FluChe
Fluorescence and Cherenkov light detection with SiPM for space applications

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Detection of Ultra High Energy Cosmic Rays (E>10^{19} eV) looking downward at the dark earth atmosphere

- There were only a few balloon flights, mostly technological and for NSB diffused measurements:
  BABY (3 flights from Trapani-Milo ASI base), EUSO-Balloon 1st flight (EUSO/CNES), EUSO-SPB1 (EUSO/NASA)

- Missions proposed in the past : EUSO (Extreme Universe Space Observatory), OWL (Orbiting Wide-angle Light-collectors), KLIPVE (Russian)

- Some path-finder missions proposed on going : MINI-EUSO (ASI/ROSCOSMOS), K-EUSO (ROSCOSMOS/EUSO)

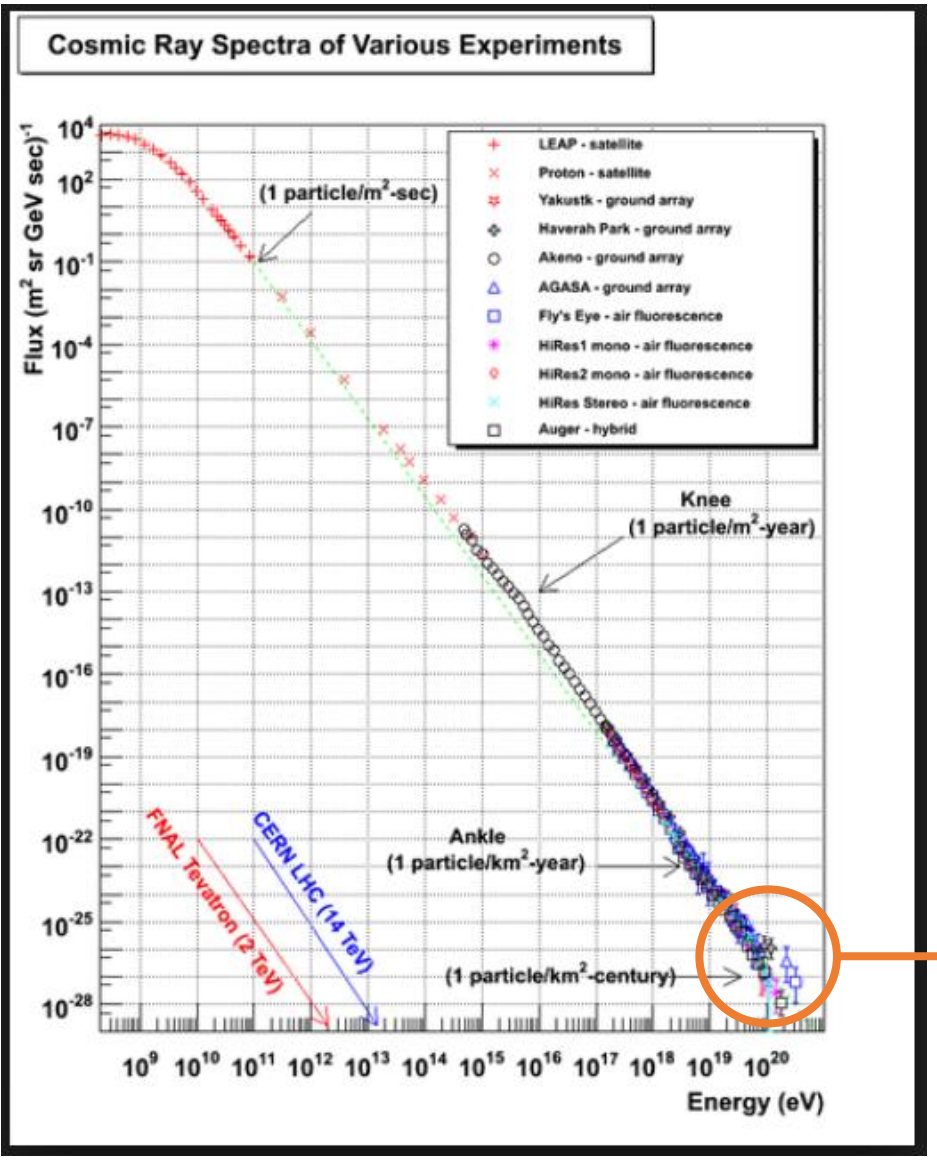
- Missions proposed in the last years :JEM-EUSO, POEMMA (Probe Of Extreme Multi-Messenger Astrophysics)

and
a very intriguing exploratory mission approved by NASA is:

EUSO-SPB2 (southern sky)

SCIENTIFIC RATIONAL : UHECR

The origin(s) of cosmic rays remains a challenging enigma of particle astrophysics.



The spectral shape can be described by a broken power law with three major breaks:

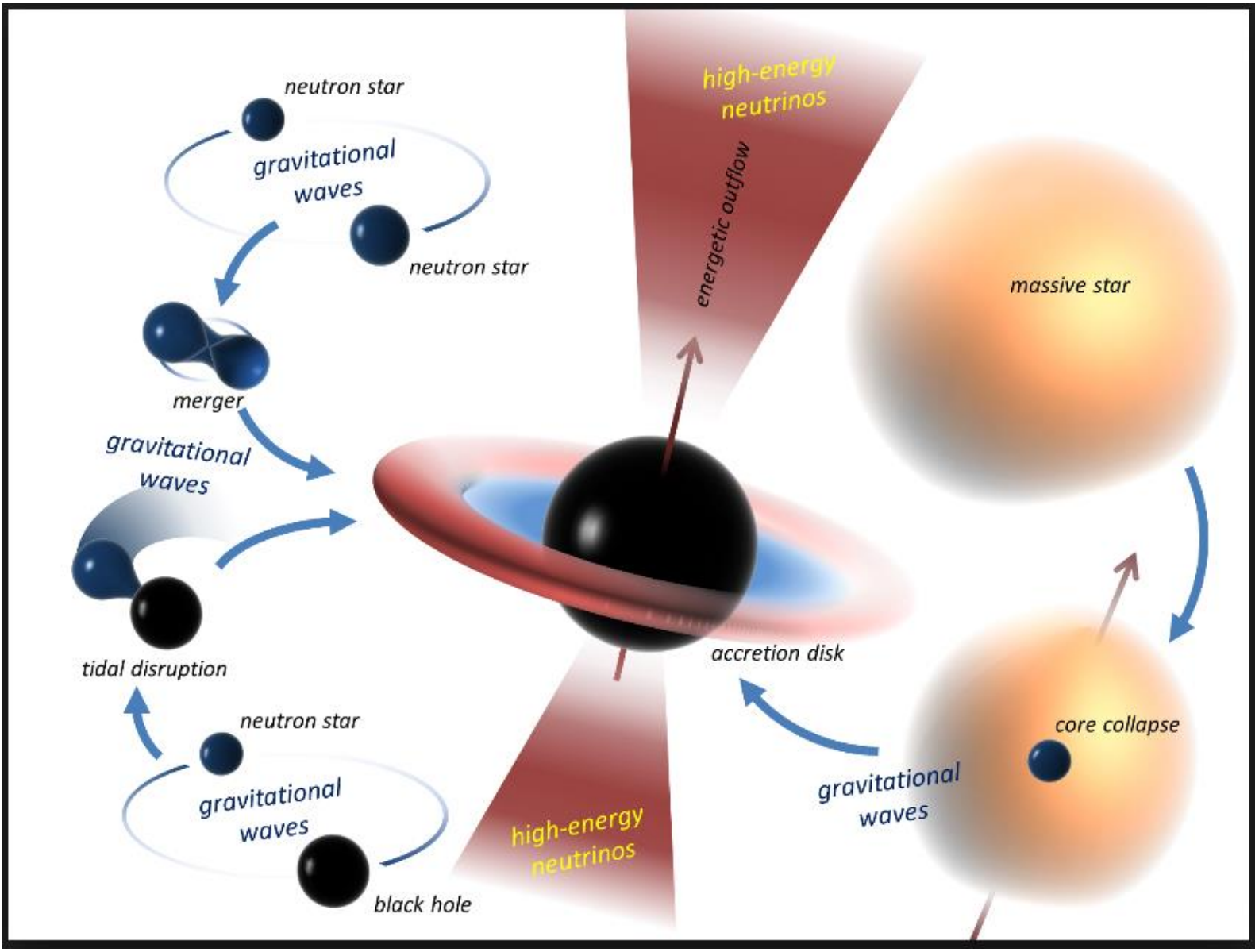
- the steepening of the spectrum dubbed the "knee" at $E \approx 4\ 10^{15}$ eV
- a pronounced hardening of the spectrum at $E \approx 4\ 10^{18}$ eV , the so-called "ankle"
- the high frequency cutoff at $E \approx 4\ 10^{19}$ eV

The variations of the spectral index in the energy spectrum reflect various aspects of cosmic ray production, source distribution, and propagation.

The simplest interpretation of the ankle is that above $4\ 10^{19}$ eV a new population emerges which dominates the more steeply falling Galactic population of heavy nuclei. The extragalactic component can be dominated either by protons or heavies ,with the highest energy particles being subject to photopion production and photodisintegration, respectively. This is the mechanism behind the well-known Greisen-Zatsepin-Kuz'min (GZK) cutoff.

Ultra High Energy Cosmic Rays RoI
Open question: arrival direction anisotropy

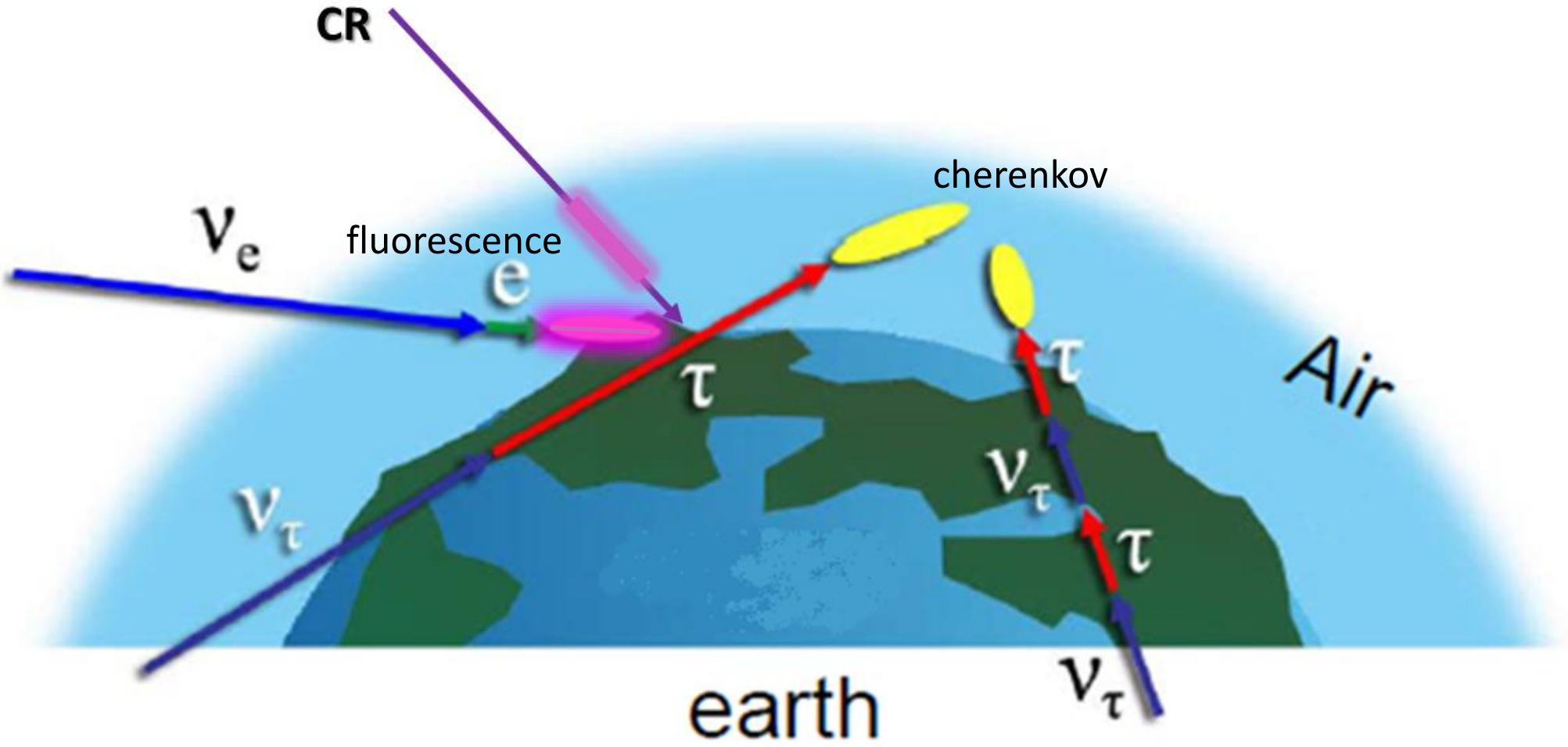
SCIENTIFIC RATIONAL : NEUTRINOS



NEUTRINO ASTRONOMY
with
Particle-physics related issues:

- Increase of the neutrino-nucleon cross section due to physics beyond the Standard Model
- Formation of mini-black holes in neutrino-nucleon scattering in theories with large extra- dimensions
- Neutrinos oscillations and τ neutrino physics

THE OBSERVABLES



THE OBSERVABLES

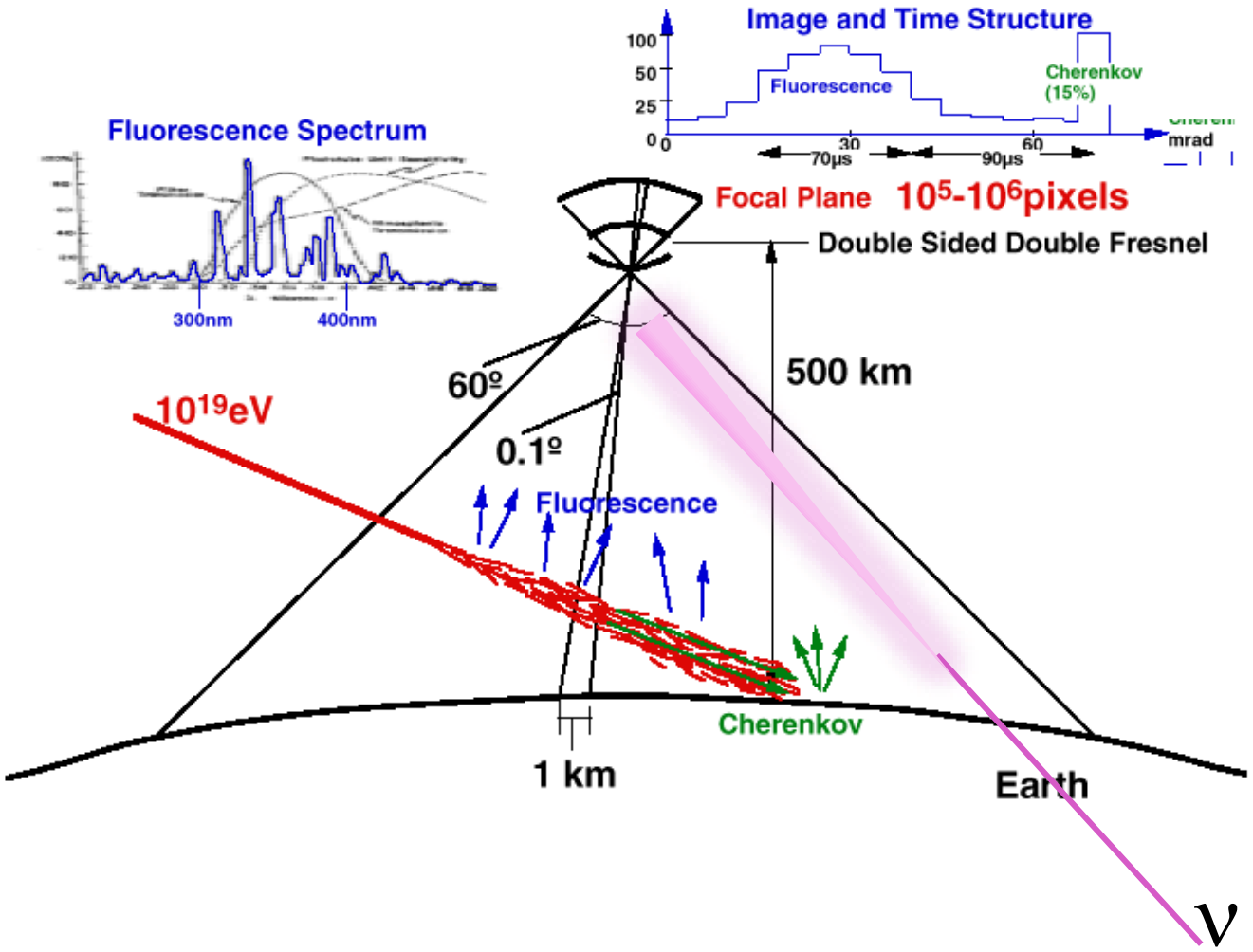
A gigantic detector at planetary scale is required to catch particles with flux values at the level of 1 particle/100 km^2/year (EECR $>10^{20}$ eV)

or

with very low interaction cross section (high energy neutrinos)

A natural detector is represented by the Earth atmosphere

THE OBSERVABLES



The measurement of the height X_{max}, where the maximum shower size N_{max} is present, is based on the Cherenkov light, isotropically diffuse by the land or sea surface: the time difference between the arrival of the fluorescence light from the primary track and the back reflected Cherenkov flash localizes the height of the event.

#pe ∝ shower size

UV integral ∝ EECR energy

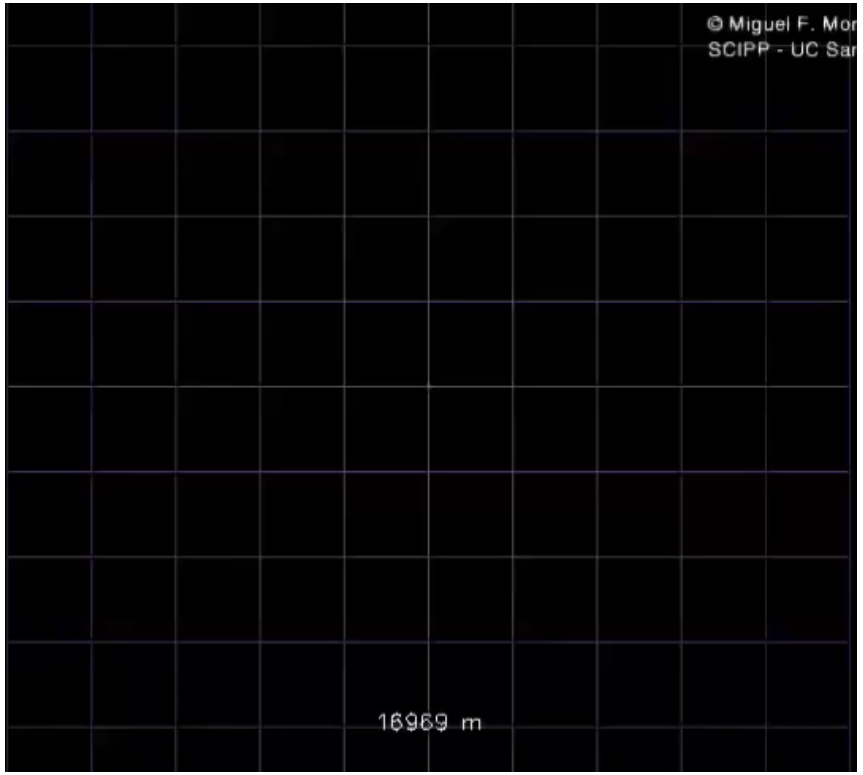
N_{max} ∝ EECR energy

Showers initiated very deep in the atmosphere (low X_{max}) indicate an origin by <u>neutrinos</u> because of neutrino-air nuclei interaction cross section hundreds times lower than the cross sections for <u>protons</u>, <u>nuclei</u>, or <u>photons</u>.

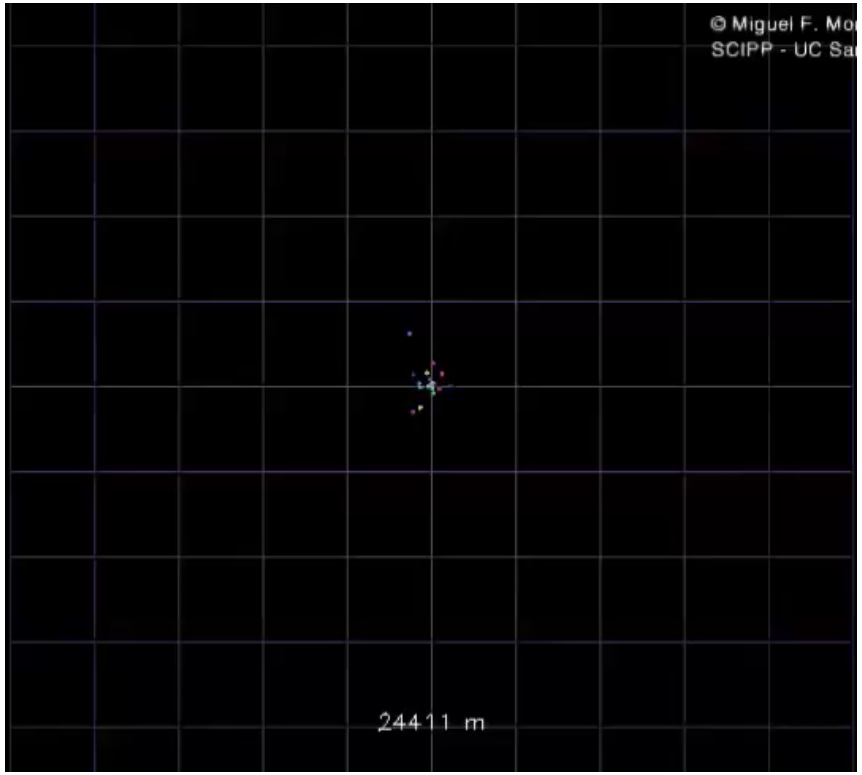
X_{max} ⇔ EECR nature

THE OBSERVABLES

electrons and gammas muons pions and kaons protons and neutrons others, nuclear fragments



gamma shower



proton shower

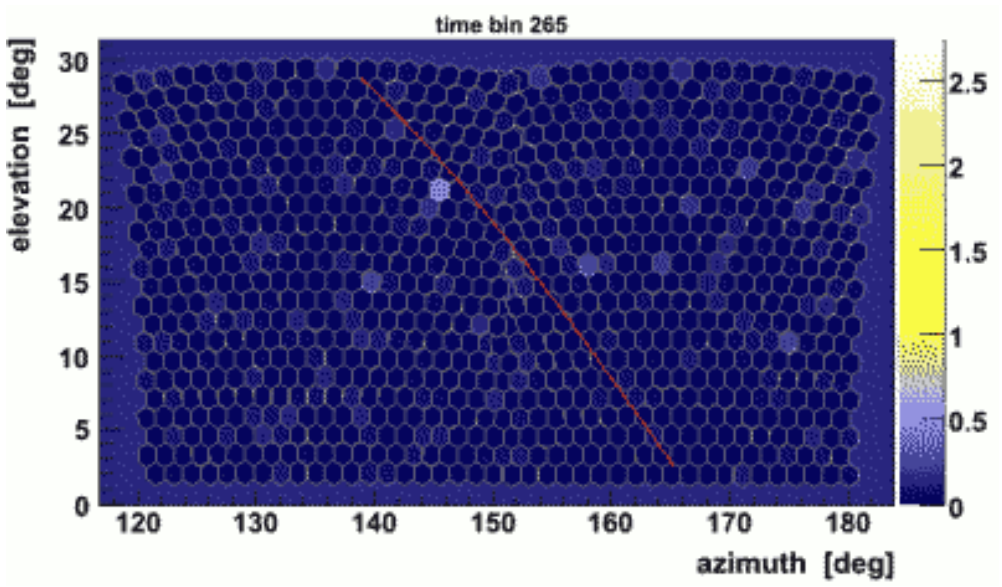
Particles component of shower

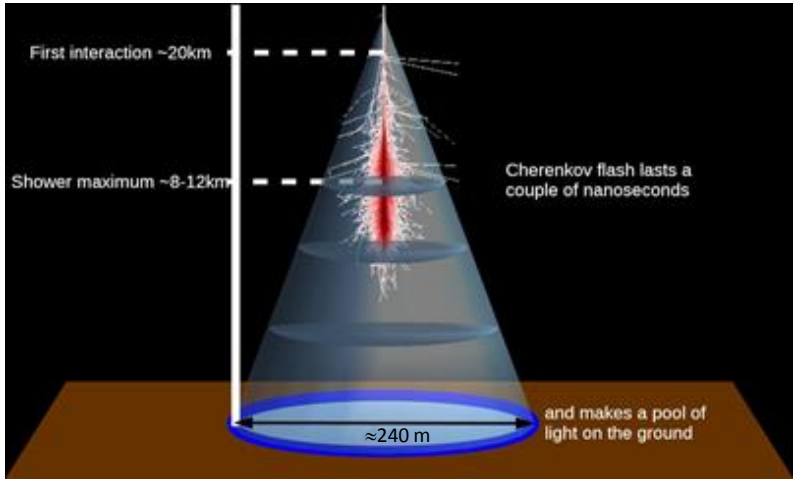
Fluorescence light emitted isotropically by secondary charged particles

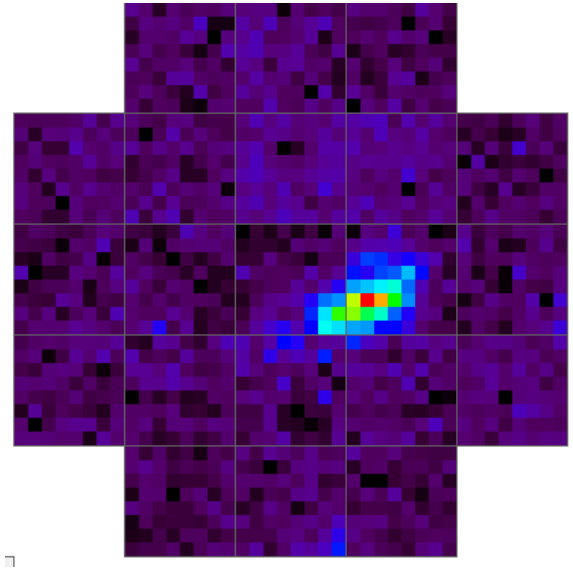
while

Cherenkov light emitted in a beamed cone by charged particles ($E_{th\_e}^{\pm}$ > 20MeV in air)

THE OBSERVABLES







Fluorescence track progression lasts tens of microseconds

Cherenkov flash lasts few nanoseconds

considerably different time scale

THE DETECTION : BASIC REQUIREMENTS

- **<u>optical system</u> with large collecting area (because of the faint fluorescence signal) and wide equivalent field of view covering a sizable half opening angle around the local Nadir (to reach geometrical factor of 10^6 km^2 sr)**

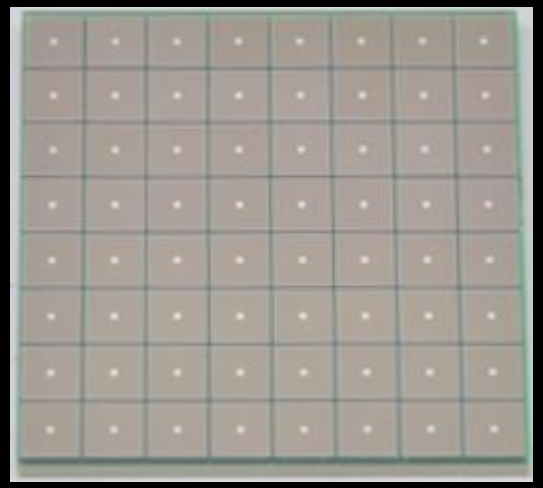
- **<u>focal plane detector</u> with high segmentation (single photon counting and high pixelization), high resolving time (~ 10 ns), weight and power contained**

- **<u>trigger and read-out electronics</u> prompt, simple, modular, capable to handle hundreds of thousands of channels, and comprehensive of an efficient on-board image processor acting as a trigger.**

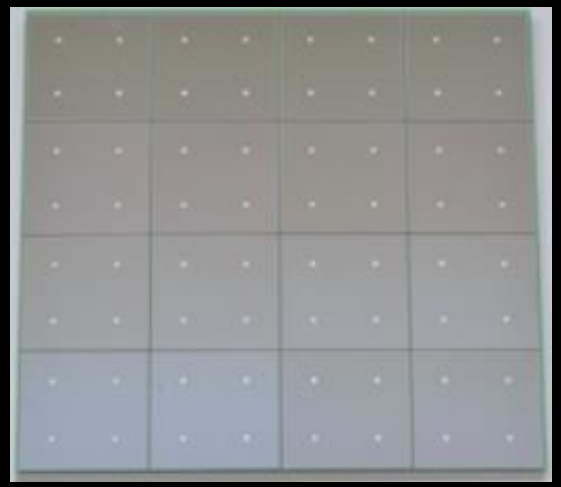
THE DETECTION : SiPM

16 pixels
2mm x 2mm

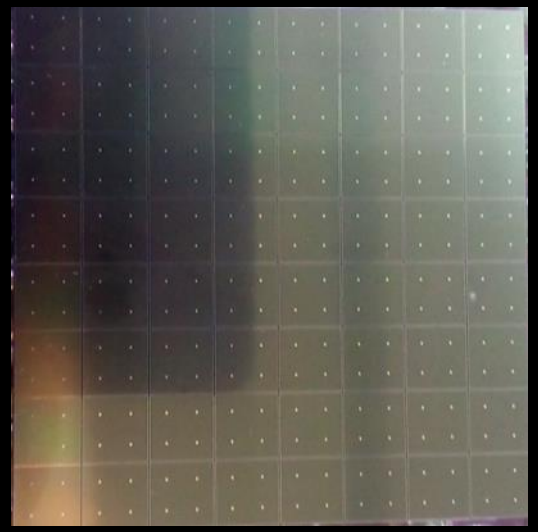
16 pixels
3mm x 3mm



64 pixels
3mm x 3mm



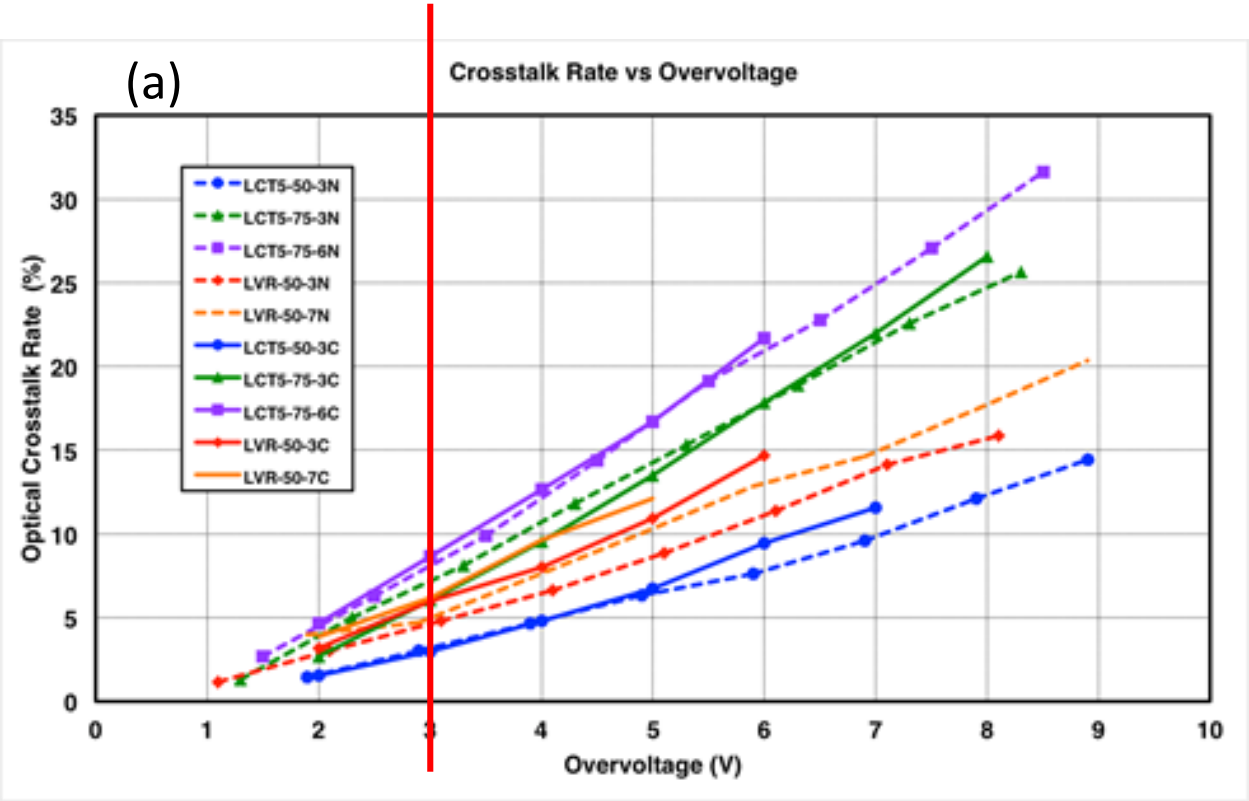
16 pixels
6mm x 6mm

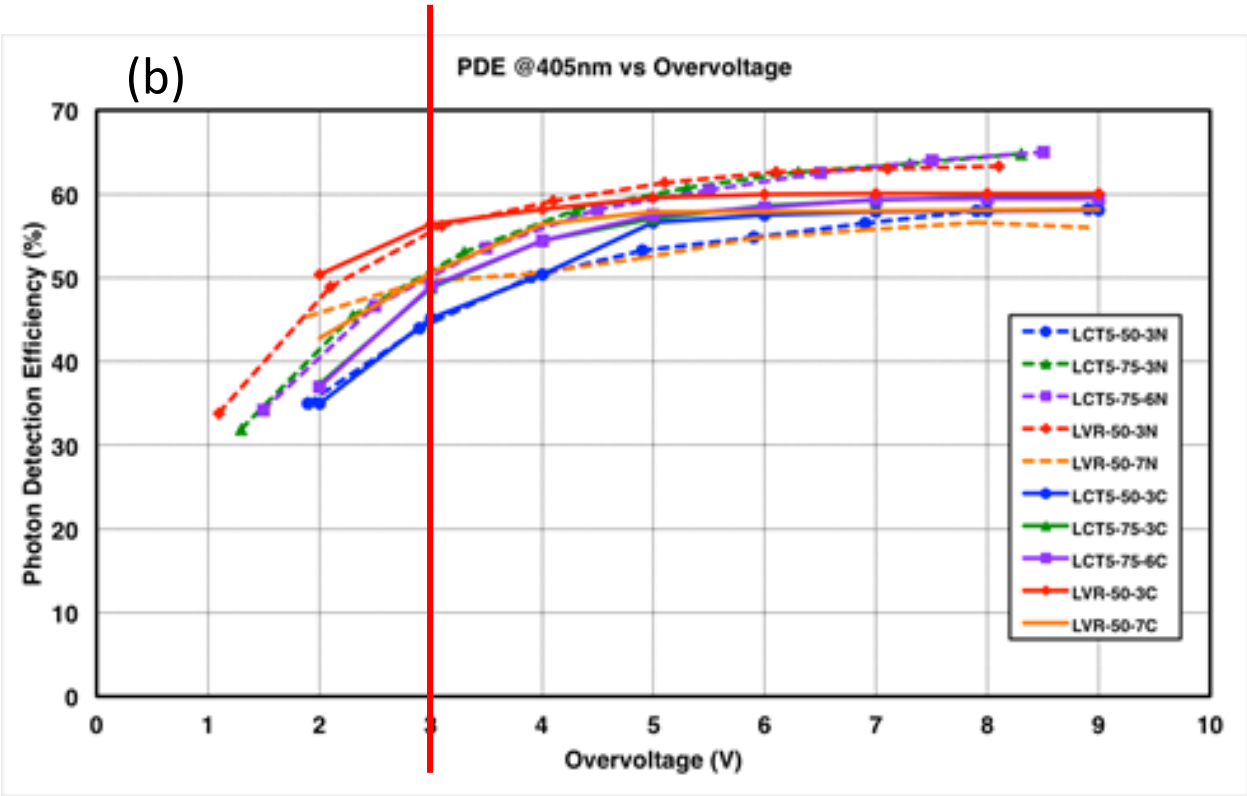


64 pixels
7mm x 7mm
(ASTRI)

The 4-side buttable structure allows arraying multiple elements in two dimensions at narrow intervals.

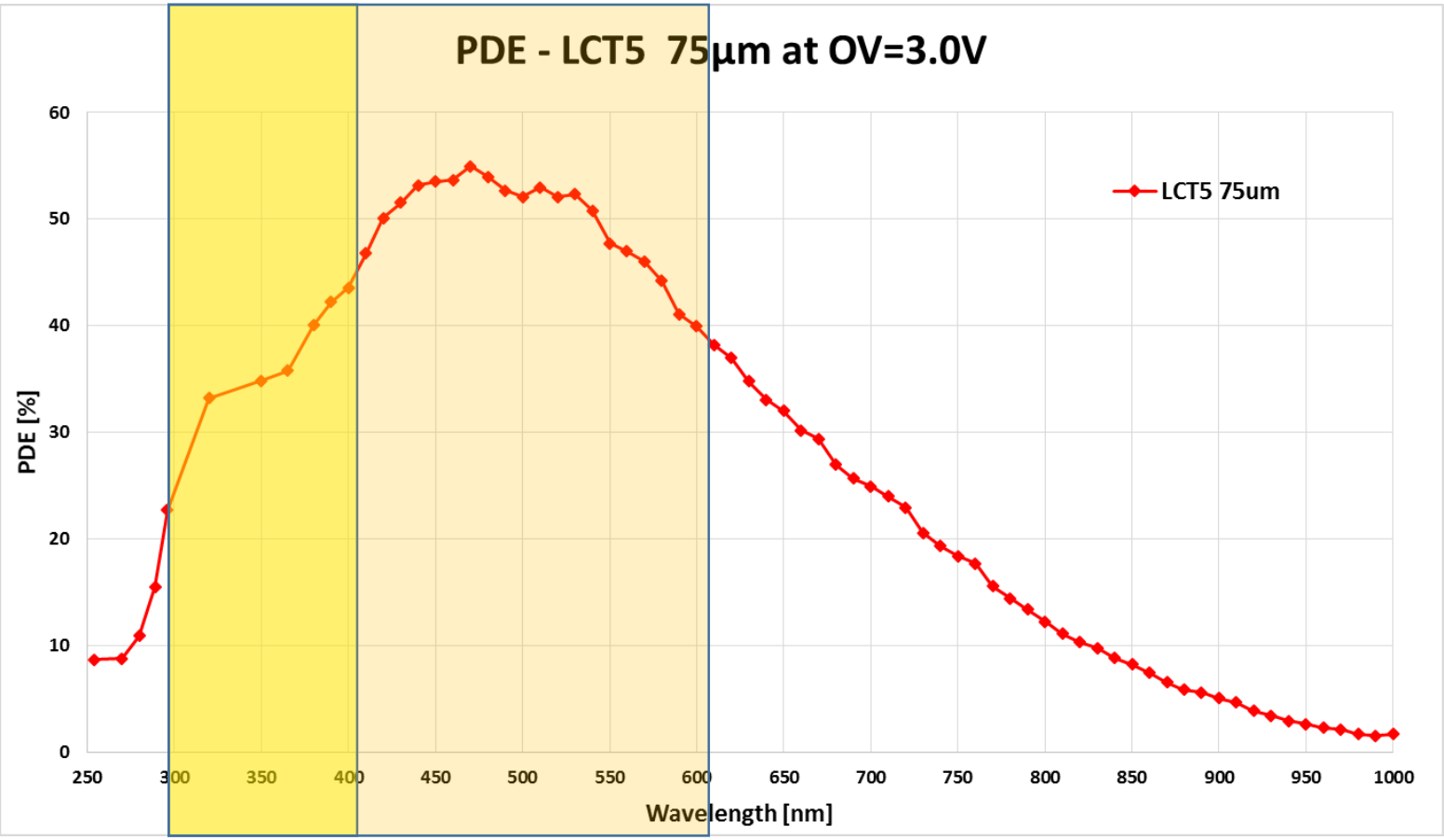
THE DETECTION : SiPM





Comparison of (a) the optical crosstalk and (b) photon detection efficiency versus SiPM overvoltage for a variety of SiPM technologies, pixel sizes (3, 6 and 7 mm) and cell sizes (50 and 75 µm), measured by groups in Nagoya, Japan (dashed lines) and Catania, Italy (solid lines).

THE DETECTION : SiPM

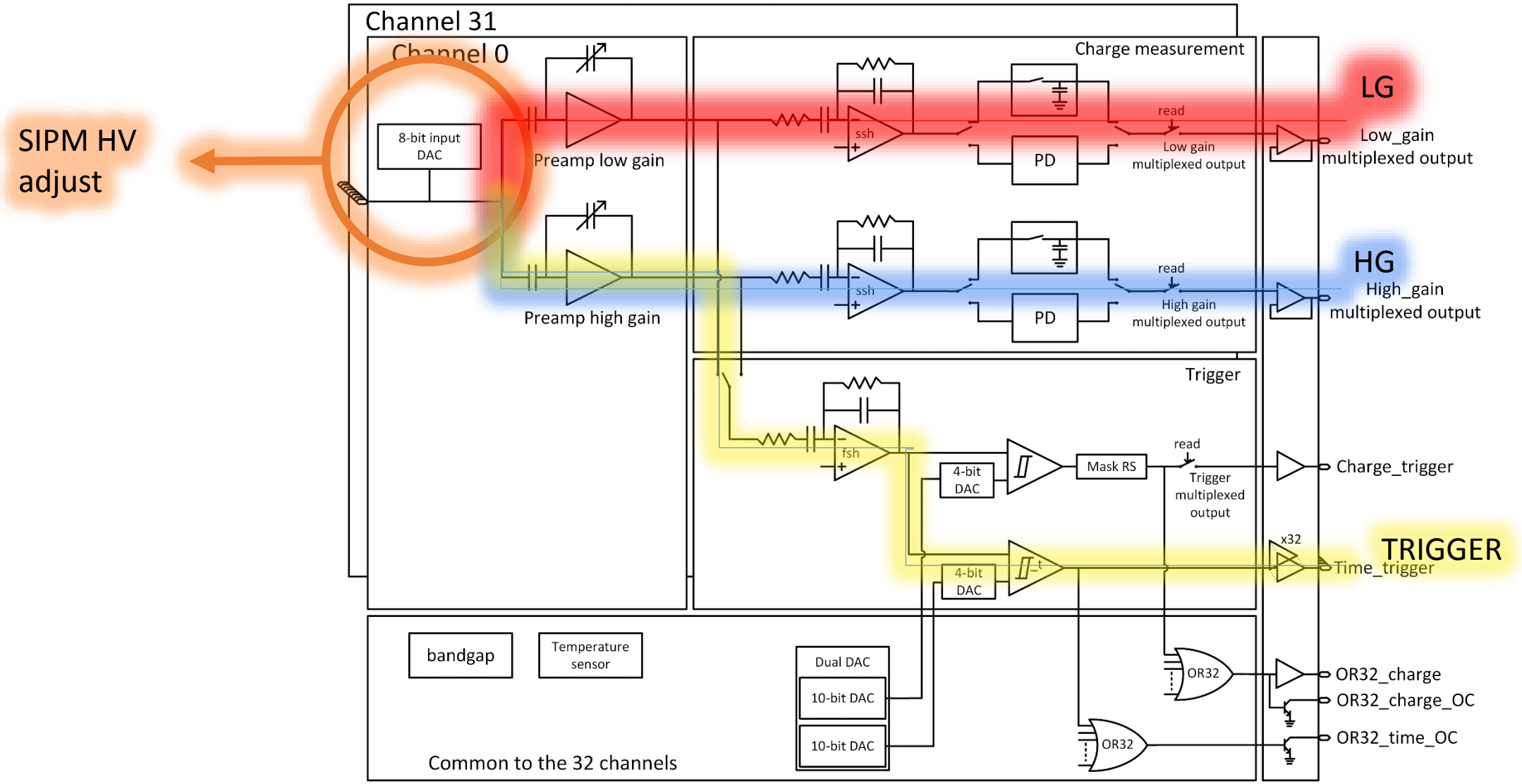


Fluorescence (300 ÷ 400 nm) : PDE ≈ 35% Cherenkov (300 ÷600) nm : PDE ≈ 40%

THE DETECTION : FRONT-END

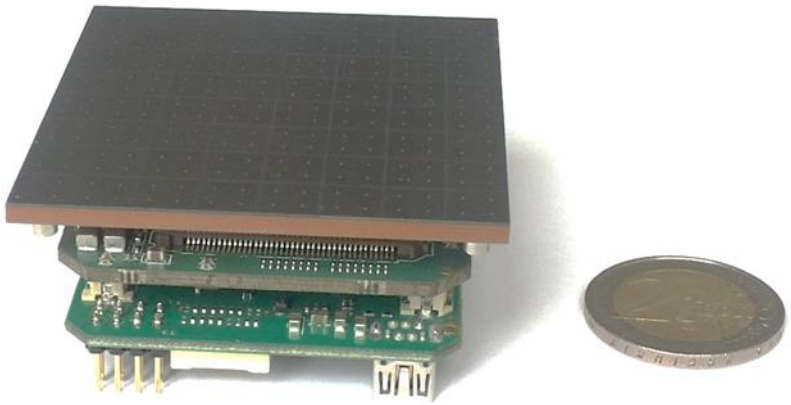
Detector Read-Out	SiPM, SiPM array
Number of Channel	32
Signal Polarity	Positive
Sensitivity	Trigger on 1/3 photo-electron
Timing Resolution	better than 100ps RMS on single photo-electron
Dynamic Range	0-400 pC i.e 2500 photo-electrons @ 10^6 SiPM gain
Packaging & Dimension	• TQFP 160 28x28mm • TFBGA 353 12x12mm
Power Consumption	225 mW when all stages on - supply voltage 3.3V
Inputs	32 voltage inputs with independant SiPM HV adjustments
Outputs	• 32 trigger outputs • 2 multiplexed charge output • 2 ASIC trigger output (Trigger OR)
Internal Programmable Features	• 32 HV adjustment for SiPM (32*8bits) • Trigger Threshold Adjustment (10bits) • Channel by channel gain tuning • 32 Trigger Masks • Trigger Latch • Internal temperature sensor

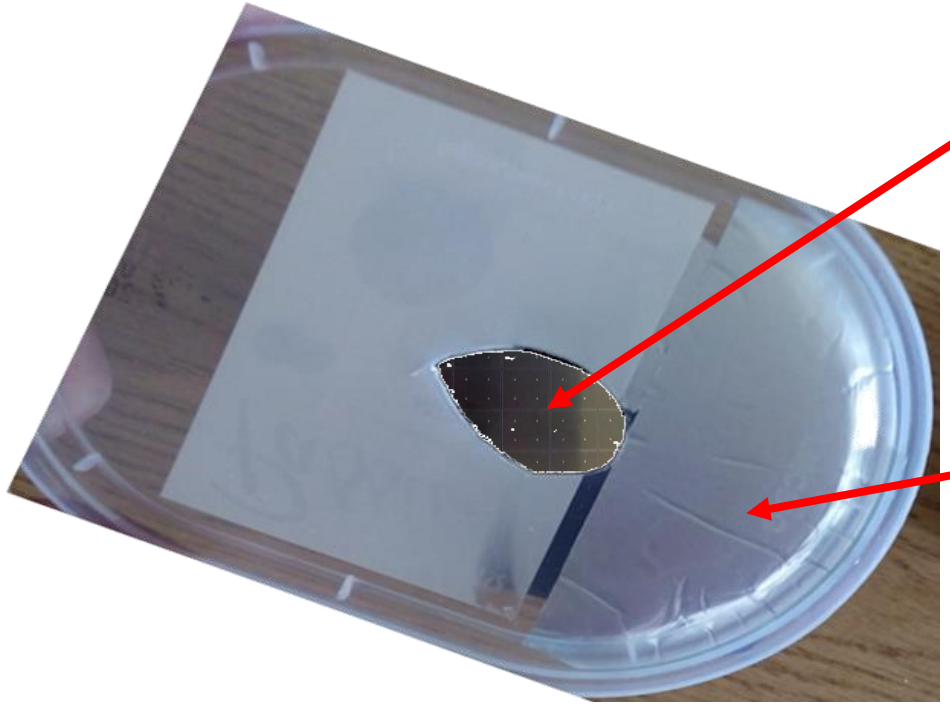
THE DETECTION : FRONT-END



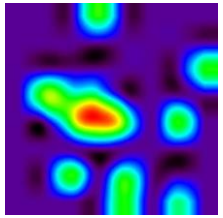
THE DETECTION : Photon Detection Module imaging capability

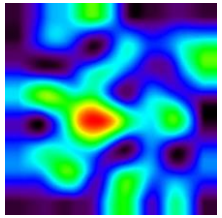
Real image of a single PDM obtained using an partially opaque PVC mask with an ellipse shaped hole and pulsed LED

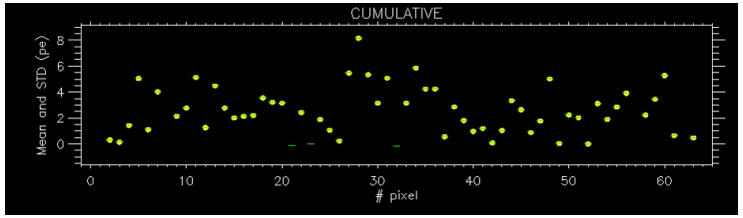


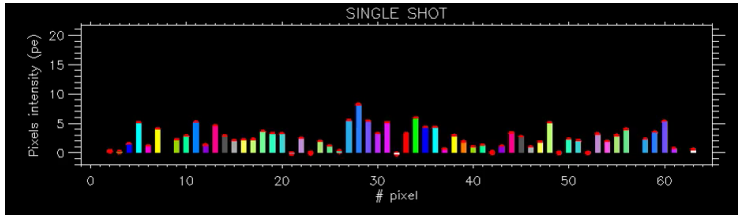


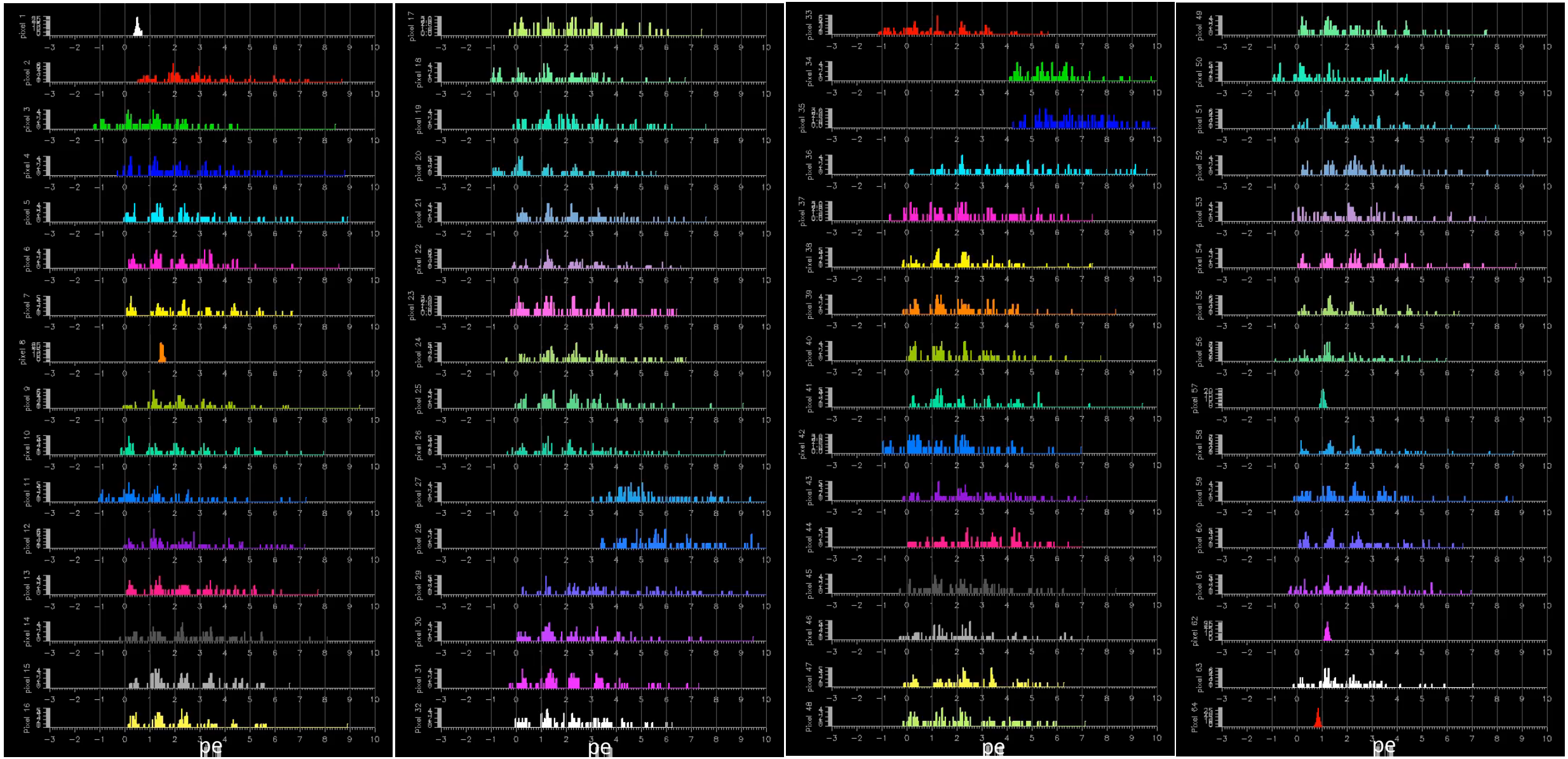
SiPM GAIN & FE GAIN NOMINAL VALUES APPLIED



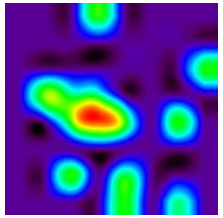


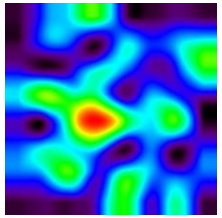


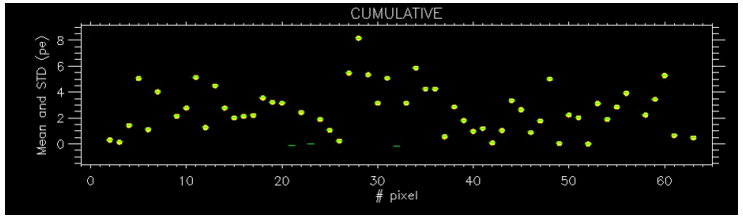


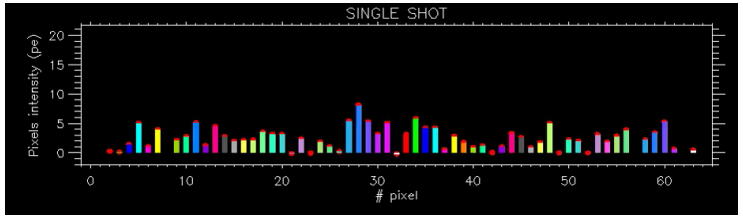


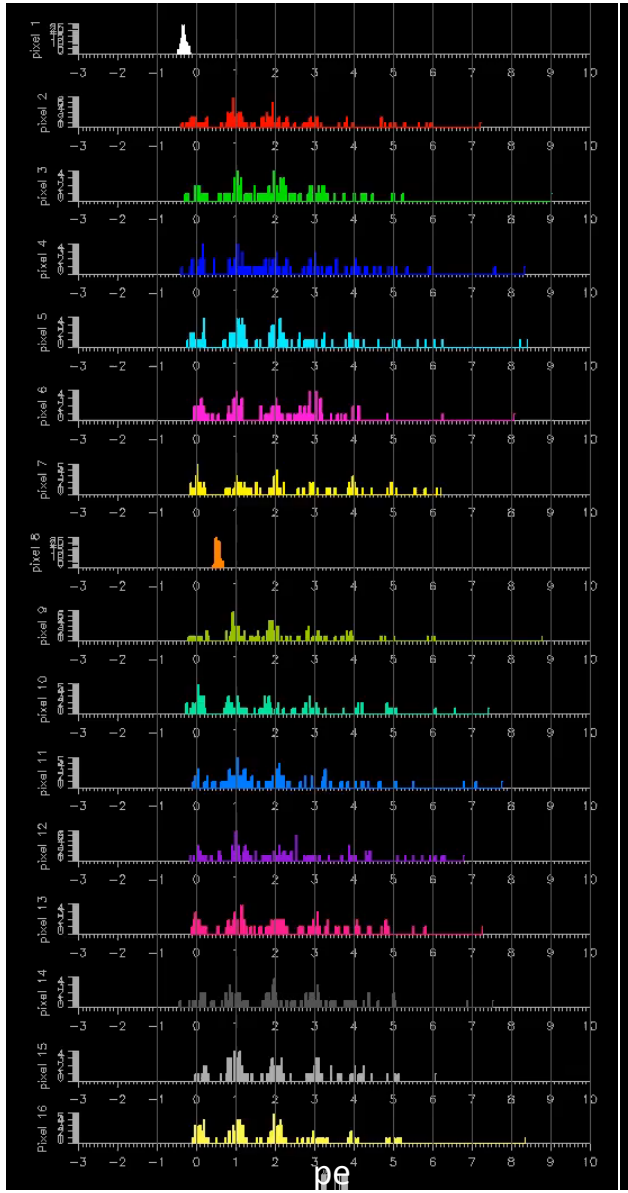
SiPM GAIN & FE GAIN CALIBRATED VALUES APPLIED

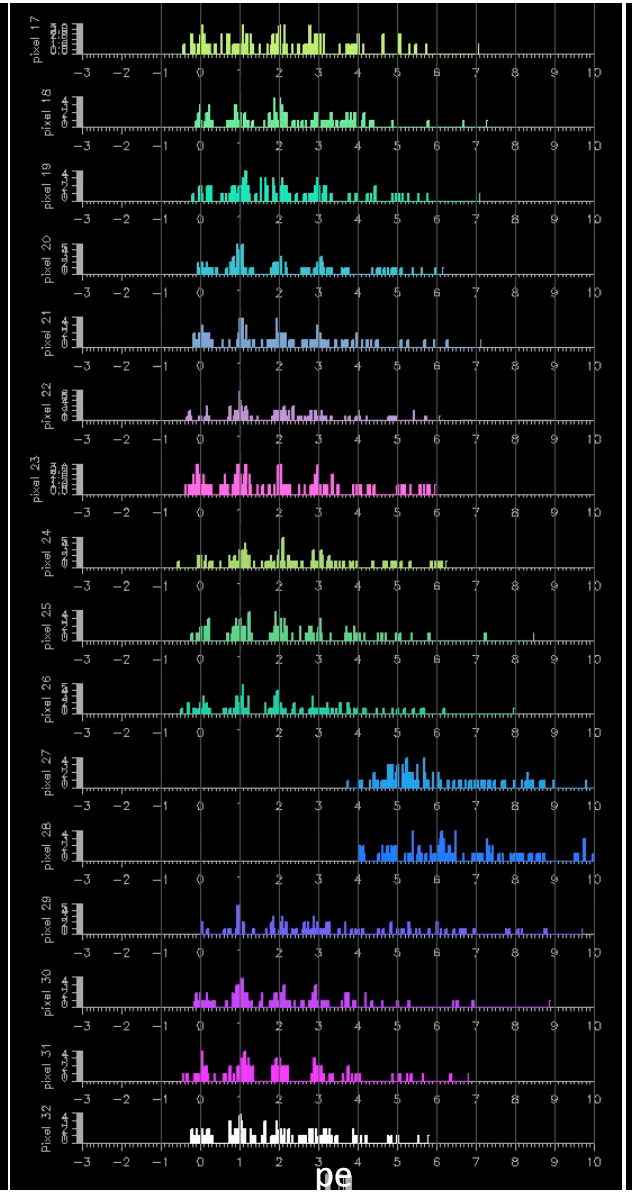


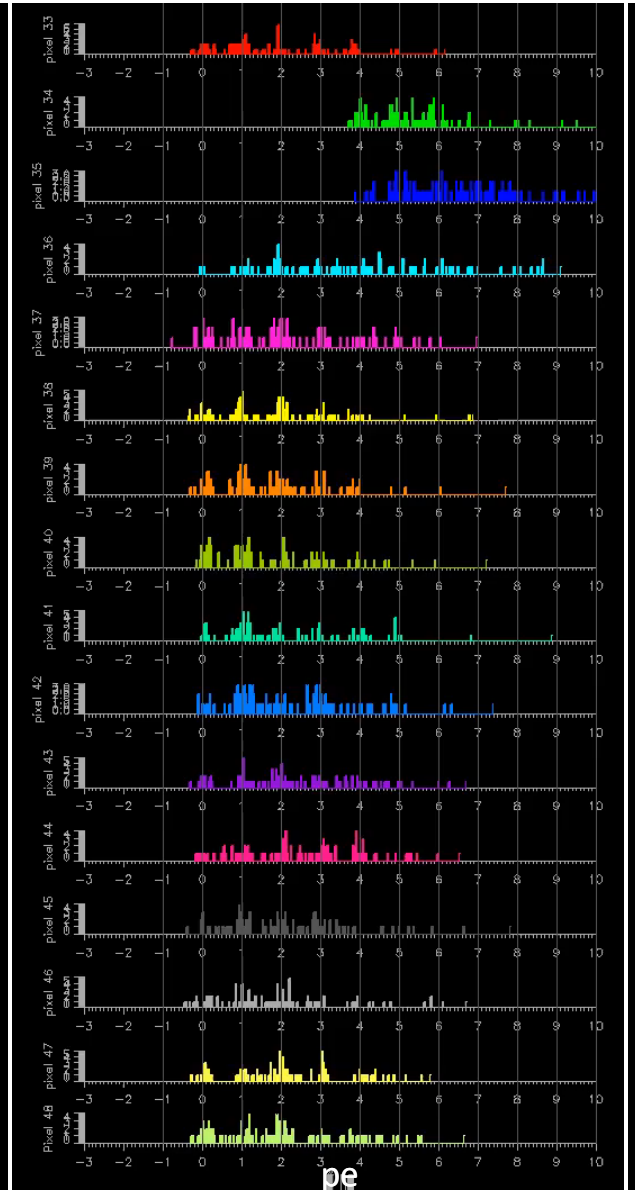


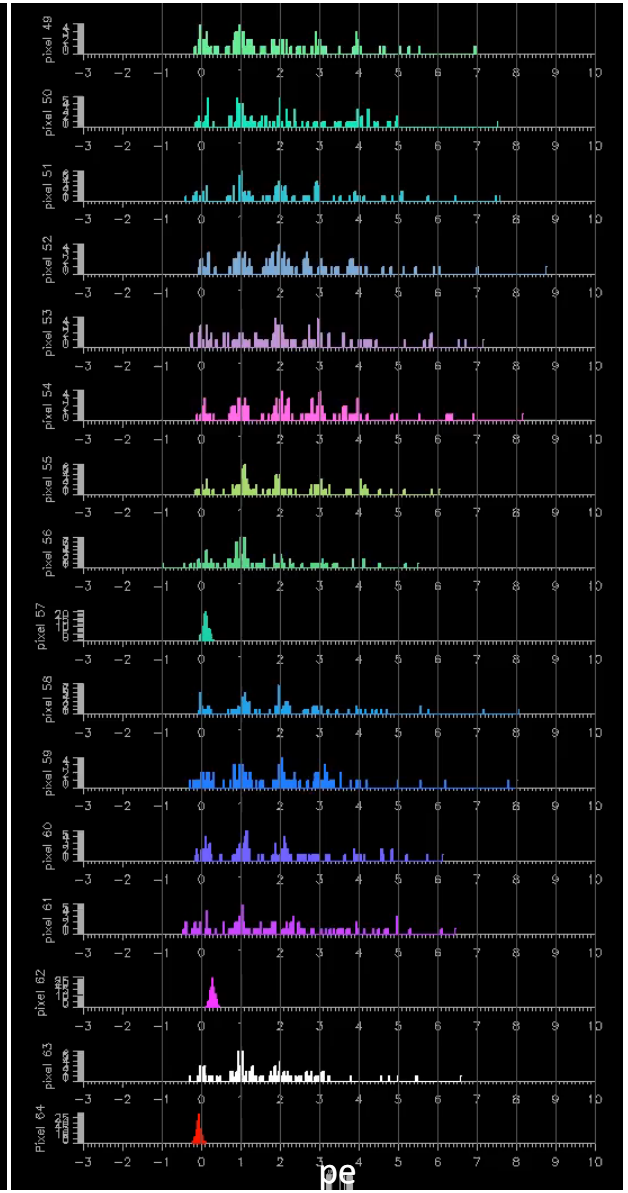




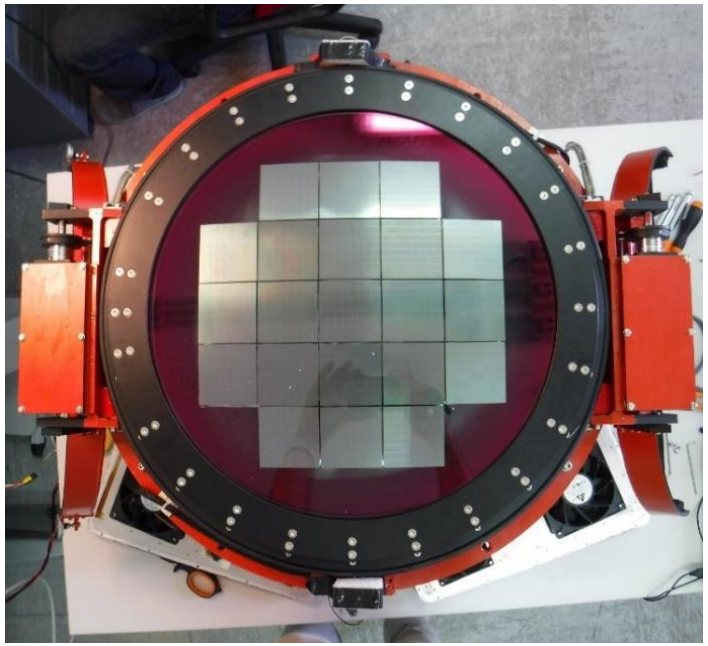




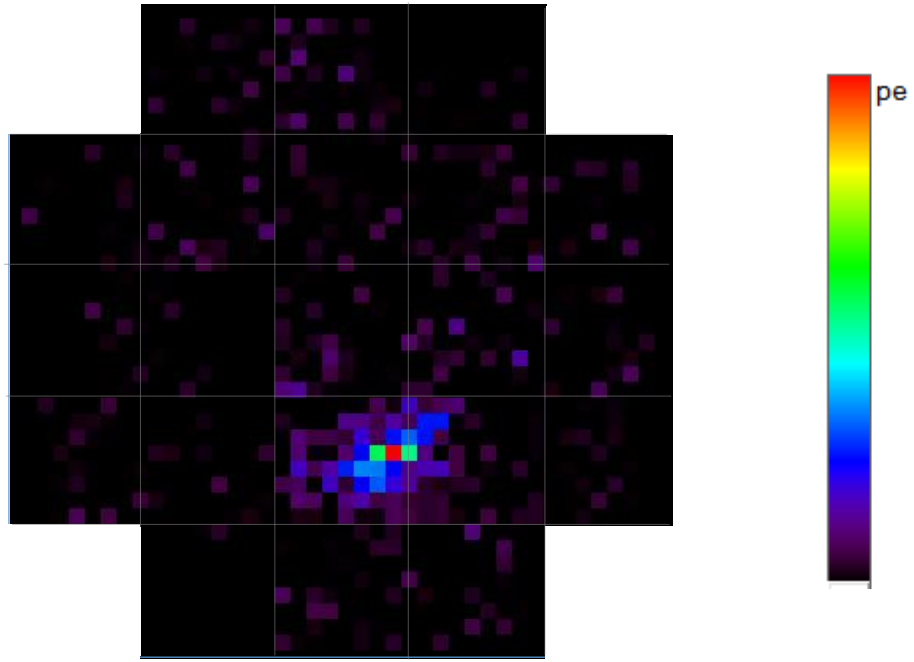




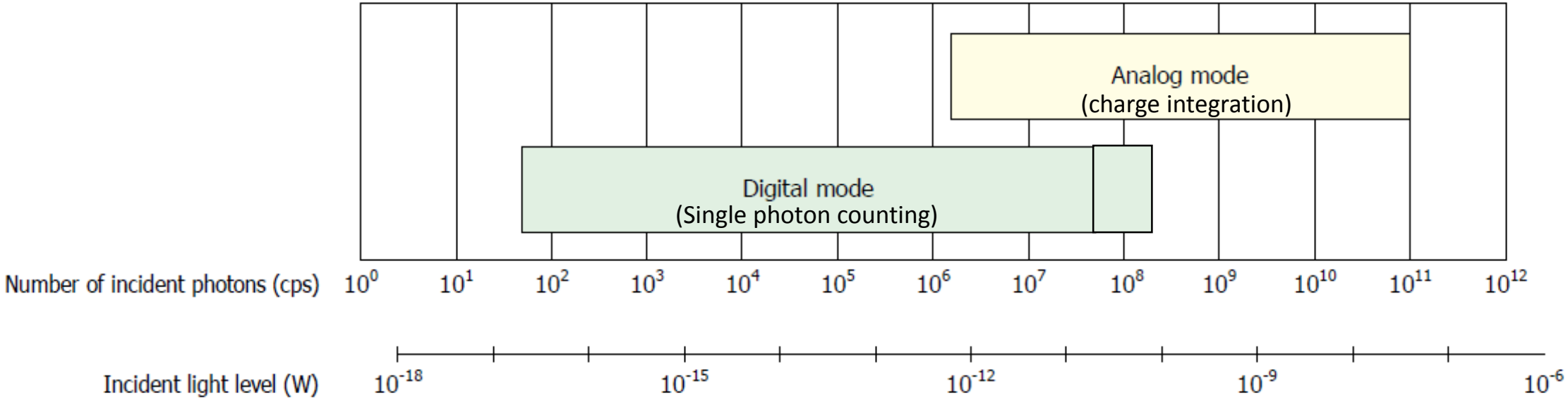
THE DETECTION : 21 PDMs



A few minutes of data taken on the 12 October 2017 at Serra La Nave Observatory
Evaluated NSB ≈ 3 times higher than the dark sky light at the final CTA site

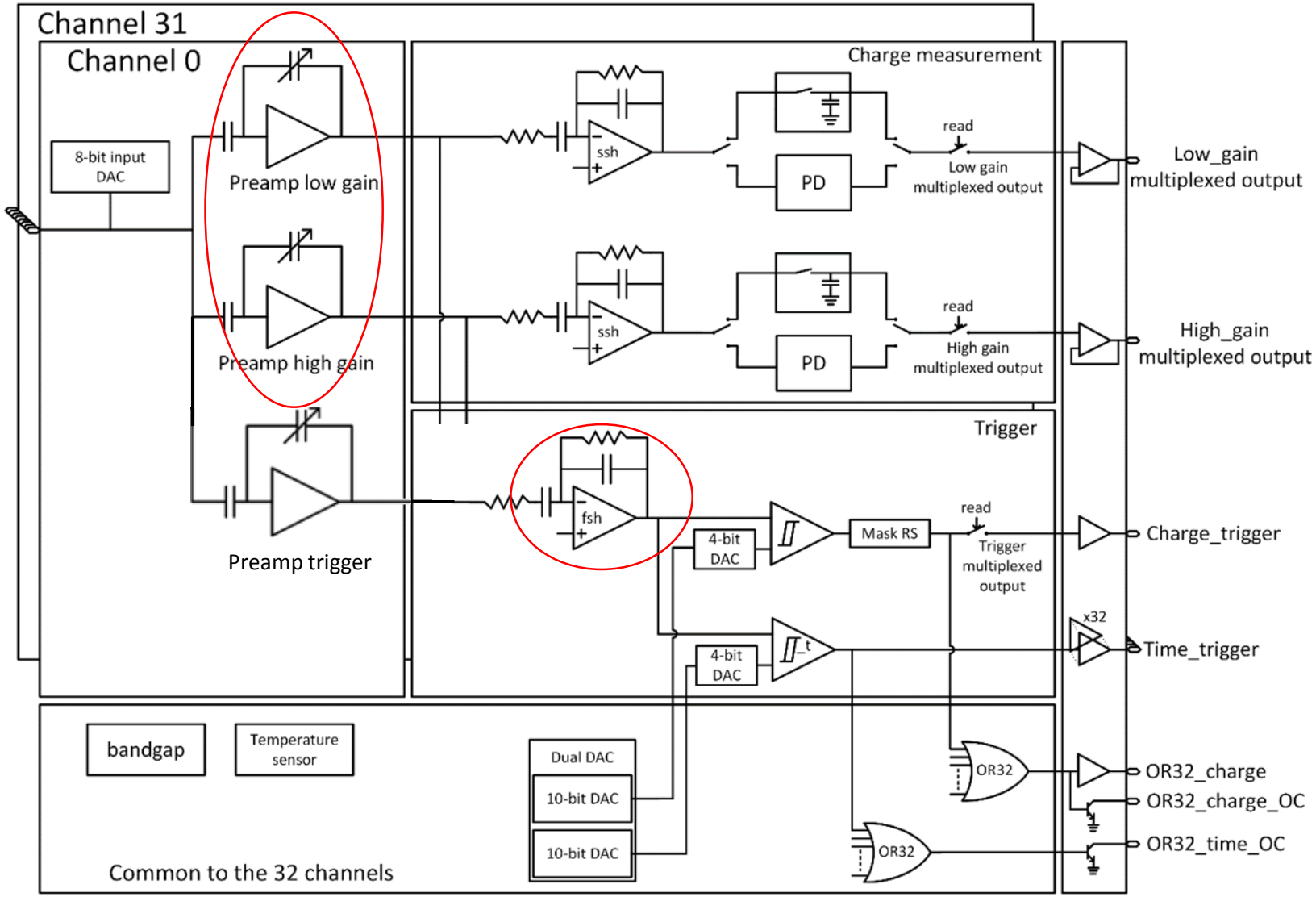


DETECTION OF VERY FAINT AND INTENSE UV-VIS LIGHT



THE PROPOSAL : ASIC MODIFICATION

Redesign Preamp.
Add preamp. Trigger
Redesign trigger fast shaper



THE PROPOSAL : MAIN SPECIFICATIONS

- SiPM high-voltage adjustment (with DACs connected to the ASIC inputs)
- Double pulse resolution of a few ns (< 10 ns) (is enough to avoid pulses pile-up)
- Programmable pole-zero cancellation trigger shaper (to cope with long tail SiPM signals)
- Analog pulse height measurement using fast peak detector
- Wide energy dynamic range (energy measurement from 1 pe up to several thousand pe)
- Analog triggers (summation of analog signals) and digital triggers implementation
- Timing measurement better than 100 ps RMS
- Masking of the digital triggers (switch off potential noisy pixels)

THE PROPOSAL : DELIVERABLES

At the completion of the first year deliverables shall be:

- FE ASIC modified in order to have Single Photon Counting and charge integration implemented and fully working
- Tests in Lab. to characterize the FE ASIC
- Implemented SW for the characterization of the FE ASIC
- FE ASIC documentations and test reports

At the conclusion deliverables shall be:

- FPGA PCB board
- SW, FW developed for FPGA
- MPDU consisting of a SiPM tile (8x8 pixels) , FE ASIC board and FPGA board
- Development of trigger logic
- PC Interface SW to the MPDU
- TurLab tests
- Comparative response between SiPM MPDU and EUSO-like MAPMT-equipped Elementary Cell
- Documentations and test reports
- Test reports of MPDU response in dark environment and at the various luminous scenes
- Final report on the outcome of the feasibility study

CONCLUSION

- As in case of space missions, measurement of fluorescence and Cherenkov light as well as atmospheric phenomena require detection, with different time scale, of very faint and very intense light
- Single-photon-counting as well as charge integration must coexist in the same FE for obtaining optimum performance
- CITIROC1A chip lends itself to the changes we have suggested in short time
- The suggested integration of SiPM, FE and FPGA in a MPDU (Monolithic Photo Detection Unit) reduce drastically power consumption and mass budgets, very important for any space mission and particularly for the proposed UHECR space missions as EUSO and POEMMA
- The progress in SiPM manufacturing, front-end ASIC and system integration associated with System on Chip (SoC) design gives hope that this outcome can be achieved
- **The financial requests are intended to design and realize a MPDU including the modification of existing ASIC front-end and Lab activities for tests, calibration and measurements**