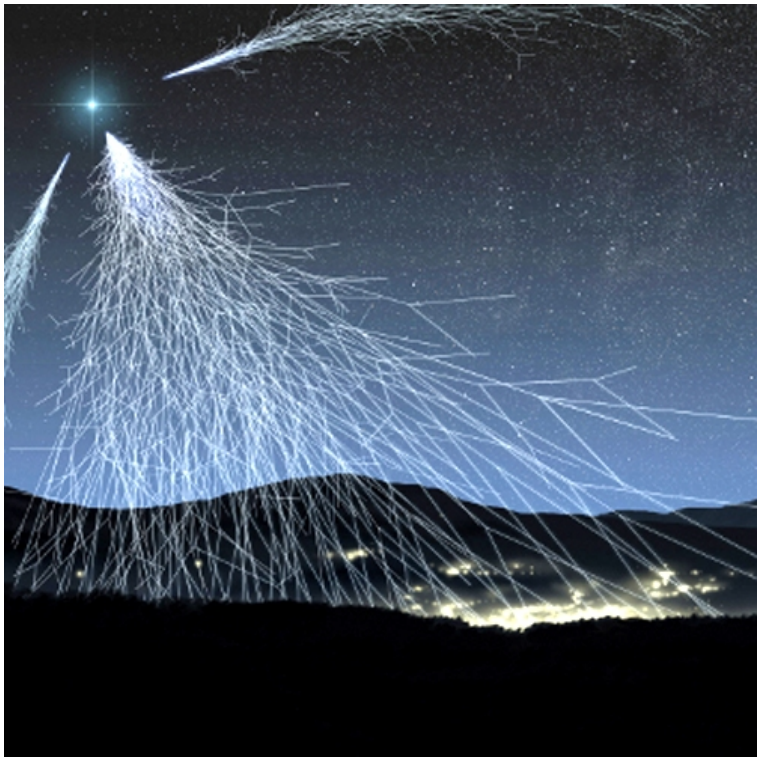
Atmospheric electricity phenomena studied with the detectors of the Pierre Auger Observatory

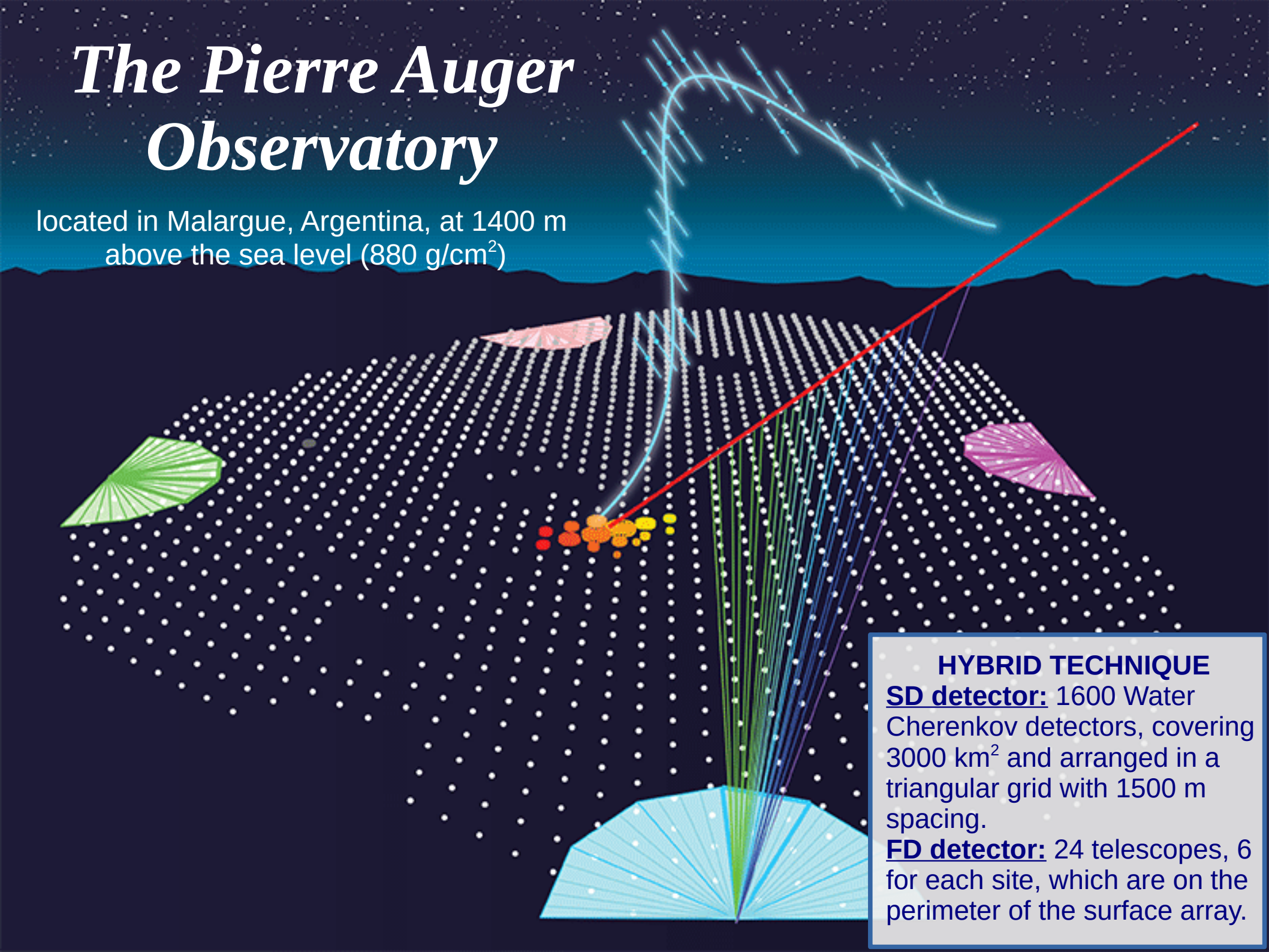


Roberta Colalillo, INFN Napoli,
for the Pierre Auger Collaboration

May 18, 2021
GCOS Workshop

The Pierre Auger Observatory

located in Malargue, Argentina, at 1400 m above the sea level (880 g/cm^2)

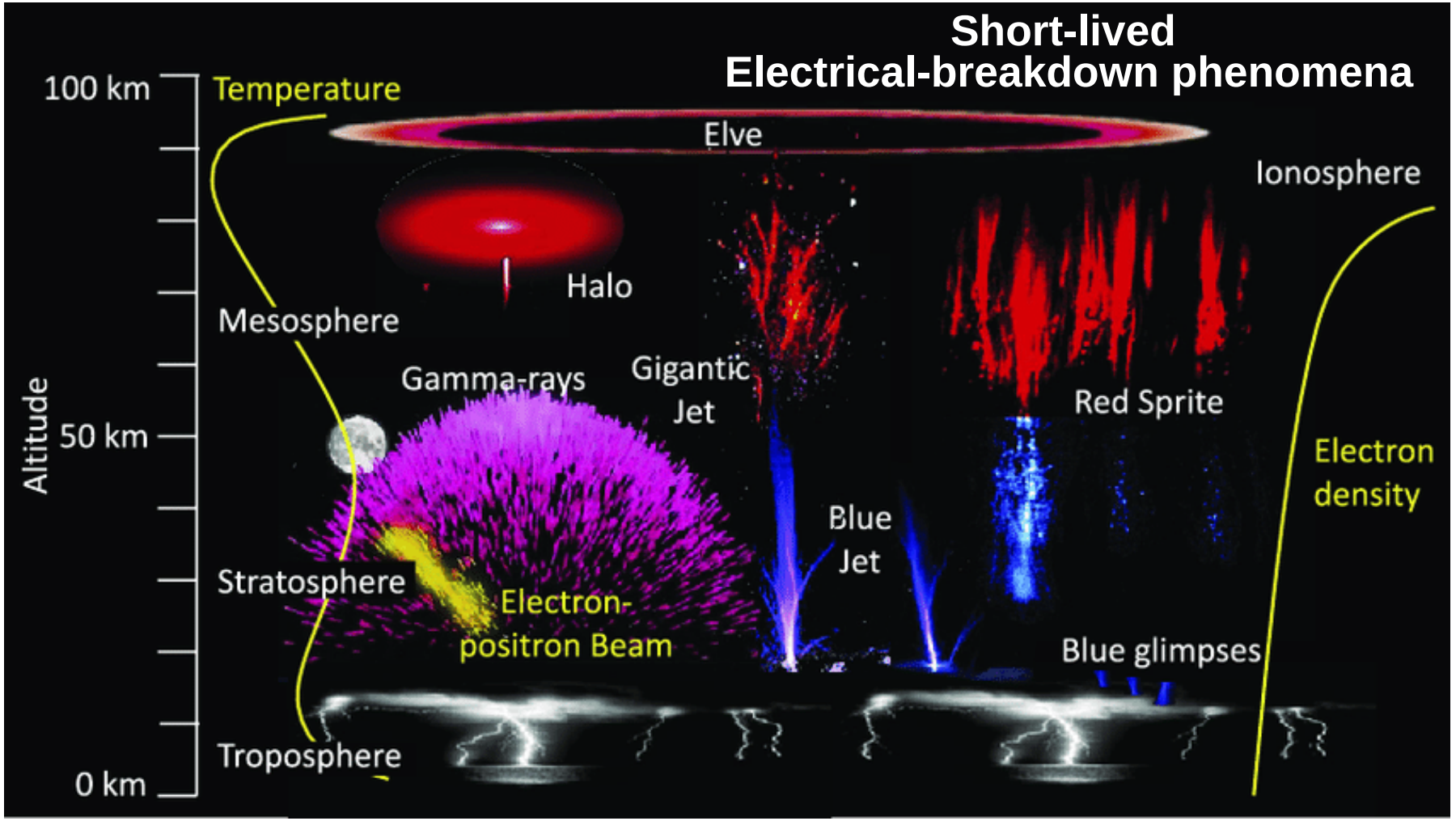


HYBRID TECHNIQUE

SD detector: 1600 Water Cherenkov detectors, covering 3000 km^2 and arranged in a triangular grid with 1500 m spacing.

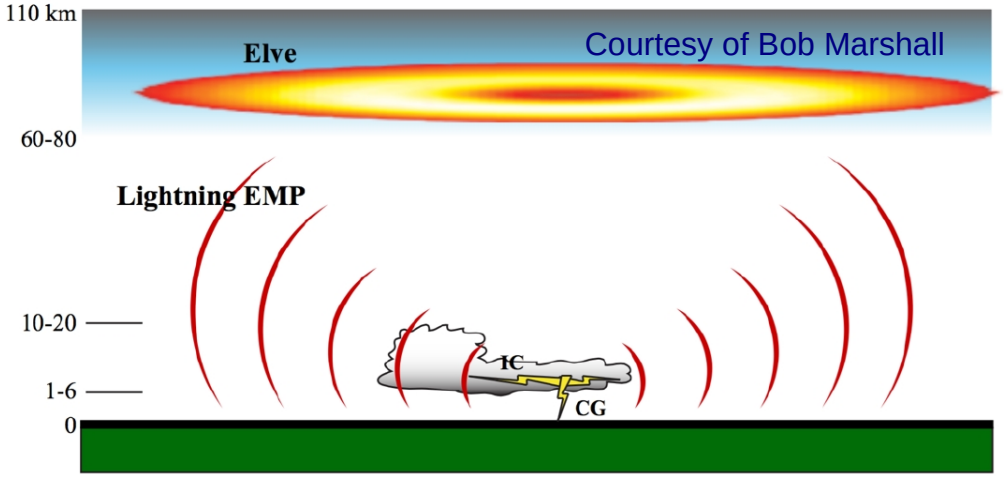
FD detector: 24 telescopes, 6 for each site, which are on the perimeter of the surface array.

Upper atmospheric phenomena powered by thunderstorms



ELVES

Emissions of Light from Very low frequency Electromagnetic pulse Sources



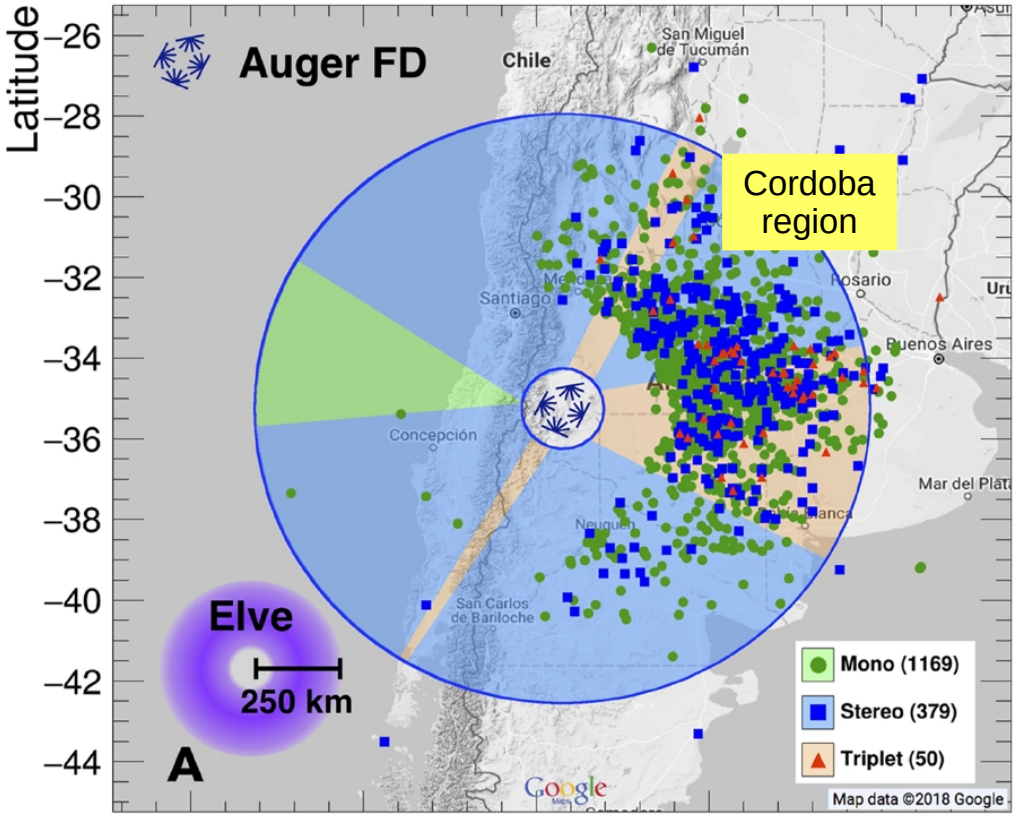
Optical signature of the lightning electromagnetic pulse (VLF EMP – 5-10 kHz) interaction with the lower ionosphere:

- EMP accelerates electrons at the base of the ionosphere (80-90km);
- Electrons collide and excite nitrogen molecules;
- Fluorescence light from de-excitation of nitrogen molecules.

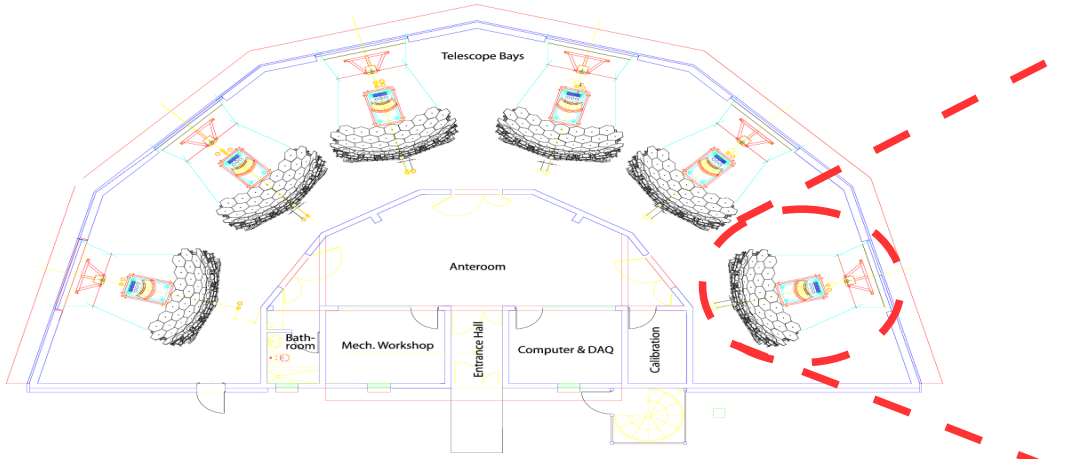
The Pierre Auger Observatory Acceptance for Elves

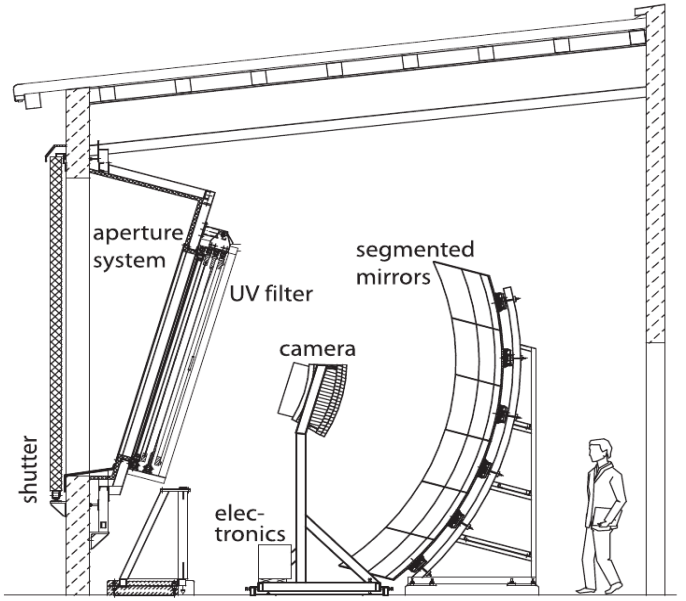
More than 95% of the observed elves are 250-1000 km away, where the FoV of a telescope crosses the ionosphere and direct light from lightning is blocked by the limb of the Earth
→ **the observatory acceptance for elves extends over 3 · 10^6 km^2**, the largest ground-based area ever used for detecting Elves.

This footprint covers portions of the Pacific Ocean, the Atlantic Ocean, Chile, the Andes mountain range, and Northern Argentina.
The latter includes the Córdoba region, known for some of the most energetic and destructive convective thunderstorm systems in the world and the highest lightning flash rate in some of the tallest thunderstorms.



The Fluorescence Detector



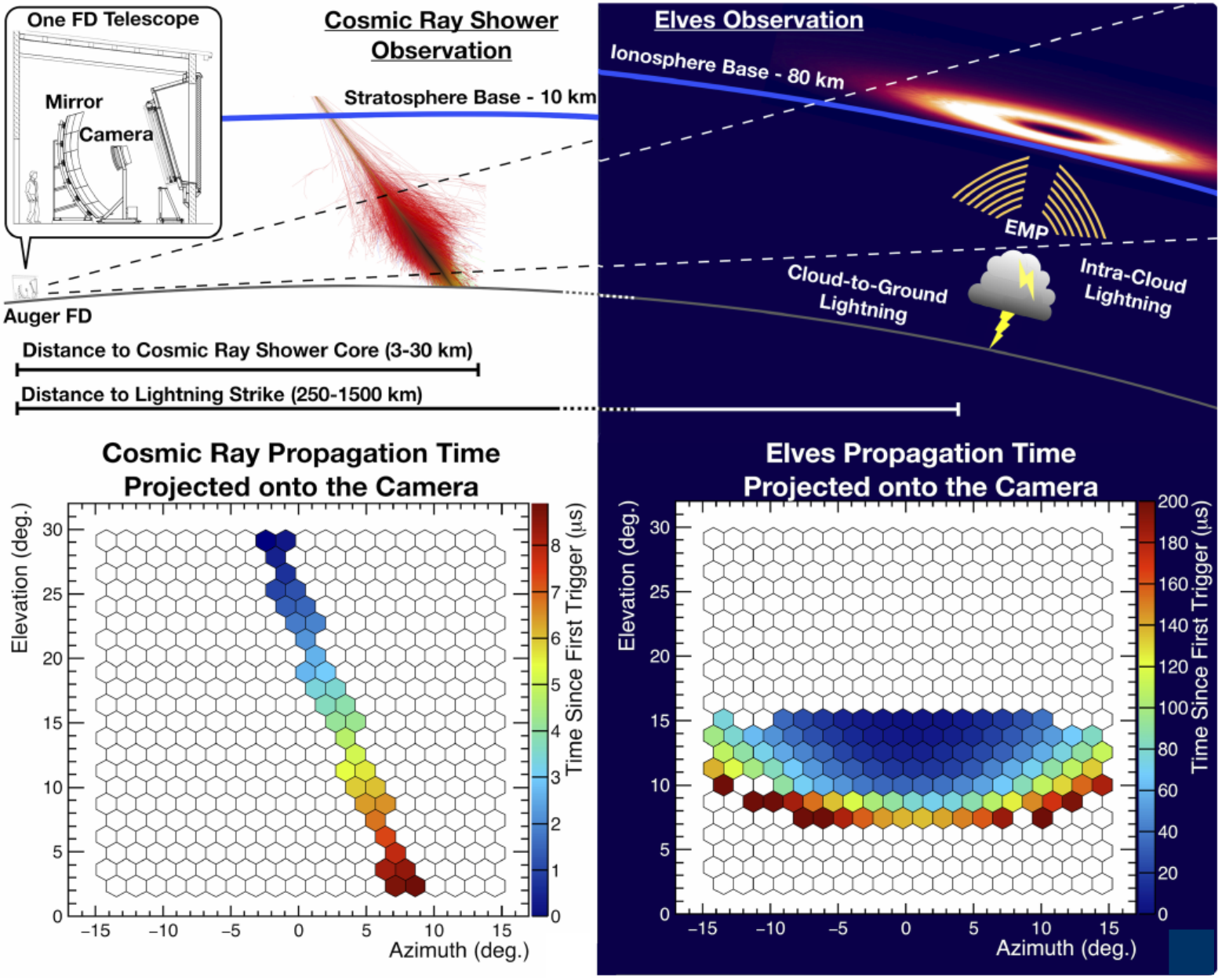


- FOV: 6x30°x30° (number of telescopes-azimuth-elevation) for each site;
- UV transmitting filter window: 300-420 nm;
- Mirror Area: 11 m^2;
- FD camera: 22x20 PMTs;
- Trace for each PMT: 1000 bins long, 100 ns per bin, **10 Mfps camera**;
- Duty cycle: 12%

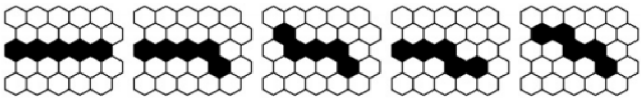
The Pierre Auger Observatory:
- the best time resolution available;
- the only detector on Earth to measure elves with year-round operation and full horizon coverage.

The **first serendipitous observation of three elves** occurred between 2005 and 2007. **Now**, the Observatory has a **dedicated trigger for elves**.

The Fluorescence detector and Elves Observation



The Fluorescence Detector Trigger

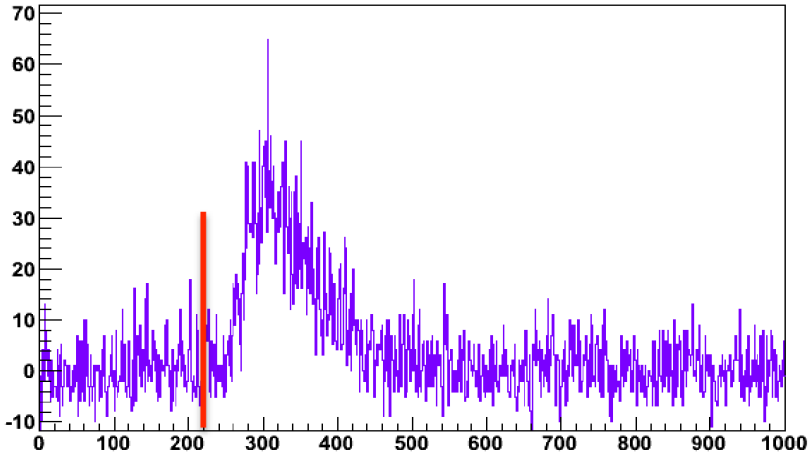
	type	purpose	event rate
First Level Trigger (FLT)	**HW**	Pixel threshold trigger	100 Hz / pixel
T1			
Second Level Trigger (SLT)	**HW**	Track shape identification	0.1-10 Hz / tel
T2			
Third Level Trigger (TLT)	**SW**	**Lightning rejection**	0.02 Hz / site
T3			

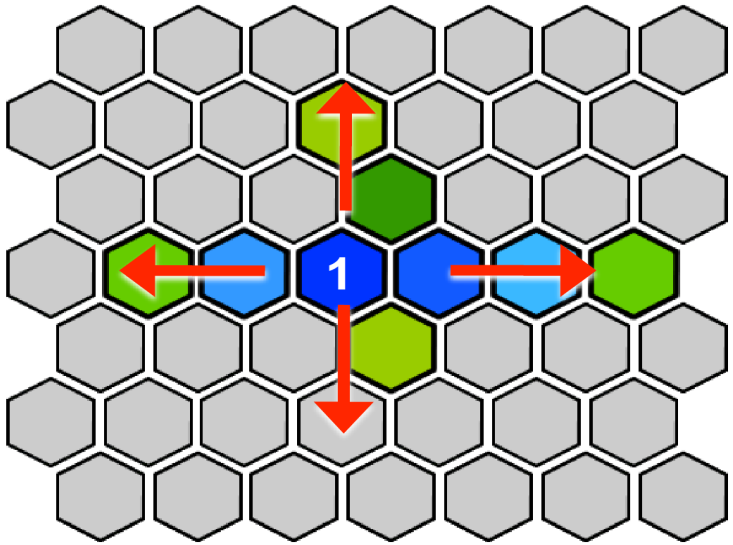
based on pixel multiplicity

prevents Elves detection

Dedicated Trigger for Elves

1) Find the First Pixel and define the Pulse Start Time





2) Check PIXELS on the same COLUMN

- at least **2 pixels before AND 2 after** the central one
- **80%** of the pixels must show an **increasing pulse time**

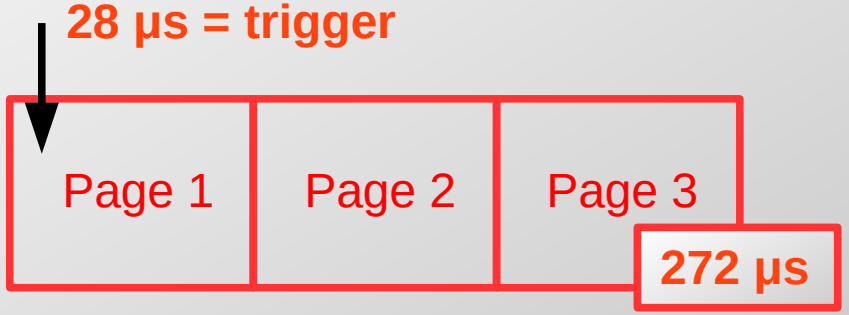
3) Check PIXELS on the same ROW

- at least **3 pixels before OR 3 after** the central one
- **80%** of the pixels must show an **increasing pulse time**

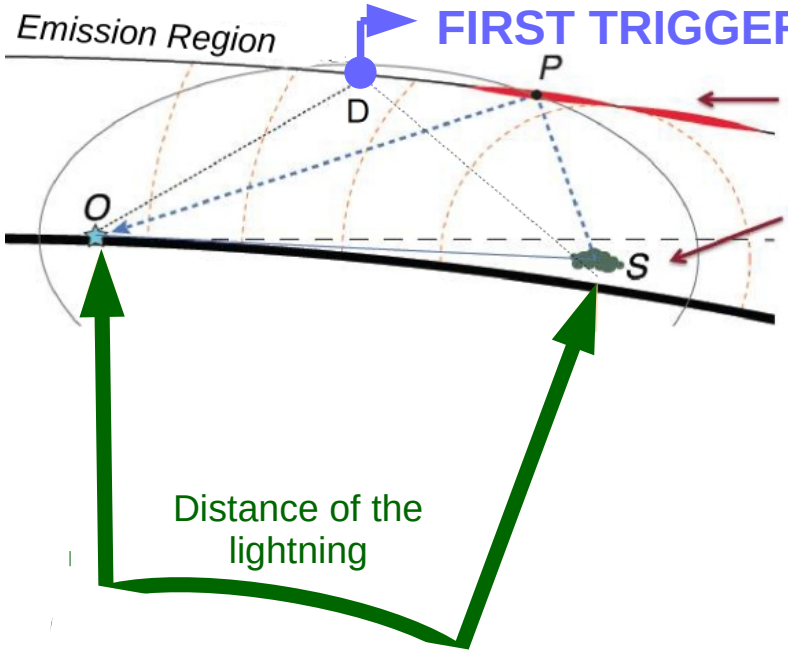
4) Check signal amplitude for each pixel

- at least **ONE pixel** with **> 50 ADC** counts

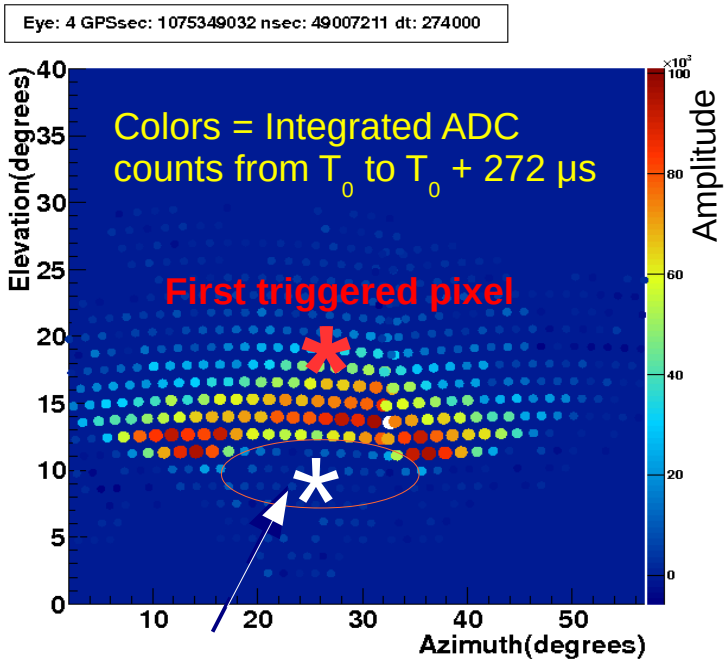
Installed in 2014 with an extended readout:
standard FD traces are 72 μs long after the trigger: this prevents to see most of the light of the Elves.
In particular, it prevents to see light from the vertical above the lightning source.



Elves in the FD camera



D is the point at the base of the ionosphere which is halfway between the FD and the lightning source ($\overline{OD} = \overline{DS}$).



This pixel is looking at light emission from the vertical above the lightning

The lack of emission due to the dipole radiation pattern above the lightning strike is noticeable with the 300 µs acquisition time, but a super-extended readout (900 µs) is necessary to observe the full region of maximum emission and give extra information on the phenomenon (since 2017).

28 µs = trigger

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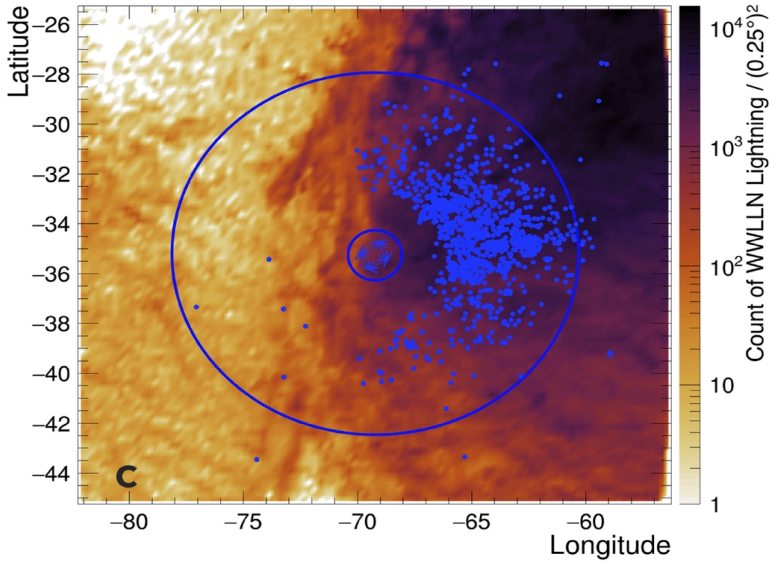
900 µs

Three-years of Elves detection (2014-2016, DOI:10.1029/2019EA000582)

Density map of WWLLN (World Wide Lightning Location Network) events with an overlay of elve-inducing lightning in coincidence (blue dots).

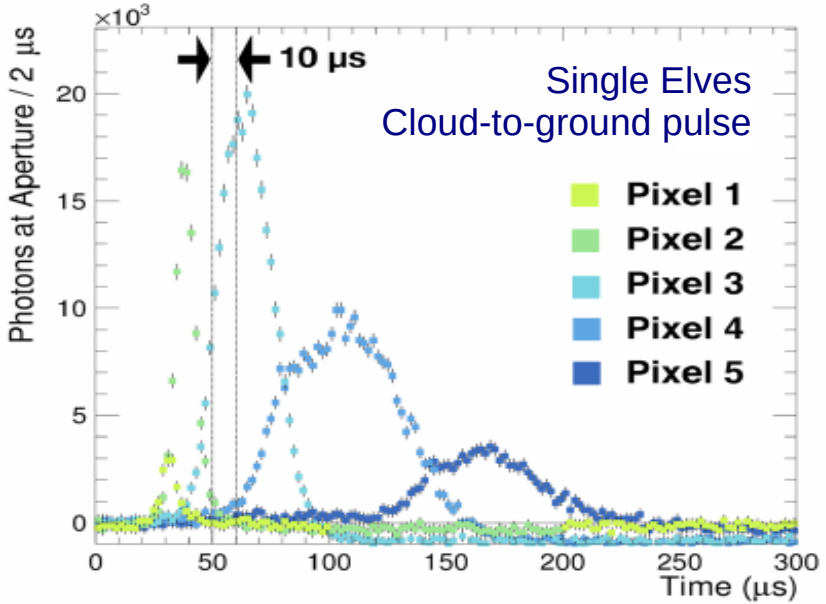


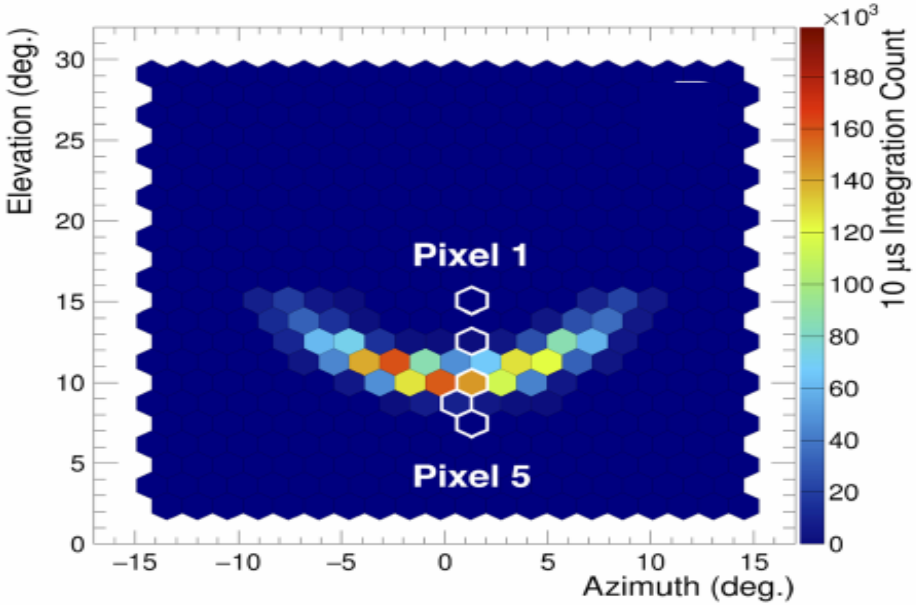
- All of the observed elves appeared east of the Andes, and just very few lightning were observed and reconstructed over the Pacific Ocean as expected.
- The observed elves locations exhibited **seasonal and geographical patterns**: 44% of the elves observed occurred during the southern-summer months, and just 2.5% occurred during winter months.

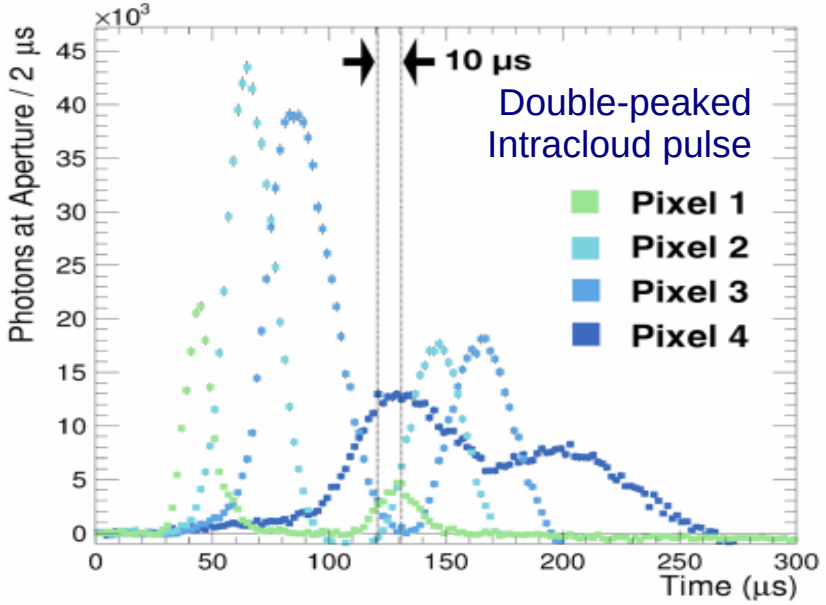
- 72% of the observed elves correlate with independent radio-frequency measurements of lightning by WWLLN (http://wwlln.net).
  → the Auger Observatory is naturally selecting intense electrical events in the severe Argentinian thunderstorms that occur during the austral summer.

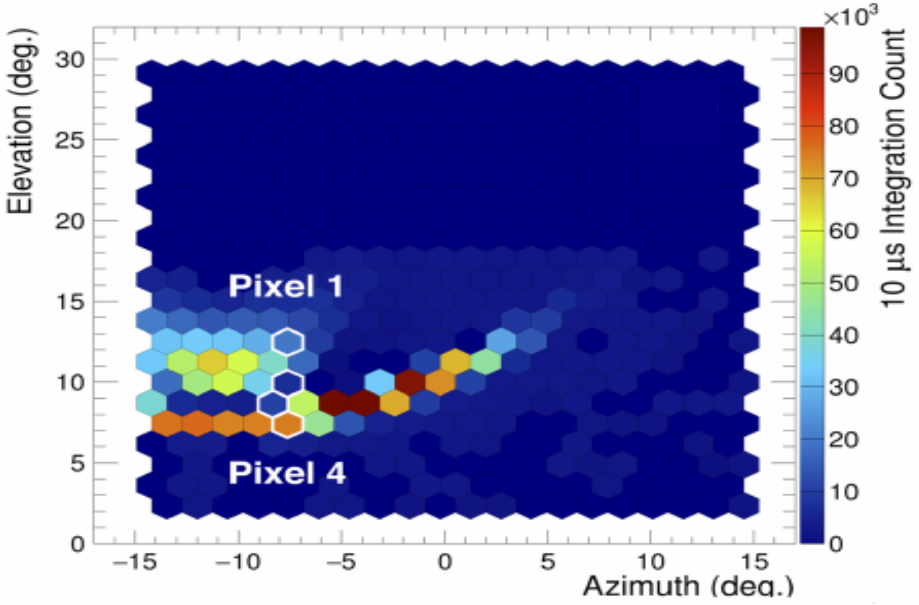
- The Auger FD time resolution enables us to see very fine the temporal structure in the light emission of elves and data can be sorted in two categories observing the photo trace:
  1310 single-peaked elves;
  288 multipeaked elves.

Single and double-peaked Elves

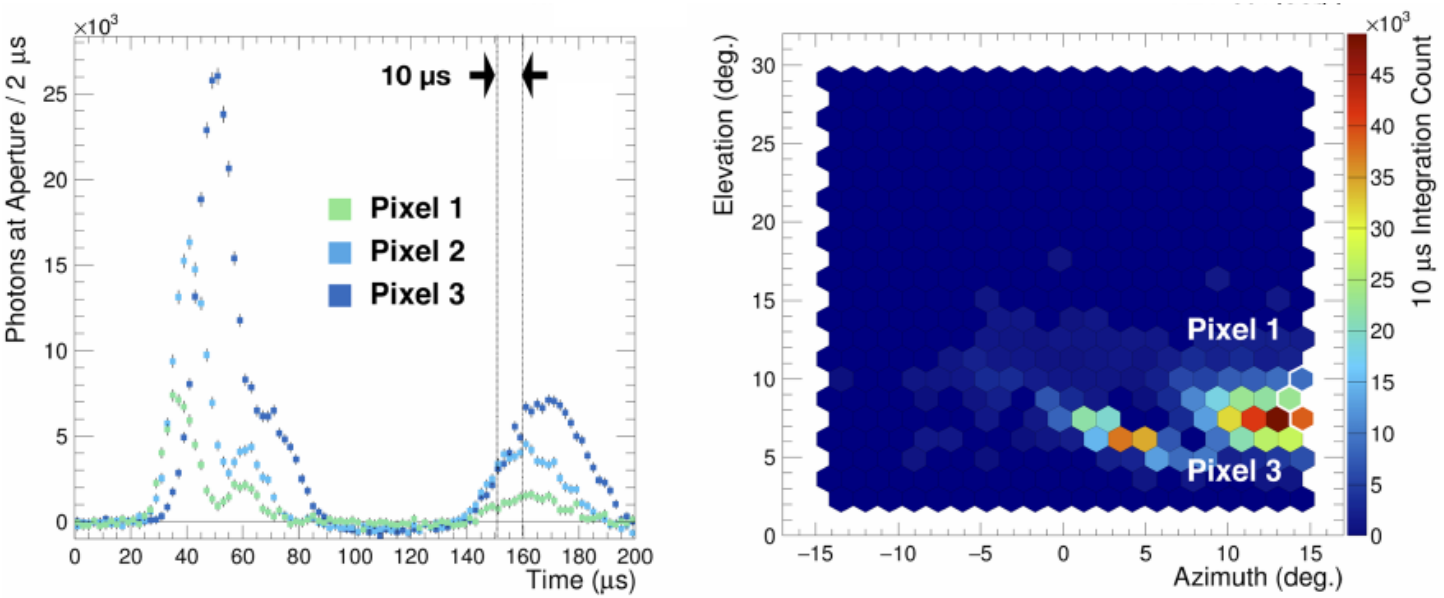








Multipeaked Elves



First observation of a triple elves

Intracloud activity could be associated with the creation of TGFs (Terrestrial Ground Flashes).
The Atmosphere-Space Interactions Monitor (ASIM - DOI:10.1126/science.aax3872) reported the first coincident observation of a TGF and an elves.
Could the triple elves be related to TGFs?

Elves Conclusions and Perspectives

The Auger Observatory acceptance for elves extends over $3 \cdot 10^6$ km^2, and it is the first and only ground-based facility that measures elves with year-round operation with full horizon coverage and 100-ns resolution.

Thanks to the dedicated trigger, we have been observing 500 to 800 events per year.

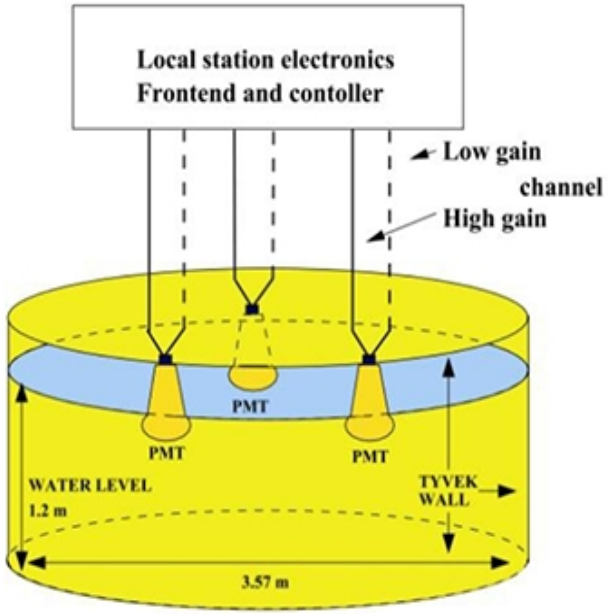
The Pierre Auger Observatory is scheduled to operate until at least 2030

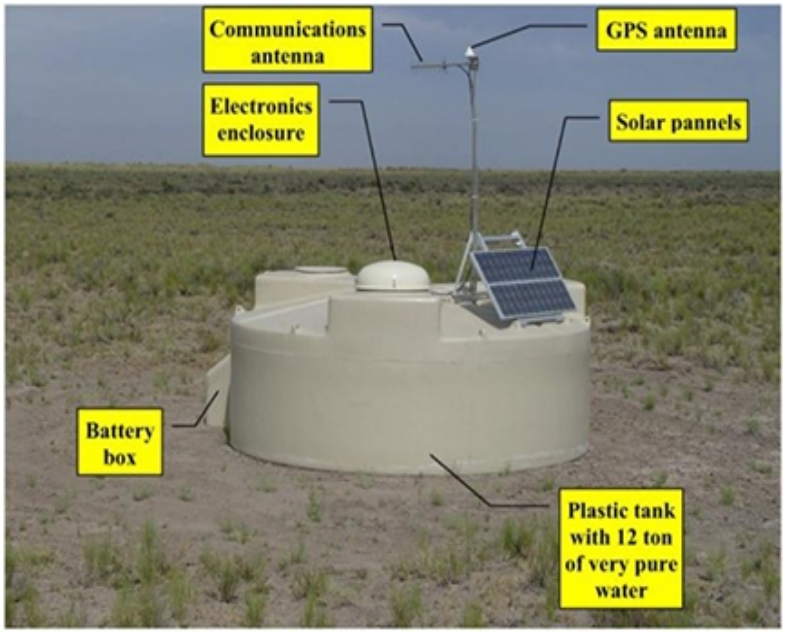
→ in 2017, a deeper readout window of 900 μs for elves was implemented to increase the quality of our current reconstruction;

→ refinements of the on-line TLE-trigger algorithm are in progress;

→ possible correlation studies between Auger data and various ongoing experiments would contribute significantly to atmospheric electricity research.

The Surface Detector

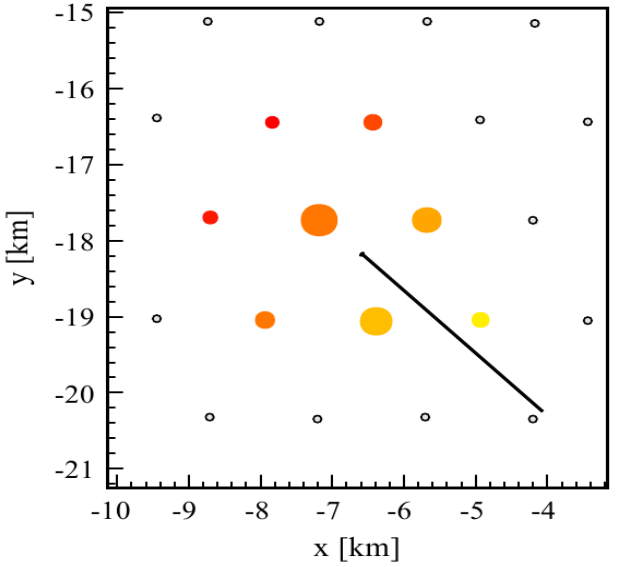


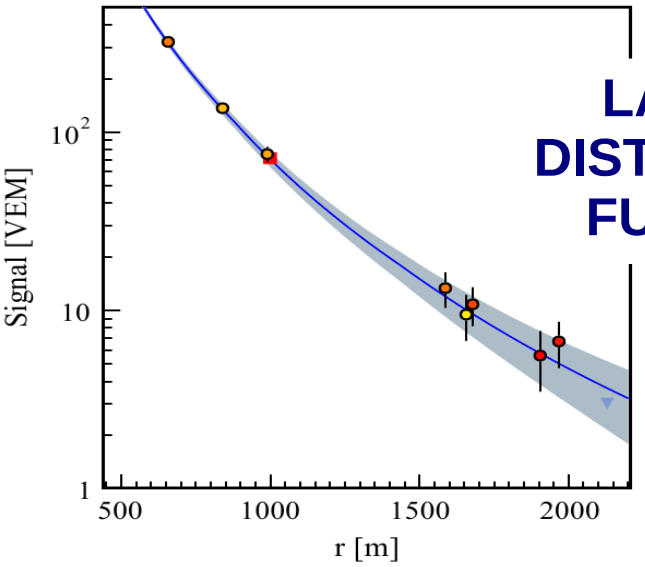


- Each WCD consists of a 3.6 m polyethylene tank containing a liner with a reflective inner surface and filled with 12,000 liters of ultra-pure water.
- Cherenkov light produced by the passage of relativistic charged particles through the water is collected by three PMTs.
- Each PMT has two readout channels, one directly from the anode (**LG channel**) and the other one from the last dynode (**HG channe**l) with an amplification factor of 32
  → the LG channel is used when the HG is saturated.
- The two output signal are processed by six FADCs with a sampling rate of 40 MHz, 25 ns per time bin. The DAQ window lasts 19.2 μs.

Cosmic Ray Signal in the SD

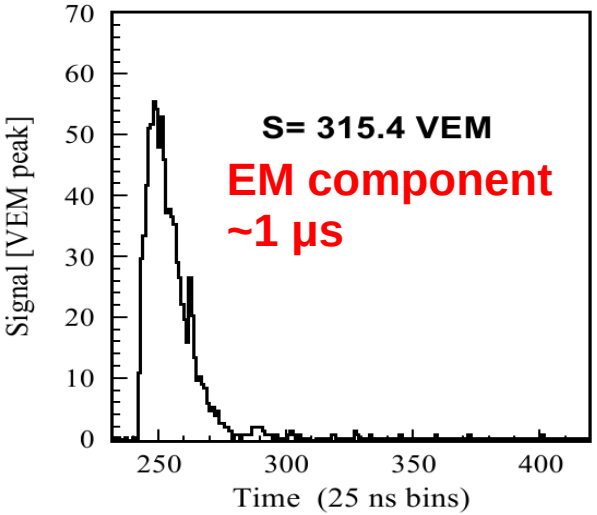
Shower with E=3x10^{19}eV, θ=28°

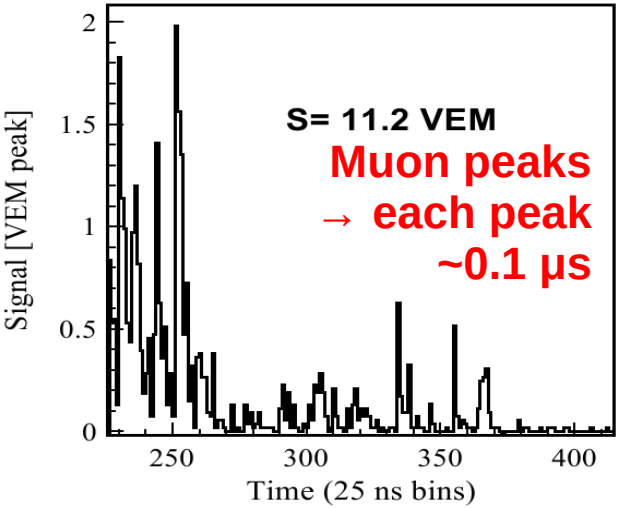




LATERAL DISTRIBUTION FUNCTION

Station at 650 m from the shower core

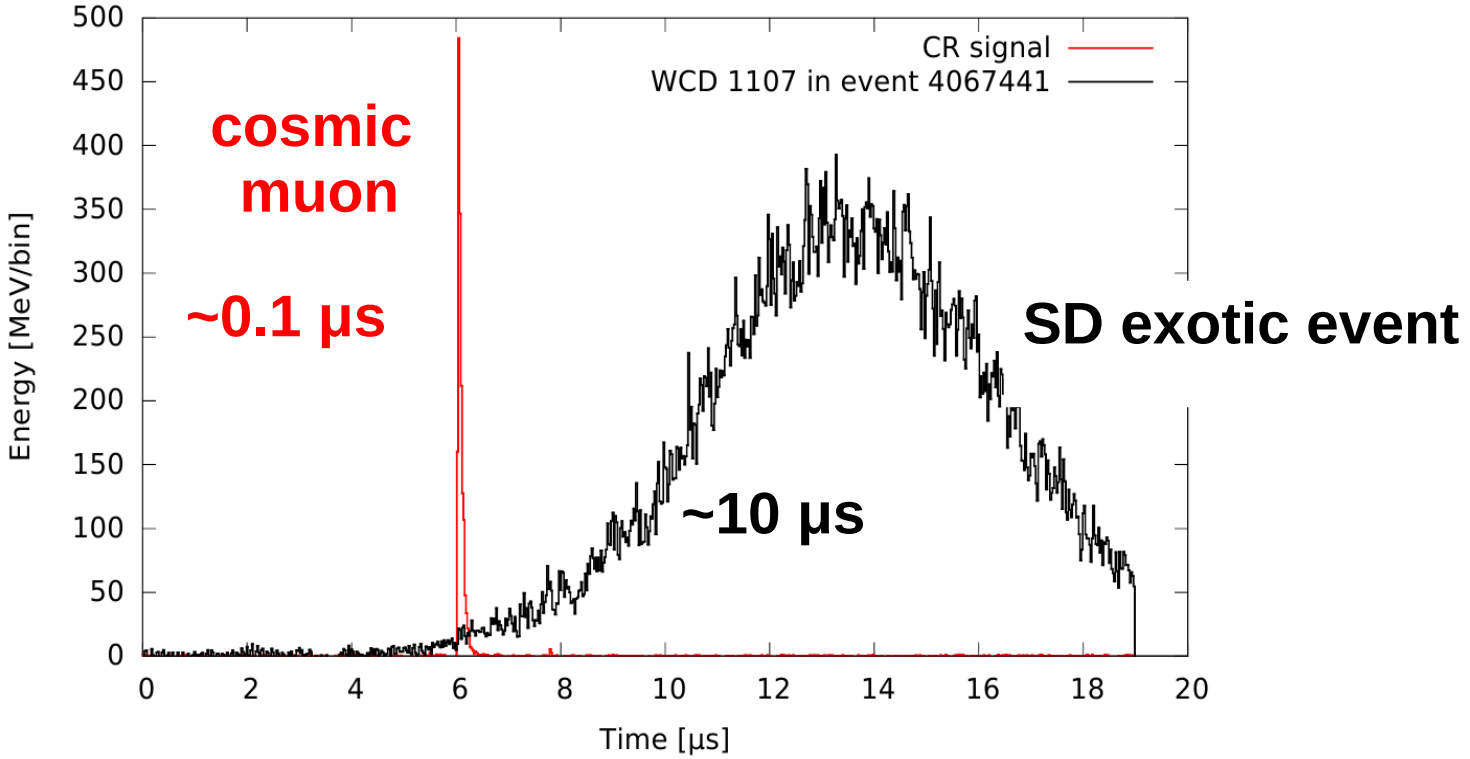




Station at 1780 m from the shower core

SD Exotic Events

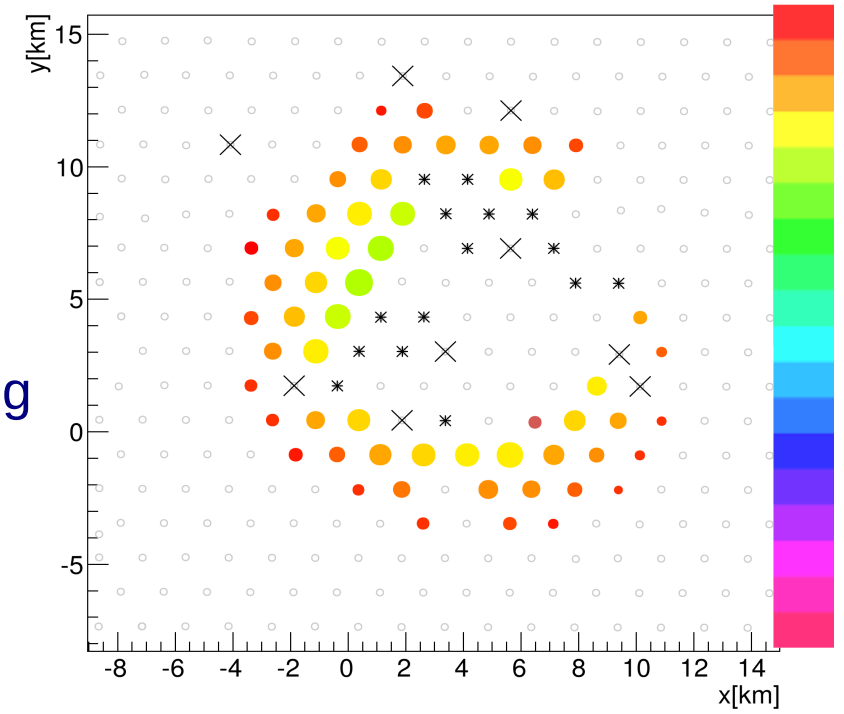
- Larger time scale (~10 μs);
- Many triggered detectors arranged in circular shape;
- Some stations have lightning induced signal
  → high frequency noise



SD Exotic Events

- Larger time scale (~10 μs);
- Many triggered detectors arranged in circular shape;
- Some stations have lightning induced signal
  → high frequency noise

The circle marker size is related to the signal of the long stations



SD Exotic Events

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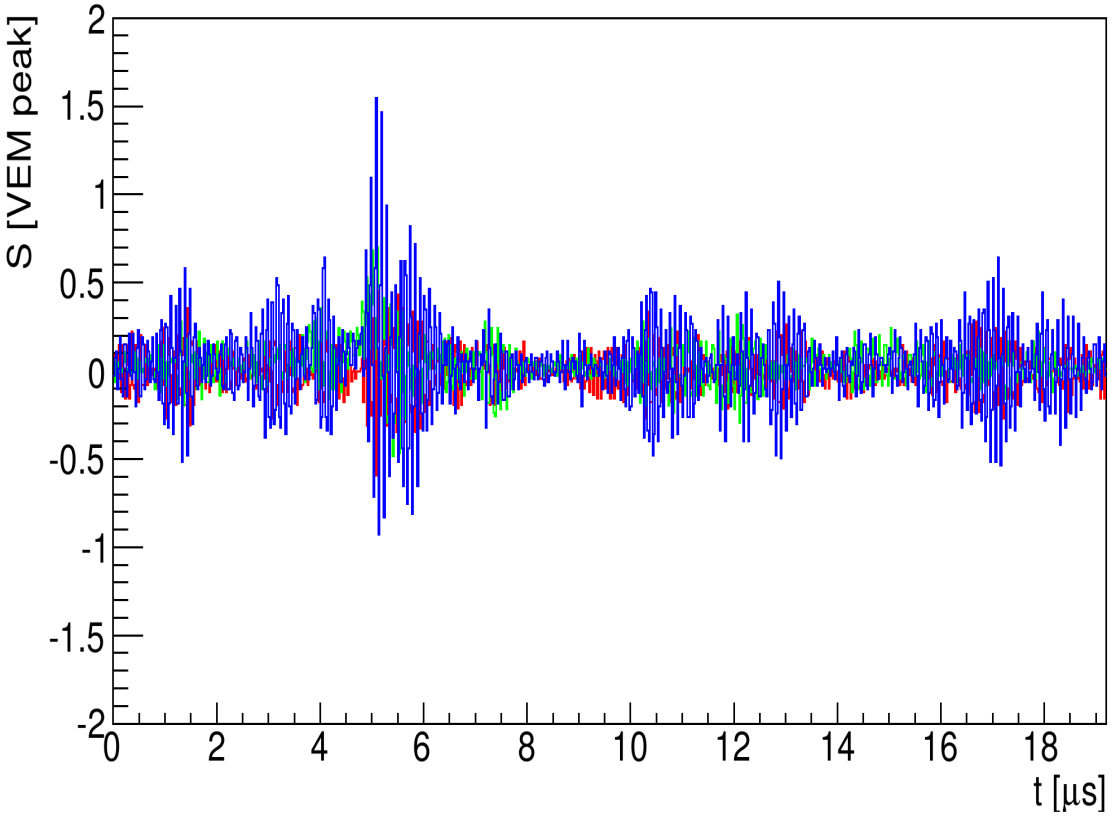
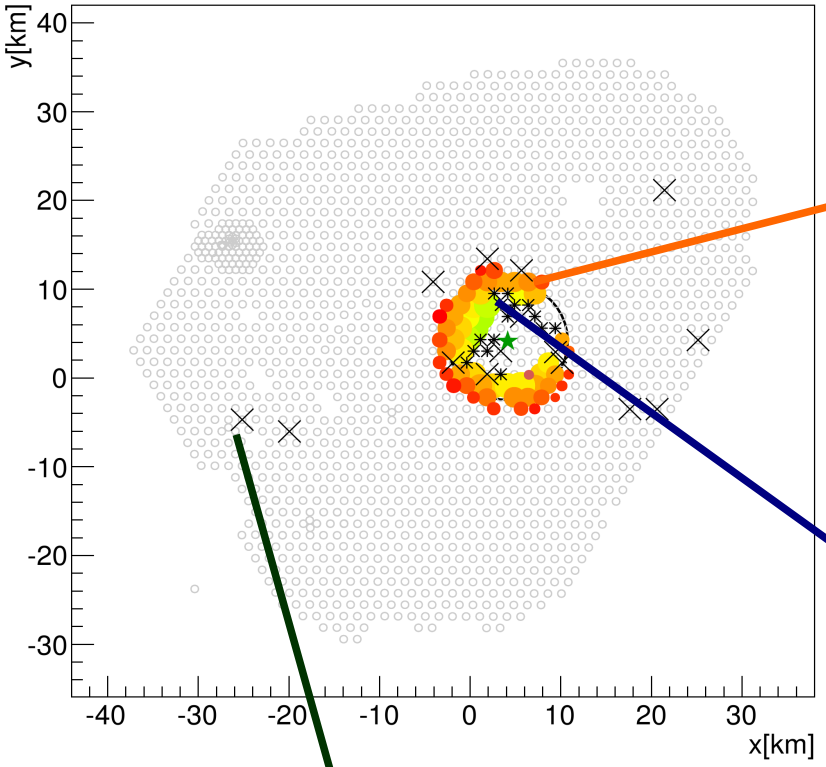
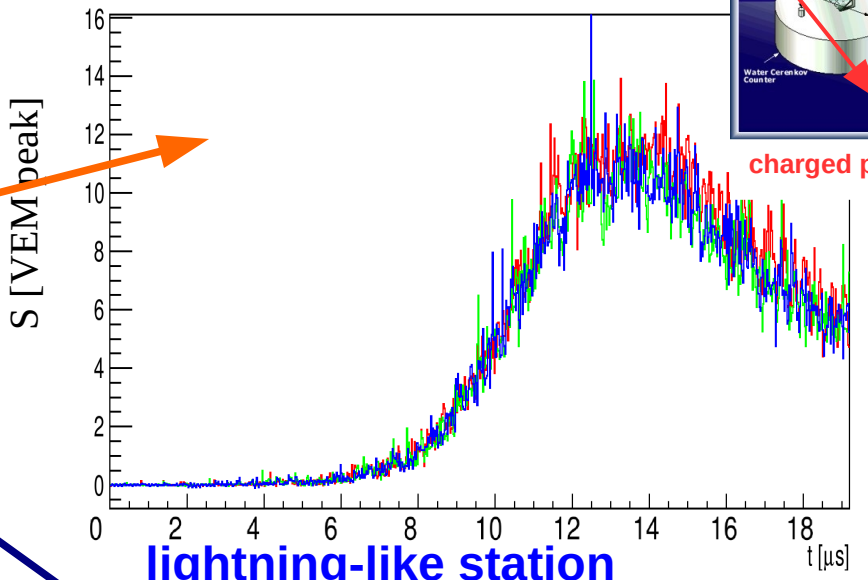
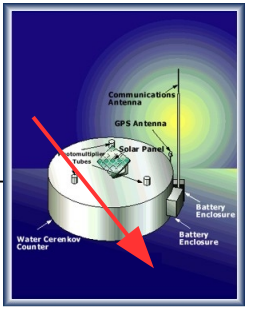


SD Exotic Events



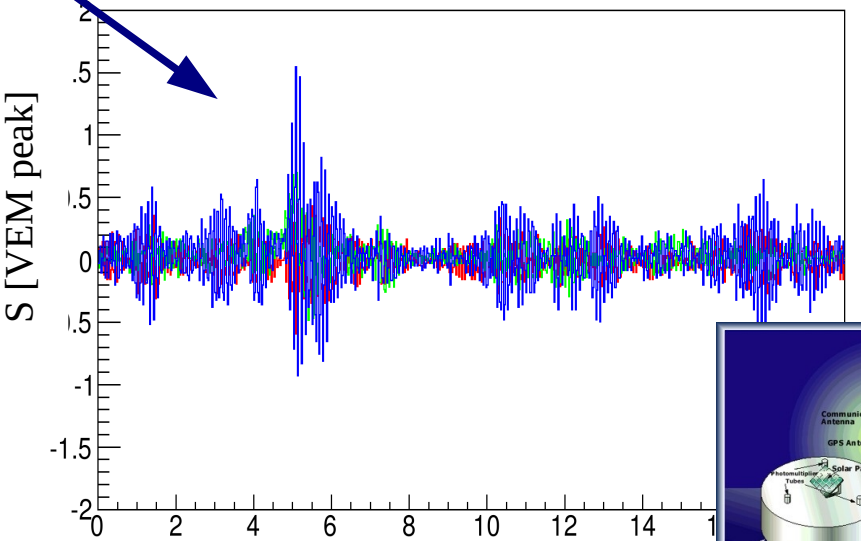
long signal station

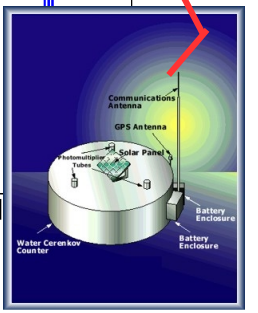




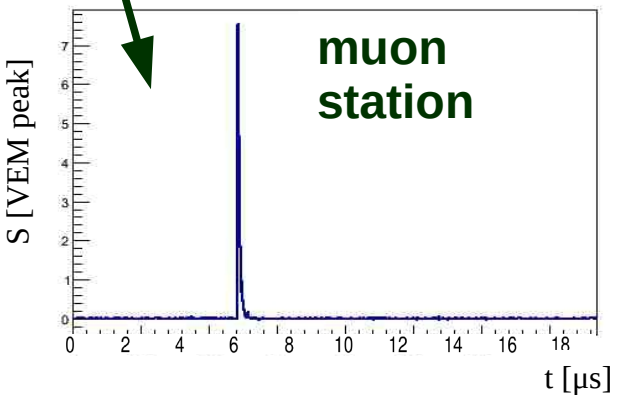
charged particle

lightning-like station





lightning

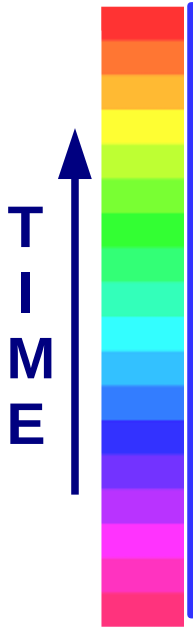


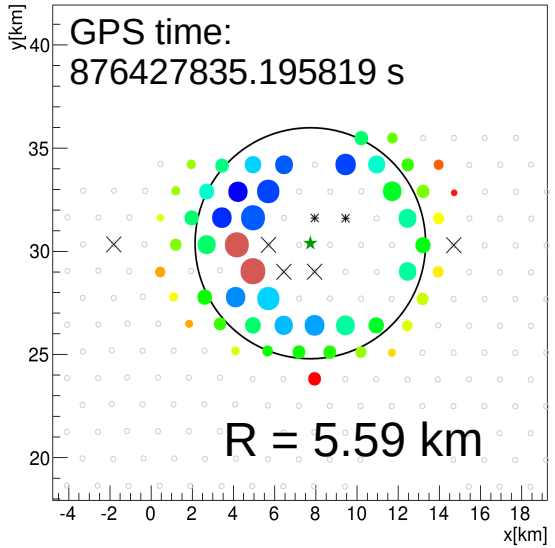
muon station

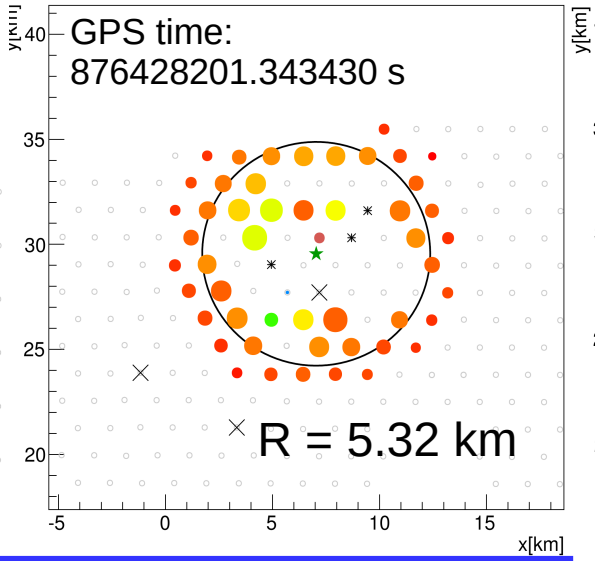
In some of these events, there are stations with a signal produced by a cosmic muon, but they are in coincidence by chance with our event

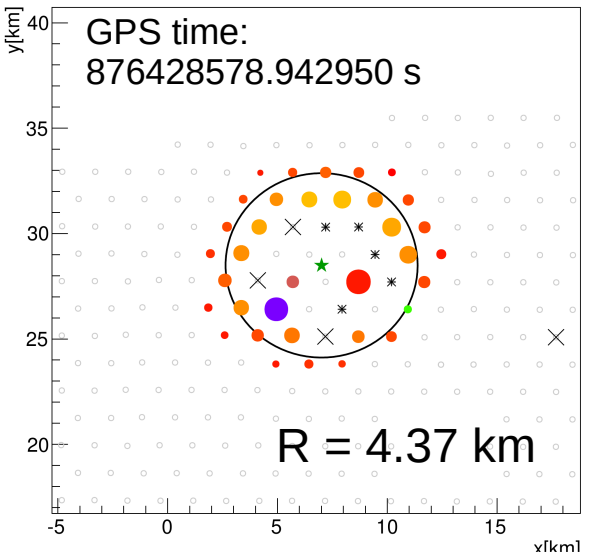
Events zoology

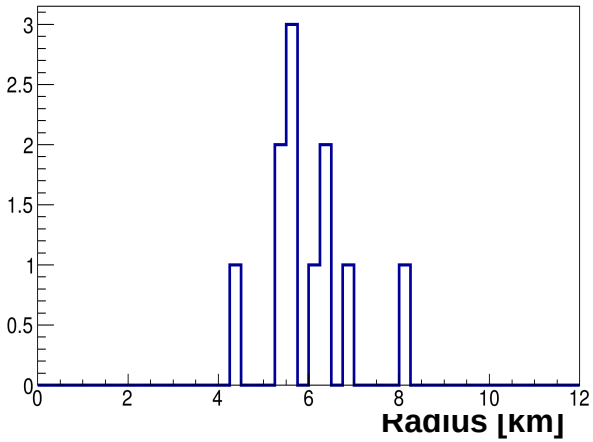
Large Events



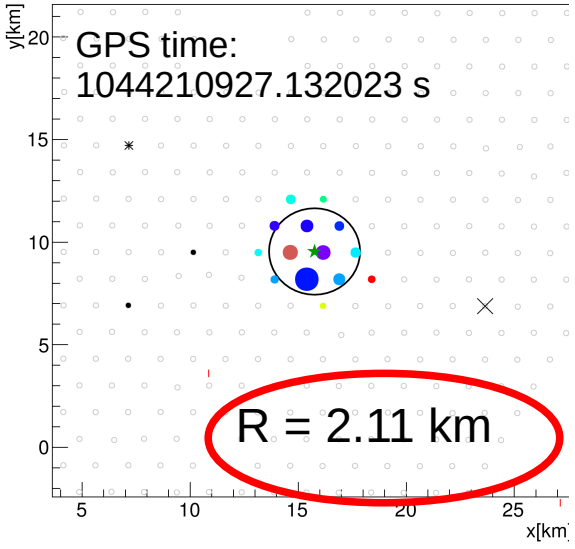


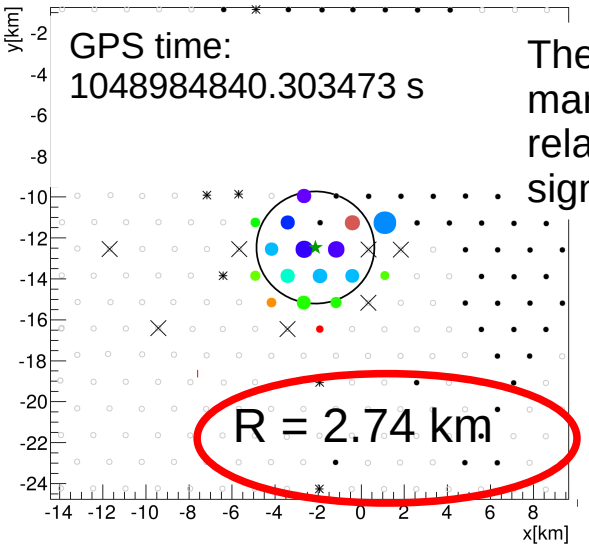






Small Events



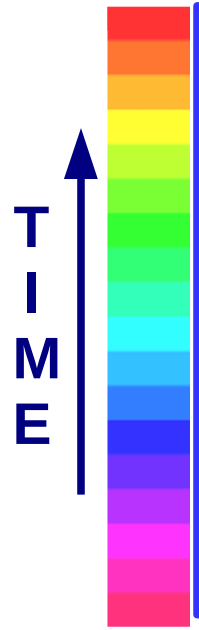


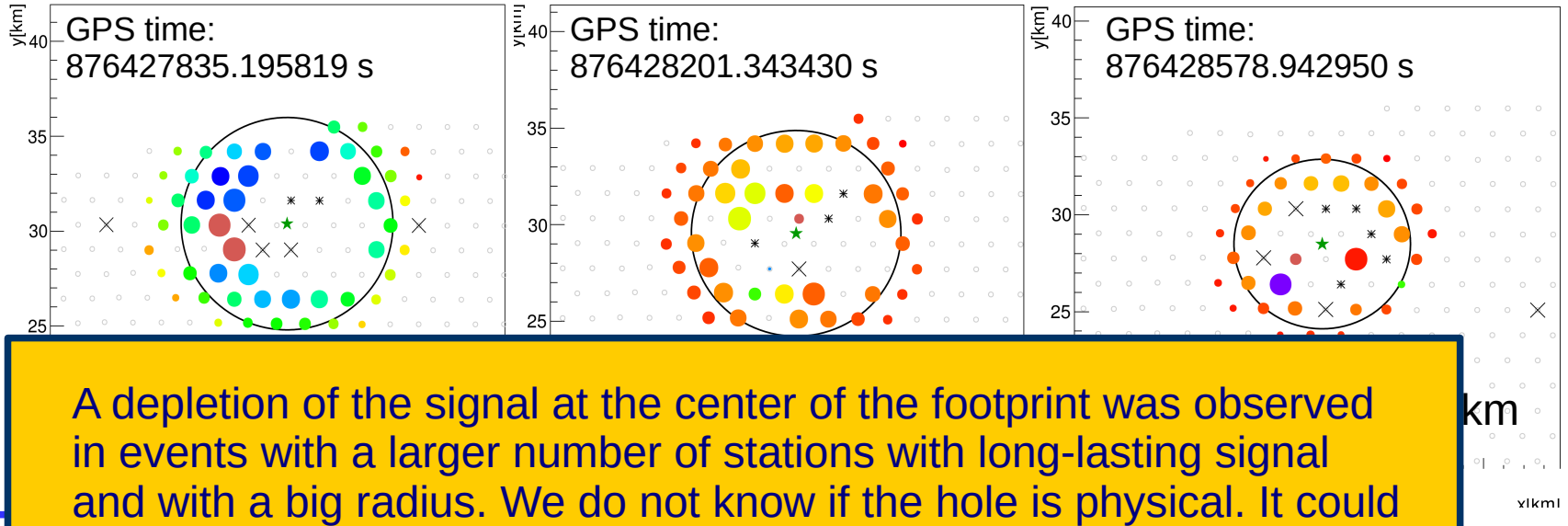
The circle marker size is related to the signal

- Long station
- * Lightning station
- X Muon station

Events zoology

Large Events

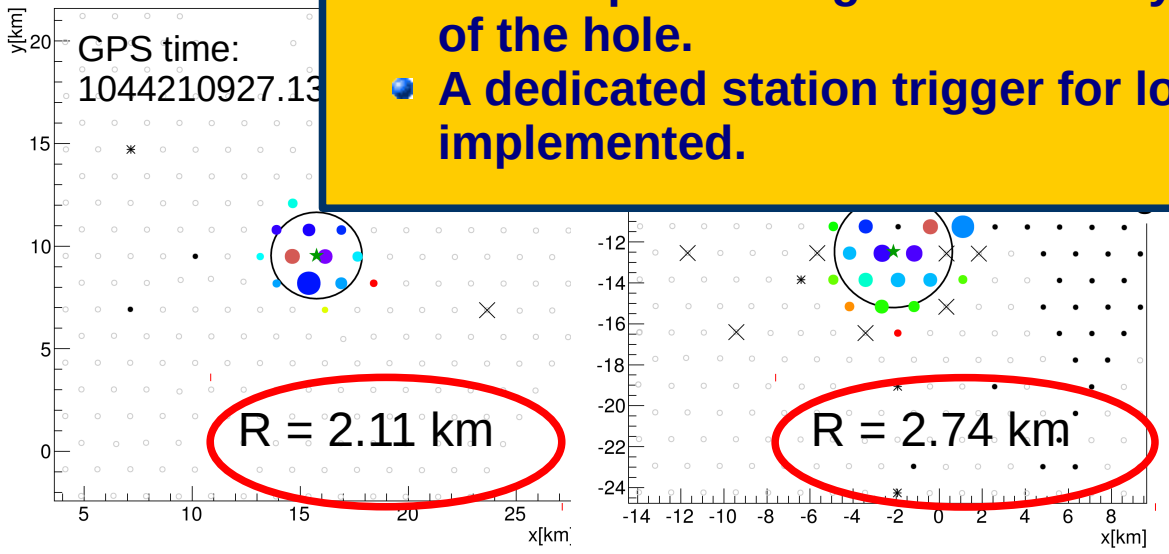


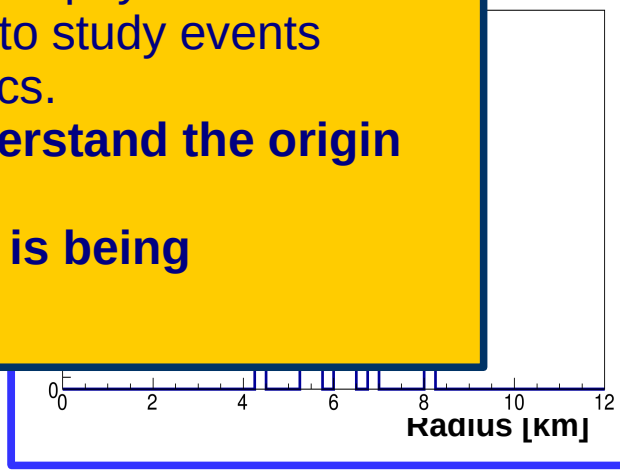


A depletion of the signal at the center of the footprint was observed in events with a larger number of stations with long-lasting signal and with a big radius. We do not know if the hole is physical. It could be caused by the Auger trigger that is optimized to study events from cosmic rays with very different characteristics.

- **We are performing several analyses to understand the origin of the hole.**
- **A dedicated station trigger for long signals is being implemented.**

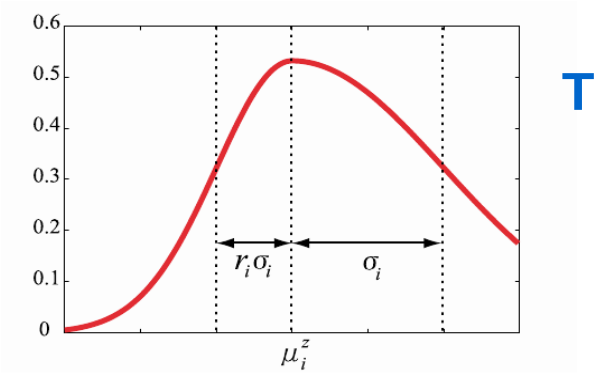
Small Eve



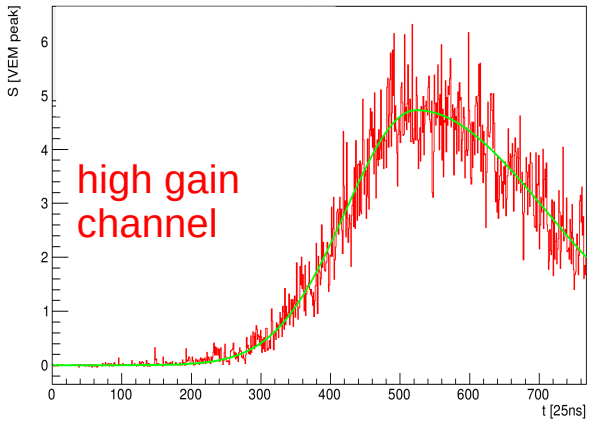


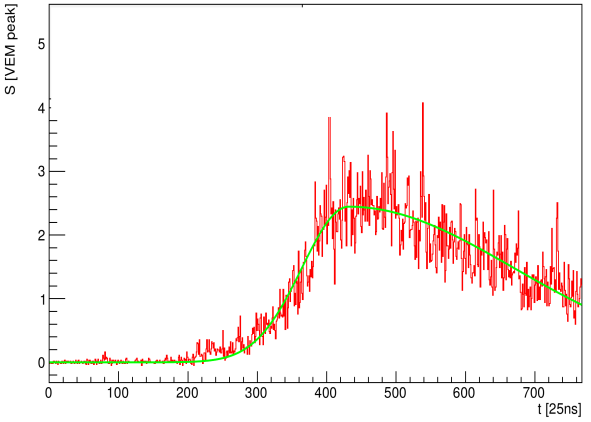
- **Long station**
- *** Lightning station**
- **X Muon station**

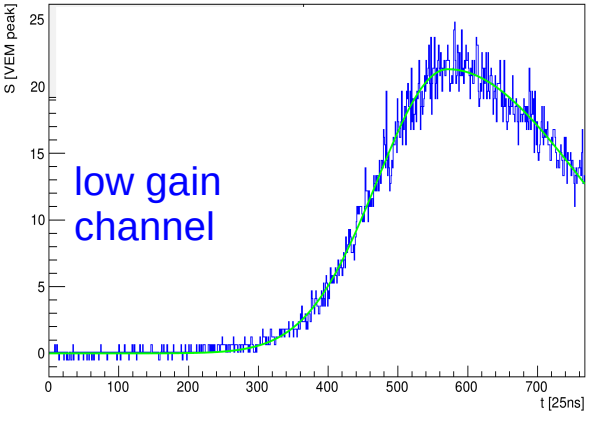
Signal Shape

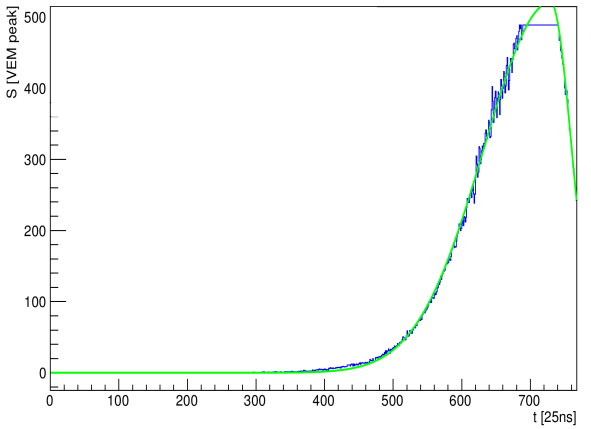


The long-lasting signals are well described by an asymmetric gaussian distribution









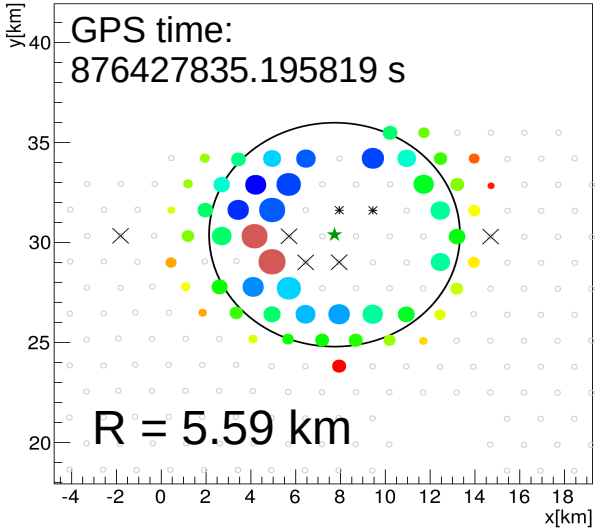
GOOD FITS:

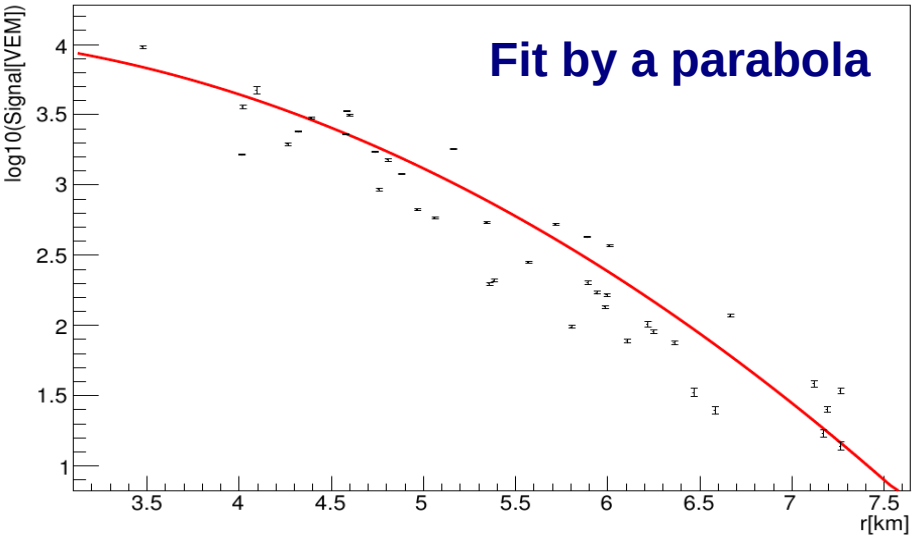
- Gaussian peak in the DAQ window;
- Difference between sum of the content of the trace bins and integral of the fitting function in our time window less than 5%;
- duration of the total fitting function less than 100 μs.
  → **an extended readout could be useful**

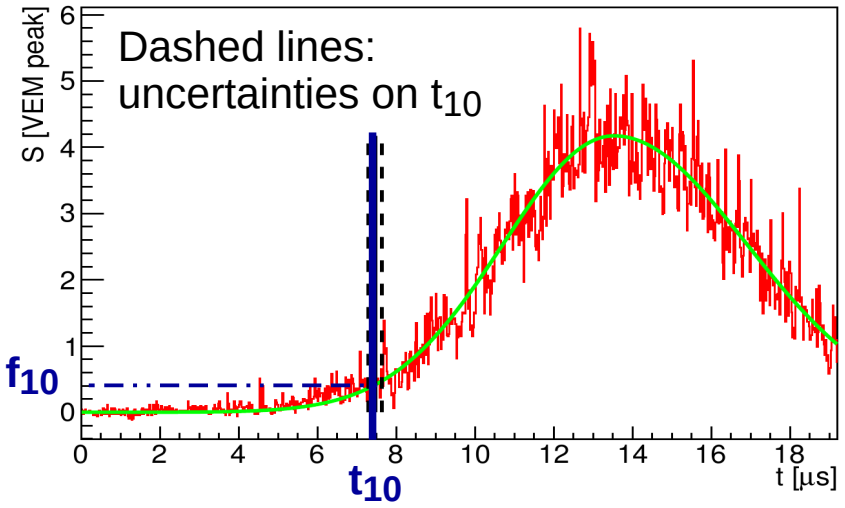
GENERAL CHARACTERISTICS:

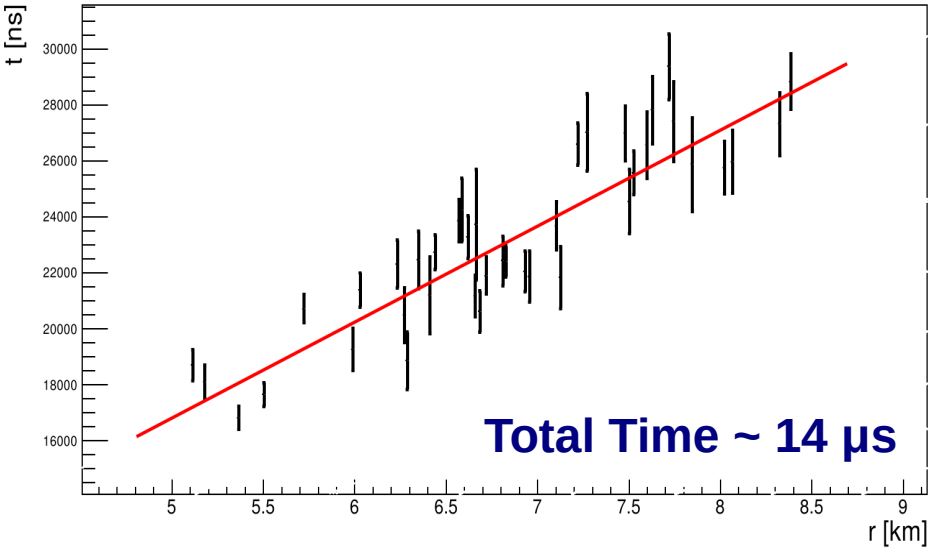
- rise time of the signal ($r_i\sigma_i$) smaller than fall time (σ_i);
- σ_i bigger than 2.5 μs.

An attempt of characterization

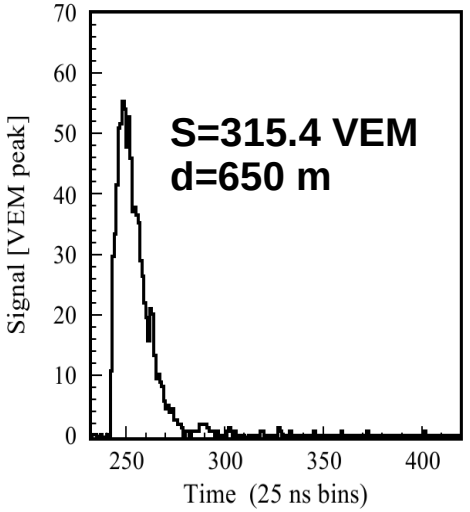




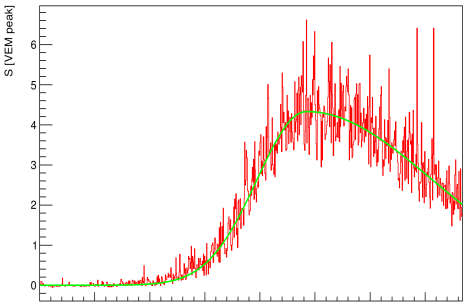




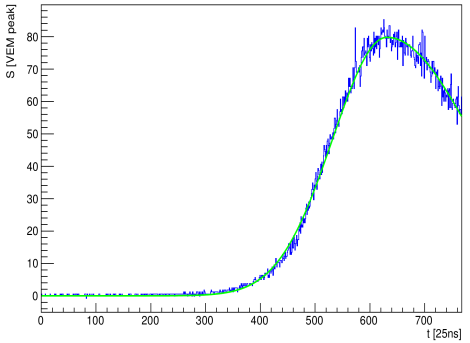
Energy deposited at ground



1 VEM (Vertical Equivalent Muon) ~ 240 MeV



S=591.4 VEM
E=1.42e+05 MeV
d=4911 m

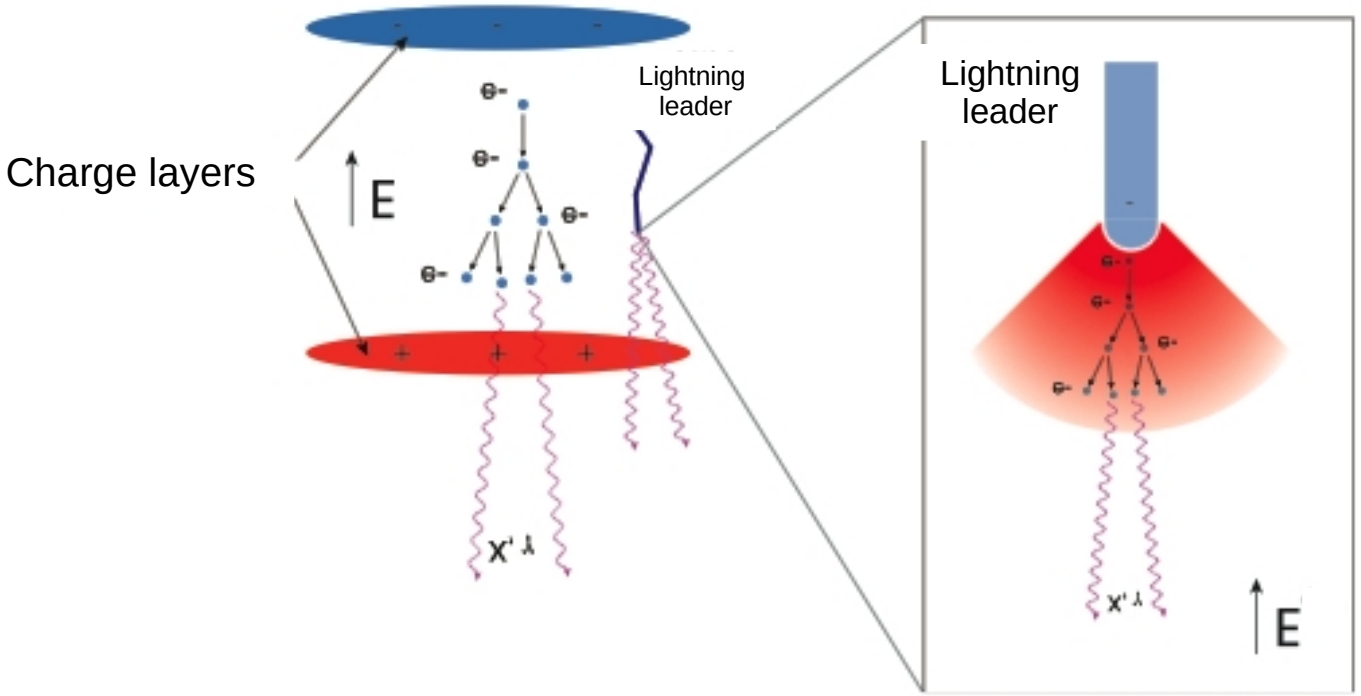


S=8038 VEM
E=1.93e+06 MeV
d=3417 m

- The **energy deposited in each long signal station** spans **from ~10^4 MeV to ~10^6 MeV**.
- The **total energy of the event** spans **between 10^{17} and 10^{18} eV.**

VERY HIGH ENERGY
The energy deposited at ground by a vertical cosmic-ray shower initiated by a proton with energy 10^{19} eV is about two orders of magnitude lower.

What is the cause of these events?



Are we observing events related to **downward TGFs** as Telescope Array (https://doi.org/10.1029/2019JD031940)?

→ there are similarities and differences;

→ Auger Observatory and TA surface detectors have different efficiency for photon detection.

Conclusions

- Very peculiar events, characterized by the presence of stations with very long-lasting signals and at least a lightning stations have been detected. Some of them have many active detectors arranged in a ring shape, with a depletion of the signal at the center
  → physical reason or hole due to Auger trigger optimized to study very different events?

- From a first characterization, we can say the events move from the center of the circle to the external part and the amplitude of the signal decreases with the increasing of the distance from the center.

- Correlation with WWLLN data.

- More statistics and a dedicated trigger and readout are necessary to better understand these events.

What we need to accomplish?

→ instrumentations to study electric fields and lightning development in coincidence with ground-array measurements;
→ comparison with simulations;
→ collaboration among different experiments and observatories.

The **GCOS idea** goes in this direction:
→ a large observatory that brings together the experiences gained with current observatories;
→ particle detectors + antennas,
which can help to study electric fields and lightning development in coincidence with particles.