# Atmospheric effects on UHECR signals:

- molecular density and pressure on shower development

- molecular density, pressure and humidity on fluorescence yields

- aerosol and molecular density on light propagation

Open questions:

- impact of large electric fields inside thunderstorms on EAS evolution, and on polarization radio signals

- role for UHECR in lightning initiation ?

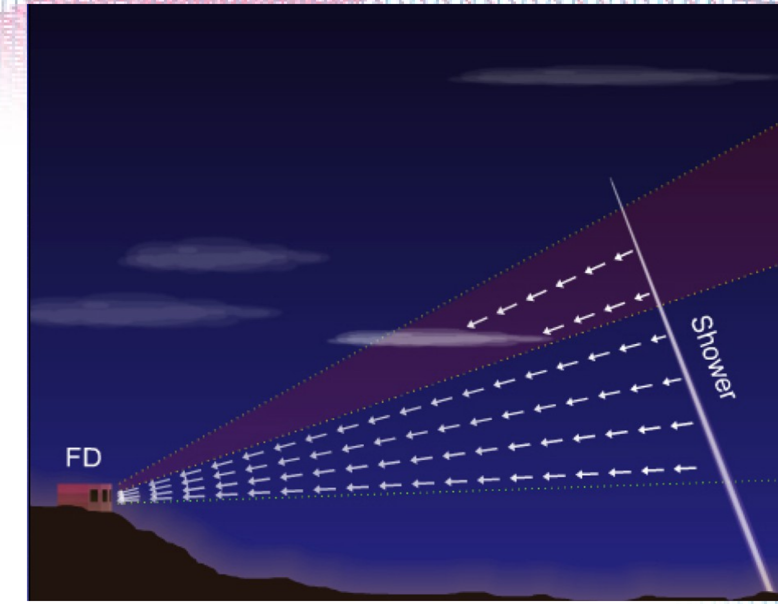
- *"background"* from lightning

*Transmission:* $T(x) = e^{-\tau}$

*Optical Depth (OD):* $\tau = \int_0^X \alpha(r)\, dr = \tau_{molec} + \tau_{clouds} + \tau_{aerosol}$

*Attenuation coefficient:* $\alpha = \sigma * N(x)$

*Attenuation Length:* $\Lambda = 1/\alpha$




Photons emitted at the passage of the shower:

$$\frac{dN_{em}}{dX} = Y(P,T,h)\frac{dE}{dX}$$

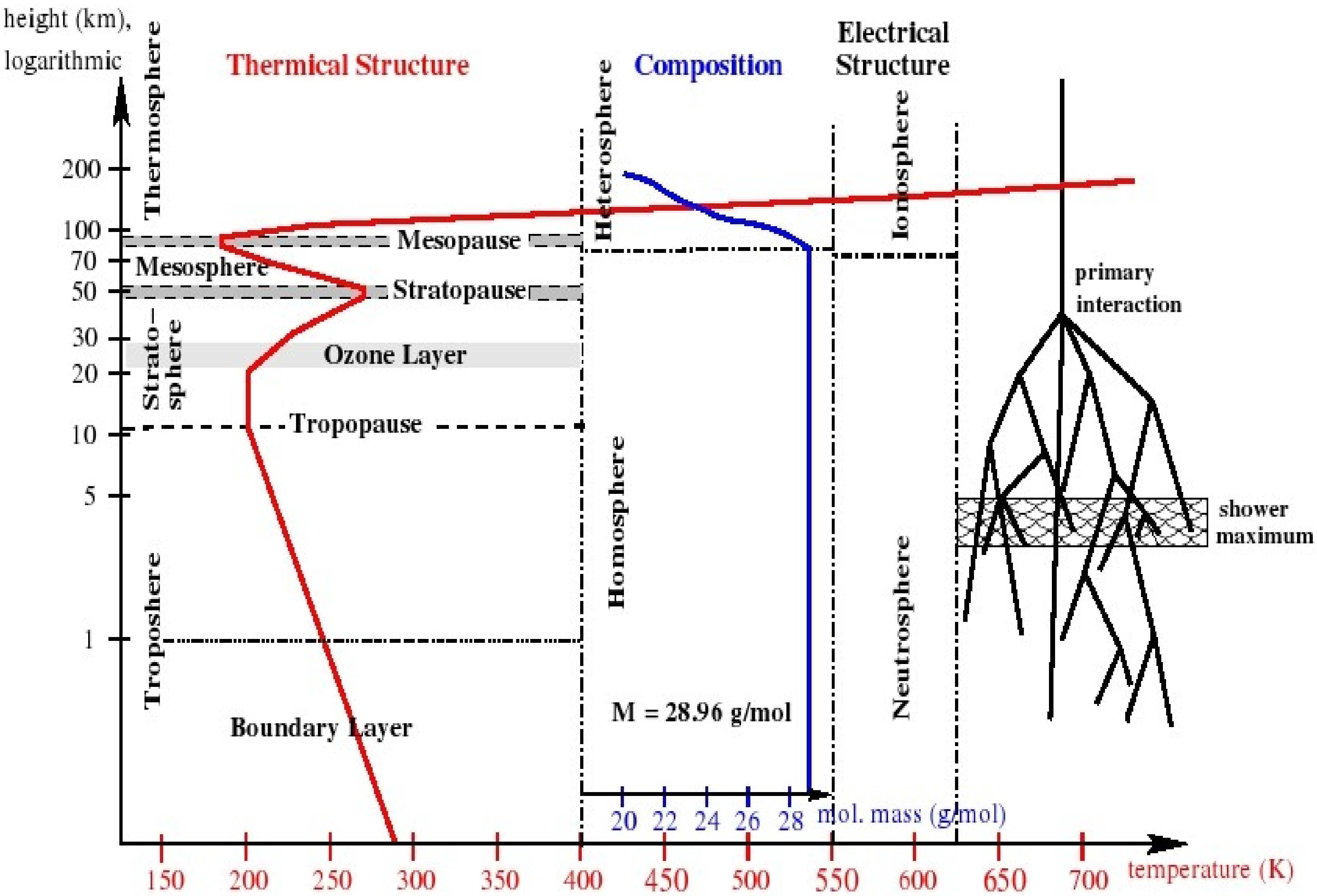
Y(P,T,h) : Fluorescence Yield (see Arqueros)

Grammage : $X(h) = \int_h^\infty \rho(z)dz$

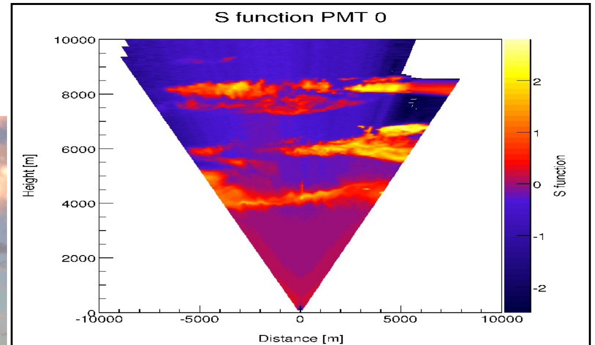
Photons arriving at FD window:

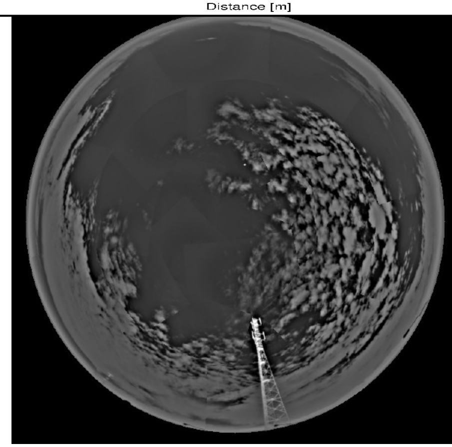
$$\frac{dN_{FD}(x)}{dX} = \frac{dN_{em}}{dX} T(x) \frac{A_{FD}}{|x|^2}$$

# Our atmosphere



# Atmospheric Monitoring Devices in AUGER




Optical properties of atmosphere require continuous measurements

*Molecular Measurements*
- Weather Stations
- Radiosonde

*Aerosol Measurements*
- Central Laser Facilities (CLF,XLF)
- LIDARs
- Photometric Robotic Telescope (FRAM)

*Cloud Measurements*
- LIDARs
- IR Cloud Cameras

# Cosmic Ray rates in single SD tanks

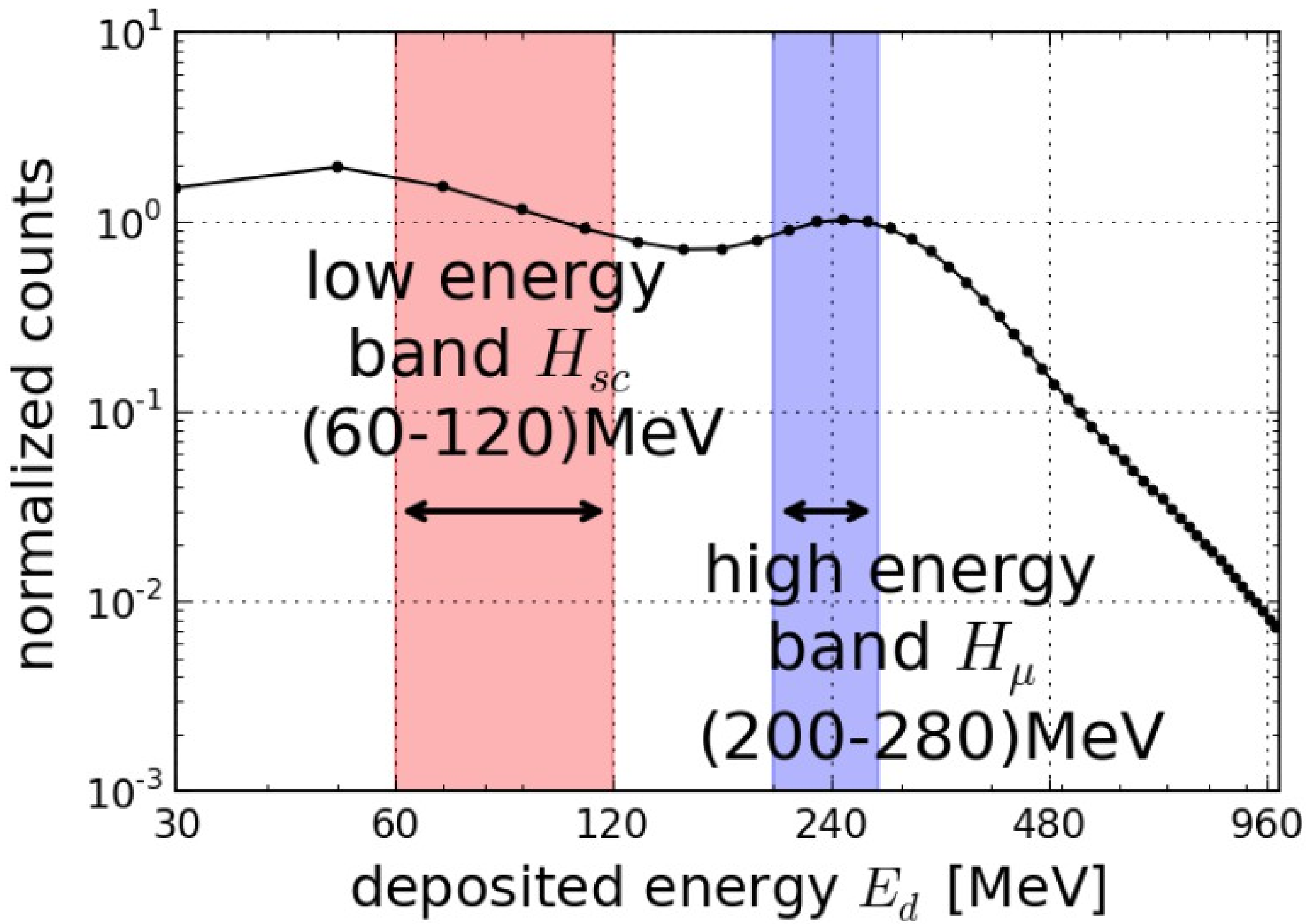
Scaler mode:

Total (1600 tanks):
$1.8 \times 10^8$ counts/min

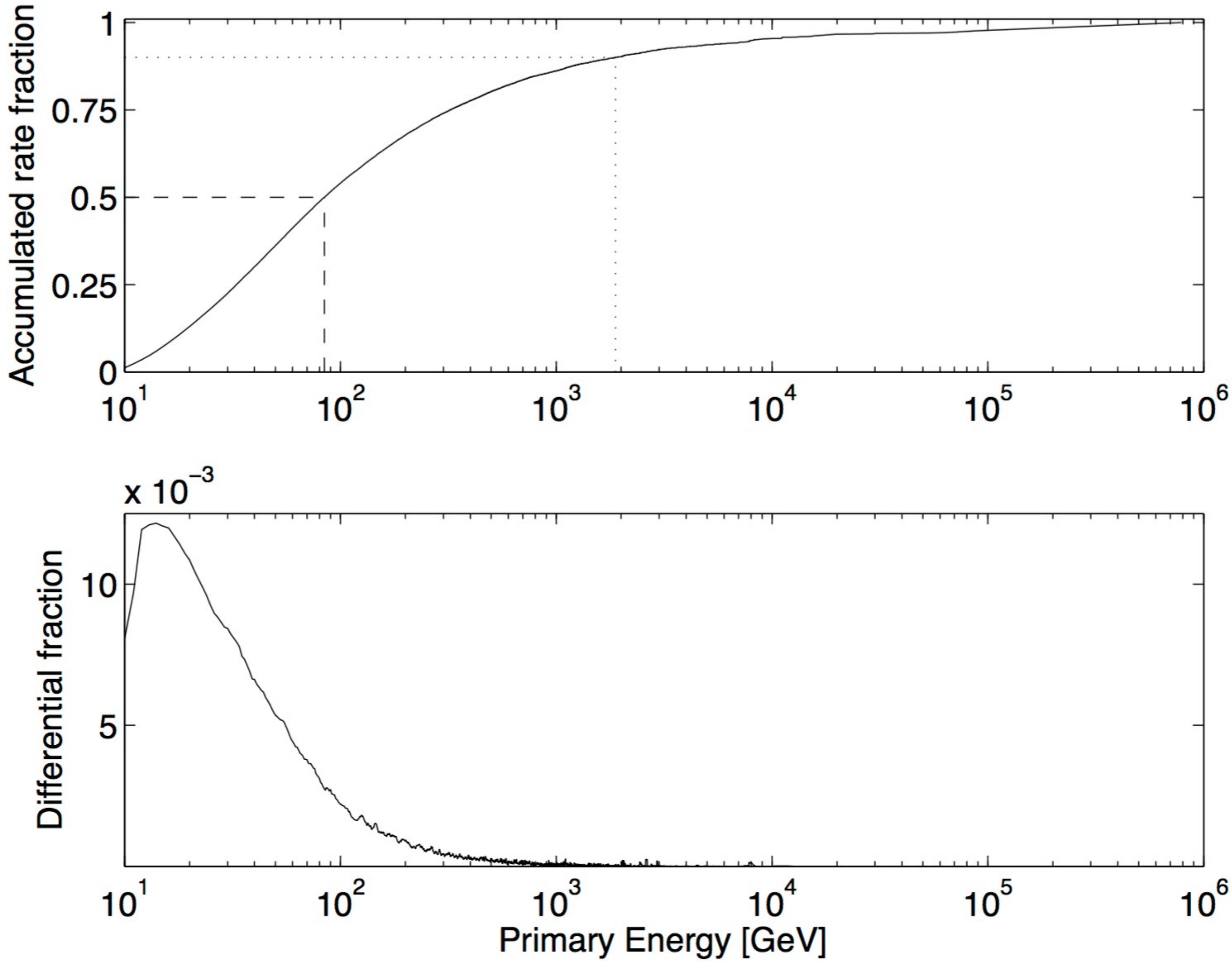
Rates per tank:
~ 2kHz/tank, i.e. 200Hz/m$^2$

The band between
3 and 20 ADC counts
corresponds to
15-100 MeV Energy deposit.

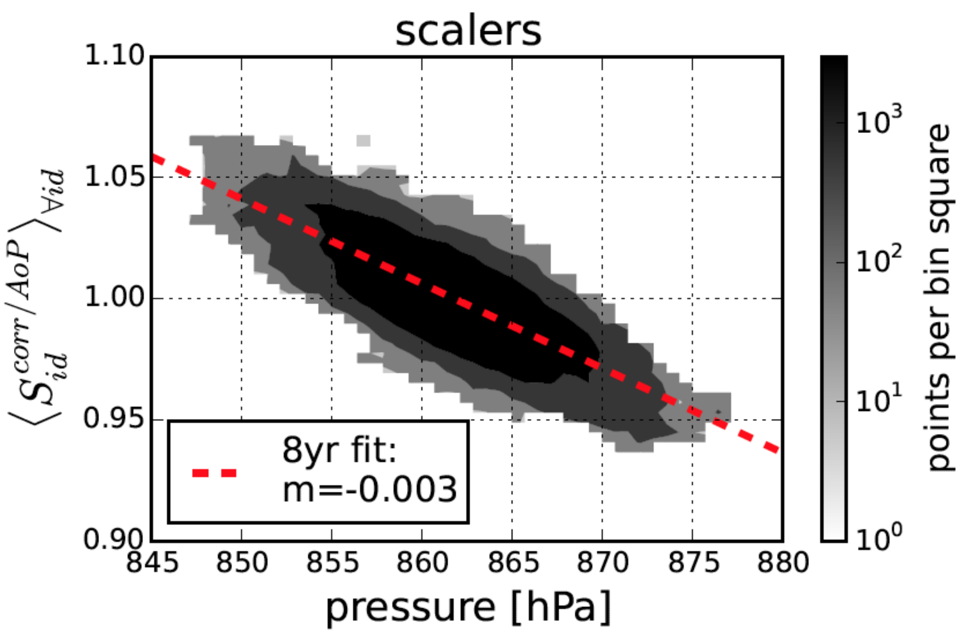
Data are recorded every sec

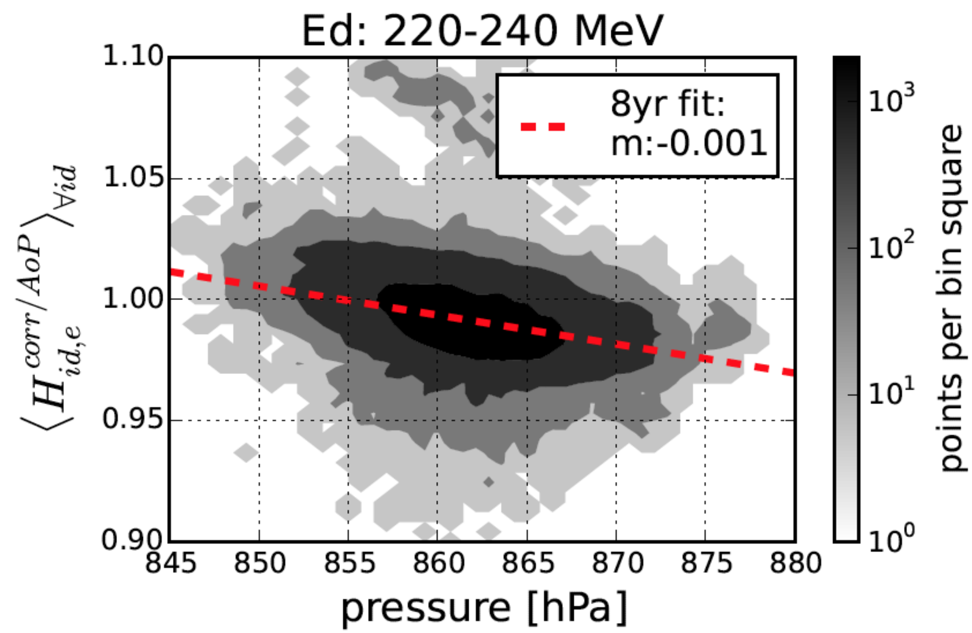


# Energy of the primary particles contributing to scaler counts



# Pressure corrections



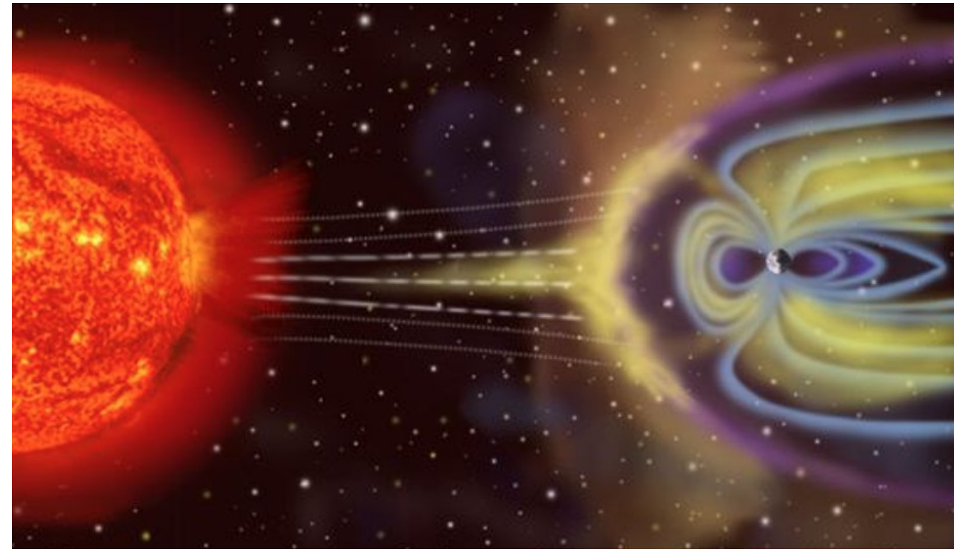

$$\langle S_{\mathrm{id}}^{\mathrm{corr/AoP}}(t)\rangle_{\forall \mathrm{id}}^{\mathrm{corr/press}} = \langle S_{\mathrm{id}}^{\mathrm{corr/AoP}}(t)\rangle_{\forall \mathrm{id}} - m^{\mathrm{S,press}}(P(t) - \langle P(t)\rangle_{\forall t})$$

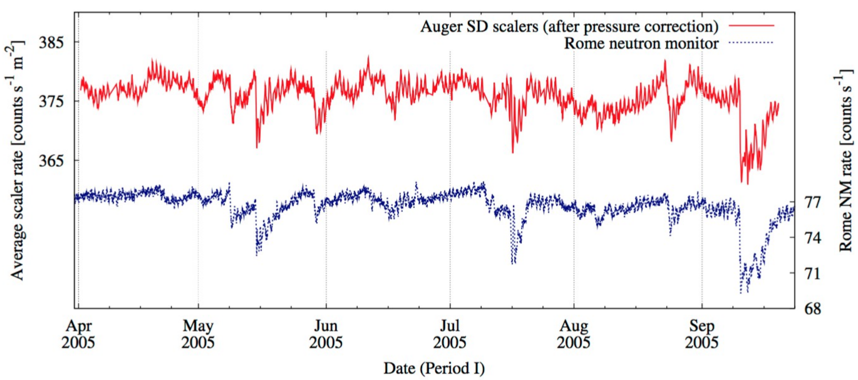
$$\langle H_{\mathrm{id,e}}^{\mathrm{corr/AoP}}(t)\rangle_{\forall \mathrm{id}}^{\mathrm{corr/press}} = \langle H_{\mathrm{id,e}}^{\mathrm{corr/AoP}}(t)\rangle_{\forall \mathrm{id}} - m_e^{\mathrm{H,press}}(P(t) - \langle P(t)\rangle_{\forall t})$$

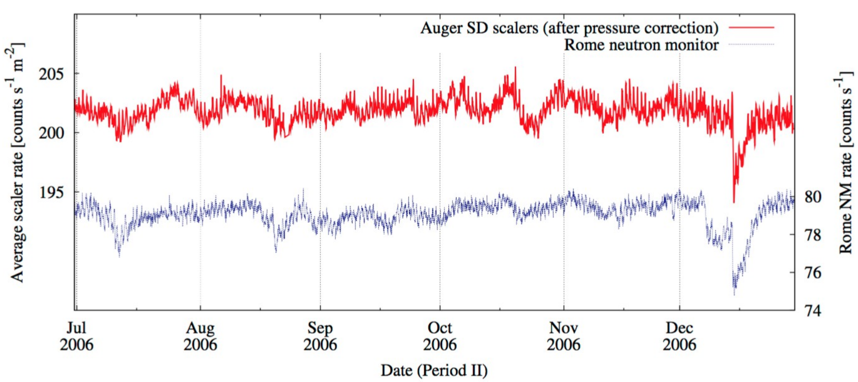
**JINST 6, P01003 (2011)**
**Adv.Space Res. 49 (2012) 1563-1569**

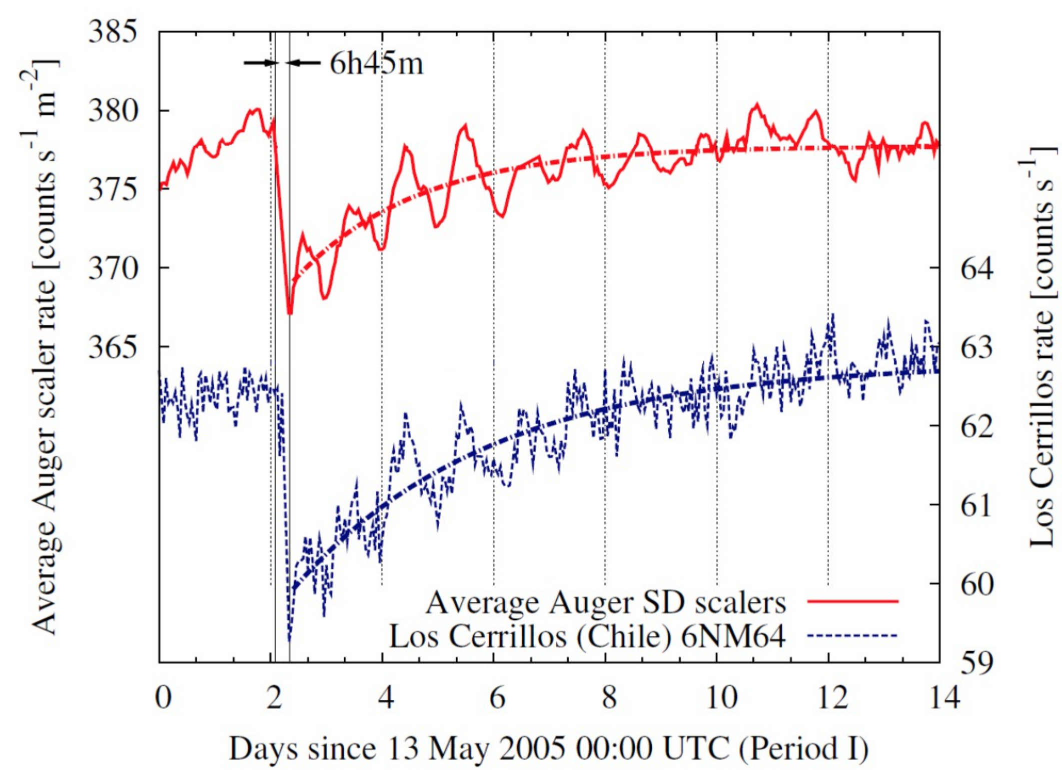
# Forbush decreases

Coronal mass ejections of low energy electrons (solar wind) from the sun towards the earth, sweep away  the flux of galactic cosmic rays reaching the earth.



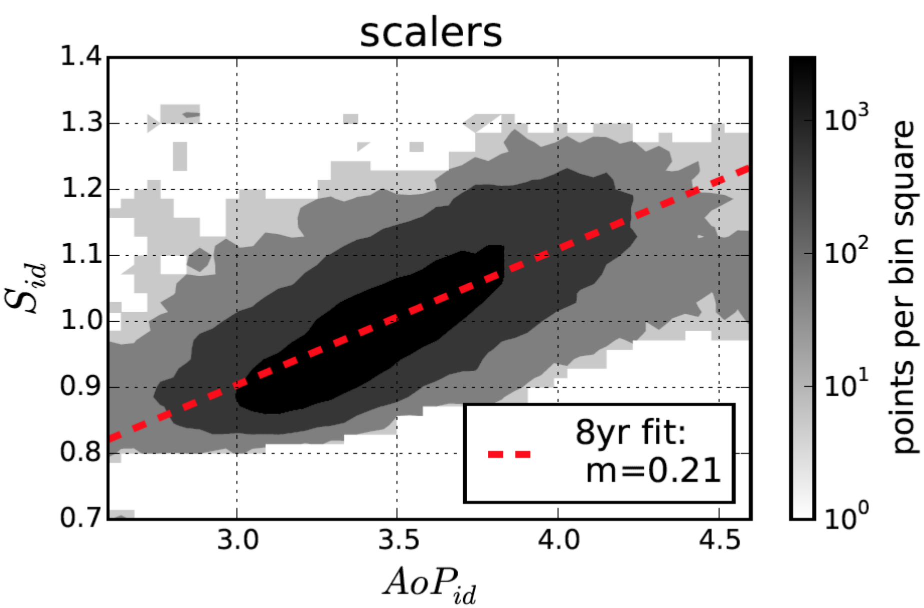


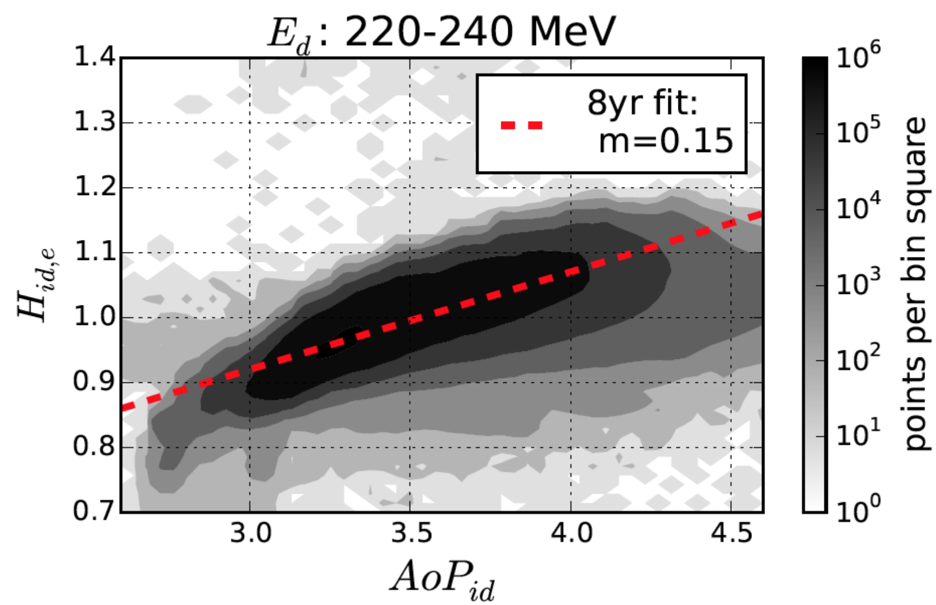



# Area-over-Peak corrections

Variation of the average AoP ratio in tanks signal has been experienced across the years: an instrumental effect whose causes are not fully understood. It is shown to correlate with scaler counts.



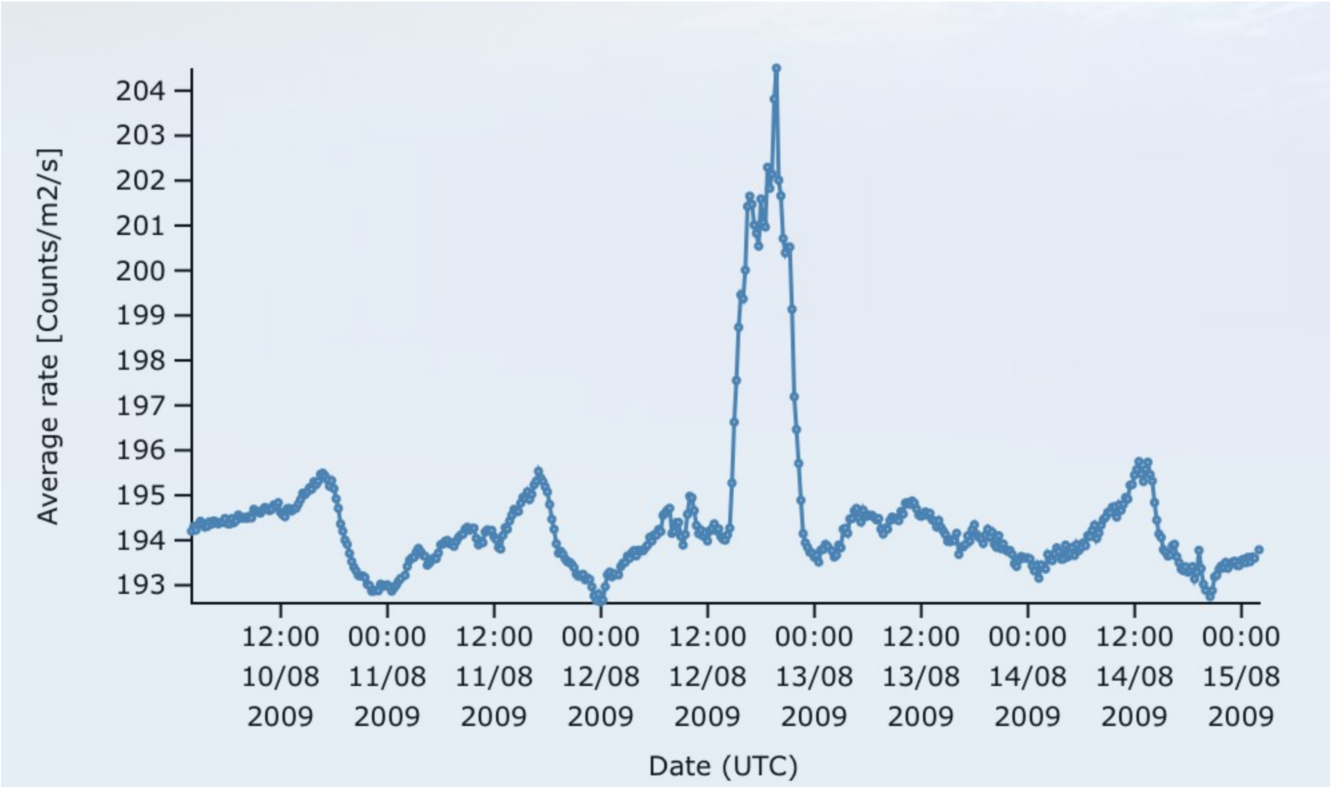



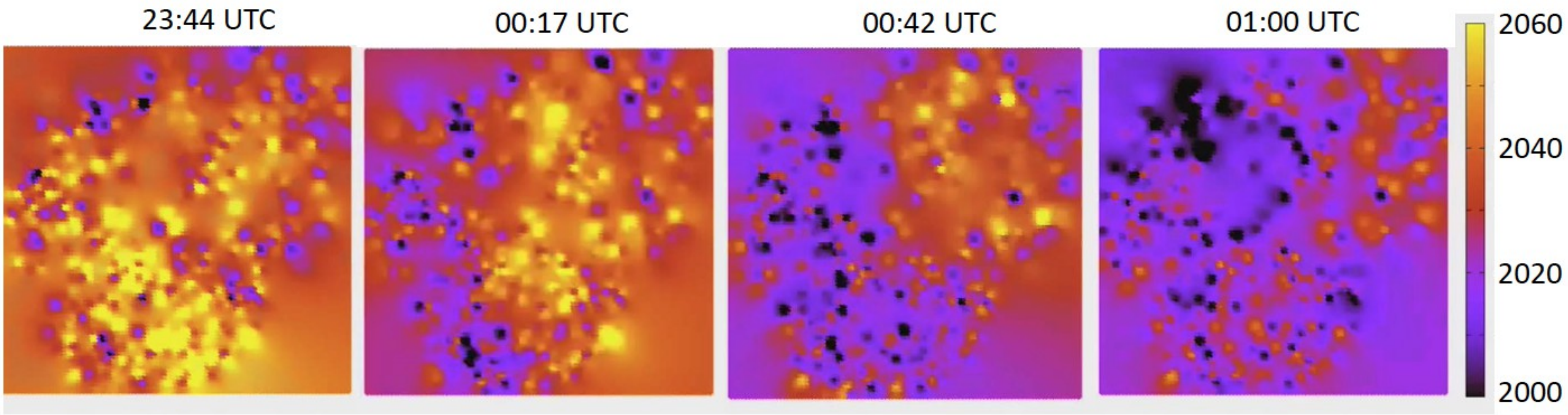

$$S_{\mathrm{id}}^{\mathrm{corr/AoP}}(t) = S_{\mathrm{id}}(t) - m^{\mathrm{S,AoP}}(\mathrm{AoP}_{\mathrm{id}}(t) - \overline{AoP})$$

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

More corrections:
Wind effects on Scaler rates

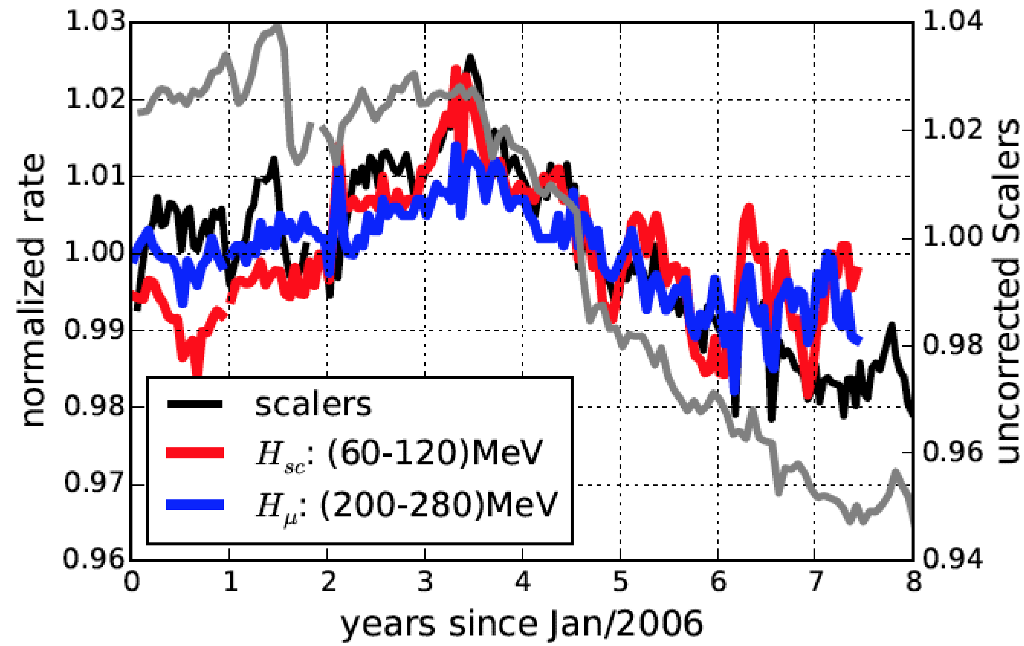
High winds (>80 kmh) on the array produce accumulation of statics on the tanks resulting in anomalous increases of scaler counts.

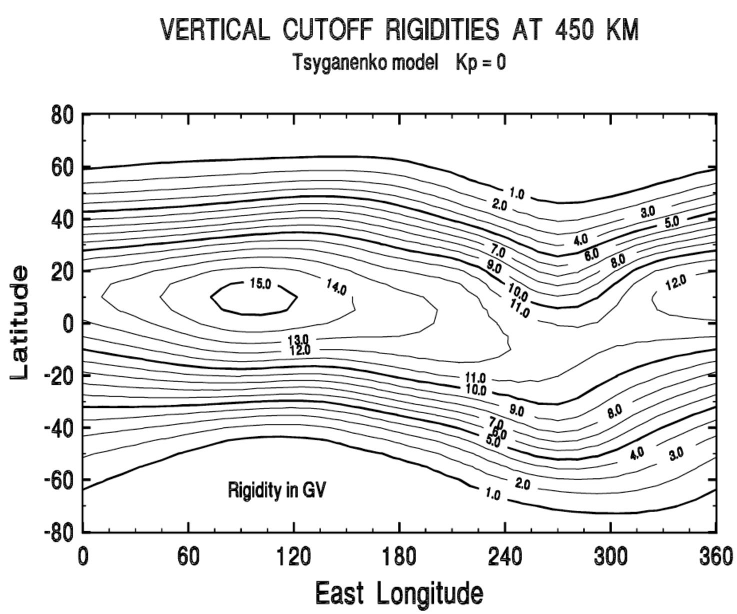


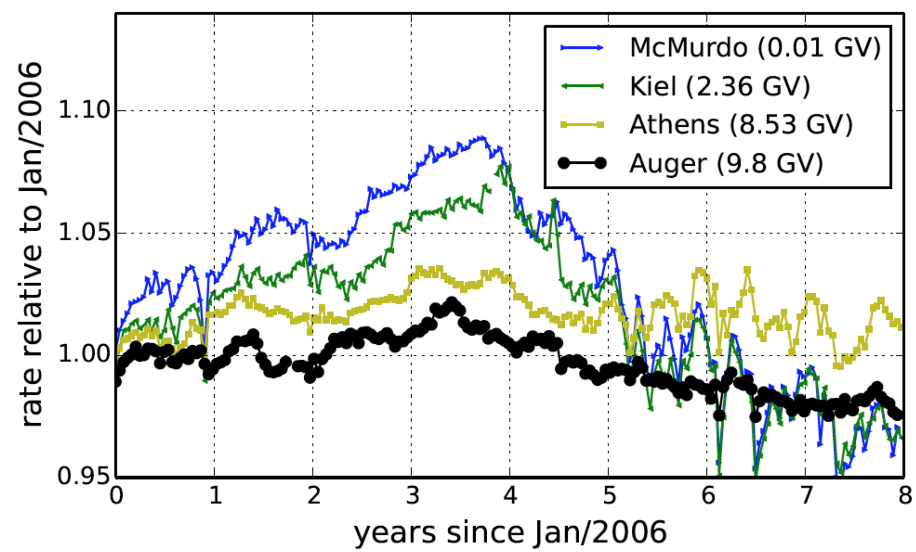



# Long term effects

After AoP and pressure corrections, we can compare the normalized rate recorded by AUGER to the rates observed by neutron monitors located at different latitiudes. Geomagnetic rigidity cutoff for CR at Auger latitude is highest, and solar cycle effects are attenuated.



# Data from scalers are public

*http://labdpr.cab.cnea.gov.ar/ED2/index.php?scaler=1*

Pierre Auger Observatory
Public Event Browser

## Space Weather page

Welcome to the Space Weather public web page of the Pierre Auger Observatory.

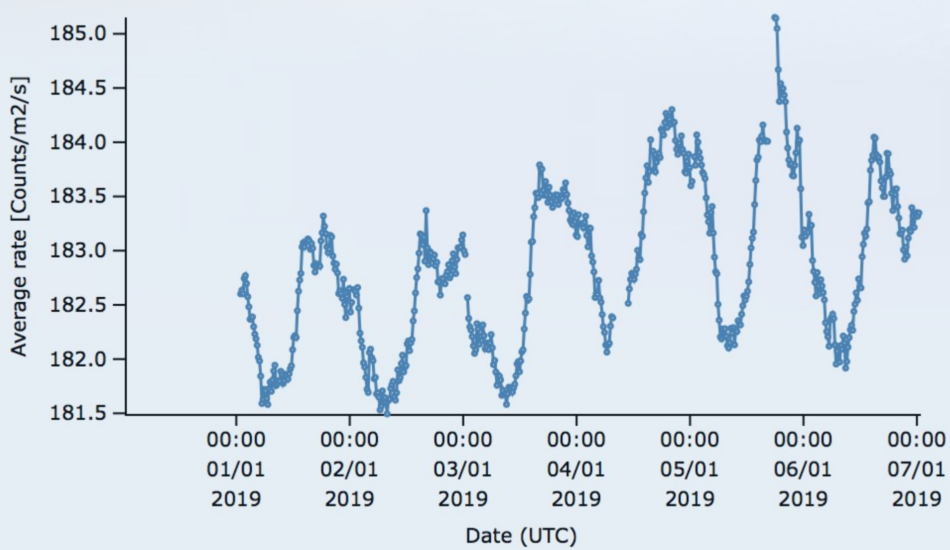
The Pierre Auger surface detectors record every second the rate of low energy particles detected and report this informartion to the central data acquisition system. This event rate is related to the flux of low energy galactic cosmic rays reaching the Earth, which is modulated by the solar activity. Therefore, by measuring with great precision the flux variations, the Pierre Auger Observatory is able to contribute to the Space Weather program, in a way similar to neutron monitors.

More information about Space Weather and cosmic rays can be found on the spaceweather.com webpage. A description of the Pierre Auger scaler mode and the data presented here (15 minutes averages of the scaler rates) can be found in "JINST 6 P01003 (2011)" (open access).

Given the peculiarity of the detector (spread over 3000 km$^2$), some unusual effects can be present in the data. A specific page is dedicated to them.

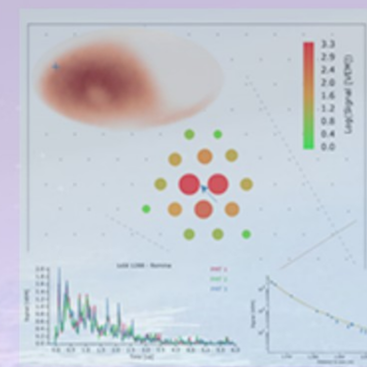
Should you use these data for any publication, acknowledgement to the Pierre Auger Observatory should be given and JINST 6 P01003 (2011) should be cited. You can also download a 20 MB ascii file with all the dataset.

### Latest scaler data




**Pierre Auger Observatory**
**Public Event Browser**

**Public Event Browser**



**Latest scaler data**

**Yearly scaler data**

**Specific graph**

| | Day | Month | Year |
|---|---|---|---|
| Start | 1 | 9 | 2005 |
| End | 1 | 10 | 2005 |

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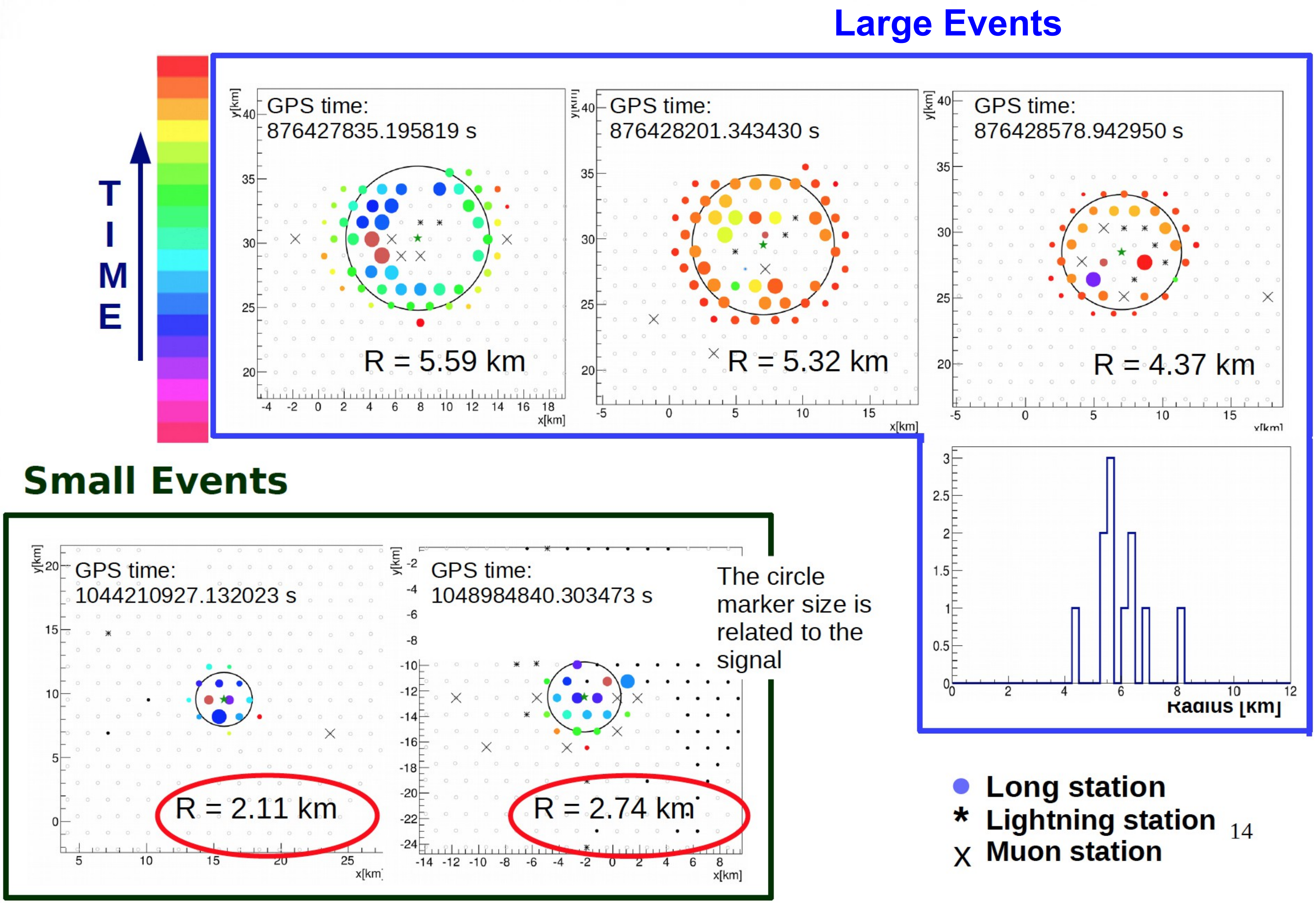
**Page hosted by LabDPR**

**Go to www.auger.org**
**www.auger.org.ar**

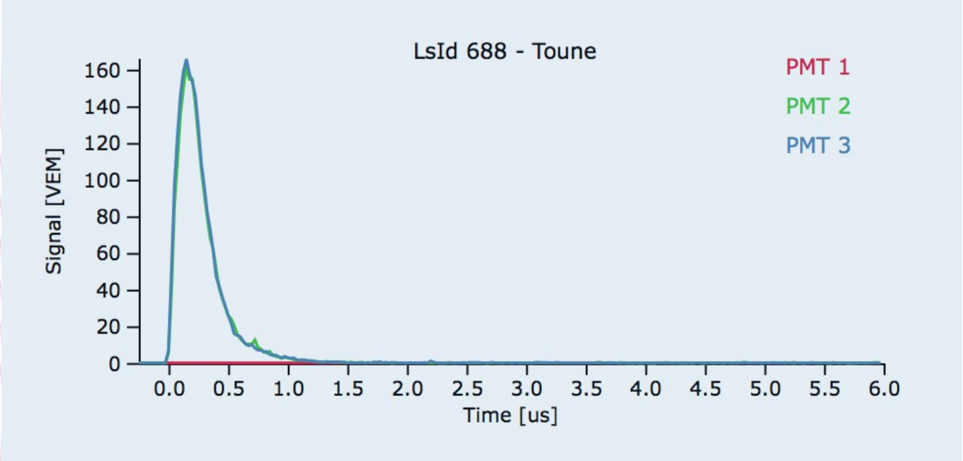
# Anomalous events in SD during thunderstorms



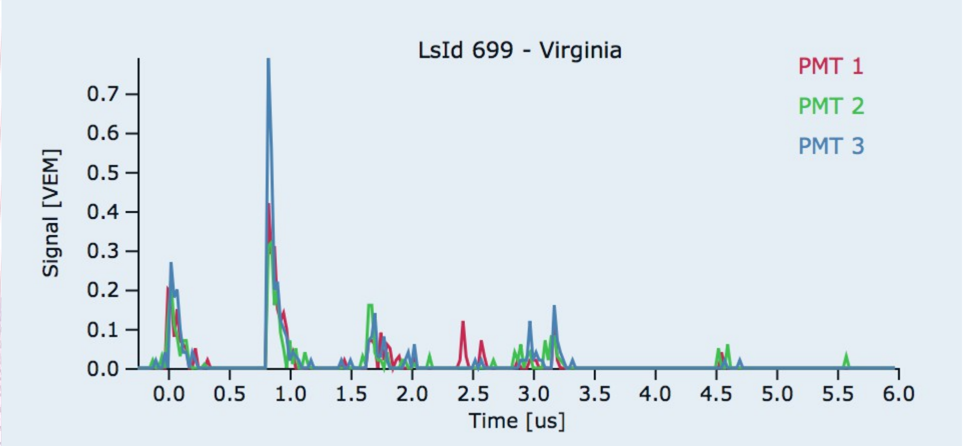

**EPJ Web Conf. 197 (2019) 03003**
**PoS ICRC2017 (2018) 314**

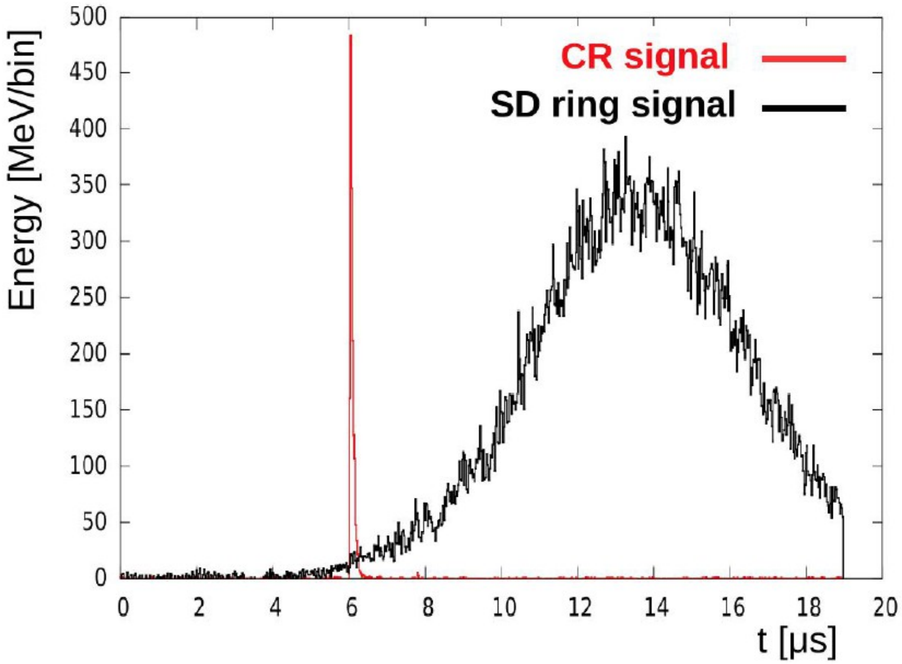
# SD ring signals

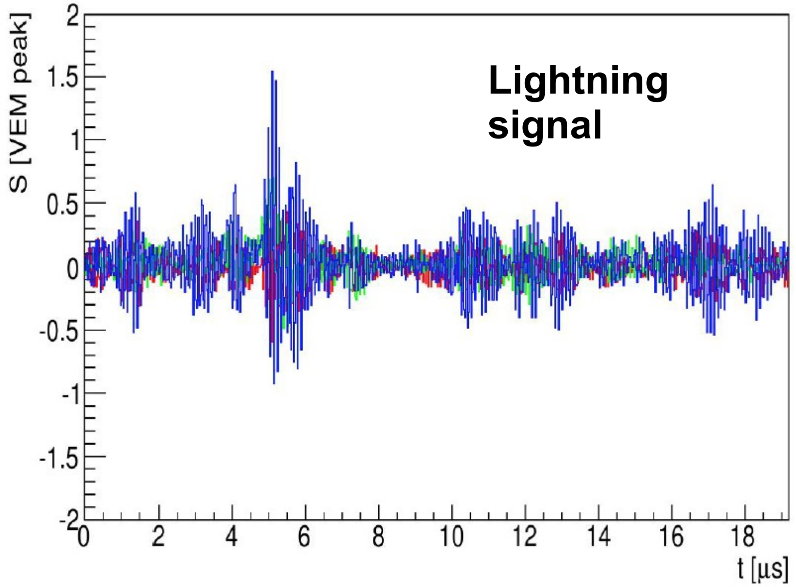
Typical signal in CR shower :
- near the core




- far from the core (mostly muons)

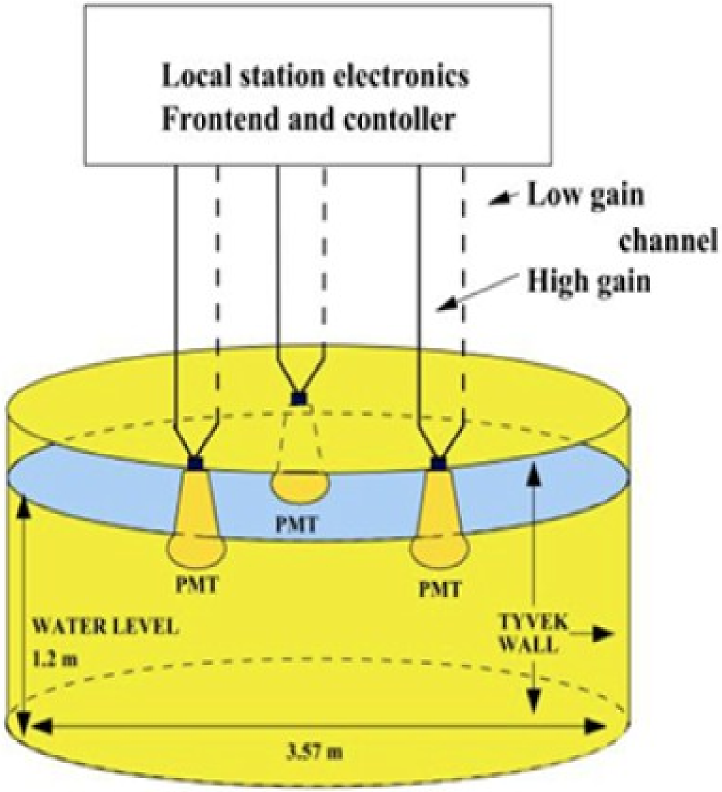


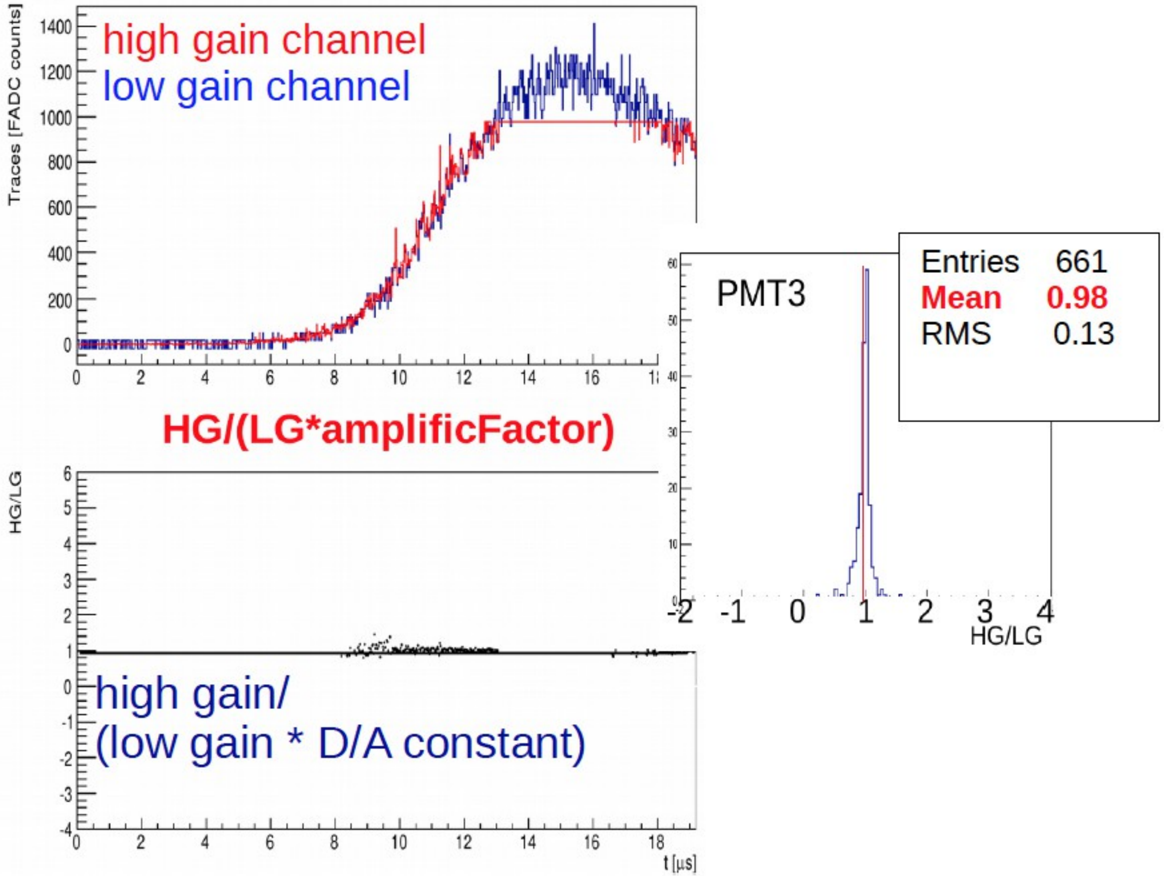



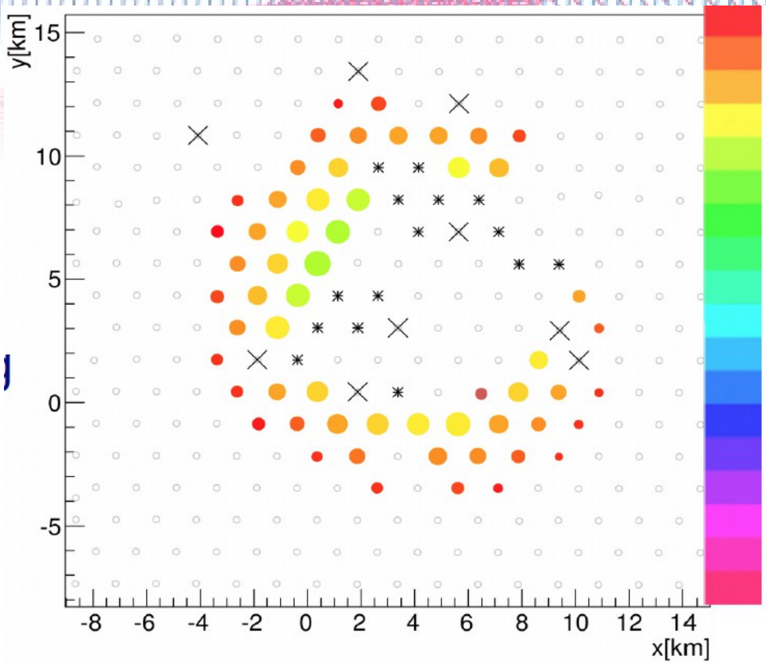
# SD ring signals

... are not RF pickup noise from lightning EMP
Low gain channel connected to last dynode
Hi gain channel conneccted to anode



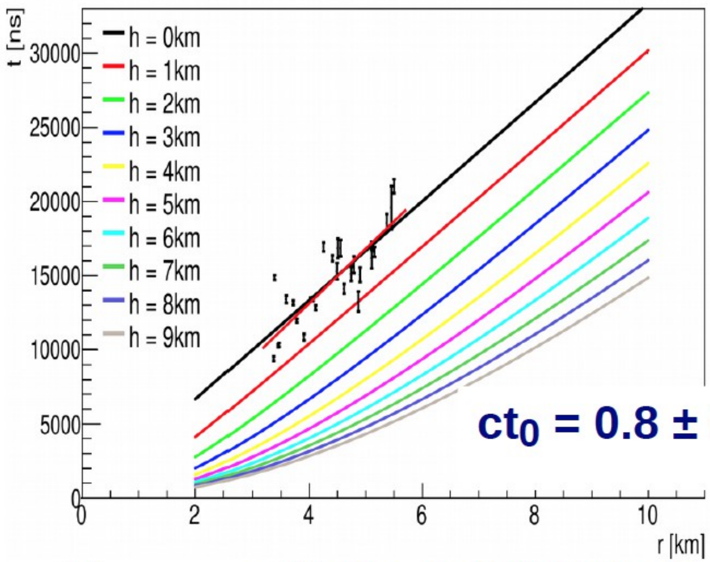



# Time evolution



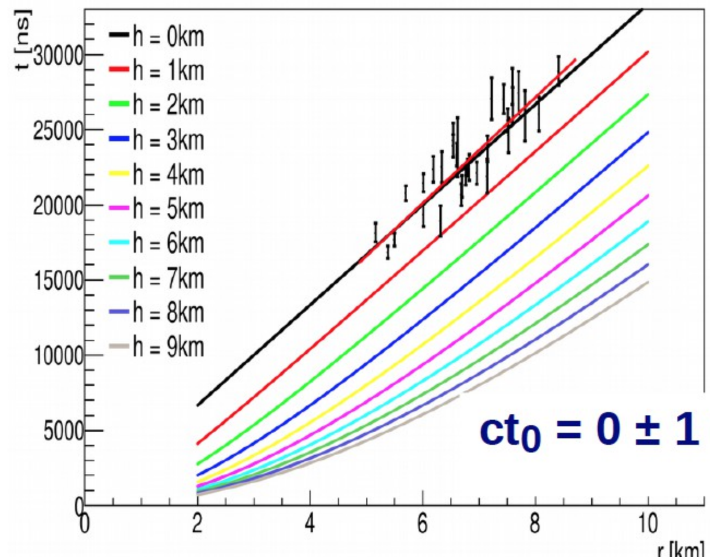

Pulse time in tank defined as the time when signal reaches 10% of the peak value

Radial expansion of the front at the speed of light.




$ct_0 = 0.8 \pm 0.3$ km

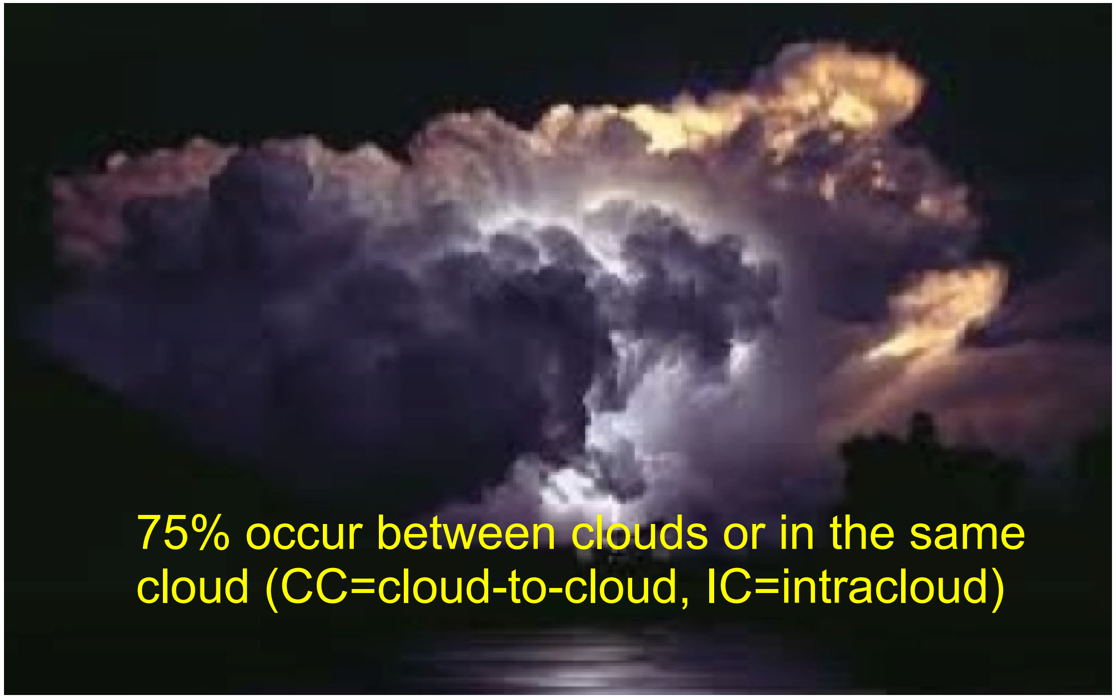
$V_{ground} = (2.8 \pm 0.4) * 10^8$ m/s



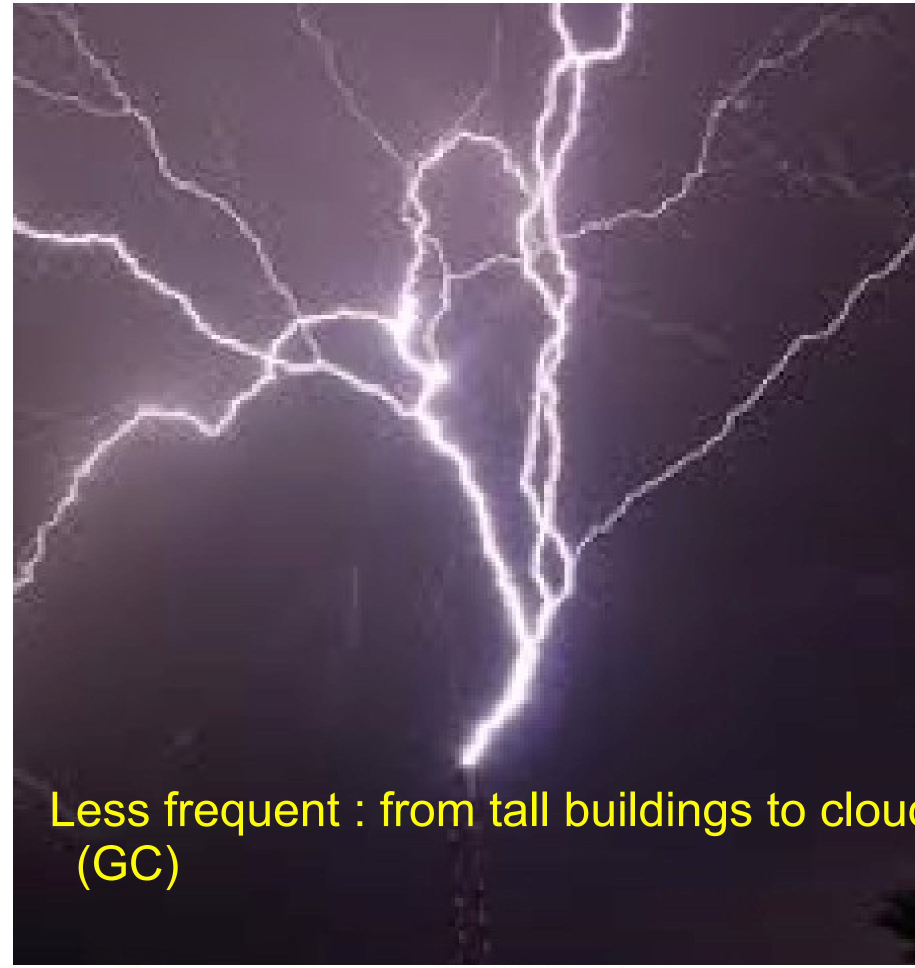

$ct_0 = 0 \pm 1$ km

$V_{ground} = (2.8 \pm 0.3) * 10^8$ m/s

# Lightning statistics



75% occur between clouds or in the same cloud (CC=cloud-to-cloud, IC=intracloud)



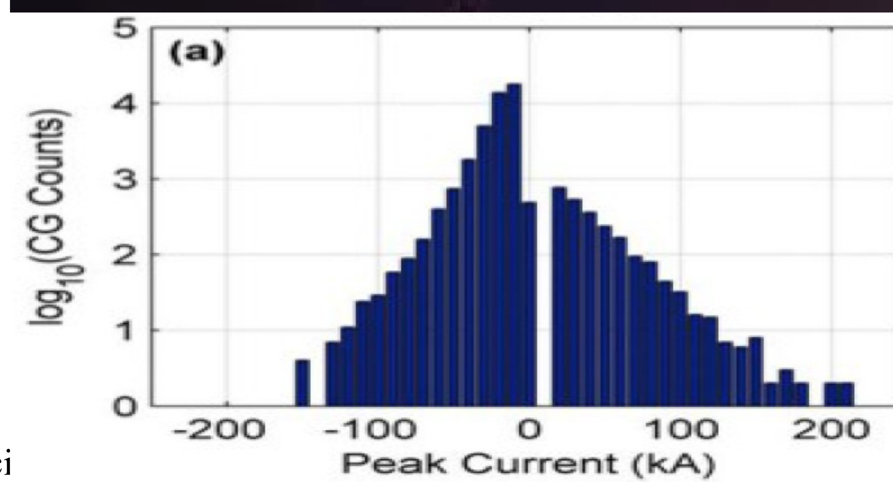
Less frequent : from tall buildings to clouds (GC)

25% go from cloud to ground

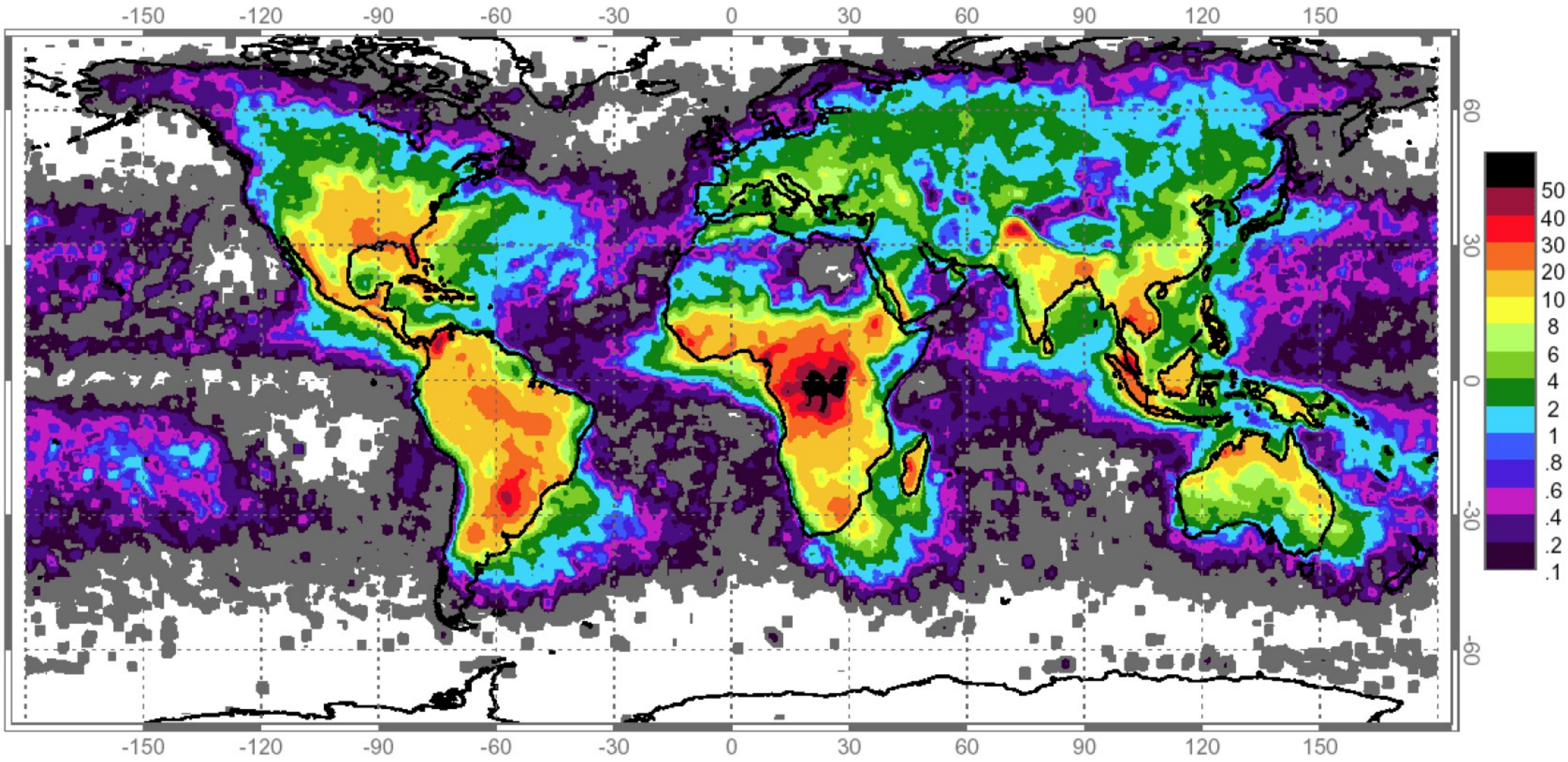
9/10 have a negative charge leader (-CG)

1/10 have positive leader (+CG)

sci



# *Lightning strikes /km$^2$/year*




Source: satellite Mikrolab-1, Optical Transient Detector

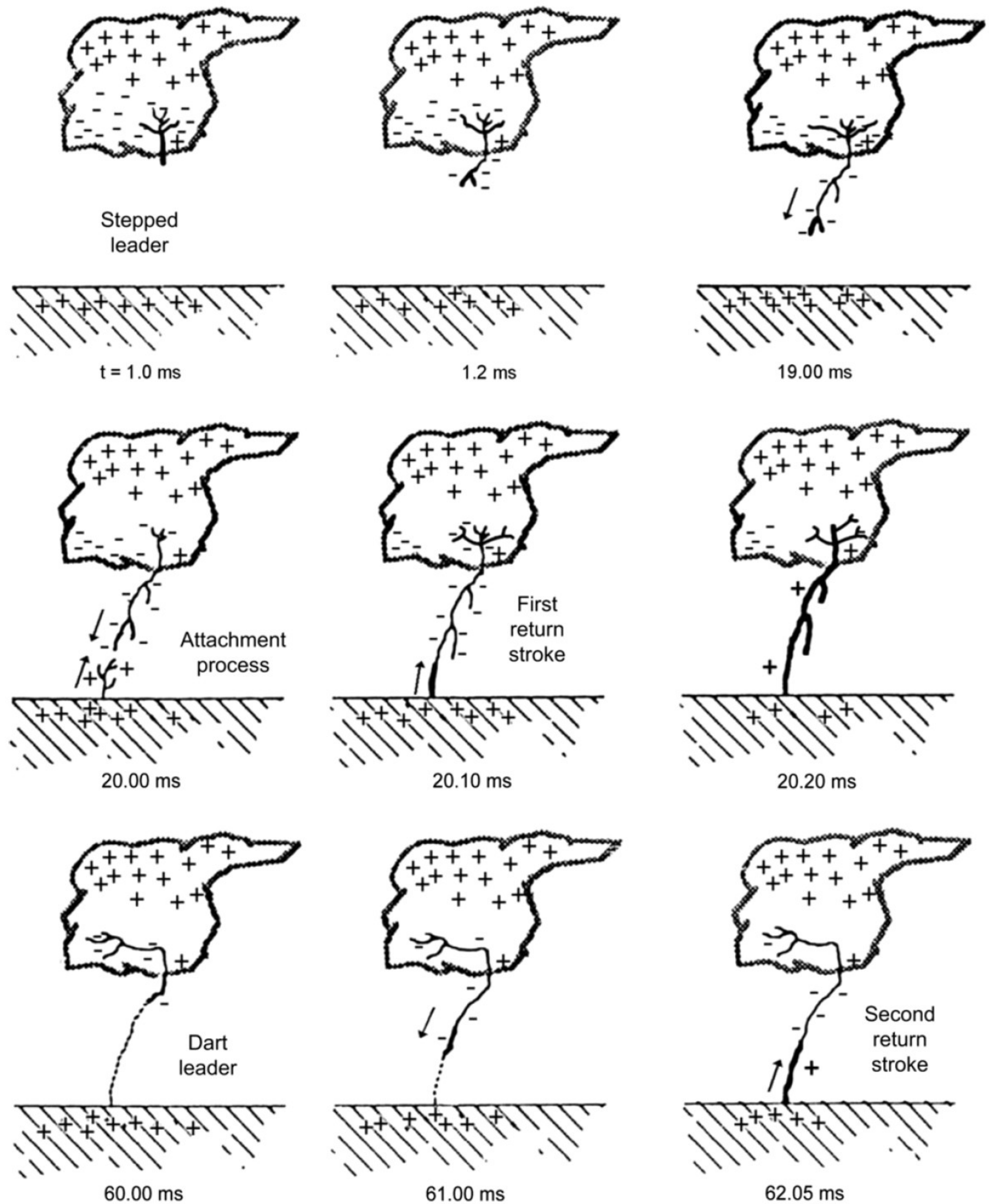
# Lightning: time scales

Typical dart leader velocities
 200 km/s

Time to touch ground:
 several milliseconds from initial breakdown to return stroke

Time lag between multiple return strokes: tens of milliseconds

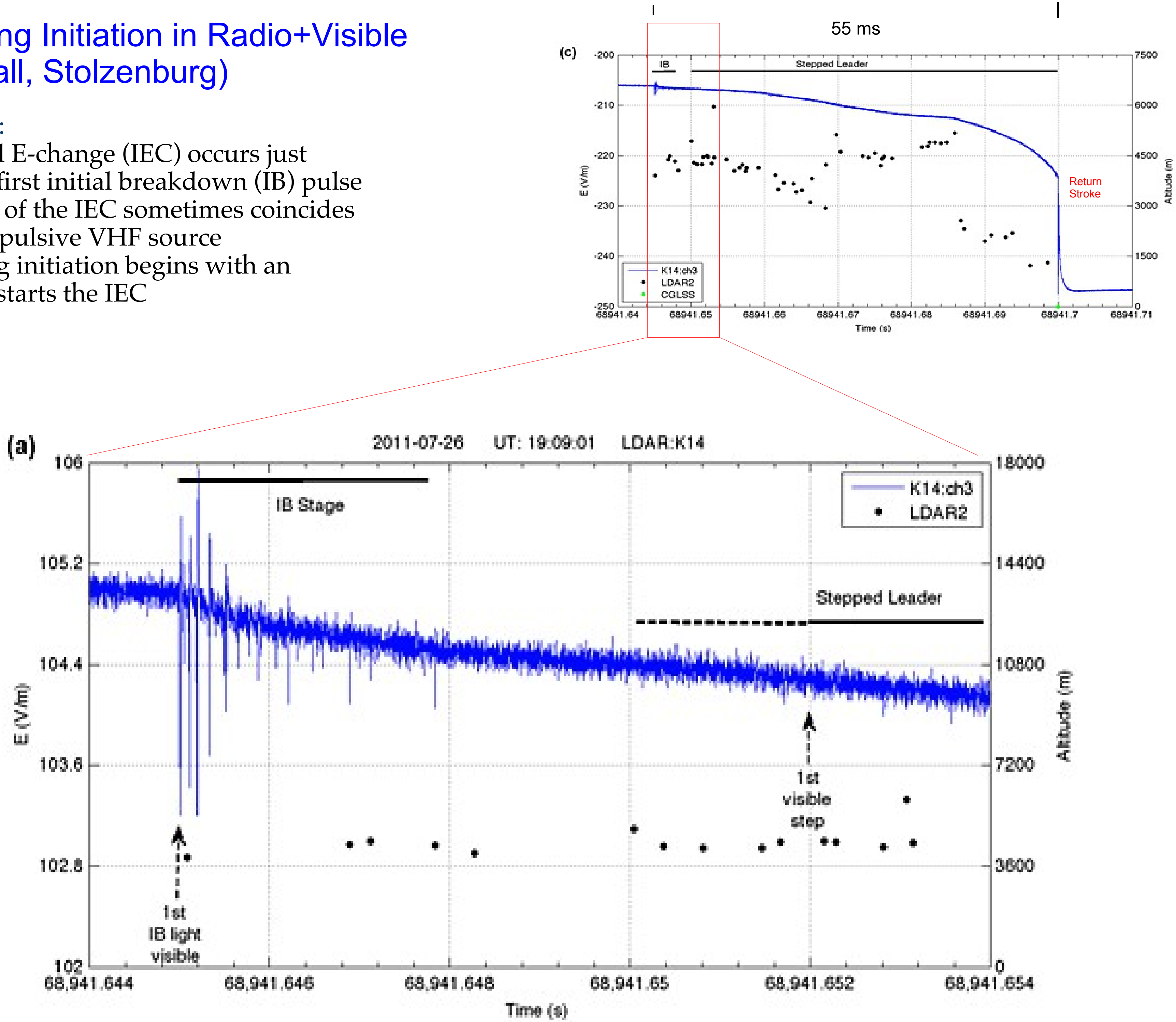
Only during last decade technologies were developed , able to visualize the initial phases of lightning formation



# Lightning Initiation in Radio+Visible (Marshall, Stolzenburg)

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

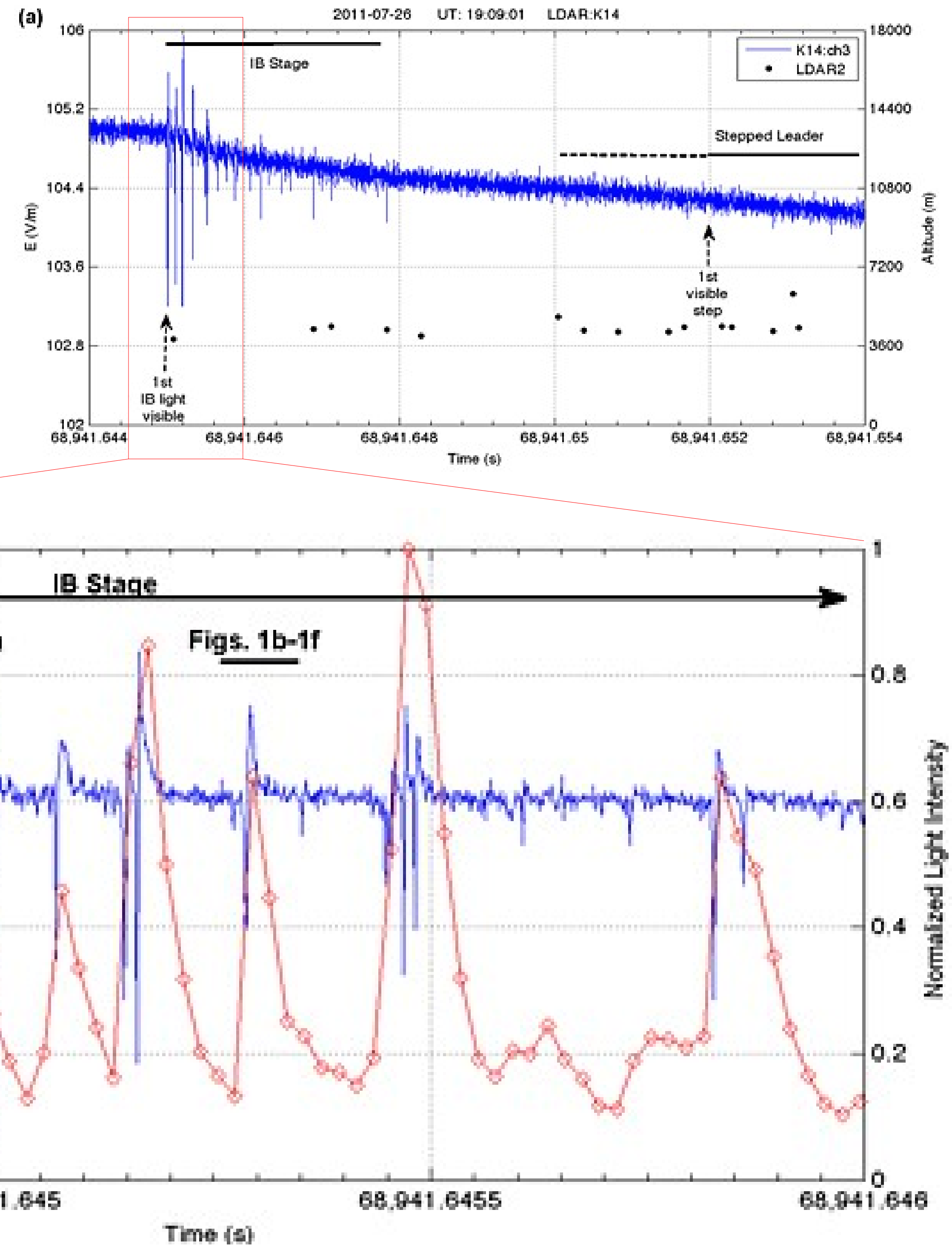


Key Points:

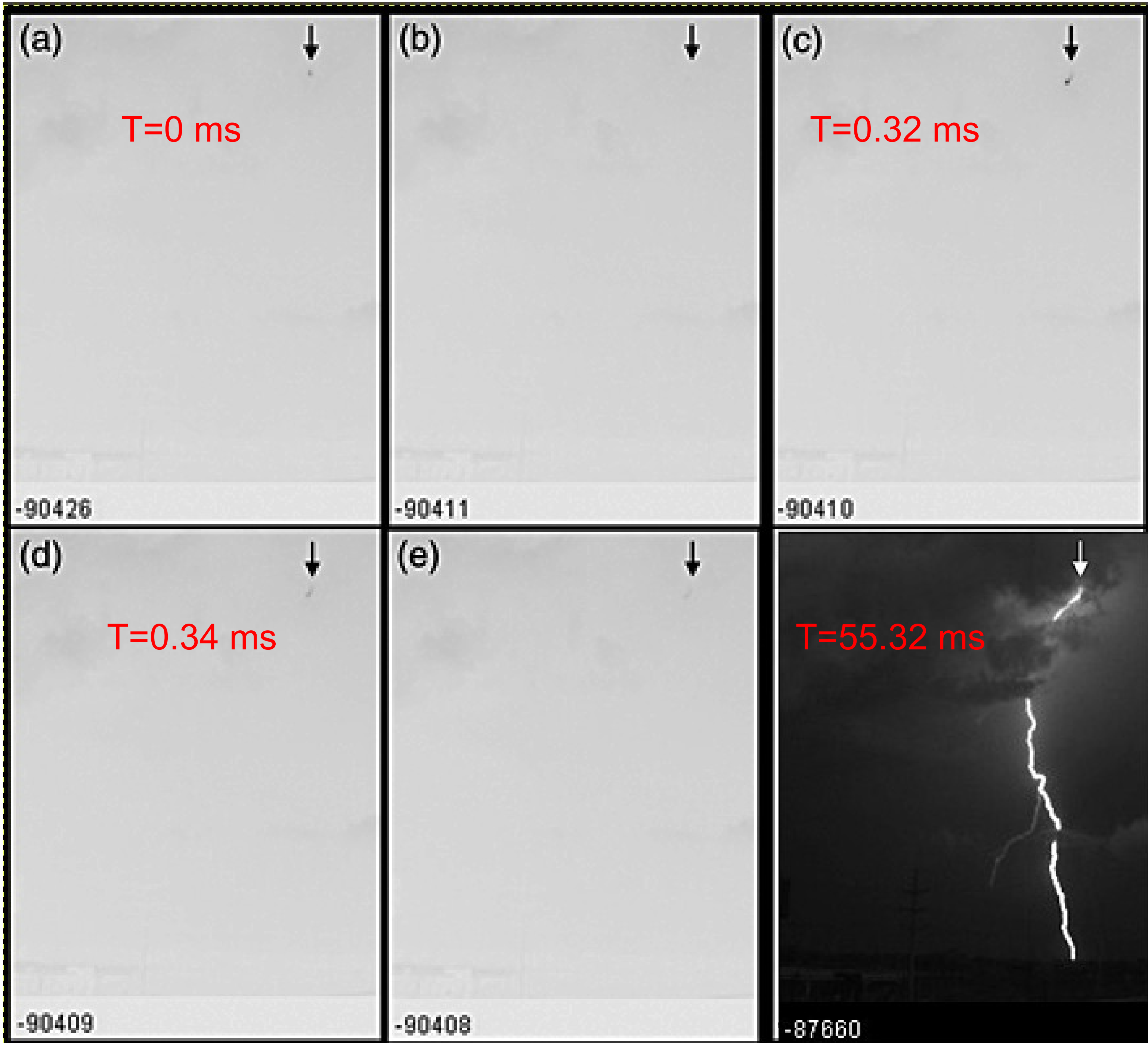
• The first initial breakdown (IB) pulse is followed by a burst of many bipolar pulses approximately 20 to 50 us apart

• The start of the IEC sometimes coincides with an impulsive VHF source

• Lightning initiation begins with an event that starts the IEC



Images of
High
Speed
Camera
( 50 kfps )

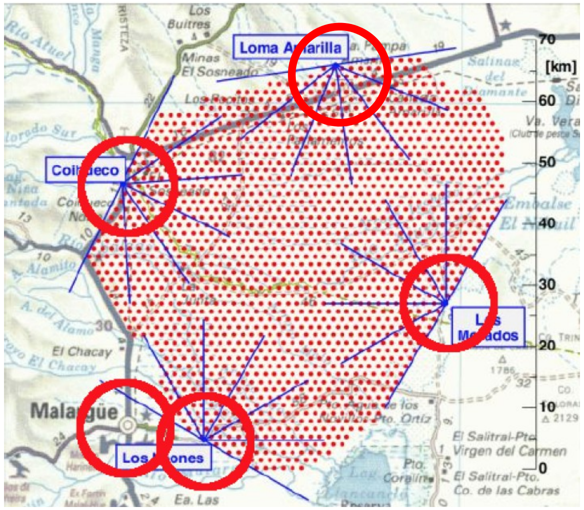


# Lightning Monitoring

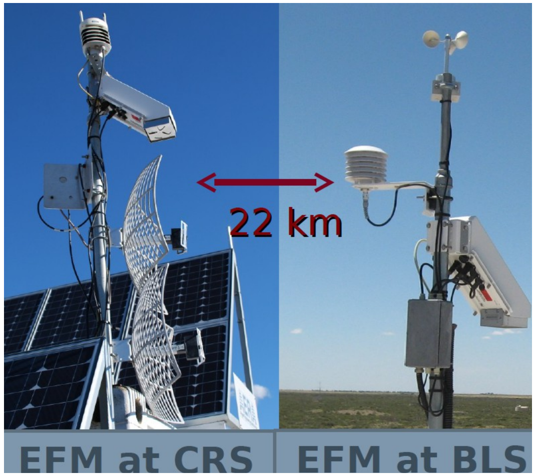
Recently, a lightning network has been installed on AUGER site

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

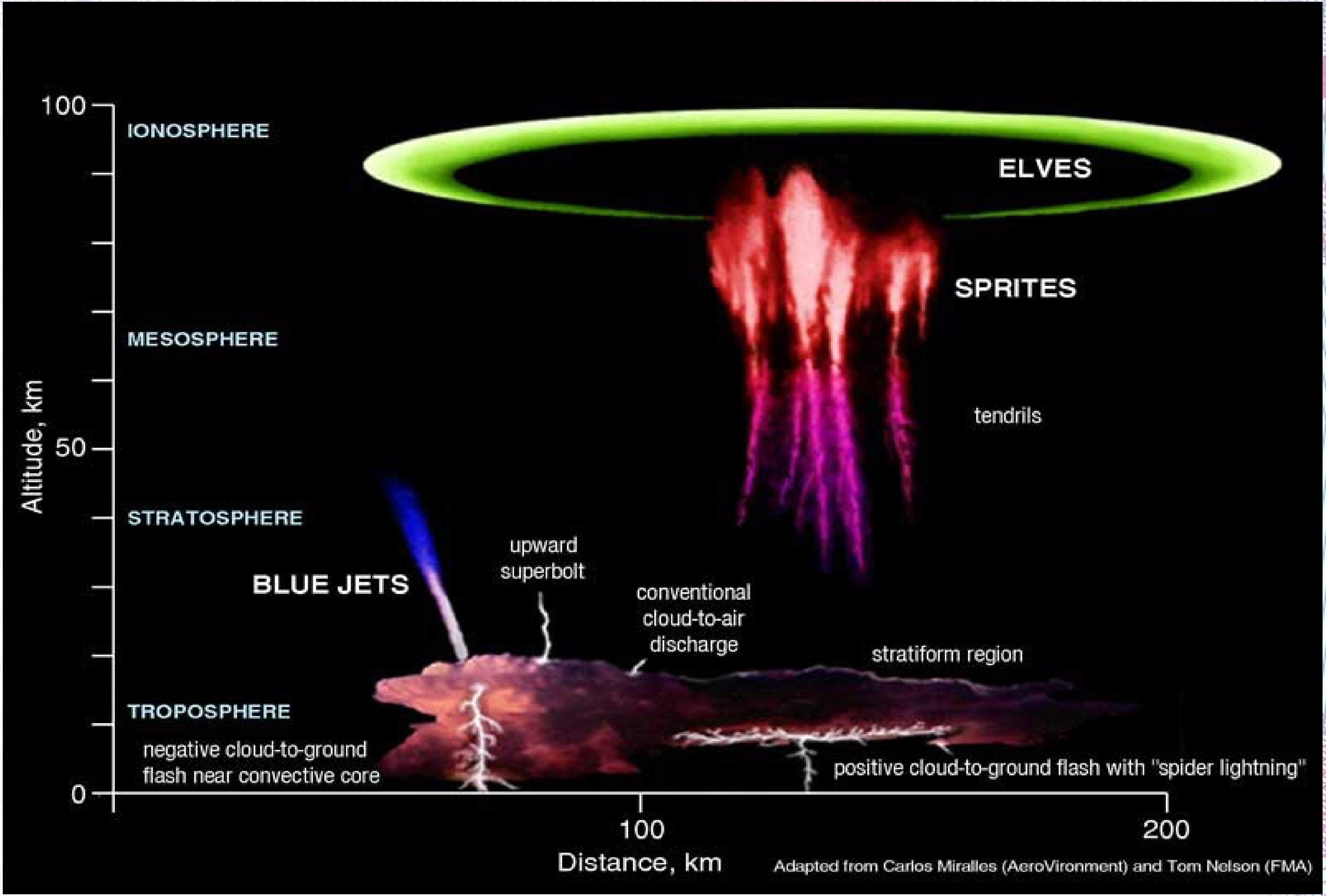

Locations:




- 2 E-field mills
Campbell Scientific CS110

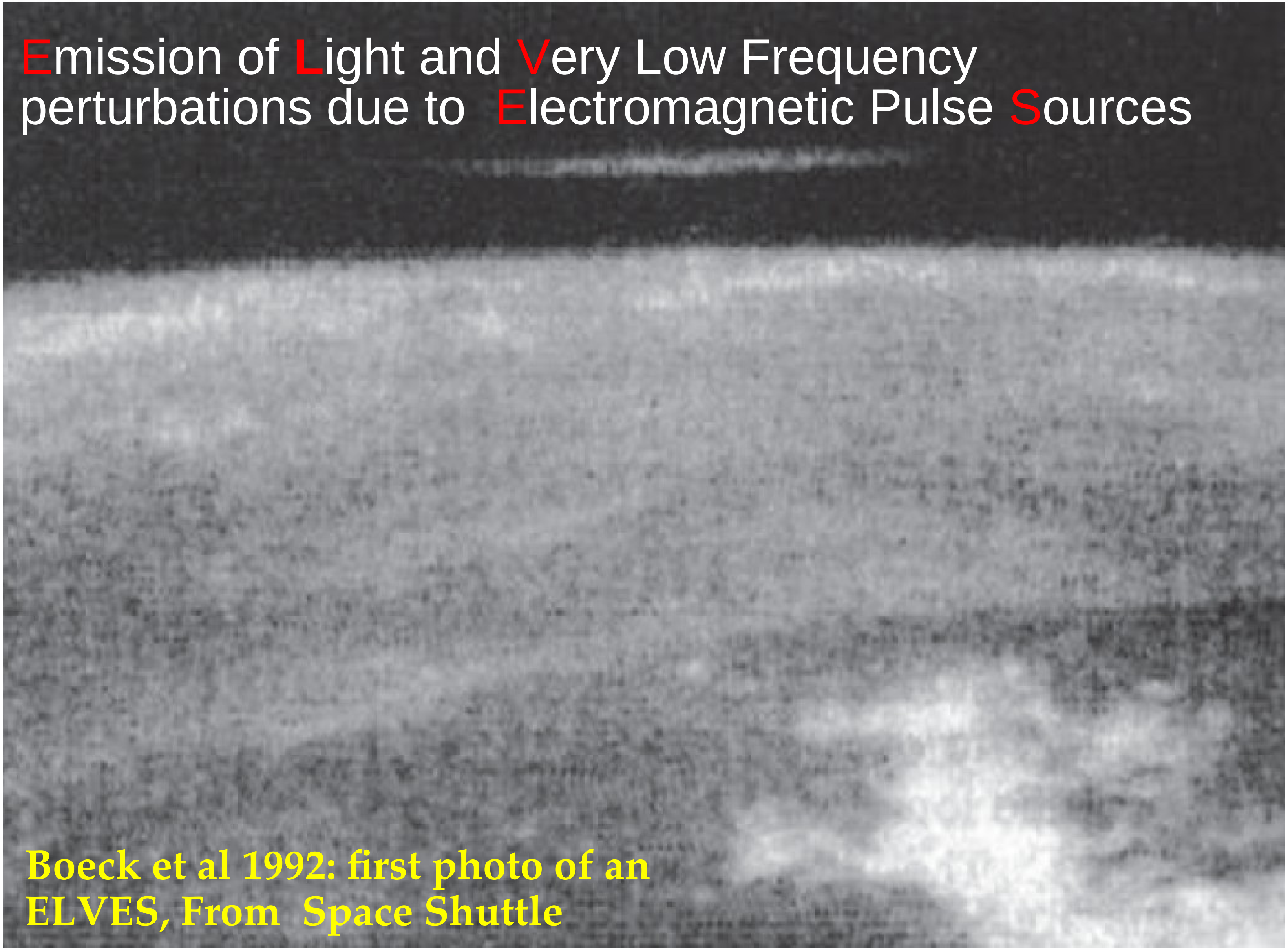


# Transient Luminous events



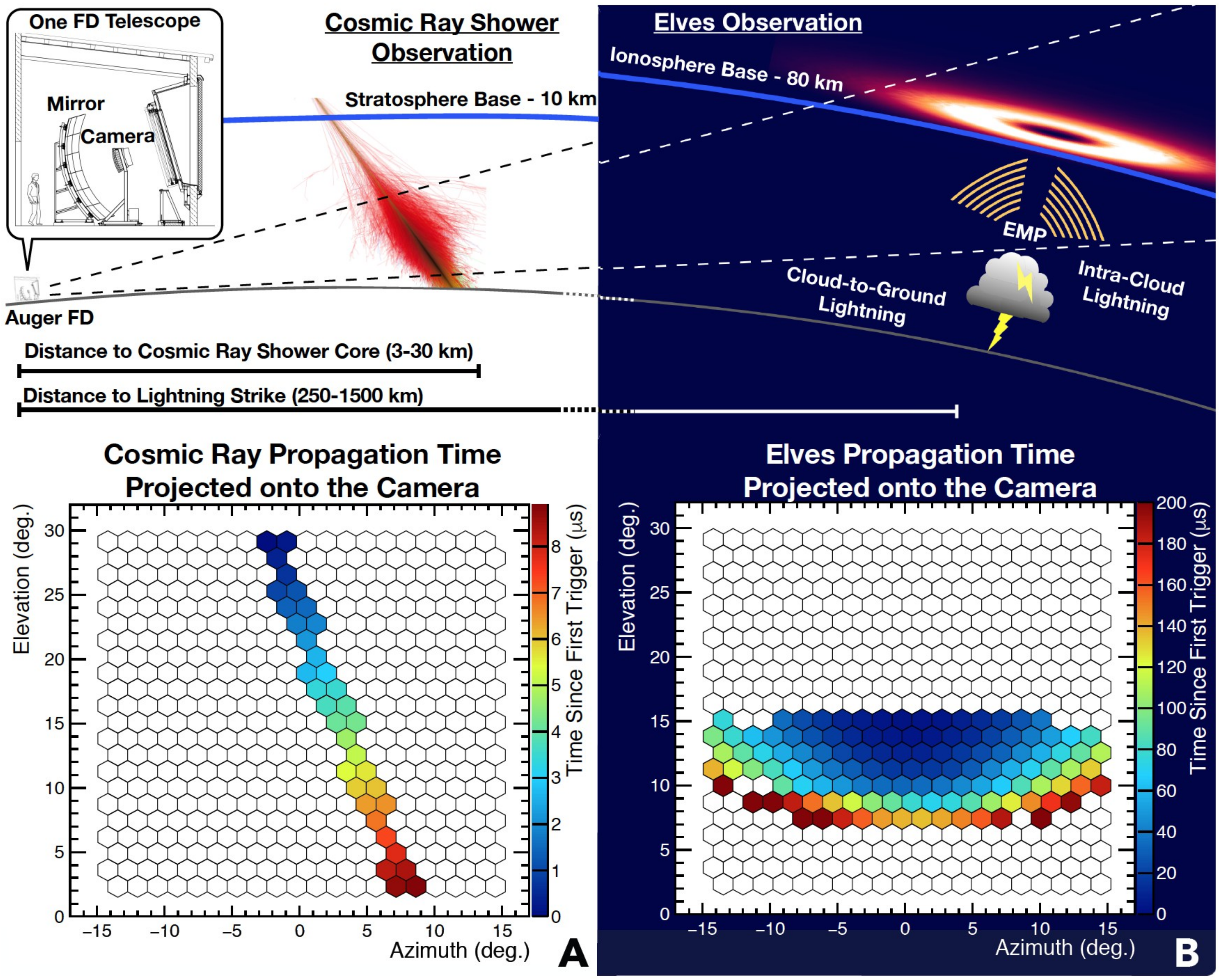
# ELVES

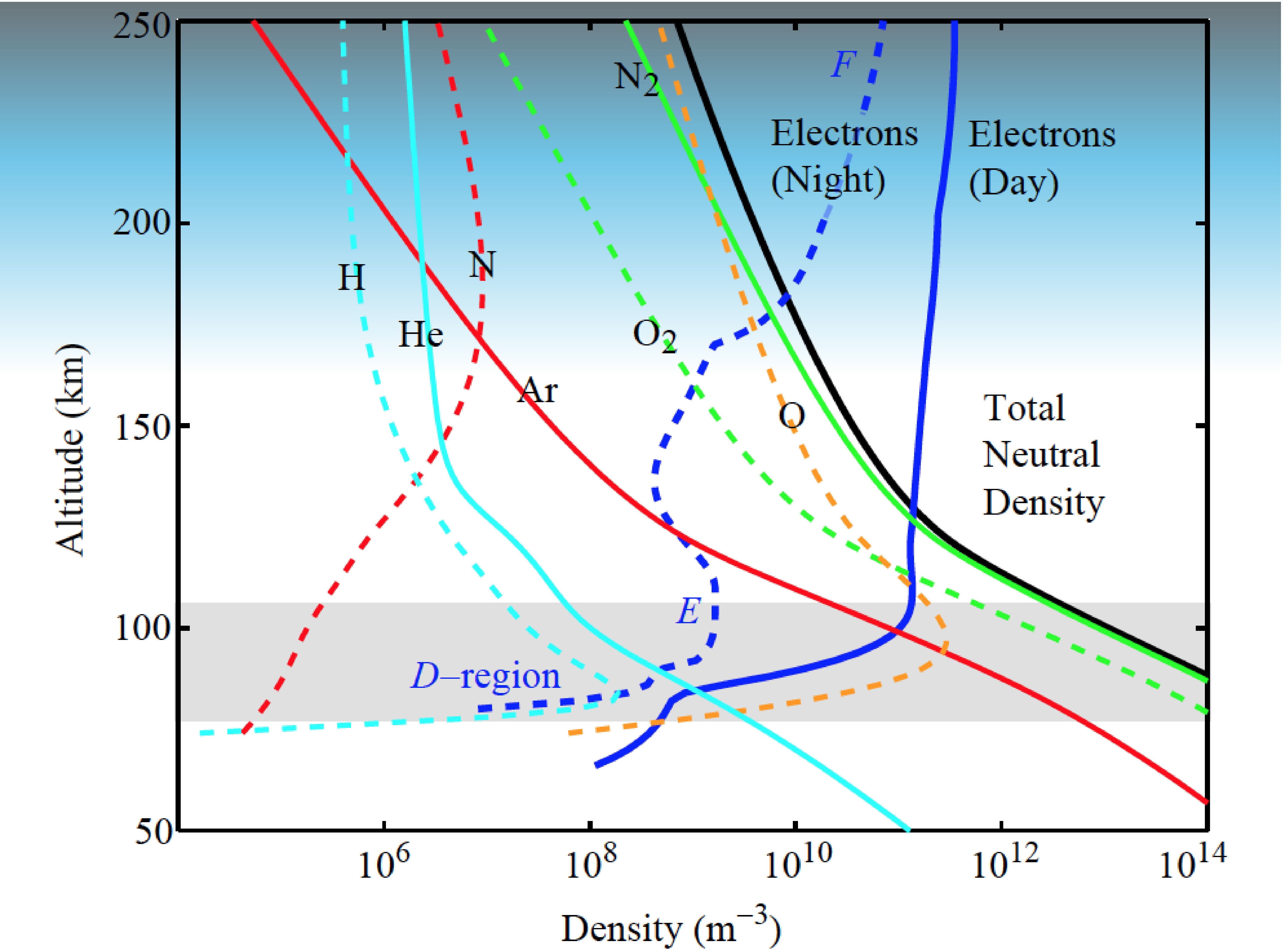
Emission of Light and Very Low Frequency perturbations due to Electromagnetic Pulse Sources



Boeck et al 1992: first photo of an ELVES, From Space Shuttle

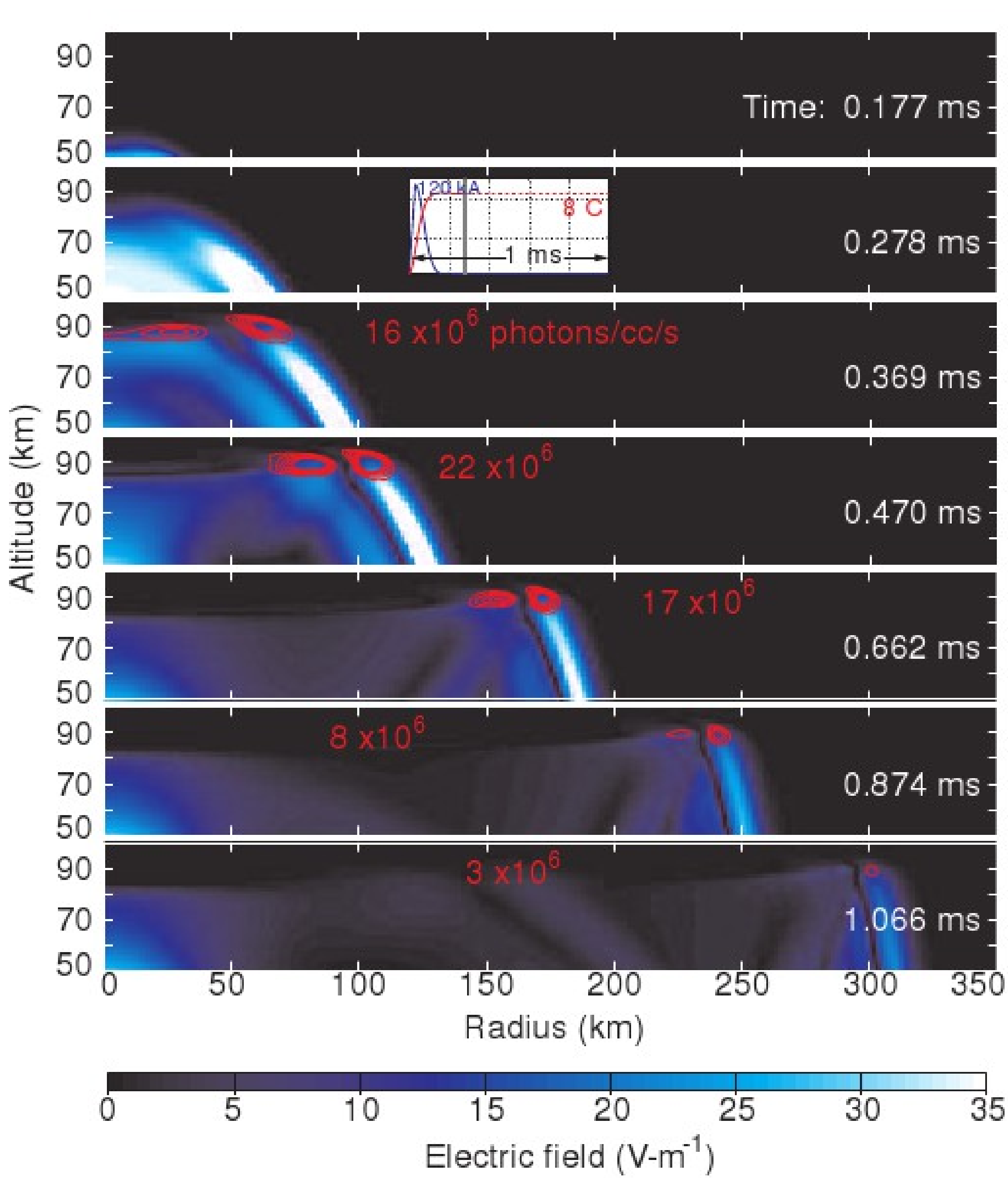
# ELVES events in FD data





250
200
150
100
50
Altitude (km)
$10^6$
$10^8$
$10^{10}$
$10^{12}$
$10^{14}$
Density ($m^{-3}$)
H
He
N
Ar
$N_2$
$O_2$
O
F
E
D–region
Electrons (Night)
Electrons (Day)
Total Neutral Density

# ELVES dynamics




BLU: Electric Field produced by lightning

RED: Fluorence light emmitted by Nitrogn molecules, excited by accelerated electrons

ELVES light transient is emitted by the thin layer where electron density increases by 3-4 orders of magnitude,

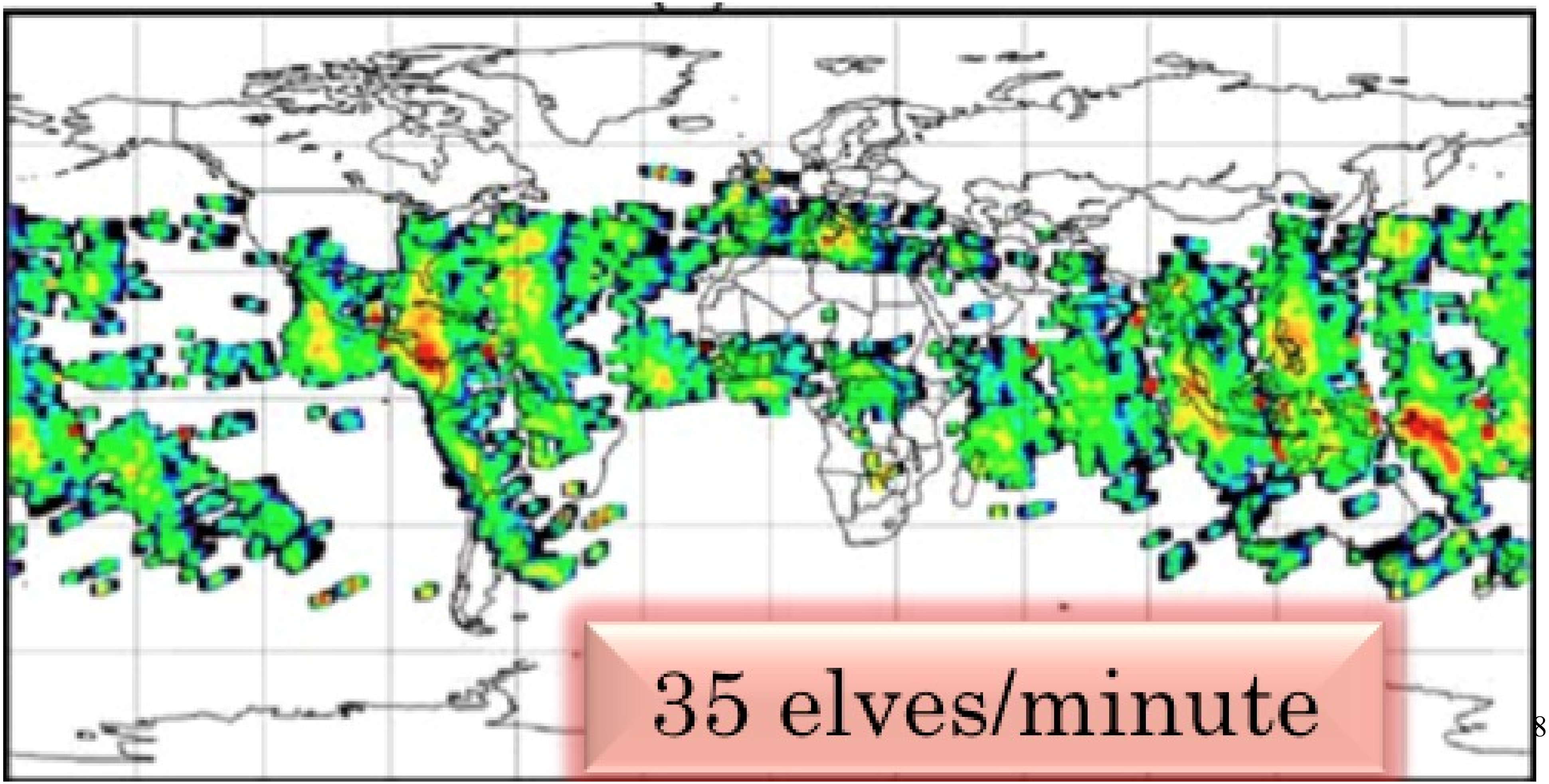
(source: R.Marshall, Stanford VLF group)

# ELVES Statistics

- how often
- where

| type | Rel.Rate | Land | Coast | Ocean |
|---|---|---|---|---|
| ELVE | 80.7% | 9% | 32% | 59% |
| Sprite | 9.4% | 49% | 23% | 28% |
| Halo | 9.8% | 21% | 40% | 39% |
| GigaJet | 0.2% | 15% | 15% | 70% |

Source ISUAL
Satellite: FormoSat-2

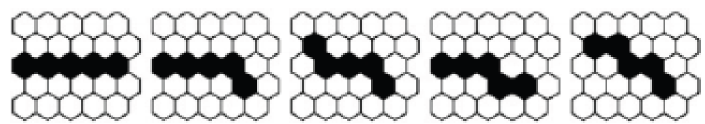


# 2004-2009: discovery of 3 ELVES events in FD data

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

# 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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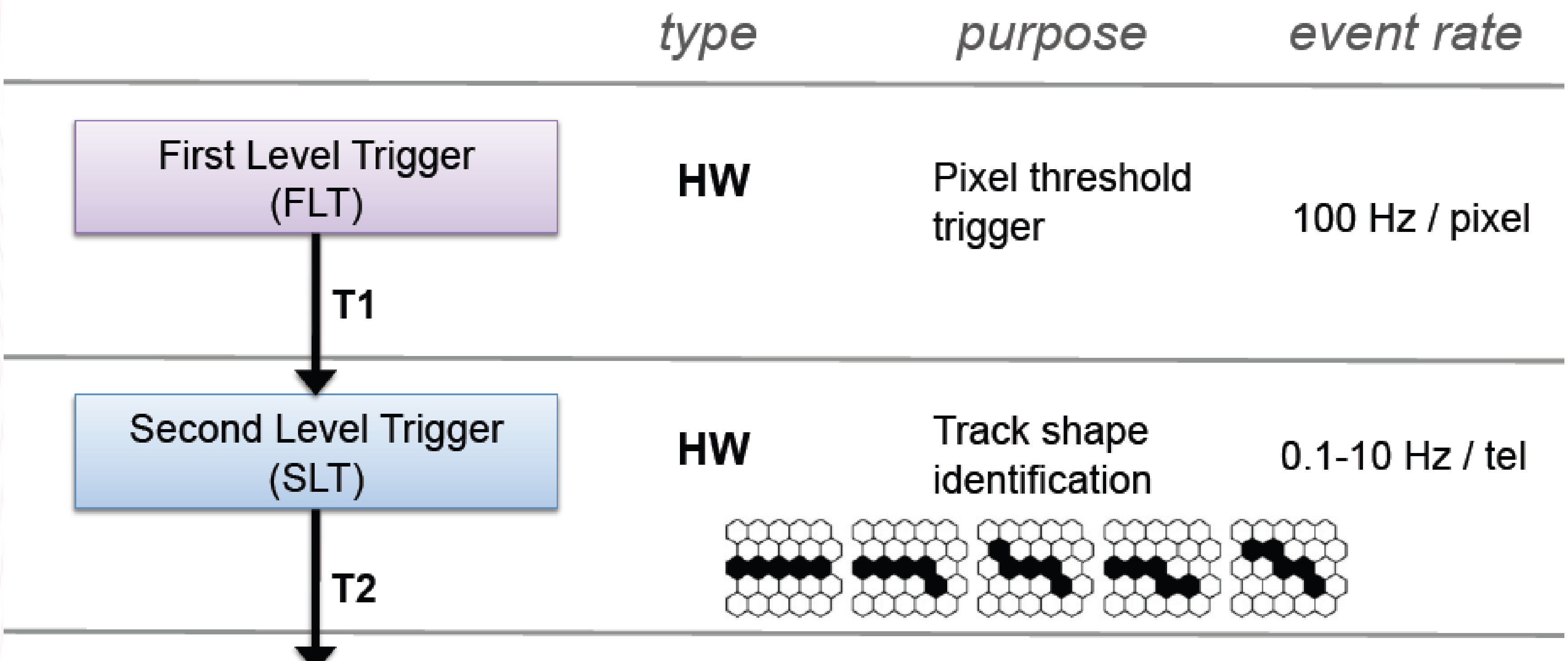
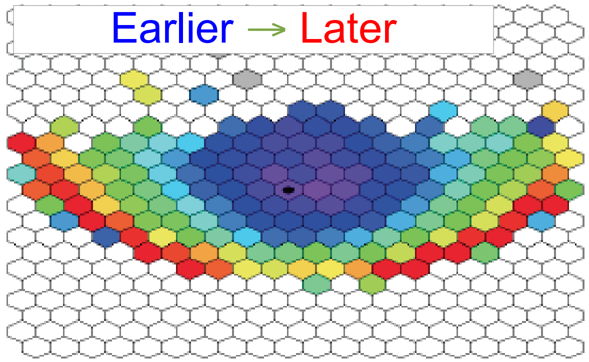


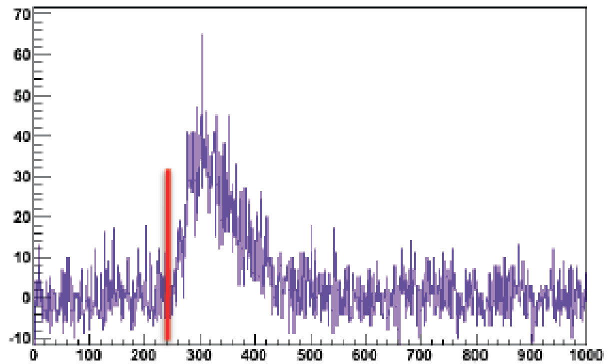

We decided to analyze the fraction of events which pass the 2nd level of trigger, which is saved with prescaling factor 1/100 in a separate data stream (*minimum bias*) and is used for measuring efficiencies and testing new trigger algorithms. 58 new events were found.
**R.Mussa et al., poster at AGU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

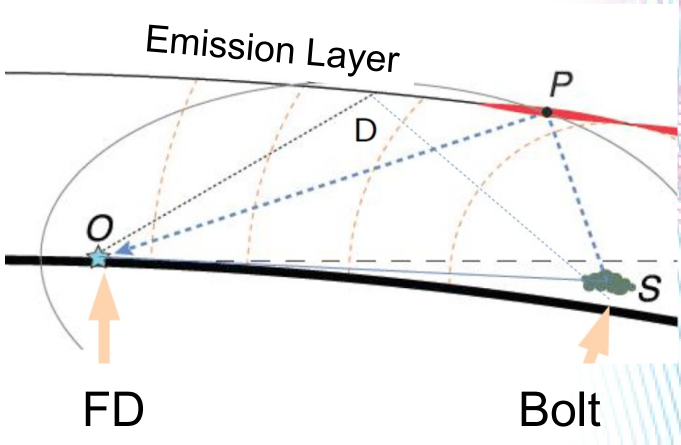
## *4) Check signal amplitude for each pixel*

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

# ELVES reconstruction: 3,4,5D Time Fit

Minimization of $\chi^2$ 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 :

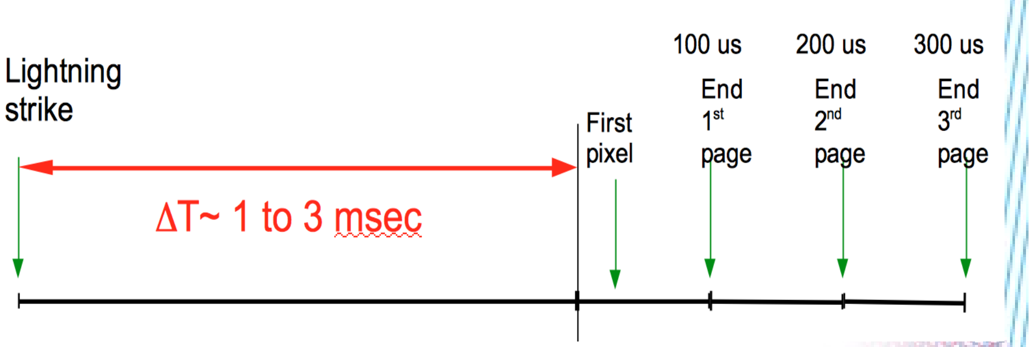
$\Delta T$ : time between the bolt and the beginning of FD trace

$Lat_b$ = Latitude of the Bolt

$Long_b$ =Longitude of the Bolt

Then, 4D-Fit , releasing :

$H_{emis}$ = height of the emission layer (starting value 92 km a.s.l.)



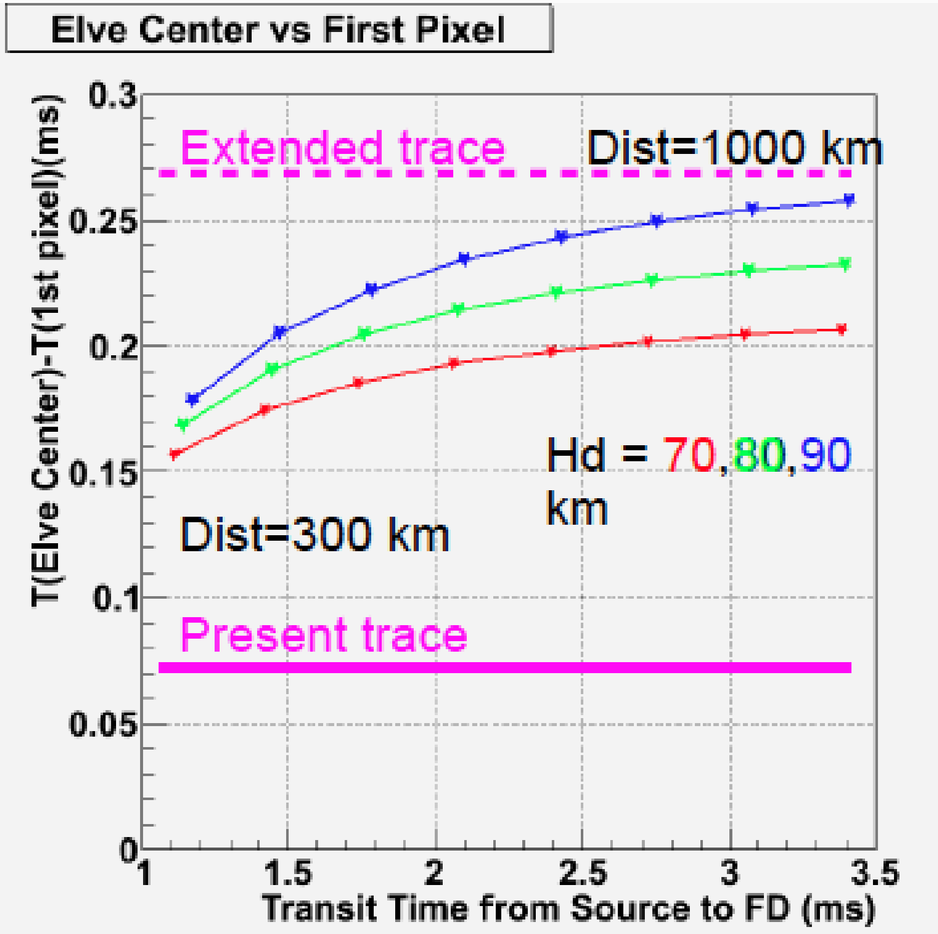

Finally: 5D-fit, releasing

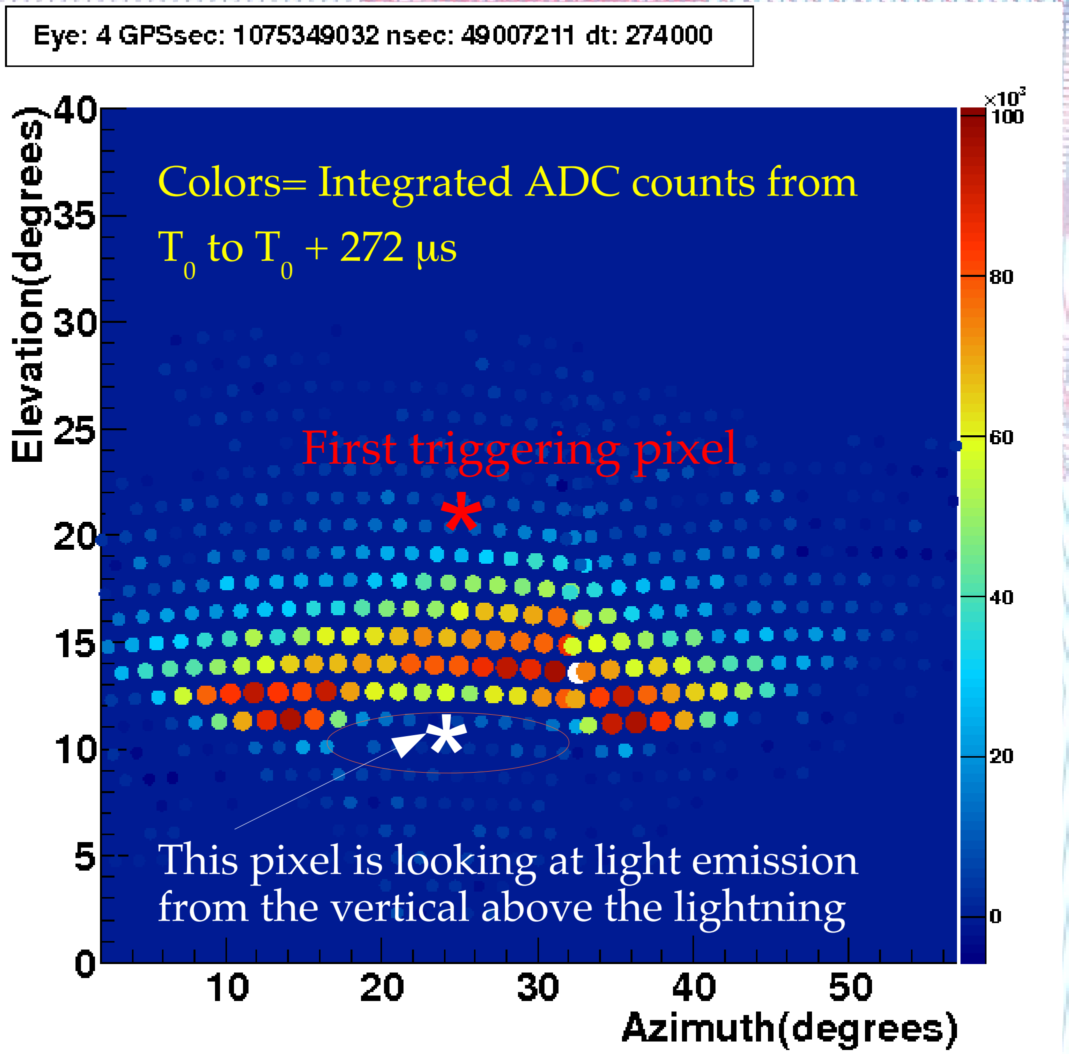
$H_b$ = height of the bolt (starting value 0 km a.s.l.)

*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%)*

# Extended readout



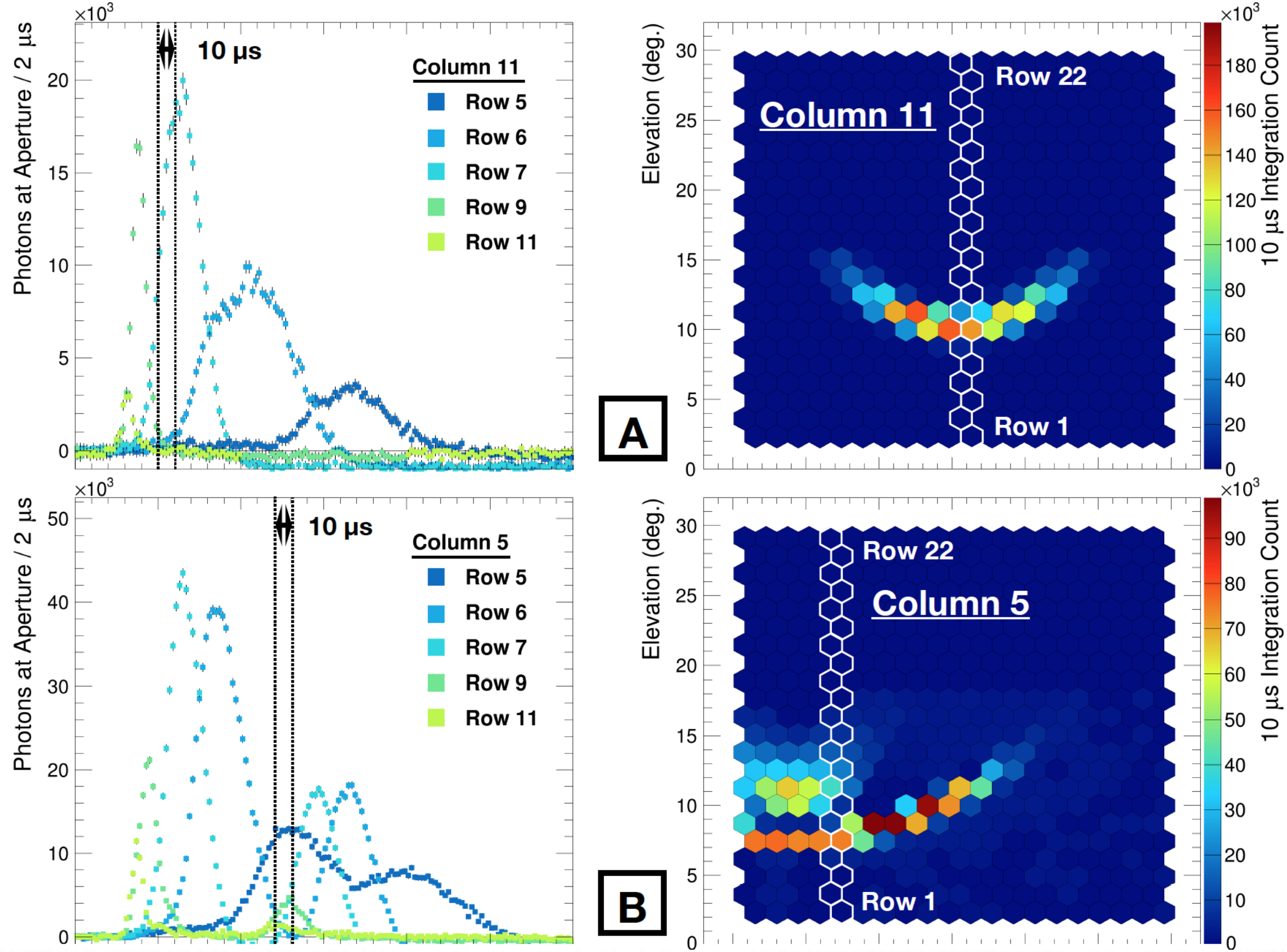




Standard FD traces are 72 μs long, after the trigger: this prevents to see most of the light of the ELVES.
In particular, it prevents to see light from the vertical above the lightning source.
The size of the central hole is connected to the maximum speed of electrons in lightning (0.3-1 c)
Therefore, 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.

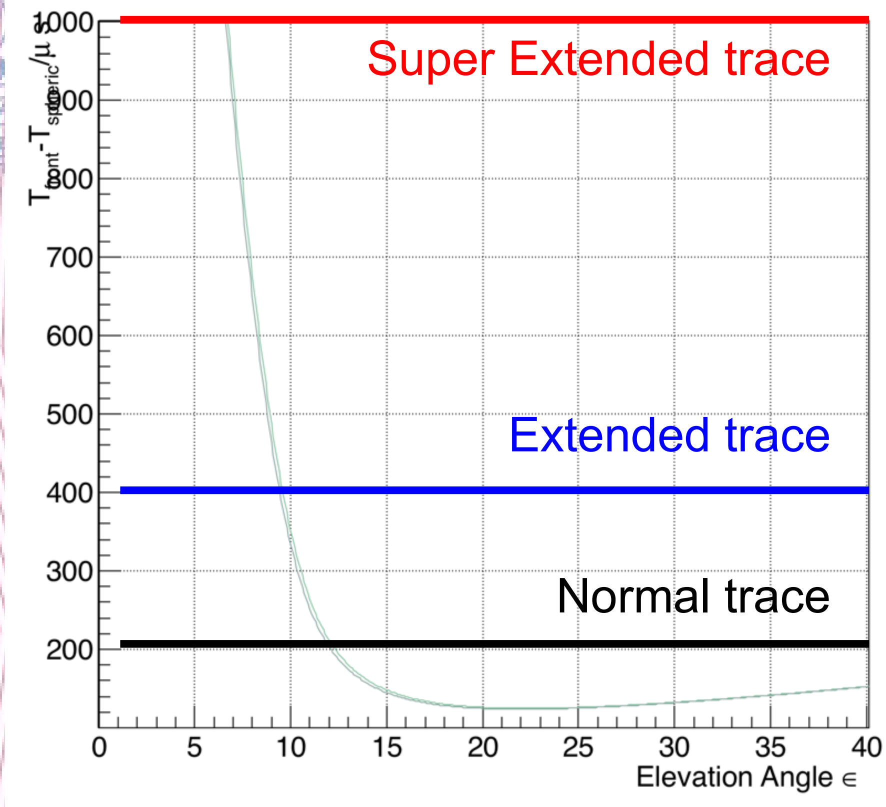
# Typical ELVES signals

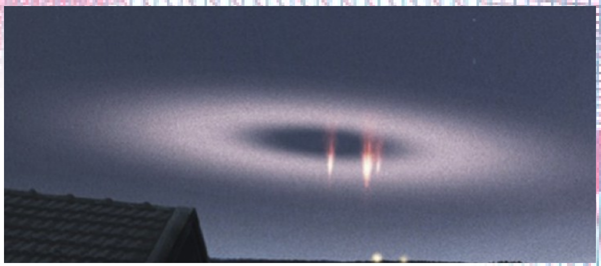
Single

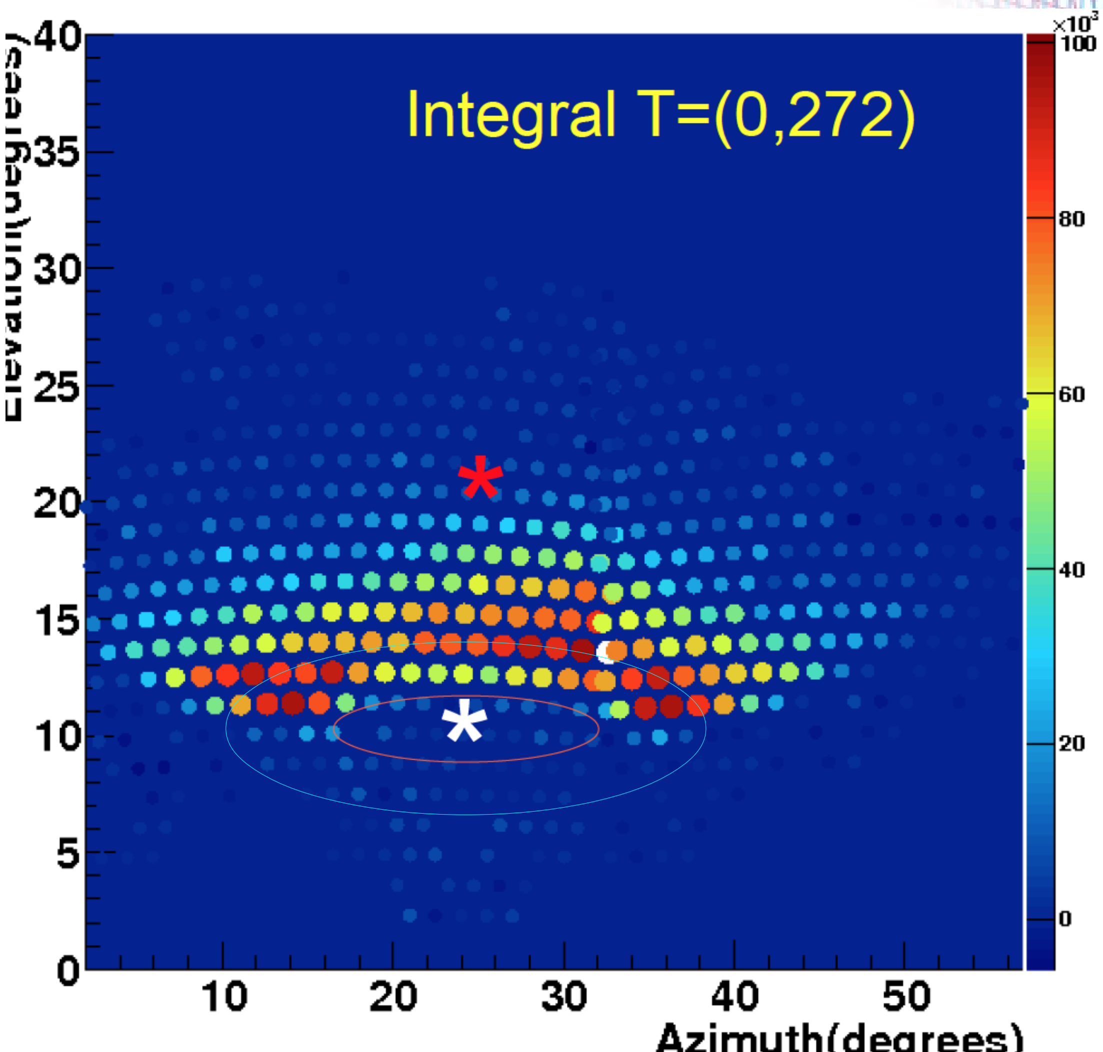
Double



# Super-Extended readout



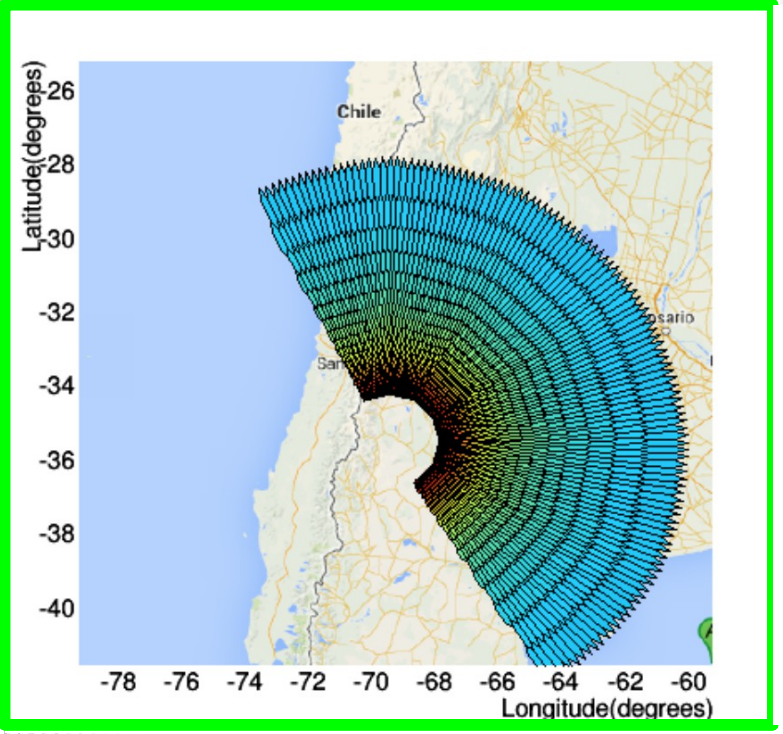



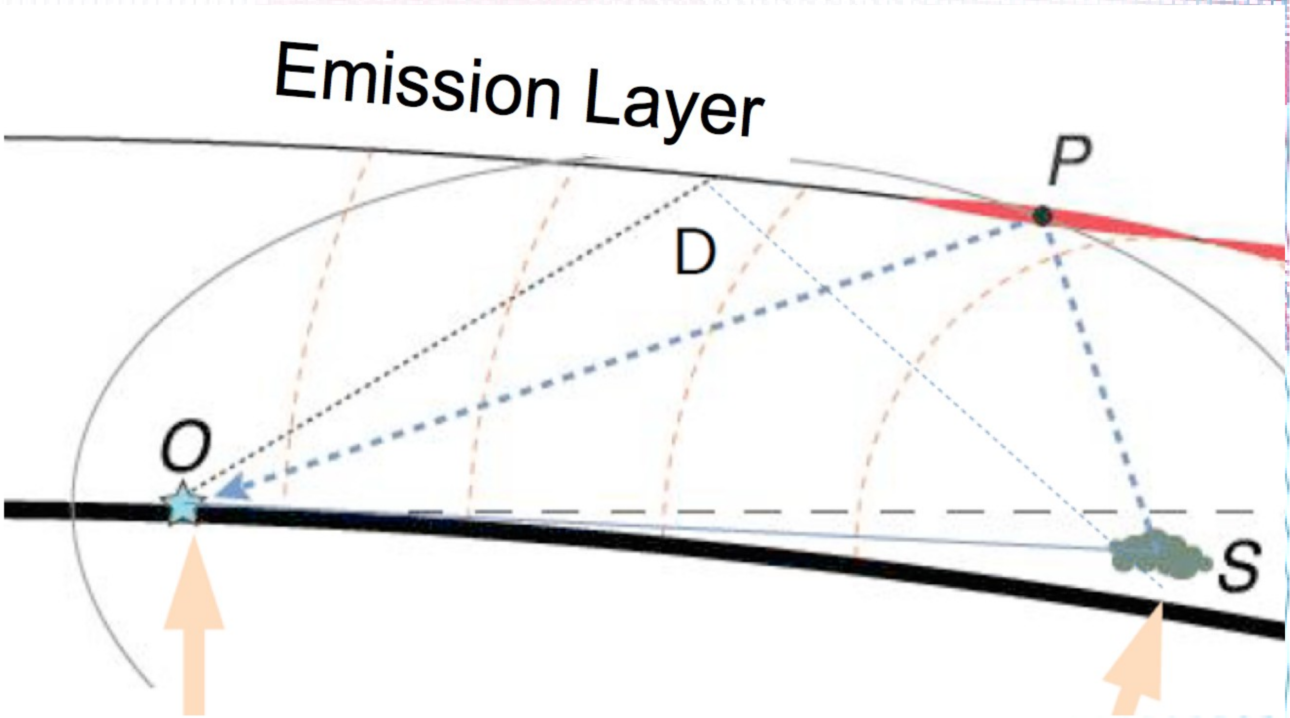



To measure light from the lower (i.e. far) part of the ring and study asymmetry with respect to the lightning center, we need to add ~0.6 ms to go 3° down.

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

# Light emission normalization



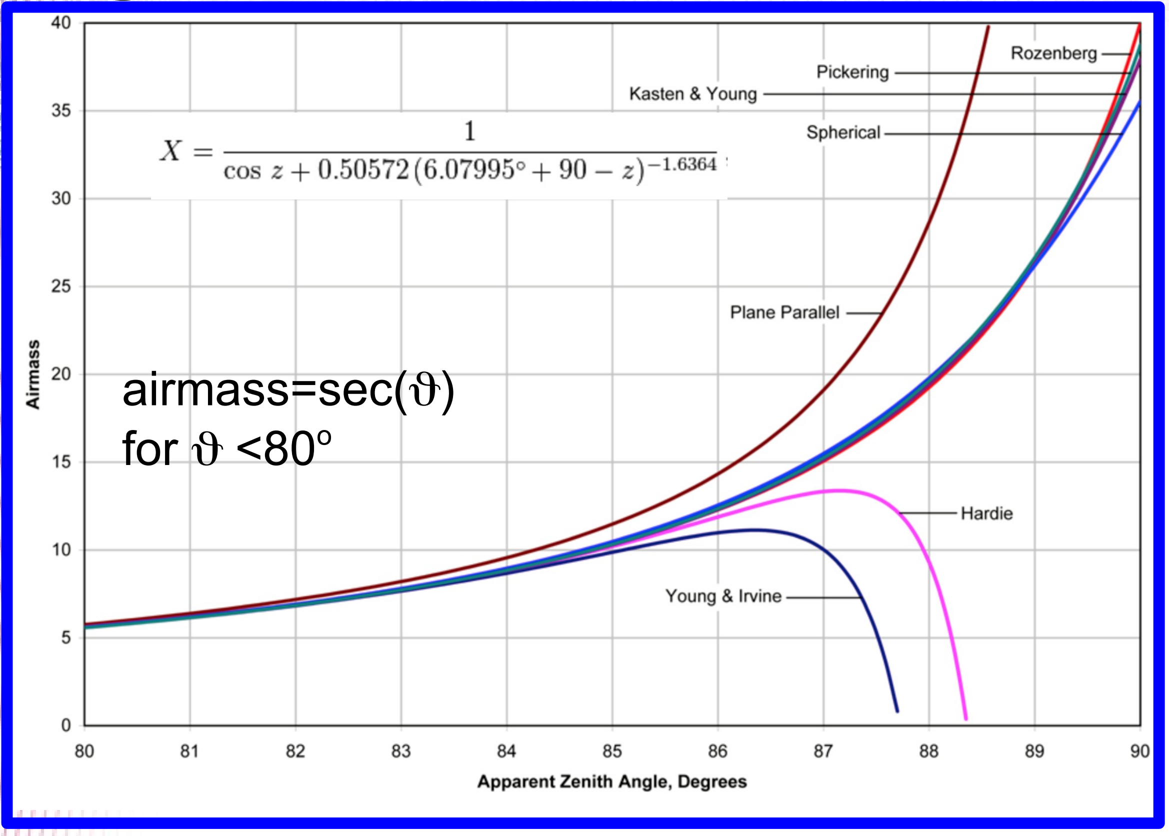



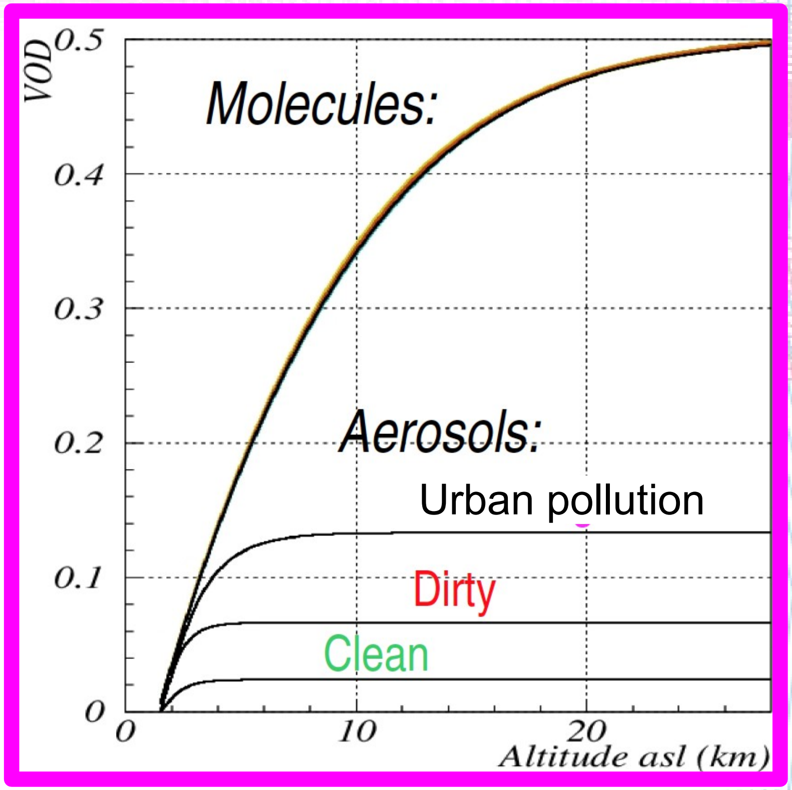

Photons detected by the FD camera are corrected for distance from the base of ionosphere and for the surface observed by each pixel:

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

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

# Light emission normalization

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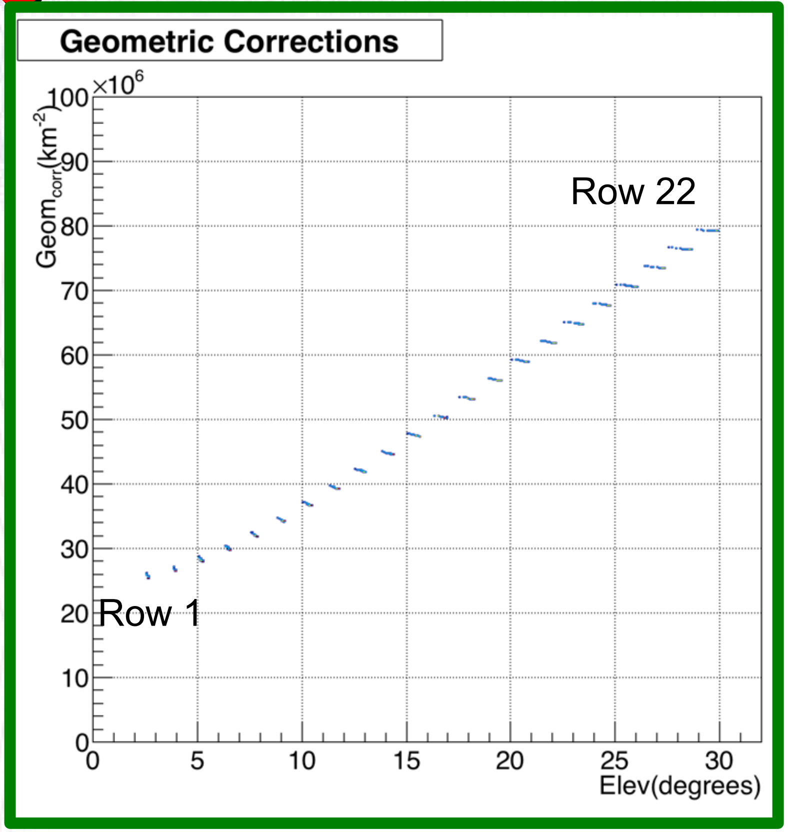
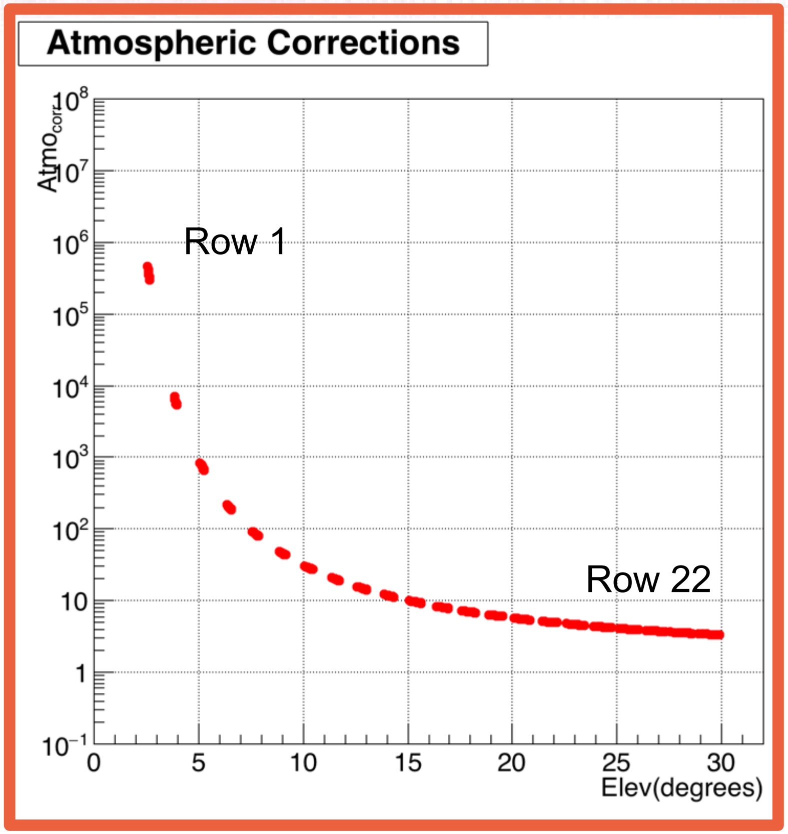
$$\Phi(i) = PFD(i) * Geom\_corr * Atmo\_corr$$

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

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*.

# Light emission normalization

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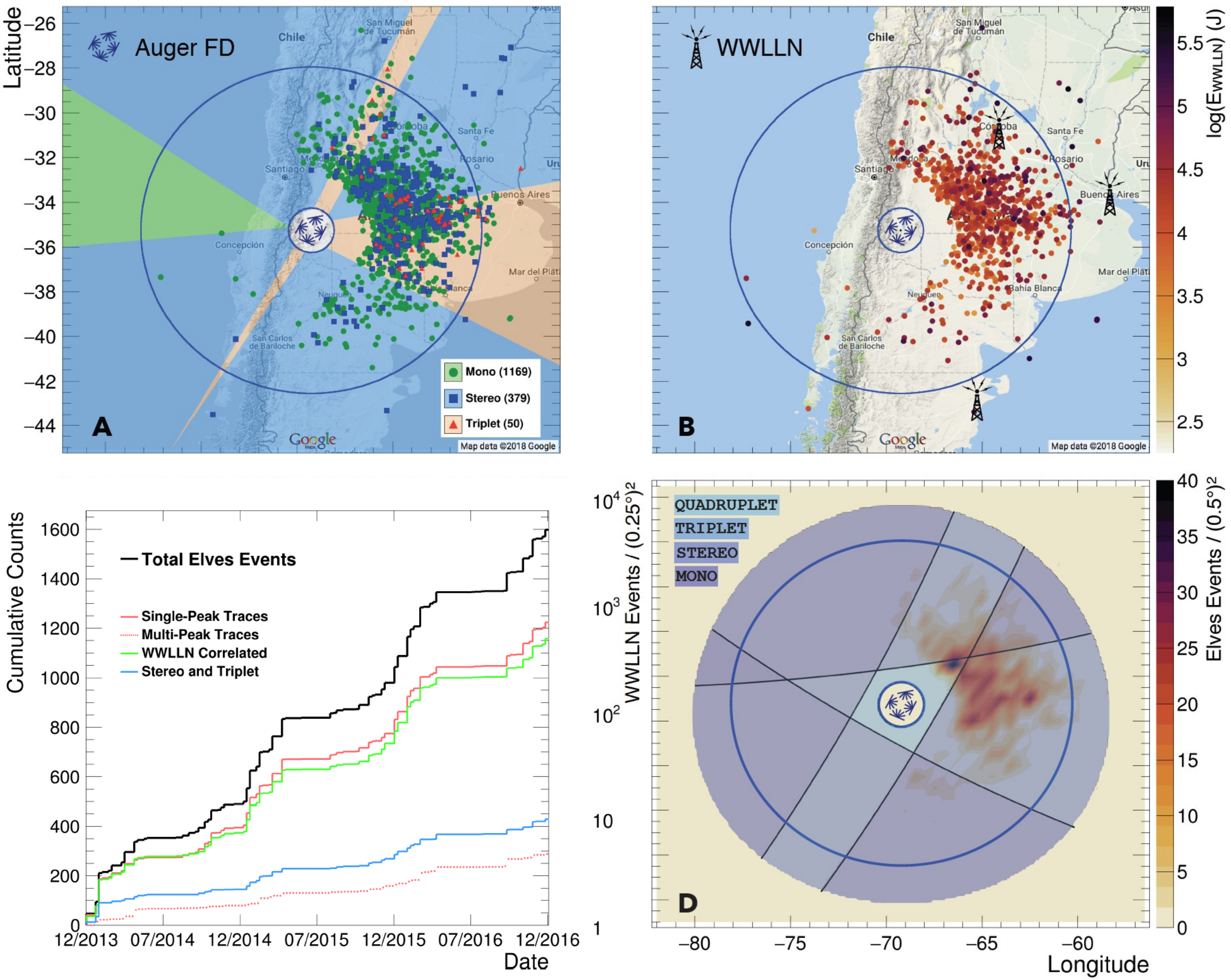
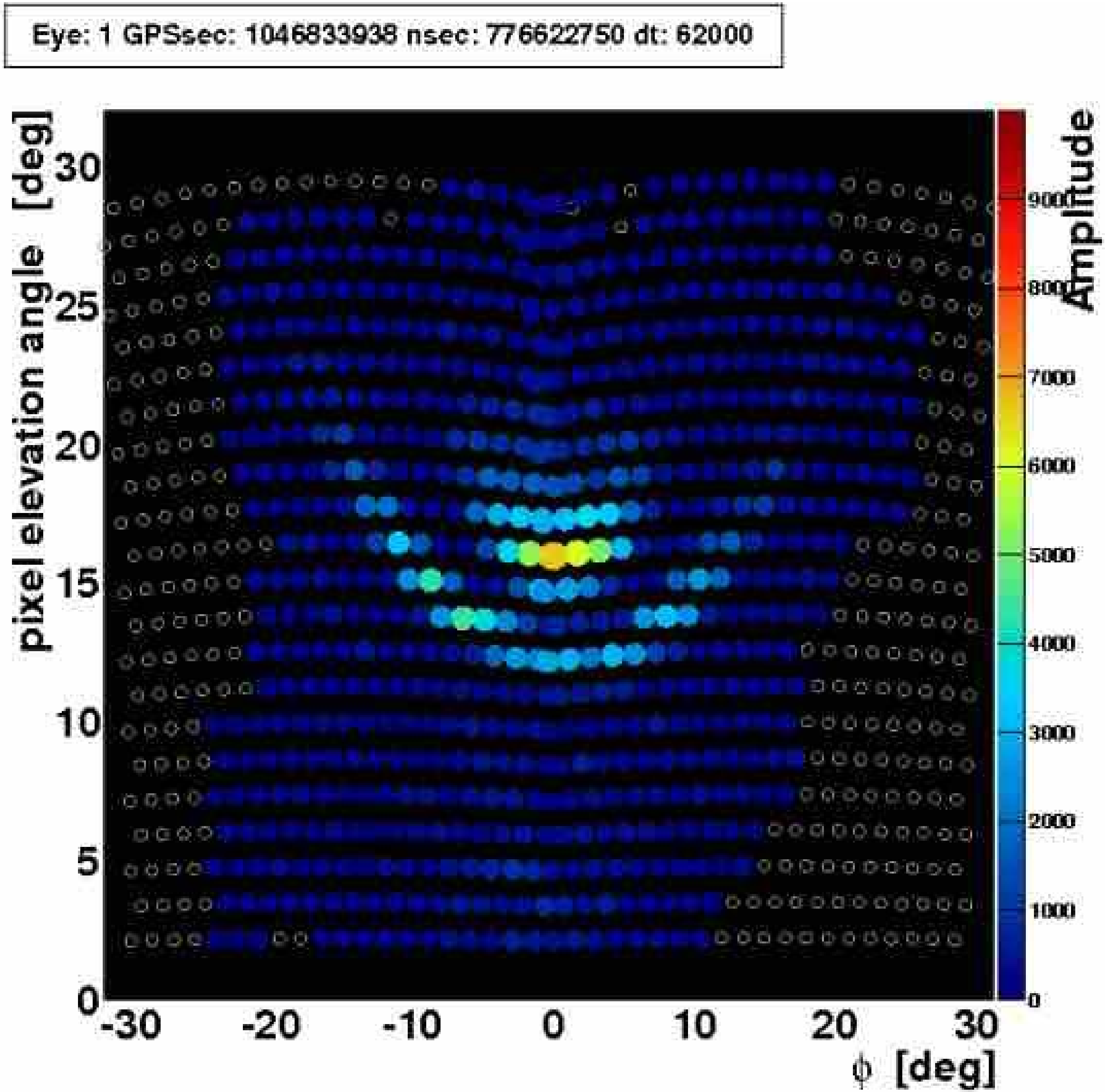
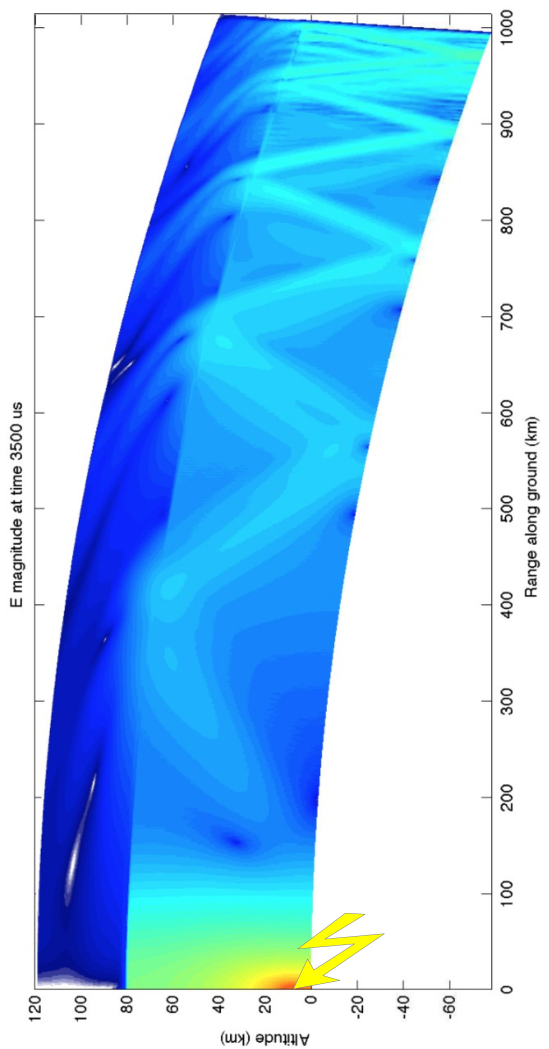
# ELVES statistics and location



Double ELVES observed by two FD's (STEREO)



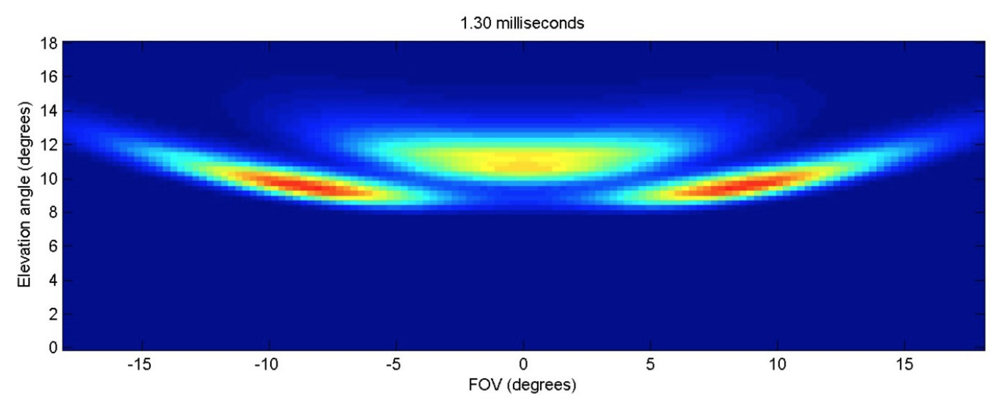
# ELVES simulations




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

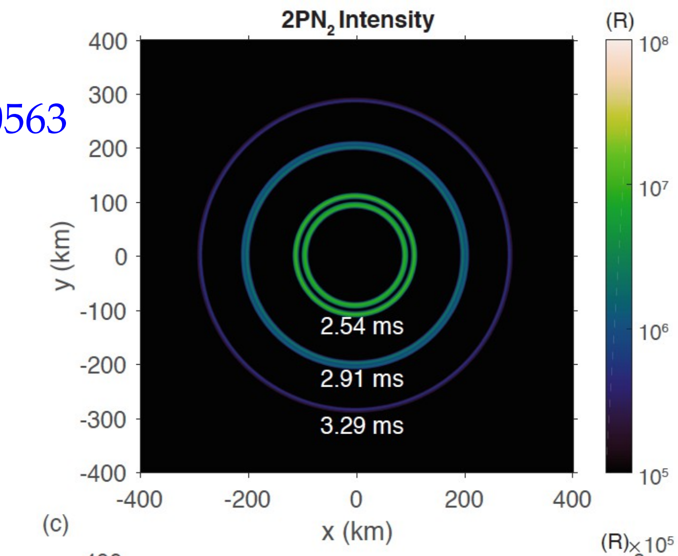
Finite element simulations of EM fields in atmosphere (from 70 to 150 km) to produce 2D and 3D models of light emission

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

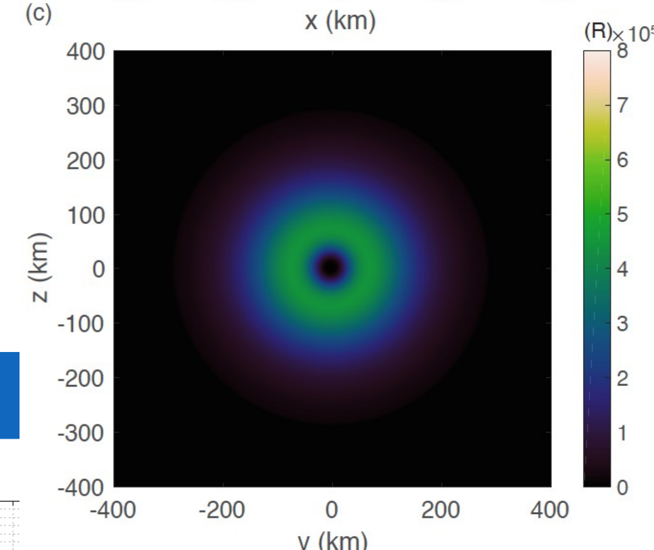


# TGF signatures: multiple ELVES

Liu et al, JGR 122(2017)10563

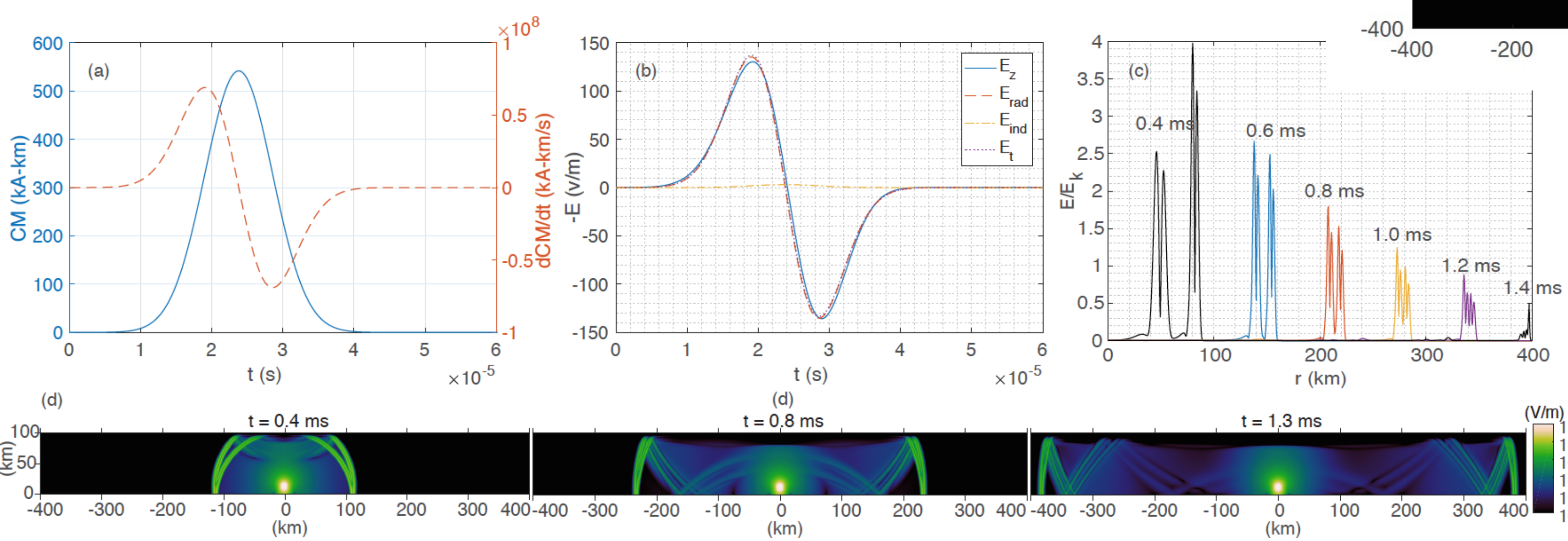



Can we detect TGF ignition at ground with the associated TLE?
What are its spectral properties?
What's its pulse duration?
Sources:
  NBE (Narrow Bipolar Events)
  EIP (Energetic In-cloud Pulses)
  CG (Cloud to Ground Lightning)

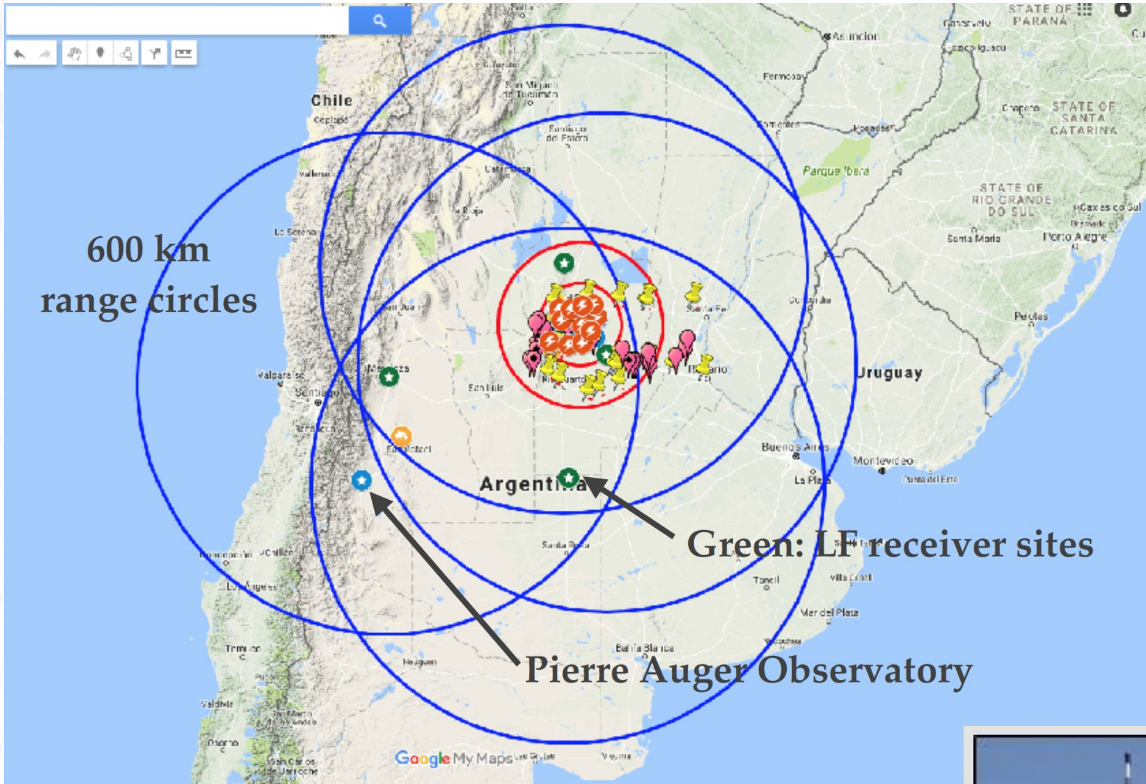



Pulses with peak currents of > 500kA can result in Multiple ELVES with light emissions in UV up to 10 MR are modeled.
Second peak originates from reflected wave on earth surface

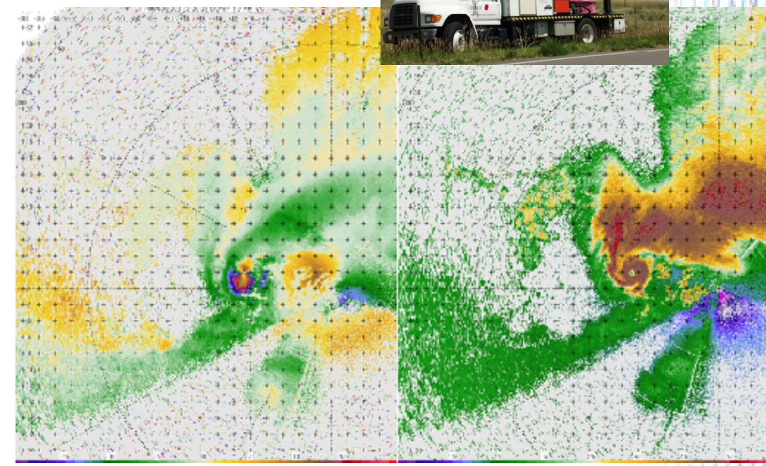
**EMP Produced by an Impulsive EIP**



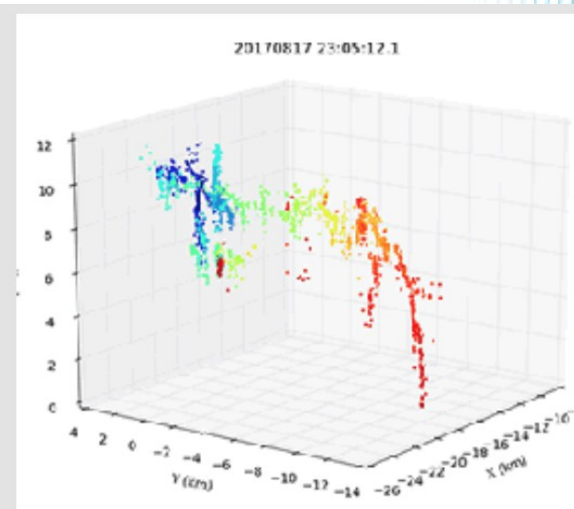
# Joint work with RELAMPAGO campaign (11-12/'18)

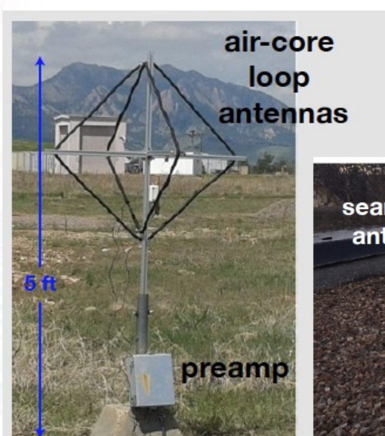



Doppler radars

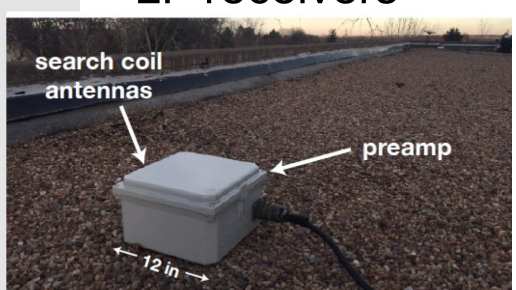


Lightning mapping array




LF receivers



# Wrapping it up ....

- In the quest of a better understanding of UHECR, we could learn about earth's atmosphere (not just troposphere, but also our ionosphere) and beyond: up to solar weather impact on their flow on earth.

- While searching for cosmic accelerators, we are finding out that lightning are behaving like particle accelerators, and the dynamics of these processes are far from being fully understood.

- Auger SD and FD detectors, with few ns time resolution, have a unique perspective to get insights on the dynamics of lightning: we serendipitously re-discovered ELVES and we are studying other anomalous events that raise questions and challenge models on atmospheric electricity.

STAY TUNED !!!