



# T2DM2\* : Status & Progress

\*  
**Temporal Tomography Densitometric by the Measure of Muons**

## Collaboration Project



Funded by



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•LSBB (UMR3538)- GEOAZUR – OCA-Observatoire de la Côte d'Azur - ° CPPM (Université de la Méditerranée)

### COLLABORATION

CERN - CEA/IRFU - – SHEFIELD UNIVERSITY - GÉOSCIENCES Montpellier – IPGP (Géophysique Spatiale et Planétaire), EMMAH (Université d'Avignon et des Pays de Vaucluse) - APC (Astroparticules et Cosmologie Université Paris7) - CFN Lisbonne

### INTERDISCIPLINARITY

ASTROPARTICULES - SEISMIC IMAGERY – GRAVIMETRIC - HYDRO GEOLOGY - ROCK MECHANICS - EM IMAGERY

\* On behalf of the T2DM2 collaboration



# SUMMARY

- **GOALS**
- **REMINDER OFF THE METHOD**
- **THE WORK ALLREADY DONE**
- **THE WORK ON PROGRESS**
- **THE WORK OFF THIS YEAR**
- **CONCLUSIONS : FUTURE**

# GOALS

- New measurement ability (km of lateral extent, multi-hm thickness) of the spatial and temporal evolution of rock density function of water saturation, total porosity, mechanical condition and damage at in situ scale
- Monitoring of aquifer resources and reserves
- Monitoring the stability of volcanoes
- Monitoring the stability of underground vacuum and rock mass instabilities
- Qualification of the prototype telescope developed in 2009-2011 at GEOAZUR & LSBB in collaboration with the consortium RD51/CERN, new and innovative tool to complement field exploration and monitoring

# **REMINDER OFF THE METHOD**

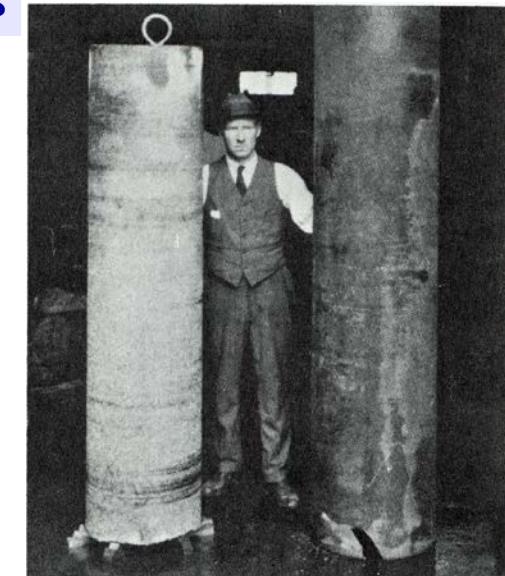
# FUNDAMENTAL QUESTION:

What are the mechanical parameters of rock across a cluster?

## Measurements on samples of small scales or large sizes



The mechanical parameters are unknown to a mass scale:  
Effective stress?  
Friction effective?  
Damage?



## Empirical methods

Measure:  
Mechanical  
parameters in  
small scale



Qualitative description of the  
rock mass  
(scale fracturing, alteration,  
hydraulic ...)



Estimation:  
at large  
scale  
Mechanica  
l parameters

Bieniawski (1976), Hoek & Brown (1980)

## Description of the rock in the elastic approximation :

- Lamé parameters and density :  $\lambda, \mu, \rho$
- Wave velocity in soil :  $\alpha = ((\lambda+2\mu)/\rho)^{1/2}, \beta = (\mu/\rho)^{1/2}$
- Young's modulus and Poisson's ratio :  $E, v$
- Uniaxial stress ( $\sigma = E \epsilon$ ),  $E = (3\lambda+2\mu) \mu / (\lambda+\mu)$ ,  $v = (2-(\alpha/\beta)^2) / (2-2(\alpha/\beta)^2)$
- Compressibility coefficient and shear modulus:  $K, G$
- Modules and elastic coefficients are related:  $1/E = 1/9K + 1/3G$

## Problems of real massive

### • A complex building

Damage (evolution of the fracture, internal erosion, ...)

Traffic fluid (chemical alteration, variation of porosity...)

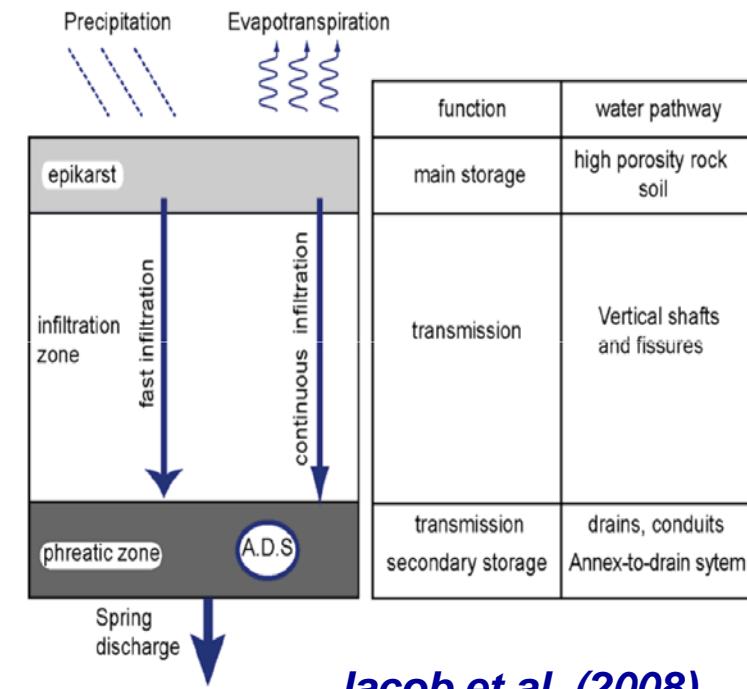
### • A temporal evolution

Ante/post-eruptive volcanoes phases

Managing resources and reserves (environment, hydrology karst)

Midfielder cashing storage ( $CO_2$ , chemical waste, nuclear, ...)

Underground Engineering (structures, mining)



Jacob et al. (2008)

# THEORETICAL PRINCIPLES

# OPEN SKY MODELS at SEA LEVEL

A model of muon flux is necessary to:

- Simulate the experiment
- Normalize the experimental measurements with those in the open sky

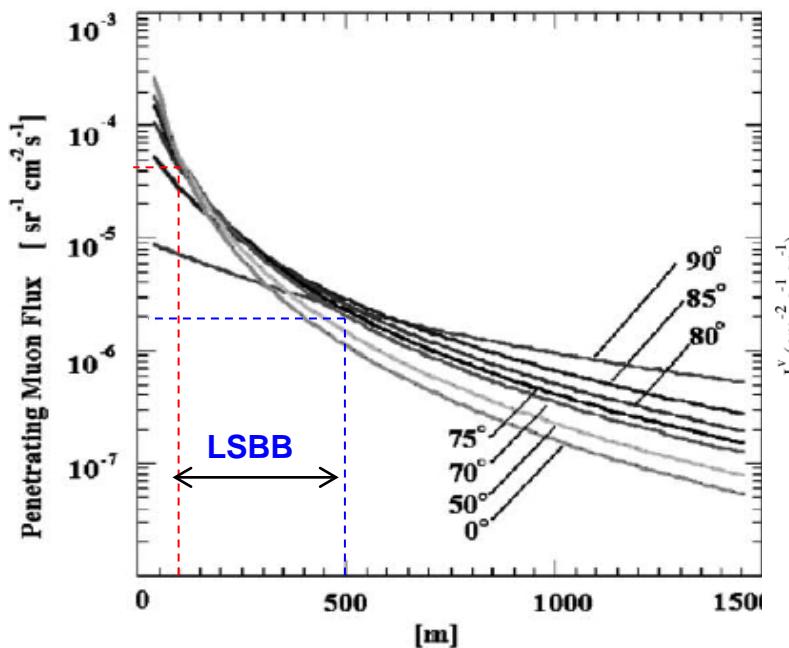
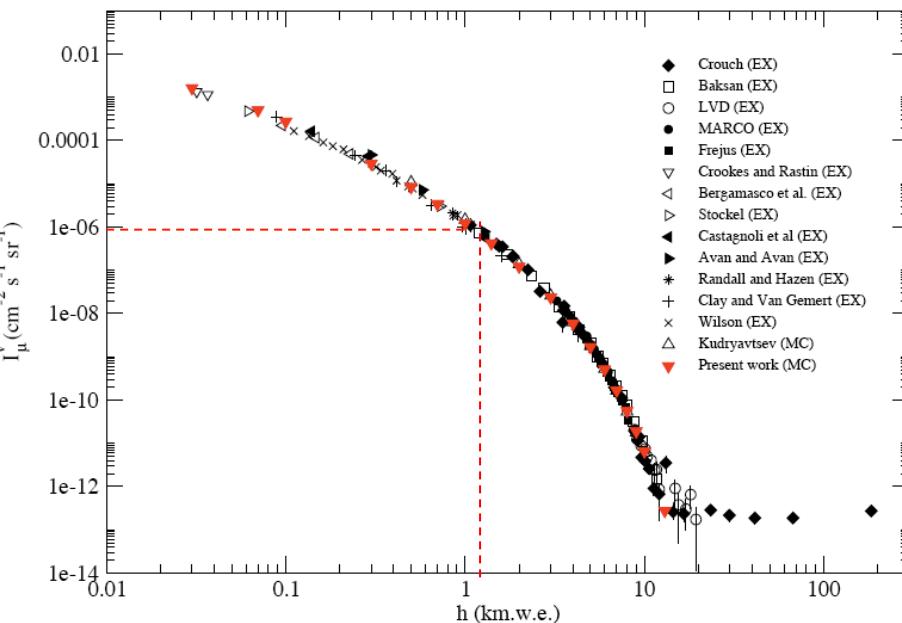


Fig. 1. Integrated flux of cosmic-ray muons at various angles penetrating through a given thickness of rock ( $m$ ) with a density of  $2.5 \text{ g/cm}^3$ , as obtained with Eqs. (1) and (2). The vertical axis of Ref. [1] was corrected.



$$\frac{dN_\mu}{dE_\mu d\Omega} \approx \frac{0,14 E_\mu^{-2,7}}{\text{cm}^2 \text{s sr GeV}} \times \left\{ \frac{1}{1 + \frac{1,1 E_\mu \cos\theta}{115 \text{ GeV}}} + \frac{0,054}{1 + \frac{1,1 E_\mu \cos\theta}{850 \text{ GeV}}} \right\}$$

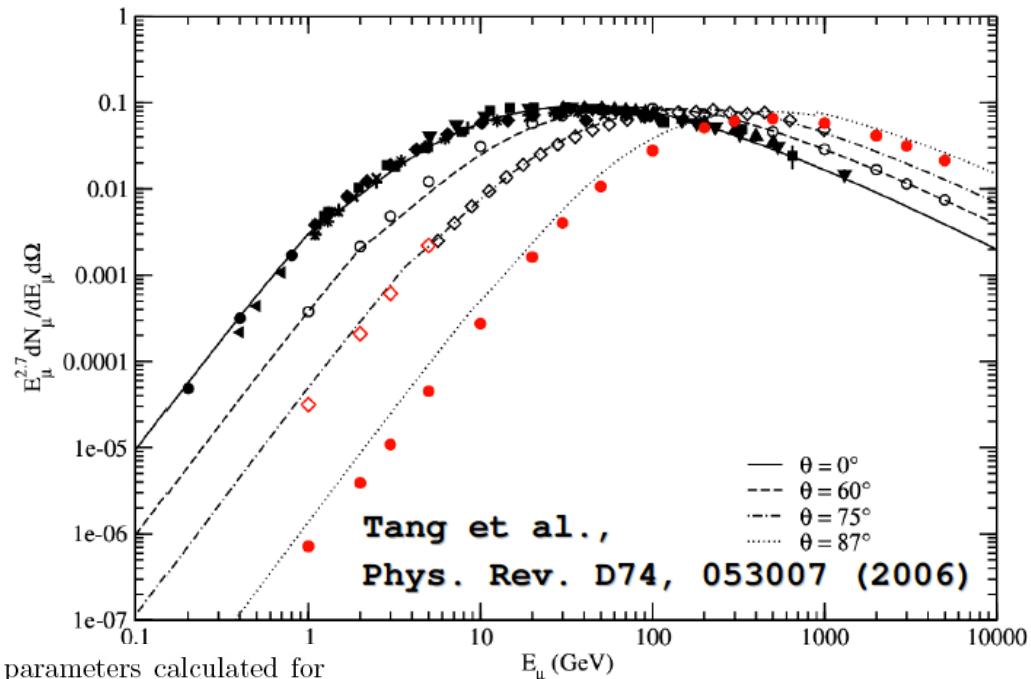
Lesparre, N., D. Gibert, J. Marteau, Y. Déclais, D. Carbone & E. Galichet, **Geophysical muon imaging: feasibility and limits**, Geophysical Journal International (2010) 181, 1-14.

**Opacity**

$$\varrho(L) \equiv \int_L \rho(\xi) d\xi$$

**Energy loss**

$$-\frac{dE_\mu}{dX} = a + b E_\mu$$



**Table 24.2:** Average muon range  $R$  and energy loss parameters calculated for standard rock [52]. Range is given in km-water-equivalent, or  $10^5 \text{ g cm}^{-2}$ .

$E_\mu$ GeV	$R$ km.w.e.	$a$ $\text{MeV g}^{-1} \text{cm}^2$	$b_{\text{brems}}$ —	$b_{\text{pair}}$ $10^{-6} \text{ g}^{-1} \text{cm}^2$	$b_{\text{nucl}}$ —	$\sum b_i$ —	$\sum b(\text{ice})$ —
10	0.05	2.17	0.70	0.70	0.50	1.90	1.66
100	0.41	2.44	1.10	1.53	0.41	3.04	2.51
1000	2.45	2.68	1.44	2.07	0.41	3.92	3.17
10000	6.09	2.93	1.62	2.27	0.46	4.35	3.78

**Threshold energy**

$$E_{\min} - \int_0^\varrho \frac{dE}{d\varrho} d\varrho = E_\mu$$

**Exiting muon flux**

$$I[\varrho, \theta] = \int_{E_{\min}(\varrho)}^{\infty} \Phi(E_0, \theta) dE_0 \ (\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1})$$

**Number of muon detected**

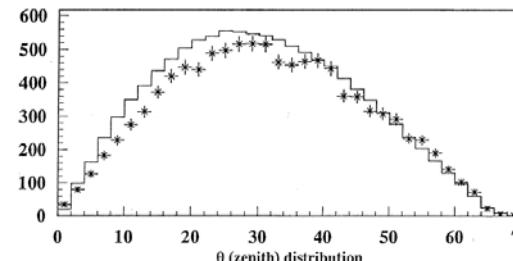
$$N(\varrho) = \Delta T \times \mathcal{T} \times I(\varrho),$$

$\Delta T$  = measurement time,  ${}^{\text{TM}}(r)$  = acceptance =  $S(r) \times \Omega(r)$   
 $r$  = view angle of each telescopes

# OLDER & RECENT EXPERIMENTS

- **Neutrino CHOOZ experiment**

Highlighting some of azimuth differences between the flux of muons expected and actual flows measured at the detector at the site of the Chooz experiment. **Baldini et al. (1995)**  
This difference is attributed to crossing a geological level higher density for these specific azimuth and zenith.



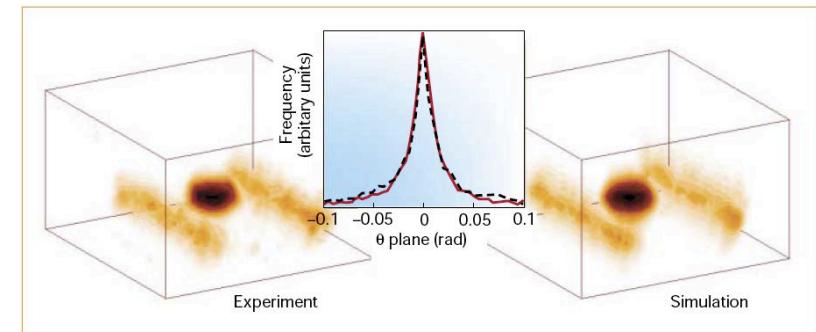
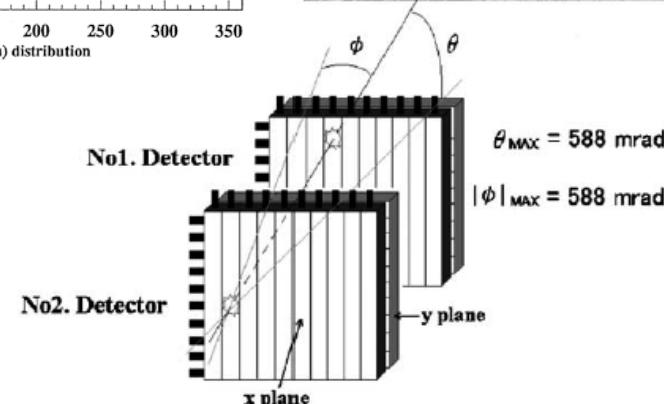
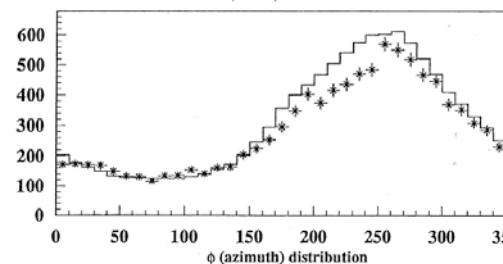
- **Other experiments**

In the case of Asama volcano **Tanaka et al. (2005)**, shows that it is possible to distinguish the density contrasts of the order of 1 to 3%.

- **Control for cross-border transport of nuclear materials.**

Radiographic imaging with cosmic-ray muons. **NATURE-Vol422- (20 march 2003)**

Natural background particles could be exploited to detect concealed nuclear materials.



# OBJECTIVES OF THE PROJECT T2DM2

- Accessing a new measure for characterizing geosciences mechanics of subsurface materials
- Develop a versatile and flexible instrument for the geosciences community

- Methodology for “muoscopy”

Constraints: Size, solid geometry, time-scale processes, ...

- Numerical simulation

MUSIC (Kudryavtsev et al., 2008), GEANT4 prior to calibration:

Duration of exposure vis-à-vis the time scale on the processes observed

Cover and geometric topology of the network of telescopes and precision field of views and the surface of each detector,

Number of detectors

Spatial resolution possible based on solid geometry / network

- Muoscopy – Densitometry

Construction of 4 prototypes and measures

Establishment of codes of tomography inversion / simulation (GEANT4, MUSIC...)

& coupling between densitometry imaging and seismic imaging (Young's modulus)

Coupling measures spatial-temporal density and field variations gravity (location, water flow dynamics in the ZNS)

# MUON TOMOGRAPHY REQUIREMENTS

## MEASUREMENT WITH STRONG CONSTRAINTS

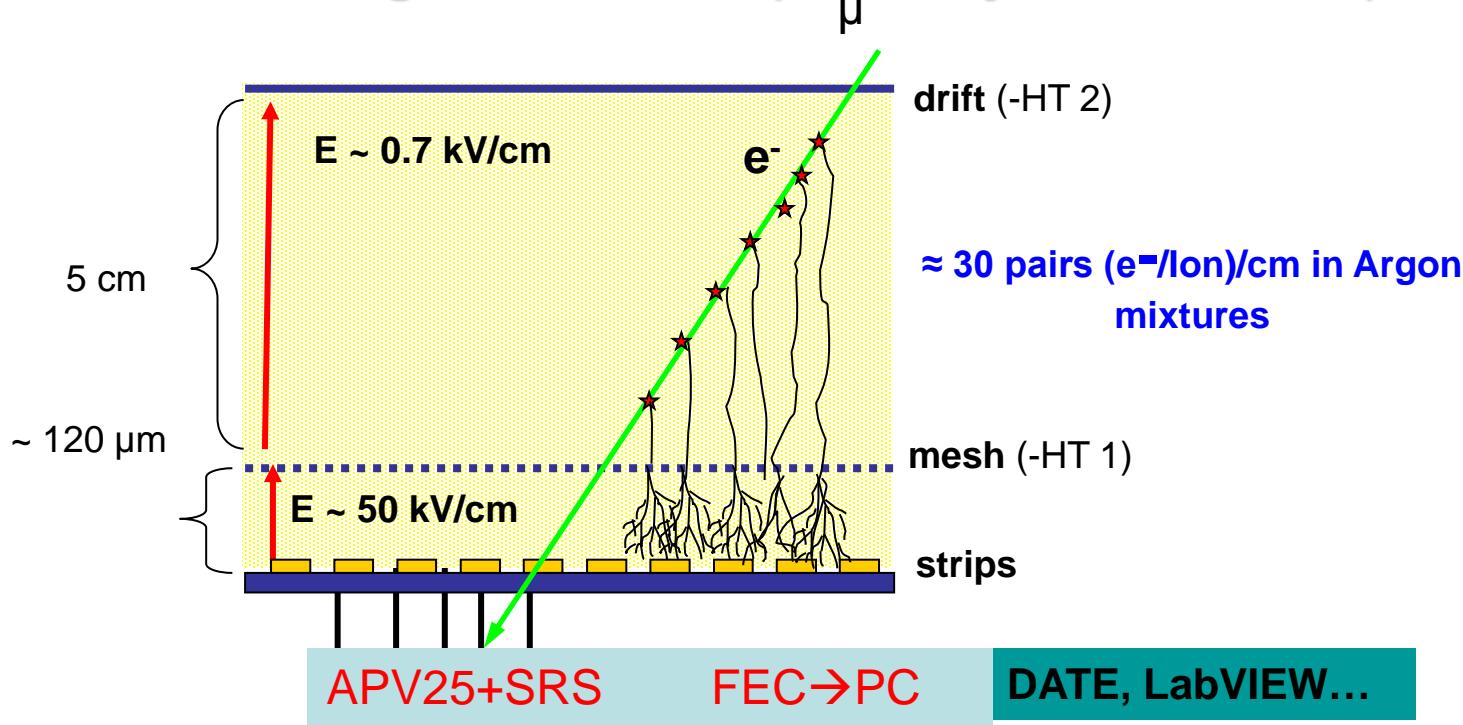
**Muon Tomography mean:**

- **low flux**
- **high efficiency detector**
- **high sensitivity**
- **high angular resolution**
- **low background noise (radiation and detector)**

# THE "TPC MICROMEGAS" MEETS THE CONSTRAINTS OF MUOSCOPIE

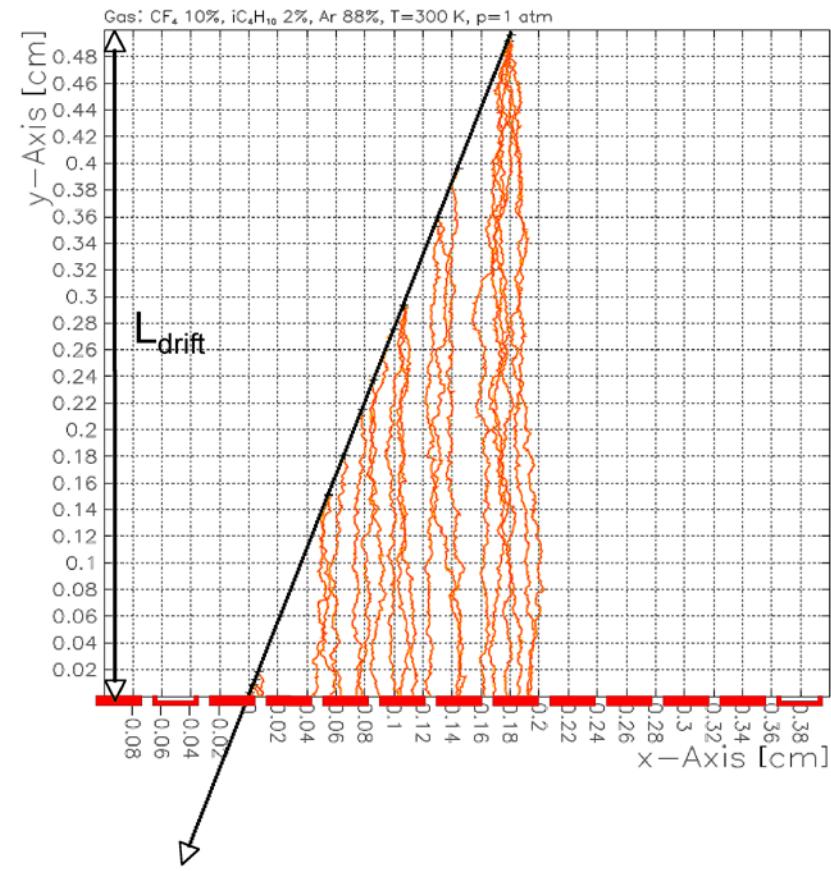
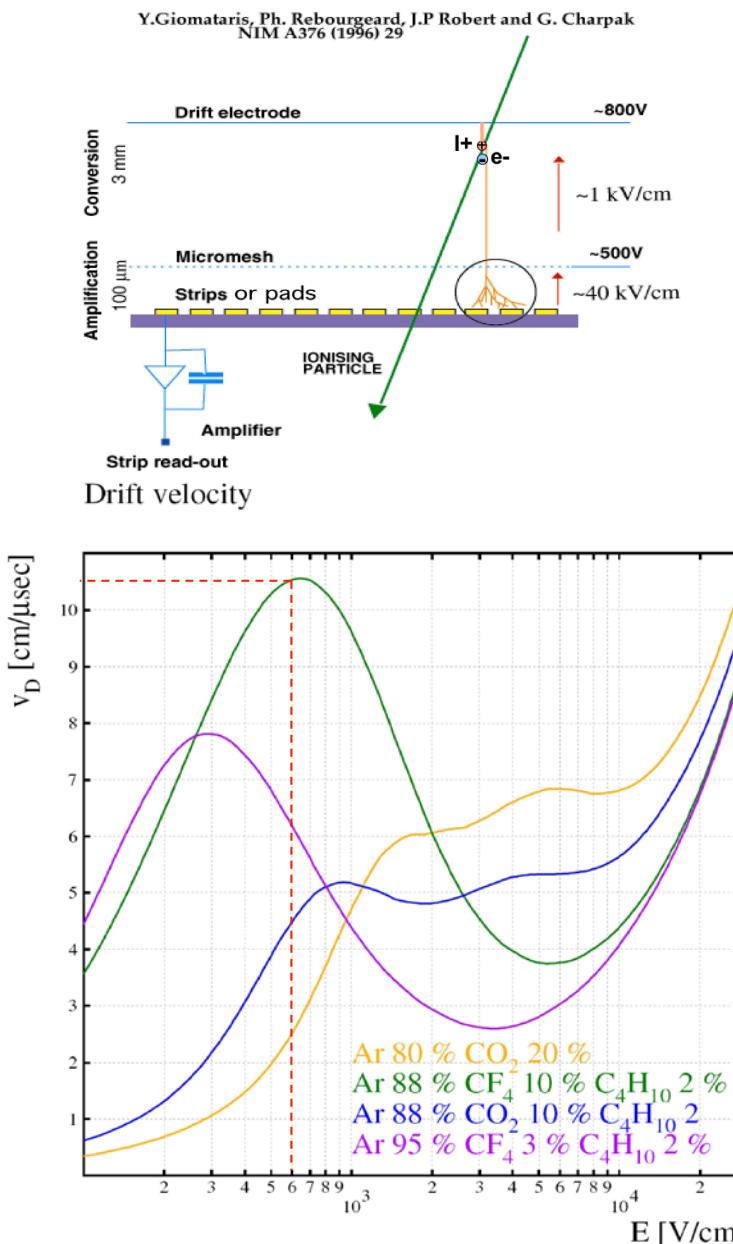
- Precise tracking capabilities
- Redundant tracking
- Improvements in background rejection
- muon direction discrimination (FW-BW)
- Event-by-event detailed analysis (hits multiplicity, pulse heights, t.o.f.)
- Long and stable operation (few months => few years) in difficult environments

# Micromegas-Bulk in TPC (Time Projection Chamber) mode



- Combine triggering and tracking functions: trigger from mesh cathode
- Spatial resolution:  $203 \mu\text{m}$  ( $\Theta_{\text{track}} < 45^\circ$ )
- Good double track resolution: low flux
- Time resolution:  $\pm 25 \text{ ns}$ ; in close future  $\pm 1 \text{ ns}$
- Efficiency:  $> 98\%$
- Rate capability  $> 5 \text{ kHz/cm}^2$
- Potential for going to large areas:  $1 \times 2 \text{ m}^2$  with industrial processes
- Cost effective:  $\approx 2000 \text{ €}/\text{m}^2 + 4500 \text{ €}$  for 2048 ch.(FEC+DAQ)

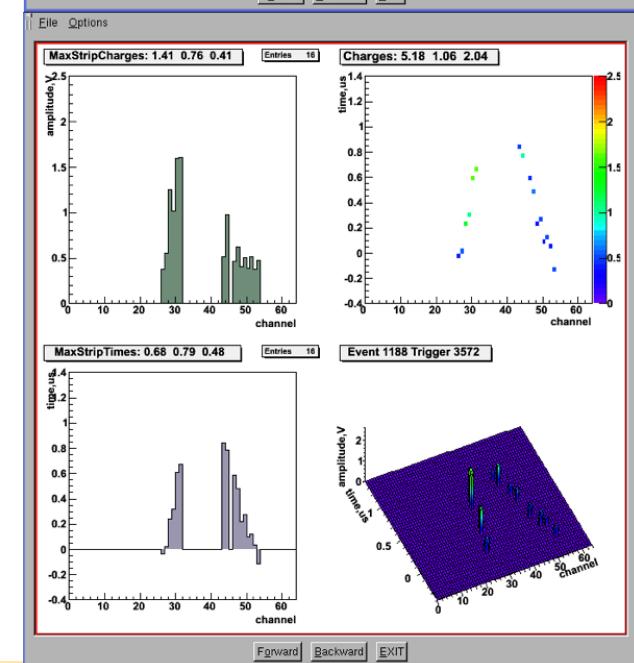
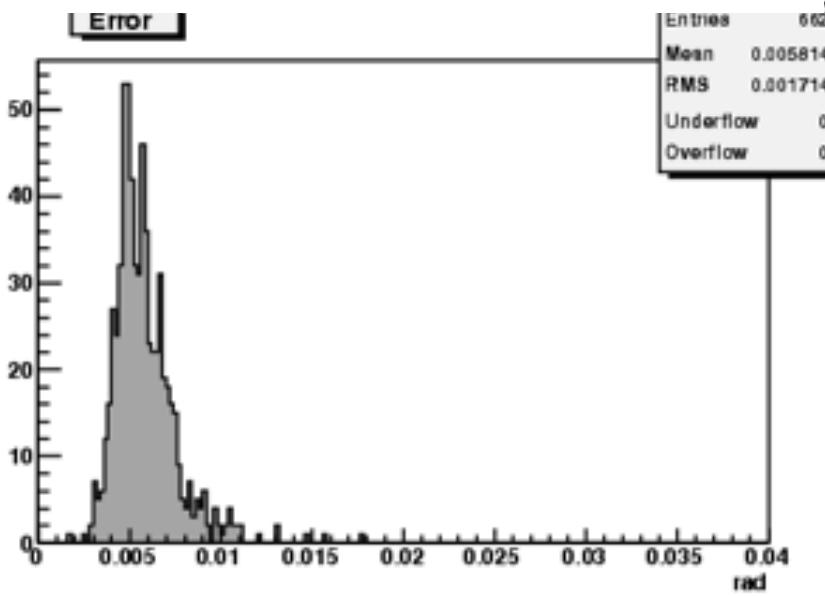
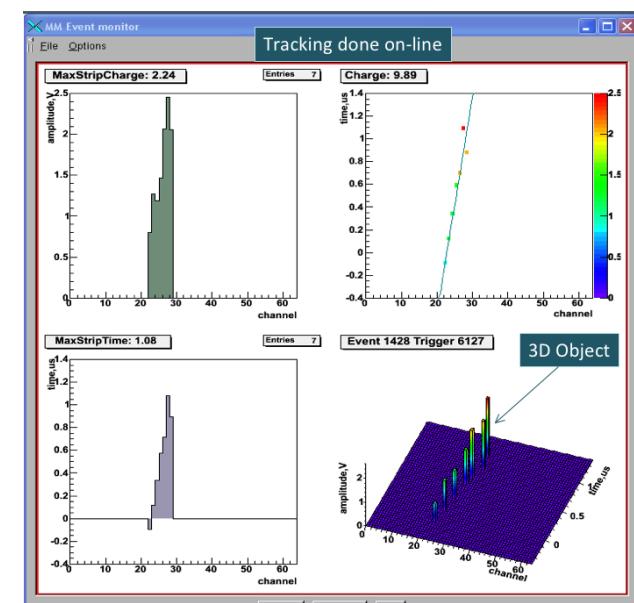
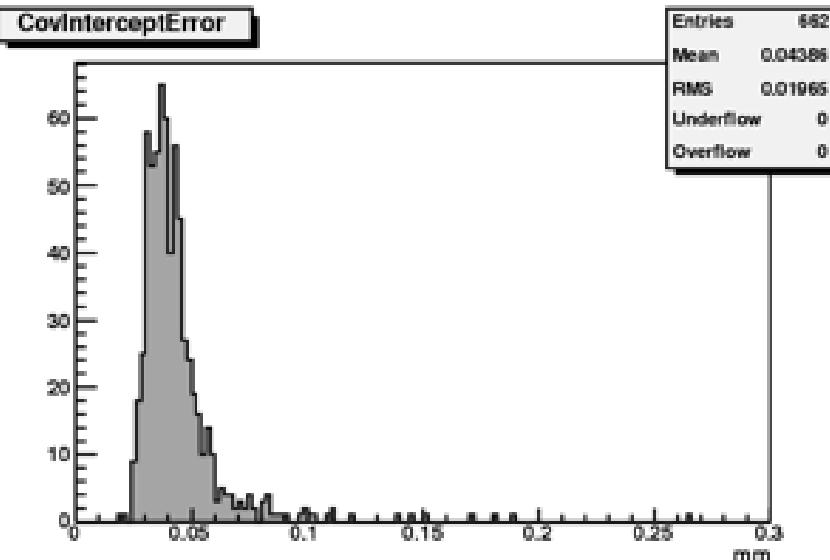
# TUNNING PARAMETERS



$$Z_i = \mu_e \cdot E \cdot \Delta t_i$$

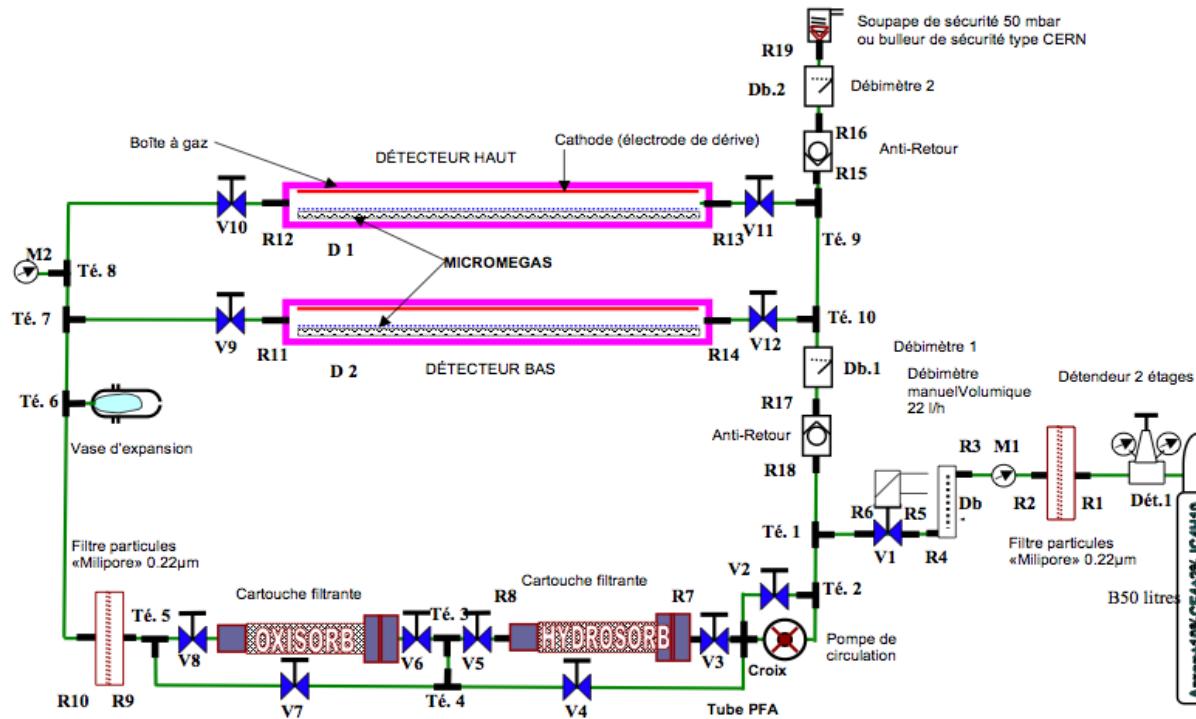
Thank to Rob Veenhoff (CERN)  
for the simulations with "GARFIELD"

# TRACK IDENTIFICATION CAPABILITIES



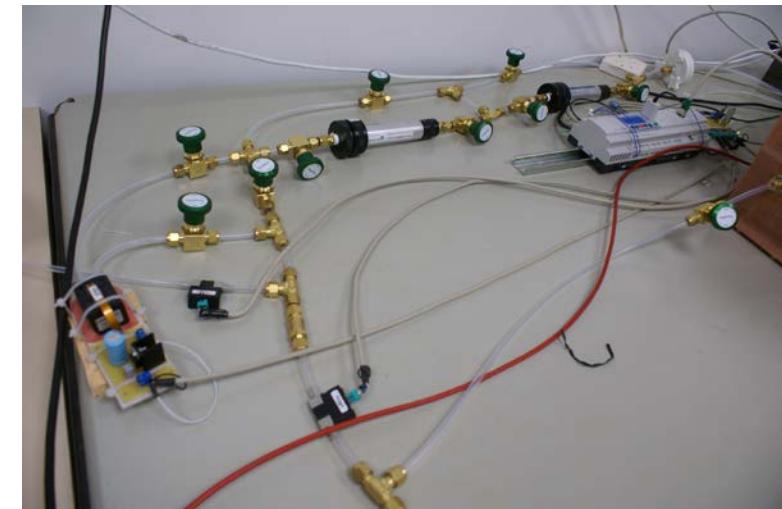
# THE WORK ALLREADY DONE

# PROTOTYPE GAS-SETUP

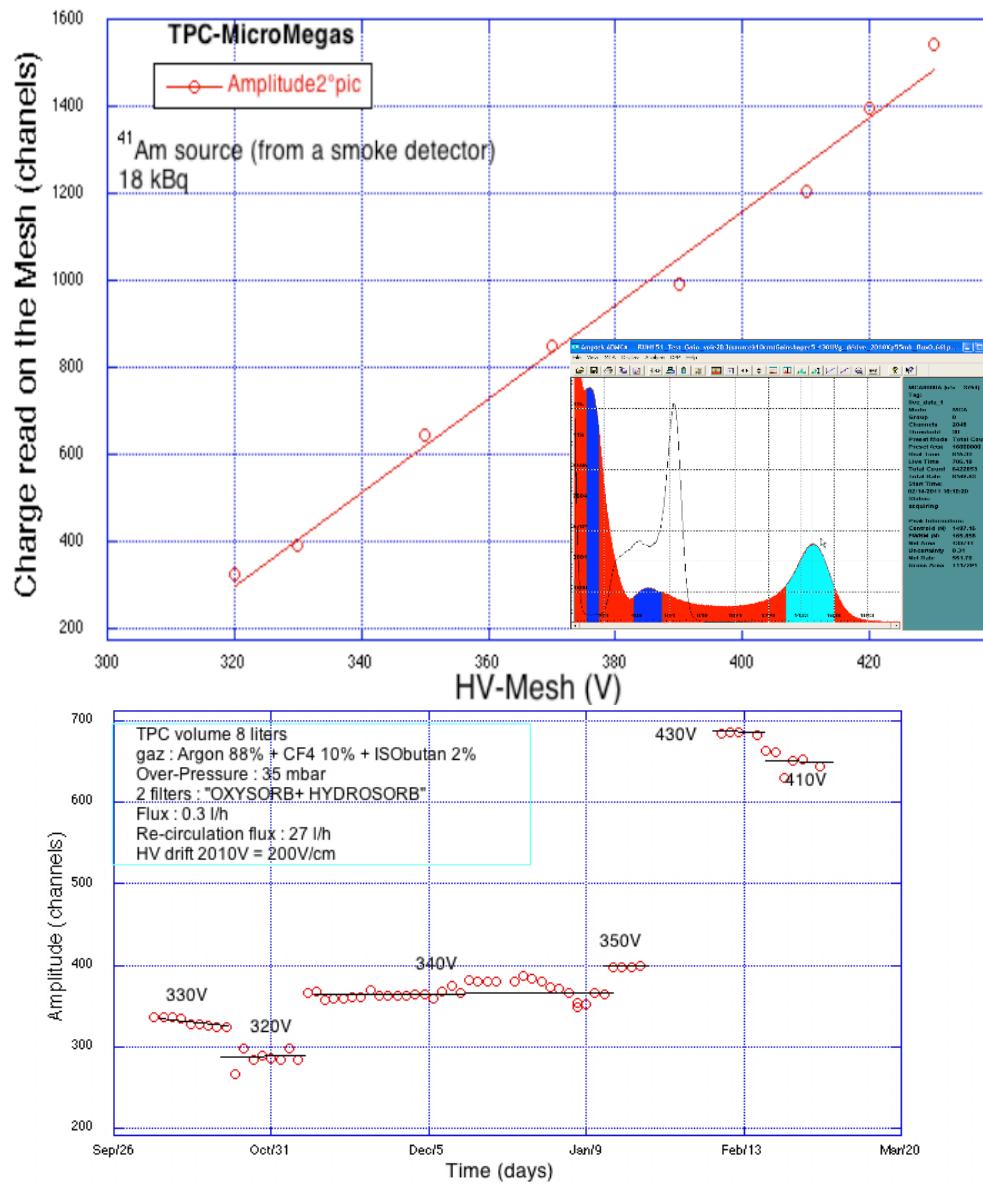


## GOALS:

- Demonstrate experimentally that it is possible to maintain the functional quality of gas for several months up to a year with a few tens liters reserve (10 l/day)
- Determine the gas mixture the more suitable (drift speed, gain, stability) to obtain the best angular and spatial resolution

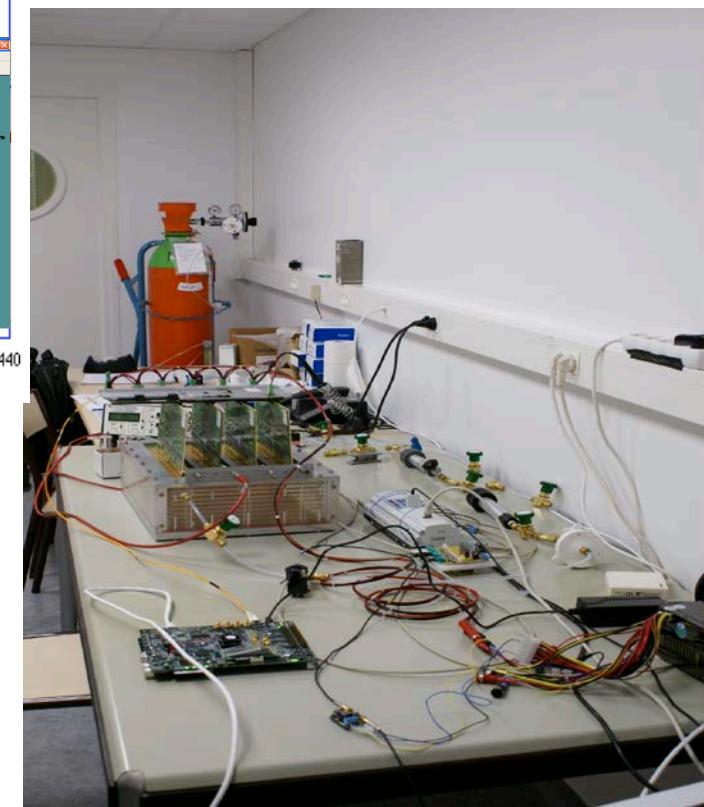


# DESIGN OF TELESCOPE AND TECHNOLOGY CHOICES



« Micromegas in a bulk » NIM A 560 (2006) 405–408

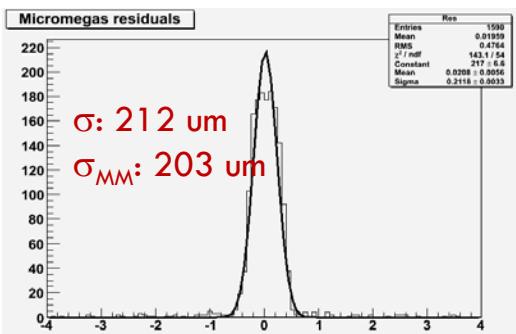
Test room @ Geoazur  
T2K-PROTOTYPE (CEA-IRFU)



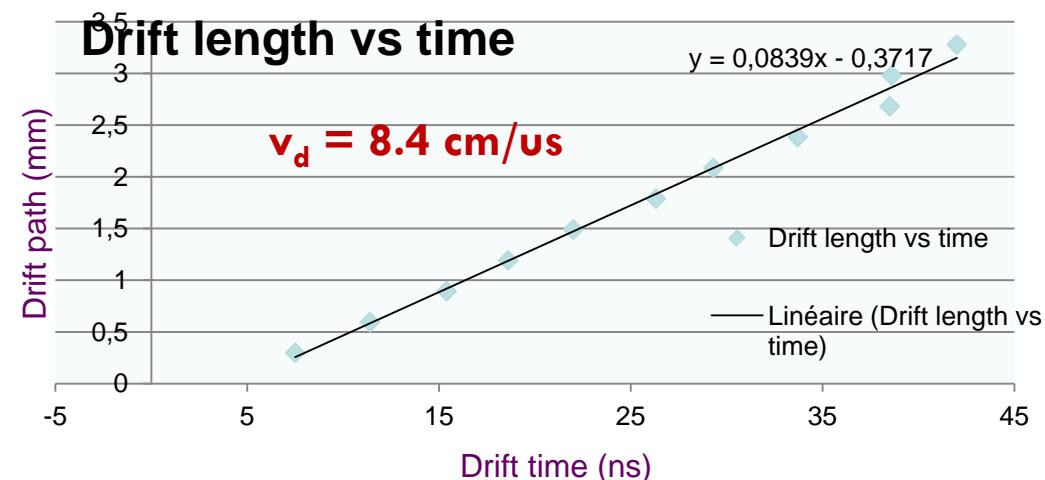
# THE WORK ON PROGRESS

# TECHNOLOGY & DIMENTIONAL CHOICES

Track inclination: 40°  
 Ar:CF<sub>4</sub>:iC<sub>4</sub>H<sub>10</sub> (95:3:2)  
 Drift field: 360 V/cm

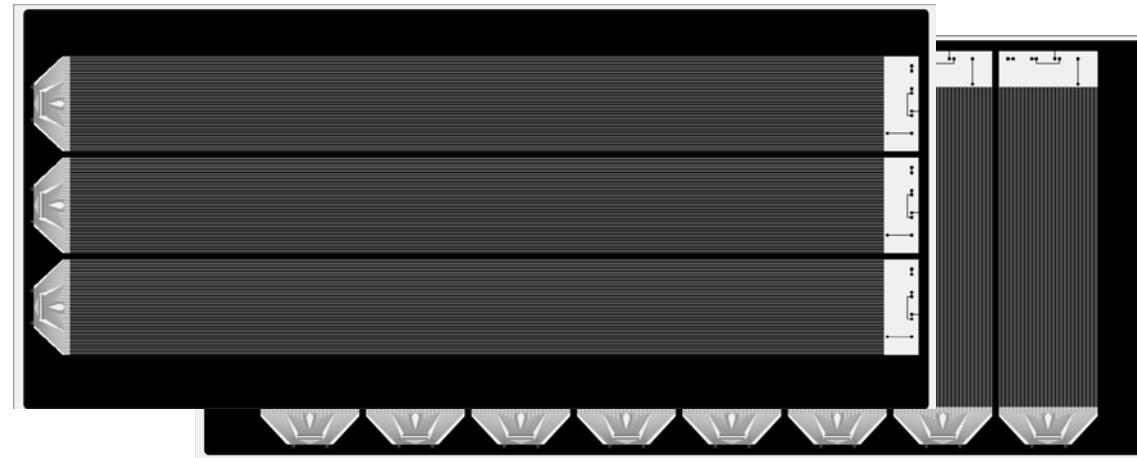
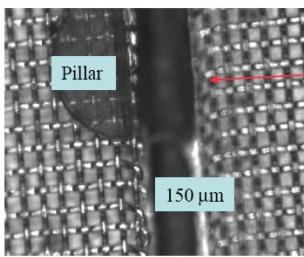


Strip pitch: 1000  $\mu\text{m}$   
 Strip width: 900  $\mu\text{m}$



P. Lengo – IEEE-NSS 21 October 2008, Dresden

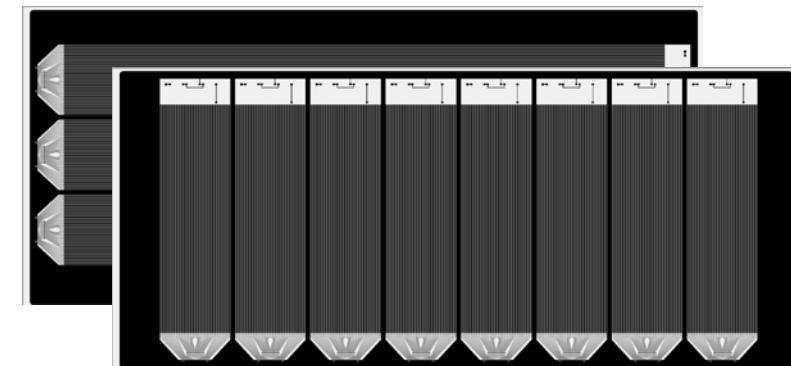
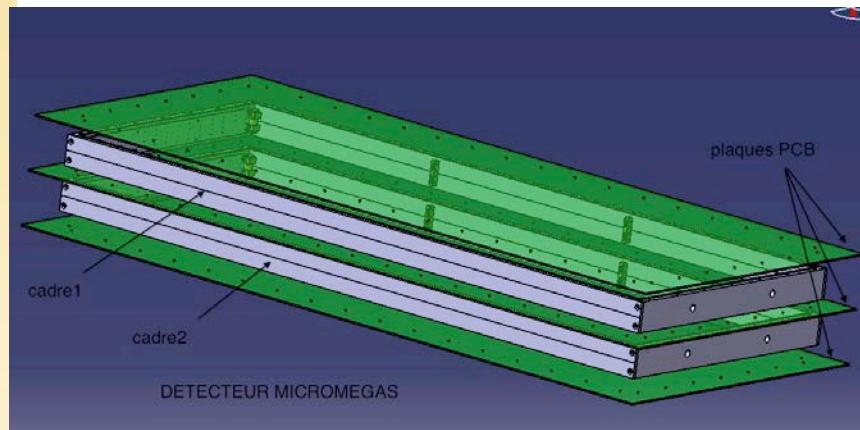
## PROTOTYPE DETECTOR



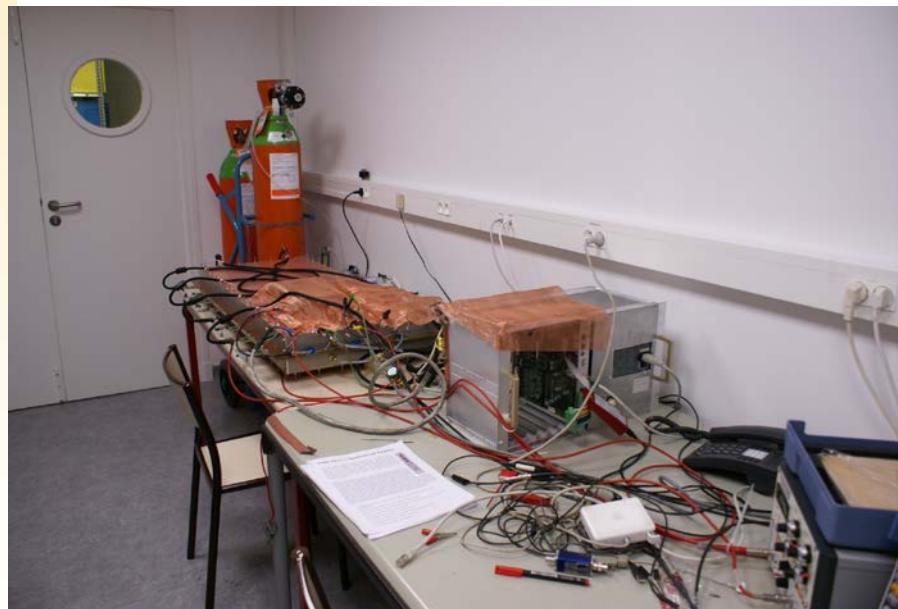
Segmentation on both sides: smaller capacitance

# NEW TELESCOPE DESIGN AND TECHNOLOGY CHOICES

## Double sides $\mu$ Megas-Bulk TPC (5 cm drift space) on the same printed-board

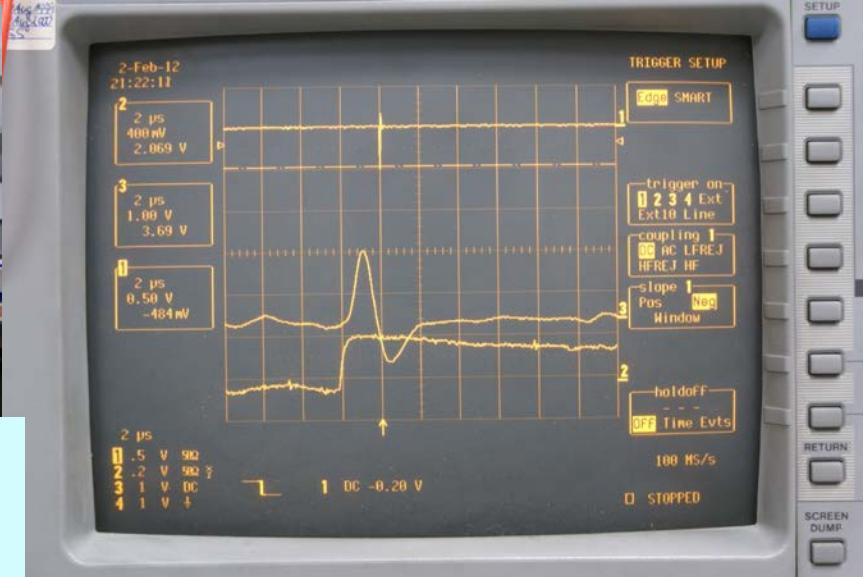
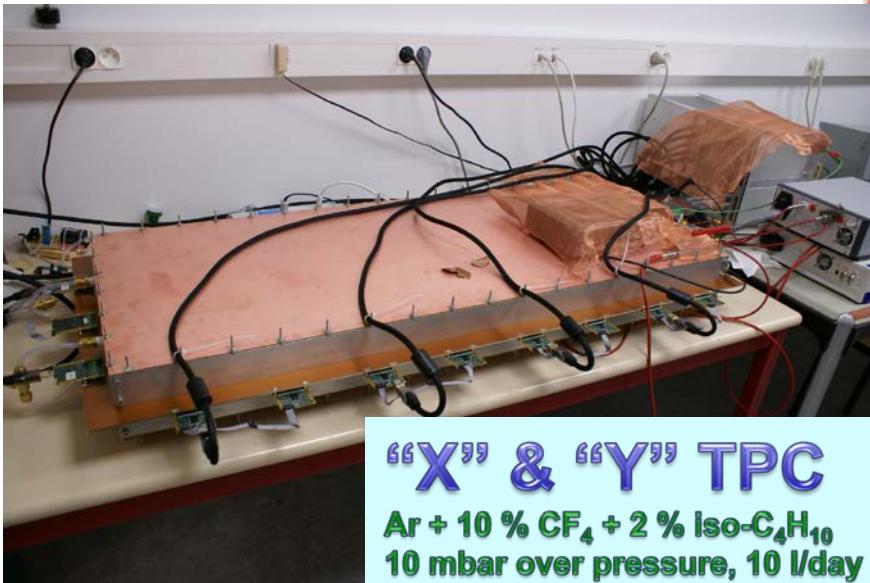


“Y” & “X” segmented

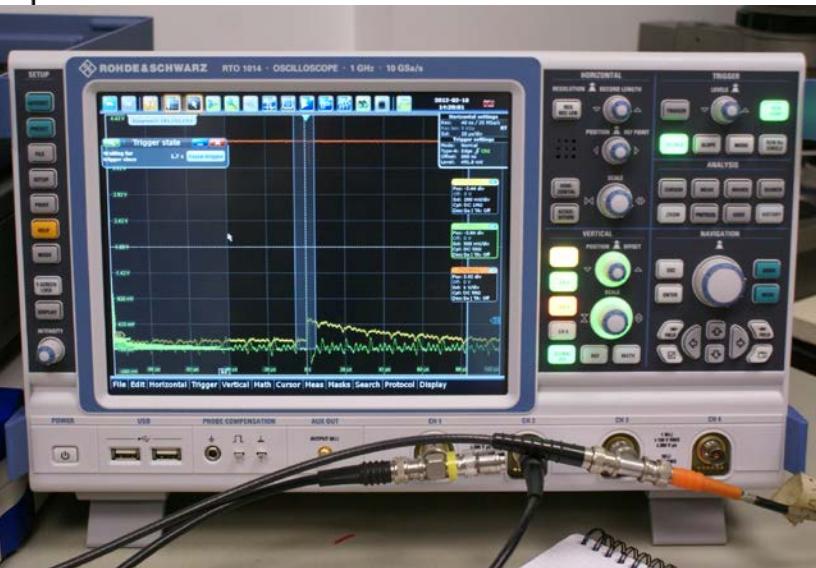
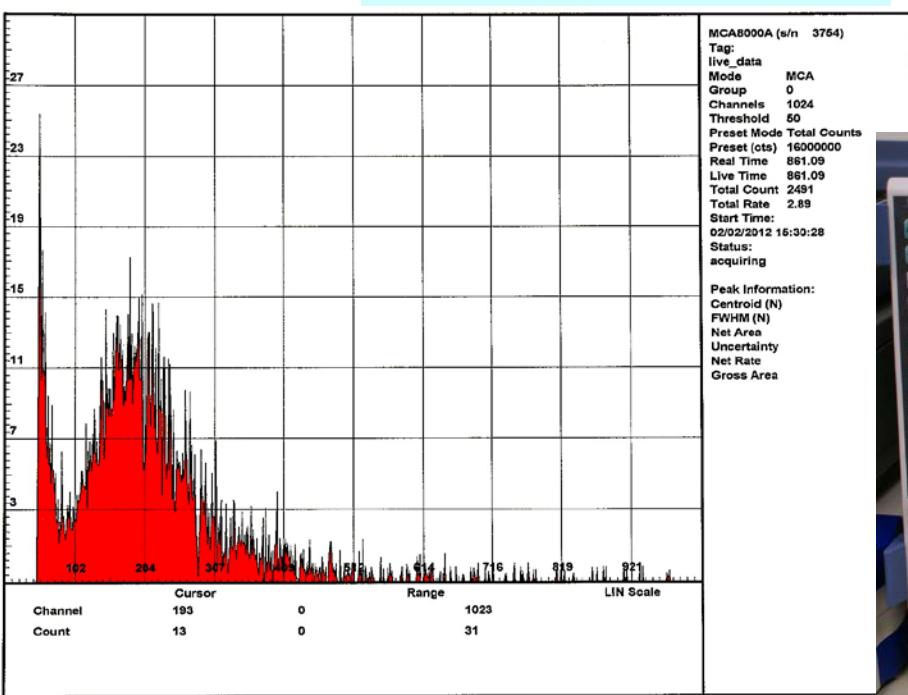


Inconvenient: 2 meshes & more expensive

ADVANTAGE: compactness and easy coincidence

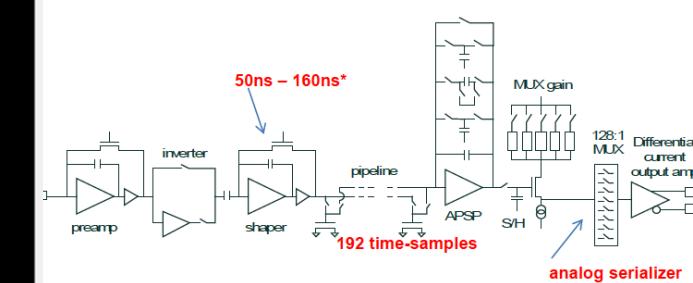
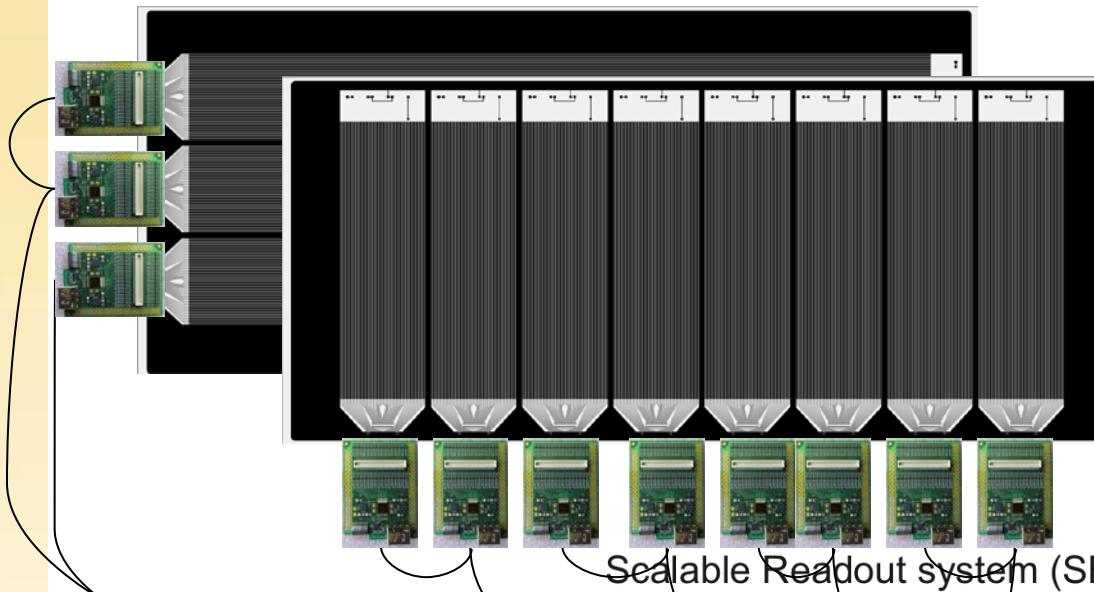


Trigger from the mesh signal Canberra 2002C charge amplifier followed by a "Silena" shaper



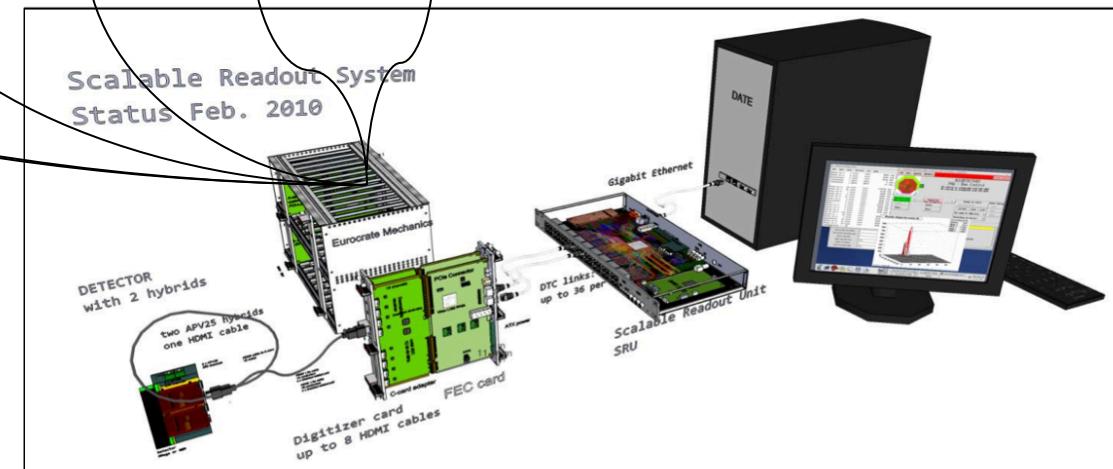
Histogram of the cosmic flux

# ELECTRONIC & DAQ



**APV25 Schematic**

**SLC-5.7  
DATE(Aleph)  
LabView  
SRSSDC**



ASIC board with spark protections connected to detector

HDMI

Digitizer card (ADC) + Front-end concentrator card

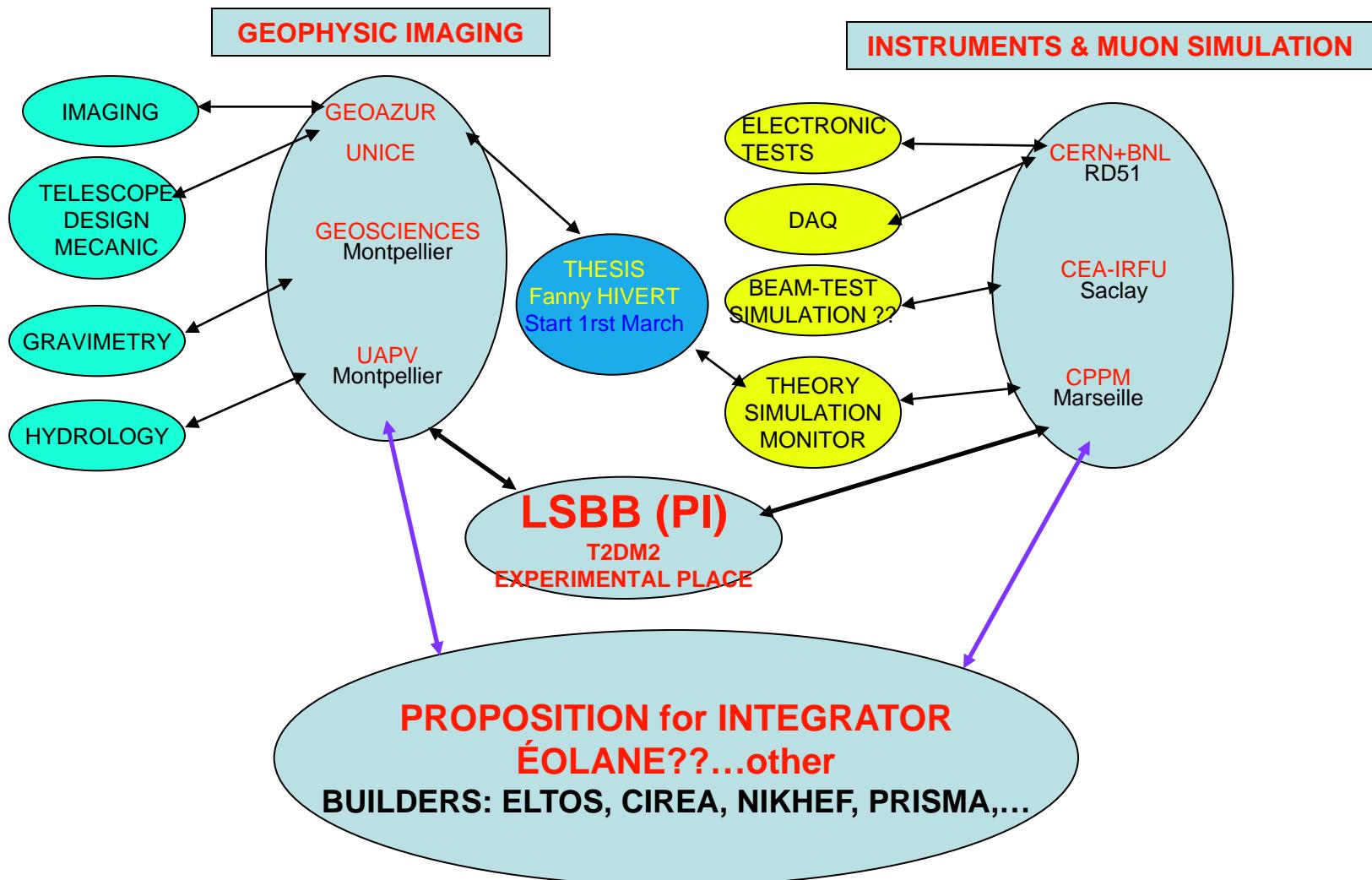
DTC link

Scalable Readout Unit For multiplexing of event data

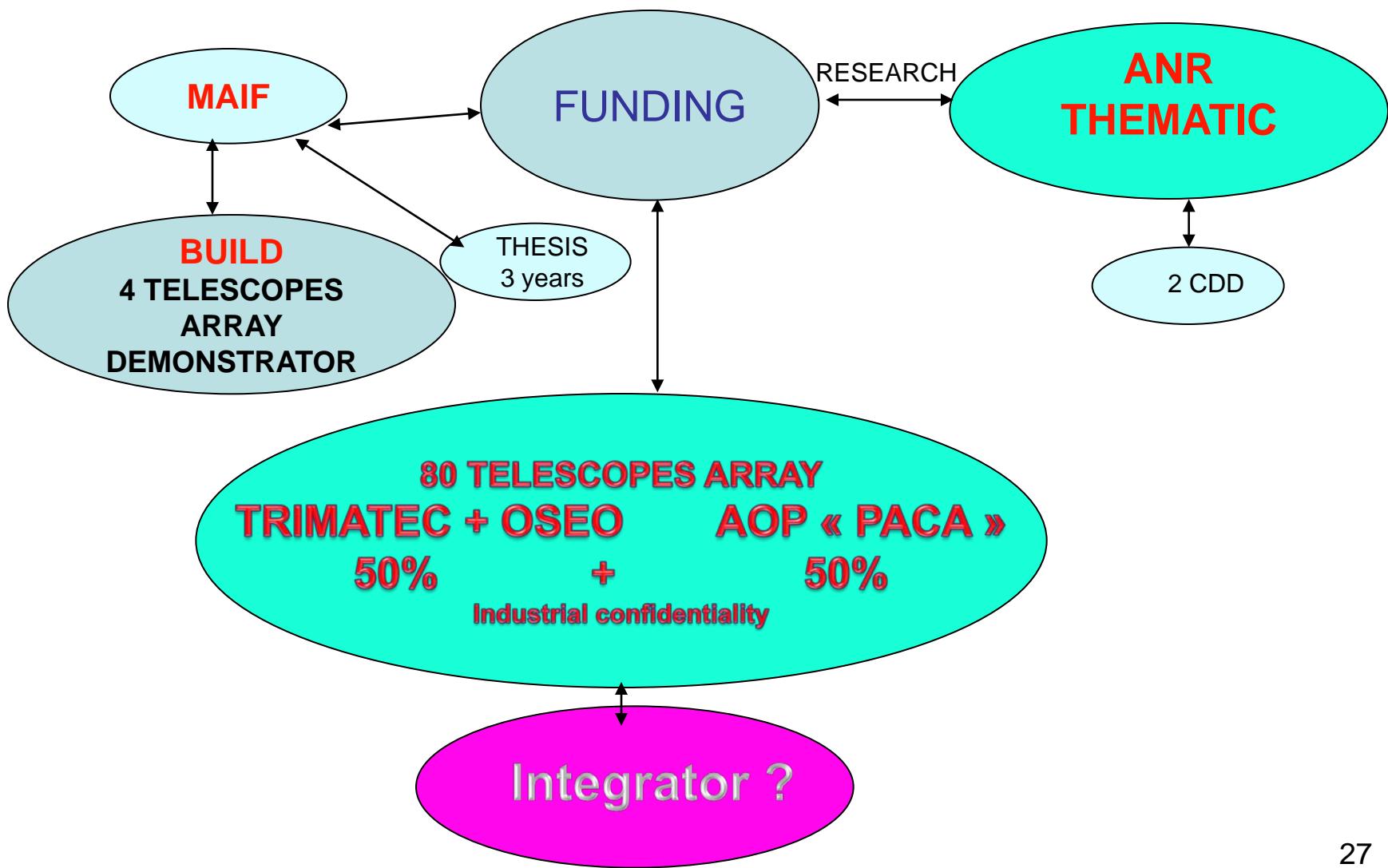
PC with DAQ slow control soft. + analysis framework

## **NEXT YEAR WORK:**

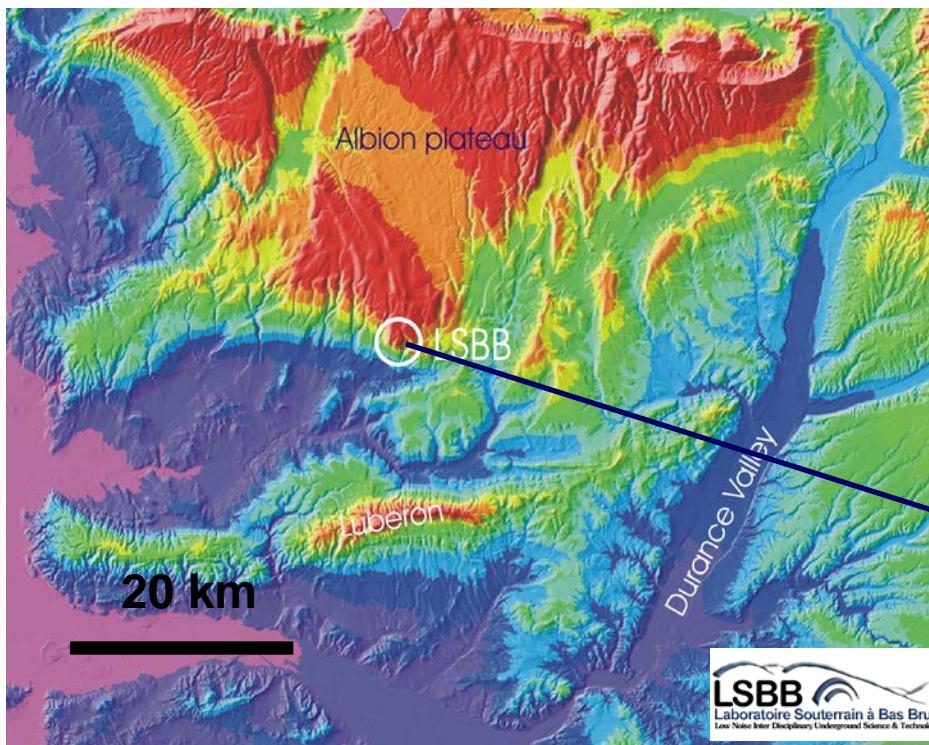
# PROPOSED STRUCTURE FOR COLLABORATION



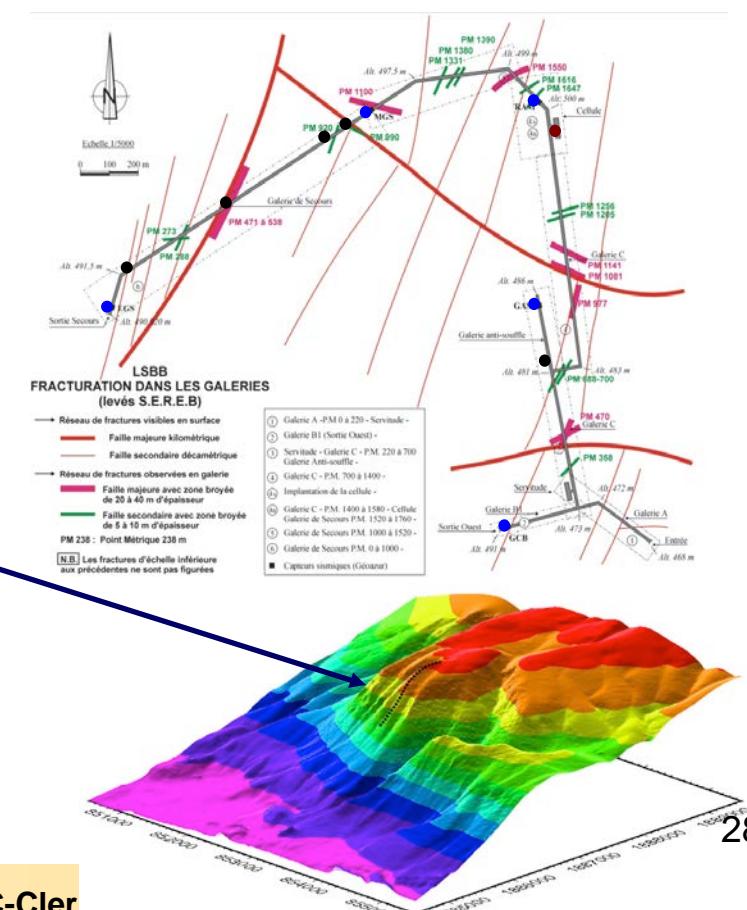
# NEW FUNDING TO BUILD A 80 TELESCOPES ARRAY

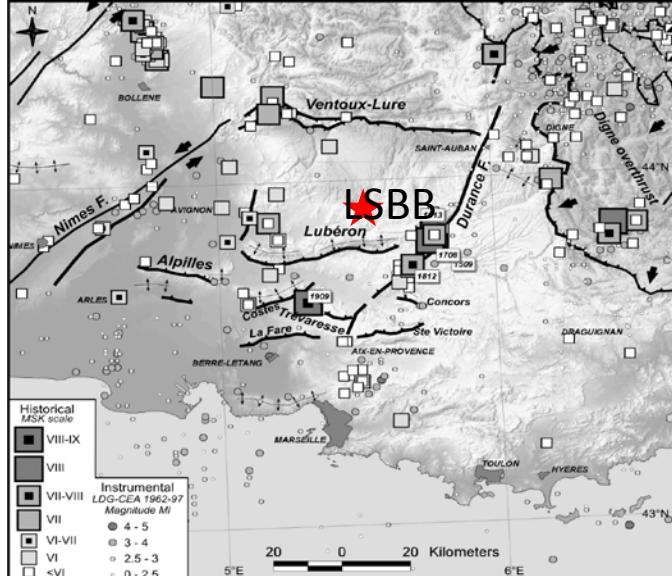
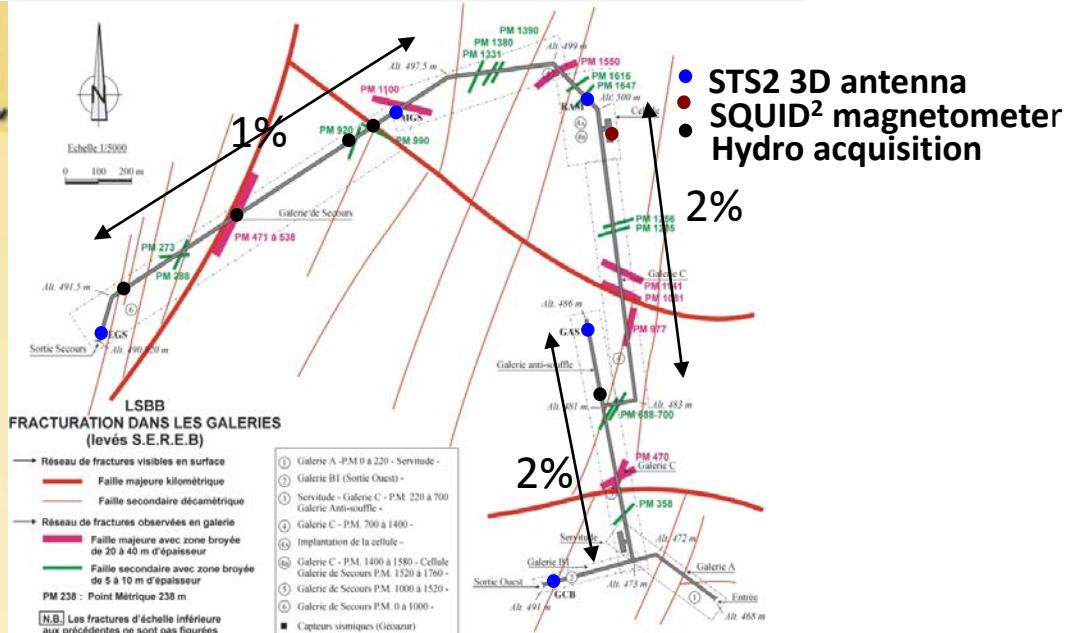


# PROTOTYPE DEVELOPMENT AND TUNING



Experimental development at LSBB (karst) to benefit from the combination of multi-parametric measurements from different scientific projects conducted in the laboratory





*From Baroux et al. (2003)*

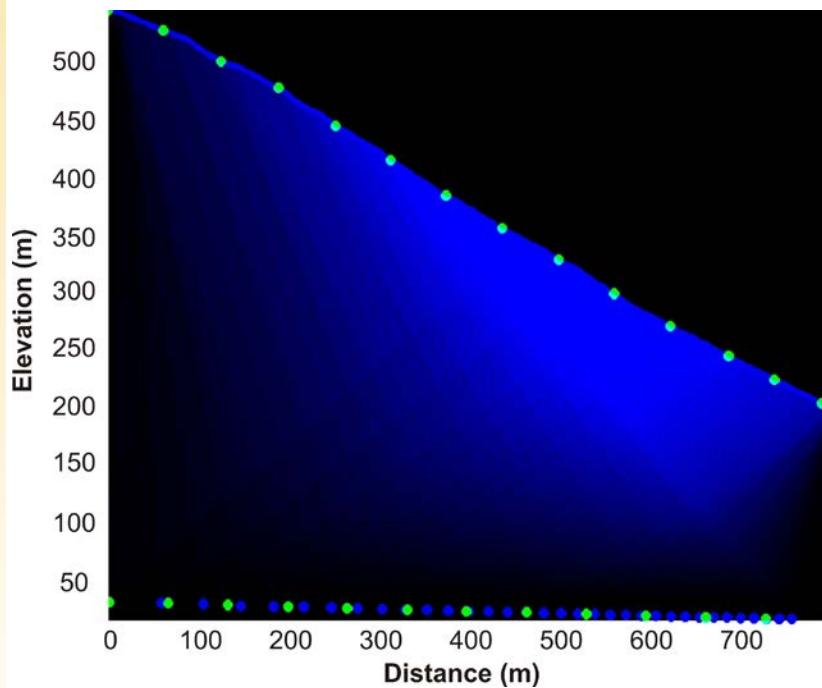
**At the heart of one of the major seismogenic regions of South-Eastern France  
Unsaturated zone of karst aquifer Fontaine de Vaucluse  
Carbonate reservoir**

# DESIGN OF TELESCOPES TO NETWORK BASED ON THE SIMULATION

## Network design:

- Spatial resolution and number of detectors

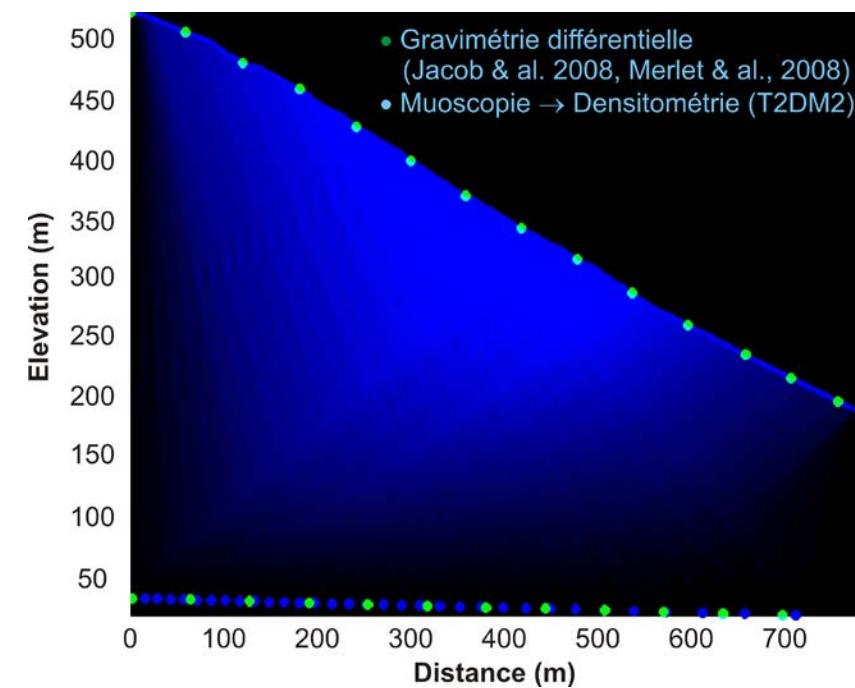
Tomography requires redundancy absorption measurements under different zeniths and / or azimuths to get a good lighting environment. Binding global opening and the angular resolution of each telescope, the network topology to deploy and the number of telescopes.



## Simulation:

- Optimizing coverage

Surface, aperture and resolution

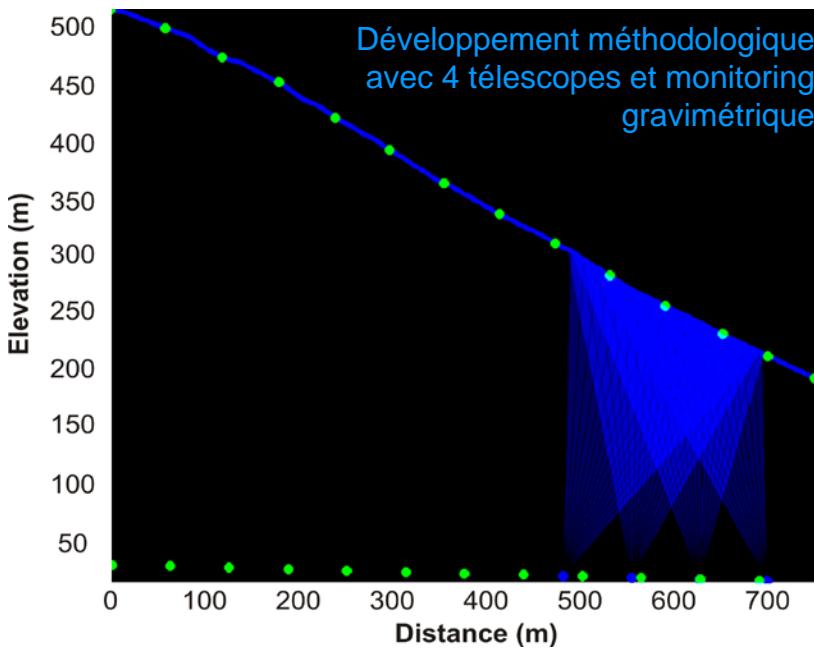


## Inversion:

Iterative process involving modeling muons flux expected from the topology

(MUSIC, Kudryavtsev et al. 2008)

# PROSPECTIVE MEDIUM AND LONG TERMS



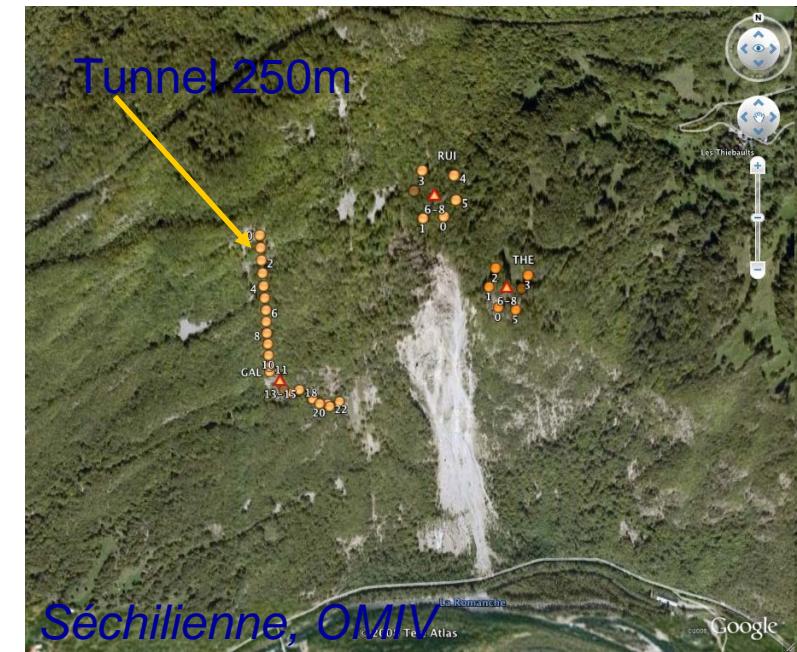
## Beyond Project T2DM2:

Exploration of different problems: corruption within the gravitational movements (eg tunnel Séchilienne, gneiss), environmental monitoring in underground storage (Bures, clays) or even oil exploration. Create a national network of portable telescopes (number 50 to 100 telescopes?)

Generation Project, ANR, Region, Europe

## Through the project T2DM2:

- Provide tools for digital modeling of device acquisition and reversal
- Develop a website to disseminate knowledge of this measure Federate a community of interest and define the outline fundamental questions that can be studied with the muoscopy





## CONCLUSIONS

### Technological choices:

- To have smaller pixels: monitoring and survey of civil engineering structures, wells (gas, oil, water, storage, ...)
- To have an overall height reduced through a measuring time on pixels (Equipment Gallery)

### Applications:

- Involvement hydrogeology : hydraulic flow
- Involvement CO<sub>2</sub> stockage : macroscopic properties of the rock
- Tunnel survey

### Calendar:

- Methodology and test LSBB 20012-2013 ==> new funding for extension up to 80 telescopes==>Financial support from the region
- Deployment then mine (water monitoring) and landslides (monitoring of damage, tunnels)

### Our needs :

- Embed a group for modeling aspects
- Generate an R&D project to develop a network of observation from 40 to 80 telescopes

We research collaborations and related applications into existing programs

**ANY HELP WILL BE WELCOME!!**

New measurement ability (km of lateral extent, multi-hm thickness) of the spatial and temporal evolution of rock density function of water saturation, total porosity, mechanical condition and damage at in situ scale

- Monitoring of aquifer resources and reserves,
- Monitoring the stability of volcanoes,
- Monitoring the stability of underground vacuum and rock mass instabilities

Qualification of the prototype telescope developed in 2009-2011 at GEOAZUR & LSBB in collaboration with the consortium RD51/CERN, new and innovative tool to complement field exploration and monitoring

### Next steps ...

Strong partnership and technology transfer possibility in collaboration with CEA / IRFU, the consortium RD51 (<http://rd51-public.web.cern.ch>), the group MAMMA (ATLAS Muon Micromegas Activity) and with support from the poles TRIMATEC and RISQUES (<http://www.pole-trimatec.fr>, <http://www.pole-risques.com>) and the association AFTES (<http://www.aftes.asso.fr>) to install a demonstrator at LSBB

Beyond T2DM2, the goal is to create a network of telescopes that will be installed and used in a first phase as a methodological demonstrator within the Low Noise Underground Laboratory (LSBB, <http://www.lsbb.eu>) before its future operation in other works and underground spaces and monitoring of unstable cliffs and gravitational movements.

# BACKUP-SLIDES

## THE HISTORICAL AND RECENT EXPERIMENTS

## Muons flux measure

- Pyramid

Using cosmic rays in order to detect the presence of a secret chamber in the Pyramid of Chephren, experiment was install in the Belzoni chamber. Muons through a cavity lose less energy by interaction compared to crossing the limestone composing the pyramid.

Luis Alvarez et al. (1970)

*“the results of all this is that we found the pyramid to be quite solid, with no chambers comparable in size to those found above the plateau level, in the Great Pyramid.”*

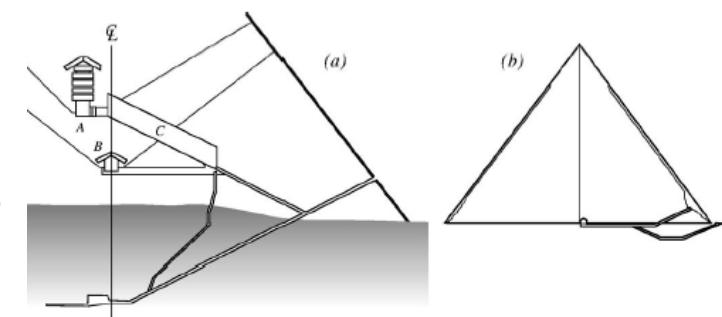
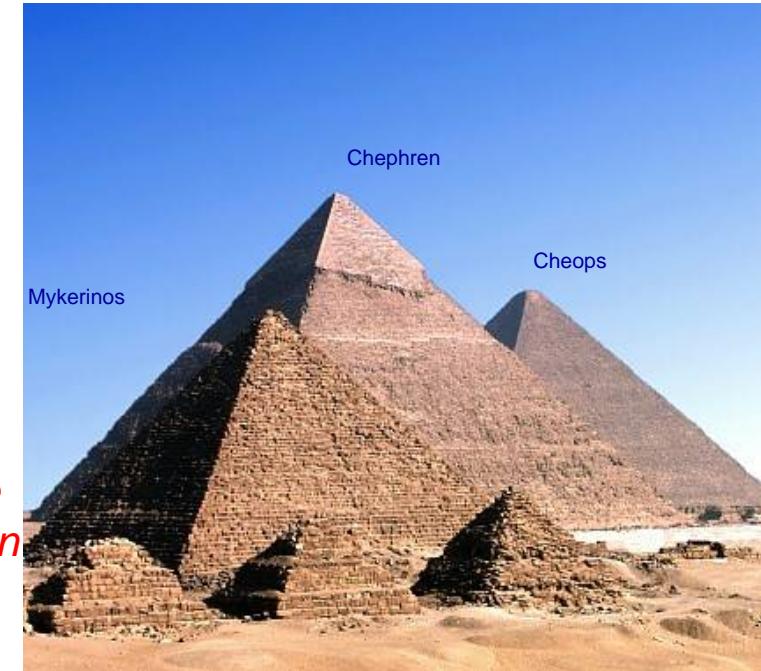
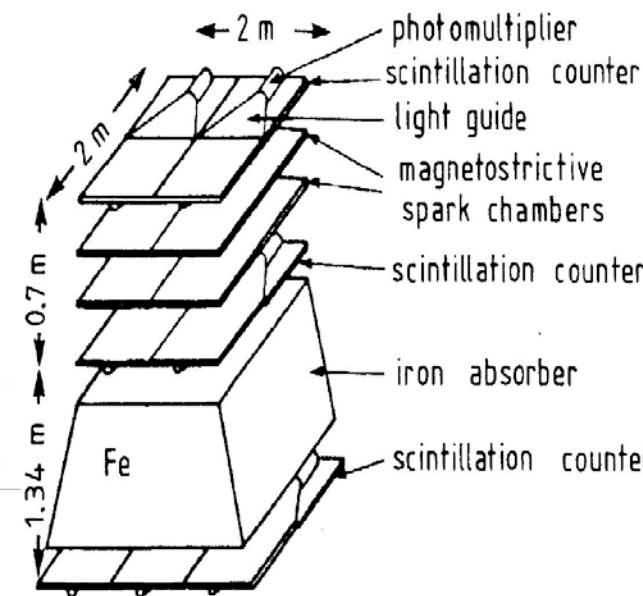
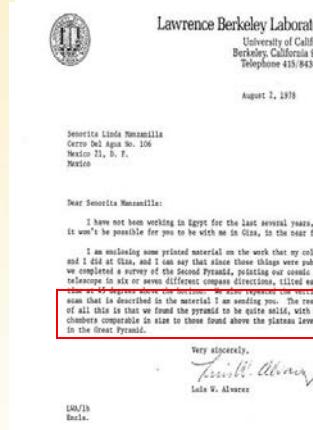


Fig. 2. (a) The known chambers in Cheops' pyramid. In the body are A, the King's Chamber; B, the Queen's Chamber; and C, the Grand Gallery. The centerline of the pyramid is indicated. (b) Are there undiscovered chambers in Chephren's pyramid?

# DESIGN OF TELESCOPES TO NETWORK BASED ON THE SIMULATION

## Build the network:

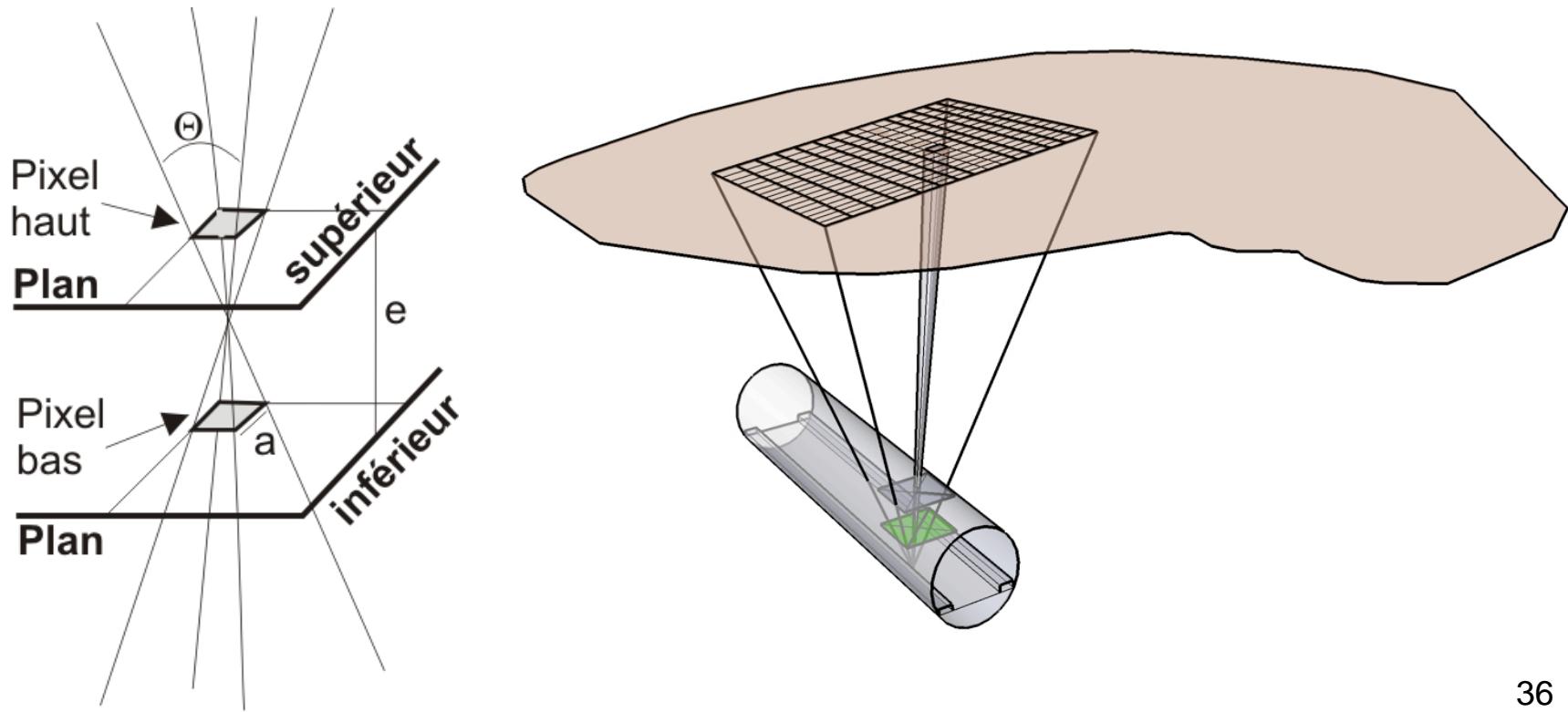
- Pixelization (strips X & Y)

The angular resolution and the distance between planes require the pixel size.

The number of pixels and the electronics require (real time processing, discrimination and signal acquisition) forcing the cost.

The time measurement requires the surface of the telescope.

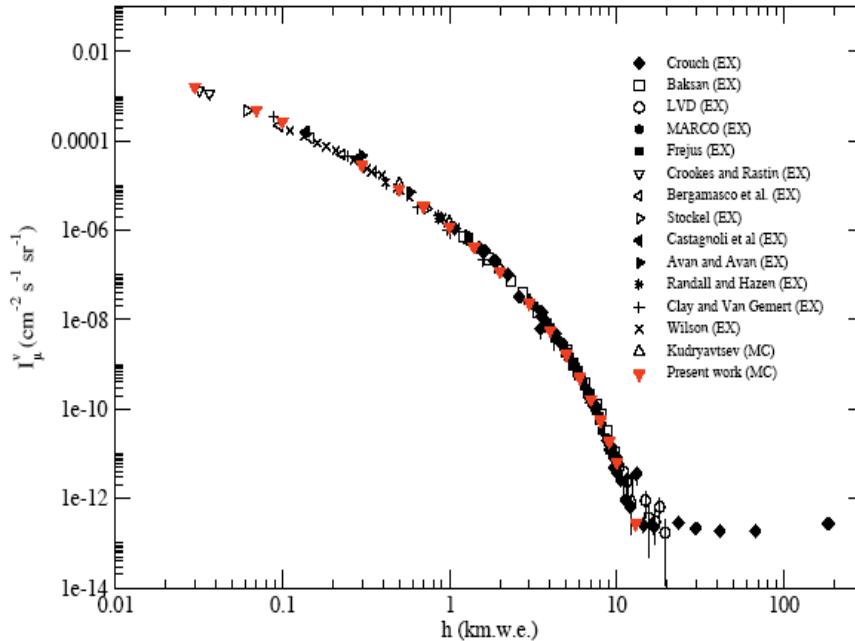
The angular resolution, the aperture, the exposed surface can vary for each, we must design a versatile and flexible telescope



# DESIGN OF TELESCOPES NETWORK TO BASED ON THE SIMULATION

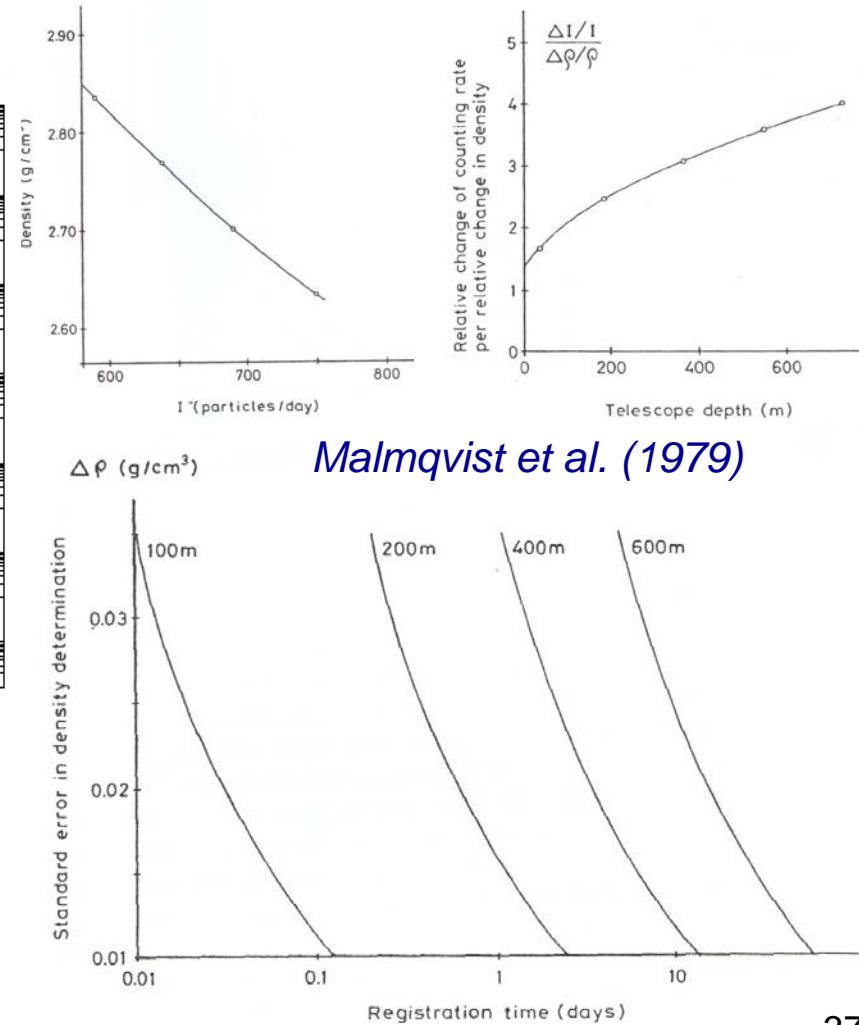
## Count rate:

**Number of muons ( $\text{m}^{-2} \text{ day}^{-1} \text{sr}^{-1}$ ): depending on the thickness, density & atomic compound of materials encountered**



Average vertical muons intensity  $I_\mu^v(h)$  versus vertical depth  $h$  beneath a flat surface in standard rock.

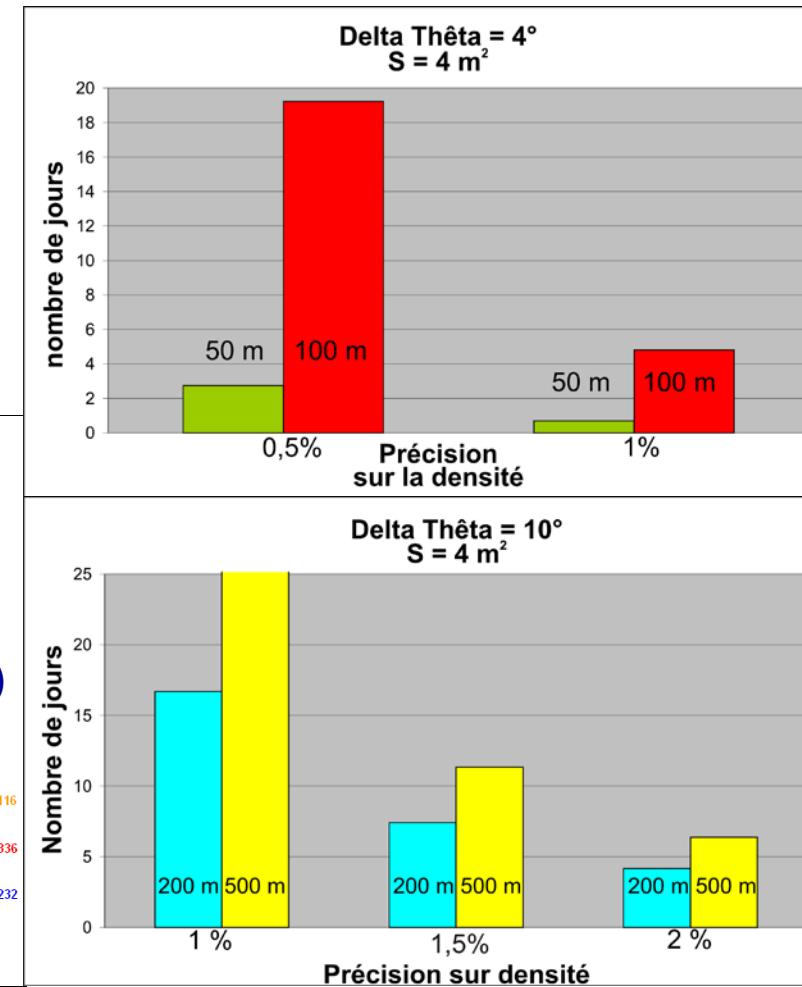
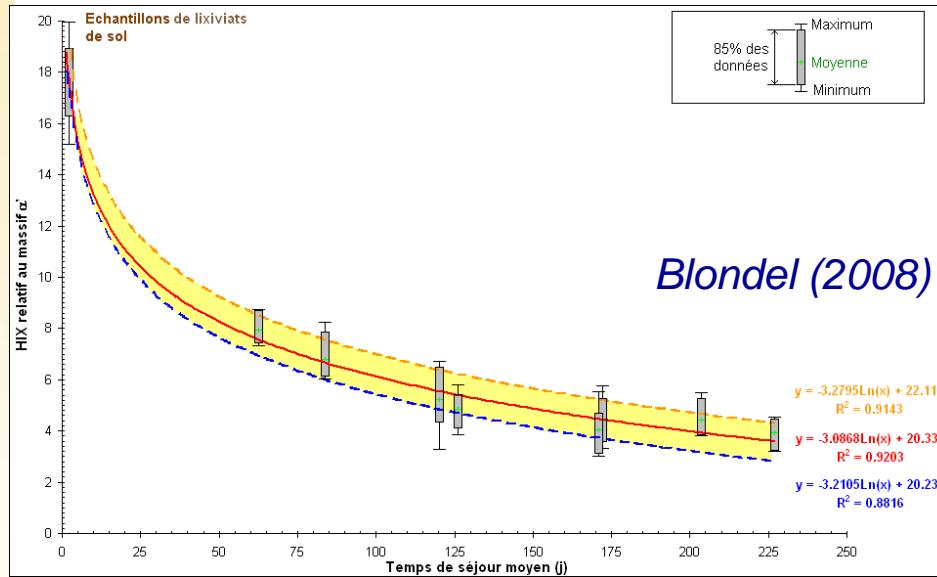
arXiv:hep-ph/0604078 v2 25 Aug 2006



# DESIGN OF TELESCOPES TO NETWORK BASED ON THE SIMULATION

## For each telescope:

- Exposure versus surface of the telescope  
The temporal resolution depends on the speed physical processes observed, which are varying density, and duration of resilience of the environment. The required area depends on the time scale processes and counting rate.



Residence time and exposure times depending on the depth and accuracy of measurement desired

