Downward Terrestrial Gamma-ray Flashes at the Pierre Auger Observatory?

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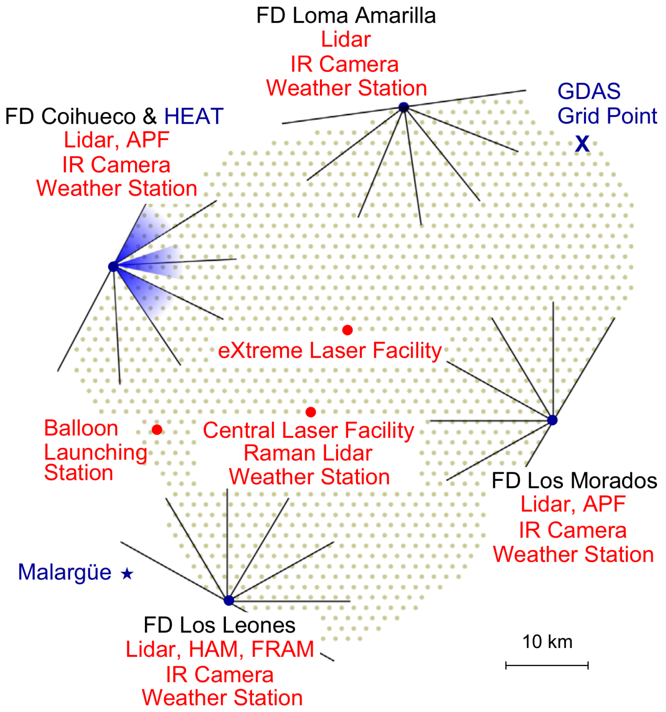
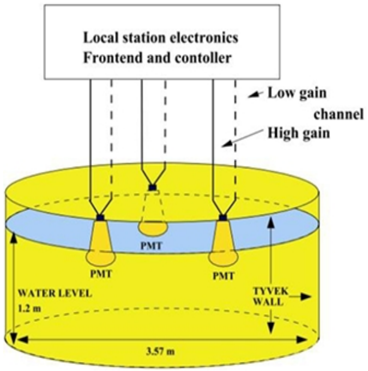
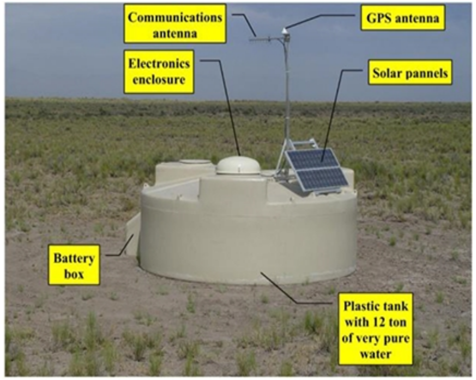
The Surface Detector of the Pierre Auger Observatory



@ 1400 a.s.l.
Hybrid technique:
fluorescence detector +
surface detector

1600 water-Cherenkov detectors are used to sample the electrons, photons and muons of the showers.



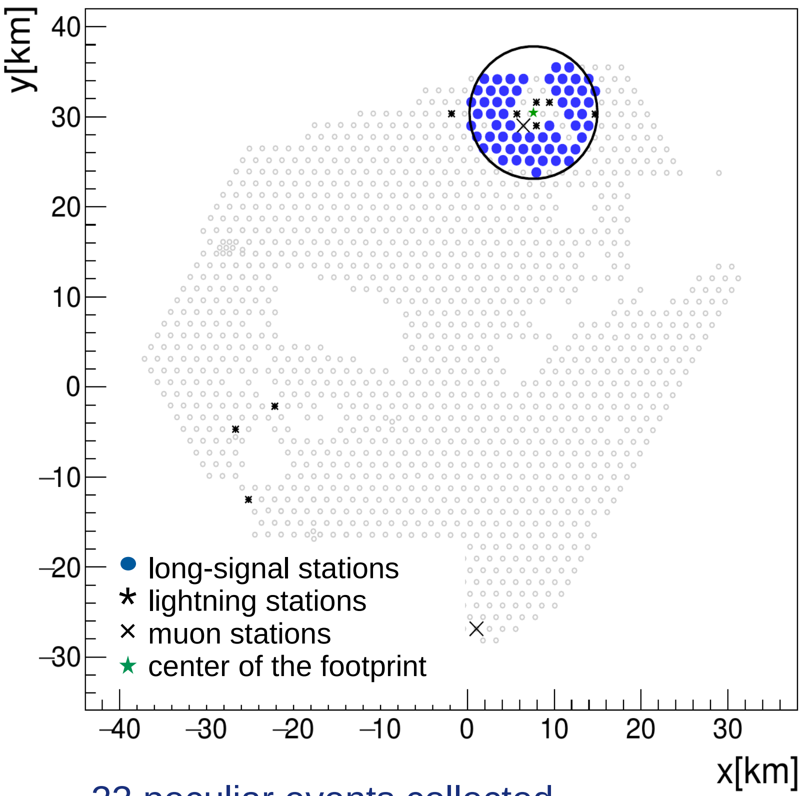


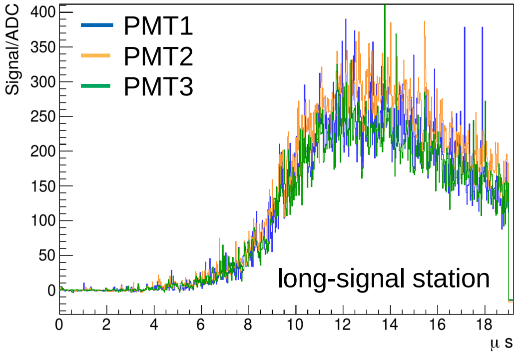
The Cherenkov signals in each SD station are collected by three PMTs and digitised using 40 MHz, 10-bit Flash Analog-to-Digital Converters (FADCs).

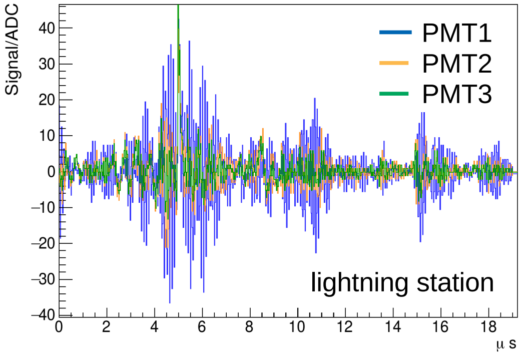
The DAQ window lasts 19.2 μs.

→ Local data acquisition generates low-level triggers @ 20 Hz
→ The timing of each local trigger is sent to the central data acquisition system (CDAS), which searches for spatial and temporal correlations among all triggered stations.

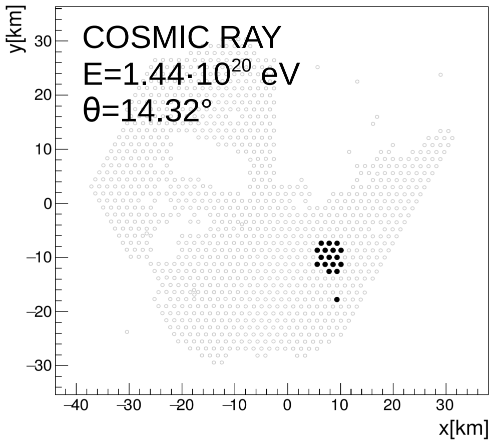
“SD-ring” events: comparison with cosmic-ray events

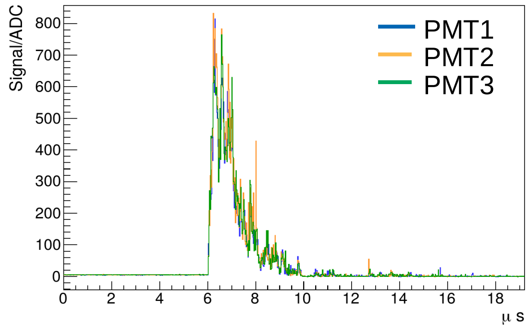


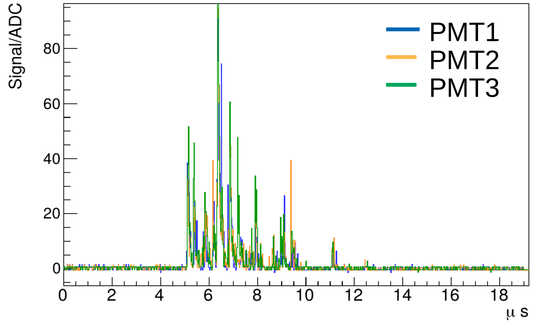




23 peculiar events collected.

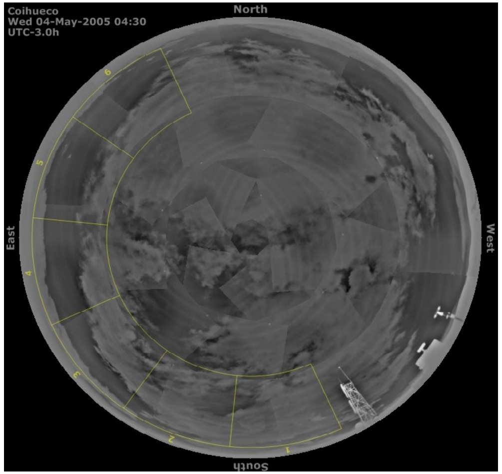


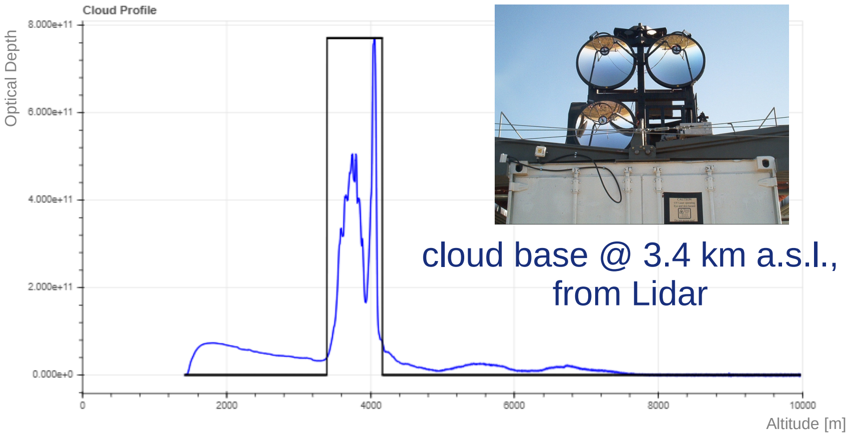




“SD-ring”events: weather measurements

IR Cloud Camera





cloud base @ 3.4 km a.s.l., from Lidar

The presence of lightning stations suggests that lightning activity had happened at the time of the event

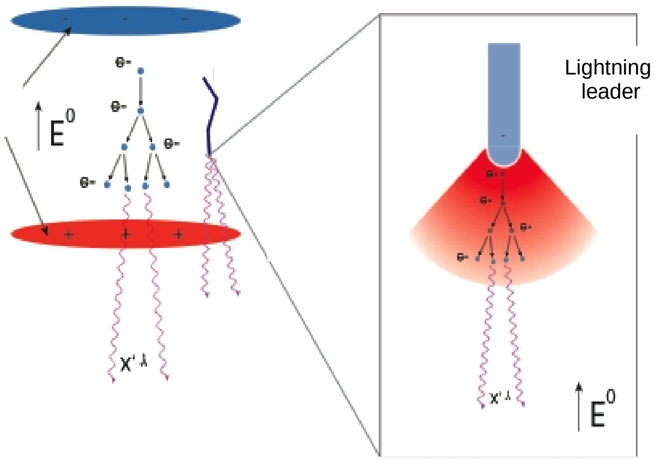
→ correlation with lightning strikes collected by the World Wide Lightning Location Network (WWLLN).

As the Observatory makes use of the atmosphere as a giant calorimeter, several atmospheric-monitoring facilities are available. They operate only during the nightly data-taking of the Fluorescence Detector:

→ a 100% cloud coverage some hours before and/or after the event from cloud cameras;
→ in many cases, clouds at ∼2 km above ground level from LIDARs and lasers.

Our peculiar events occurred during bad weather and with very low clouds.

"SD-ring" events: are they downward TGFs?



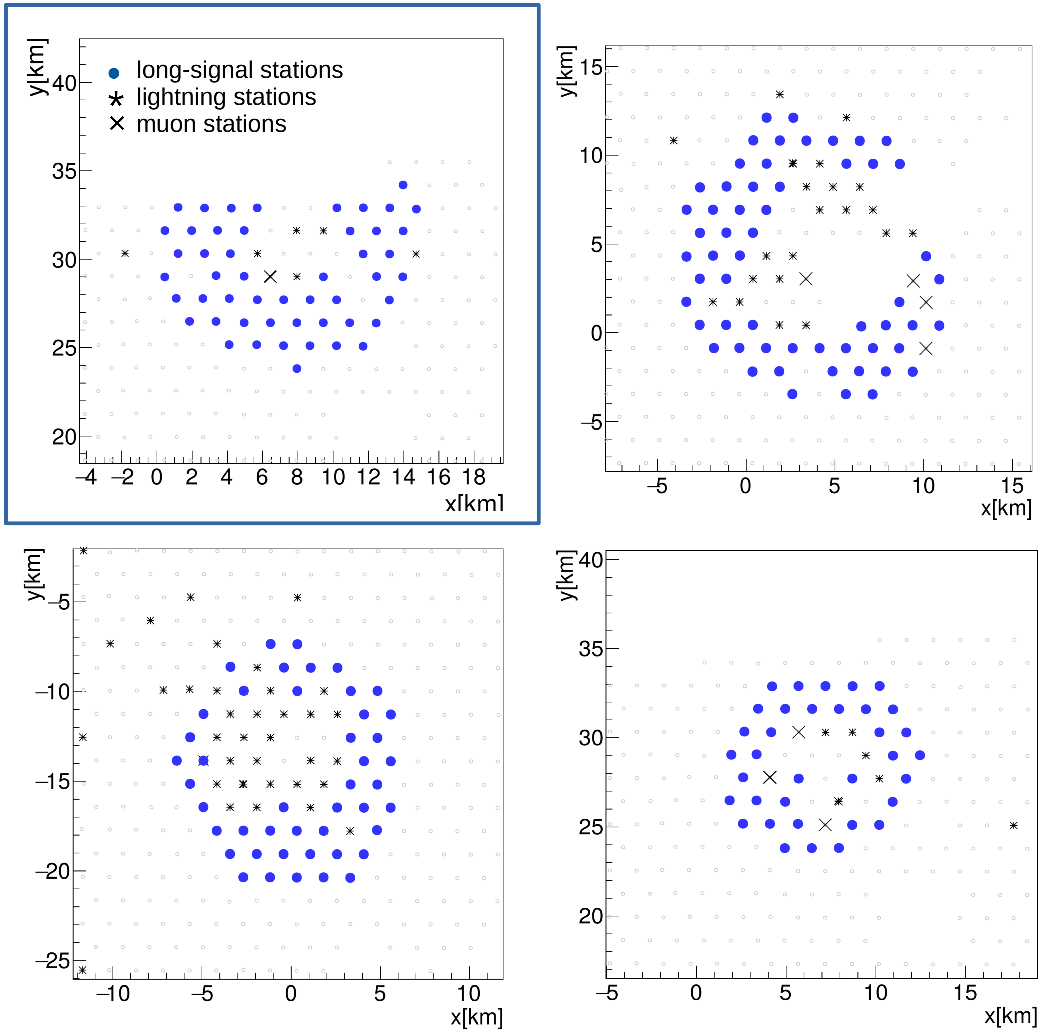
A TGF is a burst of high-energy photons originating in thunderstorms. The emission is generated, via bremsstrahlung, by energetic runaway electrons accelerated by the electric fields in thunderclouds

→ usually observed from space
(G. J. Fishman et al., June 1994Science 264(5163):1313-6)
→ simultaneous observation of TGFs and elves
(T. Neubert et al., Science, Vol. 367 (2020), Issue 6474, pp. 183-186)
→ indication of downward TGFs, occurring during strong initial breakdown pulses in the first few milliseconds of negative cloud-to-ground and low-altitude intra-cloud flashes
(J. Remington for **Telescope Array Collaboration**, these proceedings;
Y. Wada et al. - **GROWTH Collaboration**, Phys. Commun. 2 (2019) 67)

Lightning-leaders do not propagate in a continuous manner, but instead progress in a series of discrete "steps"
→ the typical duration of the process is of the order of a millisecond
→ the inter-step intervals last some tens of μs.

TGFs can easily saturate detectors far from the source.

“SD-rings” or NOT?



The most puzzling feature of many peculiar events is the **lack of signals in the center of the footprint**
→ ***SD-rings***

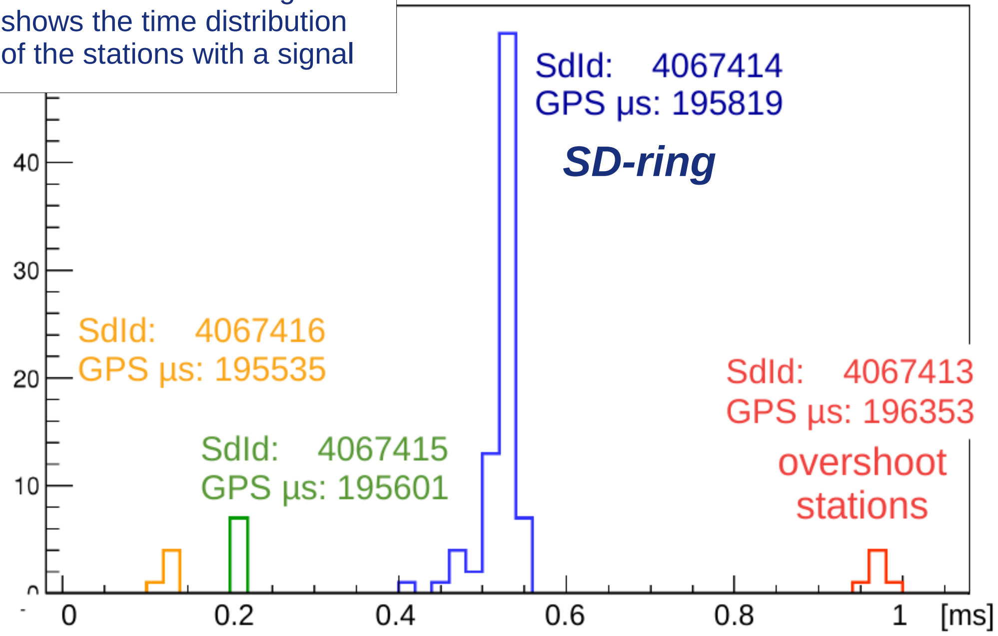
Moreover, SD-rings seem to show a **longer and more complex time and space evolution than air showers**.

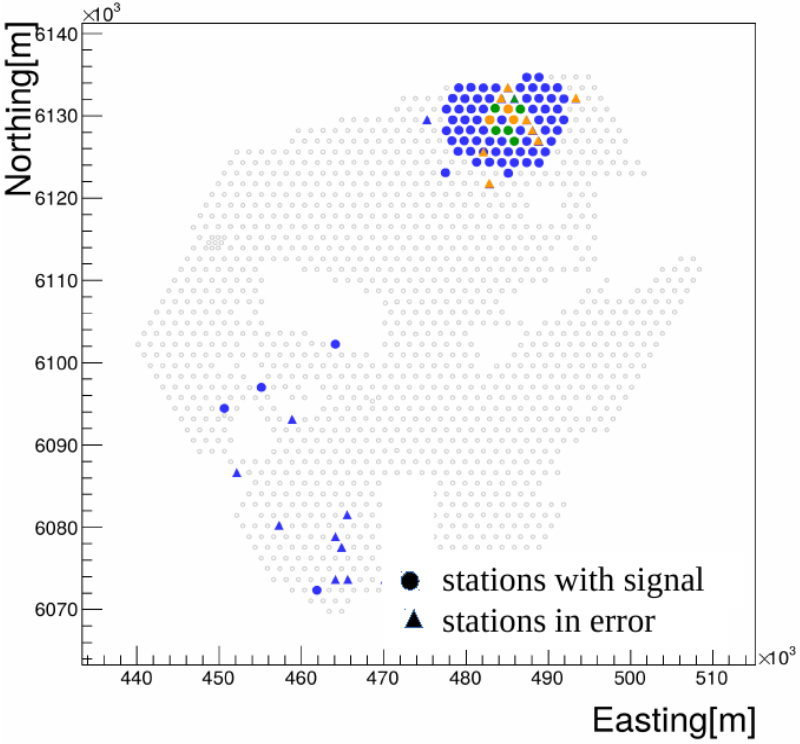
Investigations are necessary to establish if the “missing signal” in the center is an artifact due to electronics, or trigger or data acquisition, or post-acquisition processing of the Observatory, optimized for the detection of air showers.

Search for “missing signals”: the two preceding events

→ We searched for additional triggers in a time interval of ±2.5 ms with respect to the SD-ring time
→ we found accompanying events for all the identified SD-rings

Each of the four histograms shows the time distribution of the stations with a signal





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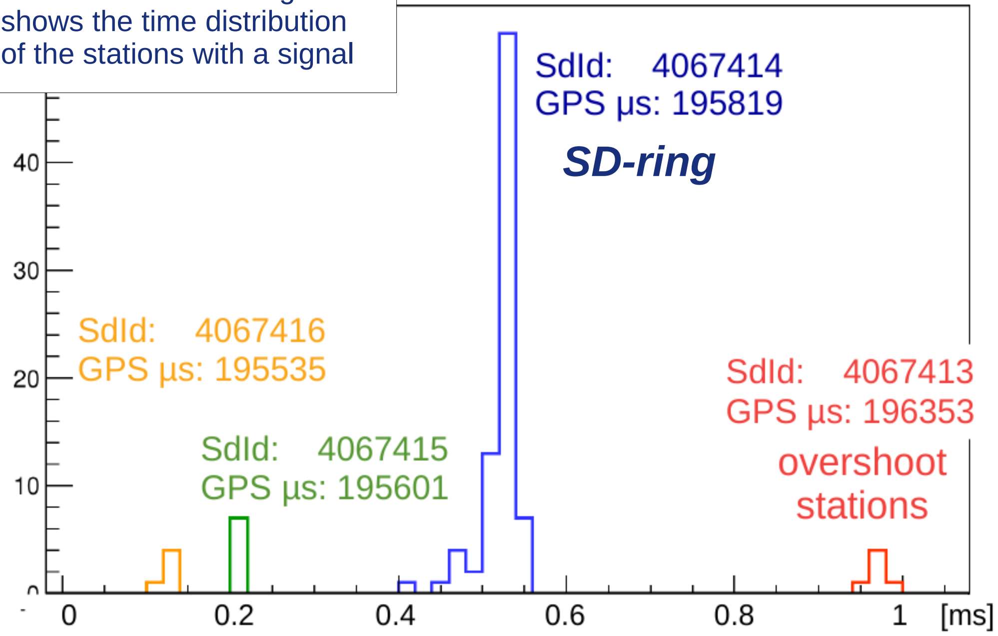
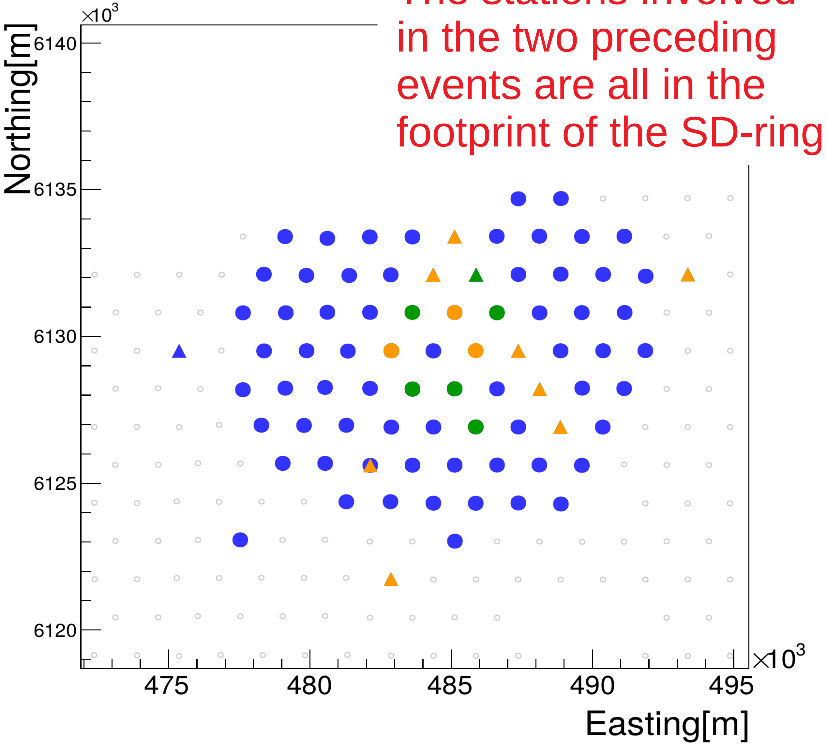


The stations involved in the two preceding events are all in the footprint of the SD-ring



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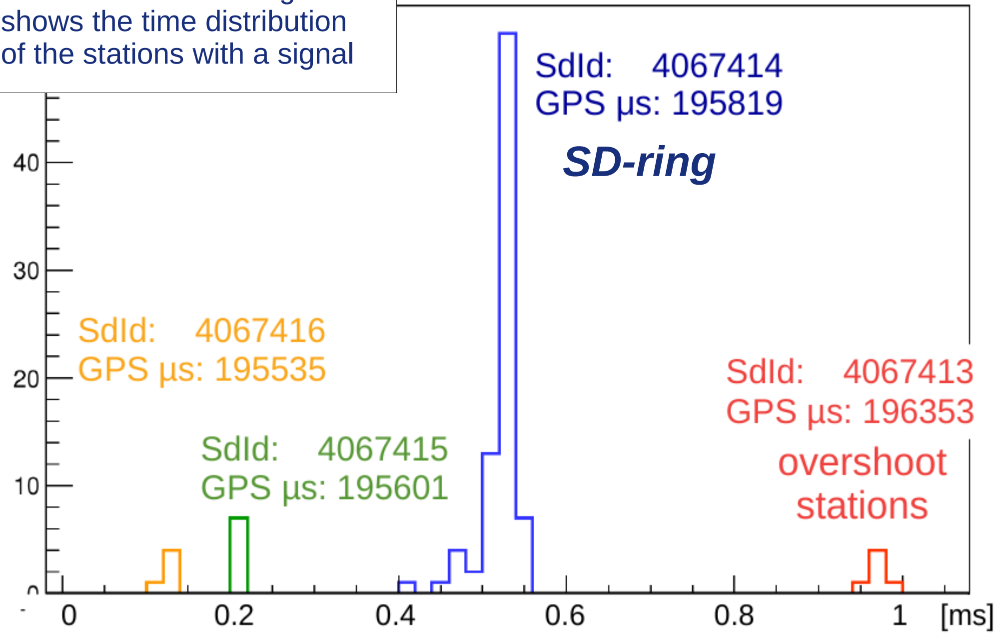
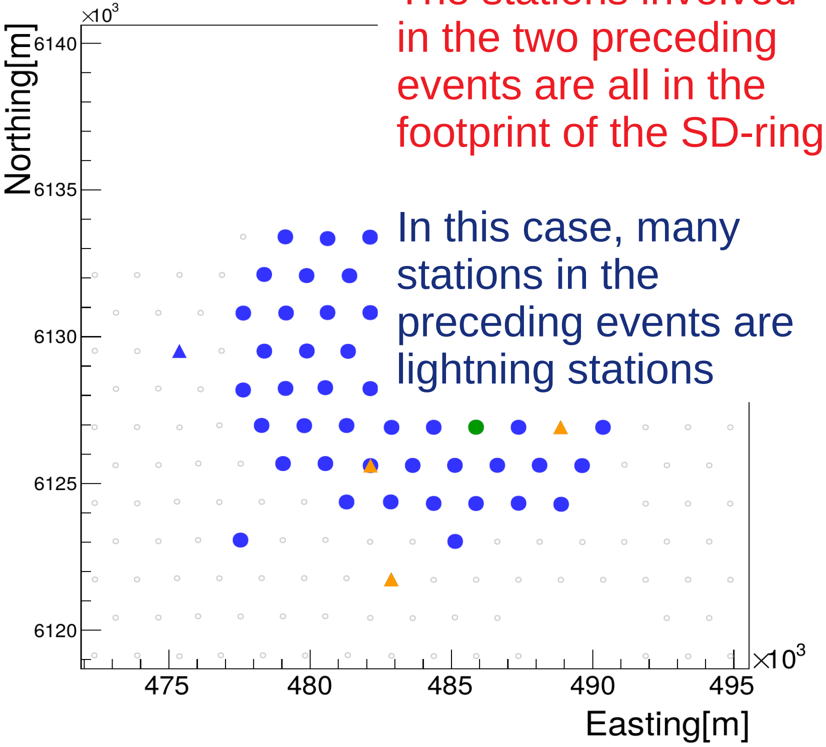
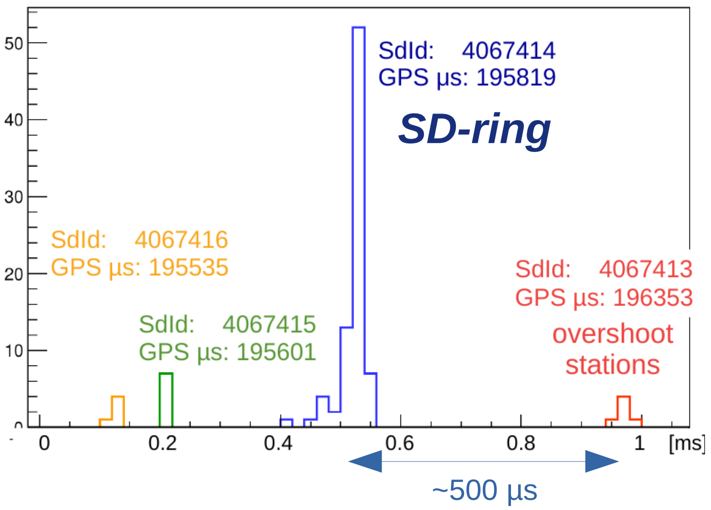


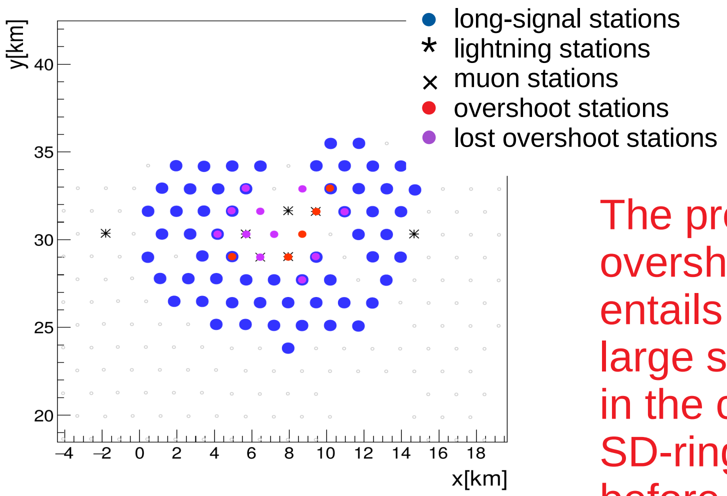


The stations involved in the two preceding events are all in the footprint of the SD-ring

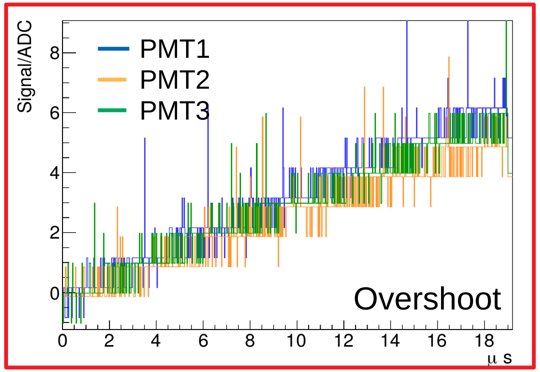
In this case, many stations in the preceding events are lightning stations

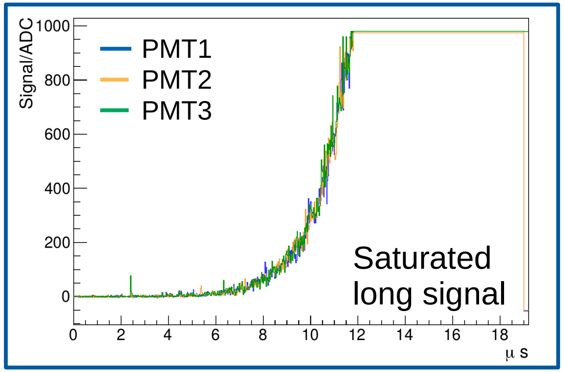
Search for "missing signals": the following event





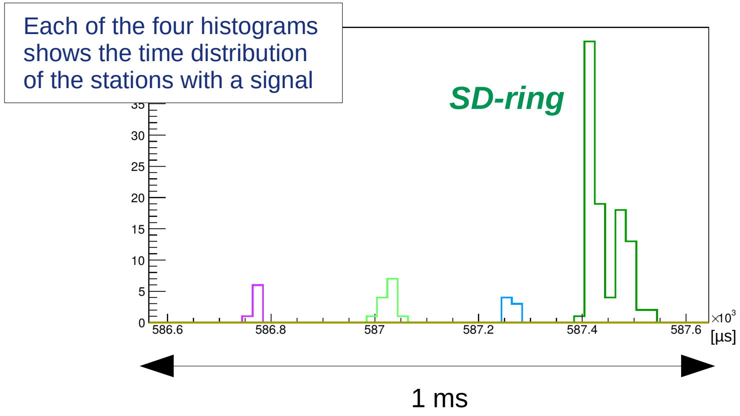
The presence of overshoot signals entails the presence of large saturated signals in the center of the SD-ring footprint 500 μs before.

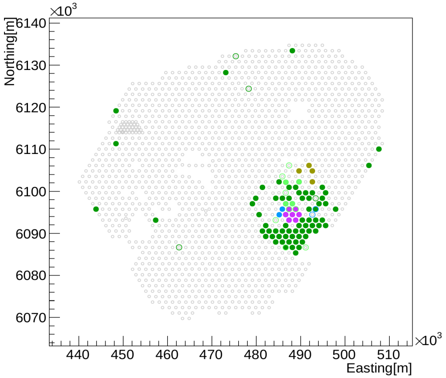


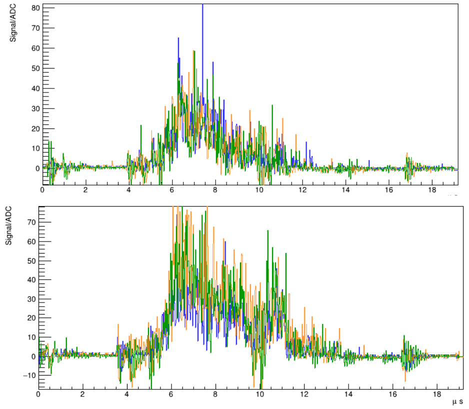


All the studies shown up to now allow us to conclude that the central hole in SD-rings is very likely an artifact of the trigger and acquisition chain.

A zoology of observations





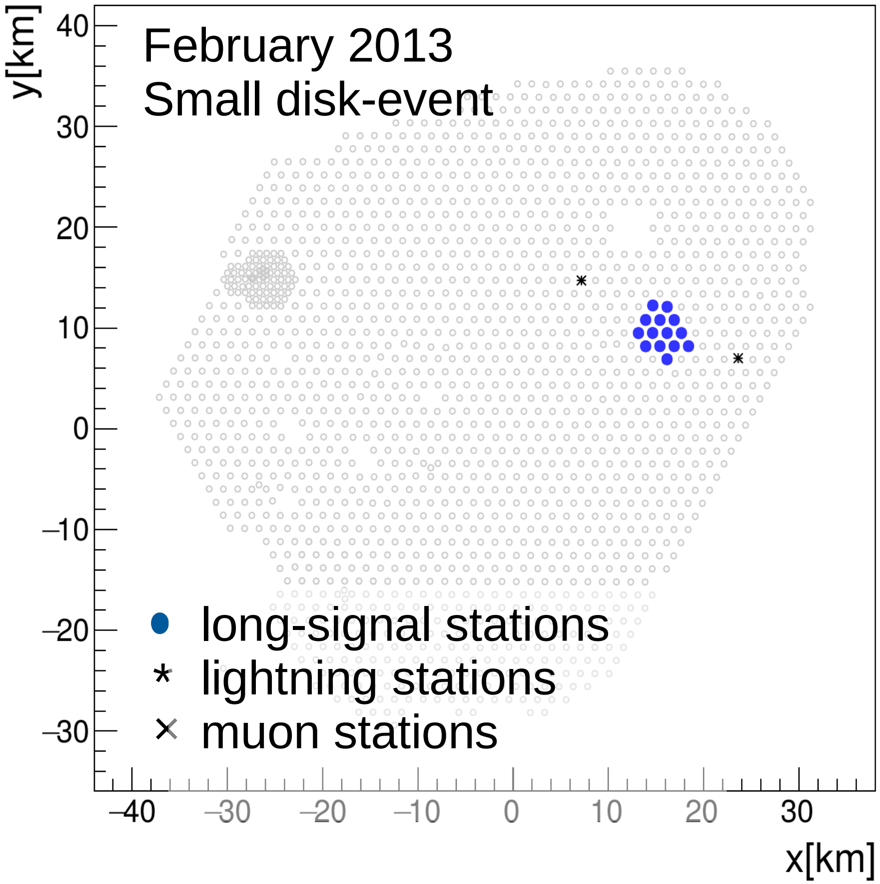


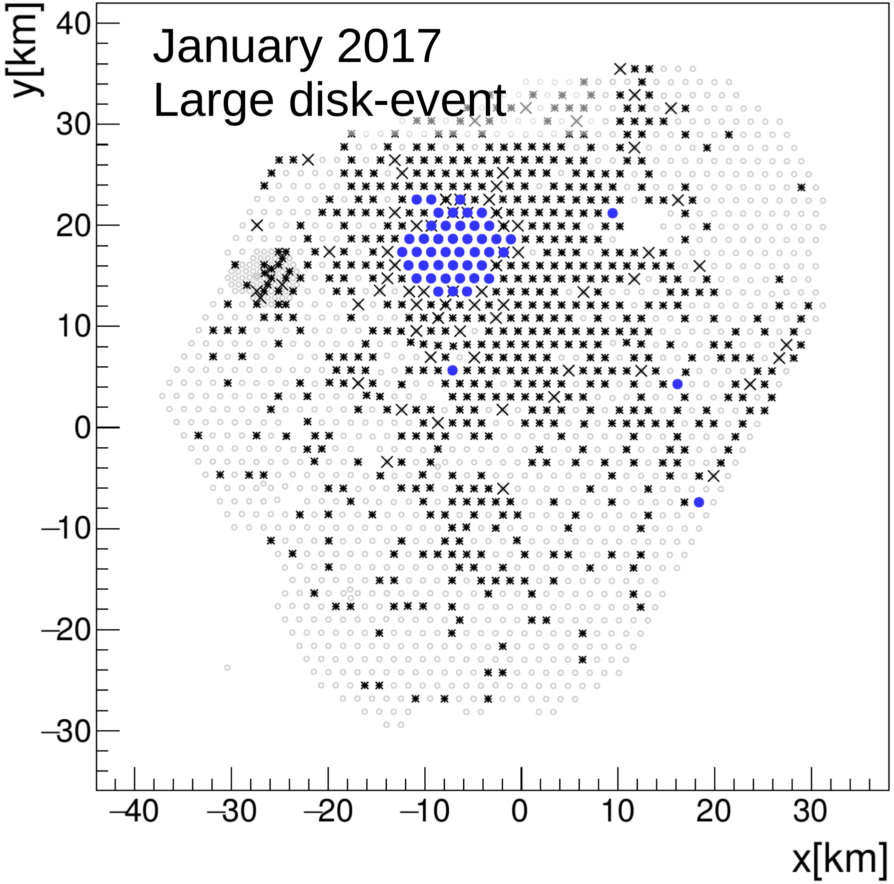
For other events, in the events preceding the SD-ring, there are also stations with long signals.

SD-rings and their accompanying events don't show a causal connection with a single point-source. Anyway, the fact they happen in the very same region of the array, and in a very short time, hints at a common source generated by a phenomenon with a long time evolution.

The peculiar events are dominated by SD-rings, but we observed also events with a compact footprint → SD-disks

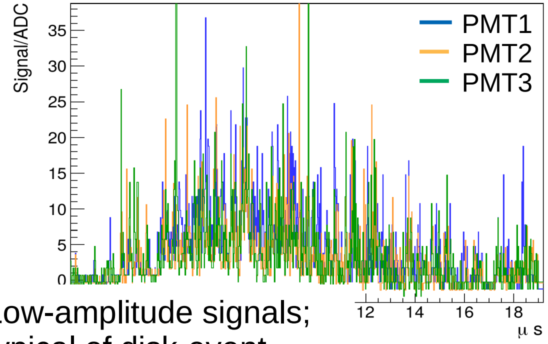
“SD-Disk” events



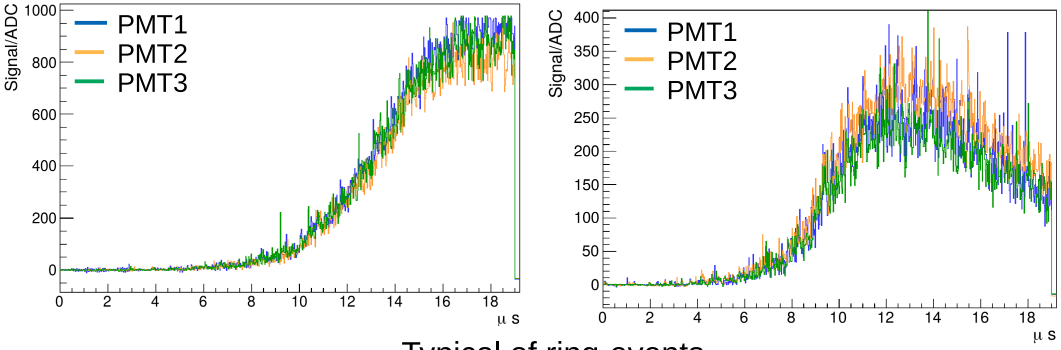


“SD-Rings” “SD-Disks”

1. SD-Disks have all stations with a very low-amplitude signals



Low-amplitude signals;
typical of disk-event



Typical of ring-events

2. SD-Disks don’t have accompanying events in the same ms

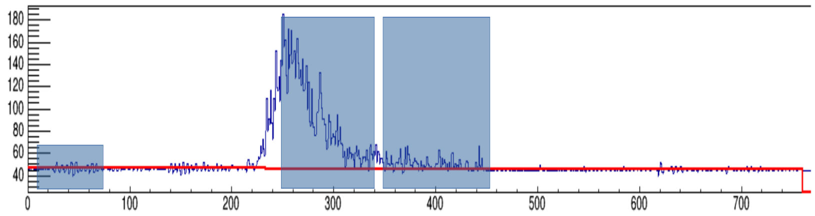
3. SD-Disks have smaller energy deposit: raw energy deposit estimation
→ SD-disks or small SD-rings (radius < 3 km) are characterized by an energy deposit from 500 to 1700 MeV/m^2 ,
while for the SD-rings with a larger footprint the deposits range from 3000 to 6500 MeV/m^2 .

New read-out trigger

The central hole in SD-rings is very likely an artifact of the trigger and acquisition chain, optimized for comic-ray showers.
This conclusion motivated the development of an ad-hoc local trigger to change the read-out and improve the detection of our peculiar events.

Moreover, it is important to increase the statistics. In 18 years, we collected only 23 peculiar events, less than 2 events/year.

Giving priority to the subset of events that contain long signals in the CDAS read-out will help to
reduce the loss of SD-rings
→ necessity to tag online long signals



compare integrals
→ more efficient for low-amplitude signals than a FADC threshold trigger

Conclusions and perspectives

Link between our peculiar events and TGFs:

→ accompanying events within 1 ms of all of our SD-rings;
→ the main single trigger (SD-ring) covers tens of microseconds.
These observations are compatible with the evolution of the lightning leaders associated with TGFs.

→ the presence of low clouds at the time of some of events is consistent with the expectations for downward TGFs.

→ the observed peculiar events seem to be intense phenomena, with energy deposits two orders of magnitude larger than in a vertical shower initiated by a particle of 10^{19} eV.

Collect new events and increase the statistics is fundamental to better understand these events and their origin:

→ comparison with data from instruments recently installed at the observatory that can monitor lightning and electric field at the ground;
→ comparison with data from AERA antennas;
→ comparison with simulations.