The observation of lightning-related events with the Surface Detector of the Pierre Auger Observatory

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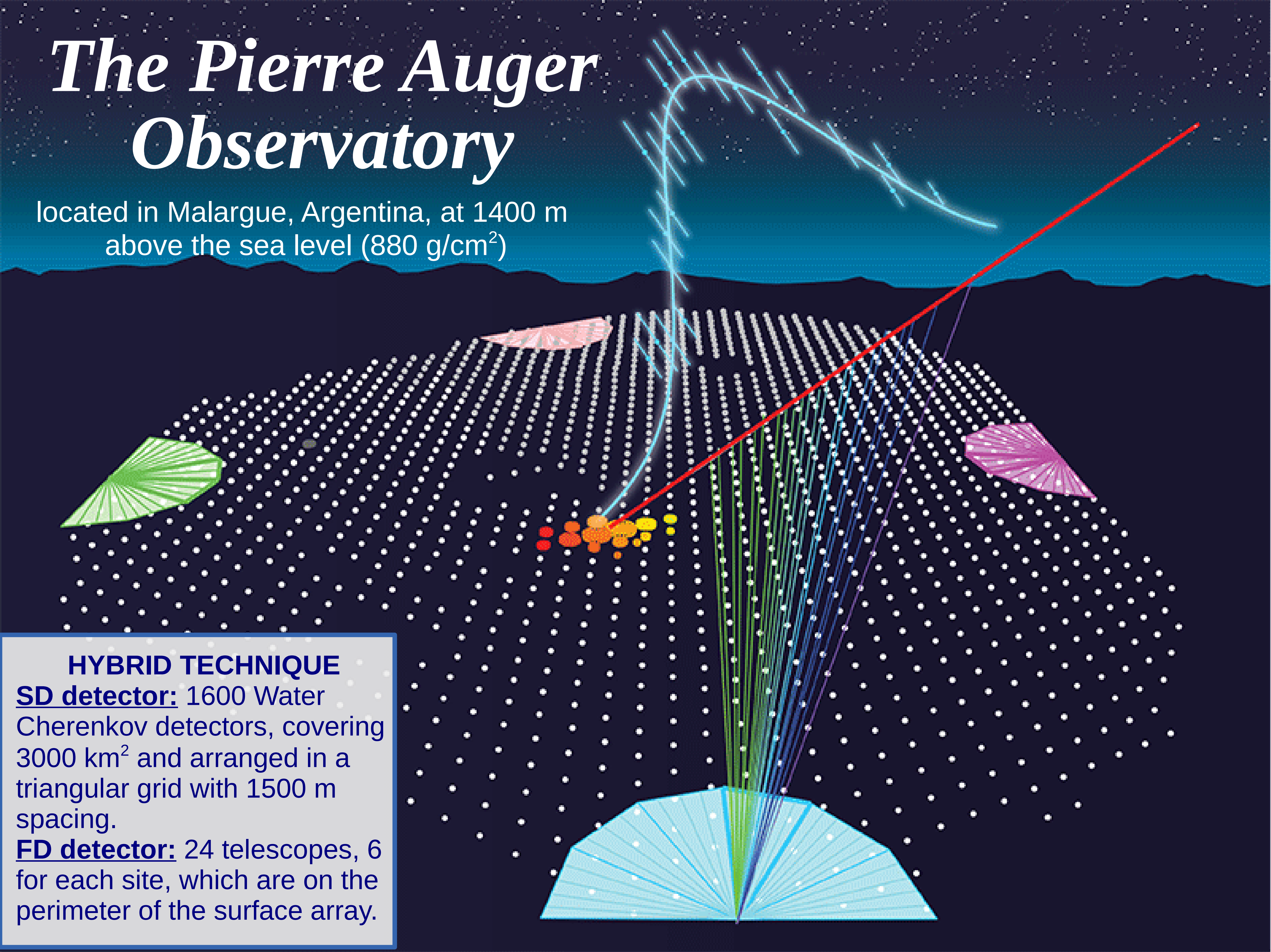
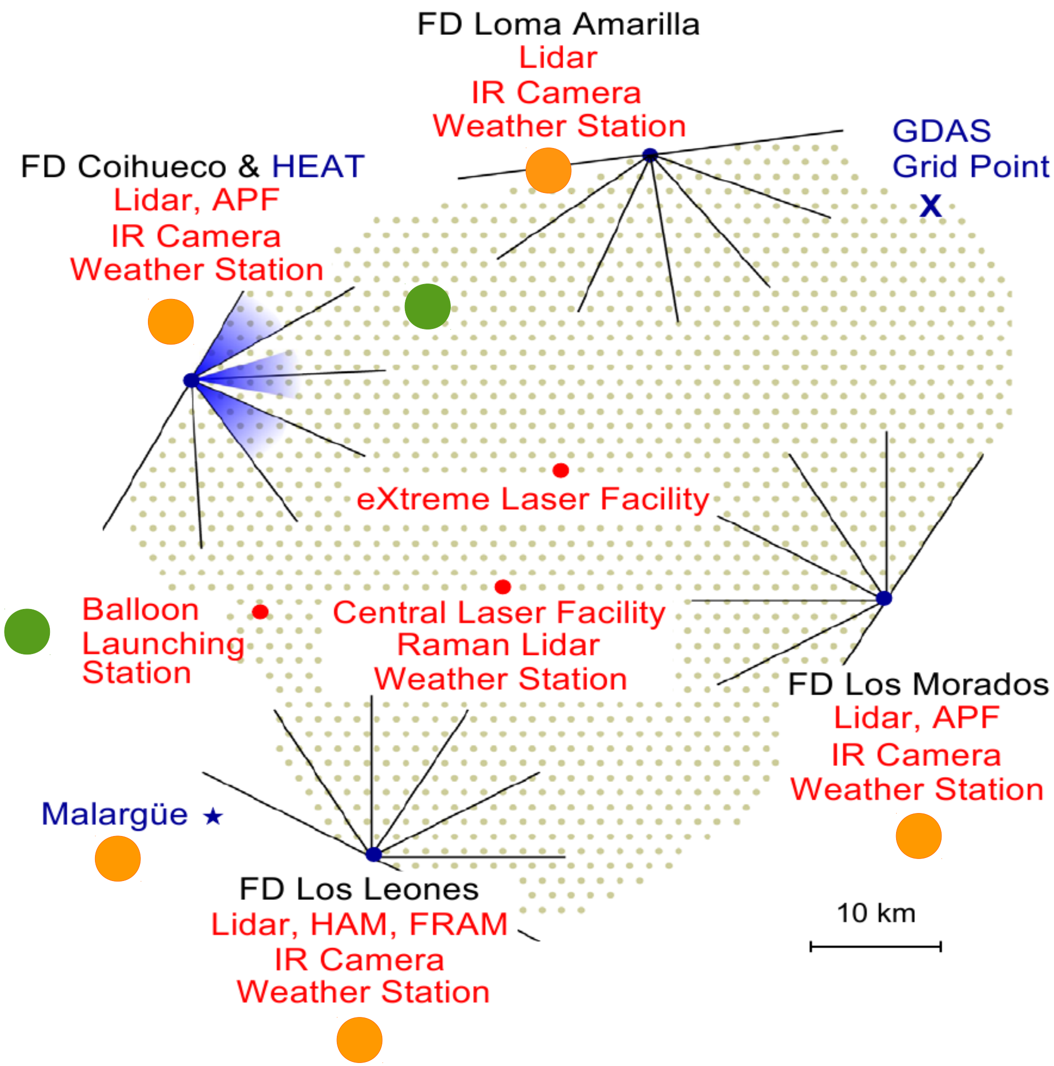
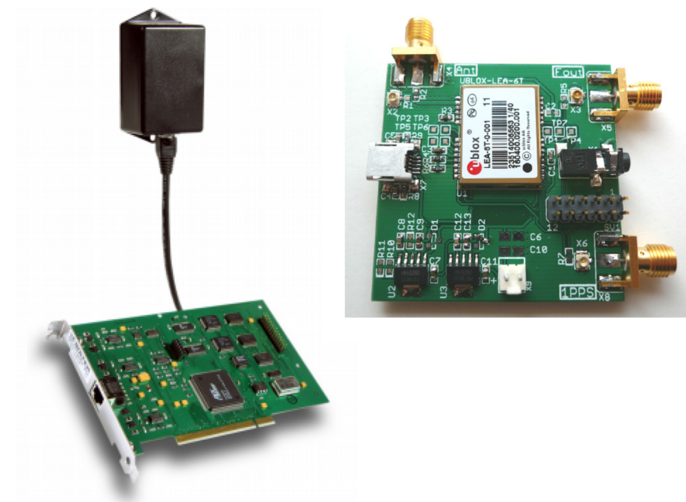
AtmoHEAD 2018

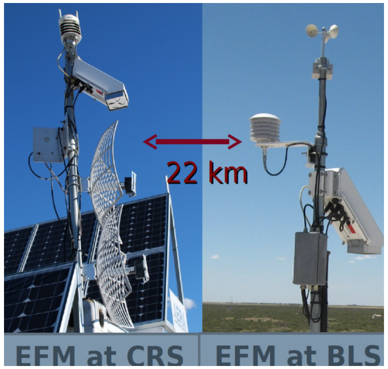

The Pierre Auger Observatory
located in Malargue, Argentina, at 1400 m above the sea level (880 g/cm^2)
HYBRID TECHNIQUE
SD detector: 1600 Water Cherenkov detectors, covering 3000 km^2 and arranged in a triangular grid with 1500 m spacing.
FD detector: 24 telescopes, 6 for each site, which are on the perimeter of the surface array.

Atmospheric Monitoring



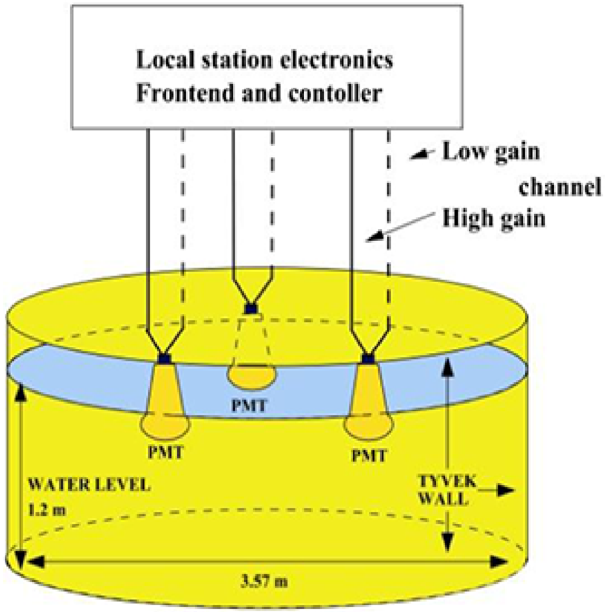


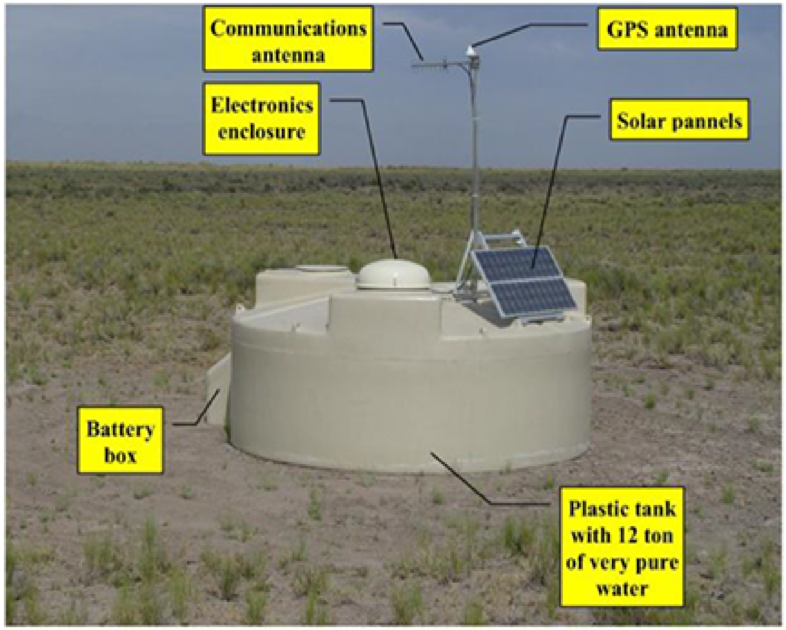
5 Boltek Storm trackers with
GPS antenna (30 ns resolution)
Range: up to 500 km



2 E-field mills
Campbell Scientific CS110

The Surface Detector

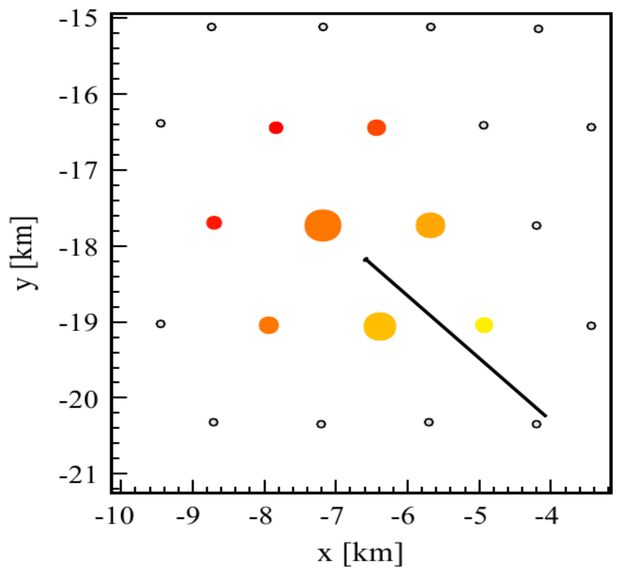


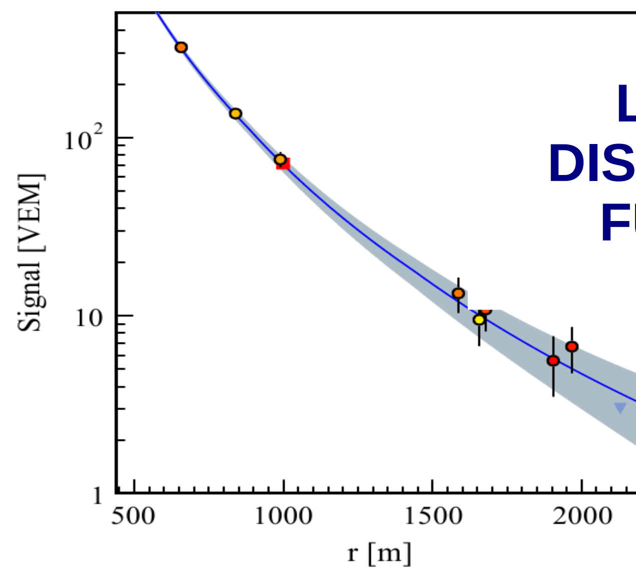


- Each WCD consists of a 3.6 m polyethylene tank containing a liner with a reflective inner surface and filled with 12,000 liters of ultra-pure water.
- Cherenkov light produced by the passage of relativistic charged particles through the water is collected by three PMTs.
- Each PMT has two readout channels,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

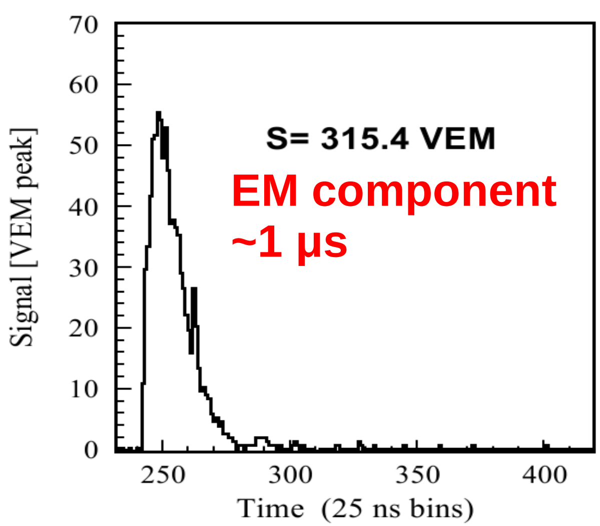
Shower with E=3x10^{19}eV, θ=28°

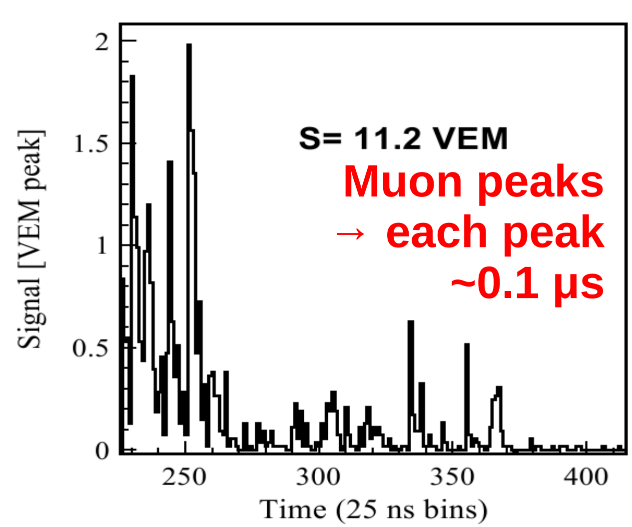




LATERAL DISTRIBUTION FUNCTION

Station at 650 m from the shower core

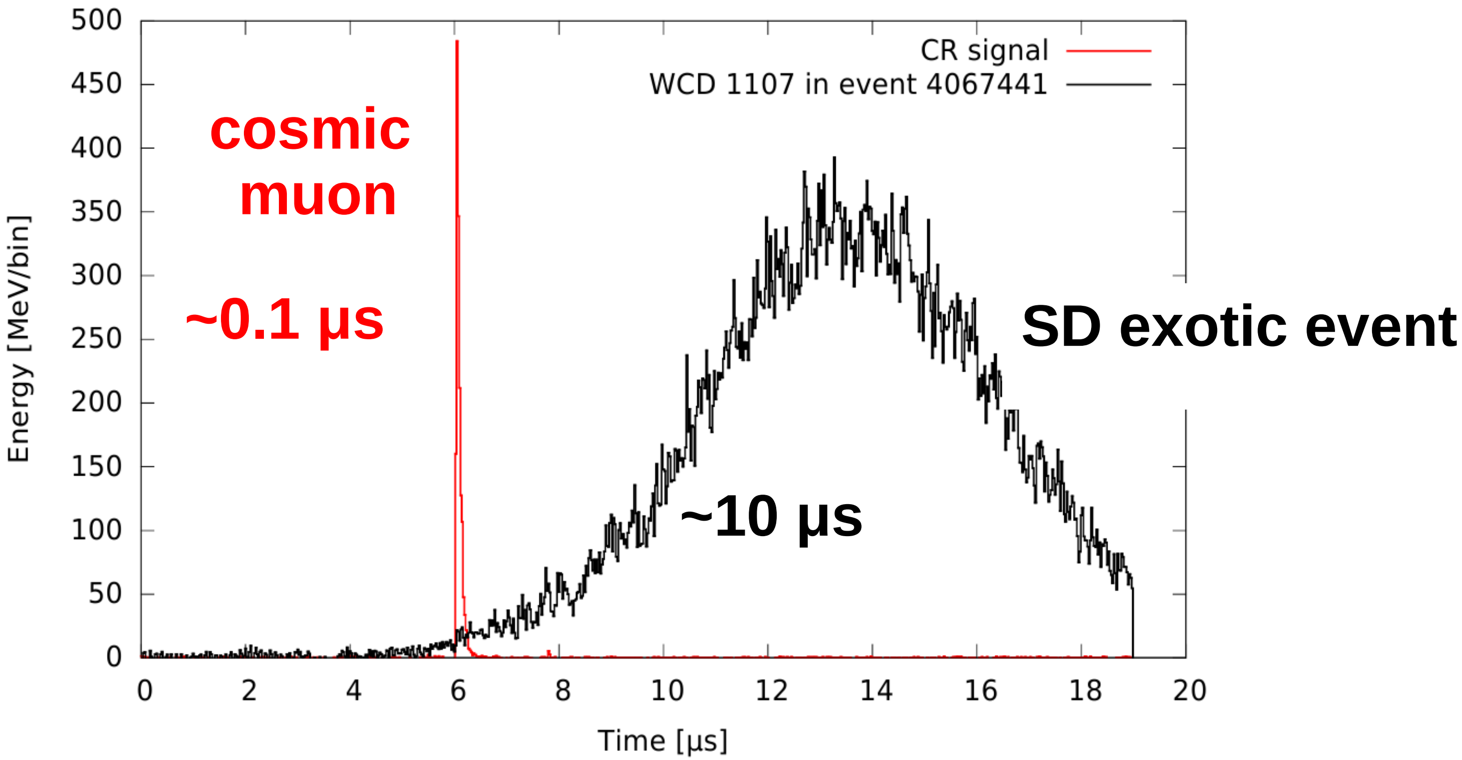




Station at 1780 m from the shower core

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

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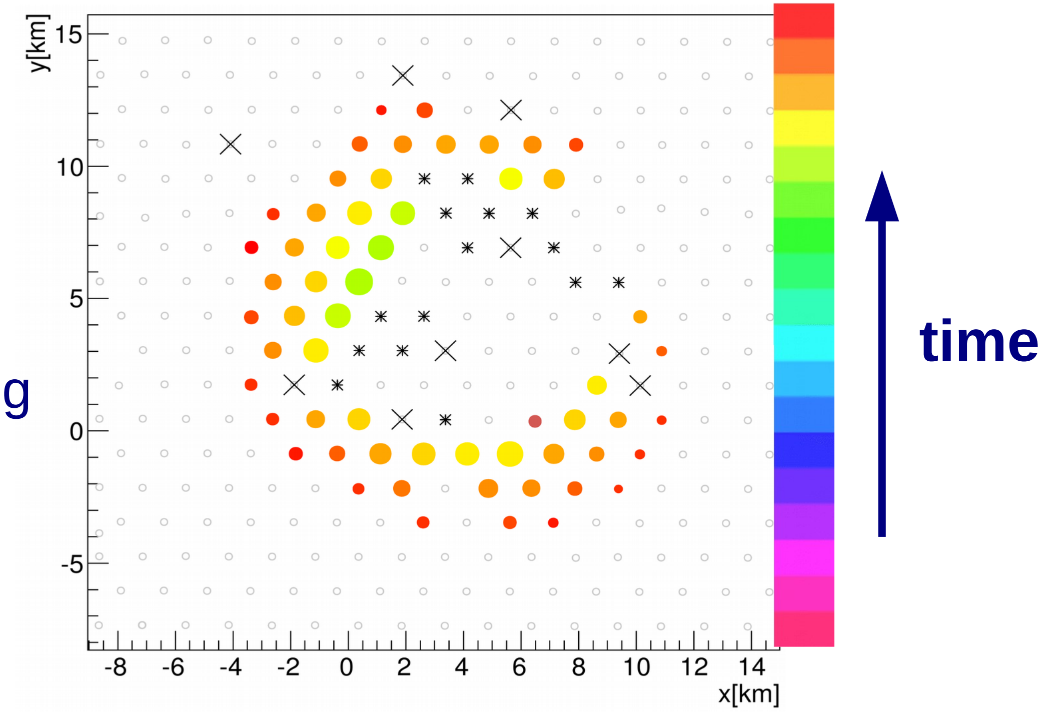
  → high frequency noise

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



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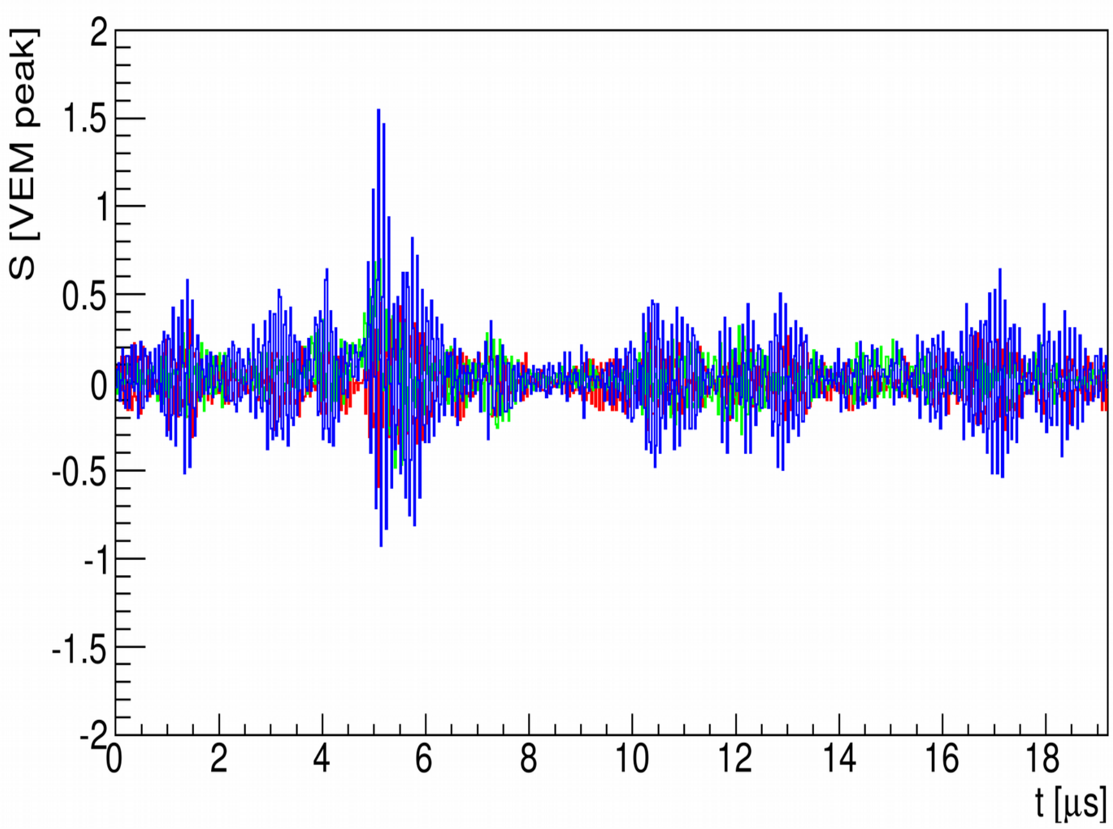
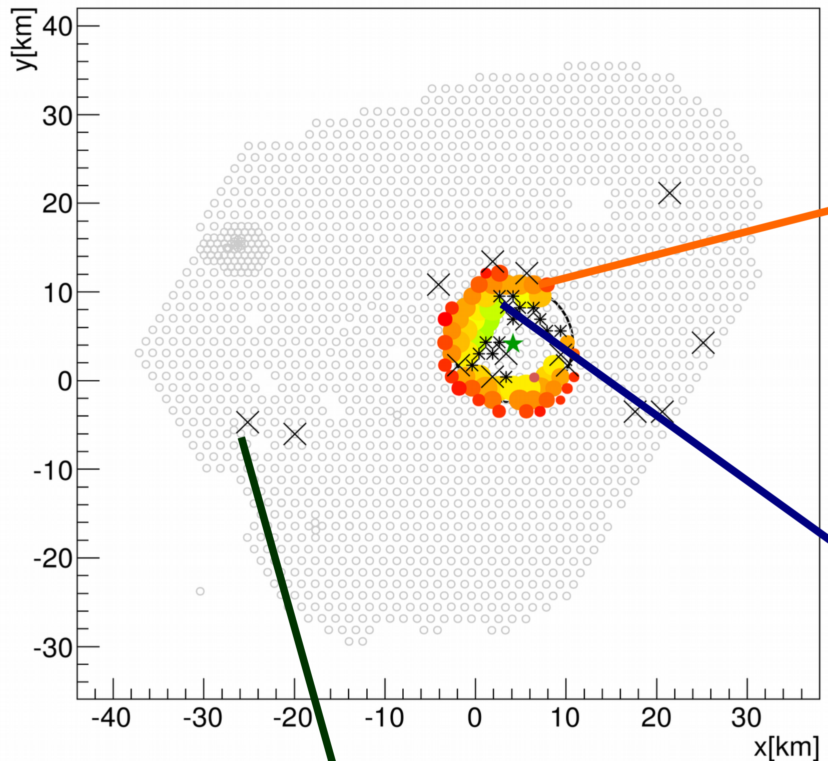
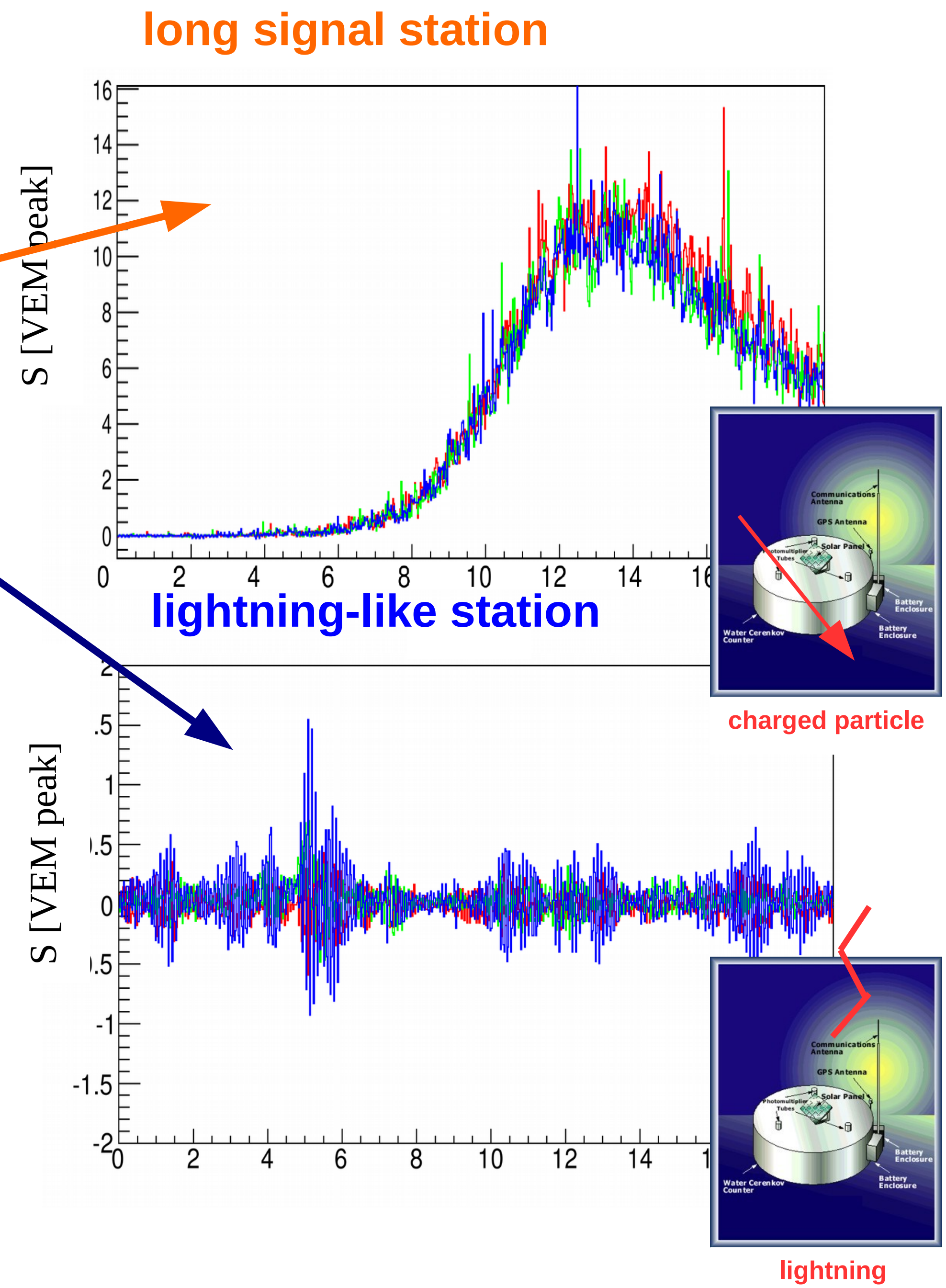
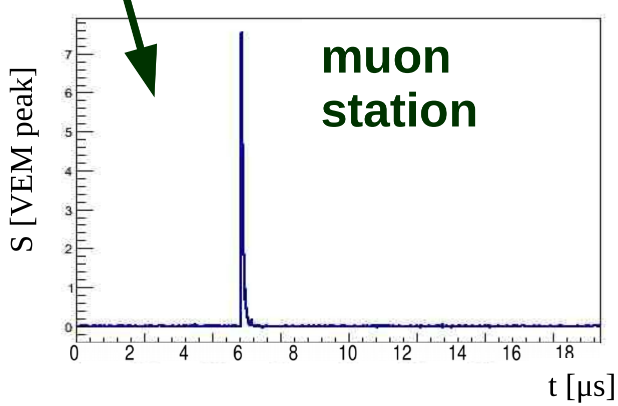


SD Exotic Events



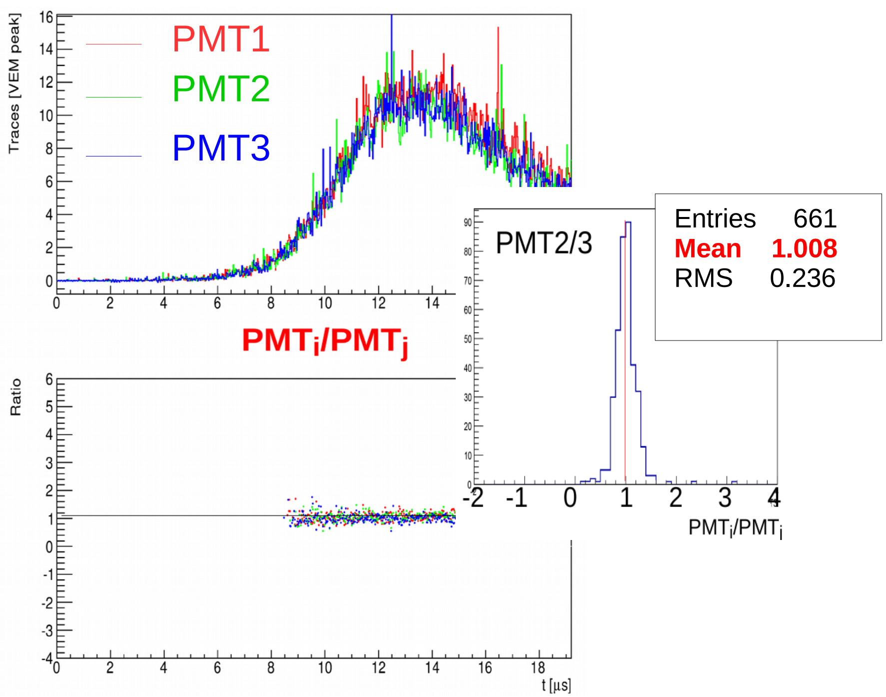


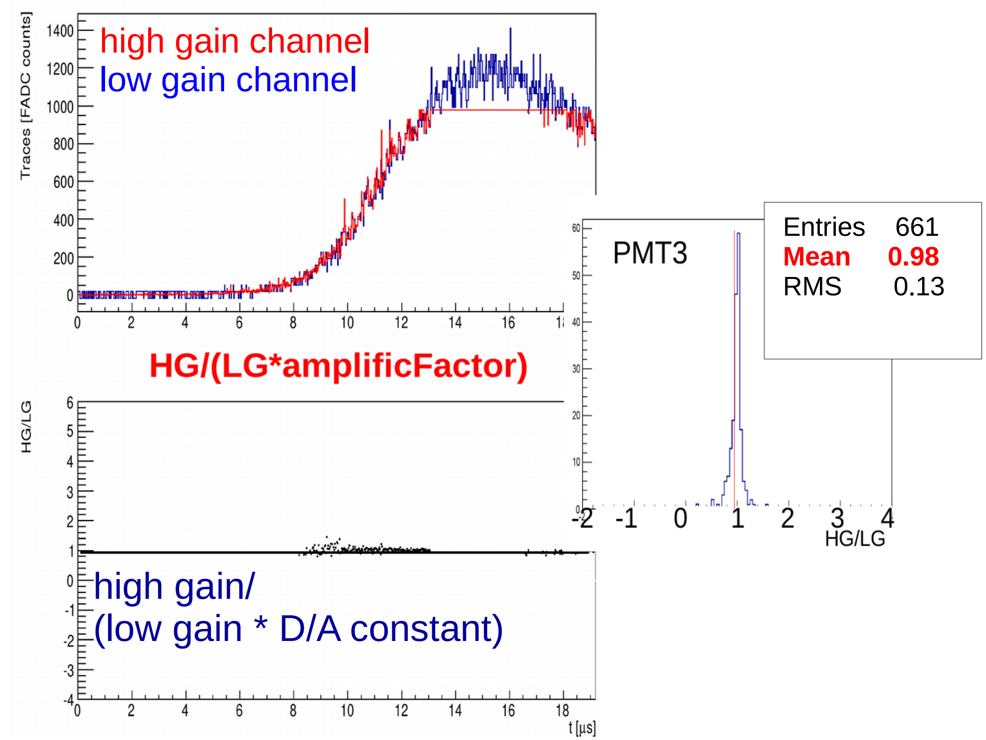
In some of these events, there are stations with a "standard" SD signal produced by a cosmic muon

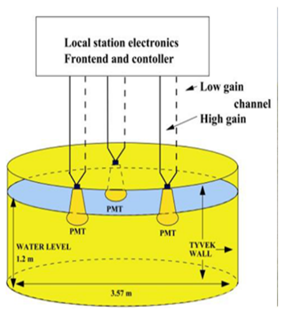


Electronics Checks
PMT Comparison

- These signals are produced by particles which crossed the water in the stations;
- They are not the result of electronics problems.







Low gain → last dynode
High gain → anode

} Amplification factor (D/A costant) ~ 30

Search Algorithm

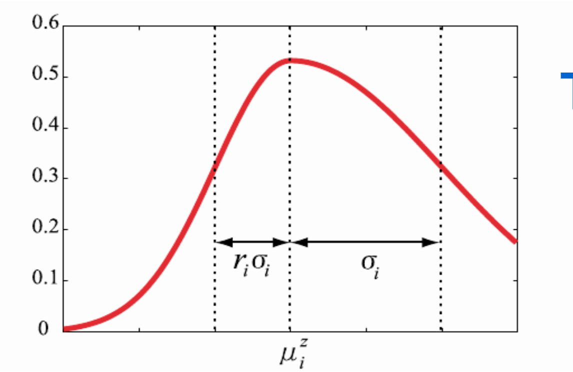
Events collected by the SD from January 2004 to 15 May 2017
→ ~ 10^7 events

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

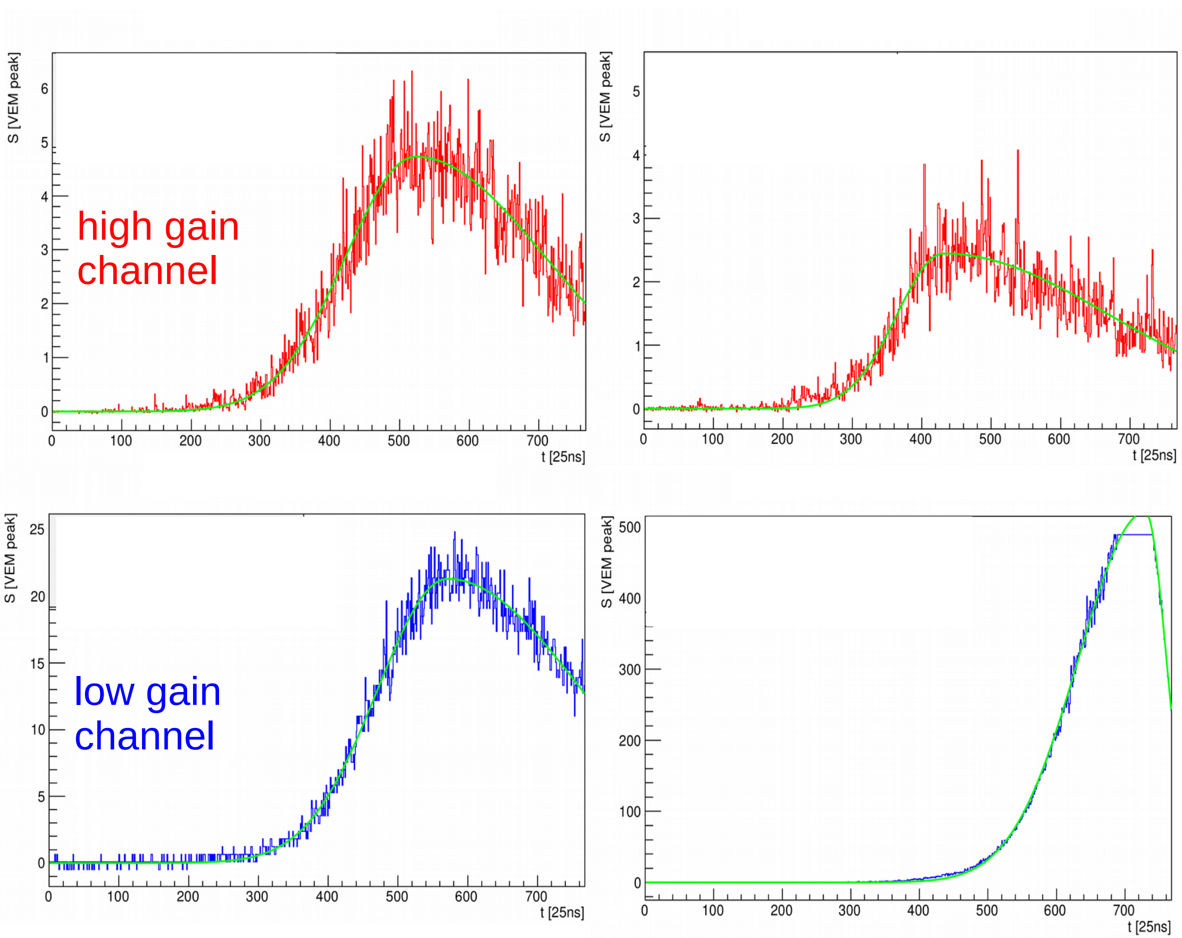
- Stations with long-lasting signals are selected.
If there are at least 10 stations with at least two PMTs with a long-lasting signal, the event is accepted.

- **28 events** with long-lasting stations were selected
→ 16 of them have more than 20 long-lasting stations, arranged in a ring shape with a radius that spans from 4 to 8 km.

Signal Shape



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



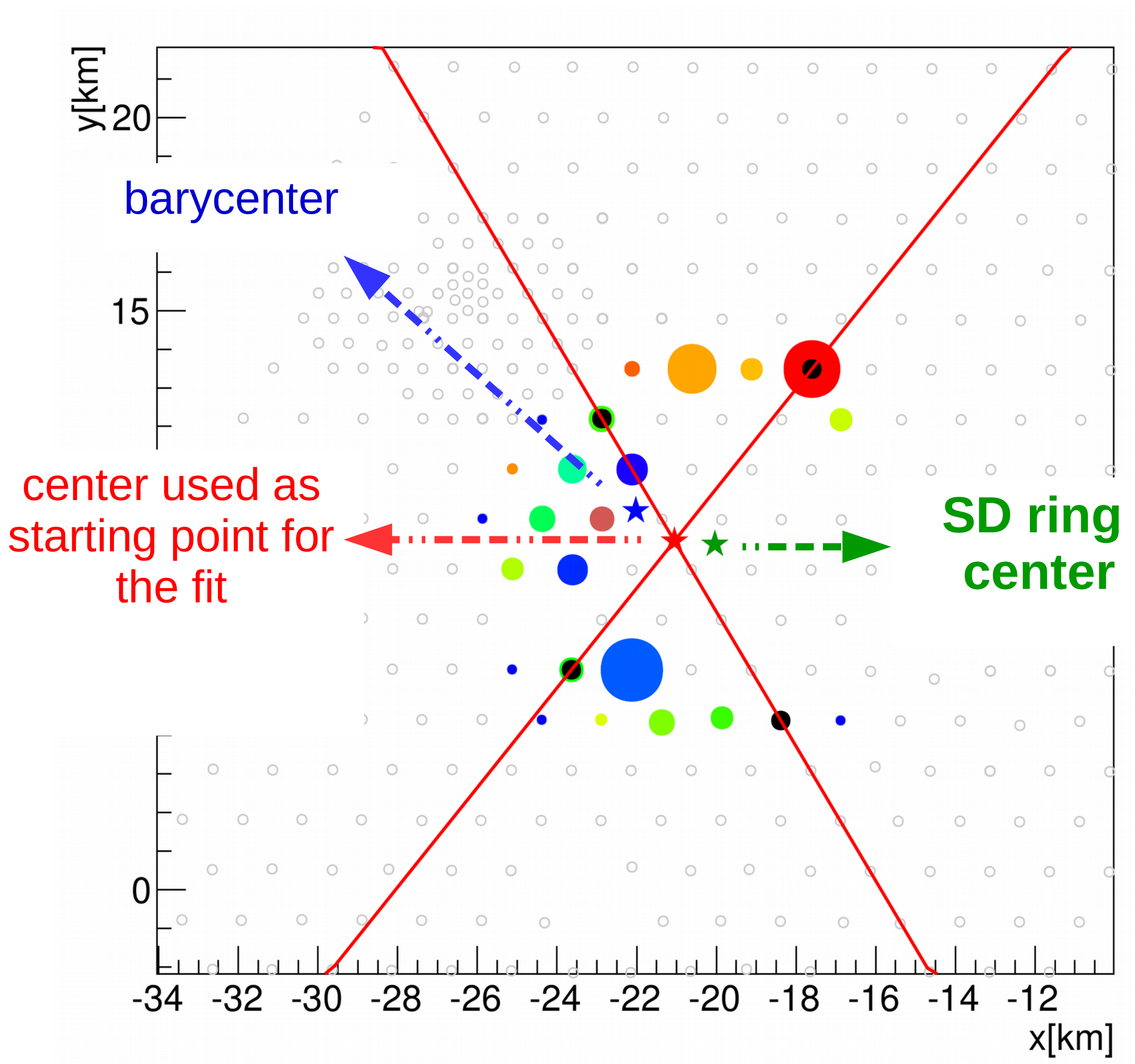
GOOD FITS:

- 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.

GENERAL CHARACTERISTICS:

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

Footprint Characterization



- Identification of the most external stations;
- Construction of the lines passing through the farthest stations;
- Intersection of the two lines to find the starting center (red star) for the fit.

FIT of the CIRCLE

$x^2+y^2-2ax-2by=c$

$c=a^2+b^2-r^2$

a=par[0]=x_center

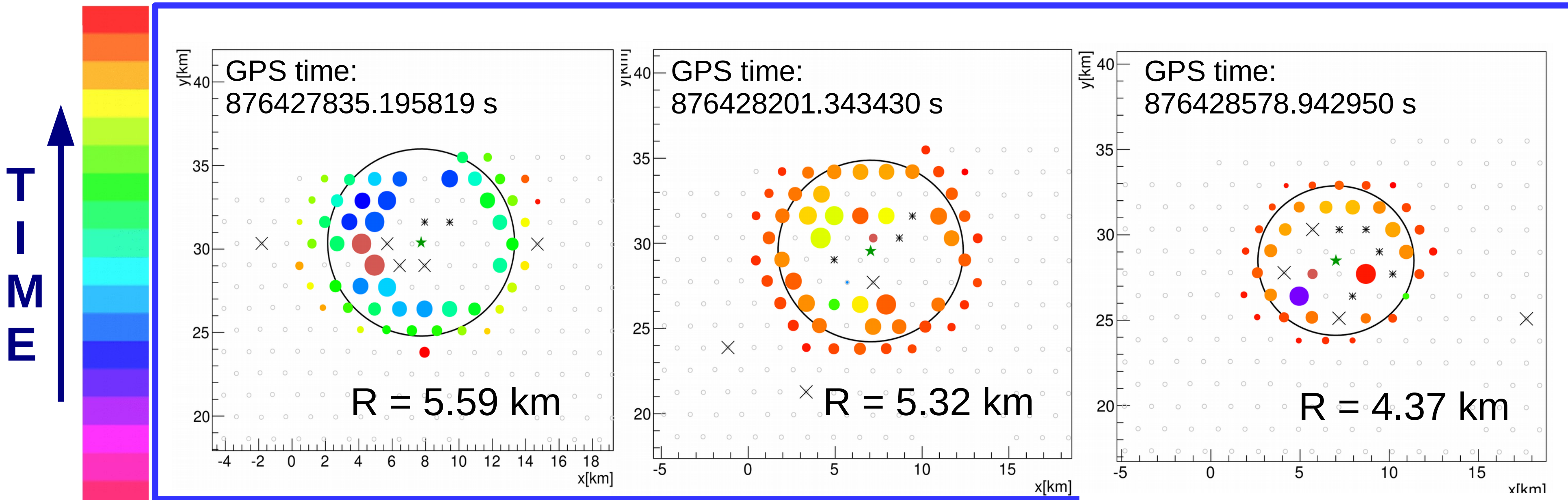
b=par[1]=y_center

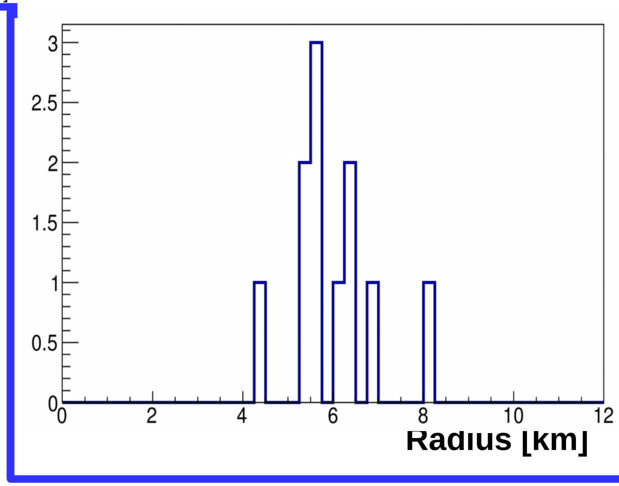
r=par[2]

$\chi 2$ minimization

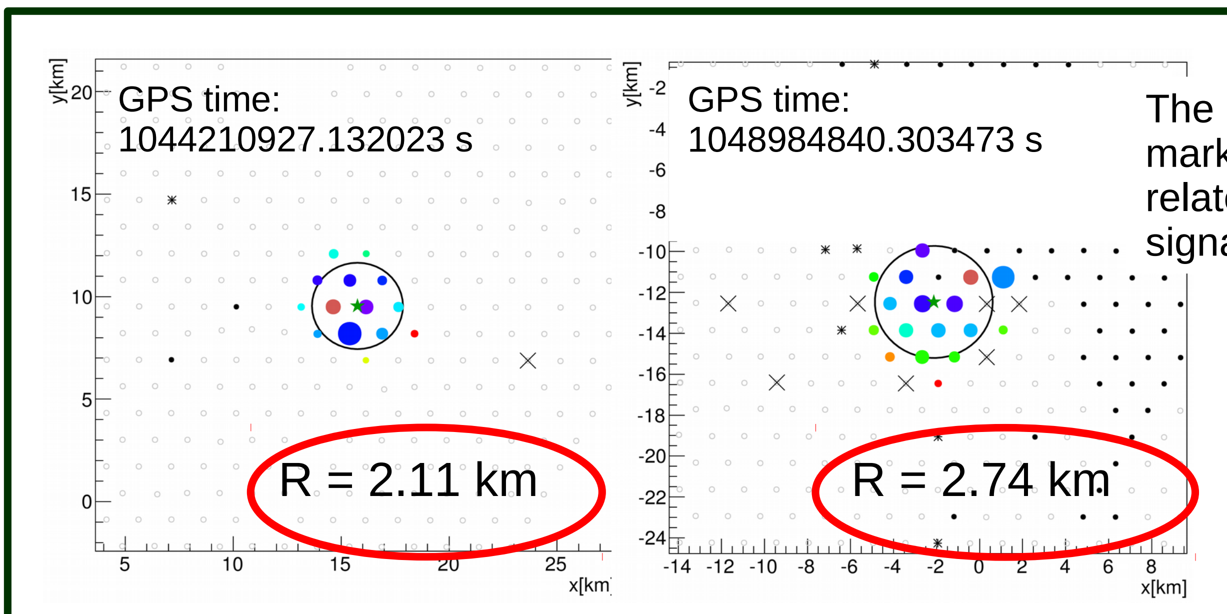
Results of the fit

Large Events





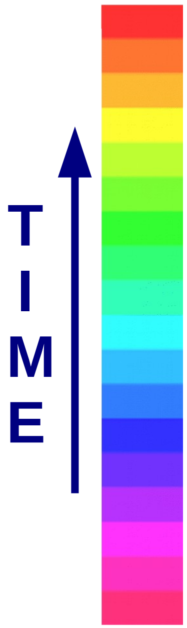
Small Events



The circle marker size is related to the signal

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

Results of the fit



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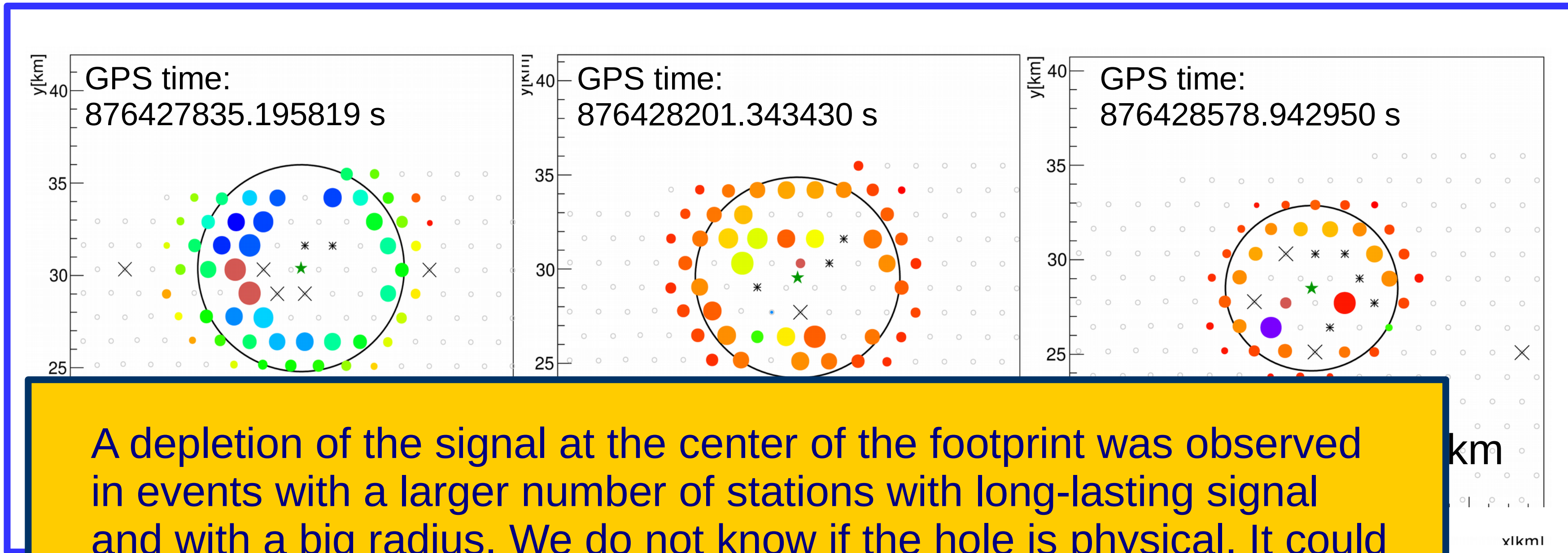
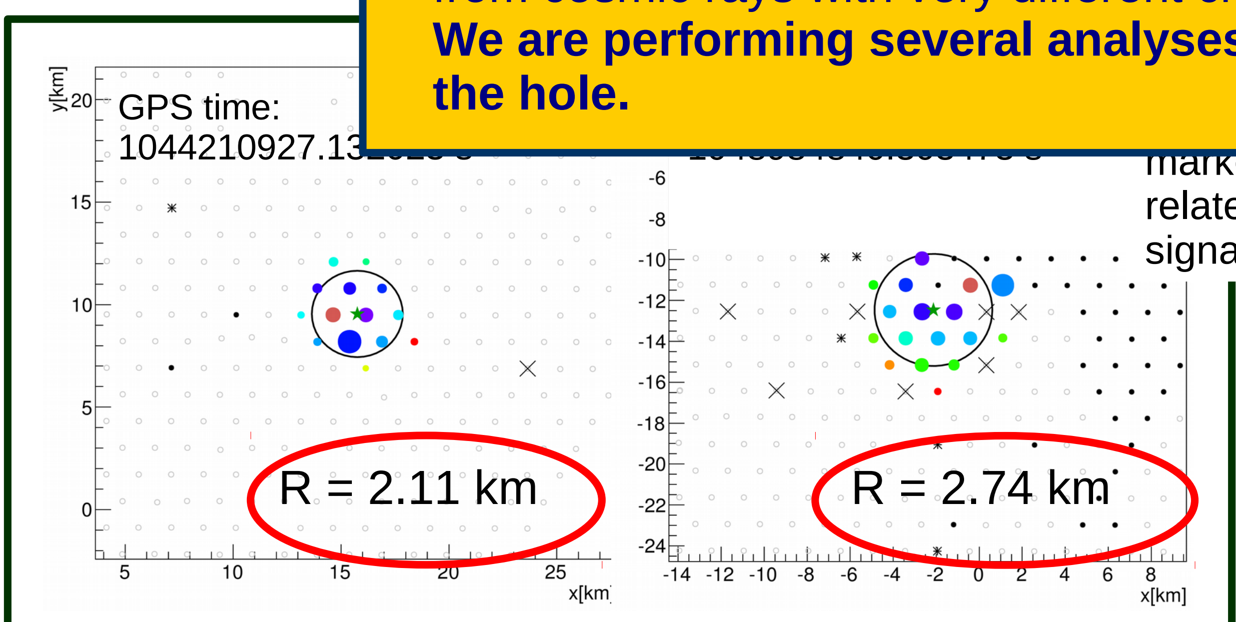
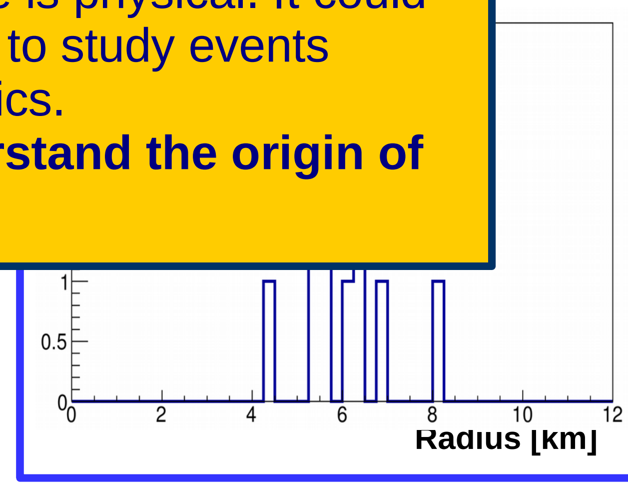


A depletion of the signal at the center of the footprint was observed in events with a larger number of stations with long-lasting signal and with a big radius. We do not know if the hole is physical. It could be caused by the Auger trigger that is optimized to study events from cosmic rays with very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

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

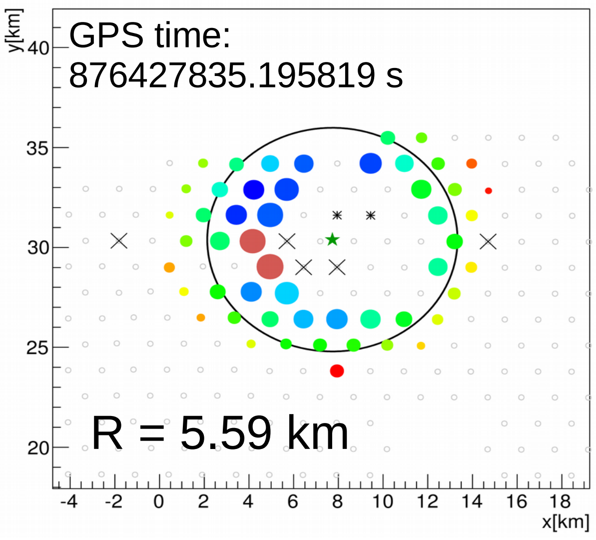
Small Eve

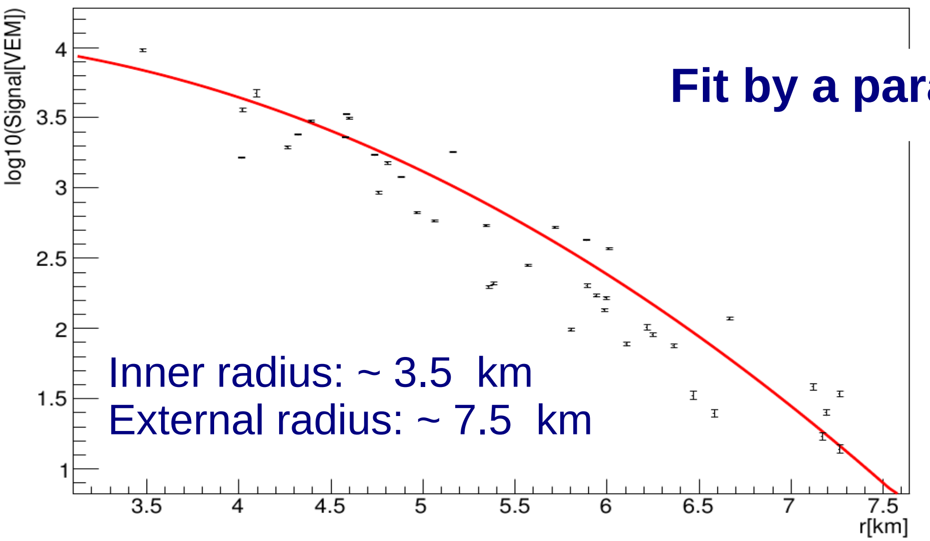




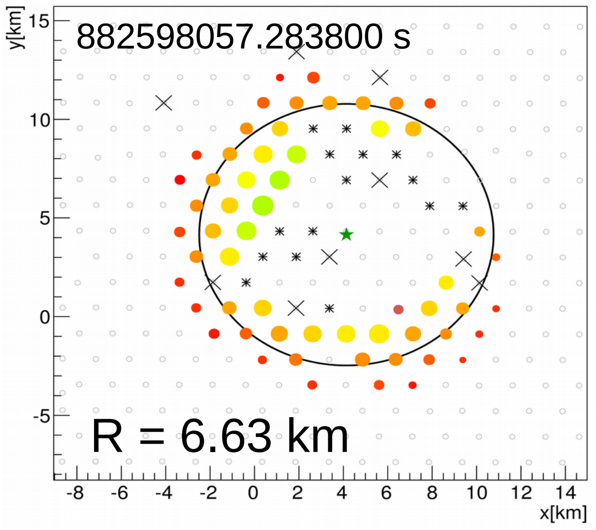
● **Long station**
* **Lightning station**
X **Muon station**

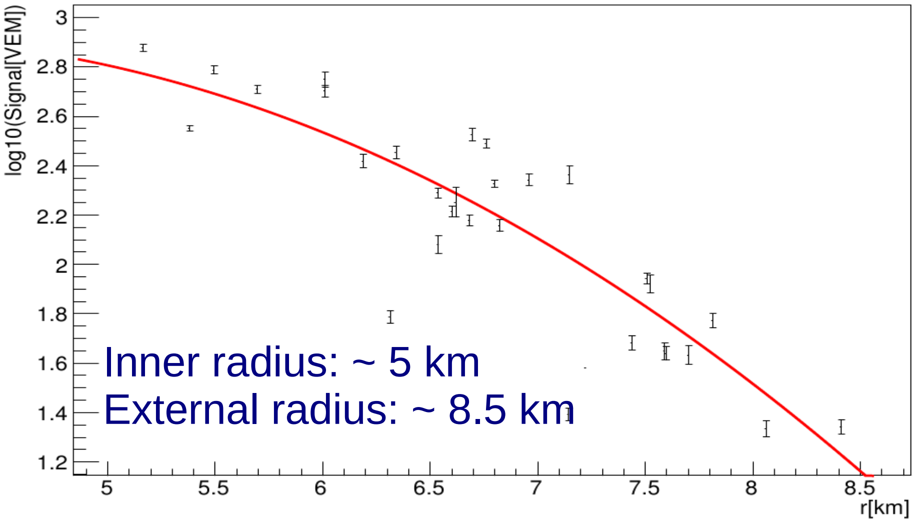
Signal vs distance from the center of the ring



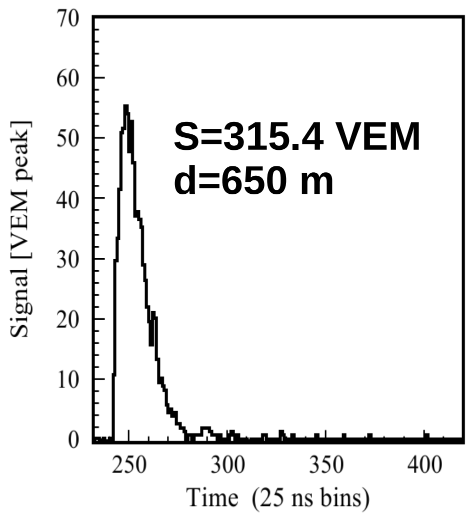


Fit by a parabola

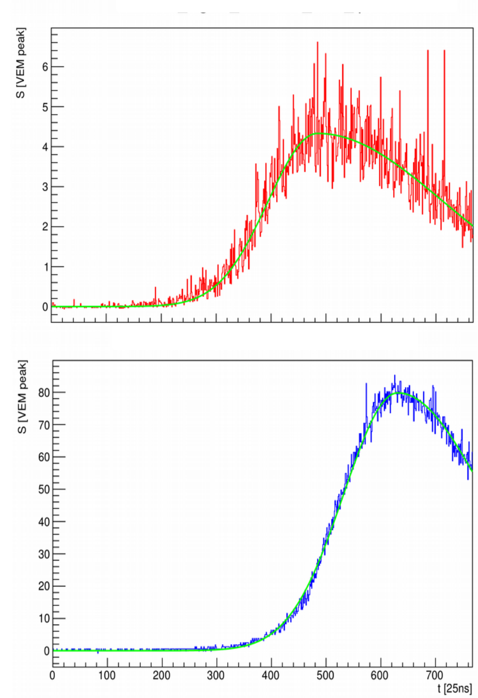




Energy deposited at ground



1 VEM (Vertical Equivalent Muon) ~ 240 MeV



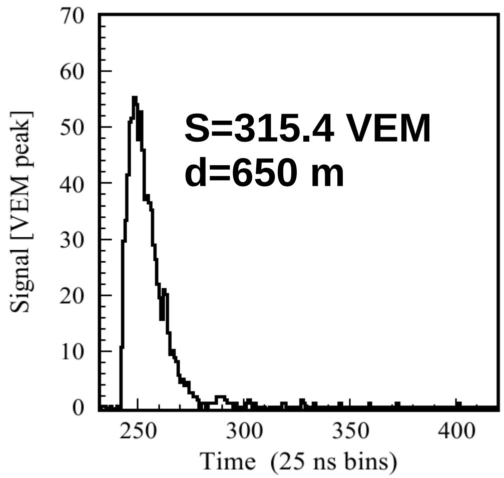
S=591.4 VEM
E=1.42e+05 MeV
d=4911 m

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.

Energy deposited at ground



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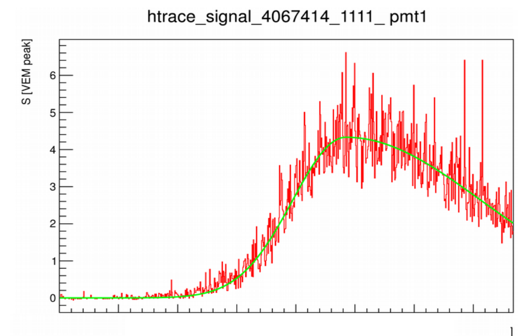

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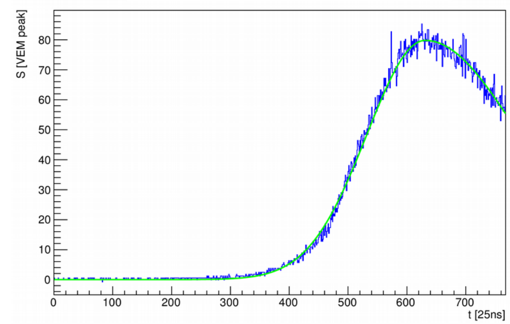

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Different experiments have observed radiation burst correlated to lightning activity:

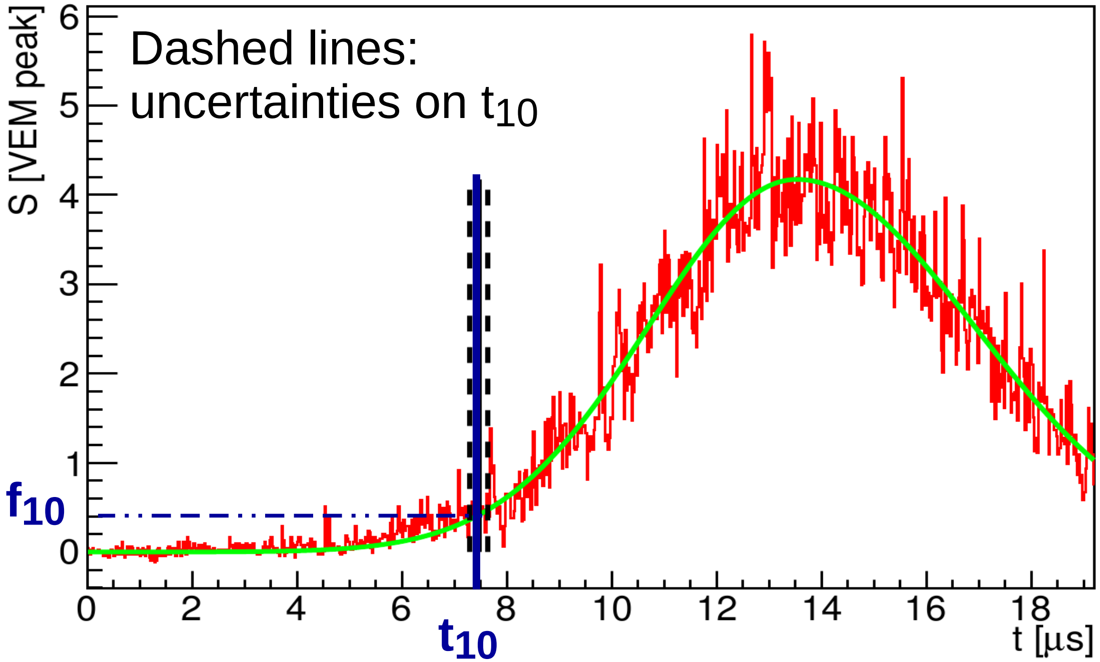
- Dwyer et al. [1] work at about 100 m from the lightning strike with NaI scintillators;
- TA works with plastic scintillator [2].

Our smallest scale of energy density (external part of the circle, ~6-7 km from the center) is consistent with the one observed in [1] for those detectors at a distance of at least 0.5 km from the center of the event, and is about two orders of magnitude larger than the energy of events quoted in [2].

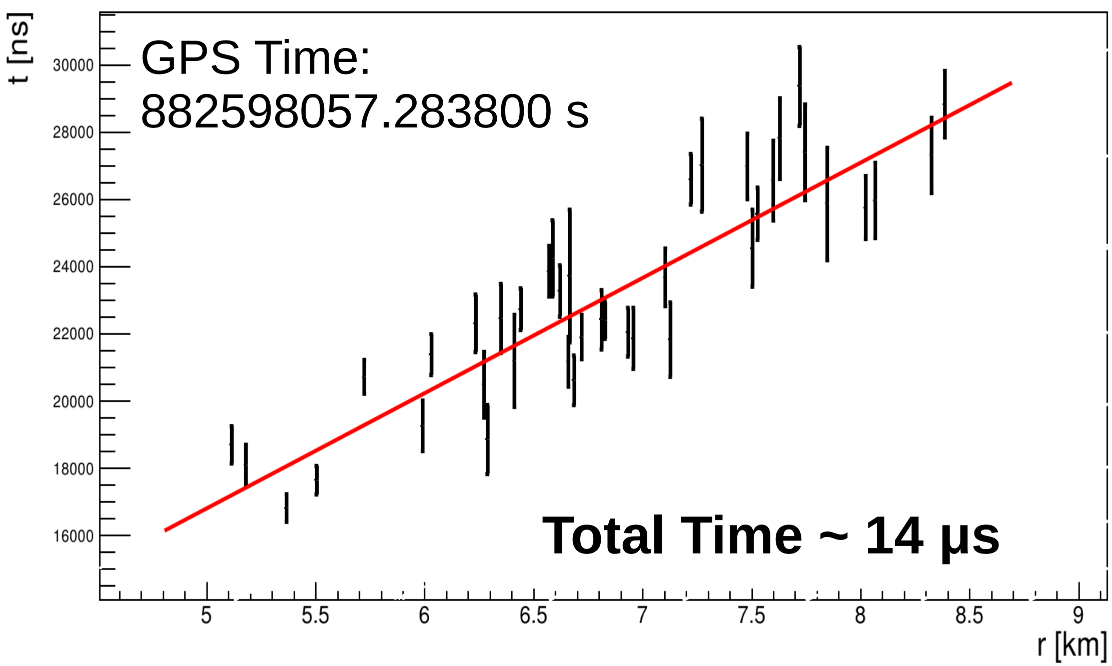
N.B. No detection efficiency considered

[1] J.R. Dwyer et al., Geophys. Res. Lett. 31 (2004) L05119.
[2] Telescope Array Collaboration, arXiv:1705.06258.

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.

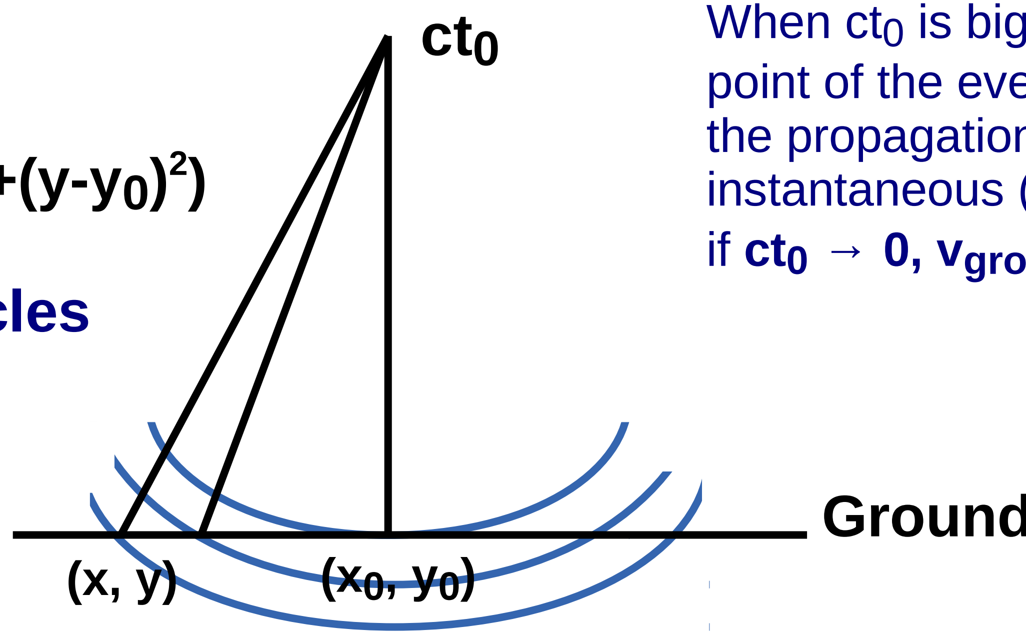


The event starts from the inner stations and then moves towards the external ones.

Spherical Front

$sqrt((ct_0)^2+(x-x_0)^2+(y-y_0)^2)$

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 $\mathbf{ct_0} \rightarrow \mathbf{0}$, $\mathbf{v_{ground}} \rightarrow \mathbf{c}$

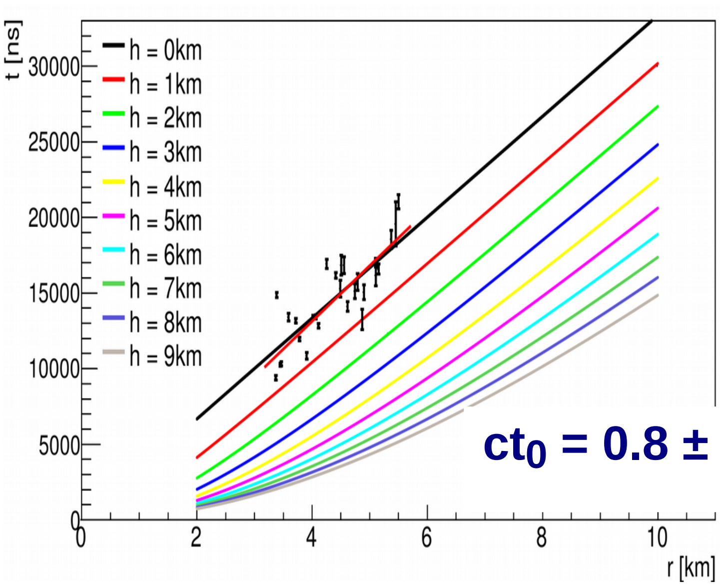
χ2 minimization: $\chi 2=Sum((t_{exp}-(t_{real}-t_{0ff}))^2/(t_{real\_err} * t_{real\_err}))$
con $t_{exp}=sqrt((ct_0)^2+(x-x_0)^2+(y-y_0)^2)/c$

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

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

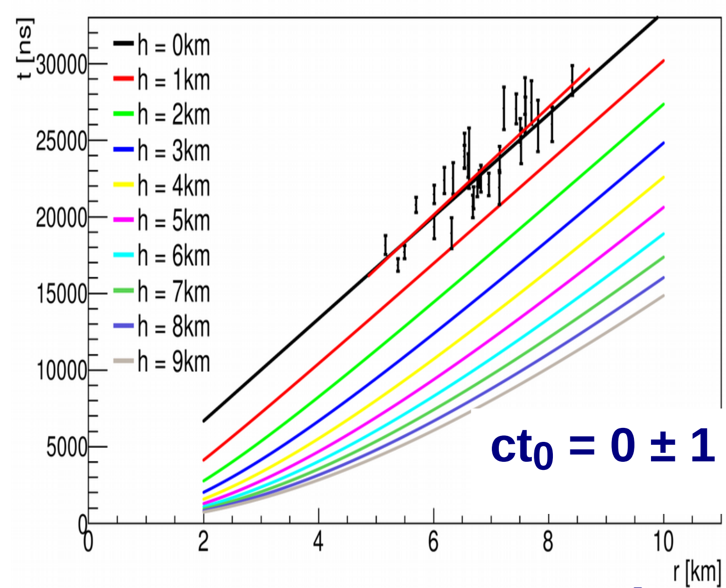
Time Propagation

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.

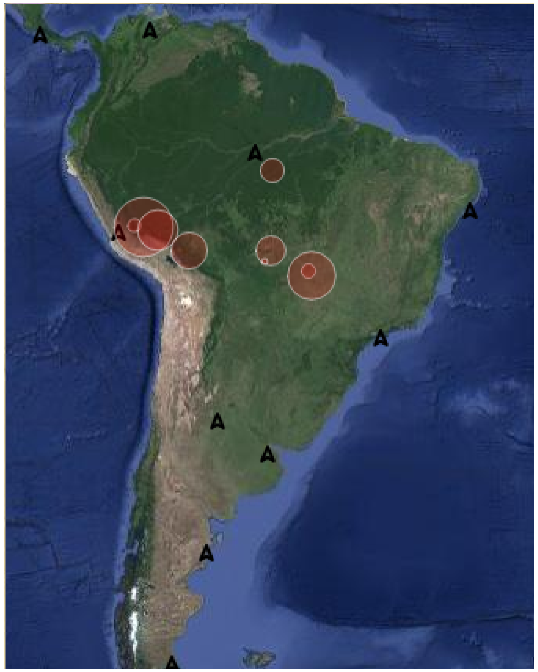
The simulated arrival times are represented by the colored lines
→ altitudes from 0 to 10 km.

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

Correlations with WWLLN

The high frequency noise observed in several stations could be associated with lightning-caused signal, which suggests that **these events happened during thunderstorms**.

The 10 best events: the events with the biggest number of stations and the events whose signals have the peak of the distribution and a good portion of the fall tail contained in our time windows → the signal in each station and the global characteristic of the event are recostructed with small uncertainties **are compared with lightning strikes of the WWLLN** (World Wide Lightning Location Network) catalogue.



In black, the WWLLN antennas in South America are shown.

The ~80% of this sample shows a time (within 50 ms) **and spatial correlation** (10 km) **with WWLLN lightning.**

Conclusions

- Very peculiar events, characterized by the presence of stations with very long-lasting signals 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?

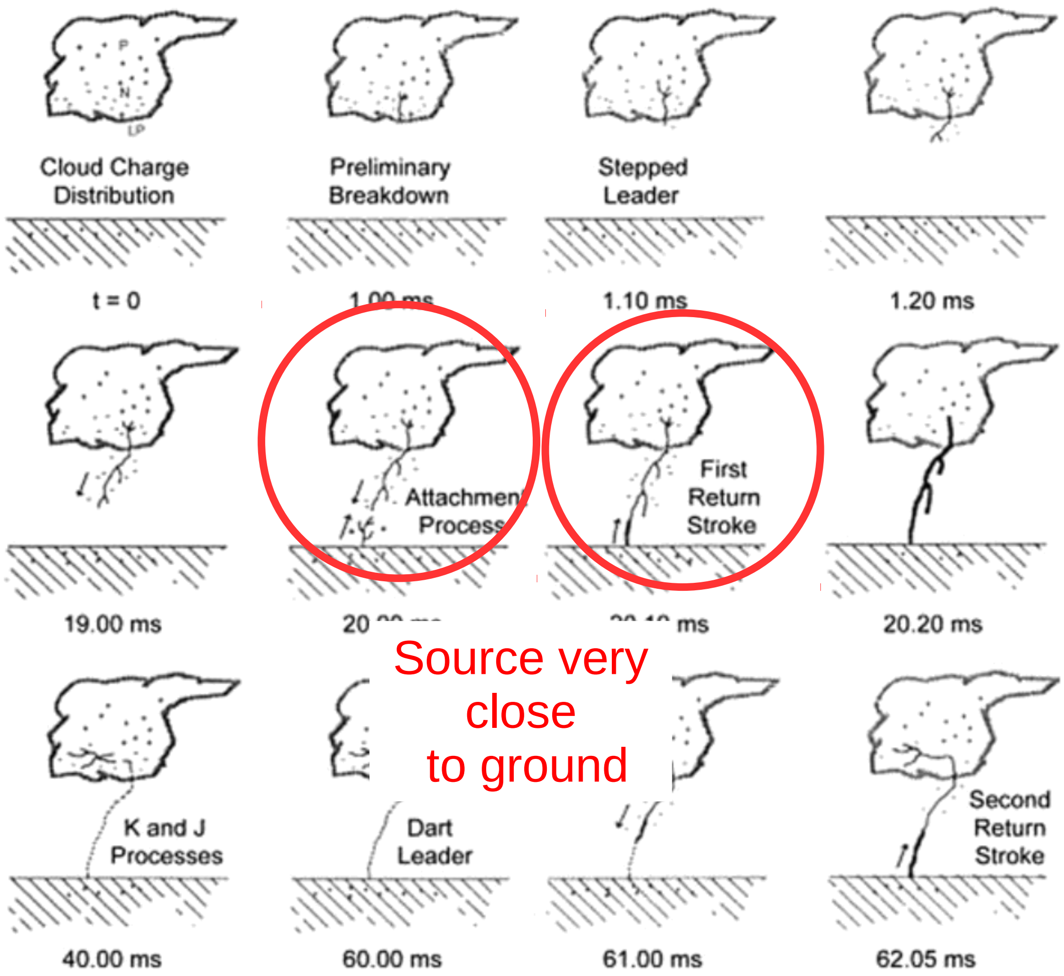
- Each event has at least a lightning station, a station with high frequency noise.

- The amplitude of the signal is bigger in the inner part of the ring and decreases with the increasing of the distance from the center.

- 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.

- What is the phenomenon which can explain these observations?

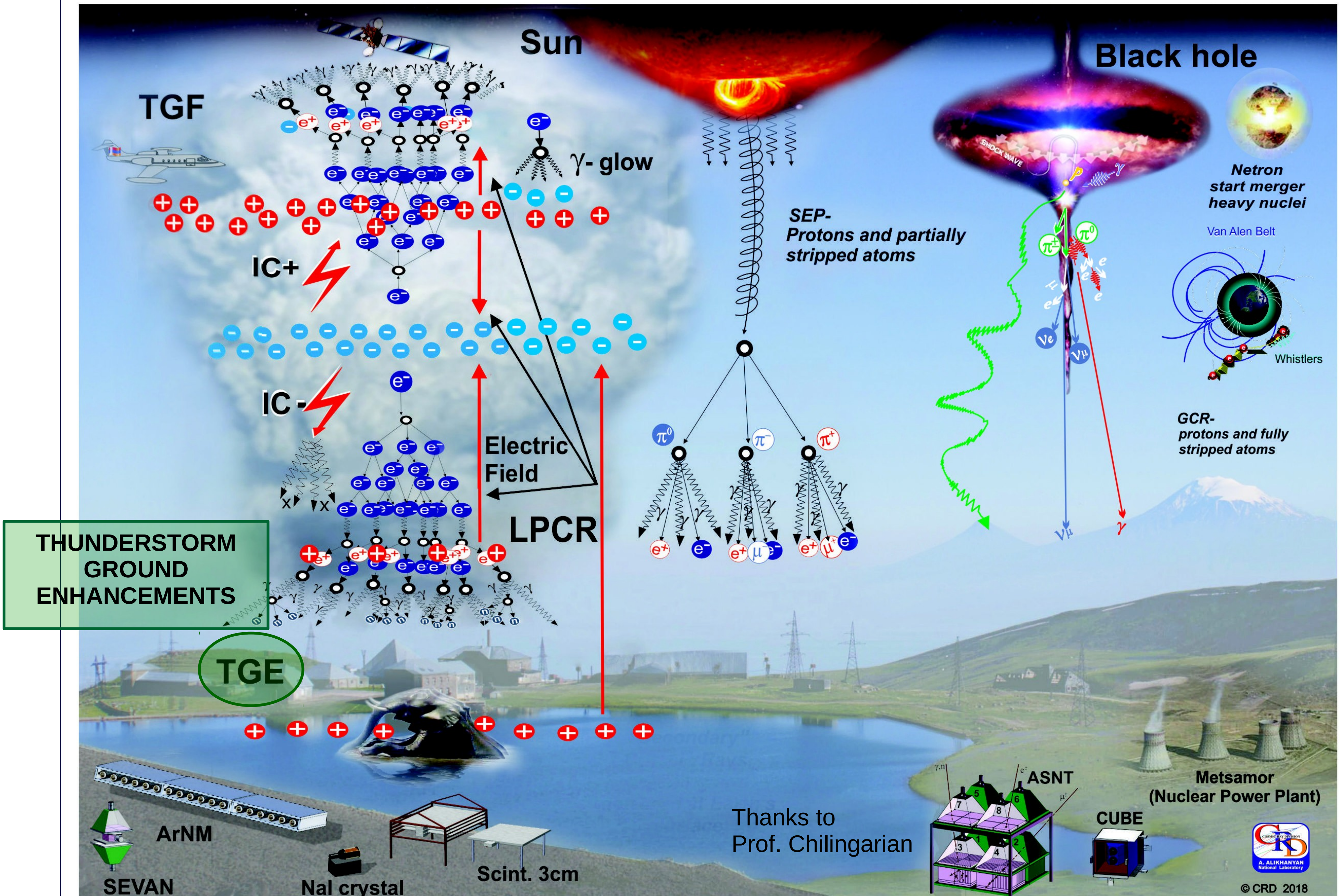
Theoretical Models



Two constraints:

- A source of “high energy” electrons (**RREAs**)
- Need a strong E-field to accelerate particles in order they can cross several km

Theoretical Models



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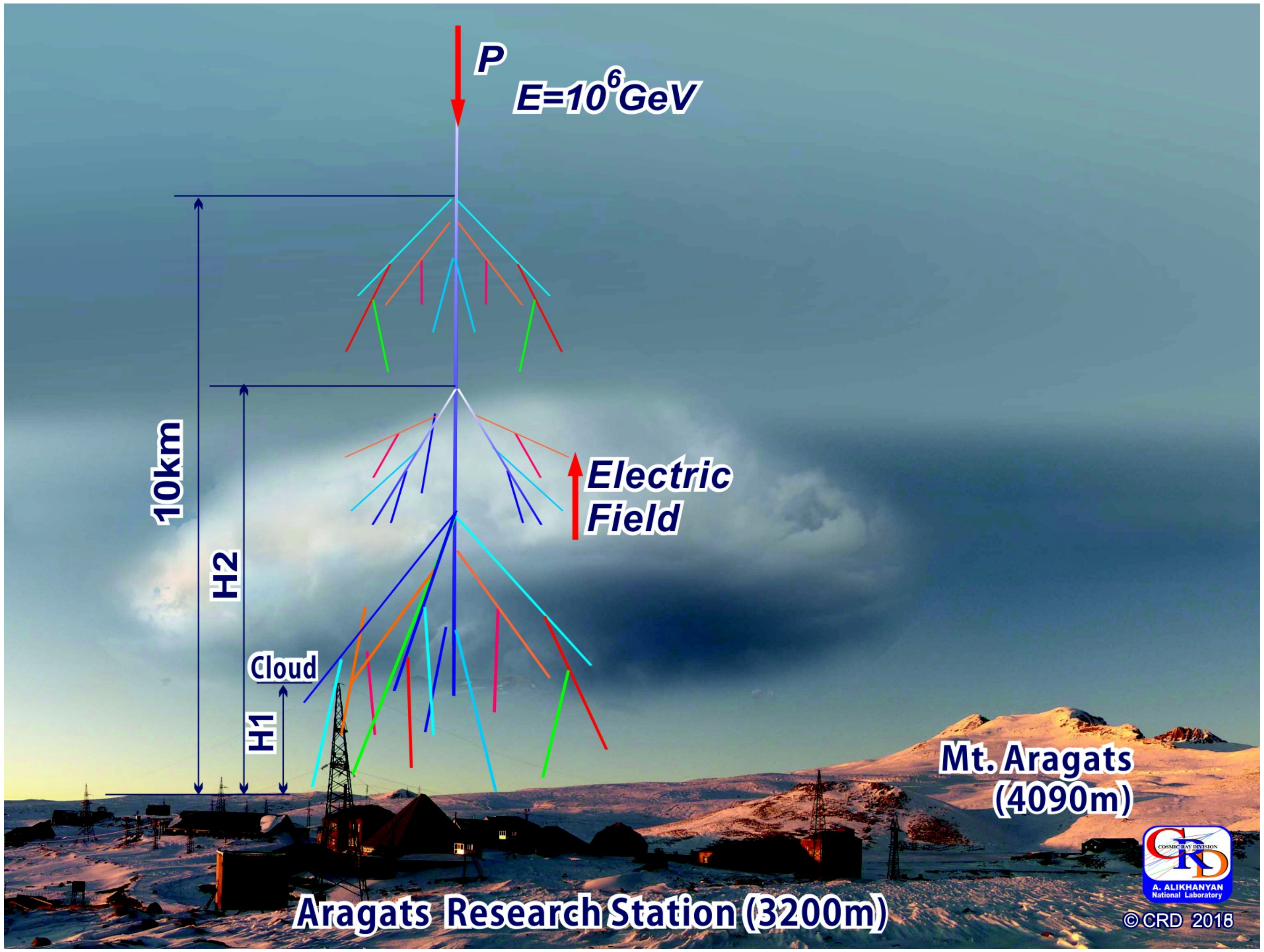
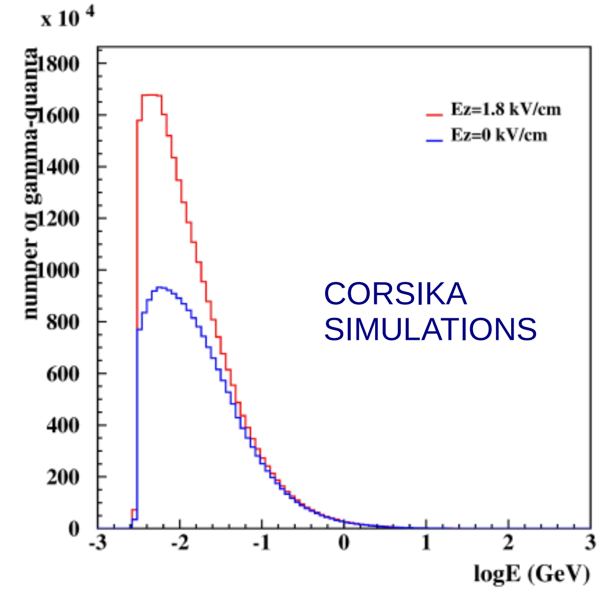
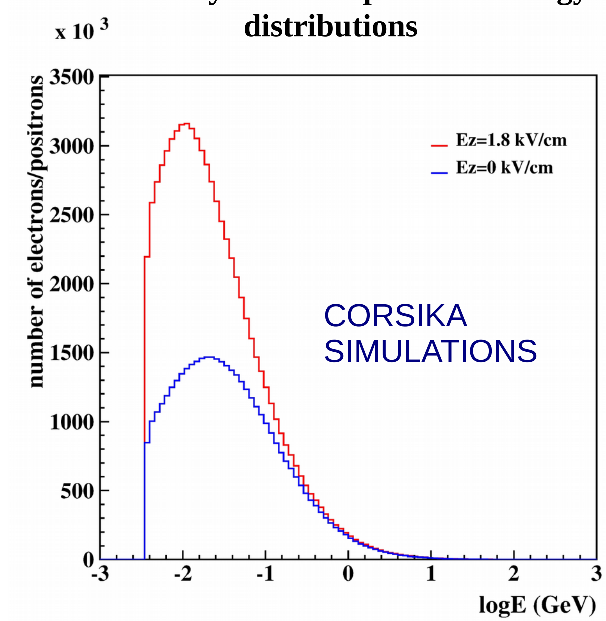


Secondary photons energy distributions



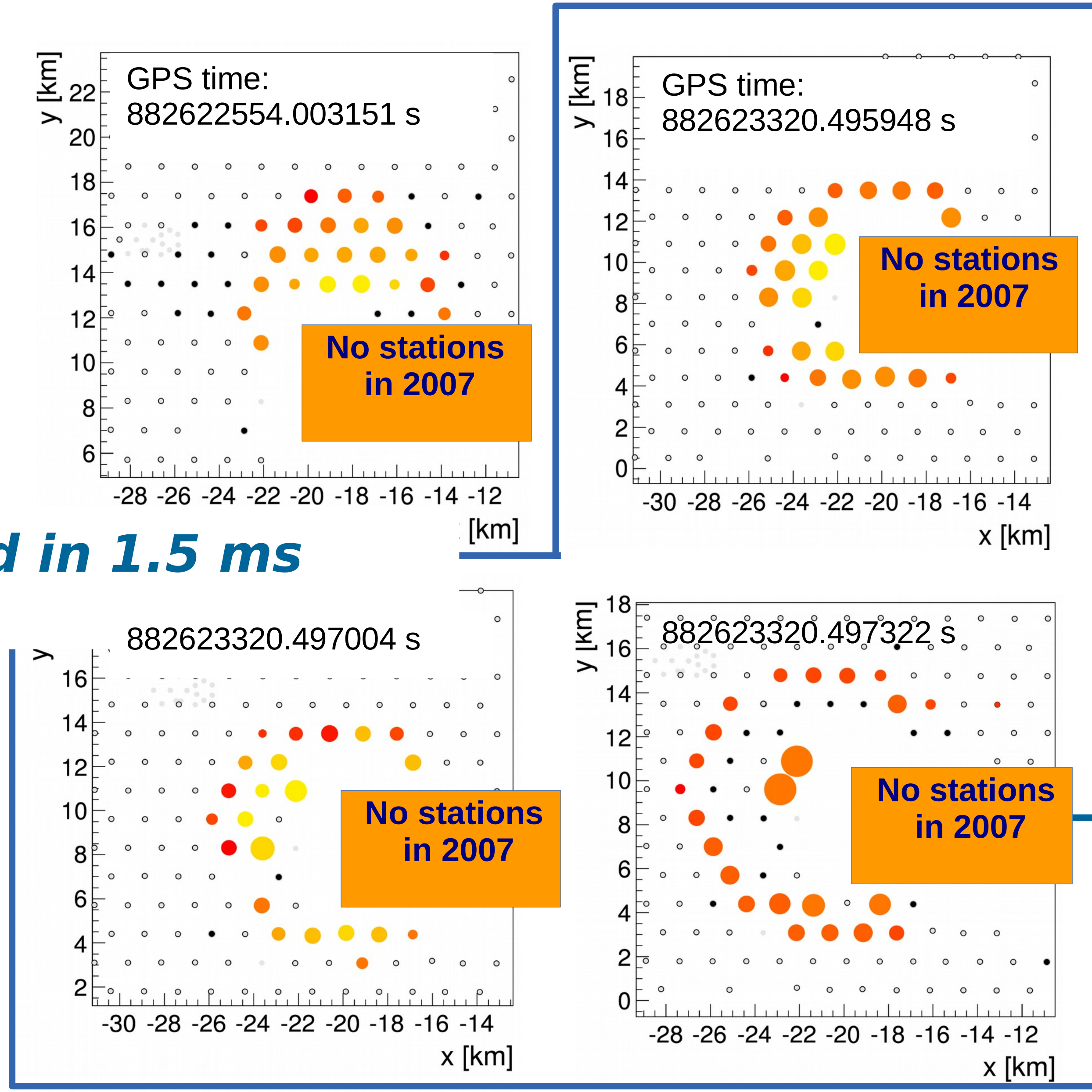
Secondary electrons/positrons energy distributions



Thanks to Prof. Mary Zazyan
Yerevan Physics Institute, Armenia

Back Up

Peculiar Event Group



Happened in 1.5 ms

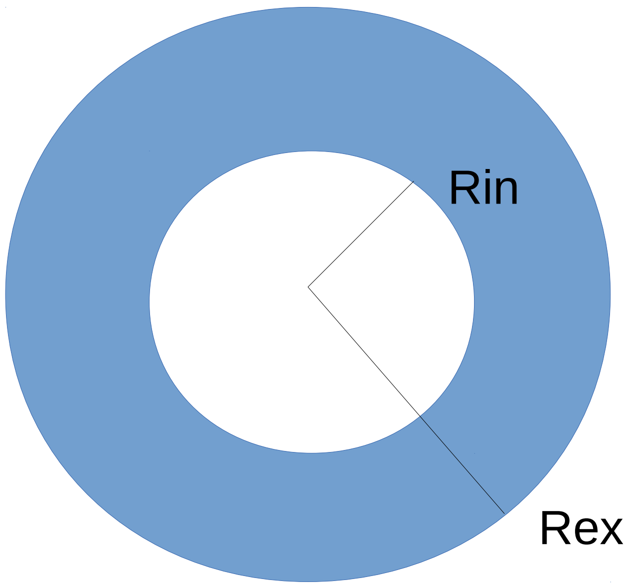
Four events were collected in 15 minutes: three of them happened in 1.5 ms.

The Observatory was completed in 2008

Energy Estimation

The total energy at ground is calculated starting from the energy collected in the all long signal stations (energy_tank *). The energy/m^2 is calculated dividing the "energy_tank" by the number of long signal stations and dividing the average energy per station by the tank surface (10 m^2).

Energy_tank = Σ (energy of long signal stations)



Energy/m^2 =
Energy_tank / (n_tank*tank_surface)

Energy_tot = Energy/m^2 * ring_surface

* Function Fit: asymmetric gaussian
Signal per tank: integral [-inf,inf]] for each PMT; Total Signal: average of the good PMTs signals, at least two good PMTs are requested to consider the tank.
Conversion in MeV: energy (MeV) = energy (VEM charge) * 240