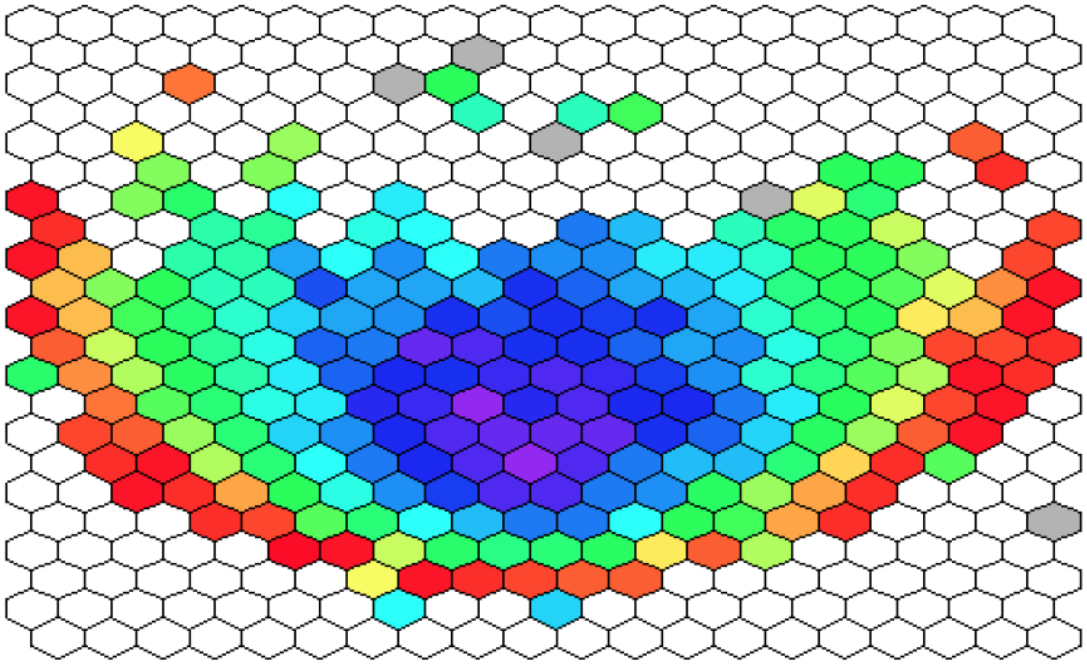
ELVES at the Pierre Auger Observatory

Roberto Mussa
(for the Pierre Auger Collaboration)

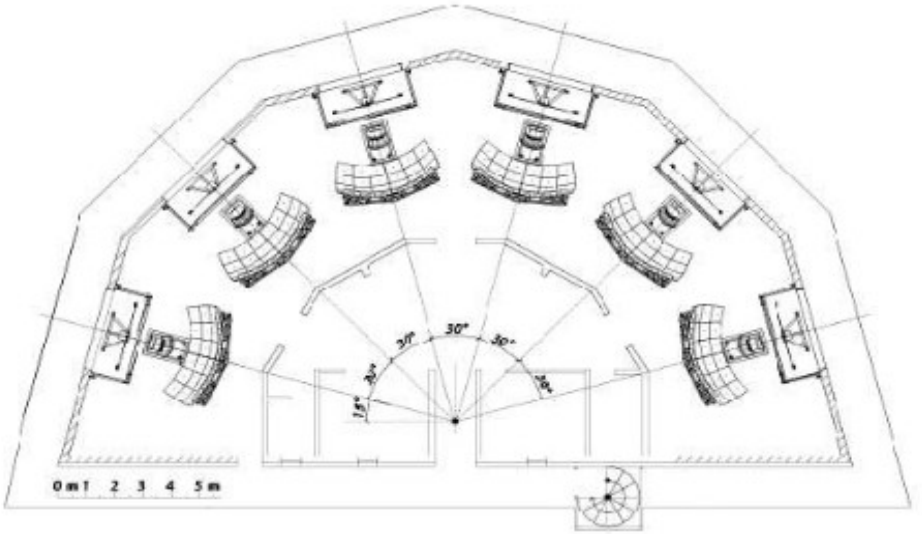


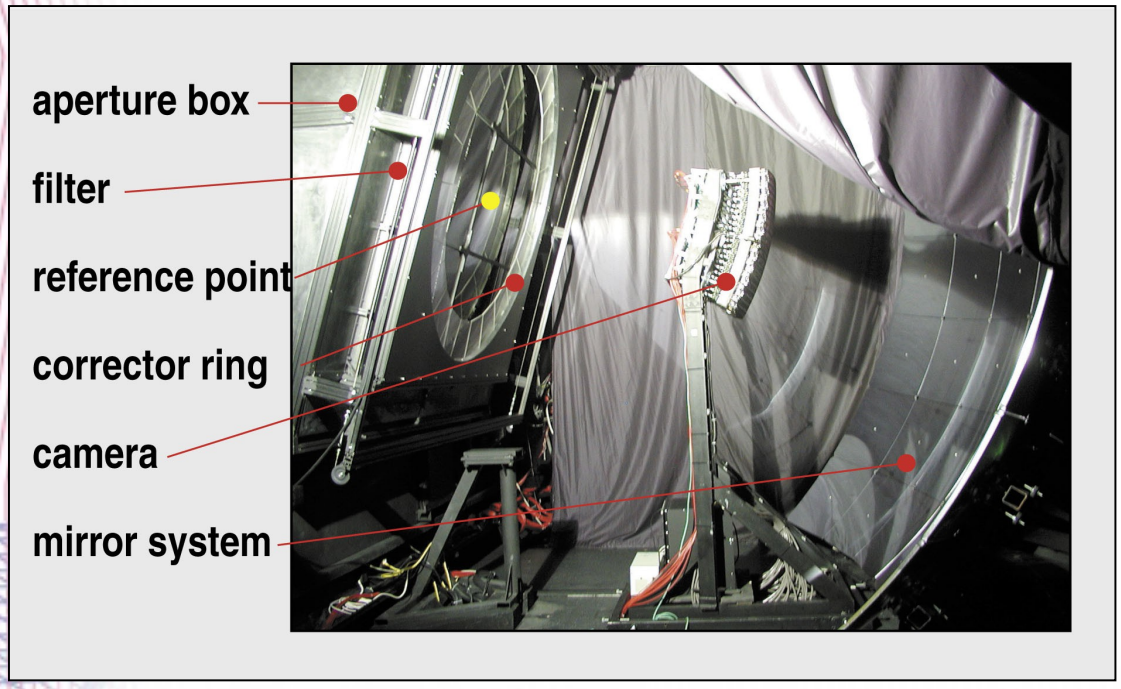
4th AtmoHEAD , Capri

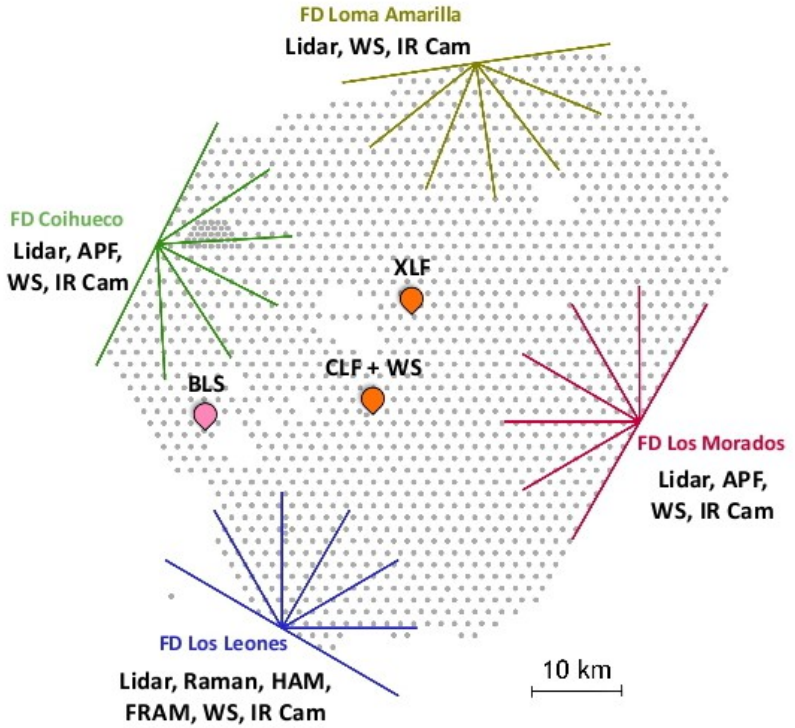
September 26th , 2018

Auger Fluorescence Detector

24 telescopes in 4 eyes
FD camera: 440 PMTs / telescope
Mirror area: 11m^2
Field of View: 6x30°x30° for each FD
UV filter: 300-420 nm
Buffering 1000 time bins, 100 ns each
A 10 Mfps camera !
Duty cycle ~12% (1/2 moon cycle)
Angular resolution ~ 0.6°



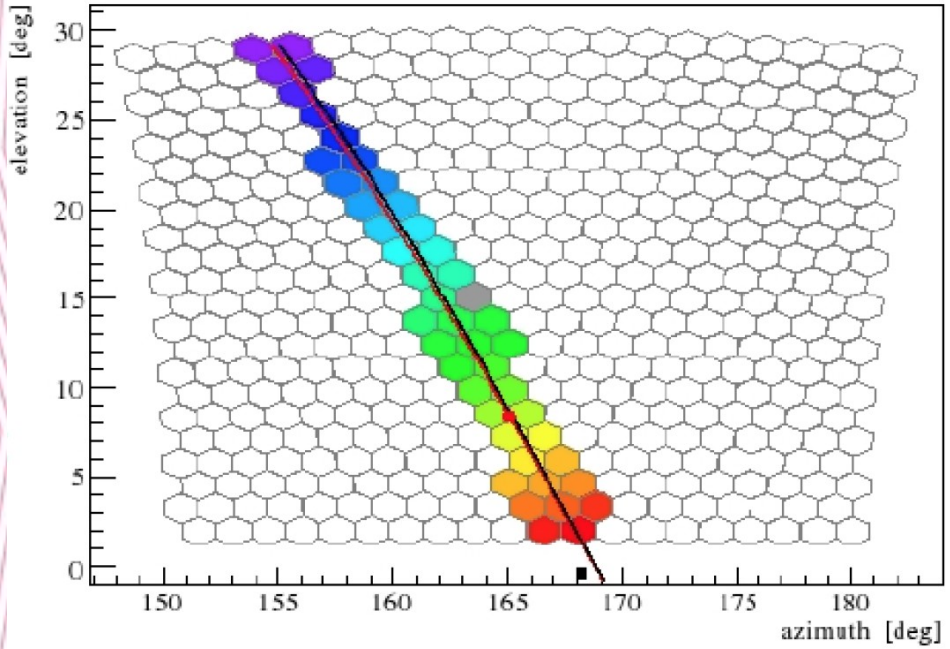




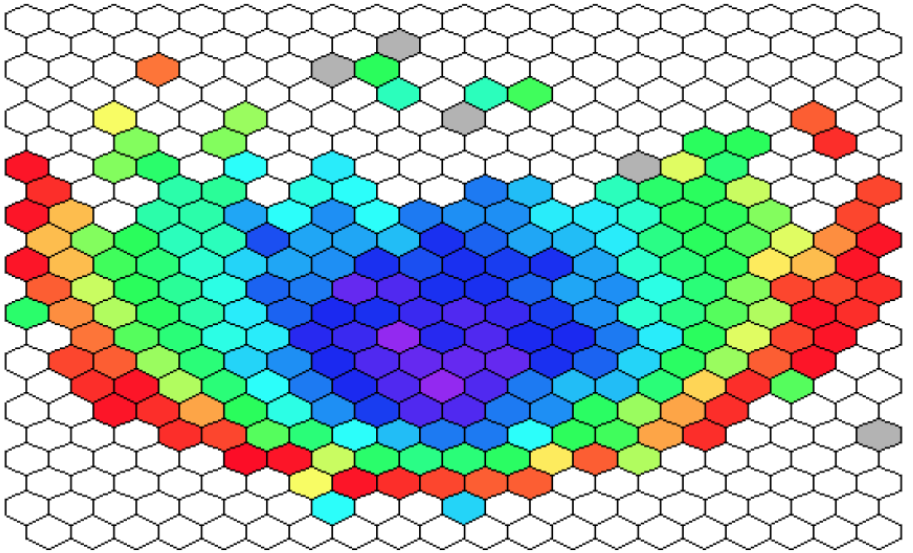
2004-2009: discovery of 3 ELVES events in FD data

R.Mussa et al., proc."IS @ AO Workshop", Cambridge, EPJ Plus 127,94 (2012)
A.Tonachini et al., proc. ICRC2011, Beijing 2011

Cosmic Ray



ELVES



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

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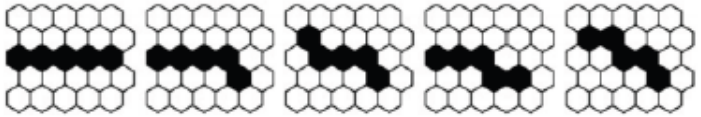
A.Tonachini et al., proc. ICRC2011, Beijing 2011

2008-2011: search for ELVES in FD-SLT data

	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



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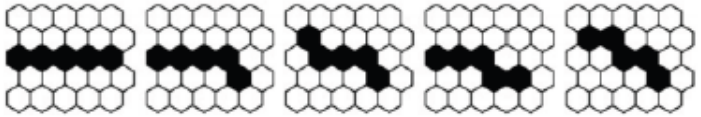


We decided to analyze the fraction of events which pass the 2nd level of trigger, which is saved with prescaling factor 1/100 in a separate data stream (*minimum bias*) and is used for measuring efficiencies and testing new trigger algorithms. 58 new events were found.

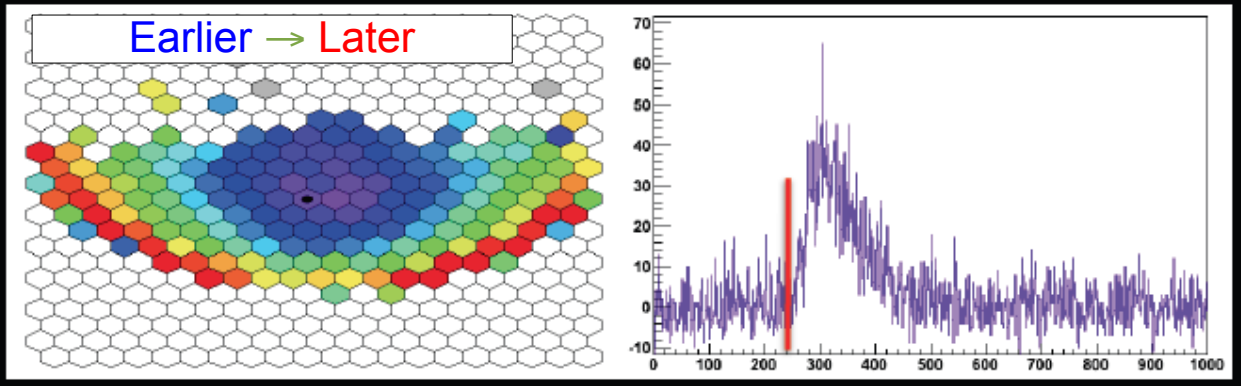
R.Mussa et al., poster at AGU FALL 2012

A.Tonachini et al., proceedings ICRC 2013

Online trigger algorithm for ELVES

Tonachini et al.
Proc. ICRC 2013

1. Find the FIRST PIXEL and define the PULSE START TIME



Pulse length must be > 25 bins

2) Check PIXELS on the same COLUMN

- at least **2 pixels before AND 2 after** the central one
- **80%** of the pixels must show an **increasing pulse time**

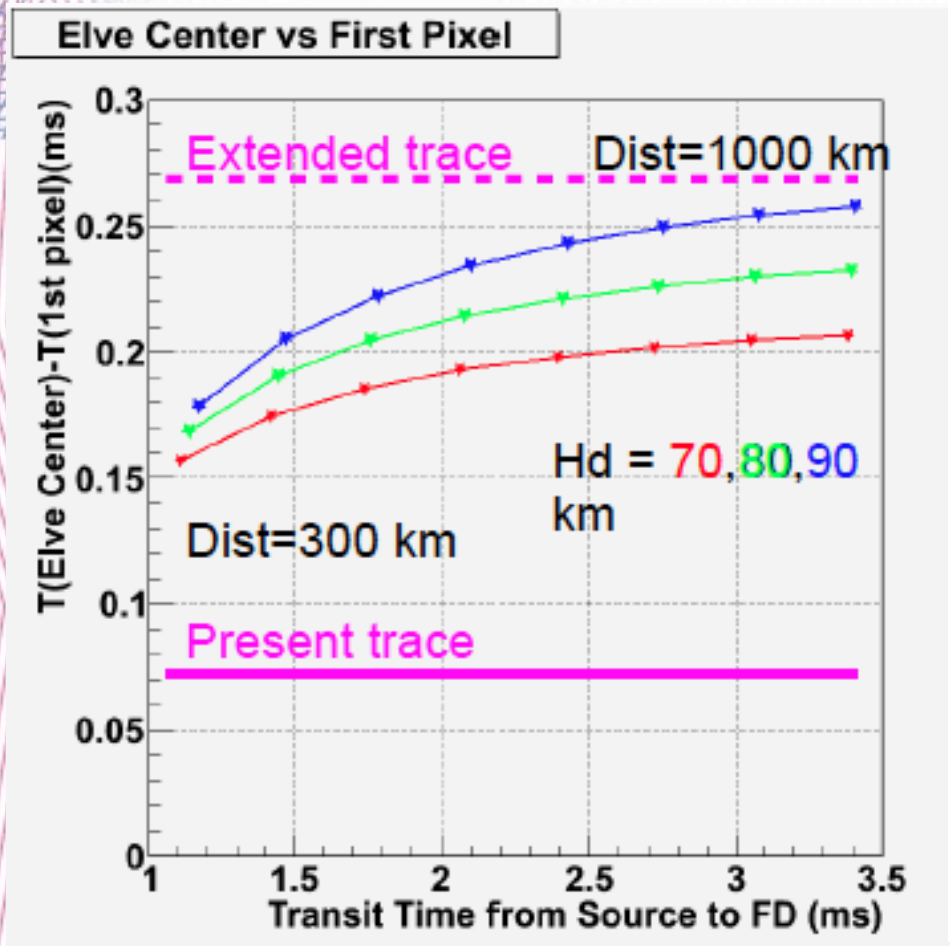
3) Check PIXELS on the same ROW

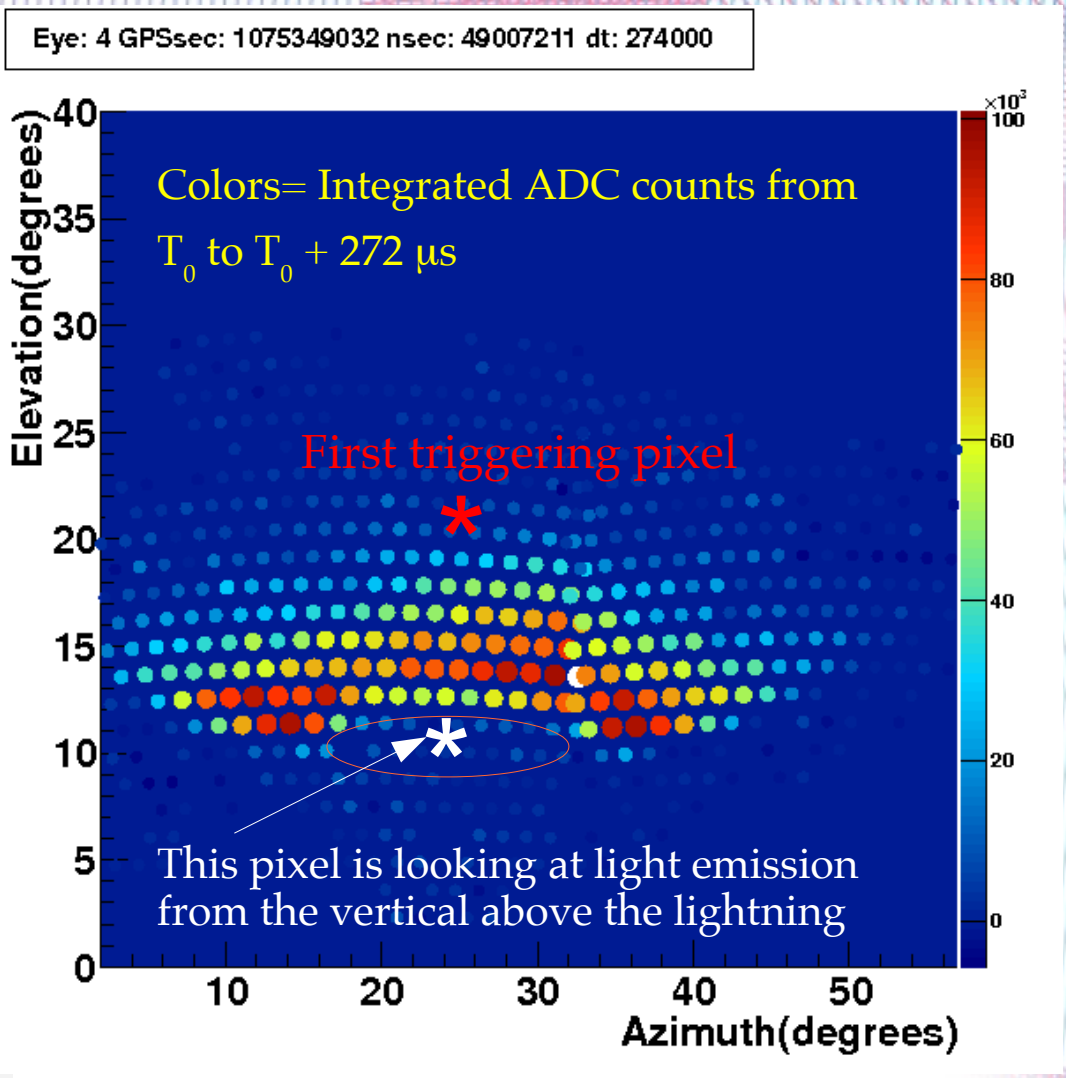
- at least **3 pixels before OR 3 after** the central one
- **80%** of the pixels must show an **increasing pulse time**

4) Check signal amplitude for each pixel

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

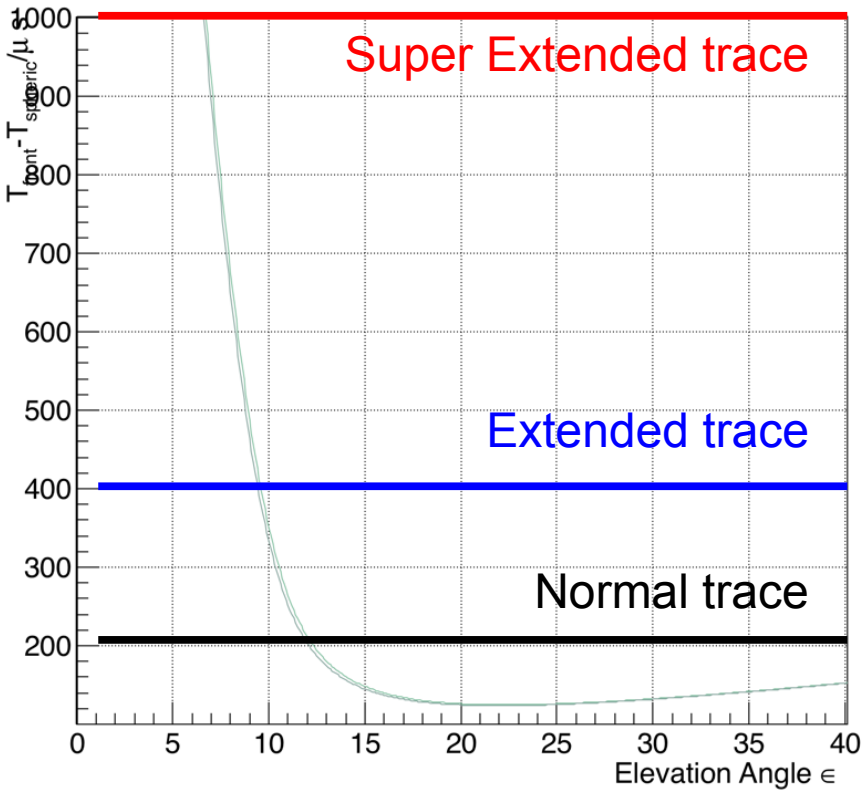
Extended readout

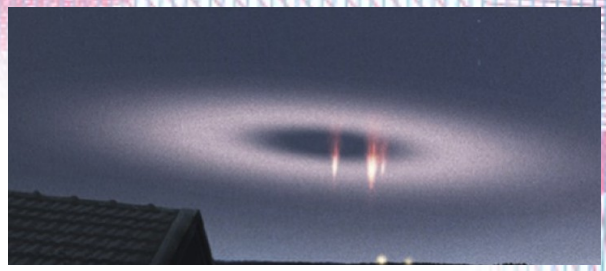


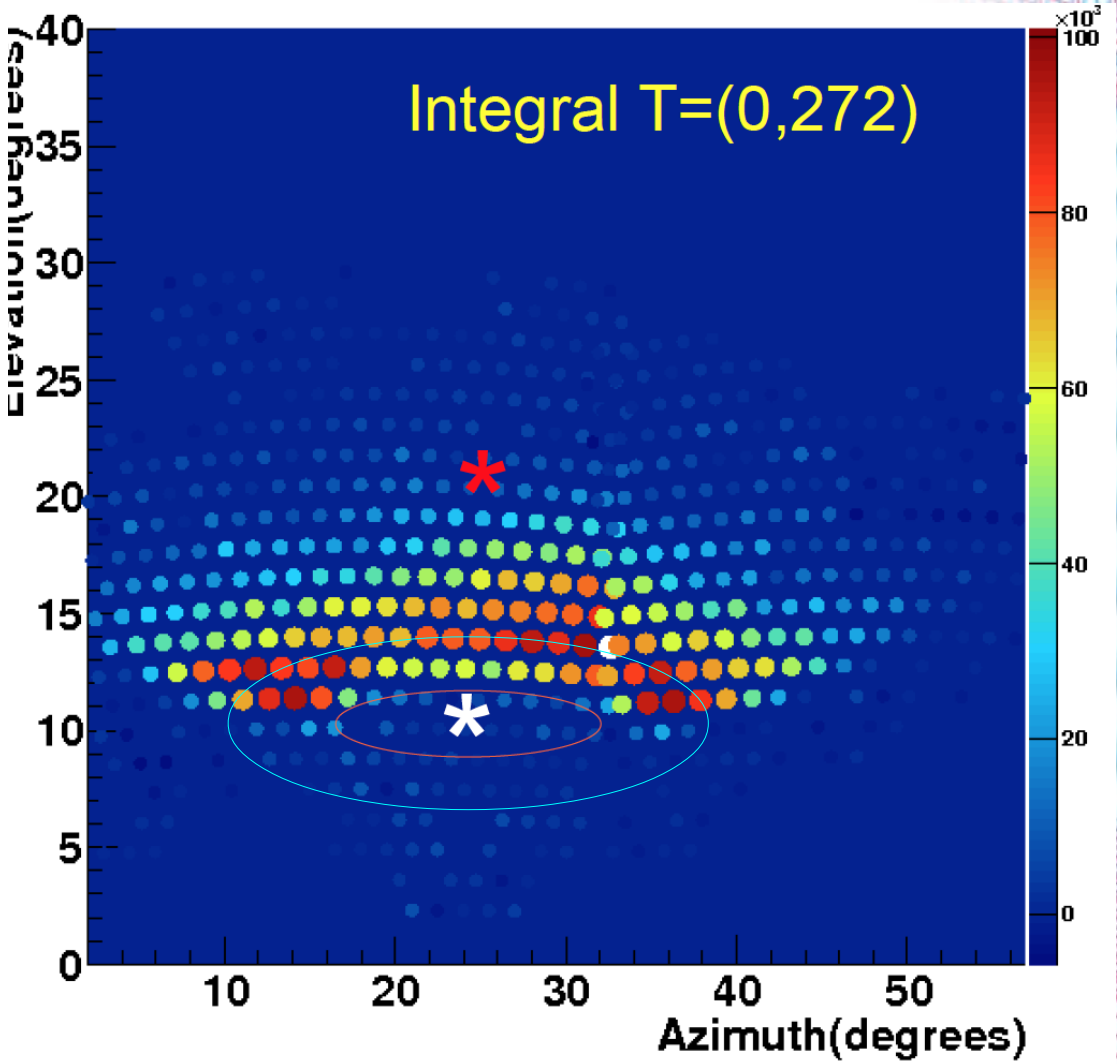


Standard FD traces are 72 μs long, after the trigger: this prevents to see most of the light of the ELVES.
In particular, it prevents to see light from the vertical above the lightning source.
Therefore, we modified the FD readout scheme, allowing to acquire 3 consecutive frames for these special triggers.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

Super-Extended readout







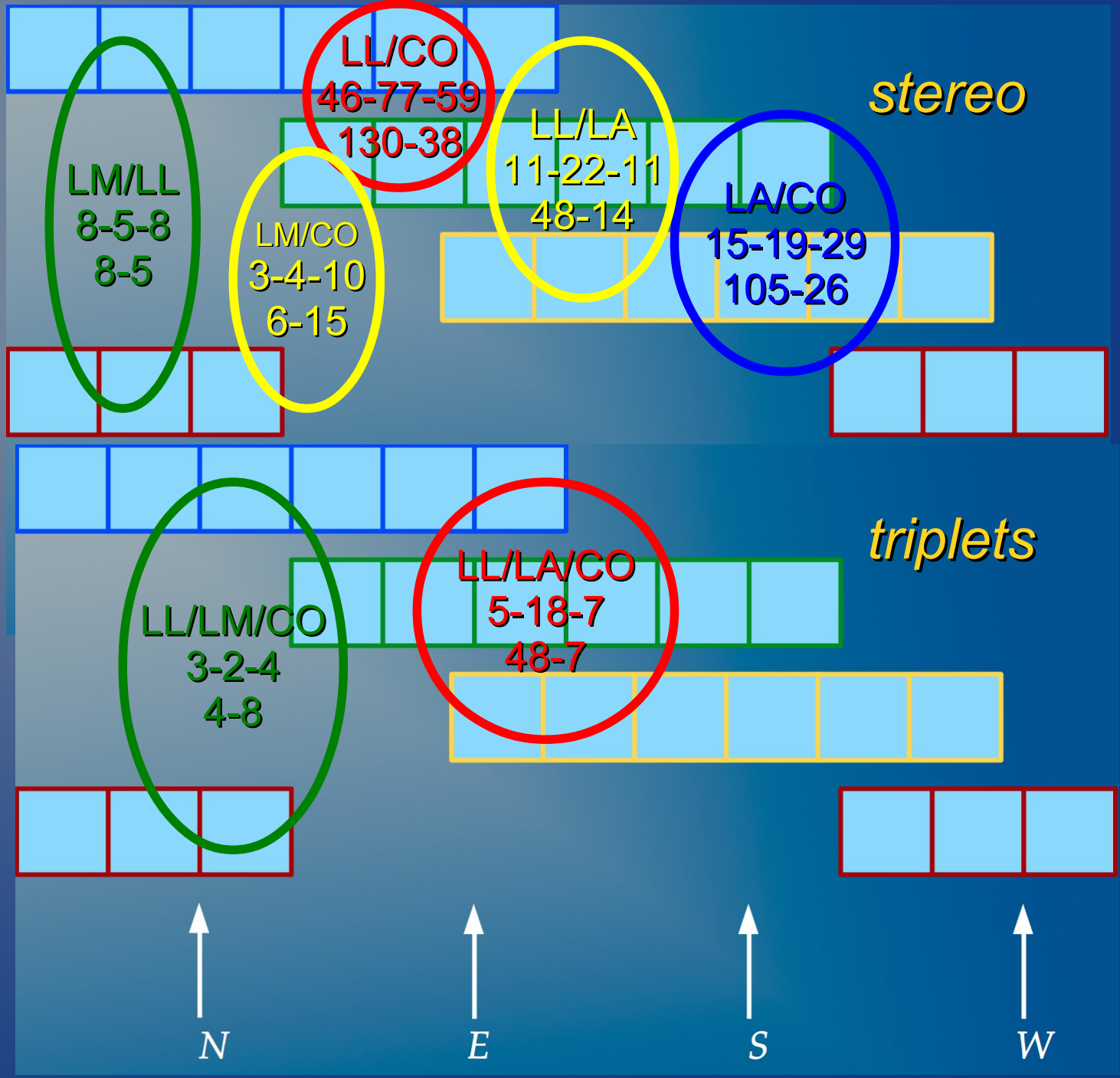
To measure light from the lower (i.e. far) part of the ring and study asymmetry with respect to the lightning center, we need to add ~0.6 ms to go 3° down.

Since Jan.20,2017 we run with trace length: 900 μs, allowing up to 8 followers.

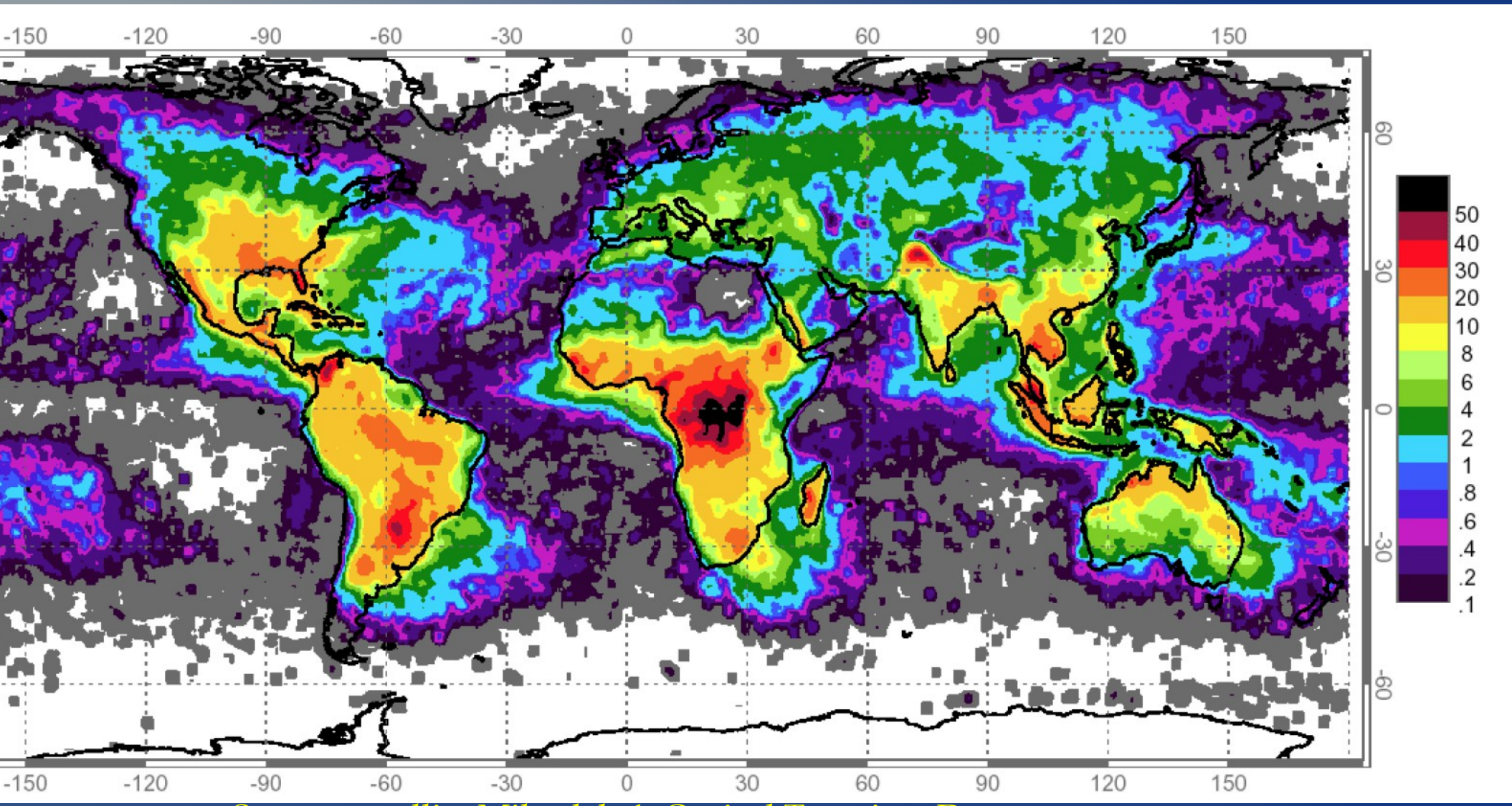
Elves triggers: statistics

Year	1-eye	2	3	tot
2013*	214	83	8	305
2014	425	128	19	572
2015	686	117	11	814
2016	673	151	21	845
2017	906	297	52	1255
2018 **	527	99	15	641
Total	3431	875	126	4432

(*) no data from Jan-Feb-May
(**) data until Sep 21



Lightning strikes /km^2/year

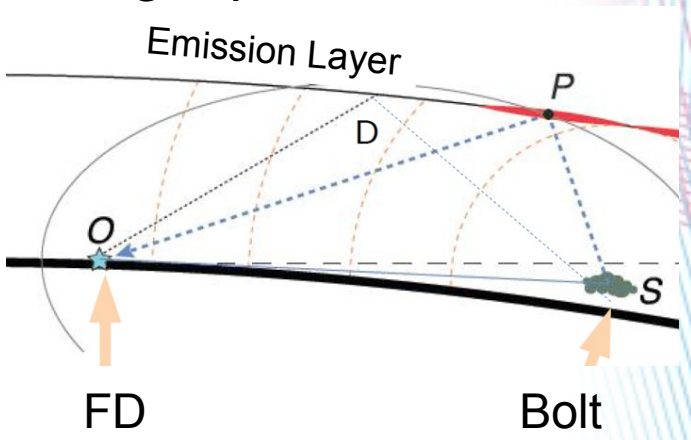


Source: satellite Mikrolab-1, Optical Transient Detector

ELVES reconstruction: 3,4,5D Time Fit

Minimization of χ^2 defined as a sum on all pixels *i* having a pulse :

$$\chi^2 = \sum_E \frac{\{T_i + \Delta T - \overline{OPS}_i(Lat_b, Long_b, H_{emis}, H_b)\}^2}{\sigma^2_{T,i}}$$



First Fit with only 3 free parameters :

ΔT : time between the bolt and the beginning of FD trace

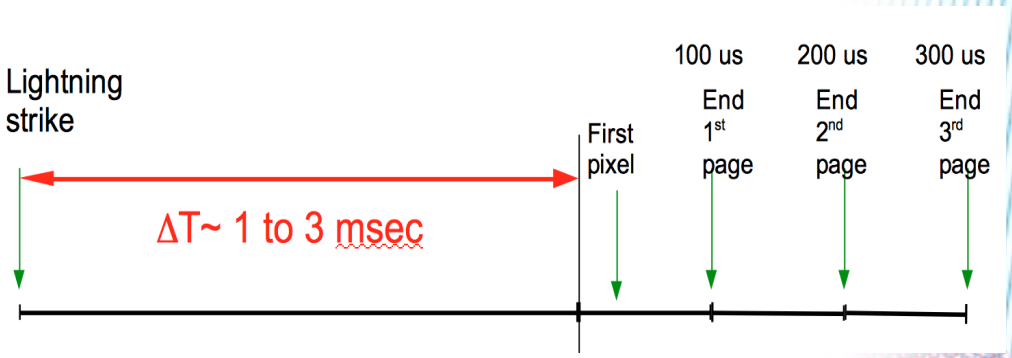
Lat_b = Latitude of the Bolt

$Long_b$ =Longitude of the Bolt

Then, 4D-Fit , releasing :

H_{emis} = height of the emission layer

(starting value 85 km a.s.l.)



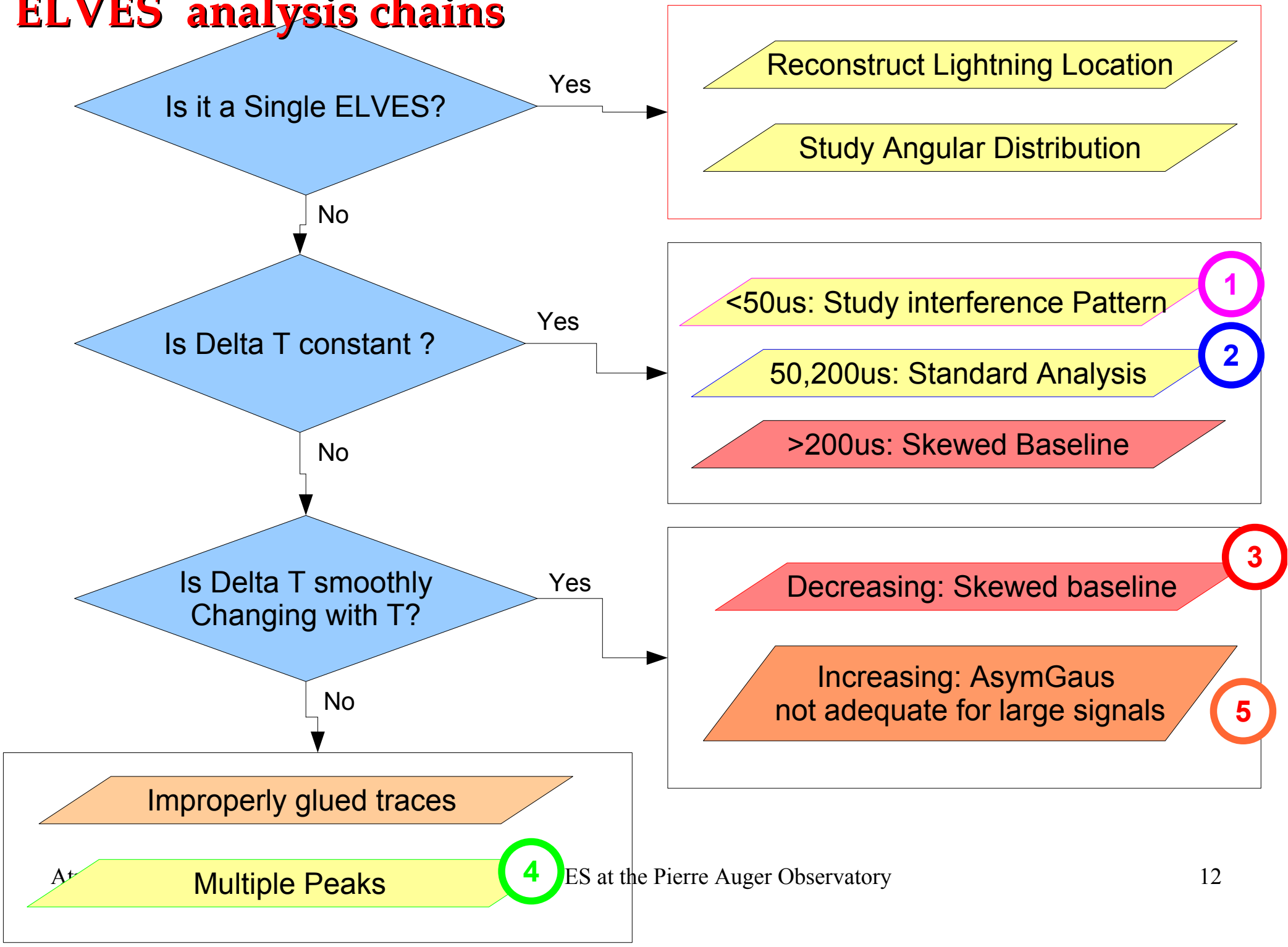
Finally: 5D-fit, releasing

H_b = height of the bolt (starting value 0 km a.s.l.)

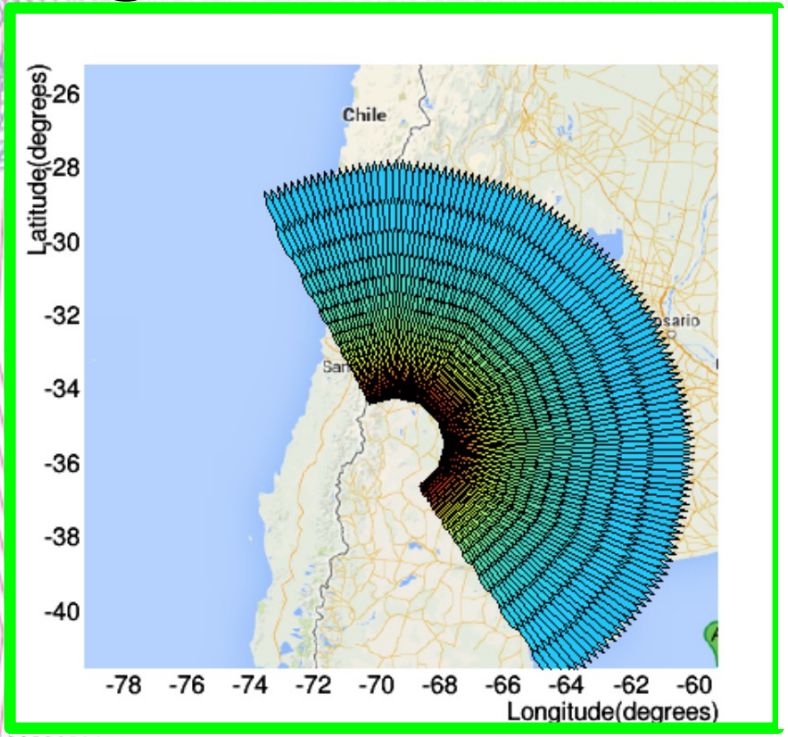
Notice: the FD's are located at their altitude, while the bolt starts at sea level.

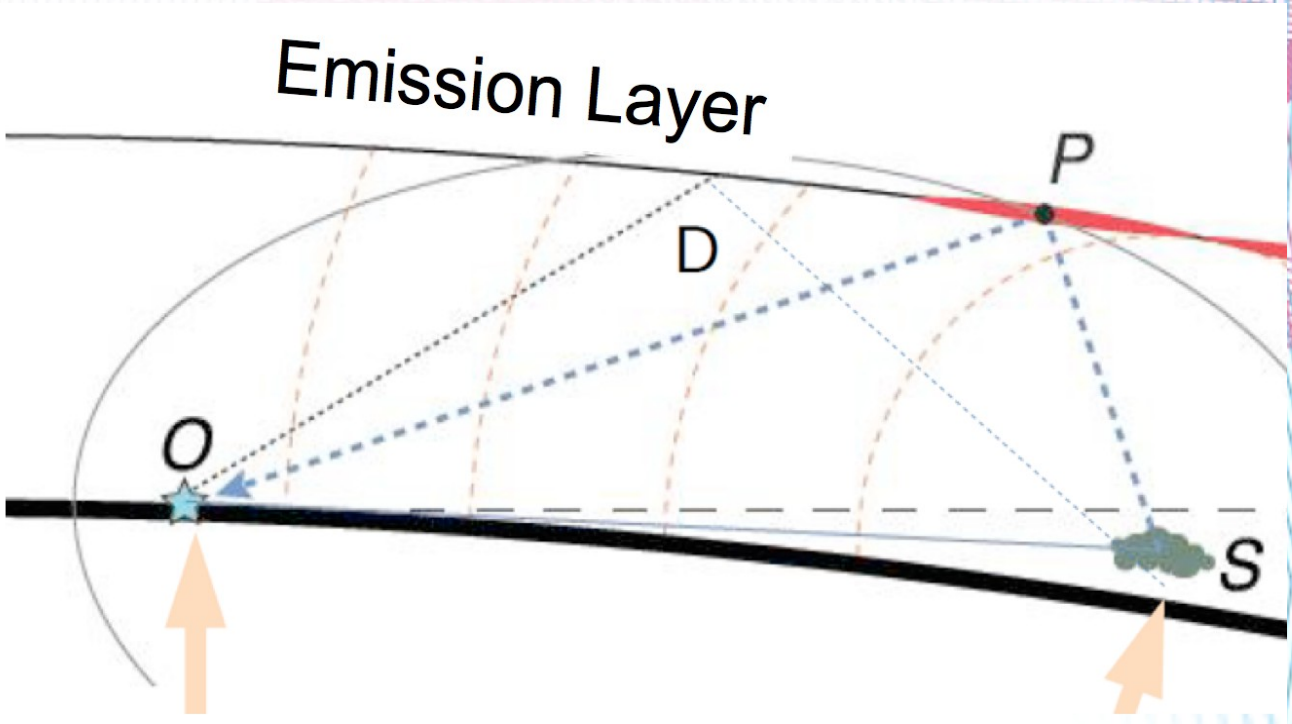
On reconstructed events , we observe a very high correlation with WWLLN data (>70%)

ELVES analysis chains



Light emission normalization





FD

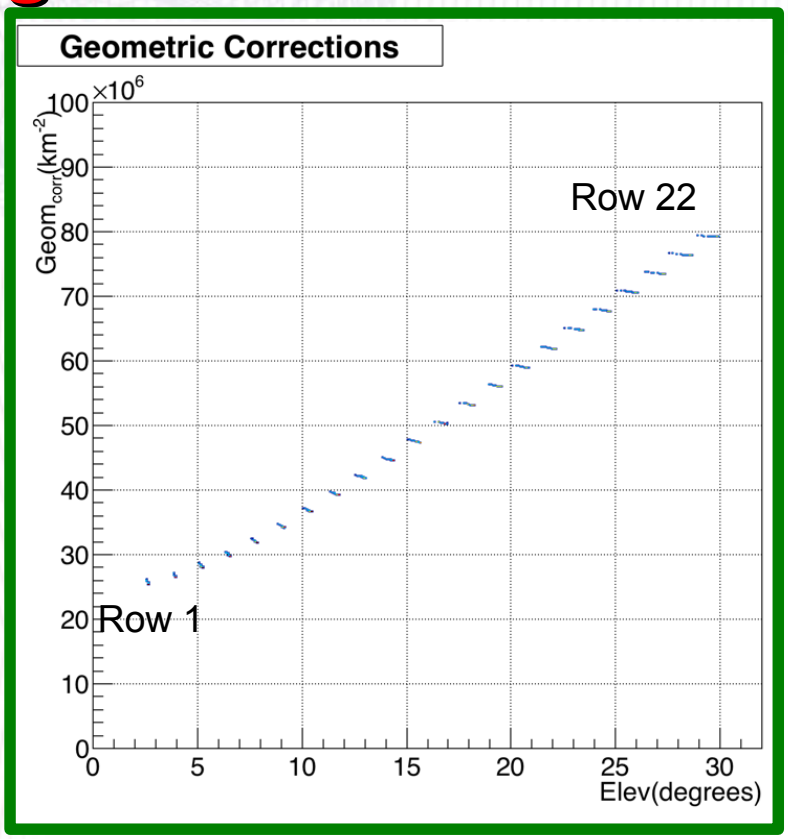
Lightning Bolt

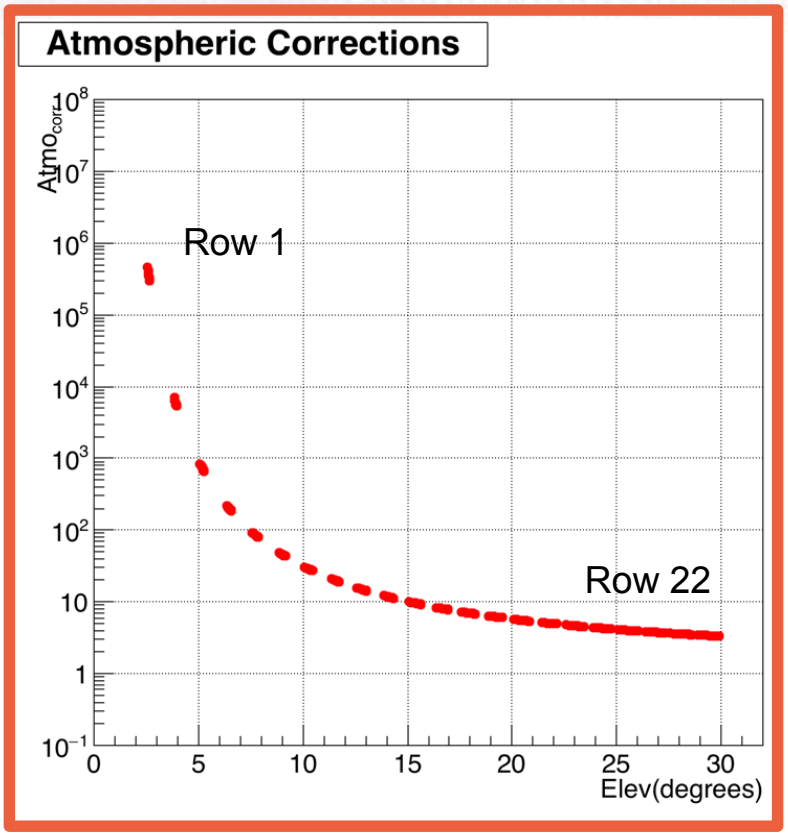
Photons detected by the FD camera are corrected for distance from the base of ionosphere and for the surface observed by each pixel:

$$\Phi(i) = PFD(i) * Geom\_corr * Atmo\_corr$$

$$Geom\_corr = (R^2_{PO}/A_{mirror})\ Area(h=Hd) \quad ; \quad Atmo\_corr = \exp((OP_{mol}+OP_{aer})*airmass(\theta))$$

Light emission normalization





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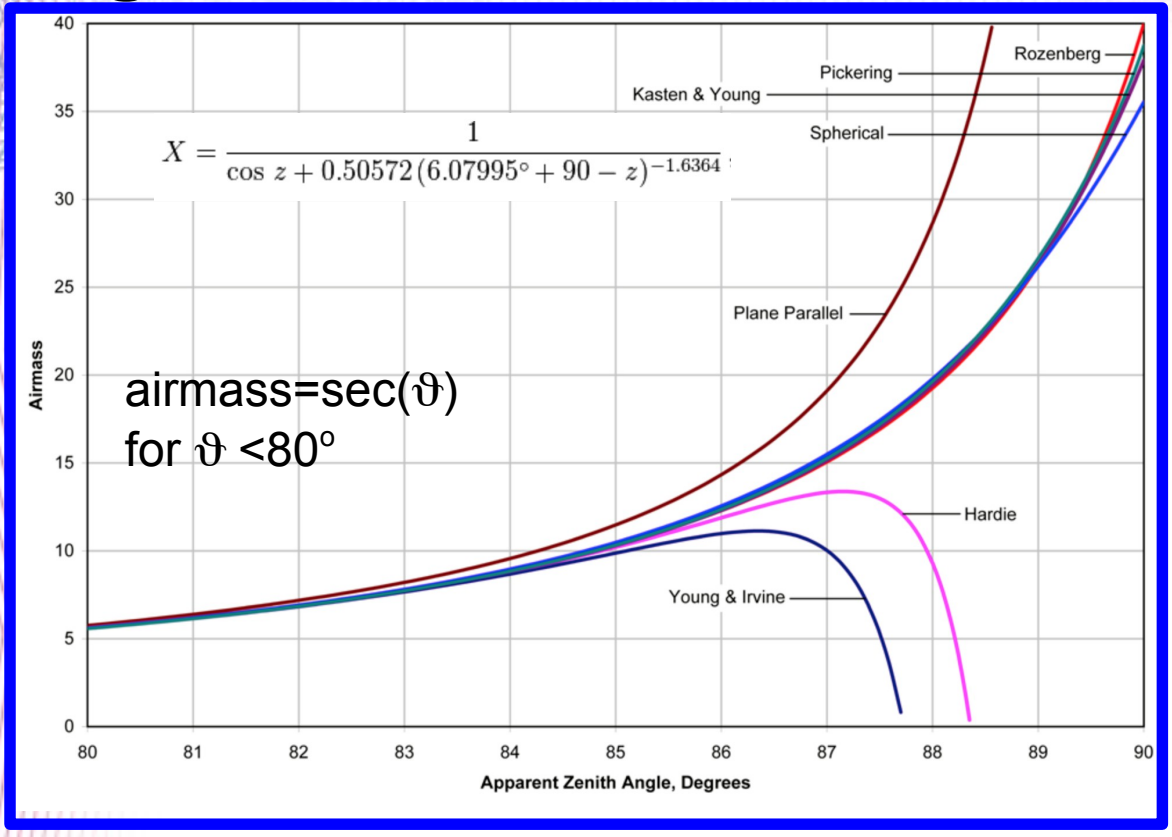

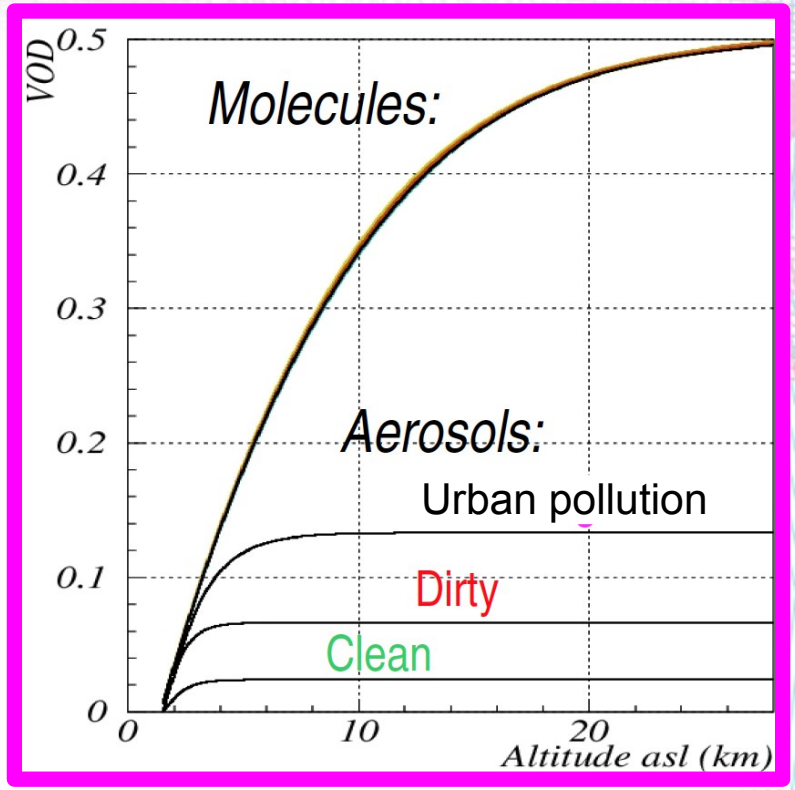

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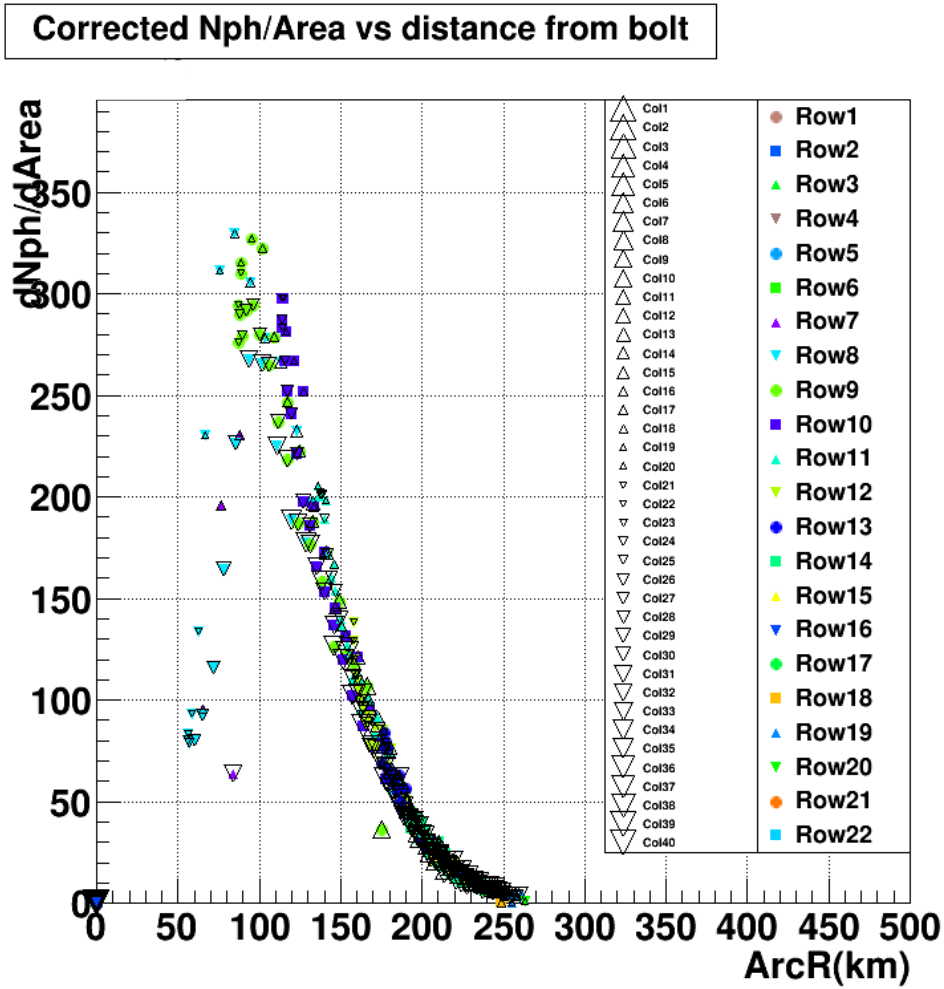
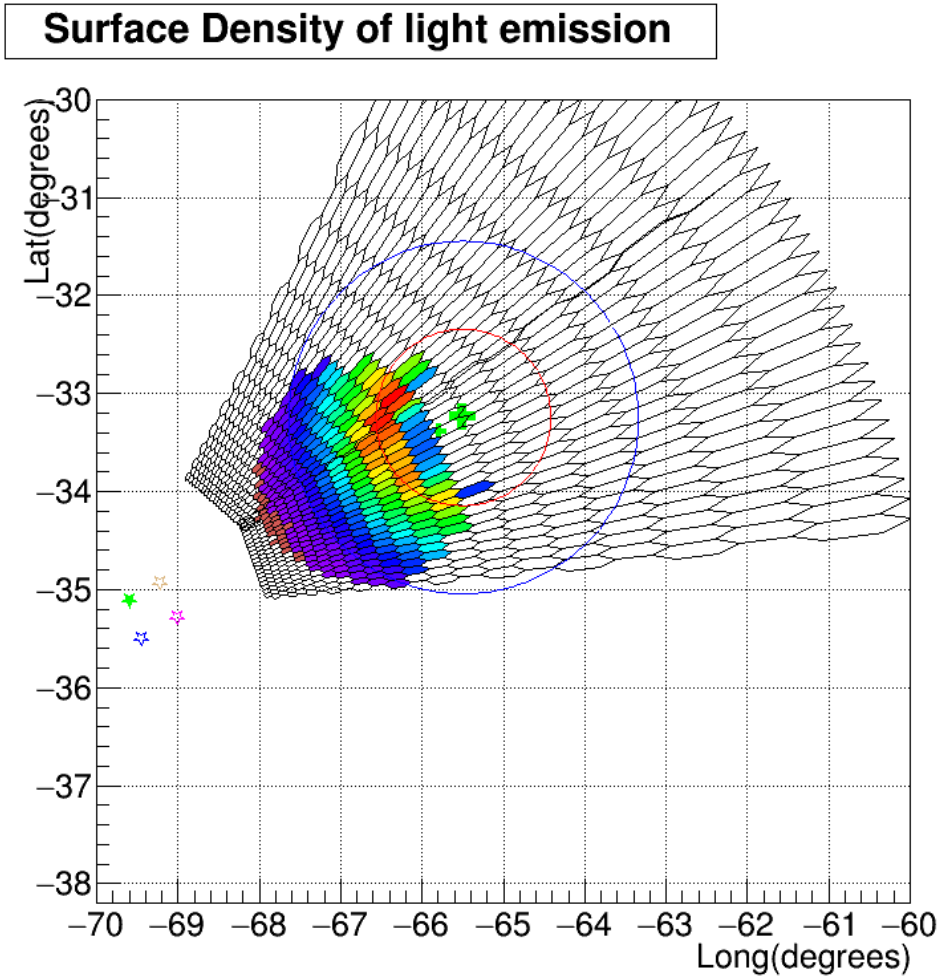
Atmospheric optical depth OD is calculated from Vertical Molecular (by weather stations, radiosondes, GDAS) and Aerosol profiles (hourly LIDAR measurements).
Airmass is calculated from *Kasten, F.; Young, A. T. (1989).. Applied Optics 28: 4735–4738*.

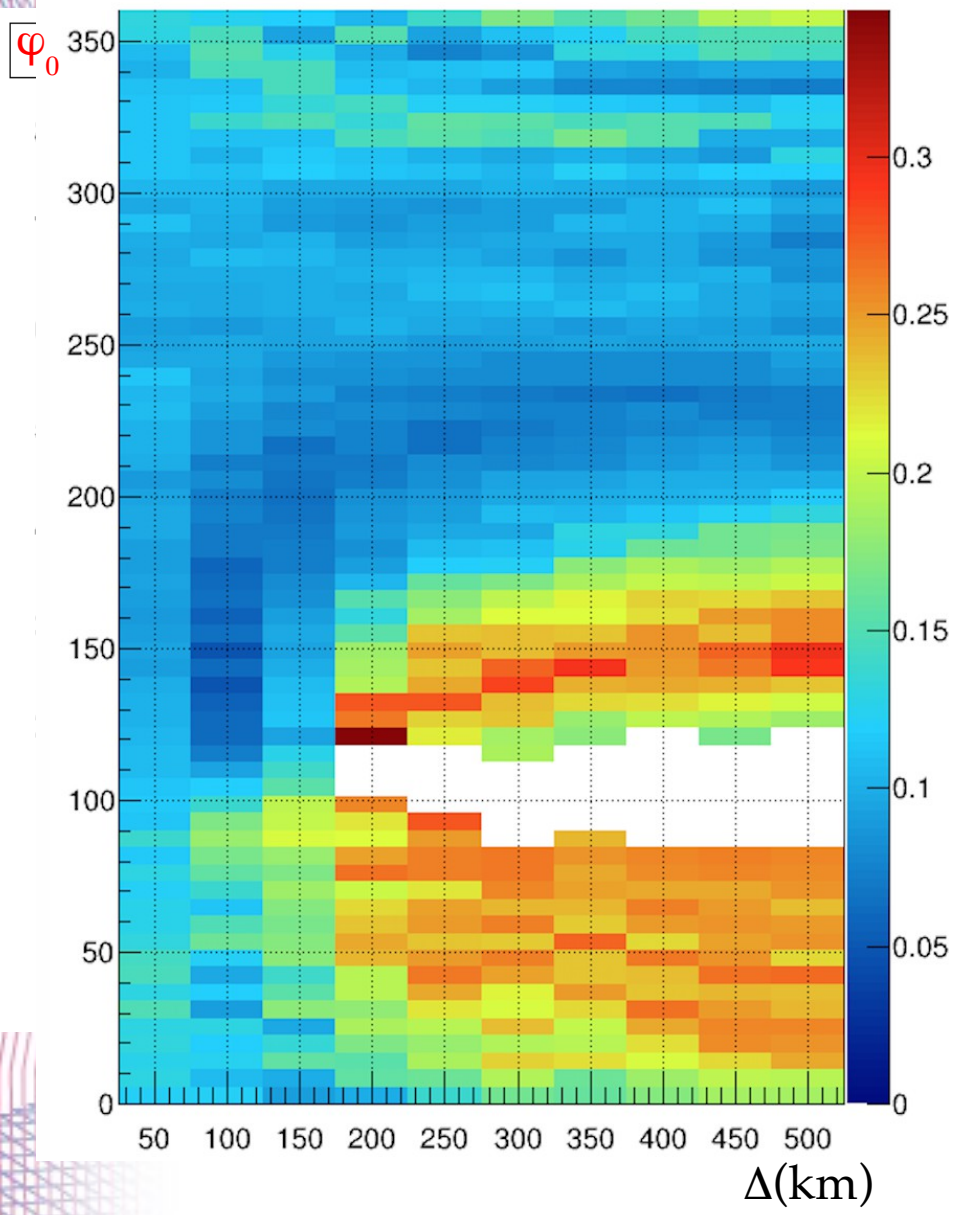
Corrected light emission versus distance from lightning strike

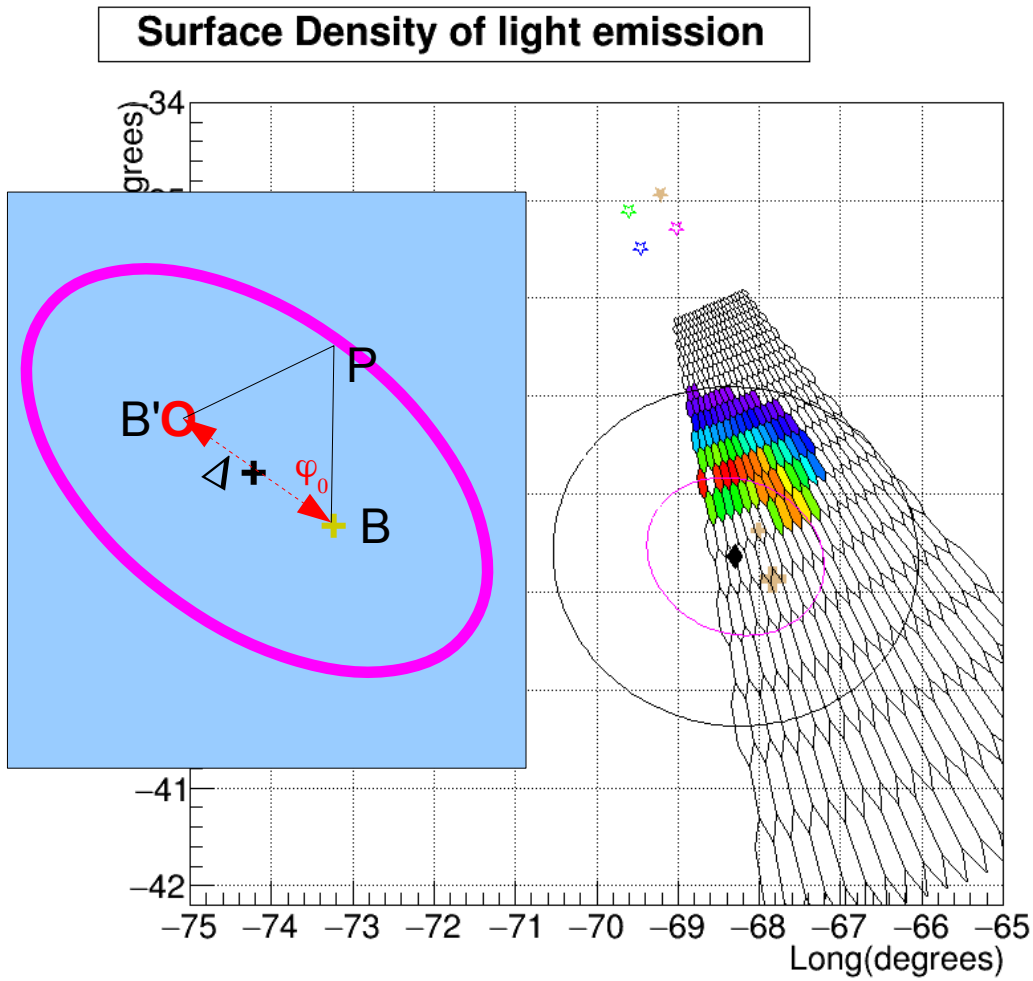




Modeling the EMP as a vertical dipole, we expect to have a doughnut shaped emission pattern, for cloud to ground lightning. The radius of the doughnut can be related to the maximum speed of the accelerated charges in the process. Residual anisotropies can be due to earth magnetic field.

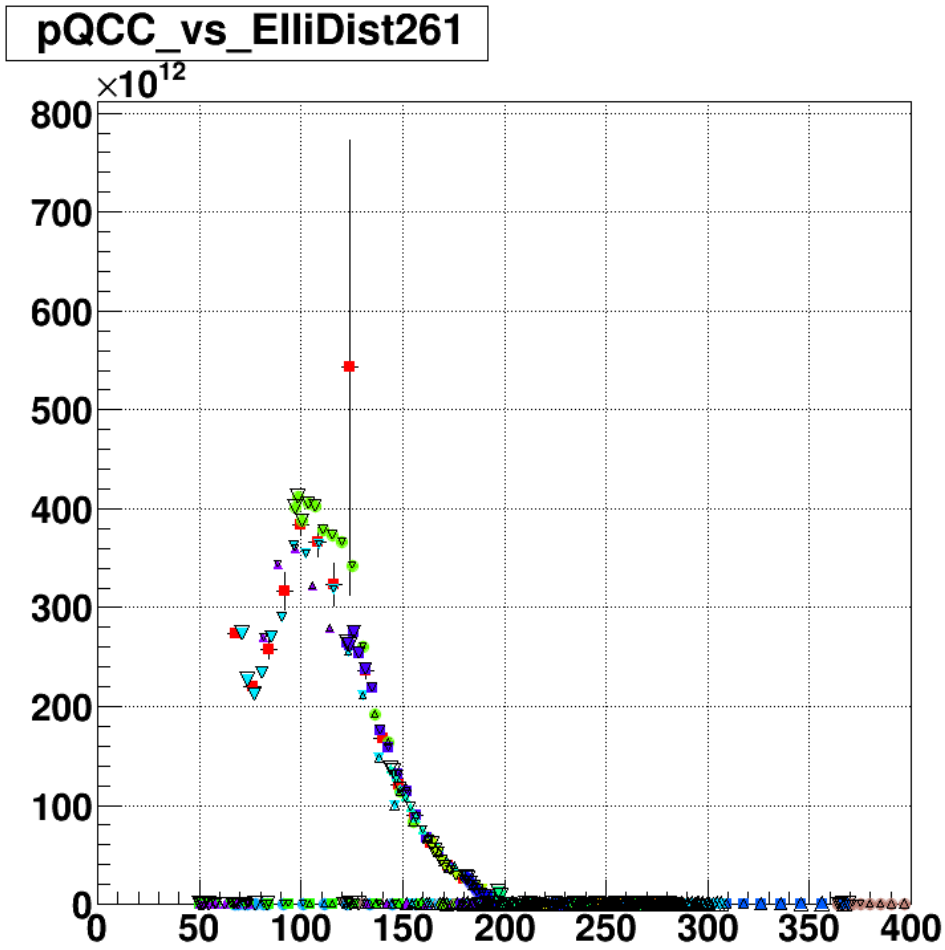
Corrected light emission for tilted dipoles

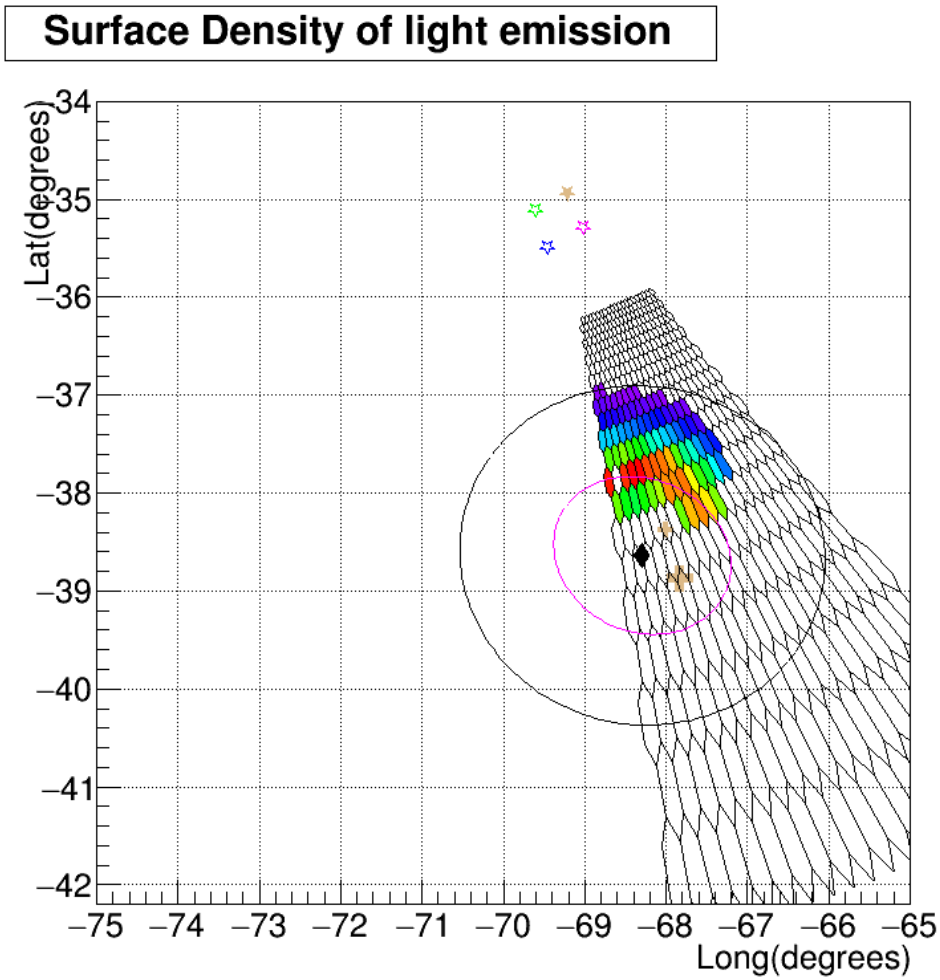




The best ellipse is obtained by finding the parameters ($\Delta=\overline{BB'}$,φ_0) that minimize the spread of corrected light density distribution vs $D_{arc} = \overline{BPB'}$

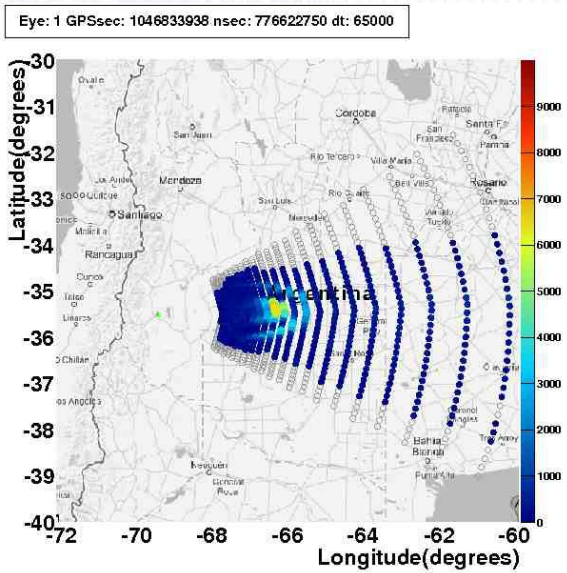
Corrected light emission for tilted dipoles

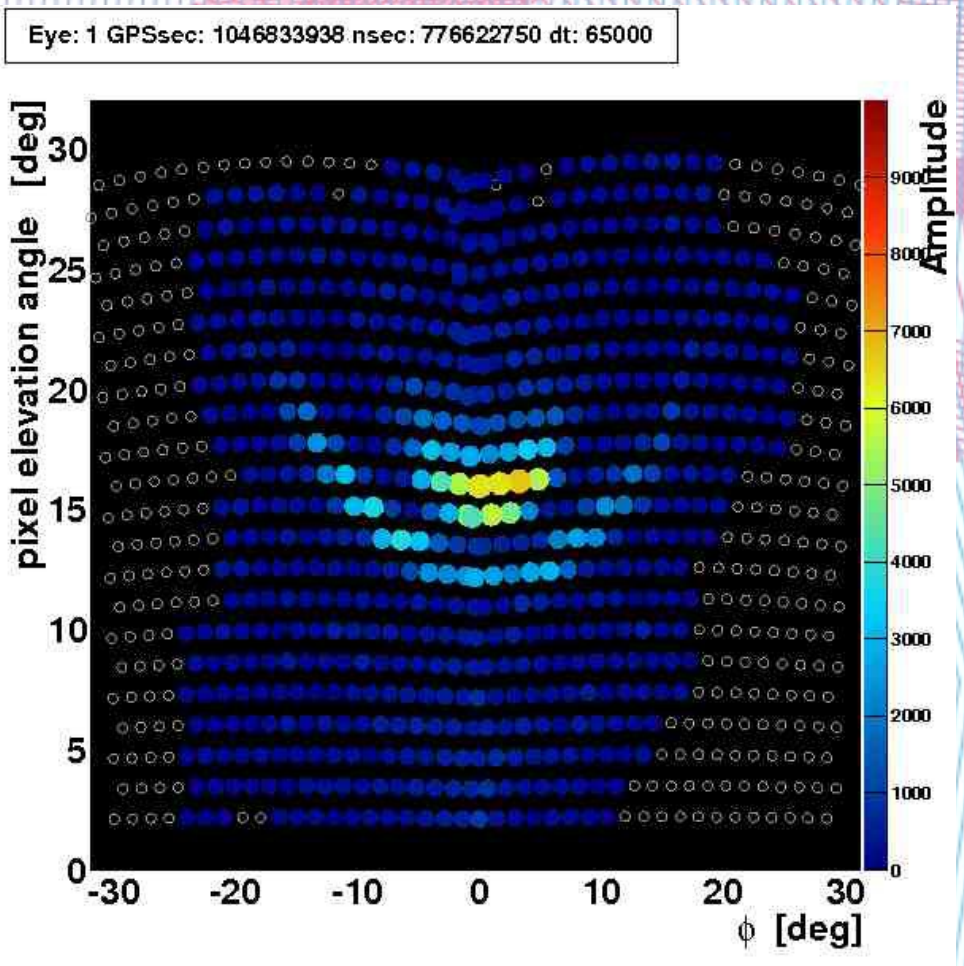




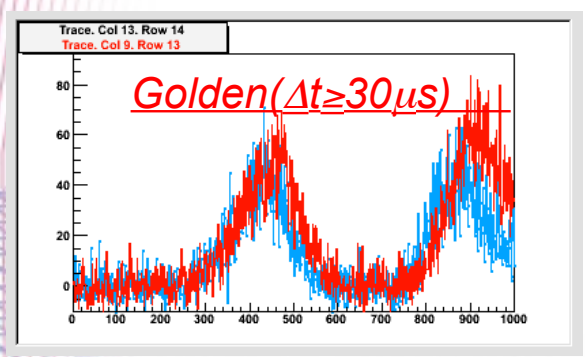
The tilted dipole hypothesis seems to work well on a fraction of events, but many other features are seen in other events, that deserve further studies

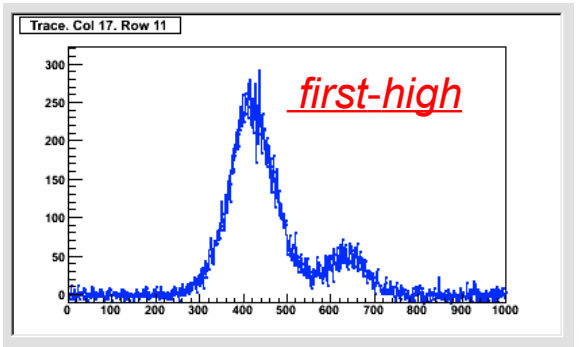
Double ELVES

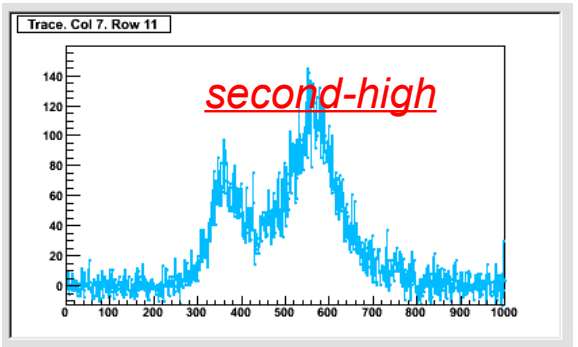




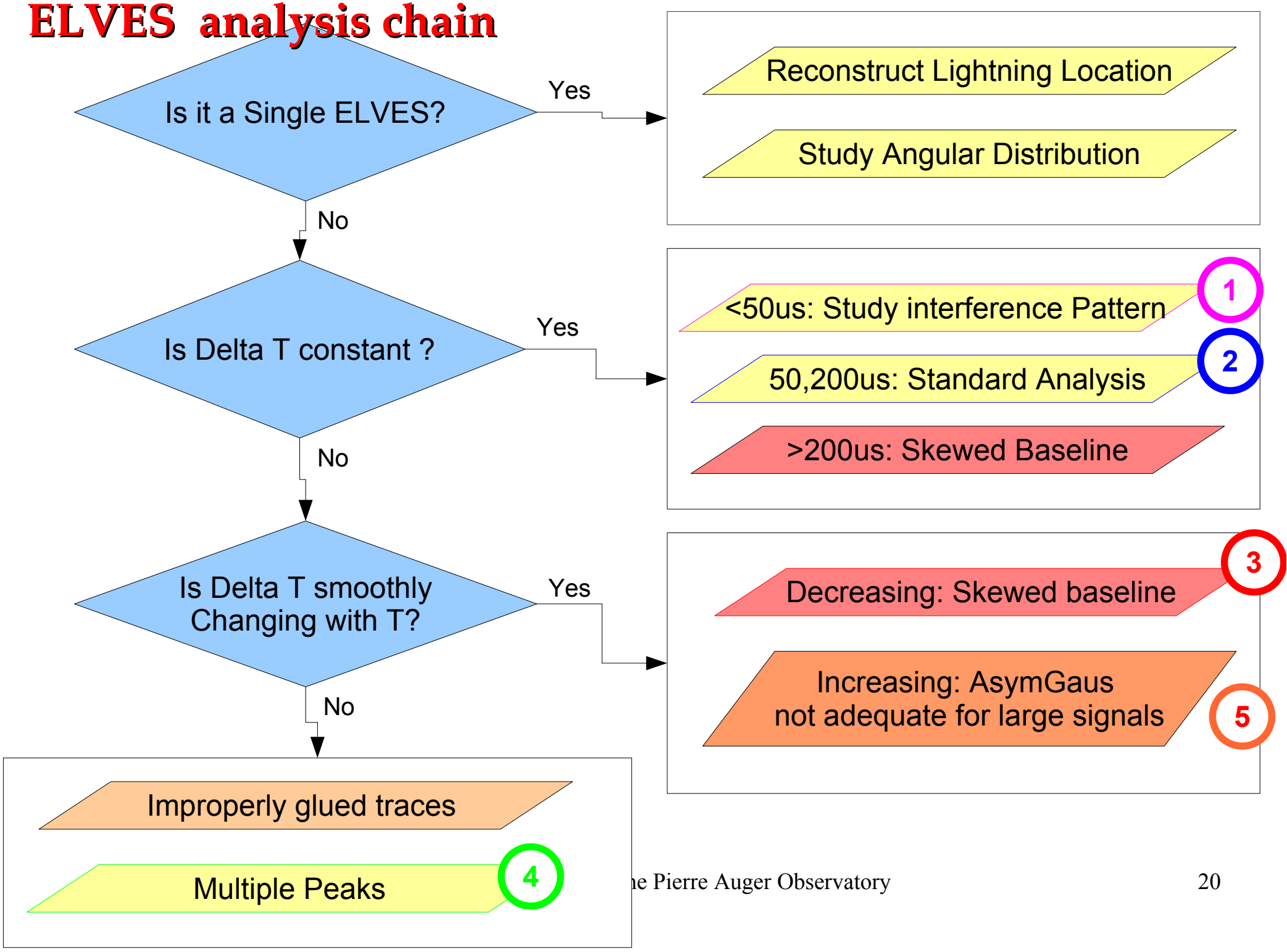
Not simply double return strokes
A rich variety of types, not completely understood. Simulations needed to compare with different models.



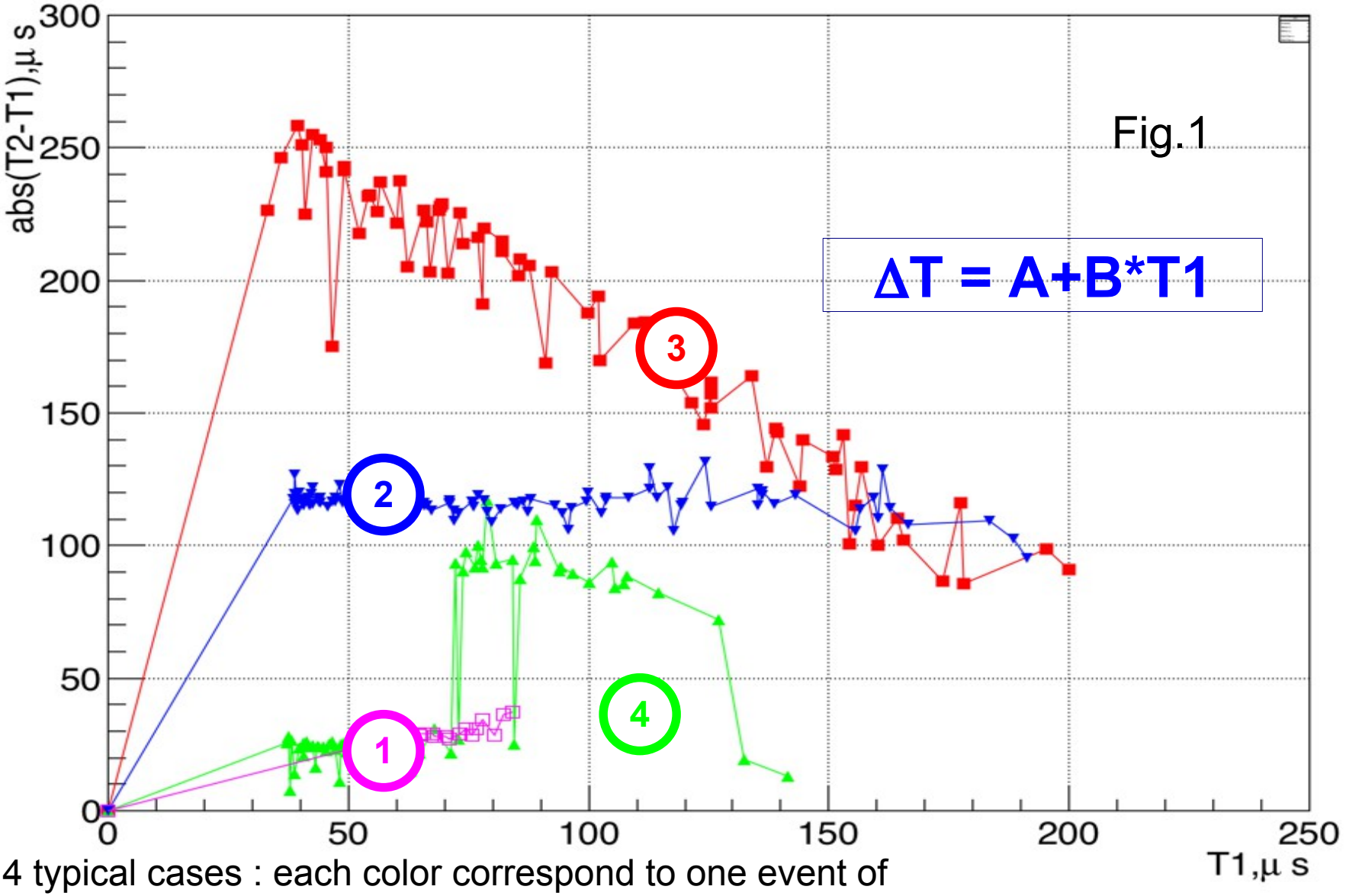




ELVES analysis chain

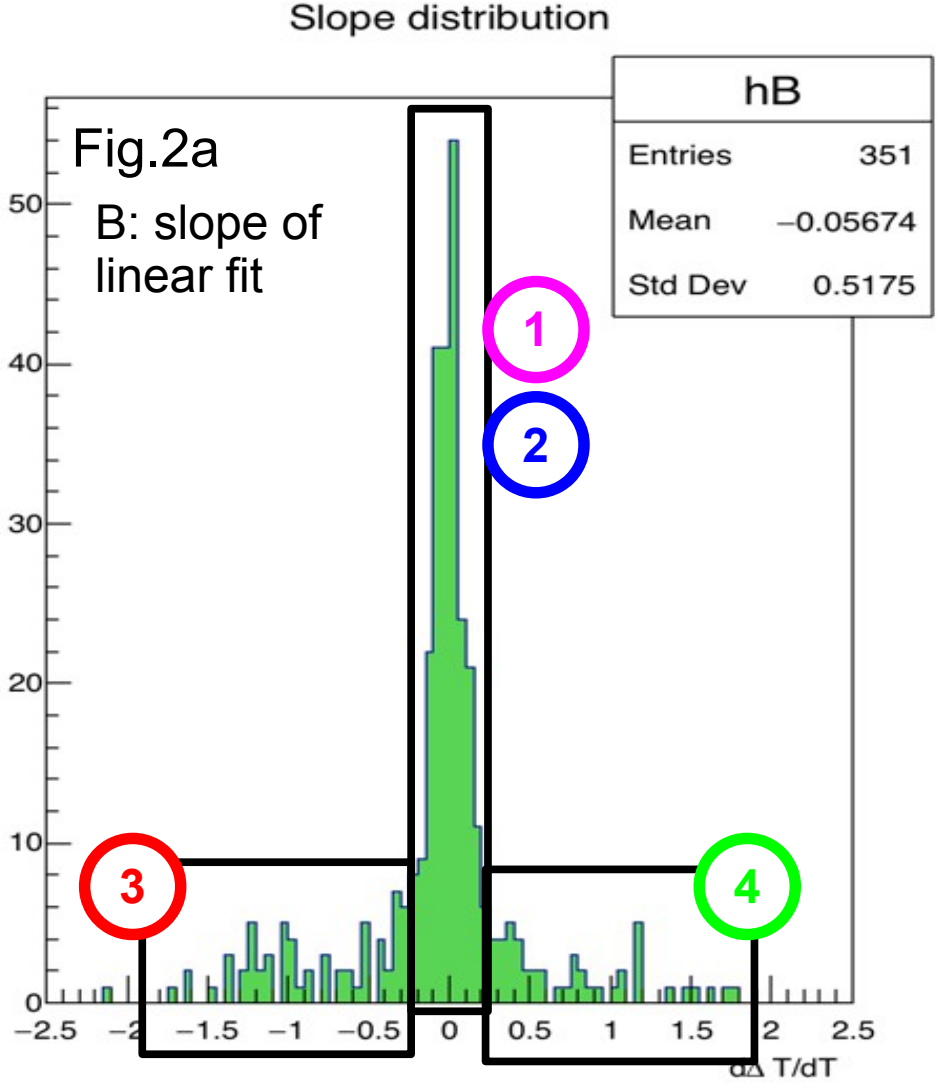


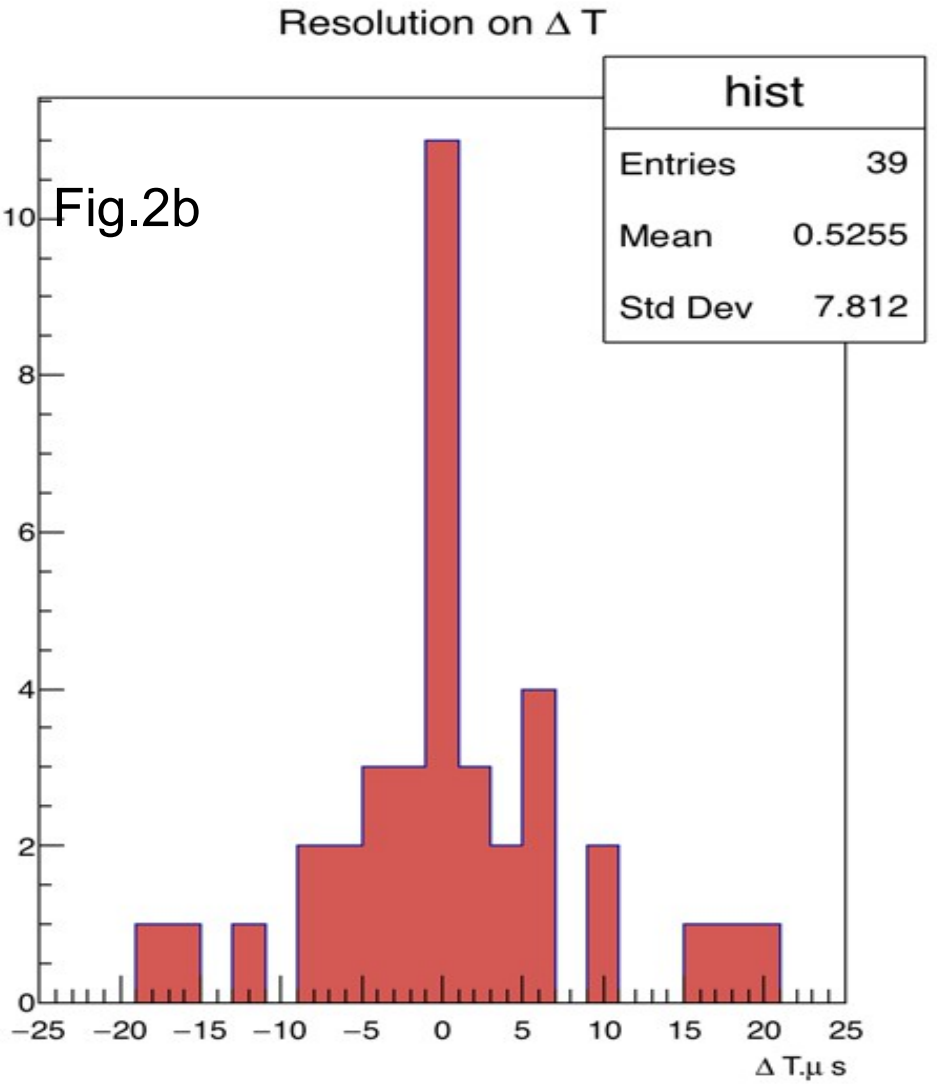
Multiple Elves



4 typical cases : each color correspond to one event of a given category

Study of the Time Gap between two flashes





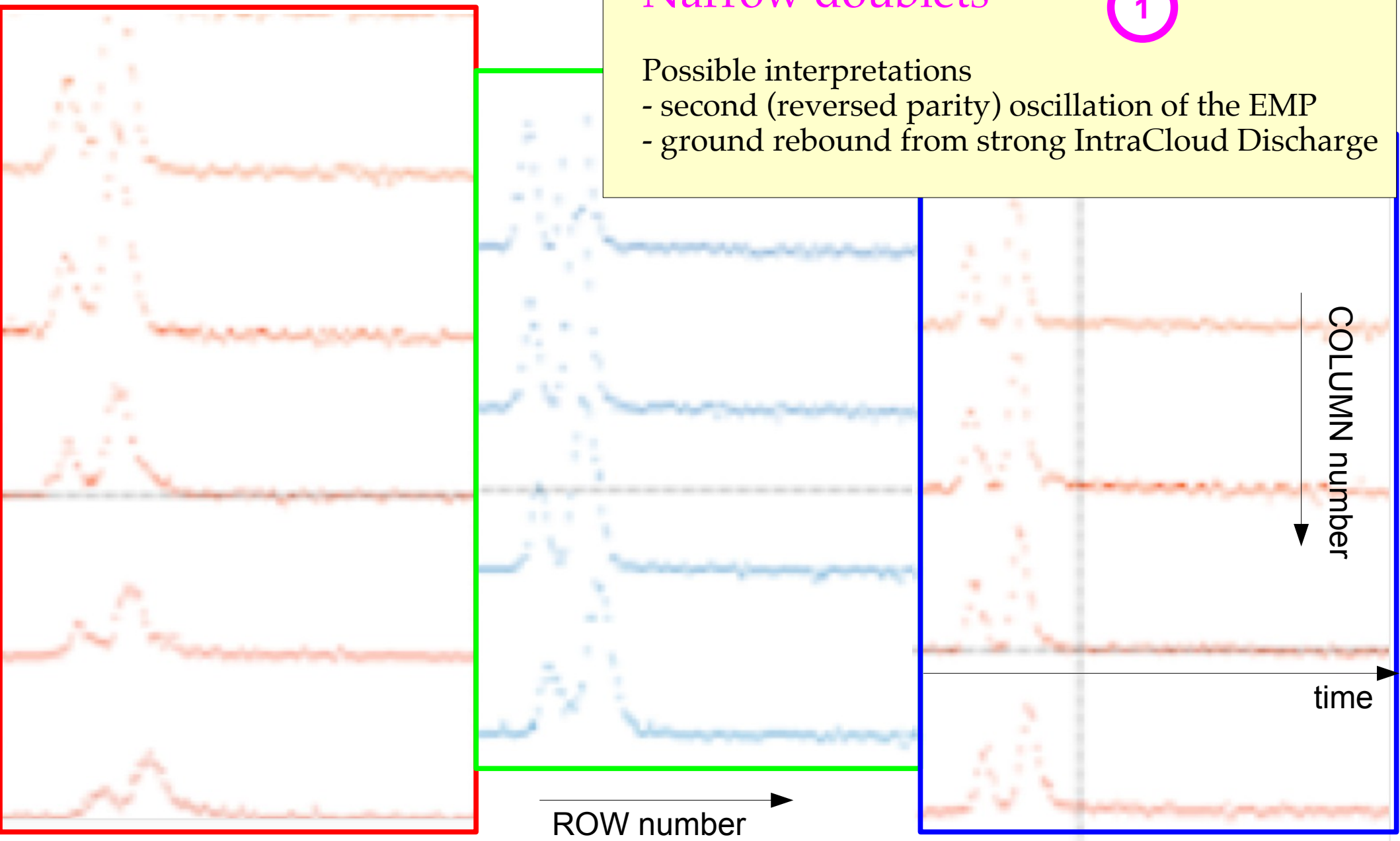
A linear fit is performed on the population of all pixels. Bad values of χ^2 and a bimodal distribution identify the multiple elves events (type 4). Large negative values for the slope B (its distribution is shown on Fig.2a) identify the fake doublets (type 3). The genuine double ELVES (types 1 and 2) are then selected by the requirement |B|<0.02. 39 STEREO and 3 TRIPLET events (out of a total of 270 multiple ELVES events) have been used to estimate the resolution on ΔT in a ELVES doublet candidate (Fig.2b).

Multiple Elves Zoology

Narrow doublets

1

Possible interpretations
- second (reversed parity) oscillation of the EMP
- ground rebound from strong IntraCloud Discharge

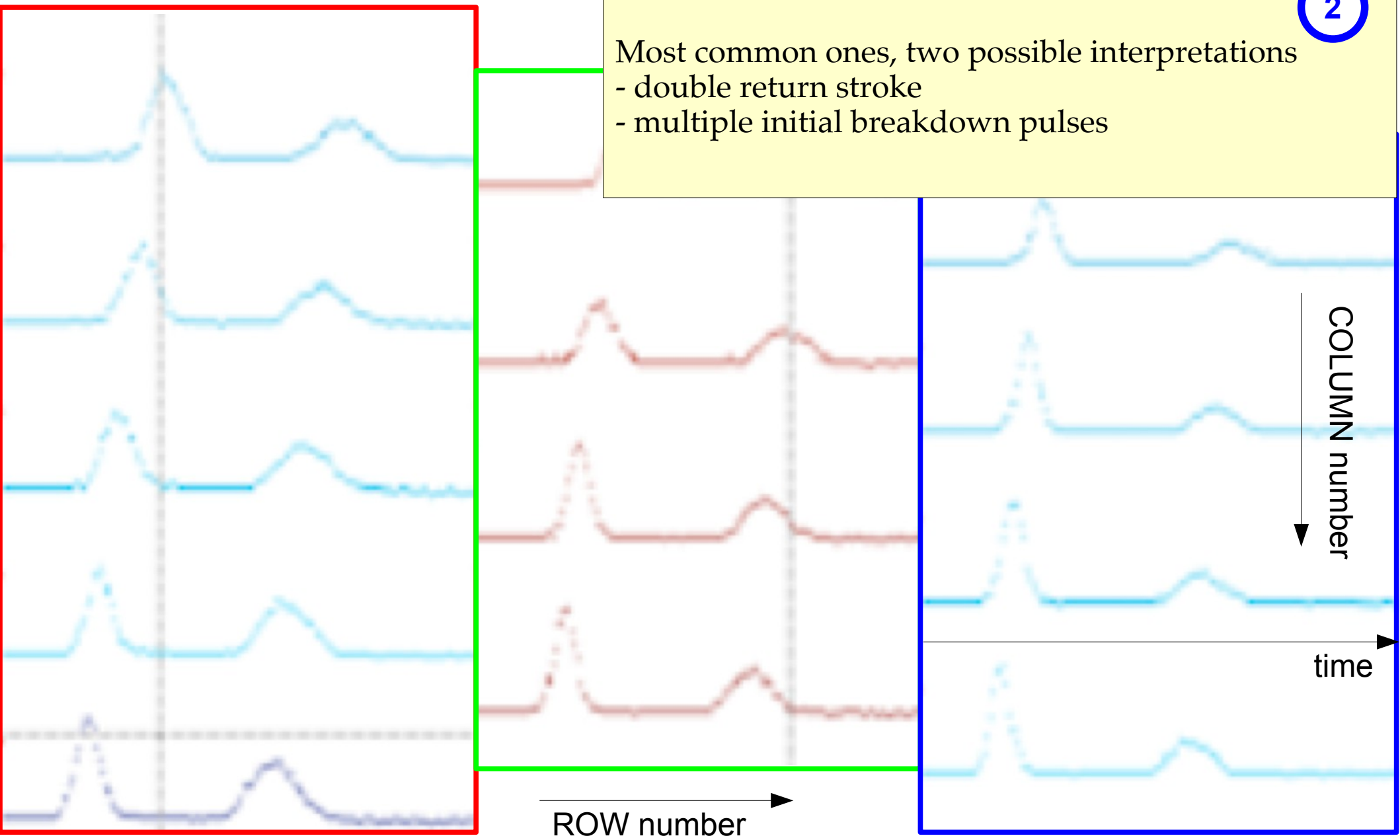


Multiple Elves Zoology

Wide doublets

2

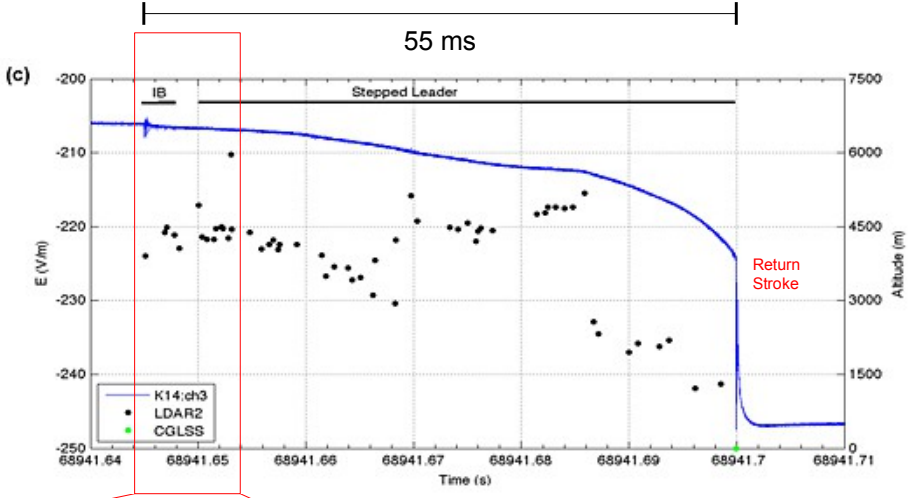
Most common ones, two possible interpretations
- double return stroke
- multiple initial breakdown pulses



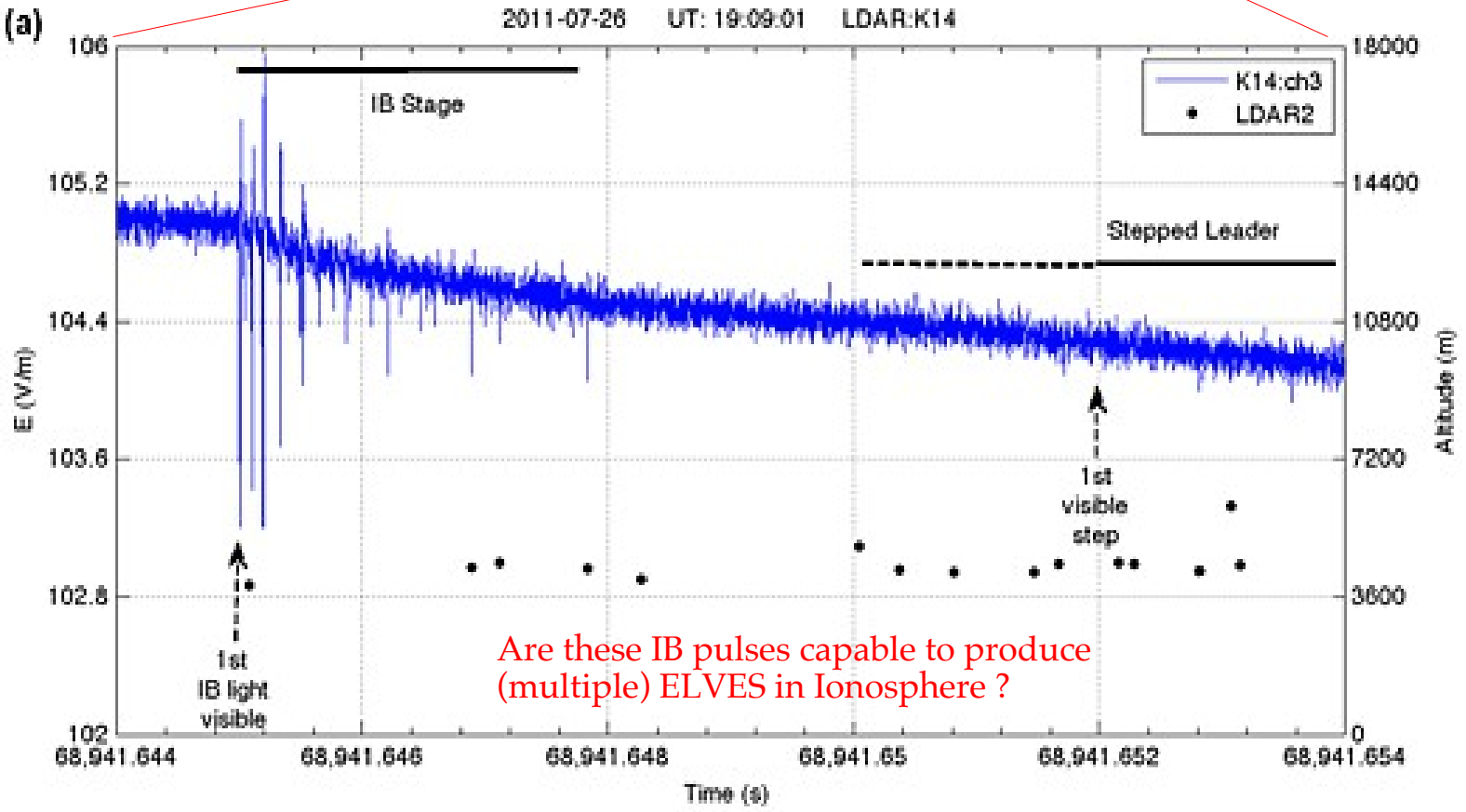
Lightning Initiation in Radio+Visible

Key Points:

- An initial E-change (IEC) occurs just before the first initial breakdown (IB) pulse
- The start of the IEC sometimes coincides with an impulsive VHF source
- Lightning initiation begins with an event that starts the IEC



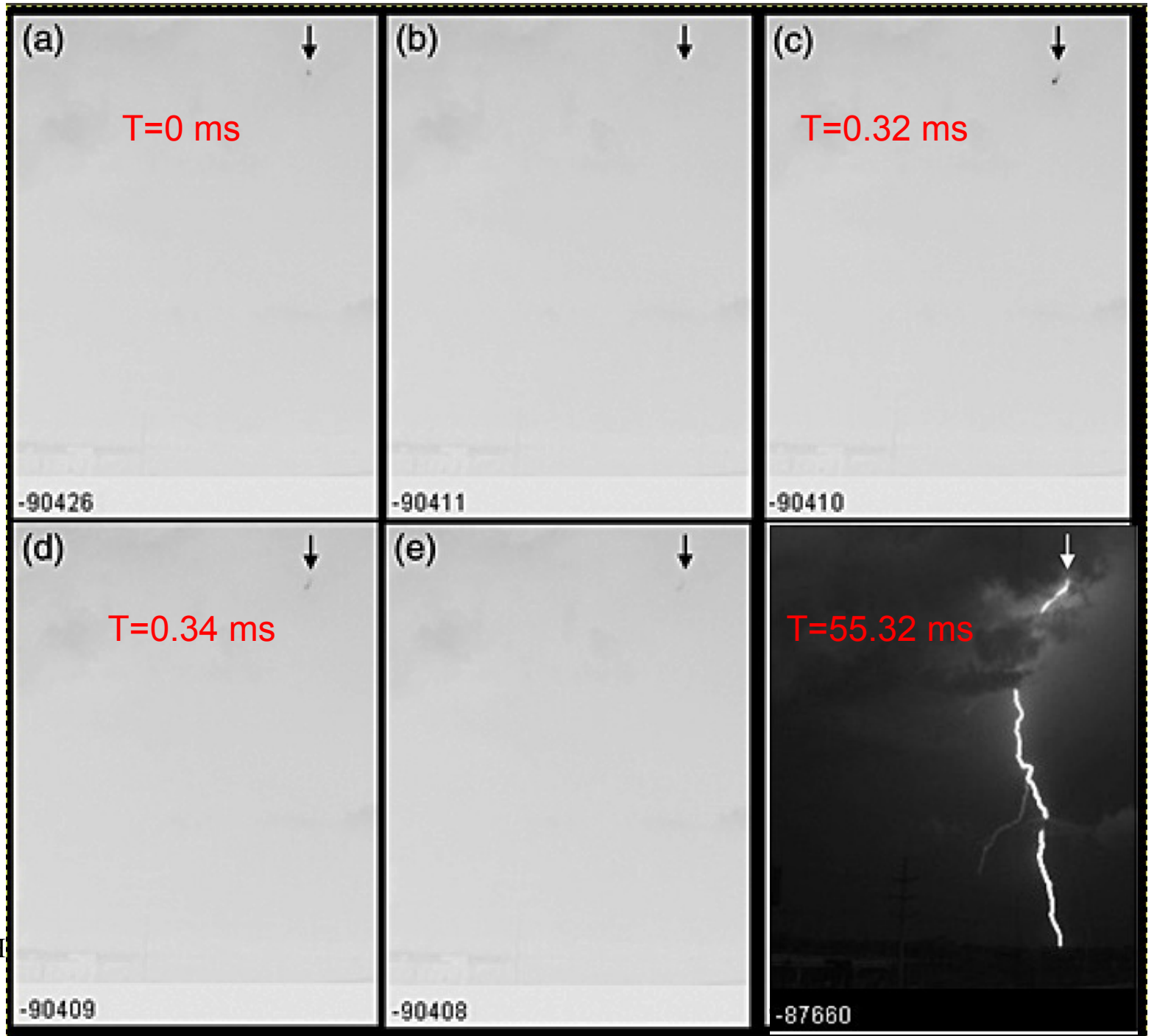
Smith E.M. et al, JGR 123 (2018)2129



Lightning Images with High Speed Camera (50 kfps)

The first 5 images are in negative, the last in positive.

The IB stage is barely visible in (a) , and the stepped leaders start appearing in (c), after 0.32 ms.



Lightning Fractal Structure

N.Liu (Florida Tech)

https://www.youtube.com/watch?v=QUIpltFo_fg

Lightning Fractal Structure

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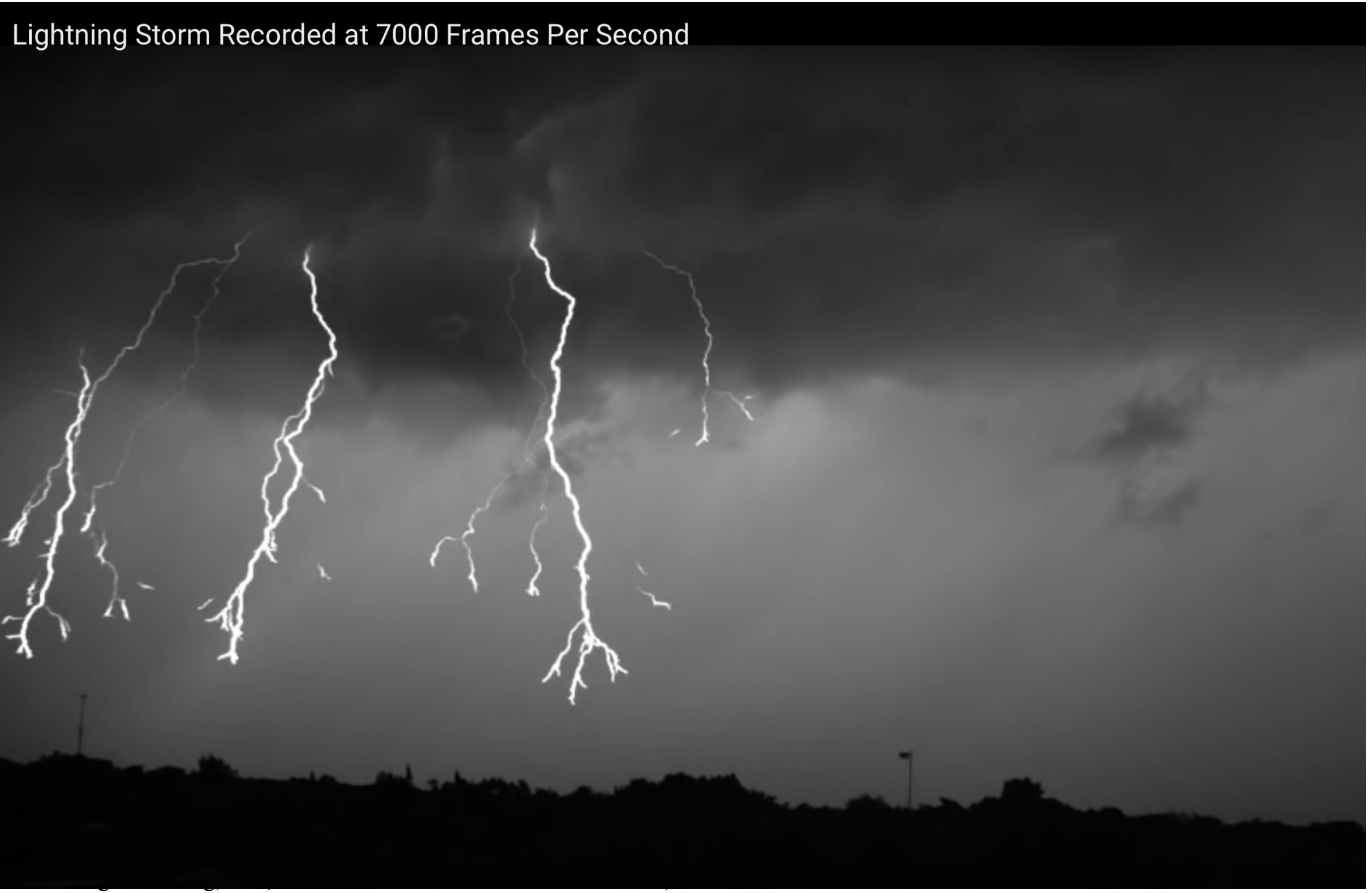

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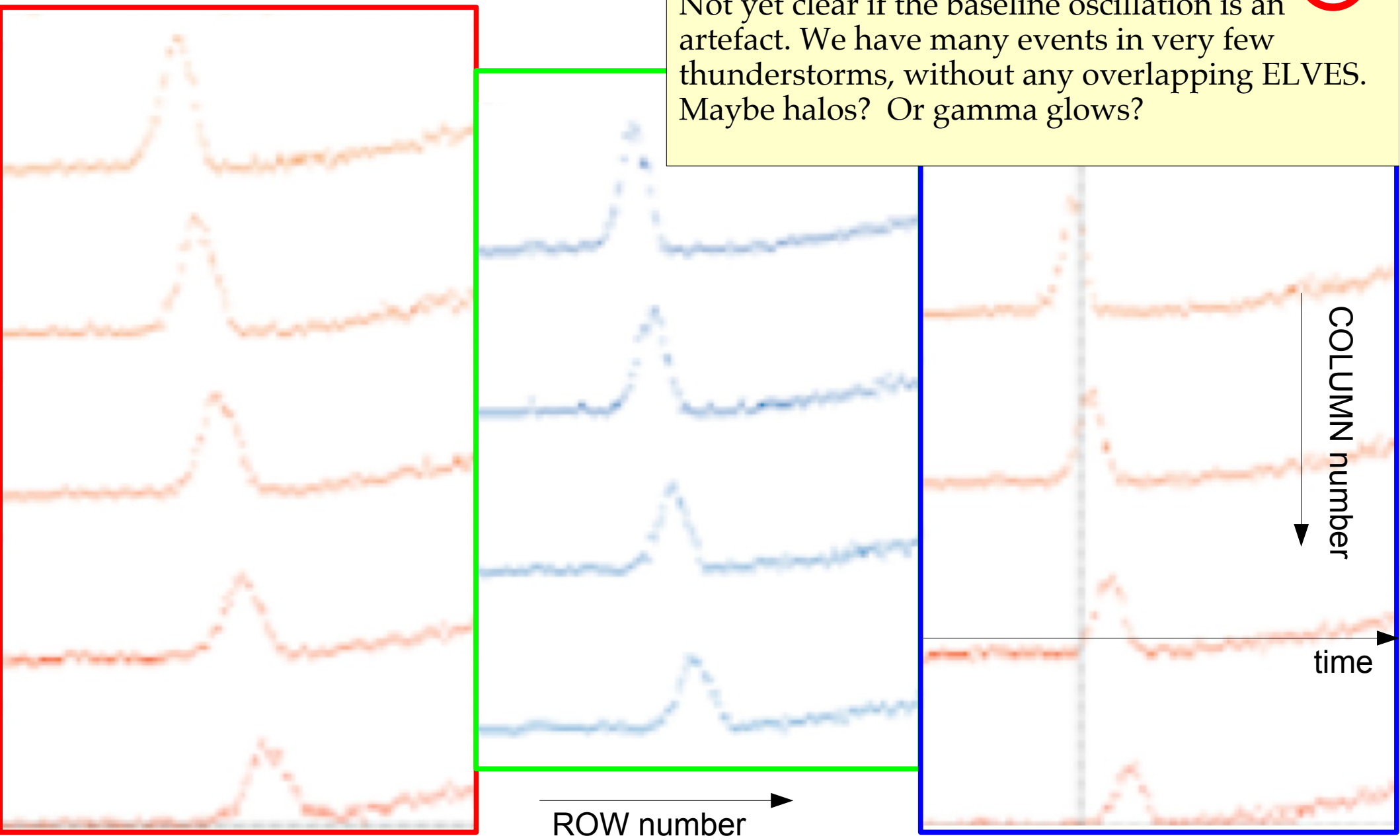
Multiple Elves Zoology

Skewed baseline

3

Not yet clear if the baseline oscillation is an artefact. We have many events in very few thunderstorms, without any overlapping ELVES. Maybe halos? Or gamma glows?

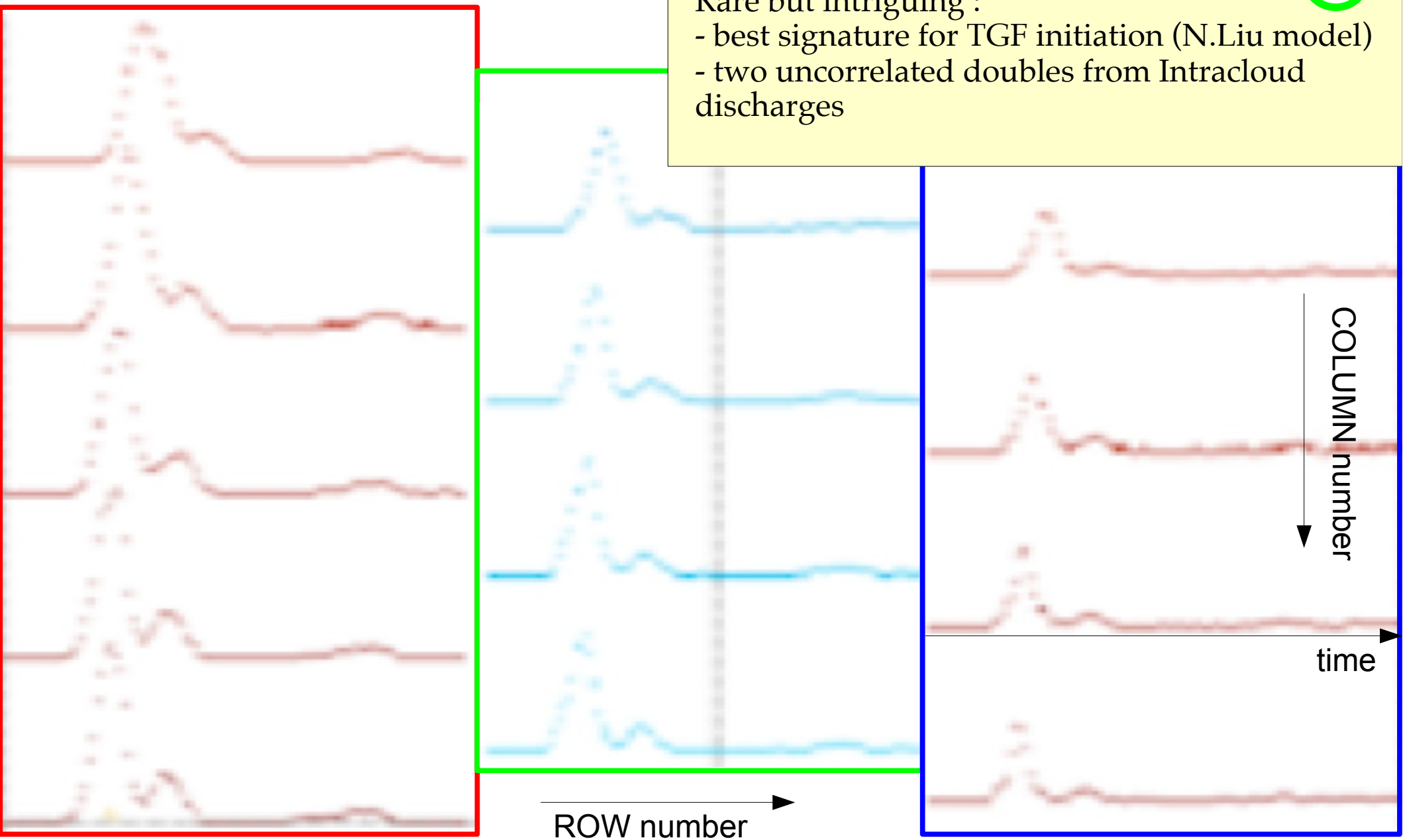


Multiple Elves Zoology

Multiplets

4

Rare but intriguing :
- best signature for TGF initiation (N.Liu model)
- two uncorrelated doubles from Intracloud discharges

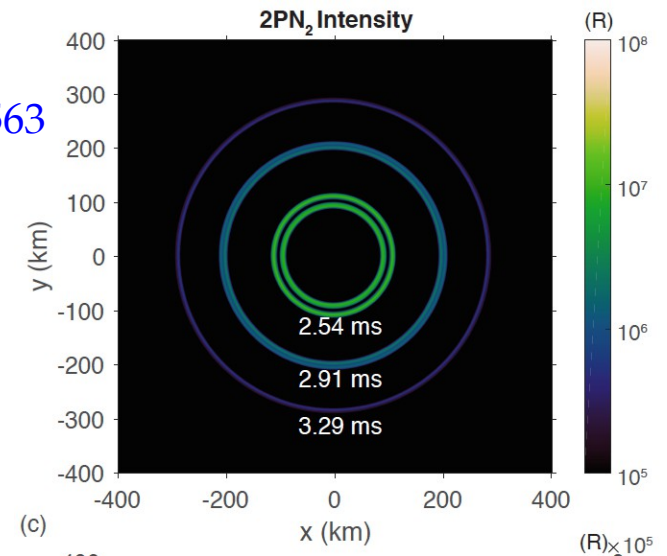


TGF signatures: multiple ELVES

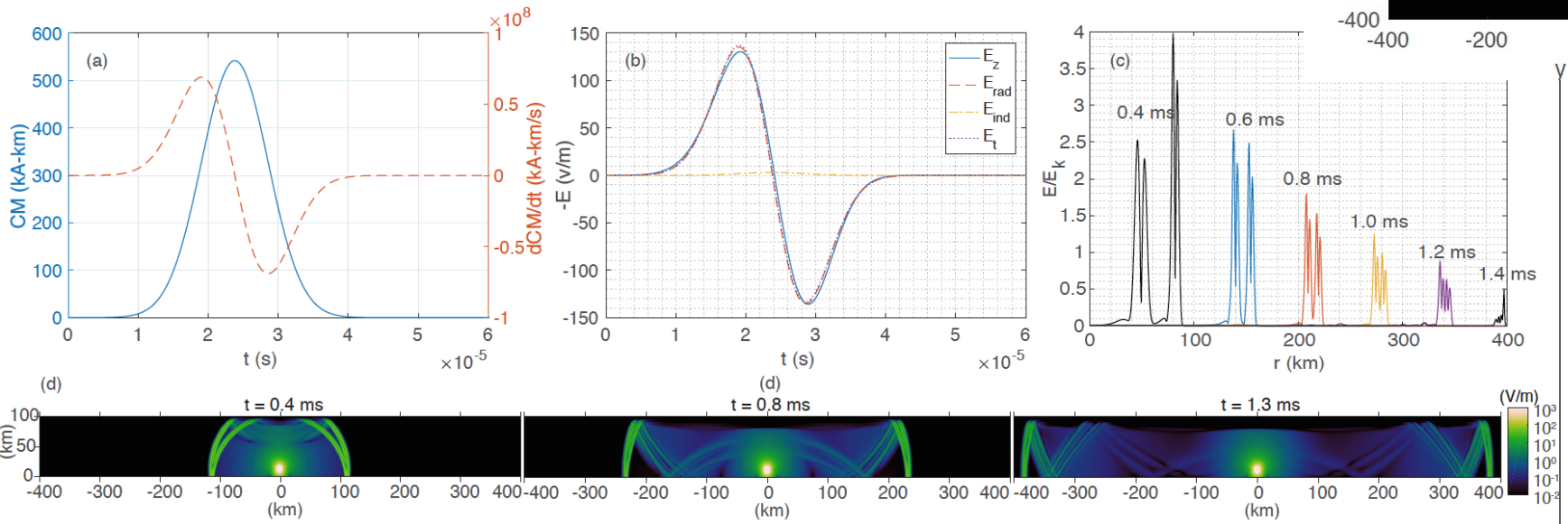
Liu et al, JGR 122(2017)10563

Can we detect TGF ignition at ground with the associated TLE?
What are its spectral properties?
What's its pulse duration?
Sources:
- NBE (Narrow Bipolar Events)
- EIP (Energetic In-cloud Pulses)
- CG (Cloud to Ground Lightning)

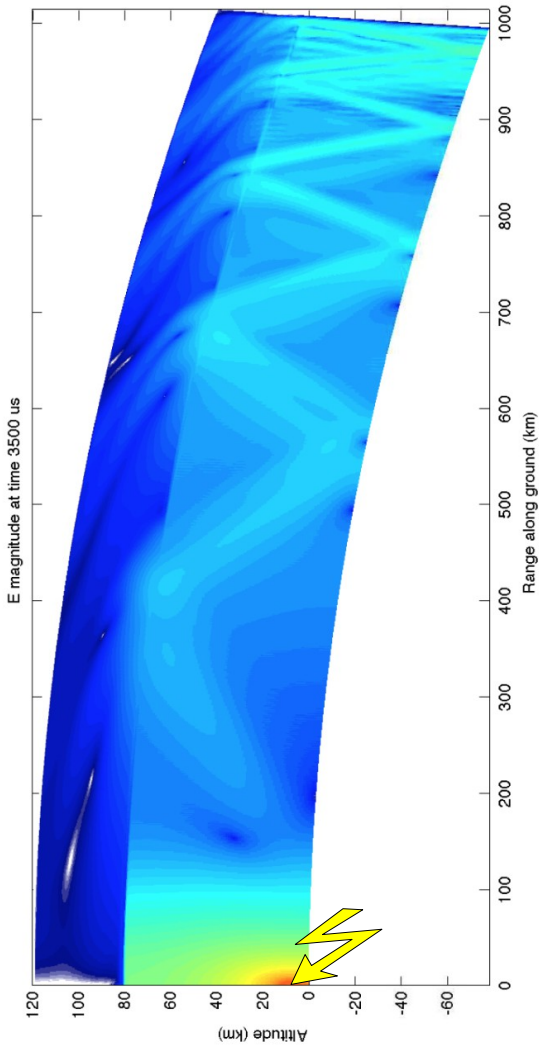
Pulses with peak currents of > 500kA can result in Multiple ELVES with light emissions in UV up to 10 MR are modeled.
Second peak originates from reflected wave on earth surface



EMP Produced by an Impulsive EIP



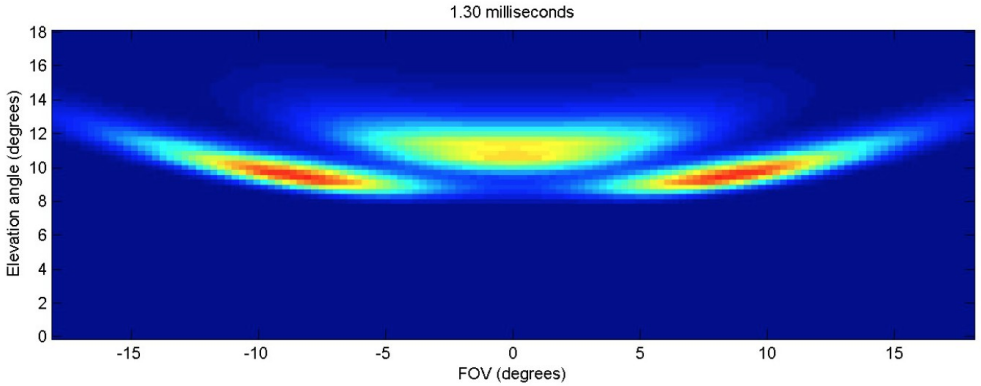
ELVES simulations



Lightning EMP model and interactions with Lower Ionosphere studied by the Stanford VLF Group

Finite element simulations of EM fields in atmosphere (from 70 to 150 km) to produce 2D and 3D models of light emission

Matlab and C++ simulations by K.D.Merenda (Colorado school of Mines) in collaboration with R.Marshall (now at U.Colorado, Denver)
- https://github.com/ram80unit/empmodel

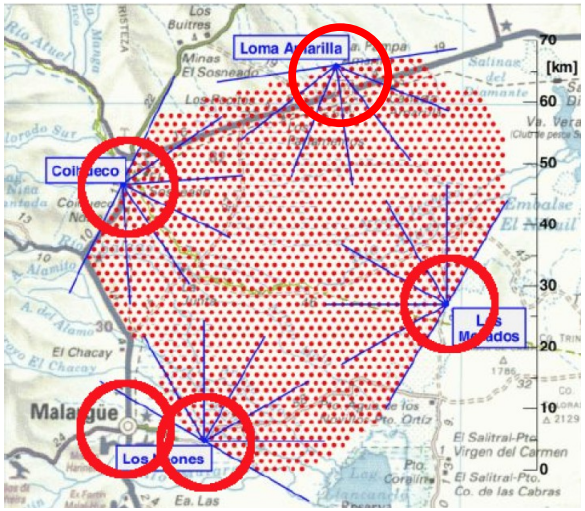


More instrumentation

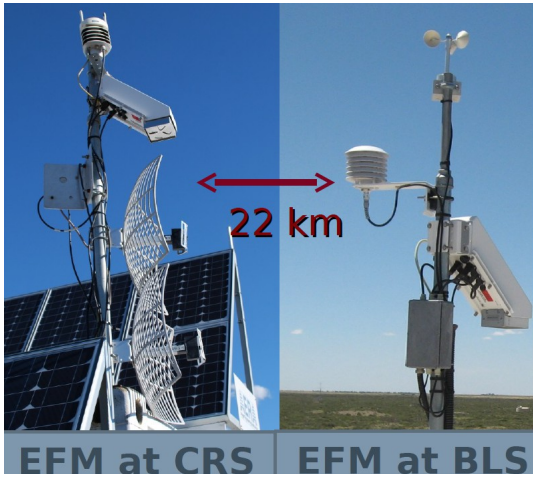
Recently started to work on data acquired with the lightning network installed on-site (AERA group) :

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

Locations:



- 2 E-field mills
Campbell Scientific CS110



Summary and prospects

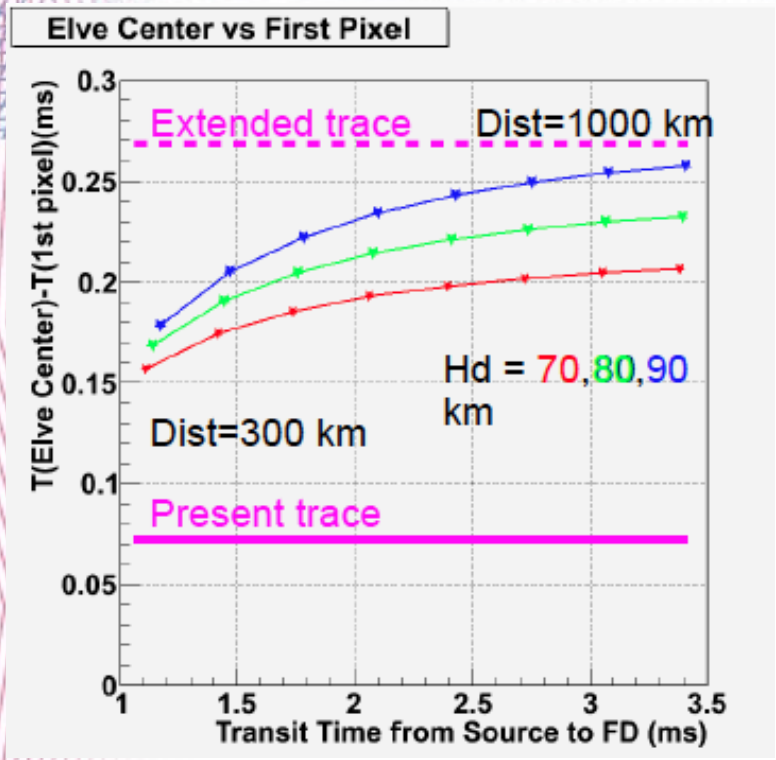
Since 2013, Auger Observatory has a very intense program of studies on ELVES using the Fluorescence detector. Since 2014, more than $4x10^3$ triggers have been acquired in extended readout mode, to record light up to 872 μs (272 before 2017) after its first appearance: a special trigger allows to extend the standard traces, in order to study the light emission from the vertical above the lightning , where we expect to see a decrease in light intensity.

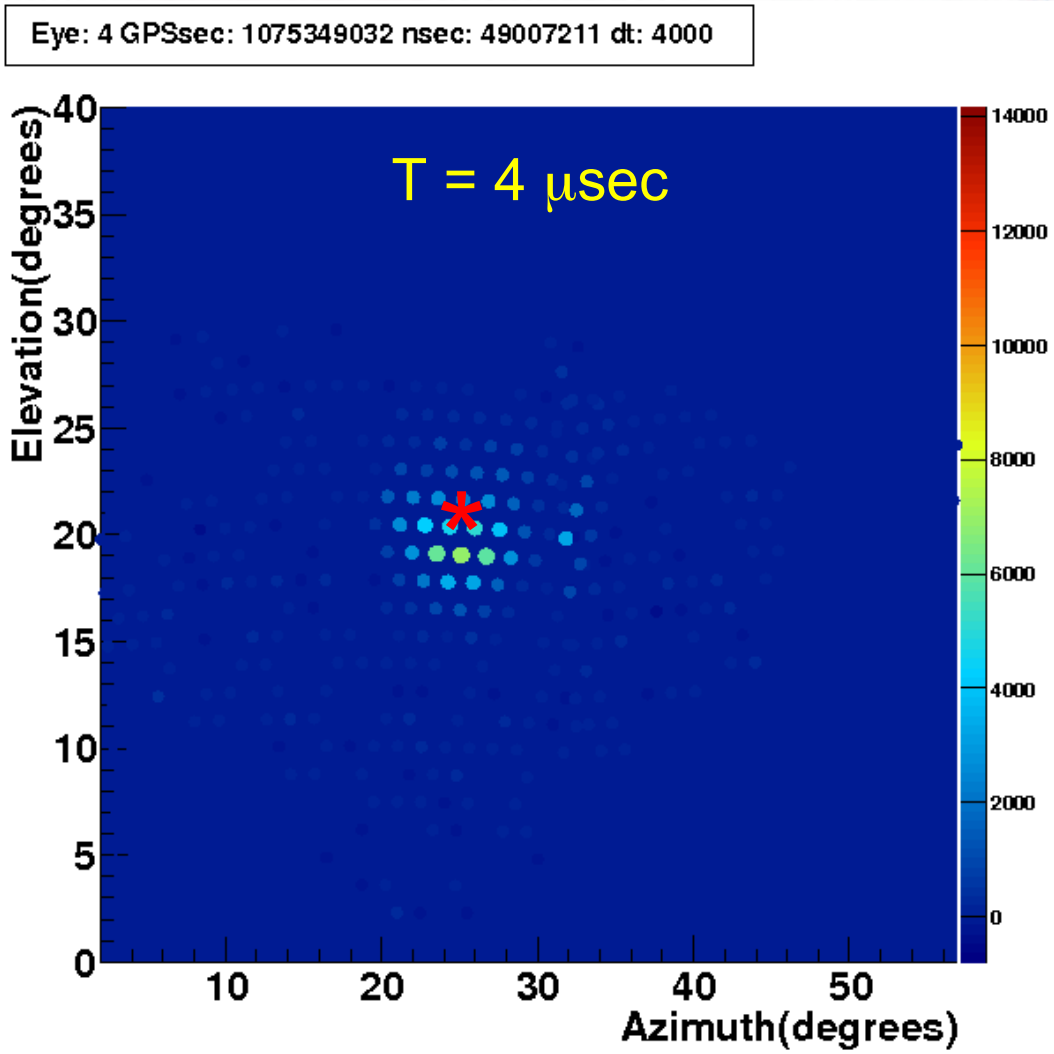
A strategy for selection and classification of multiple elves events has been optimized, and quantitative results will be available in the near future. Comparison with EMC signals recorded by a local lightning network will provide a better understanding of the physical mechanisms leading to the multiple elves generation.

After performing geometry and atmospheric corrections we can compare our results with WWLLN measurement of lightning energy to check correlations with light emission. The simple idea of a vertical or horizontal dipole emission is being compared with available data. Only a small fraction of our data seem to fit simple models.
We are planning to further upgrade the elves trigger in the future months, to increase its efficiency, based on the experience harvested in these first five years of running.
A public web page with all elves data is in preparation at INFN Torino

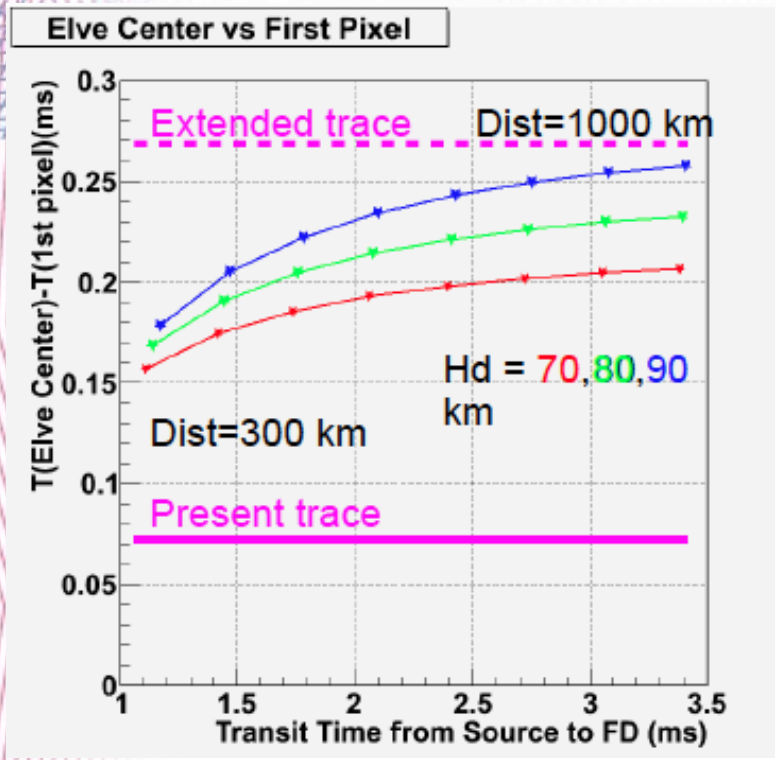

Thank you!

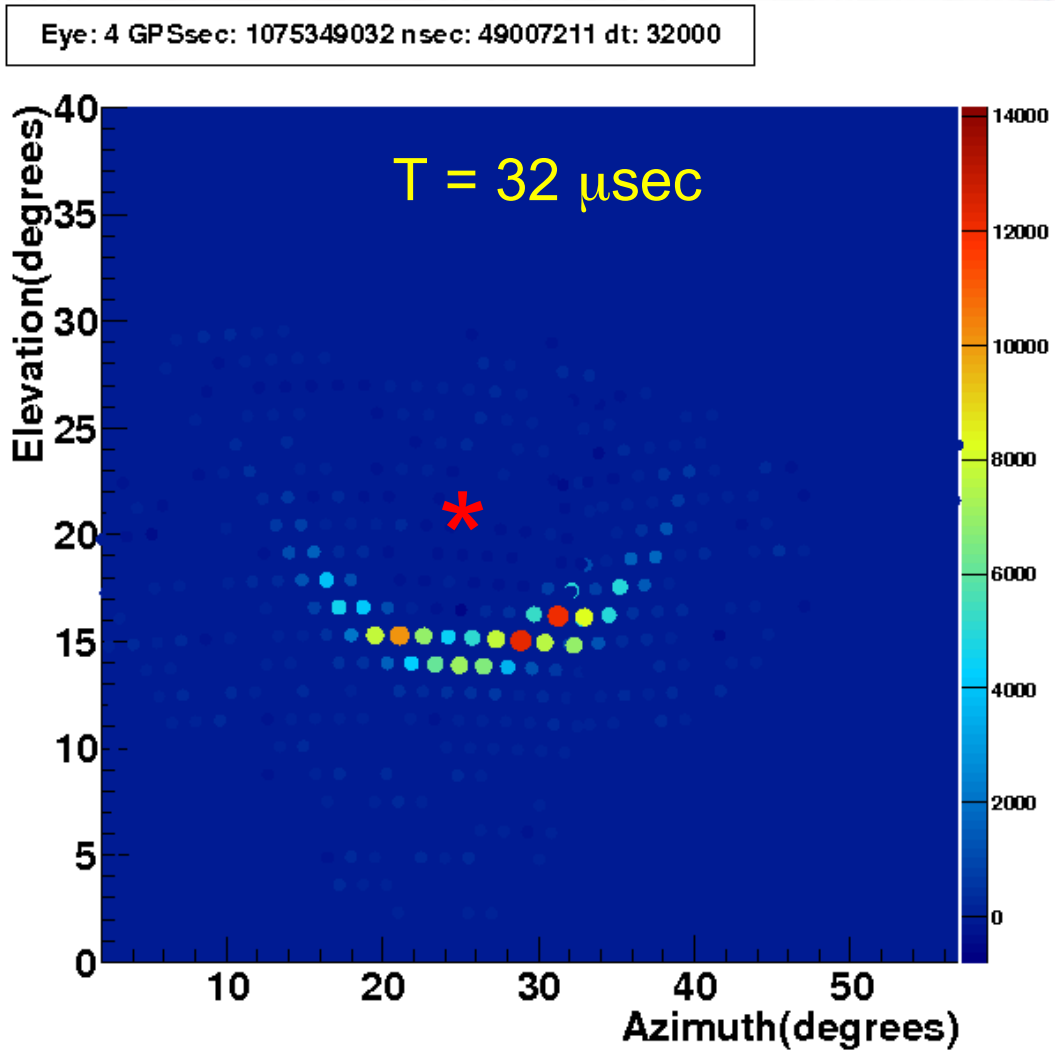
Extended readout



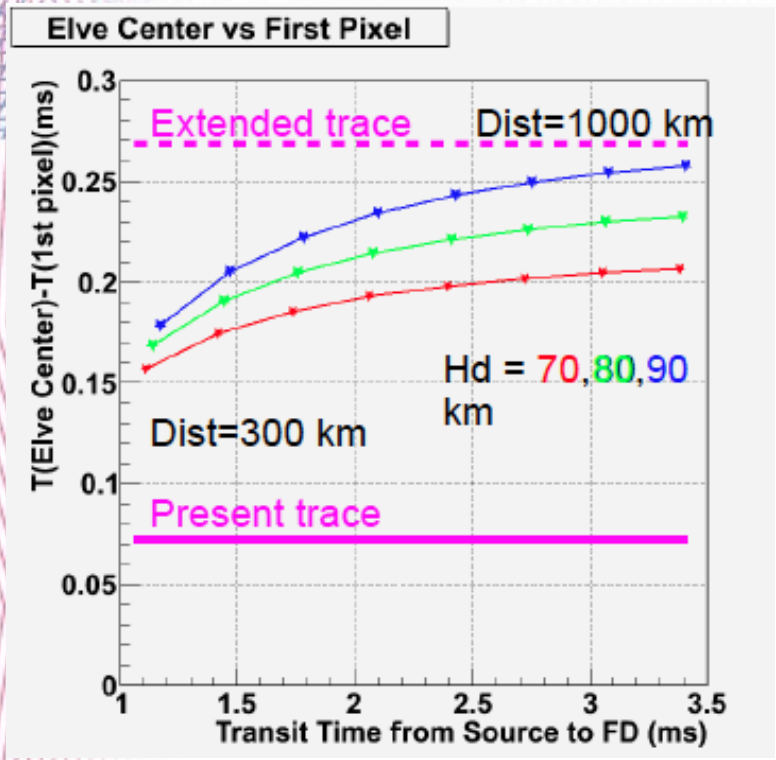


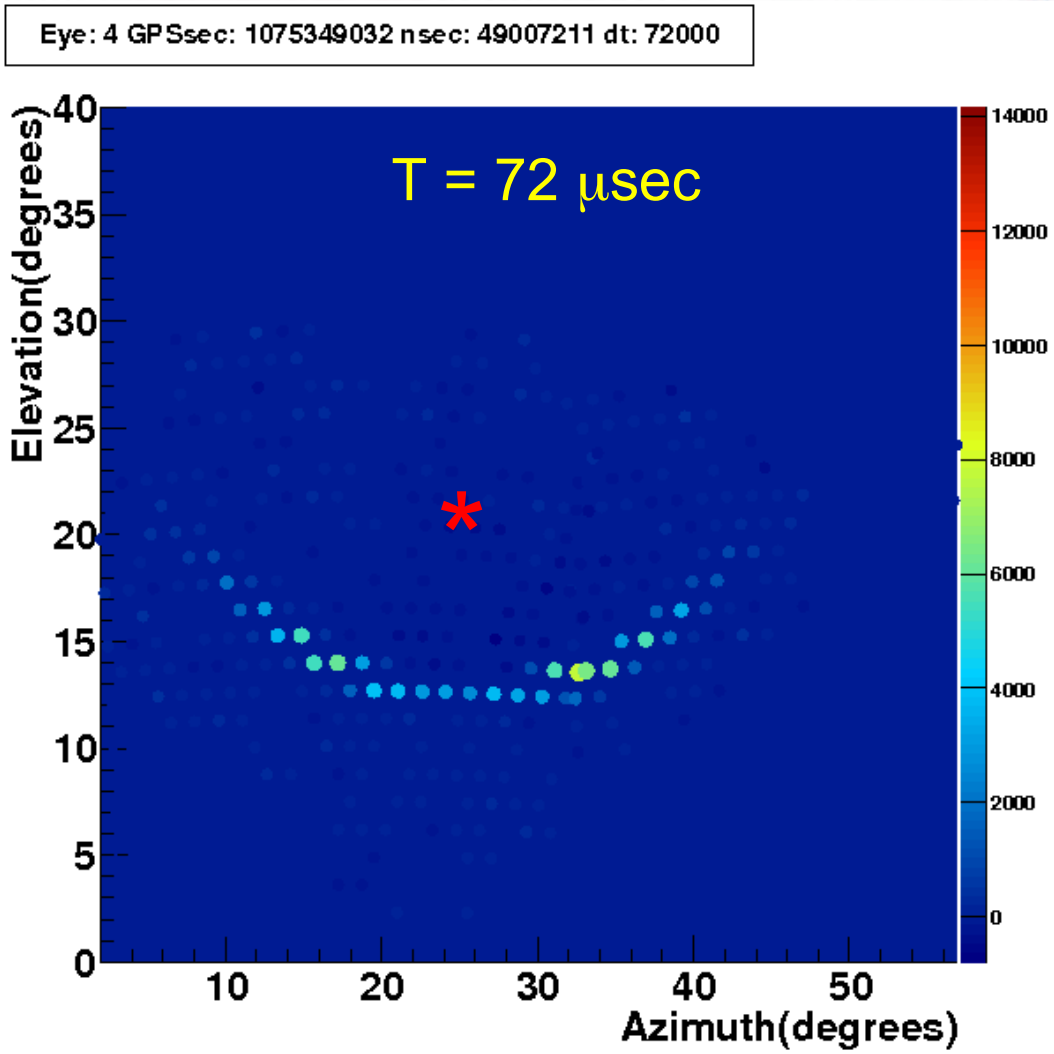
Extended readout





Extended readout





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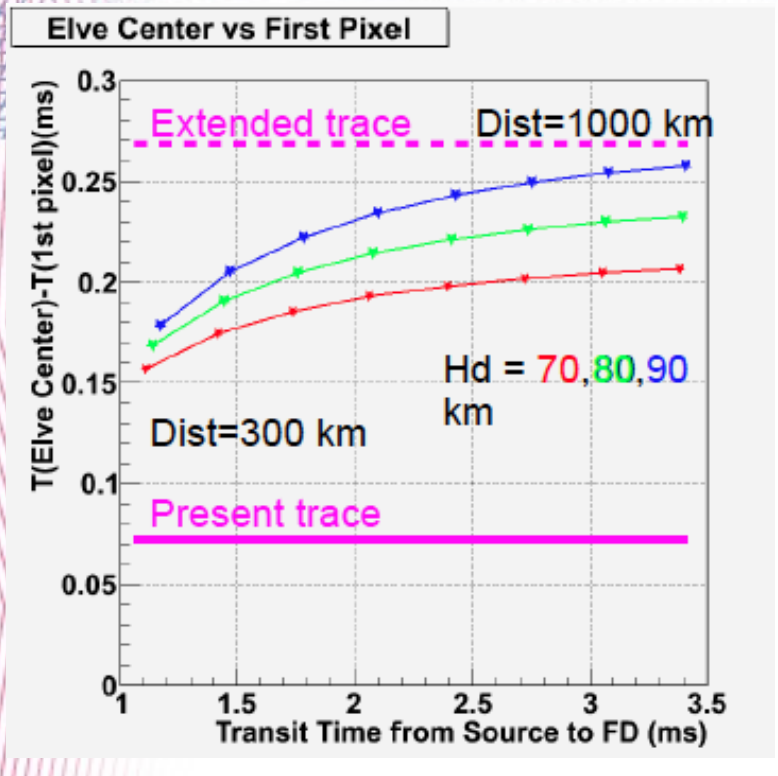
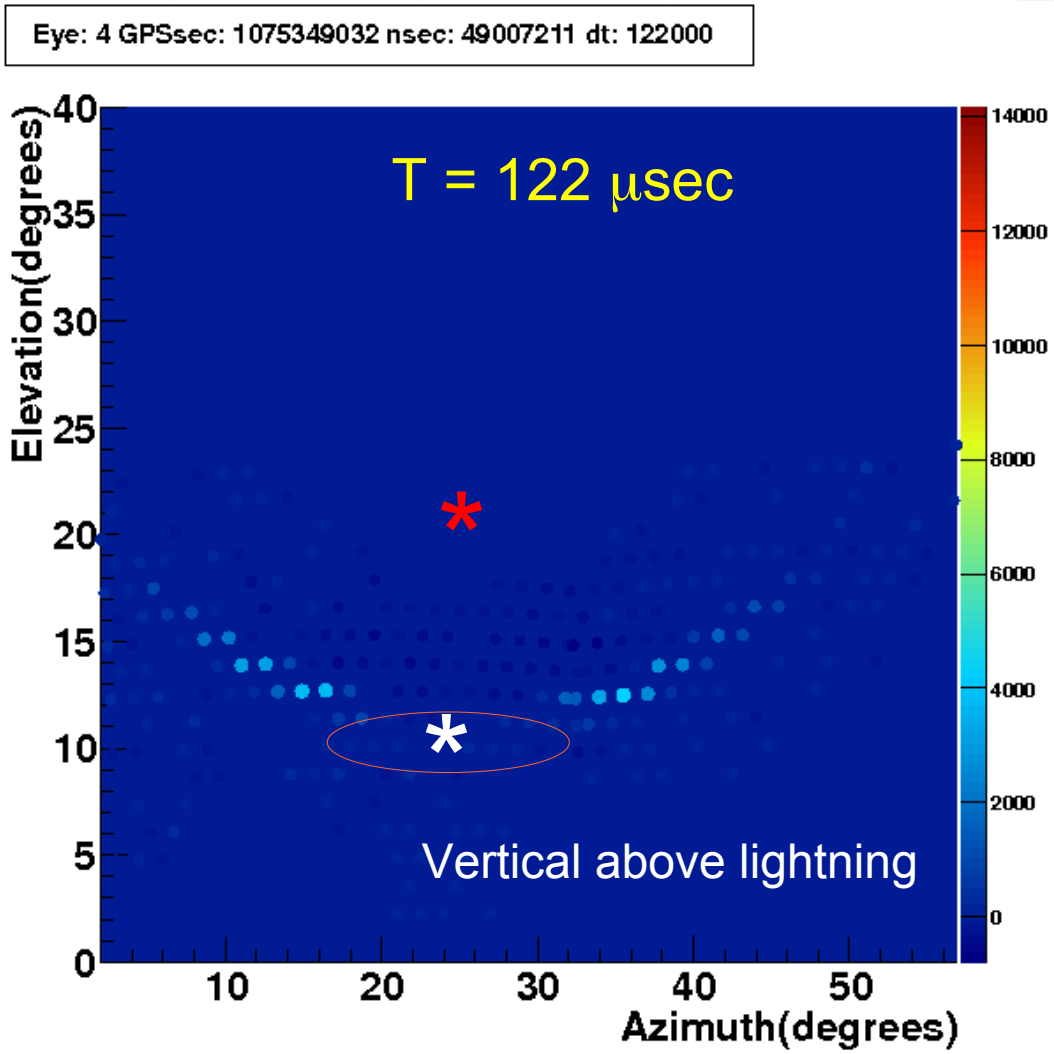
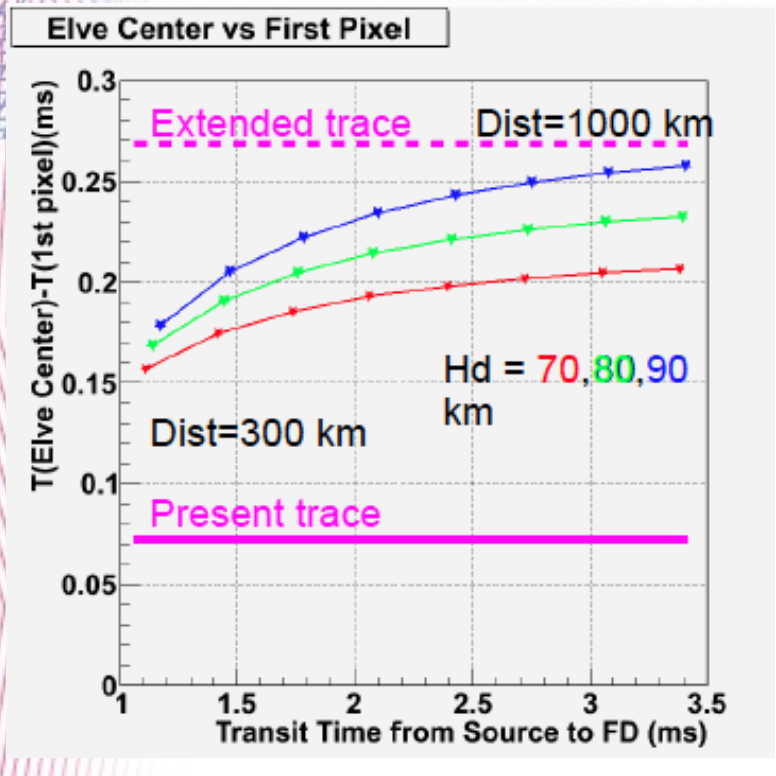
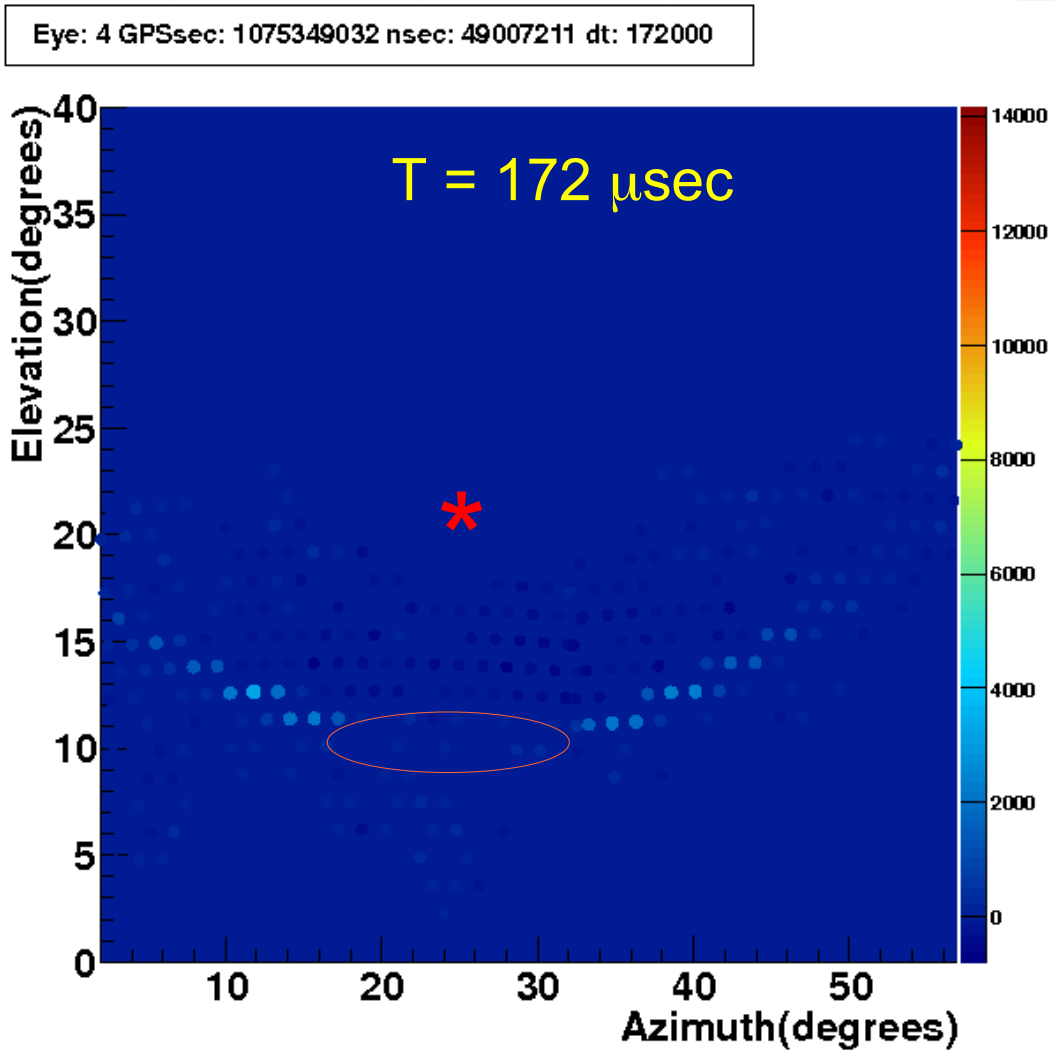




Extended readout





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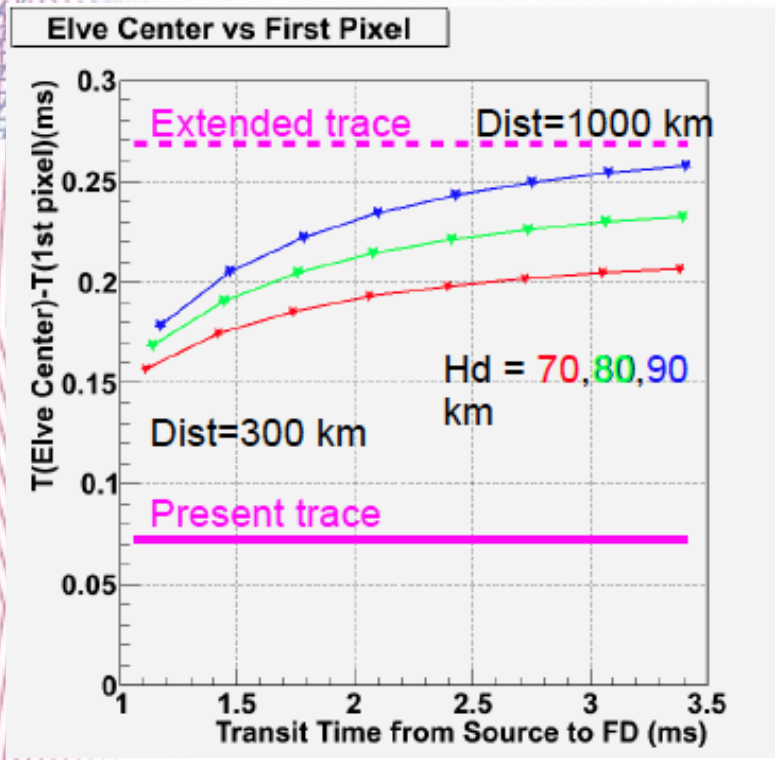

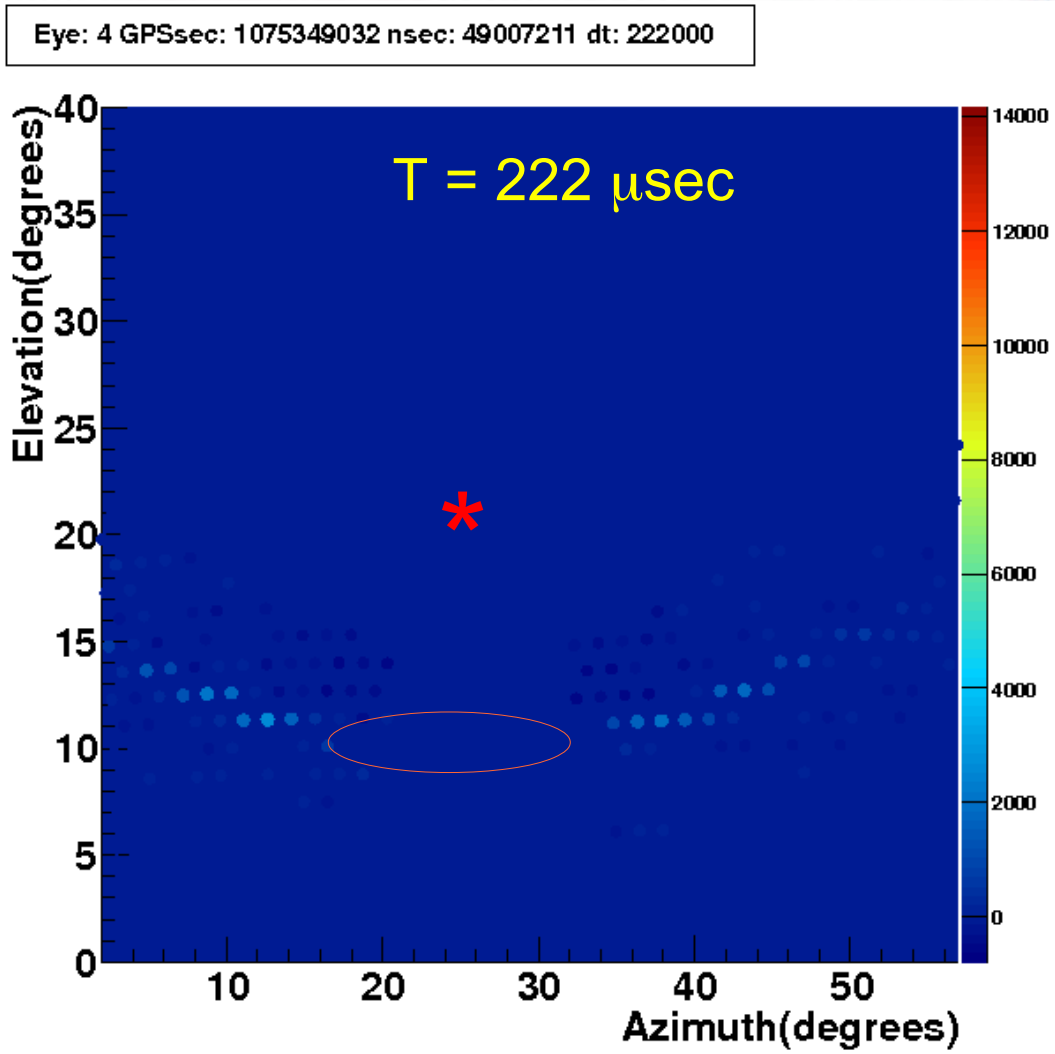

Extended readout