# Tests and calibration of multi-channel photodetectors for balloon and space-based EUSO missions

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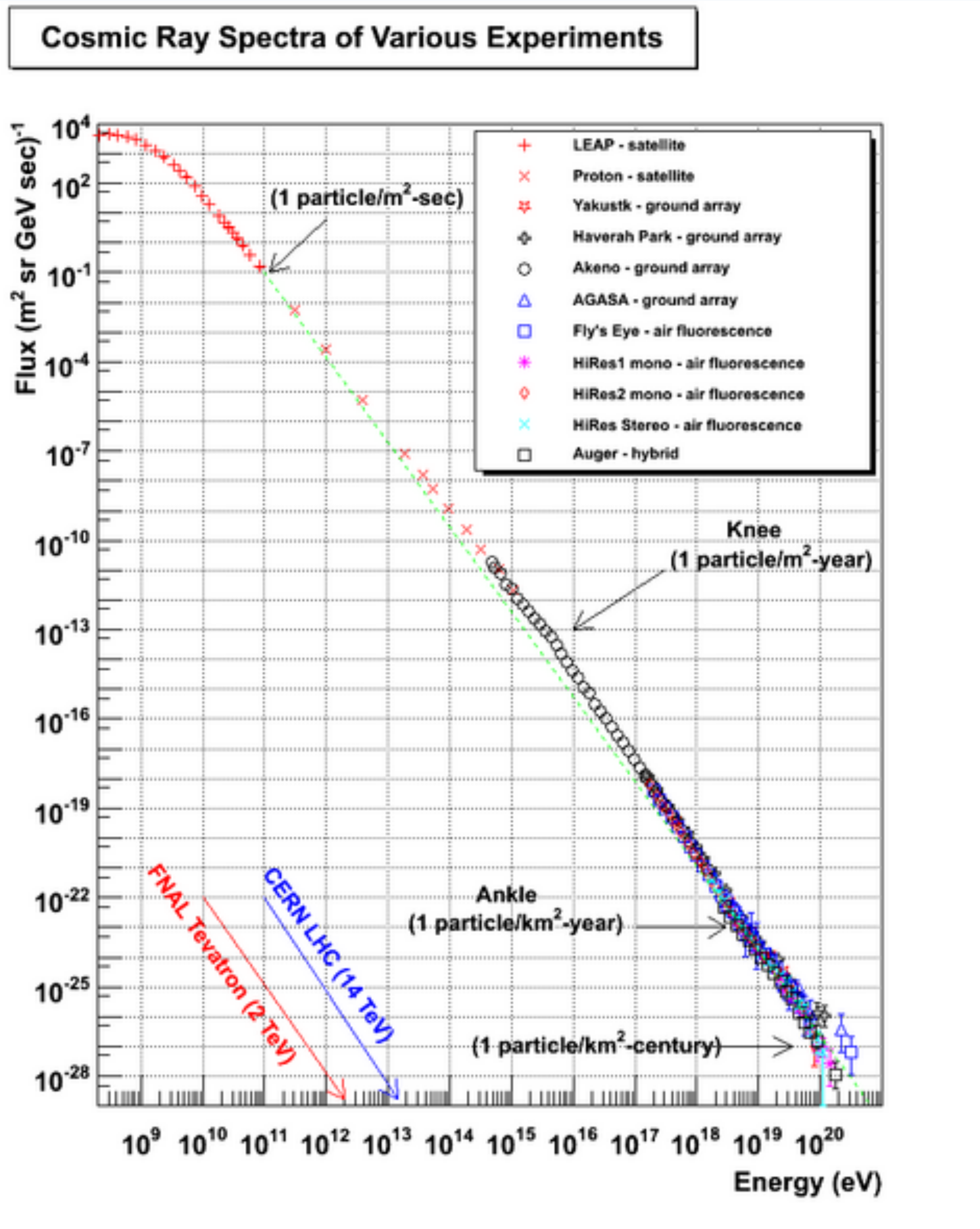
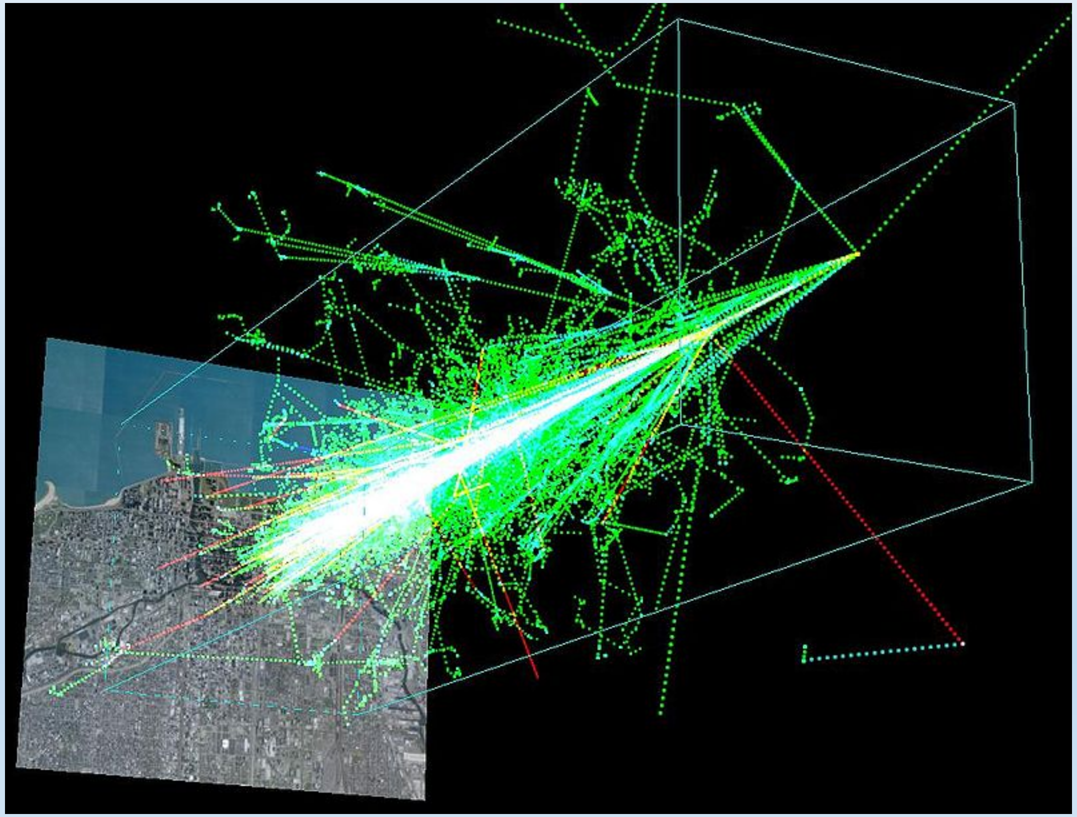
# Cosmic rays

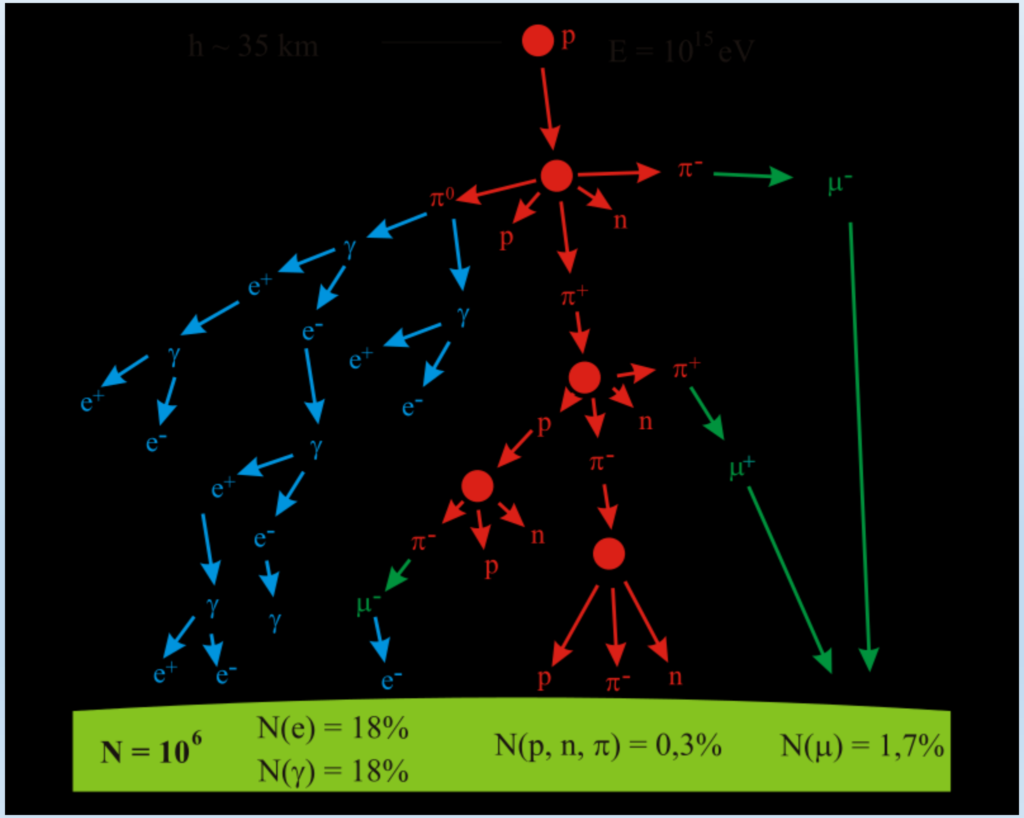
Cosmic rays are high-energy protons and atomic nuclei that move through space at nearly the speed of light. They originate from the Sun, in our own galaxy outside of the Solar system and from distant galaxies.



# Extensive air showers (EAS)

When a primary cosmic ray with high energy enters the atmosphere, it creates an extensive air shower (EAS): a cascade of energetic particles and electromagnetic radiation produced in the atmosphere



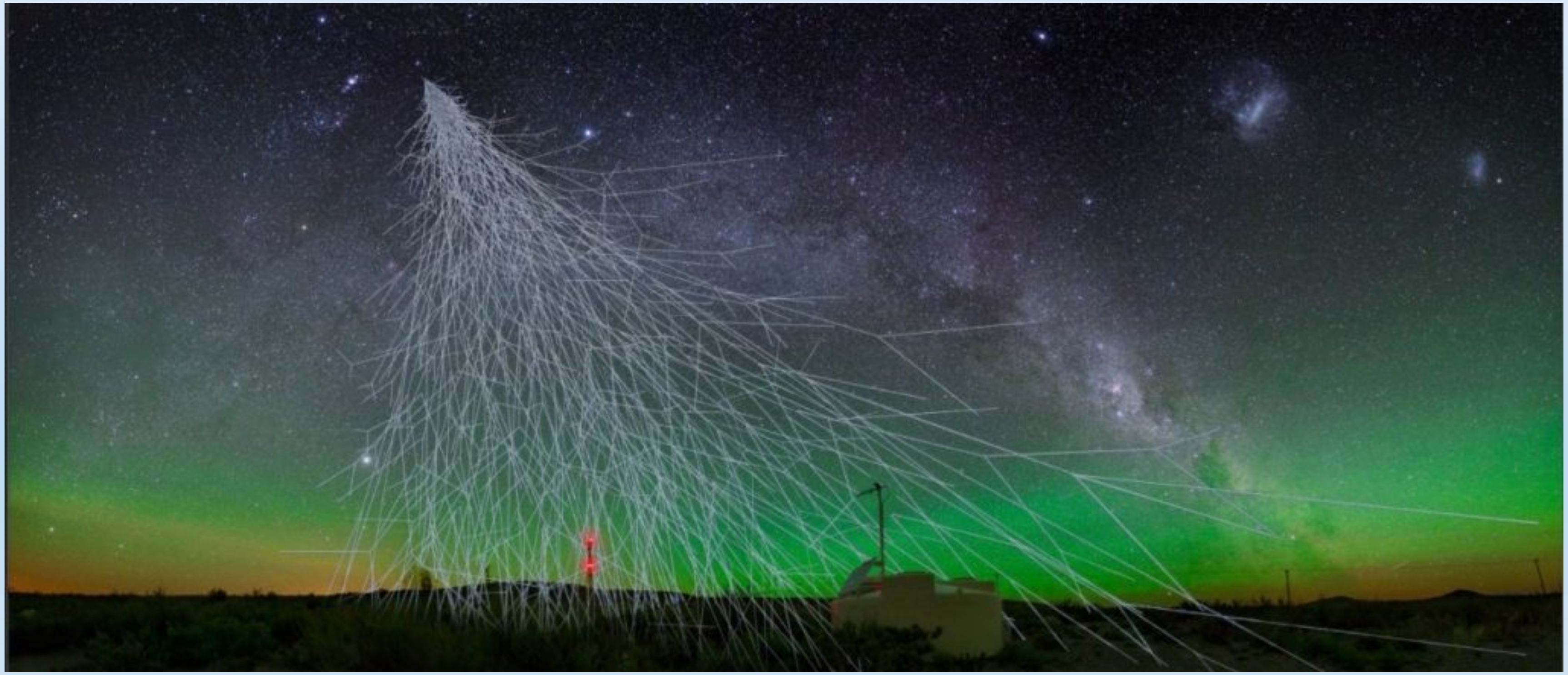


# Ultra High Energy Cosmic Rays (UHECR)

Ultra High Energy Cosmic Rays are the most energetic particles in the Universe with energies up to $10^{20}$ eV and beyond, i.e. macroscopic energies (several tens of Joules!)

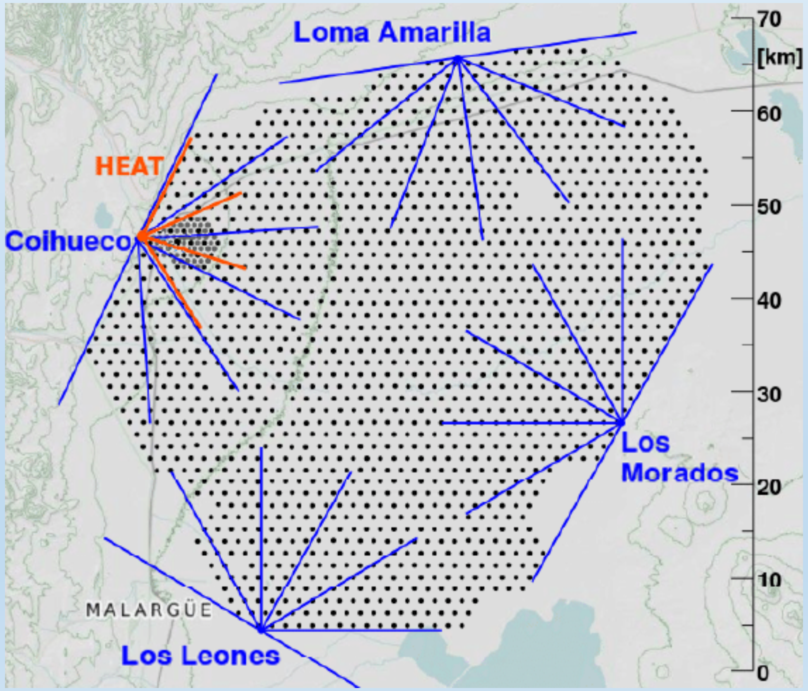
These particles are detected through the observation of extensive air showers.

The origin of UHECRs remains one of the most challenging mysteries in astrophysics



# Ground-based installations

The currently operating ground-based observatories (Auger and Telescope Array) could only detect around two dozen of events with energies exceeding $10^{20}$ eV, with very non uniform exposure of the sky in the northern and southern hemispheres. This proved insufficient to determine their sources, composition, and acceleration mechanism.



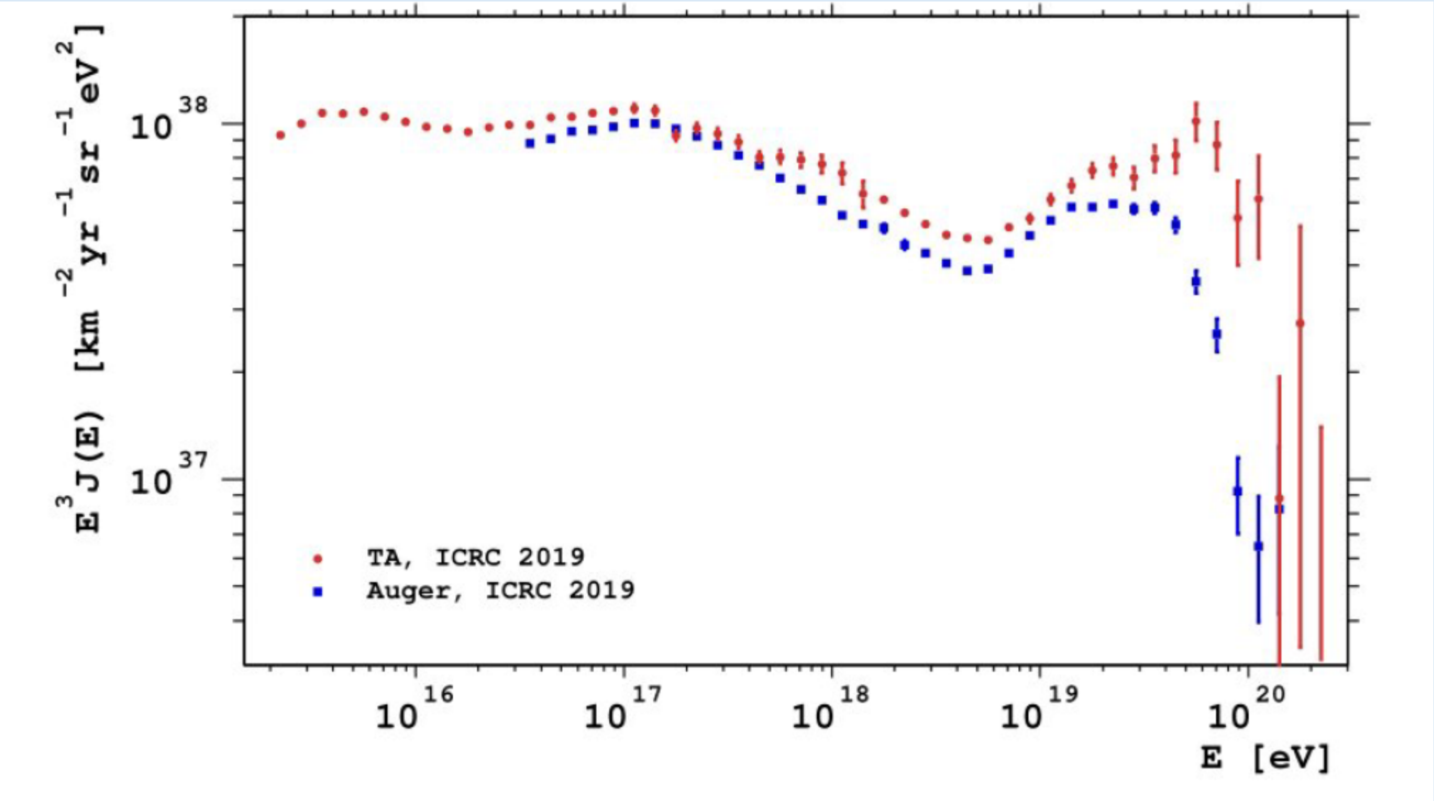

Pierre Auger Observatory map and installation unit

# UHECR spectrum

Two different spectra were obtained by 2 ground-based detectors (Auger and TA).

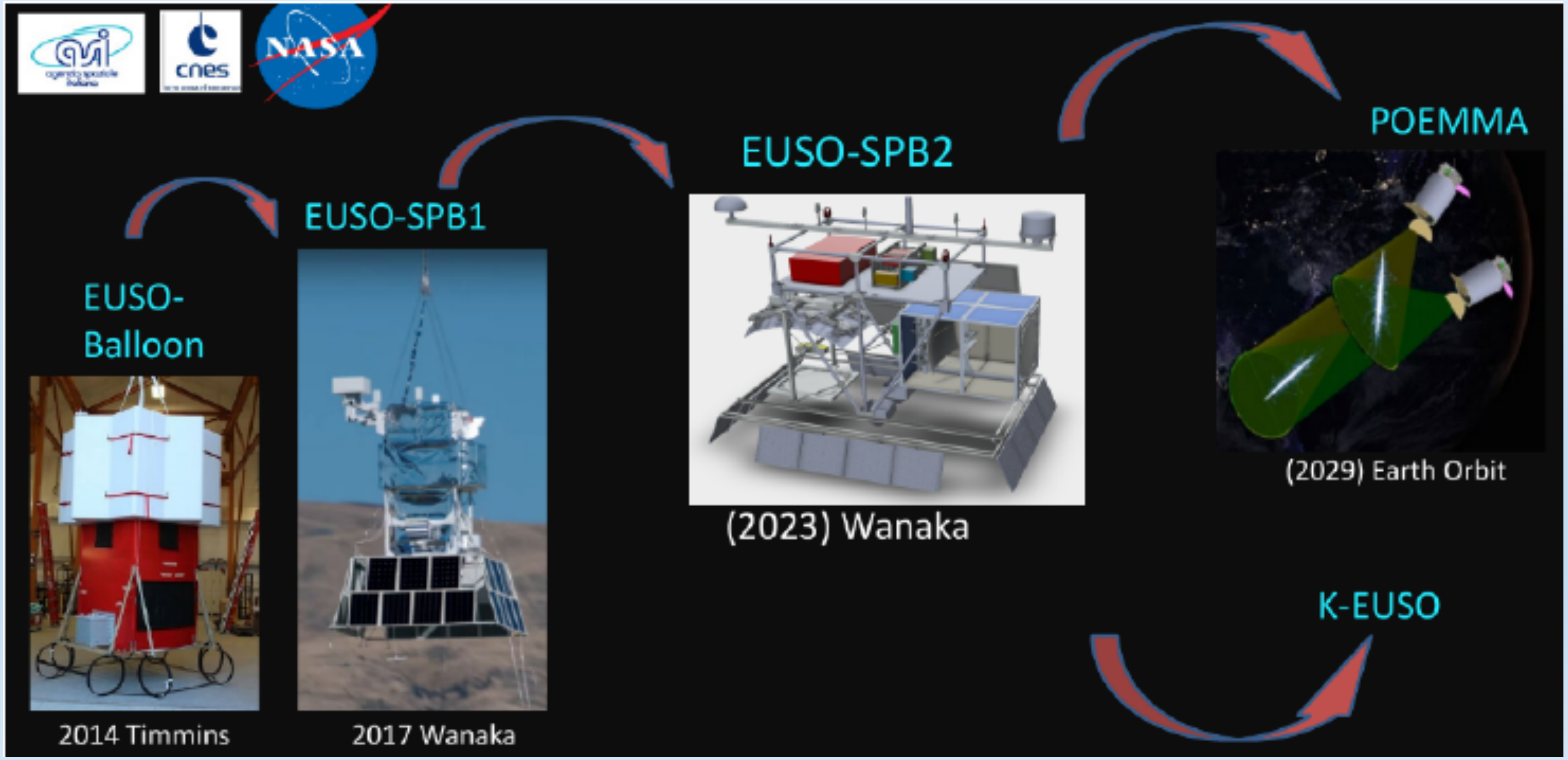
It may be due to different systematic uncertainties or to the fact that the observed regions of the sky are different (Auger in the south and TA in the north hemisphere).

Full-sky UHECR observation with one single instrument from space-based should help disentangling this issue and give improved information about UHECR anisotropies.



# The aim of JEM-EUSO projects

JEM-EUSO (Joint Experiment Missions for Extreme Universe Space Observatory) develops the technique for the UHECR and neutrino detection by fluorescence and Cherenkov light of EAS from the Earth's orbit. The SPB (Super Pressure Balloon) experiment is a stratospheric pathfinder for K-EUSO and POEMMA orbital missions.



# Scientific objectives of the EUSO-SPB2 experiment

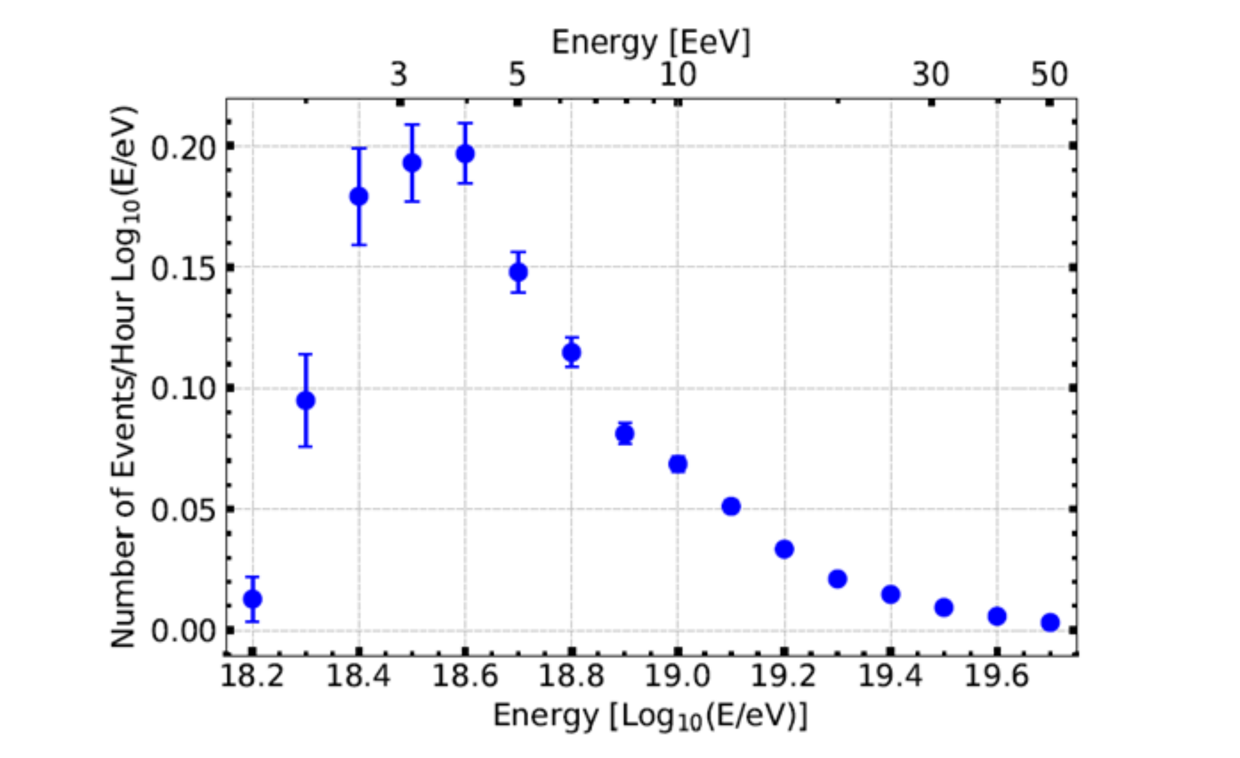
- The first observations of extensive air showers (EAS) using a fluorescence telescope from suborbital space.
- Detection of the Cherenkov light of EAS induced by high-energy cosmic rays.
- Measurement of the background for the detection of neutrino-induced ascending EAS.
- Search for neutrinos as a result of transient astrophysical events (for example, during the merger of binary neutron stars).

To solve these problems, the mission includes two instruments: fluorescence and Cherenkov telescopes.

# EUSO-SPB2 Fluorescence Telescope

The main objective of the Fluorescence Telescope of EUSO-SPB2 is to observe the first extensive air showers via the fluorescence technique from suborbital space.

Expected number of EAS events: 0.12±0.01 events/hour, or ~0.6 events per night

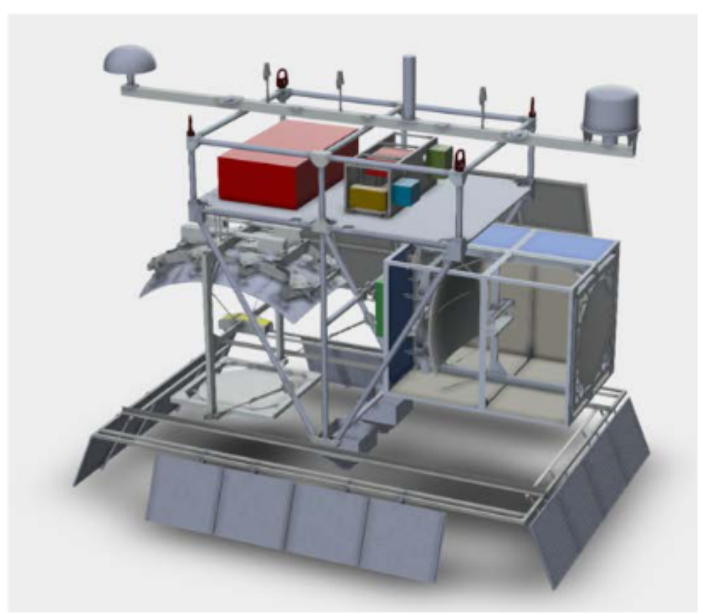


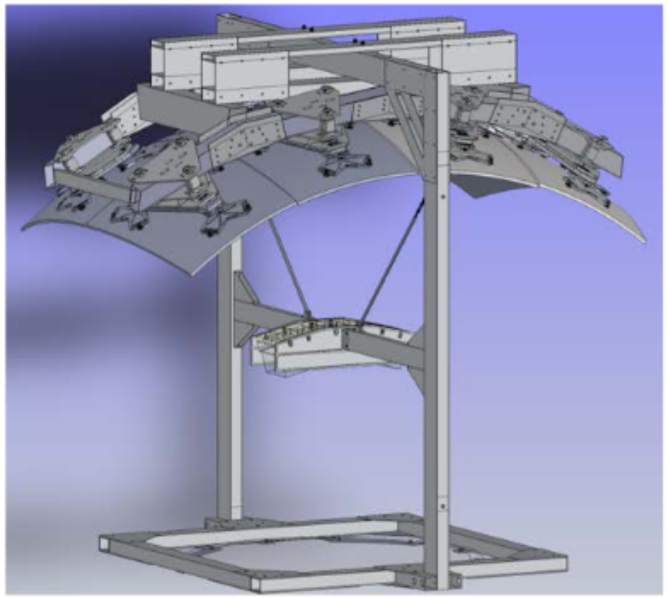

Expected number of events

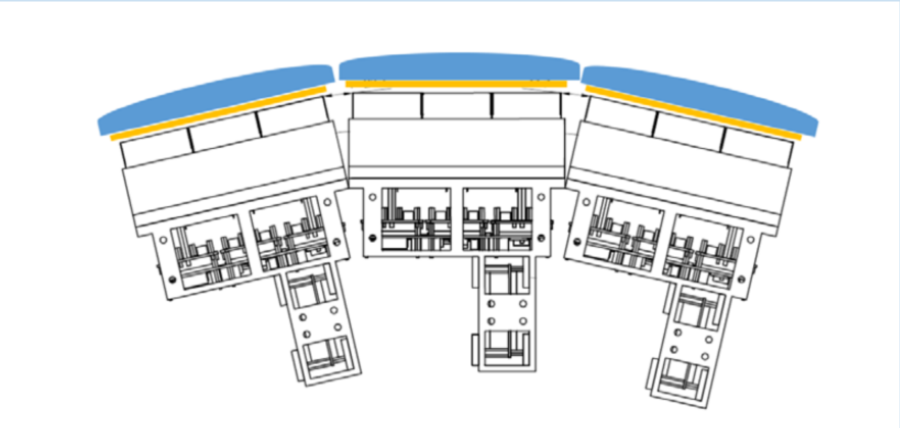
# EUSO-SPB2

Characteristics of the Fluorescence telescope:

- Altitude: 33 km
- Field of view: 37.4°×11.4°
- Aperture: 1 m
- Time resolution: 1 μs
- Number of modules/ channels: 3/ 6,912







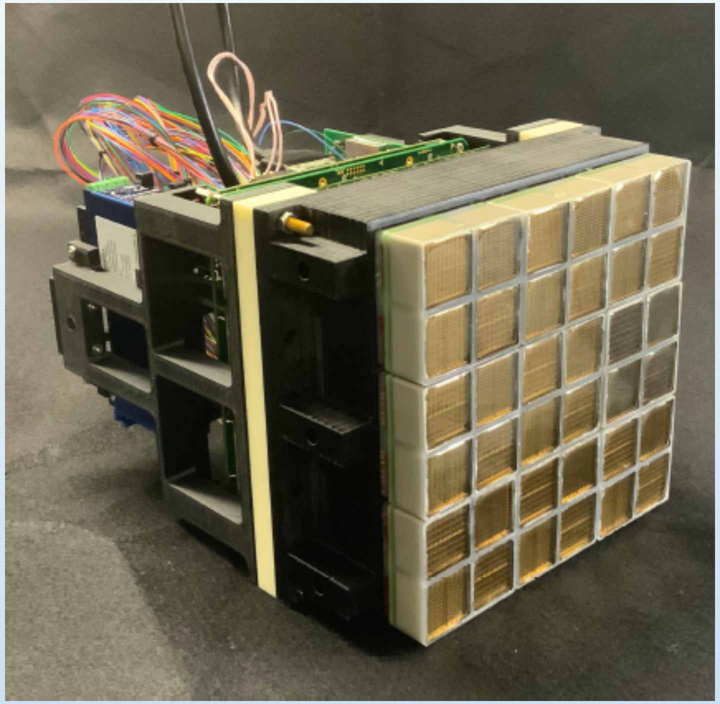
# Photodetector for EUSO-SPB2 and K-EUSO

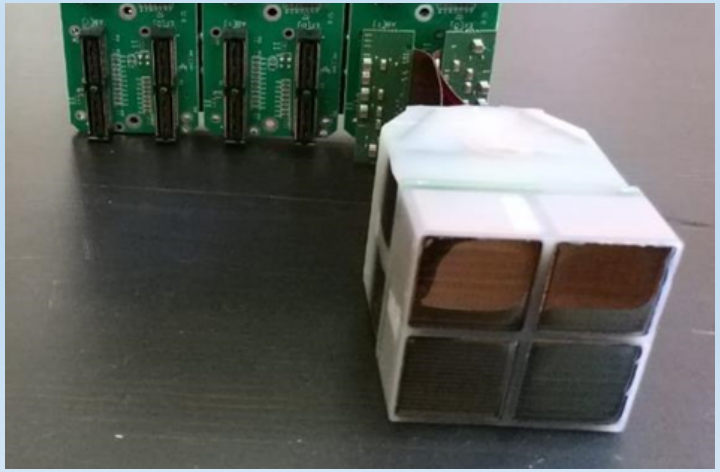
In the figure on the right: a photodetection module (PDM)

Each PDM consists of 9 elementary cells (EC-unit, bottom right figure). Each EC-unit contains a SPACIROC chip, the basis of which is a discriminator of single-photoelectronic pulses.

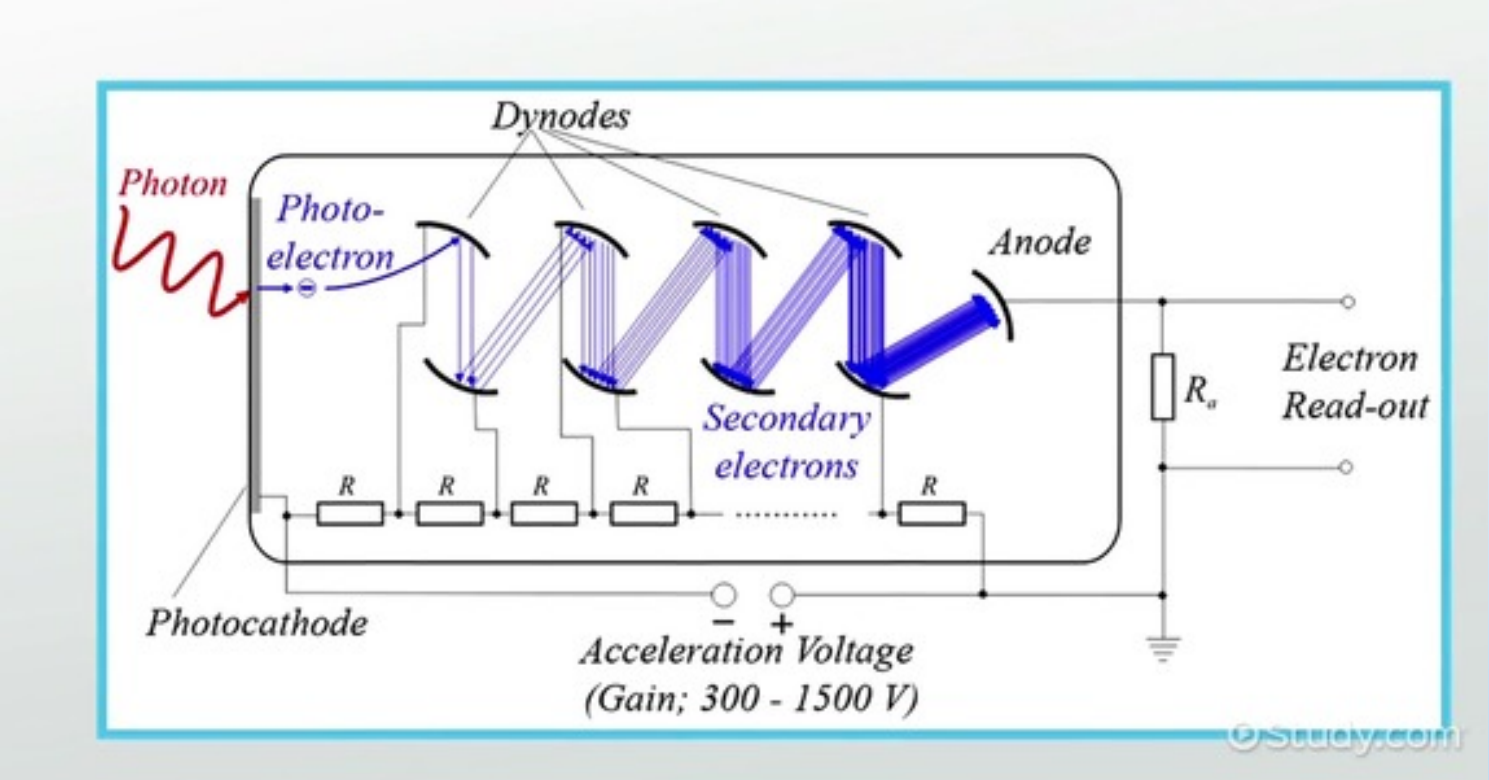
Each EC-unit consists of 4 HAMAMATSU R11265-103-M64 multi-anode photomultiplier tubes (MAPMTs), each has 64 channels (pixels).

Each PDM has 2304 channels of registration





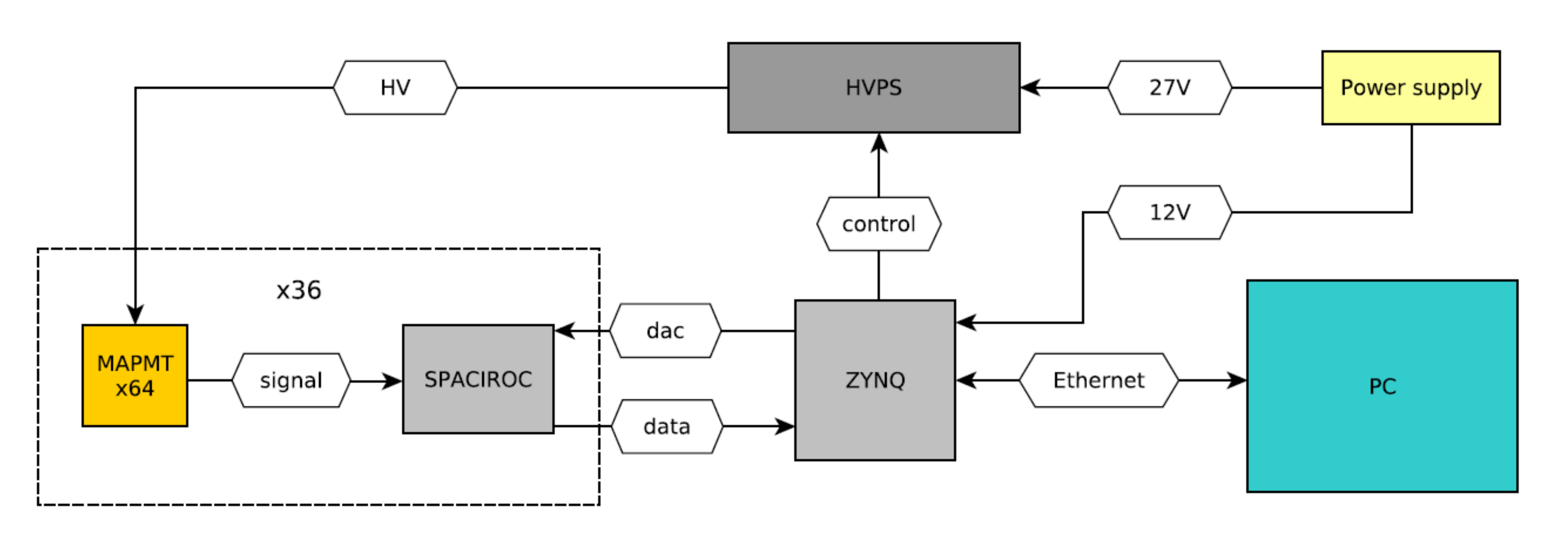
# Photomultiplier Tube (PMT)




The single-channel PMT scheme of work

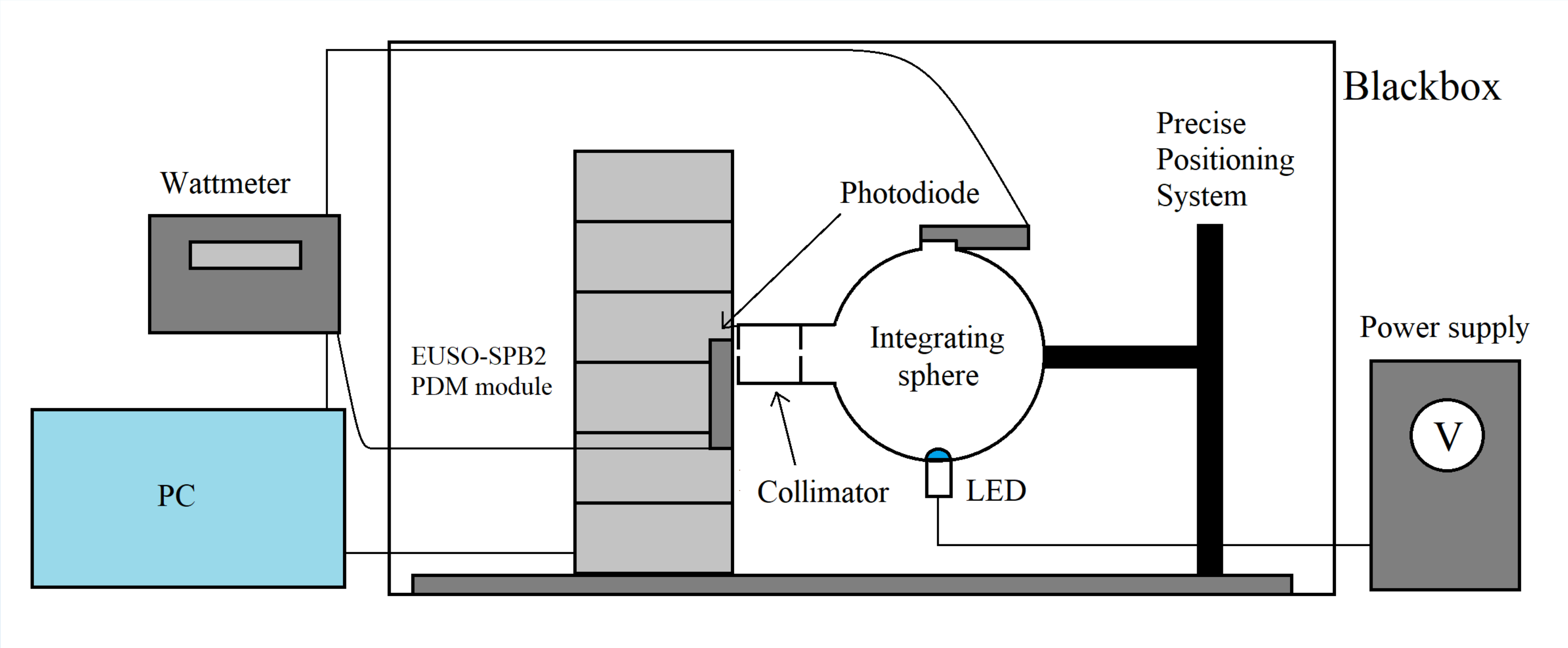
In the photo, the dynodes and the anode of the old single-channel PMT

# Diagram of the photodetector electronics




SPACIROC3 is a specialized chip designed to count photoelectronic pulses for a certain time. The basis of the chip is an amplitude discriminator, which provides the selection of single-photoelectronic pulses.

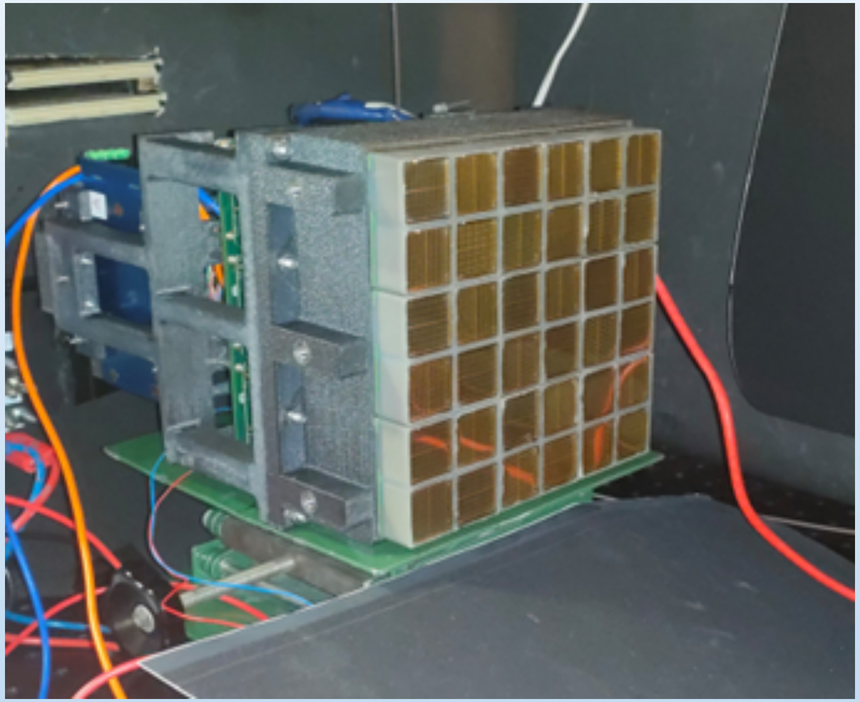
# Calibration scheme of EUSO-SPB2

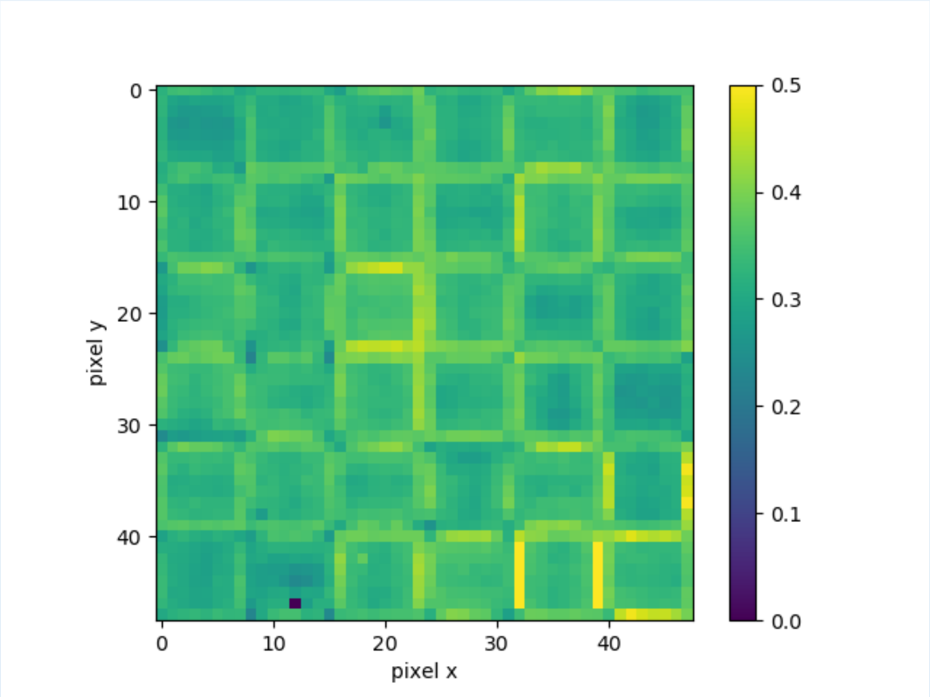



Scheme of the calibration process, with a collimator attached to the integrating sphere for single pixel illumination.

# PDM Integration

Three PDMs have been integrated. On the right – uniform illumination mode






| | | |
|---|---|---|
| EC48 | EC45 | EC58 |
| EC35 | EC47 | EC46 |
| EC50(inv) | EC43 | EC60 |

| | | |
|---|---|---|
| EC59 | EC63 | EC64 |
| EC57 | EC62 | EC53 |
| EC61 | EC49 | EC42 |

| | | |
|---|---|---|
| EC36 | EC54 | EC34 |
| EC55 | EC40 | EC52 |
| EC41 | EC39 | EC38 |

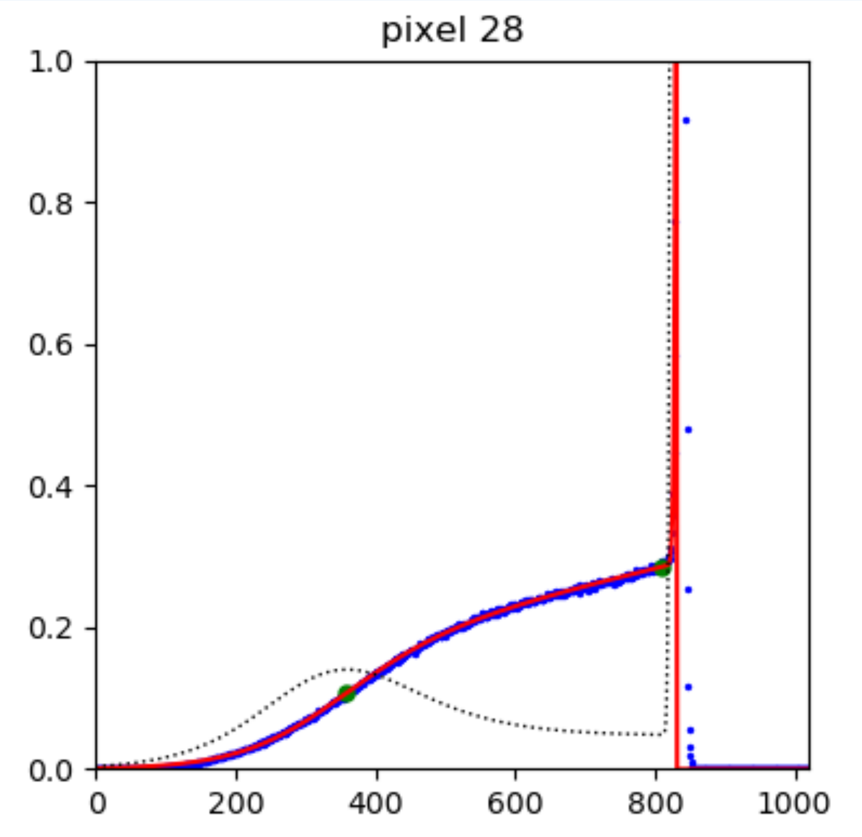
# S-curve measurements

The S-curve is measured to set the optimal thresholds on each pixel and to verify their performance.

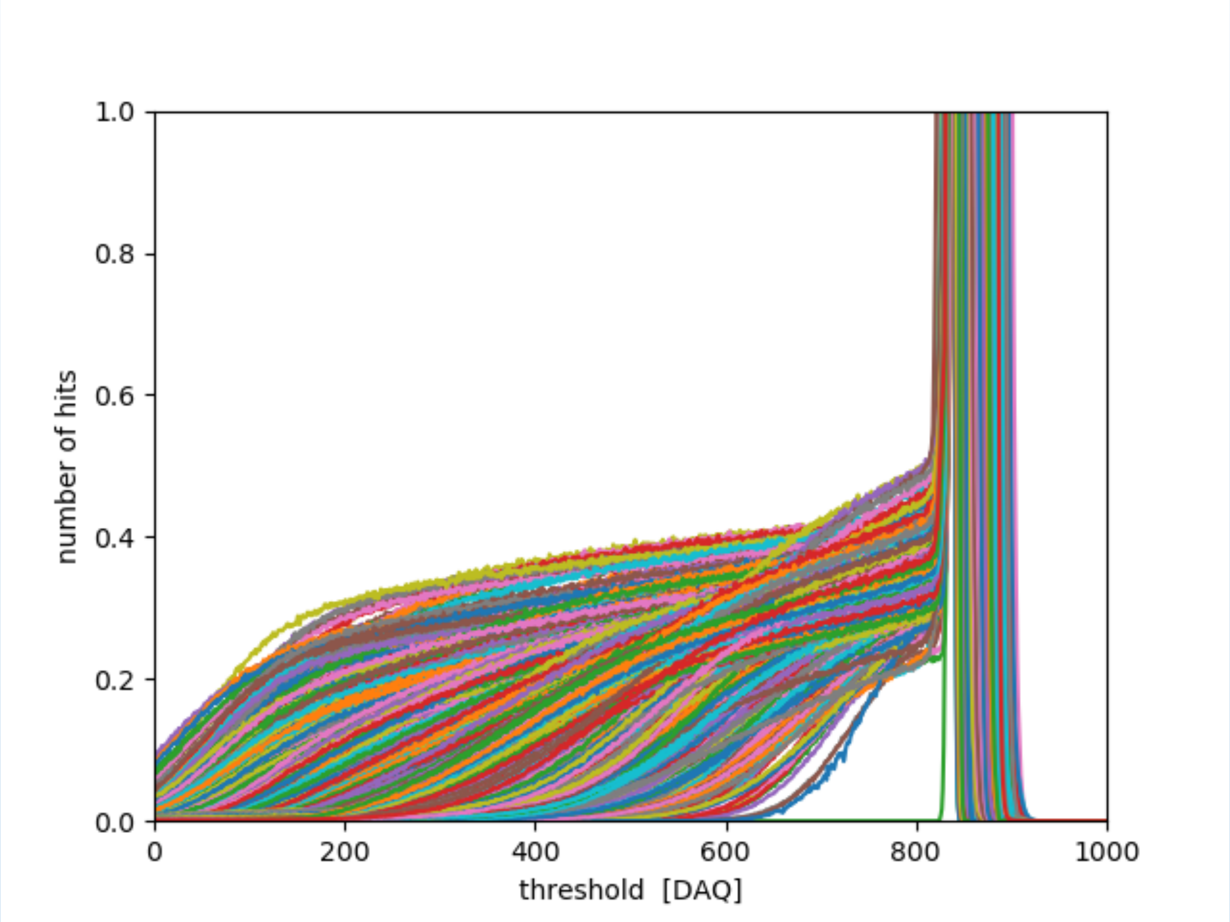
The threshold cuts off noise and counts pulses corresponding to the signal of 1 photo-electron.

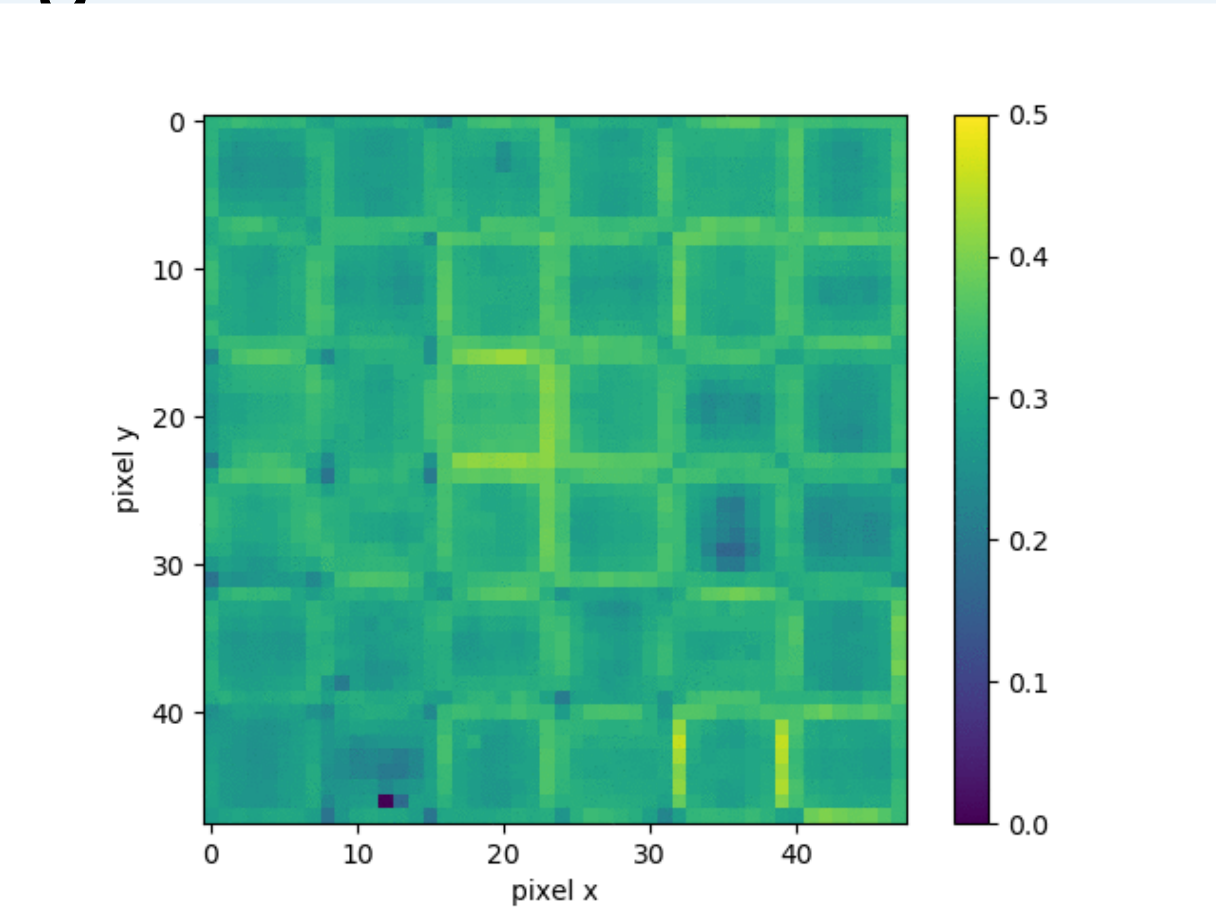
A 10-bit DAC allows to set the counting threshold at the level of each PMT, while a 7-bit DAC allows to shift the reference of the 10-bit DAC scale individually for each pixel.

In our case, we use a single 10-bit DAC threshold at 800, after adjusting all pedestals with the use of the 7-bit DAC pixel by pixel.



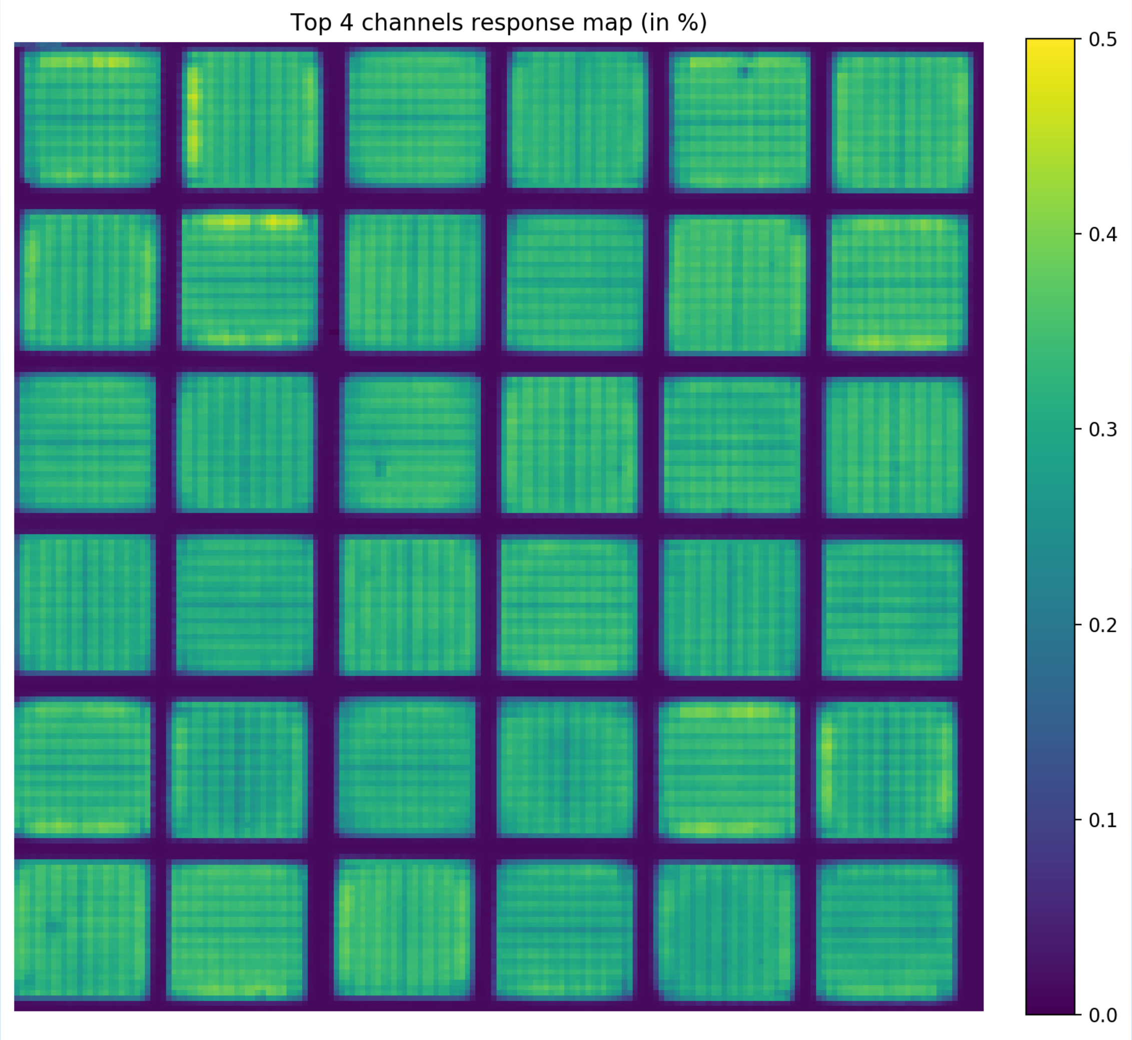
# Alignment of s-curves after individual 7-bit DAC setting

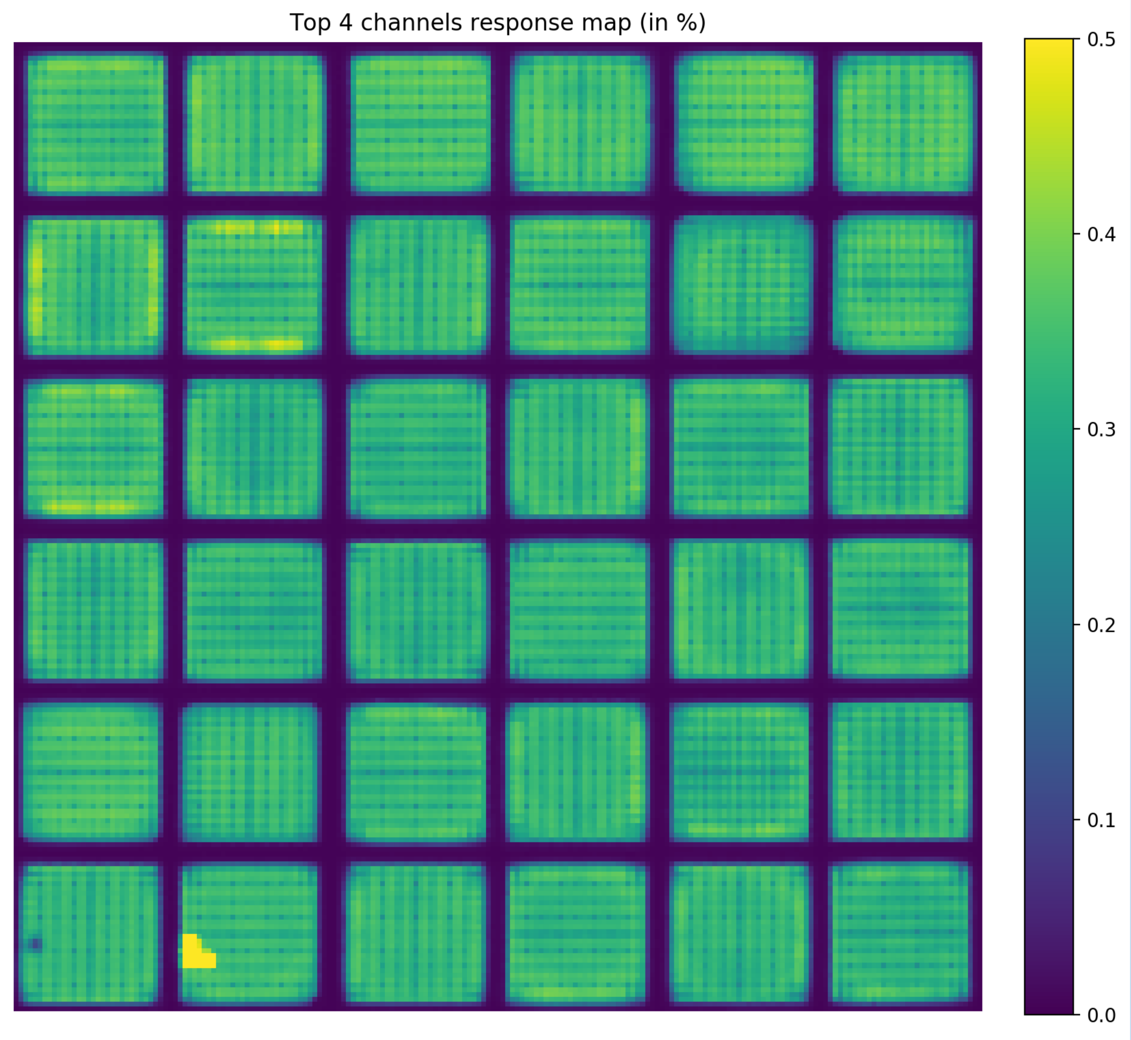



After setting the individual thresholds, you can see that in DAC10 mode, the pedestals of all pixels begin almost simultaneously

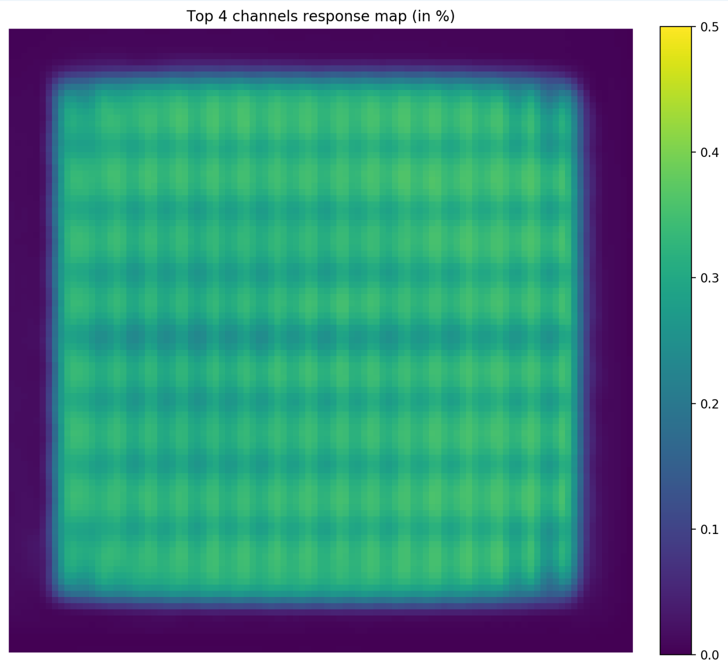
# Example of a full PDM scan

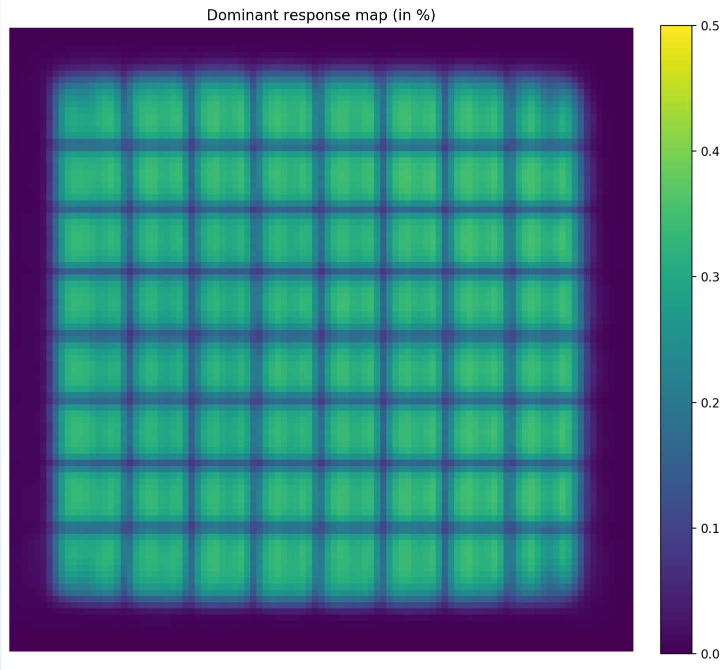



PDM3 and PDM4, wavelength 375nm, resolution is 200x200 pixels

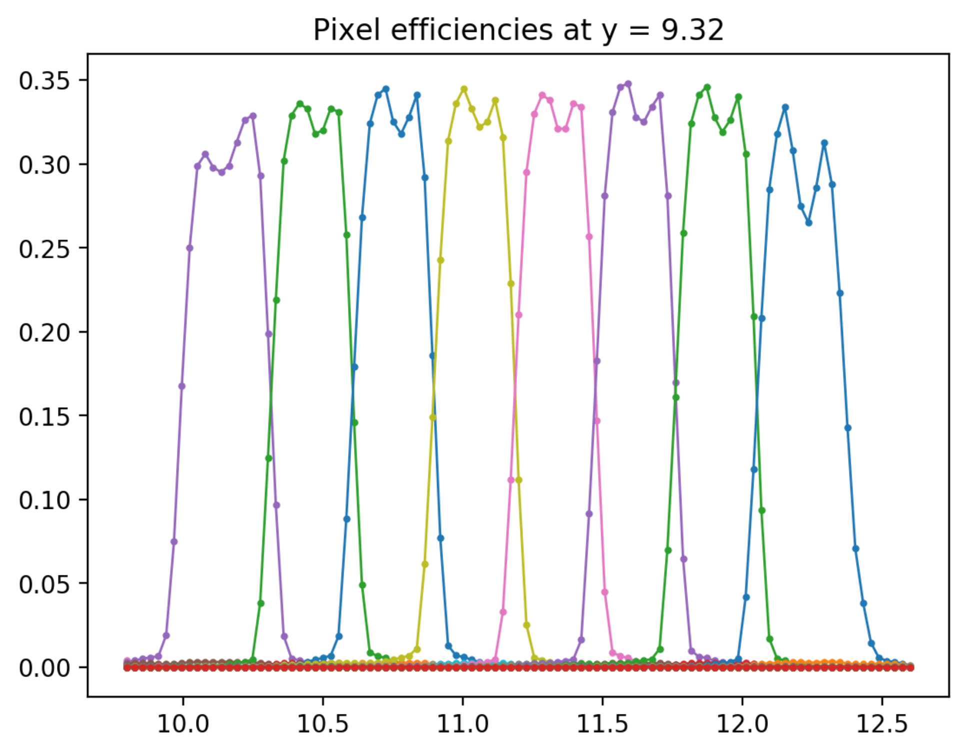
# Partial PDM Scan

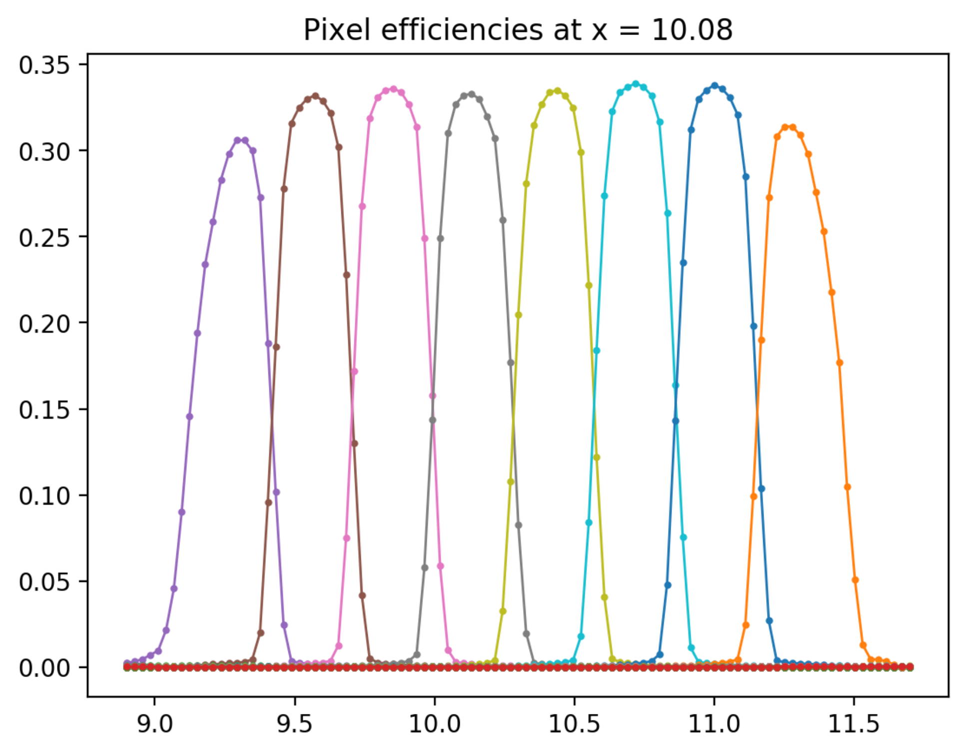



Left: top-4 channel response map (for each position, we sum the photon count of the 4 brightest pixels to derive the total detection efficiency at that position). Right: dominant response map (photon count rate of the brightest pixel only). The second figure reveals that border pixels are larger than central ones – causing “border effects” in full illumination mode (PMT22 of PDM2, λ = 405nm, 100 x 100 resolution)

# Compare pixel profiles when scanning



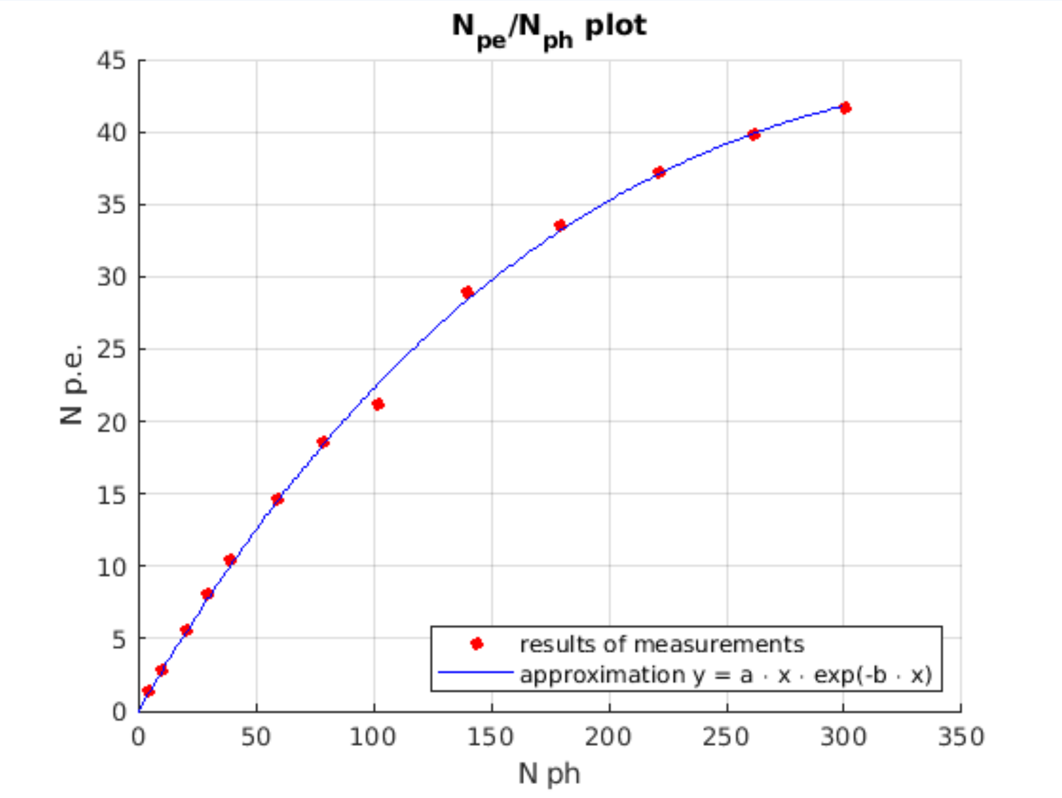

The structure of the pixels depends on the direction of scanning (vertically or horizontally)

In the center, the efficiency is less!

PMT22 of PDM2, wavelength λ = 405nm

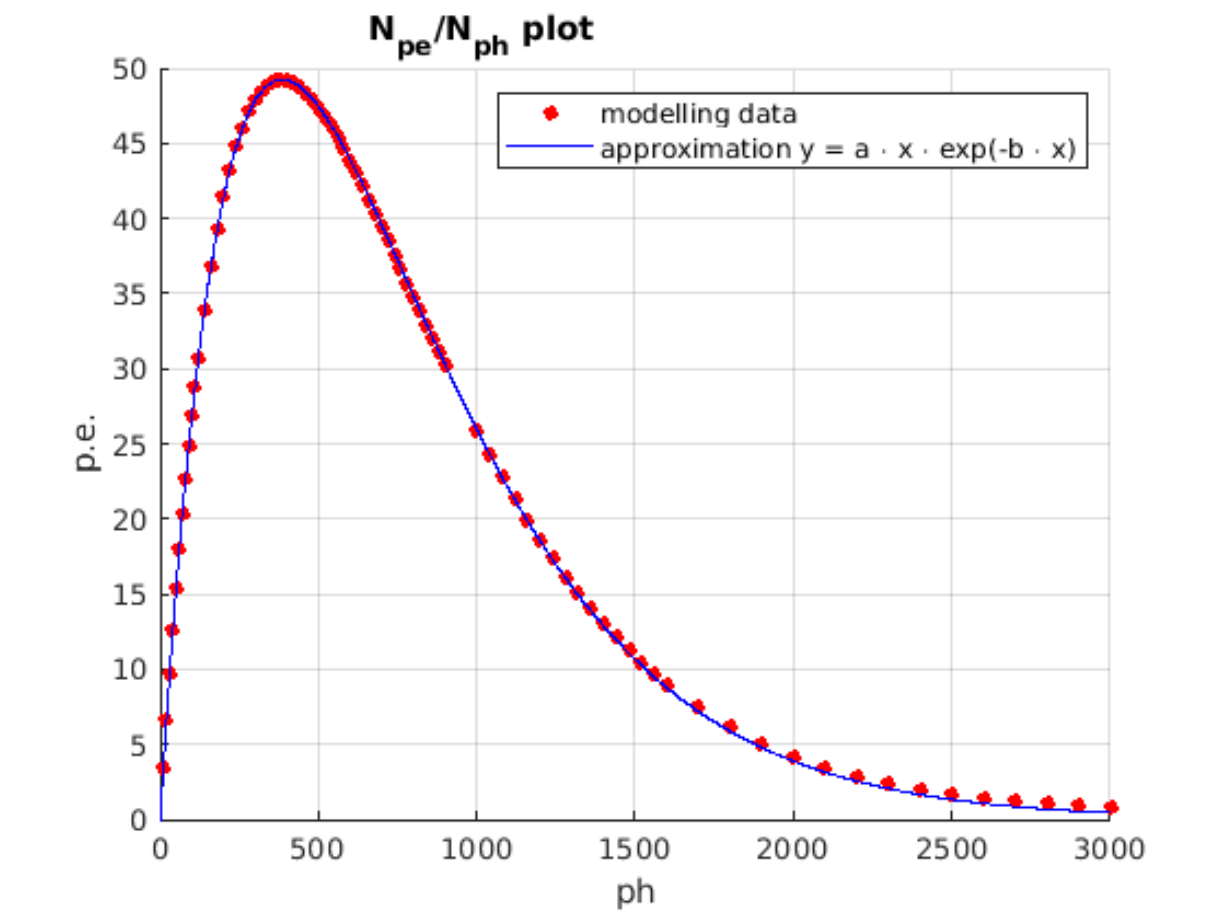
# Study of the effect of overlapping impulses (Pile-up)

For high light intensity, “pile-up” occurs when the time interval between consecutive photoelectrons is smaller than the time resolution of the ASIC (a few ns). The number of counts thus saturates and eventually decreases as the photon rate increases (more and more photons being missed). The expected counting rate is $\varepsilon N \times \exp(-\varepsilon N \delta t)$, where $N$ is the incoming photon rate, $\varepsilon$ is the detection efficiency and $\delta t$ is the double pulse resolution (dead time).



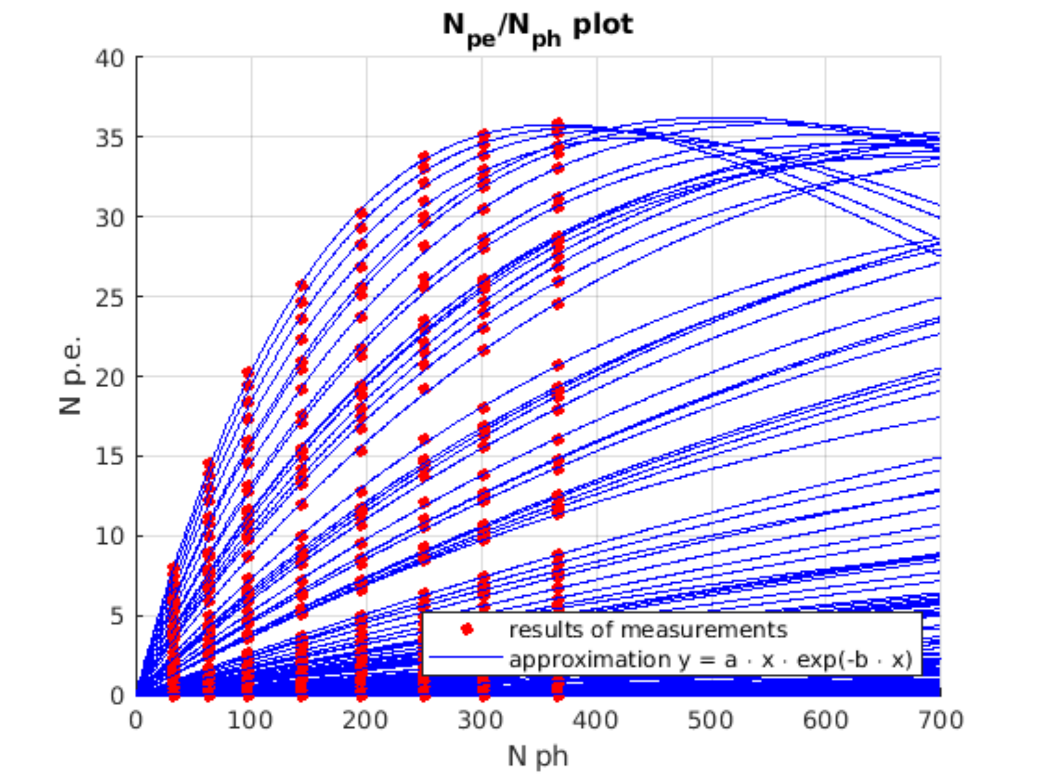

Example of a pile-up curved, measured for one pixel and fitted with $\delta t$ = 8.3 ns (LED wavelength 405 nm).

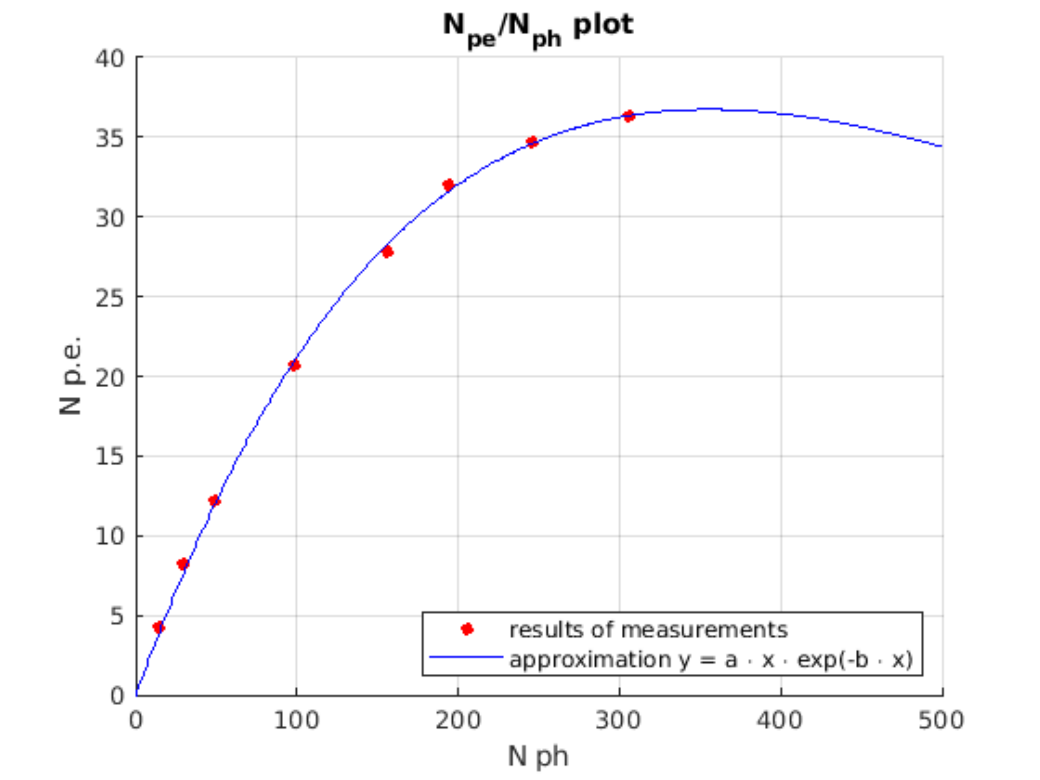
# Pile-up modelling




Simulated pile-up curve for $\delta t$ = 7.5 ns (assuming a poissonian source of photons).

# “Dead time” measurements from pile-up




Pile-up for several pixels is equal to pile-up for one pixel. The measurements with several pixel illumination and one pixel illumination were made. From both cases we can obtain the dead time for pixel(28, 45), in the first case τ = 10.3 ns and in the second τ = 10.1 ns. In the first case tau for all pixels are from 10 to 12 ns.

# The planned activities:

- Additional processing and analysis of calibration measurements of EUSO-SPB2 photodetection modules
- Estimation of EUSO-SPB2 detection thresholds and energy-dependent exposure, taking into account the obtained parameters of the photodetection modules.

# Conclusions

EUSO-SPB2 photodetector modules have been calibrated with high precision in different modes. Detailed information about the size and efficiency of each pixel will allow the analyses of extensive air showers and other events detected during the mission, which is expected to be launched in spring 2023 from Wanaka (NZ). The calibration will help us register the luminosity of EAS with higher precision.

The first observation of EAS via the fluorescence technique from suborbital space will confirm this method and open the way to orbital projects K-EUSO and POEMMA. The fluorescence detection from space will produce a huge statistics and reveal the mystery of UHECR.

Thank you for your attention