

**Joint Experiment Missions-
Extreme Universe Space Observatory**



Mini-EUSO

Implications of Mini-EUSO measurements for a space-based observation of UHECRs

**M. Battisti, M. Bertaina*, M. Bianciotto, K. Bolmgren,
F. Fenu, A. Golzio for the JEM-EUSO Collaboration**

***Univ. & INFN Torino**

45th Cospar Assembly, Busan (July 19th 2024)



JEM-EUSO¹

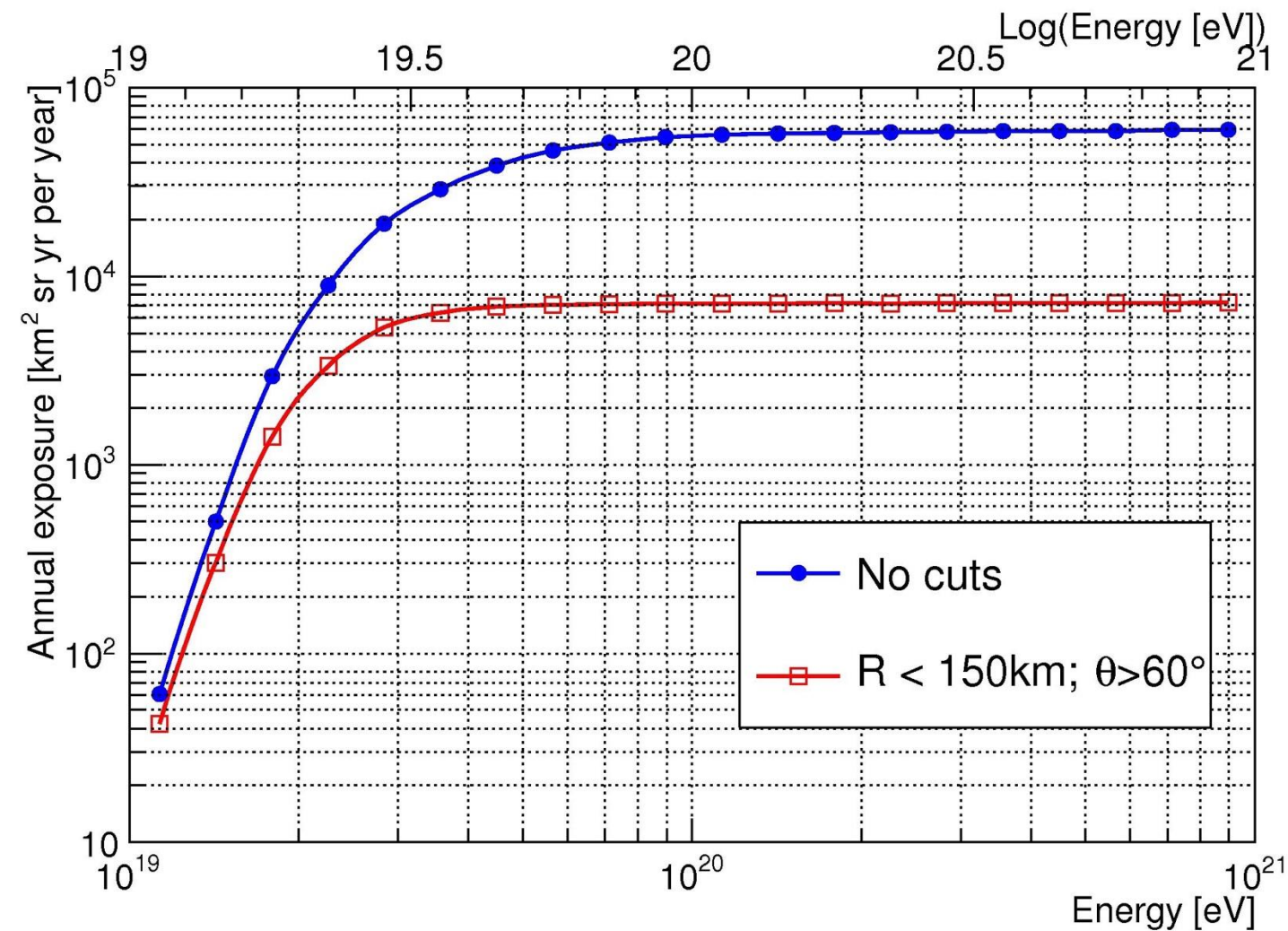
Introduction

In the following JEM-EUSO will be considered for comparisons as Mini-EUSO was designed as a small scale version of JEM-EUSO.

The results apply to K-EUSO and POEMMA as well as the exposure curves and the EAS detection principle of these two instruments have been obtained using the same approach and tools (ESAF simulation and reconstruction framework) originally developed for JEM-EUSO.

Some of the results presented in the following have to be considered still PRELIMINARY (limited data sample and still on going analyses), however, the general conclusions are not expected to change significantly.

JEM-EUSO exposure

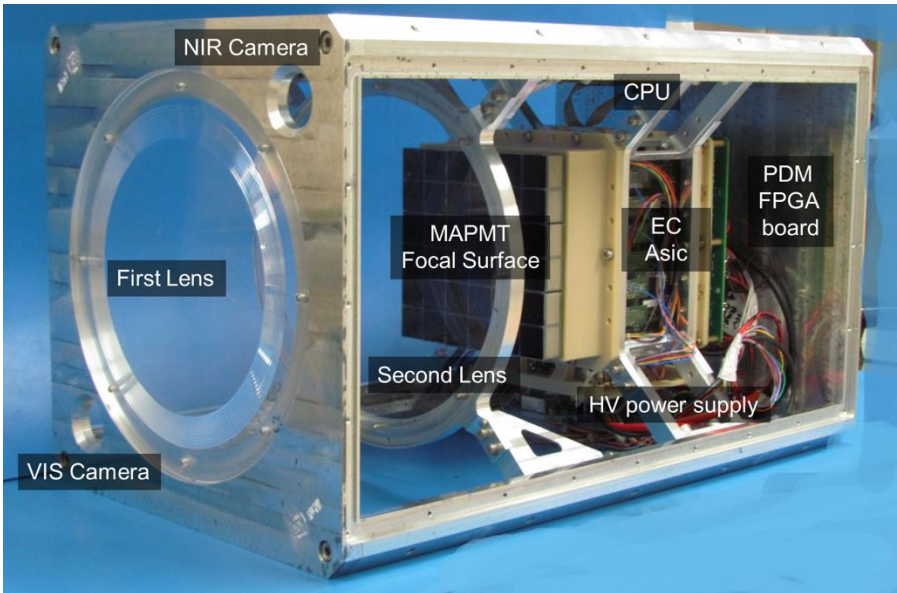


Assumptions in J.H. Adams et al. *Astrop. Phys.* 43, 76-90 (2013):
500 photons/m²/ns/sr → 1.1 counts/pix/GTU

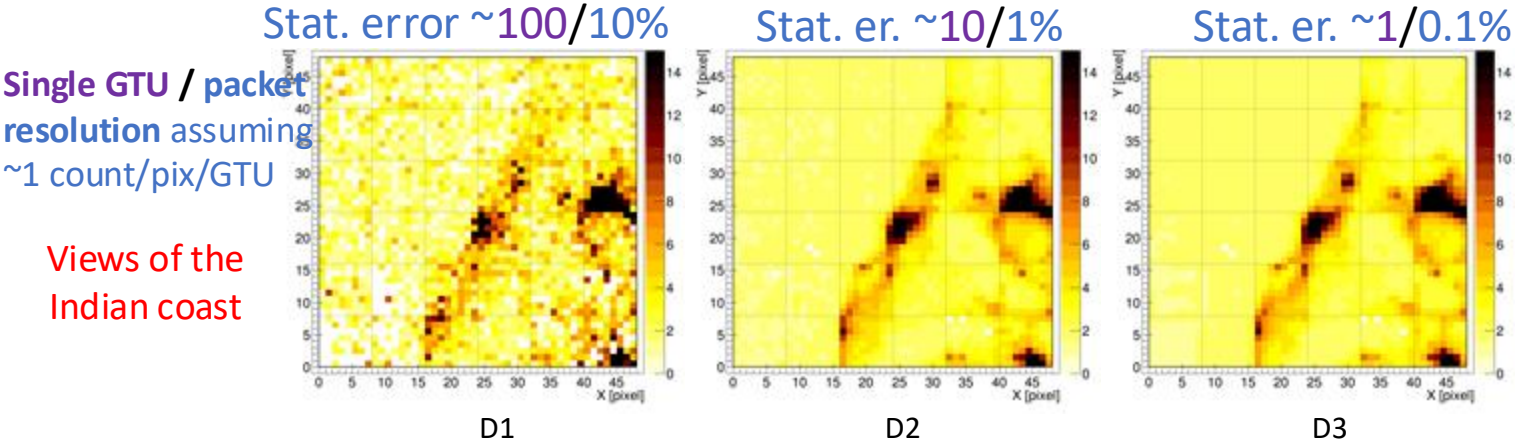
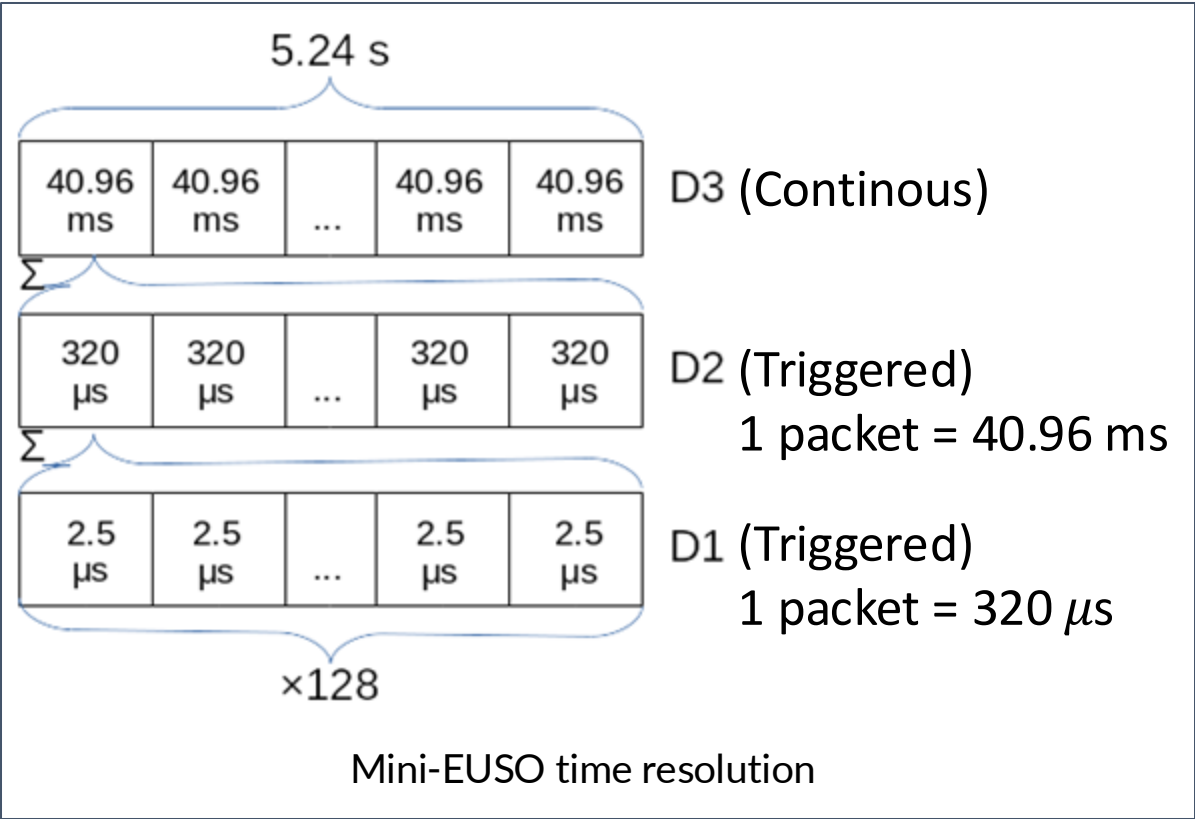
- Observational duty cycle (brightness of the sky does not hamper UHECR measurements): ~20%
 - Role of clouds: ~72%
 - City lights inefficiency: ~7%
 - Lightning ineff.: ~2%
 - Aurorae ineff.: ~1%
 - Conversion factor between Aperture and Exposure: ~13%
- $0.2 \times (1 - 0.07 - 0.02 - 0.01) = 0.18$



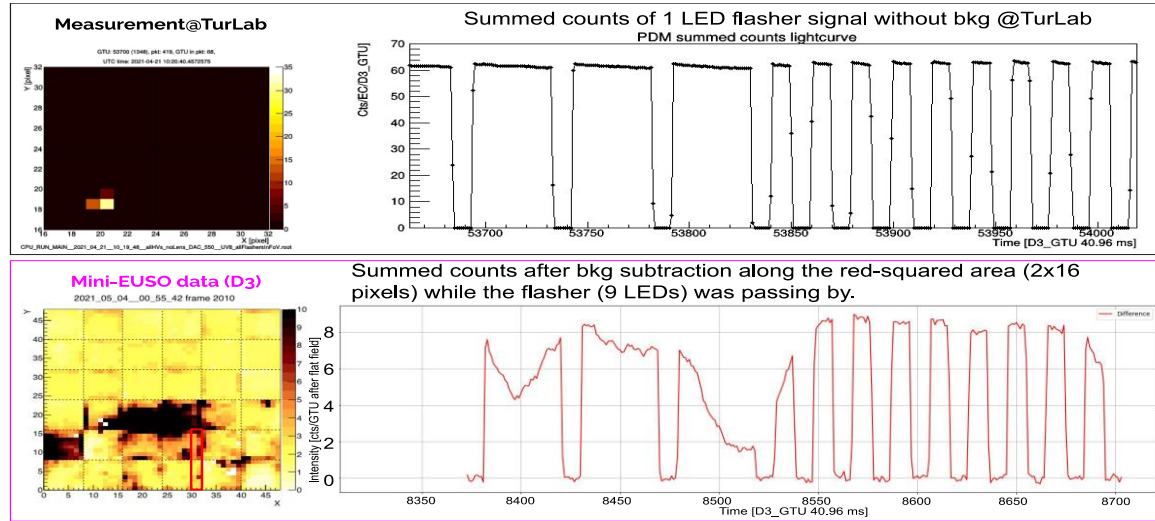
Data acquisition system of Mini-EUSO



for exposure
→
Used in the following discussion
→
for Short Light Transients events



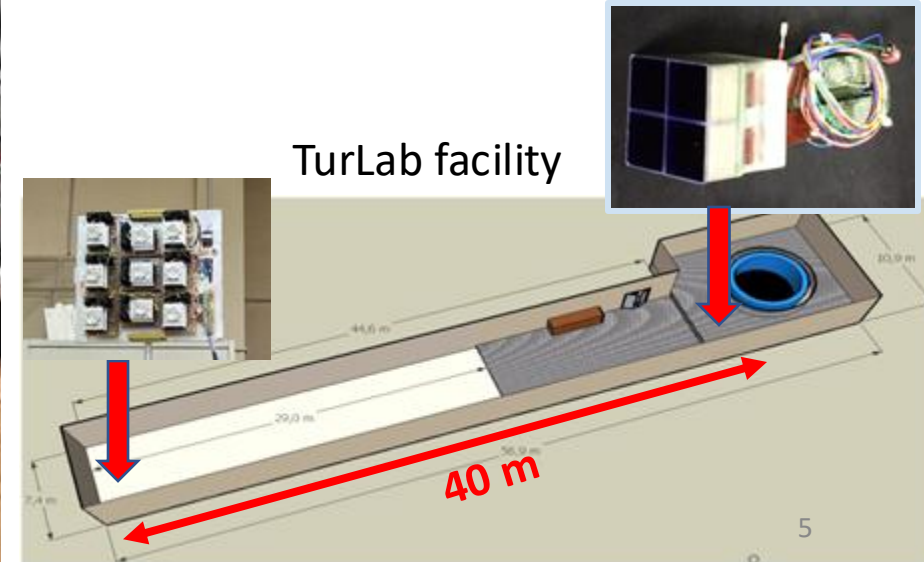
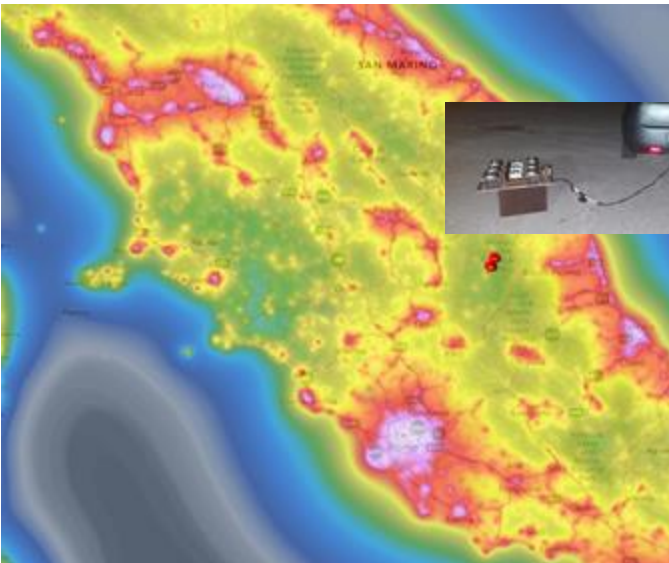
Mini-EUSO end-to-end calibration



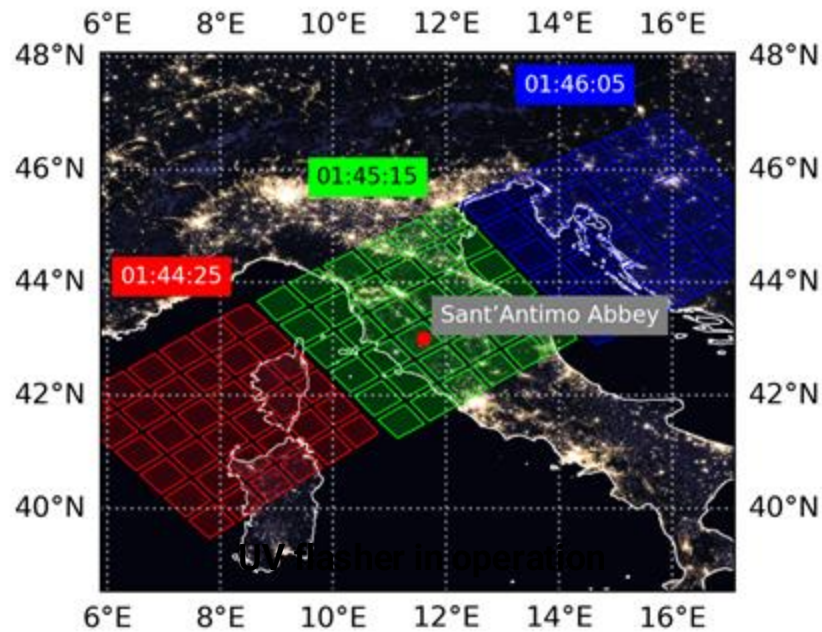
Tests @ TurLab facility

First attempt of calibration in session 40

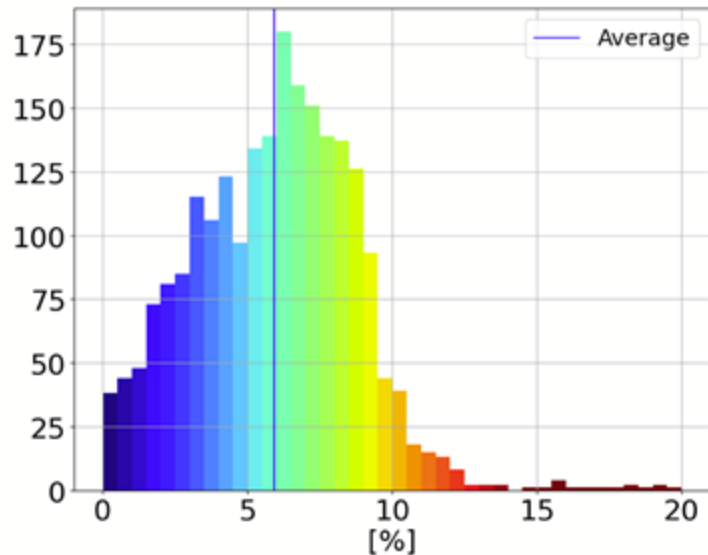
$$n_{photons}^{window} = n_{photons}^{TurLab} \times Angular_{lens} \times Abs_{atm} \times \frac{Area(ME)}{Area(To-EC)} \times \left(\frac{Distance(To-EC)}{Distance(ME)} \right)^2 \times \cos(\theta)$$



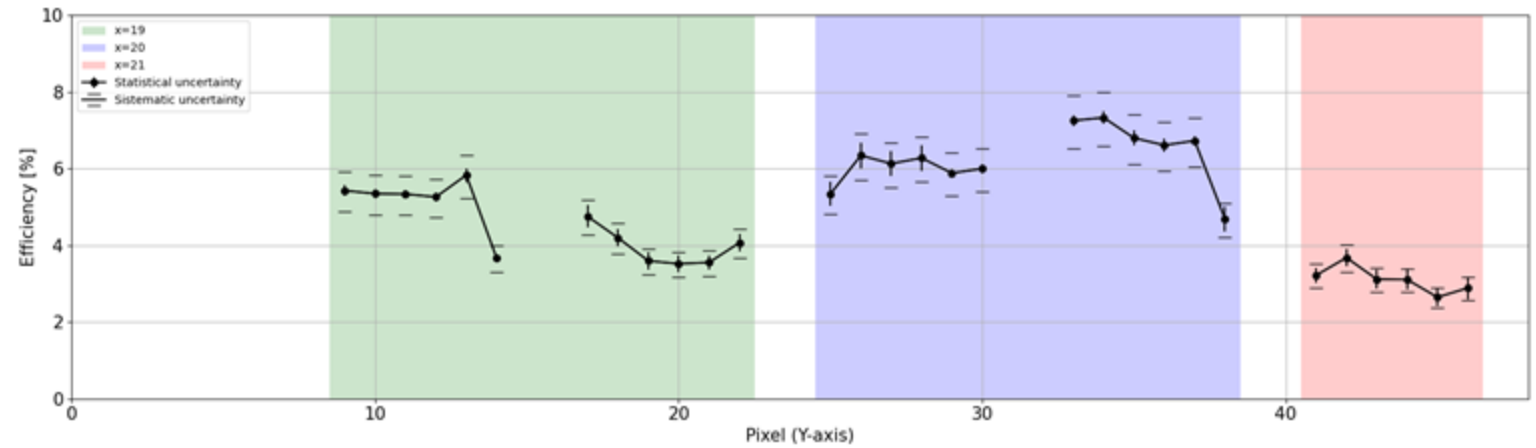
Mini-EUSO end-to-end calibration with flasher



Location of the flasher (30/10/2022)



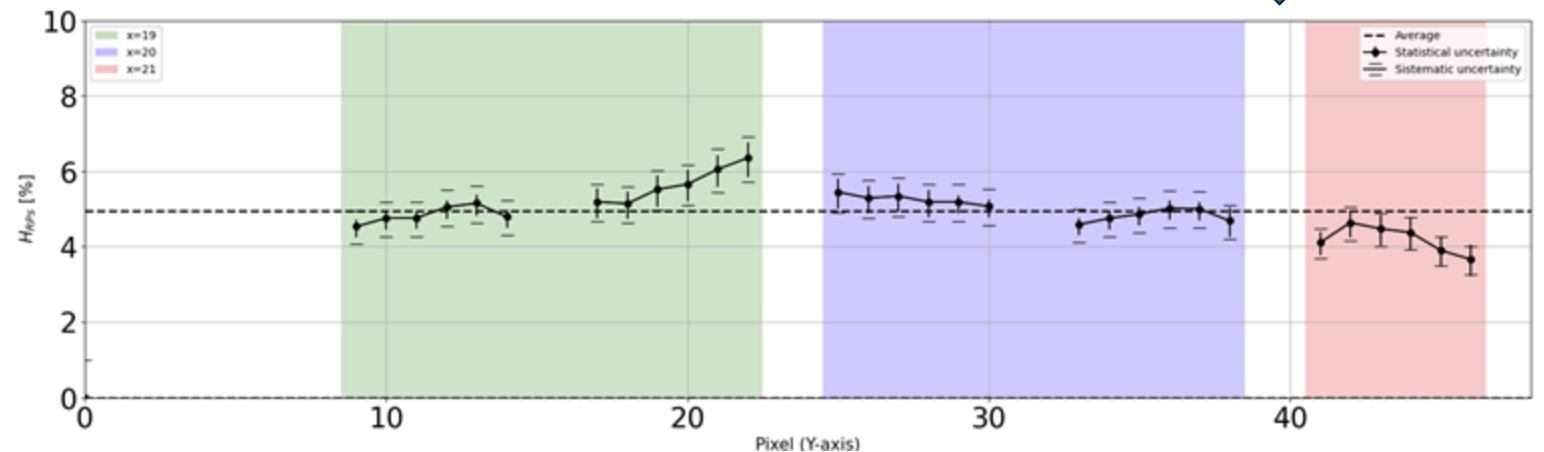
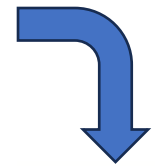
Efficiency derived for all the pixels



Measured end-to-end efficiency of 30 pixels

$$H_{RPS-S1} = (4.95 \pm 0.10 \pm 0.42)\%$$

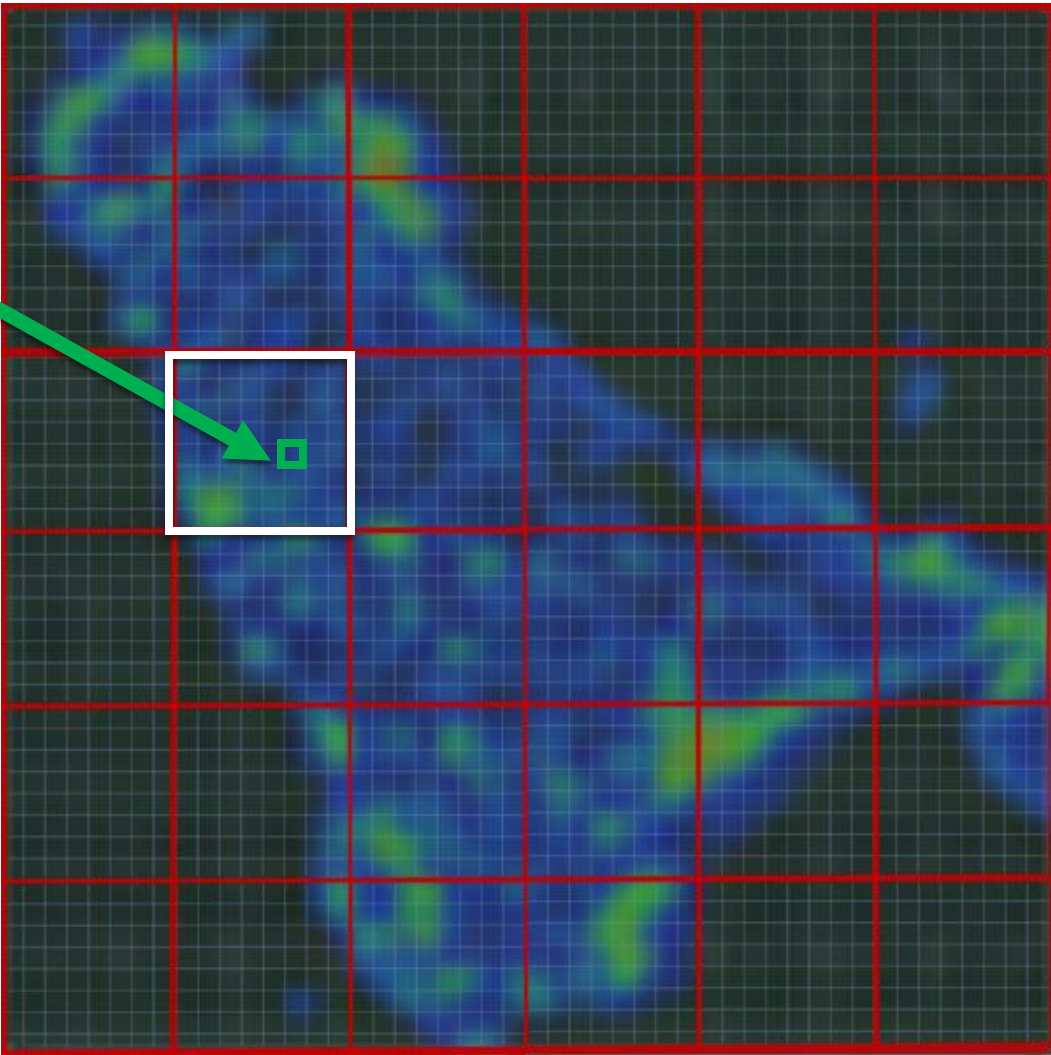
$$[H_{RPS-S2} = (8.15 \pm 0.17 \pm 0.70)\%,$$



Re-scaled efficiency considering flat-fielded data

JEM-EUSO & Mini-EUSO

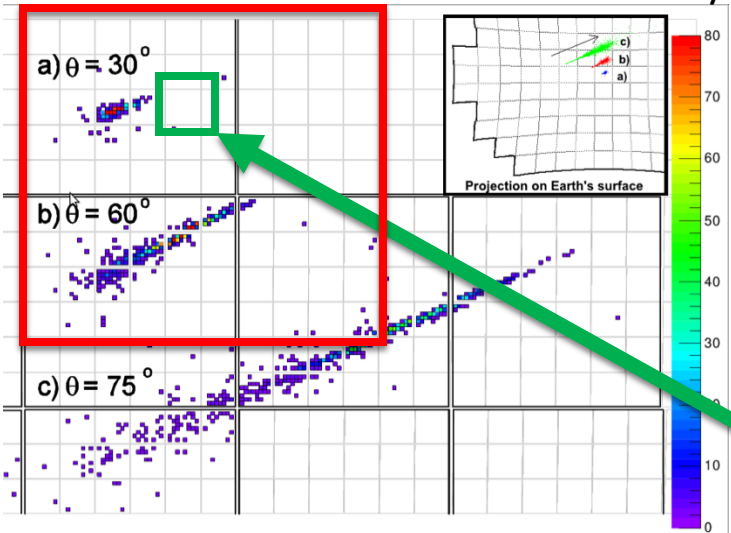
Mini-EUSO



Simulation
pre-flight

FoV

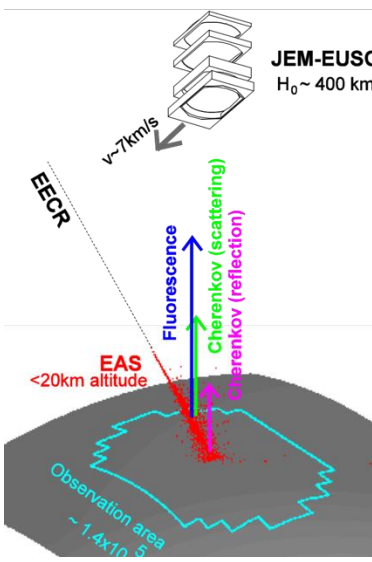
counts/GTU



Comparison @ order of magnitude level

Mini-EUSO	JEM-EUSO
~1 pixel	~ 1.5 MAPMT
~1 PMT	~ 3 PDM
~6.3 km	~0.55 km
~0.05 m ²	~4.5 m ²

JEM-EUSO



Spatial resolution

Optics aperture

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

Expected diffused UV light ratio between JEM-EUSO and Mini-EUSO by means of ESAF simulations

- JEM-EUSO: expected performance according to J.H. Adams et al. Astrop. Phys. 44, 76-90 (2013)
- Mini-EUSO: overall efficiency **$(8.0 \pm 1.5)\%$ @ 397 nm for point-like source (from calibration in session 40)**
- Flat diffused UV emission in the range $\lambda = 300 - 400$ nm

JEM-EUSO @ 500 photons/(ns sr m²)
 0-60 degrees simulation: 1.31 CTS/pixel/GTU
 0-30 degrees simulation: 1.02 CTS/pixel/GTU

Mini-EUSO @ 500 photons/(ns sr m²)
 0-60 degrees simulation: 1.33 CTS/pixel/GTU
 0-22 degrees simulation: 0.98 CTS/pixel/GTU

$$\chi = \frac{N_{CTS}}{N_{ph}} \frac{\Omega_{simu}}{\Omega_{det}} \frac{A_{simu}}{A_{det}}$$

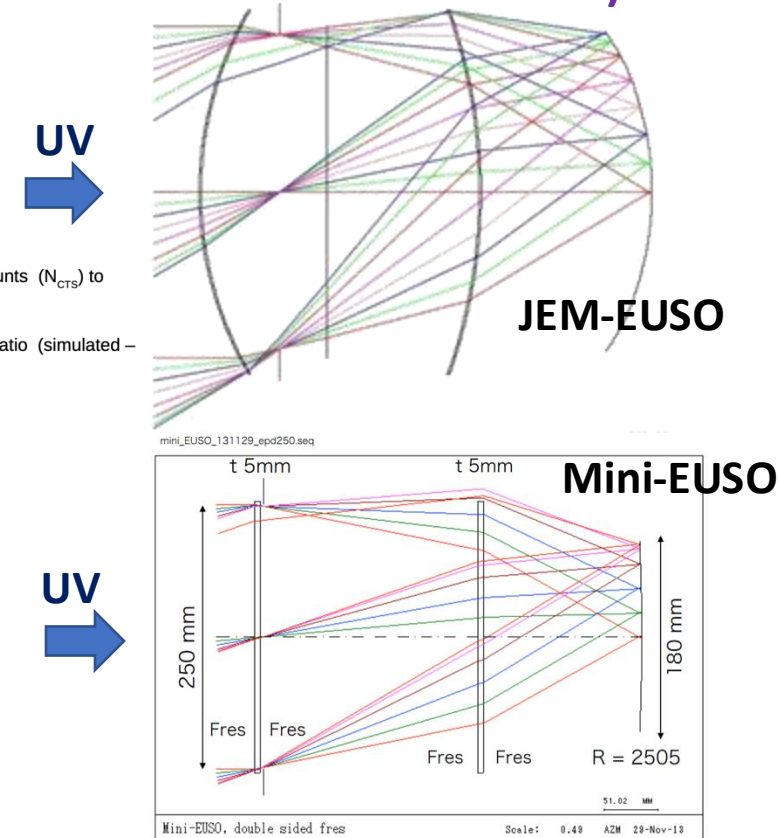
From simulations: ratio of single pixel counts (N_{CTS}) to photon number on pupil (N_{ph}).
 Normalization with solid angle and area ratio (simulated – Ω_{simu} vs. detector – Ω_{det})

$$N_{expect} = \chi * R * \Delta t * A_{det} * \Omega_{det} \eta$$

Expectation of count number
 R: Radiance
 Δt : time
 A: area of pupil
 Ω_{det} : solid angle field of view

$$\eta = \frac{\int d\theta \sin(\theta) \cos(\theta)}{\int d\theta \sin(\theta)}$$

Correction to account for planarity of the lens



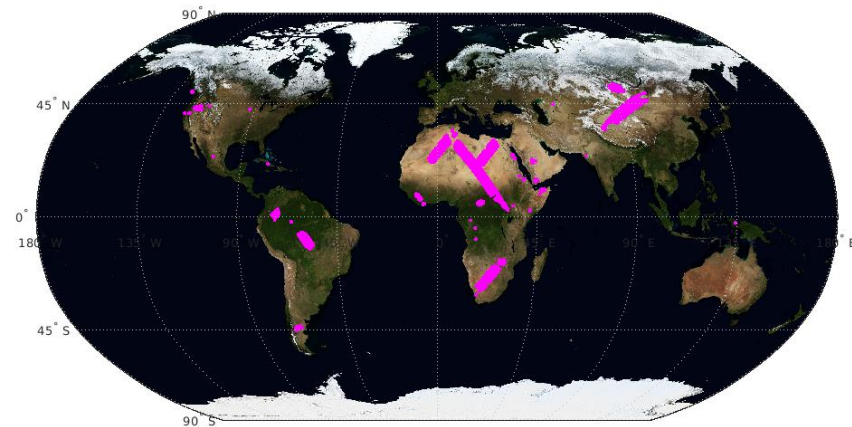
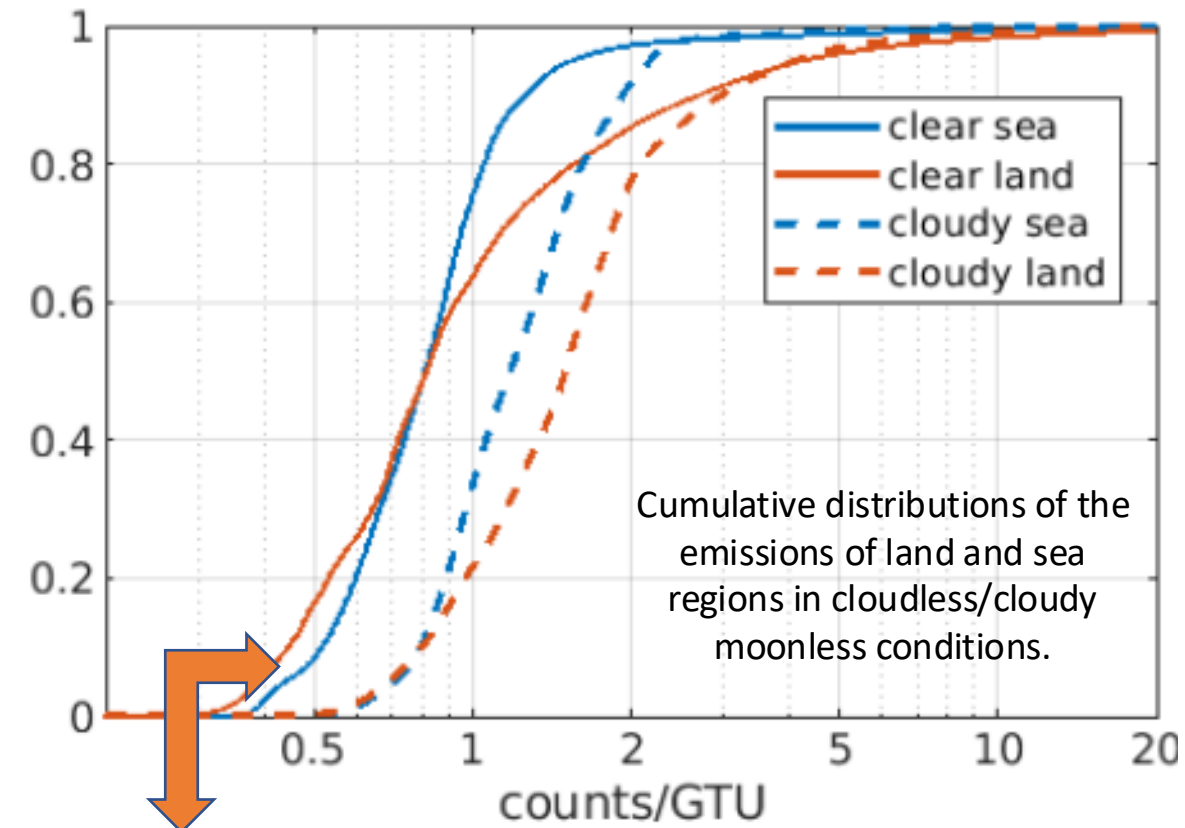
Similar UV bckg expected for Mini-EUSO & JEM-EUSO for 8% eff.

For 5% Mini-EUSO efficiency:

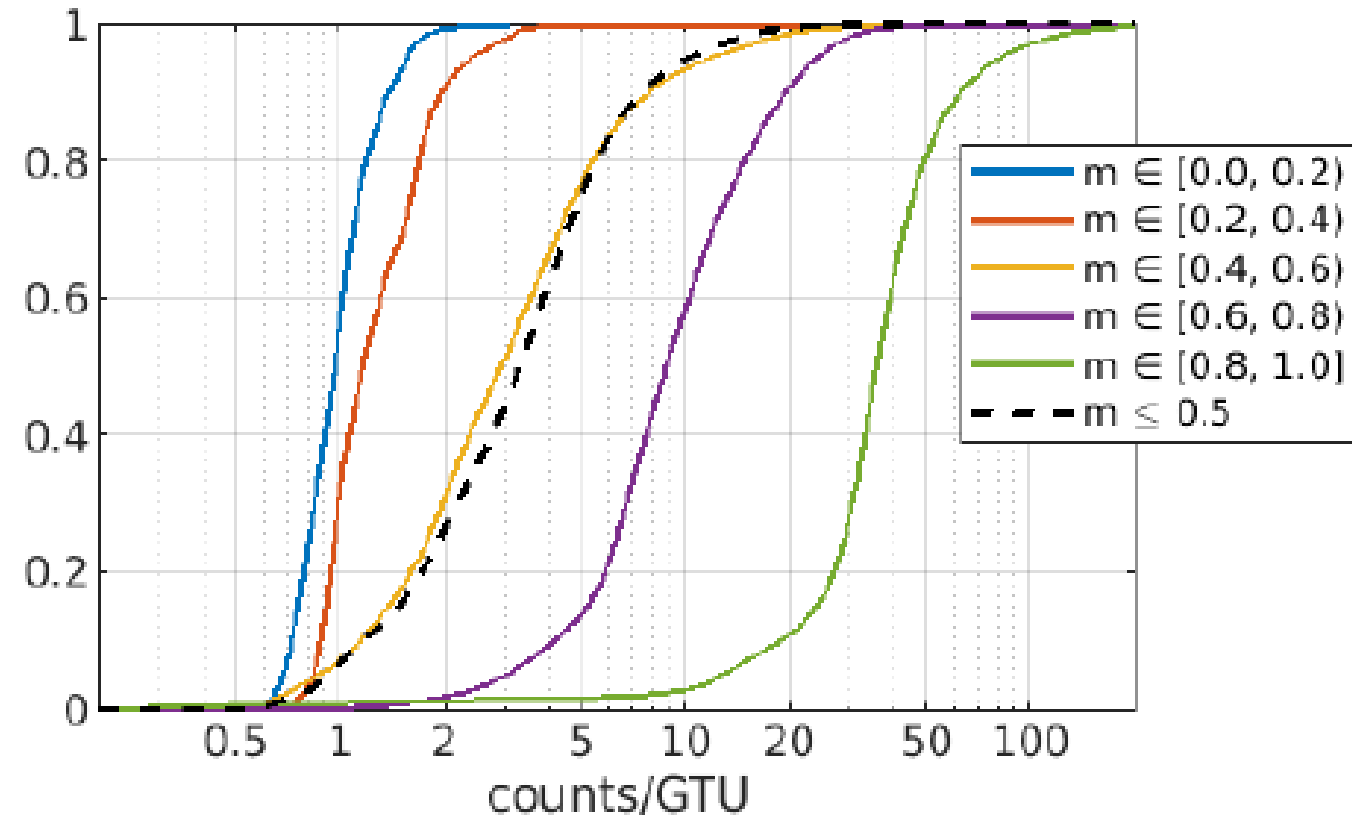
0 – 60 degrees simulation 0.83 CTS/pixel/GTU

0 – 22 degrees simulation 0.61 CTS/pixel/GTU

Moonless conditions



Moon Phases



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

Analyzed sessions: 5 - 19

Is this result reasonable?

We know from literature (i.e. Tatiana, Garipov 2005) that the background in no moon conditions is variable between 300 – 1000 photons/m²/ns/sr

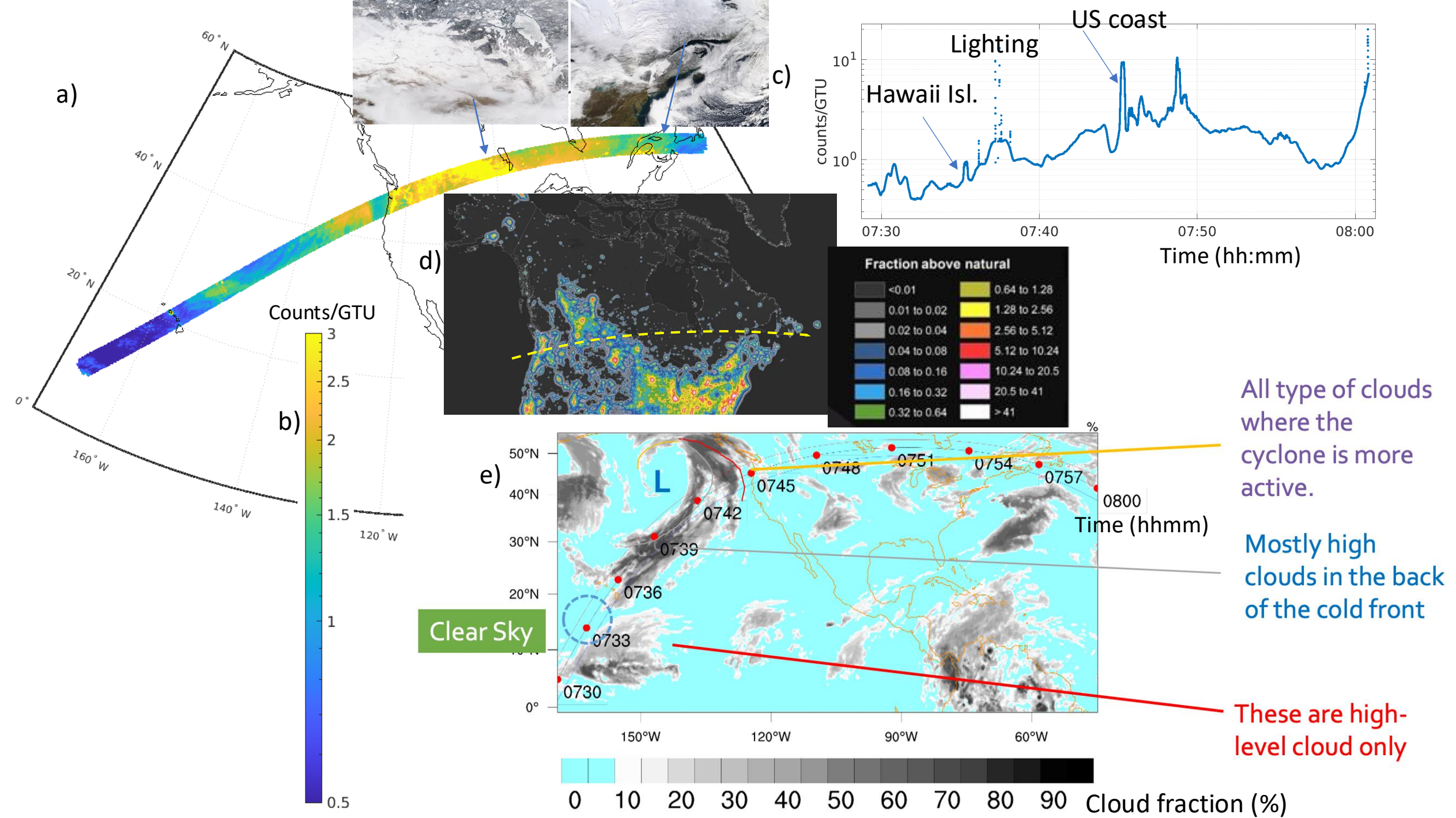
Background [ph/ns/sr/m ²]	Counts/pix/GTU	Counts/pix/GTU
300	~0,5	~0,65
500	~0,8	~1.3
1000	~1,6	~2,6

~5.0% eff.

~8% eff.

Mini-EUSO

A difference between 1.3 counts/GTU and 1.1 counts/GTU makes an energy shift in trigger efficiency by ~10% (marginal effect).



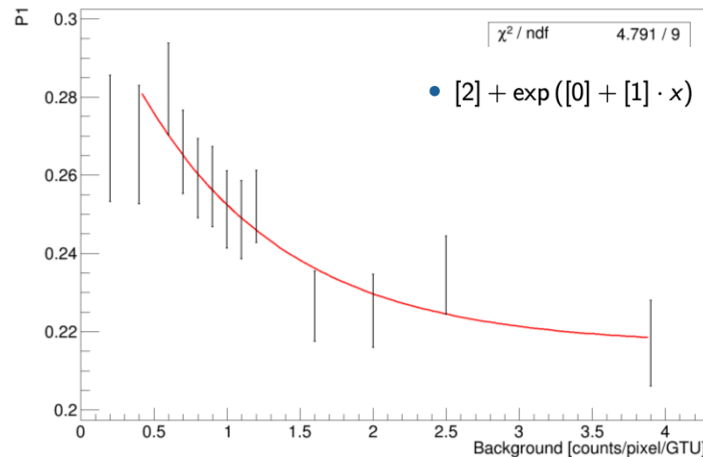
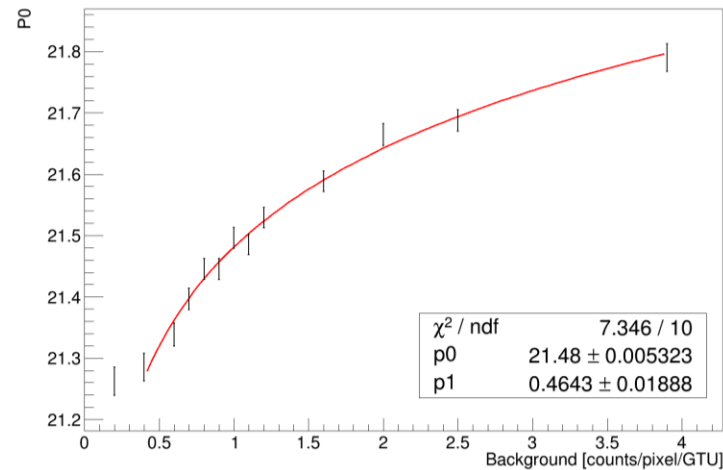
Combining bckg distrib. and efficiency curves: the integrated exposure curve

- $\epsilon(E) = \frac{N_{trigg}}{N_{simu}}(E) \frac{A_{simu}}{A_{fov}} \Rightarrow \frac{1}{2} [1 + \text{erf}(\frac{\log_{10}(E/\text{eV}) - P0}{P1})]$

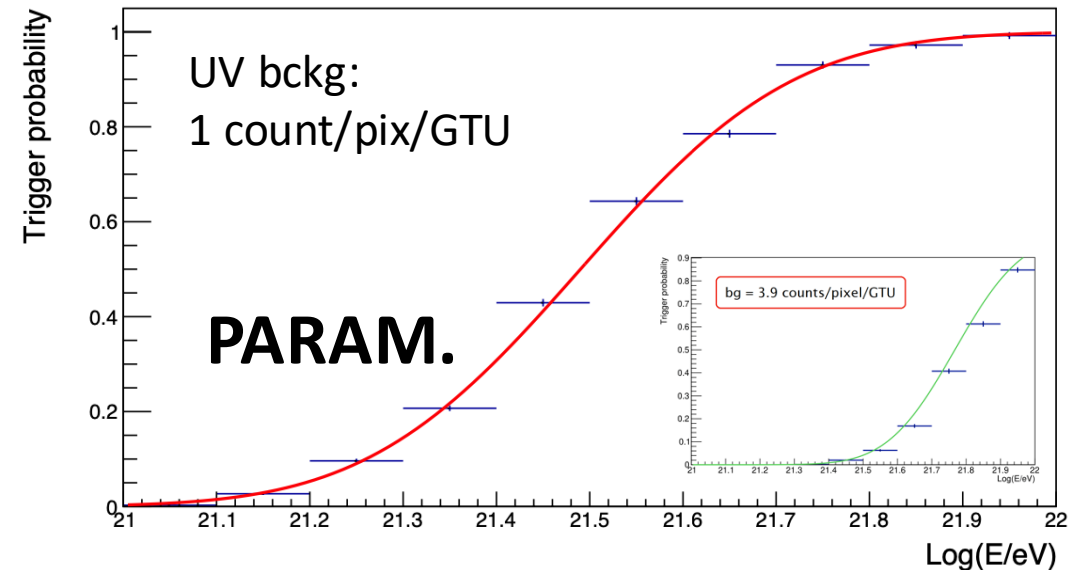
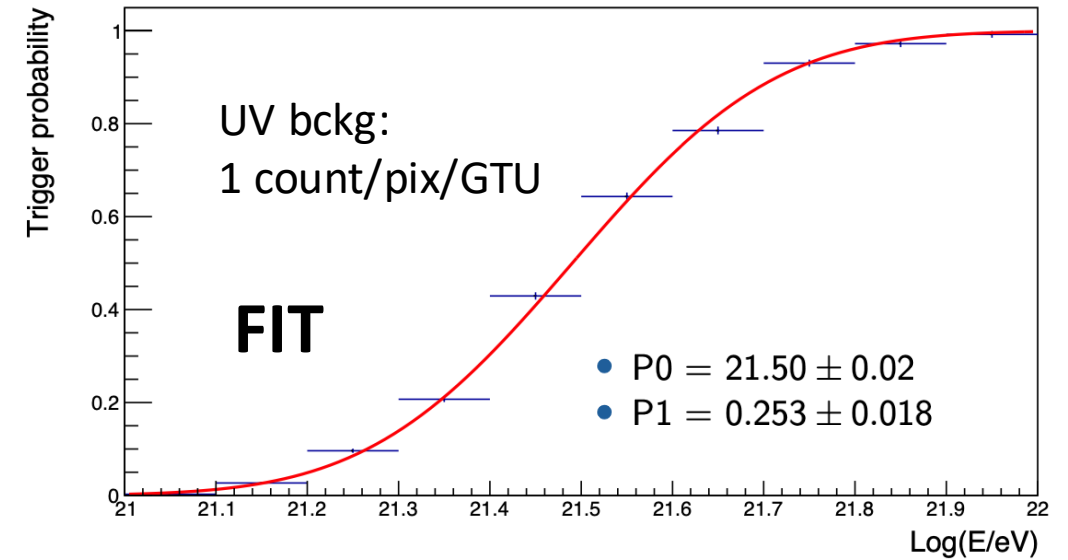
- P0 = threshold

- P1 = slope

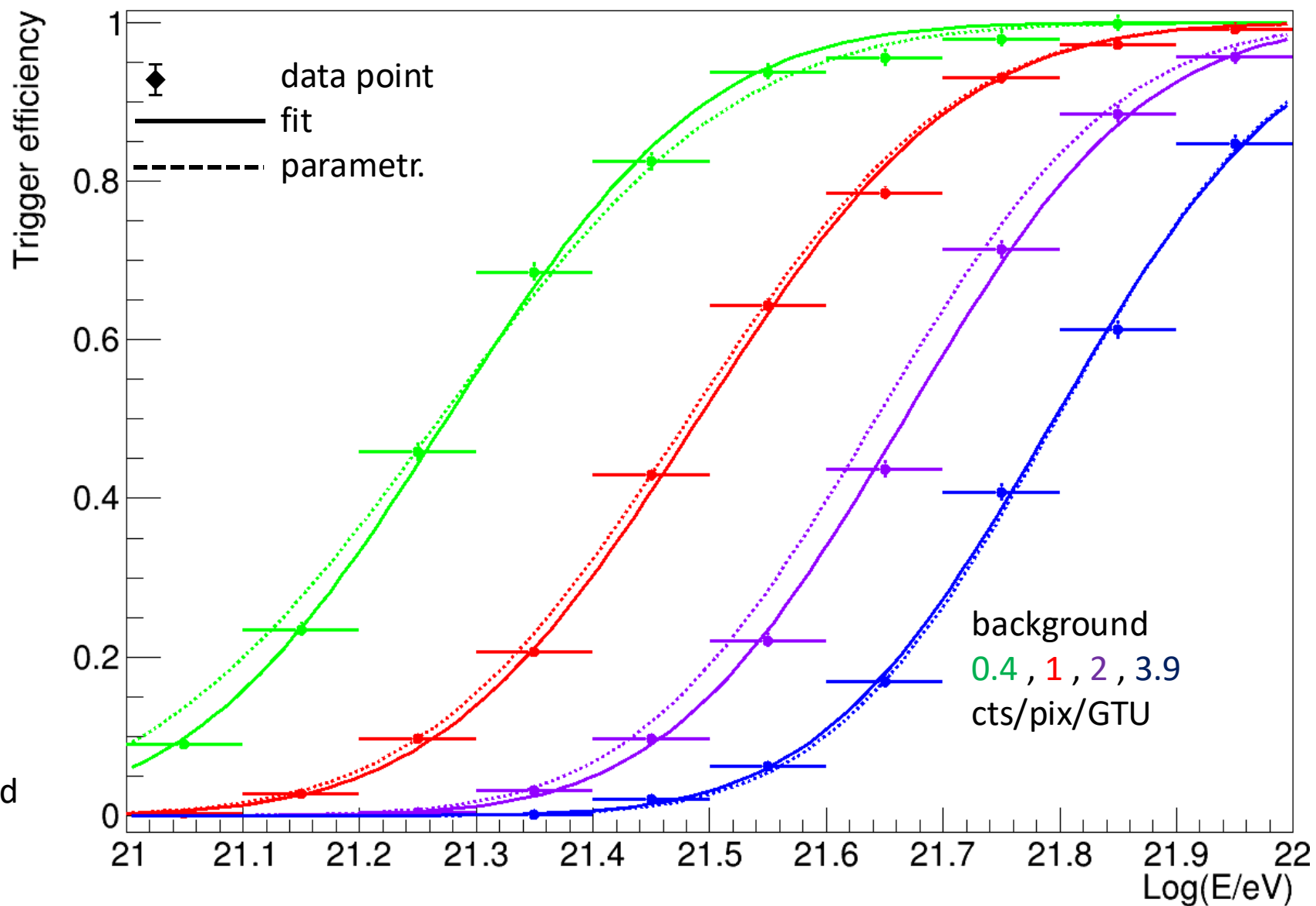
Simulations performed for fixed UV
bckg [0.4;4.0] counts/pix/GTU



PRELIMINARY

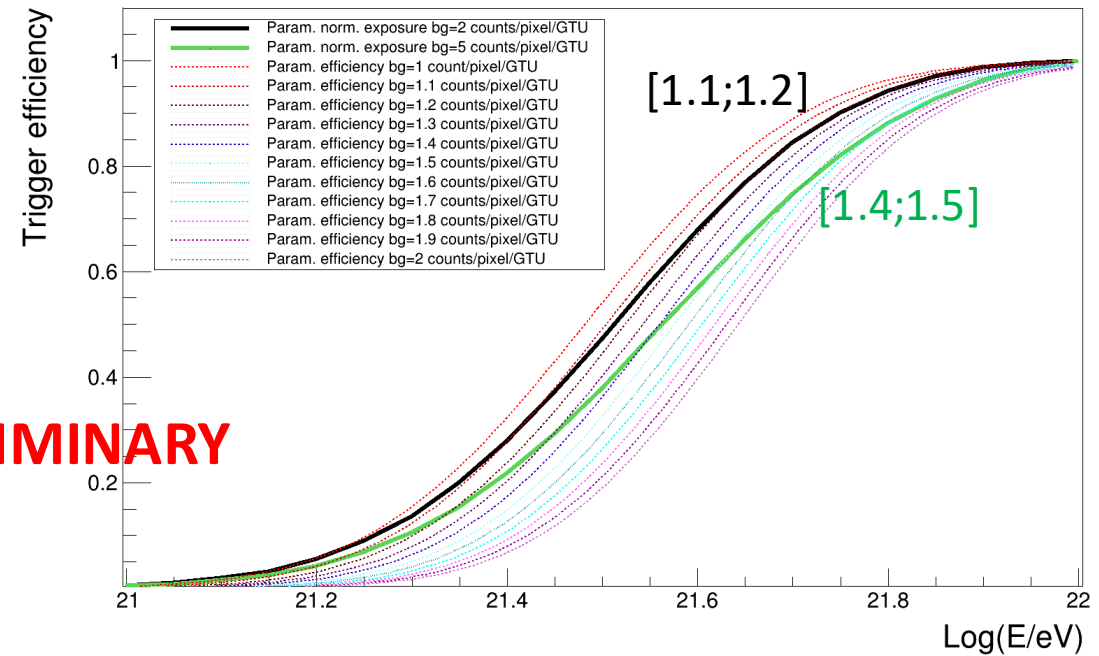
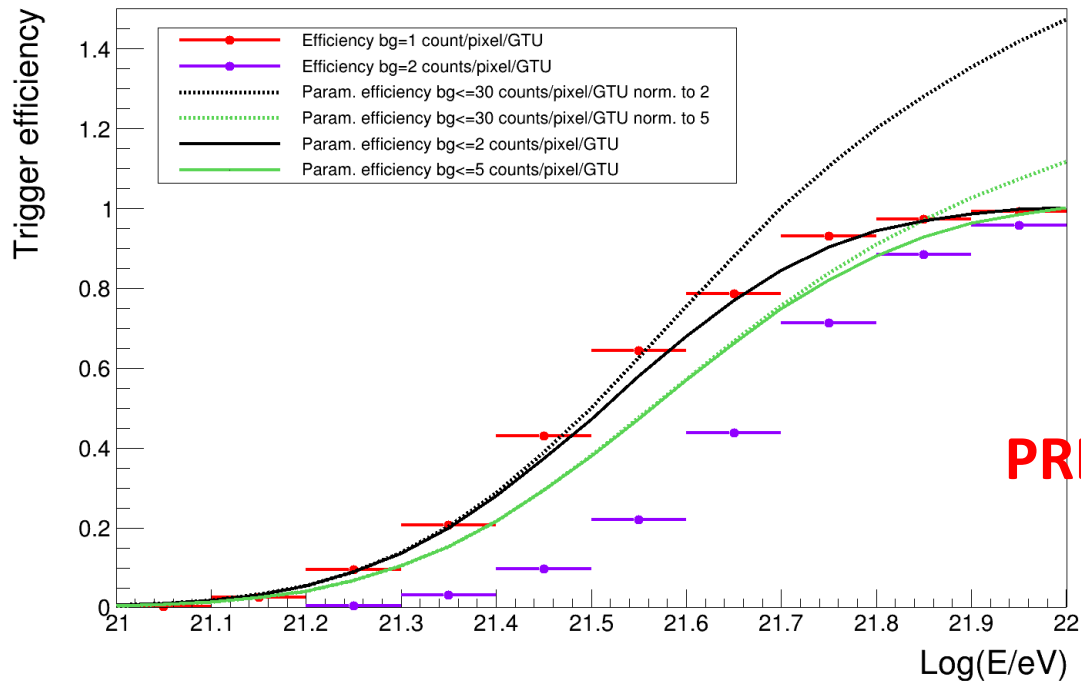
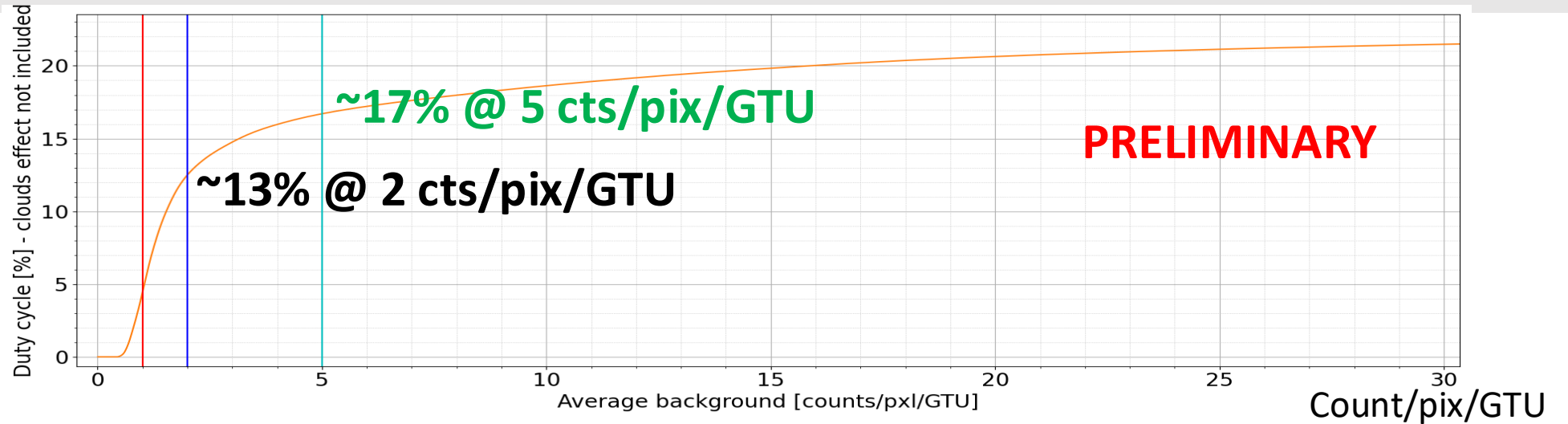


Exposure Calculation of Mini-EUSO for UHECRs



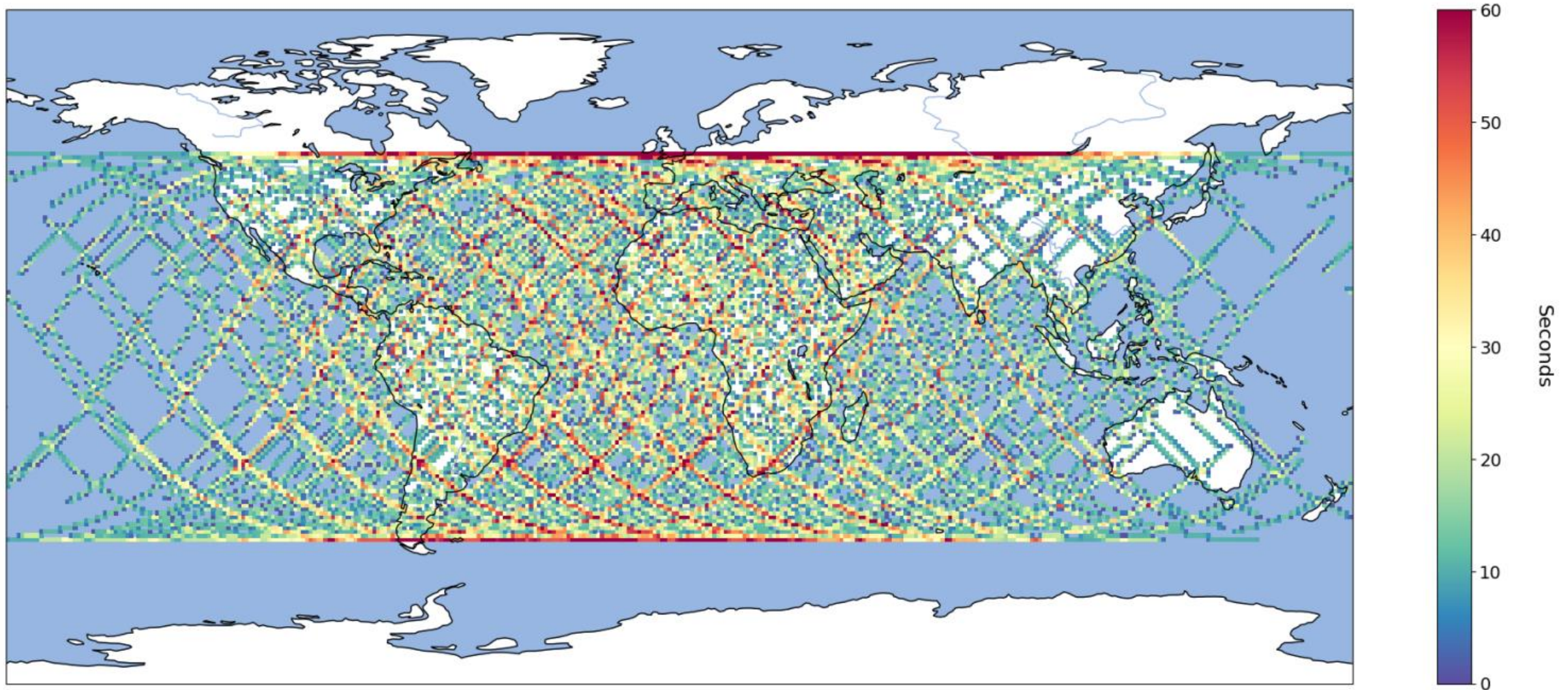
Combining bckg distrib. and efficiency curves: the integrated exposure curve

$$\eta_0 = \frac{\sum_{\text{MB}} \frac{T_{<\text{Thrs}}^{\text{MB}}}{F_{\text{Conv}}^{\text{MB}}}}{\Delta T_{\text{orbit}} \cdot N_{\text{orbit}}}$$



Overall experimental confirmation of JEM-EUSO duty cycle

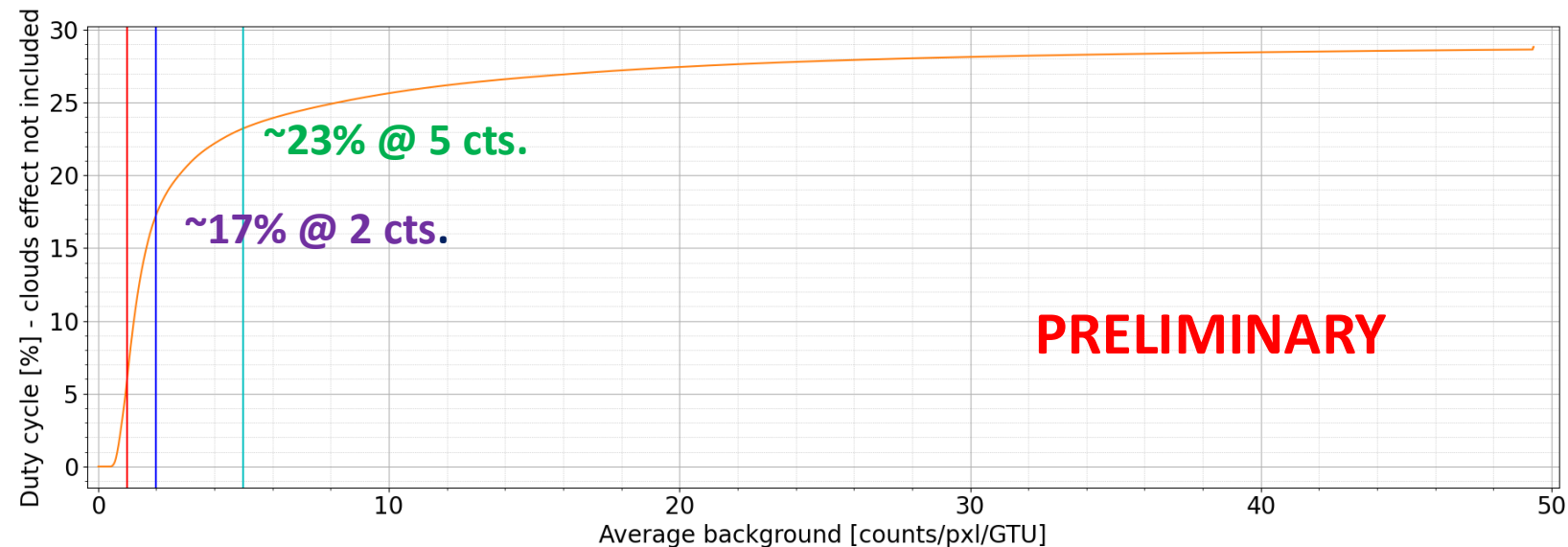
We lack Pacific Ocean... we should compute the improvement in DC



Sessions 4 - 44

From Matteo B.

Accumulated exposure by Mini-EUSO



$$T = 69.16 \text{ h} * (0.232/0.288) = 6.36\text{E-3 yr}$$

$$A = 2304 * (6.3 \text{ km})^2 = 9.15\text{E+4 km}^2$$

$$\Omega = \pi * 0.72 \text{ (cloud factor)} = 2.26$$

$$\text{Exposure} = T * A * \Omega = \sim\mathbf{1300 \text{ L}}$$

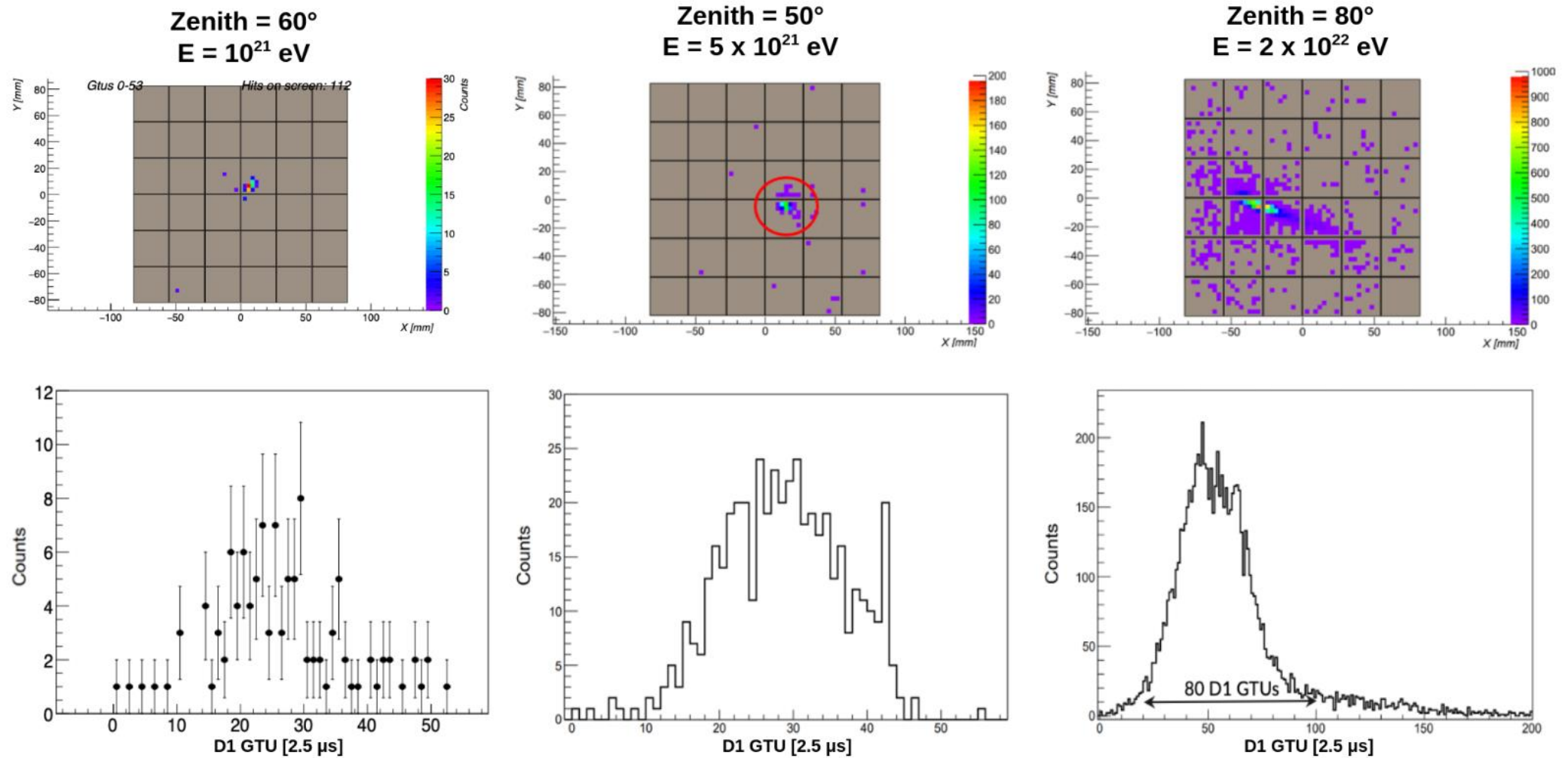
If taking into account till session **117**
(May 2024) = **~4700 L**

*If Mini-EUSO would have operated continuously
since August 2019: **~147000 L**
(exposure/day = ~84 L/day)*

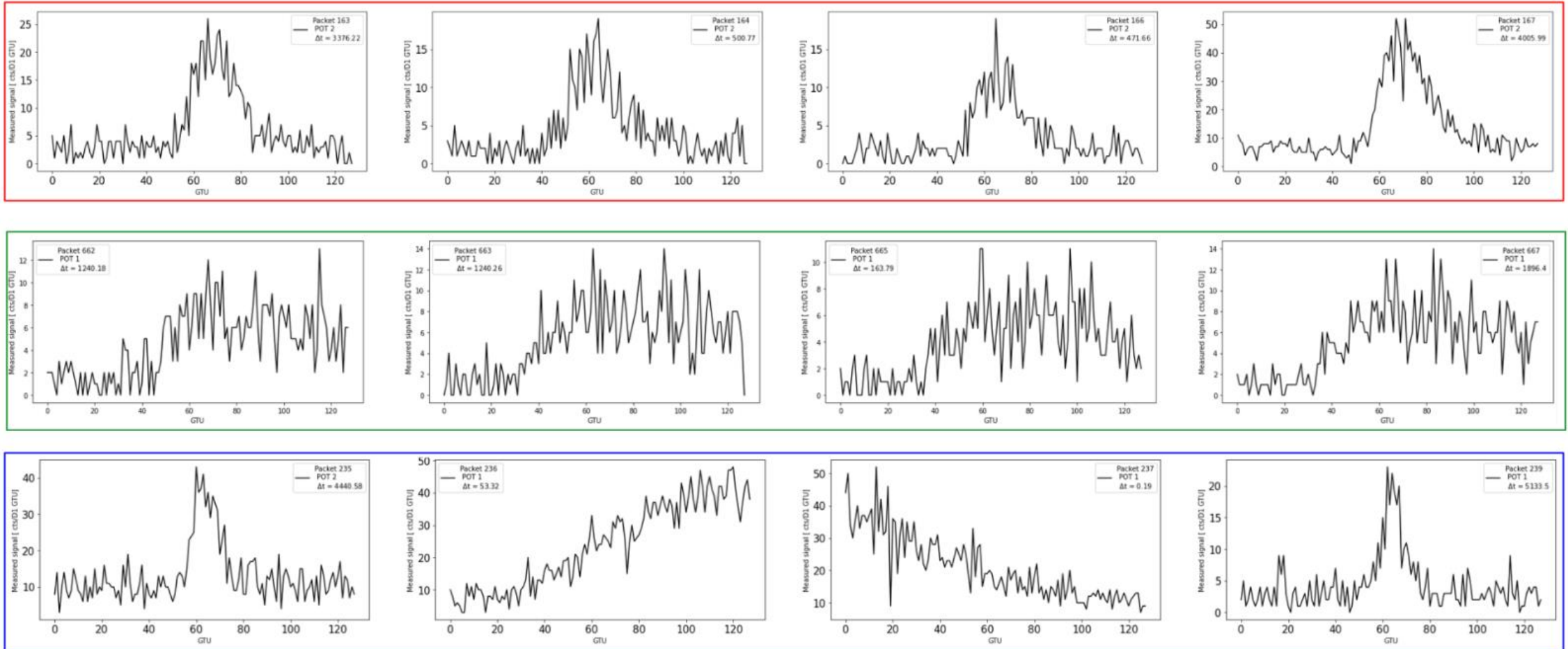
Extrapolating to all good recorded data the expected cumulated exposure for UHECRs is
~4700 L at the highest energies. **This exposure is comparable to the one collected so far by UHECR experiments using the fluorescence technique.**

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

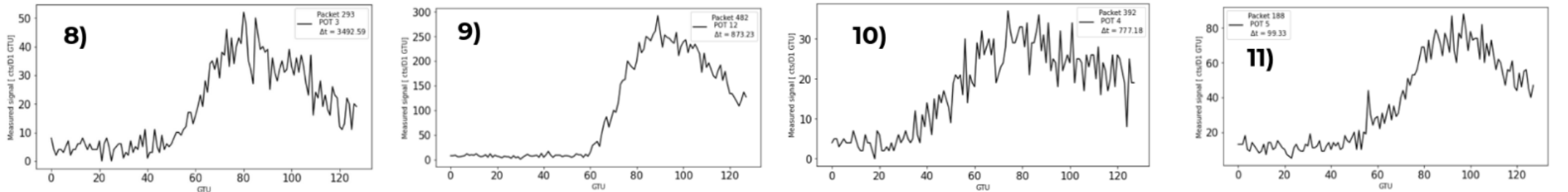
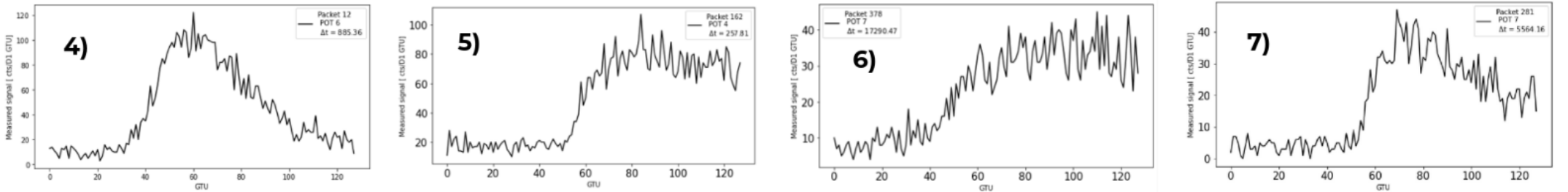
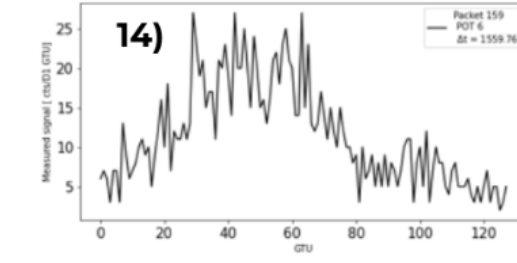
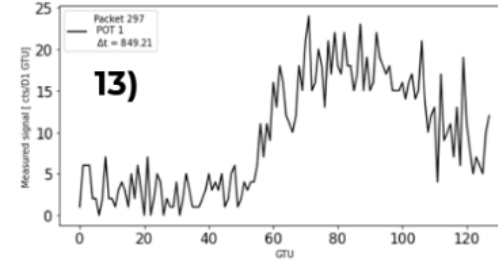
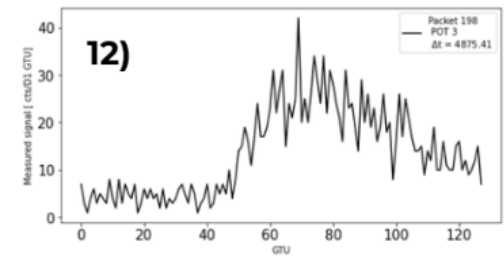
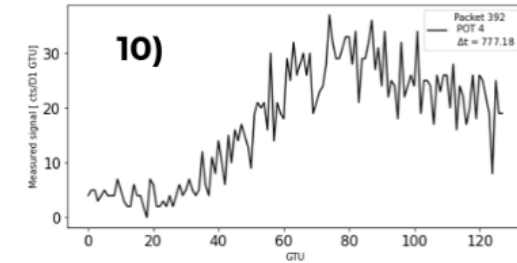
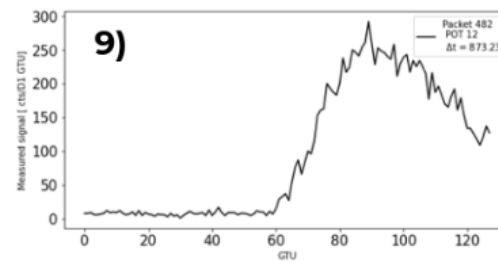
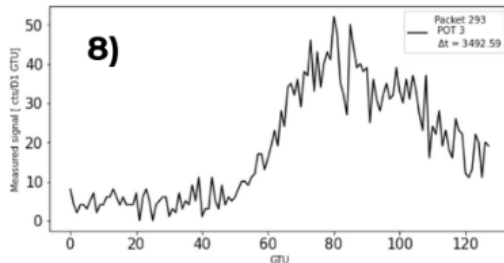
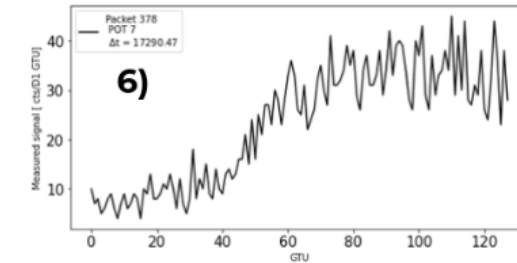
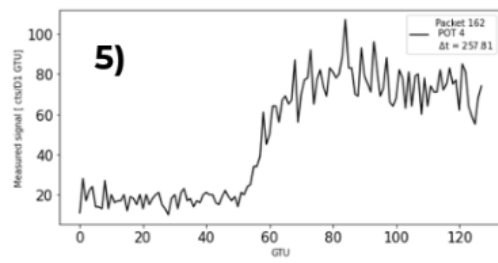
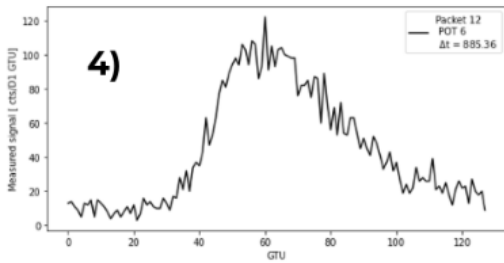
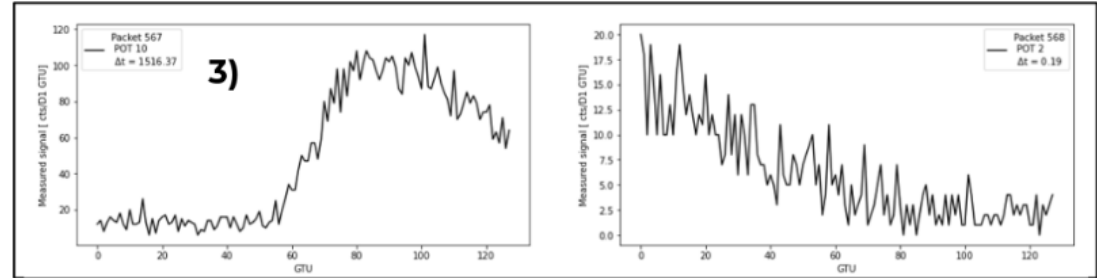
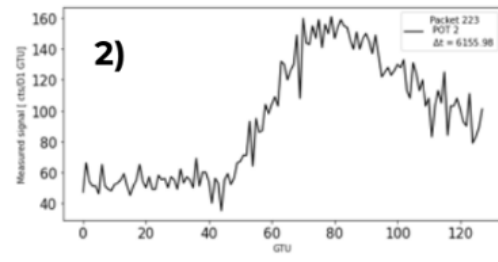
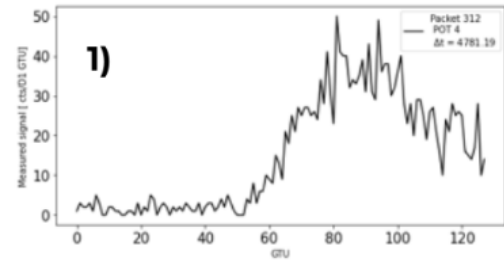
Mini-EUSO simulations of UHECRs (protons)



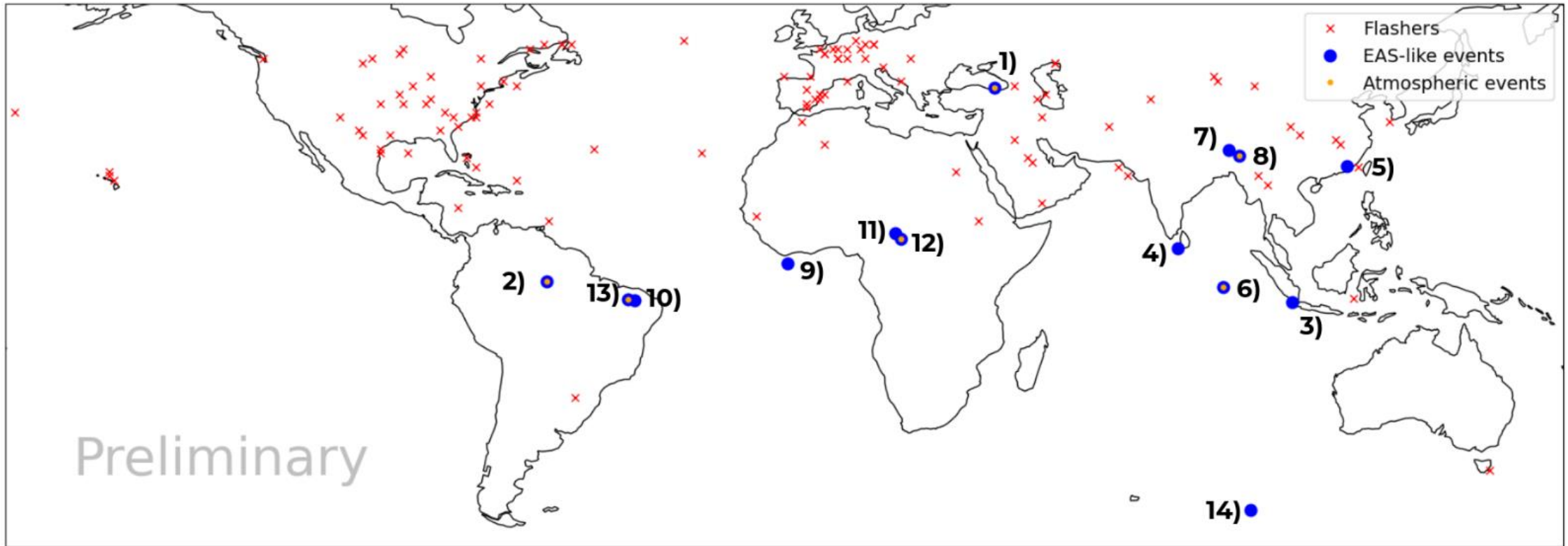
Flashers' lightcurves



Short Light Transients (SLT) lightcurves



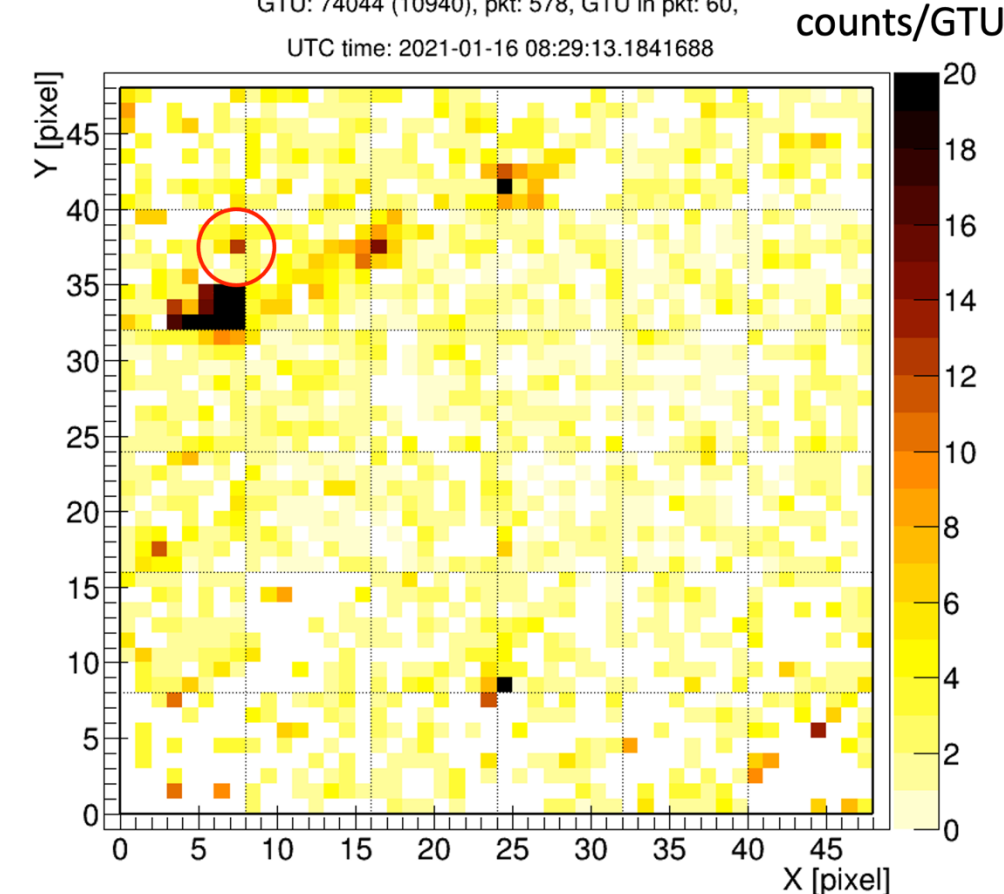
Map of the flasher (108/561) & SLT events



Ground Flashers

Michigan, US

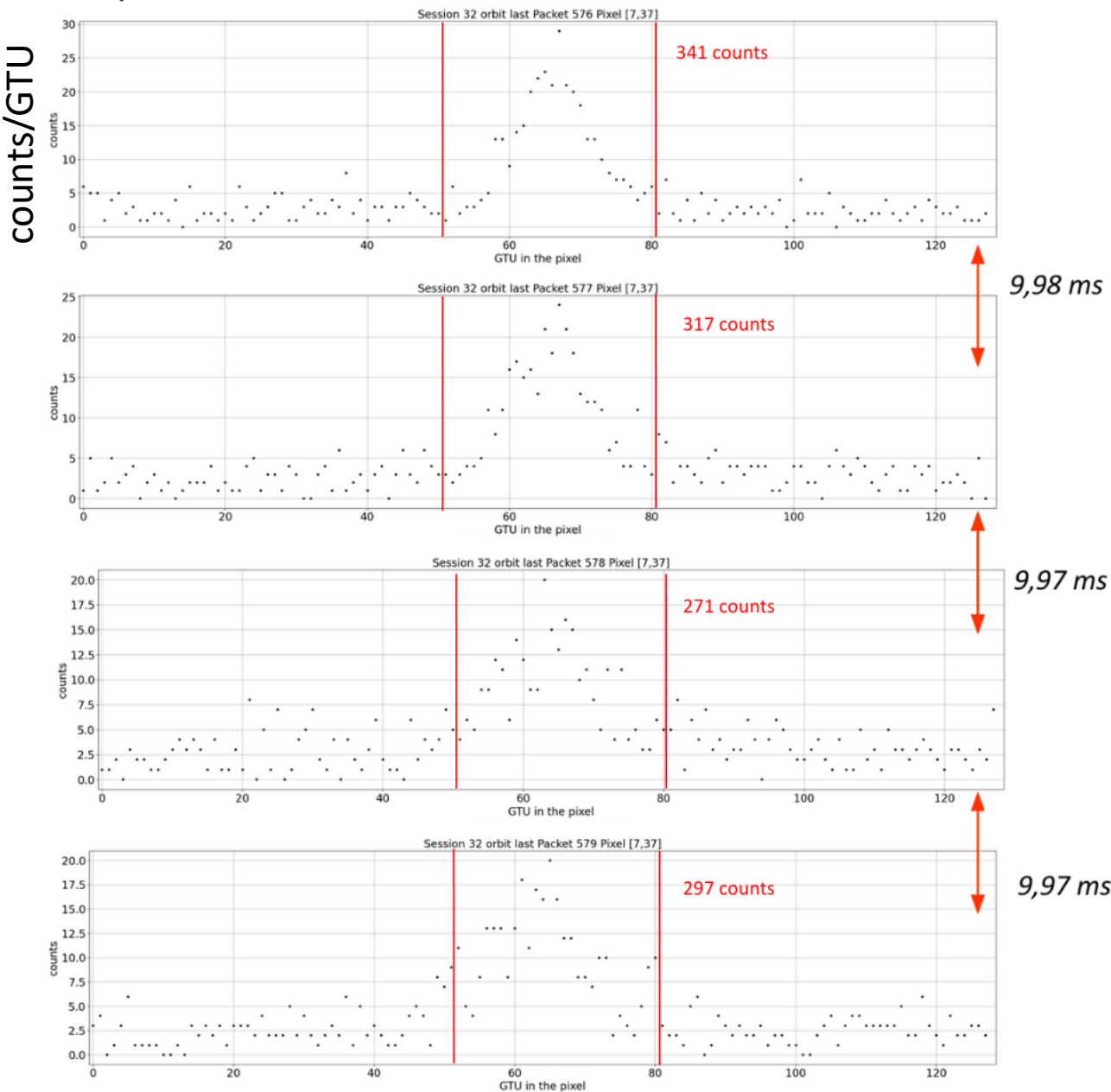
GTU: 74044 (10940), pkt: 578, GTU in pkt: 60,
UTC time: 2021-01-16 08:29:13.1841688



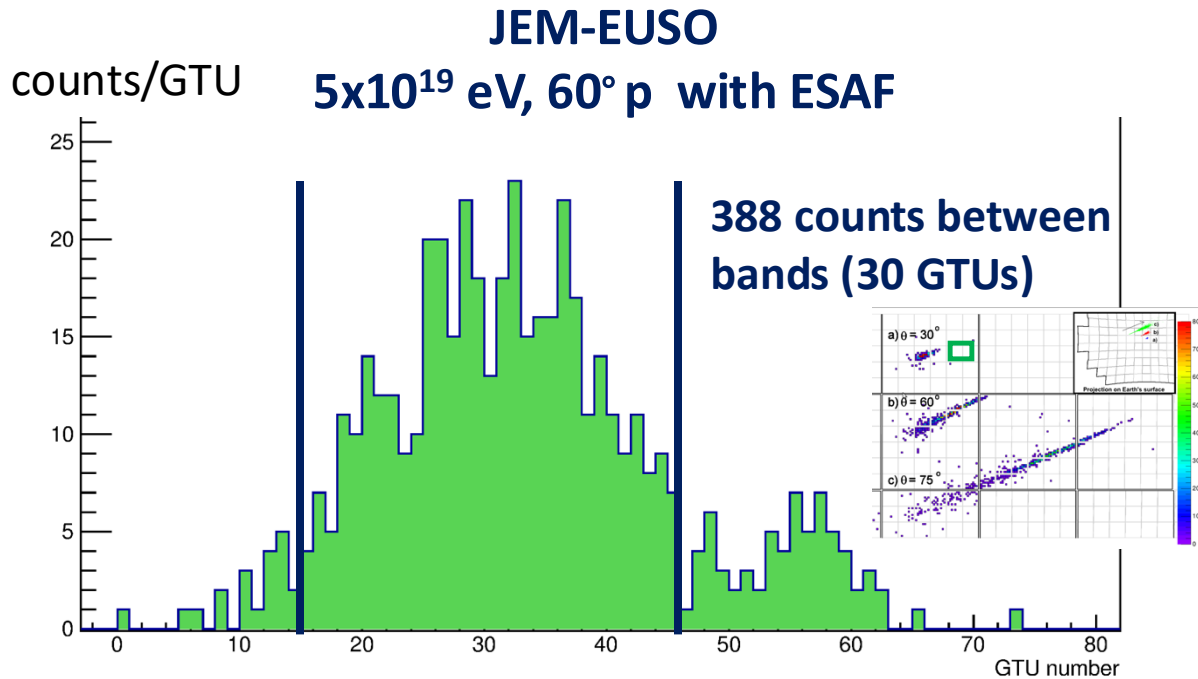
;PU_RUN_MAIN_2021_01_16_08_49_16_950Cathode3FullPDMonlyself_I1_v10r2.roc

M. Battisti

Repeated ground flashers



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

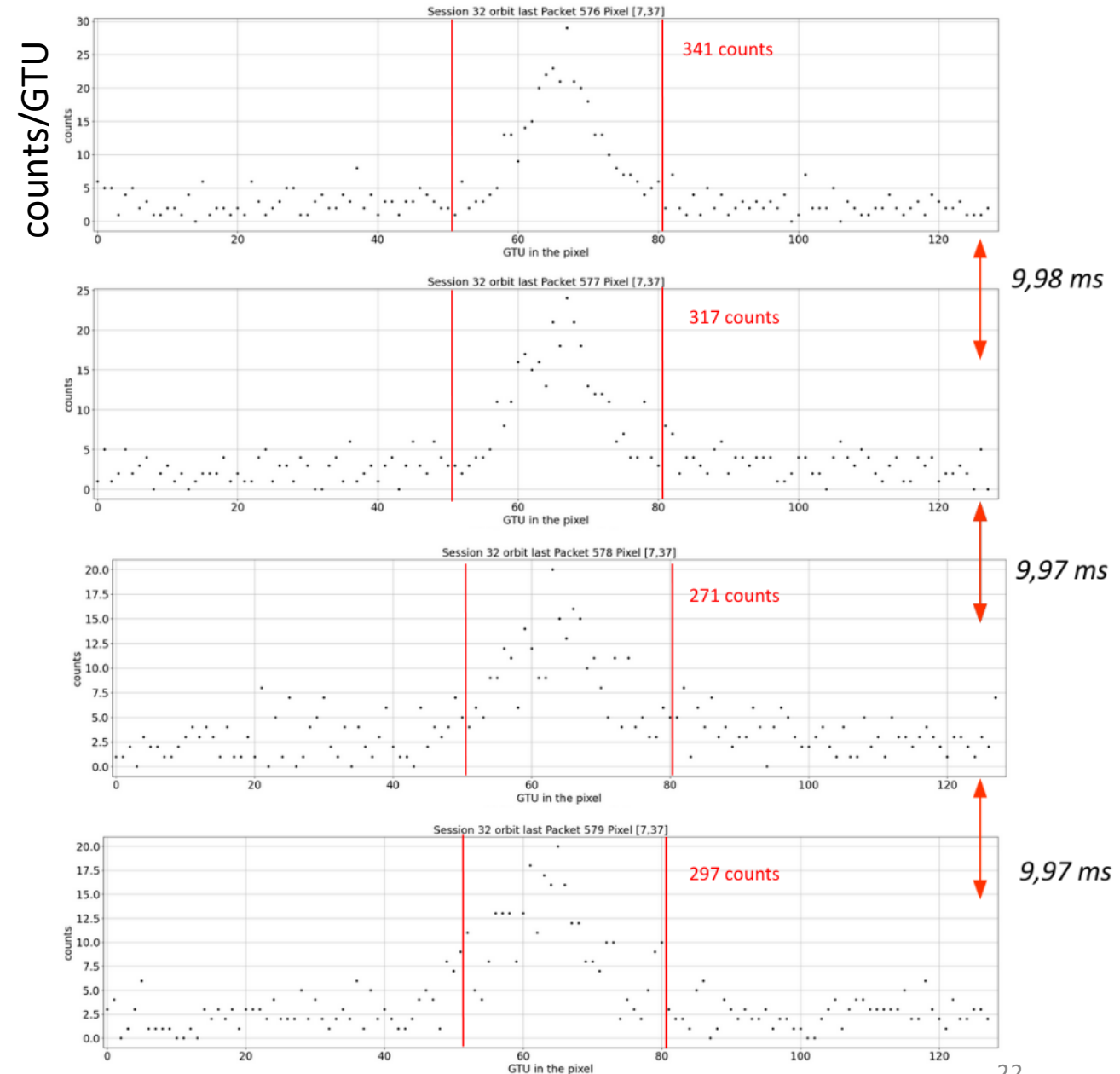


F. Fenu

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

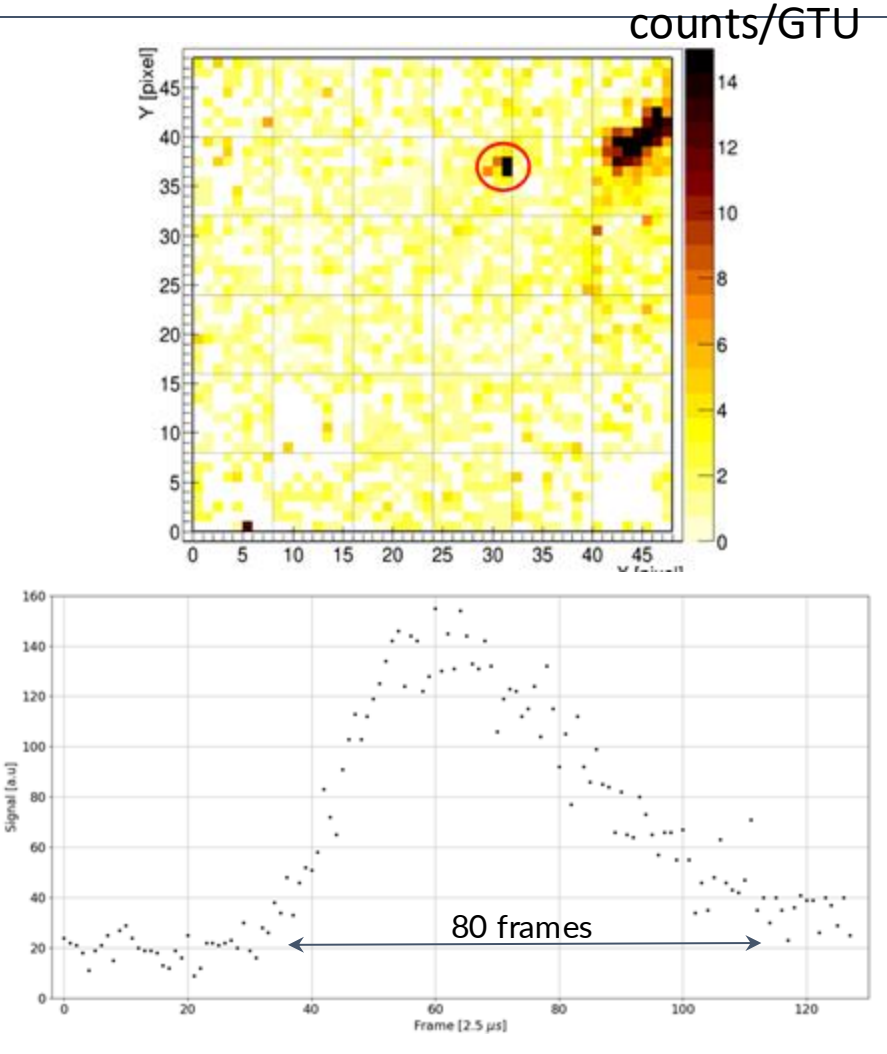
Repeated ground flashers



M. Battisti

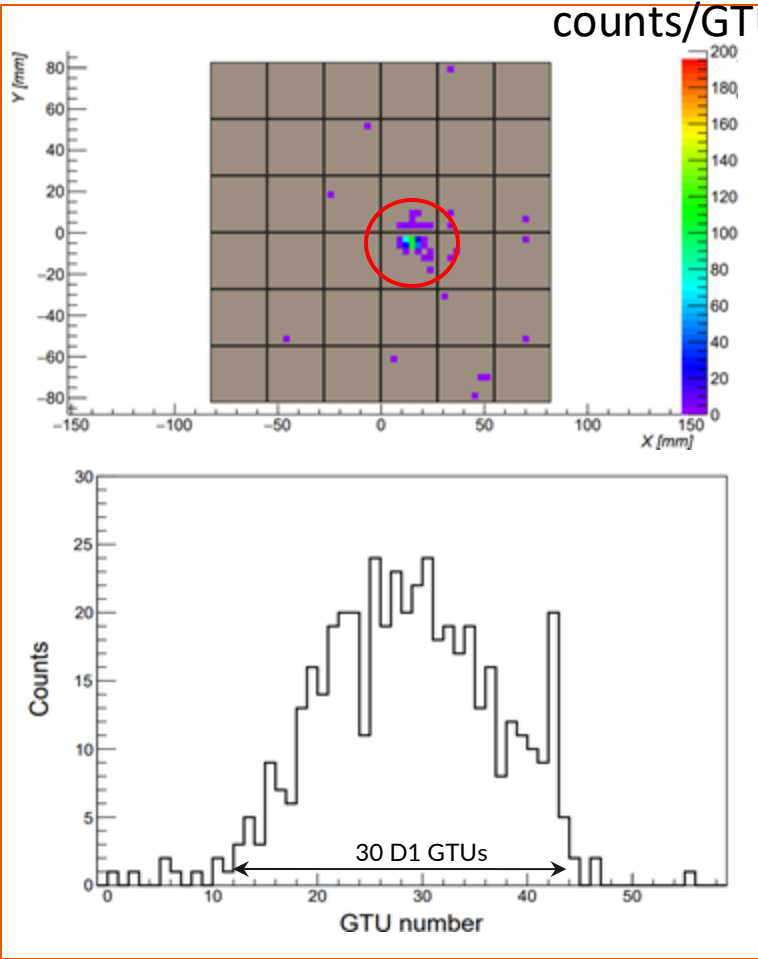
Mini-EUSO – non repetitive Short Light Transients

Mini-EUSO data

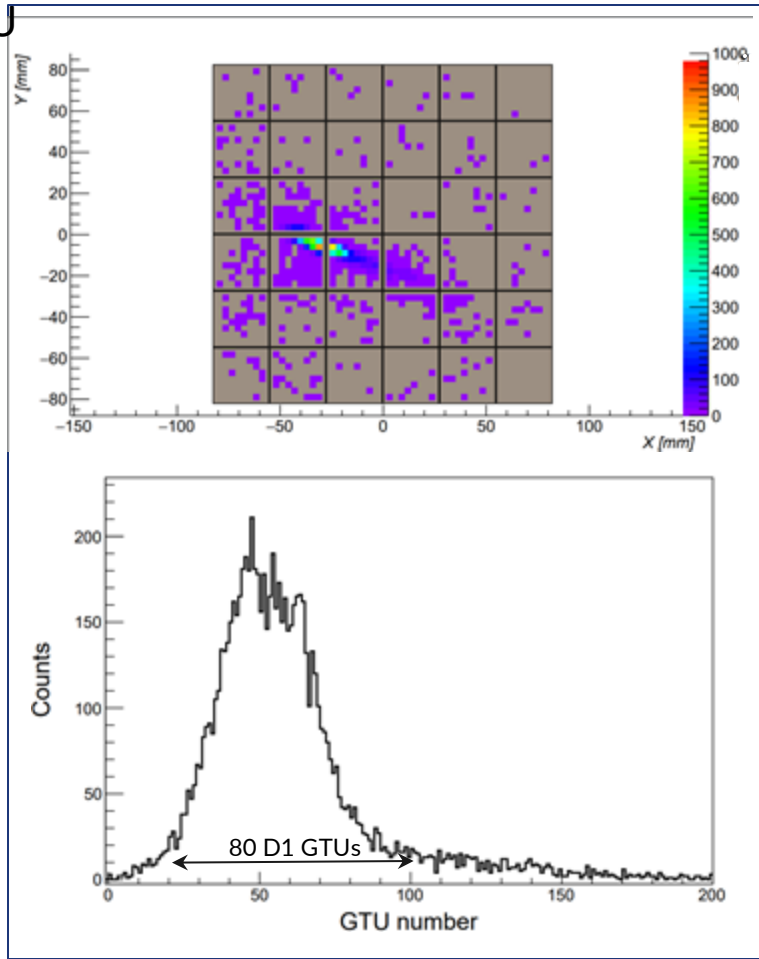


Focal plane view and lightcurve of the detected signal

ESAF p, $E = 5 \times 10^{21}$ eV Zenith = 50°

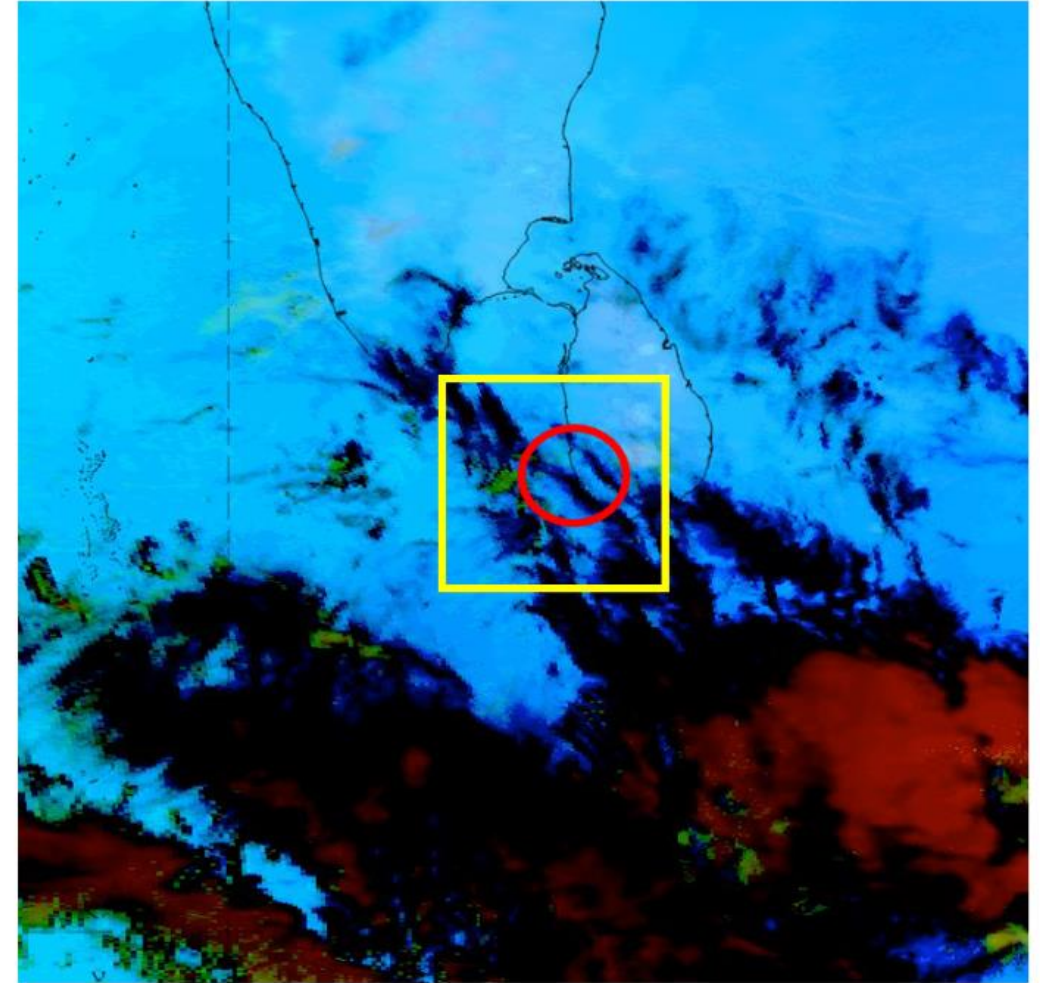
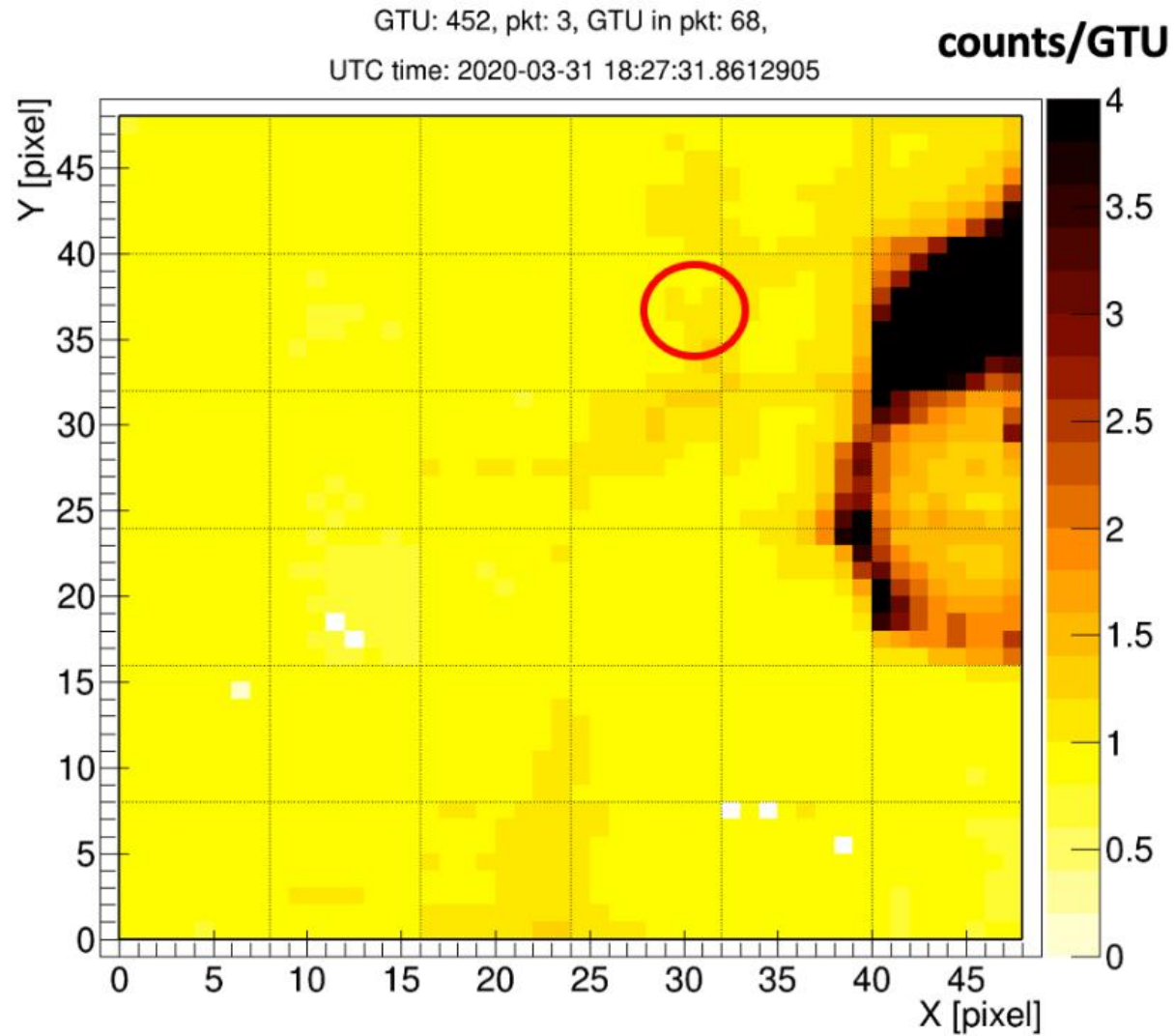


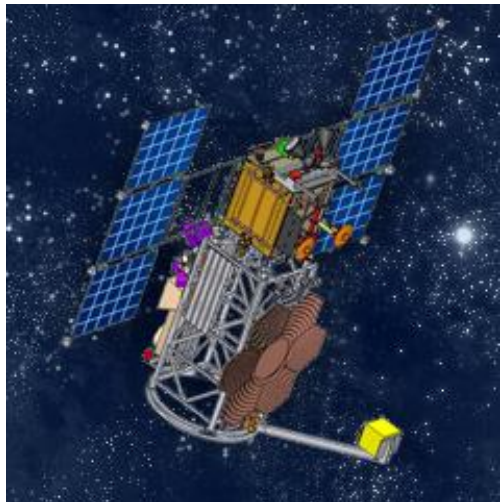
ESAF p, $E = 2 \times 10^{22}$ eV Zenith = 80°



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

Weather conditions



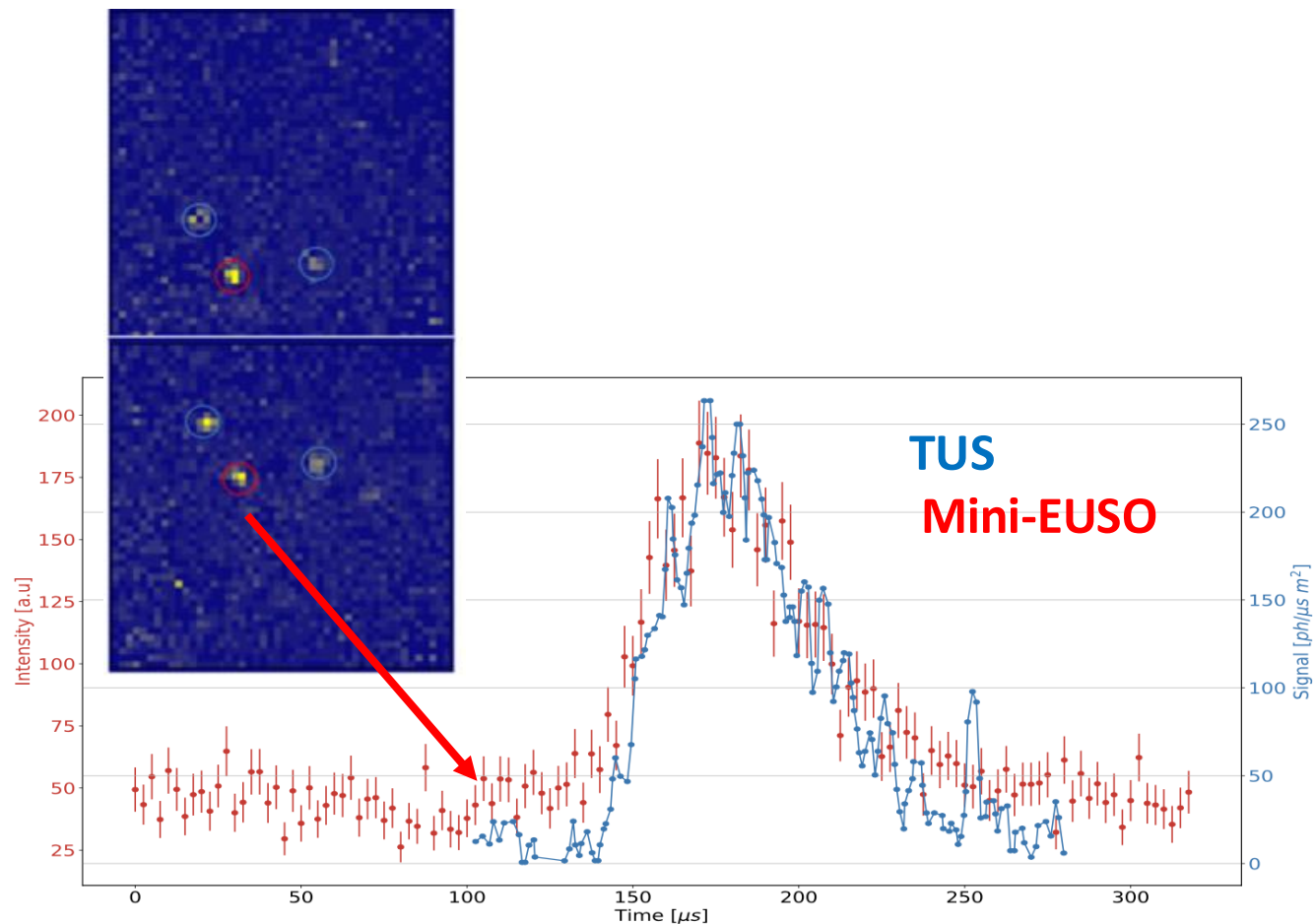
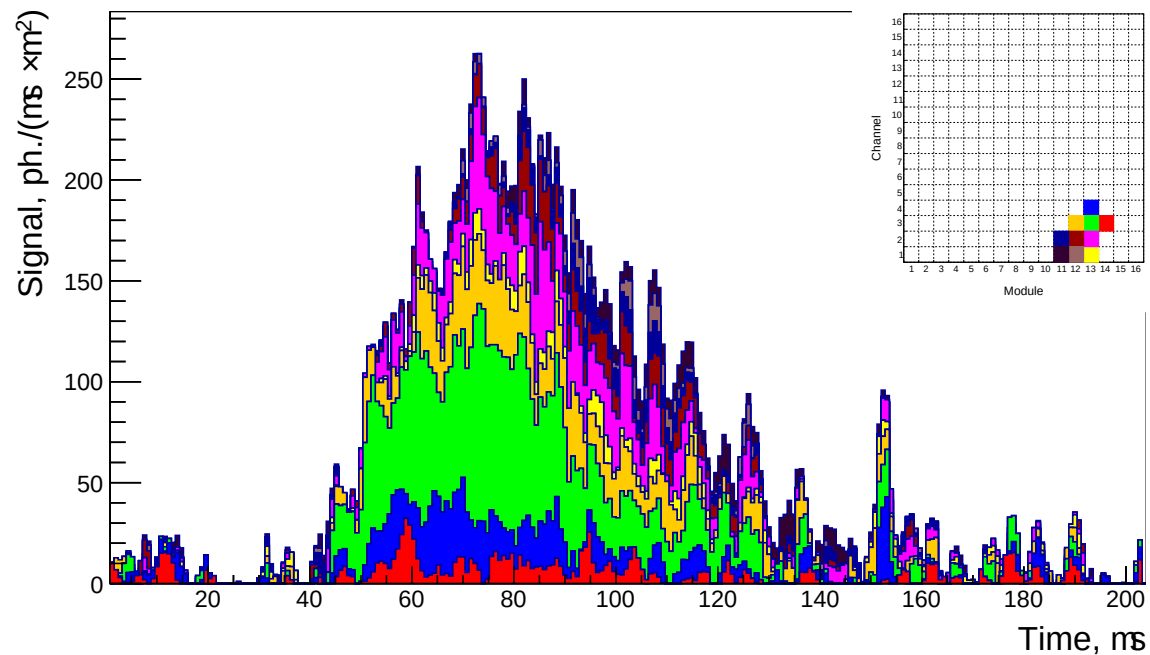


TUS EAS-like & Mini-EUSO SLTs

Mini-EUSO sees ground flashers with signal in shape similar to the TUS Minnesota event. However, in TUS event an apparent movement is visible while in Mini-EUSO the signal is static.

TUS Minnesota event

B.A Khrenov et al. JCAP 03 (2020) 033



CONCLUSIONS

- Mini-EUSO on ISS for almost five years and has collected an exposure for UHECRs comparable to ground-based experiments (even though at much higher energies).
- It proves that it is possible – with larger detectors – to perform UHECR observation from space.
- Preliminary results on exposure indicate that measurements are in general agreement with predictions from simulations performed for JEM-EUSO.
- These results can be extrapolated directly to K-EUSO and POEMMA and support the indication of the expected performance of a large space-based mission for UHECR studies.
- Mini-EUSO shows the interdisciplinary capabilities of a space-based observatory for UHECRs

THANK YOU!