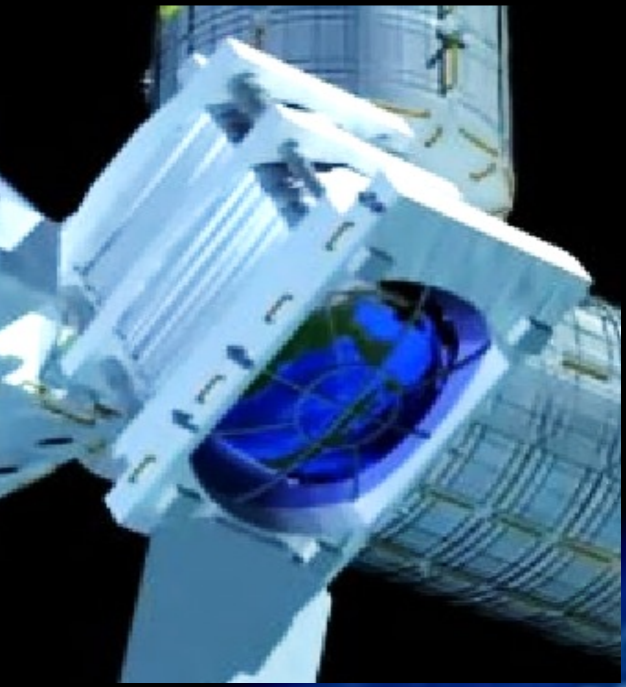


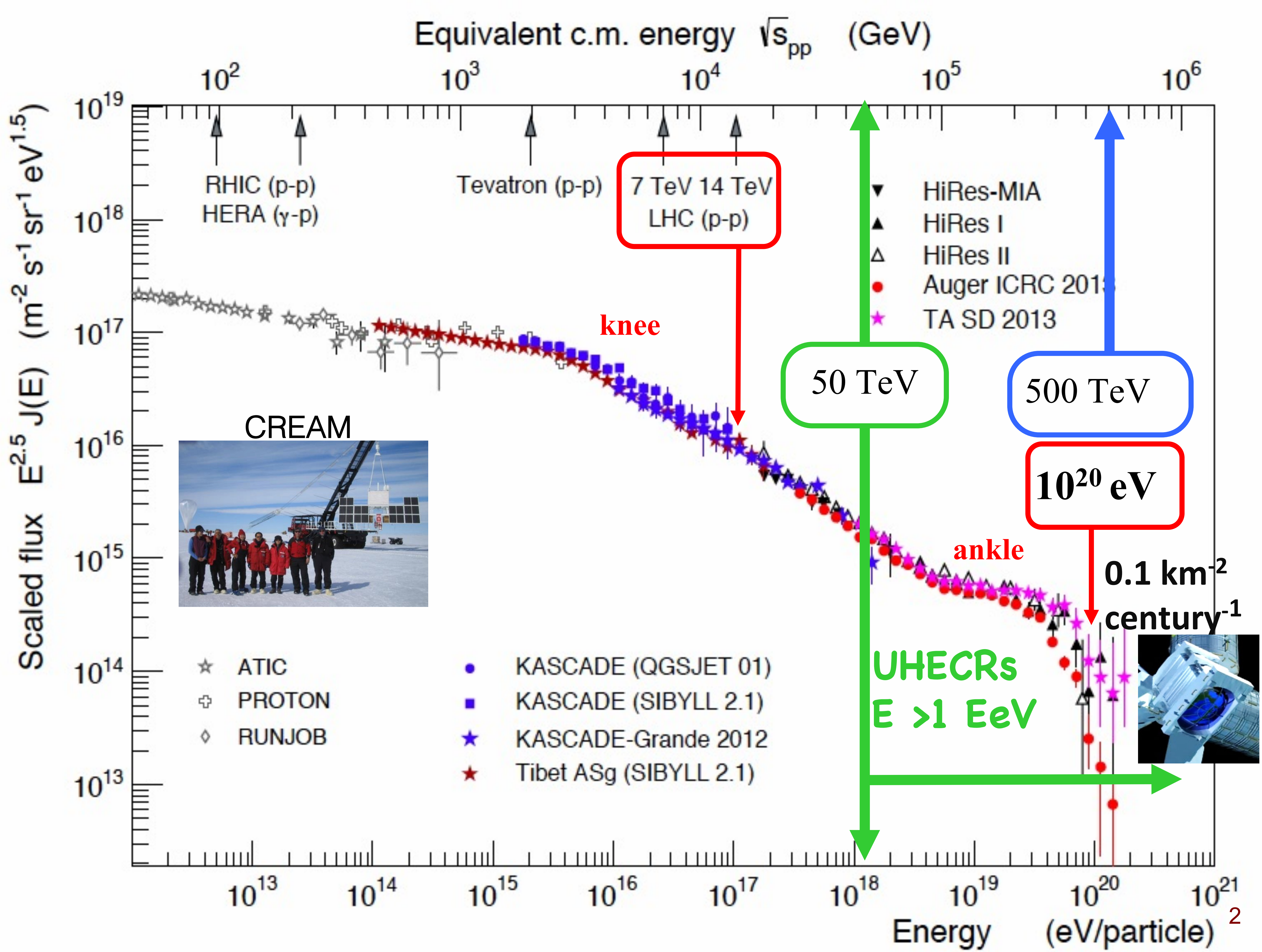
Extreme Universe Space Observatory

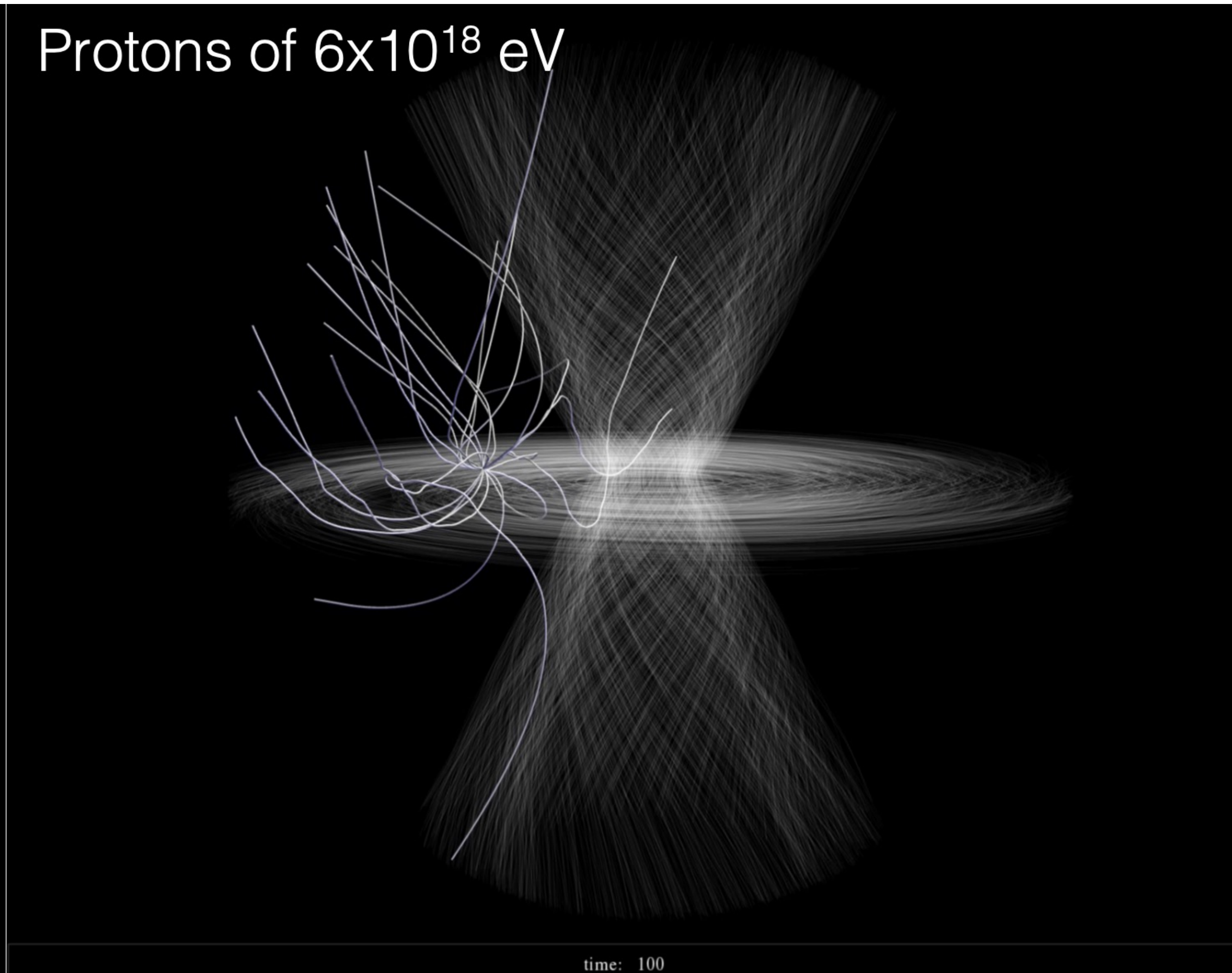
Search for UHE Cosmic Rays from Space – challenges & perspectives

M. Bertaina – University & INFN Torino

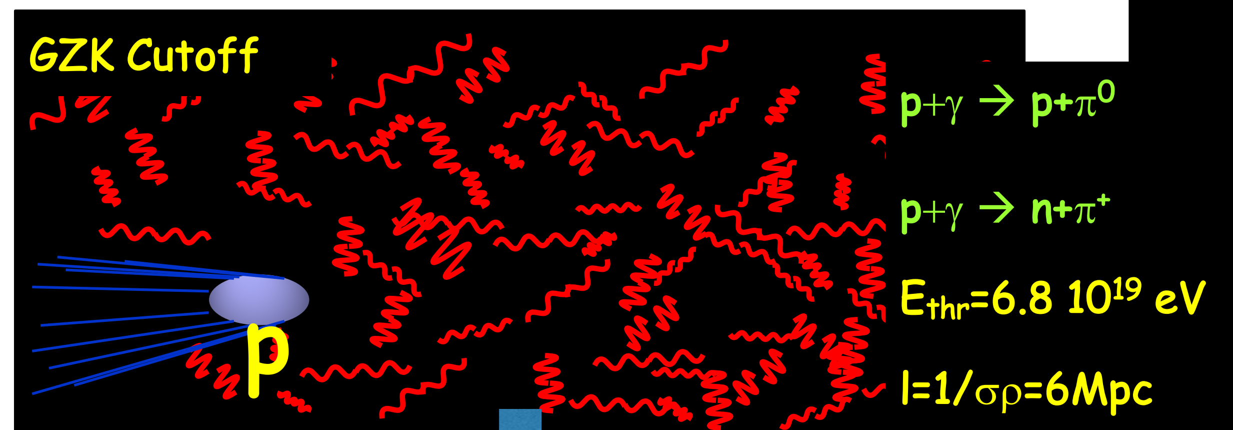
April 16th, 2021

Université Libre de Bruxelles


Equivalent c.m. energy √s_pp (GeV)
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
knee
ankle
50 TeV
500 TeV
10^20 eV
0.1 km^-2 century^-1
UHECRs
E >1 EeV
CREAM
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
Energy (eV/particle)

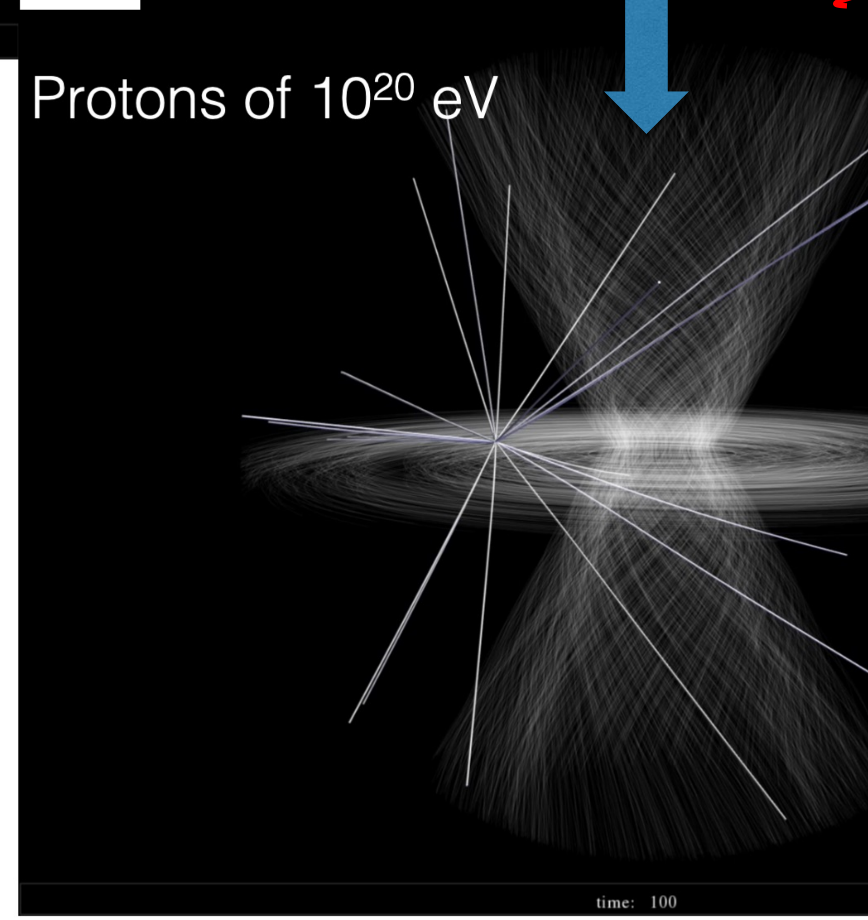


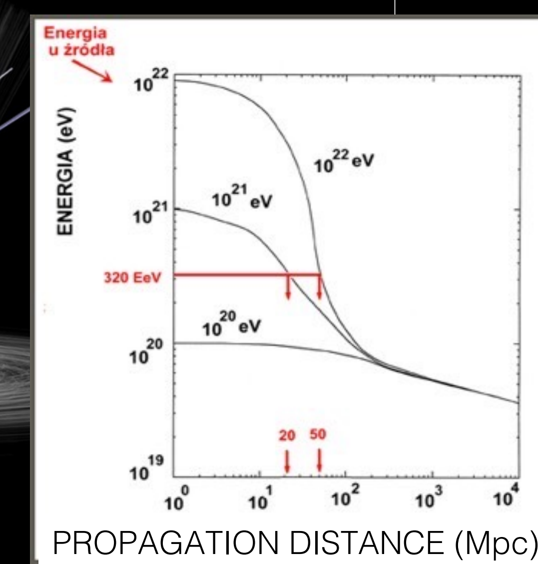
NOT POSSIBLE TO TRACK BACK THE SOURCES



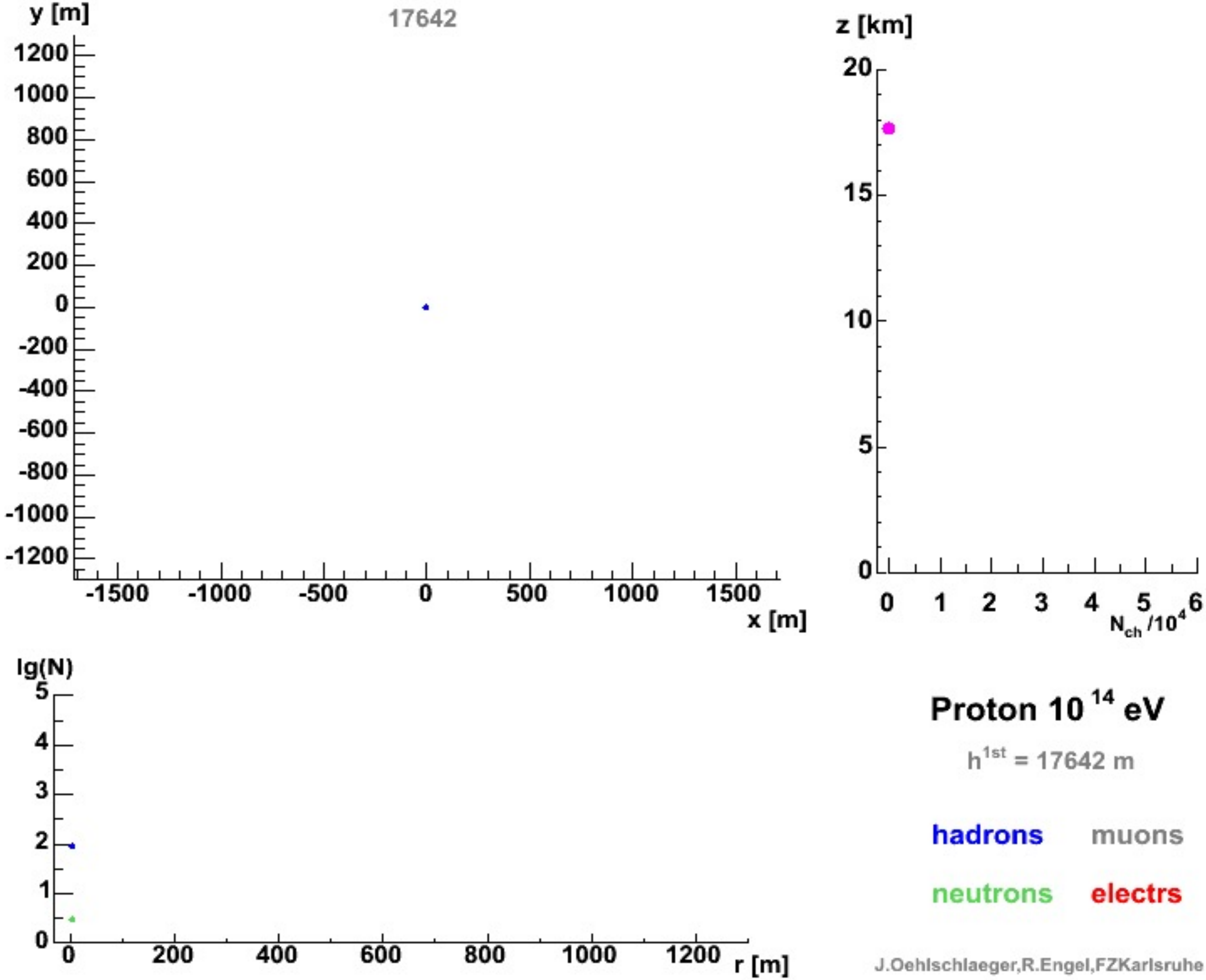
(G. Farrar & J. Sandstrom, NASA)

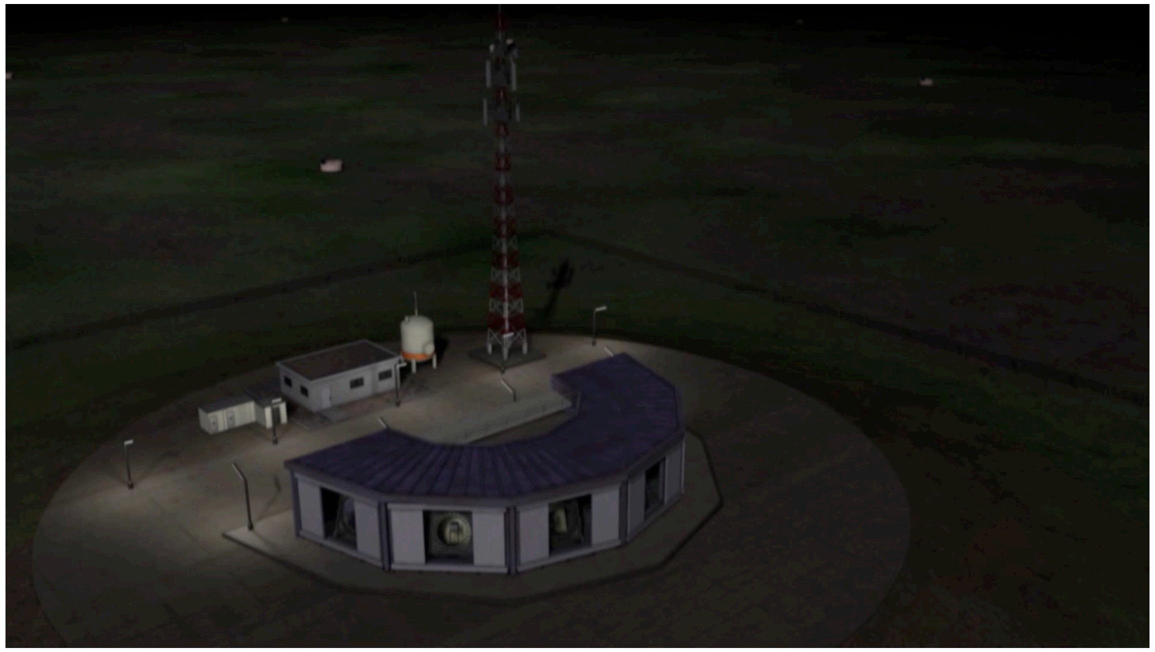
POSSIBLE TO TRACK BACK THE SOURCES

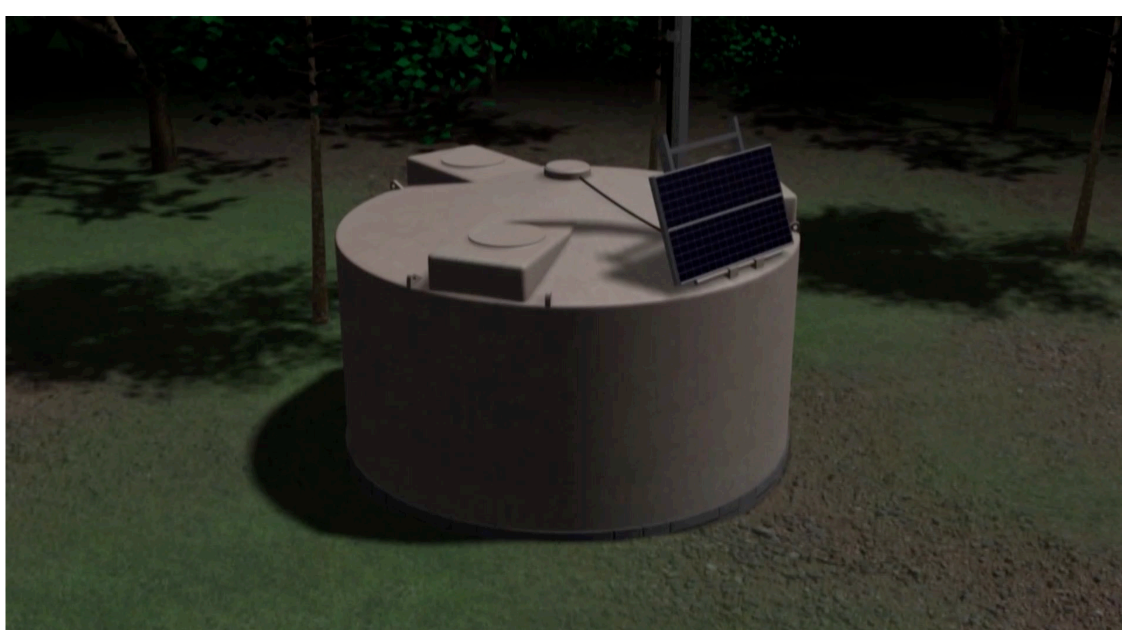


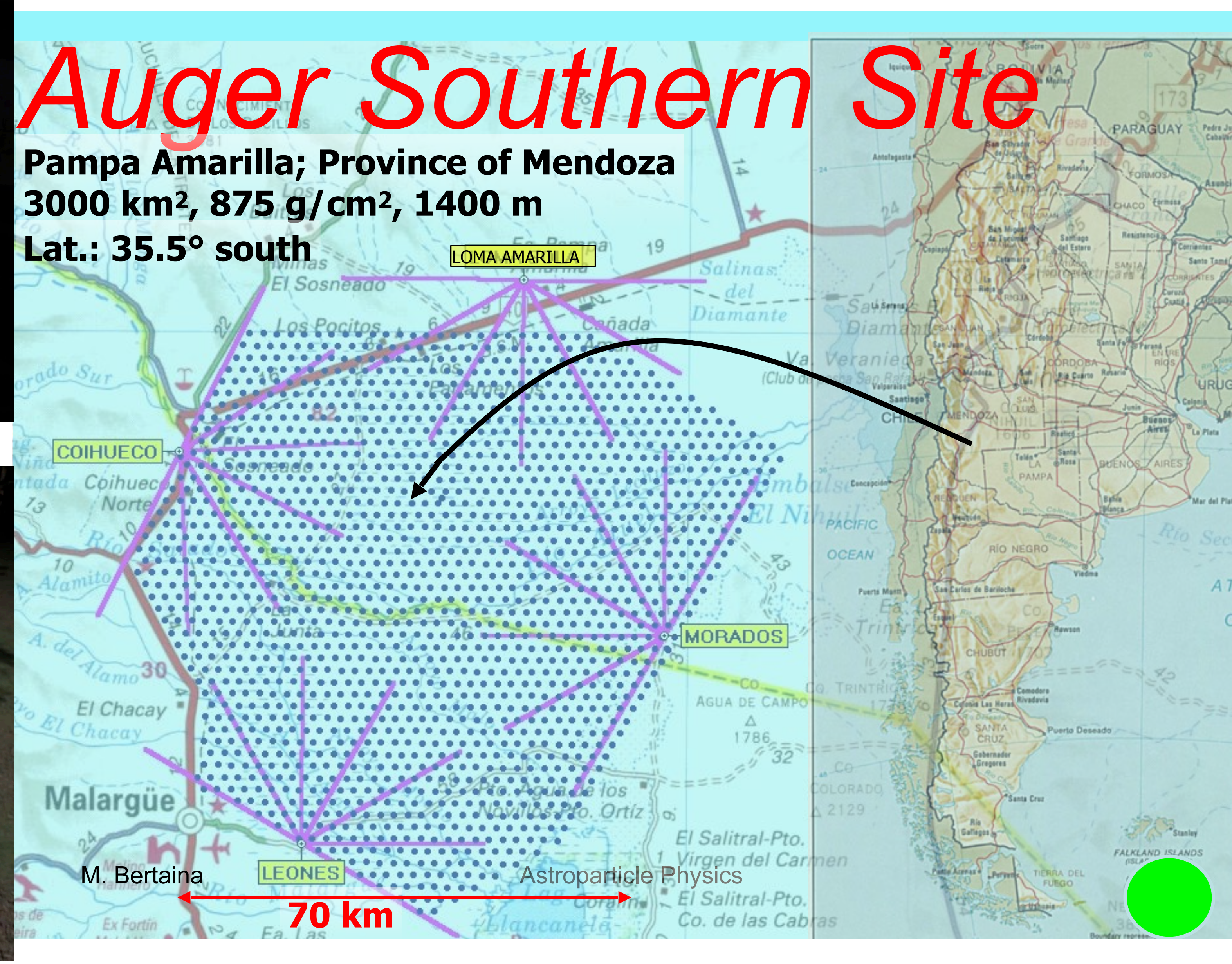


Cosmic rays with energy E> $7\cdot10^{19}$ eV must have their sources within 50Mpc


17642
y [m]
x [m]
z [km]
N_ch /10^4
lg(N)
r [m]
Proton 10^14 eV
h^1st = 17642 m
hadrons
muons
neutrons
electrs
J.Oehlschlaeger,R.Engel,FZKarlsruhe






Auger Southern Site
Pampa Amarilla; Province of Mendoza
3000 km², 875 g/cm², 1400 m
Lat.: 35.5° south
LOMA AMARILLA
COIHUECO
MORADOS
LEONES
Malargüe
M. Bertaina
Astroparticle Physics
70 km

TELESCOPE ARRAY PROJECT

Leading Observatories of Ultrahigh Energy Cosmic Rays

PIERRE AUGER OBSERVATORY

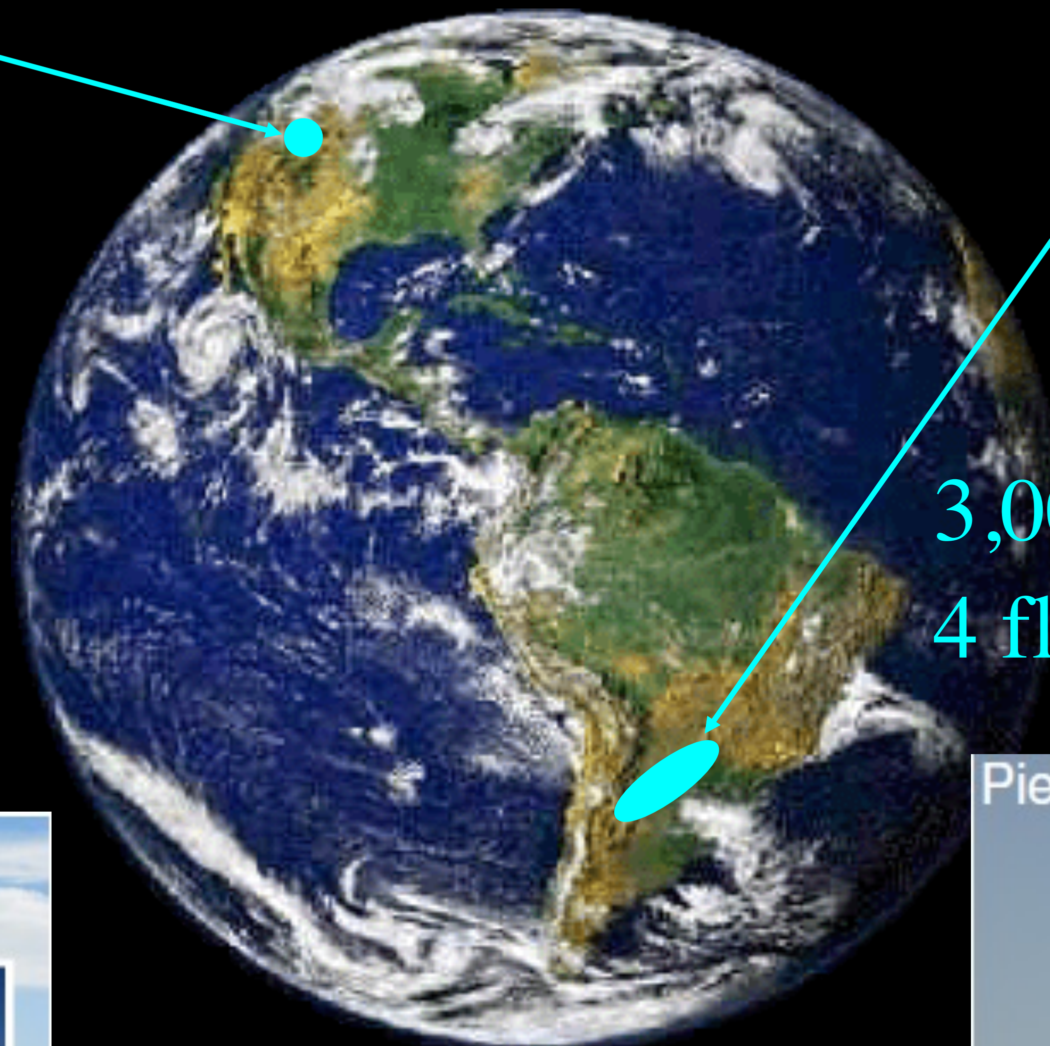
Telescope Array

Utah, US

(5 country collaboration)

700 km^2 array

3 fluorescence telescopes



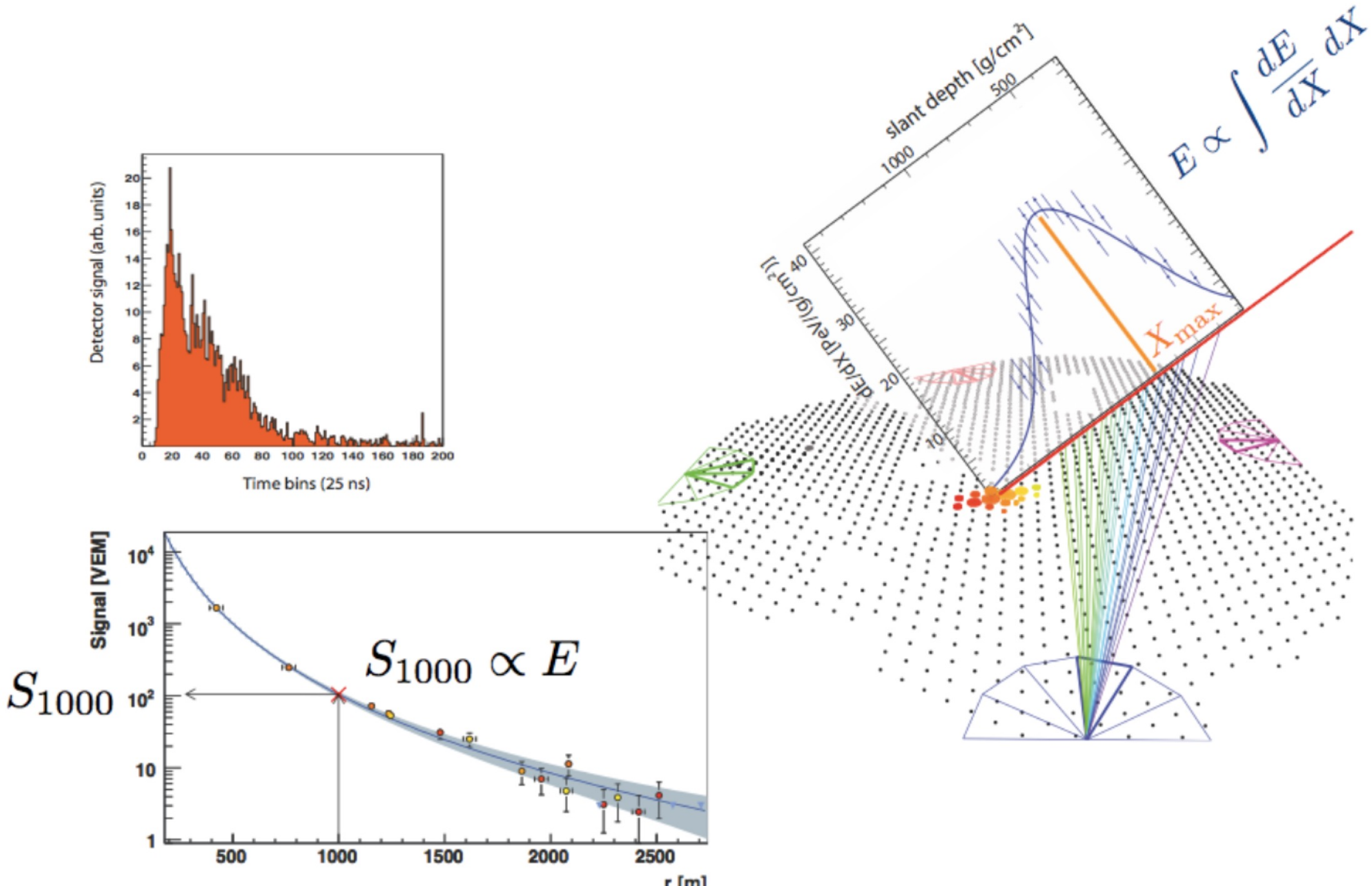
Pierre Auger Observatory

Mendoza, Argentina

(19 country collaboration)

3,000 km^2 array

4 fluorescence telescopes



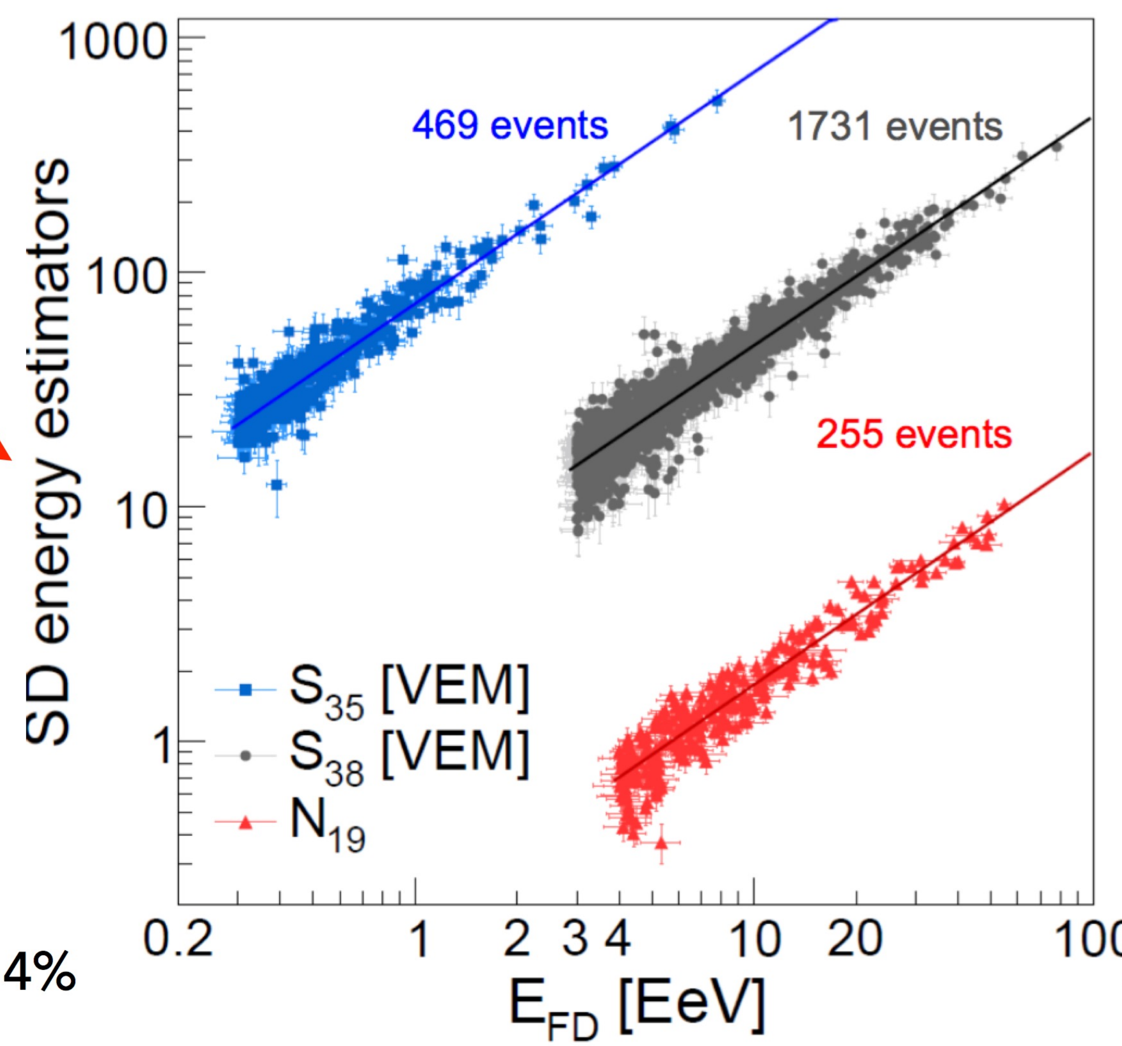
FD: calorimetric energy measurement
(13% duty cycle)

$$E_{Cal} = \int_0^\infty dX \, \frac{dE}{dX}$$

$$E_{Tot} = E_{Cal} + \underline{E_{Inv}}$$

(evaluated from data, as $E_{Inv} \propto N_\mu$)

SD: shower size at ground as energy estimator.



Hybrid events: absolute calibration of the full SD sample

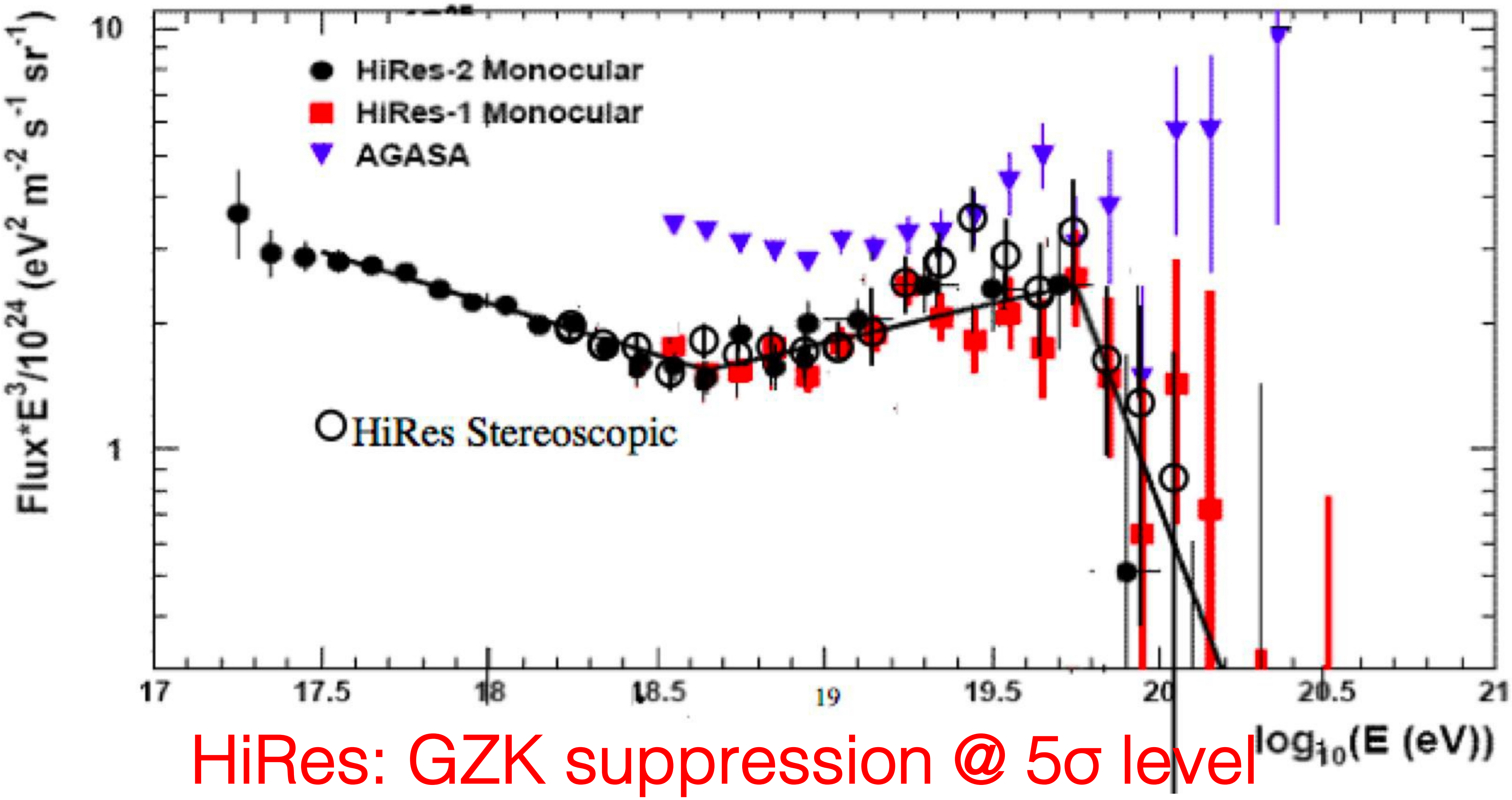
In the Pierre Auger Observatory:
Energy resolution: 15% for vertical events
Energy systematic uncertainty : FD energy scale 14%

A. Castellina

THE IMPORTANCE OF AN HYBRID DETECTOR

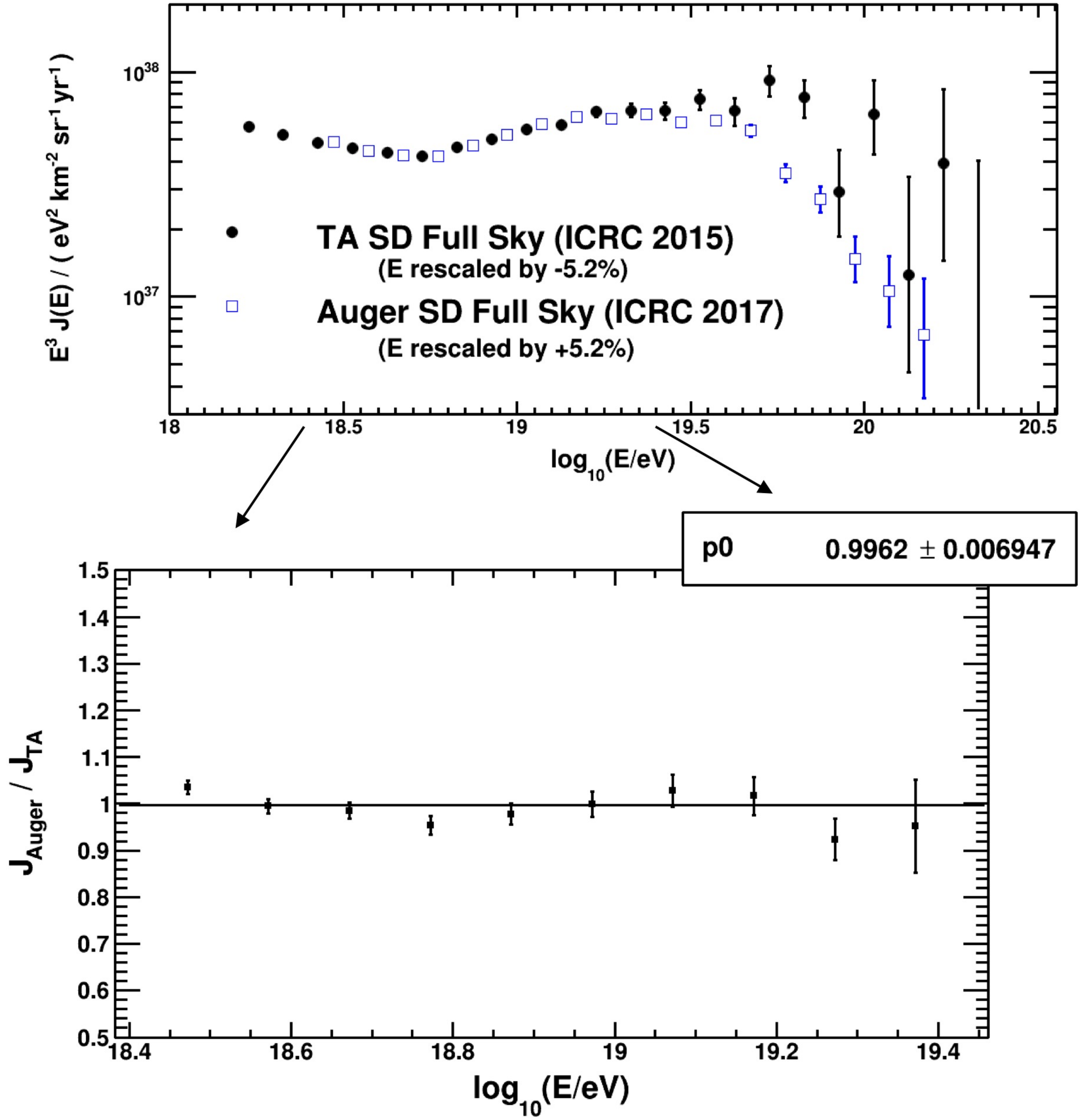
Experimental situation in early 2000s

AGASA: continuing spectrum



HiRes: GZK suppression @ 5σ level

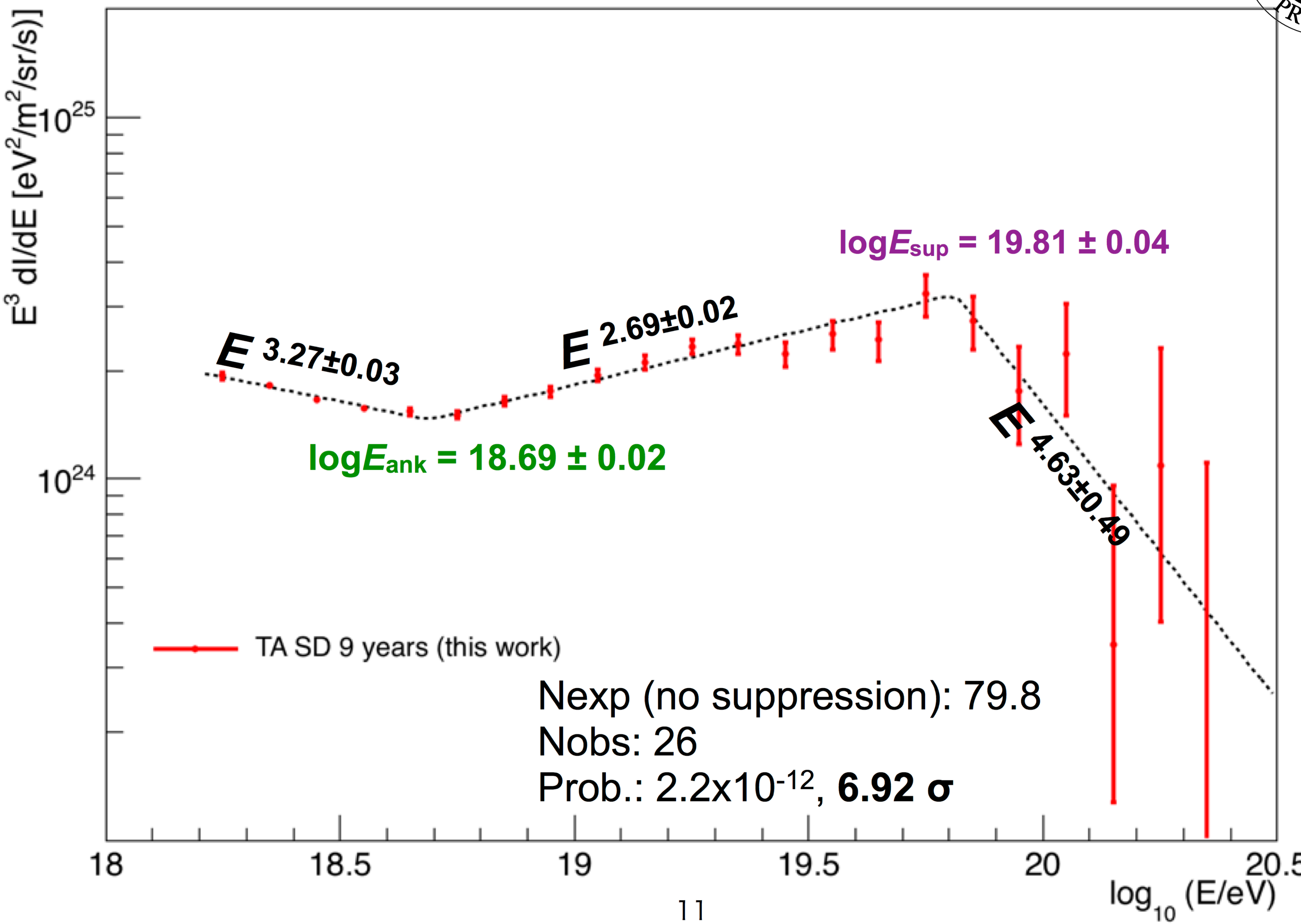
Rescale Auger and TA energies



- Constant rescaling factor of **5.2%**
    - From fitting ratio of fluxes Auger/TA into a unity in the ankle region
    - Auger energies *raised* by 5.2%
    - TA energies *lowered* by 5.2%
- Agree in the ankle region $10^{18.4}$ eV < E < $10^{19.4}$ eV after rescaling
- **Difference above $10^{19.4}$ eV persists after locking energy scales of experiments**

8

Power-Law Fit

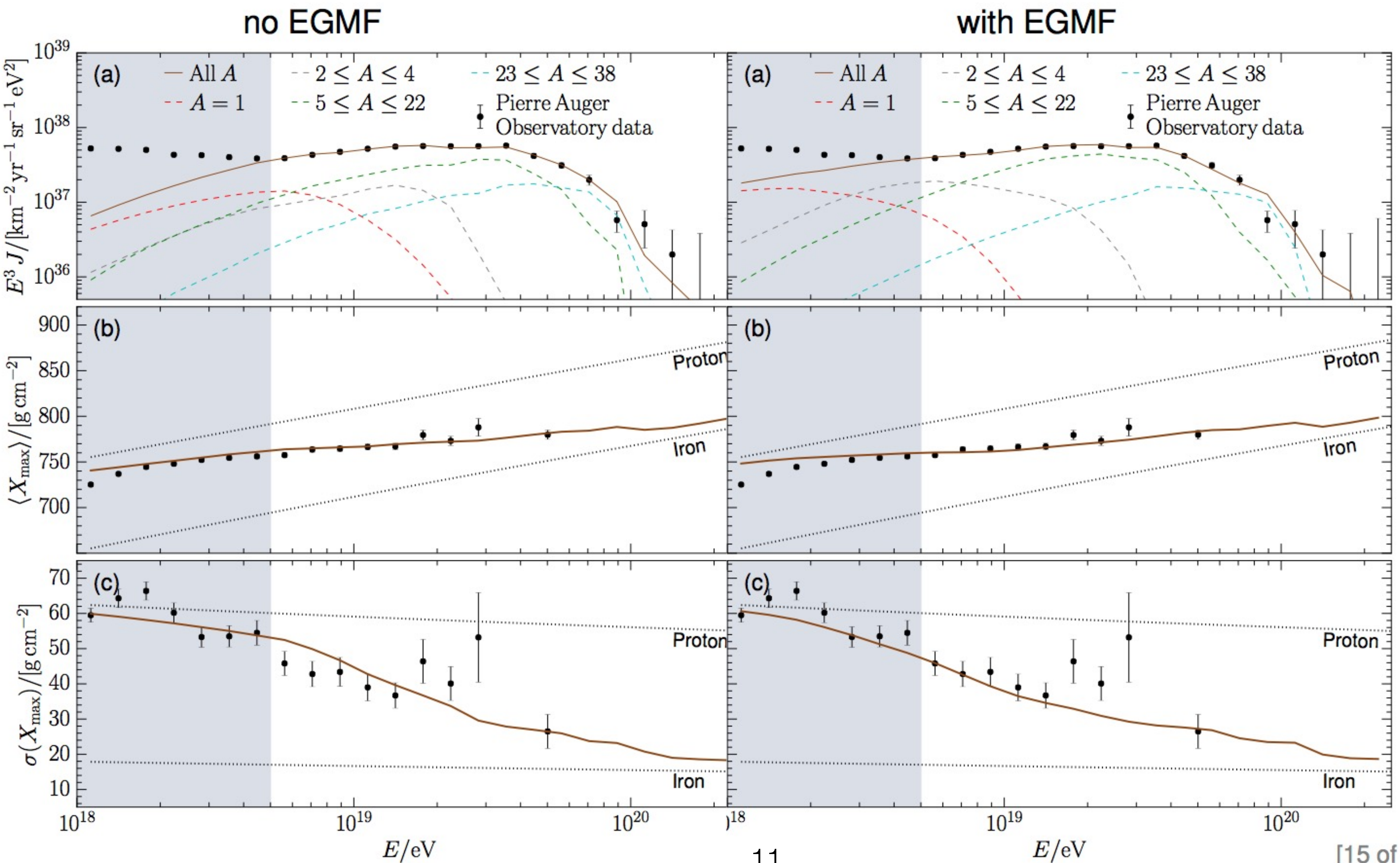


11

Y. Tsunesada - ICRC 2017

Combined Fit of Spectrum and X_{max} Distributions

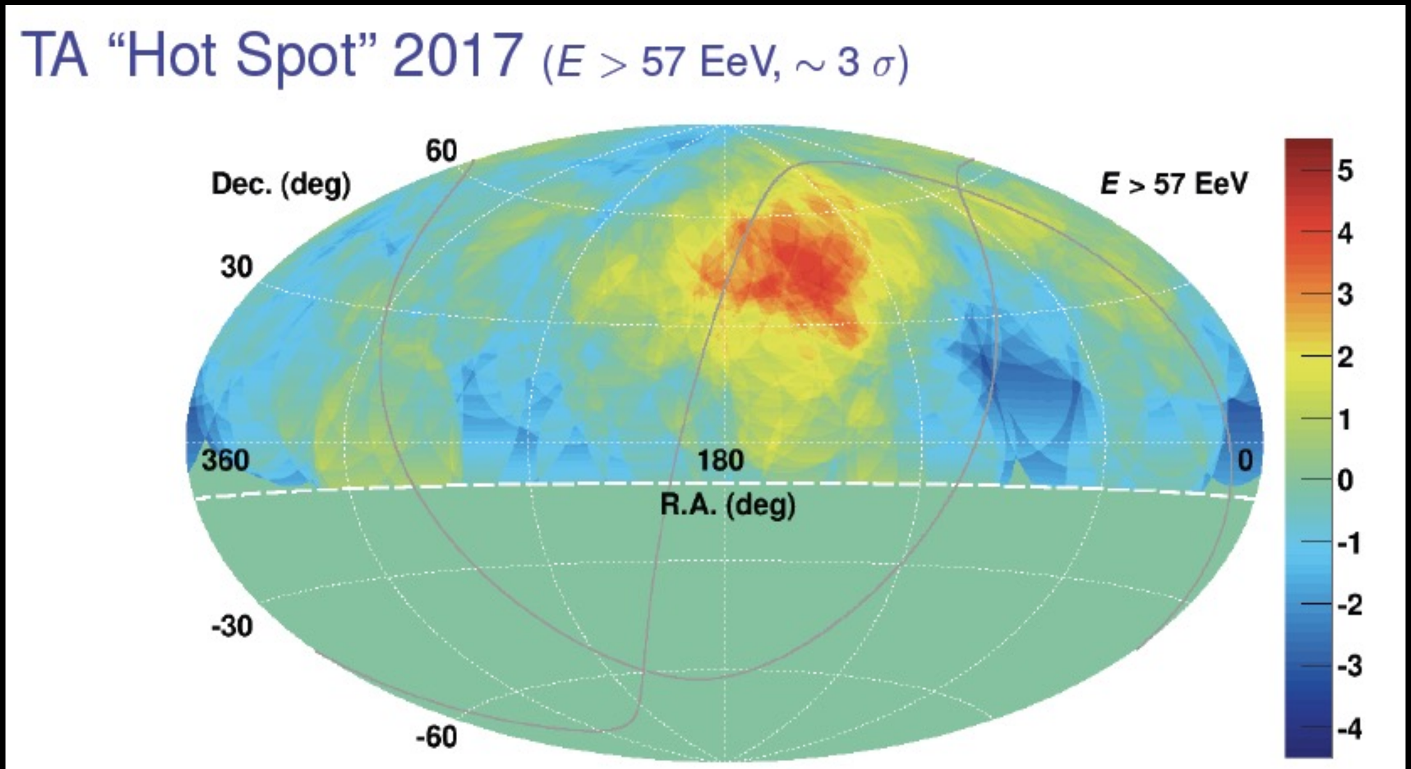
rigidity-dependent cutoff at source: $E_{max} = R_{cut}\,Z$, power law injection $E^{-\gamma}$, propagation with CRPropa3, Gilmore12 EBL, Dolag12 LSS



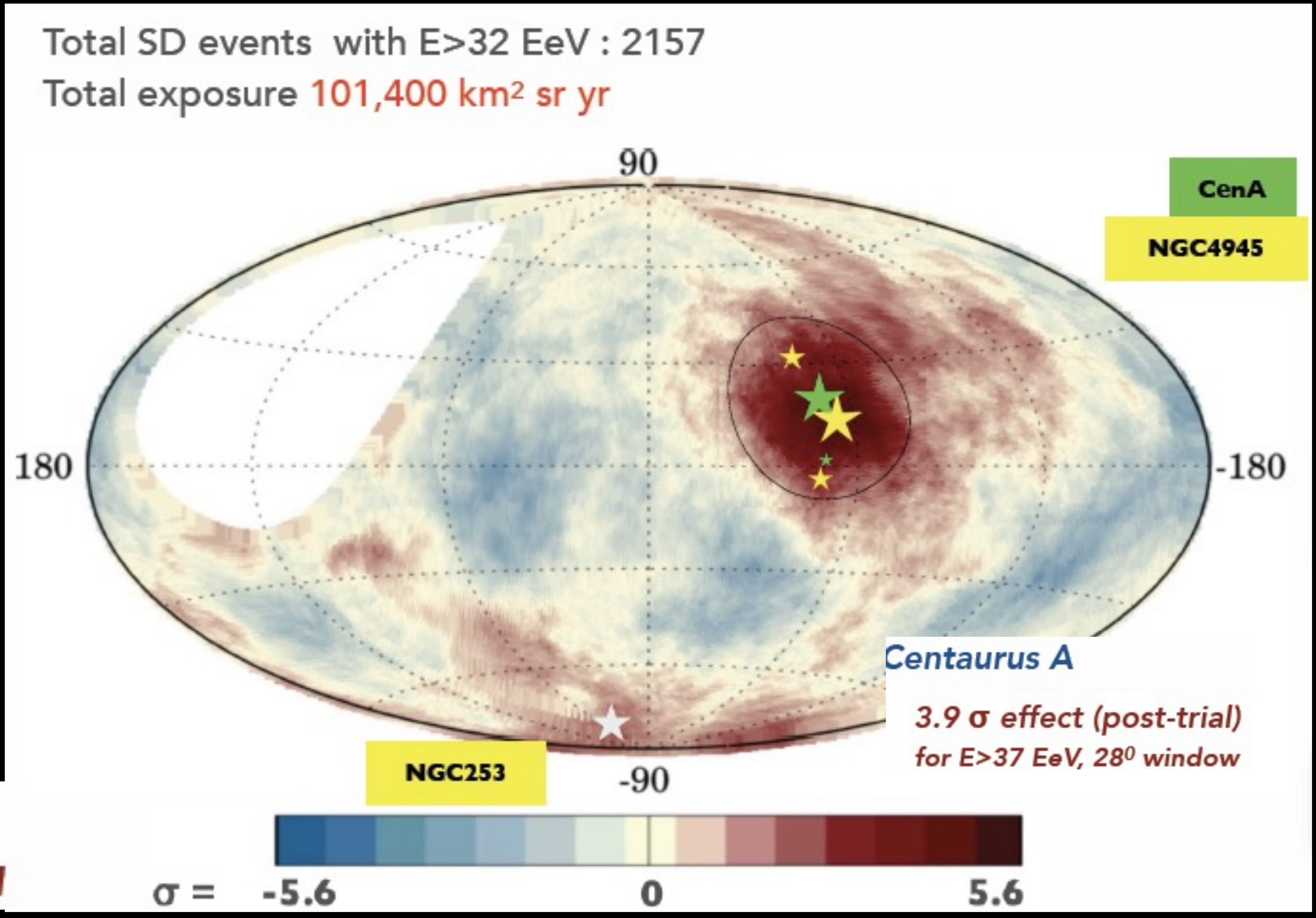
M. Unger - ICRC 2017

Anisotropy hints @ E > 40 EeV

TA



Auger



ICRC2019 4.5 σ for SBGs

[Jan 2004-Aug 2018] 3.1 σ for γ-AGN

How many UHECRs > 60 EeV?

- Auger w/ 3,000 km^2
- ~25 events > 60 EeV/ yr
- Telescope Array w/ 700 km^2
- ~5 events > 60 EeV/ yr
- Auger + TA ~ 30 events/yr

5 o.o.m to go!

- Earth - surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

Go to SPACE!

To look down on the

Atmosphere!

How many UHECRs > 60 EeV?

- Auger + TA ~30 events/yr

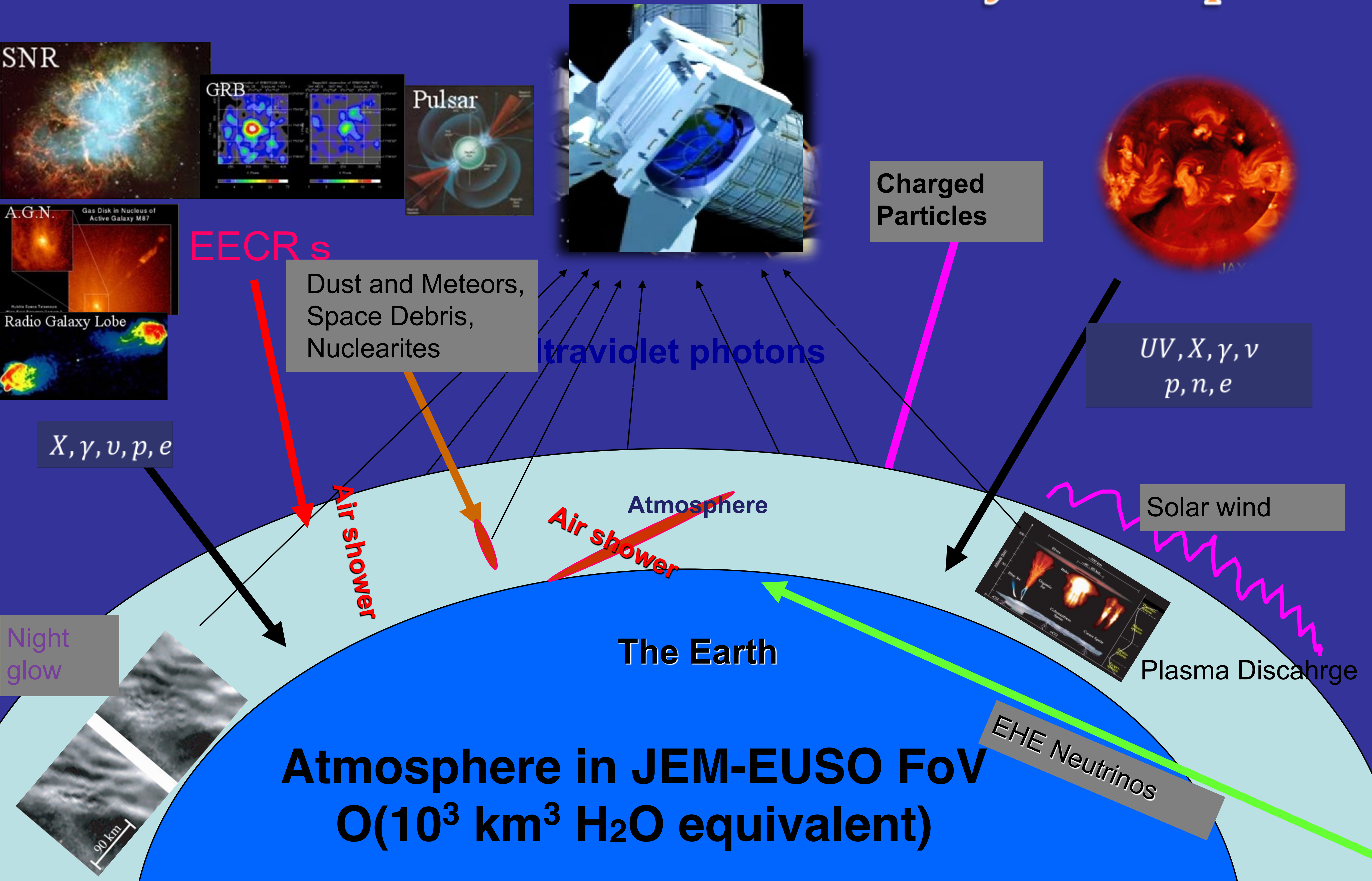
- **JEM-EUSO**
- **~200 events > 60 EeV/y**

4 o.o.m to go!

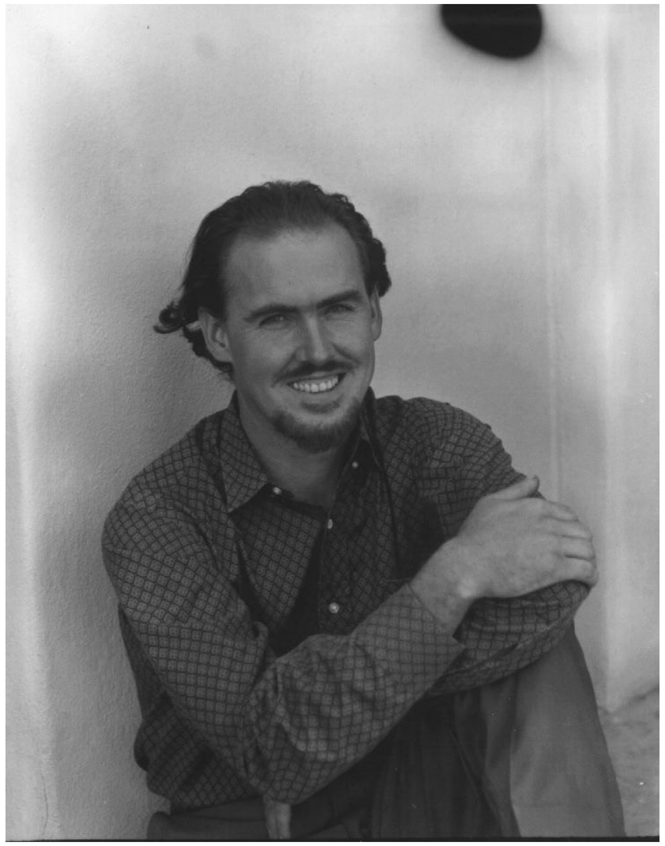
- Earth - surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

JEM-EUSO is
an Astronomical Earth Observatory from Space



1979, An idea* of John Linsley



John Linsley in 1979 in the Field Committee Report of NASA "Call for Projects and Ideas in High Energy Astrophysics for the 1980s"

The concept to observe, by means of Space Based devices looking at Nadir during the night, the fluorescence light produced by an EAS proceeding in the atmosphere

Y. Takahashi (1995): MASS: Maximum Energy Auger (Air Shower Satellite Italian Mission)

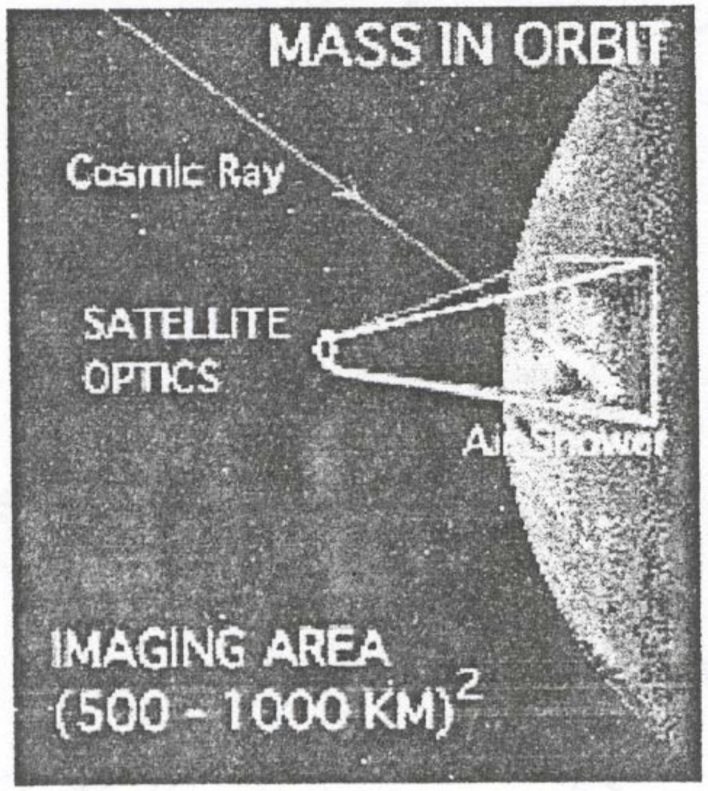
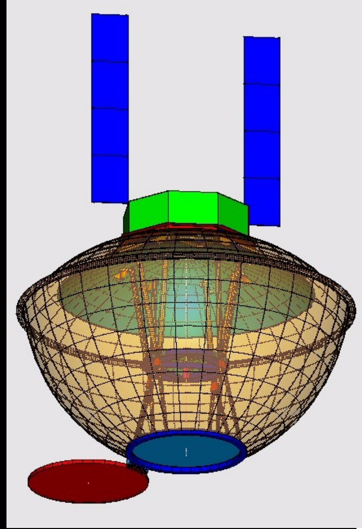
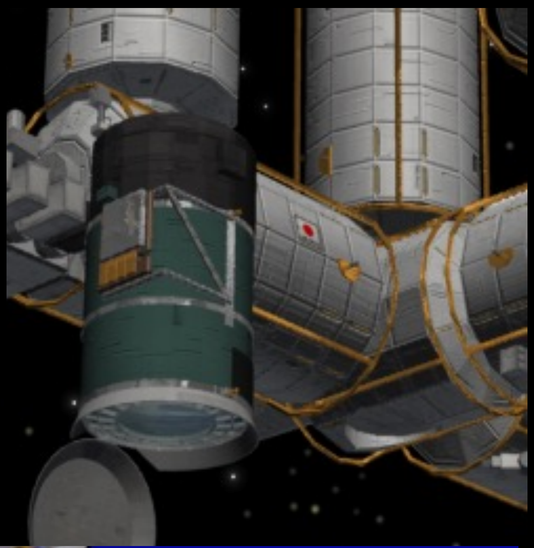


Fig. 3 Artist view of the MASS on orbit.



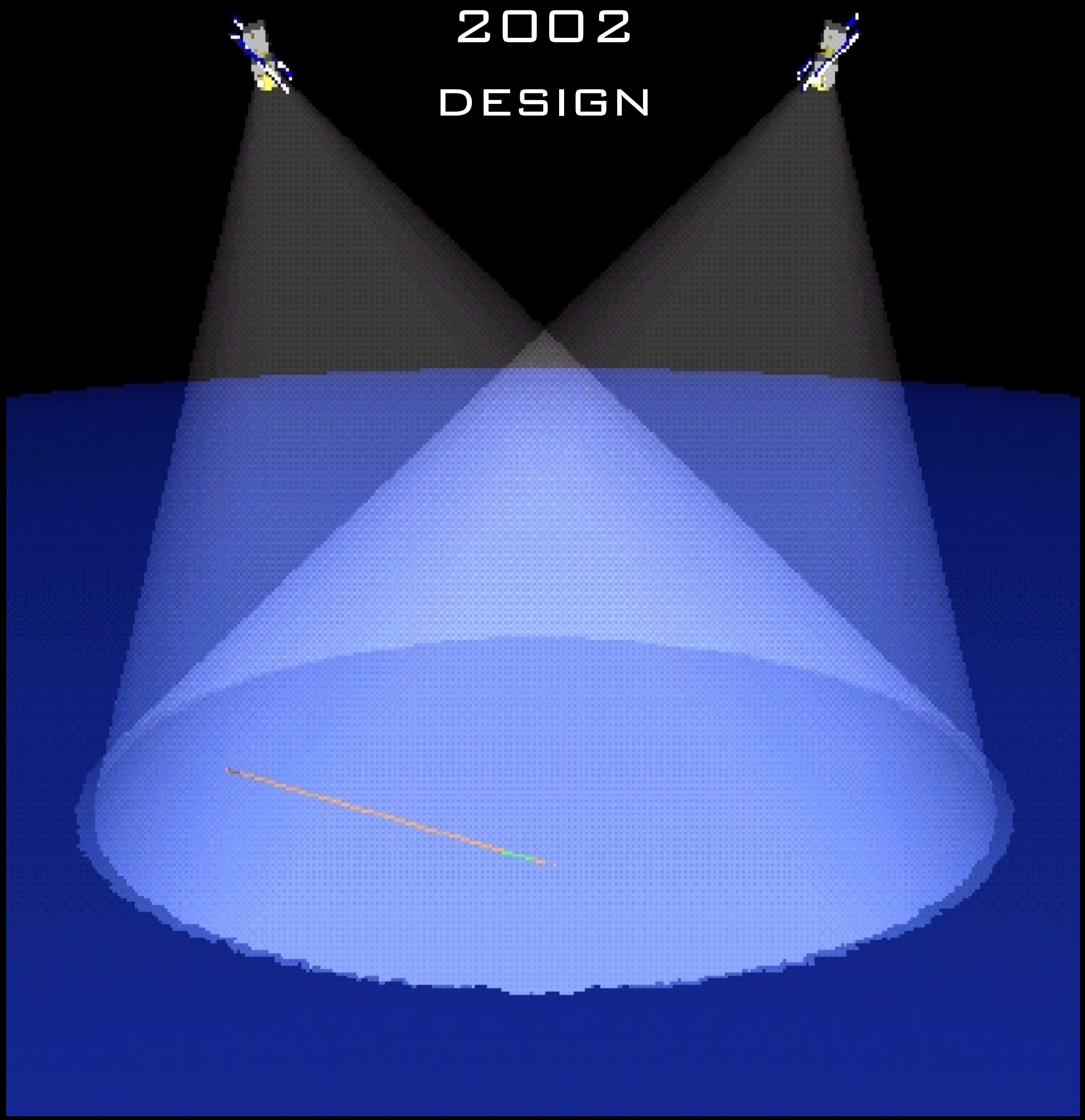
Extensive Air-shower Fluorescence from SPACE

Orbiting Wide-angle Light-collectors



EUSO

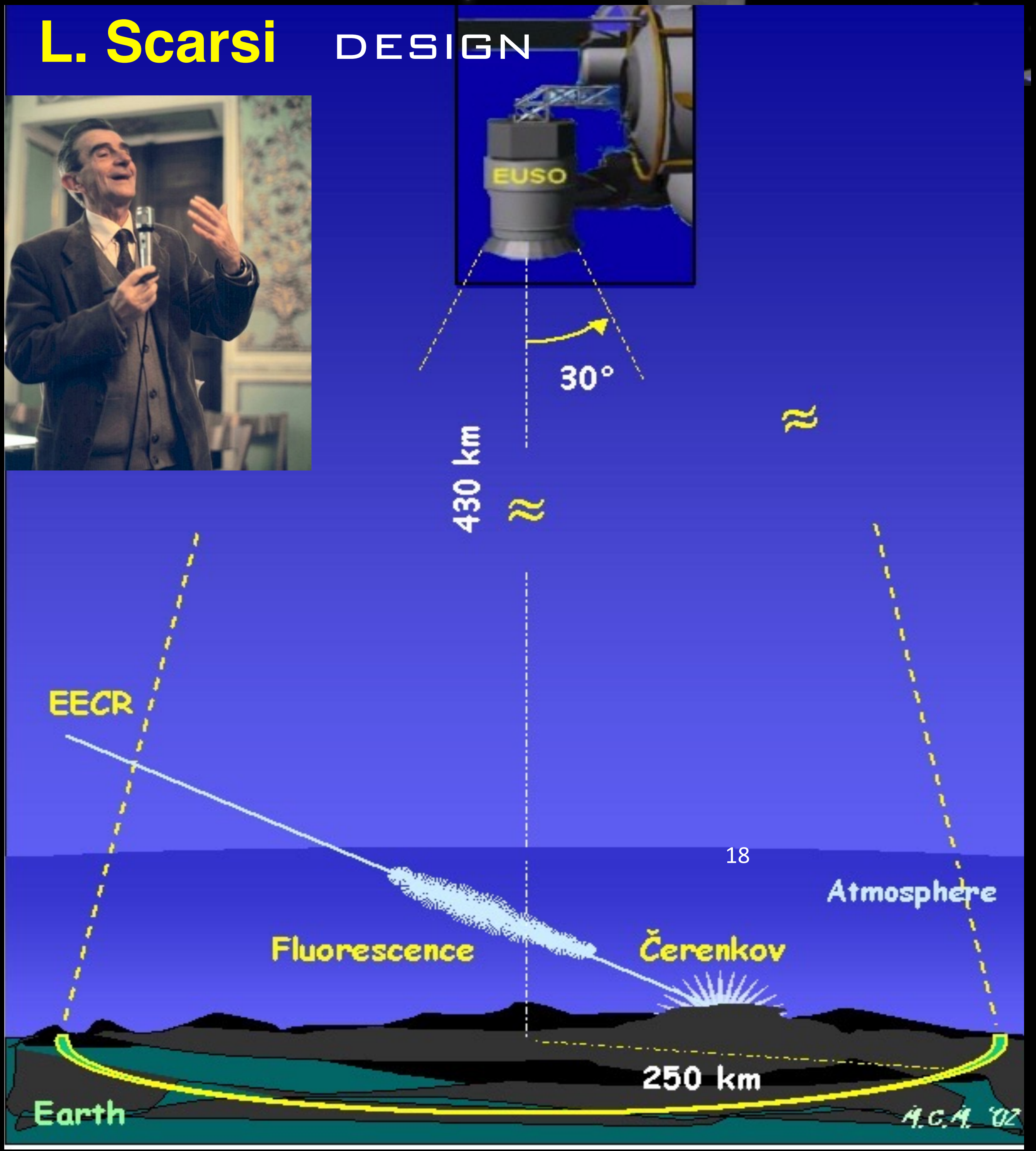
2002

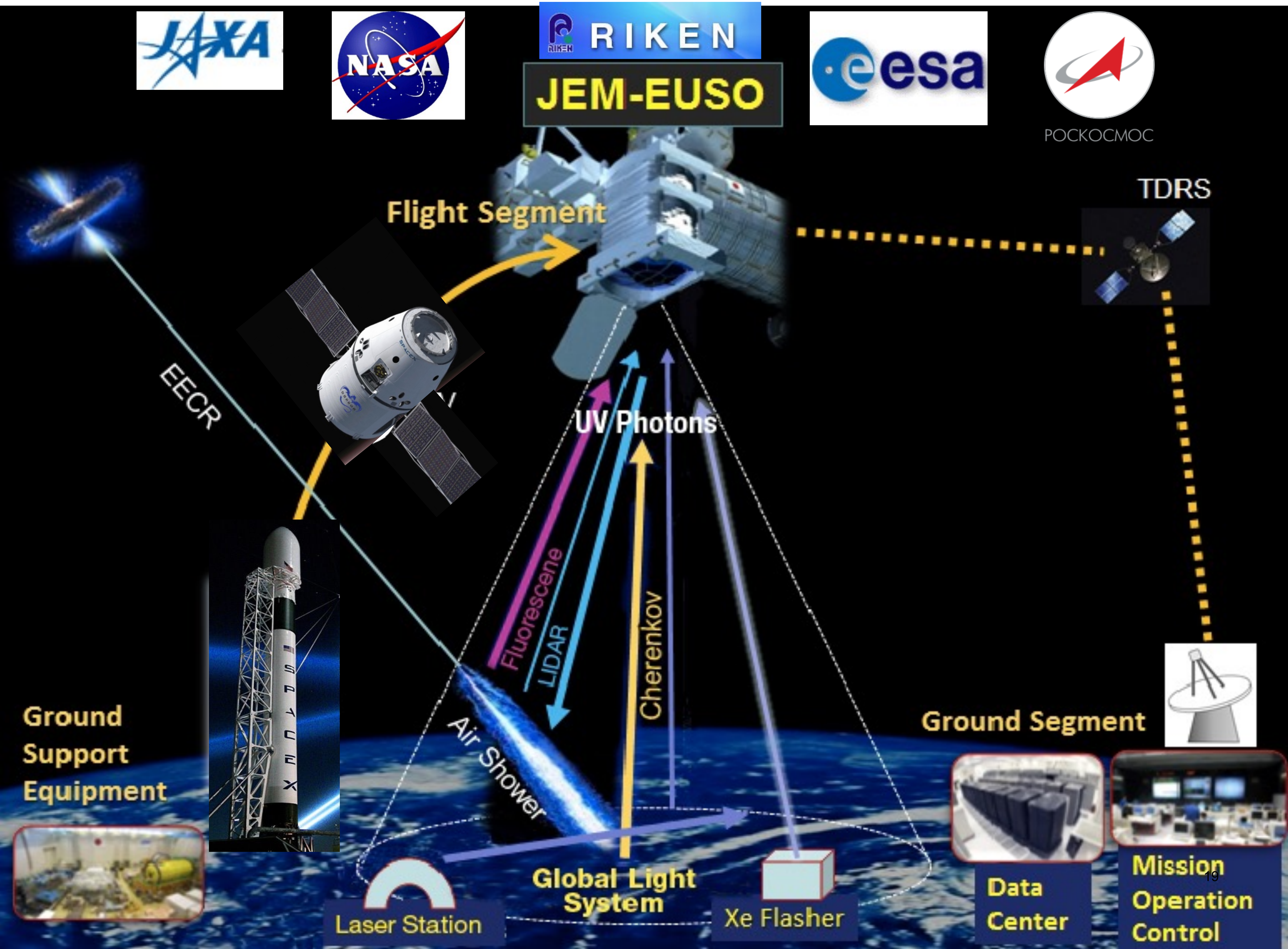


OWL

2002

DESIGN

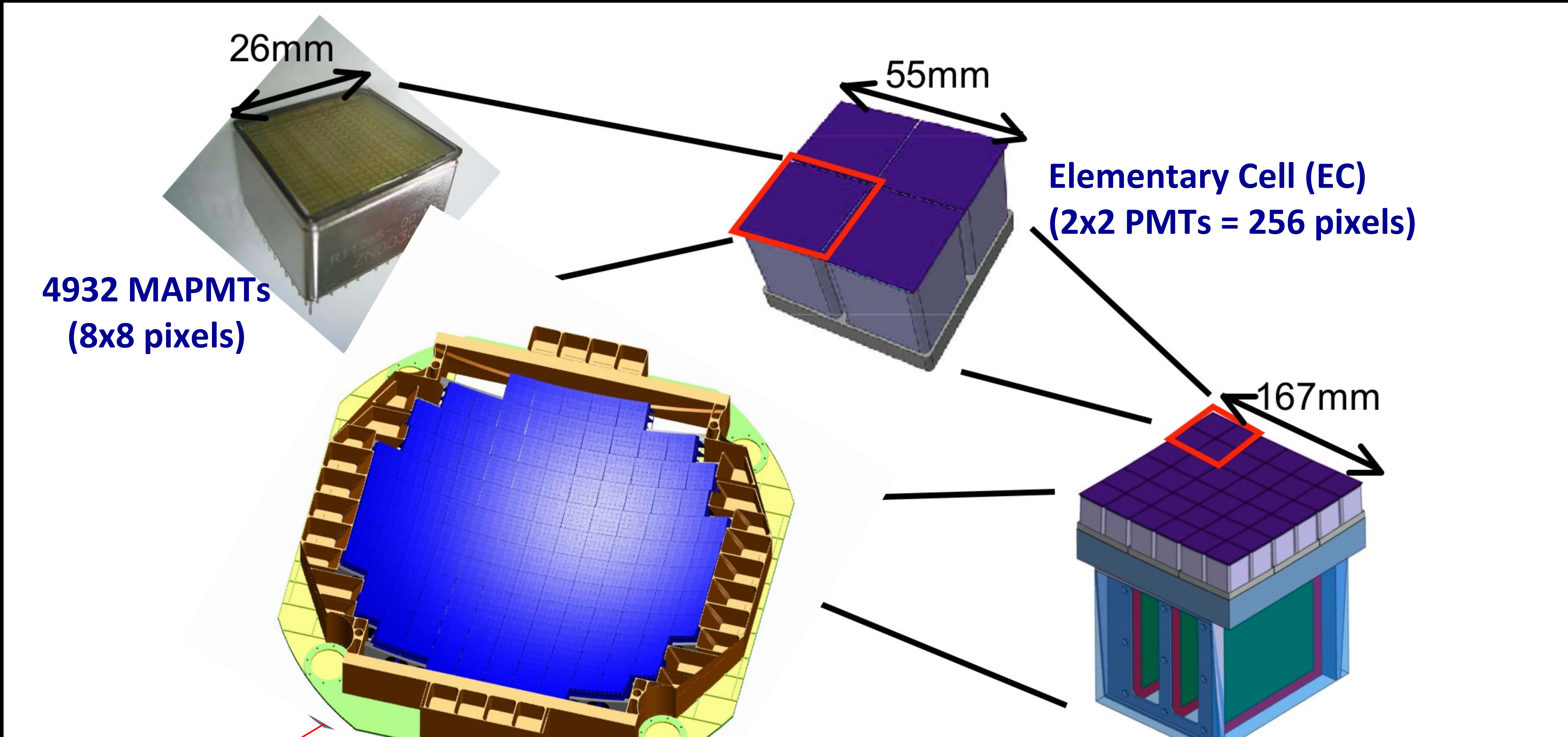


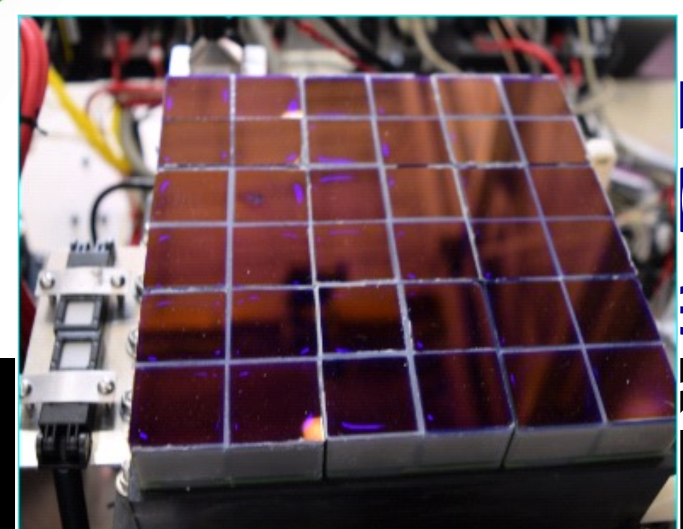

JAXA
NASA
RIKEN
JEM-EUSO
esa
РОСКОСМОС
TDRS
Flight Segment
EECR
UV Photons
Fluorescene
LIDAR
Cherenkov
Air Shower
Ground
Support
Equipment
Ground Segment
Laser Station
Global Light
System
Xe Flasher
Data
Center
Mission
Operation
Control

Science Instrument

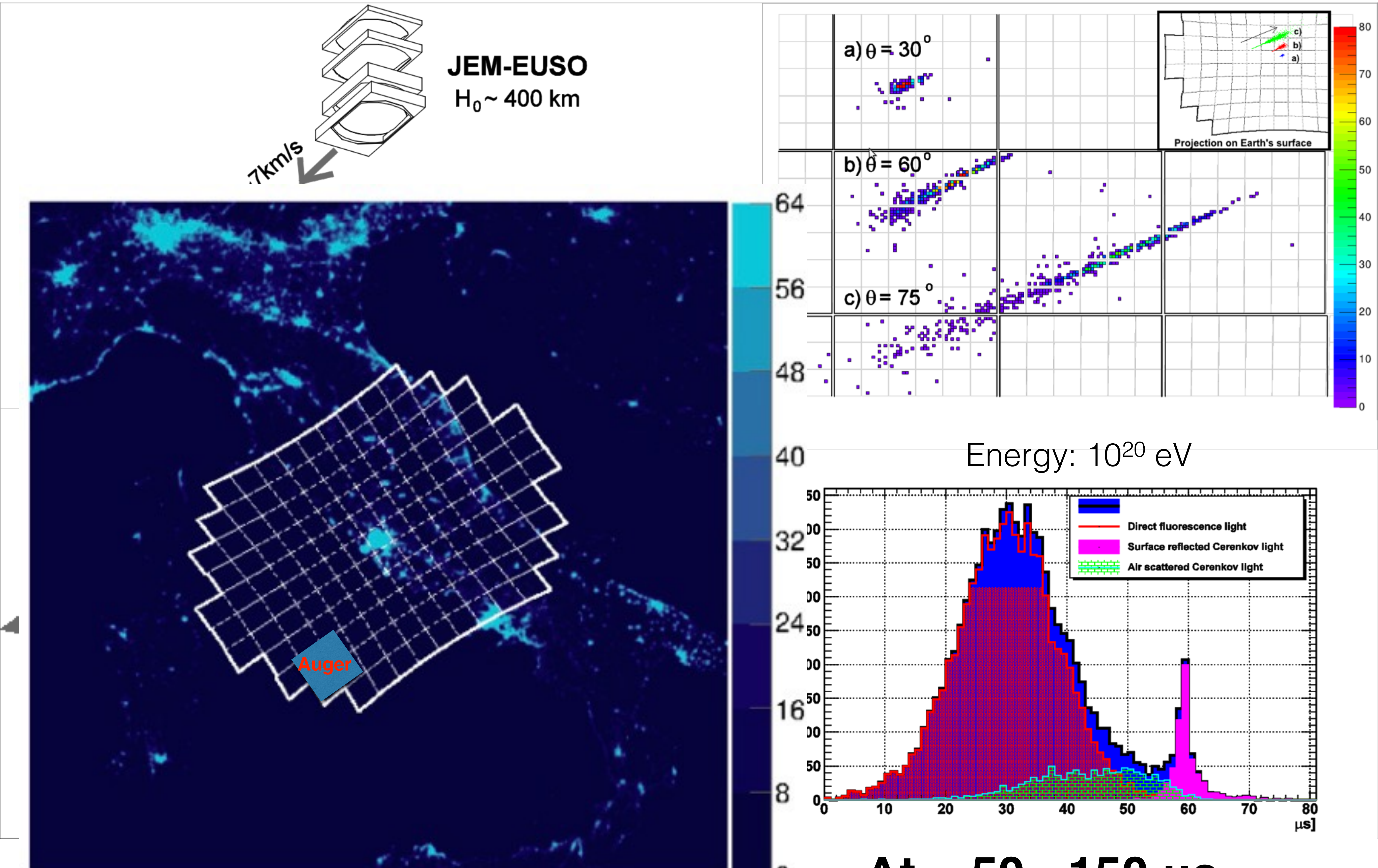
tics

Focal Surface Detector





JEM-EUSO Observation Principle

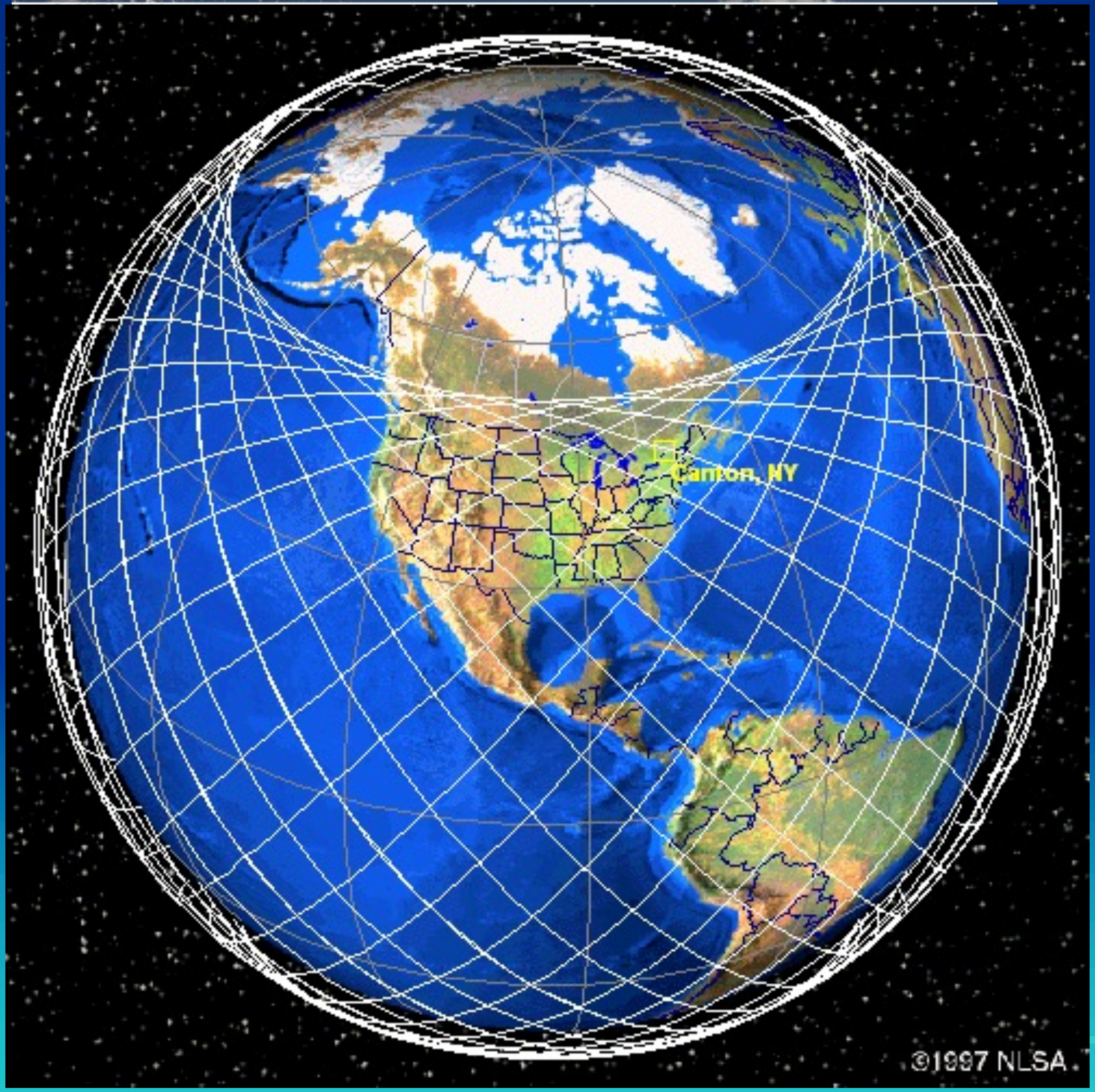


$\Delta t \sim 50$ - $150\ \mu s$

An idea of the monitored area (2)

Tilt angles: 0, 20, 30 deg.

ISS Orbit



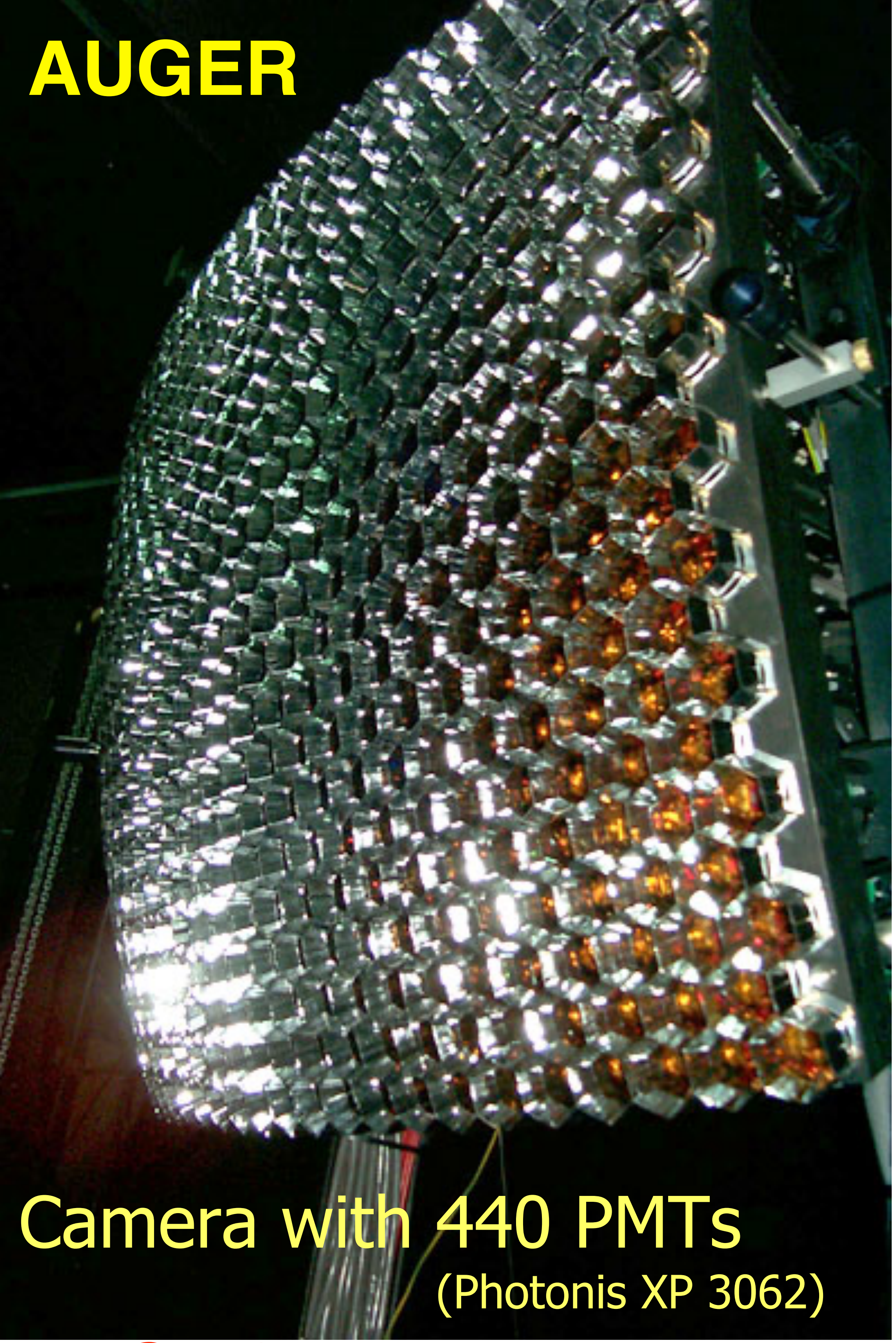
Inclination: 51.6°
Height: ~400km

JEM-EUSO can observe the arrival direction of EECR very uniformly owing to the nature of the ISS orbit.

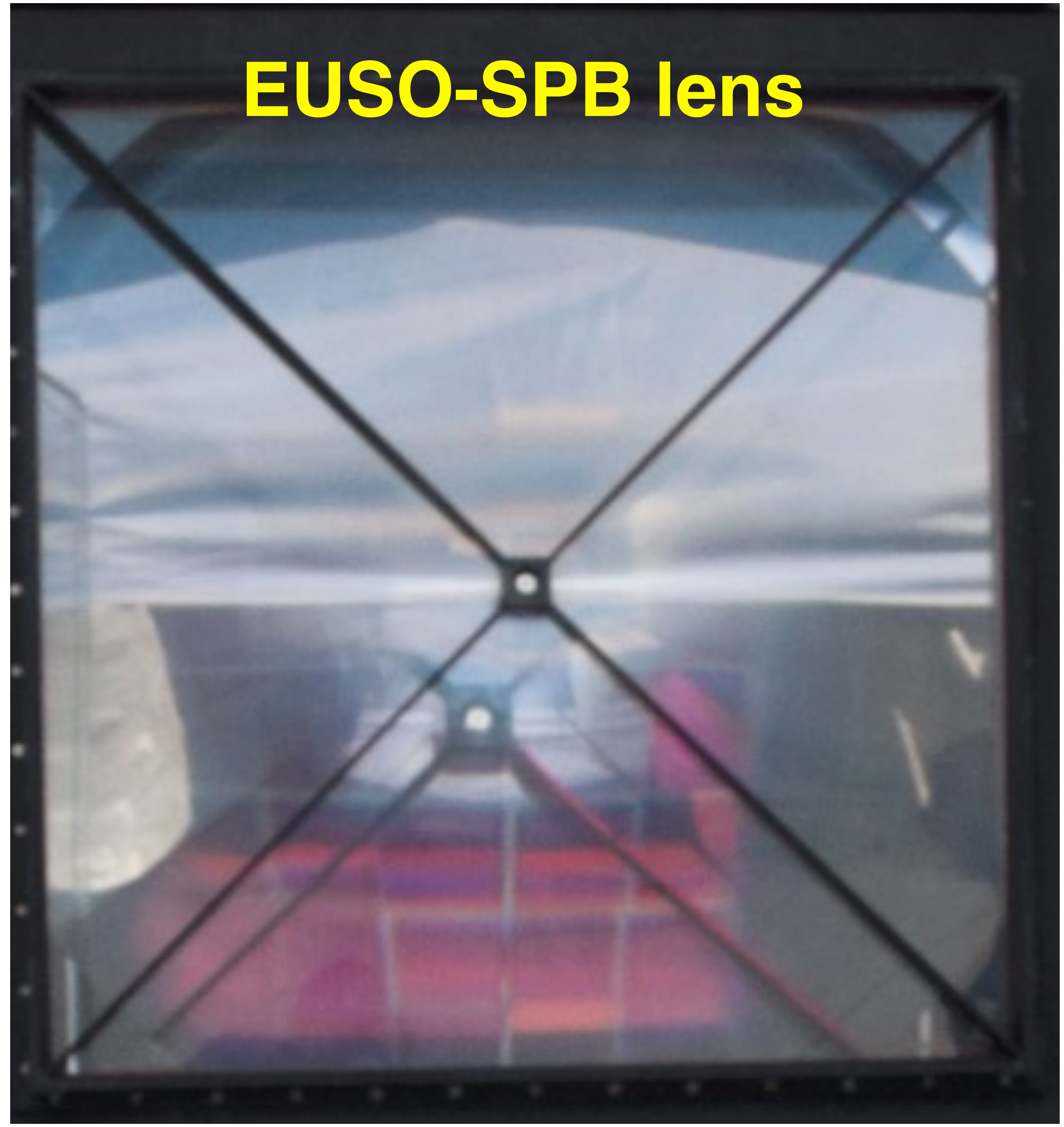
http://www.nasa.com/

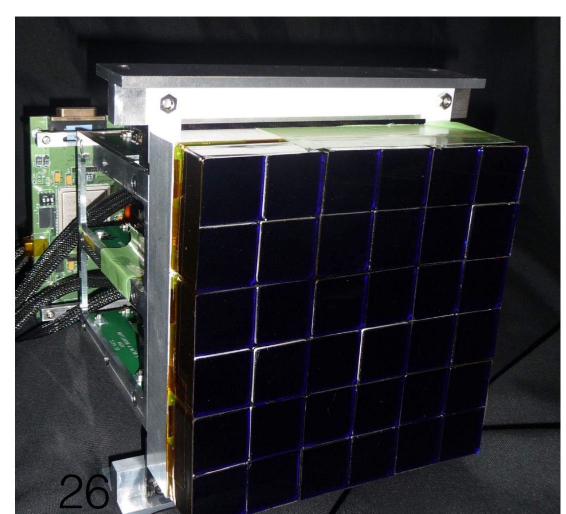
Technical challenges of the observation from space compared to UHECR detectors from ground

- Low power consumption (<1kW for JEM-EUSO - 3×10^5 pixels)
- Low mass (~1-2 tons for JEM-EUSO)
- Low telemetry (300 kbit/s for JEM-EUSO on ISS)
- Radiation hard instrumentation
- Space-qualified instrumentation (need to increase TRL)



FS of 1 mirror Auger
440 pixels (~5cm/pix)
~100x100 cm^2





FS of EUSO-SPB
2304 pixels
(3mm/pix)
17x17 cm^2

Comparing Auger FD and JEM-EUSO telescope

	Auger (1 FD site)	EUSO-SPB	JEM-EUSO
mirror size	6 x 11 m^2	1 m^2 lens	4m^2
FoV	6 x (30 x 30) deg^2	11 x 11 deg^2	4 x 4 deg^2/PDM
Ang. resolution	1.5 deg/pixel	0.2 deg/pixel	0.075 deg/pixel
Pixel size	5x5 cm^2	1 pixel 3x3 mm^2	3x3 mm^2/pixel
Camera size	6 x 440 pixels	2304 pixel	2304 pixel/PDM
EAS distance	40 km	30 km	400 km
light intensity (@40km=1)	1	1.8	0.01
time resolution	100 ns	2.5 μs	2.5 μs
signal acquisition	charge integration	photon counting	photon counting

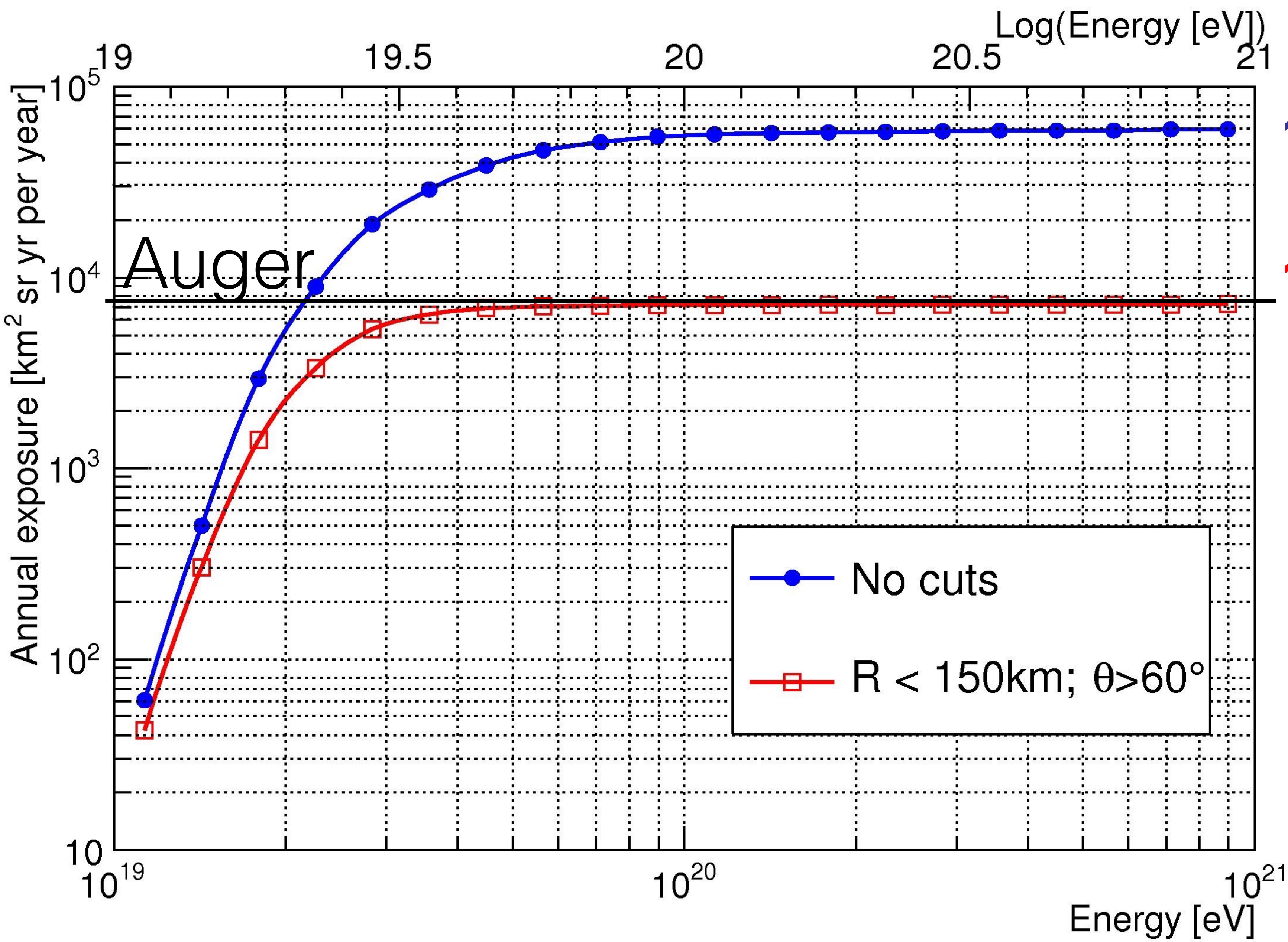
A significant difference in the detectors, a technological challenge…

Scientific challenges:

- Energy threshold below GZK cutoff (a factor of 2 higher energies means very few statistics and no inter calibration with ground experiments!).
- Light conditions continuously varying (ISS speed 7.5 km/s —> night/day change every 45 minutes).
- Atmospheric conditions (clear sky, clouds, lightning, cities and anthropic light) continuously changing.

- We need to test the capability of the instrument to adapt its working conditions to the different situations.
- We need to record and recognise the different atmospheric and anthropic conditions.

Annual Exposure nadir mode



~60,000 km^2 sr yr

~7,000 km^2 sr yr

~9 times Auger
~50 times TA

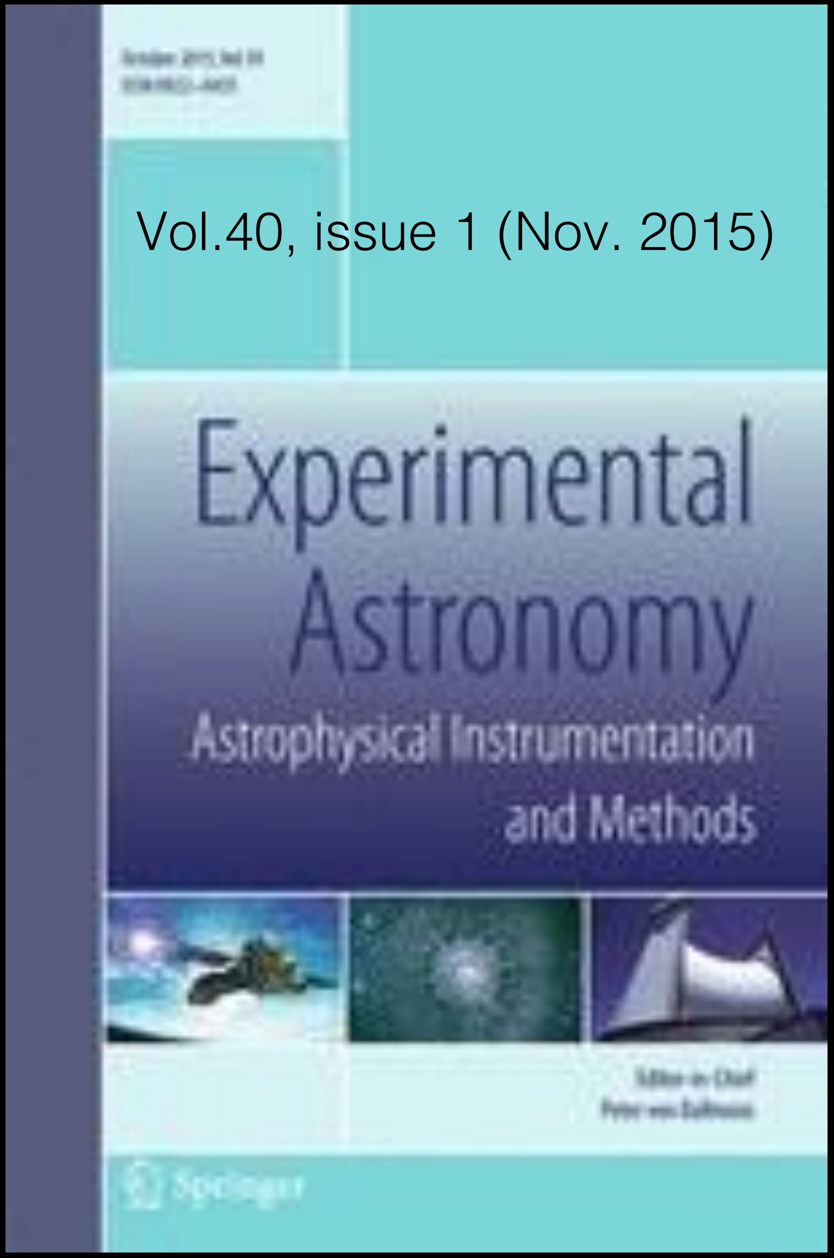
- Observational duty cycle (brightness of the sky does not hamper UHECR measurements): ~20%
- Role of clouds: ~72%
- City lights inefficiency: ~7%
- Lightning ineff.: ~ 2%
- Aurorae ineff.: ~1%

- Conversion factor between Aperture and Exposure: ~13%

Special Issue on the JEM-EUSO Mission

- 15 papers addressing science and technology of JEM-EUSO

- The EUSO-Balloon pathfinder
- The JEM-EUSO instrument
- Ground-based tests of JEM-EUSO components at the Telescope Array site, “EUSO-TA”
- Space experiment TUS on board the Lomonosov satellite as pathfinder of JEM-EUSO
- The JEM-EUSO observation in cloudy conditions
- Calibration aspects of the JEM-EUSO mission
- JEM-EUSO: Meteor and nuclearite observations
- JEM-EUSO observational technique and exposure
- Ultra high energy photons and neutrinos with JEM-EUSO
- Science of atmospheric phenomena with JEM-EUSO
- Performances of JEM–EUSO: energy and X max reconstruction
- The atmospheric monitoring system of the JEM-EUSO instrument
- The infrared camera onboard JEM-EUSO
- Proposal of a Computing Model Using GRID Resources for the JEM-EUSO Space Mission



JEM-EUSO PROGRAM

EUSO-TA (2013-)

EUSO-Balloon (2014)

TUS (2016)

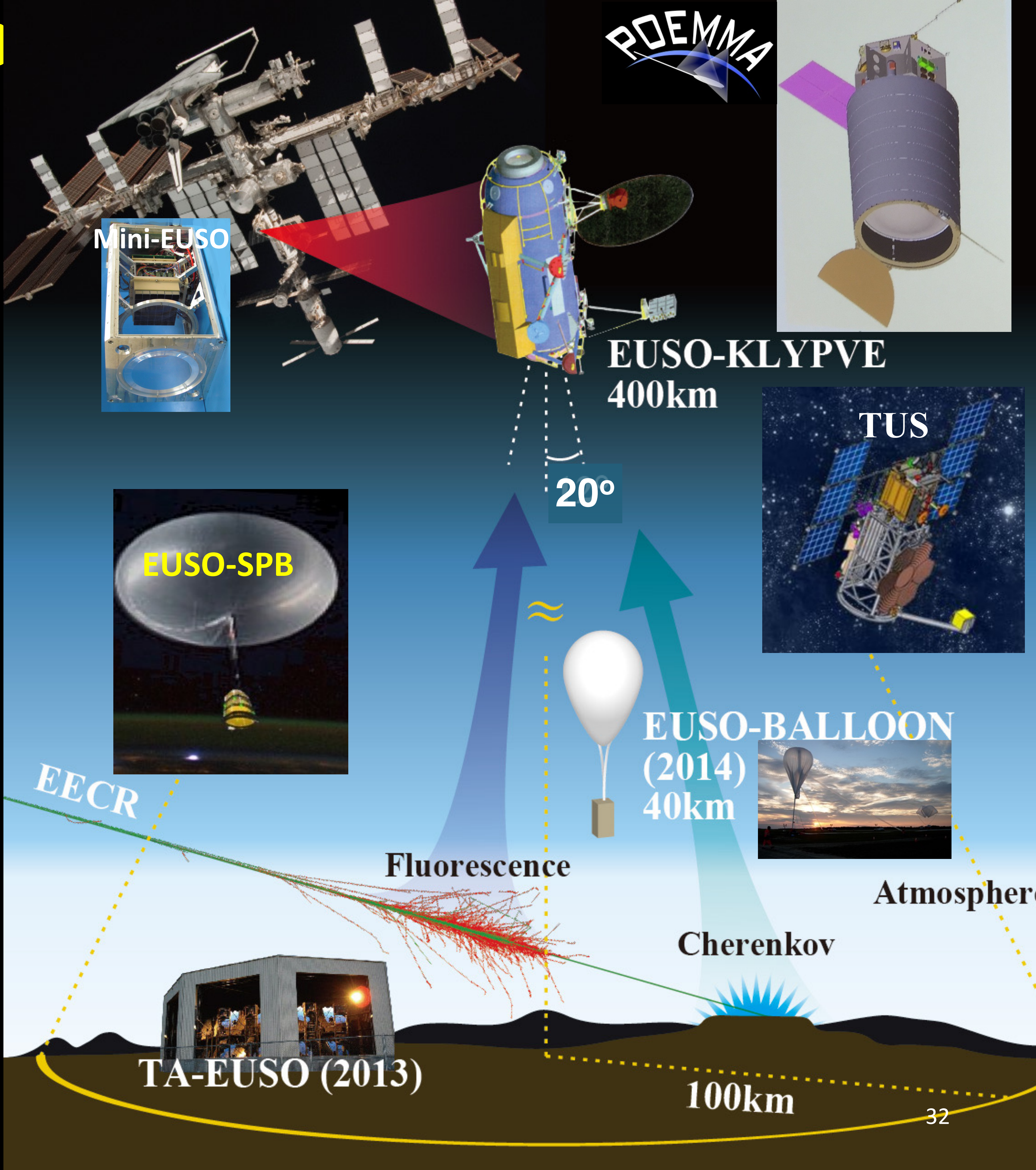
EUSO-SPB1 (2017)

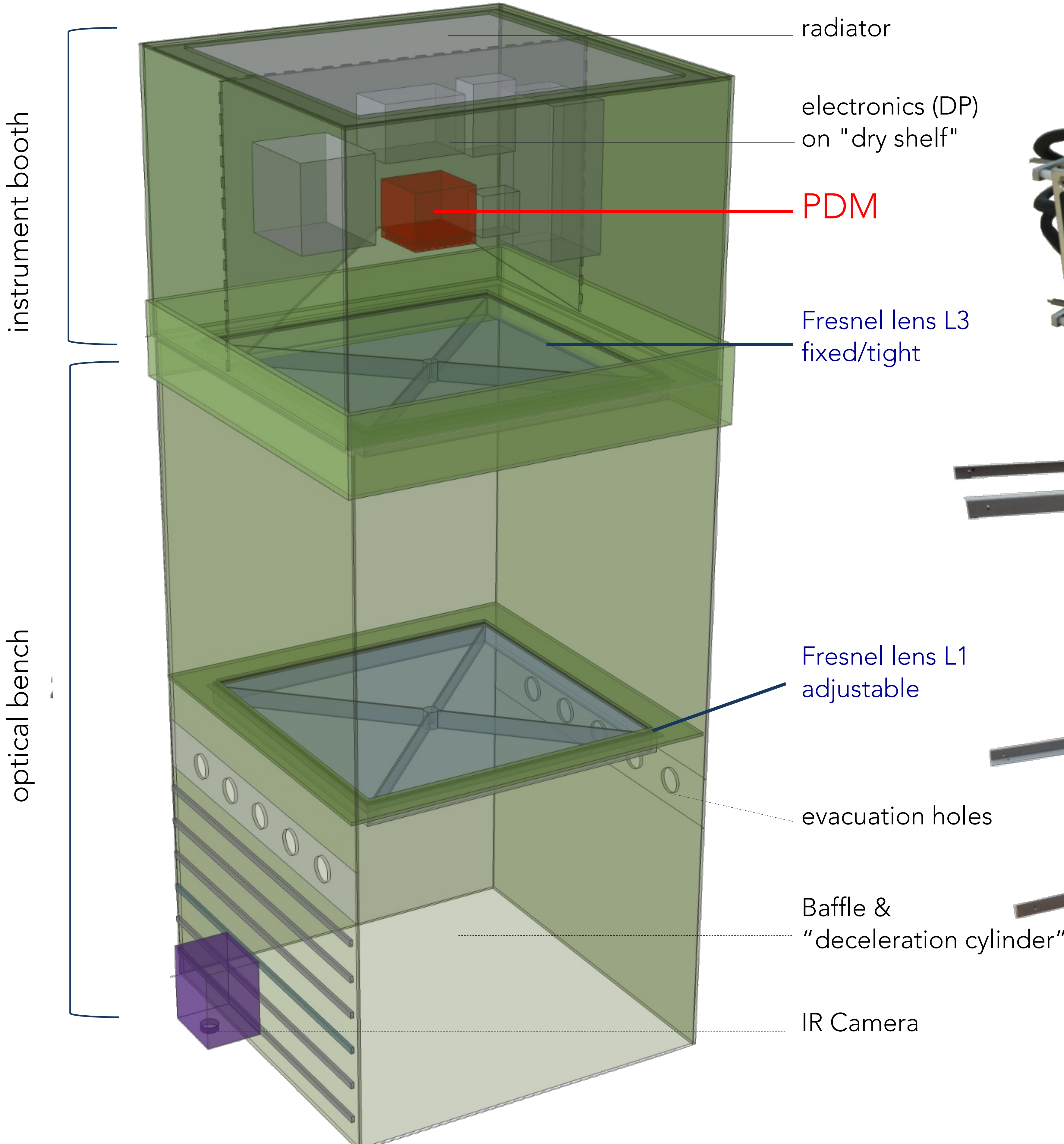
Mini-EUSO (2019)

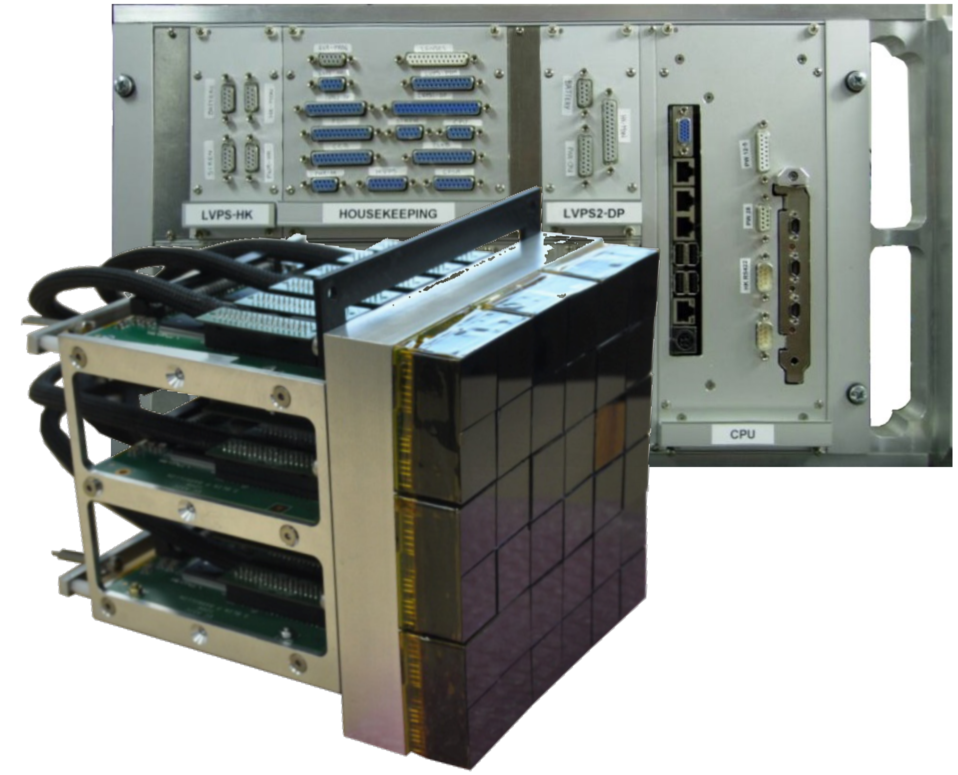
EUSO-SPB2 (2023)

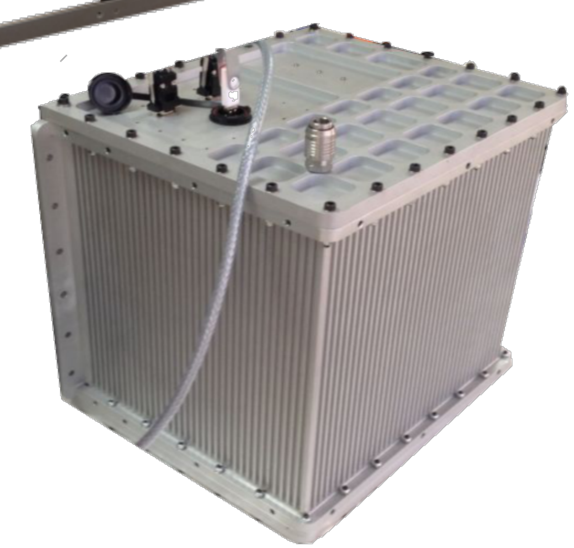
K-EUSO (2024+)

POEMMA (2028+)




instrument booth
optical bench
radiator
electronics (DP)
on "dry shelf"
PDM
Fresnel lens L3
fixed/tight
Fresnel lens L1
adjustable
evacuation holes
Baffle &
“deceleration cylinder”
IR Camera


LVPS-HK
HOUSEKEEPING
LVPS2-DP
CPU

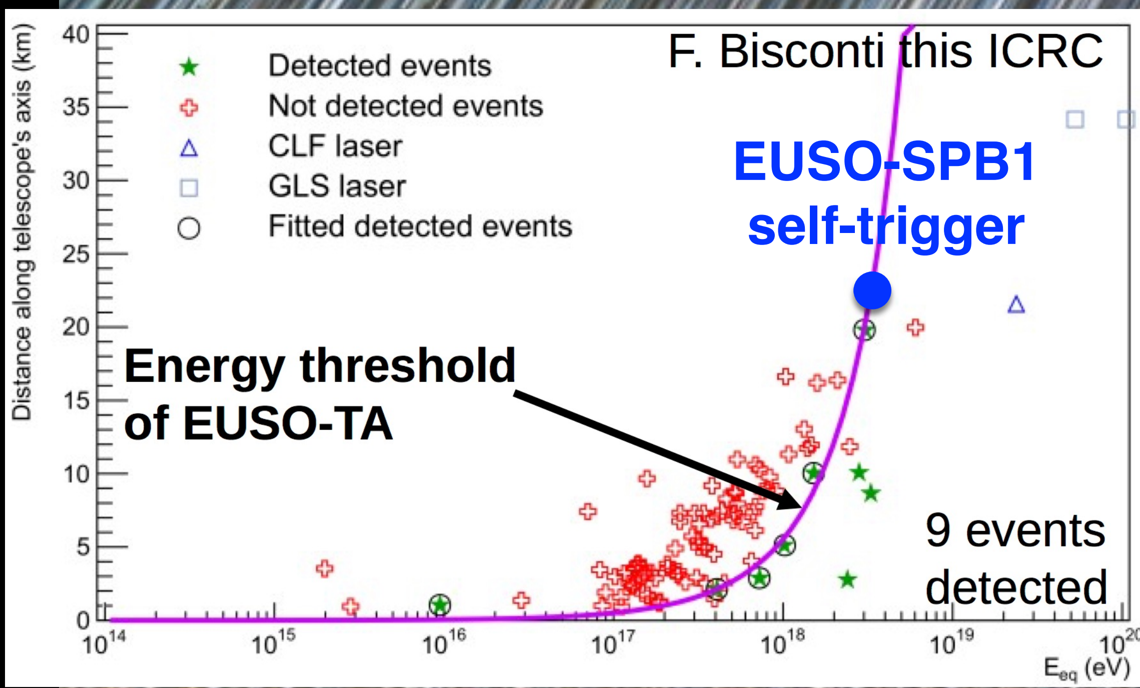


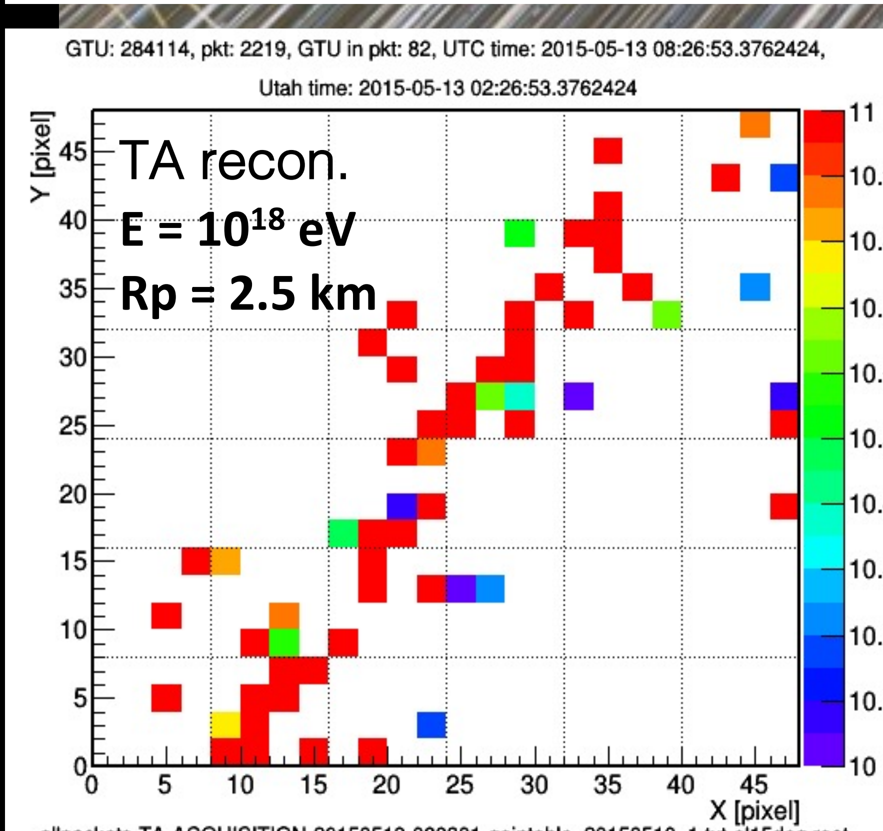
EUSO-TA

Instrument on its own
+ test platform for other pathfinders
Currently under upgrade with
Zynq board and self trigger

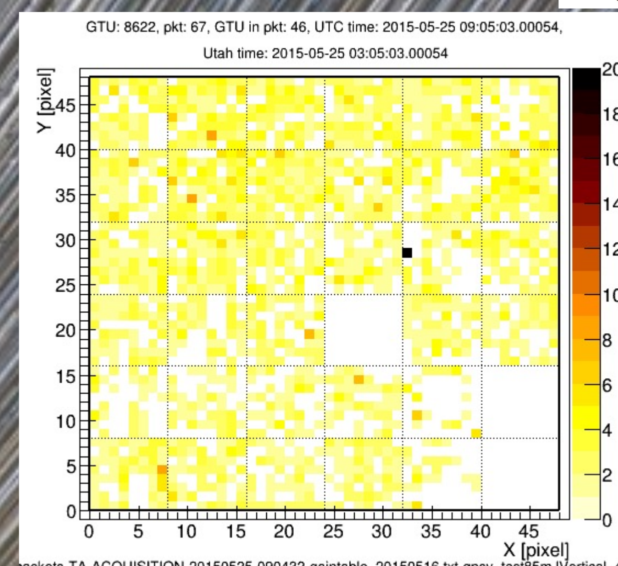
UHECRs

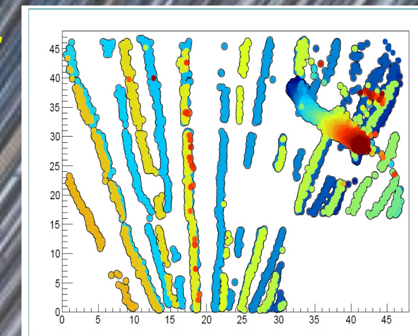
GLS laser campaigns



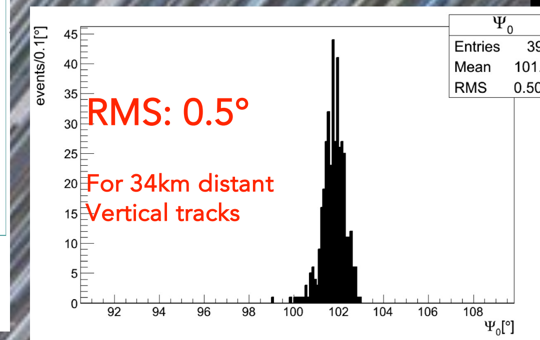


d= 100 km
E = 85 mJ





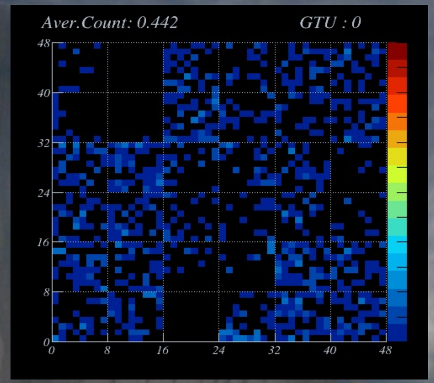
- 34km away from the detector
- Energy: 23mJ
- Sweep in azimuth with 2 different zenith angle (130°/140°)

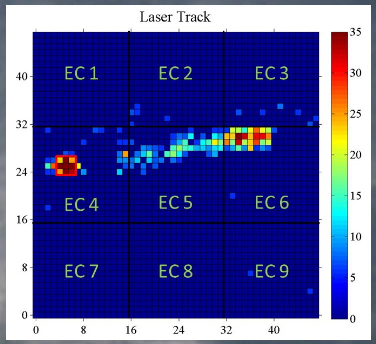


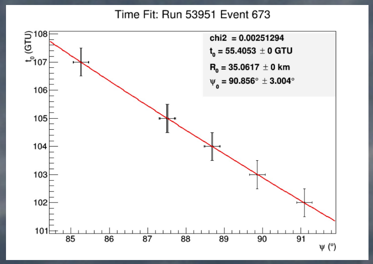
EUSO Balloon

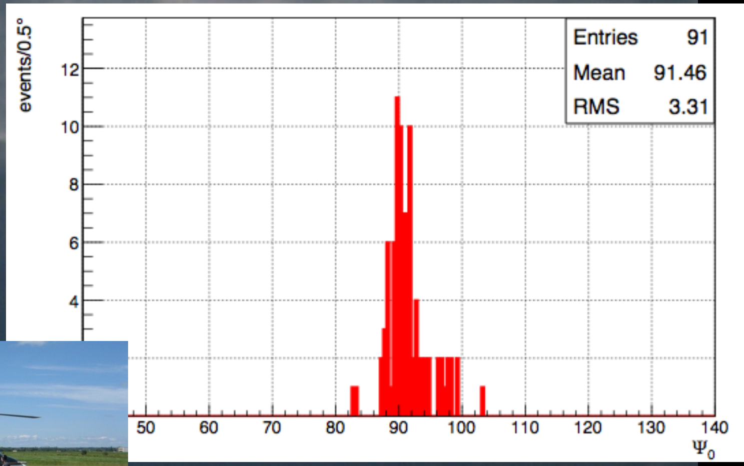
August 2014 Timmins, Canada

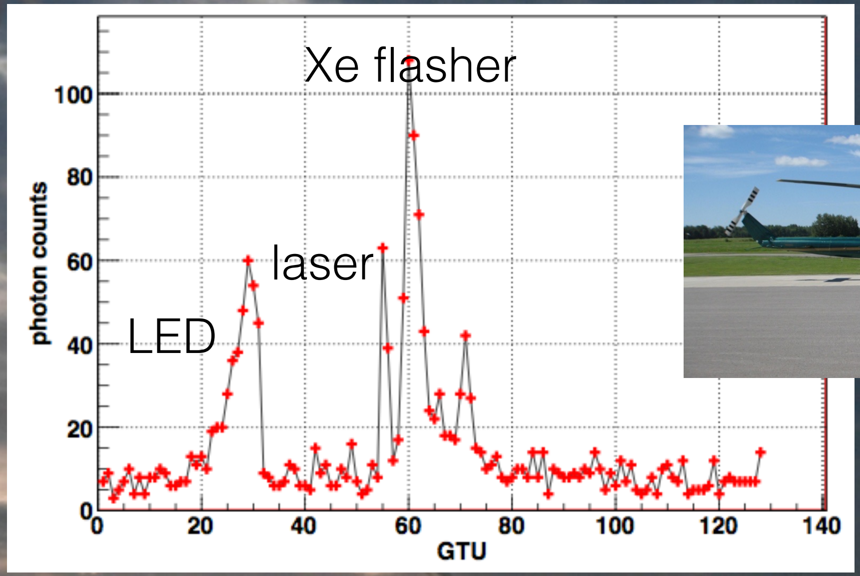
1 night flight @ 38 km a.s.l.
data: 256,000 events

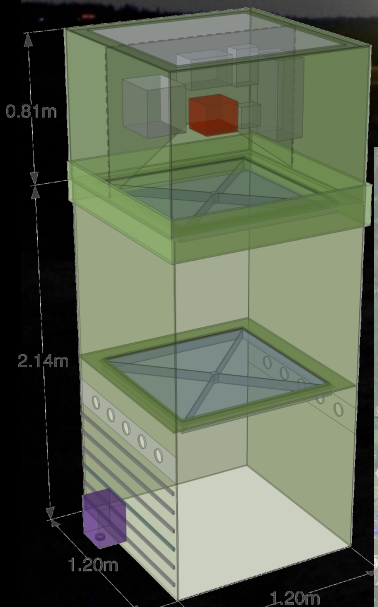


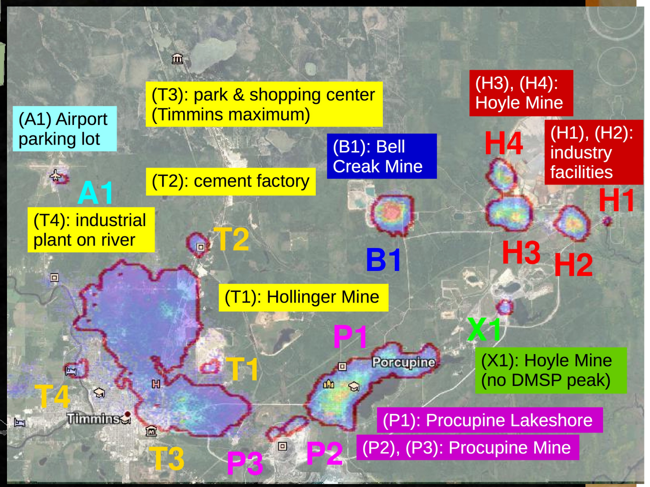


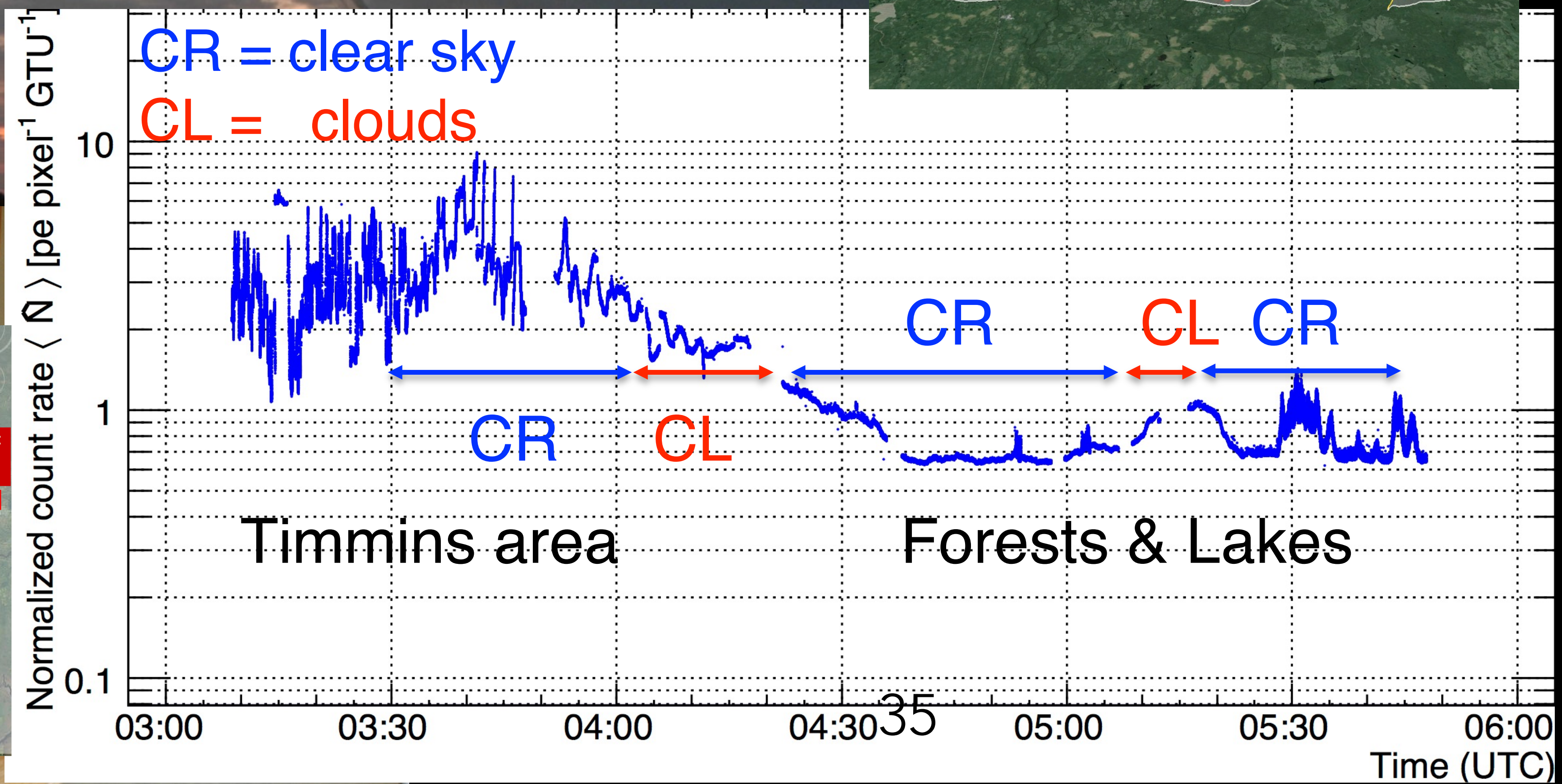








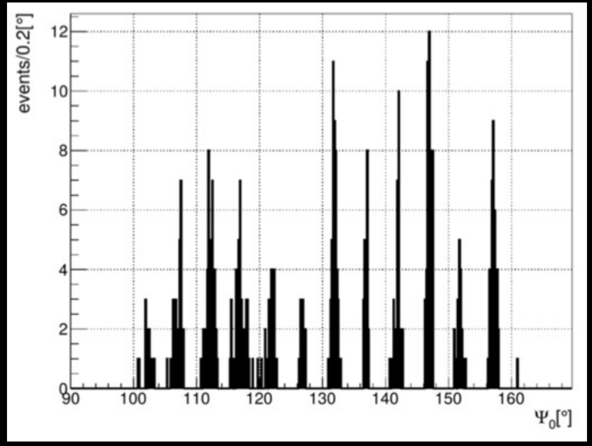




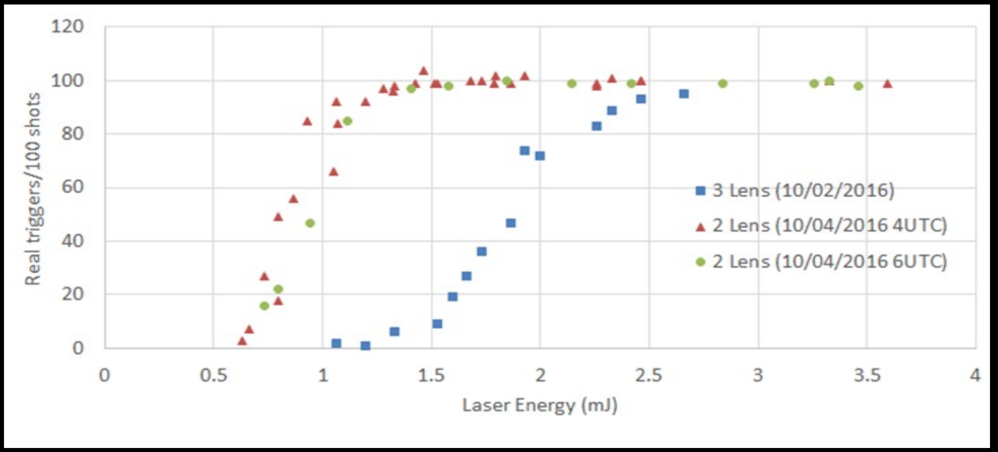
EUSO-SPB1

(2017)

Angular resolution
better than 1°



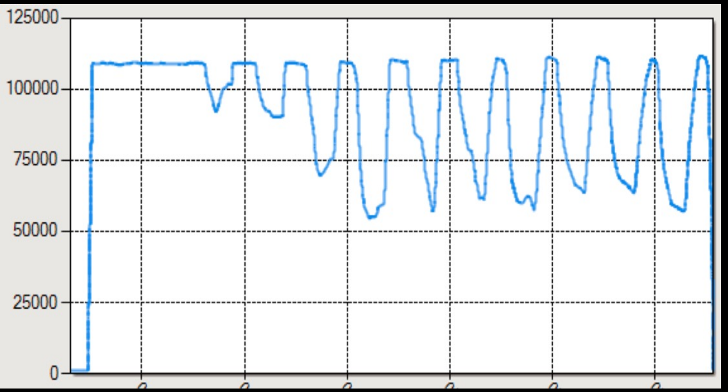
Energy-equivalent
threshold measurement



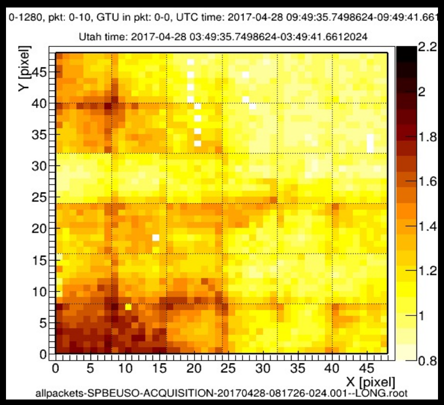
Would-be showers
E_{th} ~ 2 Eev => ~1–2 showers expected per month

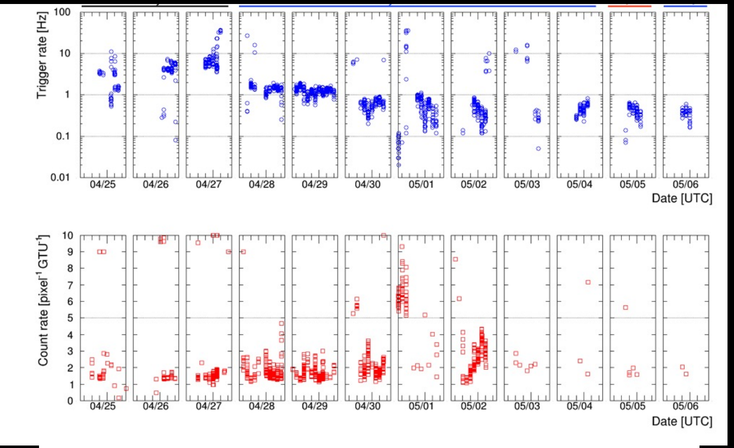
Nominally working
instrument

(unfortunately…
leaking balloon!)

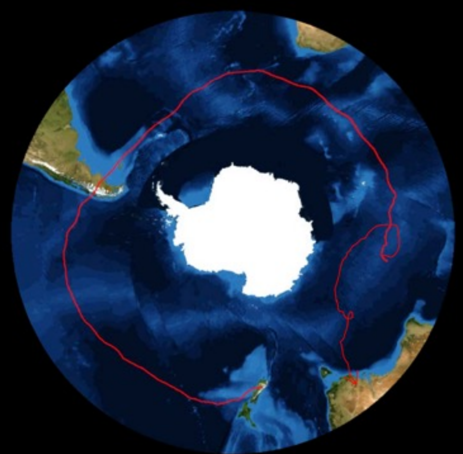


Main improvements:
- Upgraded electronics: SPACIROC 3
- Complete autonomous scheme with trigger
- Solar panels for long duration flight
- Optics performance + stability





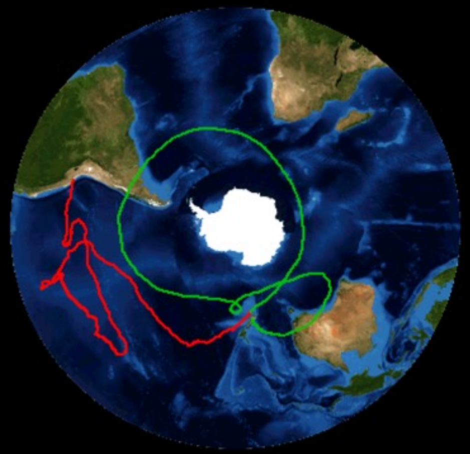
2015: 32 d 5 h



NASA Engineering Flight

6.3±0.9

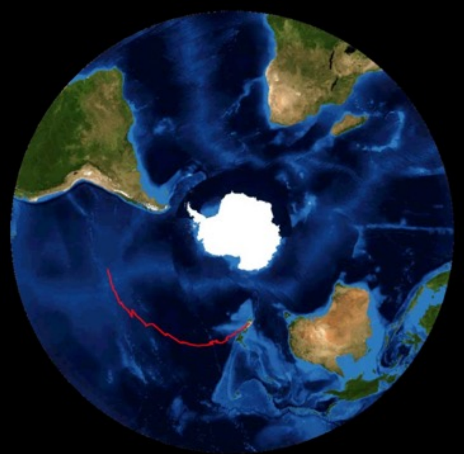
2016: 46 d 20 h



COSI

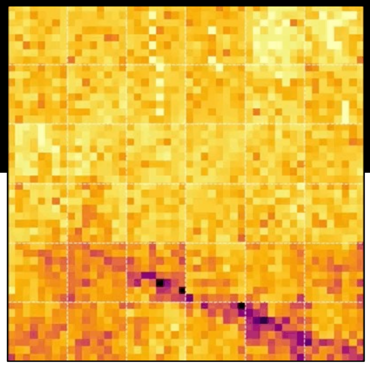
10.6±2.3

2017: 12 d 4 h

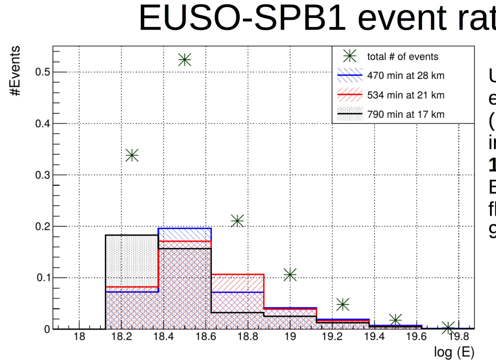


EUSO

~1



EUSO-SPB1 event rate



Upper limit on event rate (no cloud cover included): **1.26 ± 0.44** Events during the flight, assuming 9ECs

EUSO-SPB2 (2023)

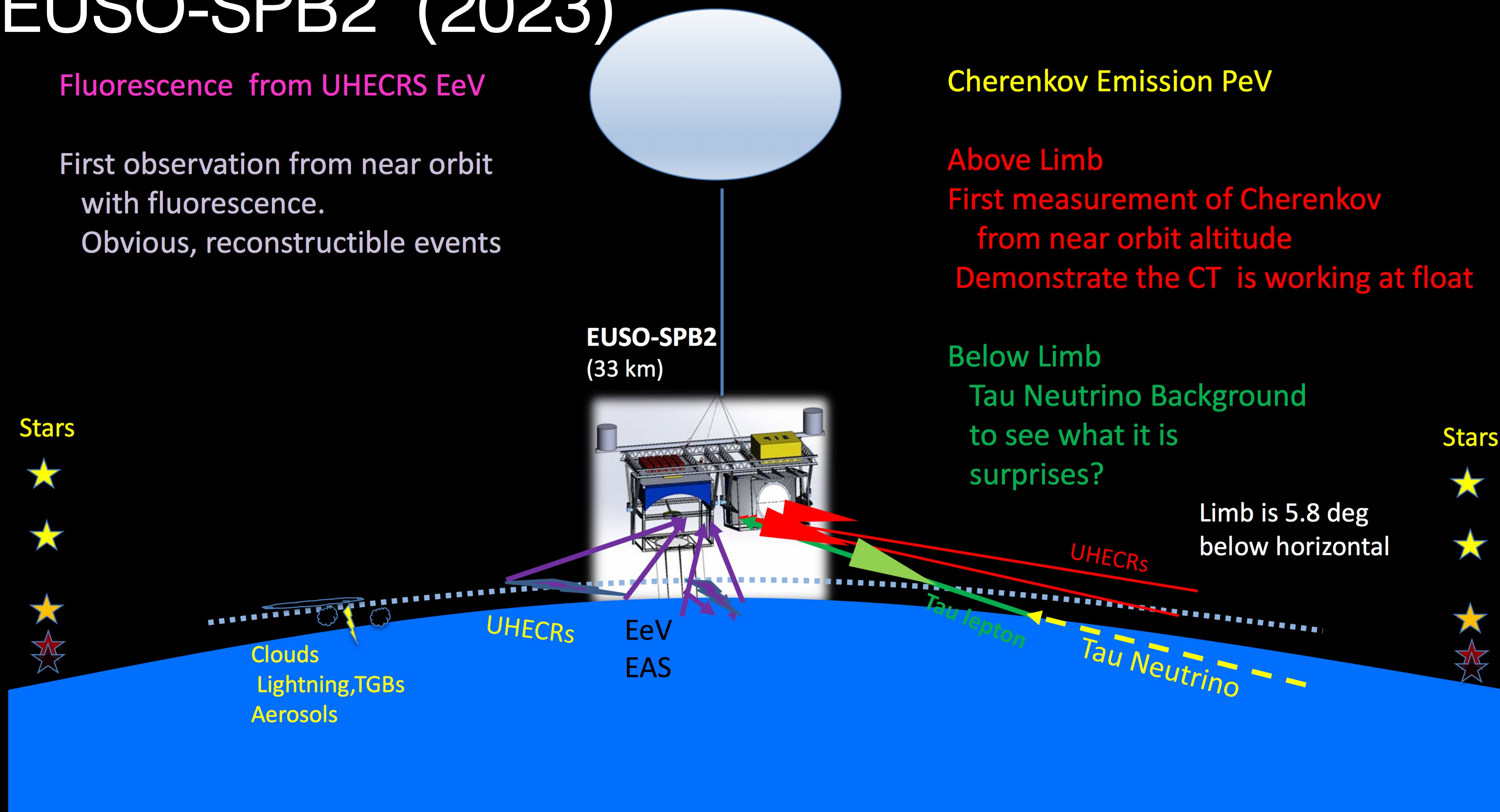
Fluorescence from UHECRS EeV

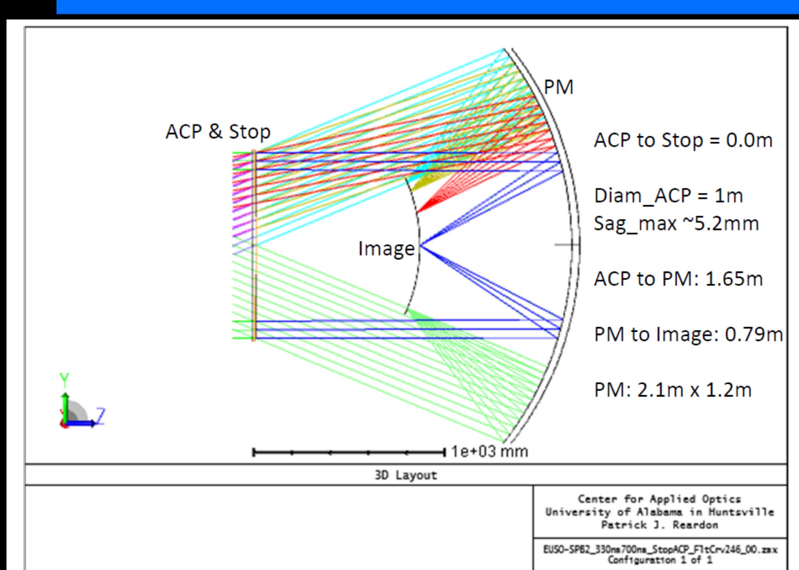
First observation from near orbit
with fluorescence.
Obvious, reconstructible events

Cherenkov Emission PeV

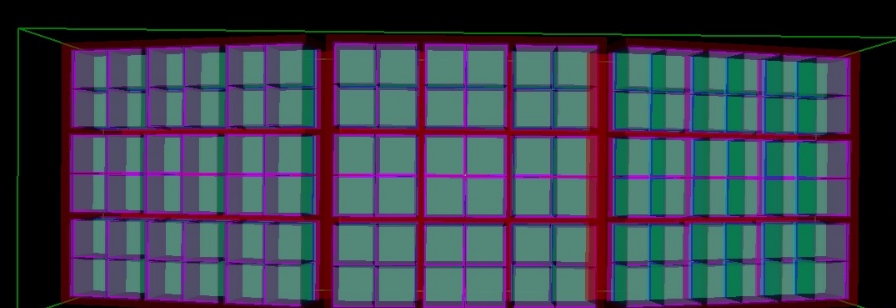
Above Limb
First measurement of Cherenkov
from near orbit altitude
Demonstrate the CT is working at float

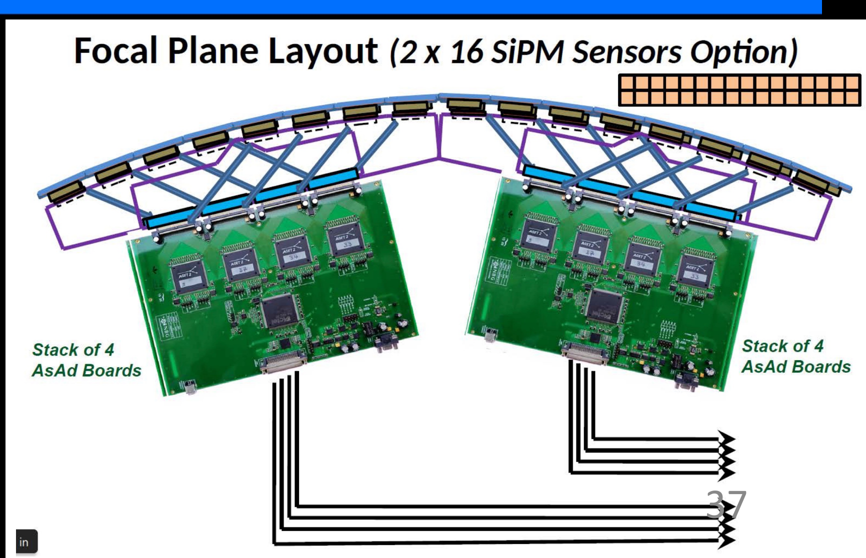
Below Limb
Tau Neutrino Background
to see what it is
surprises?



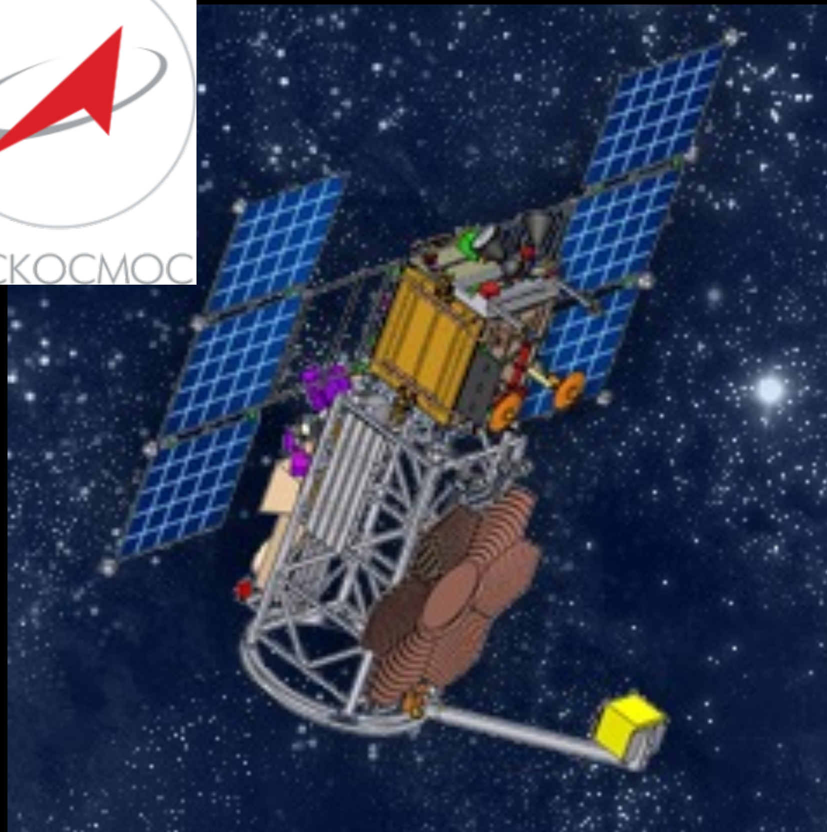


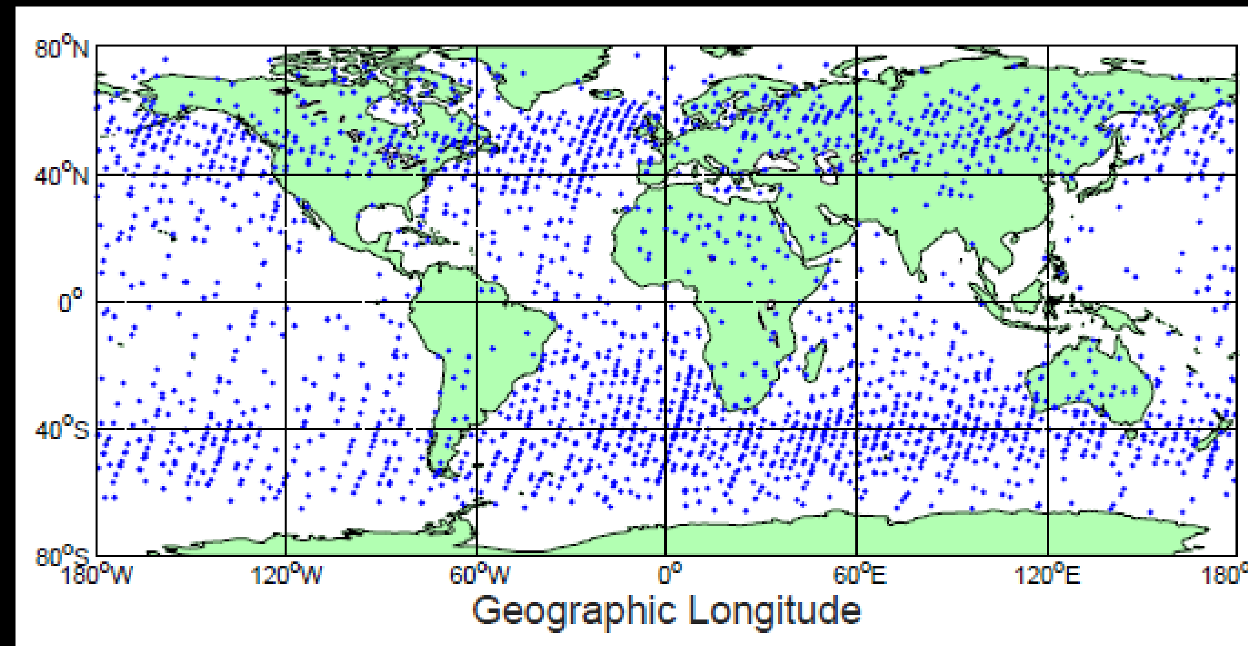
Fluorescence FS

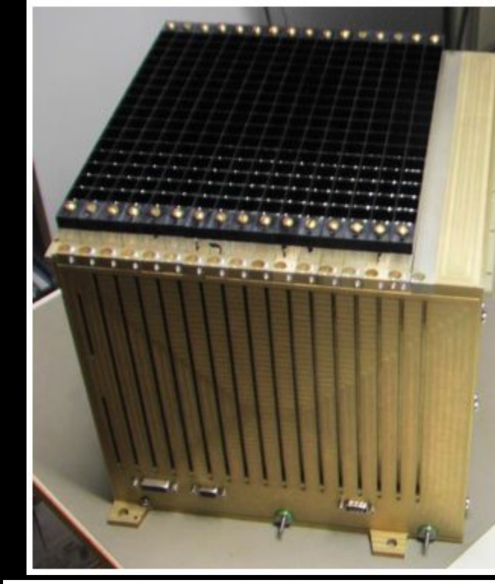


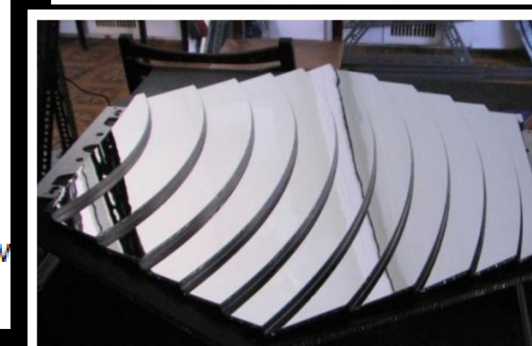


TUS (2016-2017)
Tracking Ultraviolet Setup

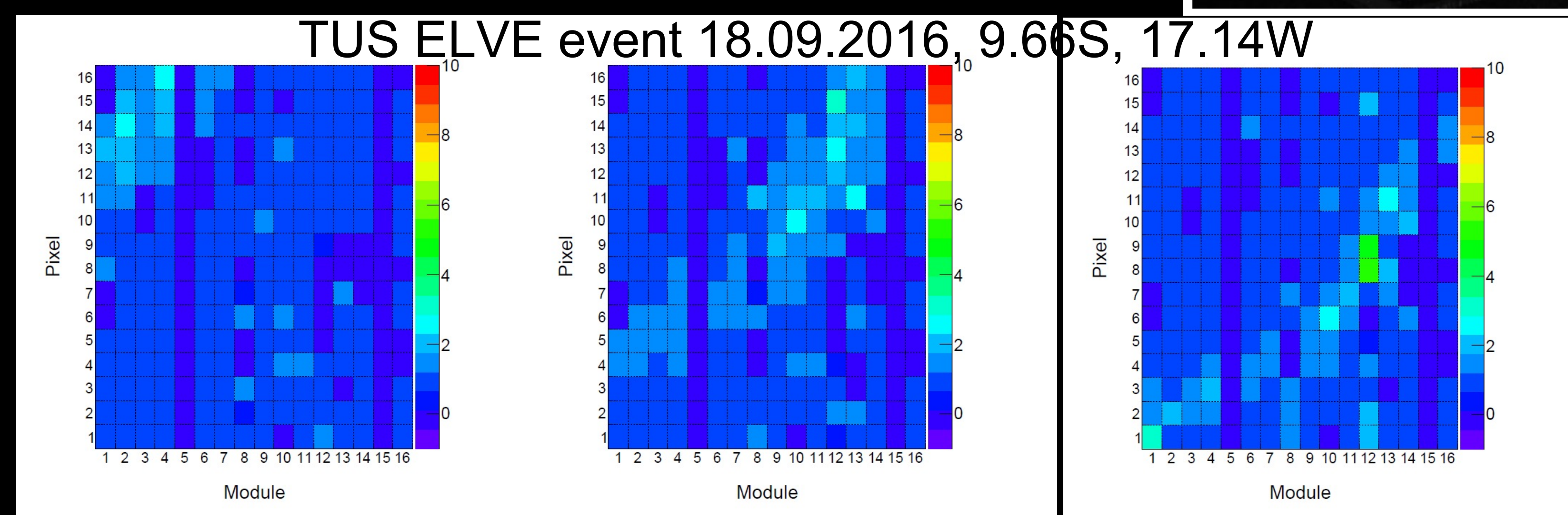


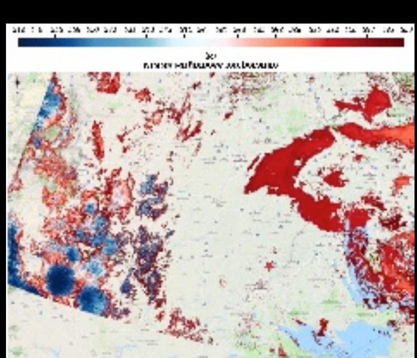


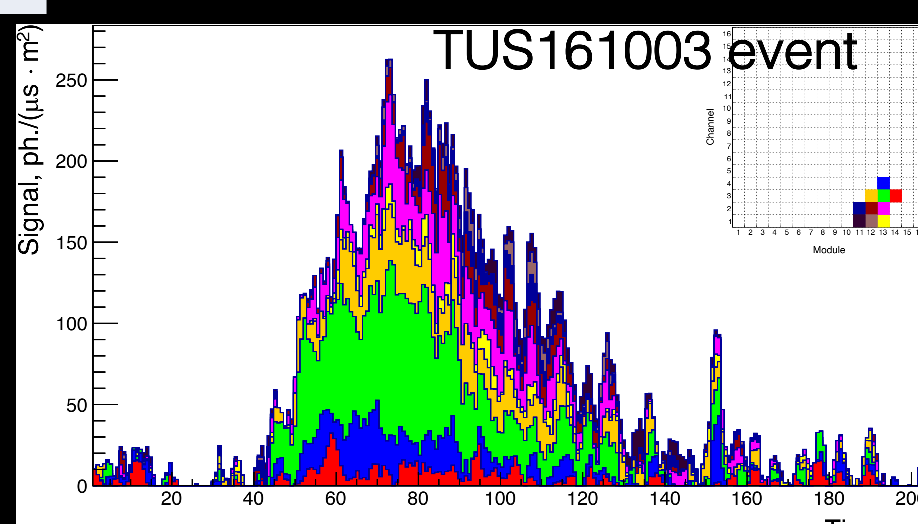


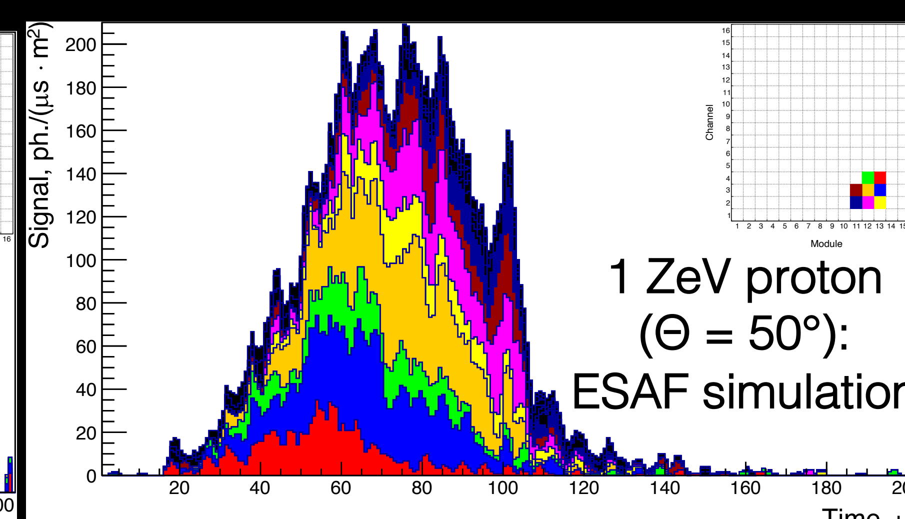


Mass	60 kg
Power	65 W
FOV	±4,5 degree
Channels	16 modules of 16 PMTs
Pixel size	10 mrad (5×5 km)
Mirror area	~2 m^2
Duty cycle	30%



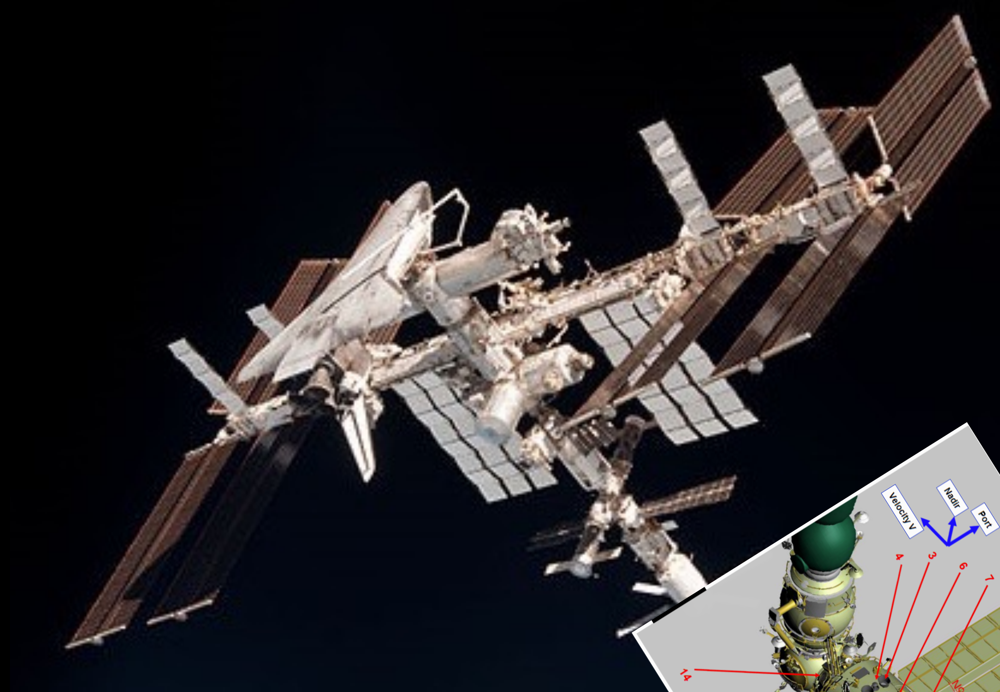


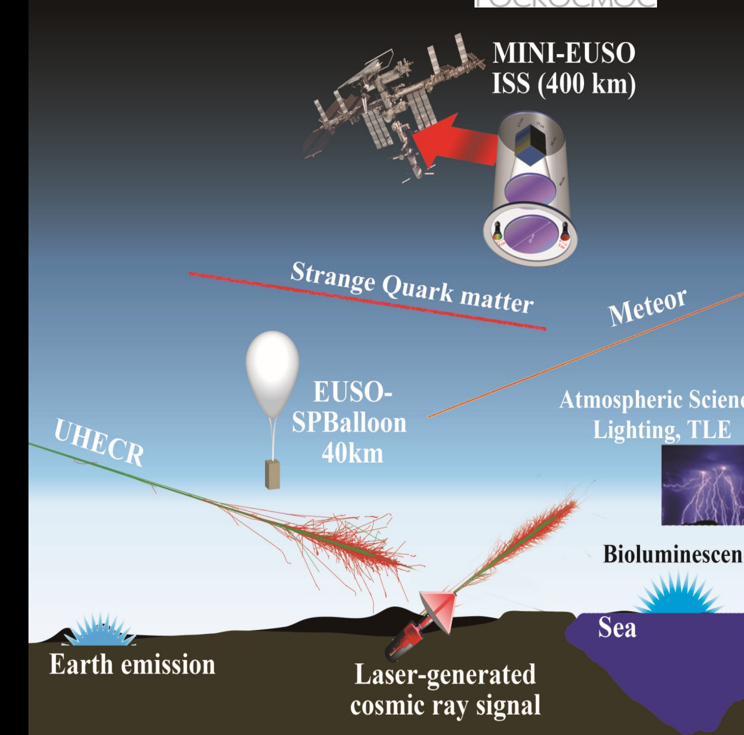




Mini-EUSO/UV-ATMOSPHERE

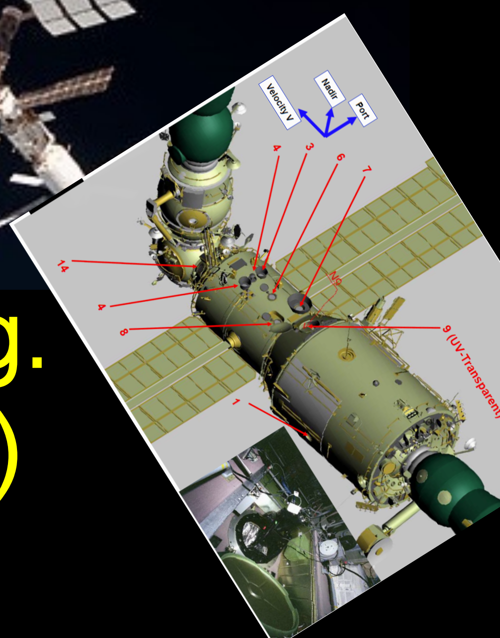
(scheduled to fly to ISS on August 22nd 2019)

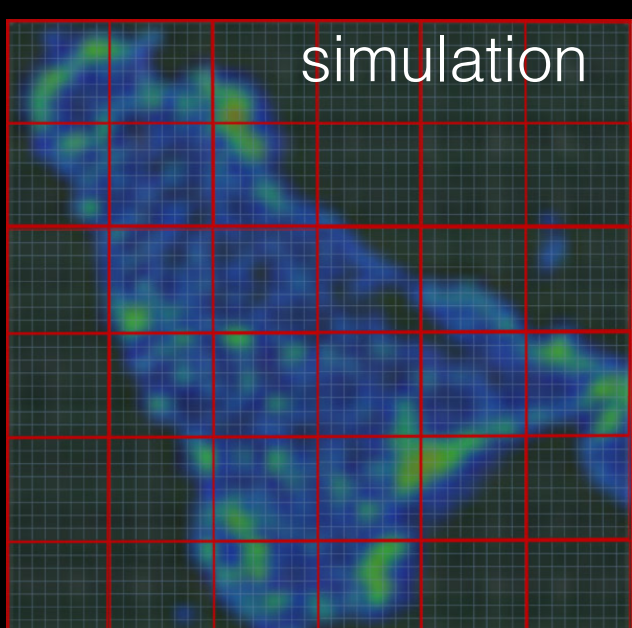


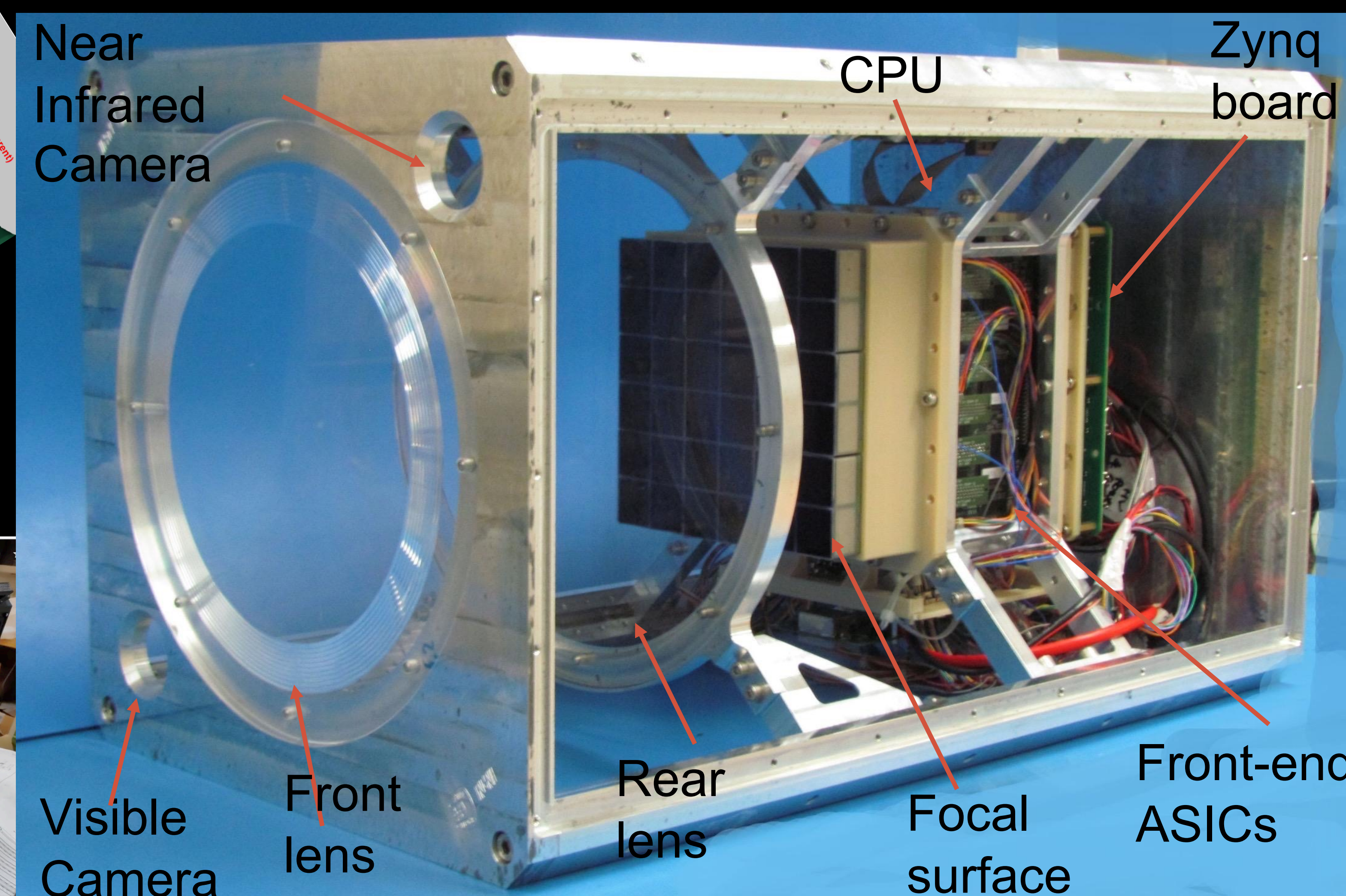


DATA with self trigger:
D1 : 2.5 μs res. (128 L1GTUs)
D2: 320 μs res. (128 L2GTUs)
D3: 40.96 ms res. (full movie)

FoV: ± 22 deg.
(9 times TUS)





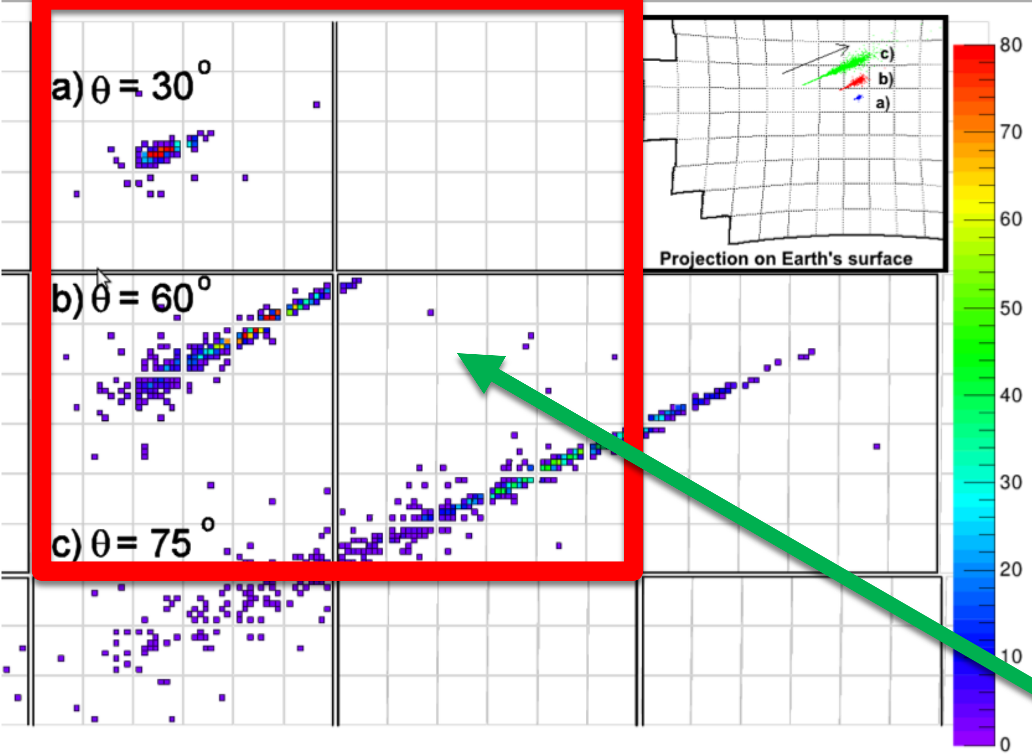


TUS & Mini-EUSO: complementarity to be exploited in view of K-EUSO & POEMMA

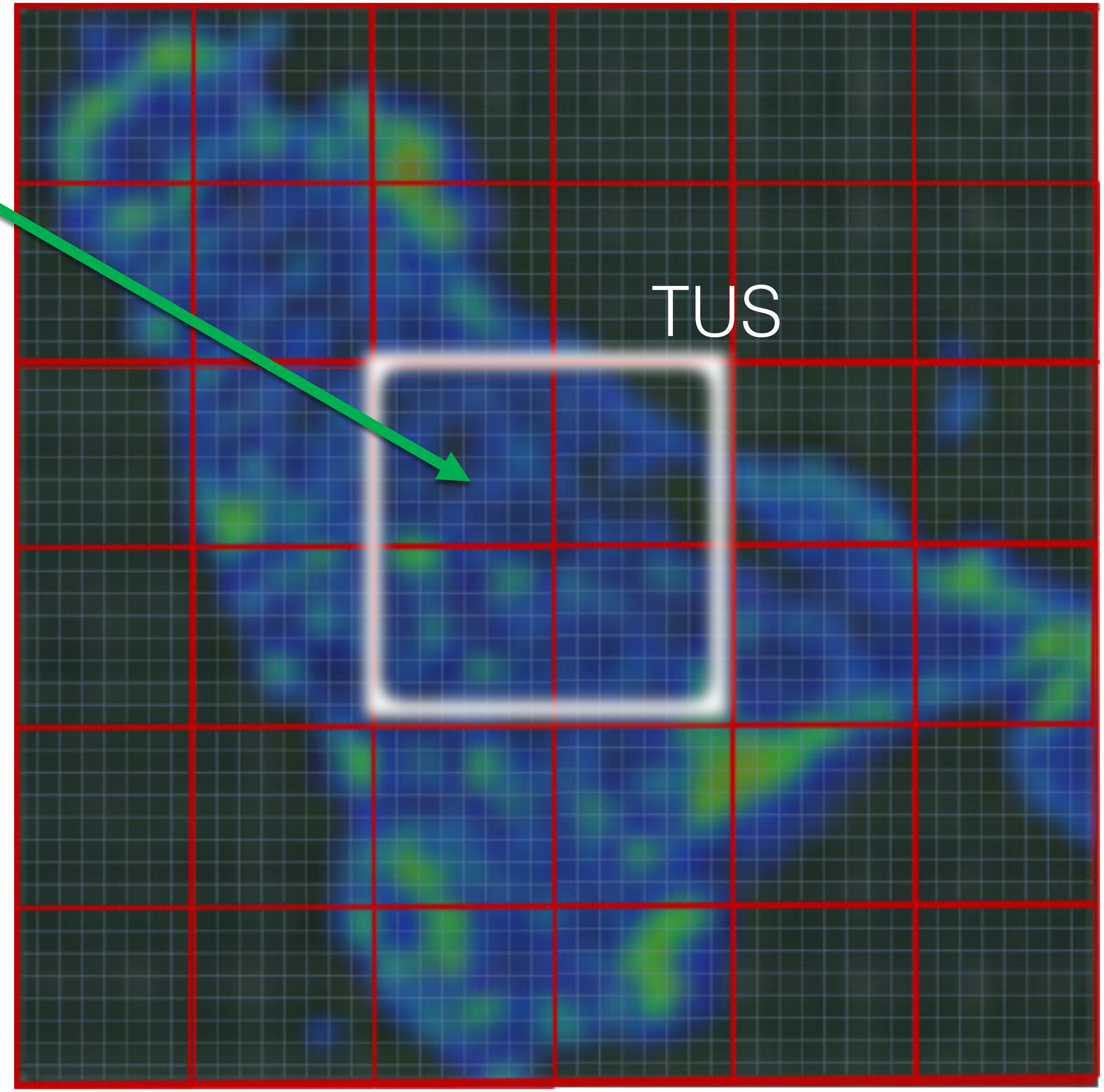
	TUS	Mini-EUSO	JEM-EUSO
Optics	Mirror	Lenses	Lenses
Optical aperture	2 m^2	0.05 m^2	4 m^2
FS	256 PMTs	2304 pixels	>3x10^5 pixels
Acquisition	Charge integration	Photon Counting	Photon Counting
Sampling rate	μs, 100μs OR ms scale	μs, 100μs AND ms scale	μs, 100μs AND ms scale
D.C.	30%	2%	13%
FoV	6400 m^2	82000 km^2	160000 km^2
deadtime	53 – 60 s every trigger	No dead time between triggers (up to 4 per 5s)	No dead time between triggers

Quite different optical systems, acquisition modes, TUS is ~10x more sensitive but similar exposure

FoV



Mini-EUSO



JEM-EUSO

Mini-EUSO & TUS	JEM-EUSO
~1 pixel	~ 1 MAPMT
~1 PMT	~ 1 PDM

Comparison @ order of magnitude level

Diffuse lights give similar signals in pixels for JEM-EUSO & Mini-EUSO

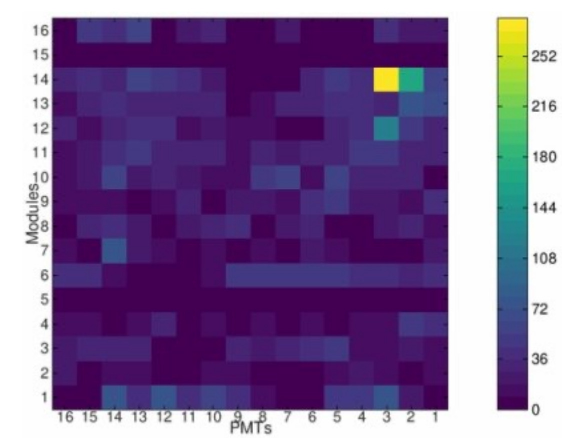
Triggers in EAS acquisition mode

B.A. Khrenov et al. JCAP. 09 (2017) 006; https://doi.org/10.1088/1475-7516/2017/09/006

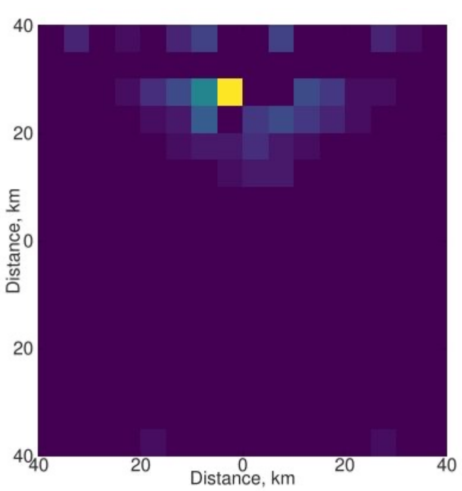
Detector operated between April 2016 and November 2017
80,000 events triggered

- noise-like waveforms including anthropogenic illumination over cities (~80%)
- slow flashes caused by distant lightning strikes
- instant track-like flashes
- events with complex dynamics (elves,...)
- Events with EAS characteristics (only a few)

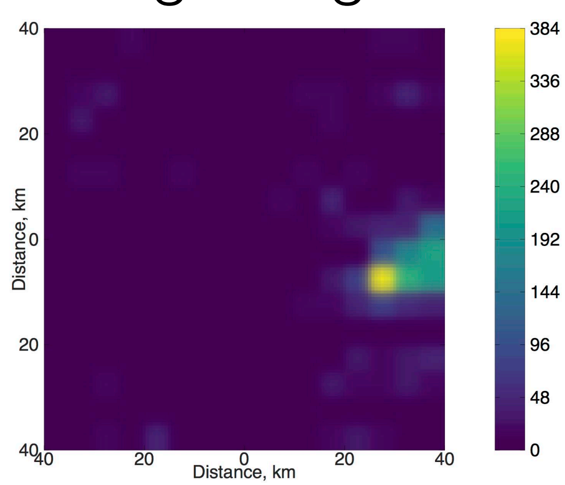
EAS-like



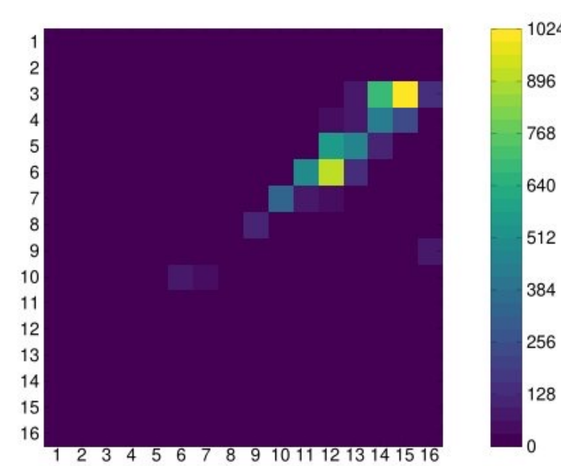
Las Vegas



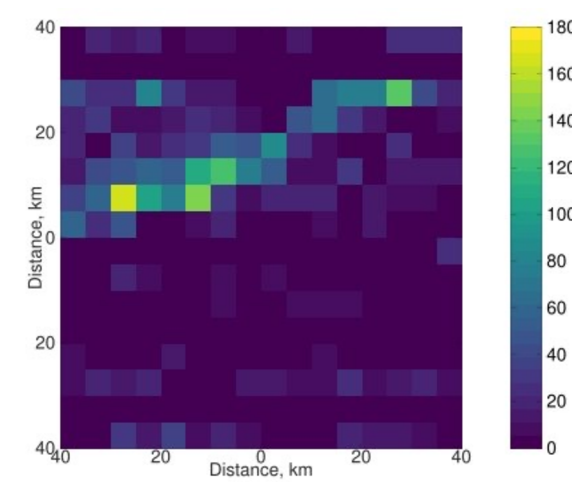
Lightning



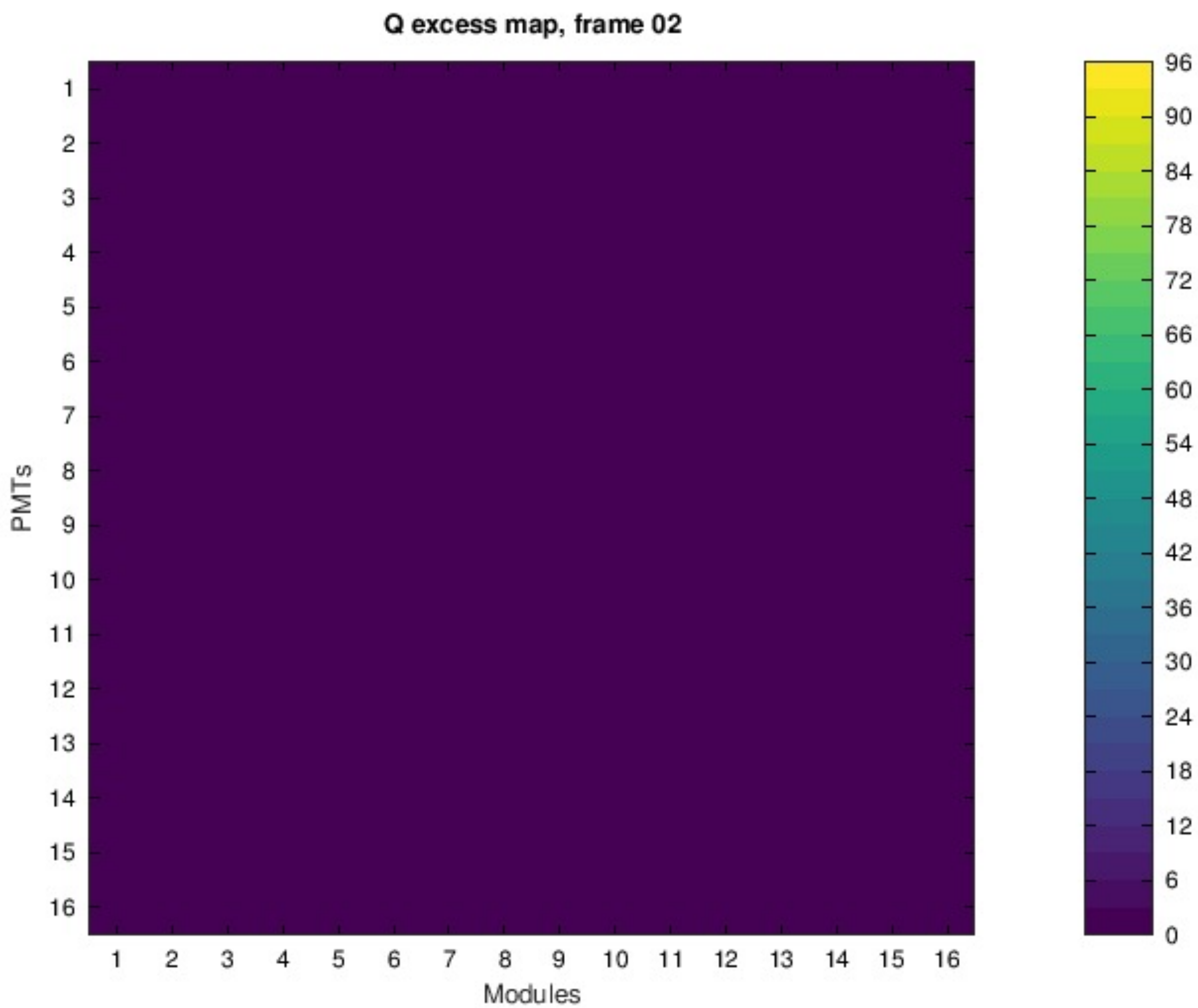
Instant tracks

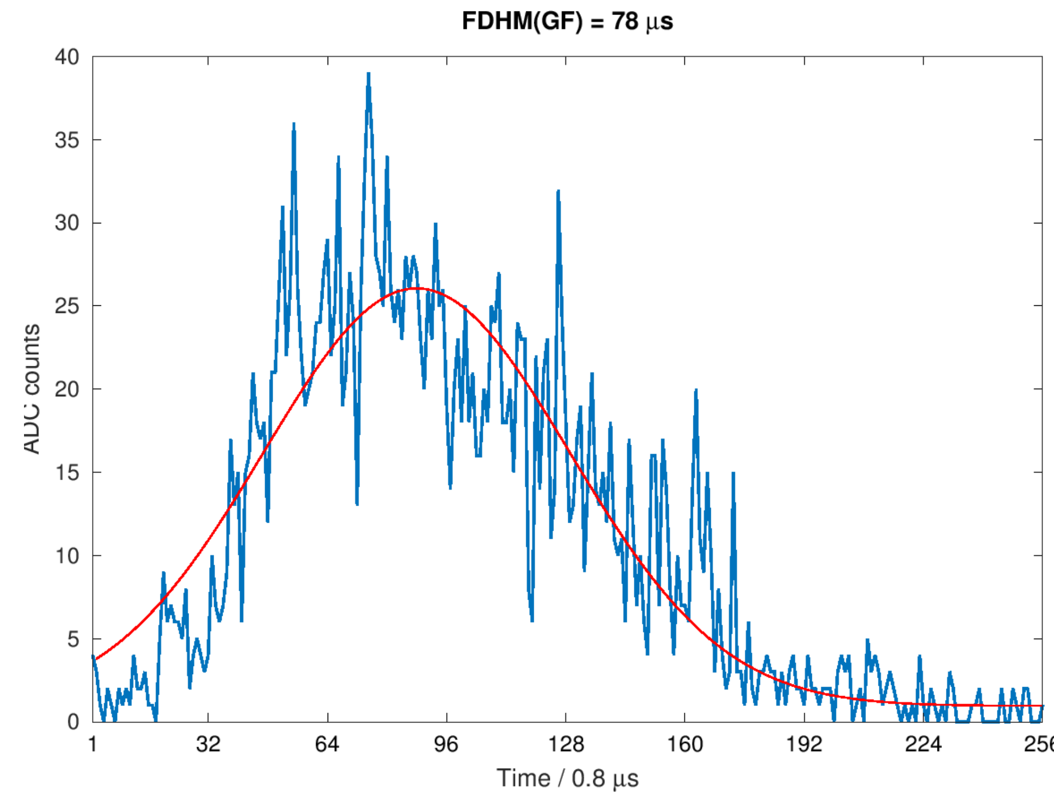


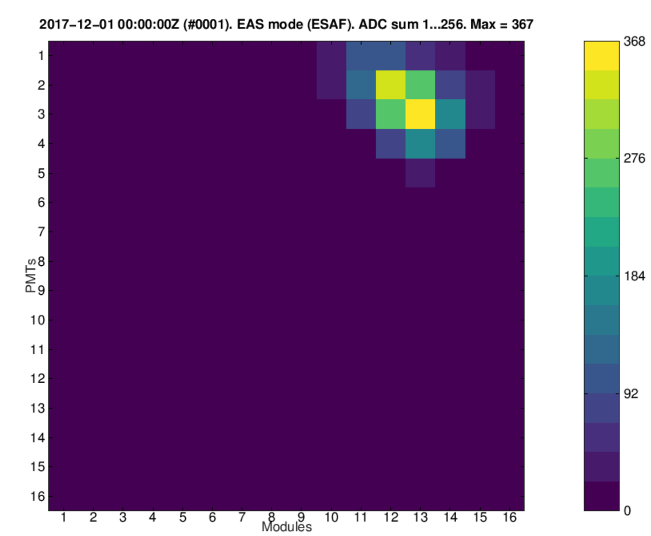
Elves



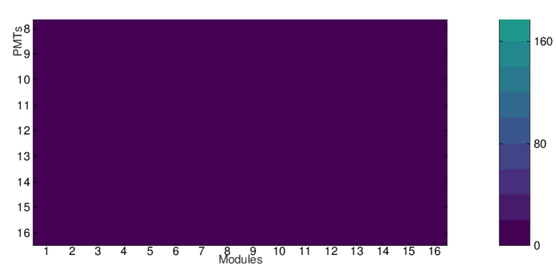
What we would expect in case of UHECRs…
EAS simulations for TUS







θ = 60°

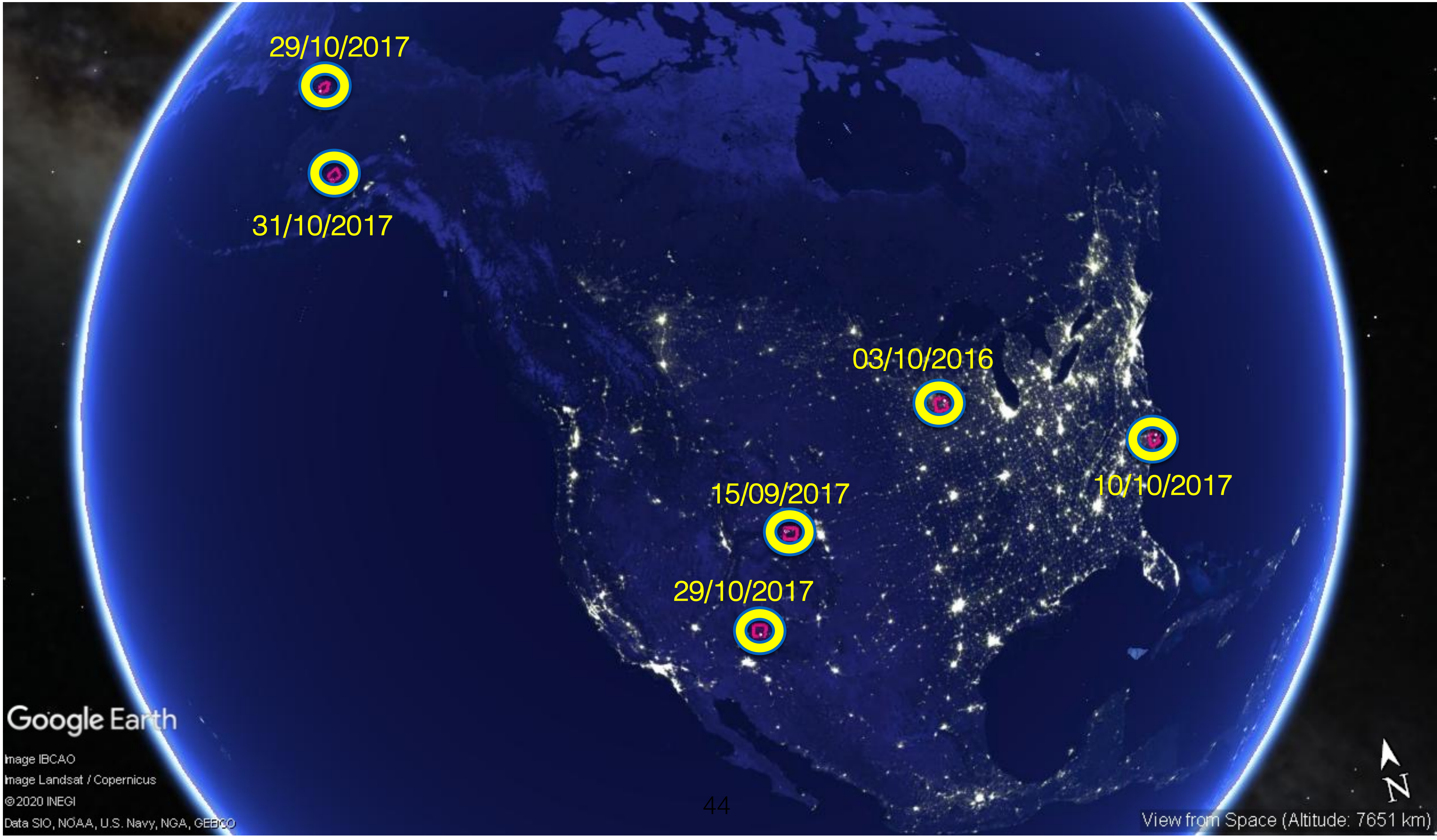


E=200 EeV

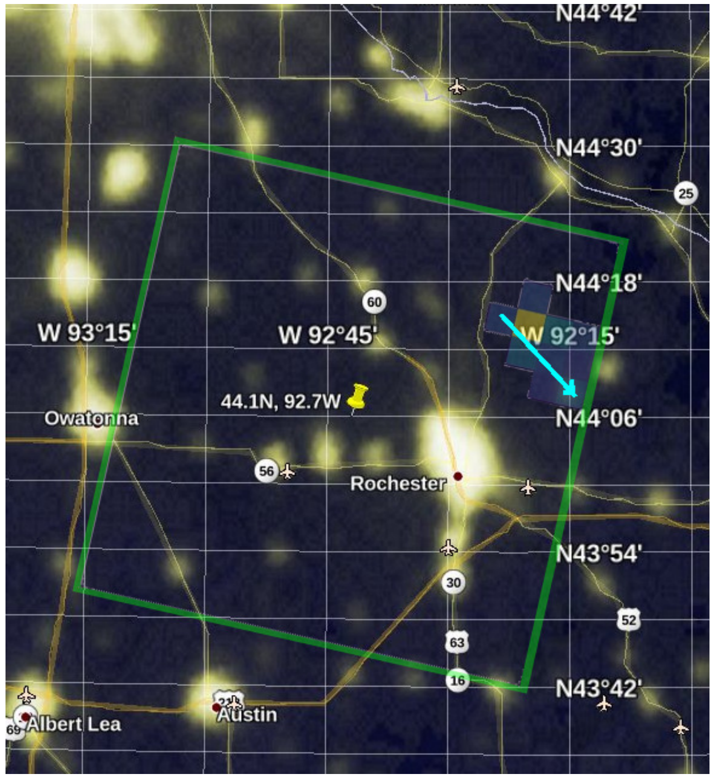
For the TUS detector simulation we use the JEM-EUSO - ESAF code with implemented TUS design.

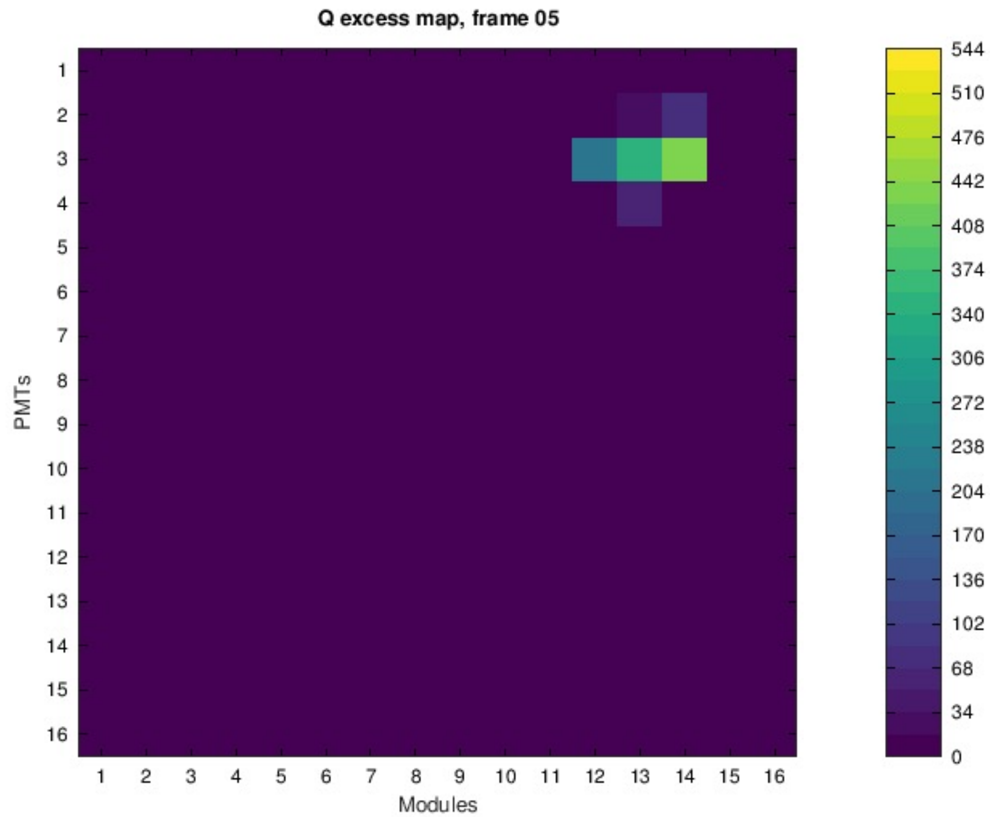
F. Fenu., *Simulations for the JEM-EUSO program with ESAF*, *PoS(ICRC2019) 252*

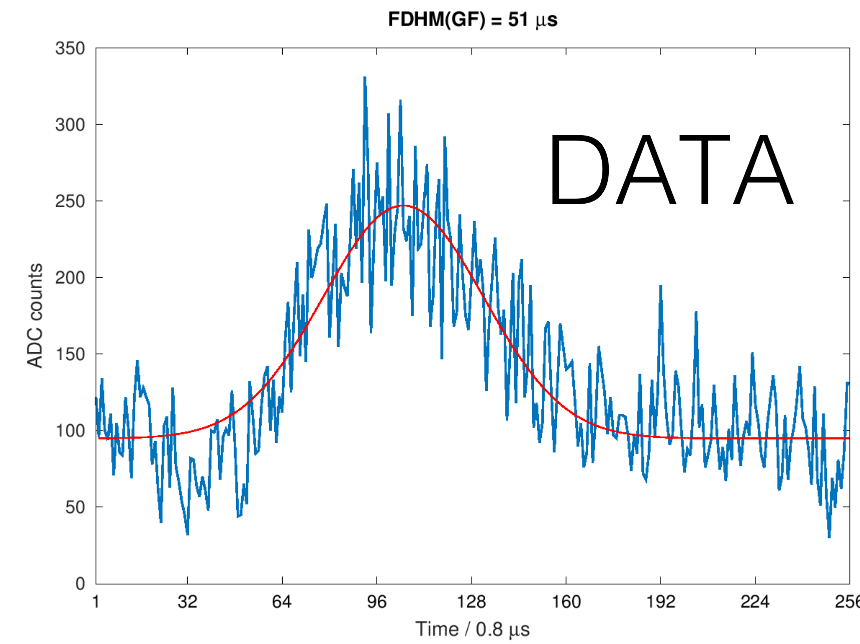
After a first screening of the triggered events, 6 of them show characteristics similar to those expected from EAS.
All of them have been recorded on North America!

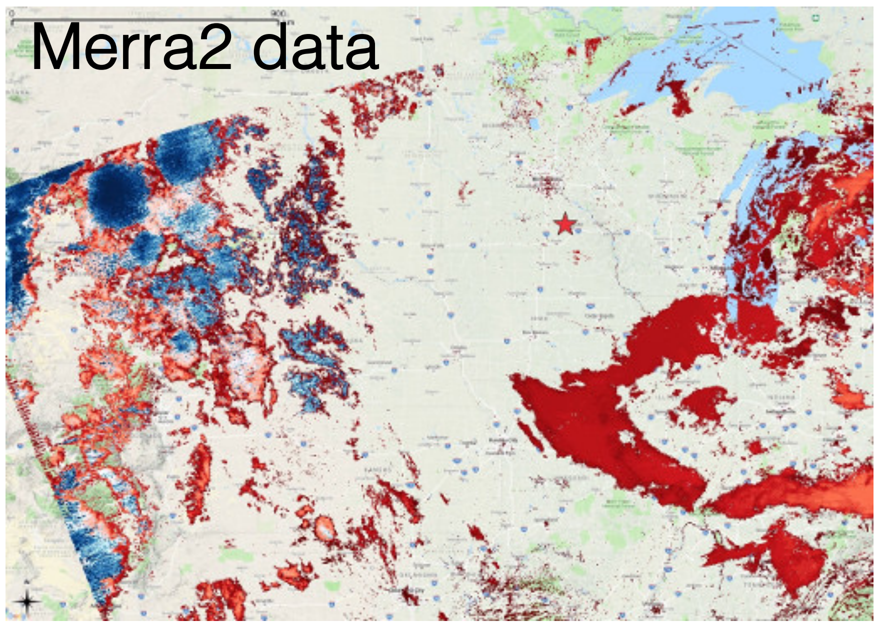


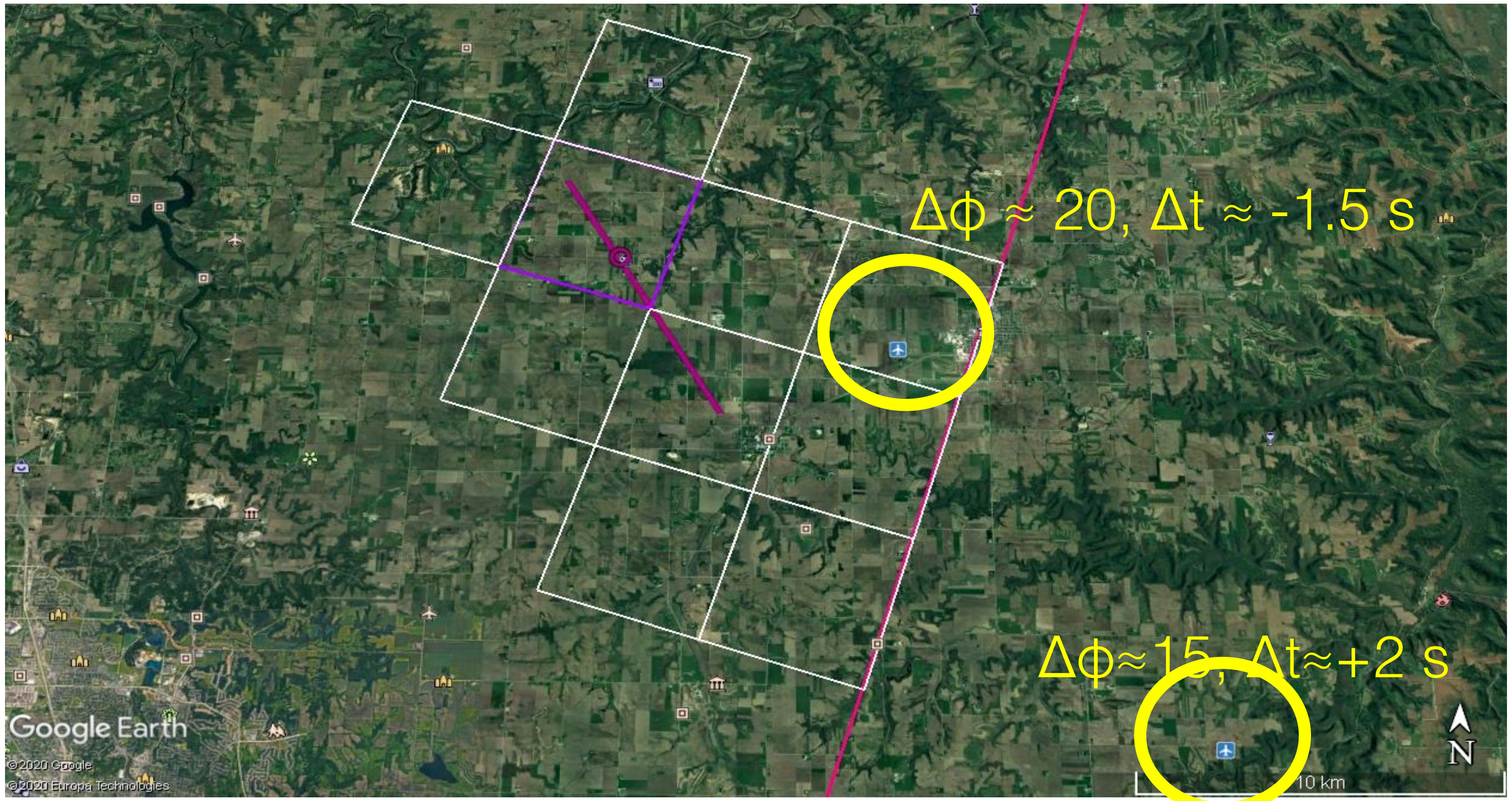
The ``Minnesota event”
Event 03.10.2016 05:48:59UTC





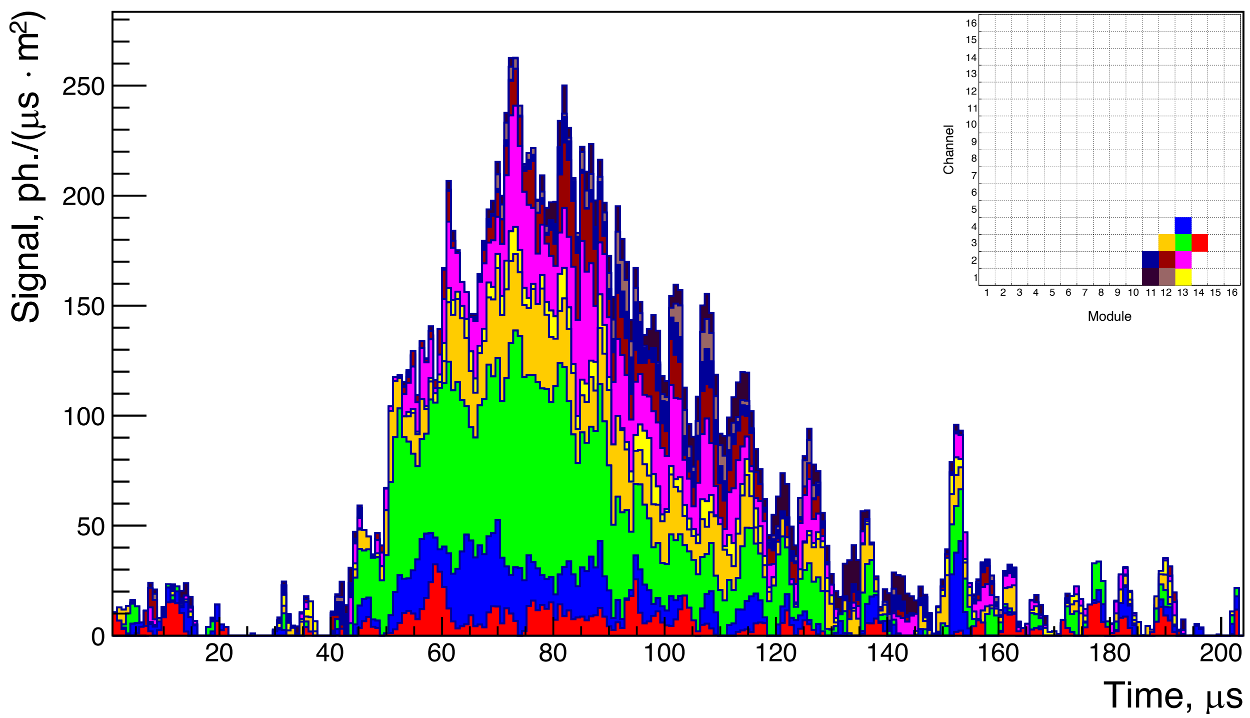




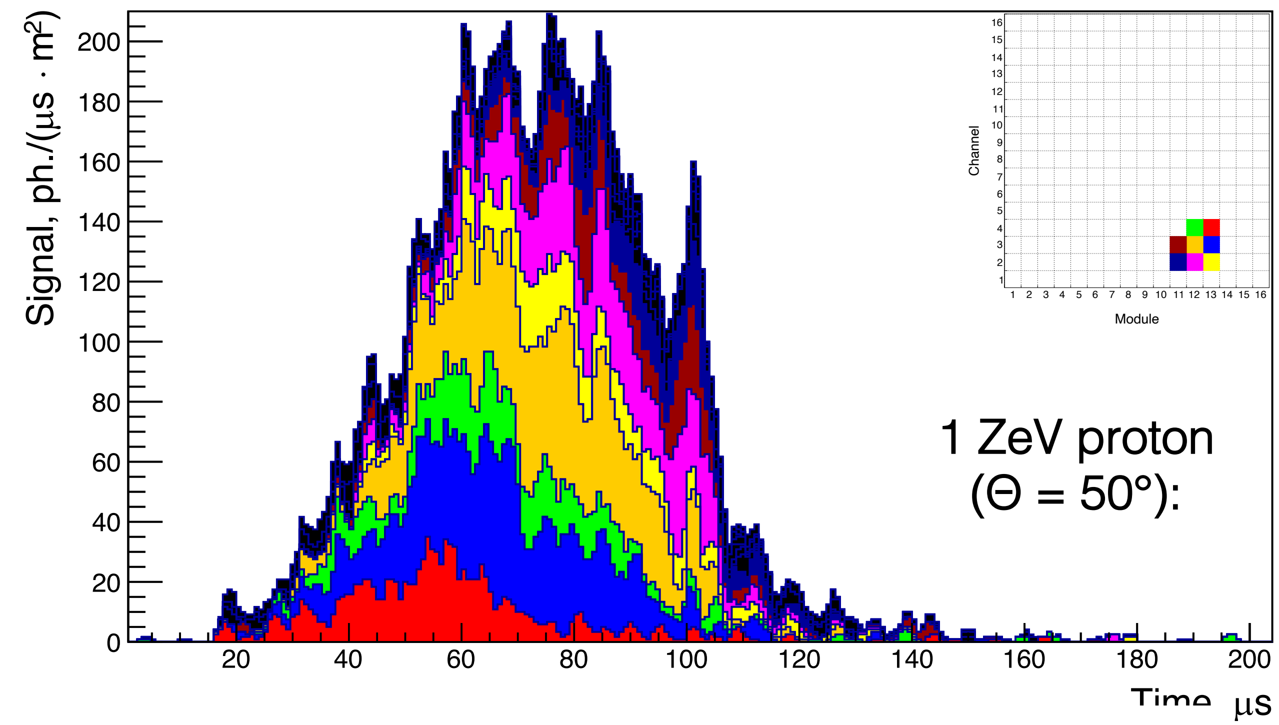


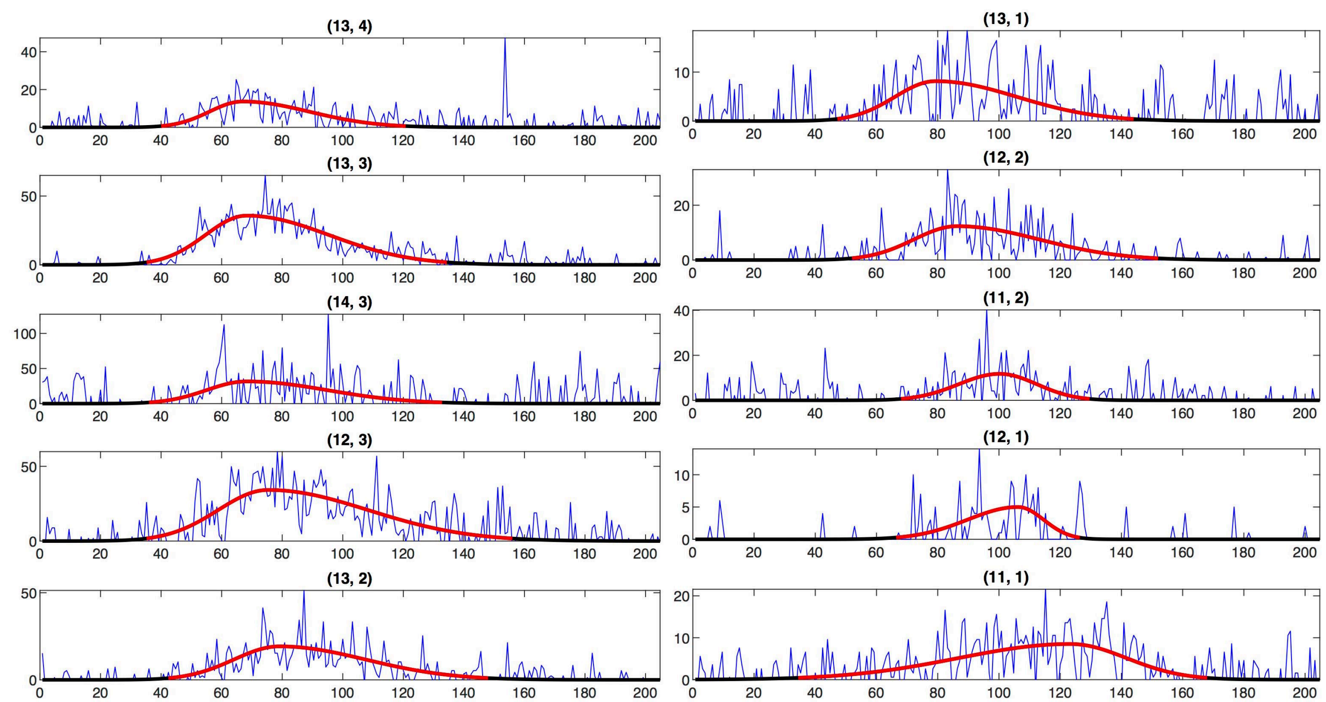
The Vaisala GLD360 ground based lightning location network did not register any lightning strikes in a region with radius of 930 km and during 10 s period around the time of the TUS event.

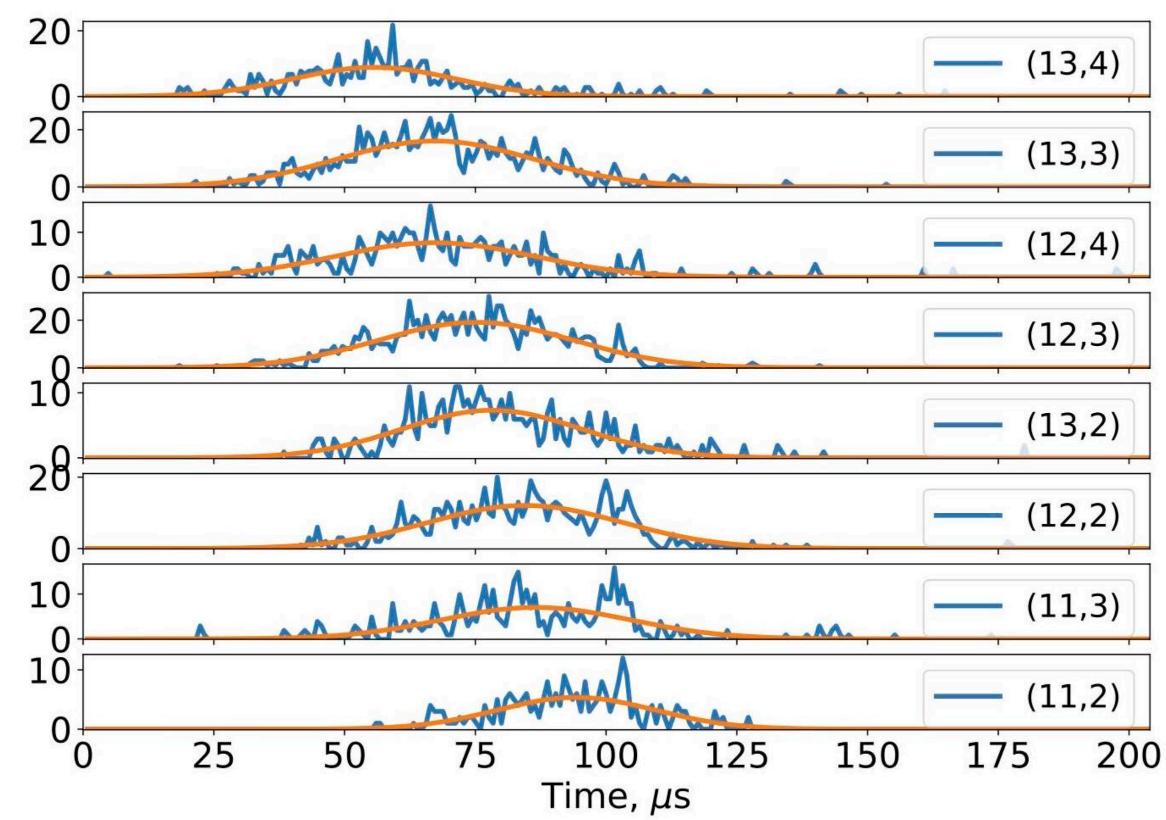
TUS161003 event (Θ = 44±4°):



ESAF simulation 1 ZeV proton (Θ = 50°):







Similarities exist but energy extremely high

B.A. Khrenov et al. JCAP. 03 (2020) 033; https://doi.org/10.1088/1475-7516/2020/03/033

Discussion & possible interpretations

B.A. Khrenov et al. JCAP. 03 (2020) 033; https://doi.org/10.1088/1475-7516/2020/03/033

UHECR interpretation:

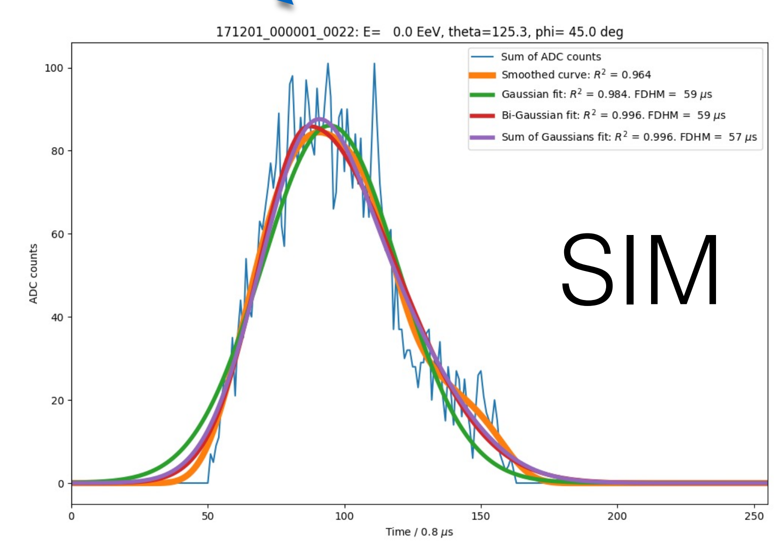
- E > 10^{21} eV makes the probability of an UHECR event extremely unlikely (10^{-3} – 10^{-5}) extrapolating UHECR spectrum
- The time difference ~60 μs between EAS maximum and end of the event implies h_{max} ~ 7.5 km --> slant depth ~550 gr/cm^2

Anthropogenic origin of the event:

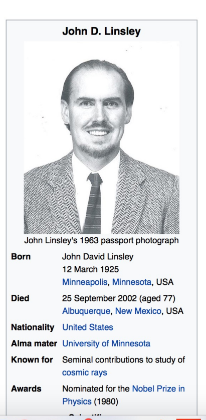
- Laser shots from an airplane, difficult to reproduce the observed light curve but can not be exlcuded…
- 2 Xenon flashers of 40-50 μs, 7-10 km apart shifted in time by 30-40 μs, the first flasher 2-3 times brighter than second one could mimic observations

Other physical origin:

- Neutrino, gamma, etc… excluded by slant depth
- Dust grains?



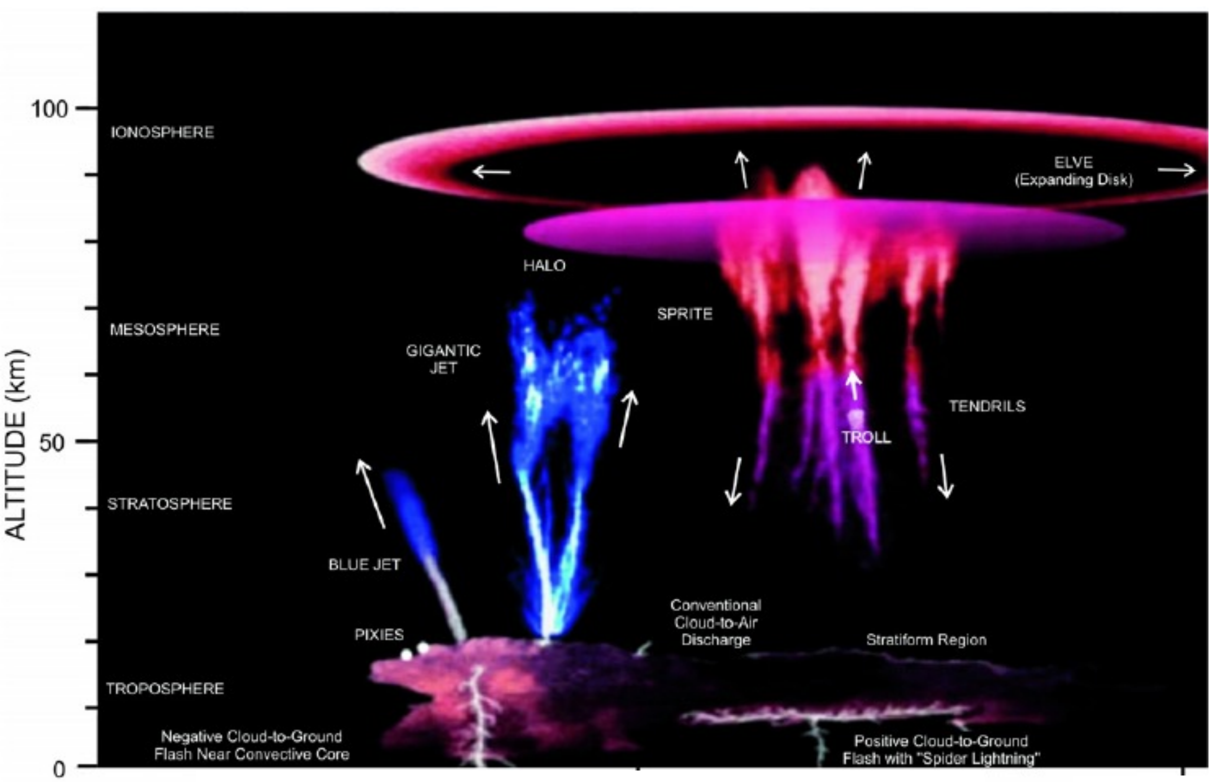
The observation of this event proves the possibility to detect from space light tracks compatible with EAS and helps developing strategies to carefully study the events



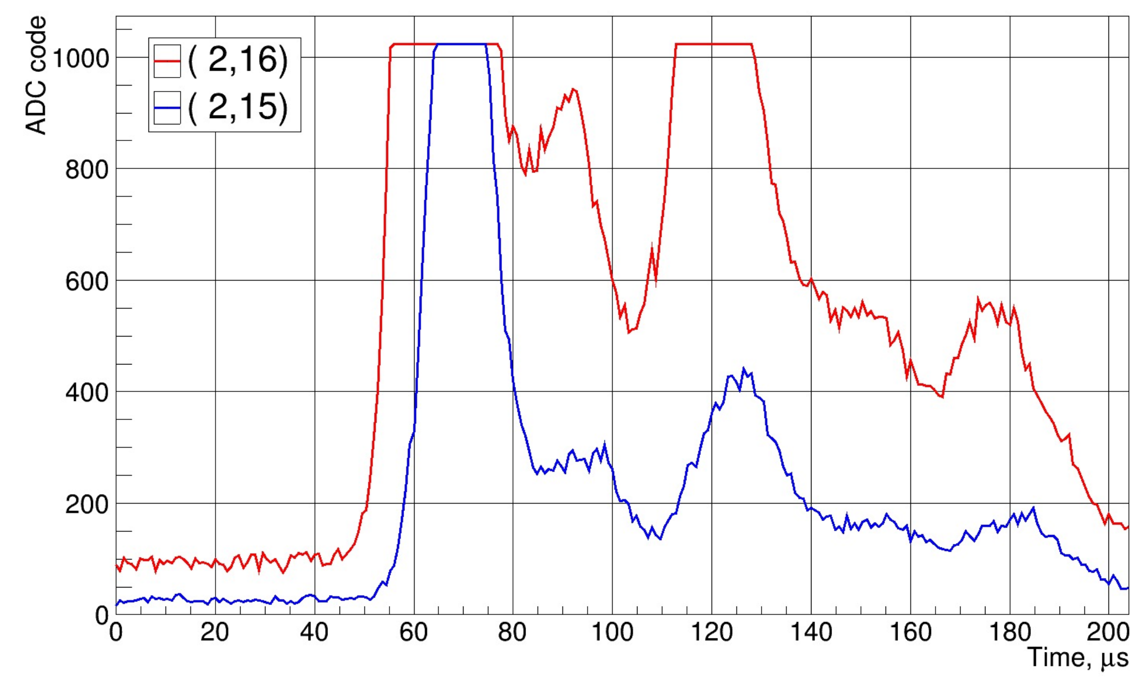
Interestingly J. Linsley, the father of EECR events, was born and graduated in Minnesota….

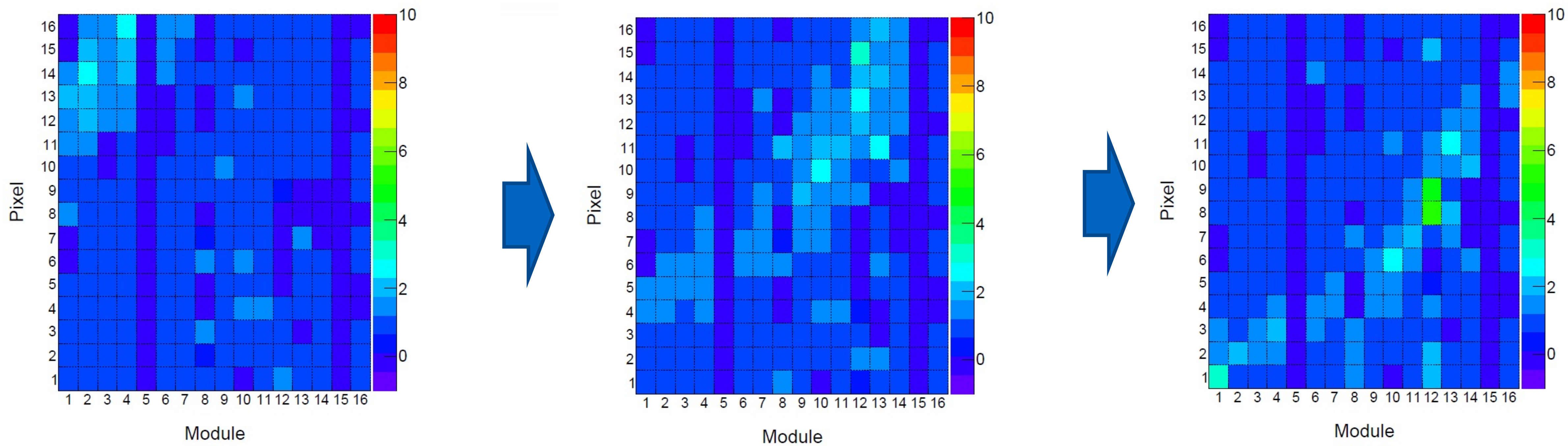
TLEs detected in EAS mode: ELVE

P. Klimov et al. Remote Sensing. 2019, 11, 2449; doi:10.3390/rs11202449



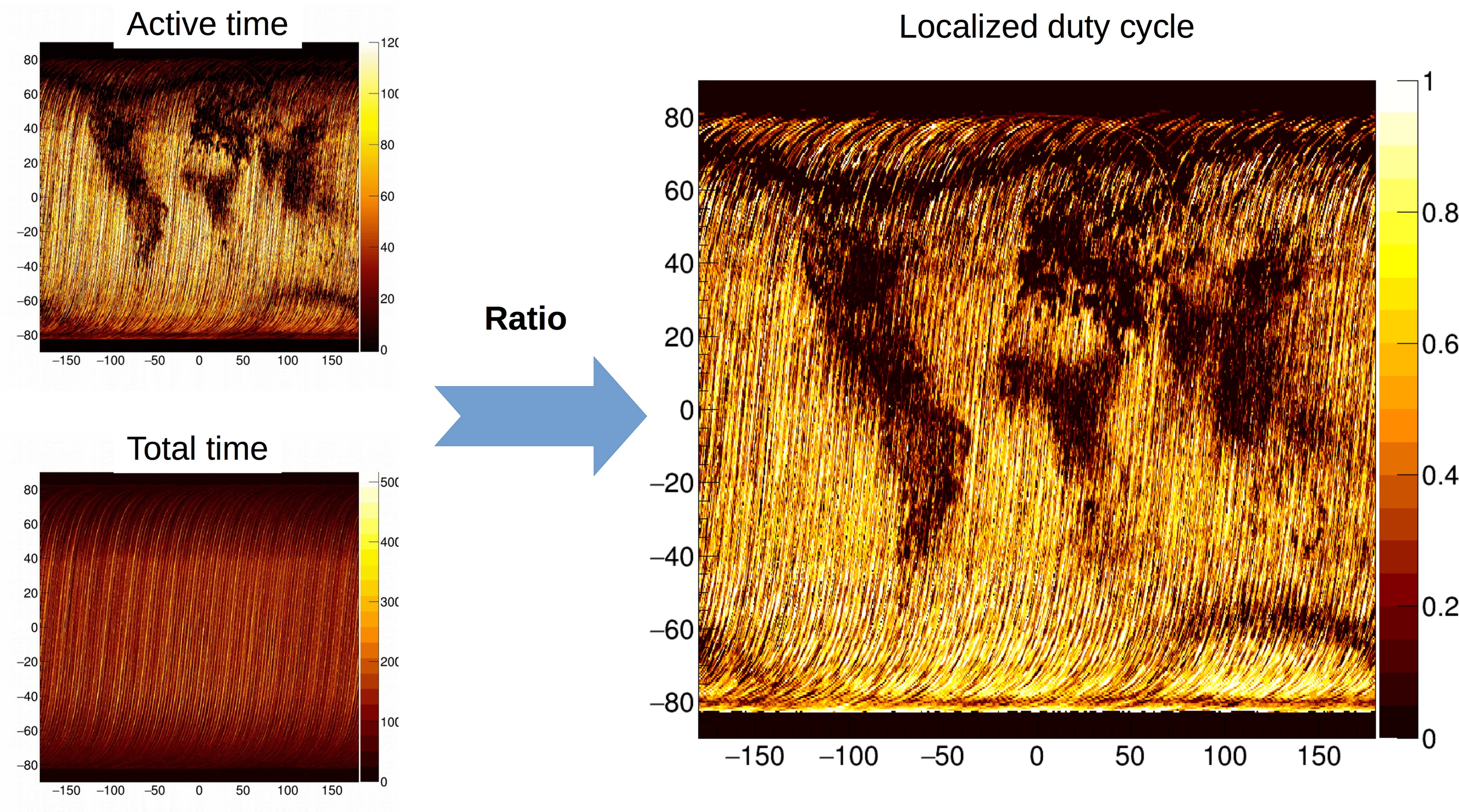
Multi-ring particularly interesting





TUS event 18.09.2016, 9.66S, 17.14W

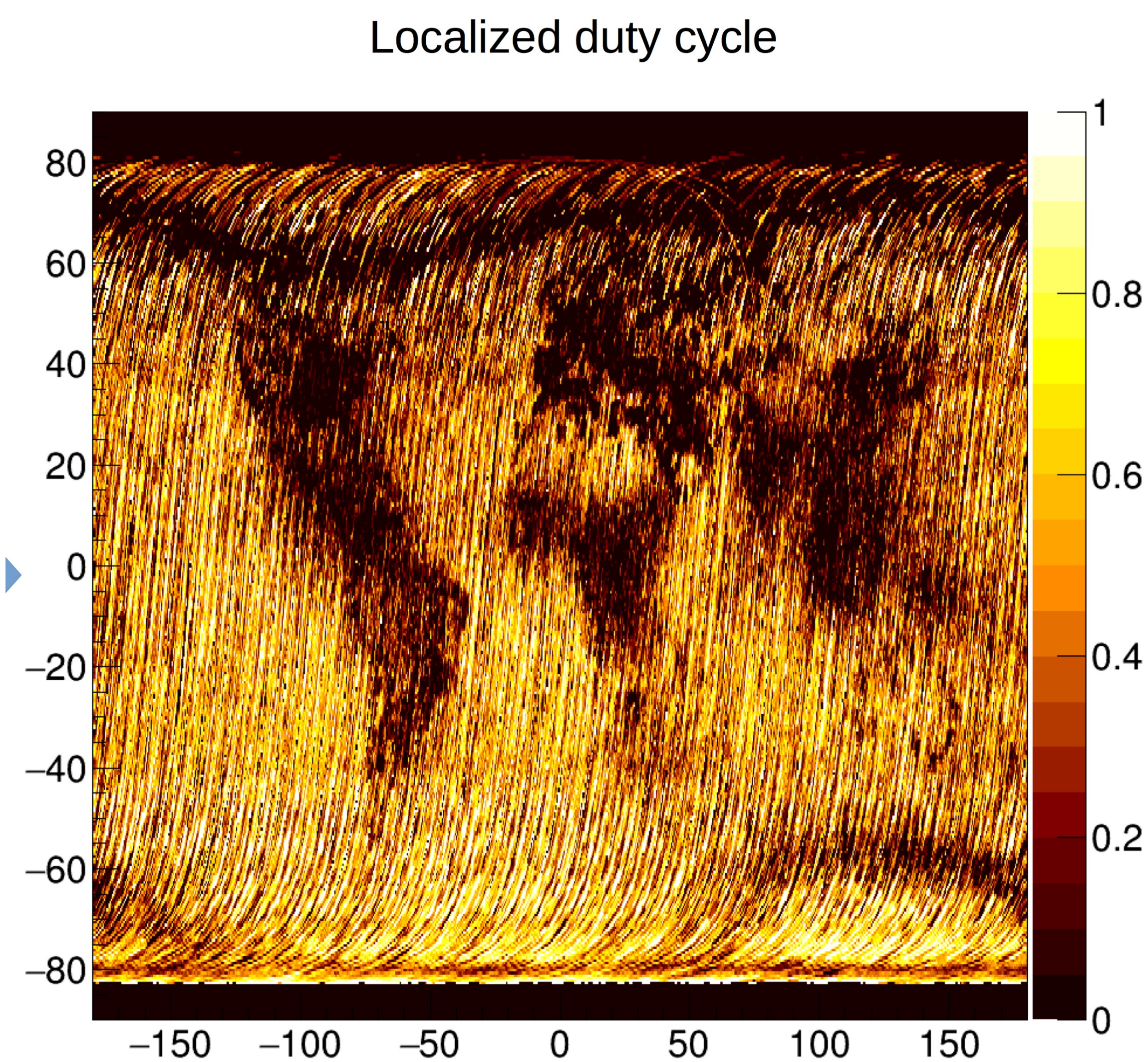
Detailed exposure study currently on going



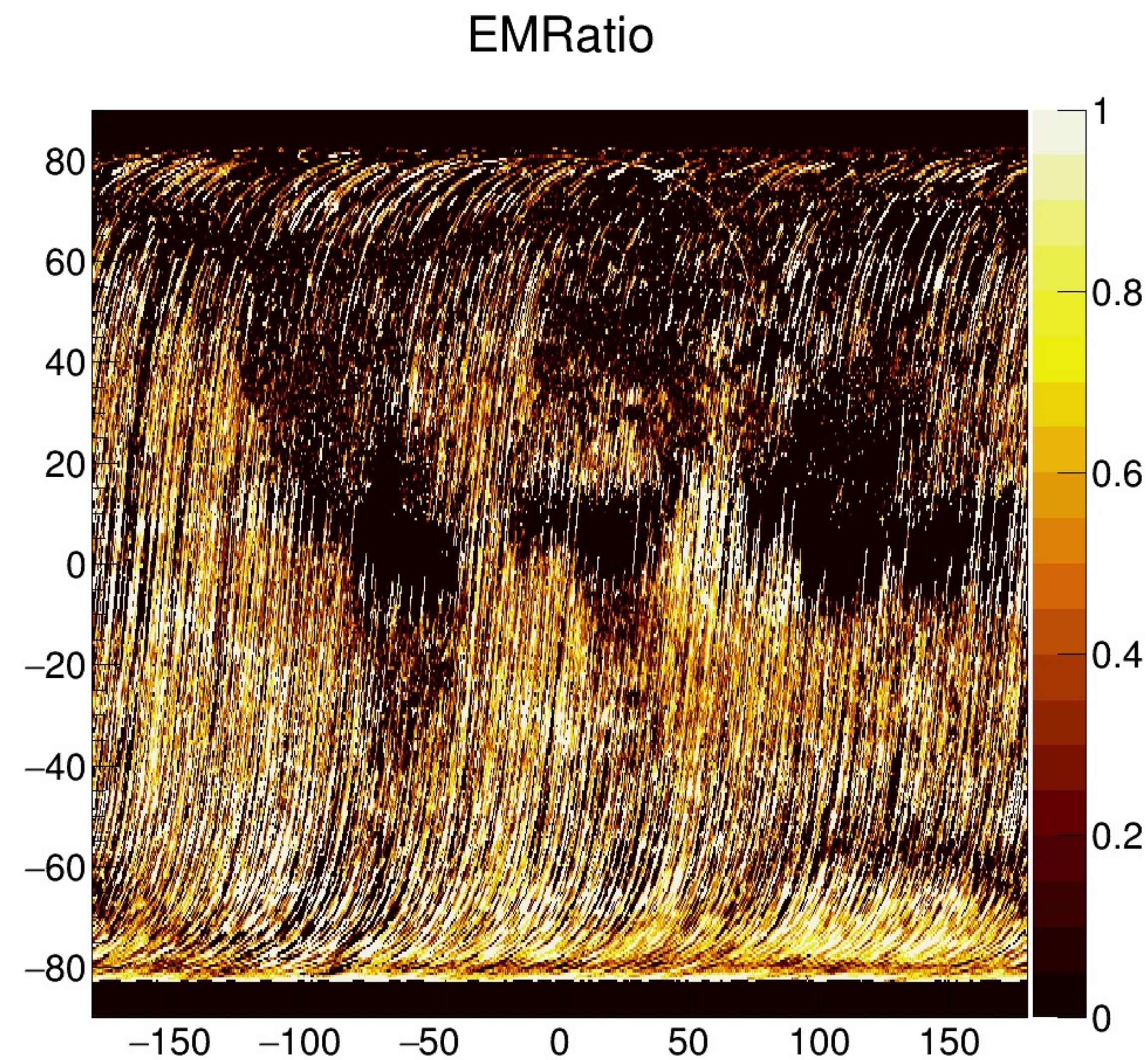
Duty cycle depends on the trigger scheme (TUS 53-60s dead time/event) but gives hints of brightest regions on Earth

Cloud impact

All data



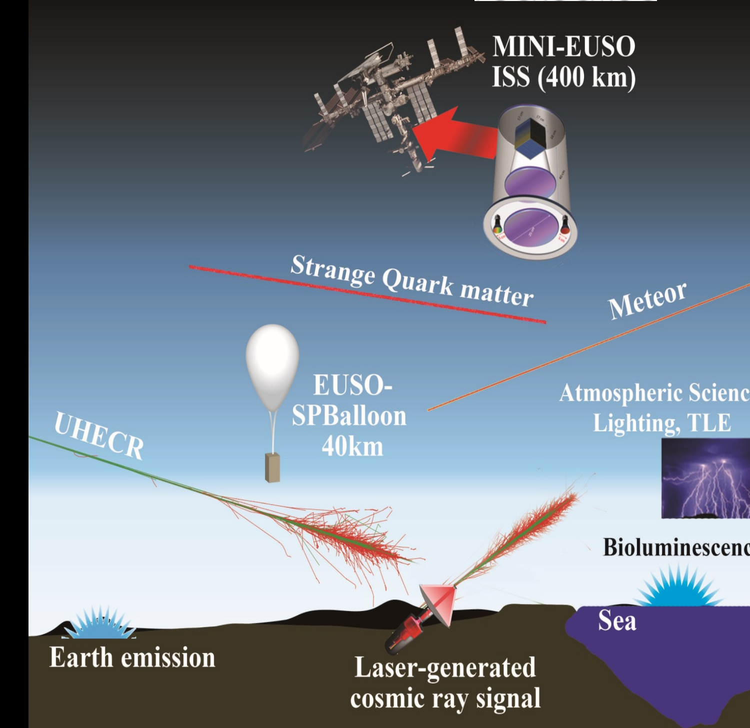
Cloud top < 4km

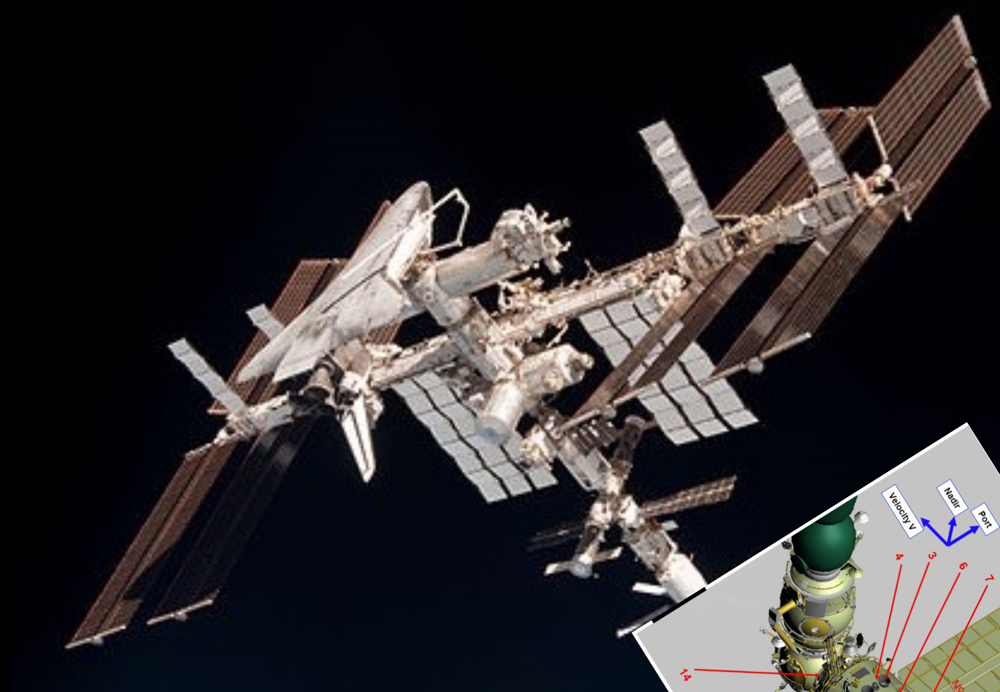


Using Merra-2 satellite data to associate cloud presence and compute exposure. Work in progress…

Mini-EUSO/UV-ATMOSPHERE

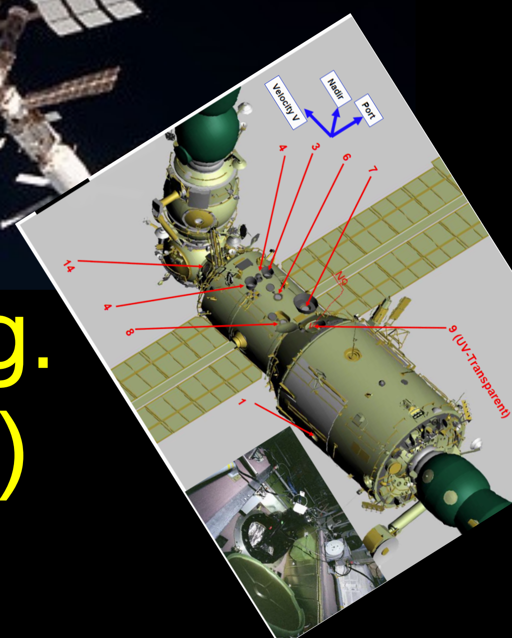
(flew to ISS on August 22nd 2019)

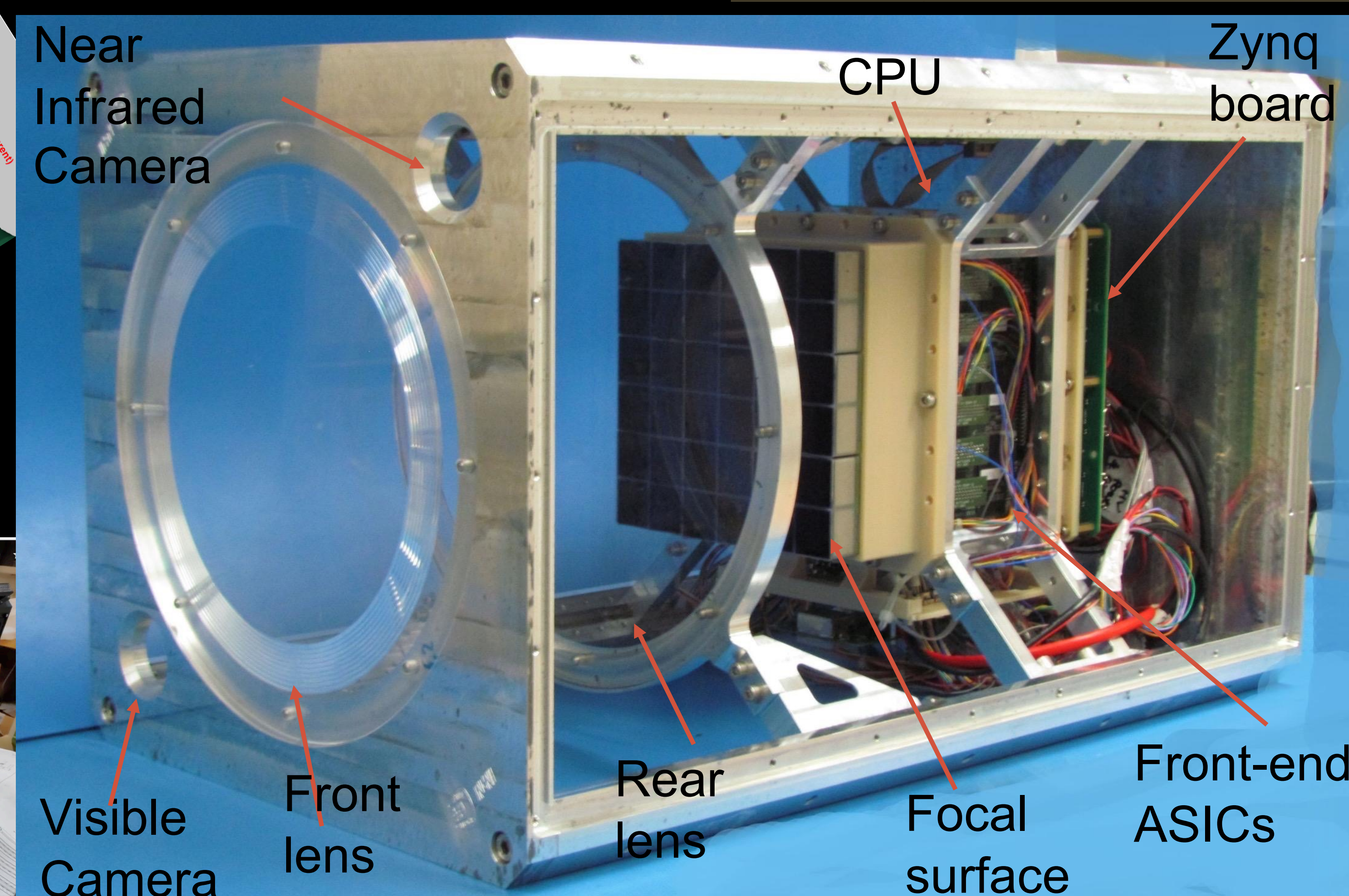


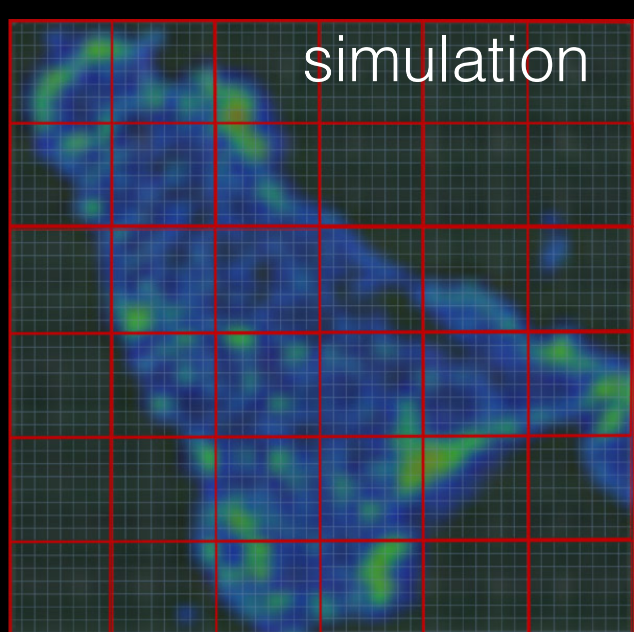


DATA with self trigger:
D1 : 2.5 μs res. (128 L1GTUs)
D2: 320 μs res. (128 L2GTUs)
D3: 40.96 ms res. (full movie)

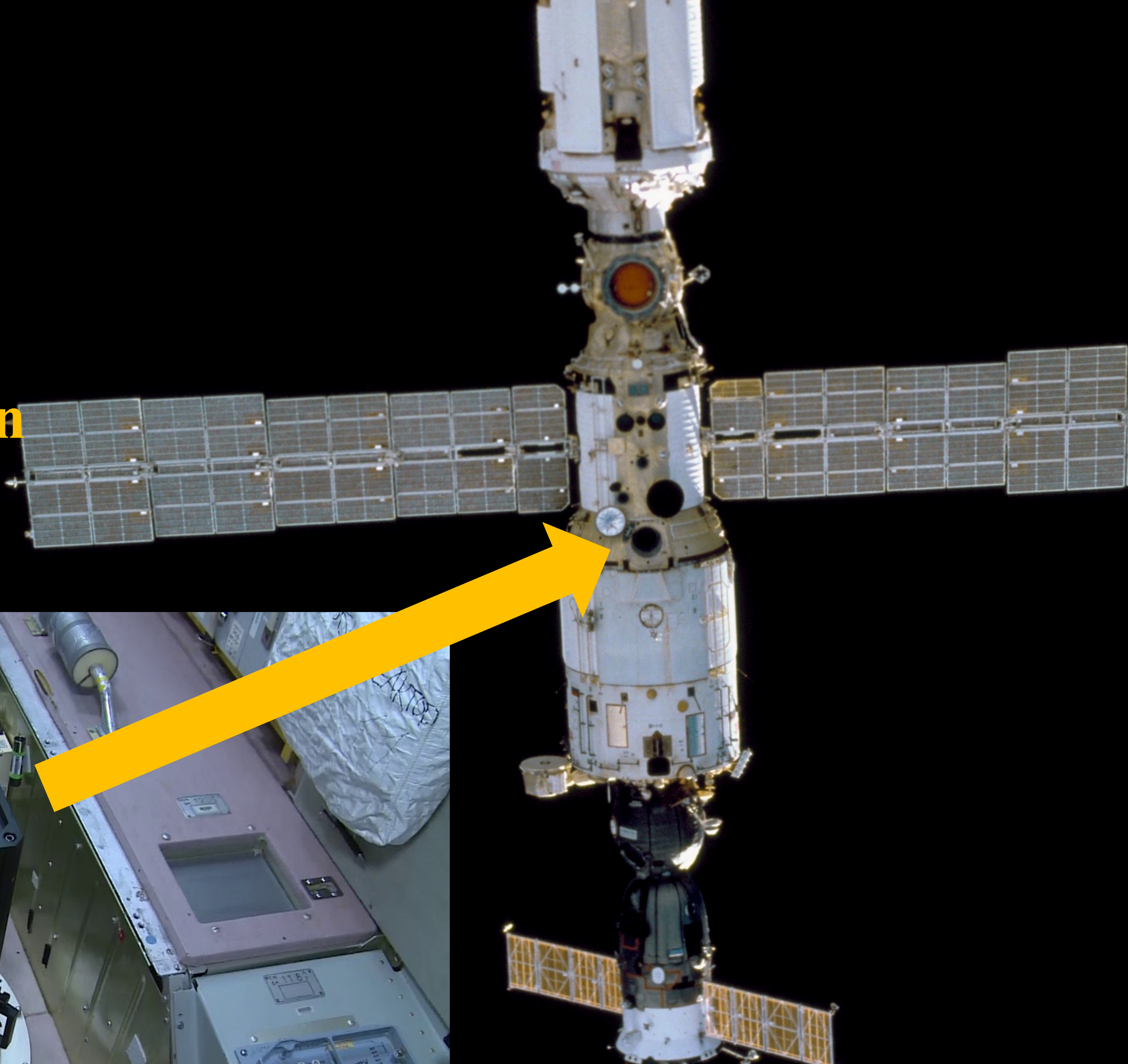
FoV: ± 22 deg.
(9 times TUS)

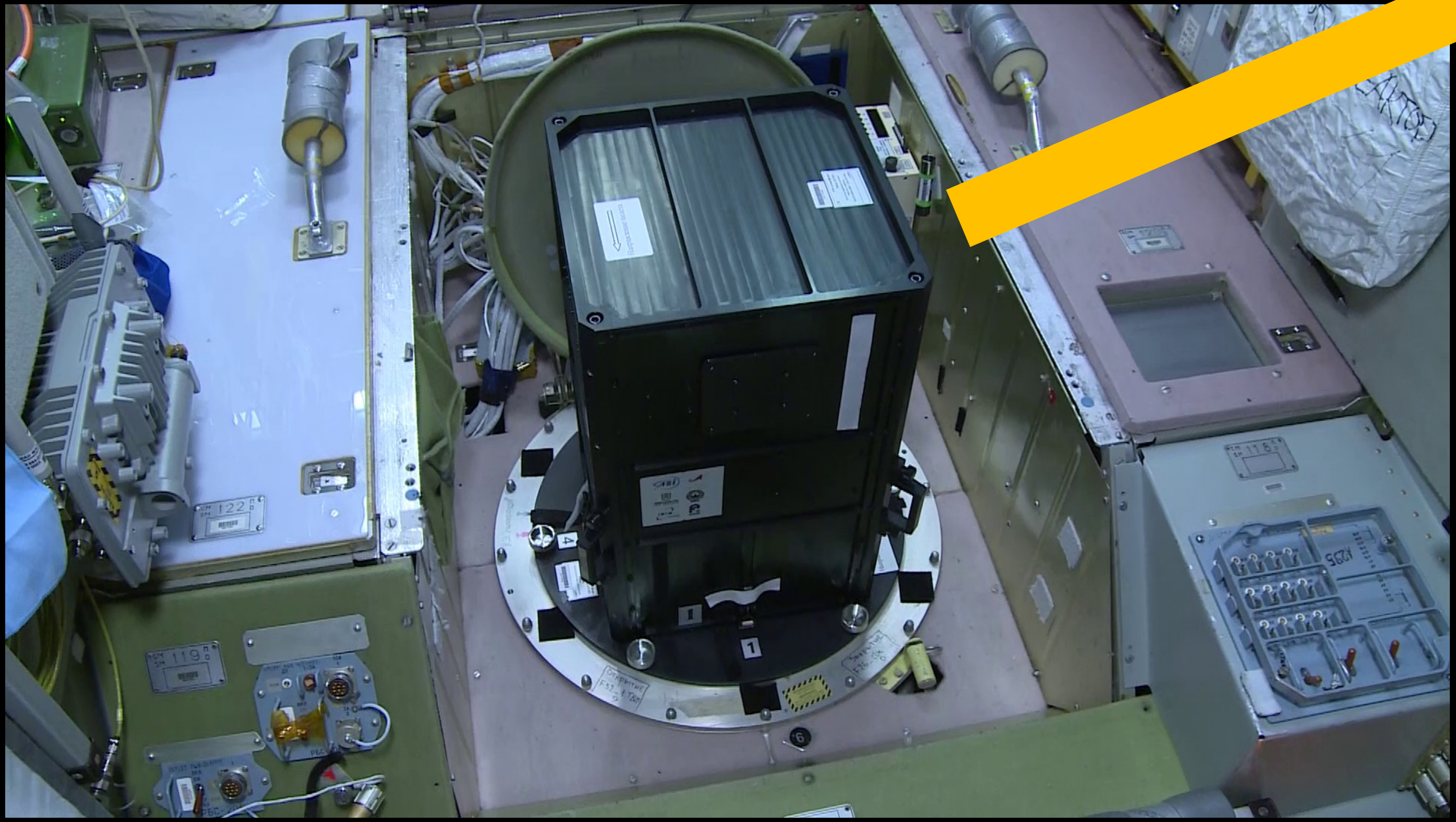




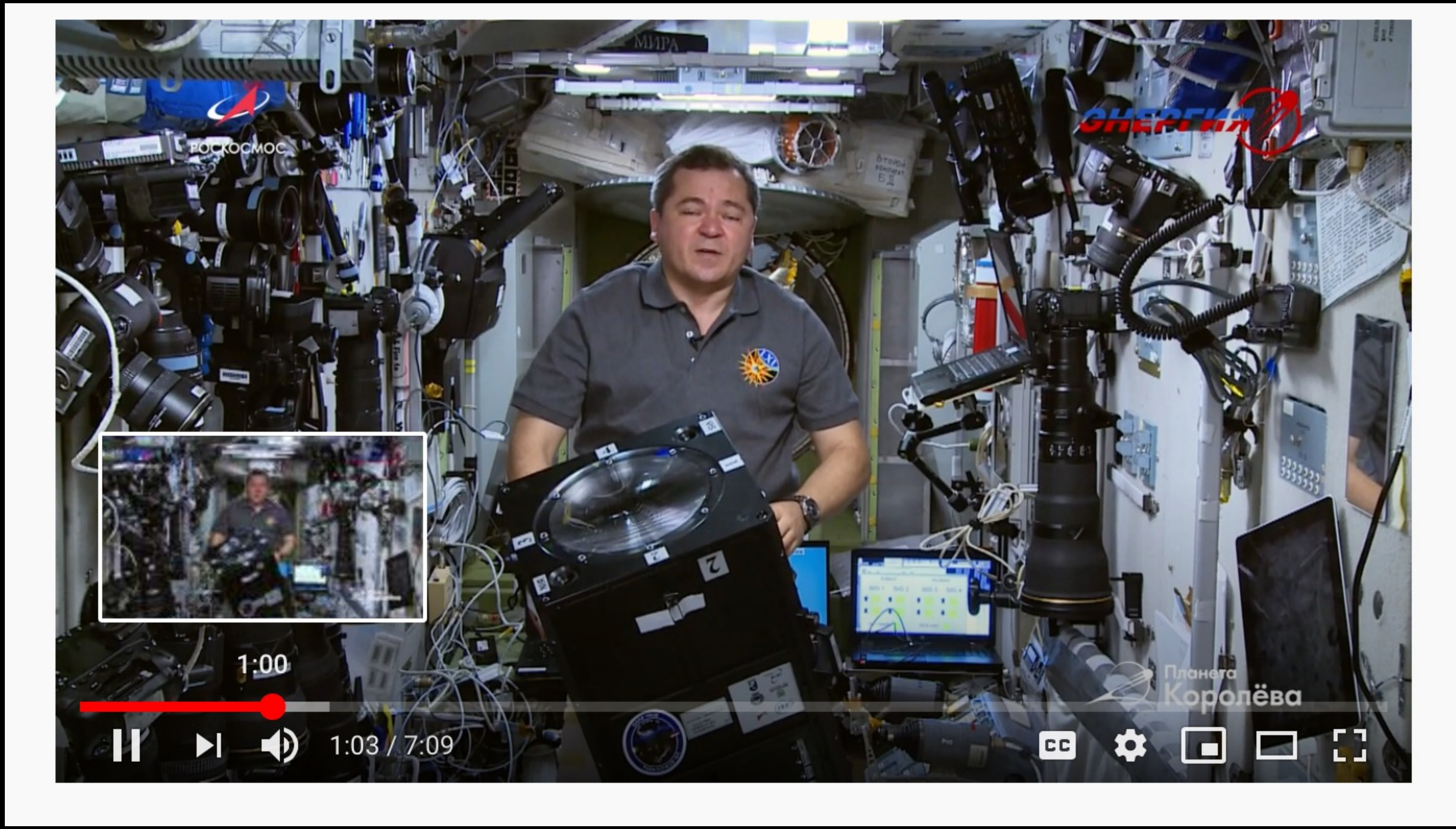


Uv transparent window,
Zvezda module,
International Space Station



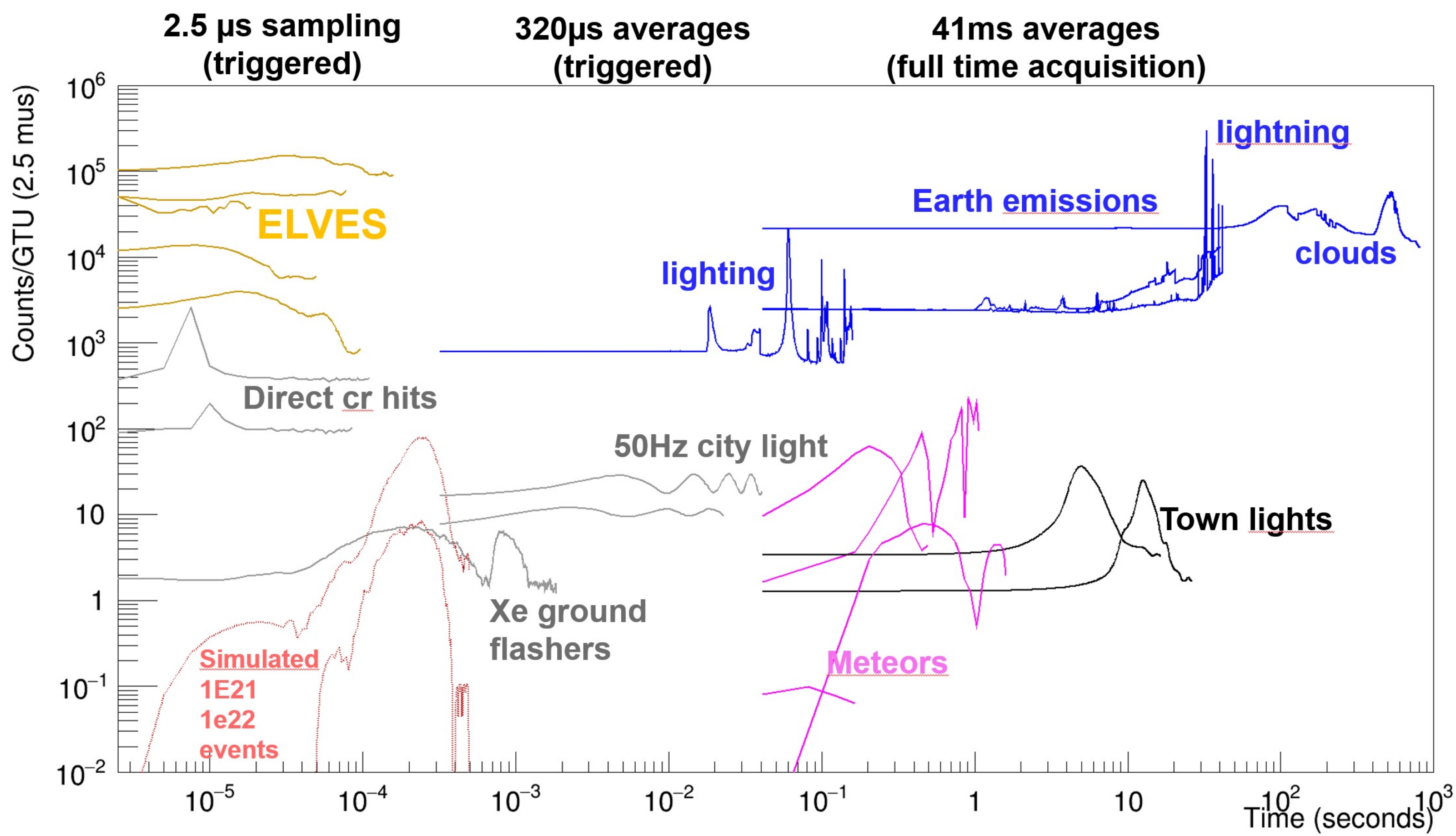


https://www.youtube.com/watch?v=lXedBGVHc4o&t=62s



Sampling rate: µs, 100µs **AND** ms scale

S. Bacholle et al., "Mini-EUSO Mission to Study Earth UV Emissions on board the ISS", The Astrophysical Journal Supplement Series, Vol. 253, pag. 36 (2021), https://doi.org/10.3847/1538-4365/abd93d
https://arxiv.org/abs/2010.01937



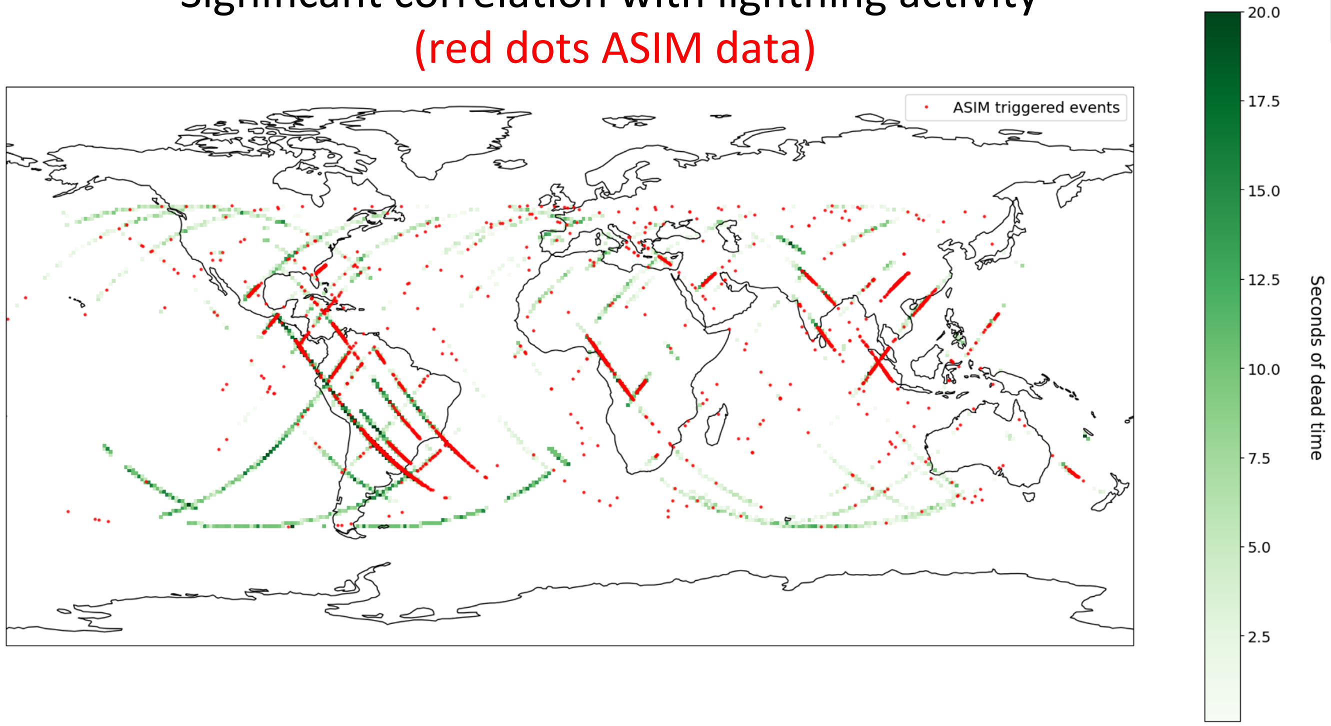
M. Casolino, L. Marcelli

Mini-EUSO - μs timescale trigger performances

Dead time (20-30%)

Significant correlation with lightning activity

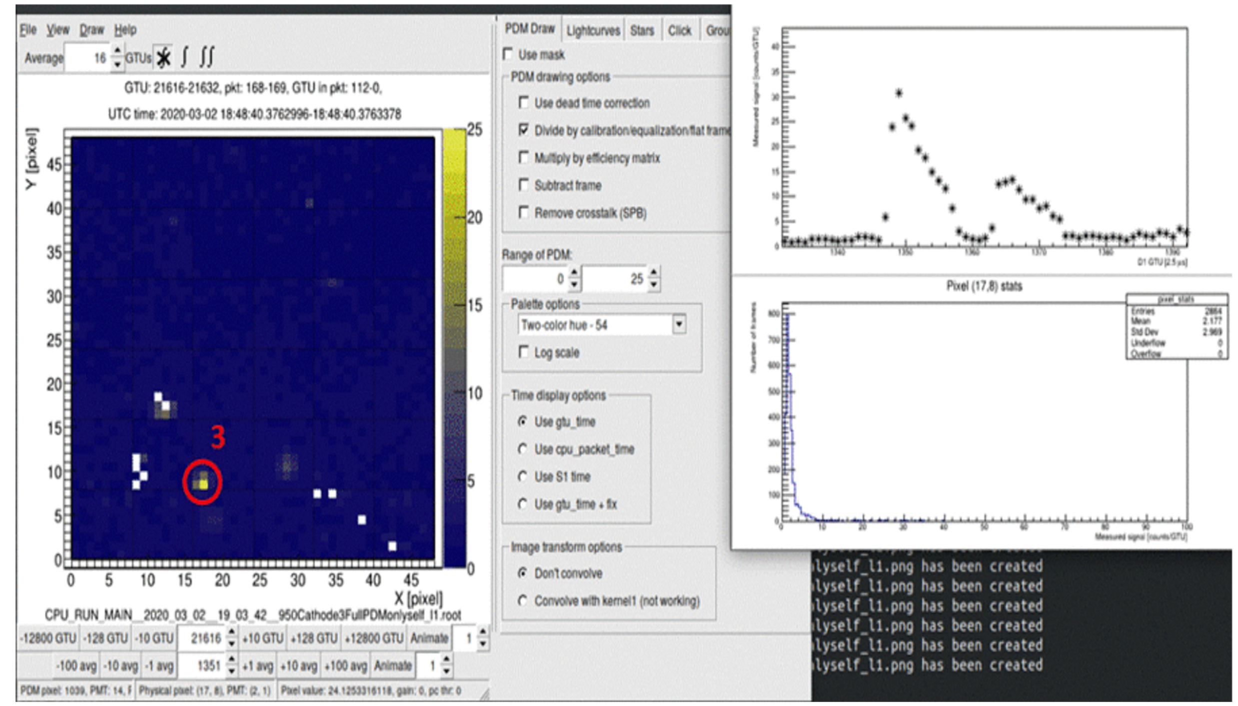
(red dots ASIM data)

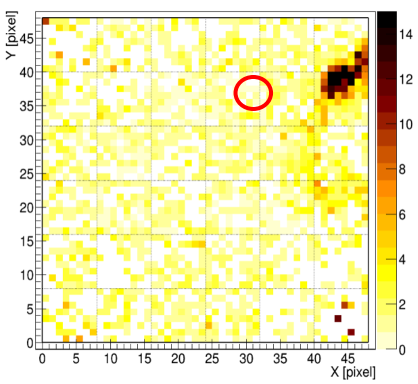


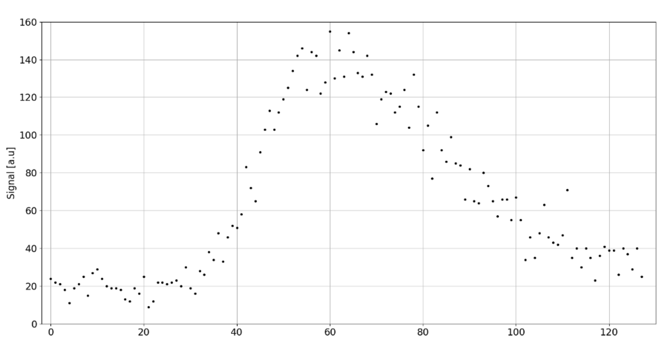
M. Battisti, F. Bisconti, P. Klimov, F. Fenu, A. Golzio

The same flasher triggered three different time. The event was located in a mountain region in China

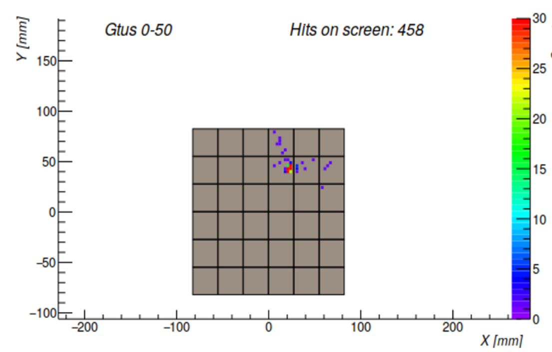
Left: flat fielded focal plane view. Right: lightcurve of the most luminous pixel

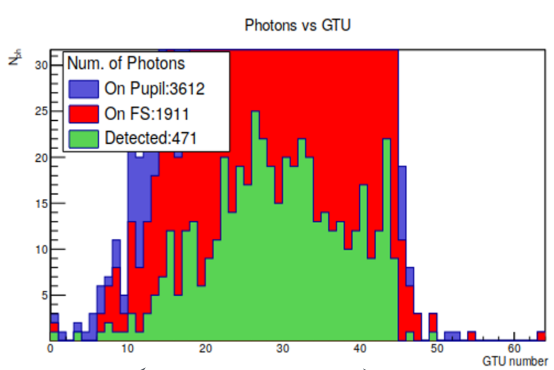






80 frames

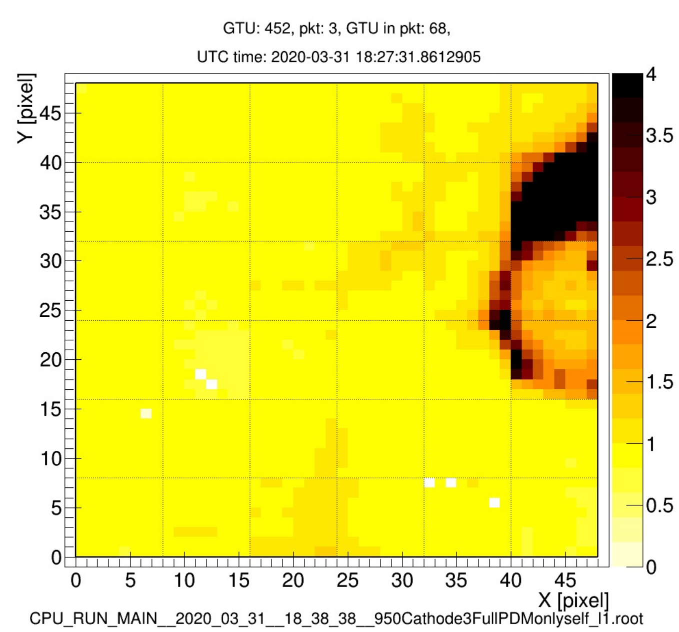


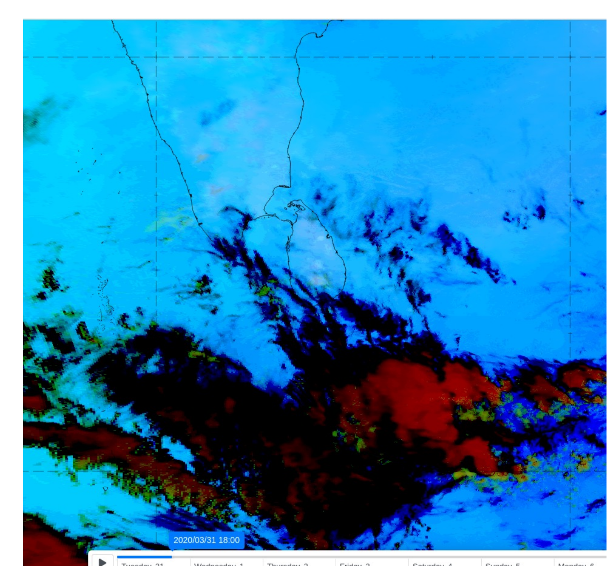


30 frames - too short

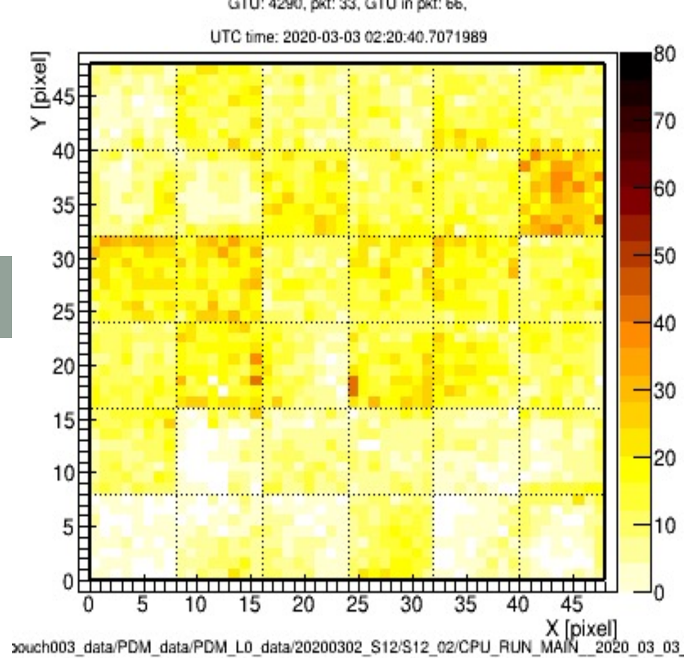
Mini-EUSO

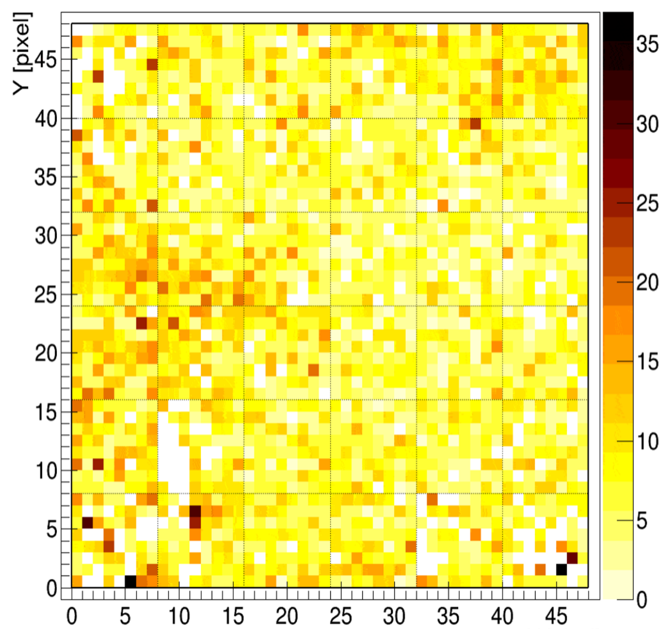
2×10^{22} eV p simulation





TLEs

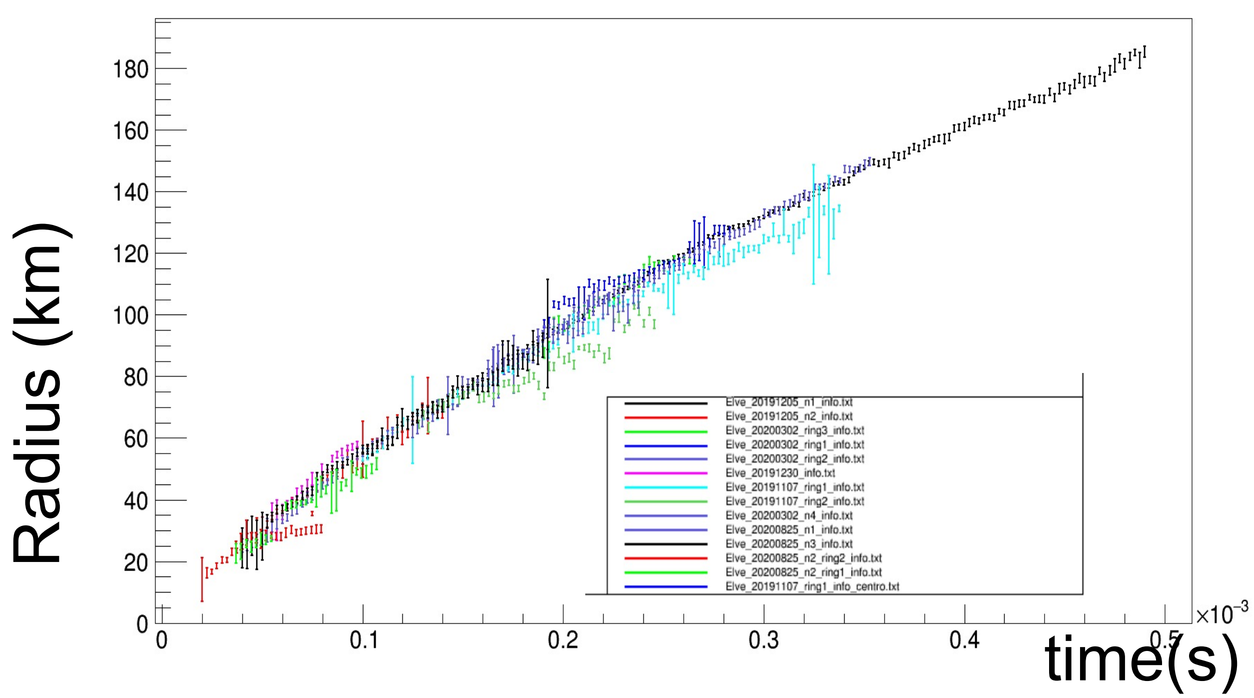


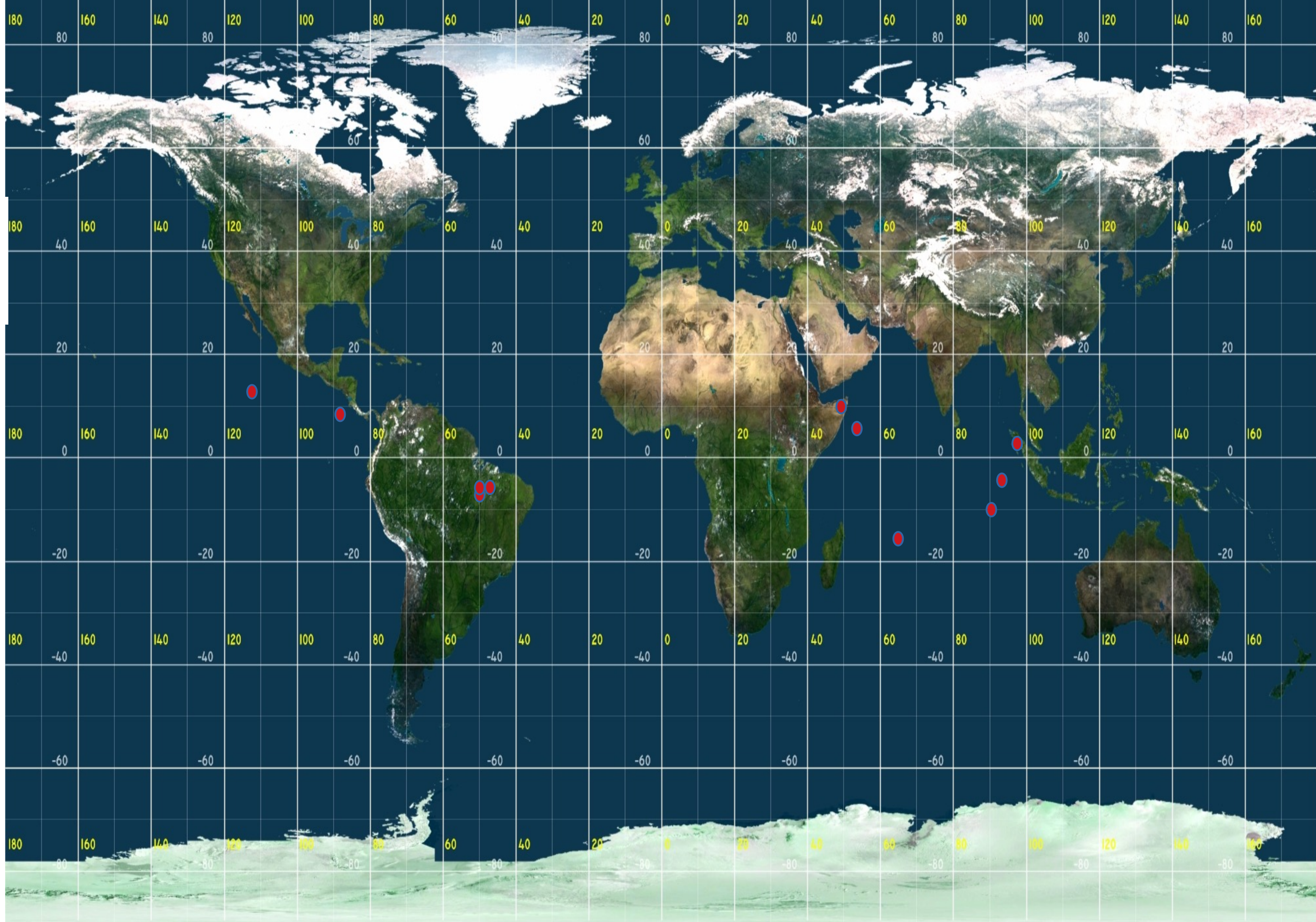


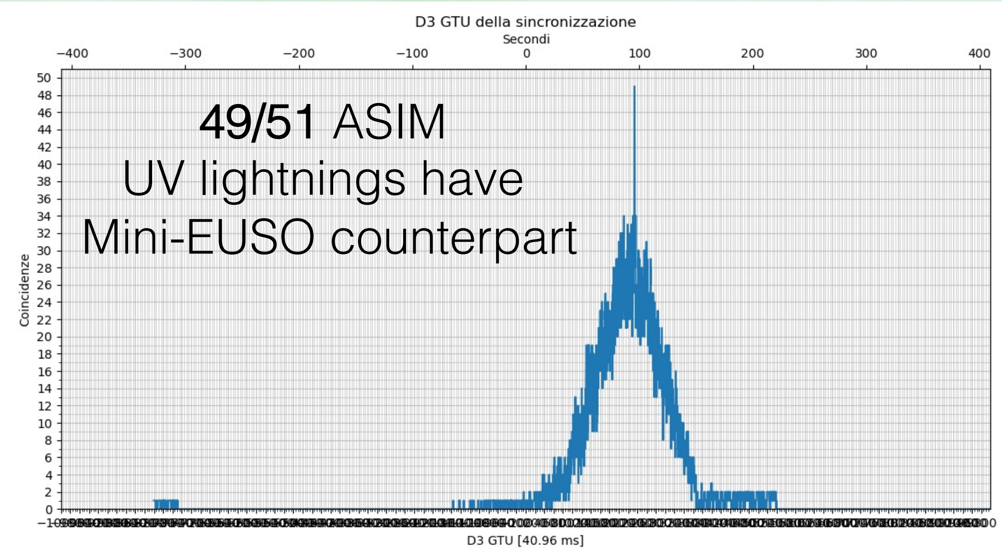
ELVES:

1) 2019, Nov 7
2) 2019, Dec 5 – n1
3) 2019, Dec 5 – n2
4) 2019, Dec 30
5) 2020, Mar 2 – n1
6) 2020, Mar 2 – n2
7) 2020, March 2 – n3
8) 2020, Mar 2 – n4
9) 2020, Aug 25 - n1
10) 2020, Aug 25 - n2
11) 2020, Aug 25 - n3

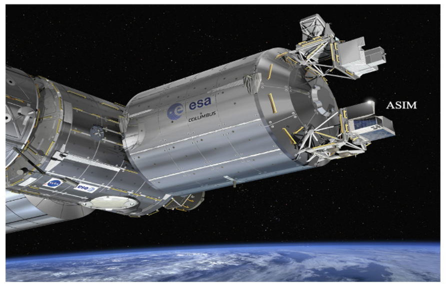
L. Marcelli, M. Casolino, M. Battisti, E. Arnone

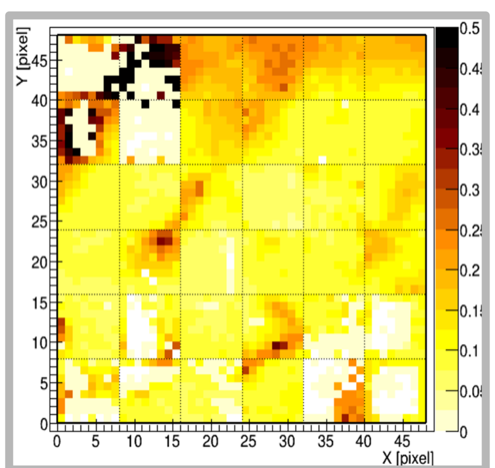






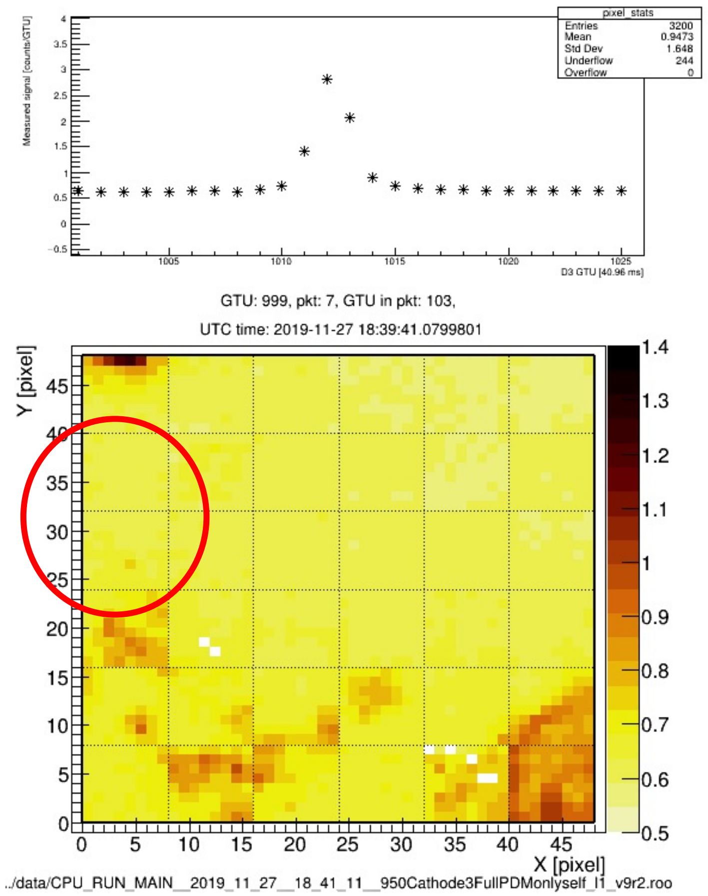
2 Elves - simultaneous detection with ASIM





Meteors

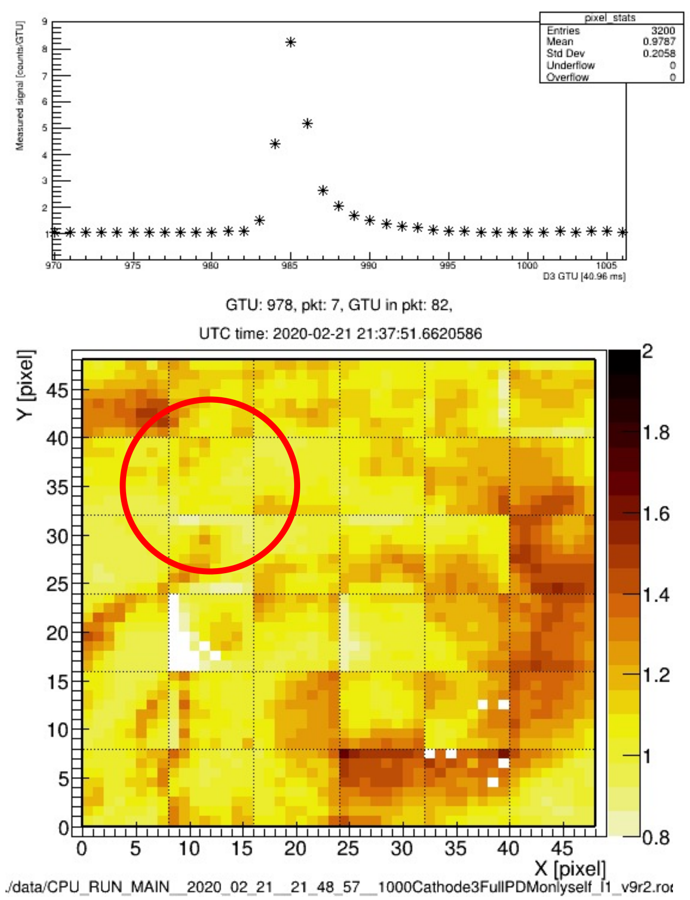
- Most of the meteors are detected where the background is lower
- The false positives rate is higher over continents

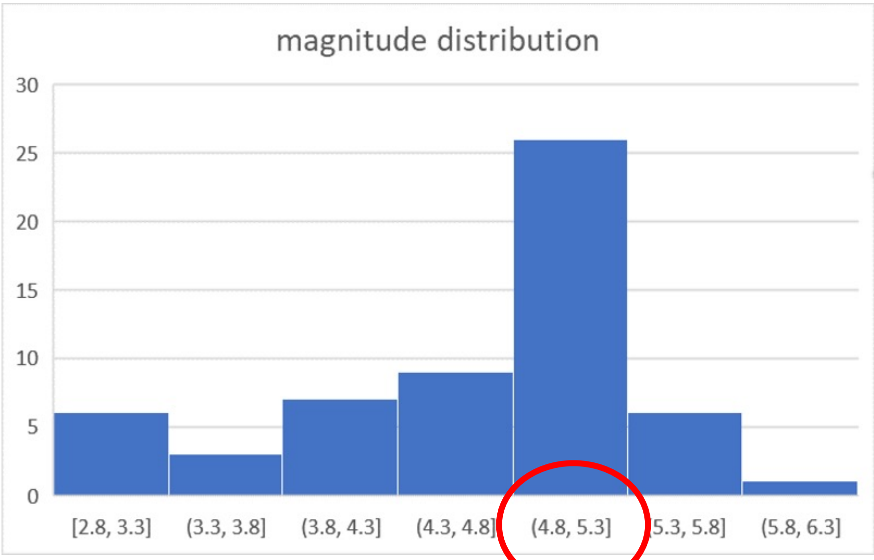


Meteors
Meteor candidates
Noise
Unidentified events

Detail from session 06

Current findings:
~1500 meteors
~1300 meteor cand.
in ~1900 min





With an efficiency of 8% the distribution peak is in a range of magnitude values of [+4.8,+5.3]

A. Cellino

Abs. mag	U-band flux (erg/s/cm^2/A)	mass (g)	event rate (Mini)
+7	$6.7{\cdot}10^{-12}$	$2{\cdot}10^{-3}$	0.4/s
+5	$4.2{\cdot}10^{-11}$	10^{-2}	2.4/min
0	$4.2{\cdot}10^{-9}$	1	0.11/orbit
−5	$4.2{\cdot}10^{-7}$	100	2.5/year

G. Abdellaoui et al., "Meteor studies in the framework of the JEM-EUSO program", *Planet. Space Sci.*, 143, 245 (2017)

Considering S06 and S11 (moon 2%):

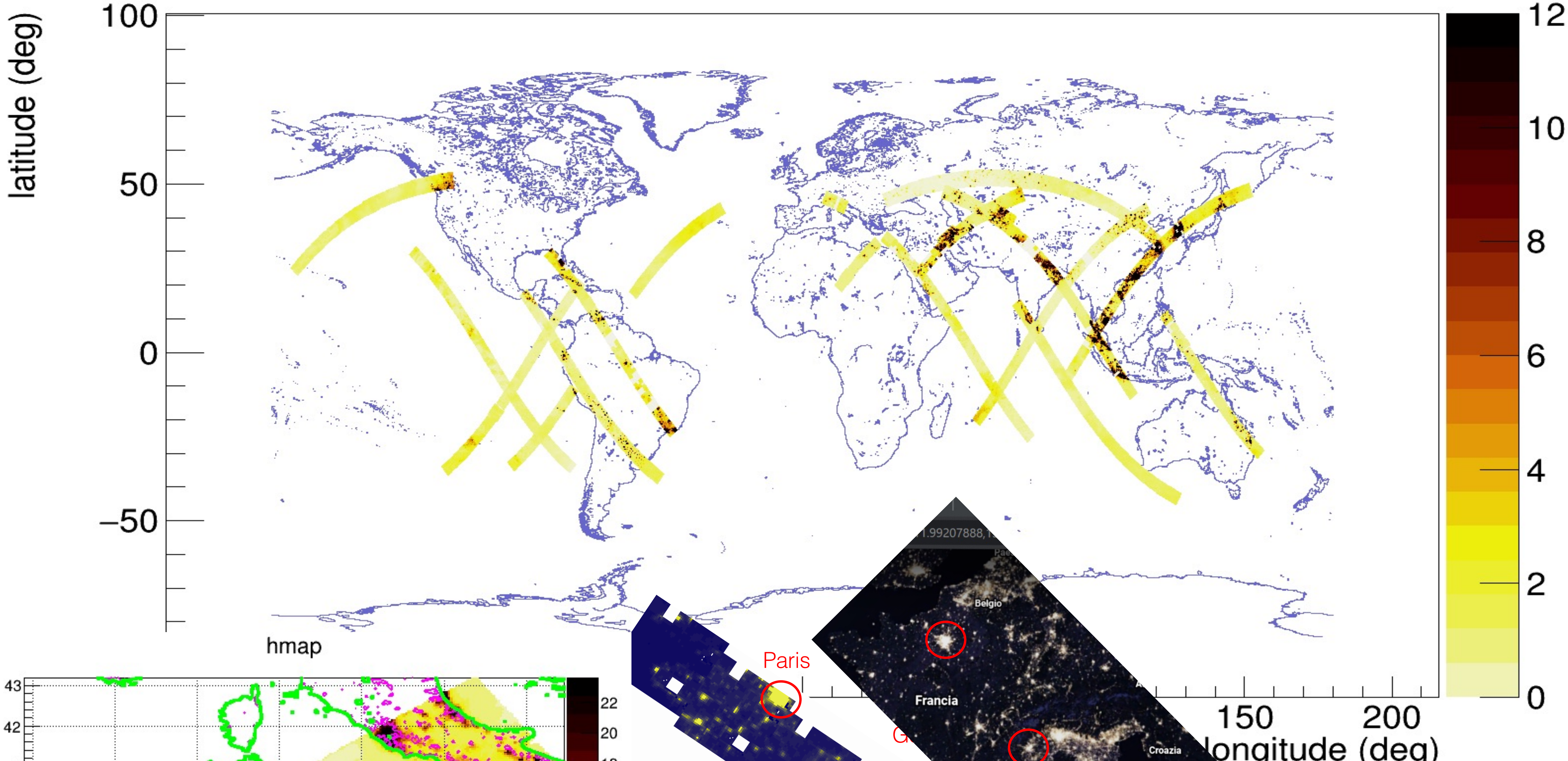
- Total number of observed meteors:
  $356 + 343 = 699$
- Total number of meteor candidates:
  $201 + 109 = 310$
- Total sessions duration:
  $282 + 168 = 450\ min$

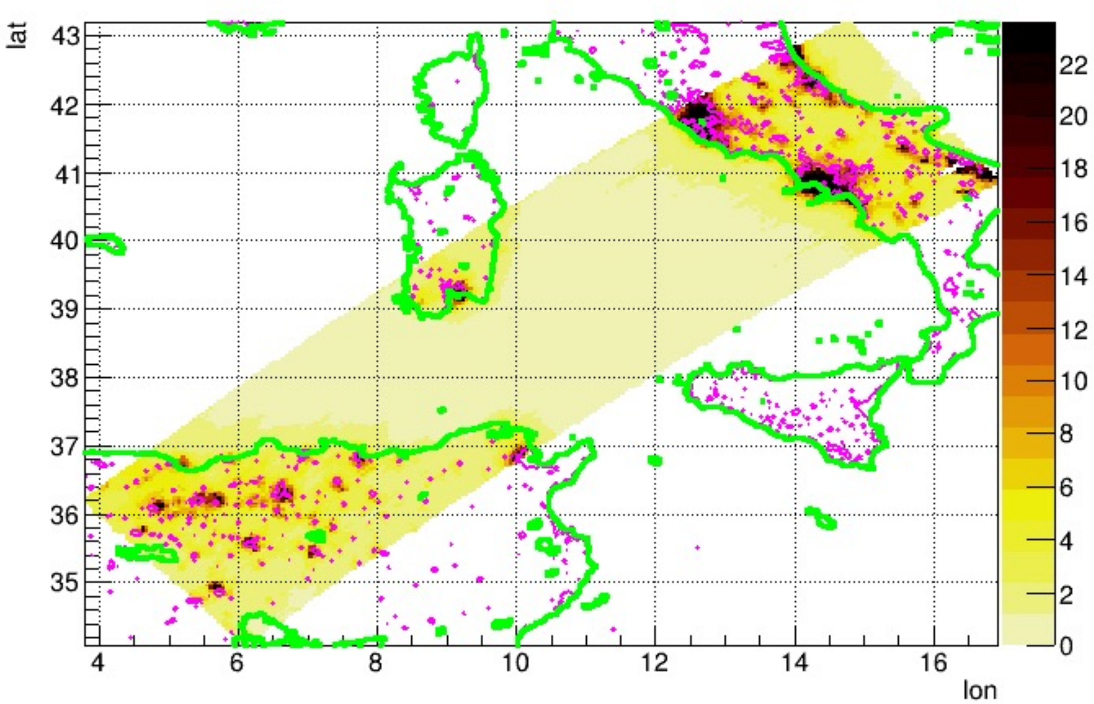
Events rate:
1.5 events/min (only M)
2.3 events/min (M+M?)

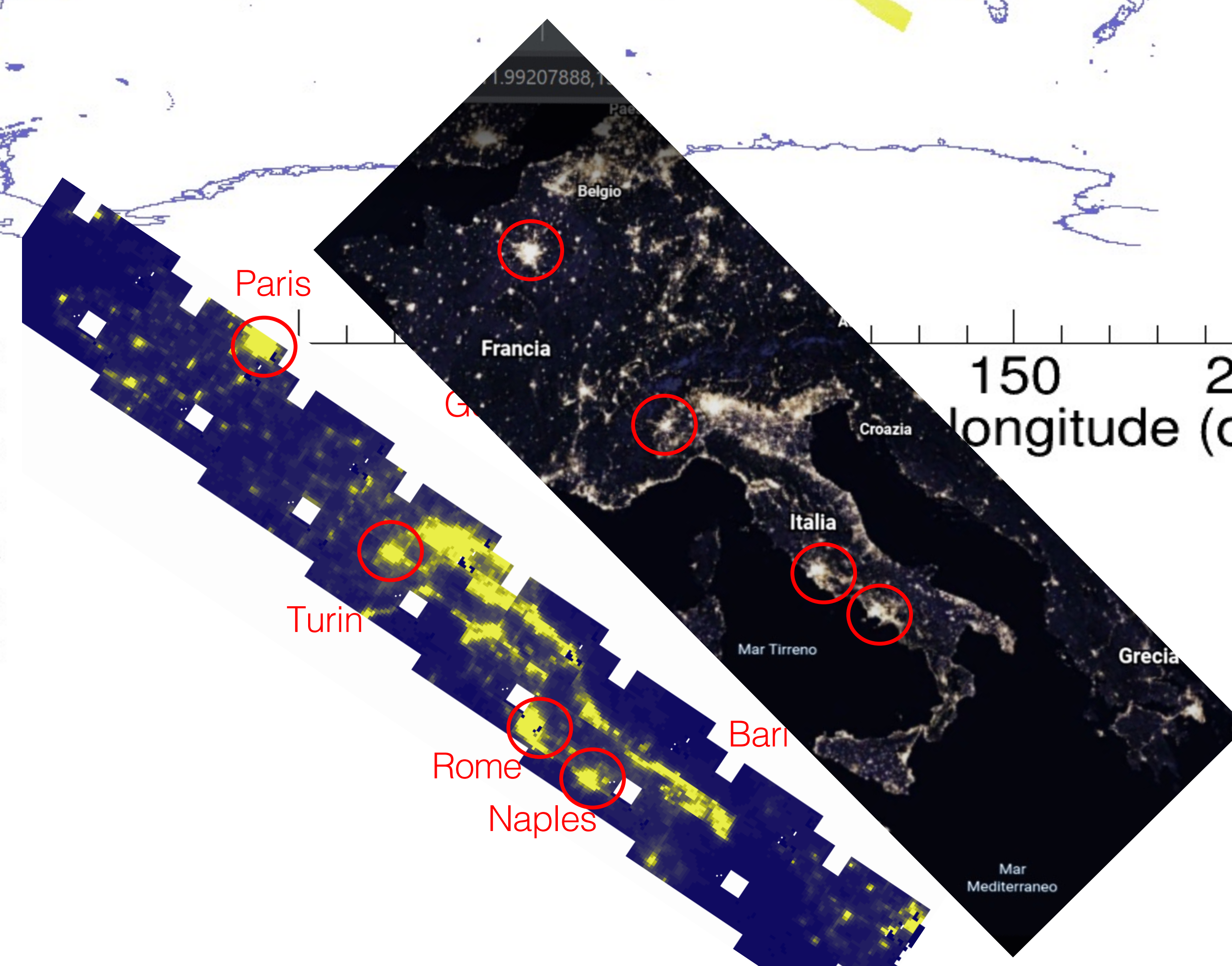
L. Piotrowski, D. Barghini, H. Miyamoto, S. Bertone & F. Reynaud

L. Piotrowski, F. Bisconti

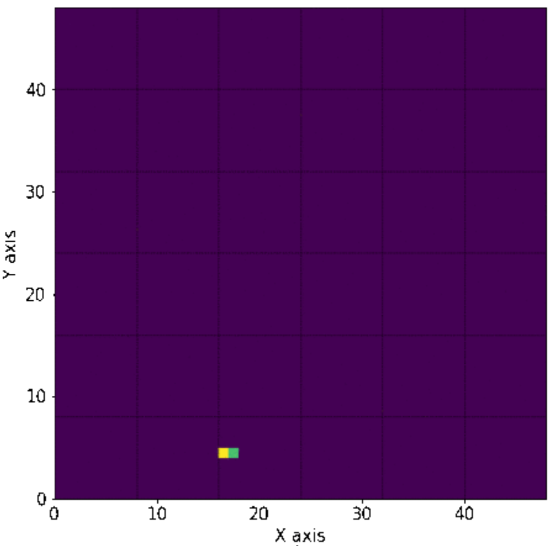
UV Maps



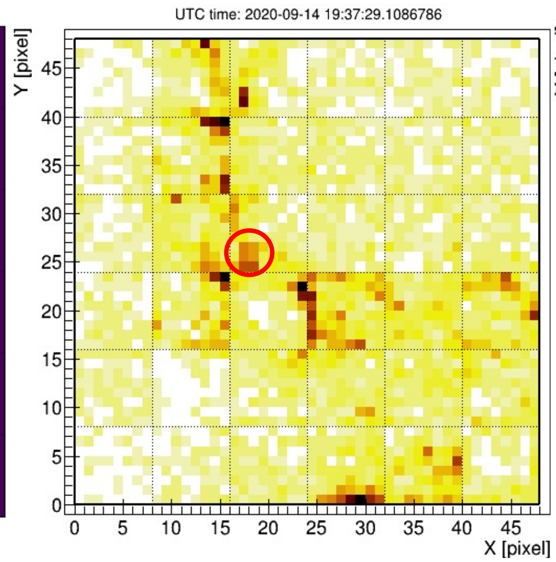




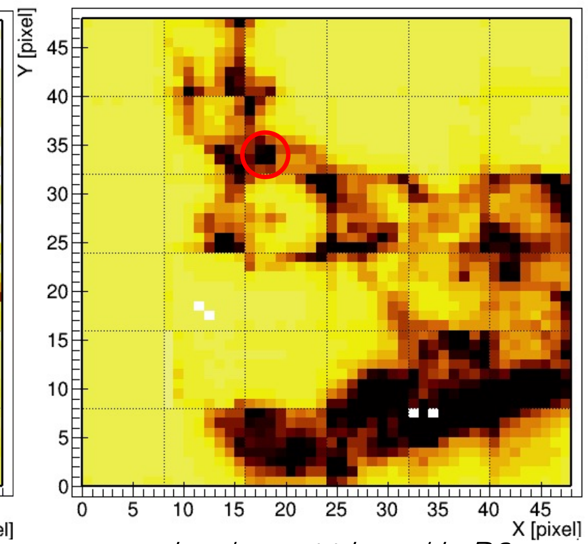
Lamezia Terme Event – Italy



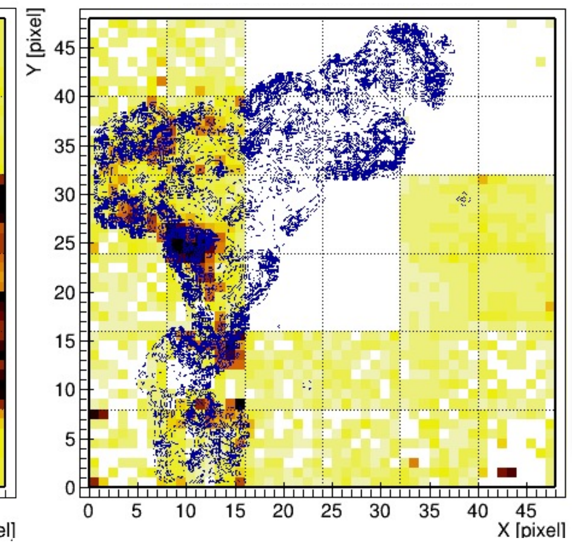
repeated event



visual event trigged in D1

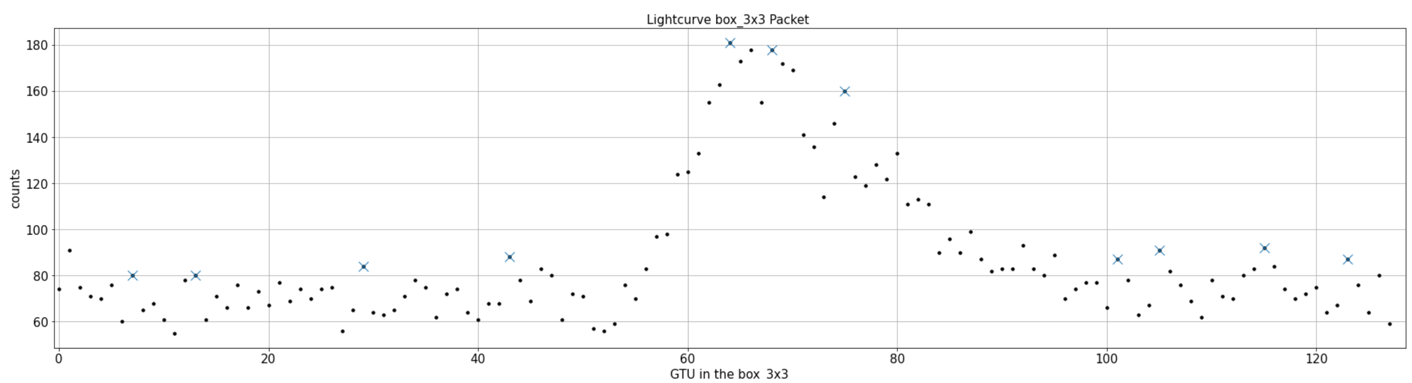


visual event trigged in D3



ISS movement

South Italy

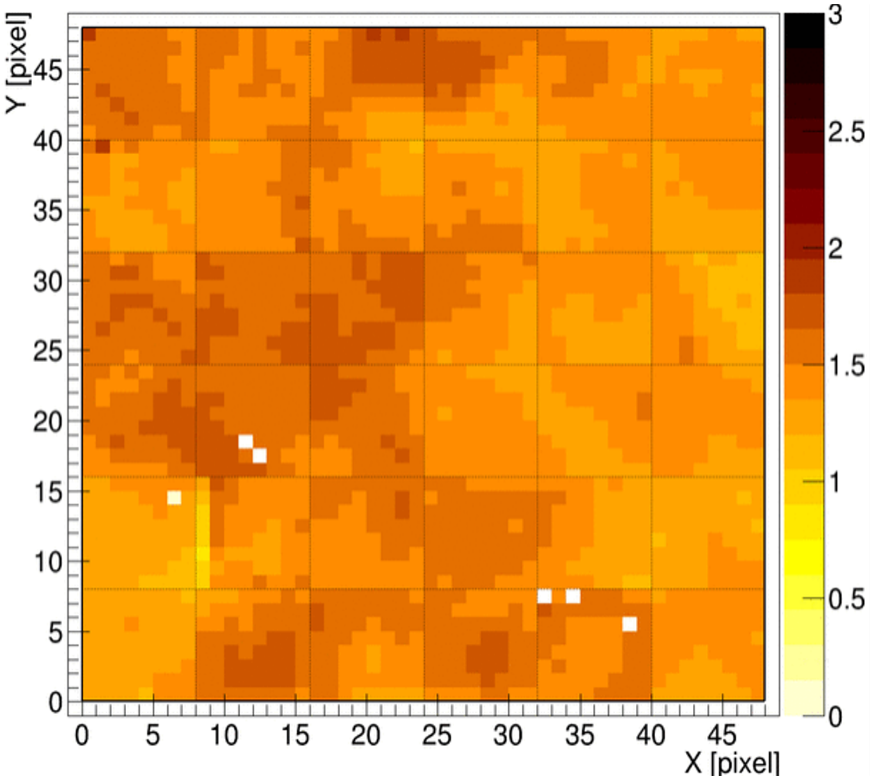


- These events have not been seen only over North America.
- A particular example is this event repeated several times with the same light curve on *September 14th, 2020*.
- With an in-depth analysis and the location of the *ISS*, it was possible to find the approximate geographic location of the event.
- The event with *ETOS* software and the *DMSP* map were superimposed and it was possible to see that it's clearly displayed around *Lamezia Terme International Airport* (*Calabria*) in Italy.

Clouds

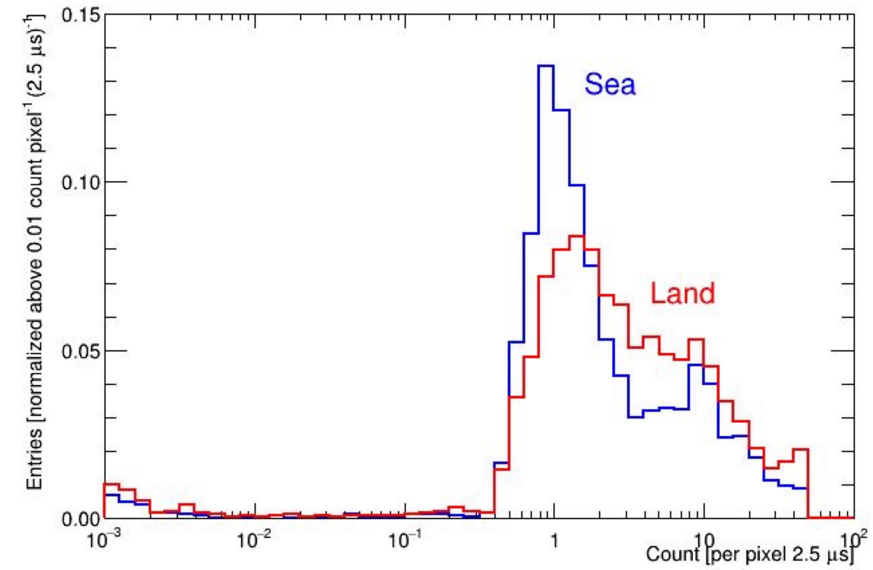
K. Shinozaki,
A. Golzio & M. Manfrin

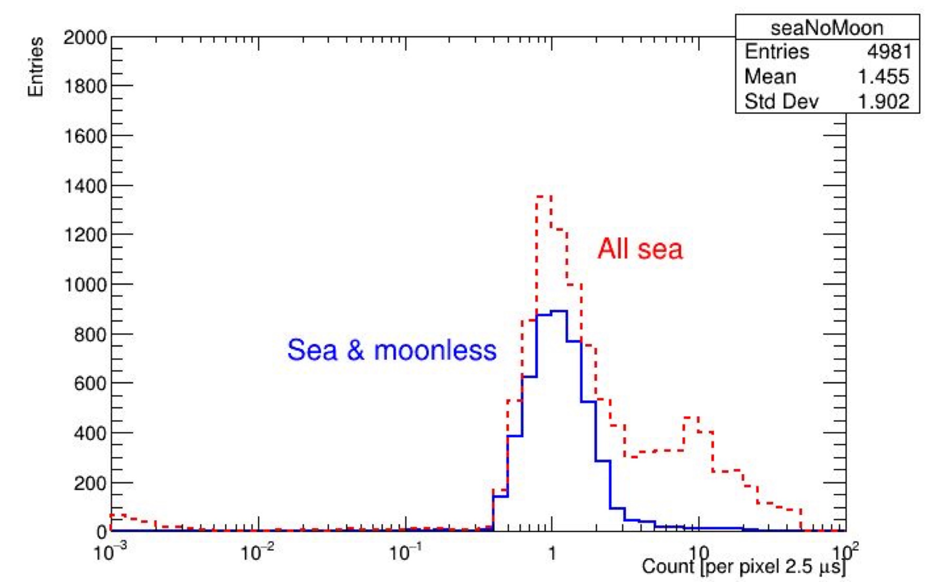
Diffuse light



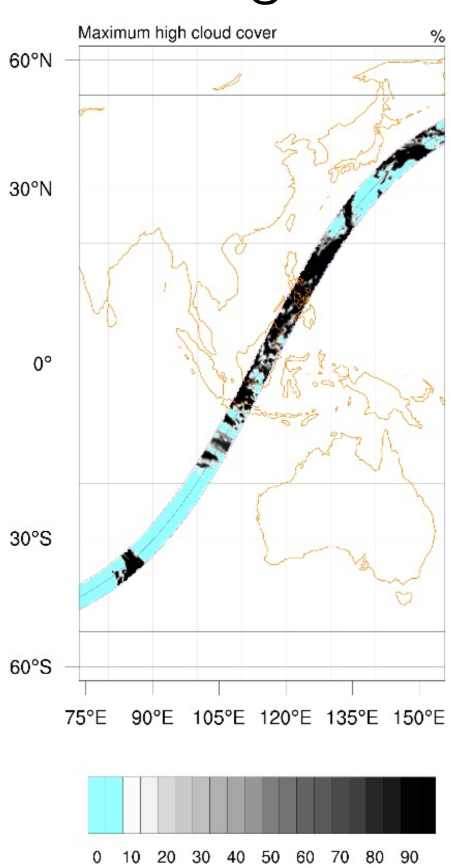
We see clouds:
which ones?

Database
under preparation

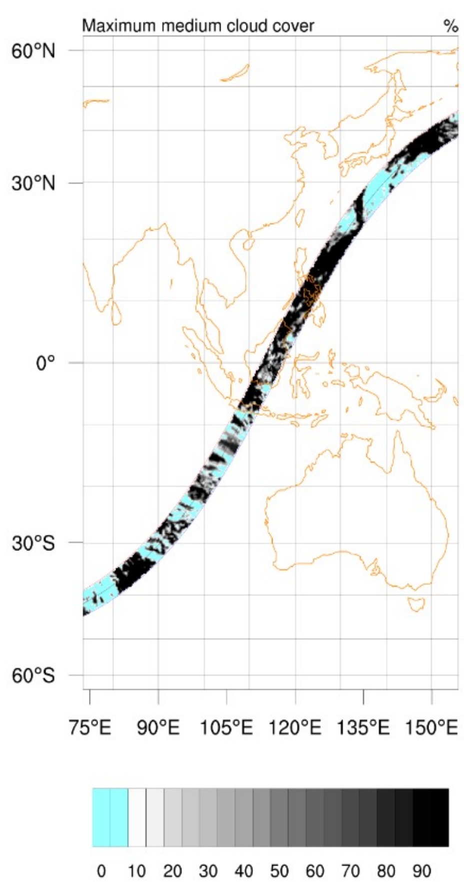




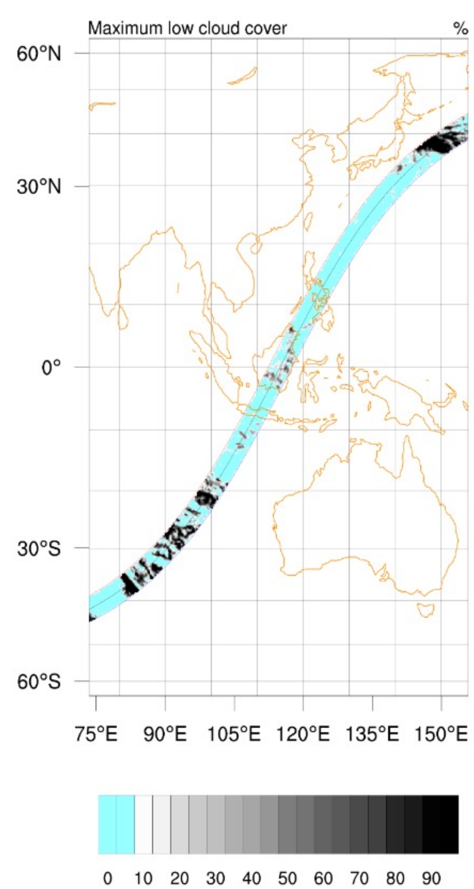
high



middle



low clouds



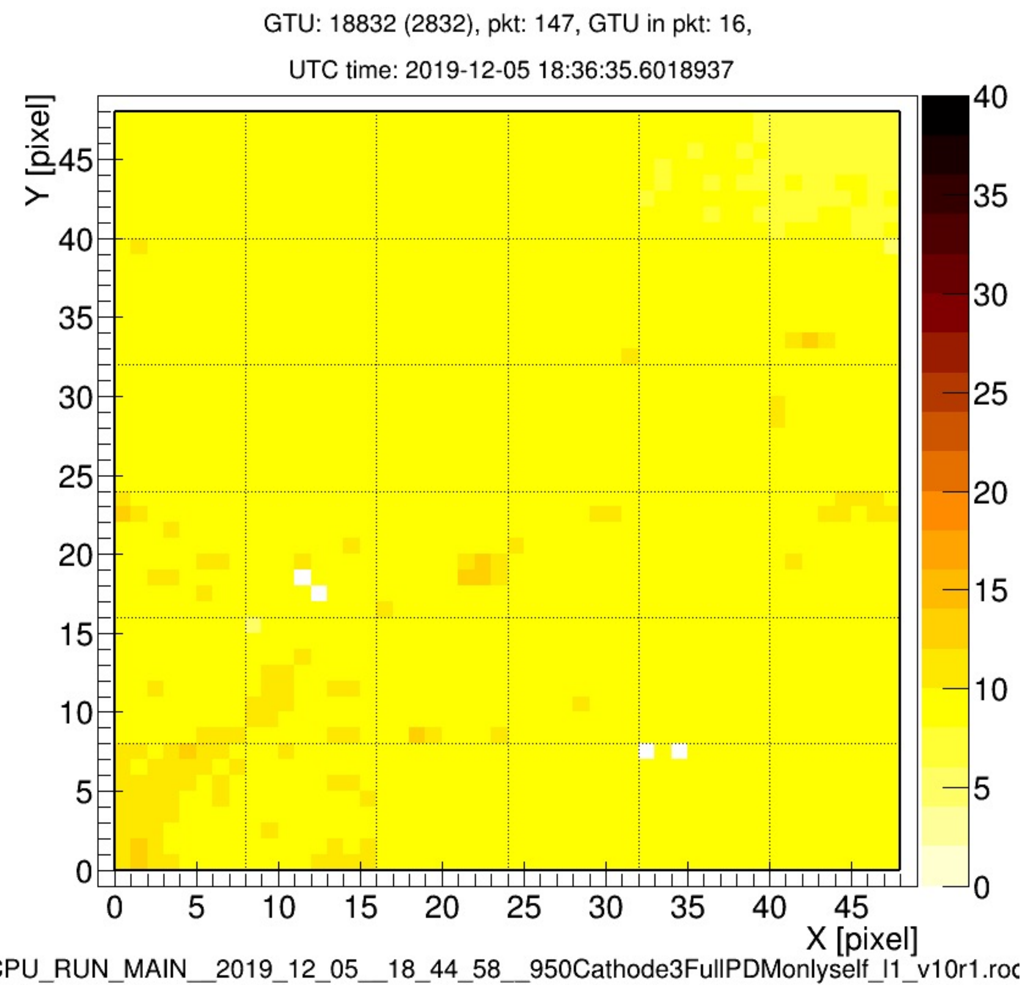
PRELIMINARY

(using same approach as EUSO-Balloon)

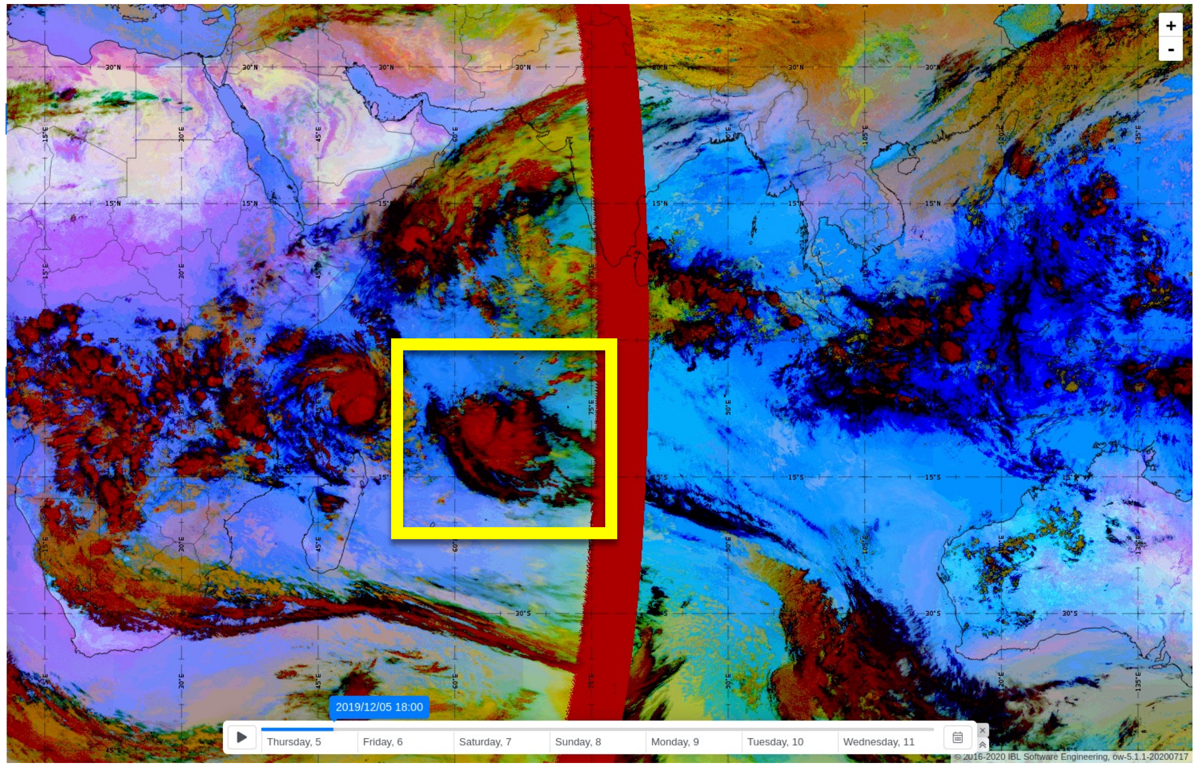
	Observation time [h]	Average rate [count / (pixel 2.5 µs)]
All data	25.9	5.2
Sea data	14.6 (56%)	4.5
Sea & no moon	7.0 (27%)	**1.5**

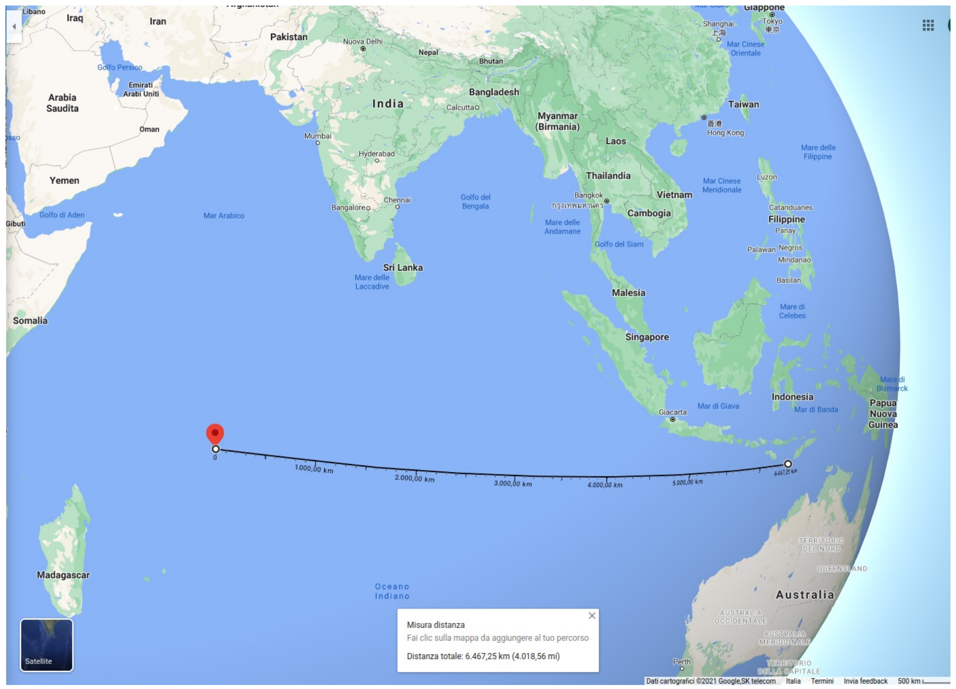
- For this condition, the average of 1.5 counts per pixel^{-1} 2.5 µs^{-1} is consistent with ~550 photons m^{-2} sr^{-1} ns^{-1} for 250--500 nm

Cloud Systems

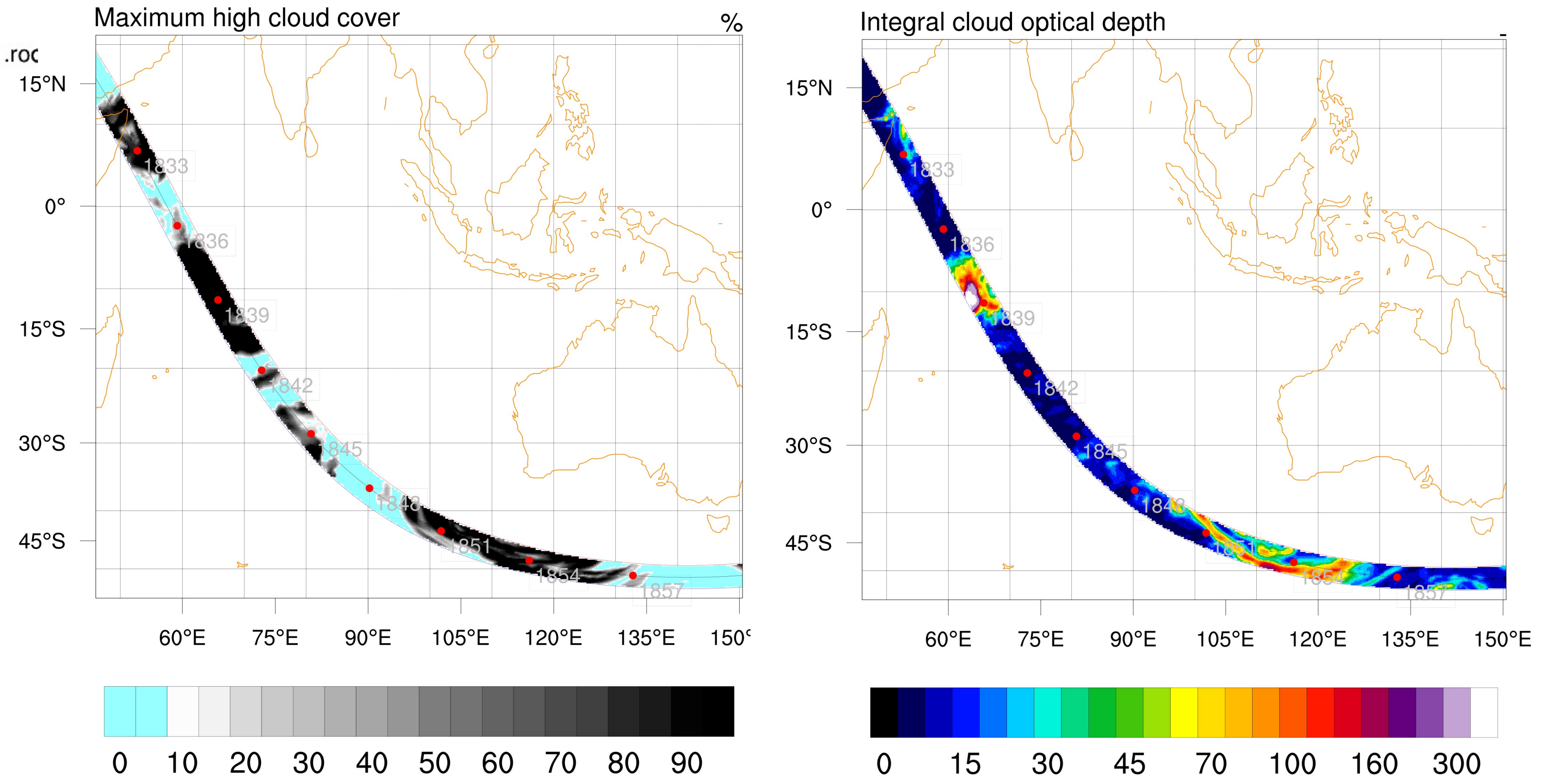


Himawari & Meteosat satellites

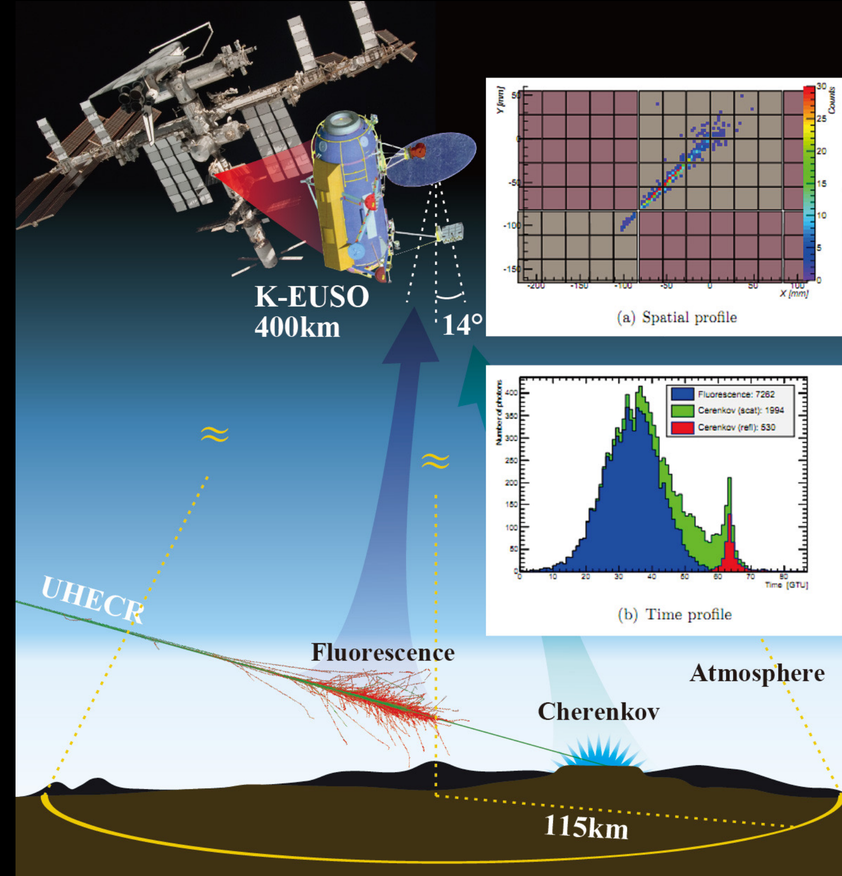




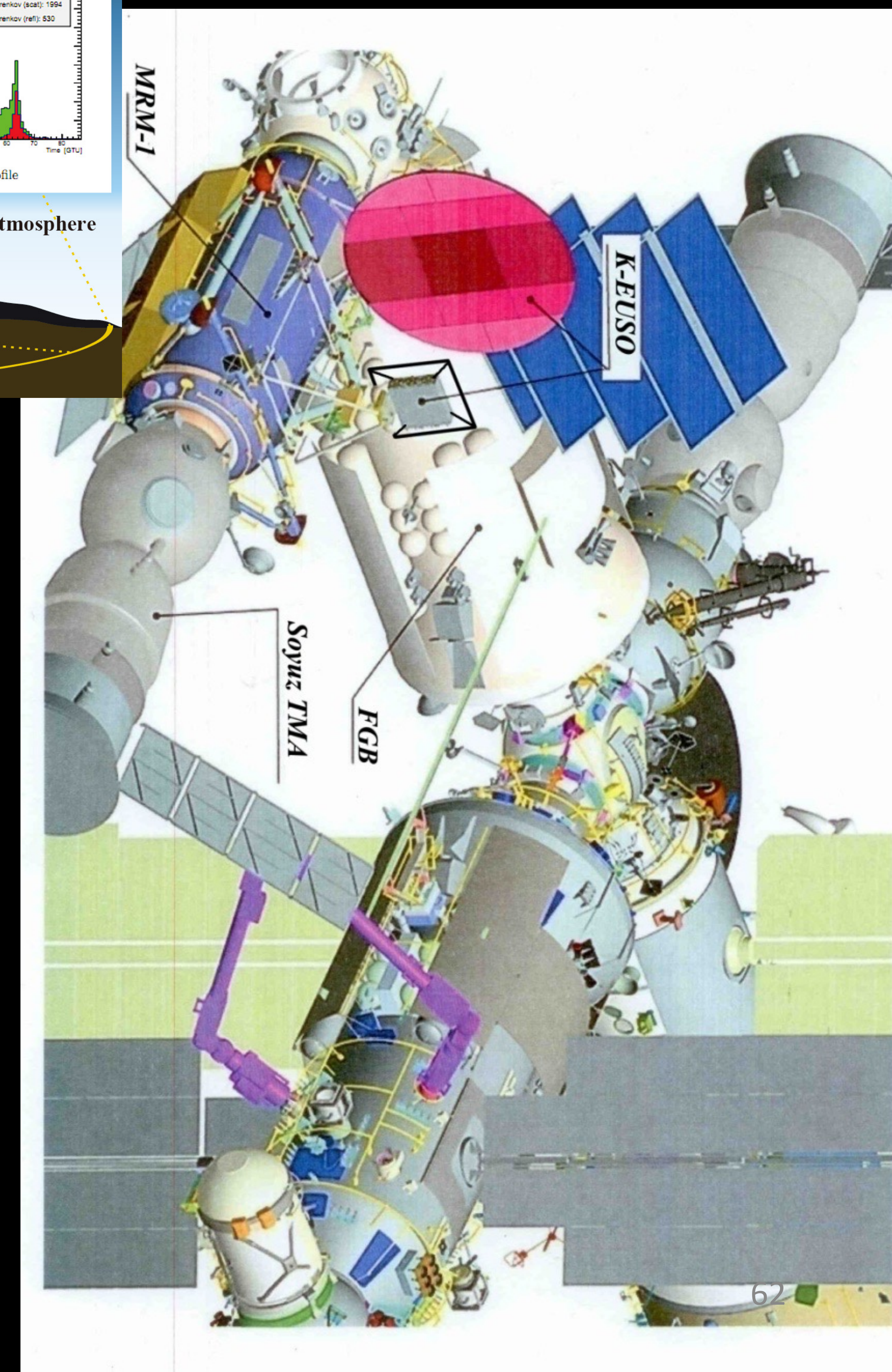
ERA model



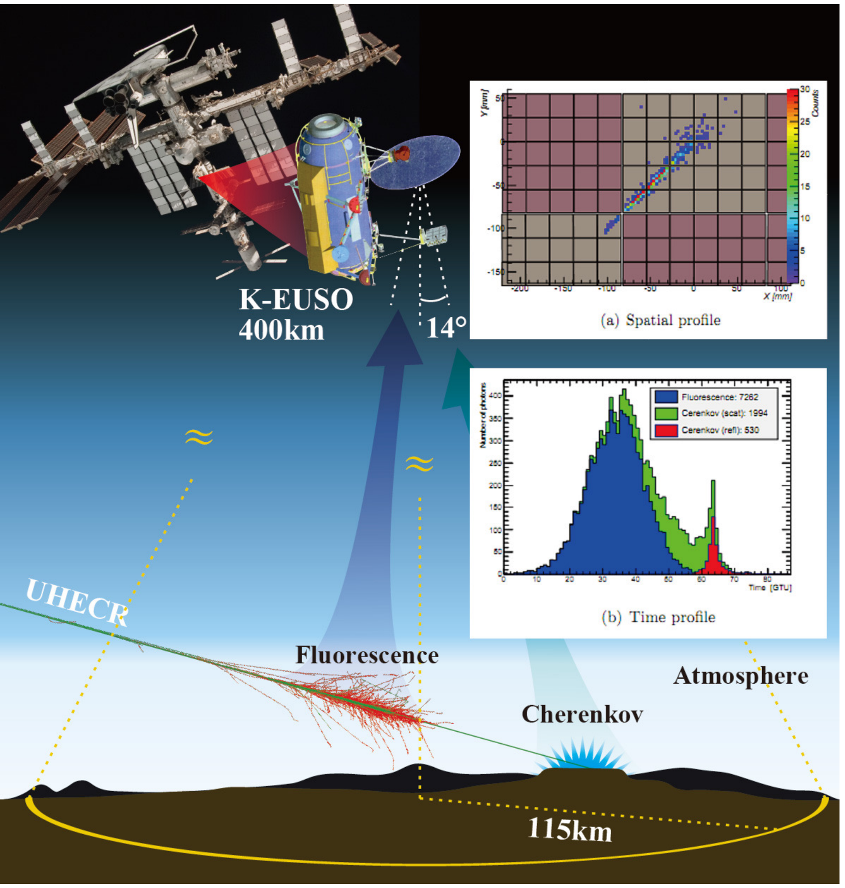
K-EUSO



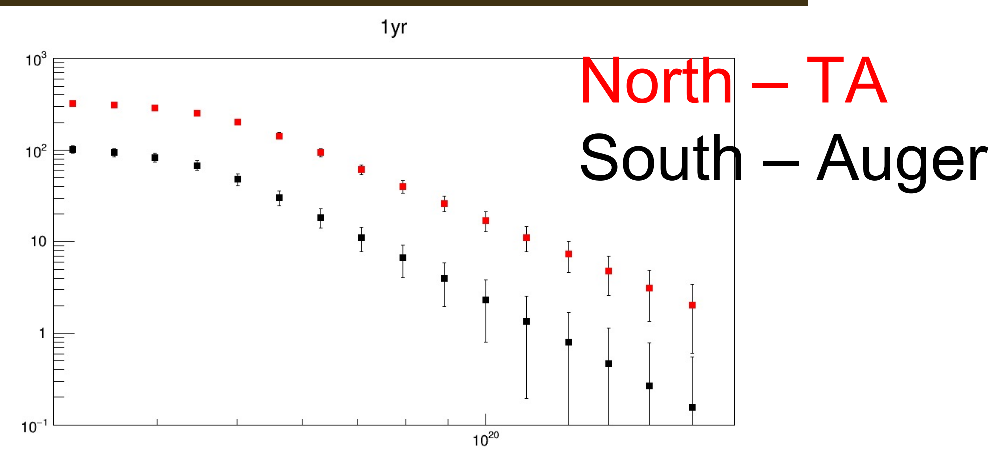
- In the Russian Federal Space Program
- Passed the stage of preliminary design with Roscosmoc
- Technical requirements, accomodation, operations study performed by Energia space corporation
- Evolution of KLYPVE Russian detector (reflector)
- Launch in 2024+

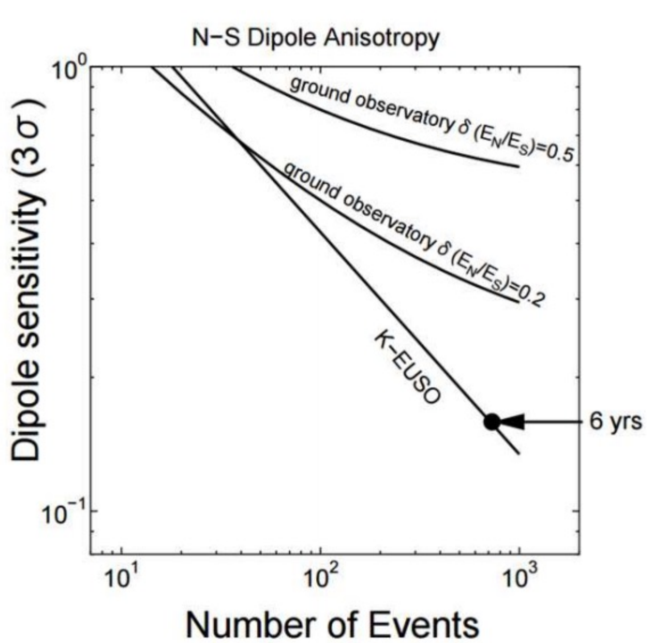


K-EUSO



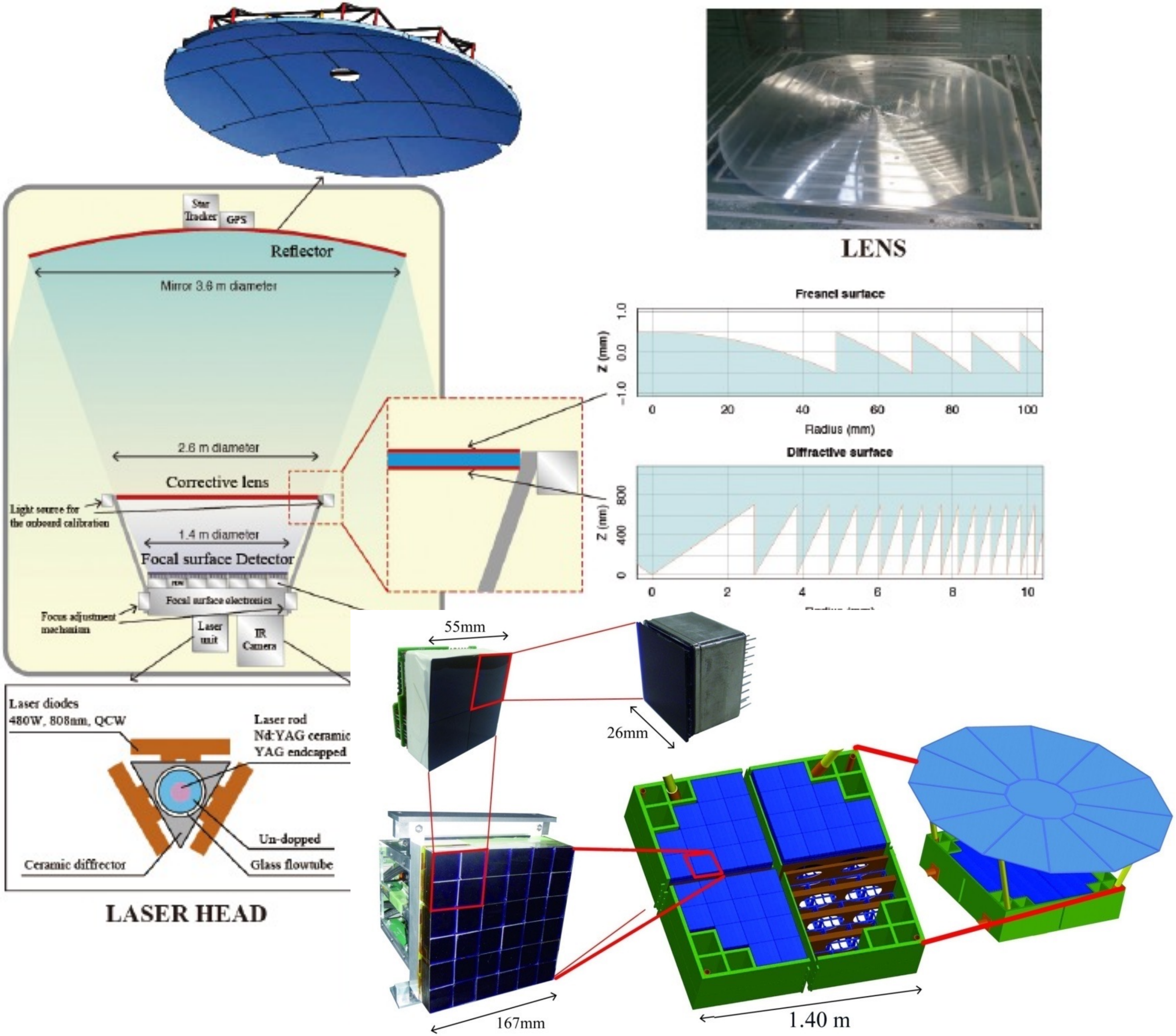
The design of the detector should provide measurements of UHECR with a threshold neat 50 EeV with statistics of ~100 events per year.





- Scientific objectives:
  UHECR fluorescent radiation measurements from space
- Placement:
  Russian Segment of the ISS
- Main technical parameters

✓ K-EUSO – Telescope with an optical Schmidt scheme (a large area of the entrance window and a wide field of view)
  - ✓ Mirror diameter – 3.6-4 м
  - ✓ Time resolution 1-2.5 us
  - ✓ FOV 40 degrees.
  - ✓ Angular resolution ~10^{-6} sr
  - ✓ Mass ~ 500 - 850 kg

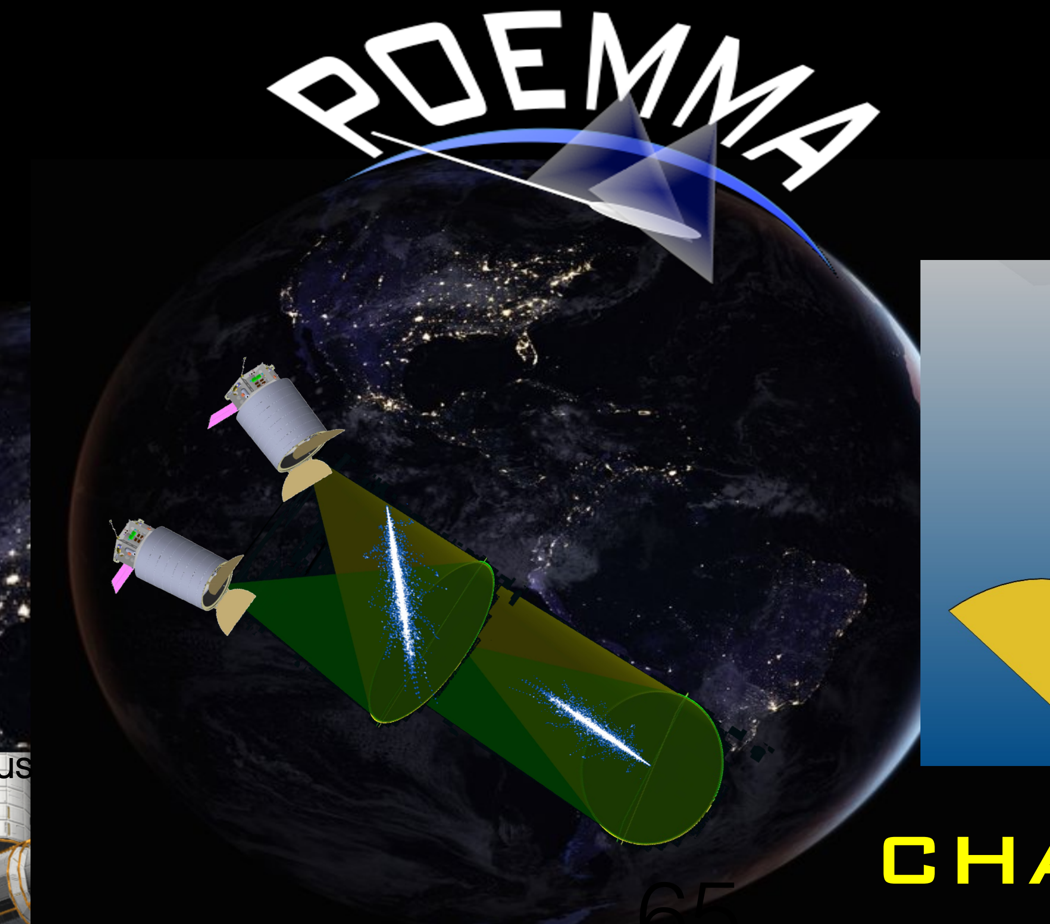


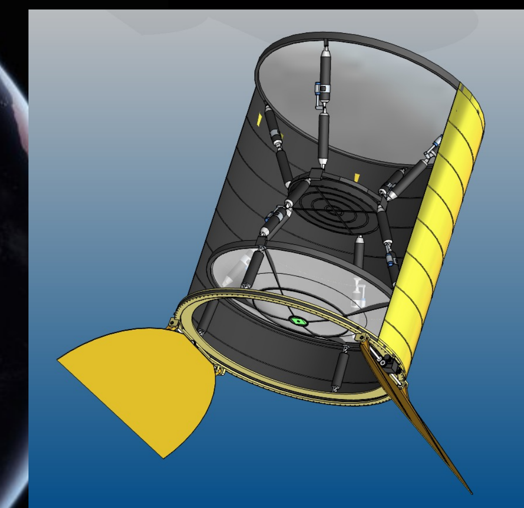
Star Tracker
GPS
Reflector
Mirror 3.6 m diameter
2.6 m diameter
Corrective lens
Light source for the onboard calibration
1.4 m diameter
Focal surface Detector
Focal surface electronics
Focus adjustment mechanism
Laser unit
IR Camera
LENS
Fresnel surface
Z (mm)
Radius (mm)
Diffractive surface
Z (nm)
Laser diodes
480W, 808nm, QCW
Laser rod
Nd:YAG ceramic
YAG endcapped
Un-dopped
Glass flowtube
Ceramic diffractor
LASER HEAD
55mm
26mm
167mm
1.40 m

POEMMA: Probe of Extreme Multi-Messenger Astrophysics

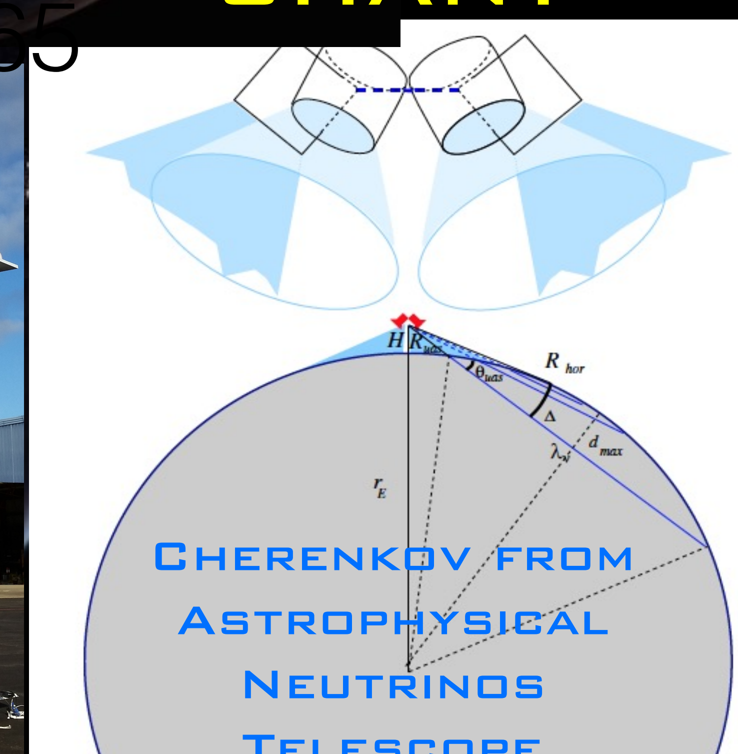
POEMMA Design based on:

OWL and JEM-EUSO studies,
EUSO balloon experience,
& CHANT concept
+ Legacy in Fluorescence from Ground

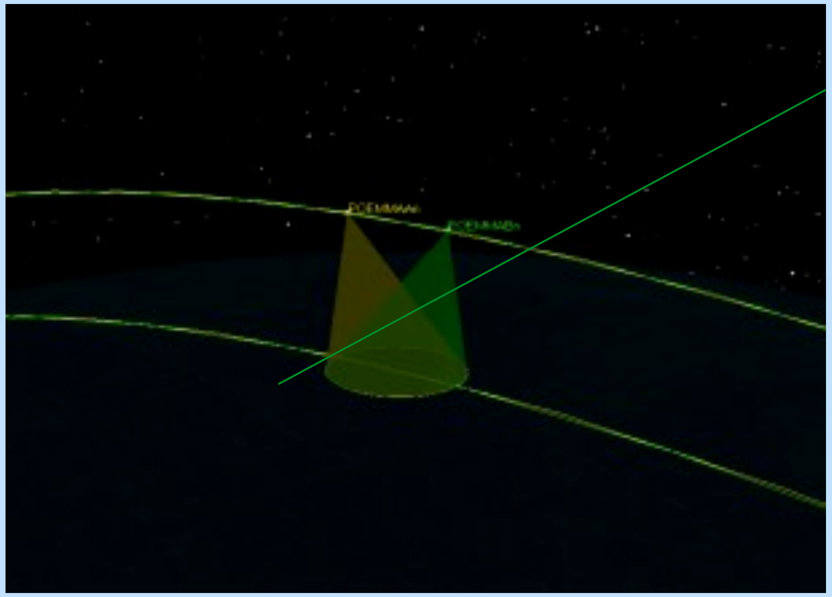




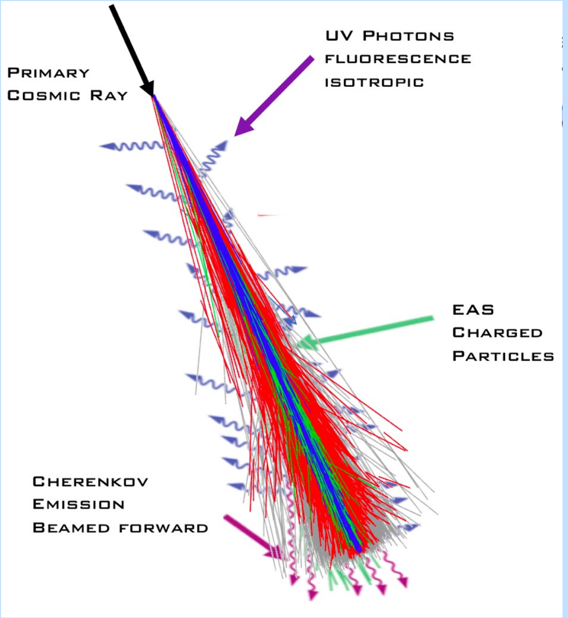
CHANT

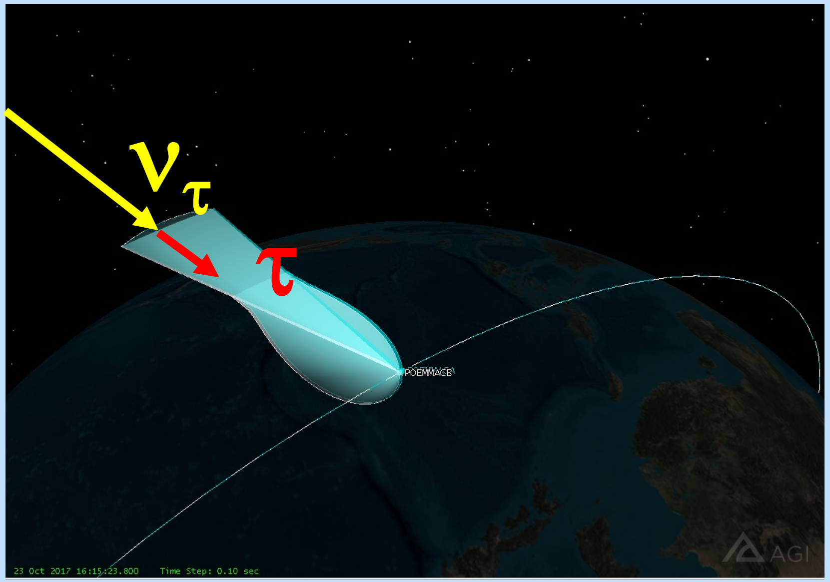


Mission Concept



Stereo Viewing of UHECRs E ≳ 20 EeV
via Fluoresence: 10's of μsec timescale





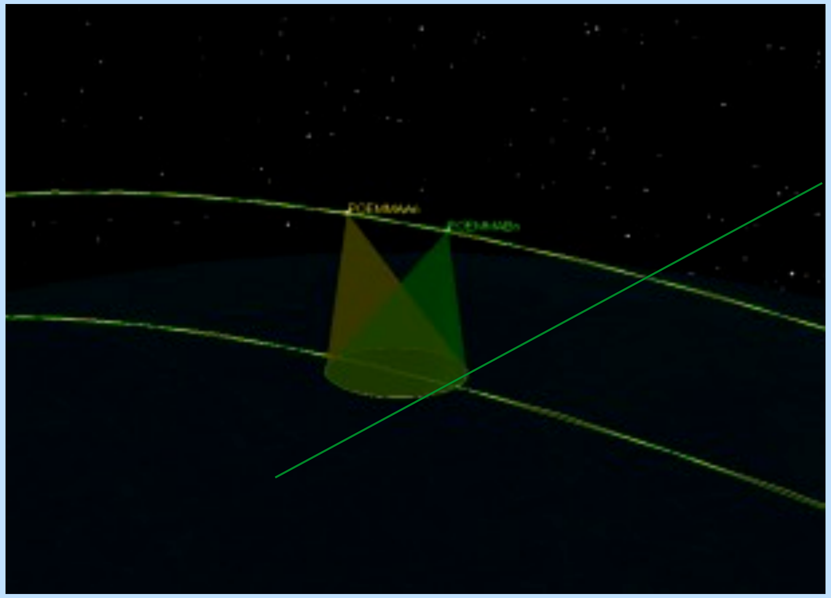
Upward τ-lepton EAS E ≳ 20 PeV
via Cherenkov: ~10 nsec timescale

POEMMA & Mission Description:
Summary of results presented in arXiv:2012.07945

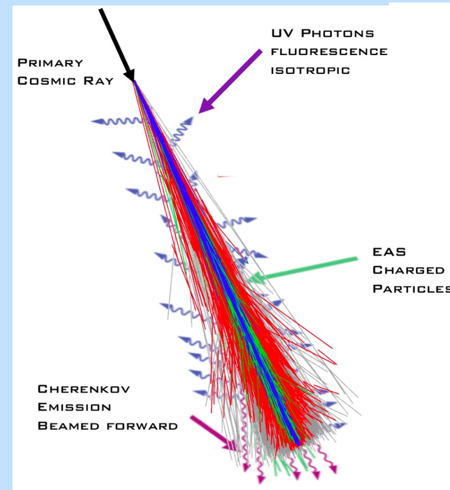
POEMMA UHECR & *UHE Neutrino Performance via air fluorescence* measurements.
Summary of results presented in PhysRevD.101.023012

POEMMA *VHE Neutrino Performance via optical Cherenkov measurements*.
Summary of results presented in PhysRevD.100.063010 and PhysRevD.102.123013

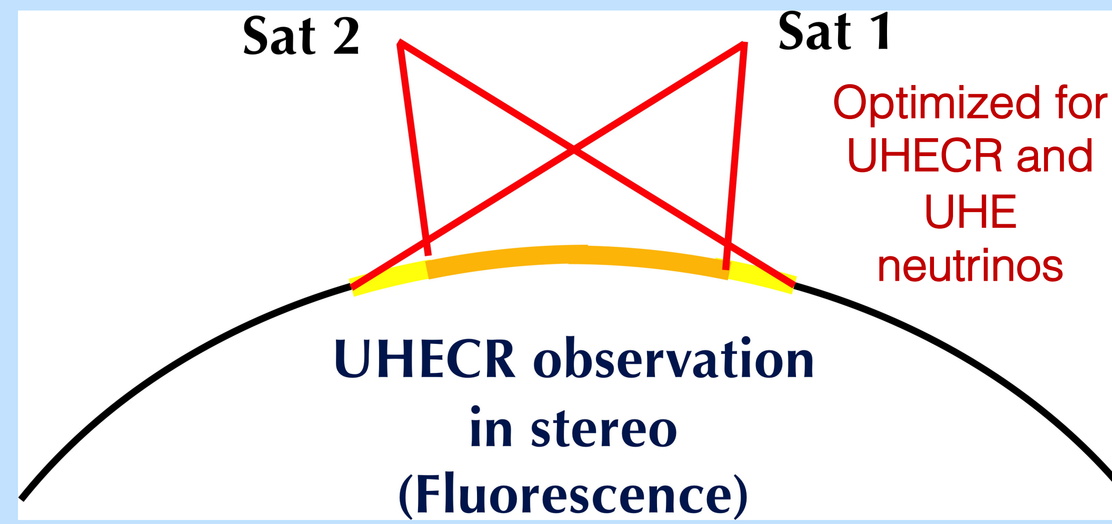
POEMMA Operational Modes: UHECR Stereo versus Limb-viewing Neutrino

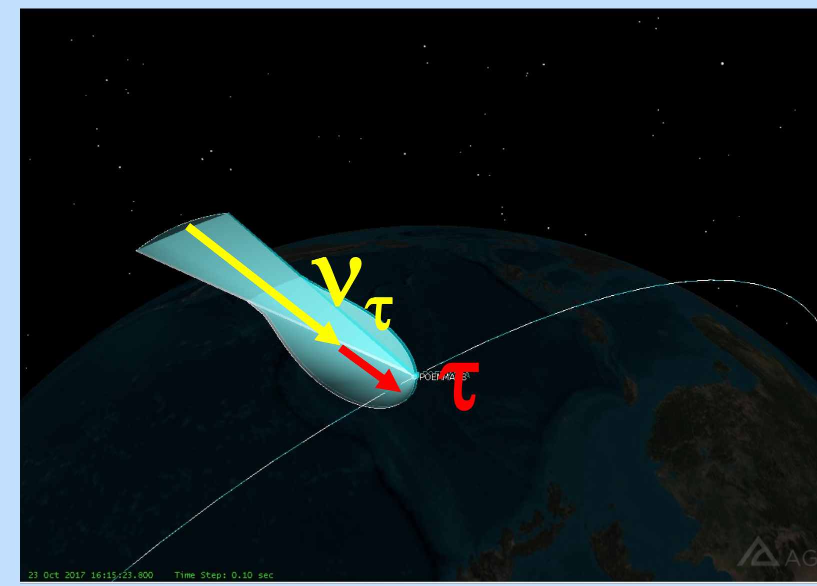


Stereo Viewing of UHECRs E ≳ 20 EeV via Fluoresence: 10's of μsec timescale

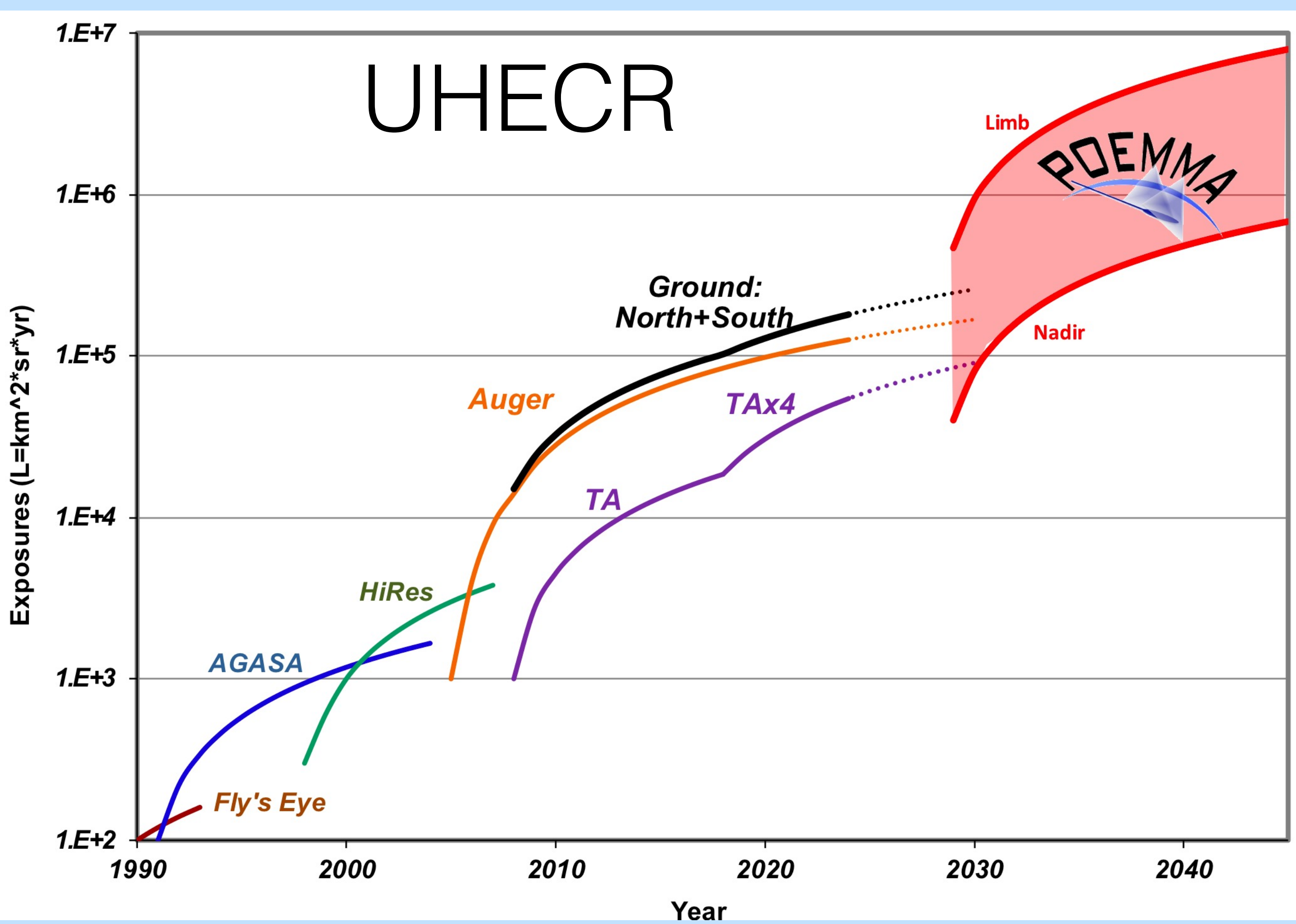


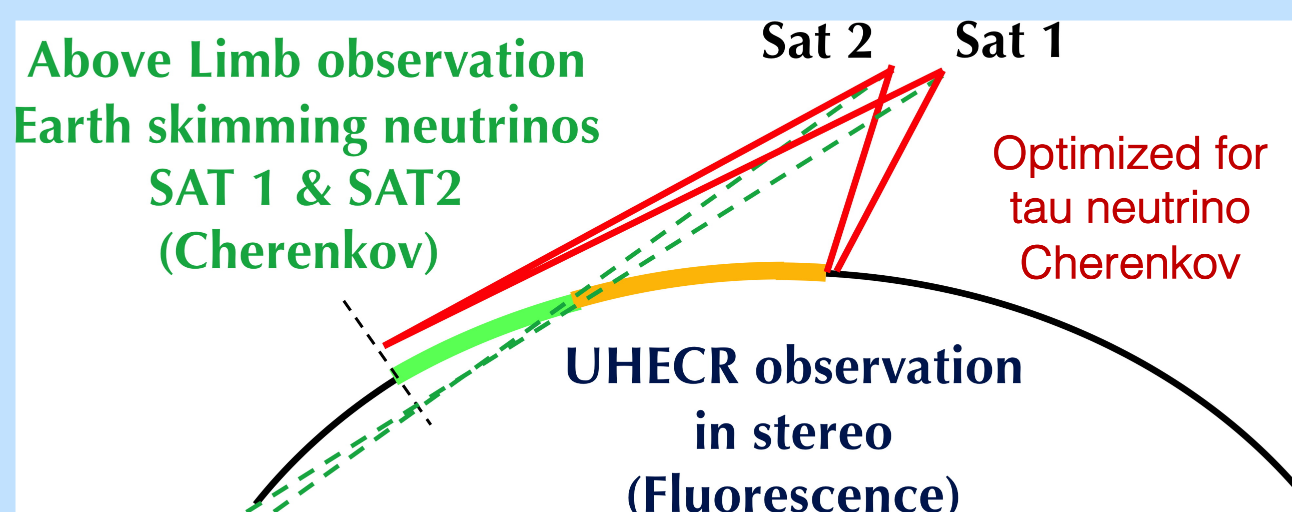
Dark, quasi-moon less nights:
Fluorescence Duty Cycle: 11%
Cherenkov Duty Cycle: 20%



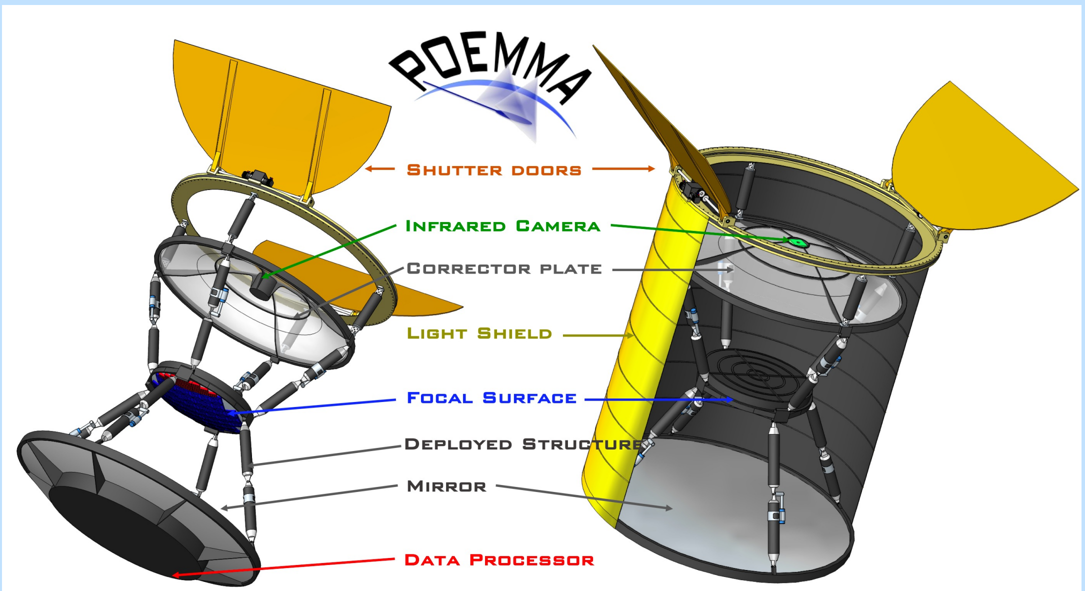


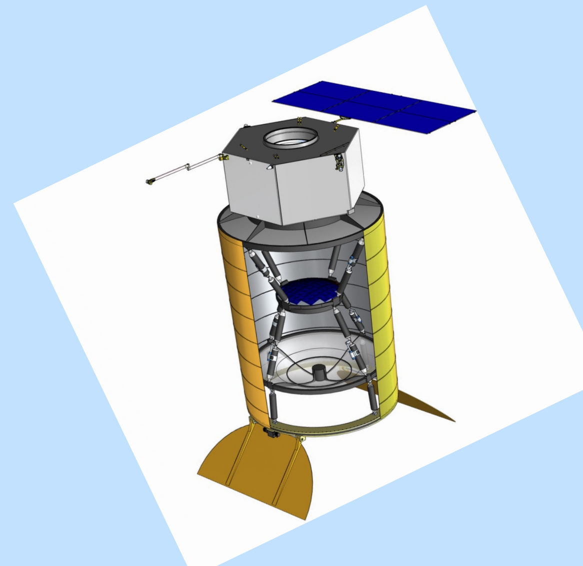
Upward τ-lepton EAS E ≳ 20 PeV via Cherenkov: ~10 nsec timescale





POEMMA: Instruments defined by weeklong IDL run at GSFC





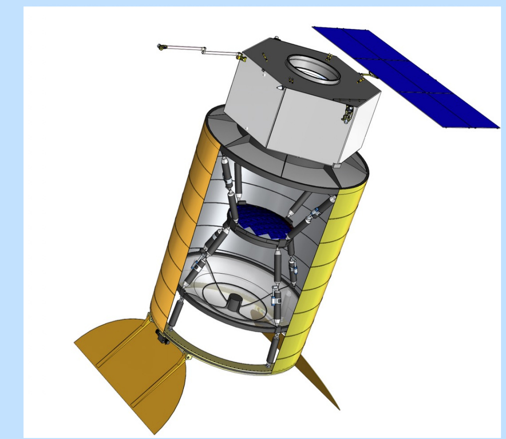
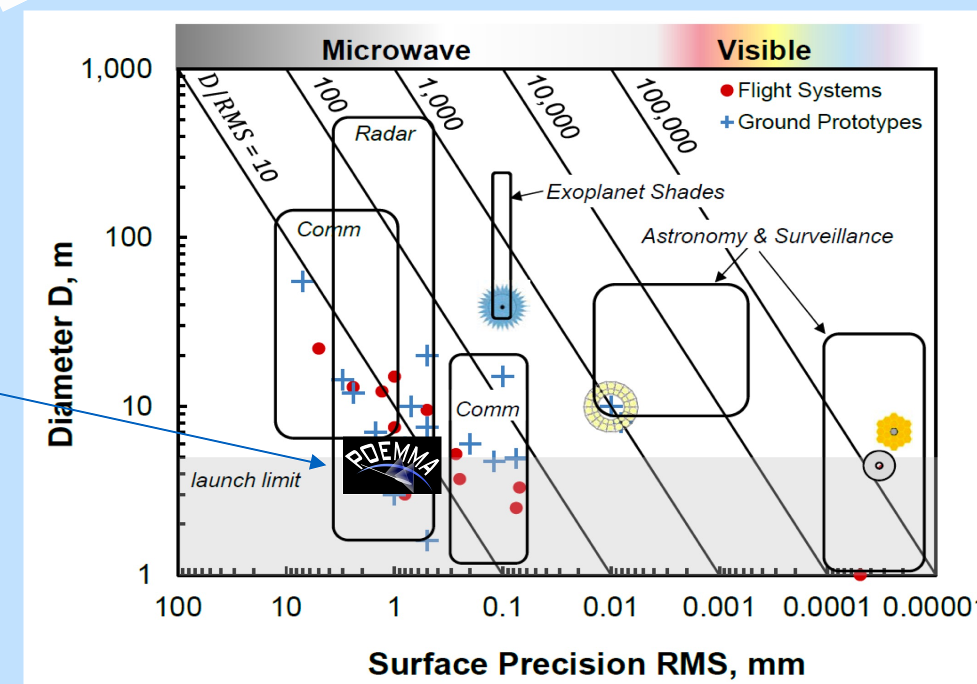


TABLE I: POEMMA Specifications:

Photometer	Components		Spacecraft	
Optics	Schmidt	45° full FoV	Slew rate	90° in 8 min
	Primary Mirror	4 m diam.	Pointing Res.	0.1°
	Corrector Lens	3.3 m diam.	Pointing Know.	0.01°
	Focal Surface	1.6 m diam.	Clock synch.	10 nsec
	Pixel Size	3×3 mm^2	Data Storage	7 days
	Pixel FoV	0.084°	Communication	S-band
PFC	MAPMT (1μs)	126,720 pixels	Wet Mass	3,450 kg
PCC	SiPM (20 ns)	15,360 pixels	Power (w/cont)	550 W
Photometer	(One)		Mission	(2 Observatories)
	Mass	1,550 kg	Lifetime	3 year (5 year goal)
	Power (w/cont)	700 W	Orbit	525 km, 28.5° Inc
	Data	< 1 GB/day	Orbit Period	95 min
			Observatory Sep.	~25 - 1000+ km

Each Observatory = Photometer + Spacecraft; POEMMA Mission = 2 Observatories

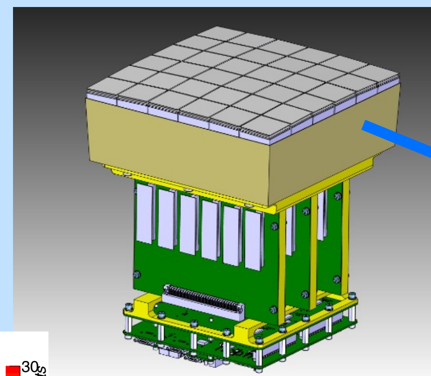


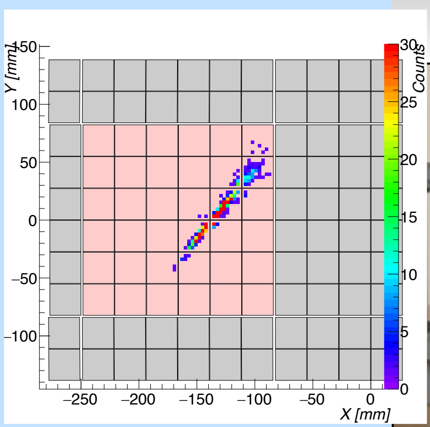
Imaging ~10^4 away from diffraction limit

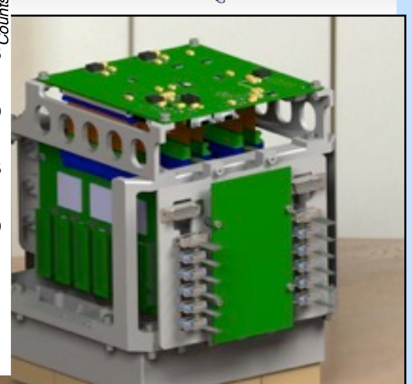
POEMMA: Hybrid Focal Plane

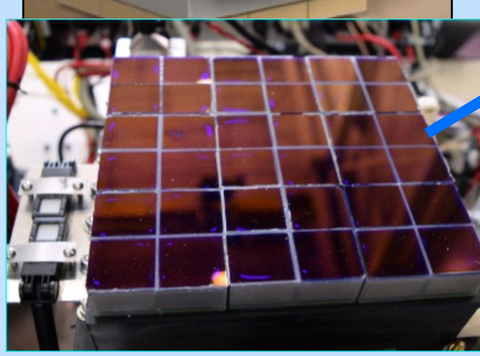
UV Fluorescence Detection using MAPMTs with BG3 filter (300 – 500 nm) developed by JEM-EUSO: 1 usec sampling

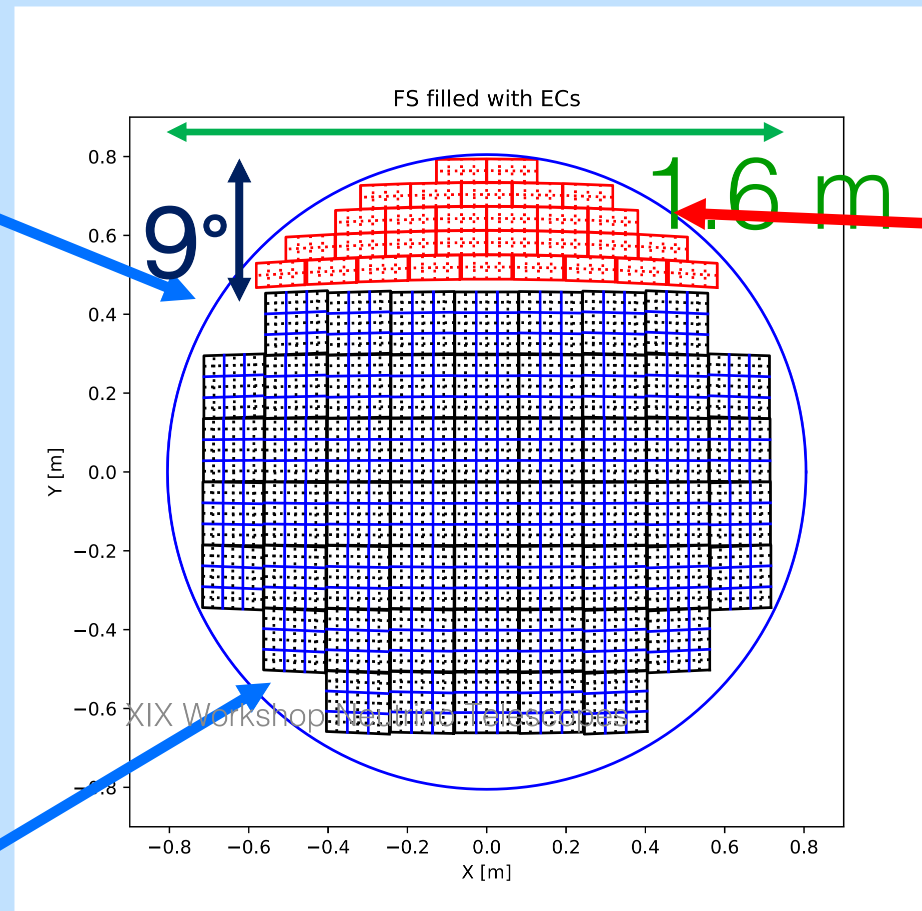
Cherenkov Detection with SiPMs (300 – 1000 nm): 20 nsec sampling

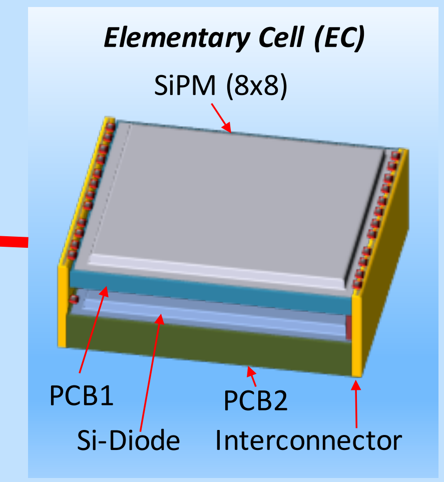








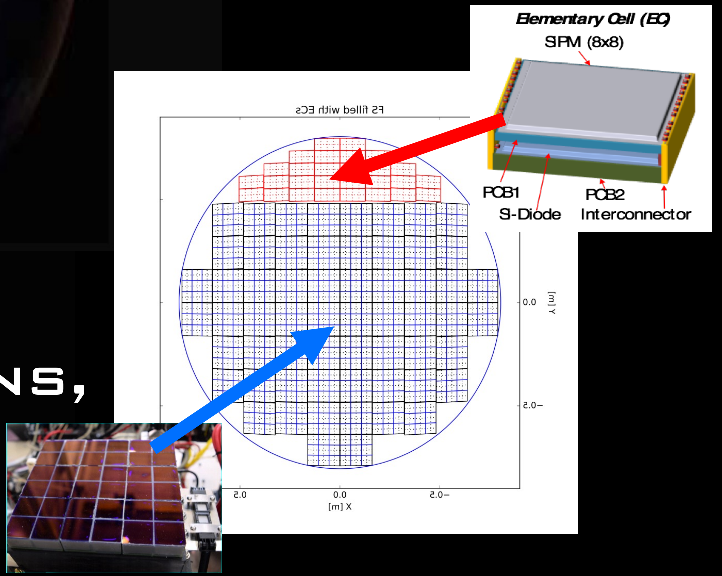




30 SiPM focal surface units
Total 15,360 pixels
512 pixels per FSU (64x4x2)
Si-Diode for LEO radiation backgrounds rejection

55 Photo Detector Modules (PDMs)= 126,720 pixels
1 PDM = 36 MAPMTs = 2,304 pixels

POEMMA UHECRs & νs



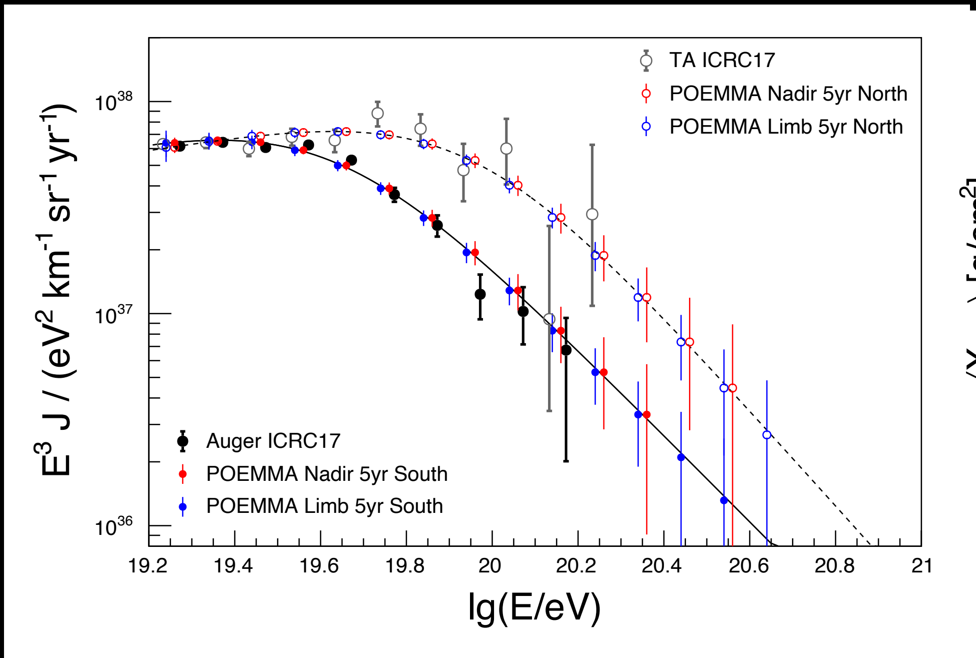
Significant increase in exposure

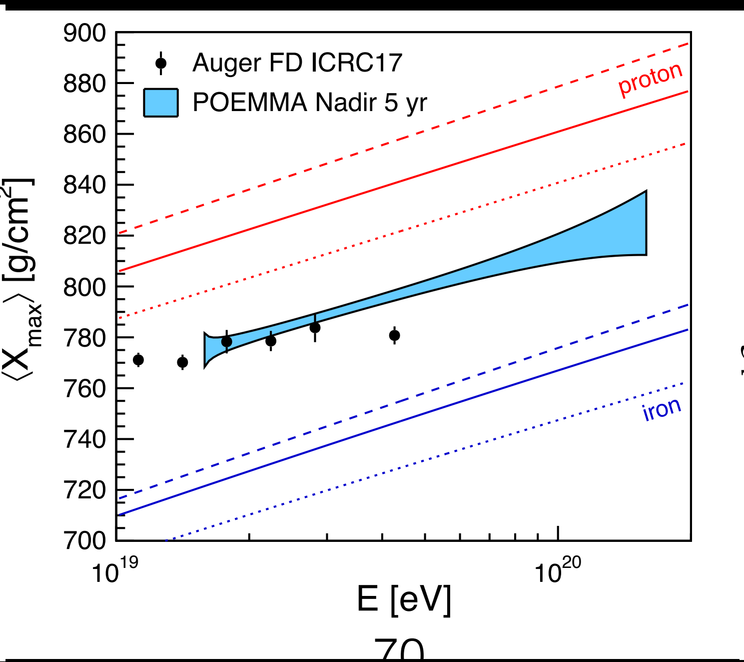
Good energy, angular, and shower maximum resolutions,

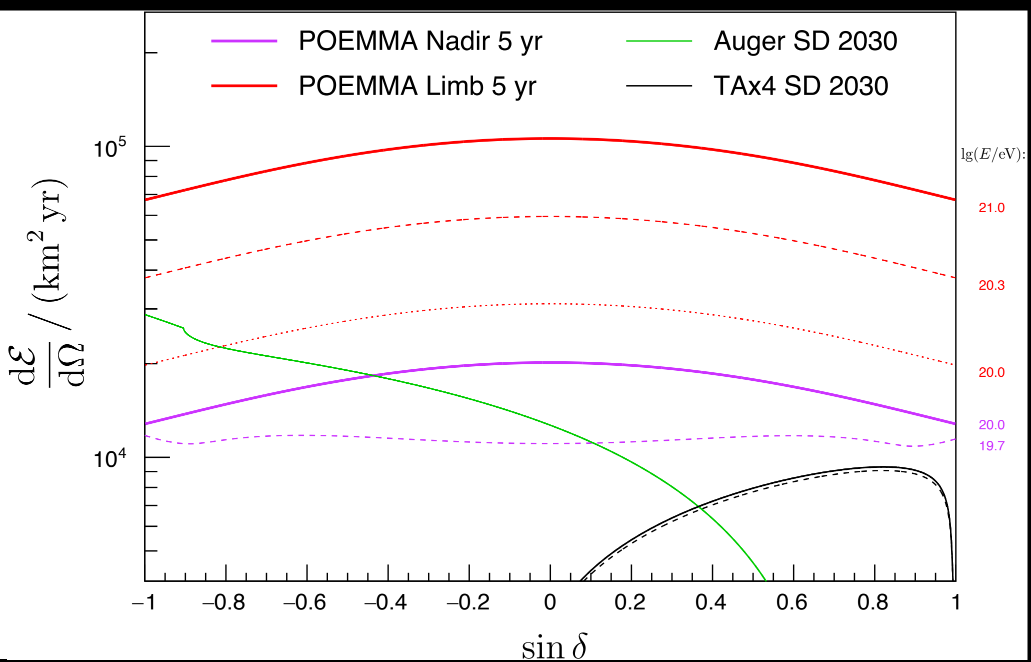
Uniform sky coverage

to guarantee the discovery of UHECR sources

Spectrum, Composition, Anisotropy E>50 EeV



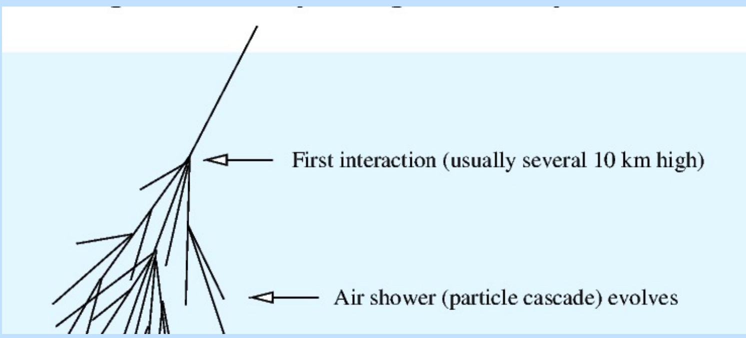


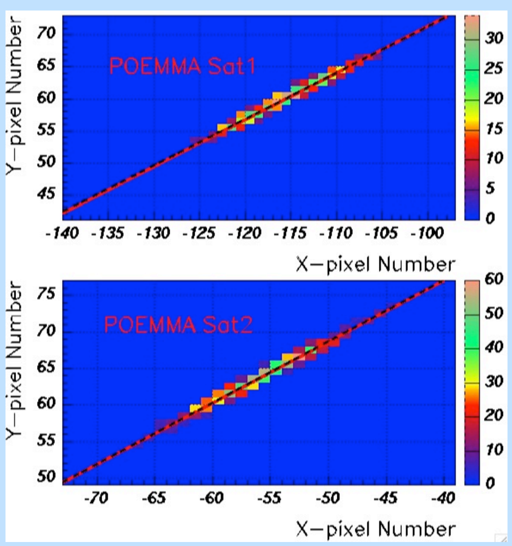


POEMMA: stereo reconstructed angular resolution: *see PhysRevD.101.023012*

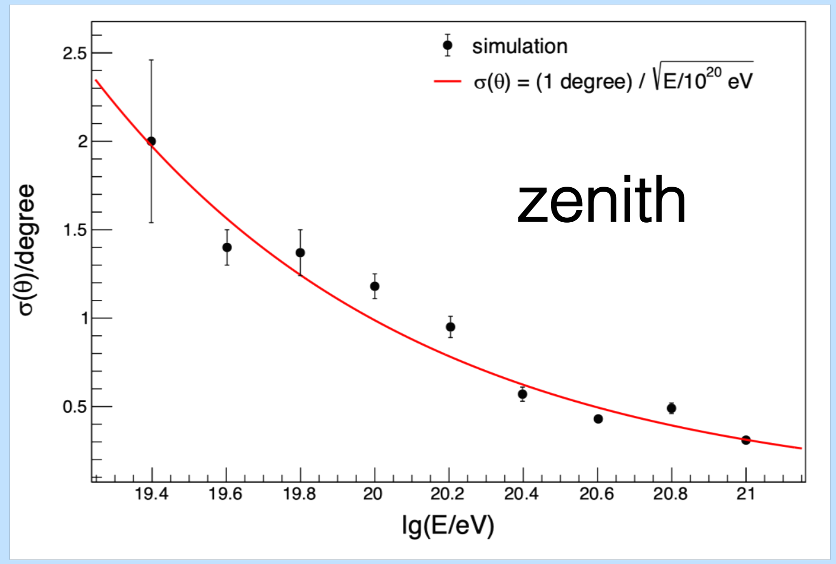
Excellent angular resolution → accurate determination of slant depth of EAS starting

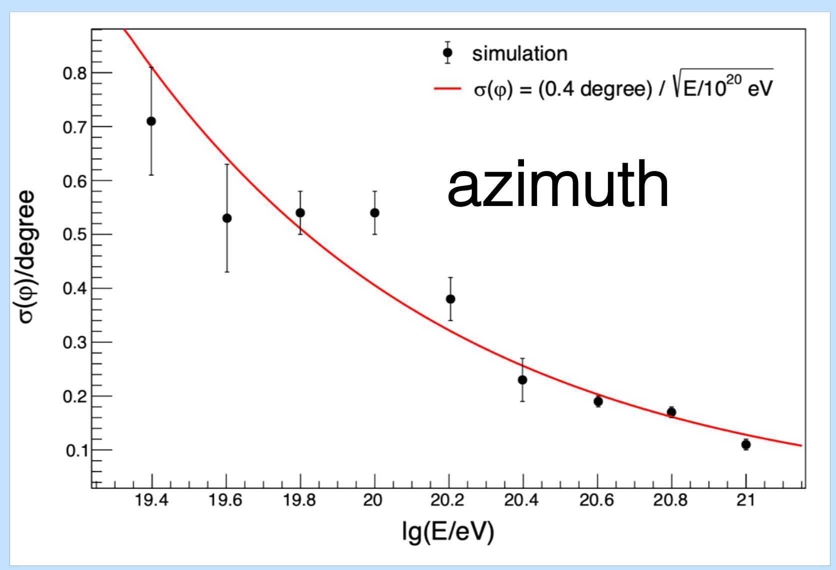
https://www.mpi-hd.mpg.de/hfm/CosmicRay/ShowerDetection.html

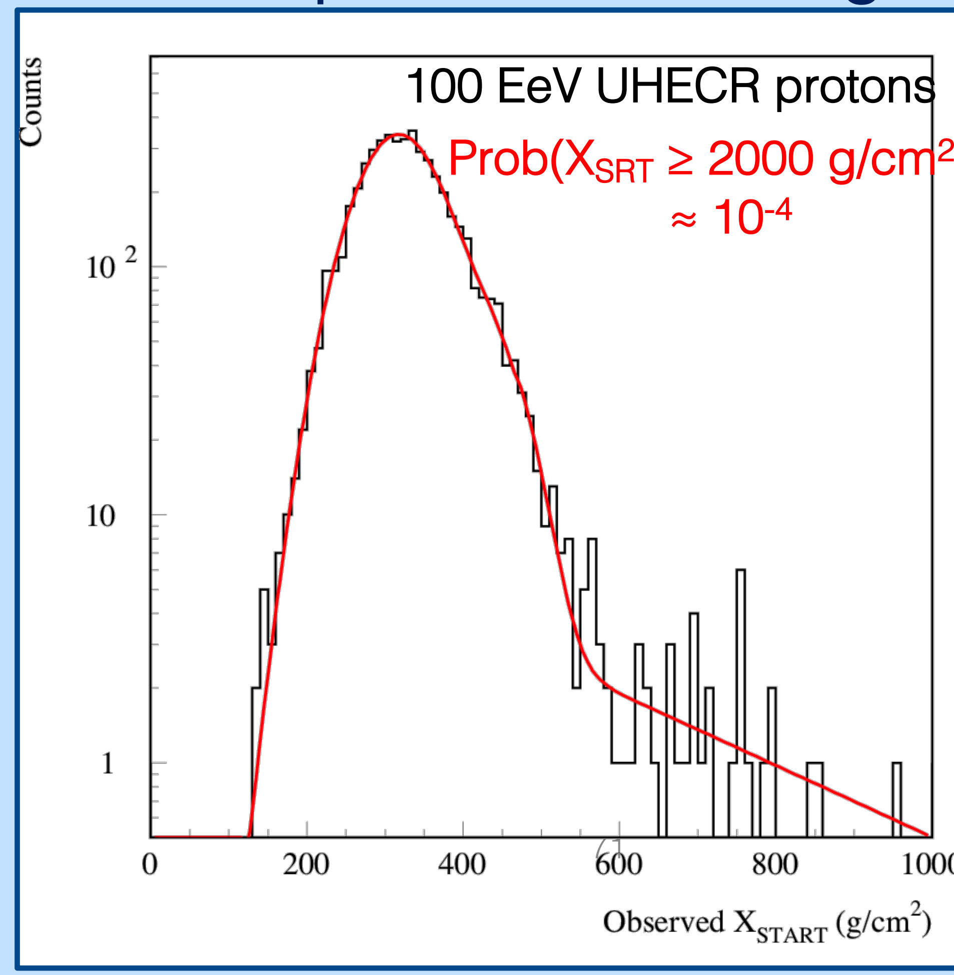




50 EeV simulated event







UHECR 100% proton assumption most conservative

Diffuse neutrino performance

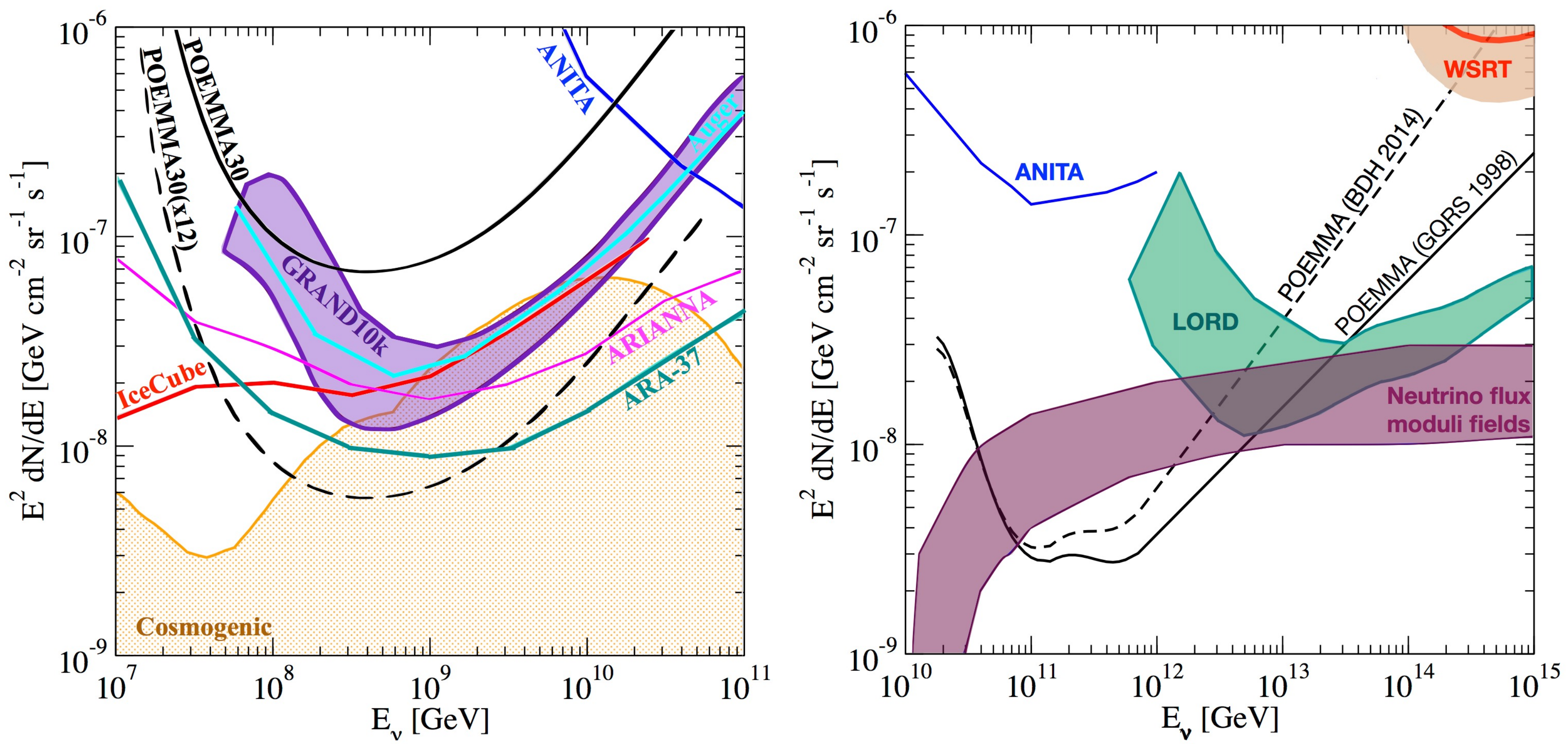
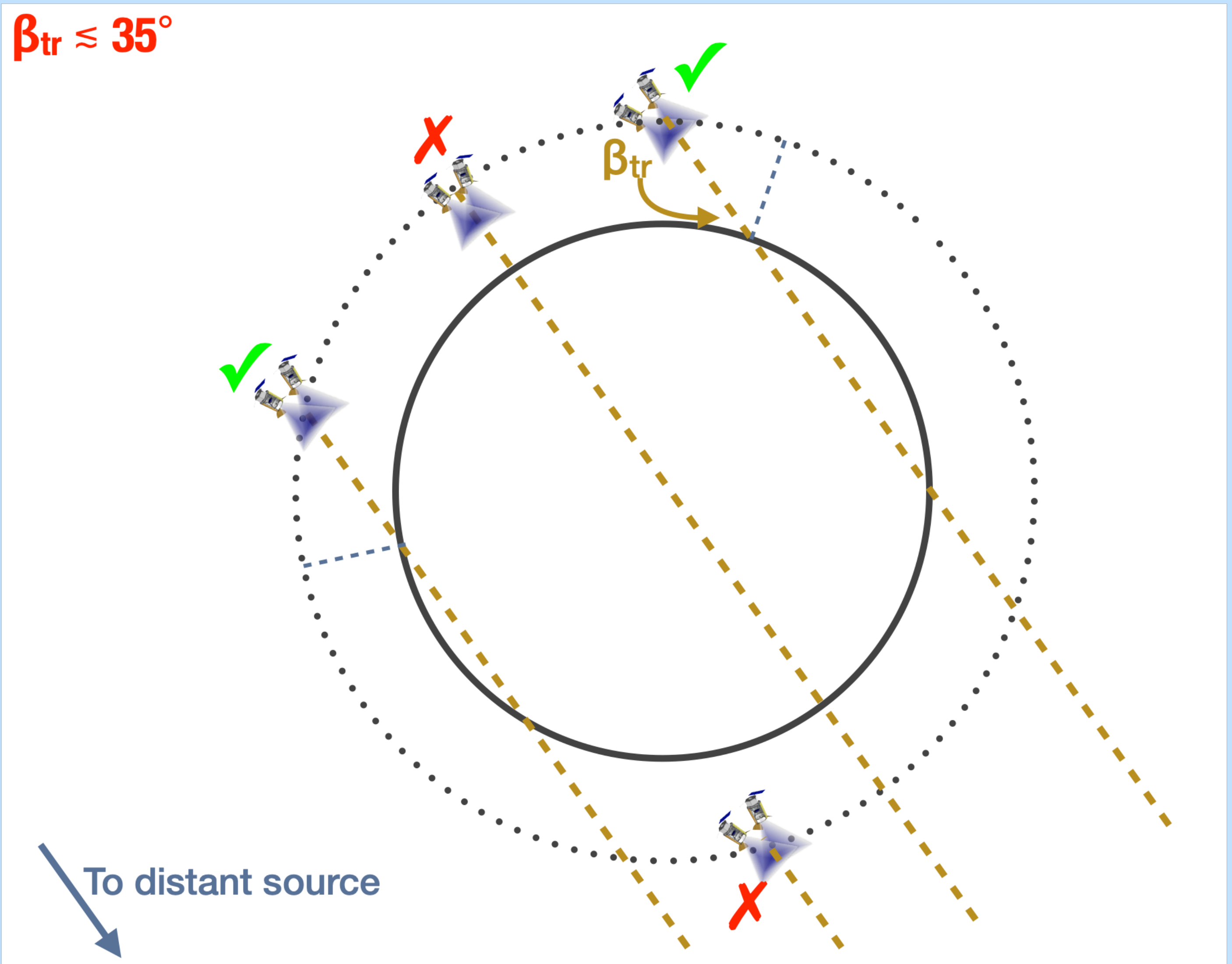
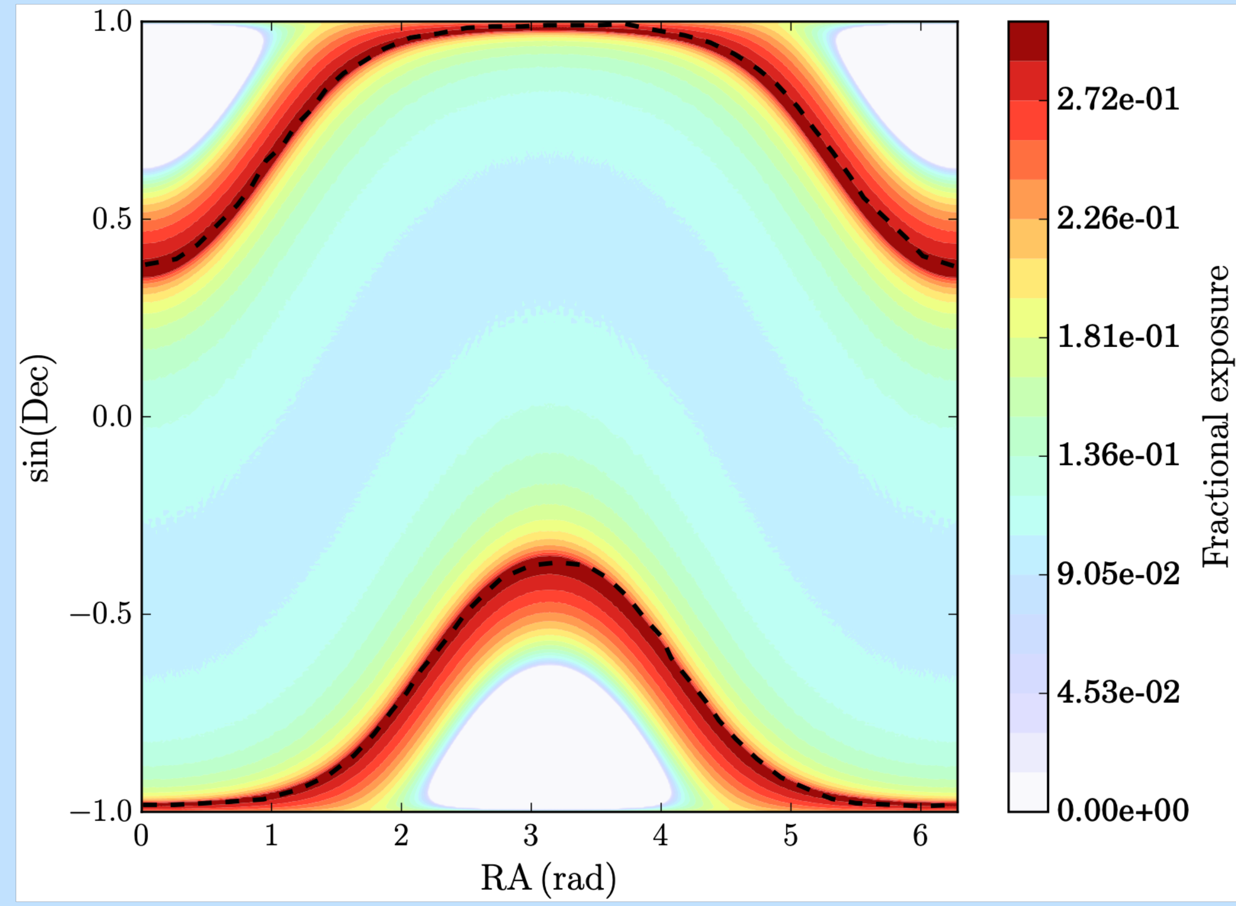
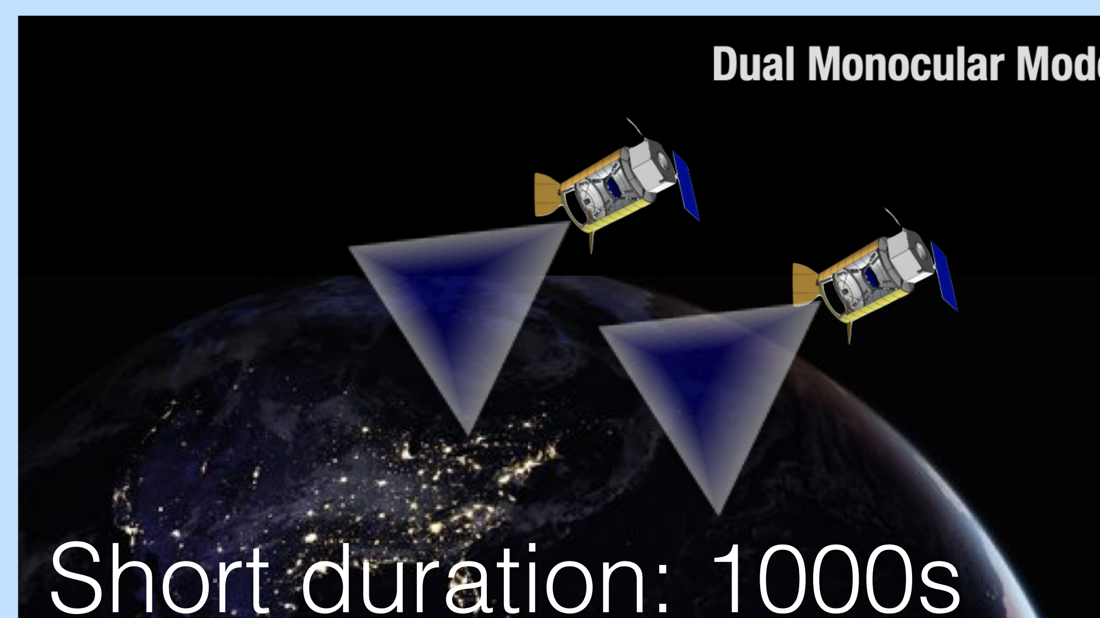


Figure 21. POEMMA 5-yr. sensitivity to EAS showers resulting from neutrino interactions in the Earth or in the atmosphere. Left: The black solid curve shows the POEMMA sensitivity to τ-induced EAS showers arising from ν_τ interactions in the Earth and detected via optical Cherenkov (scaled to three flavors) [139]. The black dashed curve is the sensitivity for POEMMA30(×12) (extrapolating the POEMMA30 sensitivity to 360° FoV in azimuth). The 90% CL upper limits from Auger (scaled for sliding decade-wide neutrino energy bins and for three flavors) [147], IceCube [148], and ANITA I-IV [149] are shown along with 3-yr. sensitivity projections for ARIANNA [150], ARA-37 [151], and GRAND10k [152]. For comparison, also plotted is the combined allowed ranges from [153] and [154] for the all-flavor cosmogenic neutrino flux arising from UHECR interactions with the cosmic microwave background. Right: Black curves show the POEMMA sensitivity to EAS showers arising from neutrino interactions in the atmosphere and detected via fluorescence from charged-current and neutral-current interactions from all three neutrino flavors. The solid (dashed) curve is calculated using cross sections from Ref. [155] (Ref. [142]). For comparison, predictions for strongly coupled string moduli (maroon band) [123] are also shown along with upper limits from ANITA I-IV (blue line) [149] and Westerbork Synthesis Radio Telescope (WSRT; red line with tan band) [156] and a projected sensitivity for LORD (green band) [157].

Exposure for ToO Observations







NEUTRINO: Target Of Opportunity (TOO)

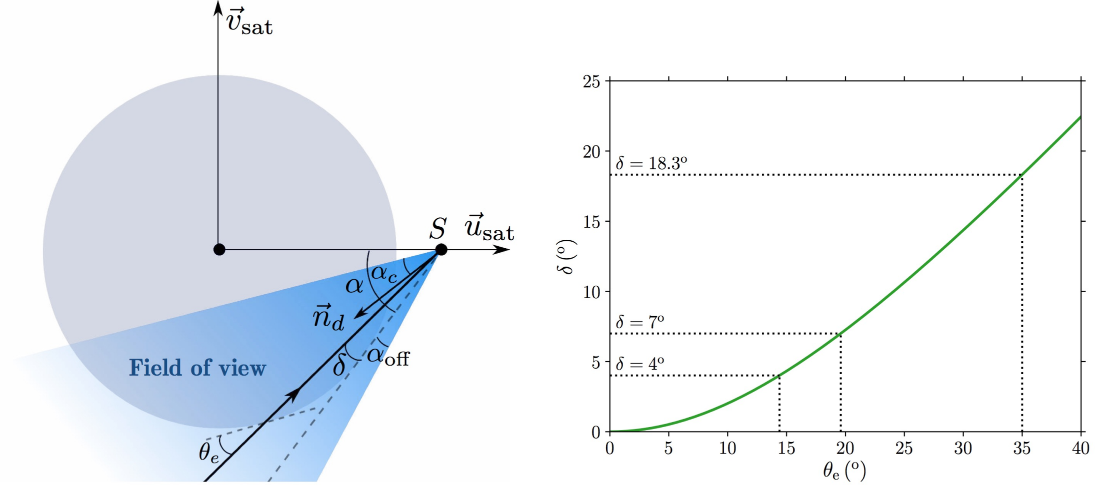


Figure 14. Left: Illustration of the geometrical configuration in the orbital plane (satellite position, $\vec{u}_{sat}$, versus satellite velocity $\vec{v}_{sat}$). The satellite is located at point S. The arrival direction of an EAS generated by a ν_τ is characterized by its Earth emergence angle θ_e and the corresponding angle away from the limb δ in the point of view of the satellite. The detector has a conical FoV of opening angle α_c, with an offset angle α_{off} (away from the Earth limb) and pointing direction $\vec{n_d}$. Right: Cherenkov viewing angle δ below the limb versus Earth emergence angle θ_e [77].

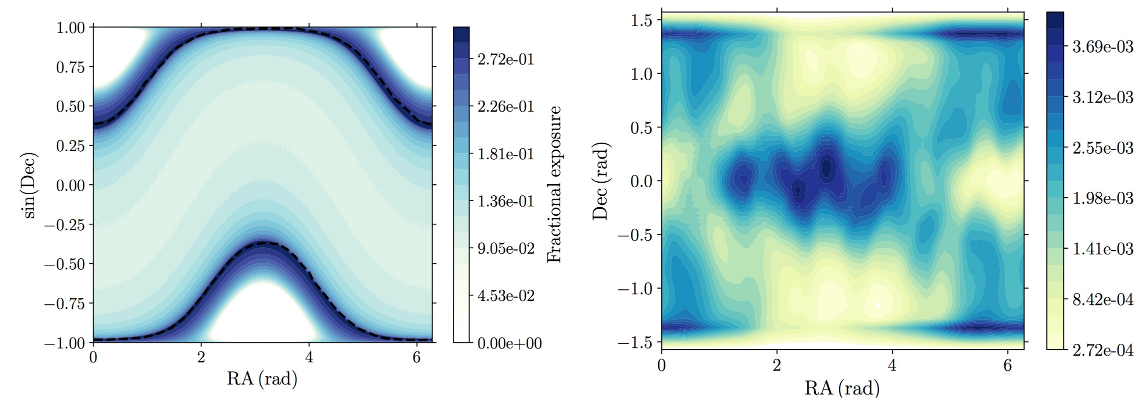


Figure 18. POEMMA cosmic neutrino sky coverage Left: Sky coverage for sources at a given orbital position in the sine of the declination and right ascension, without including the effect of the Sun, at a given time of the year for viewing angles to δ = 18.3° below the limb [2]. Right: The fractional neutrino sky exposure for one year in declination versus right ascension, assuming a defined variation in the POEMMA limb-pointing directions over the year to achieve full-sky coverage. The calculation takes into account the effects of the sun and moon on the duty cycle for observations [77].

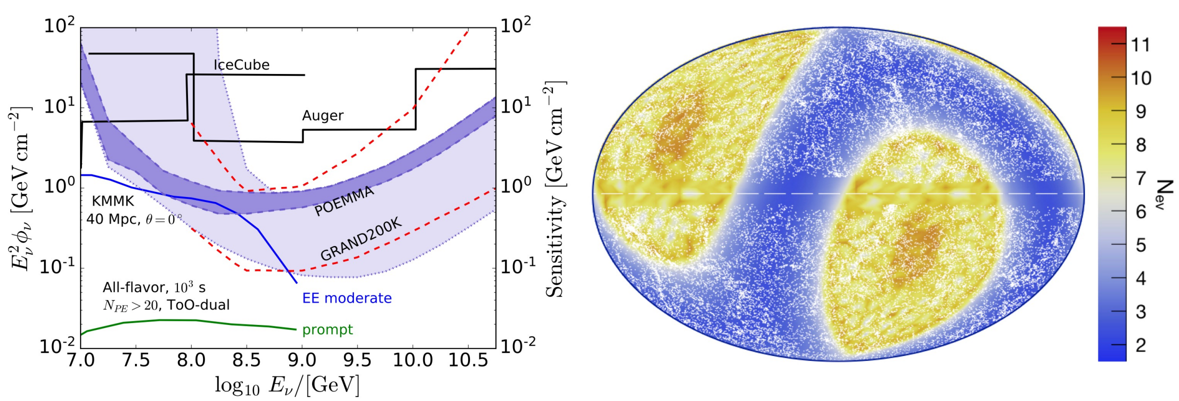
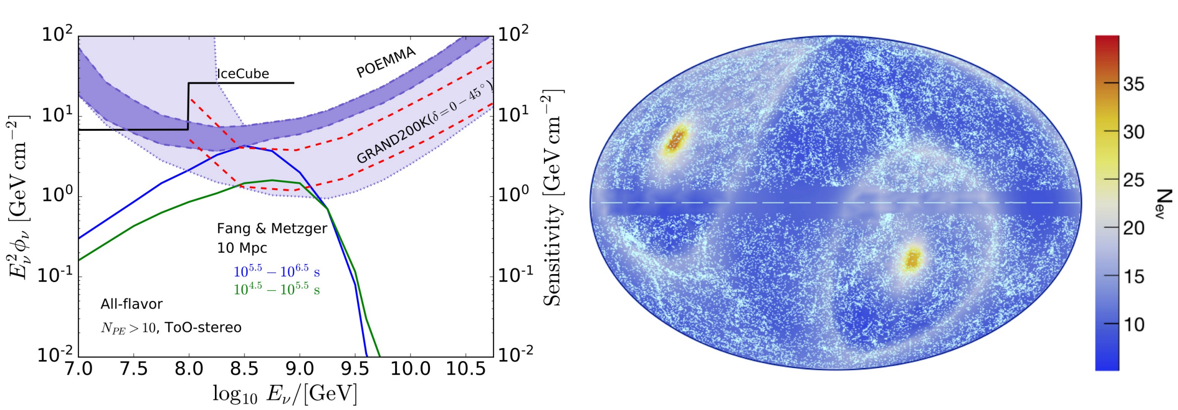
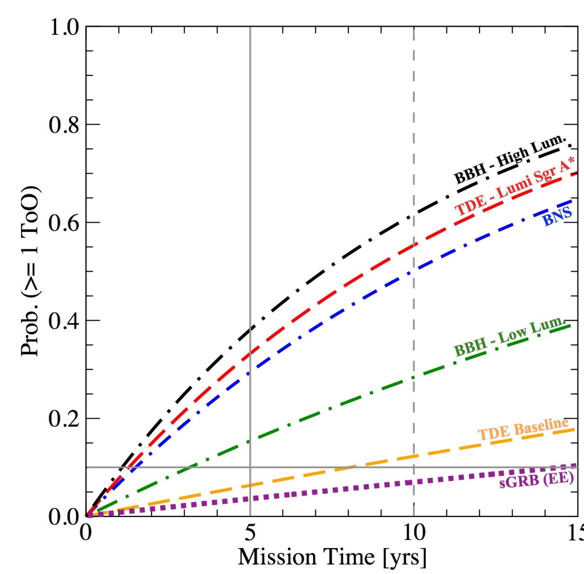


Figure 19. Left: POEMMA ToO sensitivity to a short, 1000 s burst shown by the blue band, where the dark blue band corresponds to source locations between the dashed curves in the sky coverage Figure 18. Also shown are all-flavor upper limits from IceCube and Auger (solid histograms) for neutrino searches within ±500 s around the binary neutron star merger GW170817 [145], the projected sensitivity of GRAND200k at zenith angles 90° and 94° [28], and models taken from Kimura et al. [95] of the all-flavor neutrino fluence from a short gamma-ray burst during the prompt and extended emission (EE) phases, assuming on-axis viewing (θ = 0°) and a source at D = 40 Mpc. Right: Sky plot of the expected number of neutrino events with POEMMA as a function of galactic coordinates for the Kimura et al. [95] short gamma-ray burst with moderate EE model, placing the source at 40 Mpc. Point sources are galaxies from the 2MRS catalog [146]





Source Class	ν Horizon Distance	Mission Time for 10% Prob.	Model Reference
TDE M_{SMBH} = $5 \times 10^6 M_\odot$ Lumi Scaling	128 Mpc	1.5 yrs.	[98]
TDE Base Scenario	69 Mpc	8 yrs.	[98]
BH-BH merger Low Fluence	43 Mpc	3 yrs.	[92]
BH-BH merger High Fluence	137 Mpc	1 yr.	[92]
NS-NS merger	16 Mpc	1.5 yrs.	[93]
sGRB Moderate Extended Emission	90 Mpc	14.5 yrs.	[95]

Table 2. Figure at left: Poisson probability of POEMMA detecting at least one ToO versus mission time for several modeled source classes. Table at right: Promising source classes for detecting at least one ToO event with POEMMA based on a Poisson probability of $\gtrsim$ 10%. Also included are the horizon distance for detecting one neutrino per ToO event, the mission time for 10% chance of detecting *geq*1 ToO event, and the model reference.

T. M. Venters,et al.,
POEMMA's target of opportunity sensitivity to cosmic neutrino transient sources
[arXiv:1906.07209 [astro-ph.HE]].

CONCLUSIONS

- The JEM-EUSO program is an essential element of the roadmap of the UHE Community
- Prototypes and Models of the major elements (Lenses, PDM, DP Unit) have been produced and are being tested to increase the TRLs levels.
- The First Pathfinders (EUSO-TA and EUSO-Balloon) are providing exciting technical and science-oriented data: the transition from paper work to prototyping and measurements has been done.
- The small scale missions (EUSO-SPB, Mini-EUSO and TUS) are providing new scientific results.
- Large Mission concepts are actively studied: K-EUSO is expected to provide first key results from space on the interpretation of UHECR science, and then POEMMA is expected to unveil the highest energy sky ever explored.

THANK YOU