Atmospheric electricity with cosmic-ray detectors

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Outline

- What do we know about atmospheric electricity?
- What is the connection between astroparticle physics and high-energy atmospheric electricity?
- What are the Transient Luminous Events (TLE)?
- What are the Terrestrial Gamma-ray Flashes (TGFs)?
- The ELVES detection.
- The detection of TGFs from space.
- The detection of TGFs from ground
  → TGFs @ Telescope Array,
  → TGFs @ the Pierre Auger Observatory.
- The effects of atmospheric electricity on cosmic-ray measurements.

High-Energy Atmospheric Physics

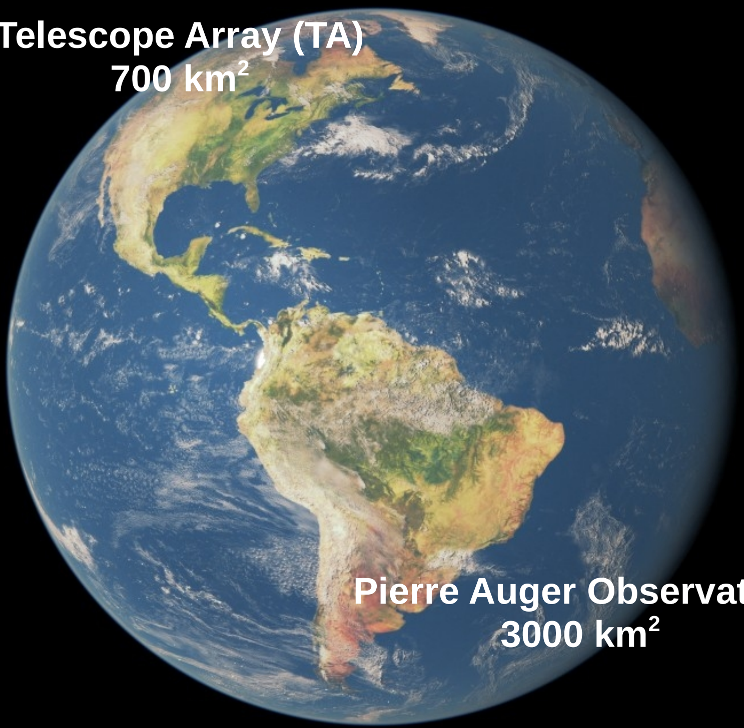
The atmosphere is never quite neutral due to
→ thunderstorms, which create lightning bolts to rapidly discharge huge amounts of atmospheric charge stored in thunderclouds
→ ionization from cosmic rays and natural radioactivity

Despite the ubiquity of thunderstorms,
that are the most energetic particles accelators on Earth,
lightning, and related electrical phenomena, and 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).

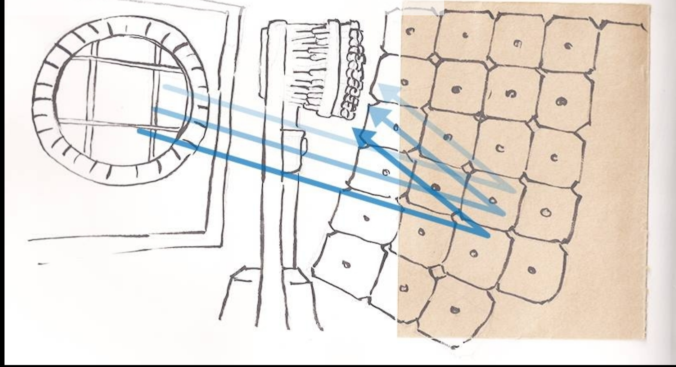
The High-Energy Atmospheric Physics & Cosmic Rays



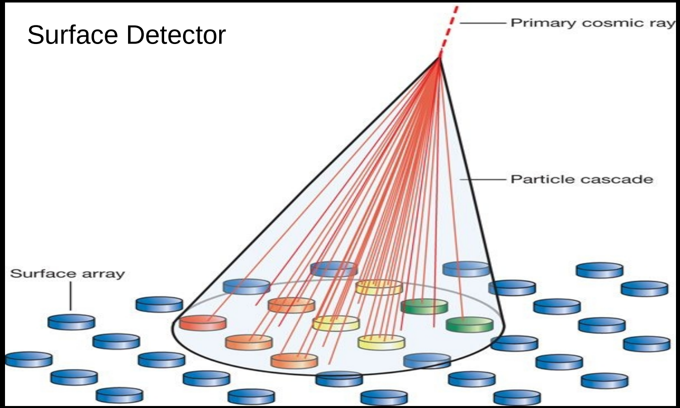
Telescope Array (TA)
700 km^2

Pierre Auger Observatory
3000 km^2

Fluorescence Detector



Surface Detector

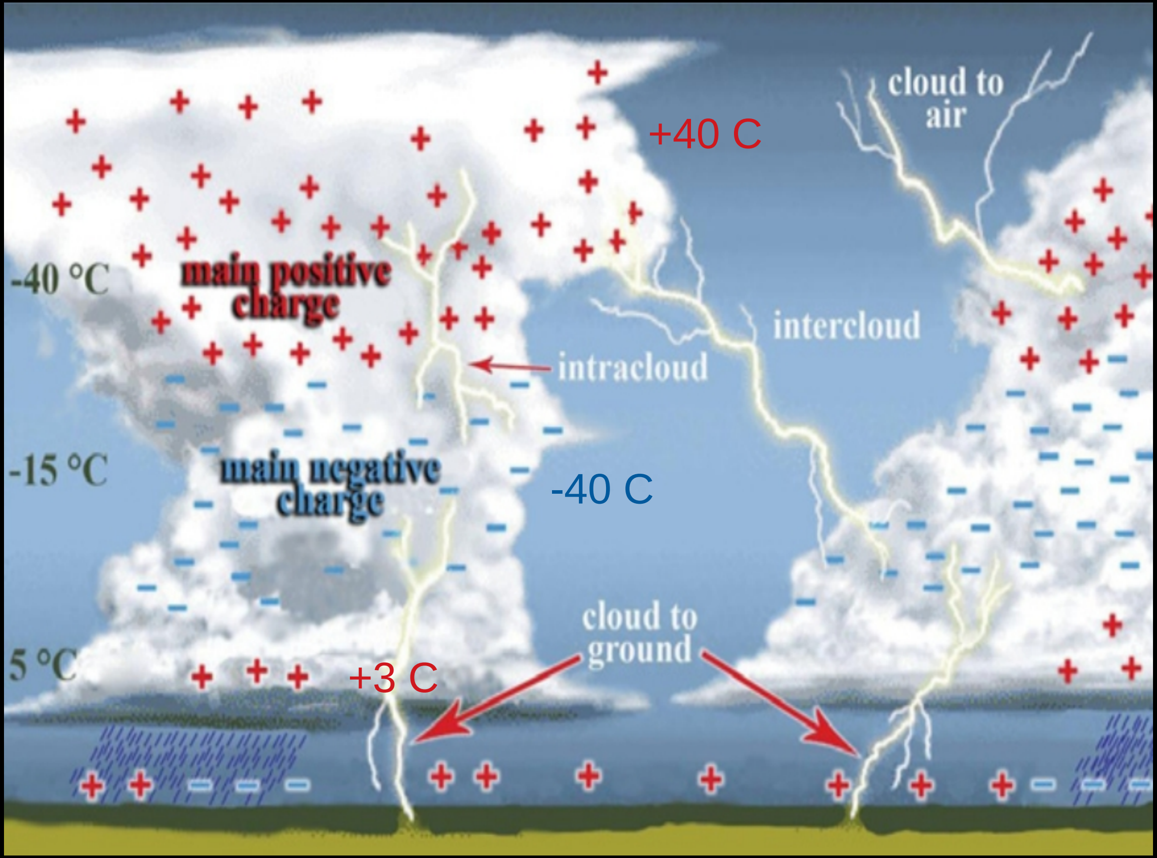


ELVES

TGF

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.

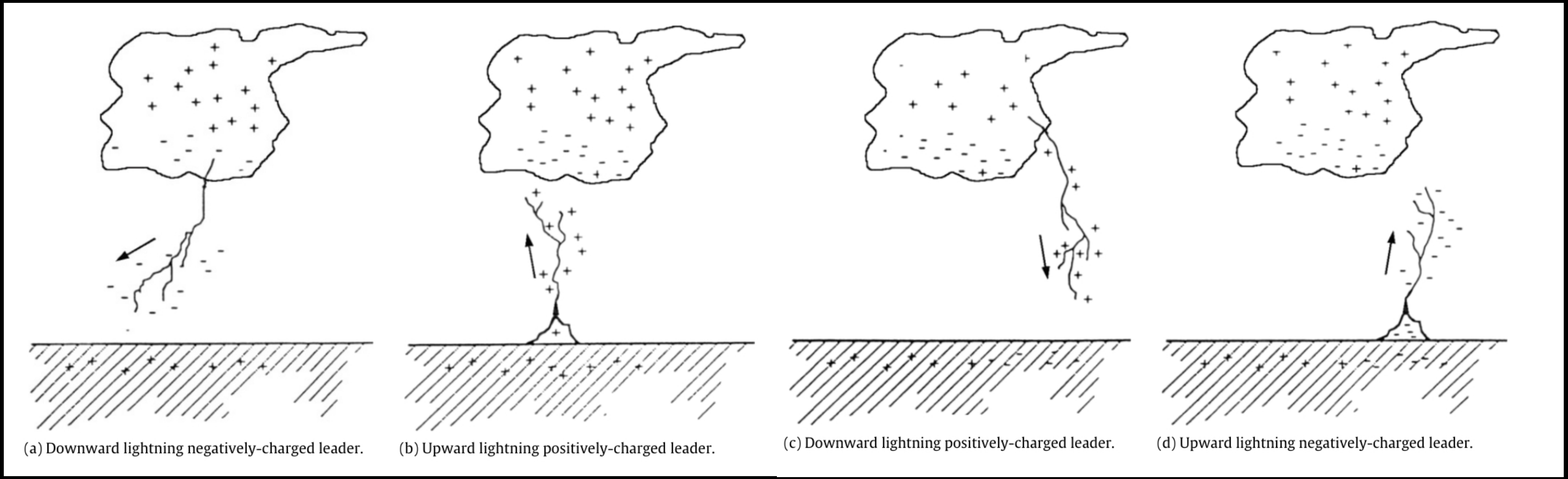
A typical small thunderstorm system produces a lightning flash to ground every 20–30 s for 40–60 min and covers an area of typically 100–300 km^2.

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?
→ ...

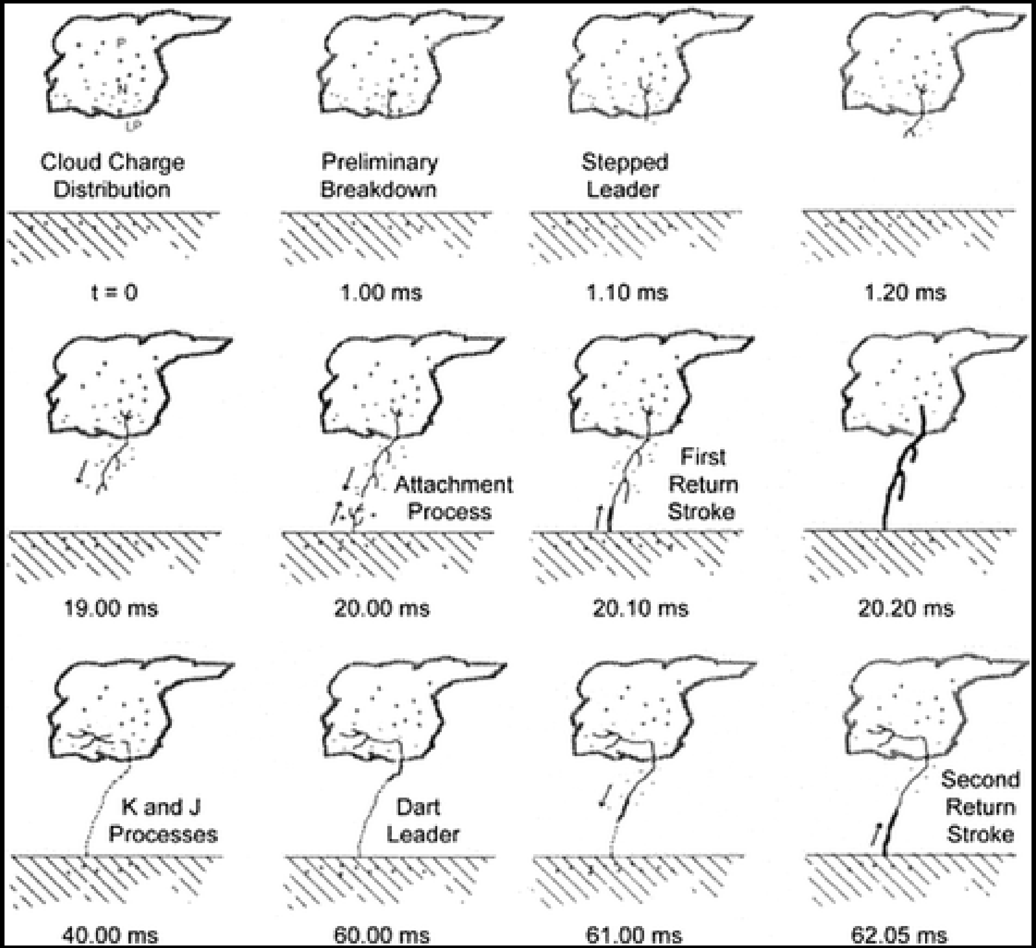
The Physics of Lightning

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



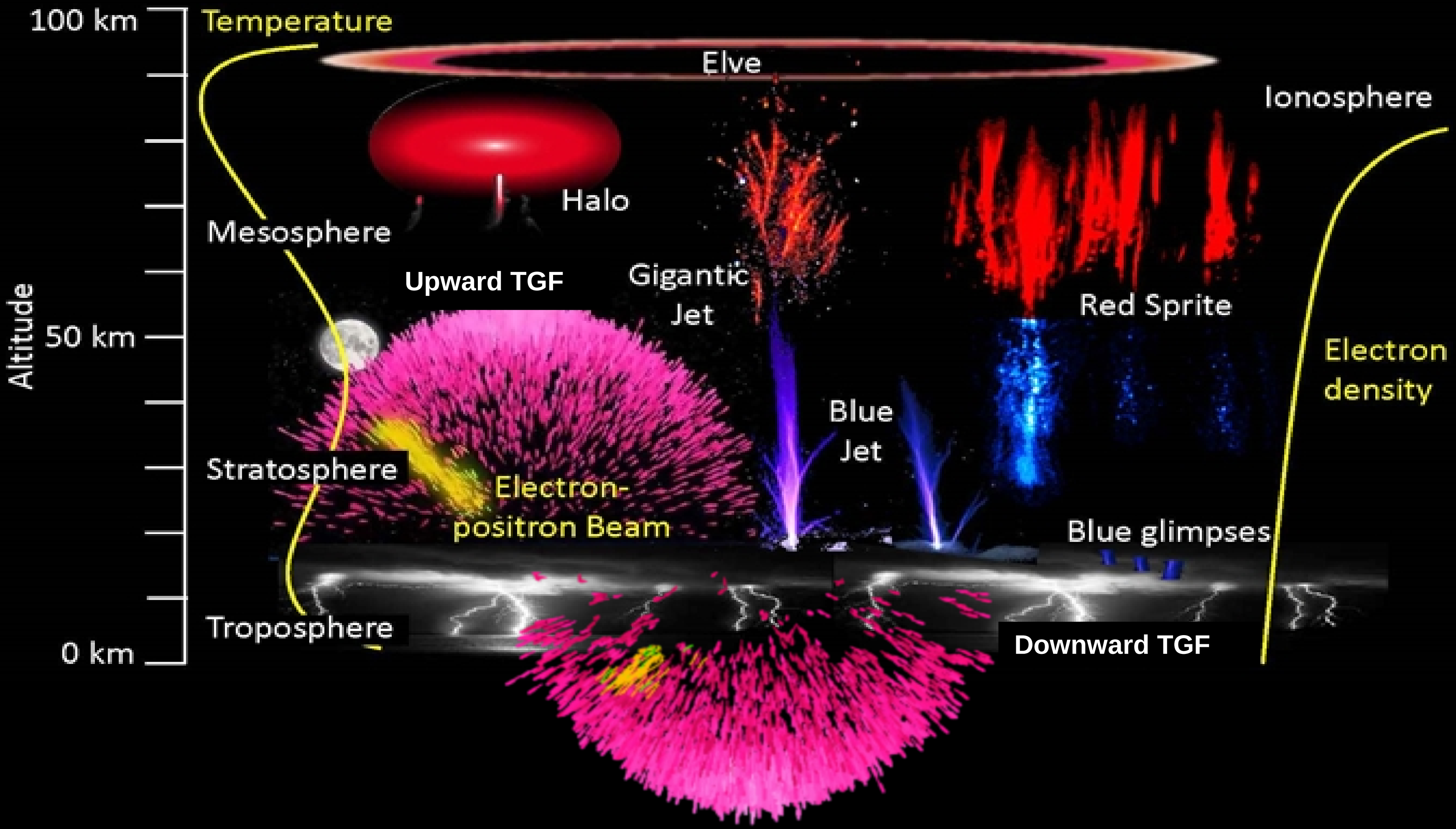
The physical mechanism for moving the negative charge to Earth is a propagating electrical discharge called the ‘‘stepped leader’’.

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.

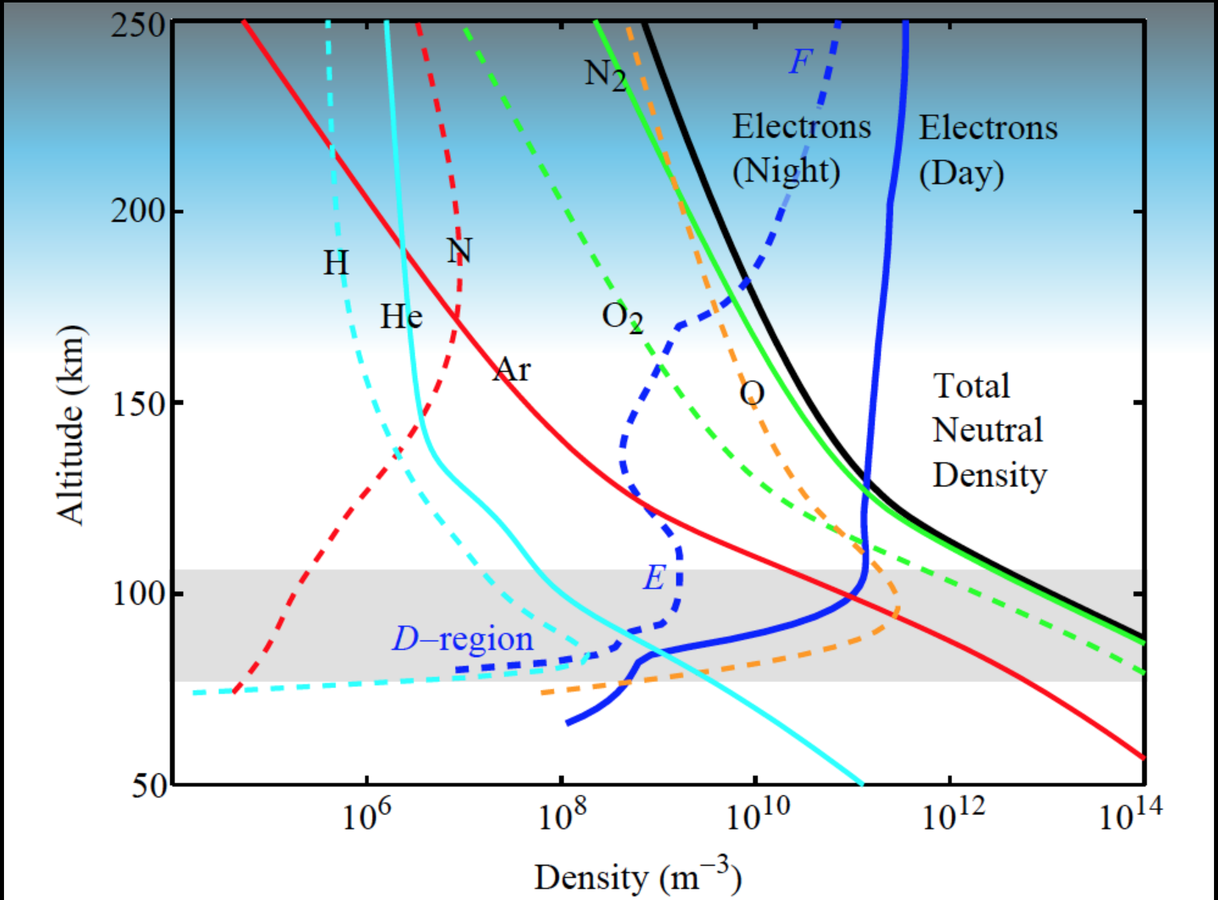
The last main step of the lightning development is the “return stroke” that happens after that the electric field intensity close to ground is large enough and an upward-going, positively-charged electrical discharges from the ground or from grounded objects is initiated.

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.

Bright events produced by lightning



Particle densities between mesosphere and ionosphere



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

This steep 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.

Red Sprites

Stratospheric/mesospheric Perturbations Resulting from Intense Thunderstorm Electrification

Their discovery was annunced 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

4 Luglio 2021, Piemonte, Italy
Exifs: Sony a7s1 – Nikkor 105mm/1.4@1.4 – 1 / 25s – ISO 30.000 – Atomos Registrator

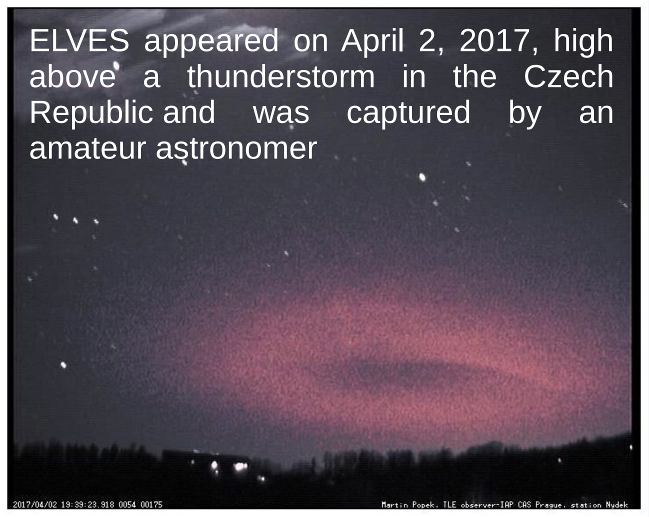
Blue jets

Time scale ~ 0.2-0.4 s   Length ~ 20-40 km Speed ~ 3 10^{-4} c

ELVES

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

ELVES and Red Sprites over Finland



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

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).

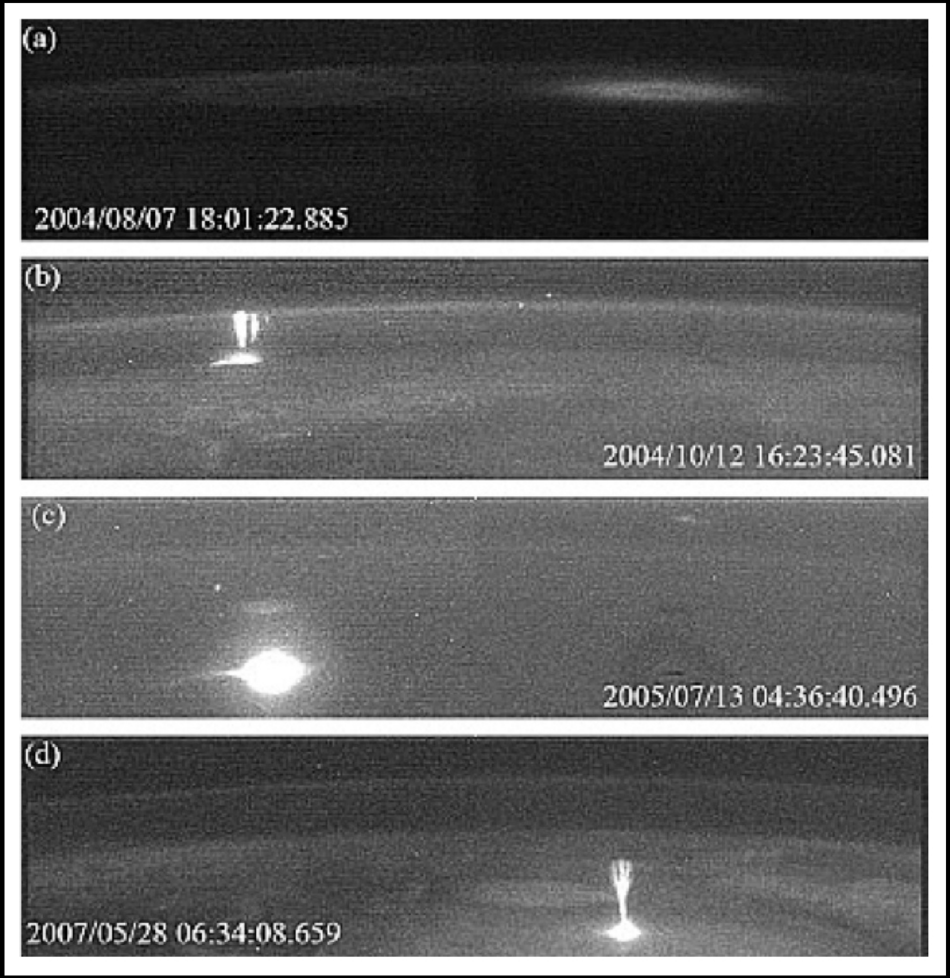
Elves were first detected from ground by Fukunishi et al. (1996) - https://doi.org/10.1029/96GL01979 - as diffuse optical flashes with a duration of < 1 ms occurring just after the onset of CG lightning.

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

They have a radius of more than 200 km and last less than a thousandth of a second.

Time scale ~ 1 ms   Diameter > 200 km   Speed > c !

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:

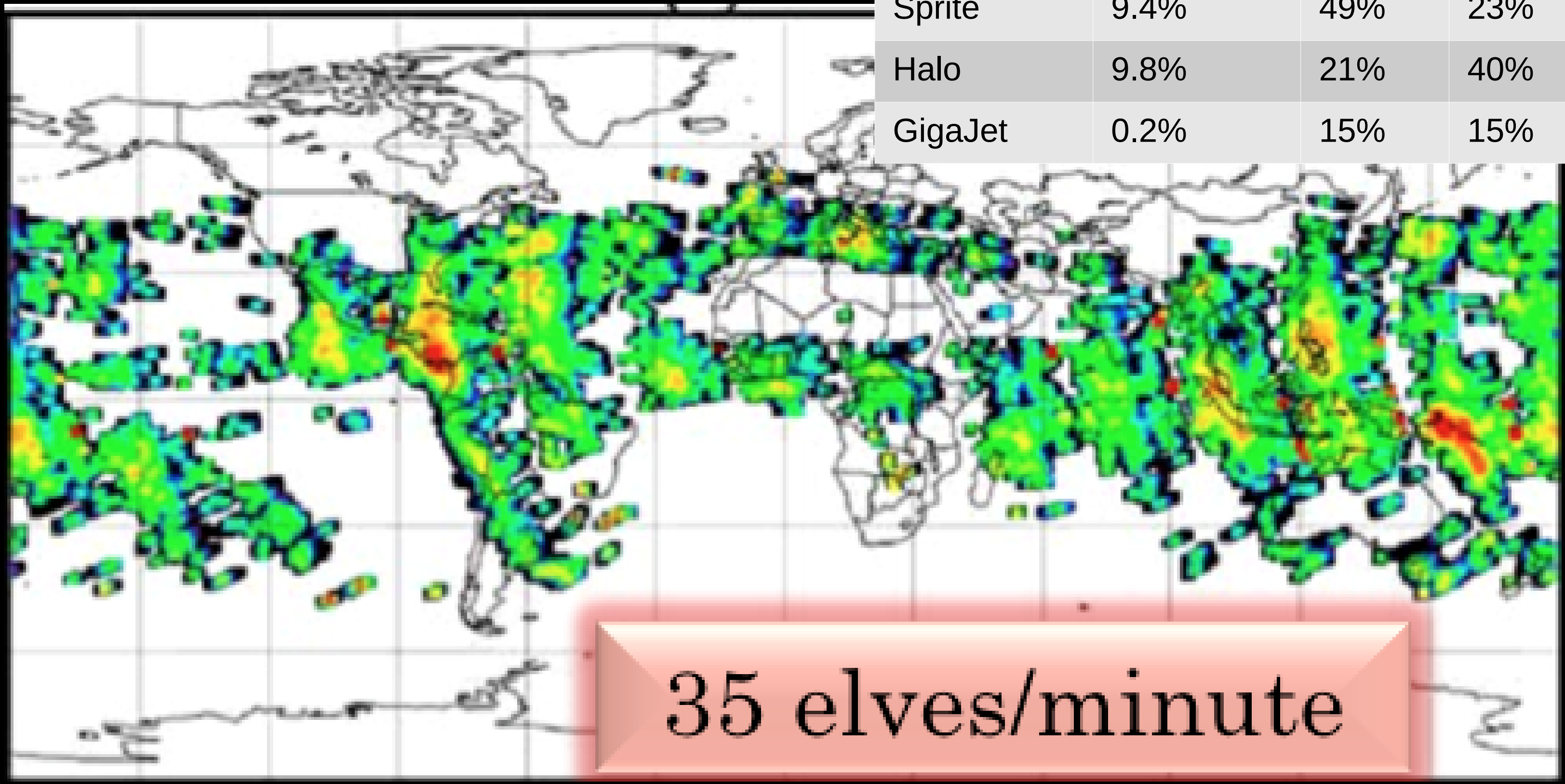
- ISUAL on board the FORMOSAT–2 satellite (2004 and 2016);
- JEM-GLIMS (2012 and 2015);
- ASIM (in operation since April 2018).

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

Frequency and location of TLEs

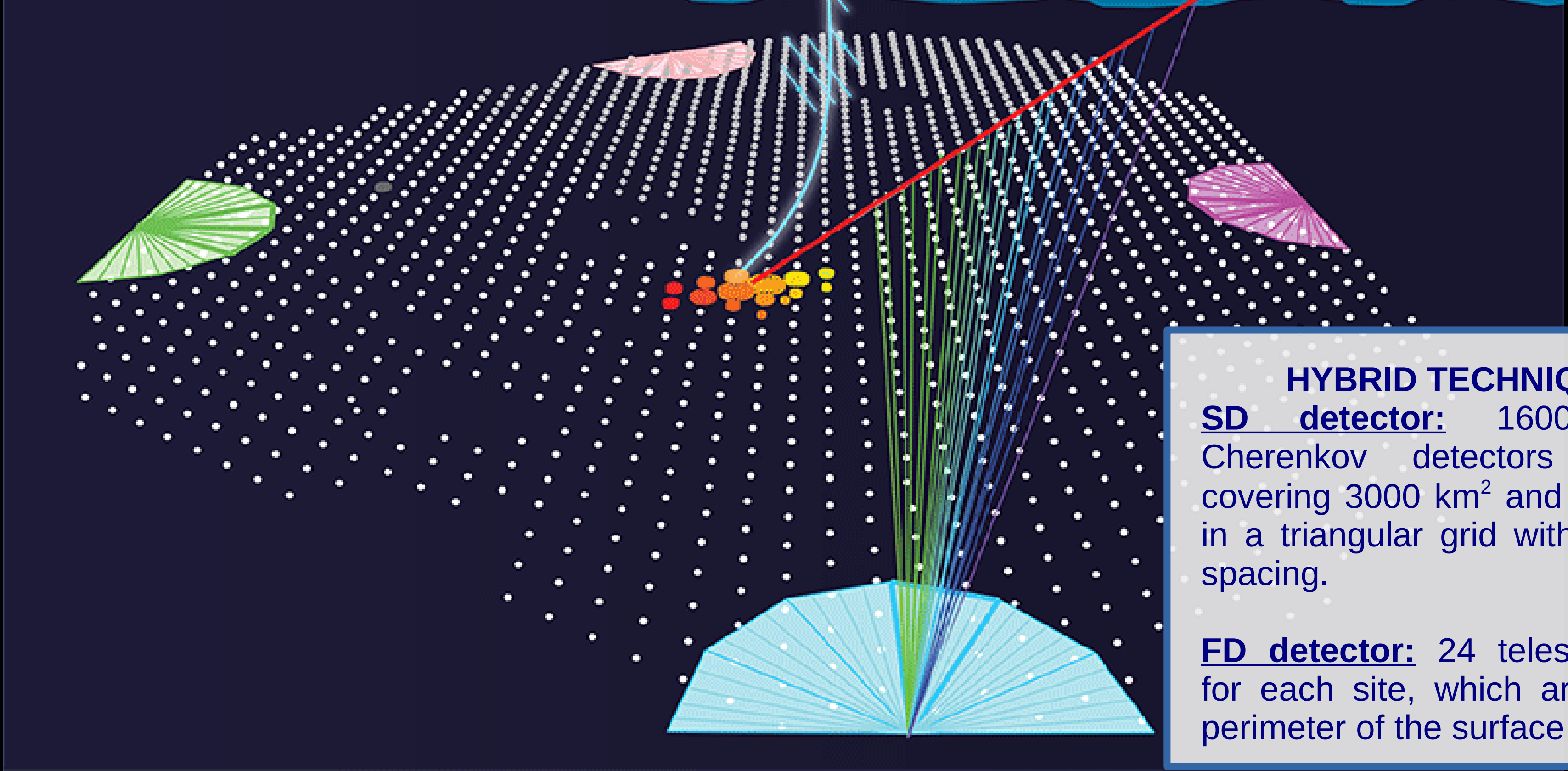
Source: ISUAL on FormoSat-2

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%



The Pierre Auger Observatory

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

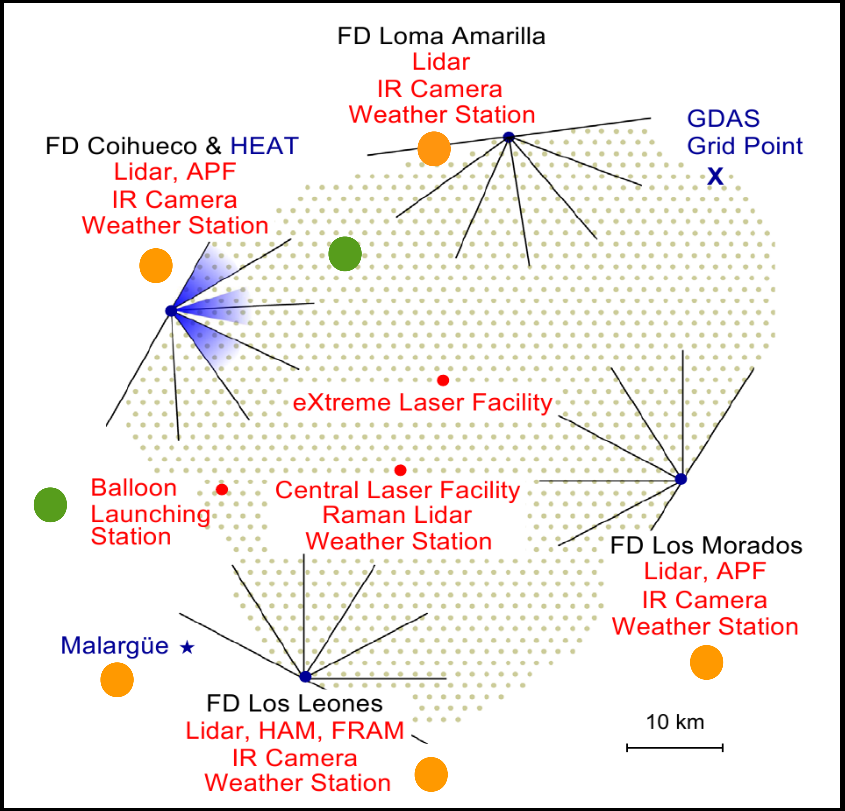


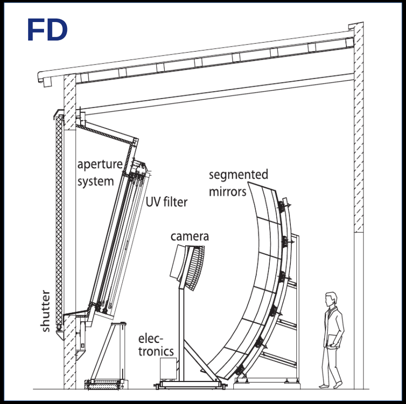
HYBRID TECHNIQUE

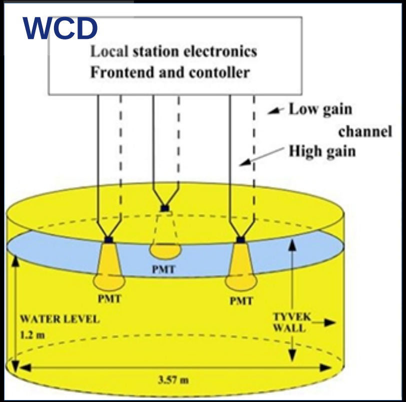
SD detector: 1600 Water Cherenkov detectors (WCD), covering 3000 km^2 and arranged in a triangular grid with 1500 m spacing.

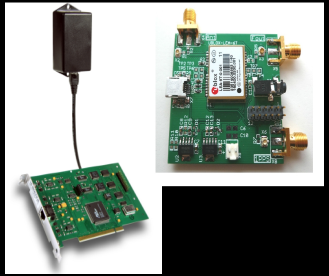
FD detector: 24 telescopes, 6 for each site, which are on the perimeter of the surface array.

The Auger detectors + atmospheric monitoring

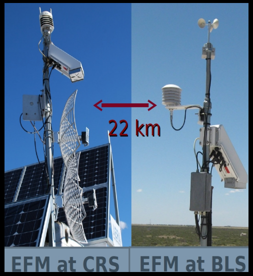






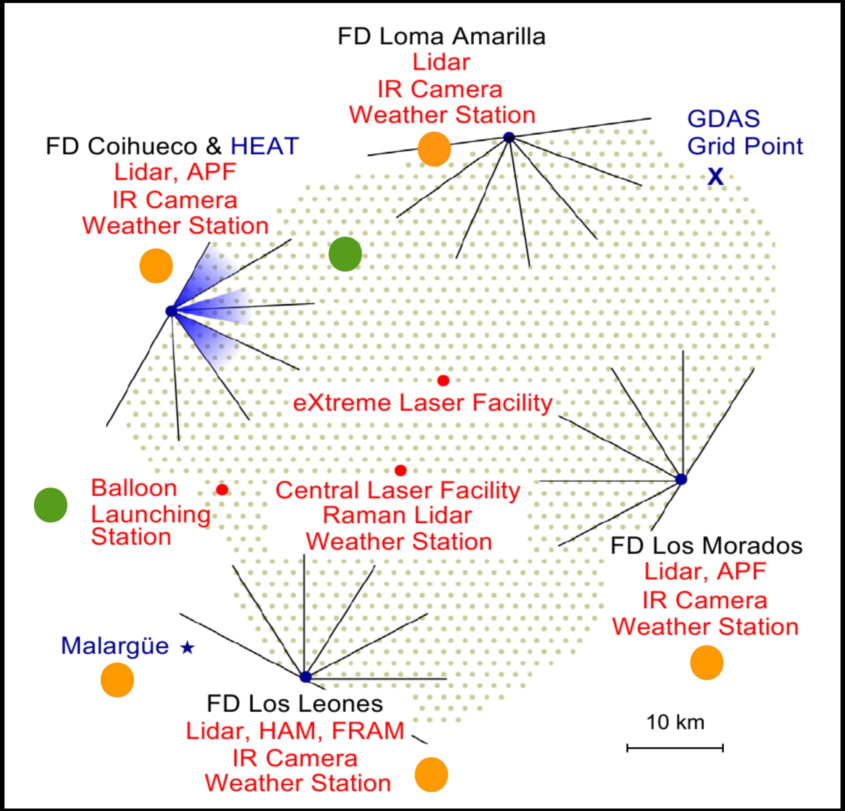


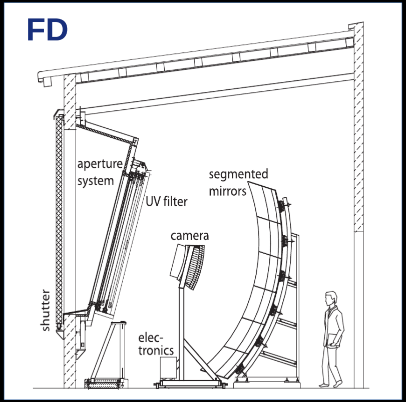
5 Boltek Storm trackers with GPS antenna (30ns resolution)
Range: up to 500 km



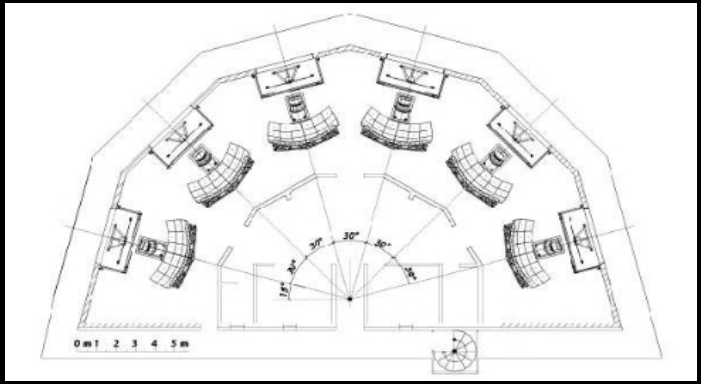
2 E-field mills
Campbell Scientific CS110

The Auger Fluorescence Detector





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

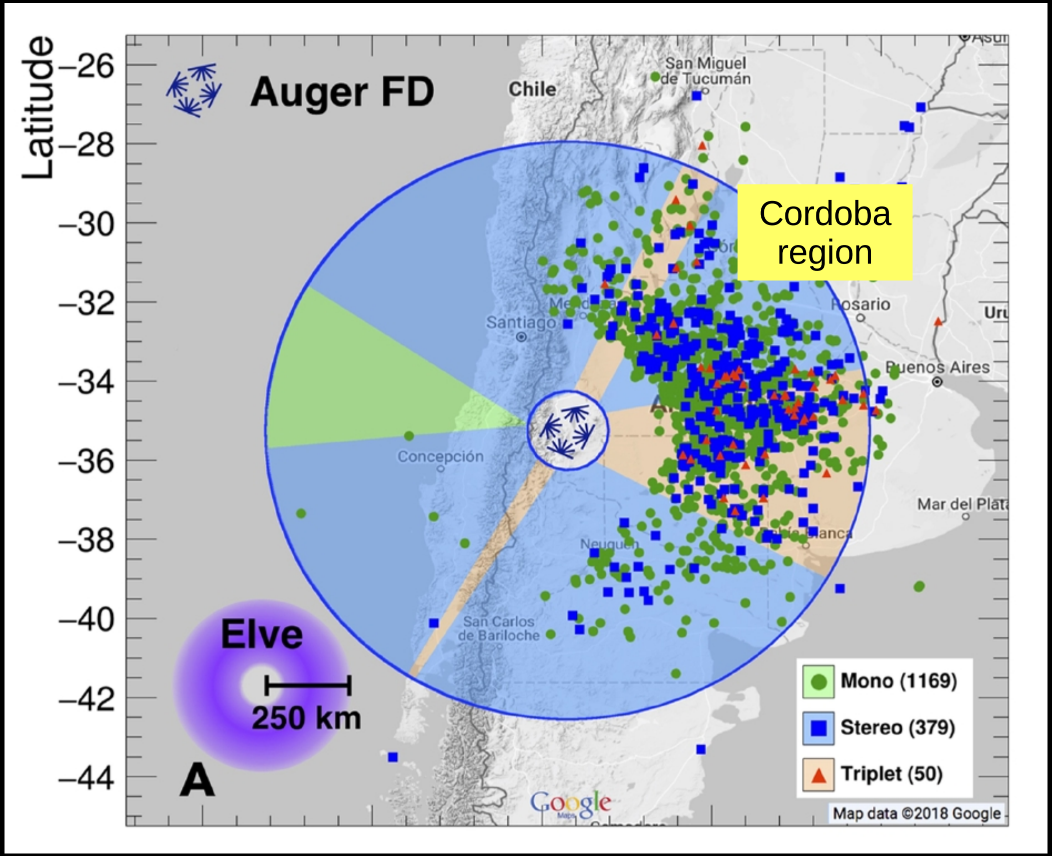


ELVES @ the Pierre Auger Observatory

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 $3 \cdot 10^6$ 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.



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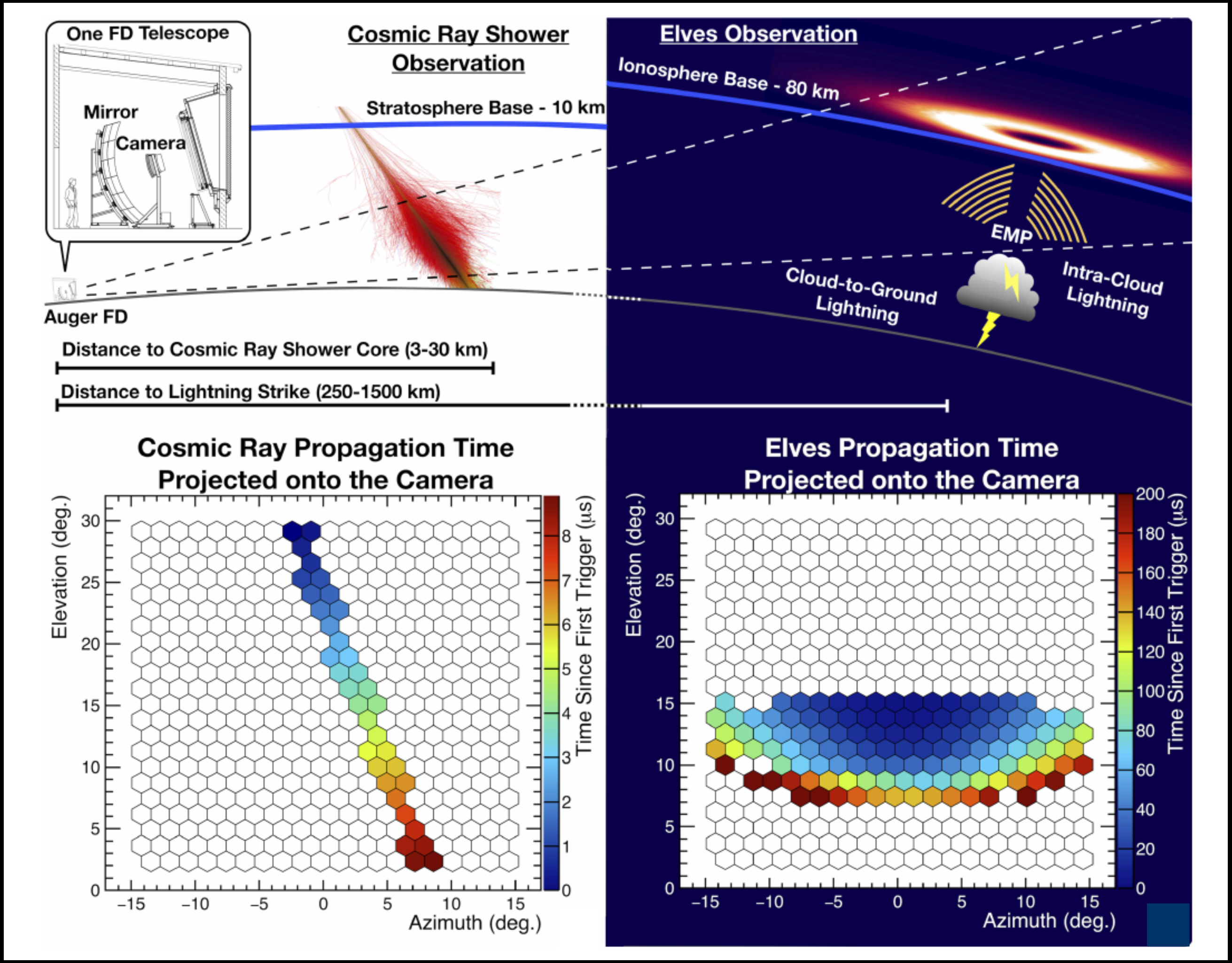

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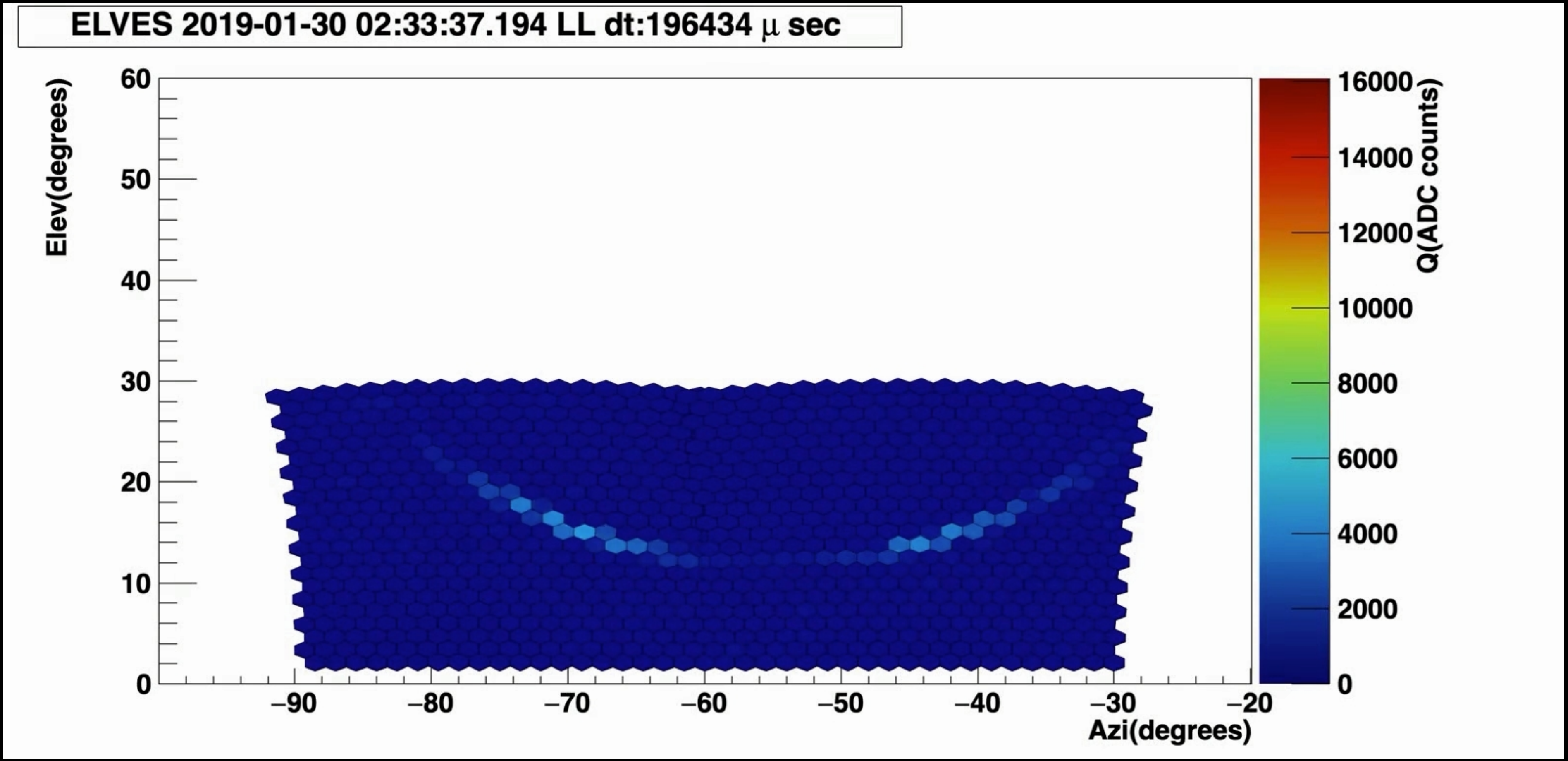
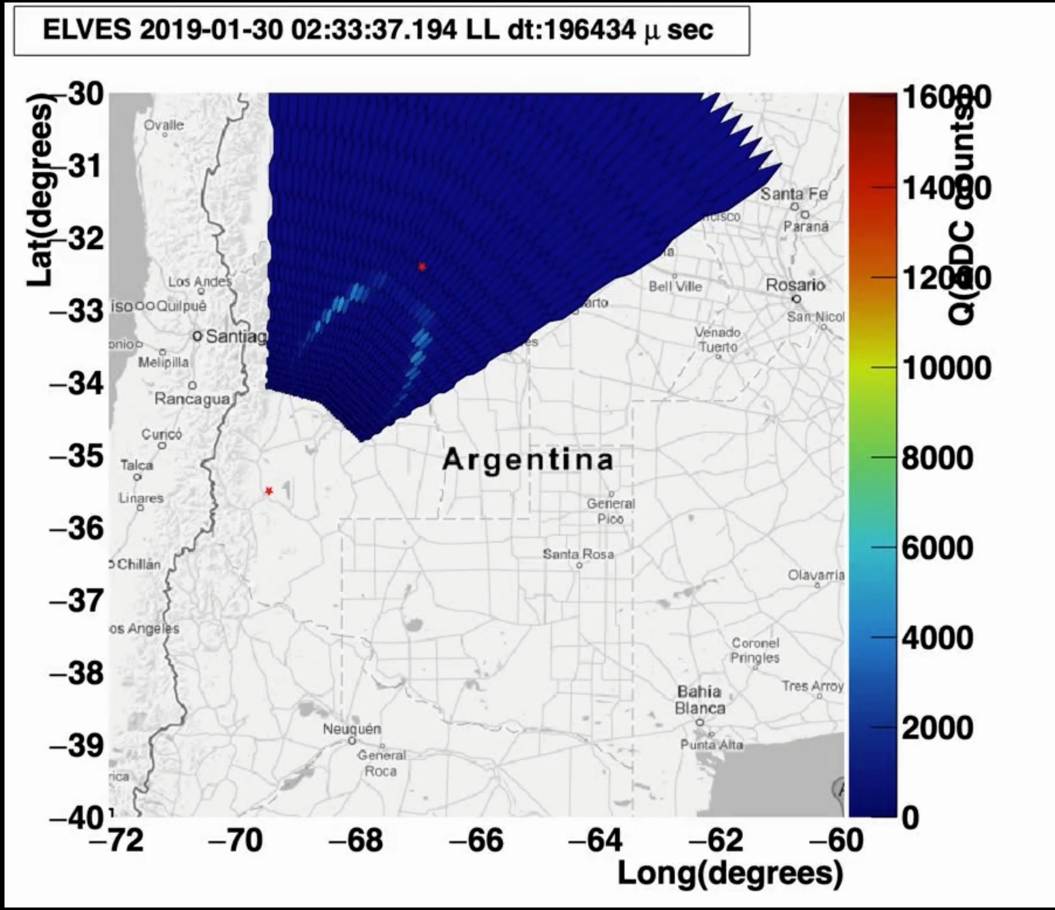


ELVES projected to Ionosphere base (~90 km)

The same event, if we project the pixels field of view at the base of the ionosphere.

200 km / 0.46 ms = 1.45 c

It looks like a rapidly expanding ring going *towards its source* at superluminal speed...



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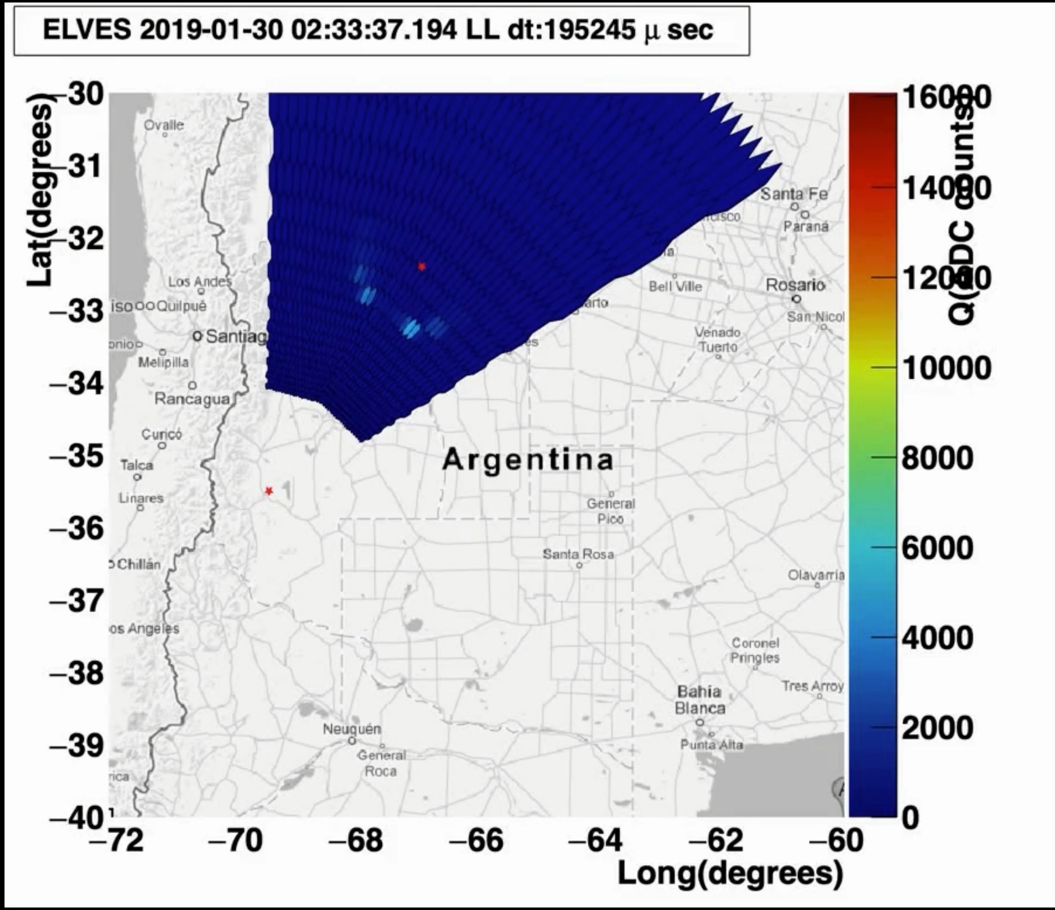
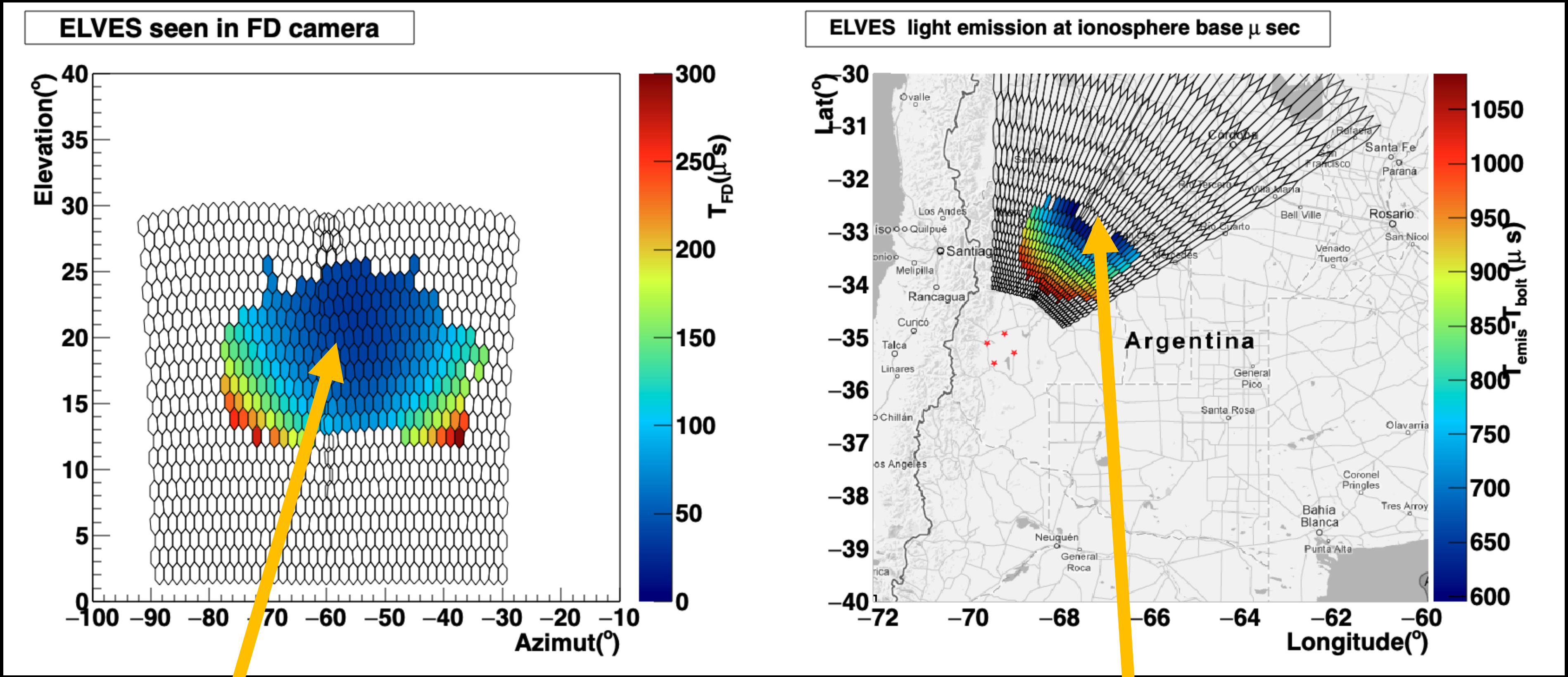
Correcting for the time delay from the emission point to the FD, the light wave changes direction, as we expect, showing an expanding ring, centered at the lightning source.



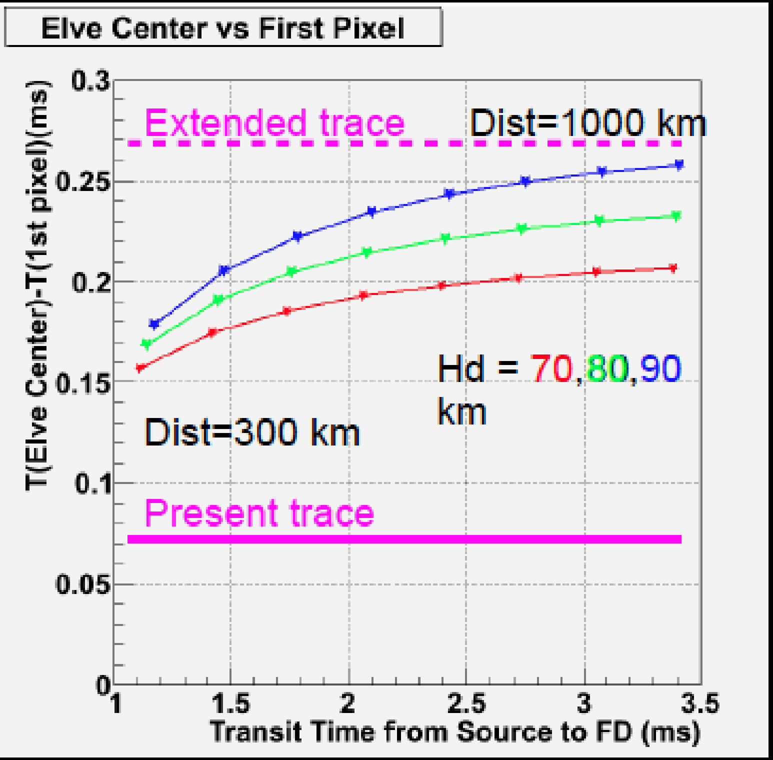
Camera View vs Ionosphere View

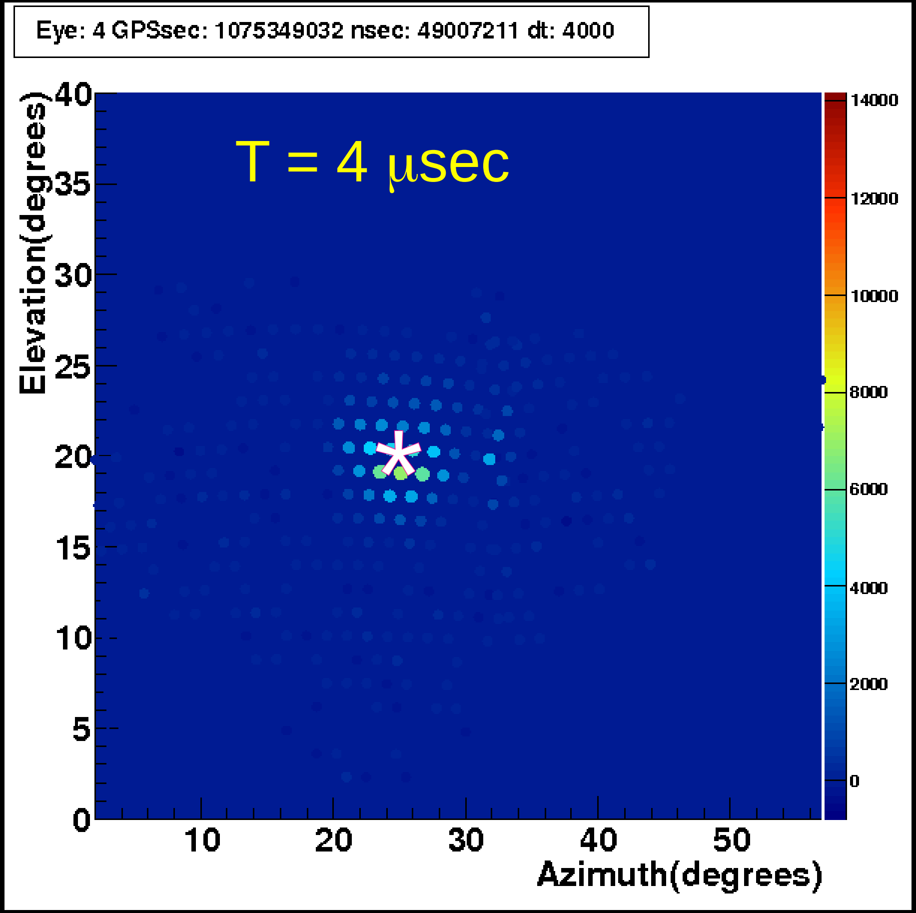


Here the center is in the direction with the shortest path between source and FD

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

ELVES Readout Format: standard (2013)

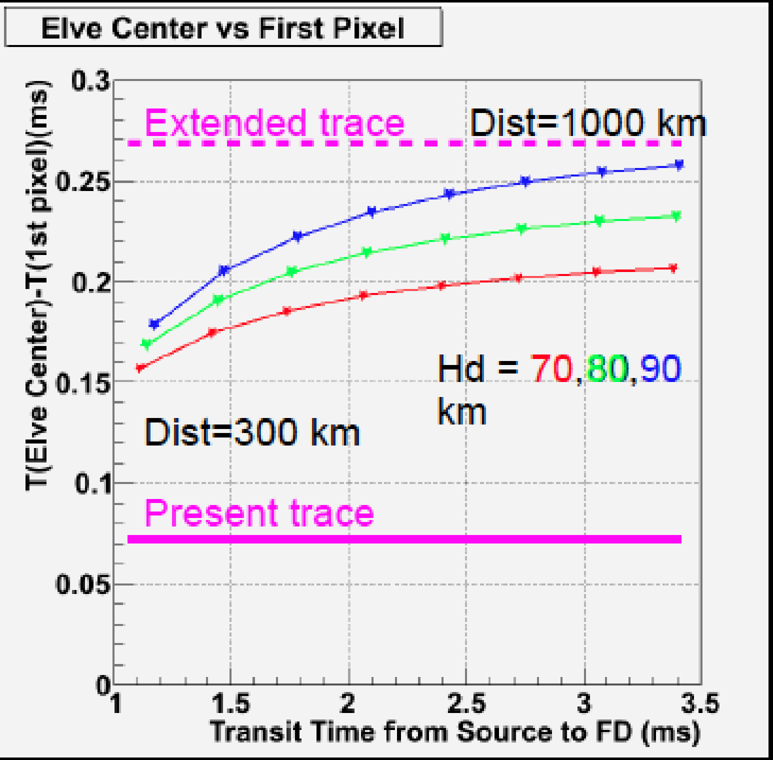


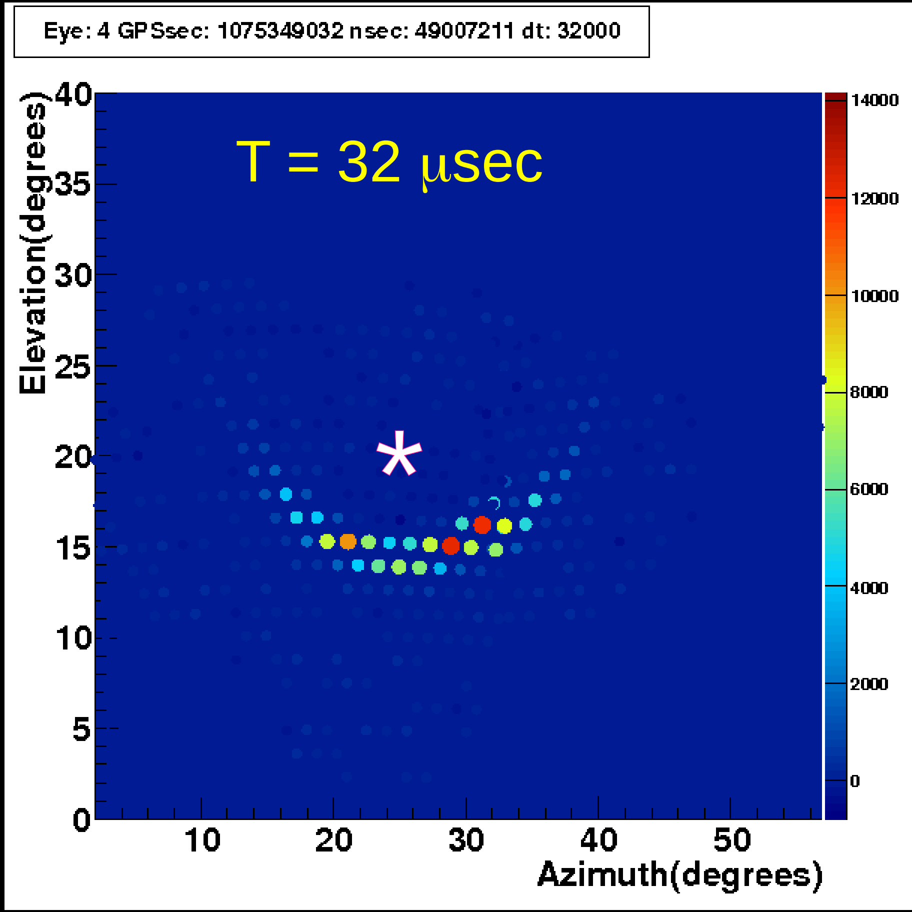


Trigger at 28 μs

Page 1

ELVES Readout Format: standard (2013)





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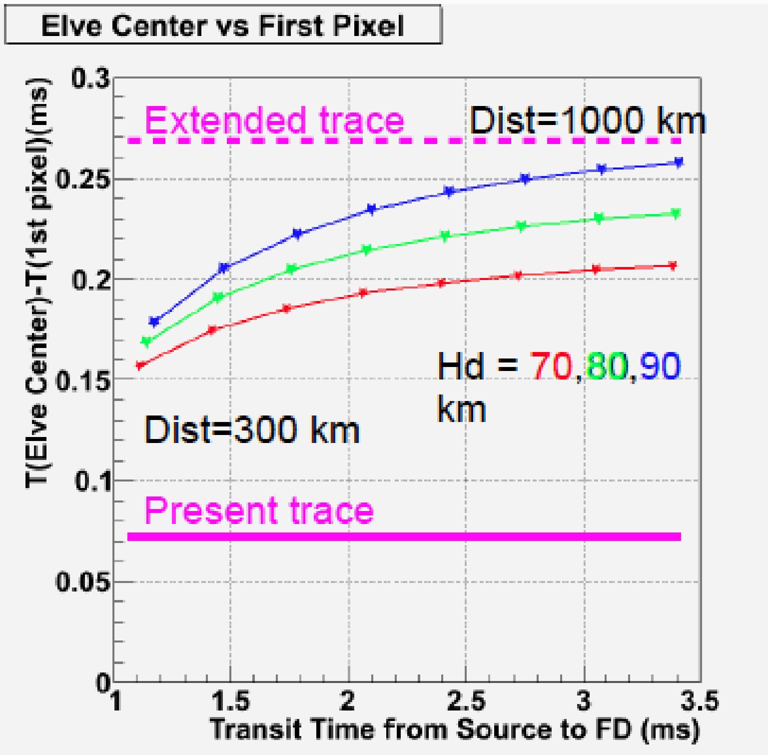
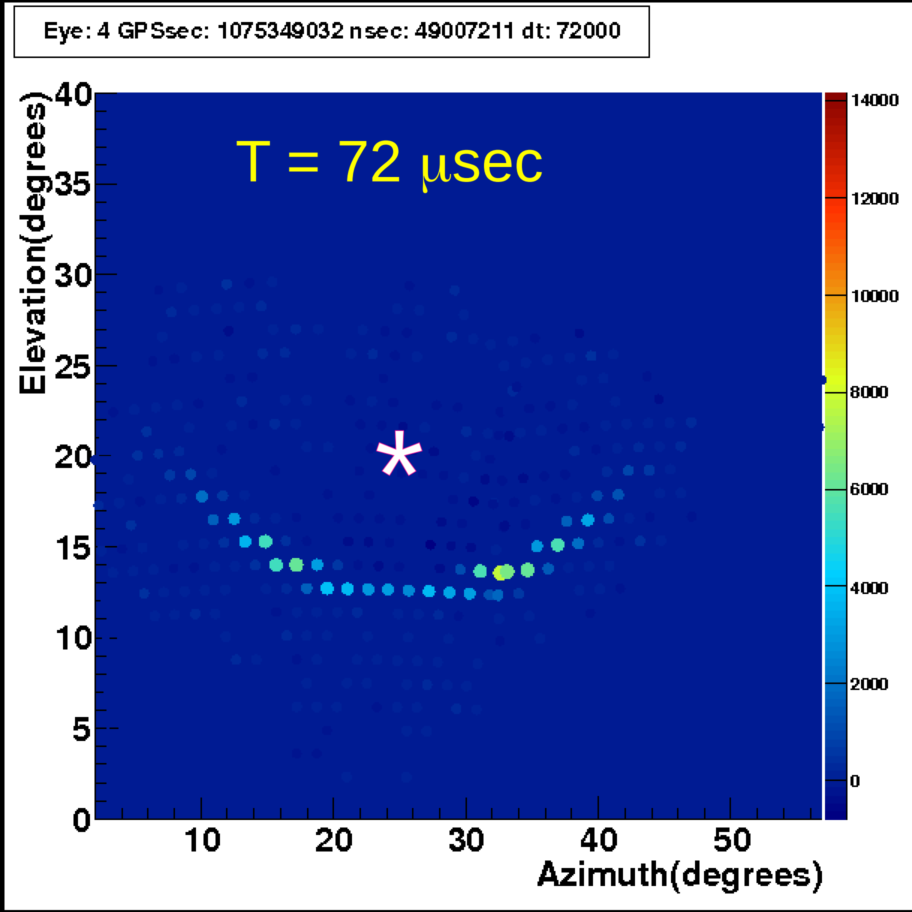
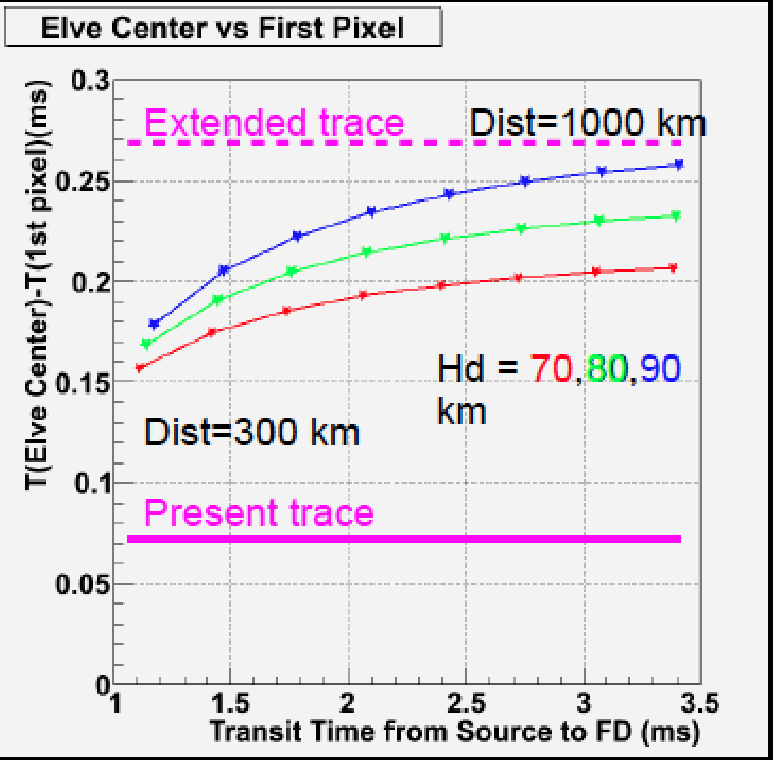


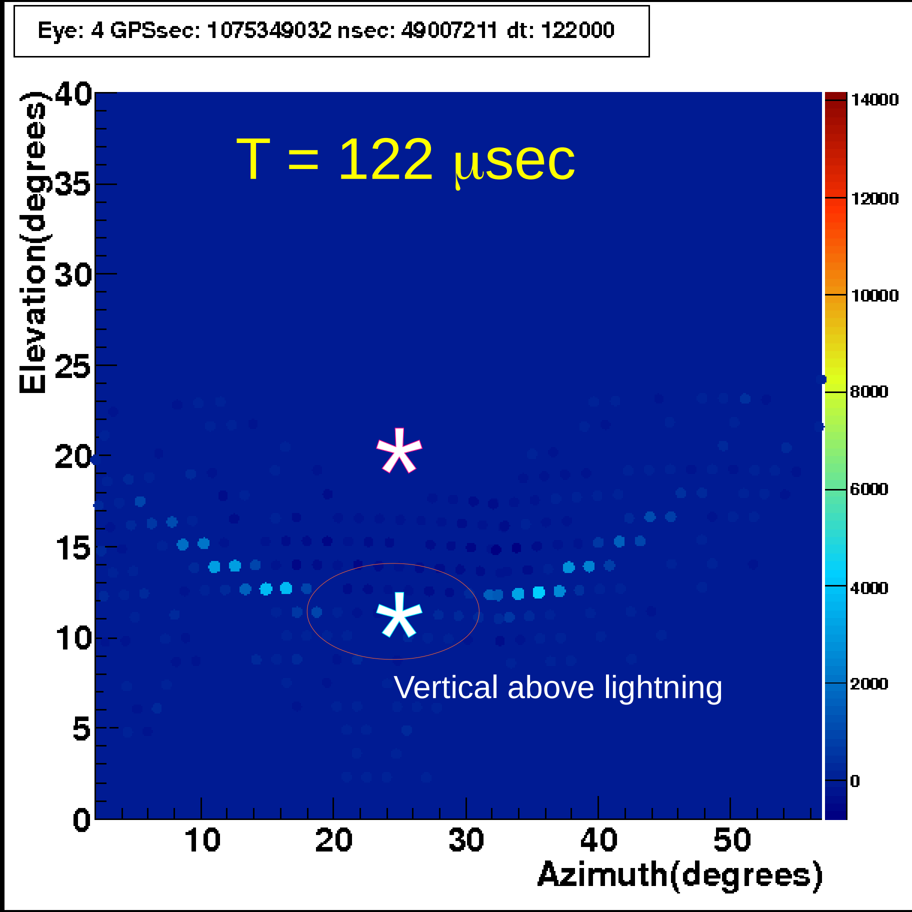


Trigger at 28 μs

Page 1

ELVES Readout Format: extended (2014-6)





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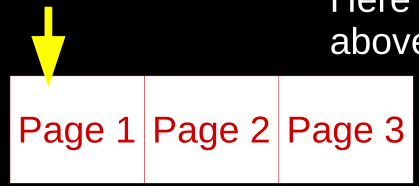
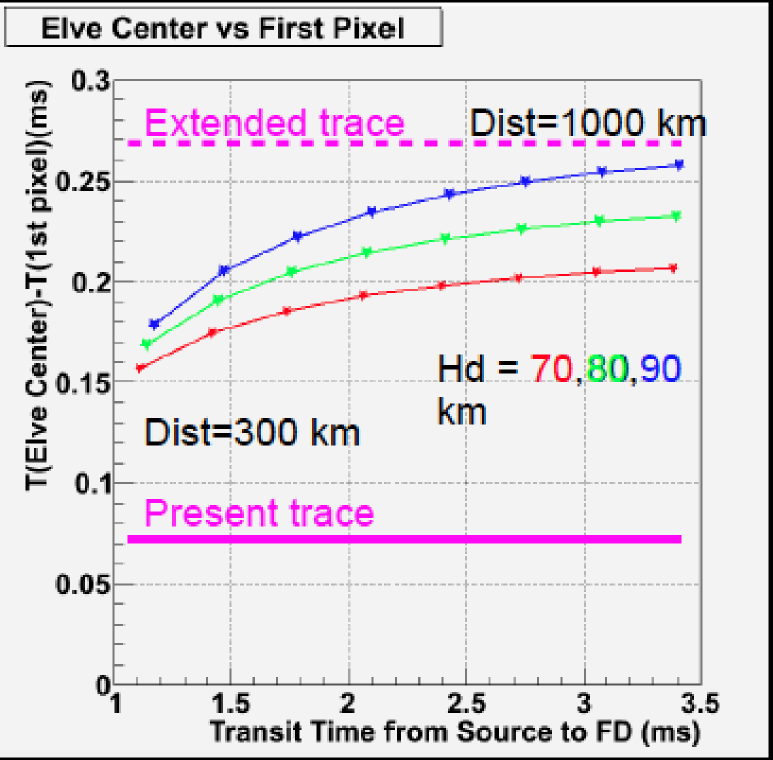
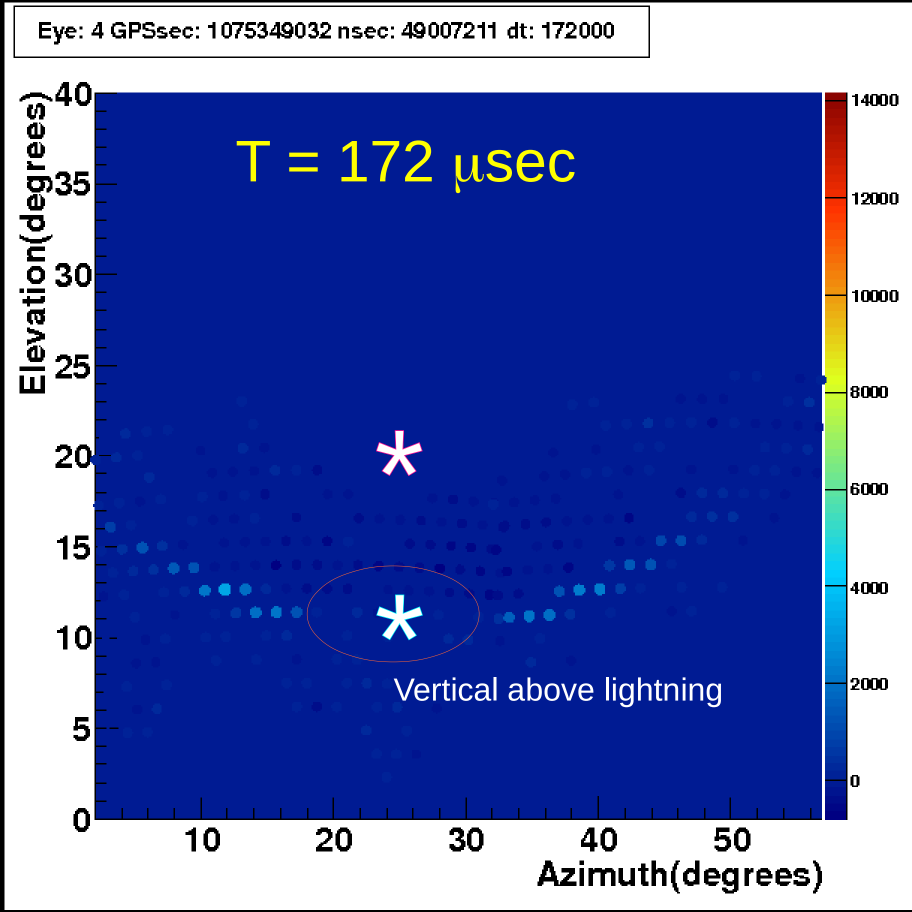


Here we start seeing the vertical above the lightning

ELVES Readout Format: extended (2014-6)

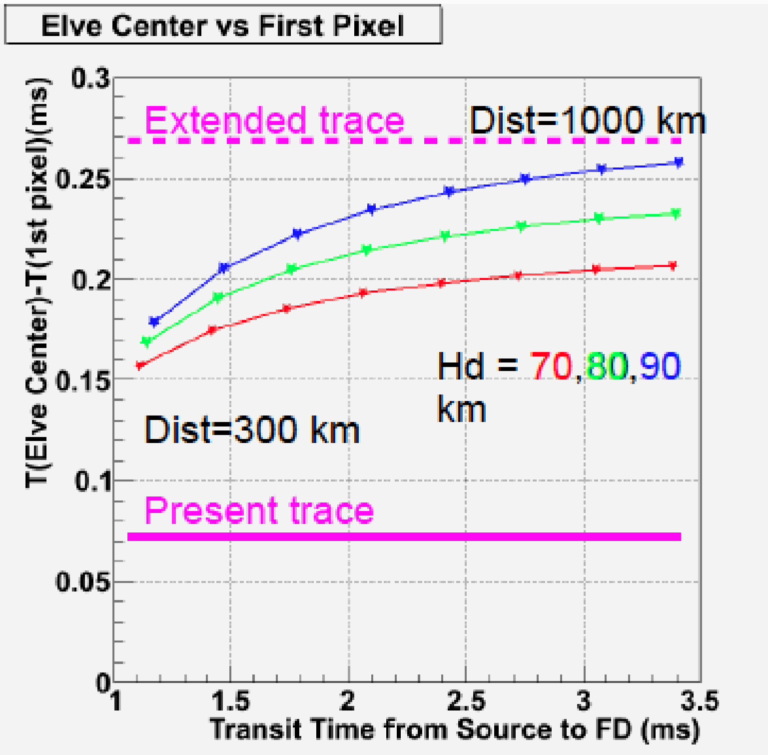


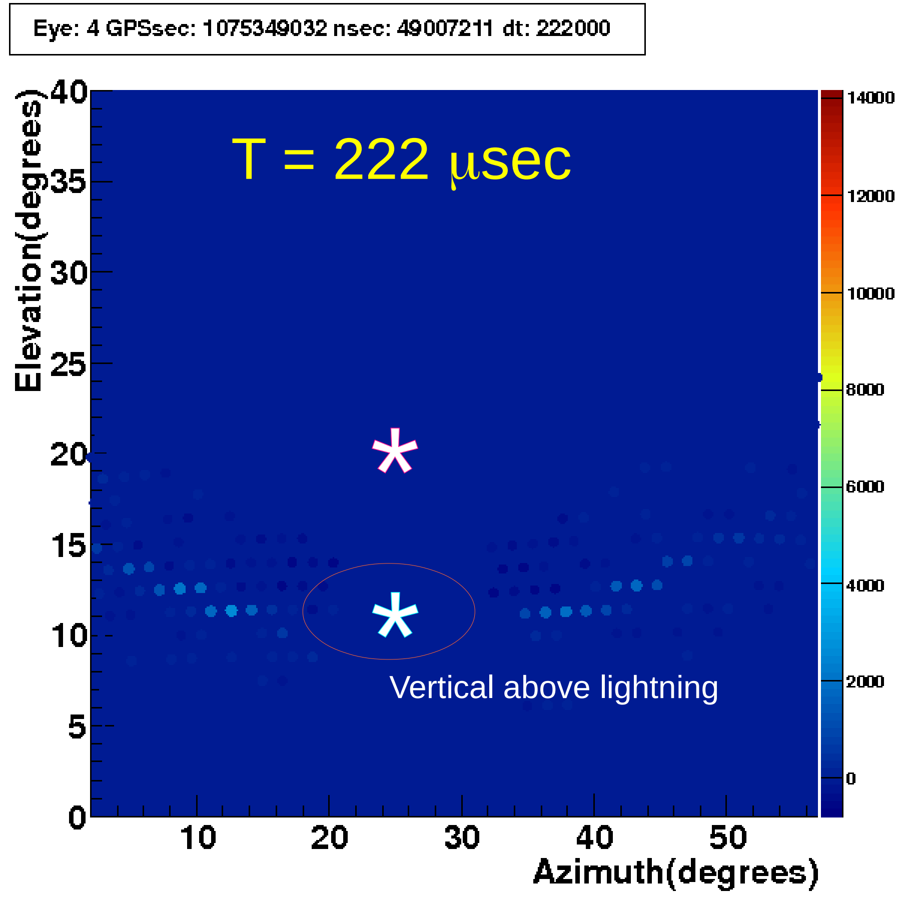


Trigger at 28 μs

Page 1	Page 2	Page 3

ELVES Readout Format: extended (2014-6)





Trigger at 28 μs

Page 1	Page 2	Page 3

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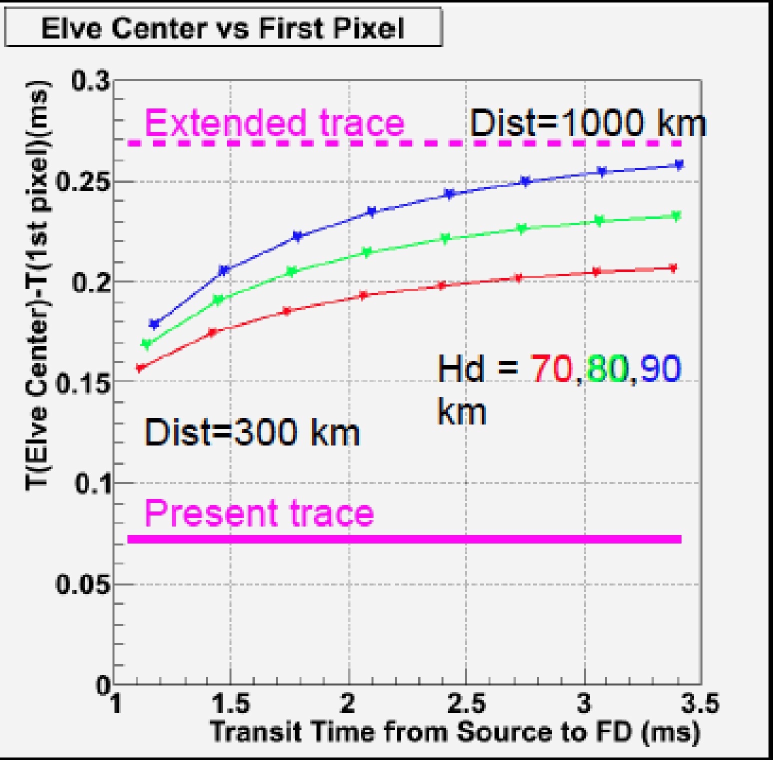
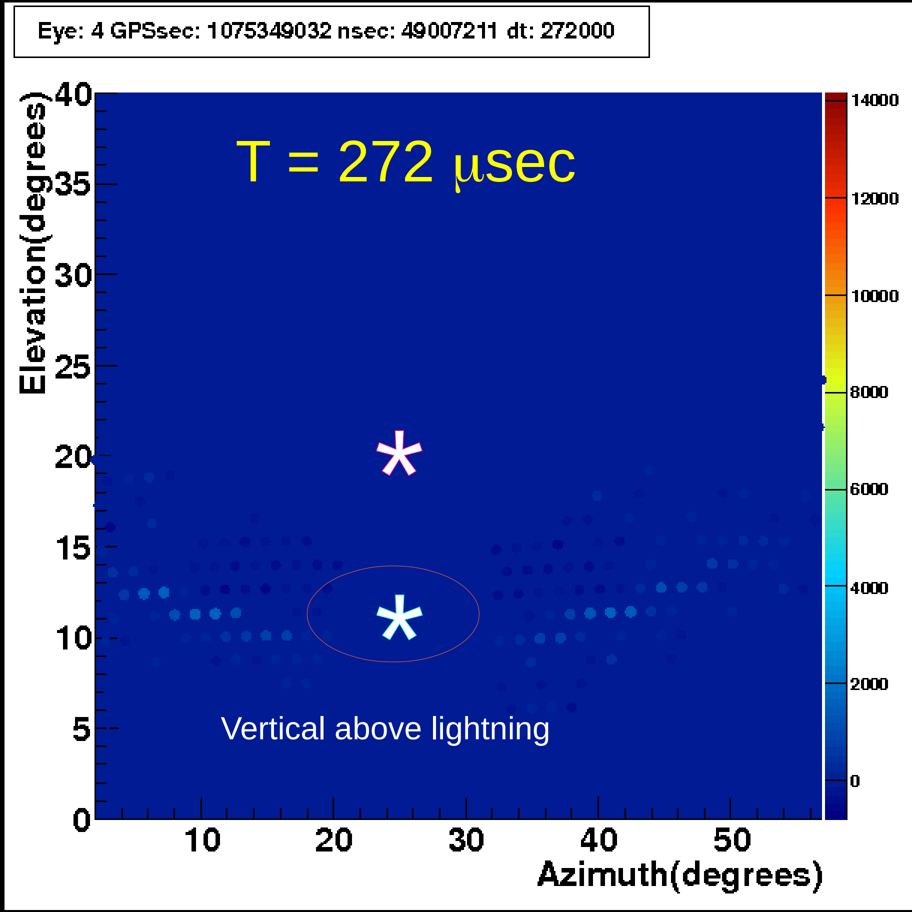
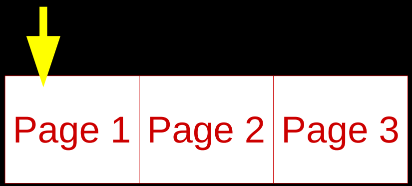




Trigger at 28 μs



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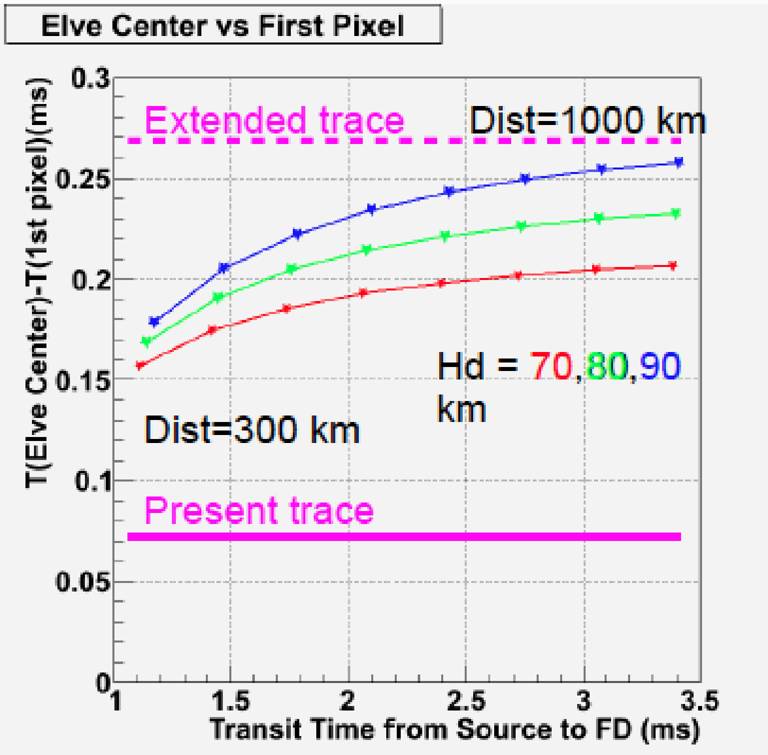
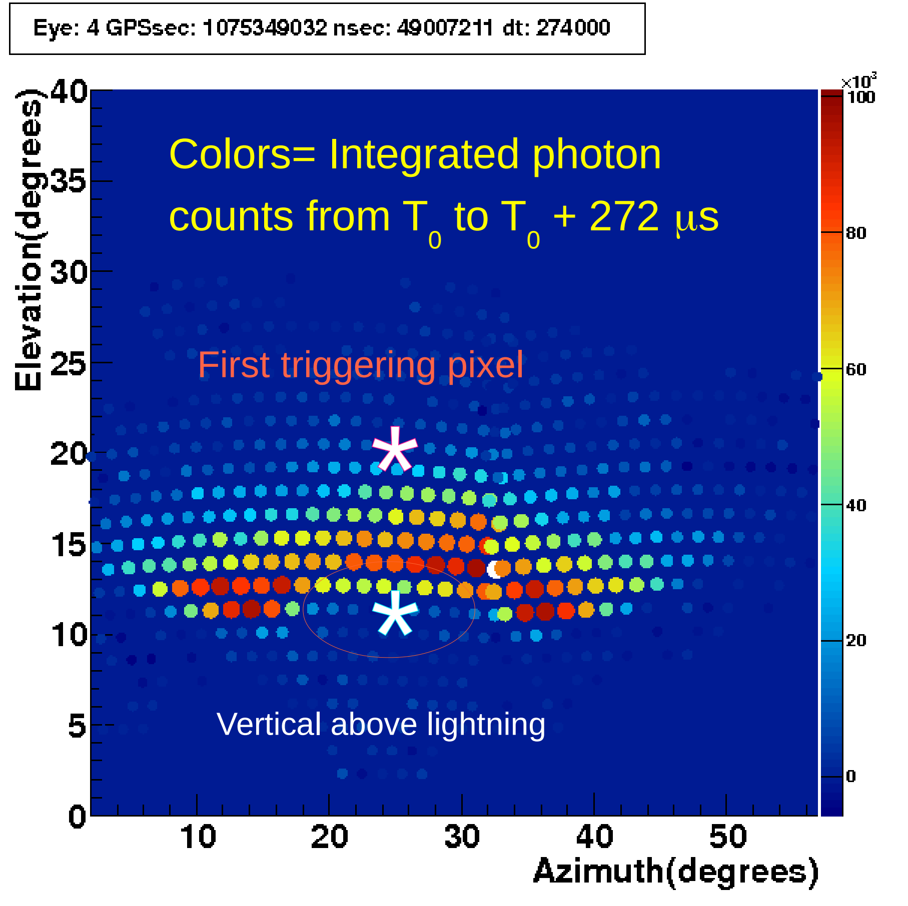
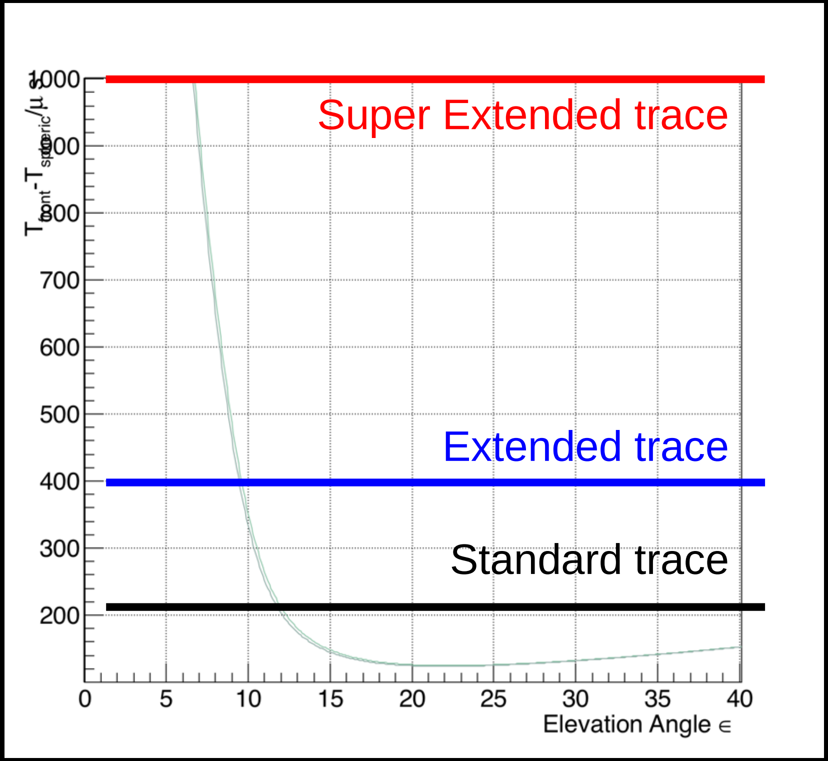


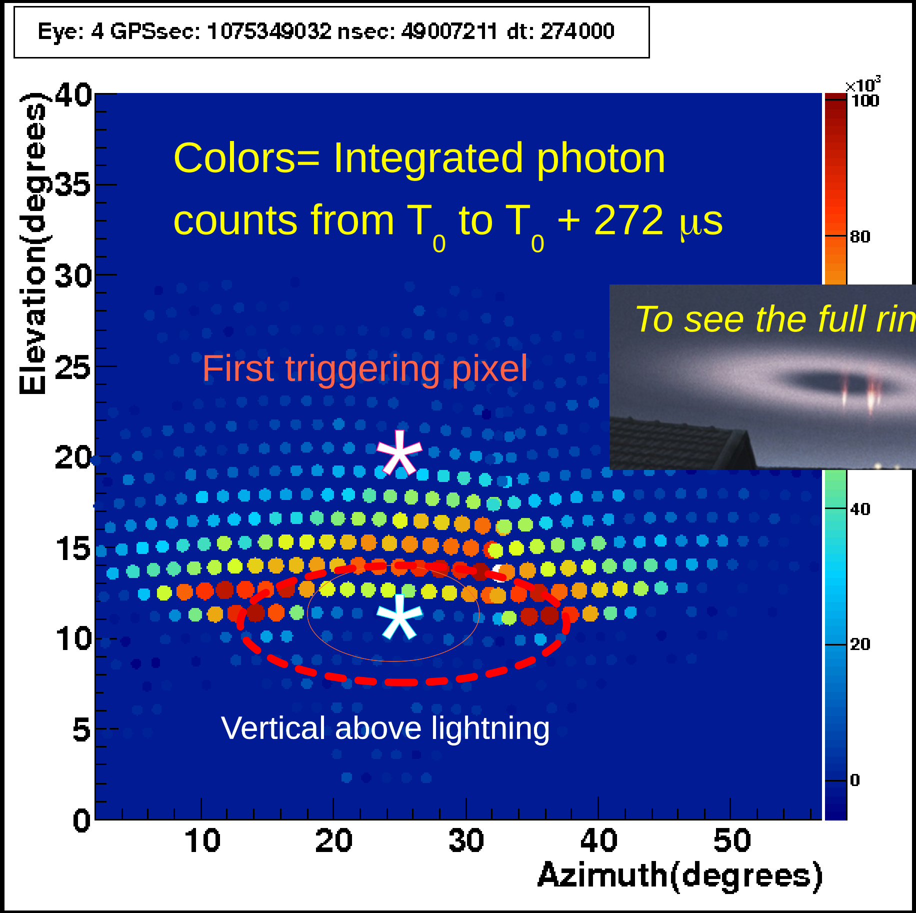


Trigger at 28 μs …Total 300 μs max

Page 1	Page 2	Page 3

ELVES Readout Format: superextended (2017-now)





Trigger at 28 μs…………...Total 900 μs max

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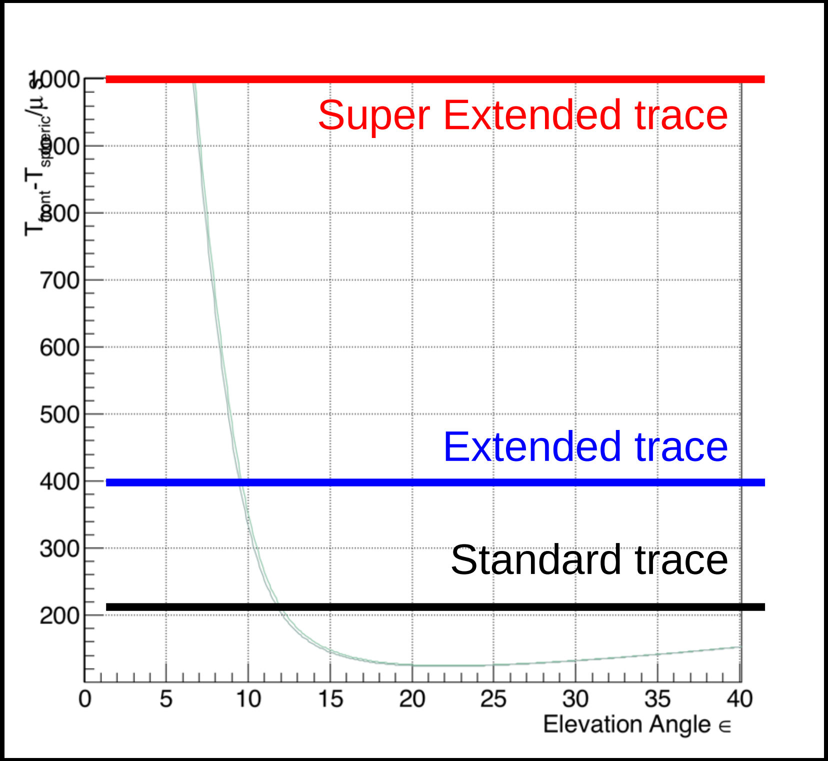
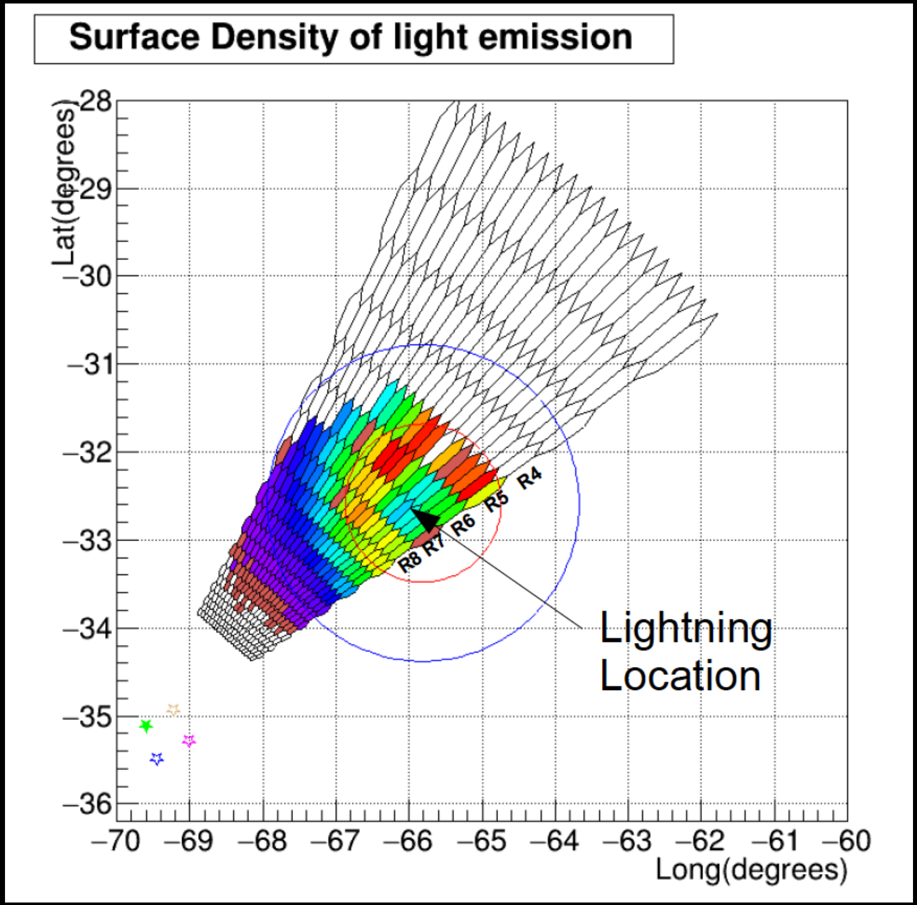
ELVES Readout Format: superextended (2017-now)





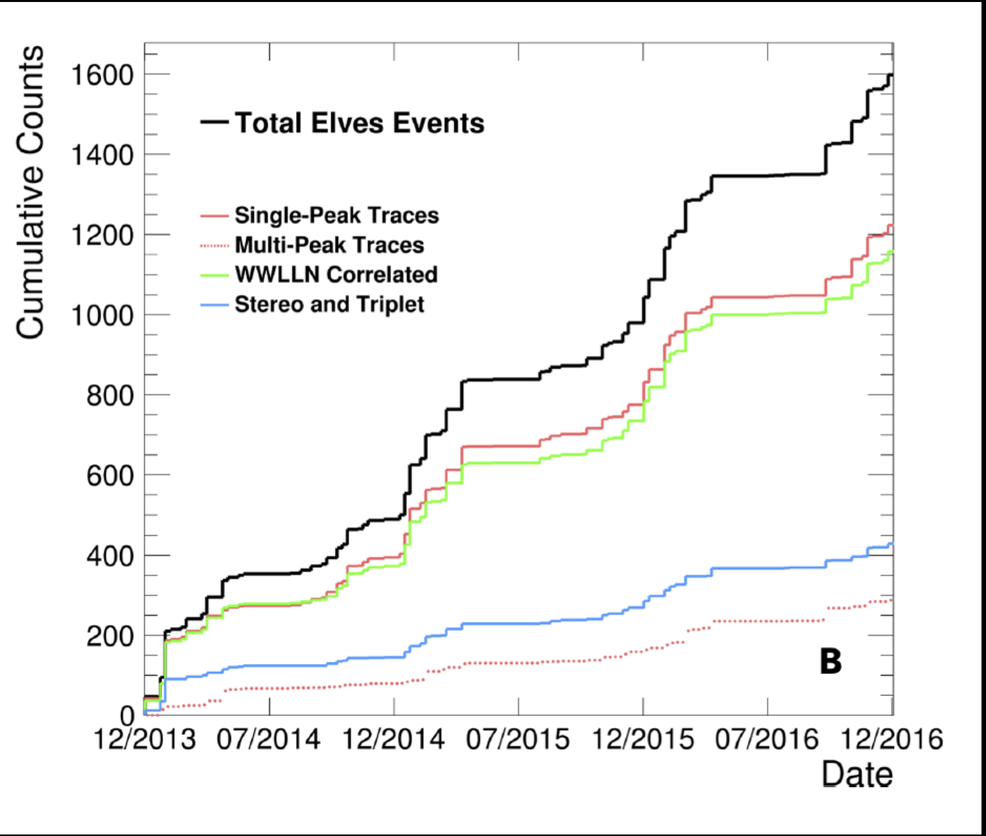
Trigger at 28 μs…………...Total 900 μs max

Page 1	Page 2	Page 3	………	Page 9

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%)

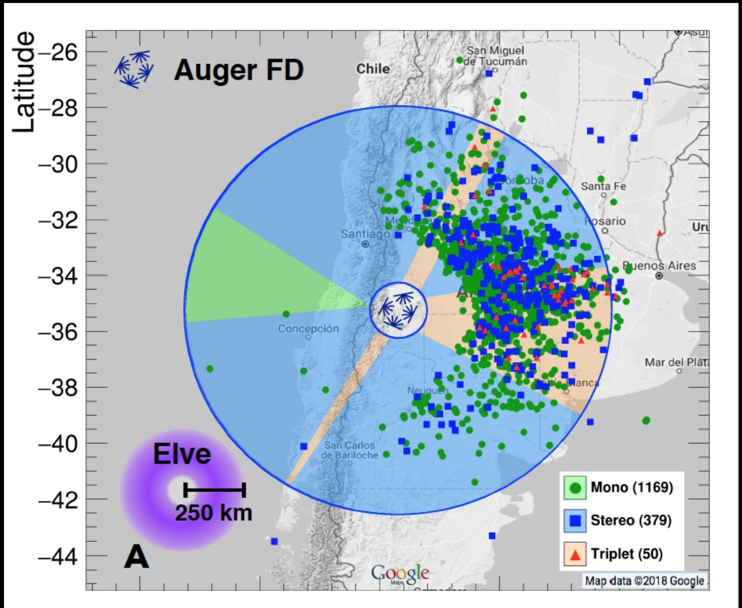


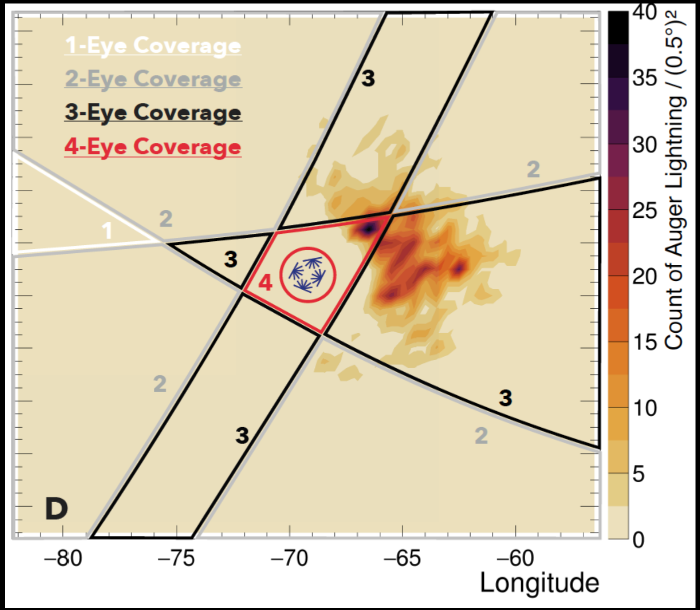
Aab et al, Earth and Space Sci.7 (2020)4
Eos Science Updates:
https://eos.org/science-updates/catching-elves-in-argentina

Trigger Efficiency

From MONO/STEREO and STEREO/TRIPLET rates, accounting for FD deadtimes, assuming an average angular extension of the light emitting region, we estimated the elves detection efficiency for a single FD site:

$$\varepsilon = 35 \pm 8\ \%$$

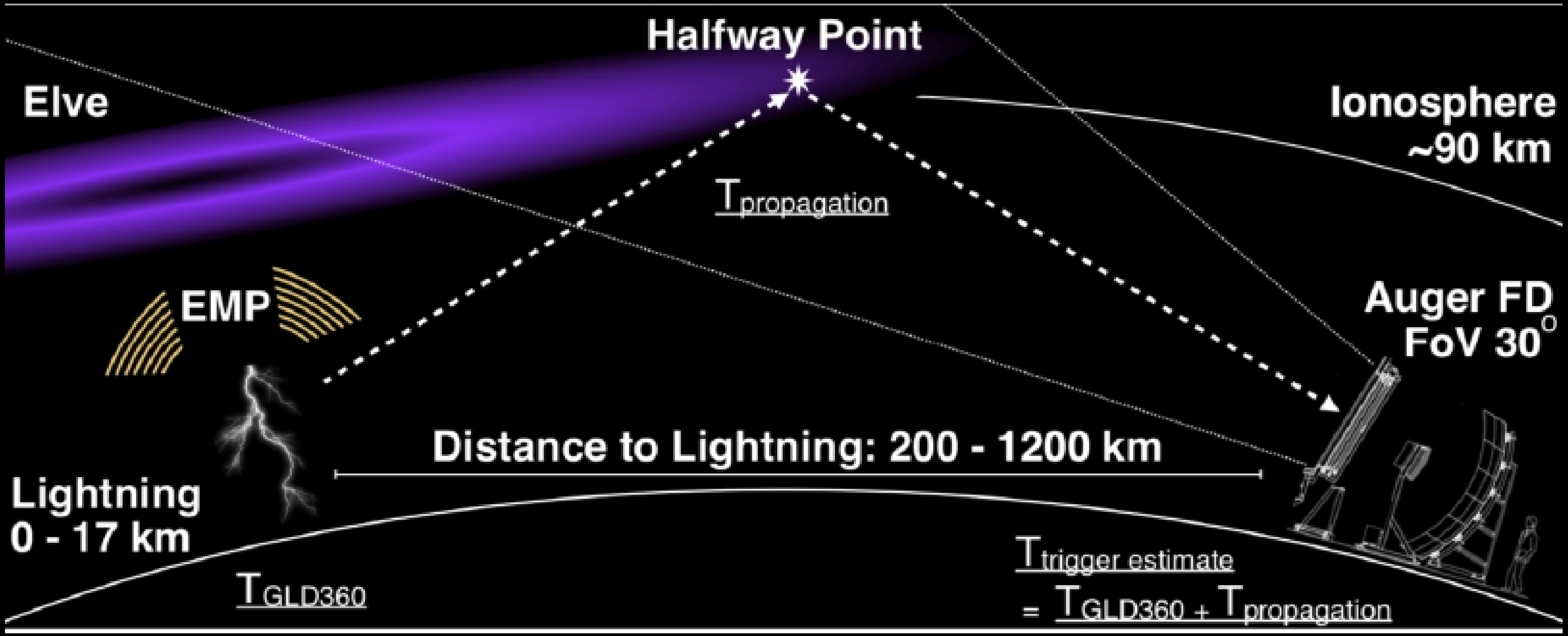




Loosening trigger conditions, the efficiency was raised without significant decrease in S/N

Year	1-eye	2-eye	3-eye	total
2017	920	298	51	1269
2018	811	193	24	1028
2019	1256	553	126	1935

Why there is a hole in the middle?



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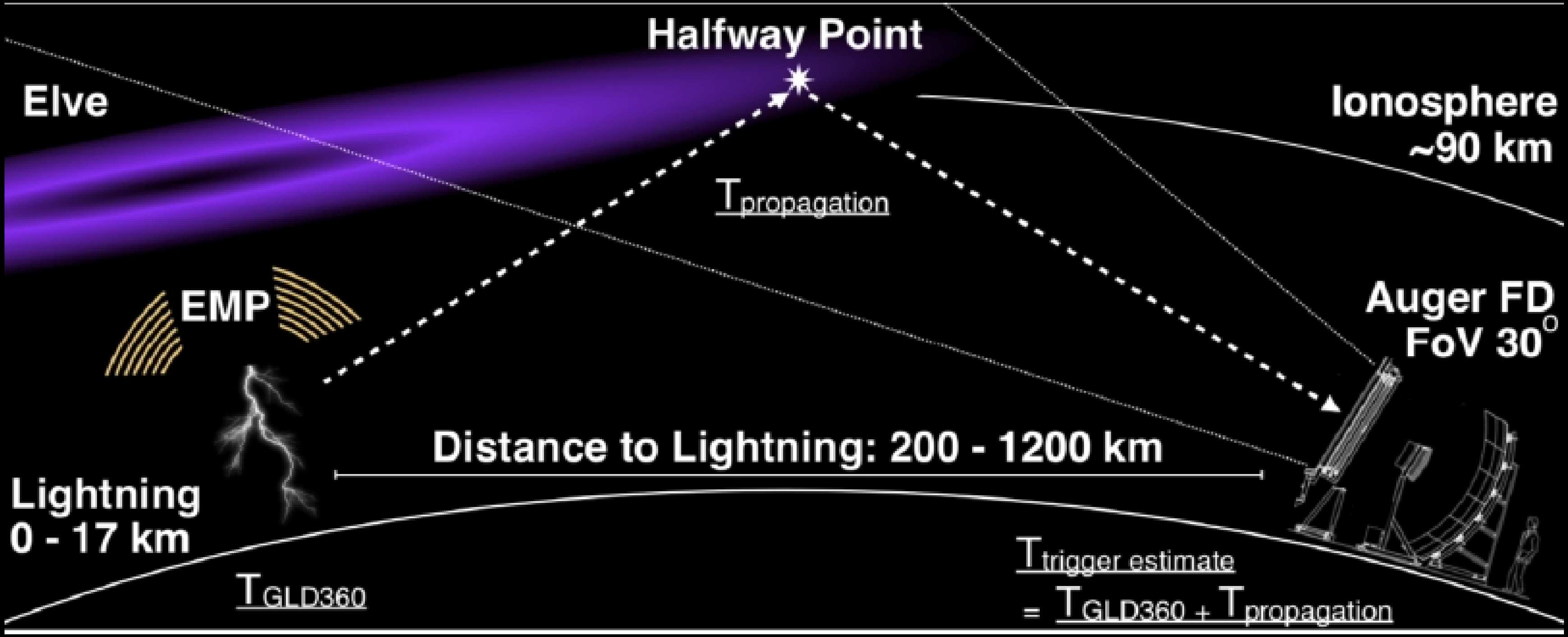
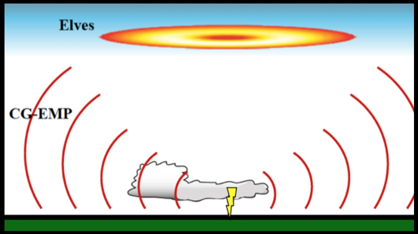
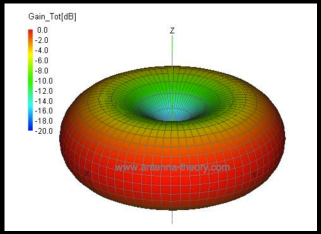




A vertical lightning is like a radiating dipole (Hertz)

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

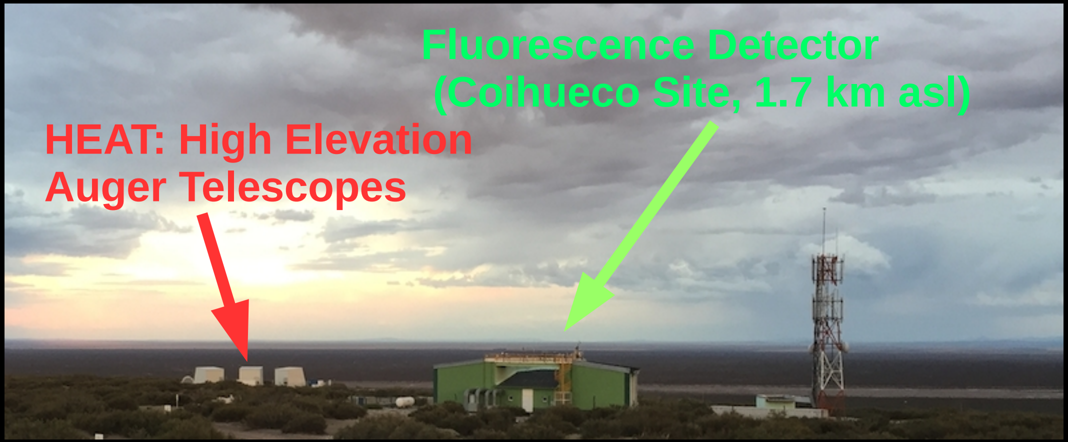


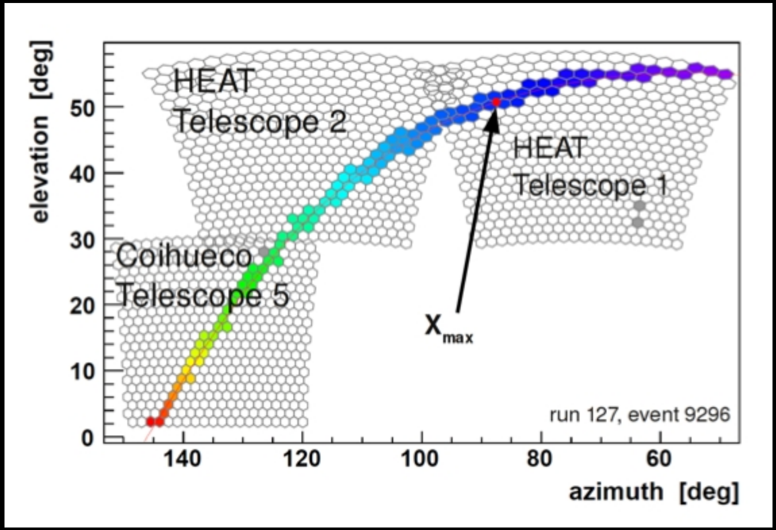
ELVES in the additional HEAT Telescopes (2011-now)

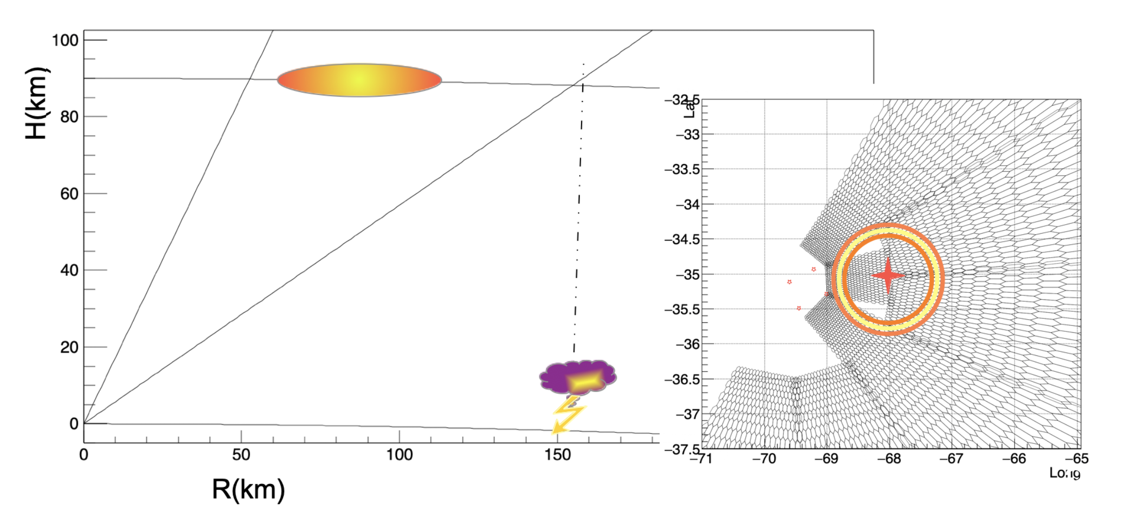
3 Fluorescence Detectors with :

- Elevation axis : 45°
- FoV = 30° – 60°
- Goal: detect low energy cosmic rays
- DAQ: 100(x3) μs traces, 50(x40) ns bins

Since Jan. 2021 we can observe ELVES from closer storms







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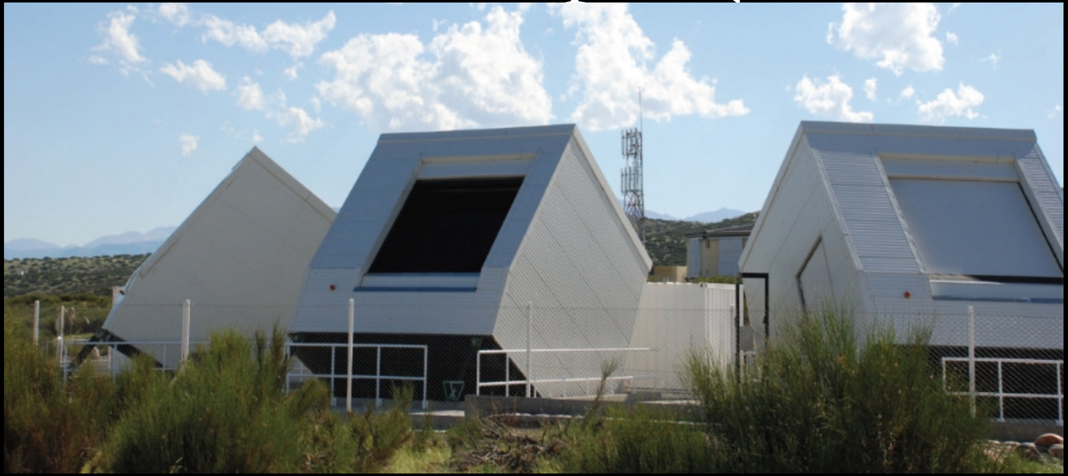
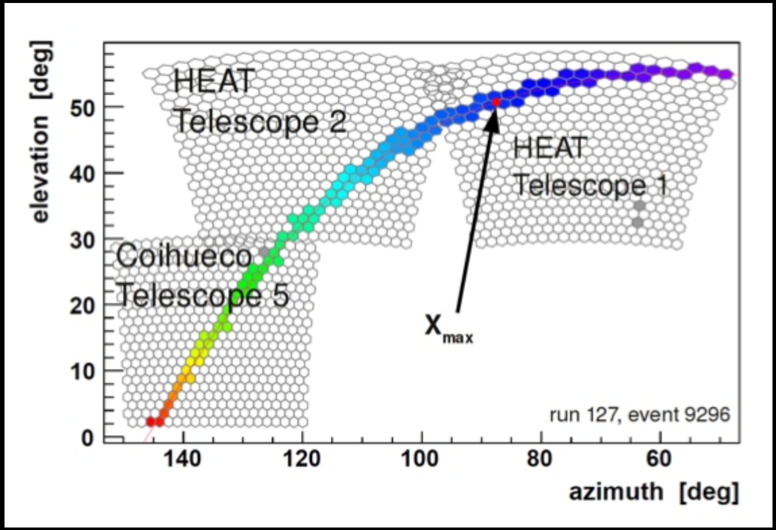
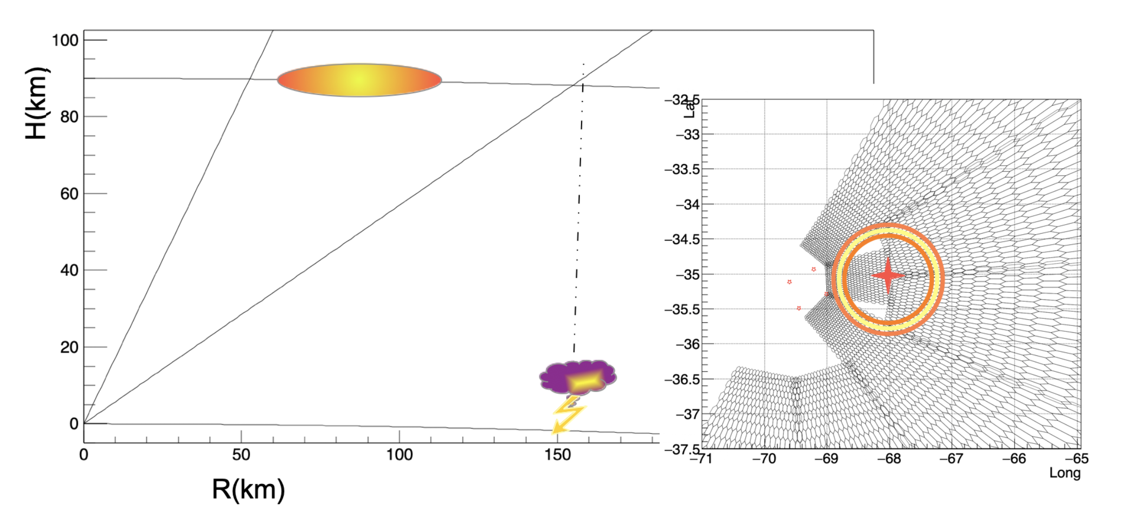
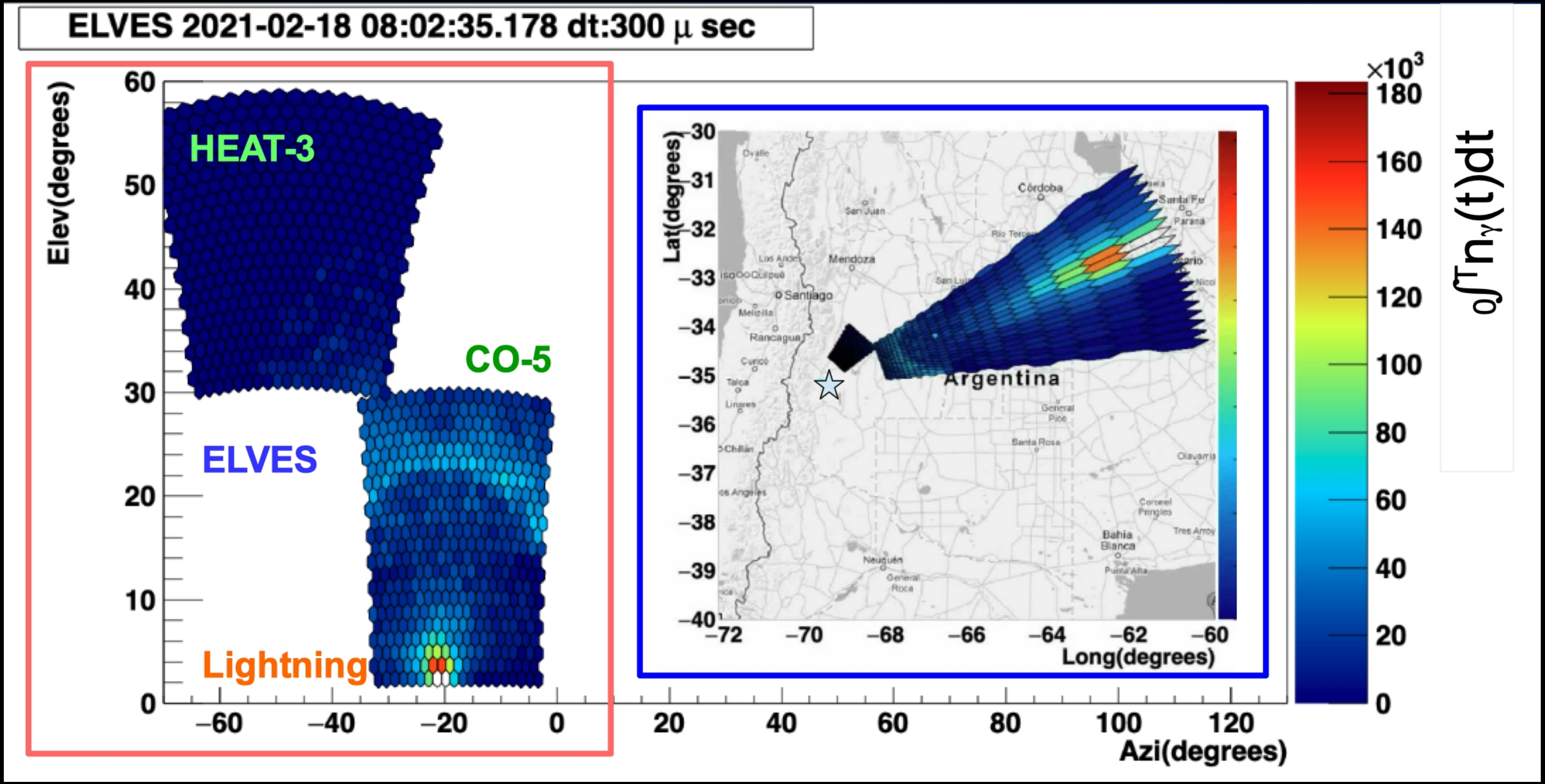


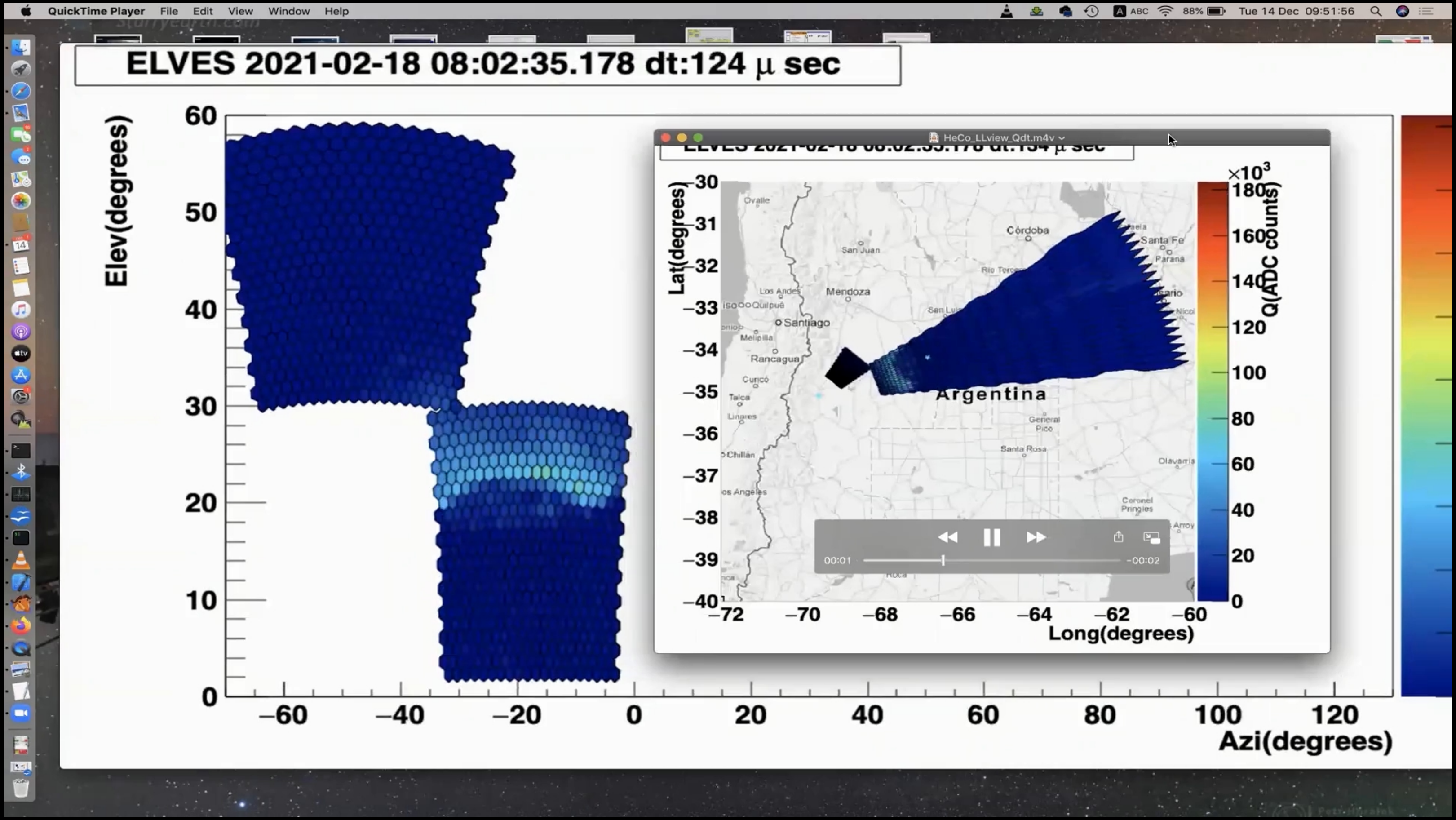




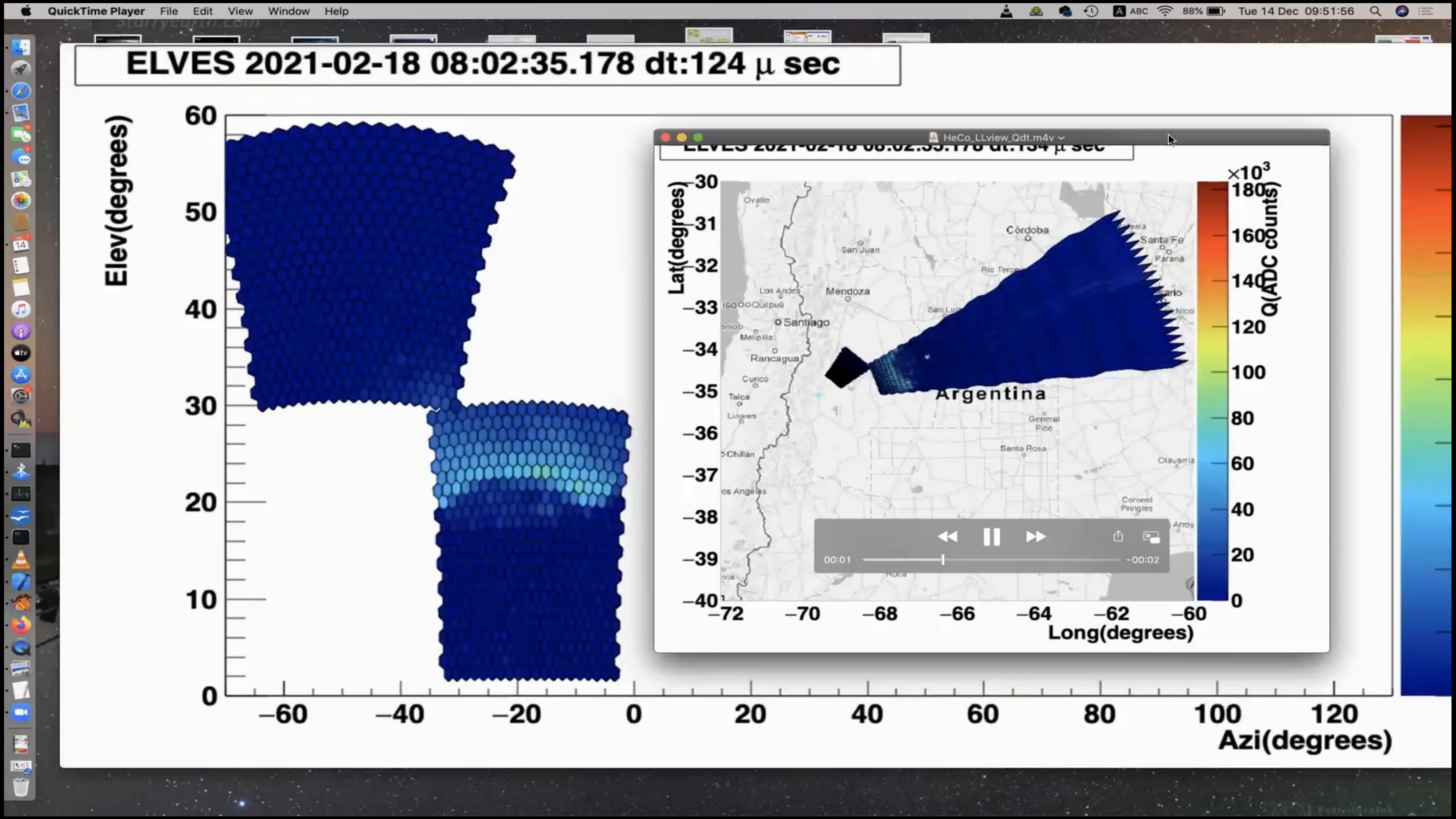
ELVES in HEAT (and other FD's)



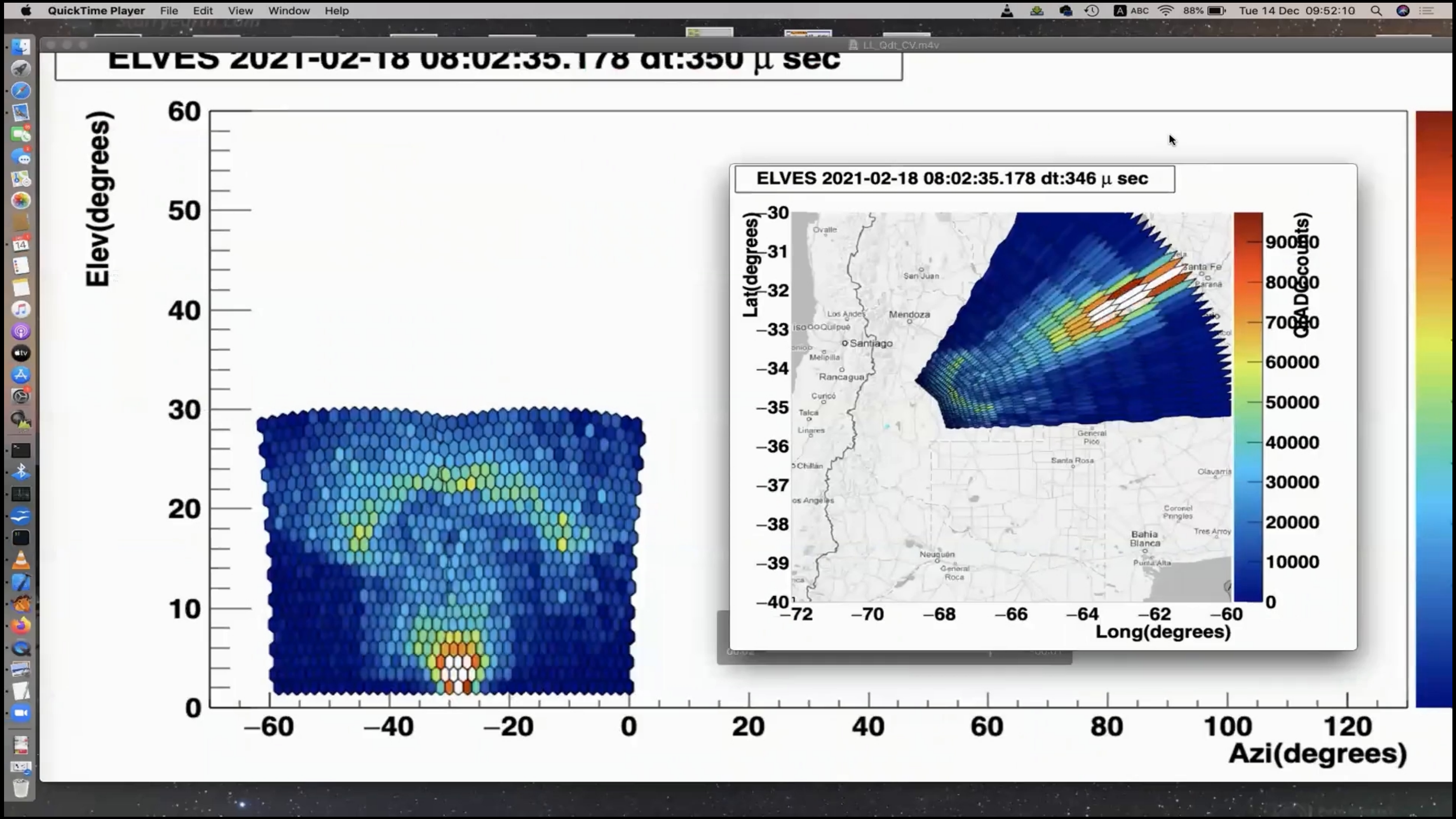
ELVES in HEAT (and Coihueco)



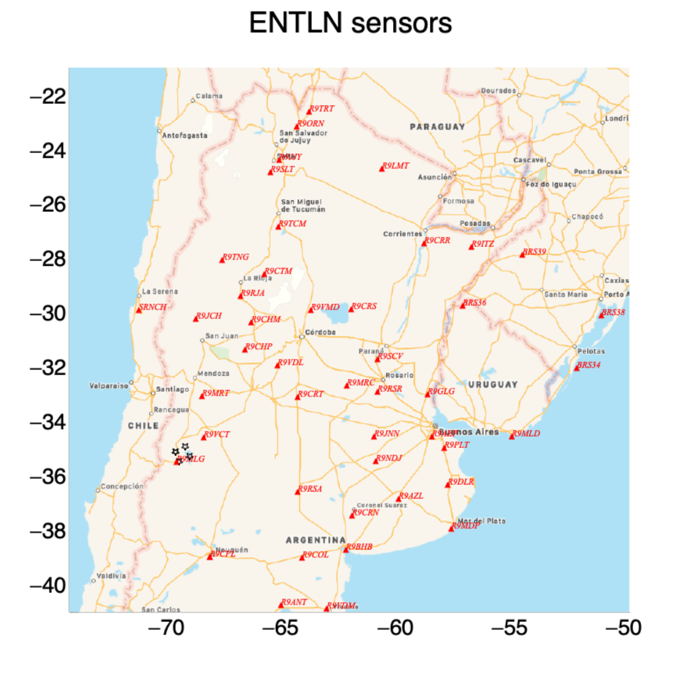
ELVES in HEAT (and Coihueco)

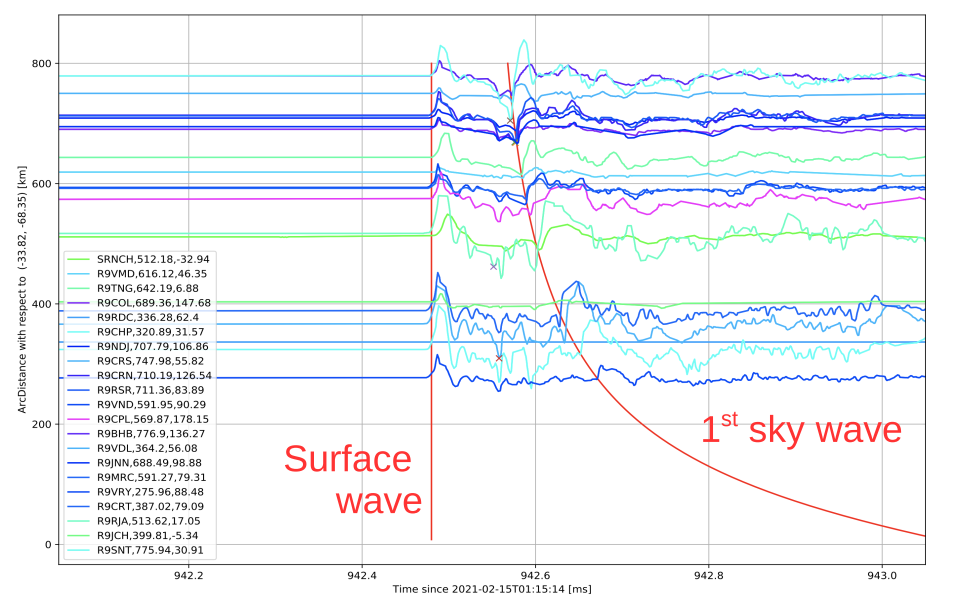


Same ELVES in Los Leones



Collaboration with Earth Networks (ENTLN)

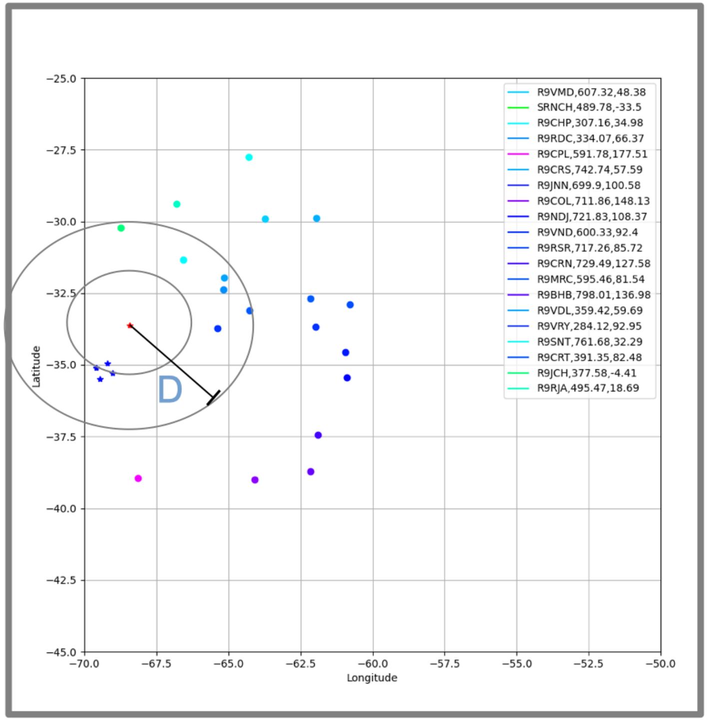


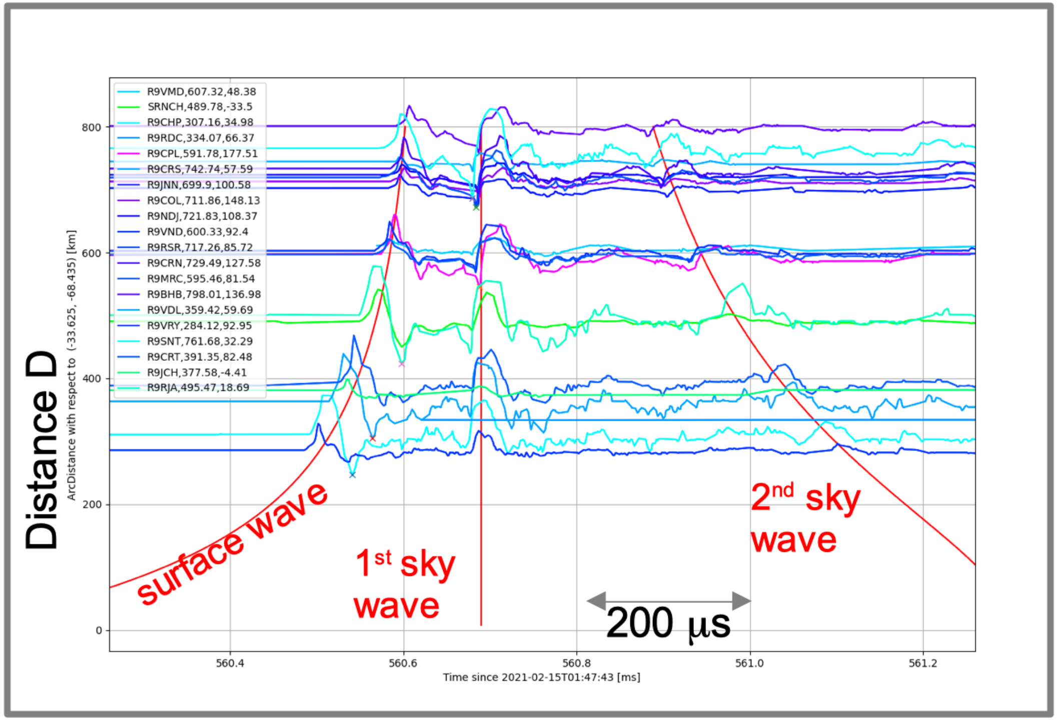


In summer 2018-9 Earth Networks installed >35 antennas in Argentina, with high bandwidth and time resolution.
WWLLN bandwidth: 1-24 kHz ($\Delta T = 40\ \mu s$)
ENTLN bandwidth : 1 Hz – 1.2 Mhz ($\Delta T < 1\ \mu s$

Semi-automated python scripts to align ENTLN traces: time axis corrected for delay from source lightning, calculated from results of elves reconstruction.

ENTLN vs ELVES reconstruction

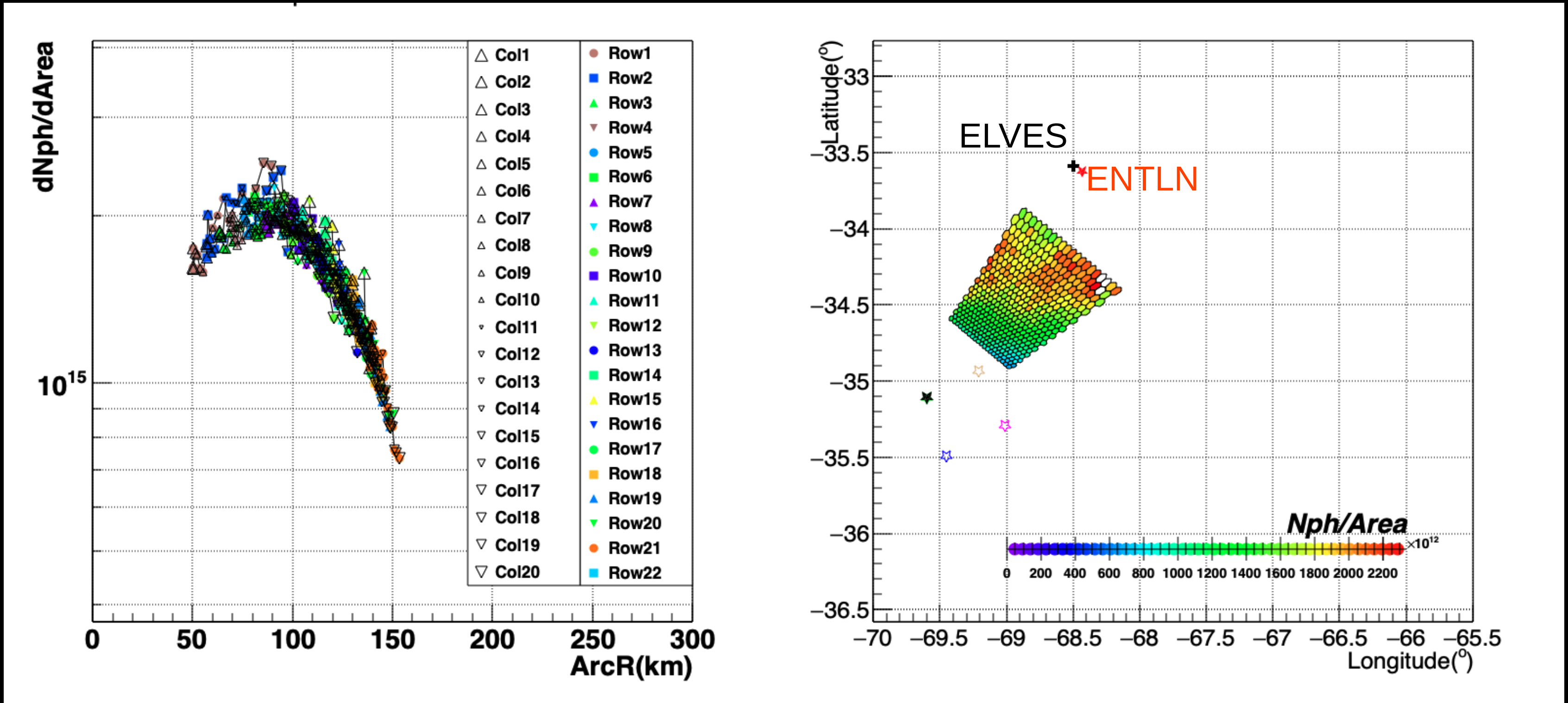




Location of the ENTLN antennas within 800 km around the lightning source location from ENTLN reconstruction. Colors are used to represent the azimuth.

Waveforms in the ENTLN stations. Baseline offsets are now given by the distance of each antenna relative to the source location from ENTLN reconstruction. The time correction accounts for the bounce at the base of the ionosphere (1^{st} sky wave). The second reflection is also visible.

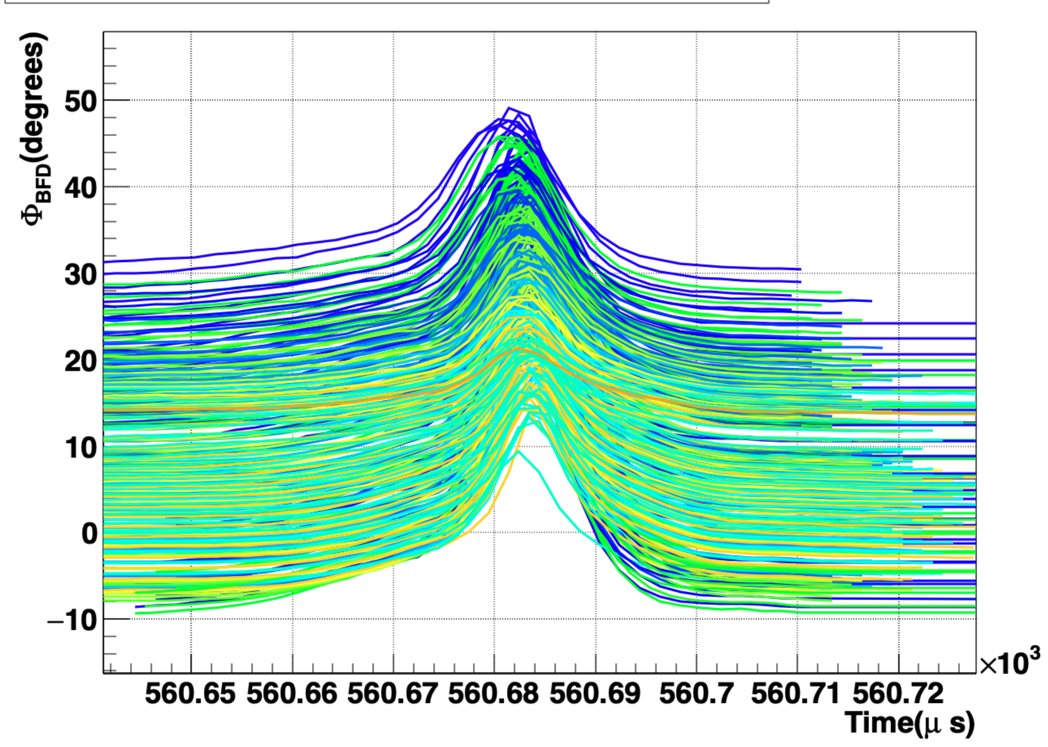
ENTLN vs ELVES reconstruction

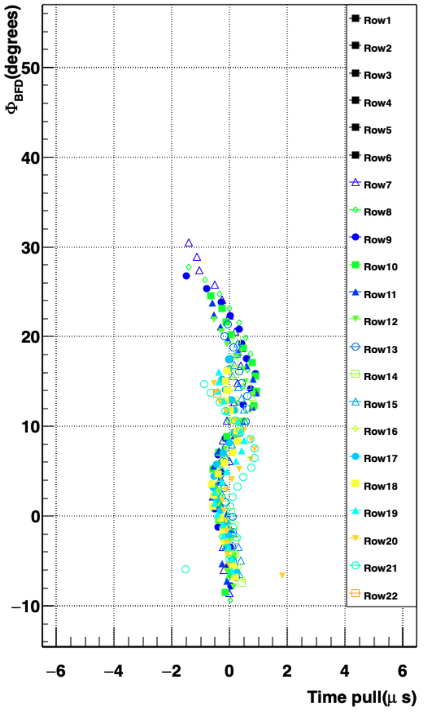


Light intensity distribution vs arc distance from lightning location

Reconstruction of lightning source location from Auger based on a 3D time fit of ELVES signals

ENTLN vs ELVES reconstruction

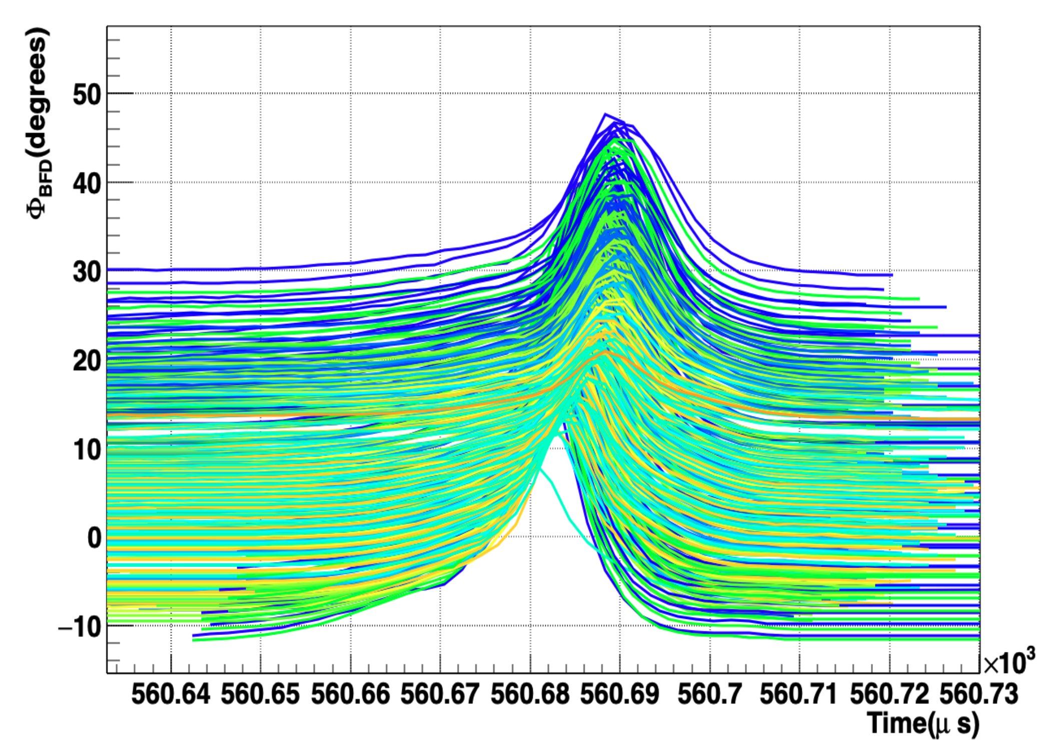




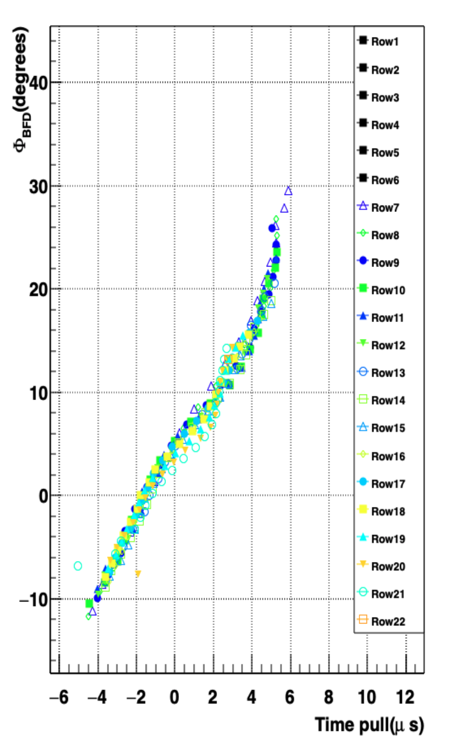
ELVES traces for all pixels realigned at source location, vs azimuth with respect to the vertical plane joining FD and lightning source location from ELVES reconstruction.

Difference between measured time and expected time

ENTLN vs ELVES reconstruction

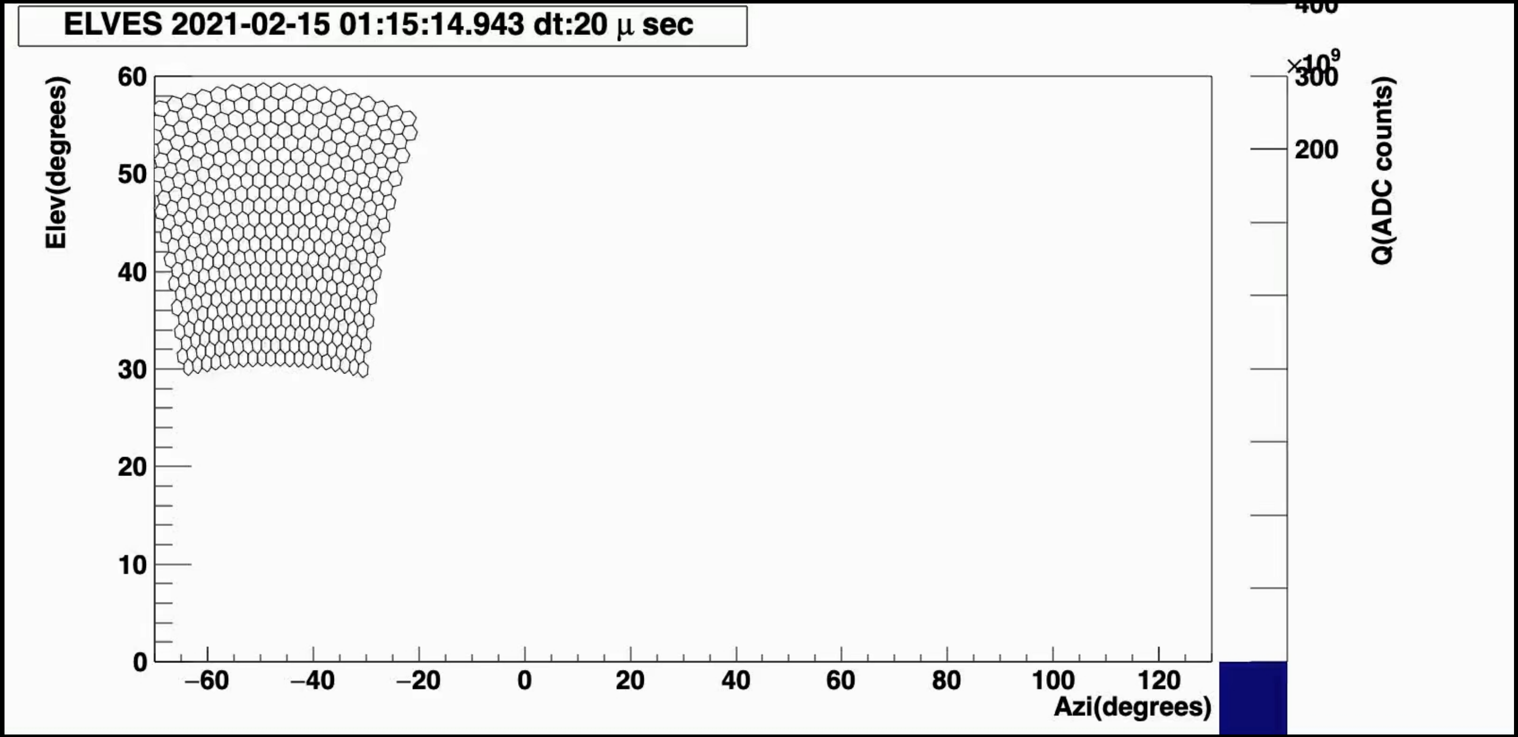


ELVES traces for all pixels realigned at source location, vs azimuth with respect to the vertical plane joining FD and lightning source location from ENTLN reconstruction (5km away)

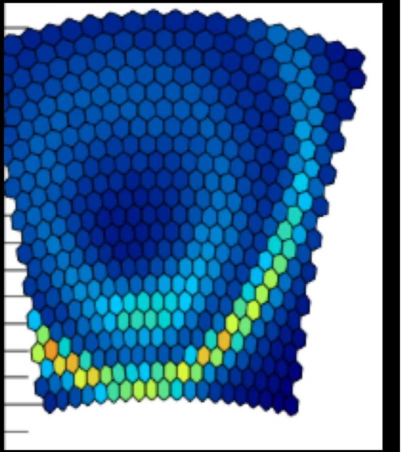


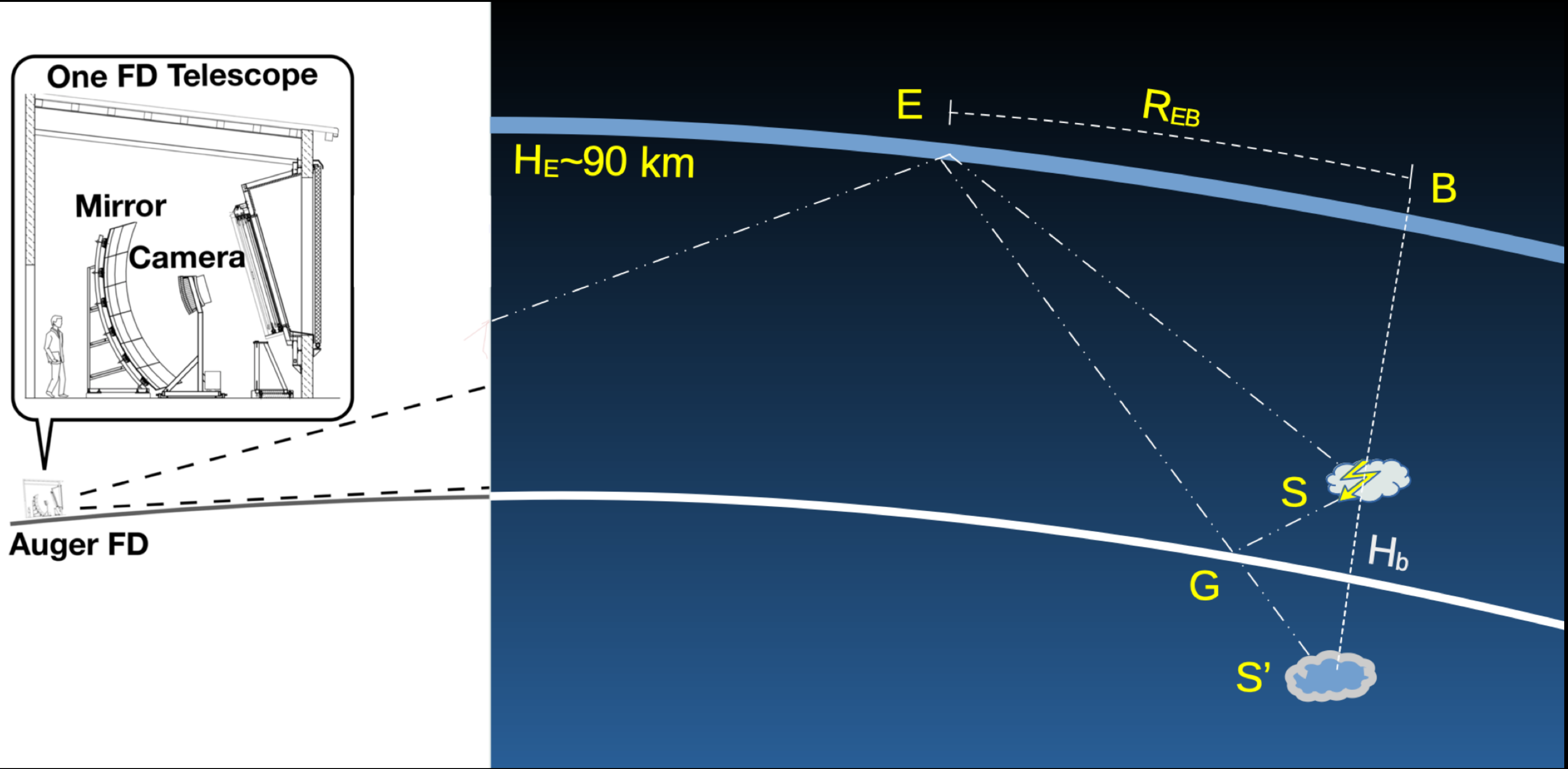
Difference between measured time and expected time

Double ELVES



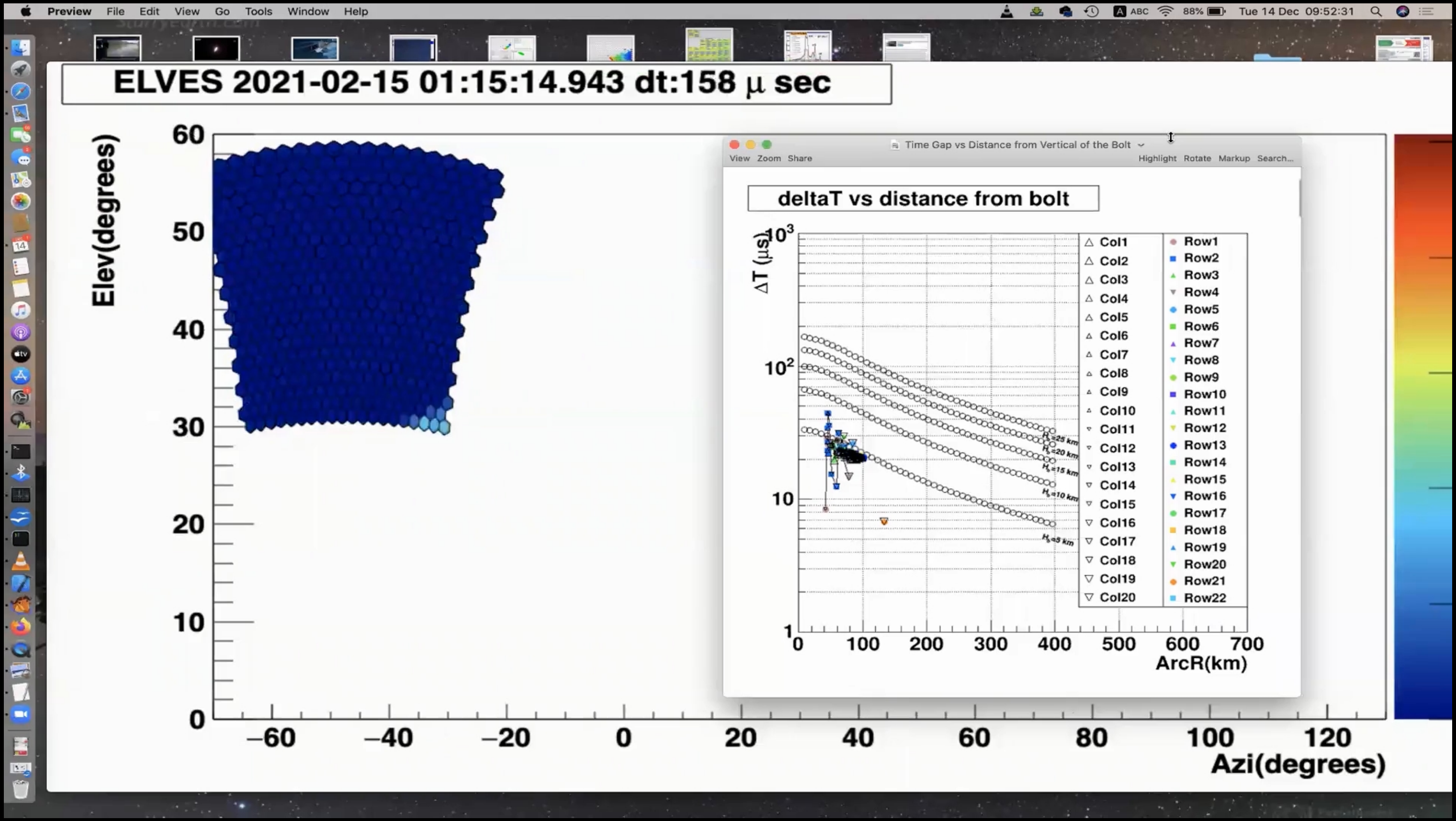
Double ELVES



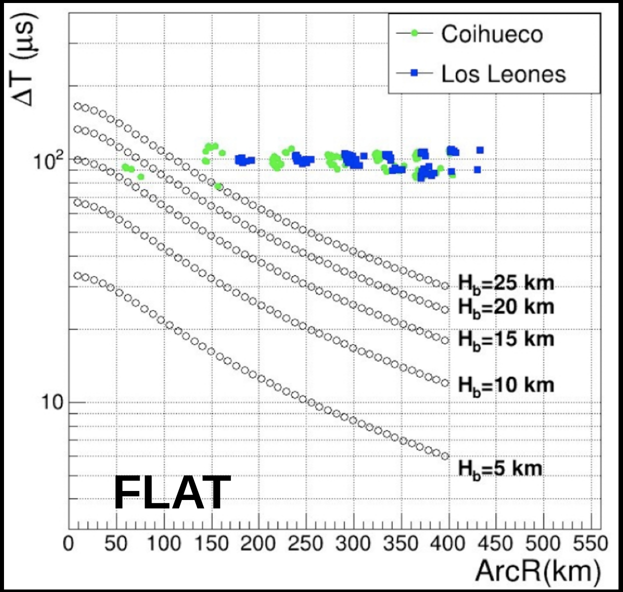


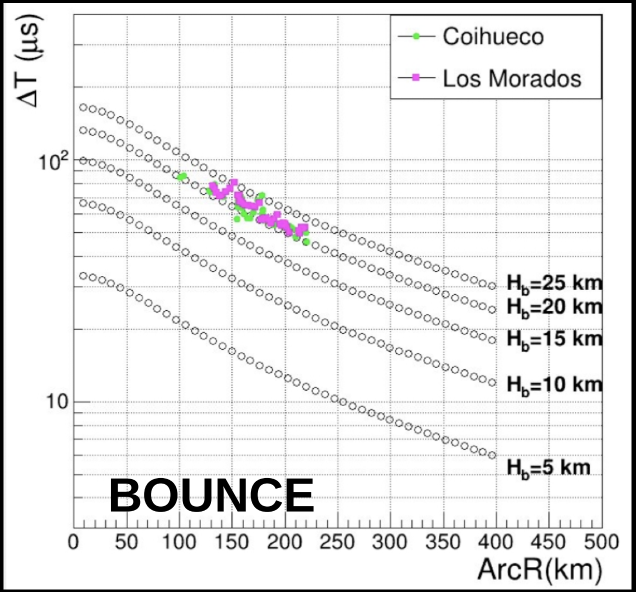
We originally thought that most double ELVES were caused by the ground relection of the EMP from intracloud discharges ....

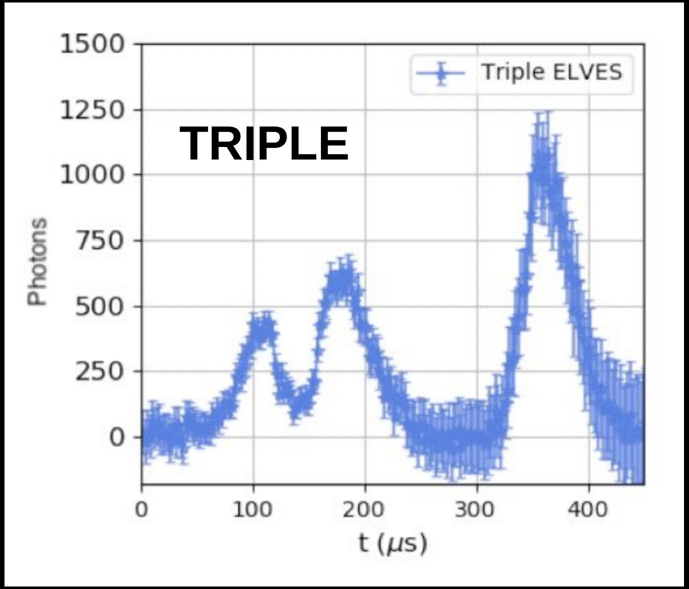
Double ELVES



Multiple ELVES zoology





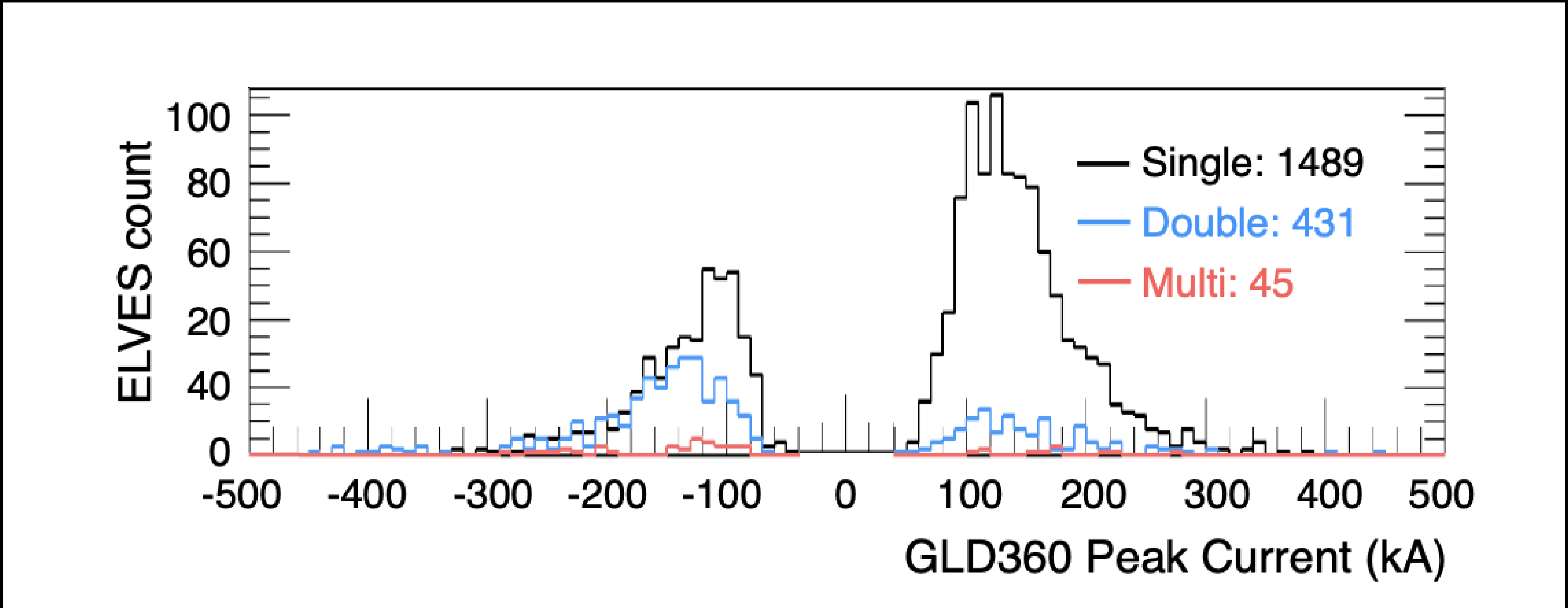


FLAT ΔT : time gaps from 80 to 250 μs , constant vs distance from source lightning

BOUNCE : time gaps decreases with distance
Hardly resolved from low clouds, in far lightning

TRIPLE flashes: <2% of multiple elves: TGF?

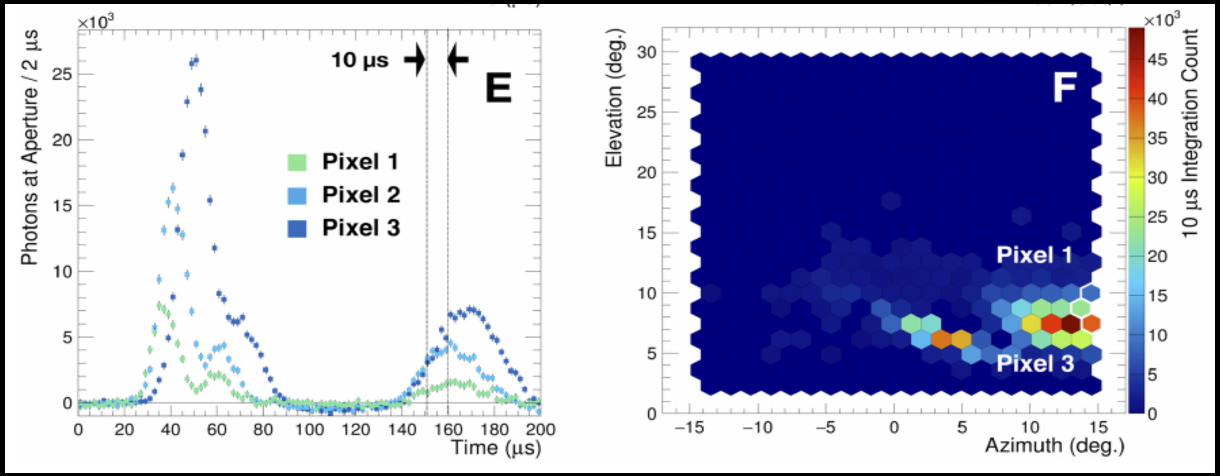
Asymmetries in multiple ELVES

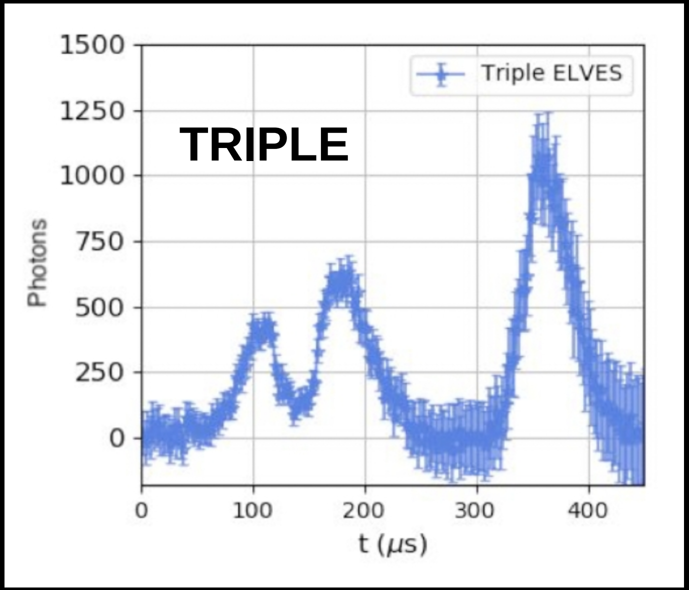


GLD360 peak current for cloud to ground (CG) sources vs correlated ELVES in the period 05/2017-12/2018 .

In the region observed by Auger, the polarity distribution of lightning producing ELVES is asymmetric. And the asymmetry is reversed when double ELVES are observed.

Triple ELVES





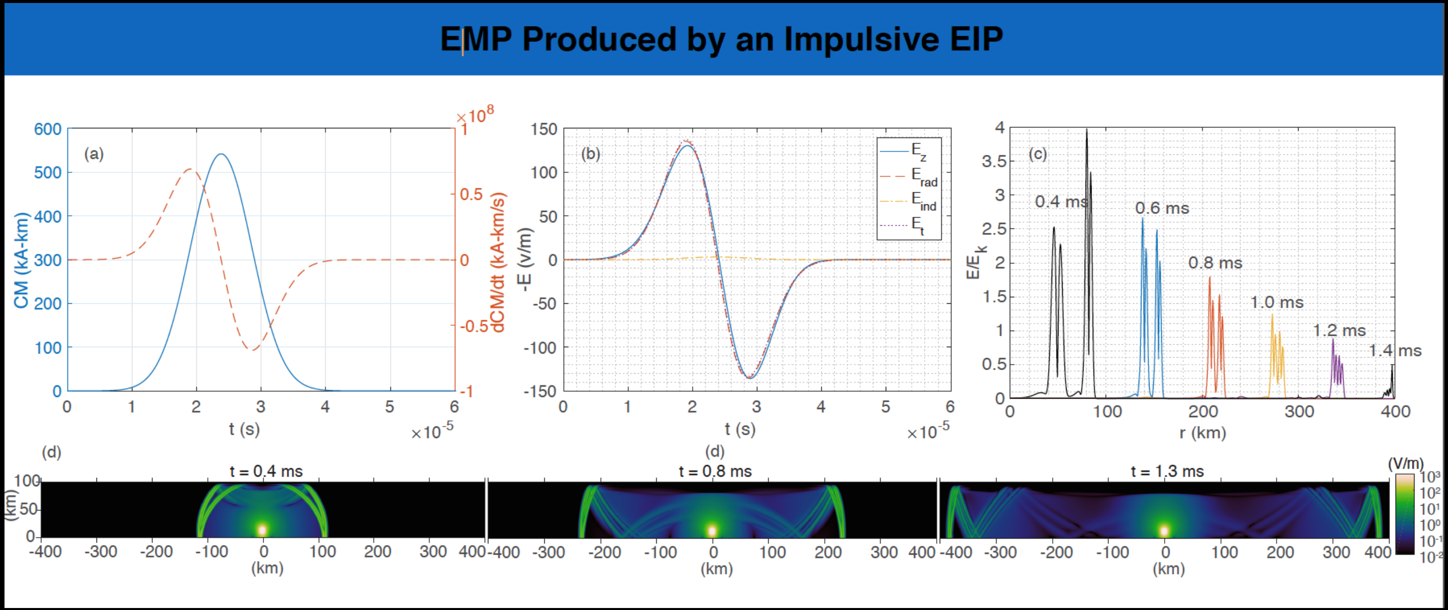
Auger: First observation of a triple elves

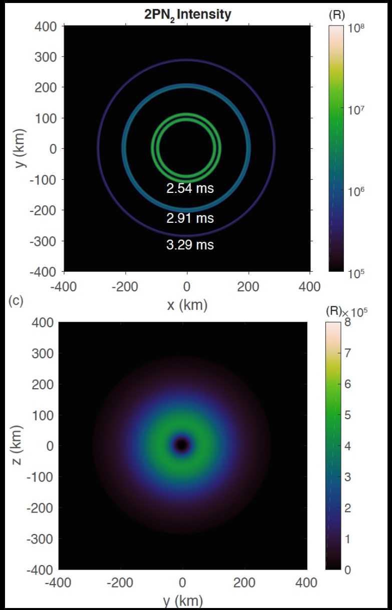
They are probably related to intracloud activity.
Intracloud activity could be associated with the creation of TGFs.

- Could the triple elves be related to TGFs?
- Could we observe ELVES associated with TGFs?

Triple ELVES

Multiple ELVES and TGF





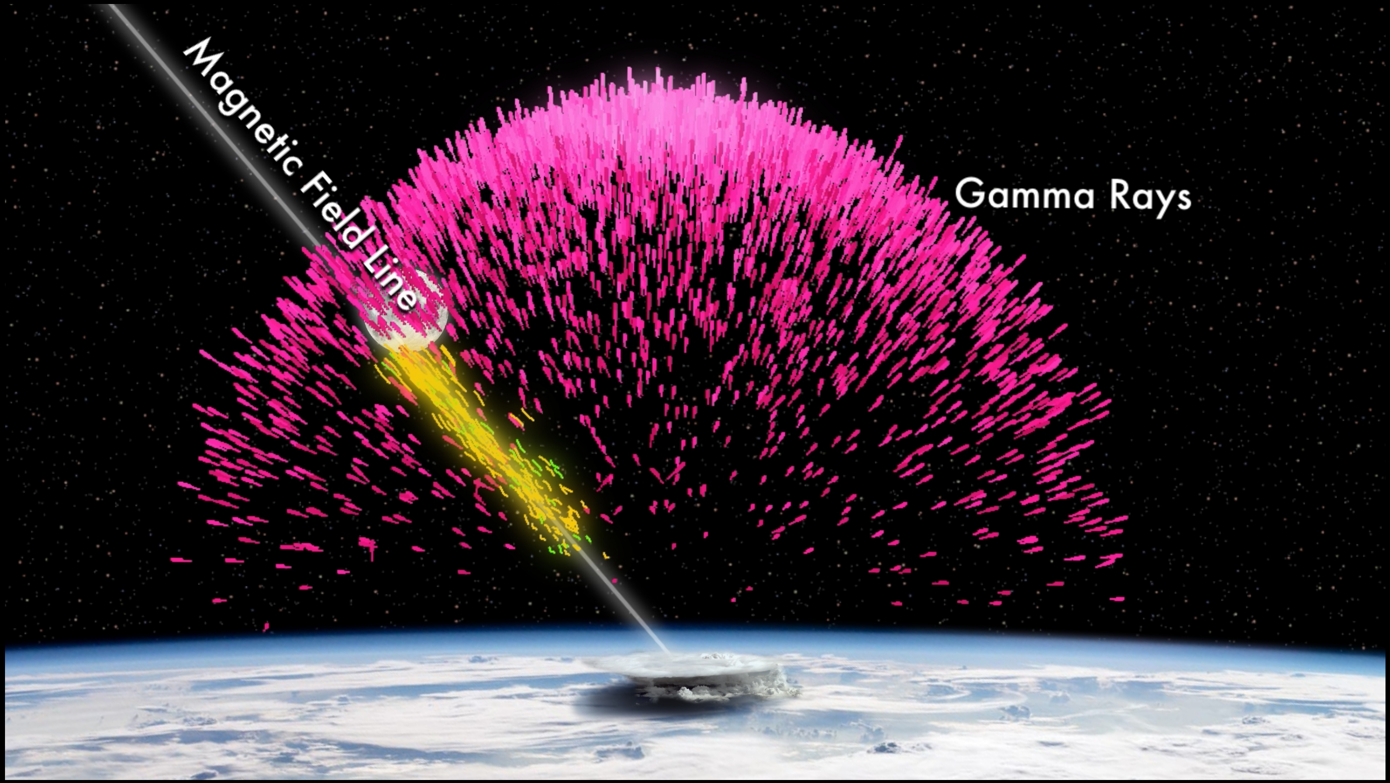
Can we detect TGF ignition at ground with the associated TLE?
What are its spectral properties?
What's its pulse duration?
Sources:

- NBE (Narrow Bipolar Events)
- EIP (Energetic In-cloud Pulses)
- CG (Cloud to Ground Lightning)

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

Terrestrial Gamma-ray Flashes (TGFs)

intense sub-millisecond (20 μs → 1 ms) 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

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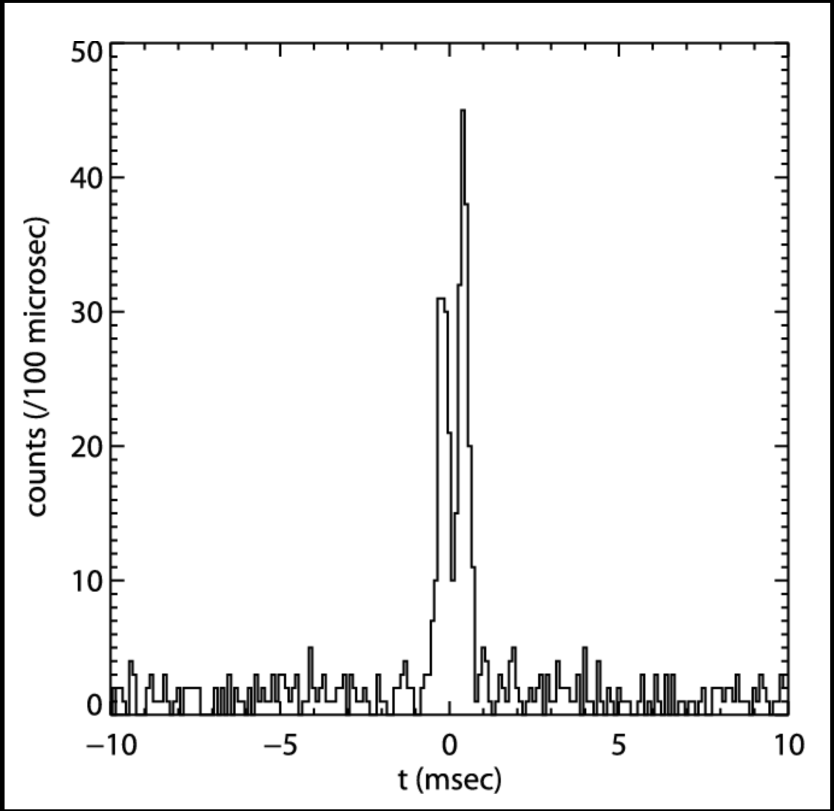


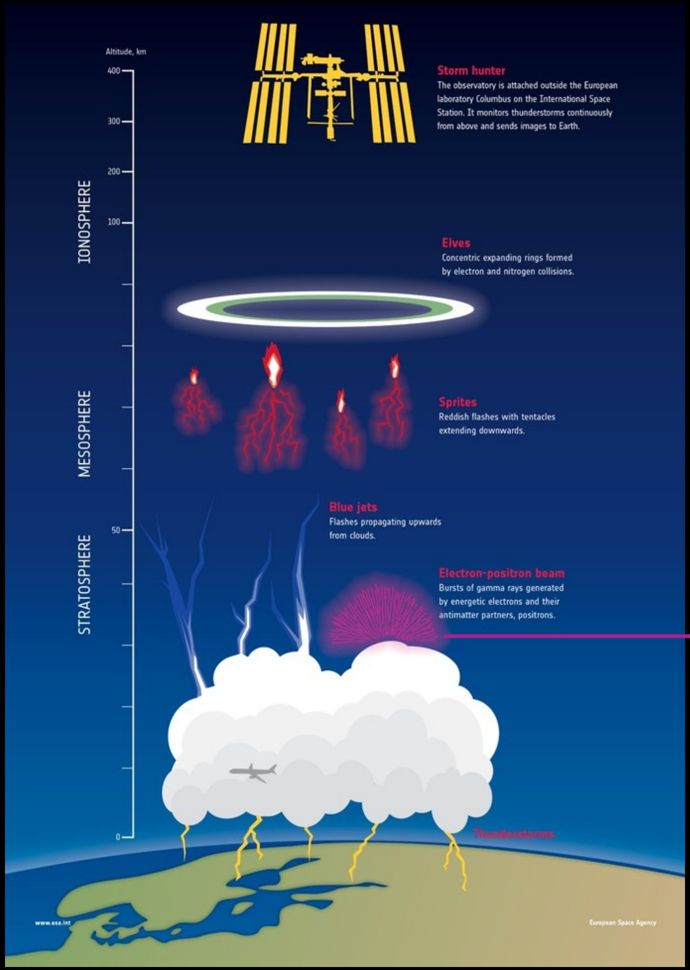
GRBs last few seconds.

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

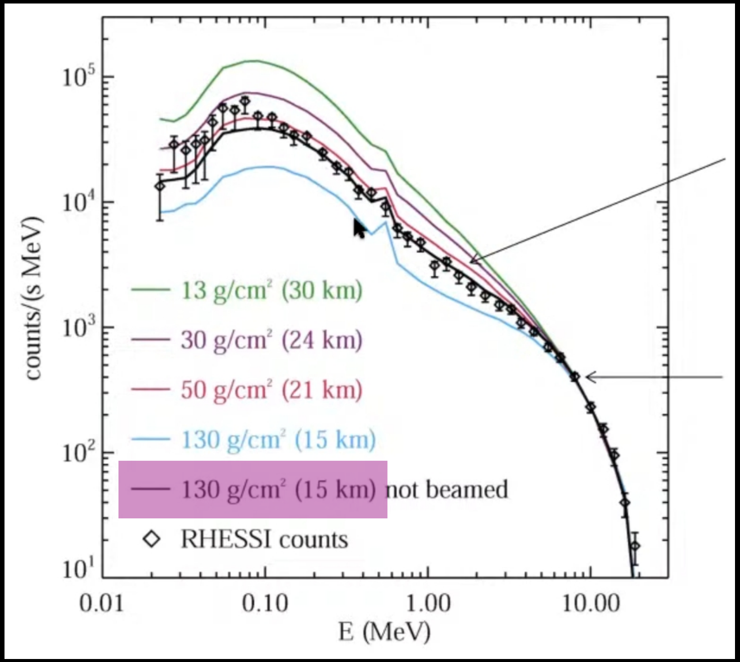
“Detectors aboard the Compton Gamma Ray Observatory have observed an unexplained terrestrial phenomenon: brief, intense flashes of gamma rays. These flashes must originate in the atmosphere at altitudes above at least 30 kilometers in order to escape atmospheric absorption and reach the orbiting detectors.”

→ 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).

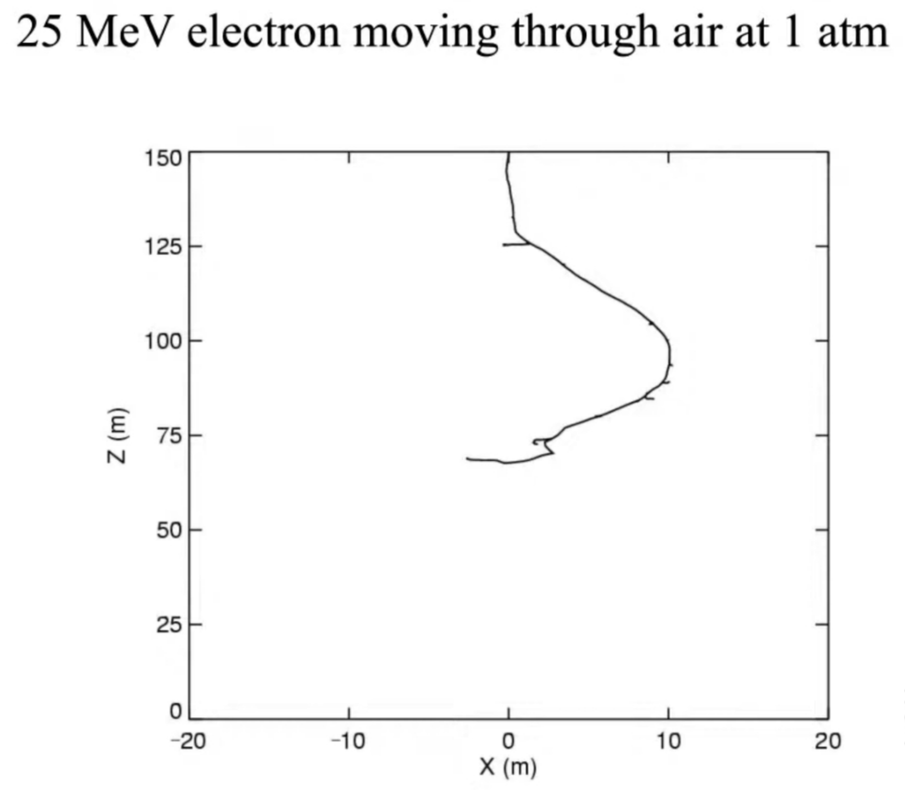


TGF spectrum too flat > 1 MeV to be from a high source altitude

TGF spectrum fits RREA model well up to 20 MeV

Relativistic Runaway Electron Avalanche (RREA) model

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



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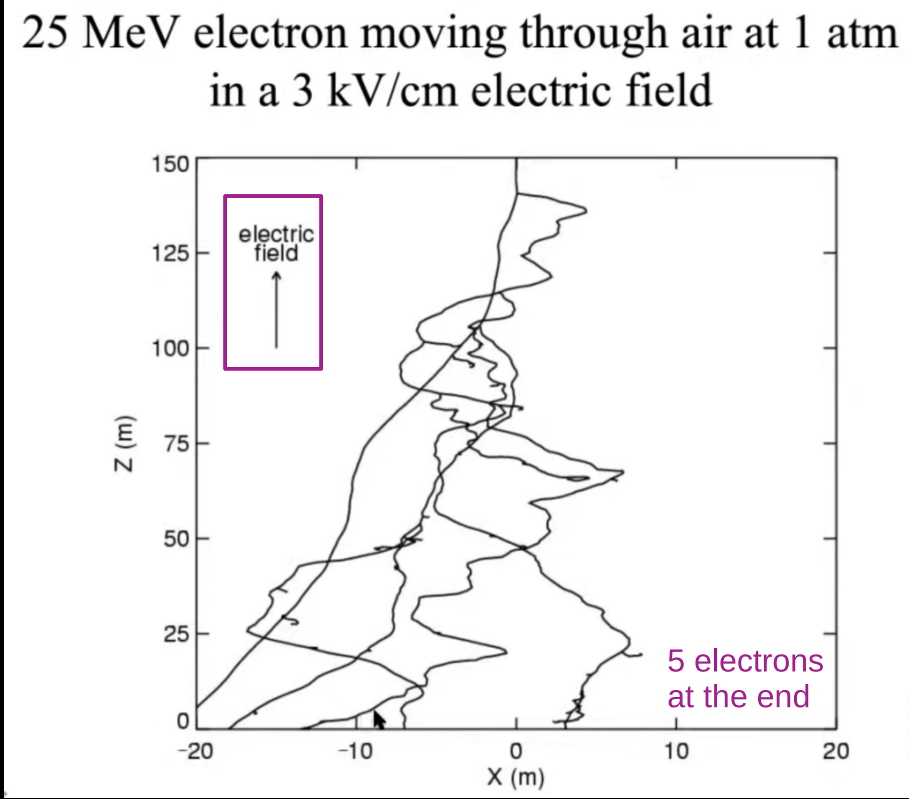

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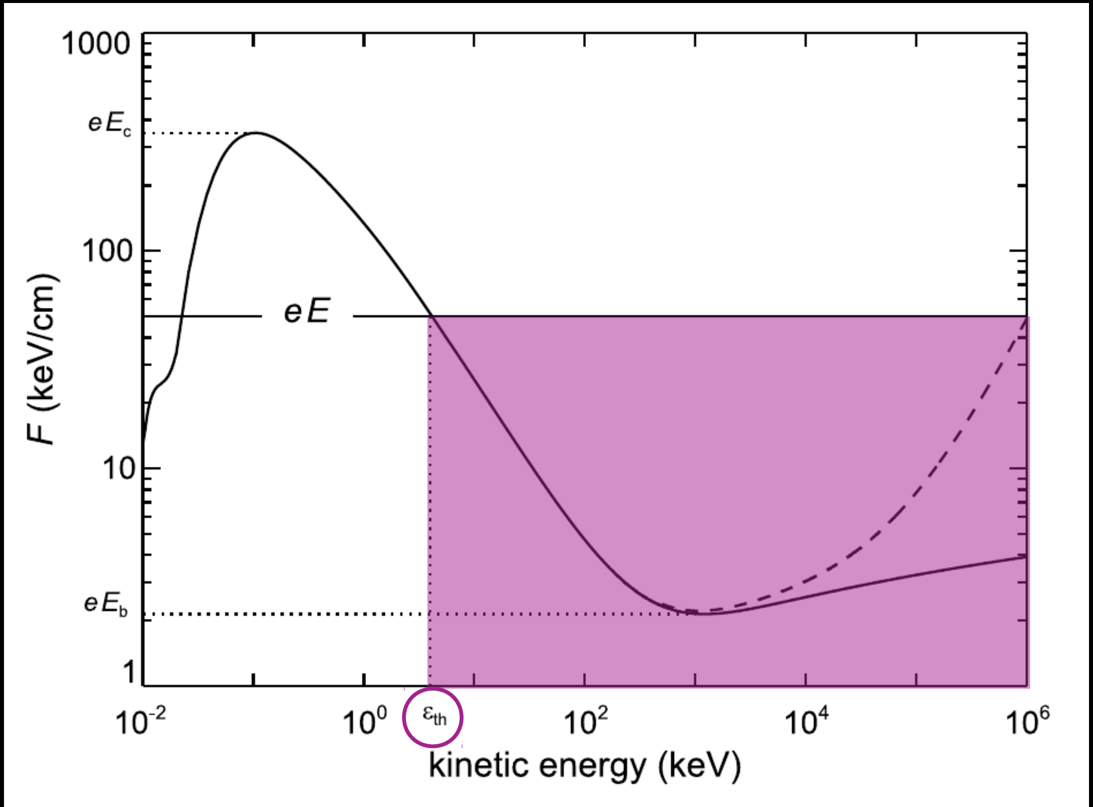


Figure shows the effective frictional force or rate of energy loss of an energetic electron moving in air.

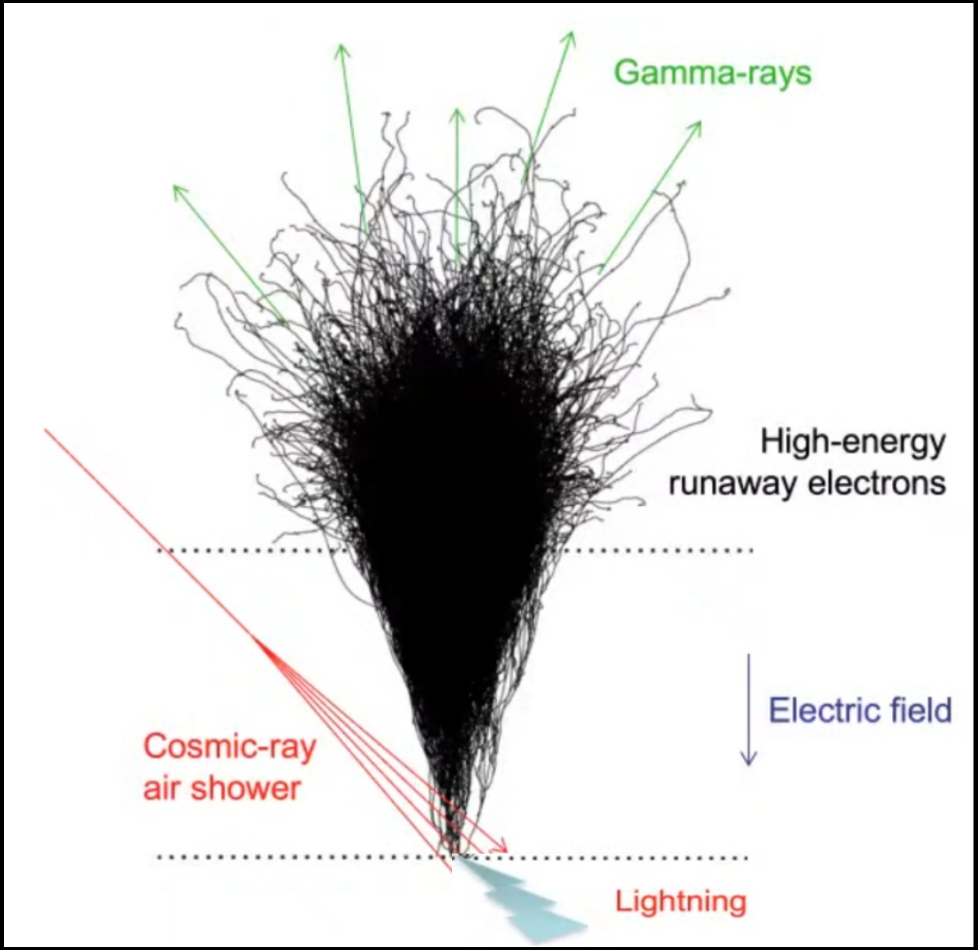
The horizontal line shows the rate of energy gain from a strong electric field.

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} .

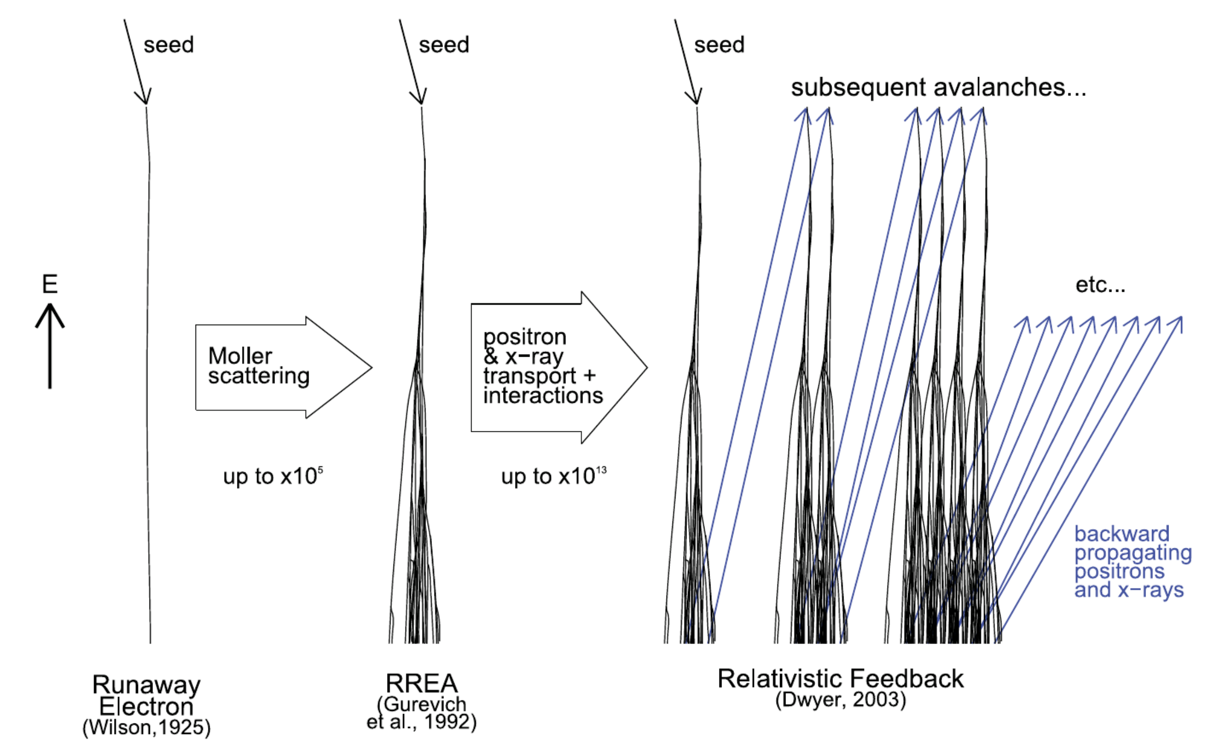
Such energetic "seed" electron, with energies above ε_{th}, may be provided from an external source.

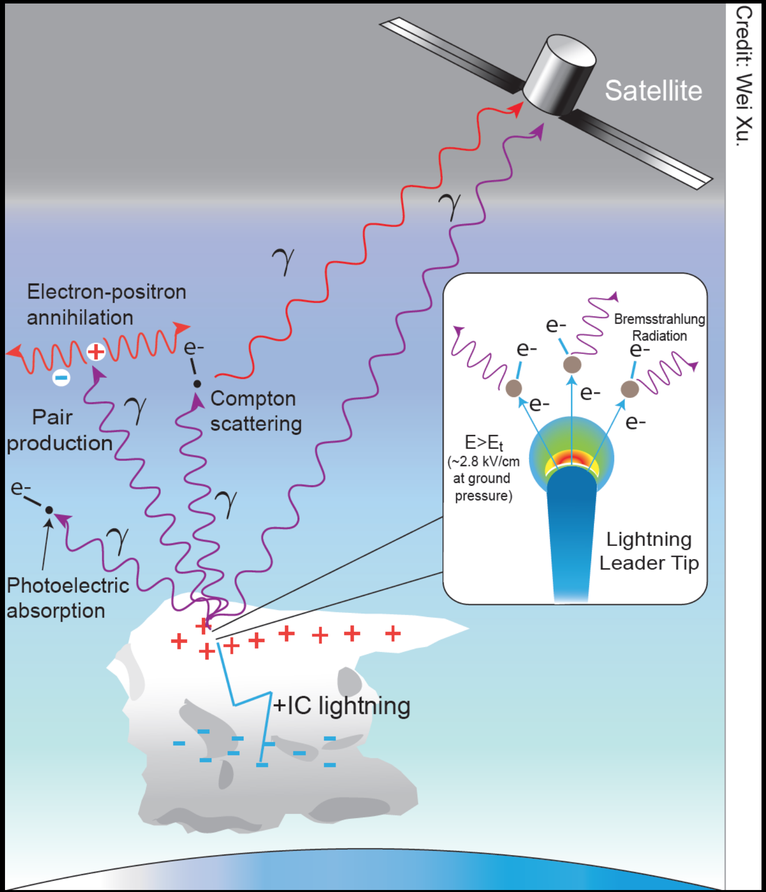
What could be the external sources?



- Cosmic-ray air showers
- Radioactive decays
- Lightning

Evolutions of the models





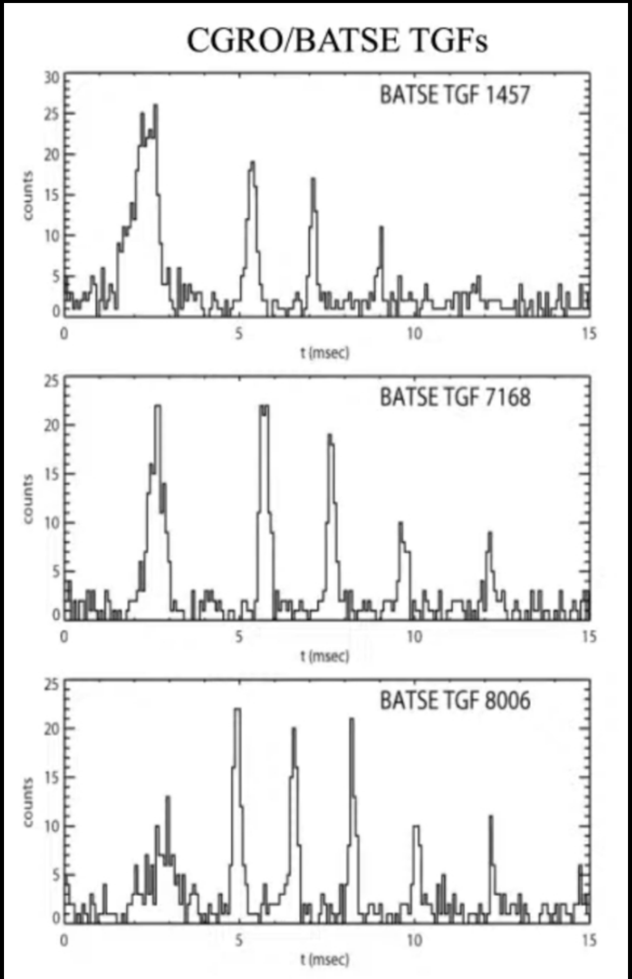
TGF production model

Runaway electrons are ubiquitous in plasmas and gaseous media in which electric fields are present. According to the Relativistic Runaway Electron Avalanche (RREA) model, an avalanche of relativistic runaway electrons is generated via hard elastic scattering of runaway electrons with atomic electrons in the gas. The threshold electric field for the production of runaway avalanches is E_{th}=284 kV/m for air at the sea level.

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.

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.

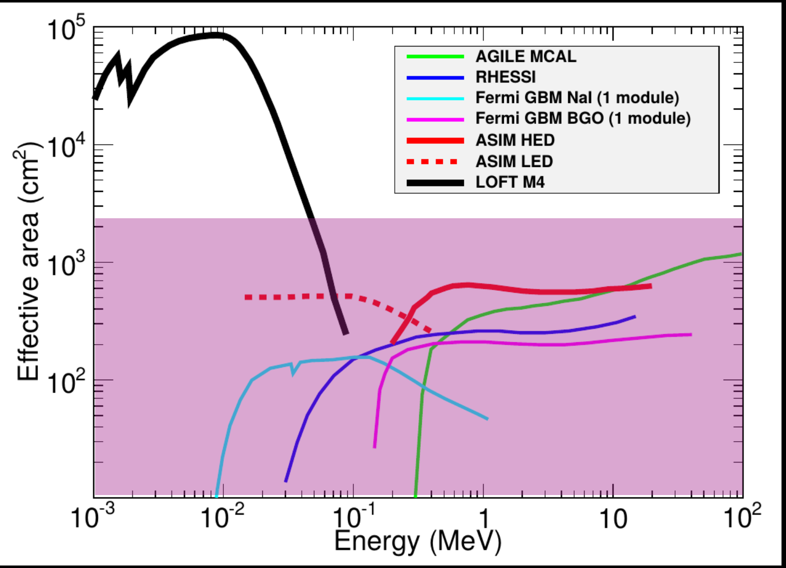
A small fraction have two pulses, and an even smaller fraction have three or more with a total duration sometimes reaching several ms.

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

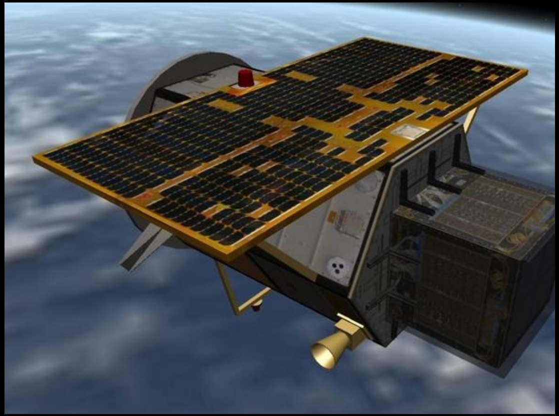
→ For the relativistic feedback discharge model, multi-pulsed TGFs naturally occur as the discharge oscillates above and below the feedback threshold.

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 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 ~100 MeV) → 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.



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.

https://doi.org/10.1007/s12210-019-00762-3

AGILE and Meteorological Studies

Rendiconti Lincei. Scienze Fisiche e Naturali (2019) 30 (Suppl 1):S259–S263
https://doi.org/10.1007/s12210-019-00775-y

A DECADE OF AGILE

Check for updates

Gamma ray storms: preliminary meteorological analysis of AGILE TGFs

Meteorology of AGILE TGF observations

Alessandra Tiberia[1] · Stefano Dietrich[2] · Federico Porcù[3] · Martino Marisaldi[4] · Alessandro Ursi[5] · Marco Tavani[5]

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Abstract
Despite the recognition from their discovery that terrestrial gamma ray flashes (TGFs) originate from thunderstorms, little is known about the TGF-producing storms. The characteristics of such thunderstorms are investigated here using meteorological data, with the aim to set up a framework of analysis to be propagated to more complete TGF archives. In this work, we present the preliminary results. As first analysis, we considered 72 events detected by the Astrorivelatore Gamma ad Immagini Leggero (AGILE) from March 2015 to June 2015, estimating their electric activity in terms of flash production. To this end, we examined World Wide Lightning Location Network lightning data in the spatial and temporal proximity of each AGILE TGFs, searching for relationship between flash rate peak and distribution and the TGF occurrence. Moreover, we analyzed the low-Earth orbiting (LEO) satellite observation of the TGF-producing storms to define, through the capabilities of microwave sensors (both active and passive), the structure of the convective storms correlated with TGF events. In particular, we focused on the Global Precipitation Measurement (GPM) observations and show here a case study observed by the dual-frequency

Not all thunderstorms produce TGFs.

Meteorological studies are another important key to better understand the TGFs production mechanisms.

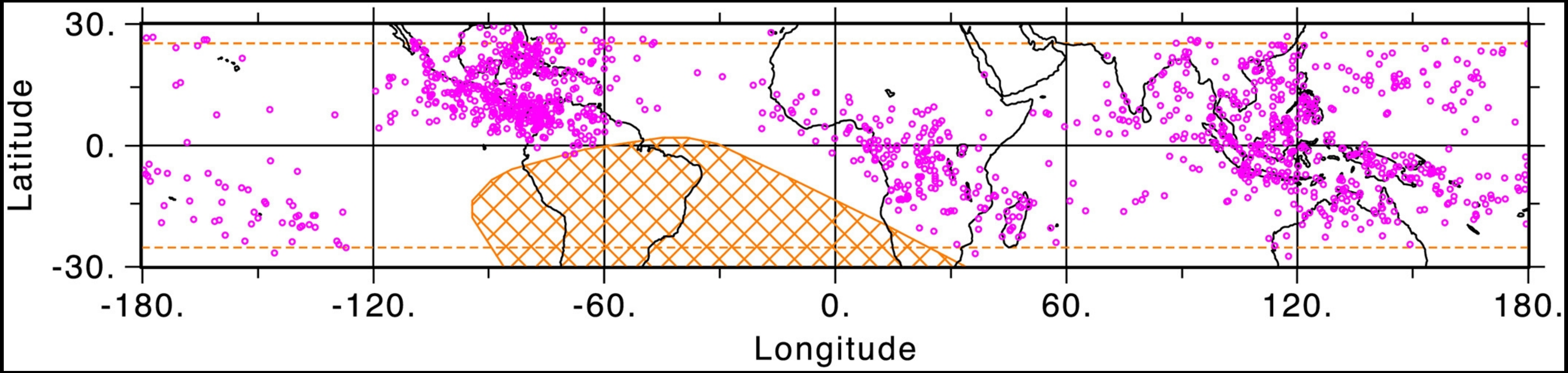
Data used in the study:
→ ERA5 Reanalysis Data
→ GPS
→ Lightning by WWLLN (World Wide Lightning Location Network)
→ GOES (Geostationary Satellite Observation)

TGFs mainly occure in convective environments
→ an increase in PWV (Precipitable Water Vapor) is observed on a timescale of about two hours before the TGF occurrence.

FERMI

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

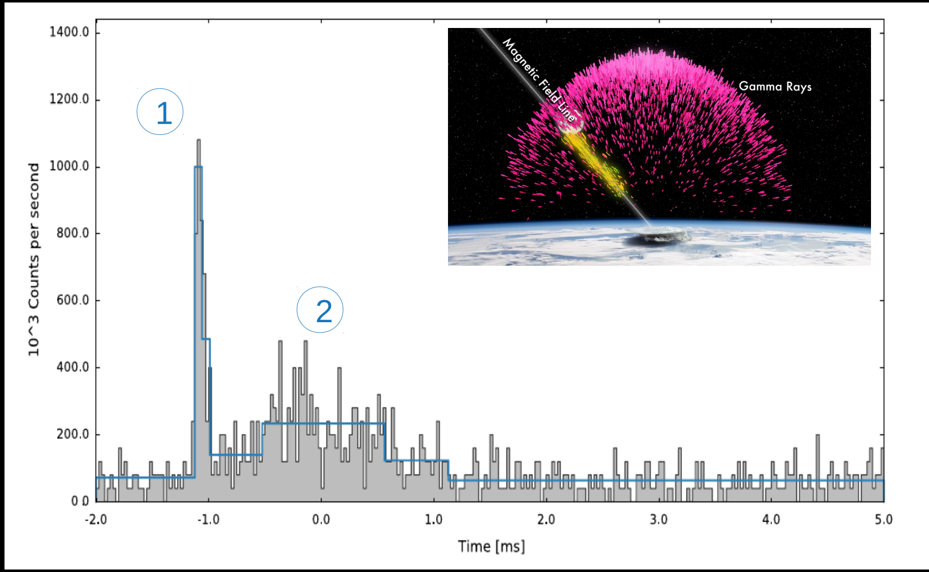
The 1st GBM TGF catalog: contains 4144 TGFs detected between 2008 July 11 and 2016 July 31
→ TGFs bright enough to trigger on board
→ TGFs recovered in an offline search for weaker events (>80%).
→ It also includes an associations table containing results for 1544 TGFs for which temporally-coincident 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.

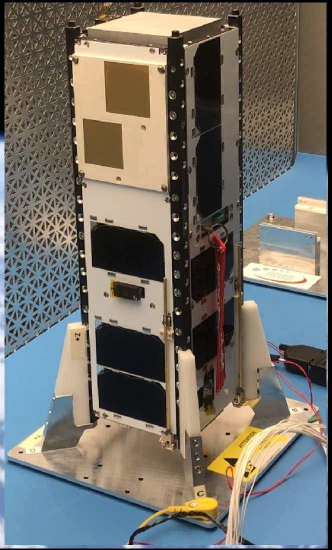
From these findings we can summarize the following:
1. The distribution of duration has a maximum in the 20-40 μs range and a median of 45.5 μs, which is significantly shorter than previously reported from space observations.
2. Due to the very good detection capability of ASIM, we have identified fine 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 ± 80 μs 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 (± 80 μs).

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



Deployment from ISS on 2022-02-03

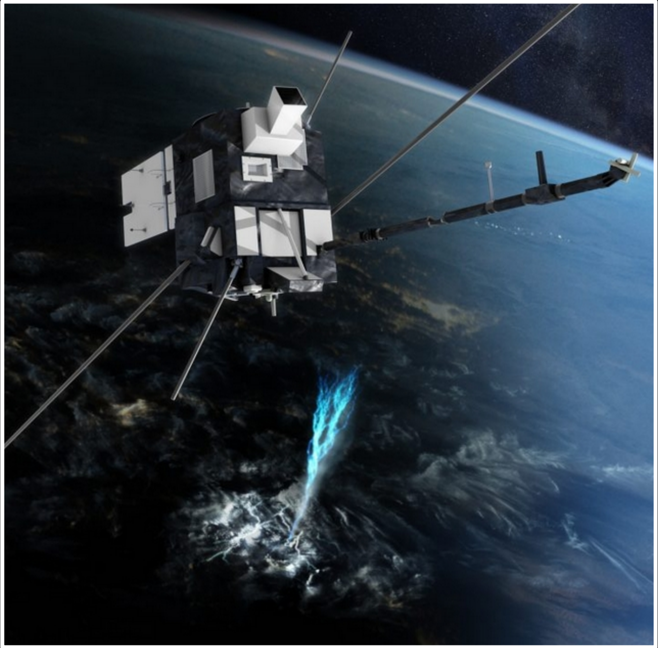
A CubeSat for the detection of X- and gamma-ray components of a TGF event

→ 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.

TARANIS 2

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

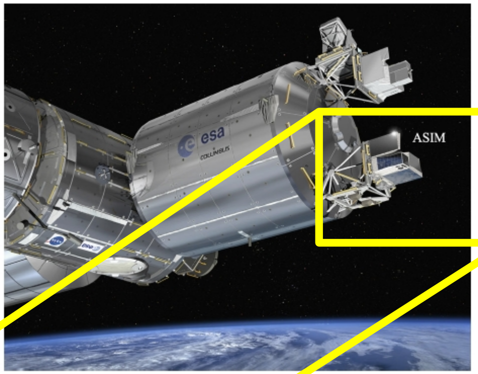
The goal is to launch TARANIS in 2025!

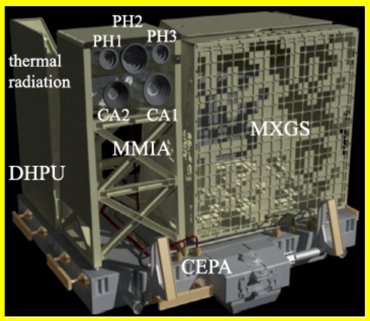


TLEs and TGFs observations	Locate geographical positions and altitudes of TLEs and TGFs source regions Model variations with LT, season, activity indices, etc.
Environmental conditions	Identify parent lightning flashes and associated EM emissions Investigate possible correlations with cosmic rays, micrometeorites, 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

Lefeuvre, F., Blanc, E., Pinçon, JL. et al. . Space Sci Rev 137, 301–315 (2008).

ASIM: ELVES-TGF Correlation





Science

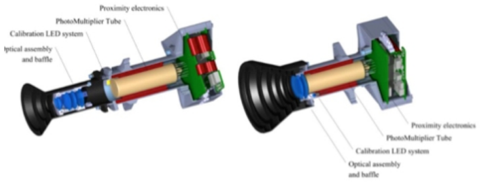
Cite as: T. Neubert *et al.*, *Science* 10.1126/science.aax3872 (2019).

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

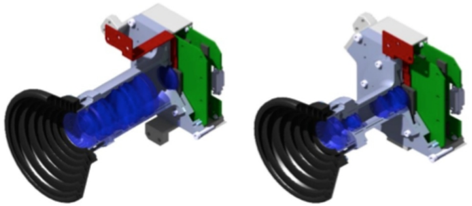
Torsten Neubert[1]*, Nikolai Østgaard[2], Victor Reglero[3], Olivier Chanrion[1], Matthias Heumesser[1], Krystallia Dimitriadou[1], Freddy Christiansen[1], Carl Budtz-Jørgensen[1], Irfan Kuvvetli[1], Ib Lundgaard Rasmussen[1], Andrey Mezentsev[2], Martino Marisaldi[2,4], Kjetil Ullaland[2], Georgi Genov[2], Shiming Yang[2], Pavlo Kochkin[2], Javier Navarro-Gonzalez[3], Paul H. Connell[3], Chris J. Eyles[3]

ASIM mission on ISS

- MMIA
(running at night)

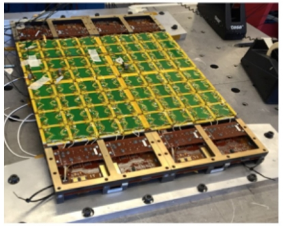


Three photometers
- PHOT 1: 337.0 nm/5 nm (TLE and lightning/streamers)
- PHOT 2: 180-230 nm (mostly TLE)
- PHOT 3: 777.4 nm/5 nm (mostly lightning/leaders)
- 100 kHz sampling (photon counting)

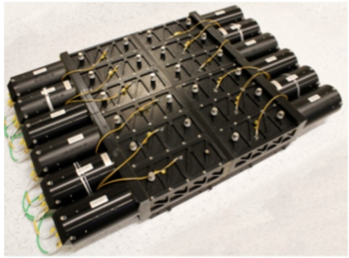


Two cameras
- 12 frames/s
- 60^o x 60^o FOV (80^o diagonal)
- ~400 m spatial resolution (1000x1000 pixels)
- CHU 1: 337.0 nm/5 nm (TLE/lightning)
- CHU 2: 777.2 nm/5 nm (mostly lightning)
- CCD with on-chip amplification (no intensifier)

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



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_{geom} 1024 cm^2



High-Energy Detector (HED) 0.4-40 MeV
- Primary TGF detector
- Characterizes the TGF high-energy spectrum
- BGO crystals A_{geom} 900 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^o

ELVES and TGFs

Science REPORTS

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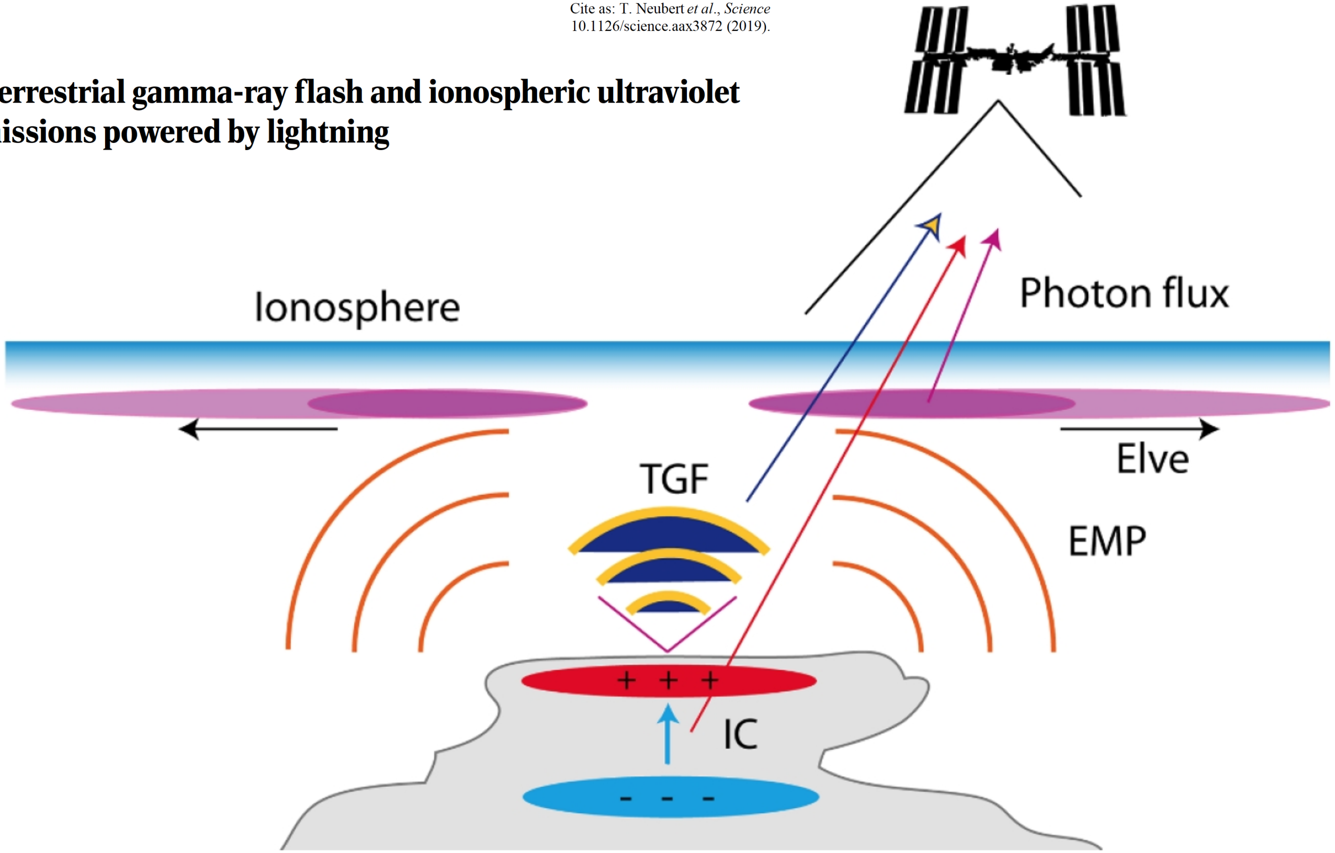
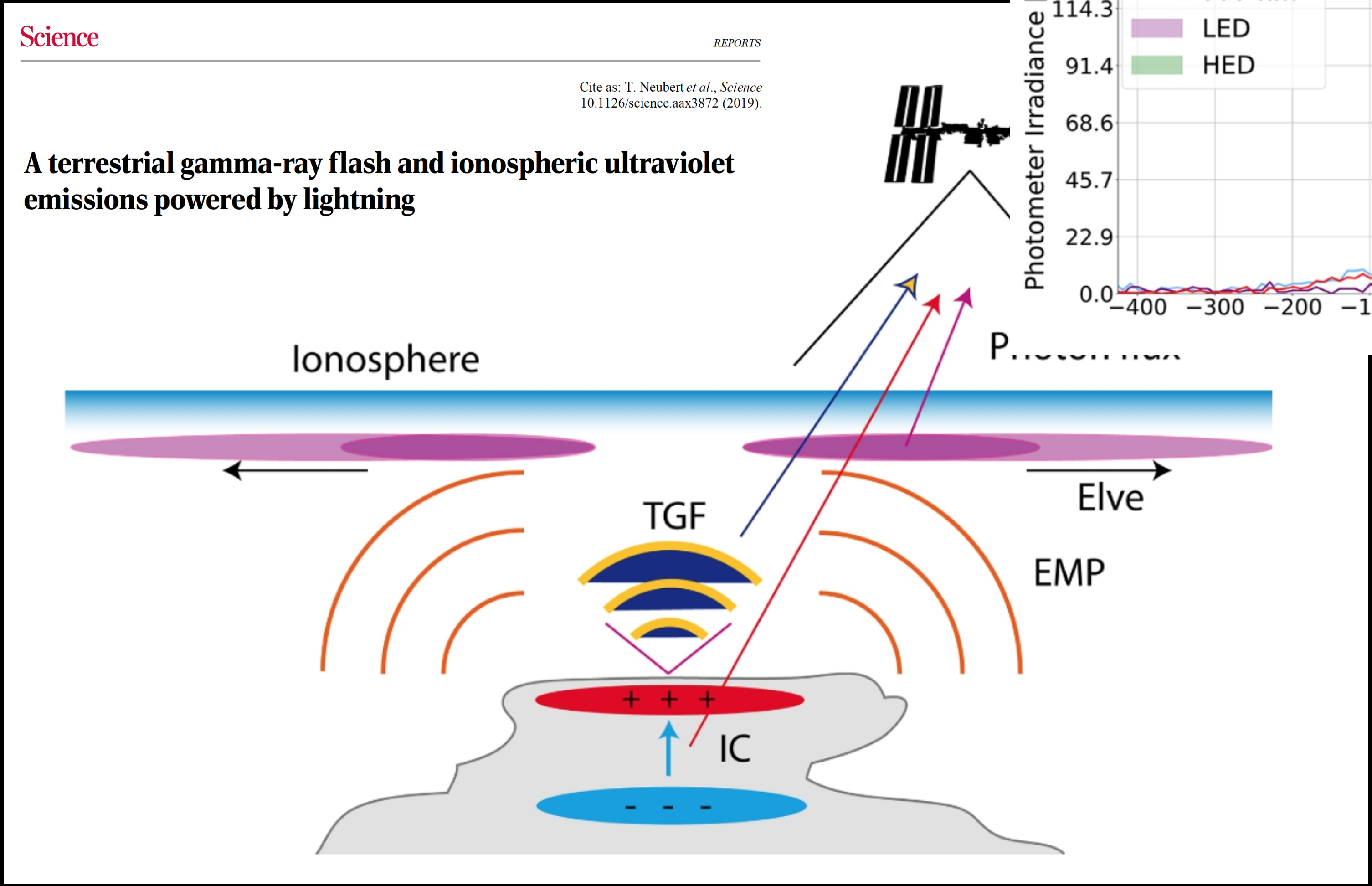
A terrestrial gamma-ray flash and ionospheric ultraviolet emissions powered by lightning

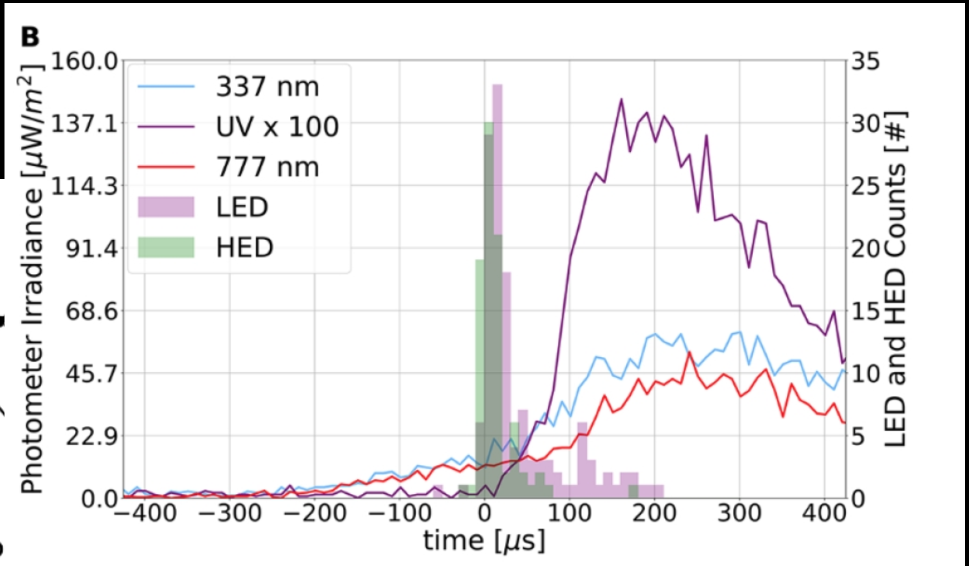


ELVES and TGFs

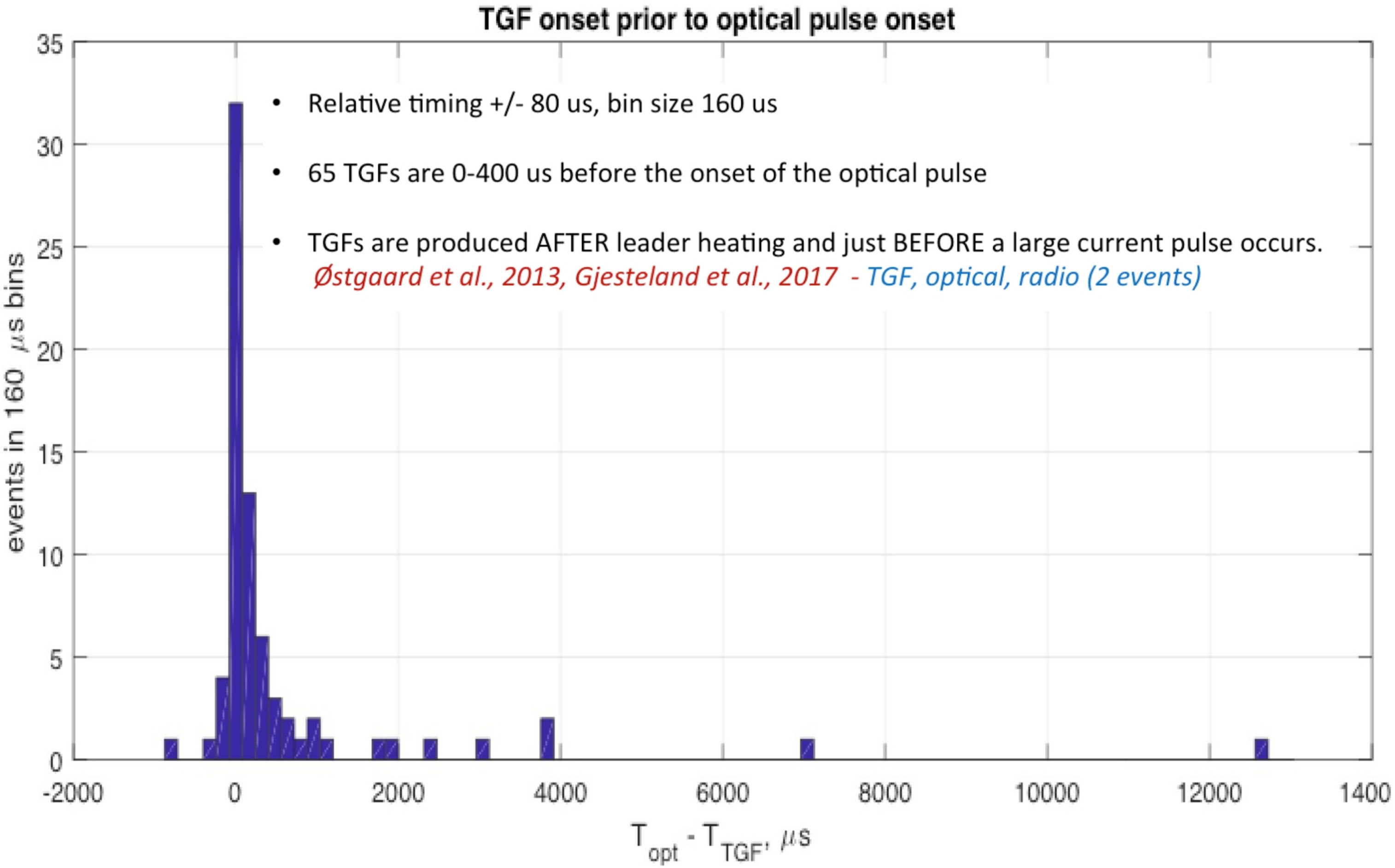

Science REPORTS

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

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

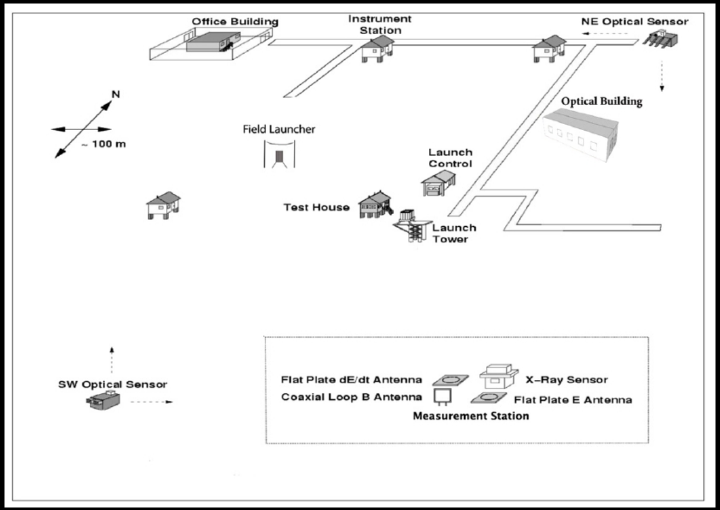


TGF/Optical correlated observations: 74(out of 94 events)



TGFs from ground

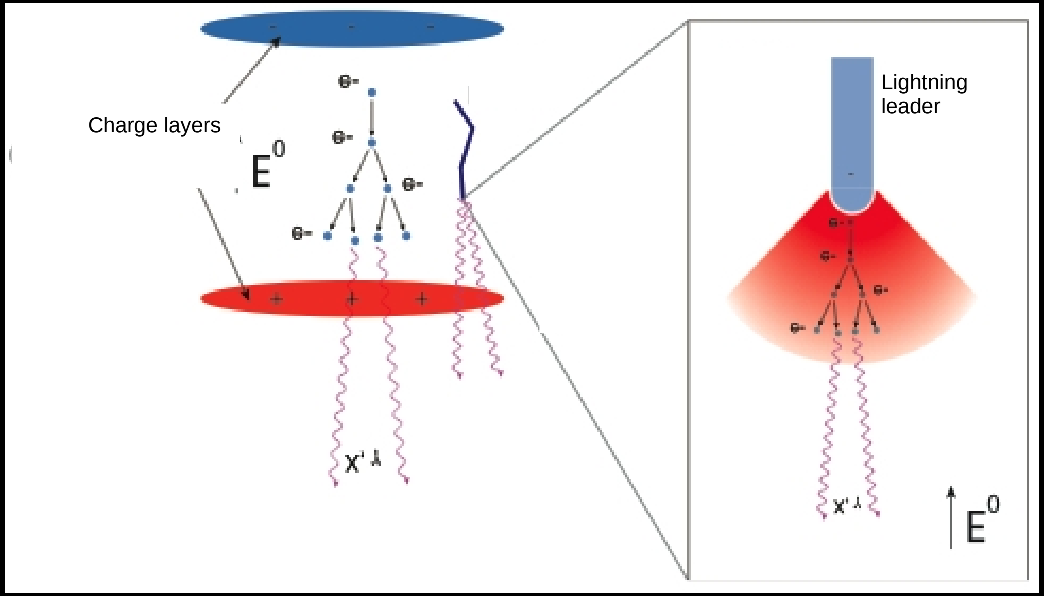
First observation of TGFs from ground
→ TGF associated with a 2003 classically triggered lightning flash at the International Center for Lightning Research and Testing (ICLRT) in North Central Florida - doi:10.1029/2003GL018771



→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.

Downward TGFs



More recent indication of downward TGFs, occurring during strong initial breakdown pulses in the first few milliseconds of negative cloud-to-ground and low-altitude intra-cloud flashes

- J. W. Belz for Telescope Array Collaboration, https://doi.org/10.1029/2019JD031940

→ first high-resolution observations of downward-directed terrestrial gamma-ray flashes (TGFs) detected by the large-area Telescope Array cosmic ray observatory, obtained in conjunction with broadband VHF interferometer and fast electric field change measurements of the parent discharge;

- Y. Wada et al. - GROWTH Collaboration, Phys. Commun. 2 (2019) 67)

The Importance of Downward TGFs

Ground-based observations of downward TGFs:

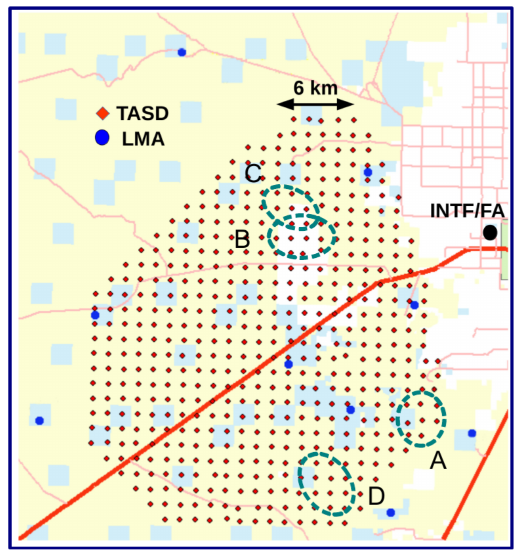
- allow to perform detailed lightning measurements at the same time;
- address a greater variety of TGF-associated lightning discharges;
- allow detailed observations making use of many independent detectors;
- allow to perform measurements close to the source (thus getting measurements more sensitive to the source geometry), which is likely going to be decisive in discriminating between models proposed in the literature.

TGFs @ Telescope Array

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.

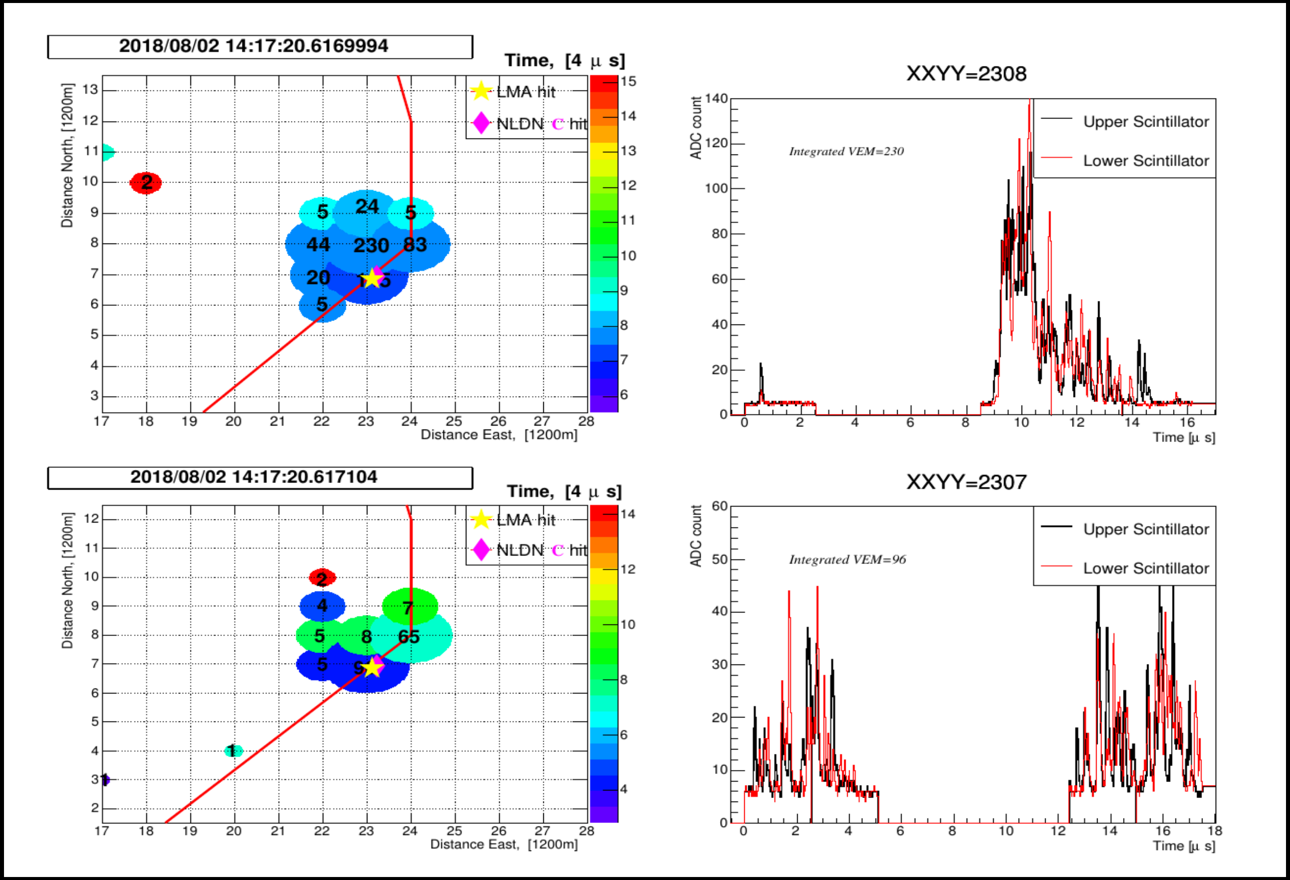


The combined use of all these instruments
+ dedicated simulations
led to an advanced understanding of events initially detected by the only TASD

TGFs @ Telescope Array

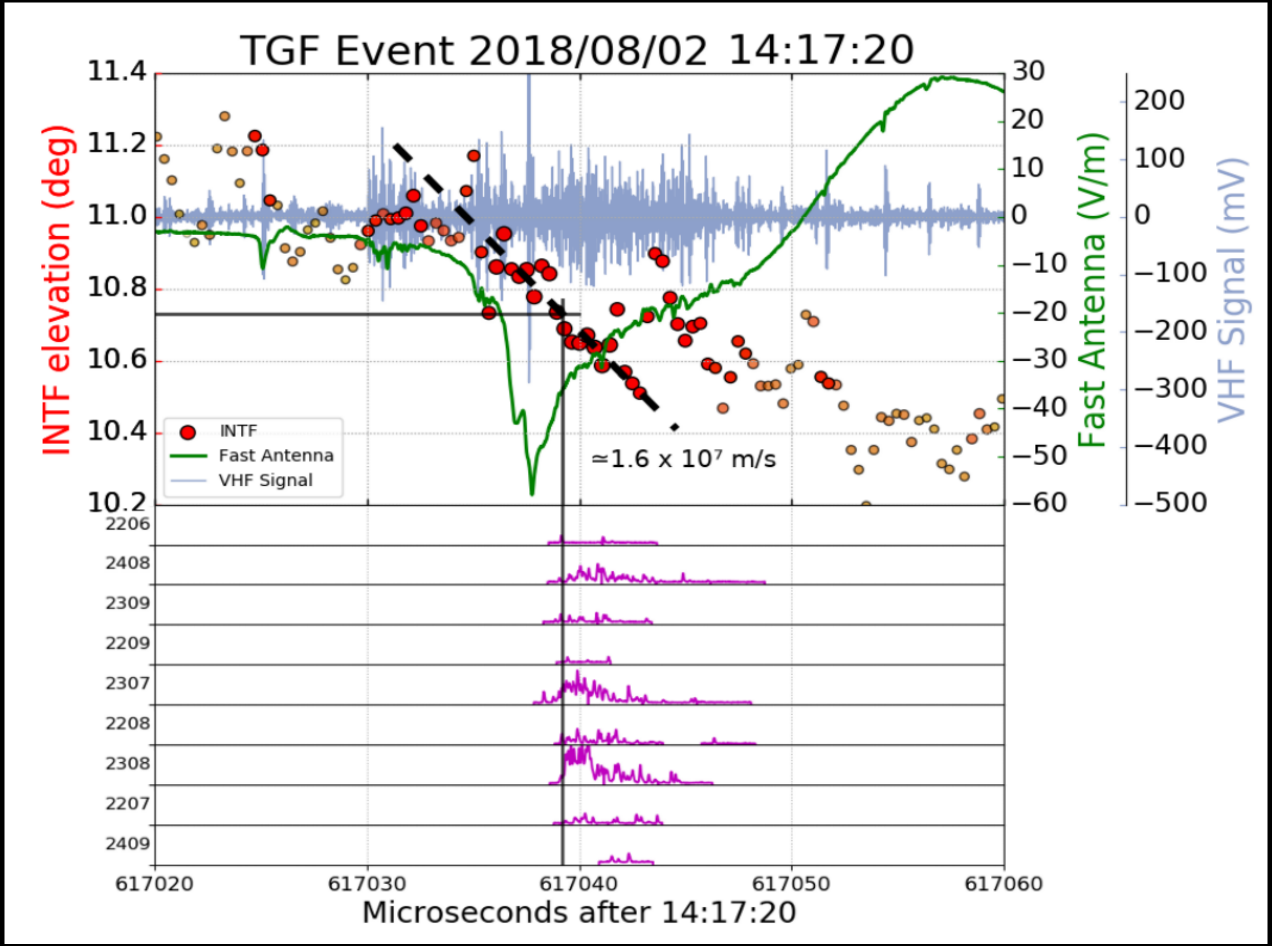
2 triggers occurred within about 100 μs of each other, in the S-E corner of the TASD → they are signatures of the same TGF

Footprint of the two events: TASD stations with signal



TASD station recording the strongest energy deposit during each trigger

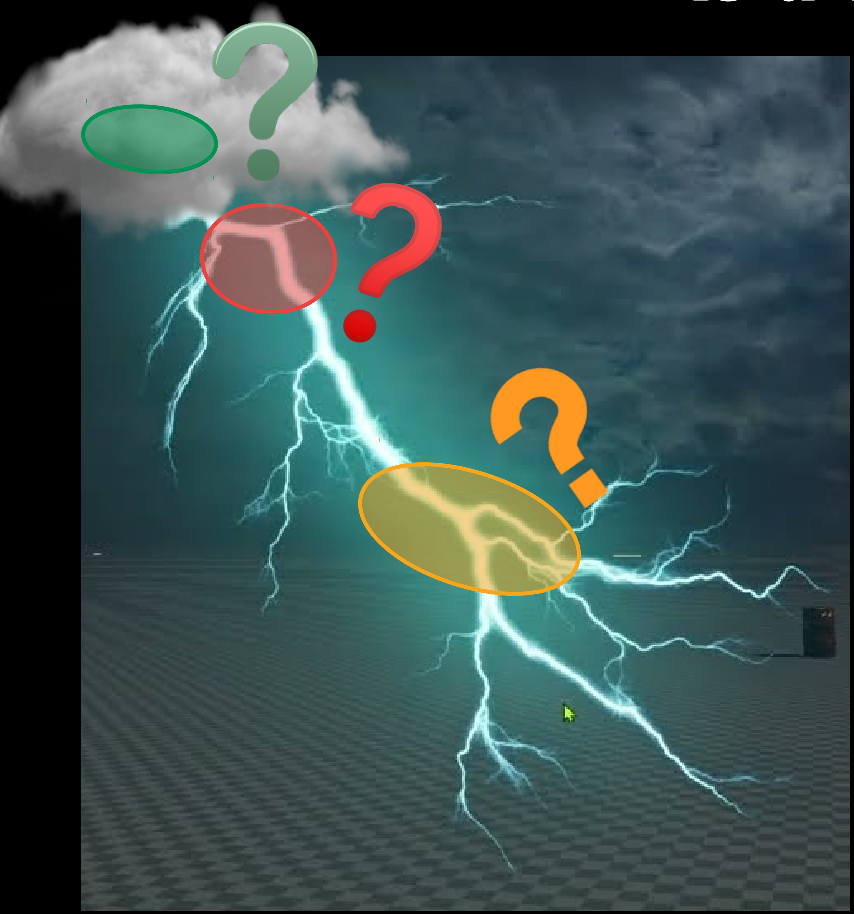
TGFs @ Telescope Array



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.

At what stage in lightning development is a TGF produced?

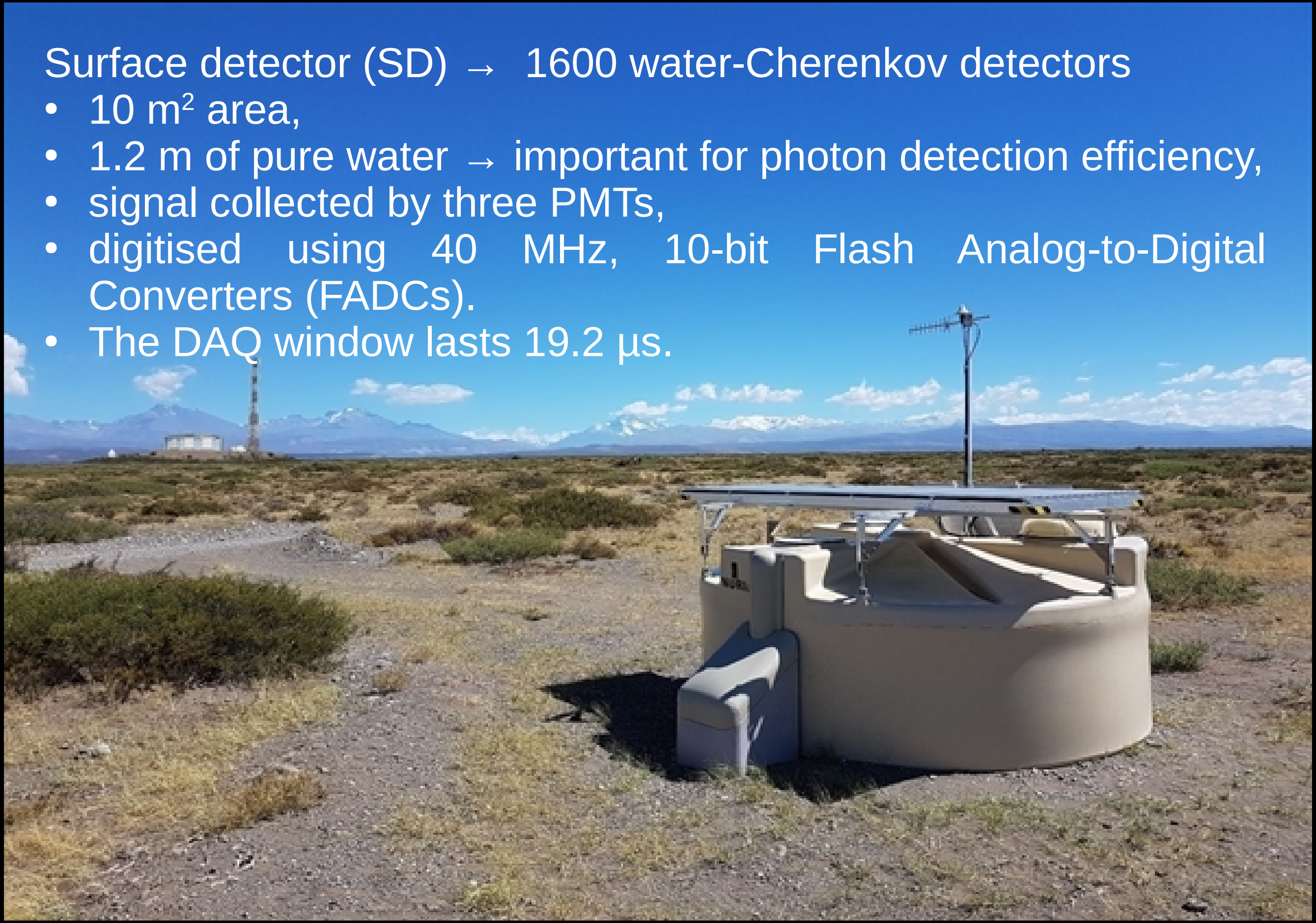


- Telescope Array, at 1.4 km above sea level, reported TGFs associated with the IBP process (Belz J W et al 2020 J. Geophys. Res.: Atmos. 125 e2019JD031940).
- The group of the Lightning Observatory in Gainesville (LOG), Florida, recently reported that the TGFs occurred well after the flash initiation processes (V A Rakov et al 2022 Plasma Sources Sci. Technol. 31 104005).

The Pierre Auger Surface Detector

Surface detector (SD) → 1600 water-Cherenkov detectors

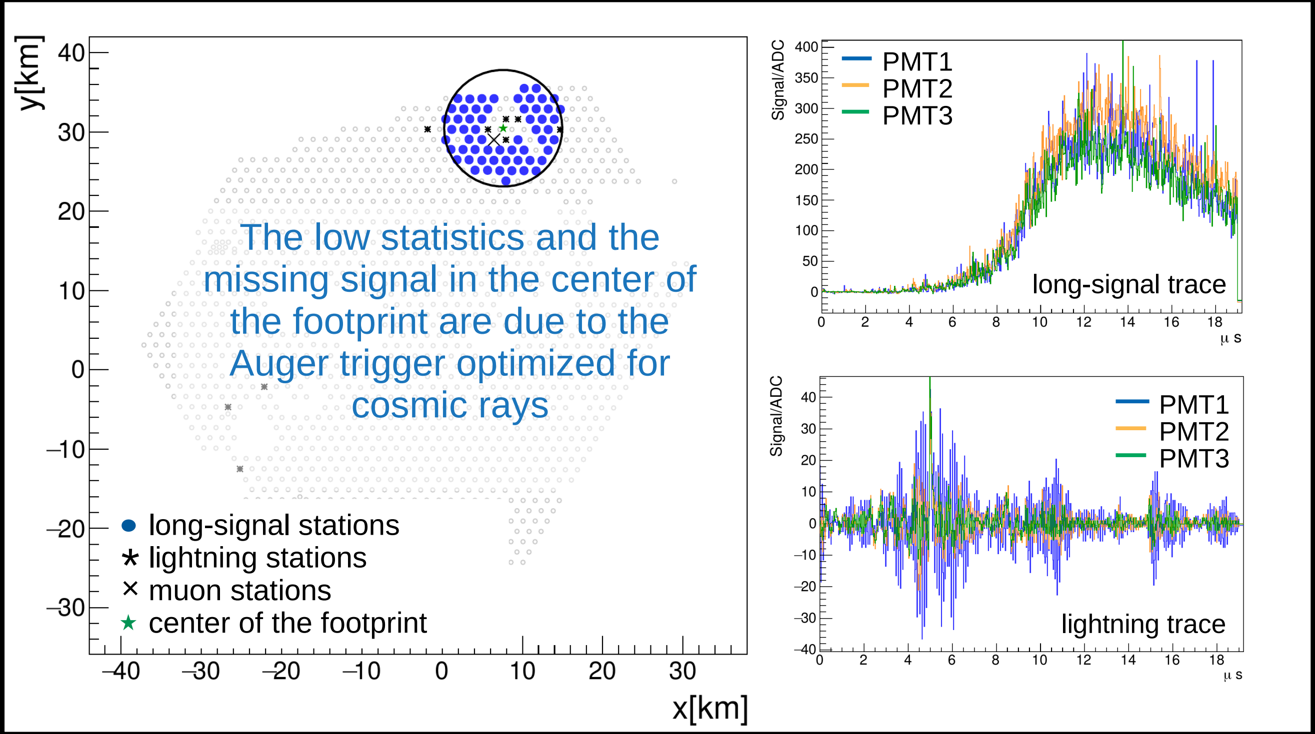
- 10 m^2 area,
- 1.2 m of pure water → important for photon detection efficiency,
- signal collected by three PMTs,
- digitised using 40 MHz, 10-bit Flash Analog-to-Digital Converters (FADCs).
- The DAQ window lasts 19.2 μs.



“TGF” events

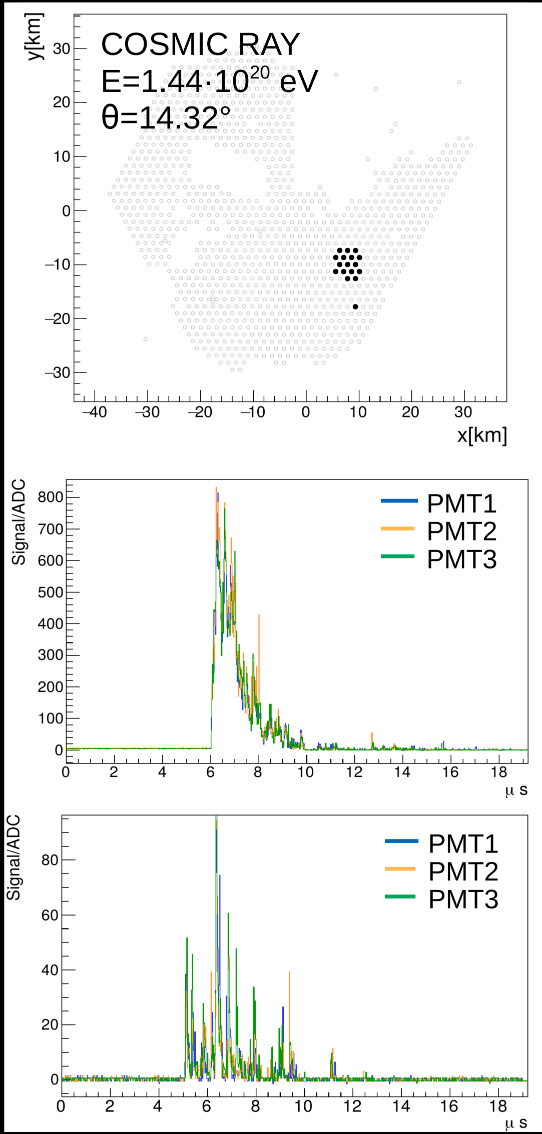
R. Colalillo at al., AtmoHEAD 2018, https://doi.org/10.1051/epjconf/201919703003
R. Colalillo et al., PoS(ICRC2021)395, https://doi.org/10.22323/1.395.0395

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



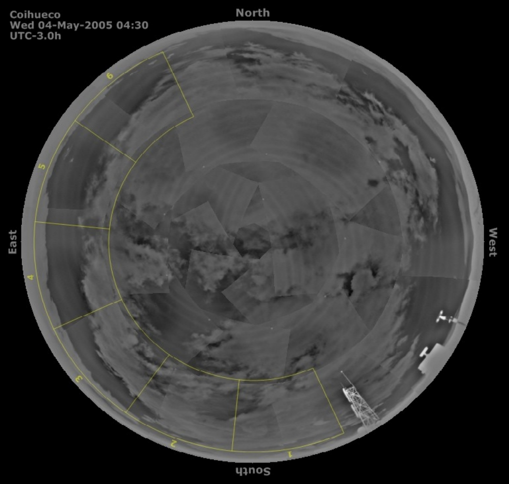
A dedicated trigger for TGF events was designed and installed.

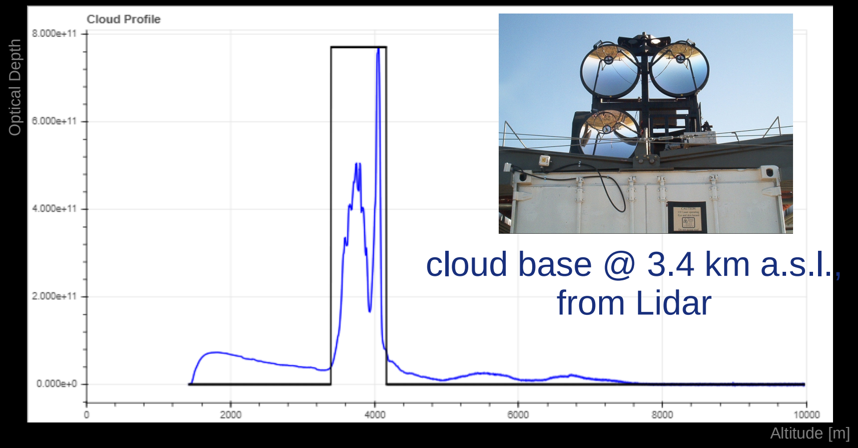
Other work is necessary because the Pierre Auger Observatory is being upgraded and the TGF algorithm needs to be optimized according to the new electronics.



“TGF” events: weather measurements

IR Cloud Camera





The presence of lightning stations suggests that lightning activity had happened at the time of the event

→ correlation with lightning strikes collected by the World Wide Lightning Location Network (WWLLN).

As the Observatory makes use of the atmosphere as a giant calorimeter, several atmospheric-monitoring facilities are available. They operate only during the nightly data-taking of the Fluorescence Detector:

→ a 100% cloud coverage some hours before and/or after the event from cloud cameras;
→ in many cases, clouds at ~2 km above ground level from LIDARs and lasers.

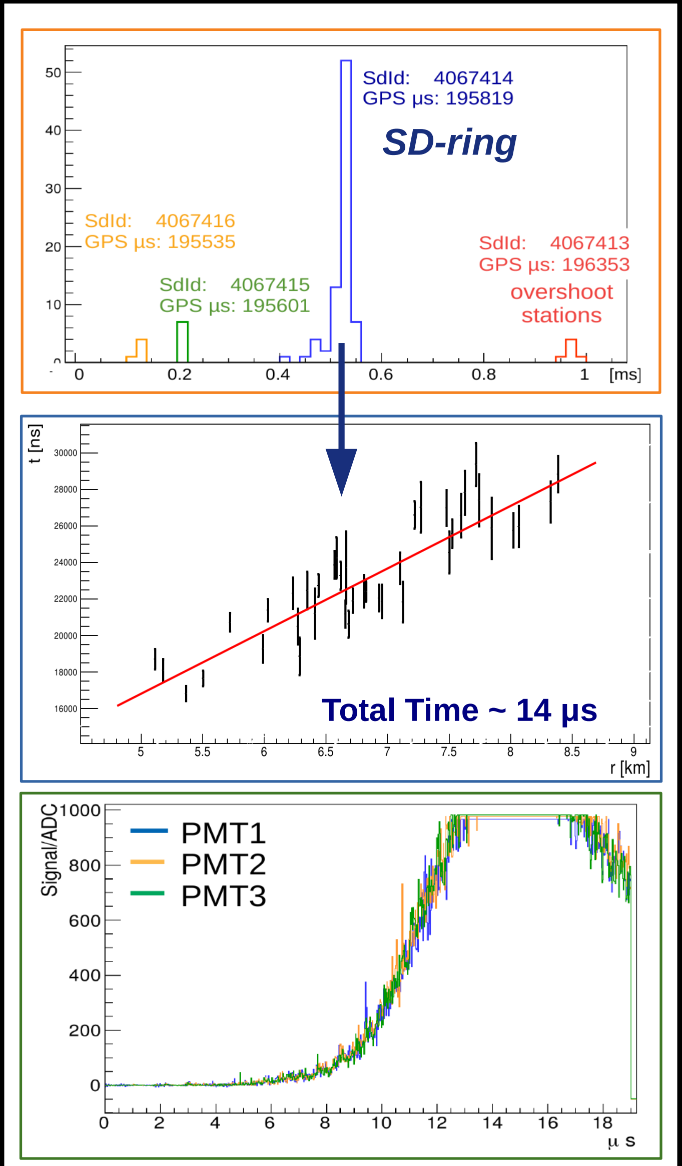
Our peculiar events occurred during bad weather and with very low clouds.

“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.

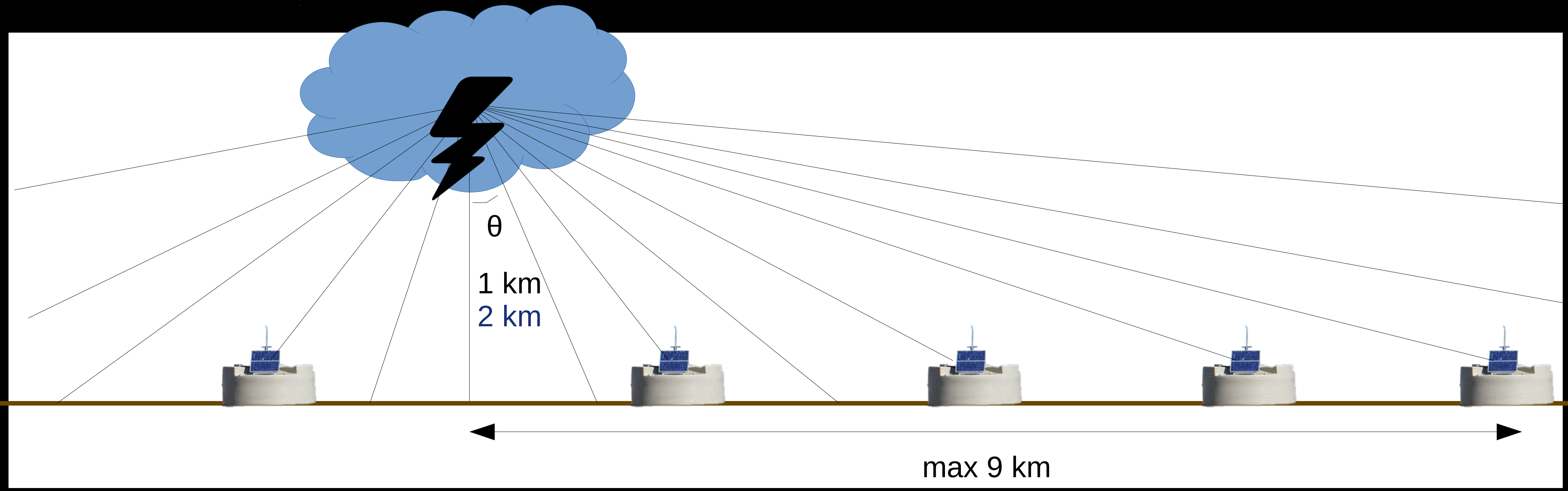
TGFs are so bright that they usually saturate also detectors far from the source.

Energy deposited at the ground:
~ 10^4 MeV/m^2 x 200 km^2 = 10^{12} MeV



First comparison between simulations and Auger data

- Simulation produced assuming a standard downward TGF at 1 and 2 km above the ground
  → this height is compatible with the source height obtained fitting the signal arrival time in the Auger detectors assuming a spherical propagation.
- Isotropic emission into the lower emisphere is assumed.



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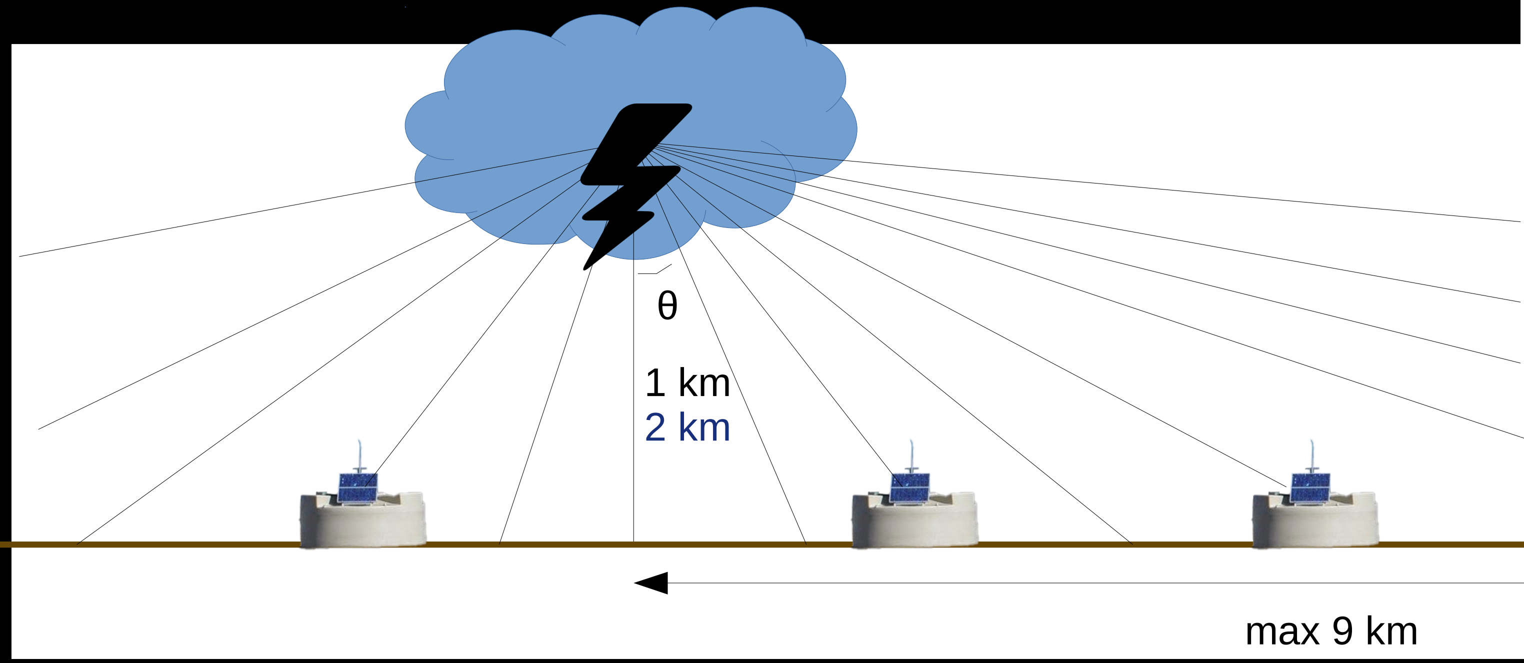
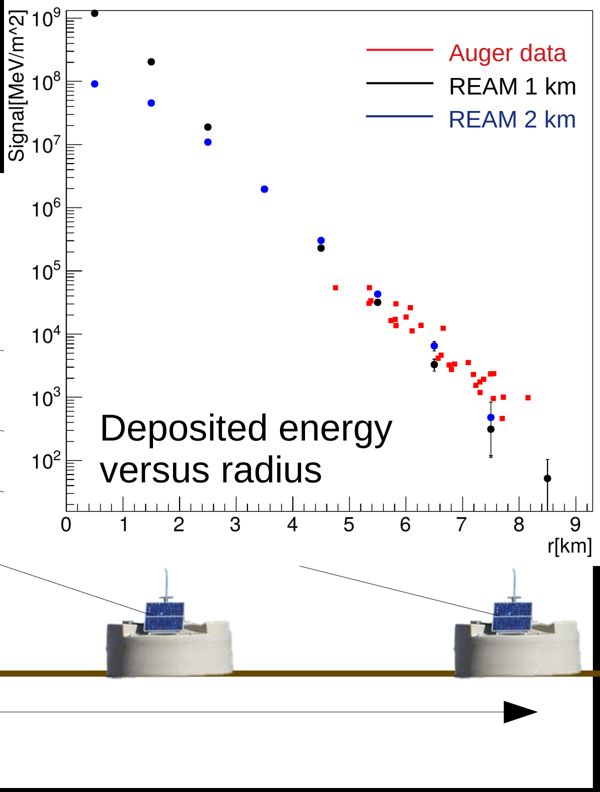
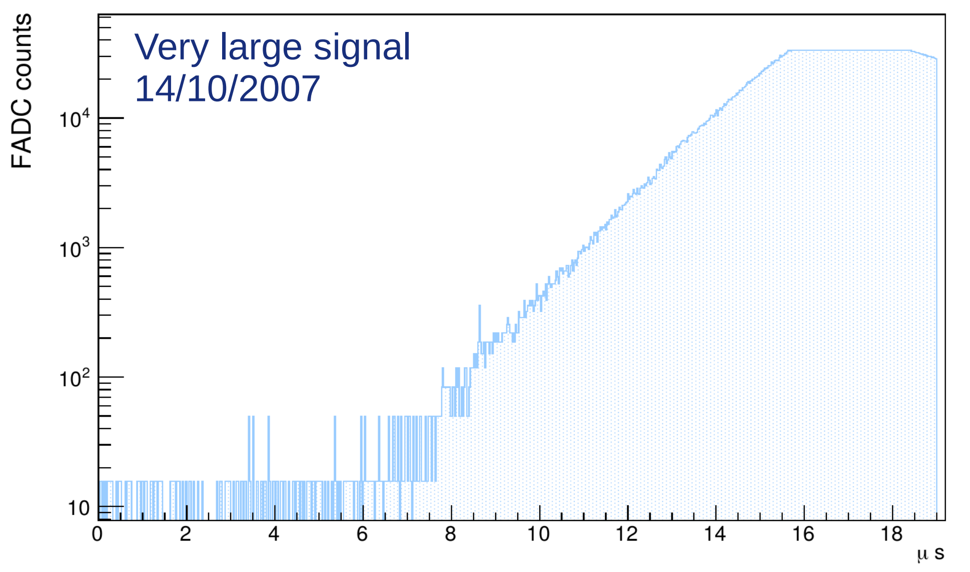
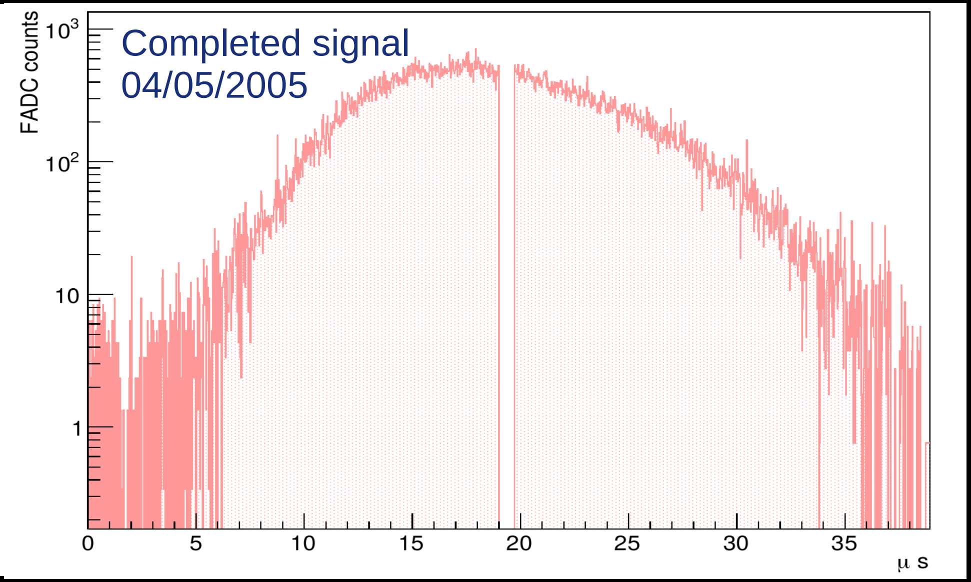




The importance of Auger signals

Both TGF production mechanisms (Lightning Leader and Relativistic Feedback) produce the same energy spectrum and so the previous comparisons are fairly model independent except for the angular distribution and the source altitude,
but **the timing shape of our signals, "counts vs times", can be useful to constrain models**
→ relativistic feedback predicts exponential rises and falls in the counts versus times





Auger “TGF”summary

Link between our peculiar events and TGFs:

→ accompanying events within 1 ms of all of our SD-rings;
→ the main single trigger (SD-ring) covers tens of microseconds.
These observations are compatible with the evolution of the lightning leaders associated with TGFs.

→ the presence of low clouds at the time of some of events is consistent with the expectations for downward TGFs.

→ the observed peculiar events seem to be intense phenomena, with energy deposits two orders of magnitude larger than in a vertical shower initiated by a particle of 10^{19} eV.

Collect new events and increase the statistics is fundamental to better understand these events and their origin:

→ comparison with data from instruments recently installed at the observatory that can monitor lightning and electric field at the ground;
→ comparison with data from AERA radio antennas;
→ further comparisons with simulations.

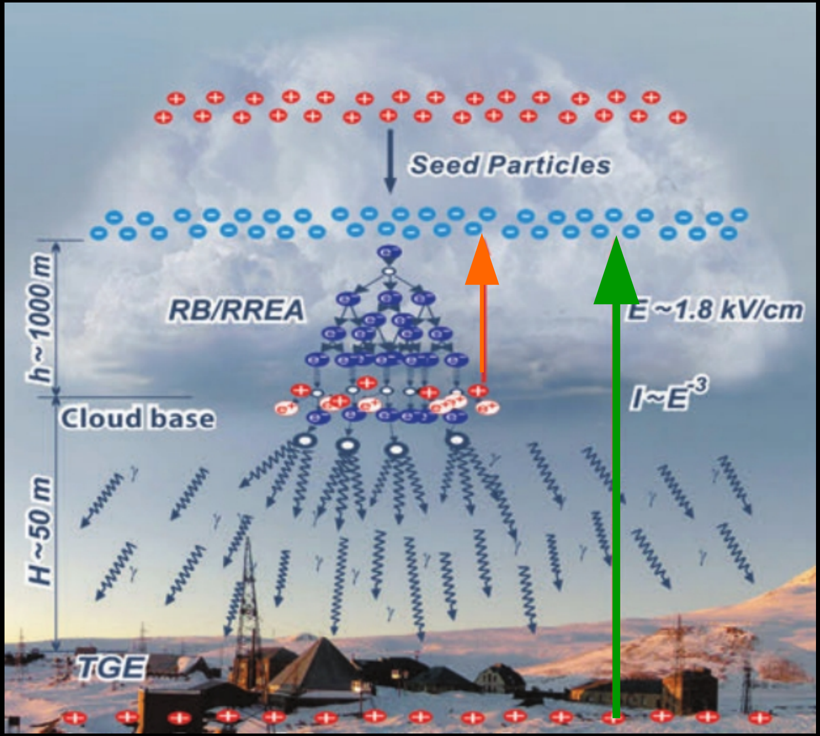
Variations in cosmic-ray flux at the ground

For decades, several high-altitude experiments have reported (Baksan Carpet array, EAS-TOP, Tibet AS-γ, ASEC, ARGO-YBJ, SEVAN at Lomnickýštít, 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.

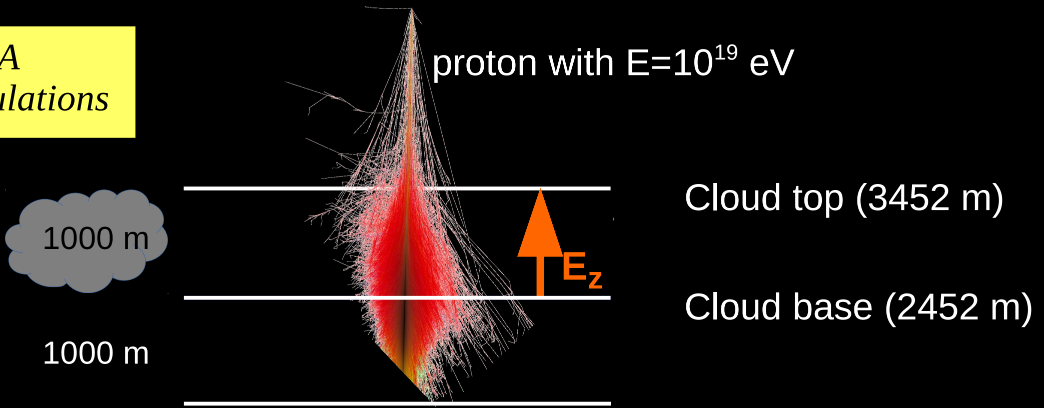
Main field:
bottom dipole between the main negative charge layer and the positively charged region at the base of the cloud.

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.

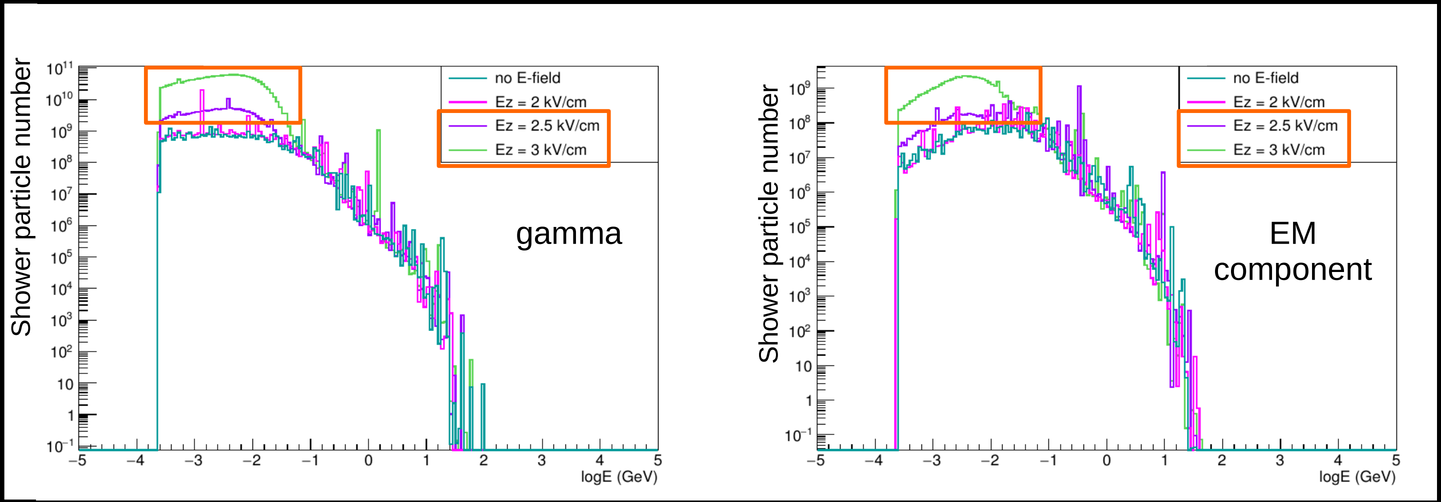


Variations @ Auger observation level

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.

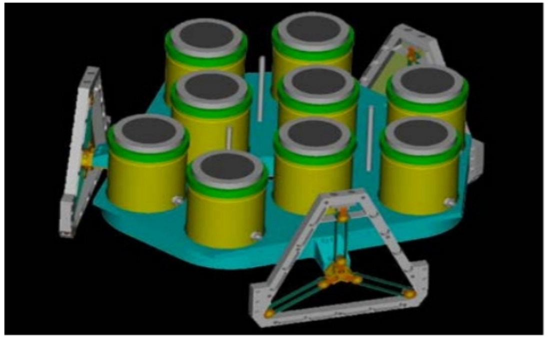
Finally, we need to investigate the possible effects that thunderstorms can have on the cosmic-ray measurements.

Thank you for your attention

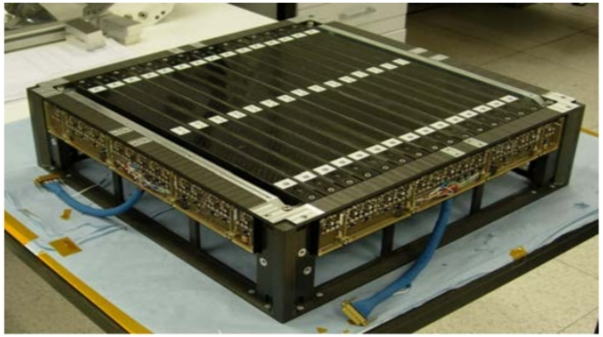
Backup

TGF detectors

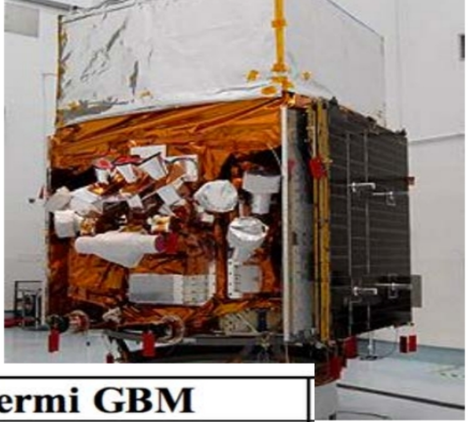
RHESSI - GeD



AGILE - MCAL

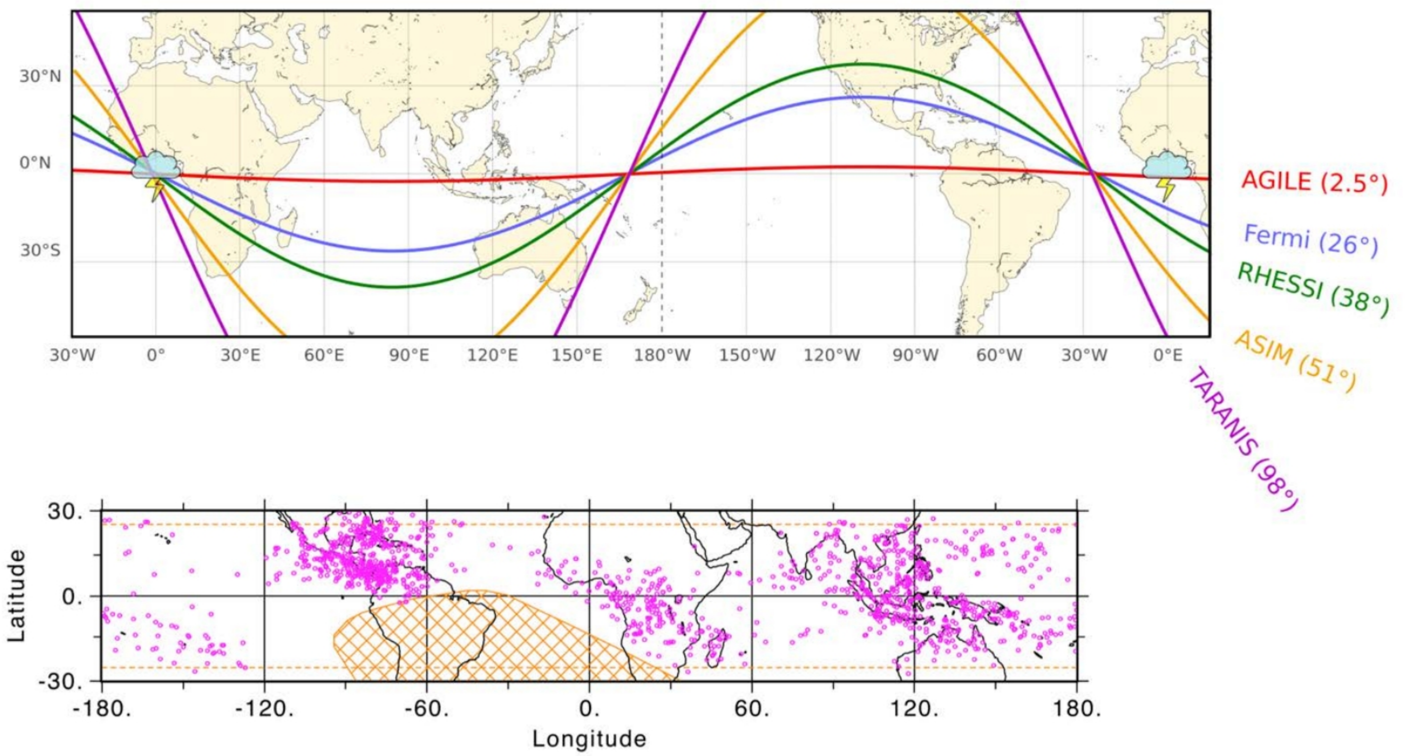


Fermi - GBM



	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

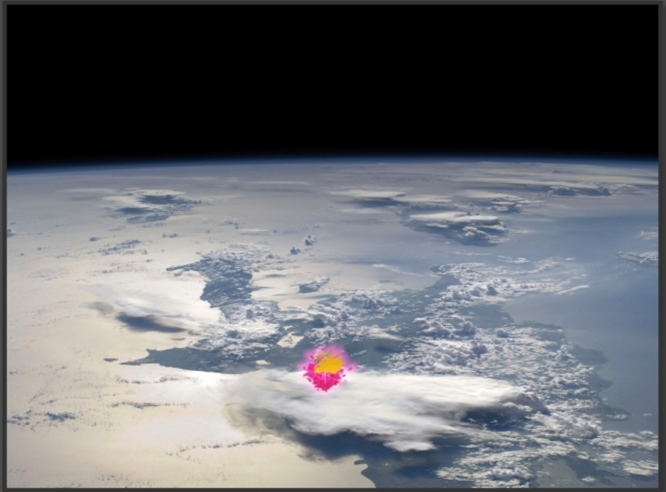
TBE & Magnetic mirroring

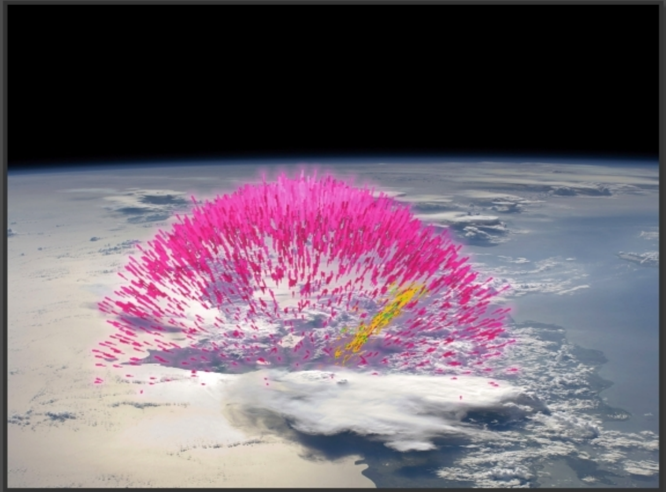
TBE characteristics:
1. Duration ≥1 ms, as the electron positron beam is dispersed along the field line.
2. Spectral line at 511 keV due to electron positron annihilation.
3. Lack of lightning activity at the spacecraft nadir but present at one of the magnetic footprints of the local field lines.
4. 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 atconjugate point from the source footprint.

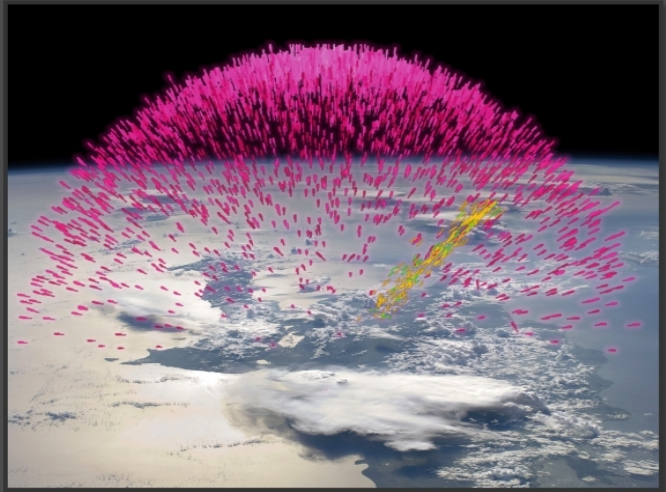
Magnetic mirroring:
Two points on the Earth’s surface, linked by a geomagnetic field line, are generally called conjugate points.

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.

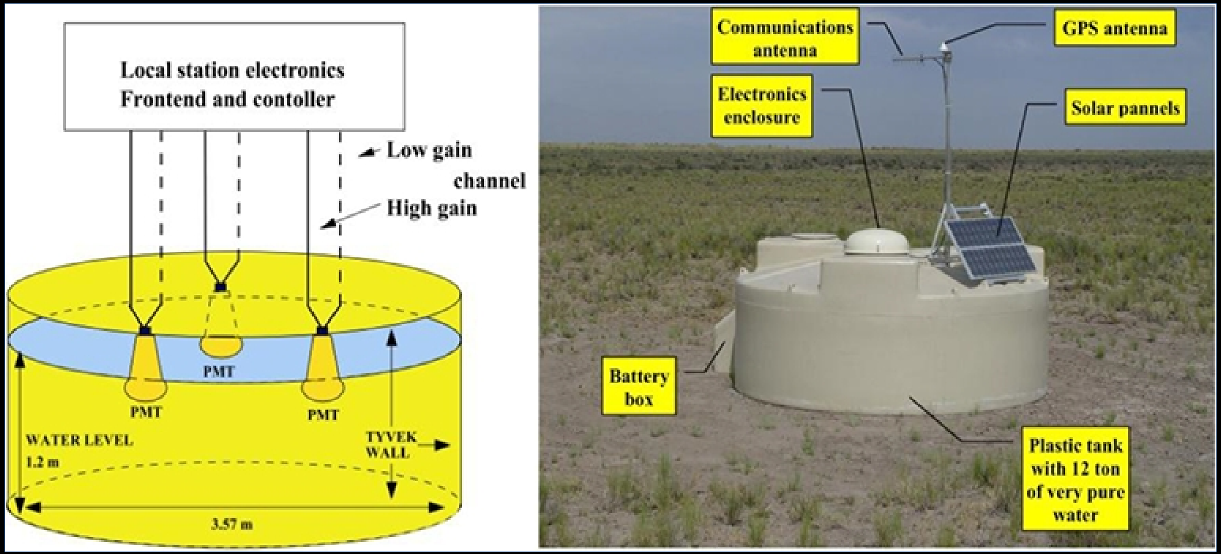
These high-energy electrons and positrons escape into space by spiraling along Earth's magnetic field. In this frame, the TGF is 1.4 milliseconds old.

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 charateristic of positron annihilation. When a positron collided with an electron on the spacecraft, the two particles transformed into gamma rays.

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

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 channe**l) with an amplification factor of 32
  → the LG channel is used when the HG is saturated.
- The two output signal are processed by six FADCs with a sampling rate of 40 MHz, 25 ns per time bin.
  The DAQ window lasts 19.2 μs.