cea irfu

Muon tomography using Micromegas technology

David Attié

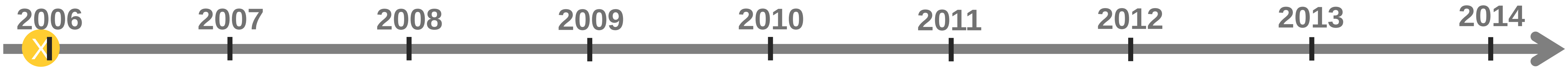
Celebrating Ioannis, October 5th, 2023

1. Preambule

My contribution to Resistive Micromegas

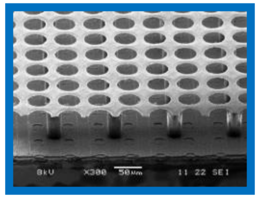
My contribution to Resistive Micromegas

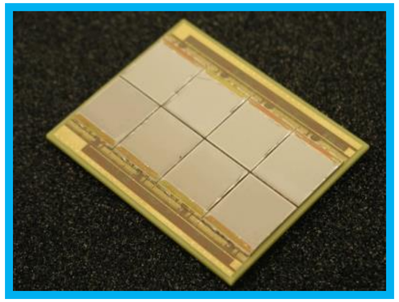
- After a PhD in Space γ-ray Astrophysics (INTEGRAL/SPI)
  - HPGe detectors
- Courtesy visit in Astrophysics Department in December 2005 → Eric Delagnes → Paul Colas X

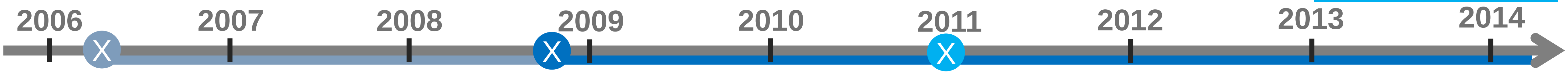


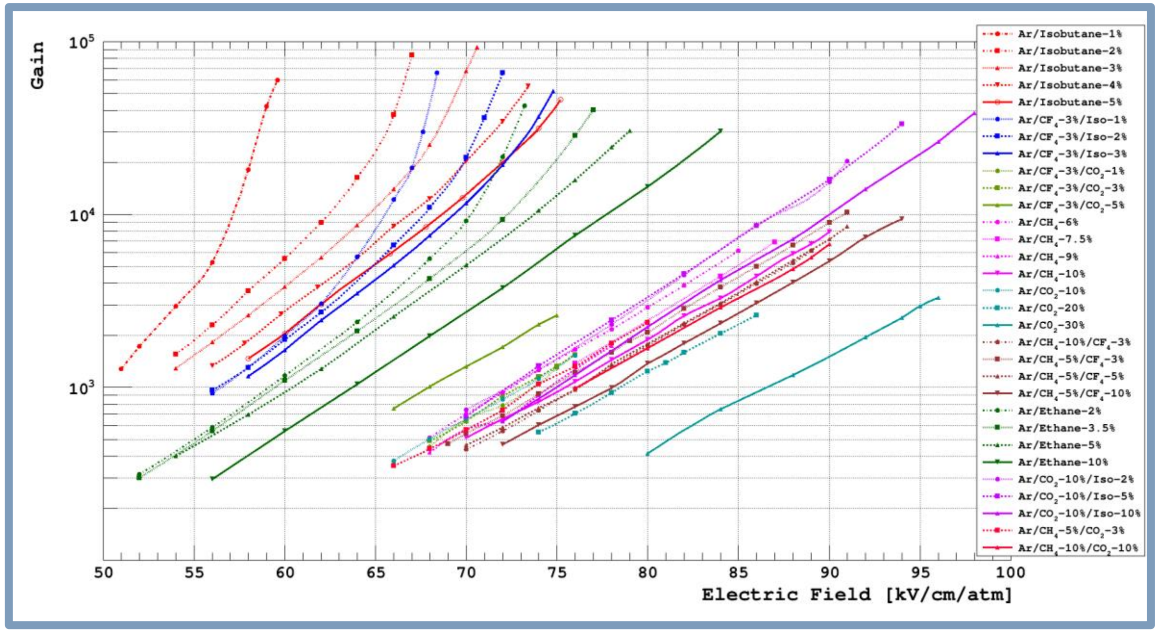
My contribution to Resistive Micromegas

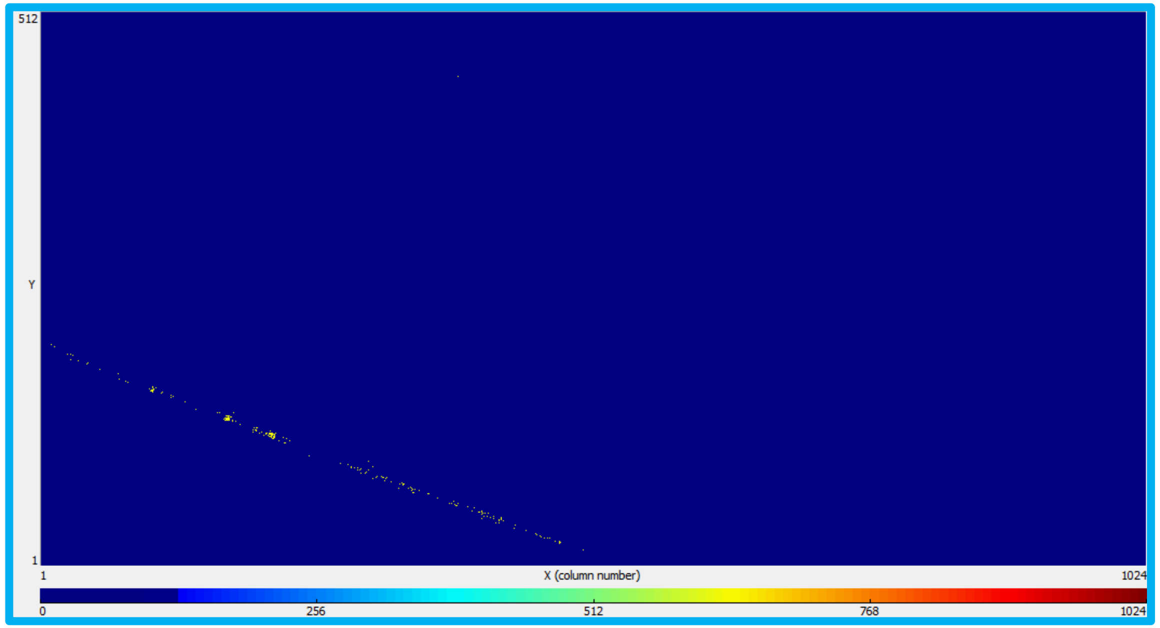
- Postdoc position on digital TPC: X
  - Gas detector novice
  - Systematic study of gas mixtures
  - First small digital TPC using TimePix + Micromegas
- Permanent position at CEA: X
  - First large digital TPC (TimePix/Ingrid) X





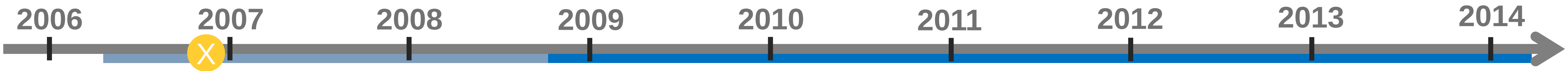


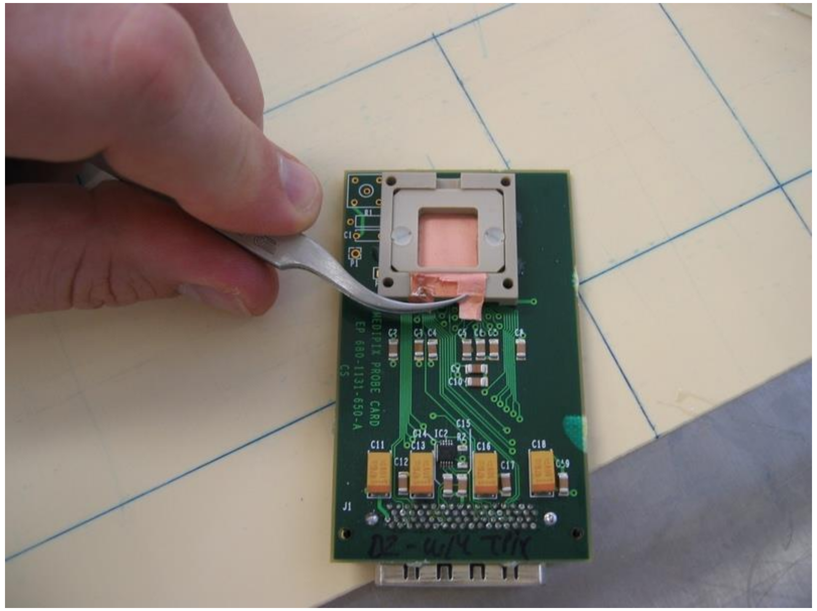


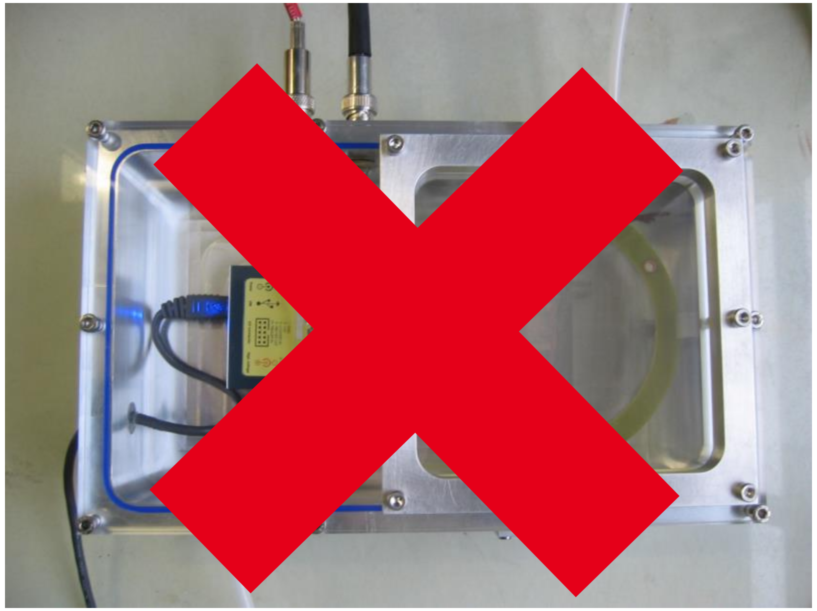


My contribution to Resistive Micromegas

- My first close interaction with Ioannis! (X)
  - Micromegas copper grid on TimePix **without** resitive layer for spark protection
  - My first gas box
  - But need **to borrow a CAEN power supply to Ioannis lab** for the first test







Conclusion:

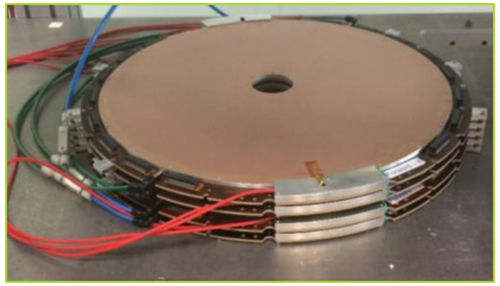
So we must find an « Ioannis' proof » solution to improve people trust in Micromegas detector!

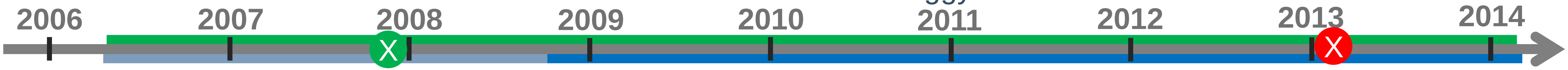
→ Resitive detectors?!

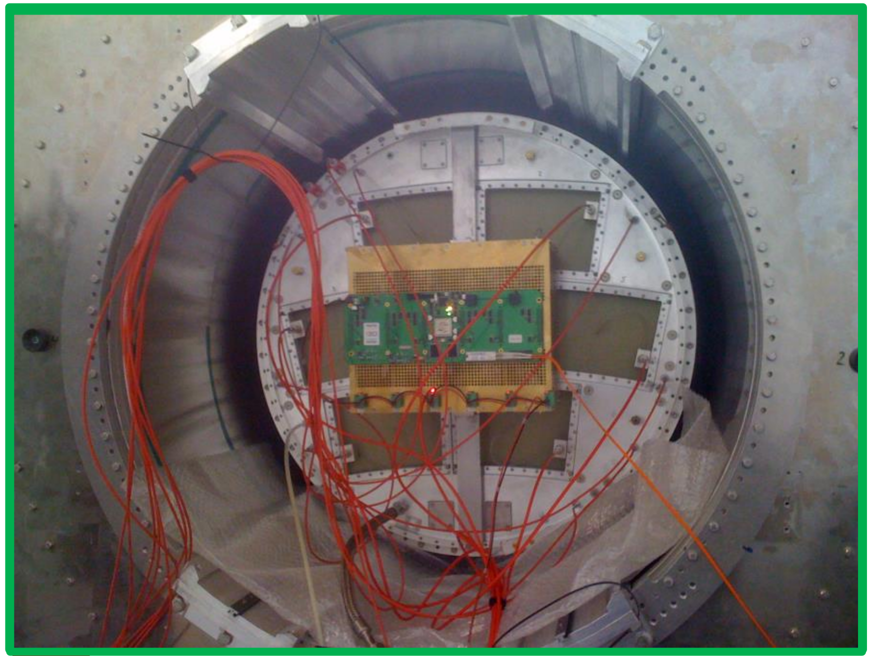
My contribution to Resistive Micromegas

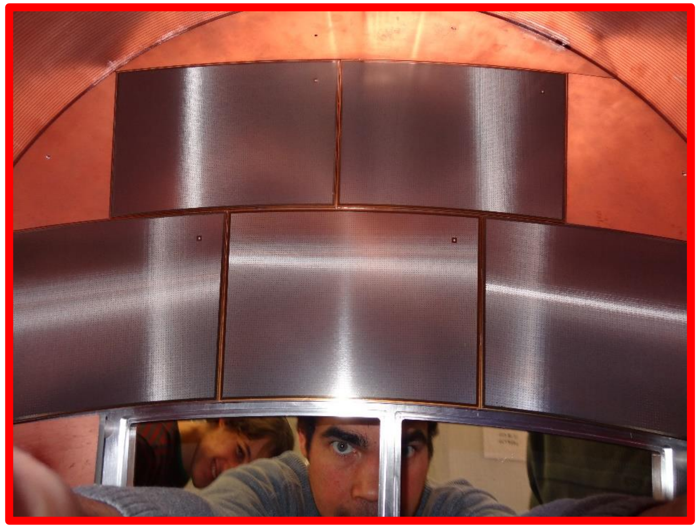
- Resistive Micromegas solution for ILC-TPC
  - Tests of several resistive coating with one module X
  - Beam tests in a large prototype TPC
  - Unprotected integrated electronics with 7 modules X

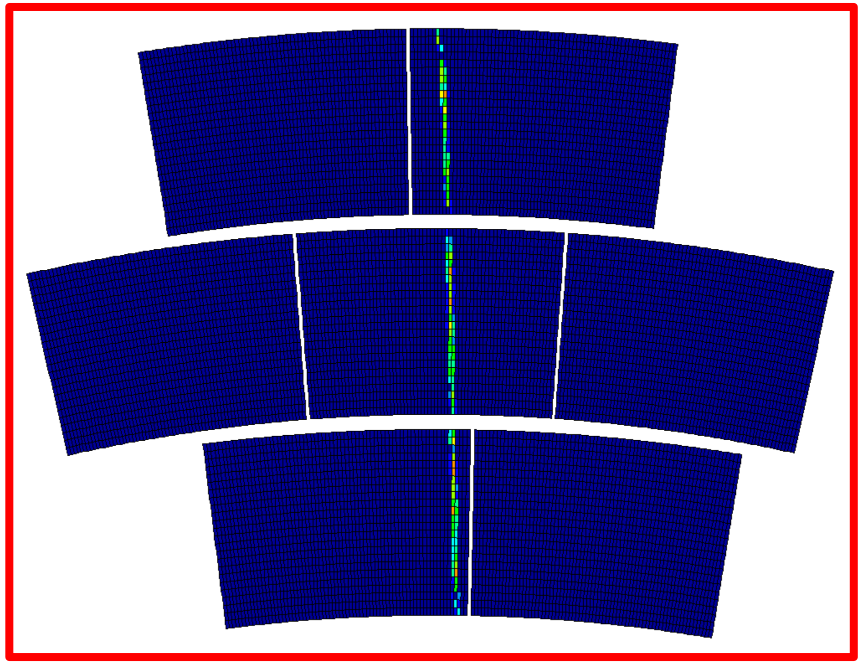
- MAMMA collaboration
- HARPO
- Clas 12
- T2K
- PiggyBack…







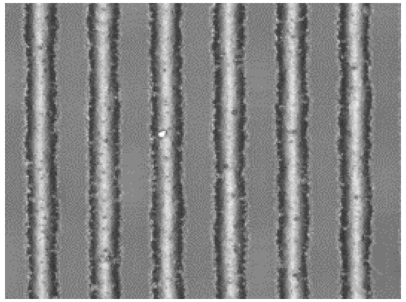




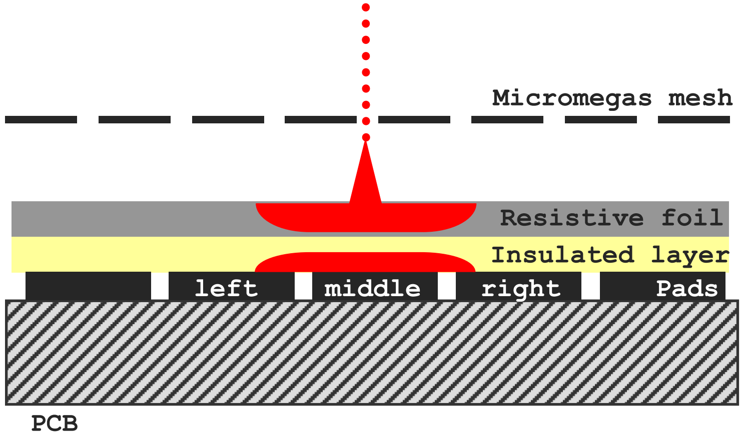
Micromegas Technology

- First introduced by Dixit *et al.* NIM A518(2004)721 to improve spatial resolution
- Use material properties (resistivity) and geometry (insulator thickness) to spread charge over several pads
  - Resistive ink
  - Carbon Loaded Kapton (CLK)
  - Diamond Like Carbon (DLC)
- Choice of resistivity: from 100 kΩ/□ to 10 MΩ/□
- Specific Pad Response Function (PRF) needed
- Advantages for resistive readout:

	Resistive Anode	
Properties	**Strips**	**Plane**
Charge dispersion	×	×
Spark protection	×	×
Multiplexing readout	×	
2D readout	×	
Readout segmentation	**Strips**	**Strips/Pixels**



Anode with strips



Plane anode

$$\sigma_r = \sqrt{\frac{2t}{RC}}$$

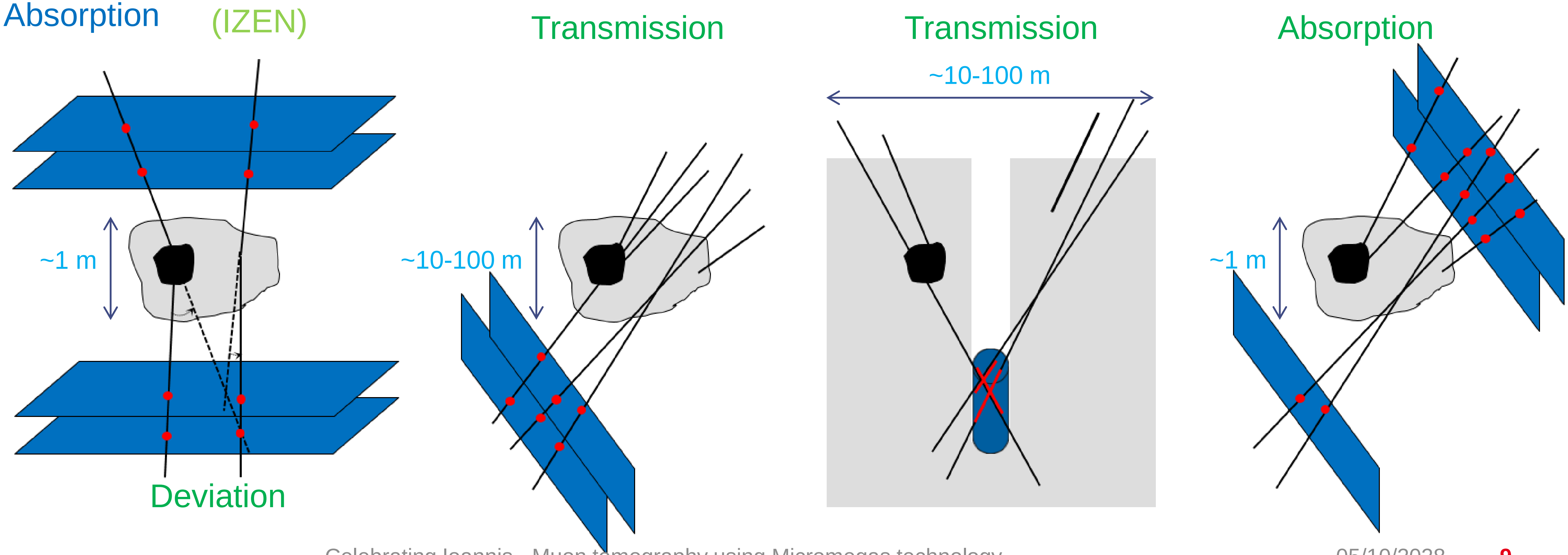
t≈ shaping time
RC from resistive layer

2. Muon Tomography

Imaging from muon flux

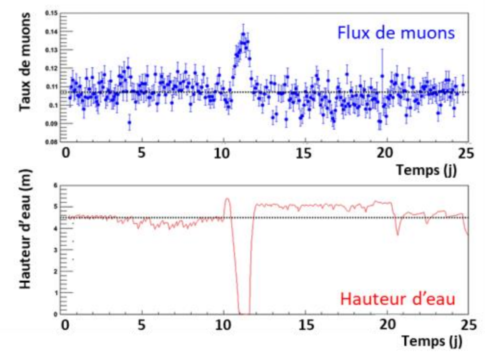
Muon tomography – Principle

- Enable a non-invasive but penetrating imaging of density contrast using natural charged particles
- Muon tomography can be done using one of the three methods:
  - Deviation (M-Cube)
  - Transmission (WatTo, Scanpyramids, G2G3, INB72, EDF, D3DT)
  - Absorption (IZEN)



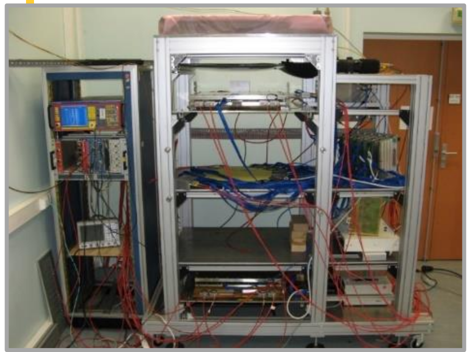
Muon tomography – Timeline

- Started with the R&D of resistive multiplexed Micromegas
- Used for hodoscope in cosmic test bench
  - Reduce channel number
  - Large area with accurate tracking



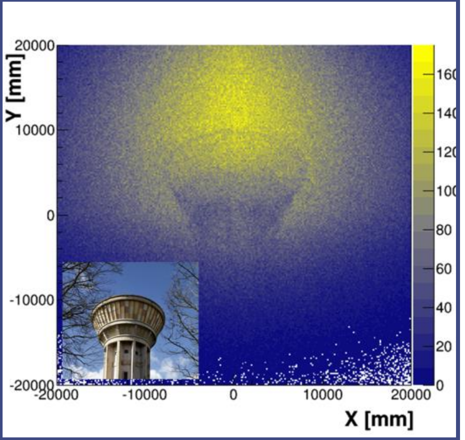
M-Cube :
U detected in less than 4 minutes

2012 — 2013 — 2014 — 2015 — 2016 — 2017



Cosmic bench for Clas12 detectors validation

M-Cube:
demonstrator for homeland security



WatTo (*Water Tower*)

1st muography HD online

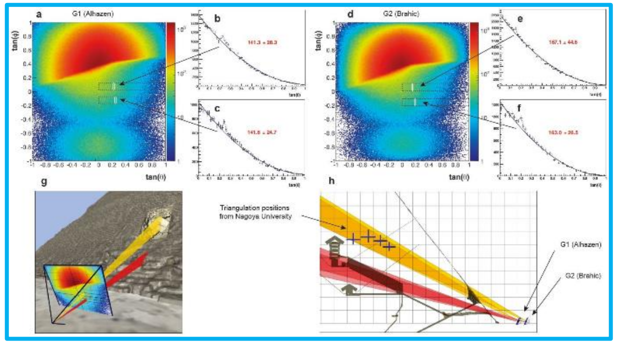
ScanPyramids

Muon tomography – Timeline

nature
International journal of science

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiro Morishima, Mitsuaki Kuno, Akira Nishio, Nobuko Kitagawa, Yuta Manabe, Masaki Moto, Fumihiko Takasaki, Hirofumi Fujii, Kotaro Satoh, Hideyo Kodama, Kohei Hayashi, Shigeru Odaka, Sébastien Procureur, David Attié, Simon Bouteille, Denis Calvet, Christopher Filosa, Patrick Magnier, Irakli Mandjavidze, Marc Riallot, Benoit Marini, Pierre Gable, Yoshikatsu Date, Makiko Sugiura, Yasser Elshayeb, Tamer Elnady, Mustapha Ezzy, Emmanuel Guerriero, Vincent Steiger, Nicolas Serikoff, Jean-Baptiste Mouret, Bernard Charlès, Hany Helal & Mehdi Tayoubi - Show fewer authors



Industrialization

IRIS INSTRUMENTS

Common lab

nature communications

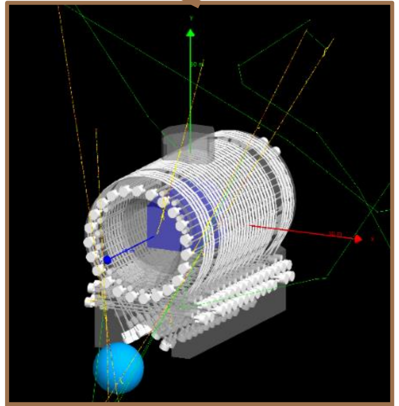
Precise characterization of a corridor-shaped structure in Khufu's Pyramid by observation of cosmic-ray muons

Sébastien Procureur[1], Kunihiro Morishima[2,3], Mitsuaki Kuno[2], Yuta Manabe[2], Nobuko Kitagawa[2], Akira Nishio[2], Hector Gomez[1], David Attié[1], Ami Sakakibara[2], Kotaro Hikata[2], Masaki Moto[2], Irakli Mandjavidze[1], Patrick Magnier[1], Marion Lehuraux[1], Théophile Benoit[1], Denis Calvet[1], Xavier Coppolani[1], Mariam Kebbiri[1], Philippe Mas[1], Hany Helal[4,5], Mehdi Tayoubi[5,6], Benoit Marini[5,7], Nicolas Serikoff[5], Hamada Anwar[4], Vincent Steiger[5], Fumihiko Takasaki[8], Hirofumi Fujii[8], Kotaro Satoh[8], Hideyo Kodama[8], Kohei Hayashi[8], Pierre Gable[9], Emmanuel Guerriero[9], Jean-Baptiste Mouret[10], Tamer Elnady[11], Yasser Elshayeb[4], Mohamed Elkarmoty[4]

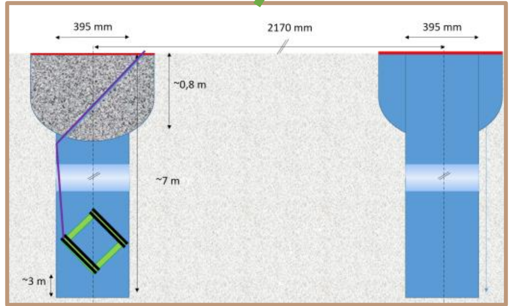
2017 — 2018 — 2019 — 2020 — 2021 — 2022

MIMOSA

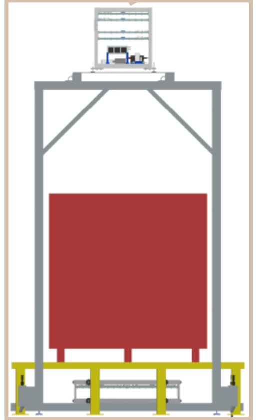
Maison de l'Imagerie Muonique Ouverte aux applications Sociétales et Académiques



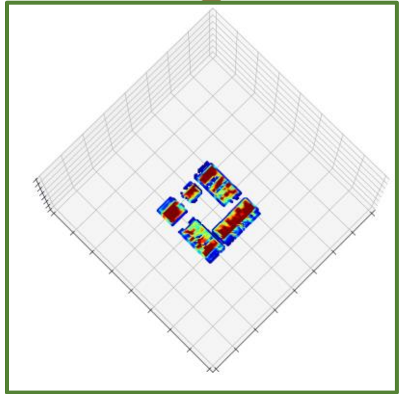
G2G3



INB72



IZEN



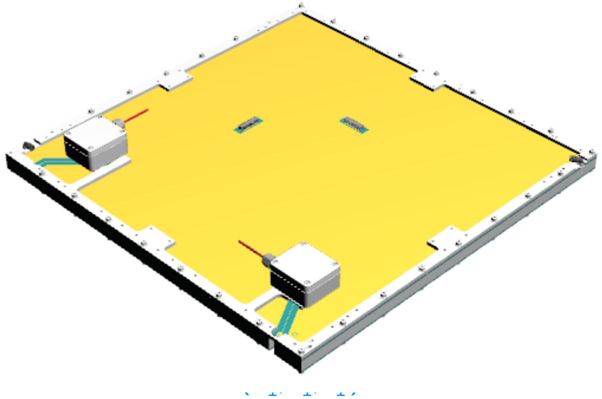
G3 nuclear reactor (NR)

1st muography of a military NR

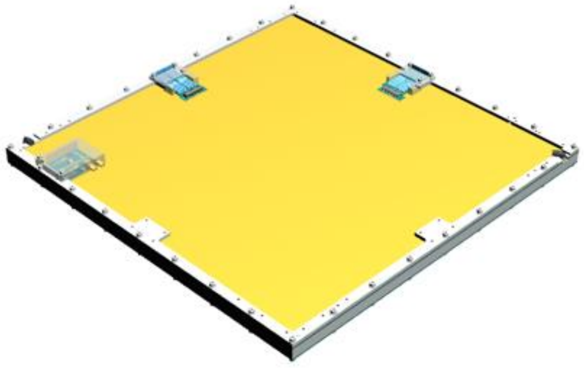
Nuclear dismantling projects

MultiGen detector – Basic element of a telescope

- MultiGen detector
  - Resistive strip bulk Micromegas
  - 2D readout (X & Y) genetic multiplexing
  - PCB size: 546×546 mm²
  - Active area: 500×500 mm²
  - Can be used in mosaic



MultiGen v2

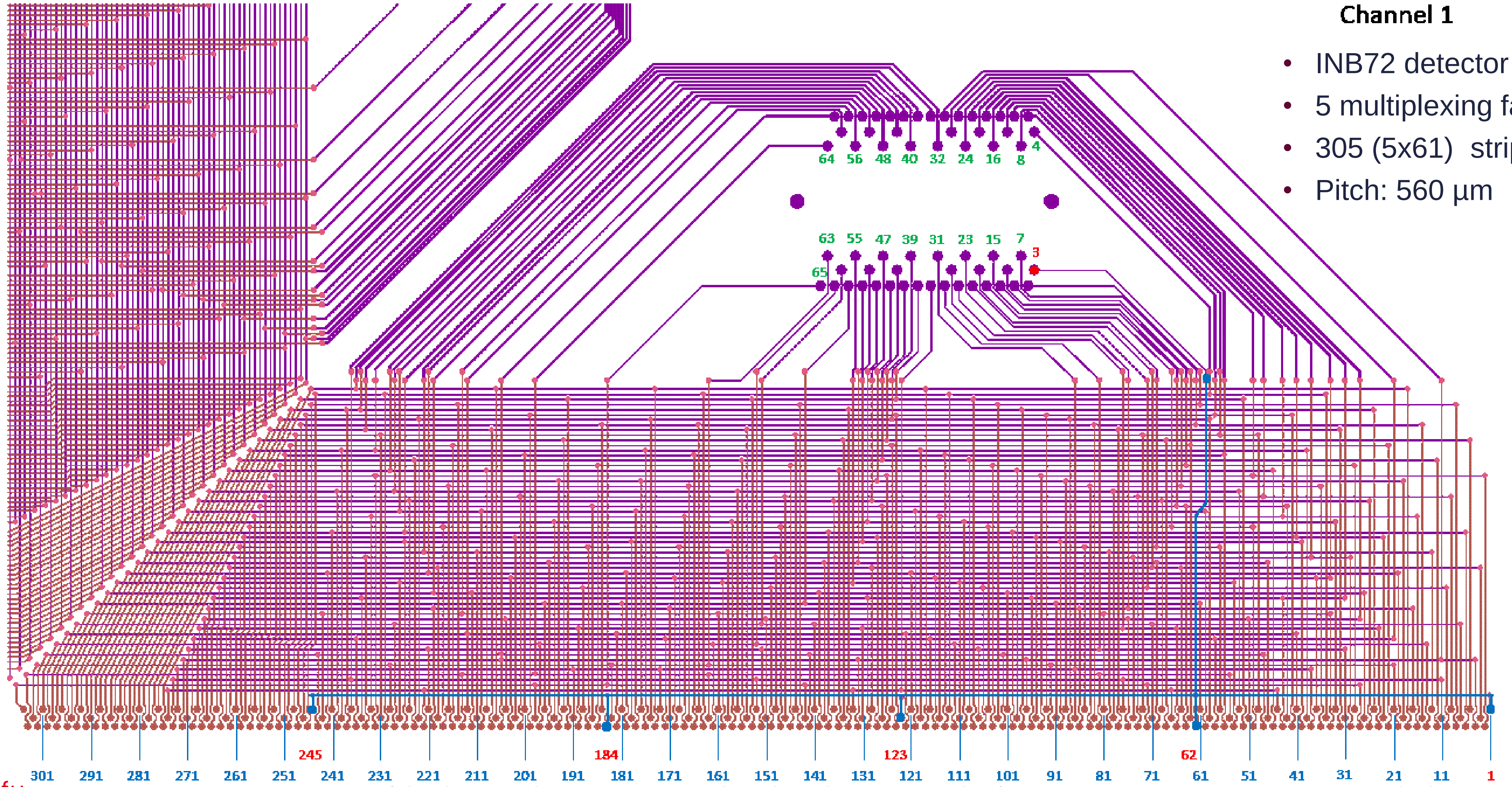


MultiGen v3-v4

- Evolution since 2014: from prototype to serial
- Since 2021 working on replacement of Pyralux by Vacrel

MultiGen Version	Multiplexing Family	Strip number	Strip pitch (µm)	Year	Produced Detector	Improvement
v1	17*	1024	488	2014	7	(*) one family incomplete: 13 strips missing
v2	17	1037	482	2015	42	Complete families; grounding plane added
v3	17	1037	482	2017	50	Connectors moved to sides; HV filters on PCB
v4	12	732	683	2019	52	Number of family reduced to 12; resistivity increased
INB72	5	305	560	2022	8	Smaller detector (200×200 mm²) for specific application

MultiGen detector – Illustration with 5 families

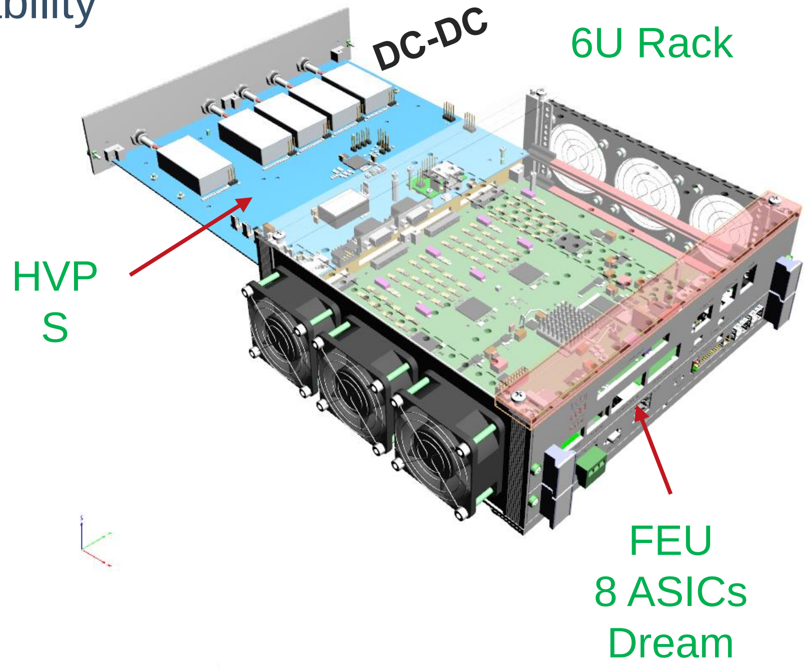


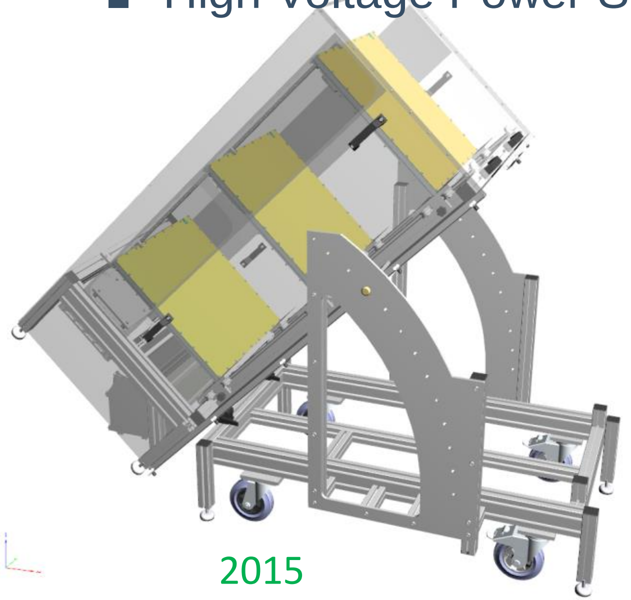
Channel 1

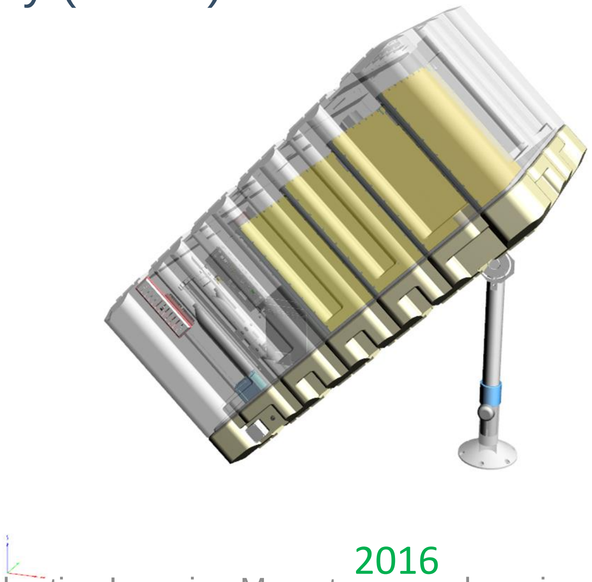
- INB72 detector
- 5 multiplexing families
- 305 (5x61) strips
- Pitch: 560 µm

Telescopes based on MultiGen

- Evolution of the CEA/Irfu telescope: towards compactness and transportability
  - 2015: WatTo, ~200 kg
  - 2016: ScanPyramids (outside), ~130 kg
  - 2018: ScanPyramids (inside) cube, ~45 kg
  - 2019: G2G3, EDF, …, optimized cube, ~45 kg
- CEA/Irfu's electronis cards
  - Front-End Unit (FEU) card developed for Clas12
  - High Voltage Power Supply (HVPS) card dedicated to muon







Benches of Muon Tomography

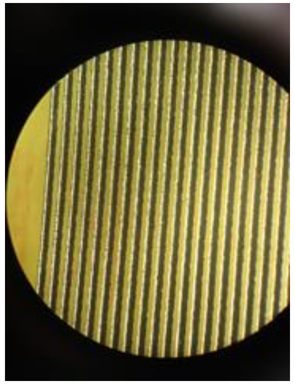
- Benches built for specific applications
  - M-Cube: smuggled "Special nuclear material" (SNM)
  - ENTRANCE: EfficieNT Risk-bAsed iNspection of freight Crossing bordErs without disrupting business
  - IZEN: waste package inspection

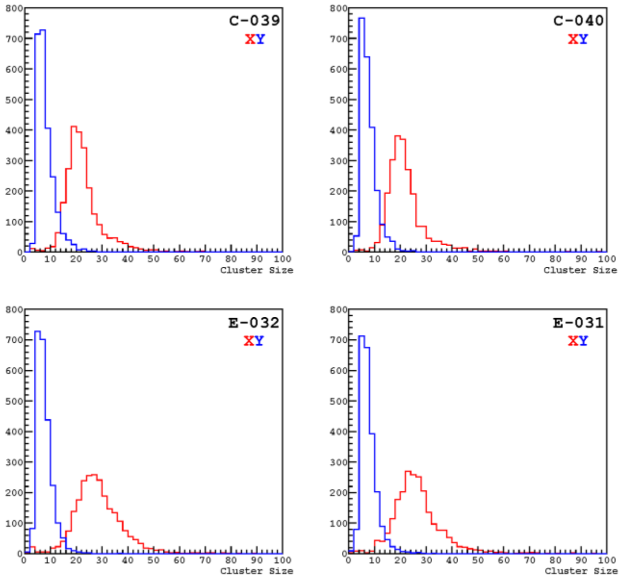
2014-2017

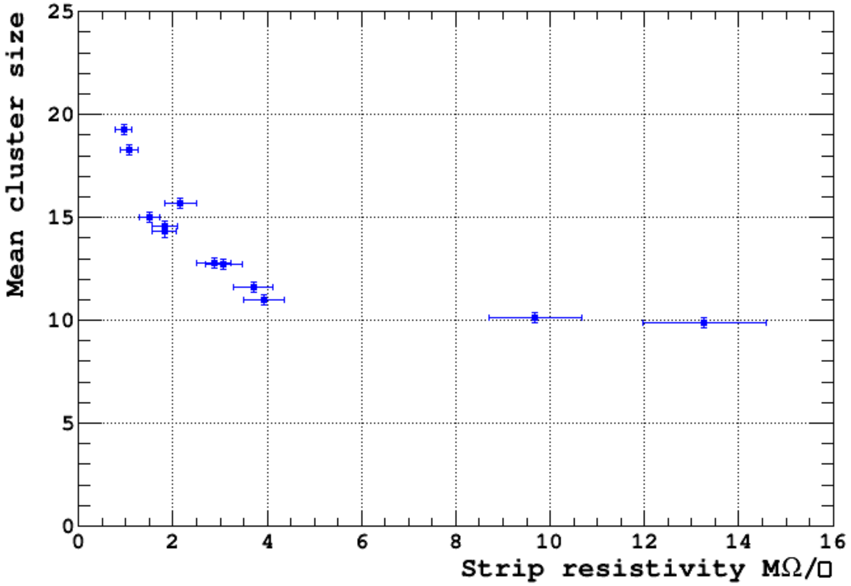
2020-2023

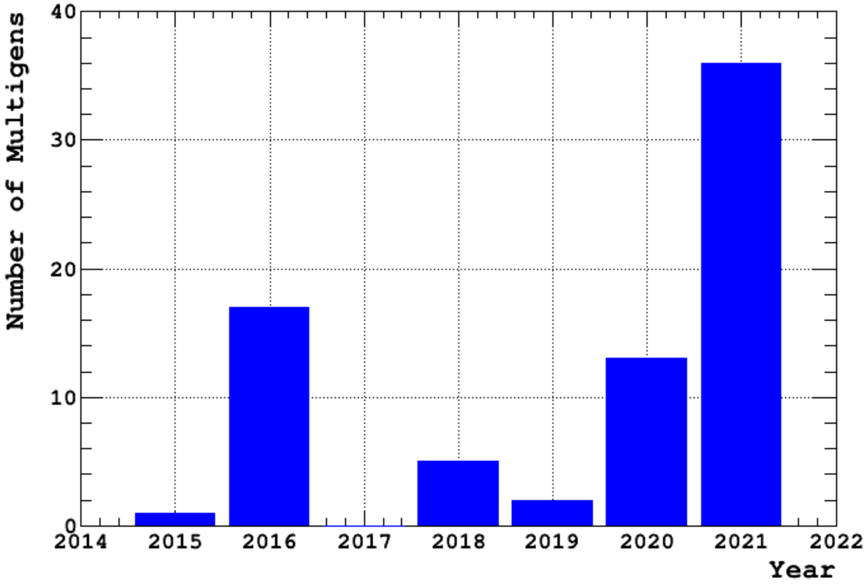
Resistive strip and detector production

- Resistive strip with high resistivity strip requested
  - R&D made over two years
  - CEA/Irfu the only producer by screen printing left
  - Target resistivity between 1&5 MΩ/□
- Detector manufacturing transfer to Elvia-PCB
  - Started in 2014
  - Succeed after many years until obsolescence of Pyralux → Vacrel









Conclusions

- Micromegas detectors made a late start in the very active field of muon tomography thanks to
  - Resistive strip readout
  - 2D multiplexing technique
  - Amplitude feedback to compensate for environmental changes (P, T)
  - PCB factory production (more than 150 detectors produced since 2015)
  - Gas tightness, recirculation and filtration
- Over a decade, the competition has been caught up, or even surpassed
  - First online HD muography (WatTo)
  - First nuclear reactor tomography with muons
  - ScanPyramids mission results (Big Void, North Face Corridor)
- Muon tomography telescope based on Micromegas technology is a success
  - The first telescope will be sale by Iris-Instruments this year
  - **Probably helped by the research process to make them “Ioannis’ proof” put in place**

Thank you!

cea irfu

1. Muon particle

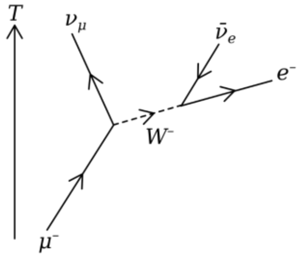
What is it?

Cosmic-rays muons

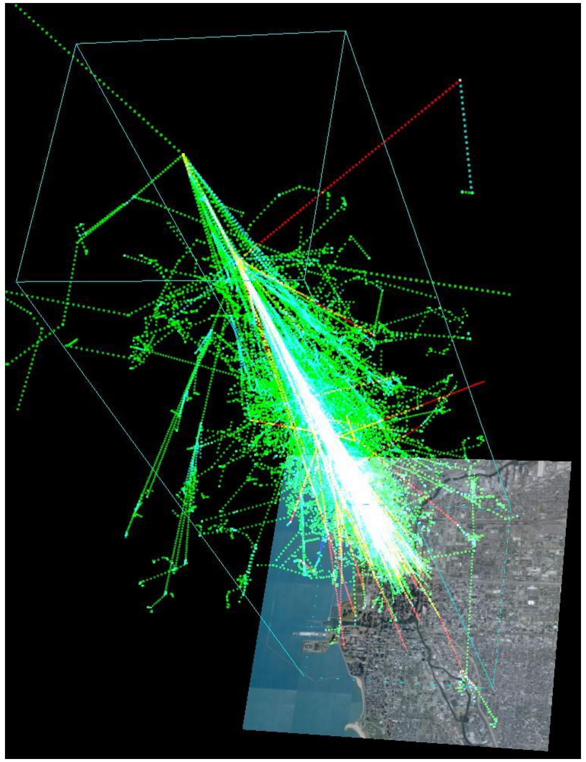
- Cosmic muons are **charged particles** produced by cascade of reactions induced by cosmic rays in the upper atmosphere coming from violent phenomena in the Universe (compact objects, supernovae, etc.)
  - Natural, free and harmless radiation
  - Flux: ~150/m²/s ∝ $\cos^2\theta$ (maximum in zenith direction θ=0)
  - Mean energy: 4 GeV
  - M_μ ~ 200×Me= 105,7 MeV/c²
  - Life time ~ 2.2

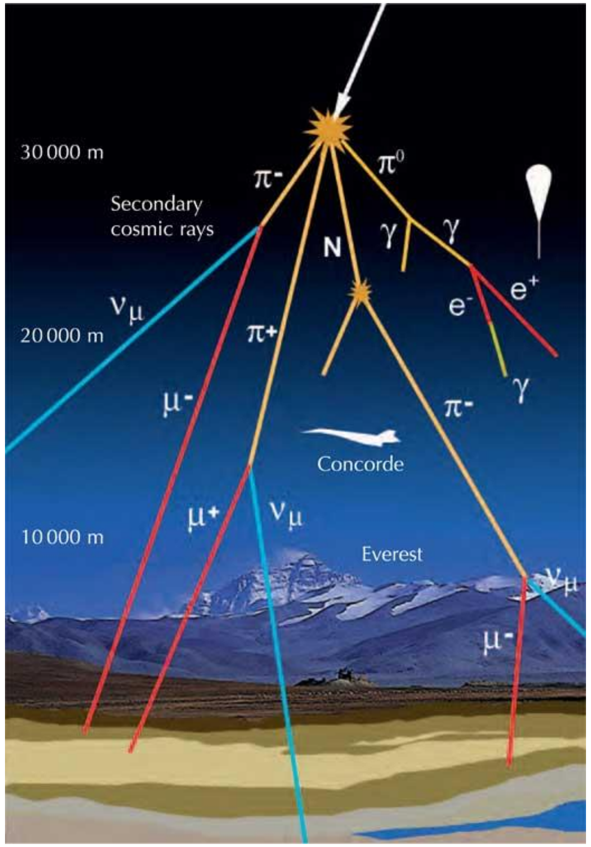
- Muon production processes:
  - $\pi^\pm \longrightarrow \mu^\pm \nu_\mu$ branching ratio of 99.99%
  - $K^\pm \longrightarrow \mu^\pm \nu_\mu$ branching ratio of 63.56%

- Muon processes:
  - Decay: $\mu^\pm \longrightarrow e^\pm \nu_\mu \nu_e$
  - Capture: $\mu^- + p^+ \longrightarrow n + \nu_\mu$



Simulated air shower created by 1 TeV proton





Muon interation with matter

- Muon trajectories are straights in mean
- Muons interact with matter and can be
  - Absorbed/stopped (decay)
  - Scattered

- Interaction processes with matter
  - Energy loss given by Bethe-Bloch ionization stopping power

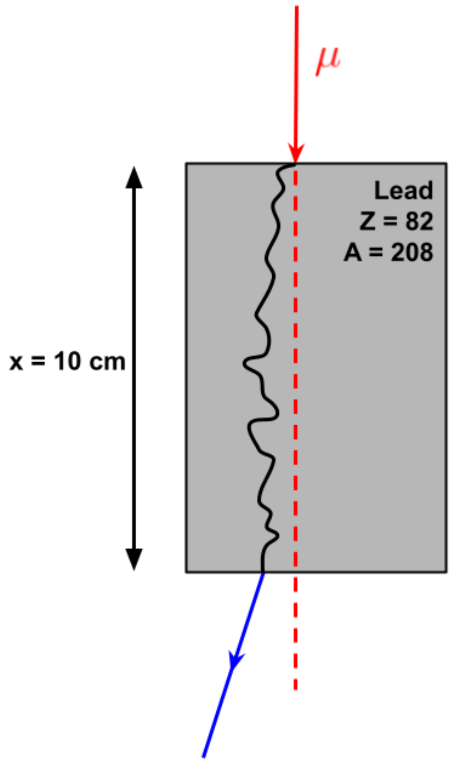
$$-\frac{dE}{ds} = \rho q^2 \frac{N_A e^4}{4\pi\epsilon_0^2 m_e c^2} \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right)$$

  - Standard deviation of the scattering angle describe by Molière theory

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

    - Radiation length is given with good approximation by:

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



p~4 GeV

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%