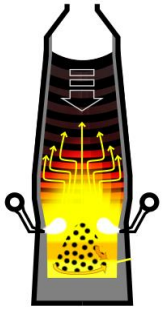




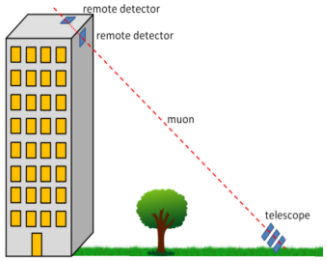
Civil engineering

Dismantling, nuclear waste

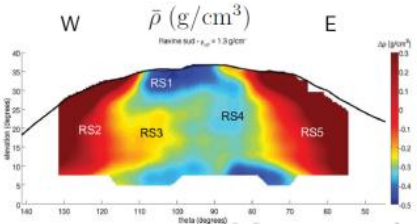
Bast furnace



(muon) metrology



Volcanology



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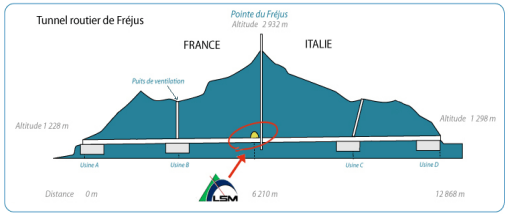
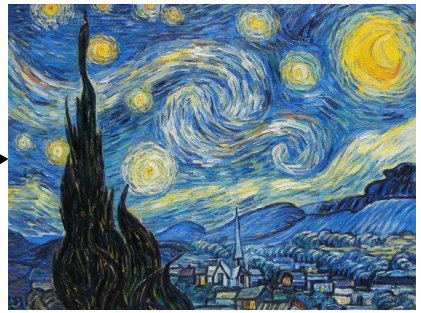
+…

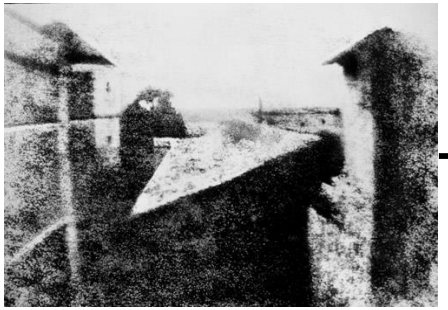


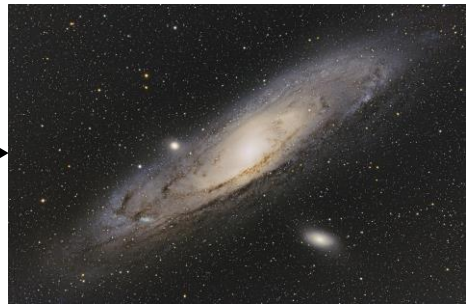
MUOGRAPHY (BEYOND IMAGINATION…)

- Painting



- Photography





- Muography?