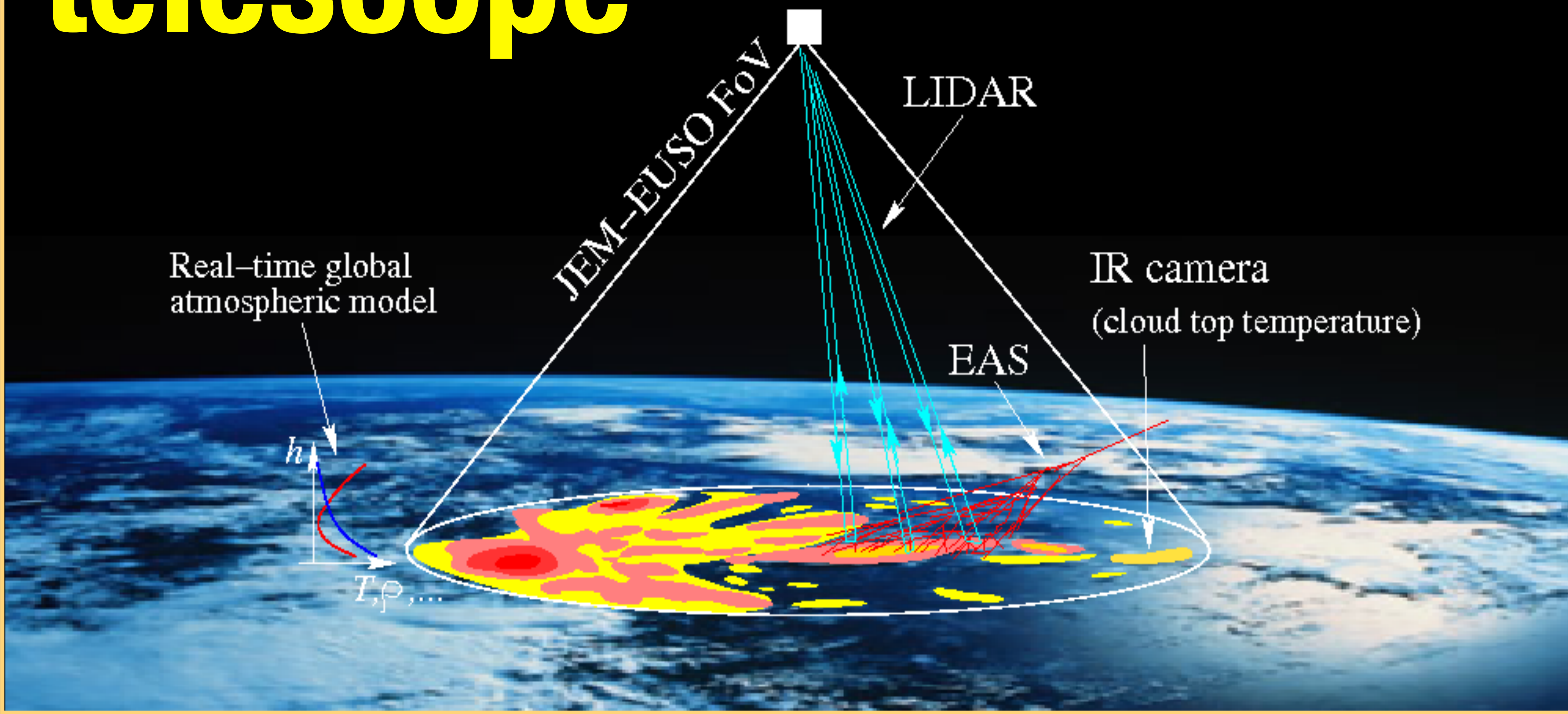
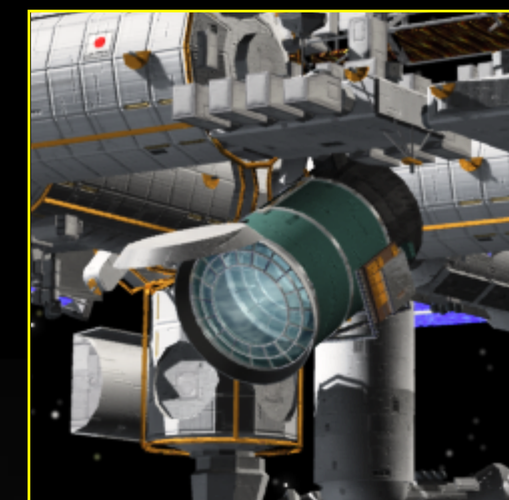
The Atmospheric Monitoring system of the JEM-EUSO telescope





Simona Toscano for the **JEM-EUSO Collaboration**
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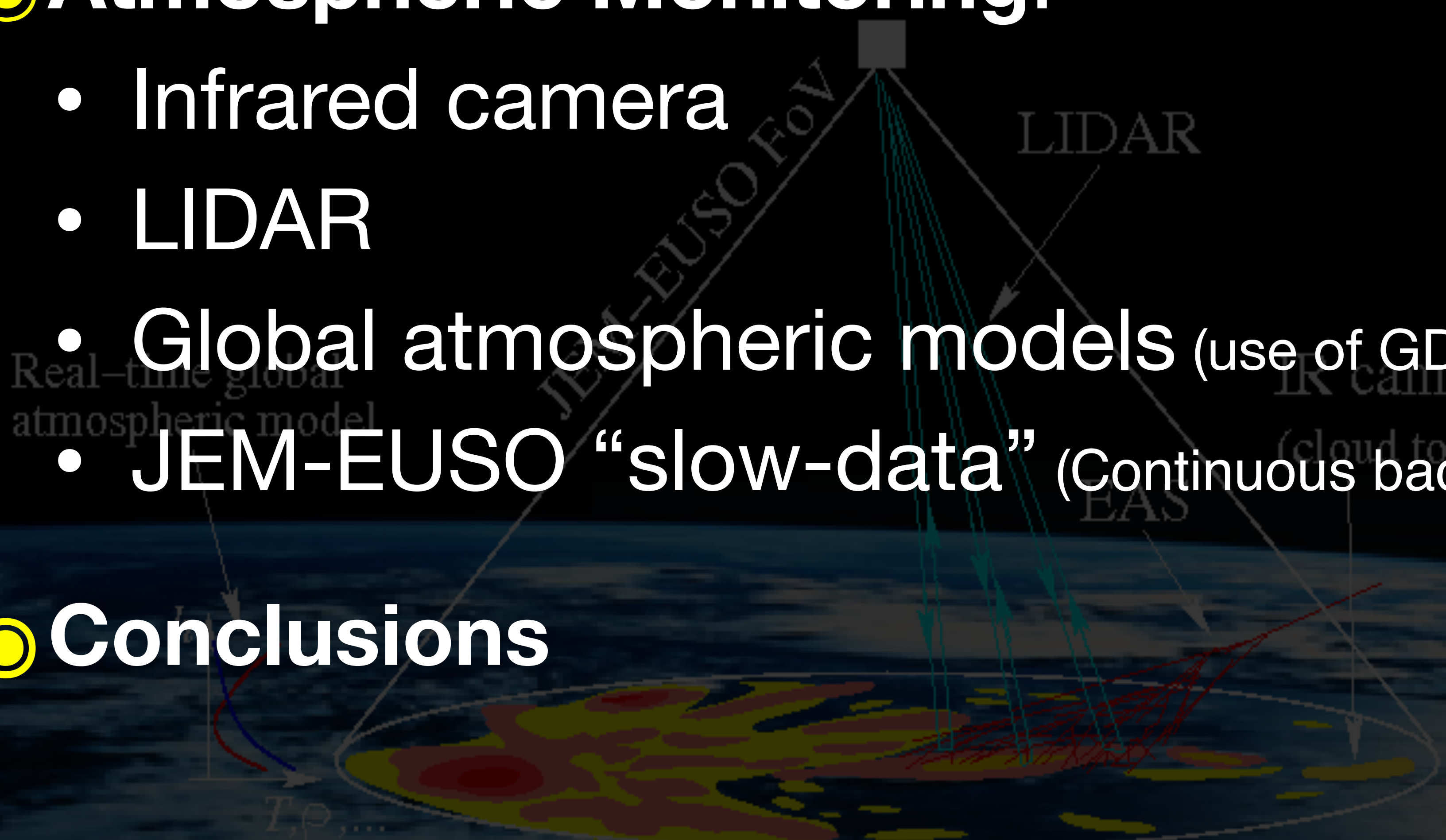
AtmoHEAD

ISDC

UNIVERSITÉ DE GENÈVE

Outline

- **General introduction on JEM-EUSO physics**
- **Atmospheric Monitoring:**
  - Infrared camera
  - LIDAR
  - Global atmospheric models (use of GDAS currently under study)
  - JEM-EUSO "slow-data" (Continuous background photon counting)
- **Conclusions**



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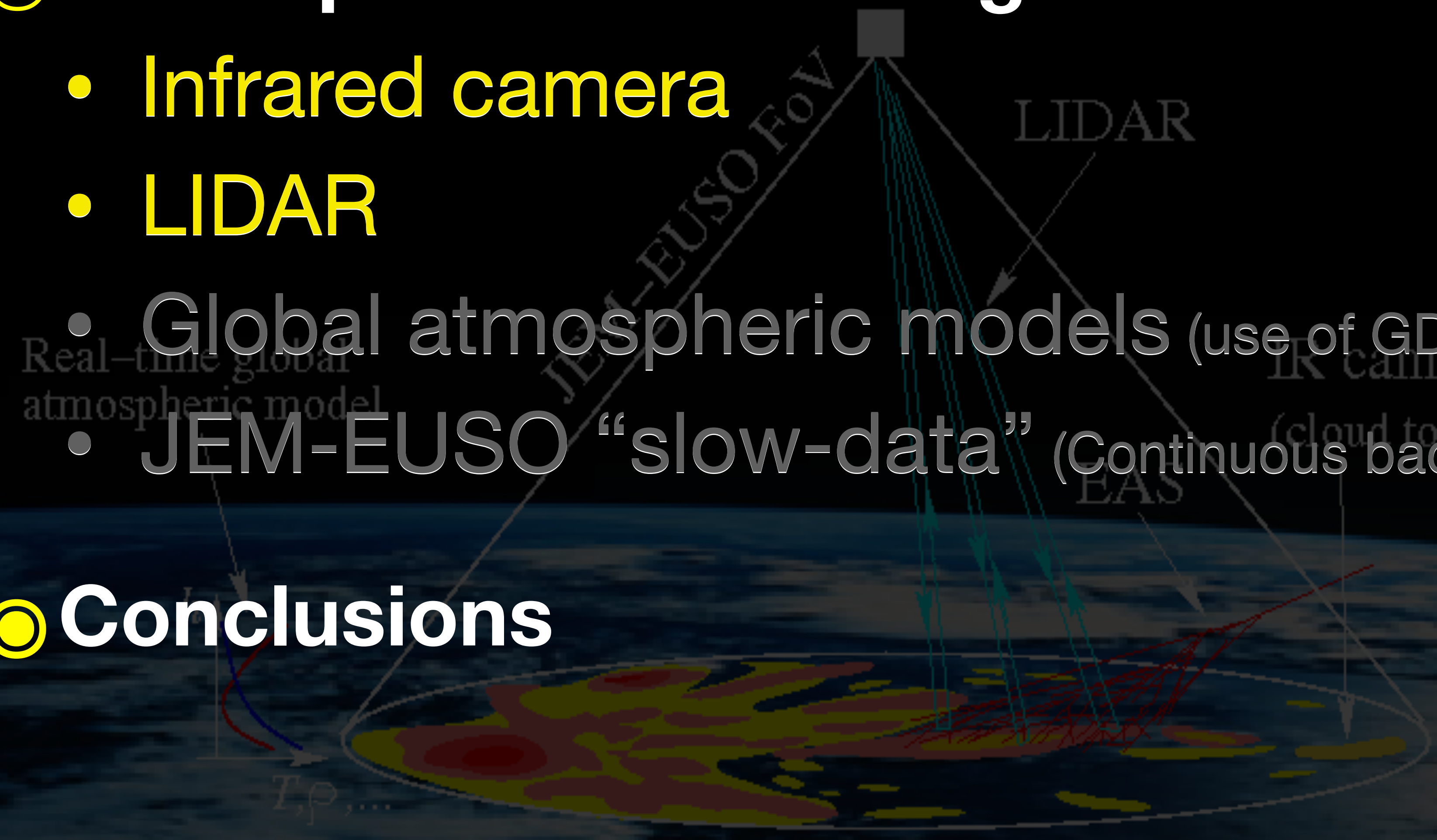


The cosmic ray spectrum

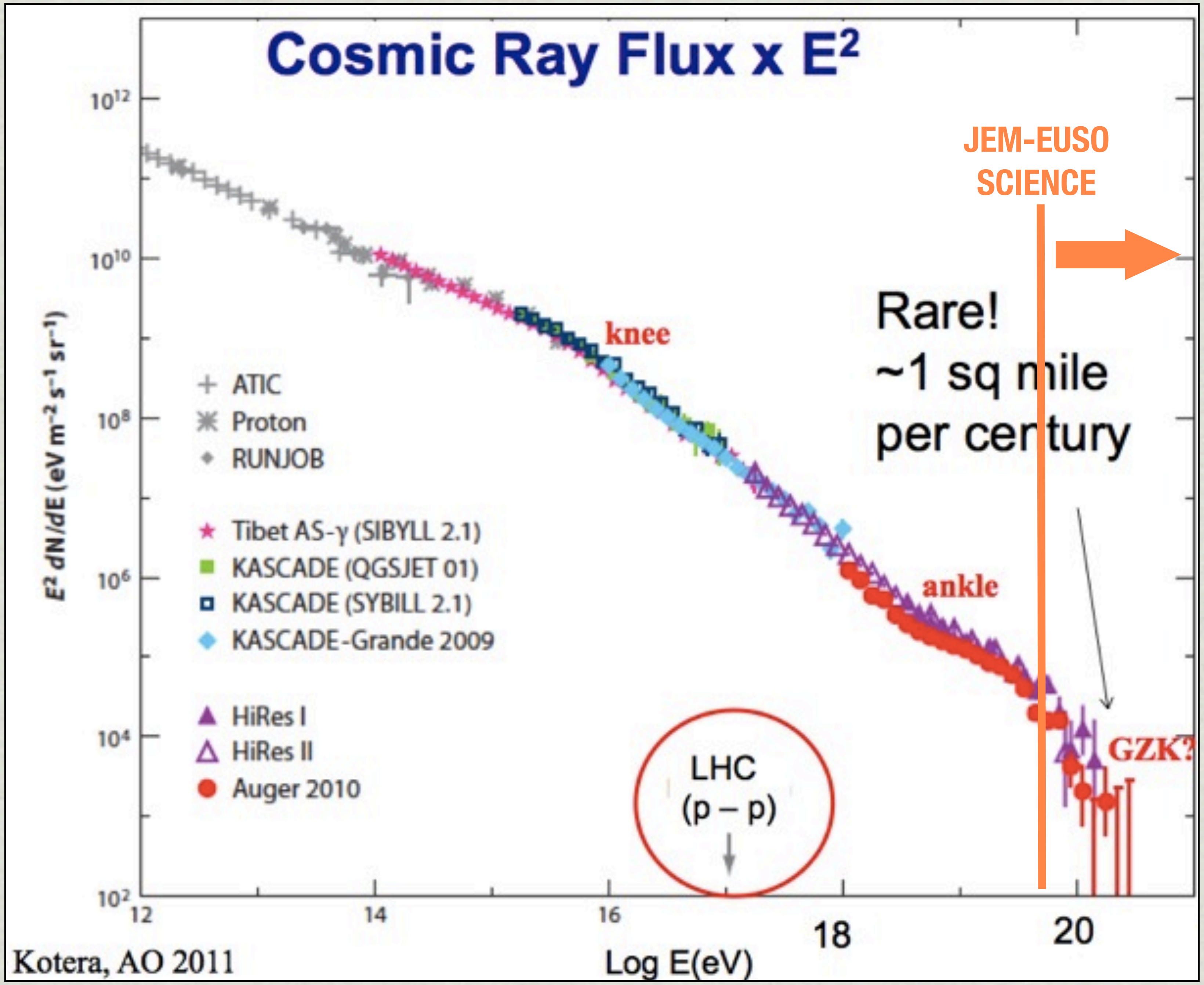
Cosmic rays above ~10^{18}-10^{19} eV are believed to have extra-galactic origin.

The highest observed cosmic ray energy is ~3×10^{20} eV (10^8 times higher than LHC energy scale). It is above the GZK cutoff (due to interaction of UHCRs with CMB).

Most of the candidate sources are incapable of accelerating particle beyond the GZK limit.

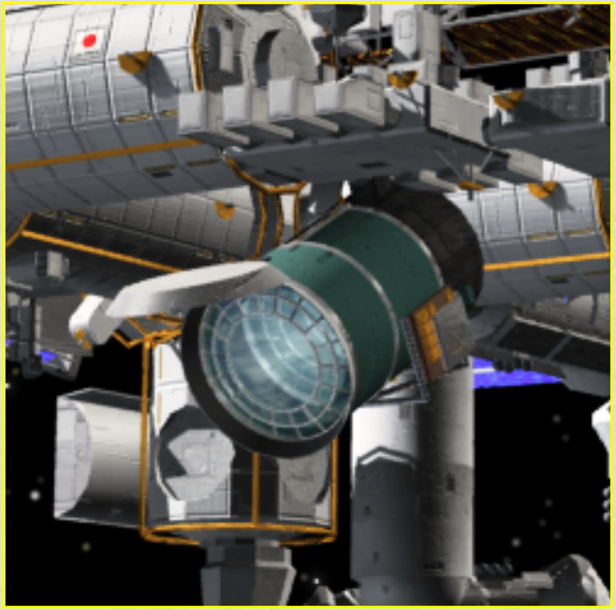
The origin of UHECRs is still an open question.

from Lawrence's talk on Monday



JEM-EUSO

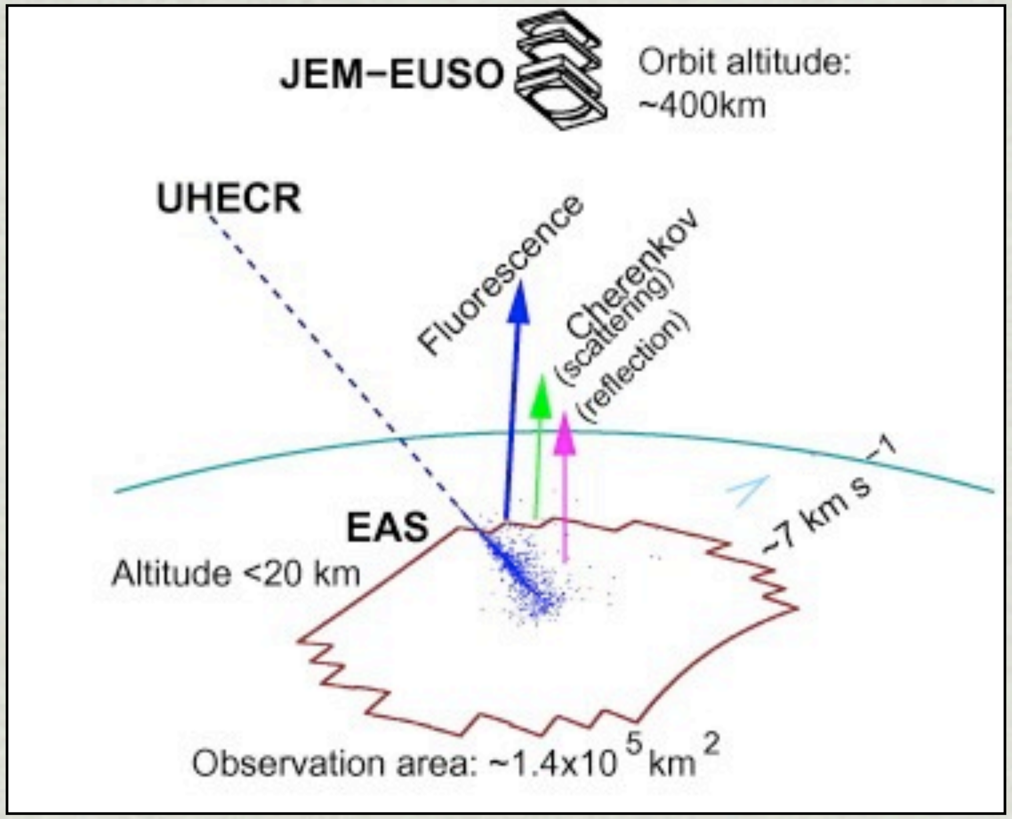
Extreme Universe Space Observatory on board the Japanese Experiment Module



- A new space-based (ISS) mission to study the origin and nature of UHECRs.
- Main objectives:
  - identification of UHECRs sources
  - study of acceleration and radiation process
  - source spectra
- Exploratory science:
  - Measurement of extreme energy gamma rays
  - Detection of extreme energy neutrinos
  - Structure of galactic magnetic field
  - Identification of relativity and quantum gravitational effect
  - Study of atmospheric luminous phenomena

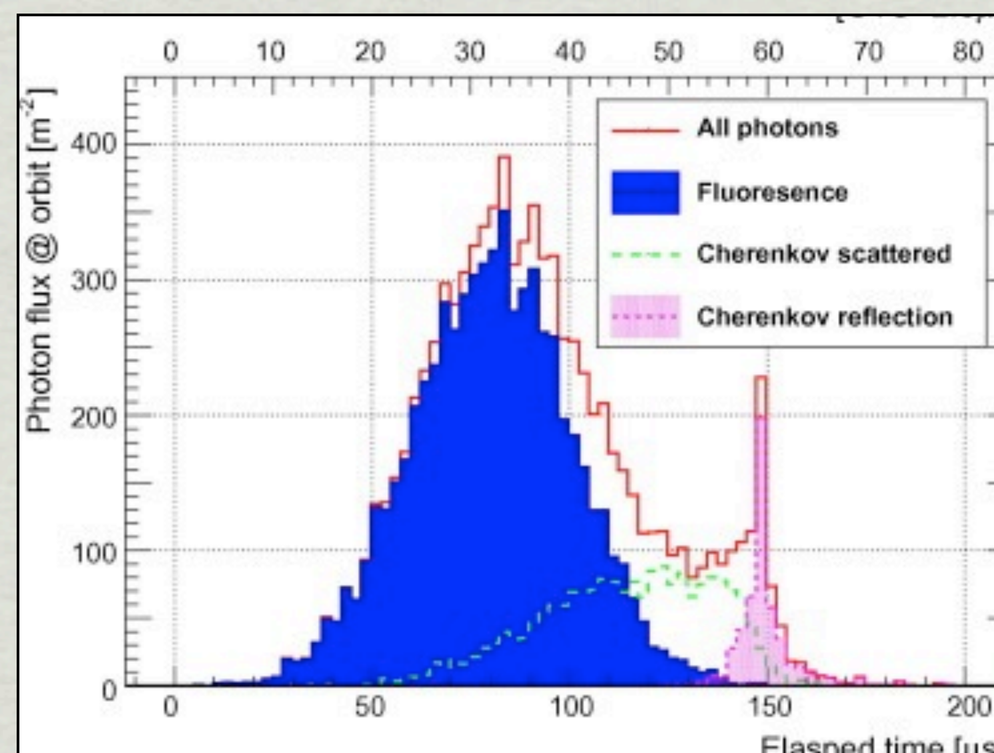
Detection Principle

Adams Jr.,J.H. et al. (2013), *An evaluation of the exposure in nadir observation of the JEM-EUSO mission,* Astroparticle Physics 44, 76-90 (2013)



- Detection of UV light emitted by EAS initiated by primary UHECRs hitting the Earth's atmosphere (our detector)
- Fluorescence light (secondary electrons exciting N_2) emitted isotropically along the EAS track and observed directly.
- Cherenkov light is forward-beamed. It's observed because of scattering and diffuse reflection (*Cherenkov mark*)
- Properties of UHECR particles (arrival direction, energy, type) are derived from the properties of the detected light.

- Photons flux at the entrance aperture:
  - 10^{20} eV shower generates ~ 10^{15} photons (thousands of them reaching the pupil)
  - fluorescence is the dominant component, with smaller contribution from reflected and back-scattered Cherenkov
  - energy can be determined with only small corrections for the Cherenkov component

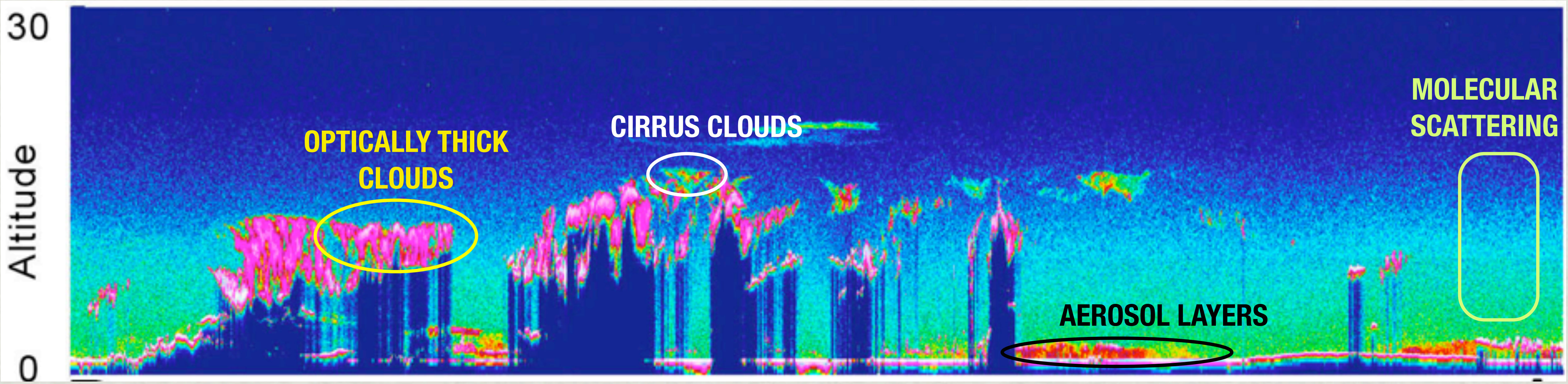


Tuesday, June 11, 13

The Earth's atmosphere

* Proper measurement of UHECRs properties can be achieved only knowing the condition of the detector (atmosphere).

* Intensity of the observed light depends on the transmittance (absorption and scattering properties) of the atmosphere, the cloud cover and clouds properties (height, optical depth...), and aerosols.



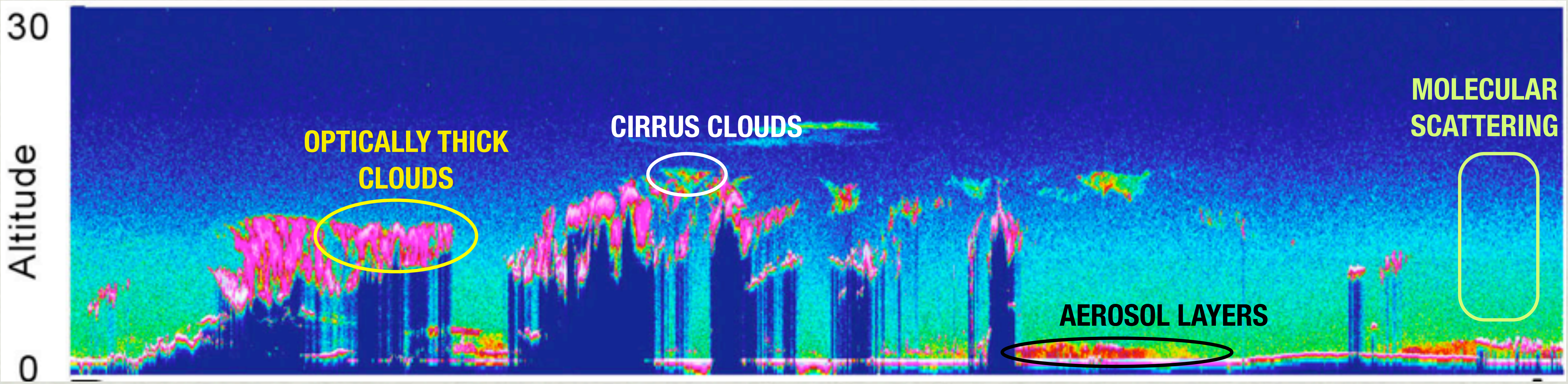
LIDAR profile from the CALIPSO spacecraft, specifically the 523 nanometer Total Attenuated Backscatter. Credit: NASA Langley Research Center.

The Earth's atmosphere

- JEM-EUSO will experience all possible weather conditions (ISS moves with v~7 km/sec).

- State of the atmosphere is continuously changing in FoV. Variations of atmospheric conditions affect:

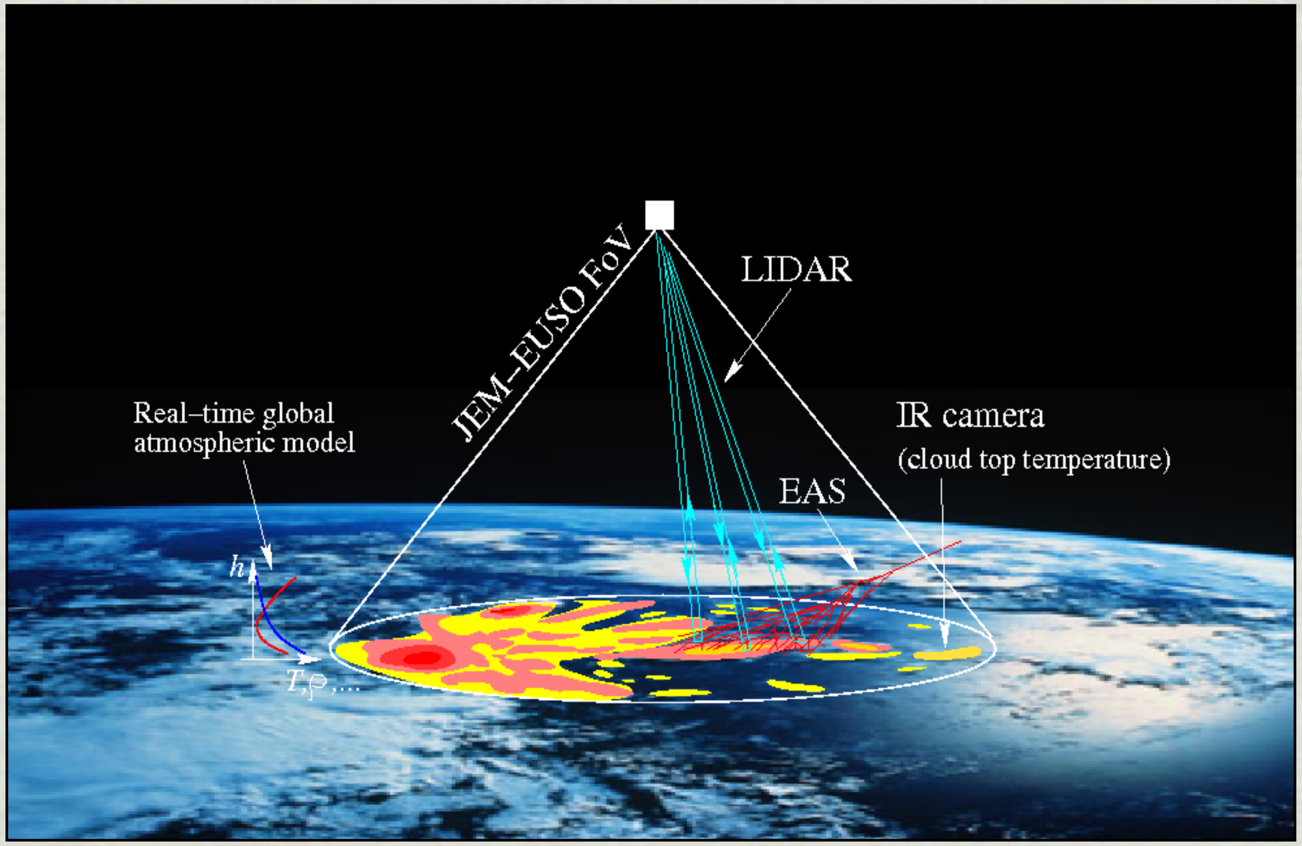
  - the development of the EAS
  - amount of UV light produced along the EAS track
  - amount of UV light reaching the telescope.



LIDAR profile from the CALIPSO spacecraft, specifically the 523 nanometer Total Attenuated Backscatter. Credit: NASA Langley Research Center.

The **A**tmospheric **M**onitoring **(AM)** system

The AM system will continuously monitor the atmosphere in JEM-EUSO FoV during data taking period.



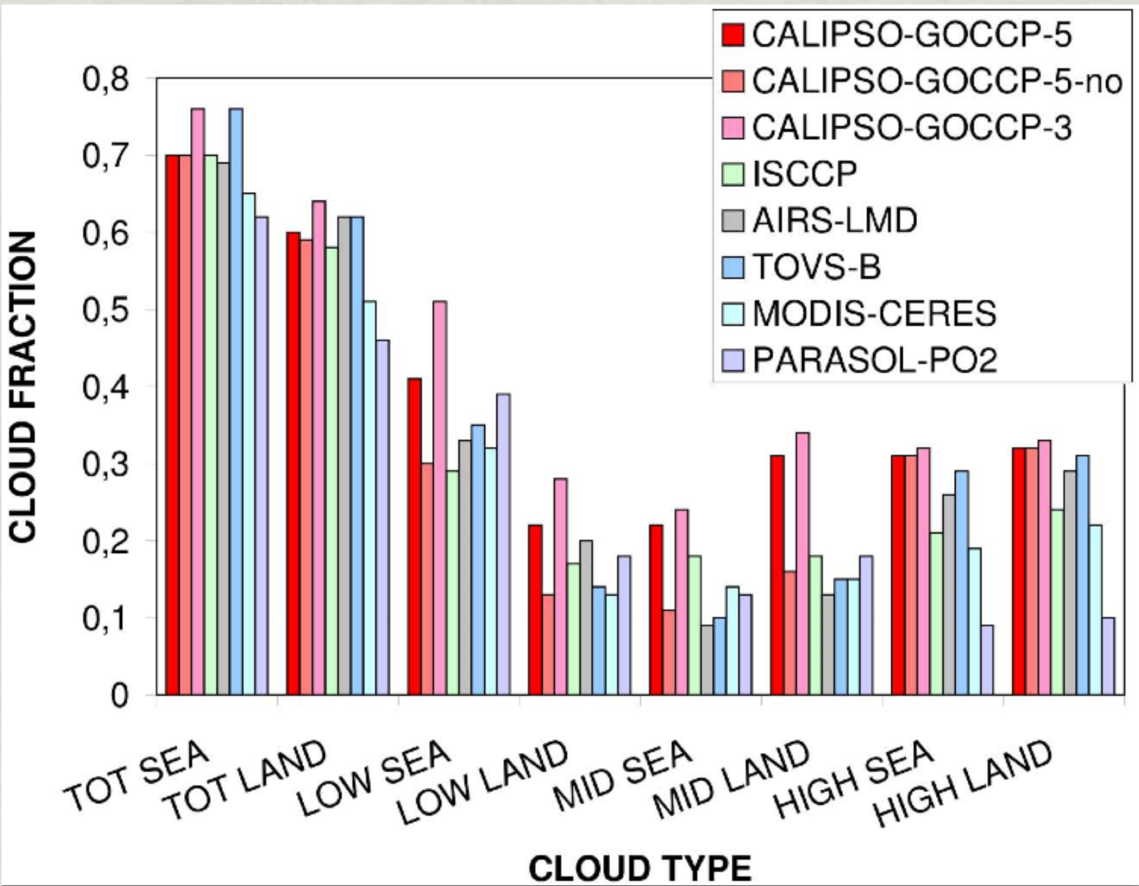
INFRARED CAMERA: information on cloud cover and measurement of top altitude of optically-thick clouds

LIDAR: detection of thin clouds with and aerosol layers

GLOBAL MODELS: physical parameters of the atmosphere from weather forecasting services such as NCEP, GMAO, ECWMF.

SLOW MODE DATA: additional information on cloud distribution and intensity of the night sky airglow

Goals of the AM system



TOVS DATA

OPTICAL DEPTH \ ALTITUDE (KM)	<3.2	3.2-6.5	6.5-10	>10
<0.1	31%	<0.1%	<0.1%	1.2%
0.1-1	6.4%	2.0%	3.2%	5.0%
1-2	6.0%	3.0%	4.2%	2.5%
>2	16%	6.0%	8.5%	5.0%

- Only 30% of events will develop in *clear sky*
- Events occurring in the remaining 70% will be rejected if not corrected for the presence of clouds.
- Minimal task of the AM system: to provide a selection criteria for *golden events* (no detection of clouds from LIDAR or IR camera).
- More advanced: correction for cloud-affected shower profiles for simple cases (i.e. low-altitude optically thick clouds).

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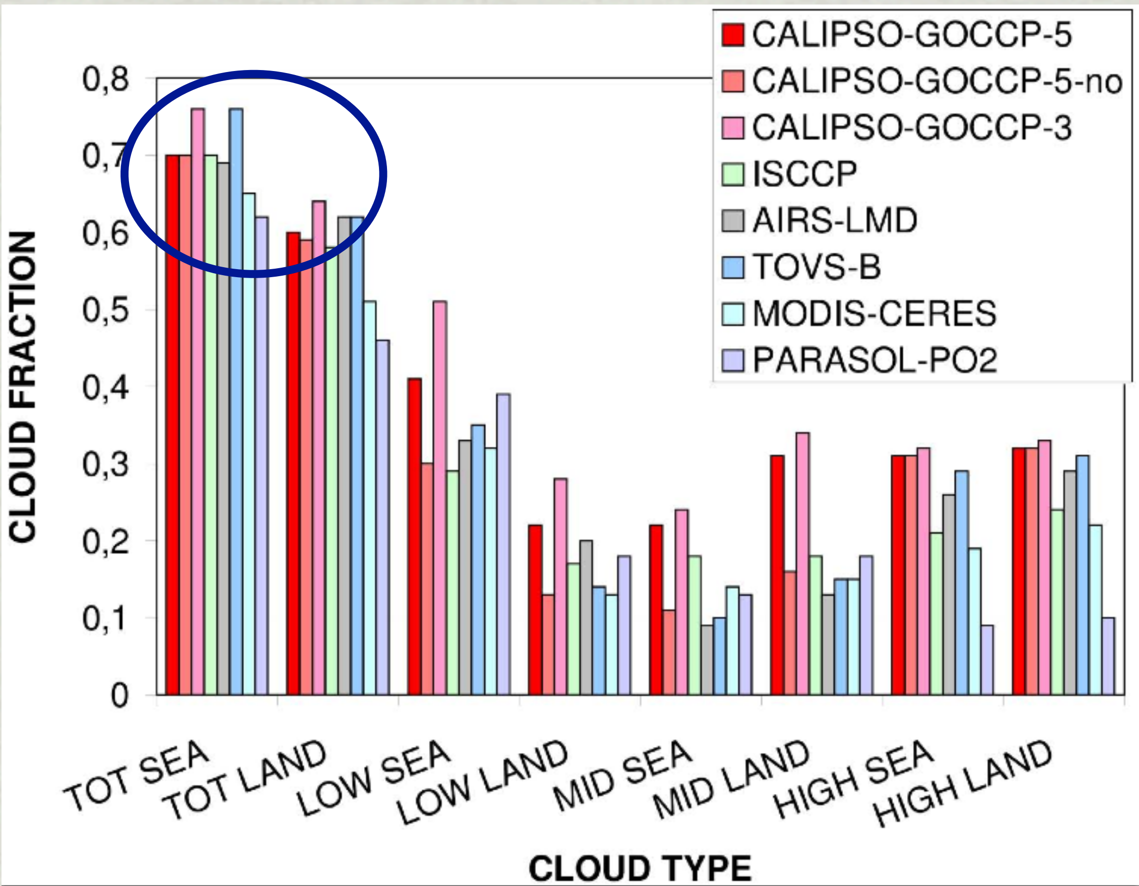

ALTITUDE (KM) — **TOVS DATA**

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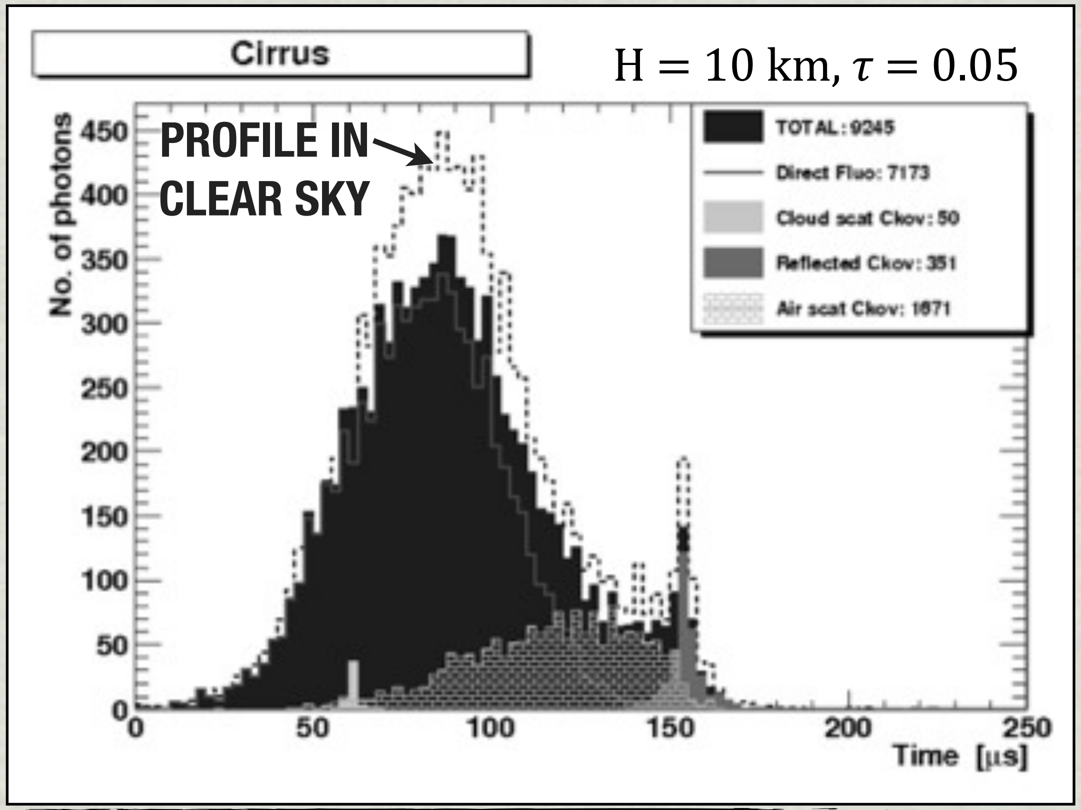
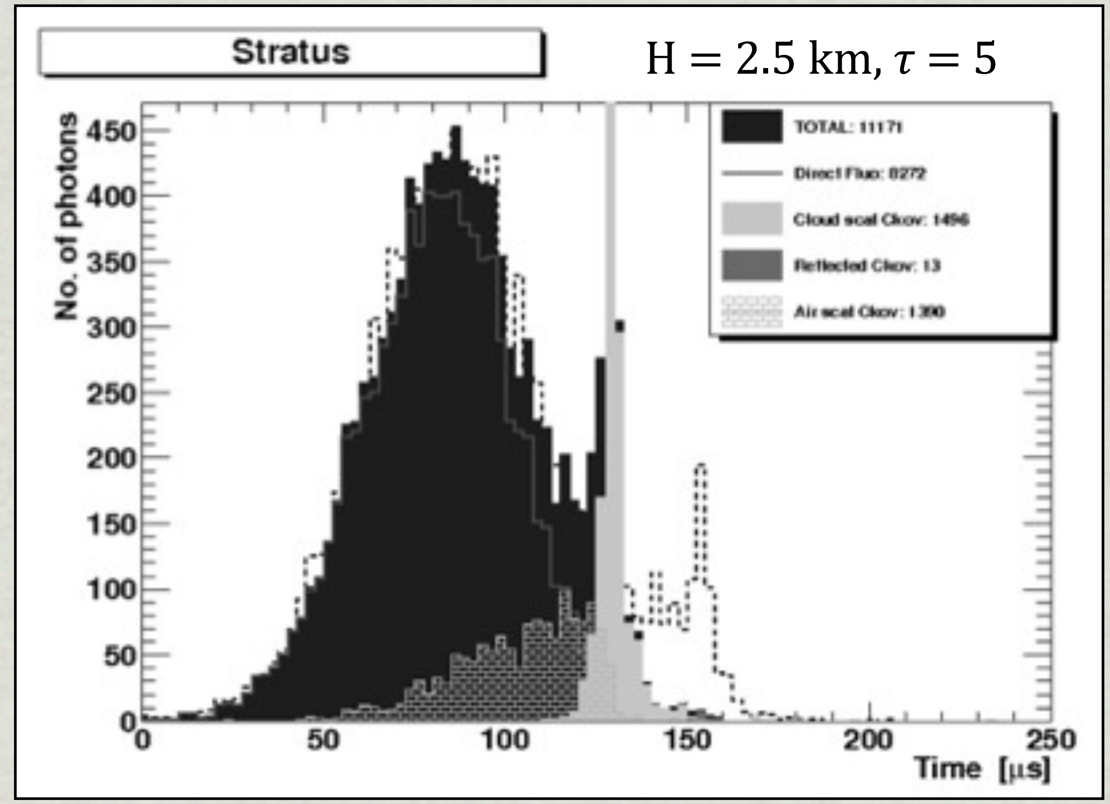
Requirements of the AM system

Saez et al. Proc. TAUP 2011





Cirrus case: signal attenuation according to the optical depth (τ) leads to an error in the estimation of the energy

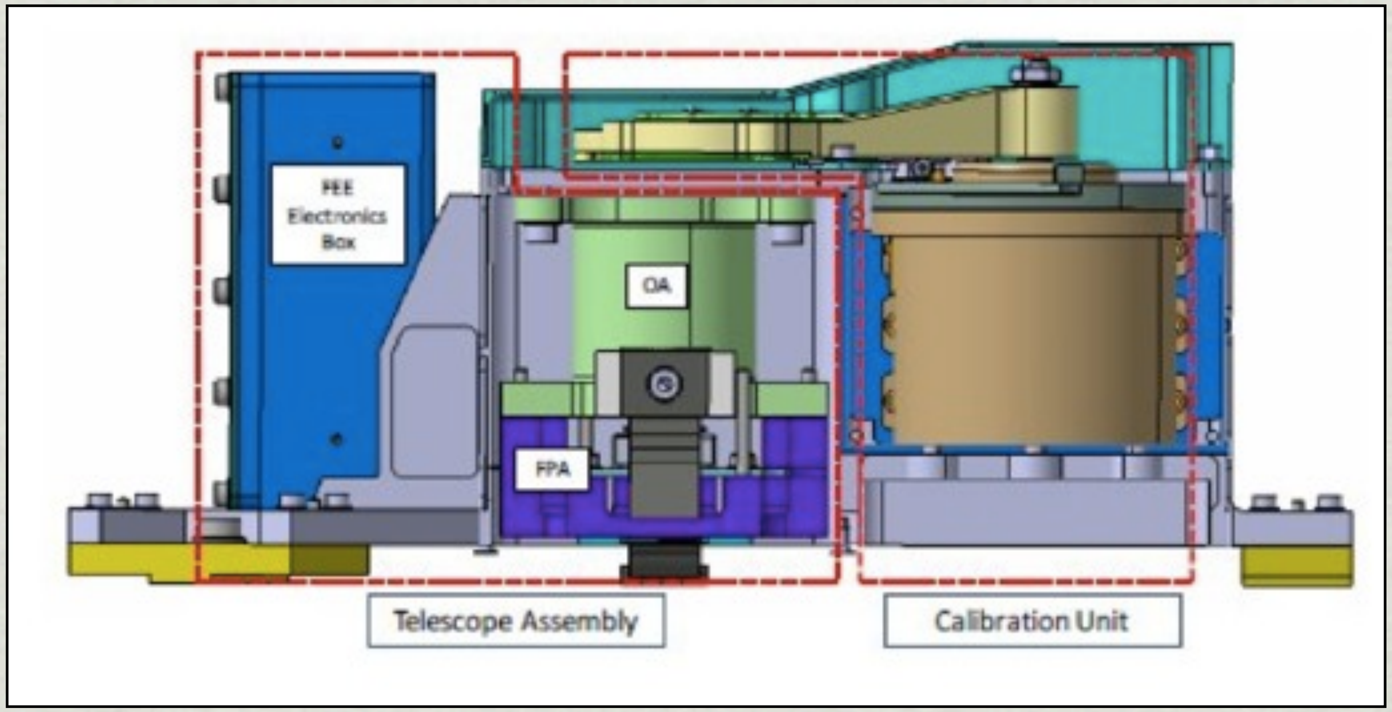
Stratus case: EAS observed w/o attenuation (cloud top below the region of development); strong Cherenkov reflection on the top of cloud instead of ground leads to an error in the geometry reconstruction and particle identification.

- General requirements on the precision of the UHECRs measurement ($\Delta E/E < 30\%$, $X_{max} < 120$ g/cm^2) impose the requirements on the precision of the atmospheric measurement:
    - measurement accuracy of optical depth profile of the atmosphere around EAS: $\Delta\tau \leq 0.15$
    - cloud top altitude measurement accuracy: $\Delta H \leq 500$ m

The InfraRed (IR) camera

Parameter	Target value	Comments
Measurement range	220 K - 320 K	Annual variation of cloud temperature plus 20 K margin
Wavelength	10-12 μm	Two atmospheric windows available: 10.3-11.3 μm and 11.5-12.5 μm
FoV	48^o	Same as main instrument
Spatial resolution	0.1^o (Goal) 0.2^o (Threshold)	@FoV center
Absolute temperature accuracy	3 K	500 m in cloud top altitude
Mass	≤ 11 kg	Inc 20% margin.
Dimensions	$400 \times 400 \times 370$	w/o Insulation and mounting bracket.
Power	≤ 15 W	Inc 20% margin.
Lifetime	5 years In-orbit	+2 years On-ground

Towards the Preliminary Design Review of the Infrared Camera of the JEM-EUSO Space Mission, M.D. Rodriguez Frias for the JEM-EUSO Collaboration, ICRC proceedings 2013.



- Micro-bolometer based infrared imaging system for cloud coverage and cloud top altitude measurements.
- Three main blocks:
  - Telescope Assembly to acquire the IR radiation with a micro-bolometer and convert into digital counts;
  - Electronic Assembly to process and transmit the image, provide the electrical system, the thermal control and secure communication with the platform computer;
  - Calibration unit to assure the accuracy of the measurement.
- Challenging mechanical and thermal design to secure IR-Camera isolation.

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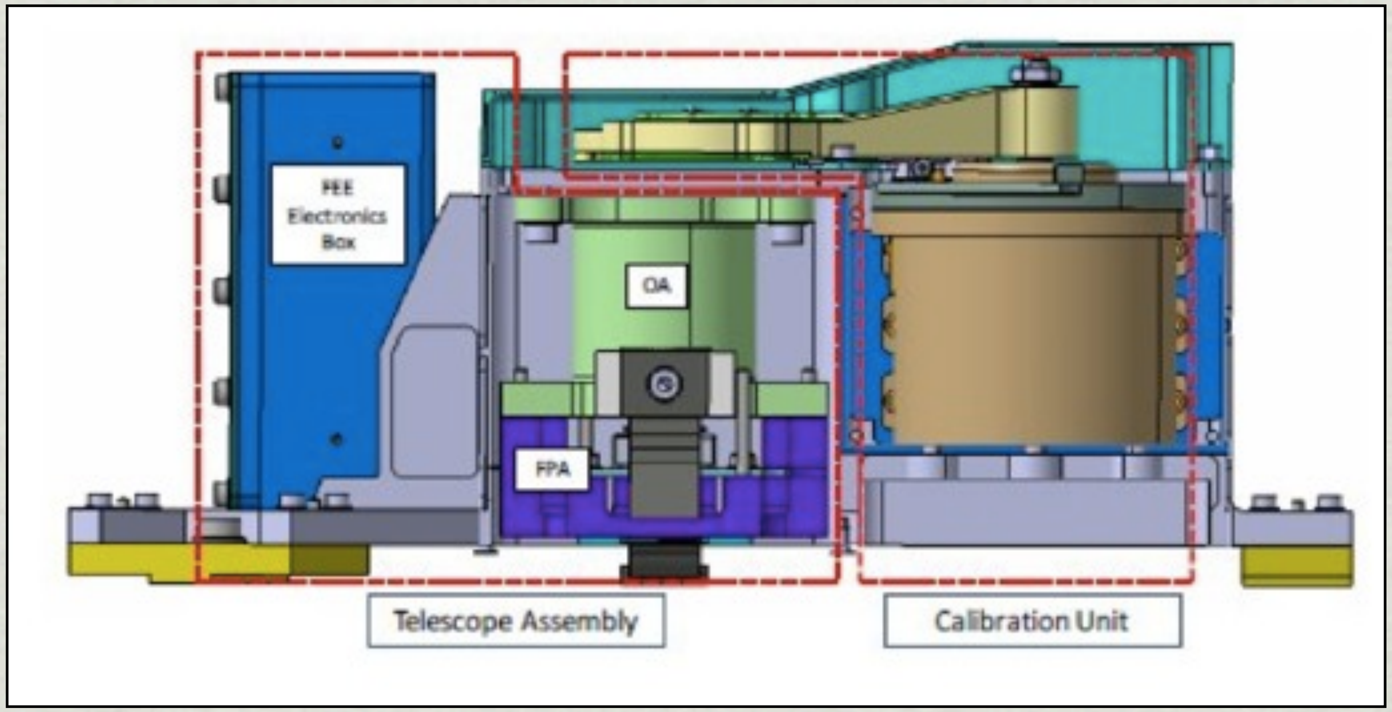
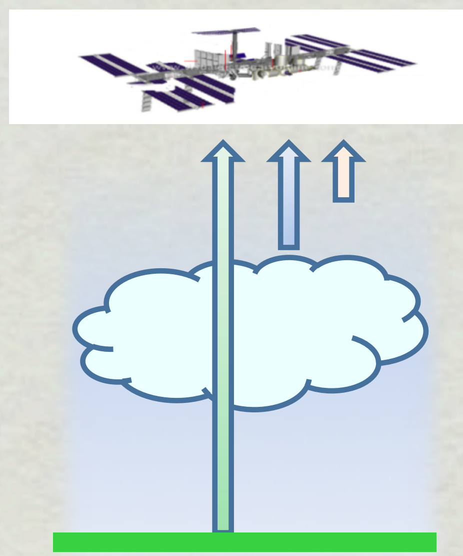


- Two approaches for Cloud Top Height (CTH) that can support each other:
  - **radiometric methods** based on the relationship between atmosphere temperature and altitude, extra info are necessary;
  - **stereo vision techniques** based only on geometrical relationships.

The IR camera: radiometric methods

- **No direct measurement**: observed radiation is related to the cloud temperature and emissivity ($L_{measured} \Rightarrow T_{retrieved}$) (radiance is the measurement)
- The atmosphere between the emitter and the sensor absorbs and emits energy:

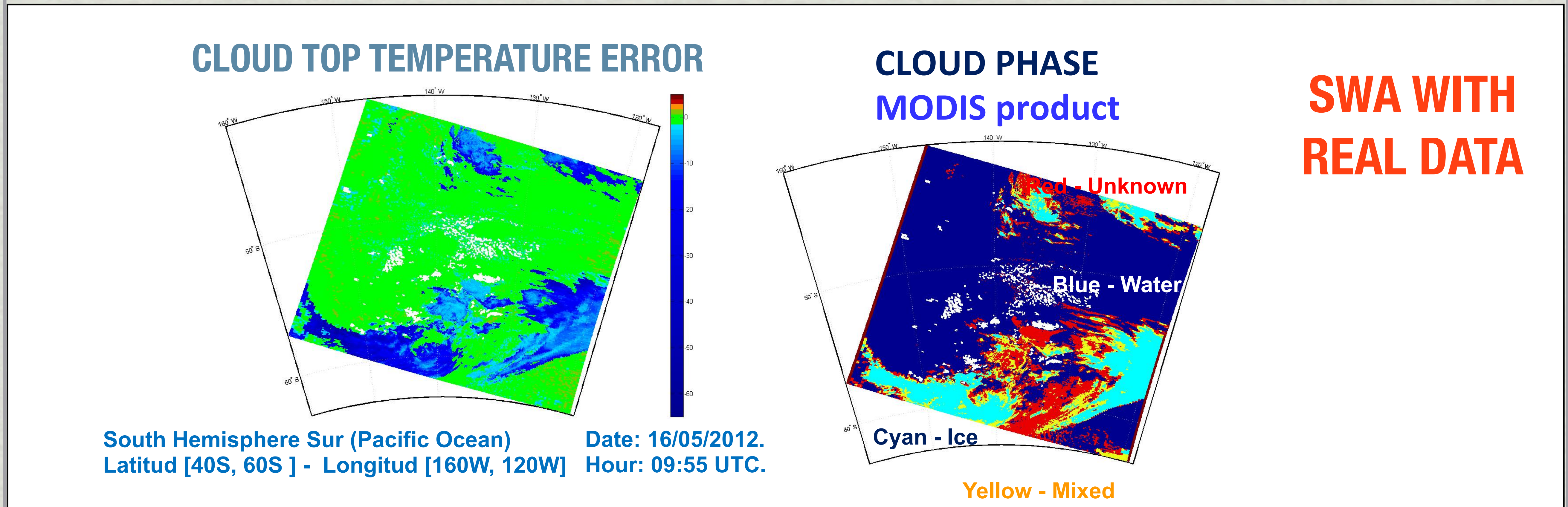


$L_{CLOUD} \neq L_{MEASURED}$

$T_{CLOUD} \neq T_{RETRIEVED}$

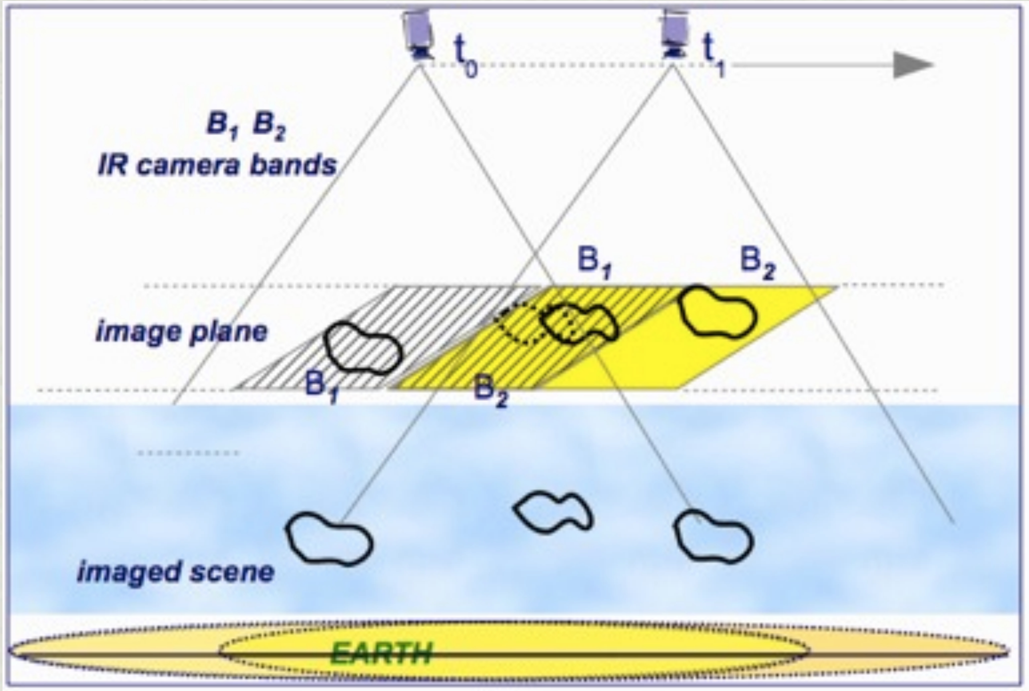
- Algorithms needed to infer the cloud temperature (T_{cloud}) from the temperature measured ($T_{measured}$) by the IR camera.
- Different clouds (emissivity, water and ice content...) need different algorithms (Split Window Algorithm, Look-Up Tables, Brightness Temperature Difference).

The IR camera: radiometric methods



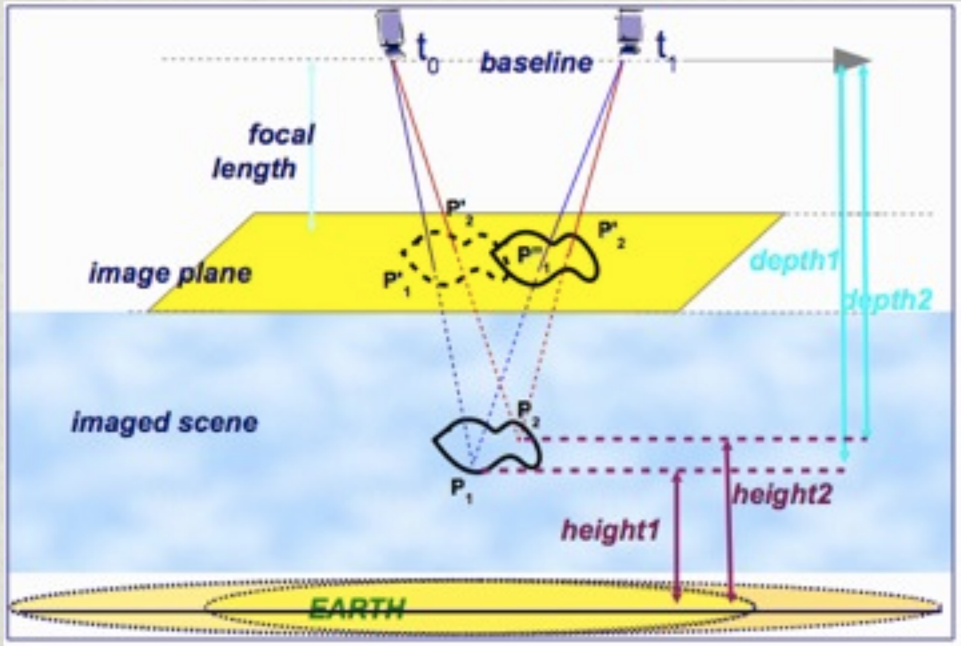
- SWA is able to retrieve temperature with high accuracy (~1 K) for optically thick water clouds ($\varepsilon = 1$)
- Work still in progress for thin clouds, broken clouds, clouds of ice [LUTs, BTD]

The IR camera: stereo vision



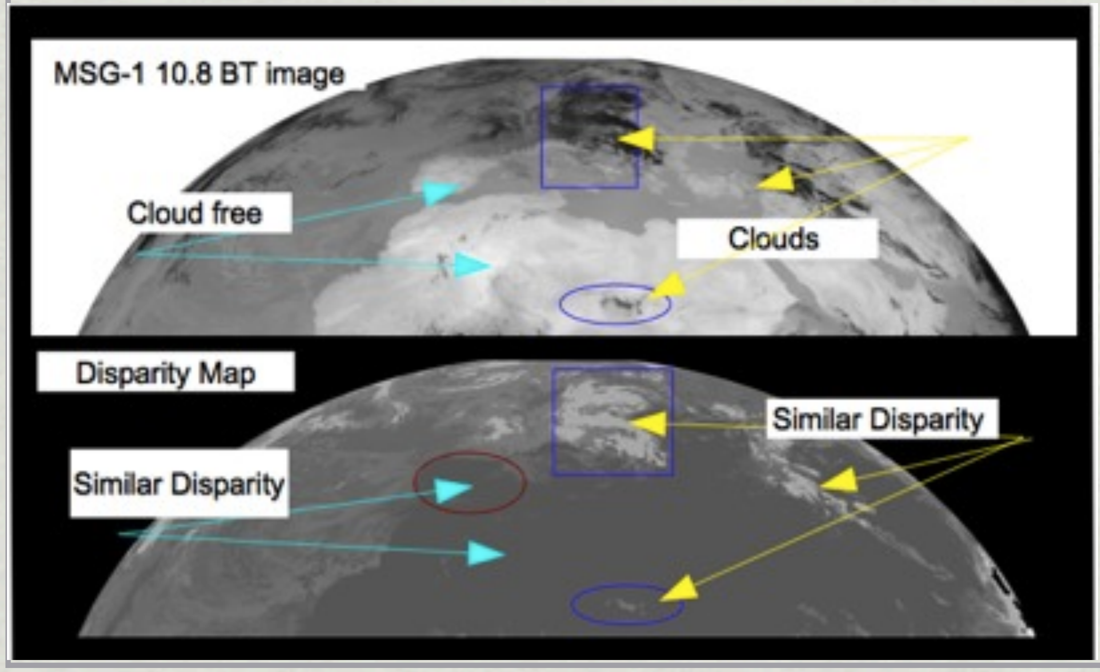
The JEM-EUSO Stereo System

The stereo imaging is accomplished by one camera moving along the observed scene, exploiting the ISS displacement. The scene results imaged from two different views and the intersection is processed to retrieve the distance from the IR device (depth). The stereo images are acquired in two different bands.



Cloud top Height Reconstruction

The depth of each point is recovered by triangulating the corresponding pairs of projected pixels. Finally the heights of each pixel is calculated subtracting the depth value from the ISS altitude. **Parallax effect (Disparity)** is crucial for the reconstruction. It appears as an apparent cloud motion on the image plane.

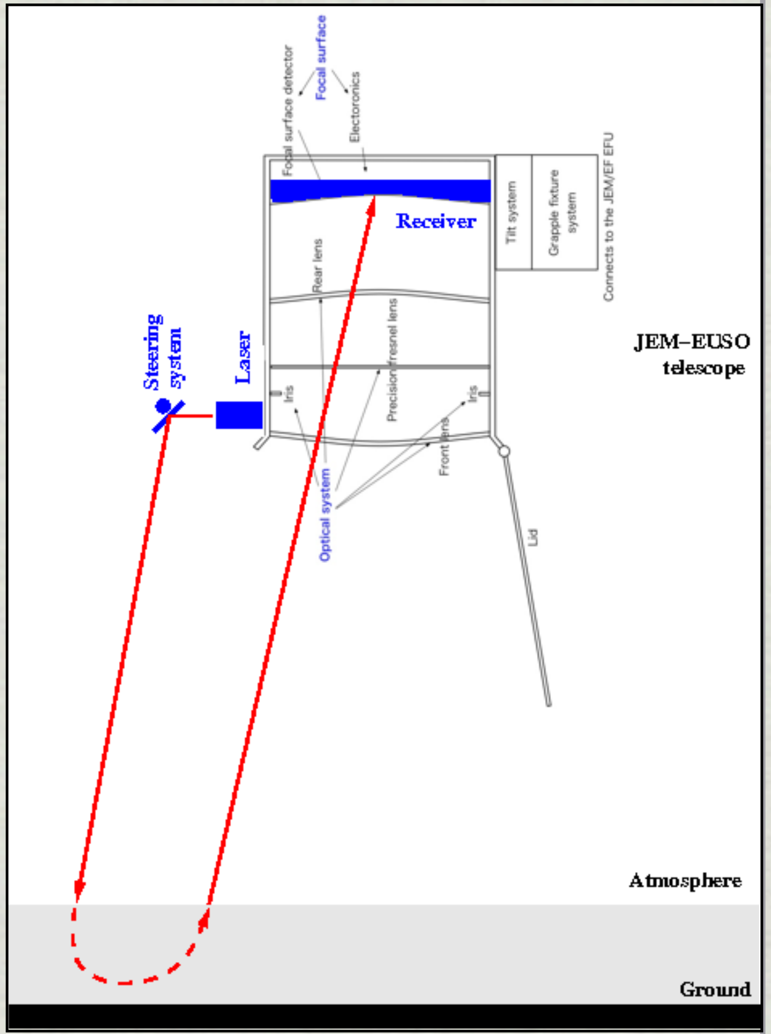


Multispectral stereo algorithms are currently under test. At the bottom of the figure an example of disparity map is shown for a 'mono band stereo system' composed by the Meteosat Second Generation geostationary satellites MSG-8 and MSG-9. The same grey level, represent points with the same depth. Further tests are in progress on different stereo satellite configuration and sensors

The **LI**ght **D**etection **A**nd **R**anging (**LIDAR**) device

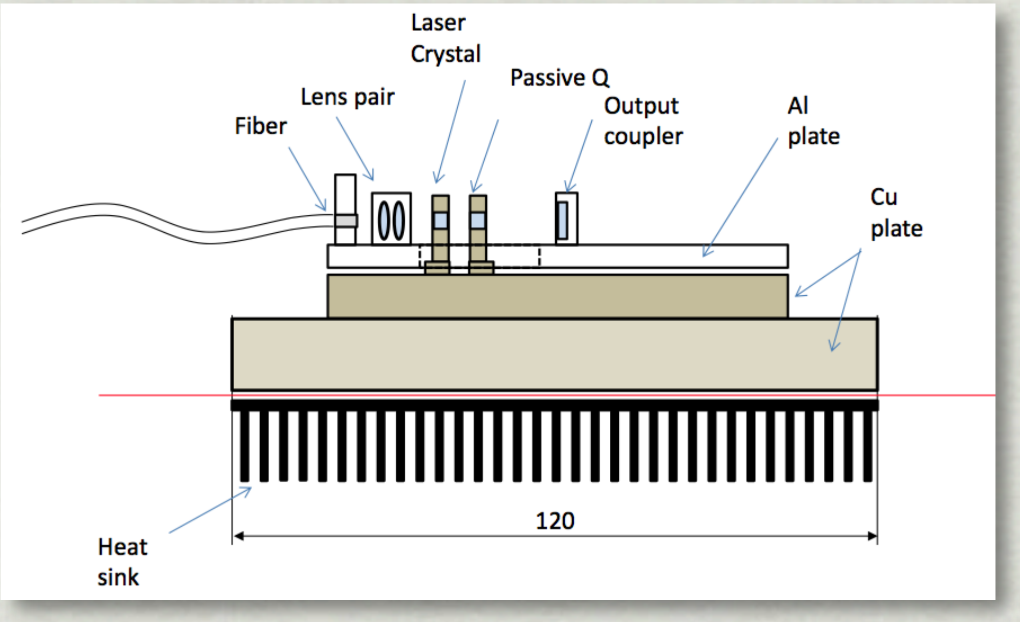
Table 1 Specification for the JEM-EUSO LIDAR.

Parameter	Specification
Wavelength	355 nm
Repetition Rate	1 Hz
Pulse width	15 ns
Pulse energy	20 mJ/pulse
Beam divergence	0.2 mrad
Receiver	JEM-EUSO telescope
Detector	MAPMT (JEM-EUSO)
Range resolution (nadir)	375 m
Steering of output beam	$\pm 30°$ from vertical
Mass	14 kg
Dimension	$450 \times 350 \times 250$ mm
Power	< 20 W

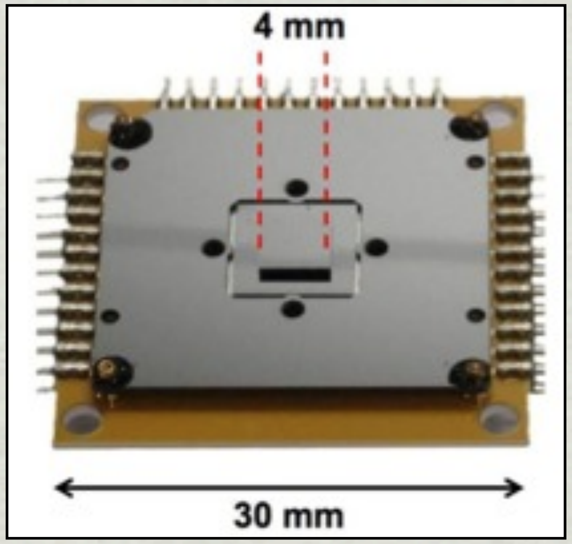


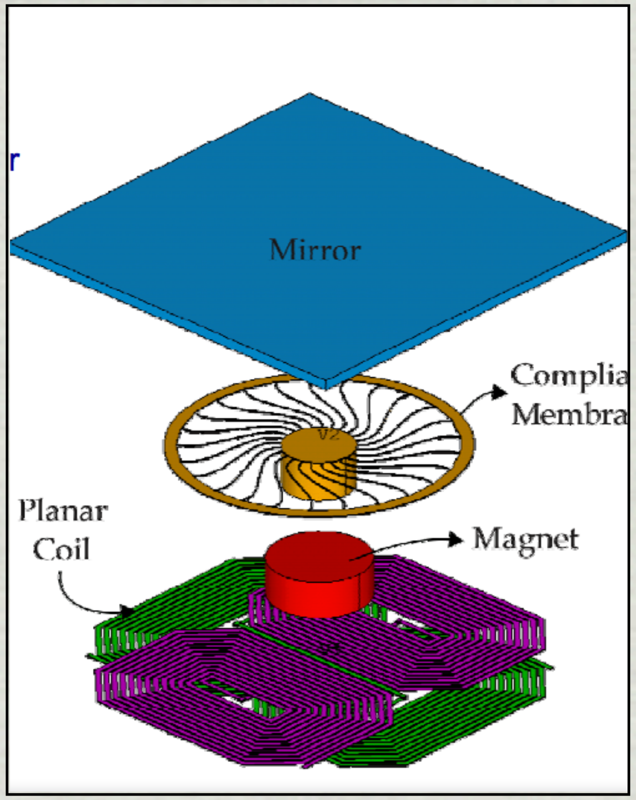
- The task of the LIDAR is to provide measurements of the scattering and extinction properties of the atmosphere in the region of the EAS development and between the EAS and JEM-EUSO.
- The **transmission** system comprises a Nd:YAG laser and a pointing mechanism to steer the laser beam in the direction of the EAS.
- JEM-EUSO will be used a receiver.

LIDAR: the transmission system



- Similar laser as for the laser ranging devices in satellites for atmospheric soundings (CALIPSO, LITE, ...)
- Operational wavelength (355 nm) is the 3rd harmonic of the Nd:YAG laser
- 3rd harmonic is conventionally achieved with the frequency-tripling crystal placed inside the laser beam





- Steering of the laser done with a mirror system.
- Mirror size: 4 mm X 4 mm.
- Tilt angle of the mirror determined by the electric current in the magnet (±15° steering angle needed to achieve the ±30° pointing).

- Footprint of the laser beam ~ 1 km (one to several pixels in JEM-EUSO telescope) achieved with a beam expander (beam conditioning optics). Properties of the atmosphere averaged over kilometer horizontal distance scale.

LIDAR: receiving system

- Properties of the LIDAR backscattered signal (@355 nm) are similar to the properties of the EAS signal [same time profile] at the telescope entrance.

- Any pixel or group of pixels from the last triggered PDM (Photo-Detector Module) of the JEM-EUSO focal surface will serve as the LIDAR receiver.

- EAS trigger generated in a PDM will also generate a command to re-point and shoot the laser. After a certain delay the pixels of the PDM will be switched in receiving mode.

- The region of the atmosphere around the EAS will be probed by the LIDAR within ~ 300 ms starting from the initial EAS trigger.

- The ~1sec time delay between the EAS trigger and the LIDAR measurement is ~10 times shorter than time between subsequent EAS triggers. The rest of time interval will be used to shoot the LIDAR in several directions around the EAS position.

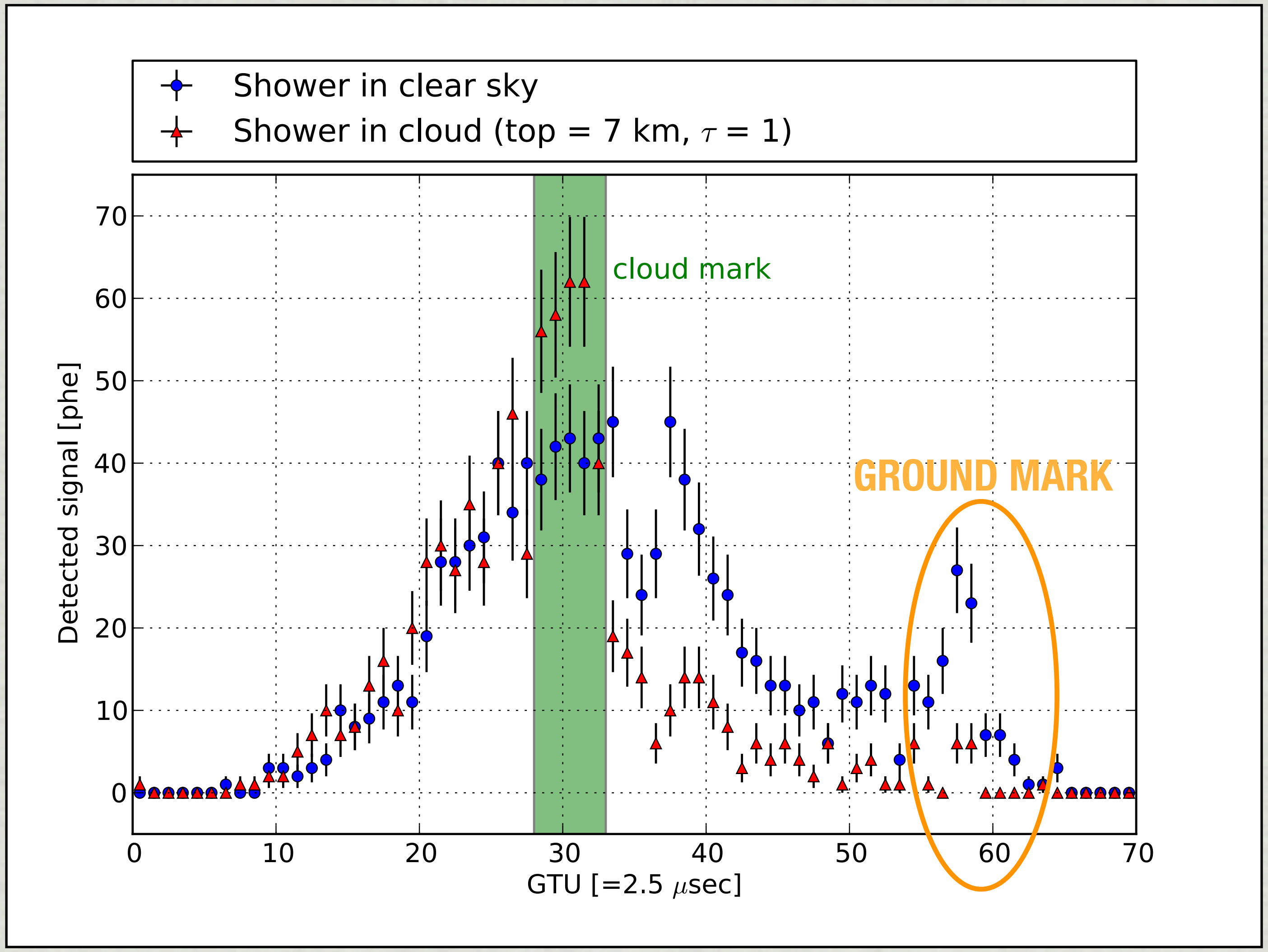
LIDAR data analysis

- Simulation chain used to reproduce a real-case observation: EAS time profile shows deviations from the *clear sky* and needs to be corrected.
- UHECR: proton, $E=10^{20}$ eV, $\theta = 60^{\circ}$ simulated in clear sky and cloudy conditions.
- Cloud: uniform layer with $H_{Top} = 7$ km, $\tau = 1$

Time profile of the detected photo-electron signal as a function of GTU for the shower in clear sky (blue) and in presence of an optically thick cloud (red).*

Ground mark: generated by Cherenkov photons hitting the ground and reflected back to the JEM-EUSO focal surface.

Cloud mark: generated by Cherenkov photons hitting the cloud and reflected in the cloud top layers back to the JEM-EUSO focal surface.

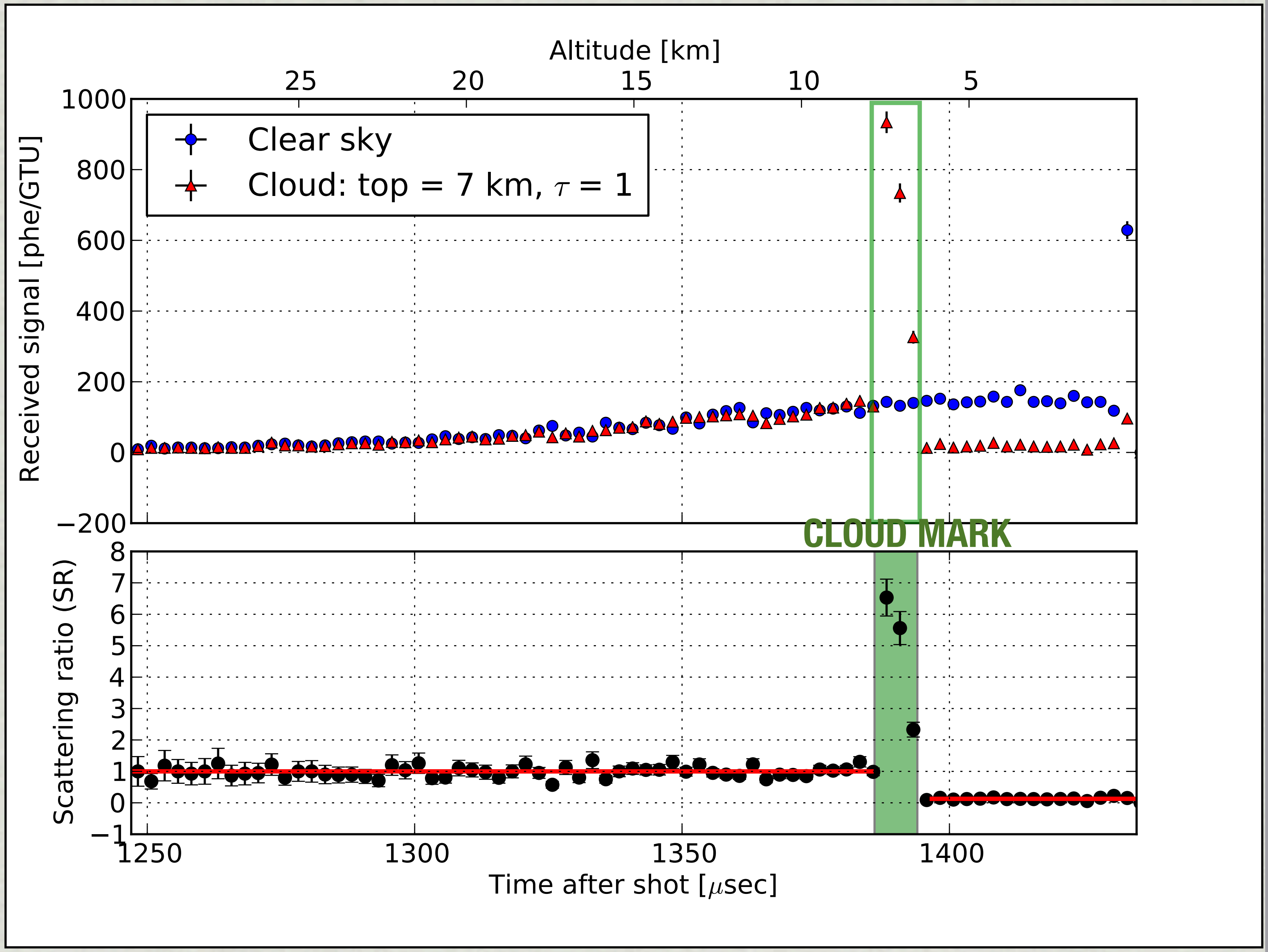


**GTU (Gate Time Unit) is the time unit of the focal surface detector: 1 GTU = 2.5 μsec*

LIDAR data analysis

- LIDAR signal simulated in the same conditions as for the shower (in a real case the LIDAR will shoot the triggered EAS to collect info on atmospheric conditions).

- Comparison of the detected signal with a reference (clear sky) will allow to:
  - classify the event (if occurring in clear sky will be *golden*)
  - apply a correction to retrieve the signal as it would be in clear sky.



- Fitting the Scattering ratio:

$$SR = -log(2\tau)$$

allow to retrieve:

$$\tau = 1.05 \pm 0.05$$

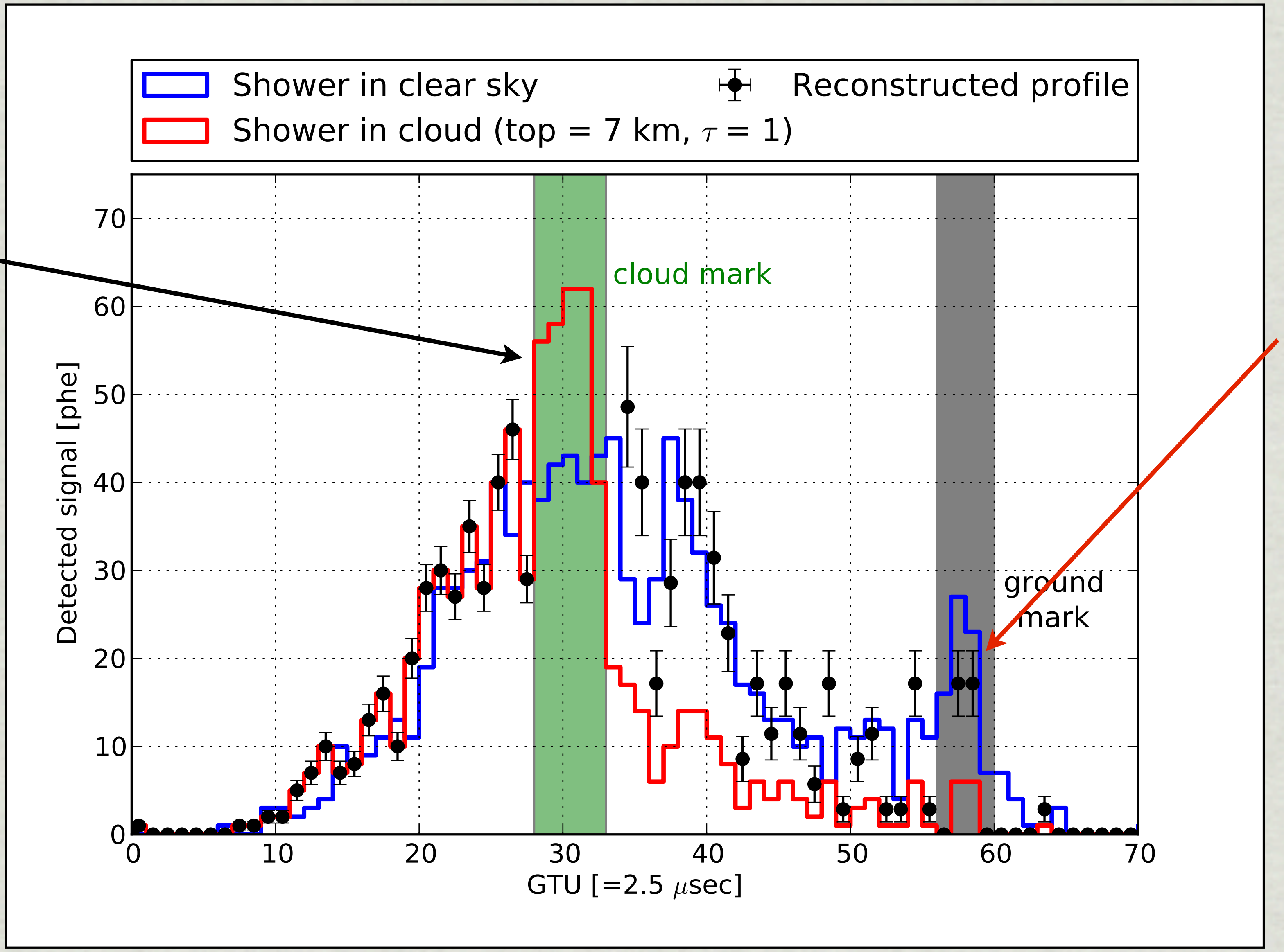
(τ = 1 simulated)

LIDAR data analysis

Once the cloud is detected and its optical depth measured the shower profile can be corrected using:

$$Signal_{cloud} = Signal_{clear}(e^{-\tau})$$

No reconstruction in the cloud region: no information about the optical depth profile inside the cloud.



Ground mark almost recovered by the correction procedure.

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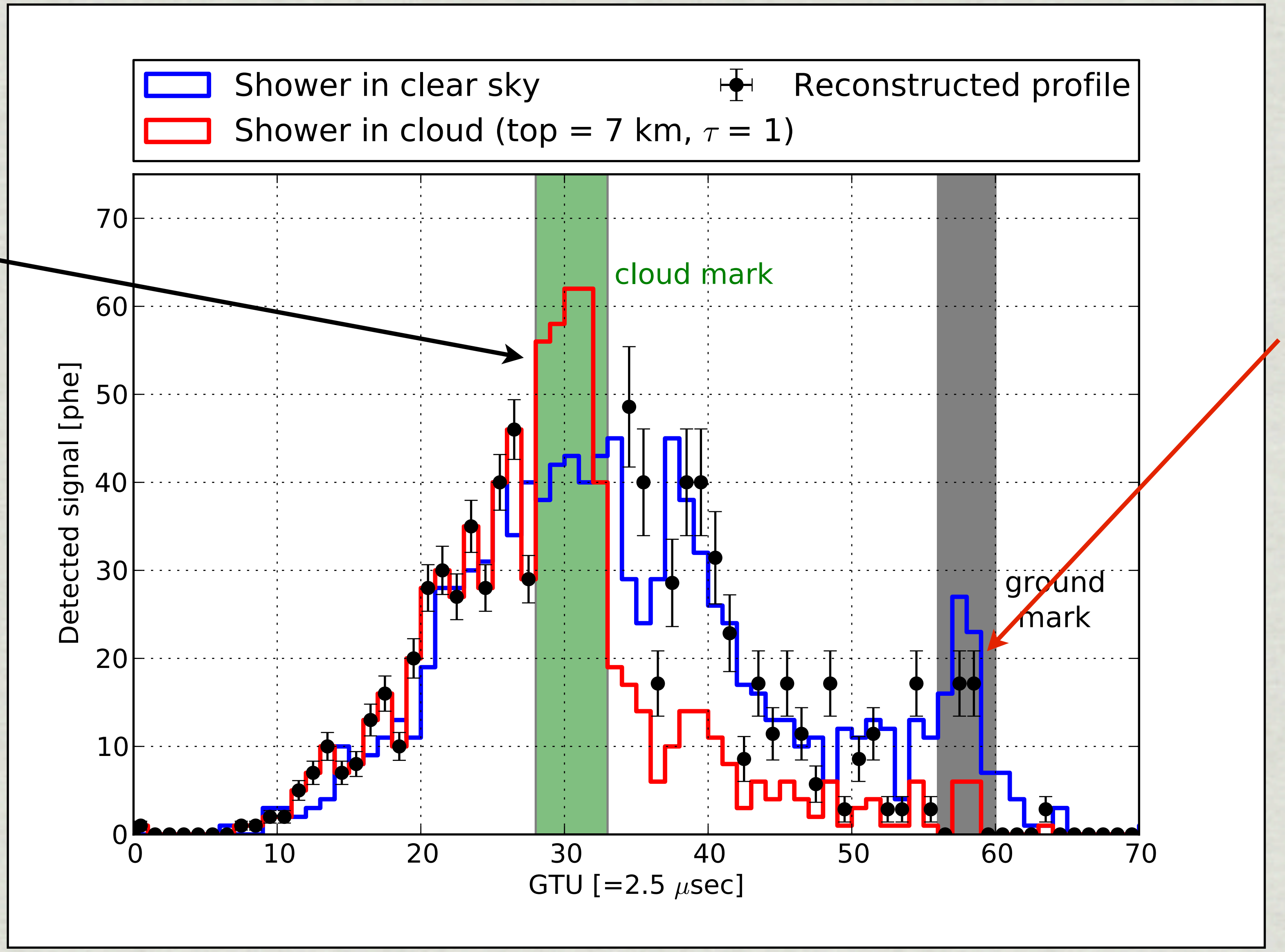


Ground mark almost recovered by the correction procedure.

Just an example of possible scenario. Ongoing work to qualify the type and quantify the number of events we will be able to correct using information from the AM system (important for duty cycle estimations)

Conclusions

- JEM-EUSO is a new space-based (ISS) mission to study the origin and nature of UHECRs (above $5x10^{19}$ eV)
- Looking downward to the Earth's atmosphere for EAS detection, It will experience all possible weather conditions.
- The AM system will be used to monitor the atmospheric condition in the region of development of the EAS with this requirements:
  - optical depth profile of the atmosphere around EAS: $\Delta\tau > 0.15$.
  - cloud top altitude: 500 m.
- First study of IR camera algorithms shows the possibility of retrieving the temperature of thick water clouds with high accuracy.
- First analysis of LIDAR (simulated) data show the capabilities of reconstructing the EAS profile for cloud-affected showers.
- GLS (Global Light System) as a part of the JEM-EUSO calibration system will serve as a complement for the AM system [see Sarazin's talk on GLS].

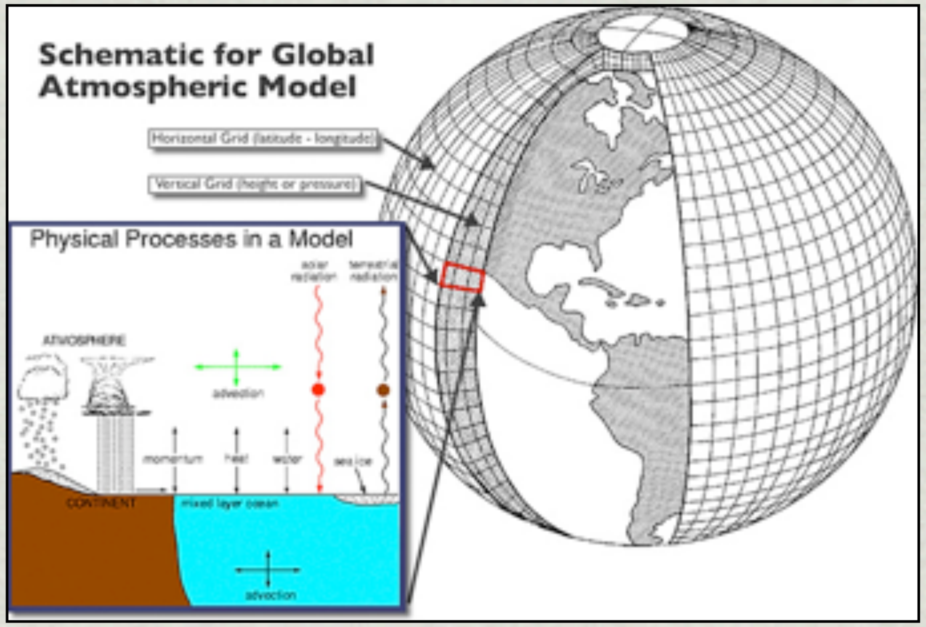
Global Atmospheric Models

- Atmospheric state variable such as the density of the air, alter the development of EAS in the atmosphere.

- Knowledge on the atmospheric condition influence the event reconstruction.

- Data from LIDAR and IR camera can be improved from the knowledge of the physical properties of the atmosphere (i.e. IR camera radiometric cloud top altitude retrieval requires knowledge of the vertical temperature profile in the troposphere; an estimate of the molecular scattering based on the Rayleigh cross section and altitude profiles of temperature and pressure are needed to model the LIDAR signal in clear sky).

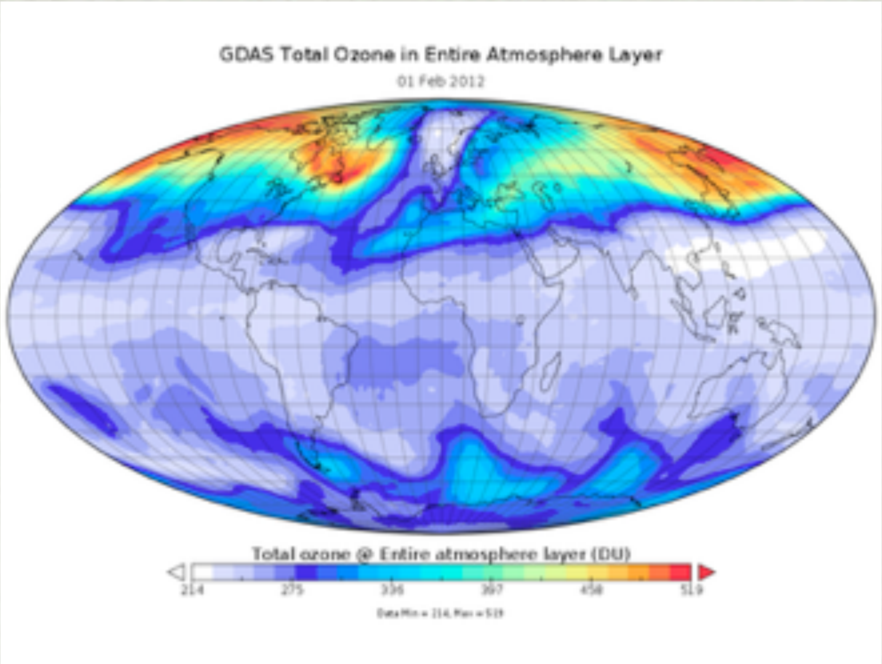
- Data products from global model developed by NCEP, GMAO, ECWMF available



Global Atmospheric Models

The Global Data Assimilation System (GDAS) is the system used by the Global Forecast System (GFS) model to place observations into a gridded model space for the purpose of starting, or initializing, weather forecasts with observed data.

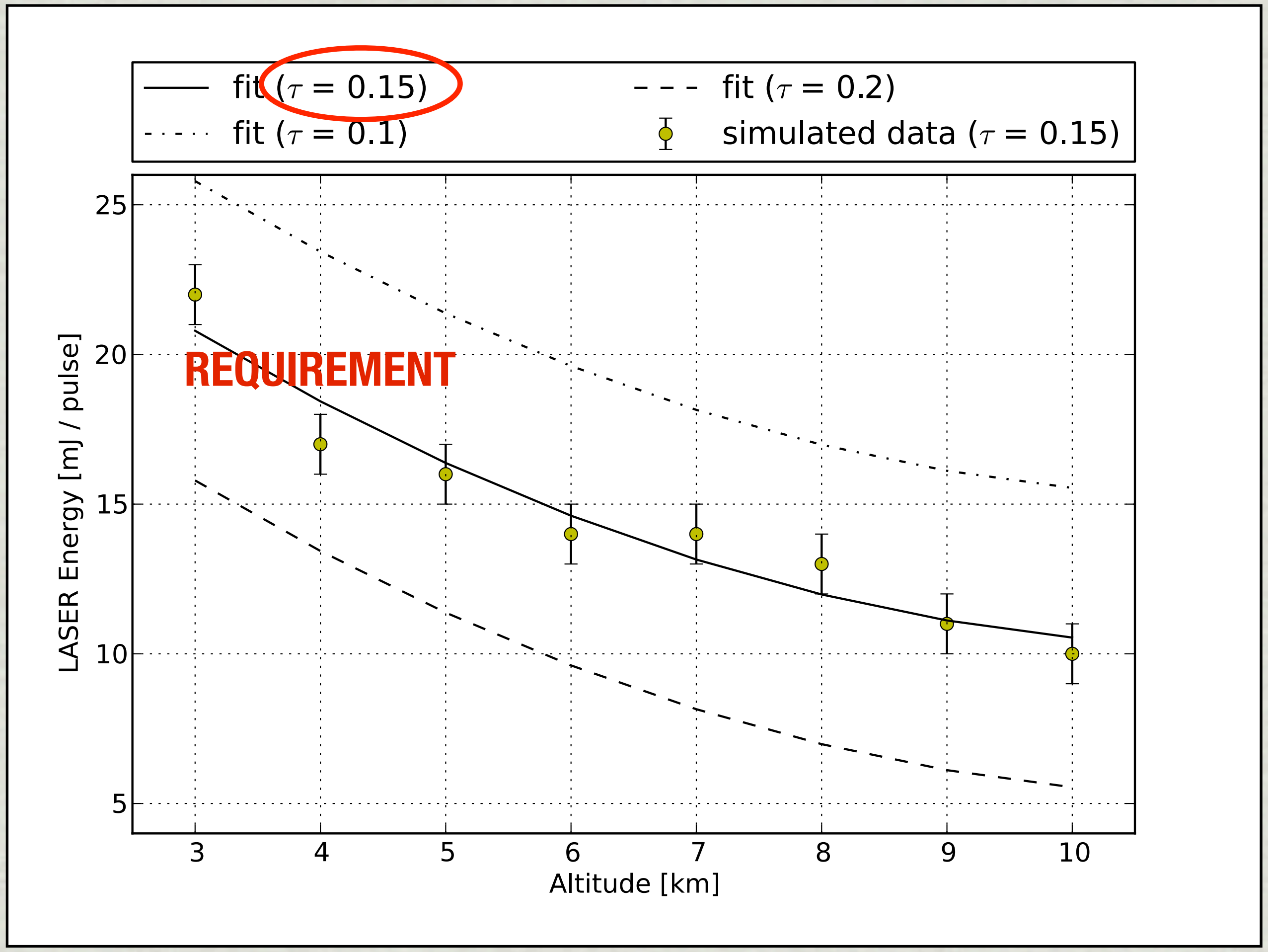
Observations used: surface observations, balloon data, wind profiler data, aircraft reports, buoy observations, radar observations, and satellite observations.



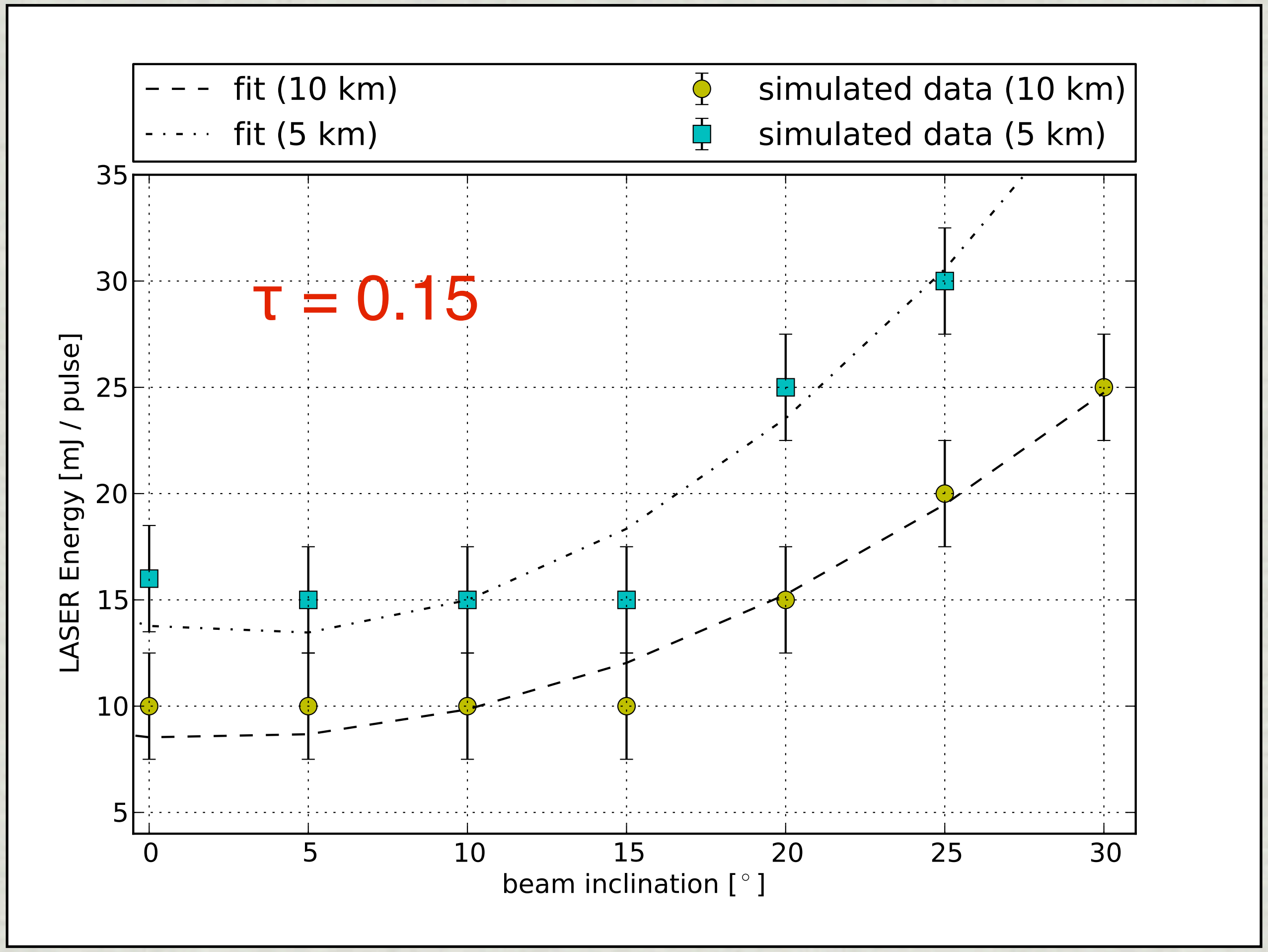
A plot of GDAS output showing total atmospheric ozone at 00UTC on February 1st, 2012. Credit: NOAA

- The GDAS provides an analysis four times a day (00, 06, 12, and 18 UTC) and 3, 6, and 9-hour forecasts.
- GDAS data set contains several state variables as a function of the altitude in form of pressure levels from 1000 hPa (sea level) to 20 hPa (~ 26 km). Data are distributed in a latitude-longitude ($181^\circ \times 360^\circ$) grid of 1° spacing
- NCEP/GDAS (http://ready.arl.noaa.gov/gdas1.php) data have been successfully incorporated in JEM-EUSO simulation of air showers.

LIDAR performance



Minimum energy per pulse needed by the LIDAR in order to detect clouds at several altitudes



Minimum energy per pulse needed to detect a clouds (with τ = 0.15) at 5 km (squares) and 10 km (circles) for different inclinations of the laser beam

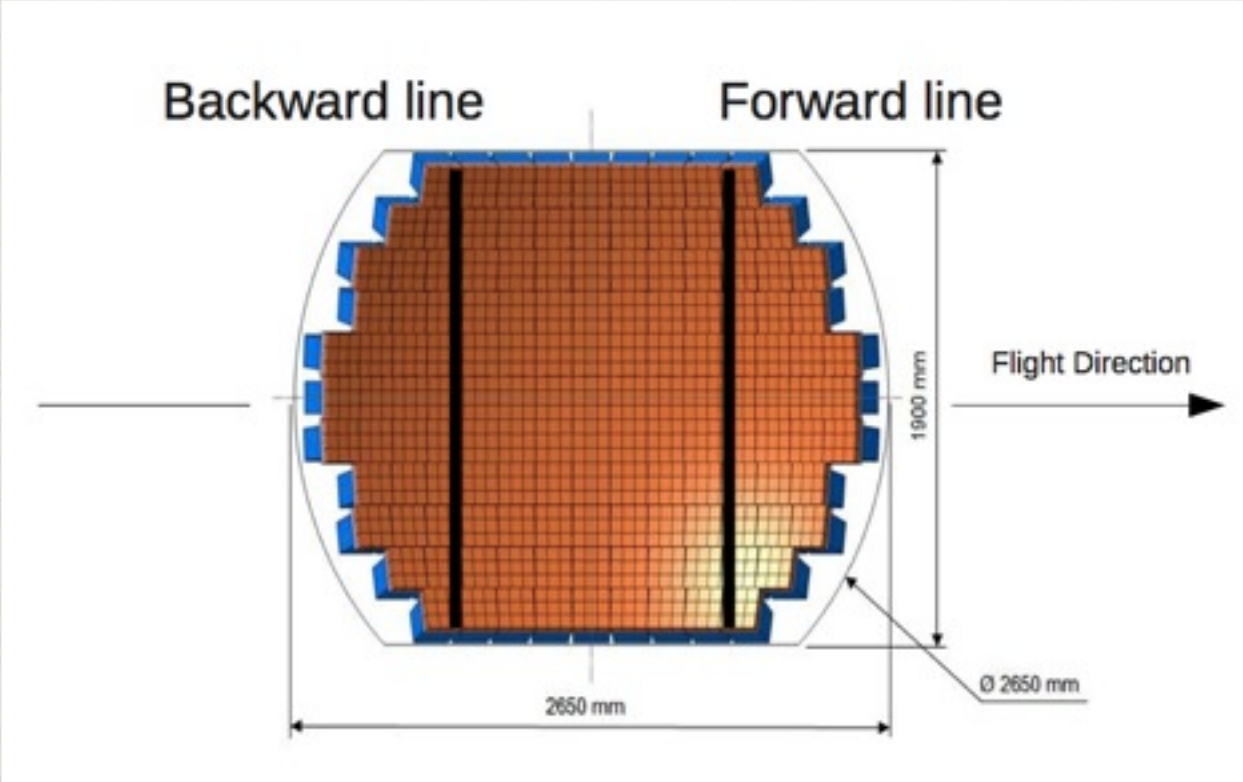
The energy of the laser pulse will be adjusted so that the backscattered signal will have enough statistics for the detection and measurement of the optical depth of optically thin clouds with $\tau \geq 0.15$ at large off-axis angles.

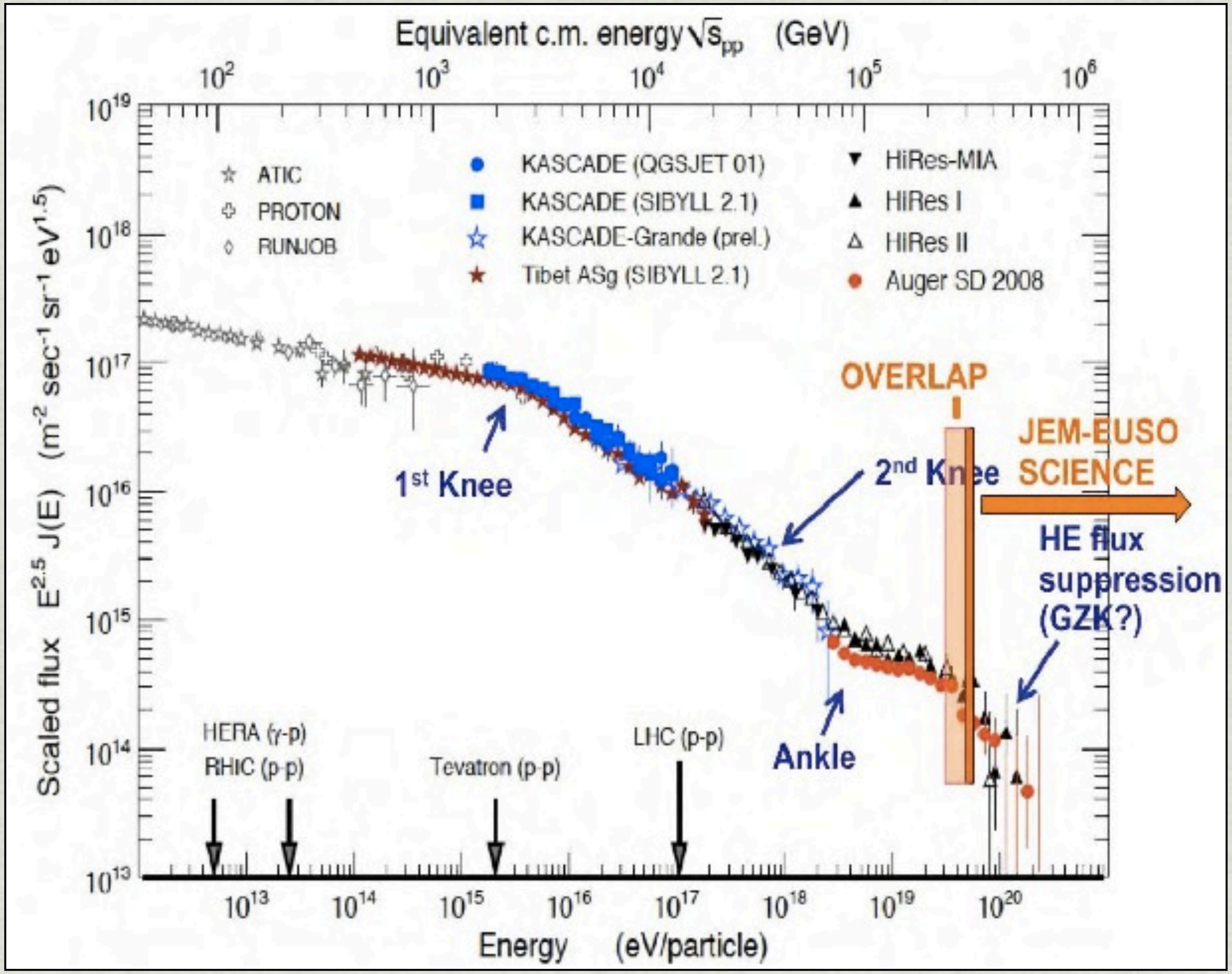
JEM-EUSO “slow-data”

- Continuous background photon counting
- Uses two pixel lines of the FS, aligned across the track direction: 528 pixels per line used to generate UV cloud (stereo-)image:

  The same area seen by the “forward” pixel line is then seen by the “backward” line after a fixed time delay

- It will provide measurement of the overall background and map the night sky airglow (weak emission of light from a planetary atmosphere)
- Reflection of the airglow from the clouds (in UV) could be used to complement information from IR camera.





Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Tibet ASg (SIBYLL 2.1)
HiRes-MIA
HiRes I
HiRes II
Auger SD 2008
OVERLAP
JEM-EUSO SCIENCE
1^{st} Knee
2^{nd} Knee
HE flux suppression (GZK?)
Ankle
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)