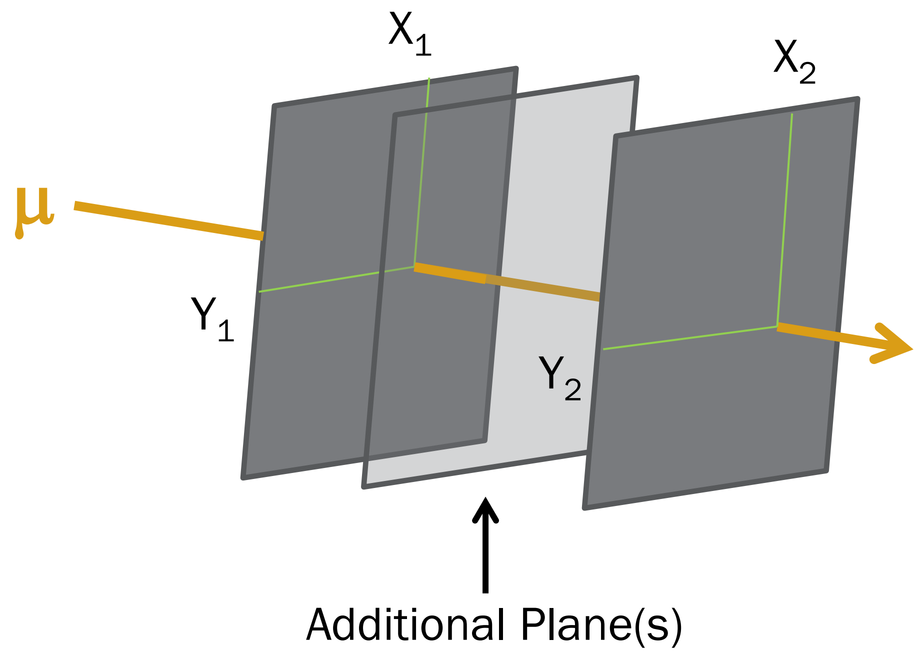
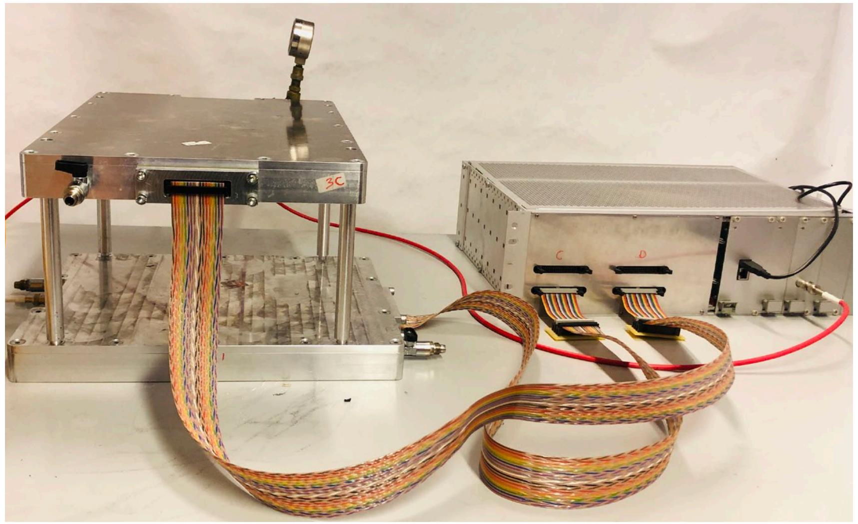
DETECTORS FOR MUOGRAPHY AND APPLICATIONS

DETECTORS FOR MUOGRAPHY AND APPLICATIONS

The detectors used in muography are made with different technologies, but they all have in common :



- Operate as trackers
- Big size
- Limited angular aperture
- Planar geometry



DETECTORS FOR MUOGRAPHY AND APPLICATIONS

The detectors used in muographic applications are mostly trackers. As seen, in order to carry out a muography, the muon direction of arrival must be reconstructed. An important factor in the design of the detector is the possibility of using it in harsh environments with limited electrical power.

In general, there is no rule for the design of a tracker for muographic uses, but its versatility will depend on how well it can be adapted to various situations. Muography is mostly used in geological, archaeological and subsoil prospecting applications in civil and mining fields.

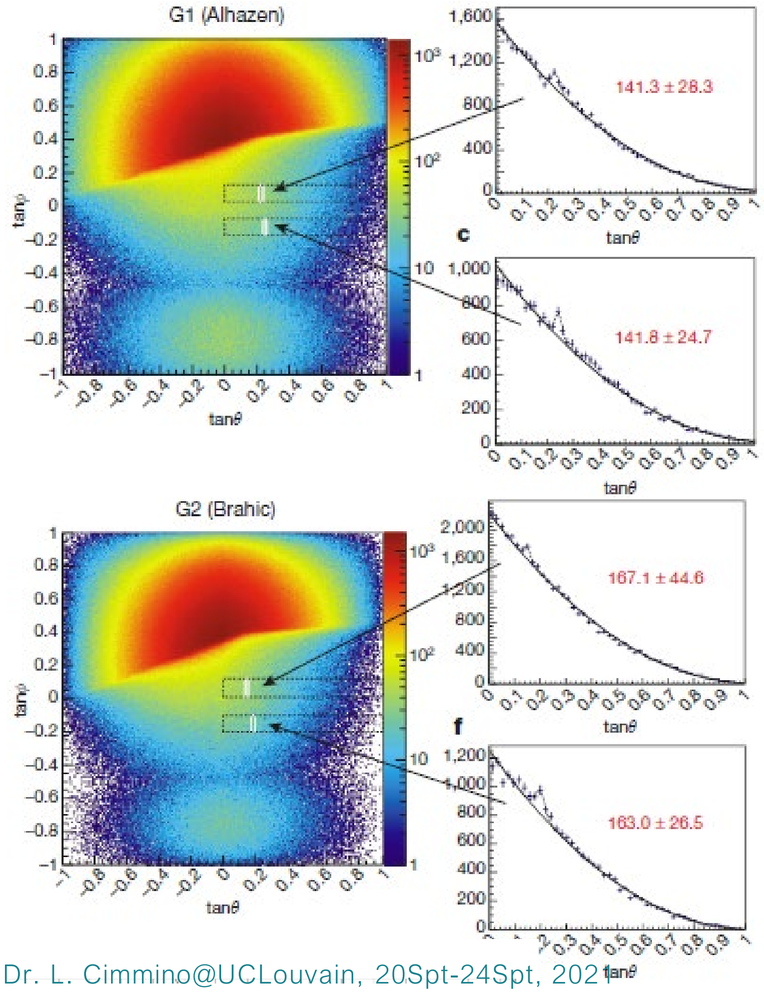
Many research project aim to use it also for nuclear protection (trafficking of nuclear material, localized and extended imaging of nuclear plants, localization and quantification of nuclear waste in barrel and silo).

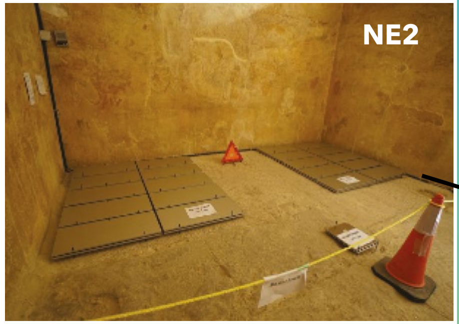
The most important muographic application is certainly the one carried out by the Scan Pyramid experiment. It was the first application, in the archeological field, to have such media coverage that it could be disseminated outside the scientific community, both for its archaeological importance and for its scientific relevance.

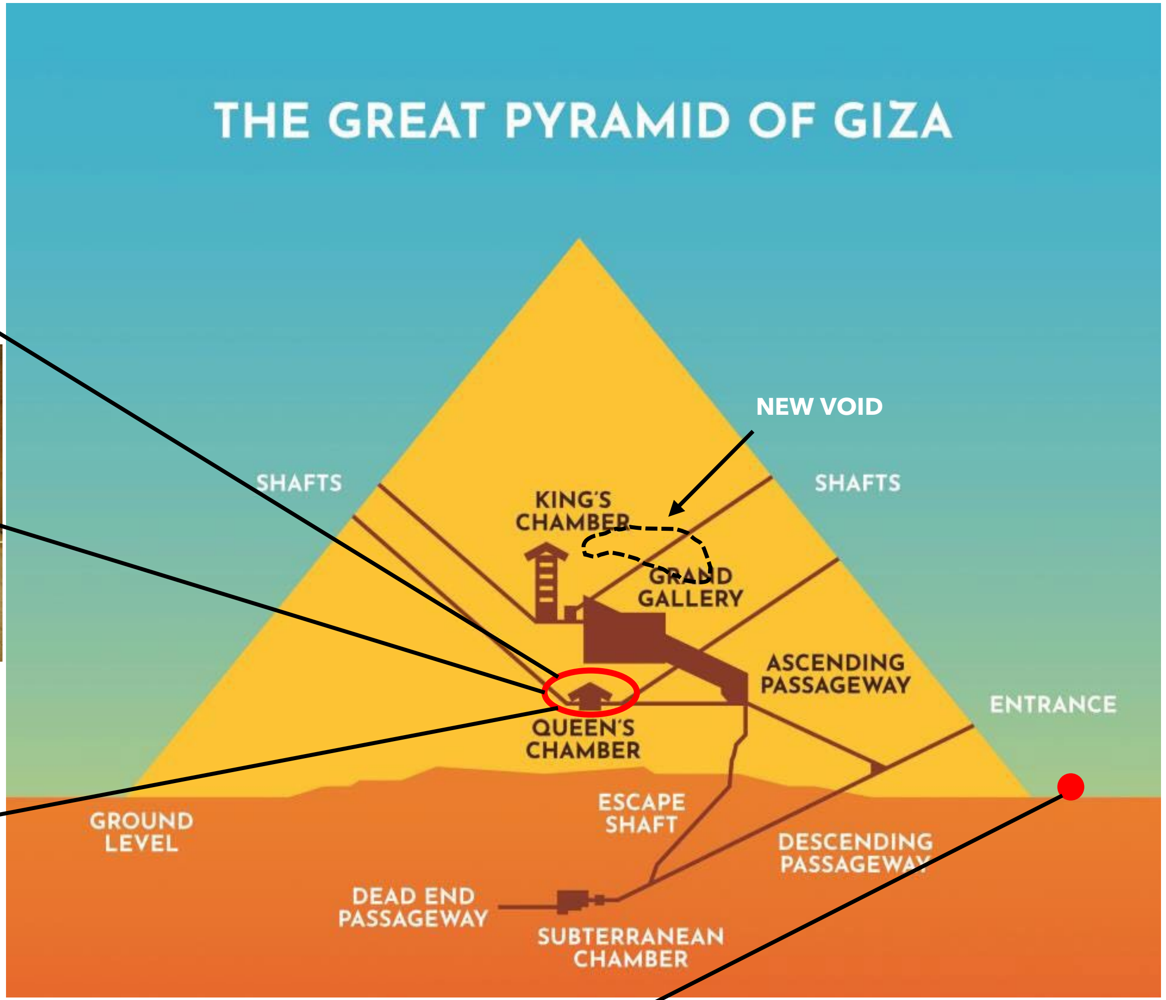
Three different type of detectors have been used and the analysis of the data collected within 1 year, made it possible to determine the existence of a hidden cavity inside the Khufu's pyramid. **Nuclear emulsion** detectors, two **micromegas** detectors and other one with **scintillators** read by MPPCs, were used.

DETECTORS FOR MUOGRAPHY AND APPLICATIONS

The best performance was achived with the nuclear emulsion detector. Muographs from the other two detectors confirmed the discovery.

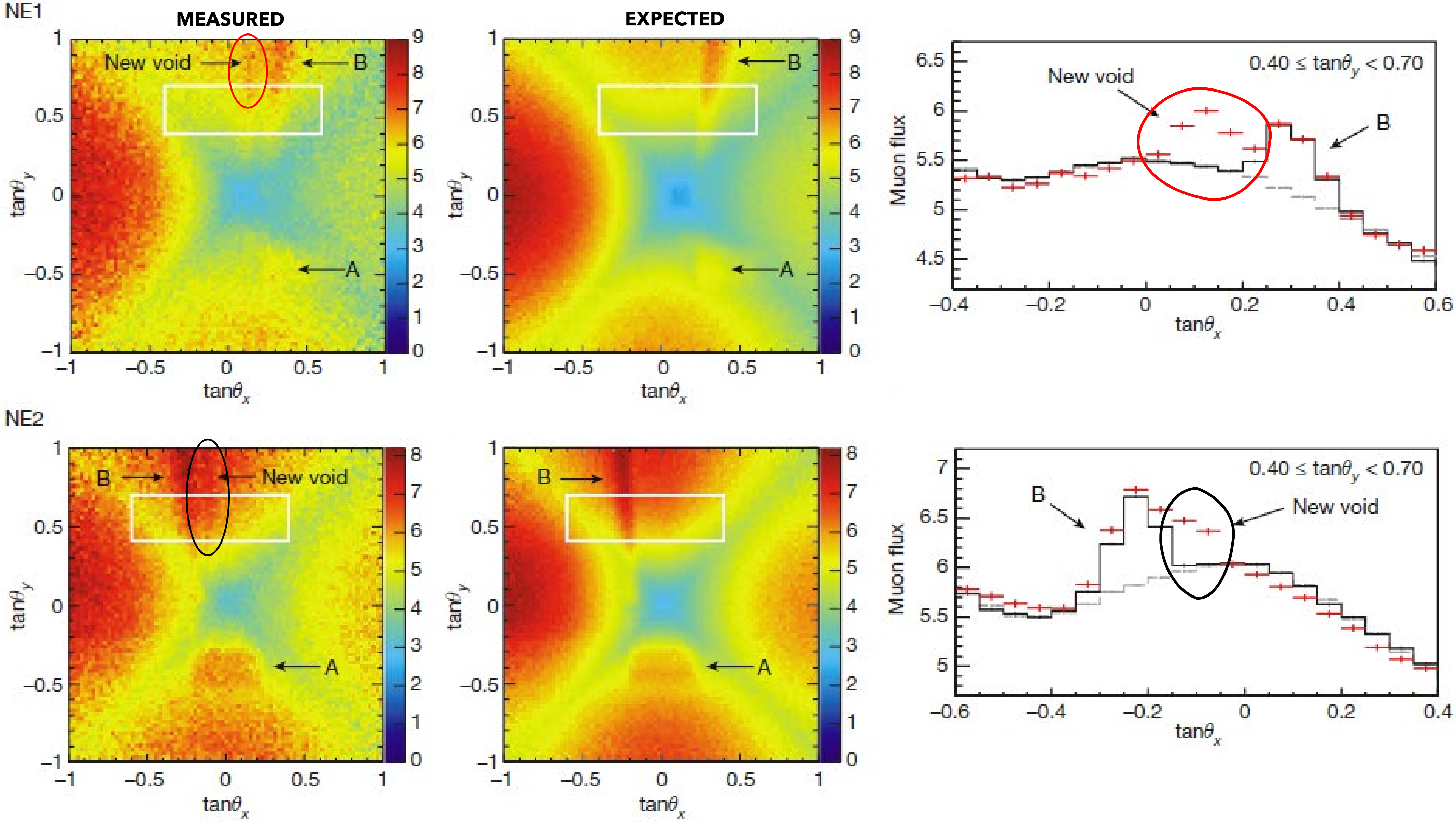






A LITTLE BIT OF PHYSICS

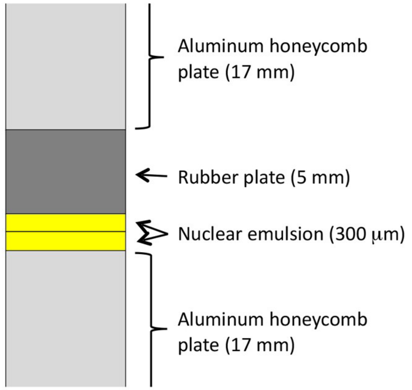
NUCLEAR EMULSION DETECTOR

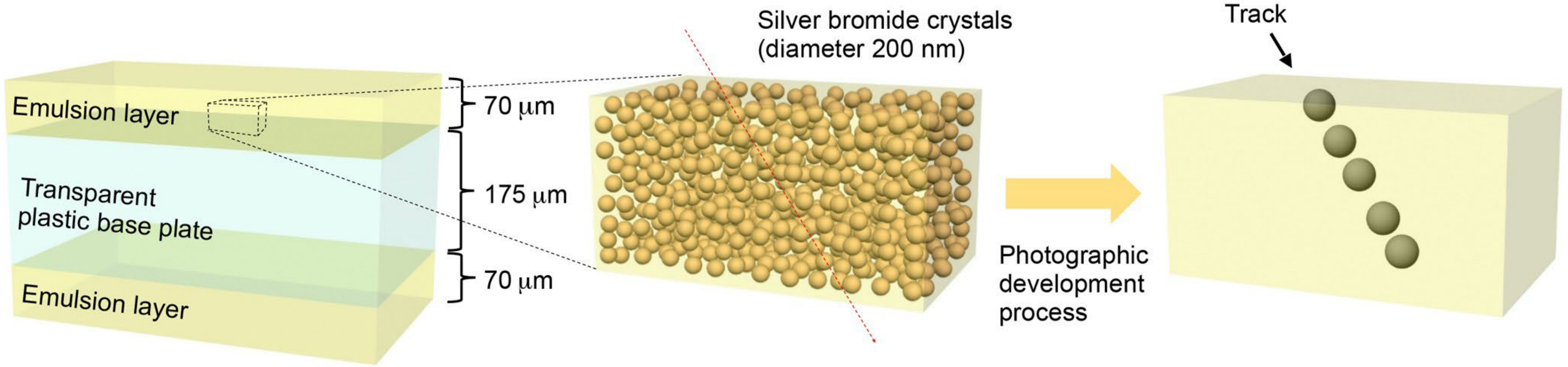


MEASURED FLUX IN THE SQUARED REGION

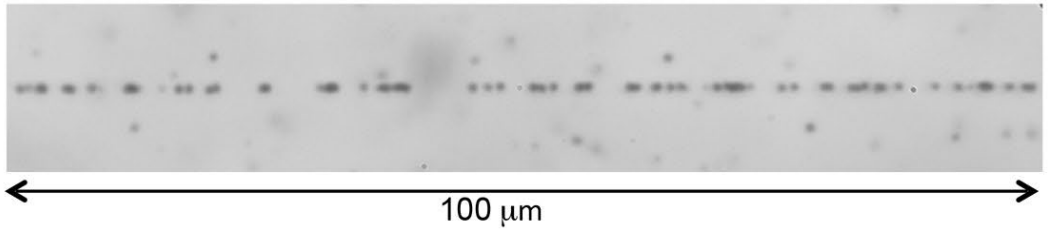
DETECTORS FOR MUOGRAPHY AND APPLICATIONS

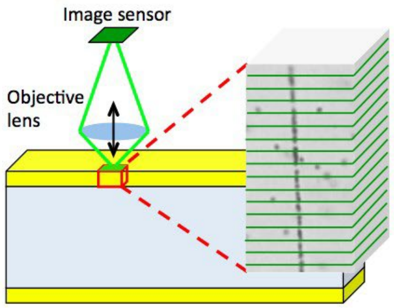
The **Nuclear Emulsion** detectors consist of photographic emulsions with a high concentration of silver fixed on a plastic glass plate. When charged particles pass, the silver bromide grains transform, appearing dark at the time of photographic development. The trajectories of the particles and their interactions are visible under the microscope.



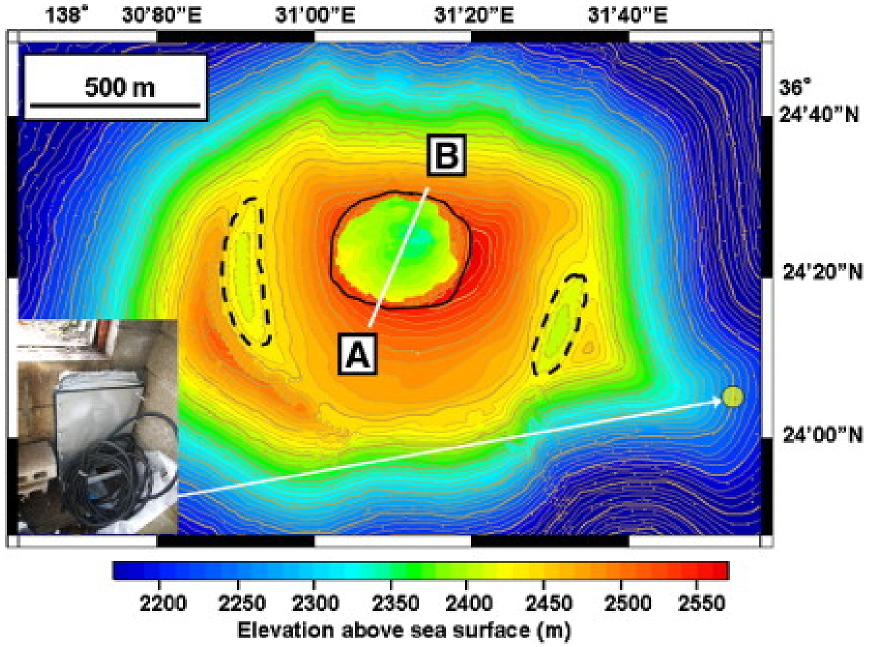


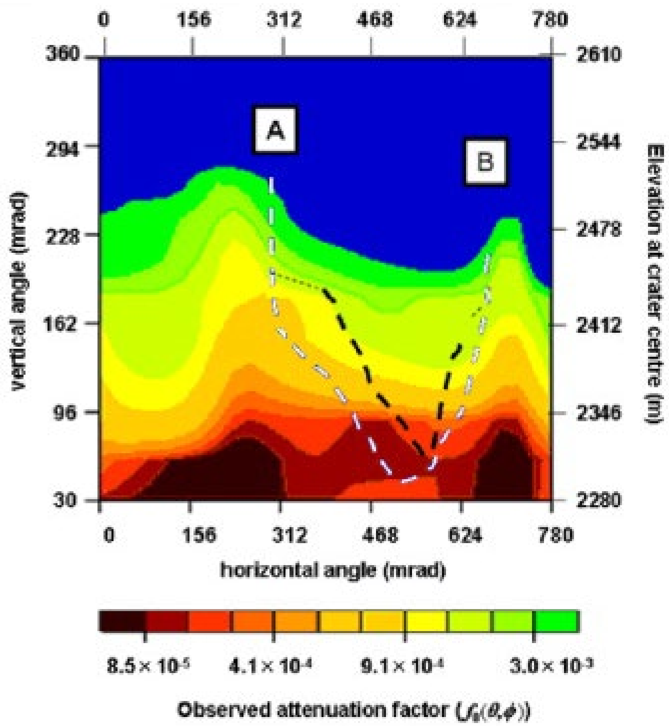
The microscope scanning system takes tomographic images divided into sixteen layers with changing the focal plane in the emulsion layer by moving the objective lens. Nuclear emulsions detector has the highest intrinsic spatial resolution (200 nm) but suffers of high background contamination and track reconstruction takes a lot of time depending on scanning resources.

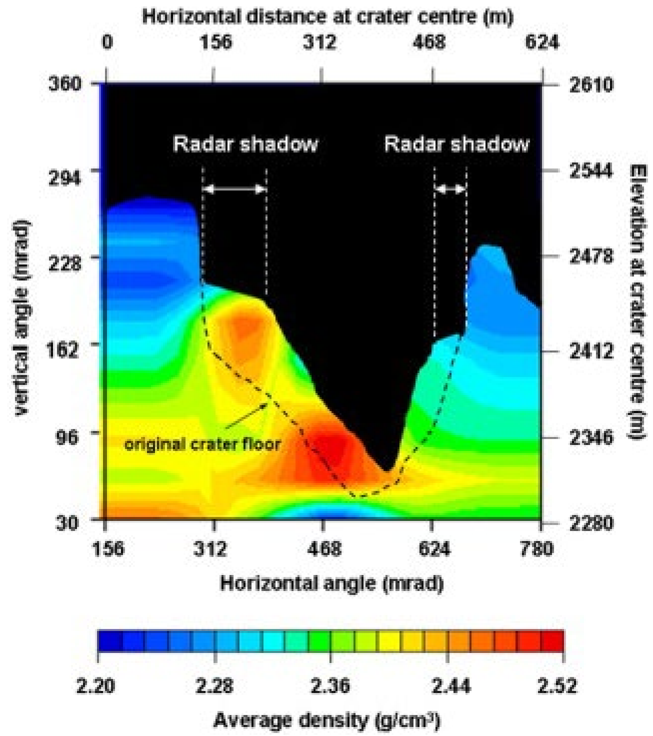


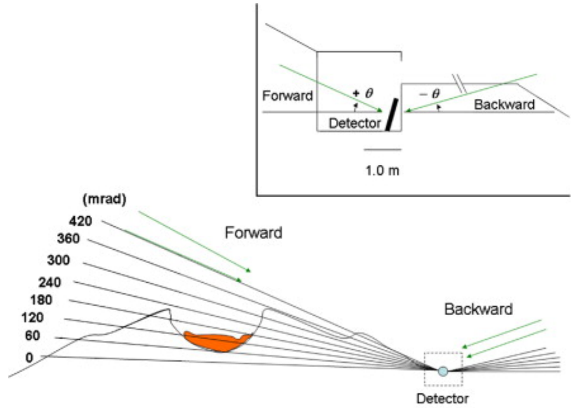


In 2007, the first muography of the summit of a volcano was performed with a 4000 cm^2 nuclear emulsion detector. This represents the first ever radiographic imaging performed with a muon source.



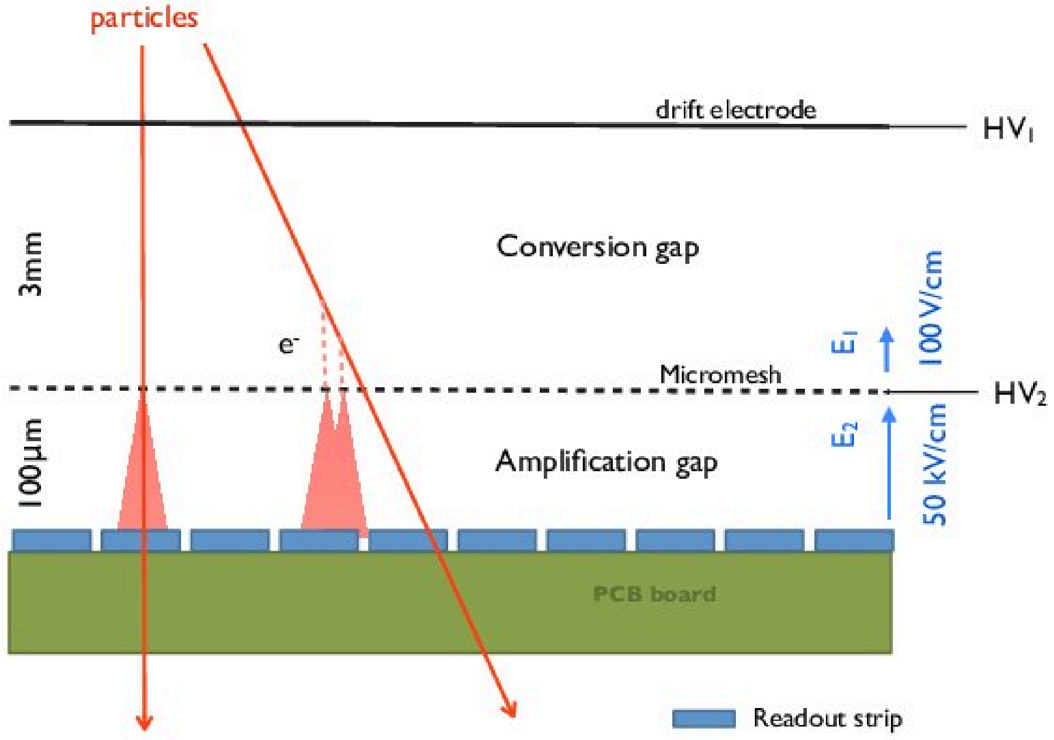


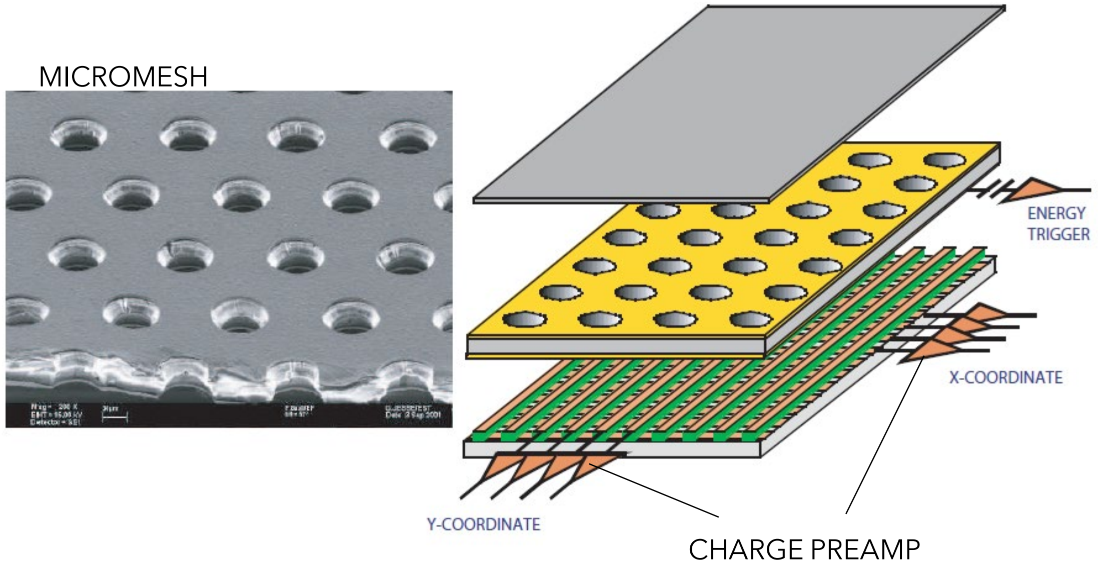




The intrinsic angular resolution of the detector has been estimated 10 mrad, which implies a spatial resolution of the target of 10 m when the observation point of the detector is placed at a distance of one kilometer. The collection of muon tracks lasted 2 months and the density results were provided with an accuracy of 1–2%.

The **MICRO MEsh GASseous** (MICROMEGAS) detector is an asymmetric double layer detector separated by a micromesh. In the conversion region, free electrons are accelerated by a low electric field, and once they pass the micromesh, generate a quick avalanche because of the high voltage applied in the amplification region. Ions generated in the avalanche are trapped and quickly gathered by the micromesh and signal collected is $\boldsymbol{neM}$, so due to both electrons and ions and gained by a factor $\boldsymbol{M}=10^8$ because of the avalanche multiplication. Note that, this is possible because of the thin gap between the micromesh and the readout strips (anode) that equalizes collection rates and manages to keep constant the electric field in the amplification region.

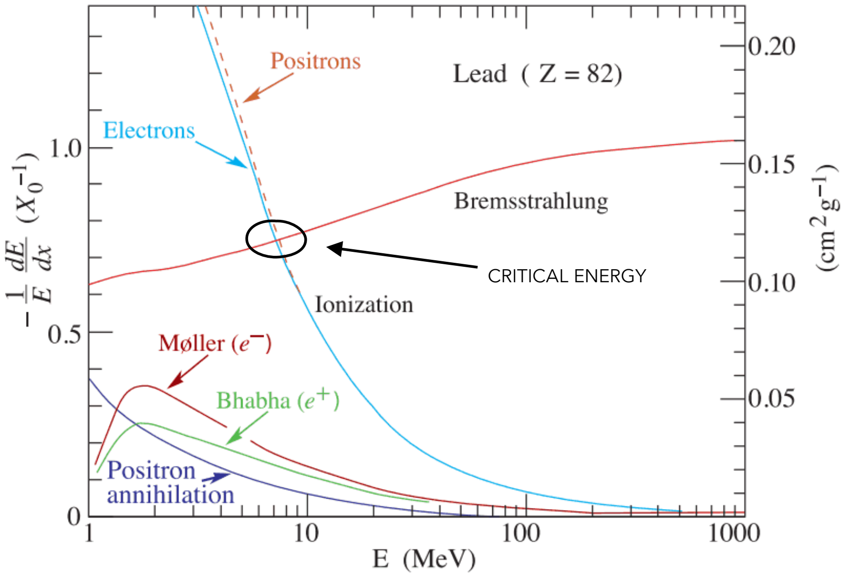


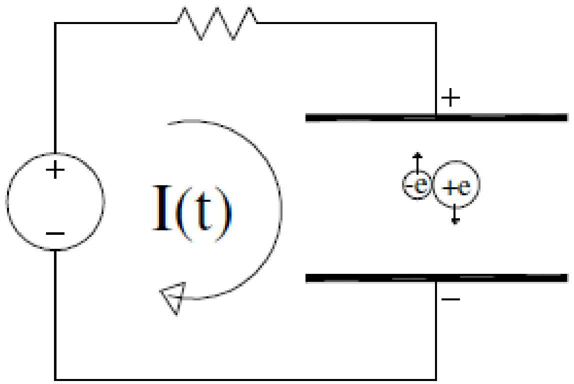


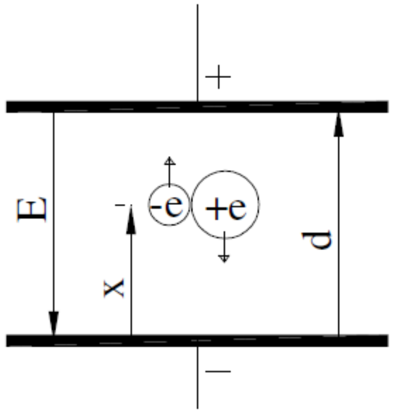
Before introducing gas detectors – RPC and MICROMEGAS – let's describe the basic operation of these devices. The passage of a charged particle through the chamber containing the gas, generates a electron-ion pairs.

The charges migrate in the volume of the detector, under the action of the electric field E, and generate a current $I(t)$ on the external circuit which carries a charge e.

The current begins as the charges move, even if we often talk about the collection of charge at the electrodes, in the sense that the signal is obtained when the charge has reached these.







$$I^+ = q\bar{v}\cdot\bar{E}_n = +e(\mu^+ E)\frac{1}{d} = \frac{e\mu^+ E}{d}$$

$$I^- = q\bar{v}\cdot\bar{E}_n = -e(-\mu^- E)\frac{1}{d} = \frac{e\mu^- E}{d}$$

$$t_s^+ = \frac{x}{\mu^+ E} \qquad t_s^- = \frac{d-x}{\mu^- E}$$

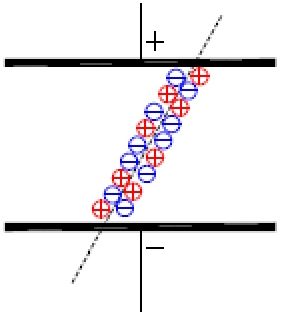
SIGNAL FORMATION

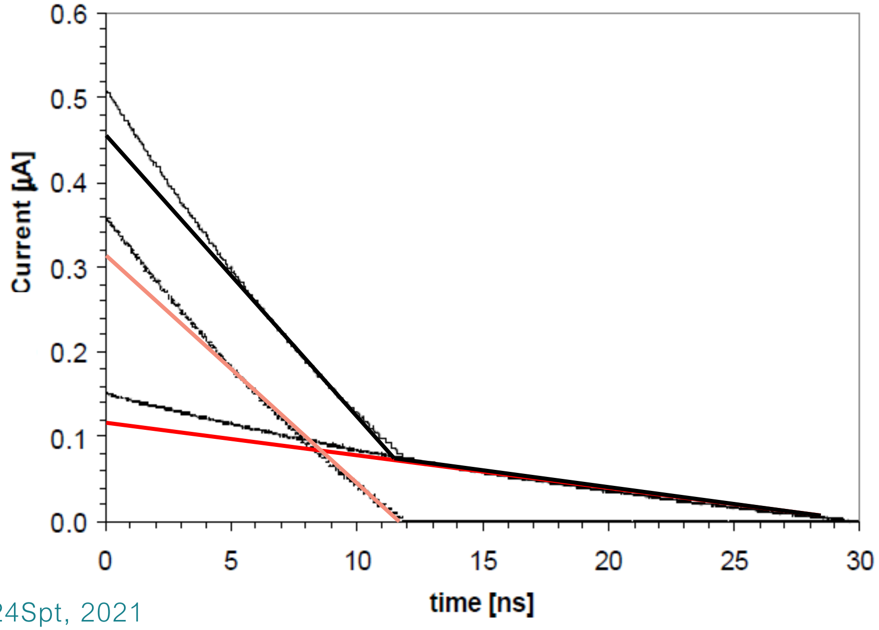
A charge pair induce mirror charges of equal magnitude on the electrodes. A negative current at the positive electrode and a positive current at the negative electrode are generated, contributing both to $I(t)$.

An ionizing particle that crosses the entire thickness of the detector, creates n pairs along the entire path, which progressively arriving at the electrodes, generate two current pulses of quasi-triangular shape, inducing a total charge

$$q = n\int (I^+ + I^-)\,\mathrm{d}t = ne$$

In general, the induced current will be predominantly due to one carrier. Then the total induced charge will be position dependent and, on the average, **the signal charge will be only $ne/2$**.



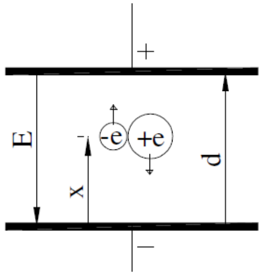


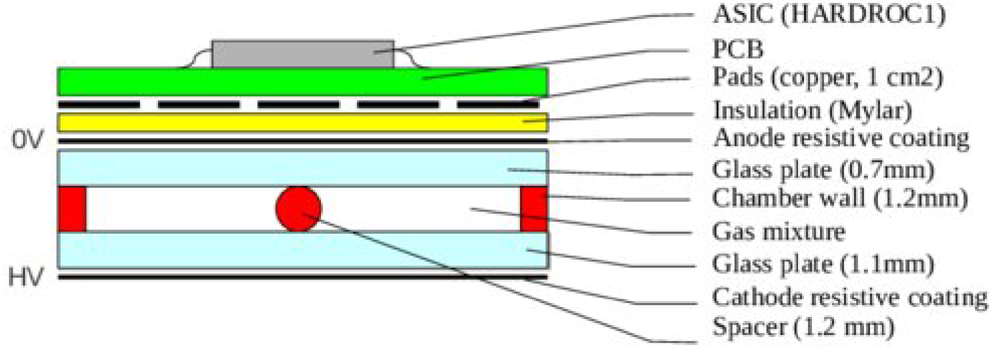
$$I^+ = q\bar{v}\cdot\bar{E}_n = +e(\mu^+E)\frac{1}{d} = \frac{e\mu^+E}{d}$$

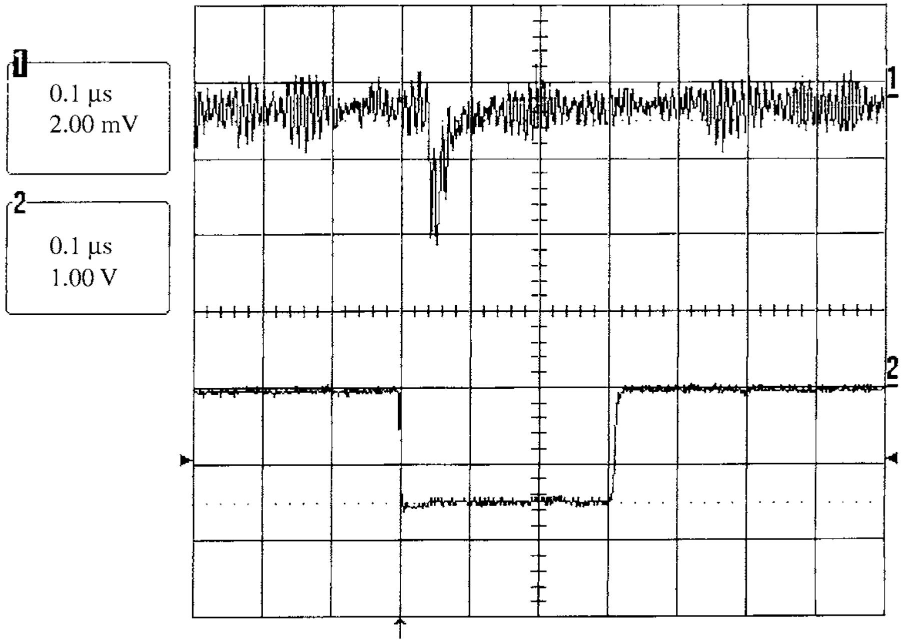
$$I^- = q\bar{v}\cdot\bar{E}_n = -e(-\mu^-E)\frac{1}{d} = \frac{e\mu^-E}{d}$$

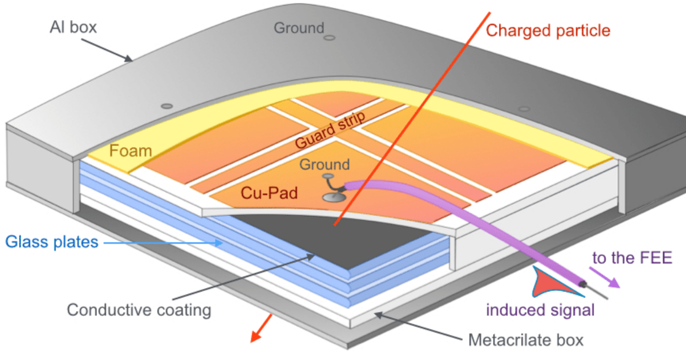
$$t_s^+ = \frac{x}{\mu^+E} \qquad t_s^- = \frac{d-x}{\mu^-E}$$

The gaseous **Resistive Plate Chamber** (RPC) works on the principle of ionization that a moving charged particle produces in the gaseous medium.





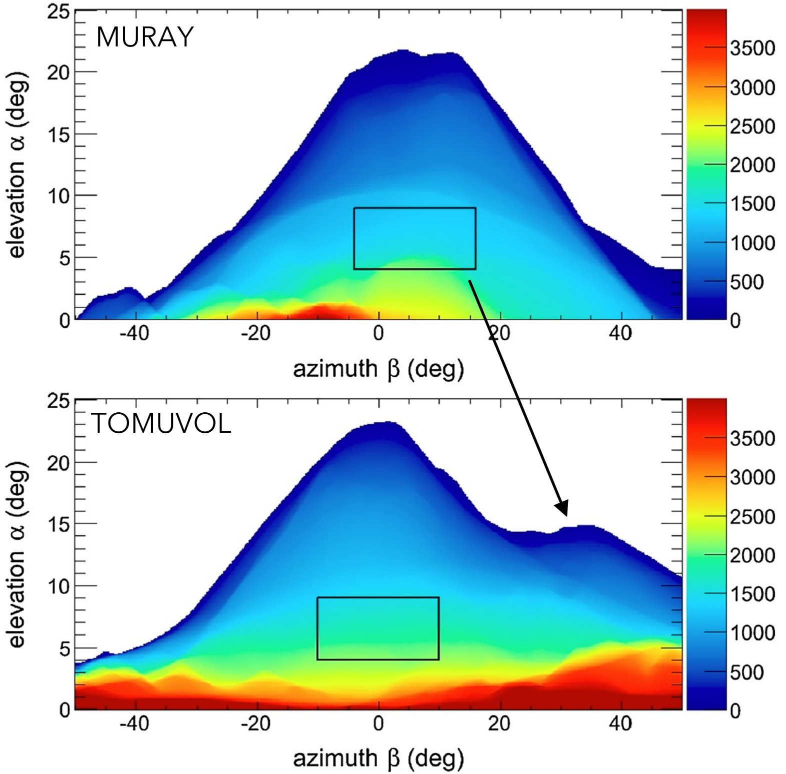


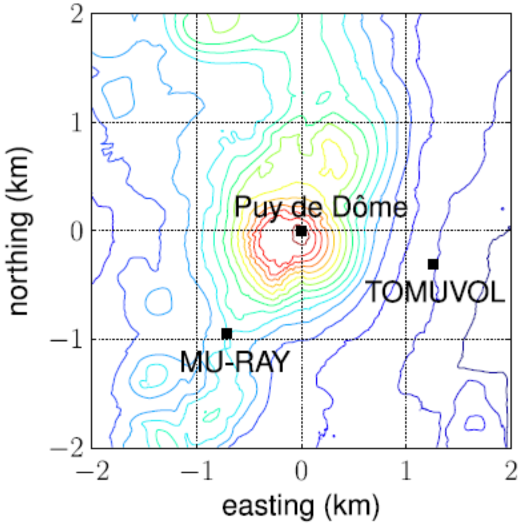


When an electric field E is applied, the development of an avalanche in an RPC and the deformations of the electric field, due to the charges of the avalanche, produce a large charge gain ($10^4 – 10^6$). Some gas atoms are ionized by the passage of a charged particle and then an avalanche is started with a size that is sufficiently large to influence the electric field in the gas gap. While the electrons reach the anode, the ions drift much slower reaching the cathode delayed of a factor 10^3. The charges in the resistive layers influence the field in a small area around the position where the avalanche developed.

The TOMUVOL detector is made of four 1 m^2 parallel planes of gaseous RPC - read by 1 cm^2 charge pads - spaced 33 cm from each other. Each hit on each floor is associated with a time stamp provided by a clock server at 5 MHz. Track are reconstructed offline based on the timestamp. Intrinsic time resolution is of few hundreds of ns due to the electronics.

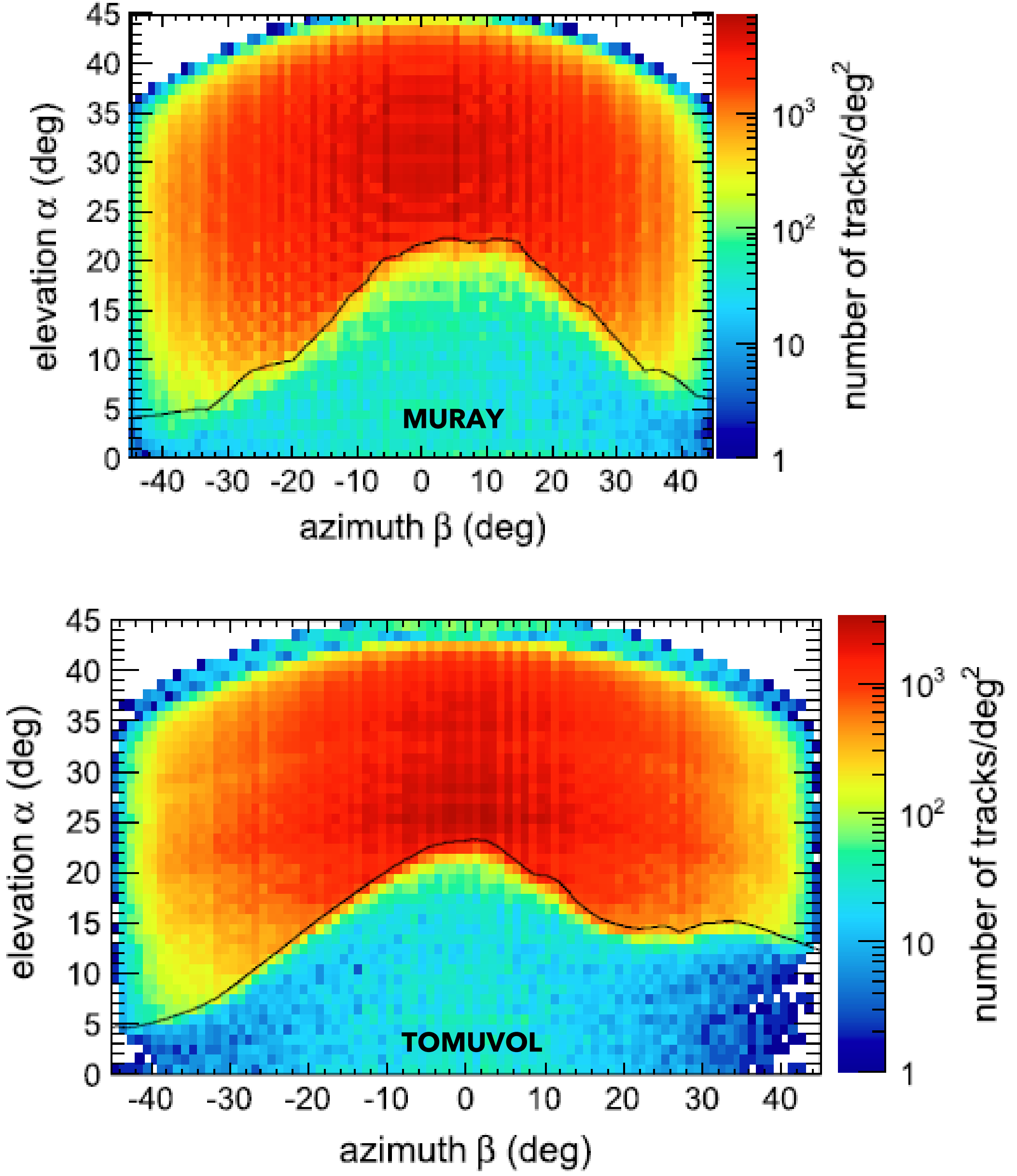
In 2013, the TOMUVOL and MURAY collaboration attempted a muography of the Puy-de-Dôme, from two different orthogonal sites, about 1.3 km from the top. Despite the short exposure time, 41 days for TOMUVOL and 92 days for MURAY, the measure provided experimental evidence of a hitherto unknown background.



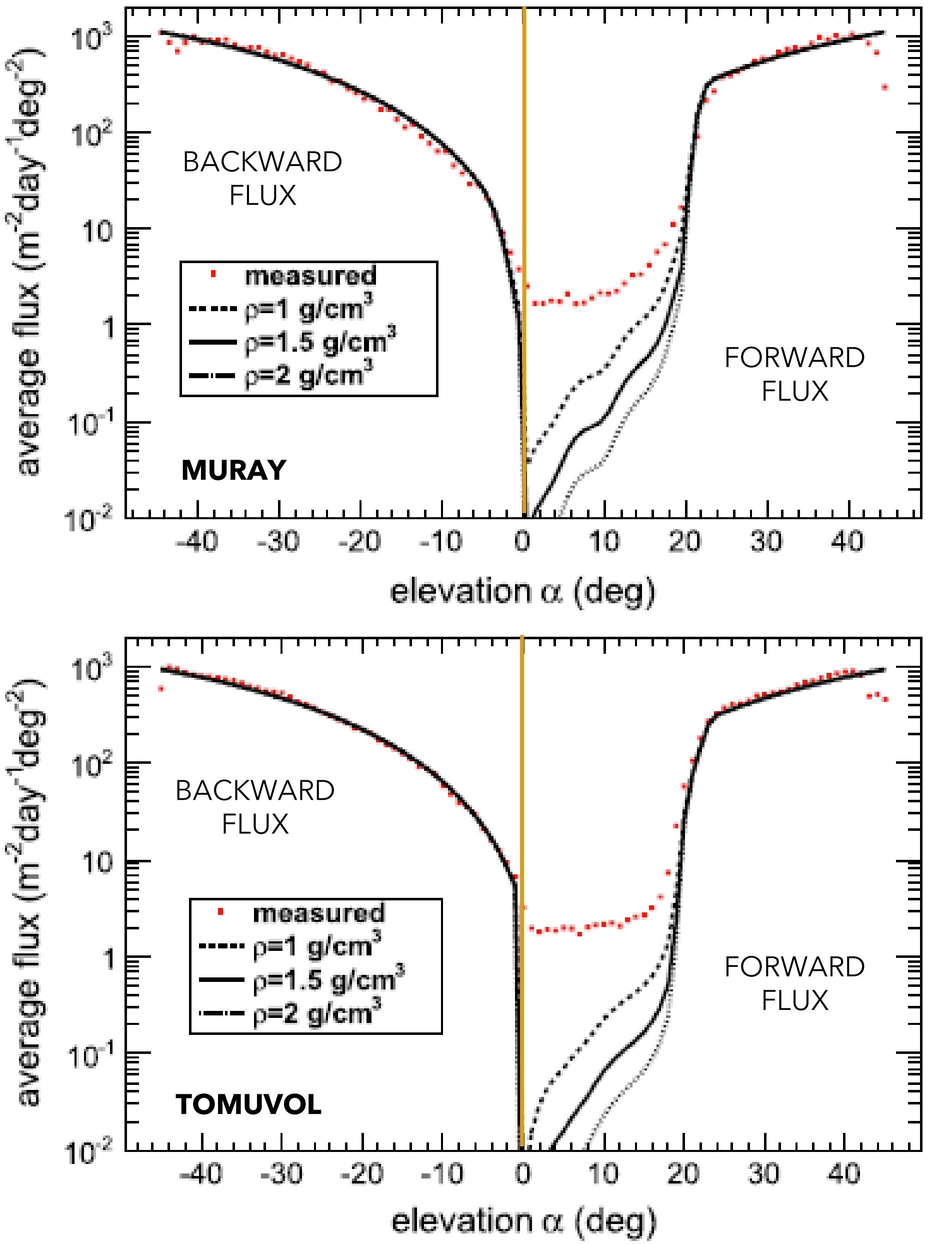


DETECTORS FOR MUOGRAPHY AND APPLICATIONS

MEASURED TRACKS



MEASURED AVERAGE FLUX



DETECTORS FOR MUOGRAPHY AND APPLICATIONS

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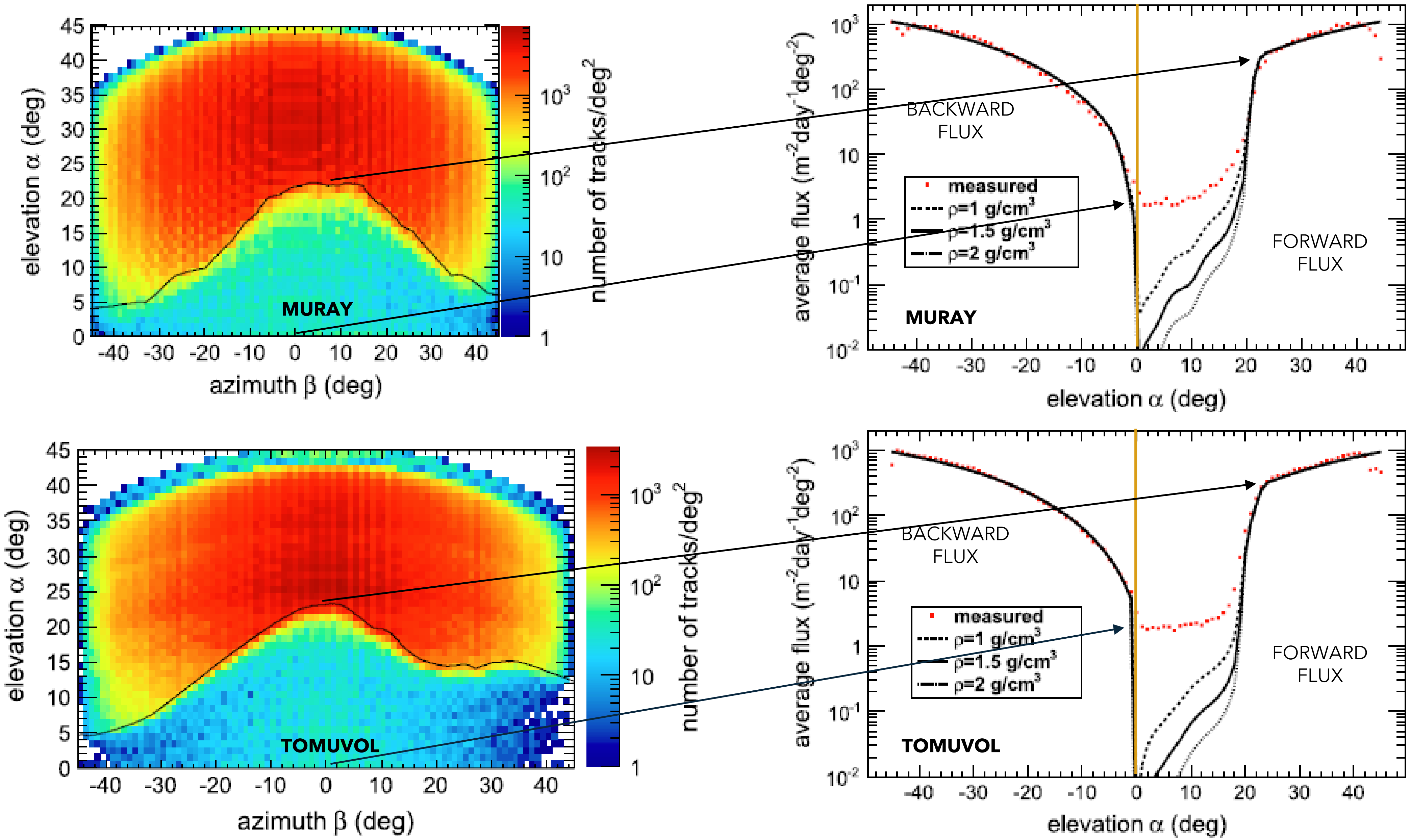

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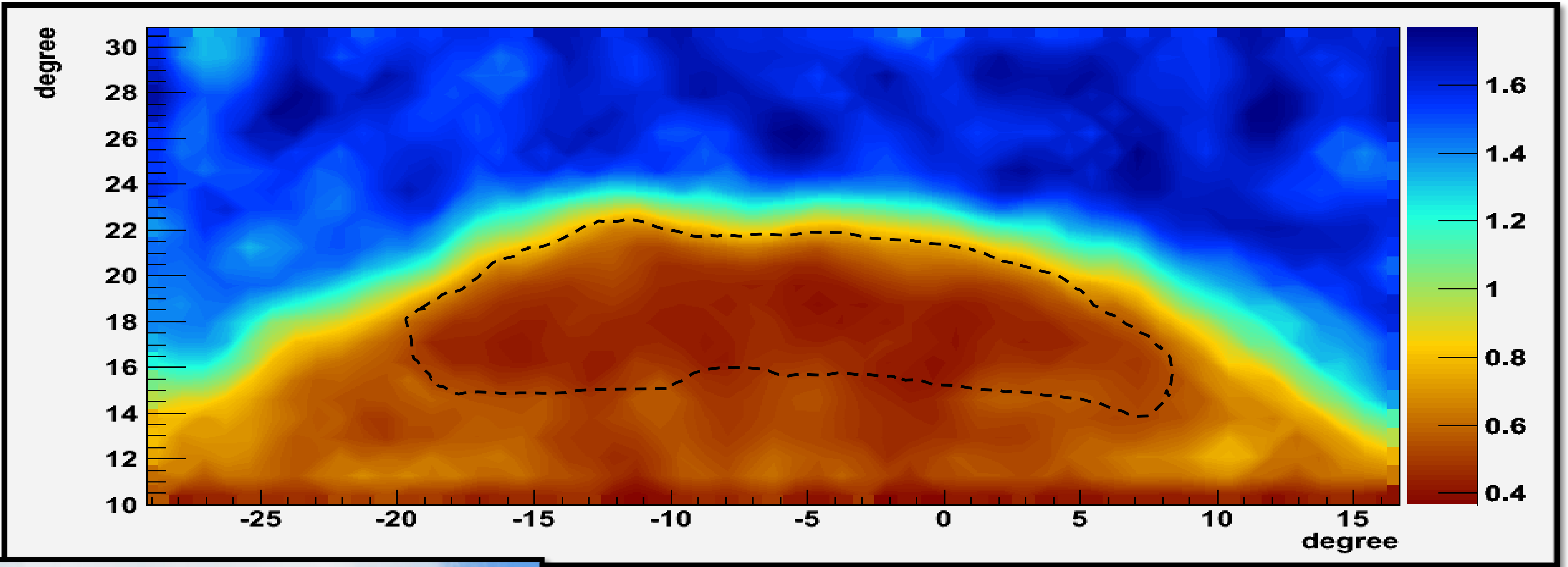
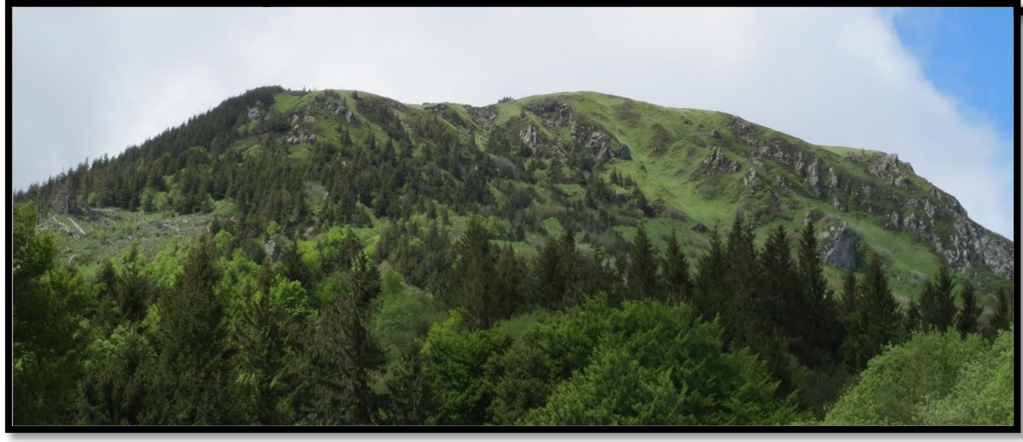
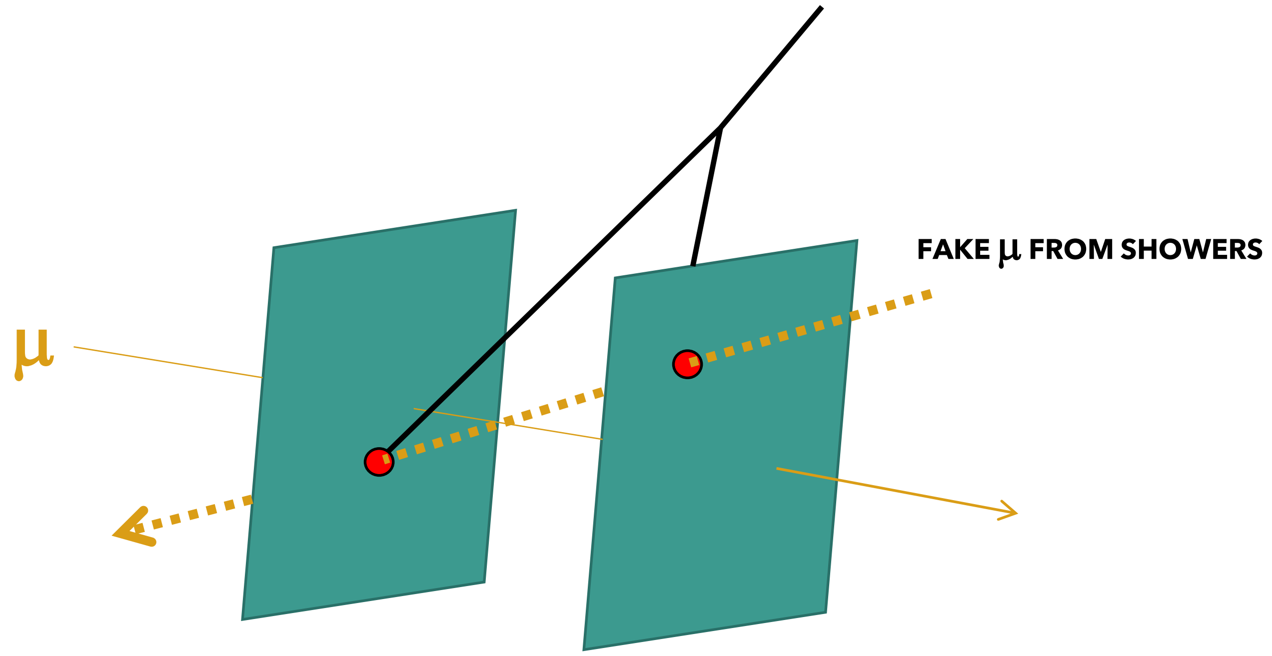


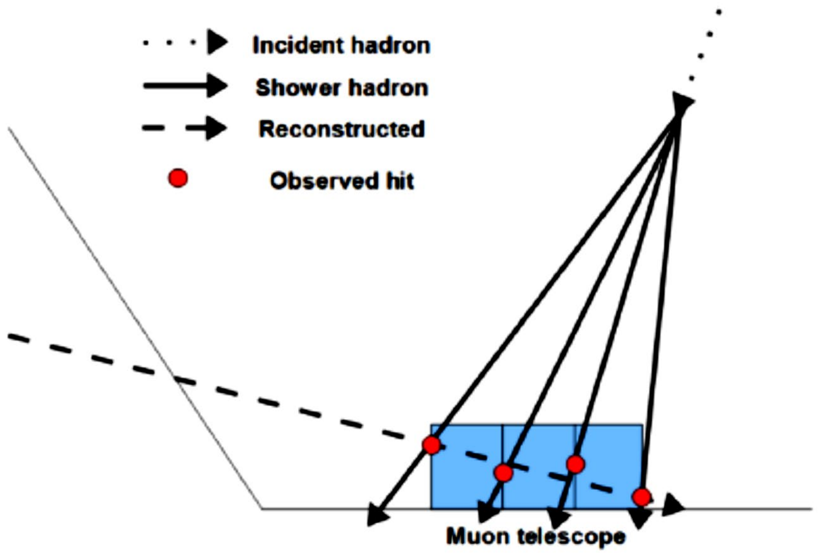


Despite the overwhelming background, the muography performed with the MURAY detector showed a higher attenuation of the muon flux in the summit region, which is qualitatively in agreement with the results obtained with geophysical techniques.

DETECTORS FOR MUOGRAPHY AND APPLICATIONS

In all applications, the background affects the collection of tracks operated by the detector, making the data analysis more complex. We can make a categorization of the background based on its nature. In a first category we can put all the ionizing radiation that mimics, more or less well, the muons coming from the target region. In the second one goes the low-energy muon component which results to come from the direction of the target.





To mitigate the effect of this background, further detector planes can be used in order to increase the multiplicity of aligned hits. Recent detectors use at least 4 planes to perform a better background rejection in the data analysis.

DETECTORS FOR MUOGRAPHY AND APPLICATIONS

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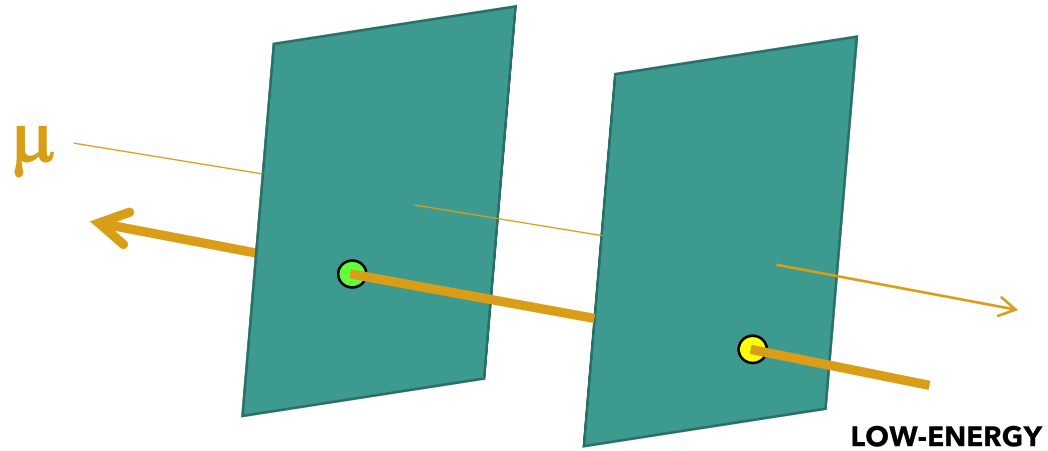
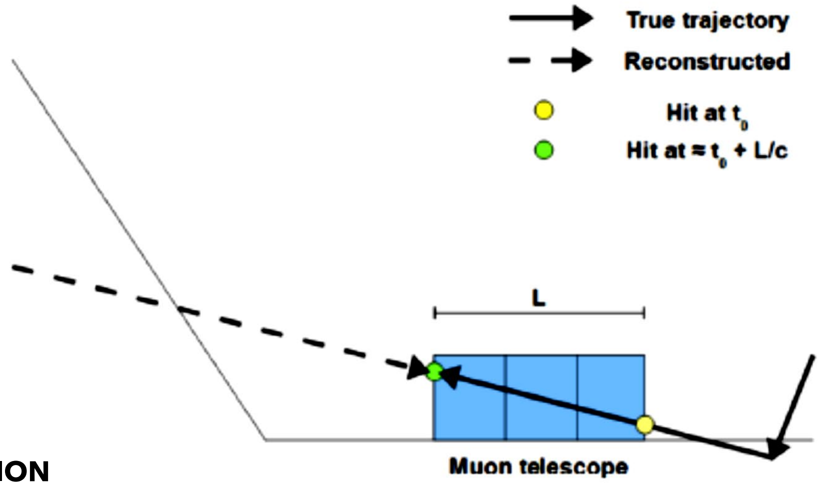
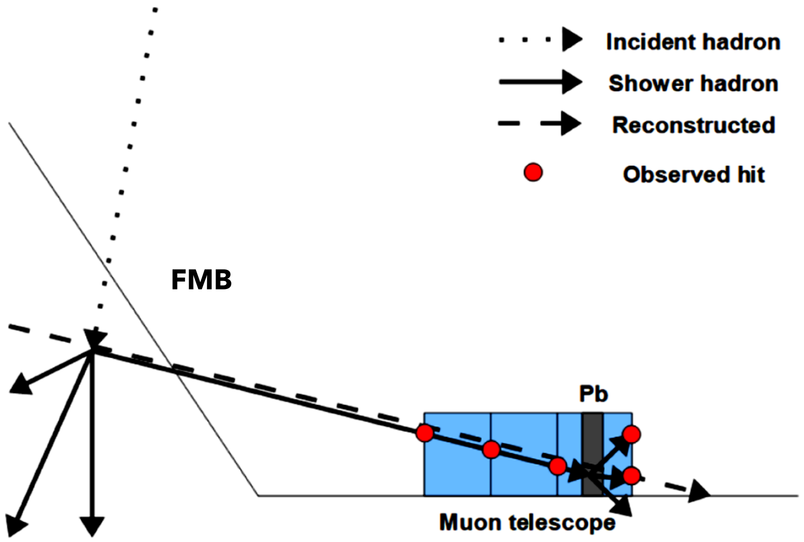


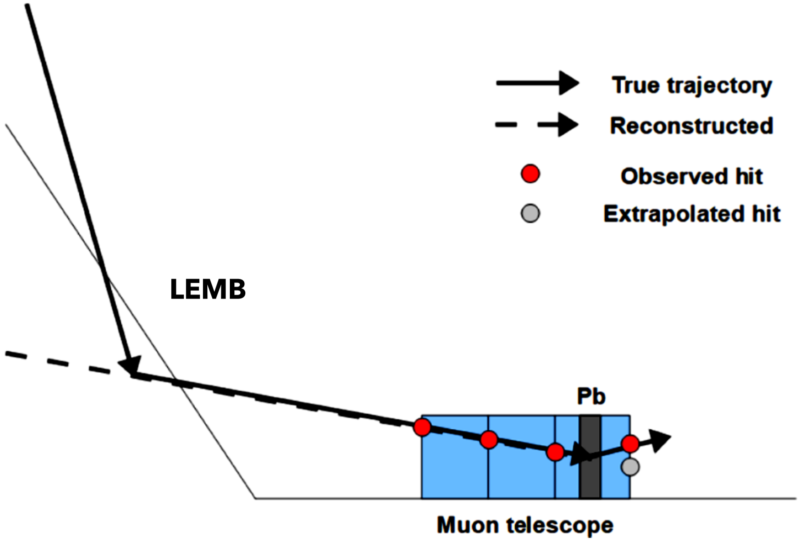
LOW-ENERGY μ FROM OPPOSITE DIRECTION



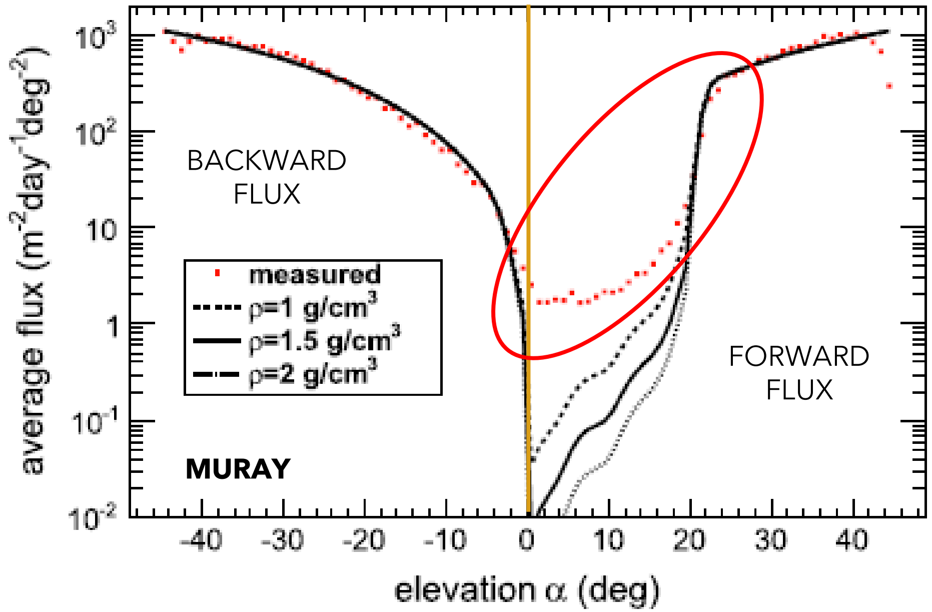
With a system for the measurement of the time of flight, one can easily discriminate the direction (forward or backward) of the muons, thus allowing to reject those traces coming from the opposite direction to the target.

DETECTORS FOR MUOGRAPHY AND APPLICATIONS



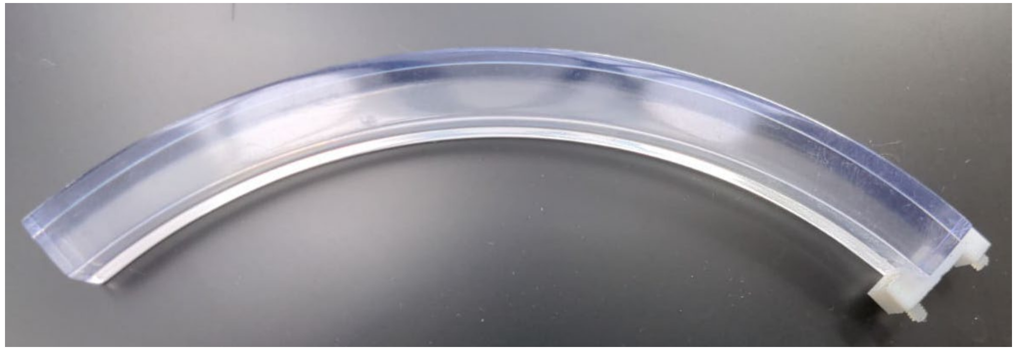


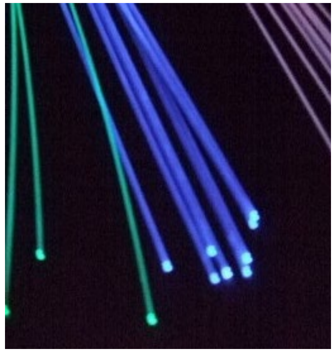
The background observed by TOMUVOL and MURAY detectors comes from ionizing radiation that scatter close to the surface of the target and accidentally produce a track in the detector. To limit this background, it is often decided to introduce volumes of high-density materials, such as lead, to absorb or deflect this component. However, this solution has several cons and it is not possible to apply it in every condition, especially if one thinks of volcanological applications.

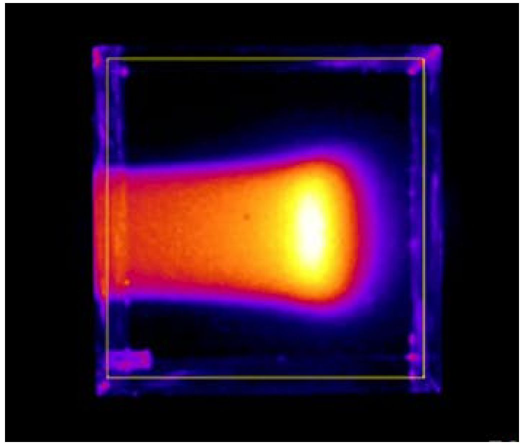


Plastic scintillators are made with a polymer base, mixed with fluorescent emitting elements that are excited by the passage of ionizing particles. The emitted light (millions of photons) is read with light sensors such as PMT or SiPM.

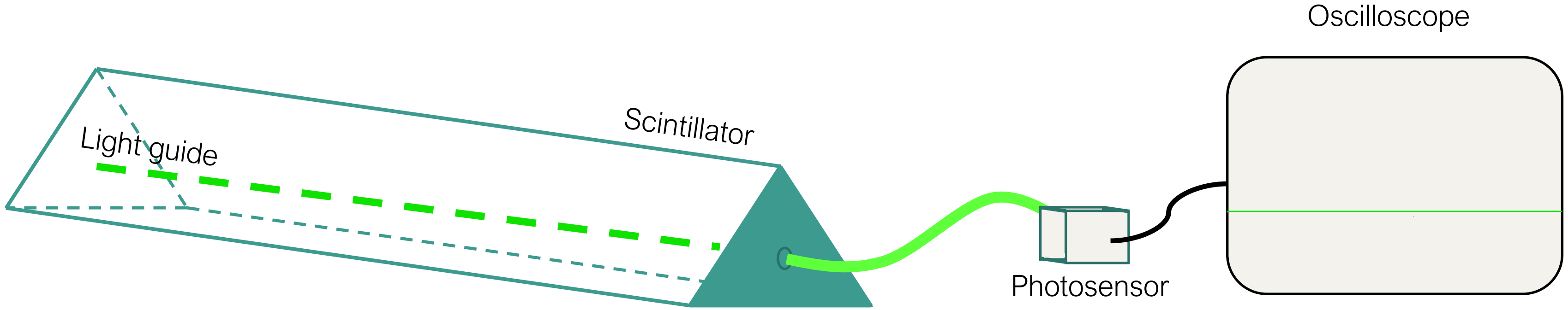
Plastic scintillators don't need maintenance and are very durable and robust. They can be shaped according to the needs. The high time resolution (< 10 ps) is compensated by several factors that influence the light transmission along the scintillator. Among all, the attenuation factor can be crucial when using too long bars that affect both the timing performance and the light collection with photosensitive devices.







SCINTILLATION LIGHT PRODUCED BY A MUON BEAM



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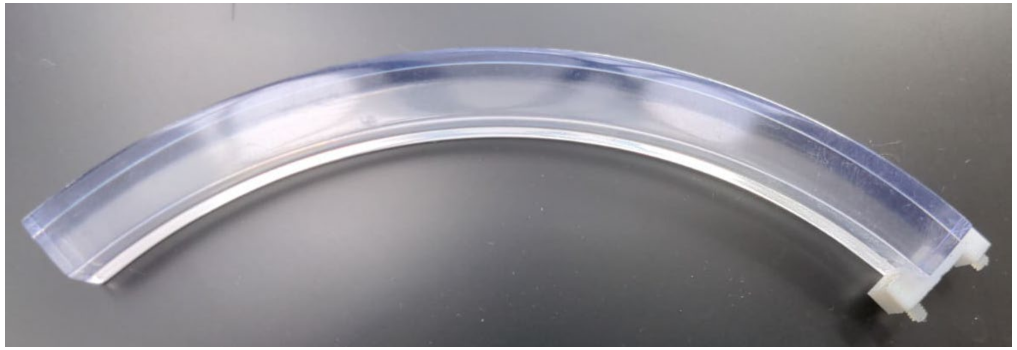

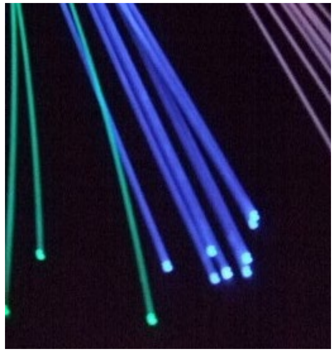

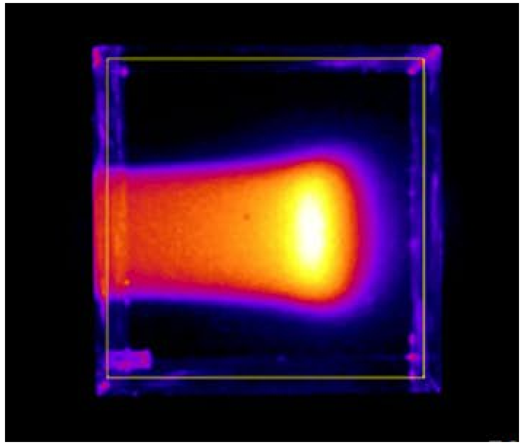

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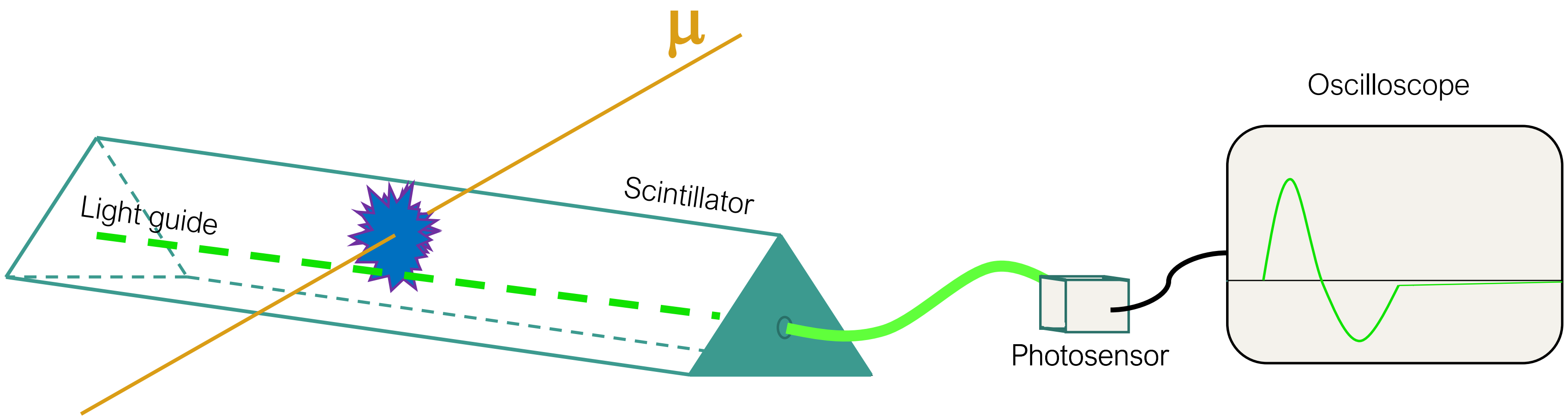
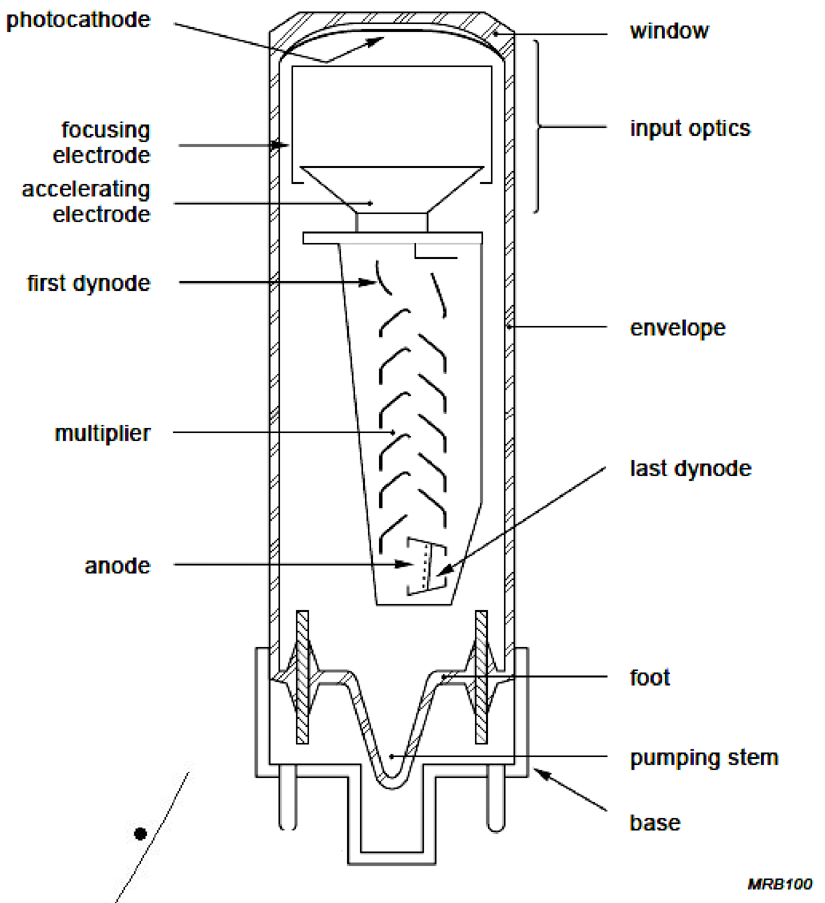
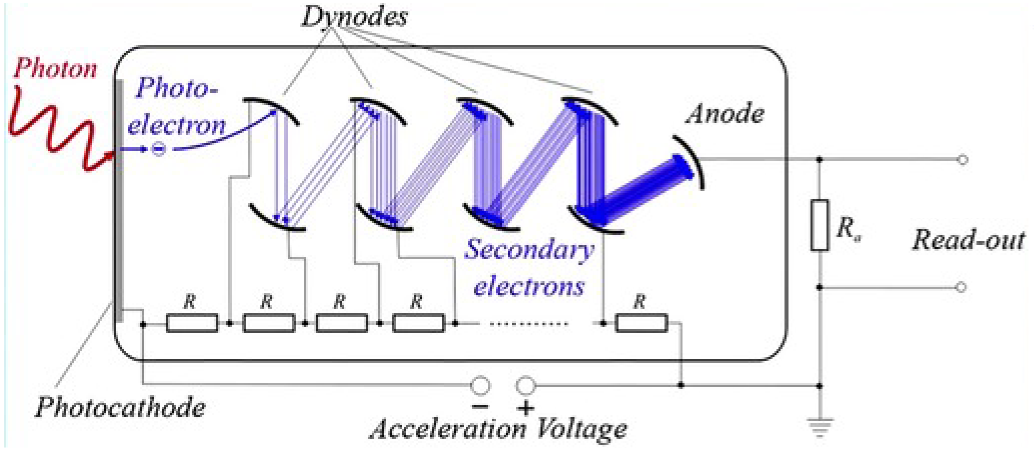
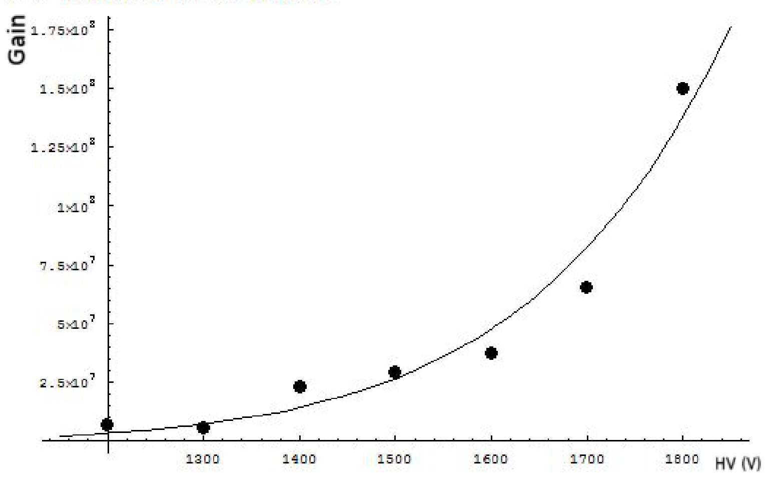


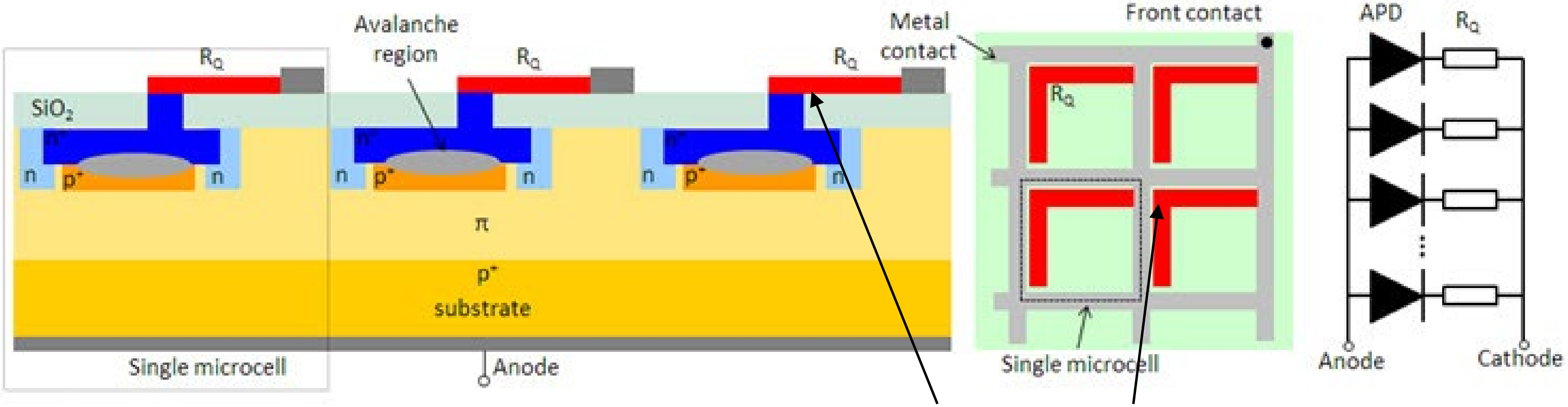
The Photomultiplier tubes (PMT) are photo sensors sensitive to the single photon. Photoelectrons are produced when one or more photons hit the photocathode , made of photoemissive semiconductor material. Electrons are accelerated under the effect of a high electric field and they are focused on the first dynode. The photoelectrons interact with the dynode producing several new electrons which are accelerated under the effect of a constant electric field, towards the next dynodes. The avalanche process goes on until a great number of electrons, of order $10^6 – 10^8$, flow to the anode, where the charge is read. PMT are, in good approximation, linear devices in respect of the number of the hitting photon and works with a power law in respect of the voltage.





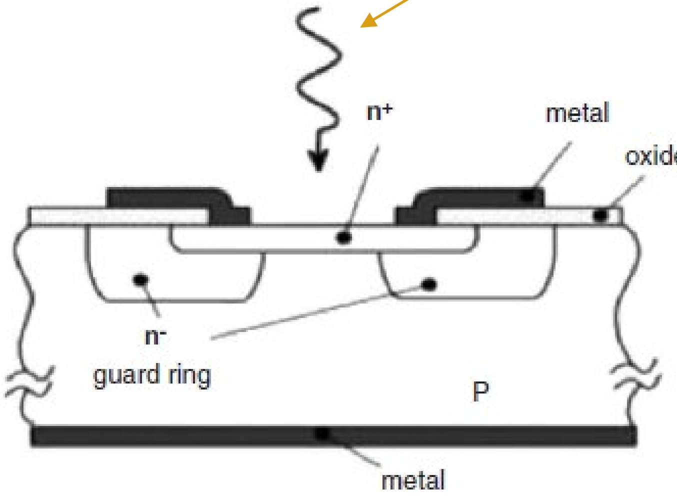


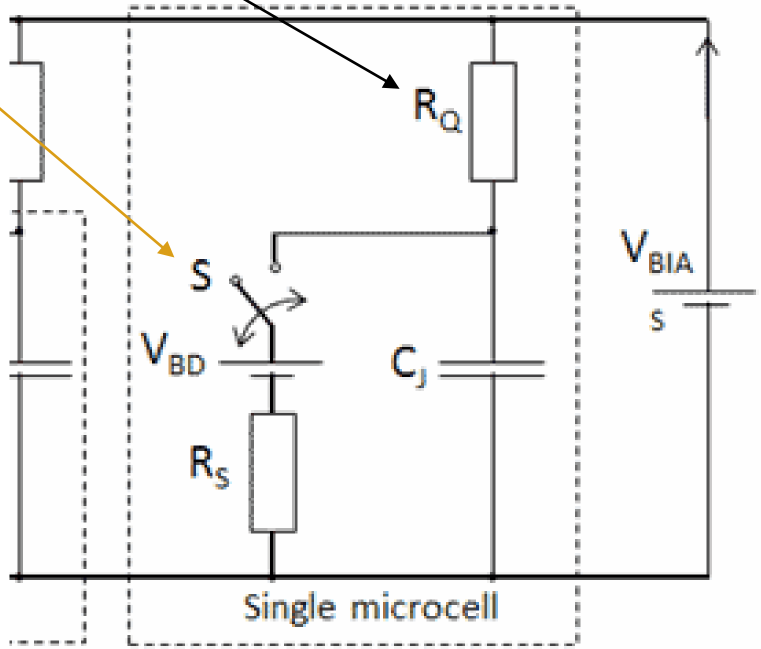
Silicon Photomultipliers **are photosensors capable to reveal the single photon**. The main characteristics of these devices are the ruggednes, the durability and the low power consumption.



Incoming photon closes the switch

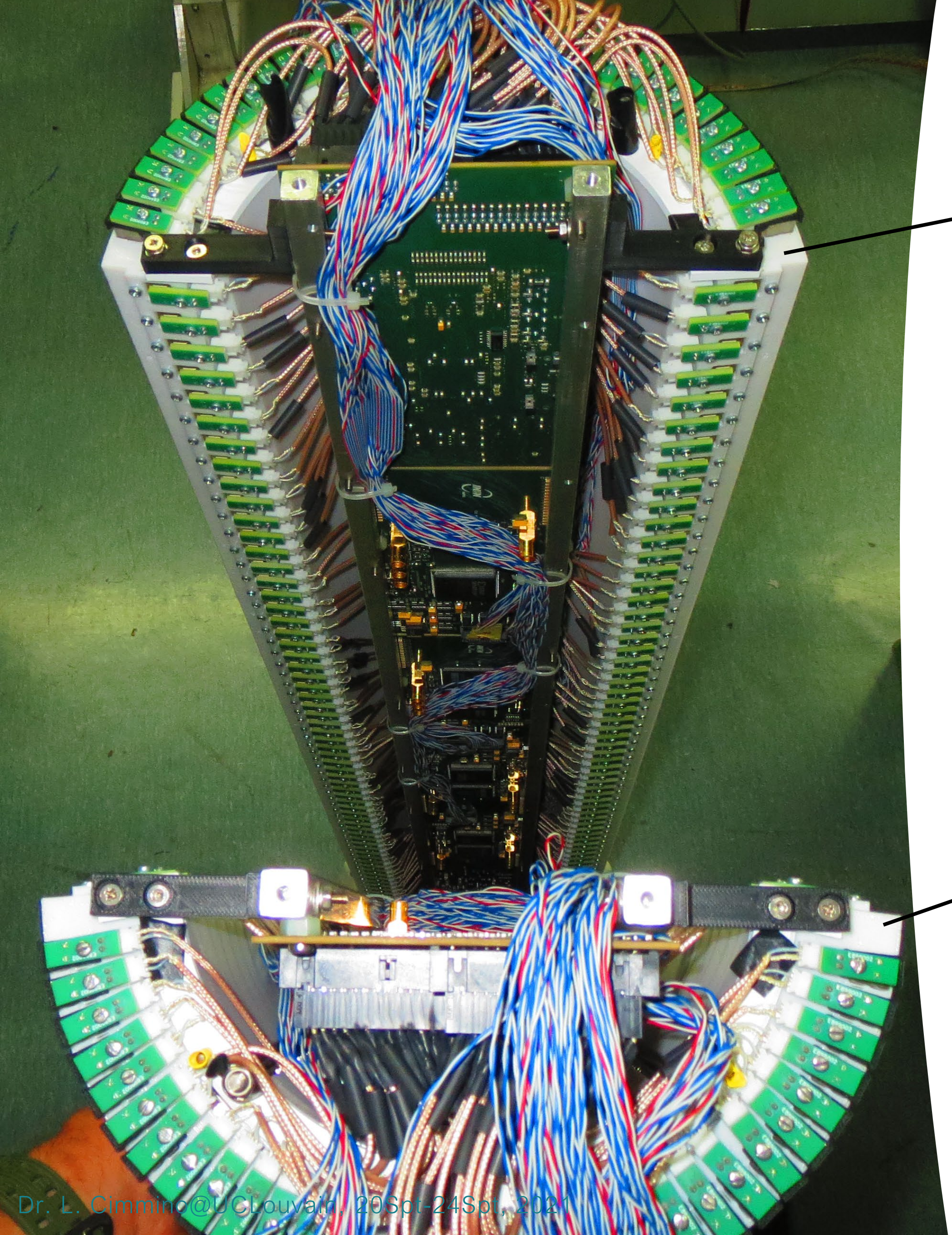
QUENCHING RESISTOR

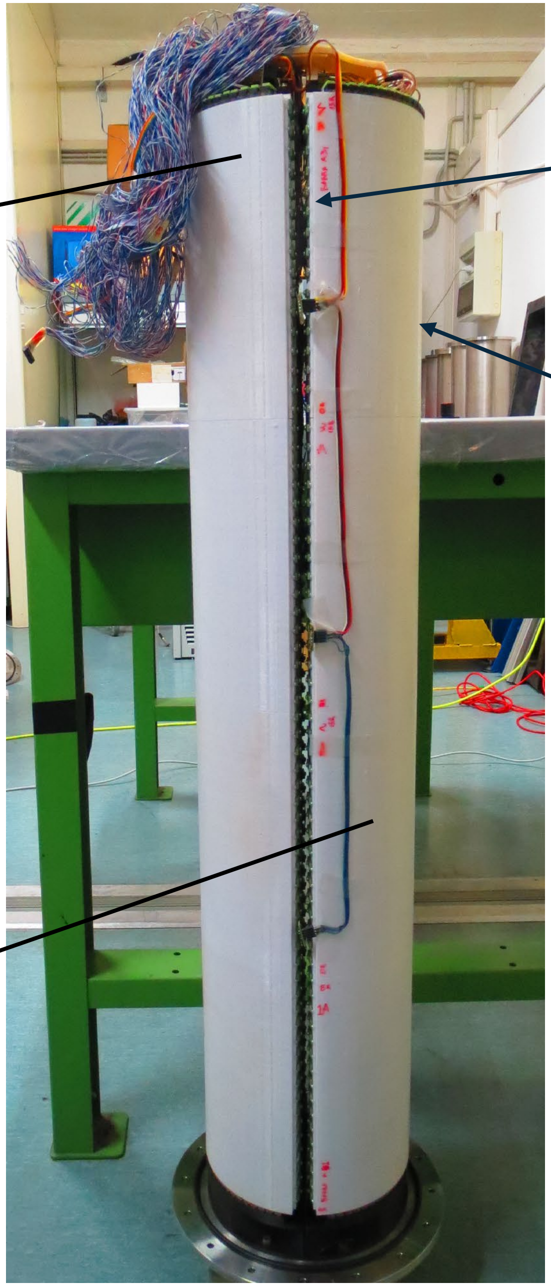


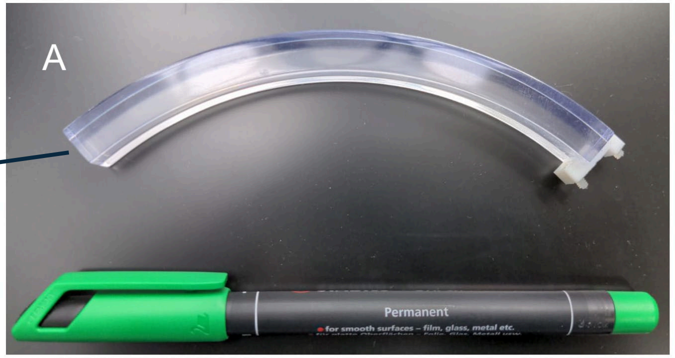


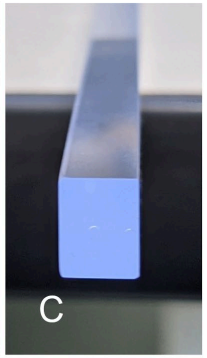
SiPMs are constituted by a parallel matrix of avalanche photodiodes working in Geiger-mode (**G-APD**). When a photon triggers an avalanche, this grows exponentially until it reaches its maximum, depending on how many cells have been activated at the same time. The SiPM is restored by meaning of the **quenching resistor** in series with the APD.

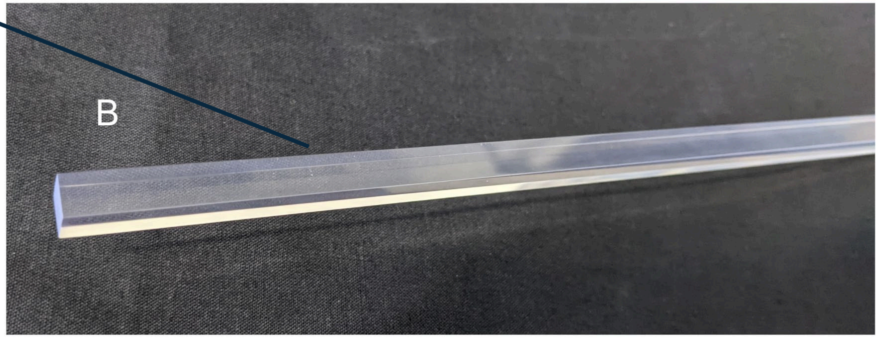
DETECTORS FOR MUOGRAPHY AND APPLICATIONS

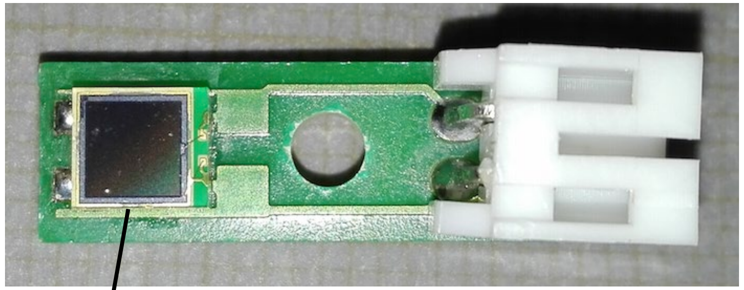


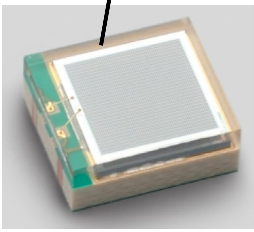


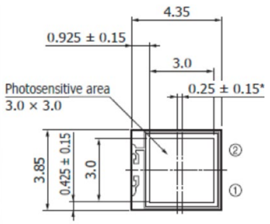




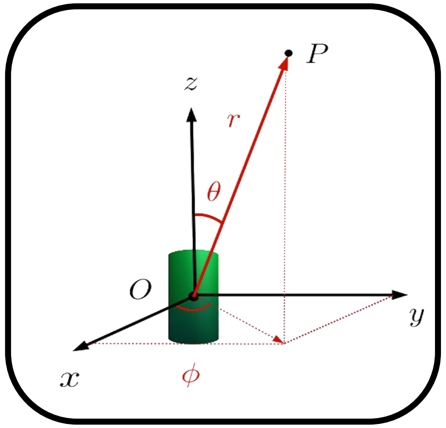








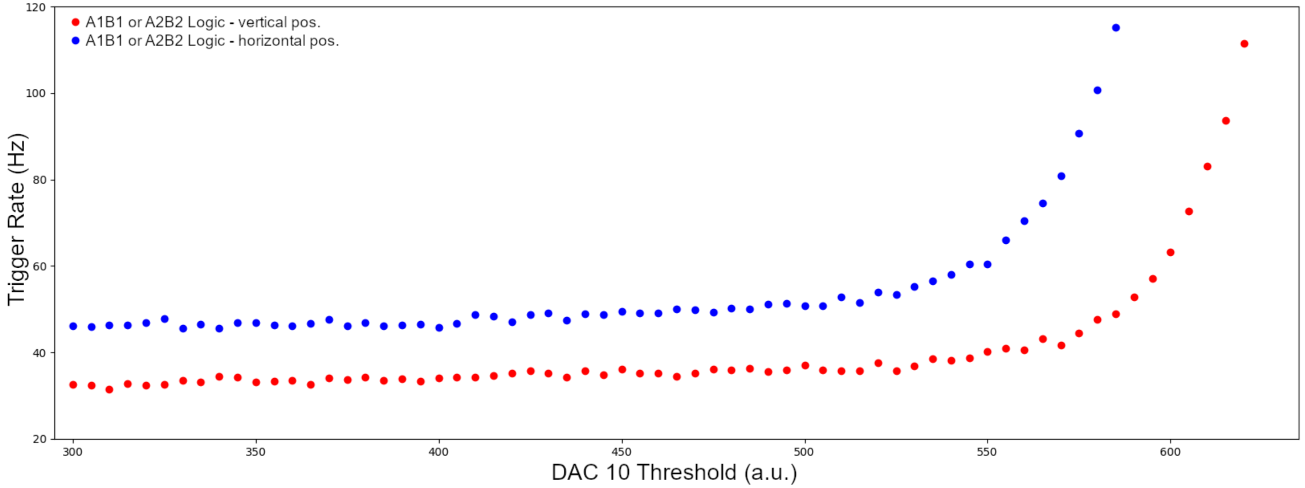
DETECTORS FOR MUOGRAPHY AND APPLICATIONS

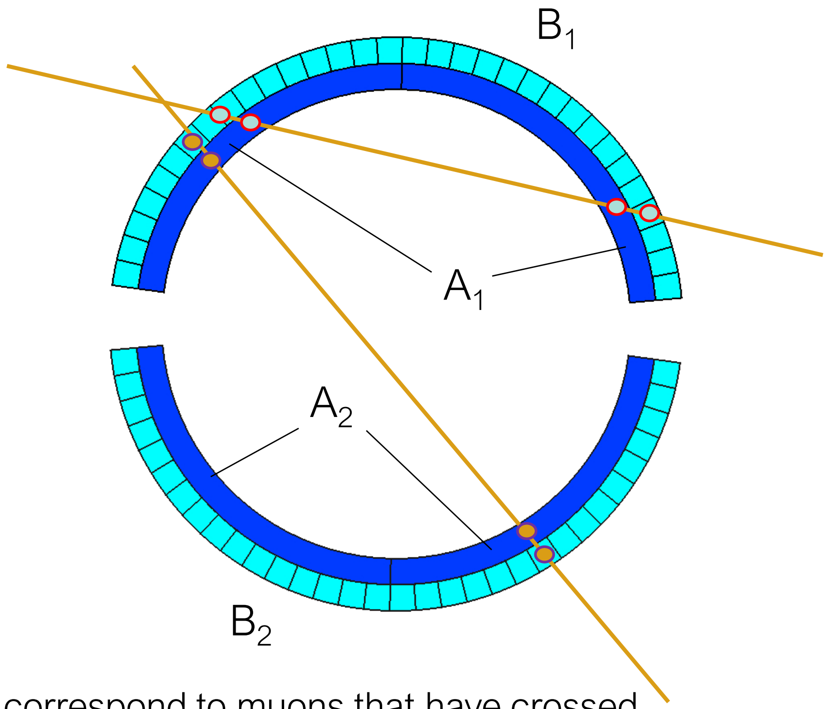


- A spherical coordinate system is used for tracking
- LT A and B are produced by FEE boards when SiPM record the passage of a muon
- The detector trigger logic is set to $(A_1 * B_1) + (A_2 * B_2)$
- For LT rates of hundreds of Hz we expect accidental coincidences of order 10^{-2} Hz

- Accidental coincidences decrease by increasing the threshold value

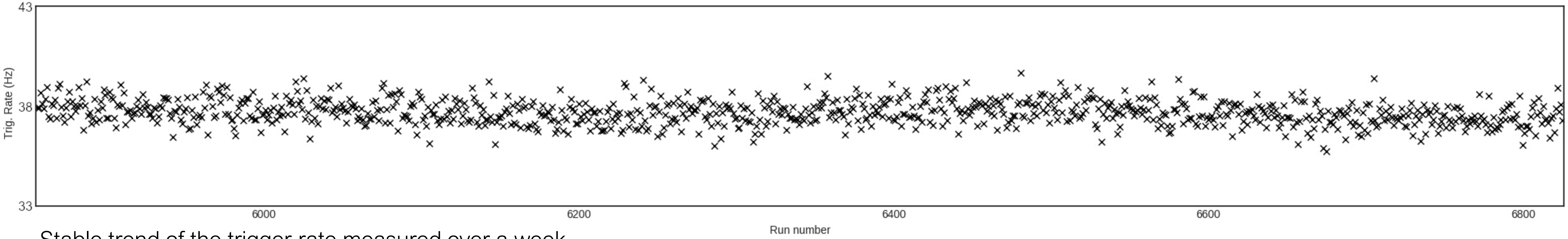
Plateau :
- 48 Hz trigger rate detector placed horizontal
- 38 Hz trigger rate detector placed vertical



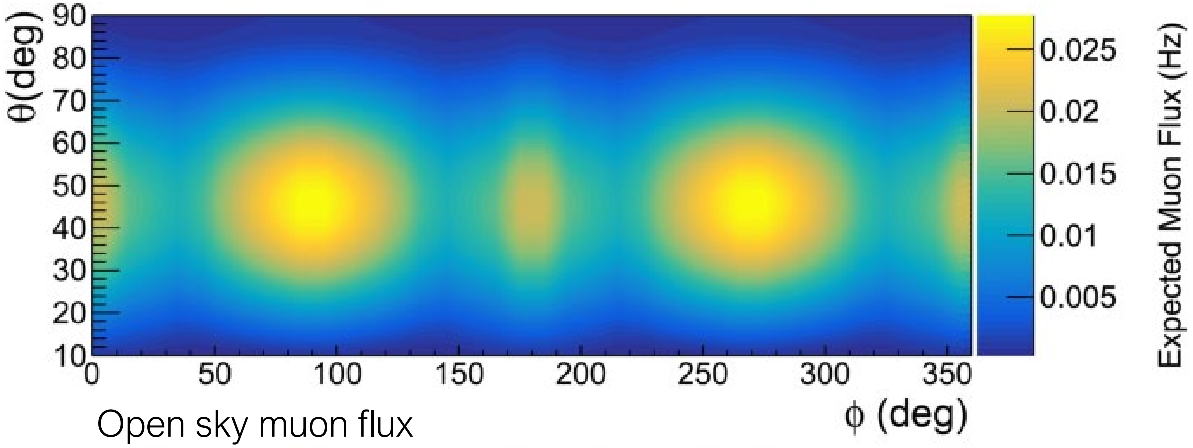


Tracks correspond to muons that have crossed both semicylinders or to muons that have crossed the same semicylinder in two points lighting up two bars and two arcs

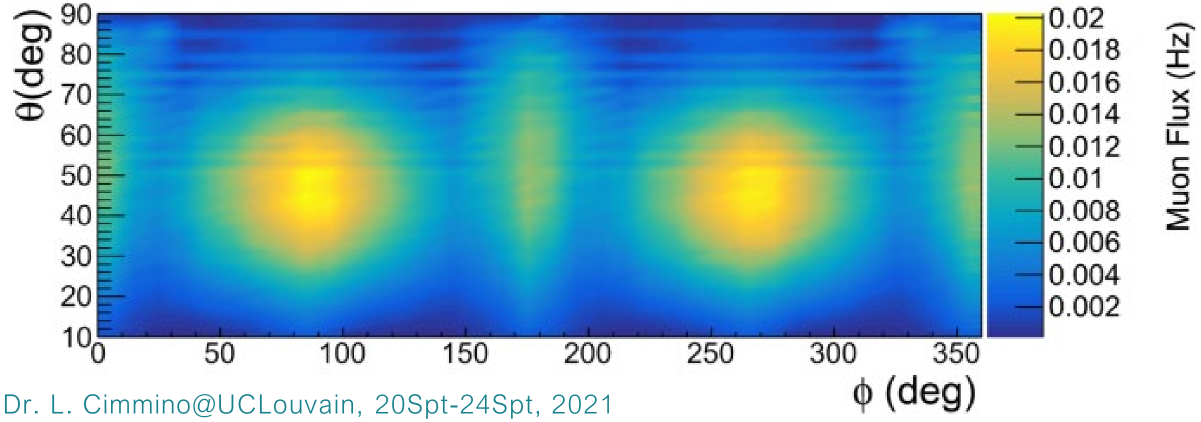
DETECTORS FOR MUOGRAPHY AND APPLICATIONS

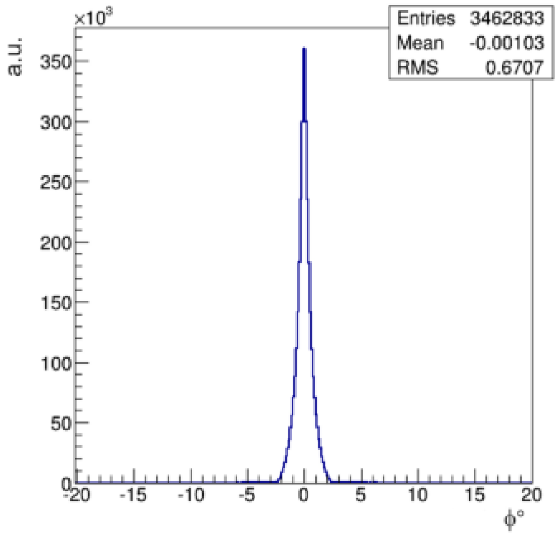


Stable trend of the trigger rate measured over a week

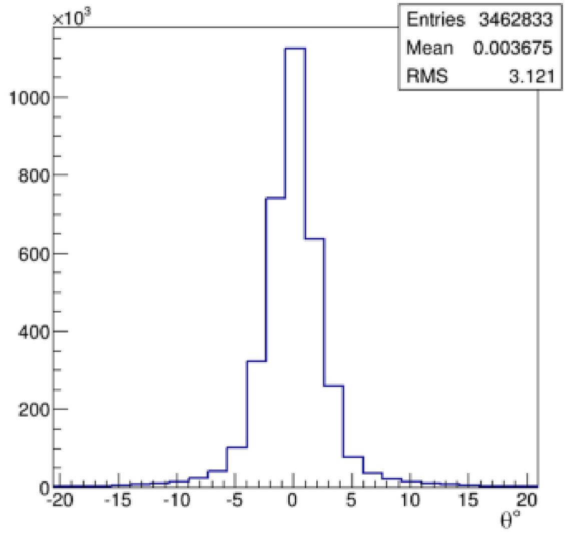


Open sky muon flux





0.67° Azimuthal resolution



3.21° zenithal resolution