Fisica multidisciplinare con l'Osservatorio Auger

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Istituto Nazionale di Fisica Nucleare

PIERRE AUGER OBSERVATORY

Cosmo-Geophysics Task

Task leaders: Roberta Colalillo (NA) and Roberto Mussa (TO)

Other involved groups: Argentina, France, Germany, Brazil, Colombia, …

Main topics:

Atmospheric electricty

→ Transient Luminous Events (ELVES, Sprites, …) - ICRC 2025, R. Mussa (TO)

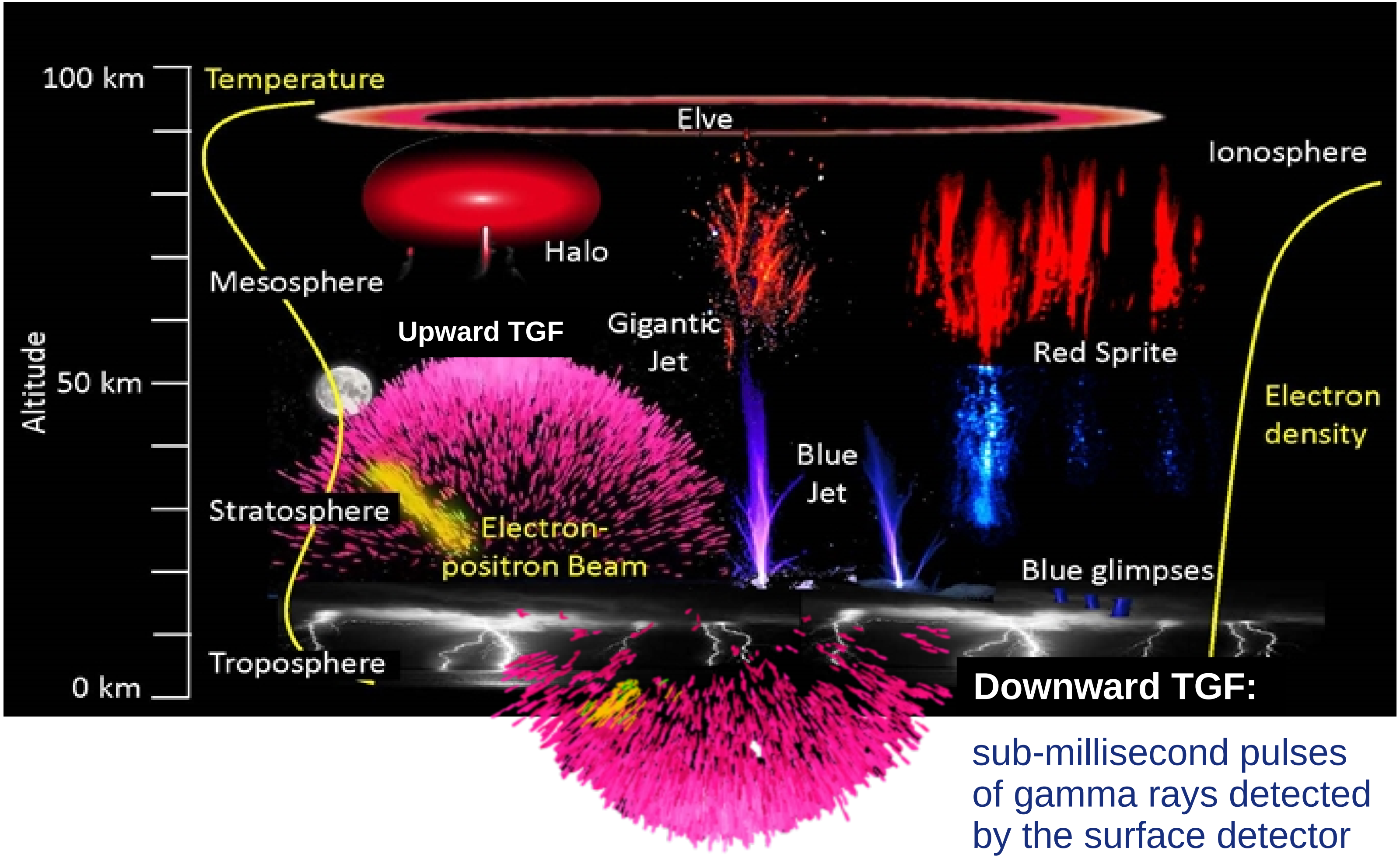
→ Terrestrial Gamma-ray Flashes - ICRC 2025, R. Colalillo (TO)

Solar Activity

→ Scale data - ICRC 2025, C. Taricco (TO)

→ Radio measurements - ICRC 2025, R. Menezes (Brazil)

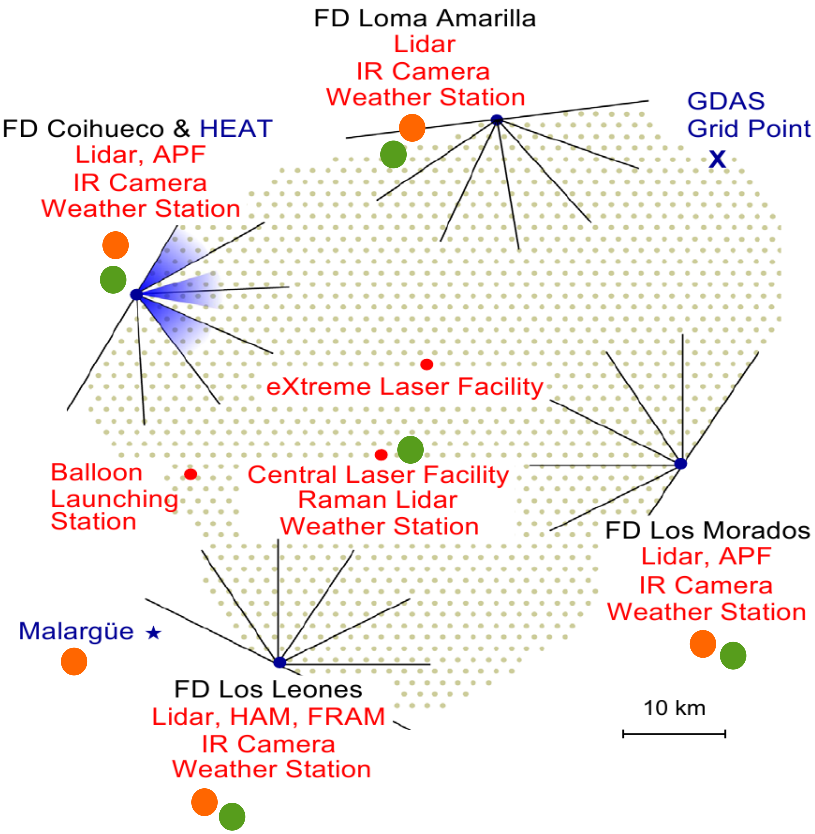
Bright events produced by lightning



Downward TGF:

sub-millisecond pulses of gamma rays detected by the surface detector

The Pierre Auger Observatory

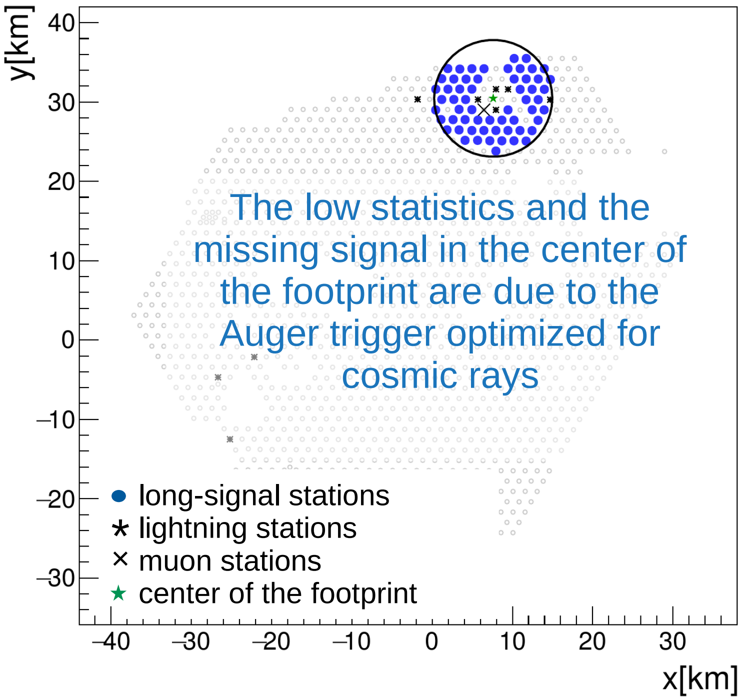


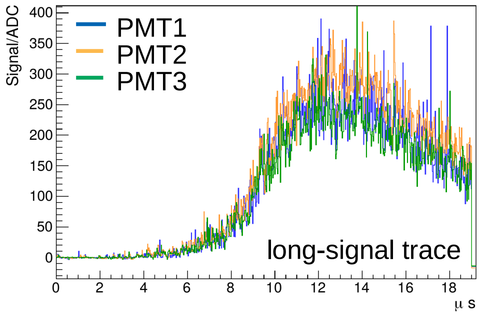
5 Boltek Storm Trackers – Lightning Detectors

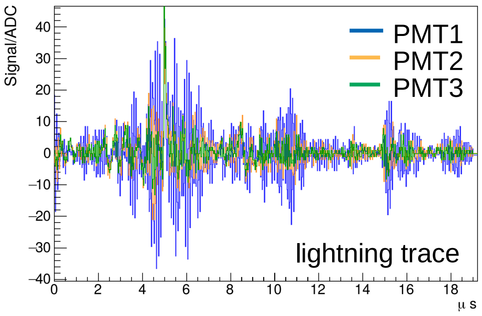
Auger Downward TGFs

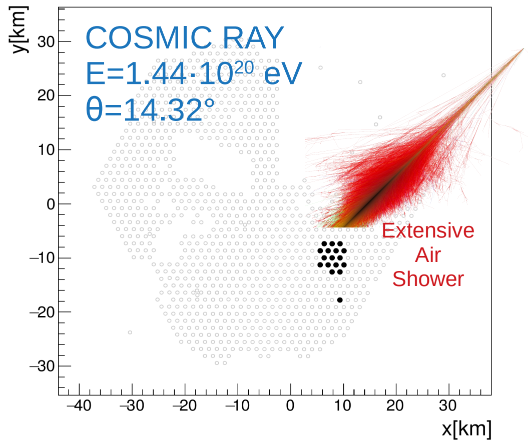
R. Colalillo [for the Auger Coll.], PoS(ICRC2021)395.

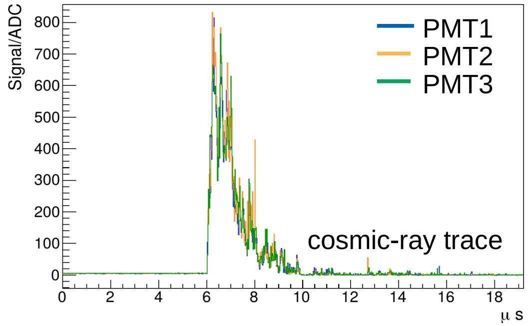
23 peculiar events collected from 2005 to 2017 (change in the SD trigger).

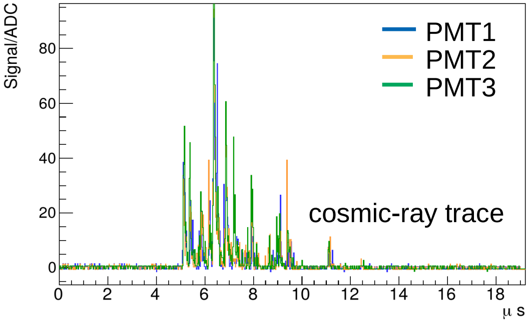








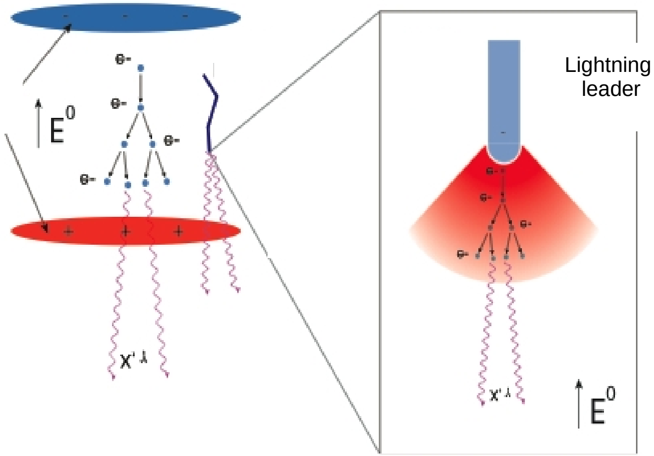




We have observed less than 2 events/year, while at least 30 events/year are expected considering the known lightning rate at the Observatory and a lightning/TGFs ratio of approximately 10^3.

It is necessary to change the trigger and acquisition system to improve TGF detection.

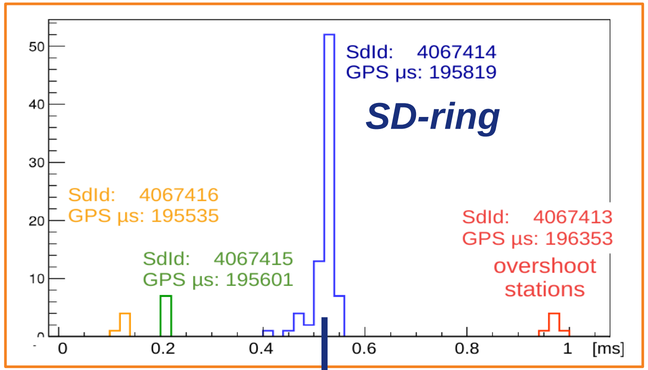
Auger Downward TGFs

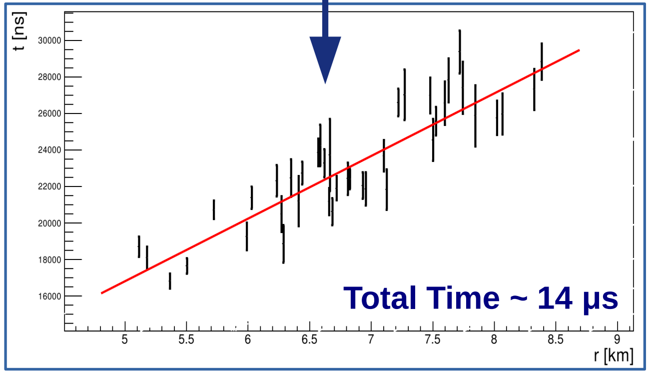


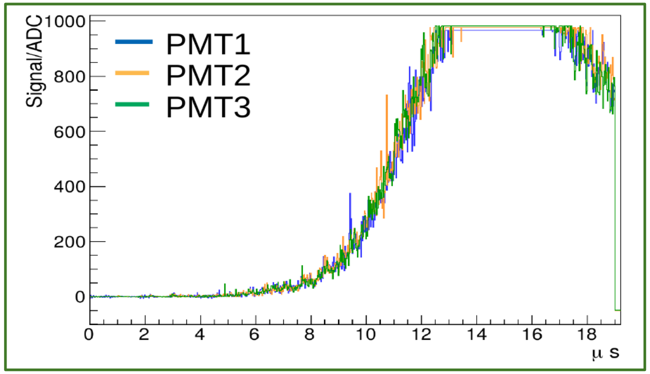
A TGF is a burst of high-energy photons originating in thunderstorms usually observed from the space.

Lightning-leaders do not propagate in a continuous manner, but instead progress in a series of discrete "steps"
→ the typical duration of the process is of the order of a ms
→ the inter-step intervals last some tens of μs.

TGFs are so bright that they usually saturate also detectors far from the source.

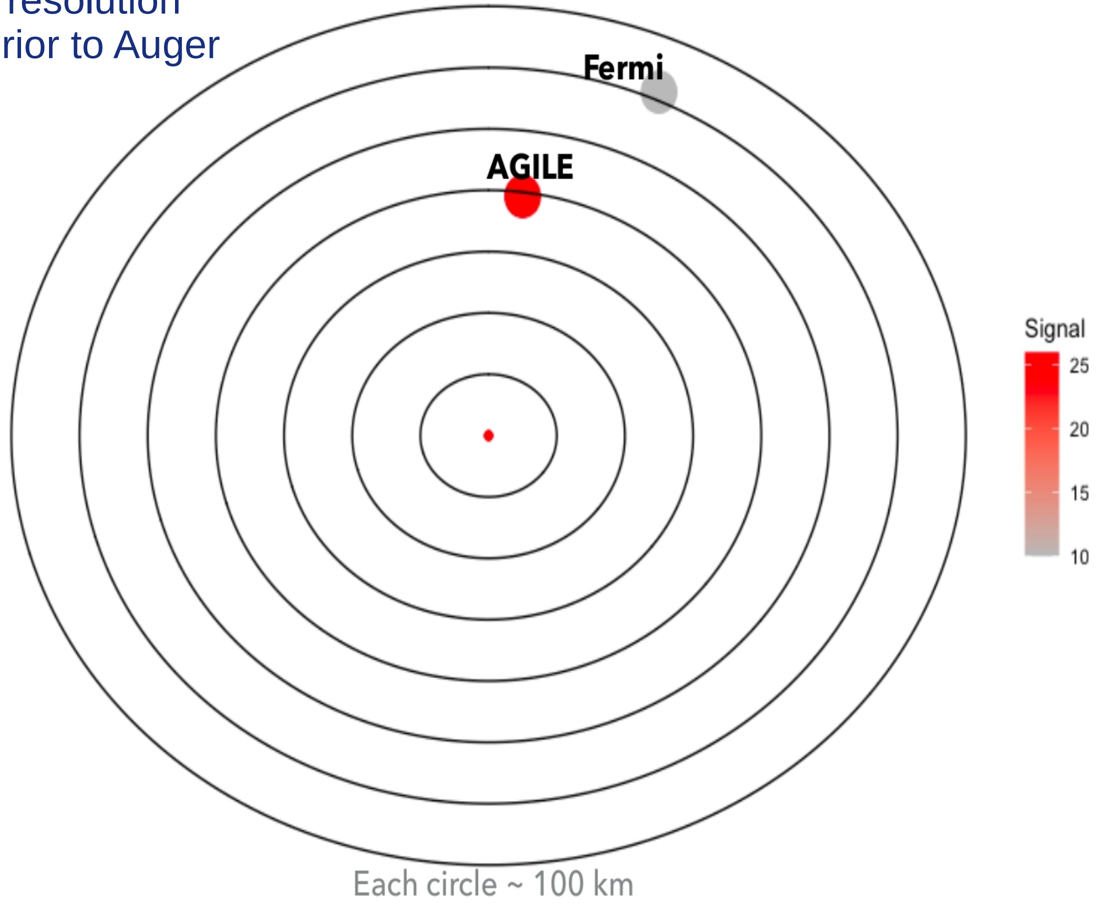


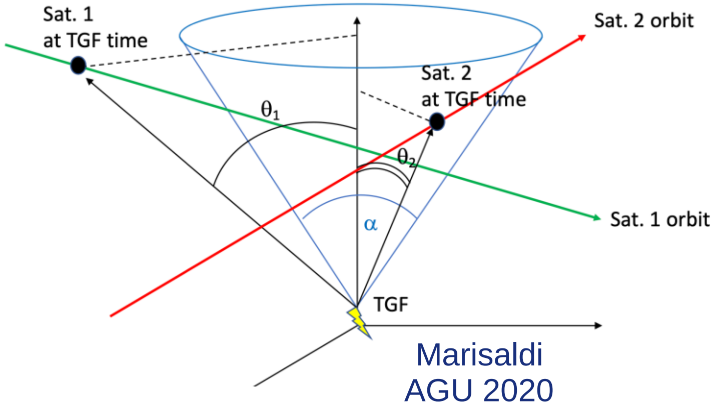




Advantages of a ground array

Greatest spatial resolution prior to Auger

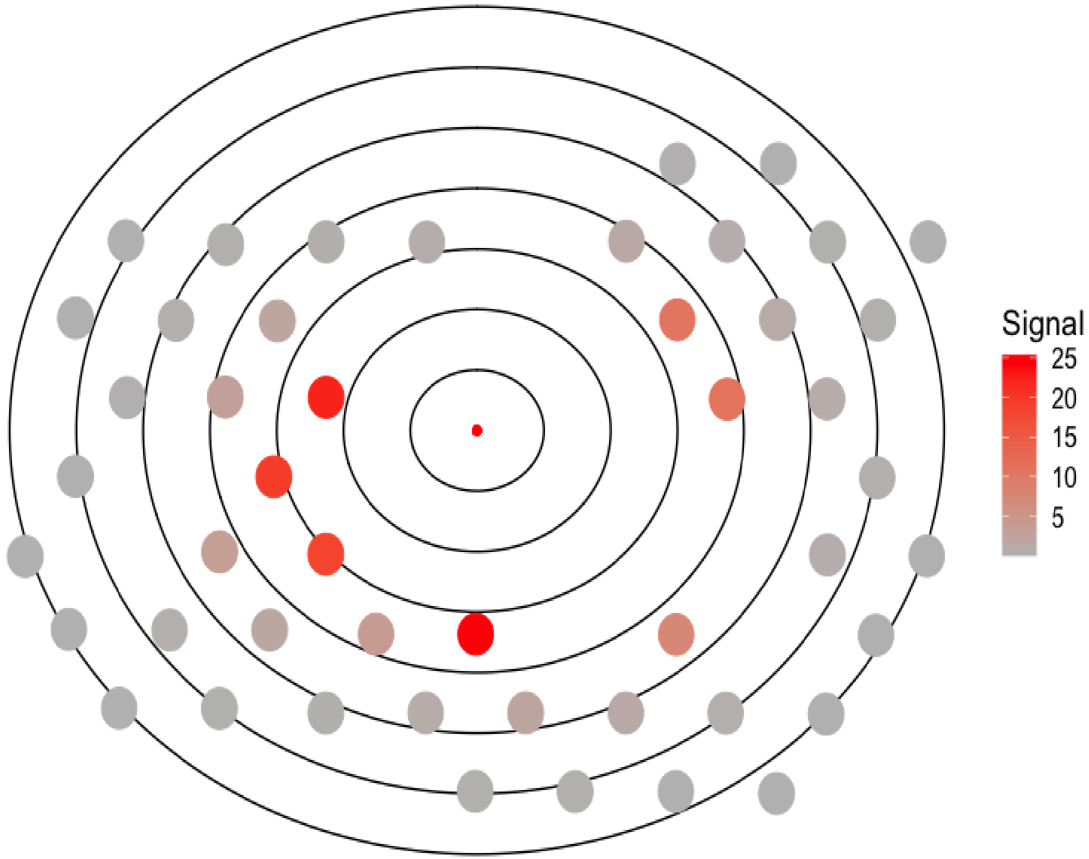




Marisaldi AGU 2020

Advantages of a ground array

@Auger



Each circle ~ 1 km

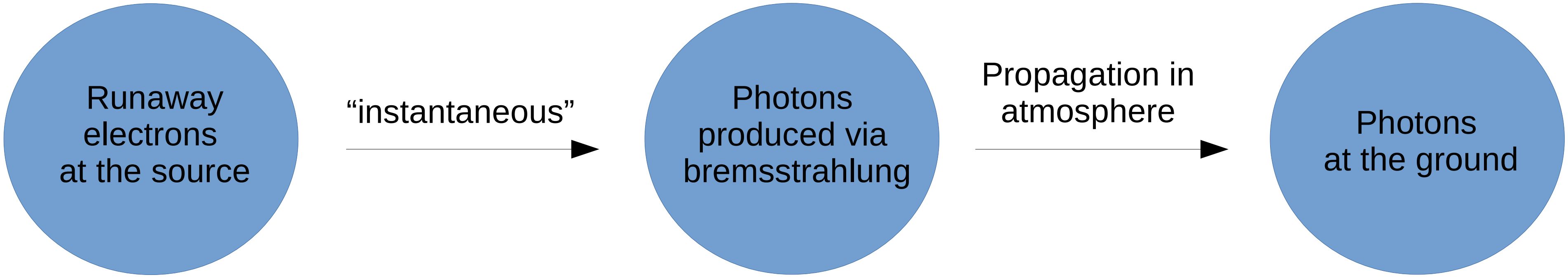
- Reconstruction of the source position (few km above the ground)
- Sampling of the cone
  → study of the signal distribution
- Very detailed signal
  → Cherenkov detectors sensitive to gammas > 1 MeV
  → smooth time profile with 25 ns time resolution

Downward TGF production models

Theoretical models are not exhaustive:
→ they are mostly based on observation of upward TGFs;
→ downward TGF observations are few and they haven’t as good time resolution as Auger data.

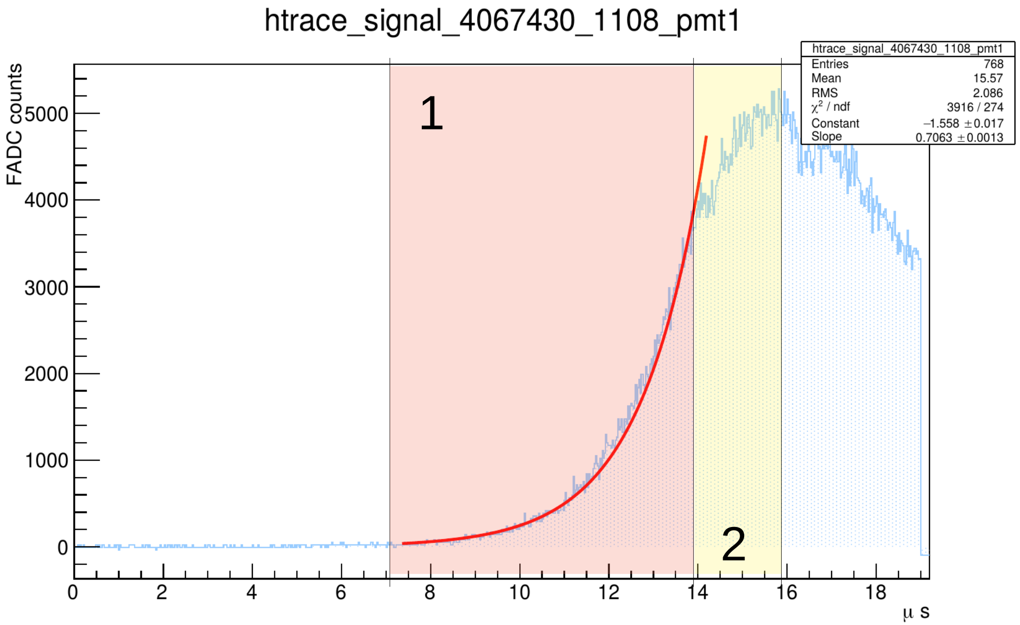
What can we learn from Auger data? Can our signals put constrains on the production models?

Relativistic feedback (an external source of energetic seed electrons is not required)
→ predicts an exponential emission at the source



A simple exponential fit could describe the rise time of Auger signals

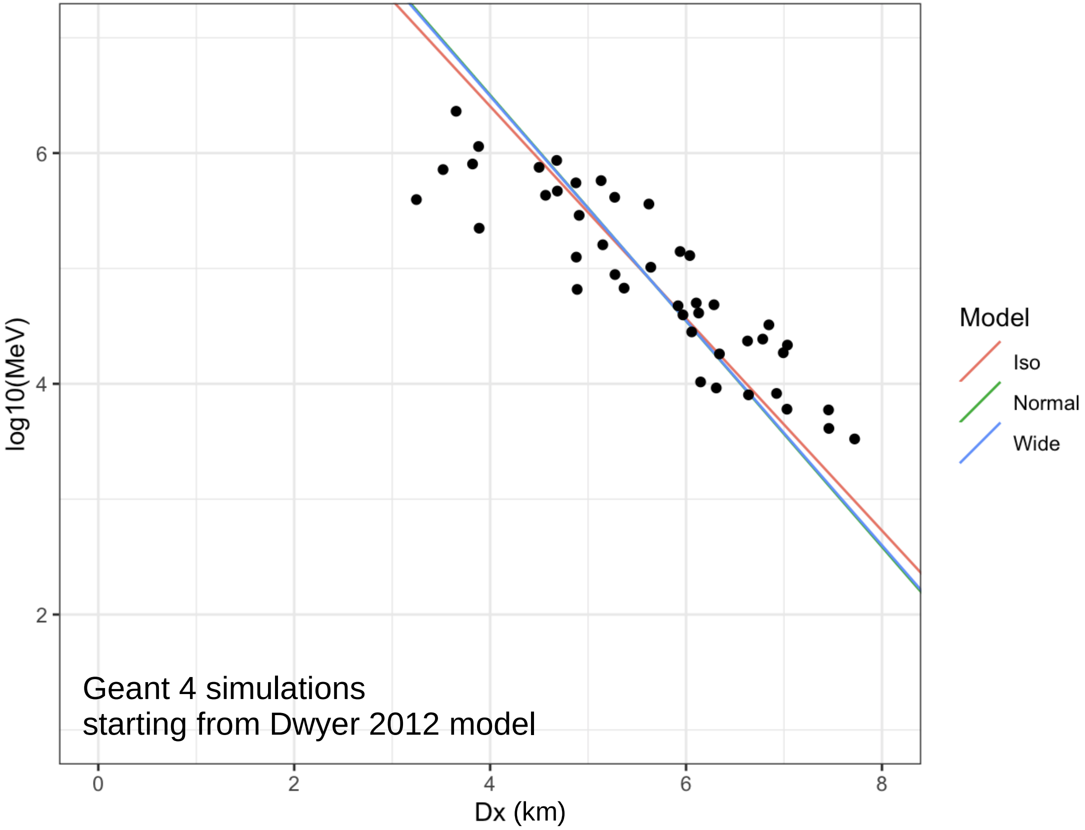
Does an exponential fit the risetime of our signals?



1. **Exponential part**: the flux is low the generated discharge current is also low and the electric field is not being modified by the RREA.
2. Once the flux reaches a large enough value, the currents lower the field and the RREA generation starts slowing down and eventually stops.

R. Colalillo [for the Pierre Auger Coll.], Proc. 38th Int. Cosmic Ray Conf., Nagoya, Japan (2023), PoS(ICRC2023)439.

Comparison with standard TGF simulations



- Auger TGFs show a brightness similar to TGFs seen from space (10^{17}-10^{18} photons)
- The slope is not very well reproduced by standard TGF models

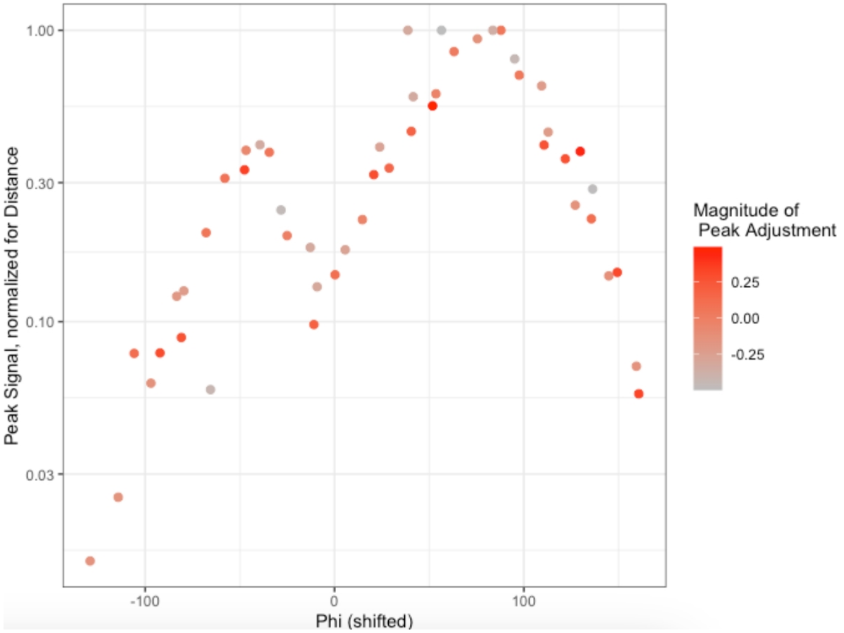
Collaboration with American TGF experts:
J. Dwyer, D. Smith, J. Ortberg

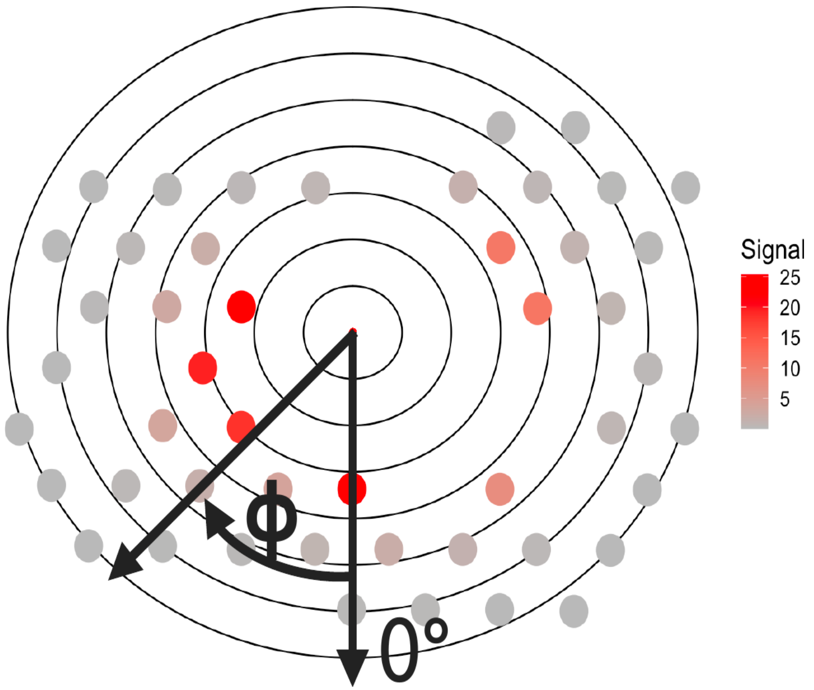
First evidence of an asymmetric TGF

Signal = f(r)*g(phi)

A correction was applied for distance dependence

An Editorial Board started to work on this paper





Indication for different sources?

Relativistic Feedback assuming an upward positive leader (Dwyer 2021);

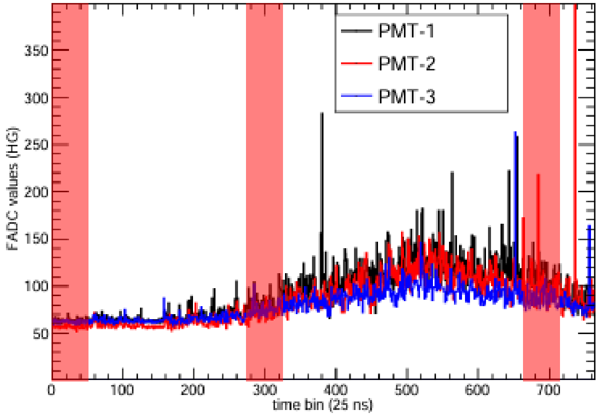
Reactor Feedback (Stadnichuk 2021)

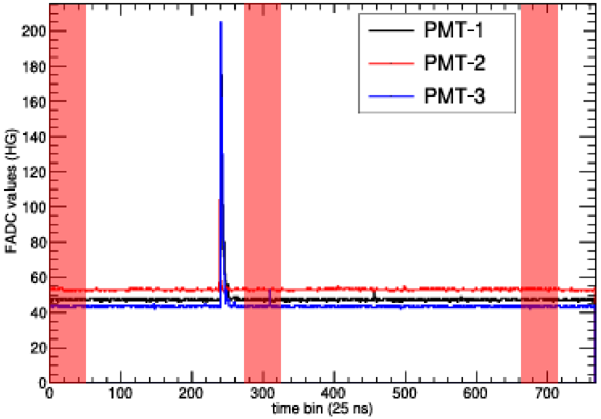
Long-signal algorithm

- When there are thunderstorms, the trigger rate increases a lot and the acquisition system (CDAS) cannot manage the saving of all events.
- In november 2021, a new algorithm, aimed to tag long signals, typical of Auger TGF events, was implemented in the old electronic boards with the idea to give prioryty to the subset of events containing long signals in the CDAS readout.
- The flag is based on the comparison among the integral of three different parts of the trace

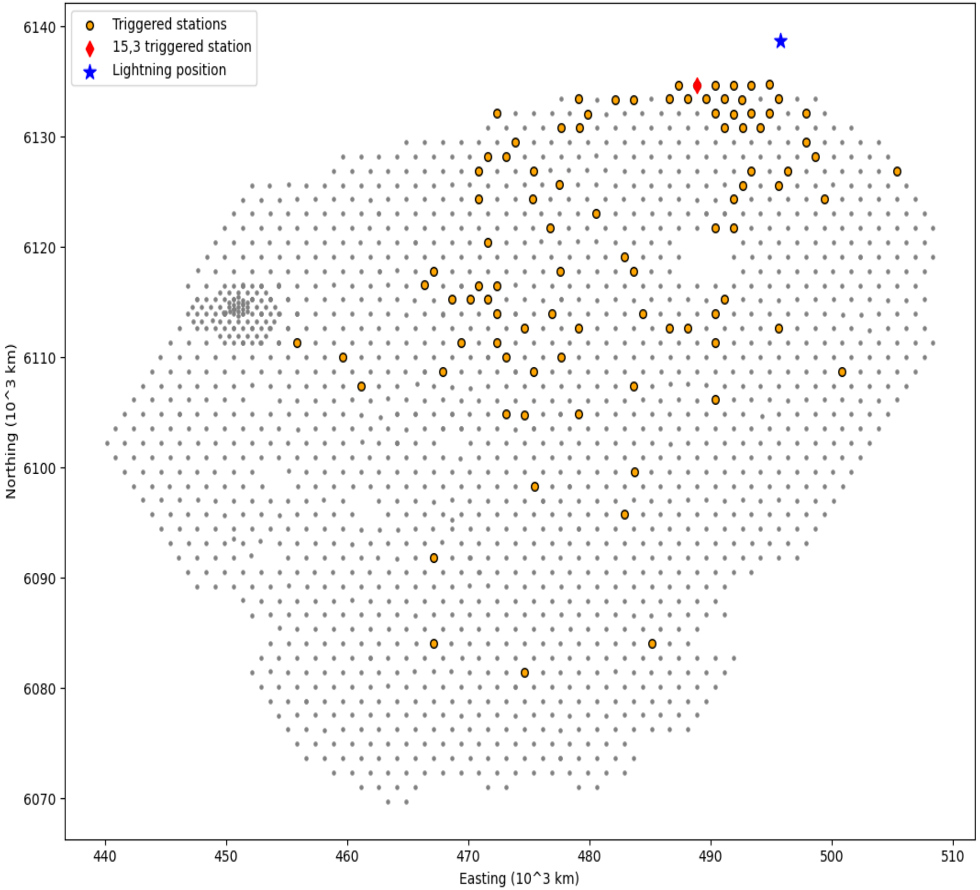
$$\sum_{i=2}^{n_{\text{inter}}} |S_i - S_1| > x_{\text{thr}}, \quad \text{where} \quad S_i = \sum_{j=a_i}^{b_i} t(j)$$

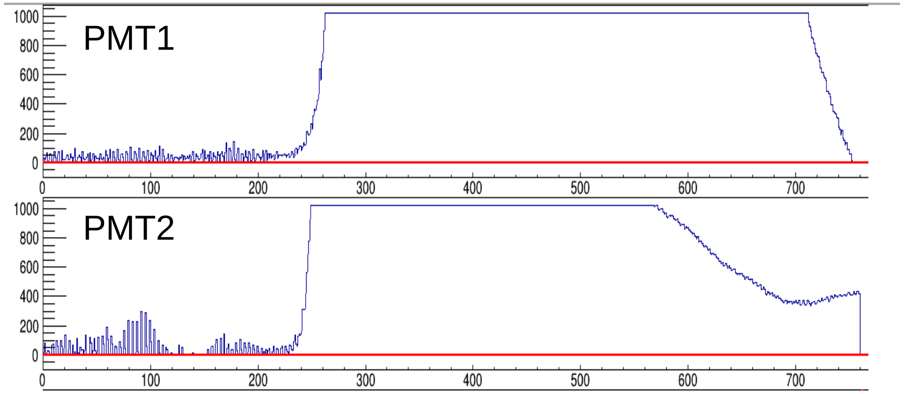
"Terrestrial Gamma-Ray Flashes at the Pierre Auger Observatory", M. Schimassek for the P. Auger Coll., DOI: 10.1088/1742-6596/2398/1/012003





First new long signal





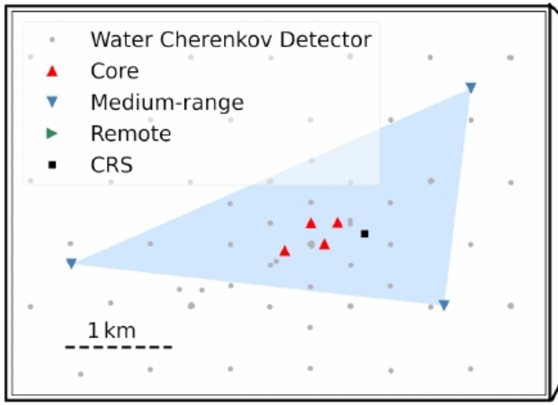
A lightning in time and spatial coincidence with this event was detected by WWLLN (blue star).

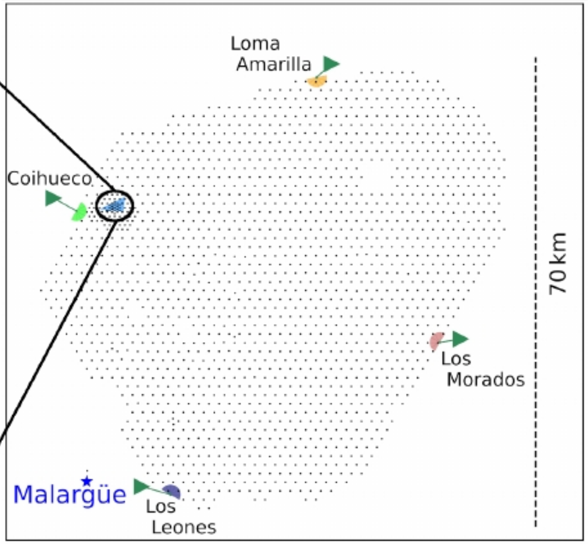
The implementation of the flag on the old WCD electronic boards has not negatively affected the detection of cosmic rays in any way
→ it will be implemented on the new SD station electronic boards before the next lightning season.

Correlation of SD data with Radio measurements

BOLT (Broadband Observatory of Lightning and TGFs)

10 upgraded AERA stations (30-80 MHz) – **the VHF range is very good for mapping lightning in 2 and 3D**
→Change trace length from μs (cosmic rays) up to s (lightning)
→Reading, storing and transmitting large data to DAQ (sub-Hz event rate for cosmic rays → 10-100 kHz for lightning)





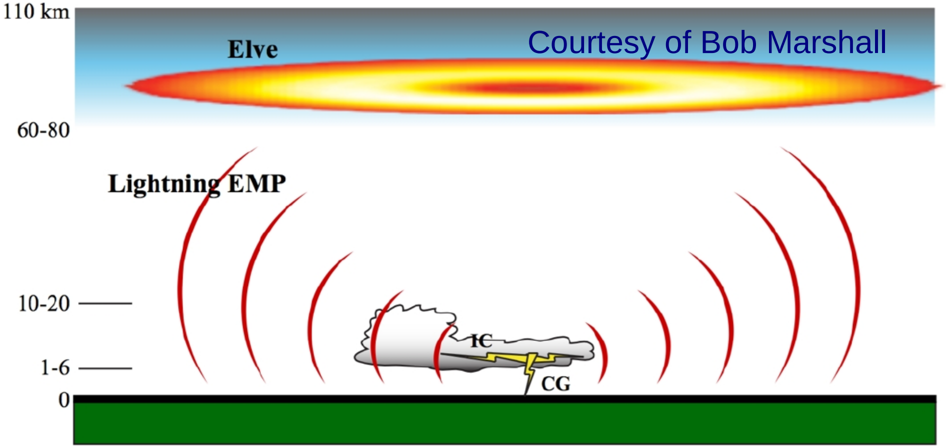
The VLF/LF range provides different types of signals, such as energetic in-cloud pulses (EIPs) and slow pulses → these information are complementary to the radio measurements in the VHF range.
A VLF/LF instrument array will be also deployed very soon (J. Sanchez et. al., "Probing the Context of TGF Events at the Pierre Auger Observatory Using VLF Sensors", AGU Fall Meeting 2024, AE23B-2585)

ELVES

Emissions of Light from Very low frequency Electromagnetic pulse Sources

ELVES and Red Sprite lightnings over Finland

ELVES appeared on April 2, 2017, high above a thunderstorm in the Czech Republic and was captured by an amateur astronomer.

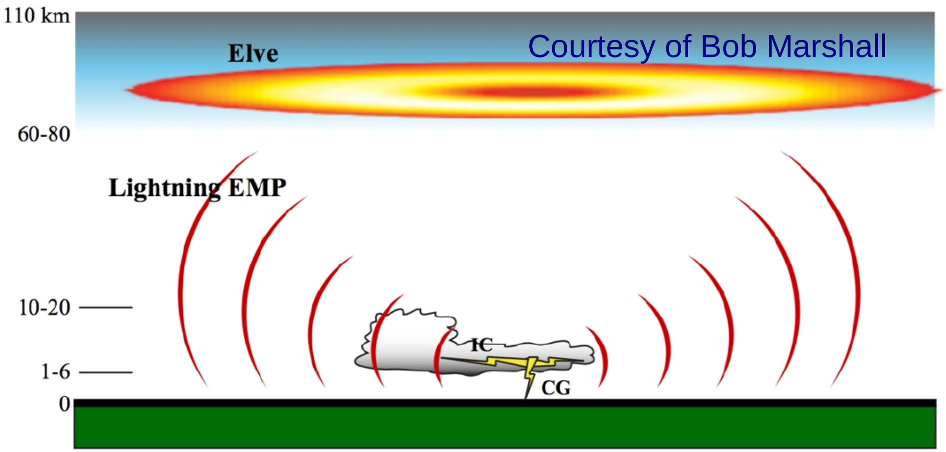


Optical signature of the lightning electromagnetic pulse (VLF EMP – 5-10 kHz) interaction with the lower ionosphere:

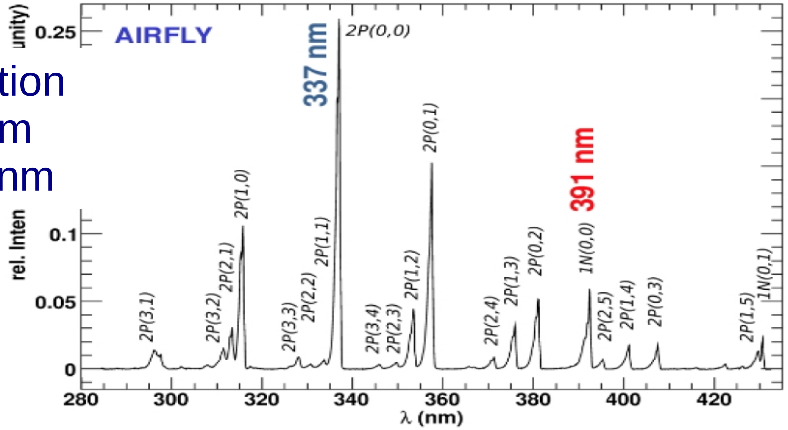
- EMP accelerates electrons at the base of the ionosphere (80-90km);
- Electrons collide and excite nitrogen molecules;

ELVES

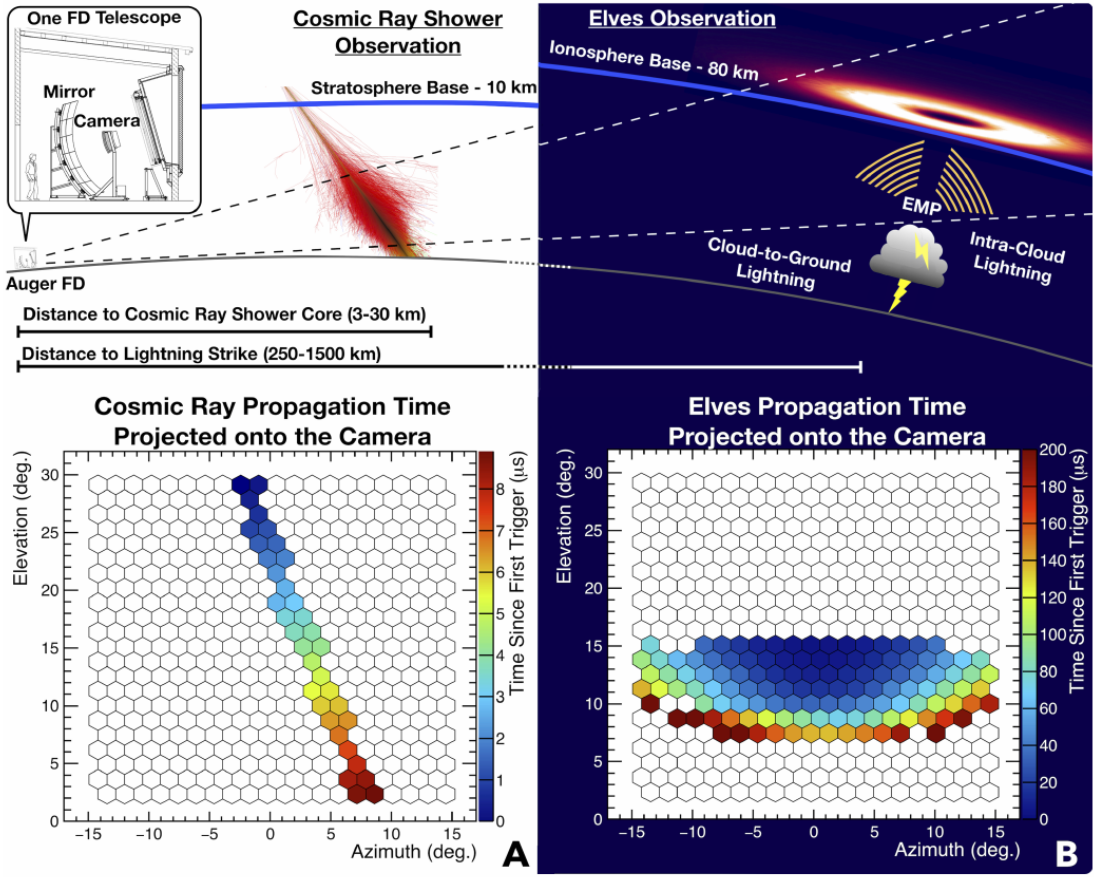
Emissions of Light from Very low frequency Electromagnetic pulse Sources

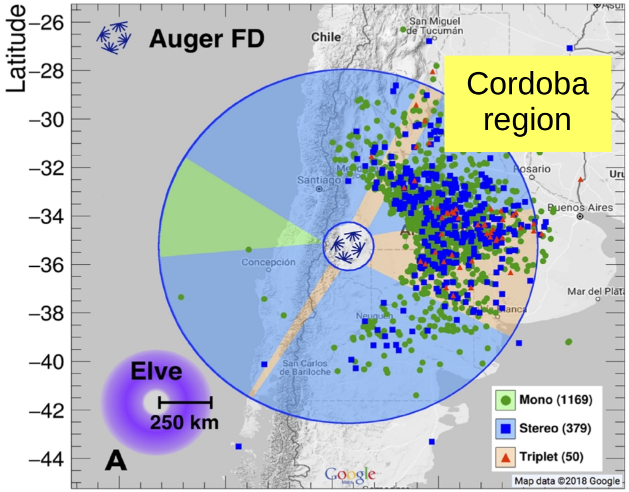


De-excitation Spectrum 300-400 nm



ELVES at the Auger Observatory





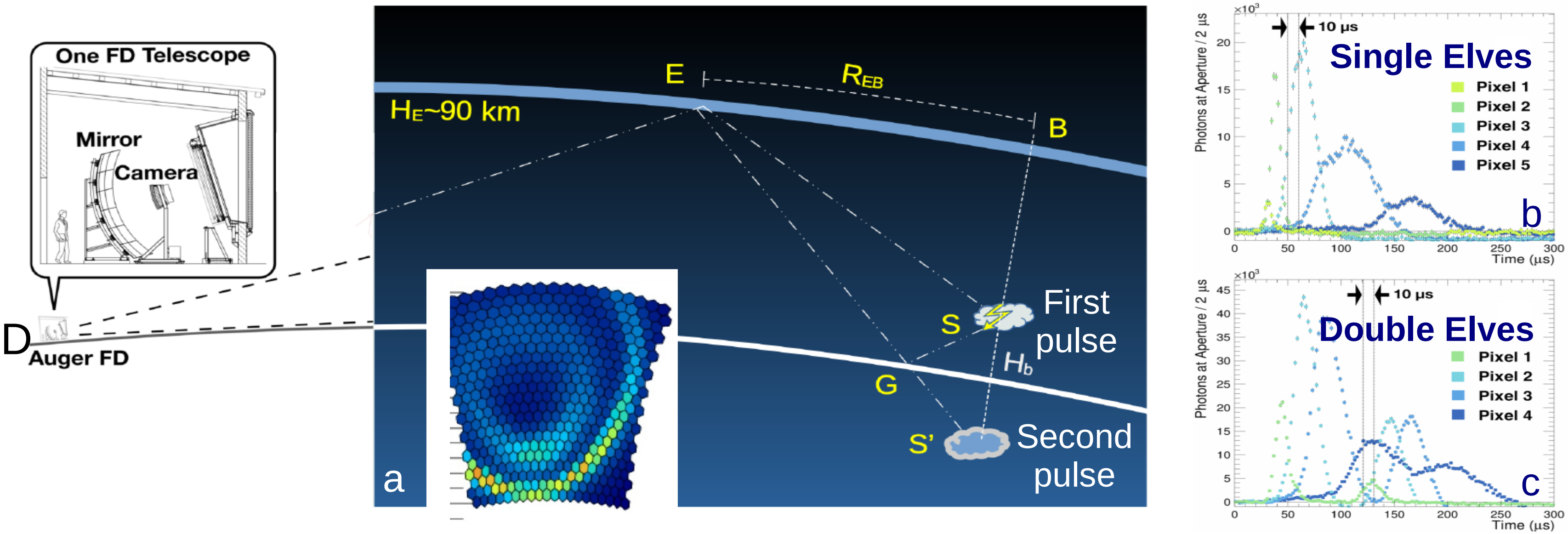
More than 95% of the observed elves are 250-1000 km away.

The Observatory acceptance for elves extends over $3 \cdot 10^6$ km^2.

Pierre Auger Coll., Earth Space Sci. 7 (2020) e2019EA000582.

Single-peaked and Multipeaked ELVES

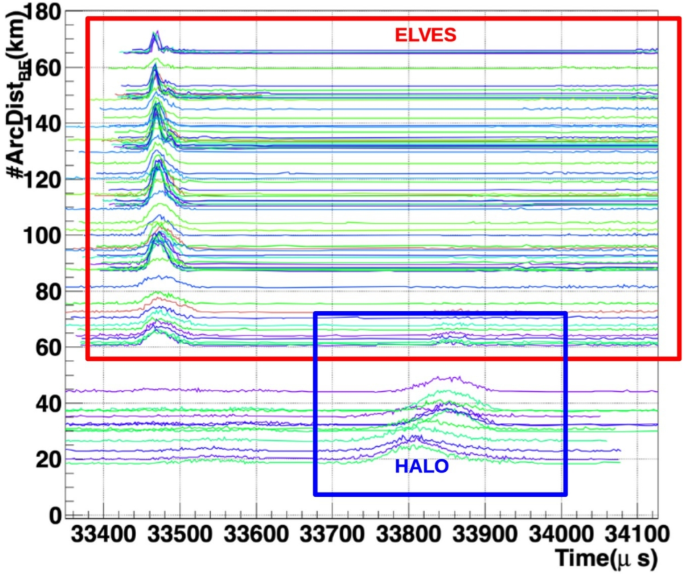
Thanks to the Auger FD time resolution (100 ns), the temporal structure in the light emission of ELVES can be observed very fine and data can be sorted in two categories studying the photon trace: single-peaked (b) and multipeaked ELVES (c)

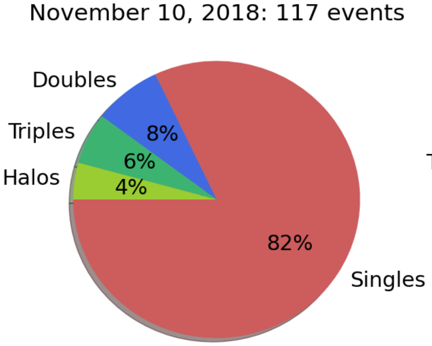


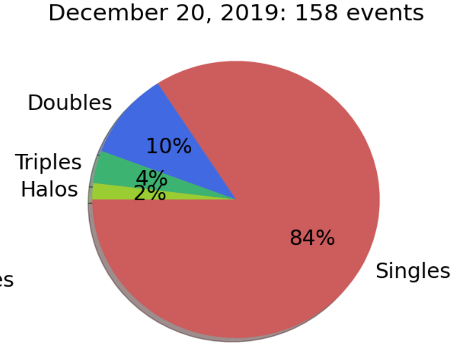
Multi-elves paper to Earth and Space Science - A. Vasquez

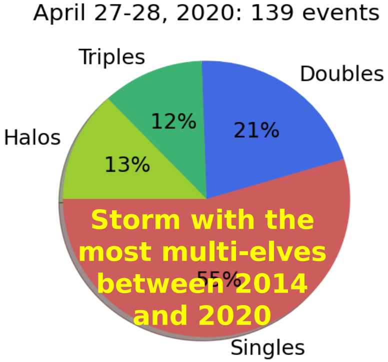
Multiple ELVES in four storms

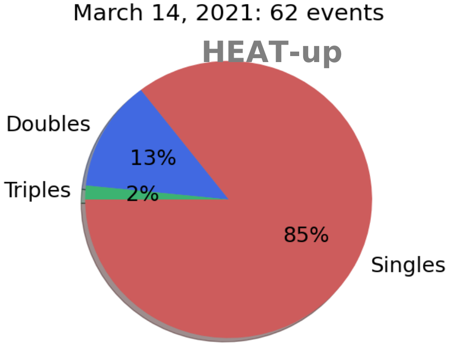
- The fraction of events with multiple elves is higher in April and December
  → **nature of multiple elves may be related to the type of storm**
- beside double elves, we see a significant number of triple elves ...
- **Auger published the first evidence of triple ELVES**
- **Auger also observes halos** thanks to the extended Readout which has allowed to read traces from ELVES triggers up to 0.9 ms long
- Halos are frequently associated to SPRITES











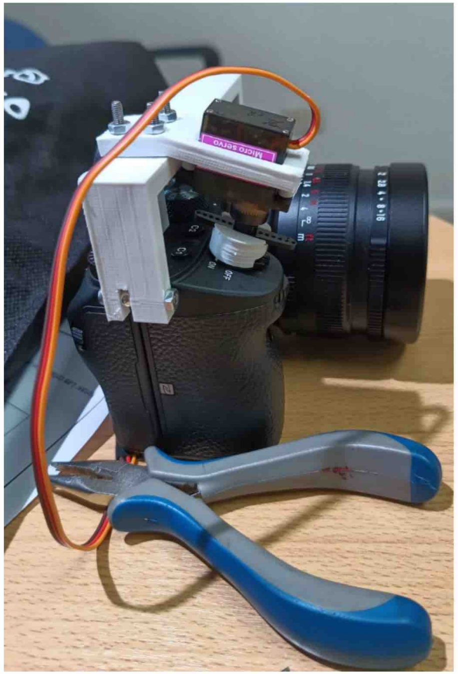
New instruments to study more TLEs

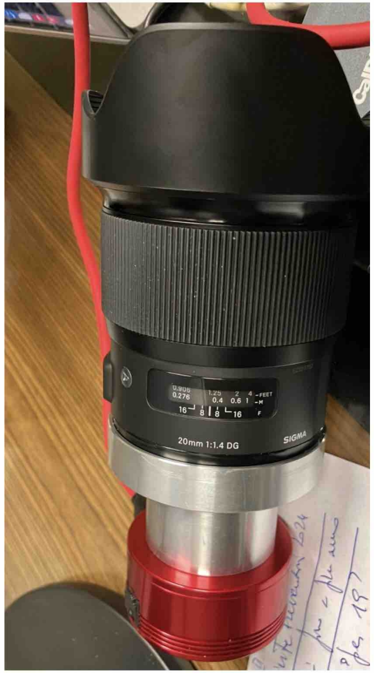
To complement the FD images of ELVES (high time resolution but poor space resolution) and study correlation with other TLEs such as sprites and blue jets, we installed two new instruments, in the proximity of Coihueco FD site

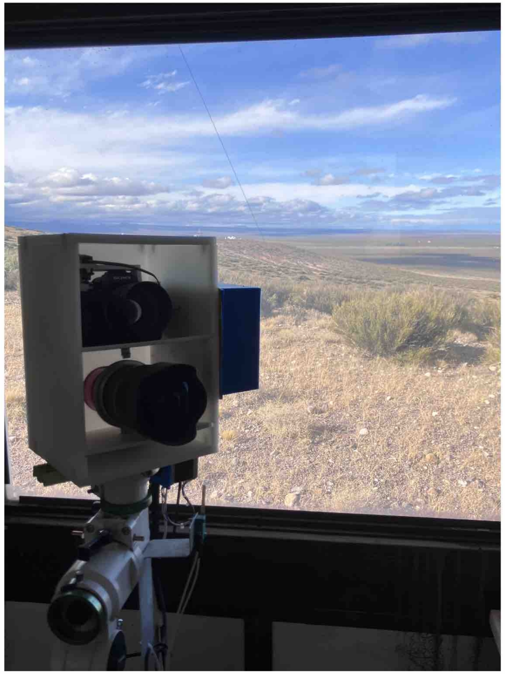
TLEcam-1 (dec.2023):
- Sony a7-III camera
7artisans 50mm f/0.95

TLEcam-2 (apr.2024):
- CMOS sensor ZWO ASI294MC
 Sigma 20mm f/1.4

Azimuth motion is controlled by an Arduino microprocessor.







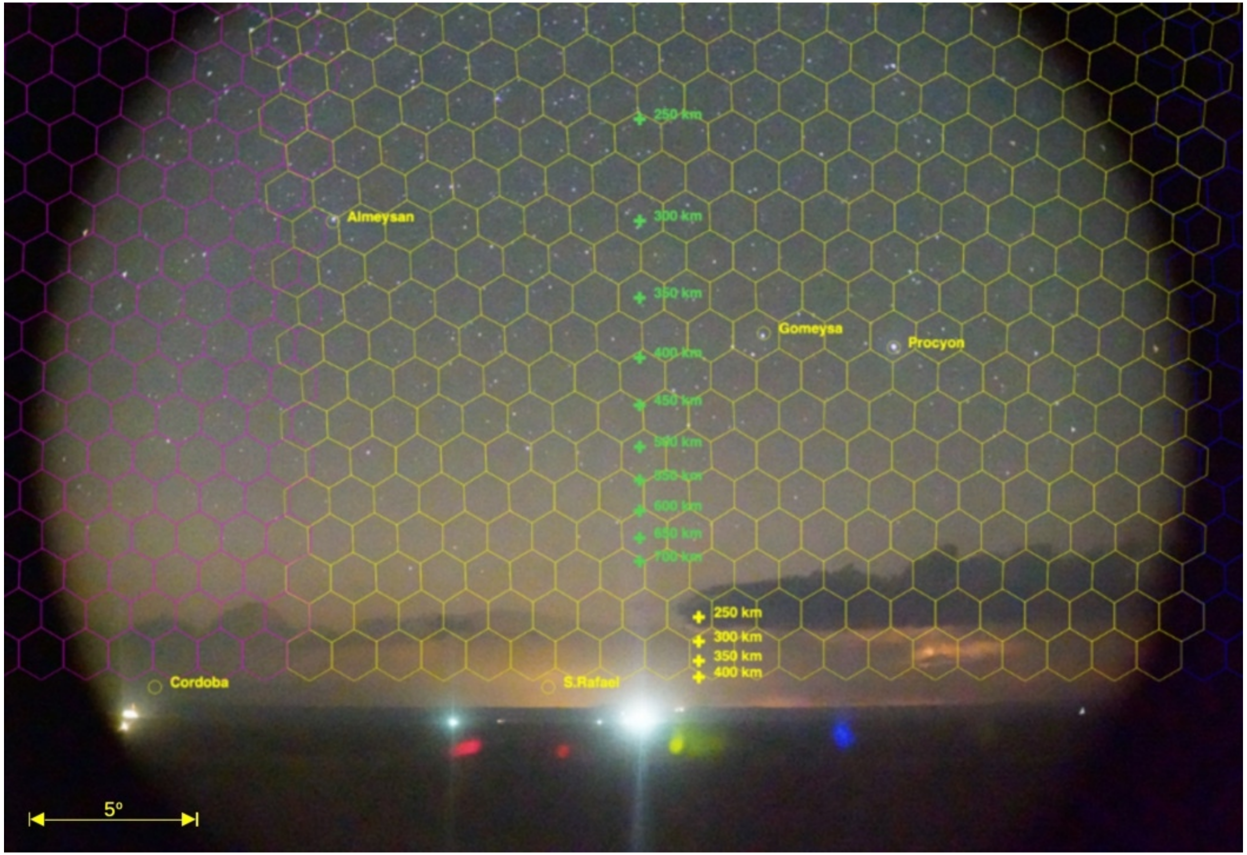
TLE cam – FD alignment

Brightest stars are used for absolute camera alignment.

Field of view of each FD pixel is represented by a hexagon. Different colors are used for each bay.

Green crosses:
Location of an ELVES center (at h=90 km) vs distance.

Yellow crosses: location of the cloud top (at h=15 km) vs distance.

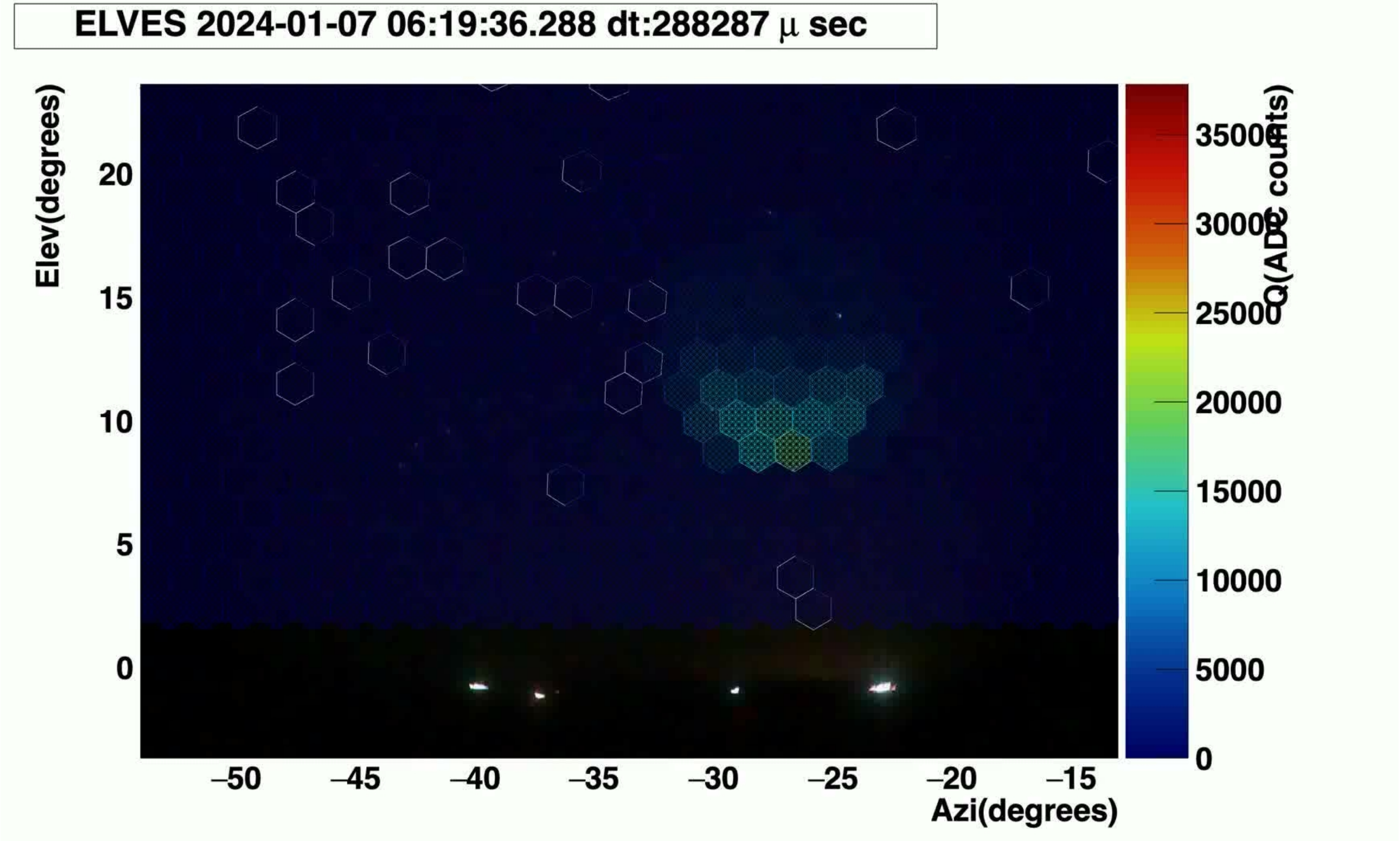


TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=2 μs

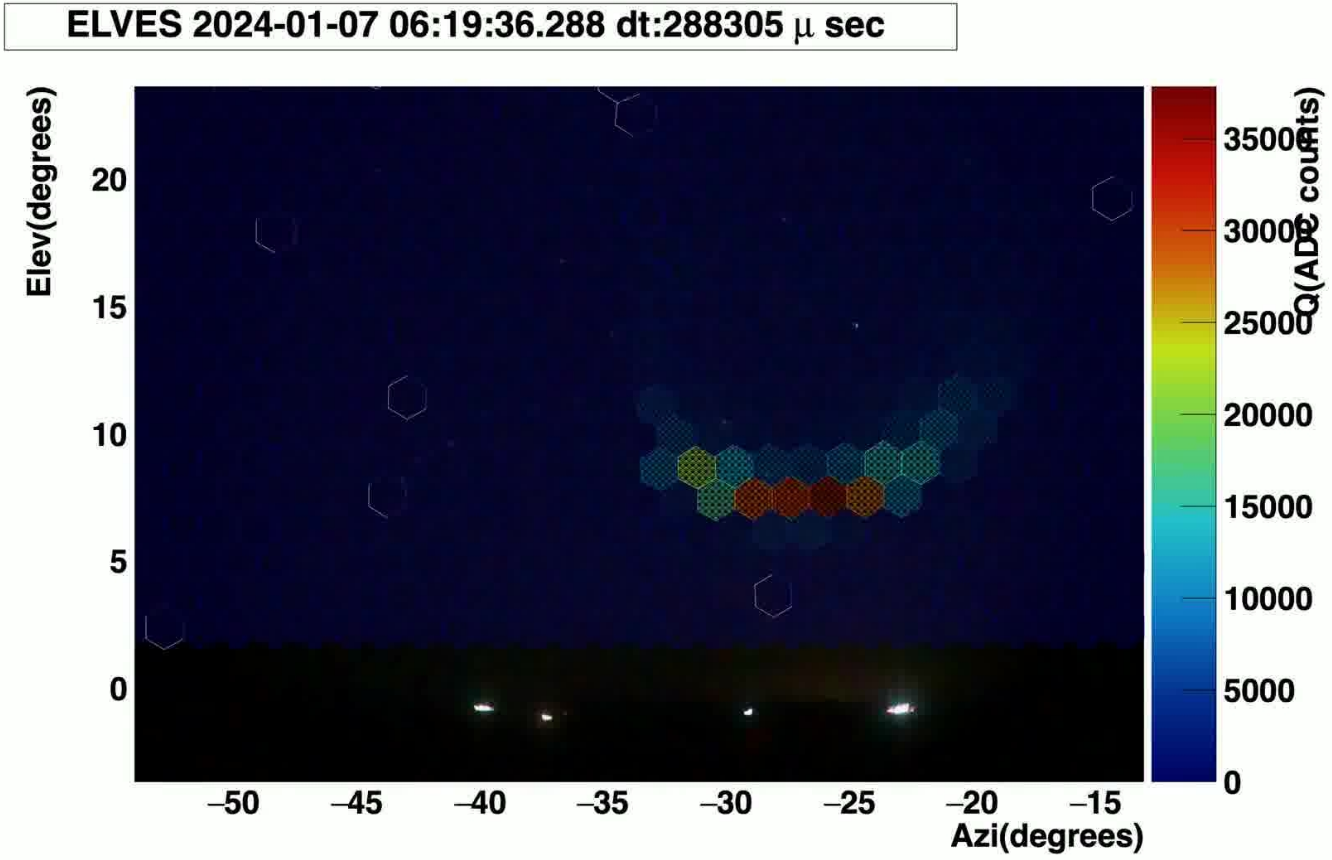


TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=20 μs

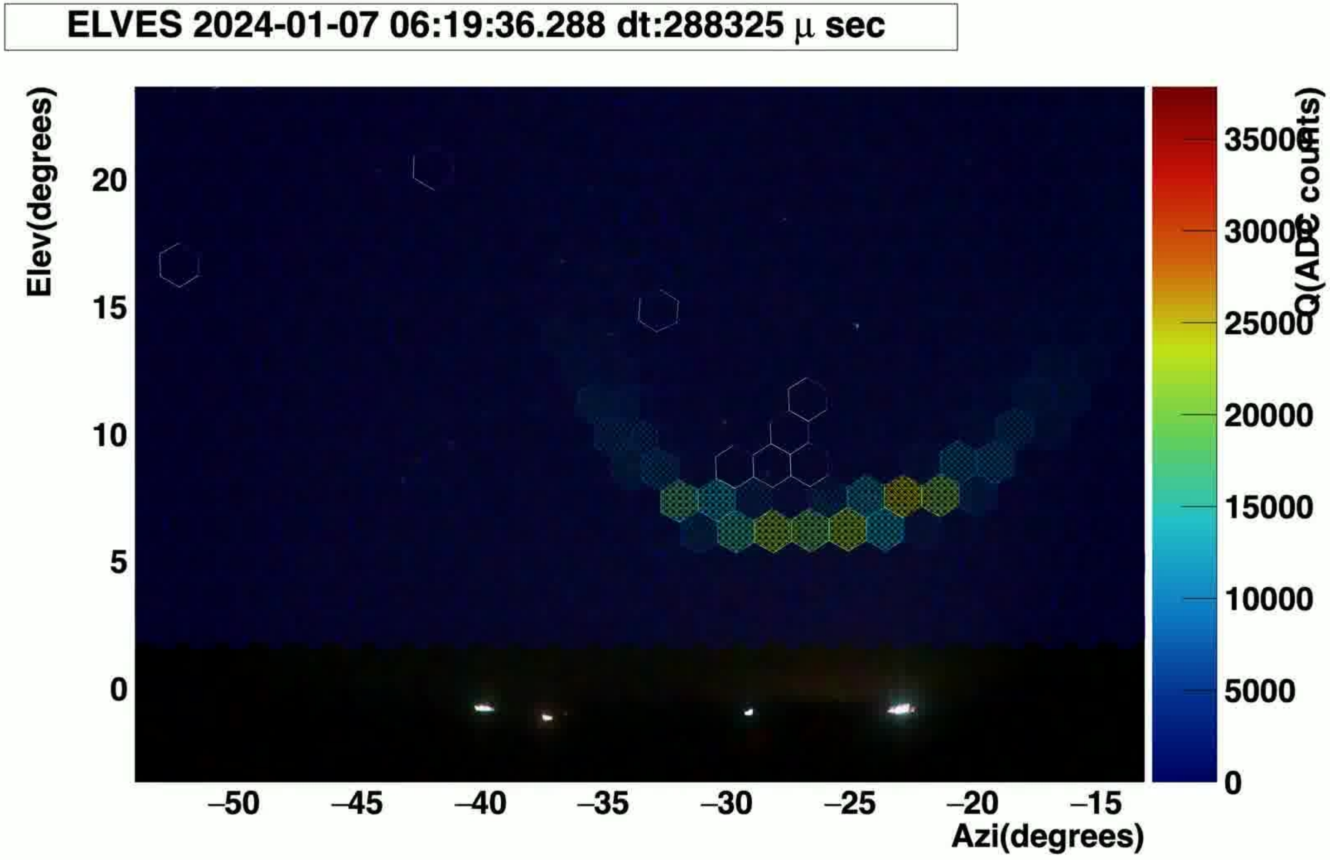


TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=40 μs

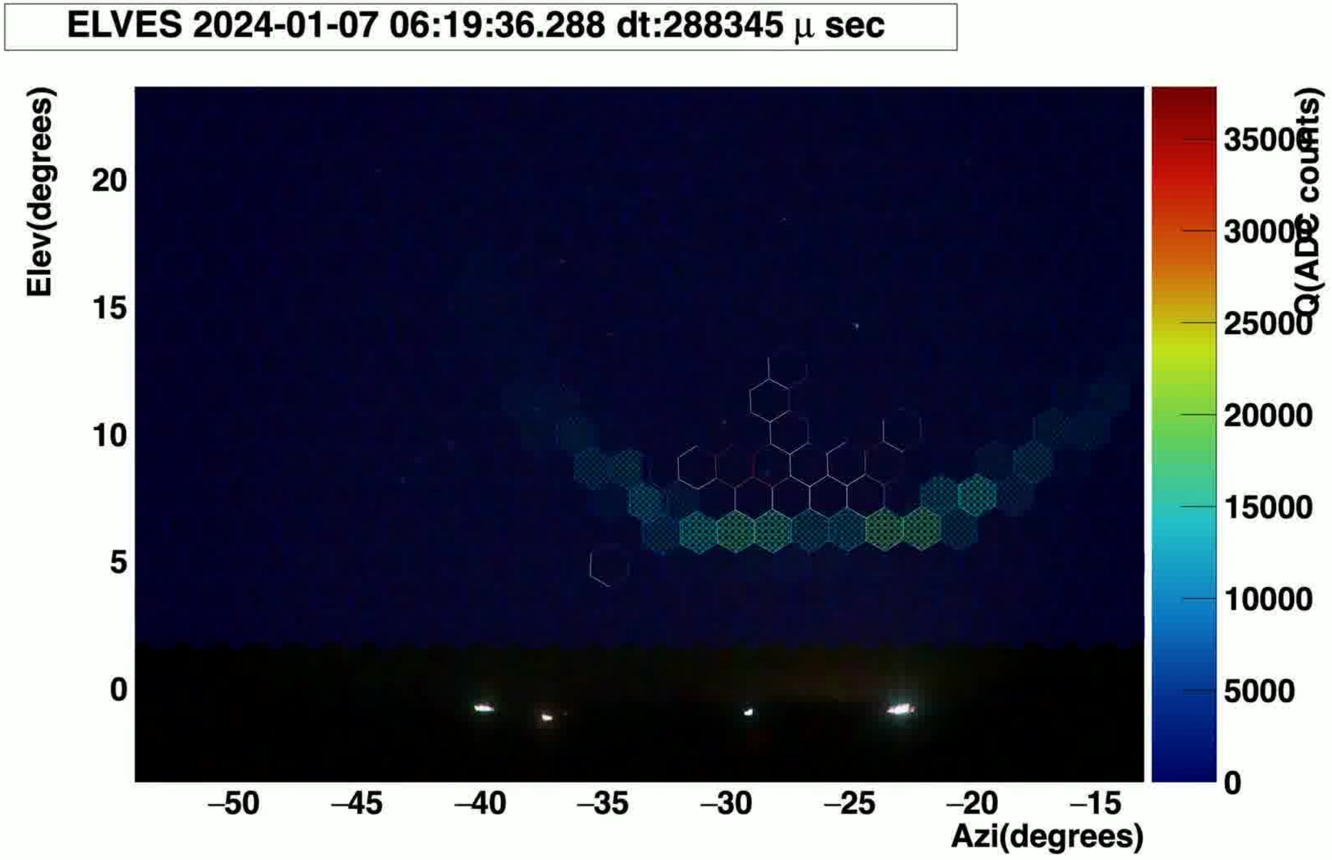


TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=60 μs

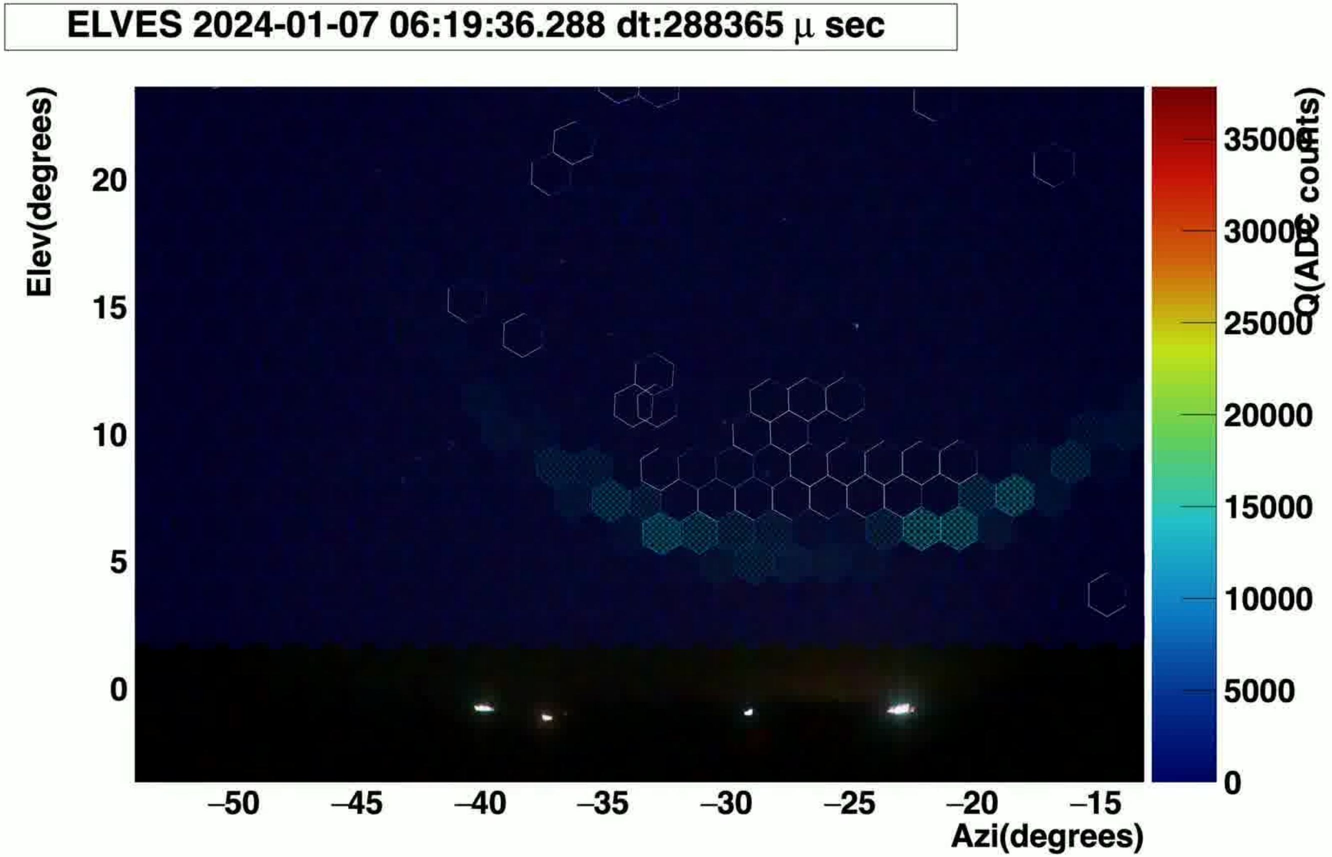


TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=80 µs

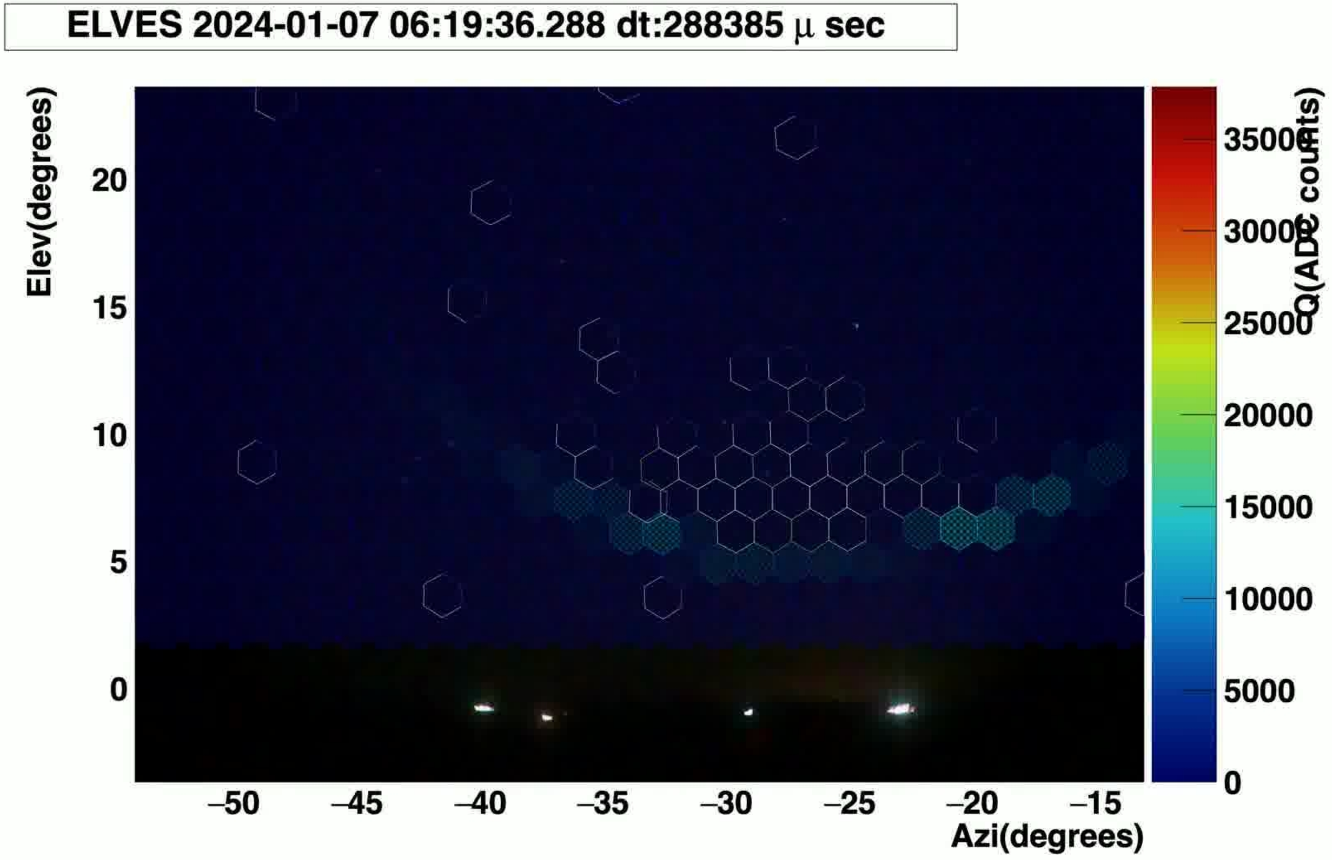


TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=100 µs

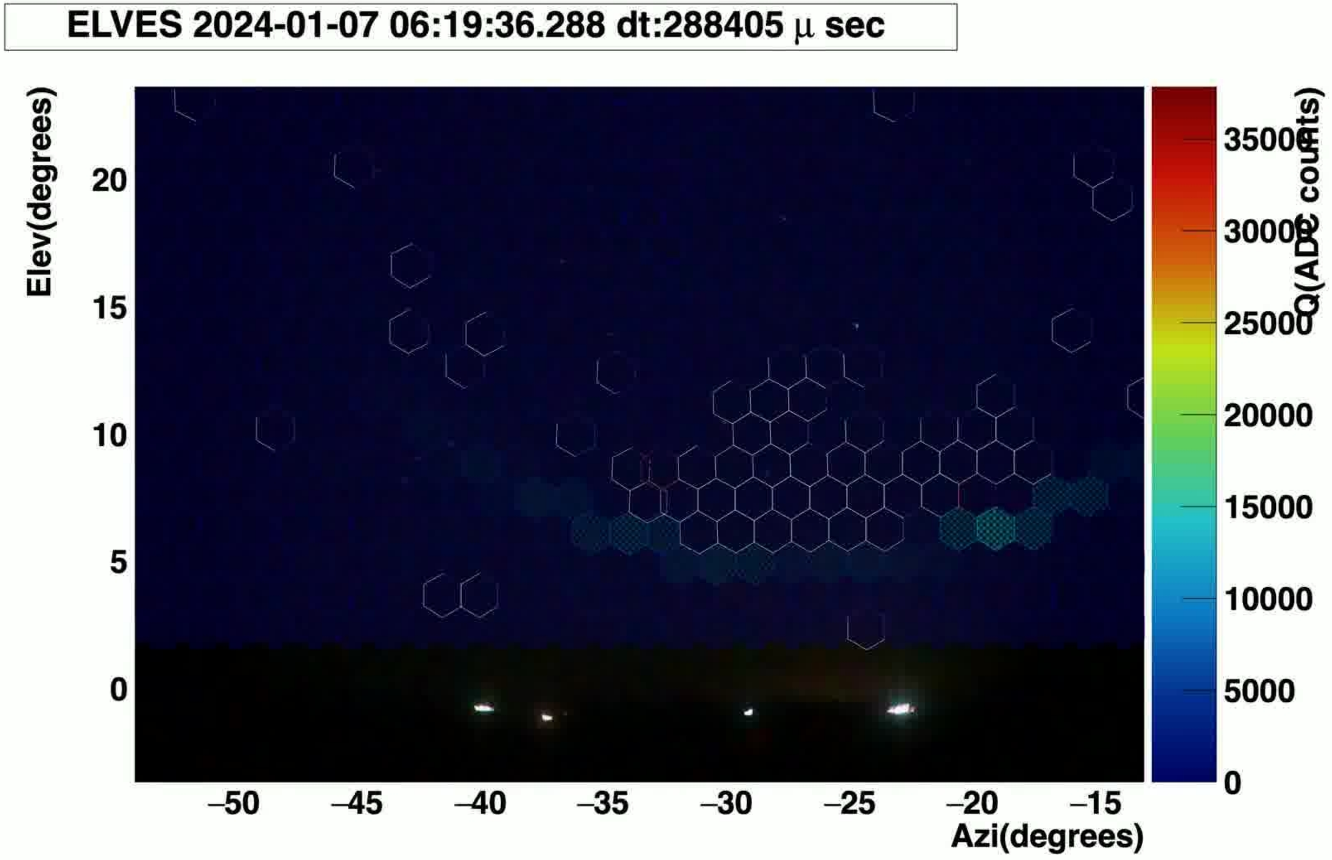


TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=120 μs

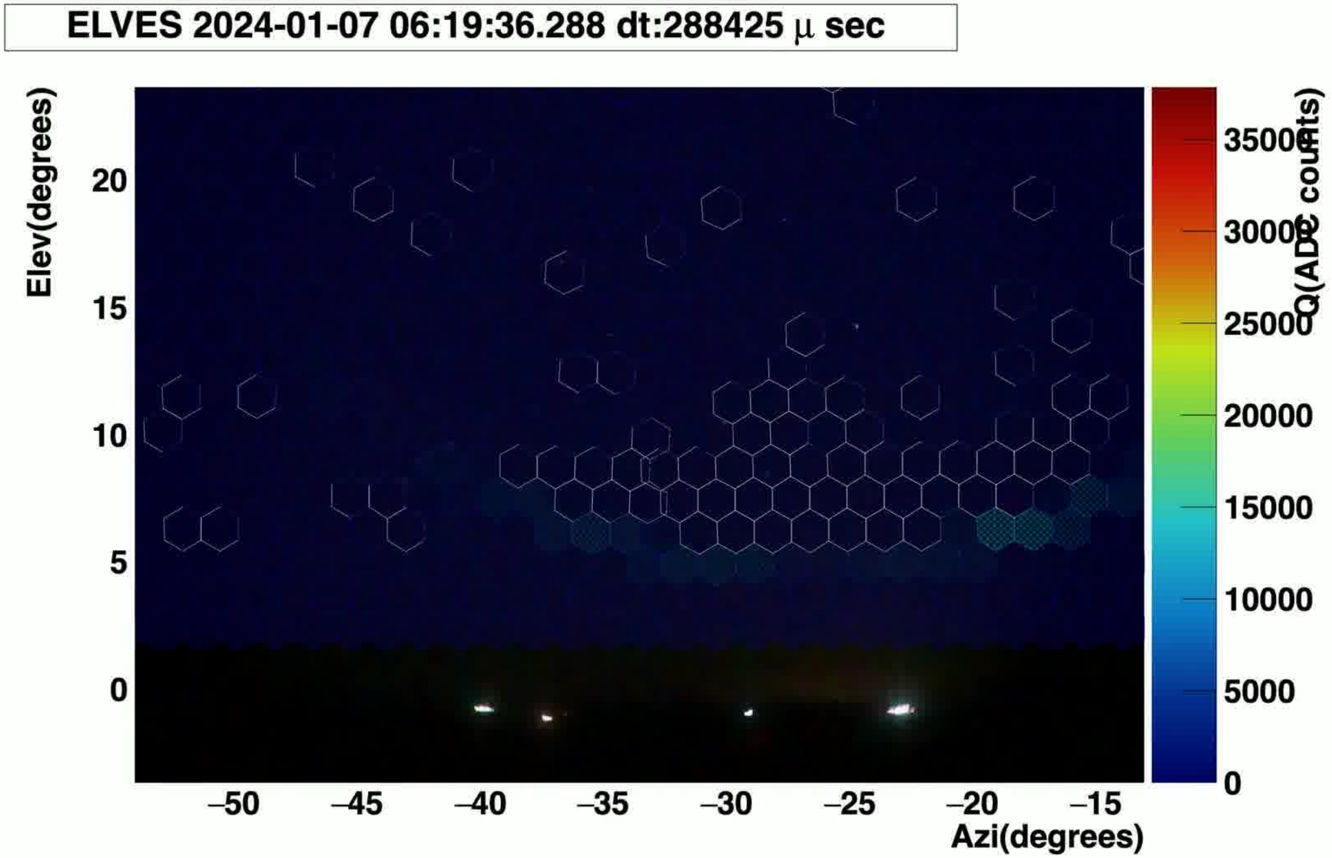


TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=140 μs



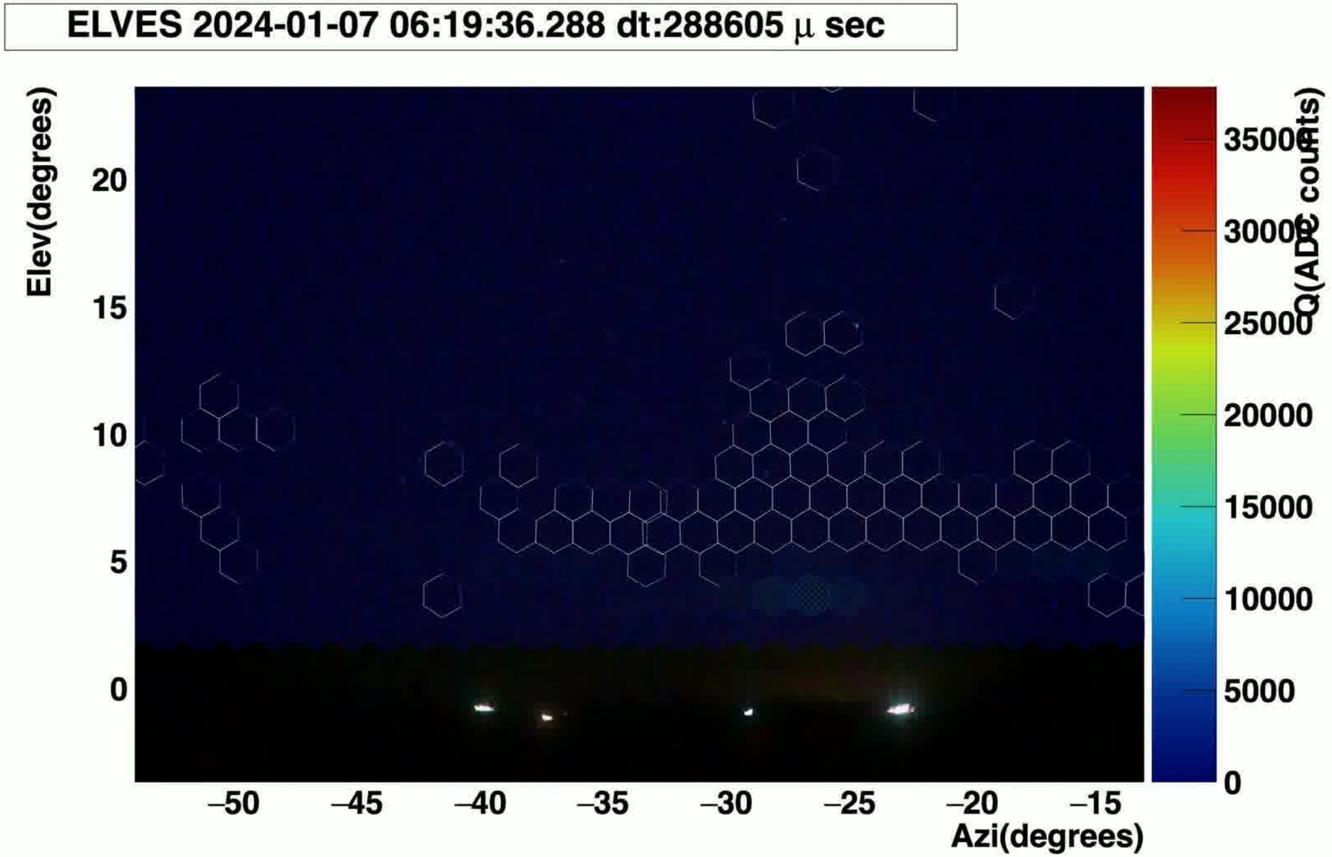
TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=320 μs

Halo



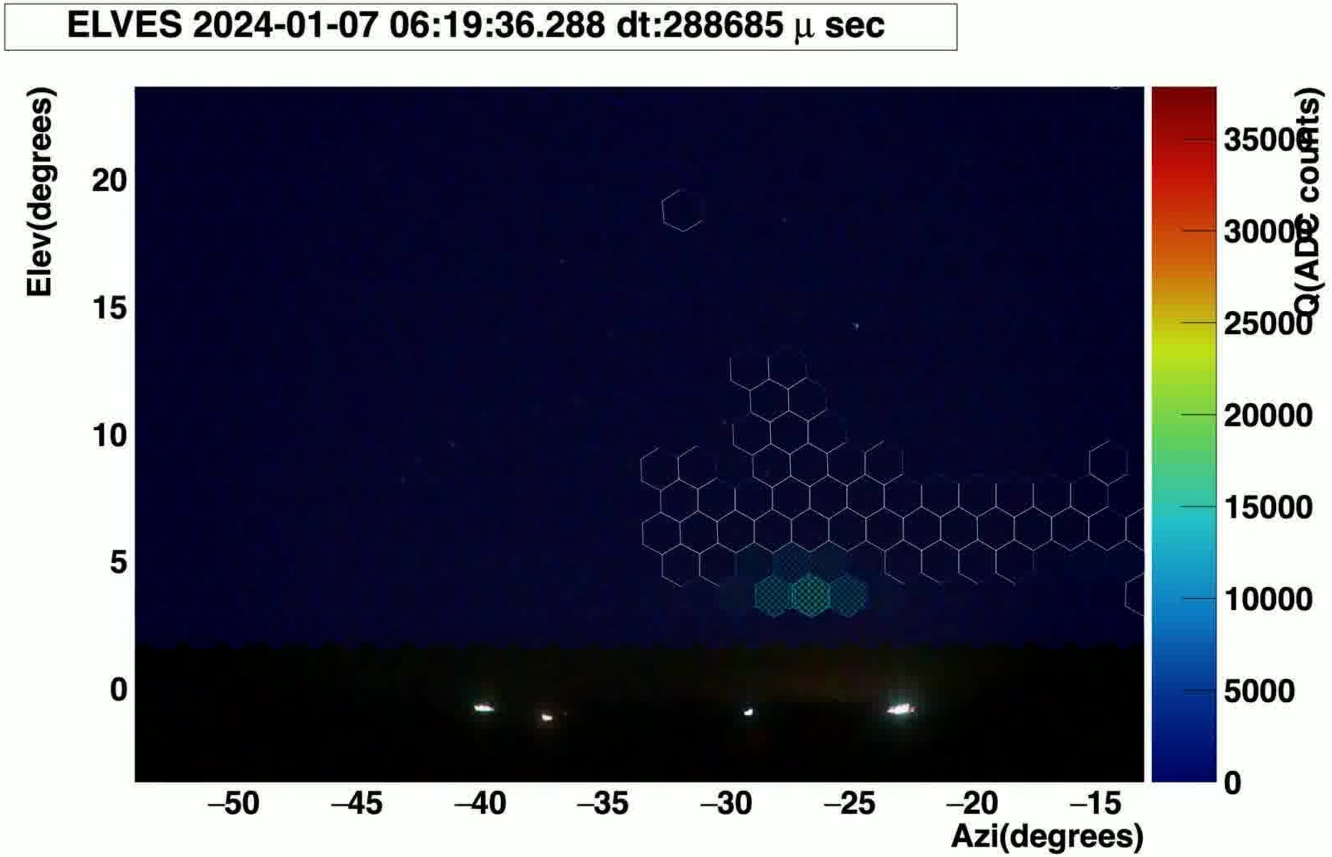
TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=400 μs

Halo



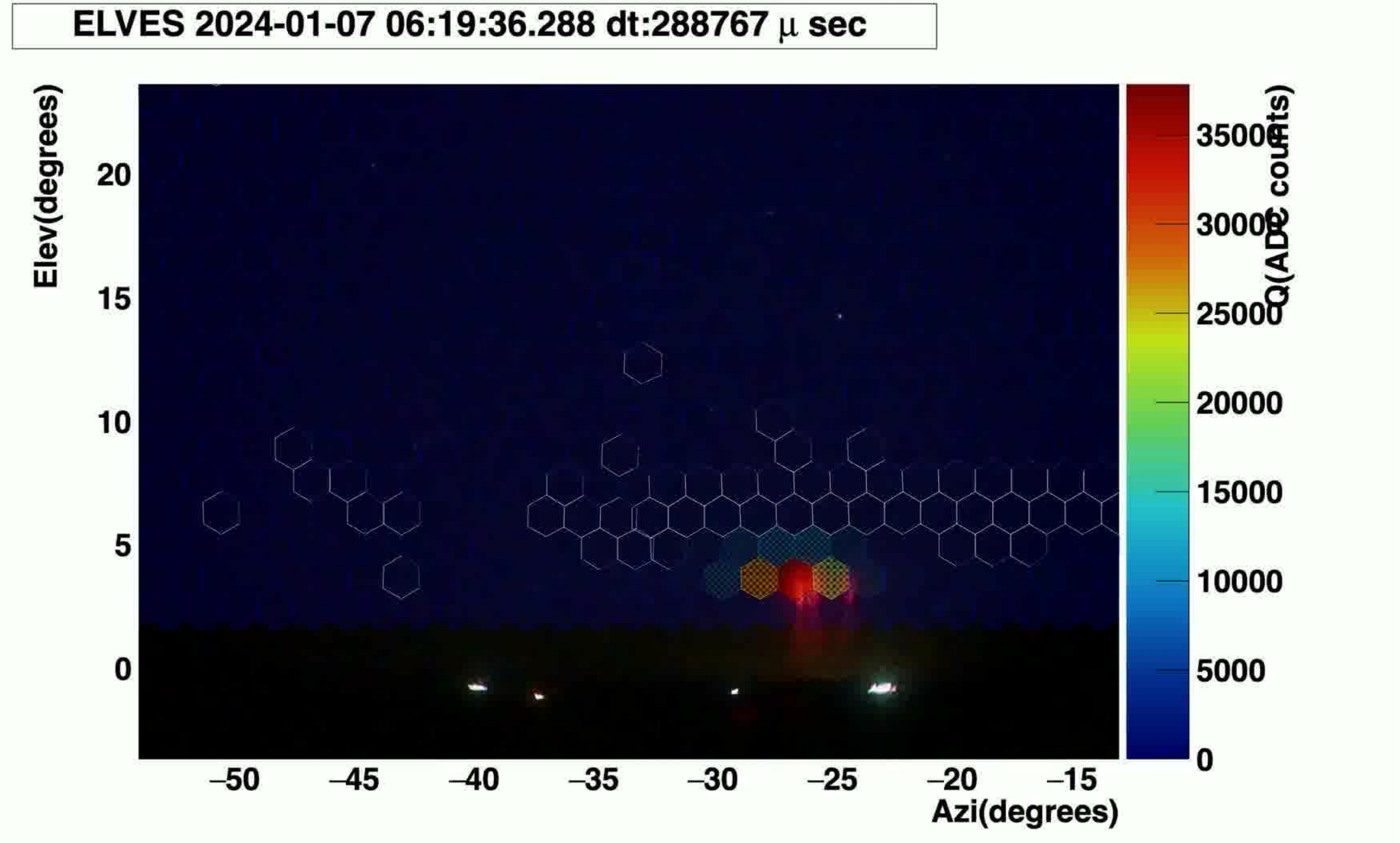
TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

T=482 μs

Halo + SPRITES



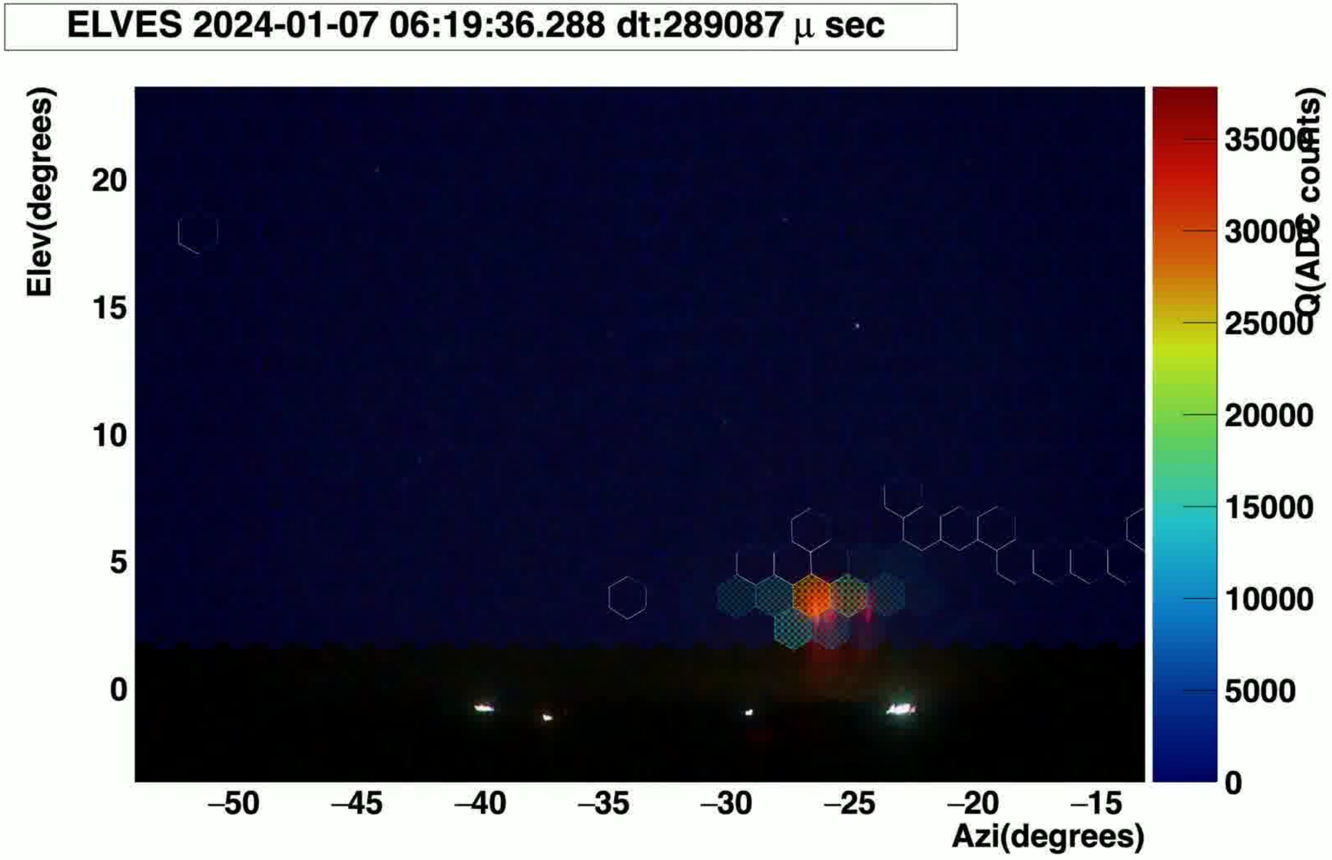
TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024

Every frame integrates 2 microseconds

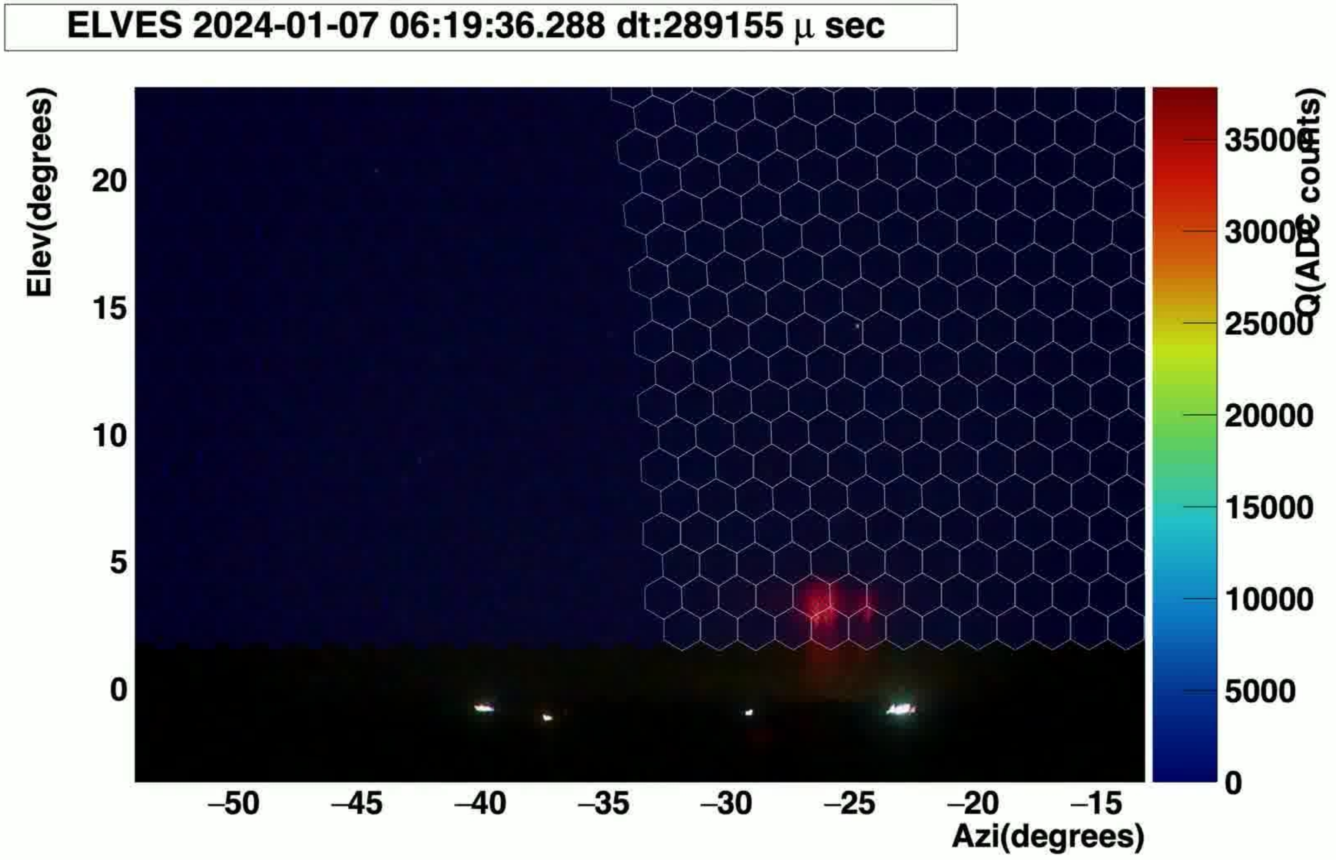
T=802 μs

Halo + SPRITES

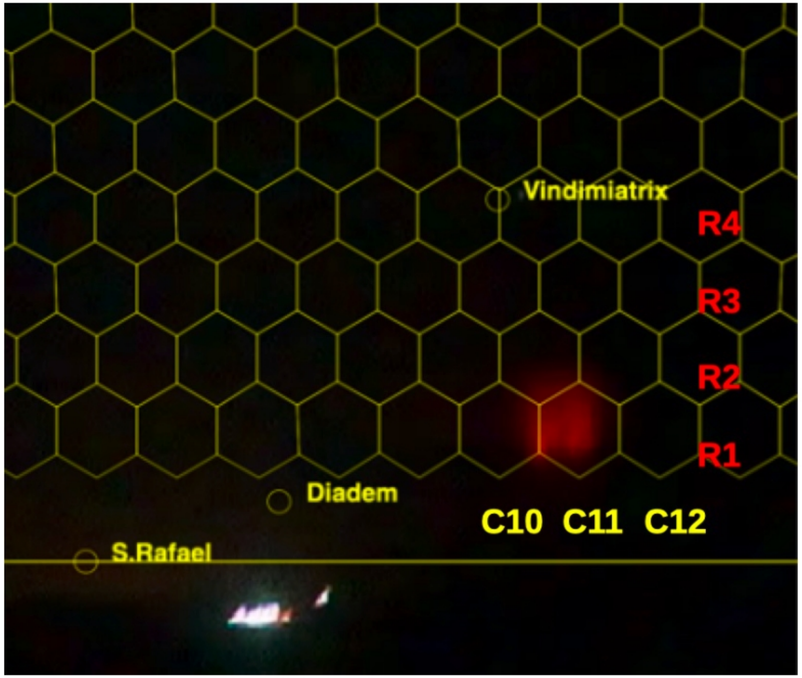


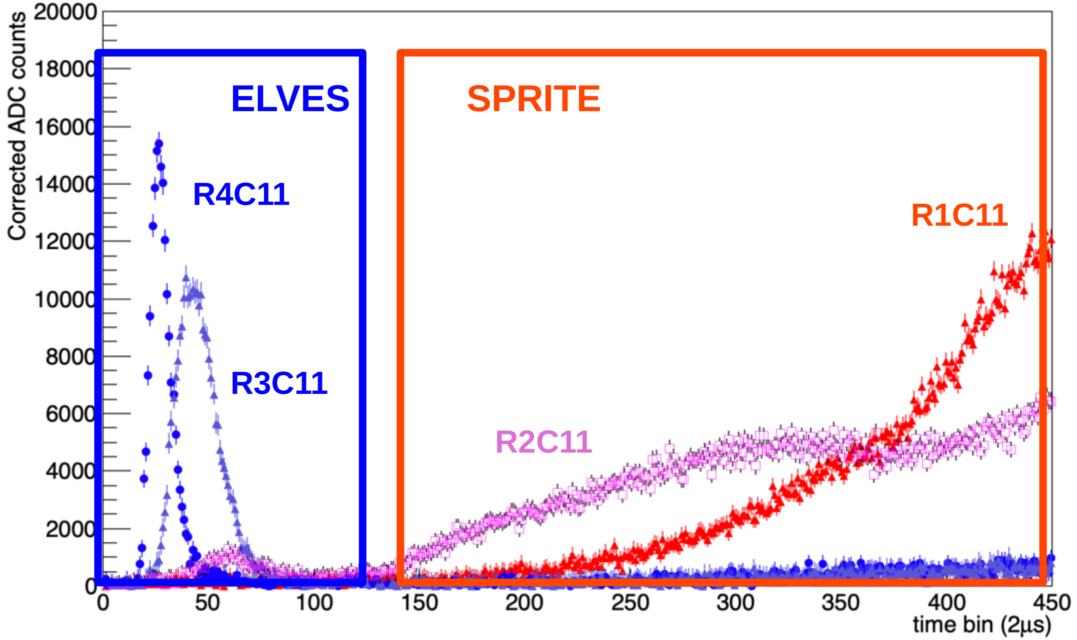
TLEcam-1: first SPRITEs on ELVES triggers

Five SPRITEs correlated (i.e. in the same second) with ELVES on Jan.7, 2024



SPRITE light vs ELVES light





The ELVES light is not visible in the TLEcam photo. The light pulses belonging to the SPRITE start after time bin 130 and last much longer than the ELVES pulses.
Few ELVES have the SPRITE light starting close enough to be visible in the traces.

Scaler rate from the Pierre Auger Observatory: a new proxy for solar activity

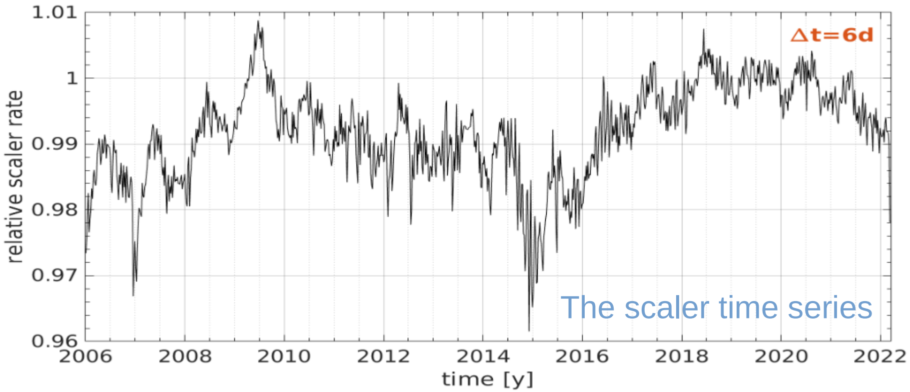
(ApJ 987(2025)41)

The modulation of low-energy galactic cosmic rays reflects interplanetary magnetic field variations and can provide useful information on solar activity

→ investigation of the low-threshold rate (scaler) time series recorded in 16 years of operation by the Pierre Auger Observatory surface detectors

→ rate of signals above a low threshold, whose dominant contribution comes from cosmic rays of energies between 10 GeV and a few TeV primary energy.

Through an advanced spectral analysis, we detected highly statistically significant variations in the time series with periods ranging from the decadal to the daily scale.



1. stored every second from each detector
2. corrected for pressure, lightning events and malfunctioning factors (M. Schimassek, 2022)
3. Gap-filling procedure based on an AR (Auto-Regressive) model

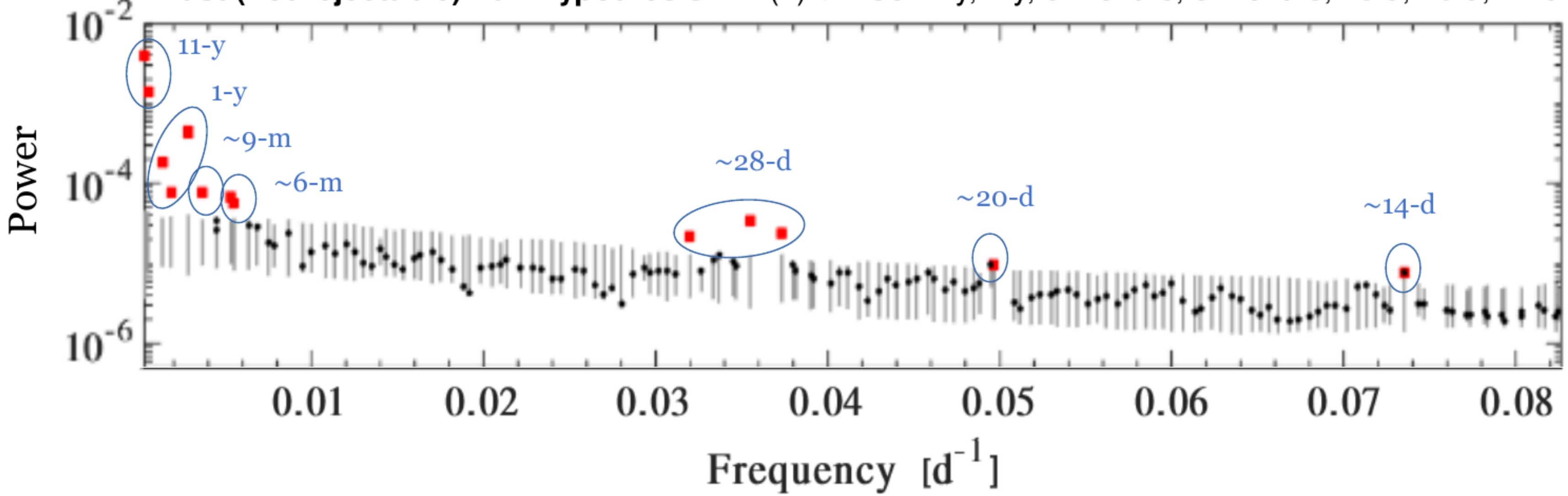
Spectral Analysis

Spectral methods:

– Singular Spectrum Analysis and Monte Carlo test (MC-SSA)
– Continuous Wavelet Transform (CWT)

Monte-Carlo approach: different null-hypothesis
Final spectrum → statistically significant spectral components (99% c.l.)

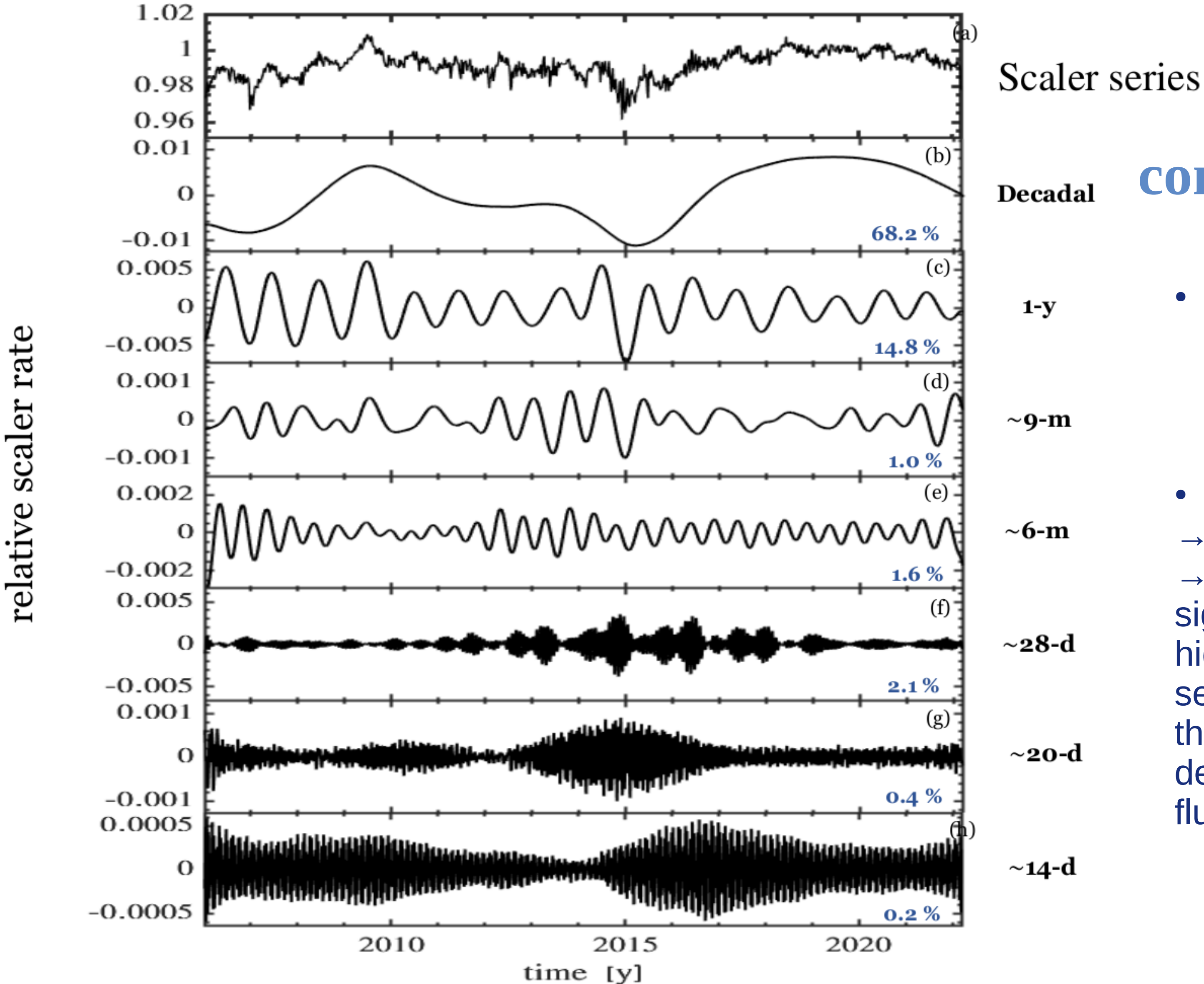
Last (not rejectable) null-hypothesis: AR(1) + RCs 11 y, 1 y, 9 months, 6 months, 28 d, 20 d, 14 d



Δt=6d
M=150

Significant reconstructed components with SSA

(APJ paper)



- Auger scaler data are complementary to those provided by neutron monitors or muon detectors

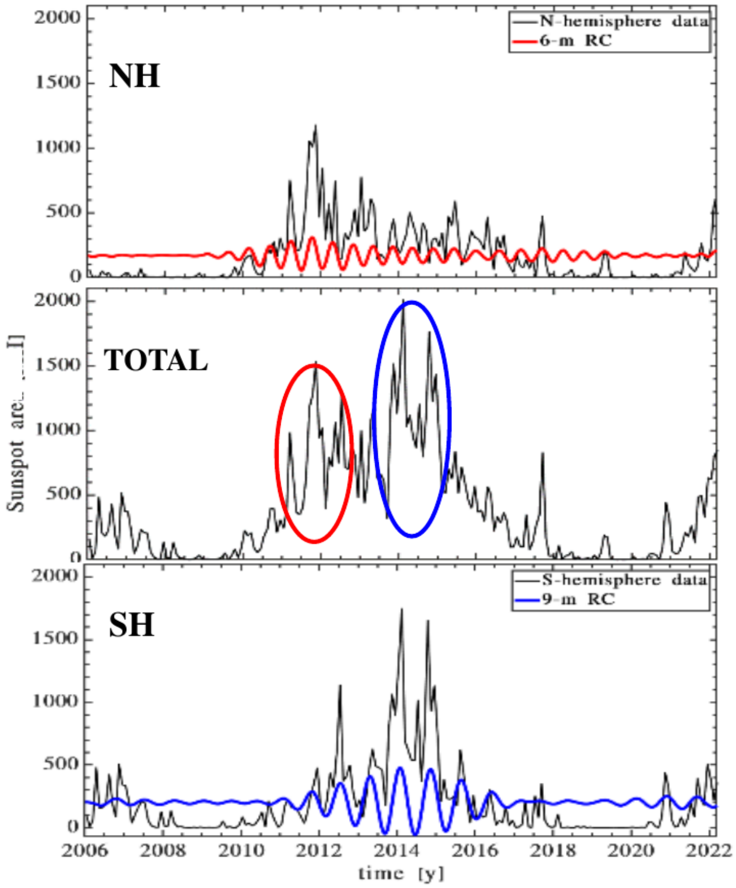
- thanks to

→ the very low noise level

→ the higher statistical significance related to the very high count rates (~10^6 counts per second)

they allow for a thorough and detailed investigation of the GCR flux variations in the heliosphere

Sunspot areas



Archive: United States Air Force (USAF) Solar Observing Optical Network (SOON)

The total sunspot-areas series shows 2 peaks:

~2012 peak **~2014-2015 peak**

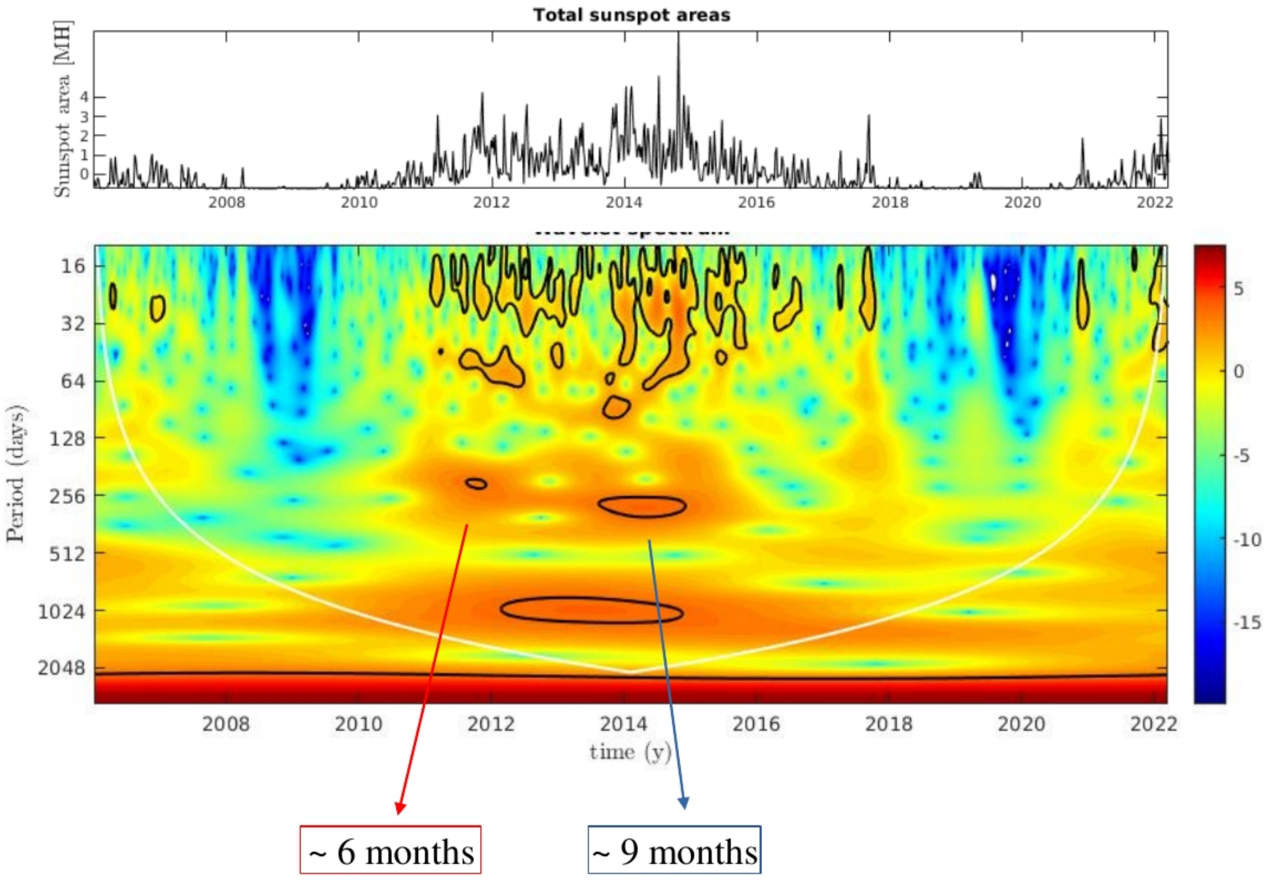
The analysis of the hemispheric sunspot-areas series shows that

the 6-months oscillation comes from the Northern hemisphere

the 9-months oscillation comes from the Southern hemisphere

SSA SIGNIFICANT COMPONENT (99% c.l.)				
	SCALERS	TOTAL SUNSPOT AREA	SUNSPOT AREA NORTH	SUNSPOT AREA SOUTH
Period	Variance [%]			
11 y	68.2	53.7	37.8	40.7
1.2 y	-	-	-	-
1 y	14.8	-	-	-
~9 months	1.0	4.0	-	6.2
~6 months	1.6	2.4	3.4*	-
~4 months	-	-	-	-
~28 d	2.1	7.0	8.1	12.0
20 d	0.4	3.0	3.5	-
~14 d	0.2	-	-	-
SIGNAL	~88%	~70%	~53%	~59%
NOISE	~12%	~30%	~47%	~41%

Results confirmed by the CWT method



The CWT spectral analysis of the total sunspot areas confirms

- the presence of the 6 and 9 months modulations
- maximum amplitudes correspond to the first (2012) and second peak (2015) respectively

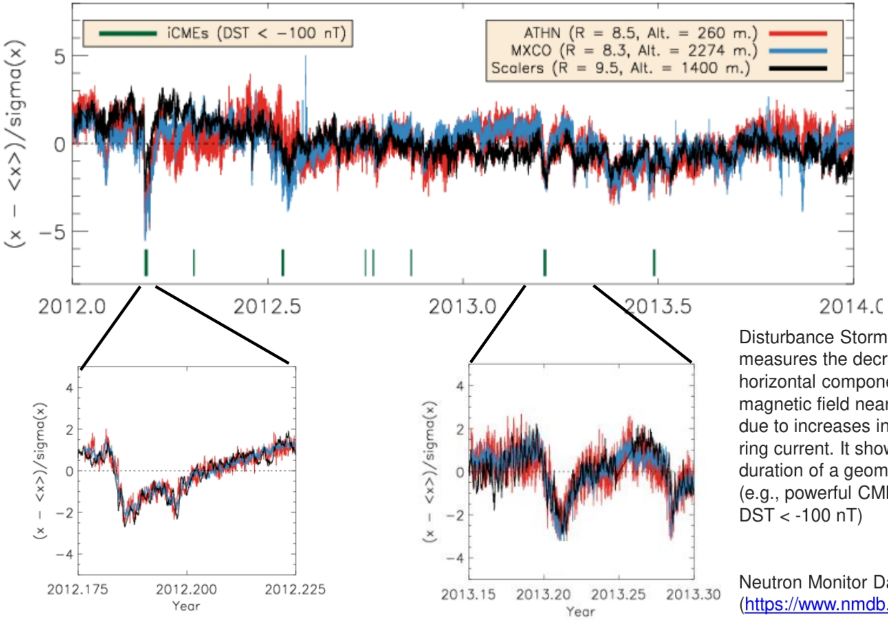
ICRC 2025
C. Taricco (TO)

Future plans and work in progress

Effect of the solar magnetic field
→ new paper in preparation

Sensitivity of scalers to **sudden solar variations**
(analysis of high resolution (1 h or less) scalers series):

- Identification of **Forbush decreases**
- Is there an inprint in the scalers of **Solar Energetic Particles** generated impulsively by powerful solar flares or gradually by coronal shocks?
- Correlation between the detected Forbush events and **Interplanetary Coronal Mass Ejections** to **identify the origin of the Forbush decreases**
- Comparison between scalers and neutron monitors at similar latitudes



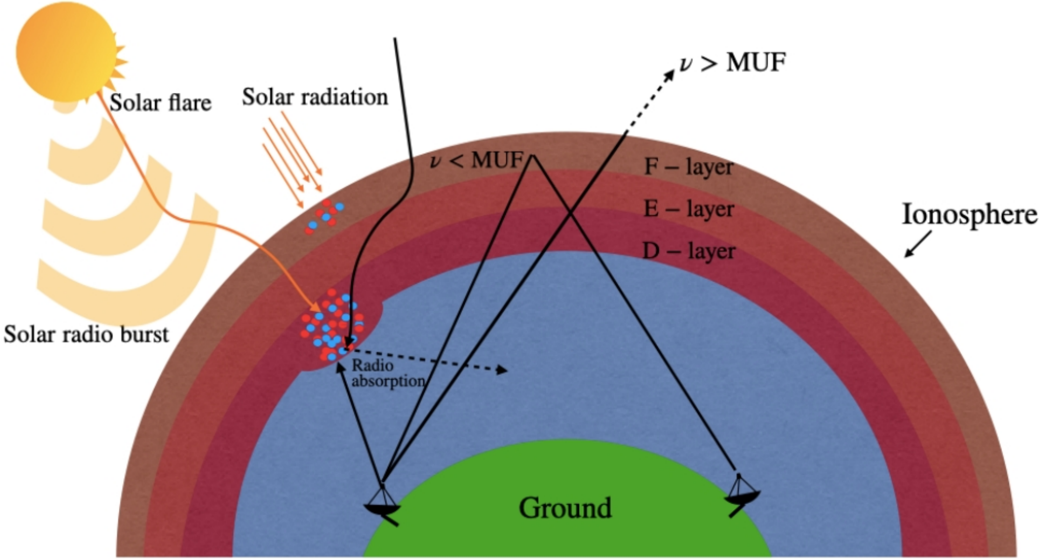
Disturbance Storm Time (DST) index: measures the decrease in the horizontal component of the Earth's magnetic field near the magnetic equator due to increases in the magnetospheric ring current. It shows the strength and duration of a geomagnetic storm (e.g., powerful CME --> strong storm --> DST < -100 nT)

Neutron Monitor Database (https://www.nmdb.eu)

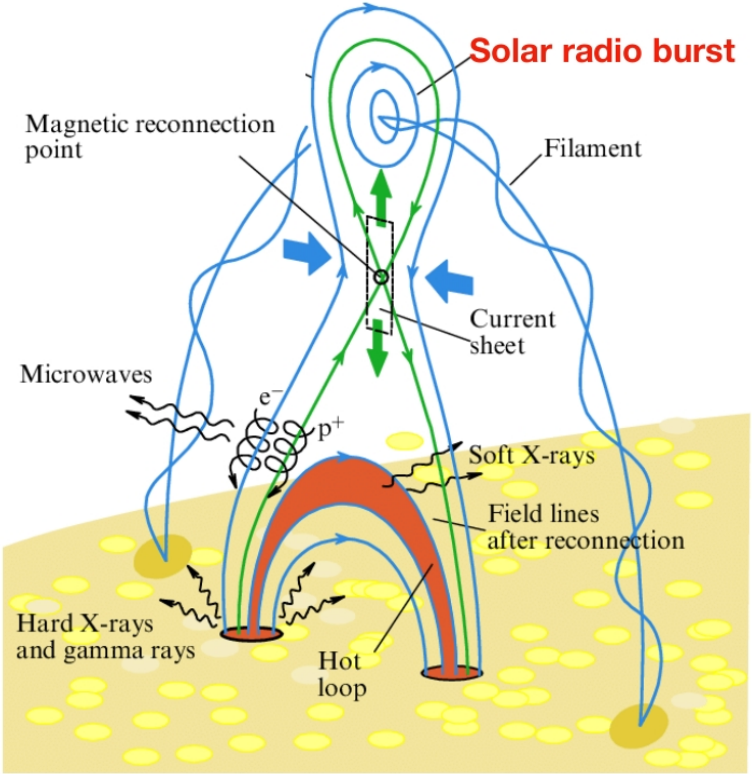
Solar activity study with radio measurements

- We investigate the effects of solar activity on AERA data:
  - Solar Radio Burst (directly)
  - Variation in the maximum usable frequency (MUF)
  - Radio blackout

Indirectly, resulting from changes in the ionosphere



AERA frequency range (30-80 MHz) corresponds to radio emission from sources located in the upper solar corona.



X-ray and gamma-ray emission of solar flares. Physics-Uspekhi. 63. 10.3367/UFNe.2019.06.038757

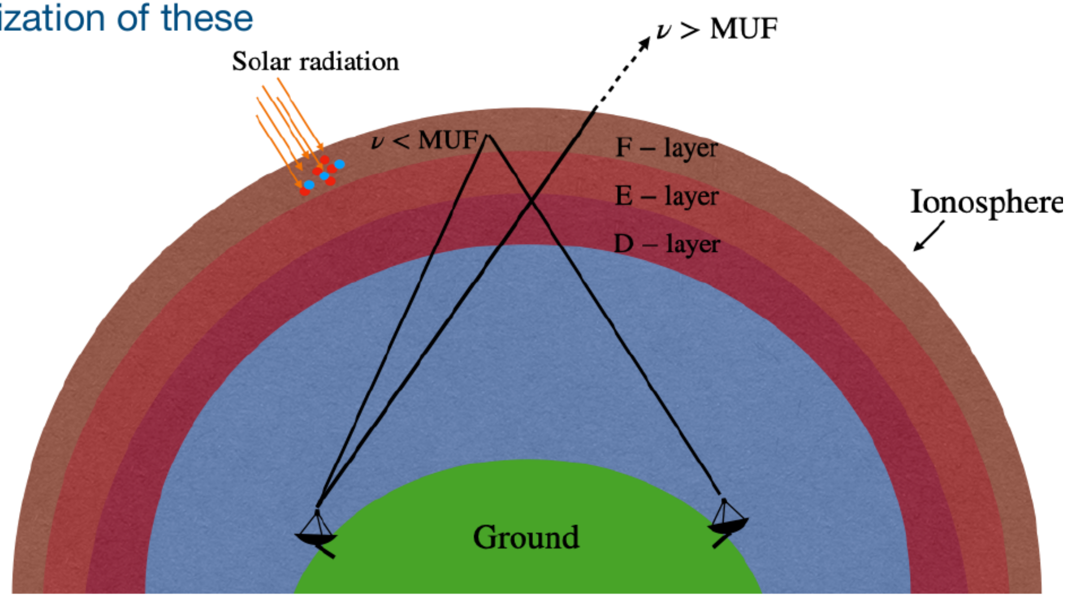
Maximum Usable Frequency - MUF

- Maximum Usable Frequency (MUF) represents the highest frequency that can be used for radio communication between two points located at Earth taking into account ionospheric conditions.

- The MUF is mainly influenced by the electron density in the ionosphere. When the electron density is high, the MUF is also high, allowing higher frequencies to be used for long-distance radio communication as these waves are reflected by the ionosphere.

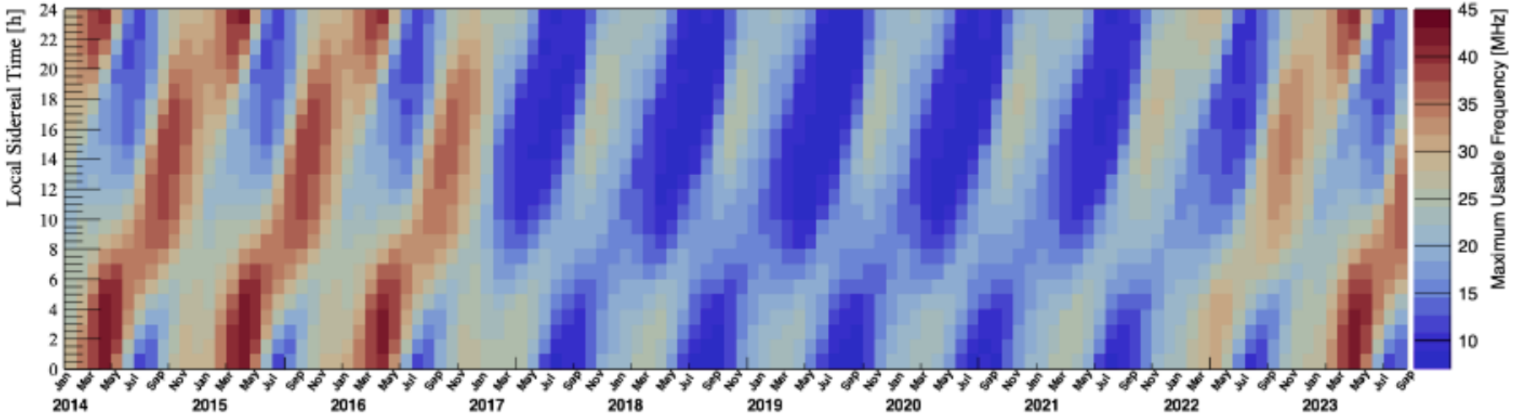
- During periods of high solar activity, the intensification of ultraviolet radiation results in a substantial increase in the ionization of these layers.

- For frequencies above the MUF, the atmosphere becomes transparent, allowing the radio wave to pass through the F layer.



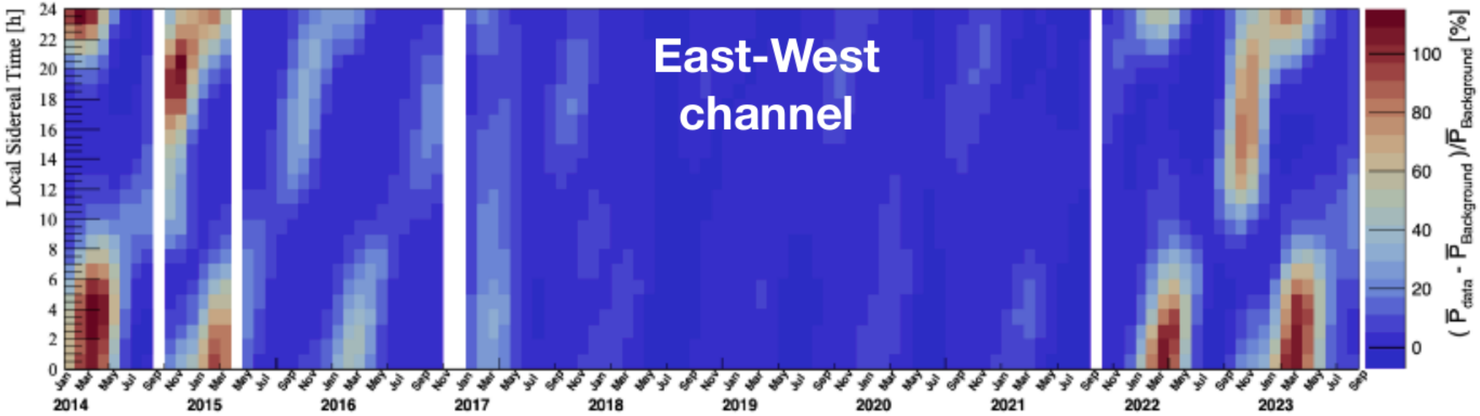
The Maximum Usable Frequency is monitored locally through various stations around the world. https://prop.kc2g.com/

Correlation between MUF and broadband noise measured by AERA within the 30-40 MHz frequency range



Maximum usable frequency

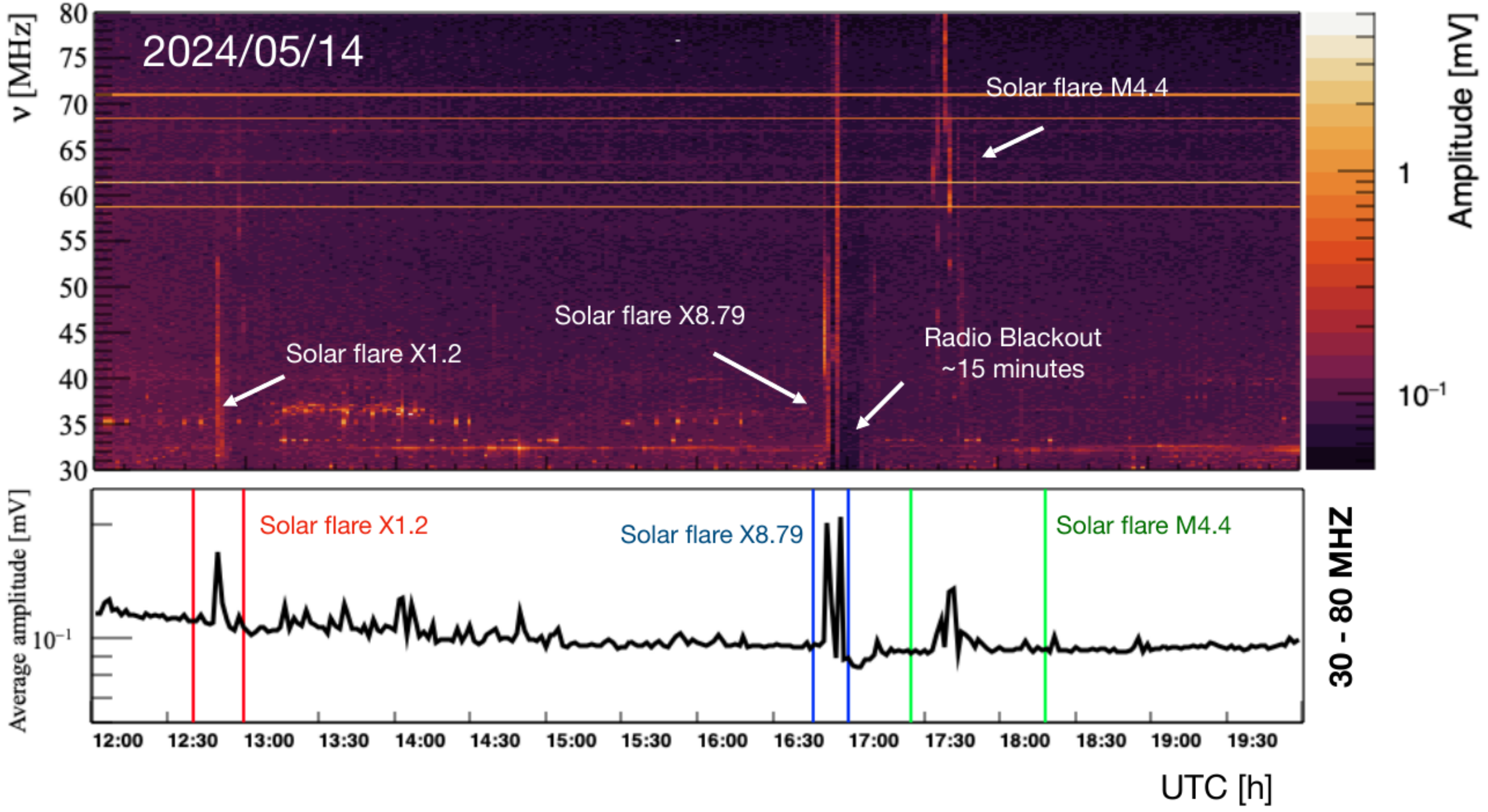
MUF



AERA data (30 - 40 MHz)

$$\frac{\bar{P}_{\text{data}} - \bar{P}_{\text{background}}}{\bar{P}_{\text{background}}}$$

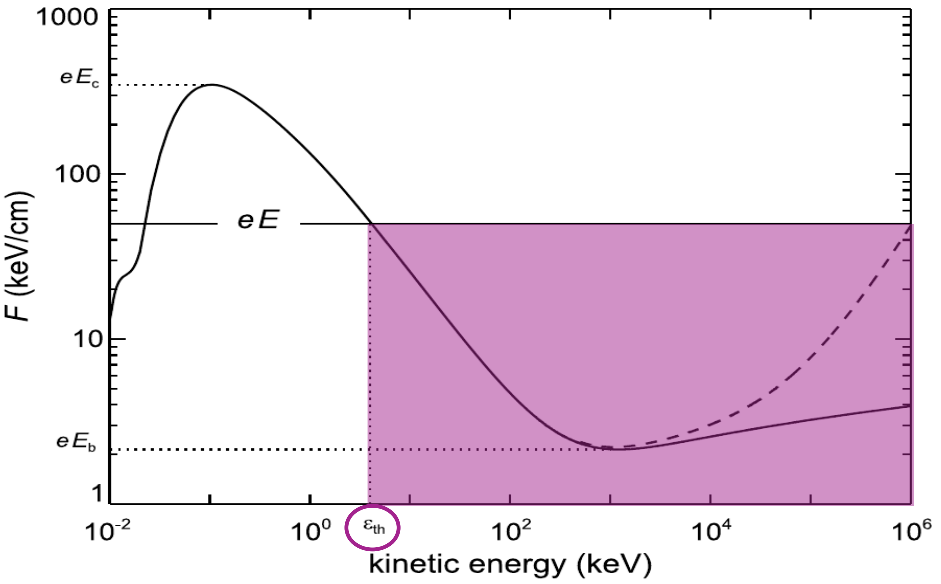
Detection of Solar Radio Burst with AERA data



Backup

Terrestrial Gamma-ray Flashes (TGFs)

TGFs are intense sub-milliseconds (20 μs → 1 ms) bursts of MeV gamma rays



Source: Relativistic runaway electron avalanches (RREA) accelerated in strong electric fields inside thunderstorms (Dwyer, 2003; Gurevich et al., 1992; Wilson, 1925)

OPEN QUESTIONS:

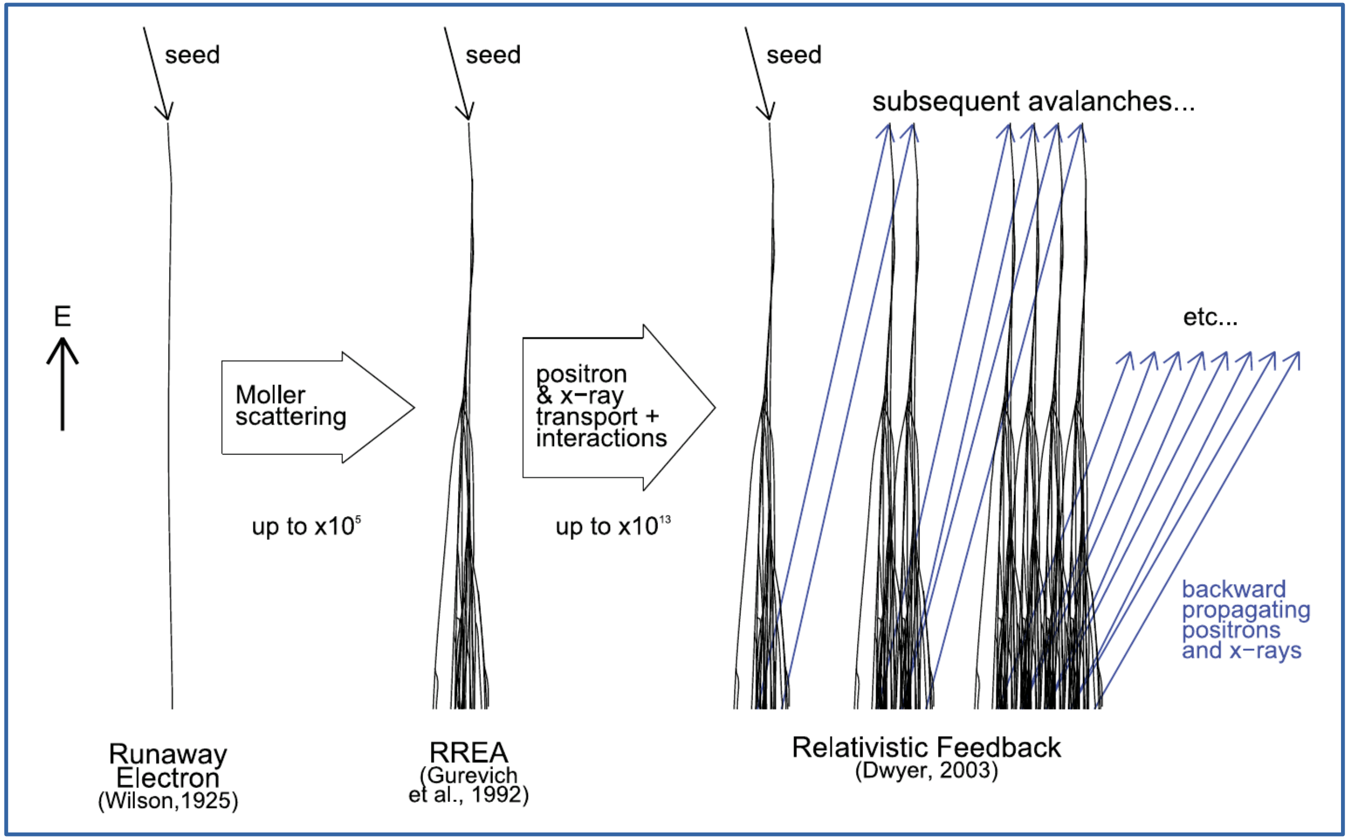
- Where these strong electric fields are located?
- How TGFs connect to lightning?

The study of the temporal relationship between TGFs and radio signatures of different lightning processes (verified by Cummer et al., 2005; Stanley et al., 2006; Connaughton et al., 2010) could improve our understanding of TGF physics.

What process starts the electron avalanche?

Lightning leader model (Köhn et al.) – Relativistic Feedback (Dwyer, 2012)

TGF production models



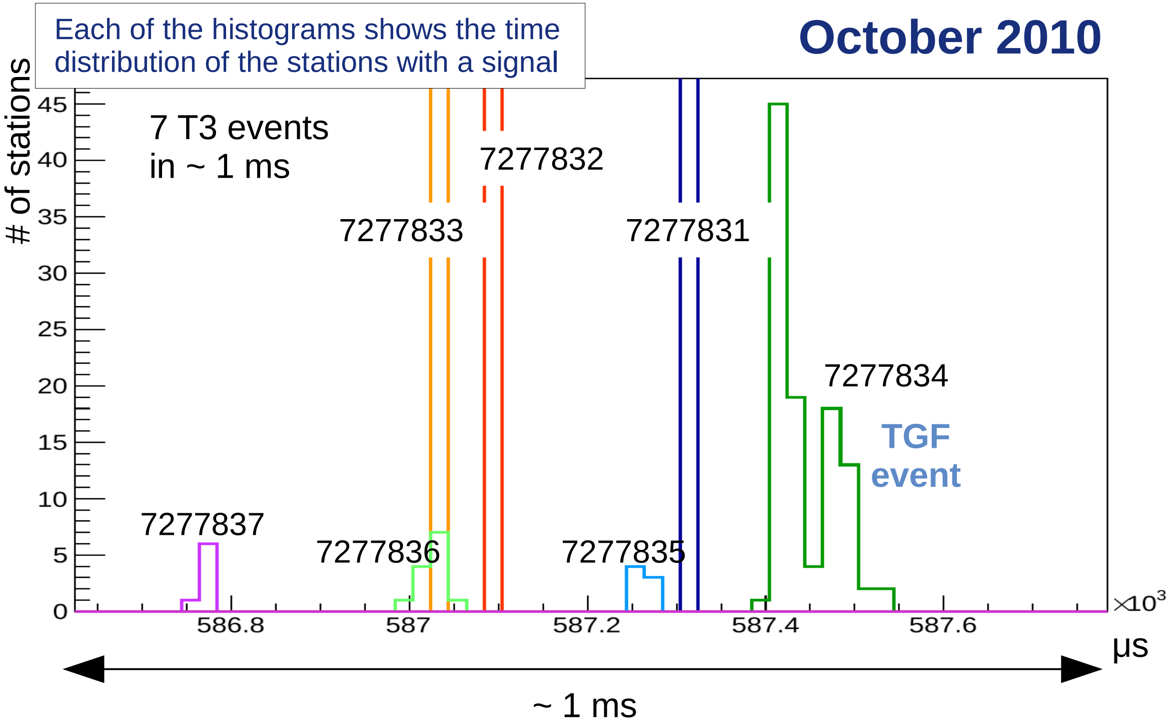
TGF production models: avalanche trigger

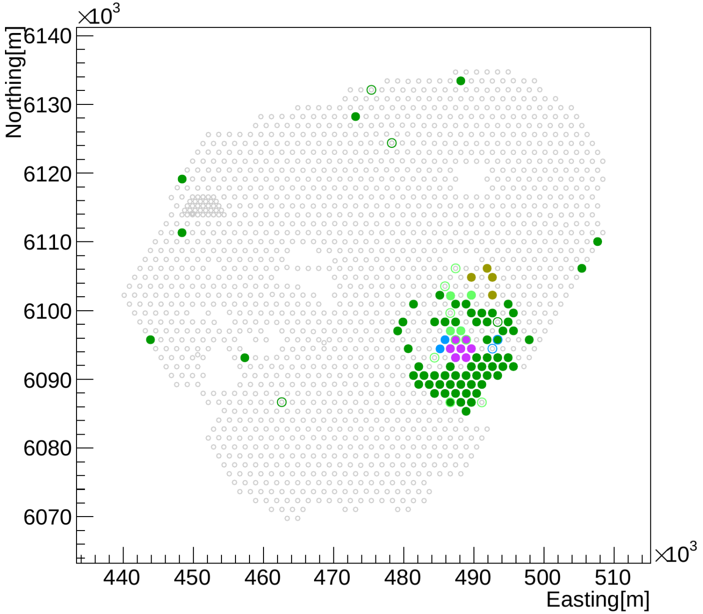
Different models try to explain how the electron avalanche starts:

Lightning leader model:
lightning leaders near the ground have been observed to emit x-rays, presumably due to runaway electron production in the high-field regions near the leader tips
→ energetic seed electrons are necessary to start the avalanche;
→ it remains unclear exactly how and where these runaway electrons are produced.

Relativistic Feedback:
involves positive feedback effects from positrons and energetic photons
→ backscattered positrons and photons can propagate to the start of the avalanche region and produce additional runaway electrons and secondary avalanches.
They can emit more x-rays that Compton scatter or produce pairs, resulting in more feedback and more avalanches.
This positive feedback effect allows the runaway discharge to become self-sustaining, no longer requiring an external source of energetic seed electrons.

What TGF type are we observing?





Behaviour similar to the events observed by the Santa Cruz group (J. Ortberg & D. Smith) in Japan and New Mexico: timing consistent with a stepped leader making a connection at that time → the upward return stroke enhances the field in the right direction for the avalanche to be aimed toward the ground with a strong horizontal component (**-CG** – negative cloud-to-ground).

Detailed lightning information not available at the time of our events…waiting for new events