From Ground to Space: the JEM-EUSO program for UHECRs and Astrophysical Neutrinos

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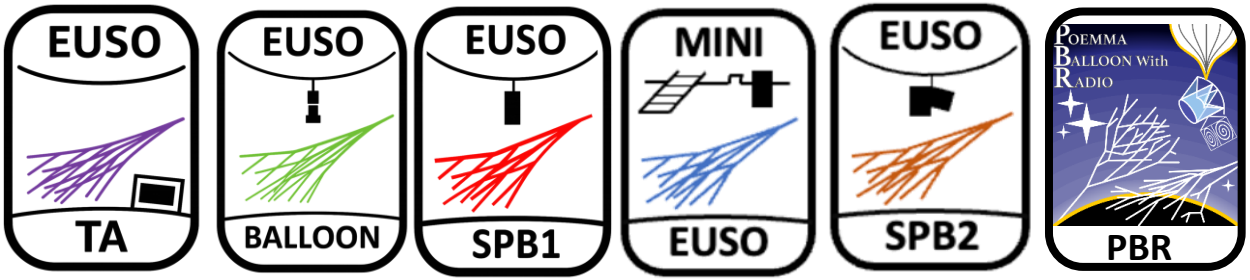
INFN - Sezione di Napoli

TeV Particle Astrophysics TeVPA Valencia 2025

The JEM-EUSO international collaboration

Joint Experiment Mission for Extreme Universe Space Observatory

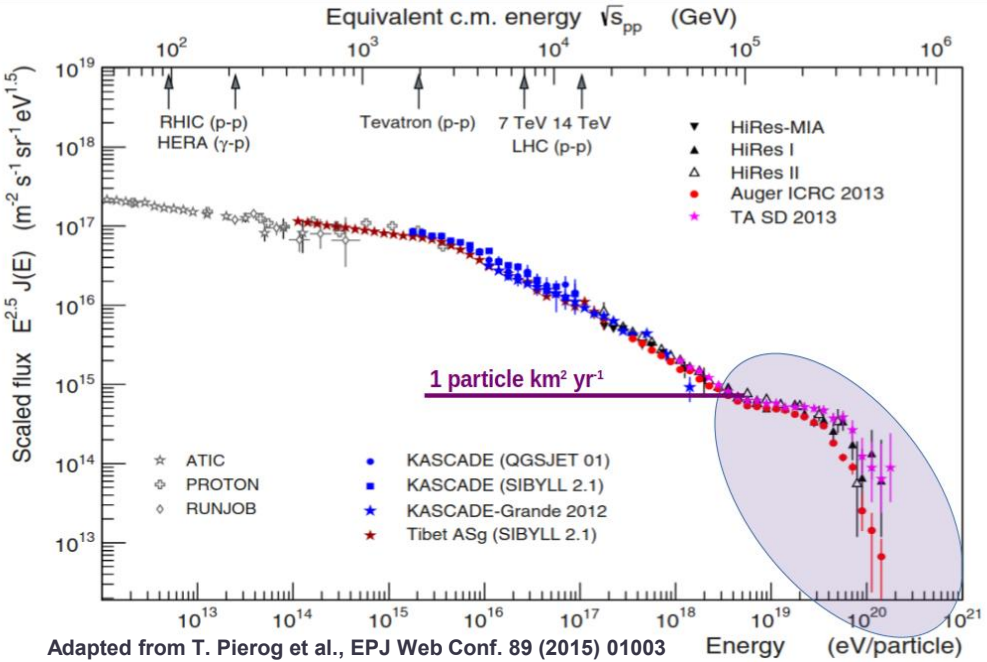
The JEM-EUSO Program in 2025



- 12 countries
- 160 scientists
- supported by the major space agencies

NASA JAXA РОСКОСМОС ASI Agenzia Spaziale Italiana cnes CENTRE NATIONAL D'ETUDES SPATIALES

Astronomy and Astrophysics through the particle channel: Ultra-High-Energy Messengers



Adapted from T. Pierog et al., EPJ Web Conf. 89 (2015) 01003

Ultra-High Energy Cosmic Rays: $E > 5\times10^{18}$eV

- Extremely low flux: < 1 event/km²year
- Ground observatories (Auger, TA): only a few detections per year → limited statistics and hemisphere bias

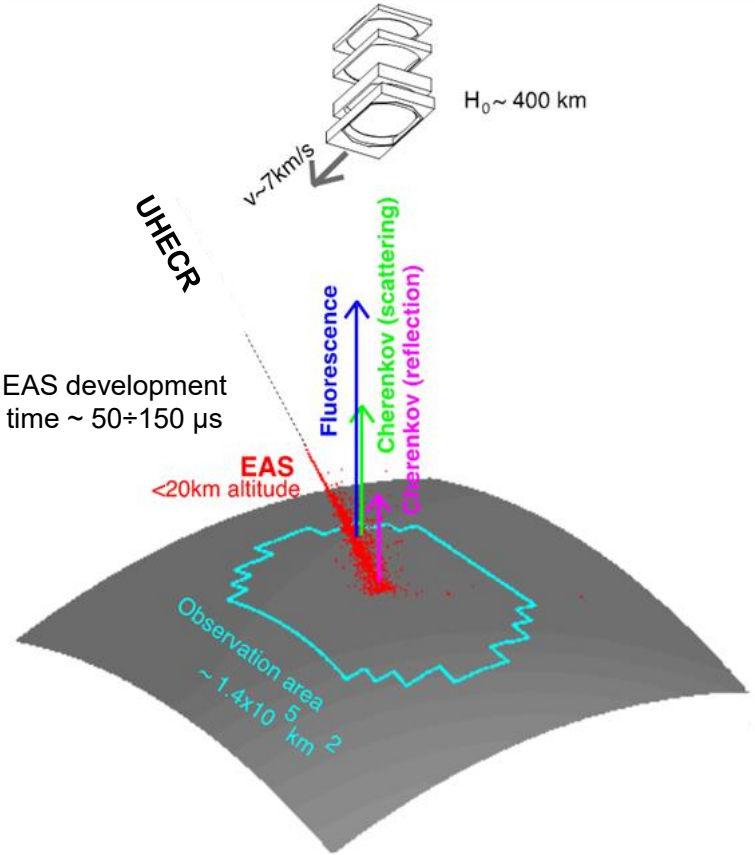
Plenary talk by J. Alvarez-Muñiz

Observing from orbit: J. Linsley 1980

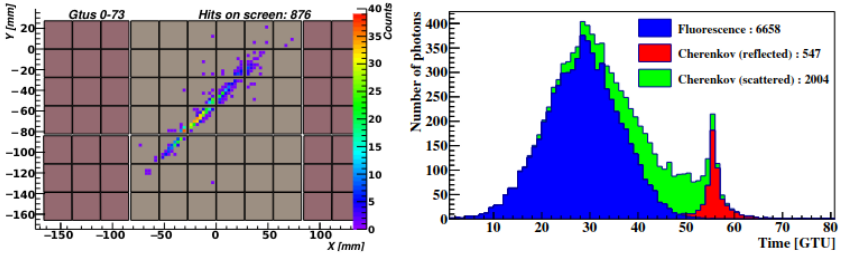
- ➢ Vastly increased exposure: ≥ 3×10^4 km²·sr
- ➢ Near-uniform, full-sky coverage
- ➢ Monitor the Earth's limb for PeV ÷ EeV ν_τ

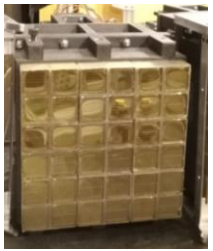
A space observatory can turn century-scale statistics into year-scale data, enabling spectrum, anisotropy and source correlation at the highest energies

Observational principle of the fluorescence camera



Observe from space transient luminous phenomena occurring in the Earth's atmosphere:
fluorescence and Cherenkov UV photons generated by Extensive Air Showers created by UHECR



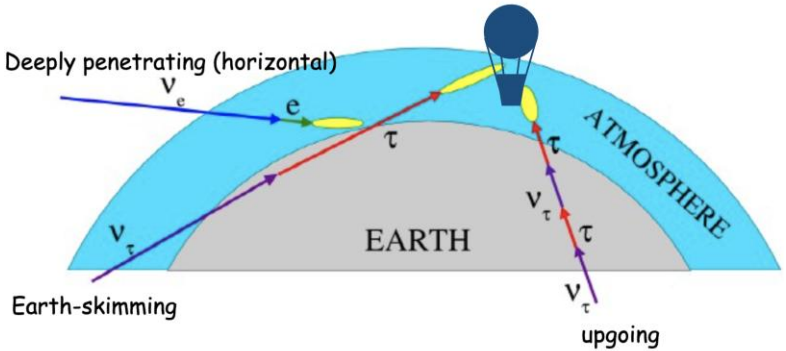


Fluorescence Camera

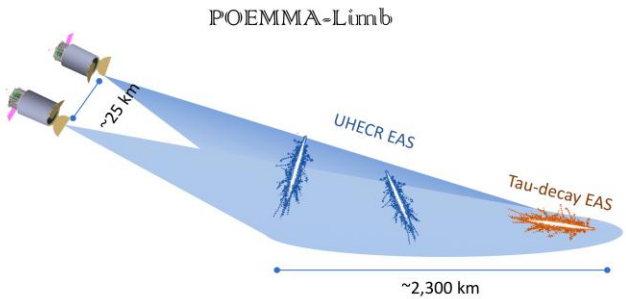
- Photo-Detection Module (PDM): 36 64-pixel MAPMT
- single photoelectron counting
- μs time unit, 1 event = 128 time units

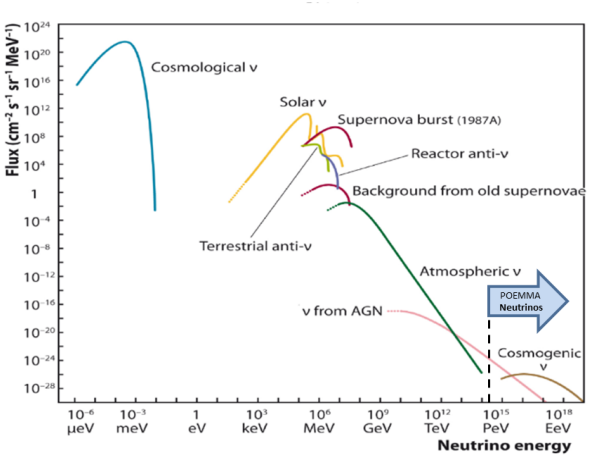
Wavelength Sensitivity	UV 300 - 420 nm (BG3 filter)
Pointing (zenith angle)	Down (nadir)
Number of Pixels per PDM	36 MAPMT × 64 = 2304

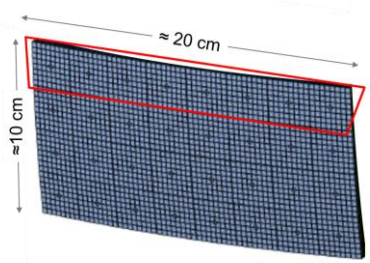
Recent addition: the Cherenkov camera

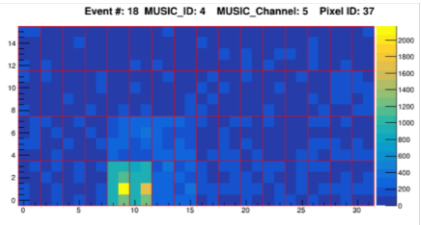


Observe from space transient luminous phenomena occurring in the Earth's atmosphere:
Cherenkov photons generated by CR or neutrinos





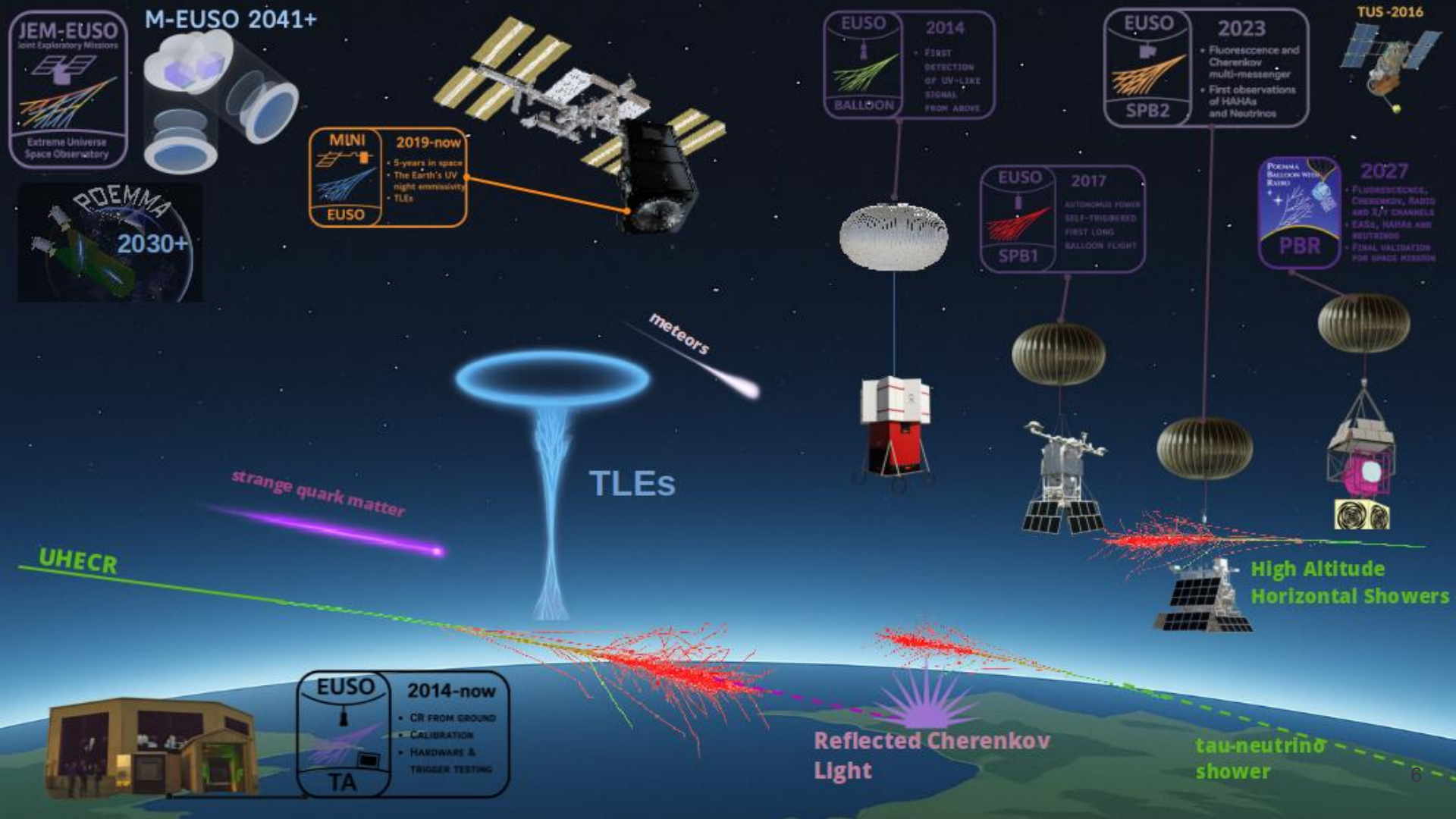




Cherenkov Camera

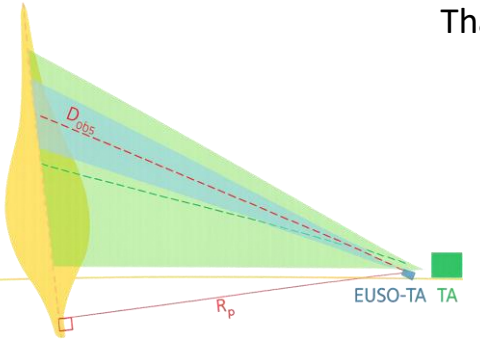
- 64-pixel-SiPM arrays (S13361-3050NE-08)
- Bifocal for background reduction
- Sampling time of 5/10 ns

Wavelength Sensitivity	320-900 nm
Pointing (zenith angle)	Tilted (limb)
Number of Pixels per PDM	8 arrays × 64 = 512

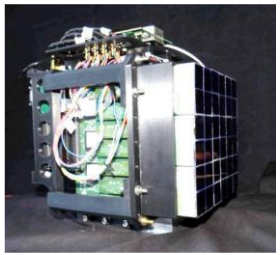

JEM-EUSO
Joint Exploratory Missions
Extreme Universe Space Observatory
M-EUSO 2041+
MINI
EUSO
2019-now
• 5-years in space
• The Earth's UV night emmissivity
• TLEs
POEMMA
2030+
EUSO
BALLOON
2014
• FIRST DETECTION OF UV-LIKE SIGNAL FROM ABOVE
EUSO
SPB1
2017
AUTONOMOUS POWER SELF-TRIGGERED FIRST LONG BALLOON FLIGHT
EUSO
SPB2
2023
• Fluorescence and Cherenkov multi-messenger
• First observations of HAHAs and Neutrinos
TUS -2016
PBR
2027
• FLUORESCENCE, CHERENKOV, RADIO AND X,Y CHANNELS
• EASs, HAHAs AND NEUTRINOS
• FINAL VALIDATION FOR SPACE MISSION
meteors
TLEs
strange quark matter
UHECR
High Altitude Horizontal Showers
EUSO
TA
2014-now
• CR FROM GROUND
• CALIBRATION
• HARDWARE & TRIGGER TESTING
Reflected Cherenkov Light
tau-neutrino shower

EUSO-TA: a ground testbed since 2014

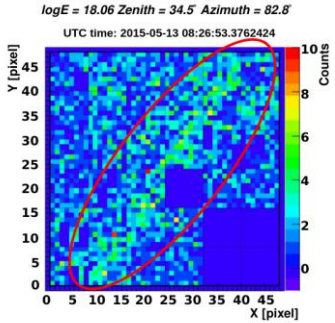
Thanks to the **Telescope Array Collaboration**

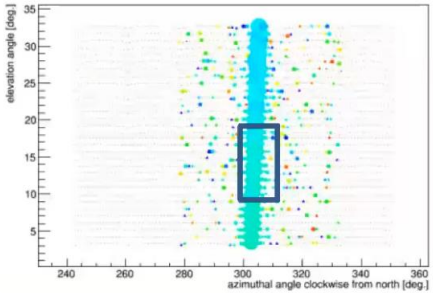


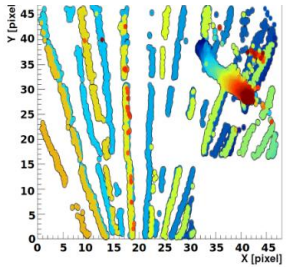
- ✓ Ground-based observations of UHECRs
- ✓ Test individual detector components
- Installed in 2014, observations from 2015 to 2022 (9 UHECRs)
- Currently being upgraded

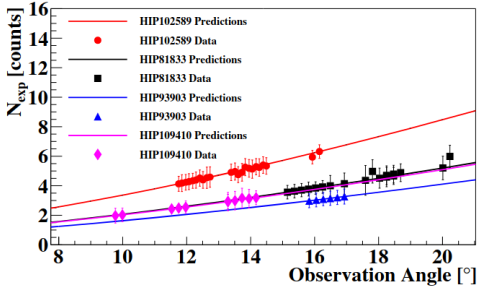


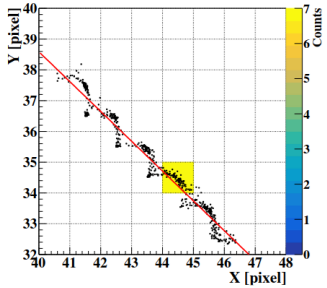
- 1 PDM: 36 MAPMTs, 2304 pixels
- Fresnel lenses: 2 × 1 m²
- FoV: 10.5°, 2.1 × 2.1 km² at 3 km
- Observations in parallel with TA









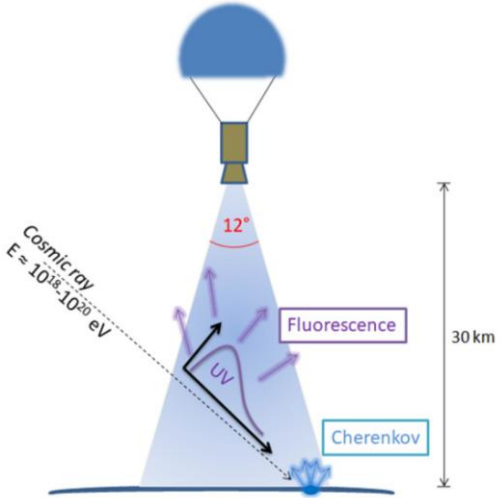


Stratospheric balloons: EUSO-Balloon (2014)

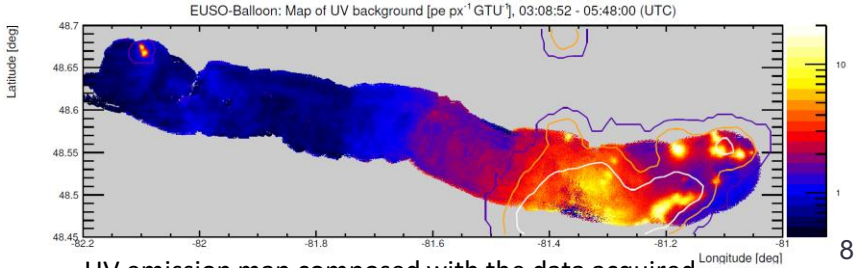
https://www.youtube.com/watch?v=64C9DxmE0sY

Technology demonstrator: 1-night flight from Timmins (Canada)

- 1 PDM pointing downward
- ➢ Validated detector, optics & trigger at 38 km (3 mbar)



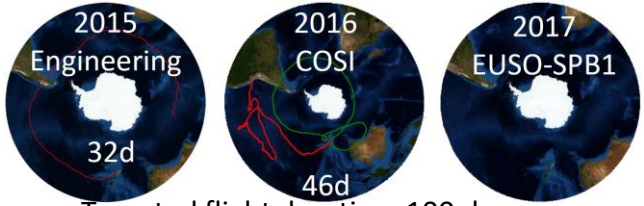
- ✓ UV emissivity w/ or w/o cloud
- ✓ UV / IR anti-correlation (expected)
- ✓ EAS-like laser events reconstruction
- ✓ Serendipitous flash source detection



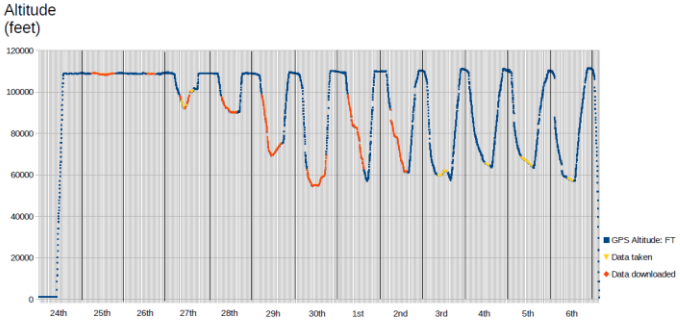
UV emission map composed with the data acquired

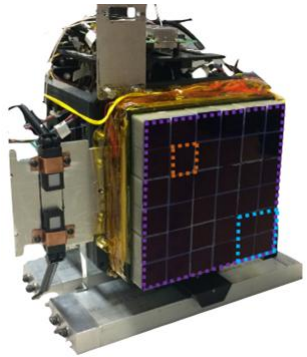
Stratospheric balloons: EUSO-SPB1 (2017)

https://www.youtube.com/watch?v=BfvMS76whEU



Targeted flight duration: 100 days





NASA mission of opportunity from Wanaka, NZ

- 1 PDM, looking downward
- 12 days: 25 hours of scientific data downloaded
- Proved long-duration power and communications systems

- ✘ Fluorescence signals from EAS
- ✓ Measurement of UV emissions over the ocean and cloud cover
- ✓ Search for fast, pulse-like UV signatures from other sources

Stratospheric balloons: EUSO-SPB2 (2023)

https://www.youtube.com/watch?v=cbghe-vWizc

NASA SPB, Wanaka, NZ

- Flight terminated after 1.5 days due to a leak in the balloon

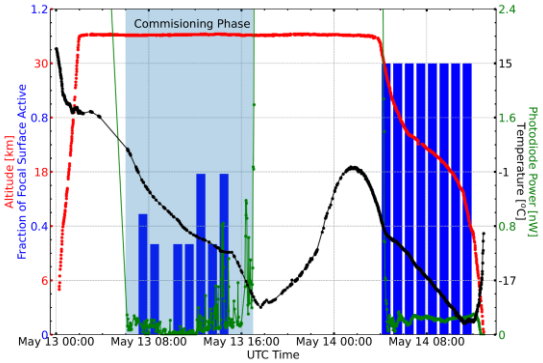
Two 1m-diameter telescopes:

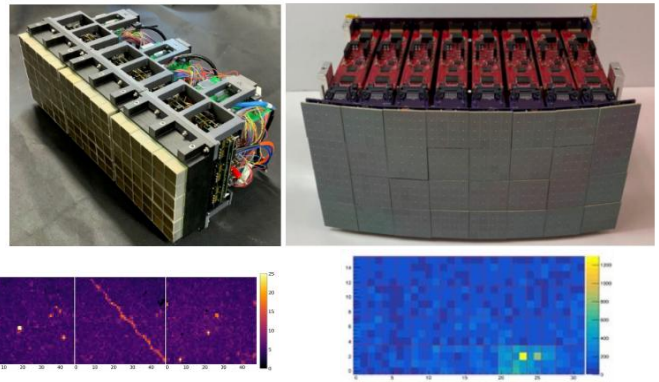
- **Fluorescence**: 3 PDM pointing downward
- **Cherenkov**: bi-focal Schmidt optics, 512 pixel, pointing at the limb

✓ 120k fluorescence and 32k Cherenkov triggers

✓ First upward-shower ν_τ search, a few PeV candidates

✓ All the instruments worked as expected, but not enough time to accomplish the main science goals

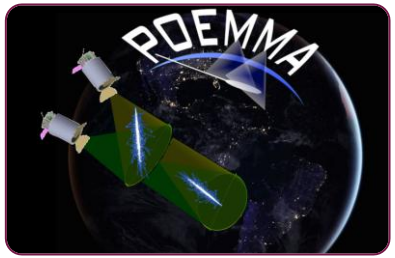




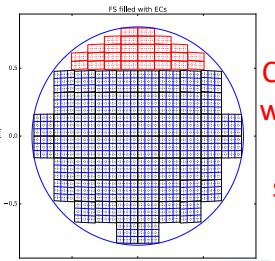
POEMMA Balloon with Radio: a multi-detector approach

See R. Caruso talk later

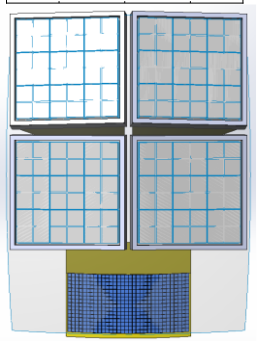
Probe Of Extreme Multi-Messenger Astrophysics

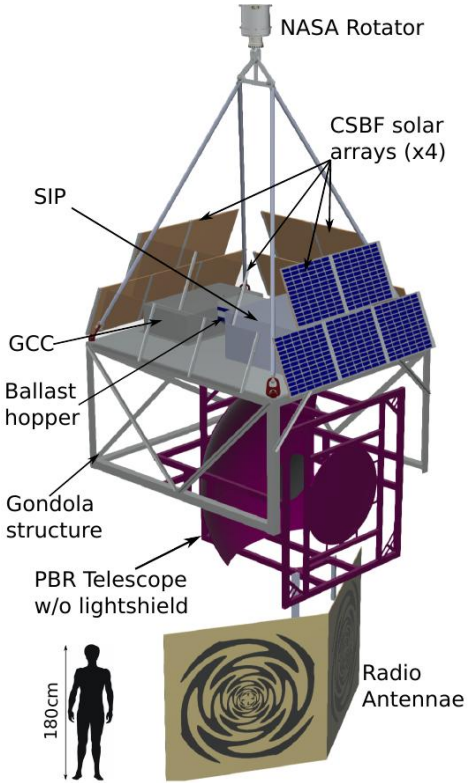


UV Fluorescence with MAPMTs 1µs sampling



Cherenkov with SiPMs 10 ns sampling



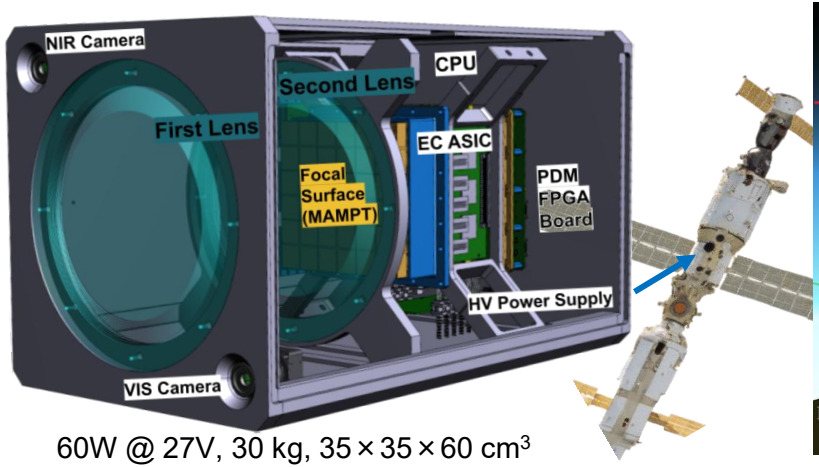


Pointing:
- 360° in azimuth
- -90°/+13° in zenith

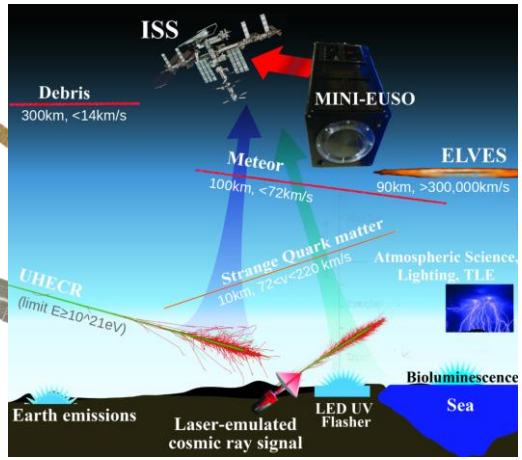
Planned launch in **2027** from Wanaka, NZ
- 1.1 m-diameter Schmidt optic telescope with **hybrid focal surface**: fluorescence and Cherenkov
- Low-frequency radio instrument
- X-ray/gamma detectors

- UHECRs from sub-orbital altitude
- High-Altitude Horizontal Showers
- Search for astrophysical ν from Target-of-Opportunity events
- First combined observation of optical Cherenkov and radio signal

Mini-EUSO: on the ISS since 2019

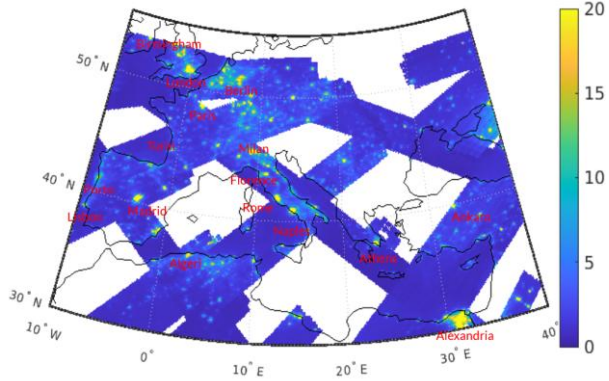


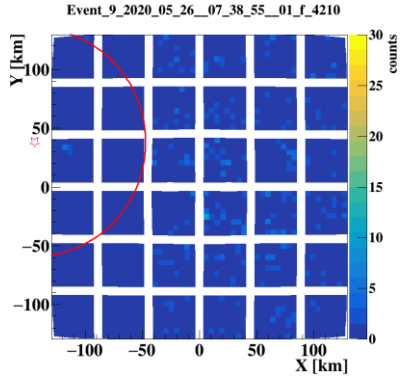
60W @ 27V, 30 kg, 35 × 35 × 60 cm^3

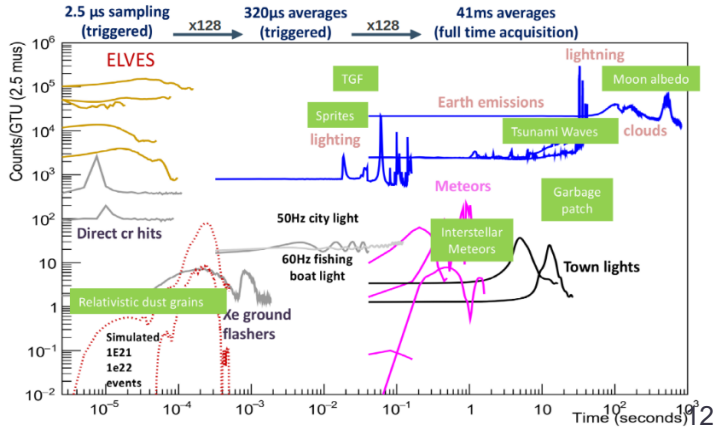


Multi-purpose instrument, 150+ data-taking sessions:

- ✓ End-to-end calibration from ground
- ✓ UV maps
- ✓ TLEs: elves and halos
- ✓ Meteors

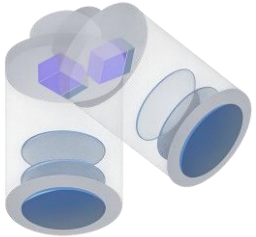






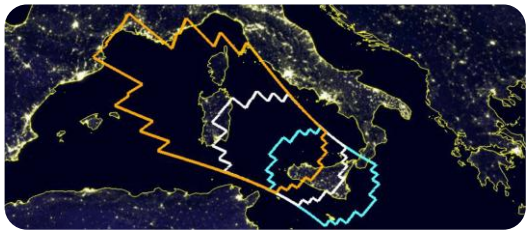
Casolino et al., Remote Sensing of Environment (2023) [2212.02353]

Multimessenger-EUSO: a study for a LEO Satellite



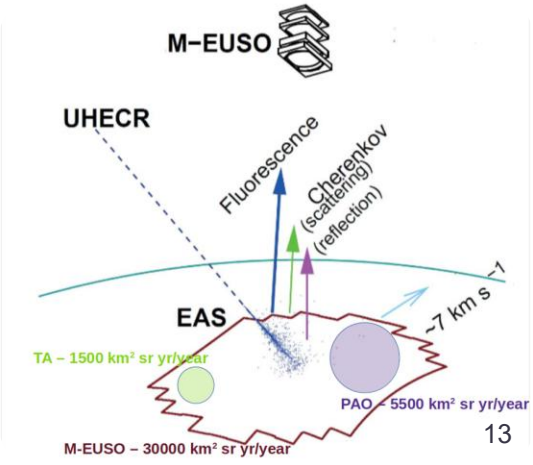
Satellite free-flyer instrument

- Double Fresnel lens Ø 2.3 m, FoV 40°×40°, 0.12°/ px
- Hybrid Focal Surface:
  - Fluorescence: 49 PDM: 10^5 pixels, 2.5 μs/320 μs/40 ms gate time
  - Cherenkov: 6 000 SiPM pixels, 10 ns sampling



Objectives:

- **UHECR > 30 EeV**: first uniform full-sky map, ≈ 250 events yr^{-1}
- ν_τ **> 40 PeV**: Earth-skimming Cherenkov, opens EeV-ν window
- Multi-messenger: fast tilt ToO for GW, GRB, blazar alerts; complements IceCube, CTA, Athena
- Atmosphere and exotica: TLE, ELVES, meteors, searches for SQM



Take home message

🚀 Space-Based Detectors for UHECR can address fundamental questions in CR physics

🌌 Core element of the UHECR community roadmap

🛰️ JEM-EUSO program: key components validated at TRL 6, **ready for large-scale space mission**

🎯 Preliminary satellite designs provide the required angular and energy resolutions for source and composition studies

🌍 Hybrid observations (space + ground): enhance measurement accuracy and enable deeper insights into the UHECR nature

Thank you!