Study and development of silicon photomultipliers for space within the JEM-EUSO Program

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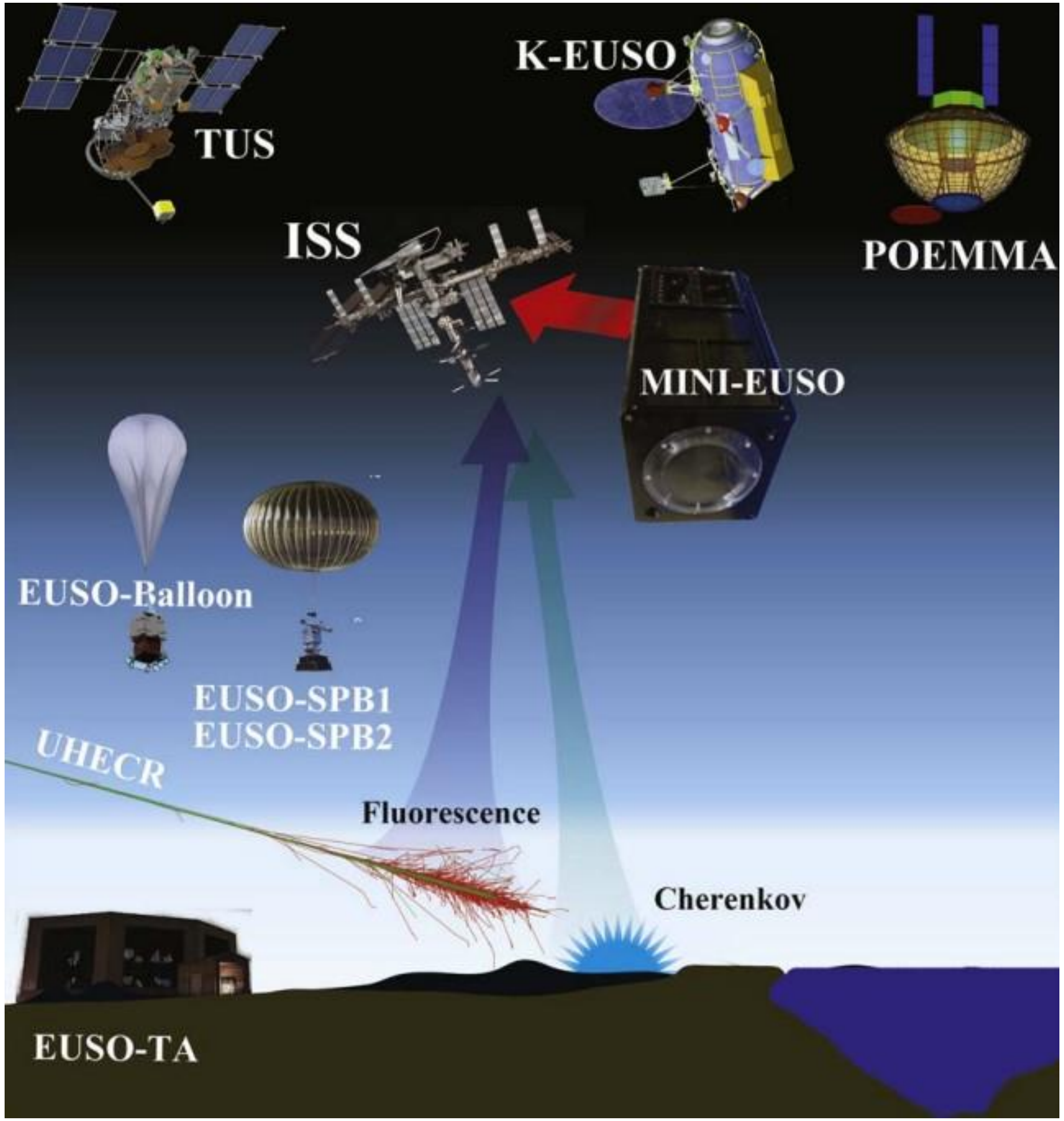
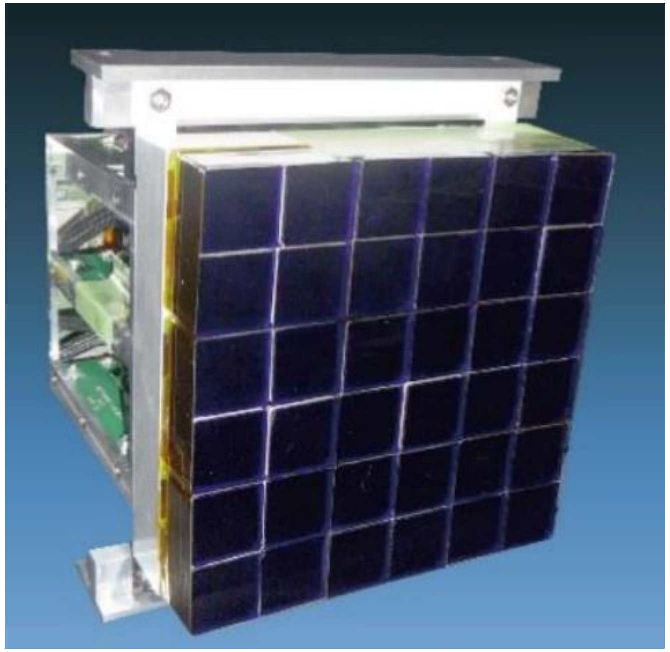
Past, present and future experiments with SiPMs

Observation of Fluorescence and Cherekov emissions for UHECR and neutrino detection

- EUSO-SPB1 /2017
- Mini-EUSO /2019
- EUSO-SPB2 /2023
- EUSO-SPB3 /2026
- POEMMA /2030+

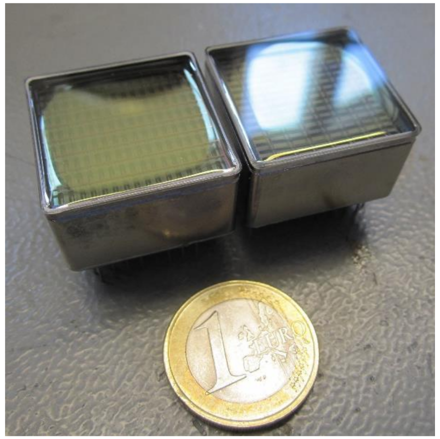


Focal surfaces in the JEM-EUSO experiments



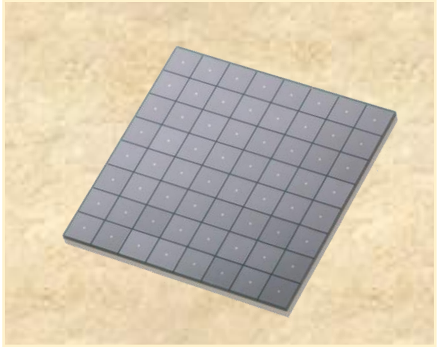
The photo-detection modules of the JEM-EUSO fluorescence telescopes are made of MAPMTs

MAPMT



- In the first missions, SiPMs were used in ancillary detectors;
- In the last years, with EUSO-SPB2, SiPMs started to be used as sensors of the main focal surface (Cherenkov telescope)

SiPM



Silicon Photomultipliers

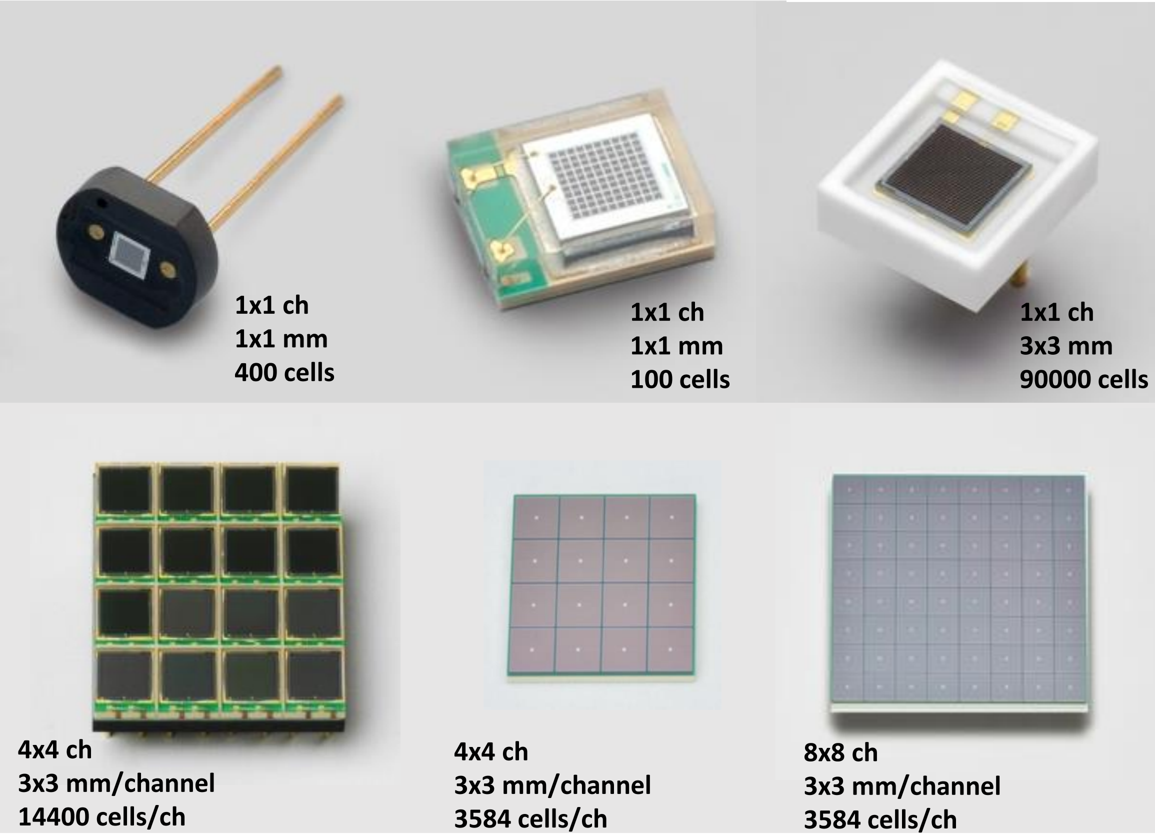
Advantages

- High gain (10^5-10^6)
- Low Voltage (<100 V)
- Excellent photon-counting capability
- Excellent time resolution
- Robust against damage from strong light emissions (can be used with moon-light)
- Insensitive to magnetic fields
- Compact size

Disadvantages

- Temperature dependency: thermal background proportional to the area (high noise for T>30° C)
- Radiation sensitivity

SiPM models from HAMAMATSU
multi-pixel photon counter (MPPC)



Experiments and R&D with SiPMs within JEM-EUSO

- Program of R&D funded by ASI in the framework of the EUSO-SPB2 project to rise the technical readiness level of SiPMs in space, by means of the development of ancillary cameras with SiPMs
  - The low voltage and low power consumption, the robustness and the compactness make SiPMs good candidates for space-based missions

- In the next slides, the past, present and future experiments of the JEM-EUSO Program hosting SiPMs are described, including the R&D activity

EUSO-Super Pressure Balloon (EUSO-SPB1)

Mission:

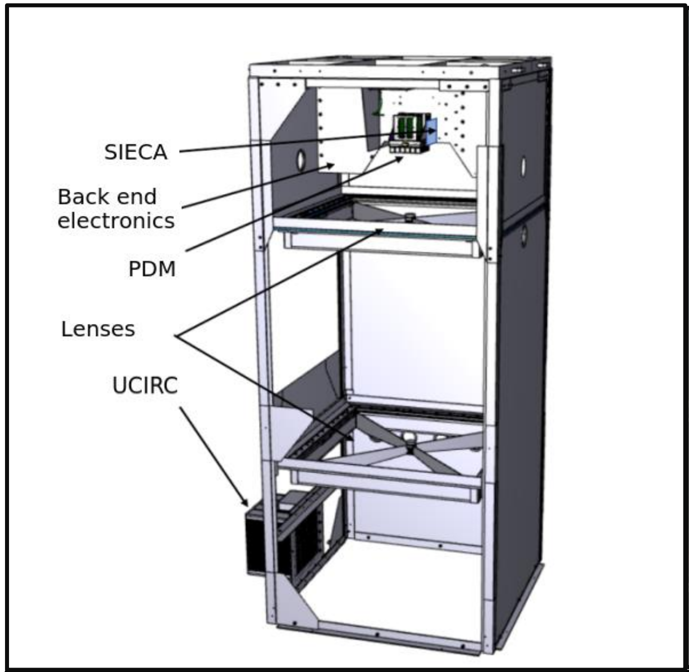
25 April - 7 May 2017

Characteristics:

- Fluorescence telescope with MAPMTs
- 1 additional fluorescence camera with SiPMs (SiECA)
- Optics: 2 Fresnel lenses

Goals:

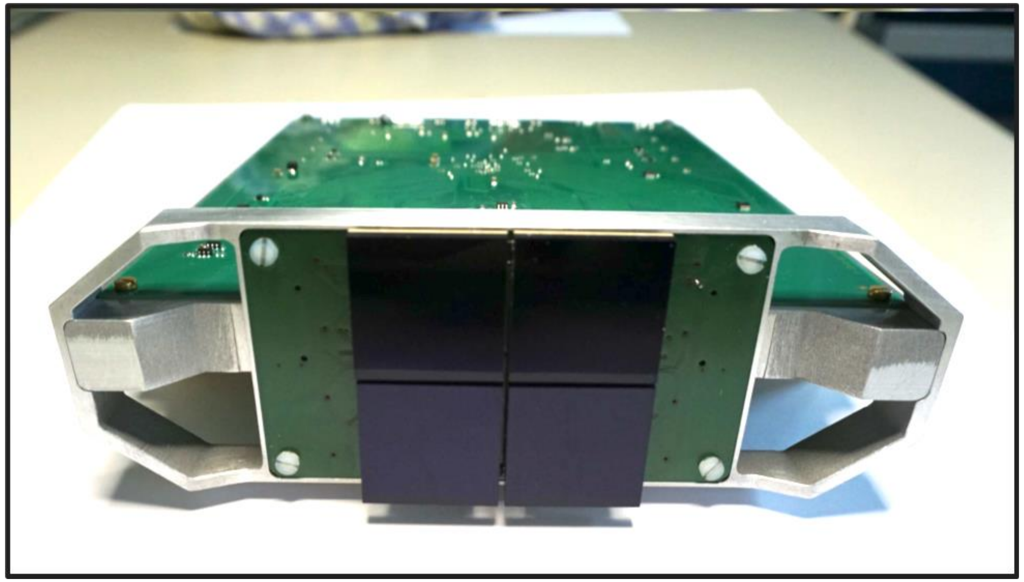
- Detect UHECRs for the first time from high altitude
- Test the detector at high altitude
- Measurement of the UV background of the atmosphere from above



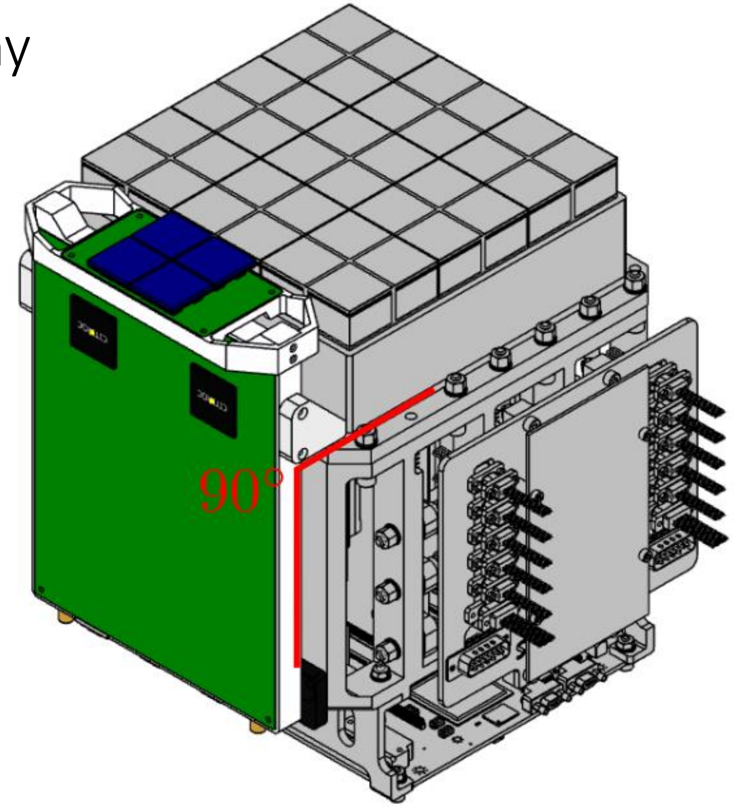
SiECA on EUSO-SPB1 (1)

Silicon photomultiplier Elementary Cell Add-on

- Developed at the Karlsruhe Institute of Technology (KIT), Germany
- Designed as an ancillary device to be easily attached to existing fluorescence telescope of EUSO-SPB1, utilizing the same optics



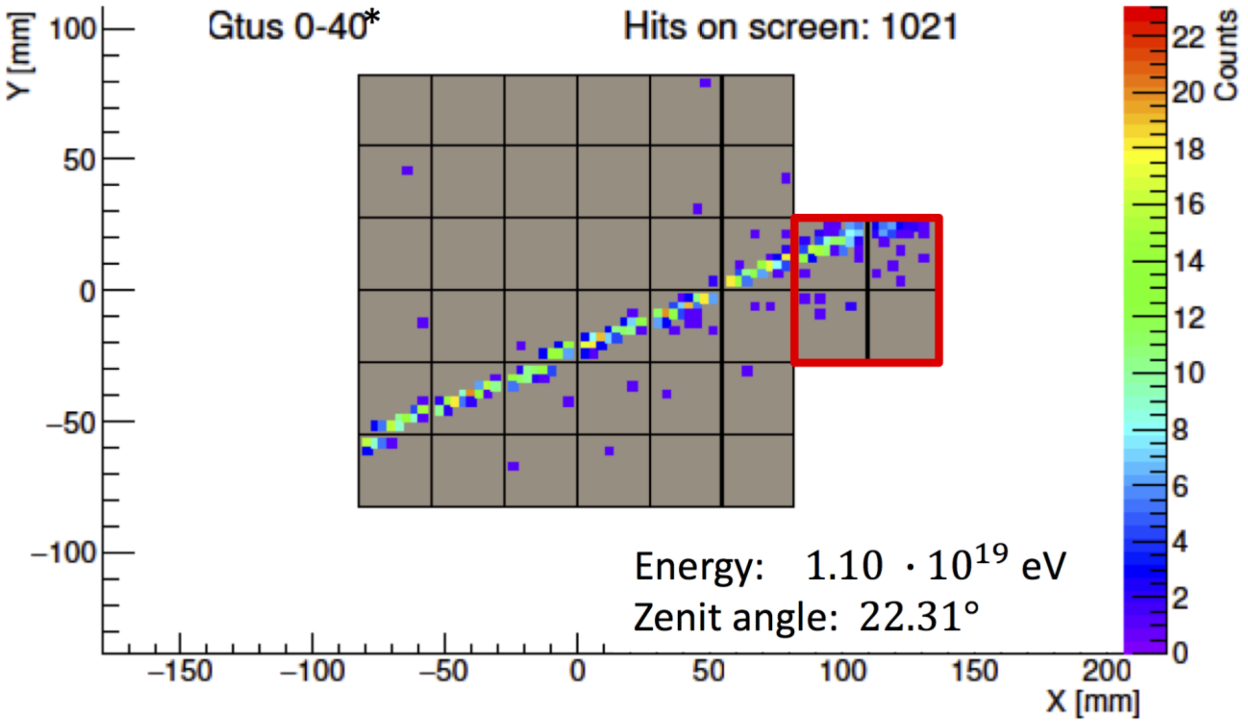
SiECA with 2x2 SiPM array, 8x8 pixels each



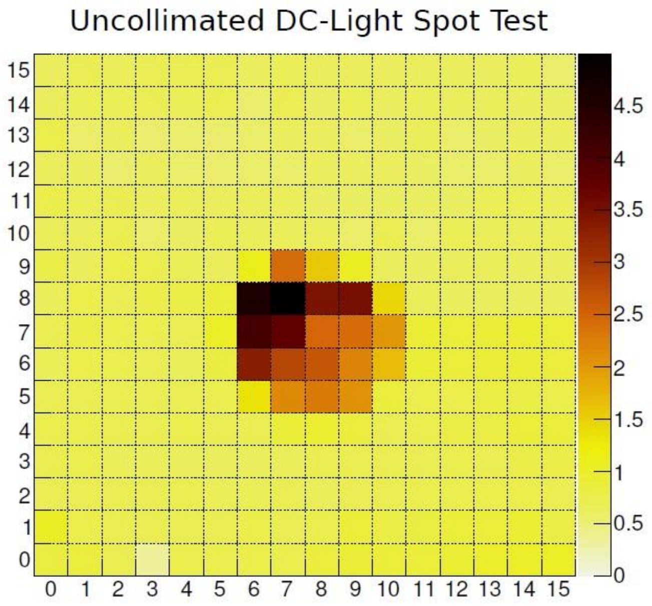
SiECA camera next to the photo-detection module made of MAPMTs

[W. Painter PhD Thesis]

SiECA on EUSO-SPB1 (2)



Simulation of a proton event of energy 1.1x10^{19} eV going through the field of view of the detector with a zenith angle 22.3°. No background is added to the plot [PoS(ICRC2017)442]



Full camera test in the lab with nonuniform light source. Response is average photons detected per 2.5 mus [PoS(ICRC2017)442]

Mini-EUSO onboard the ISS

Mission:

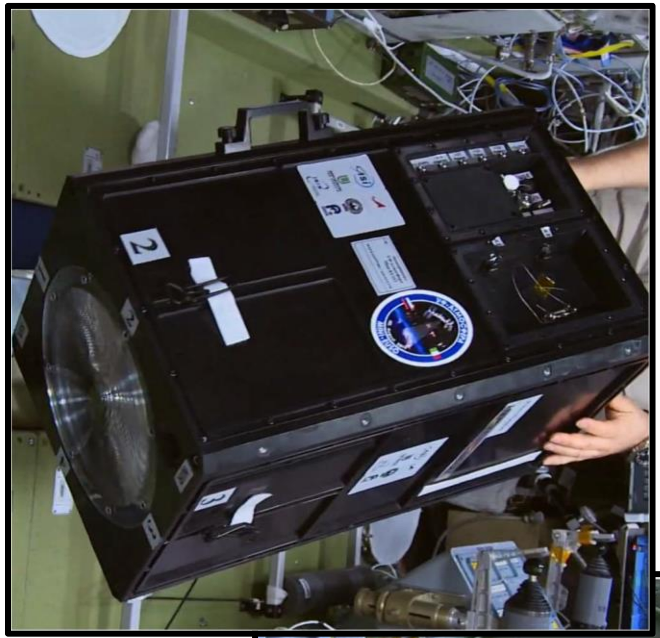
October 2019 – now

Characteristics:

- Fluorescence telescope with MAPMTs
- 2x UV-light sensors
- 1 SiPM single pixel
- 1 SiPM array 8x8 pixels
- Optics: 2 Fresnel lenses

Goals:

- Map the night-time Earth emissions in the near-UV range
- Study of atmospheric phenomena (TLEs, ELVES)
- Meteors
- Search for Extensive Air Showers (EAS) with energies above 10^{21} eV
- Search for SQM and interstellar meteors



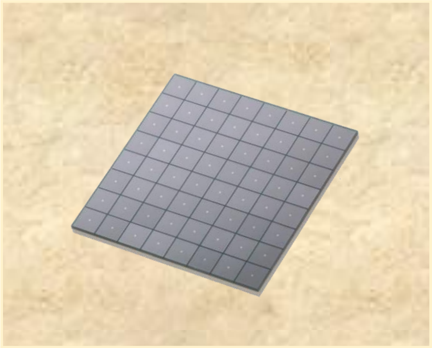
Talk by
Laura Marcelli

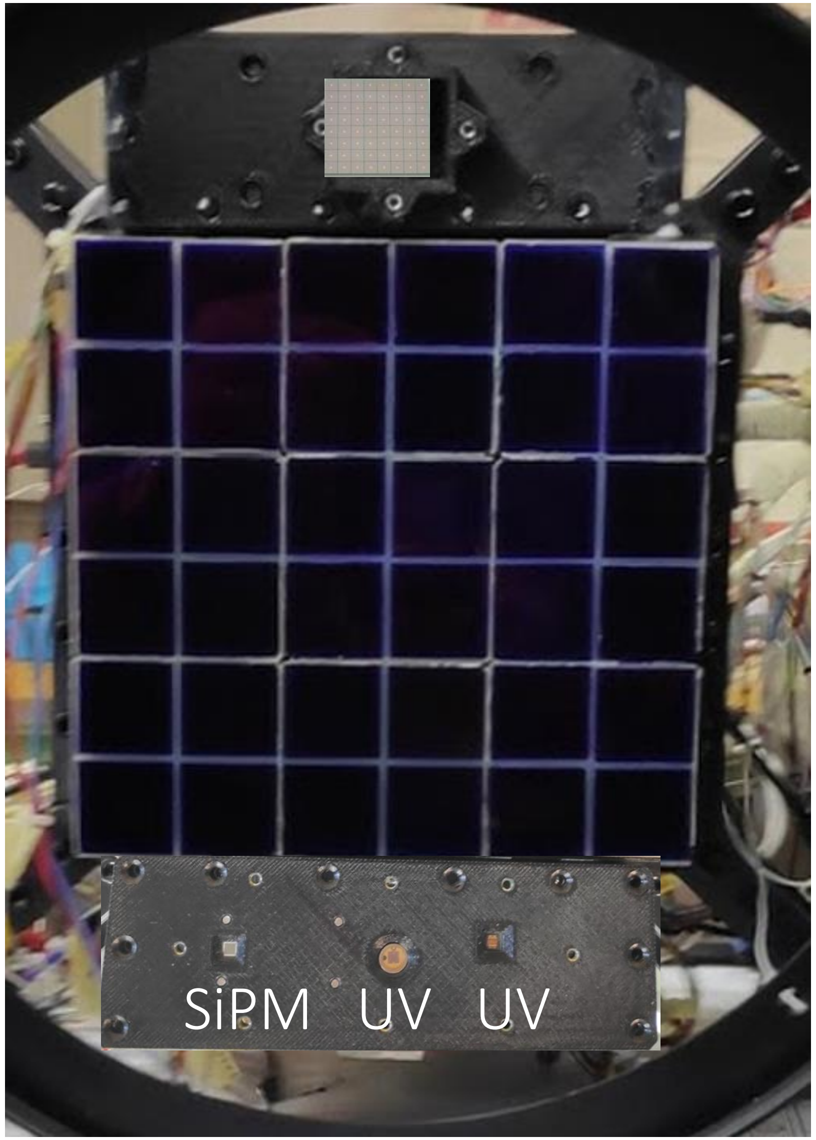
Sensors on the Focal Surface of Mini-EUSO

Main Focal Surface MAPMTs
R11265-M64 (2304 pixels)

SiPM Array
- MPPC C14047-3050EA-08
- 8x8 channels
- Read independently (Multiplexer, no FPGA)

(used in day/night transition)

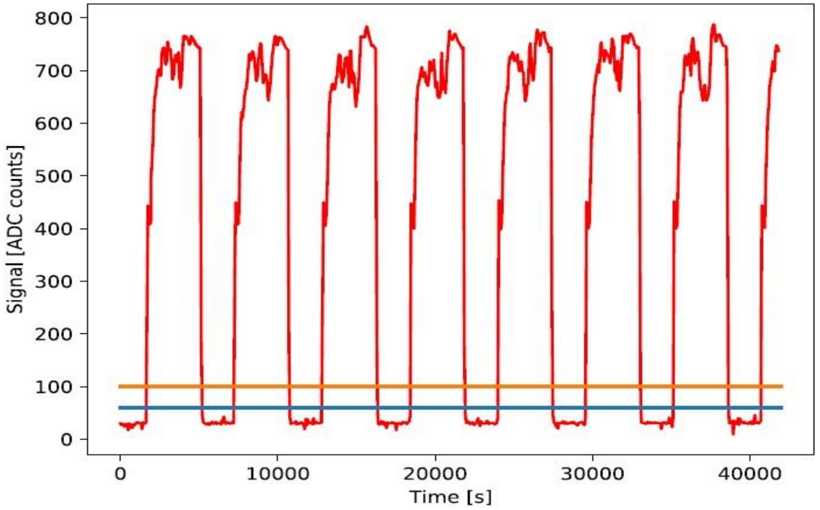




SiPM C13365 single pixel

2 UV-light sensors (photodiodes)
- S1226-5BQ log 190-1000 nm
- ML8511 linear 280-400 nm

(used for day/night transition)



EUSO-Super Pressure Balloon 2 (EUSO-SPB2)

Mission:

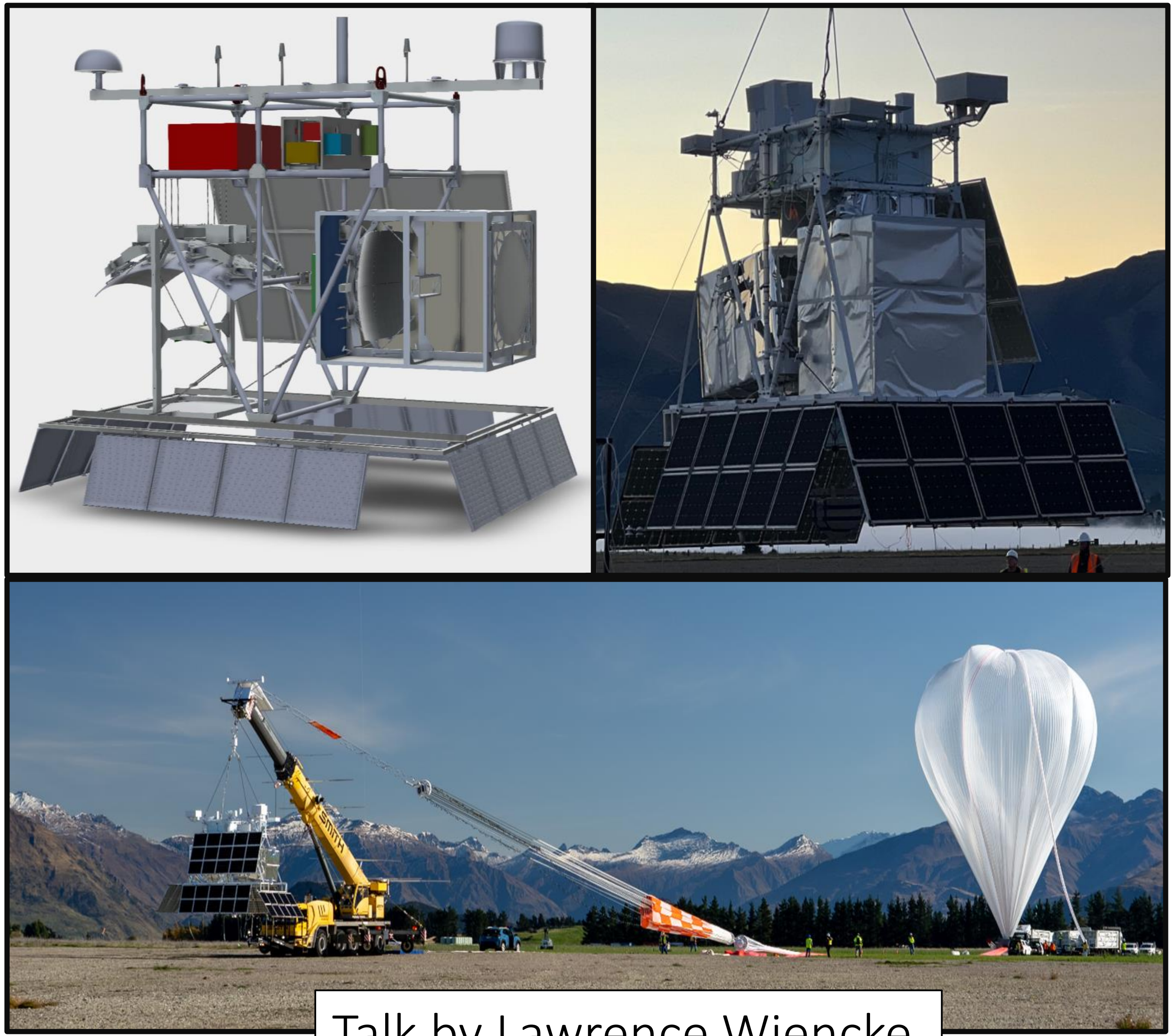
13 - 14 May 2023

Characteristics:

- 1 fluorescence telescope with MAPMTs
- 1 Cherenkov telescope with SiPMs
- Optics: Schmidt mirrors

Goals:

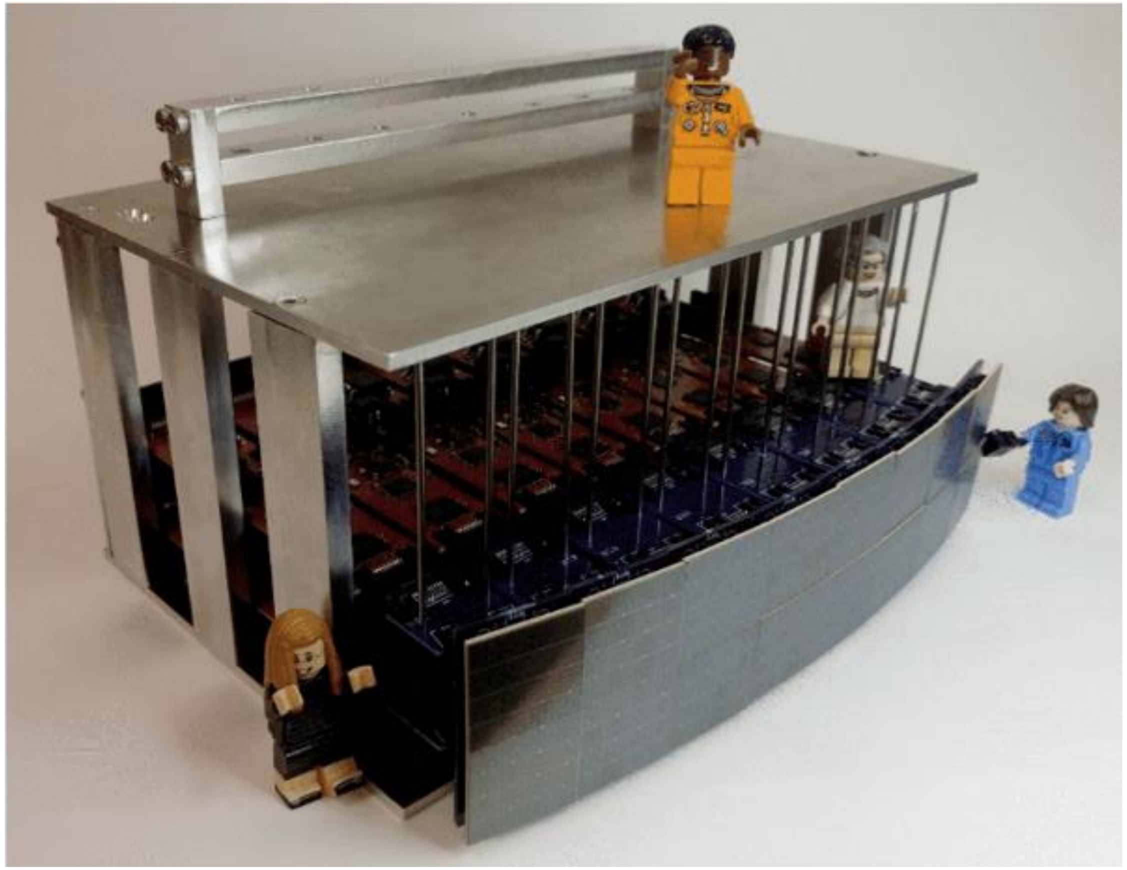
- Measurements of background for upward going neutrinos
- Observation of tau neutrinos with $E>10^{16}$ eV below the limb
- Observation of UHECRs through:
  - Cherenkov emission just below the limb
  - Fluorescence light at nadir



Talk by Lawrence Wiencke

Cherenkov Camera of EUSO-SPB2

- Developed at Georgia Tech, USA
- 8x4 SiPM arrays
- 4x4 pixels/SiPM array (pixel 6.4 mm x 6.4 mm)
- Overall field of view of 12.8° x 6.4° (H x V)
- Effective aperture area 0.78 m^2
- Wide spectral response 200-1000 nm
  (peak efficiency of 50% at 450 nm)

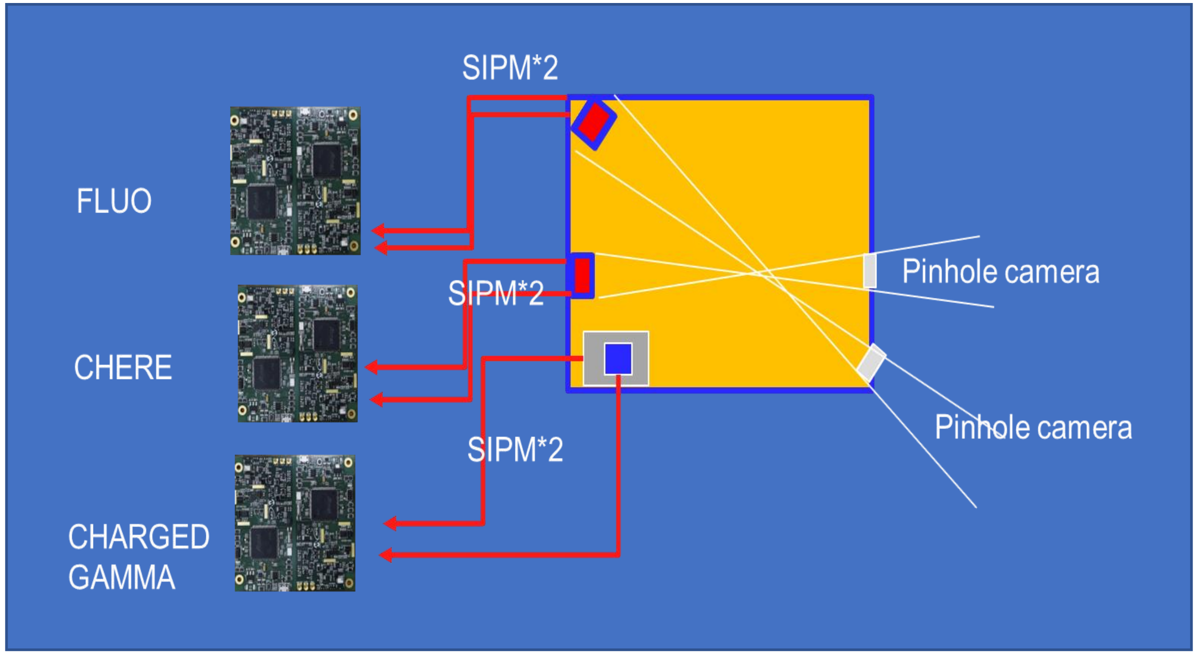


The focal surface of the Cherenkov telescope o EUSO-SPB2 made of 32 4x4 channels SiPMs S14521-6050AN-04 [PoS(ICRC2021)1191]

Ancillary cameras for EUSO-SPB2

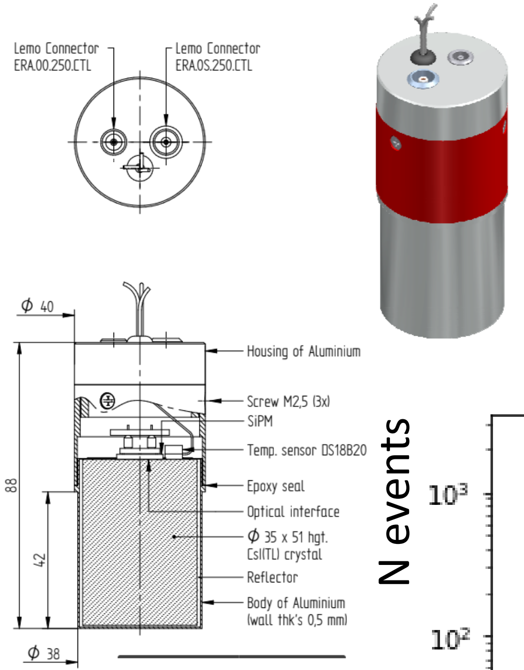
- In Italy, ASI-INFN agreement to develop and test different SiPMs, to select a few candidates to fly on EUSO-SPB2 to assess their performance with the aim of using SiPMs in space
- The main activities are the design of the ASIC board for Cherenkov cameras (Turin), the characterization of SiPMs (Catania), and implementation of SiPMs on the detectors (Rome)
- Since the schedule did not allow for the integration with EUSO-SPB2, the systems have been developed as standalone elements

- **Fluorescence detector**
  with (BG3) UV-filter working on different timescales (from ns to above)
- **Cherenkov detector**
- **Gamma ray detector**
  atmospheric events: in particular Terrestrial Gamma Flashers (TGF)
- **Charged particle detector**
  (with some Z capability)

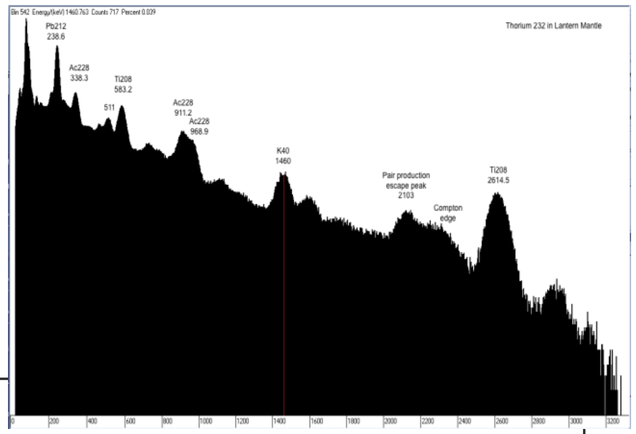


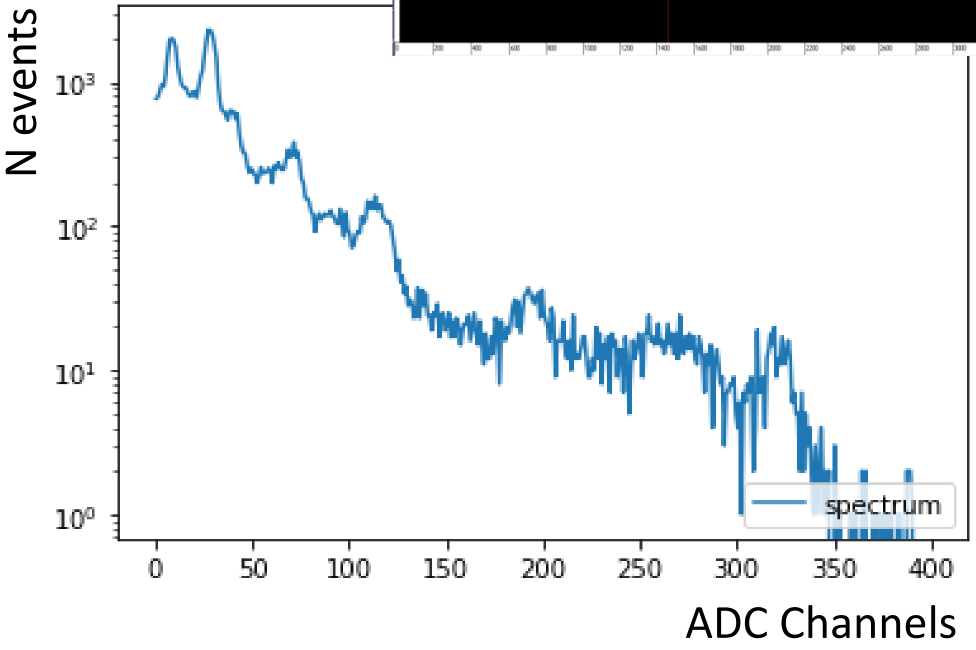
Gamma-ray detector

Cesium iodide crystal (Scionix) + SiPM readout

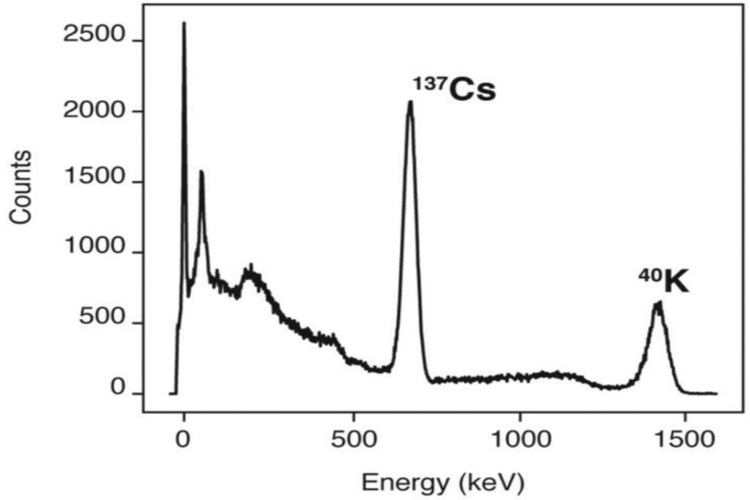


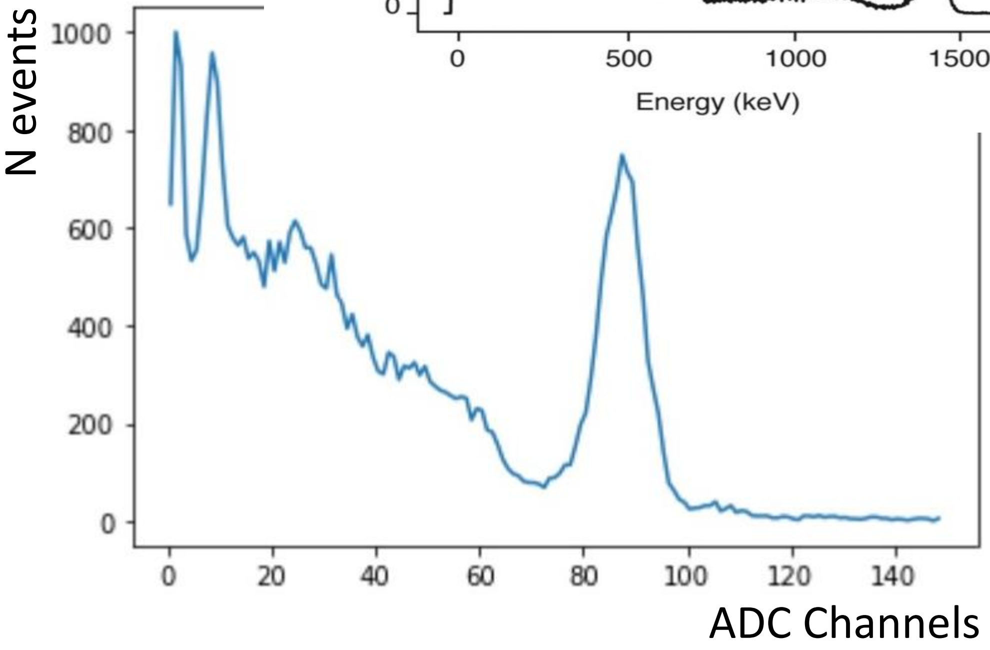
Thorium





Cesium137 from Fukushima soil (660 keV line)





Installation of the gamma-ray detector at the EUSO-TA site

Mission:

October 2015 – 2016

Upgrade is foreseen

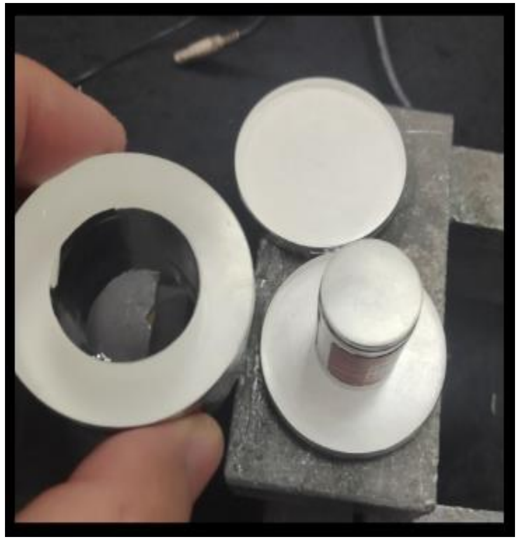
Characteristics:

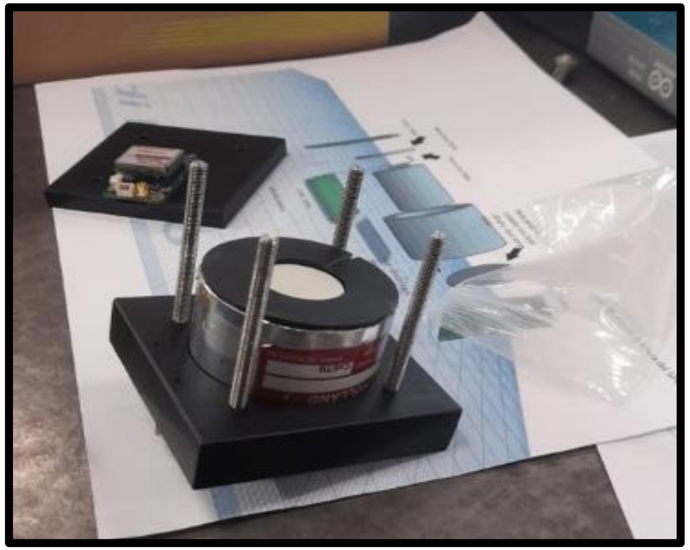
- Fluorescence telescope with MAPMTs
- Optics: 2 Fresnel lenses

Goals:

- Test the overall design of the detectors of the JEM-EUSO program on ground
- Detect cosmic ray events
- Detect meteors, stars
- Environment used to test the other experiments before launch (EUSO-SPB1, EUSO-SPB2)

Gamma-ray/charged particles detector



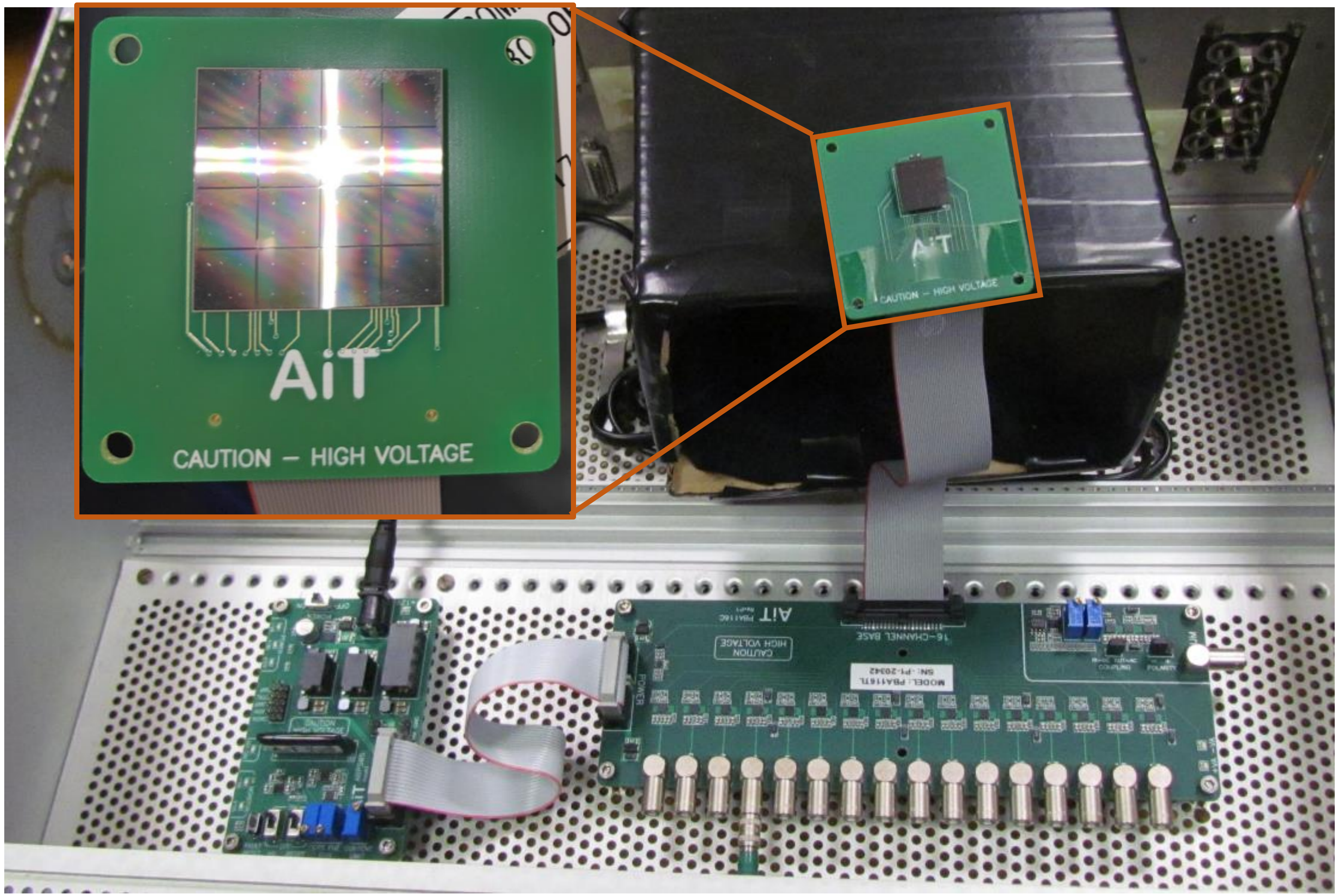


Cesium iodide crystal (CsI(Tl) - Scionix) + multi-SiPM readout

+ Anti-coincidence between inner and outer part

→ discrimination gamma-ray/charged particle

SiPM array board for the multi-pixel Cherenkov detector



- The multi-pixel Cherenkov detector moves in the direction of testing the full characteristics of the ASIC board developed in Turin (talk by Andrea di Salvo)
- AiT SiPM array module with discrete amplification electronics and power supply
- Preamplifier

Future: EUSO-SBP3

- Fluorescence + Cherenkov camera
  - Fluorescence: CR showers (nadir+inclined) + High-altitude CRs showers (tilted)
  - Cherenkov: CRs + neutrinos (tilted)
- Tiltable from 0° to 90°

- Optics: same (maybe larger) design than EUSO-SPB2 + bifocal optics only for CT to be studied
- Auxiliary devices: IR, Radio, gamma-ray, X-ray, SQM
- Goal: 2026

EUSO-Balloon

2014

EUSO-SPB1

2017

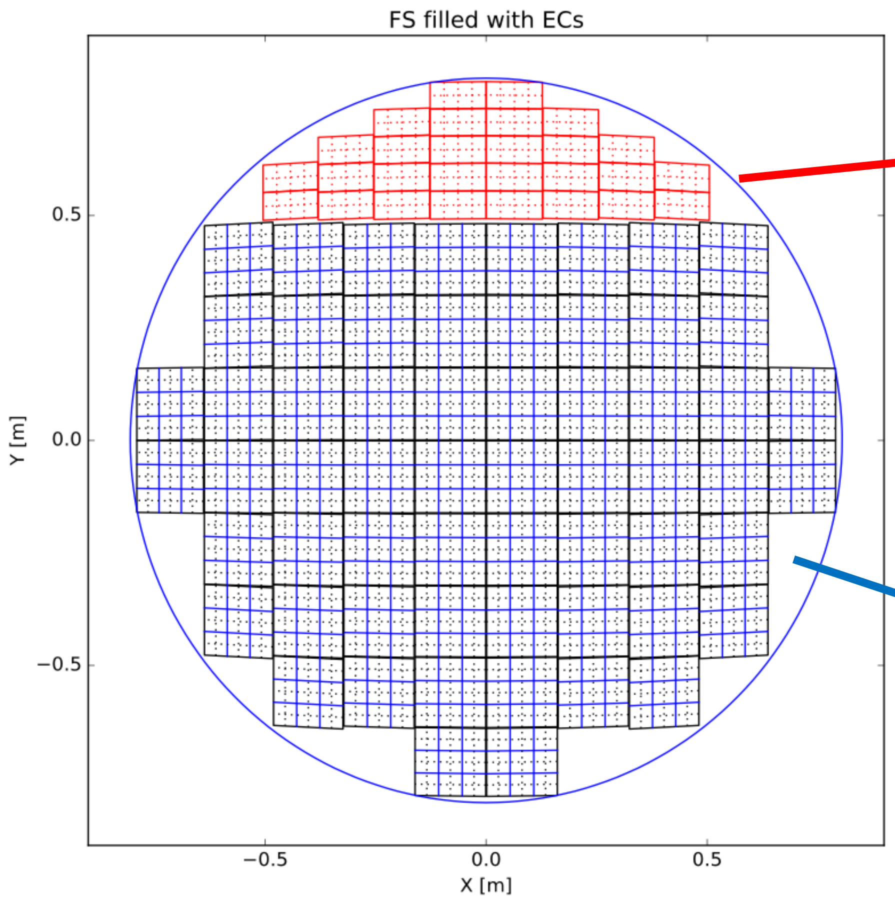
EUSO-SPB2

2023

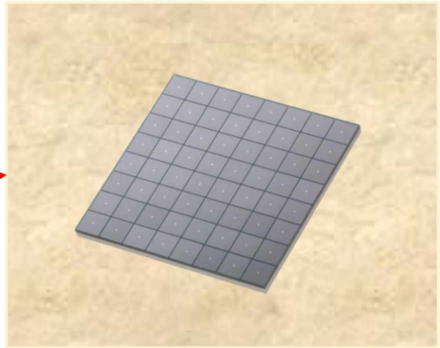
EUSO-SPB3

2026?

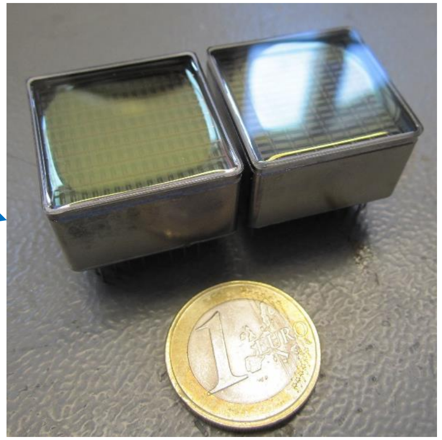
Future: POEMMA (1)



SiPM



MAPMT

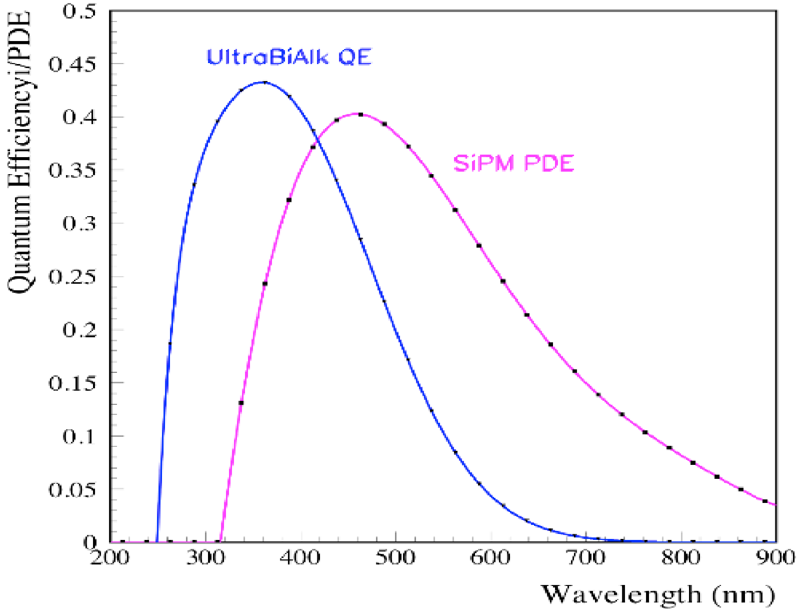


Cherenkov tel. with SiPMs (300-900 nm, ~ns)

Top of the focal surface that images the limb of the Earth

Fluorescence tel. with MAPMTs (300-400 nm, ~10 ns)

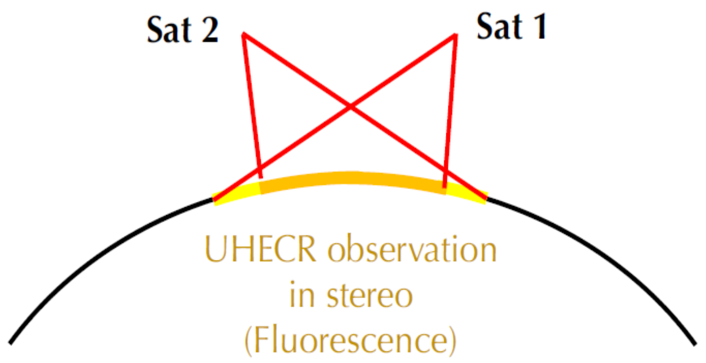
~90% of the focal surface



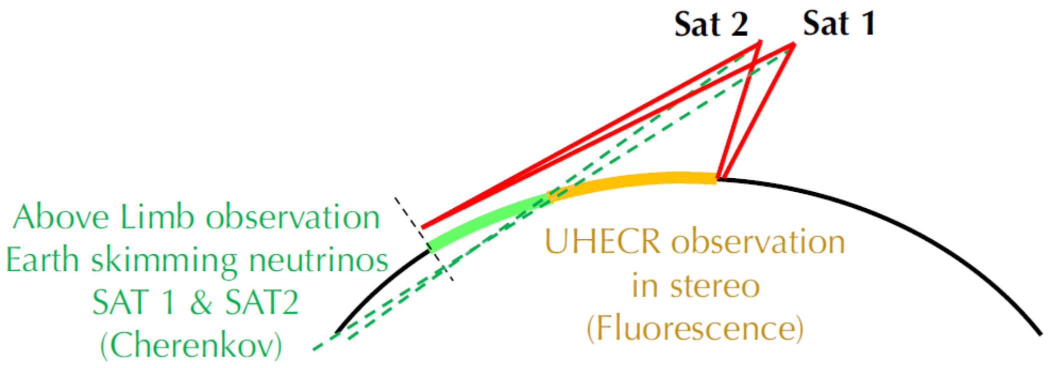
Talk by John Krizmanic

Future: POEMMA (2)

- Two Schmidt telescopes
  with variable separation (300-25 km)
- Altitude: 525 km
- Instrument Mass: 1547 kg
- Primary Mirror: 4 meter → FOV: 45 deg
- Hybrid focal surface (MAPMTs + SiPM): 1.6 m



PRIMARY UHECR OBSERVATION MODES
UHECR stereo & no neutrino observation



PRIMARY NEUTRINO & SECONDARY UHECR OBSERVATION MODES
Neutrino stereo & UHECR monocular

Summary

- Several experiments of the JEM-EUSO program hosted and host SiPMs:
    - EUSO-SPB1 with the fluorescence camera SiECA
    - Mini-EUSO with single or multi-pixel cameras to evaluate day/night transition
    - EUSO-SPB2 with the focal surface of the Cherenkov detector

- In Italy, ASI and INFN allowed the design of the ASIC board for Cherenkov cameras (Turin), the characterization of SiPMs (Catania), and implementation of SiPMs on the detectors (Rome).

- The experience acquired will be essential in view of EUSO-SPB3 and also on another experiment based on Cubesats for solar physics under development in Rome (SEE-SuncubW onE).

- All the effort is done to obtain stable and reliable detectors in view of space-based experiments, like POEMMA.

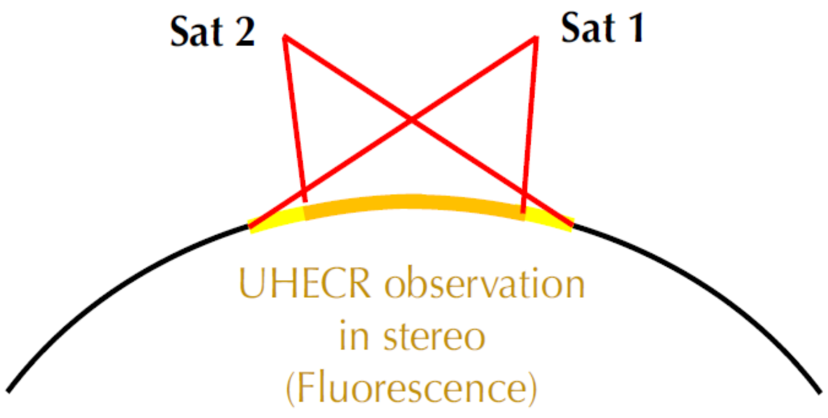
Backup slides

MAPMTs vs SiPMs

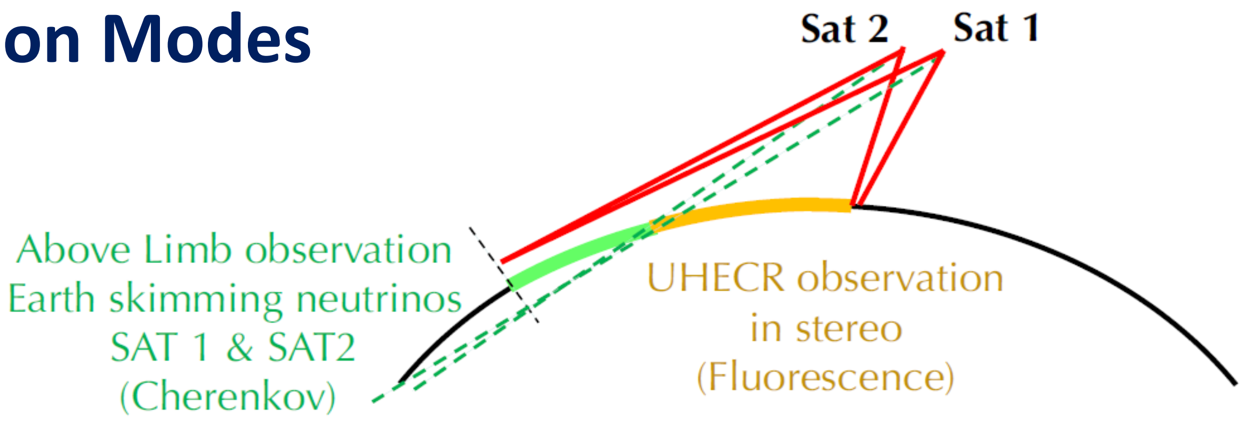
	(MA)PMTs	SiPMs
Wavelength range	300-800 nm	300-1000 nm
Internal Gain	10^5-10^7	10^5-10^7
Voltage	≤ 1100 V	≤ 100 V
Single Photon Counting Capability	Excellent	Excellent
Time Resolution	Excellent	Excellent
Power Consumption		Low
Noise	Low at ≤ 800 nm Increases with voltage and wavelength	Noisier than PMTs at ≤ 800 nm Comparable over whole range Increases with temperature (high at T>30°C)
Sensitivity to Magnetic Fields	Sensitive	Insensitive
Sensitivity to Radiation	Less sensitive to radiation than SiPMs	Sensitive
Robustness	More sensitive to intense light than SiPMs	Robust, can work under Moon light conditions
Size	Larger than SiPMs	Compact

POEMMA

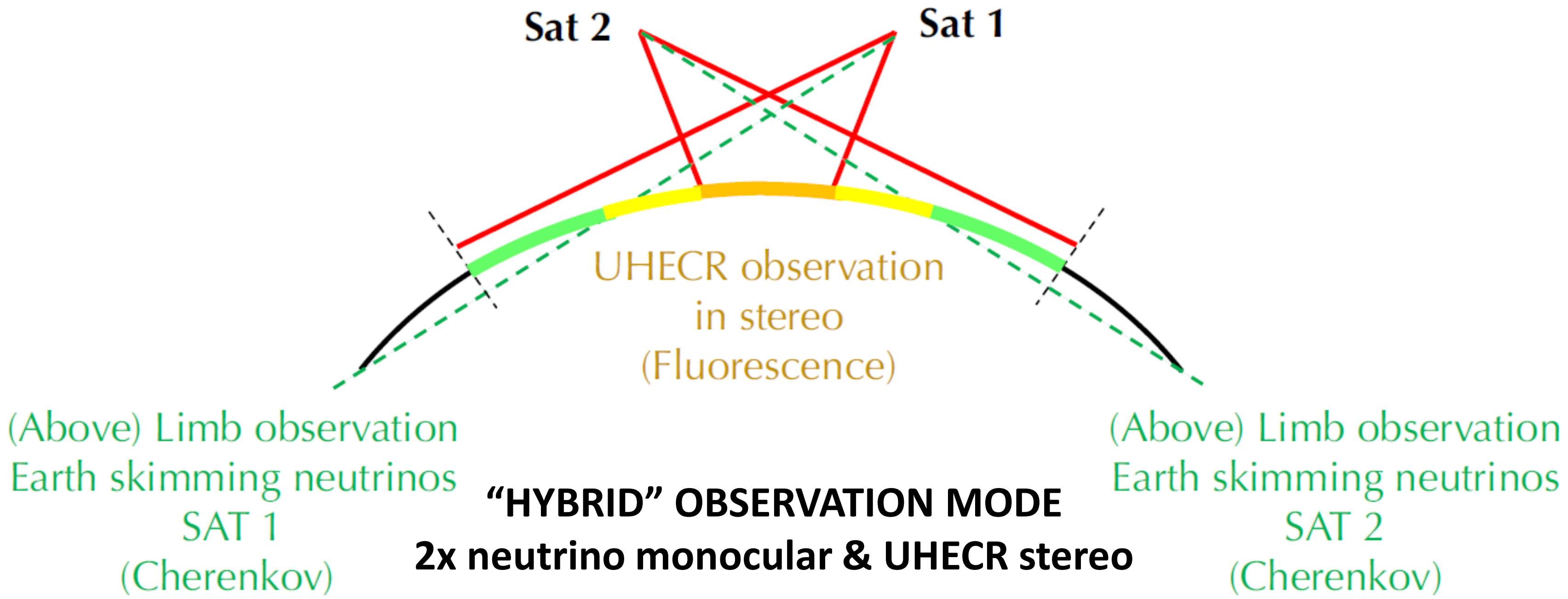
Observation Modes



PRIMARY UHECR OBSERVATION MODES
UHECR stereo & no neutrino observation



PRIMARY NEUTRINO & SECONDARY UHECR OBSERVATION MODES
Neutrino stereo & UHECR monocular

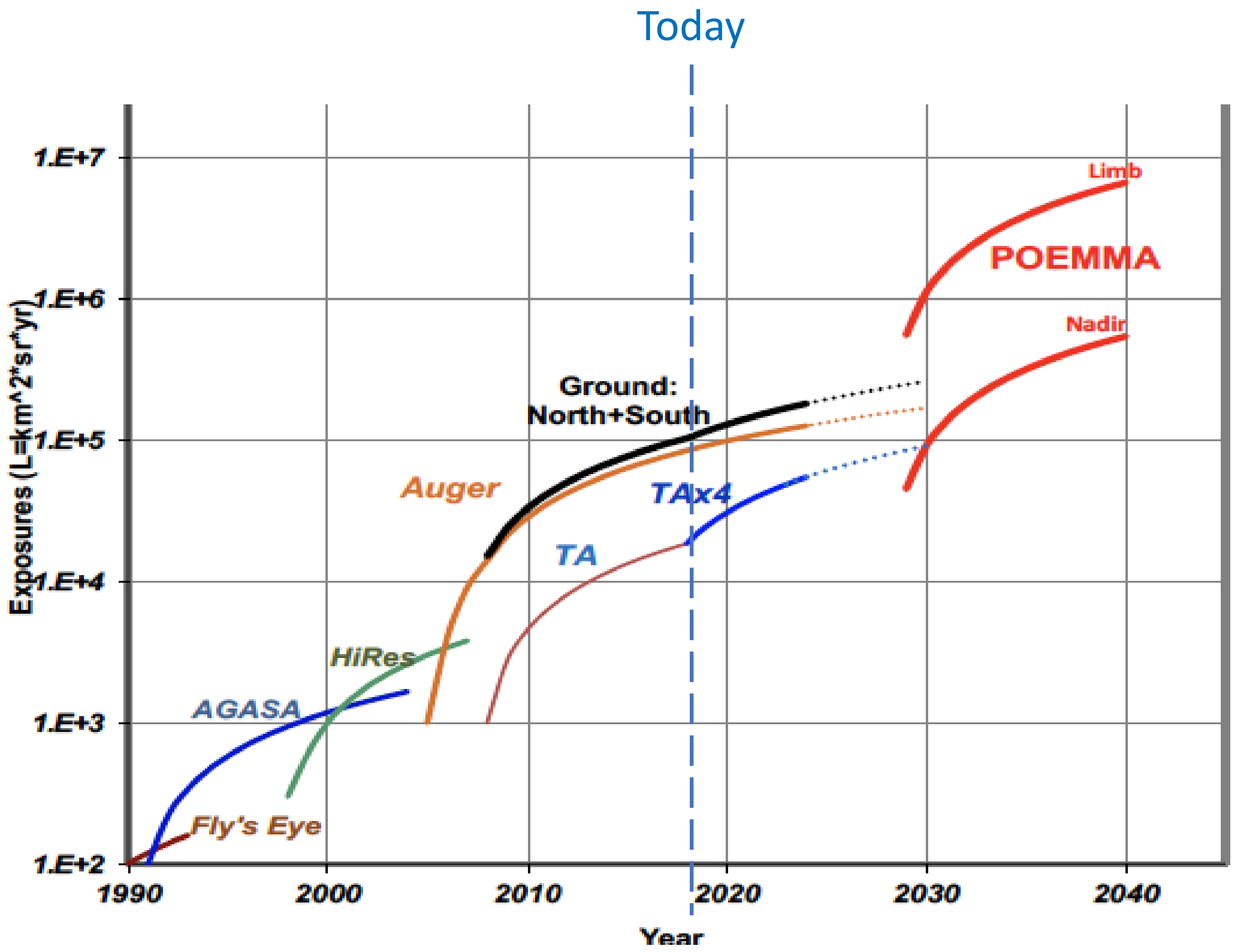


“HYBRID” OBSERVATION MODE
2x neutrino monocular & UHECR stereo

POEMMA

Primary UHECR observation mode

- POEMMA designed to observe cosmic rays with E > 10^{18} eV
- Statistics of such events higher from space than on ground
- Significant increase in exposure (~10 x ground arrays, ~100 x fluorescence detectors)
- Good energy, angular, and shower maximum resolutions, to guarantee the discovery of UHECR sources

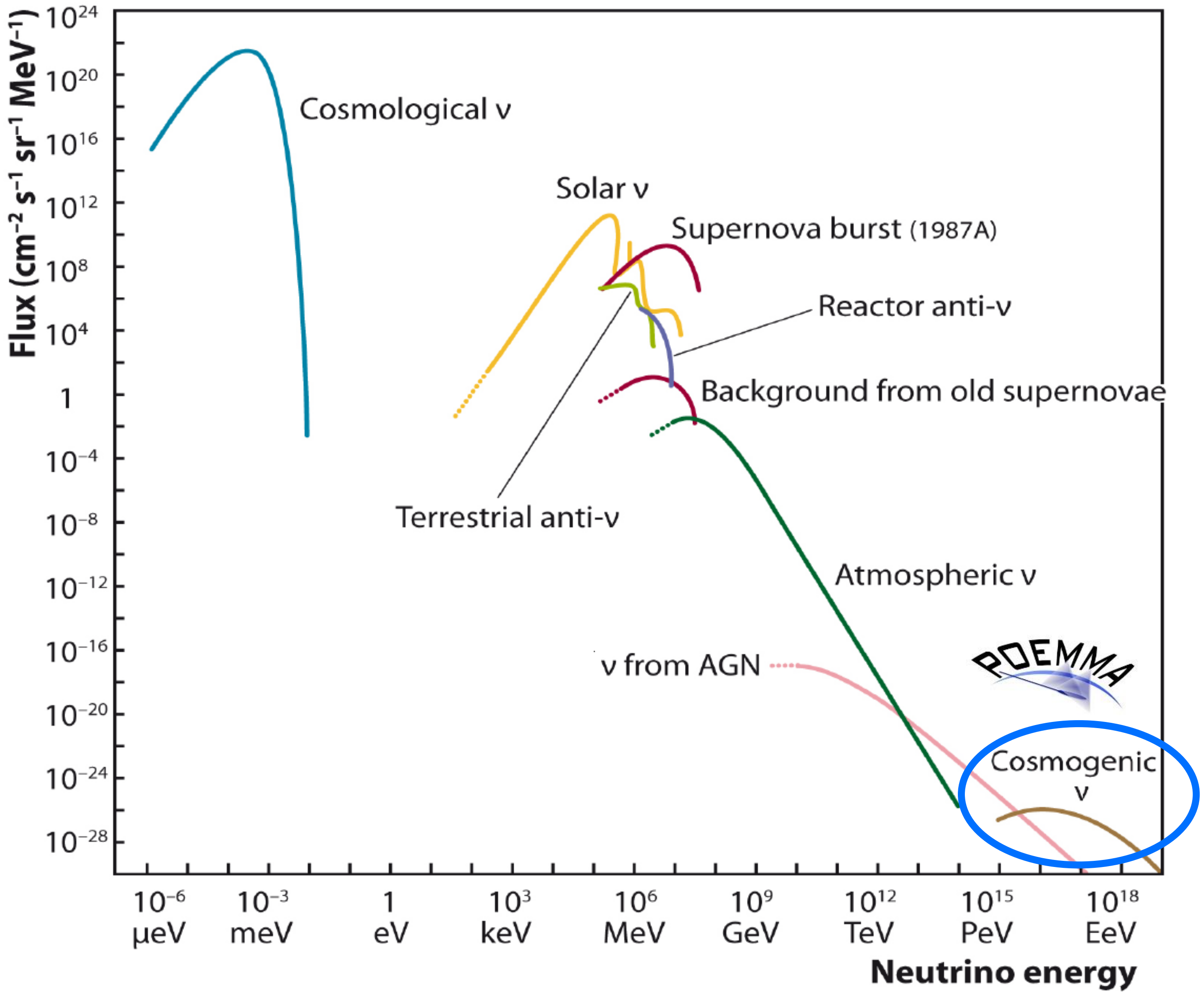


UHECR Exposure History

POEMMA

Primary neutrino observation mode

- POEMMA designed to observe neutrinos with $E > 10^{16}$ eV through Cherenkov signal of tau decays.
- The UHE neutrinos are expected to be born as ν_μ or ν_e.
  Due to vacuum oscillations, however, the astrophysical and cosmogenic neutrino flux at the Earth is expected to be almost equally distributed among the three neutrino flavours ν_μ, ν_e, ν_τ
- Some experiments search for ν_τ (ANITA, IceCube-Gen2, MAGIC…)
  → POEMMA will join the research!

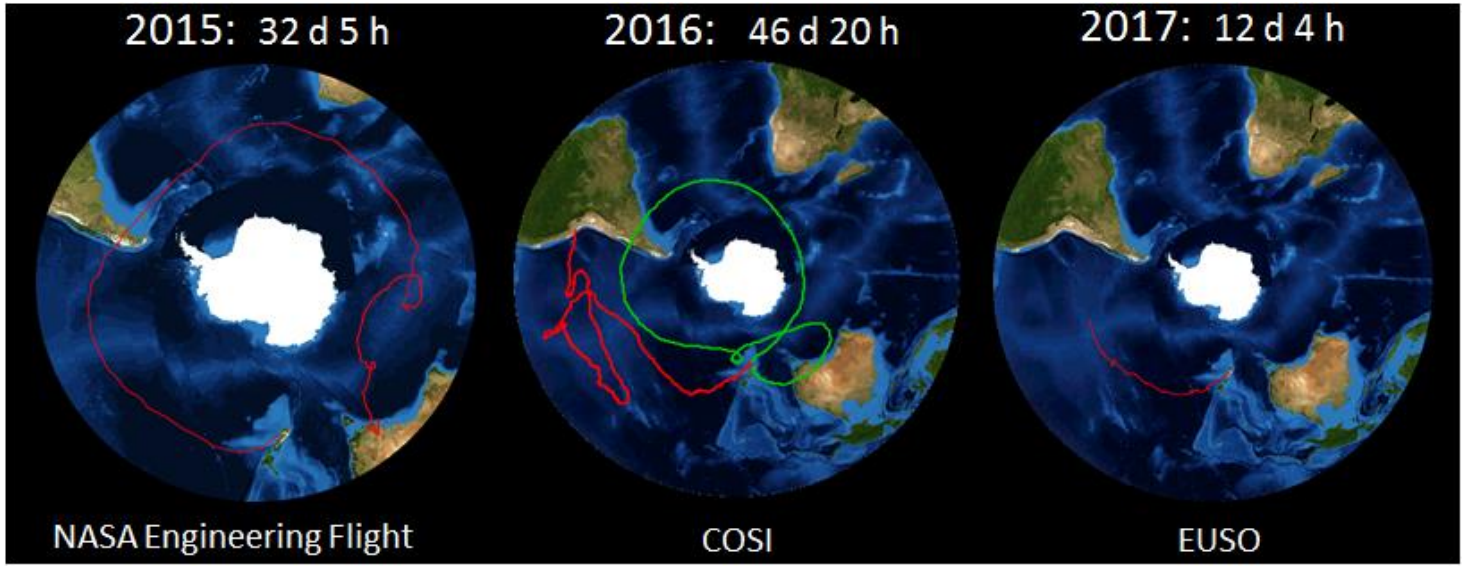


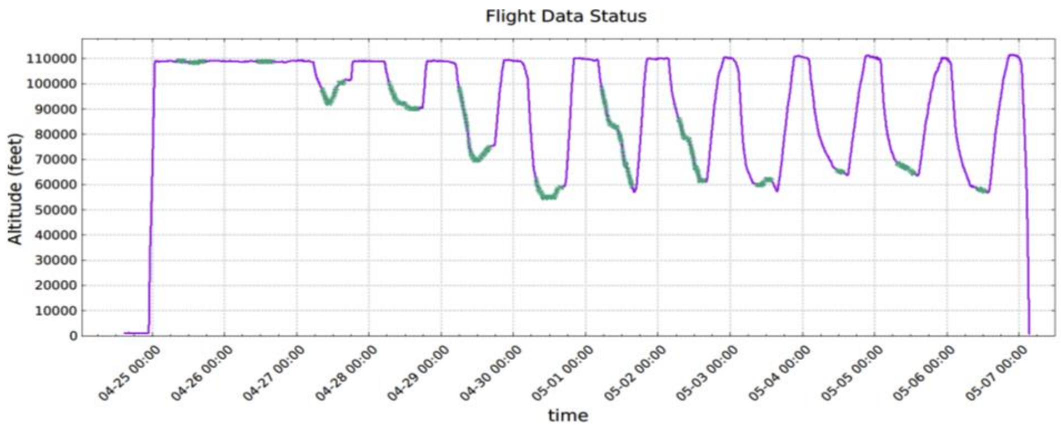
Experience from EUSO-Super Pressure Balloon (EUSO-SPB)

Goals:
- Detect UHECRs for the first time from high altitude
- Test the detector at high altitude
- Measurement of the UV background of the atmosphere from above

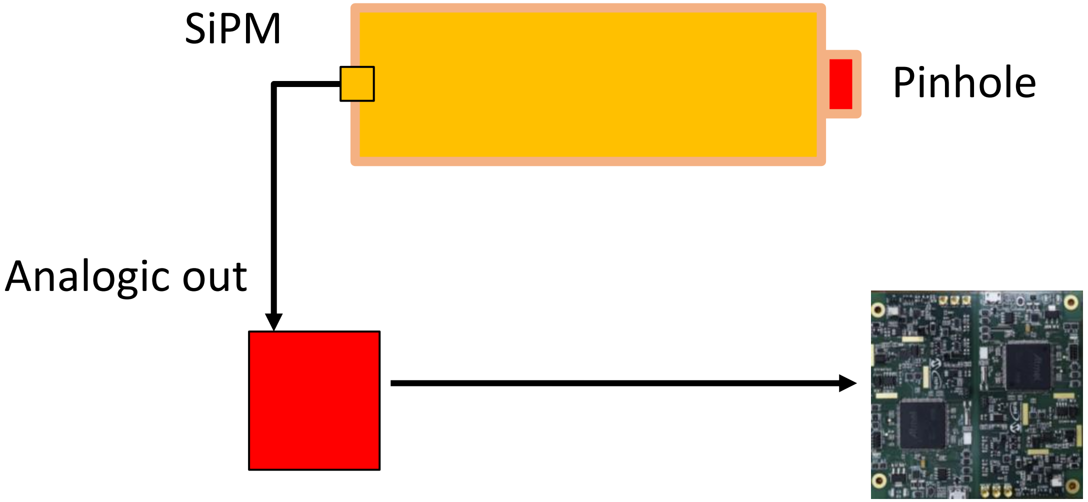
Mission start:
25 Aprile 2017 from New Zealand

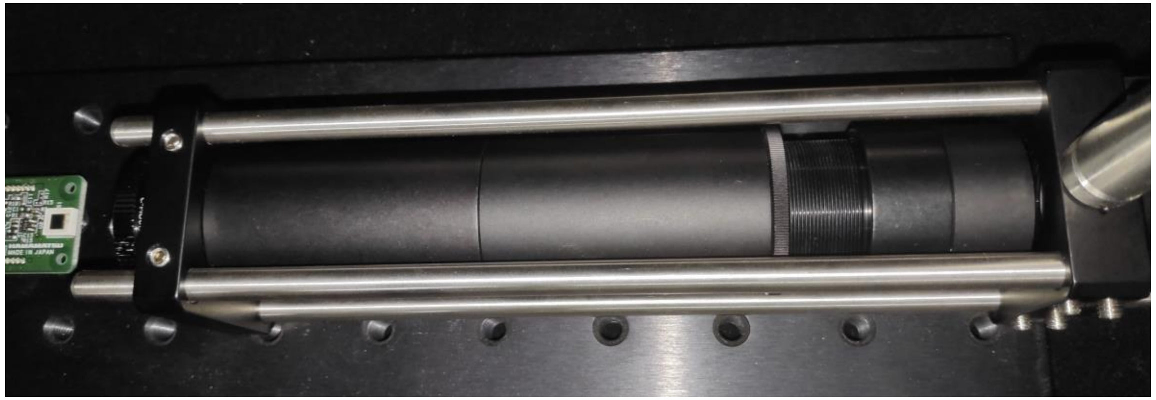
Mission end:
7 Maggio 2017 Pacific Ocean





Pinhole Camera

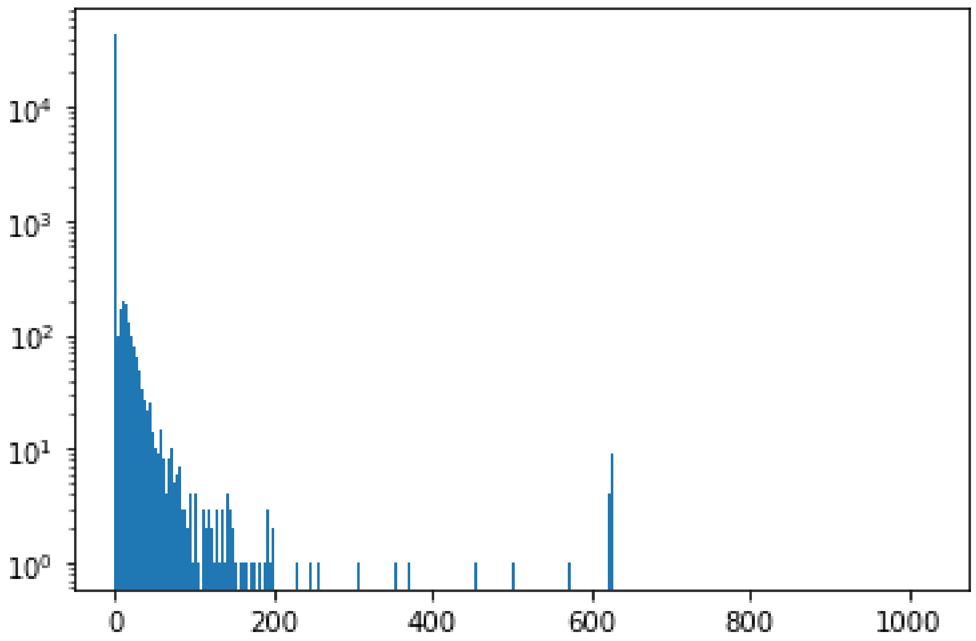


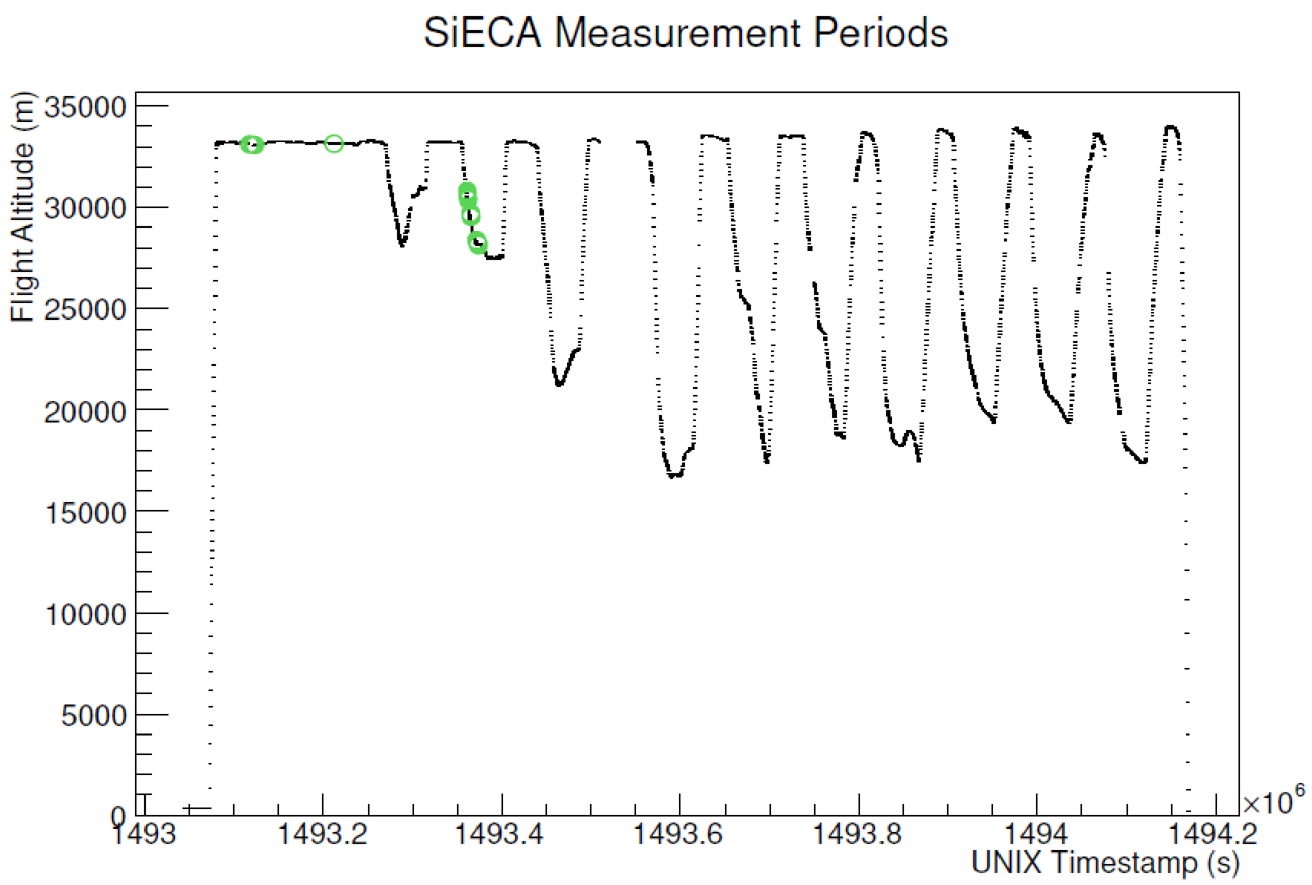


Pinholes

Radiation environment @ EUSO-TA

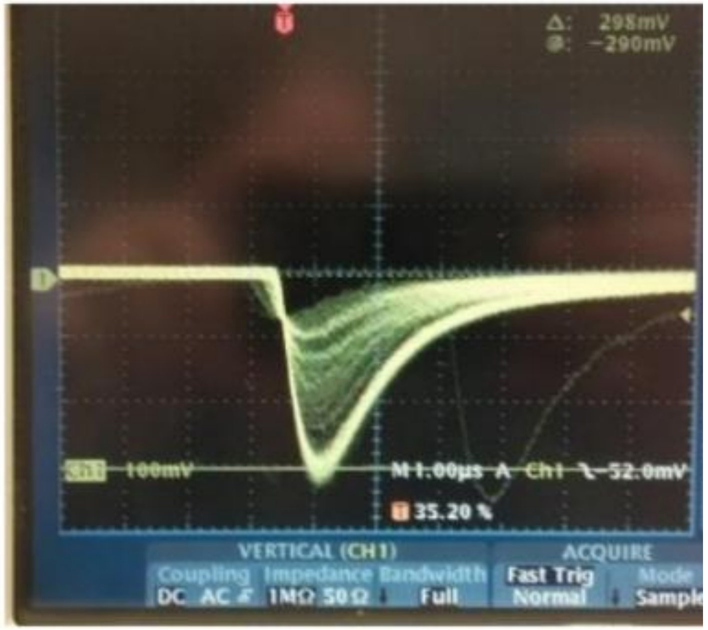
- 24/6/2022





EUSO-SPB1 altitude with SiECA operation periods indicated in green circles. Descents indicate night cold cycles, rising with heat from the sun. [W. Painter PhD Thesis]

Scionix CsI scintillation detector with SiPM readout



25.4B25.4/SIP-E3-Cs-T-X

Description: CsI(Tl) scintillation detector with SIPM readout and built-in preamplifier / bias generator and temperature sensor

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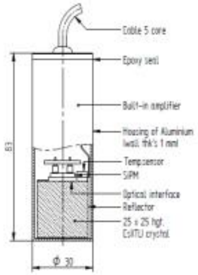
Scintillation material : CsI(Tl), 25.4 x 25.4 mm

Drawing number : VS-1426

Maximum detector diameter : 30 mm, 83 mm high

Crystal read out : SENSL: ArrayJ-60035-4P

Electronics : Trans impedance amplifier and bias generator, temperature sensor



Power supply Voltage : 5.2 - 16 V (5 mA @ 5.2 V)

SiPm Bias Voltage : 27.5 V

Temperature sensor : DS18B20

Electrical connections : Flying leads

Brown = + 5.2-16 V
Yellow = Signal
Braid = Common ground
White = DQ (DS18B20)
Green = V_{dd} (DS18B20)

PERFORMANCE

Output impedance : 50 Ω

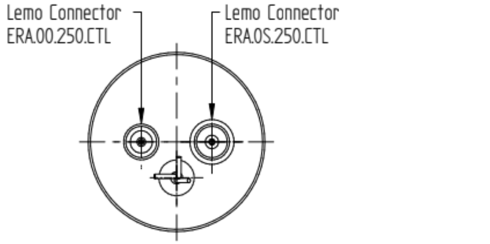
Pulse rise time : 1.3 μs (50 Ω)

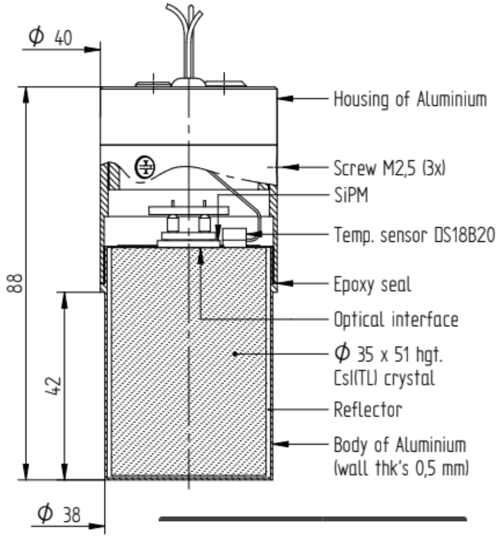
Pulse fall time (1/e) : 2.8 μs (50 Ω)

Energy resolutions (662 keV) : < 8% FWHM

Noise level : < 15 keV

Gain : Approx. -0.3 V / MeV (1 MΩ)





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- [PoS(ICRC2017)442] W. Painter et al., “SiECA: Silicon Photomultiplier Prototype for Flight with EUSO-SPB”, PoS(ICRC2017)442
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