The Surface Detector of the Pierre Auger Observatory and the observation of phenomena related to the atmospheric electricity

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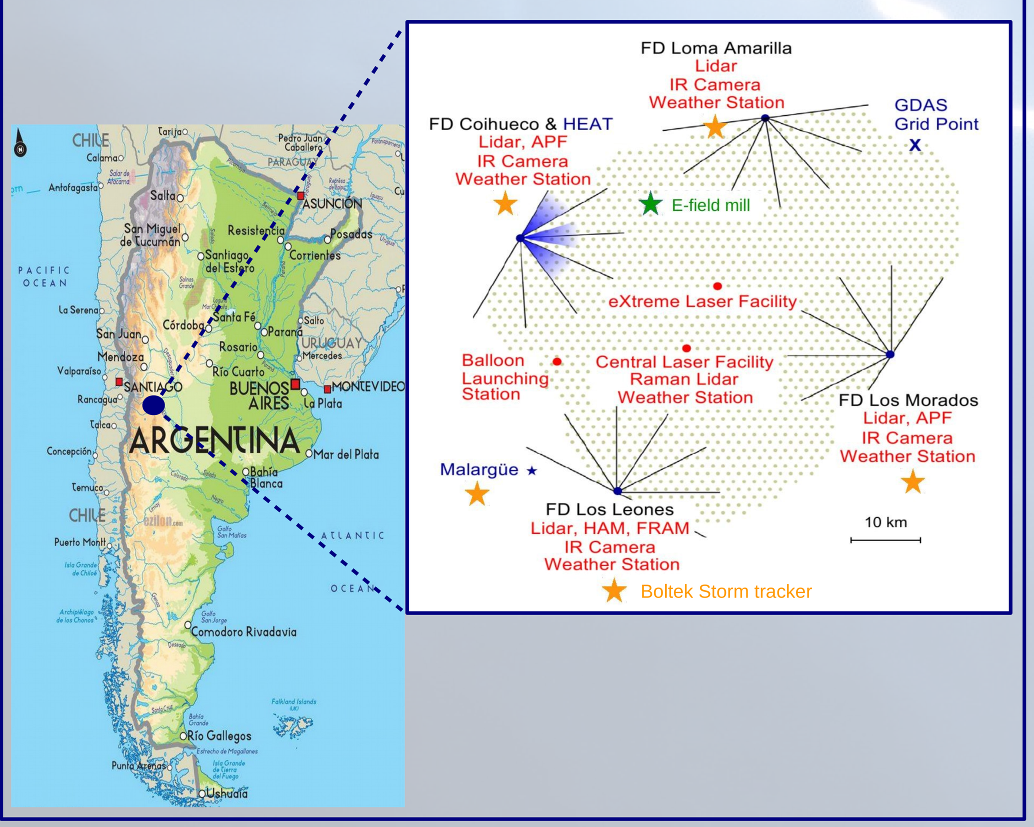
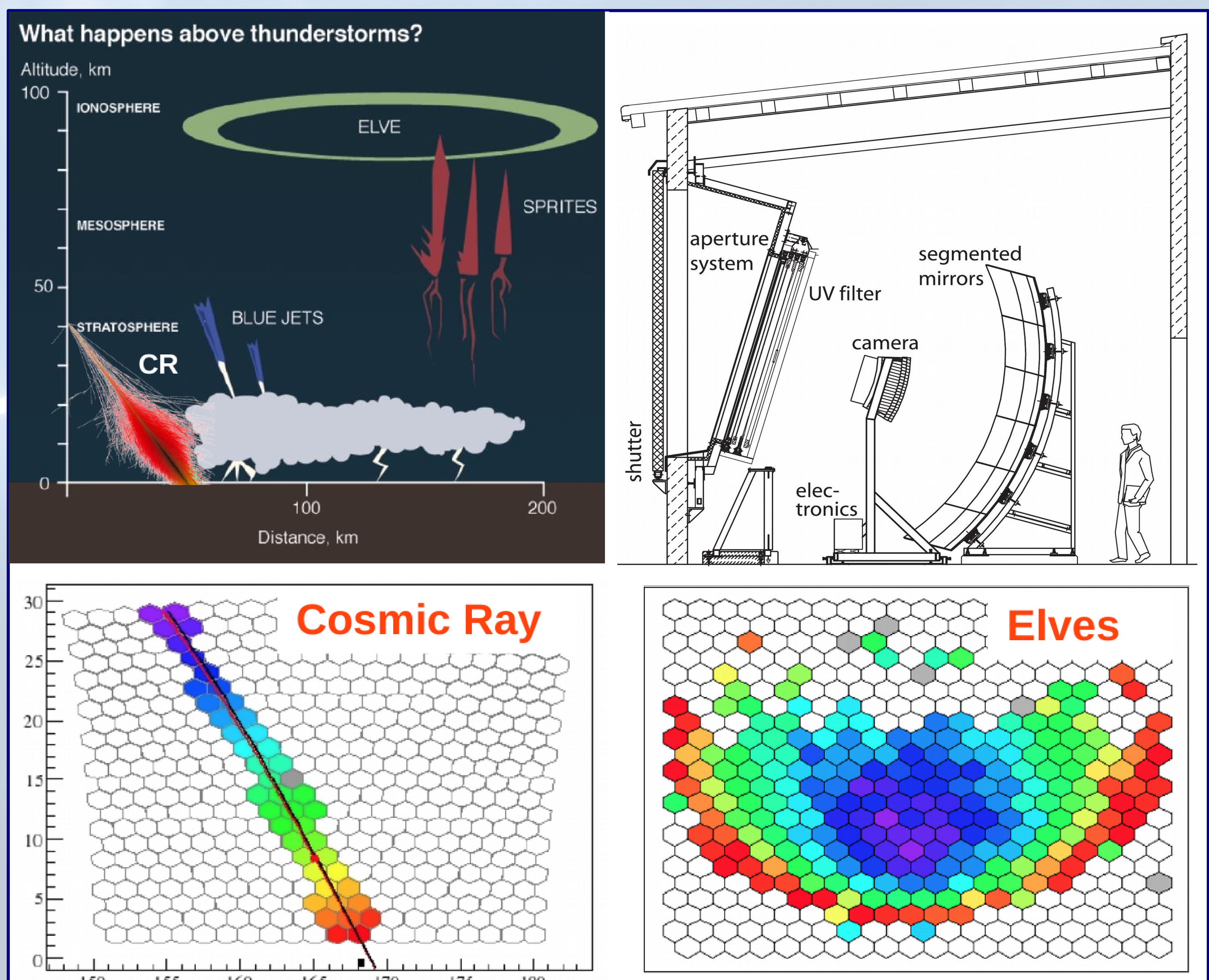
The Atmospheric Monitoring

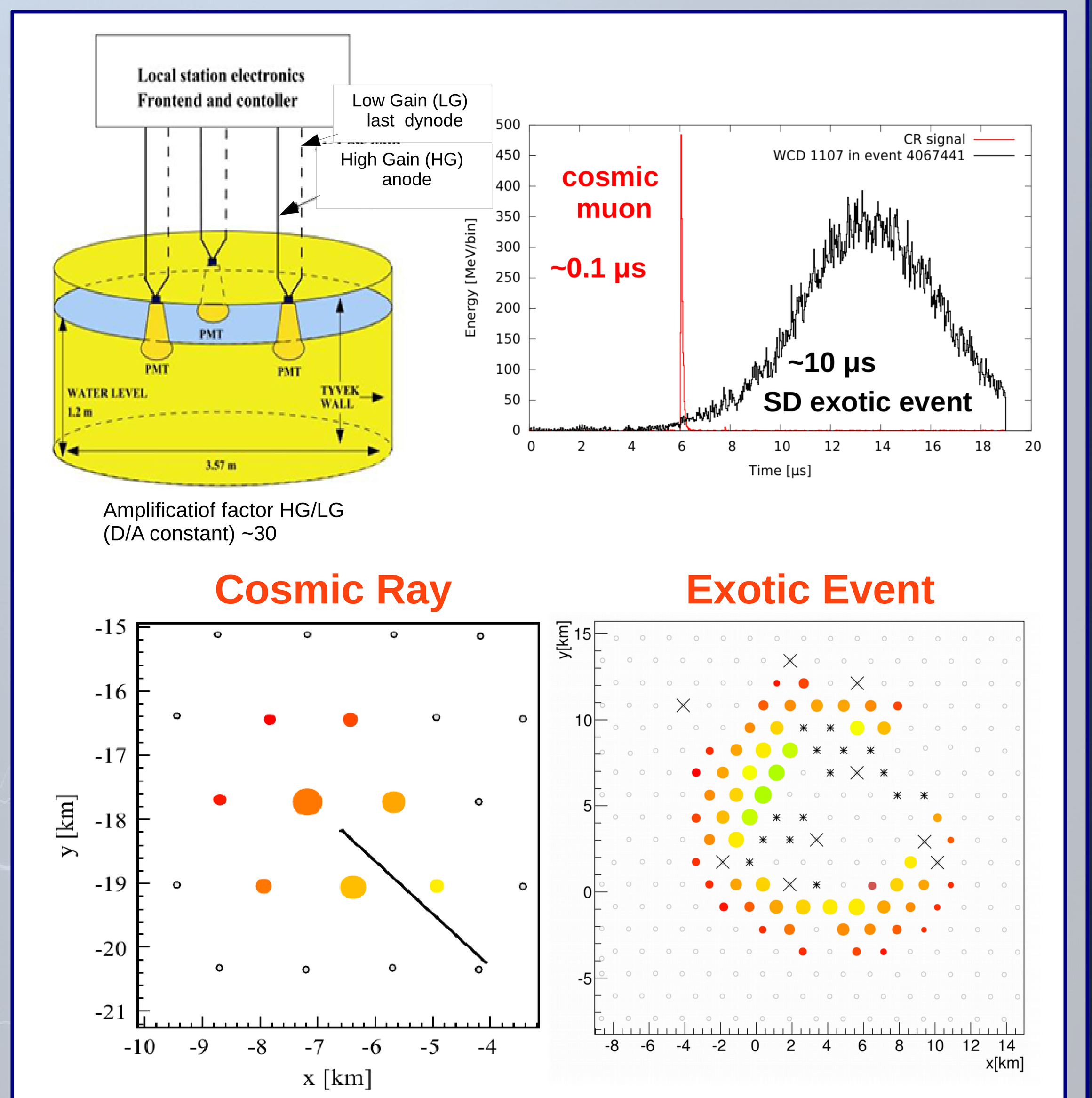
The Pierre Auger Observatory [1] is the biggest hybrid detector in the world designed to observe cosmic rays at the highest energies. The Observatory has a suite of devices for the atmospheric monitoring [2] being the atmosphere used as a large calorimeter. Moreover, it has turned out to be a valid instrument for studying transient phenomena related to atmospheric electricity. Instruments were added to measure the strength of electric fields in the atmosphere and to detect lightning strikes [3].



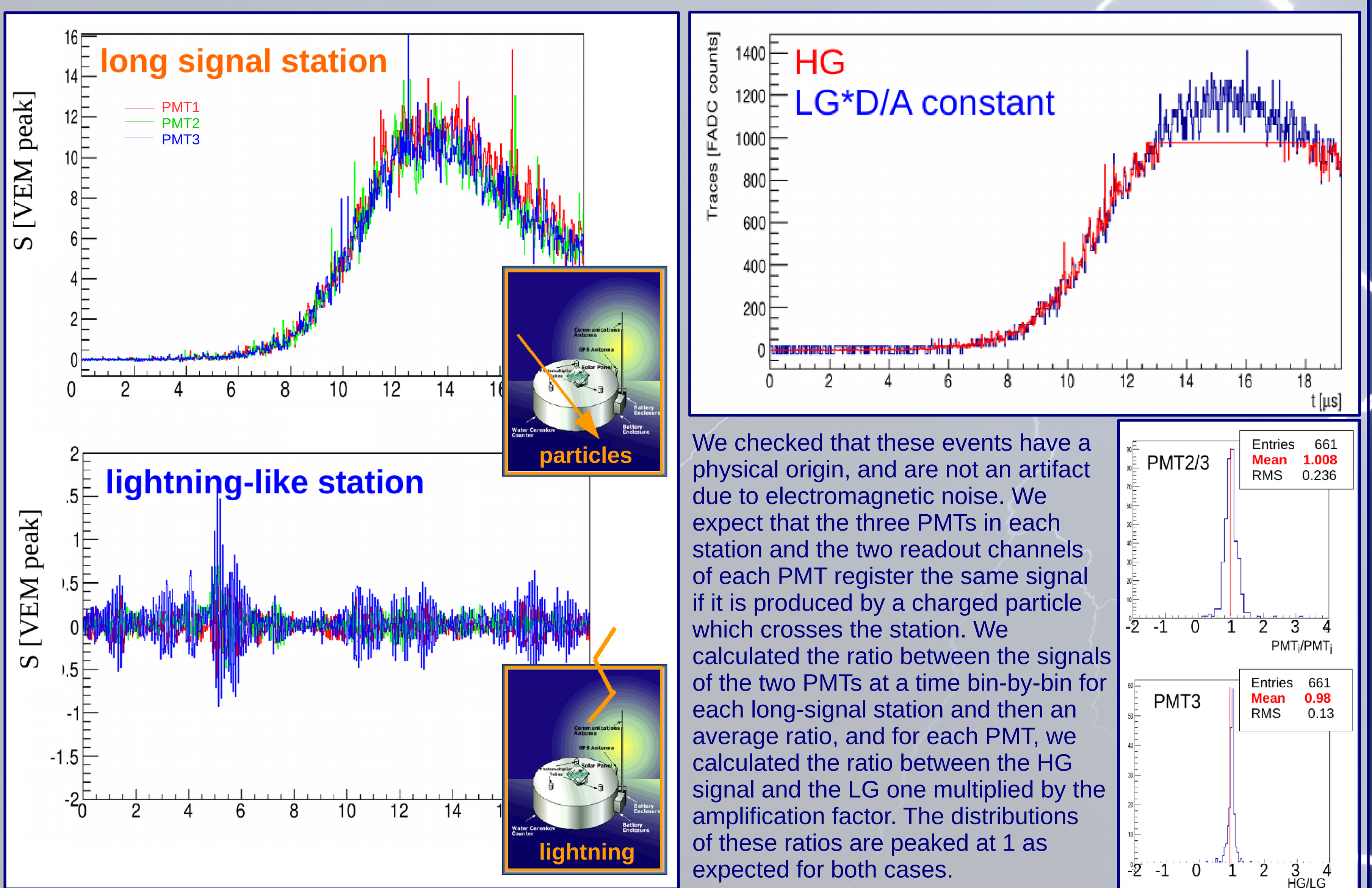
The Fluorescence Detector and the Elves Observation [4]



The Surface Detector and the Exotic Events [5]



The Typical Signals of the Exotic Events



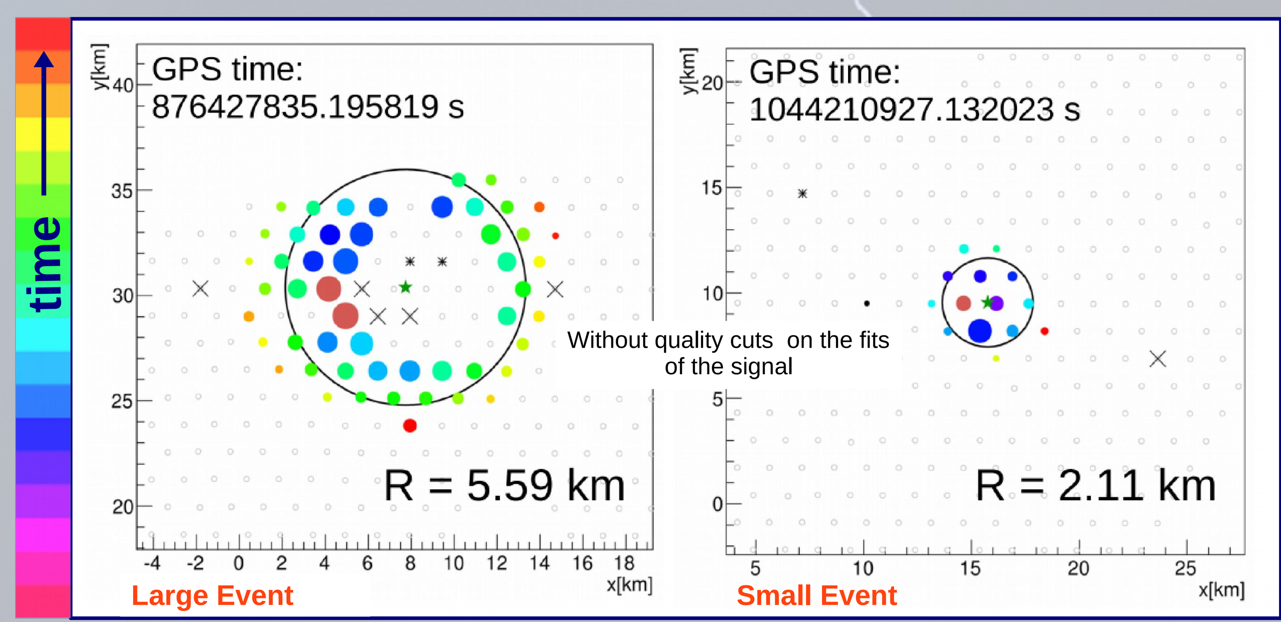
We checked that these events have a physical origin, and are not an artifact due to electronic noise. We expect that the three PMTs in each station and the two readout channels of each PMT register the same signal if it is produced by a charged particle which crosses the station. We calculated the ratio between the signals of the two PMTs at a time bin-by-bin for each long-signal station and then an average ratio, and for each PMT, we calculated the ratio between the HG signal and the LG one multiplied by the amplification factor. The distributions of these ratios are peaked at 1 as expected for both cases.

Large and Small Events

Typical footprints of our events: the colored circles represent the long-signal stations. The marker size is related to the intensity of the signal, the color to the arrival time. The asterisks represent the lightning stations, and the crosses the muon stations, which are not correlated in time with the long-signal stations.

Performing an unweighted chi-square minimization on the long-signal station coordinates, we found the center of the footprint and its radius.

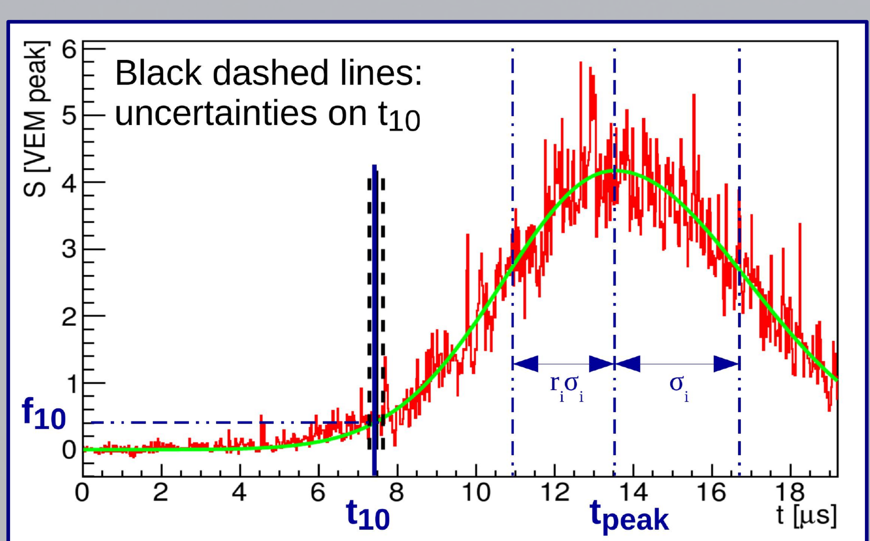
The small sample of our exotic events, about 30 events, selected among about 10^7 events collected by the SD asking at least one lightning station and ten long-signal stations, can be divided in two categories: the "large" and "small" events.



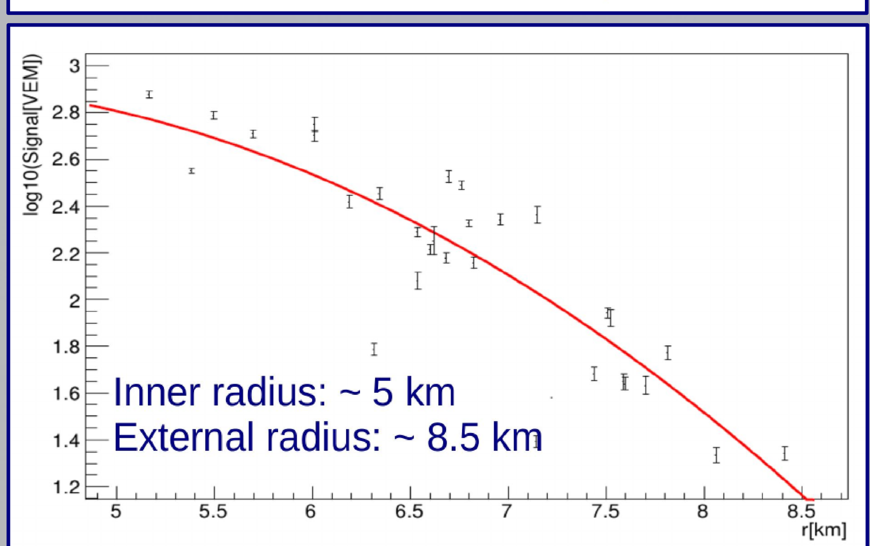
- The large events have more than 20 triggered stations and their radius spans from 4 to 8 km. A lack of the signal at the center of their footprint is visible. It could be related to physical reasons or to the Auger trigger, which is optimized to detect events with a very different signature.
- The small events have a compact footprint and their radius is about 2-3 km.

The presence of lightning stations with a signal dominated by high-frequency noise suggests that these events happen during thunderstorms. We verified this hypothesis searching for a correlation between our events and the lightning strikes collected by WWLLN (World Wide Lightning Location Network). We found a very good correlation in time and space.

The Characterization of Long Signals

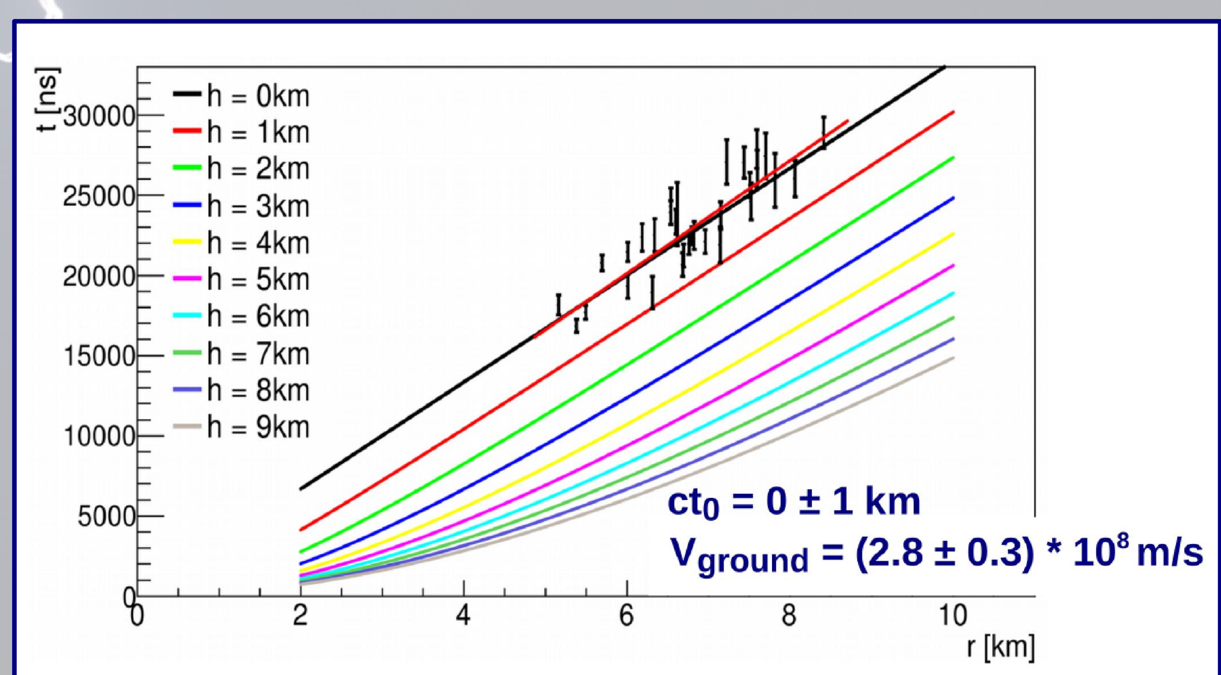


The long signals are not usually fully contained in the standard acquisition window. It is necessary to find a function which describes the signal to recover the missing part.
The best function resulted to be an asymmetric Gaussian.
A chi-square minimization is performed to fit the long signal detected by each PMT. A station is tagged as "good station" if the fitting procedure was successful for at least two PMTs. The signal detected by each PMT is given by the total integral of the fitting function.
The signal per station is the mean of the "good" signals.



The signal is bigger close to the center and decreases going towards the external stations. The logarithm of the signal as a function of the distance from the center is well described by a parabola.
The signal of each station can be transformed into deposited energy. We found that the energy per long-signal station spans from ~10^4 MeV to ~10^6 MeV, while the total energy deposited at the ground by an SD-ring varies between 10^{17} eV and 10^{18} eV. This energy is about two orders of magnitude higher than the energy deposited at the ground by a cosmic-ray shower initiated by a proton with energy 10^{19} eV.

The Time Evolution of the Propagation Front



We assumed that our events temporally develop according to a spherical propagation front.

- We performed a three-dimensional fit with four free parameters: x_0, y_0, and ct_0, that are the three coordinates of the source point of the event, and t_{Off}, which takes into account the offset between the starting time of the ideal event, t_0, and the GPS time of the real event. We obtained that **the altitude of the source never exceeds 1 km.**

- We compared our measured arrival times with the arrival times at the ground obtained by a simple geometrical Toy MC always based on a spherical propagation front. We calculated the arrival times for several altitudes of the source, from 0 to 10 km. Each colored line in the plot corresponds to an altitude. Subtracting t_{Off}, obtained with the three-dimensional fit, from the measured arrival times, we found they match the simulated times corresponding to an altitude of 0 km as expected.

- Finally, we calculated the value of the propagation velocity at the ground, that should be higher than the speed of light for a high source and equal to this quantity for a source at the ground. Fitting with a straight line the measured arrival time as a function of the distance from the center of the footprint, we found a velocity very close to the speed of light as expected.

Conclusions

Peculiar events related to lightning, characterized by long-lasting signals and very large footprint at the ground, were observed with the surface detector of the Pierre Auger Observatory. The signal expands radially at the speed of light and is bigger in the inner part of the disk and decreases with the increasing of the distance from the center. Moreover, the timing evolution of these events is compatible with a spherical front moving at the speed of light with a source very close to the ground. At this moment, we do not know which phenomenon can explain our observations. Detailed studies of the environmental conditions under which our events occur and comparisons with simulations are necessary to understand the origin of our exotic events.

Acknowledgements

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References

[1] Pierre Auger Coll., Nucl. Instrum. Meth. A 798, 172–213 (2015).
[2] B. Keilhauer, for the Auger Coll., EPJ Web Conf. 197, 02001 (2019).
[3] J. Rautenberg, for the Auger Coll., 34th ICRC, The Hague (2015).
[4] R. Mussa et al., EPJ Plus 127, 94 (2012).
[5] R. Colalillo, for the Auger Coll., 35th ICRC, Busan, Korea (2017).