Joint Experiment Missions-
Extreme Universe Space Observatory

The Atmospheric Science of Mini-EUSO space experiment: results and perspectives

M. Bertaina – Univ. & INFN Torino
for the JEM-EUSO Collaboration
AtmoHEAD 2026, Olomouc 28-30 July 2026

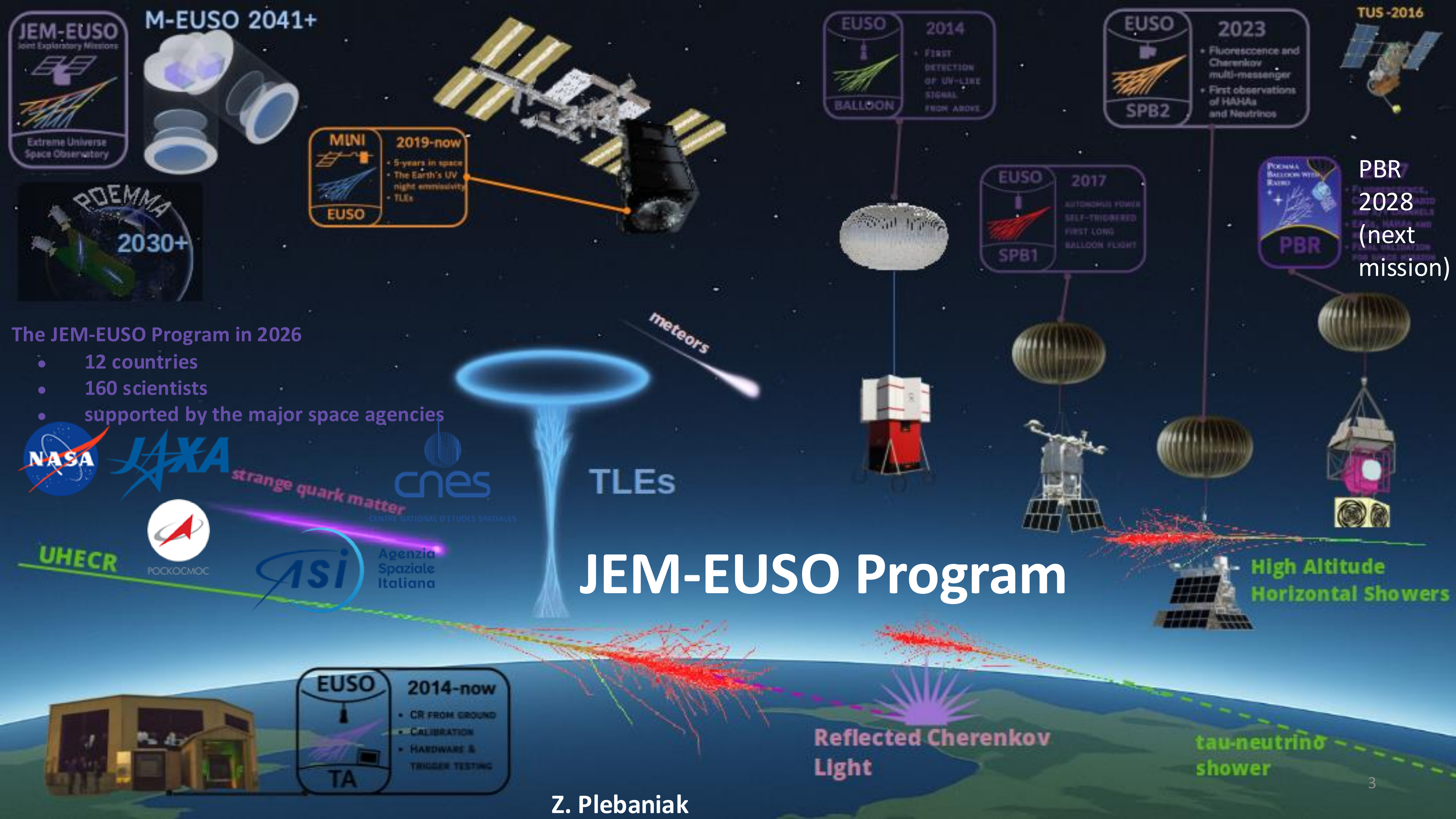
Index of presentation

- Introduction
- Calibration
- UV maps
- Clouds
- UV intensity
- UHECR efficiency curves
- Exposure
- Ground Flashers
- Short Light Transients
- Elves
- Aurorae
- Ocean whitecapping
- Fishing boats
- Meteors
- Strange Quark Matter
- Space Debris
- Conclusions

JEM-EUSO Program

The JEM-EUSO Program in 2026

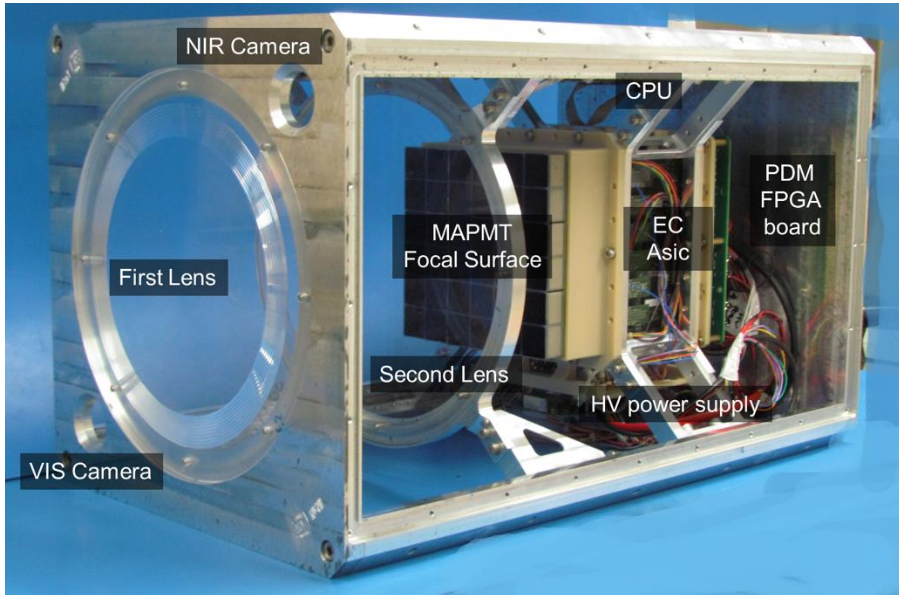
- 12 countries
- 160 scientists
- supported by the major space agencies



Z. Plebaniak

Mini-EUSO / UV- Atmosphera

- Compact detector (37 × 37 × 62 cm^3)
- 48x48 pixels, single photon counting
- UV wavelength (300-400 nm)
- Optical system: two Fresnel lenses, 25 cm diameter
- Large FOV (±21°). Pixel size at sea level ~6.3km (total of ~320x320 km^2)
- **Three different timescales**:
  - D1: 2.5 µs - EECRs and fast events (elves) - dedicated trigger logic (L1 trigger)
  - D2: 320 µs - atmospheric events - dedicated trigger logic (L2 trigger)
  - D3: 40.96 ms - slow events and UV maps - continuous data taking
- Ancillary cameras

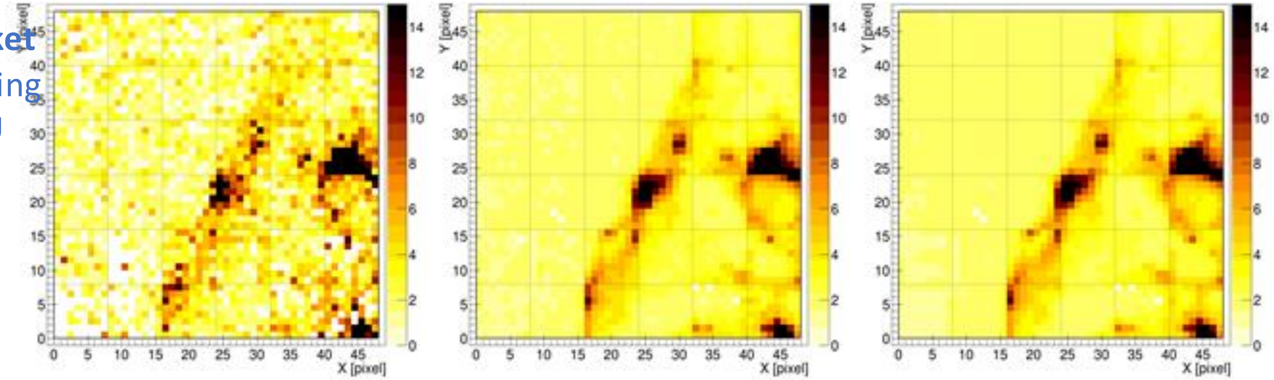


1 GTU = 2.5 µs

Single GTU / **packet resolution** assuming ~1 count/pix/GTU

Views of the Indian coast

Stat. error ~100/10% | Stat. er. ~10/1% | Stat. er. ~1/0.1%



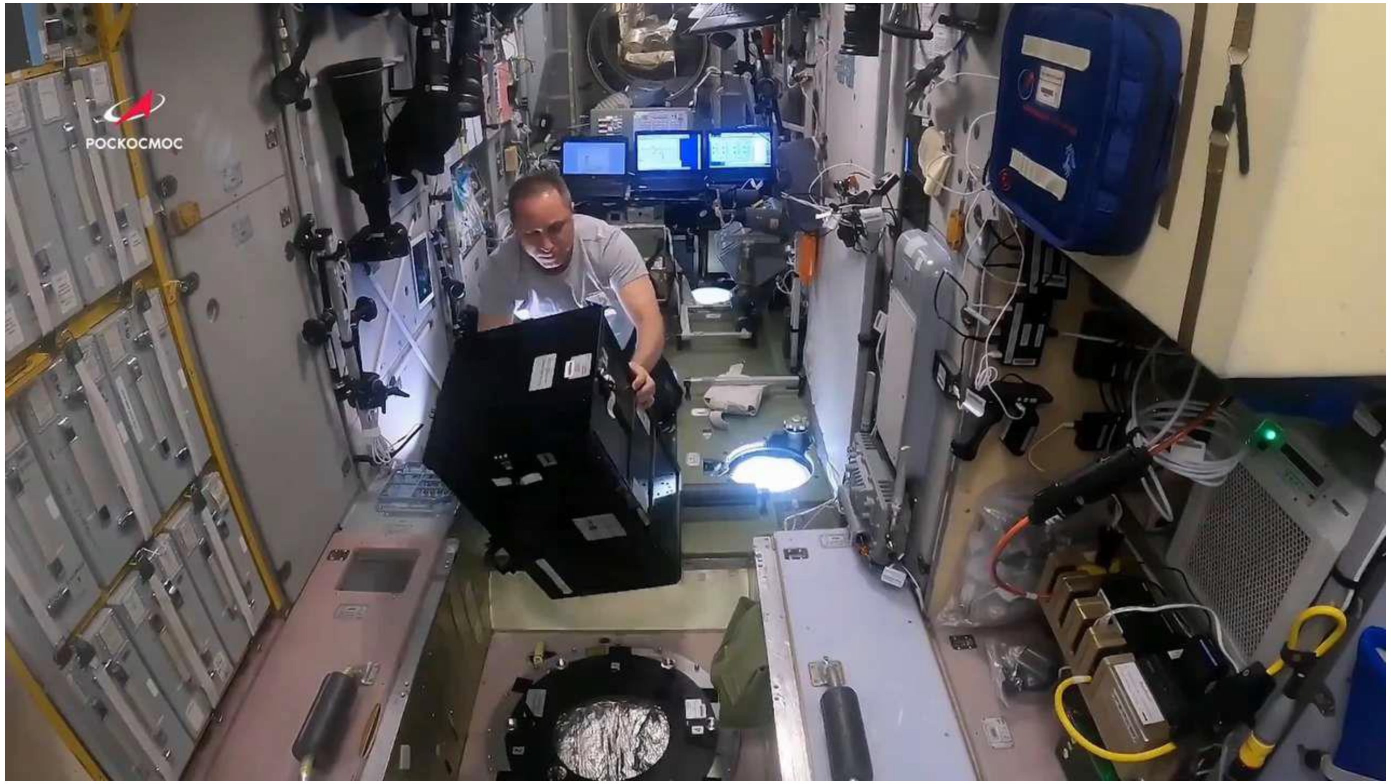
D1 **D2** **D3**

counts/GTU

M. Battisti

Mini-EUSO in flight operations

Launch: August 2019



Sessions: 1-14 Returned in April 2020

Sessions: 15-44 Returned in October 2021

Sessions 45-126 Returned in June 2025

Valuable data till session 150 - Operations terminated in 2026

START OF SESSION

- Latch on the UV-transparent window
- Connect 27V power supply cable
- Connect grounding cable
- Insert and latch the USB stick
- Turn on the switch

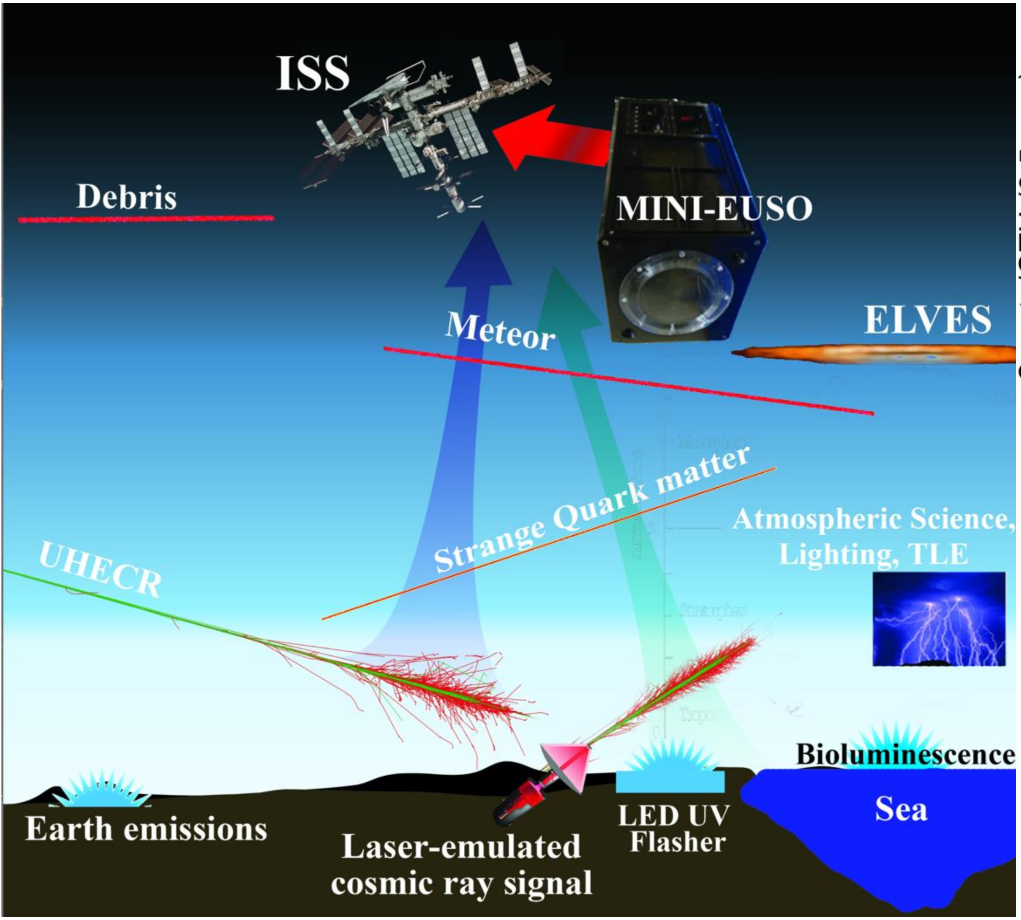
END OF SESSION

- Turn off the switch
- Remove and store USB stick
- Periodically copy of selected files on station computer for later downlink
- Unlatch and store the instrument

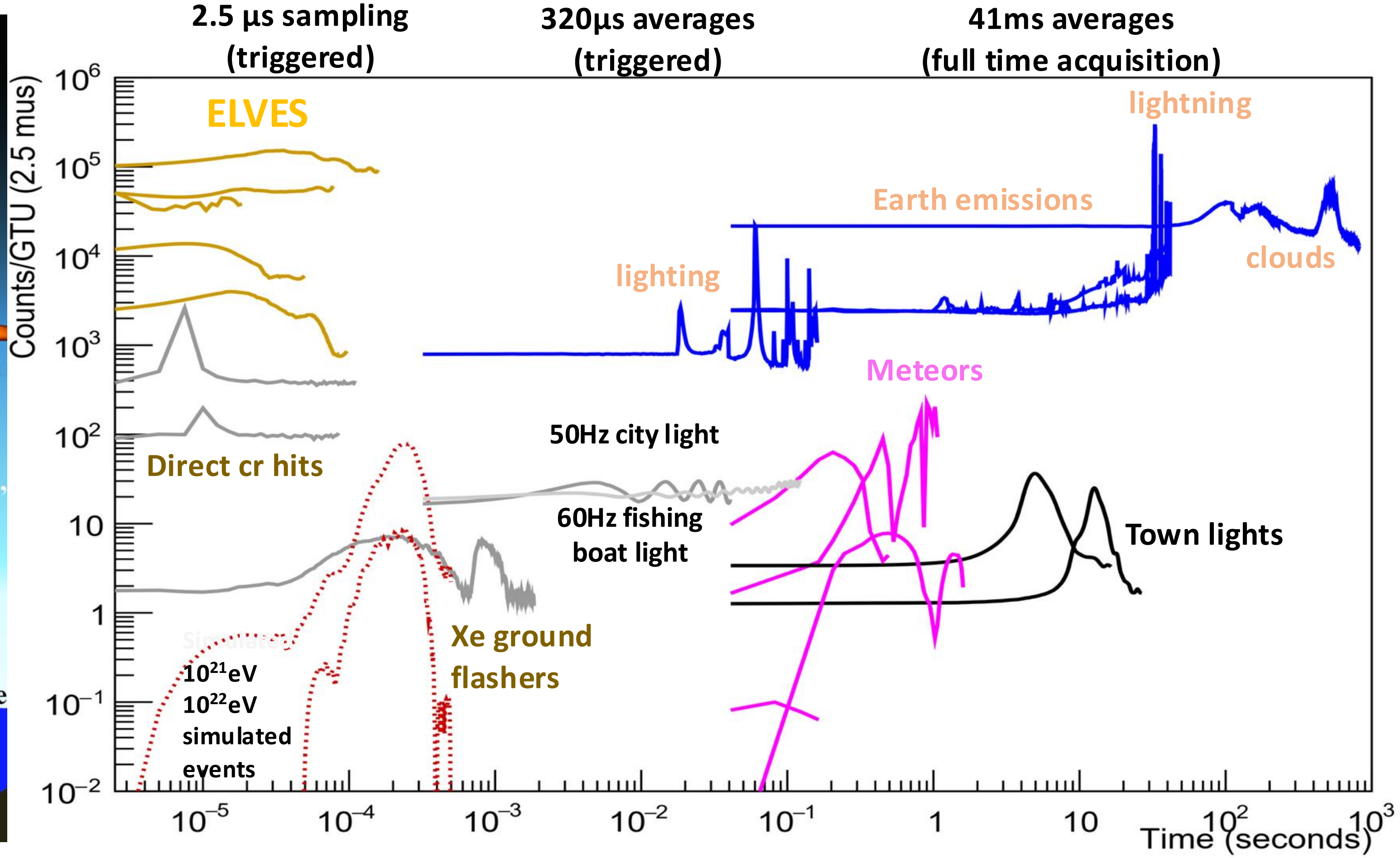
L. Marcelli

Scientific Objectives & Time Profile of Events

Sketch



Real Measurements (except EECRs)

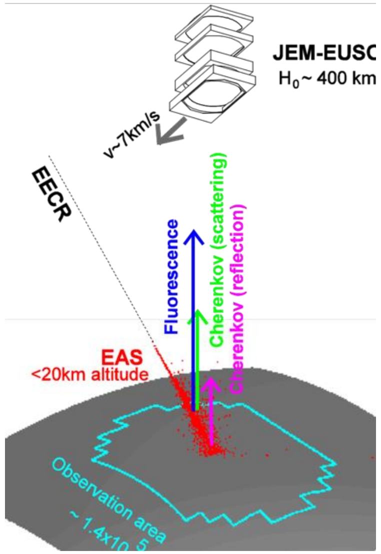


- Increase the TRL of JEM-EUSO instrumentation and test their performance in a relevant environment
- Demostrate some of the explorative objectives of JEM-EUSO (UV intensity, meteors, TLEs, strange quark matter searches, space debris observations, bio-luminscence, cloud monitoring, etc…)

M. Casolino

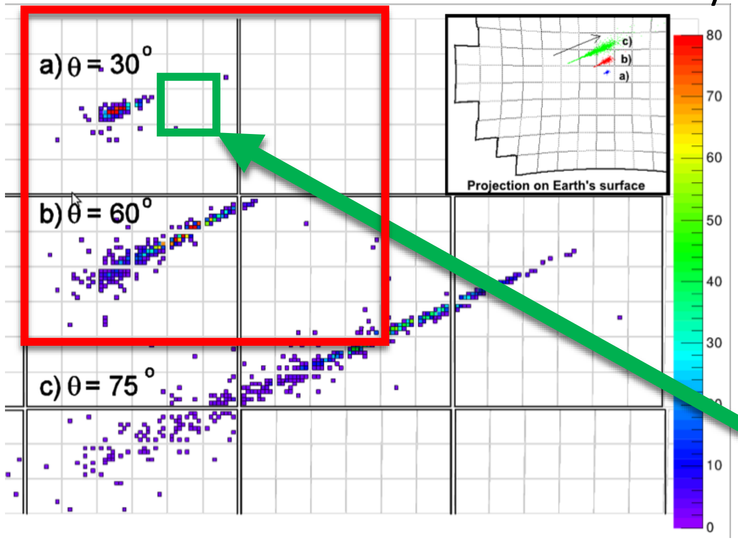
JEM-EUSO & Mini-EUSO

JEM-EUSO

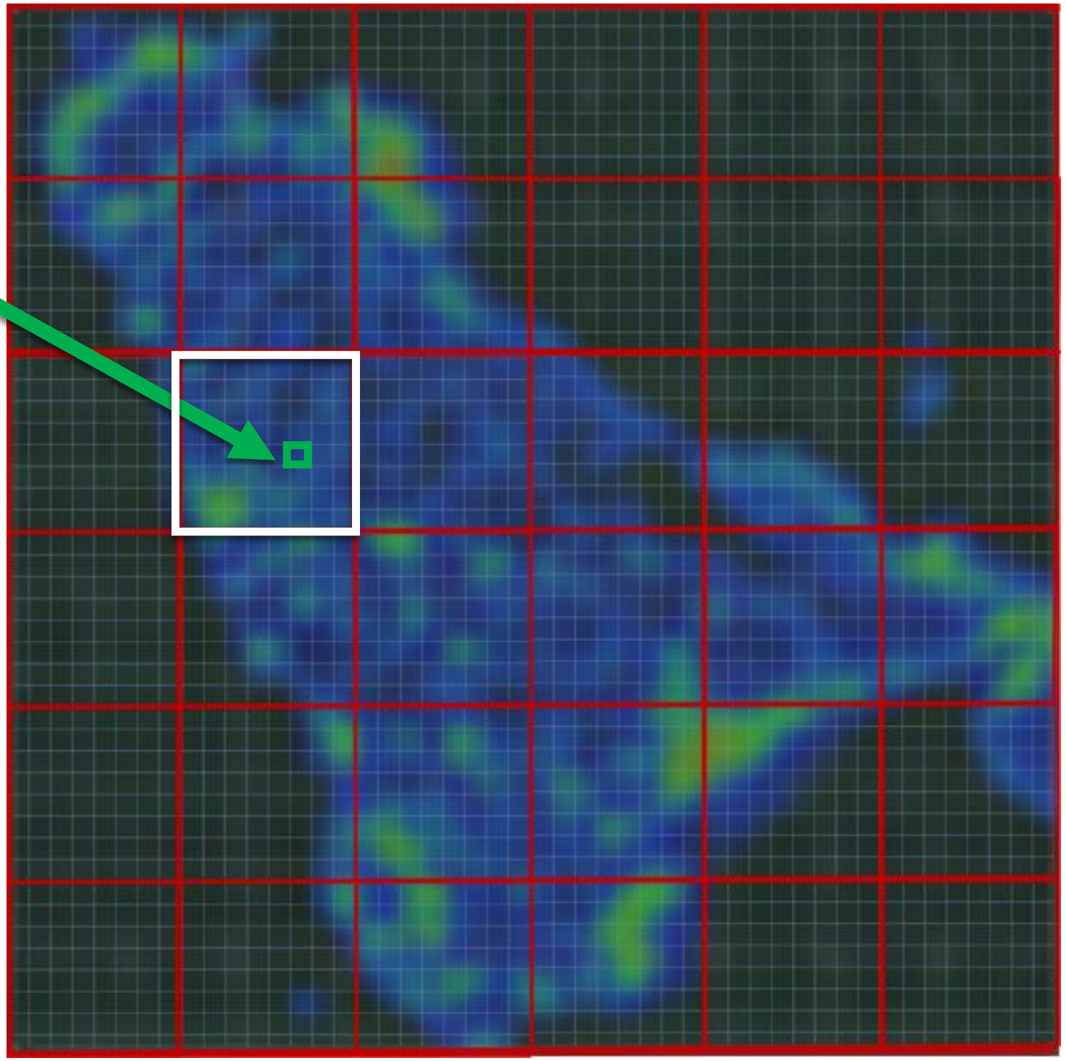


FoV

counts/GTU



Mini-EUSO



Comparison @ order of magnitude level

	Mini-EUSO	JEM-EUSO
	~1 pixel	~ 1.5 MAPMT
	~1 PMT	~ 3 PDM
Spatial resolution	**~6.3 km**	**~0.55 km**
Optics aperture	**~0.05 m²**	**~4.5 m²**

Simulation pre-flight

Similar counts/pixel from diffuse light in JEM-EUSO & Mini-EUSO
x100 light in JEM-EUSO from point-like sources

J. Adams et al. Astrop. Phys. 44 (2013) 76, S. Abe et al., Eur. Phys. J. C (2023) 83:1028

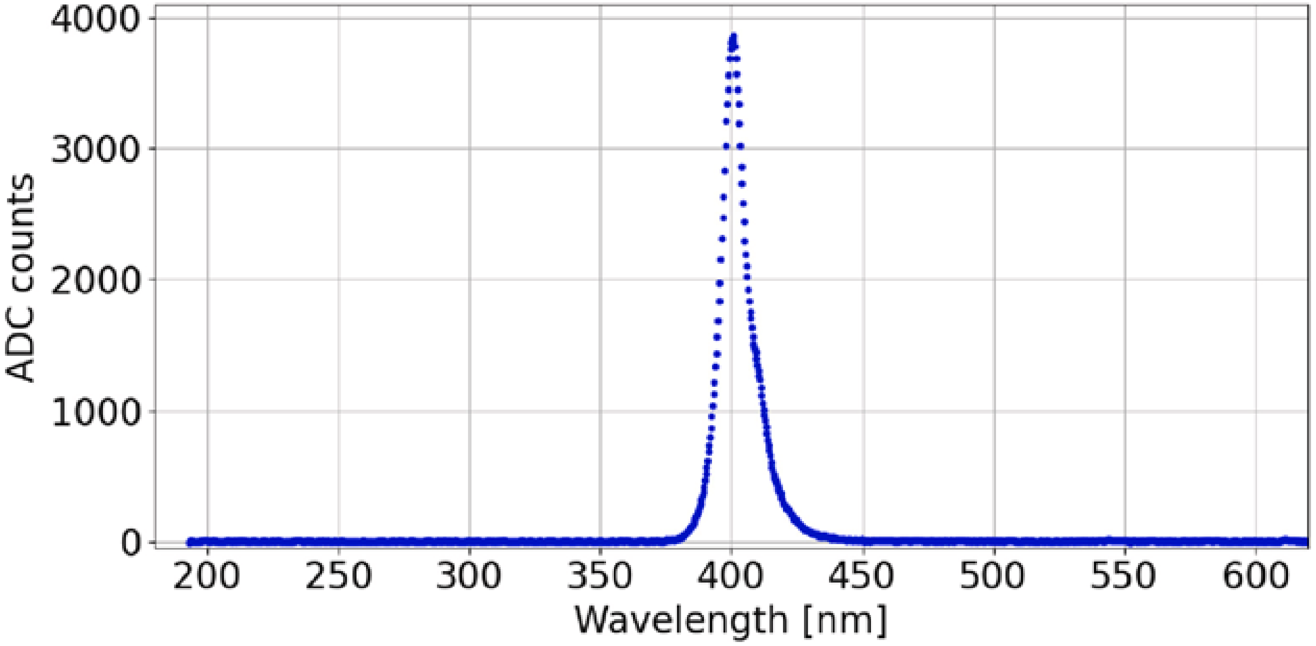
K. Shinozaki

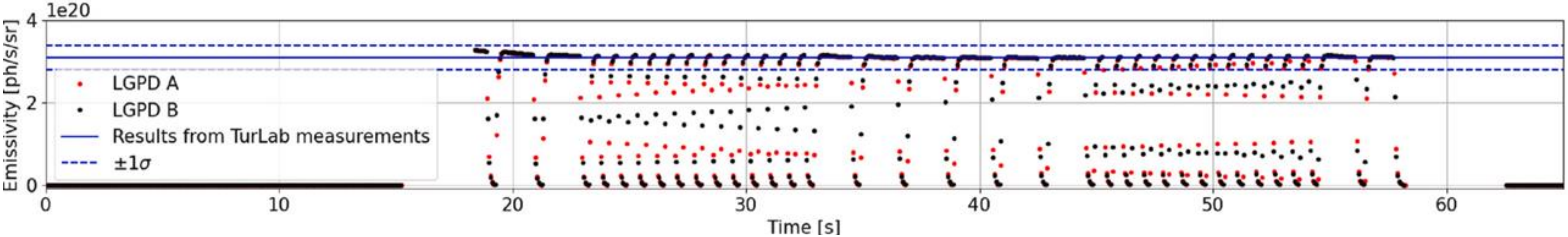
End-to-end calibration - The UV flasher array

Battisti, et al., Astroparticle Physics 165 (2025) 103057

Left: array of 9 100 W COB-UV LEDs driven by an Arduino board.

Right: Spectrum of the UV LEDs used to assemble the UV flasher

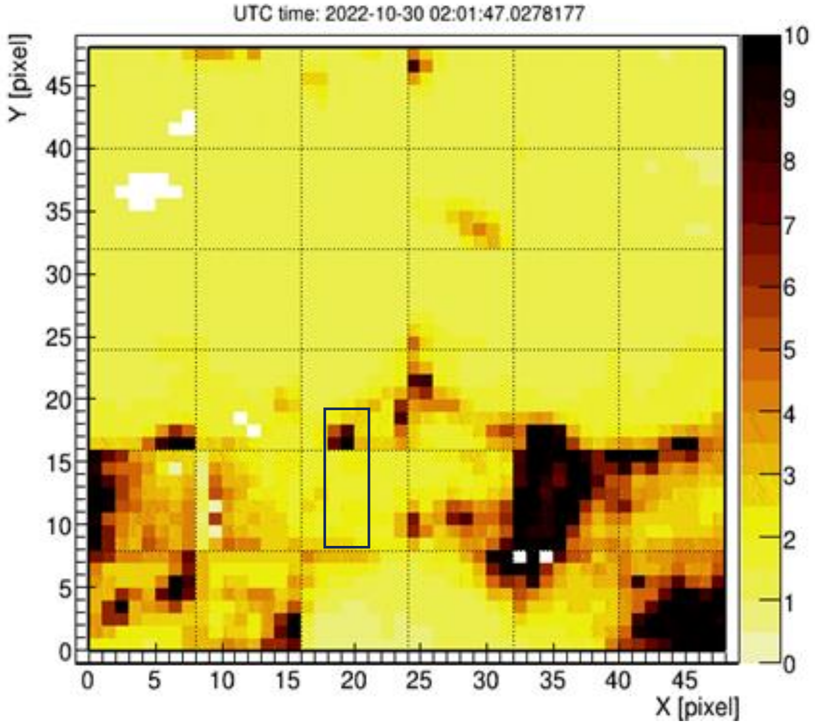


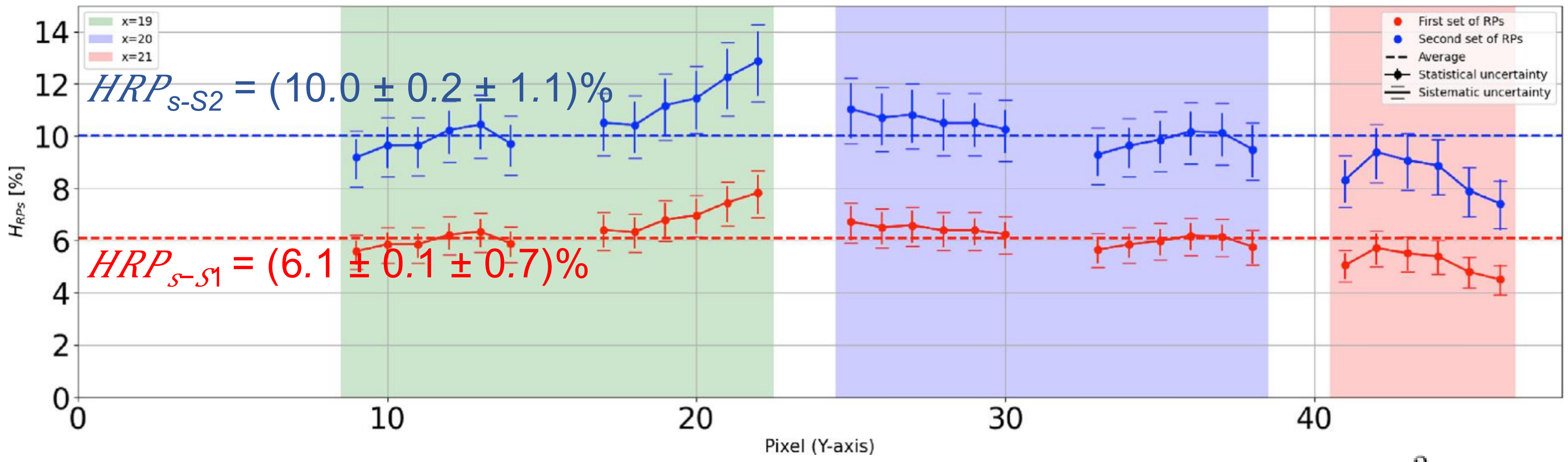


Emissivity of the UV flasher measured in open-air condition. The two colors represent the output of two photodiodes, that show the same results. The blue horizontal lines represent the value of the flasher emissivity obtained in a previous measurement in the lab.

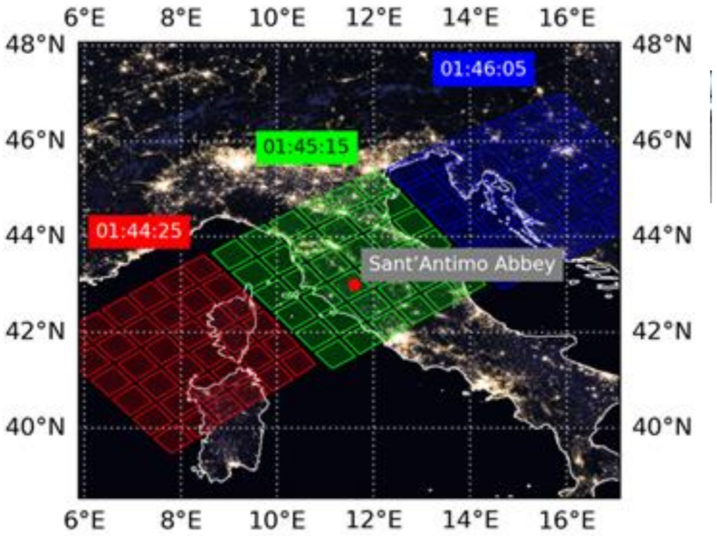
Mini-EUSO end-to-end calibration @ λ = 400 nm

M. Battisti et al. Astroparticle Physics 165 (2025) 103057

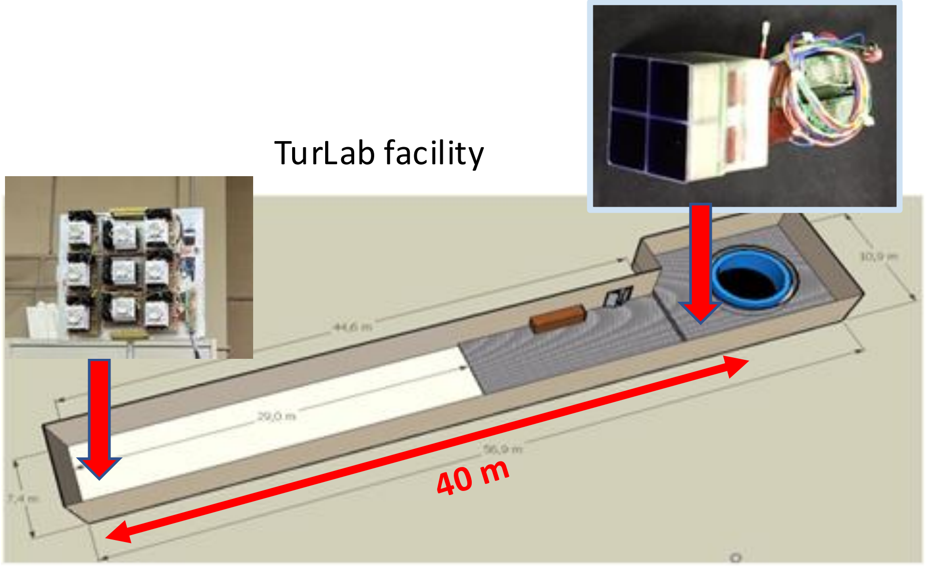




$$n^{window}_{photons} = n^{TurLab}_{photons} \times Angular_{lens} \times Abs_{atm} \times \frac{Area(ME)}{Area(To\text{-}EC)} \times \left(\frac{Distance(To\text{-}EC)}{Distance(ME)}\right)^2 \times cos(\theta)$$

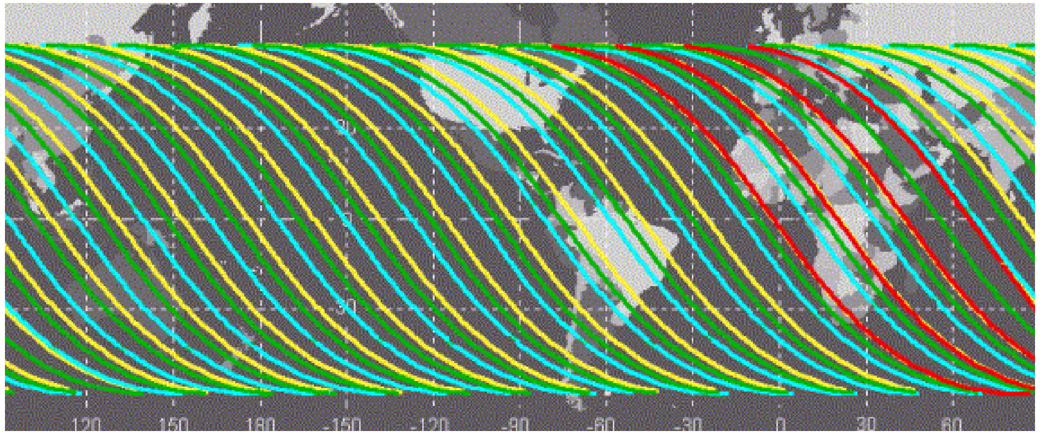


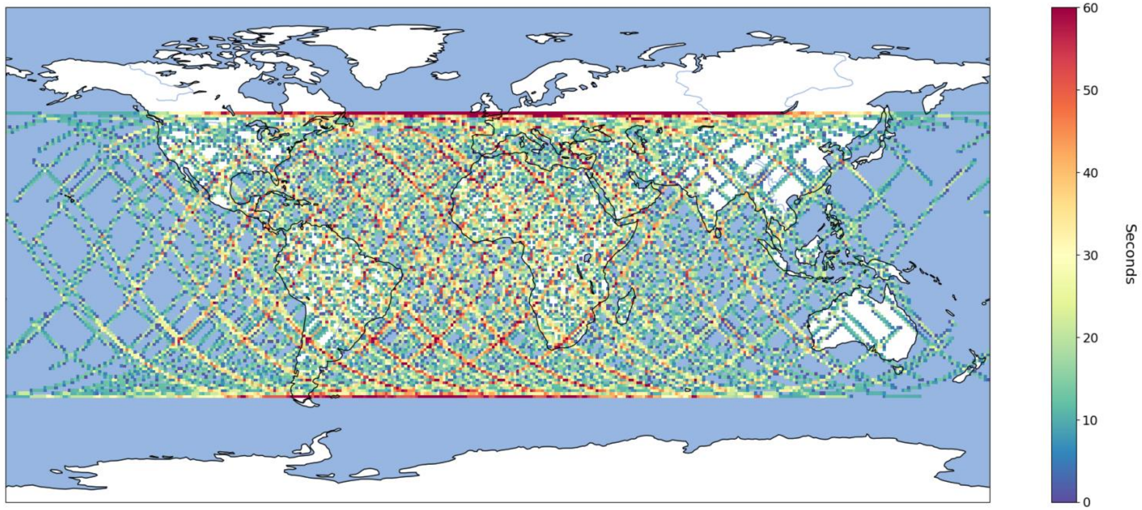
TurLab facility



Mini-EUSO provides UV intensity maps

ISS orbits, on average ~1 pass per location every 3 days…
Mini-EUSO operates **~2/month (12h)** with no isotropic coverage because usually in operation during local night time in Moscow (some areas are best spotted than others)



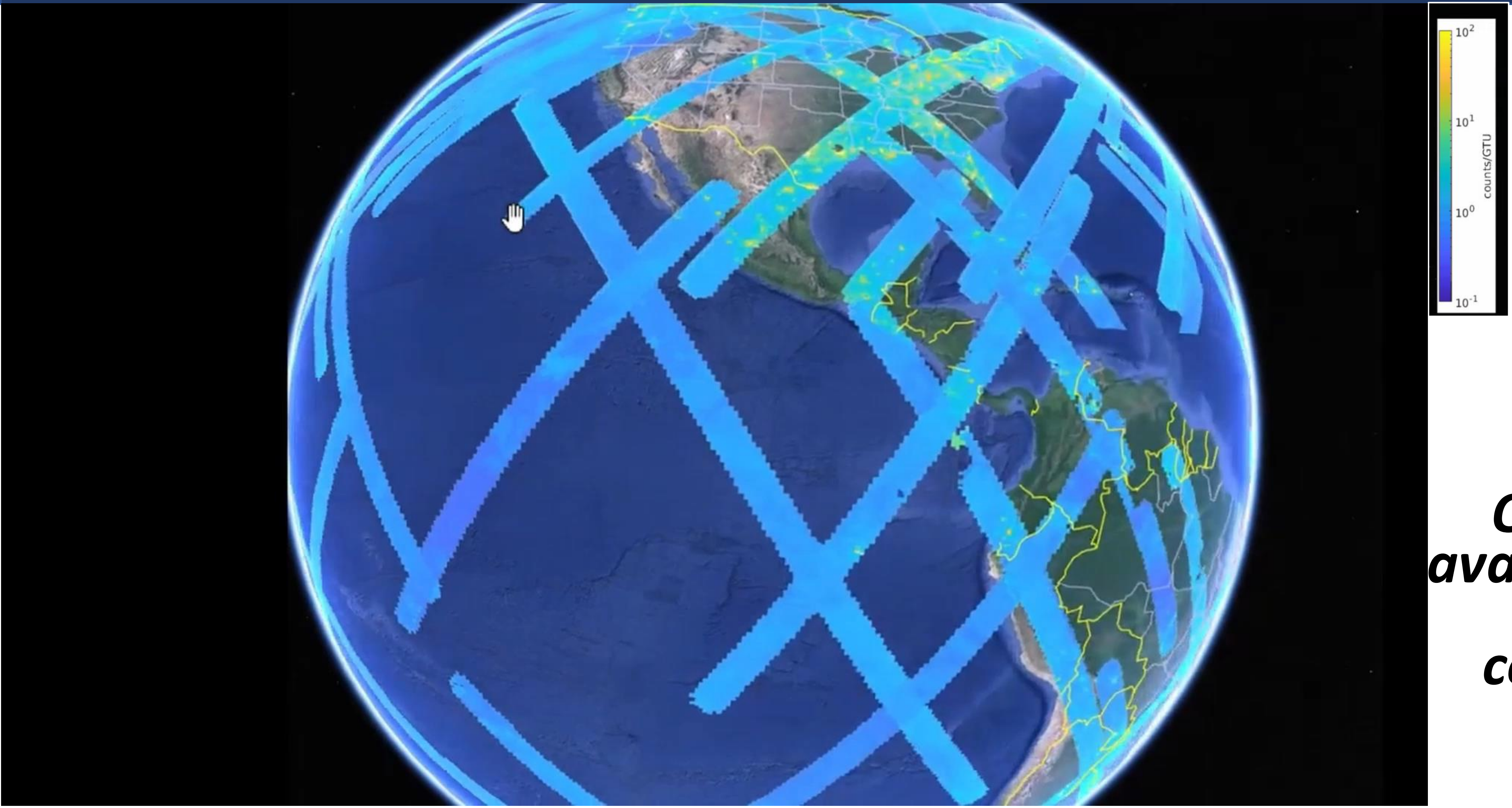


Sessions 4 - 44

From Matteo B.

M. Battisti

So, in this picture, we can imagine that yellow is Monday, green is Tuesday, and Blue is Wednesday.
Red is Thursday. Red is overlapping yellow.



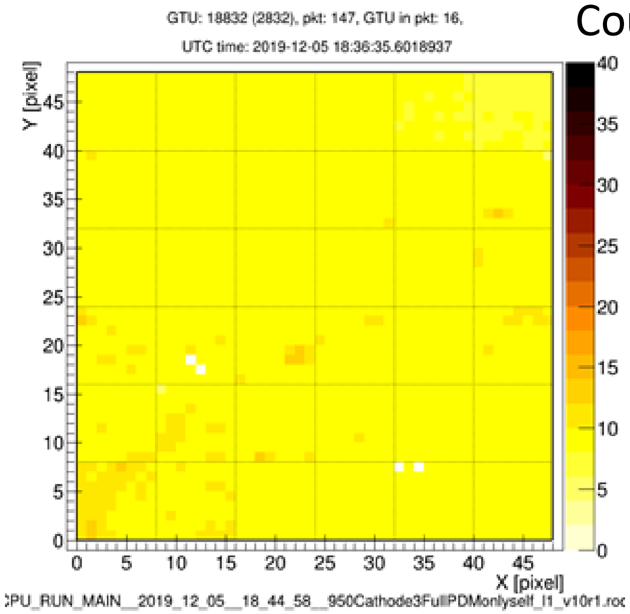
Open data available to the scientific community

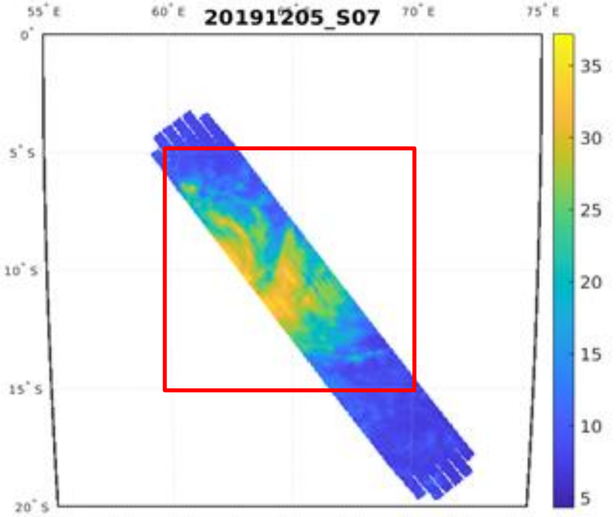
ASI ADSC data centre:

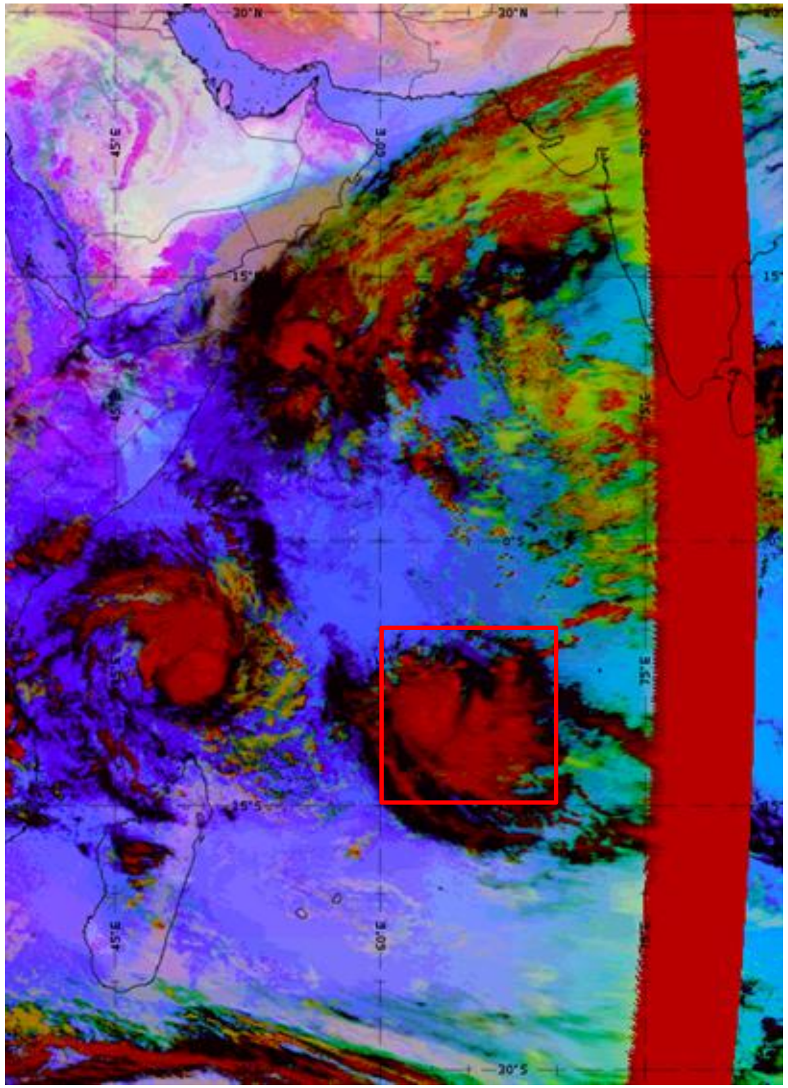
- Casolino M. et al. *Observation of night-time emissions of the Earth in the near UV range from the International Space Station with the Mini-EUSO detector*, **Remote Sensing of Environment** 284 (2023) 113336
- Marcelli L. et al., *Dataset of night-time emissions of the Earth in the near UV range*, **Data in Brief 48 (**2023) 109105

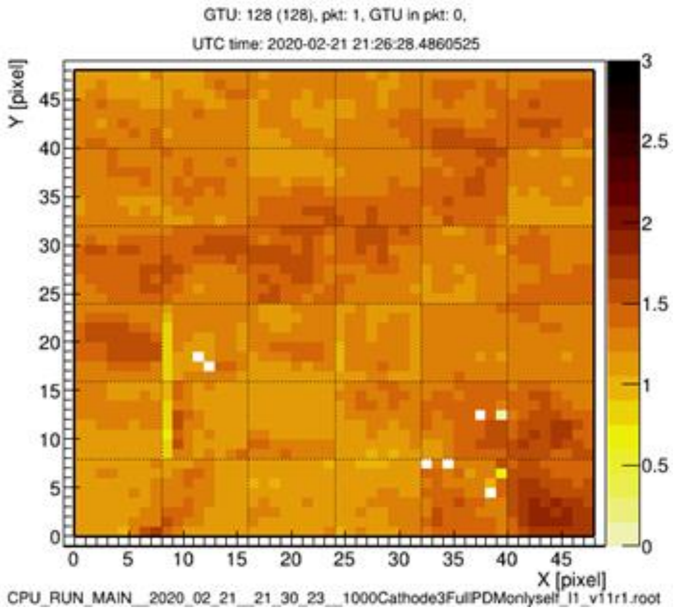
Cloud observation and Moon impact

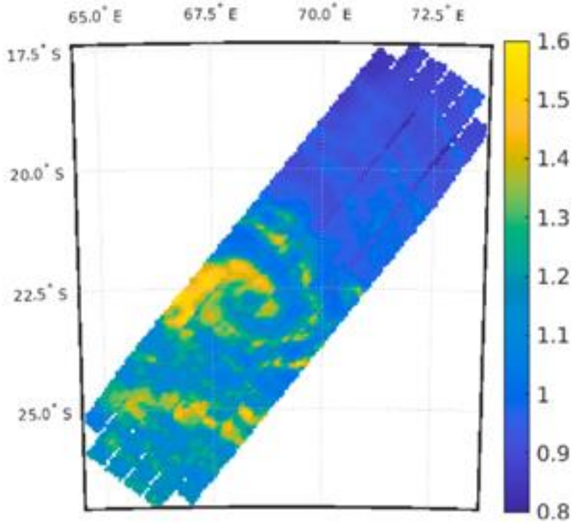
Counts/pix/GTU









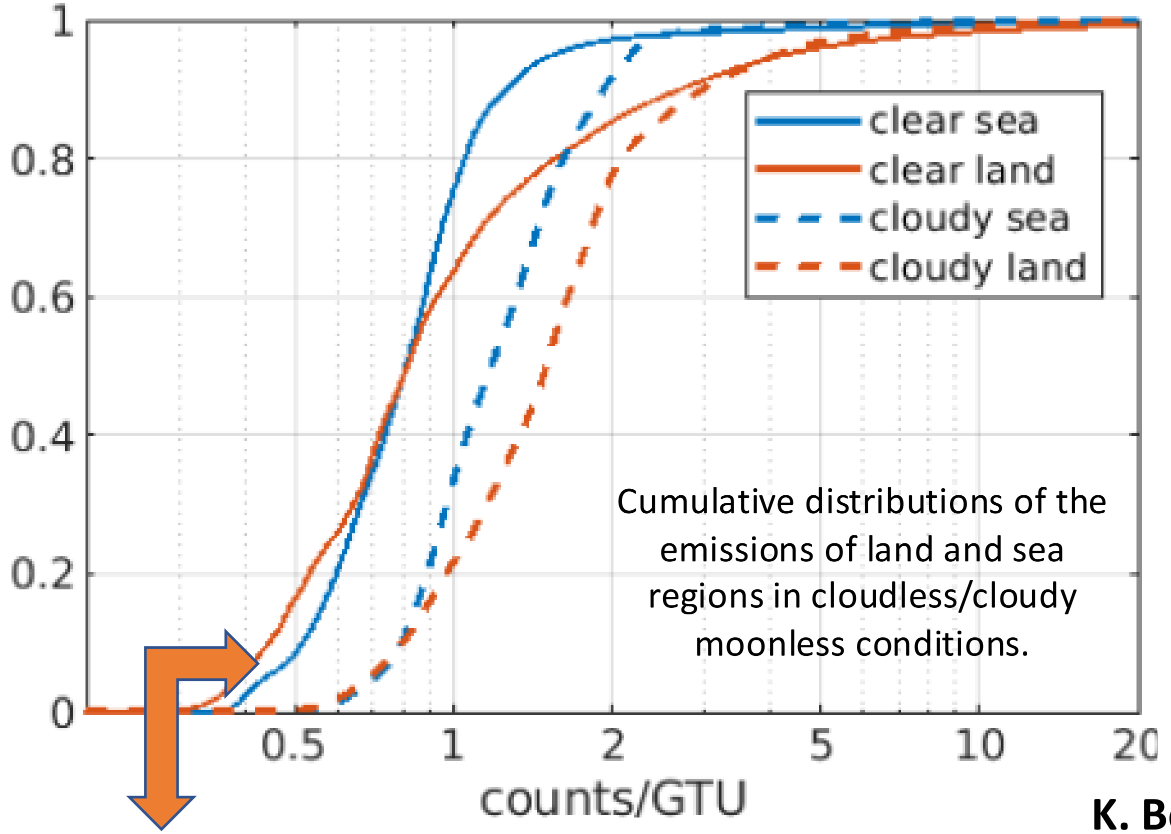


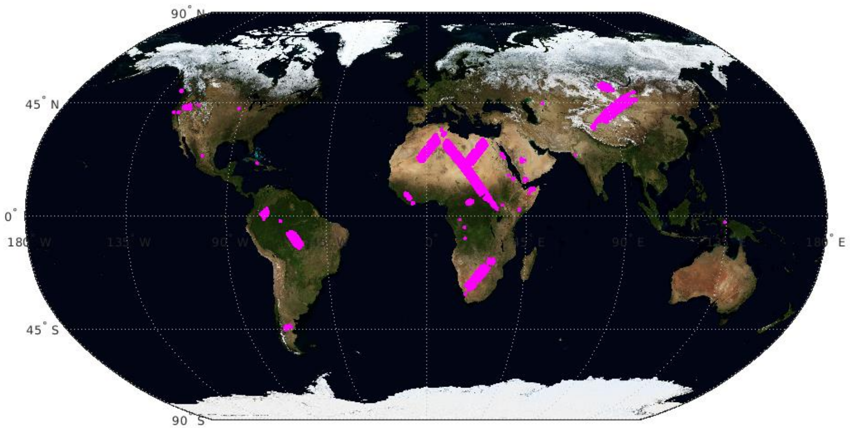
M. Battisti
A. Golzio

Cyclone on 2019-12-05, 18:30 UTC. Moon illumination 64%.
TopLeft: Mini-EUSO data. BottomLeft: UV map. Right: data from Himawari satellites

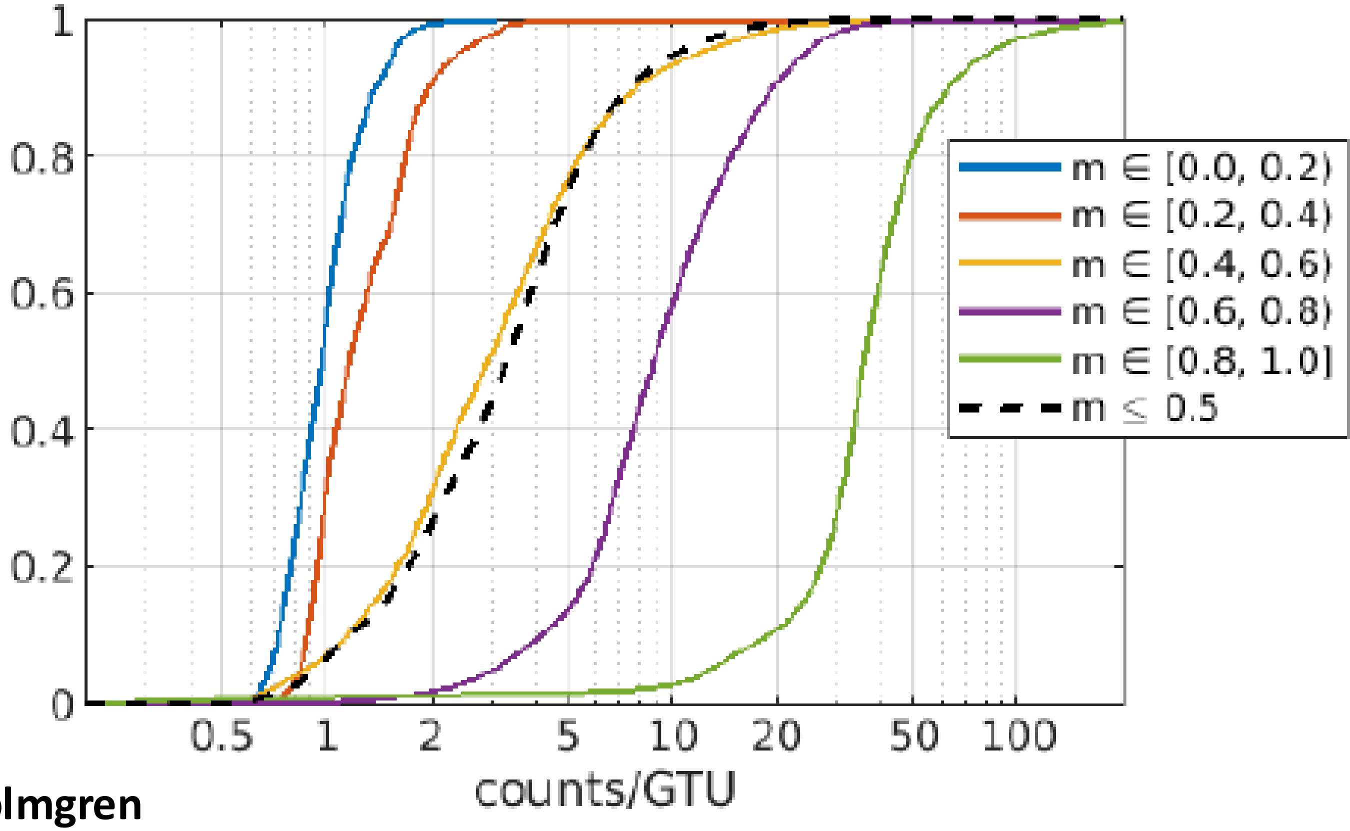
Cyclone on 2020-02-21, 22:00 UTC. Moon illumination 5%.
Top: Mini-EUSO data. Bottom: UV map.

Moonless conditions





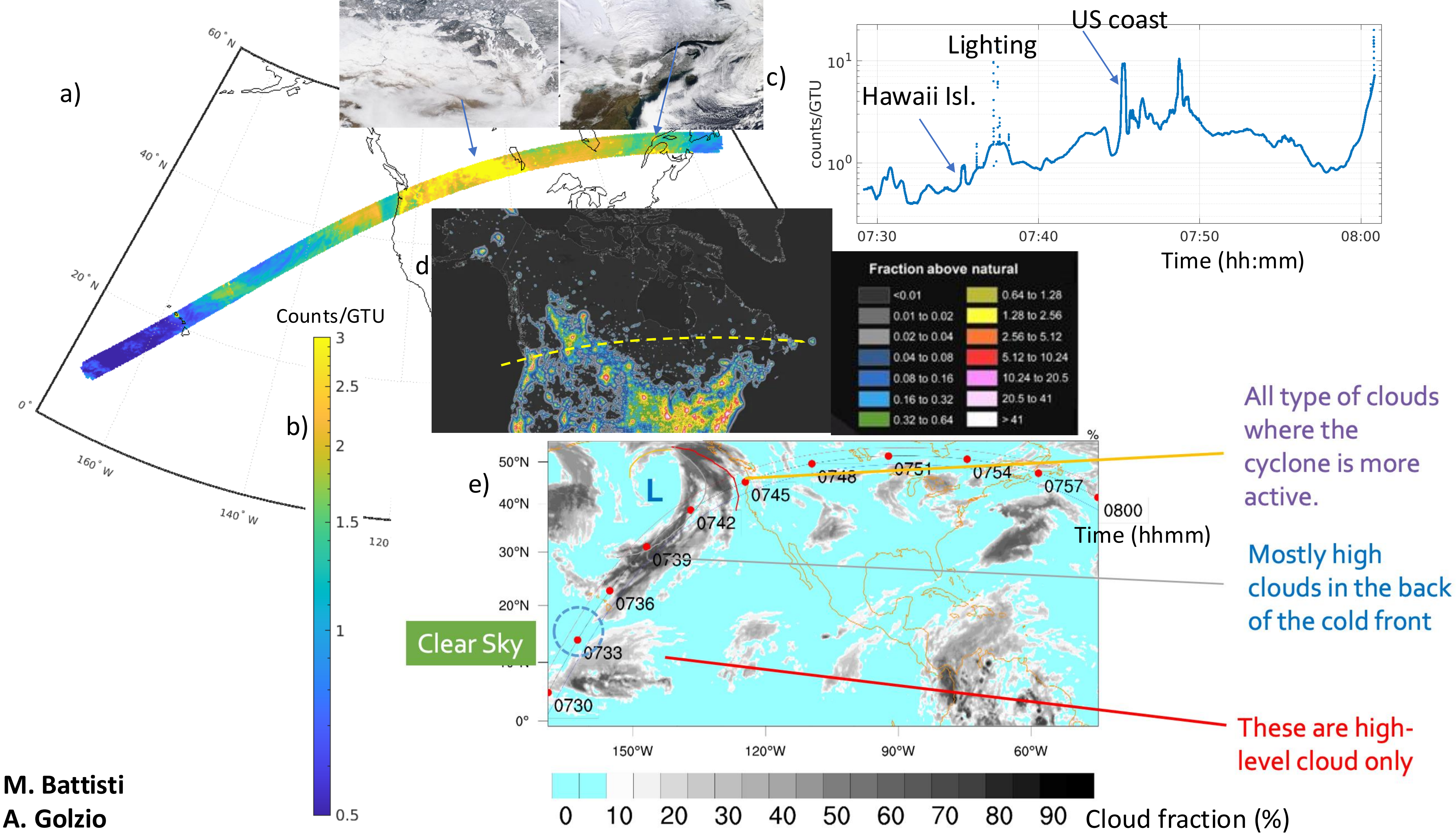
Moon Phases



K. Bolmgren

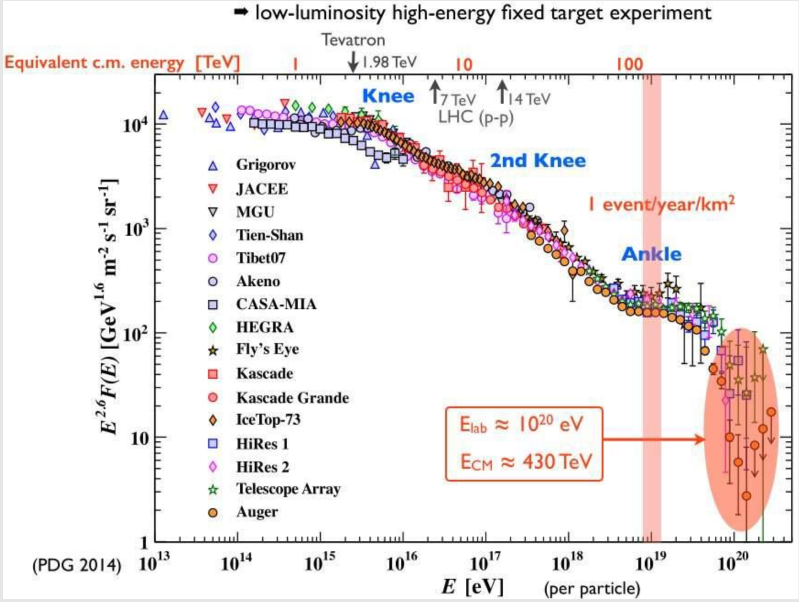
M. Casolino et al.: Remote Sensing of Environment 284 (2023) 113336
ArXiv: 2212.02353

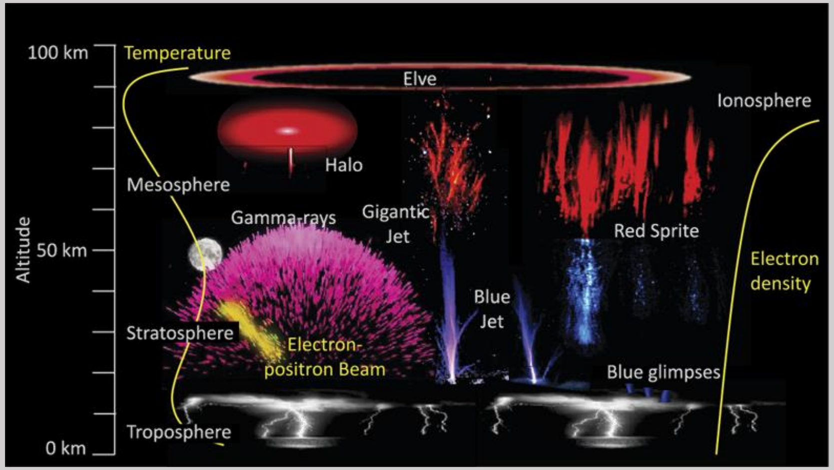
Analyzed sessions: 5 - 19



M. Battisti
A. Golzio

High energy astrophysics:	**High energy physics of atmosphere:**	**Relativistic electrons in magnetosphere:**
Ultra-high-energy cosmic rays	*TLE, TGF, TGE etc*	*Acceleration and precipitation of energetic electrons*





T. Neubert

ISAS JAXA

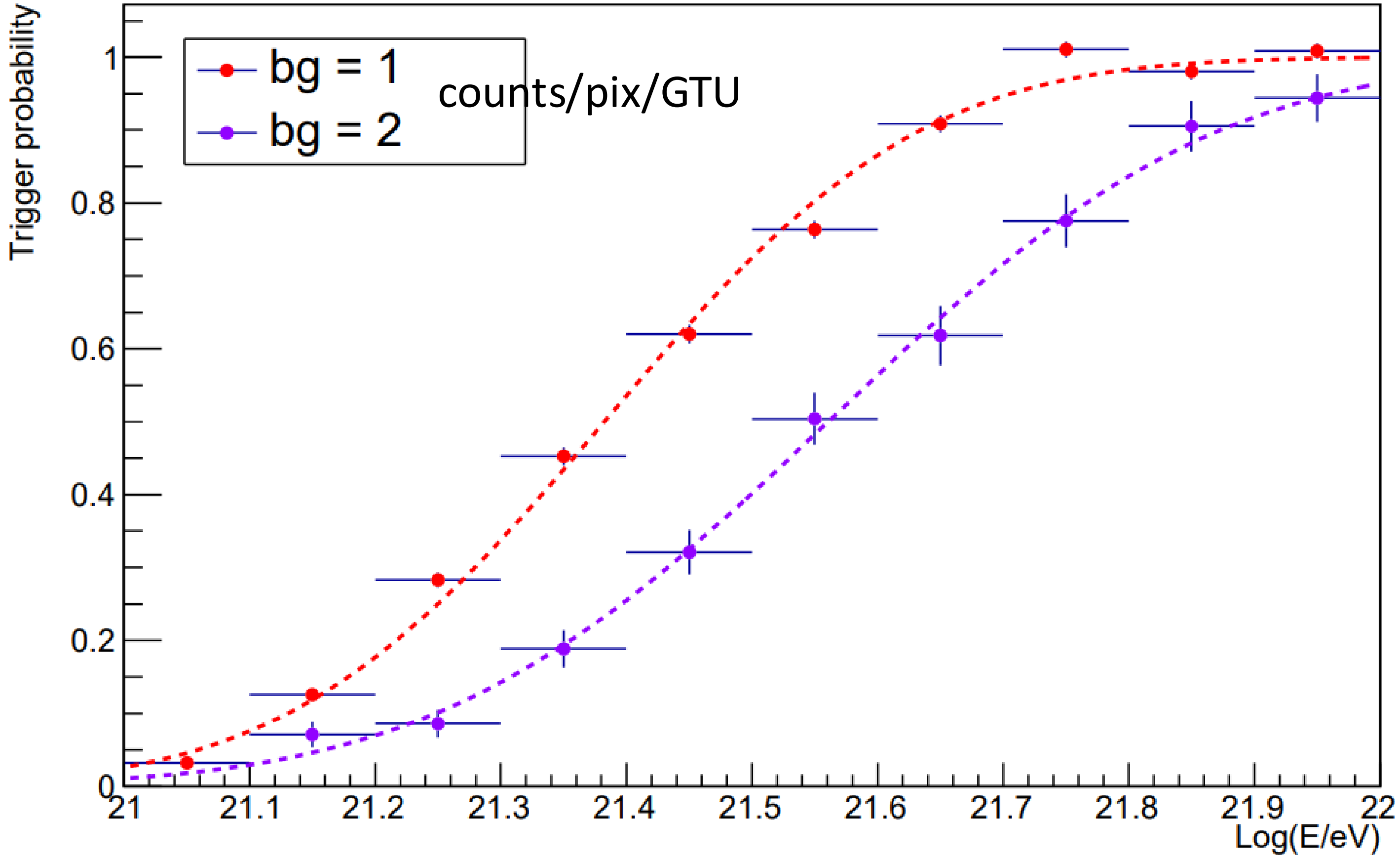
Optical measurements using fast imaging photometers, using the atmosphere as a particle detector, allow us to study the spatial structures, energy, and temporal characteristics of radiation and reconstruct the parameters of particle sources.

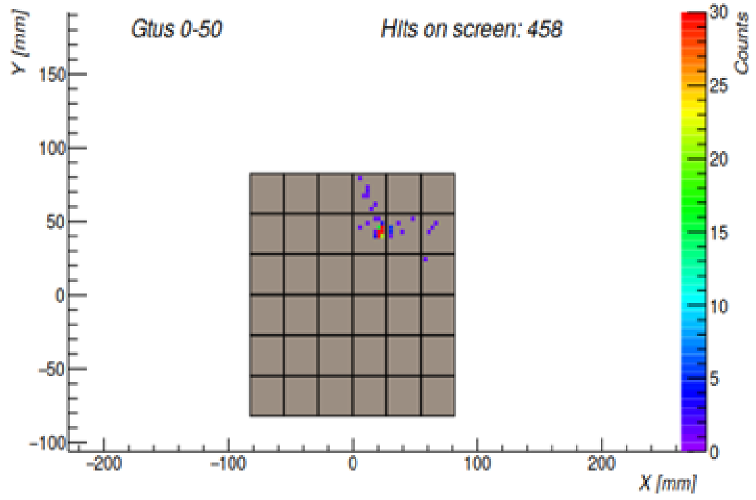
Study of accelerator operation in the Universe, magnetosphere, and atmosphere

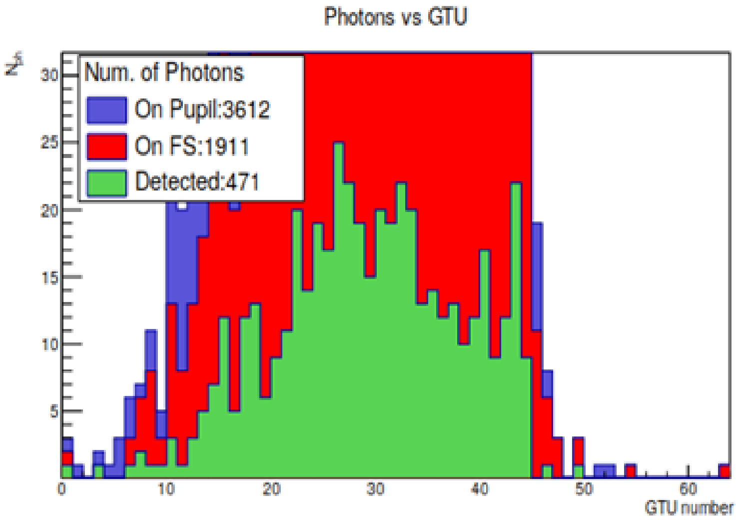
P. Klimov

Mini-EUSO EAS trigger probability

Proton E = 5×10^{21} eV, 50°





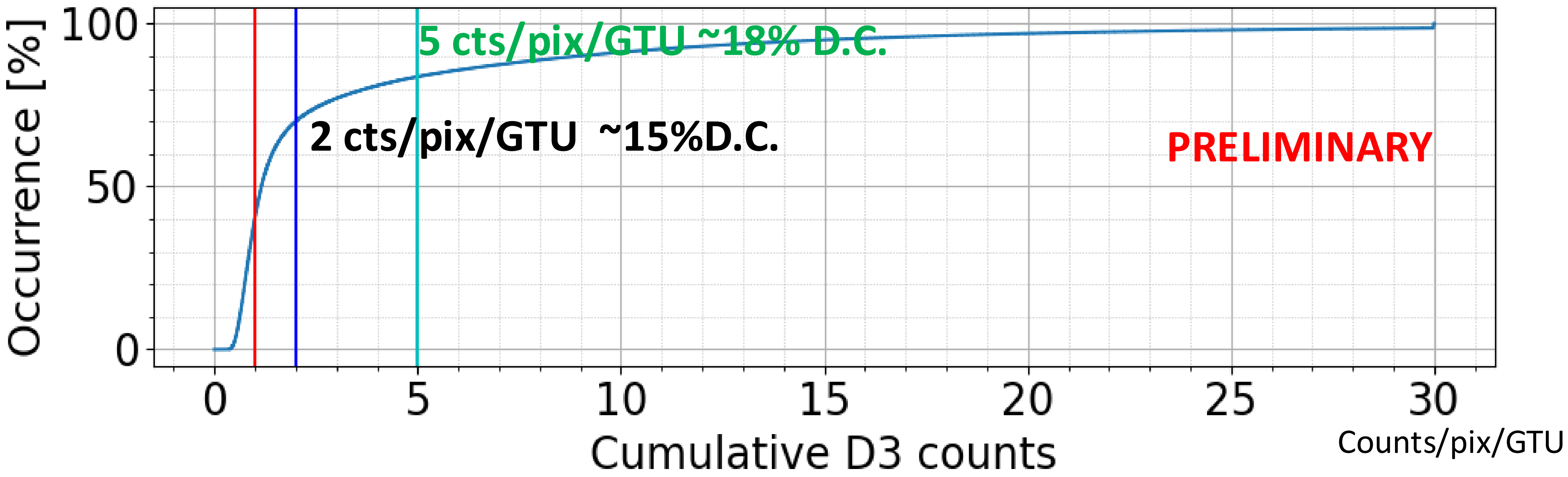


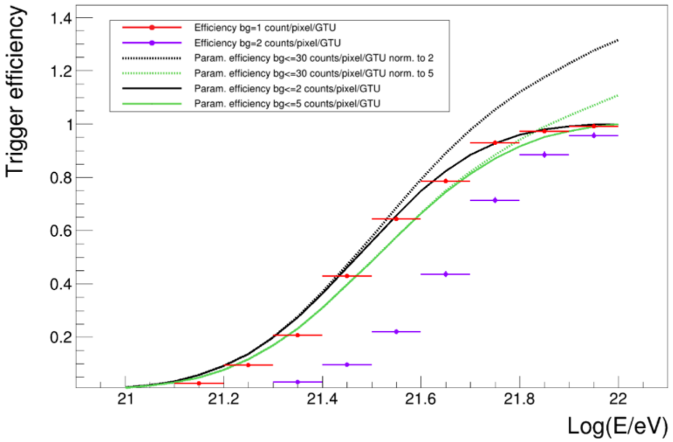
Obtained using ESAF simulations

Proton EASs

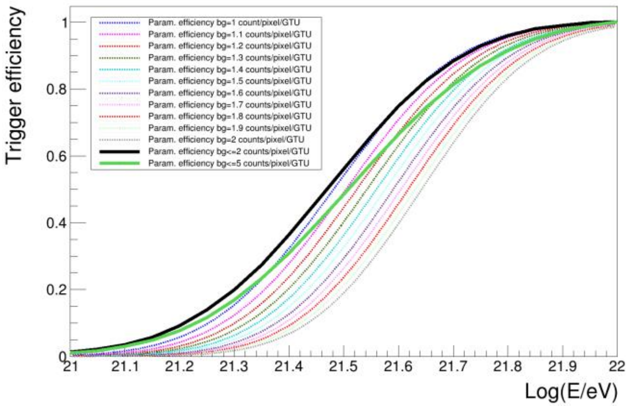
S. Abe et al., Eur. Phys. J. C (2023) 83:1028

Combining bckg distrib. and efficiency curves: the integrated exposure curve





PRELIMINARY



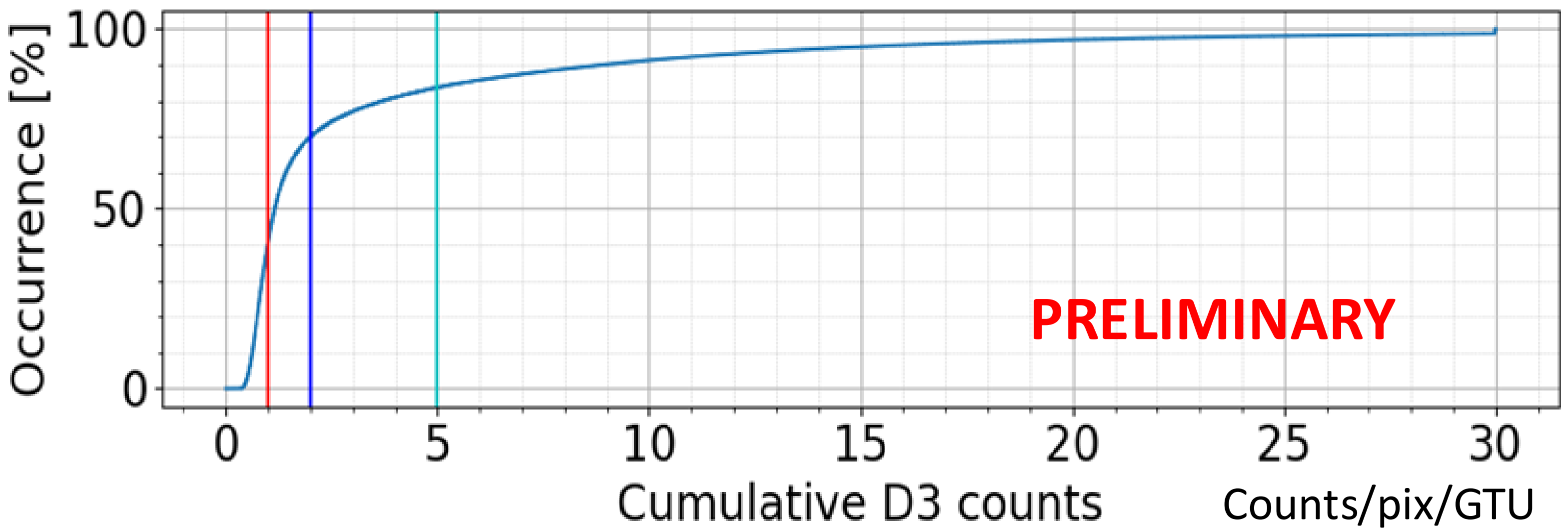
M. Battisti
M. Bianciotto
F. Fenu

M. Bertaina, UHECR2022

Overall experimental confirmation of JEM-EUSO duty cycle

J.H. Adams et al. (JEM-EUSO coll.), Astroparticle Physics, v. 44 (2013) p. 76-90

Accumulated exposure by Mini-EUSO



T = 68. 1 h * 0.837 = 6.51E-3 yr
A = 2304 * (5.9 km)^2 = 7.97E+4 km^2
Ω = π * 0.72 (cloud factor) = 2.26
Exposure = T x A x Ω = **~1200 L**

If taking into account till session **150** (June 2025) = **~6500 L**

If Mini-EUSO would have operated continuously since August 2019: ***~165000 L***
(exposure/day = ~76 L/day)

M. Battisti

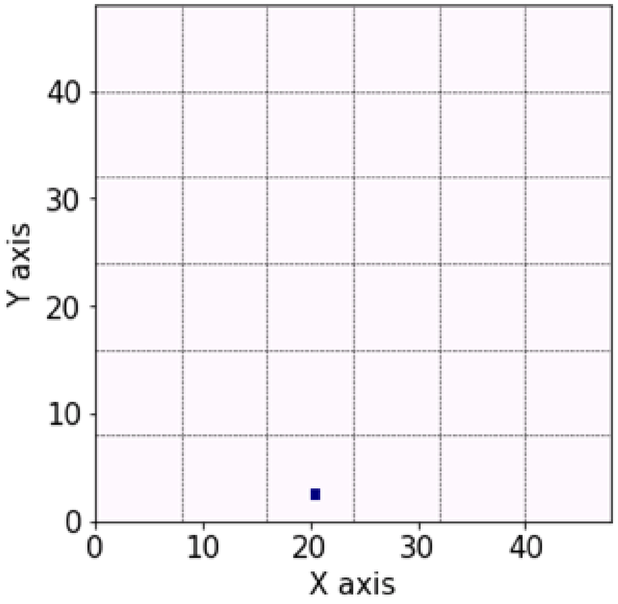
Extrapolating to all good recorded data the expected cumulated exposure for UHECRs is **~6500 L** at the highest energies. **This exposure is comparable to the one collected so far by UHECR experiments using the fluorescence technique.**

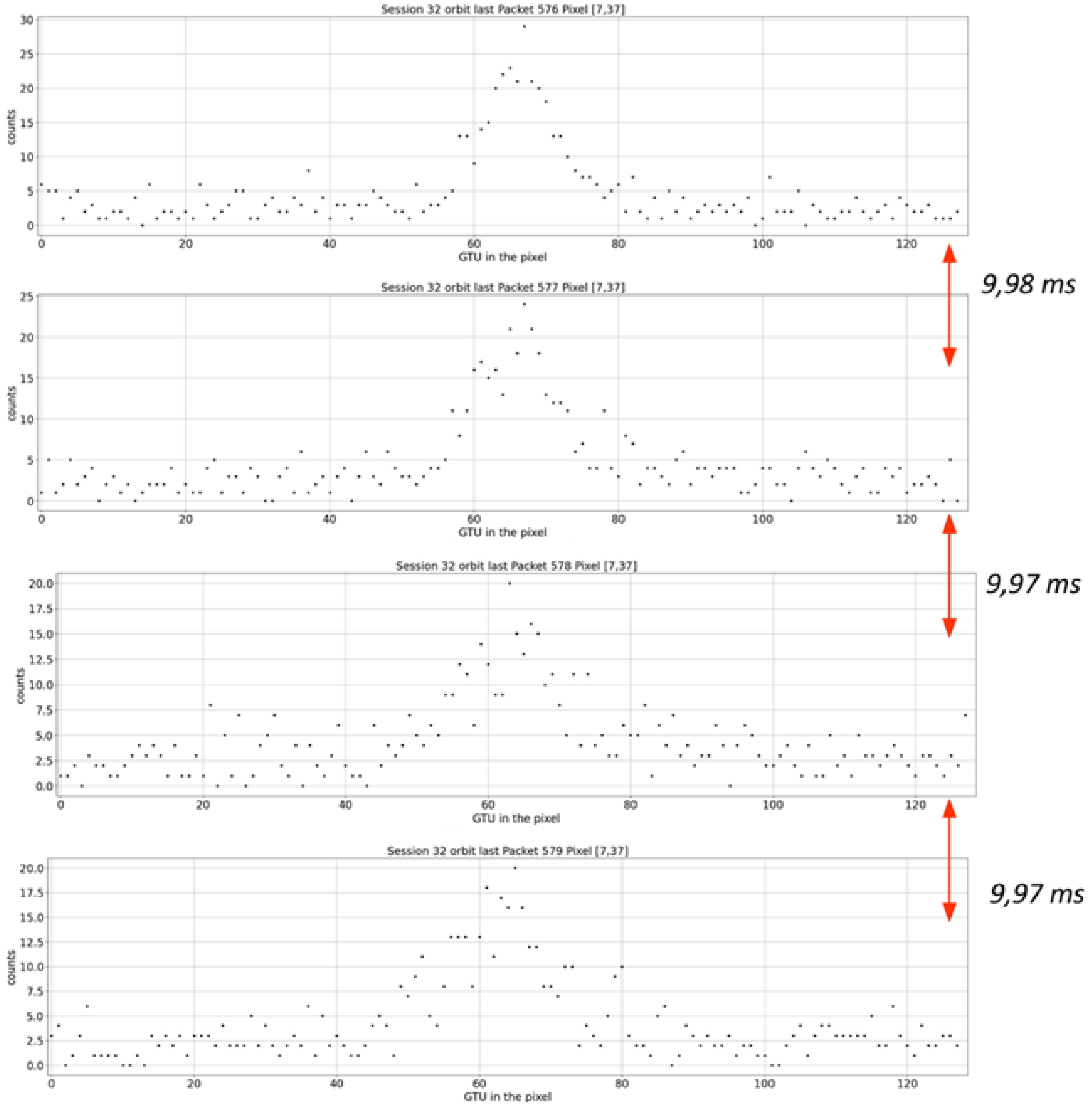
If Mini-EUSO would have operated continously in the past ~5 years it would have accumulated the exposure collected so far by ground-based experiments.

What we found in the data - Ground flashers

Ground-located light source flashing at a constant rate.
They might have a lightcurve resembling a UHECR.
However, ground flashers

1. are triggered several times in different positions of the focal plane
2. do not present any apparent movement
3. have a focal plane footprint compatible with a point-like source smeared by the PSF



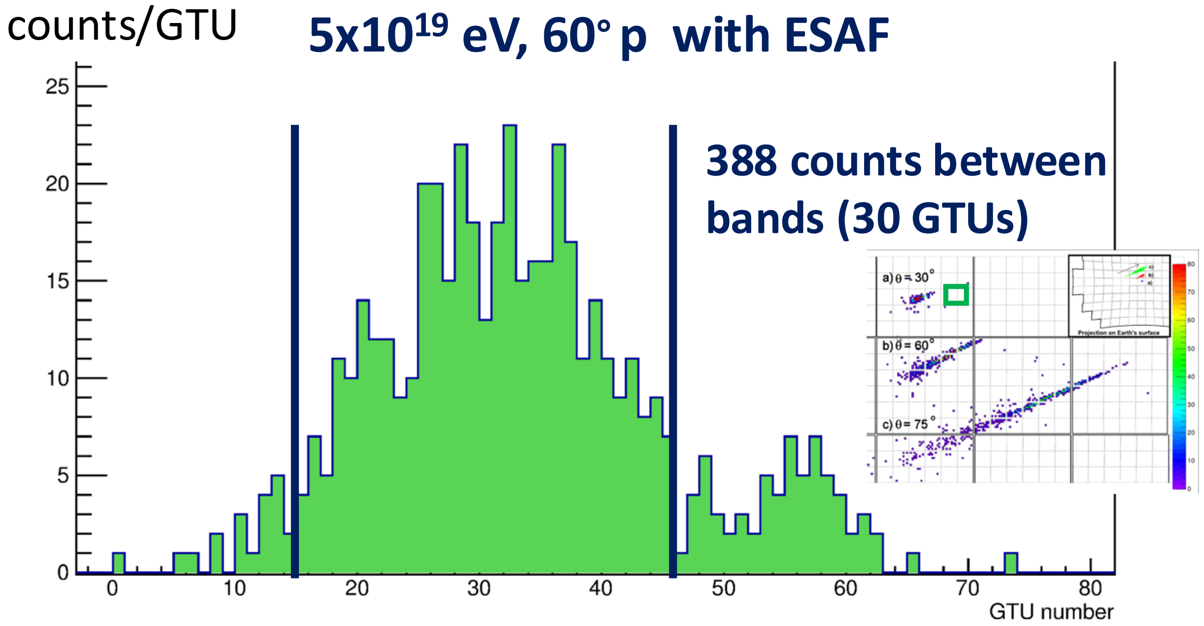


M. Battisti

1 GTU = 2.5 µs

UHECRs in JEM-EUSO & ground flashers in Mini-EUSO

JEM-EUSO
5×10^{19} eV, 60° p with ESAF

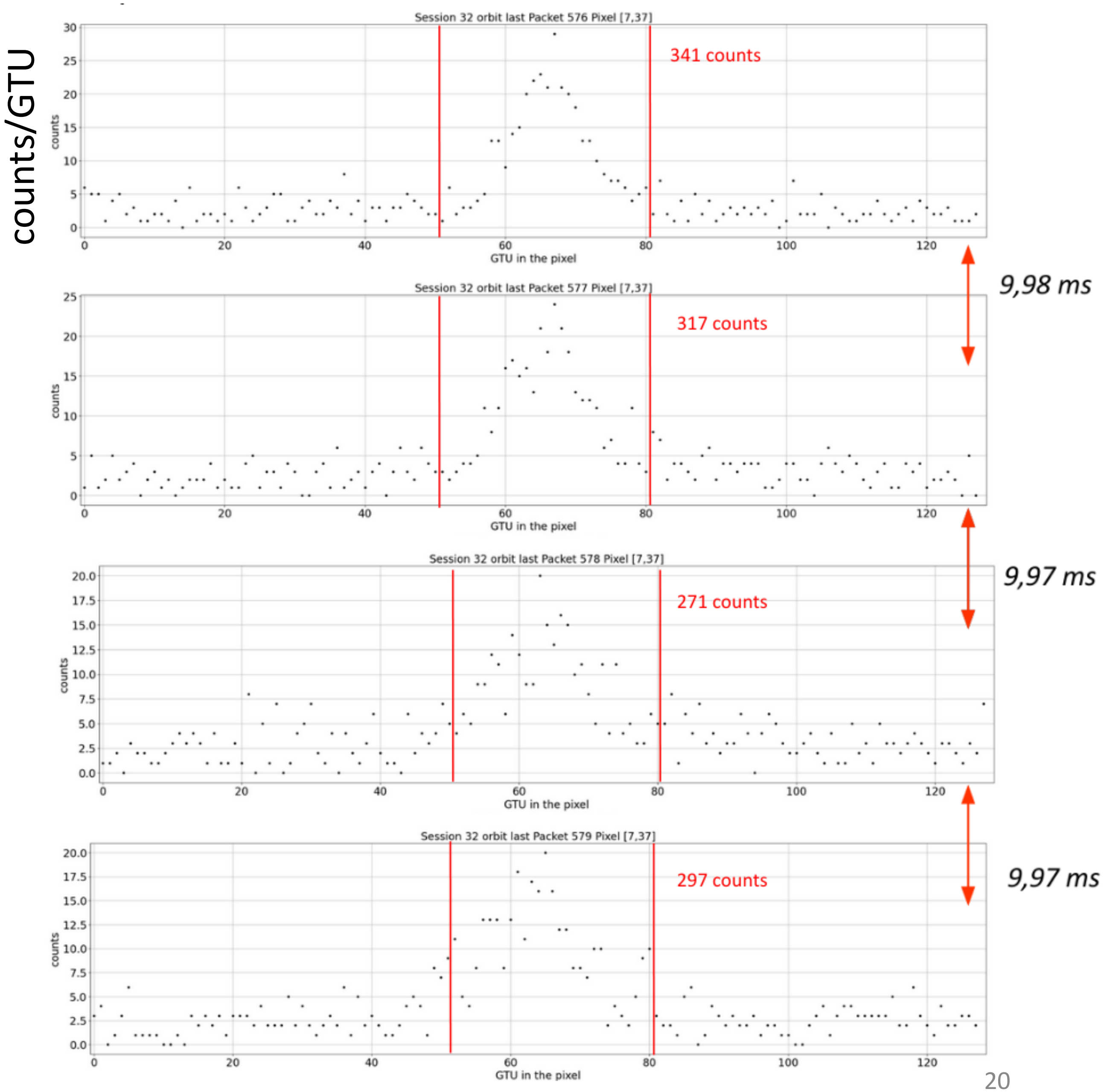


F. Fenu

Average counts: 307 counts
Spread: 35 counts
Relative error: 35/307 = 0.11
Expected Poissonan fluct.: 17 counts (5.5%)

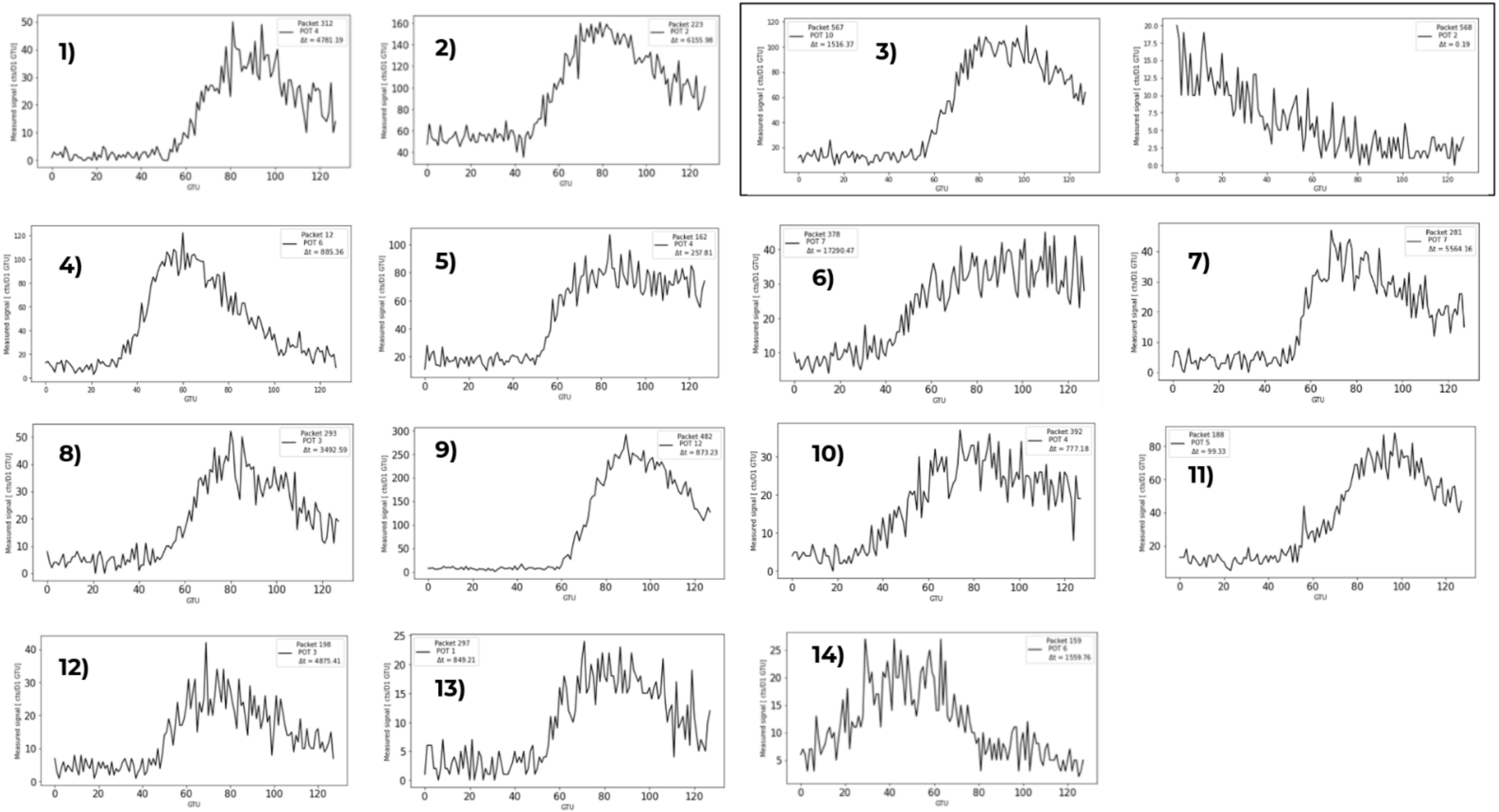
Proof of the detection principle of UHECRs from space with signals in Mini-EUSO comparable to those expected in JEM-EUSO

Repeated ground flashers



M. Battisti

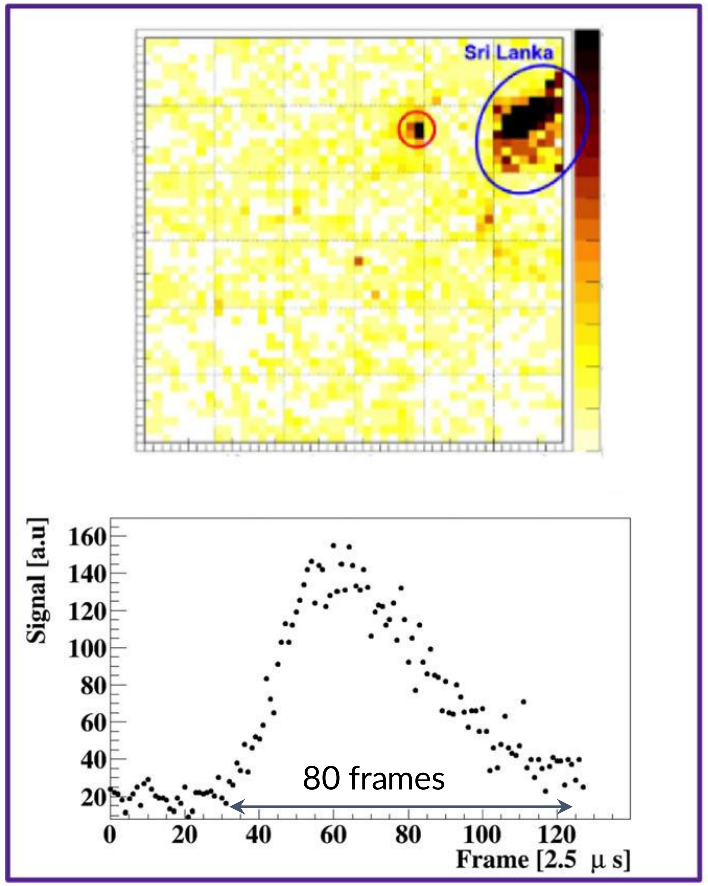
Short Light Transients (SLT) lightcurves



M. Battisti

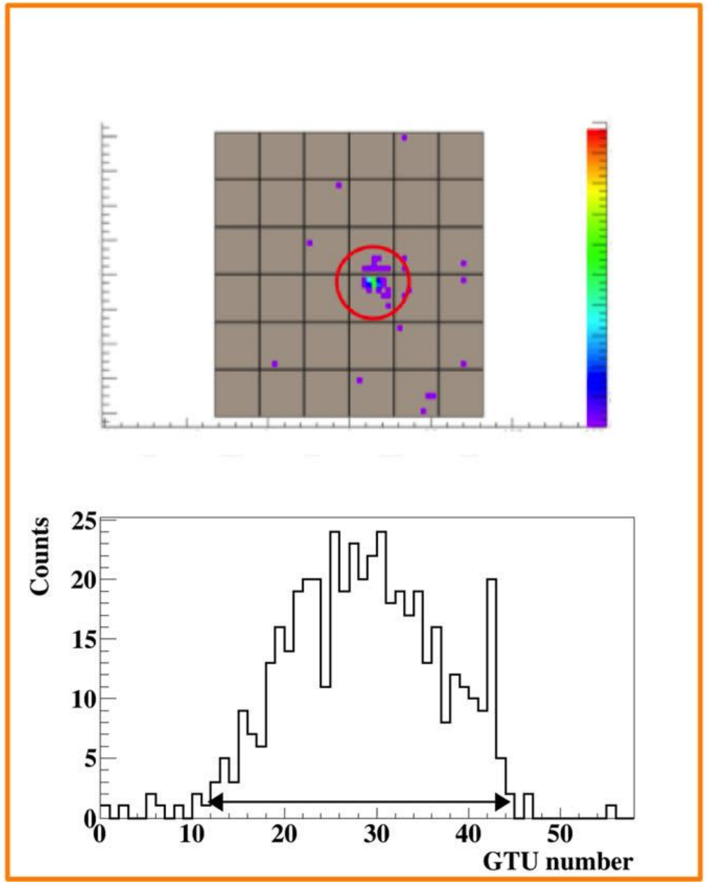
Mini-EUSO – non repetitive 'EAS-like' signal

Mini-EUSO data

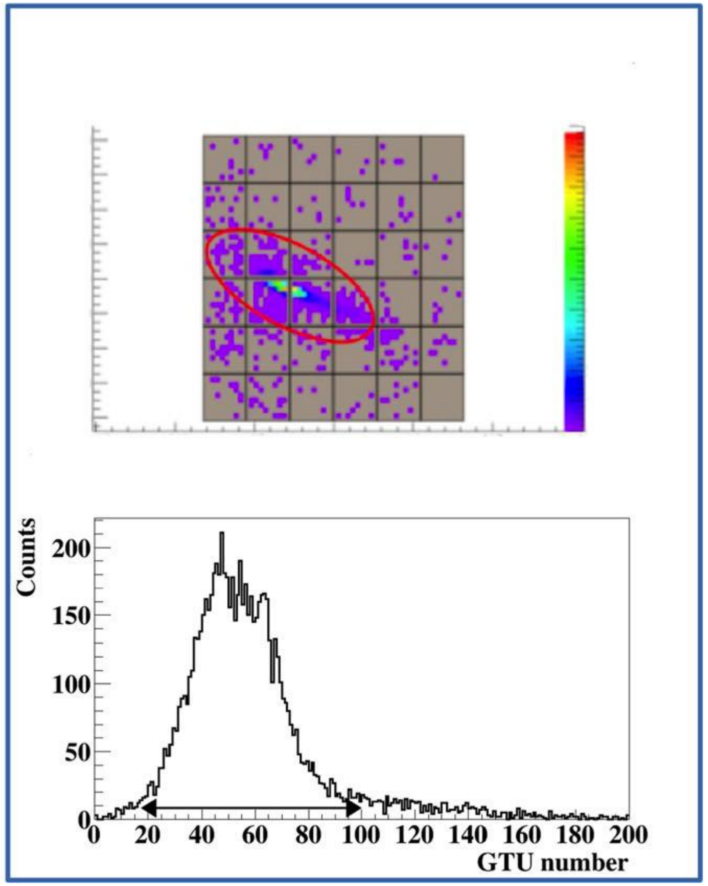


Focal plane view and lightcurve of the detected signal

ESAF p, E = 5x10^{21} eV Zenith = 50˚



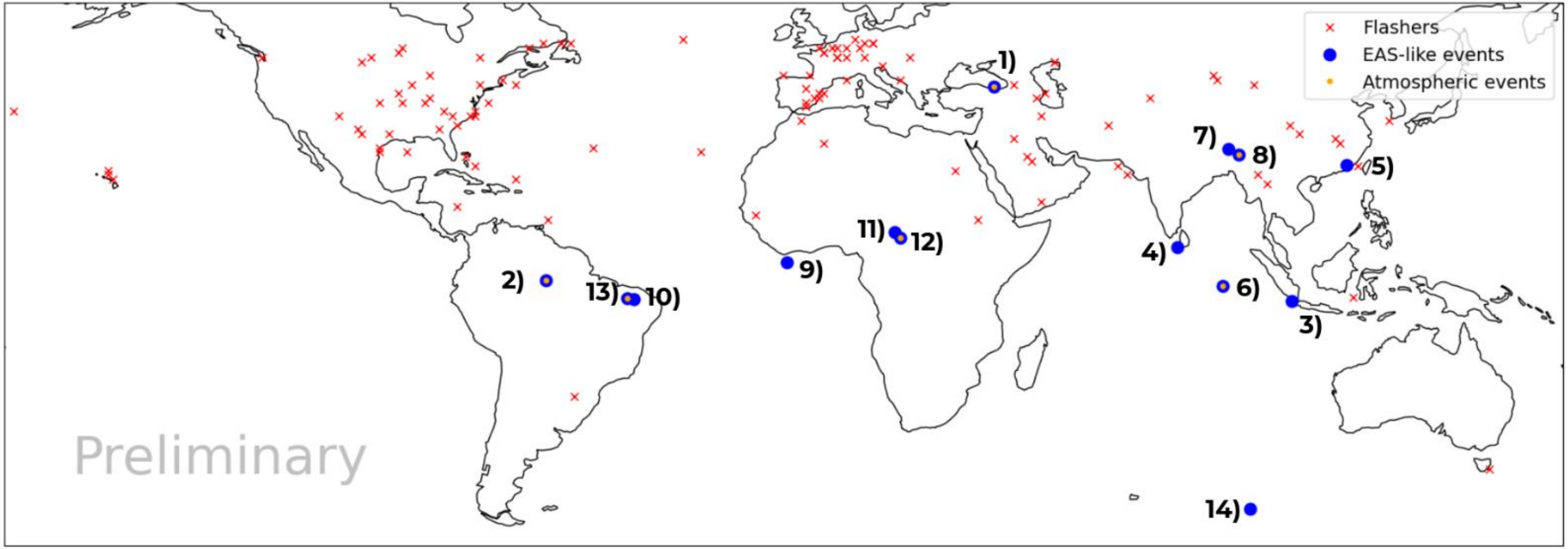
ESAF p, E = 2x10^{22} eV Zenith = 80˚



- Cosmic ray simulations. Top: focal plane view. Bottom: lightcurves. Left: Zenith angle = 50˚. Right: Zenith angle = 80˚

F. Fenu & M. Battisti

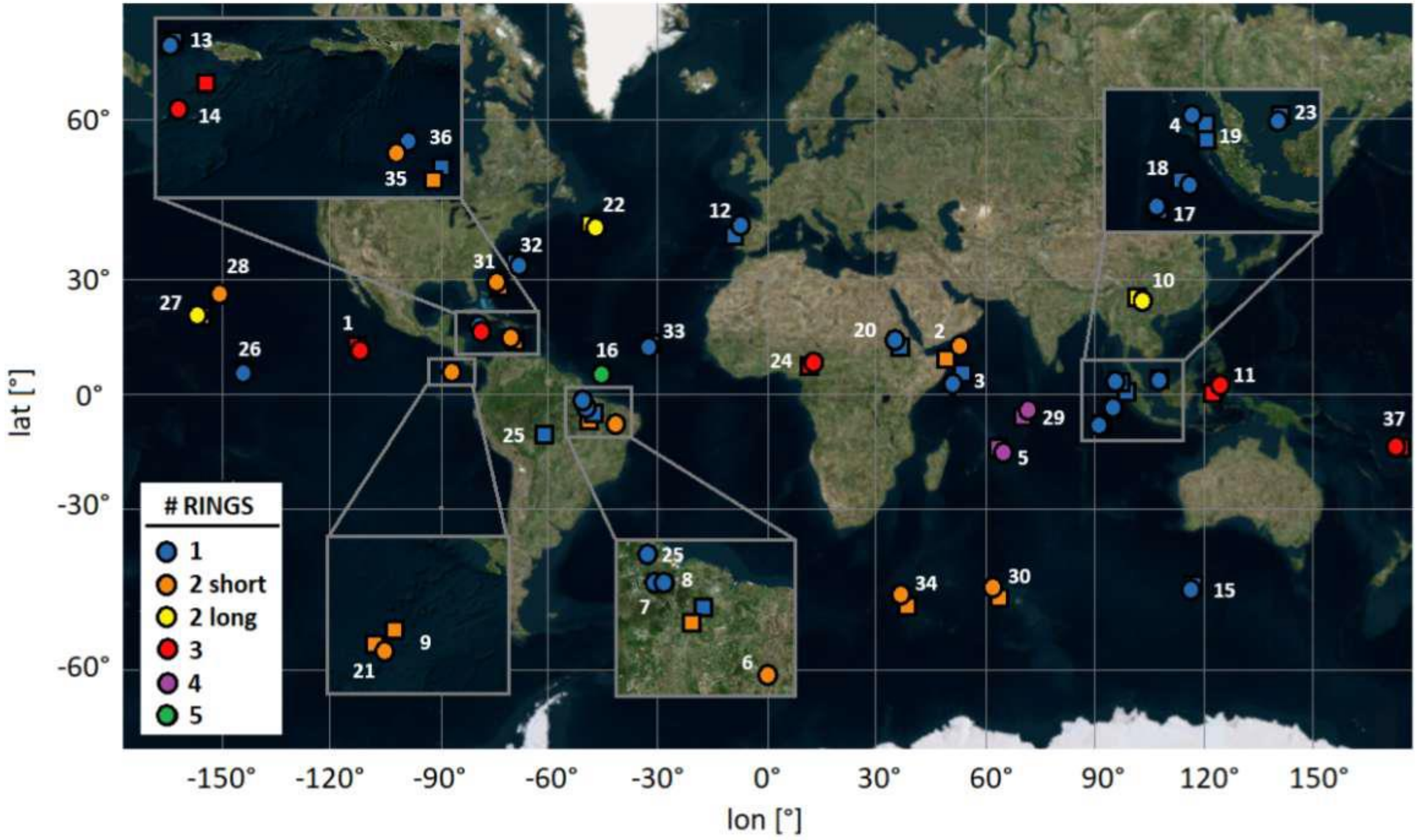
Map of the flasher (108/561) & SLT events

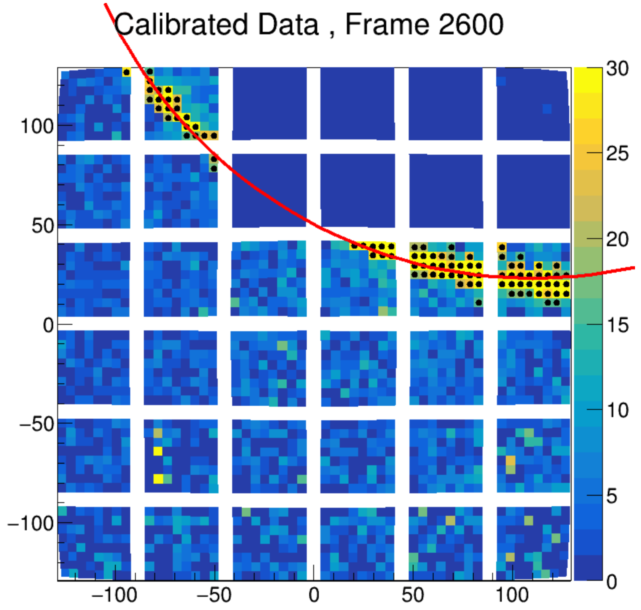


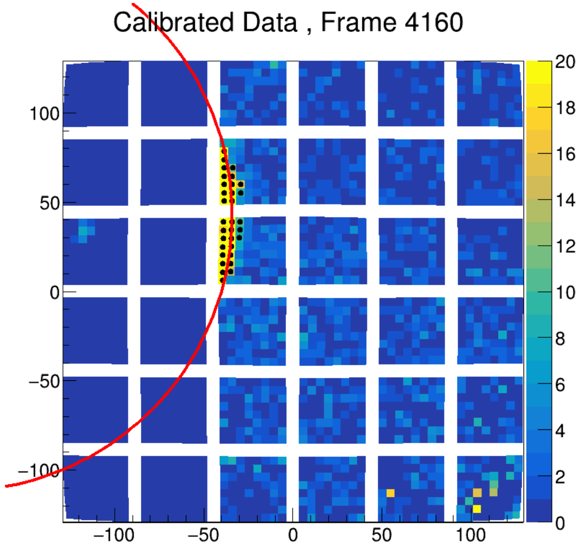
M. Battisti

ELVES:

37 ELVES detected so far
(<1/2 dataset received)
mostly in the equatorial region

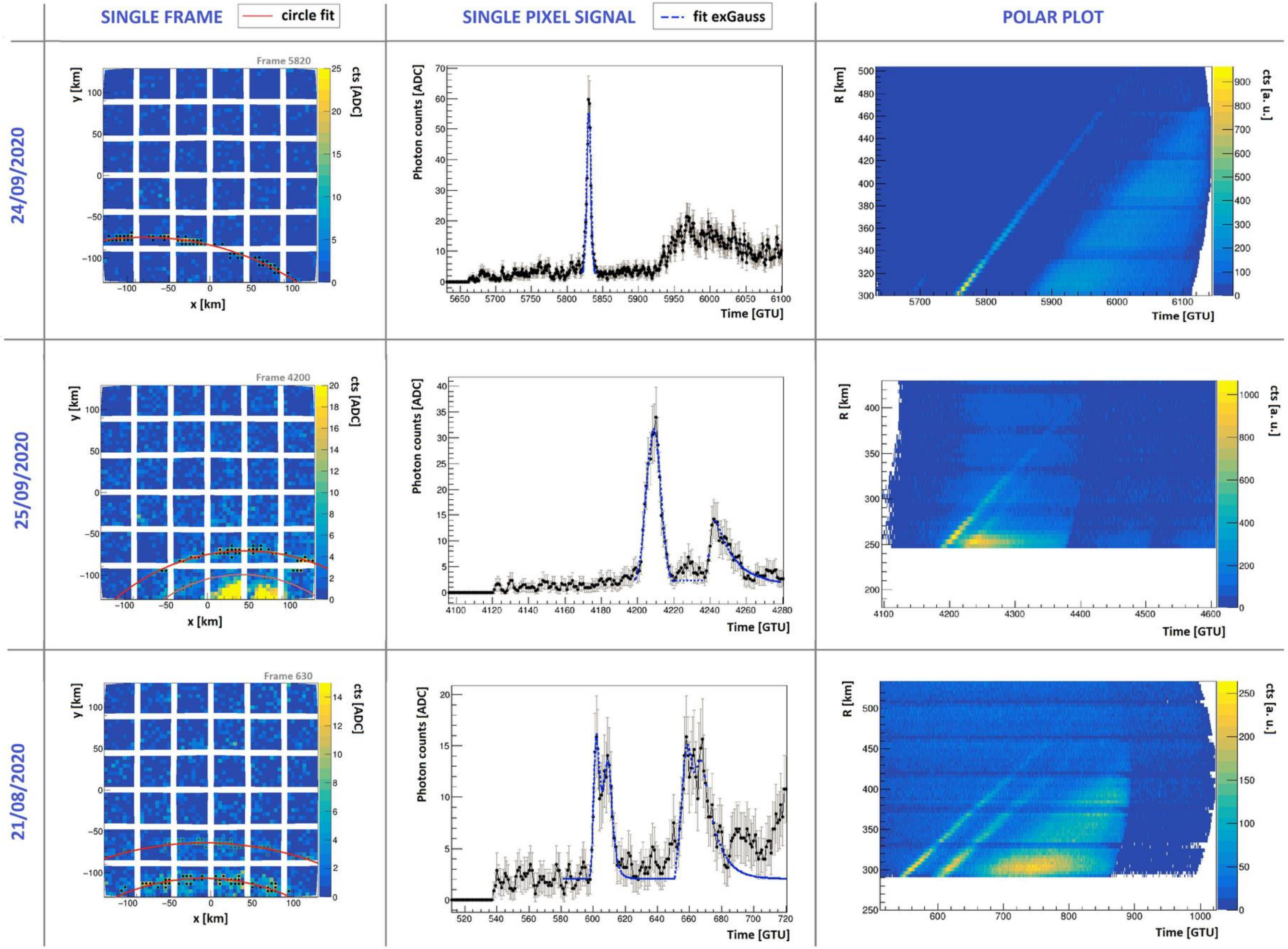






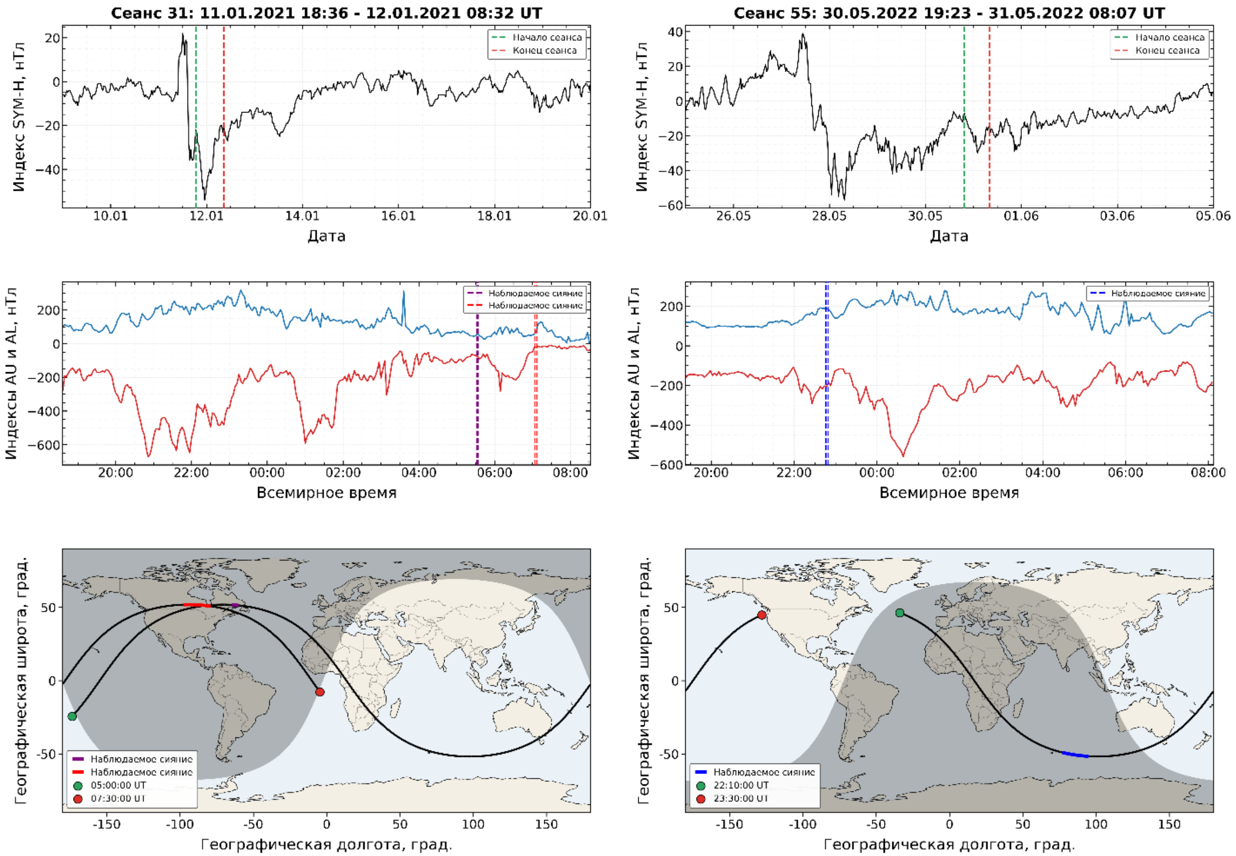
Z. Plebaniak

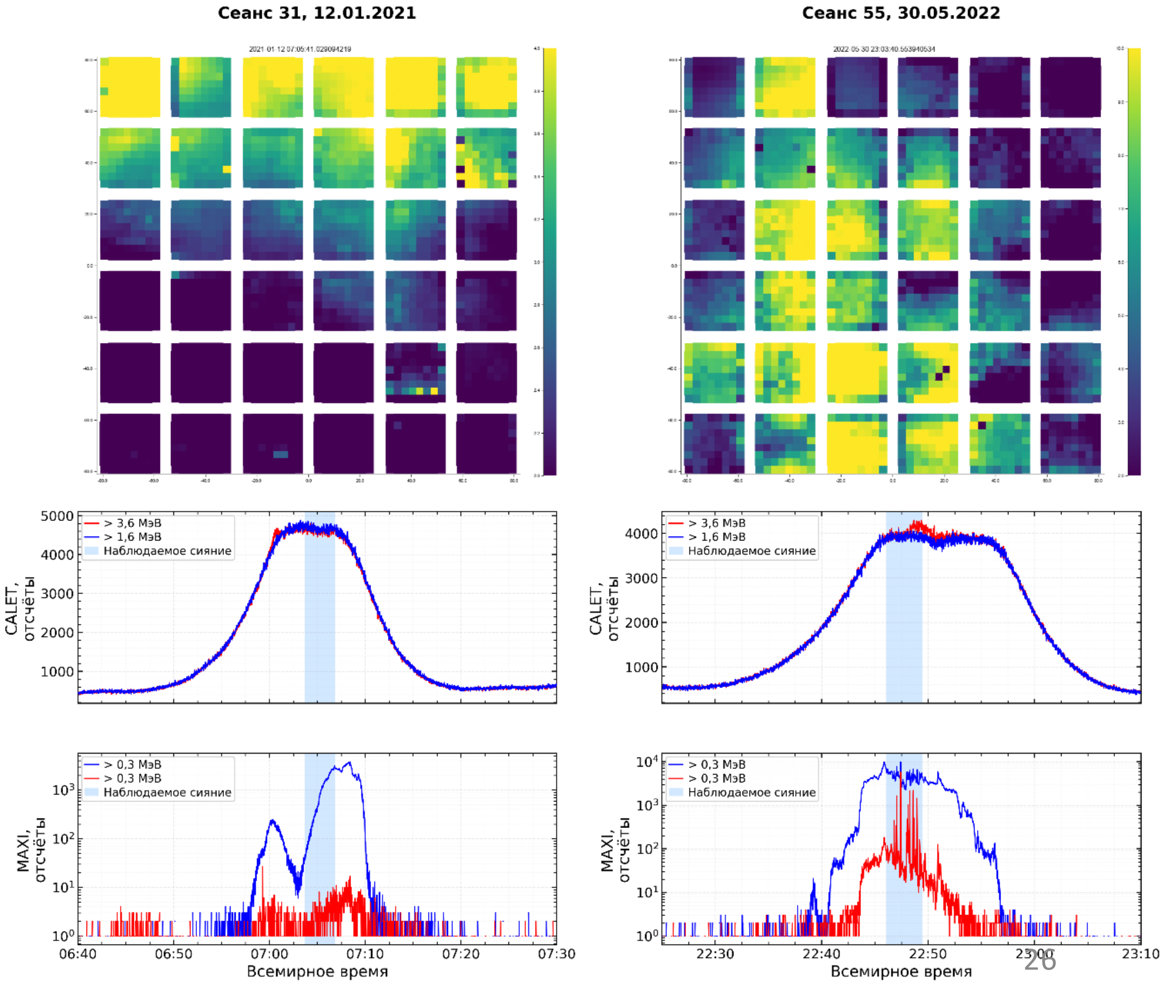
ELVES:



Z. Plebaniak

Aurora emission and charged particles precipitation



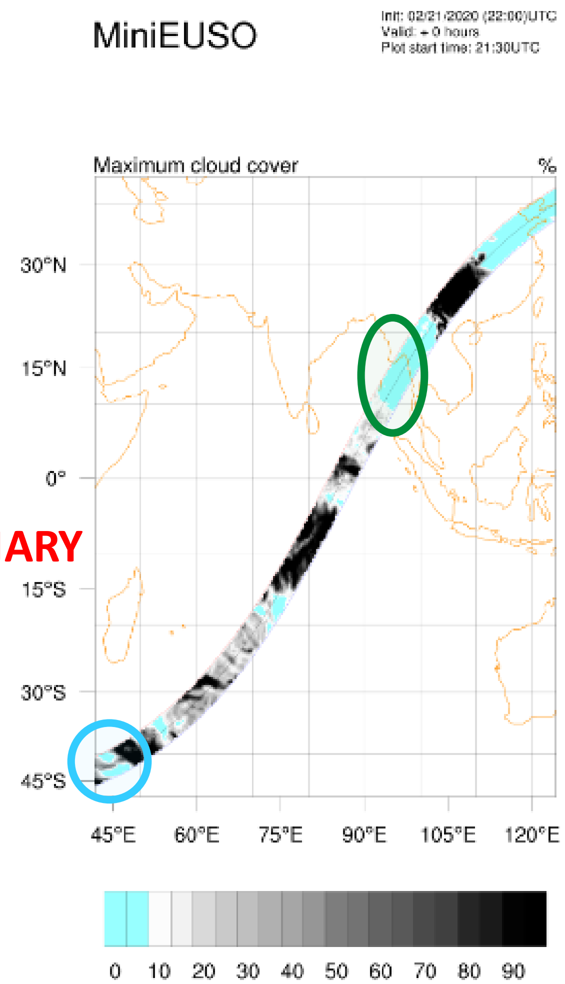


P. Klimov

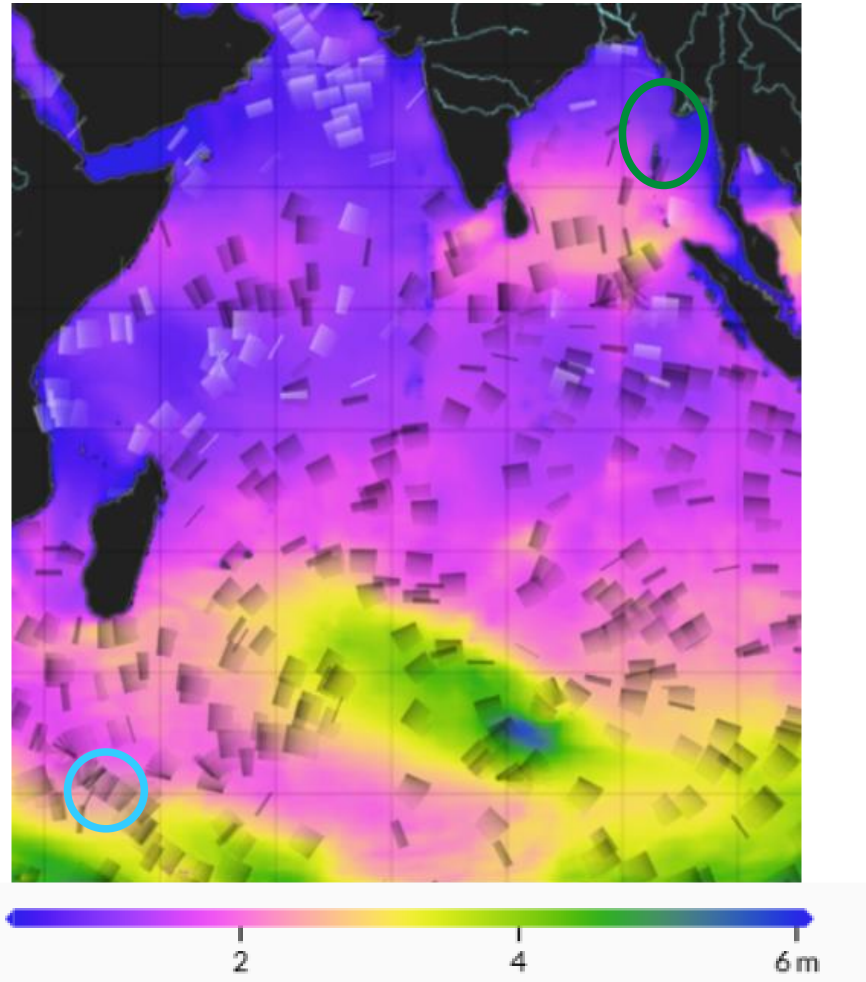
Studying the ocean conditions

GFS maximum cloud cover

PRELIMINARY



Copernicus wave height



Significant Wave Height VHM0 (m)

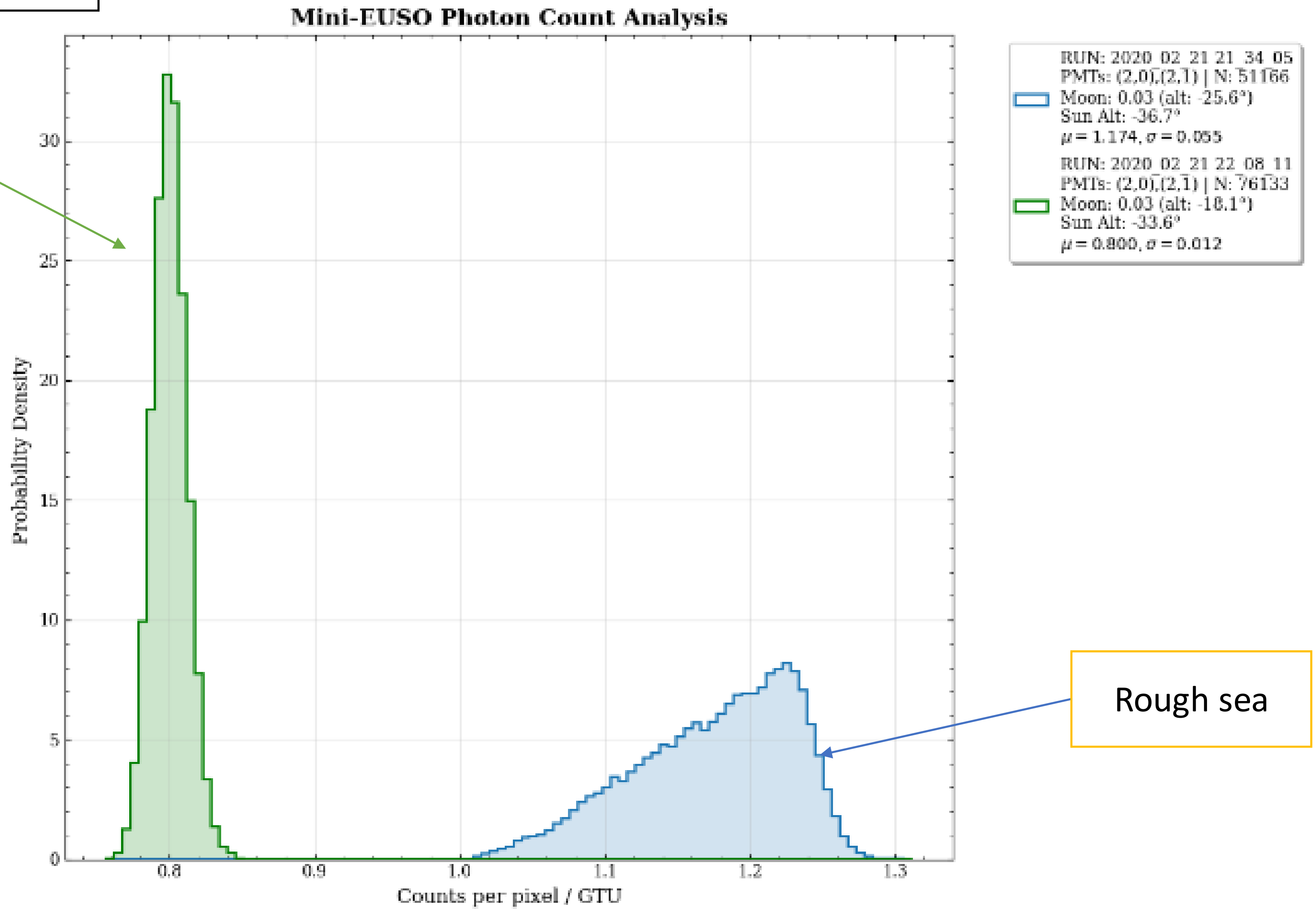
whitecapping

F.Fantino & M.Manfrin

From S11: 21/02/2020

Calm sea

PRELIMINARY

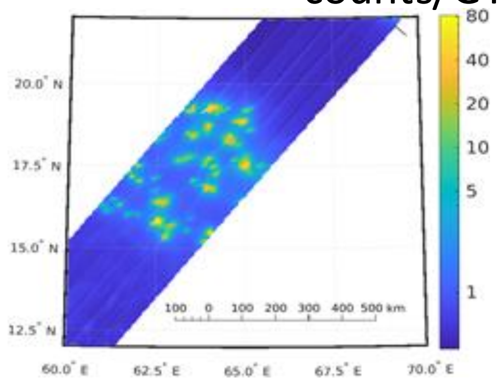


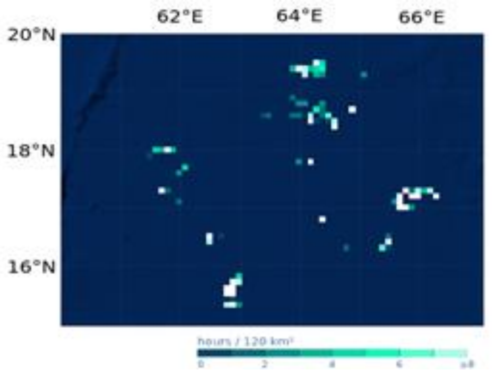
Rough sea

$$\Delta \sim 0{,}3/0{,}4\ \frac{\text{counts}}{\text{GTU}}$$

F.Fantino & M.Manfrin

Fishing boats and AC modulation

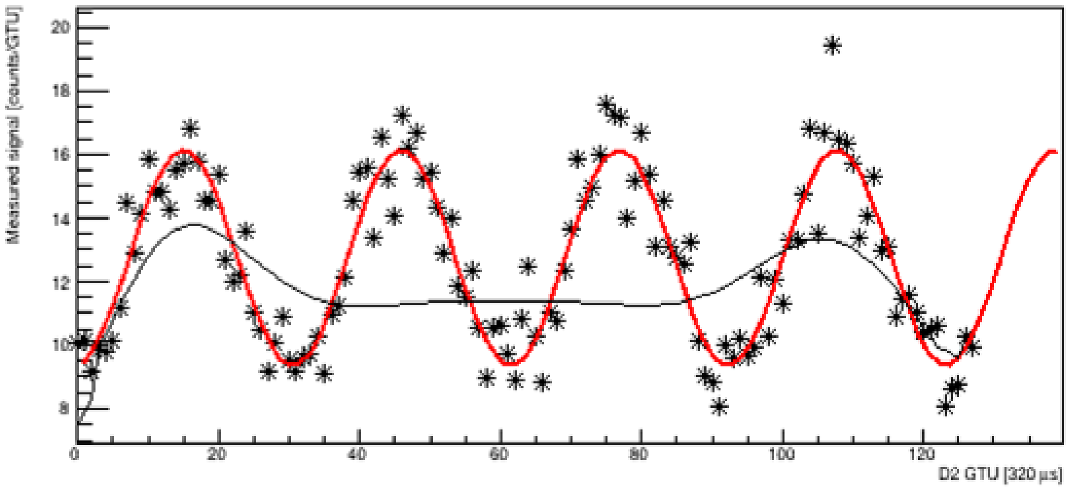




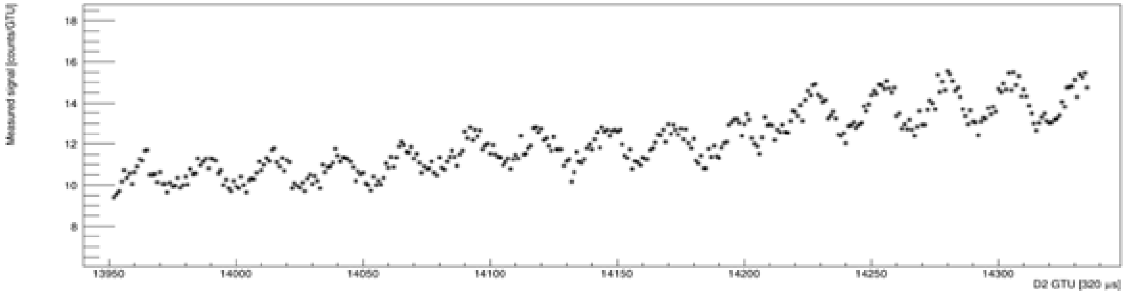
Fishing boats in the Arabian sea. Left: Mini-EUSO data. Right: Data from the Global Fishing Watch [https://globalfishingwatch.org]

Mini-EUSO visible camera off the coast of Argentina

Squid fishermen use bright lights to draw fish and squid toward the sea surface at night. (©2012 Jay Lawler)



50 Hz modulation over an Indonesian city



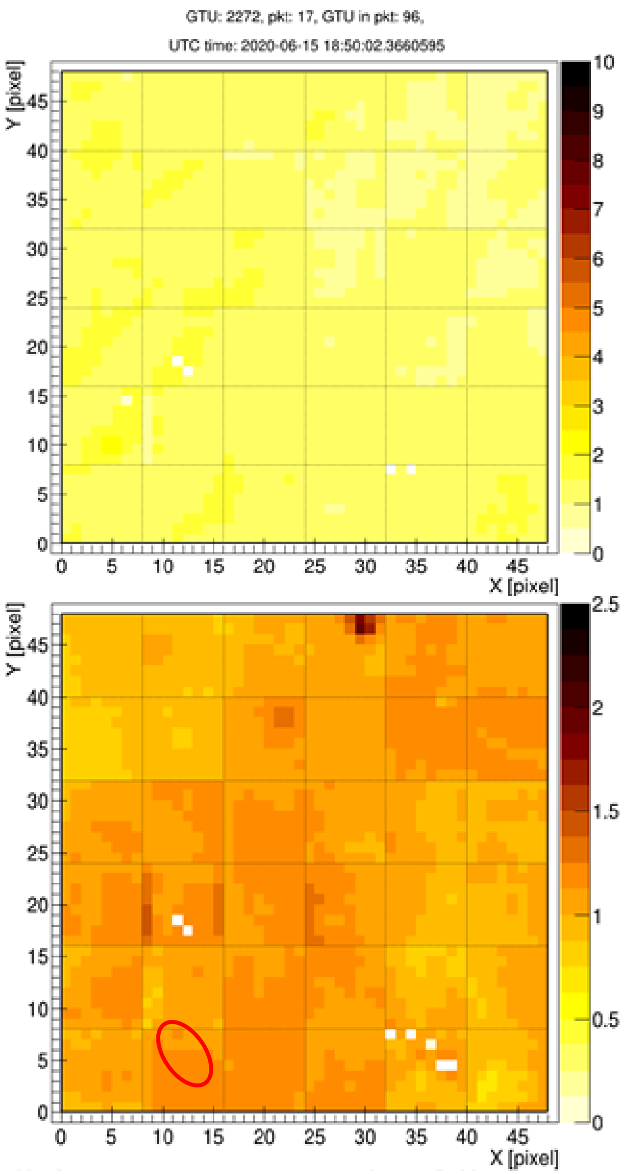
60 Hz modulation produced by the fishing boats off the coast of Argentina

K. Bolmgren

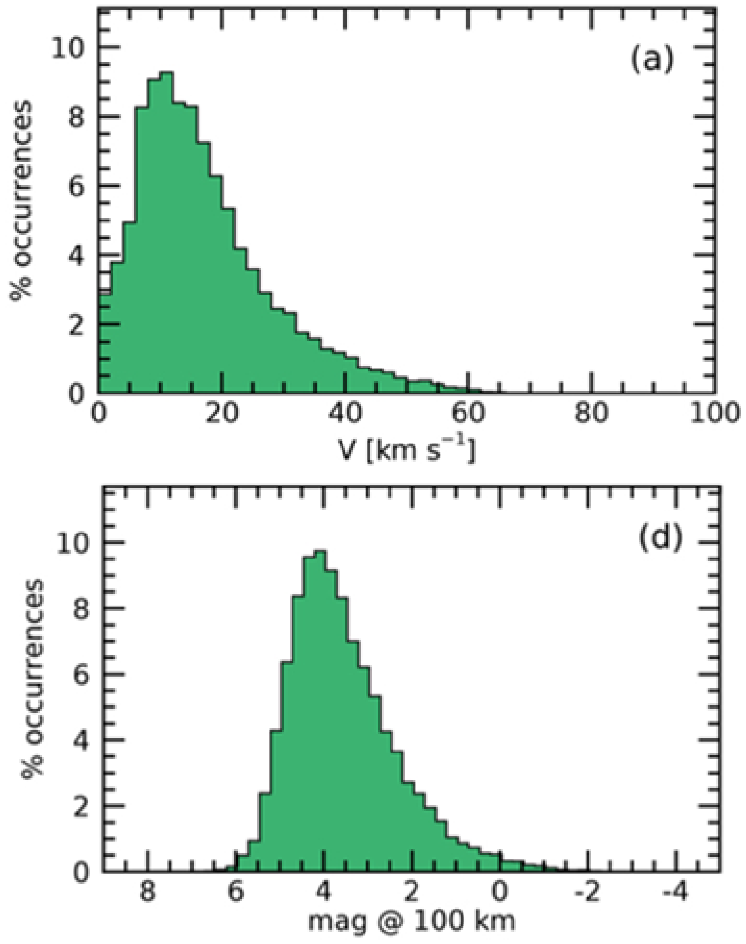
Meteors - Examples and parameters

Barghini, et al., AA 687 (2024) A304

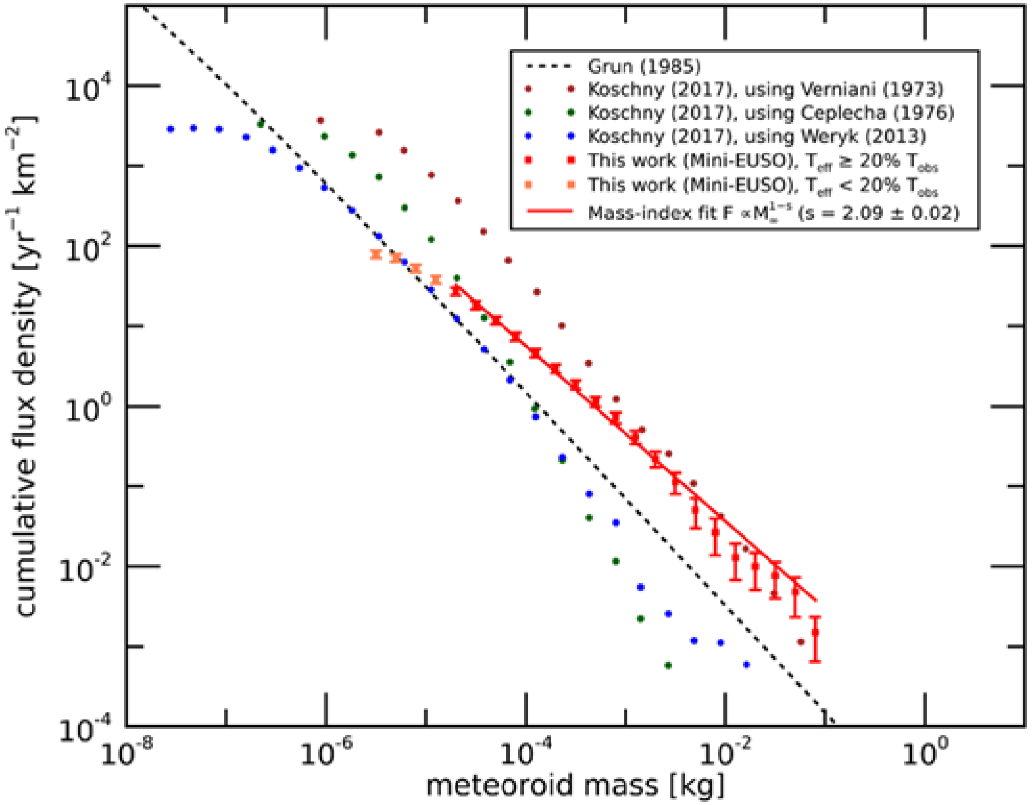
First ever systematic observation of meteors from space. In the dataset analyzed so far, corresponding to less than 50% of the total Mini-EUSO data, over **24,000 meteor** events have been found, at an average **rate of 2.92 per minute**.



A bright and a dim meteor detected by Mini-EUSO



Horizontal speed (Top) and absolute magnitude (bottom) of the 24 thousand meteors detected.

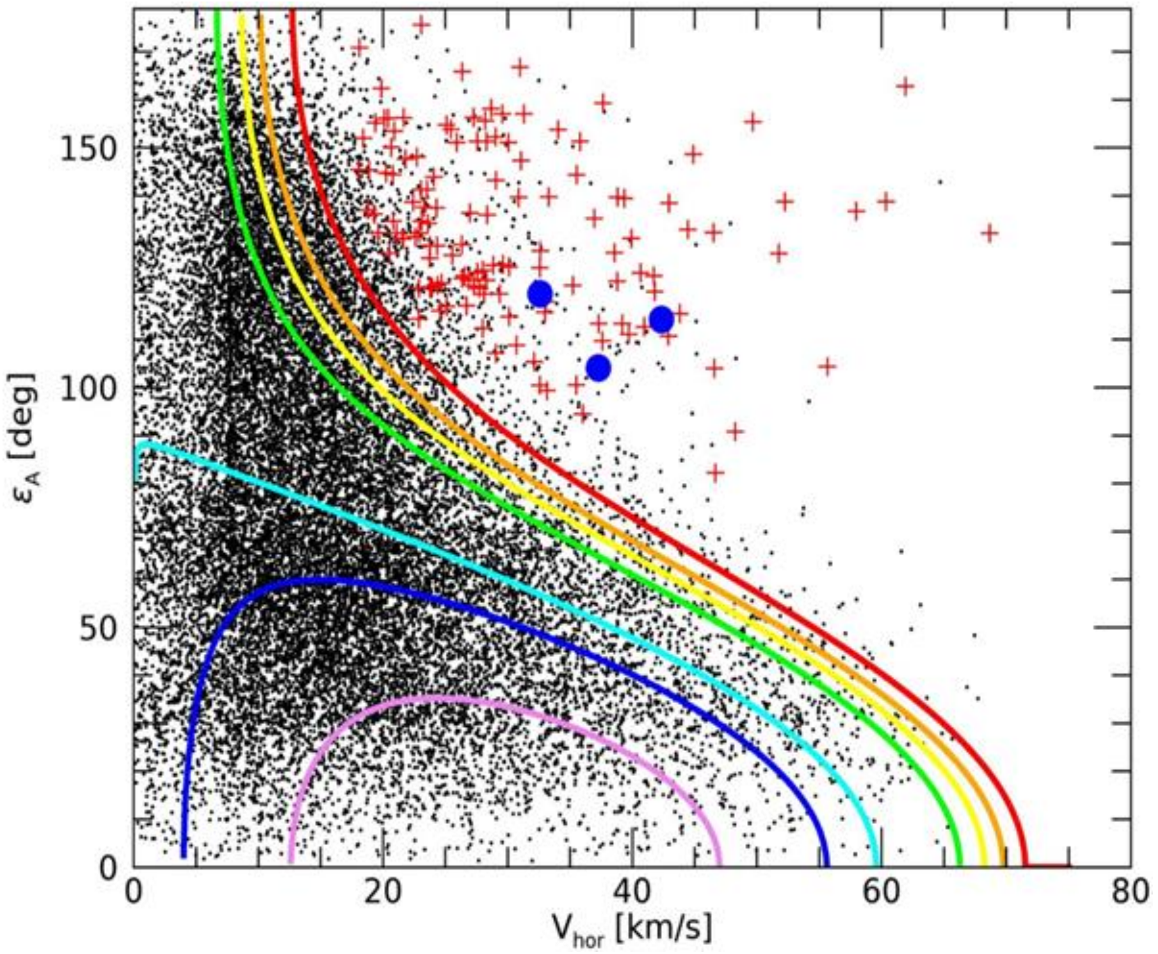


Cumulative flux density of meteors as a function of the preatmospheric mass of the meteoroid.

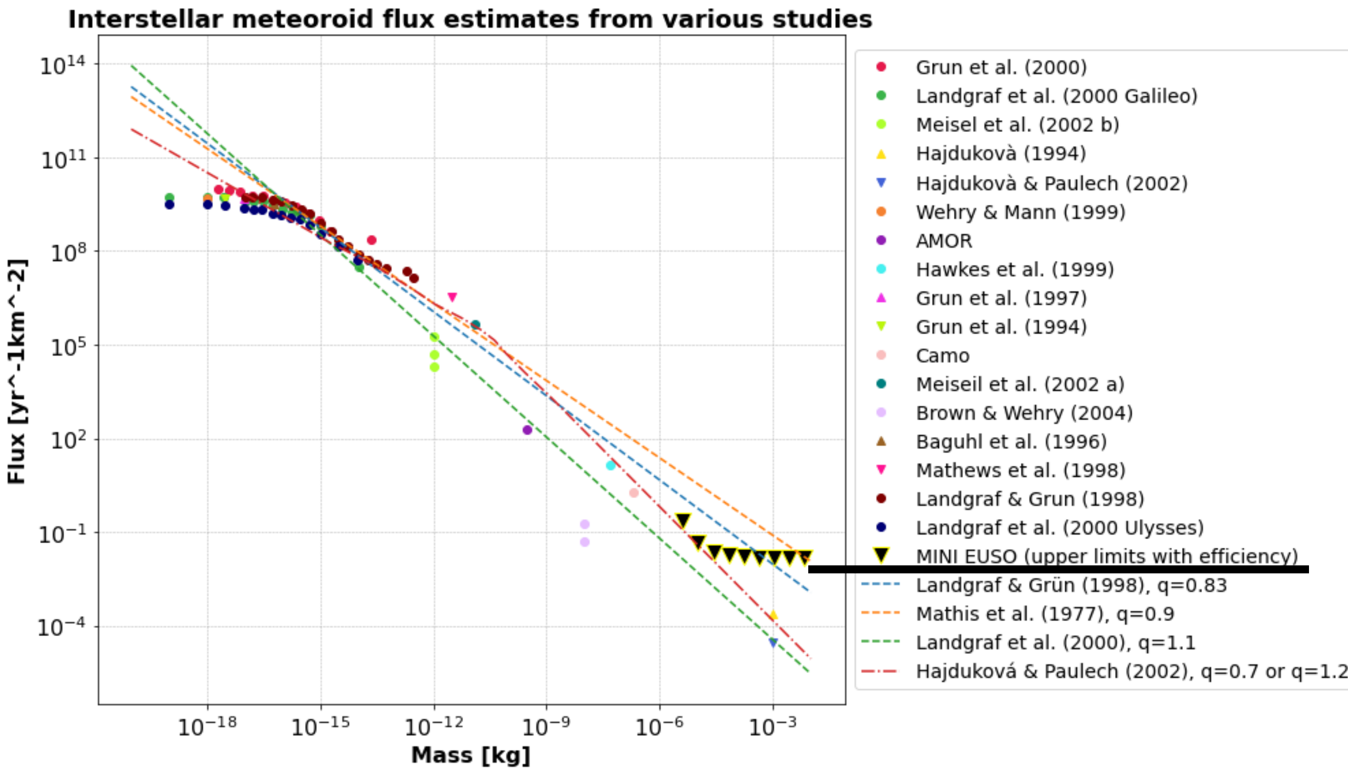
Meteors - Search for interstellar meteors

PRELIMINARY

Performed through the Kresaks' diagram, where the geocentric speed is plotted against the angle between the meteor and the speed velocity of the Earth. Meteors bound to the solar system end up on the left of the red curve.

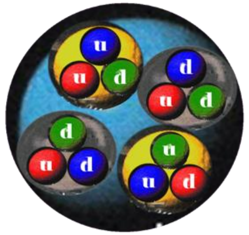


Kresaks' diagram for the Mini-EUSO meteors. The 3 blue points indicated the interstellar meteor candidates with a 3-σ confidence level. The red crosses indicate other candidates below the 3-σ confidence level.



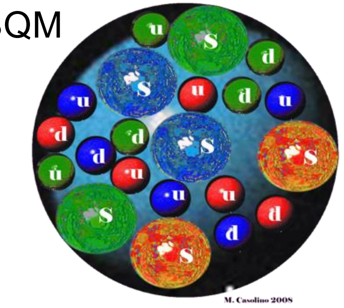
D. Barghini & F. Tosone

Ordinary matter



Z=2 A=4 (4He)
Z/A=0.5

SQM

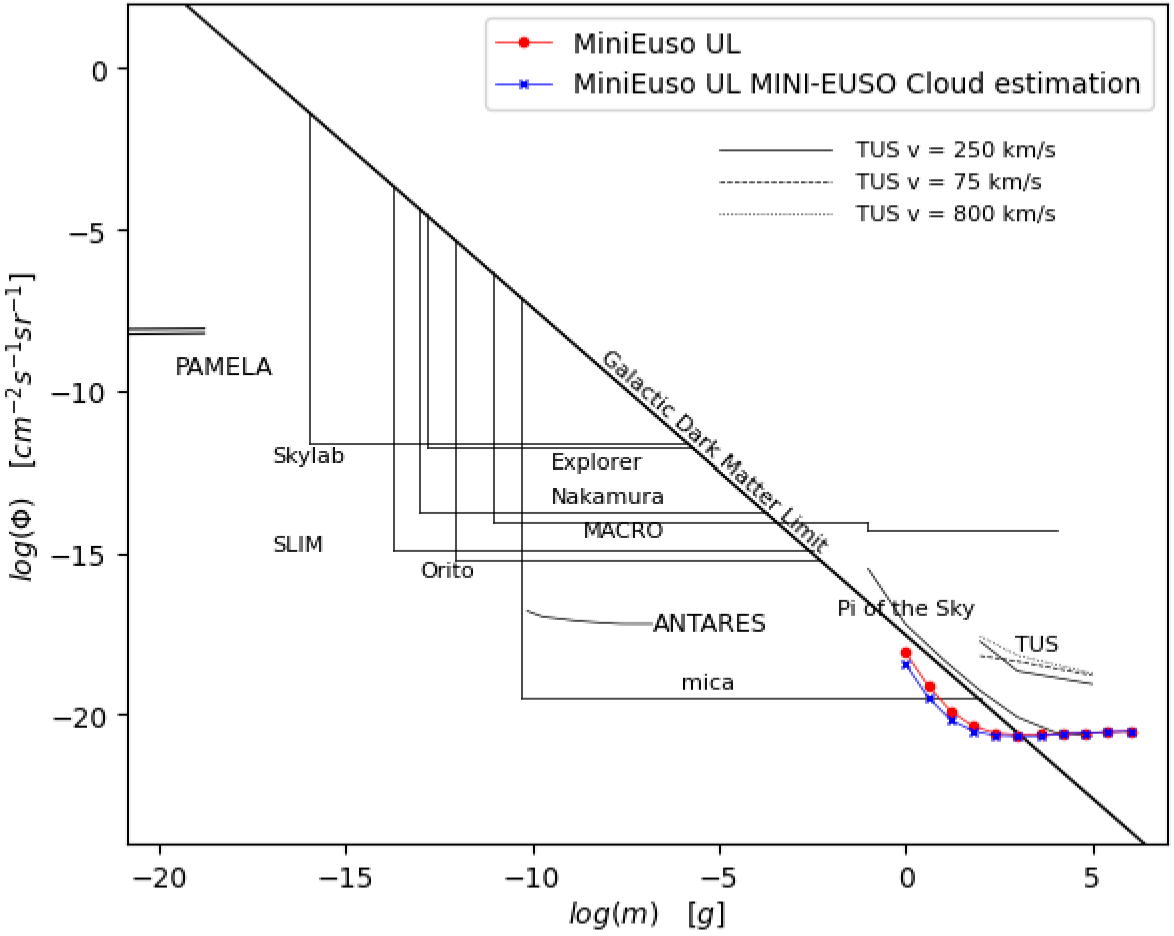


Z=2 A=/ Z/A=0.286

Witten E., Phys. Rev. D 30 (1984) 272-285.
De Rujula, A. and Glashow, S.L., Nature, 312,(1984) 734-737.

Velocity distribution	$f(v) = (\pi v_{\rm vir}^2)^{-3/2}\, 4\pi v^2 \exp[-(v/v_{\rm vir})^2], \quad v_{\rm vir} \simeq 250\ \mathrm{km\,s^{-1}}$
Interaction with atmosphere	$\dfrac{dE}{dx} = -\sigma\, \rho_{\rm atm}\, v^2$
Velocity loss	$v(L) = v_0 \exp\left[-\dfrac{\sigma}{M}\int_0^L \rho_{\rm atm}(x)\, dx\right]$
Apparent magnitude	$M_{\rm app} = 2.5 \ln\left[3.31\times 10^{11}\left(\frac{1\,\mathrm{km/s}}{v}\right)^3\right] - 1.67 \ln\left(\frac{M}{1\,\mu\mathrm{g}}\right) + 5 \ln\left(\frac{h}{10\,\mathrm{km}}\right)$
Minimum mass for emission	$M_{\rm min} = 122.5\left(\frac{1\,\mathrm{km/s}}{v}\right)^3\ \mathrm{g}$
Minimum velocity for emission	$v_{\rm min} = 1\,\mathrm{km/s}\left(\frac{122.5\,\mathrm{g}}{M}\right)^{1/3}$
Maximum emission height	$h_{\rm max} = 3.3\,\mathrm{km}\ \ln\left[\frac{M}{122.5\,(\frac{1\,\mathrm{km/s}}{v})^3\,\mathrm{g}}\right]$

PRELIMINARY

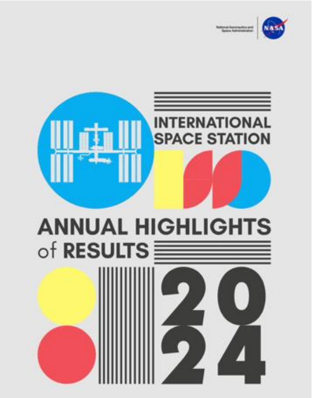


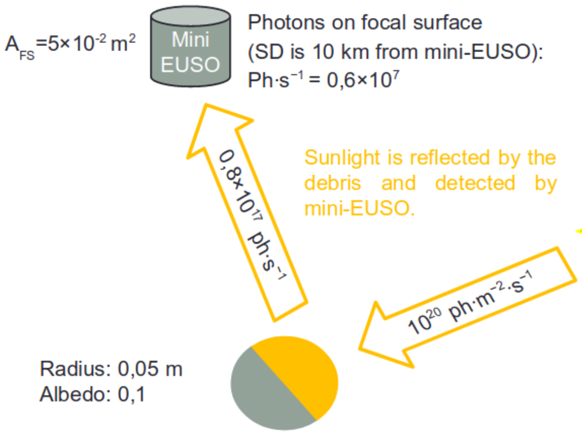
R. Pullano, D. Barghini

APPLICATION to Space Debris Detection

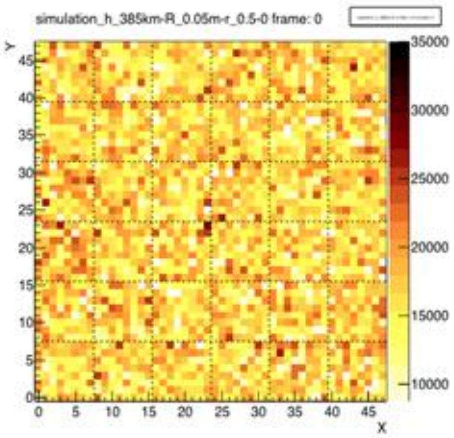
No possibility to detect space debris because of Earth-pointing of the detector

L. Olivi et al. (Mini-EUSO team), "Refined STACK-CNN for Meteor and Space Debris Detection in Highly Variable Backgrounds"
IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING, VOL. 17, 2024





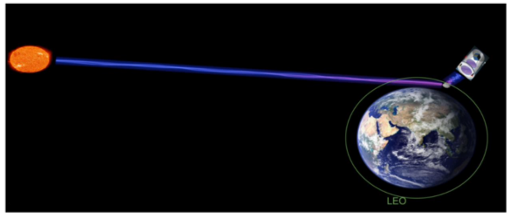
ESAF simulation: Space debris event in the FoV of Mini-EUSO detector



Space Debris – Mini-EUSO

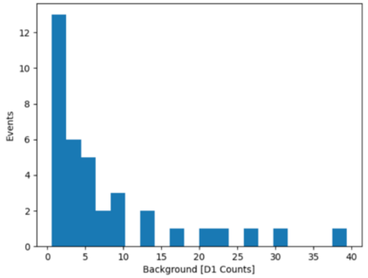
- Focus back on **Space Debris** → **Twilight** → **Low statistics** and **High background**
- **Low statistics** → **~ 1h 6m 22s** / ~ 141h 12m 15s (**0.75%**)
- **High background** → No **protection** to cover **Mini-EUSO**
- **Stack-CNN** → **No triggered** events

SD DETECTION IN MINI-EUSO



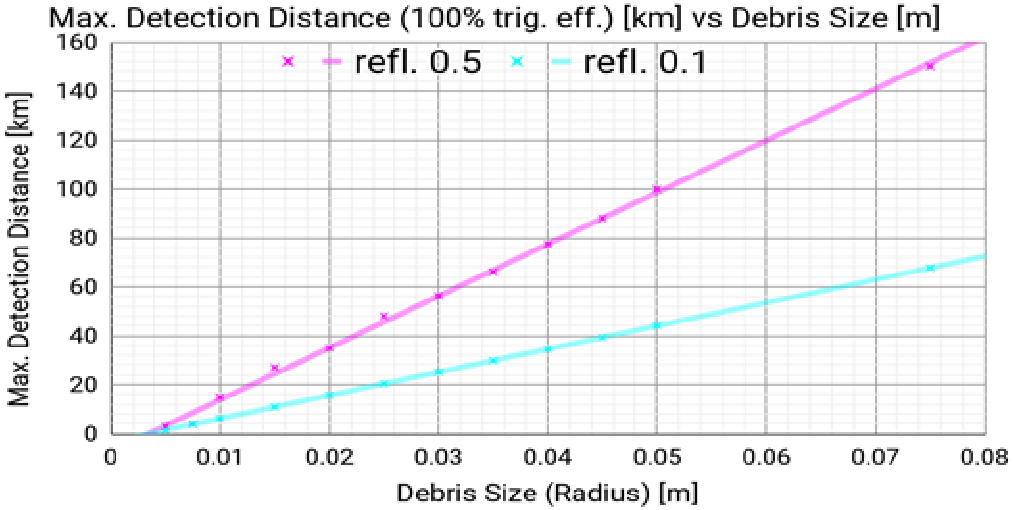
Illuminated Detector

TWILIGHT BACKGROUND DISTRIBUTION



- Other **configurations** in **Mini-EUSO**?
- **Full Moon** reflection? → Much **lower intensity** than **Sun**
- **Stack-CNN** → Need **big** (~ 5 m^2) and **close** (10 km) objects

- **Starlink** (**SpaceX**) satellites → **Big** (~ 5 m^2), **high statistics** (~ 3000 in **LEO**), extremely **reflective**
- **Prediction** of time (**GTUs**) and **pixels** → No **crossing** at **twilight** or **Full Moon** → **No trace**



CONCLUSIONS

- Mini-EUSO shows that high-speed UV imaging from space is both feasible and scientifically powerful.
- The data reveal a rich variety of atmospheric events that is still largely unexplored.
- It allows us to detect fast and faint atmospheric phenomena that are otherwise difficult to observe.
- It provides a complementary view with respect to existing atmospheric instrument.
- This highlights the strong potential for future dedicated EUSO-like missions with improved capabilities.
- It opens the door to broader, community-driven analysis and new interdisciplinary studies.

THANK YOU