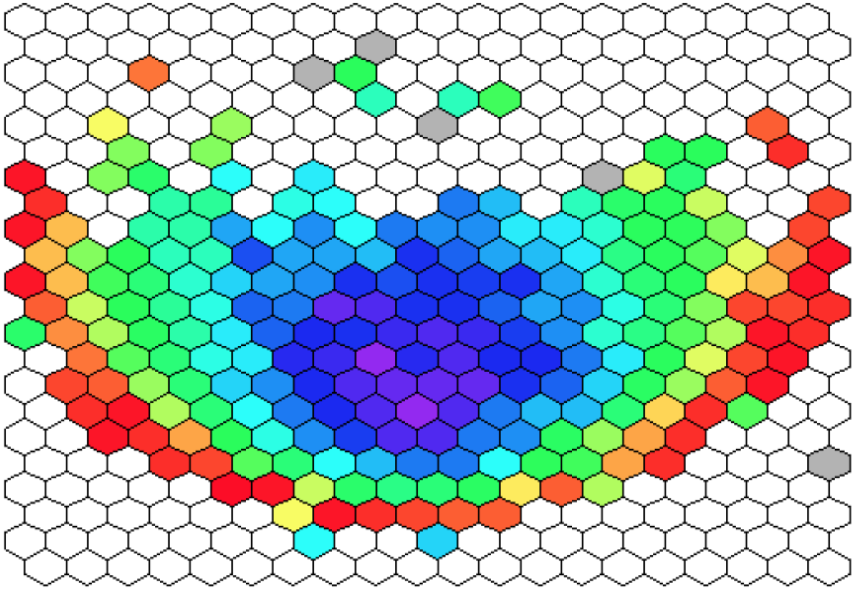
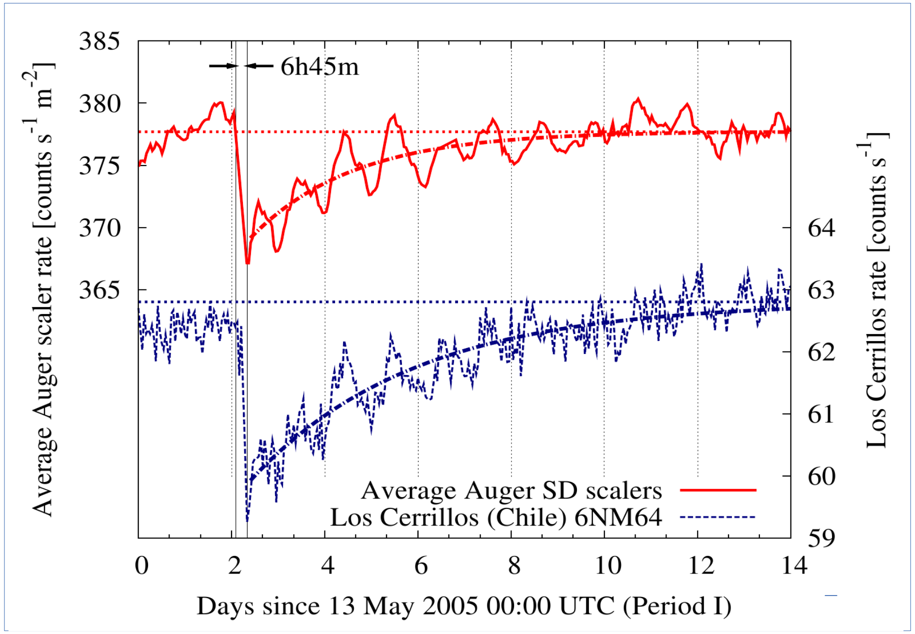
Elves, Forbush decreases and solar activity studies at the Pierre Auger Observatory

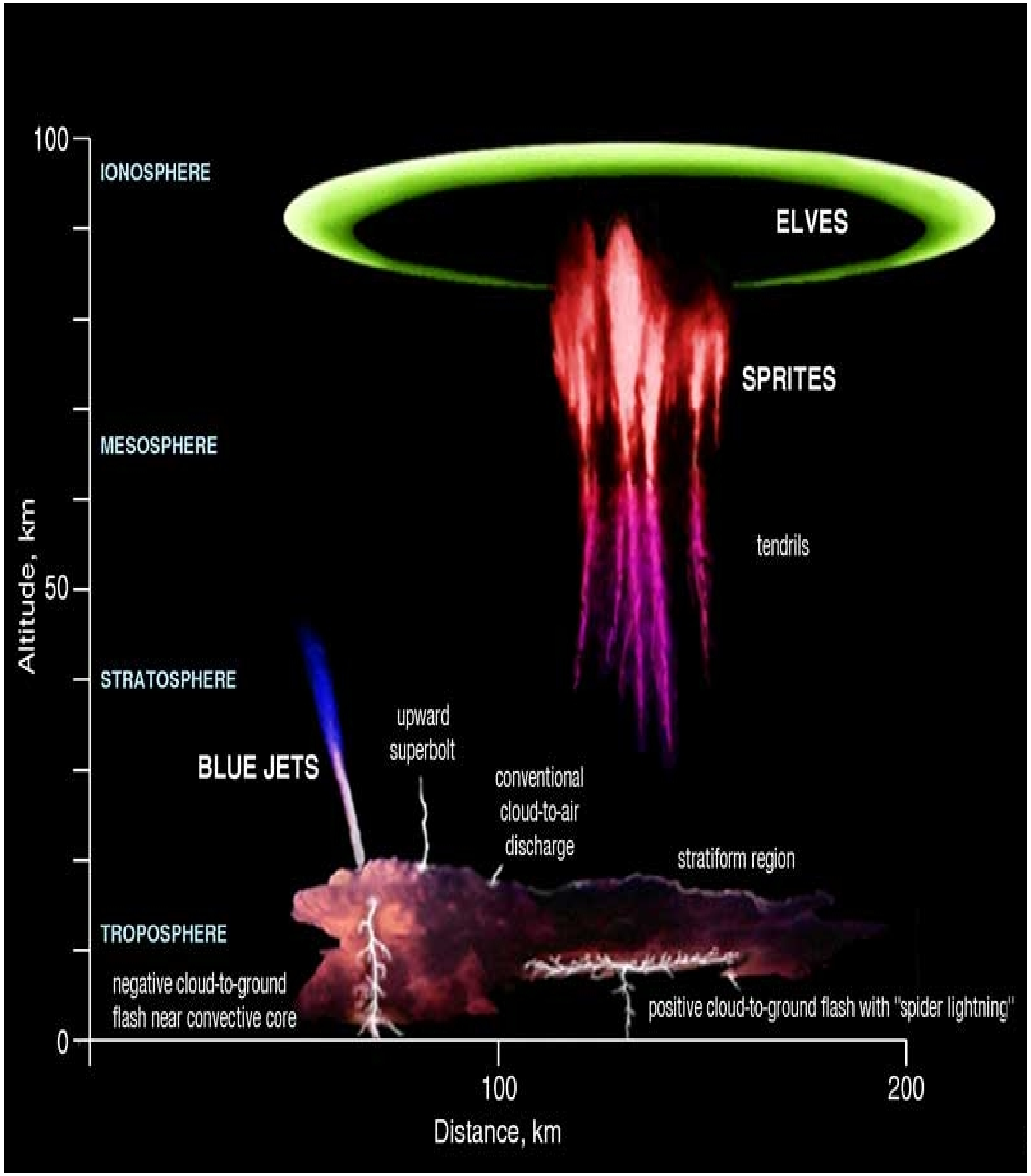




Roberta Colalillo for the Pierre Auger Collaboration
INFN and University "Federico II" of Naples

UHECR 2016, Kyoto
13/10/2016

Transient Luminous Events: ELVES



Optical signature of the lightning electromagnetic pulse (EPM) interaction with the lower ionosphere.

- Confined to 80-95 km altitudes (D layer of ionosphere);
- They extend up to 600 km;
- Short duration: < 1ms;
- Bright: > 1MR.

First clear observation in 1995 by using a **high speed photometer** pointed at altitudes above those of sprites.

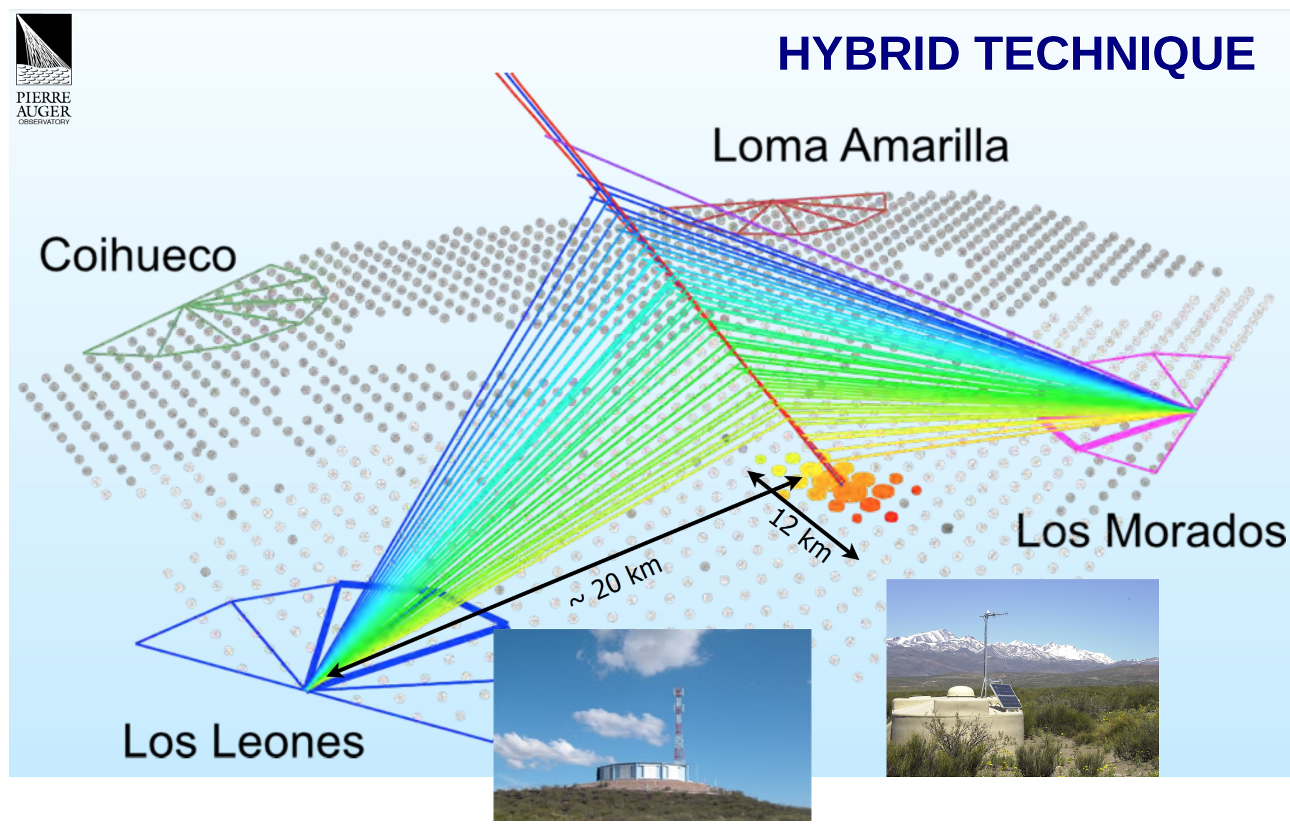
PRESENT MEASUREMENTS:

- **array of photometers** with a resolution of 40 μs → study of the lateral expansion
- **Data from space** → global rate: 35 elves/min; the biggest rate is on the ocean (59%).

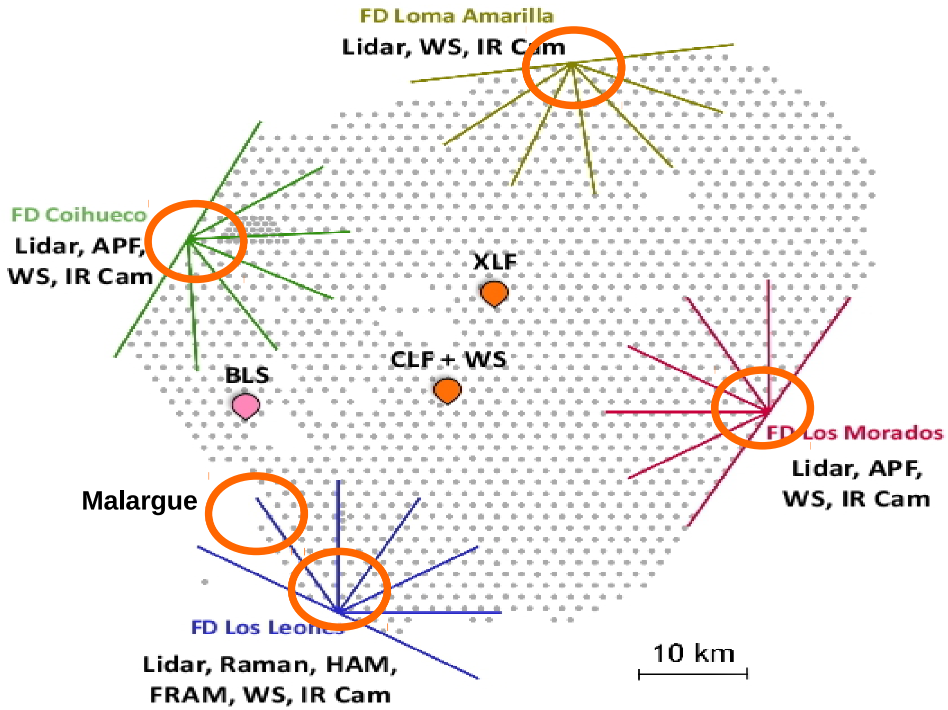
The Pierre Auger Observatory

ELVES DETECTION
sampling above land, cost and ocean

The Pierre Auger Observatory is located in Malargue, Argentina, at 1400 m above the sea level (880 g/cm2).
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.

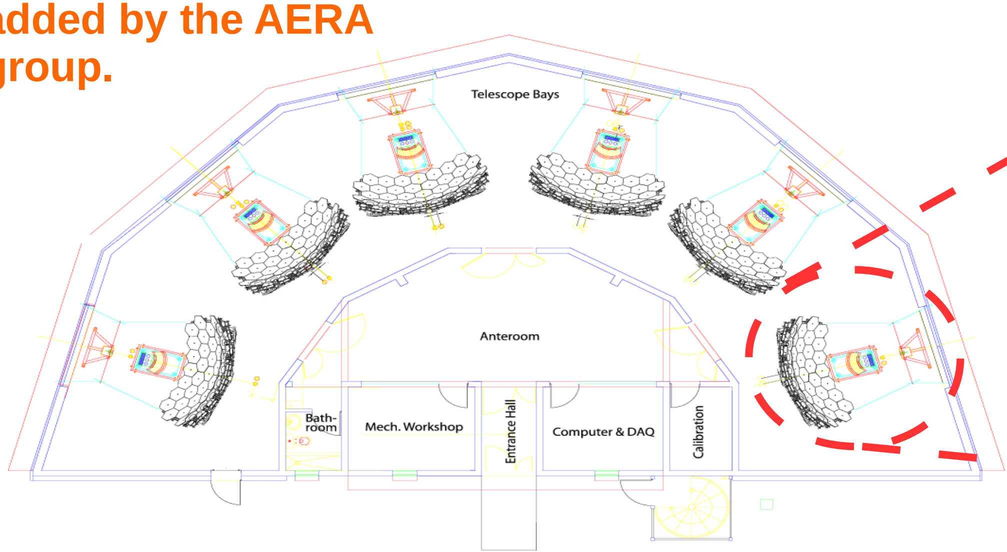


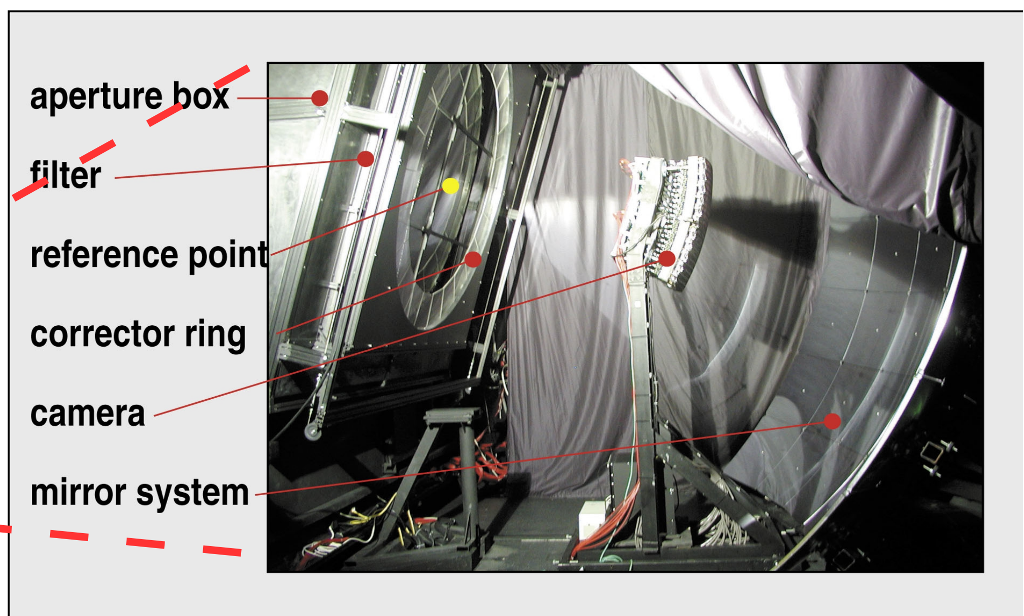
The Fluorescence Detector



- FOV: 6x30°x30° (number of telescopes-azimuth-elevation) for each site;
- UV transmitting filter window: 300-420 nm;
- Mirror Area: 11 m2;
- FD camera: 22x20 PMTs;
- Trace for each PMT:
  1000 bins long,
  100 ns per bin,
  10 Mfps camera;
- Duty cycle: 15%

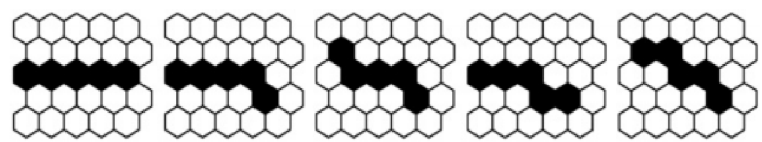
5 lightning stations added by the AERA group.





The Fluorescence Detector Trigger

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



T1

T2

T3

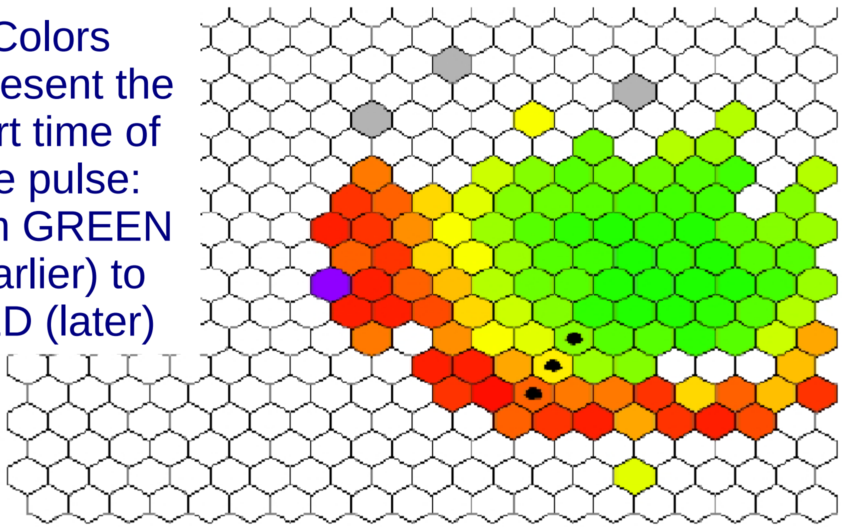
Also Elves rejection

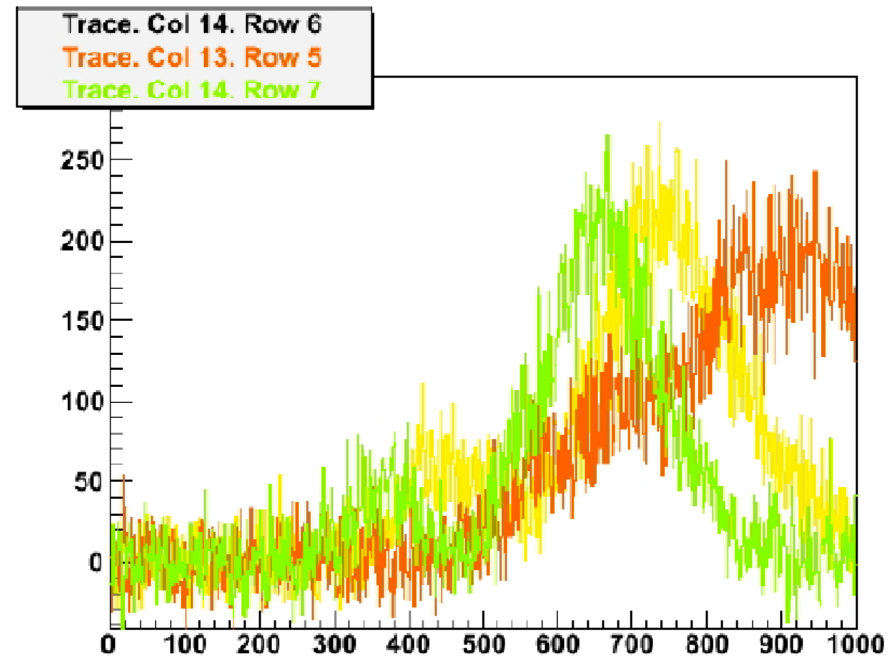
First Elve Detected by FD

May 18th, 2005 → passed T3 trigger in bay 6 of Los Morados

LM6-800414142

Colors represent the start time of the pulse: from GREEN (earlier) to RED (later)



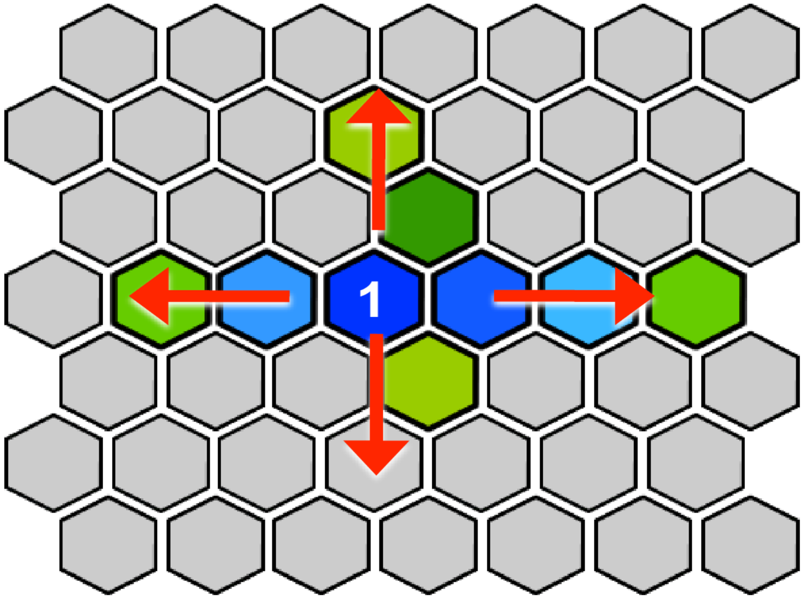


A light transient of the same duration was recorded in the adjacent camera (LM-5), according to the T2 logs, but did not pass the T3 level trigger requirements.

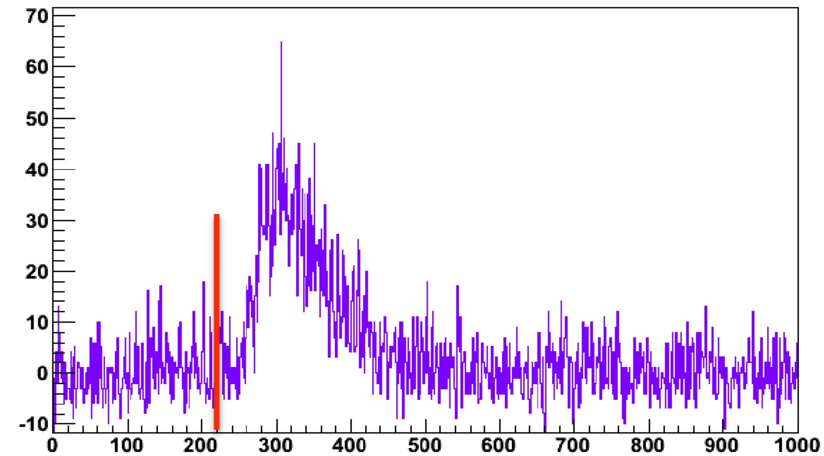
Analyzing the fraction of events which pass the 2nd level of trigger, which is saved in a separate data stream (*MINIMUM BIAS*) and is used for measuring efficiencies and testing new trigger algorithms

58 new events were found

Dedicated Trigger for Elves



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



2) Check PIXELS on the same COLUMN

- at least **3 pixels before AND 3 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**

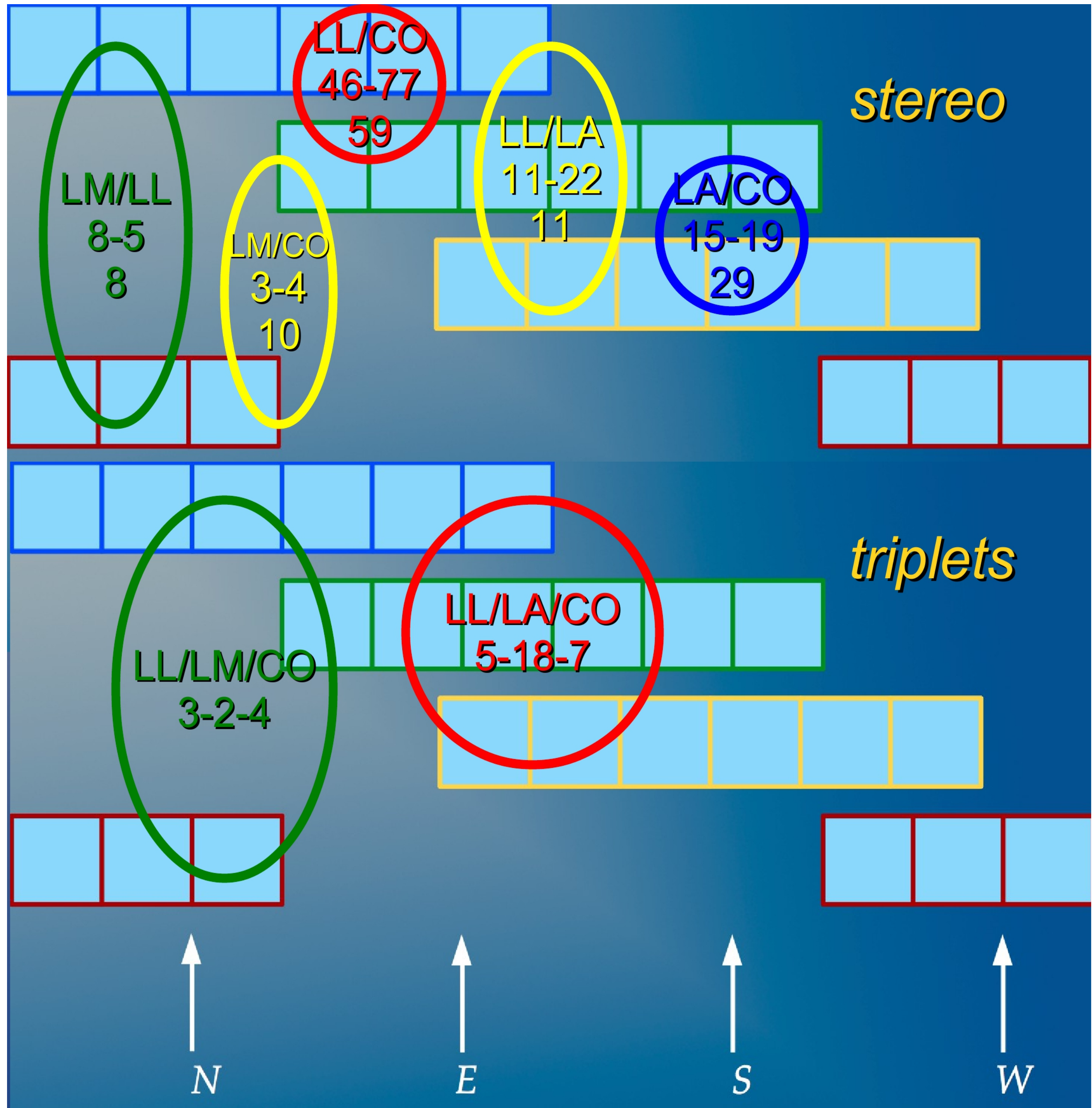
4) Check signal amplitude for each pixel

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

Elves Statistics

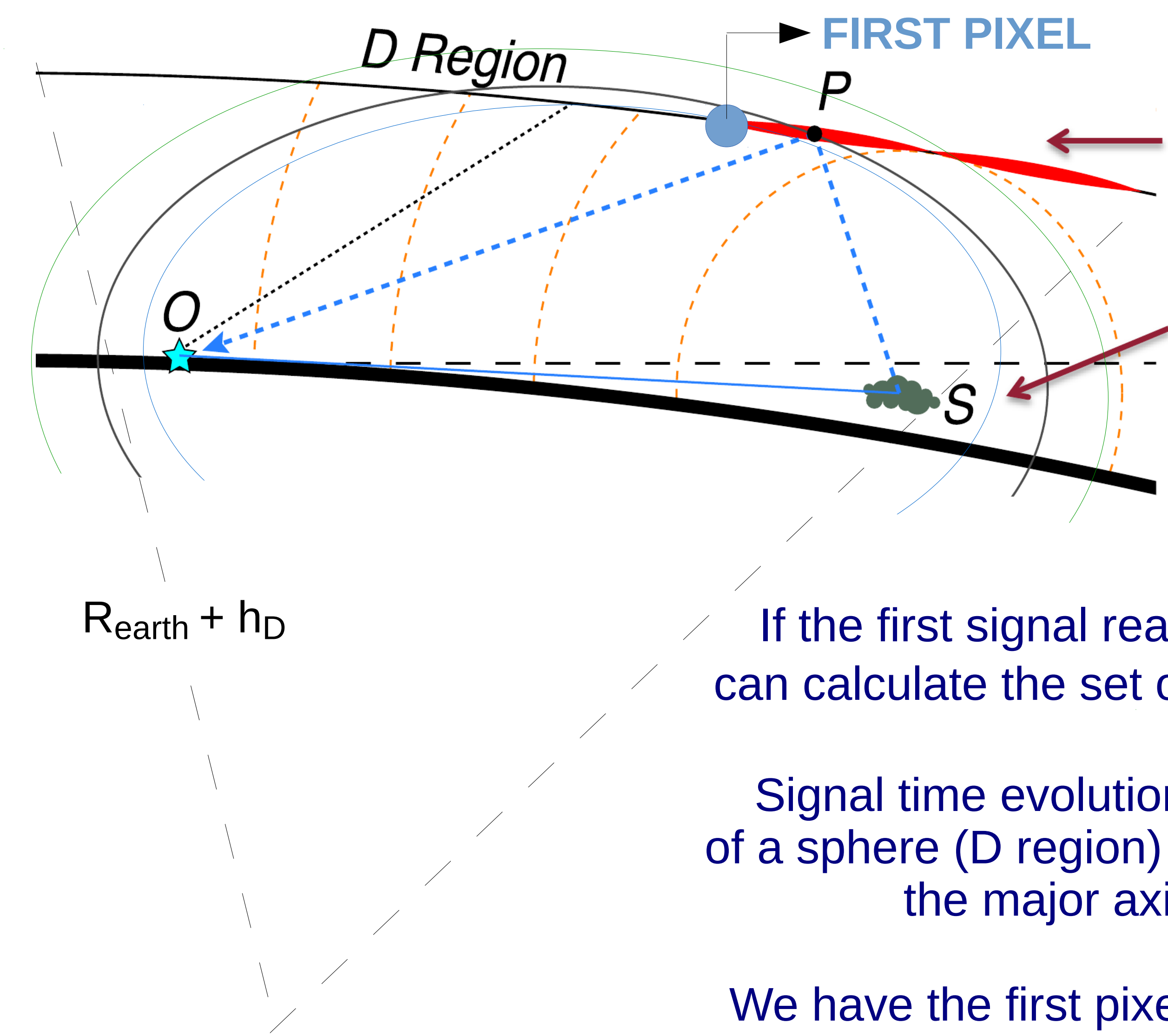
	2013(*)	2014	2015
1-eye	214	434	625
2-eye	83	127	117
3-eye	8	20	11
Total	305	581	753

(*) no data from Jan-Feb-May



Los Leones
Coihueco
Loma Amarilla
Los Morados

Geometrical Model for the Light Front Propagation



Optical emission takes place at 80-95 km altitudes.

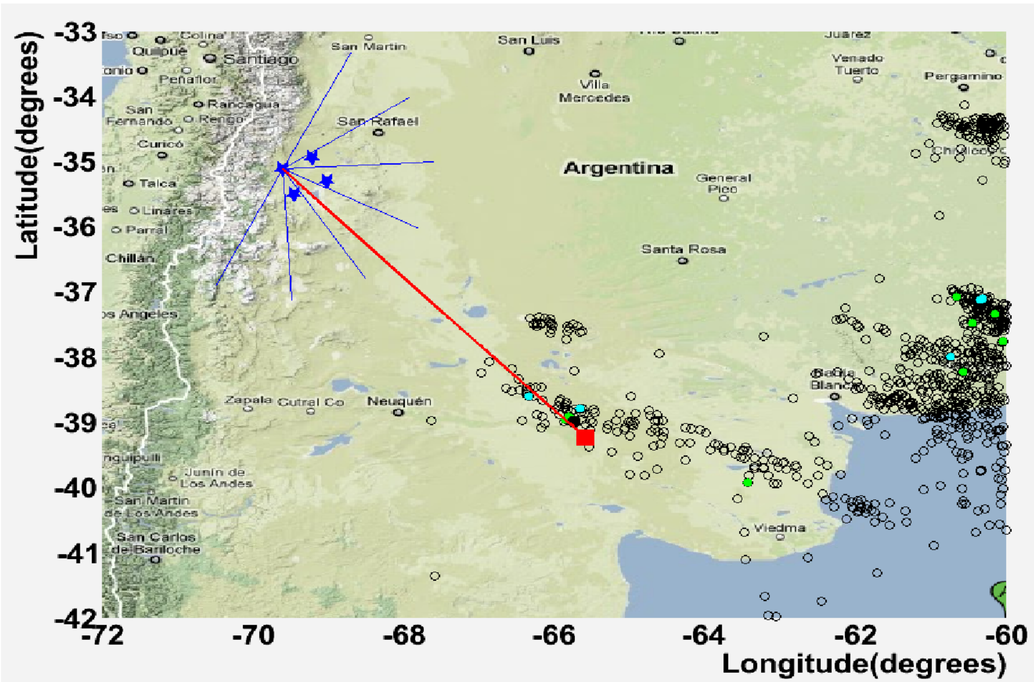
EMP source confined inside the troposphere.

If the first signal reaches the observer at time T_0, we can calculate the set of points at a generic time T_0+dT.

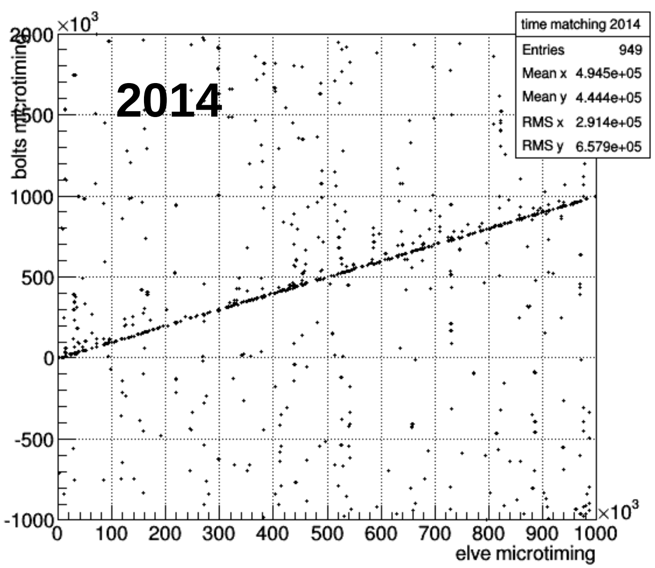
Signal time evolution is described by the intersection of a sphere (D region) with ellipsoids with foci O and S; the major axis of ellipsoids is a function of dT.

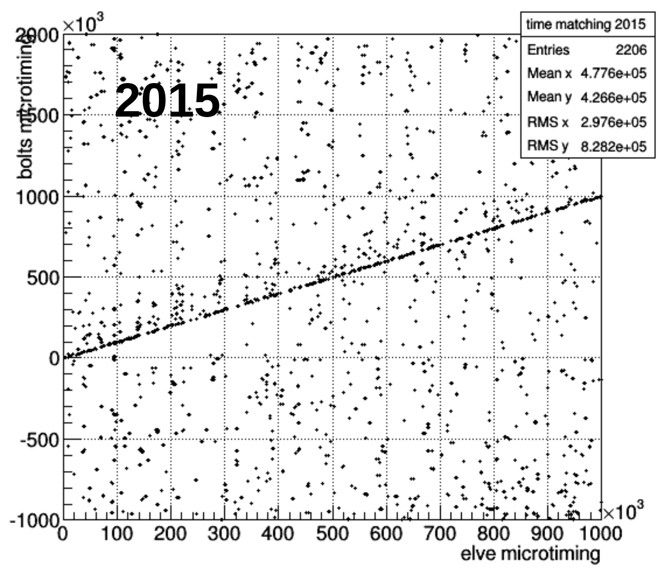
We have the first pixel when the ellipsoid is tangent to the sphere.

Comparison with WWLLN data



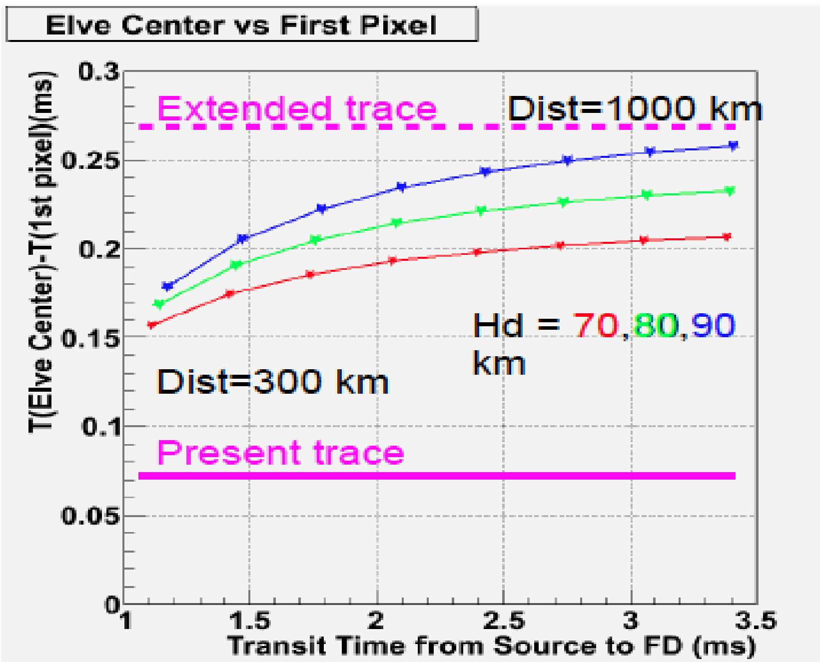
With the geometrical model, we can obtain the **altitude of light emission** and the **position of the lightning**.
In the figure, the reconstructed source position (red) of one event collected the 2sd of April, 2007 is compared with the lightning strike locations recorded by the WWLLN network within 20 μs with respect to our event GPS time (black dots).



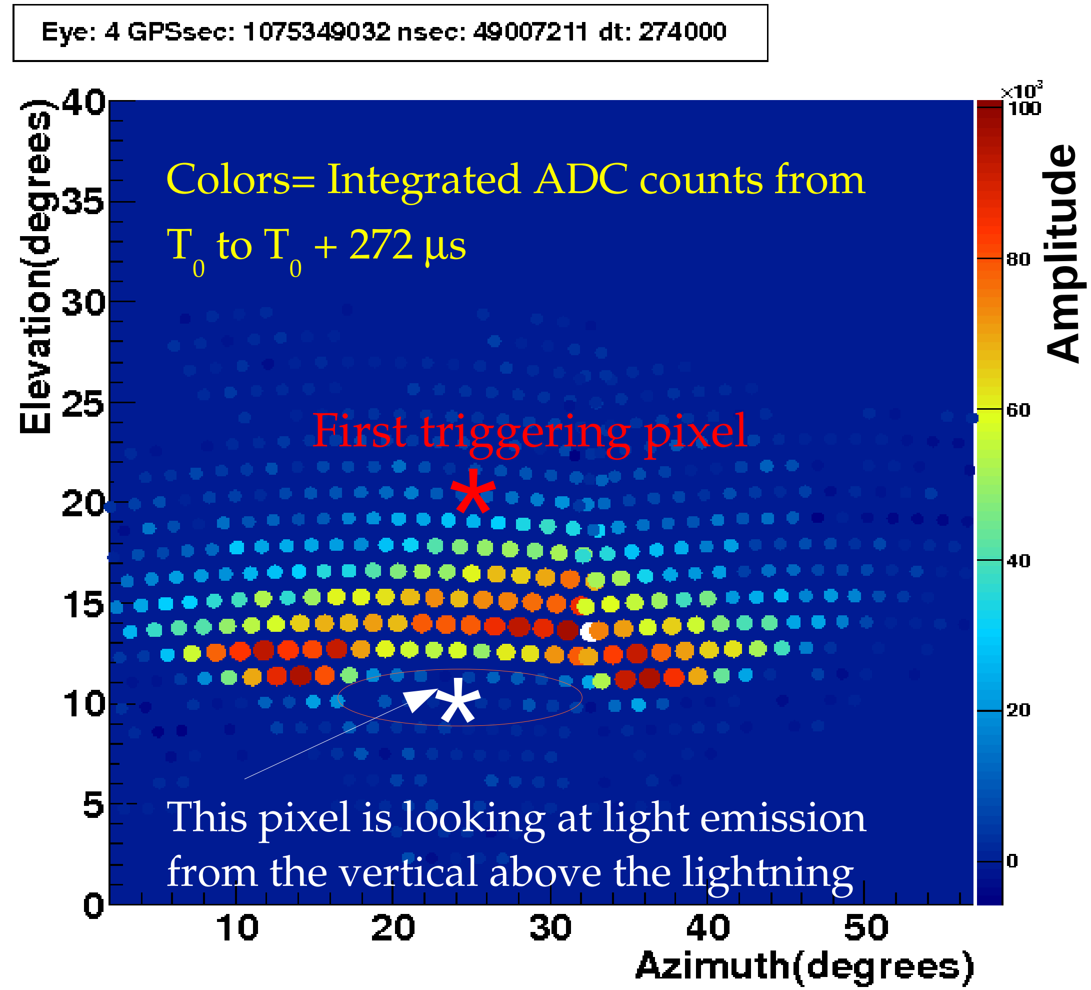


Selection of WWLLN lightnings in a 2000x2000 km^2 region around Auger Observatory.
More than 40% of the ELVES have a WWLLN correlation within 20 μs.

Extended Readout



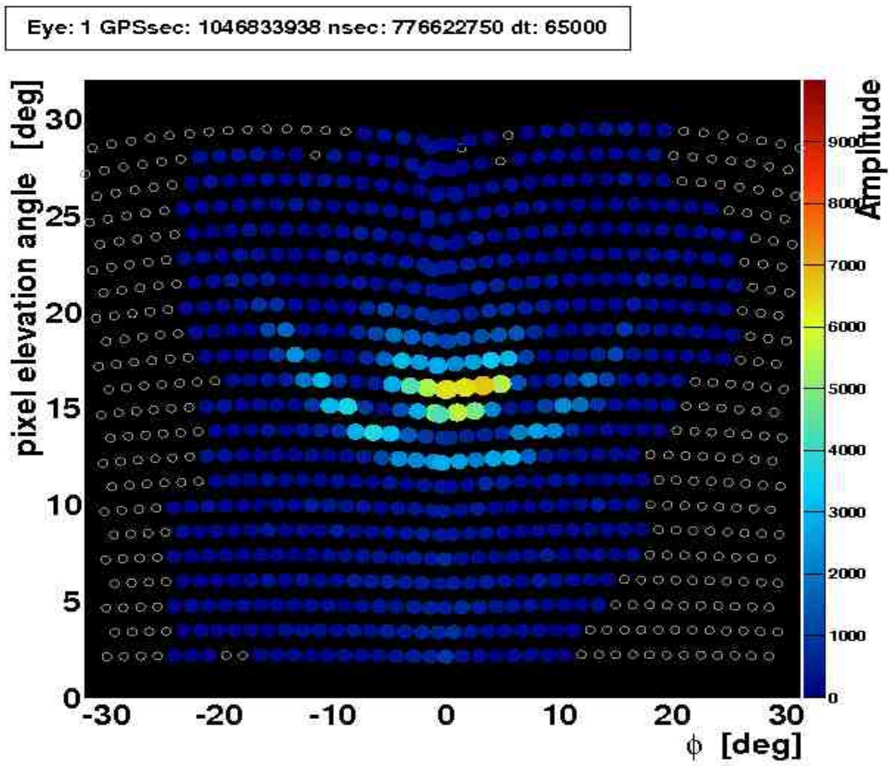
Standard FD traces are 72 μs long after the trigger: this prevents to see most of the light of the ELVES.
In particular, it prevents to see light from the vertical above the lightning source.
Therefore, we modified the FD readout scheme, allowing to acquire 3 consecutive frames for these special triggers. This allows to study the angular distribution of light emission above the lightning.



The size of the central gap is related to electron speed in the lightning stroke.

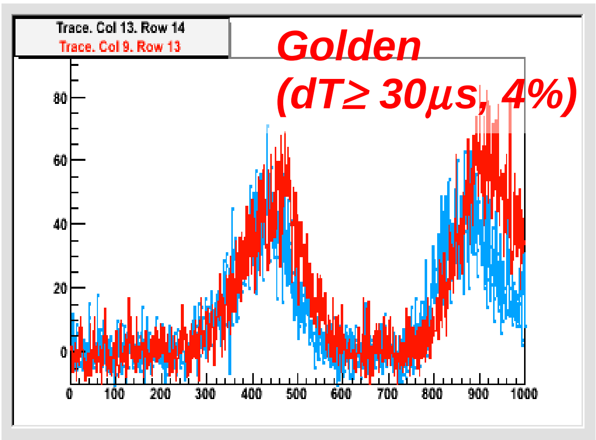
Matlab and C++ simulations to produce 2D and 3D models of light emission
→ which model better describes the observed size?

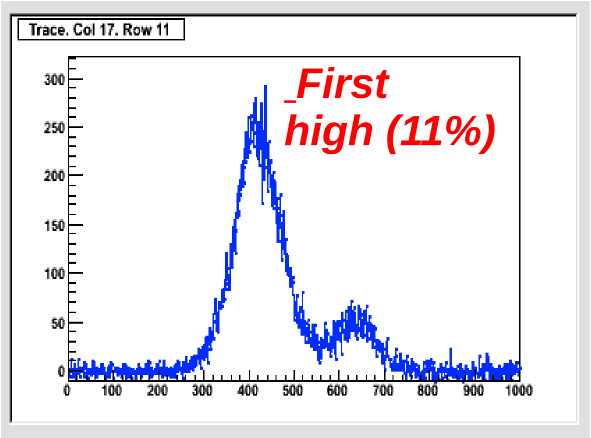
Double Elves

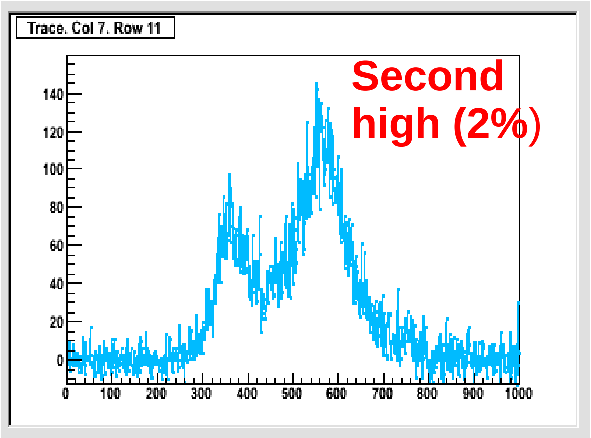


Not simply double return strokes
A rich variety of types, not completely understood.

Also in this case, simulations needed to compare with different models.



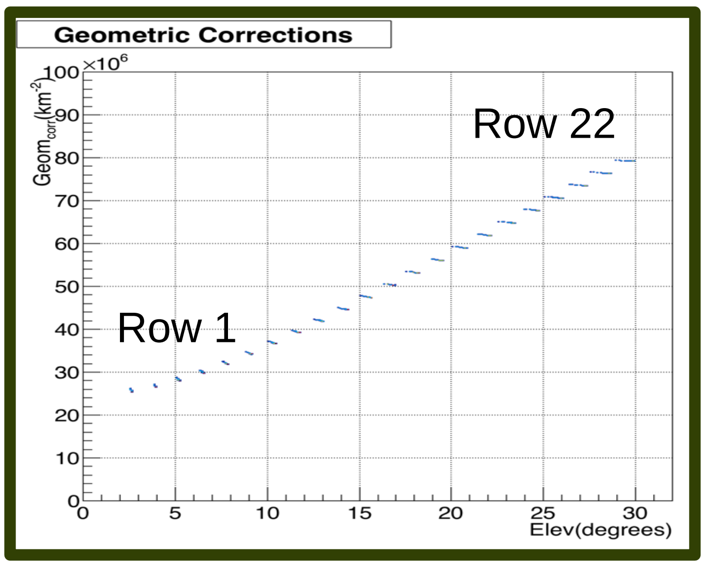


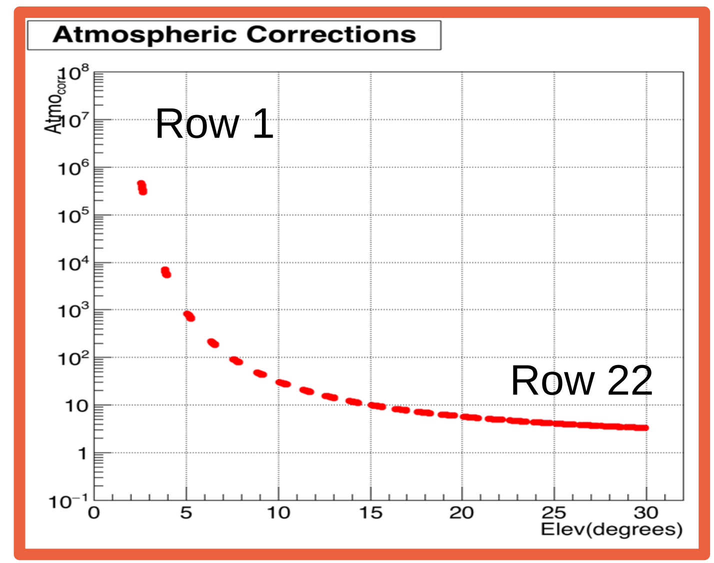


Light Emission Normalization

Photons detected by the FD camera are corrected for distance from the base of ionosphere (assumed at 85 km), and for the surface observed by each pixel. Moreover, we have to consider the atmospheric attenuation.

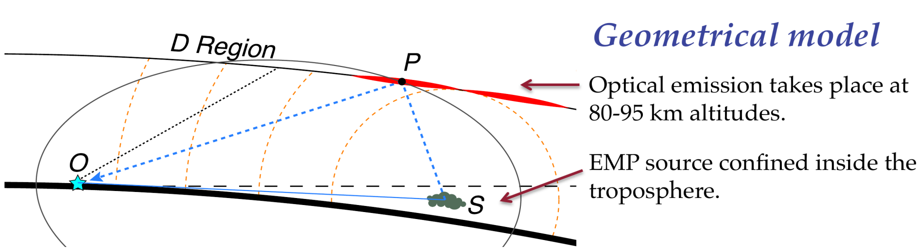
$$\Phi(i) = P_{FD}(i) * Geom\_corr * Atmo\_corr$$





$$Geom\_corr = (R^2_{PO}/A_{mirror})/Area(h=Hd)$$

$$Atmo\_corr = \exp((OD_{mol}+OD_{aer}) * airmass(\theta))$$



OD is calculated from Vertical Molecular (by weather stations, radiosondes, GDAS) and Aerosol profiles (hourly LIDAR measurements)

Elves Summary

- The Auger Observatory has been studying elves systematically since 2013. More than 1200 events have been collected with the extended readout mode → light recorded up to 272 μs after its first appearance (3 times normal acquisition)
  → **the extended readout mode allows to study the light emission from the vertical above the lightning , where we expect to see a decrease in light intensity**;

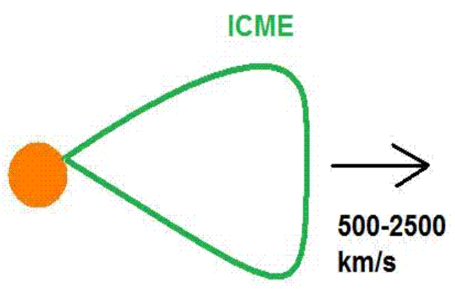
- After performing Geometry and Atmospheric corrections, we can compare our results with WWLLN measurements of lightning energy to check correlations with light emission;

- The Auger Observatory is currently being upgraded to continue operations until 2023. A proposal is under way to extend operations through the whole moon cycle, with reduced PMT gain
  → **ELVES statistic per year doubled;**

- A public web page with all elves data is in preparation at INFN Torino.

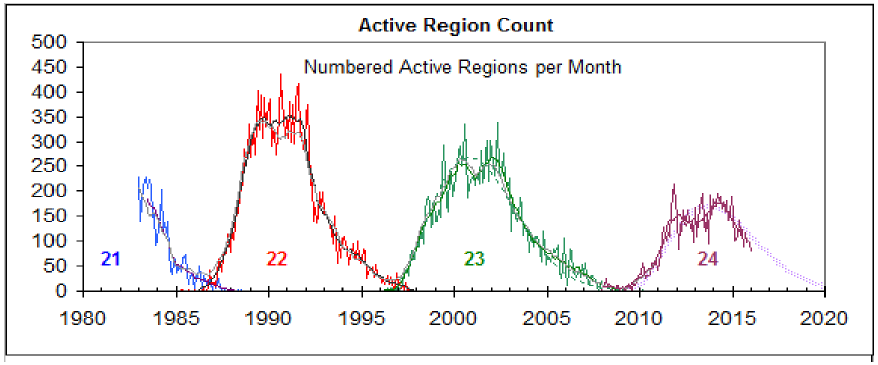
Space Weather & Space Climate Studies

detection of low energy CR fluxes and studies of their variations



Delayed effects at Earth of **Coronal Mass Ejection** → Geomagnetic Disturbance

WUWT Solar Reference Page



- **Day variations → Forbush decreases** → galactic cosmic ray suppression
- **Year variations → Solar Cycle**

Ground-Bases Detectors usually used for the Observation of Galactic Cosmic Rays

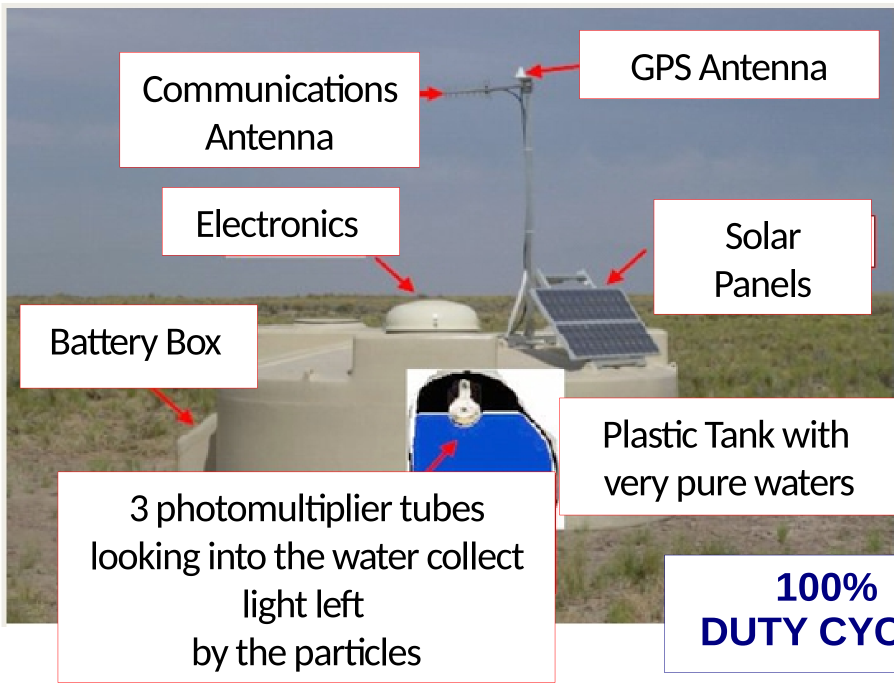
Neutron Monitor

Typical energy of primary: ~1 GeV for solar cosmic rays, ~10 GeV for Galactic cosmic rays;

Muon Detector / Hodoscope

Typical energy of primary: ~50 GeV for Galactic cosmic rays (surface muon detector)

Surface Detector

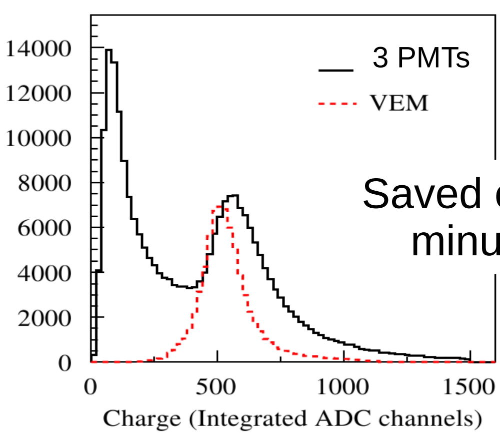


100% DUTY CYCLE

- 10 m^2 of effective area per tank → **16000 m^2 of collection area for the full SD array**;
- 12 tons of high purity water.

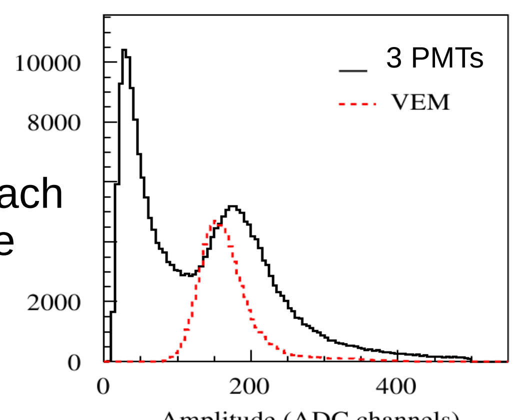
Calorimeter for γ and $e^{\pm}$;
the energy deposited by energetic muons (E>350 MeV) is proportional to the track length of the muon through the detector → hump in a background charge histogram

The SD electronics uses six 40 MHz AD9203 10-bit flash analog-to-digital converters (FADCs) to digitize the signals from the 3 PMTs.



AREA

Saved each minute



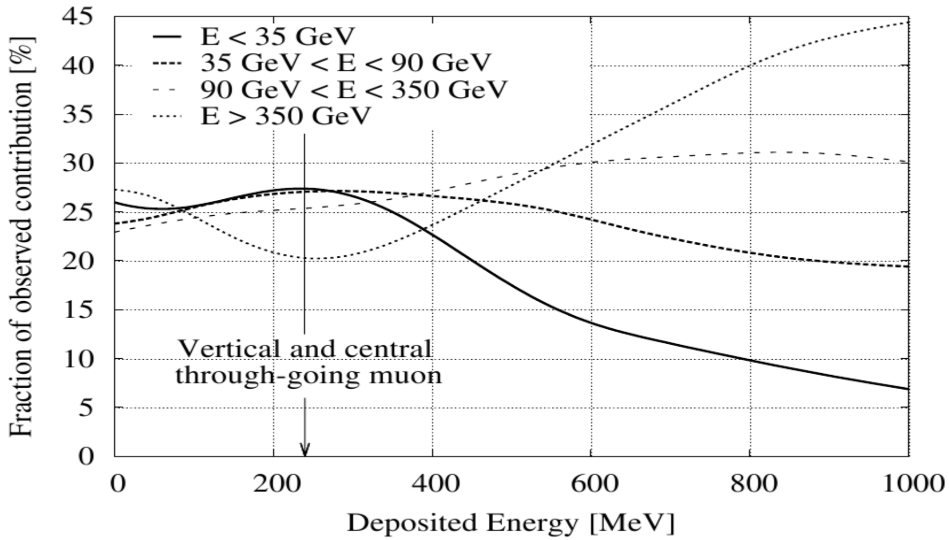
PEAK

first peak → low energy particles;
second peak → vertical through-going atmospheric muon

1 VEM = 240 MeV → energy deposited by a vertical and central muon in a detector with 1.2 depth of water

1 FADC = 5 MeV

Auger Low Energy (LE) Modes:



DETECTOR RESPONSE:
for Ed ~ 240 MeV, the typical deposited energies for single muons, the contribution is dominated by primaries of Ep < 350 GeV,
at Ed > 600 MeV the contribution becomes dominated by GCRs of higher energies.

Scaler Mode: number of signals detected per second in each tank above a very low threshold: 3 FADC (Ed ≤ 15 MeV) < counts < 20 FADC (Ed ≤ 100 MeV) with a typical counting rates of ~ 1.8×10^8 counts per minute.

Energy of primaries (~ 90 GeV) → EM dominated

Histogram Mode: the scaler mode is related to the area of the peak histogram between two limits, given by the lower and upper scaler trigger bounds. By integrating the peak histograms with other bounds, it is possible to obtain a rate related to the flux of secondary particles in a specific interval of deposited energy.

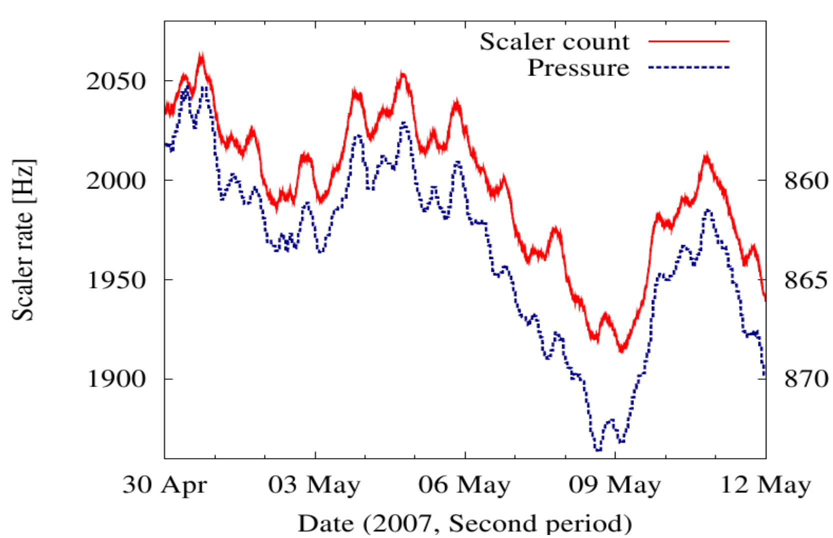
- **Scaler from histograms (H_{SC}: 60 MeV < Ed < 120 MeV):** energy of primaries < 100 GeV → EM dominated
- **Muon Counter (H_{μ}: 200 MeV < Ed < 280 MeV):** energy of primaries up to 10^4 GeV → muon dominated

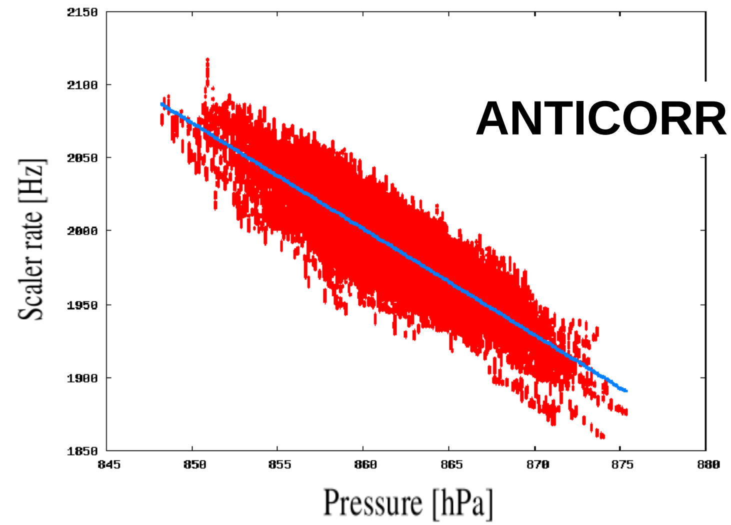
Data Treatment

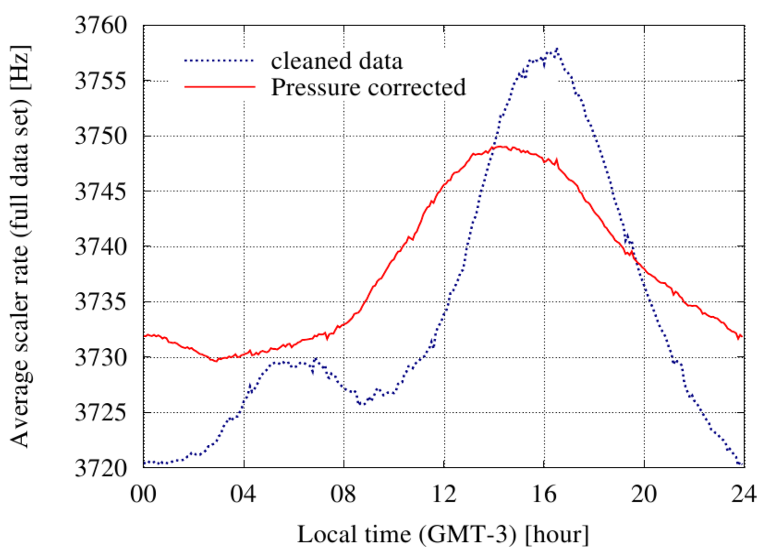
- Exclude from the analysis the detectors with an abnormal rate distribution and the ones that record counts at less than 500 Hz;
- Skip 2.5% of both highest and lowest counts;
- Discard periods with less than 97% of the array in operation;
- Correct for the atmospheric pressure;
- Correct for the Area over Peak ratio. This parameter is related to detector aging (for long-term analysis).

Pressure Effect and Daily Dependence

Atmospheric pressure variations modify the flux of secondary particles at ground level due to the different mass of atmosphere above the detector: an increase in the atmosphere pressure is correlated with a reduction in the background rate.

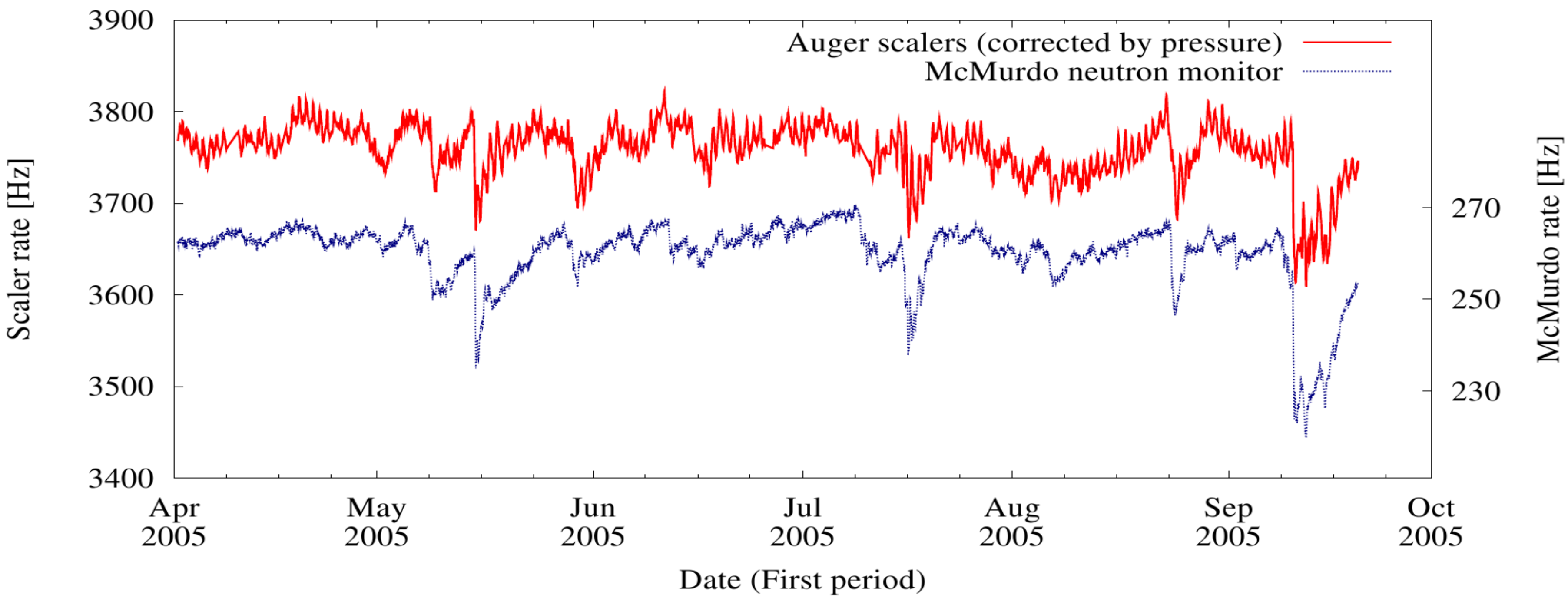


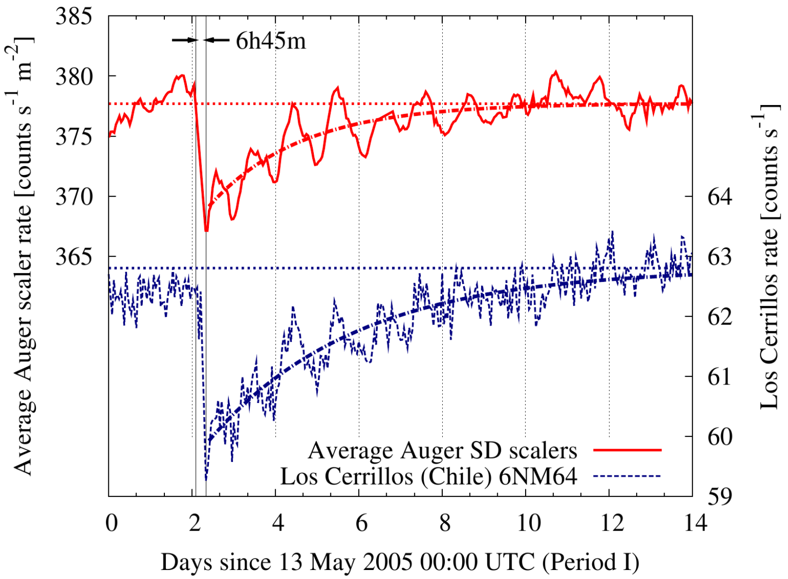




After atmospheric pressure correction, a 0.25% modulation remains, peaked at 17h45 UTC

Forbush Decrease





- 2.9% decrease peaked at 15 May 2005 08:05 UTC (about 6h45);
- Exponential recover up to the scaler rate average for May 2005 in 9 days.

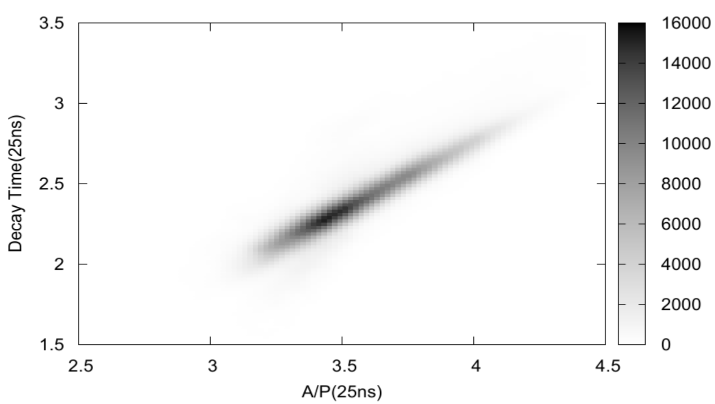
Different reduction percentage and time costant of the exponential function for the close Los Cerrilos Observatory neutron monitor (Chile)
→ similar rigidity cut-off, so difference related to the higher energy threshold of the Auger SD scalers.

Long Term Performance

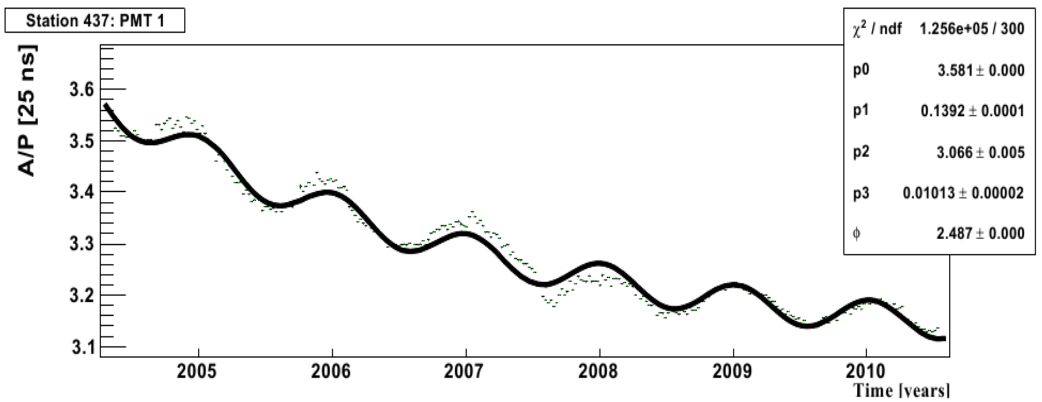
AREA: charge produced by PMTs in response to a single vertical muon;
PEAK: maximum current due to a single vertical muon.

These two quantities, that provide the basis for calibration of each station, together with others such as the baseline values and the dynode/anode ratio (the ratio of the output signal from the last PMT dynode to that of the anode) are available to evaluate the behavior of the stations.

The output signal from the PMTs of a single vertical muon has a fast rise and decays exponentially with time. The fast rise is dominated by the Cherenkov radiation which is only reflected once at the Tyvek, while the exponential decay is dominated by multiple reflections. As a consequence, the exponential decay has a strong dependence on the reflection coefficient of the tank wall and the transparency of the water.



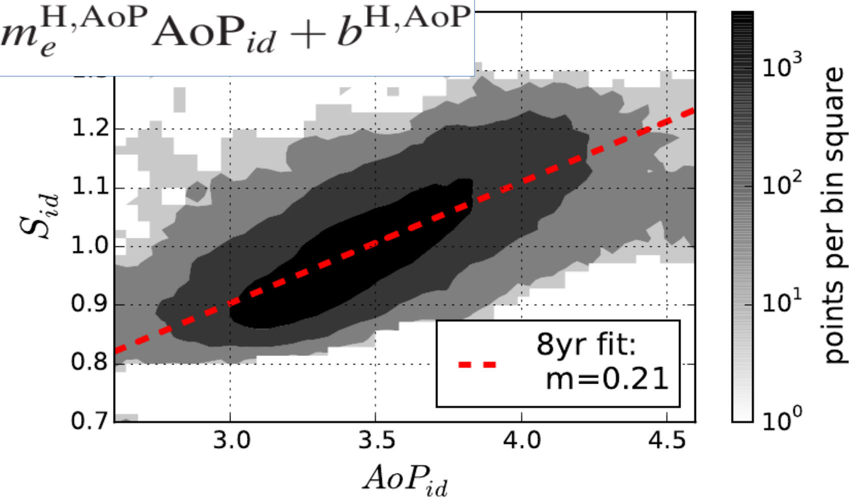
Correlation between the area to peak ratio (A/P) and signal decay constant for muon signals in SD array.

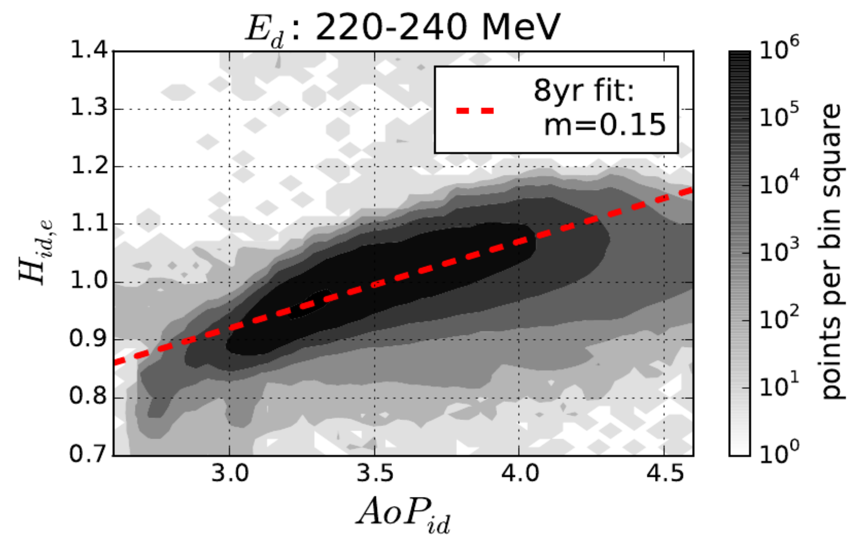


A/P as a function of time for PMT1 of station 437. The dots are the average of the A/P over 7 day.

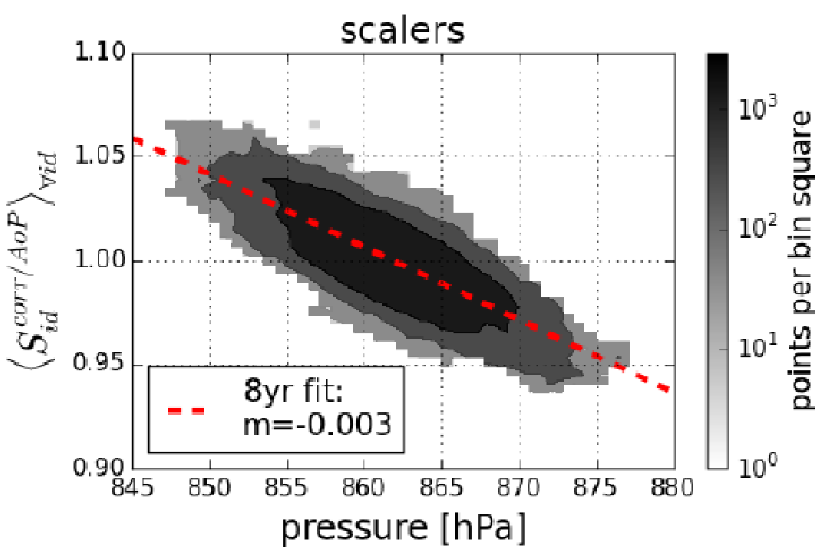
Area over Peak and Pressure Corrections

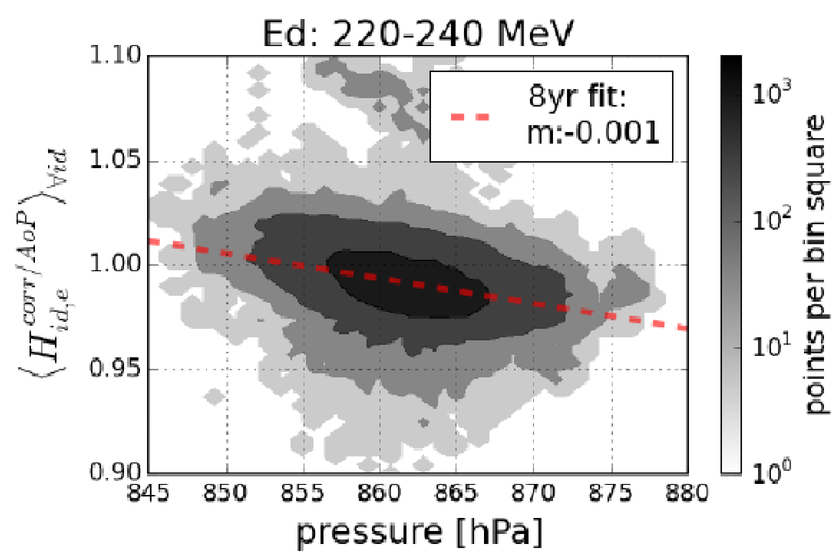
$$S_{\mathrm{id}} = m^{\mathrm{S,AoP}} \mathrm{AoP}_{id} + b^{\mathrm{S,AoP}}$$
$$H_{\mathrm{id,e}} = m_e^{\mathrm{H,AoP}} \mathrm{AoP}_{id} + b^{\mathrm{H,AoP}}$$



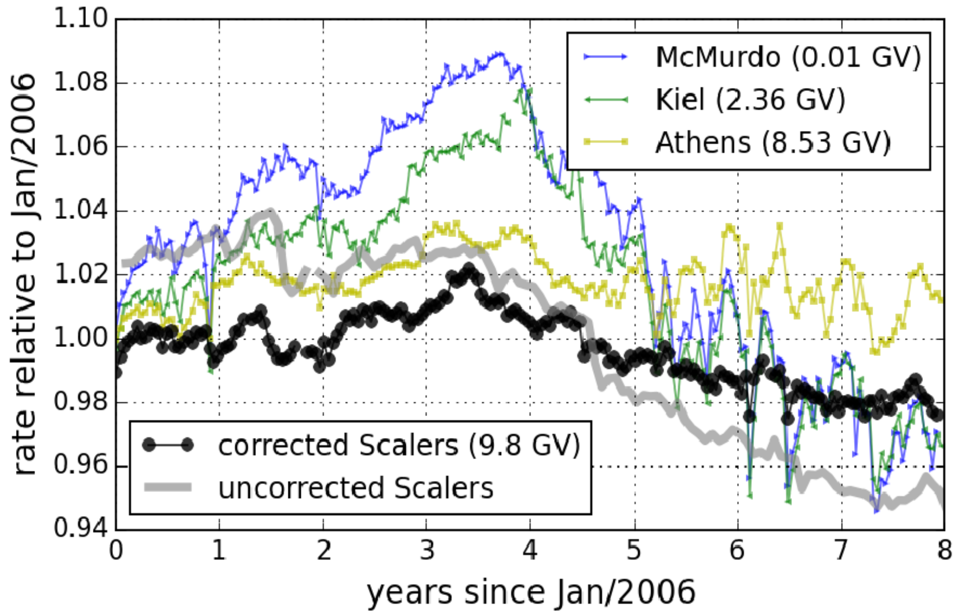


$$S_{\mathrm{id}}^{\mathrm{corr/AoP}}(t) = S_{\mathrm{id}}(t) - m^{\mathrm{S,AoP}}(\mathrm{AoP}_{\mathrm{id}}(t) - \overline{AoP})$$
$$H_{\mathrm{id,e}}^{\mathrm{corr/AoP}}(t) = H_{\mathrm{id,e}}(t) - m_e^{\mathrm{H,AoP}}(\mathrm{AoP}_{\mathrm{id}}(t) - \overline{AoP})$$



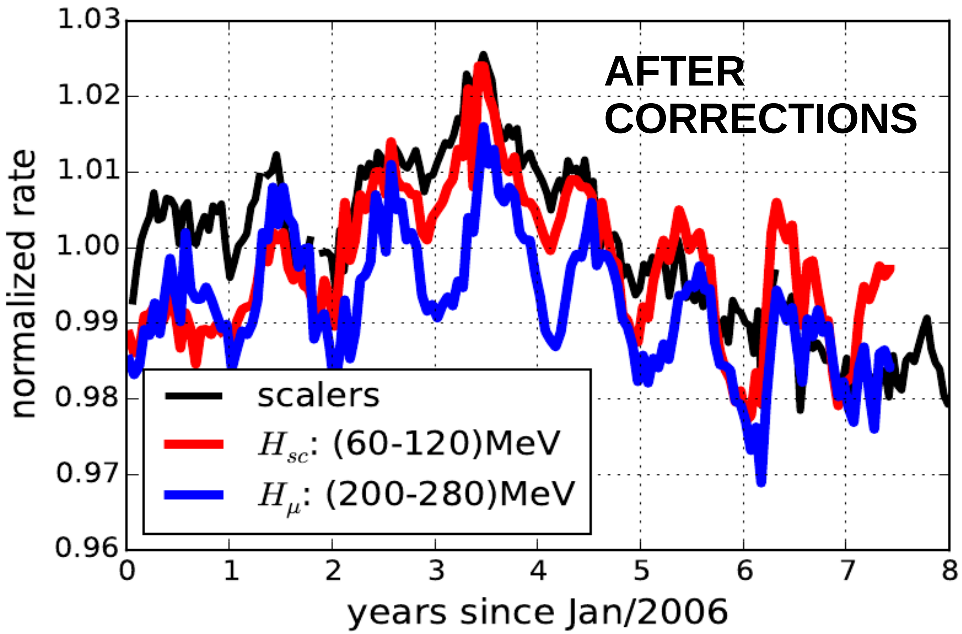


Solar Cycle Modulation



Long-term of pressure-corrected Scalers with AoP correction (black dots) and without AoP correction (gray line), compared with different NMs (inset shows geomagnetic rigidity cut-off).

The lower Auger amplitude of the solar cycle modulation is consistent with the decreasing trend for high rigidity NMs.



- The three profiles show a global peak at the solar minimum.
- The global peak at lower energies is stronger than at higher energies.

Space Studies Summary

- The Auger low energy modes (S(t), H_{sc} (t), H_{μ} (t)) are very competitive in space weather & space climate studies:
  Auger measures the low energy CR flux with high statistical accuracy
  → 16000 m^2 of collection area;
  → low energy threshold (~ 15 MeV) for each individual station;

- A good correlation is found between Auger low energy modes and Neutron Monitors for different rigidity cut-offs;

- Daily CR flux modulations due to Forbush decreases are observed by the Auger scaler mode;

- The low energy modes monitor the solar cycle modulation and explore its effects in different ranges of deposited energy Ed → (15-100 MeV), (60-120 MeV) & (200-280 MeV);

- A global maximum in GCRs flux is recorded in 2009 by Auger low energy modes and Neutron Monitors, as a consequence of the solar minimum;

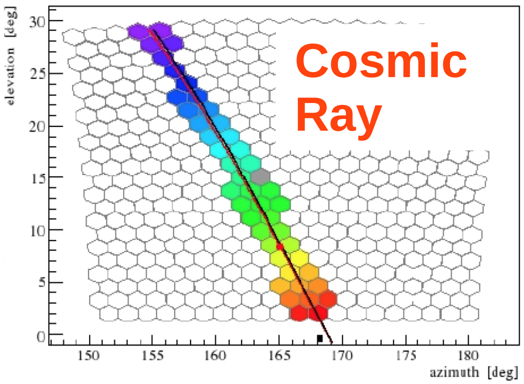
- The full scaler dataset (2005-present) for the whole surface detector is publicly available. The data can be downloaded from the Pierre Auger Observatory public event display website:

http://auger.colostate.edu/ED/scaler.php

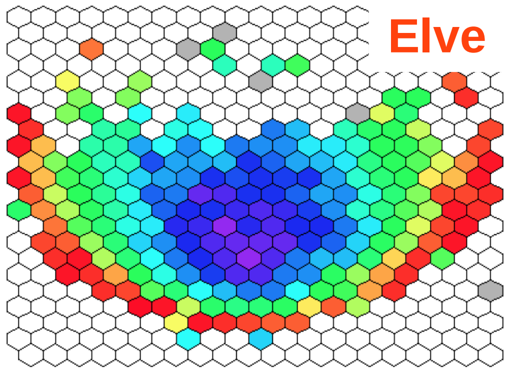
Back Up

A Brief History of Elve Research

- *Inan, 1991* first theorized that lightning EMPs could heat the D-region and produce optical emissions.
- *Boeck et al. 1992* provided first the unambiguous recording of an elve
- *Taranenko 1991, 1993* developed a model to predict optical emissions from the EMP-ionosphere interaction.
- *Fukunishi et al. 1996* convincingly showed that elves are distinct from sprites
- *Inan et al. 1997* provided experimental evidence of the rapid lateral expansion of elves.



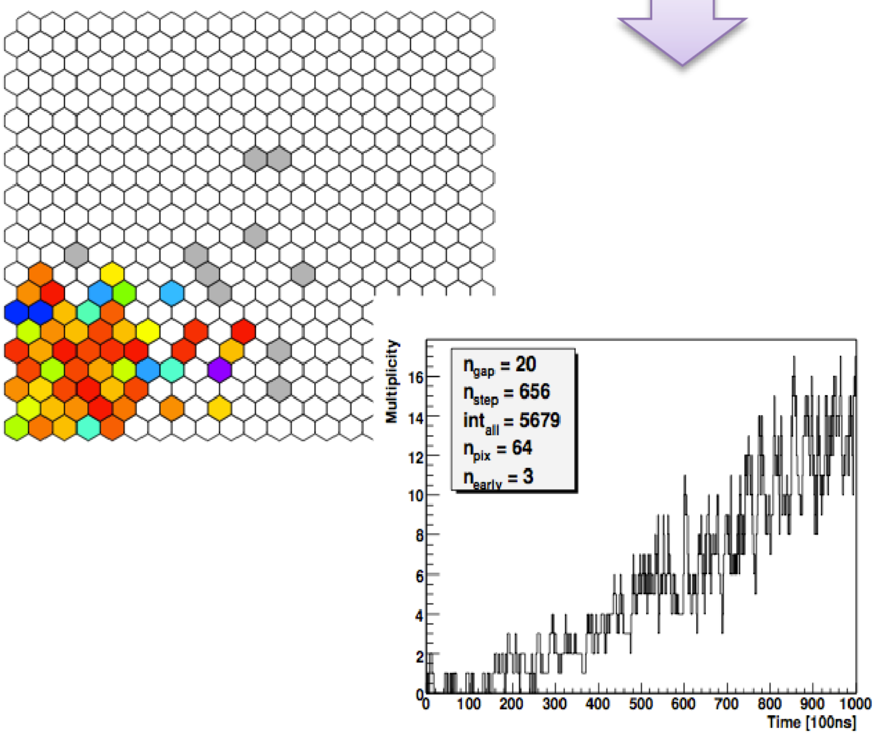
Lightning Cut

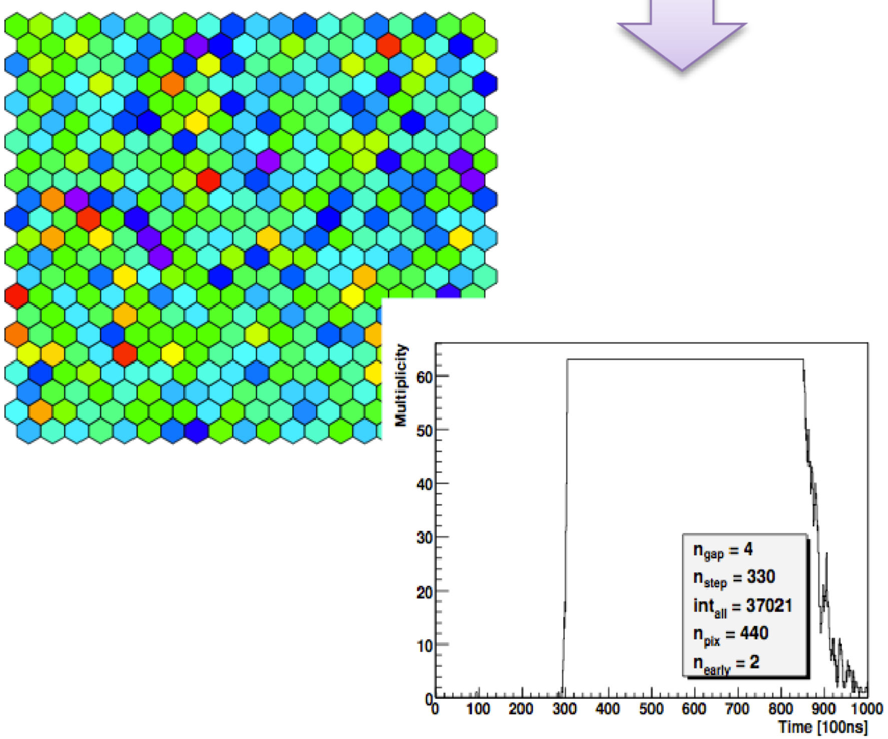


It is made of 5 different cuts

The first three ones remove accidental noise
(e.g. uncorrelated pulses)

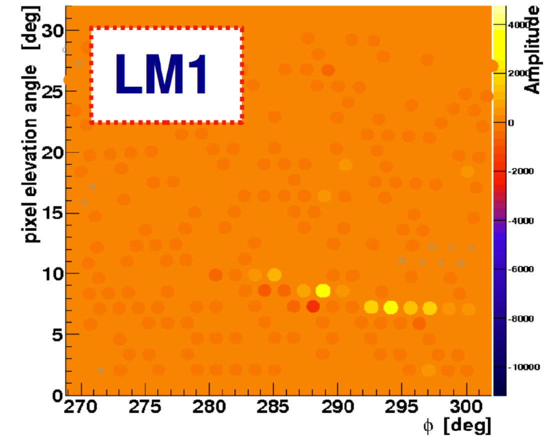
Fluctuation of the multiplicity is bigger than for shower events	During very intense lightning the multiplicity signal gets saturated

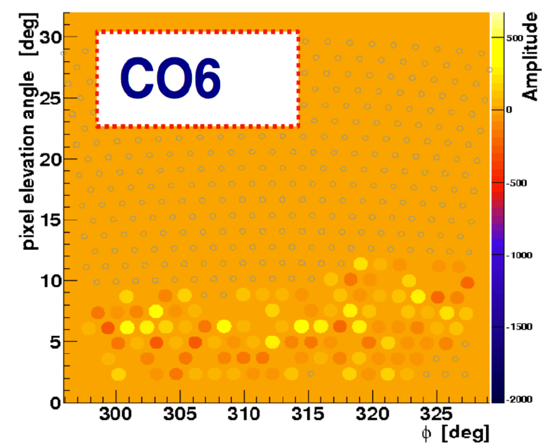


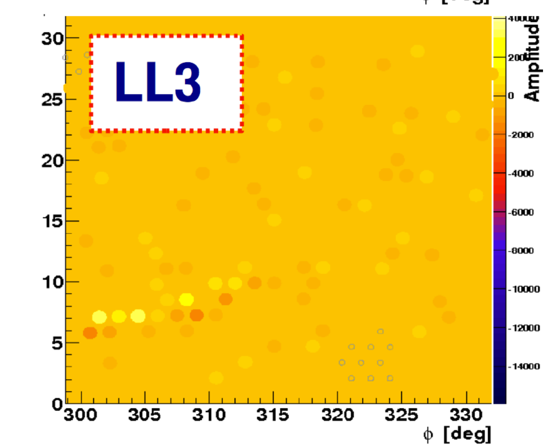


Spatial Information

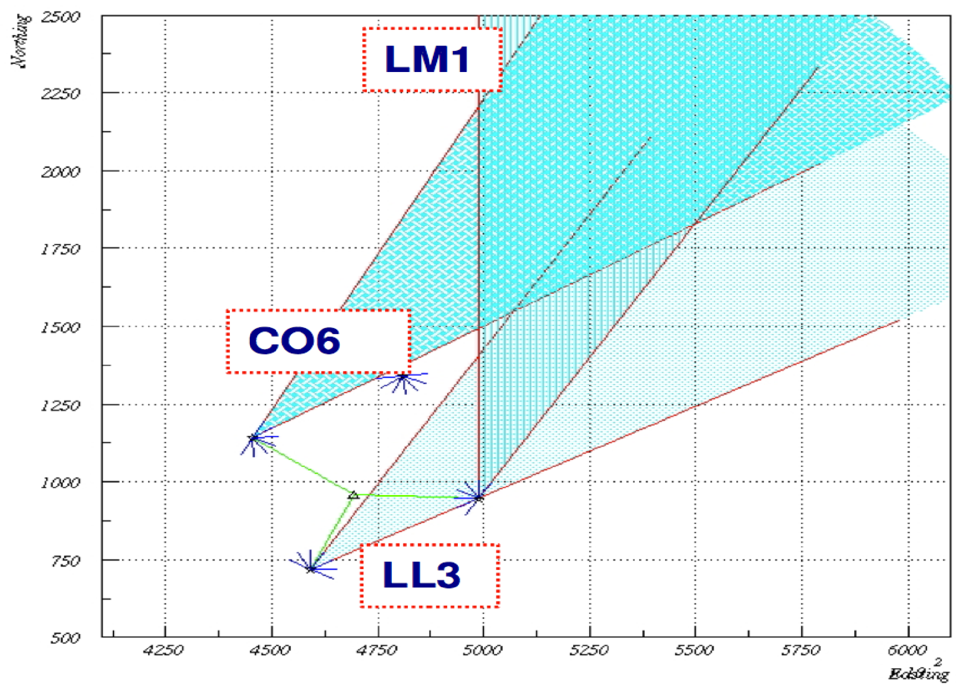
In elves, an electromagnetic pulse launched by a lightning stroke impinges on the lower ionosphere, is partially absorbed, and causes optical emissions, expanding radially with a velocity of the order of c, between 80 and 95 km altitudes over a horizontal region several hundred kilometers wide and over a period of ~ 1 ms. Due to the competing factors of obscuration by the causative storm clouds **elves have been most frequently observed from the ground at ranges of 300 to 800 km. At such ranges, the causative storm system is well below the observer's horizon**, and lightning is not directly visible. Nevertheless elves and scattered light from lightning may be detected optically.



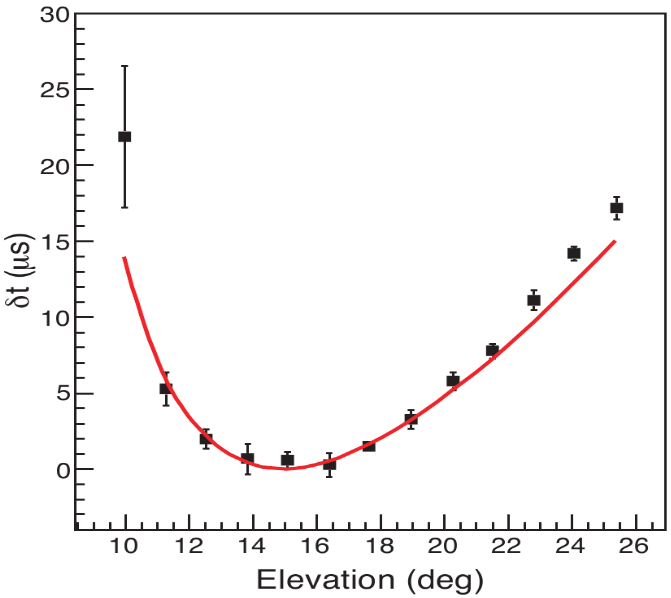


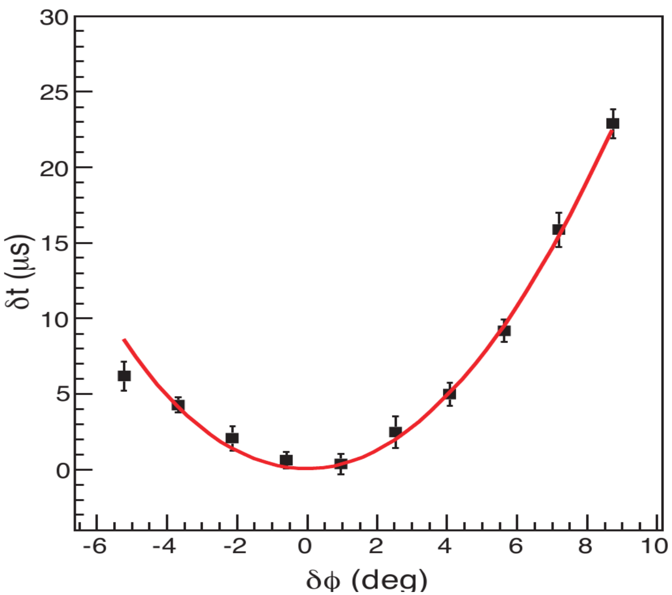


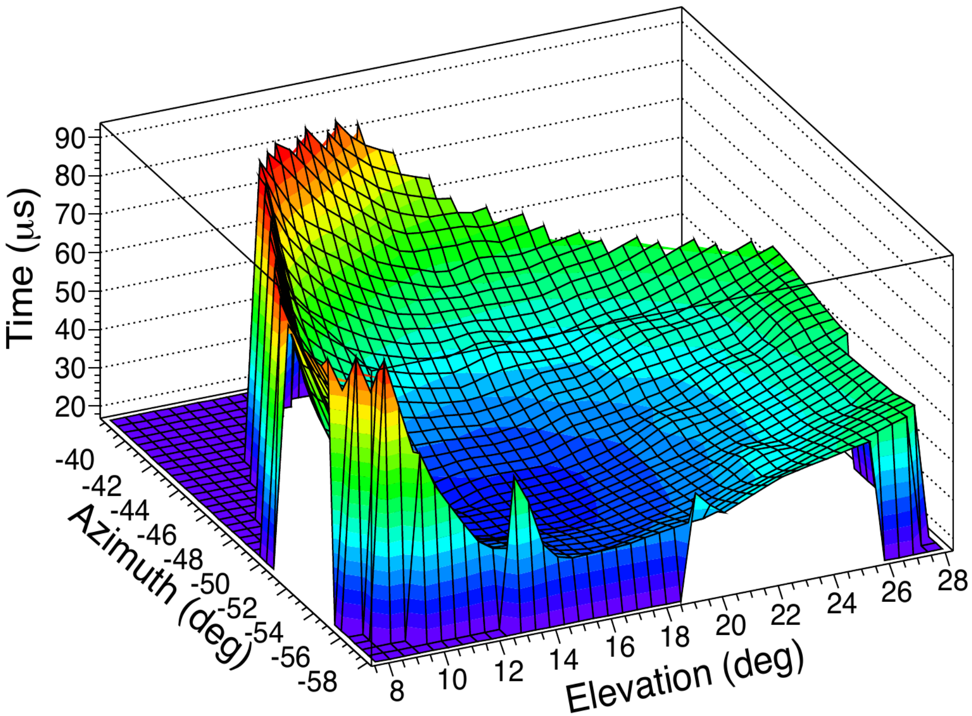
Events observed simultaneously by different FD telescopes
→ At very large distance from the Observatory"



Time Development



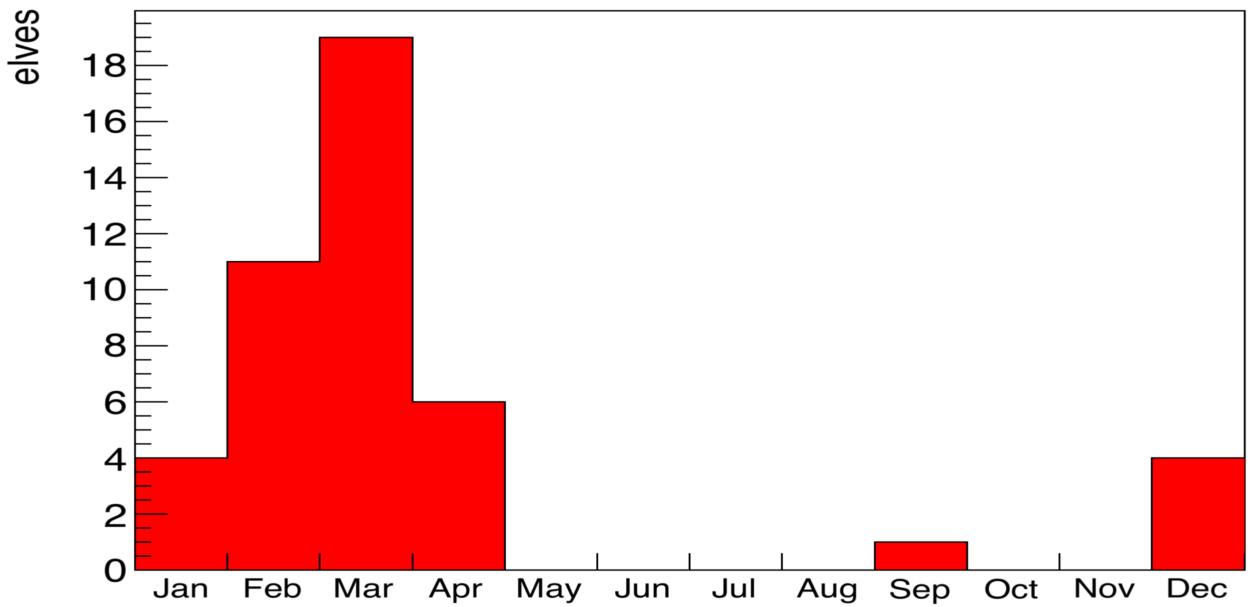




Interpolated 3D curve representing the time of arrival of photons at the FD diaphragm.

Best fit compared to real data for the column and row passing through the centre of the event.

Statistics

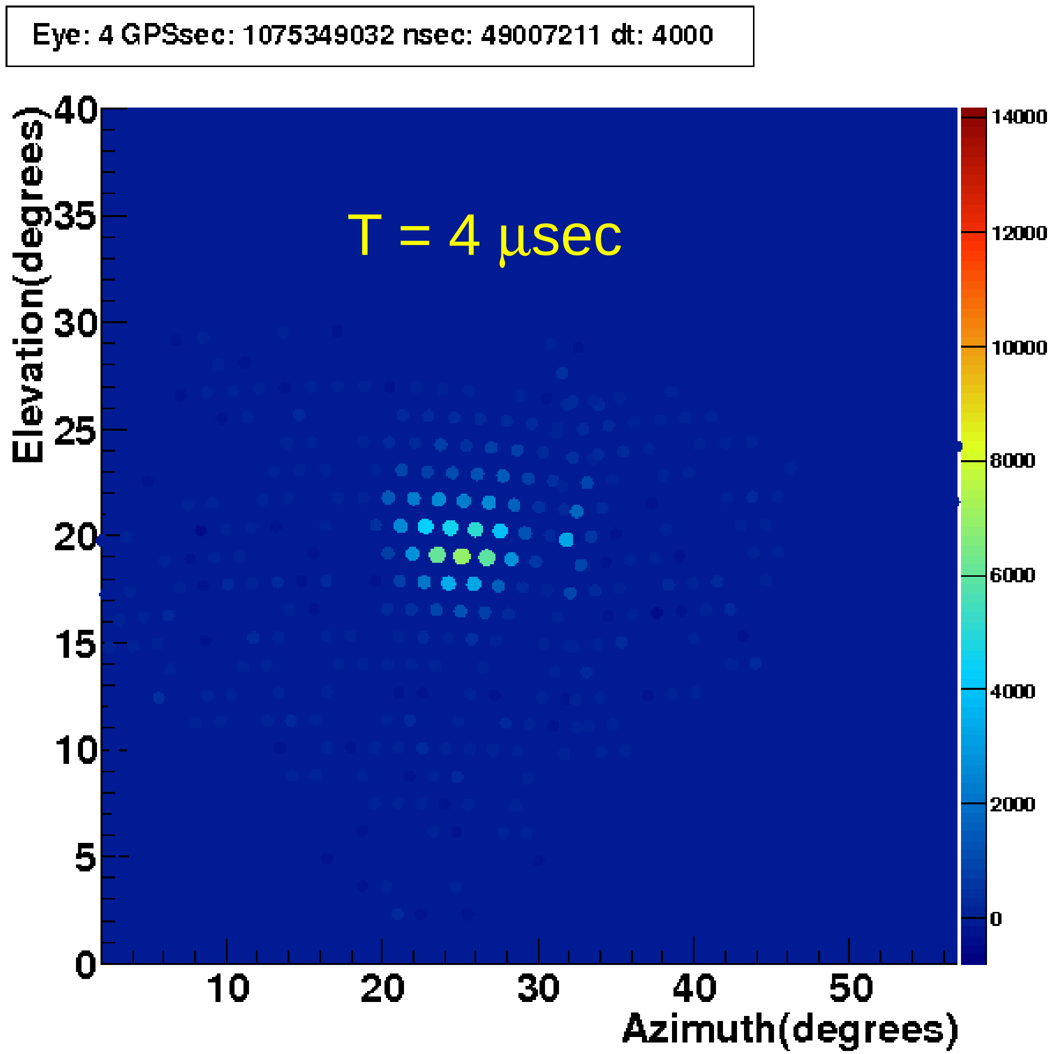


Most of the events were detected during the warmest months

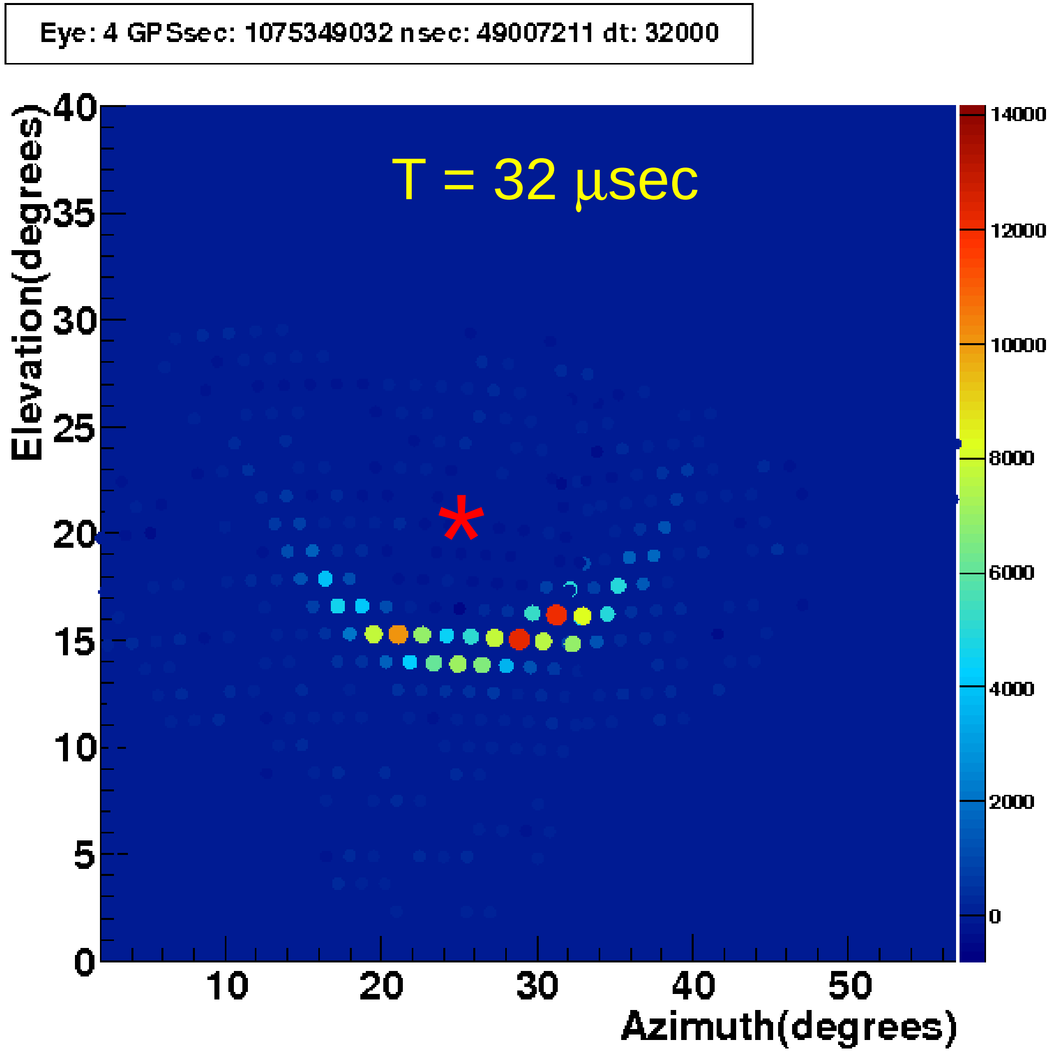
About 8 strokes/s on all Earth.
360 strokes/minute with WWLLN efficiency, rate 10 times bigger than elves rate.
We expect to observe 1000-1500 elves /year.
Among 500 elves, only 5 comes from coast.
About 20% of elves are double elves.

Elves are always produced if current > 80 kA;
EMP lasts around 20 microS.

Extended Readout



Extended Readout



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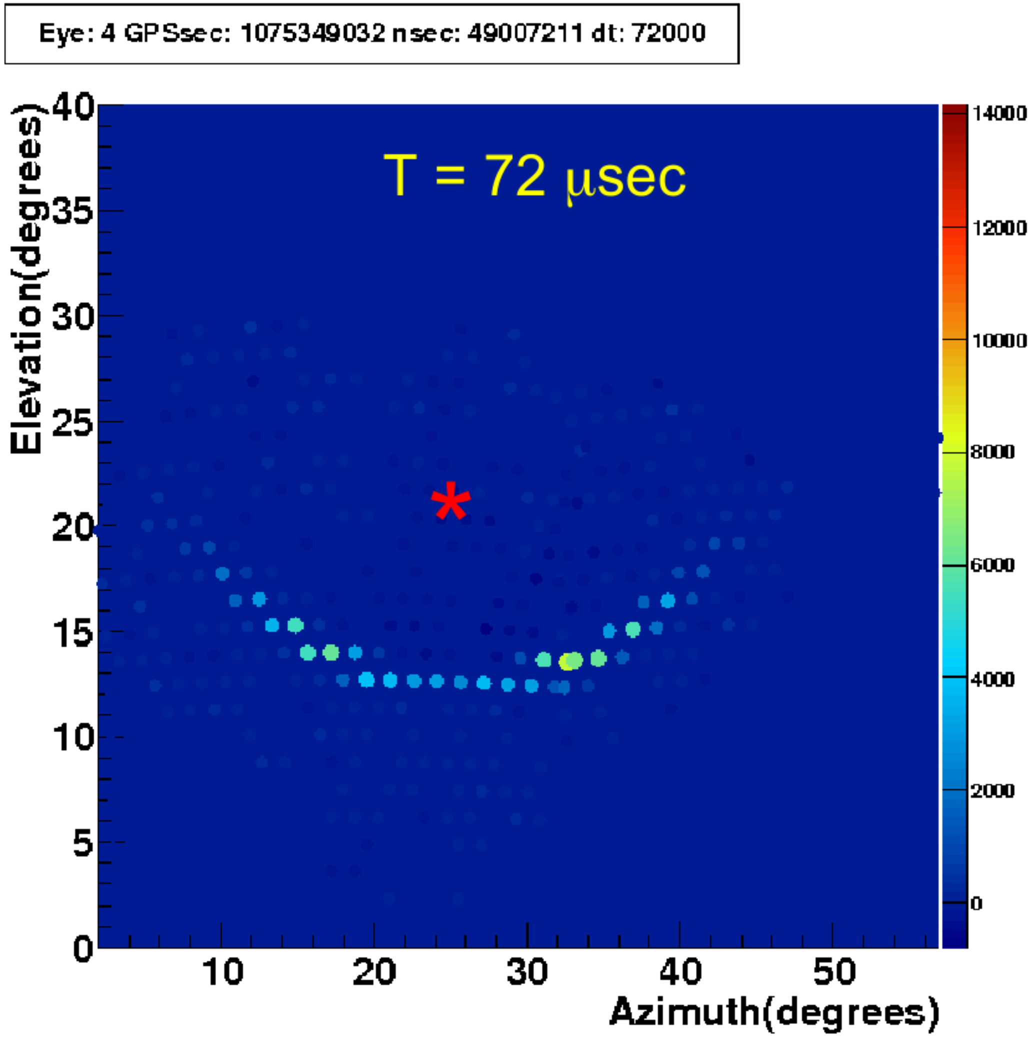

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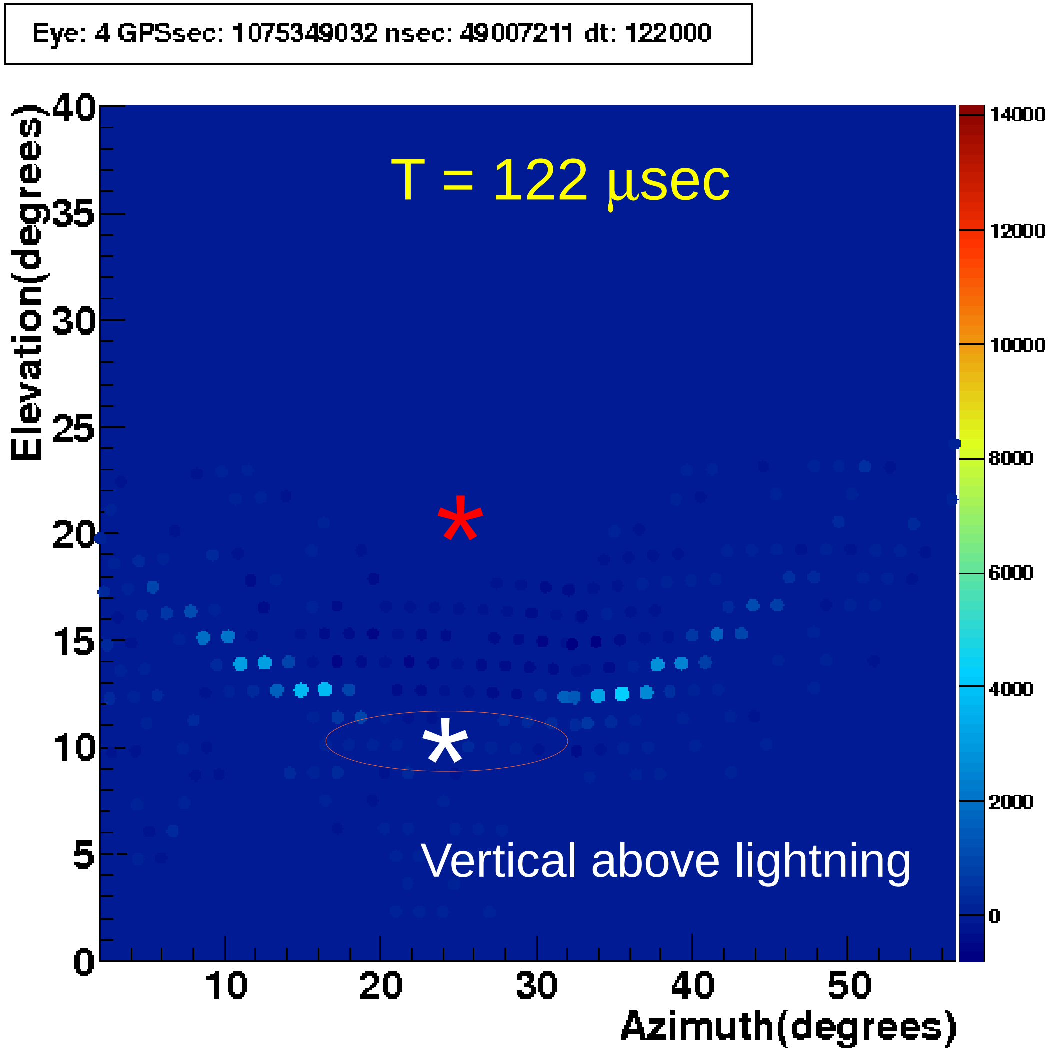

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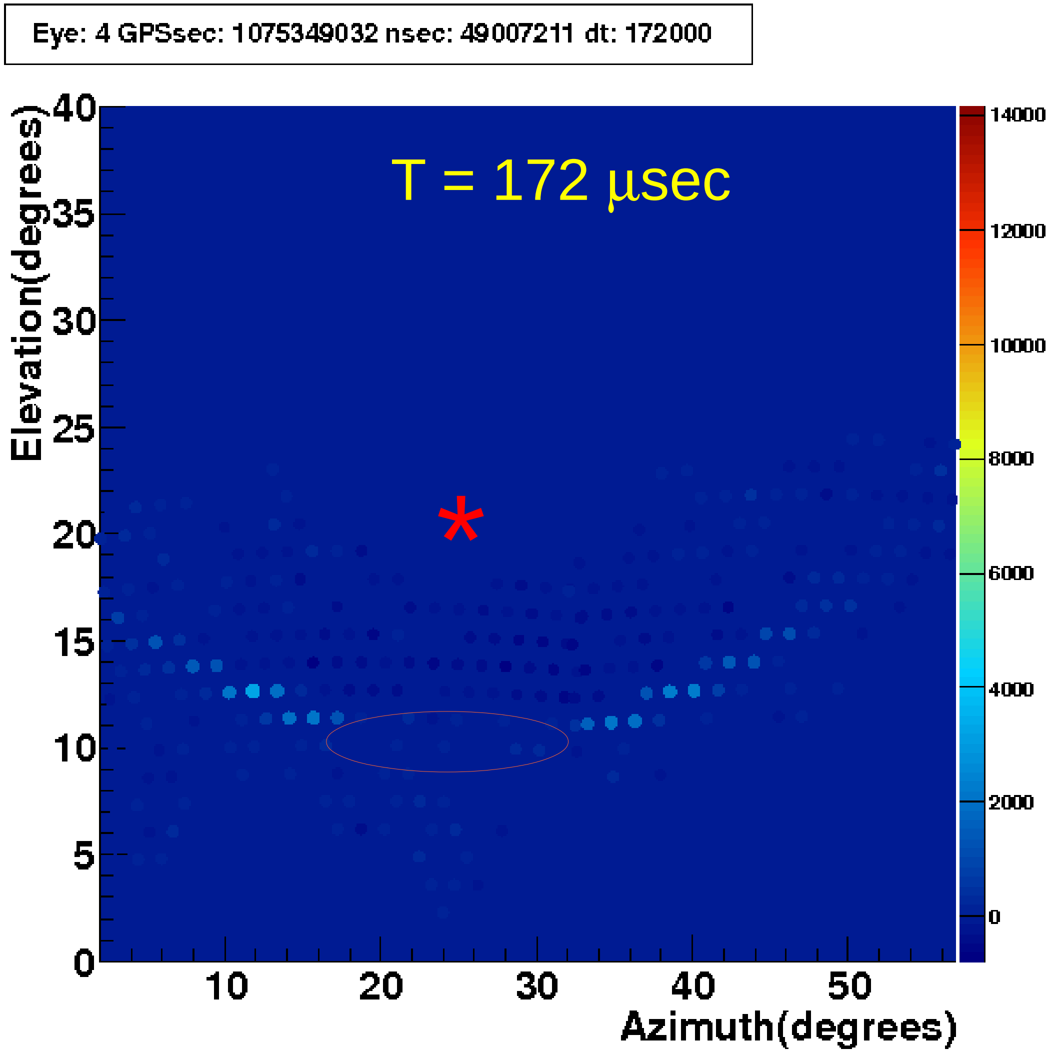

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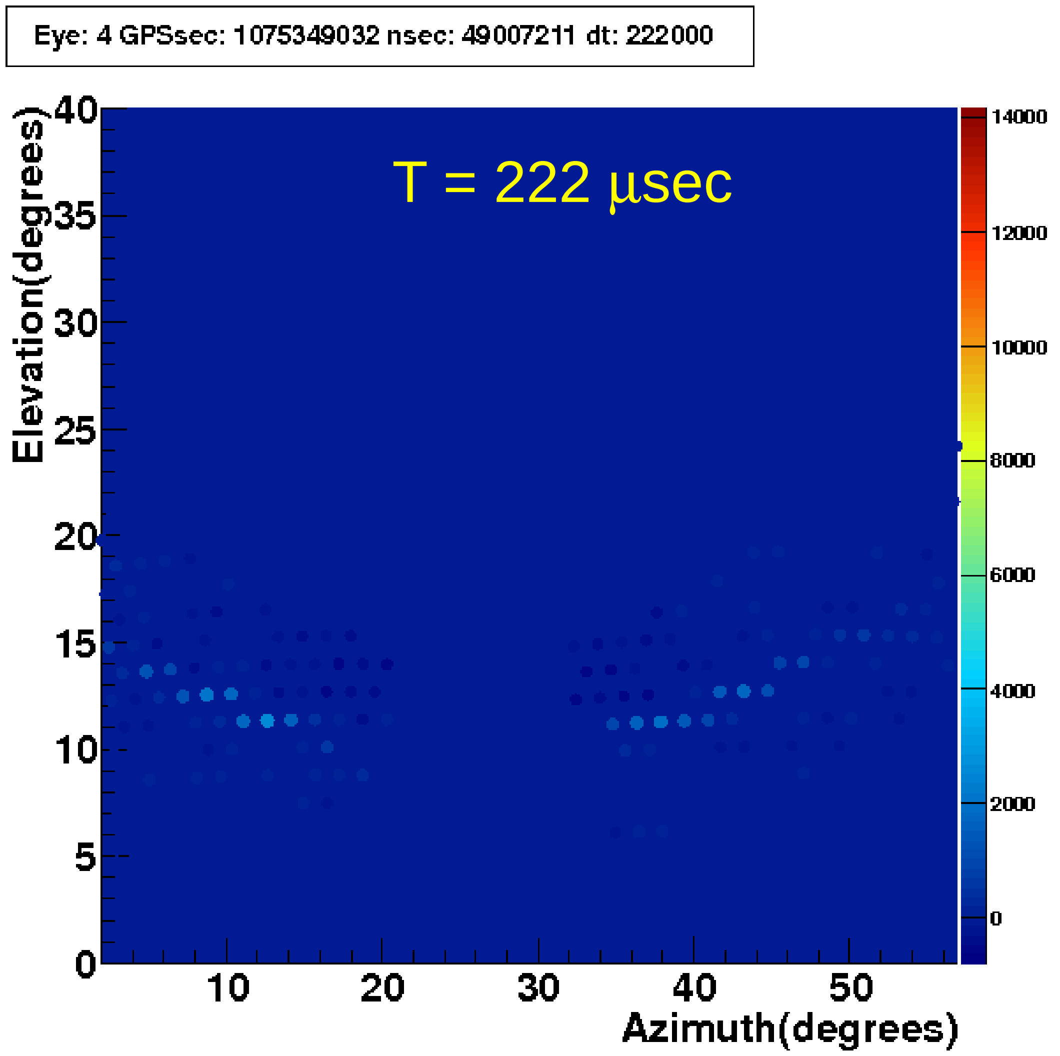

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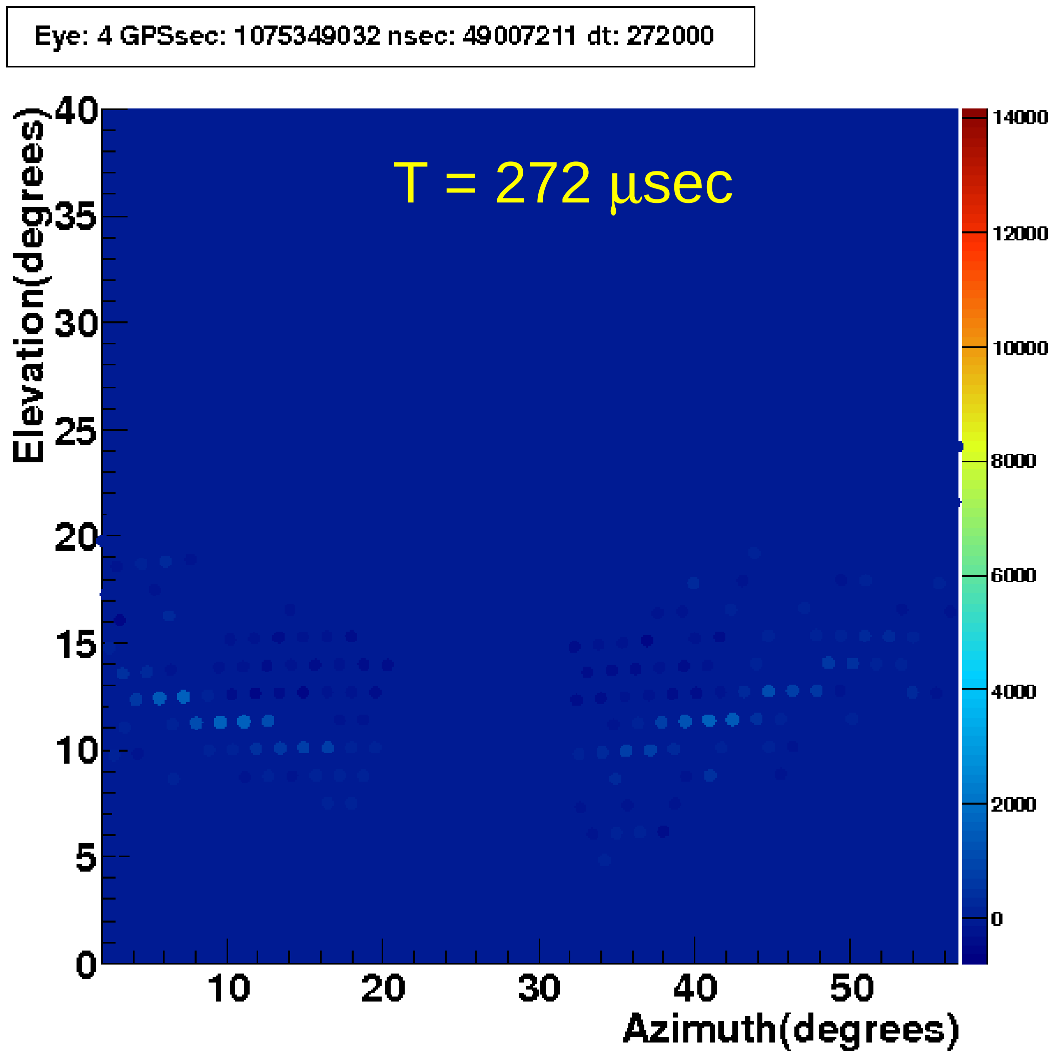
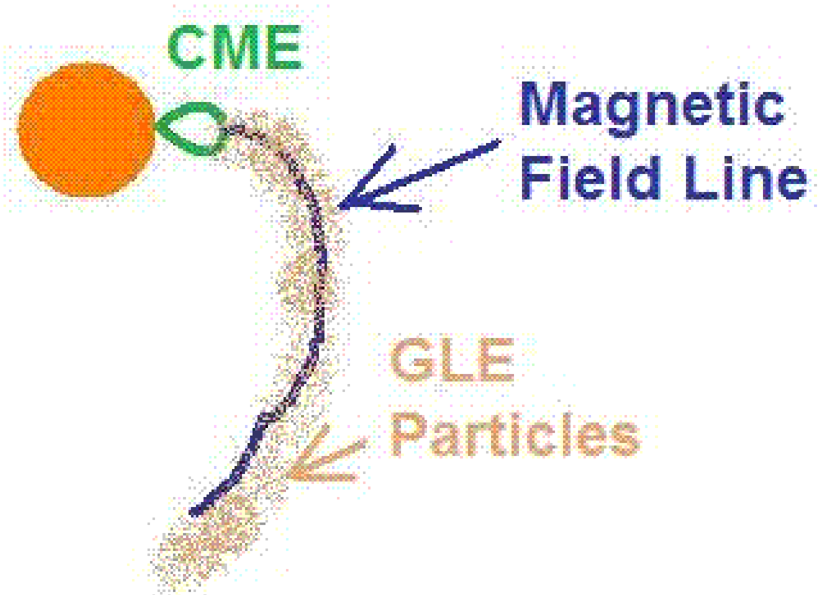


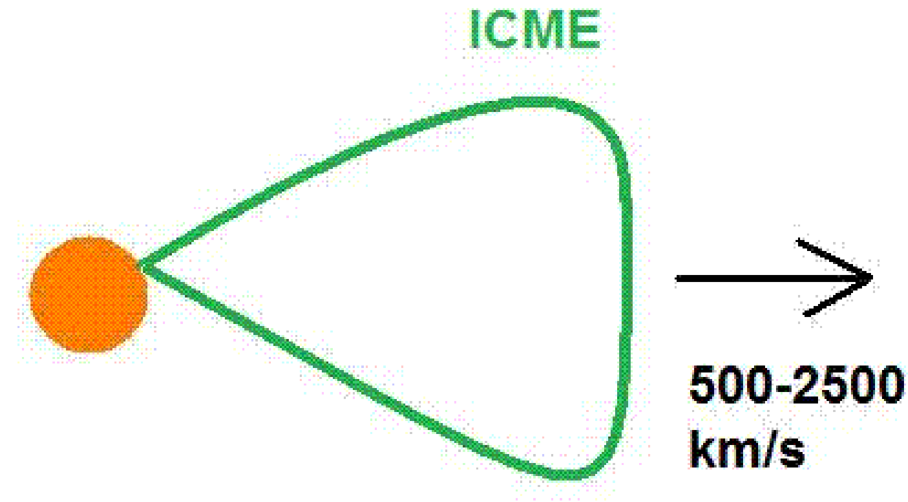
Coronal Mass Ejection Effects at Earth

Prompt Effect: Energetic Particles (GLE)



- Energetic particles (~ 1 GeV) accelerated near Sun
- Occurs 5-20 min after CME lift-off
- Charged particles follow magnetic field line
- Particles arrive at Earth 10-30 minutes later, if Earth is near the right magnetic field line

Delayed Effect: Geomagnetic Disturbance



- *Interplanetary* CME arrives at 1 AU 18 hours to 4 days later
- Impact of the ICME plasma with Earth's magnetic field causes a geomagnetic disturbance
- The ICME suppresses Galactic cosmic rays, an effect called a *Forbush decrease*