JEM-EUSO Program, Italy

Alessandro Liberatore

Cosmic rays
UHECRs and EECRs
Extended Air Shower

JEM-EUSO program
ESAF
JEM-EUSO missions

EUSO-SPB2
Vertical configuration
Horizontal configurations

POEMMA
Tilted configuration
Reconstruction of events

Conclusions

The use of ESAF software to simulate the performance of the future missions of the JEM-EUSO program

Alessandro Liberatore

University of Torino

Torino, 11/04/2018

Overview

1. Cosmic rays
   - UHECRs and EECRs
   - Extended Air Shower
2. JEM-EUSO program
   - ESAF
   - JEM-EUSO missions
3. EUSO-SPB2
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4. POEMMA
   - Tilted configuration
   - Reconstruction of events
5. Conclusions

Ultra-High Energy and Extreme Energy cosmic rays

High-energy particles arriving from outer space.

UHECRs energy: $\boxed{E_{CR} \geq 10^{18}\,\mathrm{eV}}$

UHECRs flux: $\sim 1 \frac{\textit{particle}}{\mathrm{km^2\,month}}$

EECRs energy: $\boxed{E_{CR} \geq 5 \cdot 10^{19}\,\mathrm{eV}}$

EECRs flux: $\sim 1 \frac{\textit{particle}}{\mathrm{km^2\,century}}$

(on Earth: $\sim 1\,\mathrm{EECR/5seconds}$)

GZK limit: energy limit of protons with $E \gtrsim 5 \cdot 10^{19}\,\mathrm{eV}$ due to the interaction with the γ of the Cosmic Microwave Background (CMB):

- $p + \gamma_{CMB} \to \Delta^+ \to n + \pi^+$;
- $p + \gamma_{CMB} \to \Delta^+ \to p + \pi^0$.

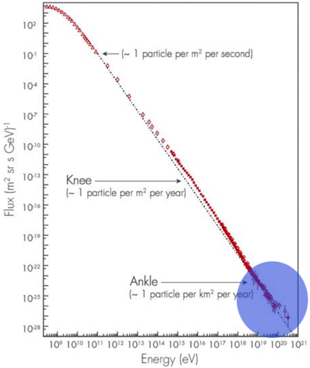
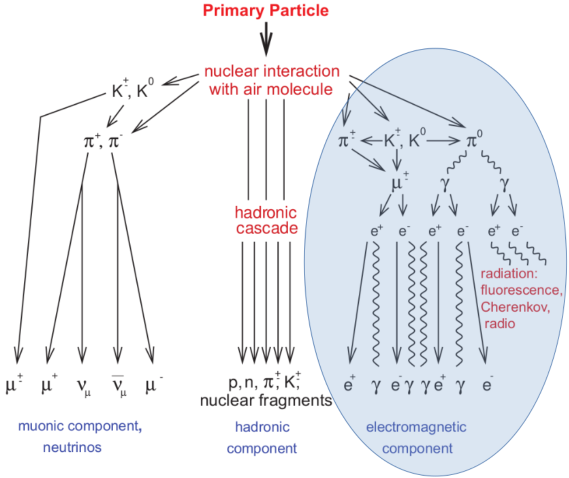


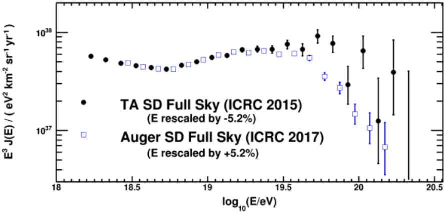
Figure: Fluxes of cosmic rays; UHECRs and EECRs in blue.

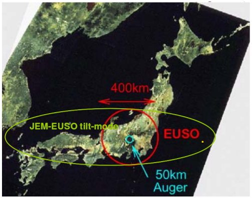
Extended Air Shower (EAS)

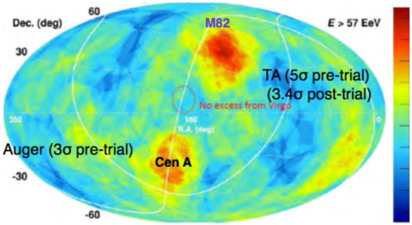
Primary cosmic rays interact with Earth's atmosphere $\rightarrow$ EAS.



Extreme Energy cosmic rays







Auger+TA $\approx 3000 + 700\,\text{km}^2 \rightarrow\sim 30\,\text{events/yr}$;

... we need more statistic! $\Rightarrow$ JEM-EUSO.

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Let's go to space!

A super-wide-field telescope:

- **research of EECRs**;
- study of TLEs, lightning, meteors, . . . ;
- UV emissions from Earth;
- search for strange quark matter.

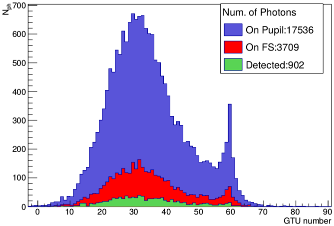


Figure: An EAS curve of light.

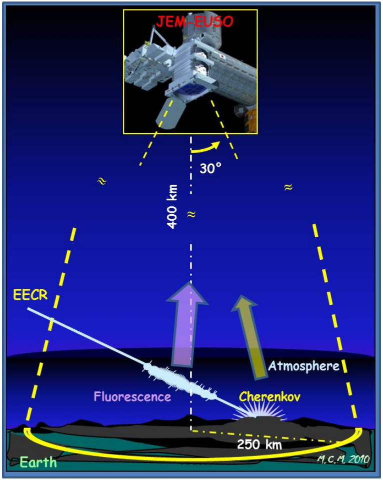
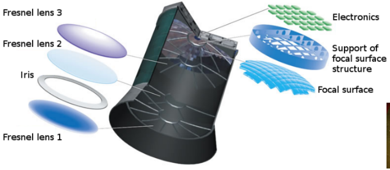
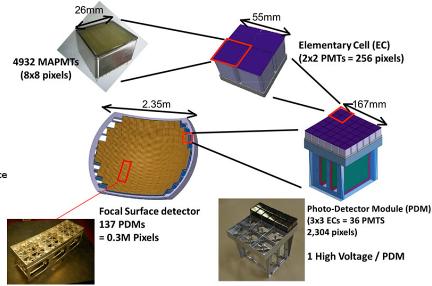


Figure: JEM-EUSO; a quick look.

Telescopes main features

Parameter	Value
FoV	$\pm 30\,^\circ$
Resolution in angle	$0.075\,^\circ$
Time resolution	$2.5\,\mu s$ (1 GTU -*GateTimeUnit*-)





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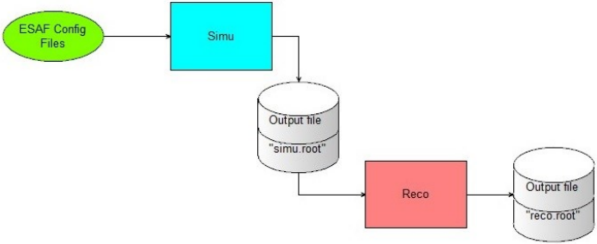
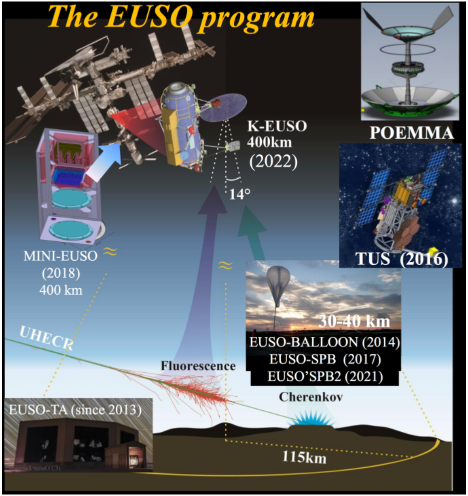
ESAF: EUSO Simulation and Analysis Framework.

- Developed in the framework of EUSO missions ($\sim 10^5$ lines).
- Based on ROOT (CERN) realized with C++ object oriented.



Simu: Event generation, photons production and their transport to the detector, optics and electronics response.
Reco: reconstruction of air shower parameters (energy, X_{max}, direction, etc. . .)

Joint Experiments Mission: Extreme Universe Space Observatory (JEM-EUSO)



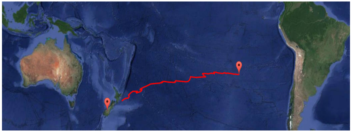
Several pathfinder have been performed, others are now at work and a lot of them will be carried out.

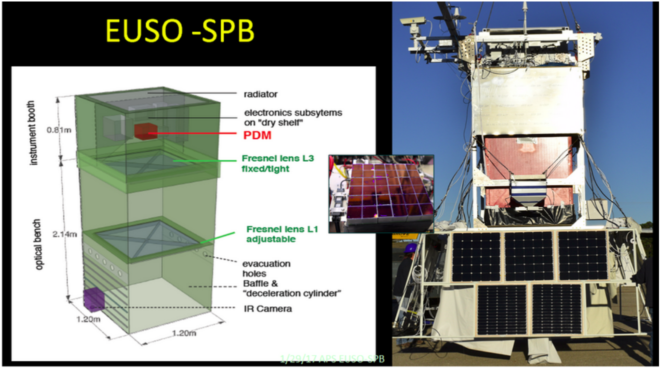
Studied in my Thesis:

- Mini-EUSO (2018);
- EUSO-SPB2 (2021);
- POEMMA (> 2025).

EUSO-SPB1 (launched in 2017)

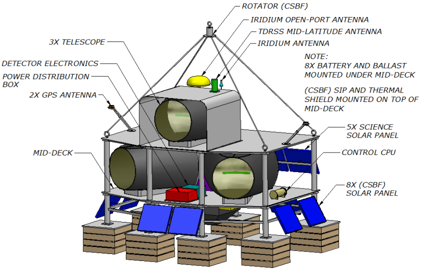
- From Wanaka (New Zealand);
- 100 days $\rightarrow$ 12 days flight;
- Altitude: 30 km.





EUSO-SPB2 (will be launched in 2021)

- EAS fluorescence and Cherenkov photons.
- Possible to look nadir **or tilted** → neutrino events! (ν_τ)
- Just the EUSO-SPB1 features are implemented in ESAF.



GONDOLA ASSEMBLY

Features	**Value**
Mirror area	$1\,\mathrm{m}^2$
FoV	$\pm 6\,°$
Altitude	$30\,\mathrm{km}$

Efficiency	**Value**
Optics	50%
Focal surface	10 – 40%
Total	5 – 20%

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Vertical configuration

STEP 1

Vertical configuration:

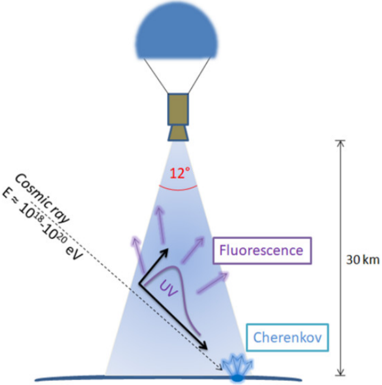
- Altitude Detector = 30 km;
- Mirror area = 1 m^2;
- FoV = ± 6°;
- **Tilt Detector:** (x, y, z) = (0°, 0°, 0°).

- CR energy [eV] = $1 \cdot 10^{19}$;
- CR_{ϑ} = 85°;
- CR_{ϕ} = 150°.

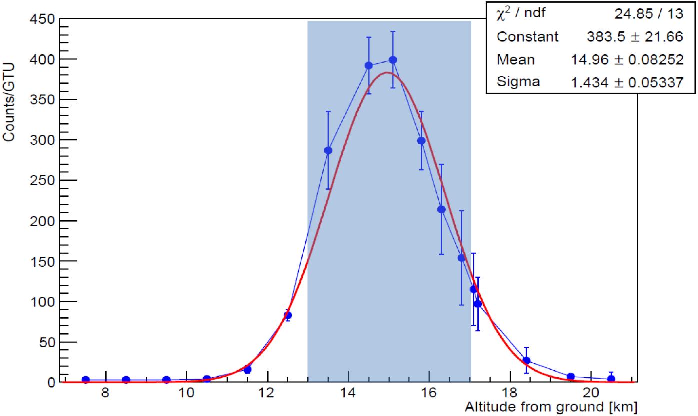
- Optical Efficiency: 50%;
- Quantum Efficiency: 10%;

→ **Total Efficiency:** 5%.

- **Background:** 0.25 counts/μs.



Trigger area for $1 \cdot 10^{19}$ eV



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First Horizontal configuration

STEP 2

Horizontal configuration:

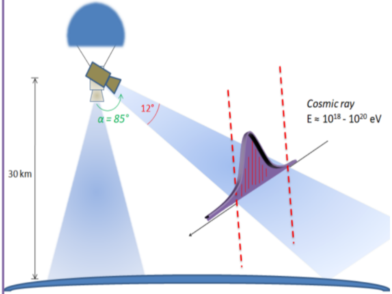
- Altitude Detector = 30 km;
- Mirror area = 1 m^2;
- FoV = ± 6°;
- **Tilt Detector:** (x, y, z) = (85° ÷ 65°, 0°, 0°).

- CR energy [eV] = $1 \cdot 10^{18} \div 1 \cdot 10^{20}$;
- CR_ϑ = 85°;
- CR_ϕ = 180°.

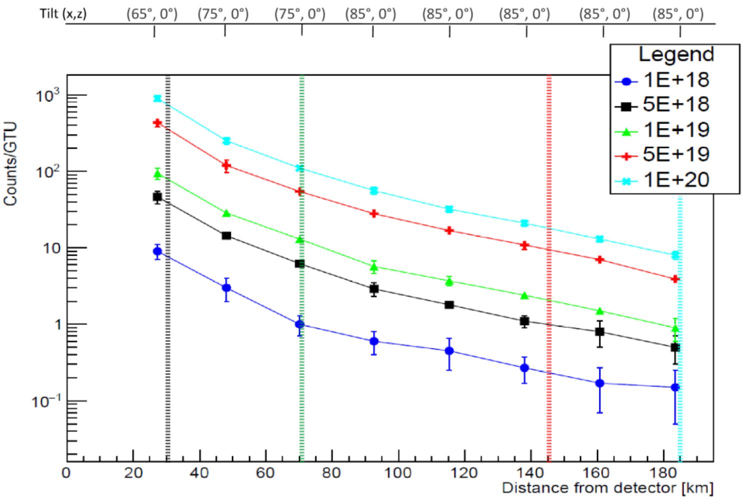
- Optical Efficiency: 50%;
- Quantum Efficiency: 10%;

→ **Total Efficiency:** 5%.

- **Background:** 0.25 counts/µs.



Counts/GTU and Trigger



Second, Third, Fourth Horizontal configuration

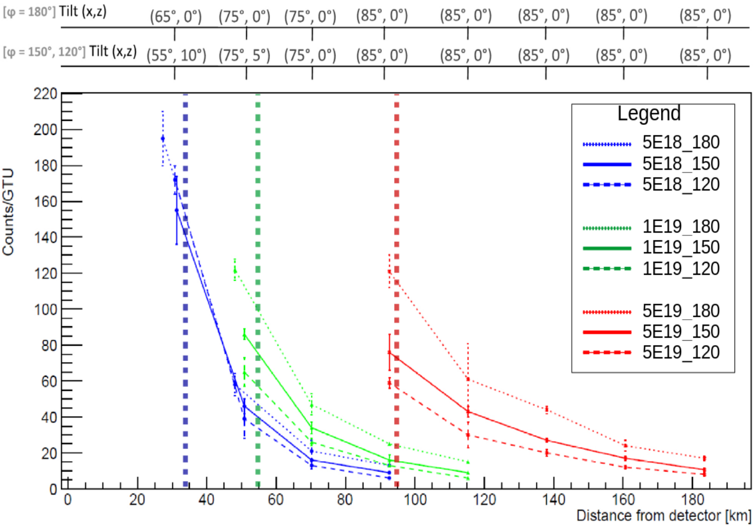
Main features:

- Altitude detector: $30\,\mathrm{km}$;
- Mirror area: $1\,\mathrm{m}^2$;
- FoV: $\pm 6°$;
- Optical efficiency: 50%;
- Tilt detector (x, y, z): $(85° \div 55°, 0°, 0° \div 10°)$;
- CR energy [eV] $= 1 \cdot 10^{18} \div 1 \cdot 10^{20}$;
- $CR_\theta = 85°$.

Config.	CR_ϕ	**Quantum eff.**	**Tot. eff.**	**BG** $[(\mu\mathrm{s})^{-1}]$
First	180°	10%	5%	0.25
Second	180°	40%	20%	1
Third	180°	40%	20%	2.5
Fourth	180° ÷ 120°	40%	20%	2.5

Table: Main features for each configuration.

Trigger *vs* distance from detector

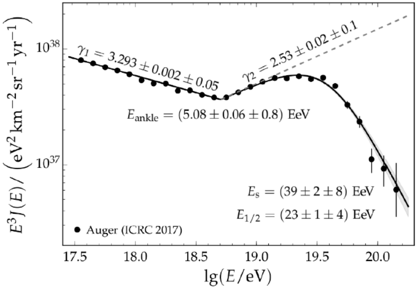


So. . . how many "trajectories" of cosmic rays?

- I would estimate how many "trajectories" of UHECRs cross above a given energy E within a given distance R_{max} per unit "observation time".
- Cosmic ray fluxes may be referred to Auger ICRC proceedings (Fenu et al. 2017).

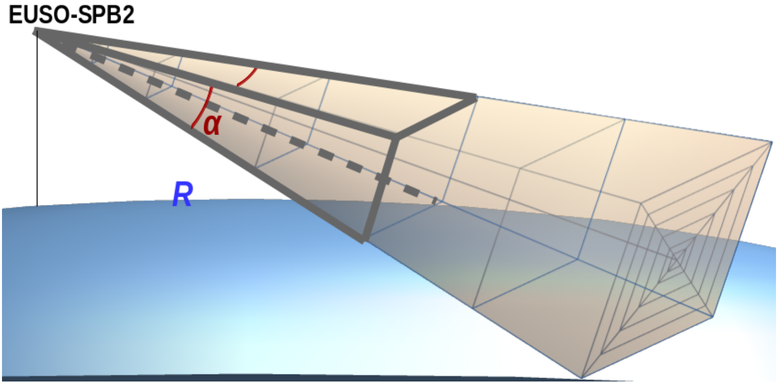
Integral **flux above given energy** E:

$$J(>E) = -\frac{J_0 E_a}{1+\gamma}\left(\frac{E}{E_a}\right)^{1+\gamma}.$$



So...how many "trajectories" of cosmic rays?

Instantaneous aperture can be calculated in an approximate way. We have to consider the geometry:



We obtain that the instantaneous aperture is equal to:

$\boxed{0.41 R^2 \, [\mathrm{km}^2 \mathrm{sr}]}$ (for $\alpha = 15°$).

So. . . how many "trajectories" of cosmic rays?

So, in the end, we have:

E [eV]	$\sim 5 \cdot 10^{18}$	$\sim 1 \cdot 10^{19}$	$\sim 5 \cdot 10^{19}$
R [km]	~ 35	~ 55	~ 95
CRs/hour	0.04	0.03	0.009

For a 100 days flight: $\sim 24\,\mathrm{hours} \cdot 100\,\mathrm{days} \cdot 20\%_{DC} \longrightarrow 480\,hours$;

E [eV]	$\sim 5 \cdot 10^{18}$	$\sim 1 \cdot 10^{19}$	$\sim 5 \cdot 10^{19}$
CRs	≤ 20	≤ 15	≤ 5

$\Rightarrow$ we expect to detect about 20 events with $E > 5 \times 10^{18}\,\mathrm{eV}$.

POEMMA (after 2025)

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- **P**robe **O**f **E**xtreme **M**ulti-**M**essenger **A**strophysics (POEMMA) is a "long-term project" (born in 2017).
- POEMMA consists of **two telescopes**; in ESAF just one telescope → no stereoscopic view.
- Parametric optics (Schmidt optics).

Parameter	**Value**
Altitude	400 km and 525 km
FoV	$\pm 22.5°$ ($\approx 0.08°$ per pixel)
Number of PDM	~ 80
Focal surface radius	830 mm
Pixels side	3 mm
Quantum efficiency	0.27
Time resolution	2.5 μs
Optics Radius	1650 mm
Background (per pixel)	1.54 counts/μs

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Ranges

20.000 events simulations with the following ranges:

- Energy: $5 \times 10^{18}\,\mathrm{eV} \leqslant E \leqslant 5 \times 10^{20}\,\mathrm{eV}$;
- Zenith angle: $0 \leqslant \theta \leqslant \pi/2$;
- Azimuth angle: $0 \leqslant \phi \leqslant 2\pi$;

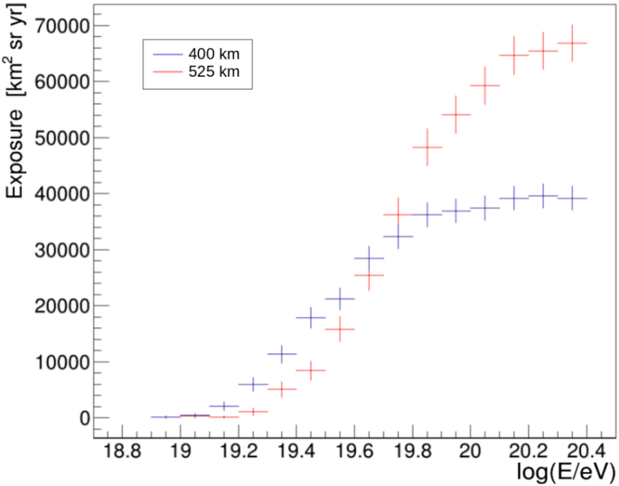
...and with: *Duty cycle*$= 20\% \cdot 72\%\,\mathrm{clouds} \approx 14\%$.

The simulated and field of view surfaces are:

$h[km]$	$S_{sim}[km^2]$	$S_{FoV}[km^2]$
400	160000	85530
525	271127	144935

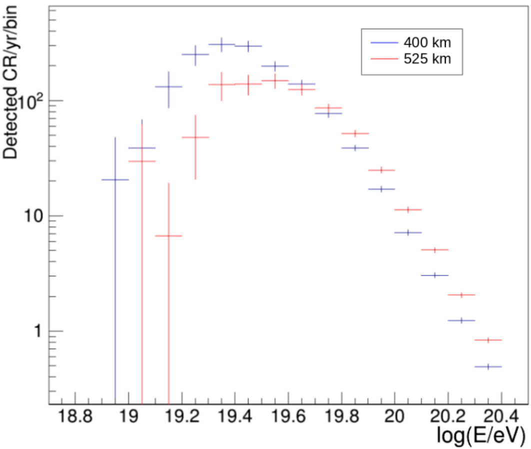
Exposure (altitude: 400 km and 525 km)

$$\Psi(E) = A(E) \cdot t \cdot DC \qquad (t = 1 year; DC = 14\%)$$



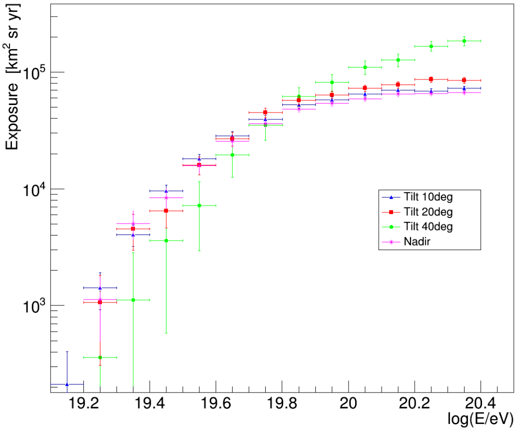
Triggered spectrum at different altitude

$$\Phi(E) = \int \phi \cdot S_{FoV} \cdot \epsilon \cdot \pi \cdot t \cdot DC \qquad (t = 1year; DC = 14\%)$$

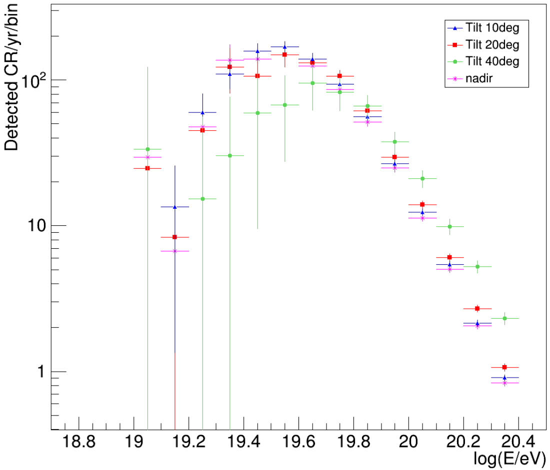


Tilted configurations: Exposure (altitude: 525 km)

The background increases with the tilted angle ϑ.



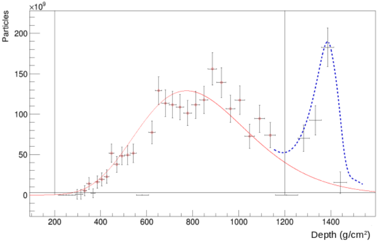
Tilted configurations: Triggered spectrum (altitude: 525 km)

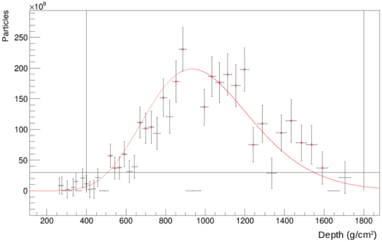


Reconstruction of events

I used the reconstruction chain developed for JEM-EUSO program to reconstruct the parameters of the primary particle.

Cherenkov method vs *Slant depth method*





Reconstruct energy, X_{max}, direction.

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Automatic reconstruction

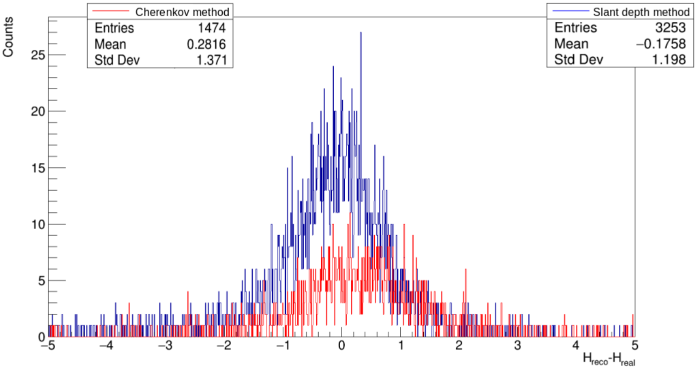
The set of conditions that must be satisfy to start a reconstruction are:

- $DOF > 4$;
- $0.1 < \chi^2 < 3$;
- for Cherenkov method $\rightarrow$ Cherenkov peak.

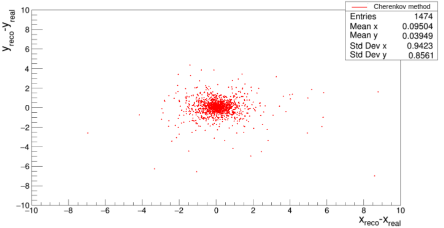
	Cherenkov method	*Slant depth method*
Events	11200	11200
Triggered	3879	3879
Reconstructed	1472	3253
	(38%)	**(84%)**

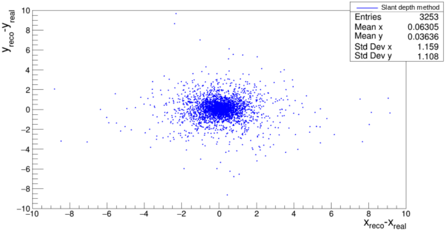
EAS **maximum** altitude (H)

	Cherenkov method	Slant depth method
$(H_{reco} - H_{real})$	0.28 km	−0.18 km
Resolution	1.4 km	1.2 km



(x, y) position of EAS **maximum**



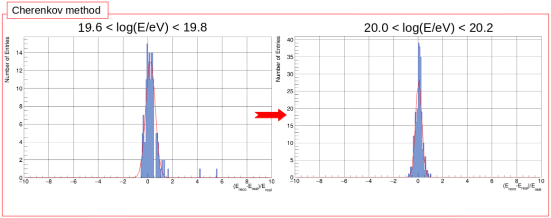


	Cherenkov method
$(x_{reco} - x_{real})$	0.09 km
$(y_{reco} - y_{real})$	0.04 km
$Resolution_x$	0.9 km
$Resolution_y$	0.9 km

	Slant depth method
$(x_{reco} - x_{real})$	0.06 km
$(y_{reco} - y_{real})$	0.04 km
$Resolution_x$	1.2 km
$Resolution_y$	1.1 km

Energy resolutions $\left[\frac{E_{reco}-E_{real}}{E_{real}}\right]$

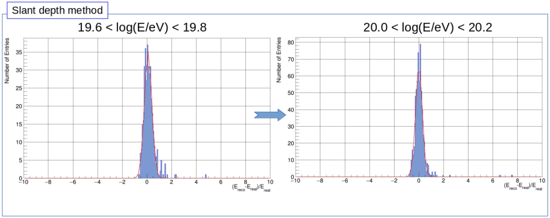
Cherenkov method



Lower E	
Bias	21%
Resolution	37%

Higher E	
Bias	4%
Resolution	20%

Slant depth method



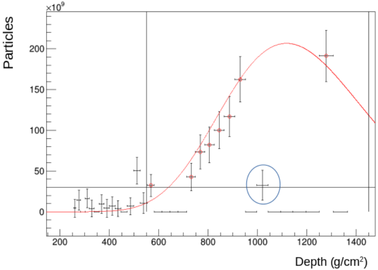
Lower E	
Bias	9%
Resolution	30%

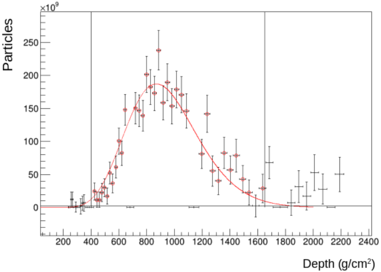
Higher E	
Bias	0.5%
Resolution	27%

Manual reconstruction

Manual reconstruction to compare with the automatic ones.
Procedure:

- $DOF > 4$;
- $0.1 < \chi^2 < 3$;
- background and fit interval;
- points exclusion.



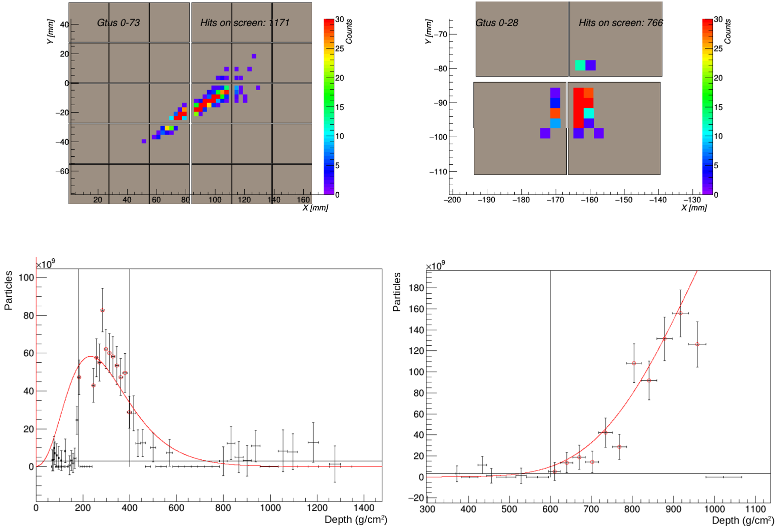


Manual vs Automatic reconstruction

Results from the automatic and manual E and X_{max} reconstruction:

X_{max} **Cherenkov method** $[\mathrm{g/cm^2}]$	**Bias**	σ
Automatic	12	128
Manual	-22	204
E **Cherenkov method** $(\%)$	**Bias**	σ
Automatic	-10	25
Manual	-11	25
X_{max} **Slant depth method** $[\mathrm{g/cm^2}]$	**Bias**	σ
Automatic	37	100
Manual	34	110
E **Slant depth method** $(\%)$	**Bias**	σ
Automatic	8	21
Manual	11	21

Focal plane observation



After focal plane observation (removed 4 events)

New results from the automatic and manual reconstruction:

X_{max} **Cherenkov method** $[\mathrm{g/cm^2}]$	**Bias**	σ
Automatic	12	128
Manual	-13	107
E **Cherenkov method** $(\%)$	**Bias**	σ
Automatic	-10	25
Manual	-11	25

X_{max} **Slant depth method** $[\mathrm{g/cm^2}]$	**Bias**	σ
Automatic	37	100
Manual	34	110
E **Slant depth method** $(\%)$	**Bias**	σ
Automatic	8	21
Manual	11	21

Manual vs Automatic reconstruction

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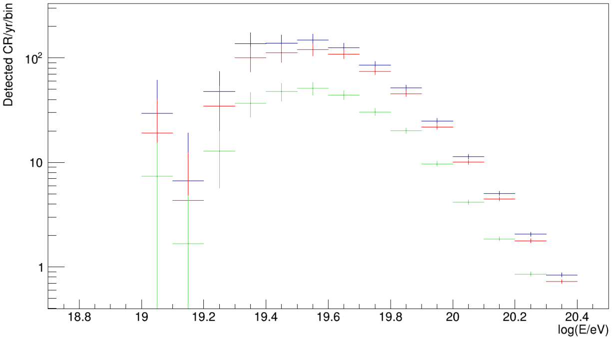
Comparing these preliminary results of reconstruction, it is possible to conclude that what is obtained from the automatic reconstruction algorithms is consistent with what would be expected to be obtained with the manually one.

	Cherenkov method	**Slant depth method**
Both	31	58
Just Manual	3	4
Just Automatic	7	12
Neither	4	11

Triggered: 91 $\longrightarrow$ $(31+7)/91 = 41\%$; $(58+12)/91 = \mathbf{77\%}$.

It is possible to manually reconstruct each event during the real data acquisition.

Reconstructed trigger spectrum



$[log(E/eV) > 19.6]$	Cherenkov method	Slant depth method
Trigg. (per year)	305	305
Reconstr. (per year)	110 (36%)	**267 (88%)**

Conclusions

- **Mini-EUSO**
  - Optimization of the second level of trigger parameters to the study of TLEs events.
- **EUSO-SPB2**
  - Trigger distances for horizontal CRs in tilted configuration $\rightarrow$ $R(1 \times 10^{19}\,\mathrm{eV}) \approx 55\,\mathrm{km}$; $R(5 \times 10^{19}\,\mathrm{eV}) \approx 95\,\mathrm{km}$.
  - For a 100 days mission (altitude: $30\,\mathrm{km}$) $\rightarrow$ 20 events with energy above $5 \times 10^{18}\,\mathrm{eV}$.
- **POEMMA**
  - Triggered events above $E = 4 \times 10^{19}\,\mathrm{eV}$ for one year data taking at an altitude of $525\,\mathrm{km}$ $\rightarrow$ $Events(> E) = 305$.
  - Triggered events in tilted simulations $\rightarrow$ $Events(> E, 10^\circ) = 330$; $Events(> E, 20^\circ) = 350$.
  - Reconstructed $\rightarrow$ 267 (slant depth); 110 (Cherenkov).

Thanks for your attentions!

Backup Slides

JEM-EUSO Program, Italy

Alessandro Liberatore

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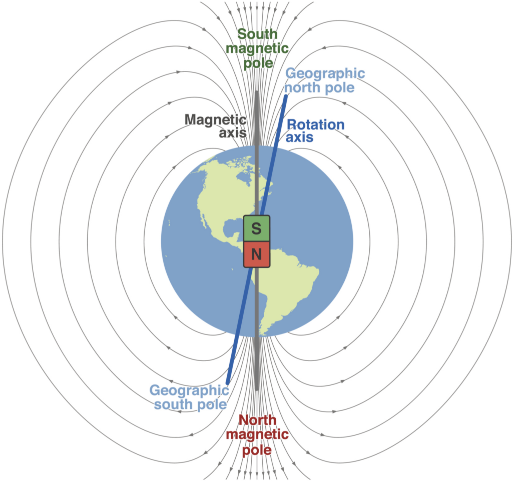
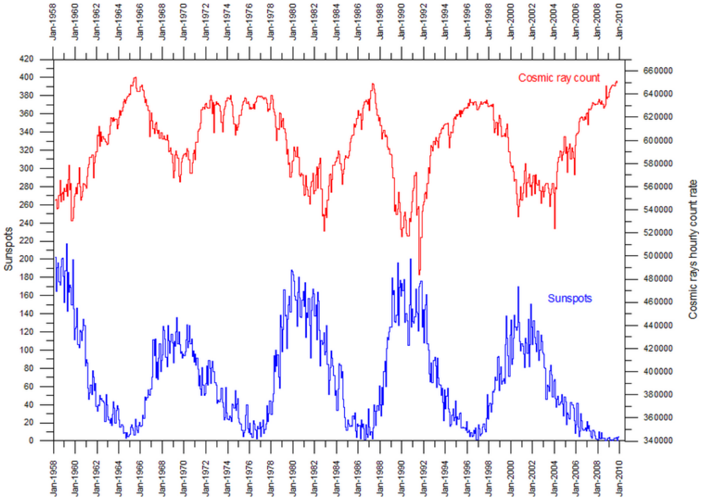
Backup Slides - Earth's magnetic field



Backup Slides - Sunspots and CR counts



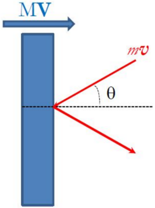
Backup Slides - Fermi mechanism (2^{nd} order)

Second order Fermi acceleration (1949)

Fermi proposed that charged particles were reflected by "magnetic mirrors" associated to galactic magnetic filed irregularities. Is possible find that the variation of particles energy, for each collision, is equal to:

$$\frac{\Delta E}{E} \sim \frac{2V}{c} \cos\theta$$

If we consider all kind of collisions ("*Head on*": $\theta < \pi/2 \rightarrow \Delta E/E > 0$ and "*Following*": $\theta > \pi/2 \rightarrow \Delta E/E < 0$) is possible find that, in the end, we have a positive $\Delta E/E$:



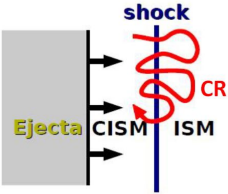
$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{8}{3}\left(\frac{V}{c}\right)^2$$

...so there is an acceleration; but there are some problems! For example, this process is too *slow*.

Backup Slides - Fermi mechanism (1^{st} order)

First order Fermi acceleration (1979)

Similar to the second order but, this time, the idea is that for each collision the energy increase (i.e. no difference between *head on* and *following* collisions). Is possible demonstrate that this mechanism is possible with *strong shock waves* with $v \gg v_{sound}$ (e.g. shock waves from Supernovae → Super Novae Remnants (SNR)).



After a full tour around the shock waves, the increment of the particle energy is:

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\frac{V}{c}$$

...this process is faster than the previous one; is better!

There are other models that consider also the magnetic field that the particle generate during his accelerations.

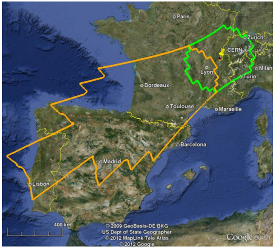
Backup Slides - JEM-EUSO *vs* other experiments

Experiment	Aperture km² sr	Status	Start	Lifetime (years)	Duty cycle (incl. clouds)	Exposure (km² sr y)	Relative to Auger
Auger	7,000	Operations	2006	4 (16)	1.0	27,370 (110,000)	1
TA	1,200	Operations	2008	2 (14)	1.0	2400 (16.000)	0.1
TUS	30,000	developed	2012	5	0.14	18,750	0.2
JEM-EUSO (E~100 EeV) Nadir-Mode	470,000 (10xAuger including DC)	proposed	2017	5	0.14	330000 (5 years Nadir)	3
JEM-EUSO (highest Energies) Tilted-Mode	1,300,000 (26xAuger including DC)	proposed	2017	5	0.14	910000 (5 years tilted)	8

Backup Slides - JEM-EUSO: spatial exposure

Figure: Vertical mode.

Figure: Tilted mode.



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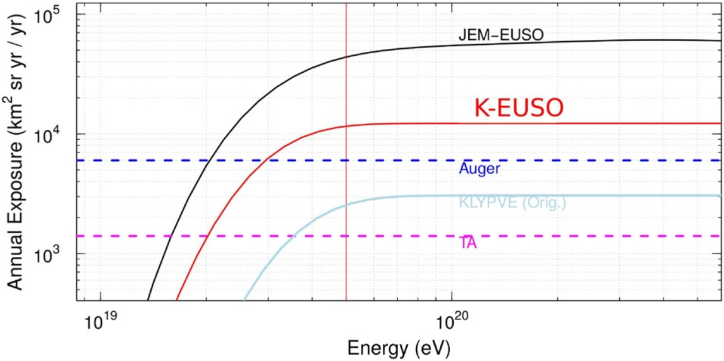
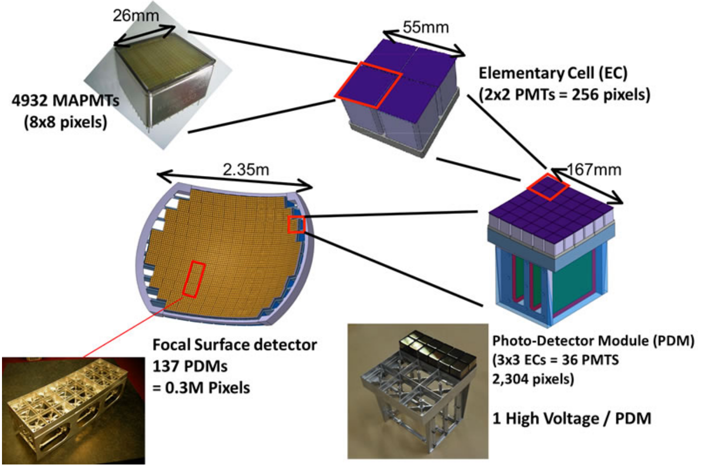
JEM-EUSO Exposure

Larger exposure ⟶ higher statistic.

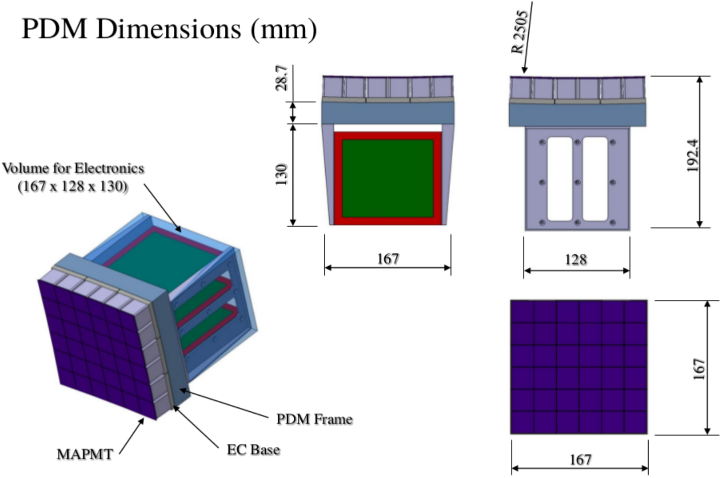


JEM-EUSO Focal Surface (FS)

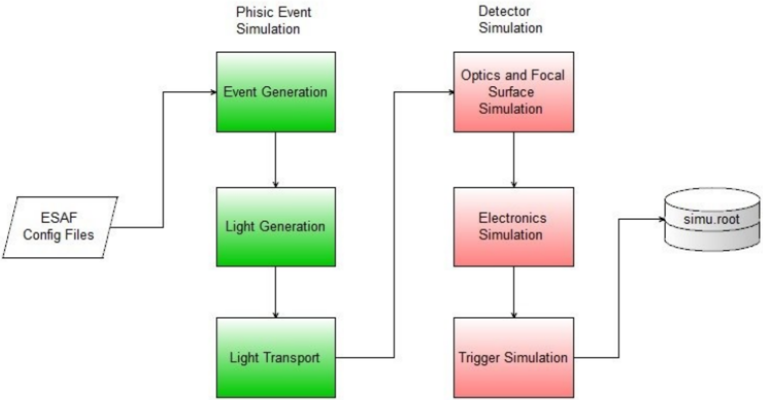
Pixel size: $2.9 \times 2.9\,\mathrm{mm}^2$.
UV filter for light in band $290 \div 430\,\mathrm{nm}$.



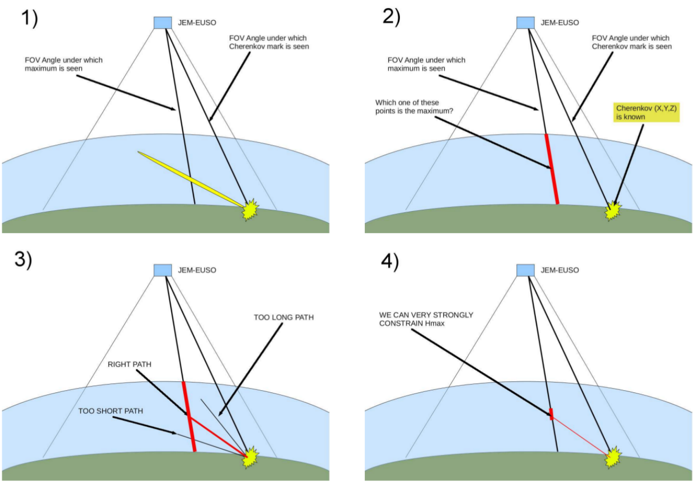
PDM dimensions



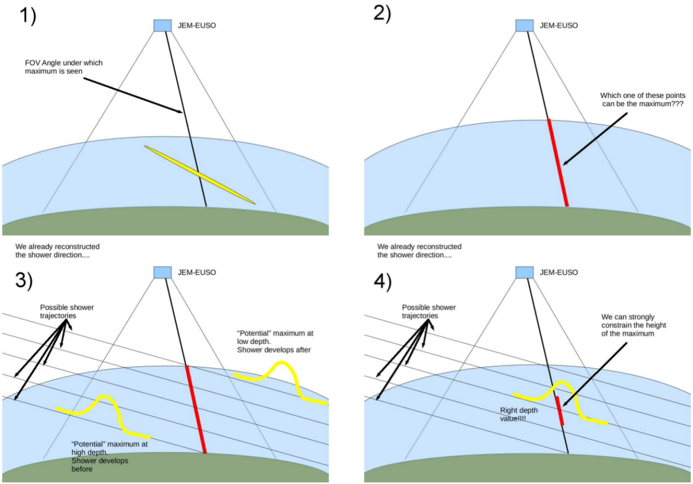
ESAF -Simu-


Phisic Event Simulation
Detector Simulation
ESAF Config Files
Event Generation
Light Generation
Light Transport
Optics and Focal Surface Simulation
Electronics Simulation
Trigger Simulation
simu.root

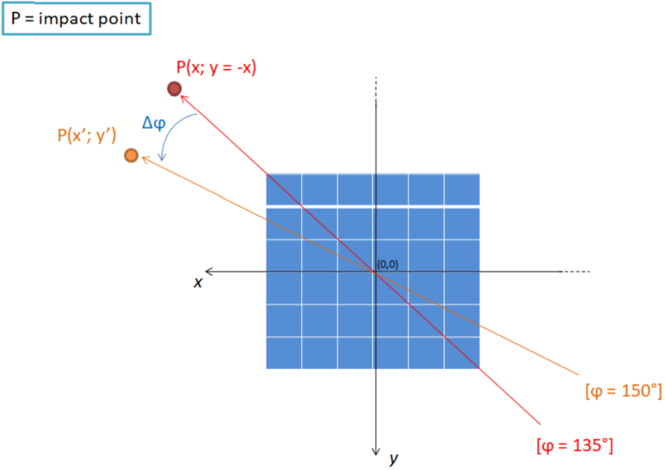
EUSO -Reco- (Cherenkov method)



EUSO -Reco- (Slant depth method)

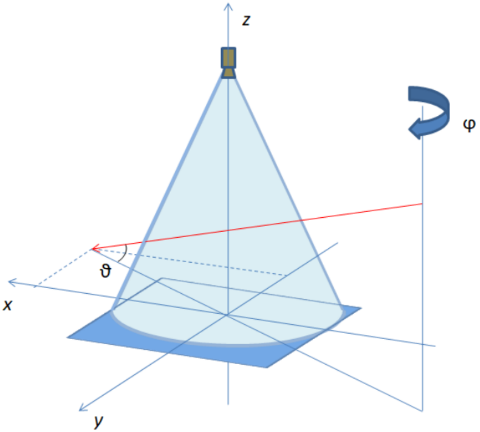


Backup Slides - Impact point (2D)



Backup Slides - Impact point (3D)

3D vision



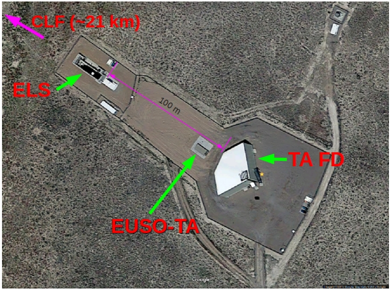
EUSO-TA (working since 2013)

EUSO-TA is a pathfinder experiment for the space based JEM-EUSO mission for the detection of ultra-high energy cosmic rays; is an high-resolution fluorescence telescope installed Located in front of one of TA experiment, in Utah (USA). EUSO-TA points in the direction of the Electron Light Source and Central Laser Facility.

Main features:

- Two $1\,\mathrm{m}^2$ Fresnel lenses
- FoV: $\sim 10.5^{\circ}$
- 1 Photo Detector Module (PDM)

Up to now 5 observation campaigns have been performed (for a total of 48 observation nights).



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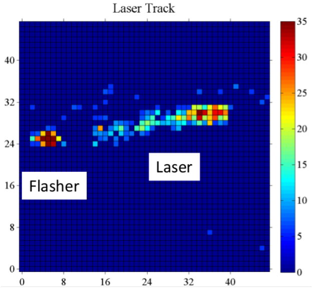
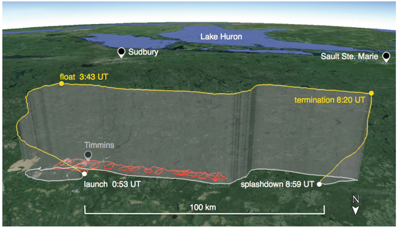
EUSO-Balloon (launched in 2014)

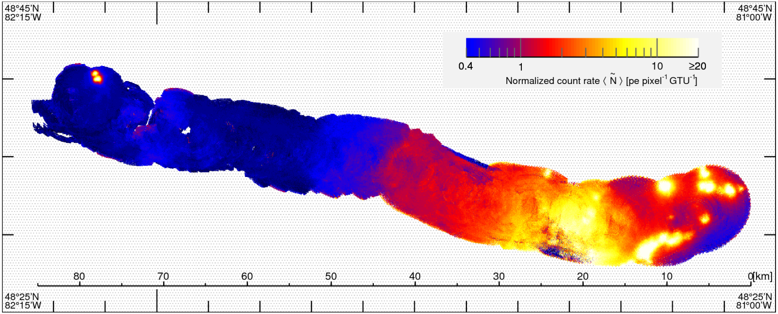
- 1 PDM (2304 pixels);
- optical system: two Fresnel lenses (side of 1 m);
- field of view: $\pm 6^\circ$.



- Night of August 25, 2014 (Ontario, Canada).
- Altitude of 38 km
- More than 5 hours before descending to ground.



EUSO-Balloon



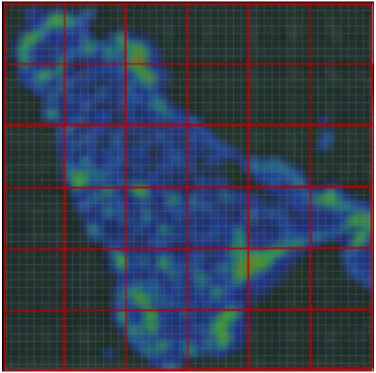
- 5 hours of flight
- All sub-systems successfully tested
- UV background map

Mini-EUSO (will be launched in 2018)

Onboard of the ISS, Mini-EUSO will looks nadir in the near UV range: $290 - 430\,\mathrm{nm}$.

Main features

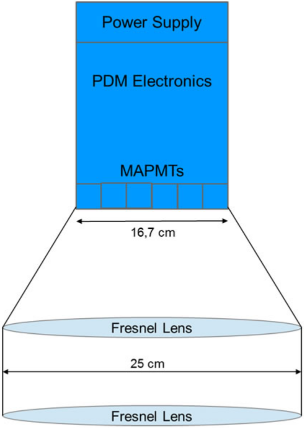
- FoV: $\pm 19^{\circ}$
- Spatial resolution: $\sim 6.5\,\mathrm{km}$
- Temporal resolution: $2.5\,\mu\mathrm{s}$
- Multi-levels of trigger
- 2 Fresnel lens
- 1 PDM

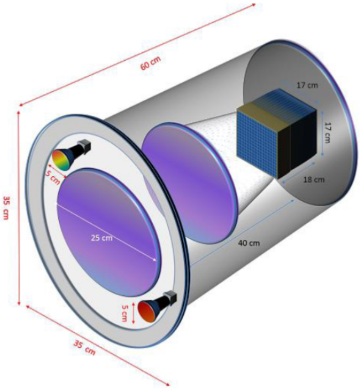


Main scientific goals

- Study of UHECRs
- UV emissions from night-Earth
- Study of meteors

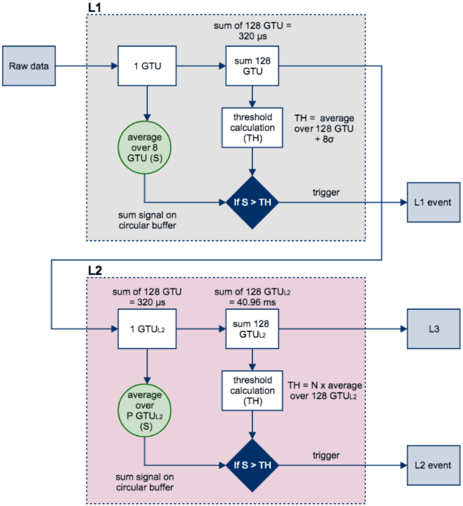
Mini-EUSO structure





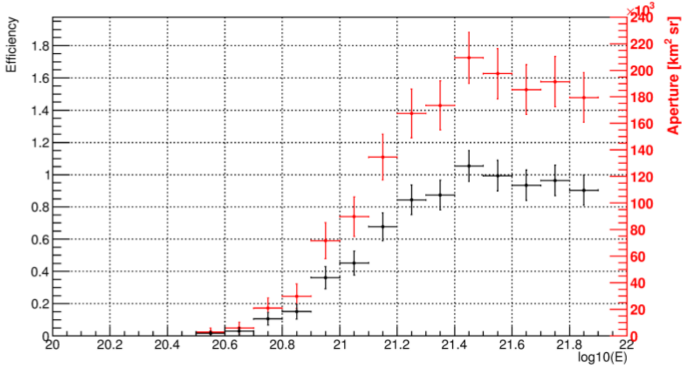
Levels of trigger -**L1** and **L2**-

- In **L1**, pixel signal are integrated over 8 consecutive GTU.
- Threshold independent for every pixel (8σ above the average of $128\,\mathrm{GTU}$).
- If signal $>$ threshold I have a trigger.
- The data integrated over $128\,\mathrm{GTU}$ ($320\,\mu\mathrm{s}$) is also passed to the **L2** trigger $\rightarrow 1\,\mathrm{GTU_{L2}}$.



EECRs with Mini-EUSO

(Plot carried out by Francesco Fenu)



⟹ go to the second level of trigger! → TLEs
(Traineeship at Royal Institute of Technology; Stockholm, Sweden).

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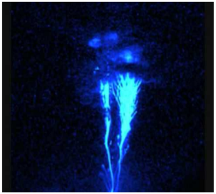
TLEs with Mini-EUSO

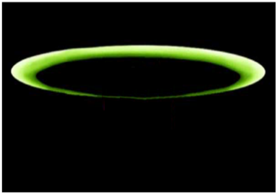
The Transient Luminous Events (TLEs) are short-lived phenomena that occur well above the altitudes of normal lightning and storm clouds. There are several types of TLEs. We'll consider 3 kinds of TLEs:

Blue Jet



Sprite

Elves



Typical duration: $\sim 1 \div 40\,\mathrm{ms}$.

Blue Jet

Example of one Blue Jet simulation result:

Coordinates: (x; y; h[km]) = (16; -20; 80)
Direction: vertical → (0, 0, 1)
Time step [s]: 0.0000025 ≡ 1 GTU
TLE step size [km]: 0.05
Jet speed [km/s]: 200
Absolute magnitude: +1
Jet angle: 15°
Jet extension [km]: 2
Max Event Radius* [km]: 0.263
Event Duration** [ms]: 10

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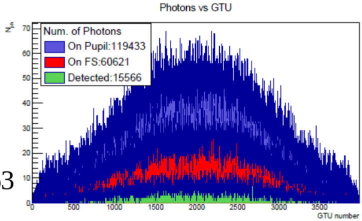

* Max Event Radius = "Jet extension" $tan(("\text{Jet angle}"/2)\ \pi/180)$
** Event Duration = "Jet extension" / "Jet speed"

Sprite

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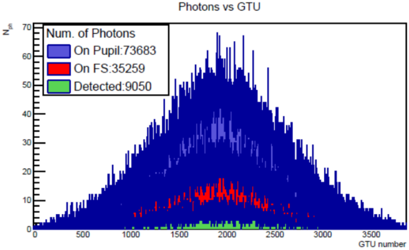
Example of one Sprite simulation result:

Coordinates: (x; y; h[km]) = (16; -20; 80)
Direction: vertical → (0, 0, 1)
Time step [s]: 0.0000025 ≡ 1 GTU
TLE step size [km]: 0.02
Absolute magnitude: +1
TLE Radius [km]: 1
Event Duration [ms]: 10
Extension* [km]: 2



* Extension = 2 "TLE Radius"

Elves

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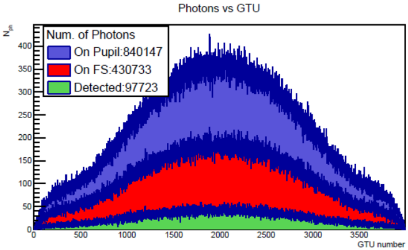
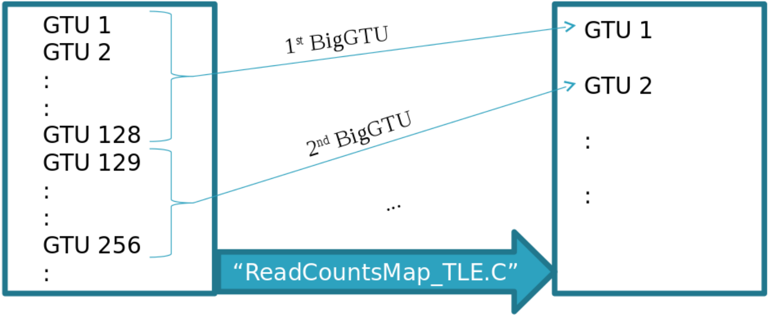
Example of one Elves simulation result:

Coordinates: (x; y; h[km]) = (16; -20; 80)
Direction: vertical → (0, 0, 1)
Time step [s]: 0.0000025 ≡ 1 GTU
TLE step size [km]: 0.005
Absolute magnitude: -1
TLE Radius [km]: 25
Elves height [km]: 1
Event Duration [ms]: 10



Second level of trigger

Esaf give me a map of pixels GTU by GTU. But I need a sequence of BigGTU → ROOT macros to sum 128 single GTU to create a sequence of "BigGTU".



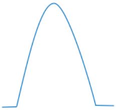
Events + Background

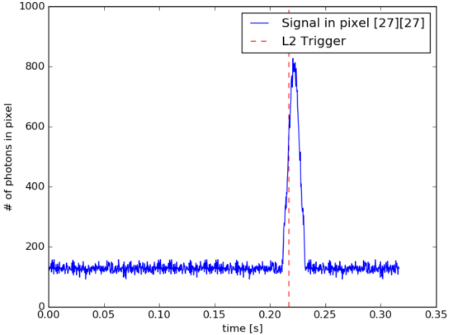
For each GTU, I added a poissonian background (with an expected value = 1). I made a macro to put different files of "events + background" and "just background" in one bigger file.
If we put these kinds of file in the L2 trigger algorithm file we obtain (changing "p" and "n" parameters in the best possible way):

Blue Jet

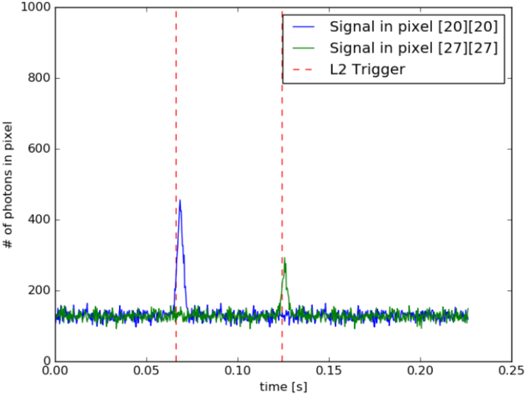
speed:	200 km/s
extension:	4 km
duration:	20 ms
abs. magnitude:	1
jet angle:	17°

Curve of light:





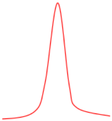
Events + Background



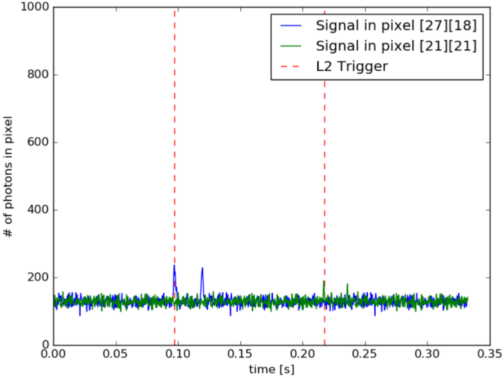
Sprite1
extension: 0.5 km
duration: 10 ms
abs. magnitude: 2

Sprite2
extension: 0.5 km
duration: 10 ms
abs. magnitude: 1

Curve of light:



Events + Background

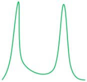


Elves1

radius: 25 km
duration: 25 ms
abs. magnitude: 1

Elves2

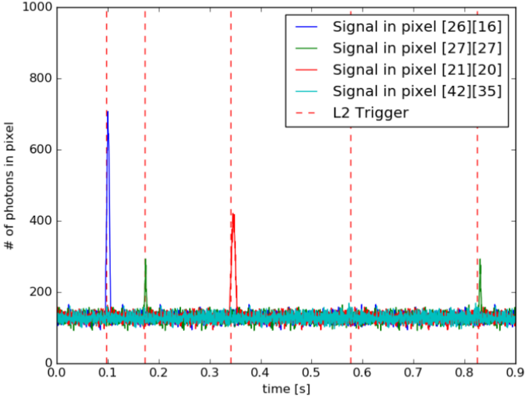
radius: 50 km
duration: 20 ms
abs. magnitude: 1

Curve of light: 

Events + Background

Best values for (p, n) parameters:

- (p,n) = (10,5);
- (p,n) = (8,4).



5 Events

↓

5 Triggers

...final choices:

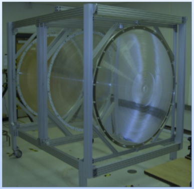
$p = 8;$
$n = 4.$

EUSO-SPB2

We'll see some ESAF simulation results with these kind of informations:

Num. of Photons
- On Pupil: #####
- On FS: ####
- Detected: ###

3 *Fresnel lenses* focuses incoming photons onto the pixelated focal surface consisting of an array of MAPMTs (multi anode photomultipliers → 8x8 pixels).

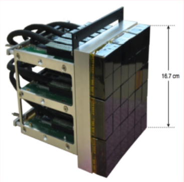


The "*detected photons*" are the photons that hit the PDM after crossing *pupil* and *focal surface*.

Quantum efficiency:
Before: 10%
After: 40%

1 Photon Detection Module (PDM):

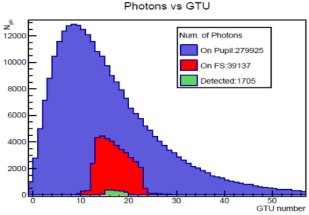
- *1 PDM = 36 MAPMTs (4 MAPMTs form an elementary cell «EC»);*
- 48x48 = 2304 pixels;
- 2.5 μs (≡ 1 GTU) time bins.

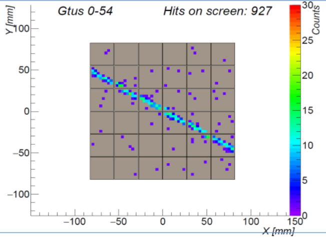


Example of histograms and FS views $(1 \cdot 10^{19}\,\mathrm{eV})$

Altitude ≈ 13 km (Trigger: YES)

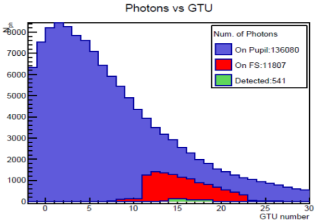
E = $1\cdot10^{19}$ eV; ϕ = 150°; ϑ = 85° ; $P_{x,y}$ = (133.5; -77.1)

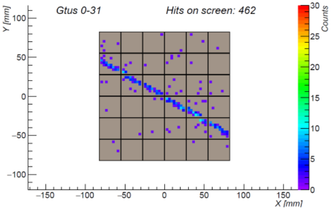




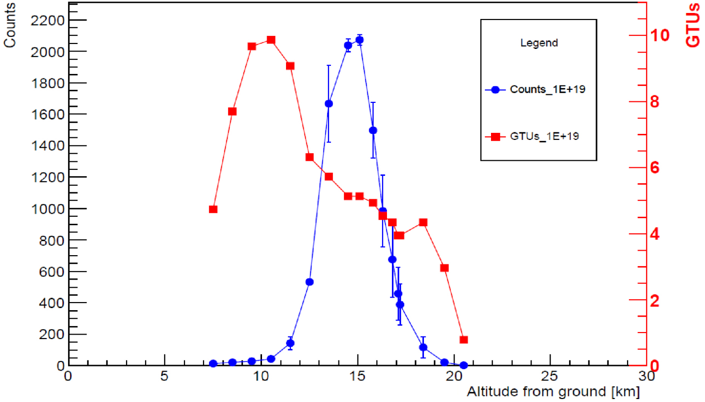
Altitude ≈ 12 km (Trigger: YES)

E = $1\cdot10^{19}$ eV; ϕ = 150°; ϑ = 85° ; $P_{x,y}$ = (123.7; -71.4)





Counts and GTUs with distance



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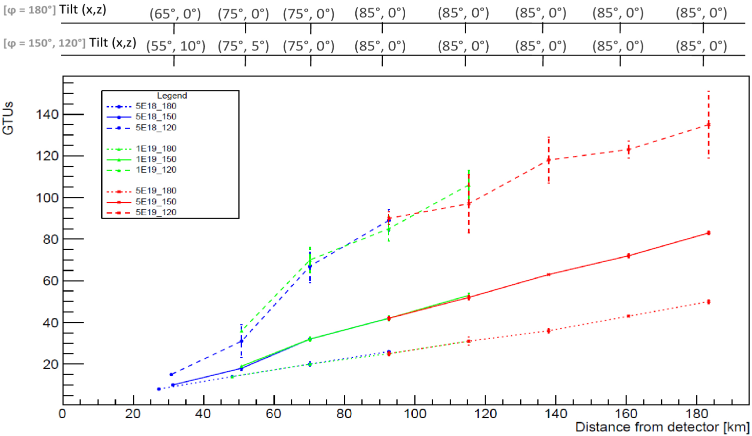
Conclusions

Event duration *vs* distance from detector



Example of histograms and FS views ($1 \cdot 10^{19}\,\mathrm{eV}$)

JEM-EUSO Program, Italy

Alessandro Liberatore

Cosmic rays
- UHECRs and EECRs
- Extended Air Shower

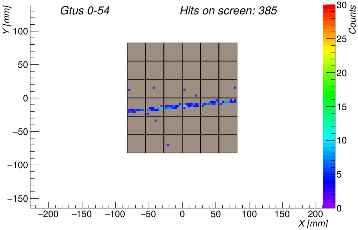
JEM-EUSO program
- ESAF
- JEM-EUSO missions

EUSO-SPB2
- Vertical configuration
- Horizontal configurations

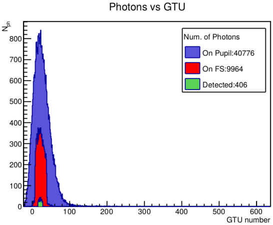
POEMMA
- Tilted configuration
- Reconstruction of events

Conclusions

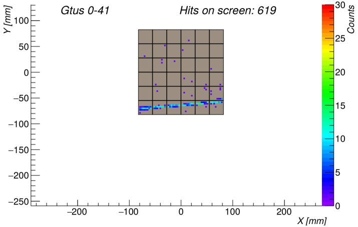
CR energy: $1 \cdot 10^{19}\,\mathrm{eV}$



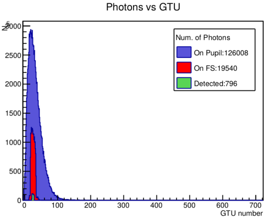
Distance from detector: $\sim 46\,\mathrm{km}$



CR energy: $1 \cdot 10^{19}\,\mathrm{eV}$



Distance from detector: $\sim 23\,\mathrm{km}$



Energy spectrum

From Auger spectrum (ICRC2017):

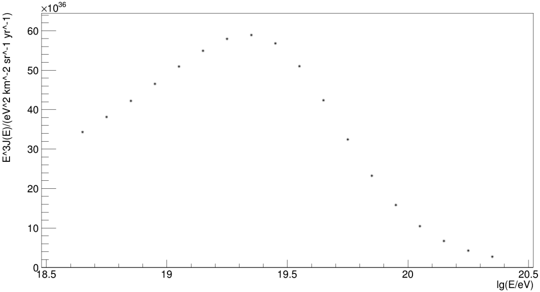
$$J(E) = J_0\left(\frac{E}{E_{ankle}}\right)^{-\gamma_2}\left[1+\left(\frac{E_{ankle}}{E_s}\right)^{\Delta\gamma}\right]\left[1+\left(\frac{E}{E_s}\right)^{\Delta\gamma}\right]^{-1} \qquad (E > E_{ankle})$$

...where: $\gamma_2 = 2.53 \pm 0.02$

$\Delta\gamma = 2.5 \pm 0.1$

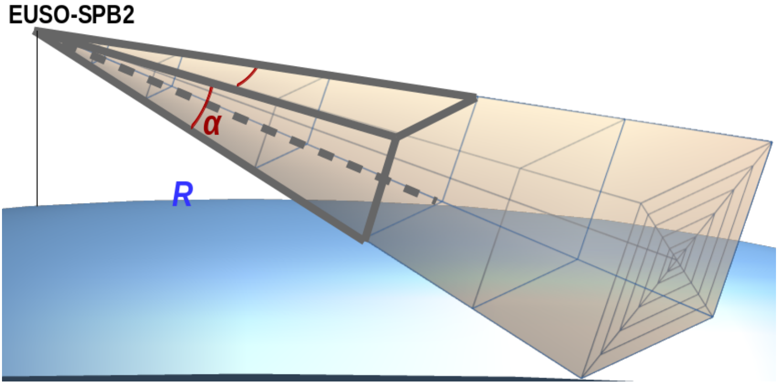
$E_{ankle} = (5.08 \pm 0.06)\,\mathrm{EeV}$

$E_s = (39 \pm 2)\,\mathrm{EeV}$



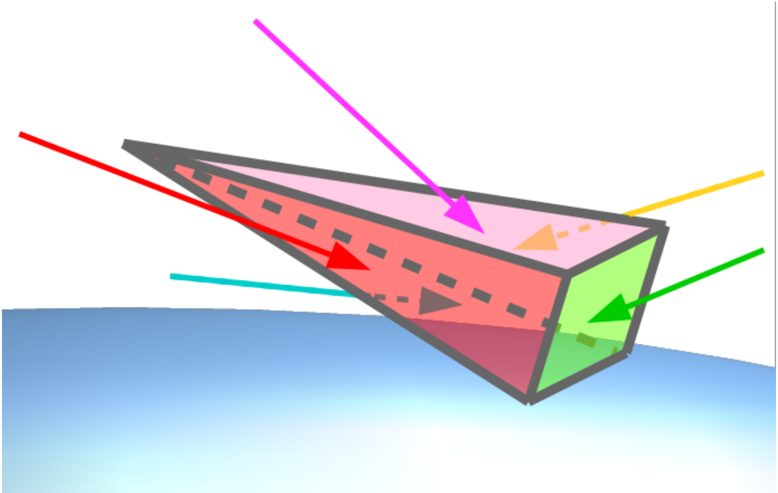
So. . . how many "trajectories" of cosmic rays?

Instantaneous aperture can be calculated in an approximate way. We have to consider the geometry:



So. . . how many "trajectories" of cosmic rays?

Five faces of entrances in to FOV:



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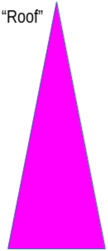
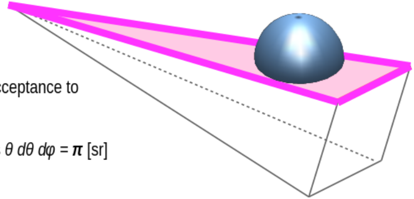
So...how many "trajectories" of cosmic rays?

$$S_R = \frac{1}{2}\alpha R^2$$

$\Omega_R \sim \pi$ [sr]

"Roof"





In general, solid angle acceptance to 1 hemisphere sky is

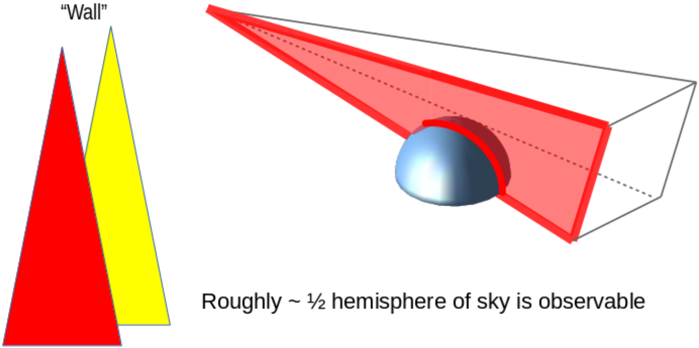
$$\Omega_{1/2} = \int_{-\pi}^{+\pi}\int_0^{\pi/2} \sin\theta \cos\theta \, d\theta \, d\varphi = \pi \text{ [sr]}$$

In practice, ~ hemisphere of sky is observable

So... how many "trajectories" of cosmic rays?

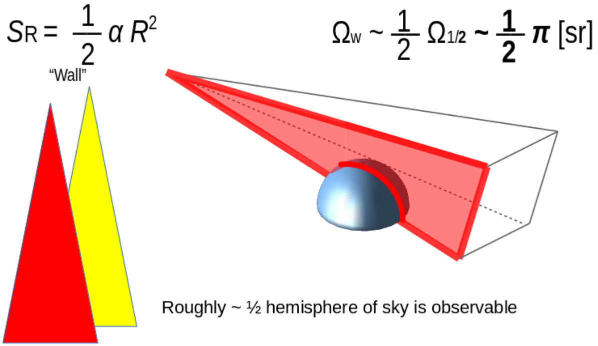
$$S_R = \frac{1}{2} \alpha R^2$$

$$\Omega_W \sim \frac{1}{2} \Omega_{1/2} \sim \frac{1}{2} \pi \text{ [sr]}$$



Roughly ~ ½ hemisphere of sky is observable

So... how many "trajectories" of cosmic rays?

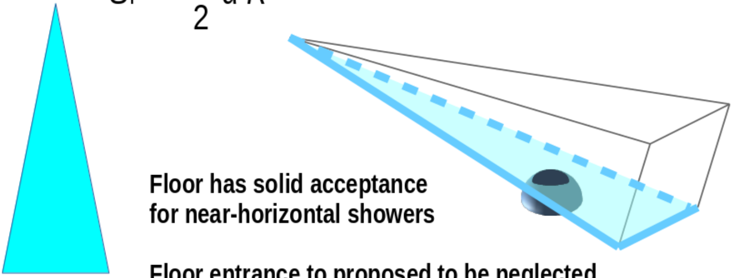


In case of 1 PDM:

$$2S_{Rw}\Omega_w = \frac{1}{2}\pi\alpha R^2 = \boxed{0.41R^2\ [\mathrm{km}^2\mathrm{sr}]}\ (\text{for } \alpha = 15^\circ)$$

So. . . how many "trajectories" of cosmic rays?

$$S_F = \frac{1}{2}\alpha R^2$$



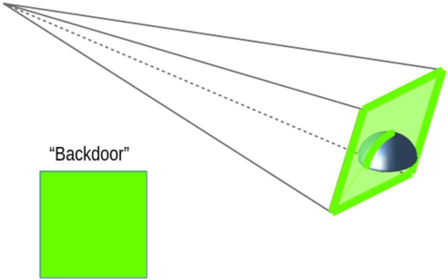
Floor has solid acceptance for near-horizontal showers

Floor entrance to proposed to be neglected as "roof" solid acceptance overestimated

So. . . how many "trajectories" of cosmic rays?

$$S_D = \alpha^2 R^2$$

$$\Omega_D < \frac{1}{2}\pi \text{ [sr]}$$



This time, it is proposed to omit the contribution from backdoor events

This contribution is irrelevant unless tiling angle large

So... how many "trajectories" of cosmic rays?

- **In case of 1 PDM**:

  $S_R\Omega_R + 2S_{Rw}\Omega_w = \pi\alpha R^2 = 0.82R^2\,[\mathrm{km}^2\mathrm{sr}]$ (for $\alpha = 15°$)

- **In case of 2 PDMs horizontally aligned** ("roof" must be two times larger):

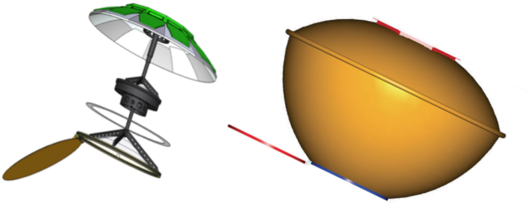
  $2S_R\Omega_R + 2S_{Rw}\Omega_w = 1.5\pi\alpha R^2 = 1.23R^2\,[\mathrm{km}^2\mathrm{sr}]$ (for $\alpha = 15°$)

- **Note:**
  the contribution from the "backdoor" $S_D\Omega_D$ in case of 1 PDM:

  $< \frac{1}{2}\pi\alpha^2 R^2 = 0.1R^2\,[\mathrm{km}^2\mathrm{sr}]$ for $\alpha = 15°$ ($\equiv 0.26\,\mathrm{rad}$)
  ...so it is not comparable with $S_R\Omega_R$ & $S_{Rw}\Omega_w$.

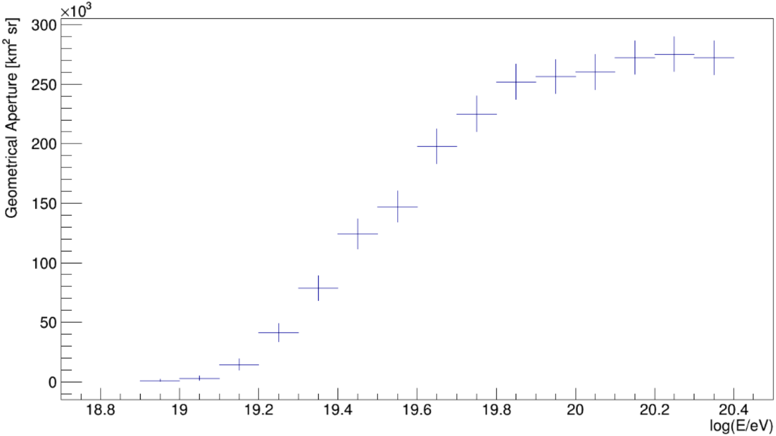
POEMMA

- **P**robe **O**f **E**xtreme **M**ulti-**M**essenger **A**strophysics (POEMMA) is a "long-term project" selected by NASA in early 2017.
- It is a re-examination of the JEM-EUSO telescope but that, instead of being a single telescope on the International Space Station, consists of **two telescopes** in flight formation at an altitude of about 525 km above sea level.



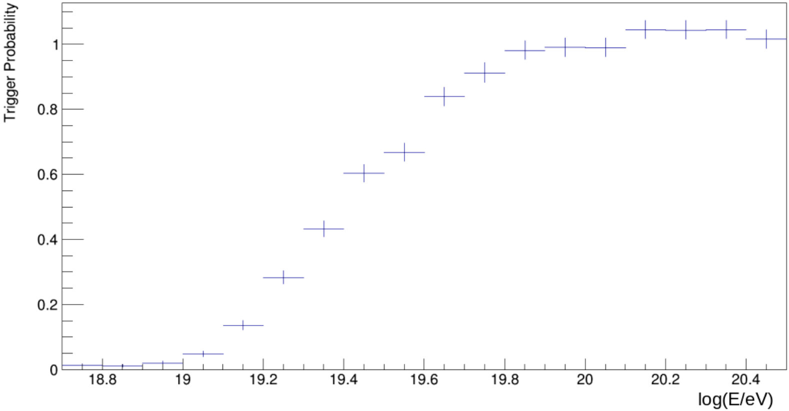
Aperture $A(E)$ (Altitude: $400\,\mathrm{km}$)

$$A(E) = \int_{S_{sim}} dS \int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} d\theta \cos\theta \cdot \sin\theta \cdot \epsilon$$



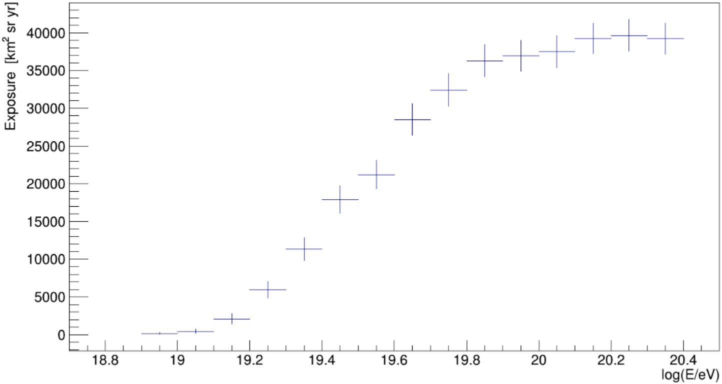
Efficiency (Altitude: 400 km)

$$\epsilon(E) = \frac{N_{trigg}}{N_{sim}} \frac{S_{sim}}{S_{FoV}}$$

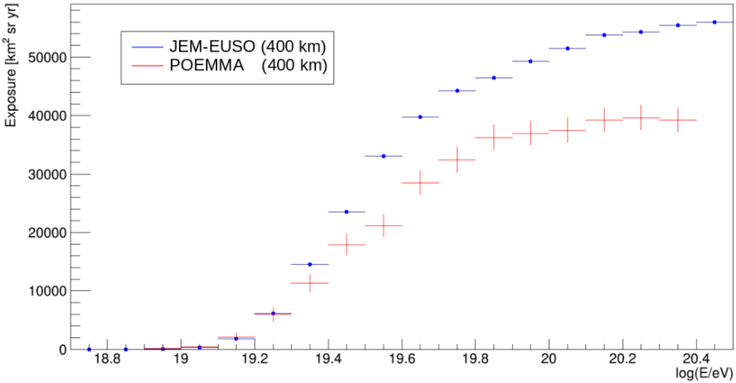


Exposure $\Psi(E)$ (Altitude: $400\,\mathrm{km}$)

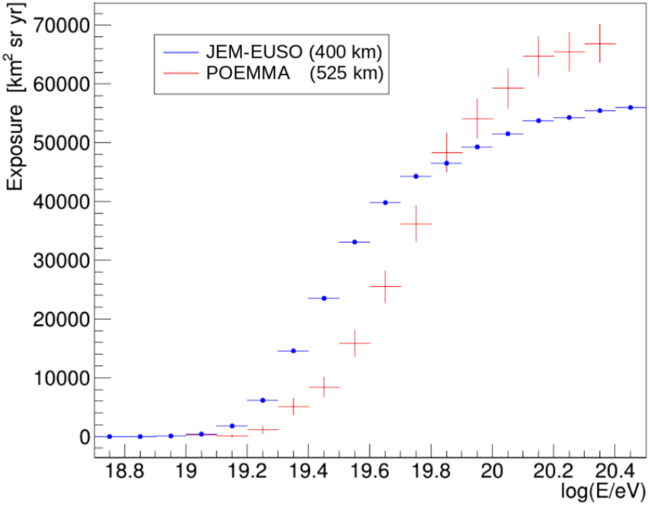
$$\Psi(E) = A(E) \cdot t \cdot DC \qquad (t = 1 year; DC = 20\% \cdot 72\%\,\mathrm{clouds})$$



Exposure: JEM-EUSO (400 km) vs POEMMA (400 km)

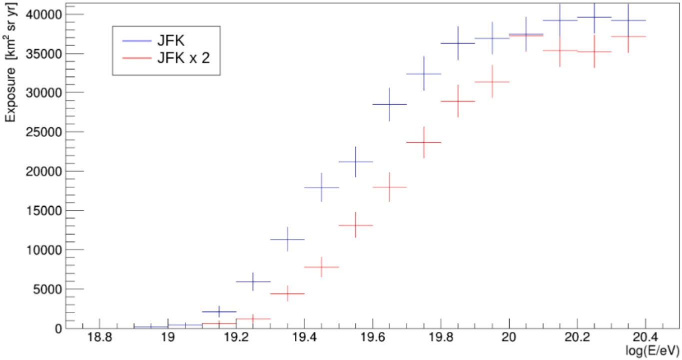


Exposure: JEM-EUSO (400 km) vs POEMMA (525 km)



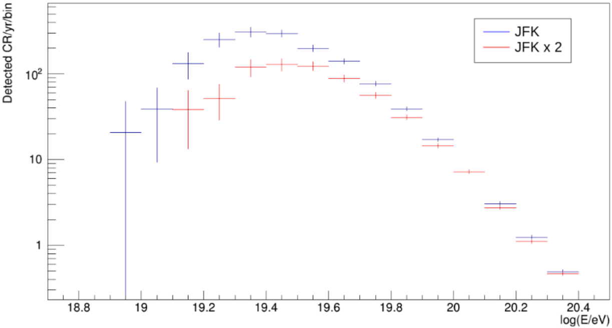
Different spot size (JFKx2) -Exposure-

$$\Psi(E) = A(E) \cdot t \cdot DC \qquad (t = 1year; DC = 20\% \cdot 72\% \,\text{clouds})$$



Different spot size (JFKx2) -Triggered spectrum-

$$\Phi(E) = \int \phi \cdot S_{FoV} \cdot \epsilon \cdot \pi \cdot t \cdot DC \qquad (t = 1 year; DC = 20\% \cdot 72\% \, \text{clouds})$$



Above log(E/eV)=19.6: $\frac{Integral\ \ counts\ \ (JFK \times 2)}{Integral\ \ counts\ \ (JFK)} \approx \frac{200}{280} \approx -28\%.$

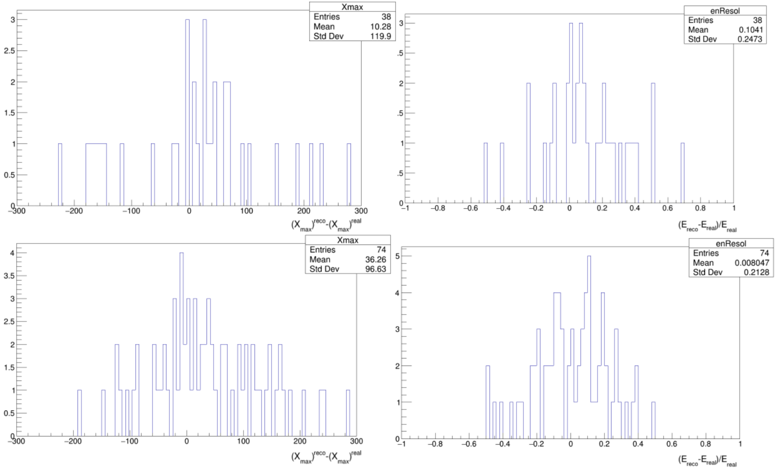
Manual vs Automatic reconstruction

(Automatic)	*Cherenkov method*	*Slant depth method*
Events	300	300
Triggered	91	91
Reconstructed	38	74

(Manual)	*Cherenkov method*	*Slant depth method*
Events	300	300
Triggered	91	91
Reconstructed	34	66

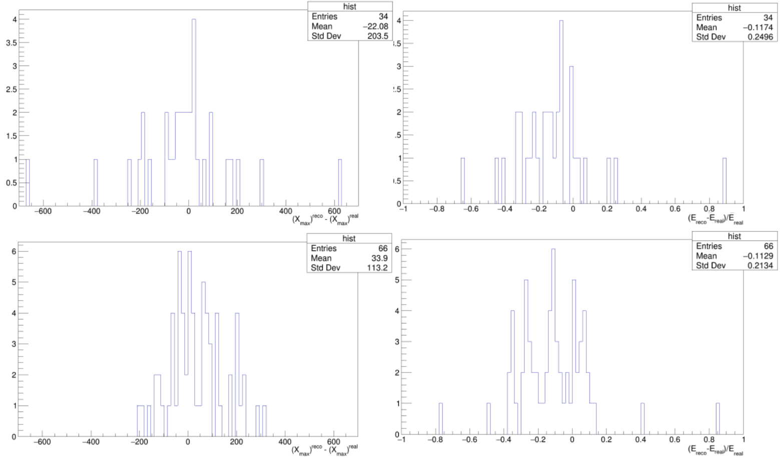
Manual vs Automatic reconstruction

Results from automatic reconstruction:



Manual vs Automatic reconstruction

Results from manual reconstruction:



Focal plane observation