Using muons for archeology ARCHé

Γιάννης Καρυωτάκης*

LAPP Annecy, CNRS France

Yannis.Karyotakis@lapp.in2p3.fr

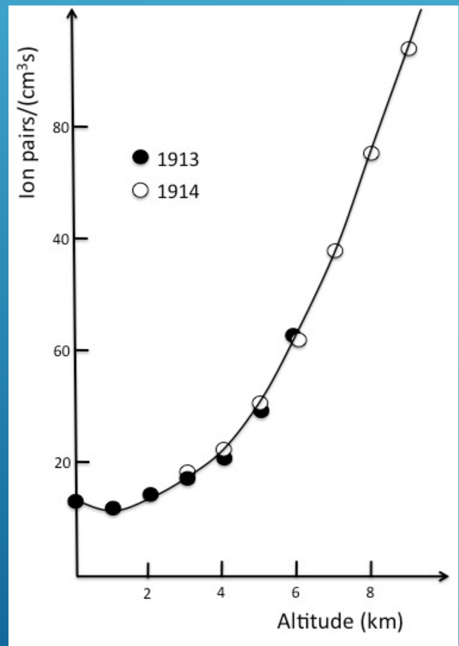
Αθήνα, April 16th 2019

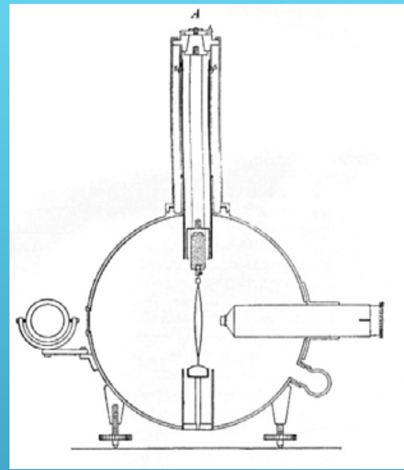
**) C.Goy Θ.Αυγητας, J.Marteau et al, Σταύρος Κατσανεβας,*
Χαρά Πετριδου et al.
Γ.Τσοκας et al.

Our planet is continuously hit by cosmic rays !

First hints for cosmic rays

- Electrometers discharge because the air is ionised by radiation (Julius Elster and Hans Geitel 1900)
  - What is the radiation origin ???
    - Radioactive elements on earth's surface ???
    - Viktor Hess : Radiation comes from sky. First balloon experiments. Seven flights.
      - The number of ion pairs increases with altitude
      - Do not come from sun ! Data taking in an solar eclipse

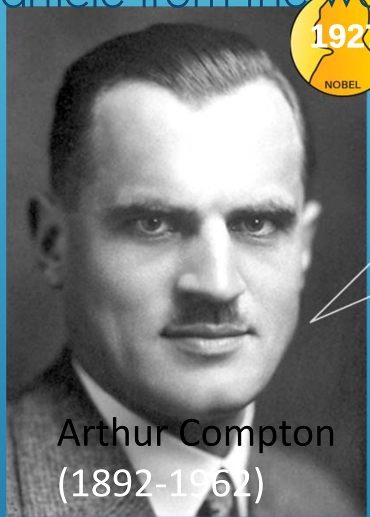




Theodor's Wulf Strahlungsapparat

Friendly (fierce) debates

- Their intensity varies depending on where we are on Earth…
- Cosmic rays are charged particles!
  - More particle from the western direction: **positively charged**



They are electrically charged particles!

The New York Times

VOL. LXXXII...No. 27,370. December 31, 1932

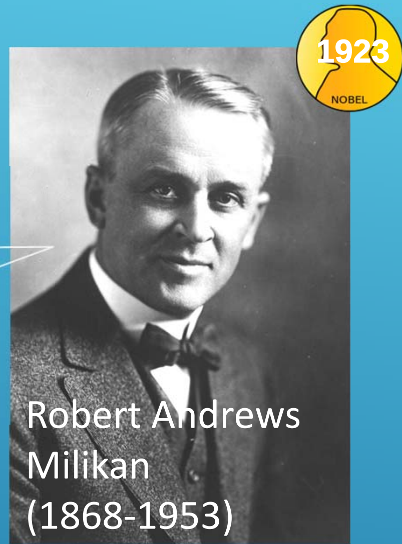
MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

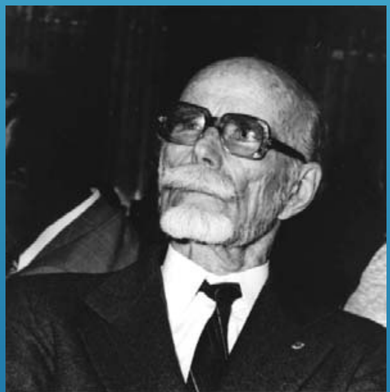
They are neutral particles!



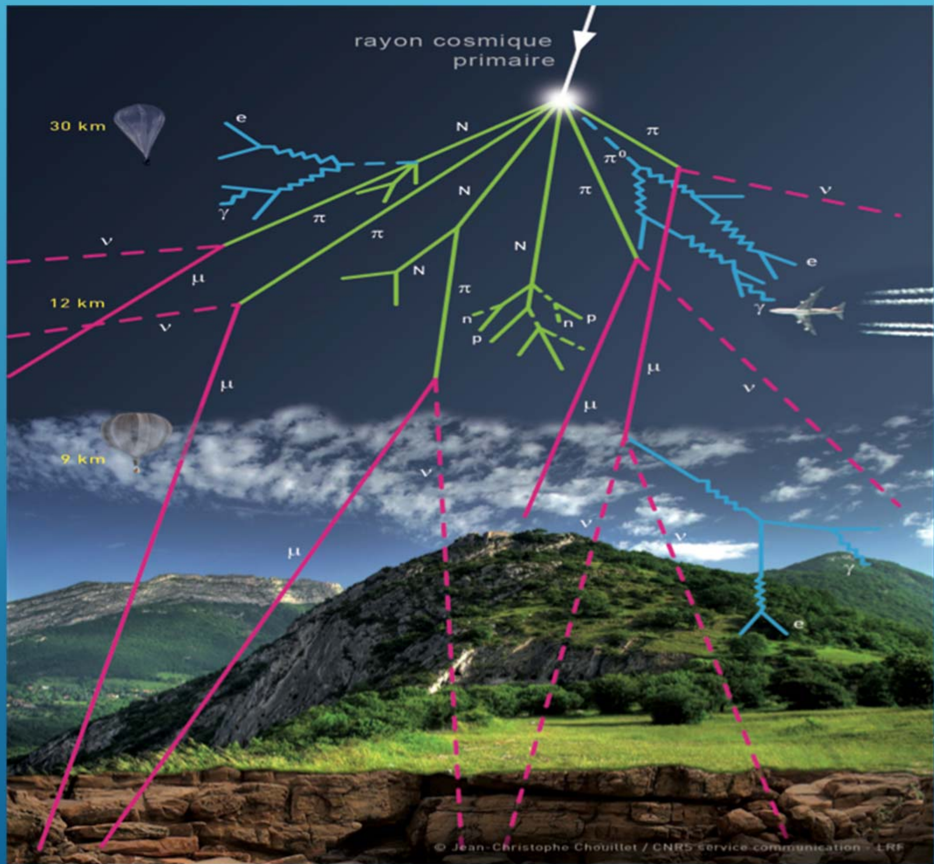
1925: very high energy gammas → « cosmic rays »

We see showers, particles arrive in group

- 1937: Pierre Auger positions three Geiger counters separated by 70 m at le Pic du midi
  - Observes coincidences

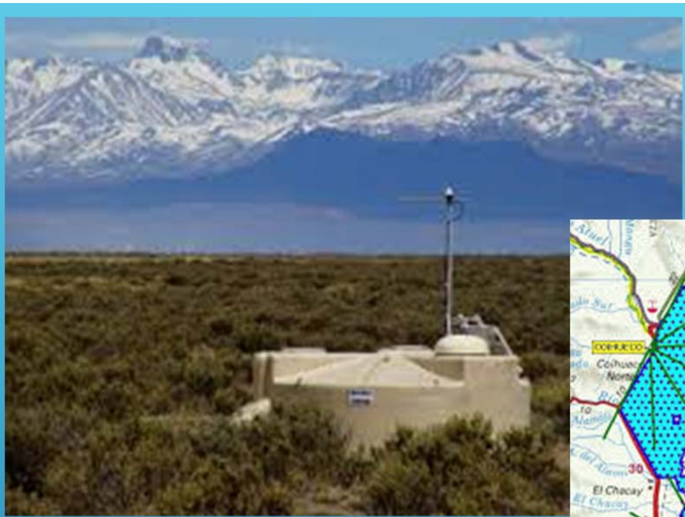


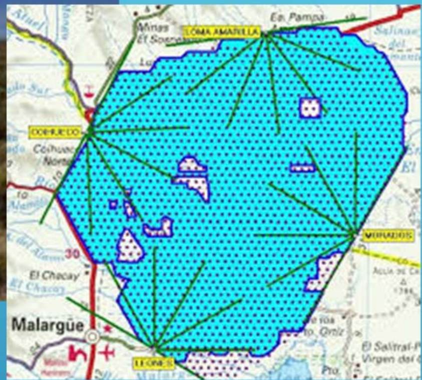
Pierre Victor Auger
(1899-1993)



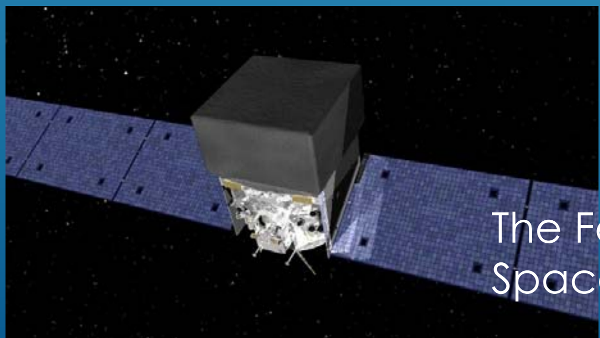
Modern experiments

AMS at the international space station looks for anti-matter !



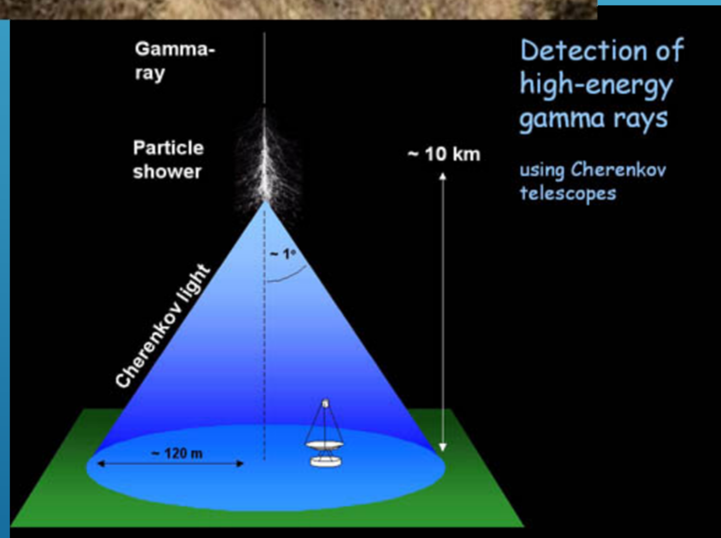


Pierre Auger observatory at Argentina's pampa detects high energy charged particle induced showers using 1600 water tanks of 12K liters separated by 1.5 Km each other. Complemented by fluorescence detectors.



The Fermi Gamma-ray Space Telescope

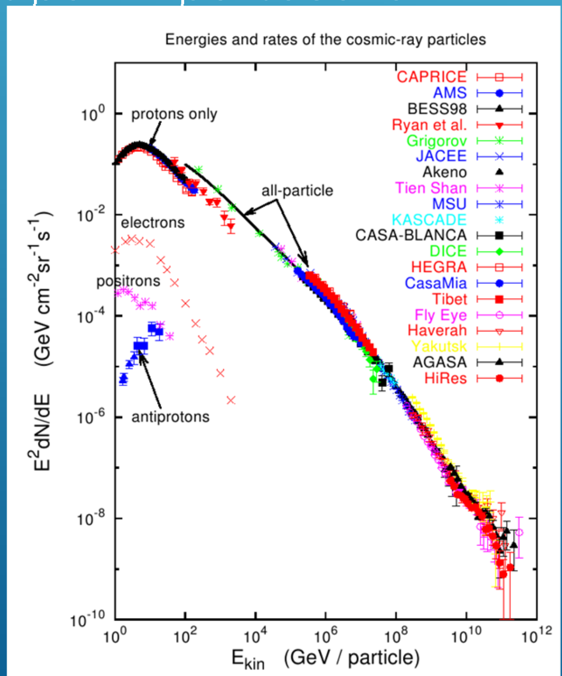
The HESS experiment in Namibia looks for high energy photons

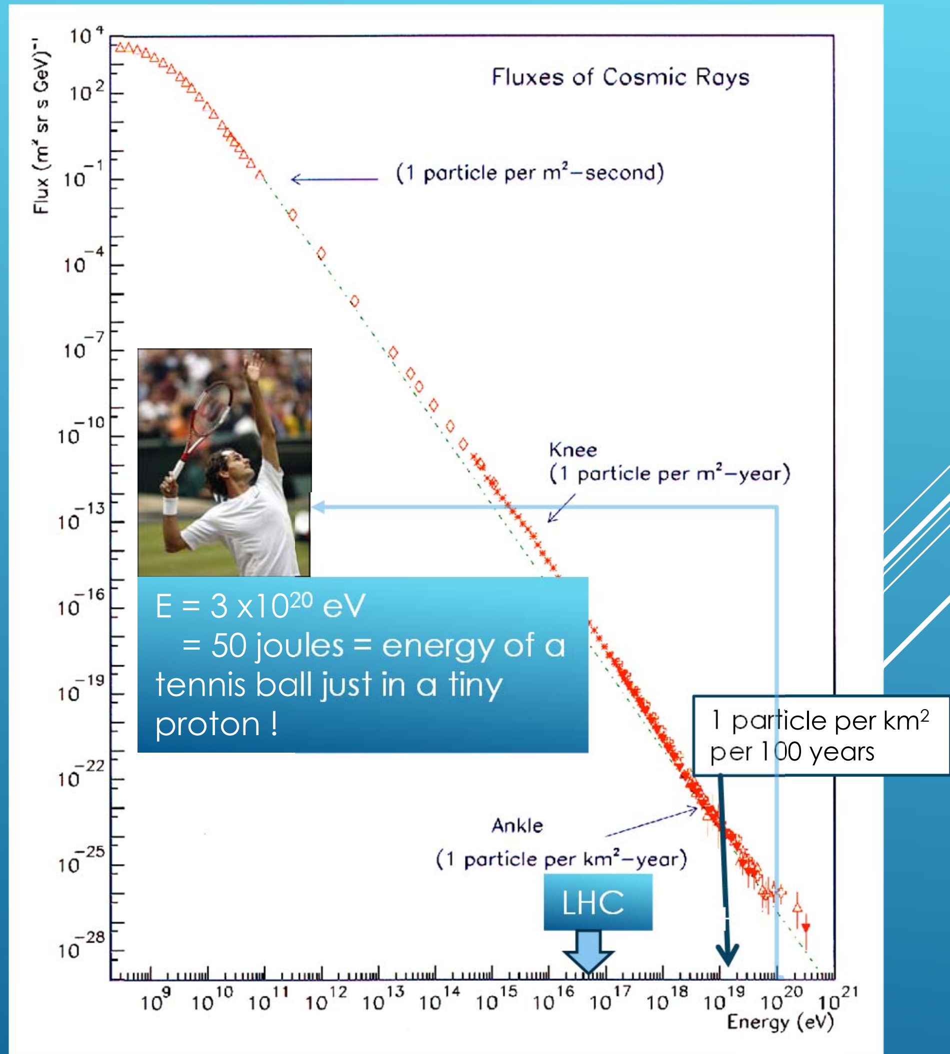


What we know today !

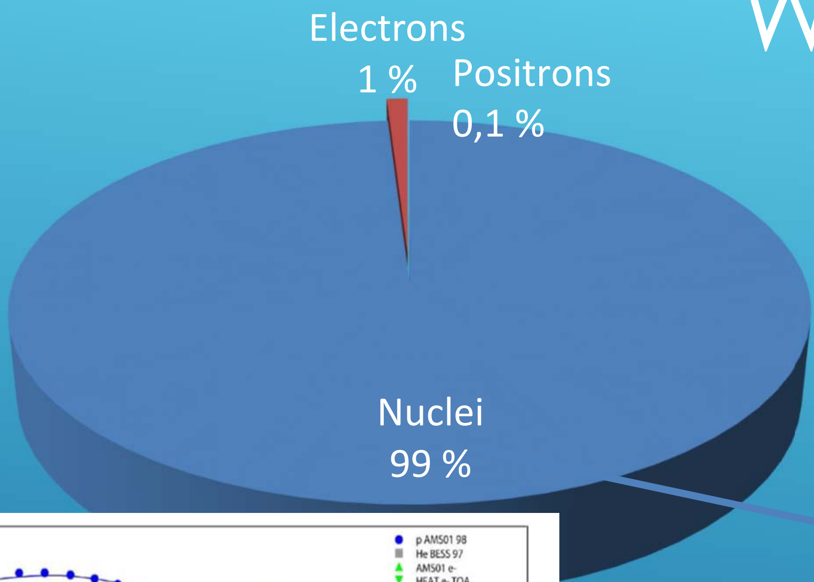
How many particles and what energy ???

- The energy spans over 12 orders of magnitude
  - Energy spectrum follows $E^{-\gamma}$ where γ = 2.7-3.5
- The flux spans over 32 orders of magnitude !
  - Sea level : 150 particles per m^2 per second

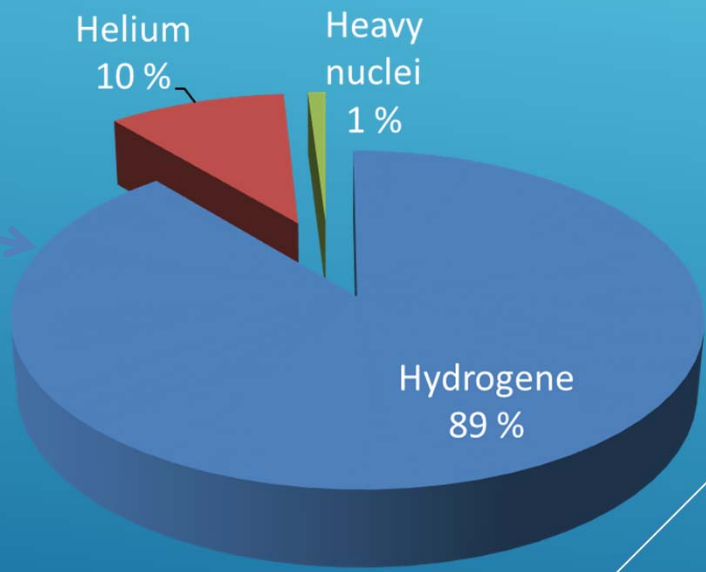




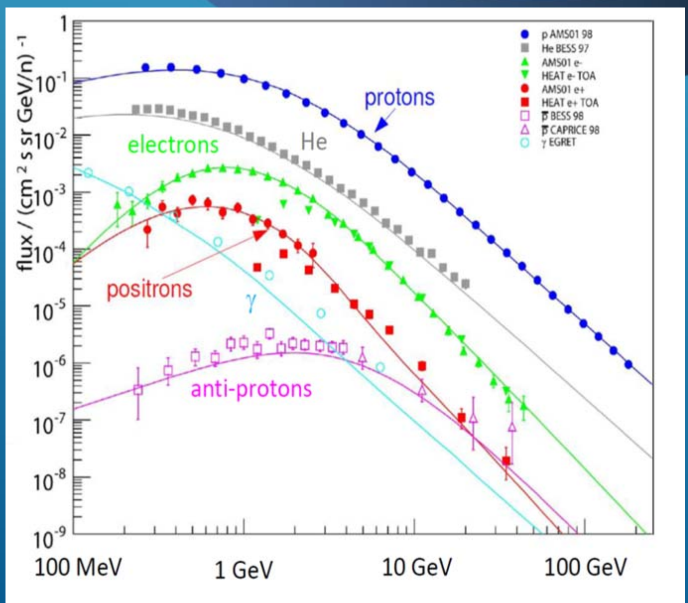
Who are they ???



Electrons
1 %
Positrons
0,1 %
Nuclei
99 %



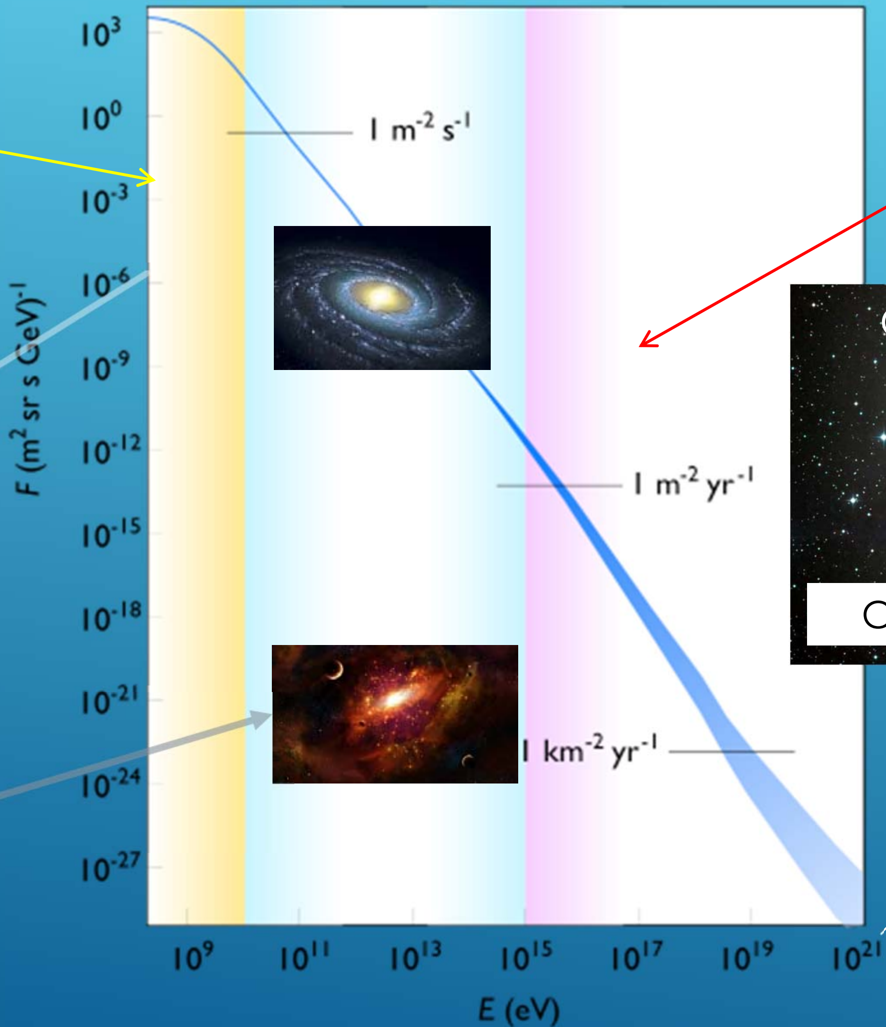
Helium
10 %
Heavy
nuclei
1 %
Hydrogene
89 %



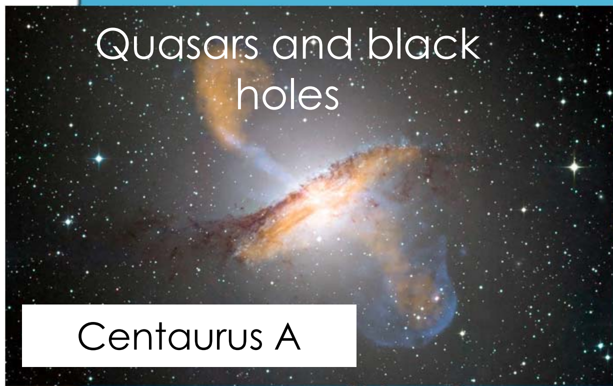
p AMS01 98
He BESS 97
AMS01 e-
HEAT e- TOA
AMS01 e+
HEAT e+ TOA
p̄ BESS 98
p̄ CAPRICE 98
γ EGRET
protons
He
electrons
positrons
γ
anti-protons
flux / (cm² s sr GeV/n)⁻¹
100 MeV
1 GeV
10 GeV
100 GeV

Where do they come from ??

Our sun



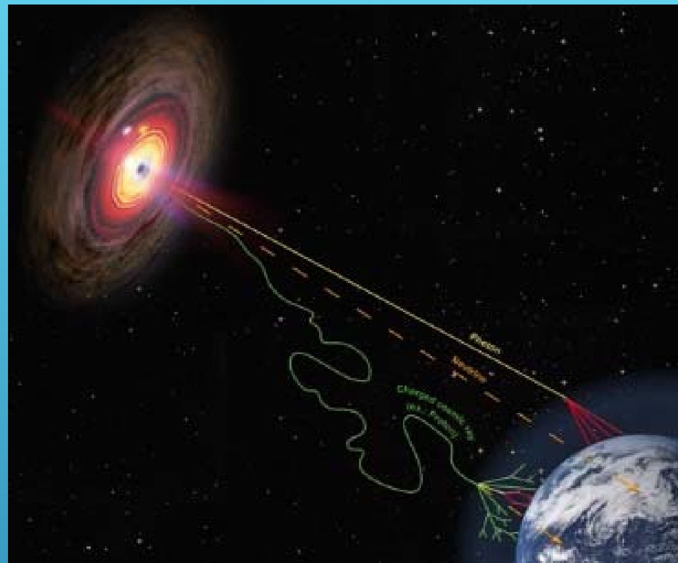
Extra galactic

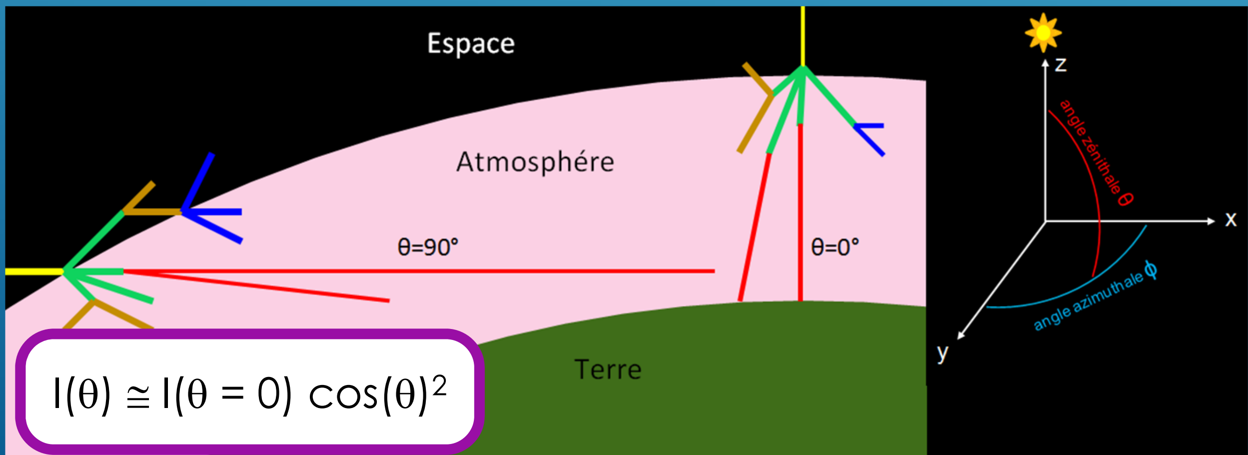


Supernova explosion
and remnants

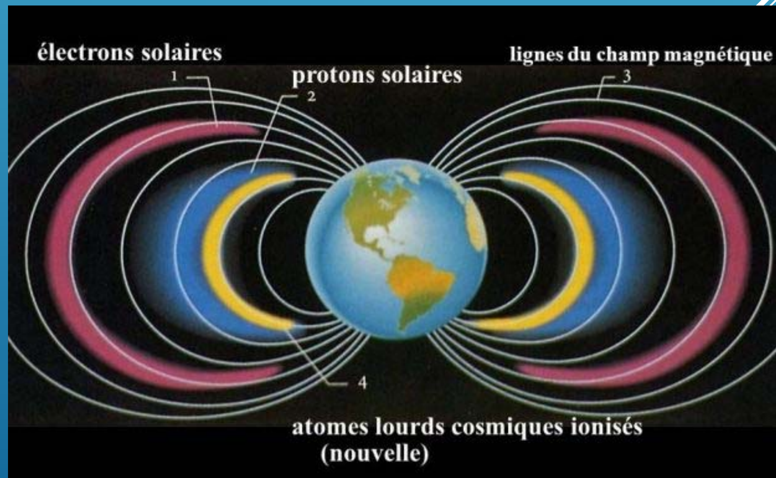
Coming to earth

- Acceleration mechanisms rather unknown !
- Propagation through space
  - Charged particles are deflected, loose source direction. Photons and neutrinos, the history books of our universe
  - Particles interact with interstellar medium
  - The sun and the earth protect us !
    - Solar wind, heliosphere, solar magnetic field ! Low energy particles (E<20 GeV) reduced
    - Earth's magnetic field captures the solar wind. Von Allen belts



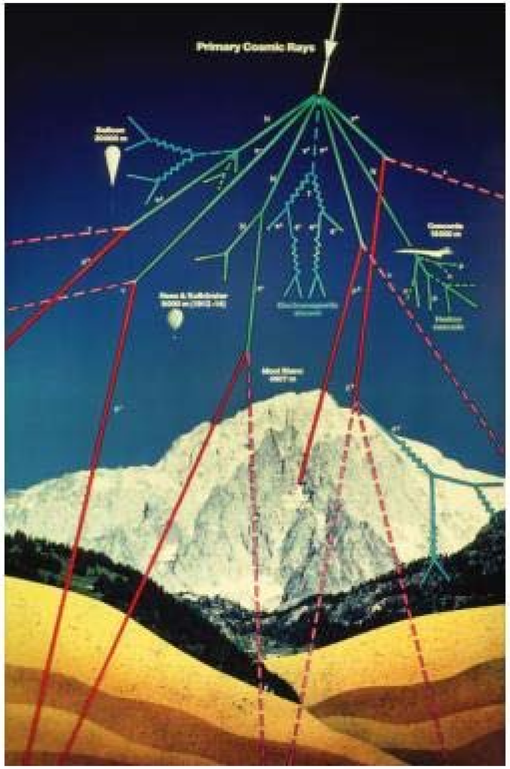


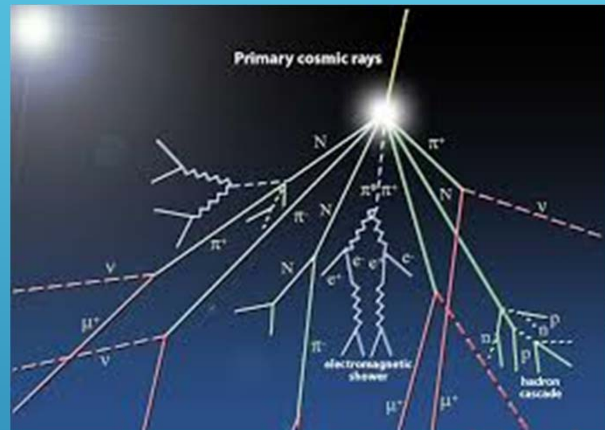
$$I(\theta) \cong I(\theta = 0)\cos(\theta)^2$$



Secondary Cosmic Rays

- Collision of primary cosmic rays with atoms in the upper atmosphere produce mostly neutral and charged pions.
- Decay mode of pion, muon
  - 7.8045m $(c\tau)$
    $$\pi^{\pm} \longrightarrow \mu^{\pm} \nu_{\mu}$$
  - 21.1m
    $$\pi^{0} \longrightarrow 2\gamma$$
  - 658.654m
    $$\mu^{\pm} \longrightarrow e^{\pm} \, \overline{\nu}_{e} \, \nu_{\mu}$$
- At sea level, most of them are muons.





Muons and the matter

Muons will :

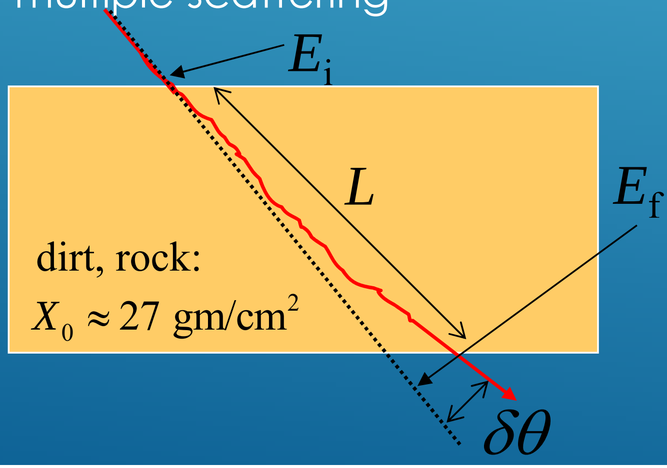
- Interact with matter and will loose their energy by ionization

$$\frac{dE}{dx} \approx 2.3 \text{ MeV/gm/cm}^2 \approx 0.6 \text{ GeV/m in rock}$$

- Change their direction because of multiple scattering

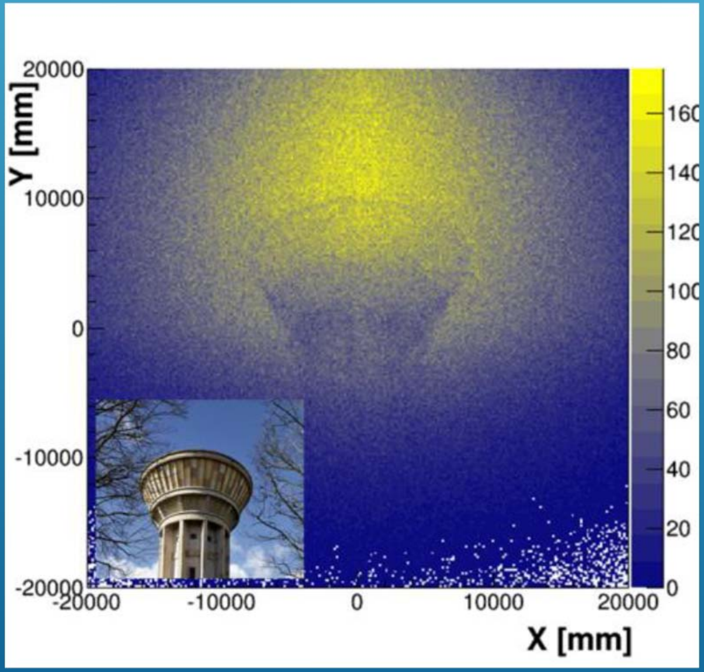
$$\delta\theta = \frac{13.6 \text{ MeV}}{\sqrt{E_i E_f}} \sqrt{\frac{L}{X_0}}$$

$$E_i - E_f = L\frac{dE}{dx}$$



Using muons for scanning !

- Muons are very penetrating particles
- Muons will be absorbed by heavy structures or may cross large voids without stopping.
- Muon variation density should image the structures they cross !



The birth of the idea

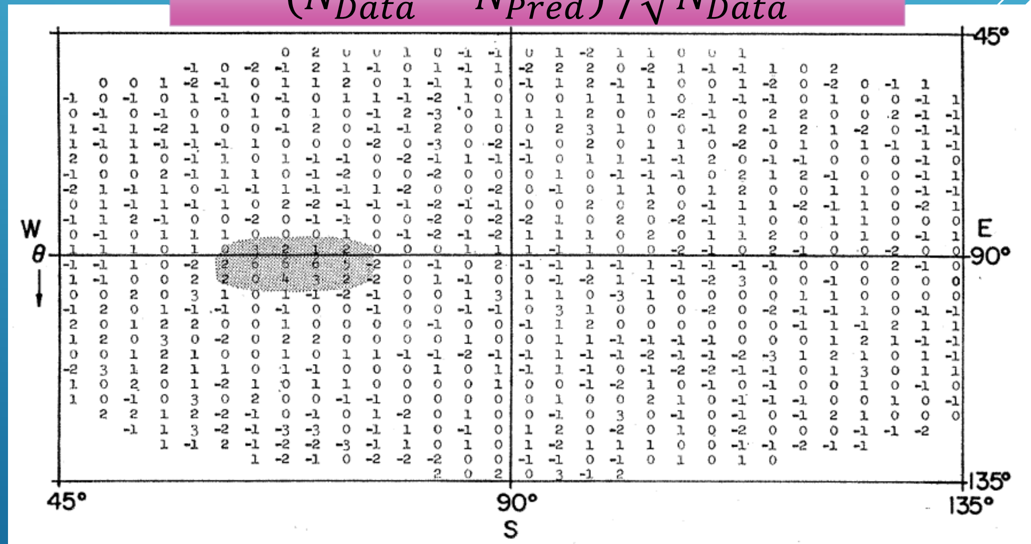
Luis Alvarez* invented muon tomography in 1960's to study the 2nd Pyramid of Chephren

Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

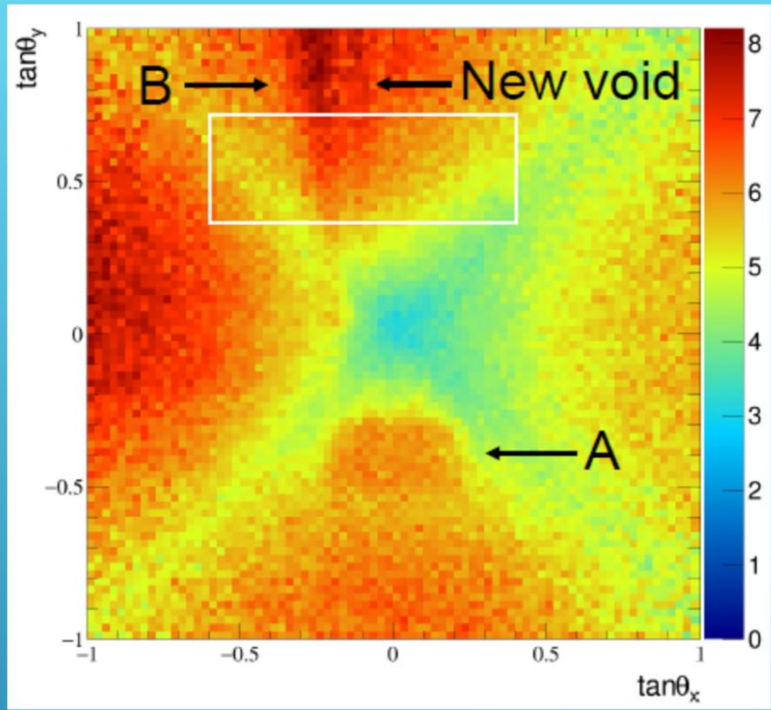
$$(N_{Data} - N_{Pred})\,/\sqrt{N_{Data}}$$

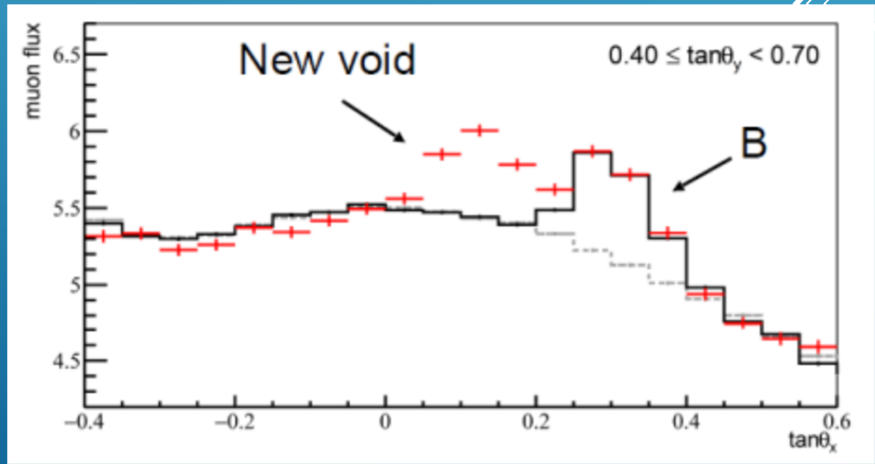


L.W. Alvarez, *et al*, *Search for Hidden Chambers in the Pyramids Using Cosmic Rays*, Science **167**, 832-839, 1970.

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

388 | Nature | VOL 552 | 21/28 DECEMBER 2017





A MORE DIFFICULT CASE : TUMULUS

The Apollonia tumulus as a benchmark for the method

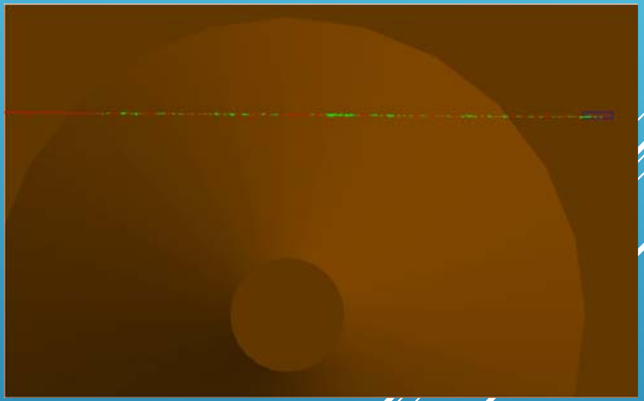
- Existing monument
- Density anomalies detected by other methods

Difficulties :

- Looking for an object with similar density as the surrounding materials $\rho \sim 2.3$ gr/cm^3 for dirt and 2.5 for marble !
- If any monument, it must be at the horizon level. Very low number of muons, wait a LONG time !
- Muons must cross a lot of dirt. Need high energy muons, their number is even less !

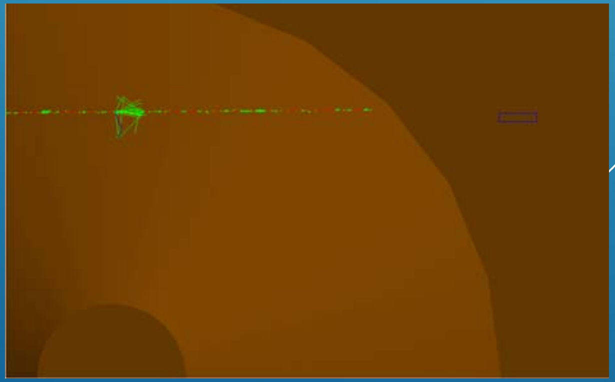
How do we do ?

- We measure the number of muons per surface unit
  - Use at least 3 layers of detectors to reconstruct the muon direction and the number of muons in bins of polar and azimuthal angle



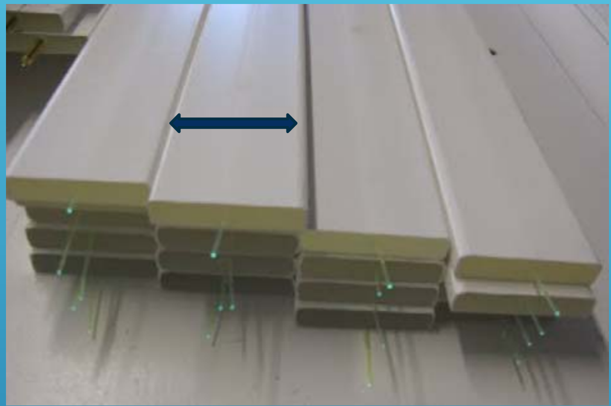
Simulation

- We simulate the real tumulus geometry and material assuming no internal structure
- We simulate the angular and energy distribution of the cosmic muons
- We propagate the simulated muons through the tumulus taking into account all possible interactions
- We simulate our detector
- We obtain the same information as the real data

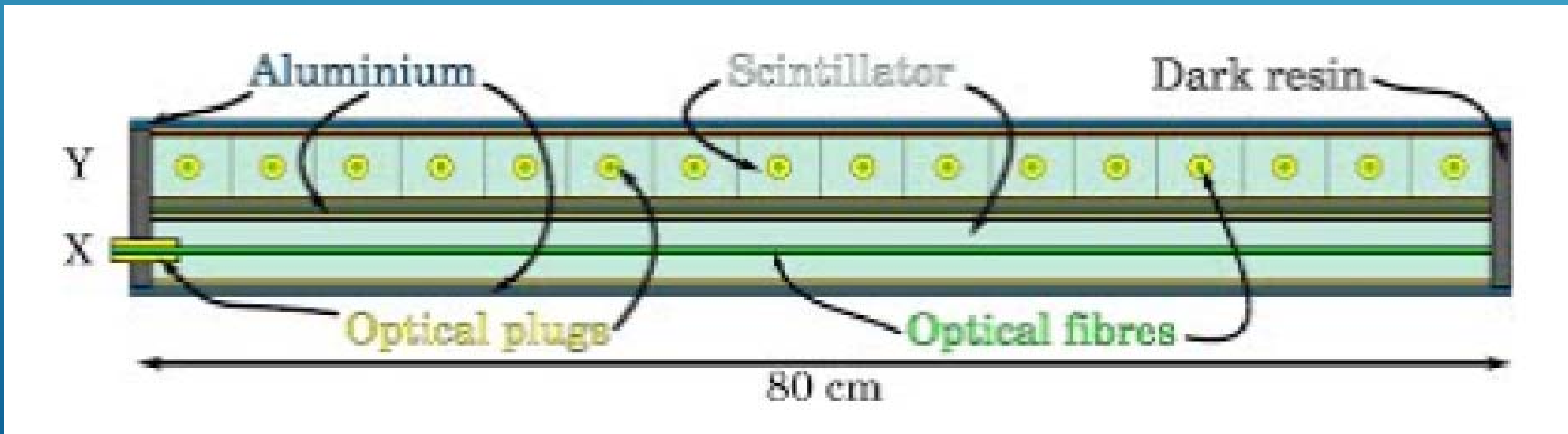


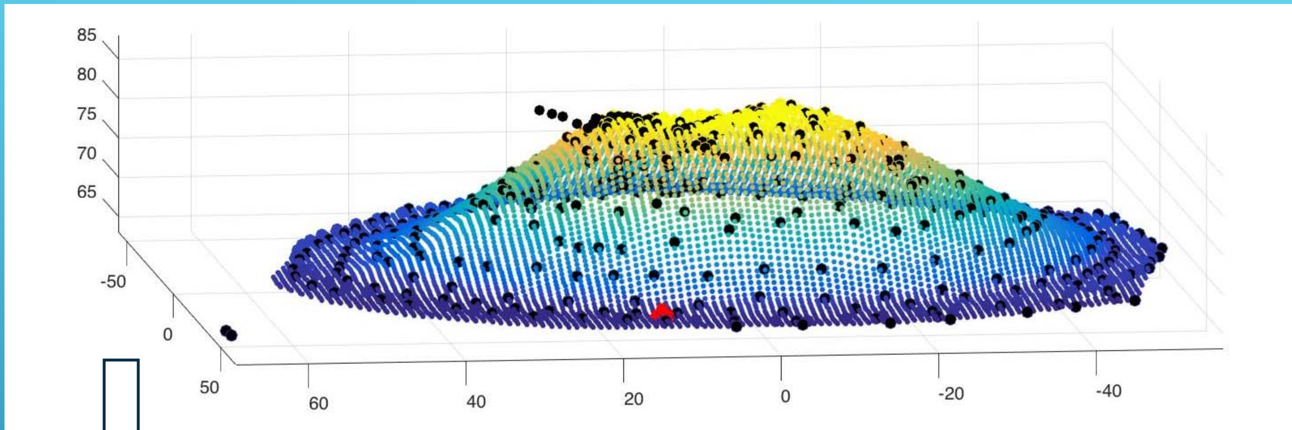
Debon
UnivEarthS

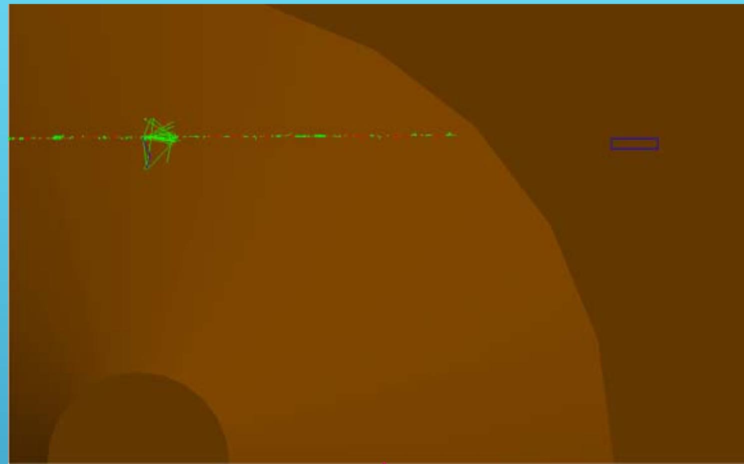
DETECTOR : SCINTILLATOR PLANES

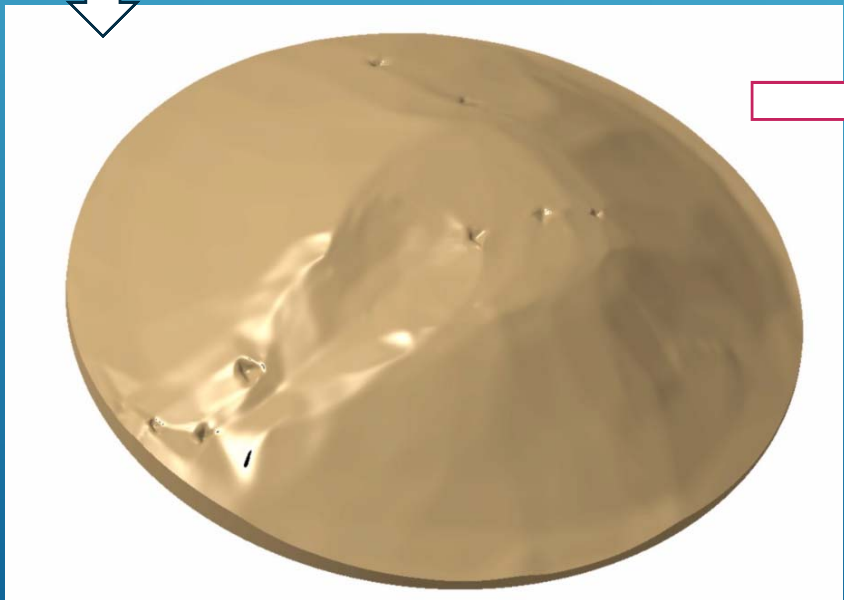


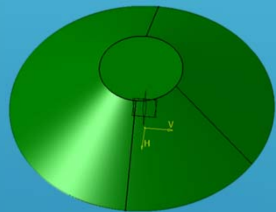
5cm : middle layer
2.5 cm : outer layers

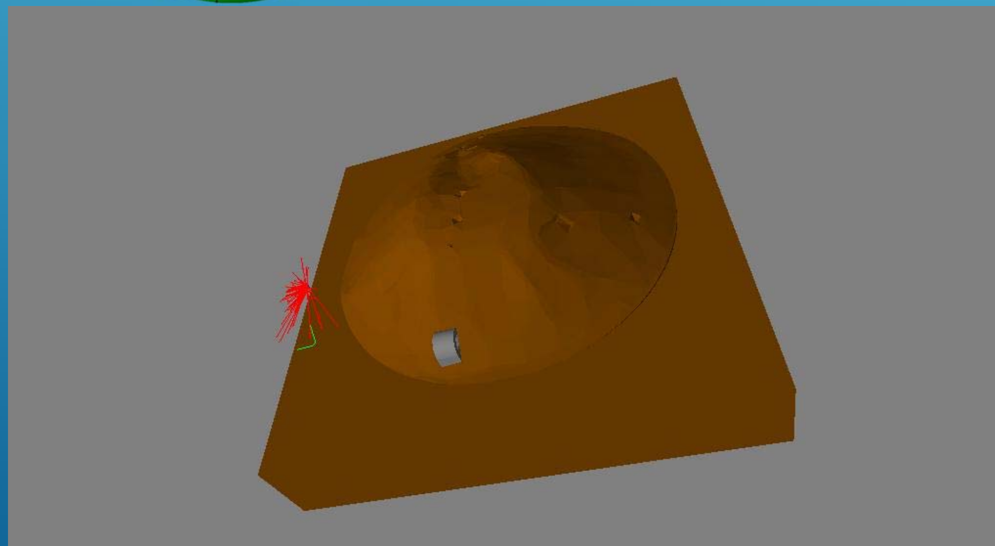



85
80
75
70
65
-50
0
50
60
40
20
0
-20
-40







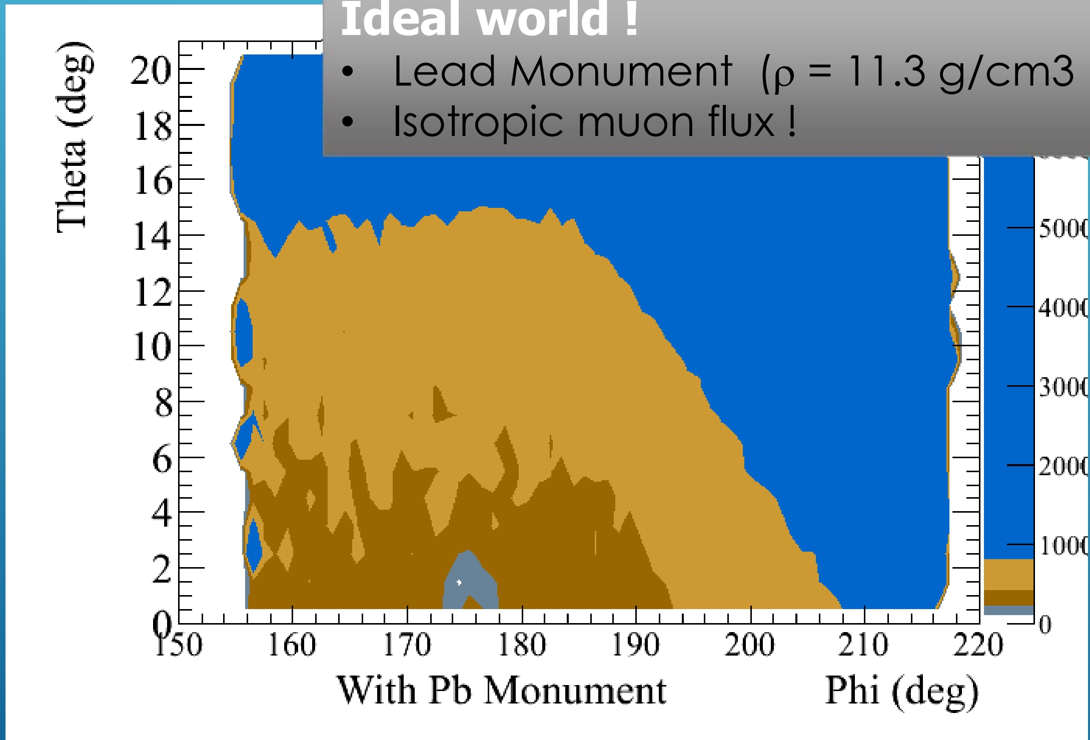


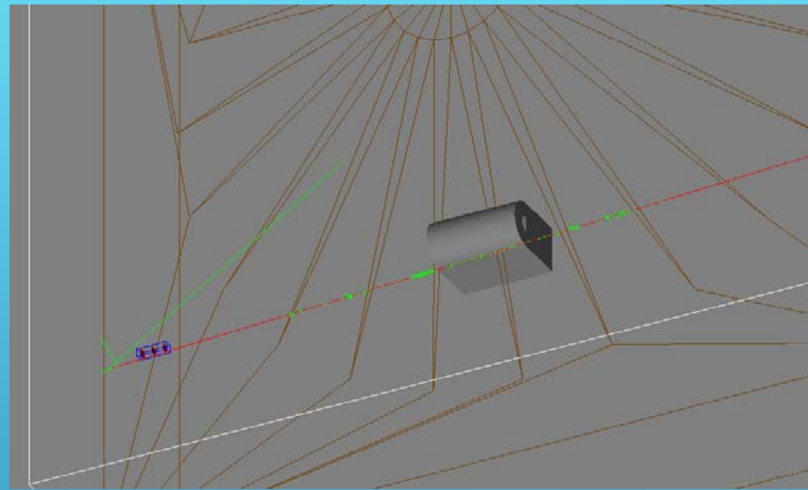
Before we get real data

- We put a virtual monument inside our tumulus model
  - Ex : A large monument 10 x 12 x 7 m^3 (L x l x h) and wall thickness 2 m

Ideal world !

- Lead Monument (ρ = 11.3 g/cm3)
- Isotropic muon flux !

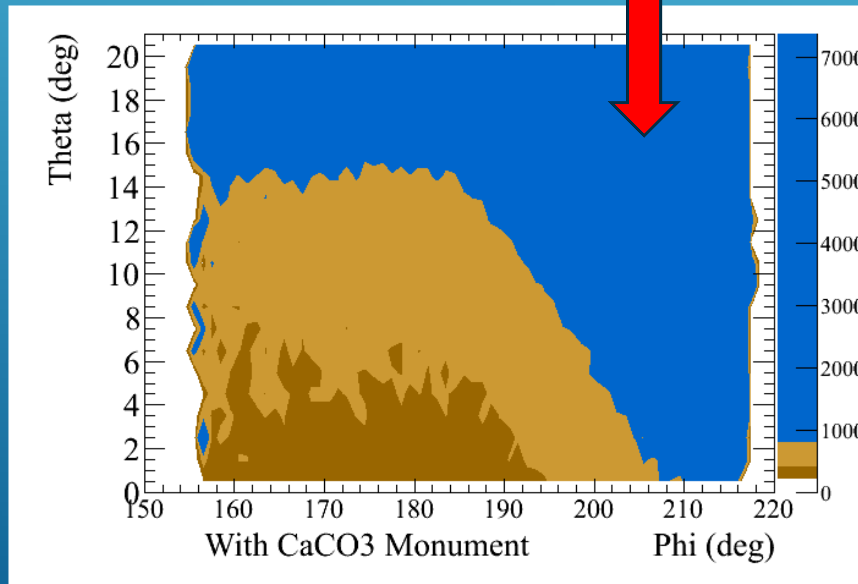




Large Monument filled with dirt

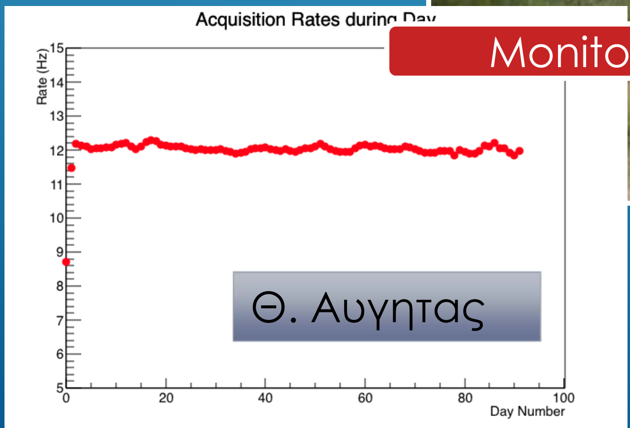
Pb Walls

CaCo3 Walls



REAL WORLD

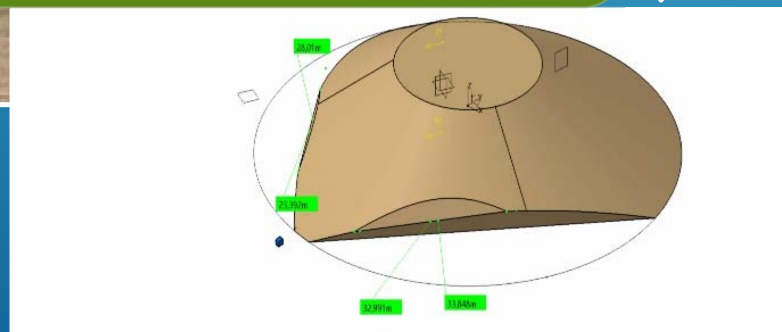
We took data starting July 7th and for 3 months



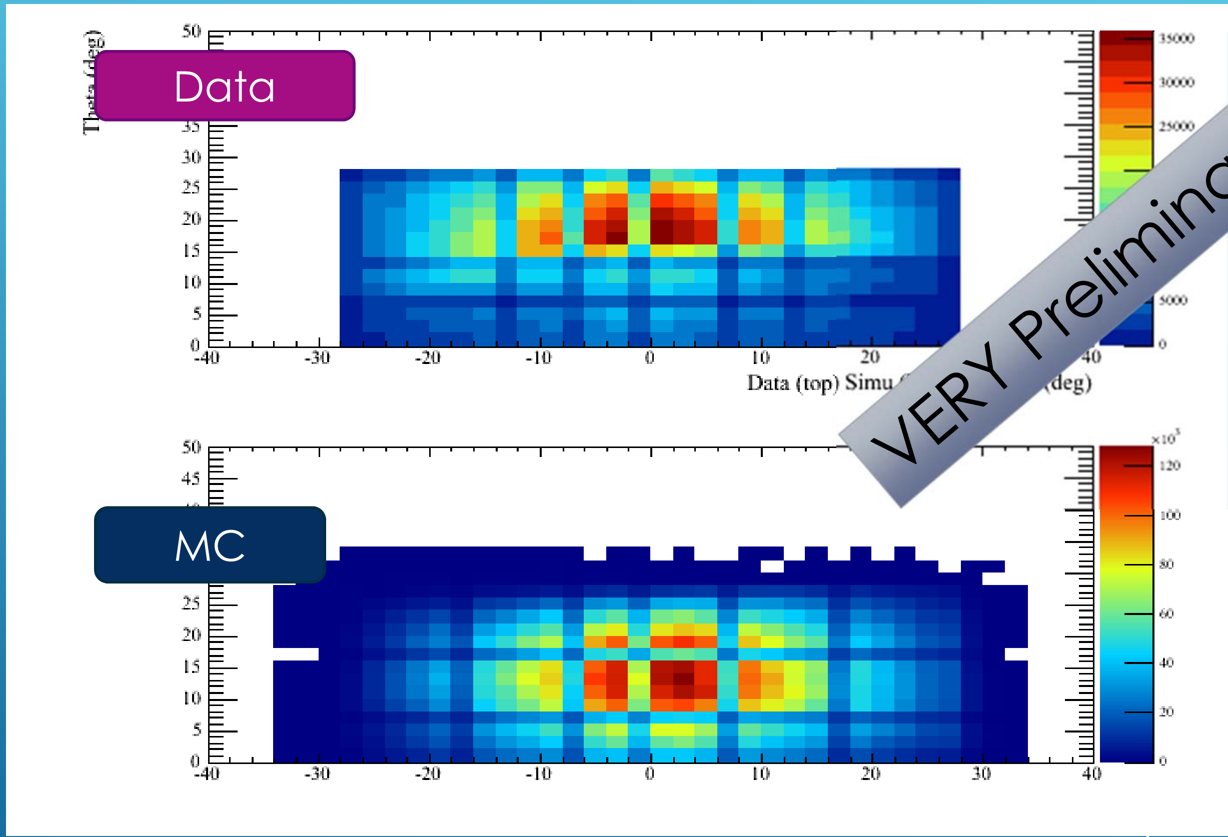
Monitoring

Θ. Αυγητας

Solid angle covered (catia)



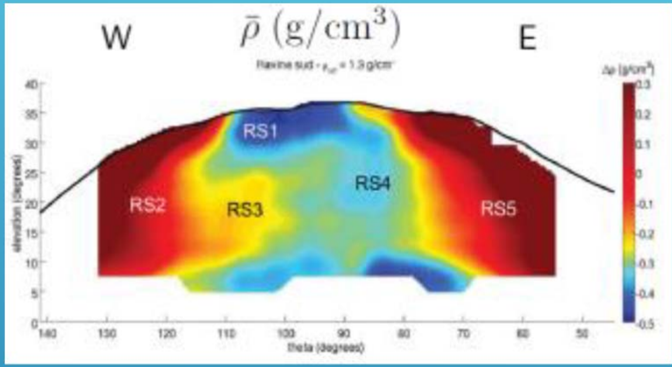
COMPARISON DATA / MC



θ (deg)

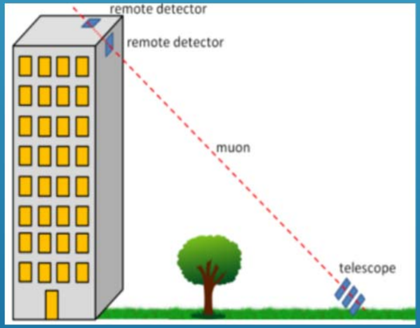
φ (deg)

Other applications for muon scanning

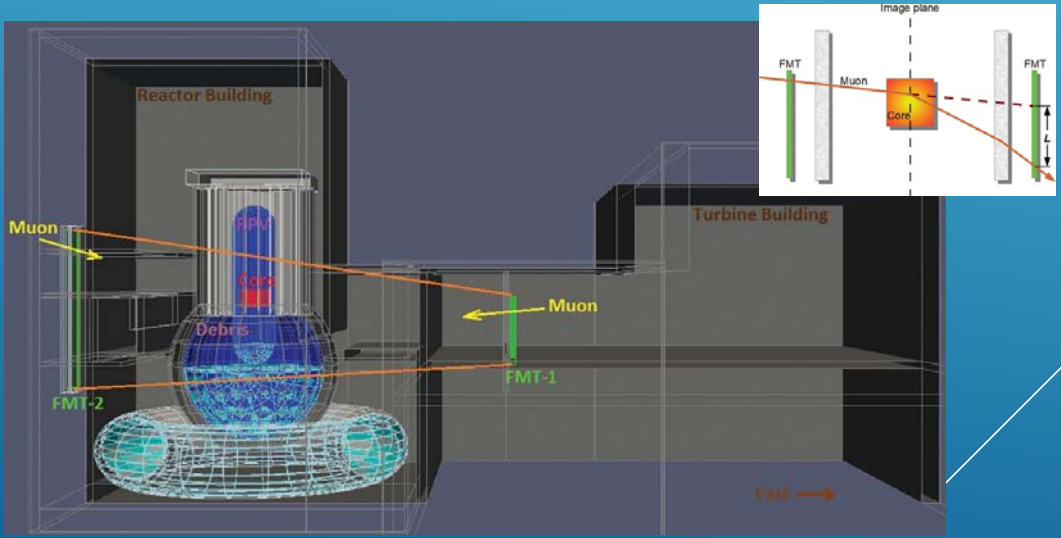


Volcano surveillance, looking to its internal density

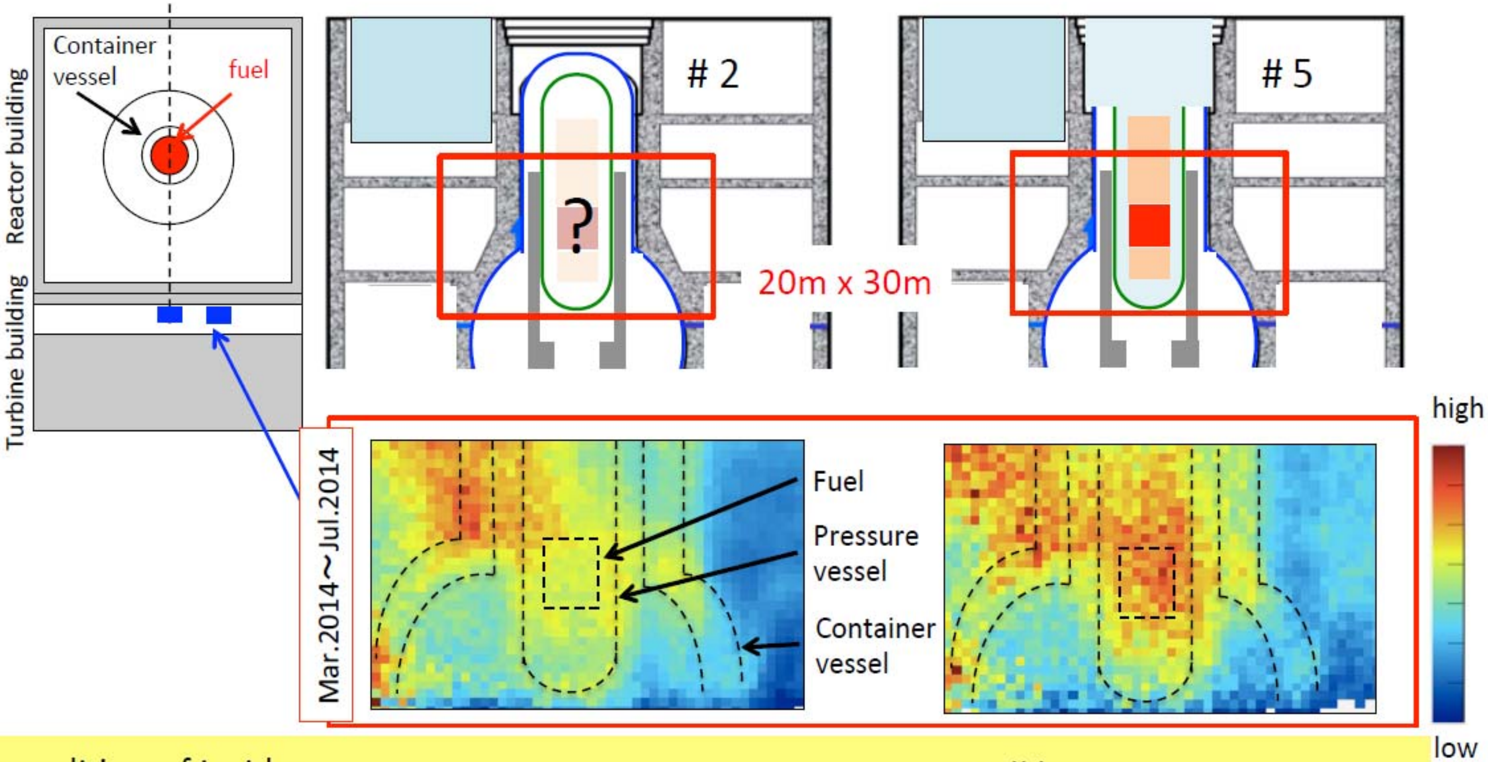
Civil engineering



Metrology



Fukushima Daiichi Nuclear Power Plant



condition of inside of pressure vessel	Unknown	Well known (Fuilled with fuel and water)

・Significant differences between 2nd and 5th → Melt down is confirmed

CONCLUSION

- Muons are a probe that can detect hidden objects, under some circumstances
- The detector technology is known and not very difficult to handle
- Ideal project to involve young people !

Can we improve the discovery potential ??

- More muon stations (= more money)
- Increase muon statistics by placing the detectors below the surface level. Authorizations

Can we make a project together ???

- We can build the detectors
  - Internships for you
- Data taking detector monitoring and data analysis
  - Can be done together with few classes of young students !

How many muons reach the earth's surface ???

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

- ~70 / m^2 /steradian/second for $E_\mu > 1$GeV
- ~ 1 / cm^2 for horizontal detectors
- Angular distribution $\propto \cos^2\theta$ for $< E_\mu > \approx 3$ GeV

TUMULUS ELSEWHER