Cosmic ray science with EUSO-SPB1

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Outline

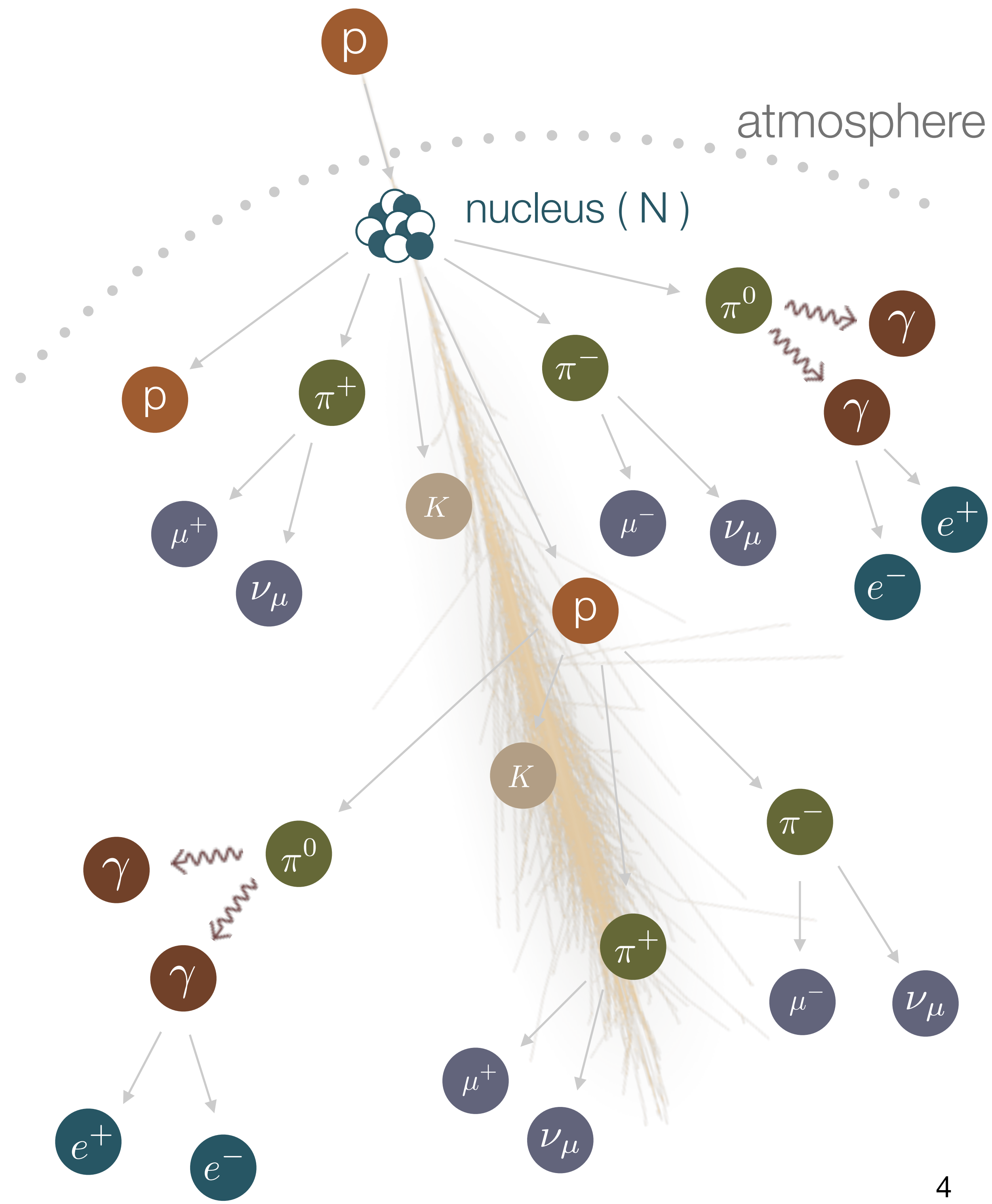
- Cosmic rays & Atmosphere
  - Extensive Air Showers
  - Fluorescence light
  - Cherenkov light
- The Extreme Universe Space Observatory
- The EUSO's Super Pressure Balloon
- Tools & Theory
  - ESAF
  - Trigger
  - Aperture
- Simulations & Results
  - EAS study
  - Aperture study
  - SPB1 aperture
- Cloud condition
- Conclusions

Cosmic Rays & Atmosphere

- Extensive Air Showers
- Fluorescence light
- Cherenkov light

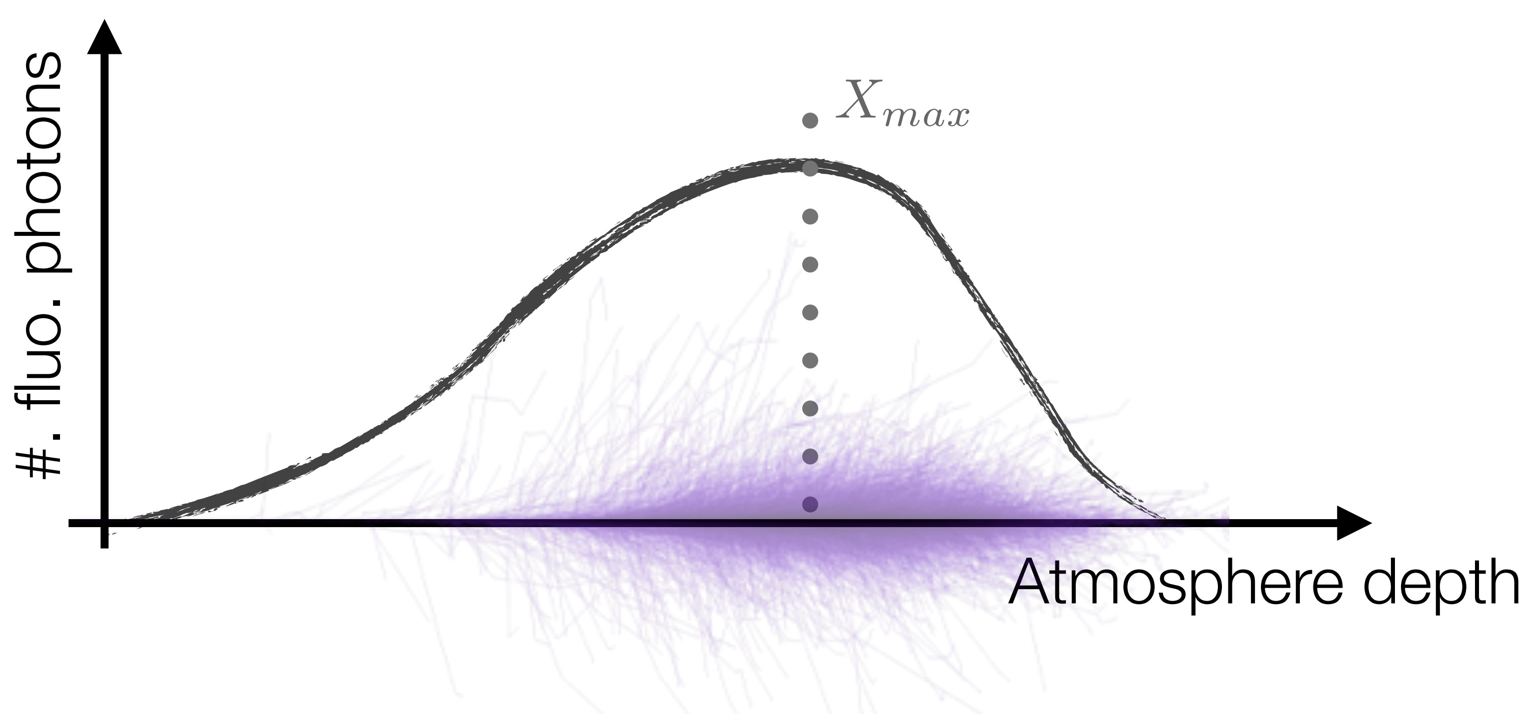
Extensive Air Showers (EAS)

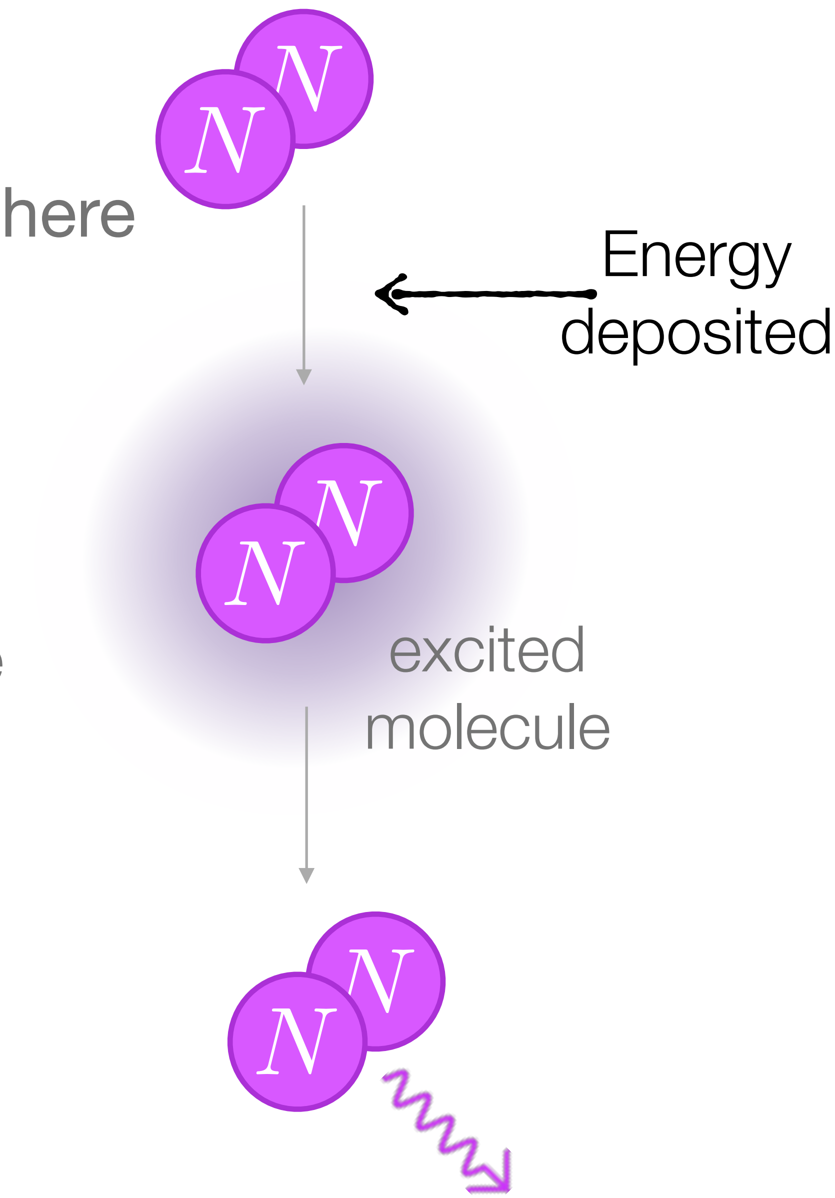
- **Primary Cosmic Ray** (CR) : high energy particle produced in an astrophysical environment
- **Collision** with atmosphere nuclei
- Cascade of secondary particles
- In each collision :
  - Kinetic energy is converted into mass energy + kinetic energy
- Chain reaction is finite :
  - Creation process is stopped
  - Shower maximun X_{max}



Fluorescence

- Fluorescence light production:
  - Particles (mostly e^-) moving through the atmosphere excite metastable energy levels in molecules
  - **Ionizing excitation** of mostly **Nitrogen** molecules
  - Spontaneous **de-excitation**
  - **Isotropic emission** of fluorescence light along the EAS

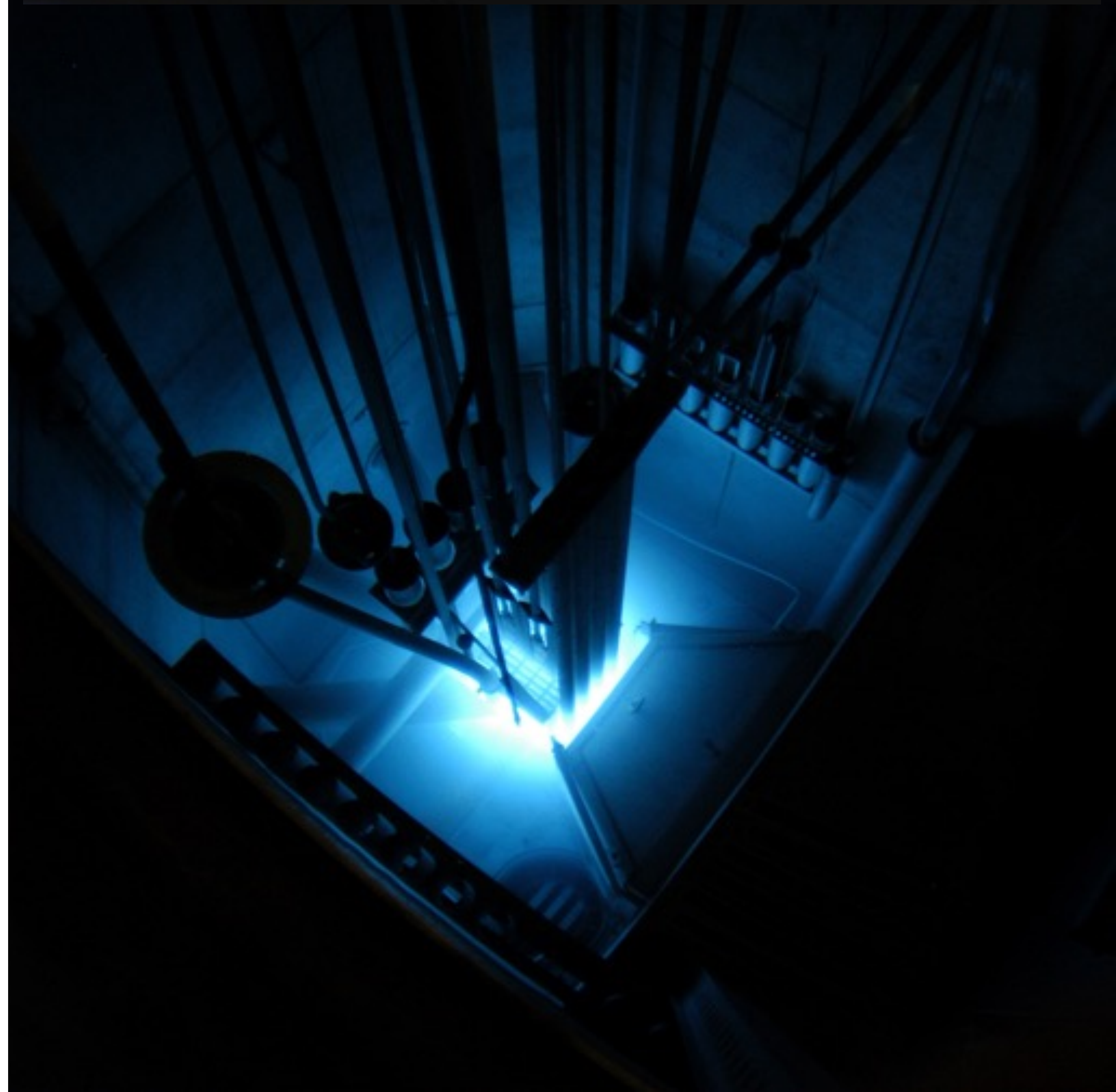




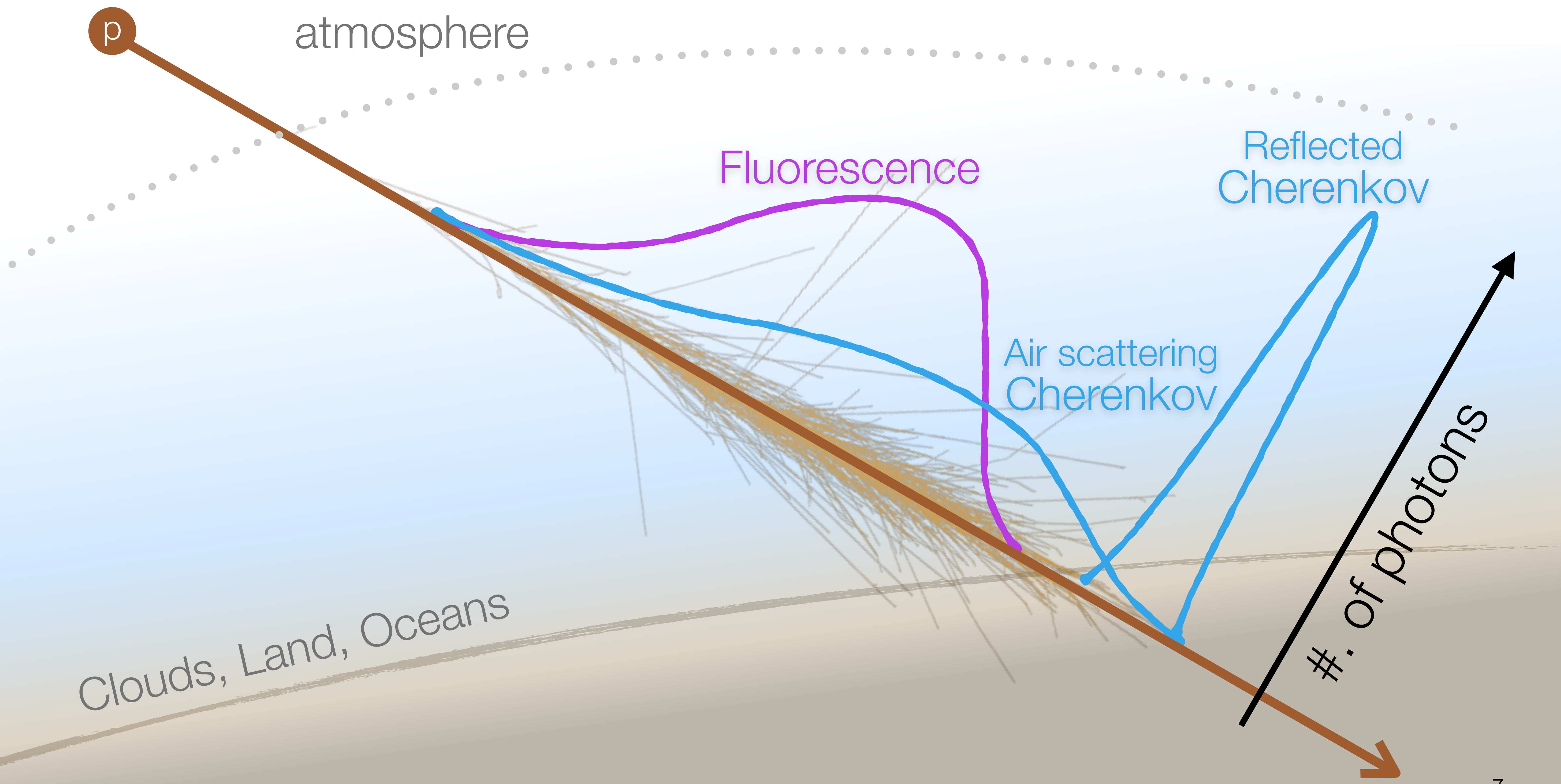
Cherenkov

- Numerous secondaries have velocities **higher than the speed of light** ($v > \frac{c}{n}$)

- Cherenkov emission :
  - Photons are **beamed in a cone** (~1,3°) along the trajectory
  - **Scattering** by the molecular and aerosol content of the atmosphere
  - **Reflexion** when particles reach land, sea or clouds



Light development in an EAS

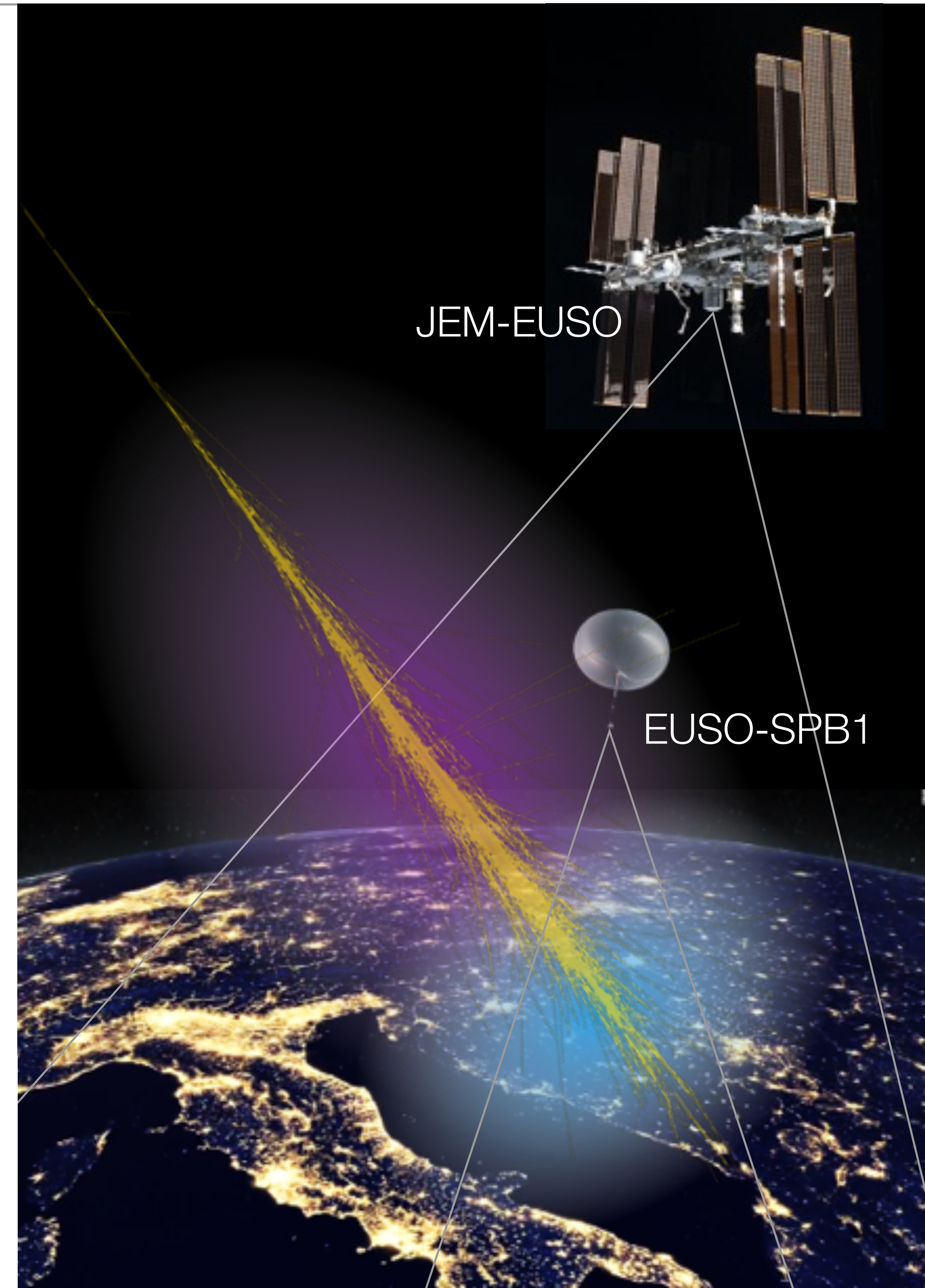


The Extreme Universe Space Observatory

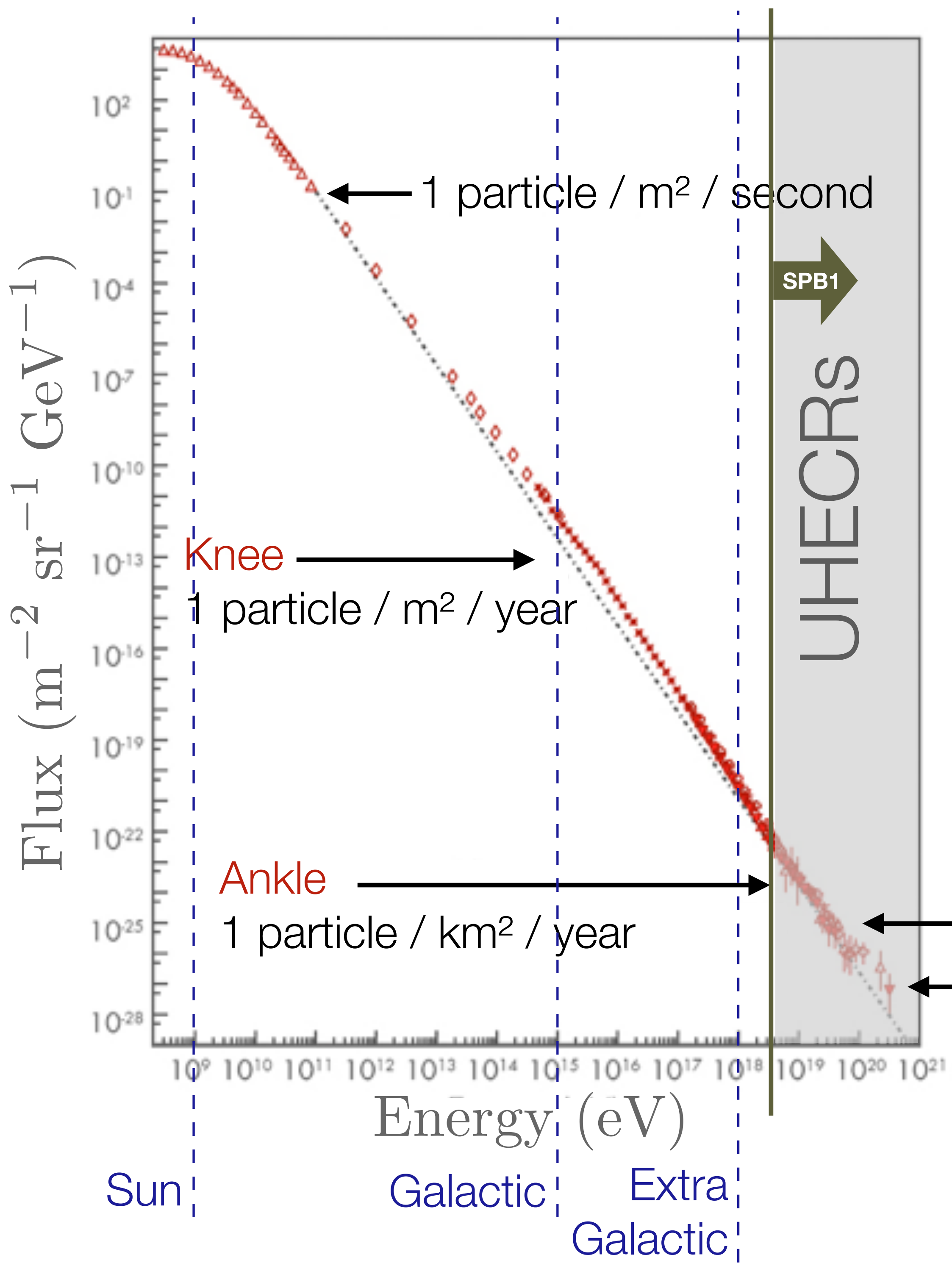
The Extreme Universe Space Observatory (EUSO)

- 16 Countries, 91 Institutions, more than 300 researchers

- EUSO's aim : JEM-EUSO **Space telescope** on the ISS **J**apanese **E**xperiment **M**odule
- Image the Nitrogen UV Fluorescence and Cherenkov track from above
- Aim to efficiently detect the highest CRs
- JEM-EUSO and its pathfinders:
  - EUSO-TA (2013-), EUSO-Balloon (2014), TUS (2014), **EUSO-SPB1** (2017)
  - Mini-EUSO (2018), SPB2 (2021), K-EUSO (2023), POEMMA (2025)



Ultra-High Energy Cosmic Rays (UHECRs)



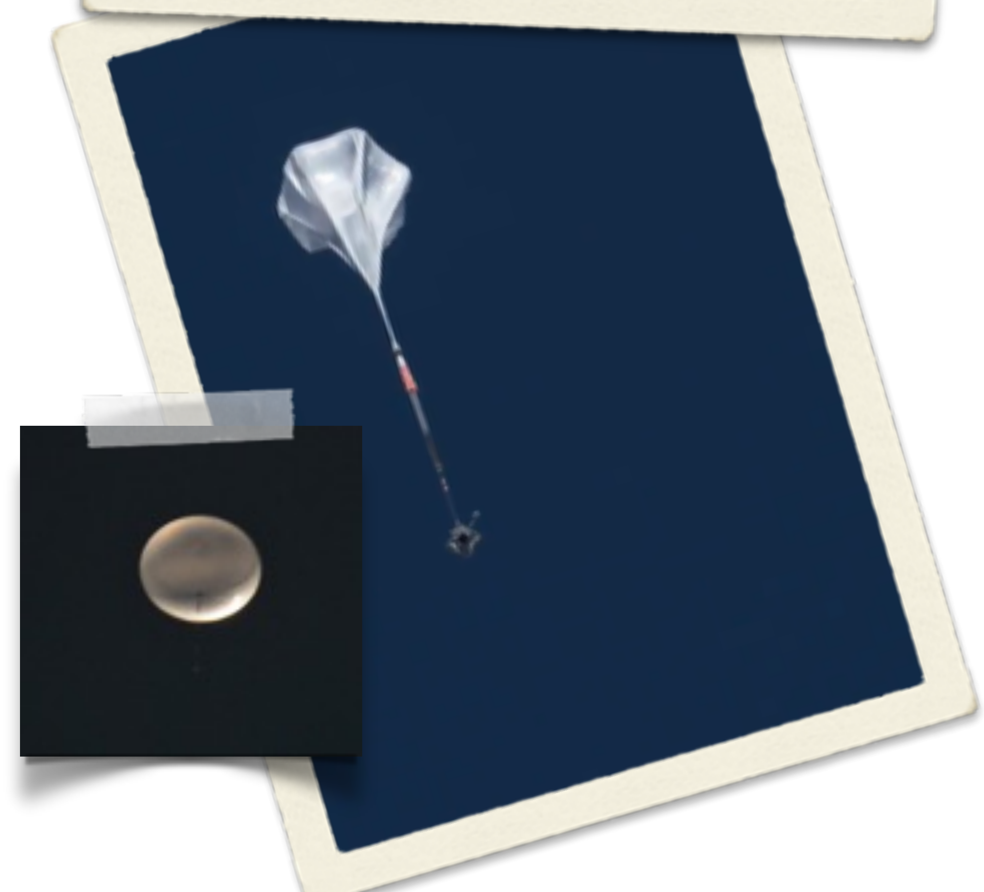
- UHECRS : $E > 10^{18}\mathrm{eV}$
- Extreme low flux
- Need for great exposure instruments

Exposure x **Flux**
= **Number of expected particles**

The EUSO-SPB1

The EUSO on a Super Pressure Balloon (SPB1)

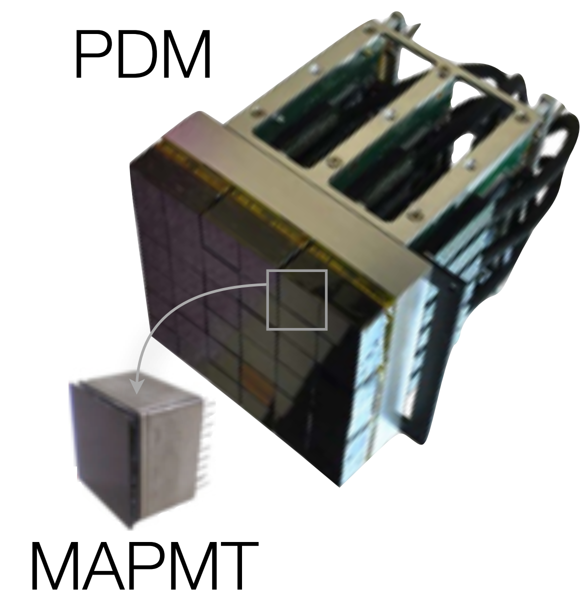
- The EUSO-SPB1
  - 8 countries, 50 researchers
- Objectives
  - Establish techniques and methods for large scale UHECRs space observatory (JEM-EUSO)
  - Measure the terrestrial UV background light
  - Make the first observation of UHECRs
  - Launch : April, 24th 2017 at 23:51 UTC
- The super pressure balloon :
  - able to fly at **33km high** up to **100 days**
  - 1 football stadium carrying 2 cars
  - Field of view ~11°
- **UV camera looking down** at night

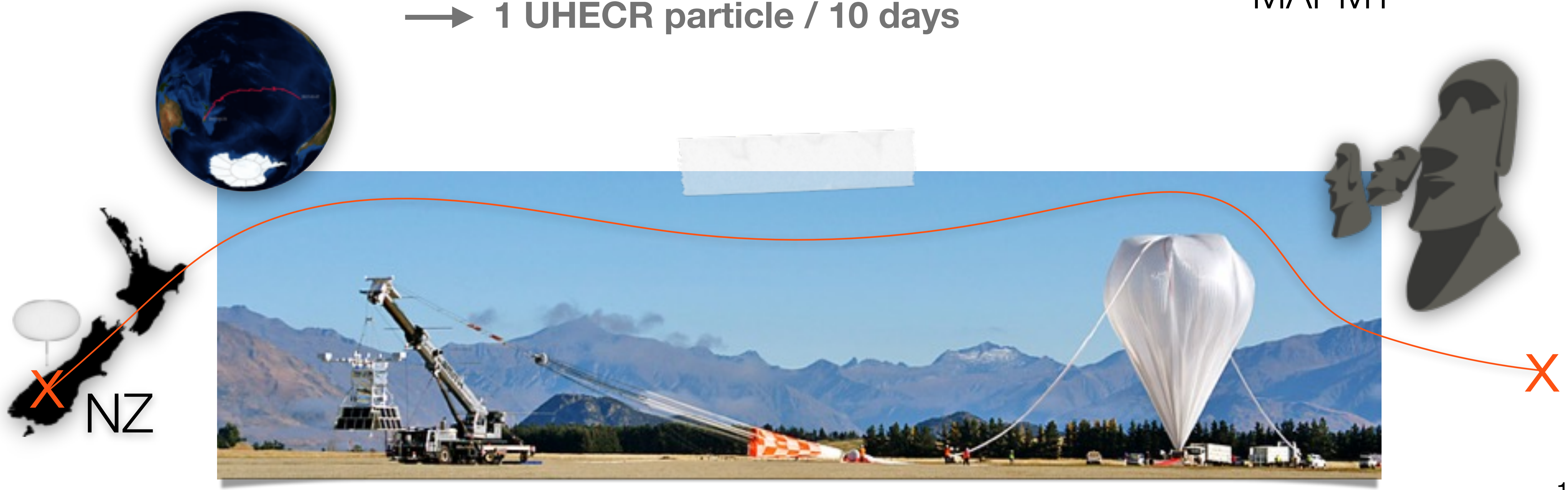


The EUSO on a Super Pressure Balloon (SPB1)

- The Photo-Detection Module (**PDM**)
  - 3x3 Elementary Cells (ECs)
  - 1 EC = 2x2 Multi-Anode Photo-Multipliers Tubes (MAPMTs)
  - 1 MAPMT = 8x8 pixels
  - **2 304 pixels** (JEM-EUSO : 137 PDMs = 315 648 pixels)
  - Time integration : 2,5 μs = 1 Gate Time Unit (GTU)
  - Observational area : 40 km²

→ **1 UHECR particle / 10 days**



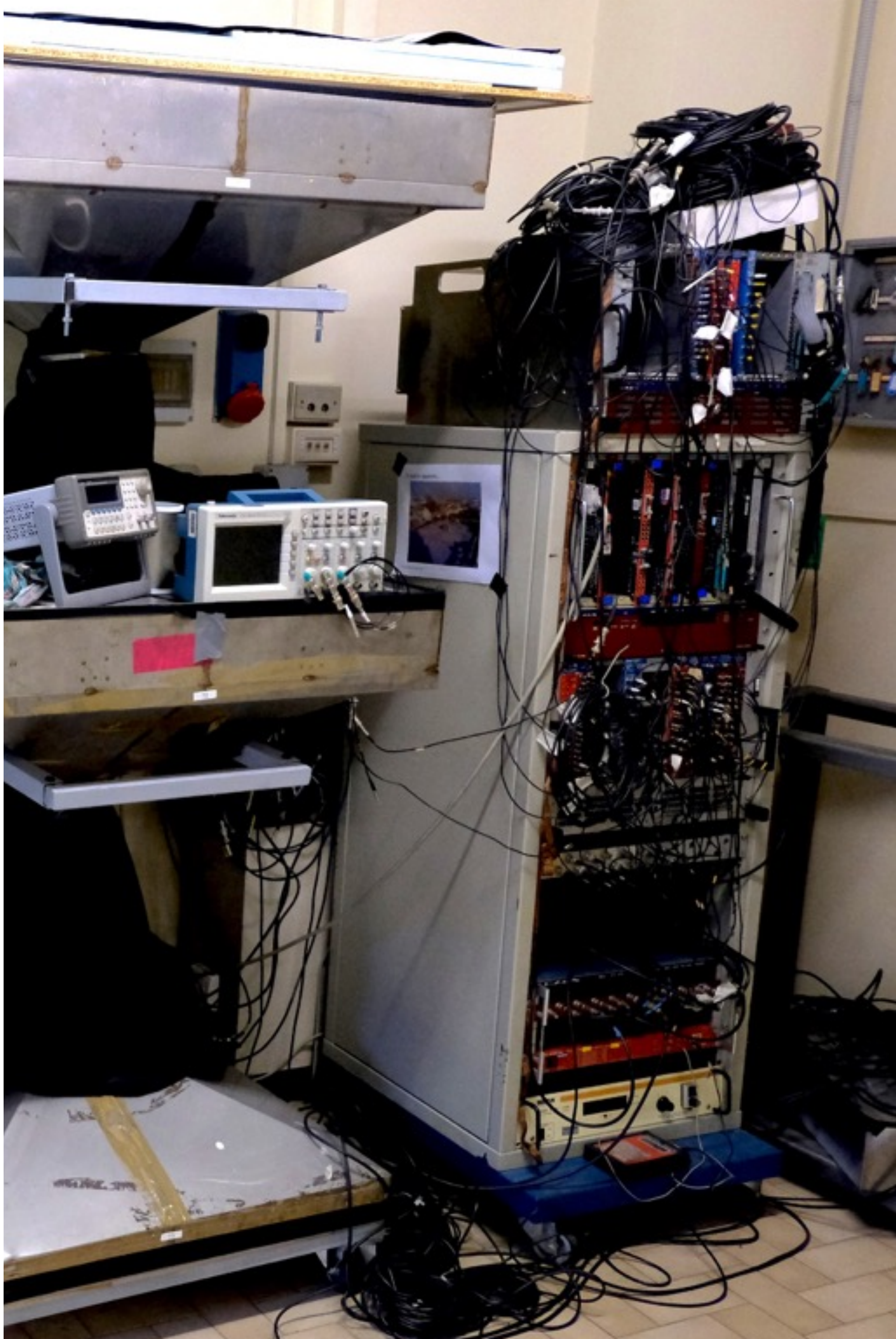


Tools & Theory

- ESAF
- Trigger
- Aperture

ESAF

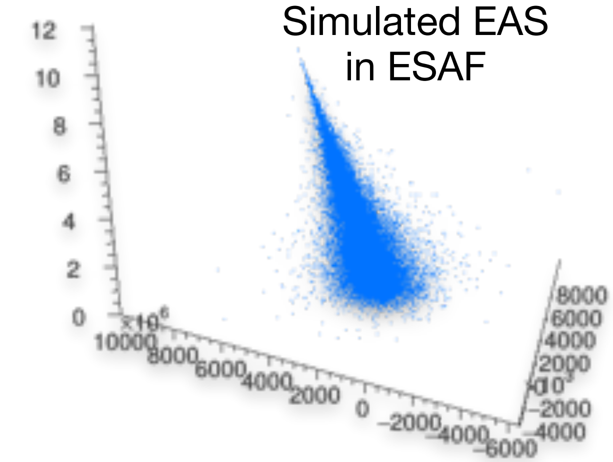
- **E**USO **S**imulation and **A**nalysis **F**ramework
- **Simu** executable : Simulation of the entire physical process (from shower to telemetry)
- Air shower
- Atmosphere
- Optics
- PMT, Electronics
- Trigger



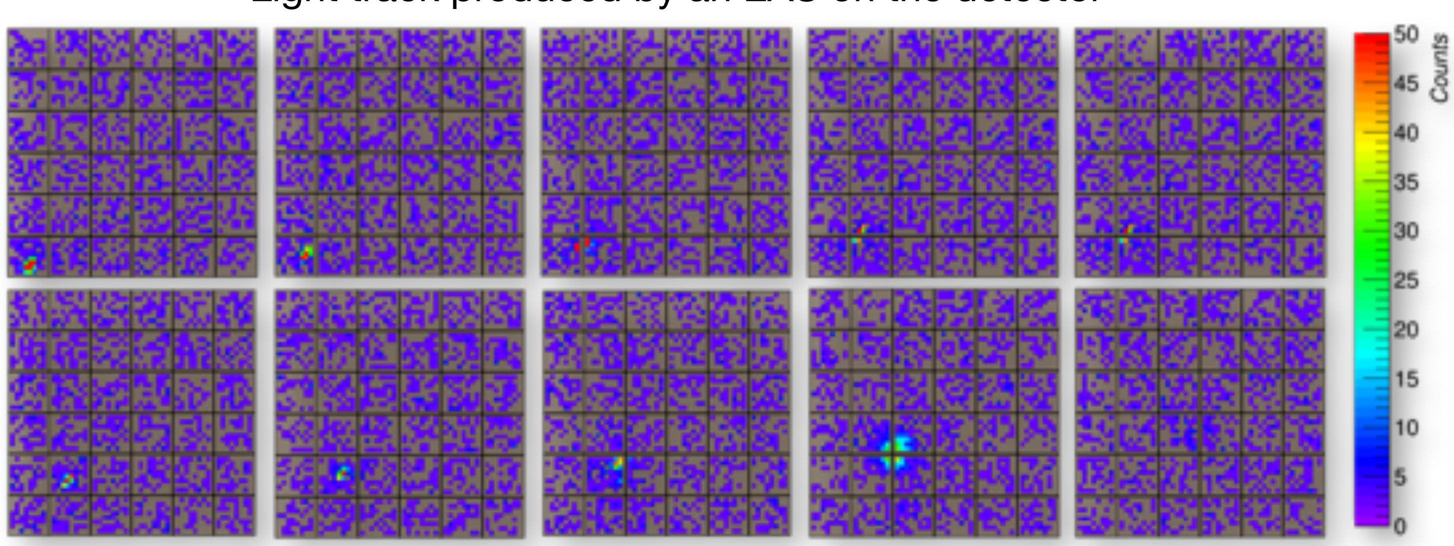
Trigger

- Trigger logic needed to save **only significant EAS events**
- Exploit **peculiarities of the signal morphology** with respect to the background
- Look for **high concentration of photo-electron counts**
  - in a **limited region** of the focal surface
  - within a certain **time window**
- MAPMT Threshold based on the average pixel count
- Massive screening to recognize an EAS signal

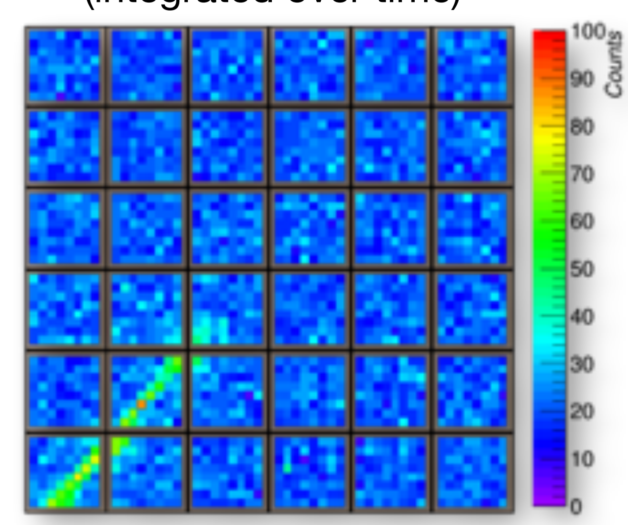
Simulated EAS in ESAF



Light track produced by an EAS on the detector



EAS light track (integrated over time)



Aperture

- Trigger **efficiency** - Probability to trigger an event :

$$\epsilon = \frac{N_{\rm trig}}{N_{\rm sim}}$$

- Geometrical **aperture** :

$$A = \epsilon \times k \times \Omega_0 \times S_{\rm sim}$$

Simulated region on ground

due to simulation selection

Solid angle were events are injected

- **Exposure** :

$$E = \int {\rm d}t \; A \times \lambda_i$$

Working status of the PDM
Clouds
Steady or transient lights sources

Simulations & Results

- EAS study
- Aperture study
- SPB1 aperture

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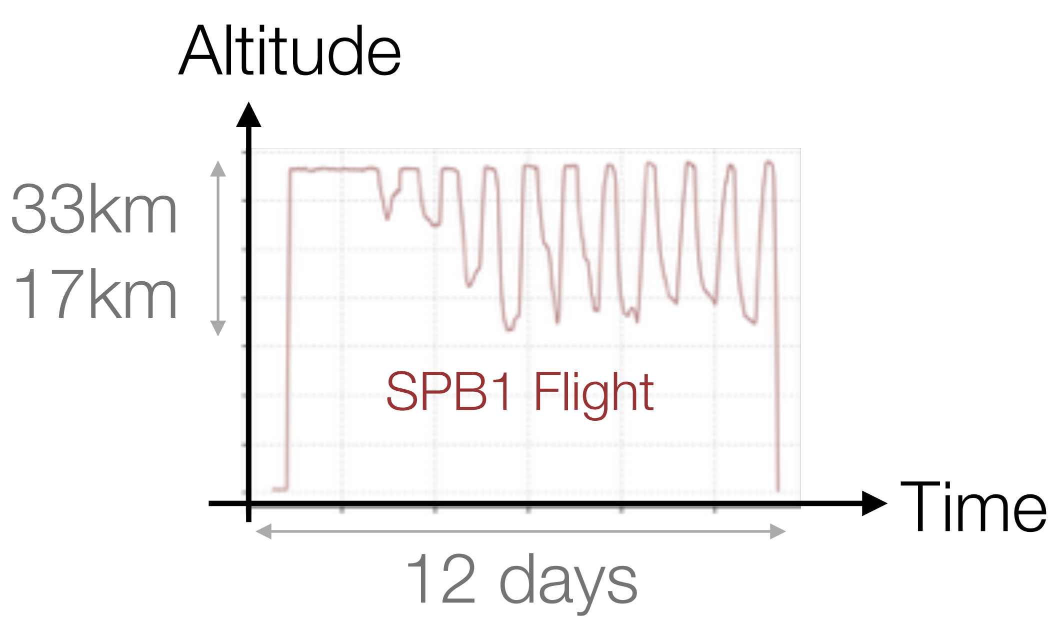
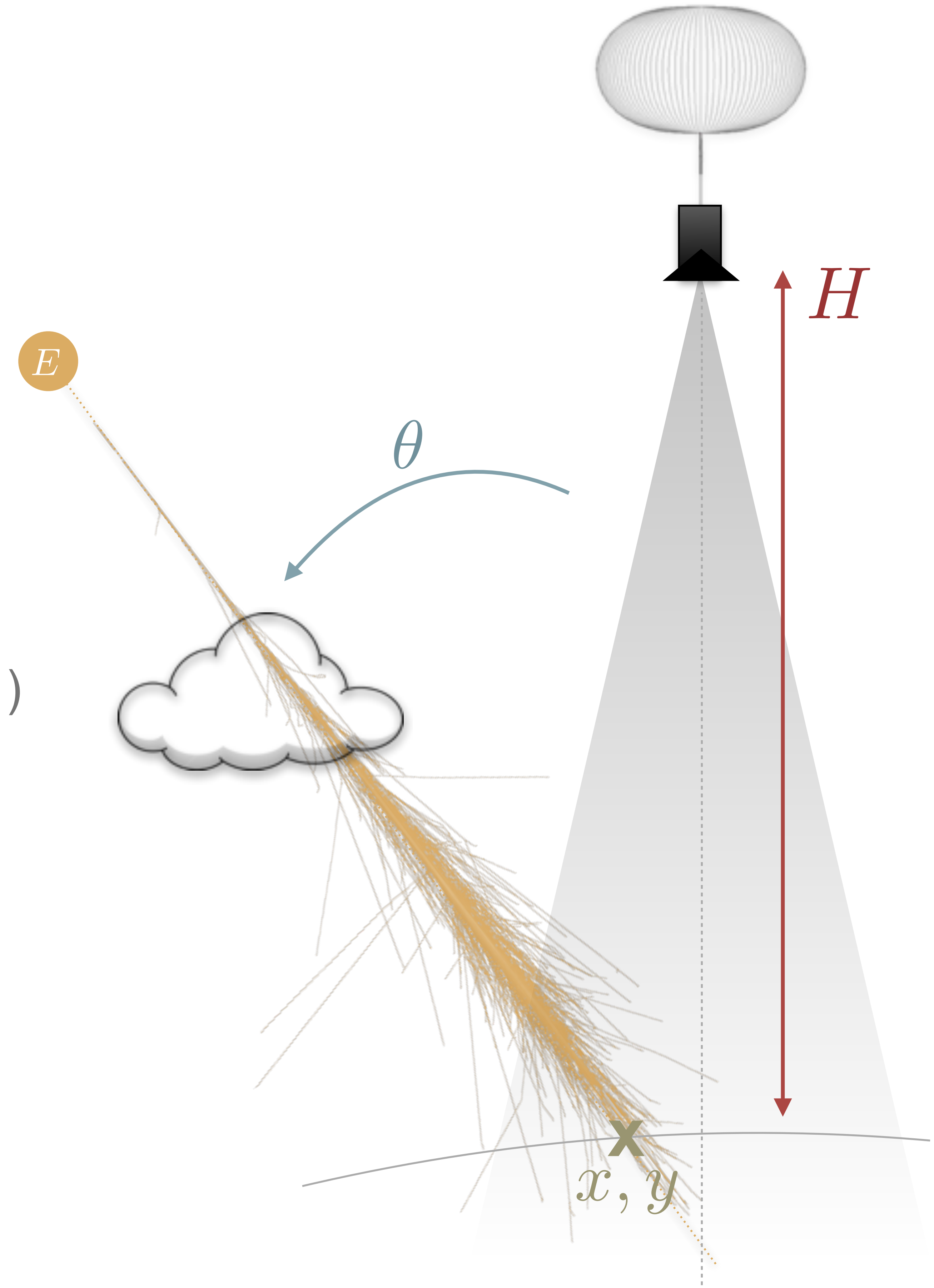
Simulations in ESAF

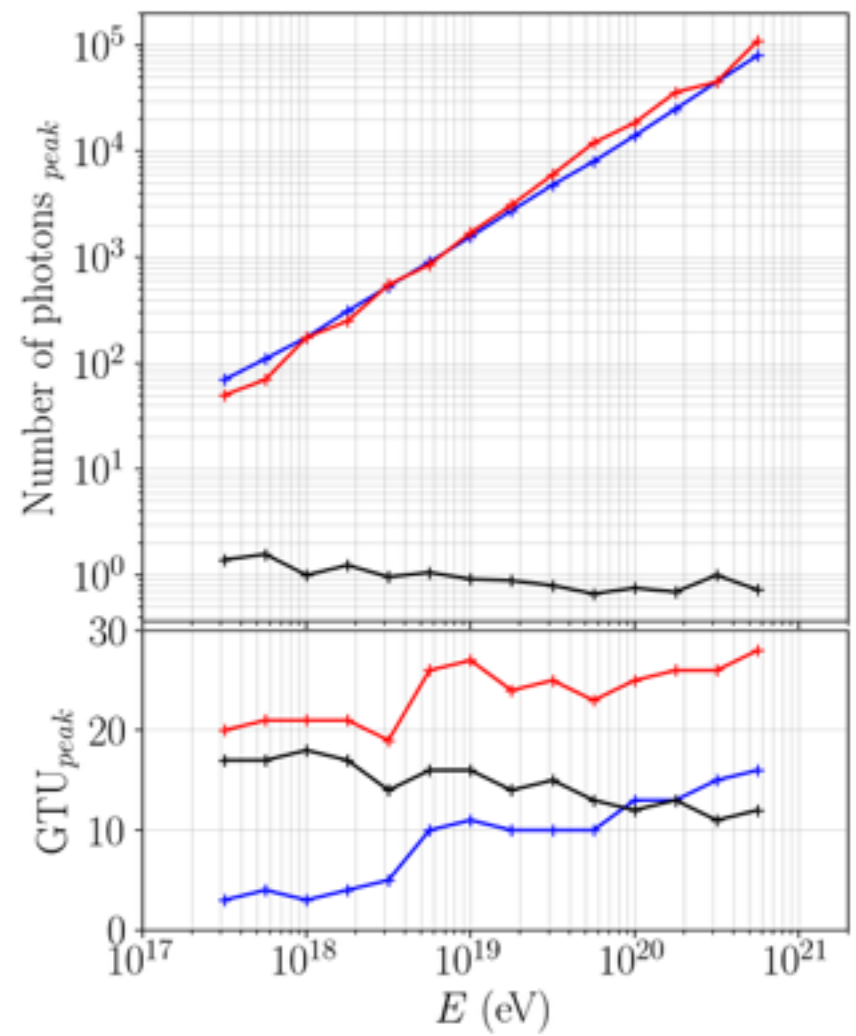
- Parameters :
  - Cosmic Ray energy (E)
  - EAS zenith angle (θ)
  - x, y of the EAS « impact »
  - Balloon Altitude (H)
  - Clouds (optical depth and altitude)

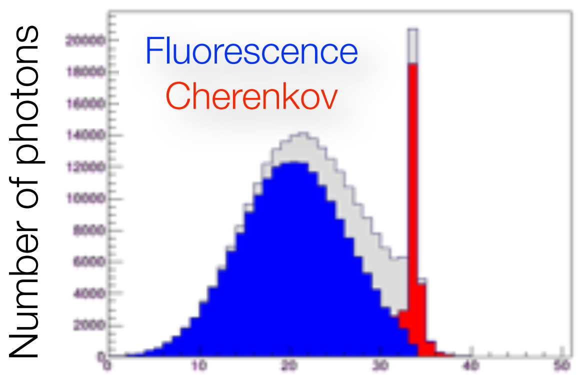




EAS Study

- **Energy**
  - More the CR is energetic
  - More photons are produced in the shower

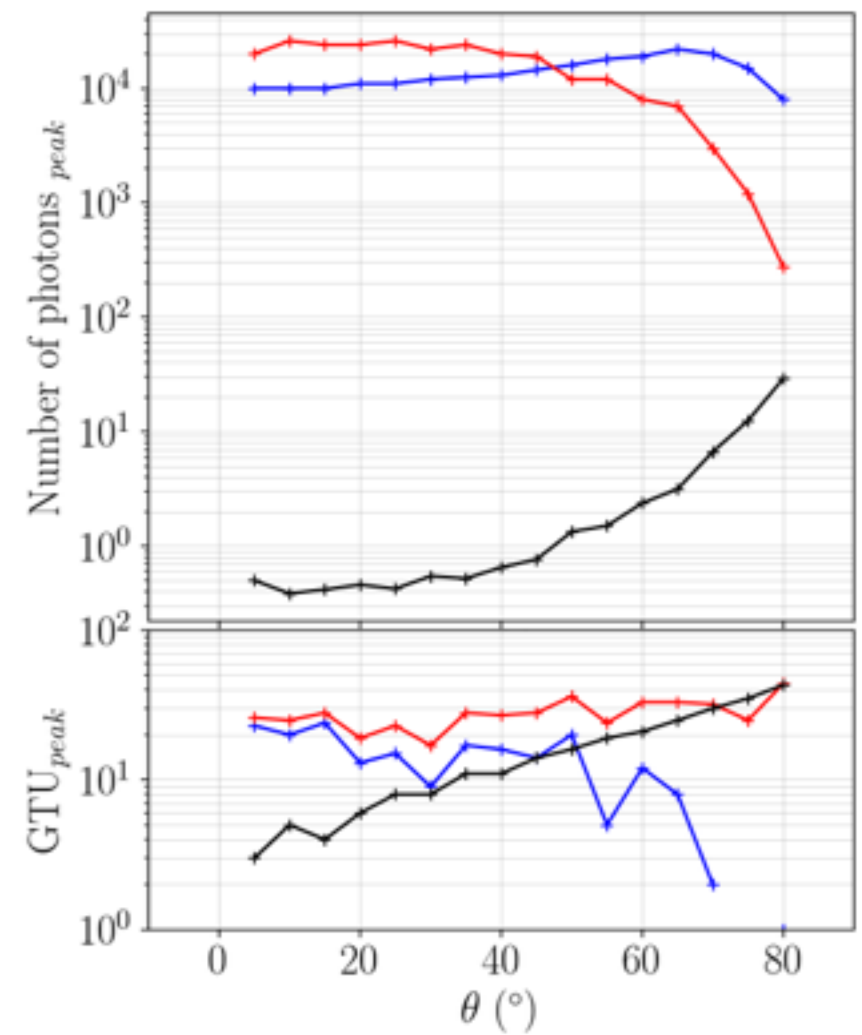


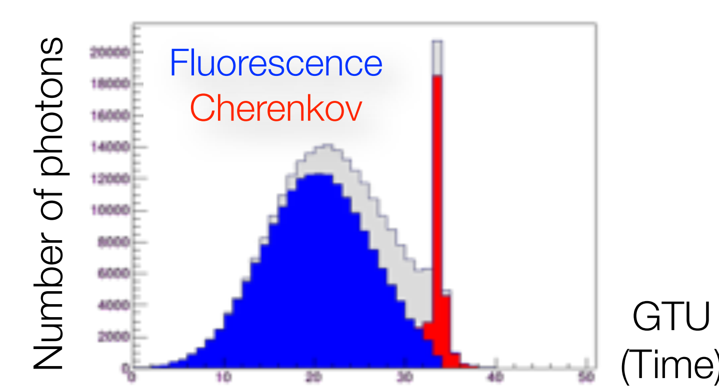


EAS Study

- **Energy**
  - More the CR is energetic
  - More photons are produced in the shower

- **Zenith angle** (θ)
  - More inclined is the shower, brighter is the signal



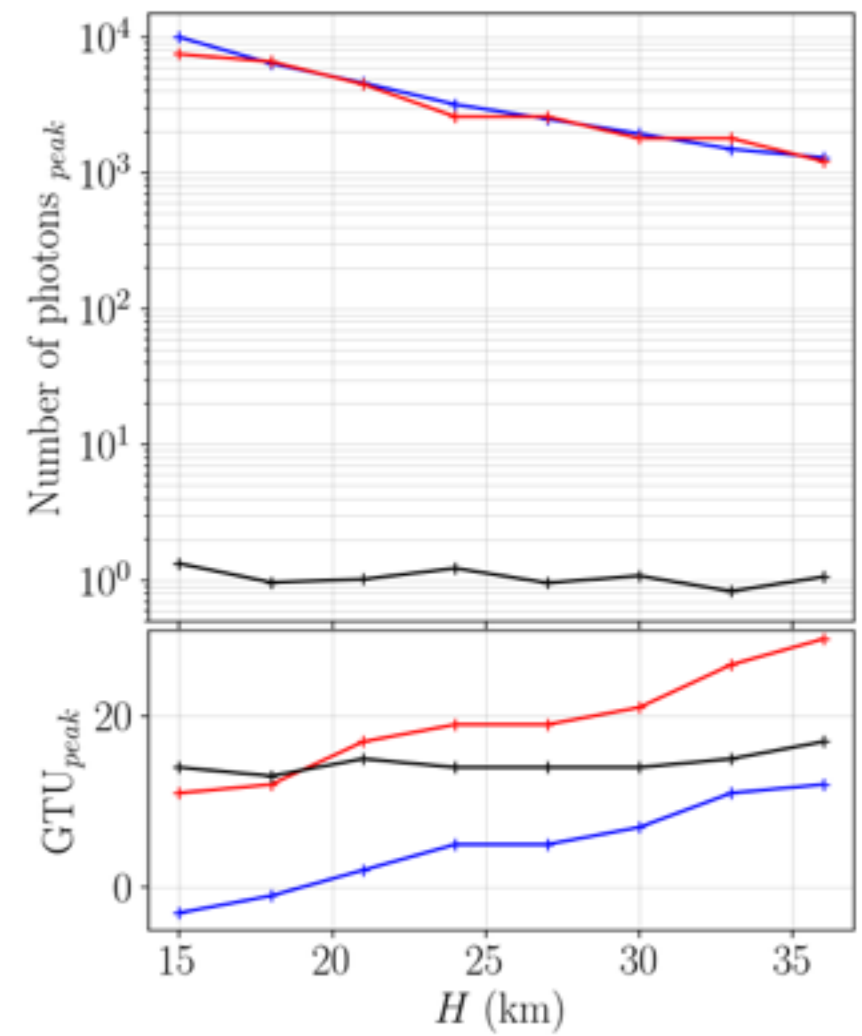


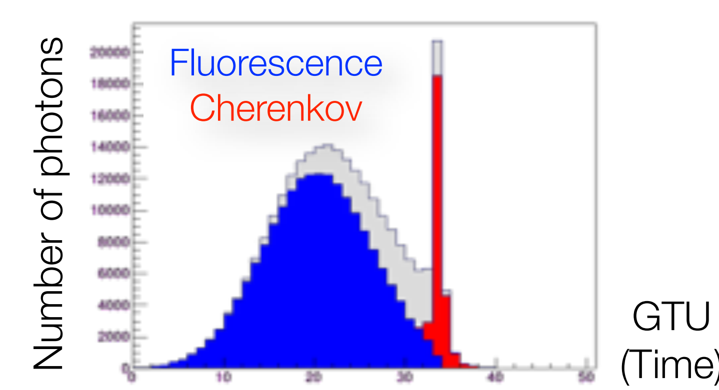
EAS Study

- **Energy**
  - More the CR is energetic
  - More photons are produced in the shower

- **Zenith angle** (θ)
  - More inclined is the shower, brighter is the signal

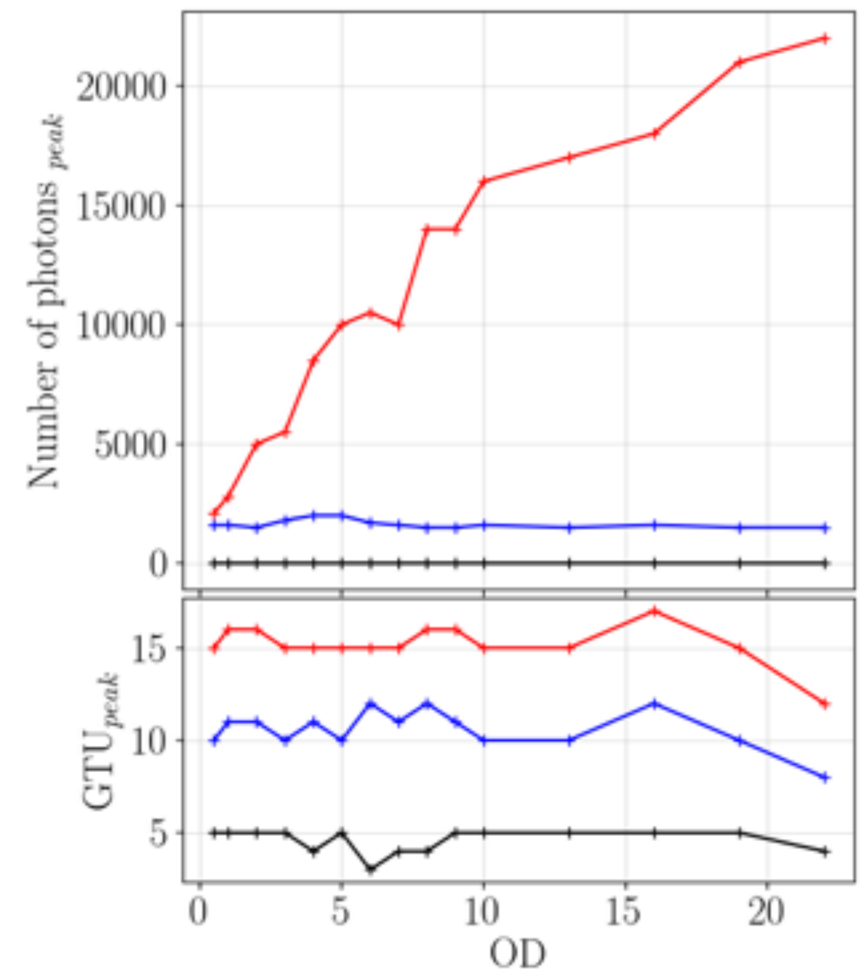
- **Altitude of the detector** (H)
  - Higher is the detector, Less photons are collected
  - But wider is the field of view

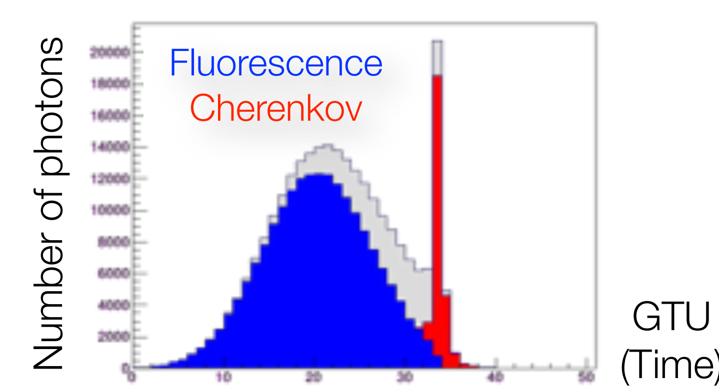




EAS Study

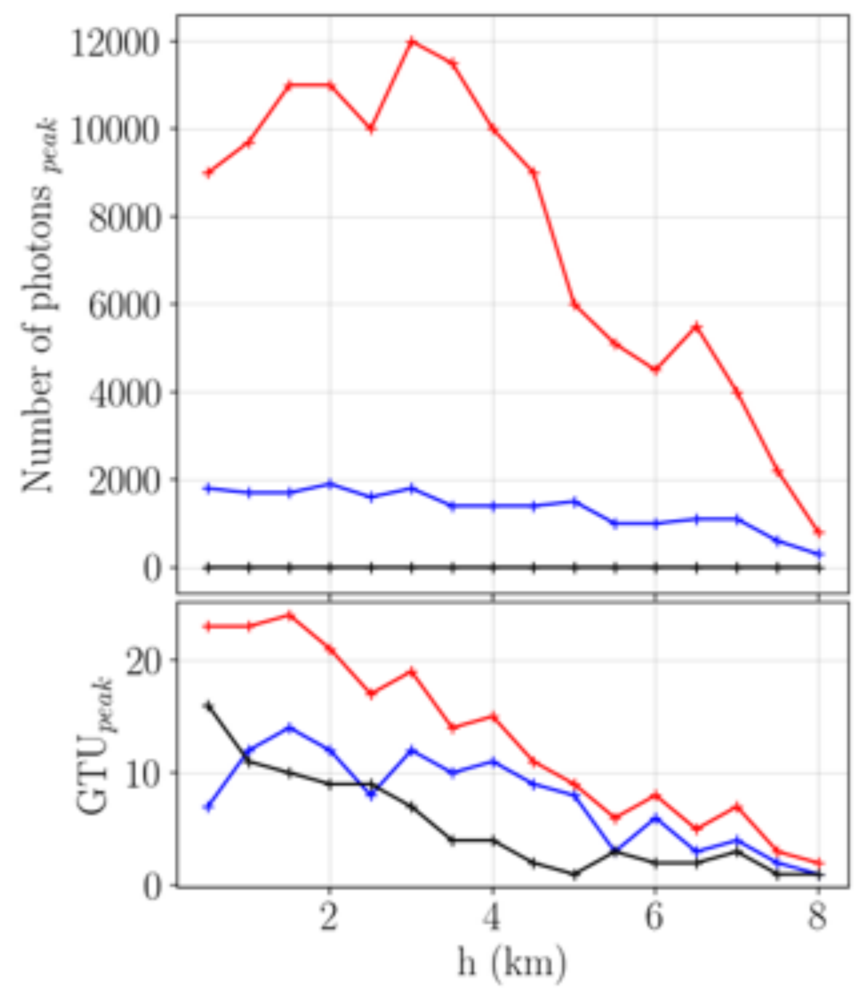
- **Energy**
  - ✤ More the CR is energetic
  - ✤ More photons are produced in the shower
- **Zenith angle** (θ)
  - ✤ More inclined is the shower, brighter is the signal
- **Altitude of the detector** (H)
  - ✤ Higher is the detector, Less photons are collected
  - ✤ But wider is the field of view
- **Clouds** : Optical Depth (OD)
  - ✤ Clouds induce greater Cherenkov emission
  - ✤ Thicker are the clouds, brighter is the Cherenkov light

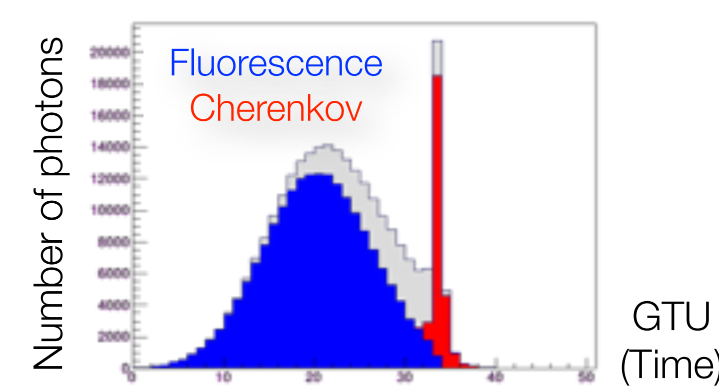




EAS Study

- **Energy**
  - More the CR is energetic
  - More photons are produced in the shower
- **Zenith angle** (θ)
  - More inclined is the shower, brighter is the signal
- **Altitude of the detector** (H)
  - Higher is the detector, Less photons are collected
  - But wider is the field of view
- **Clouds** : Optical Depth (OD), altitude (h)
  - Clouds induce greater Cherenkov reflexion
  - Thicker are the clouds, brighter is the Cherenkov light
  - Higher are the clouds, fainter is the light detected





Simulations & Results

- EAS study
- Aperture study
- SPB1 aperture

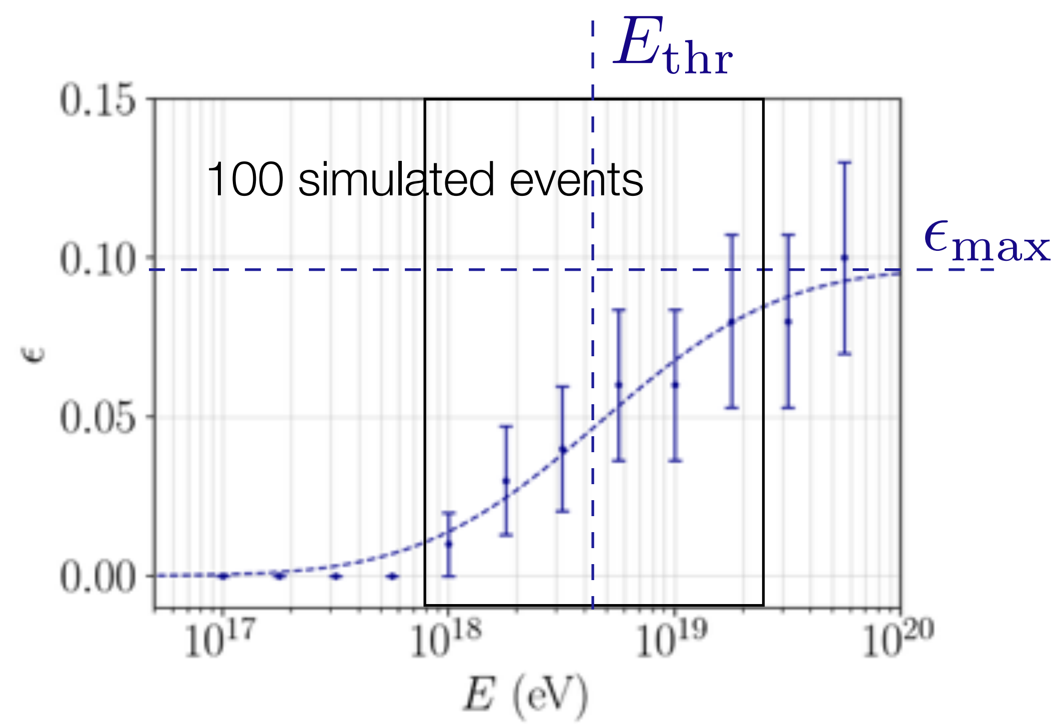
Aperture Study - Energy

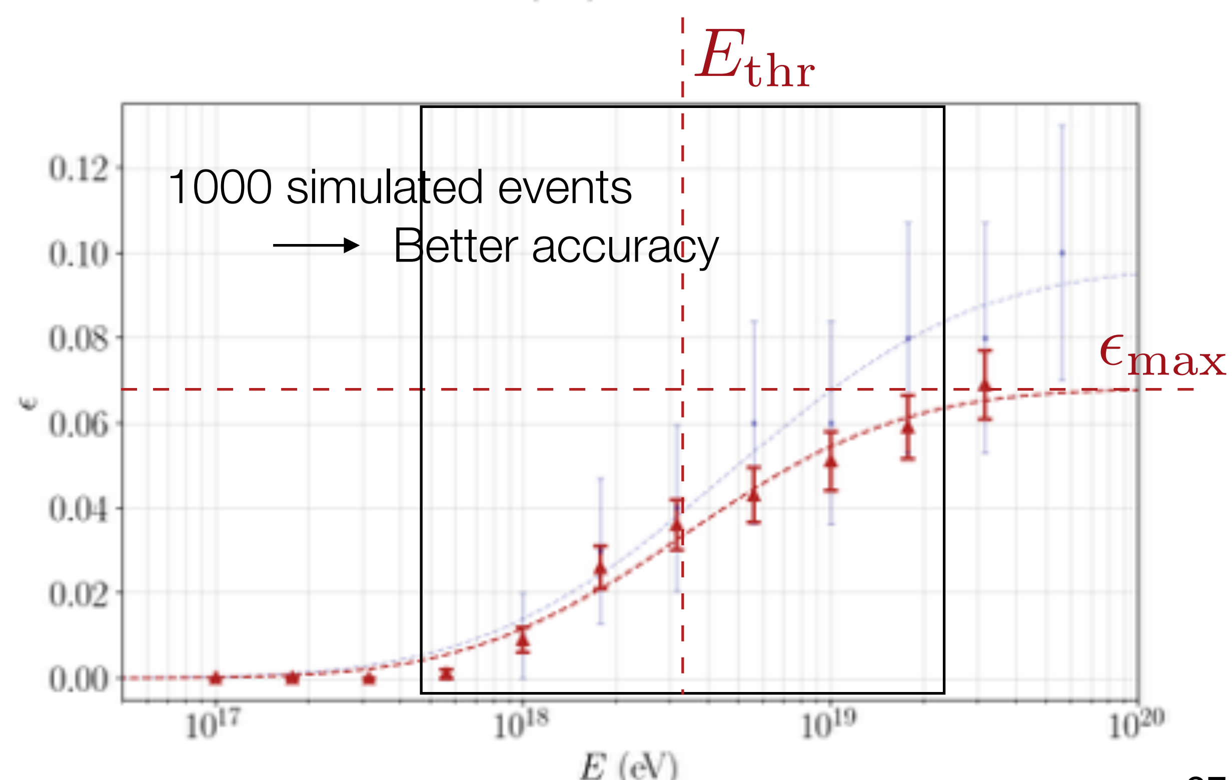
- Energy
  - Efficiency maximum : $\epsilon_{\max}$
  - Energy threshold : E_{thr}

$$\delta\epsilon = \sqrt{\frac{\epsilon \times (1-\epsilon)}{N}}$$

- Number of events
  - Better accuracy

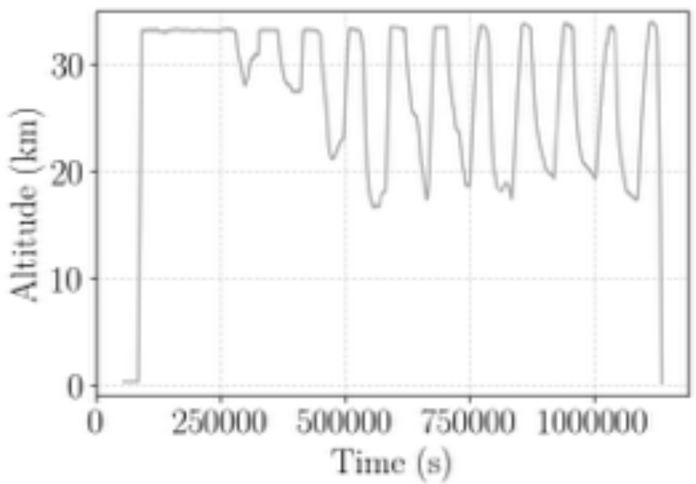
$$\left(A = \epsilon \times \underbrace{k \times \Omega_0 \times S_{\text{sim}}}_{\text{constant}} \right)$$

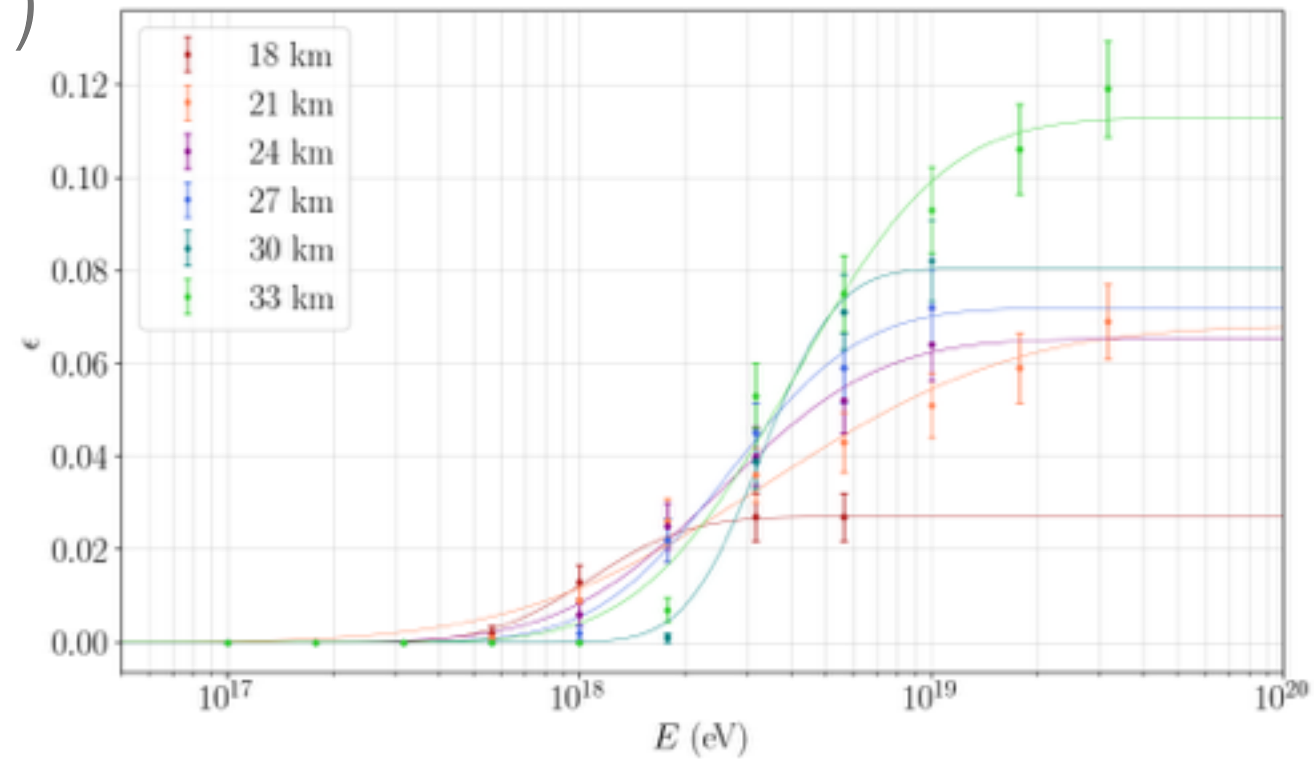




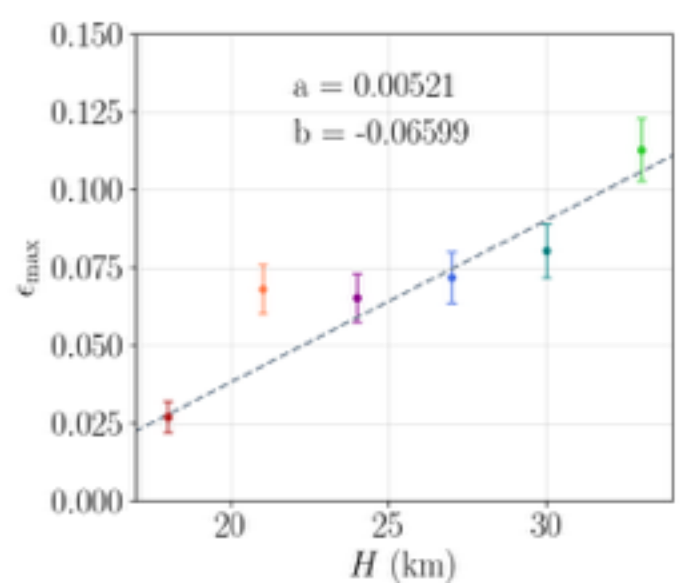
Aperture Study - Altitude

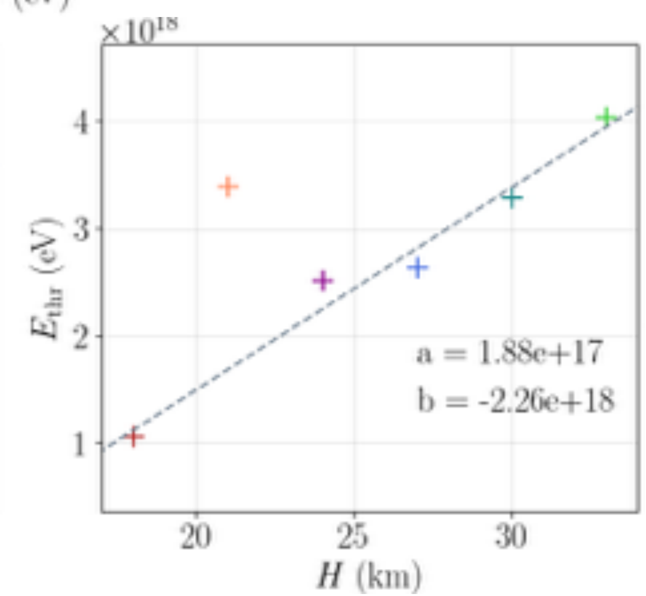
- Altitude of the balloon (H)





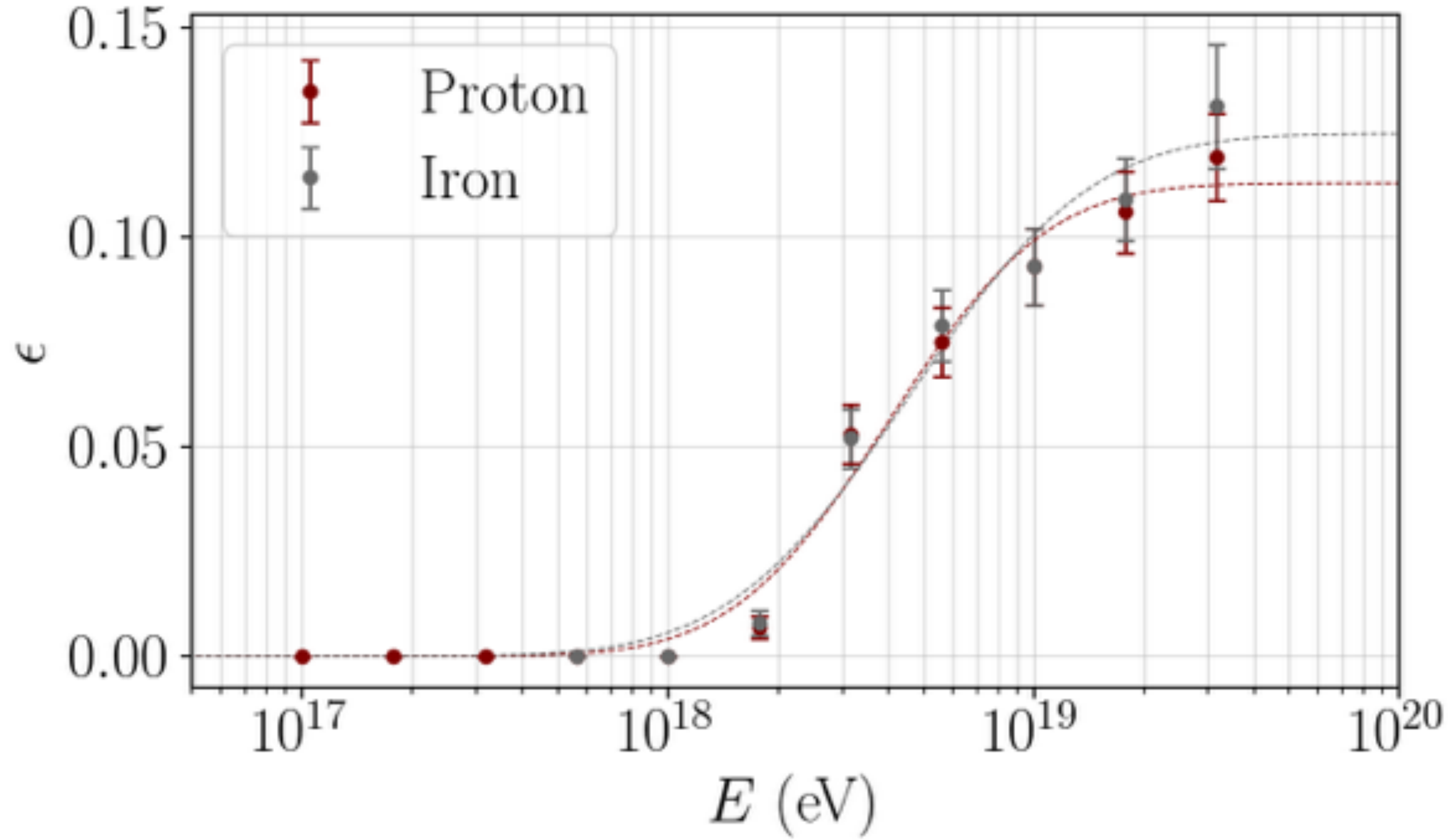
- Linear evolution with the altitude:
  - Energy threshold (E_{thr})
  - Efficiency maximum ($\epsilon_{\max}$)





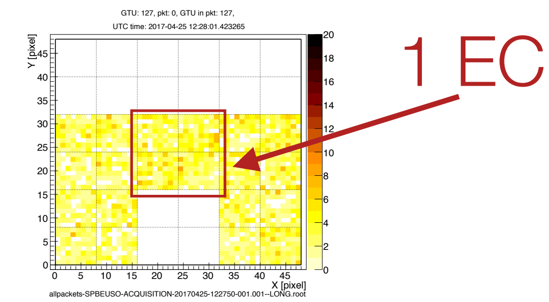
Aperture Study - Primary particle

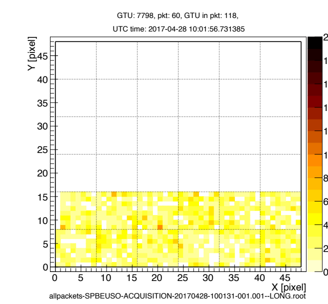
- CR particle : Proton or Iron ?
  - No difference



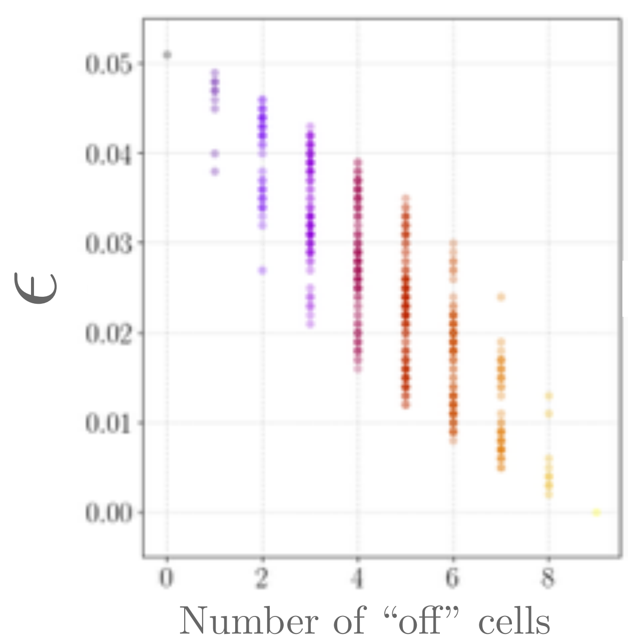
Aperture Study - Number of working ECs

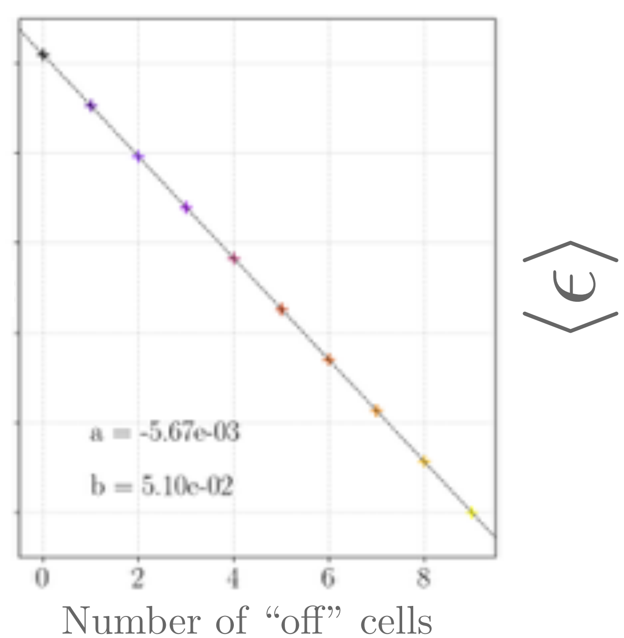
- Number of working Elementary Cells (ECs)
  - 9 ECs - 2 possible configurations : ON/OFF
  - Total number of PDM configurations : $2^9 = 512$
    - Compute efficiency for each configuration
    - Efficiency average for each set of same number of « OFF » ECs

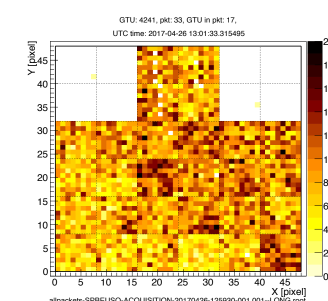


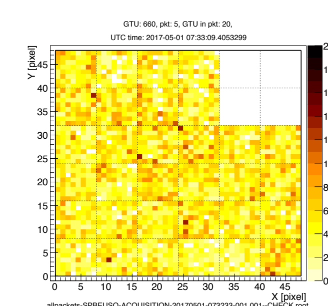


- Efficiency proportional to the number of working EC :



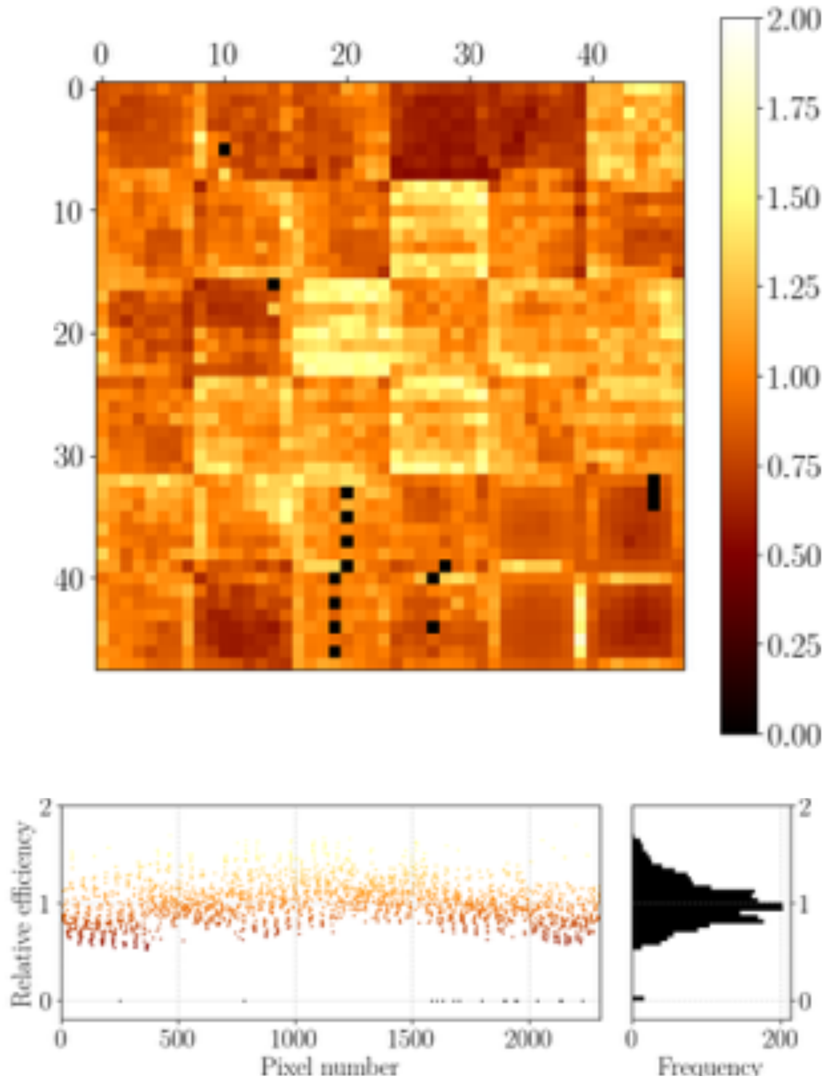




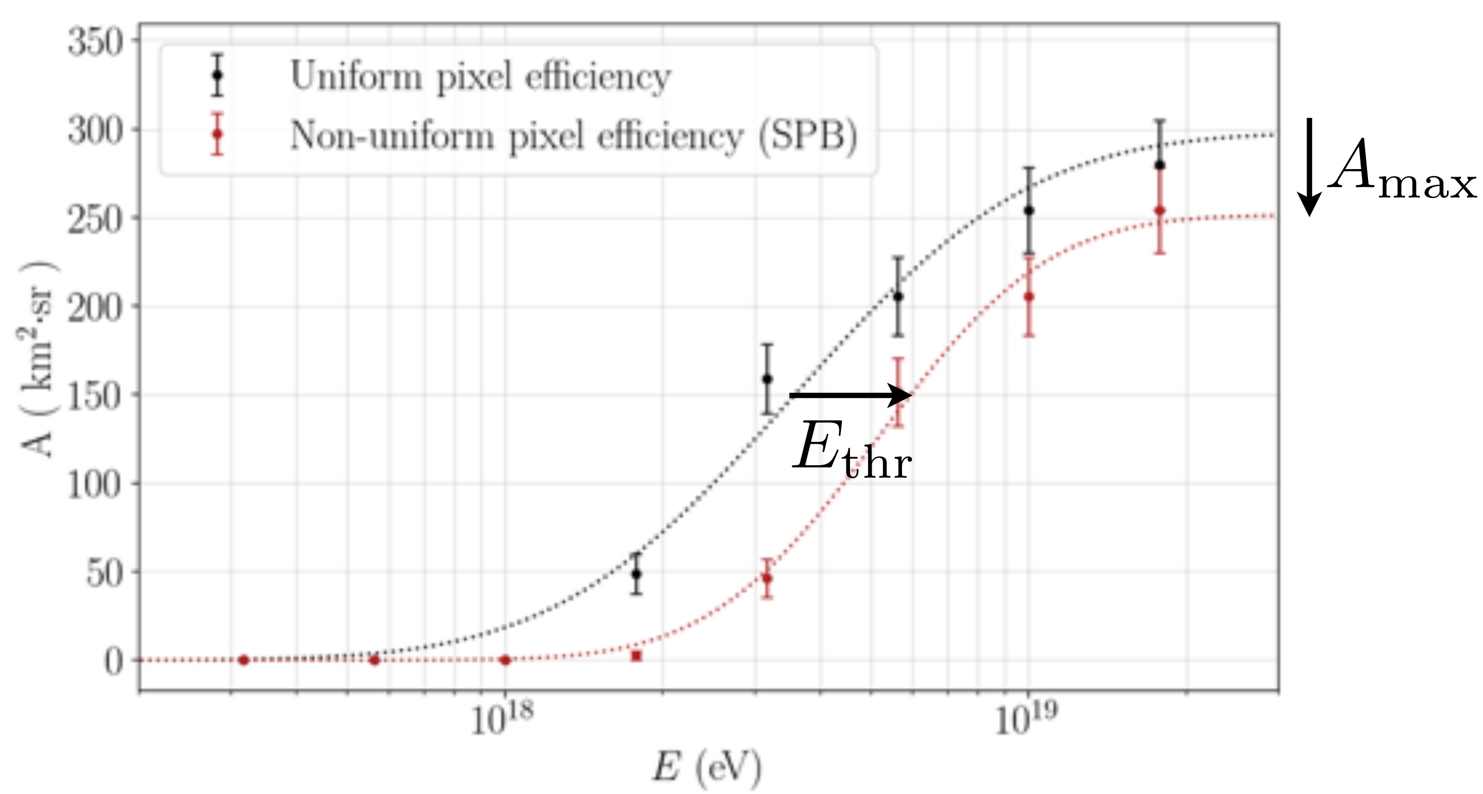


Aperture Study - Non uniform PDM efficiency

- **Different pixel efficiency** in the PDM :



- Effect of the real SPB1 PDM:
  - The maximal aperture is **reduced** : 84%
  - The energy threshold is 1,45 times greater

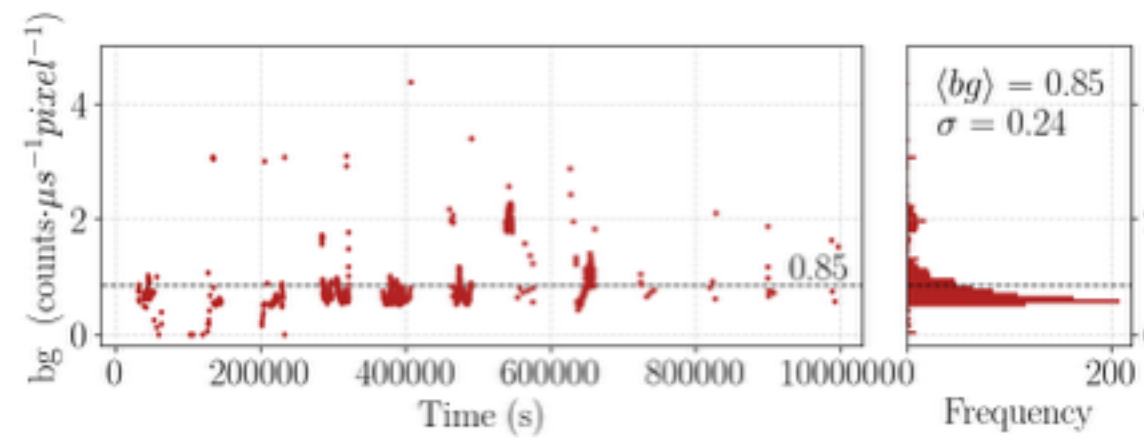


Aperture Study - Background level

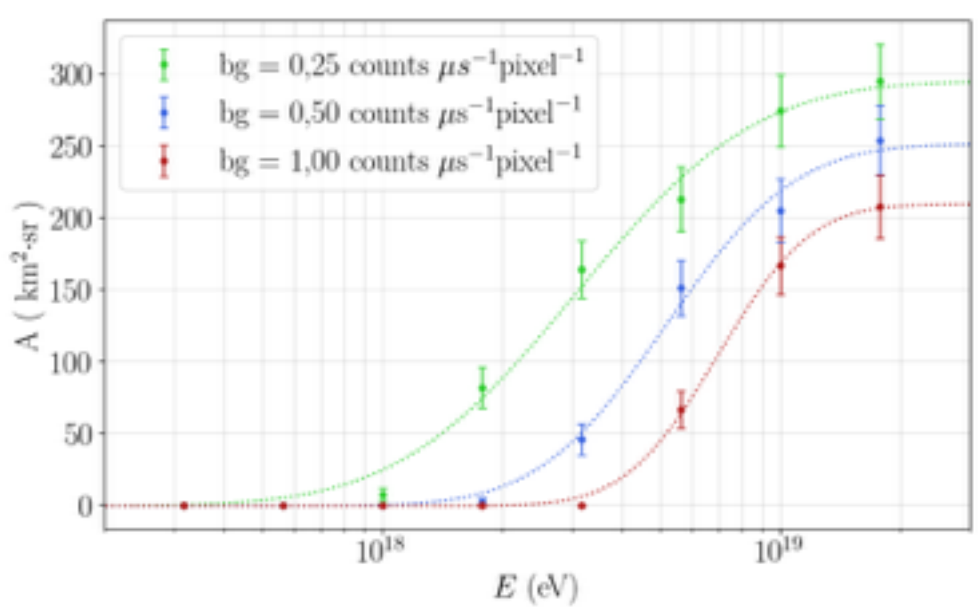
- **Background** level :

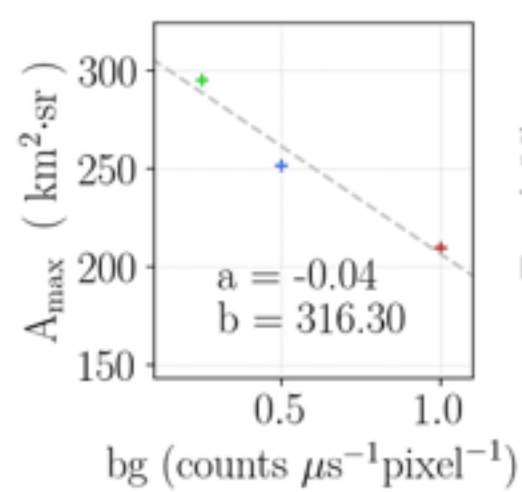
  average number of counts on PDM pixels

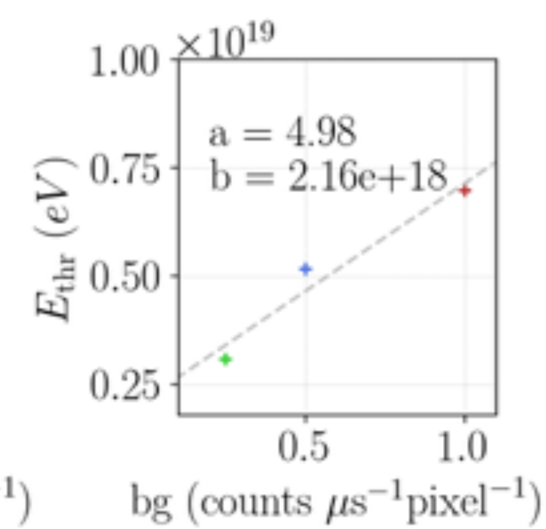
- During the SPB1 flight :
  - Average : 0,85 counts / μs / pixel



- $A_{\text{max}} \downarrow$ and $E_{\text{thr}} \uparrow$ $\propto$ background level :





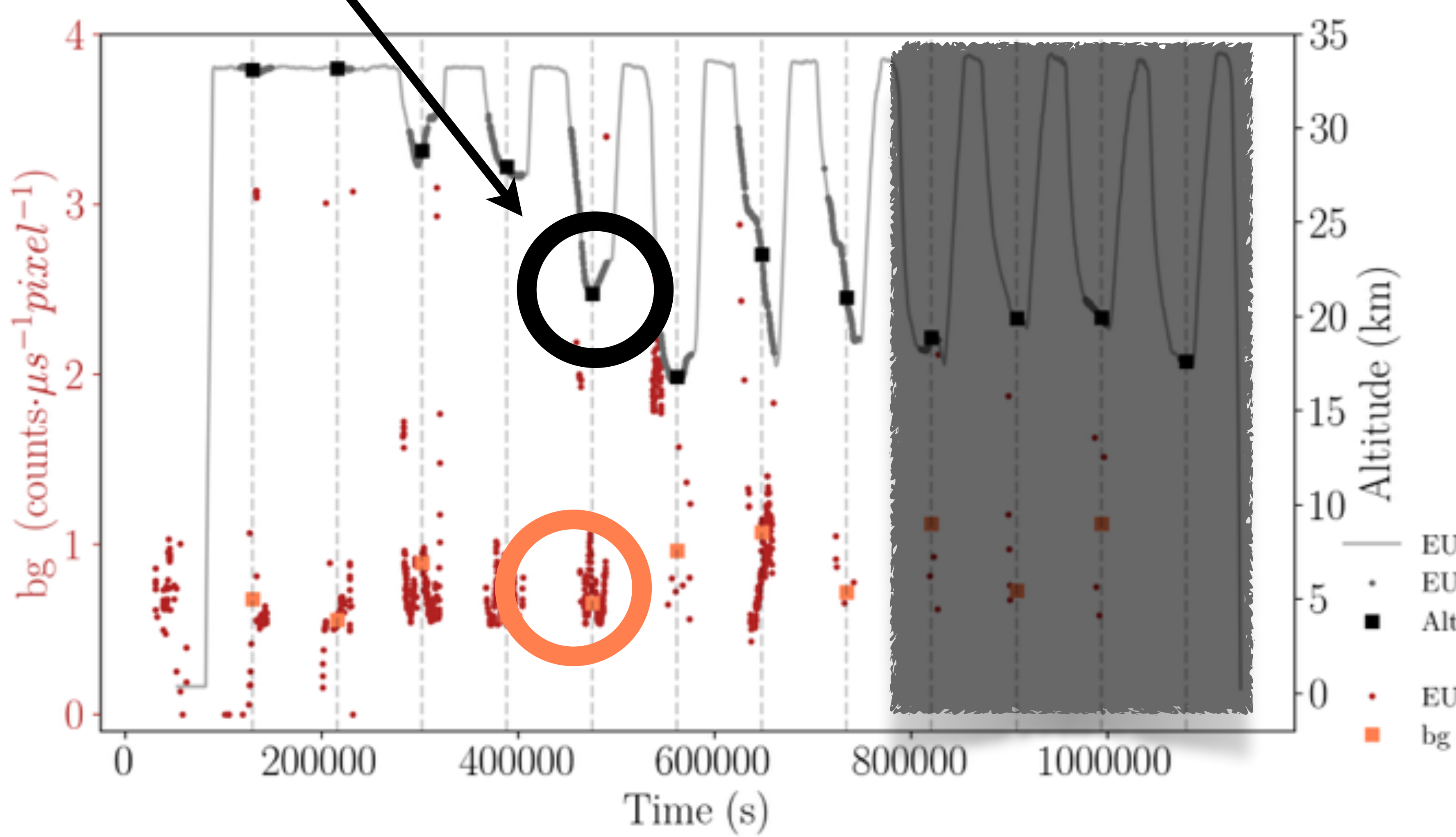


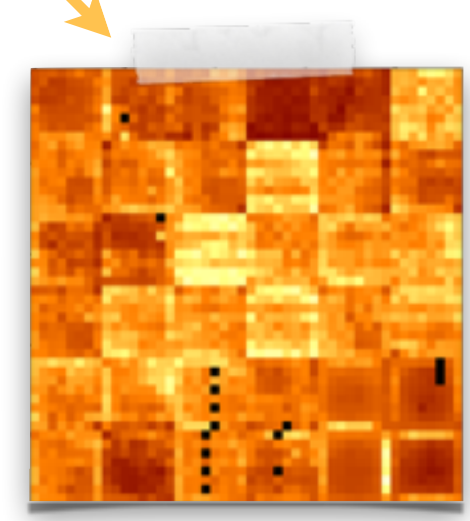
Simulations & Results

- EAS study
- Aperture study
- SPB1 aperture

Estimation of the EUSO-SPB1 aperture

- Simulated in flight conditions at **12 UTC** for the **8 first days**
- **Altitude** of the balloon + average **background** level
  + **Non-uniform efficiency** of the SPB1 PDM





Estimation of the EUSO-SPB1 aperture

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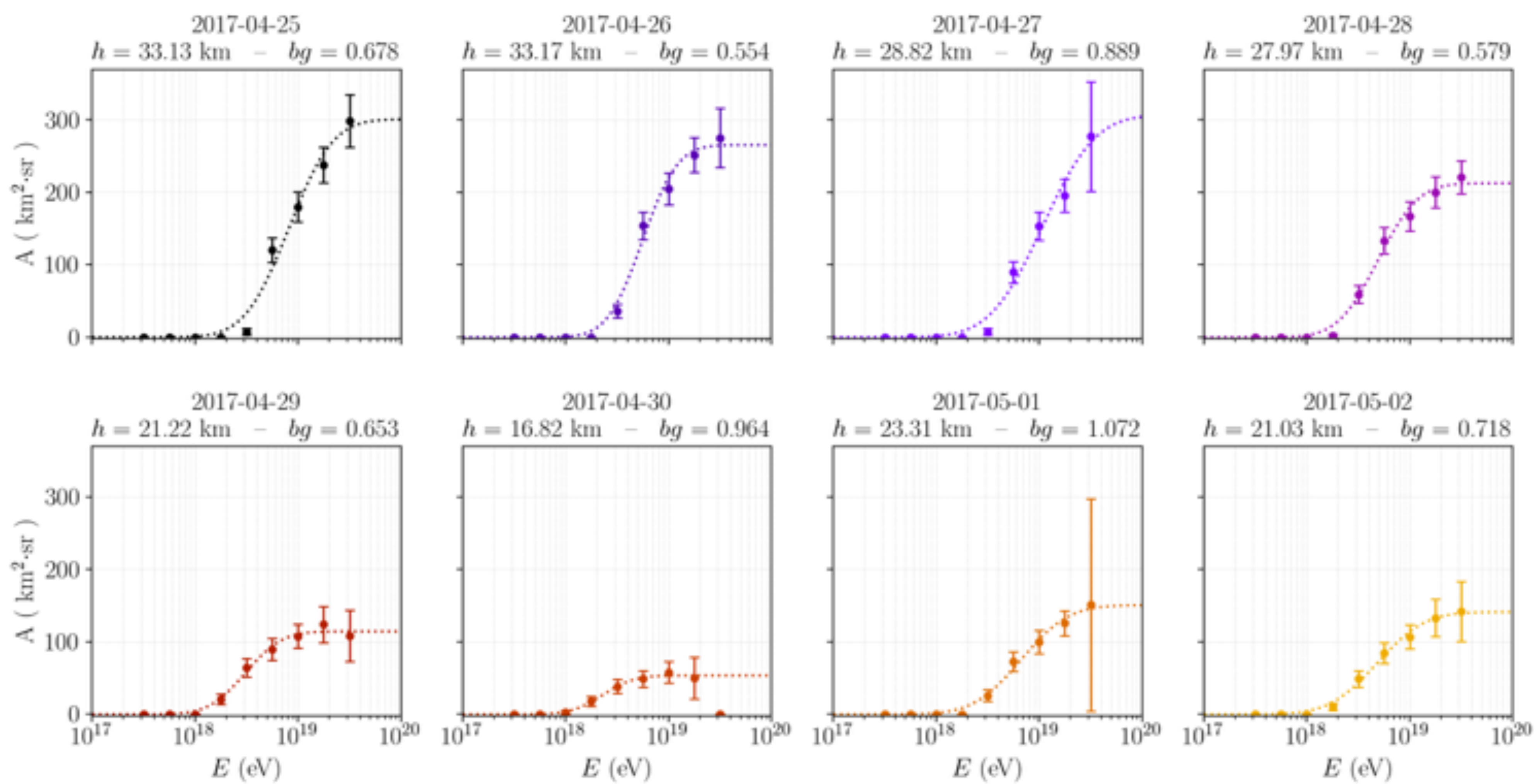

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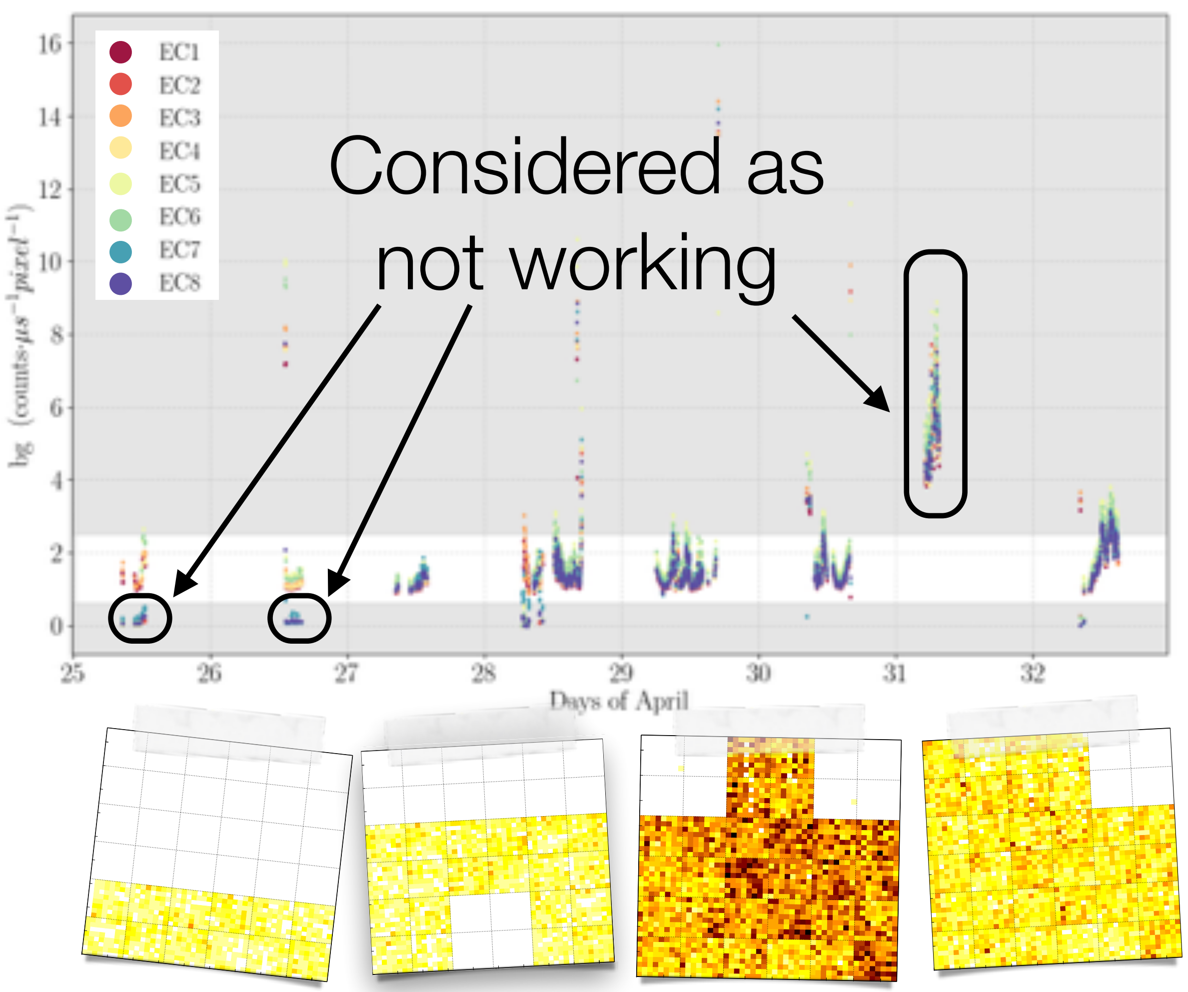
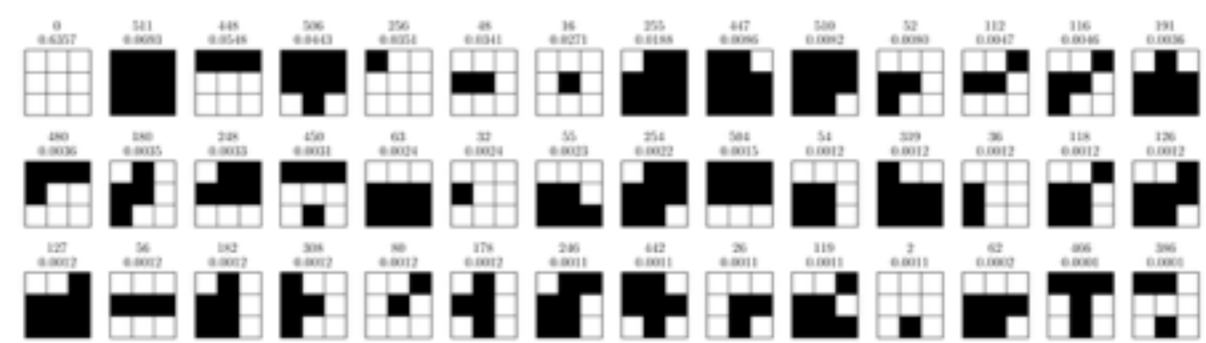


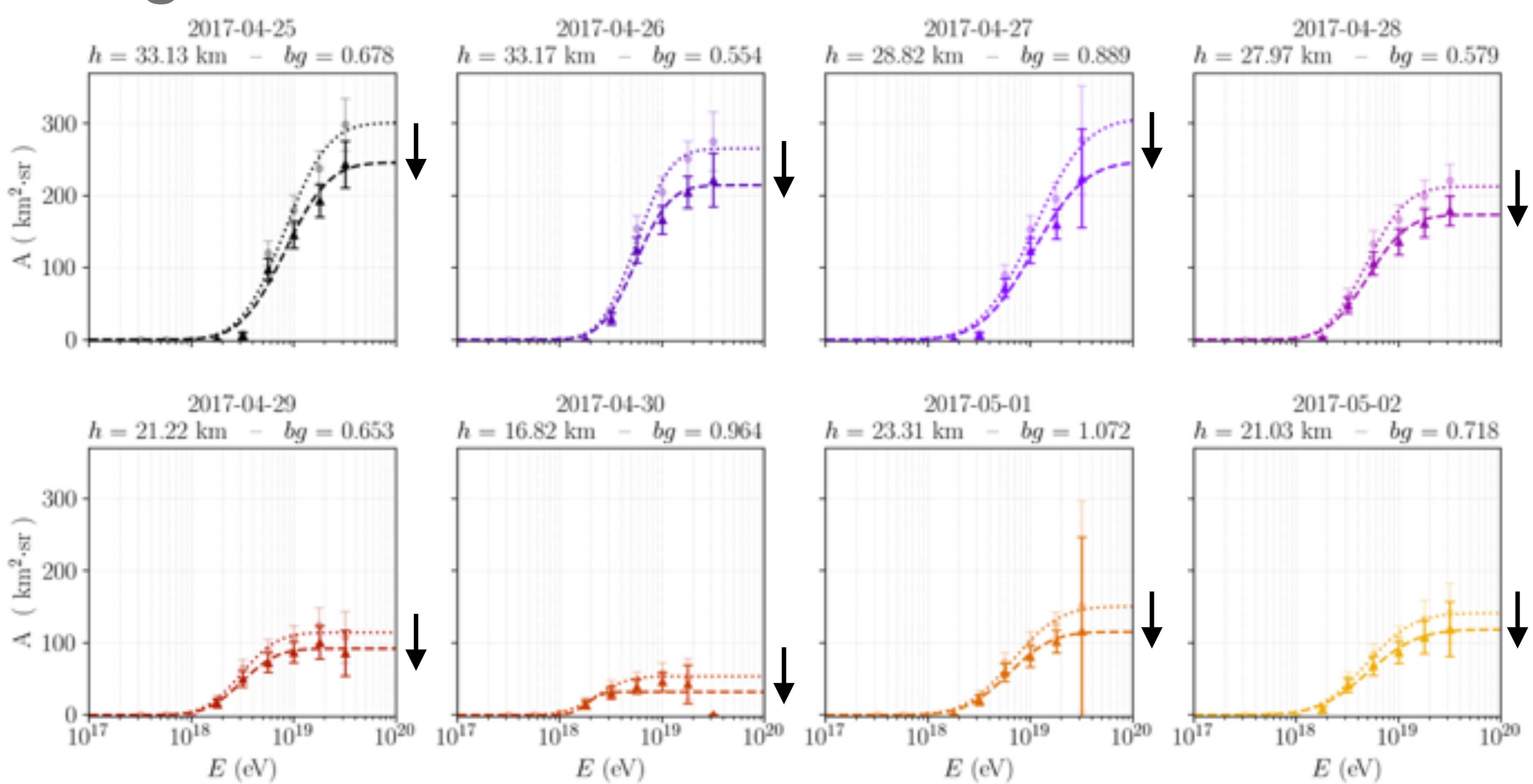
- Average of the working PDM status on the whole flight

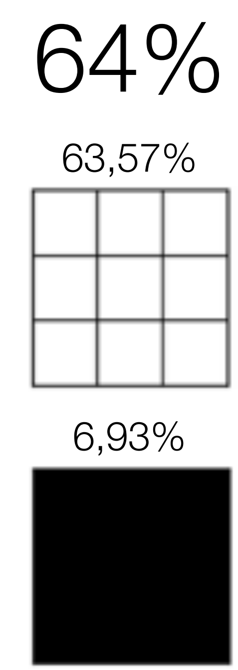


Probability <> Appearance frequency

Estimation of the EUSO-SPB1 aperture

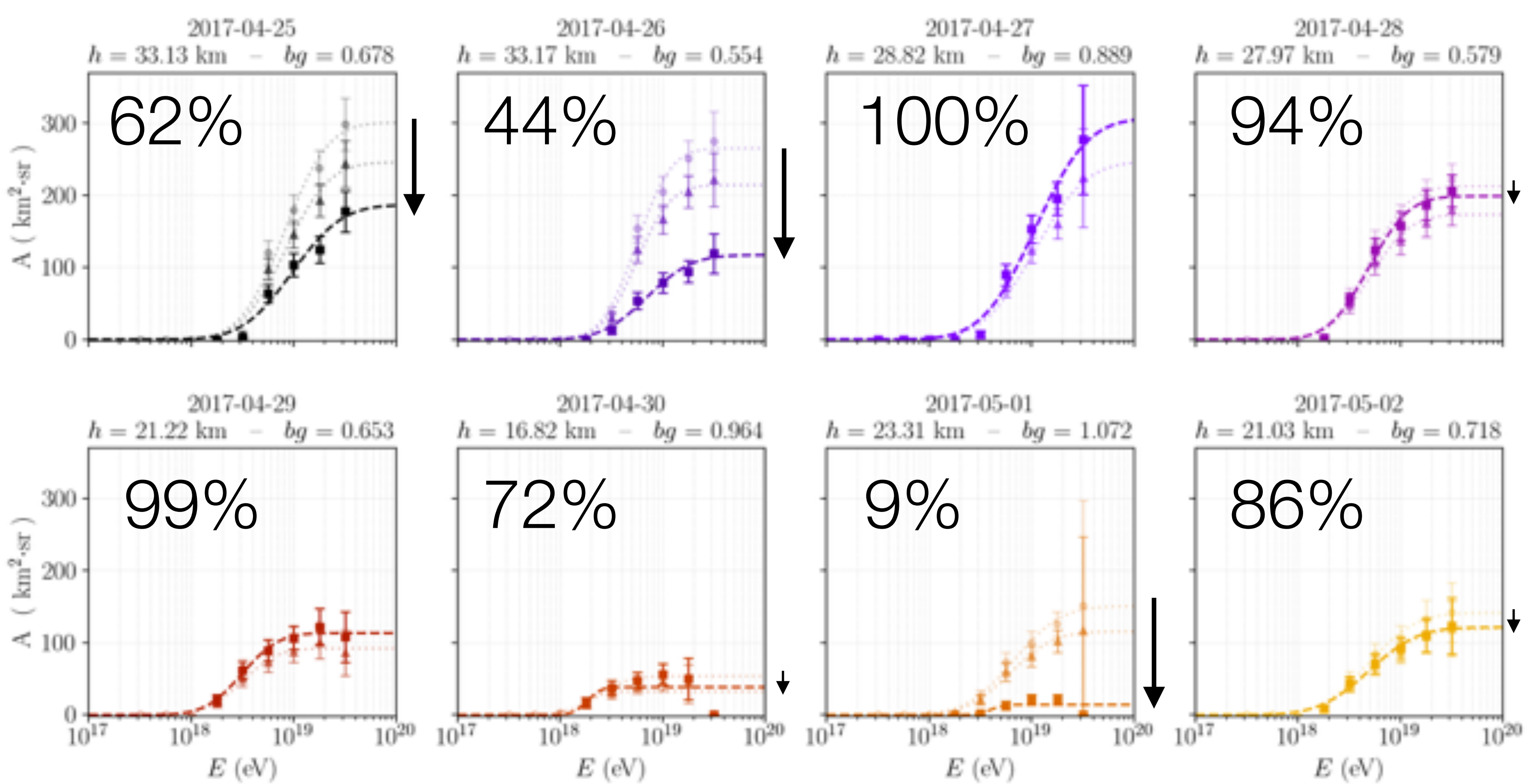
- Simulated in flight conditions at 12 UTC for the 8 first days
- Altitude of the balloon + average background level
  + Non-uniform efficiency of the SPB1 PDM efficiency
- Average of the **total PDM status** on the whole flight





Estimation of the EUSO-SPB1 aperture

- Simulated in flight conditions at 12 UTC for the 8 first days
- Altitude of the balloon + average background level
  + Non-uniform efficiency of the SPB1 PDM efficiency
- Average of the **daily PDM status** (finer)



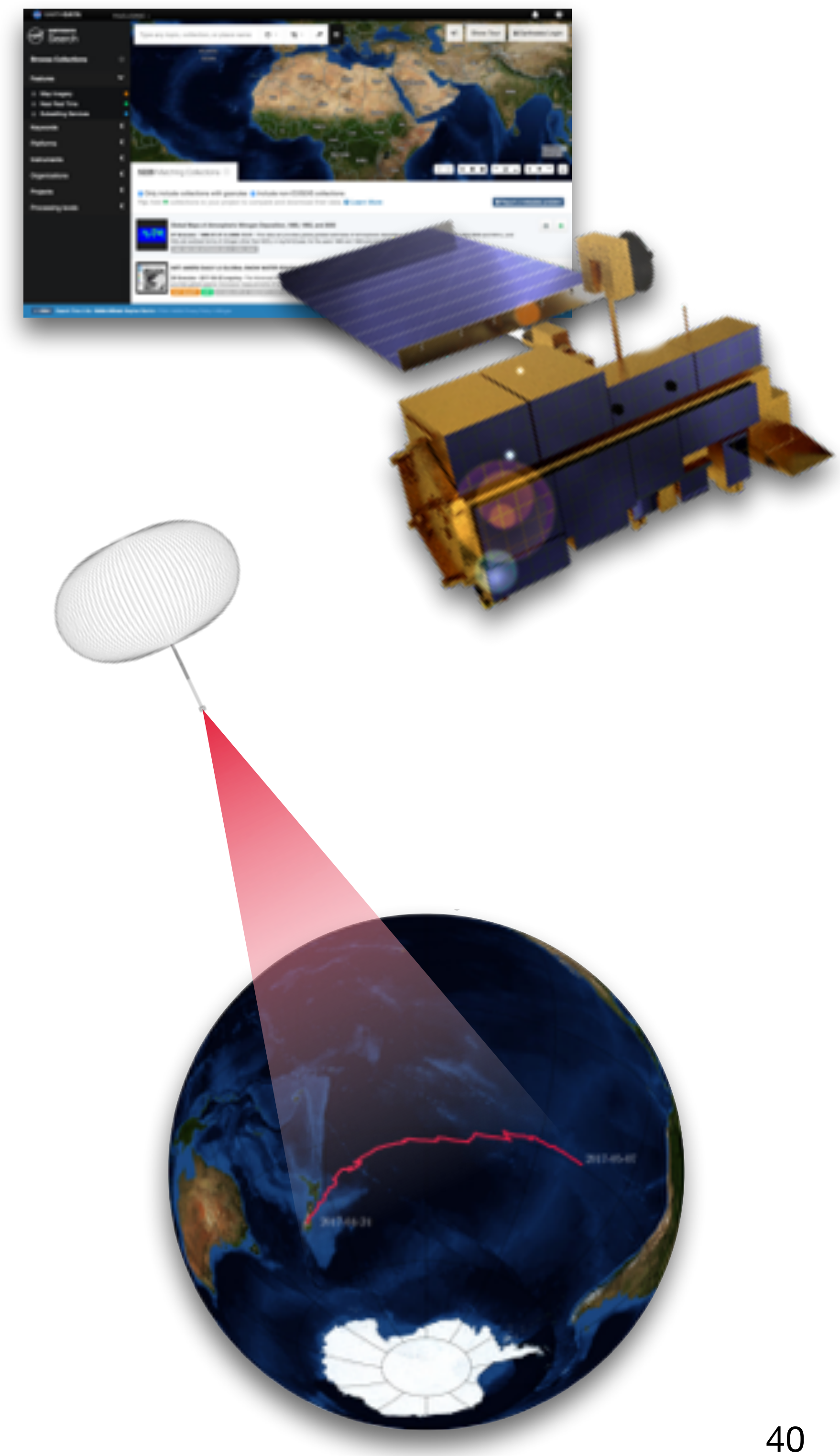
Clouds

Cloud MODIS satellite

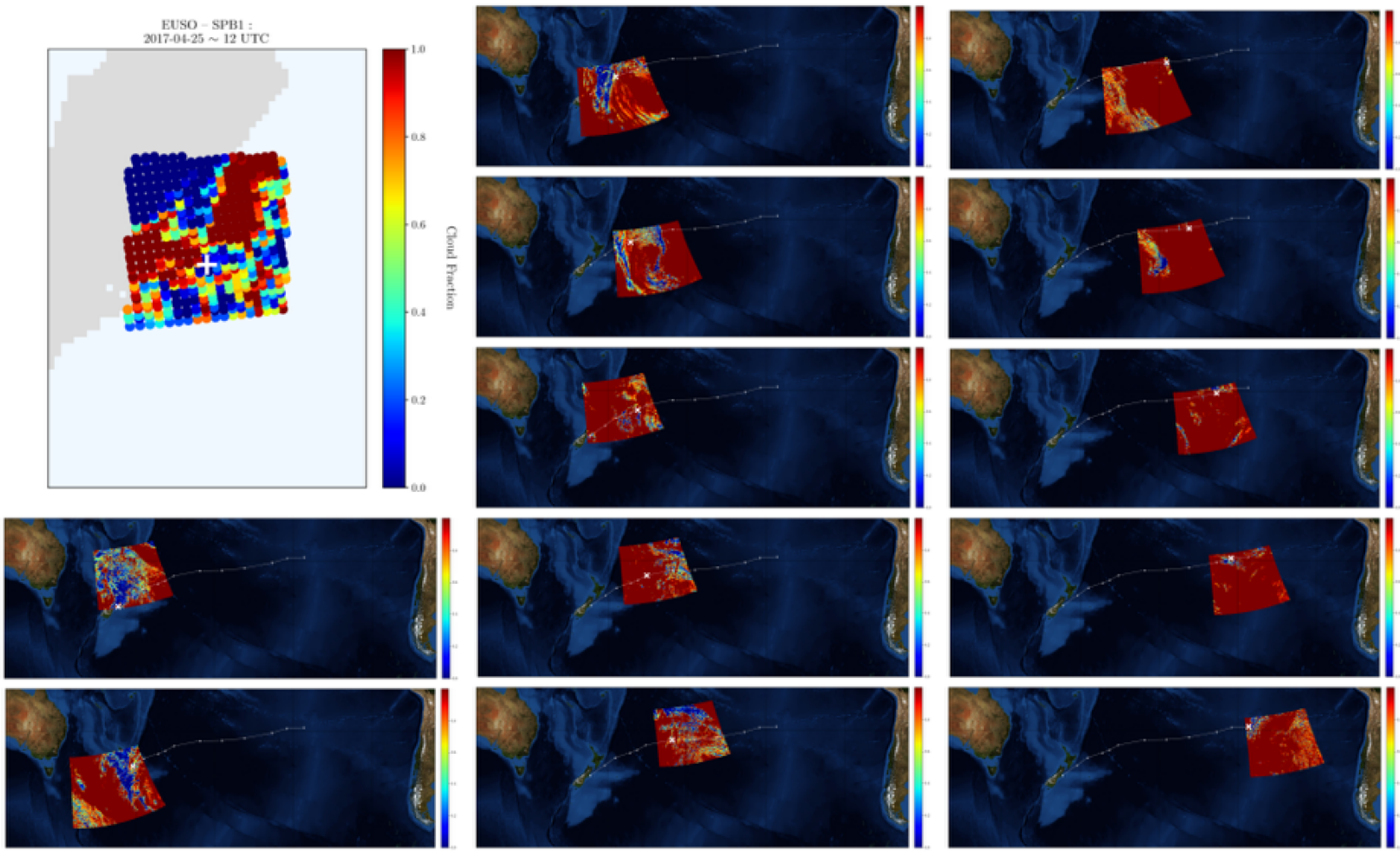
- Database : NASA Earth Data Search
- Terra NASA's Satellite (700km)
  - MODIS payload
- **Date**, **12 UTC** , **Location** of SPB1
- **Cloud fraction** :

  1 : Total cloud coverage

  0 : No clouds



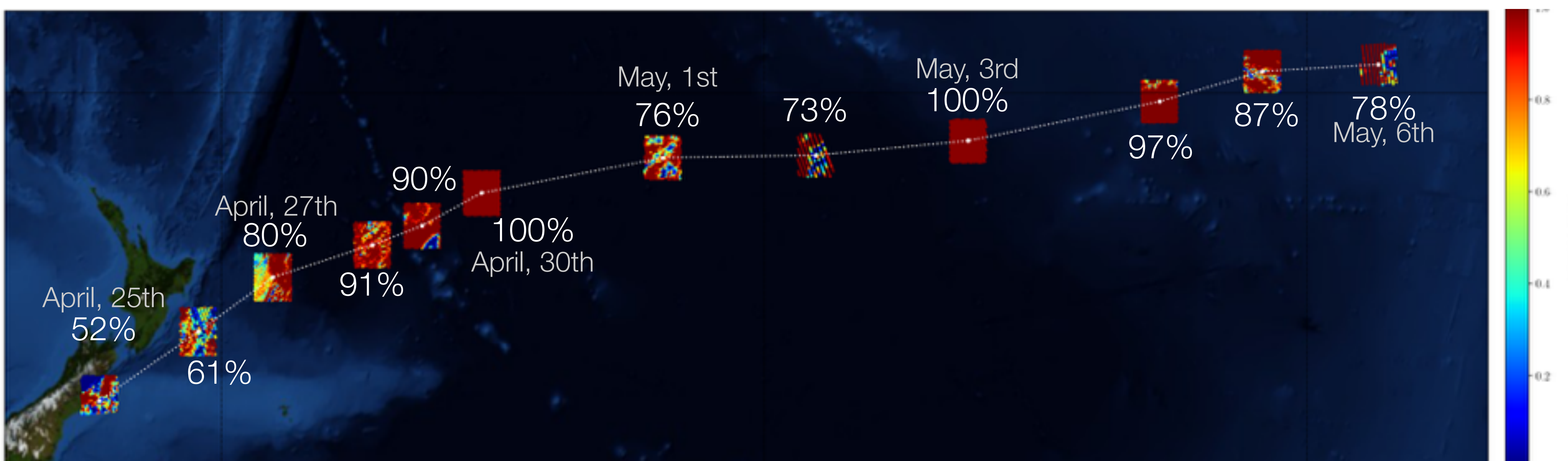
SPB1 cloud coverage



SPB1 cloud coverage

- Cloud fraction average on a $\pm 1°$ area : Cloudy !
- Significant parameters unknown :
  - **Cloud top altitude** or **optical depth**

✤ *There is still hope*



Conclusions

Conclusions

- Aperture of EUSO-SPB1
  - **Studied** and **quantified** the aperture dependency on :
    - The energy of the primary cosmic ray
    - The altitude of the balloon and background level
    - The status and real efficiency of the PDM
  - **Estimated** of the aperture for each day at 12 UTC

- What can be done :
  - **More precise estimation** of the aperture by finer parameters
  - Repeat for times in the flight to get the **expected number of events**
  - Look for more significant data on clouds


Grazie mille a tutti per questa
bella esperienza