# The Pierre Auger Observatory and the study of atmospheric electricity phenomena

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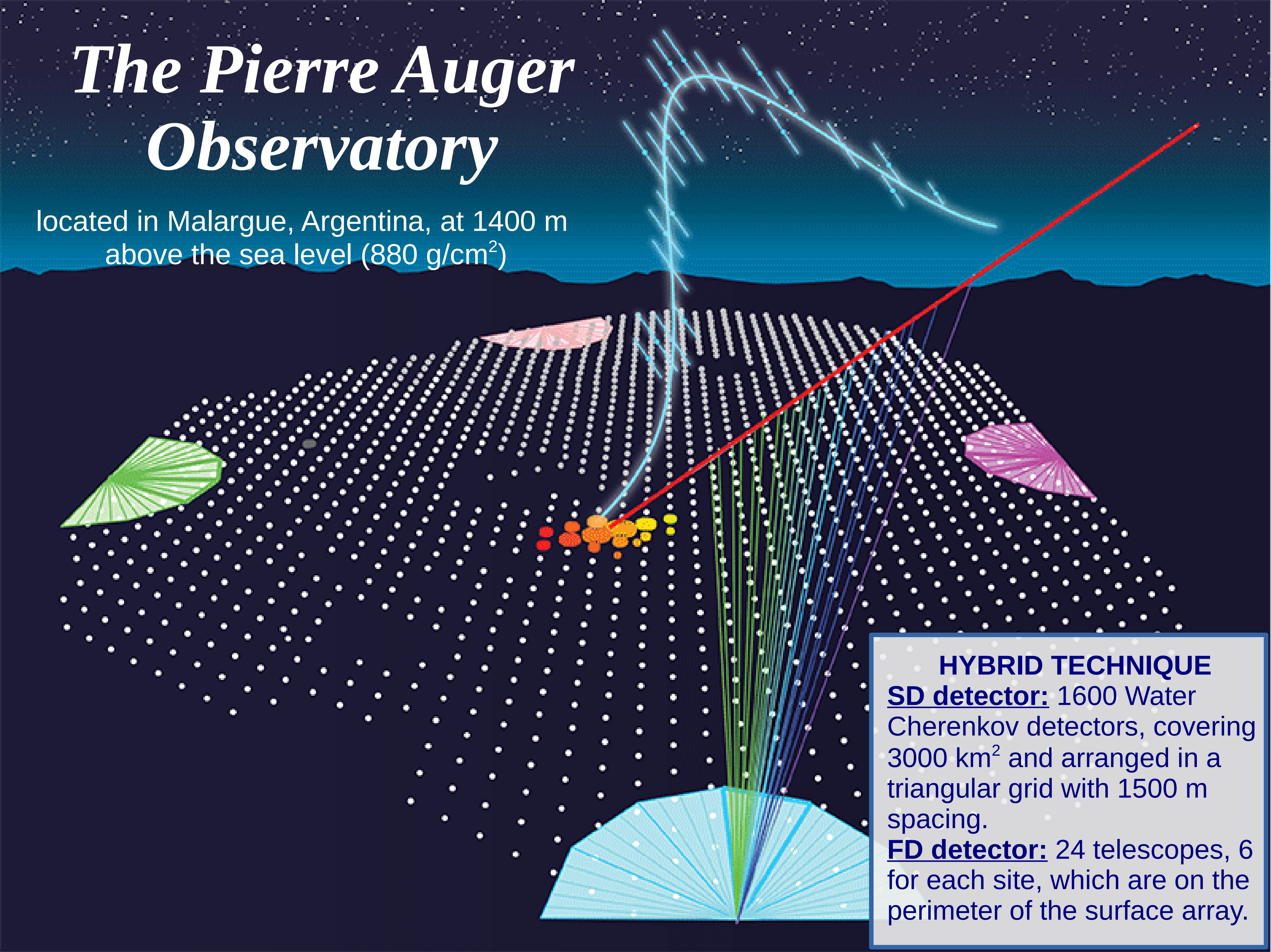
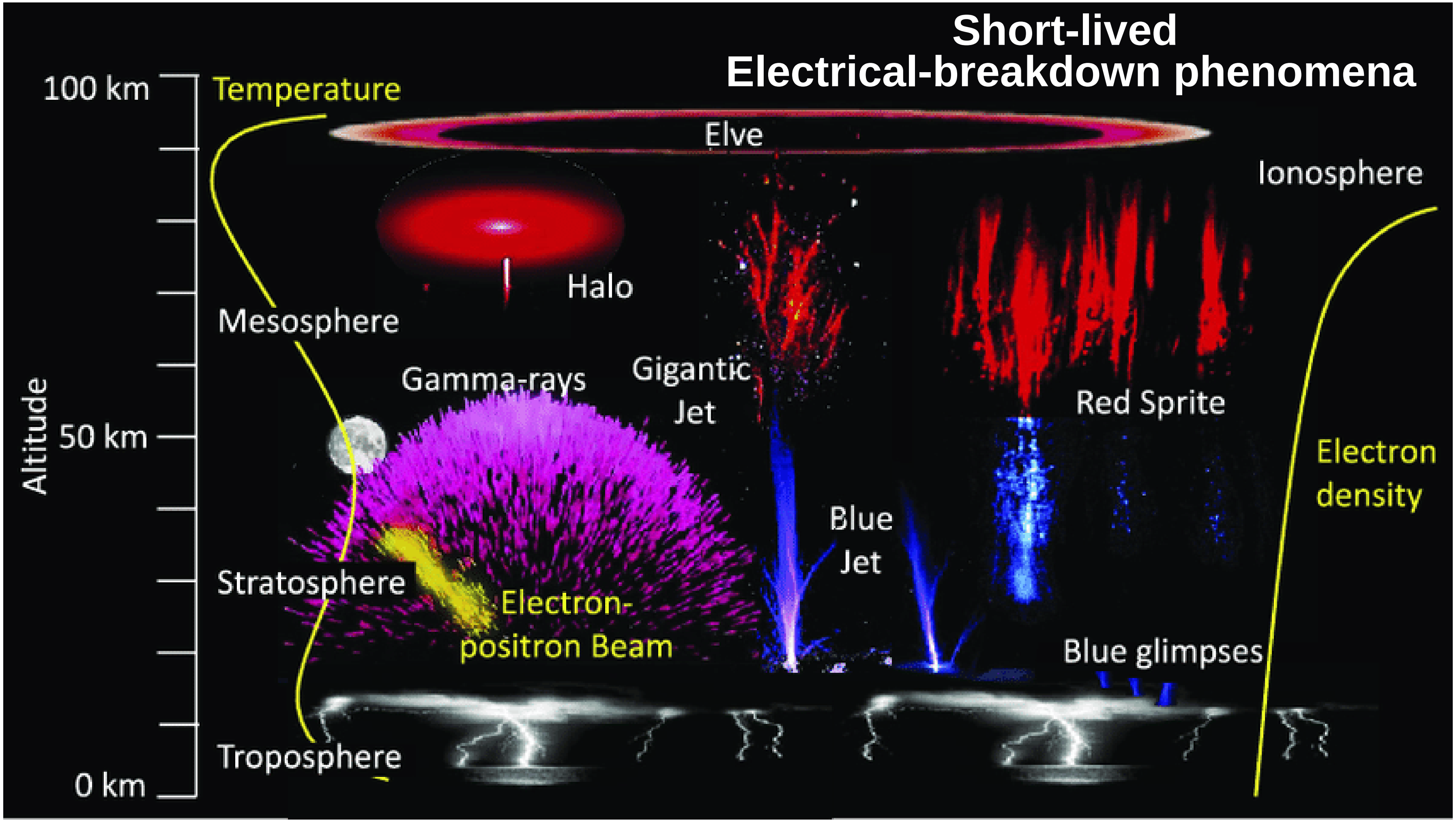
for the Pierre Auger Collaboration

December 8, 2020
YITP 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.

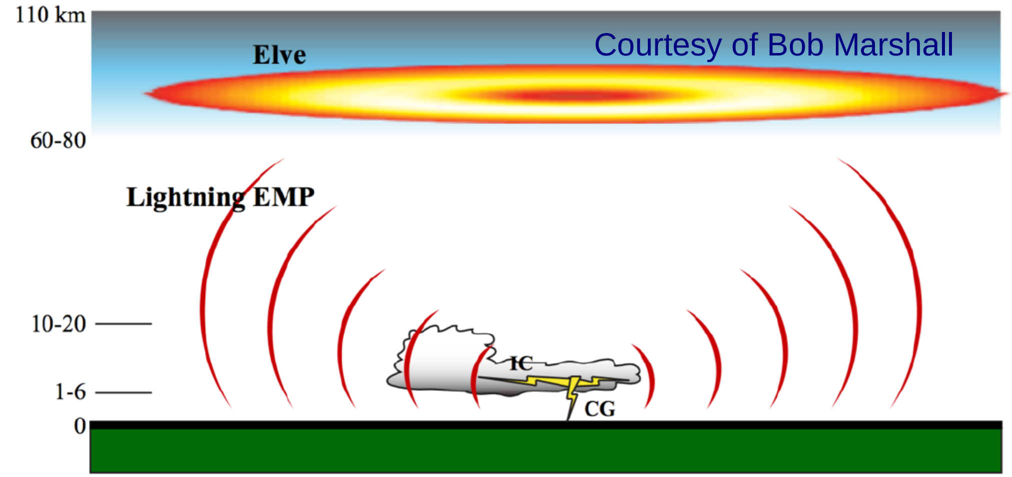
# *Upper atmospheric phenomena powered by thunderstorms*



# ELVES

## *Emissions of Light from Very low frequency Electromagnetic pulse Sources*

ELVES and Red Sprite lightnings over Finland.





ELVES appeared on April 2, 2017, high above a thunderstorm in the Czech Republic and was captured by an amateur astronomer.

**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;

# ELVES

## *Emissions of Light from Very low frequency Electromagnetic pulse Sources*

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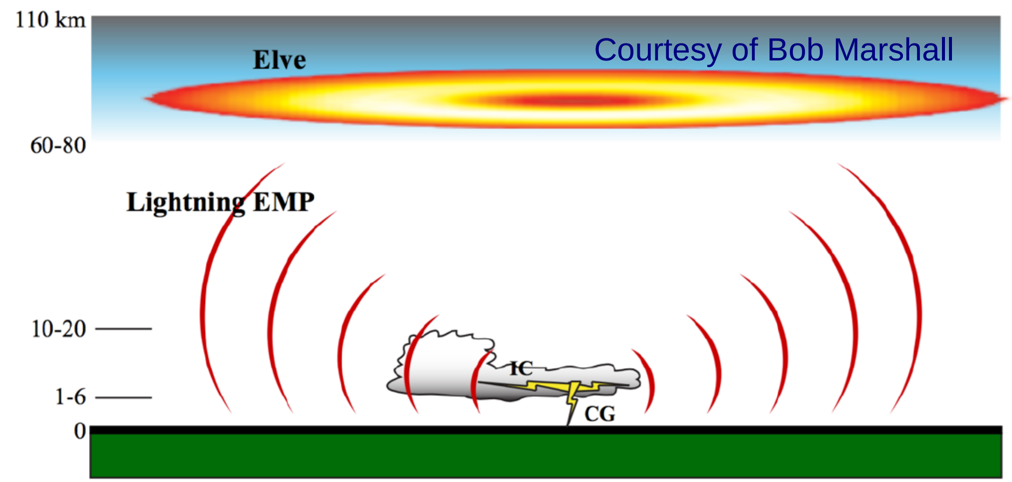
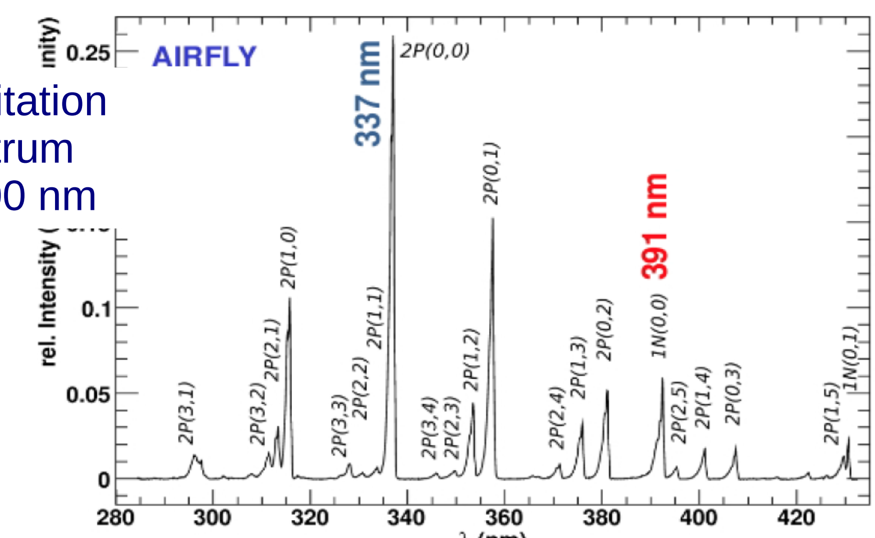




ELVES appeared on April 2, 2017, high above a thunderstorm in the Czech Republic and was captured by an amateur astronomer.

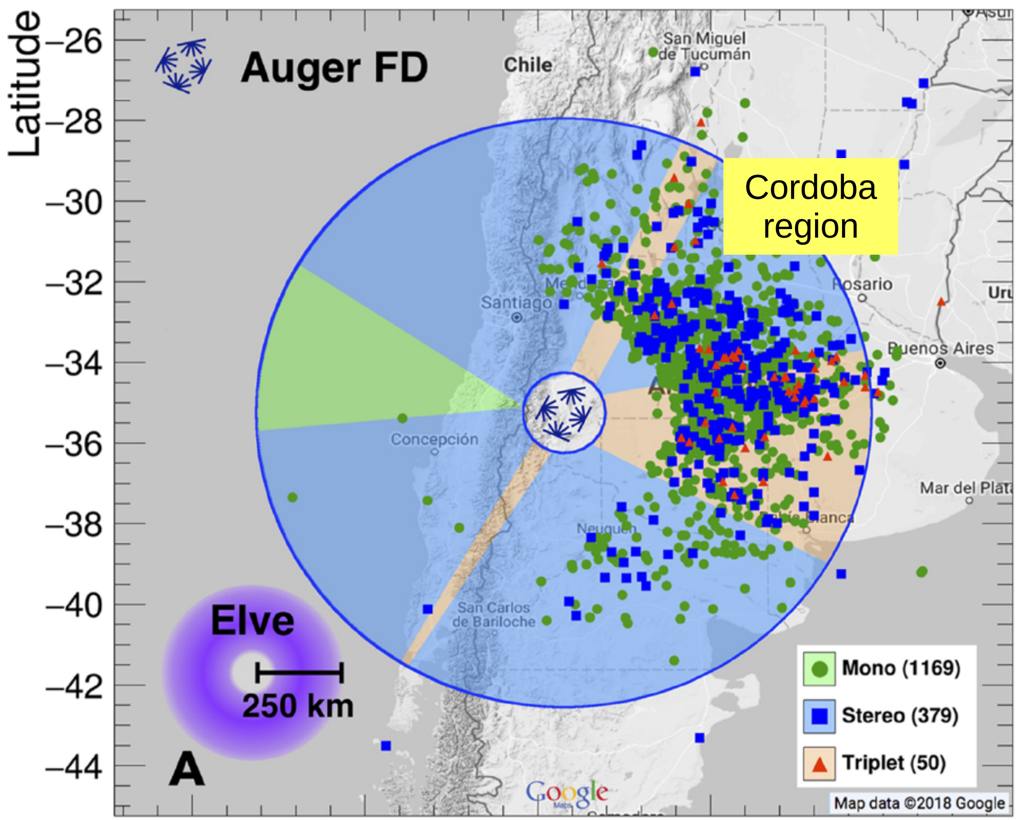
De-excitation Spectrum 300-400 nm



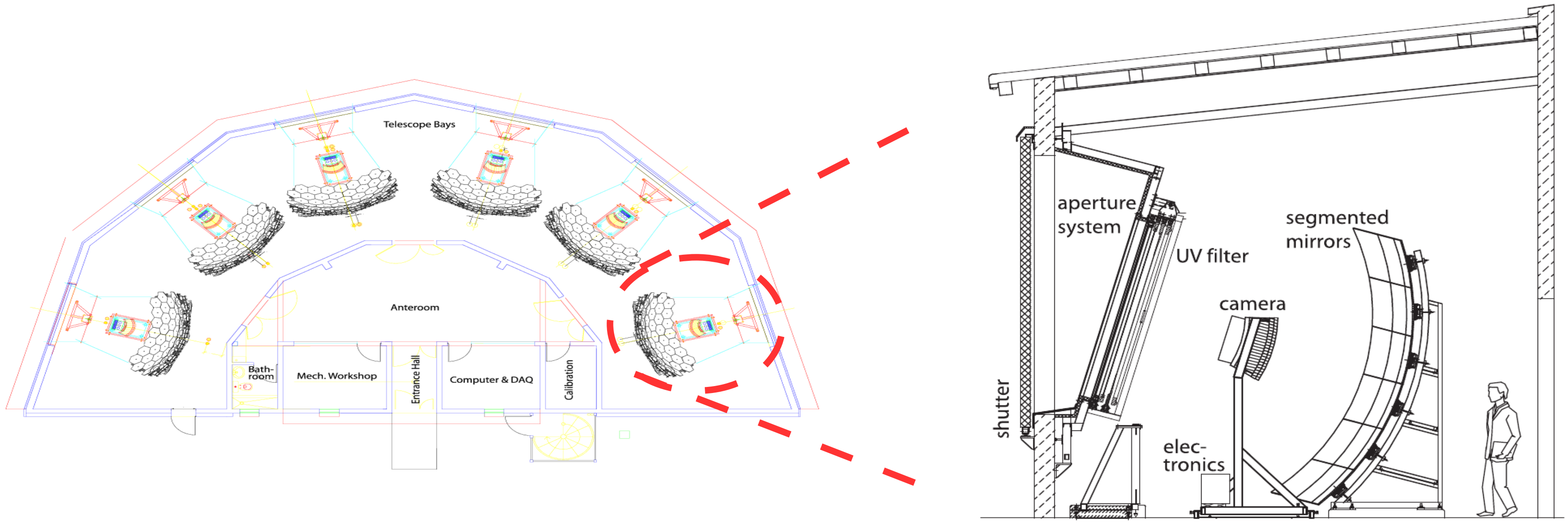
# The Pierre Auger Observatory Acceptance for Elves

**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

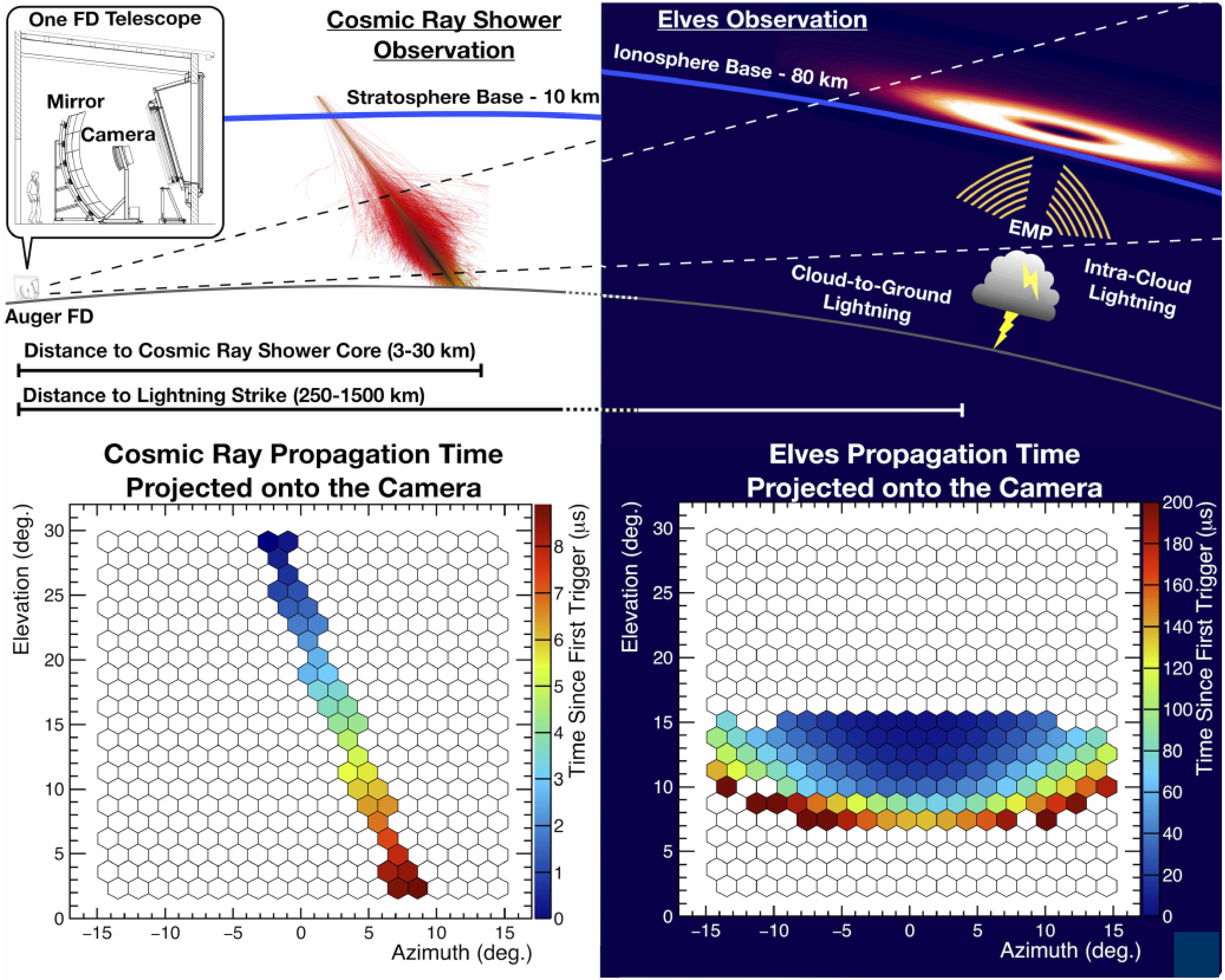



- FOV: 6x30°x30° (number of telescopes-azimuth-elevation) for each site;
- UV transmitting filter window: 300-420 nm;
- Mirror Area: 11 $m^2$;
- FD camera: 22x20 PMTs;
- Trace for each PMT:
  1000 bins long,
  100 ns per bin,
  **10 Mfps camera**;
- Duty cycle: 12%

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.

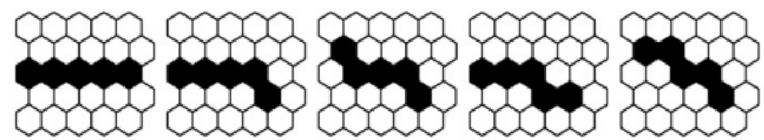
The **first serendipitous observation of three elves** occurred between 2005 and 2007**. Now**, the Observatory has a **dedicated trigger for elves**.

# The Fluorescence detector and Elves Observation



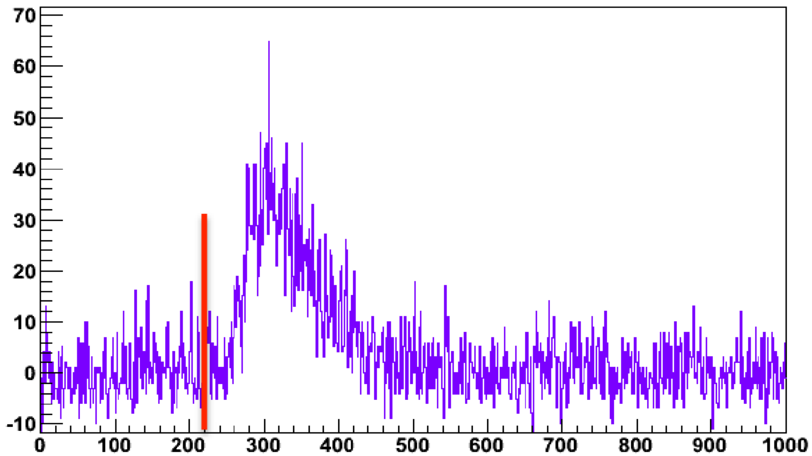
# The Fluorescence Detector Trigger

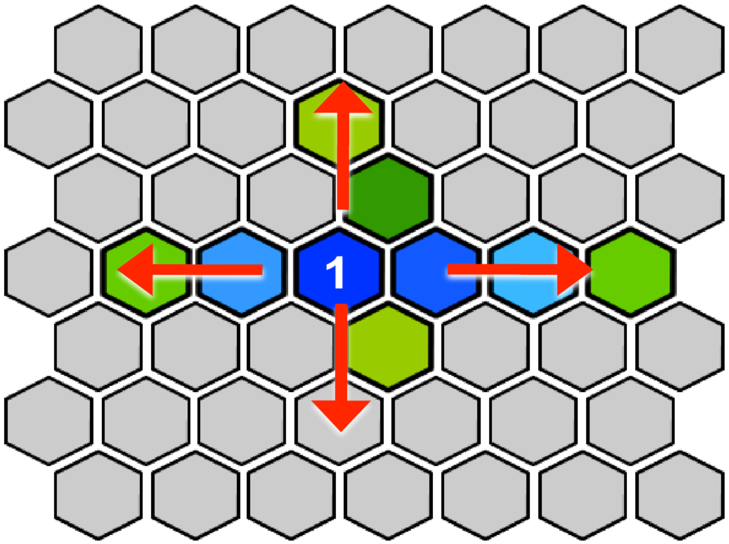
| | *type* | *purpose* | *event rate* |
|---|---|---|---|
| First Level Trigger (FLT) | **HW** | Pixel threshold trigger | 100 Hz / pixel |
| ↓ **T1** | | | |
| Second Level Trigger (SLT) | **HW** | Track shape identification | 0.1-10 Hz / tel |
| ↓ **T2** | | | |
| Third Level Trigger (TLT) | **SW**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



# 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***

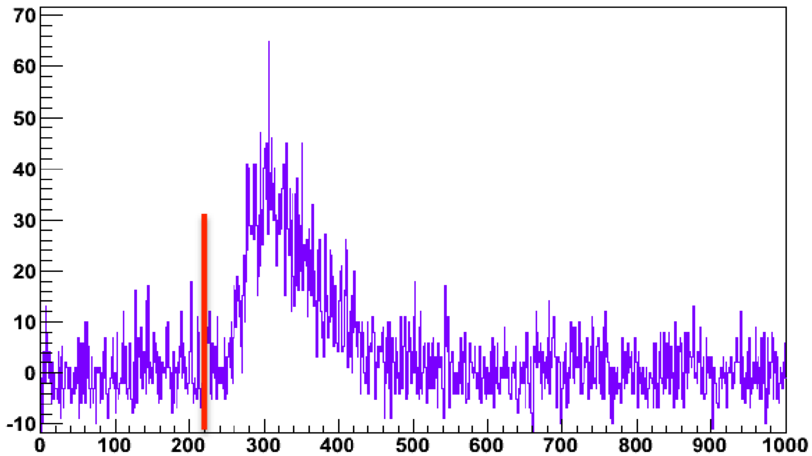
- at least **3 pixels before OR 3 after** the central one
- **80%** of the pixels must show an **increasing pulse time**

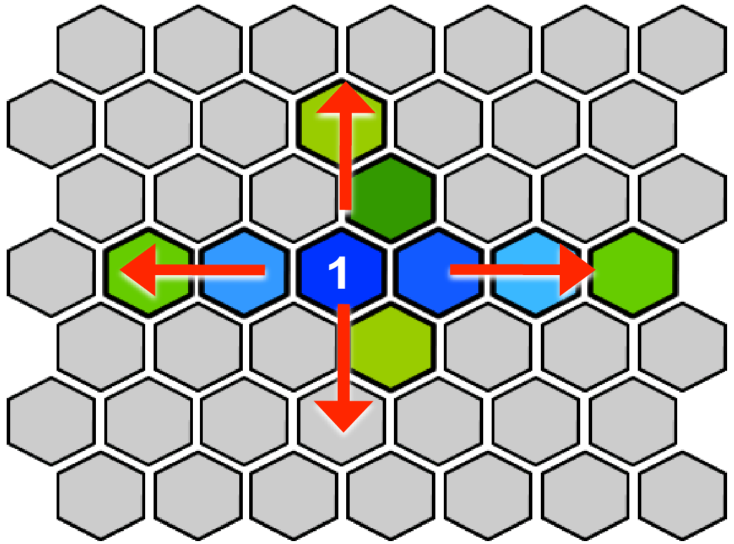
***4) Check signal amplitude for each pixel***

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

# Dedicated Trigger for Elves

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

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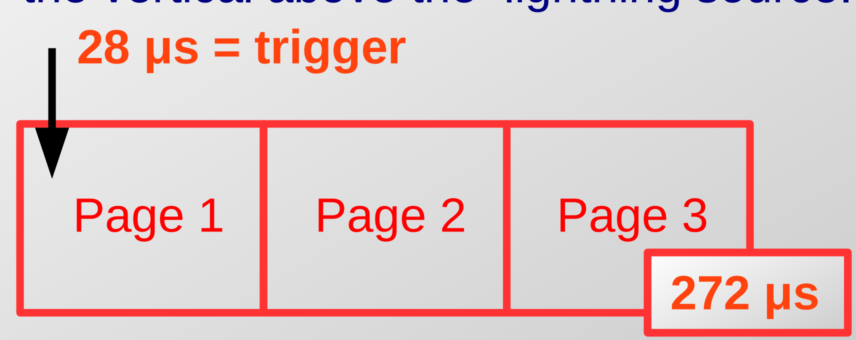
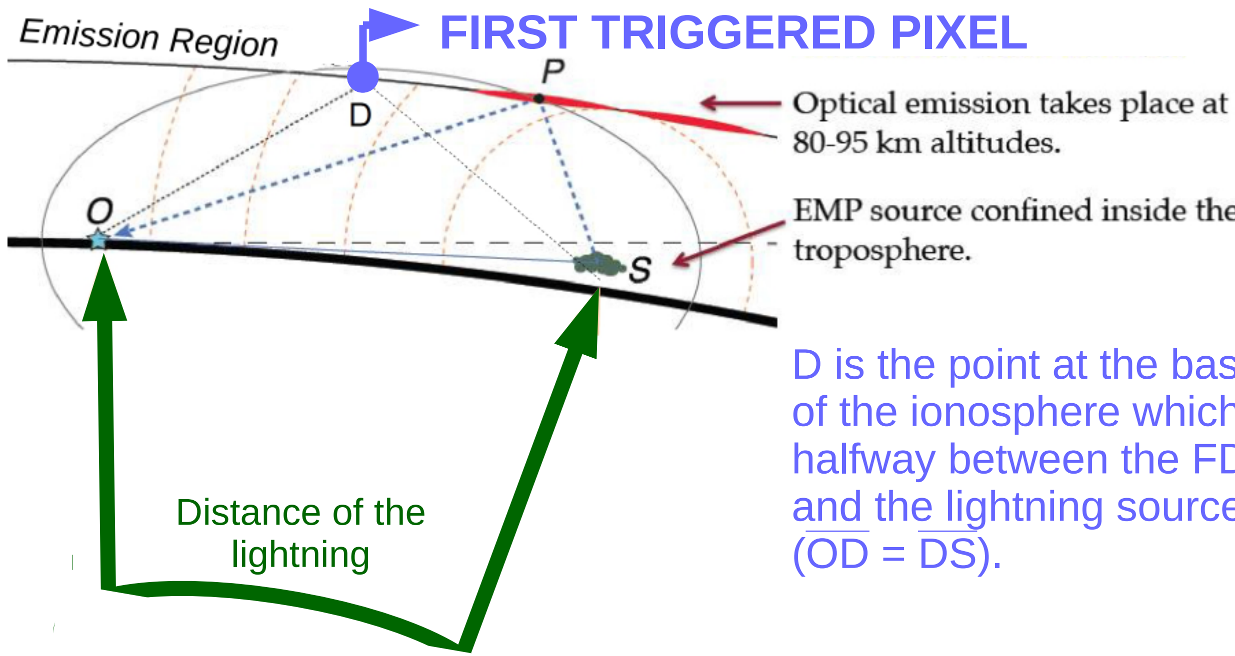
***4) Check signal amplitude for each pixel***

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

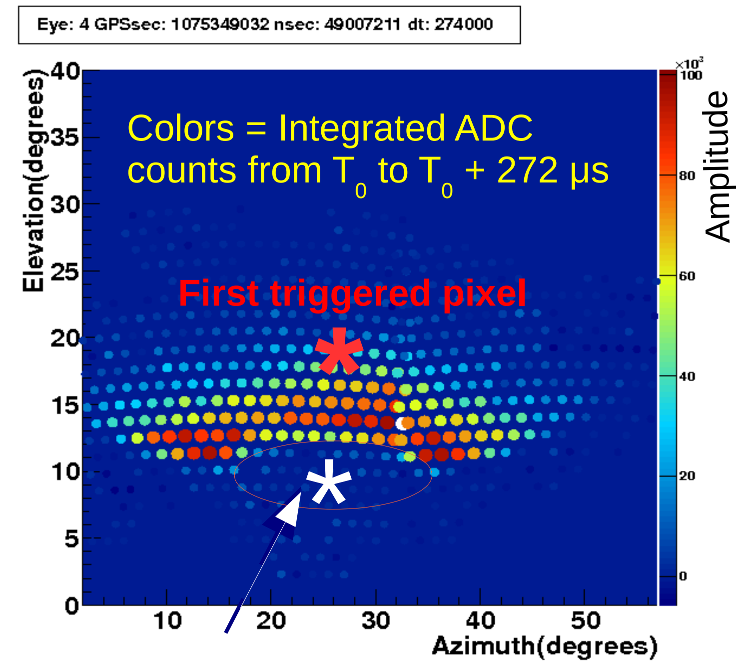
**Installed in 2014 with an extended readout:**
standard FD traces are 72 μs long after the trigger: this prevents to see most of the light of the Elves.
In particular, it prevents to see light from the vertical above the lightning source.



# Elves in the FD camera

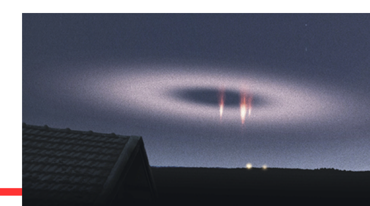



D is the point at the base of the ionosphere which is halfway between the FD and the lightning source ($\overline{OD} = \overline{DS}$).




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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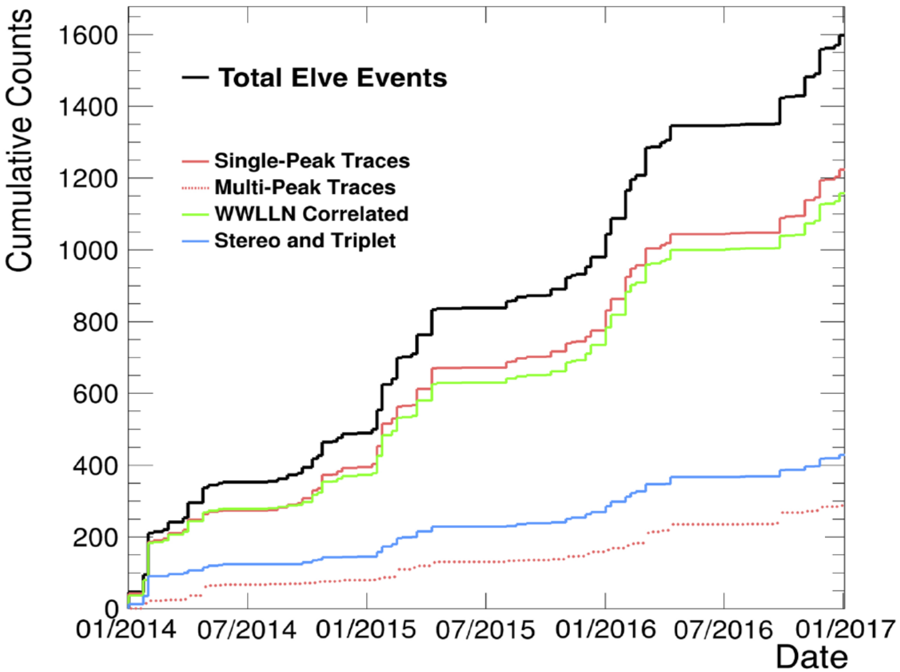
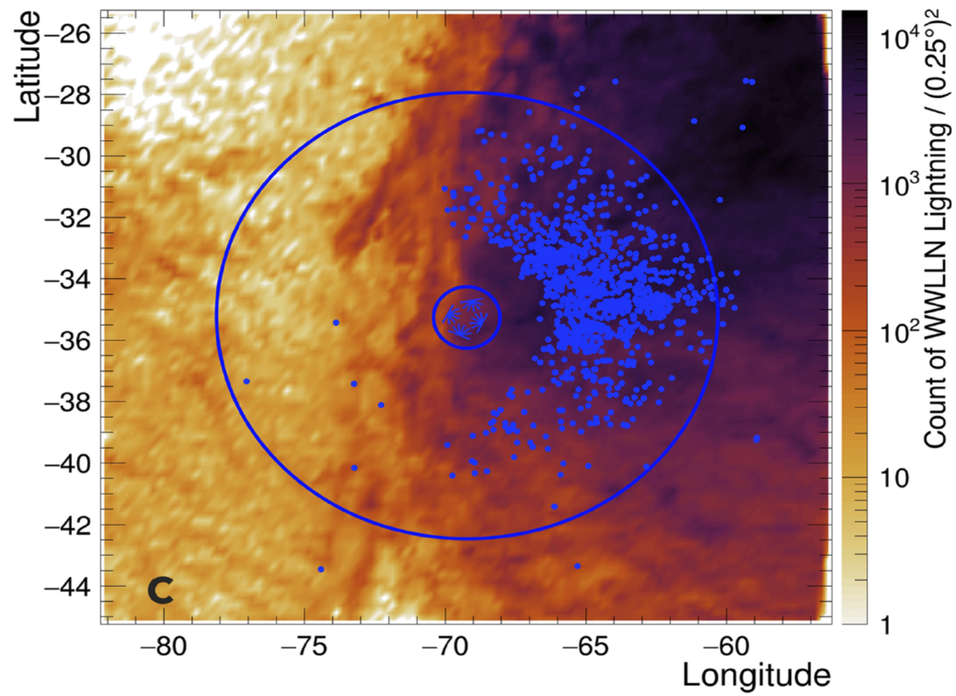
900 μs

# 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).




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.

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.

# Three-years of Elves detection

*Elves Counts Through Different Stages of the Analysis*

| Stage | Mono | Stereo | Triplet | Total | Note |
|---|---|---|---|---|---|
| Triggered | 1,864 | 396 | 51 | 2,311 | Independent of FD on-time |
| Verified | 1,287 | 390 | 50 | 1,727 | Features typical elve profile |
| Confirmed | 1,169 | 379 | 50 | 1,598 | Reconstructed at least one site |
| WWLLN correlated | 836 | 284 | 38 | 1,158 | 5-ms coincidence |

*Note*. Each row is a subset of the one above.

**72% of the observed elves correlate with independent radio-frequency measurements of lightning by WWLLN** (http://wwlln.net).

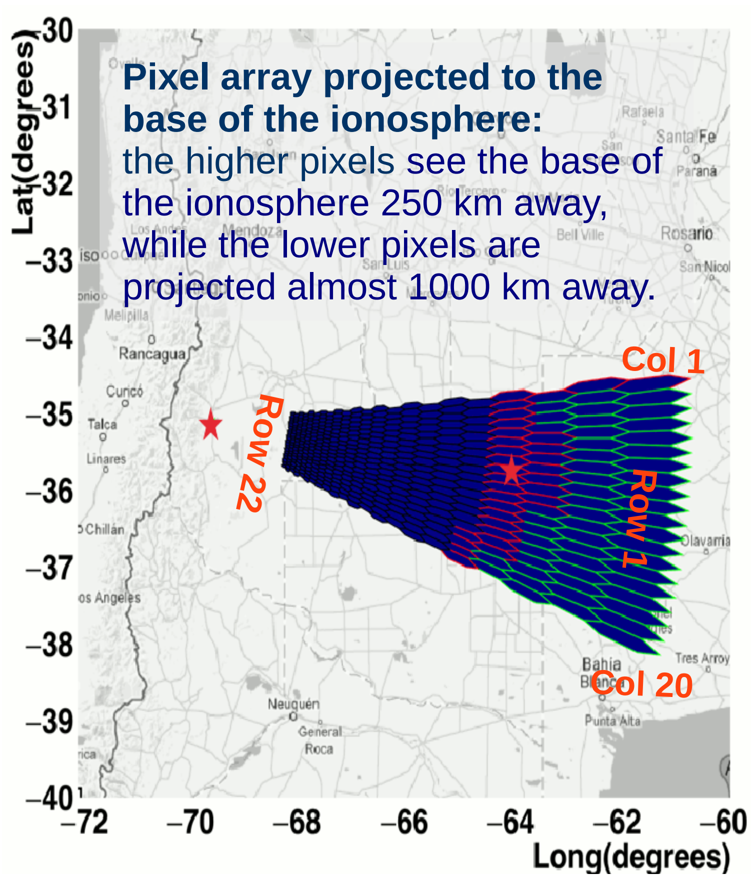
- For a quality subset of these correlated events (474), the lightning energy as measured by WWLLN had a median of 16 kJ;
- the median energy of all lightning measured by WWLLN that occurred inside the elve footprint while the telescopes were taking data was 1.3 kJ
  → **the Auger Observatory is naturally selecting intense electrical events in the severe Argentinian thunderstorms that occur during the austral summer.**

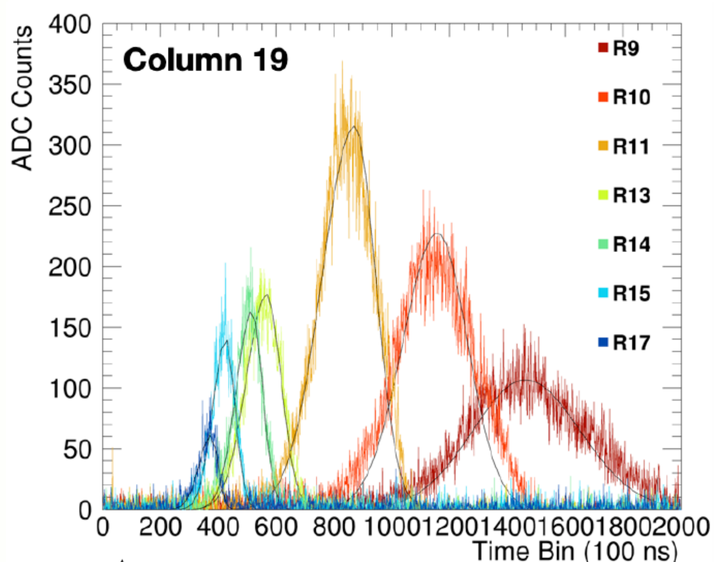
The Auger FD enables us to see very fine structure in the light emissions of elves and data can be sorted in two categories observing the photo trace:
1310 single-peaked elves;
288 multipeaked elves.

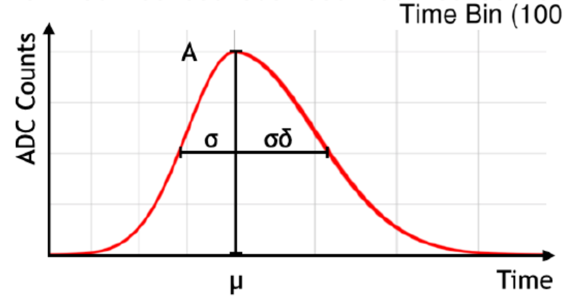
# Reconstruction Steps

**The location and time of the elve-inducing lightning will be reconstructed.**

1) ADC trace for each pixel is fitted with an asymmetric Gaussian parametrized with the mean time ($T_{peak,i}$), the signal amplitude ($A_{peak,i}$) and the skewness ($\sigma_{left,i}$ , and $\sigma_{right,i} = \sigma_{left,i} \cdot (1 + \delta)$), where *i* is the index of the pixel.
Each pulse had to pass four quality criteria to be part of the reconstruction of the lighting location and time.




- The signal propagates down the rows with a rise in total photon count and pulse start time, until the hole above the lightning is reached;
- the amplitudes of the traces are strongly affected by the amount of atmosphere between the emission and the mirror;
- the increased asymmetry of the pulses down the camera rows are a result of a wider observation area for pixels pointing at low elevation angles.

# Reconstruction Steps

**The location and time of the elve-inducing lightning will be reconstructed.**

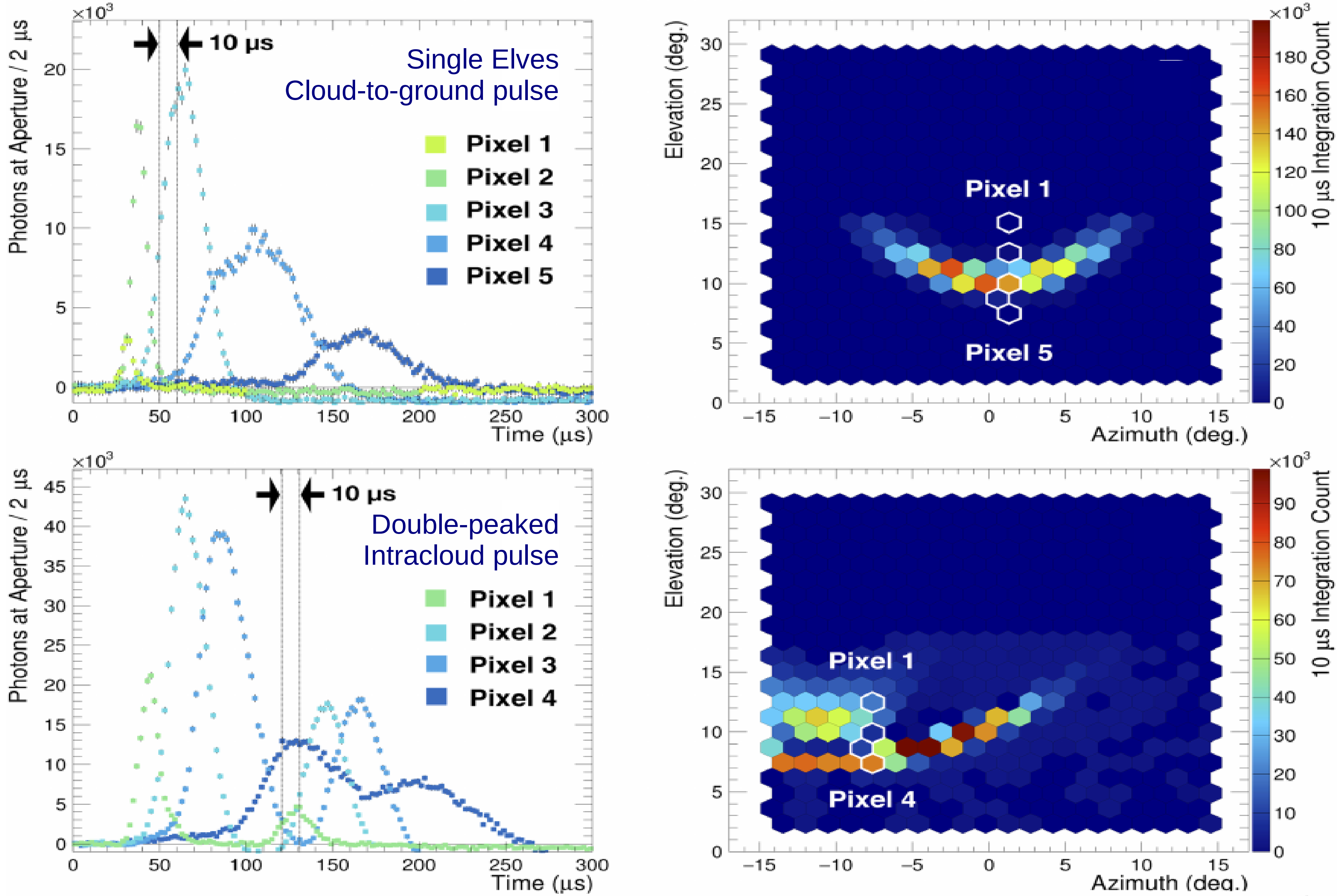
2) The parameters from the first fit were inputs to the second fit of the reconstruction, where we used a χ2 minimization to obtain 5 parameters: the **time, latitude, longitude, and height ($H_S$) of the lightning strike, and the height of the emission region at the base of the ionosphere ($H_E$)**

$$\chi^2 = \Sigma_{i=1}^{N_{\text{pix}}} (T_{\text{peak},i} - T_{\text{estimate},i})^2 / \sigma_i^2(T)$$

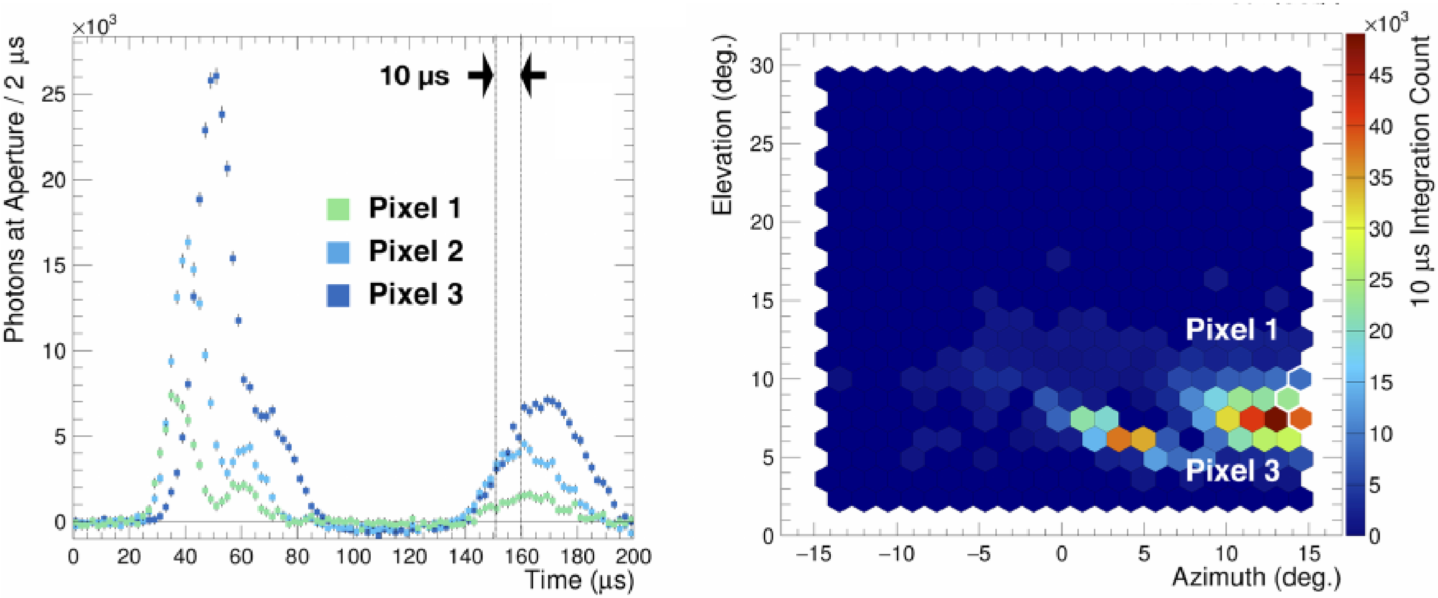
where $T_{\text{estimate},i} = T_0 + \Delta T(\text{Lat, Lon}, H_E , H_S)$ was the estimated time at which light reached the detector after the propagation time, ΔT , when added to the time of the lightning strike, $T_0$.

To simplify the reconstruction, **we fixed $H_E$ at 92 km and $H_S$ at the ground**.
The $H_E$ value was chosen studying the time correlation with WWLLN.

# 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.

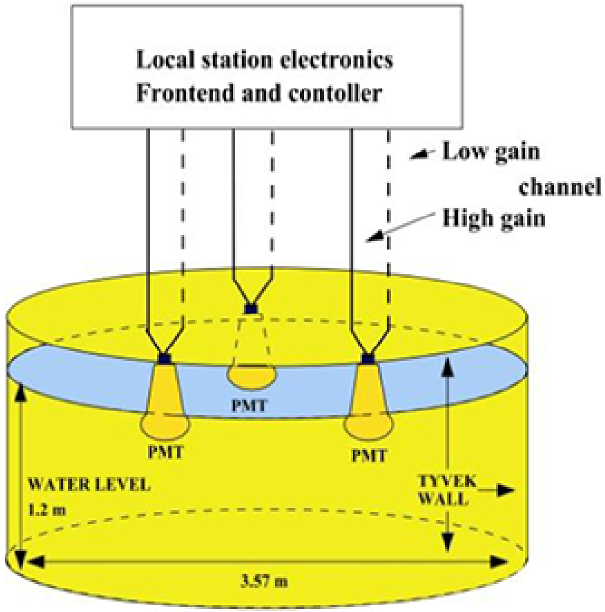
The Pierre Auger Observatory is scheduled to operate until at least 2030

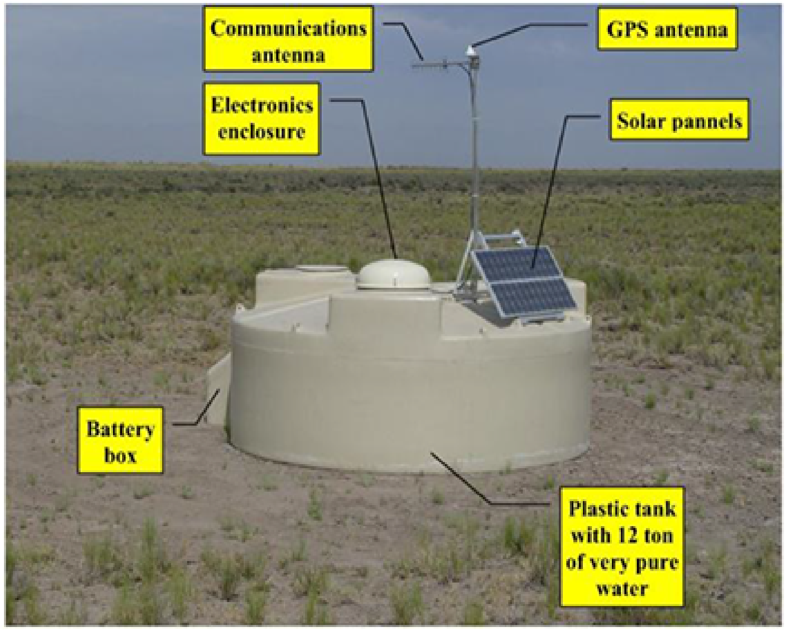
→ in 2017, a deeper readout window of 900 μs for elves was implemented to increase the quality of our current reconstruction;

→ 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

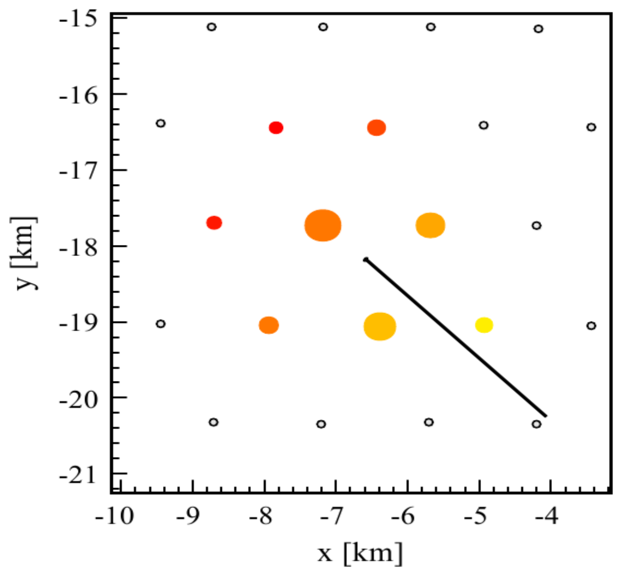


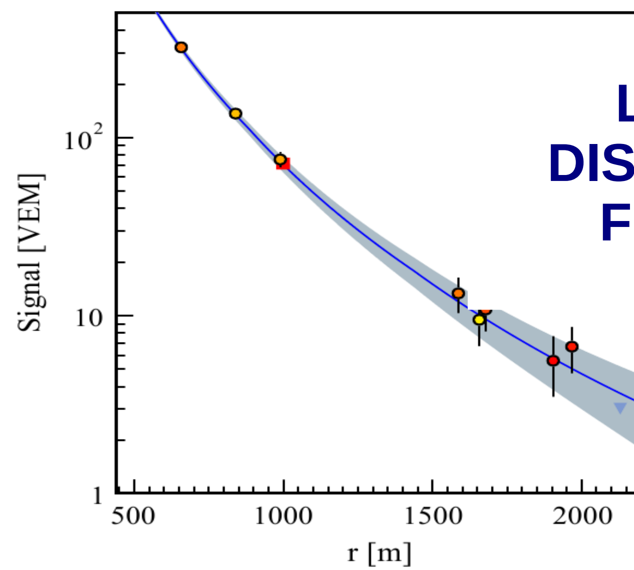




- Each WCD consists of a 3.6 m polyethylene tank containing a liner with a reflective inner surface and filled with 12,000 liters of ultra-pure water.
- Cherenkov light produced by the passage of relativistic charged particles through the water is collected by three PMTs.
- Each PMT has two readout channels, one directly from the anode (**LG channel**) and the other one from the last dynode (**HG channel**) 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

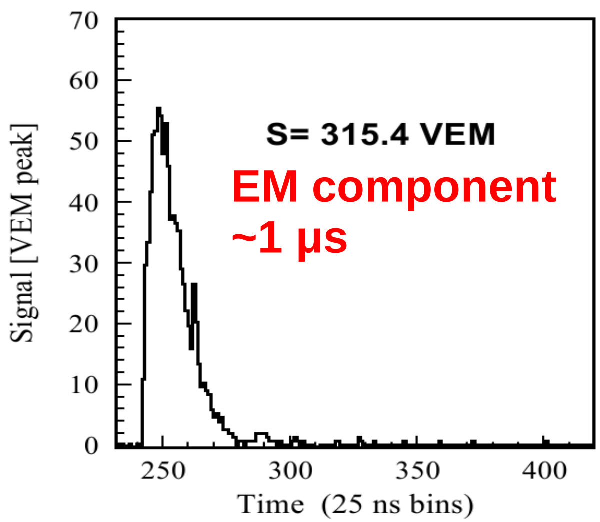
**Shower with E=3x10$^{19}$eV, θ=28°**

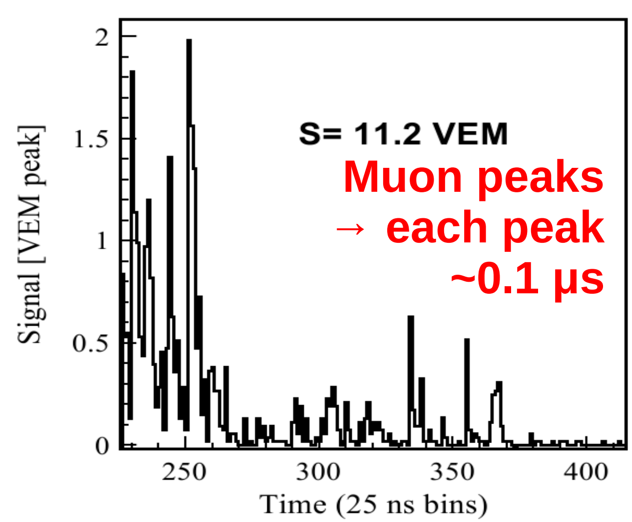



**LATERAL DISTRIBUTION FUNCTION**

**Station at 650 m from the shower core**

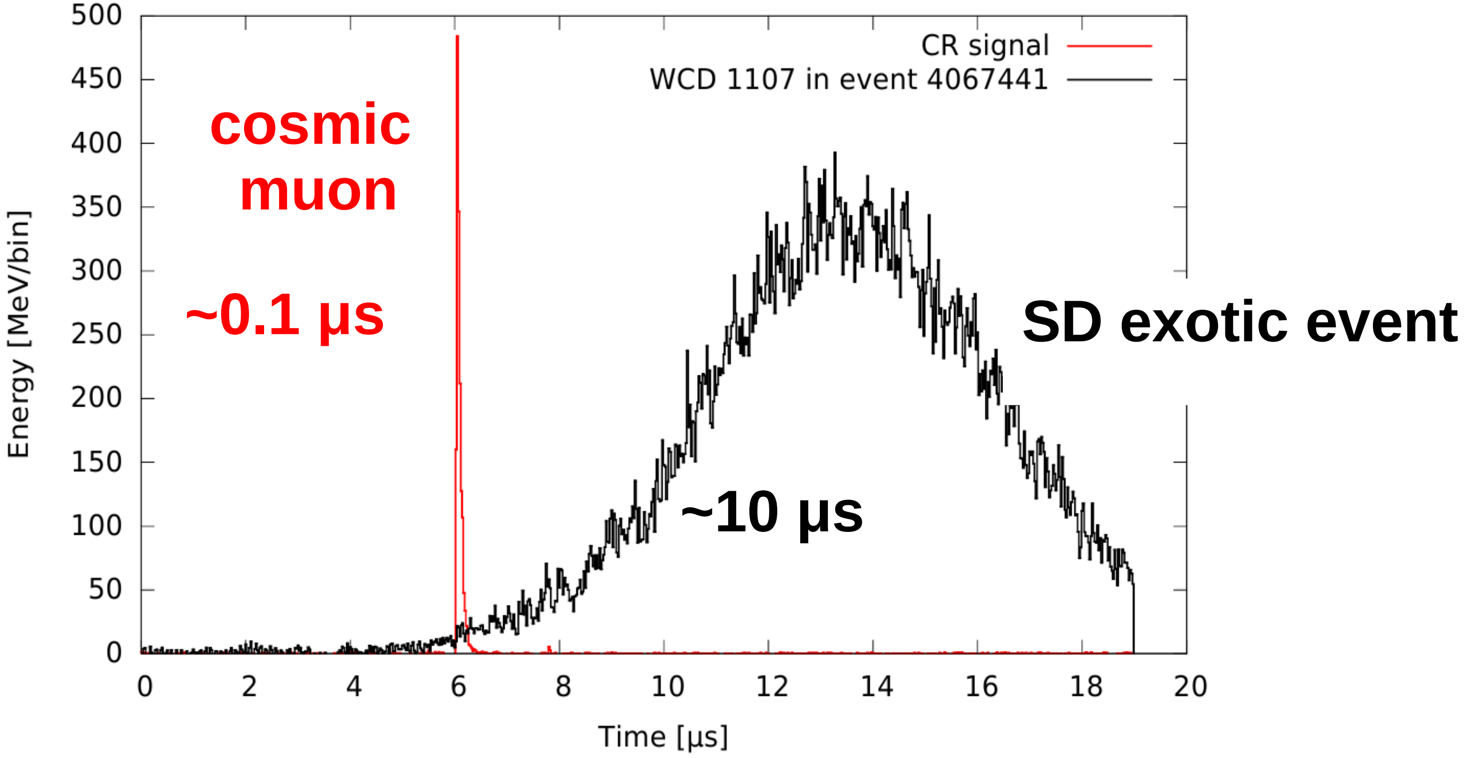



**Station at 1780 m from the shower core**

# 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);
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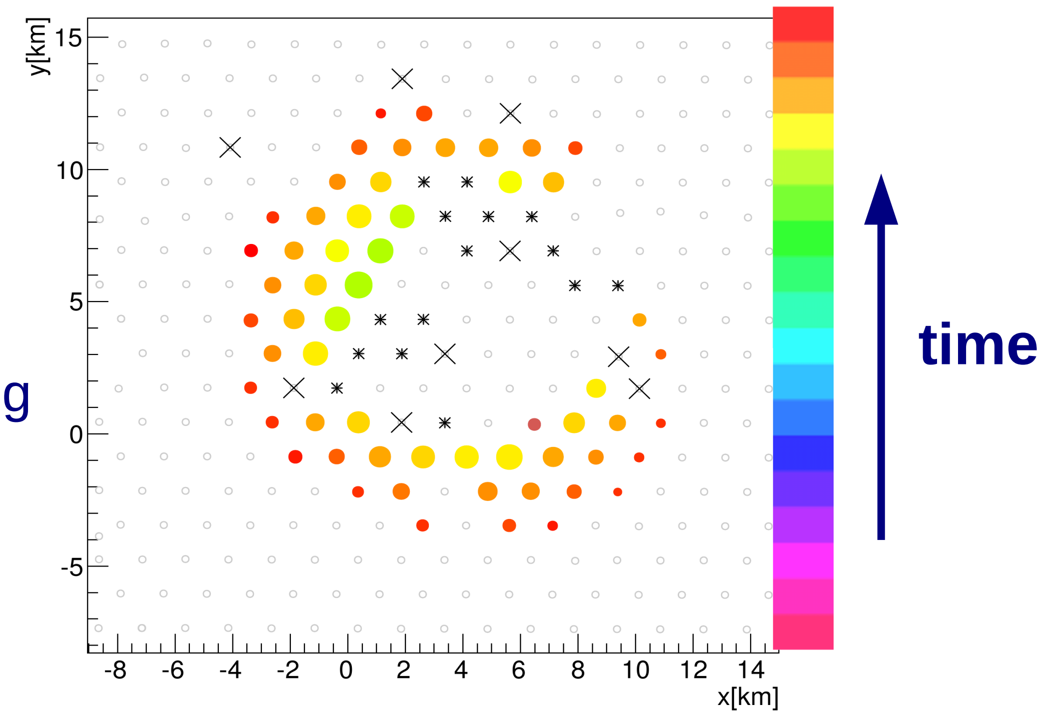
  → high frequency noise

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



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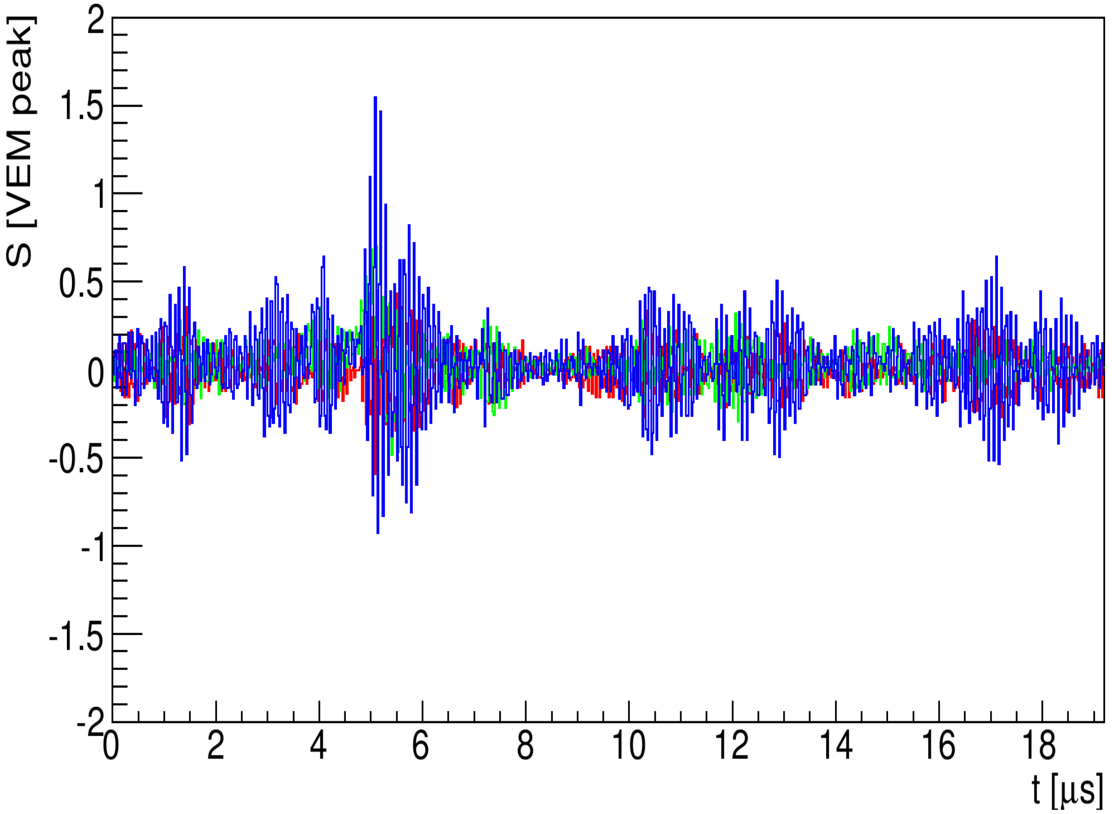
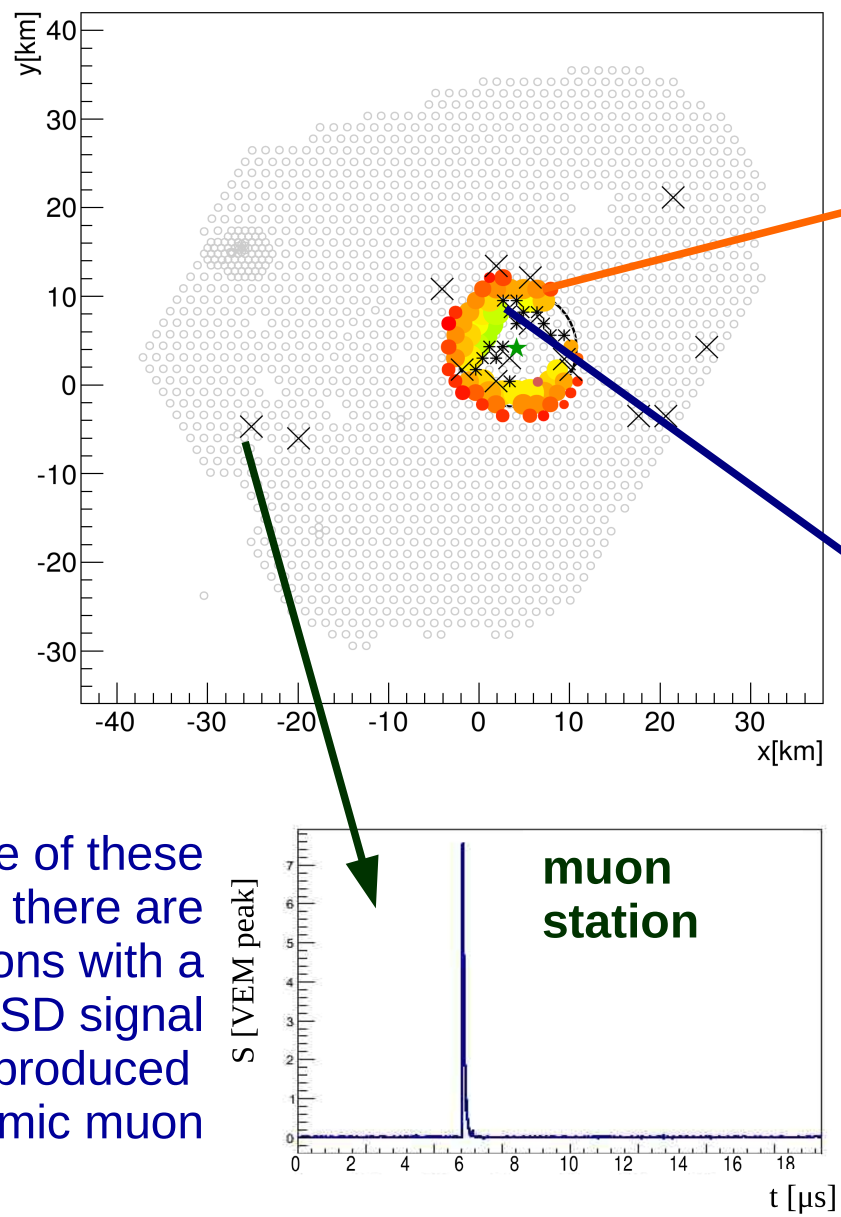
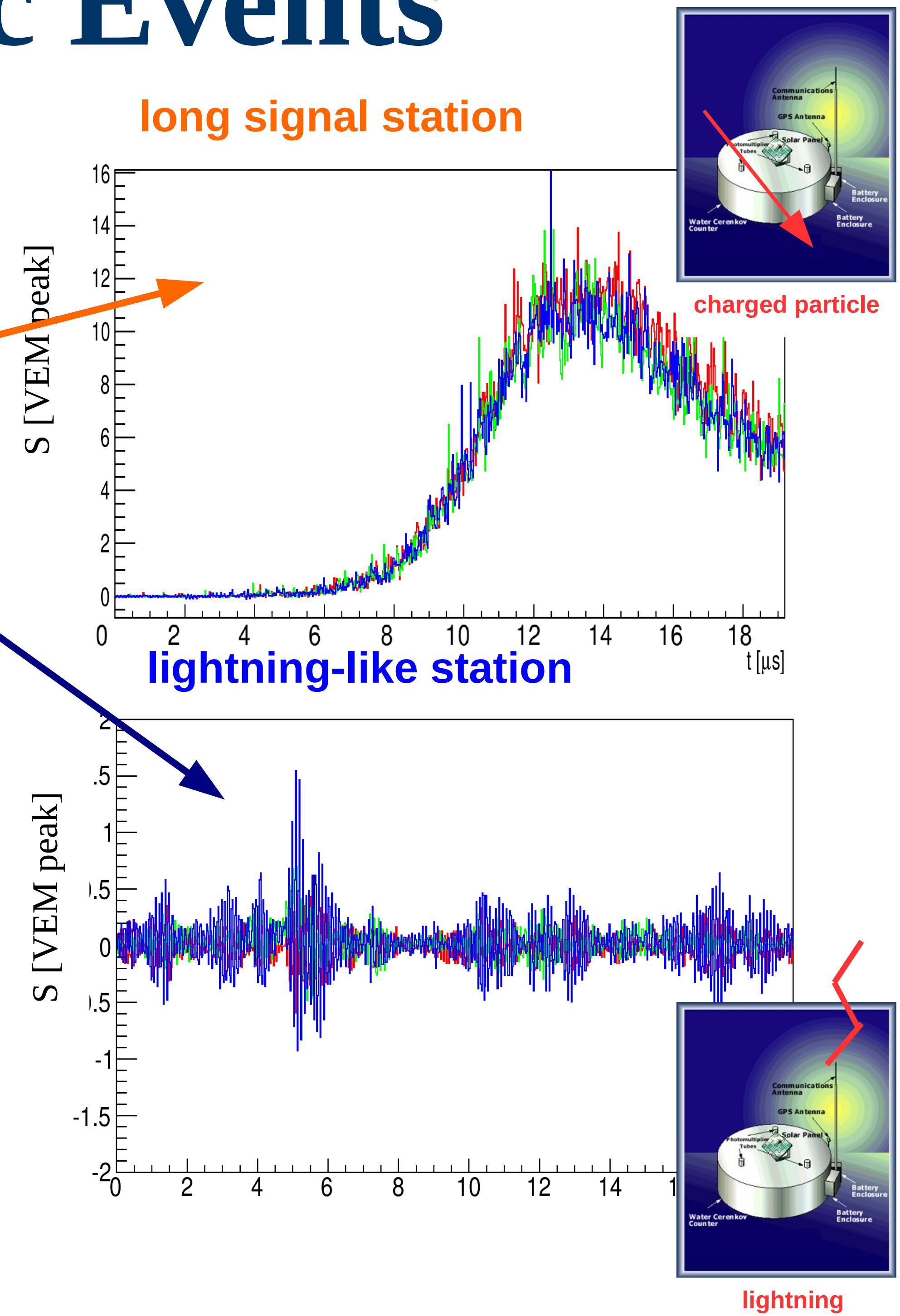


# SD Exotic Events

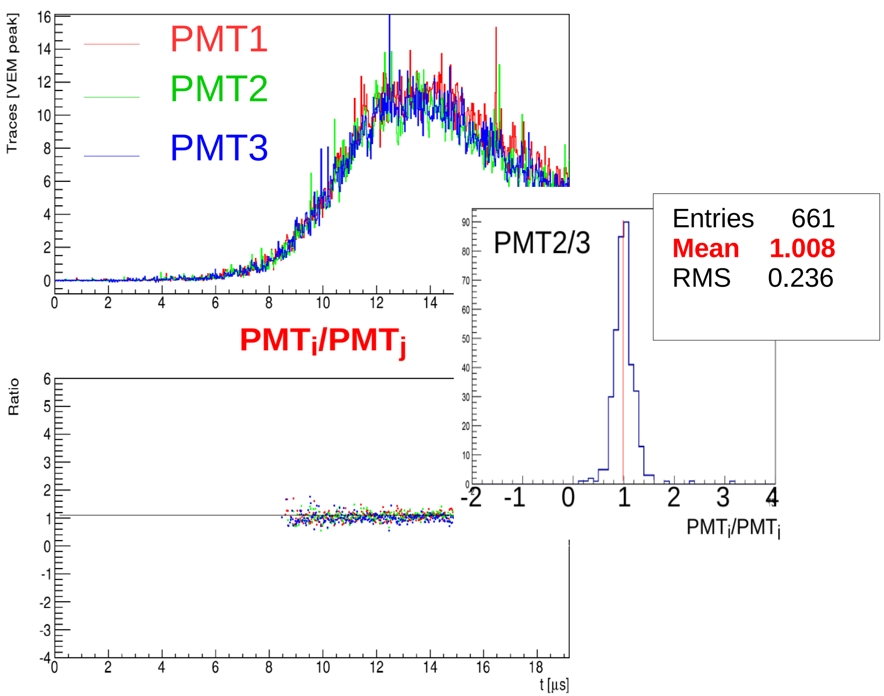


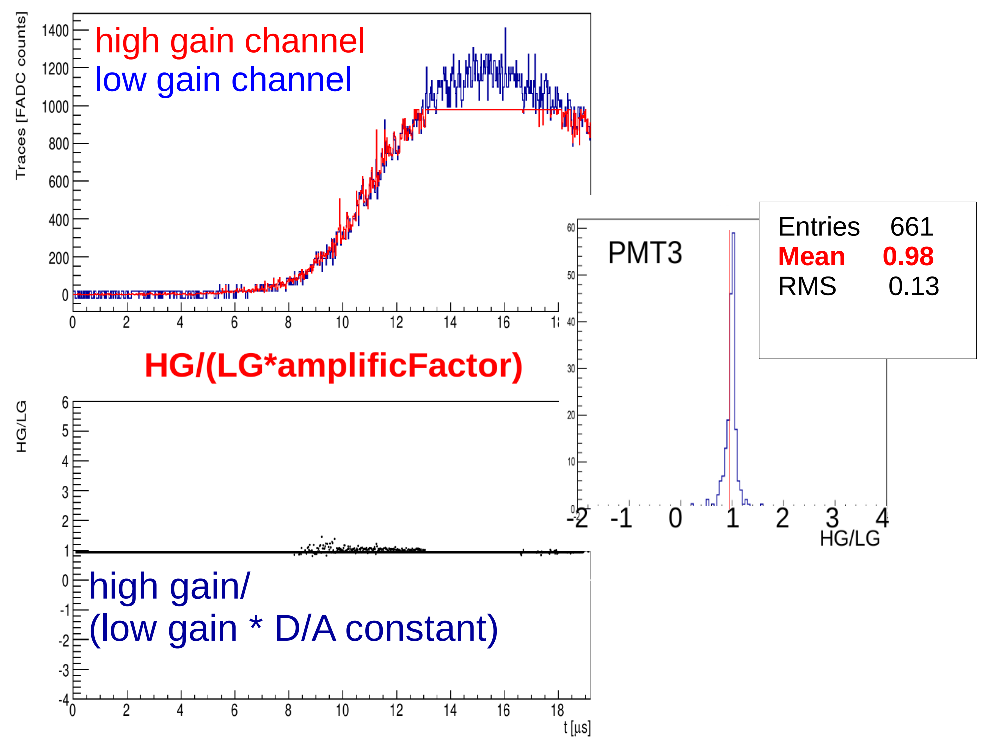

In some of these events, there are stations with a “standard” SD signal produced by a cosmic muon

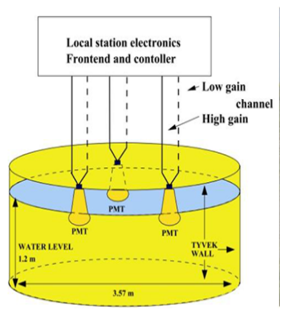


# Real Events?
# PMT Comparisons

- These signals are produced by particles which crossed the water in the stations;
- They are not electromagnetic noise artifacts.




Low gain → last dynode
High gain → anode

} Amplification factor (D/A costant) ~ 30

# Search Algorithm

Events collected by the SD from January 2004 to October 2019
→ ~ $10^7$ events

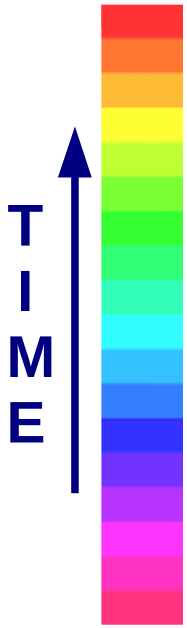
- A first cut is applied on data to select events with at least one lightning station (200000 selected events).

- Stations with long-lasting signals are selected.
If there are at least 10 stations with at least two PMTs with a long-lasting signal, the event is accepted.

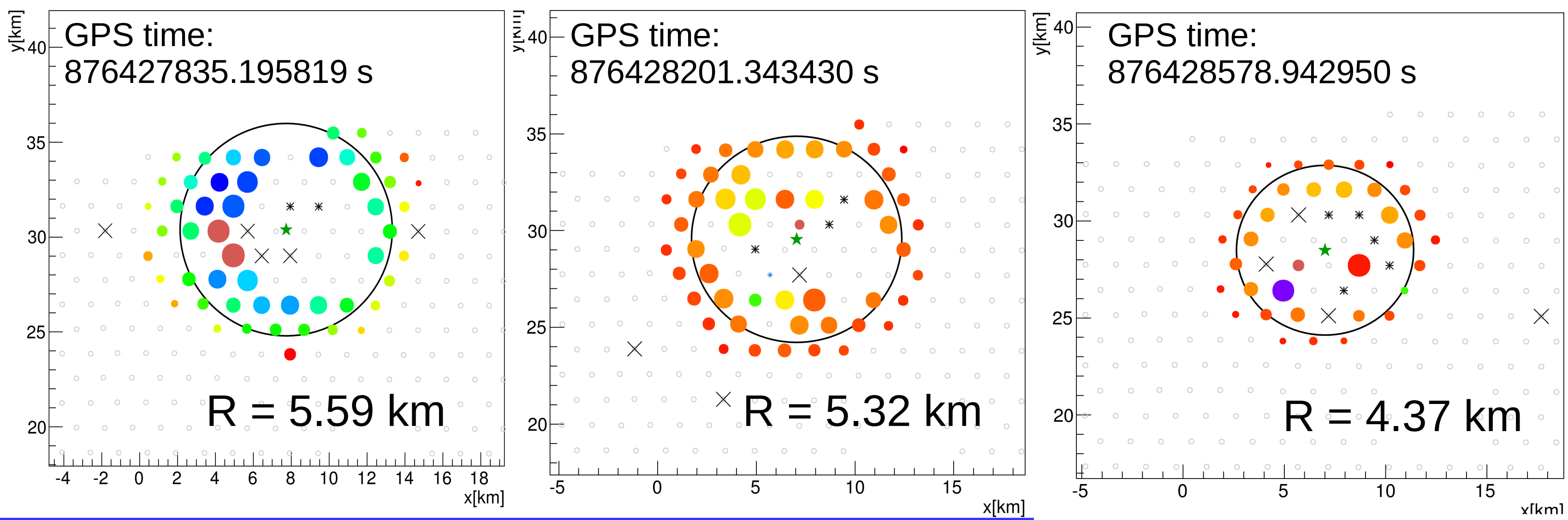
- **23 events** with long-lasting stations were selected
→ 15 of them have 20 or more than 20 long-lasting stations, arranged in a ring shape with a radius that spans from 4 to 8 km.

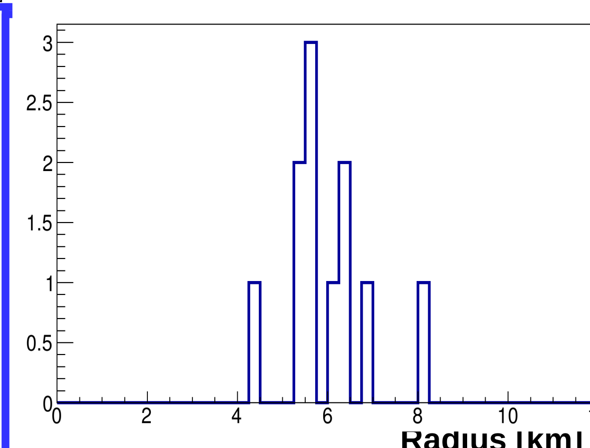
- 10 “well reconstructed” events: ~80% of this sample shows a time and spatial correlation with WWLLN lightning.

# Events zoology

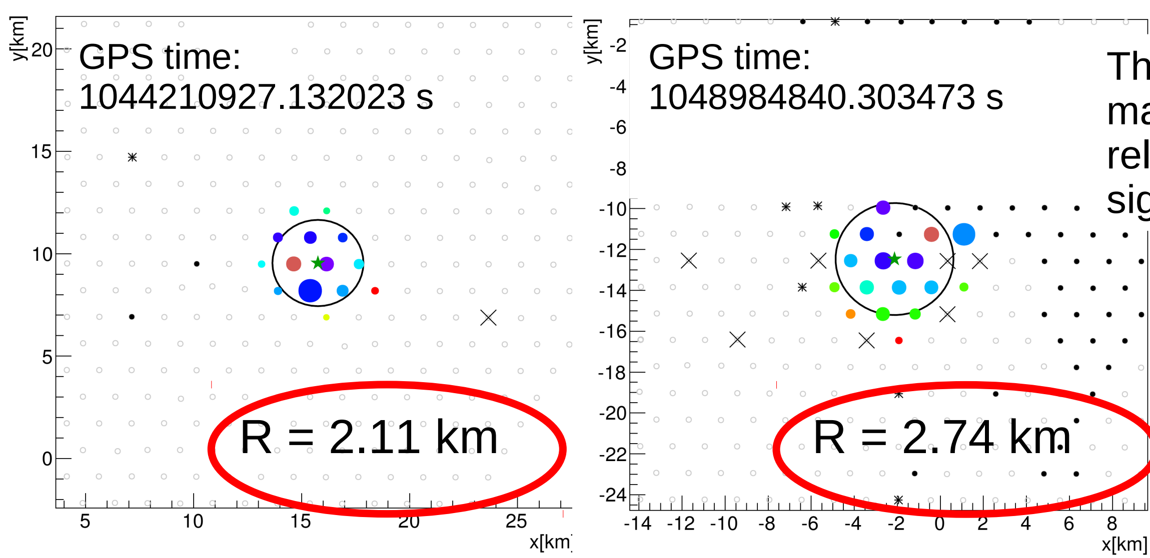



## Large Events



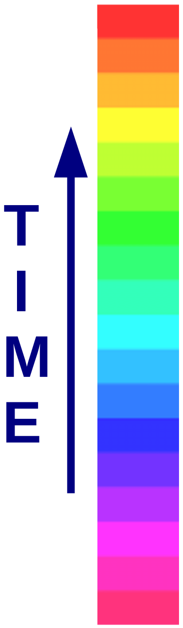

## Small Events



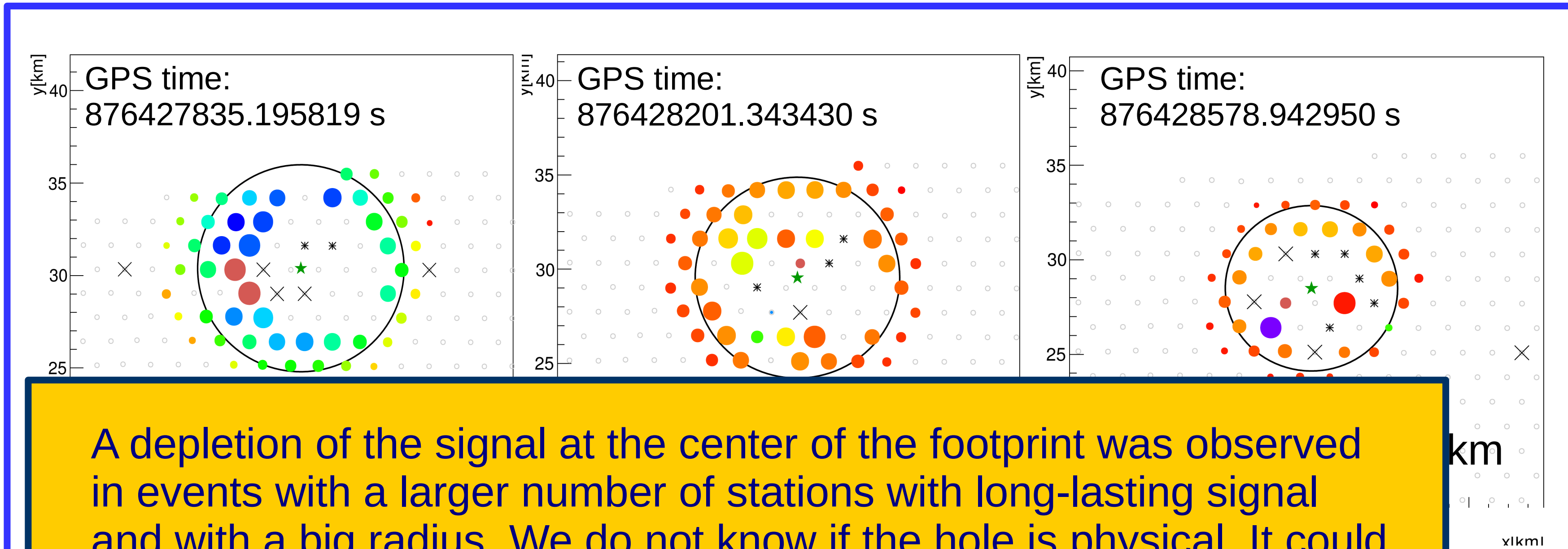

The circle marker size is related to the signal

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

# Events zoology



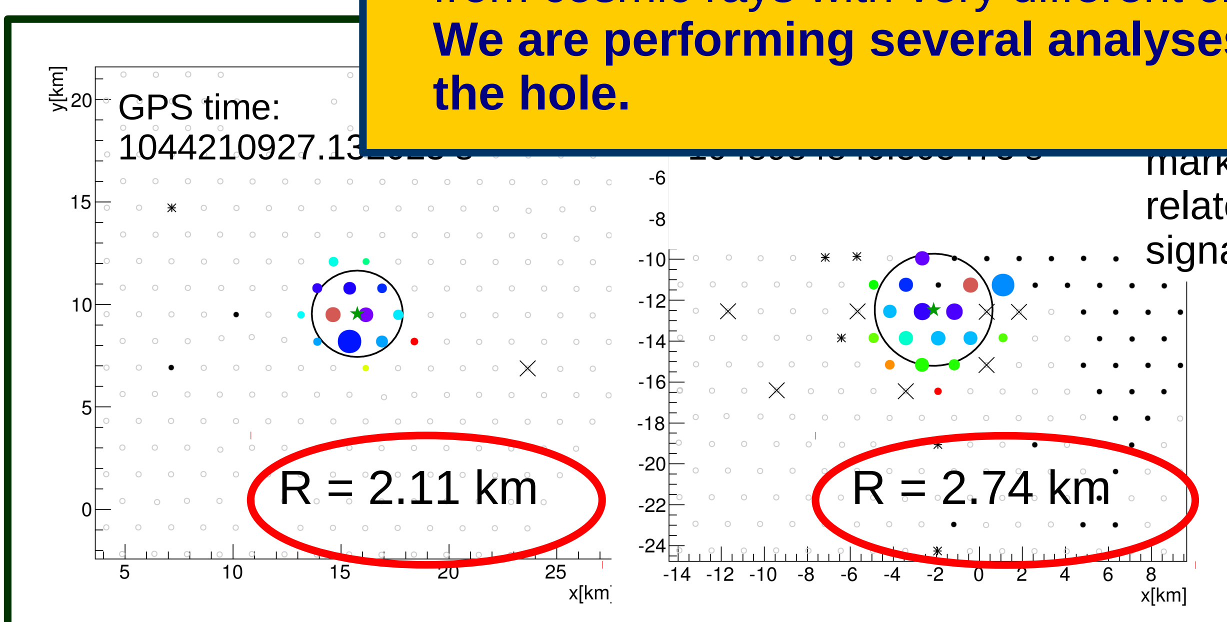

**Large Events**

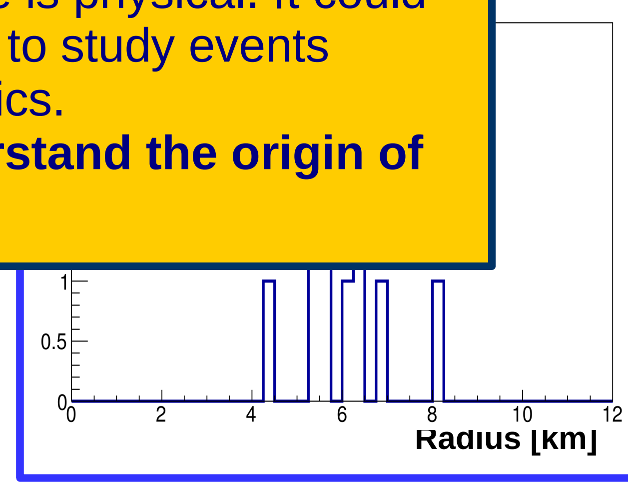



A depletion of the signal at the center of the footprint was observed in events with a larger number of stations with long-lasting signal and with a big radius. We do not know if the hole is physical. It could be caused by the Auger trigger that is optimized to study events from cosmic rays with very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

**We are performing several analyses to understand the origin of the hole.**

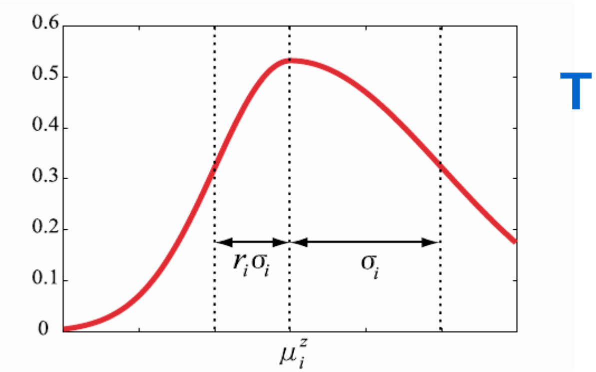
**Small Eve**



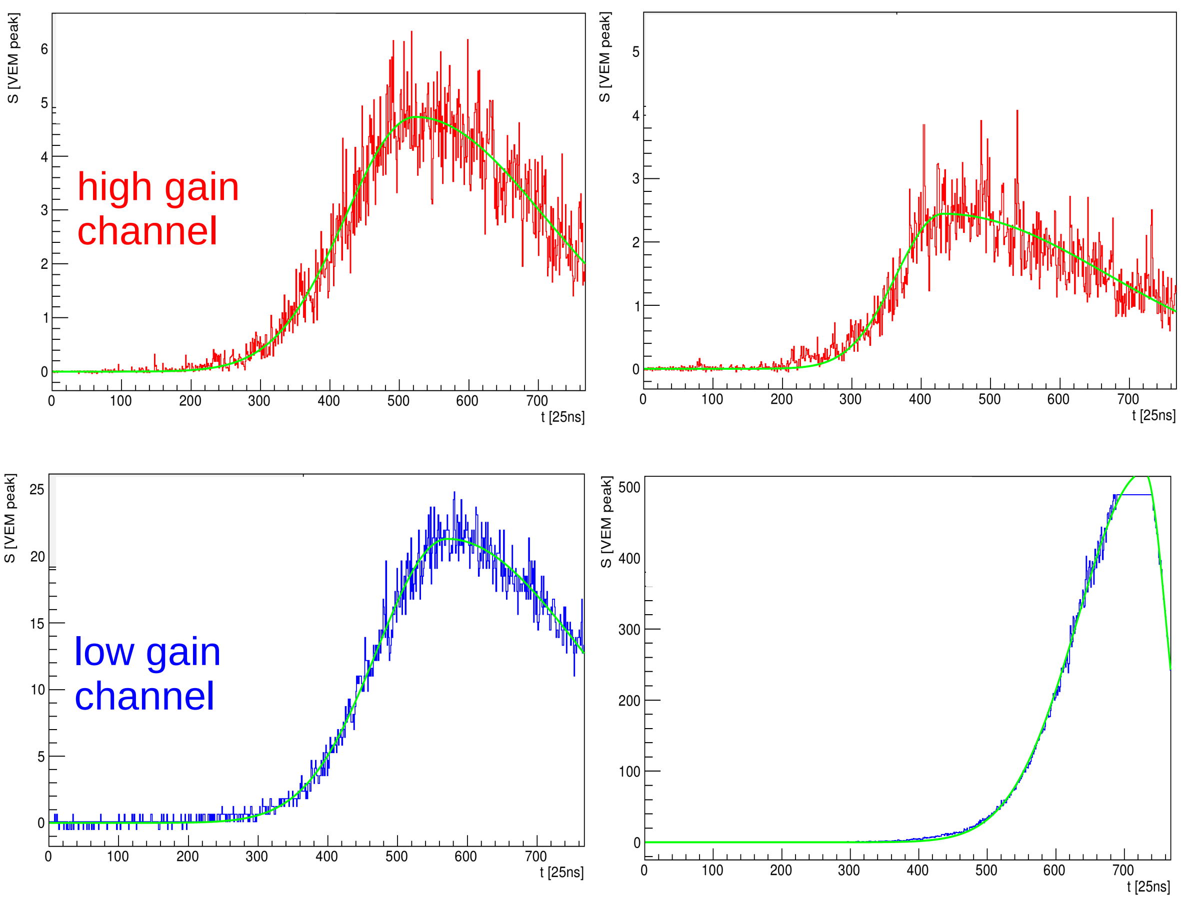




- ● **Long station**
- * **Lightning station**
- X **Muon station**

# Signal Shape




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




**GOOD FITS:**

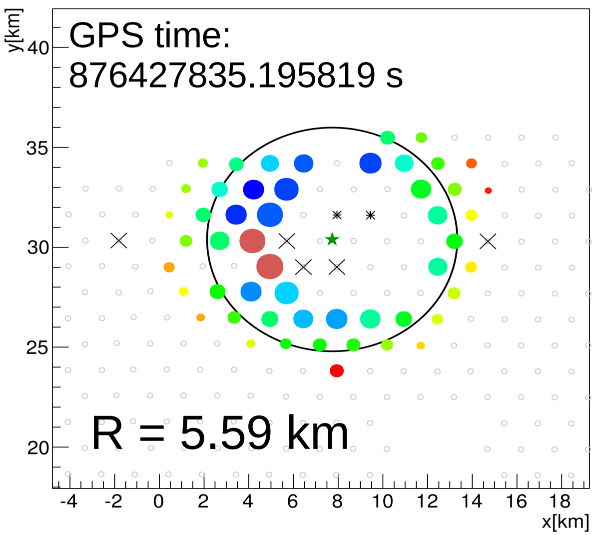
- Gaussian peak in the DAQ window;
- Difference between sum of the content of the trace bins and integral of the fitting function in our time window less than 5%;
- duration of the total fitting function less than 100 μs.

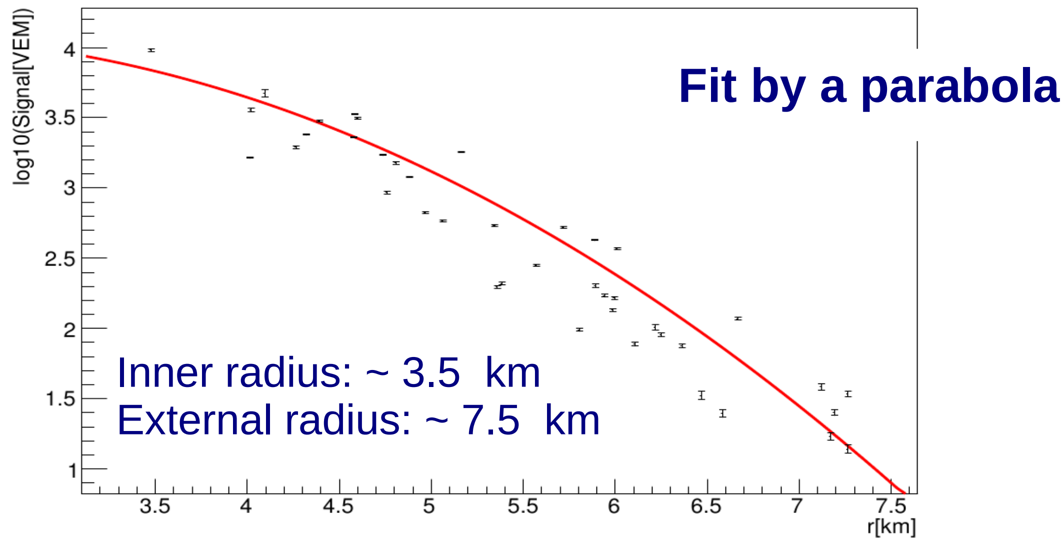
  → **an extended readout could be useful**

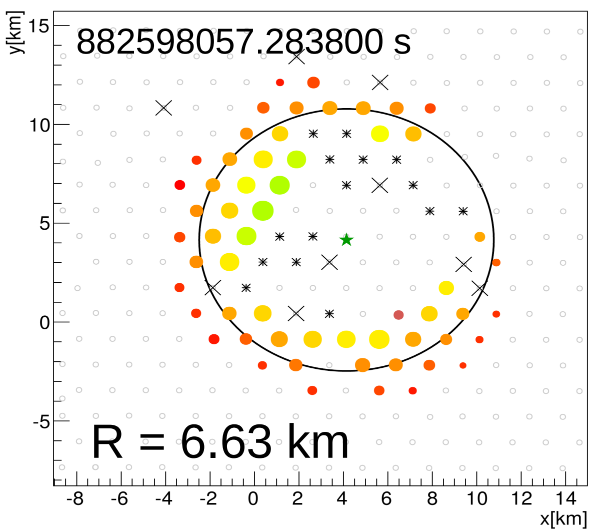
**GENERAL CHARACTERISTICS:**

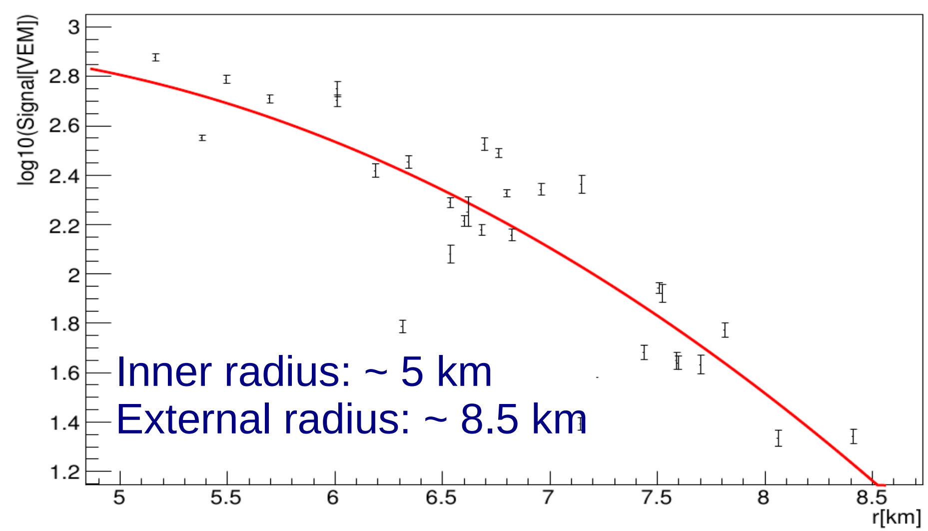
- rise time of the signal ($r_i\sigma_i$) smaller than fall time ($\sigma_i$ );
- $\sigma_i$ bigger than 2.5 μs.

# Signal vs distance from the center of the ring

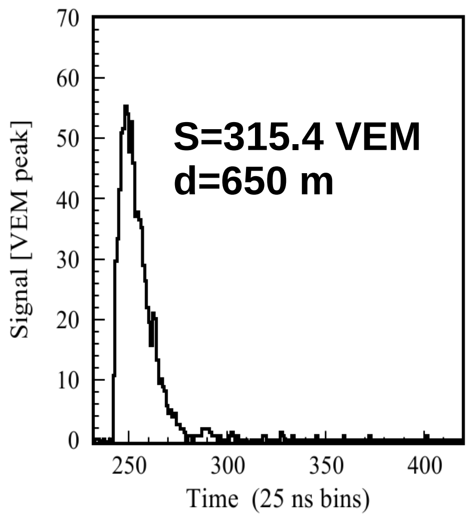


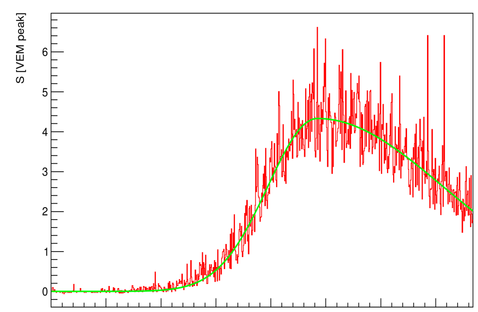



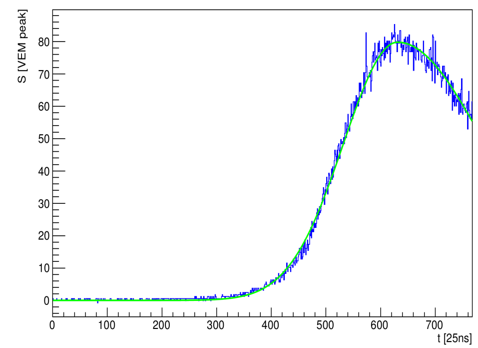



# Energy deposited at ground




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



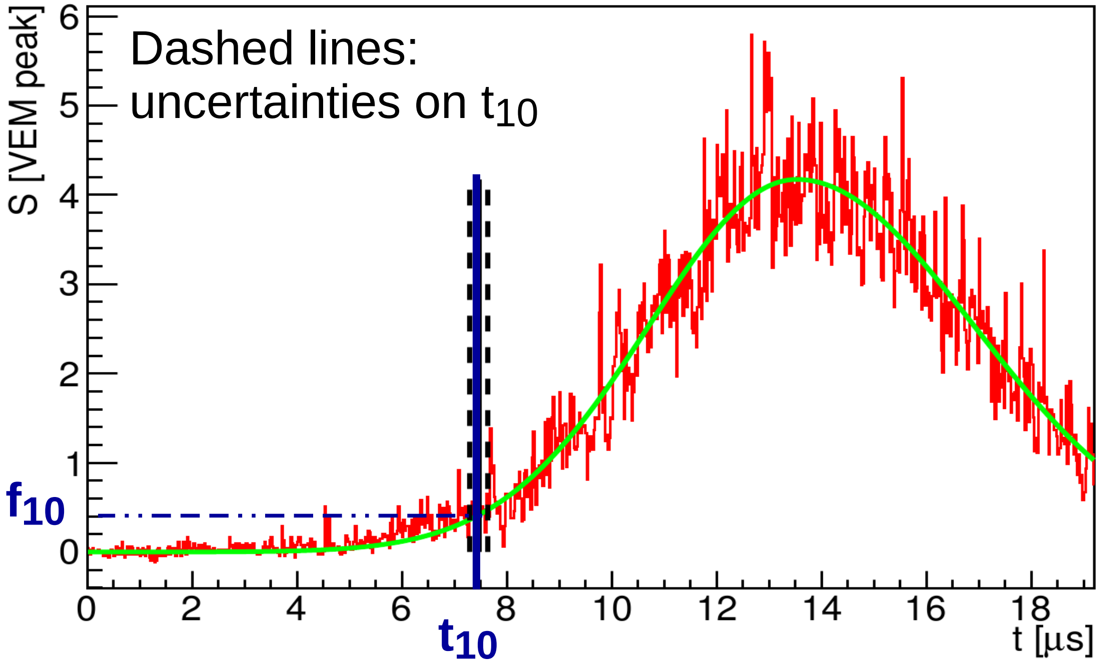

S=8038 VEM
E=1.93e+06 MeV
d=3417 m

1 VEM (Vertical Equivalent Muon) ~ 240 MeV

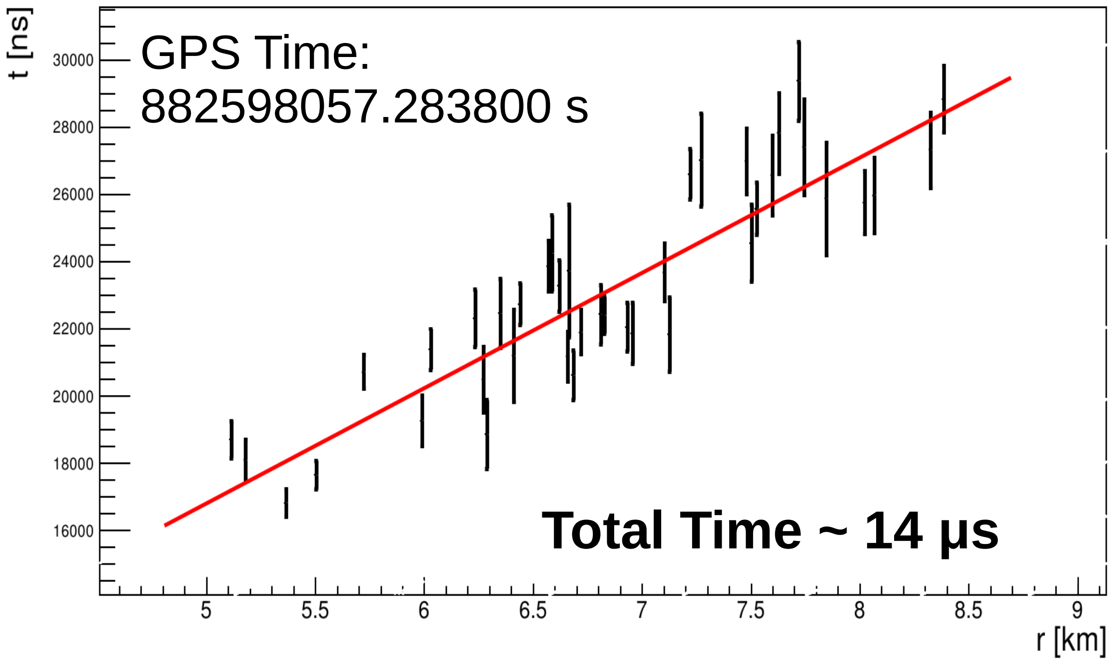
- The **energy deposited in each long signal station** spans **from ~$10^4$ MeV to ~$10^6$ MeV**.
- The **total energy of the event** spans **between $10^{17}$ and $10^{18}$ eV.**

**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.

# Time Evolution




The start time of each station is the sum of the event time and $t_{10}$, which is the time corresponding to the 10% of the value of the asymmetric gaussian in its peak.

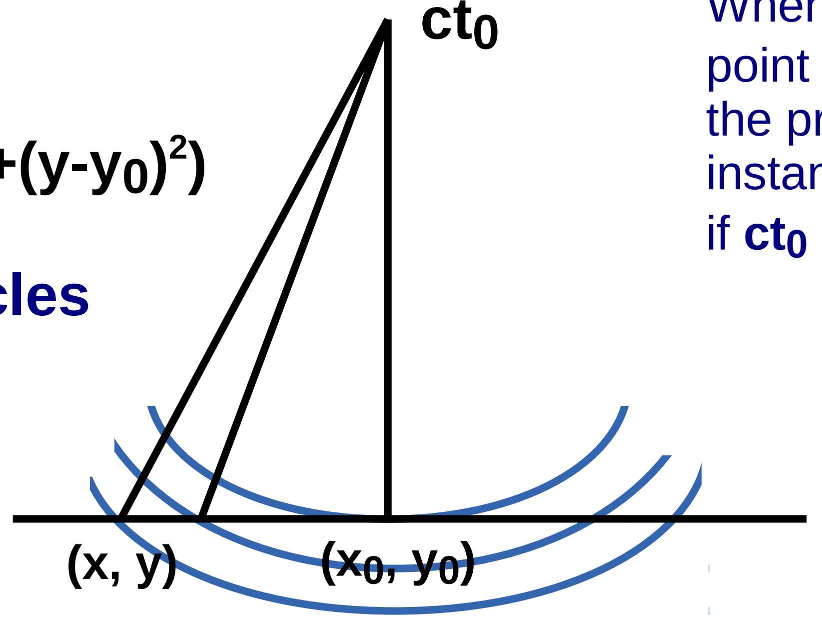



The event starts from the inner stations and then moves towards the external ones.

# Spherical Front

**$\mathrm{sqrt}((ct_0)^2+(x-x_0)^2+(y-y_0)^2)$**

**relativistic particles**




When $ct_0$ is big (the origin point of the event is very high), the propagation at ground is instantaneous ($v_{ground}$ > c),
if **$ct_0$ → 0, $v_{ground}$ → c**

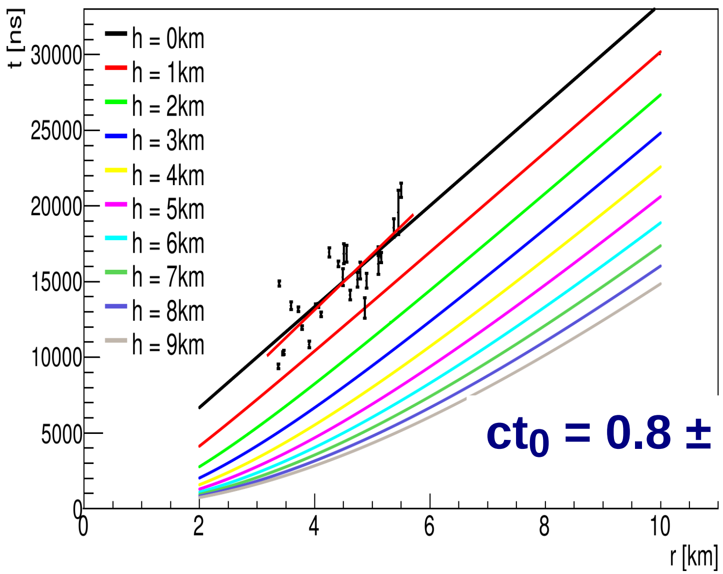
χ2 minimization: $\chi 2=\mathrm{Sum}( (t_{exp}-(t_{real}-t_{0ff}))^2/(t_{real\_err}*t_{real\_err}) )$
con $t_{exp}=\mathrm{sqrt}((ct_0)^2+(x-x_0)^2+(y-y_0)^2)/c$

4 parameters: **$x_0$, $y_0$, $ct_0$, $t_{0ff}$** <u>*$t_{real}$ = time_start_station*</u>

**$x_0$, $y_0$**, and **$ct_0$** → the coordinates of the origin point of the event
**$t_{0ff}$** → takes into account the offset between the event time and $t_0$

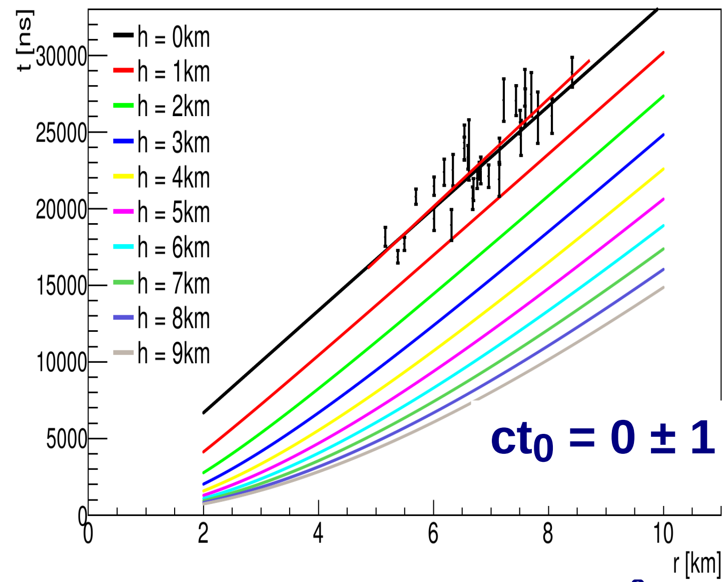
# Time Propagation

**Altitude of the origin point very low, compatible with a source at ground.**




**$ct_0$ = 0.8 ± 0.3 km**

**$V_{ground}$ = (2.8 ± 0.4) * $10^8$ m/s**




**$ct_0$ = 0 ± 1 km**

**$V_{ground}$ = (2.8 ± 0.3) * $10^8$ m/s**

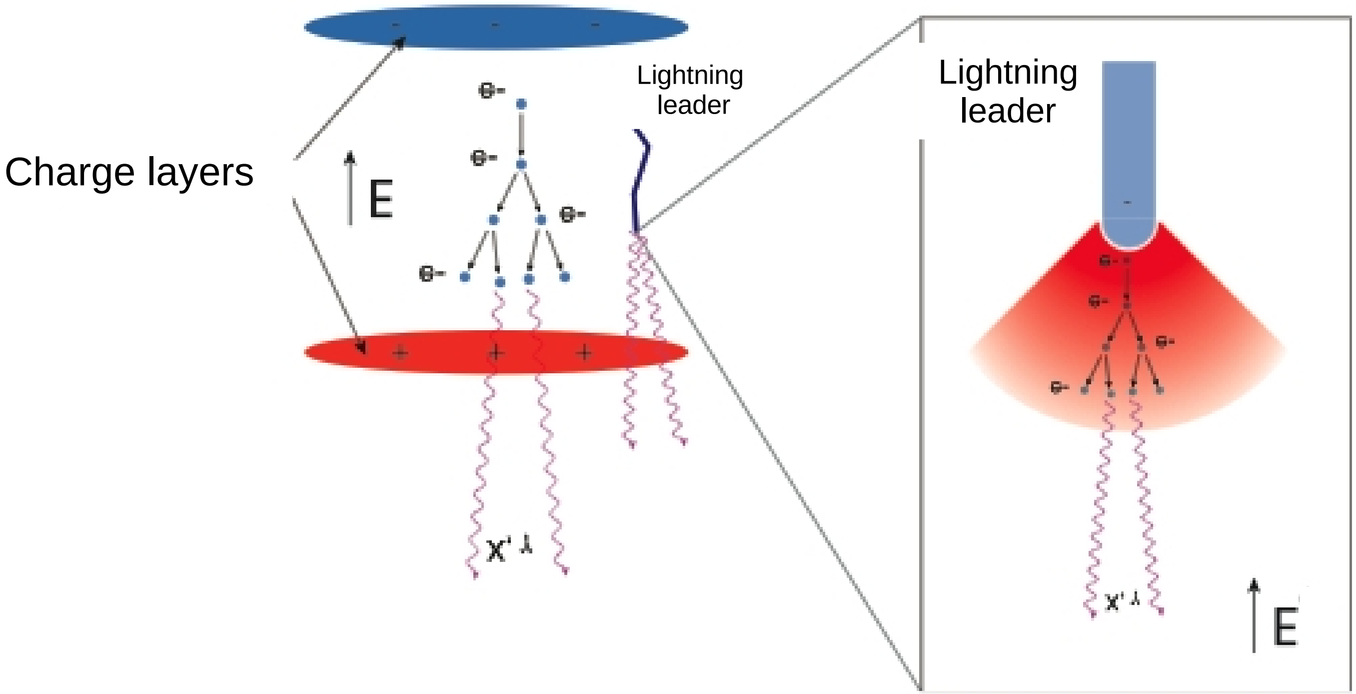
A simple MC assuming a spherical front was performed:

- origin point of the event fixed at different altitudes;
- for each impact point at ground, the distance from the origin point is calculated;
- assuming relativistic particles, the arrival time is obtained.

The simulated arrival times are represented by the colored lines
→ altitudes from 0 to 10 km.

**Subtracting $t_{off}$ from the measured arrival times, they superimpose to the simulated line corresponding to an origin point at 0 km.**

# 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?

- The event moves from the center of the circle to the external part, the observed timing is consistent with a spherical front expanding at the speed of light with an origin point very close to ground or to a cylindrical front. 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's your targeted physics in next decades?** (on this topic)

→ understand the atmospheric electricity physics behind the observed events;
→ investigate acceleration mechanisms still not well known related to rapid variations of electric fields.

**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.