



Results and prospects in atmospheric electricity studies at the Pierre Auger Observatory

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High-Energy Atmospheric Physics

The atmosphere is never quite neutral due to

- thunderstorms, which create lightning bolts to rapidly discharge huge amounts of atmospheric charge stored in thunderclouds
- ionization from cosmic rays and natural radioactivity

Despite the ubiquity of thunderstorms, lightning, and related electrical phenomena, many important electromagnetic processes in our atmosphere are poorly understood.

For example, many questions remain about thundercloud electrification and discharge mechanisms, lightning initiation, propagation and attachment processes, compact intra-cloud discharges, the global electrical circuit, and transient luminous events.

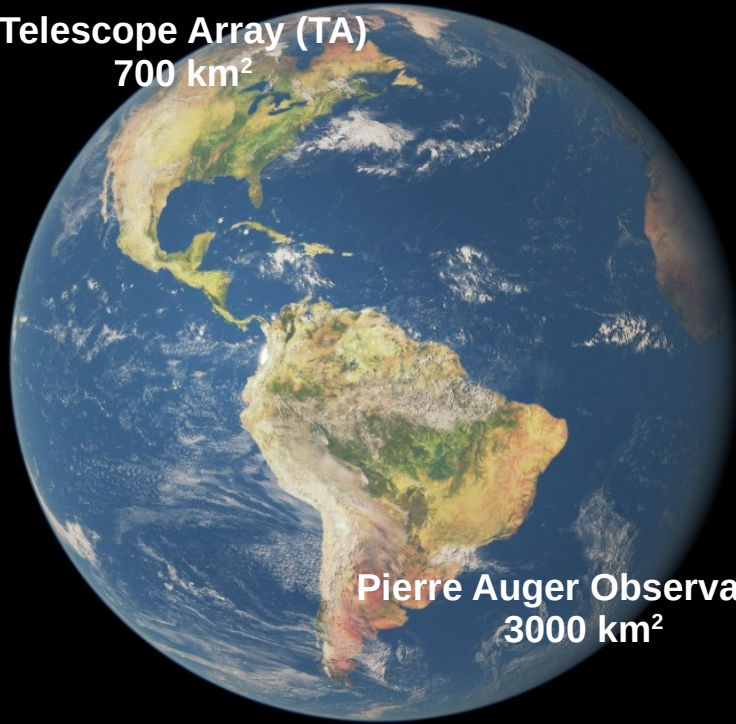
However, in the last few years, a growing body of literature has emerged that describes the production, transport and interactions of energetic particles in our atmosphere.

It is now well established that thunderclouds, lightning, and long laboratory sparks in air produce

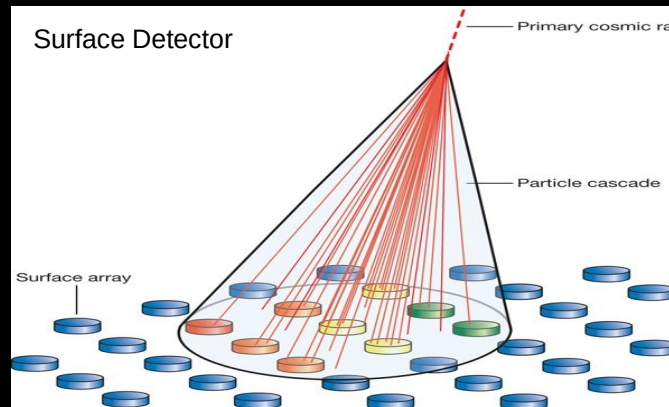
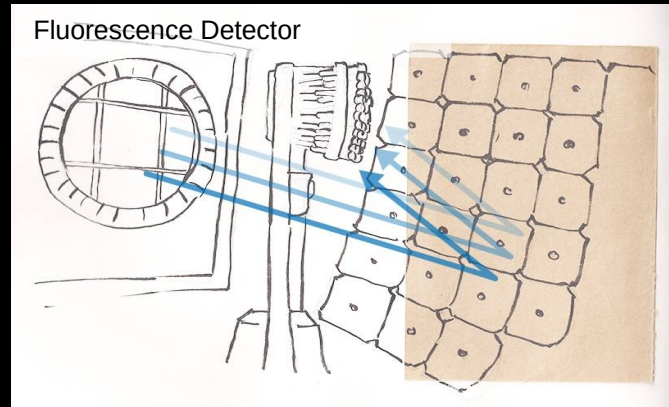
- energetic runaway electrons and accompanying x-ray and gamma-ray emissions (TGFs);
- Transient Luminous Events (TLEs).

The High-Energy Atmospheric Physics & Cosmic Rays

Telescope Array (TA)
700 km²



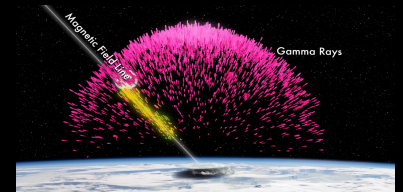
Pierre Auger Observatory
3000 km²



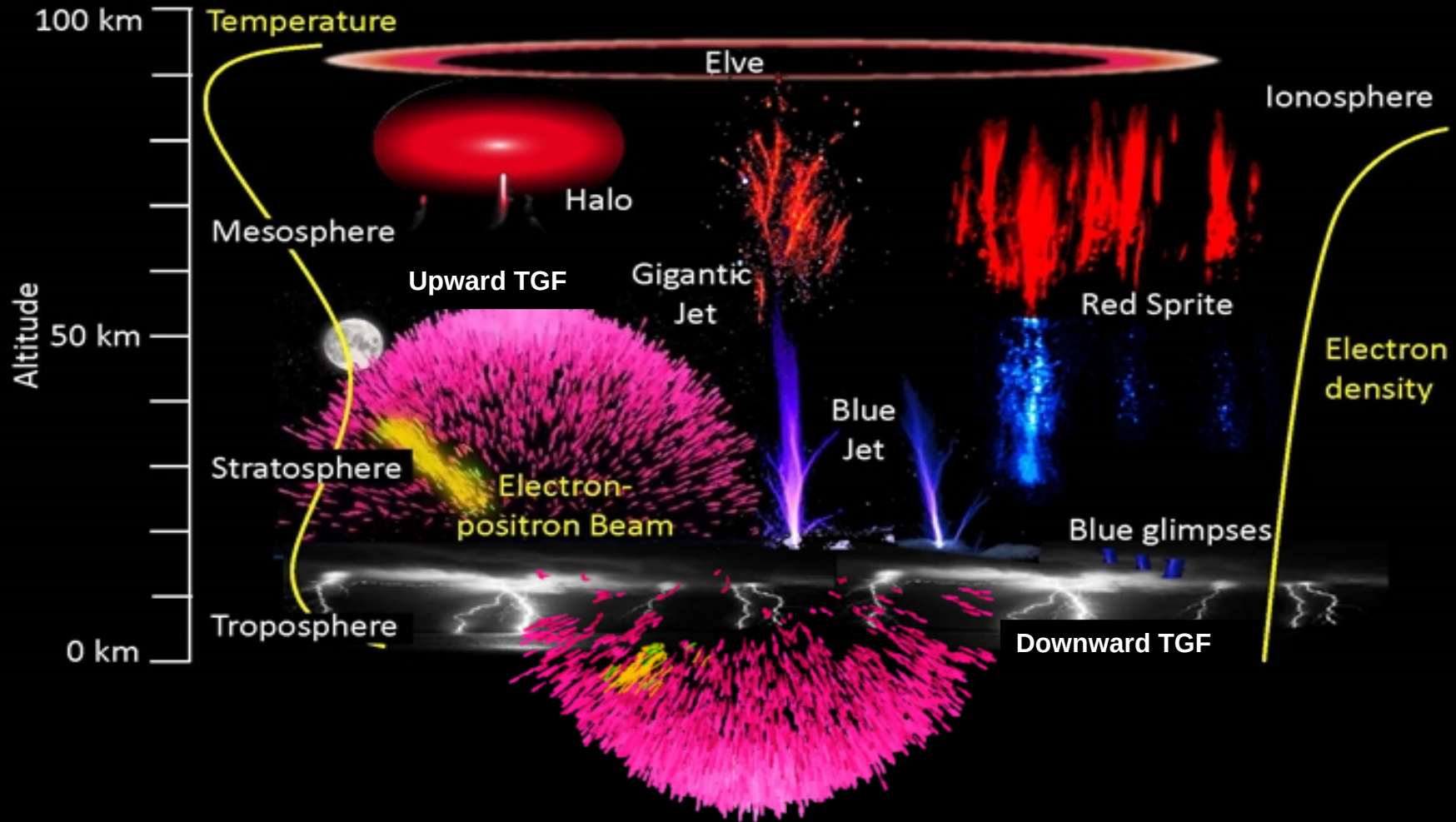
ELVES + other TLEs



TGFs



Bright events produced by lightning



Red Sprites and Halos

Stratospheric/mesospheric Perturbations Resulting from Intense Thunderstorm Electrification



Their discovery was announced thirty years ago (in July 1990) by Franz et al. - <https://doi.org/10.1126/science.249.4964.48>.

Sprites had been originally recorded the year before (1989) as two transient luminous columns of light over a large thunderstorm in the mid-western United States.

Following studies demonstrated that sprites

- are mesospheric phenomena with tops reaching over 90 km, essentially the base of the ionosphere;
- last few milliseconds;
- are coincident with powerful positive cloud-to-ground lightning strokes.

Time scale ~ 10 ms Size ~ 40 km x 2-3 km

July 4, 2021, Piemonte, Italy

Exifs: Sony a7s1 – Nikkor 105mm/1.4@1.4 – 1 / 25s –
ISO 30.000 – Atomos Registrator

Blue jets

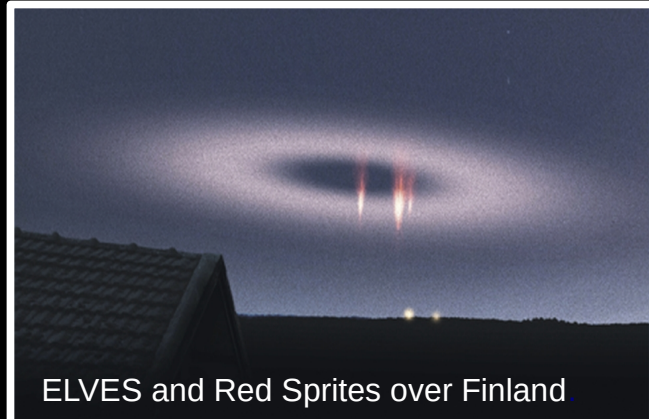


Mauna Kea, Hawai'i

Time scale $\sim 0.2-0.4$ s Length $\sim 20-40$ km Speed $\sim 3 \cdot 10^{-4} c$

ELVES

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



They were predicted by Inan et al. (1991) - <https://doi.org/10.1029/91GL00364> - as the manifestation of the impulsive electric field component of lightning.

The first observation of elves from space was accomplished by the Space Shuttle (Boeck et al., 1992).

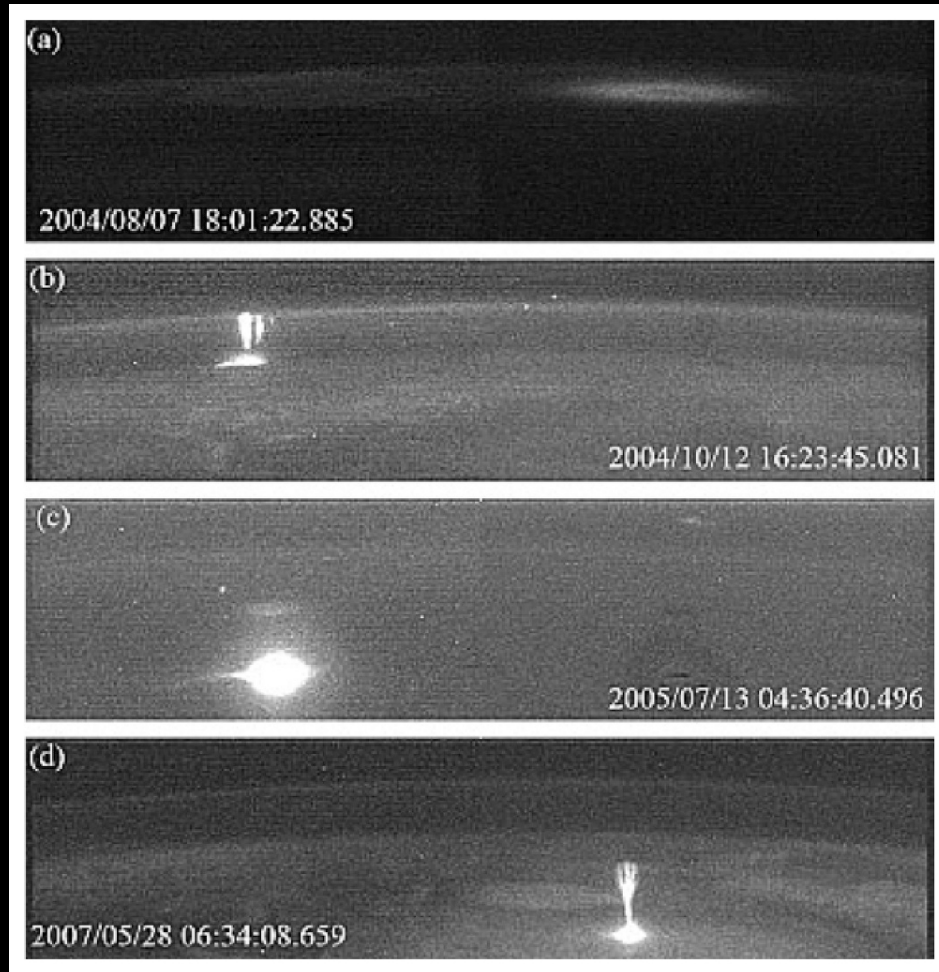
Elves were first detected from ground by Fukunishi et al. (1996) - <https://doi.org/10.1029/96GL01979> - as diffuse optical flashes with a duration of < 1 ms occurring just after the onset of CG lightning.

Usually observed as a disk-shaped luminosity region at the base of the ionosphere where the free electrons are heated by an energetic lightning-generated electromagnetic pulse (EMP).

Time scale ~ 1 ms Diameter > 200 km

35 elves/minute, the most frequent TLEs

Detection of TLEs



A number of space, balloon, aircraft and ground-based instruments have been designed and operated for the observation of TLEs since their discovery in 1989.

TLEs emit **flashes of light, radio and acoustic signals in the form of infrasound.**

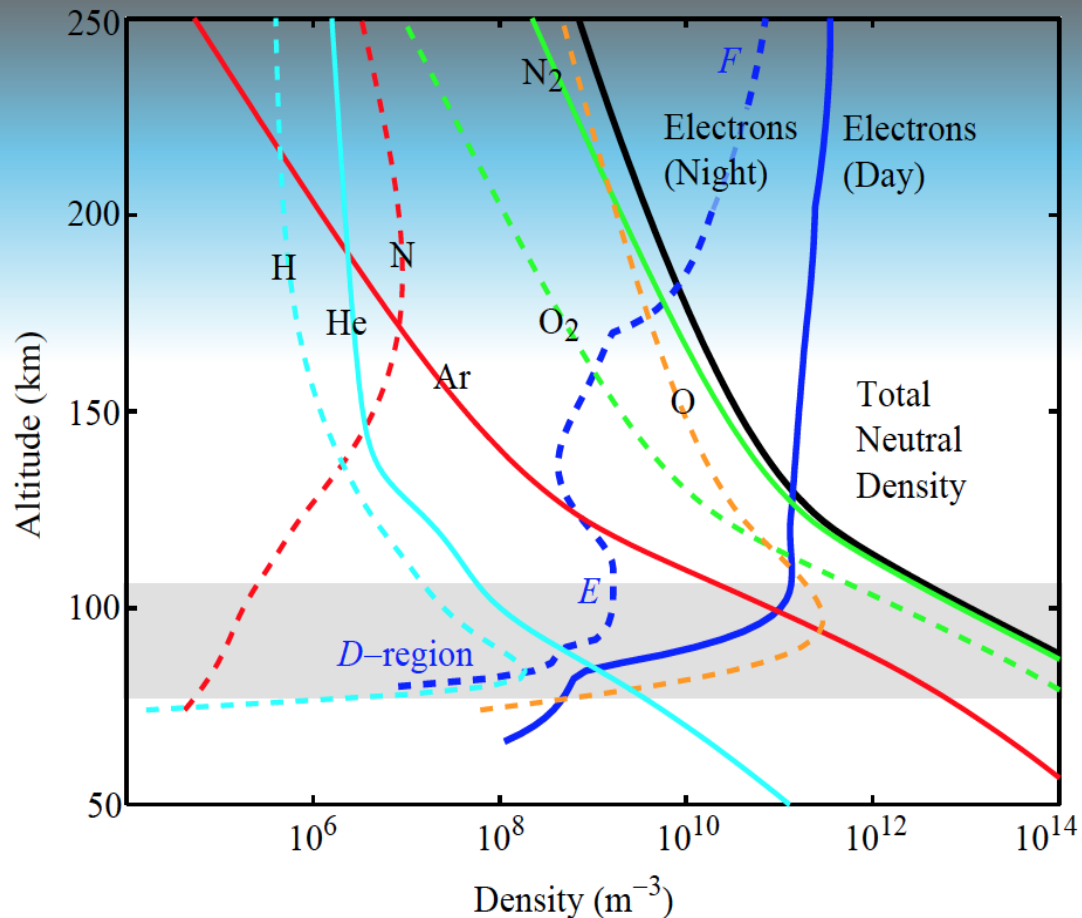
All these different types of signatures have been used to detect them.

In particular, long term space instruments have been developed to study the frequency of occurrence, global distribution and key optical emissions from TLEs:

- **ISUAL** on board the FORMOSAT-2 satellite (2004 and 2016);
- **JEM-GLIMS** (2012 and 2015);
- **ASIM** (in operation since April 2018).

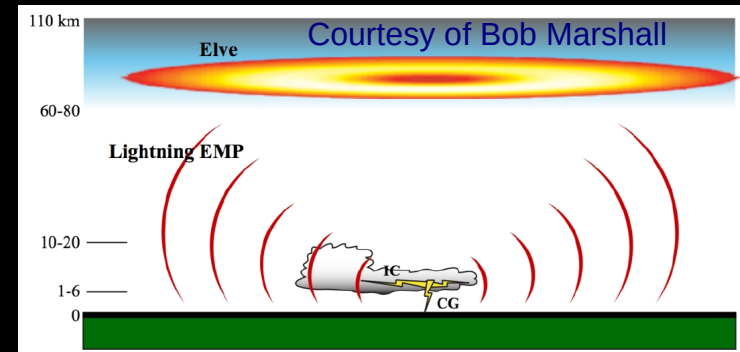
Both JEM-GLIMS and ASIM were on board the International Space Station (ISS).

Particle densities between mesosphere and ionosphere and ELVES production mechanism



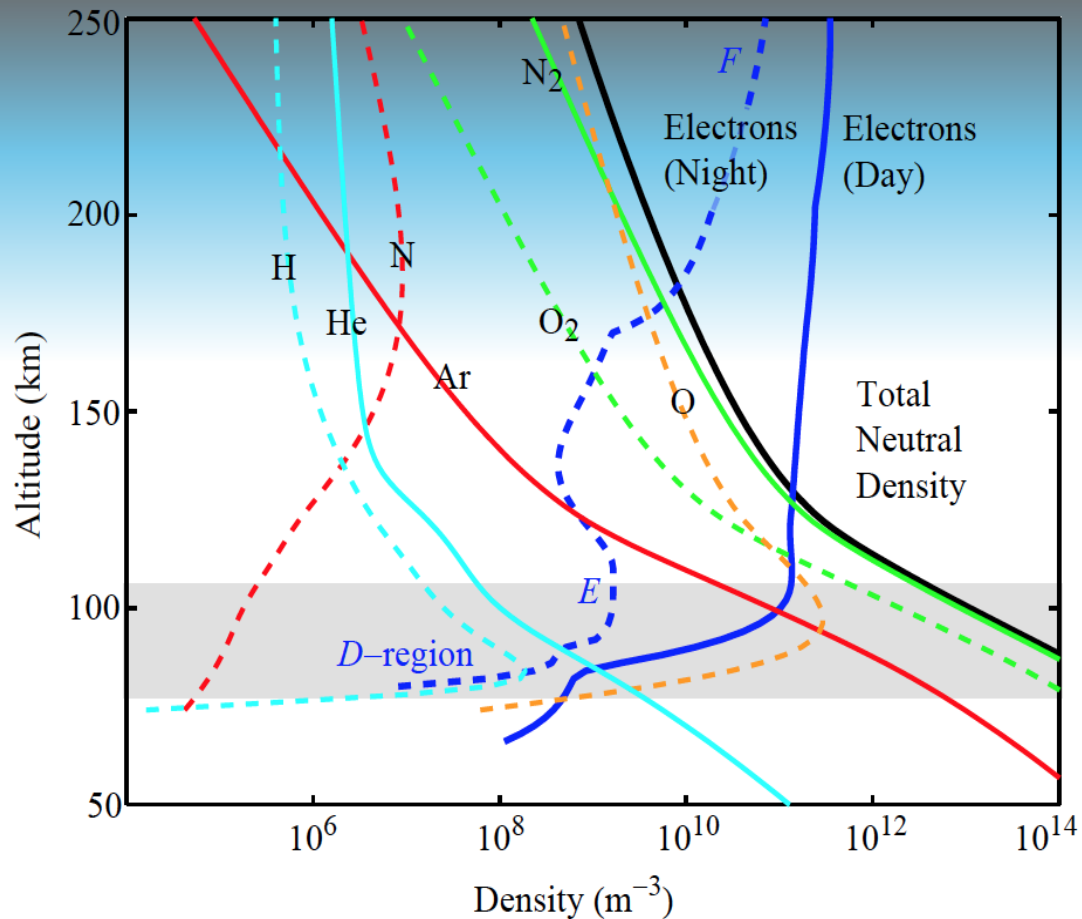
In less than 10 km, electron density increases by three orders of magnitude.

This step variation is responsible for both reflection of radio waves and emission of light at visible frequencies caused by the arrival of the electromagnetic pulse produced by the lightning.



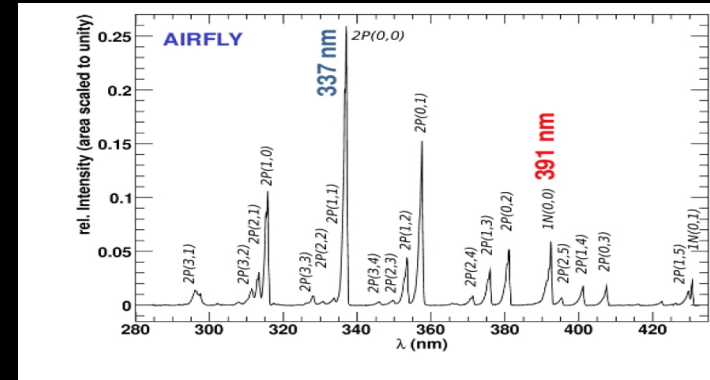
- EMP accelerates electrons at the base of the ionosphere (80-90km);
- Electrons collide and excite nitrogen molecules;

Particle densities between mesosphere and ionosphere and ELVES production mechanism



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This step variation is responsible for both reflection of radio waves and emission of light at visible frequencies caused by the arrival of the electromagnetic pulse produced by the lightning.



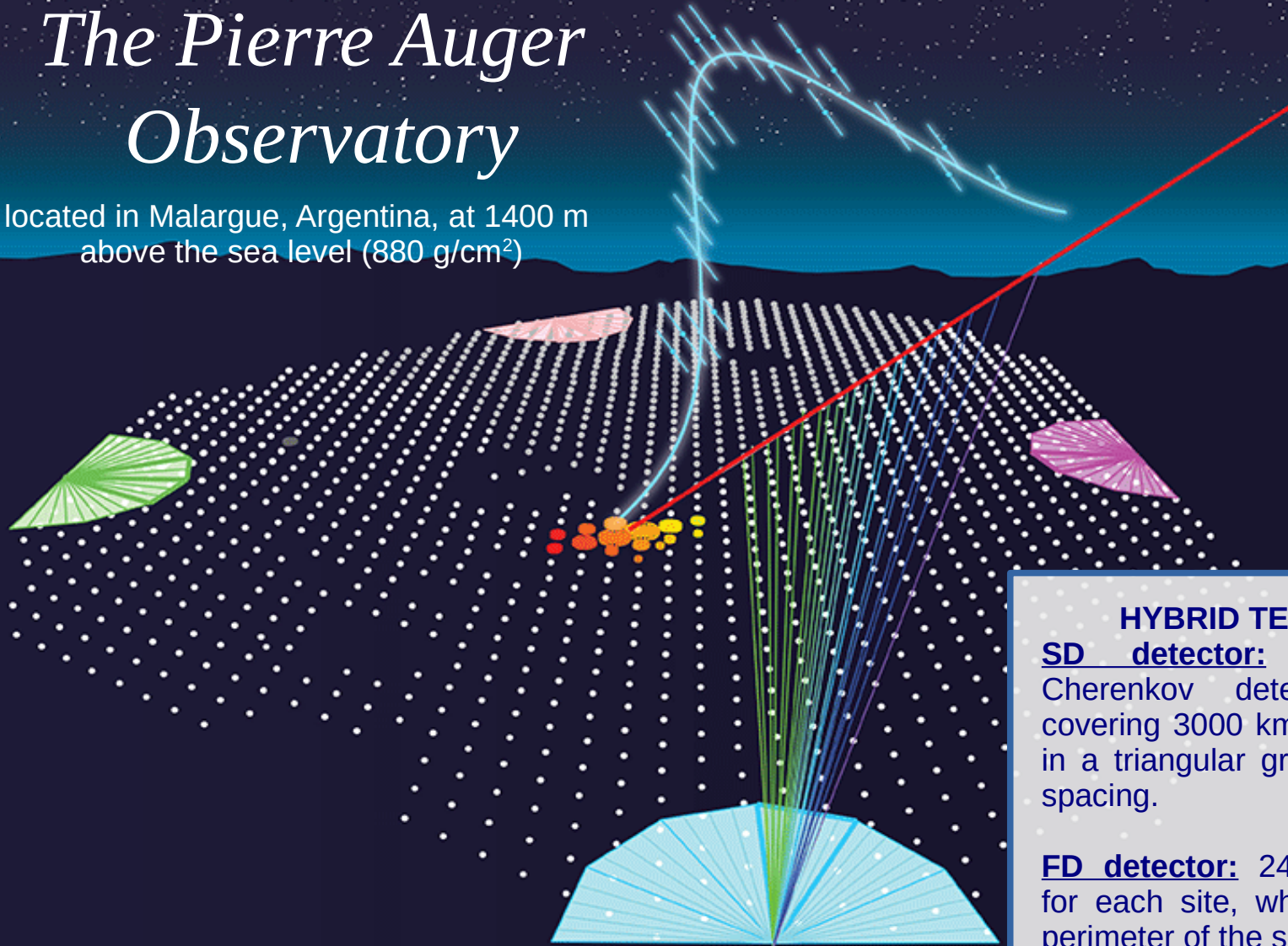
De-excitation Spectrum: 300-400 nm

A vertical lightning is like a radiating dipole

Shape can be distorted if the dipole is tilted (e.g. in intracloud lightning)

The Pierre Auger Observatory

located in Malargue, Argentina, at 1400 m
above the sea level (880 g/cm^2)

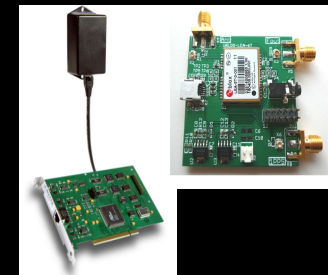
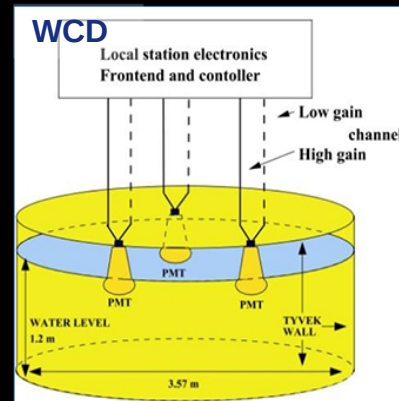
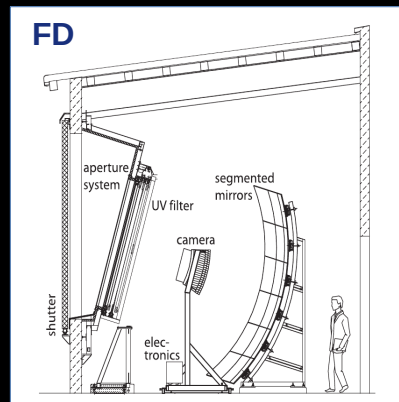
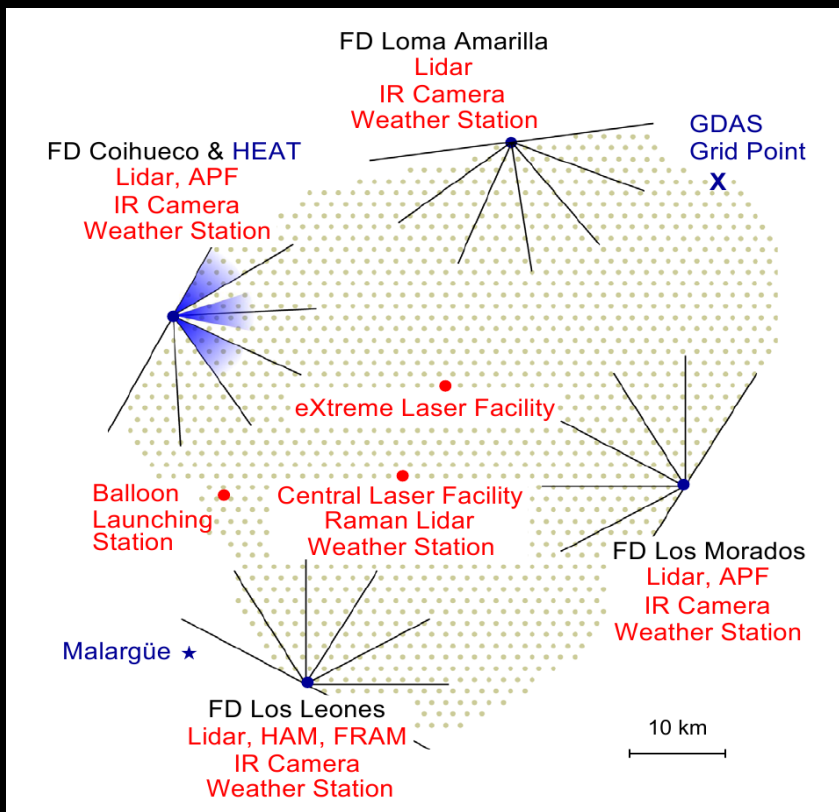


HYBRID TECHNIQUE

SD detector: 1600 Water Cherenkov detectors (WCD), covering 3000 km^2 and arranged in a triangular grid with 1500 m spacing.

FD detector: 24 telescopes, 6 for each site, which are on the perimeter of the surface array.

The Auger detectors + atmospheric monitoring

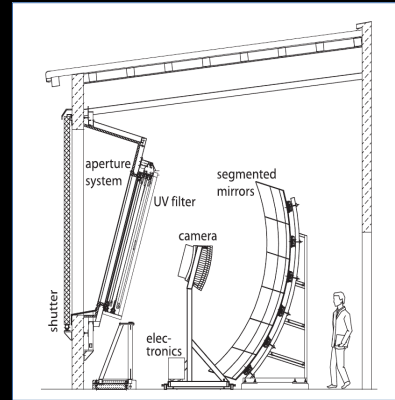
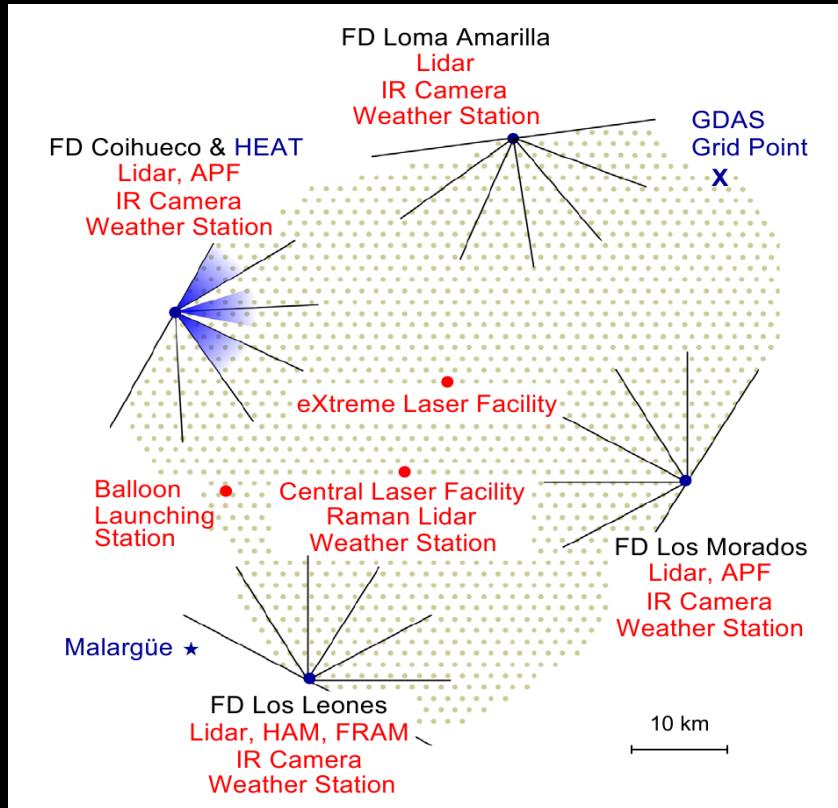


5 Boltek Storm trackers with GPS antenna (30ns resolution)
Range: up to 500 km

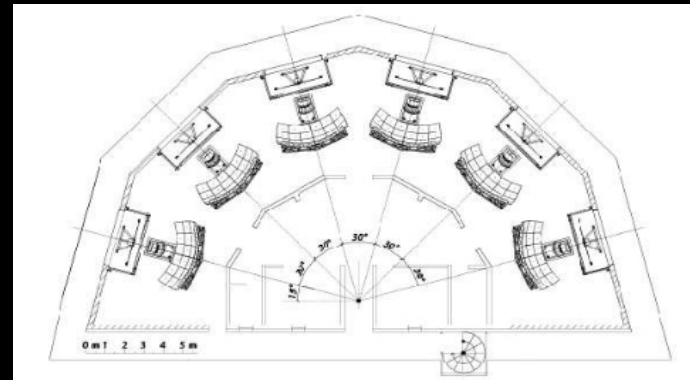


2 E-field mills
Campbell Scientific CS110

The Auger Fluorescence Detector



24 (+3) telescopes in 4 sites
 FD camera: 440 PMTs / telescope
Mirror area: 11m²
 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°



ELVES @ the Pierre Auger Observatory

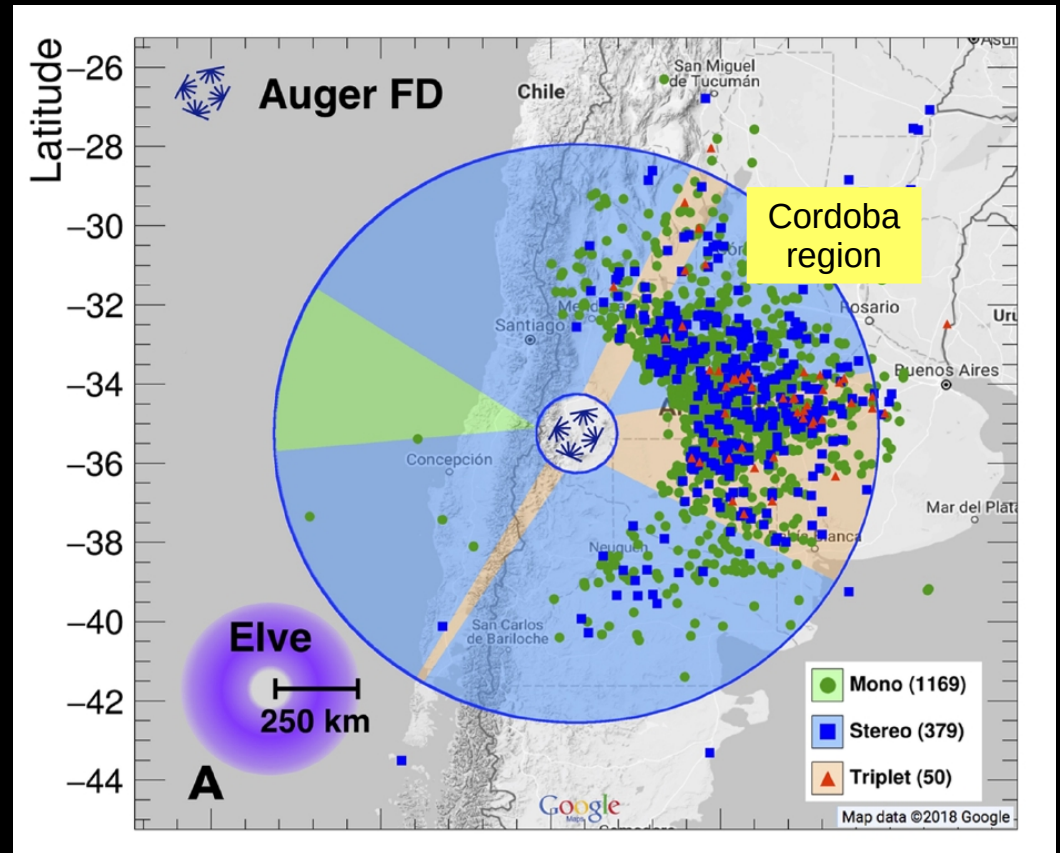
More than 95% of the observed elves are 250-1000 km away, where the FoV of a telescope crosses the ionosphere and direct light from lightning is blocked by the limb of the Earth

→ the observatory acceptance for elves extends over $3 \cdot 10^6 \text{ km}^2$, the largest ground-based area ever used for detecting Elves.

This footprint covers portions of the Pacific Ocean, the Atlantic Ocean, Chile, the Andes mountain range, and Northern Argentina.

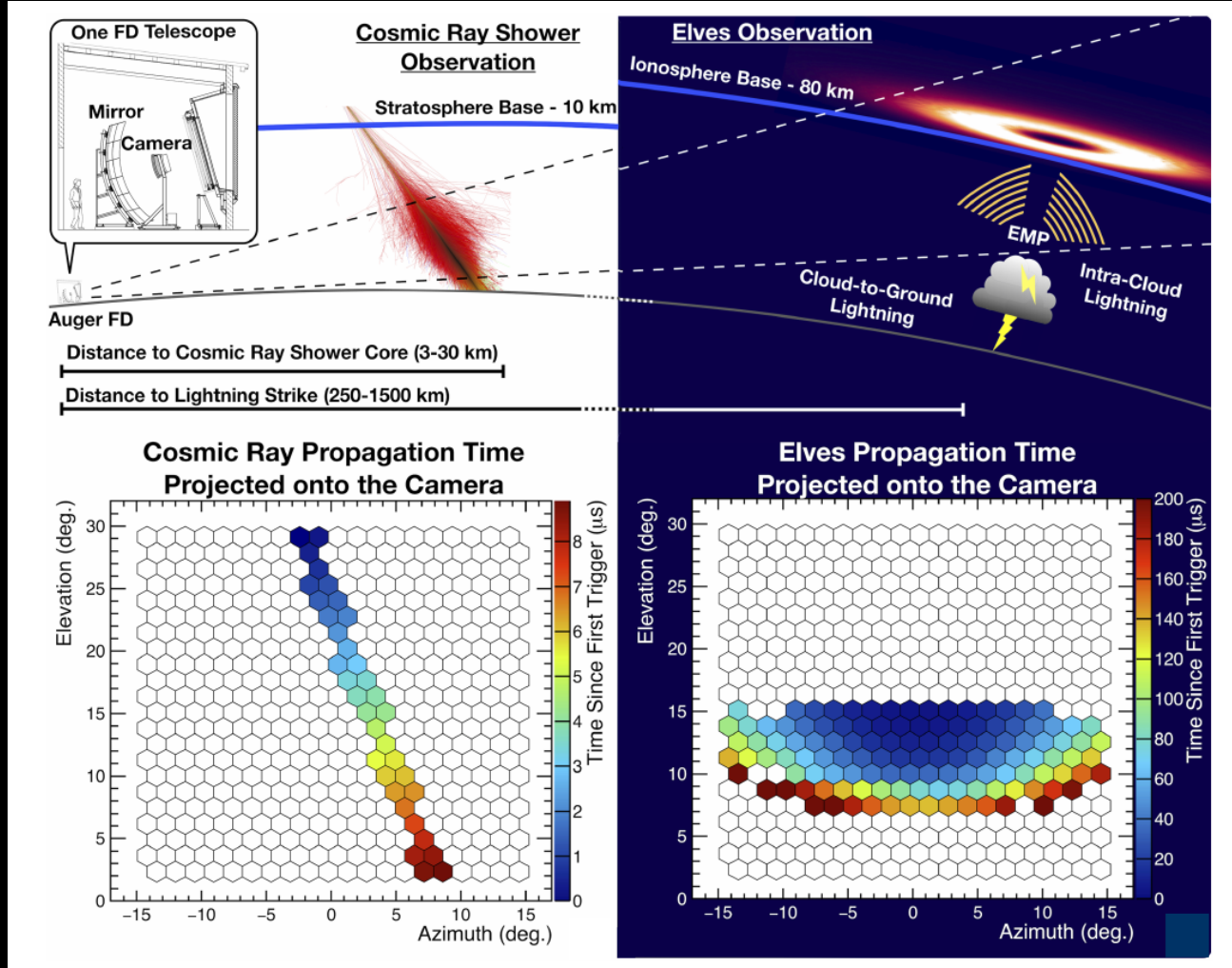
The latter includes the Córdoba region, known for some of the most energetic and destructive convective thunderstorm systems in the world and the highest lightning flash rate in some of the tallest thunderstorms.

Thanks to HEAT (High Elevation Auger Telescopes), we can reduce the lower limit of the acceptance and observe other events very close to the array.

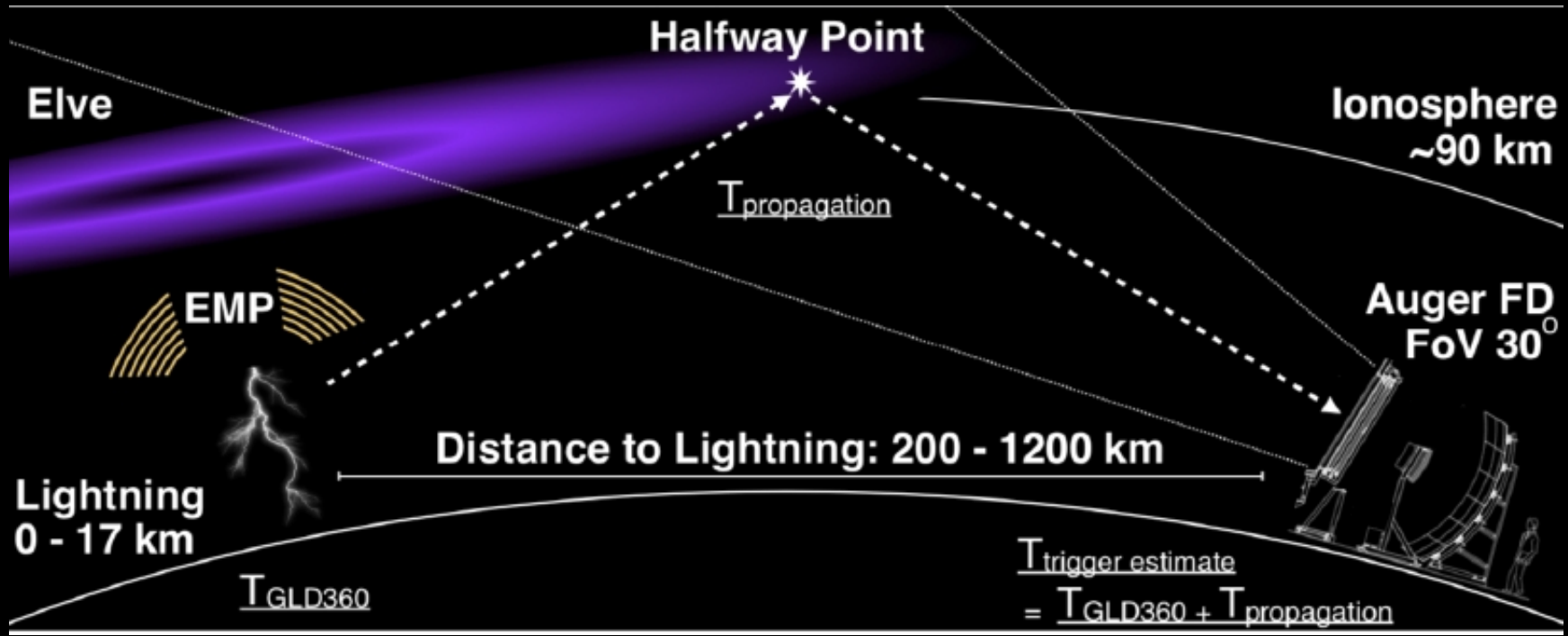


Very good time resolution (100 ns)

ELVES @ the Pierre Auger Observatory

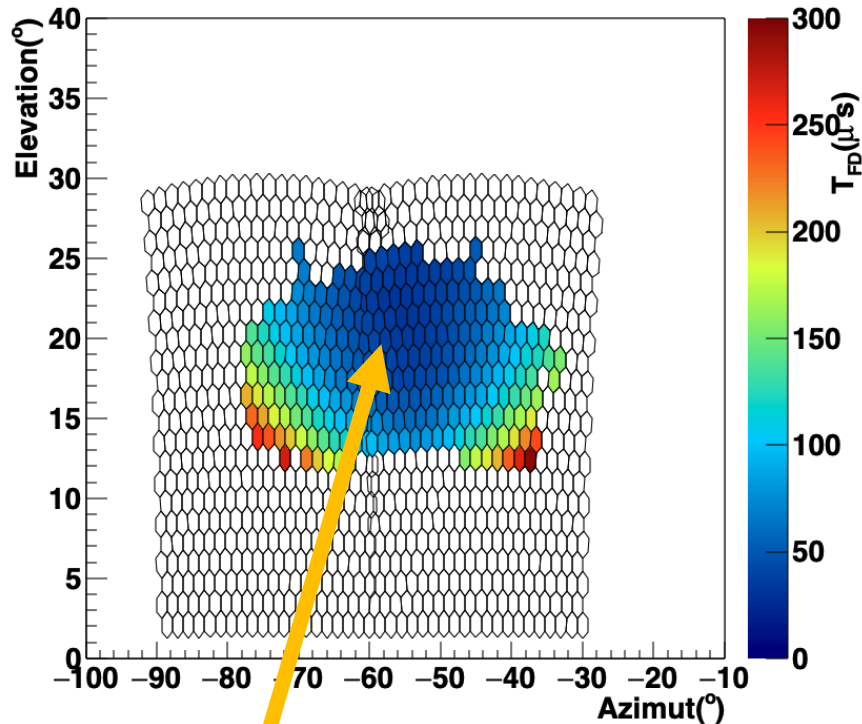


ELVES propagation



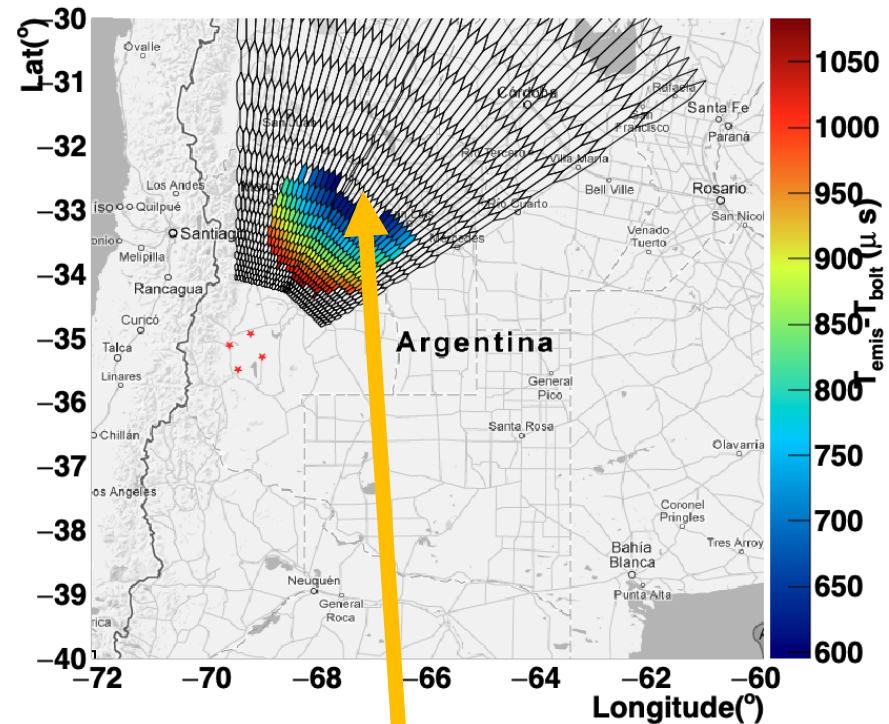
Camera View vs Ionosphere View

ELVES seen in FD camera



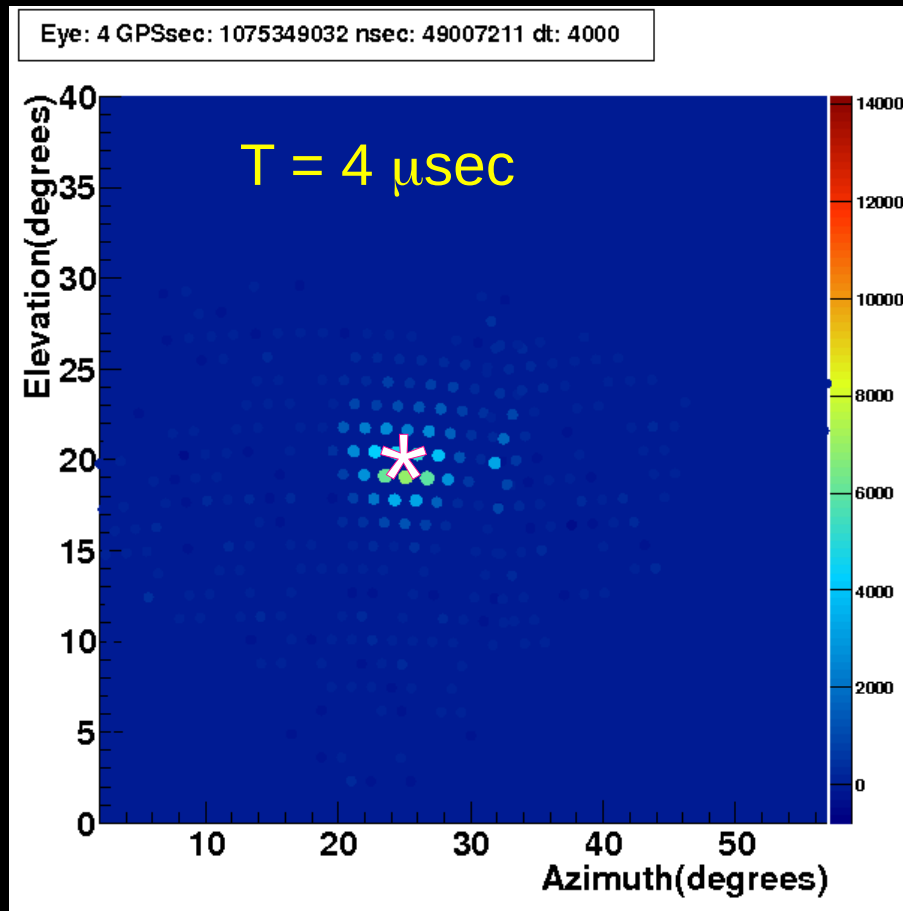
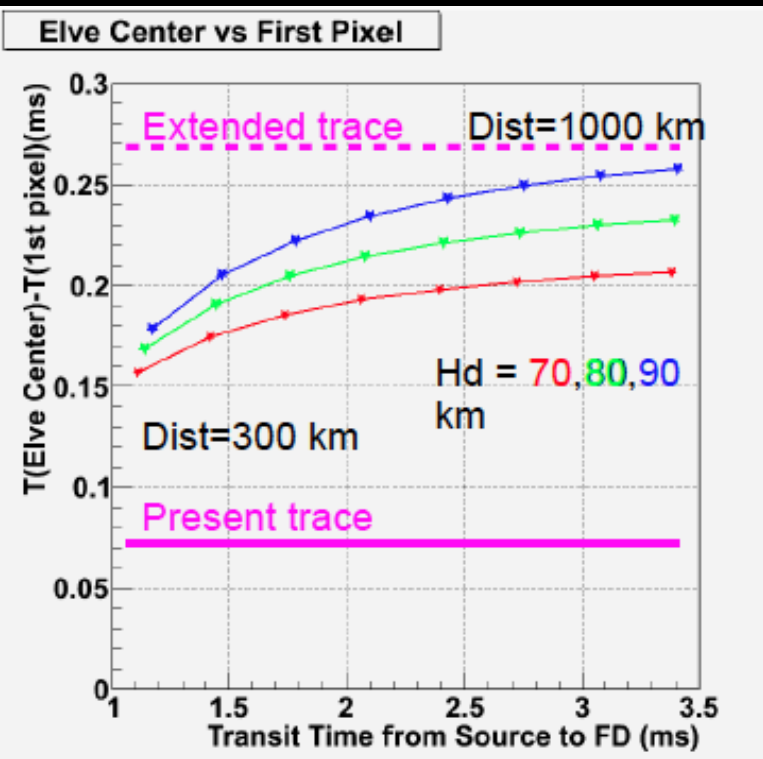
Here the center is in the direction with the shortest path between source and FD

ELVES light emission at ionosphere base μs



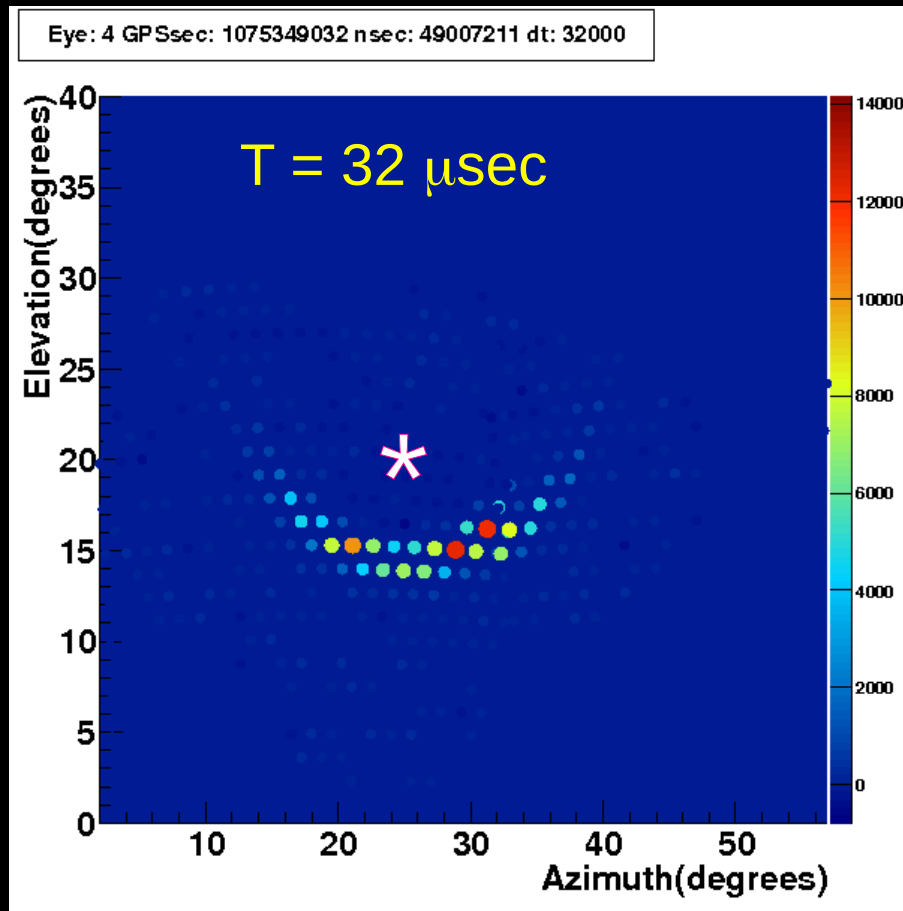
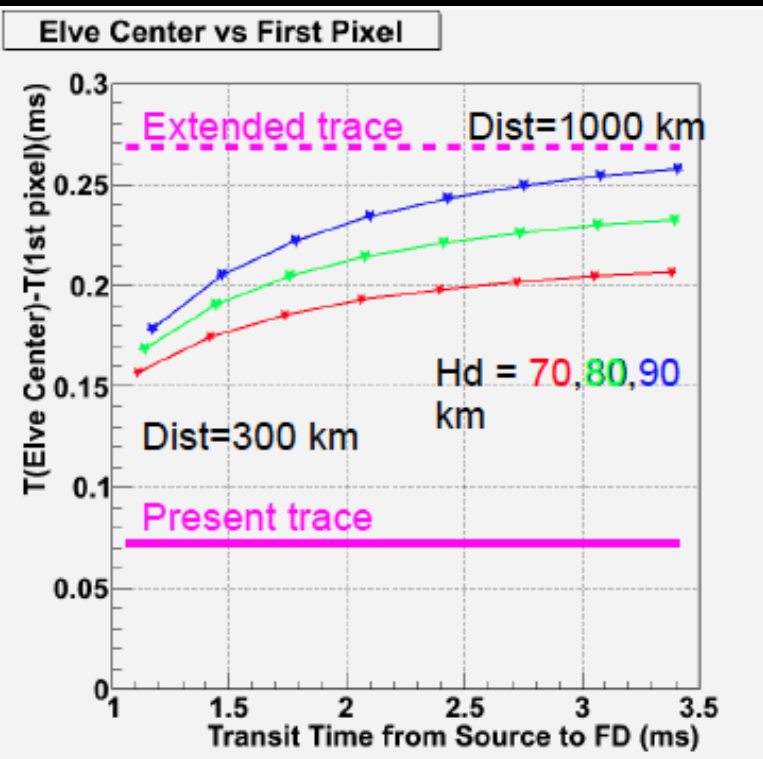
After correcting for time delay, the center is at the lightning source location

ELVES Readout Format: standard (2013)



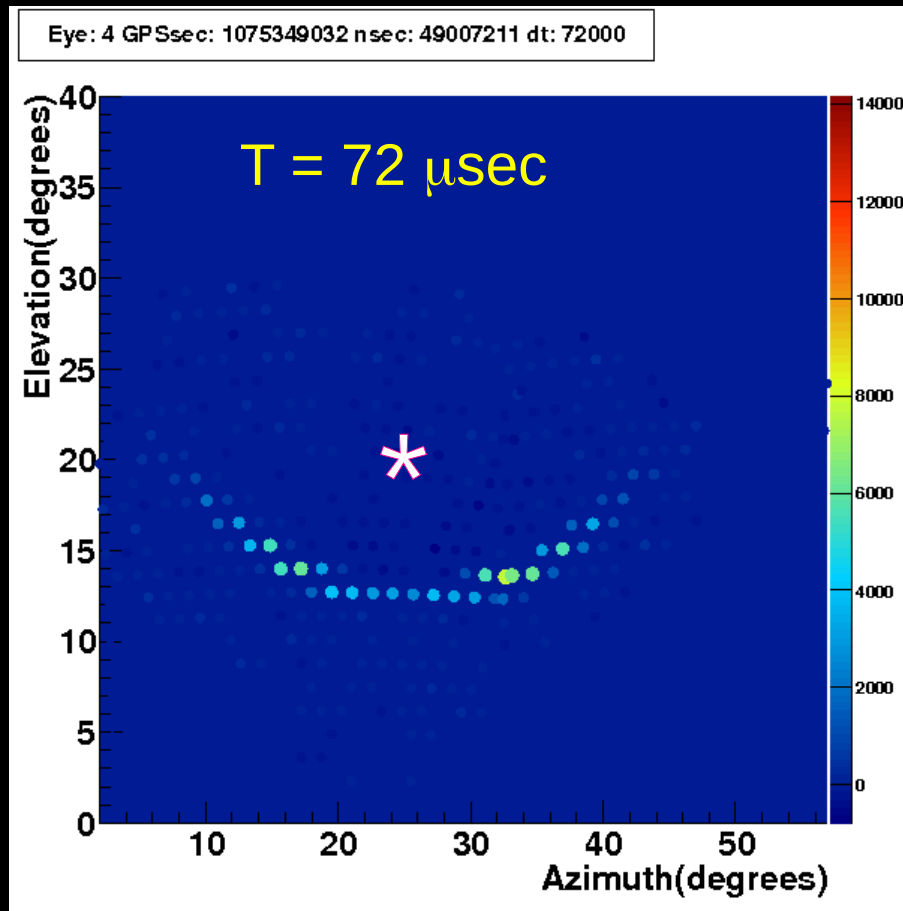
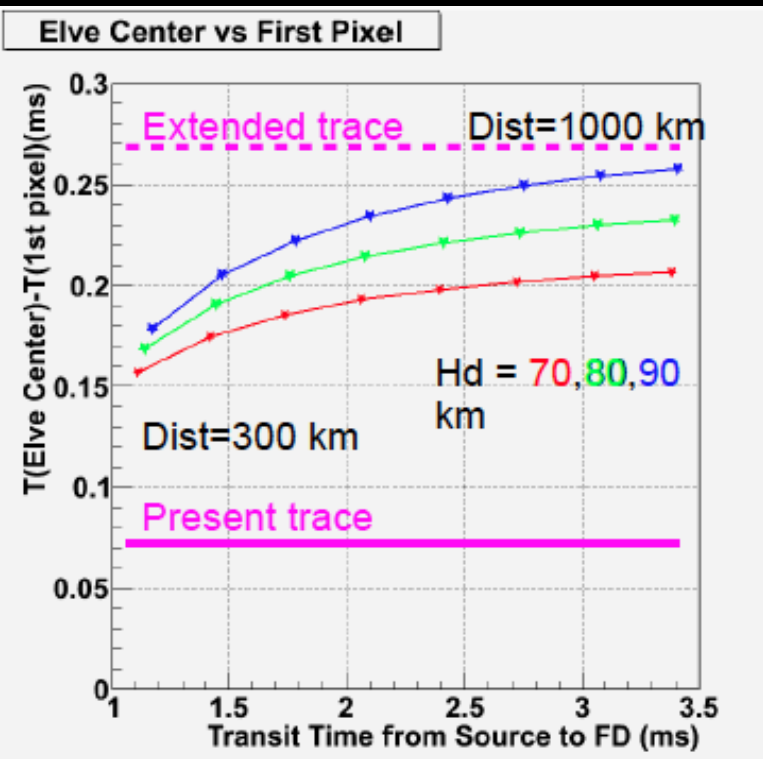
Trigger at 28 μs

ELVES Readout Format: standard (2013)



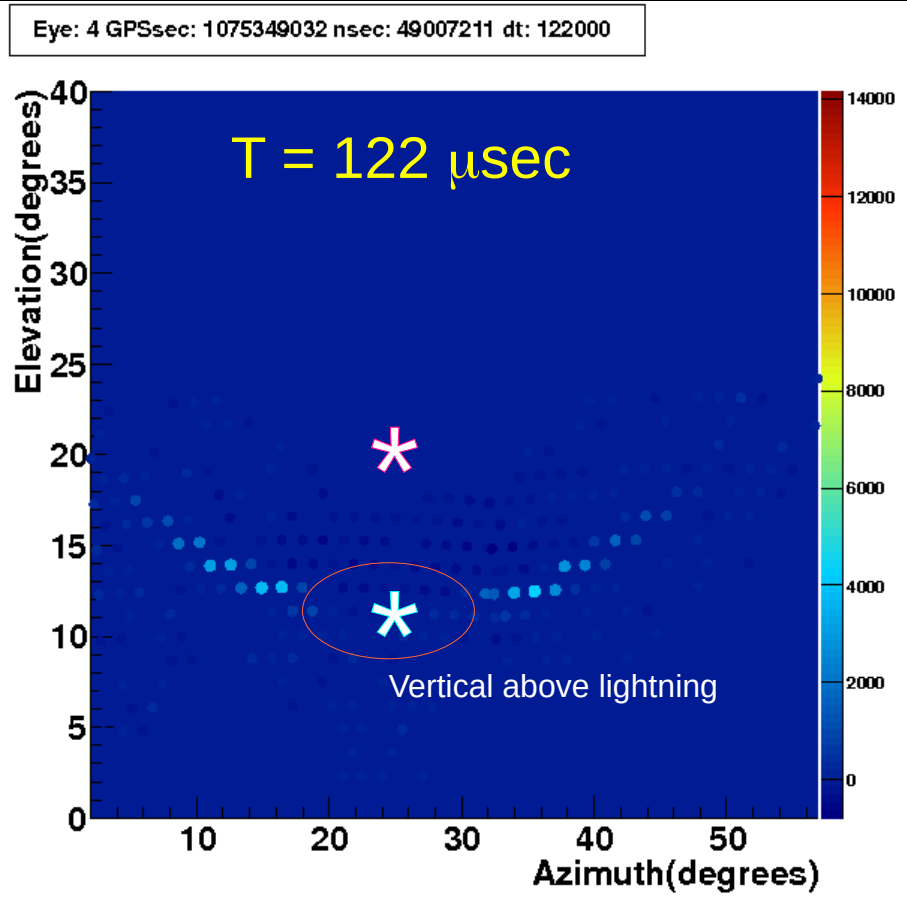
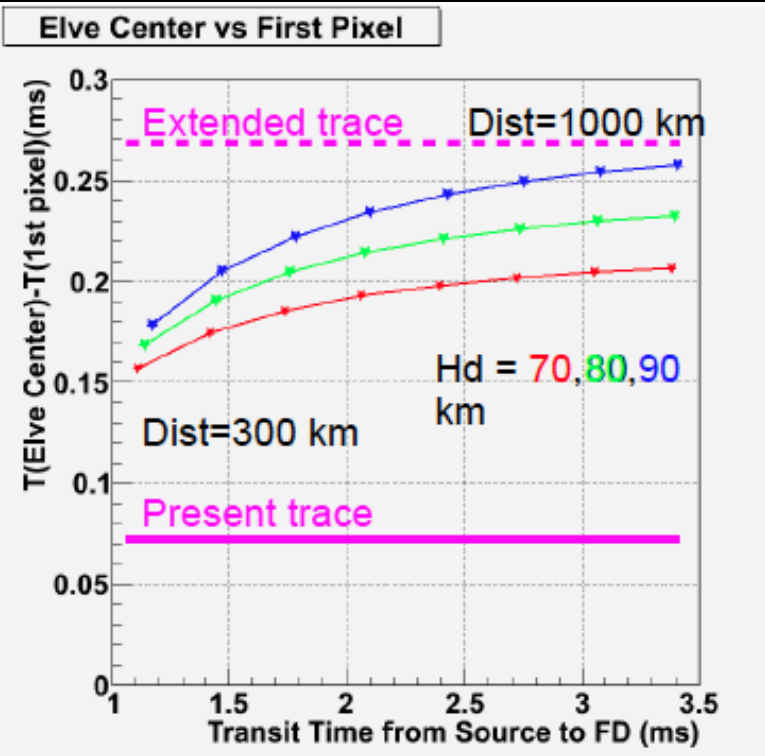
Trigger at $28 \mu\text{s}$

ELVES Readout Format: standard (2013)



Trigger at $28 \mu\text{s}$

ELVES Readout Format: extended (2014-6)

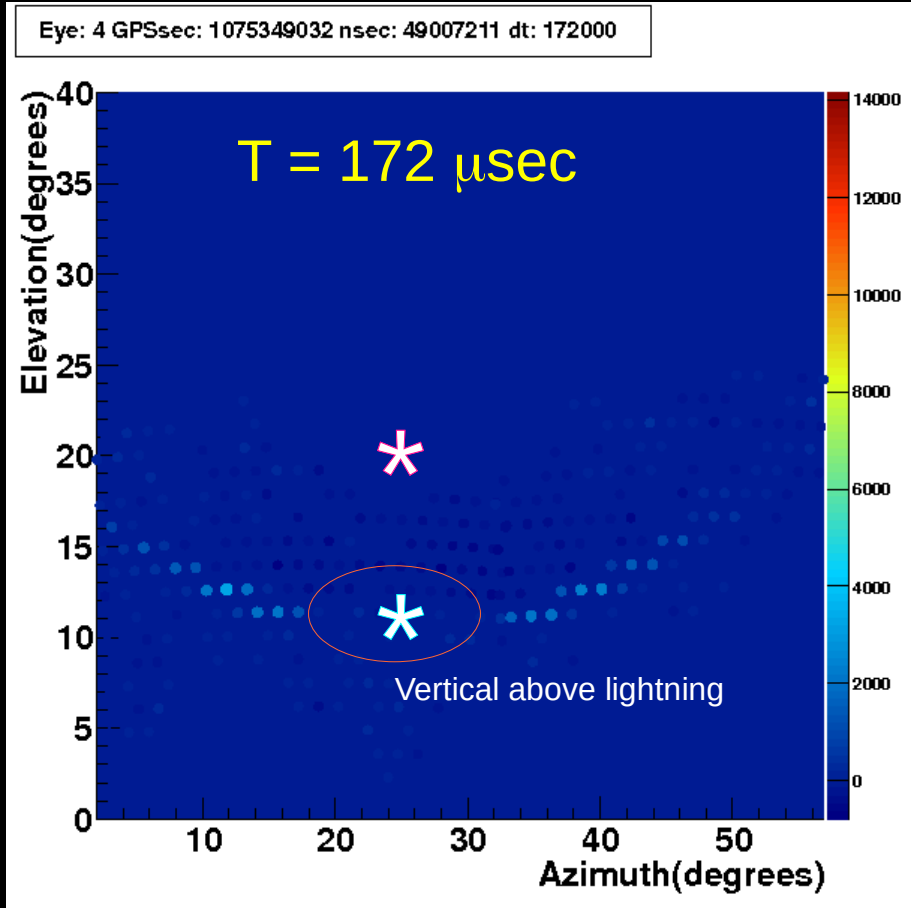
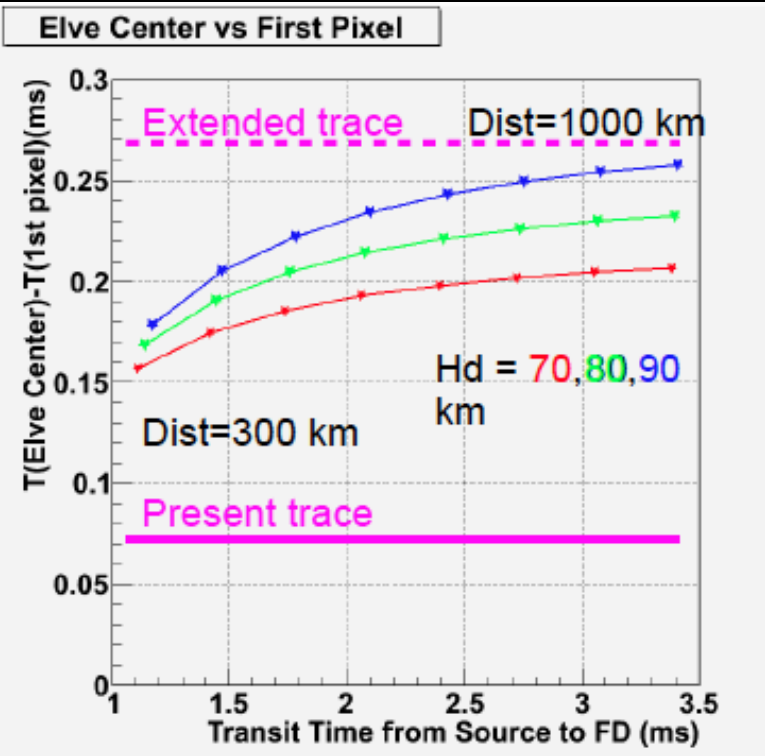


Trigger at 28 μs



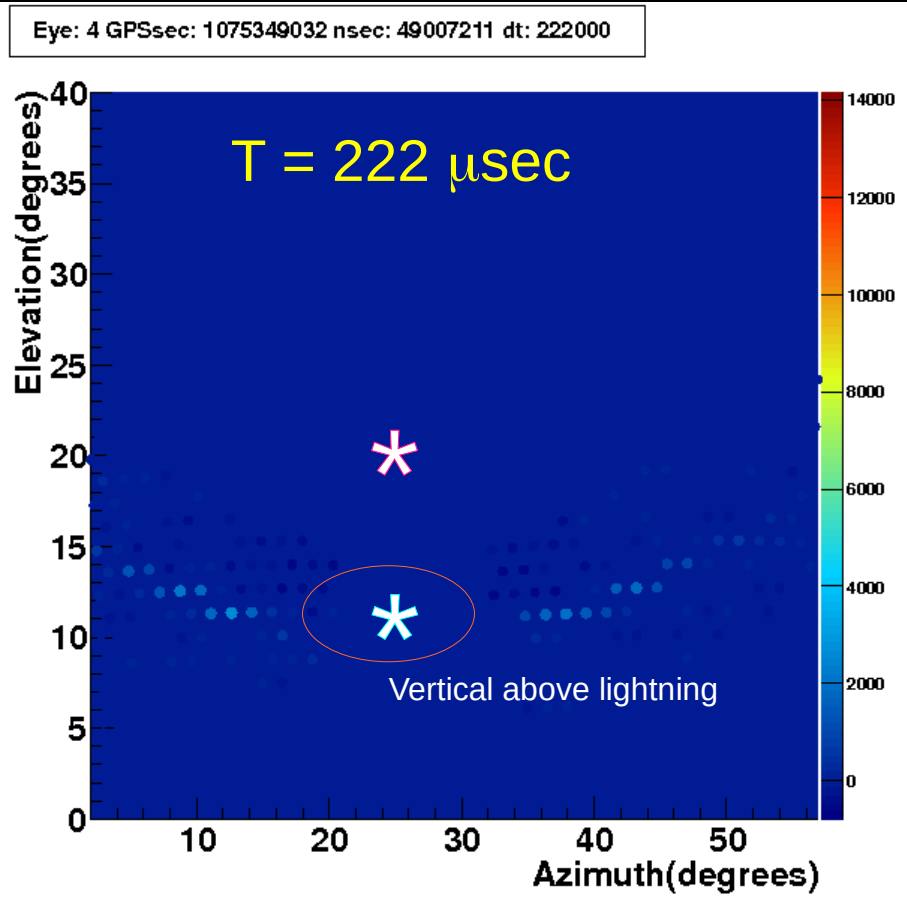
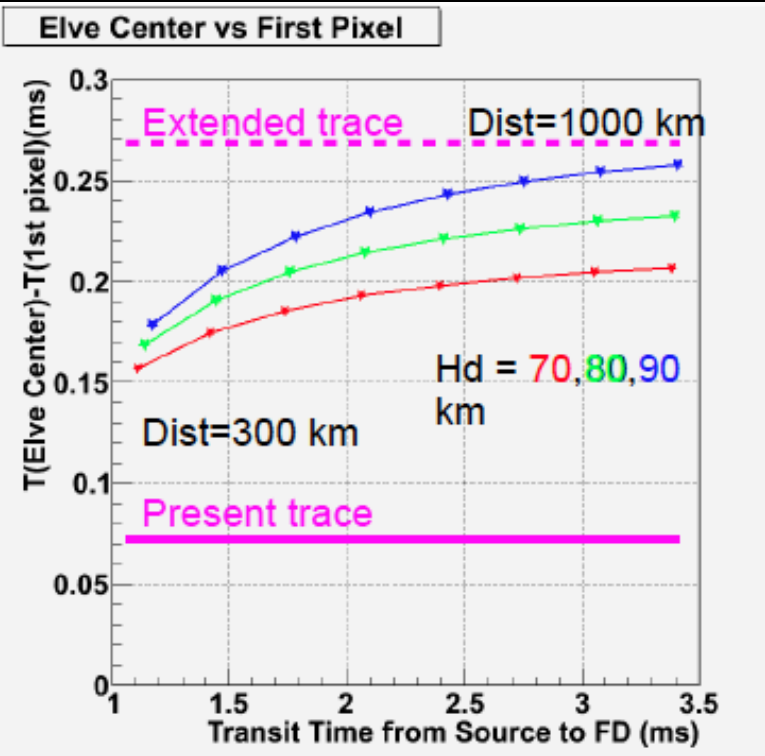
Here we start seeing the vertical above the lightning

ELVES Readout Format: extended (2014-6)



Trigger at 28 μs

ELVES Readout Format: extended (2014-6)

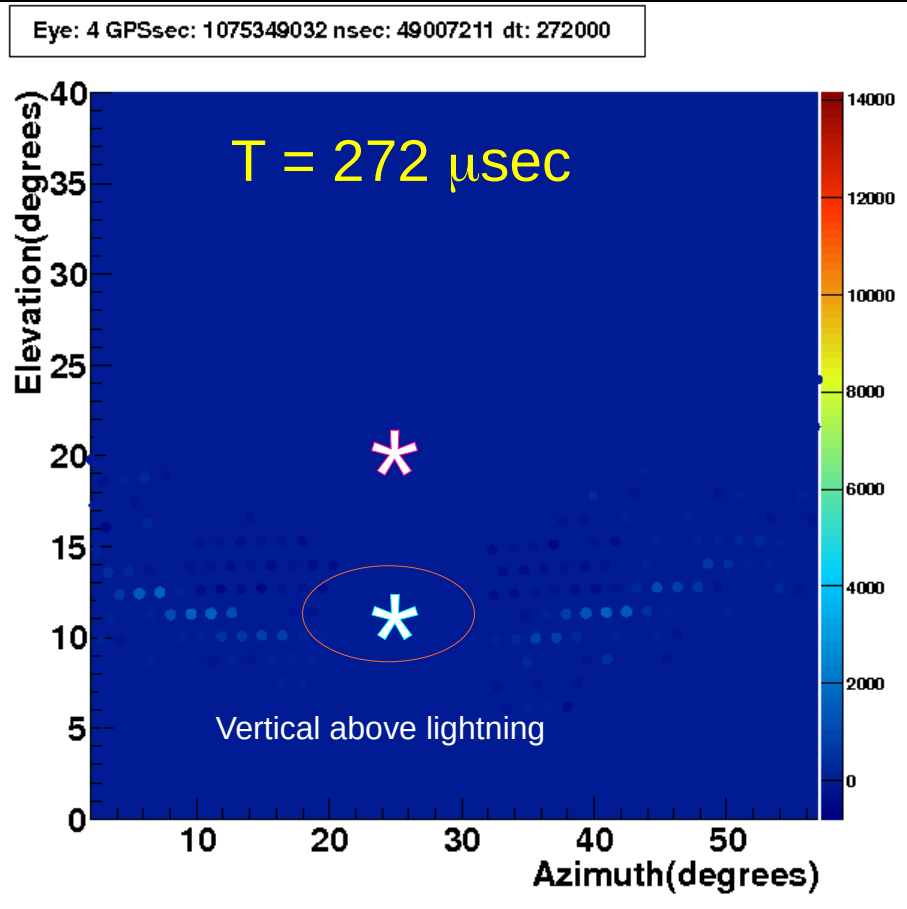
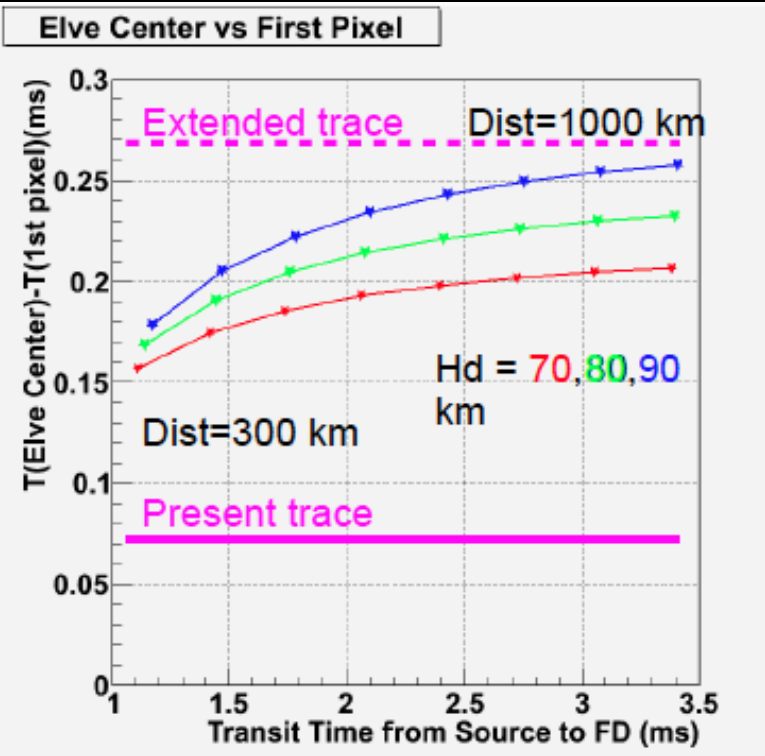


Trigger at $28 \mu\text{s}$



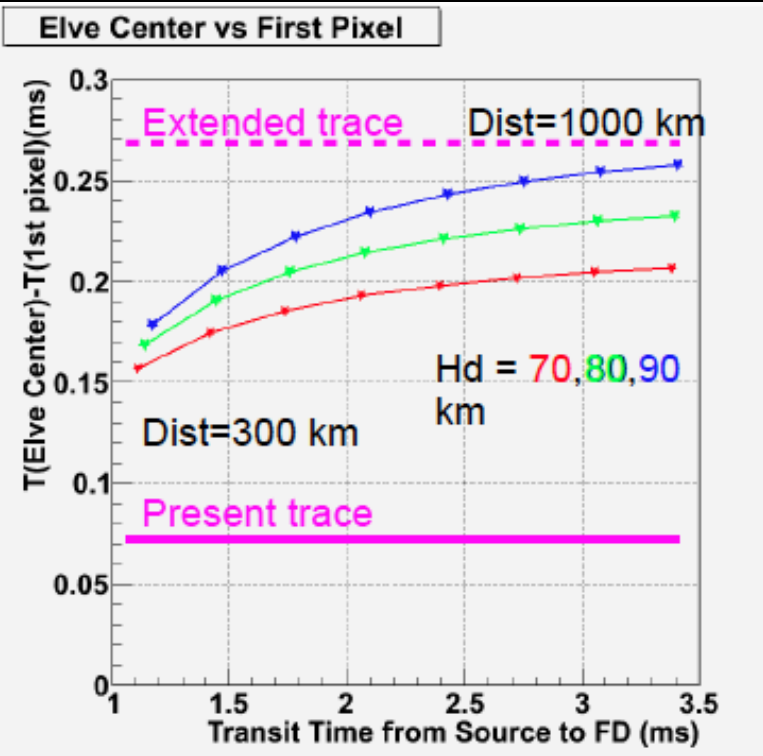
Here we start seeing the vertical above the lightning

ELVES Readout Format: extended (2014-6)

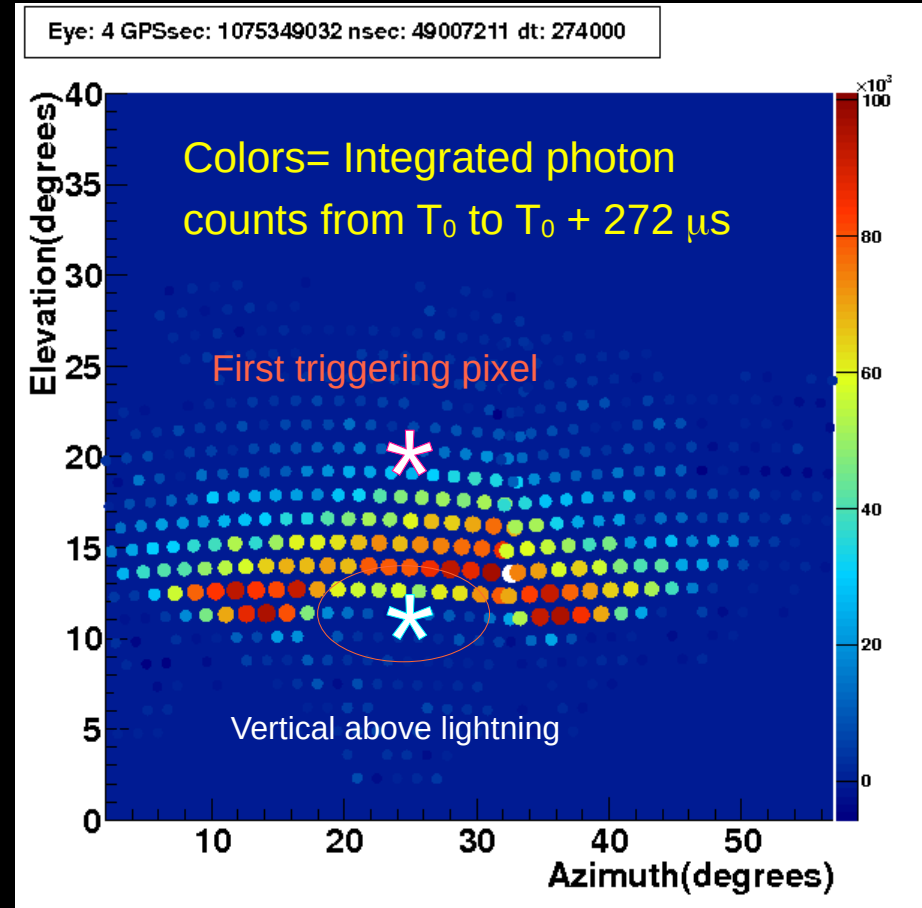
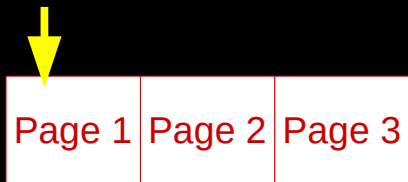


Trigger at 28 μs

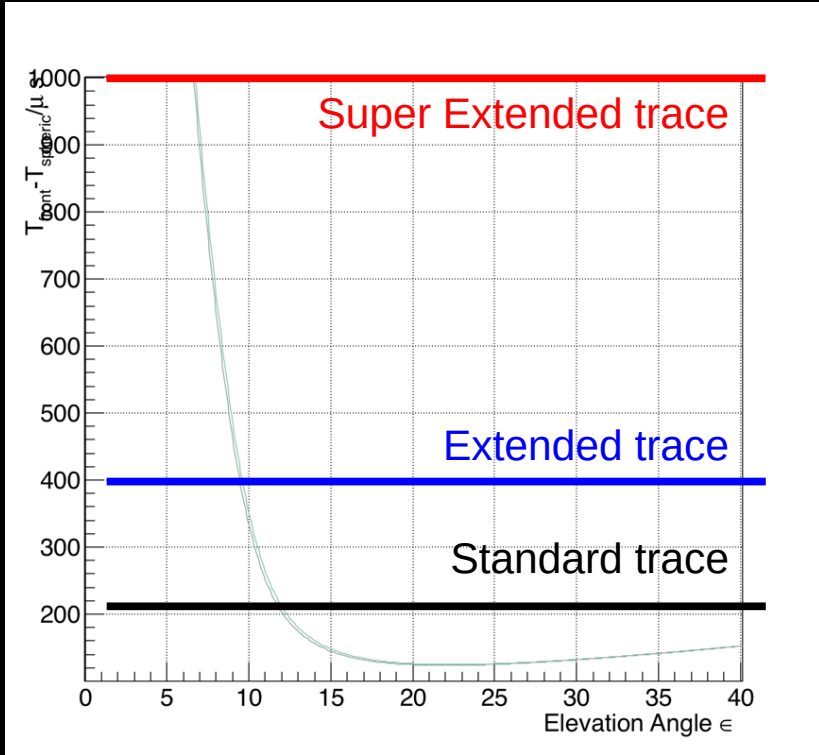
ELVES Readout Format: extended (2014-6)



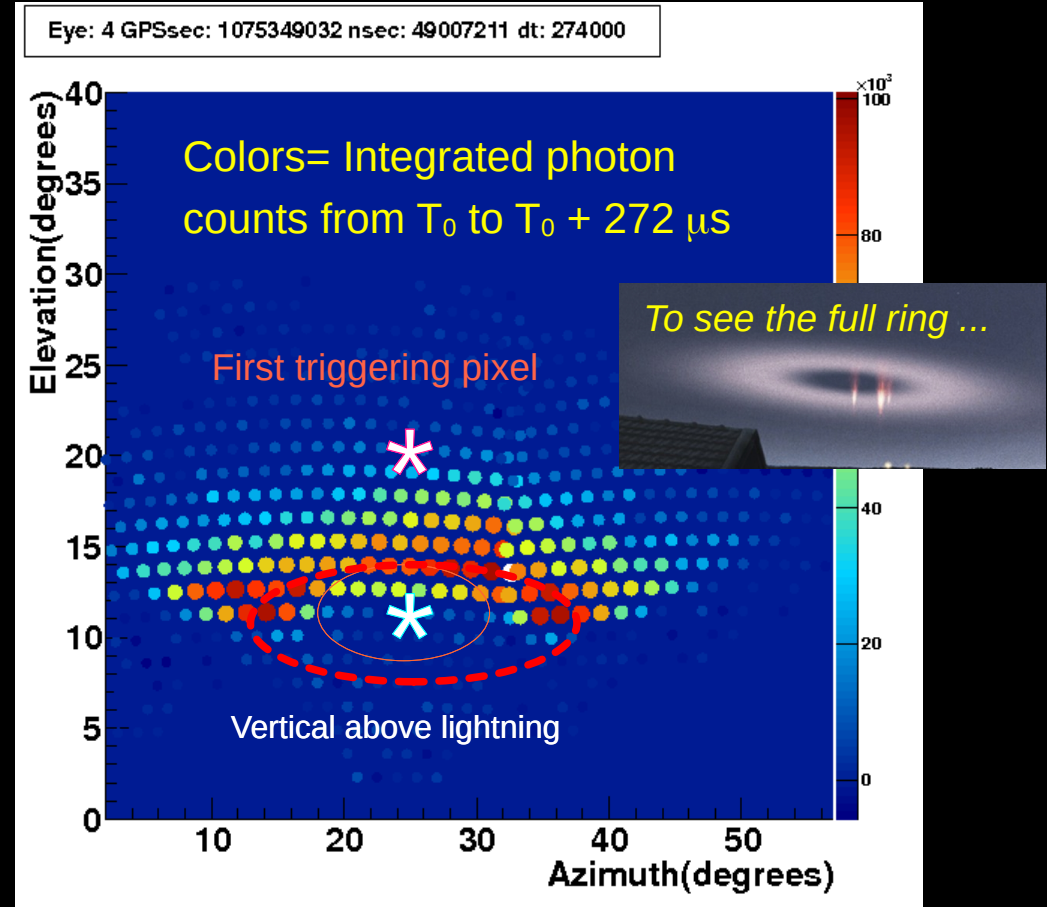
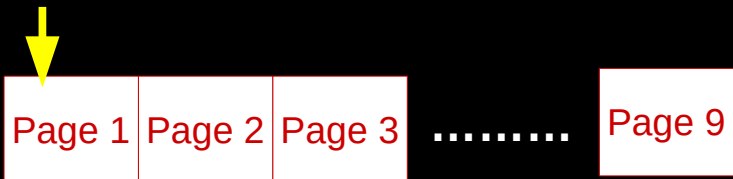
Trigger at 28 μs ... Total 300 μs max



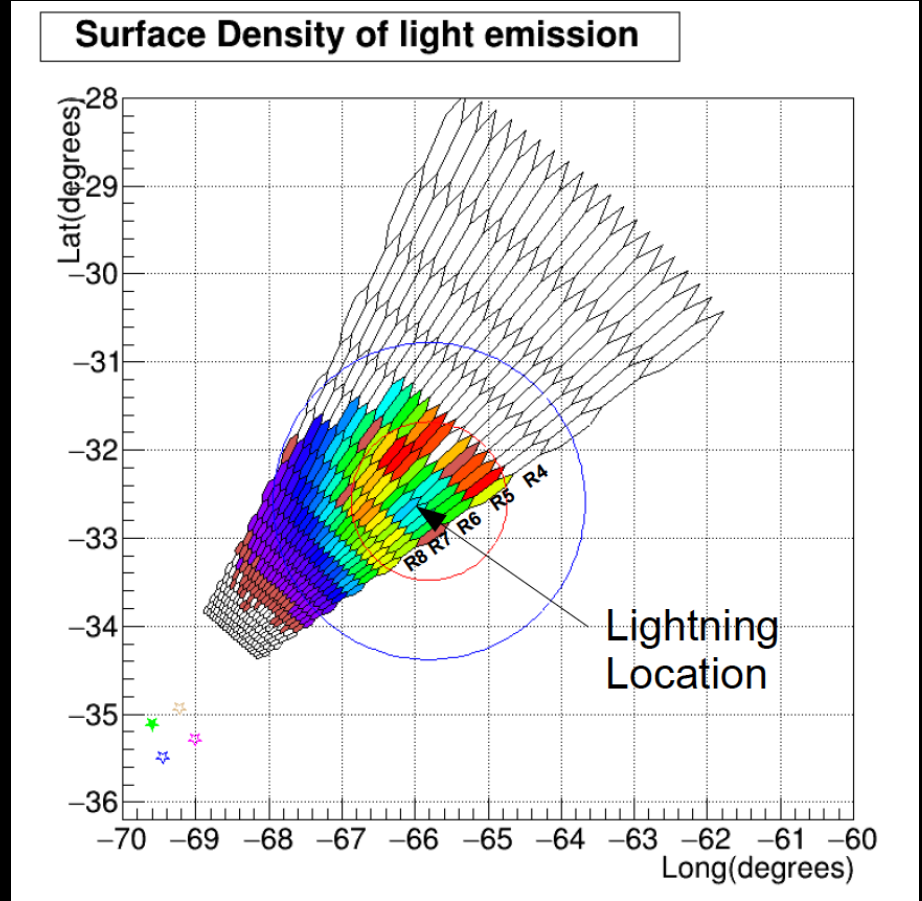
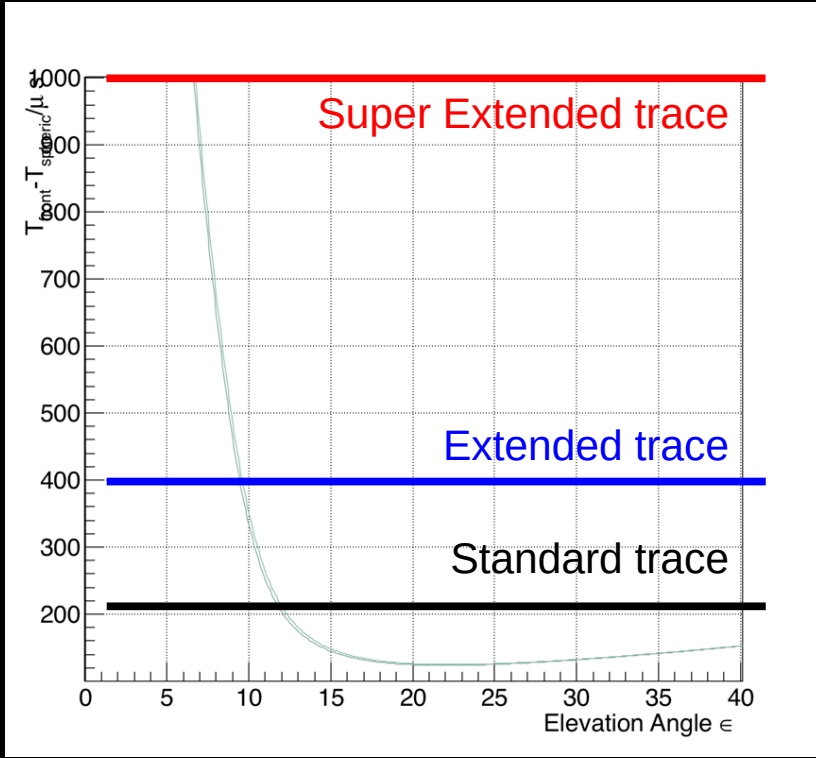
ELVES Readout Format: superextended (2017-now)



Trigger at 28 μsTotal 900 μs max



ELVES Readout Format: superextended (2017-now)



Trigger at 28 μ s.....Total 900 μ s max



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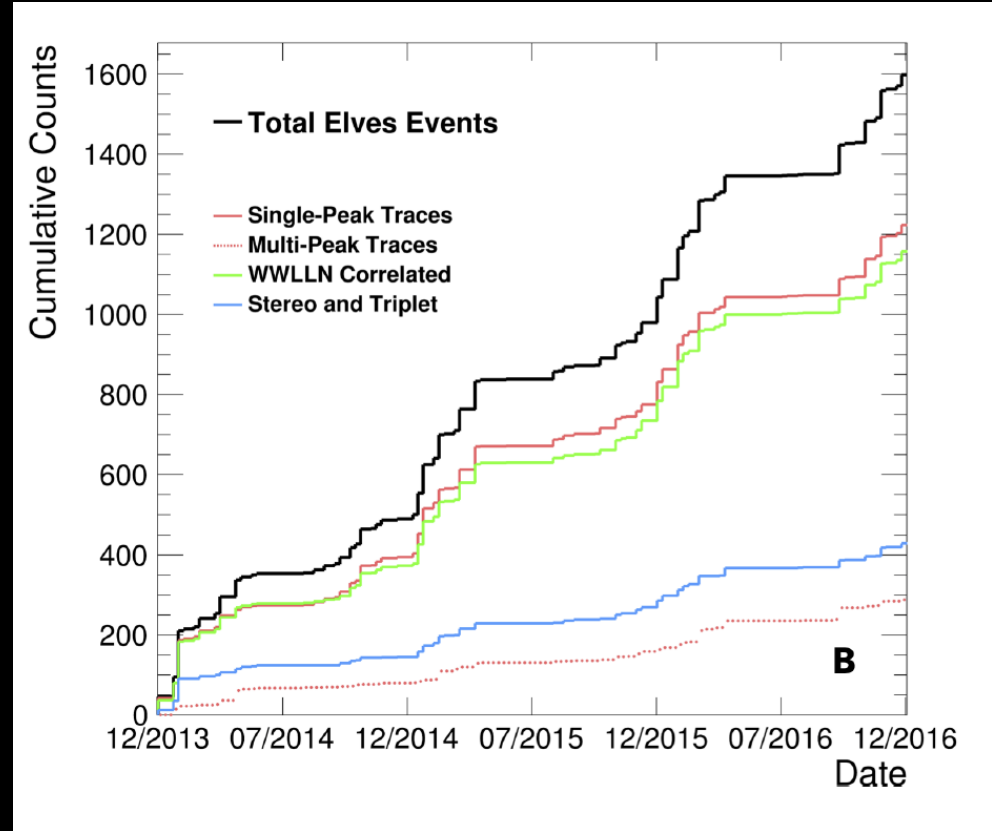
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Trigger statistics

Year	1-eye	2	3	Tot
	MONO	STEREO	TRIPLET	
2013*	214	83	8	305
2014	425	128	19	572
2015	686	117	11	814
2016	673	151	21	845
TOTAL	1784	396	51	2231

RECONSTRUCTED
1169 379 50 1598

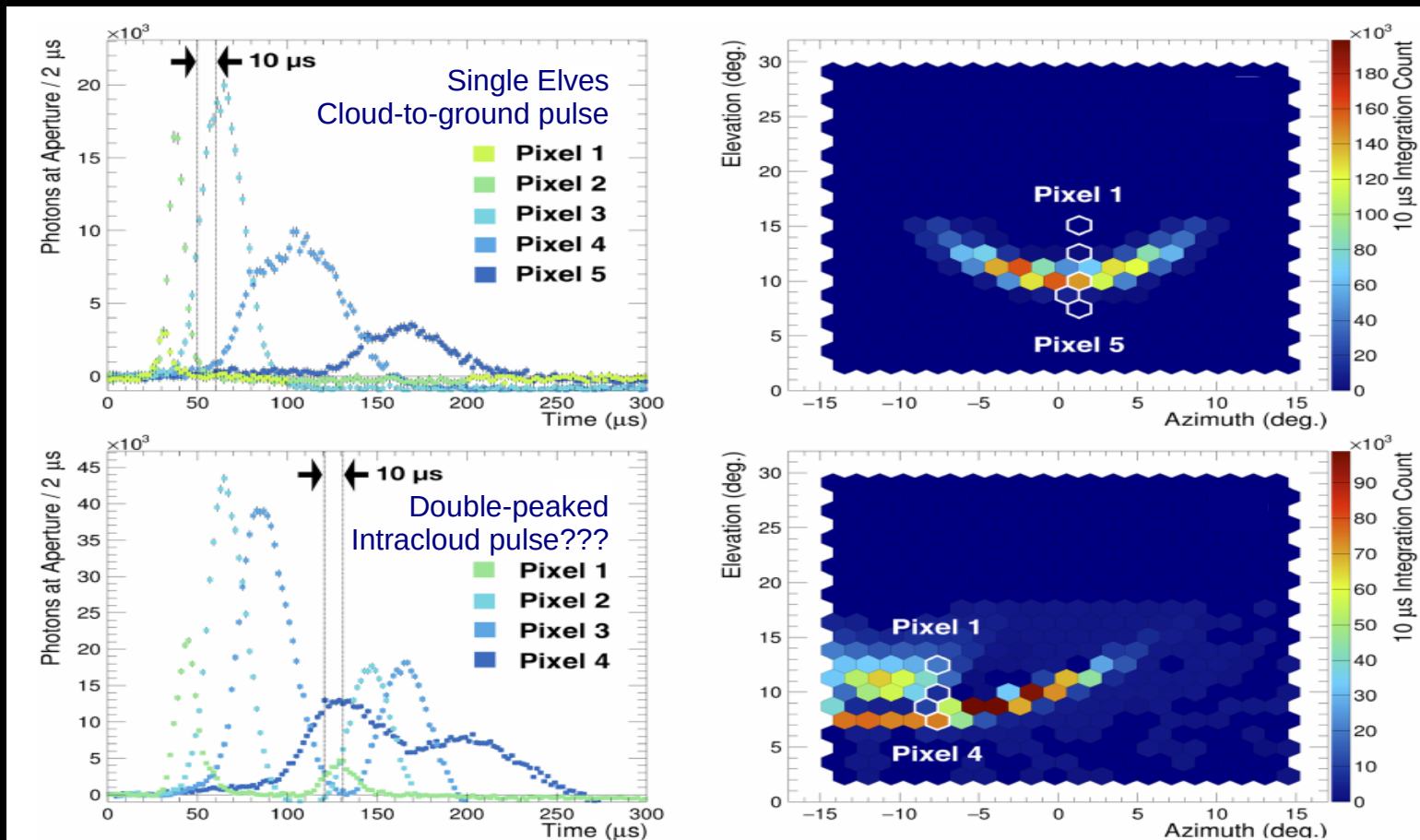
Correlated (within 5ms) with
WWLLN 836 284 38 1158
(72%)



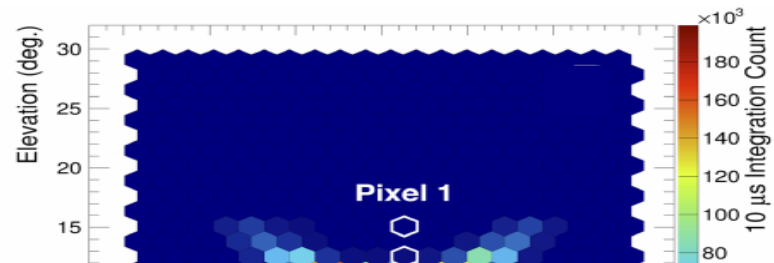
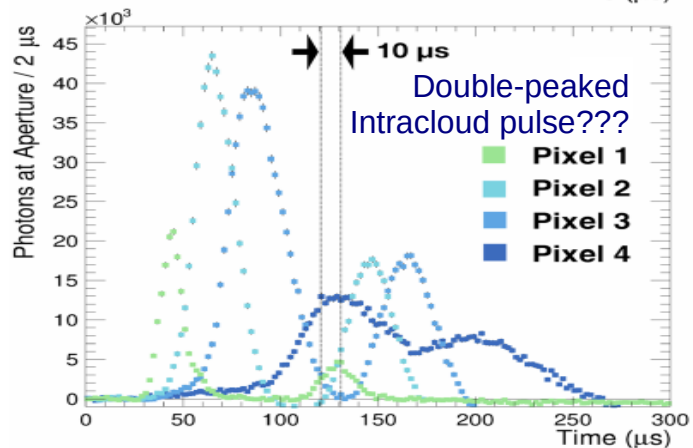
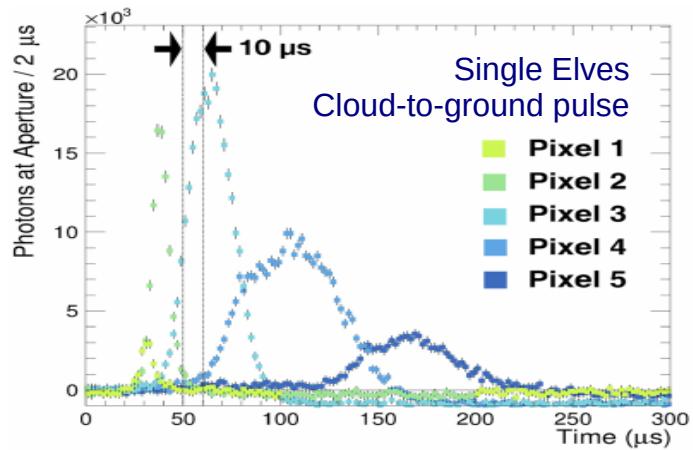
Aab et al, Earth and Space Sci.7 (2020)4
Eos Science Updates:

<https://eos.org/science-updates/catching-elves-in-argentina>

ELVES @ the Pierre Auger Observatory → zoology



ELVES @ the Pierre Auger Observatory → zoology



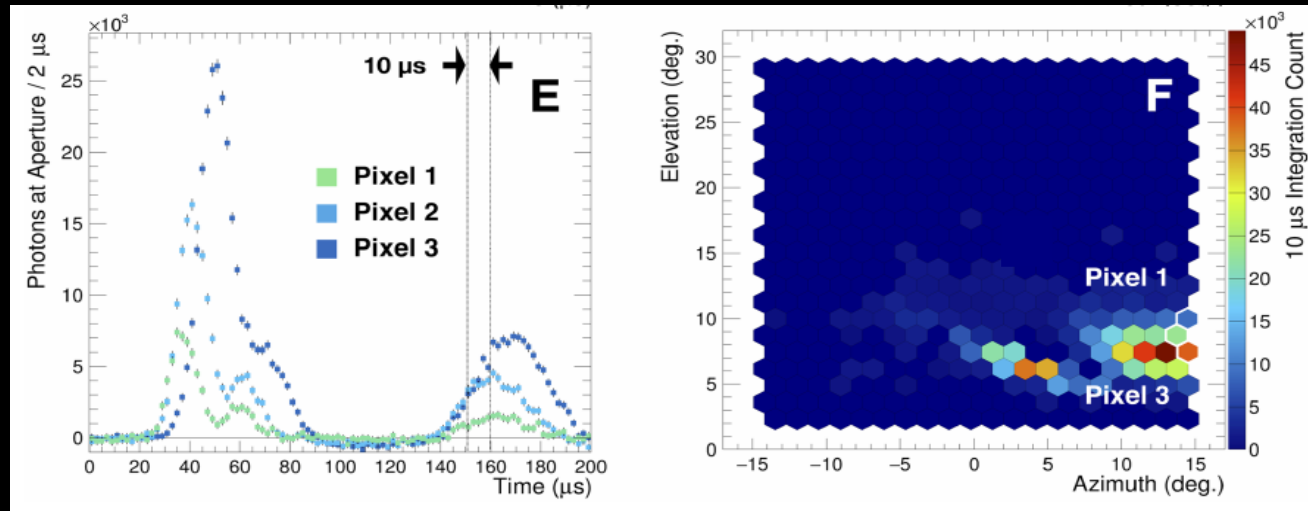
It is important to study the distance between the peaks and their intensity ratio to understand the origin of double ELVES. It is also fundamental the connection of Auger measurements with radio measurements.

(Halim et al., Earth and Space Science, 12, e2025EA004321.

<https://doi.org/10.1029/2025EA004321>)

ELVES @ the Pierre Auger Observatory

→ *zoology*



First observation of a triple elves

They are probably related to intracloud activity.
Intracloud activity could be associated with the creation of TGFs.

- Could the triple elves be related to TGFs?
- Could we observe ELVES associated with TGFs?
 - Are we observing other TLEs?

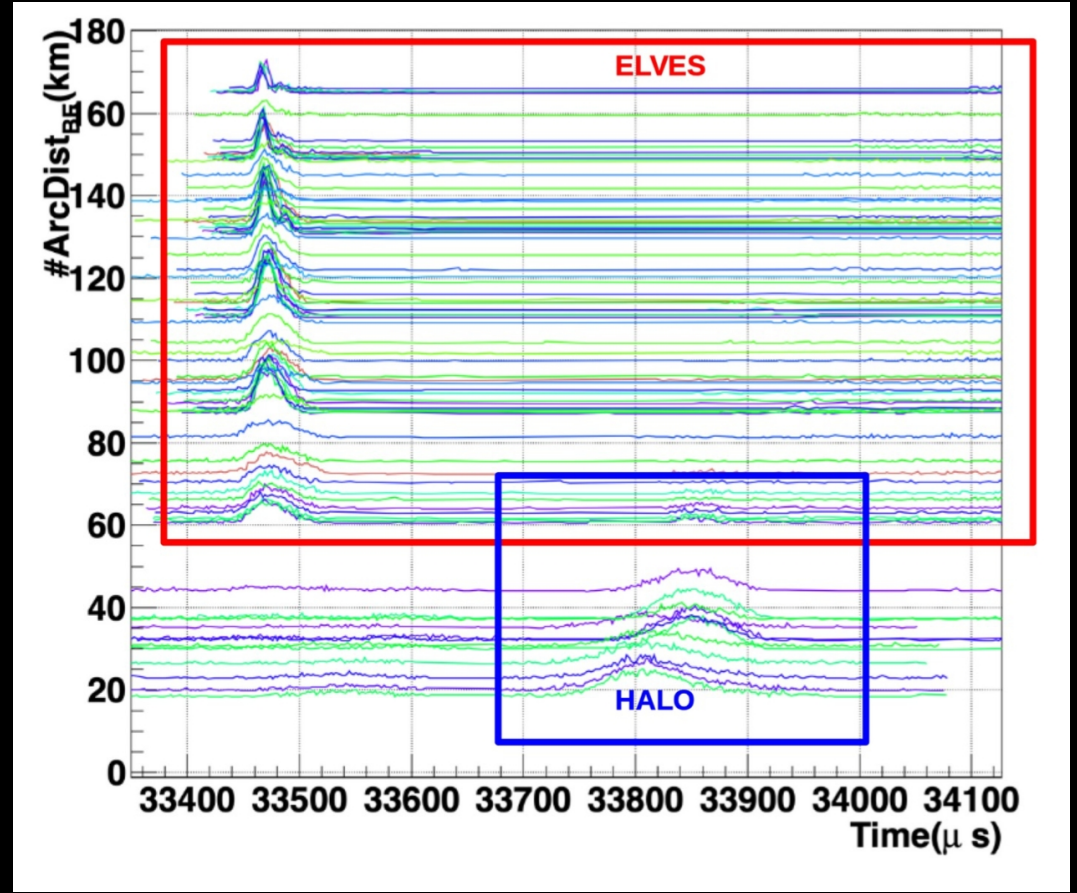
Observations of Halos in Auger

The extended Readout has allowed to read traces from ELVES triggers up to 0.9 ms long.

This allowed to see halos few hundred μs after ELVES

Halos are disks of 100 km diameter, at 70-80 km altitude, lasting longer than ELVES.

Halos are frequently associated to SPRITES



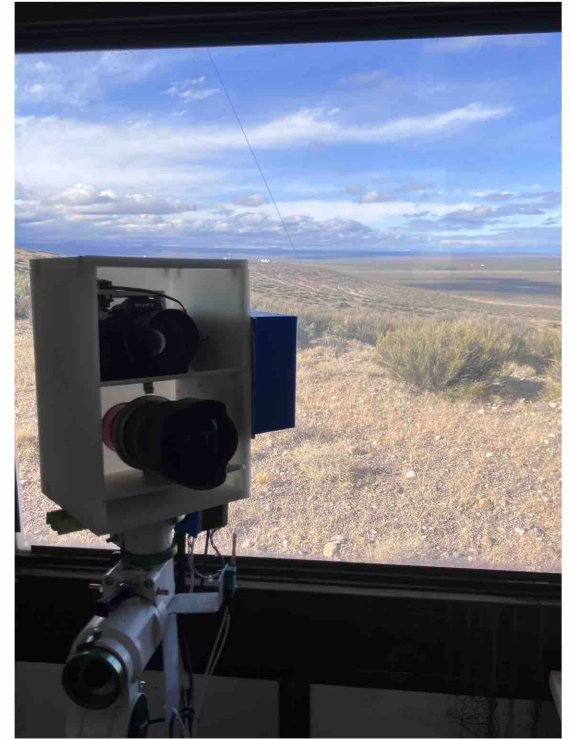
A new instrument to study more TLEs

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.

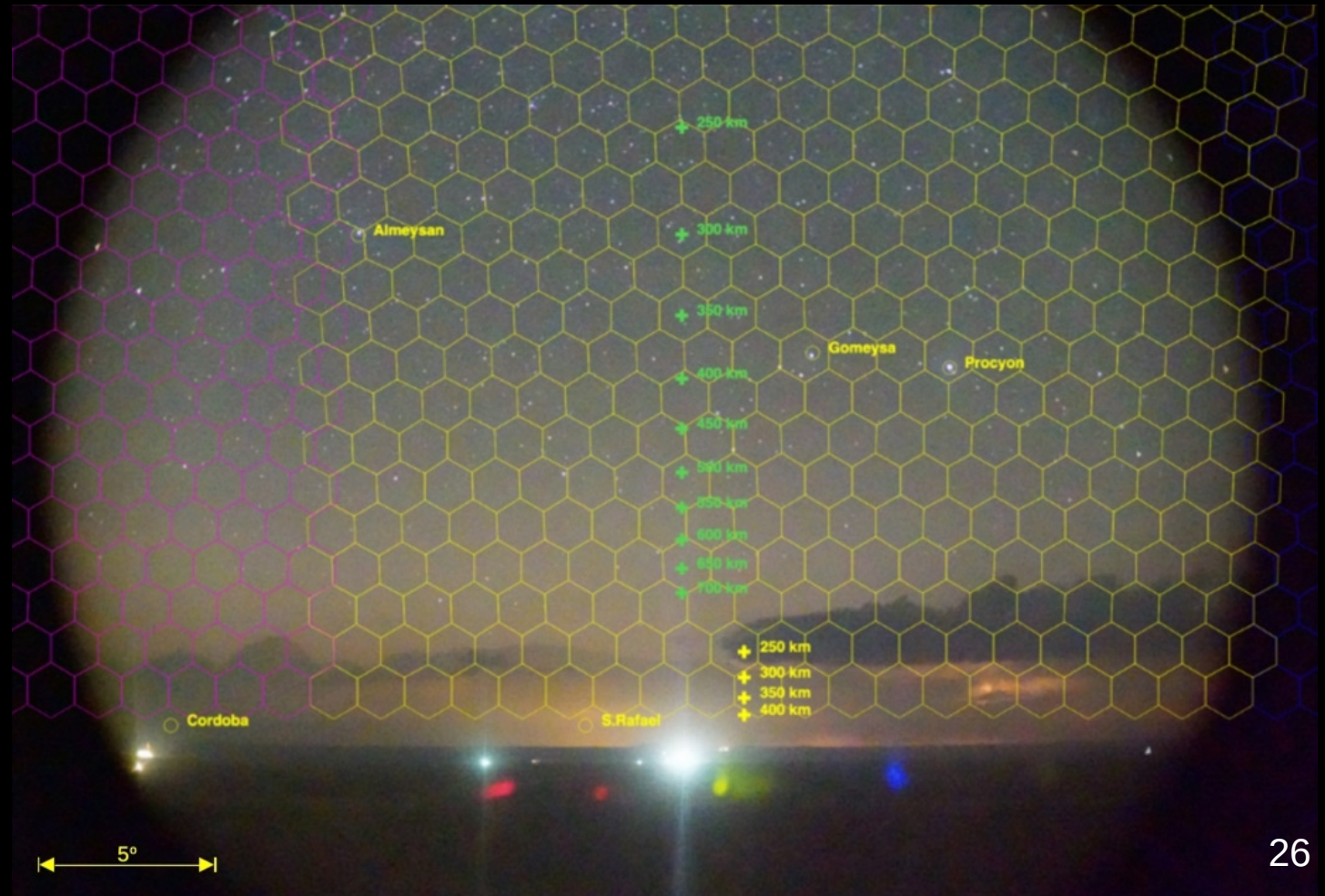


TLE cam – FD alignment

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

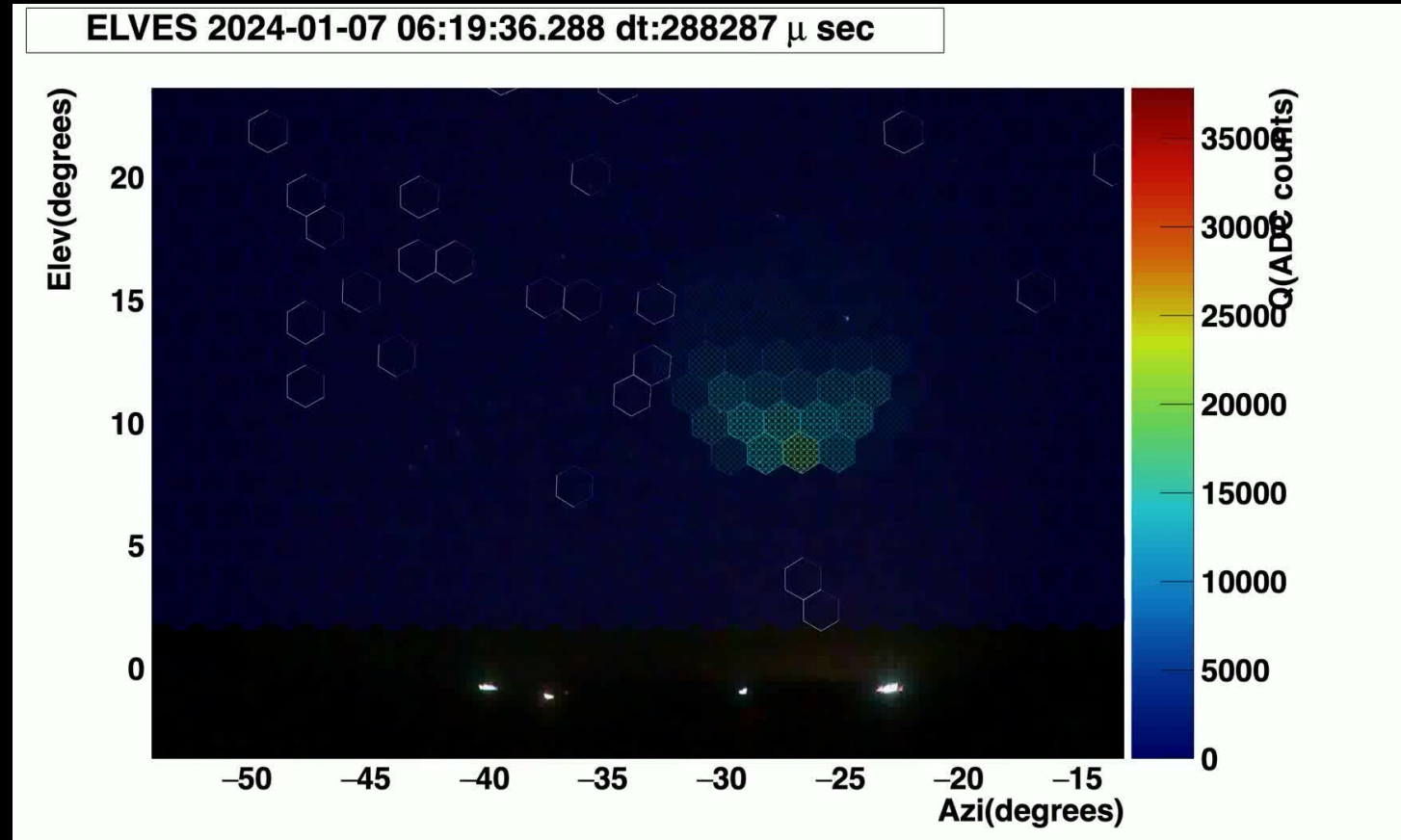


TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=2 \mu\text{s}$

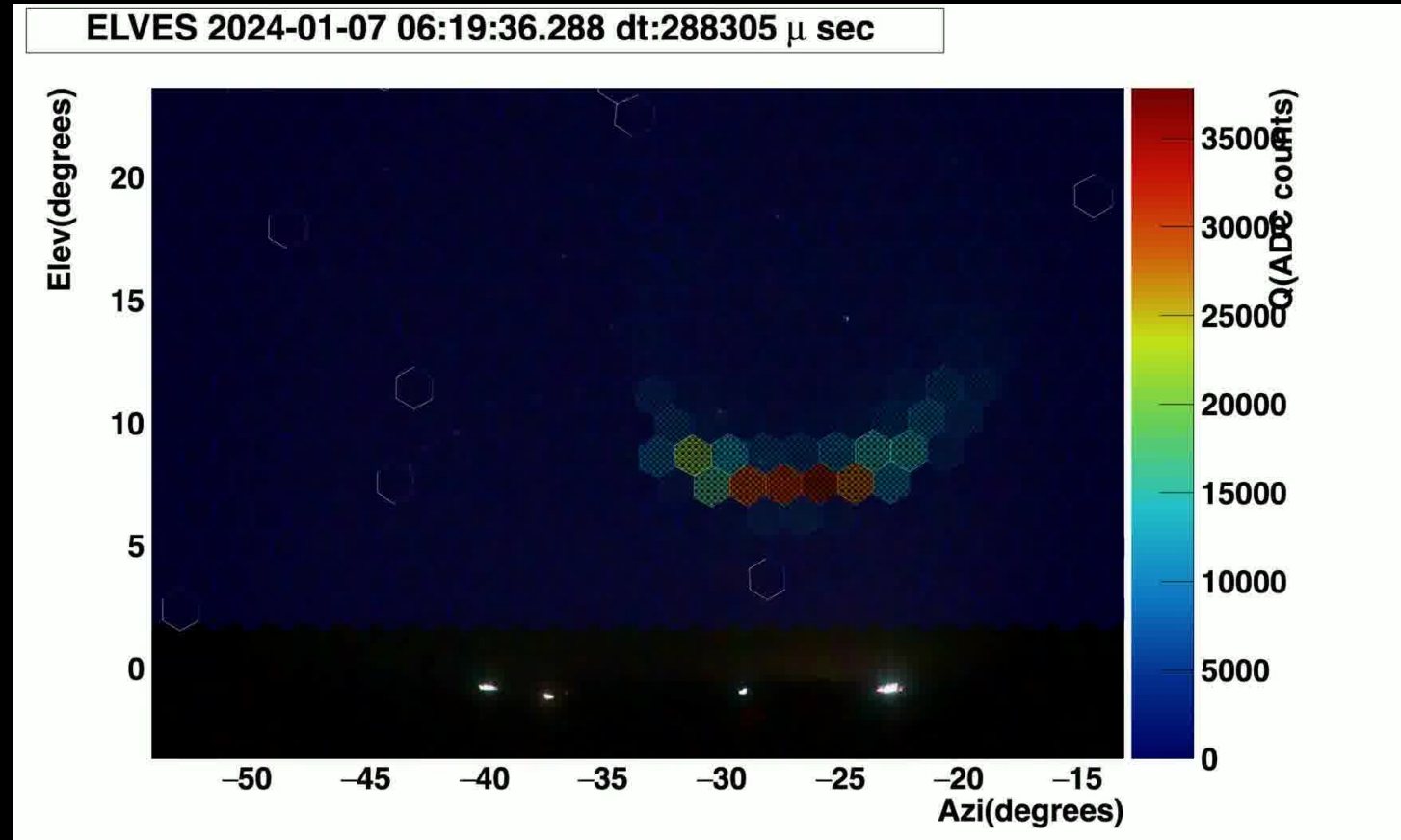


TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=20 \mu s$

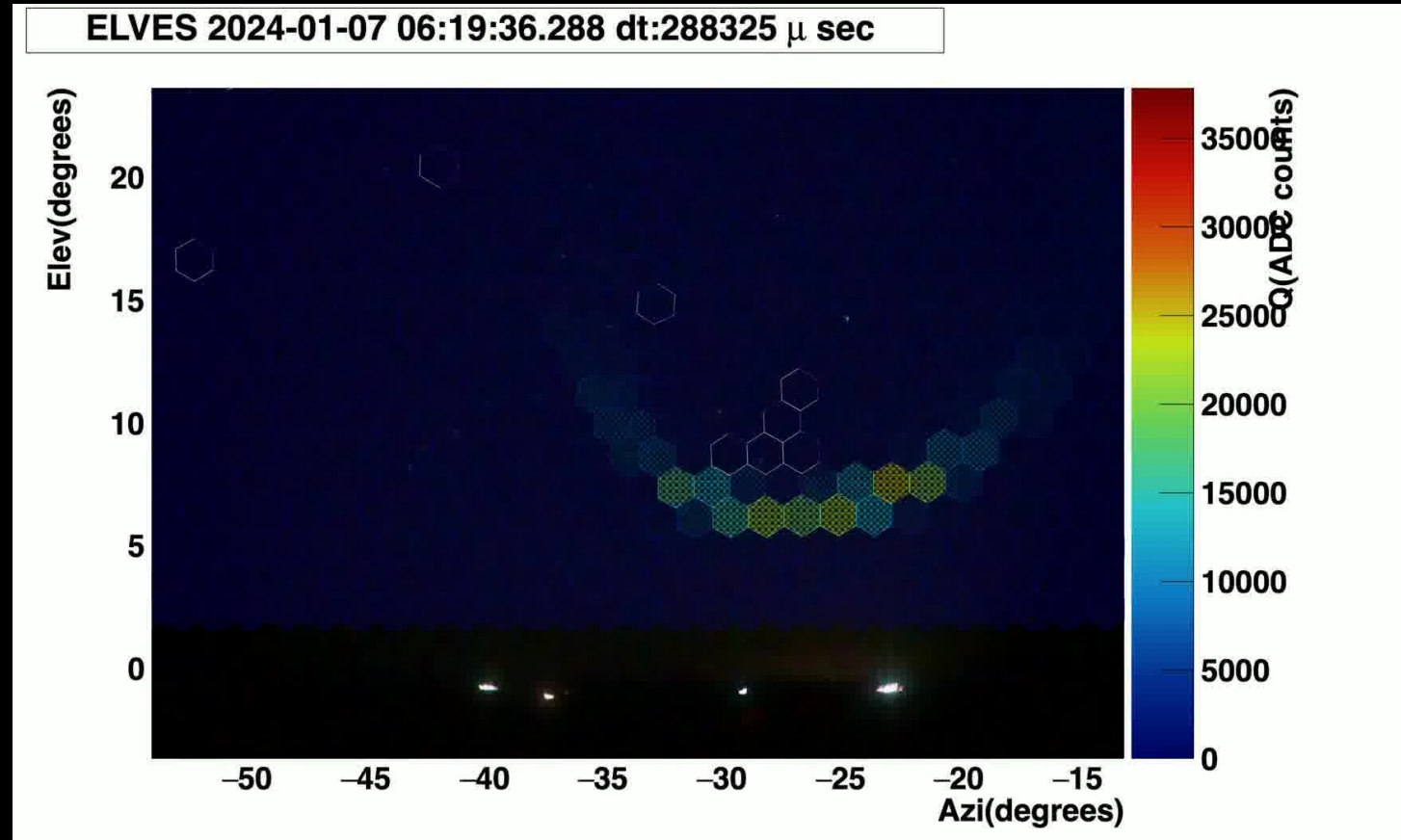


TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=40 \mu\text{s}$

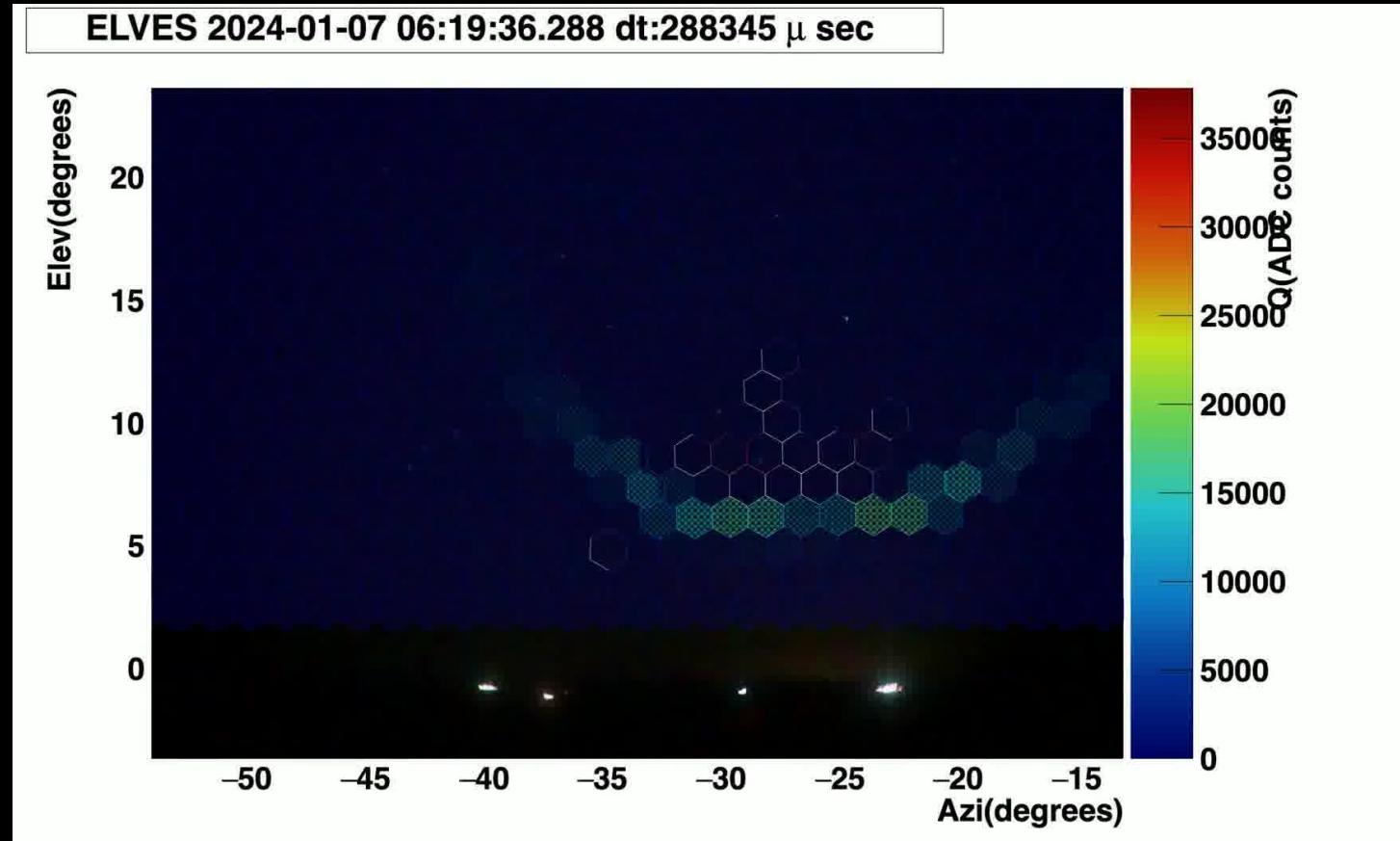


TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=60 \mu s$

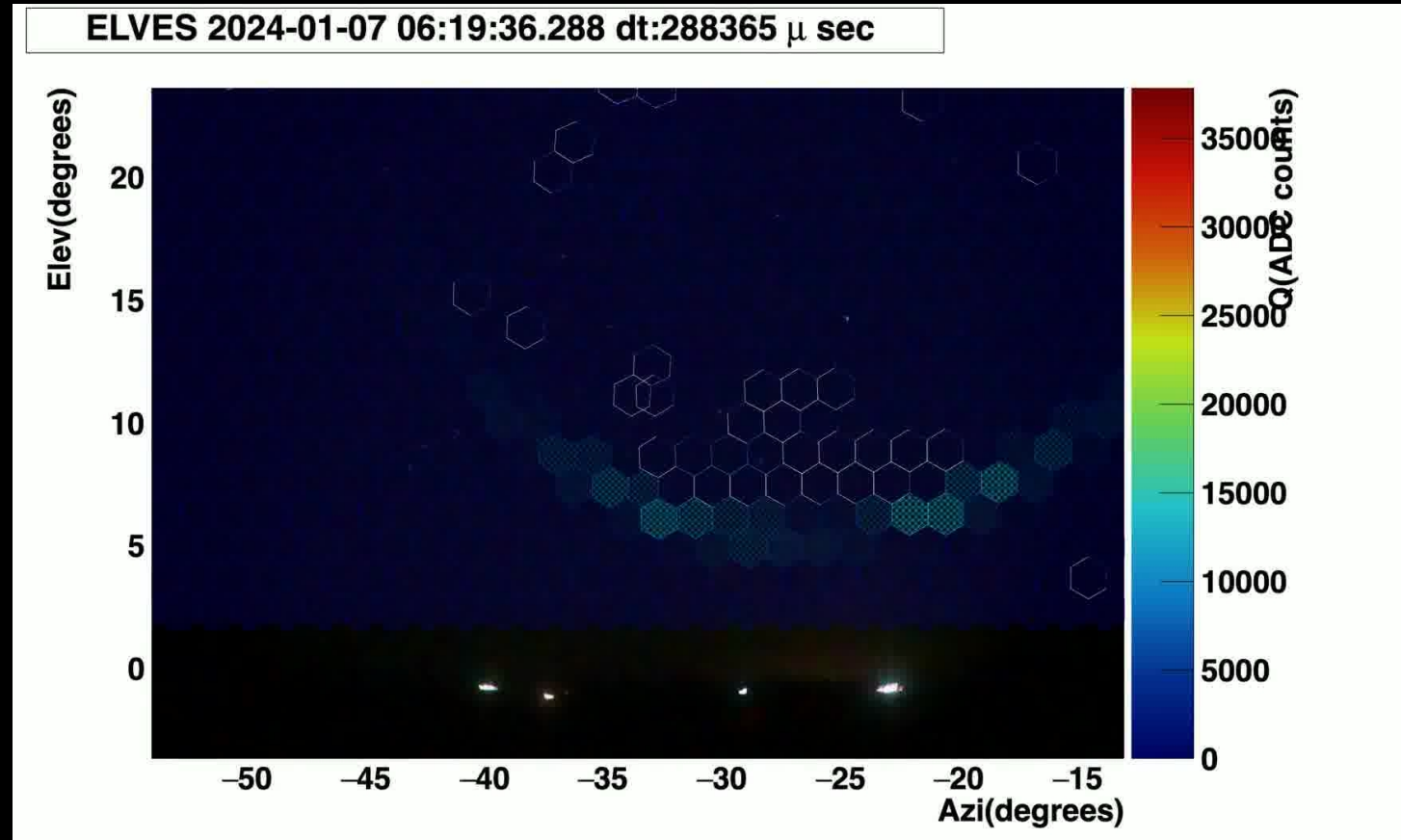


TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=80 \mu s$

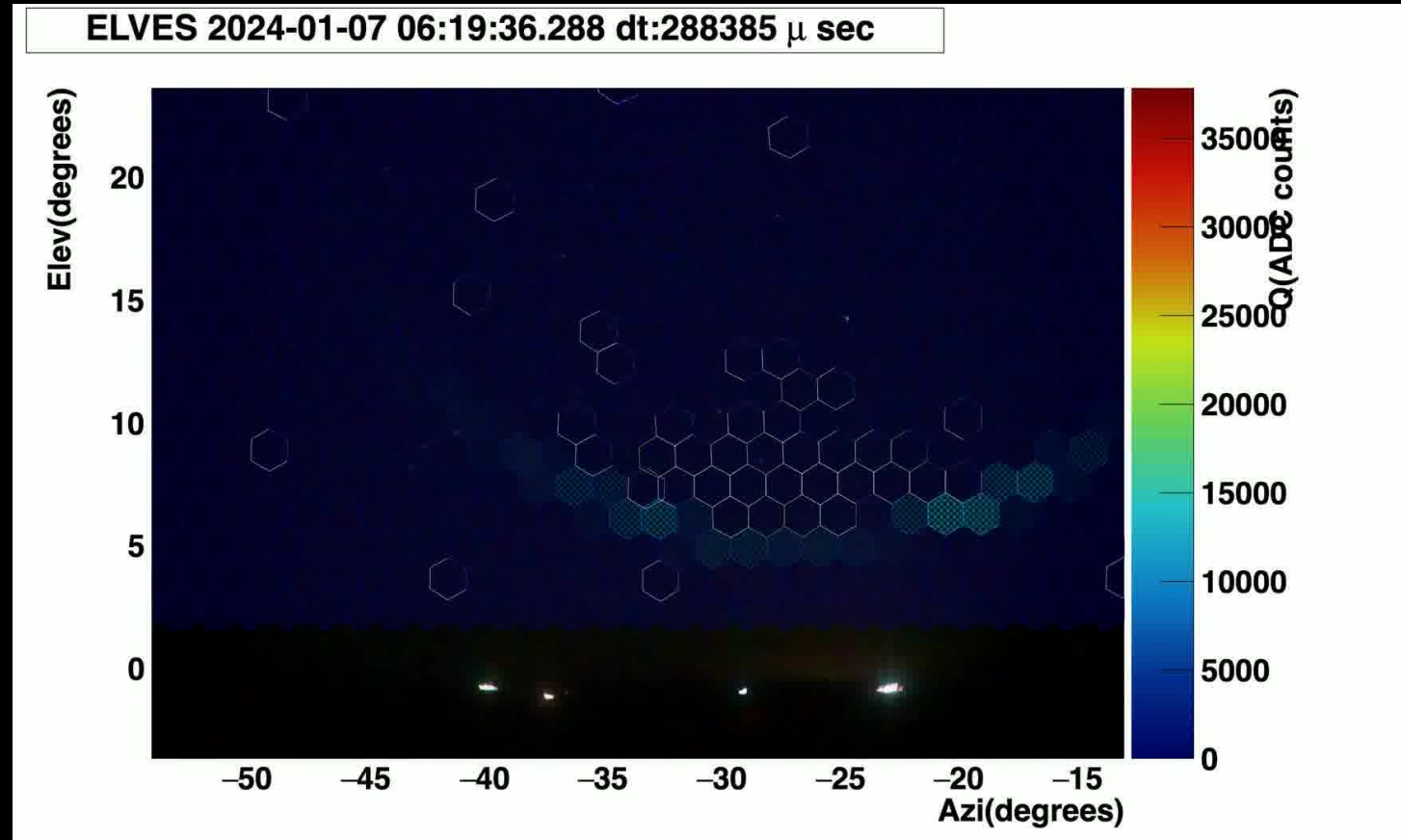


TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=100 \mu\text{s}$

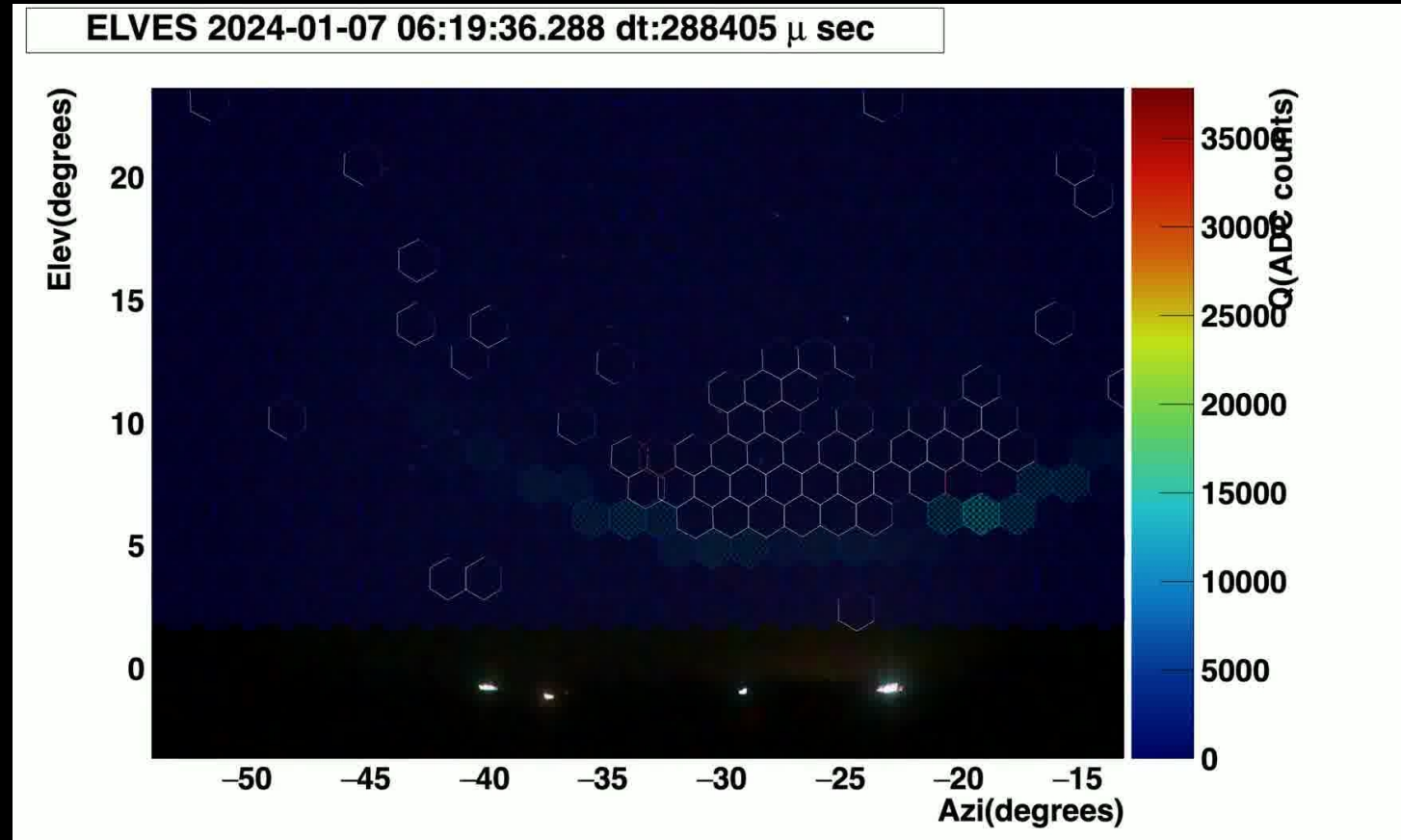


TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=120 \mu\text{s}$

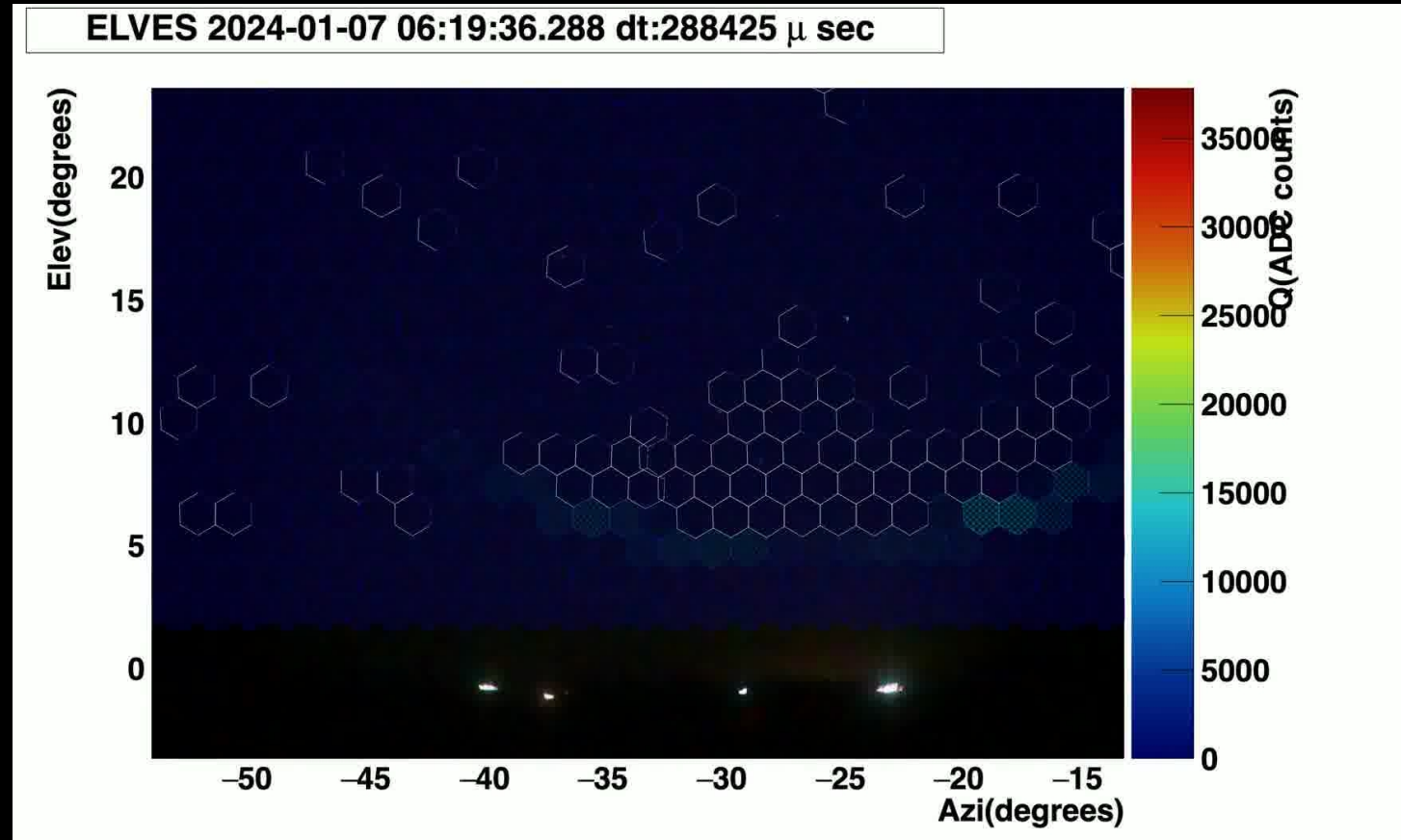


TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=140 \mu\text{s}$



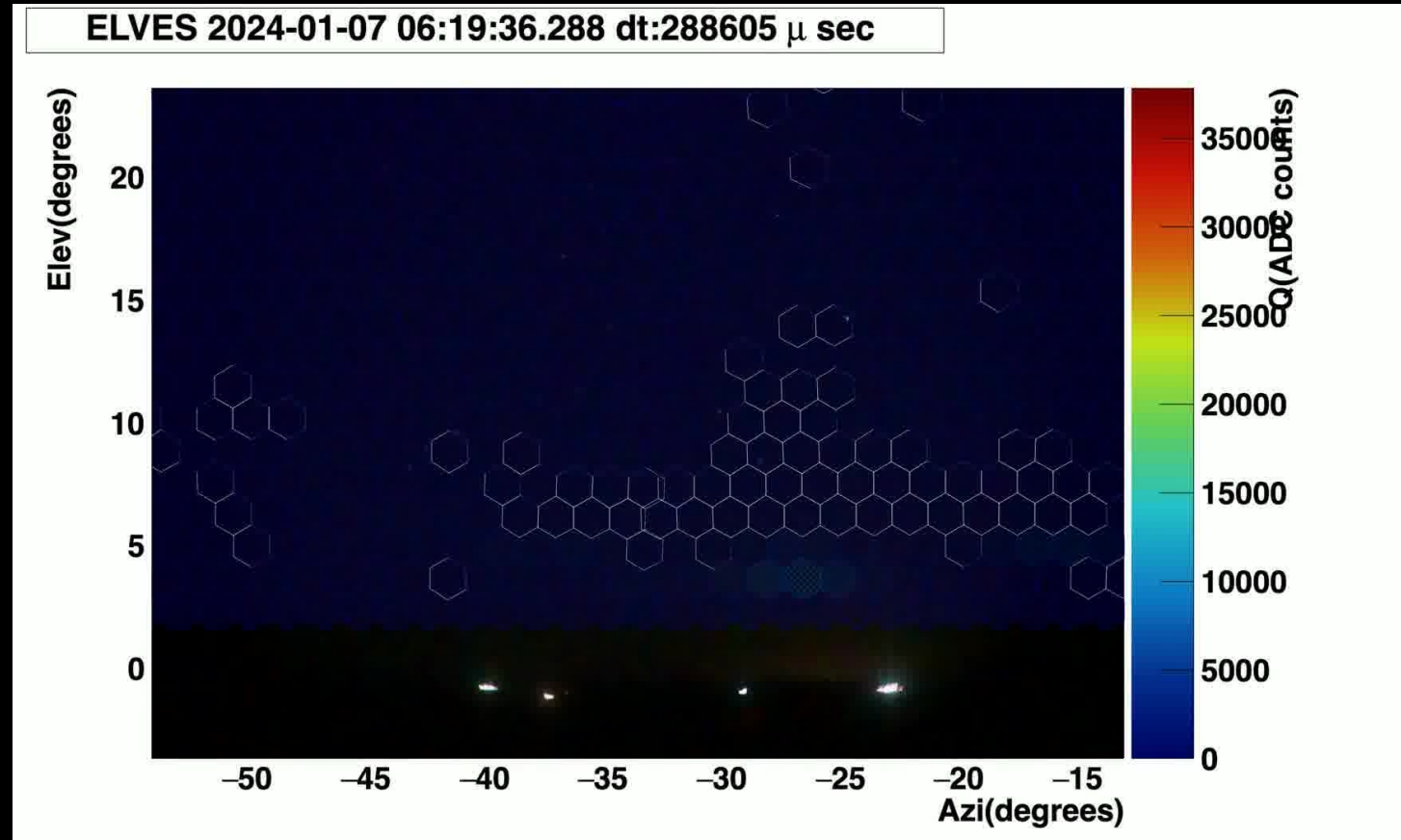
TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=320 \mu\text{s}$

Halos



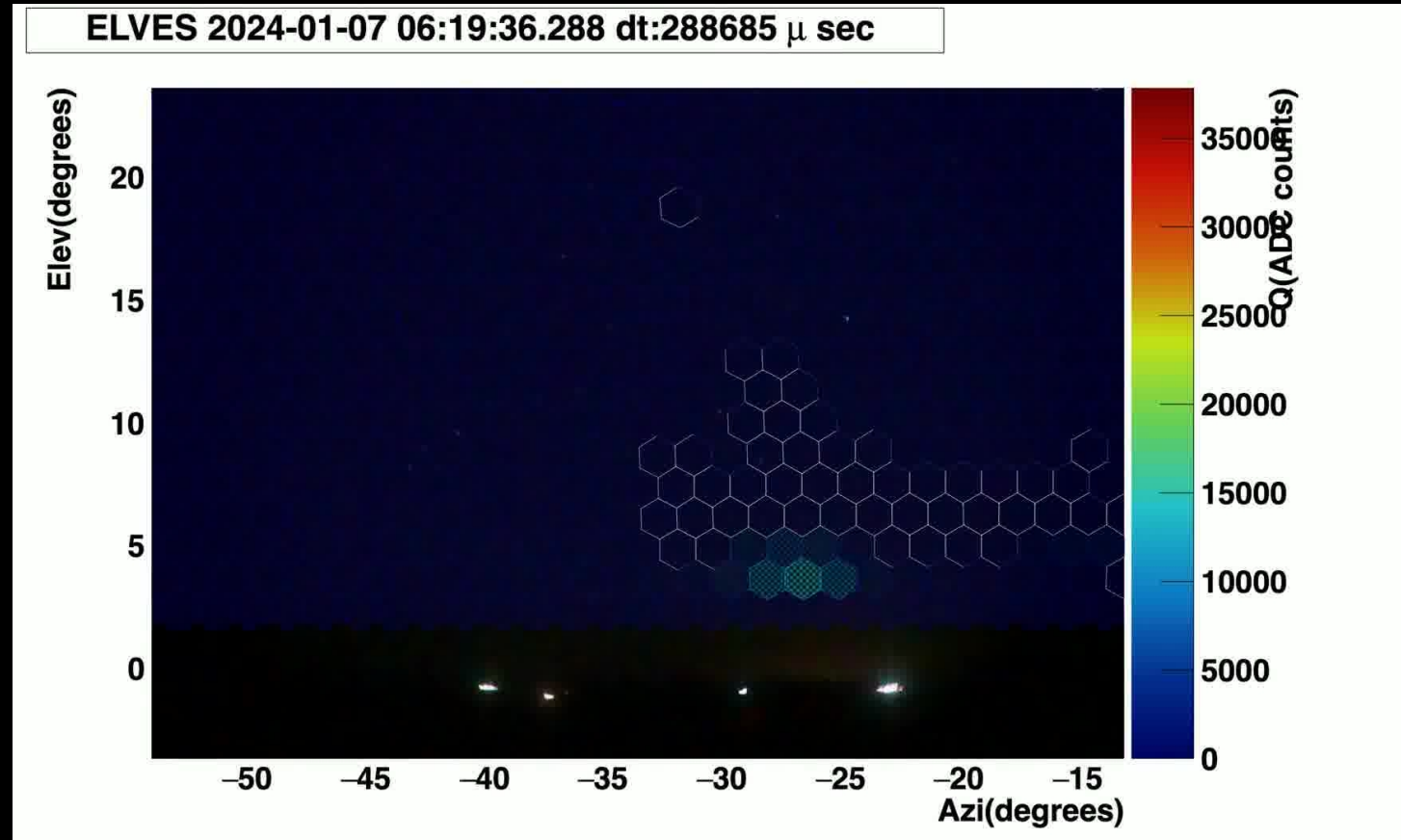
TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=400 \mu\text{s}$

Halos



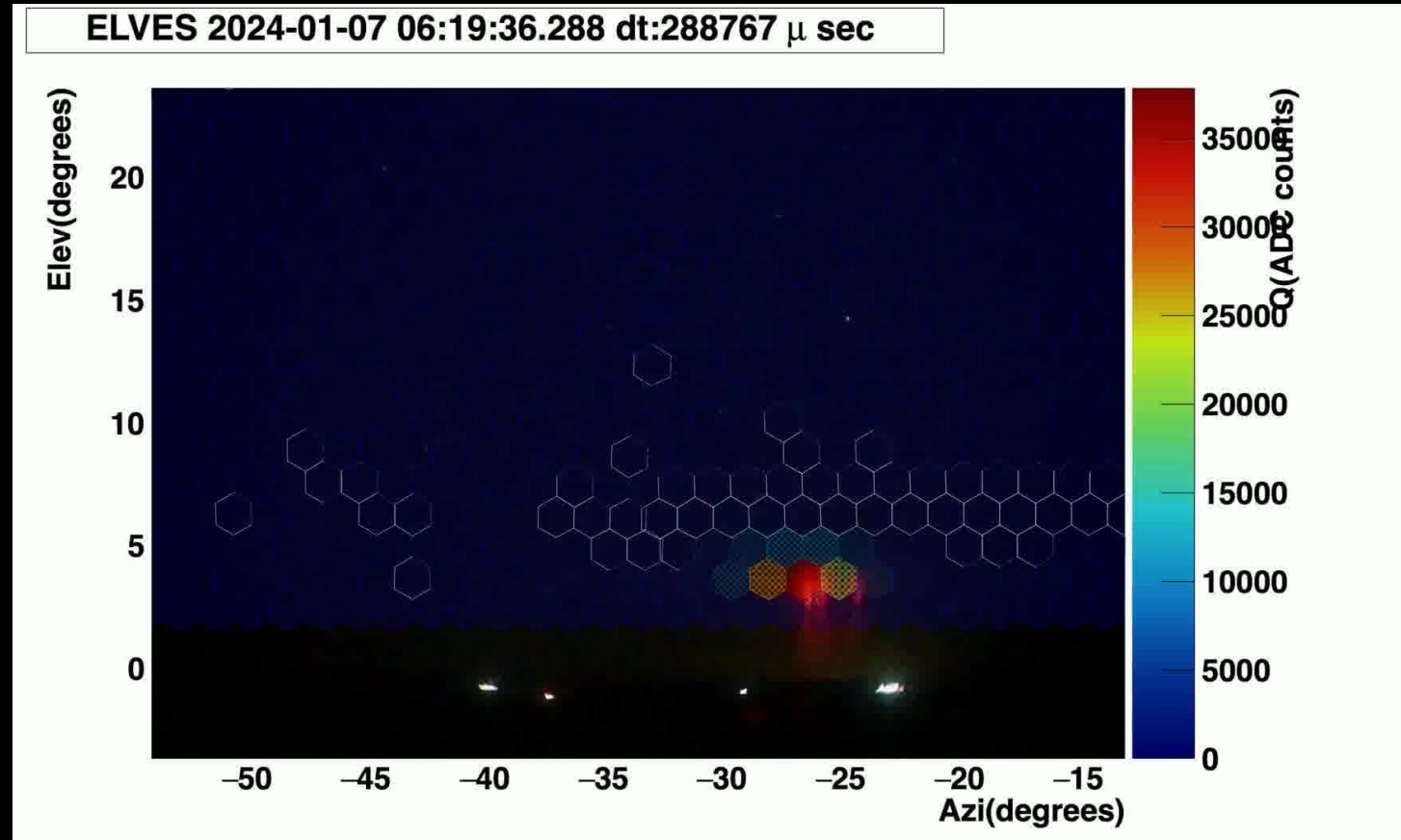
TLE cam-1: first SPRITES on ELVES trigger

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

Every frame integrates 2
microseconds

$T=482 \mu\text{s}$

Halos + SPRITES



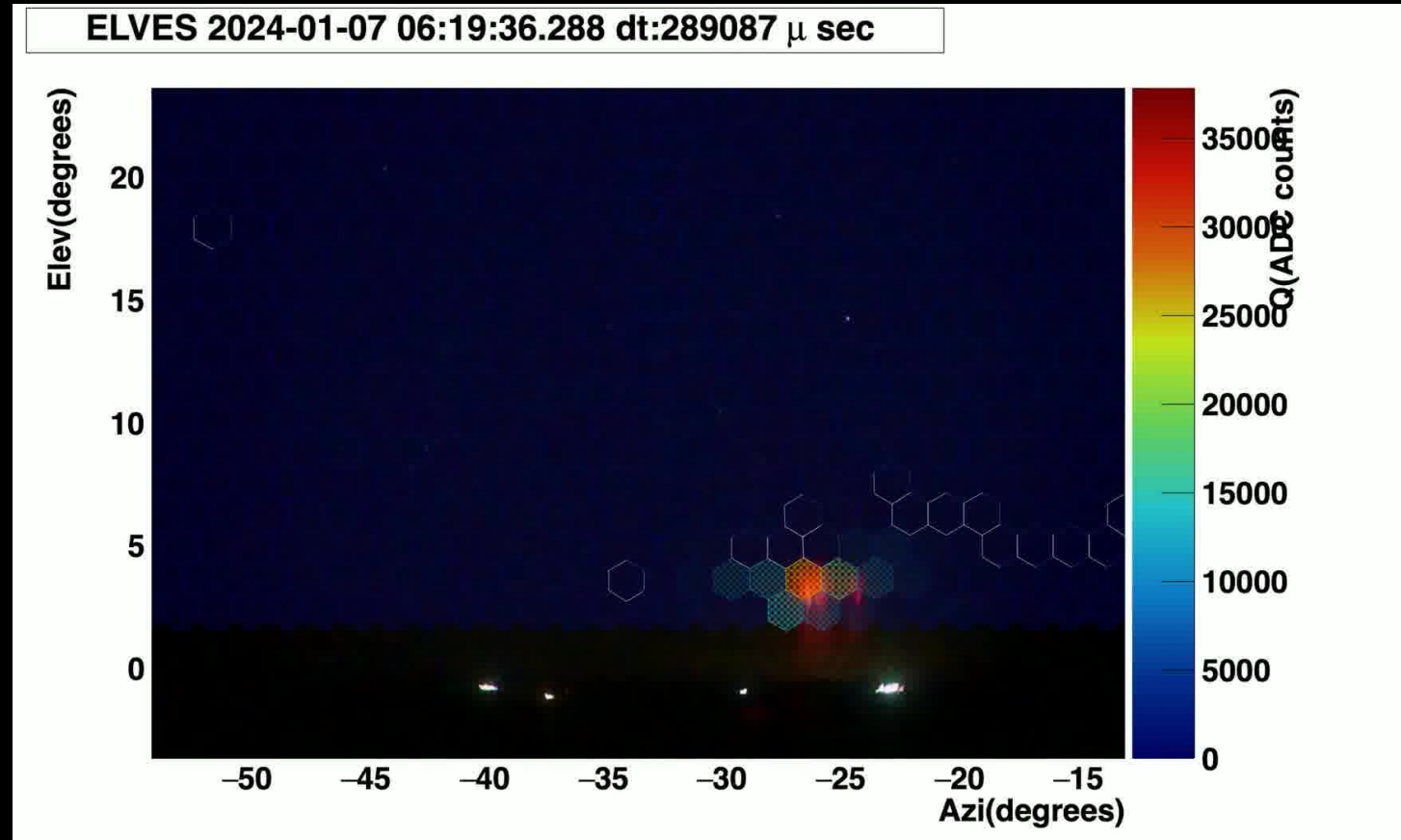
TLE cam-1: first SPRITES on ELVES trigger

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

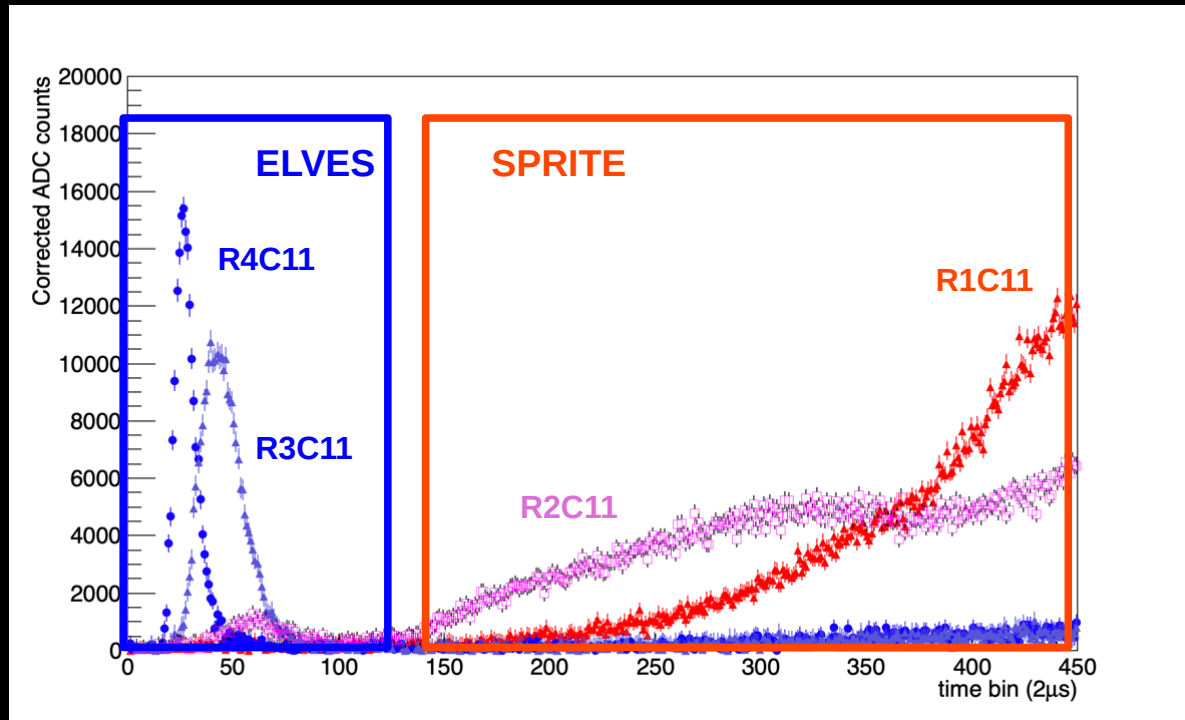
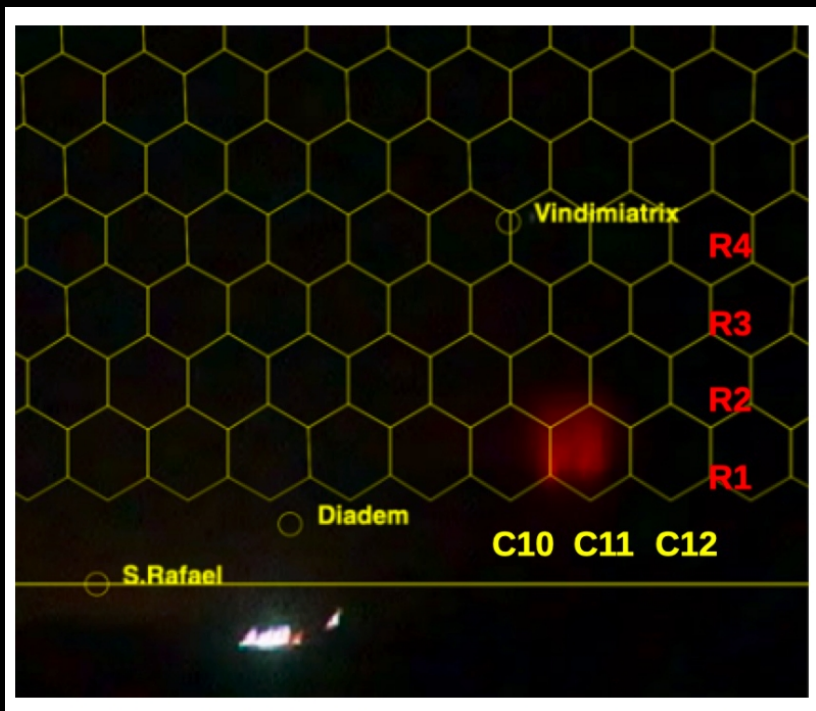
Every frame integrates 2
microseconds

$T=802 \mu\text{s}$

Halos + SPRITES



SPRITES 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.

But ... many SPRITES without ELVES triggers

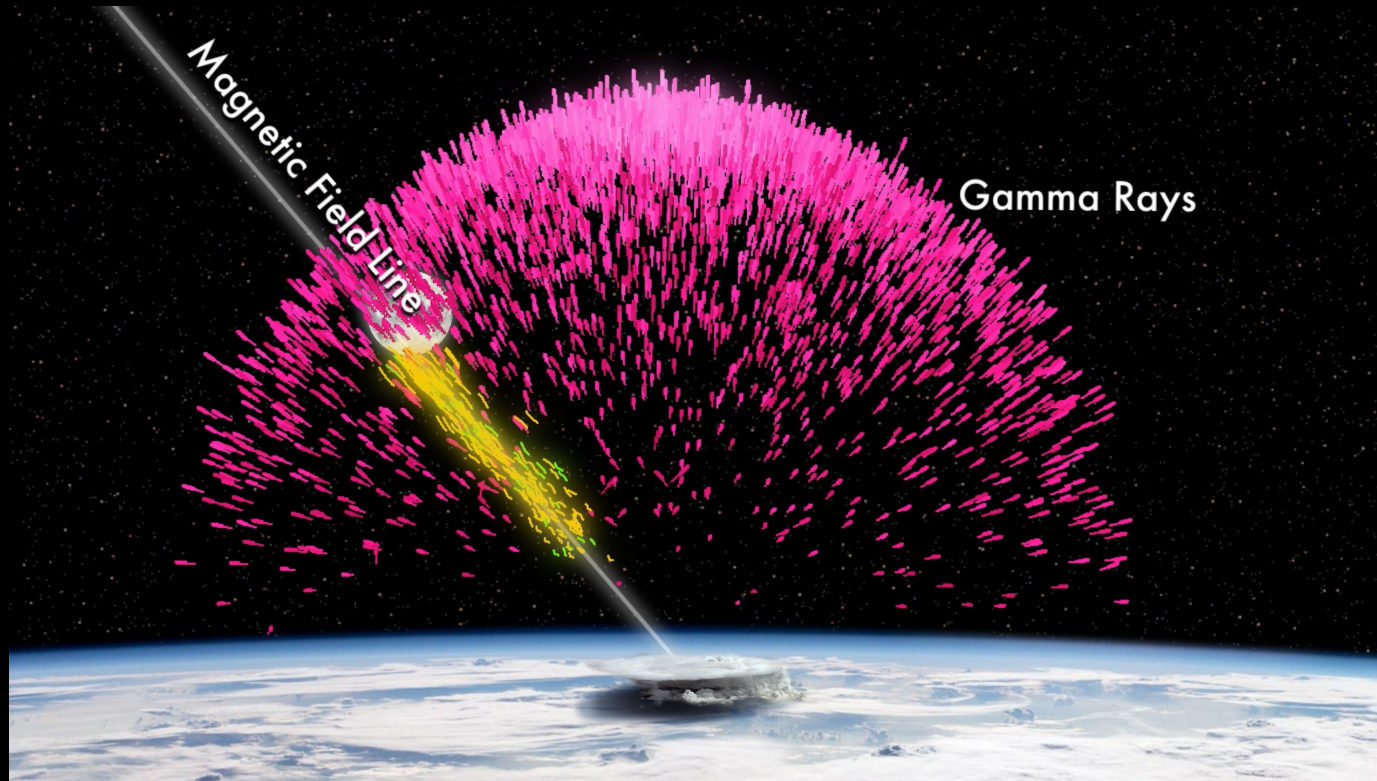
March 9, 2024: SIX SPRITES in less than half an hour ! None with an ELVES trigger in the same second.



We are also now observing the first ELVES in TLE cams ...

Terrestrial Gamma-ray Flashes (TGFs)

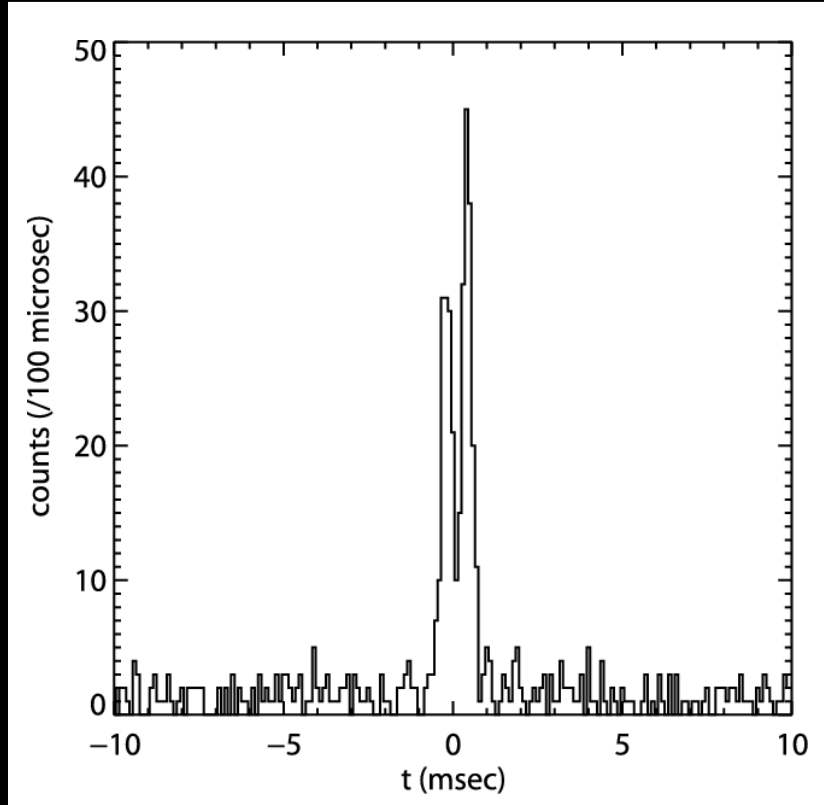
intense sub-millisecond bursts of MeV gamma rays discovered in 1994 – <https://doi.org/10.1126/science.264.5163.1313>



Credit: NASA/Goddard Space Flight Center/J. Dwyer/Florida Inst. of Technology

Terrestrial Gamma-ray Flashes (TGFs)

intense sub-millisecond bursts of MeV gamma rays discovered in 1994 – <https://doi.org/10.1126/science.264.5163.1313>



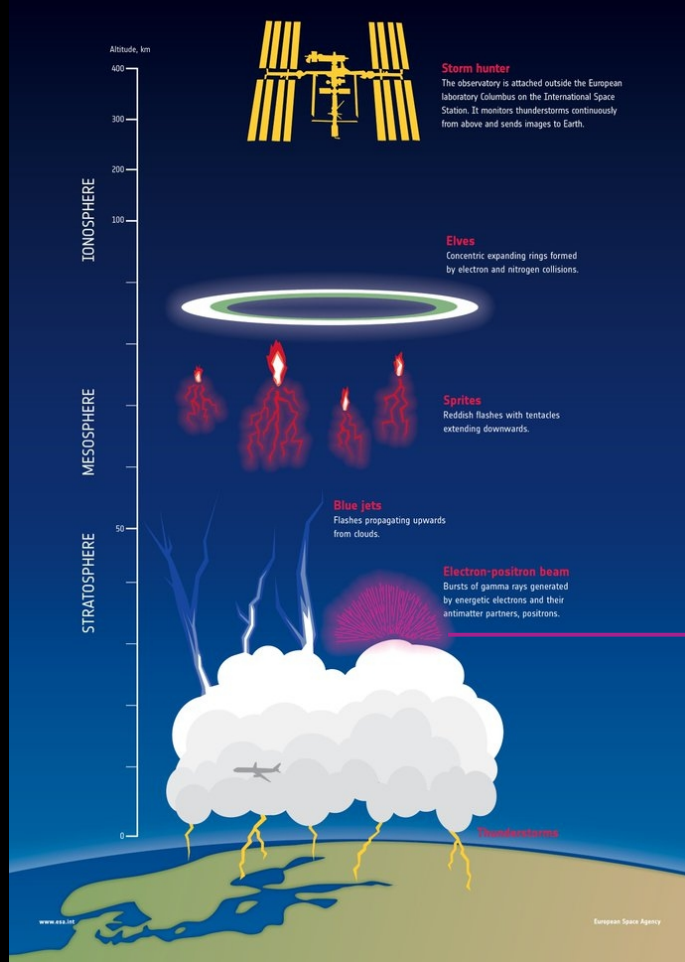
BATSE onboard CGRO 1991 – 2000
looking up to space...



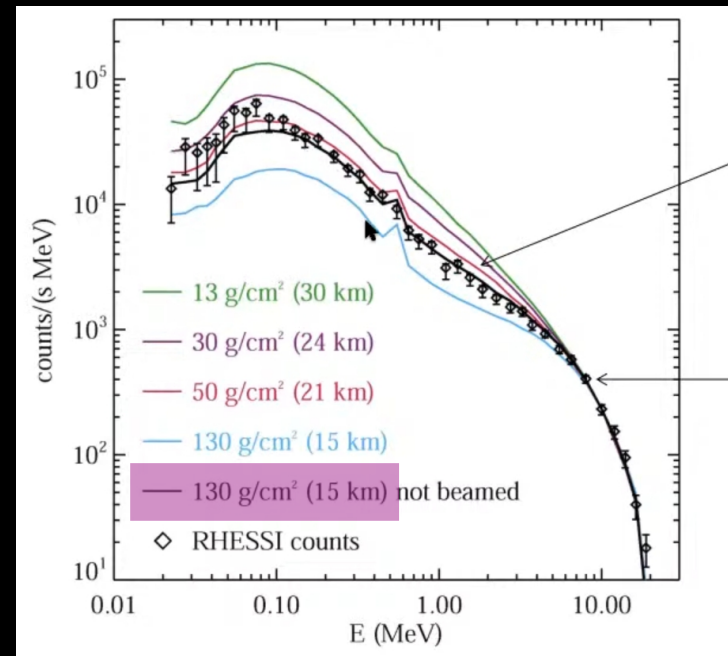
“Detectors aboard the Compton Gamma Ray Observatory have observed an unexplained terrestrial phenomenon: brief, intense flashes of gamma rays. These flashes must originate in the atmosphere at altitudes above at least 30 kilometers in order to escape atmospheric absorption and reach the orbiting detectors.”

→ at the beginning they were associated with sprites.

TGFs and thunderstorms



RHESSI (Reuven Ramaty High-Energy Solar Spectroscopic Imager) TGF spectrum and results of Monte Carlo simulations for different source altitudes from Dwyer and Smith (2005).



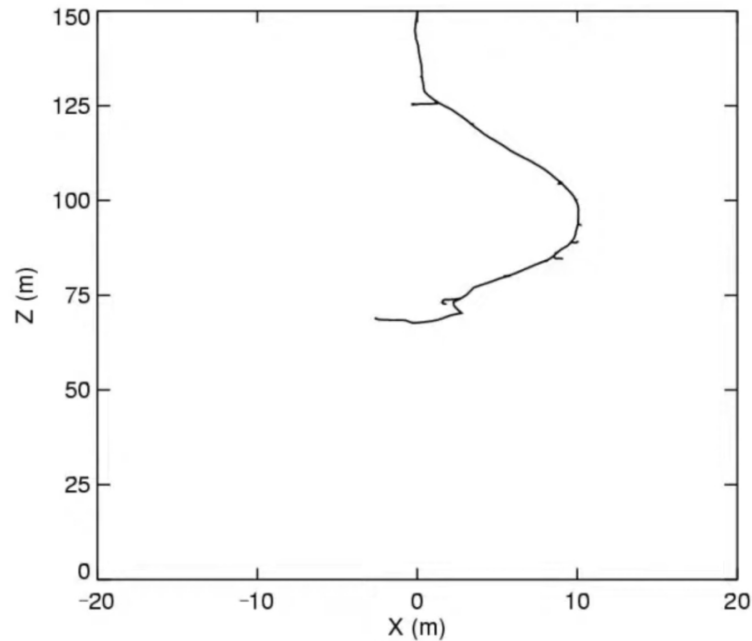
TGF spectrum too flat > 1 MeV to be from a high source altitude

TGF spectrum fits RREA model well up to 20 MeV

Relativistic Runaway Electron Avalanche (RREA) model

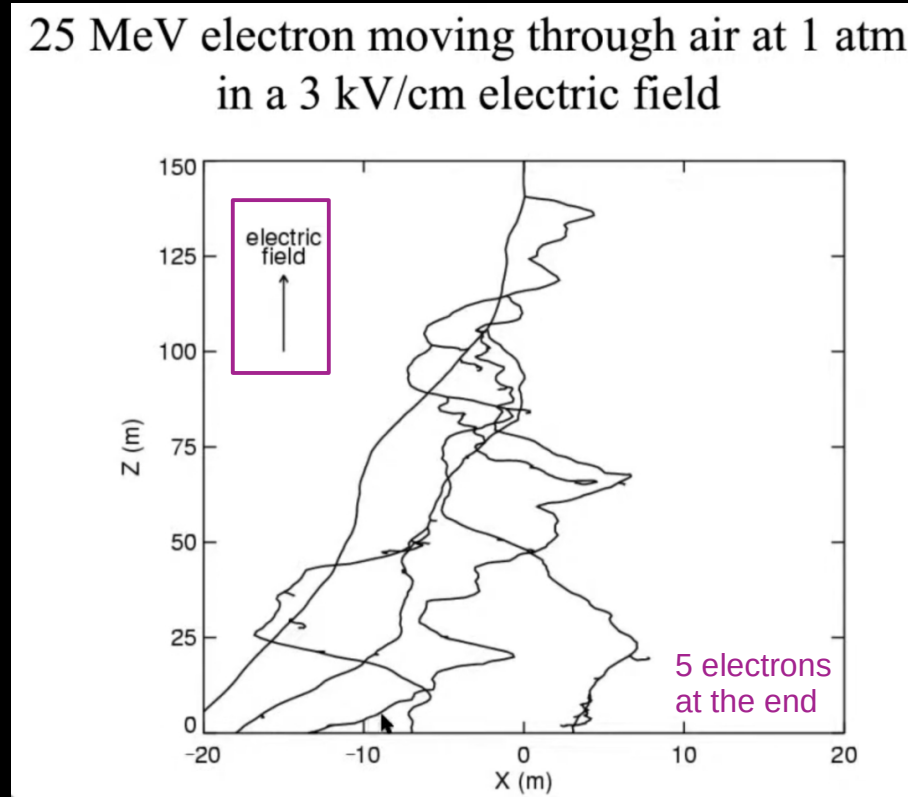
The high-energy gamma-rays are produced, via bremsstrahlung, by energetic runaway electrons accelerated by the electric fields in thunderclouds.

25 MeV electron moving through air at 1 atm



Relativistic Runaway Electron Avalanche (RREA) model

The high-energy gamma-rays are produced, via bremsstrahlung, by energetic runaway electrons accelerated by the electric fields in thunderclouds.



Relativistic Runaway Electron Avalanche (RREA) model

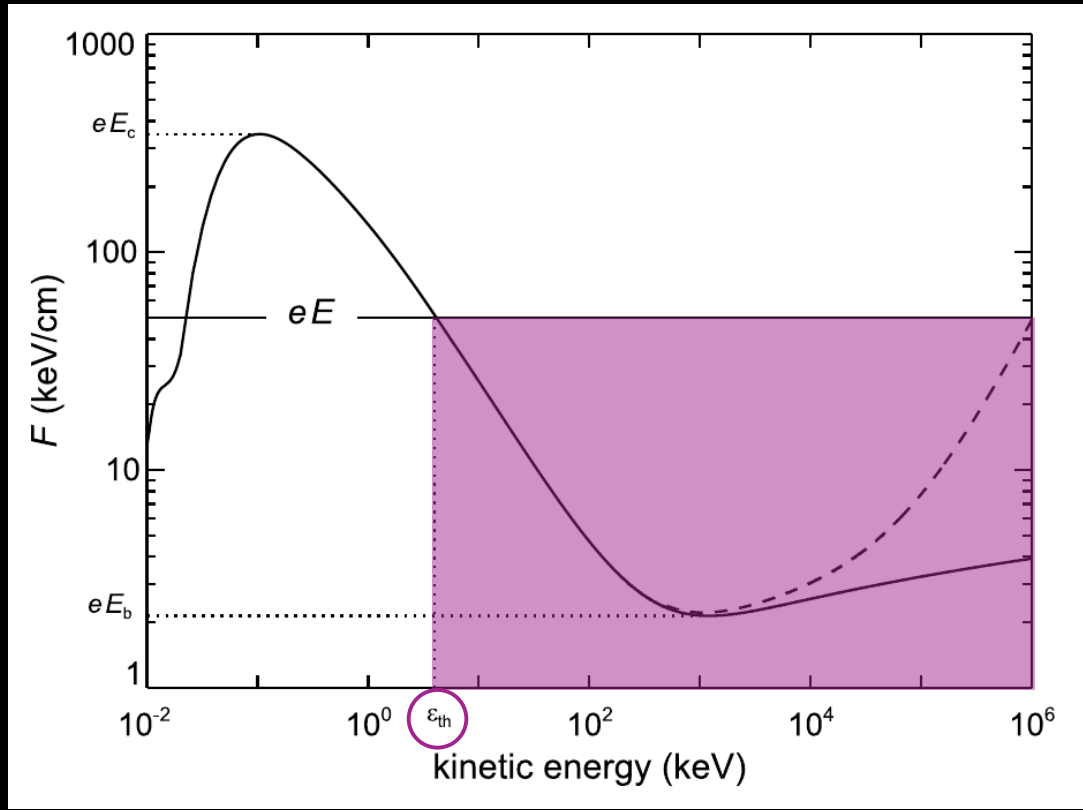


Figure shows the effective frictional force or rate of energy loss of an energetic electron moving in air.

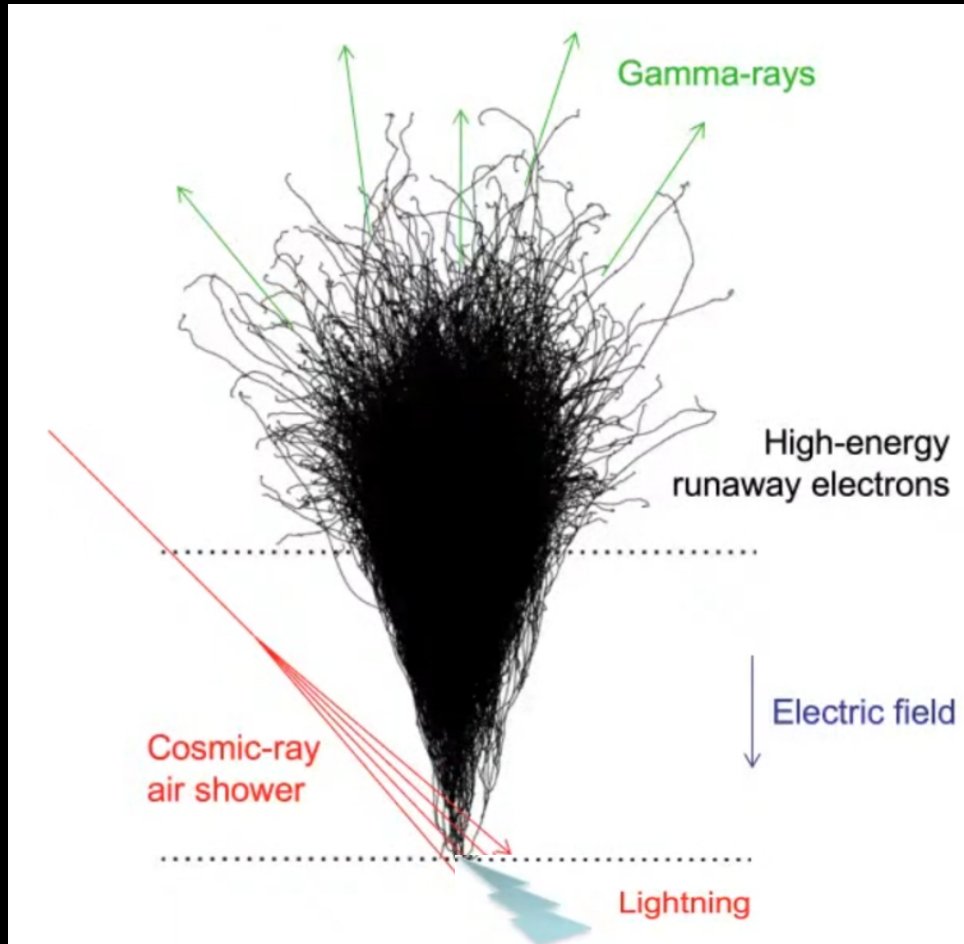
The horizontal line shows the rate of energy gain from a strong electric field.

When the rate of energy gain from an electric field exceeds the rate of energy loss from interactions with air then the energy of an electron will increase and it will “run away.”

In order for an electron to run away, it must have an initial kinetic energy above the threshold, ϵ_{th} .

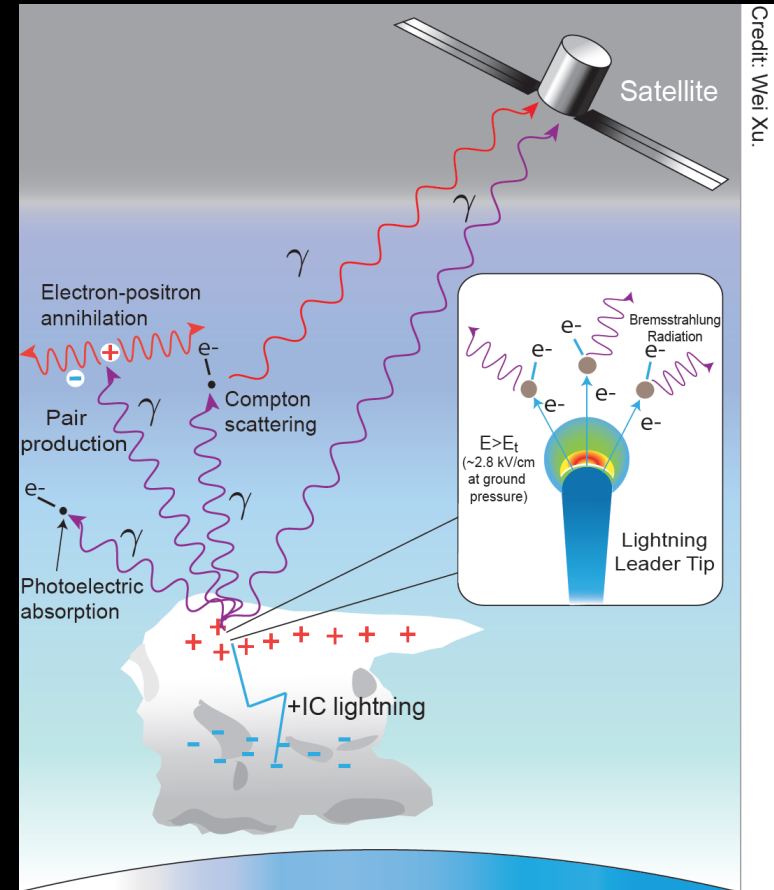
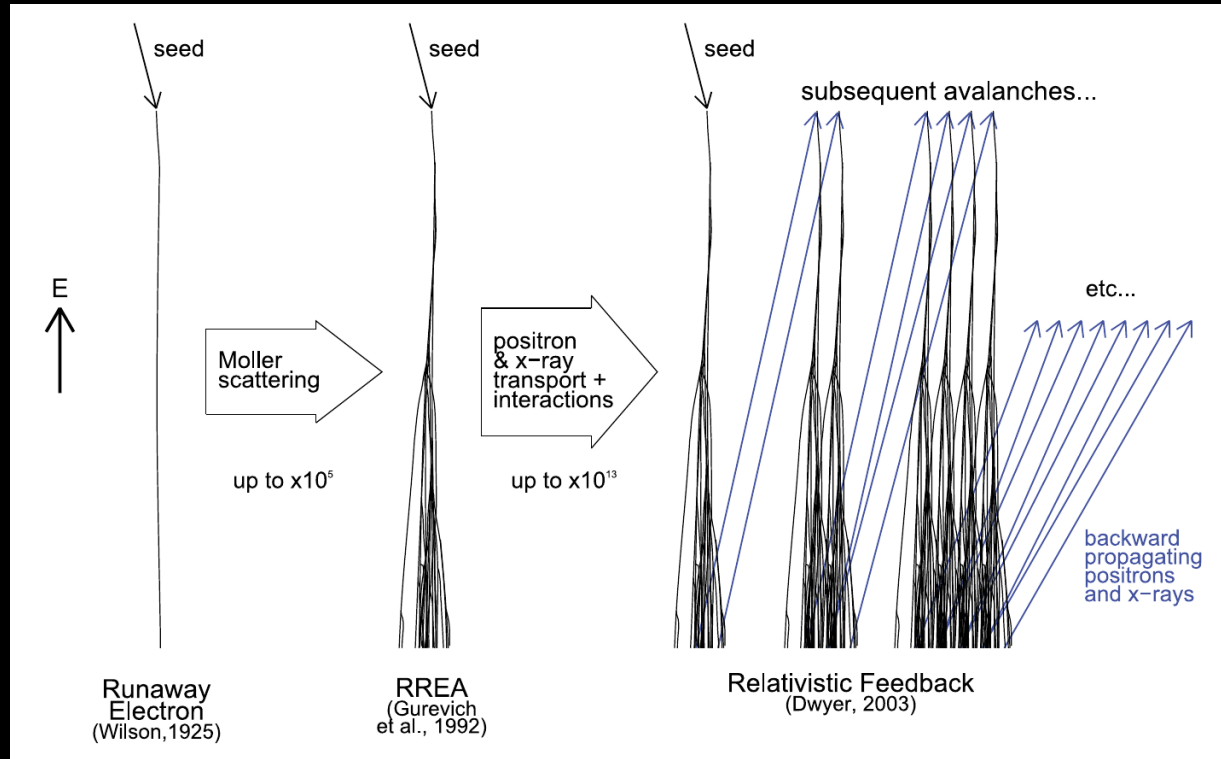
Such energetic “seed” electron, with energies above ϵ_{th} , may be provided from an external source.

What could be the external sources?



- Cosmic-ray air showers
- Radioactive decays
- Lightning

Evolution of the models



Credit: Wei Xu.

Open Questions



- Where are these strong electric fields located?
- What is the structure of their sources
- 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)

TGFs @ Telescope Array – *Ground Observation*

Telescope Array Surface Detector (TASD): 507 scintillator detectors arranged on a 1.2 km square grid. Each detector has two scintillator planes.

Lightning Mapping Array (LMA): 9 stations located within and around the TASD.

It provides accurate 3-D images of the very high frequency (VHF) radiation produced by lightning inside storms

- shows large scale structure and development of flashes and the lightning flashing rate;
- determines the plane distance to the TGF events;
- calibrates the VHF lightning interferometer azimuth and elevation values.

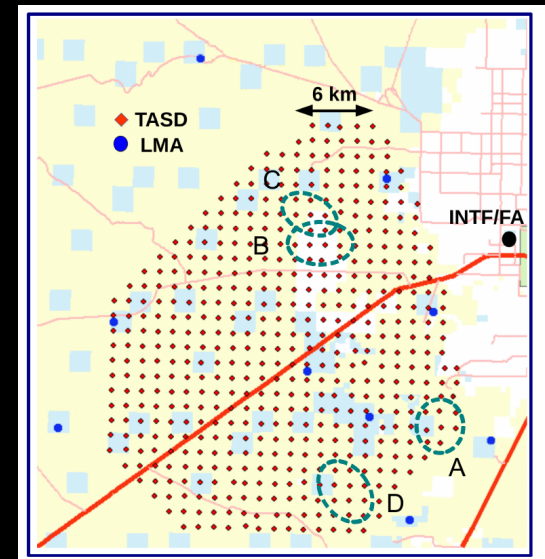
VHF lightning interferometer (INTF) and fast electric field change antenna (FA)

→ The INTF records broadband (20–80 MHz) waveforms at 180 MHz from three flat-plate receiving antennas, and determines the two-dimensional azimuth and elevation arrival directions of the VHF radiation with sub-microsecond resolution.

→ The FA provides high resolution (180 MHz) measurements of the low frequency (LF/ELF) discharge sferics that are key to interpreting the INTF and LMA observations.

**The combined use of all these instruments
+ dedicated simulations**

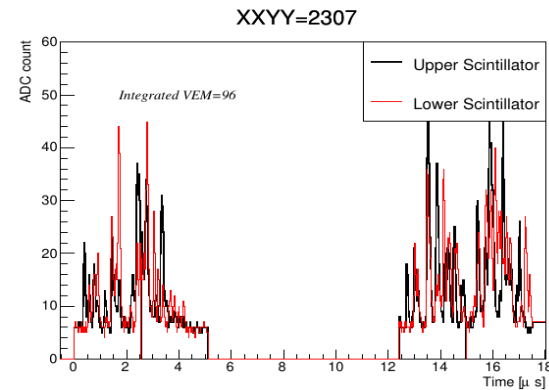
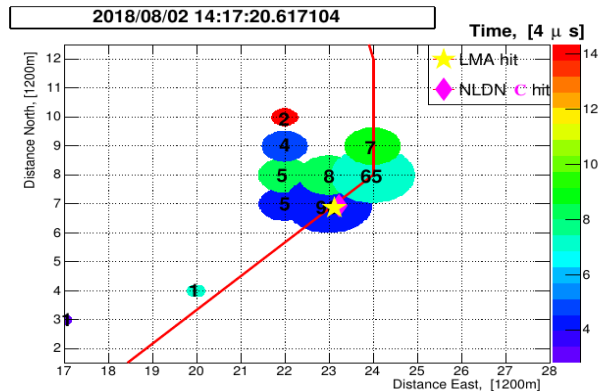
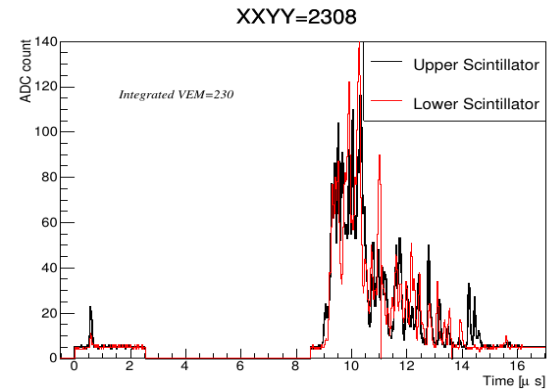
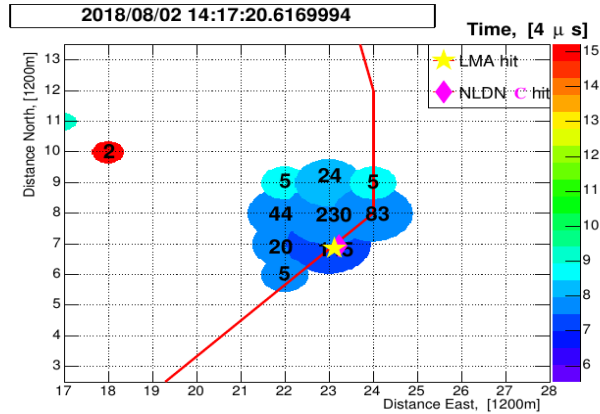
led to an advanced understanding of events initially detected
by the only TASD



TGFs @ Telescope Array

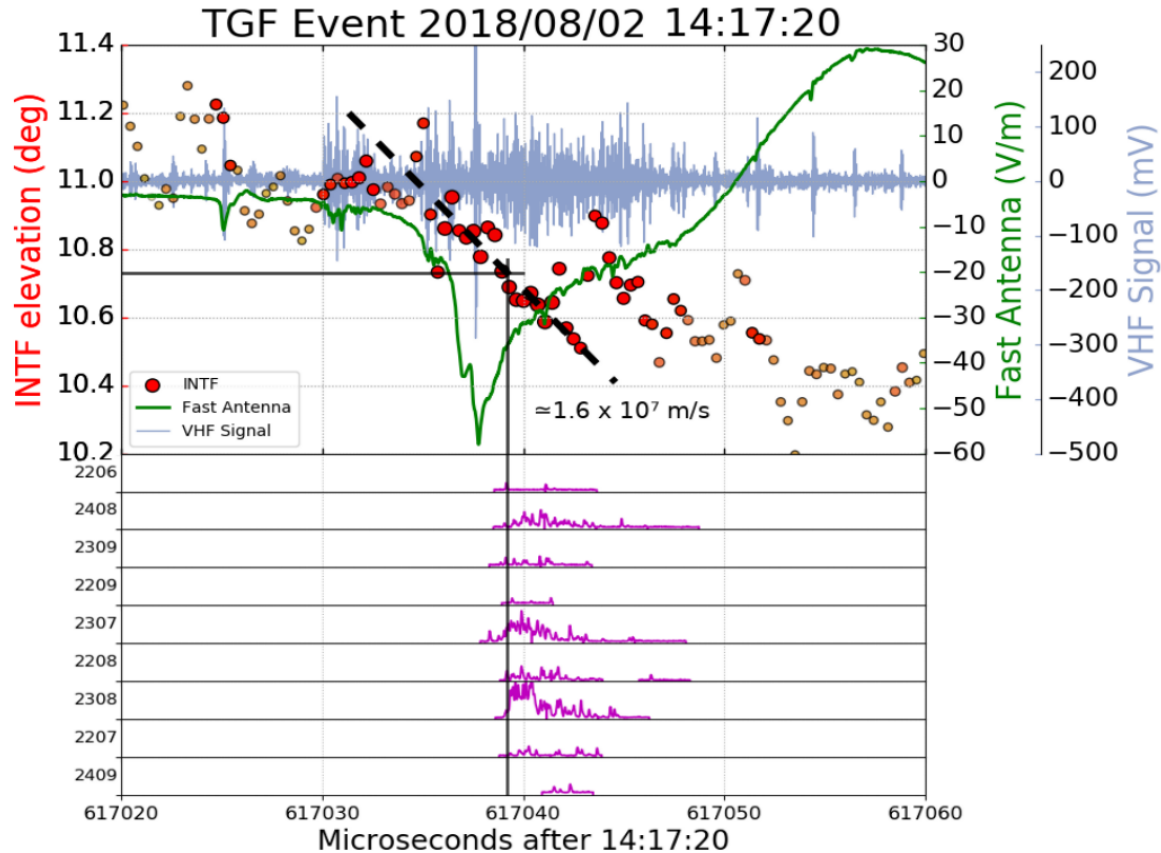
2 triggers occurred within about 100 μ s of each other, in the S-E corner of the T ASD \rightarrow they are signatures of the same TGF

Footprint of
the two
events:
T ASD
stations with
signal



T ASD
station
recording
the
strongest
energy
deposit
during each
trigger

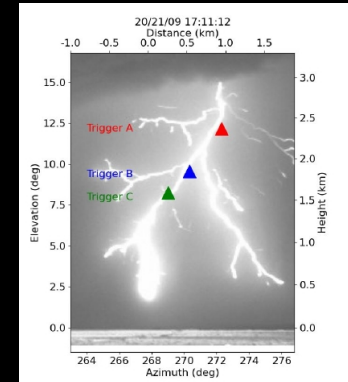
TGFs @ Telescope Array



The black vertical line shows the median onset time of the TGF relative to the INTF and fast antenna data. Purple traces in the lower panels are particle detector responses.

The detection times are in good agreement with one another as well as the median, indicating the onset time of the TGF during the sferic and the VHF radiation development.

New instrument:
High-speed video camera
R. Abbasi et al.,
PoS (ICRC 2023) 250



The Pierre Auger Surface Detector

Surface detector (SD) → 1600 water-Cherenkov detectors

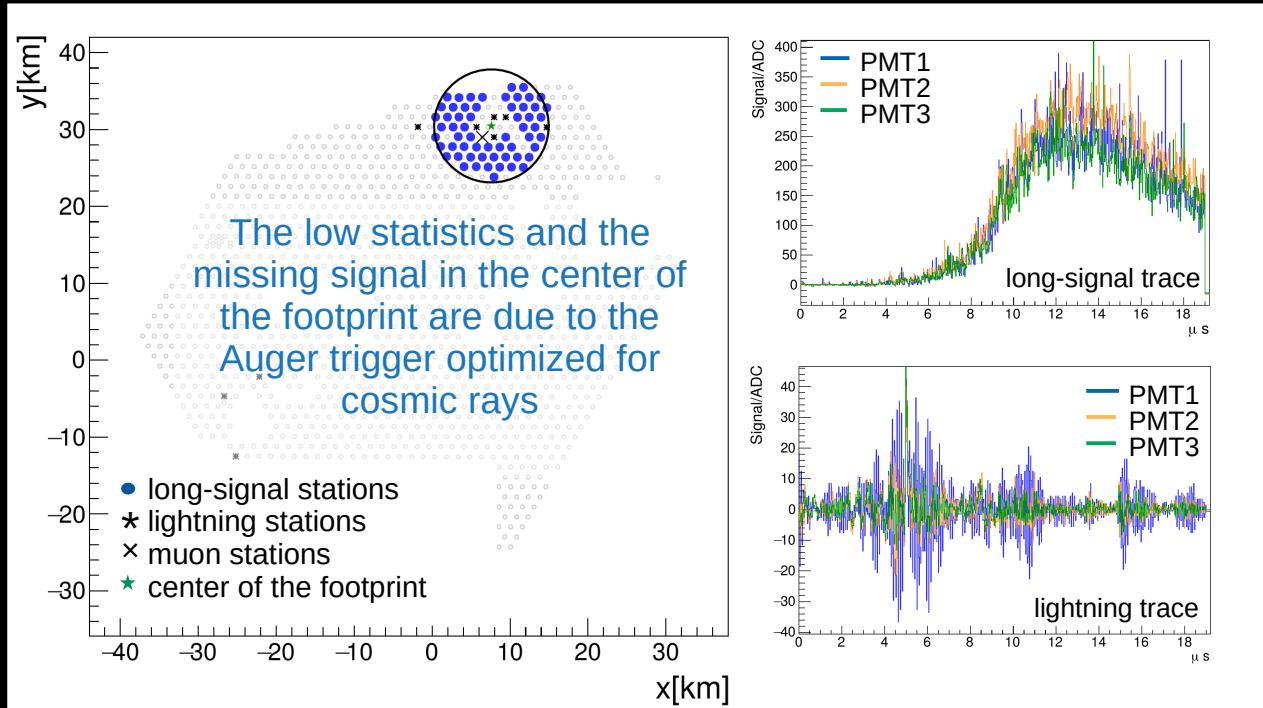
- 10 m² area,
- 1.2 m of pure water → important for photon detection efficiency,
- signal collected by three PMTs,
- digitised using 40 MHz, 10-bit Flash Analog-to-Digital Converters (FADCs).
- The DAQ window lasts 19.2 μs.



“TGF” events

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

R. Colalillo et al., doi: 10.22323/1.301.0314



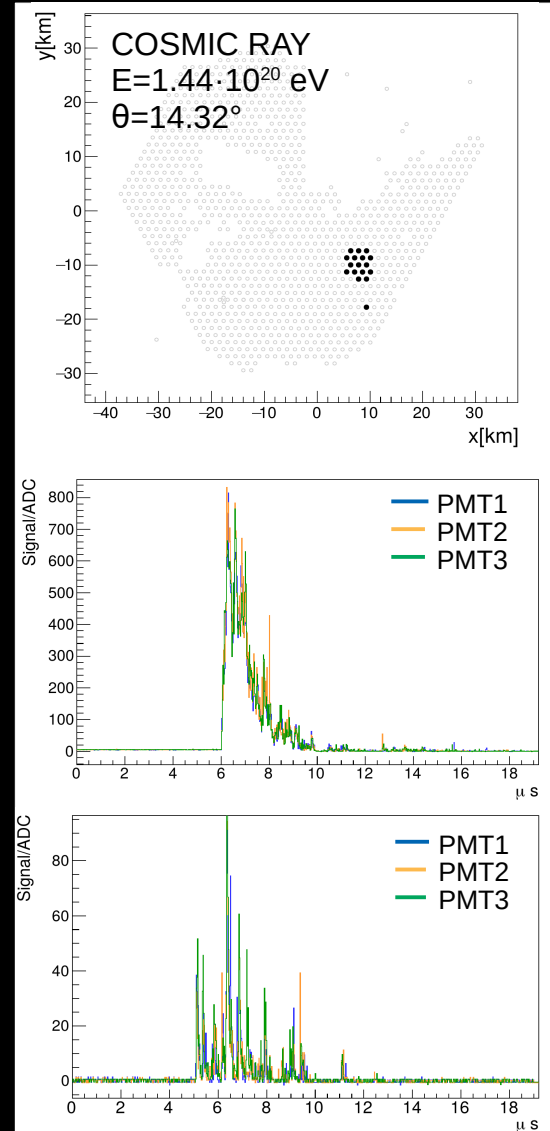
A dedicated trigger for TGF events was designed and installed –

Schimassek et al., <https://dx.doi.org/10.1088/1742-6596/2398/1/012003>.

It will be soon installed also in the new upgraded electronics –

R.Colalillo et al., ICRC 2025 .

Upgraded SD station: WCD + scintillator → comparison with TA

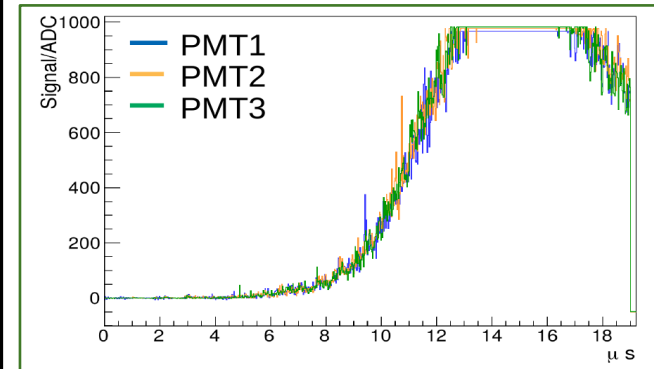
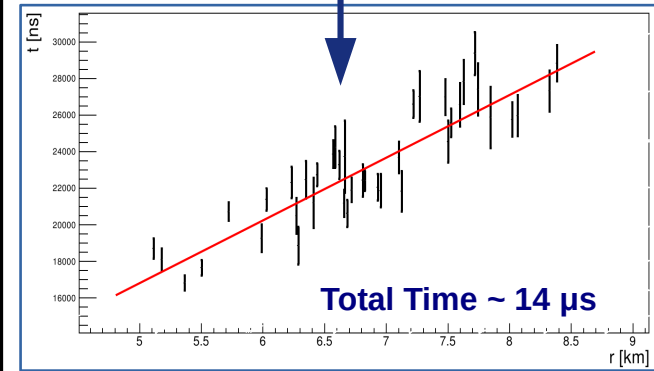
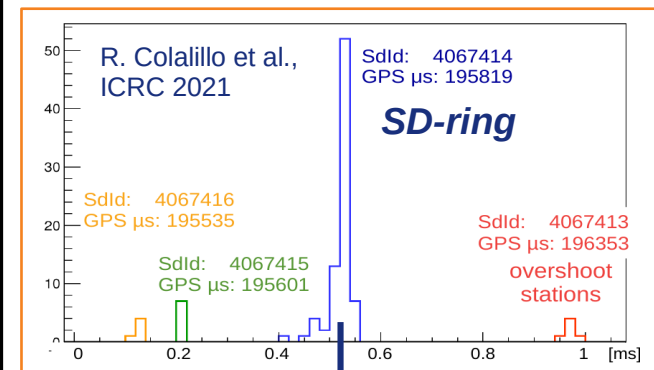


“TGF” events characteristics

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 .

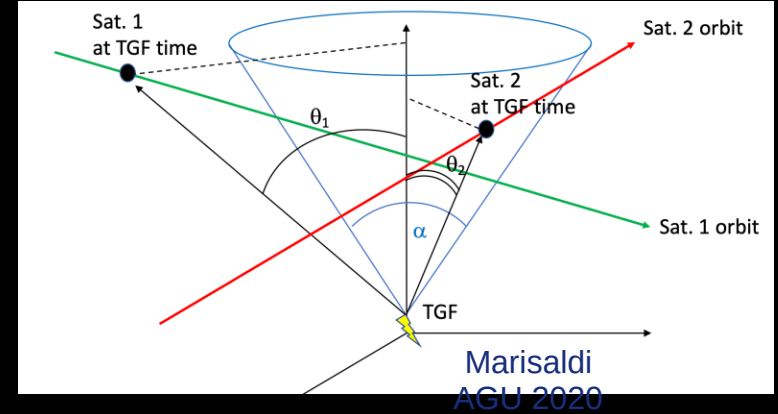
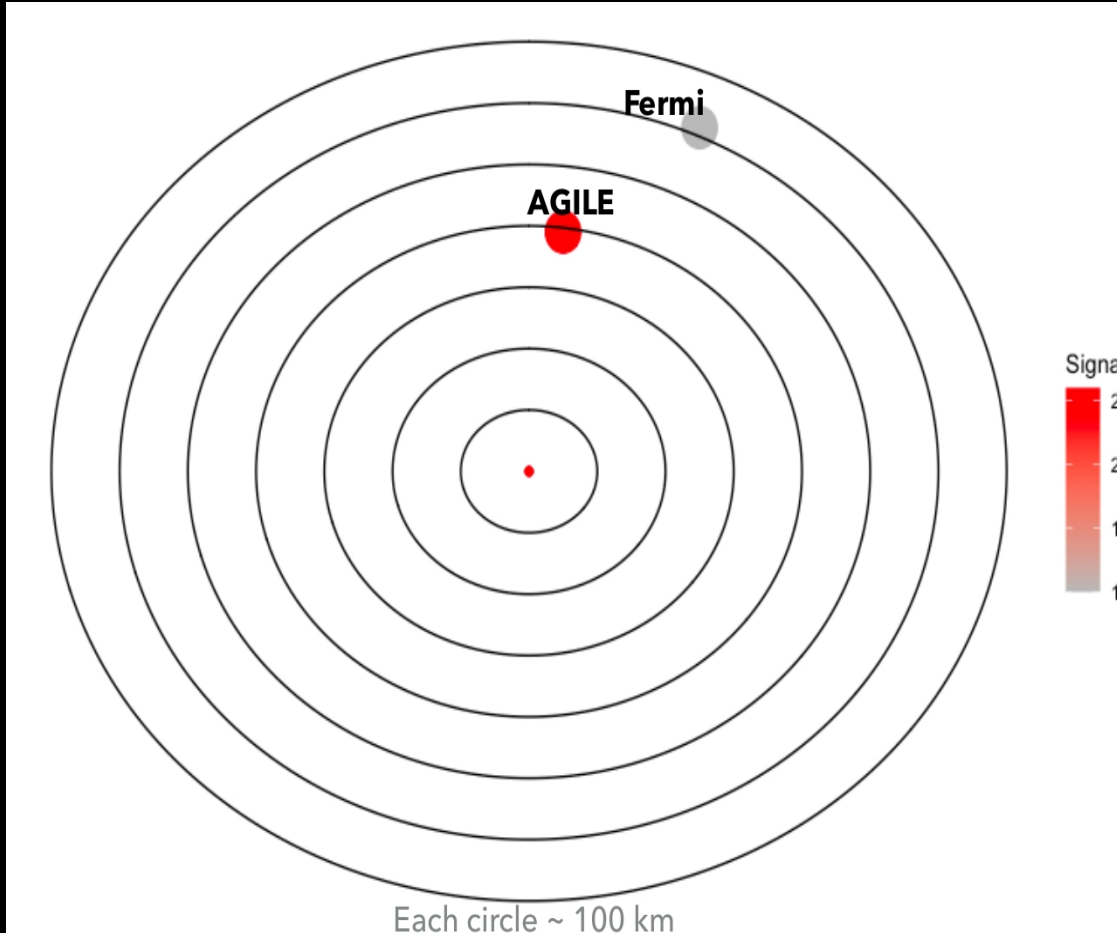
TGFs are so bright that they usually saturate also detectors far from the source.

Energy deposited at the ground:
 $\sim 10^4 \text{ MeV/m}^2 \times 200 \text{ km}^2 = 10^{12} \text{ MeV}$



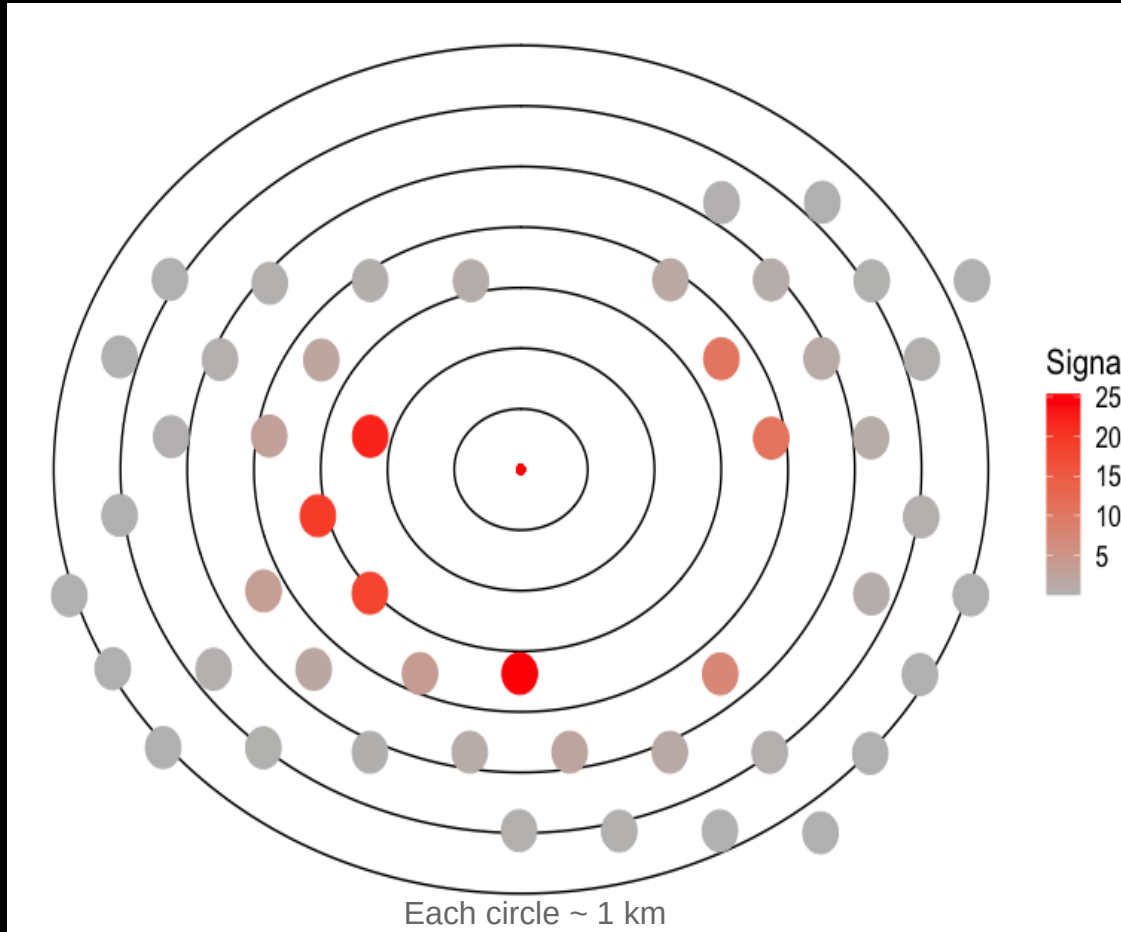
Greatest spatial
resolution
prior to Auger

Advantages of a Ground Array



Advantages of a Ground Array

@Auger



- 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

Relativistic feedback model

Relativistic Runaway Electron Avalanche (RREA) mechanism
+
positive feedback effects from positrons and energetic photons

Positrons and photons of the electromagnetic cascade can propagate to the start of the avalanche region and can produce additional runaway electrons. **The number of runaway electron avalanches increases exponentially on a timescale measured in microseconds.**

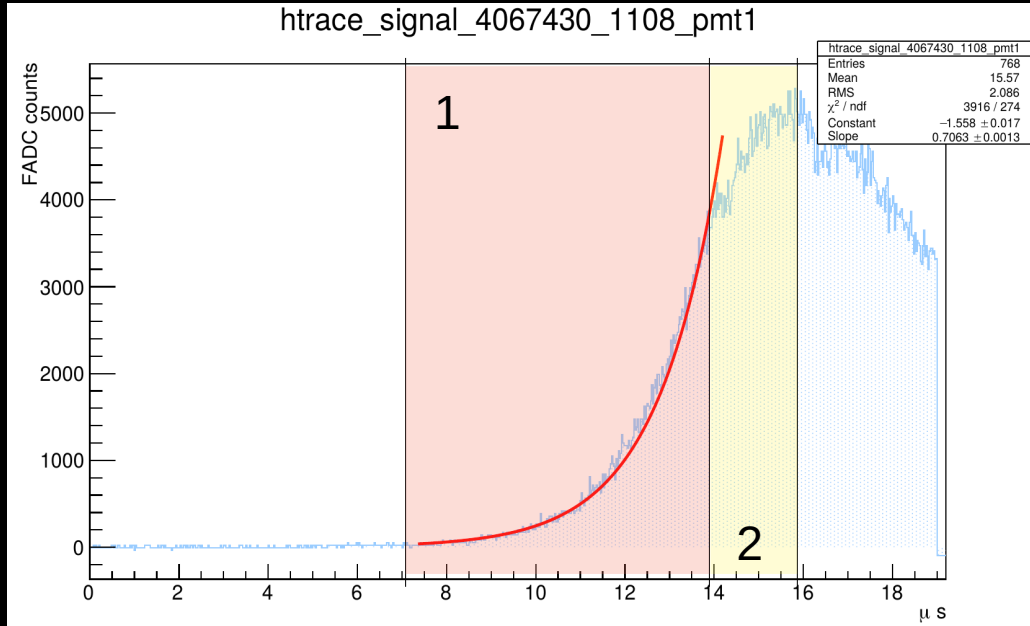
The runaway electron flux at time t is given by:

$$F_{RF} \propto \exp(t/\tau')$$



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

Does an exponential fit the rising edge of our signals?



1. Read part - Exponential part:

- the runaway electron flux is low
- the generated discharge current is also low
- the electric field is not being modified by the RREA.

2. Yellow part

Once the flux reaches a large enough value, the currents lower the field and the RREA generation starts slowing down and eventually stops.

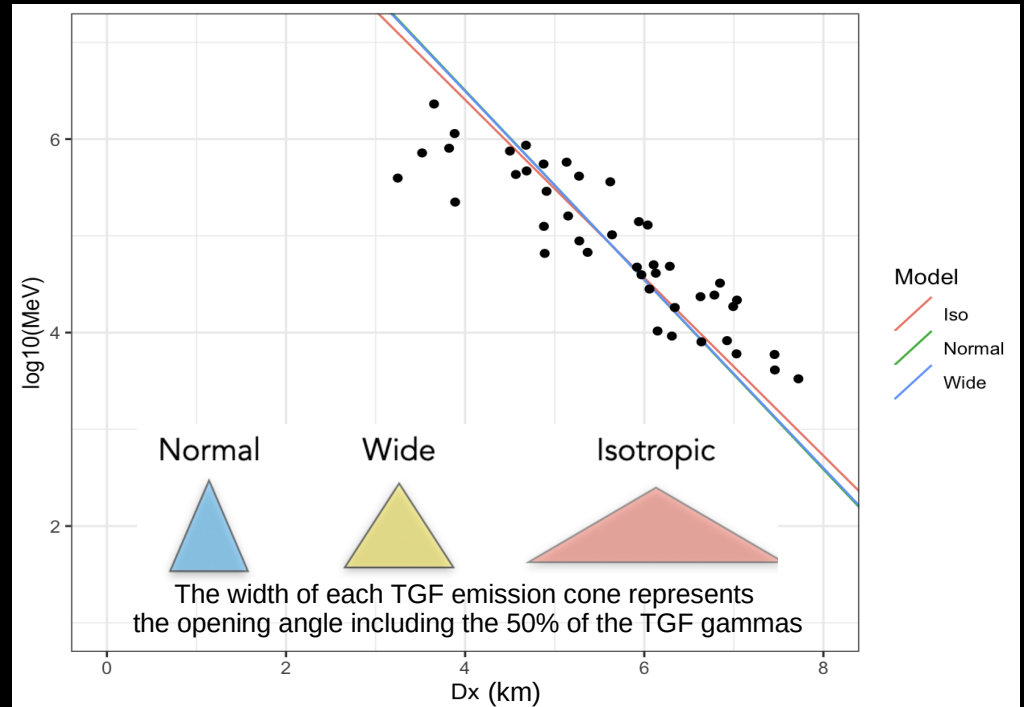
Comparison with models

→ Geant 4 simulations starting from Dwyer 2012 Relativist Feedback model (doi:10.1029/2011JA017160)

→ **compatible with the shape of our long signals – see my talk at ICRC 2023**

→ Source at 2 km

→ **compatible with the source altitude reconstructed with our data**

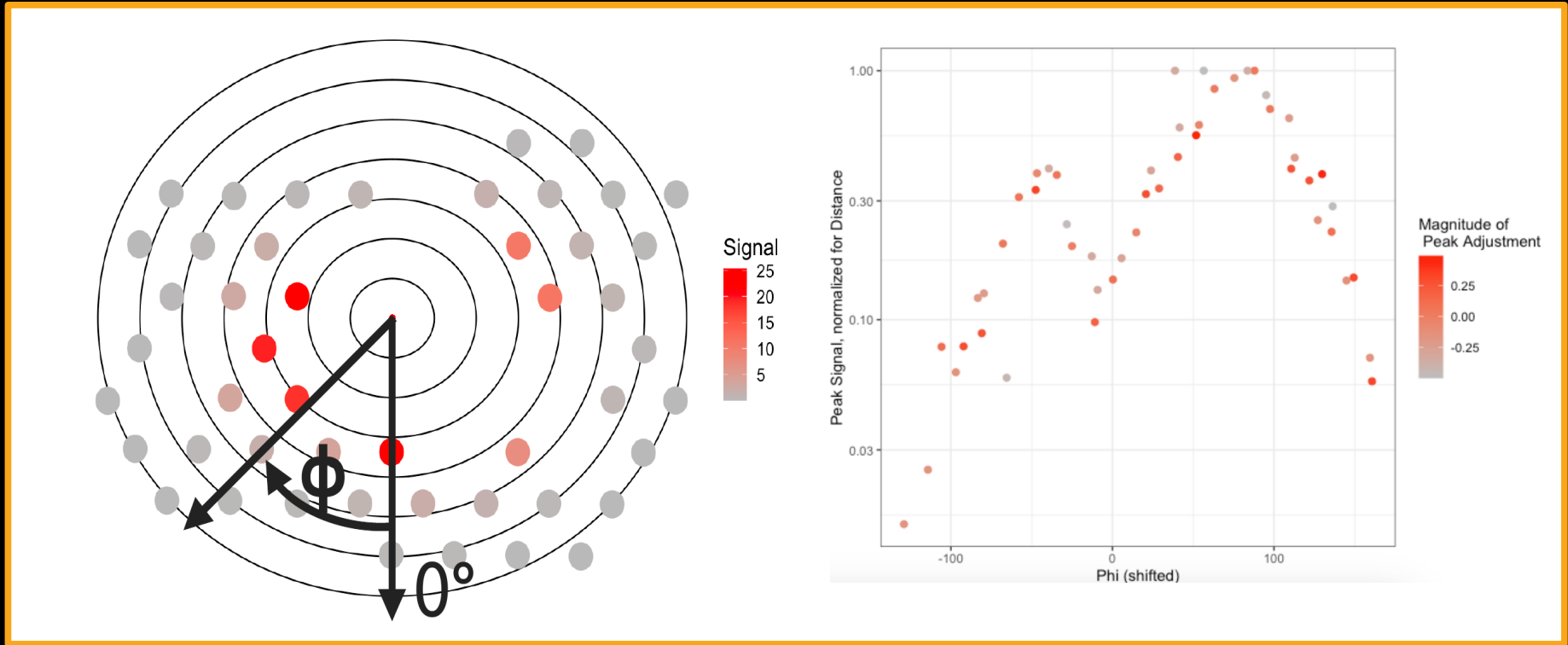


Auger TGFs show a brightness similar to TGFs seen from space (10^{17} - 10^{18} photons)



The slope is not very well reproduced by standard TGF models

First evidence of an asymmetric TGF



Indication for not standard electric field sources?

Relativistic Feedback assuming an **upward positive leader** (Dwyer, Phys. Rev. D 104 (2021) 043012); **Reactor Feedback** (Stadnichuk et al., J. Geophys. Res. Atmospheres 126 (2021) e2021JD035278)

What TGF type are we observing?

TGF classification by D. Smith et al., AGU Fall Meeting 2024

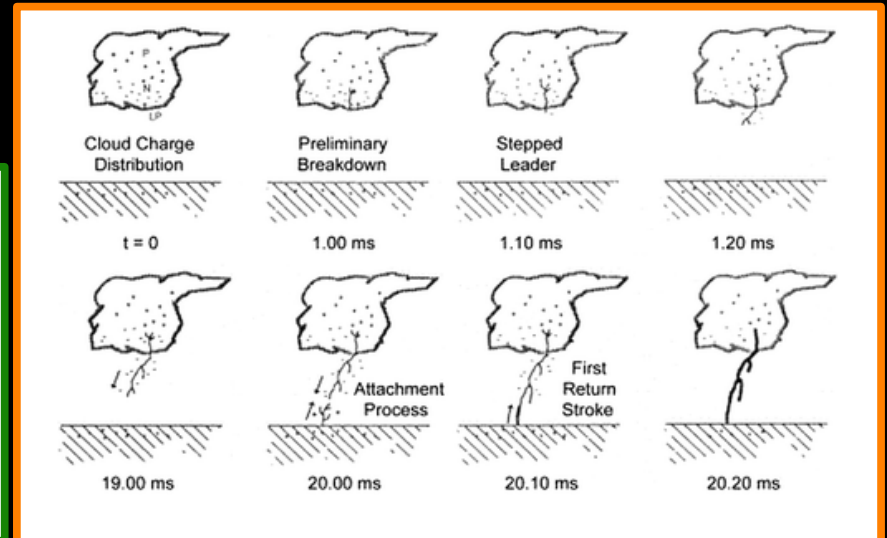
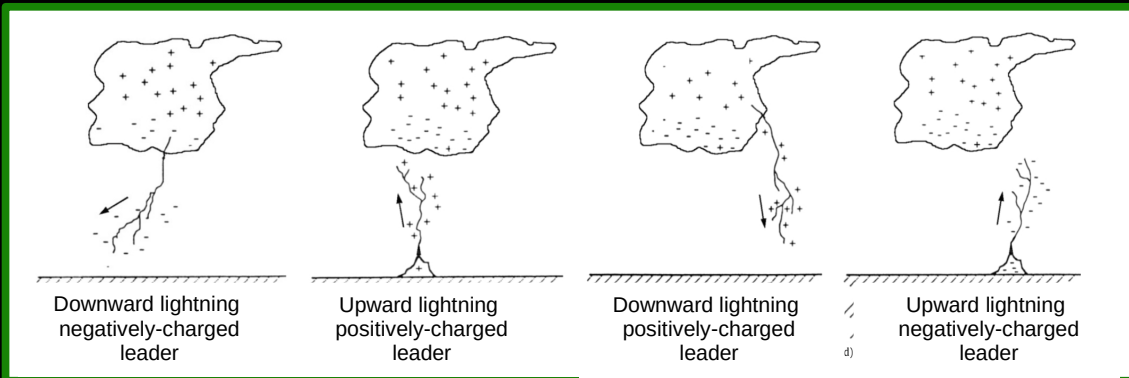
TGF1: produced at one end of an intracloud channel unconnected to ground (even if it will be eventually). These form one end of a continuum of behaviors, with x-ray bursts from stepped leaders at the other end.

TGF2: produced at the upper (generally positive) end of a channel already connected to ground (-CG lightning).

TGF3: produced without any evidence of an existing leader / channel but rather through a glow instability, probably leading to the relativistic feedback streamer.

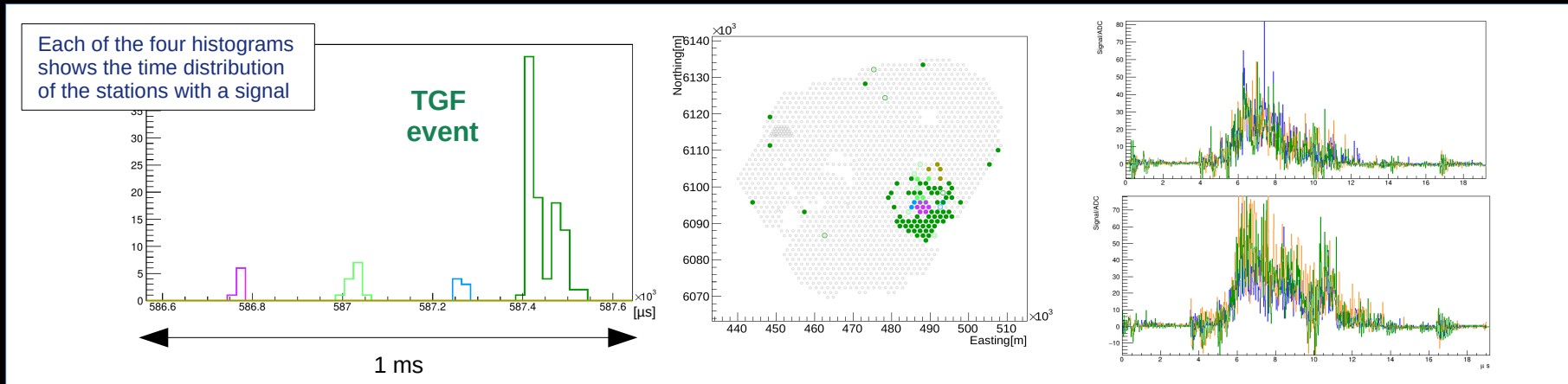
Different types of lightning

The TGF can be produced at different stage of lightning development



What TGF type are we observing?

In our sample of events, different behaviours were observed. Most TGF events are preceded by other events that occur within a few milliseconds in the same area of the arrays. Sometimes, the precursor events only have lightning signals; in some cases, they also include long stations.



Behaviour similar to the events observed by the UC Santa Cruz group (J. Ortberg & D. Smith) in Japan and New Mexico: TGF in coincidence 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).

Compatible with TGF 2 type (generated at the upper end of a channel already connected to ground – generally negative CG lightning)

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

Present and future Lightning Local Networks at the Pierre Auger Observatory

Radio emissions cover several wavelength bands and several instruments can be used for lightning studies:

→ **E-mills array (DC signal) + Lightning sensor array** (Boltek Storm Tracker) already available at the Observatory

→ **VLF/LF instruments array will be installed 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).



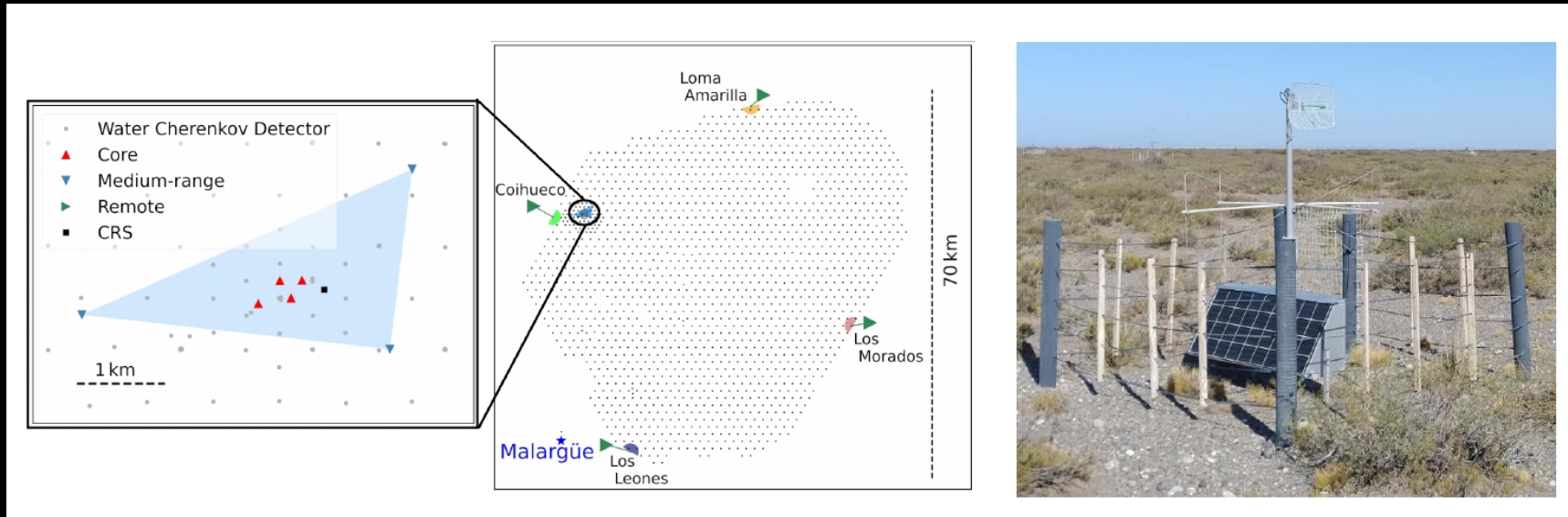
BOLT

(Broadband Observatory of Lightning and TGFs)

11 modified AERA (Auger Engineering Radio Array) stations (30-80 MHz) – **the VHF range for a broadband lightning interferometer in 4D (3 spatial + 1 time)**

→ 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)



→ Each station includes low- and high-gain channels for a wide dynamic range, capturing both strong and weak VHF pulses without saturation

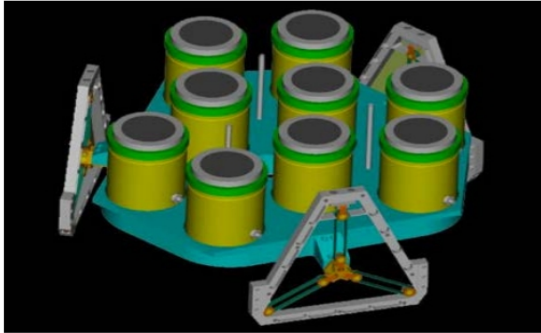
→ The system can accept external triggers from Lightning Sensors and the SD

→ **The array is almost completed (M. Weitz et al., EGU 2026)**

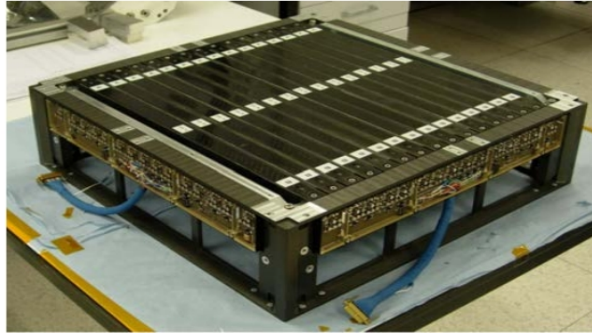
Backup

TGF detectors

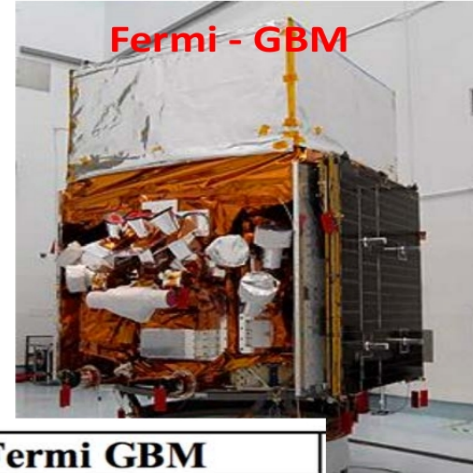
RHESSI - GeD



AGILE - MCAL

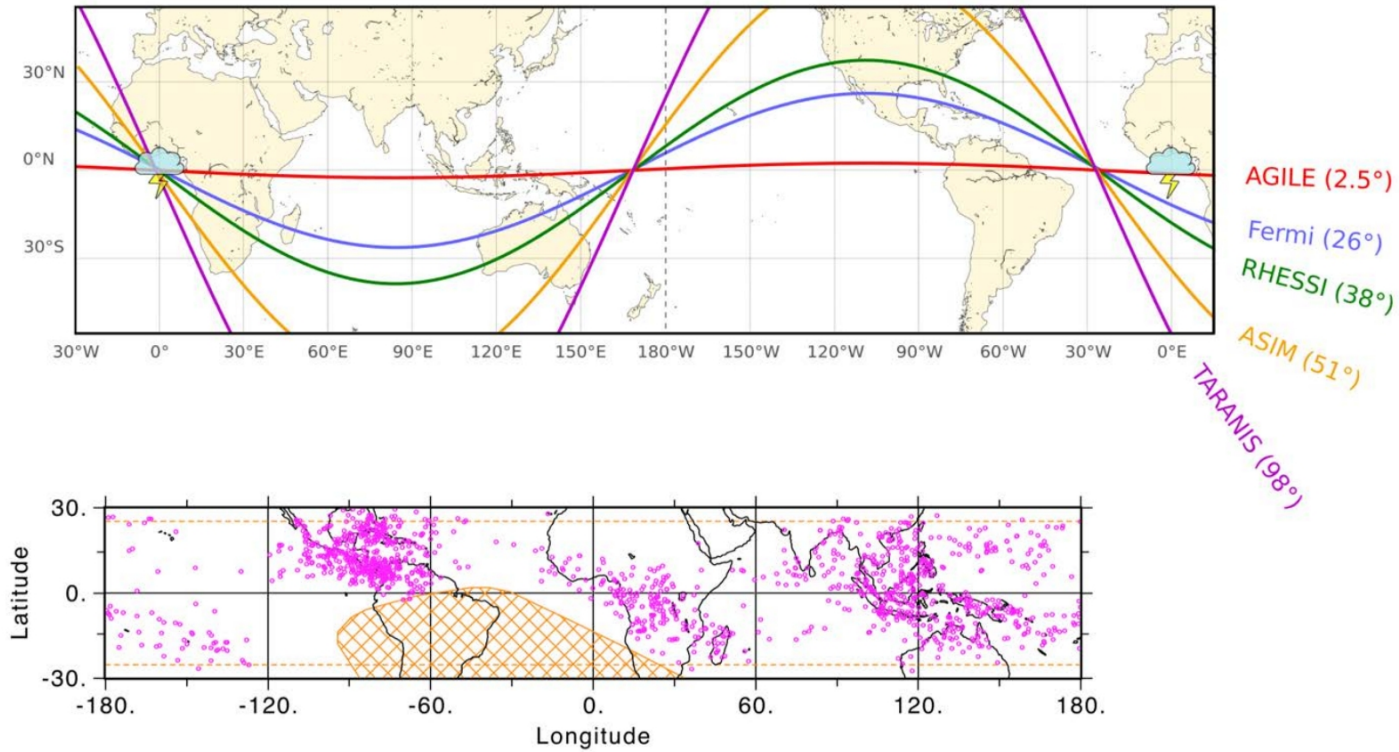


Fermi - GBM



	RHESSI	AGILE MCAL	Fermi GBM
Operative since	2002	2007	2008
Orbit inclination and altitude	38° 600 km	2.5° 540 km	26° 540 km
Detector type	HPGe	CsI(Tl) scintillator with solid state readout	NaI(Tl) and BGO scintillator with PMT
Energy range	0.015 – 20 MeV	0.35 – 100 MeV	0.015 – 40 MeV
Effective area for typical TGF spectrum	260 cm ²	220 cm ²	160 cm ² (1xBGO)
Acquisition type	continuous	triggered	continuous
TGFs/year	~340	~800	~800

Mission profile (orbital inclination)



Roberts+2017

TBE & Magnetic mirroring

TBE characteristics:

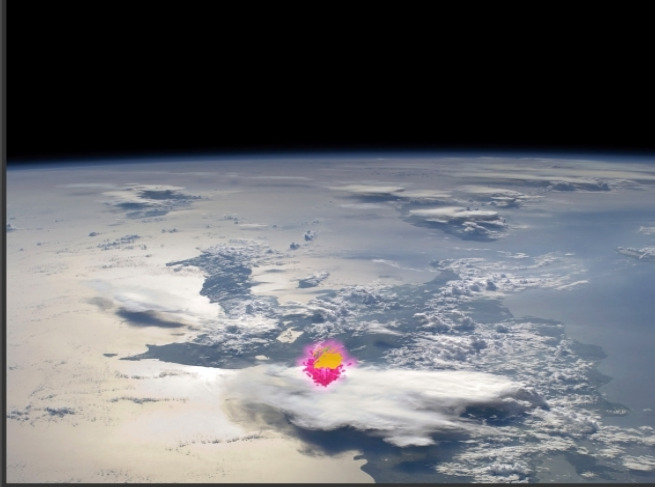
1. Duration ≥ 1 ms, as the electron positron beam is dispersed along the field line.
2. Spectral line at 511 keV due to electron positron annihilation.
3. Lack of lightning activity at the spacecraft nadir but present at one of the magnetic footprints of the local field lines.
4. Unequal signals in the two BGO detectors, due to spacecraft blockage which becomes more prominent for softer events.
5. An observed mirror pulse in the lightcurve, which is only expected if the magnetic field is stronger at conjugate point from the source footprint.

Magnetic mirroring:

Two points on the Earth's surface, linked by a geomagnetic field line, are generally called conjugate points.

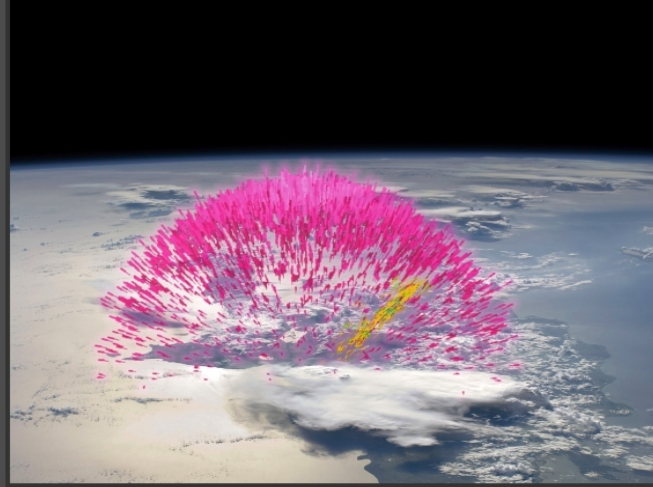
Charged particles travel along the magnetic field, and as they approach their conjugate point, the particles will either be absorbed into the atmosphere or, in cases where the magnetic field is strong enough, reflected (mirrored).

How thunderstorms launch particle beams into space



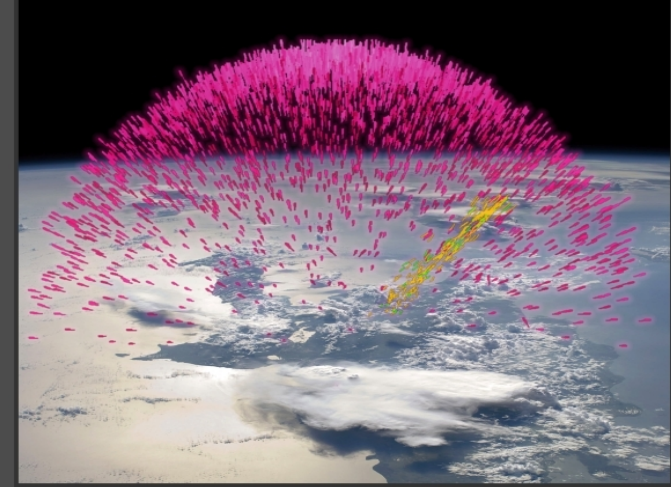
- 1.** Electric fields near the top of the storm create an upward-moving avalanche of **electrons**. When their paths are deflected by molecules in the air, these electrons emit **gamma rays**, the highest-energy form of light.

These images are based on a TGF simulation by Joseph Dwyer at the Florida Institute of Technology. This frame tracks the gamma rays and particles from a 0.2-millisecond-old TGF that began at an altitude of 9.3 miles (15 km).



- 2.** When gamma-ray energy collides with electrons, they accelerate to near the speed of light. Some gamma rays pass near the nuclei of atoms. When this happens, the gamma ray transforms into an electron and its antiparticle, a **positron**.

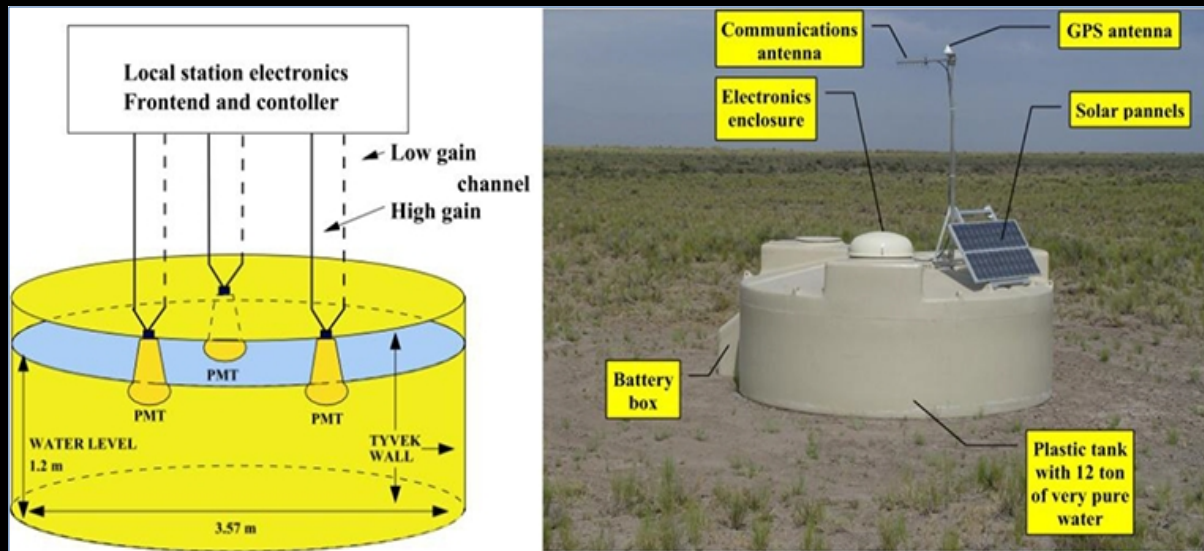
These high-energy electrons and positrons escape into space by spiraling along Earth's magnetic field. In this frame, the TGF is 1.4 milliseconds old.



- 3.** Here the TGF is 1.98 milliseconds old, and its electron/positron beam is reaching altitudes where it may intercept spacecraft, such as NASA's Fermi Gamma-ray Space Telescope.

Fermi's Gamma-ray Burst Monitor detected a signal characteristic of positron annihilation. When a positron collided with an electron on the spacecraft, the two particles transformed into gamma rays.

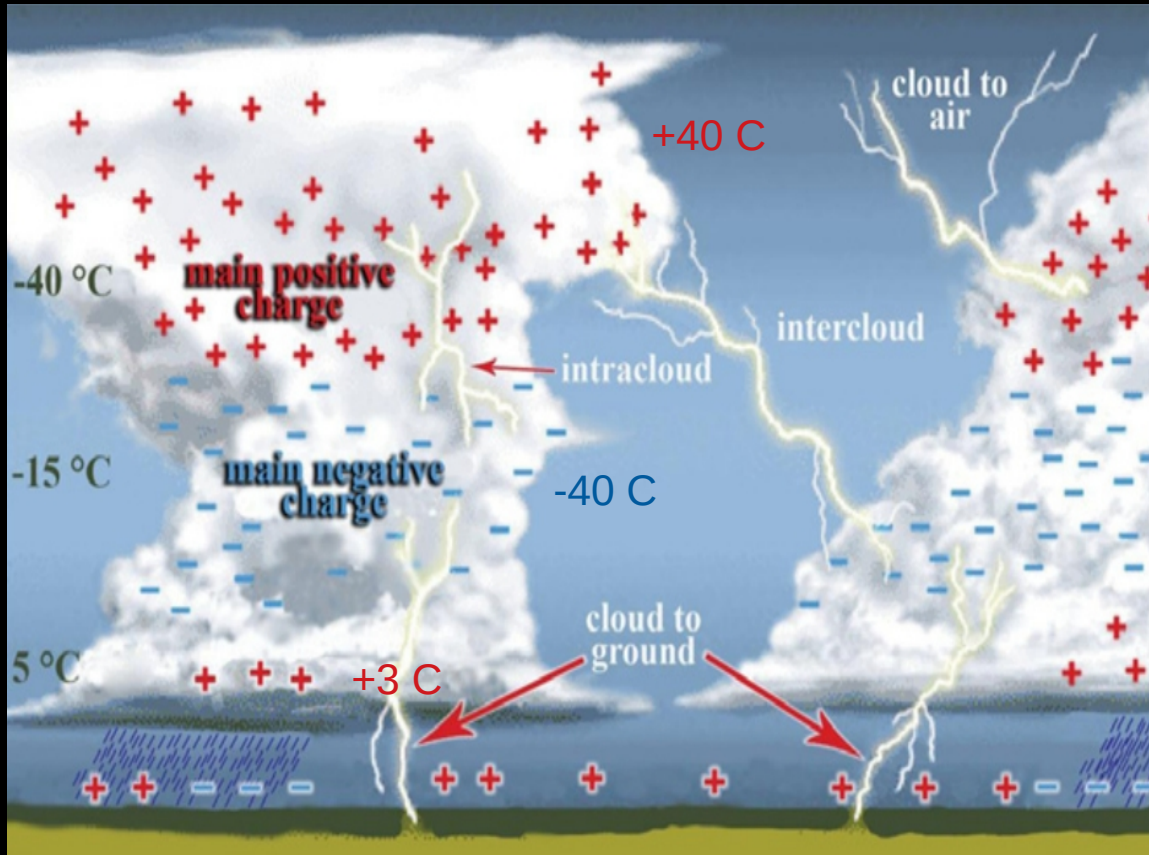
The Pierre Auger Surface Detector



- Each WCD consists of a 3.6 m polyethylene tank containing a liner with a reflective inner surface and filled with 12,000 liters of ultra-pure water.
- Cherenkov light produced by the passage of relativistic charged particles through the water is collected by three PMTs.
- Each PMT has two readout channels, one directly from the anode (**LG channel**) and the other one from the last dynode (**HG channel**) with an amplification factor of 32
→ the LG channel is used when the HG is saturated.
- The two output signals are processed by six FADCs with a sampling rate of 40 MHz, 25 ns per time bin. The DAQ window lasts 19.2 μ s.

The Physics of Lightning

J.R. Dwyer, M.A. Uman, Physics Reports 534 (2014) 147–241



Lightning can be defined as a very long electrical spark
→ length of 5–10 km, at the extreme over 100 km.

A typical small thunderstorm system produces a lightning flash to ground every 20–30 s for 40–60 min and covers an area of typically 100–300 km².

The tripole model illustrated in the picture is a simplified sketch of the charge structure, that is usual more complex and varies from storm to storm.

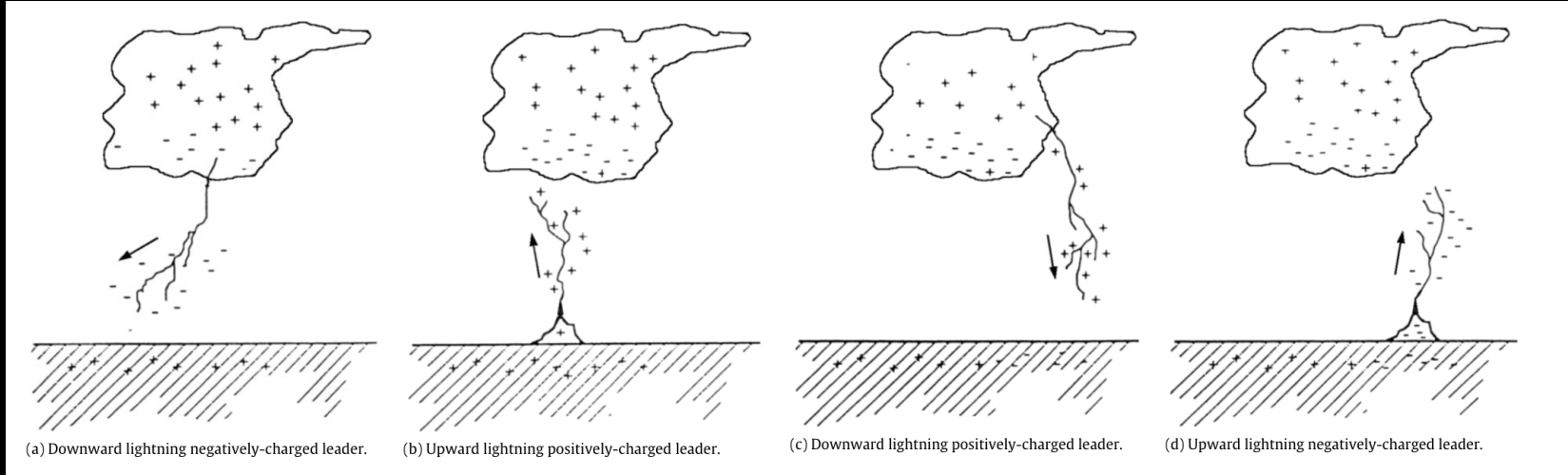
How is lightning initiated (creation of a propagation hot leader channel) **inside thunderstorm?**

Measured electric field strengths are not large enough to make a spark

- wrong measurements?
- incomplete models?
- ...

The Physics of Lightning

J.R. Dwyer, M.A. Uman, Physics Reports 534 (2014) 147–241

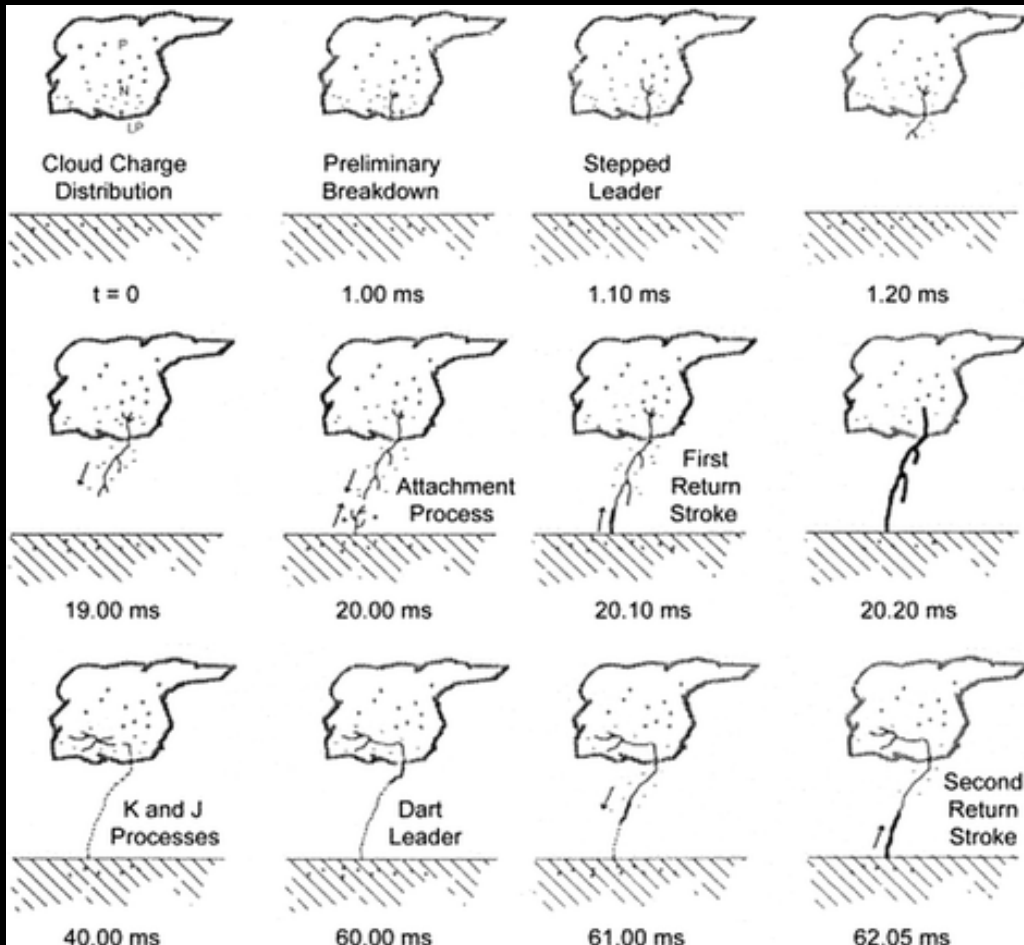


The terms “lightning flash”, “lightning discharge”, and “**lightning**” are used interchangeably in the literature to describe either cloud lightning or cloud-to-ground lightning, generally **the whole event lasting about 0.5 s**.

There are four types of lightning flashes that occur between the cloud and ground. The four types are distinguished from each other by the sign of the electrical charge carried in the initial “leader” and by the direction of propagation of that leader.

About 90% of cloud-to-ground lightning flashes are initiated by a negatively-charged, downward-propagating leader, and result in the lowering of negative charge from the main negative charge region in the middle part of the cloud to the ground.

Development of a negative cloud-to-ground lightning flash



The physical mechanism for moving the negative charge to Earth is a propagating electrical discharge called the “stepped leader”.

Prior to observations of the discharge, there are often larger electric field pulses associated with a “preliminary” or “initial” breakdown in the cloud charge region.

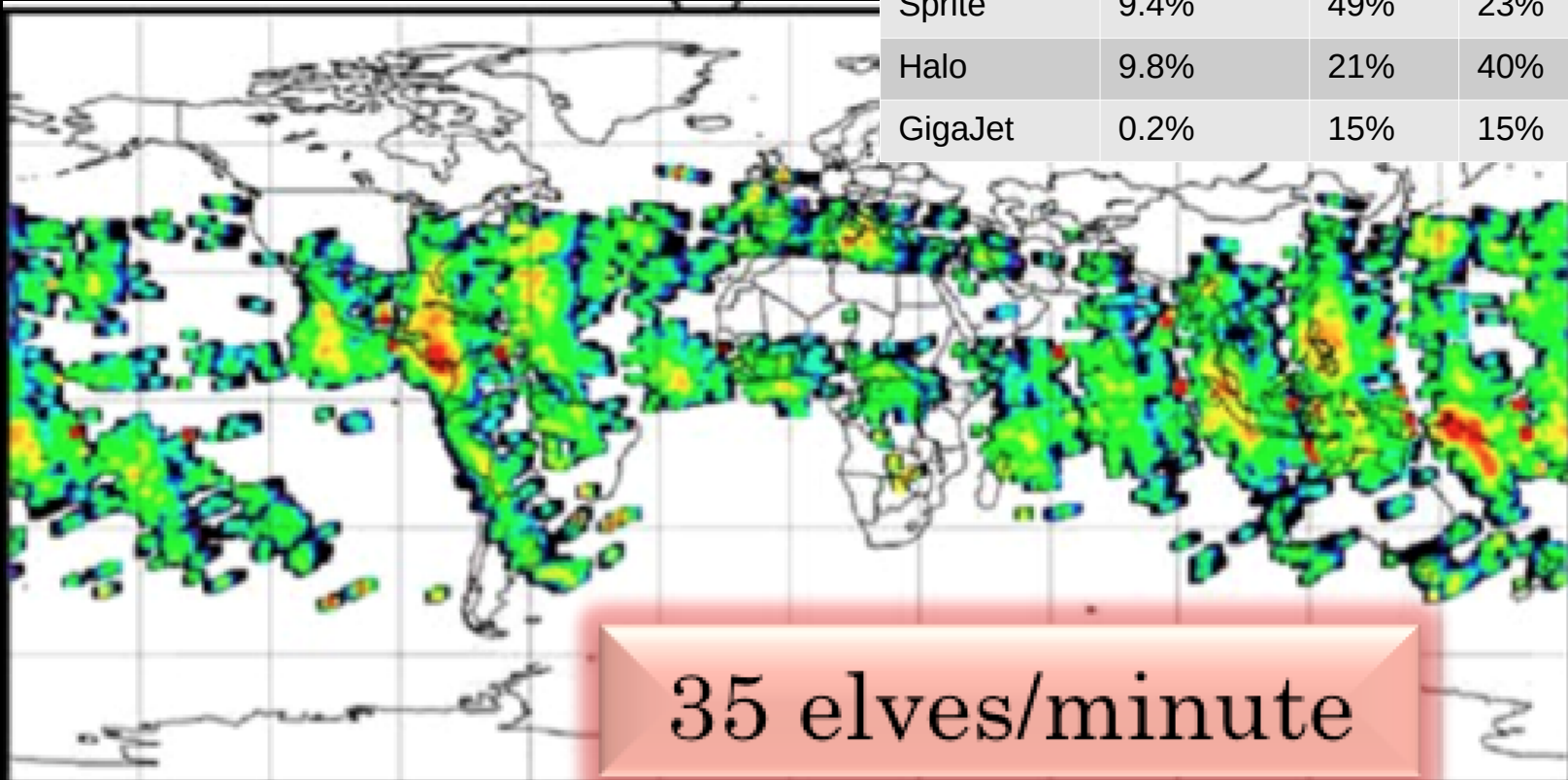
The last main step of the lightning development is the “return stroke” that happens after that the electric field intensity close to ground is large enough and an upward-going, positively-charged electrical discharges from the ground or from grounded objects is initiated.

Each negative leader step produces a pulse of visible light, a pulse of radio-frequency energy, and a pulse of X-rays, primarily in the 200 keV range.

Frequency and location of TLEs

Source: ISUAL on FormoSat-2

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%



An Italian ELVES

TECNOLOGIA
INNOVAZIONE
SCIENZA
LOGIN:
CORRIERE DELLA SERA

IN: EVIDENZA ▾

Domande & Guide Quiz & Meme La Scelta Giusta CampBus A Scuola con Corriere Chi Siamo

Cosa sono gli Elves: l'anello rosso fuoco comparso nel cielo di Ancona aveva un diametro di 360 chilometri

di Chiara Barison

L'immagine di Valter Binotto ha fatto il giro del mondo. Il primo a registrare il fenomeno elettromagnetico è stato lo Space Shuttle Sts-41 nel 1990. Ora si è manifestato ad Ancona e il merito è dei fulmini di un temporale



La prova di Sky Stream, il decoder di Sky che integra le app di streaming

March 2023

Picture taken by Valter Binotto in Treviso province.

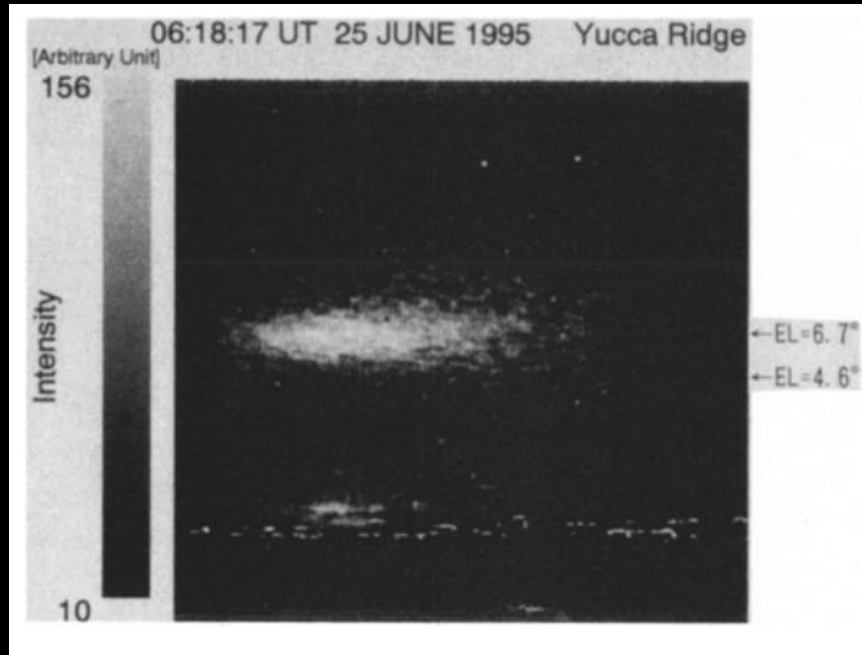
The ELVES wa originated by a lightning that occurred in Ancona, located approximately 300 km from Binotto's observation point.

First ELVES observation from ground

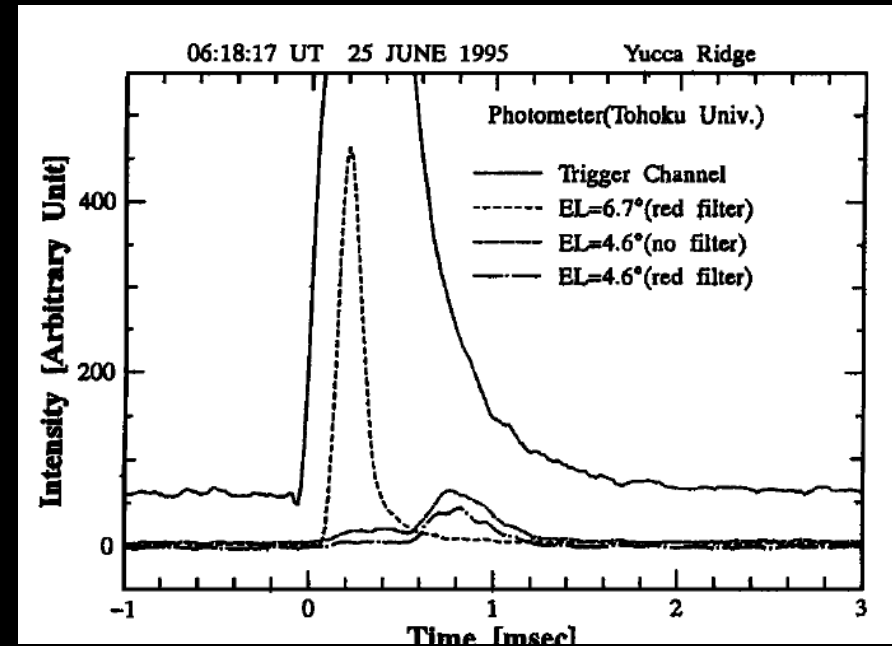
Fukunuishi et al., 1996, <https://doi.org/10.1029/96GL01979>

SPRITES'95 campaign, Yucca Ridge Field Station, Colorado

CCD camera



Multichannel high-speed photometer

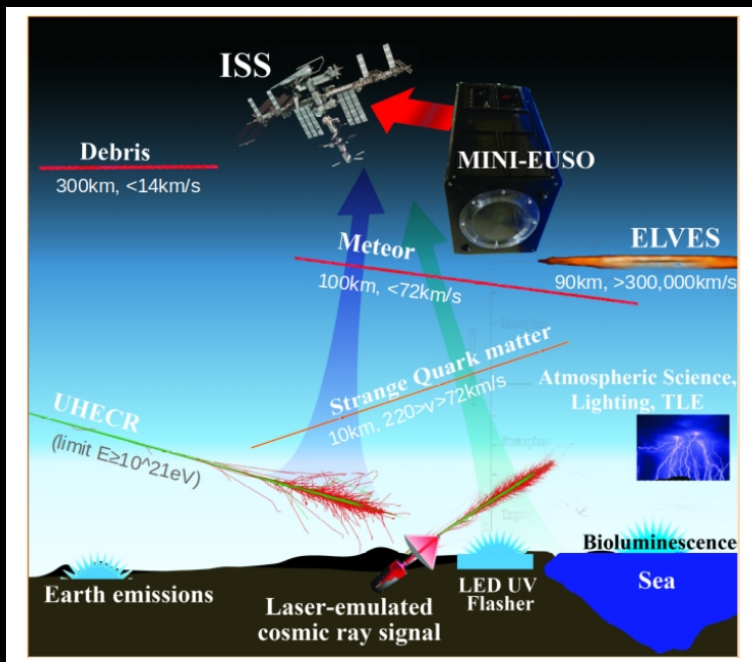


ISUAL (Imager for Sprites and Upper Atmospheric Lightning): first dedicated mission

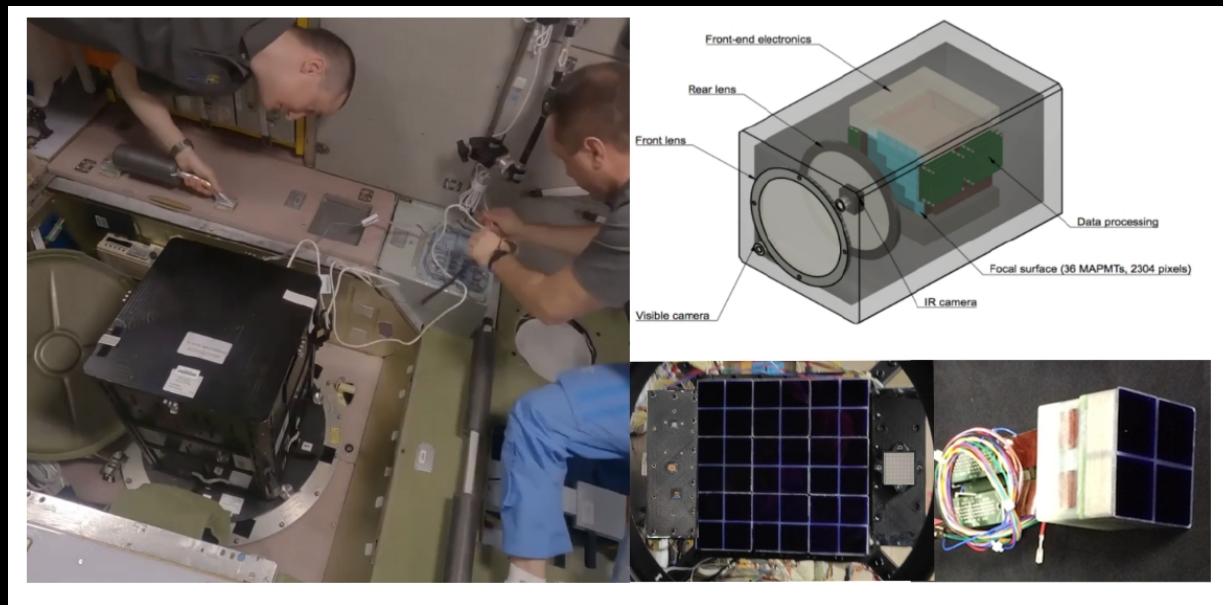
ELVES and the Mini-EUSO experiment

Mini-EUSO (Multiwavelength Imaging New Instrument for the Extreme Universe Space Observatory) experiment is part of the **JEM-EUSO program** (Joint Exploratory Missions for an Extreme Universe Space Observatory) – L. Marcelli for the JEM-EUSO Coll., <https://pos.sissa.it/444/001/>

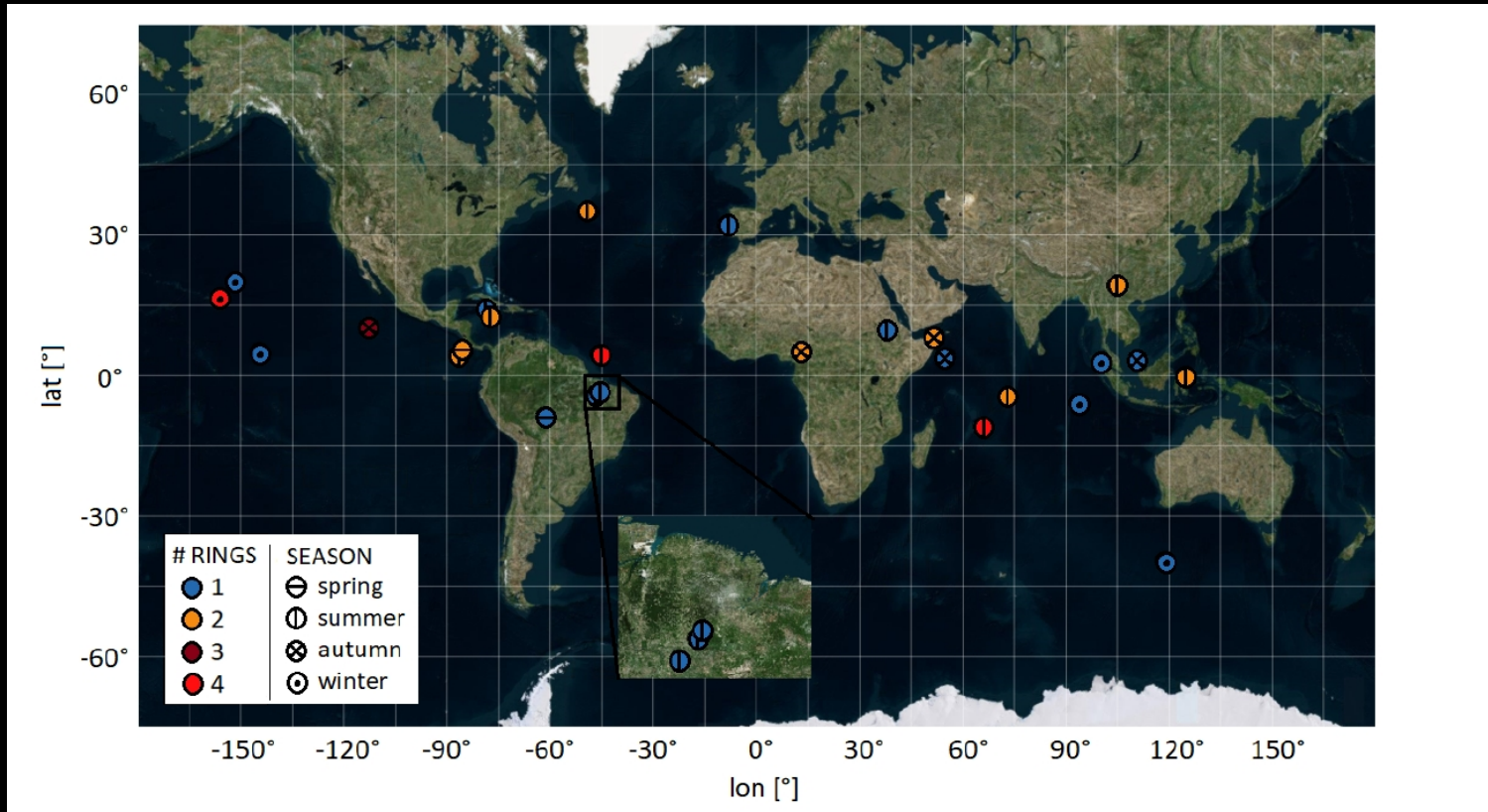
Mini-EUSO
main scientific goals



Mini-EUSO installed inside the ISS on the nadir-facing UV-transparent window of the Zvezda module and a schematic view of the instrument

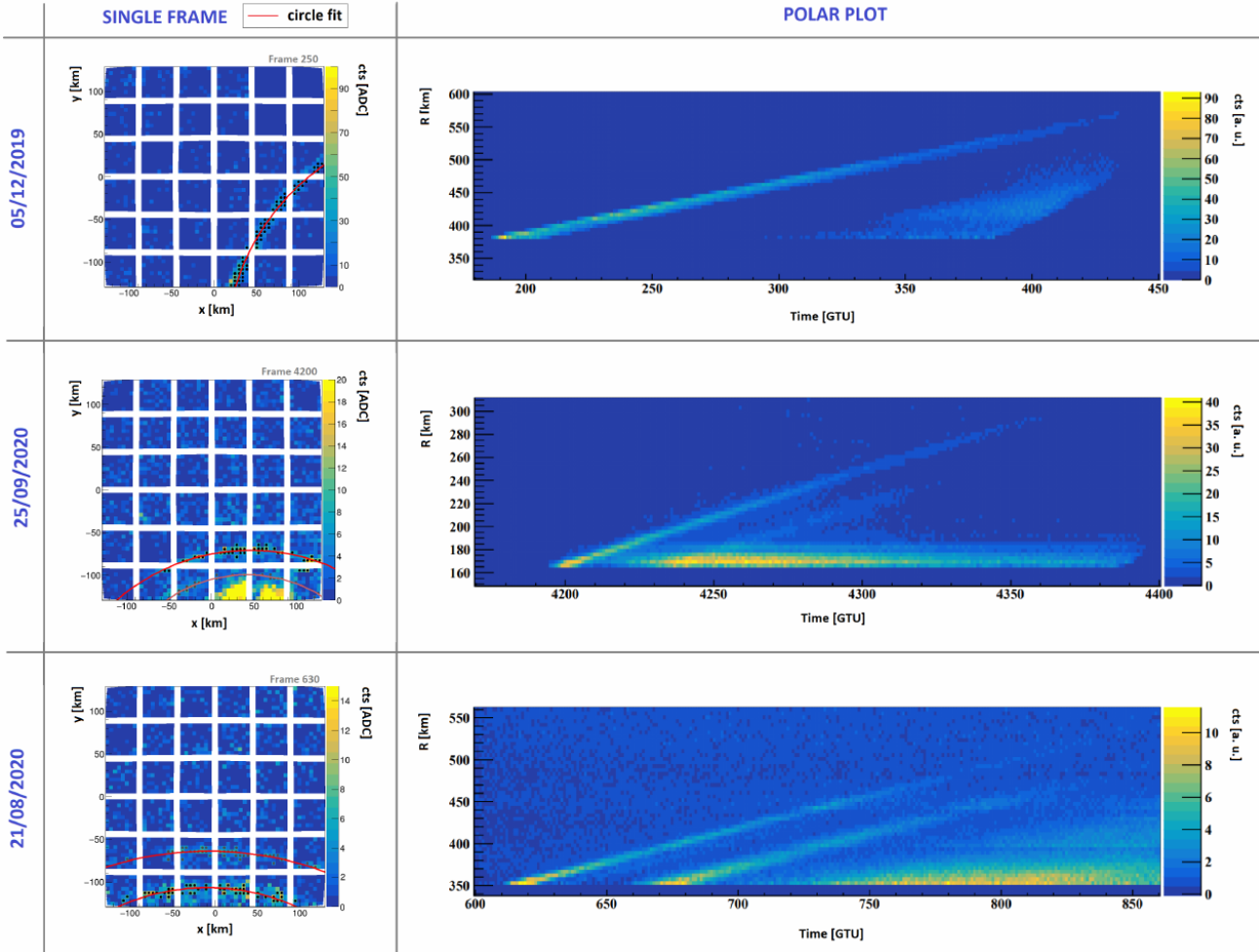


ELVES detected by Mini-EUSO



Most of them are distributed in the equatorial region

ELVES detected by Mini-EUSO

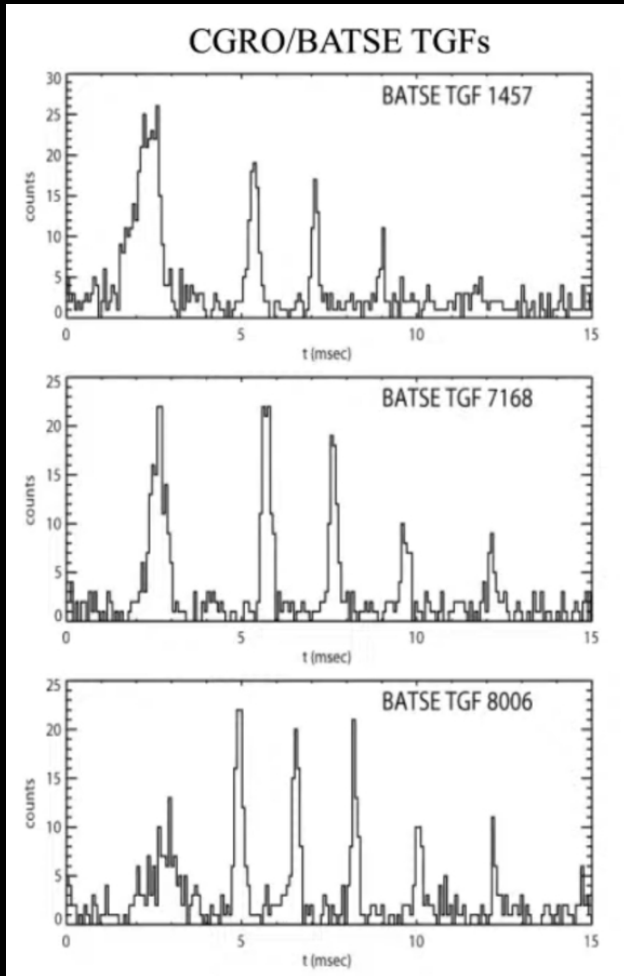


Single-ringed event

Double-ringed event with a halo concurrent with ELVES

Double-ringed event with a halo following the ELVES

Multi-pulsed TGFs



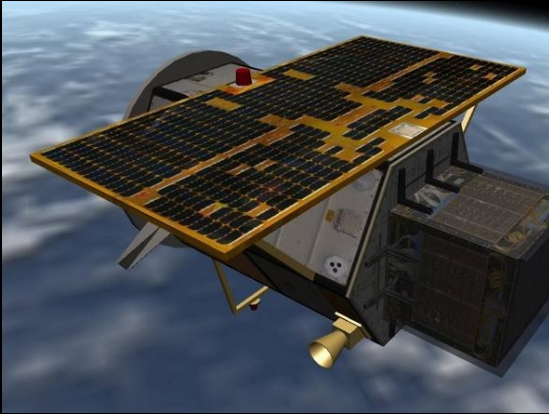
Most of the many TGFs seen from space and the few observed within Earth's atmosphere consist of a single pulse with a duration of some tens of μs .

A small fraction have two pulses, and an even smaller fraction have three or more with a total duration sometimes reaching several ms.

→ For the lightning leader model, multi-pulsed TGFs may potentially be associated with the step wise propagation of the upward negative leaders.

→ For the relativistic feedback discharge model, multi-pulsed TGFs naturally occur as the discharge oscillates above and below the feedback threshold.

AGILE (April 23, 2007)



- The AGILE MiniCALorimeter (MCAL), an all-sky monitor, sensitive in the range 0.4–100 MeV, detected a total of 2210 TGFs in 8 years activity.
 - The largest fraction of these events (1711 TGFs) has been detected from 23 March 2015 to 27 November 2017 thanks to a new onboard trigger configuration, that enhanced the TGF detection rate up to more than 50 TGFs/month.
-
- These new TGF sample shows geographic and energetic distributions compatible with the sample acquired in the previous MCAL configuration, but a substantially different time duration distribution: the new configuration increased the detection capabilities of MCAL for shorter duration events, allowing to reveal **events with duration down to tens of μs** .
 - Moreover, the new sample includes **a large number of multiple TGFs**, with tens of events detected either at the same orbital passage or at successive overpasses over the same active storm.

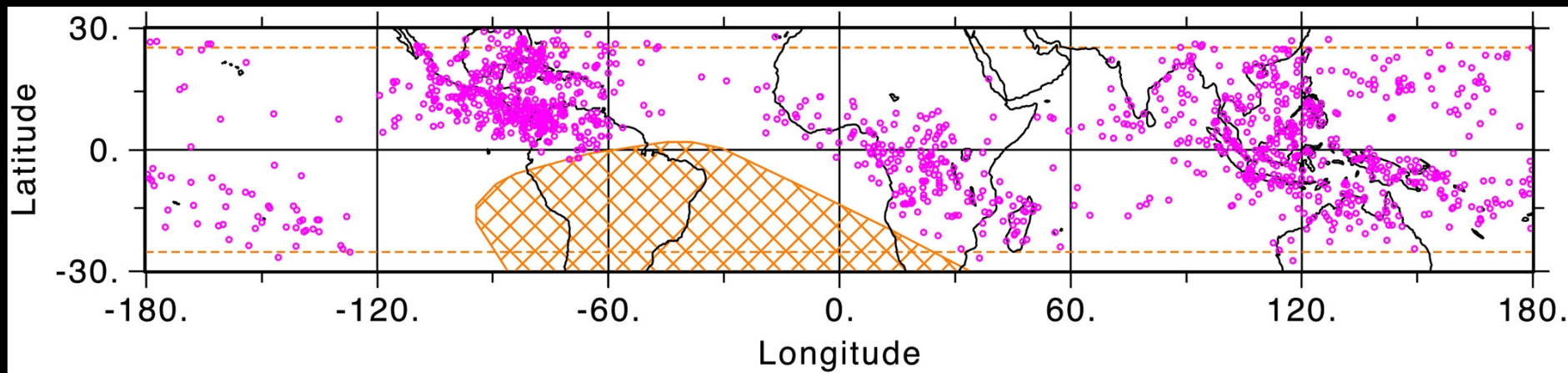


FERMI

Both instruments on Fermi - the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT) have detected TGFs.

The 1st GBM TGF catalog: contains 4144 TGFs detected between 2008 July 11 and 2016 July 31

- TGFs bright enough to trigger on board
- TGFs recovered in an offline search for weaker events (>80%).
- It also includes an associations table containing results for 1544 TGFs for which temporally-coincident radio signals of the World Wide Lightning Network (WWLLN) were found. These associations provide **accurate localizations of the TGFs**. (<https://doi.org/10.1029/2017JA024837>)





FERMI & TBE observations

Terrestrial Electron Beam (TEB): secondary electrons and positrons that are produced from Compton scattering and pair production interactions of gamma rays, typically at altitudes greater than 30 km. They travel along local geomagnetic field lines in helical trajectories .

Simulations show that the majority of the electrons are bound to a 10 km radius (Dwyer et al., 2008), and thus TEBs are expected to be observed at 2% of the rate of TGFs

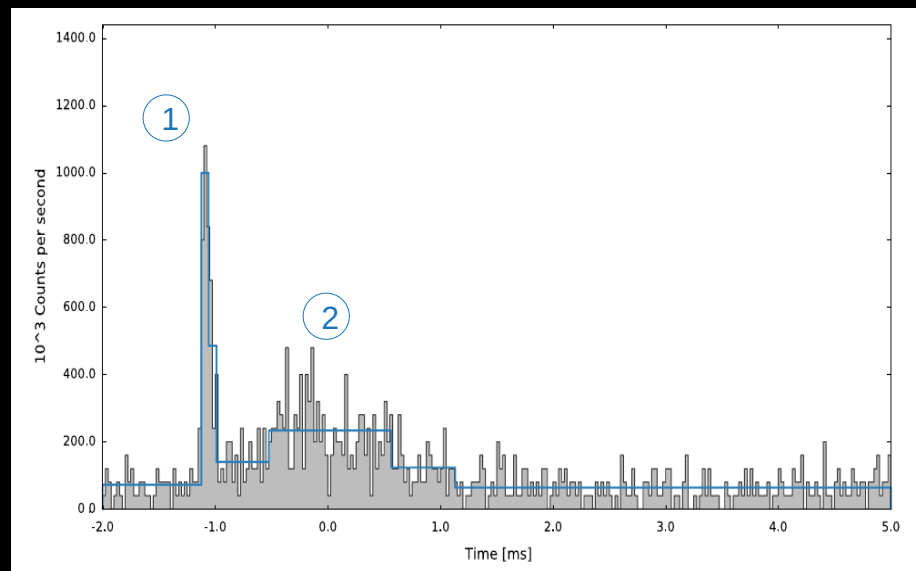
→ from Fermi's TGF catalog, GBM observed 20 reliably classified TEBs and 10 likely TEBs → ~ 3% of triggered TGFs are TEBs.

Fermi GBM event 140204581 is the first direct confirmation of this association between TGFs and TEBs
DOI:10.1029/2019JA026749

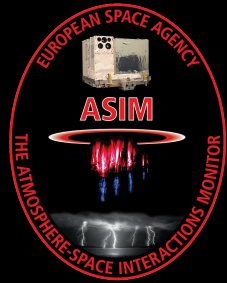
→ an initial pulse, which occurred 1 ms before the Fermi GBM trigger time, has a typical TGF structure with a 0.2 ms duration;

→ a second pulse, occurred shortly after and with a 1.2 ms duration, shows all characteristics of a TEB including a strong 511 keV line (these events not only consist of energetic electrons but are made up of 10% to 35% of positrons);

→ a third pulse, known as the mirror pulse of the TEB, is found at 89.6 ms from trigger time.



ASIM on the ISS



ASIM is the first space mission designed for simultaneous observations of Transient Luminous Events, TGFs, and optical lightning.

First 10 Month of TGF Observations by ASIM (DOI:10.1029/2019JD031214):

1. simultaneous TGFs observations by ASIM MXGS and Fermi GBM;
2. TGFs and Elves are seen from the same lightning flash;
3. the first imaging of TGFs;
4. the sequence of TGFs and optical signals.

From these findings we can summarize the following:

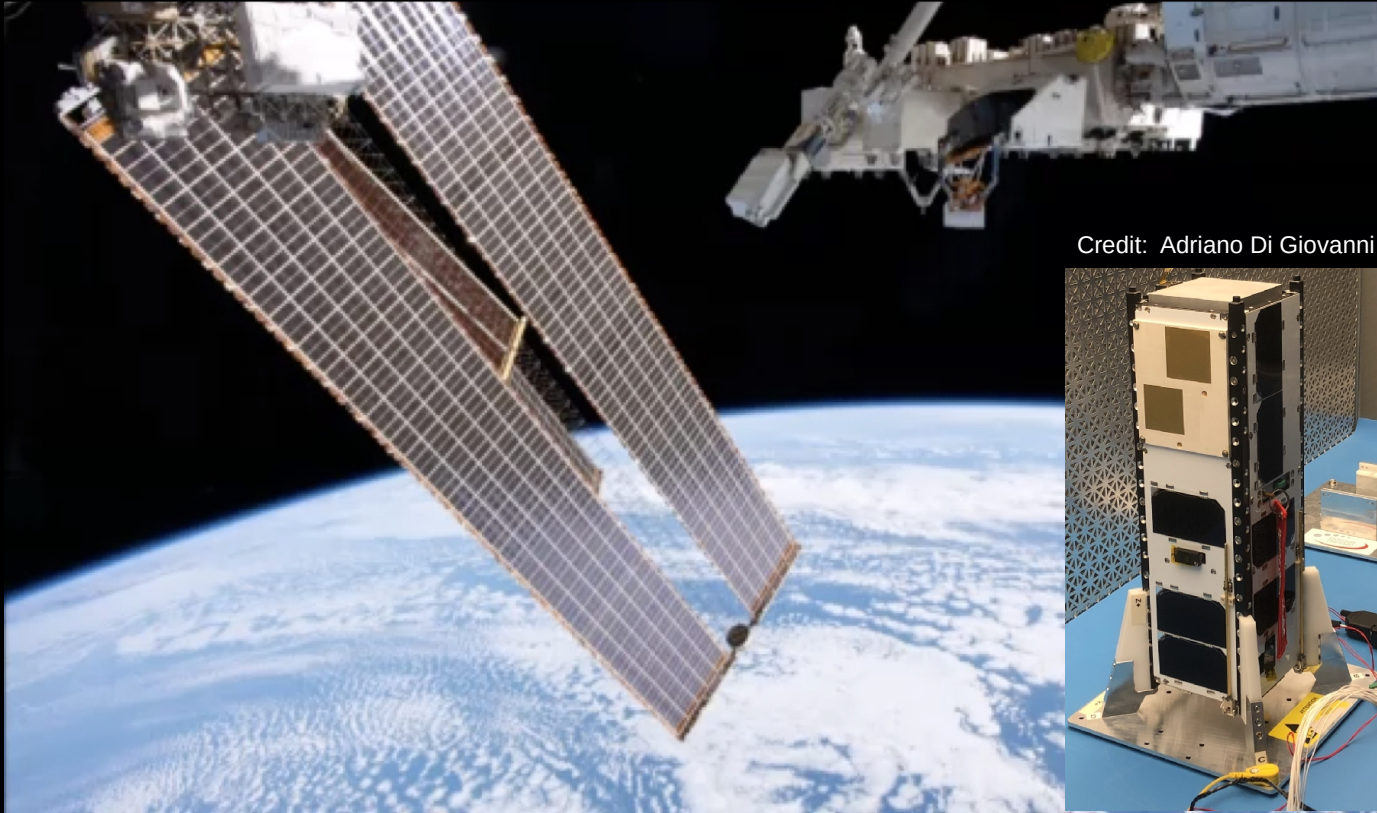
1. The distribution of duration has a maximum in the 20-40 μs range and a median of 45.5 μs , which is significantly shorter than previously reported from space observations.
2. Due to the very good detection capability of ASIM, we have identified fine structures in TGFs that cannot be seen by other missions that currently observe TGFs.
3. From 94 events where both gamma ray and optical measurements were available and with a relative timing accuracy of $\pm 80 \mu\text{s}$ it is found that a majority of TGFs are produced during the upward propagation of a leader just before a large current pulse heats up the channel and emits a strong optical pulse. The onset of the TGFs precedes the onset of the optical pulse by 0–320 μs ($\pm 80 \mu\text{s}$).

More observations are needed to understand the system of conductive channels that are involved in order to make such a strong current pulse.

Science 367 (6474), 183-186. DOI: 10.1126/science.aax3872

→ October 10, 2018, observation of a TGF and an associated elve using ASIM

LIGHT-1



Credit: Adriano Di Giovanni

A CubeSat for the detection of X- and gamma-ray components of a TGF event

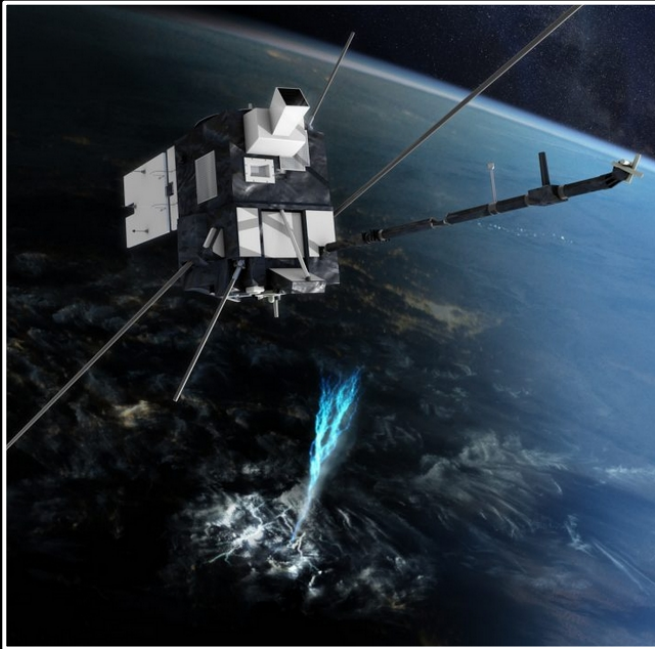
→ an instrument capable of providing **time** (in the order of hundreds of microseconds) **and spectroscopic** (from several tens of keVs up to tens of MeV) **measurements**.

Deployment from ISS on 2022-02-03

TARANIS 2

(Tool for the Analysis of RAdiation from lightNING and Sprites)

The goal is to launch TARANIS in 2025!



TLEs and TGFs observations

Locate geographical positions and altitudes of TLEs and TGFs source regions Model variations with LT, season, activity indices, etc.

Environmental conditions

Identify parent lightning flashes and associated EM emissions Investigate possible correlations with cosmic rays, micrometeorites, volcanoes, etc.

Transfers of energy between the radiation belts, the ionosphere and the atmosphere

Detect and characterize burst of precipitated electrons (LEPs) and of accelerated electrons (RBs)

TLEs and TGFs generation mechanisms

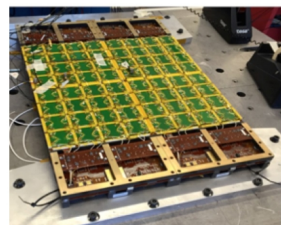
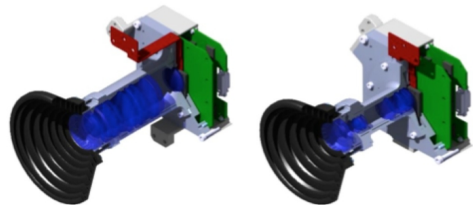
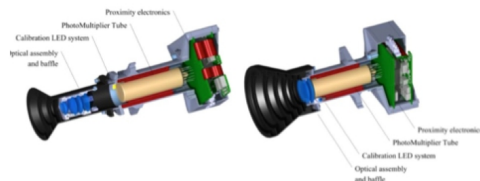
Provide input data (TLEs and TGFs source regions, association with lightning activities and other environmental parameters like EAS, bursts of precipitated and accelerated electrons) to test generation mechanisms

Contribution to the modelling of the effects on the atmosphere and on the global electric circuit

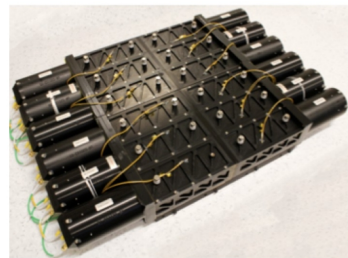
Provide information on sources of energy (TLEs, TGFs, bursts of precipitated and accelerated electrons) or/and on large scale ionospheric perturbations

ASIM mission on ISS

- **MMIA**
(running at night)



- **MXGS**
(LED running at night)
(HED running 24/7)
* OFF above SAA



Three photometers

- PHOT 1: 337.0 nm/5 nm (TLE and lightning/streamers)
- PHOT 2: 180-230 nm (mostly TLE)
- PHOT 3: 777.4 nm/5 nm (mostly lightning/leaders)
- 100 kHz sampling (photon counting)

Two cameras

- 12 frames/s
- 60° x 60° FOV (80° diagonal)
- ~400 m spatial resolution (1000x1000 pixels)
- CHU 1: 337.0 nm/5 nm (TLE/lightning)
- CHU 2: 777.2 nm/5 nm (mostly lightning)
- CCD with on-chip amplification (no intensifier)

Low-Energy Detector (LED) 15-400 keV

- Characterizes the low-energy spectrum (individual TGFs)
- Estimates the direction to the TGF source.
- CZT pixelated detector (16384 pixels) $A_{\text{geom}} 1024 \text{ cm}^2$

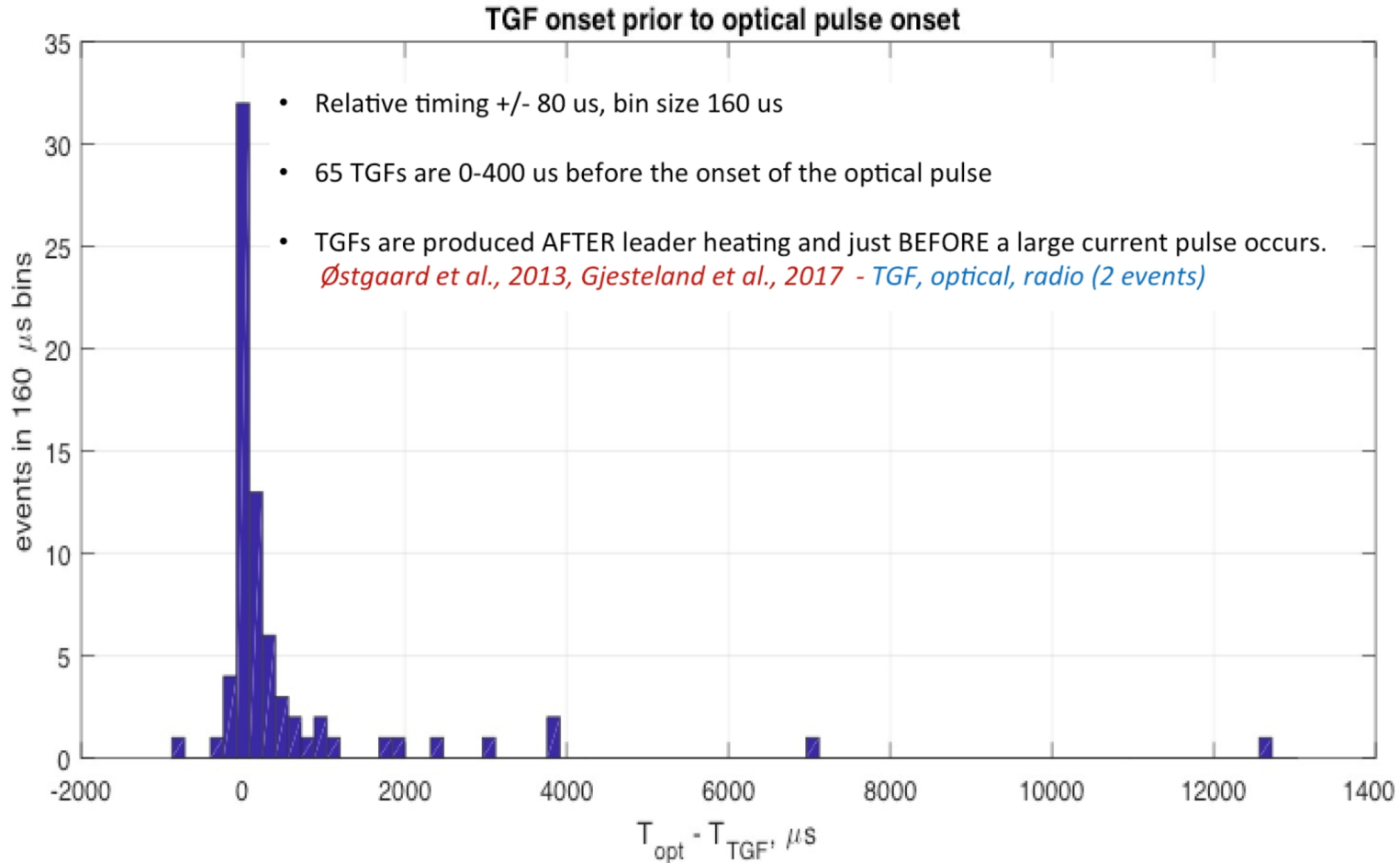
High-Energy Detector (HED) 0.4-40 MeV

- Primary TGF detector
- Characterizes the TGF high-energy spectrum
- BGO crystals $A_{\text{geom}} 900 \text{ cm}^2$

Hard X-ray imaging system

- Coded mask: (4x4)x4 Perfect Binary Array
- Pixel size: 4.6 cm x 4.6 cm Tungsten 1mm thick
- Angular resolution (point source, stronger events) $< 0.7^\circ$

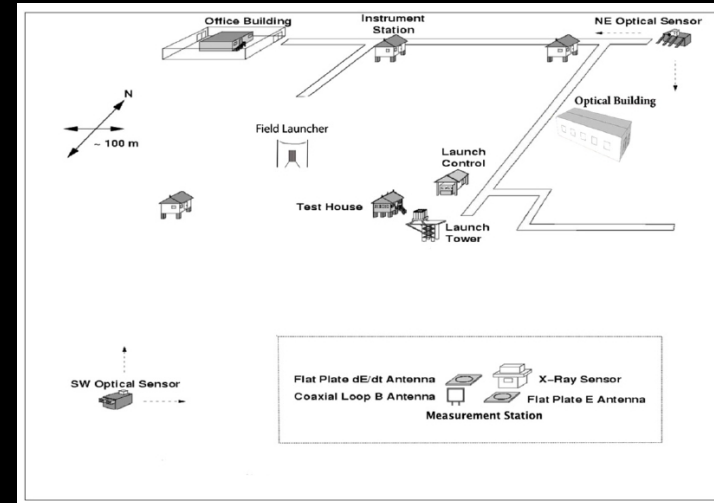
TGF/Optical correlated observations: 74(out of 94 events)



TGFs from ground

First observation of TGFs from ground

→ TGF associated with a 2003 classically triggered lightning flash at the International Center for Lightning Research and Testing (ICLRT) in North Central Florida - doi:10.1029/2003GL018771



→ in 2009, a second TGF followed a return stroke in a natural cloud-to-ground flash was detected at the same facility – doi:10.1029/2012JA017810

→ in 2014, another TGF was associated with a negative single-stroke flash. According to the NLDN (National Lightning Detection Network), it terminated at a distance of 7.5 km from the LOG (Lightning Observatory in Gainesville – Florida) – doi:10.1016/j.jastp.2015.10.010

In all cases, NaI/PMT detectors were used.



The ALOFT campaign is a unique suborbital campaign to advance the science of high-energy radiation emissions from thunderstorms.

ALOFT is a collaboration between NASA and the University of Bergen that will fly the ER-2 aircraft over tropical thunderstorms around the Gulf of Mexico, Central America, and the Caribbean.

The payload consists of lightning detectors, gamma-ray scintillators, and a mixture of passive and/or active microwave sensors. Supporting the flights there were a diverse ground-based network of lightning instruments spread across the region of interest.

Evidence of a new class of TGFs?

Stay tuned!!!

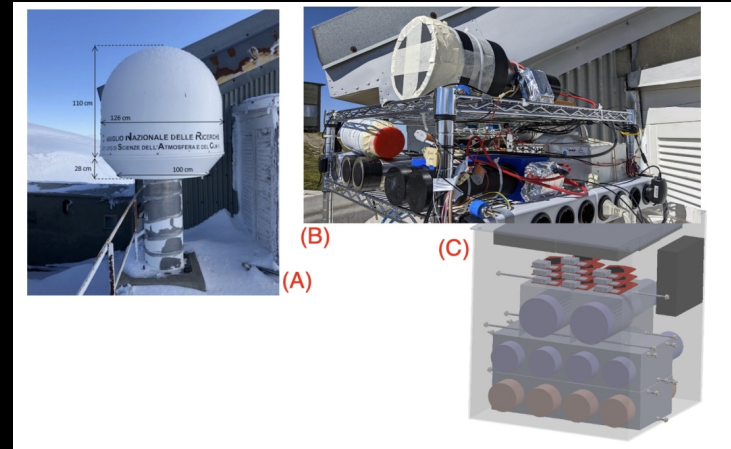
Gamma-Flash:

an Italian program devoted to the investigation of radiation and particles produced during lightning and thunderstorms

Funded by the Italian Space Agency (ASI) and led by the National Institute for Astrophysics (INAF). The program led to the development of two main detection systems: a **ground-based system**, installed at the “O. Vittori” Observatory on top of Mt. Cimone (Northern-Central Italy), and an **airborne payload**, installed on a Cessna CITATION Mustang aircraft, for in-flight campaigns.

The ground-based detection system consists of five γ -ray and three neutron detectors, and has been collecting data from Jul 2022 to Oct 2023, overall experiencing 95 days of thunderstorm activity (36% of the total). During this first observational survey, a gamma-ray glow of 1.5 min was revealed.

The avionic payload consists of 6 γ -ray and 2 neutron detectors. Up to now, only a first test flight with clear sky was performed, in December 2023. Further flights are planned to be conducted in June-September 2024.



Variations in cosmic-ray flux at the ground

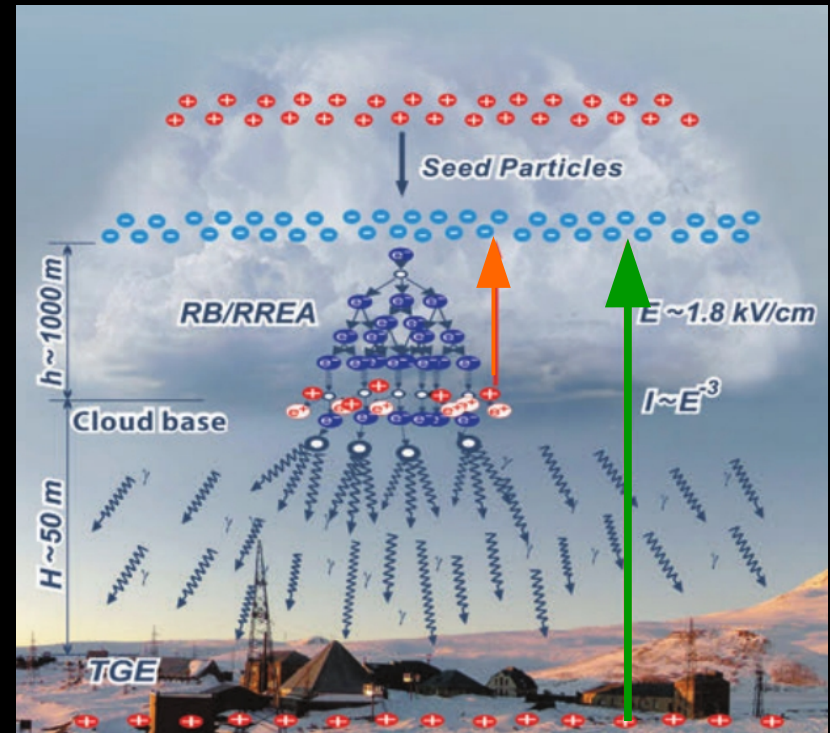
For decades, several high-altitude experiments have reported (Baksan Carpet array, EAS-TOP, Tibet AS- γ , ASEC, ARGO-YBJ, SEVAN at Lomnický štít, a network of thermal neutron detectors and detectors on Mount Norikura, and Mount Fuji), at lower energies than those accessible to the Auger Observatory, cosmic-ray flux variations associated to thunderstorms, concerning different shower components, namely electrons, gammas, muons, neutrons.

The number of particles in an extensive air shower, produced by the interaction of a primary cosmic ray with the atmosphere, can grow crossing the strong electric fields in thunderclouds.

Main field:

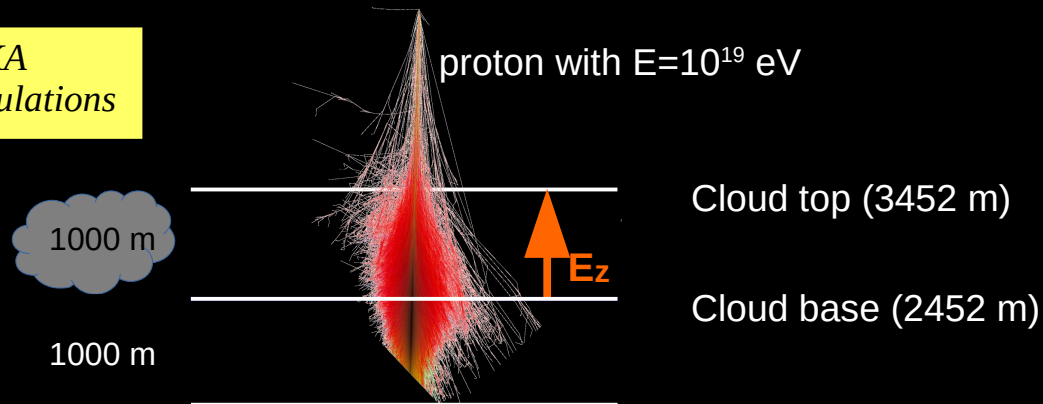
bottom dipole between the main negative charge layer and the positively charged region at the base of the cloud.

The main negative charge region induces a positive charge at the ground
→ the electric field between these two regions accelerates cosmic-ray electrons in the Earth's direction.

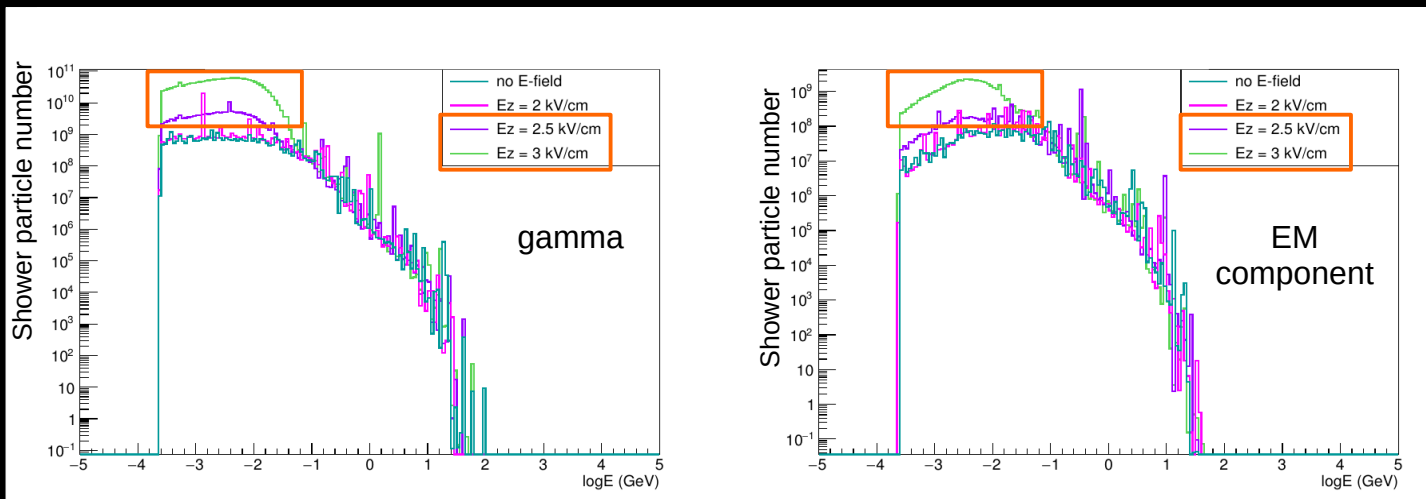


Variations @ Auger observation level

CORSIKA
MC Simulations



Gamma and e^+/e^- fluxes expected at the Pierre Auger Observatory altitude for different E-field strengths (different colors). The orange box highlights the particle enhancement.



The reconstructed energy of the primary cosmic ray, related to the number of particles in an extensive air shower, increases of almost one order of magnitude considering a proton of energy $E_p = 10^{19}$ eV and an electric field of 2.5 kV/cm.

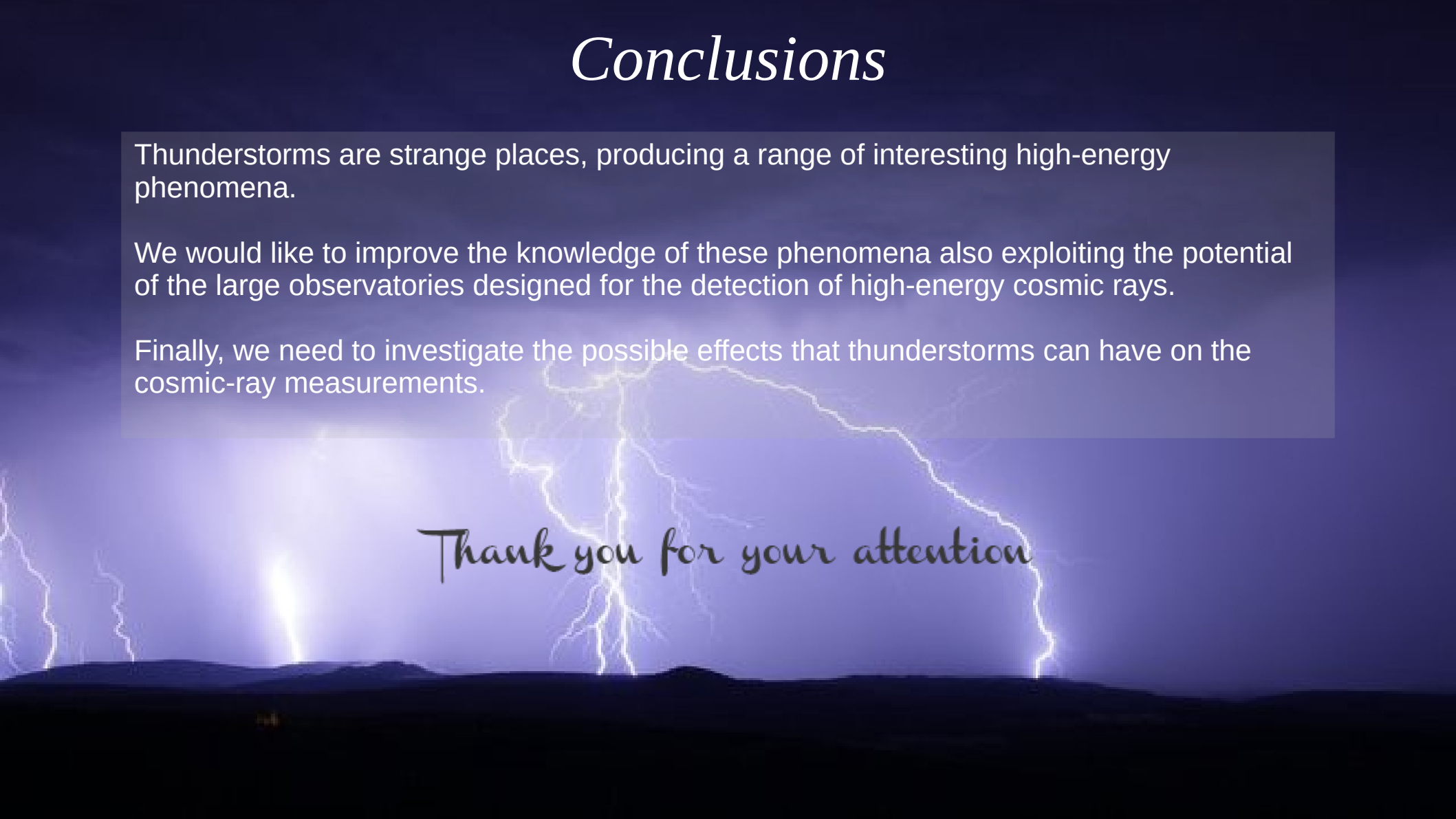
Conclusions

Thunderstorms are strange places, producing a range of interesting high-energy phenomena.

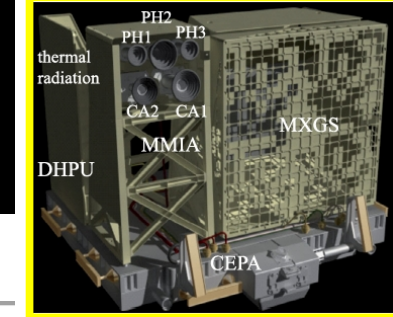
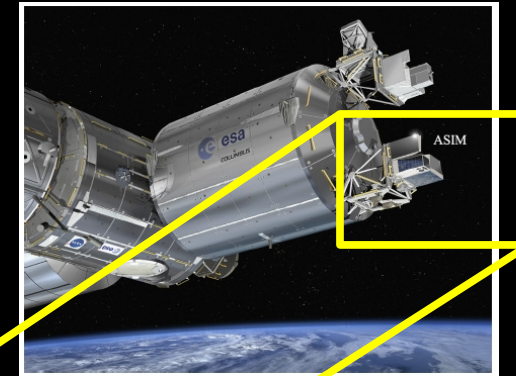
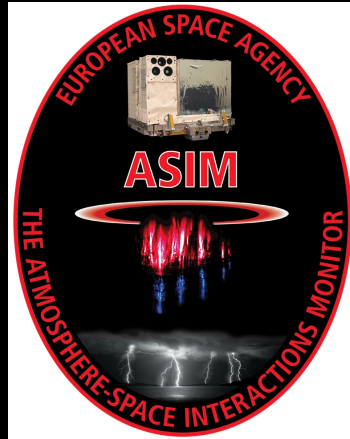
We would like to improve the knowledge of these phenomena also exploiting the potential of the large observatories designed for the detection of high-energy cosmic rays.

Finally, we need to investigate the possible effects that thunderstorms can have on the cosmic-ray measurements.

Thank you for your attention



ASIM: ELVES-TGF Correlation



Cite as: T. Neubert *et al.*, *Science* 10.1126/science.aax3872 (2019).

A terrestrial gamma-ray flash and ionospheric ultraviolet emissions powered by lightning

Torsten Neubert^{1*}, Nikolai Østgaard², Victor Reglero³, Olivier Chanrion¹, Matthias Heumesser¹, Krystallia Dimitriadou¹, Freddy Christiansen¹, Carl Budtz-Jørgensen¹, Irfan Kuvvetli¹, Ib Lundgaard Rasmussen¹, Andrey Mezentsev², Martino Marisaldi^{2,4}, Kjetil Ullaland², Georgi Genov², Shiming Yang², Pavlo Kochkin², Javier Navarro-Gonzalez³, Paul H. Connell³, Chris J. Eyles³

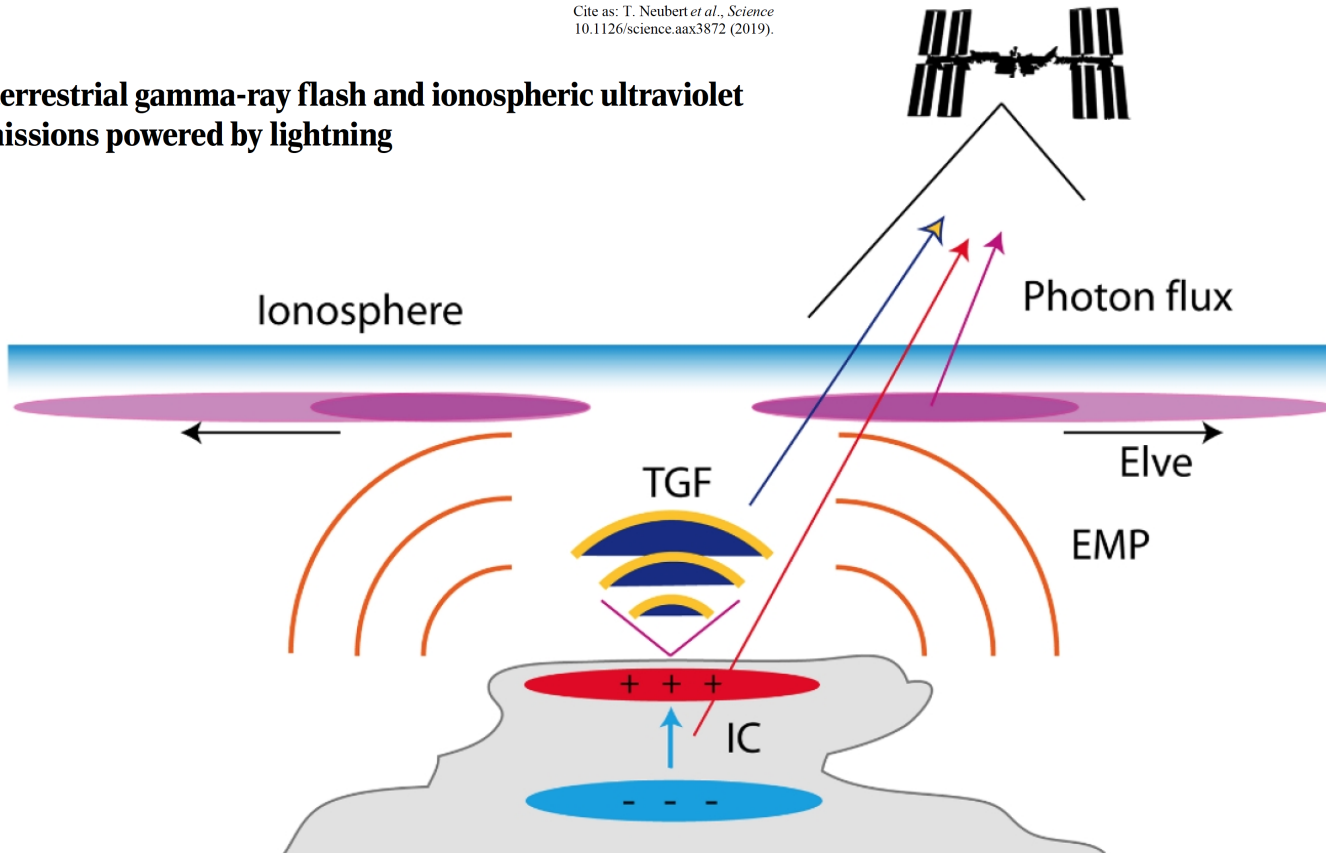
ELVES and TGFs

Science

REPORTS

Cite as: T. Neubert *et al.*, *Science*
10.1126/science.aax3872 (2019).

A terrestrial gamma-ray flash and ionospheric ultraviolet emissions powered by lightning



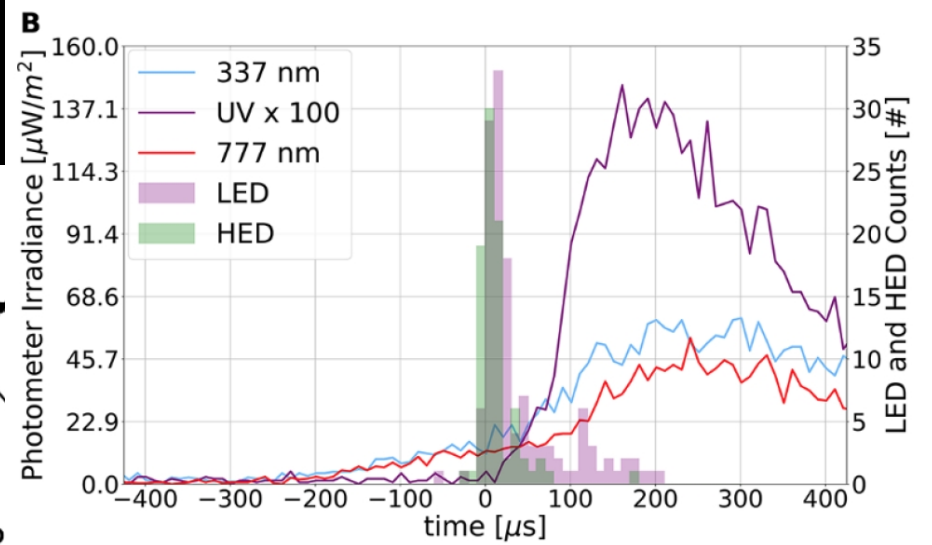
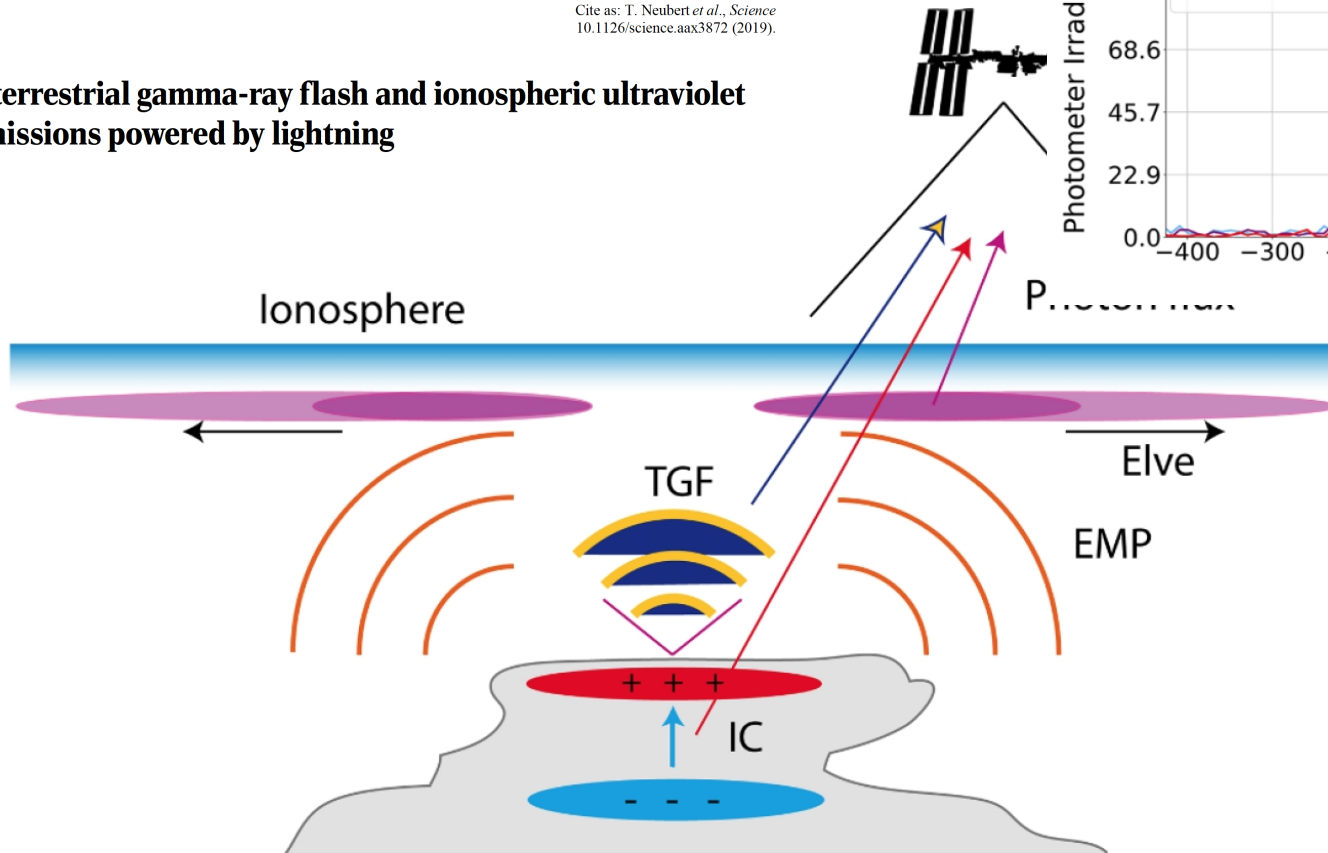
ELVES and TGFs

Science

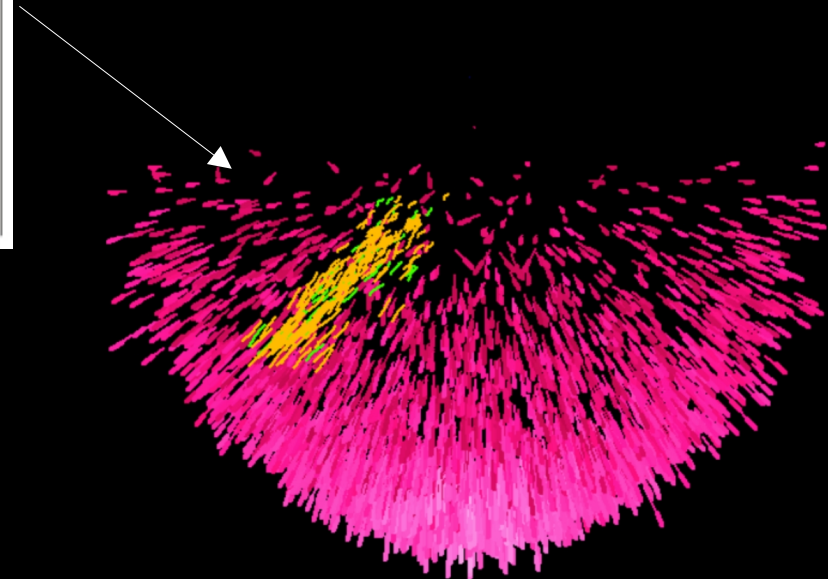
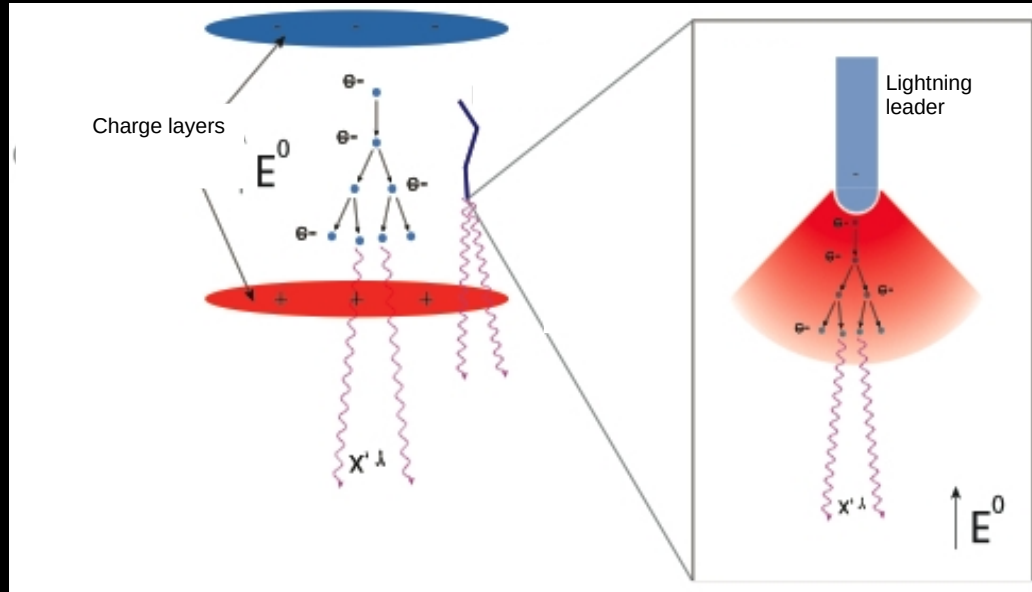
REPORTS

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A terrestrial gamma-ray flash and ionospheric ultraviolet emissions powered by lightning



Downward TGFs



TGFs Summary

- TGFs are the manifestation of the highest-energy natural particle accelerators on Earth
- They come from 10^{17} - 10^{19} high-energy electrons produced inside thunderstorms in a few tens of microseconds; Average energy of the high energy electrons is 7 MeV
- Role of the RREA process widely accepted, but difficult to explain very high energies ($E \sim 100$ MeV) \rightarrow relativistic feedback
- Acceleration sites correlated to IC lightning at 10-14 km altitude, possibly during leader formation
- Climatology studies show discrepancies with lightning distribution: possible sub-class of lightning?
- TGFs produce some of the largest radio pulses from the thunderstorm
- The rate of TGFs is estimated to be 500 per day worldwide (one for every thousand lightning events), but most go undetected, and this rate is uncertain. Recent estimates are higher.

