Muon tomography

Non destructive imaging for societal applications

Rencontres des Jeunes Physicien·ne·s

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DE LA RECHERCHE À L'INDUSTRIE
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Looking through objects

And reconstructing their volume

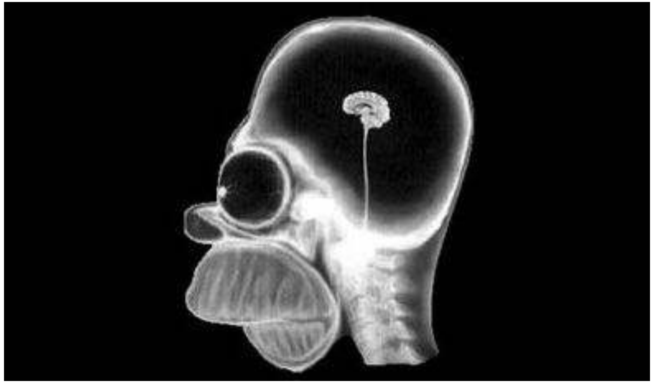
Non destructive imaging

Detector

Source

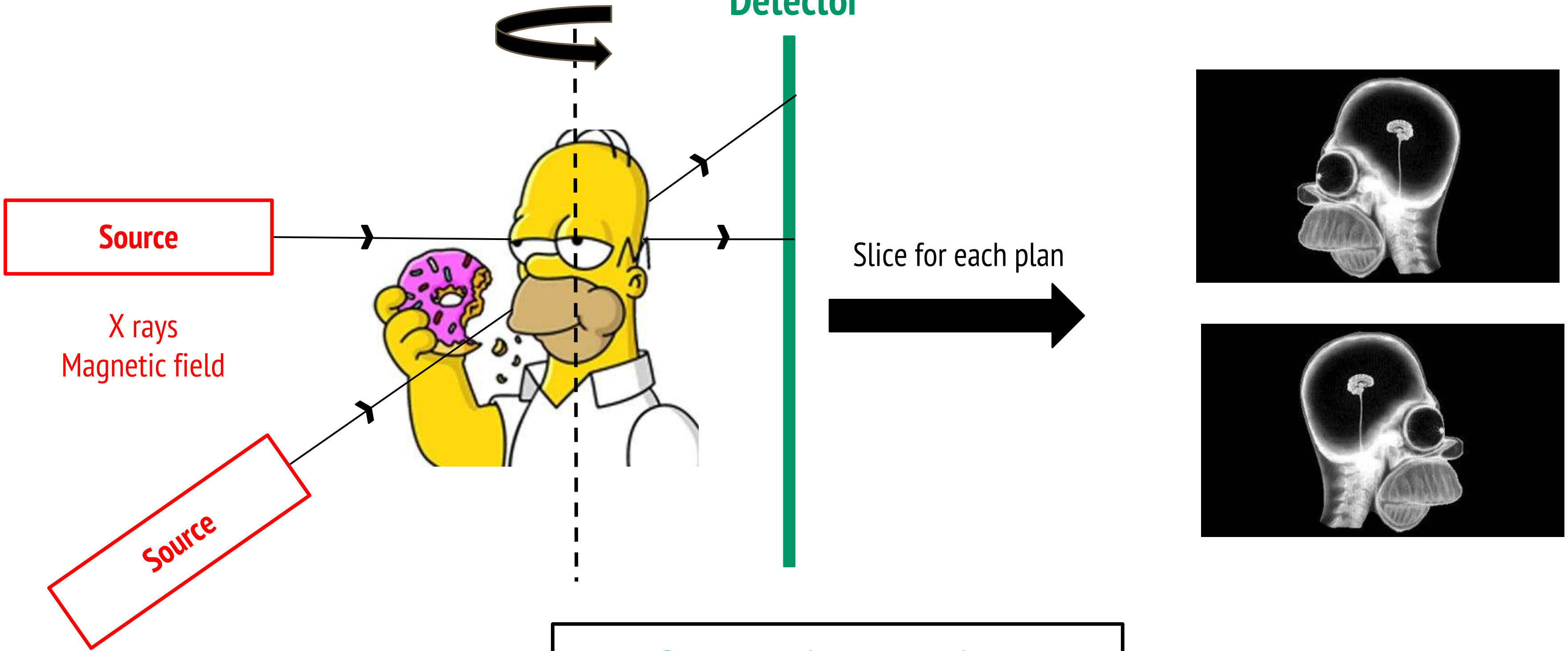
X rays
Magnetic field

Slice for this plan



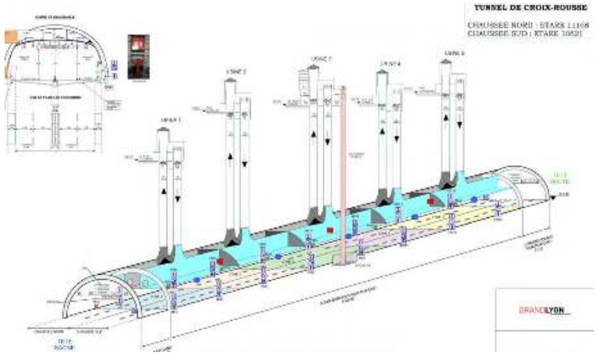
- Good spatial resolution
- High level of contrast

Non destructive imaging



- Good spatial resolution
- High level of contrast
- Imaging by tomography

Non destructive imaging

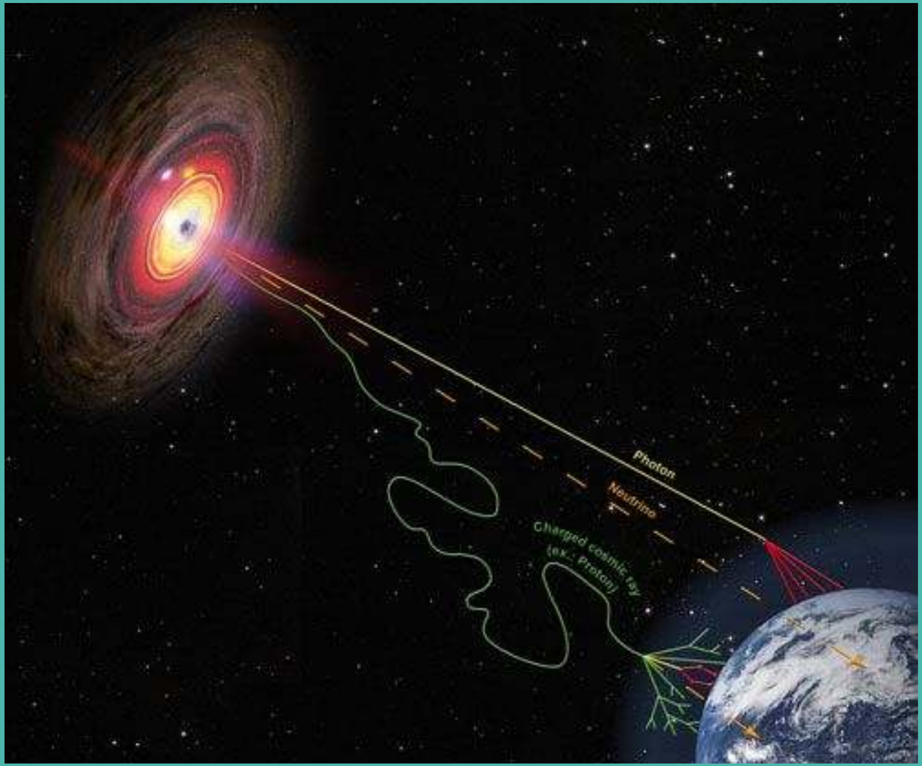


Expectations

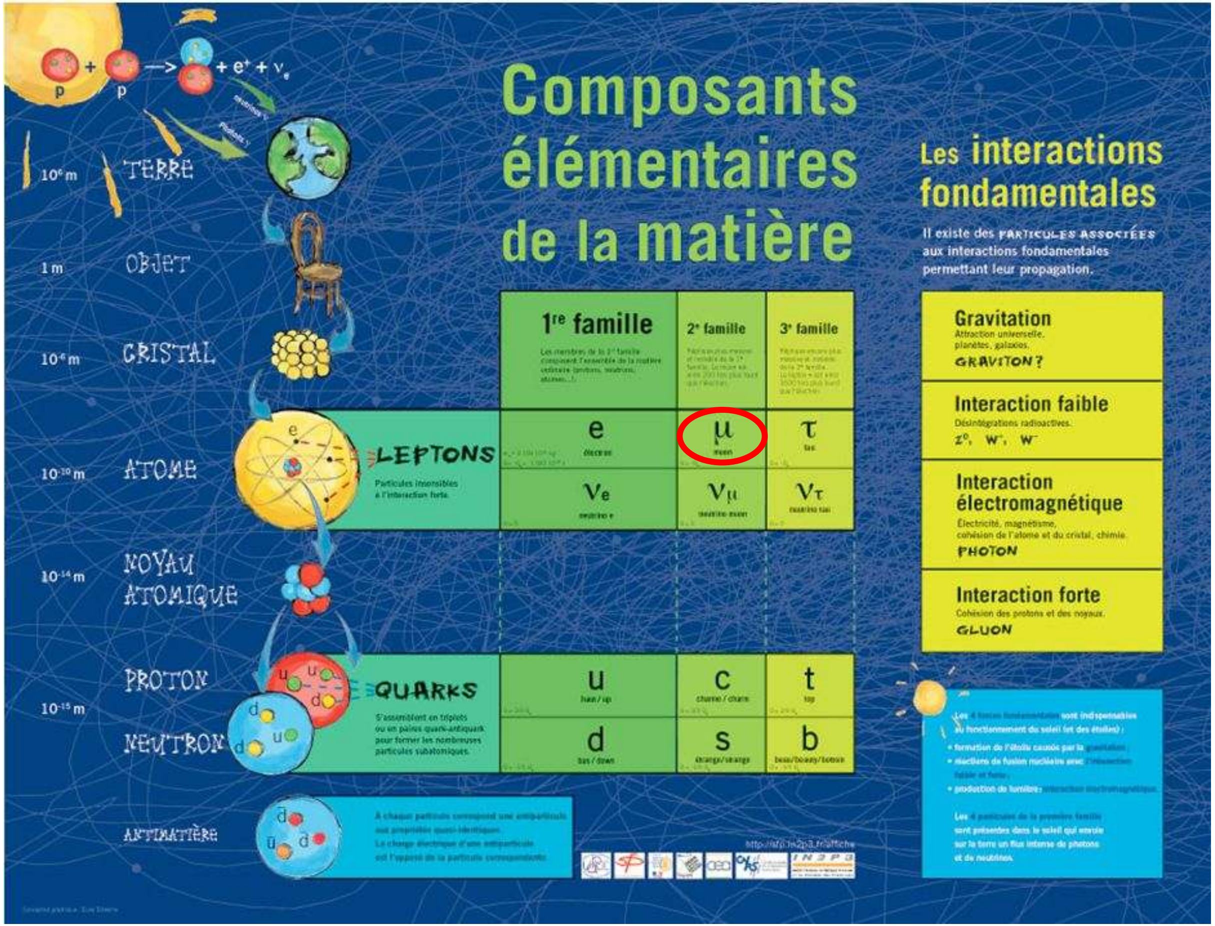
- **High power of penetration (~100m)**
- **Harmless**
- **For high opacity object**
- **Free**

Close encounters of the Third Kind

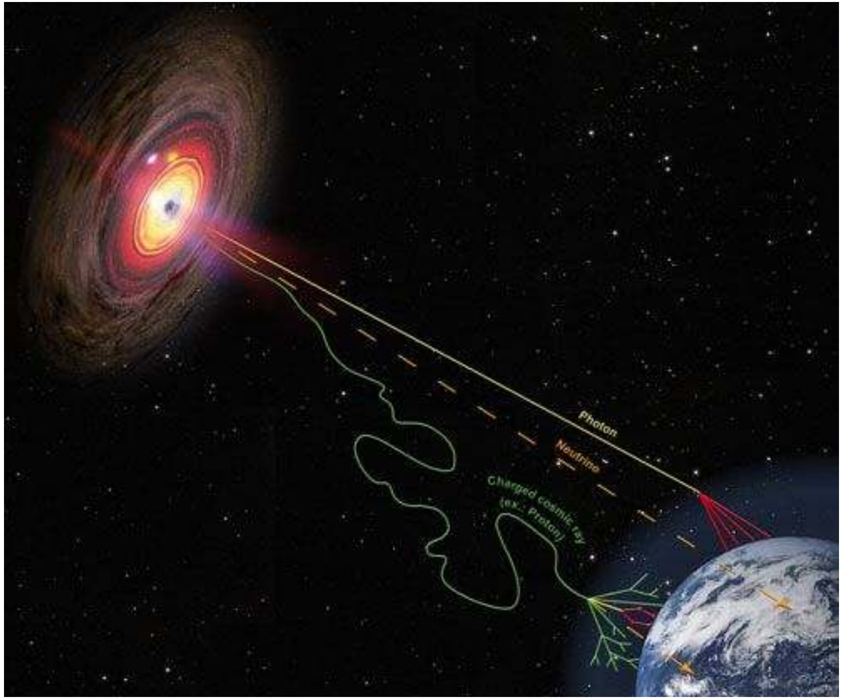
A permanent cosmic bombing raid



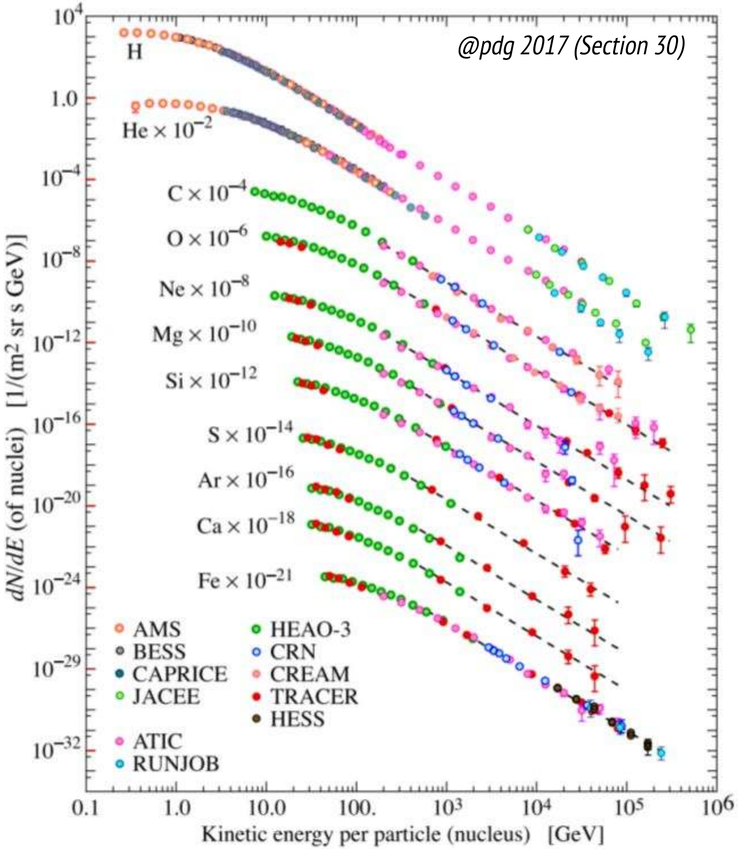
Particle physics rules the world



A cosmic shower

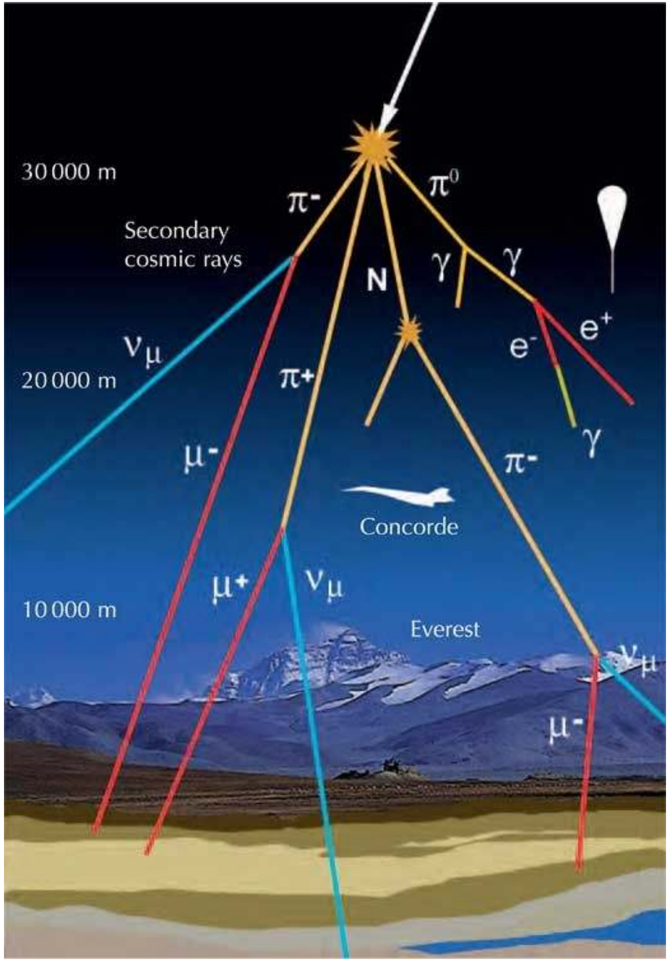


Known cosmic accelerators : Quasars, Active galaxies, Remanent supernovae, ...



Primaries mainly composed by protons and helium.

A cosmic shower



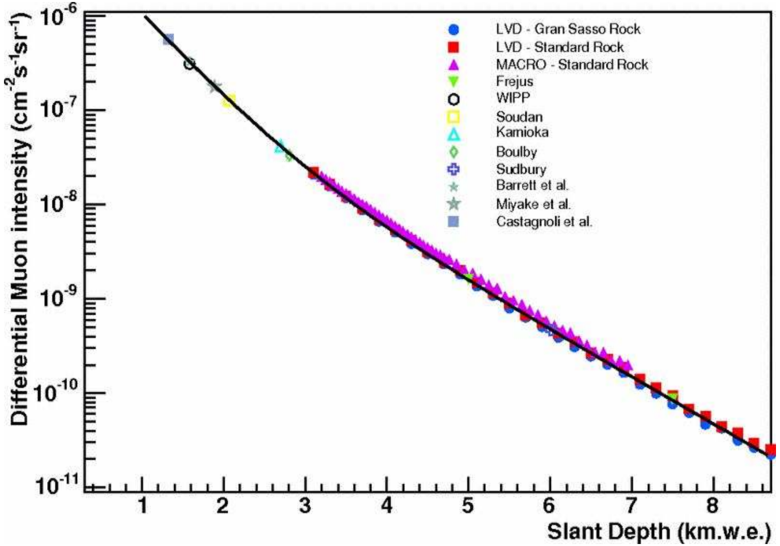
Muon flux at ground : 150/m^2/s ➡ cos(θ)^2 distribution

Mean Energy ~ 4GeV ➡ Kinetic energy of grain of sand at 1m/s

Celerity ~ c

Lifetime ~ 2μs

Natural radiation, free and harmless !

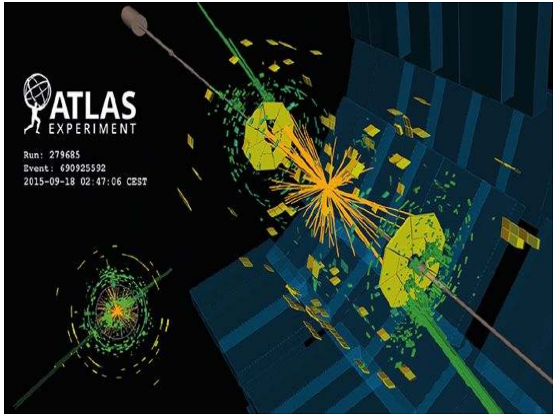


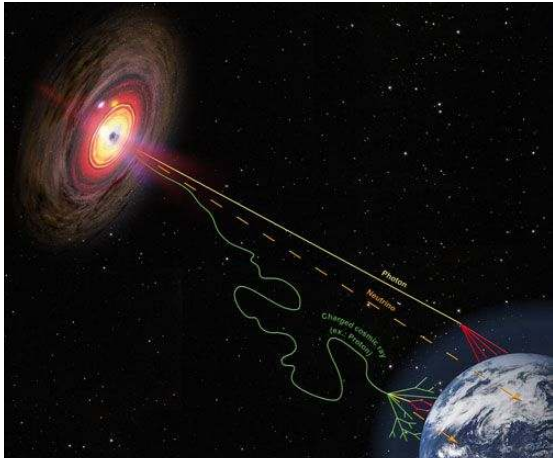
MicroMegas detectors

From fundamental research to social applications

How to detect a particle

Source





Conversion / Detector

Gas

Liquid (ex: Scintillator)

Solid (ex: Silicon)

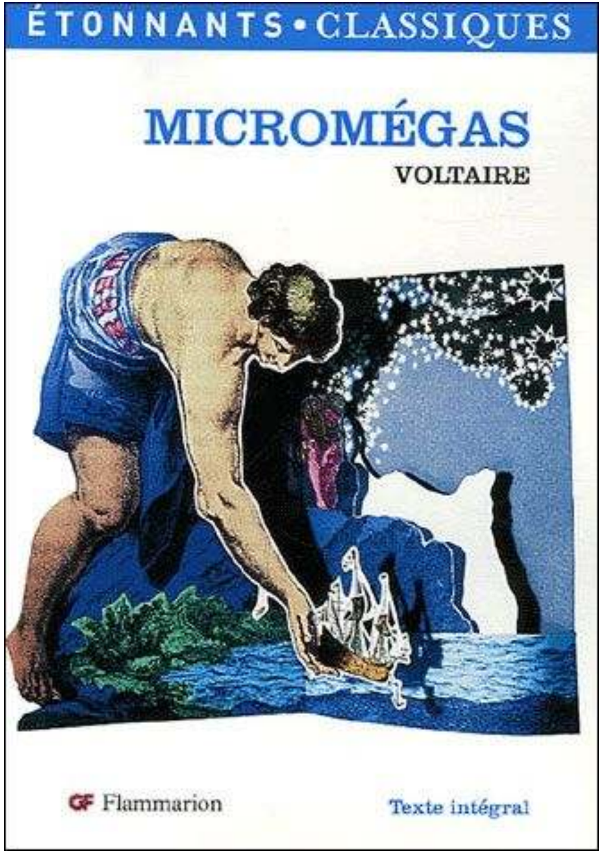
Storage of information

I(t)

How to detect a particle

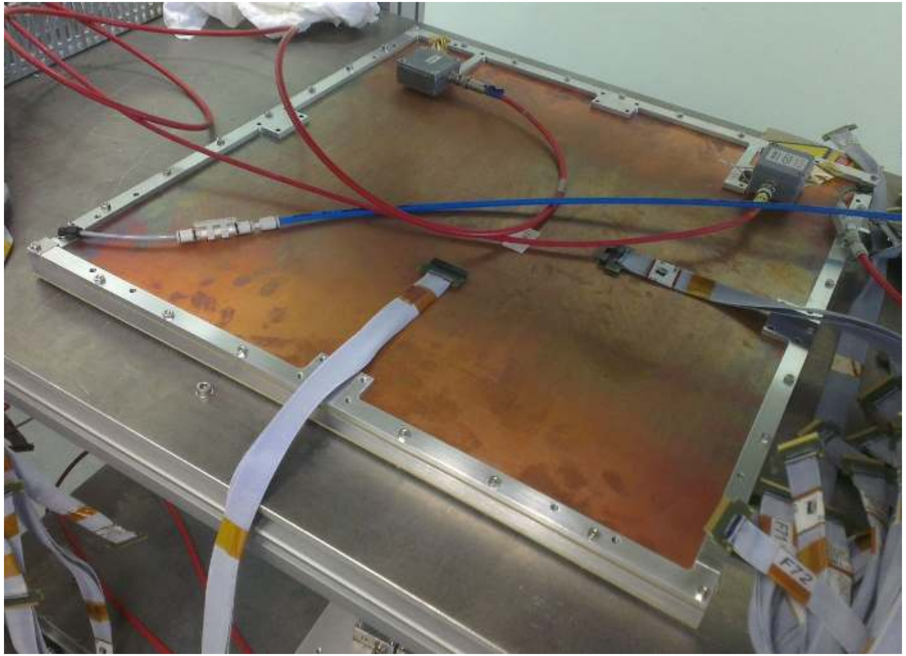
Source / Conversion / Detector / Storage of information

MicroMegas detector

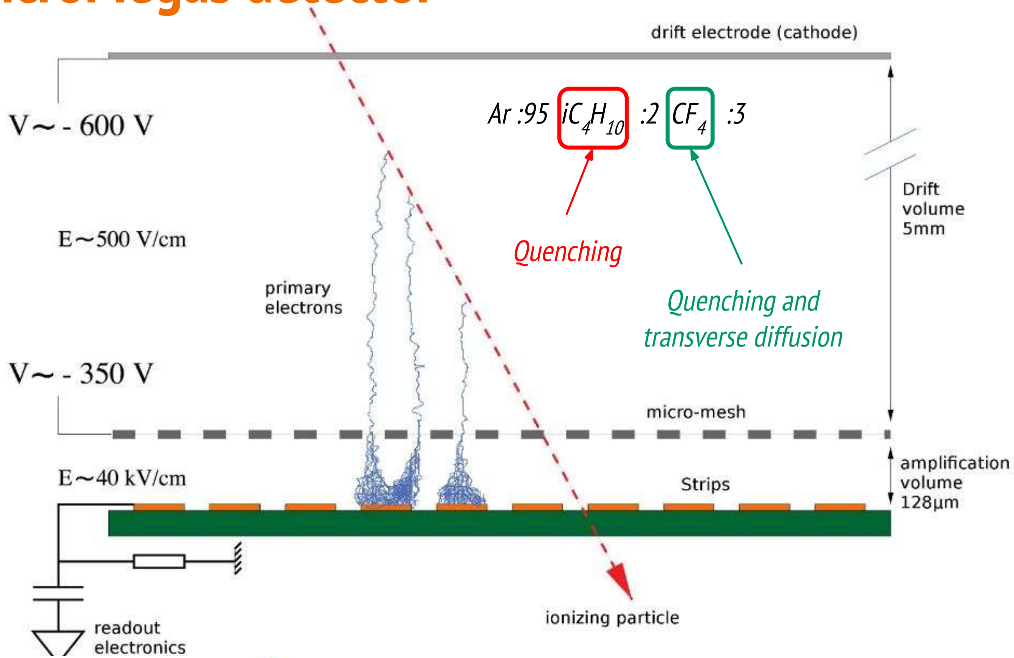


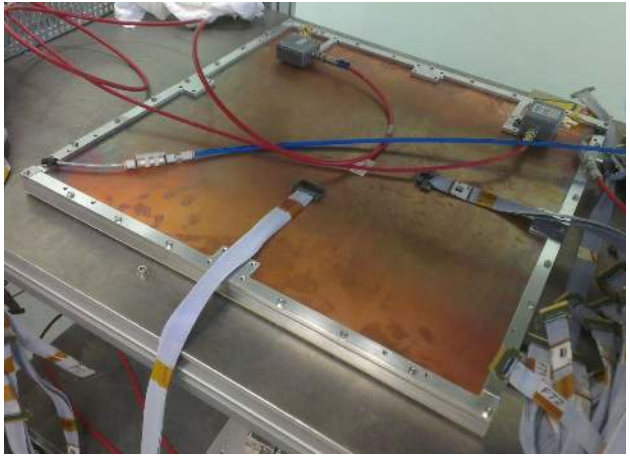
MICROMEGAS = **MICRO MEsh GAseous Structure**

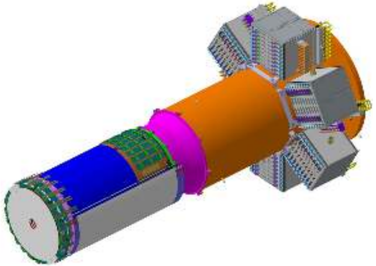
Gaseous Detector developed at CEA Saclay in 1996 by I. Giomataris, Ph. Rebourgeard et G. Charpak (Nobel prize 1992)



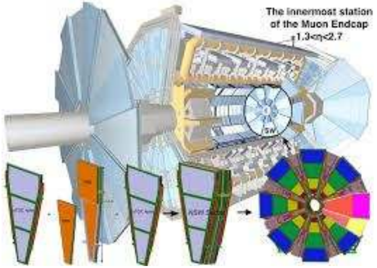
MicroMegas detector







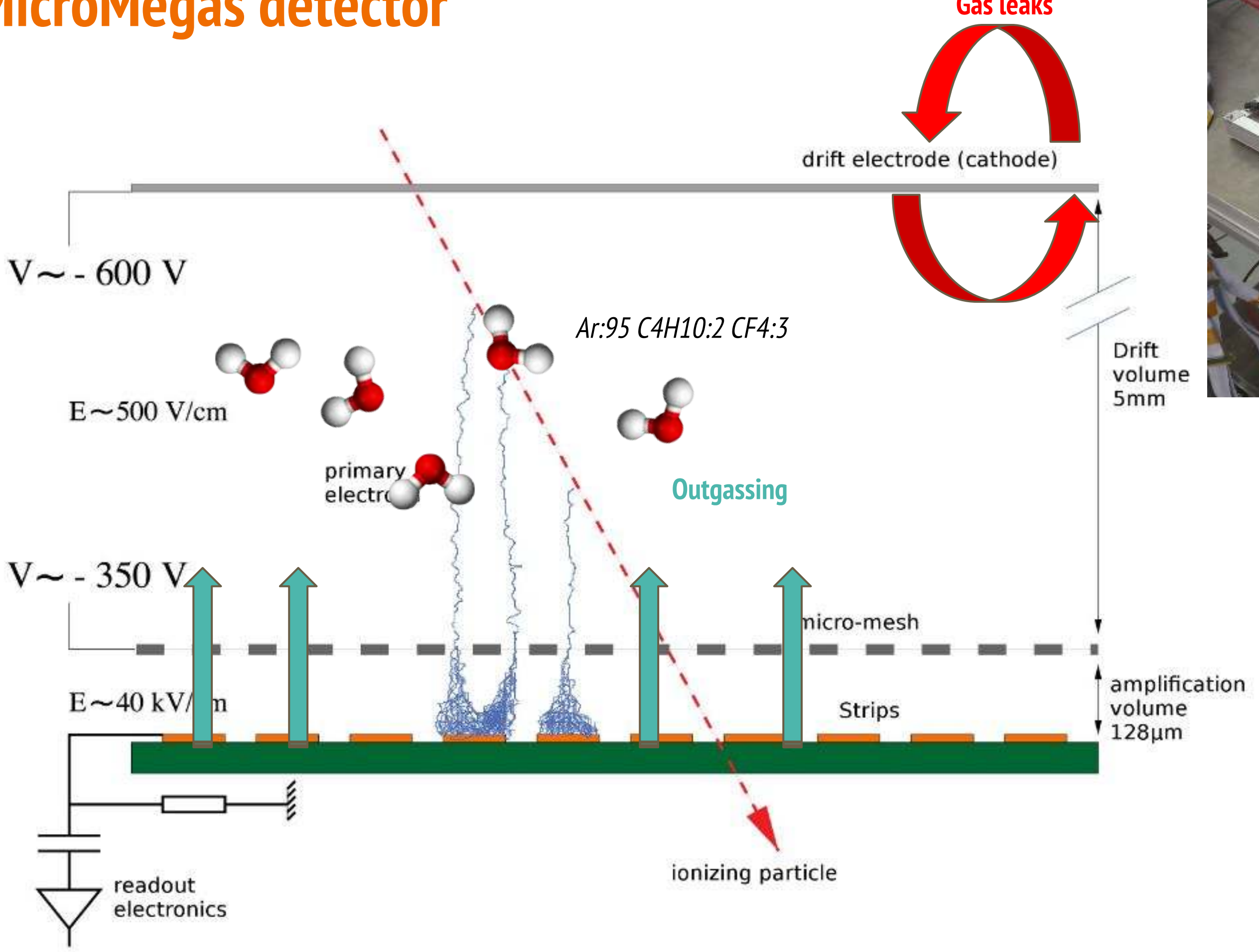
CLAS12
@Jefferson Lab

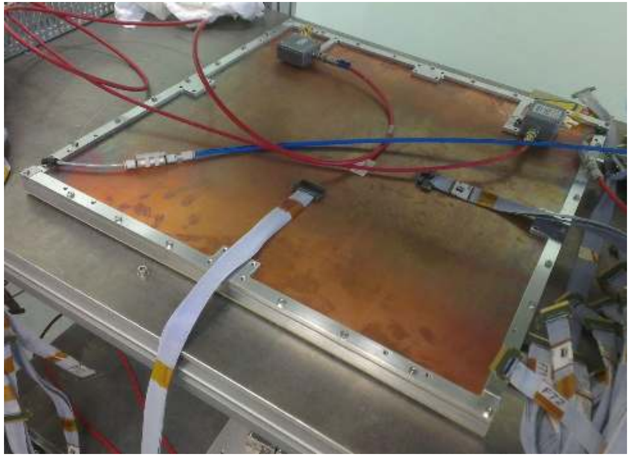


ATLAS
@CERN

Gain ~ 10^4-10^5
Time resolution ~ 10ns
Spatial resolution ~ 100µm

MicroMegas detector

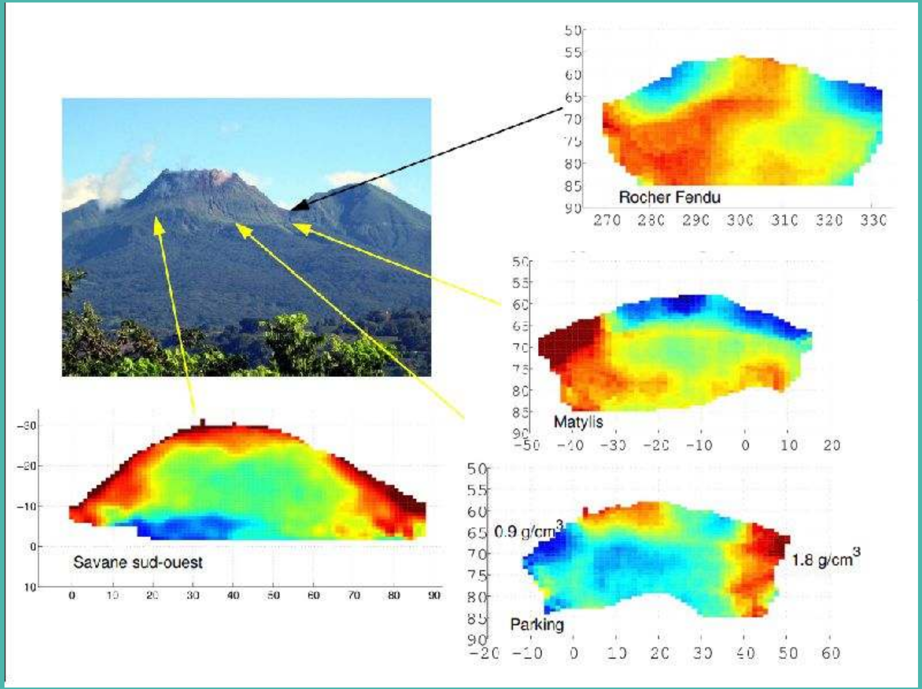




Main issues :
Gas leaks and outgassing

Muon Tomography / Muography

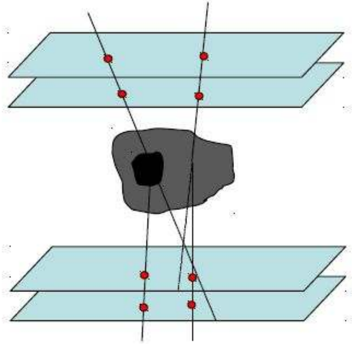
Different modes for several applications

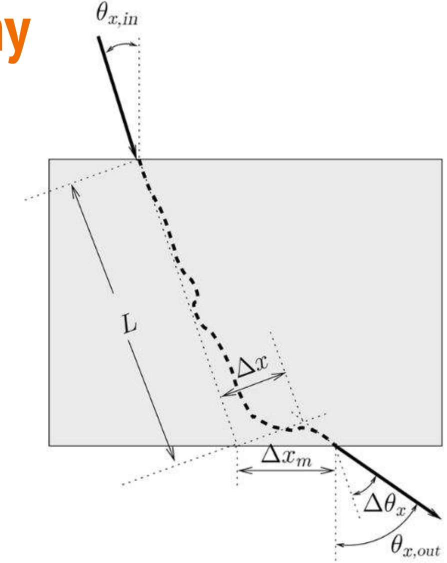


DIAPHANE Project (2016)

Two modes of muography

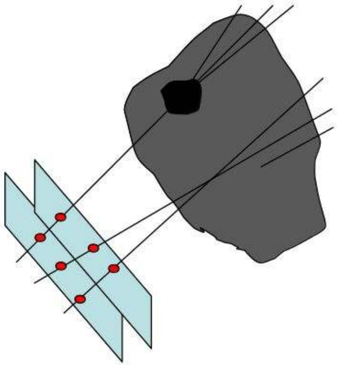
Deviation





- Coulomb diffusion
  - ➞ deflection angle depends on density
  - ➞ 10 cm of lead ~ 1° of deflection
- 3D Imaging
- Use for homeland security
- Spatial resolution is drastic
- Faster than transmission

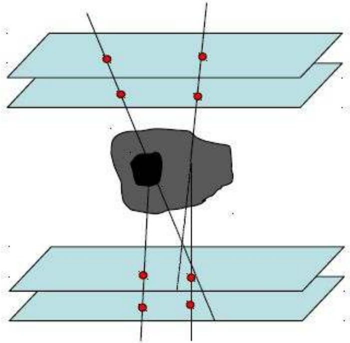
Transmission

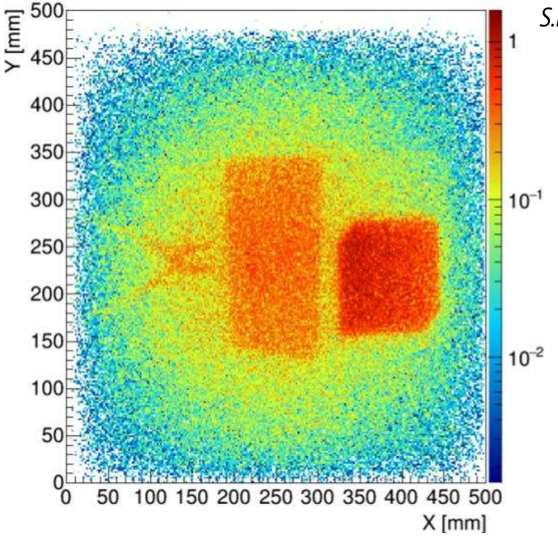


- Muon survival probability depends on the density
  - ➞ A density map can be made from the muon flux
  - ➞ Volcanoes
  - ➞ Geological prospection
- Muon flux at ground : 1 muon/cm^2/mn
  - ➞ Tradeoff between sensitivity and acquisition time
  - ➞ Better precision can extract the most information of each muon

Two modes of muography

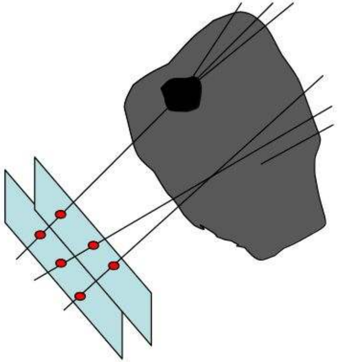
Deviation

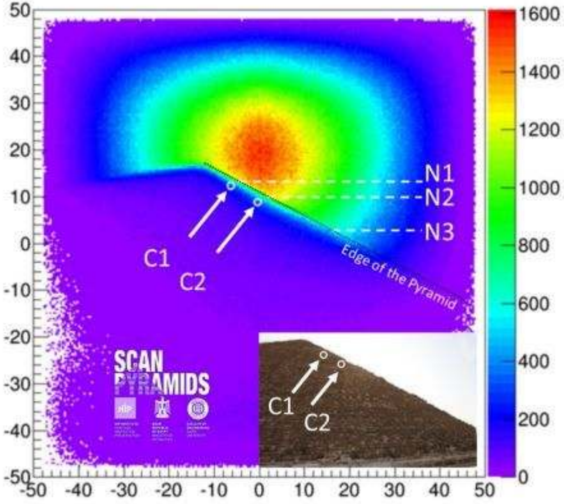


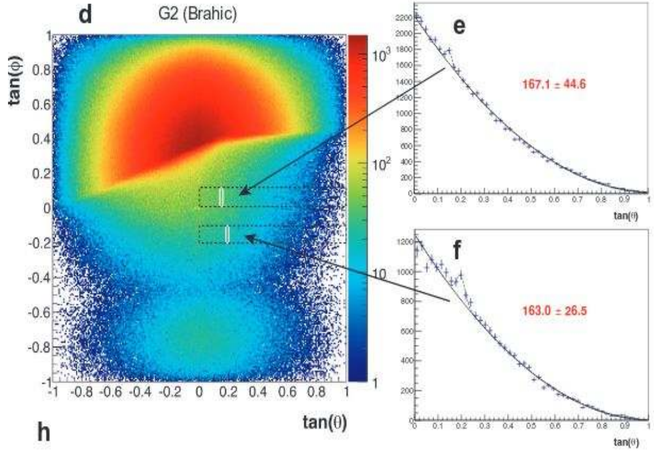


S.Bouteille (2017, Thesis)

Transmission



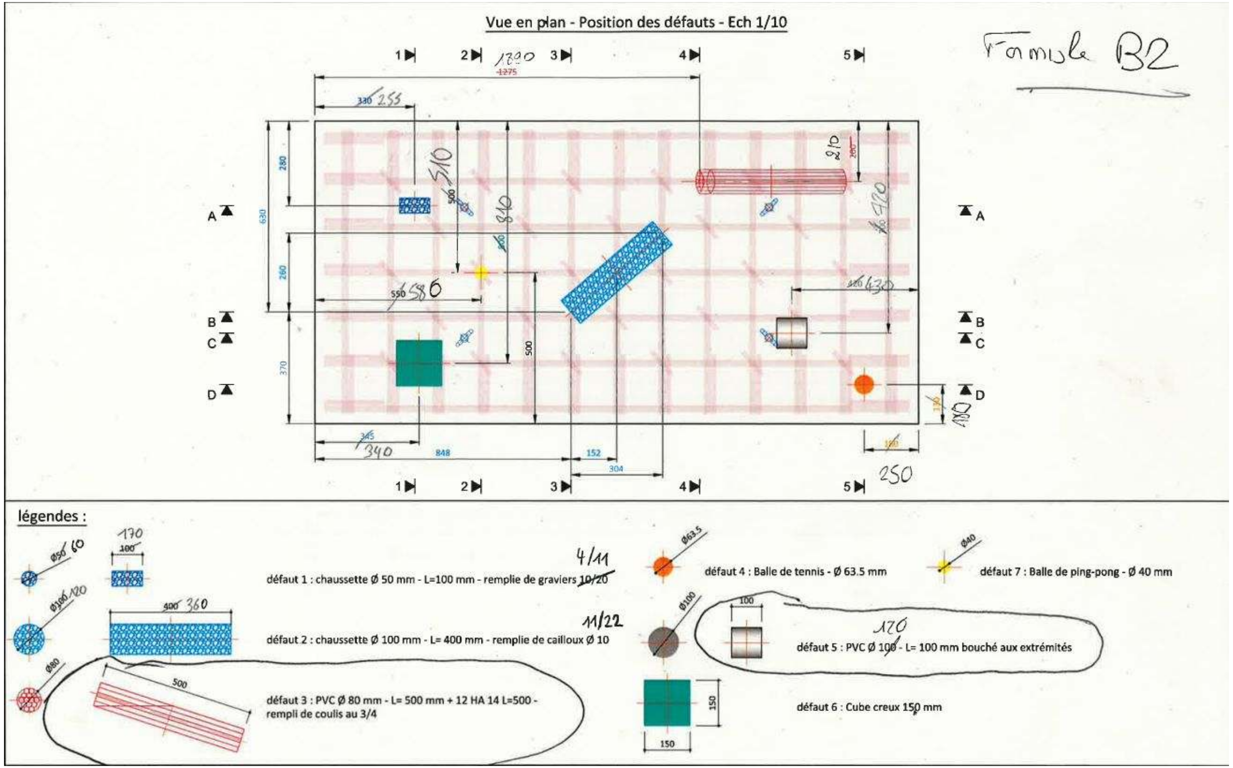




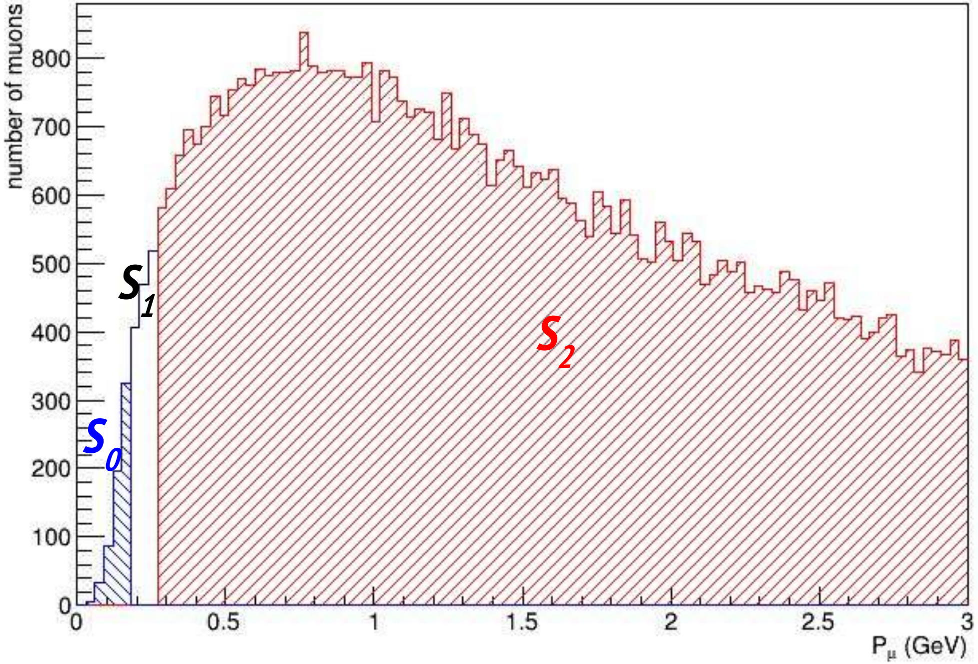
ScanPyramids (2016 2017 (Nature))

Detection of defaults

Imaging faults in a concrete slab



New mode in Tomomu : absorption

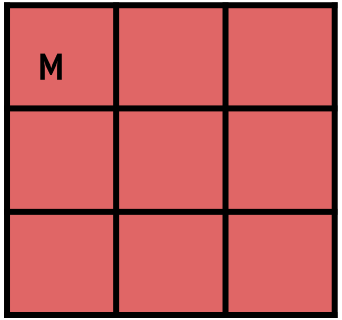


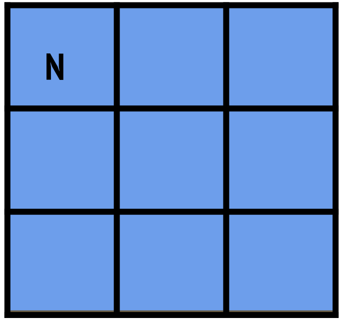
Corsika simulation of muon flux at ground . Blue = E_μ < 180 MeV. Red = E_μ > 270 MeV.

Relative muons excess in transmission = S_1 / S_2 ➡ Object with high density (pyramids, volcanoes, buildings)

Relative muons excess in absorption = $S_1 / (S_1 + S_0)$ ➡ Object with low/intermediate density

Results - Simulations





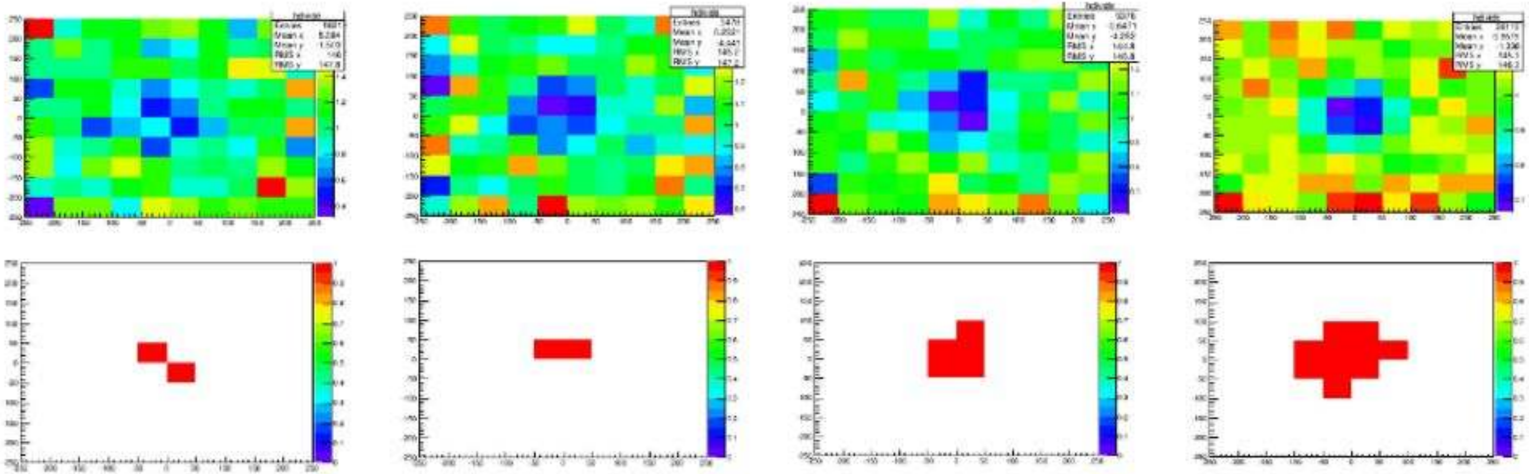
- H0 : M and N are distributed with the same Poisson distribution with λ.
- H1 : M and N are distributed with differents Poisson distribution (λ and μ)

f(M|N,λ)

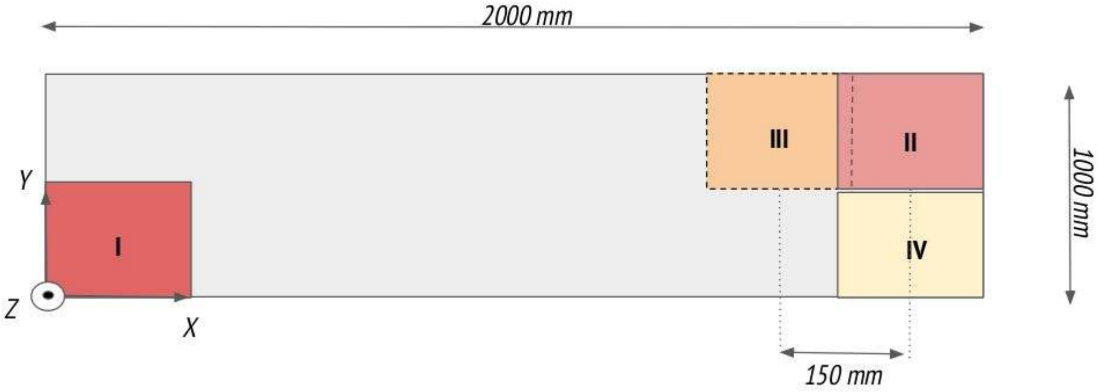
4h 8h 24h 120h

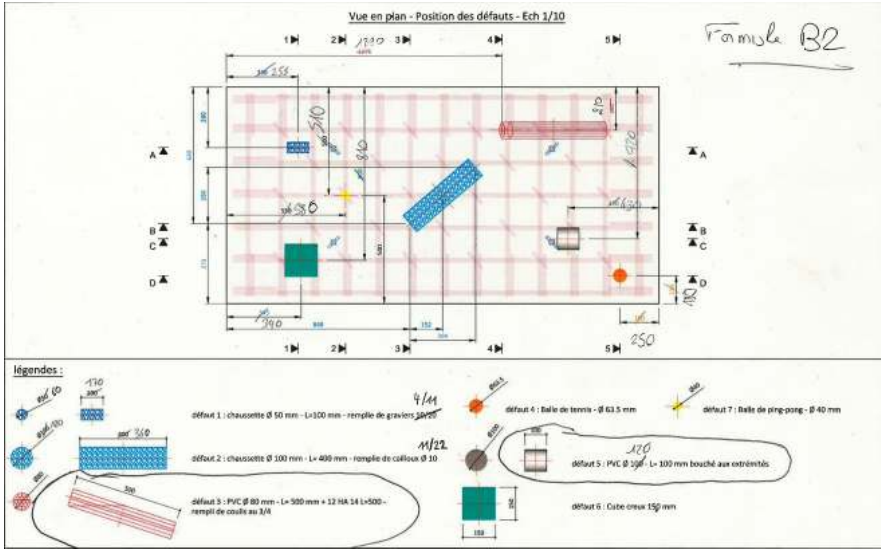
Ratio between H0 and H1

CL 99,7%



Imaging faults in a concrete slab

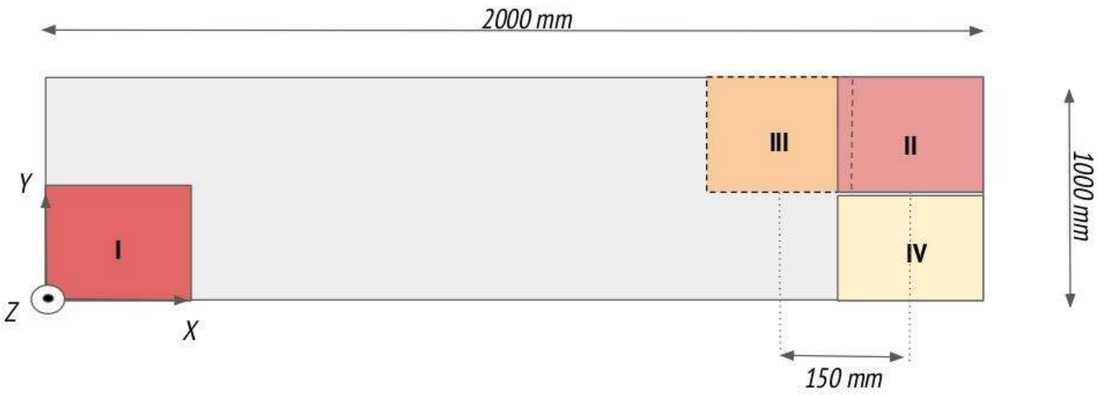


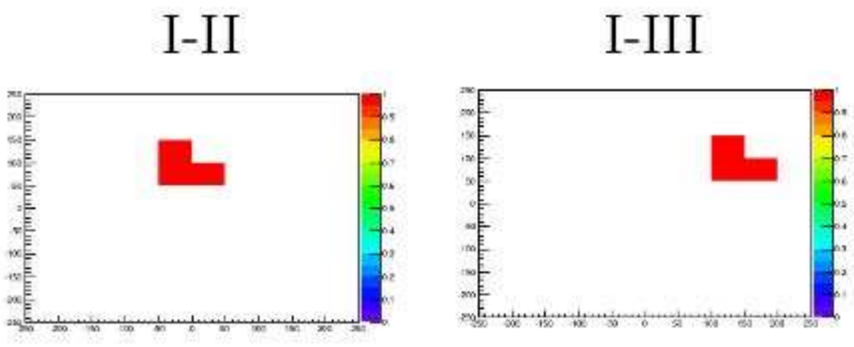


- Two positions allowed for the void
  - ➡ Symmetry by 180° rotation

- Analysis done between I vs II and I vs III
  - ➡ Detectors were moved by 15cm
  - ➡ No faults appeared after dividing the two histograms
  - ➡ Blurring due to acceptance (geometry and efficiency) and diffusion of muons in the concrete slab

Imaging faults in a concrete slab



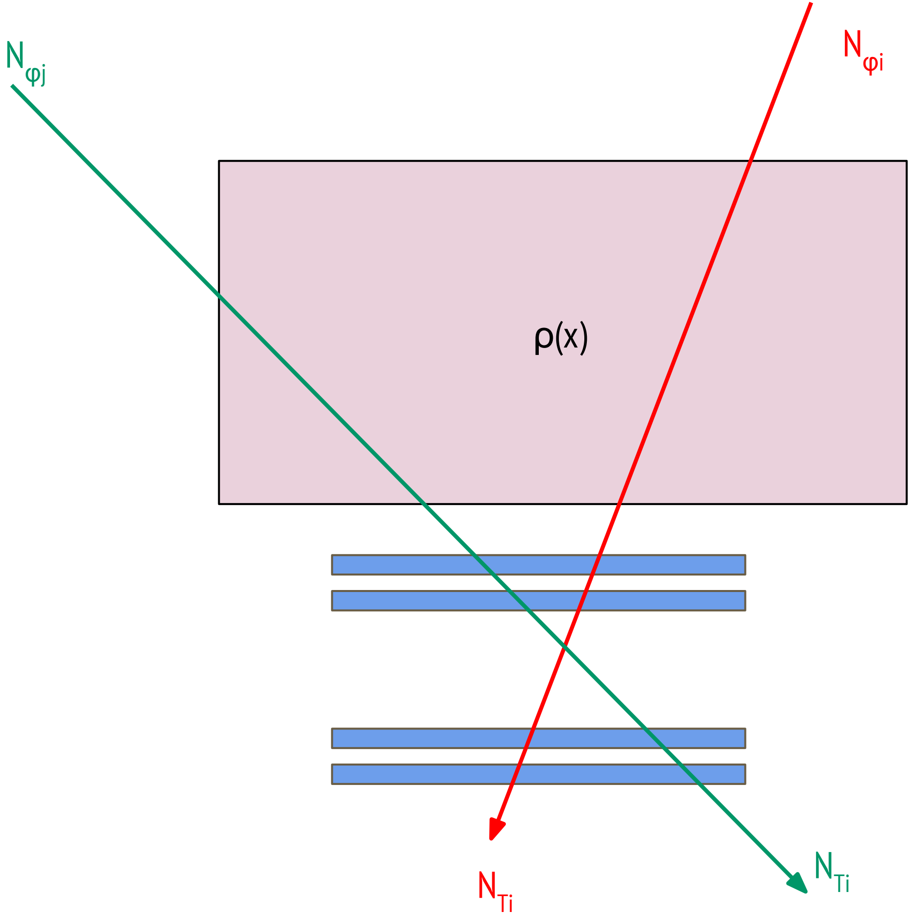


CL 99,7%

- Two position allowed for the void
  - ➡ Symmetry by 180° rotation
- Analysis done between I vs II and I vs III
  - ➡ Comparison shows a significant difference
  - ➡ the fault moved by 15cm as we hoped

Inverse problem

Direct problem



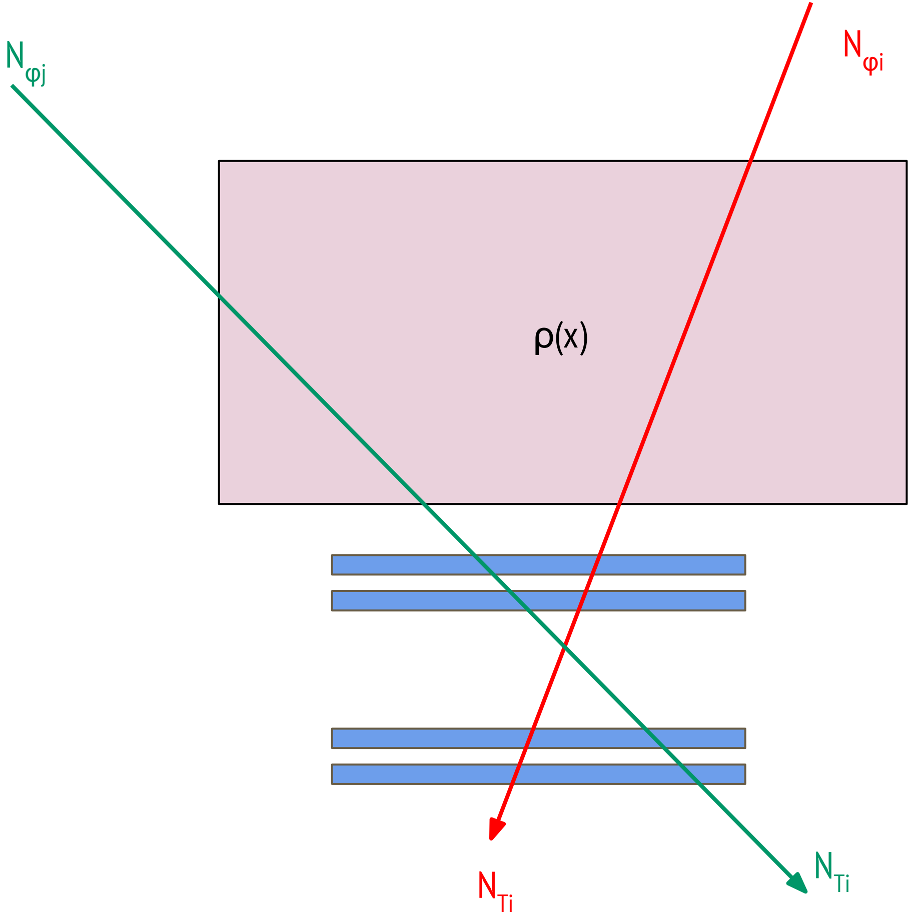
Parameters $\mathbf{p}$ = (ρ(x) for x in object)

Data $\mathbf{d}$ = $((N_{\varphi 1}, N_{T1}), \ldots, (N_{\varphi d}, N_{Td}))$

$$\mathcal{M} : \mathcal{P} \longrightarrow \mathcal{D}$$

$$\mathbf{p} \longrightarrow \mathbf{d} = \mathbf{M.p}$$

Inverse problem



Parameters **p** = (ρ(x) for x in object)

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$$\mathcal{M} : \mathcal{P} \longrightarrow \mathcal{D}$$

$$\mathbf{p} \longrightarrow \mathbf{d} = \mathbf{M.p}$$

INVERSION

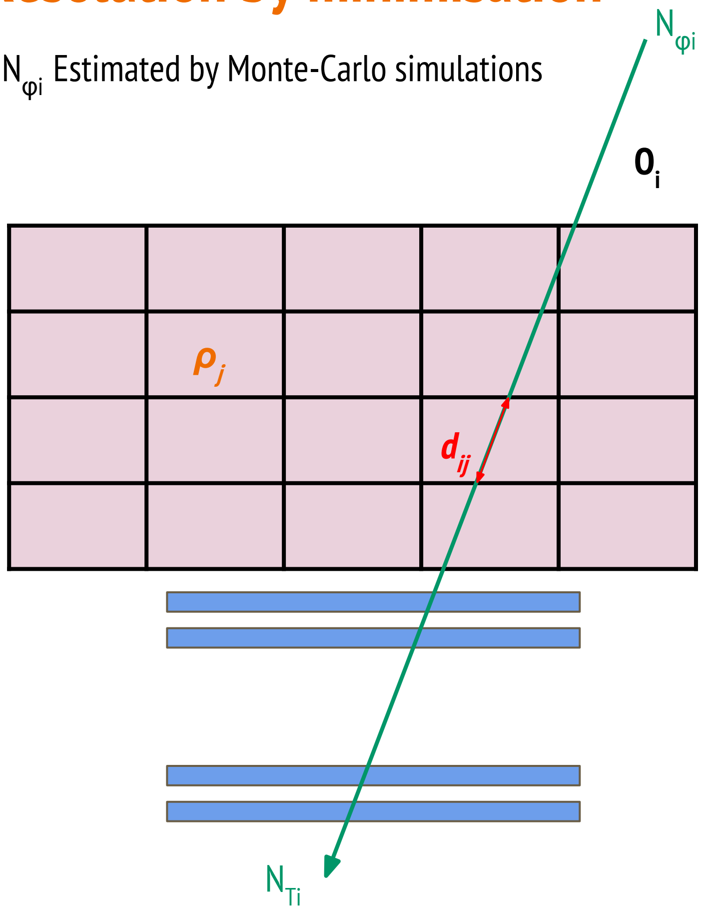
existence, uniqueness and stability

$$\mathcal{N} : \mathcal{D} \longrightarrow \mathcal{P}$$

$$\mathbf{d} \longrightarrow \mathbf{p} = \mathbf{N.d}$$

Resolution by minimisation

$N_{\varphi i}$ Estimated by Monte-Carlo simulations



Parameters **p** = $(\rho_1, \dots, \rho_N)$

Data **d** = $((N_{\varphi 1}, N_{T1}), \dots, (N_{\varphi d}, N_{Td}))$

d_{ij} = path travelled by muons in the voxel j for the LOR i (cm)

ρ_j = density in the voxel j (g.cm^{-3})

O_i = opacity along the LOR i (g.cm^{-2}) = $\Sigma_j d_{ij}\, \rho_j$

Inversion = Find $\rho \in R^N$ such as $\| D\rho - O \|^2$ is minimal

Conclusions

- **Muography**
  - → A promising non-invasive technique for imaging and scanning objects of different types and opacities
  - → Development of robust and stable detectors
  - → R&D on gas degradation and gas consumption

- **Reconstruction**
  - → Detection of faults in concrete slab with a new method
  - → Work in progress : inverse problem

THANKS

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