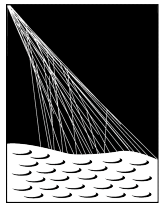

PIERRE AUGER OBSERVATORY

Elve observation with the Fluorescence Detectors of the Pierre Auger Observatory

AURELIO S. TONACHINI[1]

FOR THE PIERRE AUGER COLLABORATION[2]

(Full author list: http://www.auger.org/archive/authors_2012_06.html)

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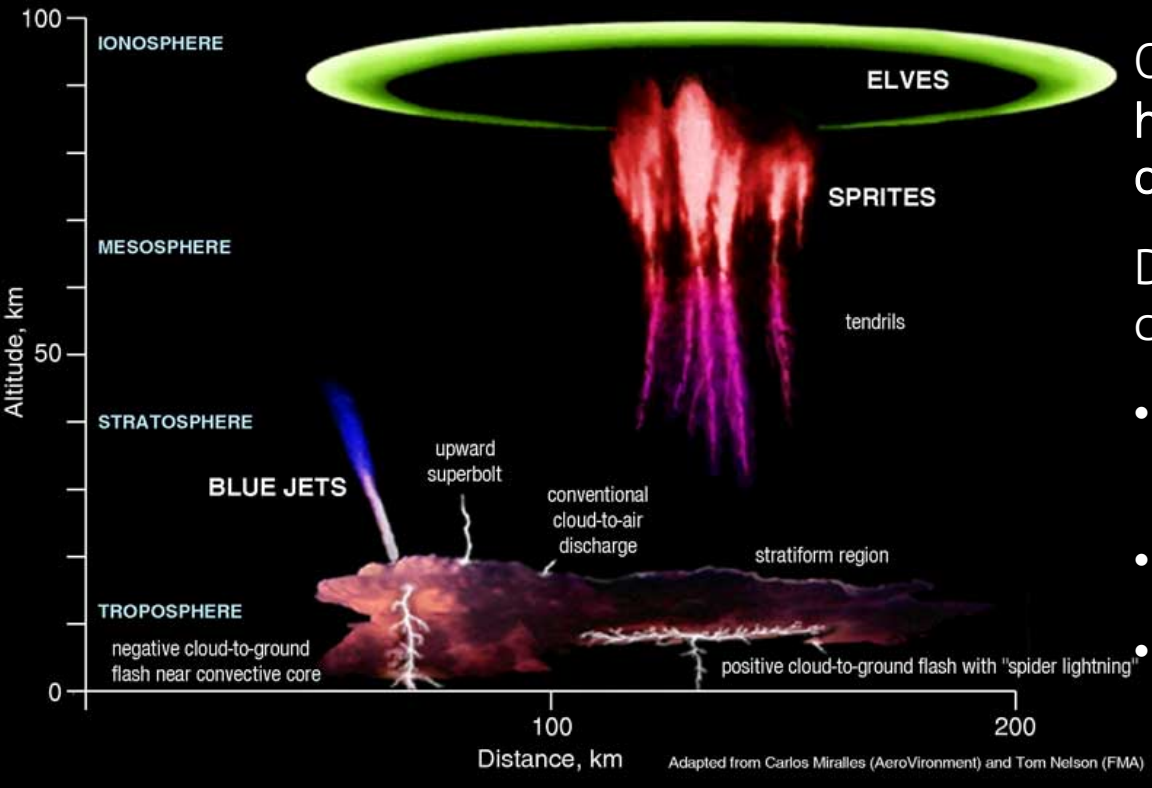
Transient luminous events

Electrodynamic coupling between electromagnetic fields produced by lightning discharges and the lower ionosphere.

Several observed phenomena, including various **transient luminous events**, such as Sprites and Elves.



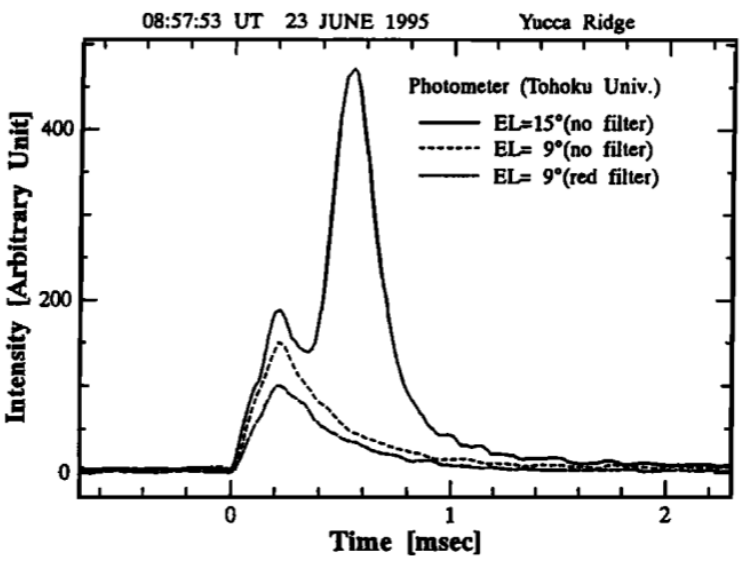
Elves

Optical flashes produced by **heating**, **ionization**, and subsequent **optical emissions**.

Due to intense **EMPs** launched by cloud-to-ground lightning strokes.

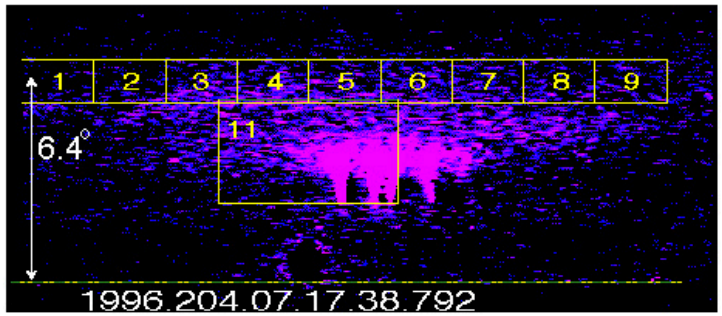
- Confined to **80-95 km** altitudes *(D layer of the ionosphere)*
- They extend up to **600 km**
- Duration: **< 1 ms**

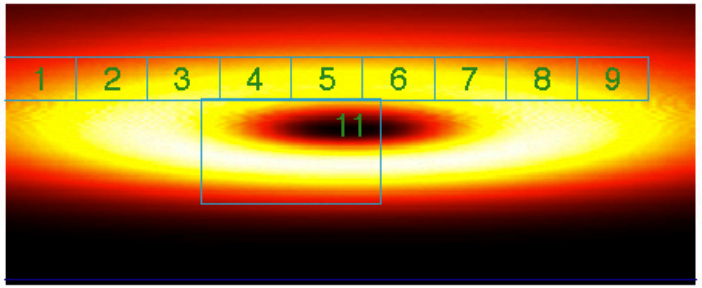
First observations of elves



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

← H. Fukunishi at al., Geophys. Res. Lett., 1996, **23**: 2157-2160





http://www-star.stanford.edu/~vlf

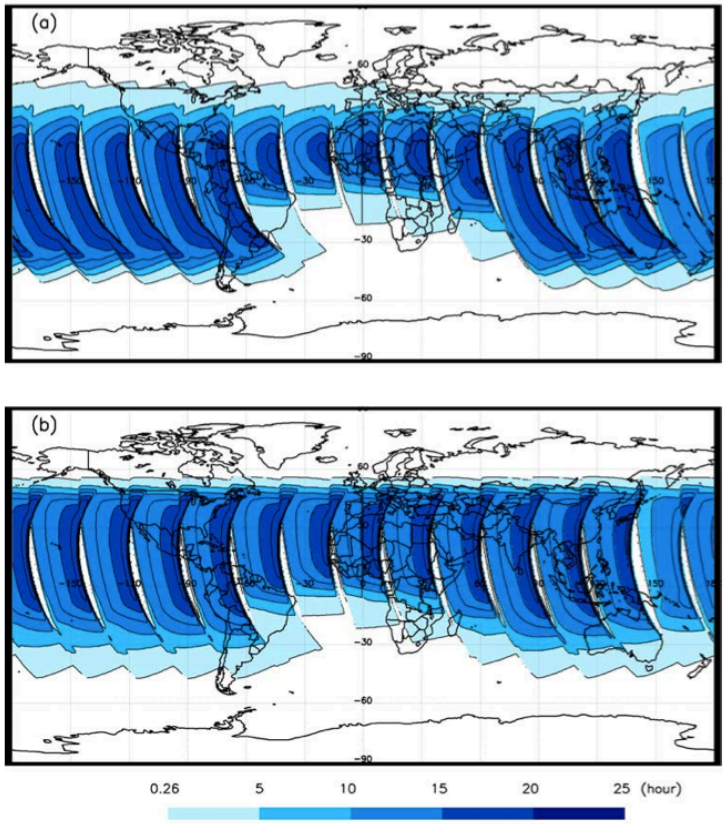
Fly's Eye and PIPER

They adopted linear arrays of photometers with a resolution of **~40 μs**
➔ study of the lateral expansion.

Data from space

ISUAL/Formosat-2 mission collected TLE data for three years.

ISUAL: observations from satellite

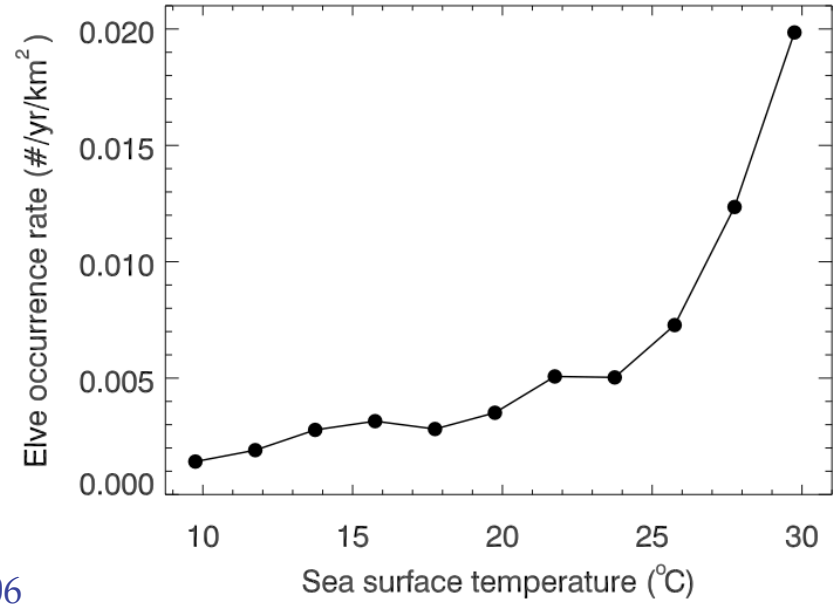


Elves recorded from June 2004 to July 2007:

Number	Land	Coast	Ocean
5434	9%	32%	59%

Global rate: 35 elves / min

Elve rate strongly dependent on sea temperature



A. Chen at al., J. Geophys. Res., 2008, **113**: A08306

The Pierre Auger Observatory

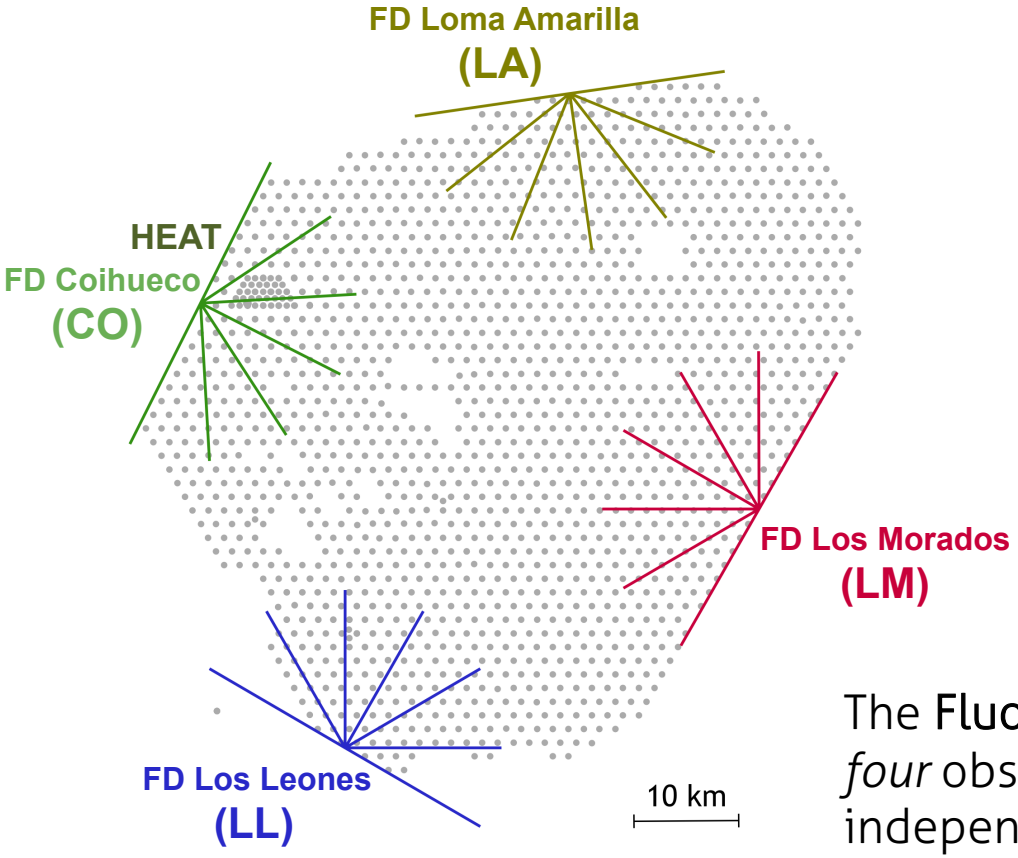
Ultra high energy
cosmic ray observatory
in the southern hemisphere

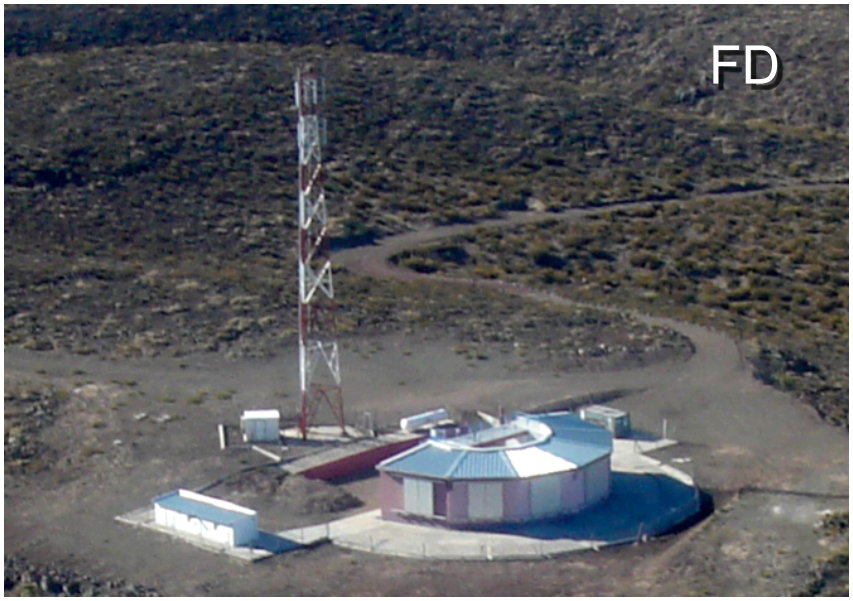
CR detection with 2 techniques (*hybrid*):

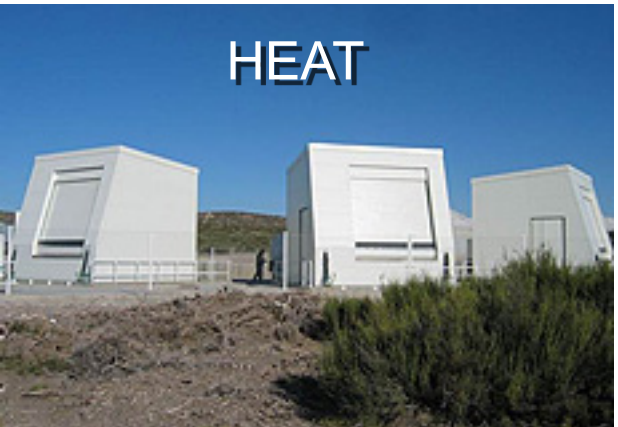
- water Cherenkov array
  1600 tanks, 3000 km²
- 27 Fluorescence detectors
  overlooking the array

Located at 1400 m a.s.l.
Dry zone with low pollution
Infrustructures

Fluorescence Detectors







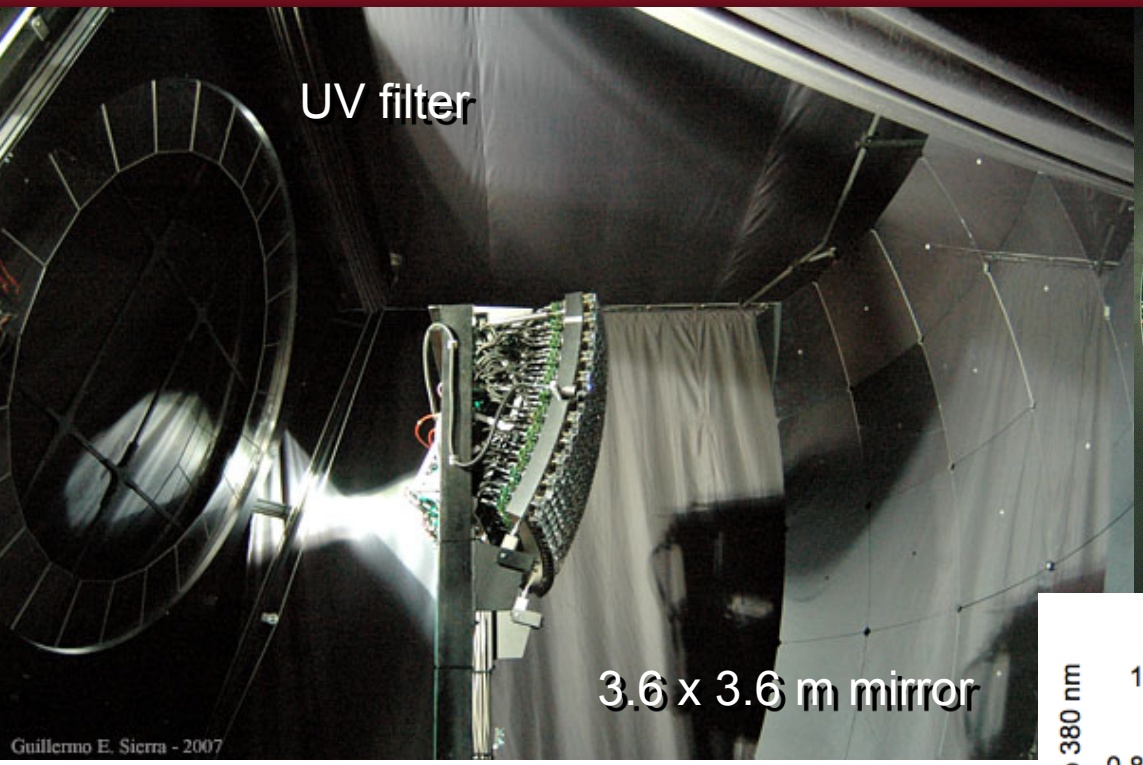
The **Fluorescence Detector** (FD) comprises *four* observation sites, each with six independent telescopes (FOV of 30° × 30°)

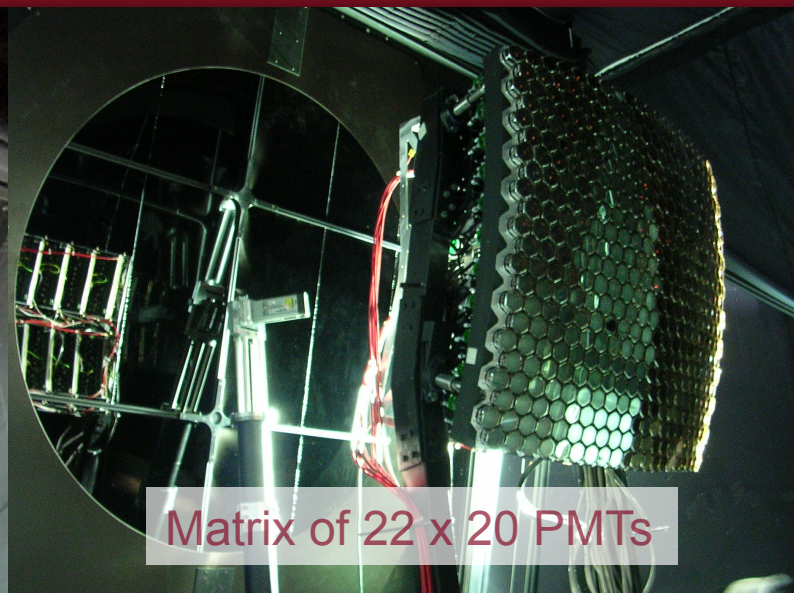
FD camera: **22 × 20** hexagonal **PMTs**

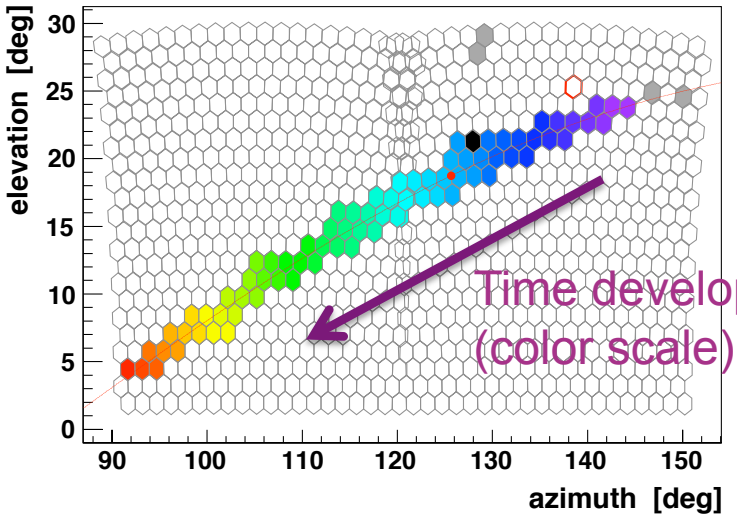
Wavelength range: 300 – 420 nm

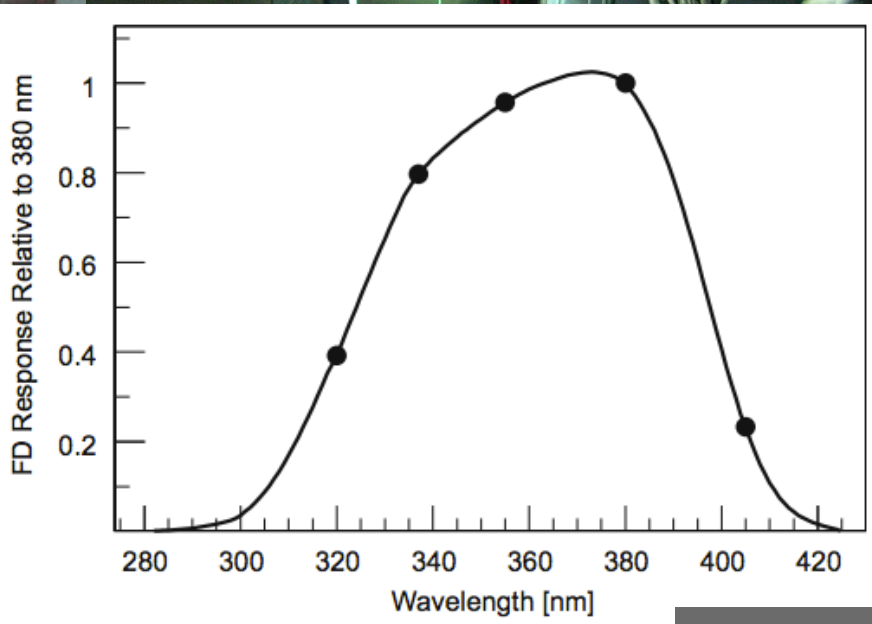
Time resolution: **100 ns**

Fluorescence Detectors - inside



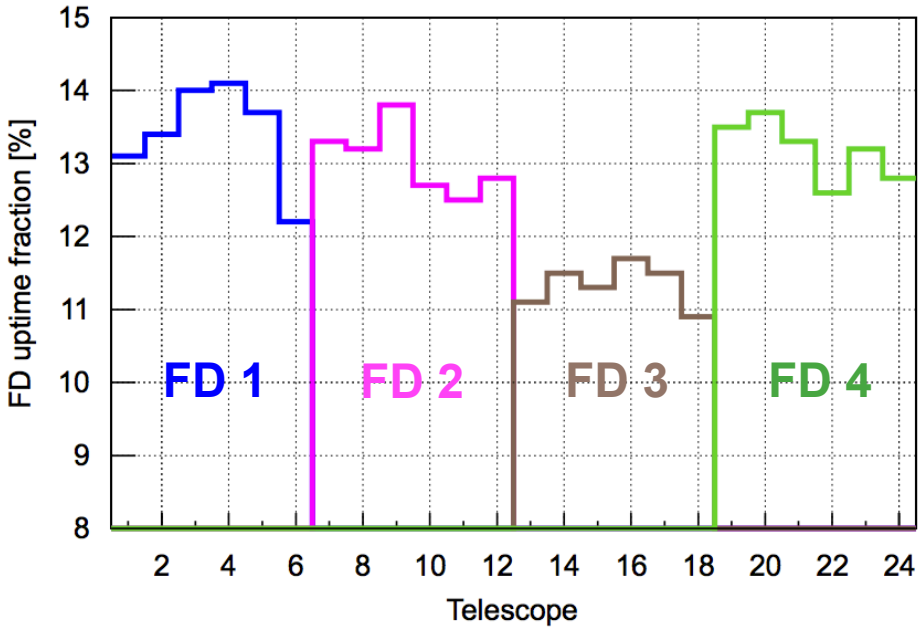






FD Performances

Uptime fraction



Main contributions to deadtime:

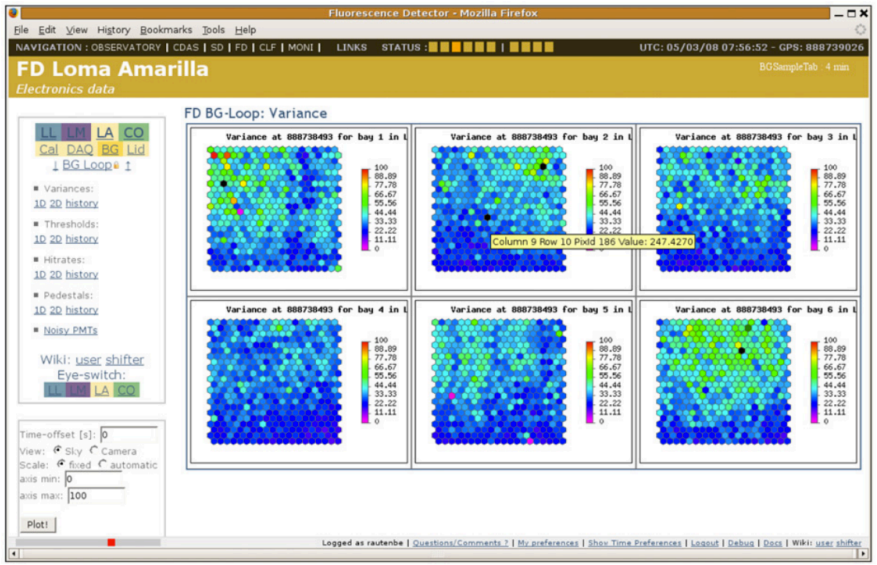
- sun and nearly full moon
- poor weather

Average uptime: ~13%

Constant monitoring

FD is continuously monitored by shifters during data acquisition.

- Background properties
- Weather conditions
- Trigger rates

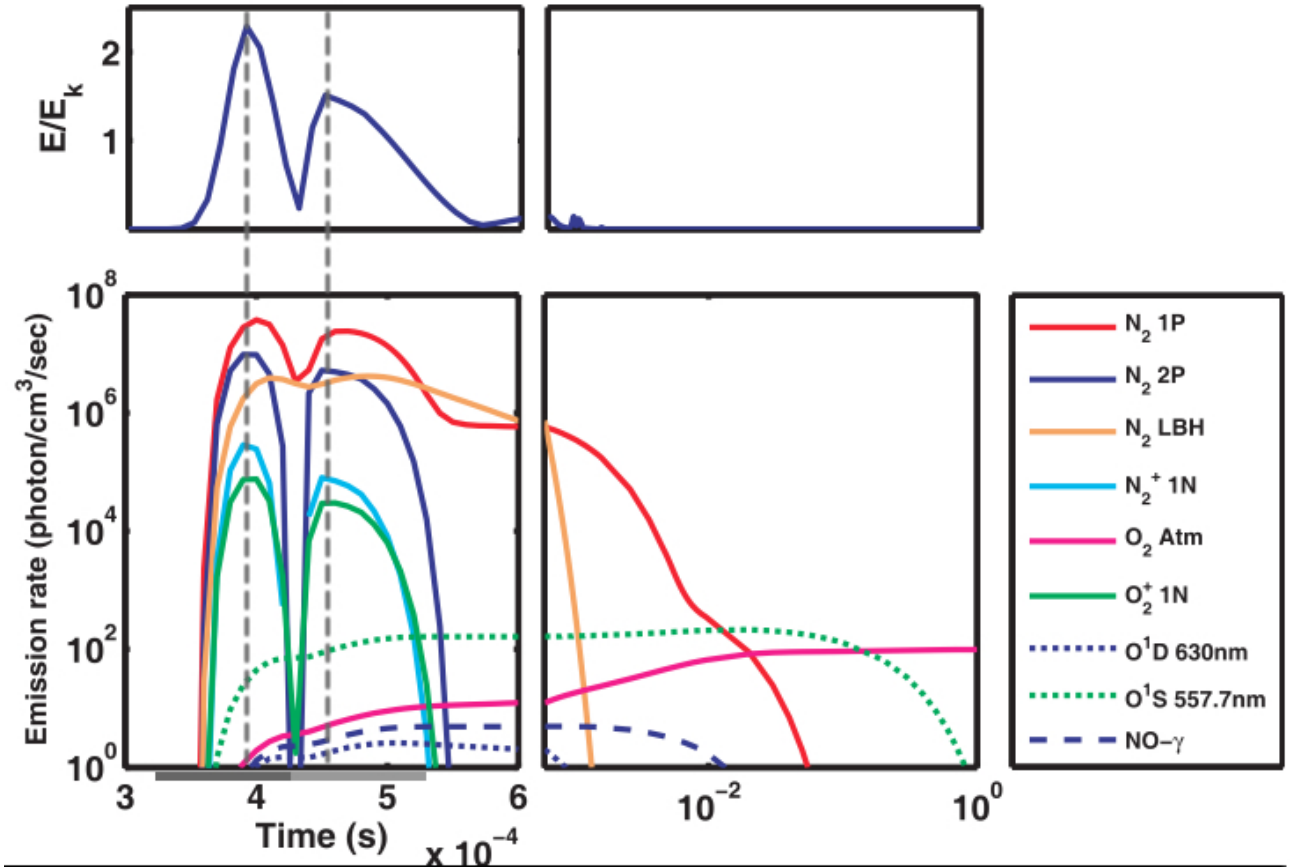


Excitation of the lower atmosphere

Elves are due to the heating of the electrons near the low ionosphere boundary by EMPs launched during *cloud-to-ground* discharges.

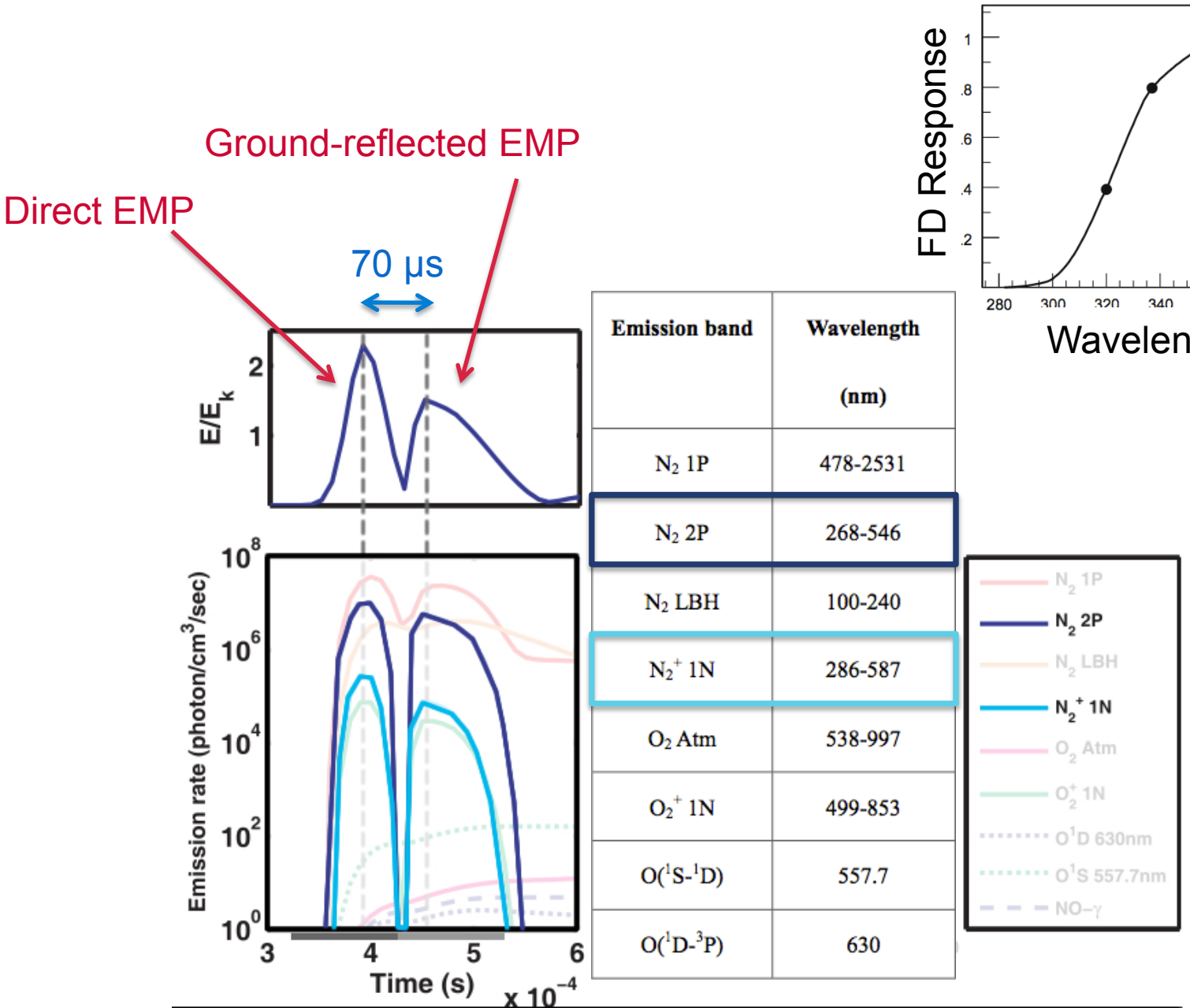
Collision of electrons with N_2 and O_2 → prompt fluorescence light emission

Subsequent light emission by chemiluminescence



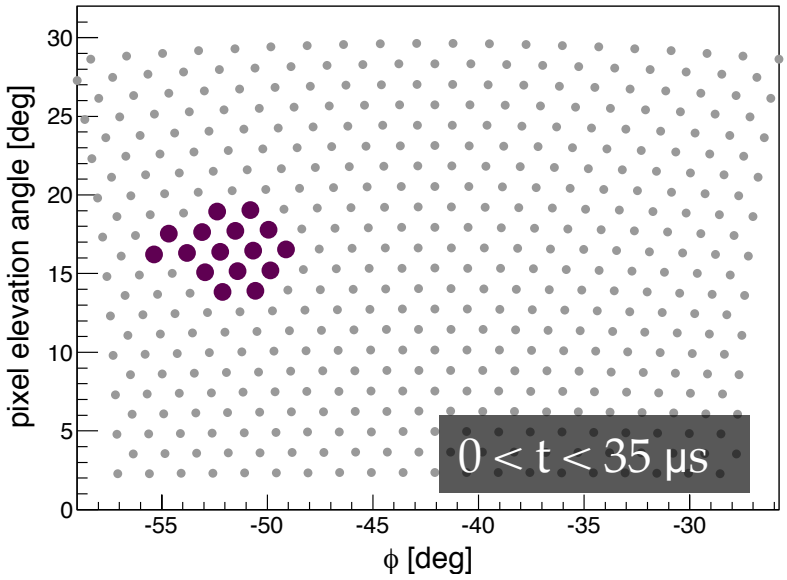
Kuo et al. (2012)

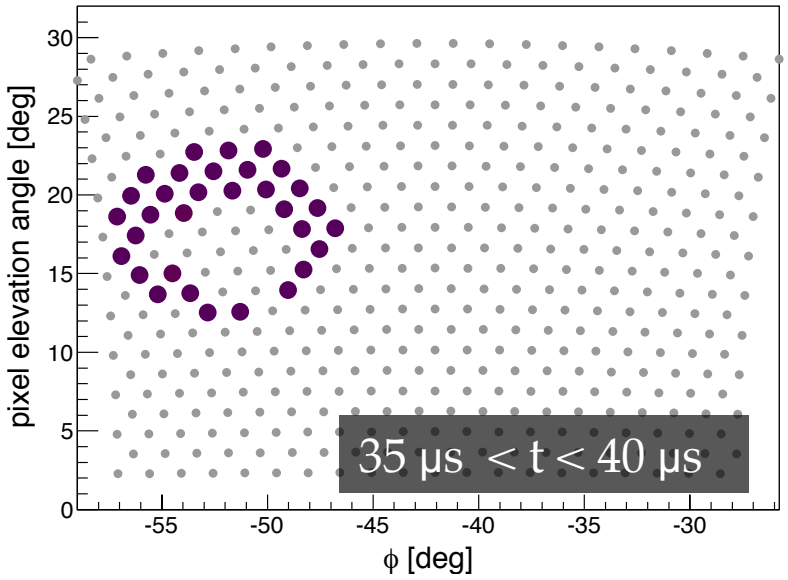
Excitation of the lower atmosphere

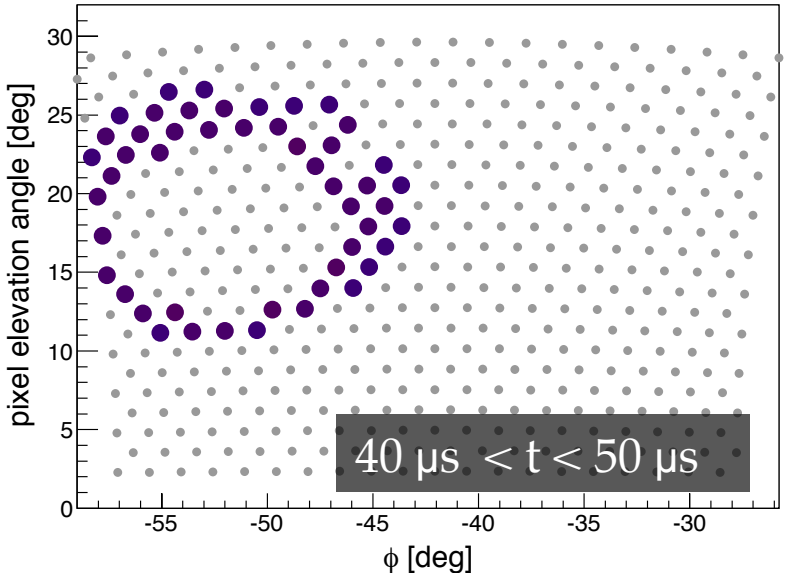


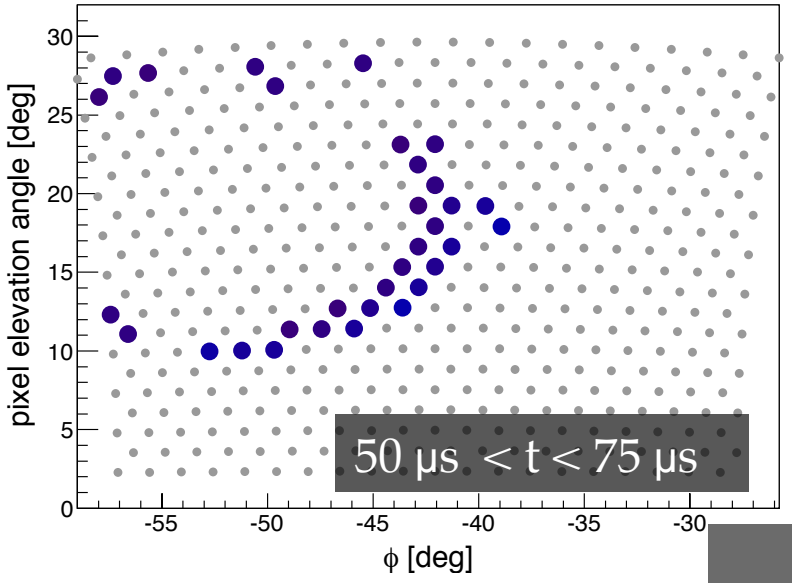
Emission band	Wavelength (nm)
N_2 1P	478-2531
N_2 2P	268-546
N_2 LBH	100-240
N_2^+ 1N	286-587
O_2 Atm	538-997
O_2^+ 1N	499-853
$O(^1S\text{-}^1D)$	557.7
$O(^1D\text{-}^3P)$	630

First serendipitous observation



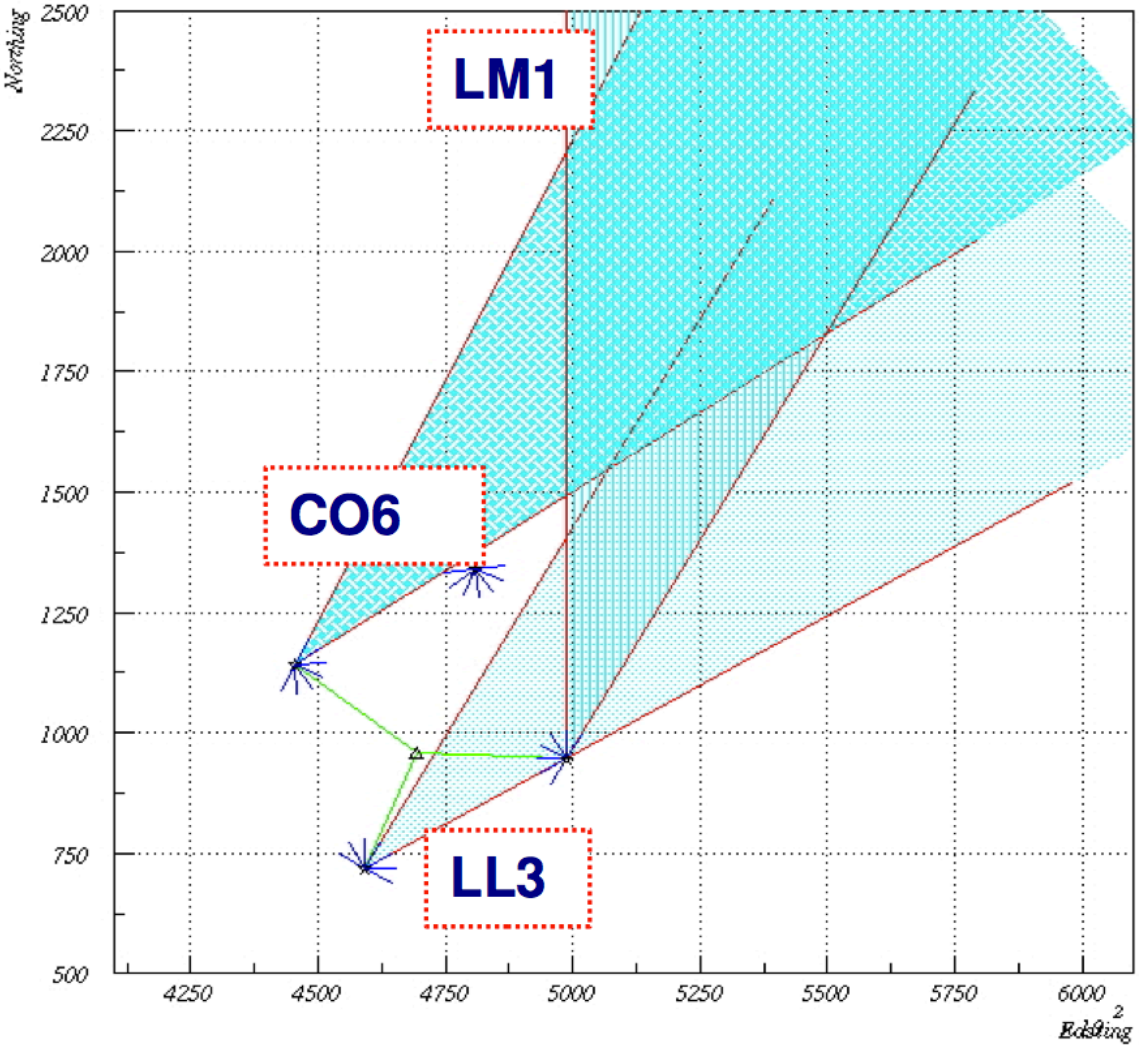


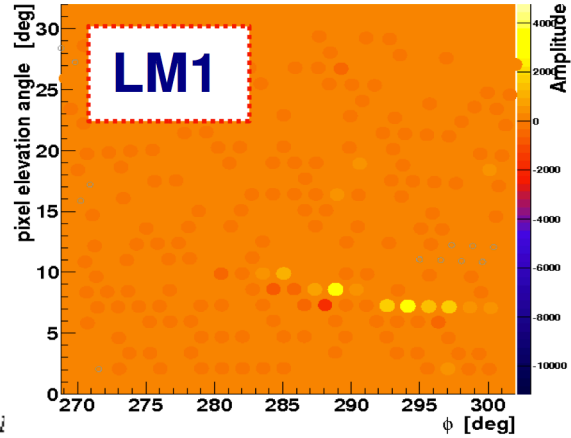


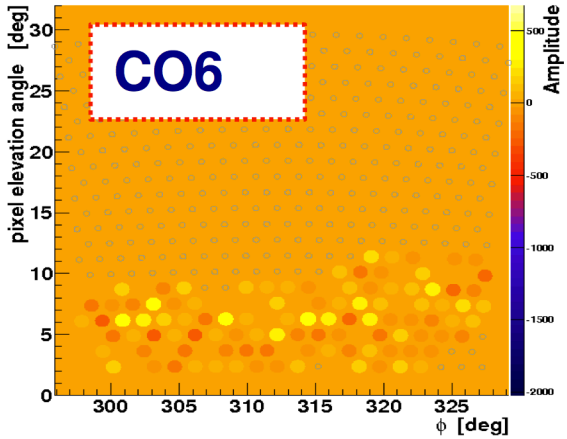


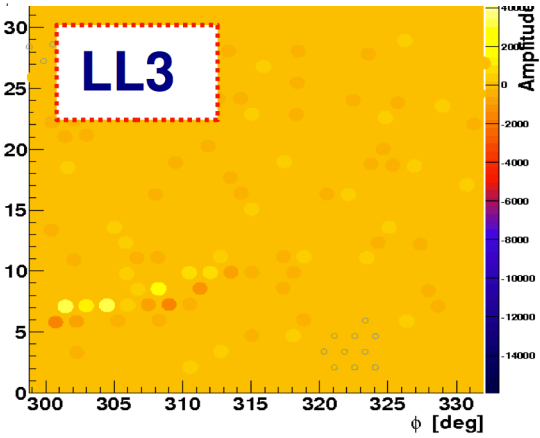
The tail of elves

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

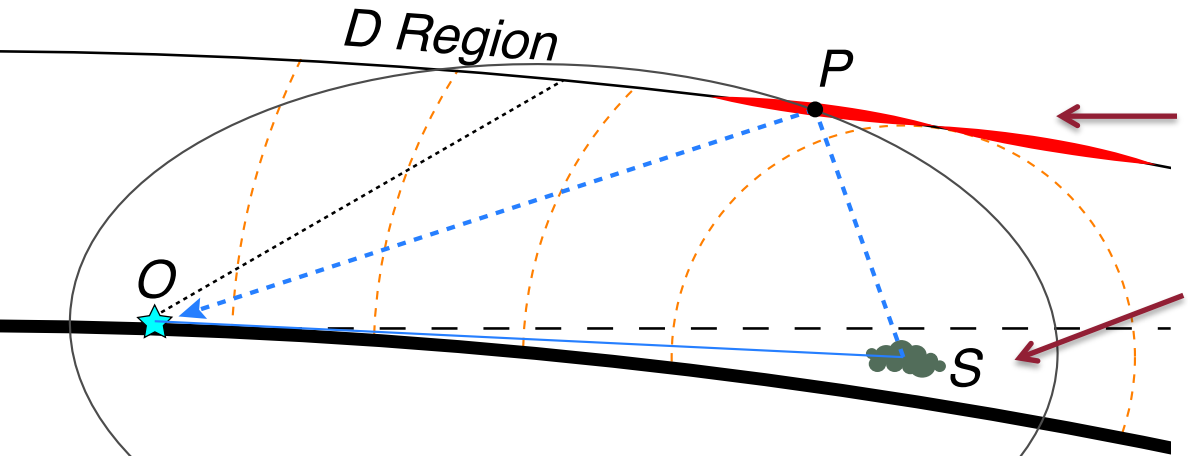








Front propagation reconstruction



Geometrical model

Optical emission takes place at 80-95 km altitudes.

EMP source confined inside the troposphere.

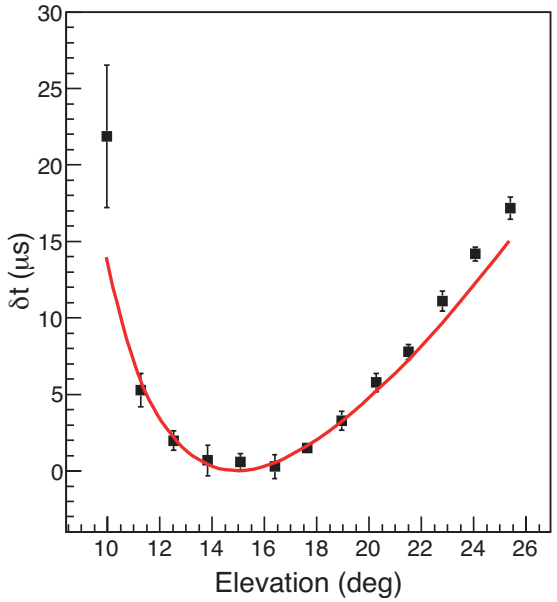
Signal time evolution described by the intersection of a **sphere** (the D region) with **ellipsoids** with foci *O* and *S*.

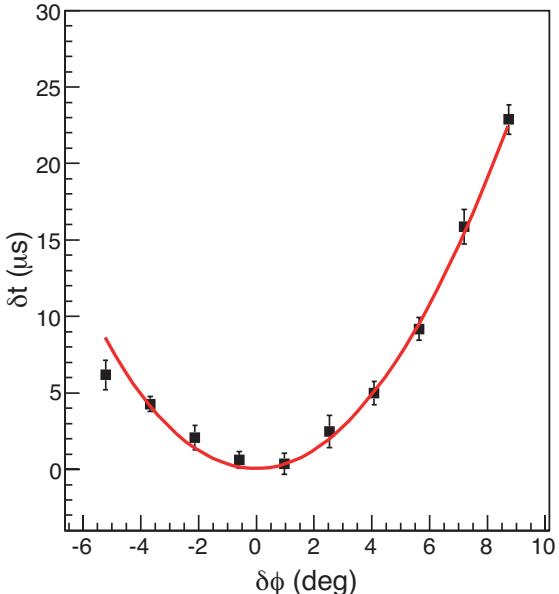
First light when the ellipsoid is *tangent* to the sphere.

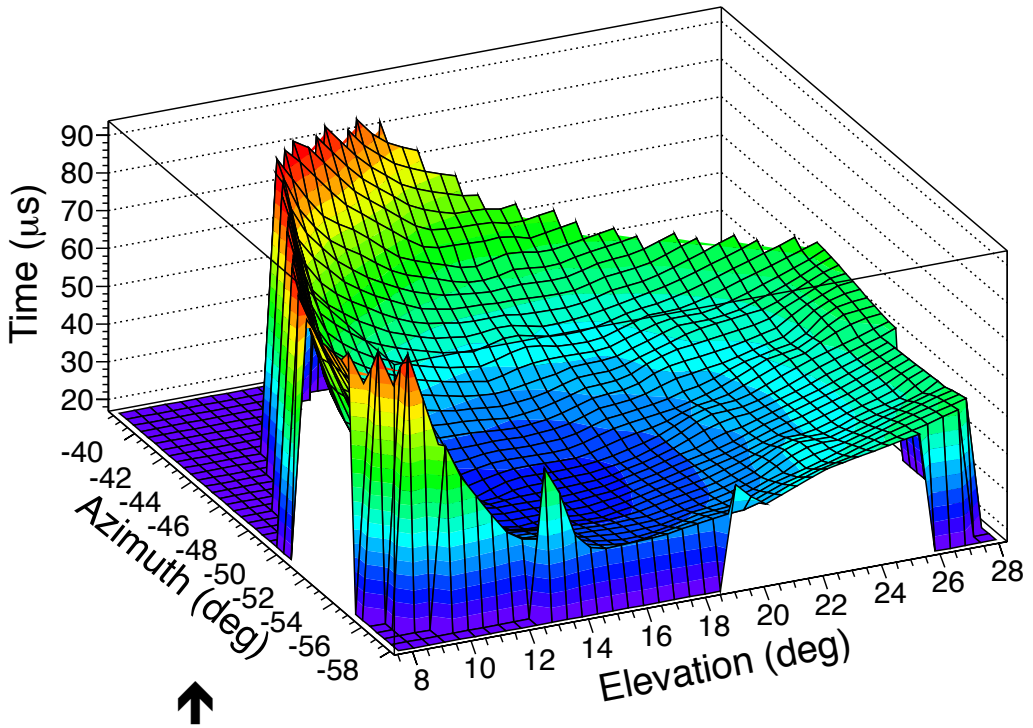
↓

Strong constraints on the location of the EMP source.

3D reconstruction



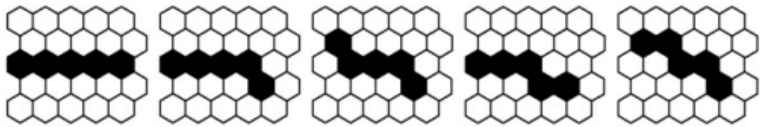




Interpolated *3D curve* representing the time of arrival of photons at the FD diaphragm.

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

Fluorescence Detector Trigger

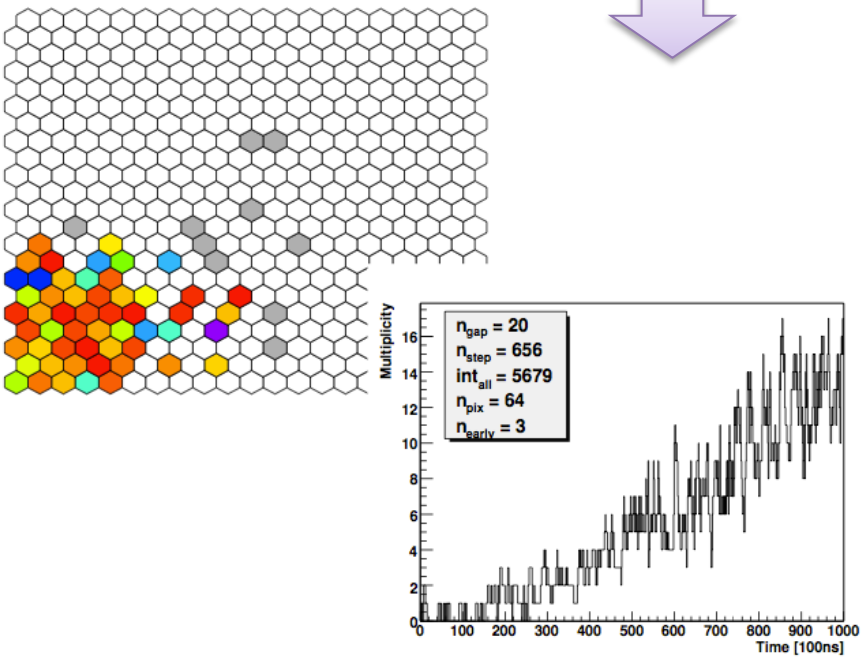
	type	purpose	event rate
First Level Trigger (FLT)	HW	Pixel threshold trigger	100 Hz / pixel
T1			
Second Level Trigger (SLT)	HW	Track shape identification	0.1-10 Hz / tel
T2			
Third Level Trigger (TLT)	SW	Lightning rejection	0.02 Hz / site
T3			

Lightning Rejection

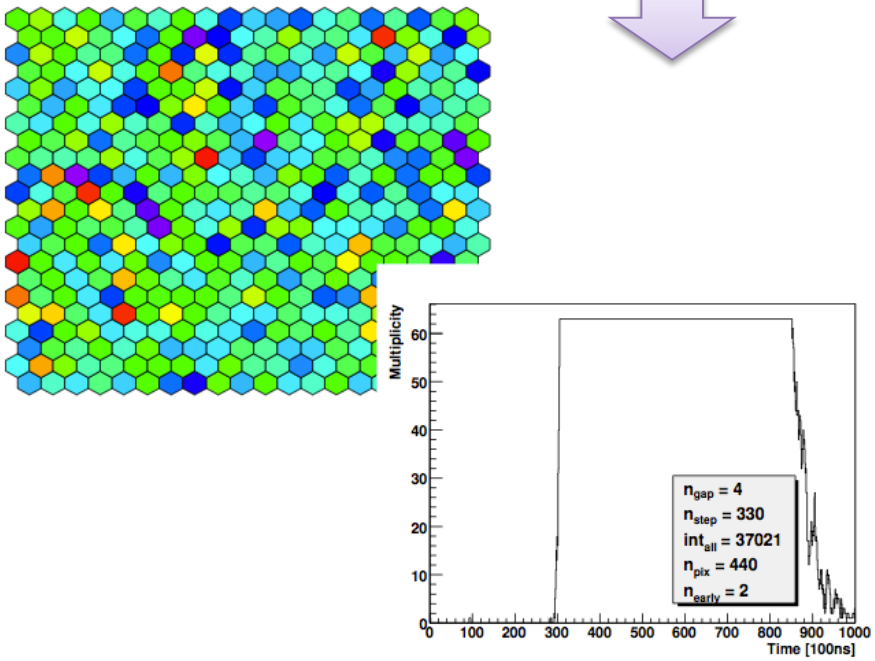
It is made of 5 different cuts

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

Fluctuation of the multiplicity
is bigger than for shower events

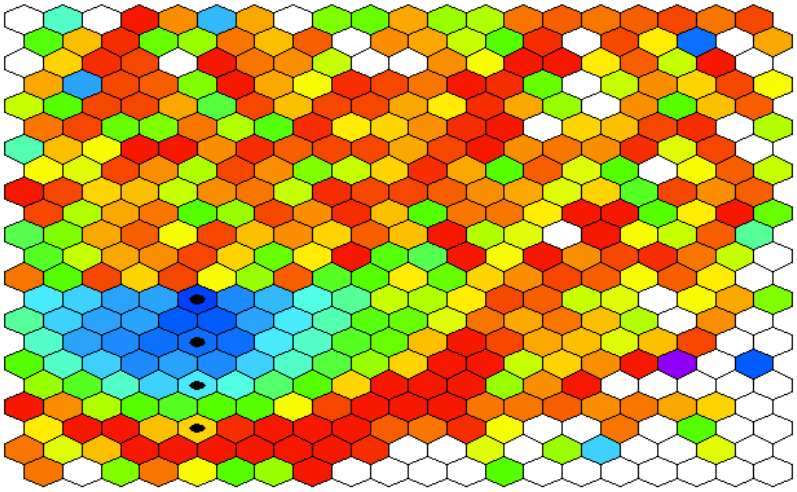


During very intense lightning the
multiplicity signal gets saturated

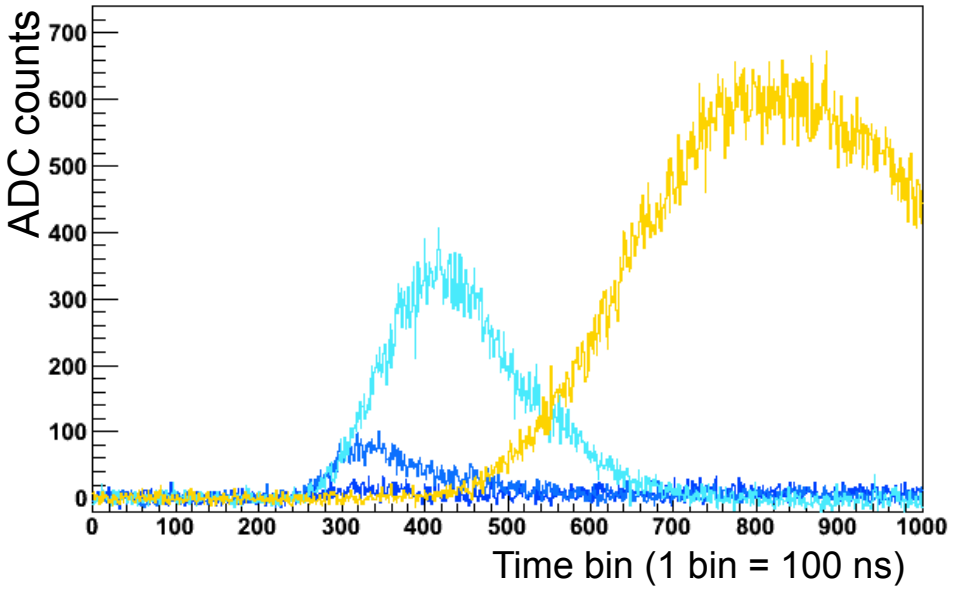


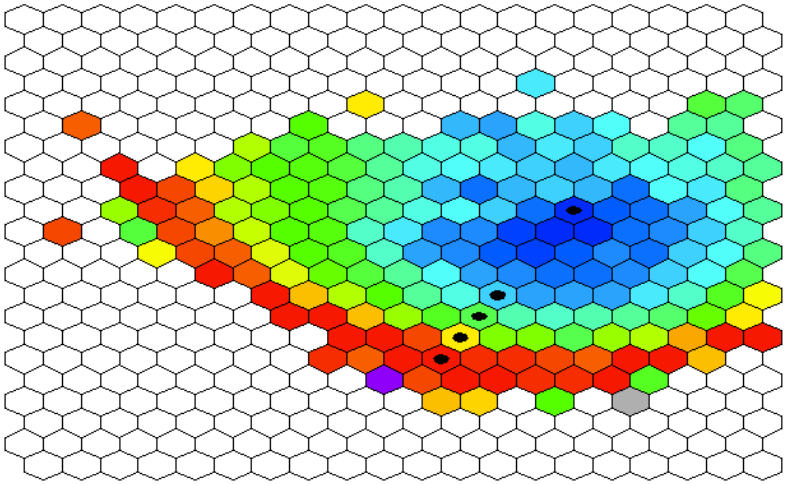
These cuts were removing elves too!

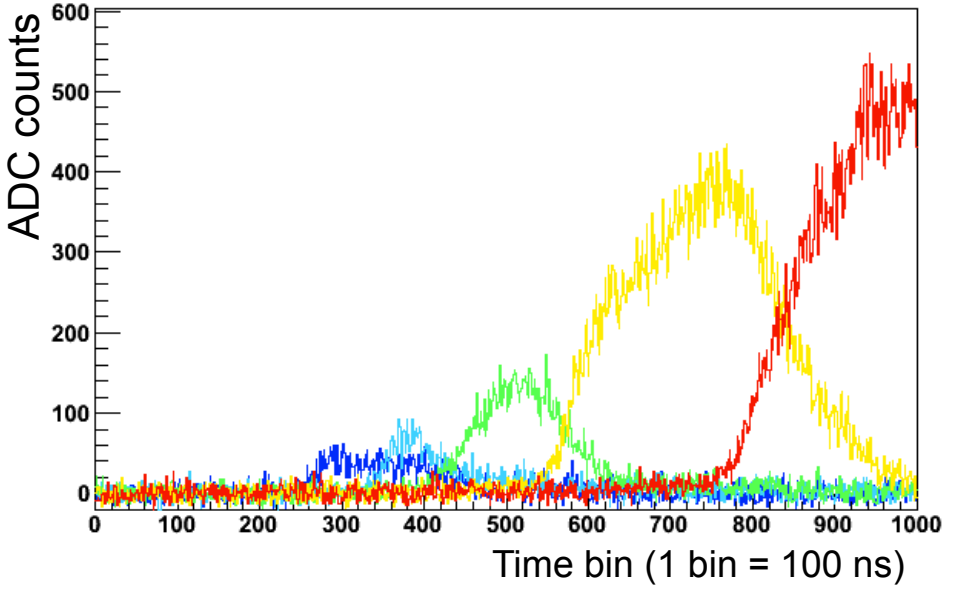
Examples



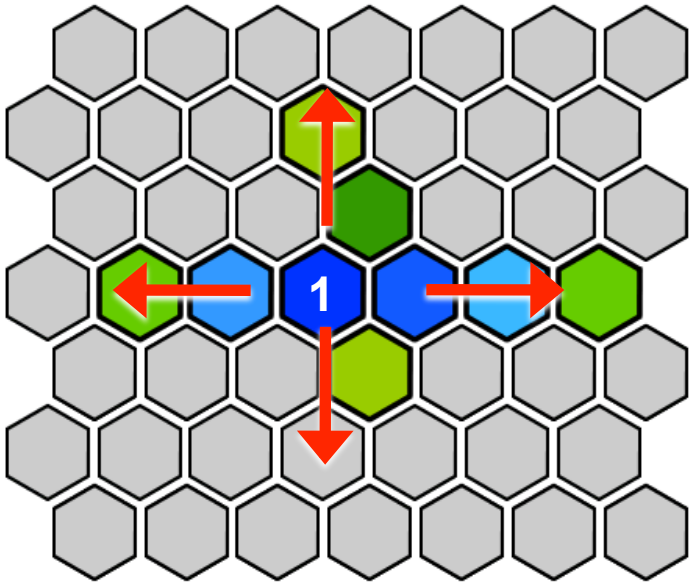
Extreme case: Elve + noise



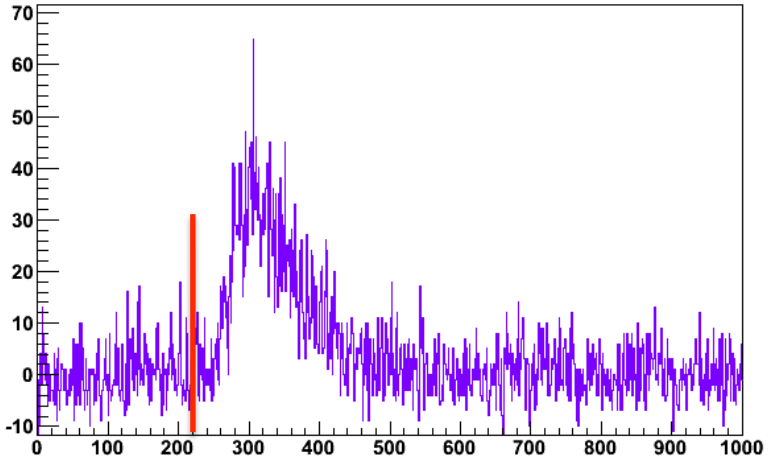




Elve trigger step by step

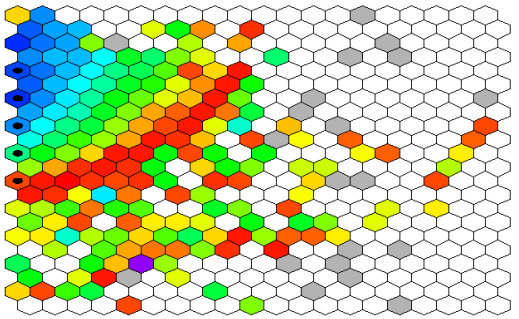


1 Find the FIRST PIXEL and define the PULSE START TIME



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

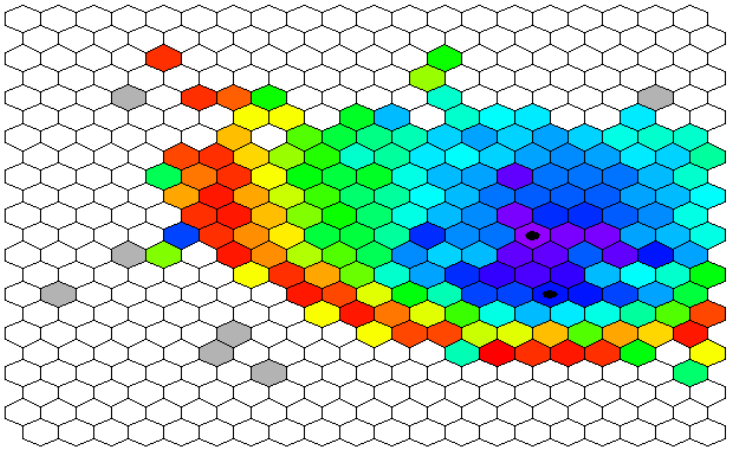


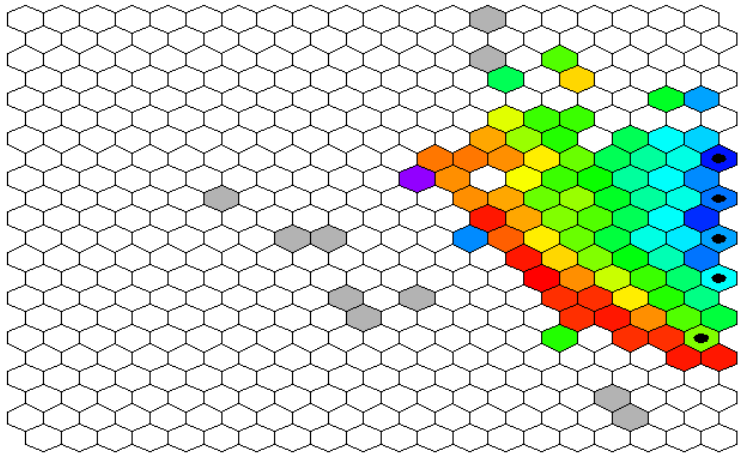
4 Check signal amplitude for each pixel
- at least ONE pixel with > 50 ADC counts

Trigger applied to minimum bias events (2008-2011)

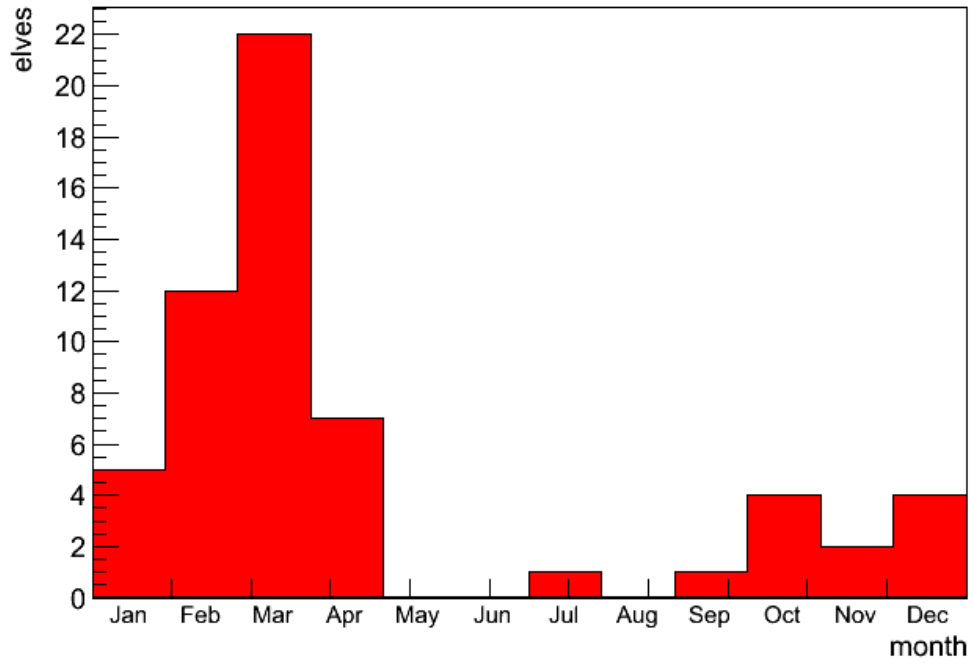
FD site	Elves	Reconstructable
Los Leones	21	17
Los Morados	6	3
Loma Amarilla	12	9
Coihueco	19	10
TOTAL	**58**	**39**

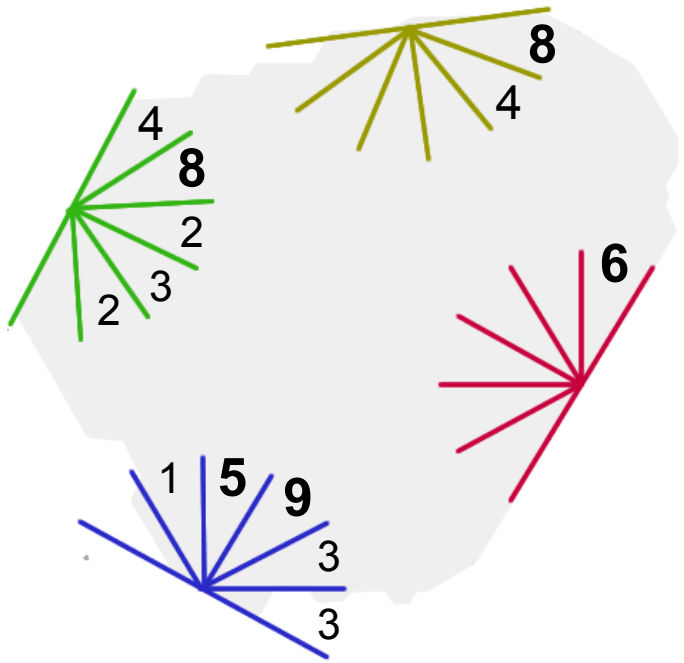
18 elves out of 58 have their center outside the triggered FD bay





Event distribution

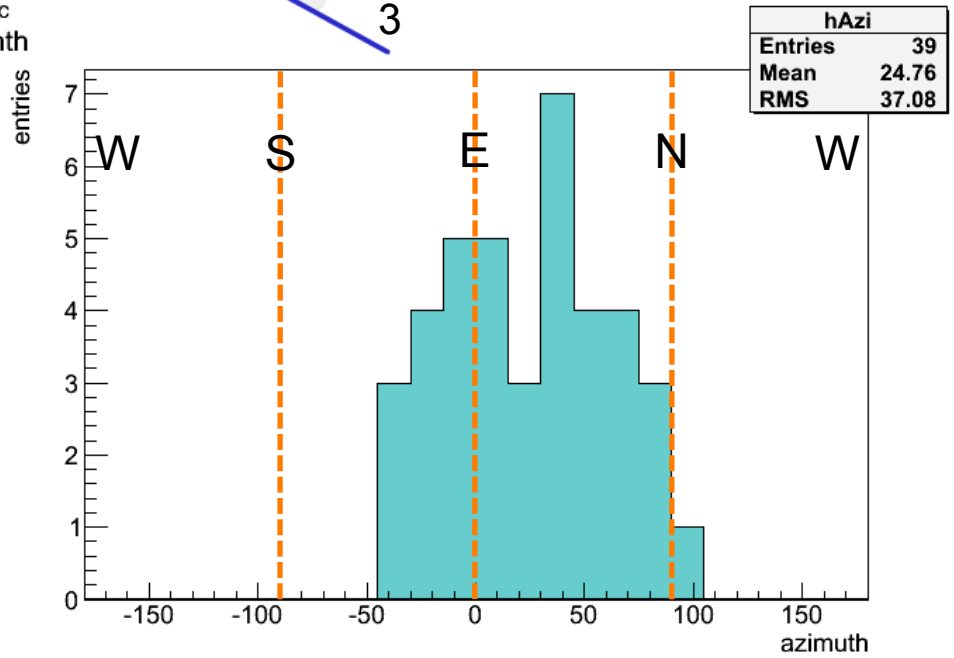




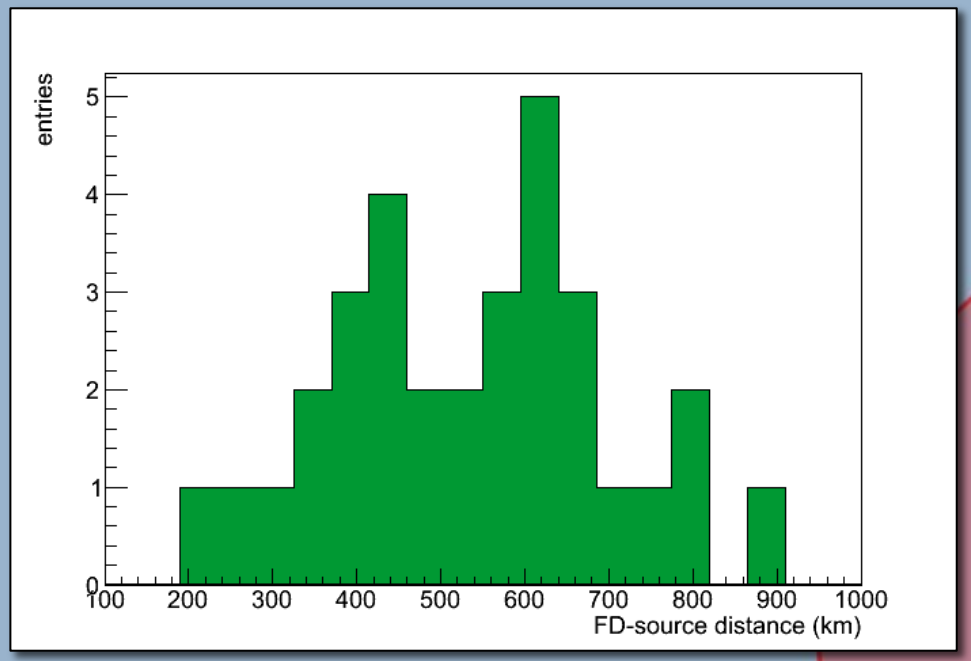
The event distribution is not homogeneous neither in time nor in space.

Most of the events detected during warm months.

No events from the Pacific Ocean so far.

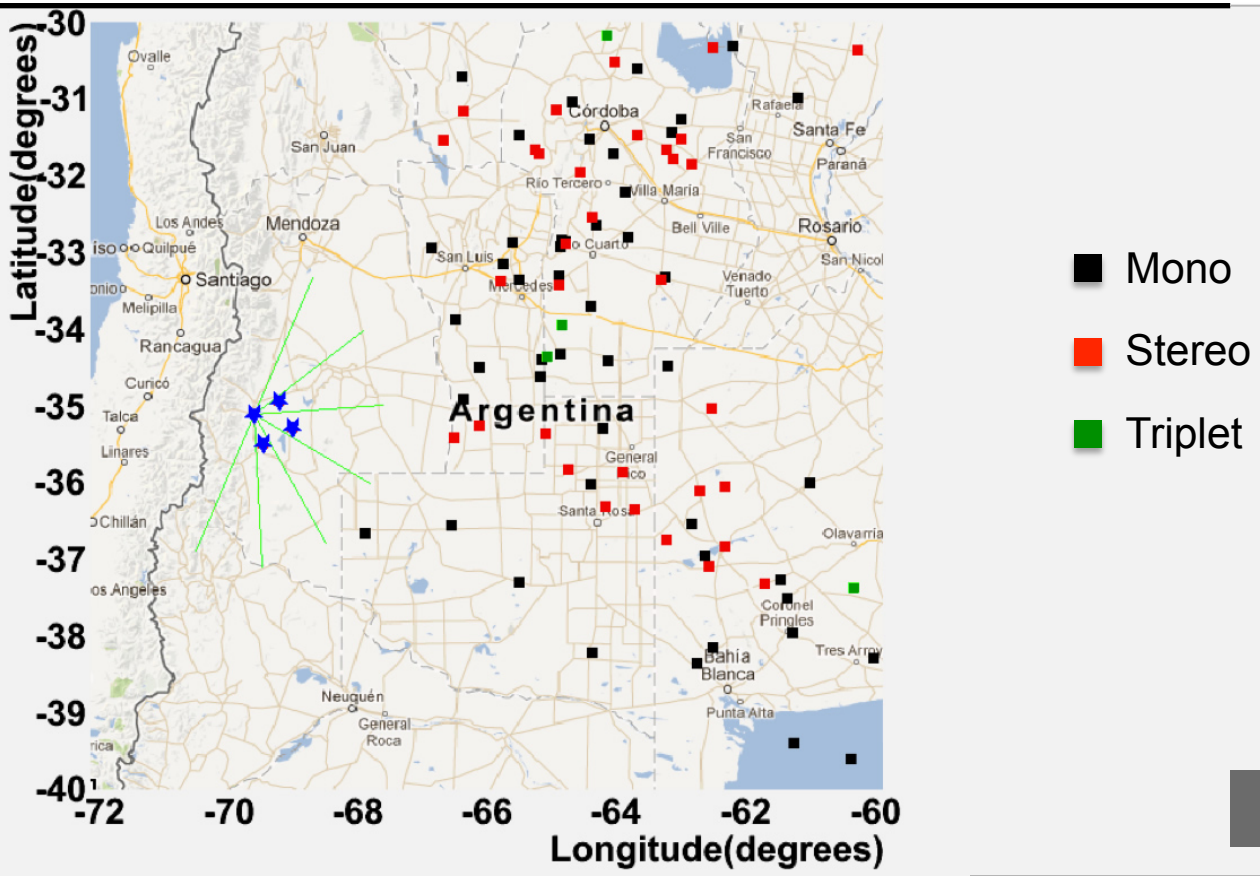


Distance of observed events



Events detected in March-April 2013

FD site	Elves	Reconstructed	Stereo
Los Leones	41	29	26
Los Morados	8	2	7
Loma Amarilla	32	26	13
Coihueco	52	40	22



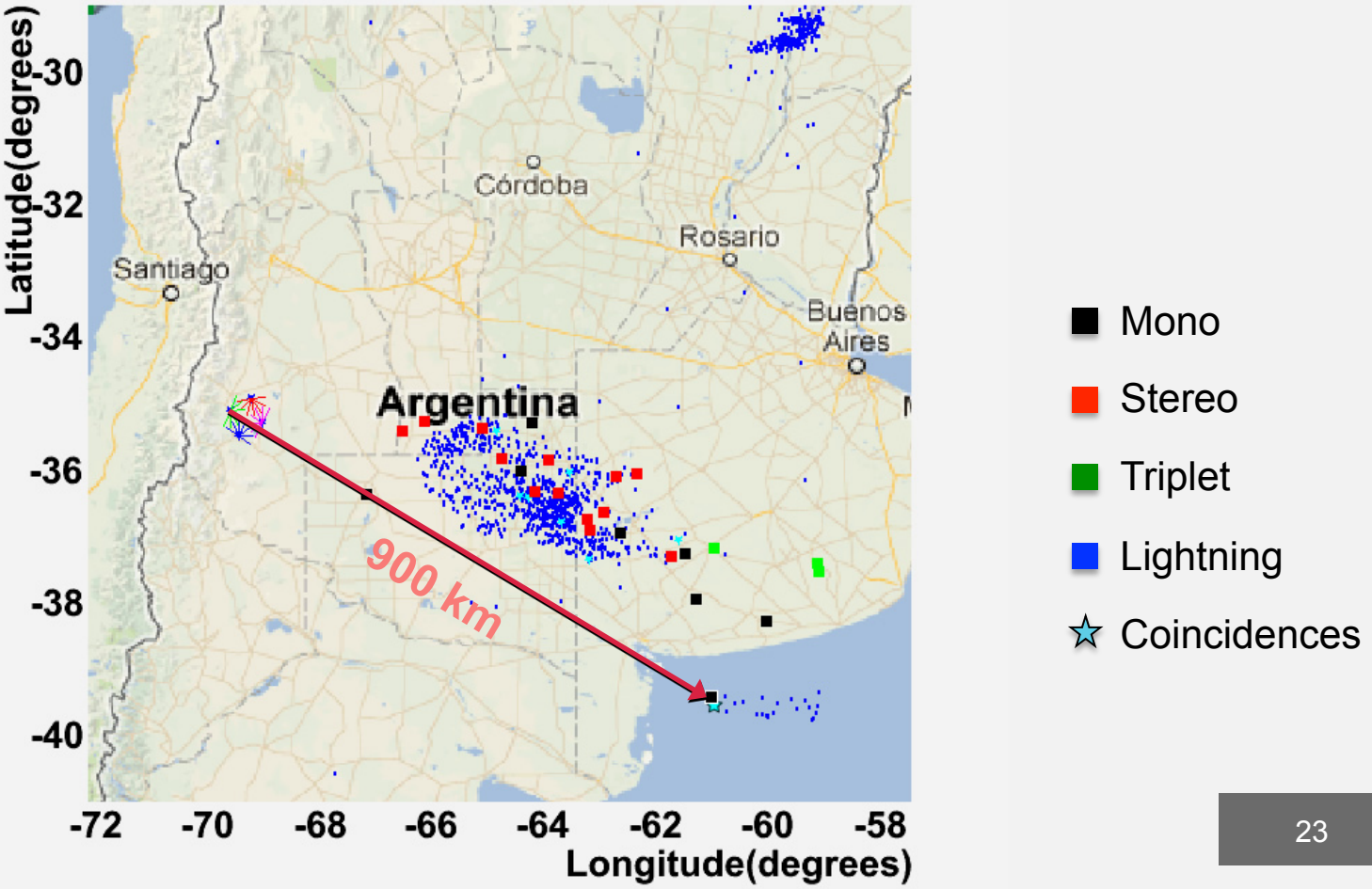
Comparison with lightning data

Most impressive match: GPS 1046828190, 900 km away, *on Atlantic Ocean*

match with WWLLN within 15 km

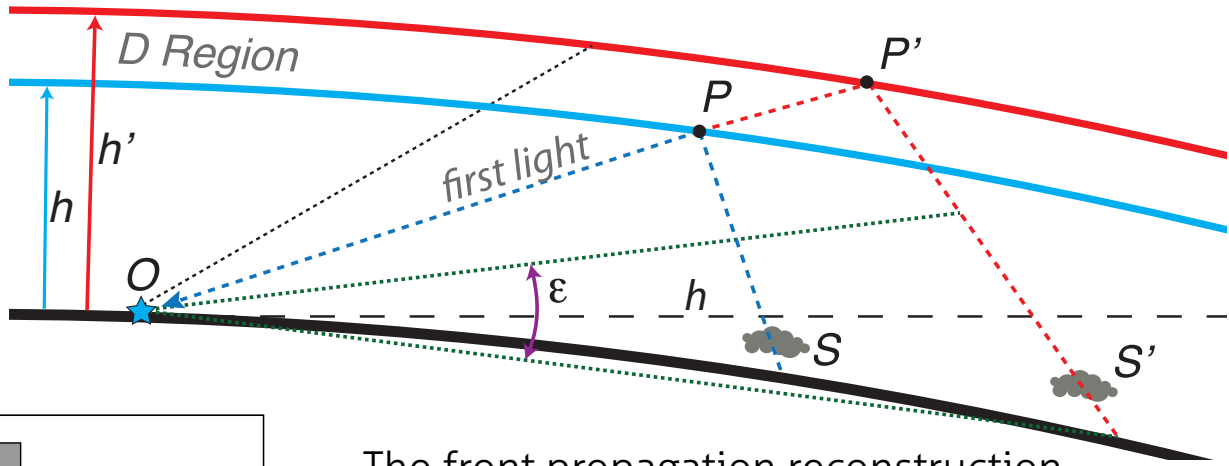
On this, we know the lightning strike current, 160 kA*

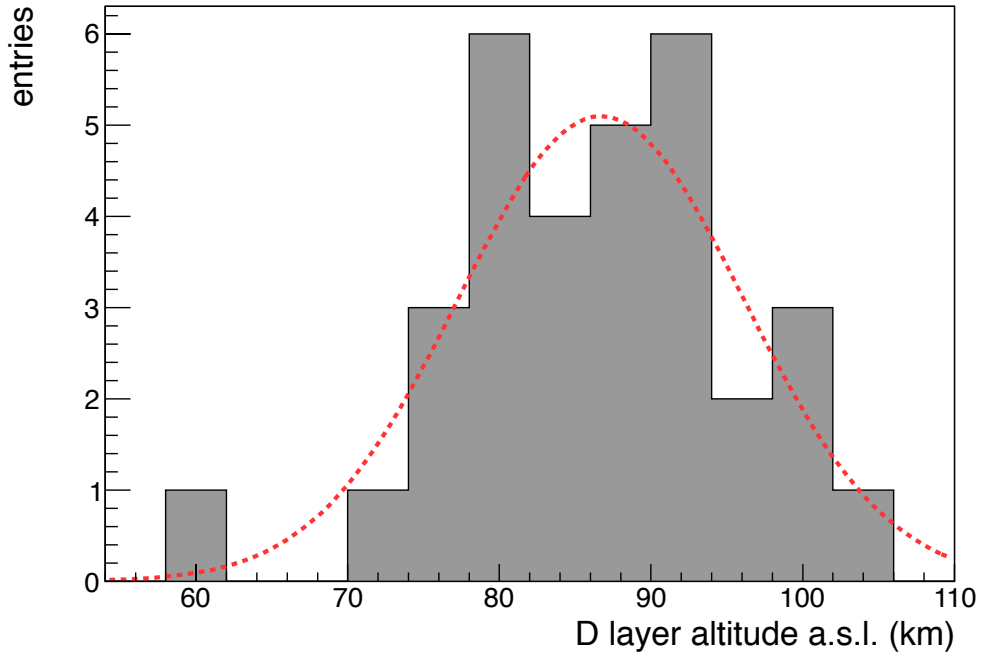
* from GLD360 network, courtesy of Stanford VLF Group



Measuring the D Layer altitude with elves

Precise information about the lightning location combined with Auger measurements allow to use elves as probes for studying the low ionosphere.



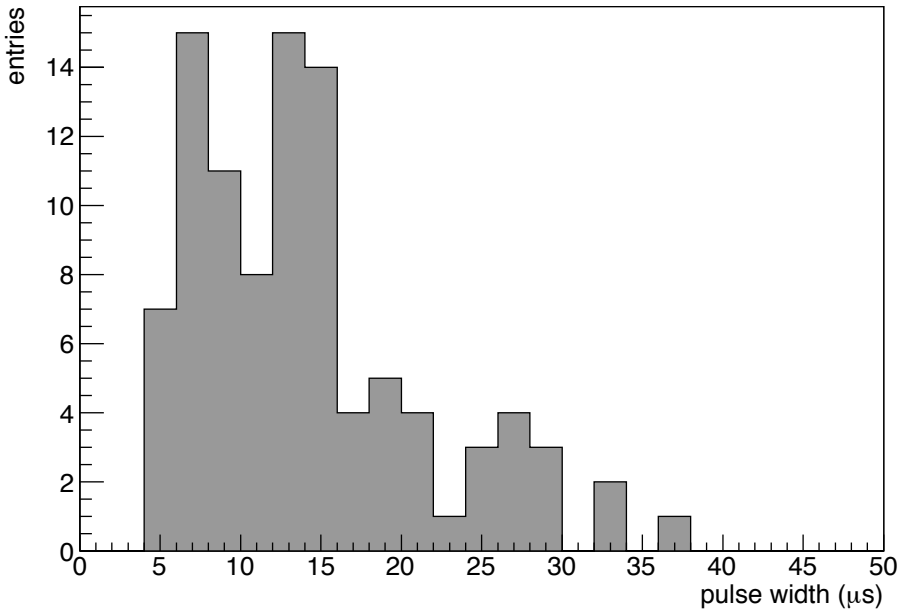


The front propagation reconstruction depends on **two parameters**:

- the source elevation angle ***ε***
- the D layer altitude ***h***

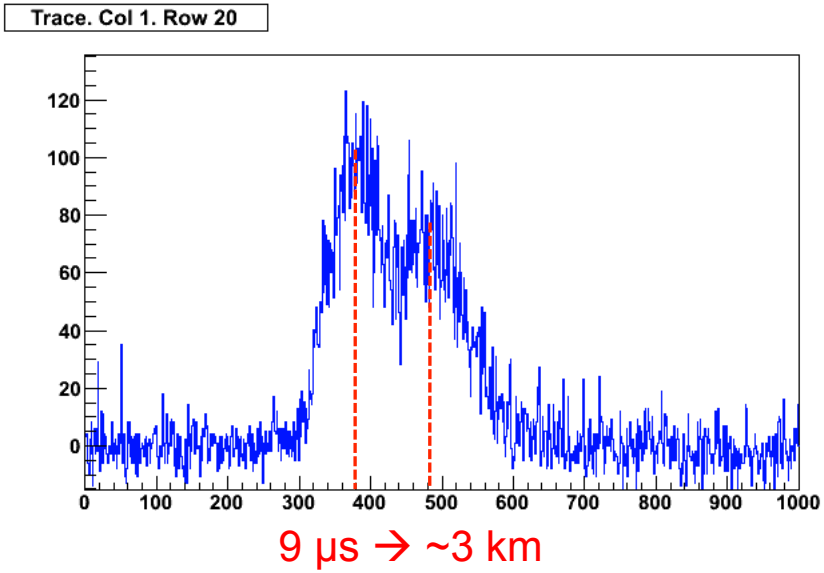
*The distribution of the **D layer altitudes** has mean value at ~ **86 km** and RMS of 9 km*

Measuring the pulse duration

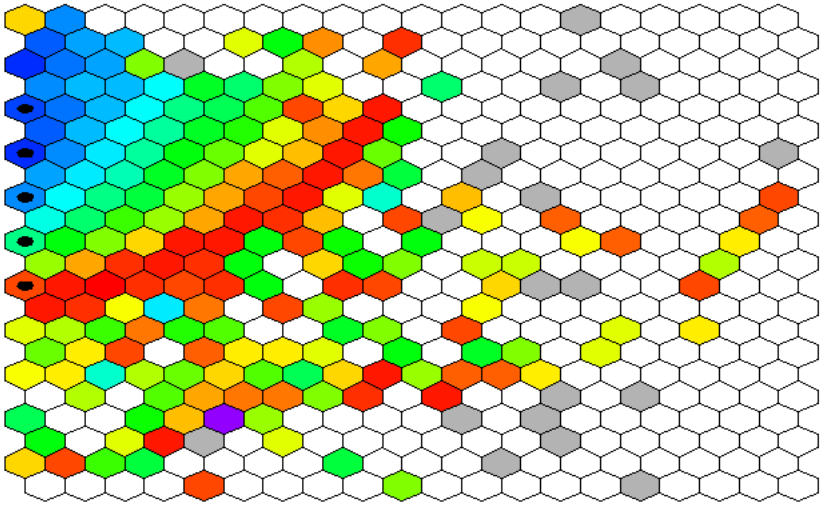


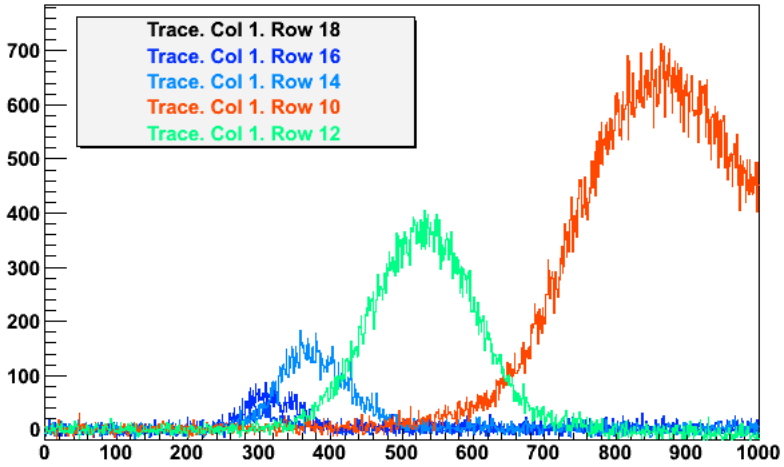
The FWHM of the pulse in the first pixel is related to either the size of the initial pulse, or the thickness of the light emitting layer.
6 -12 μs correspond to ~ 2-4 km.

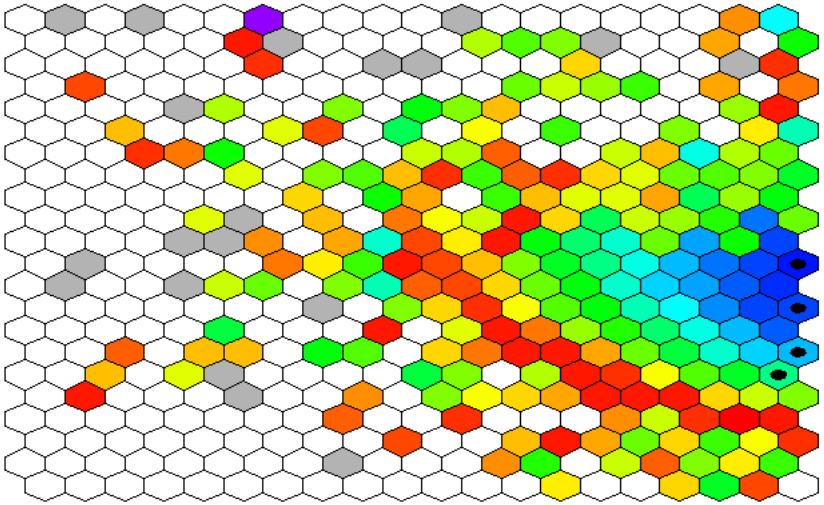
About 20% of the detected elves show two different pulses.

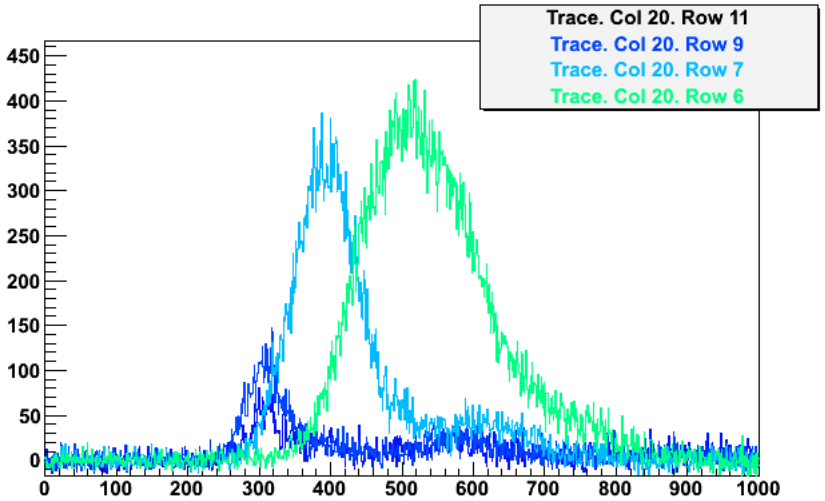


Gallery

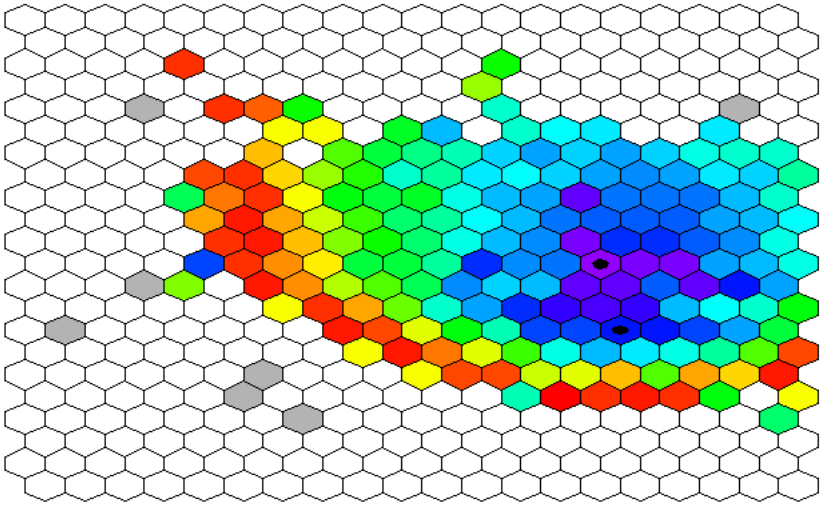


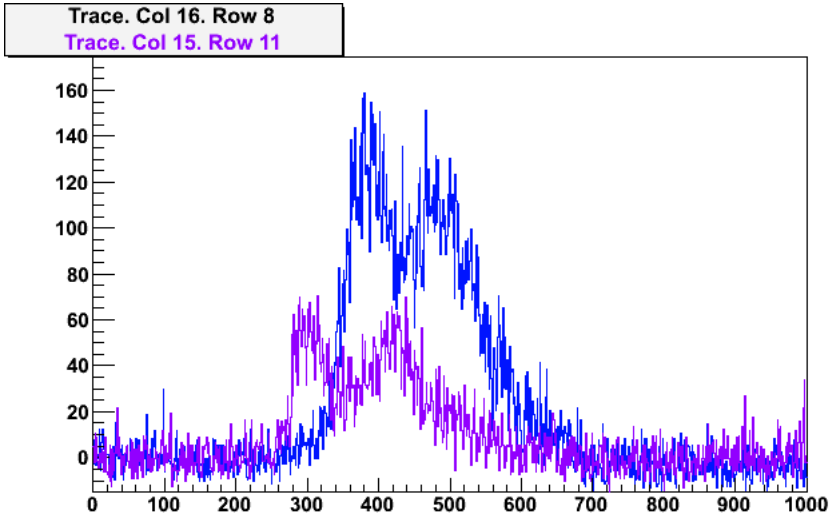

Trace. Col 1. Row 18
Trace. Col 1. Row 16
Trace. Col 1. Row 14
Trace. Col 1. Row 10
Trace. Col 1. Row 12
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000

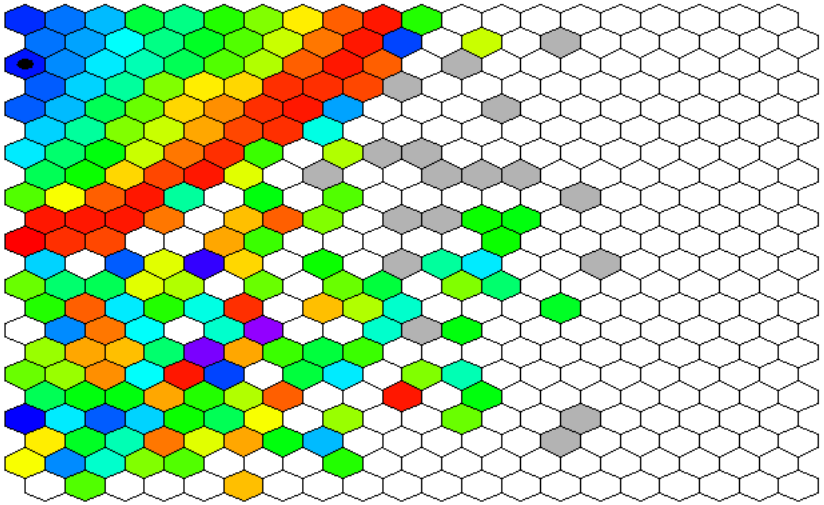


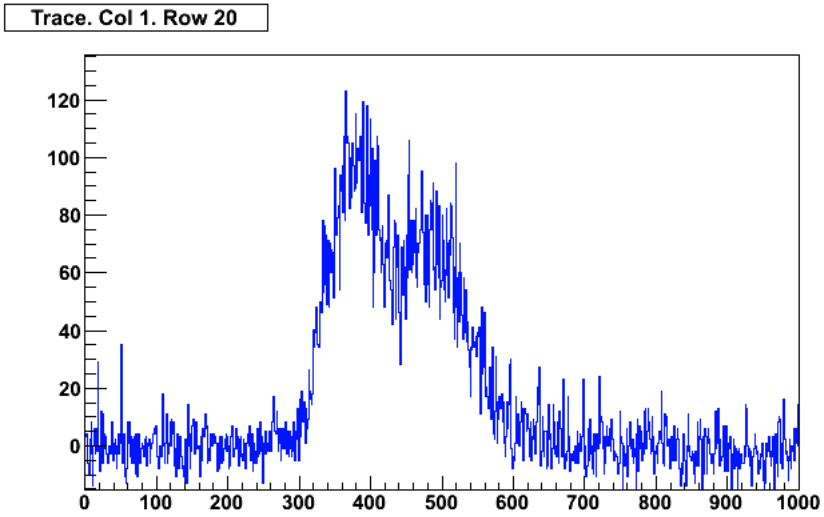

Trace. Col 20. Row 11
Trace. Col 20. Row 9
Trace. Col 20. Row 7
Trace. Col 20. Row 6
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
800
900
1000

Gallery




Trace. Col 16. Row 8
Trace. Col 15. Row 11
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
900
1000




Trace. Col 1. Row 20
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
900
1000

Conclusions

A dedicated trigger for recording elves with the FD of the Pierre Auger Observatory has been recently implemented

133 events detected in 2 months

The FD records 2D images of elves with a time resolution 50 times better than previous observations

Many events recorded in stereo

thank you!