Atmospheric electricity: Transient Luminous Events, Terrestrial Gamma-ray Flashes and their observation from space and ground

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IJCLab, Orsay, 27/09/2021

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 detection of TGFs from space.
- The detection of TGFs from ground
  → TGFs @ the Pierre Auger Observatory & CALLiStO project.
- TGFs and ELVES @ the Pierre Auger Observatory.
- The effects of atmospheric electricity on cosmic-ray measurements.

High-Energy Atmospheric Physics

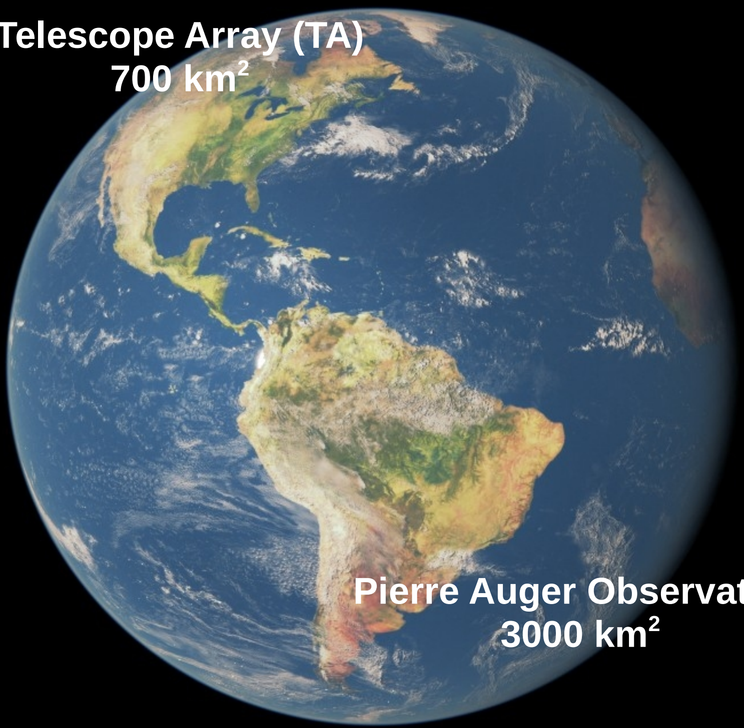
The atmosphere is never quite neutral due to
→ thunderstorms, which create lightning bolts to rapidly discharge huge amounts of atmospheric charge stored in thunderclouds
→ ionization from cosmic rays and natural radioactivity

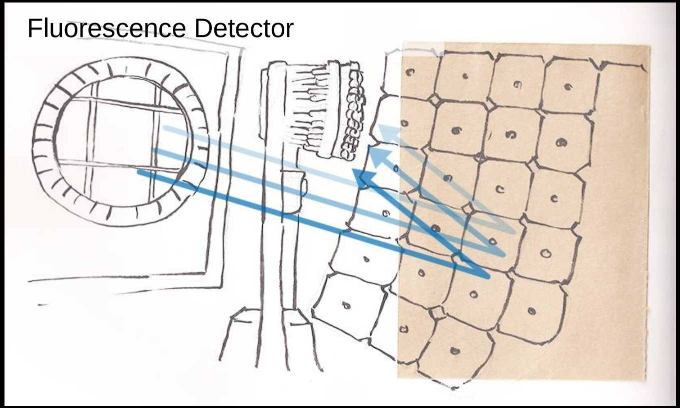
Despite the ubiquity of thunderstorms, lightning, and related electrical phenomena, many important electromagnetic processes in our atmosphere are poorly understood.
For example, many questions remain about thundercloud electrification and discharge mechanisms, lightning initiation, propagation and attachment processes, compact intra-cloud discharges, the global electrical circuit, and transient luminous events.

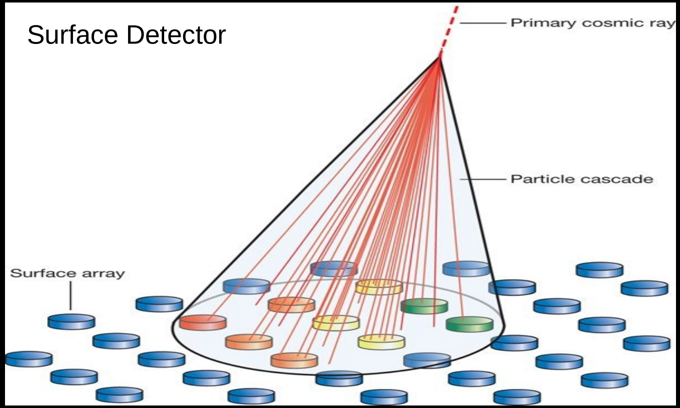
However, in the last few years, a growing body of literature has emerged that describes the production, transport and interactions of energetic particles in our atmosphere.

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



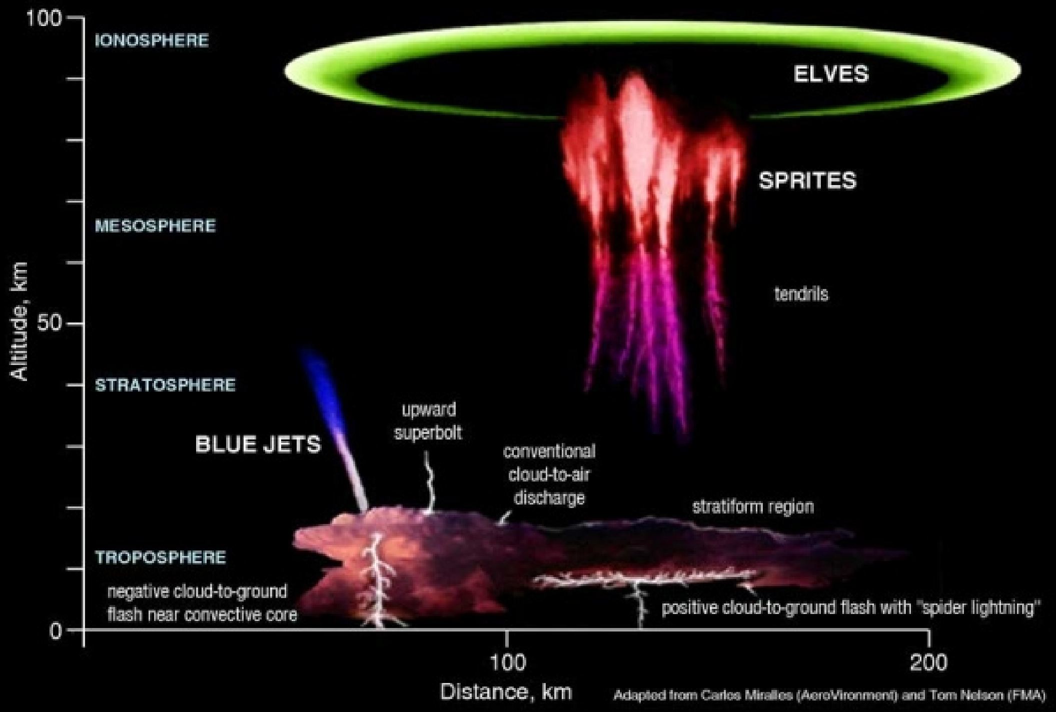




ELVES

TGF

Transient Luminous Events (TLE)



Short-lived electrical-breakdown phenomena which happen in the upper atmosphere, above the normal altitude of lightning and thunderclouds.
Triggered by lightning in the troposhere.

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.

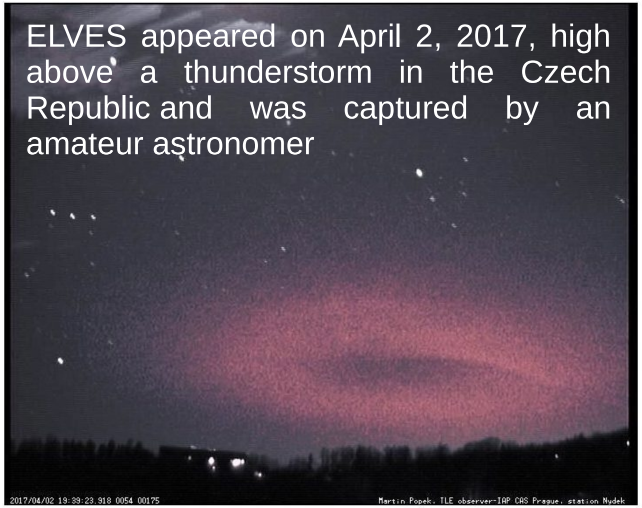
Following studies demonstrated that sprites
→ are mesospheric phenomena with tops reaching over 90 km, essentially the base of the ionosphere;
→ last few milliseconds;
→ are coincident with powerful positive cloud-to-ground lightning strokes.

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

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.

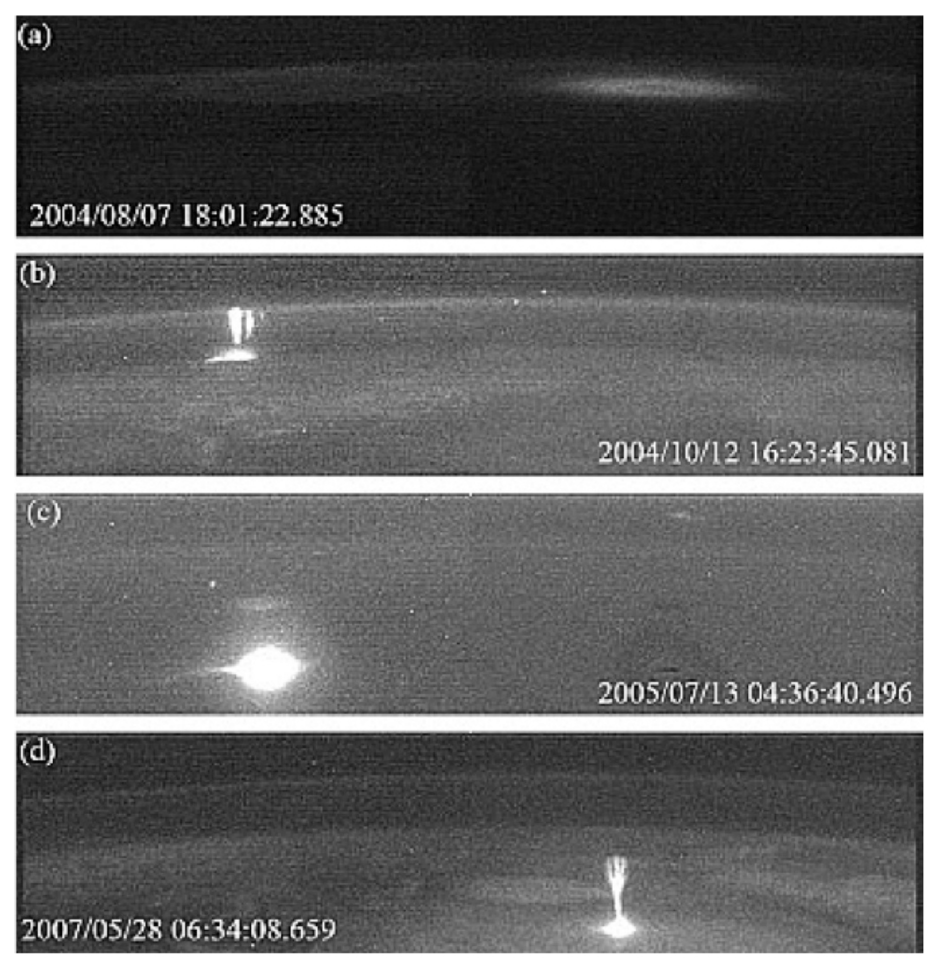
The first observation of elves from space was accomplished by the Space Shuttle (Boeck et al., 1992).

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.

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.

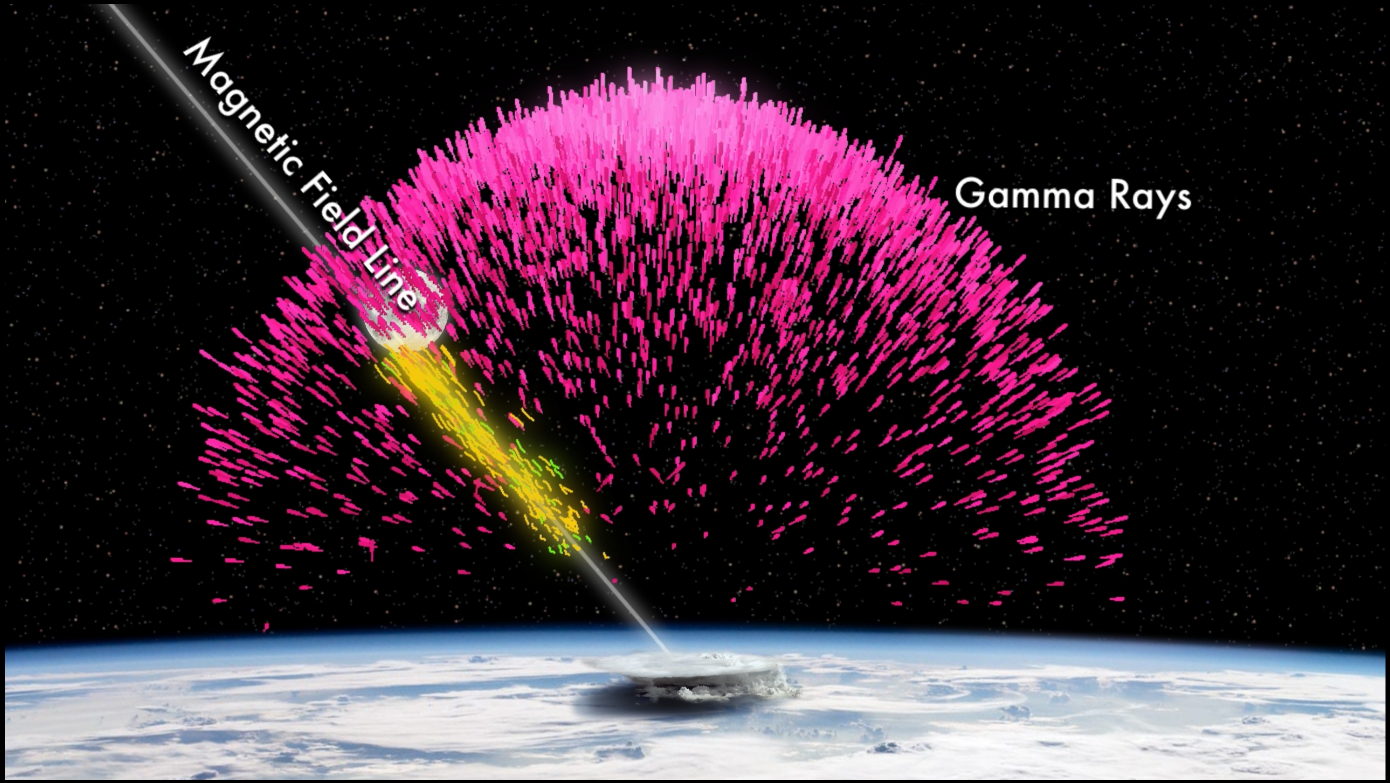
In particular, long term space instruments have been developed to study the frequency of occurrence, global distribution and key optical emissions from TLEs:

- 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).

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

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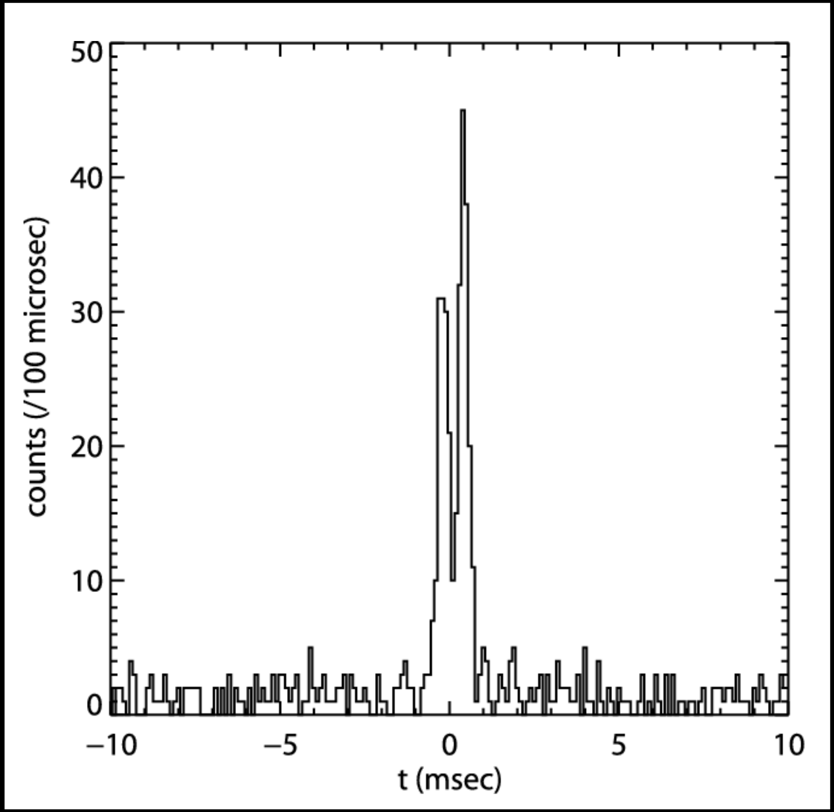
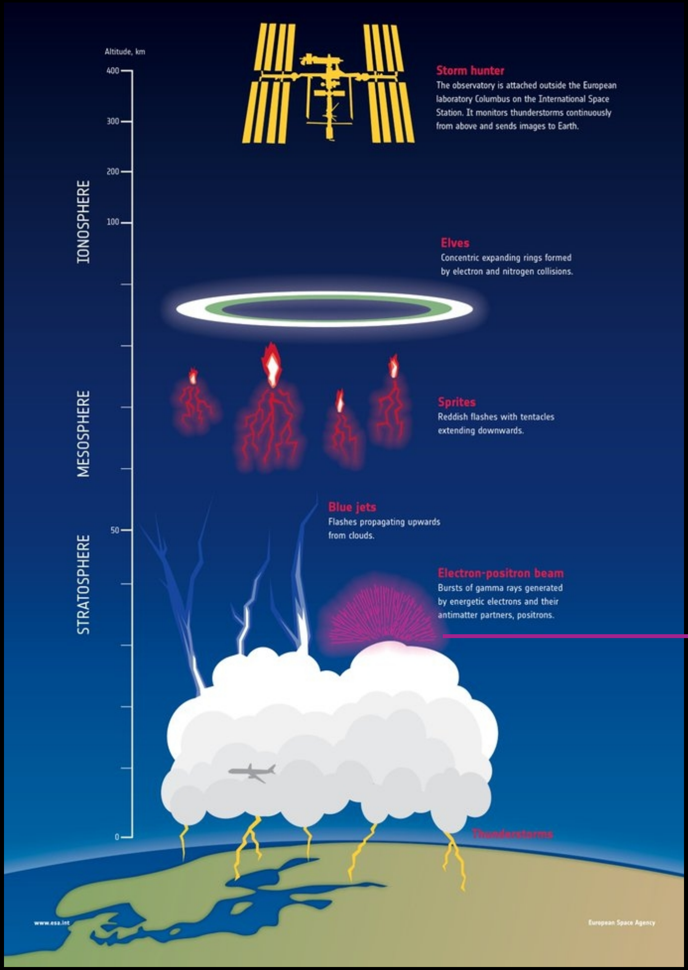


BATSE onboard CGRO 1991 – 2000
looking up to space...

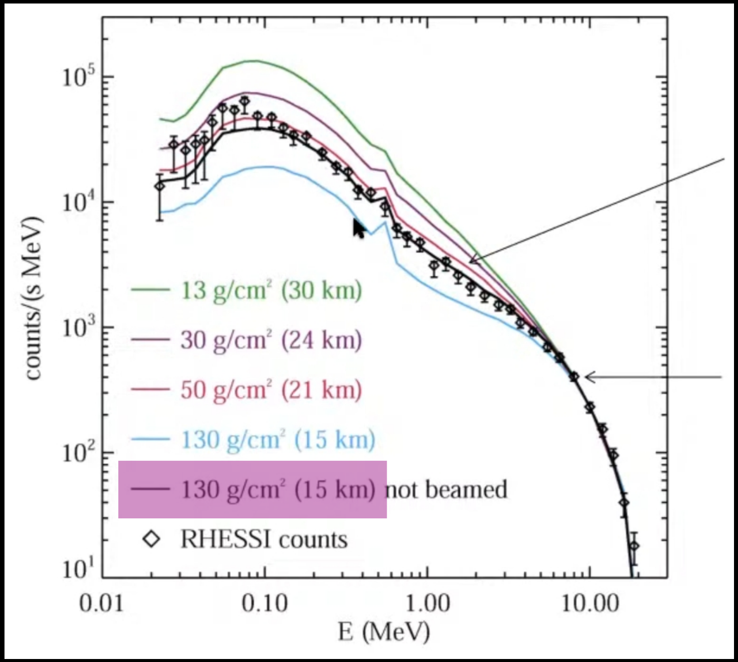
"Detectors aboard the Compton Gamma Ray Observatory have observed an unexplained terrestrial phenomenon: brief, intense flashes of gamma rays. These flashes must originate in the atmosphere at altitudes above at least 30 kilometers in order to escape atmospheric absorption and reach the orbiting detectors."

→ 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).

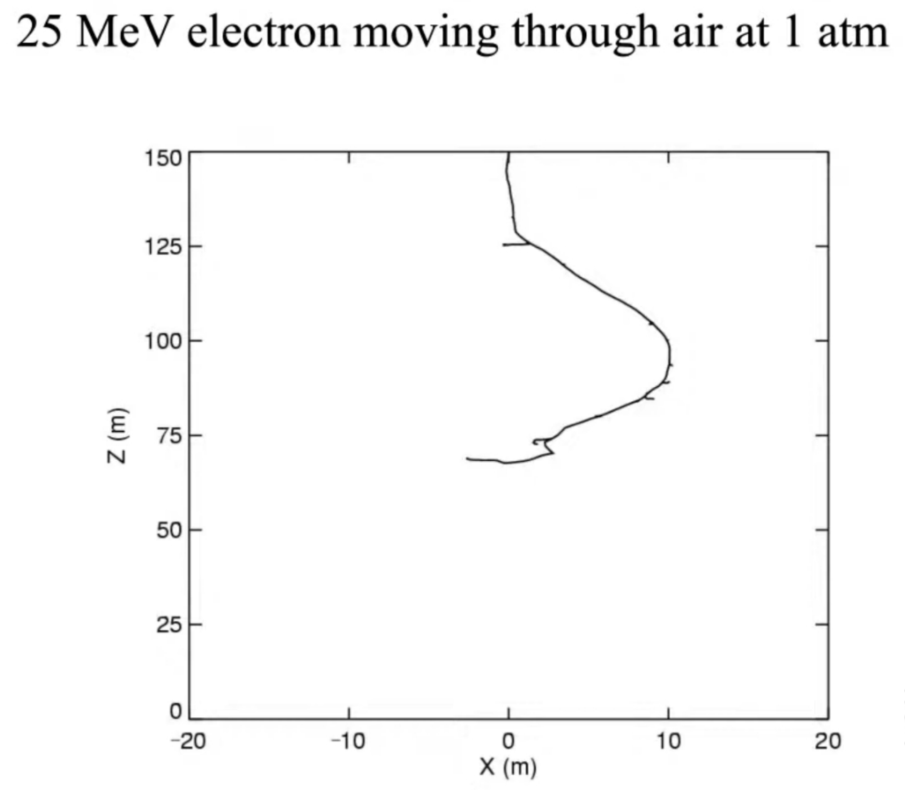


TGF spectrum too flat > 1 MeV to be from a high source altitude

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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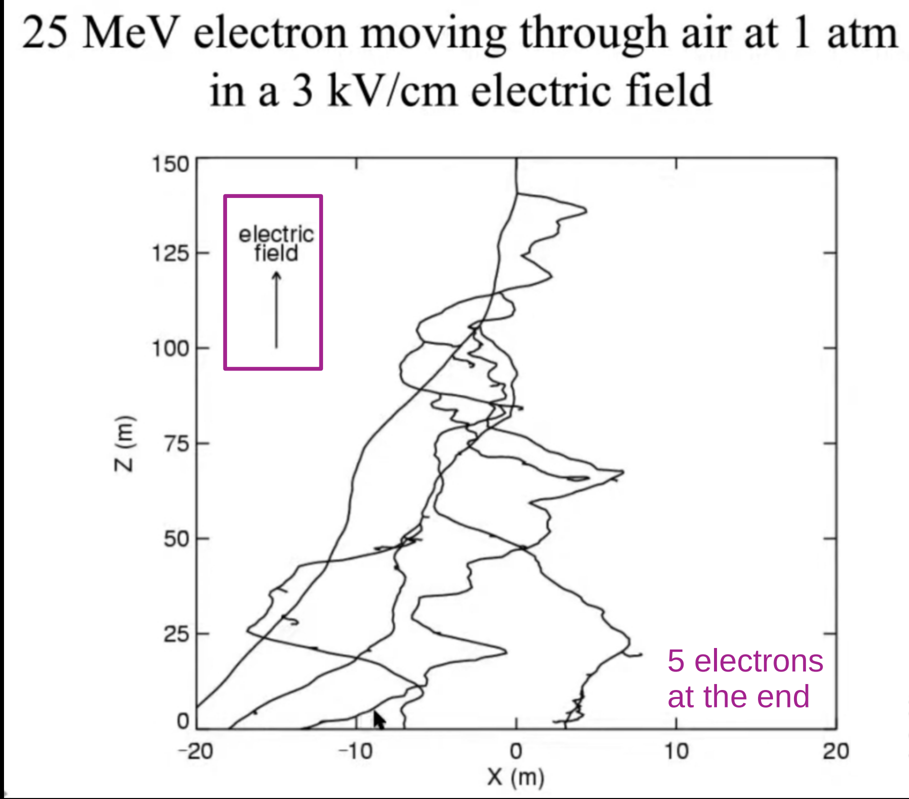

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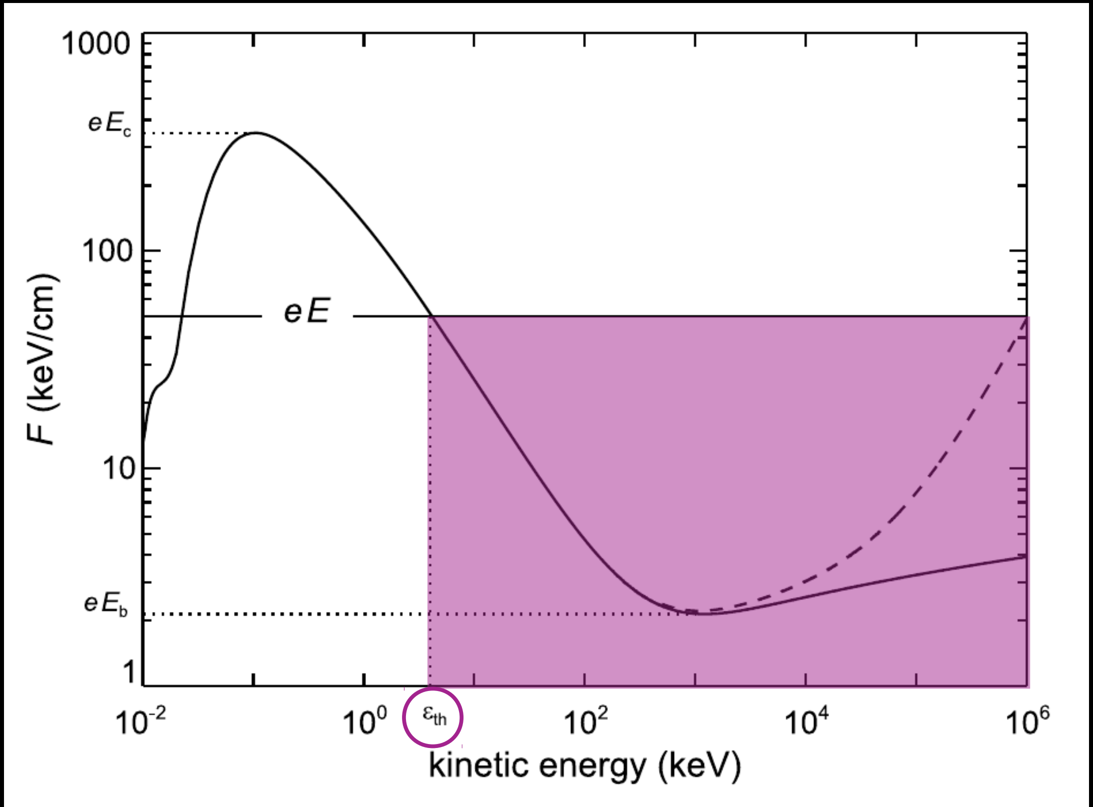


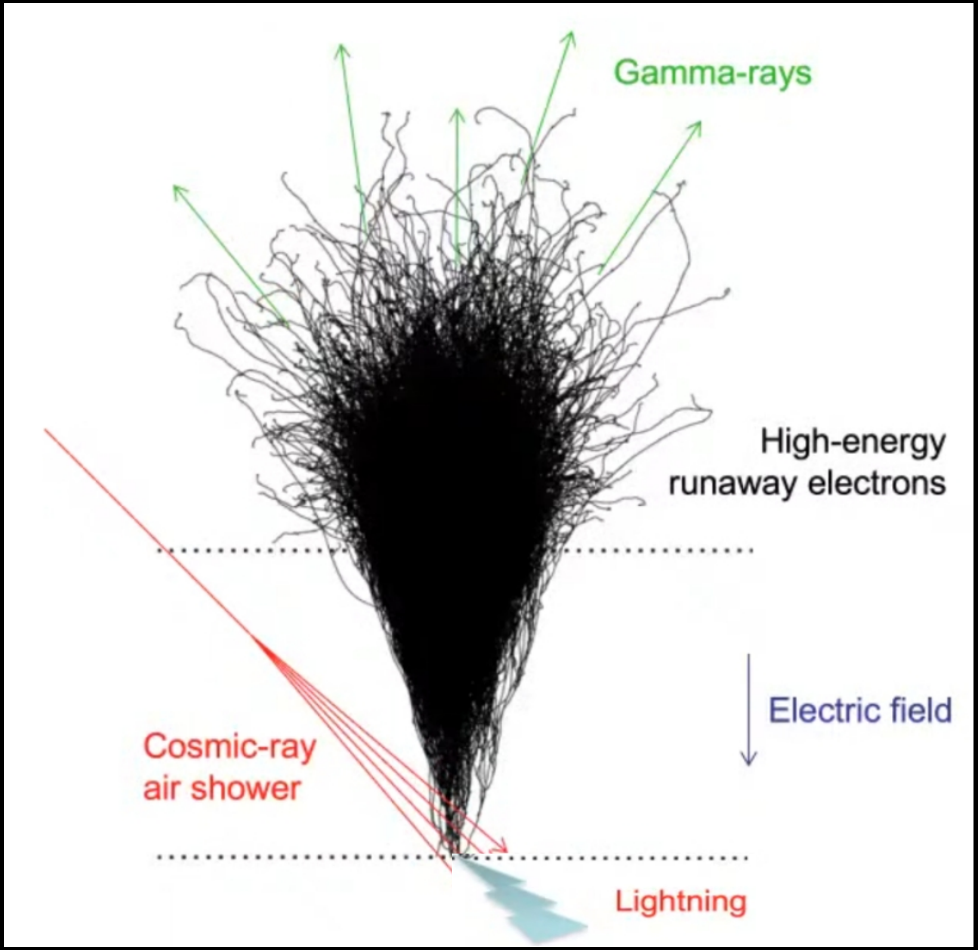
Figure shows the effective frictional force or rate of energy loss of an energetic electron moving in air.

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.”

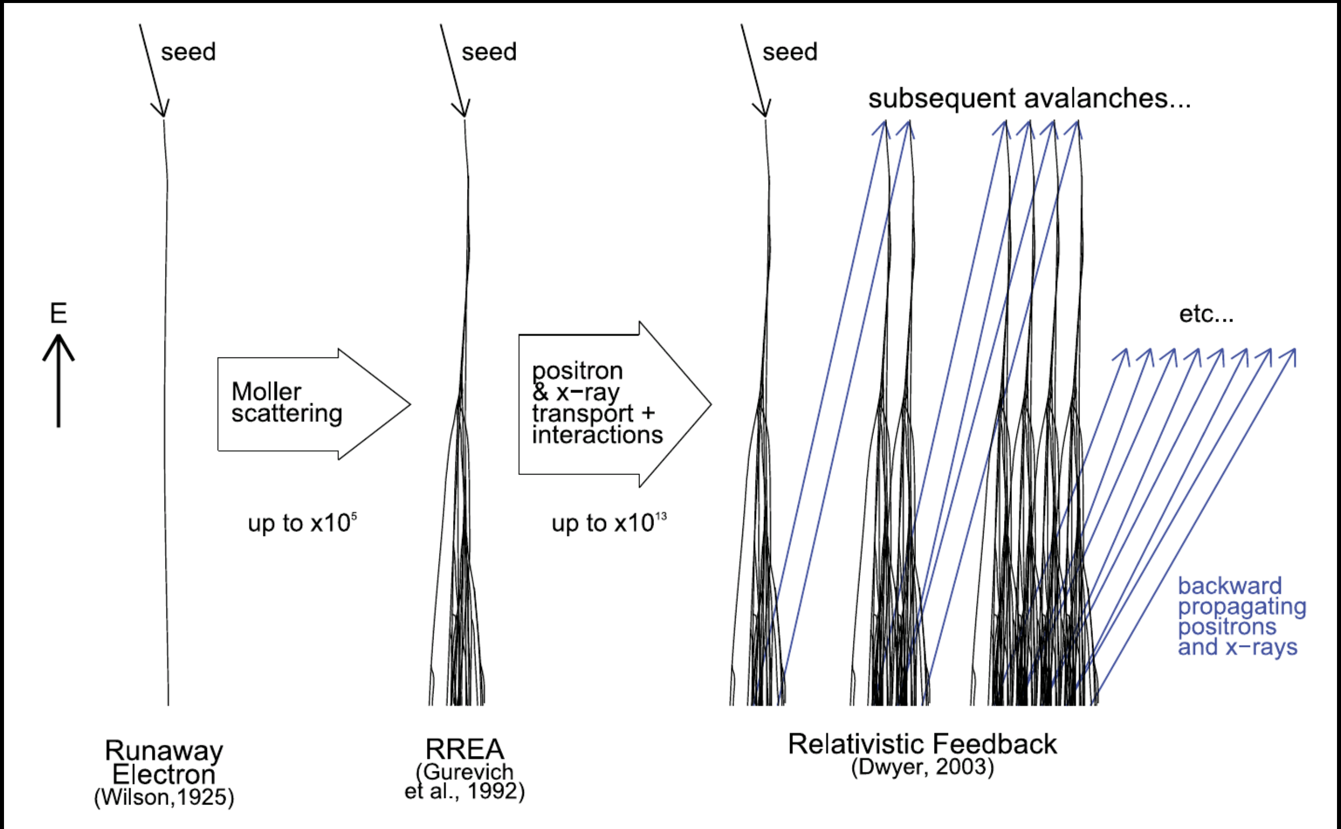
In order for an electron to run away, it must have an initial kinetic energy above the threshold, ε_{th} .
Such energetic “seed” electron, with energies above ε_{th}, may be provided from an external source.

What could be the external sources?



- Cosmic-ray air showers
- Radioactive decays
- Lightning

Relativistic feedback discharge model

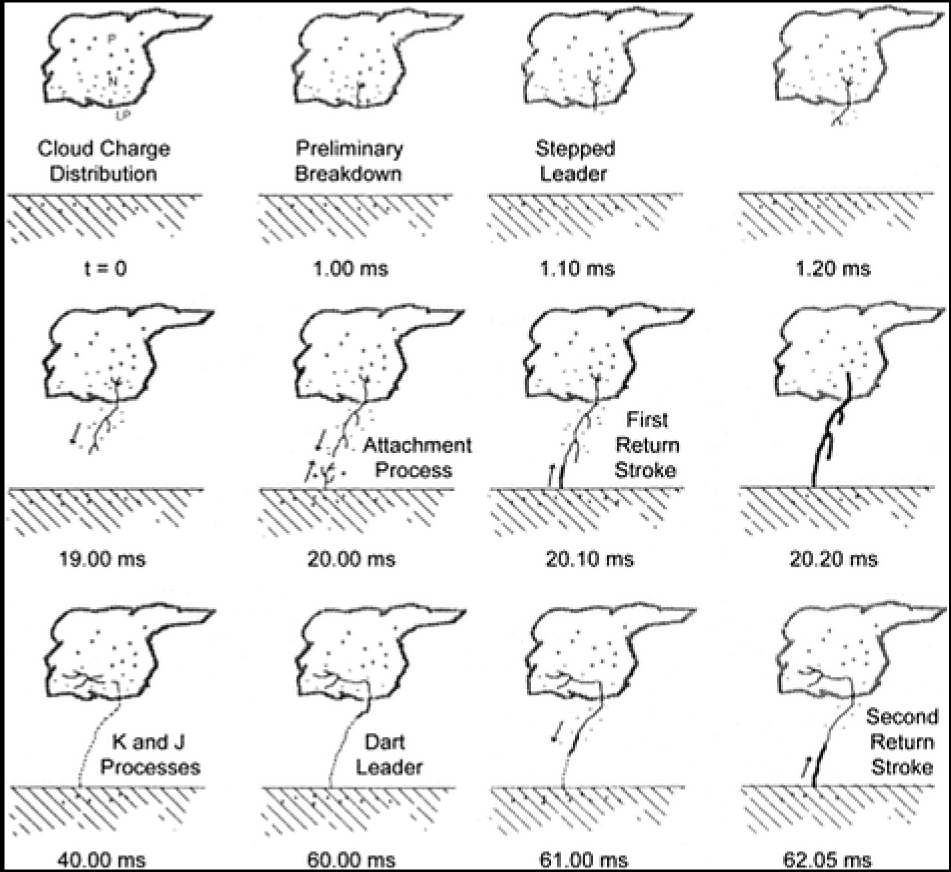


The relativistic feedback process increases the number of runaway electrons produced.

It builds on the RREA process by including the physics of backscattered gamma rays and positrons from gamma-ray pair production.

Both of which propagate to the start of the avalanche region and generate new avalanches, producing an exponential growth in the number of avalanches.

Lightning leader model

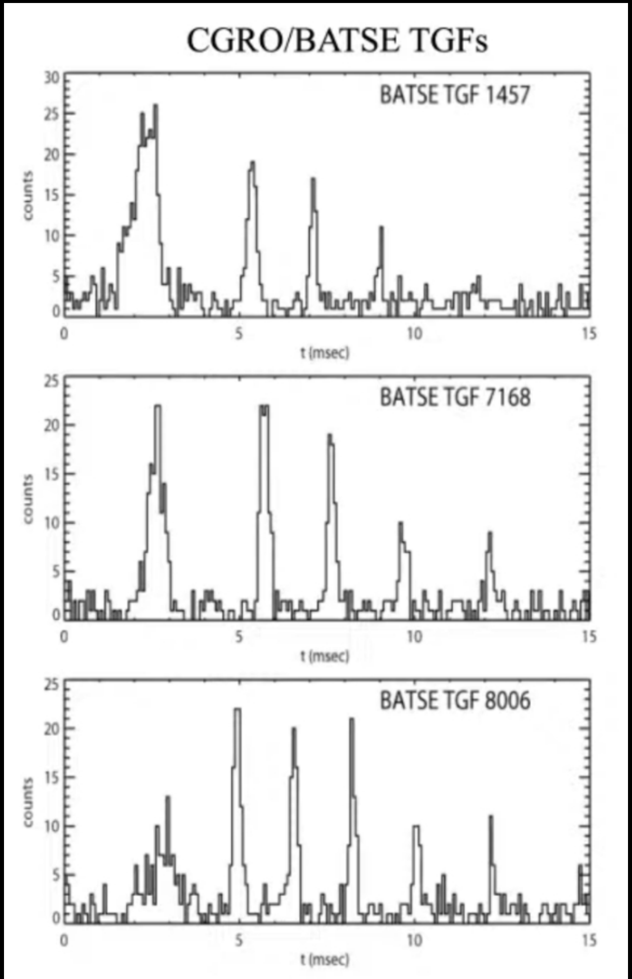


The Physics of lightning - DOI 10.1007/s10712-013-9230-6

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
→ models of TGFs have been developed by several groups that assume a similar production mechanism of runaway electrons from lightning leaders propagating through thunderclouds.

However, it remains unclear exactly how and where these runaway electrons are produced, since lightning propagation at thunderstorm altitudes remains poorly understood.

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.

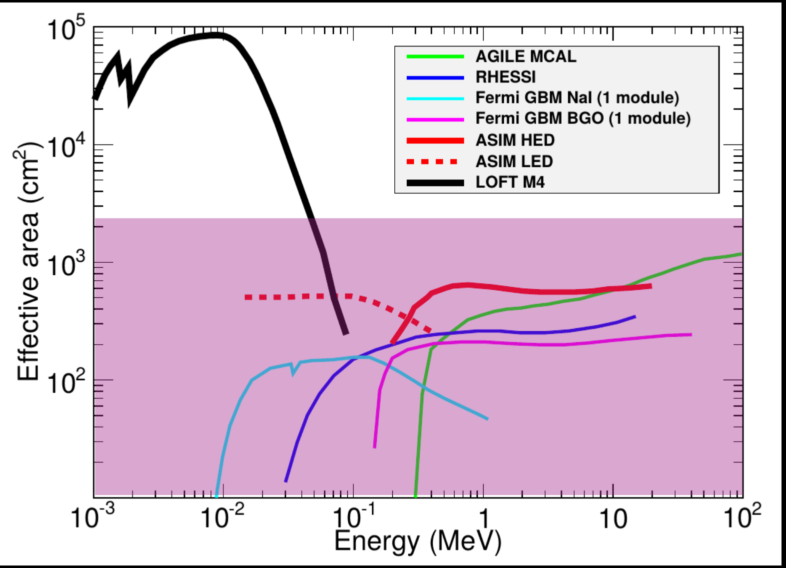
A small fraction have two pulses, and an even smaller fraction have three or more with a total duration sometimes reaching several ms.

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

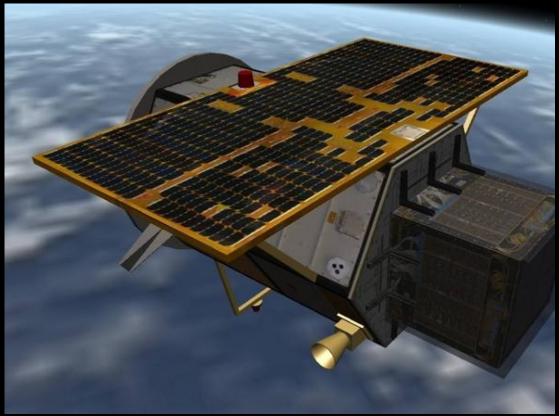
→ For the relativistic feedback discharge model, multi-pulsed TGFs naturally occur as the discharge oscillates above and below the feedback threshold.

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.

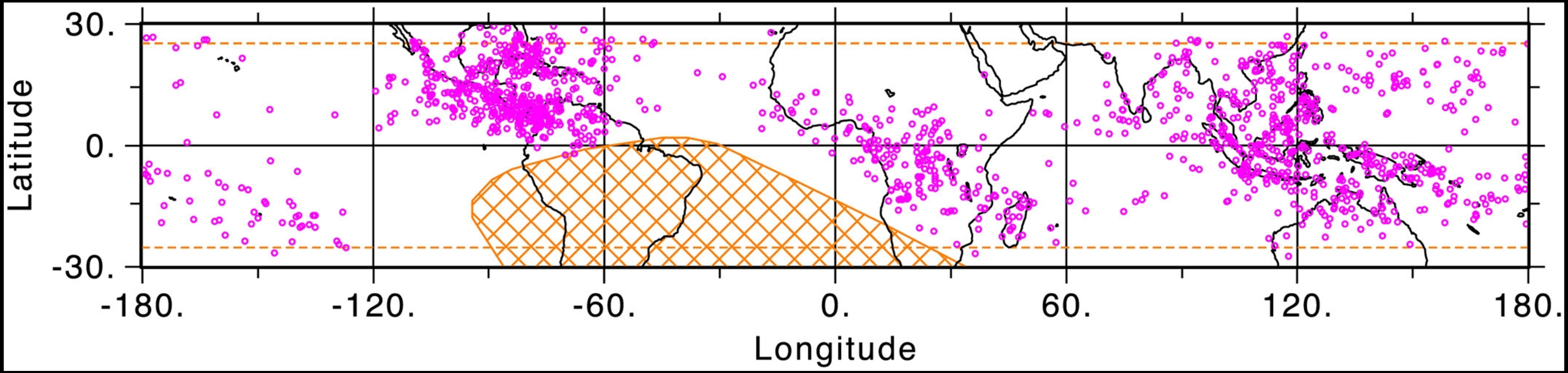
- These new TGF sample shows geographic and energetic distributions compatible with the sample acquired in the previous MCAL configuration, but a substantially different time duration distribution: the new configuration increased the detection capabilities of MCAL for shorter duration events, allowing 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

FERMI

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

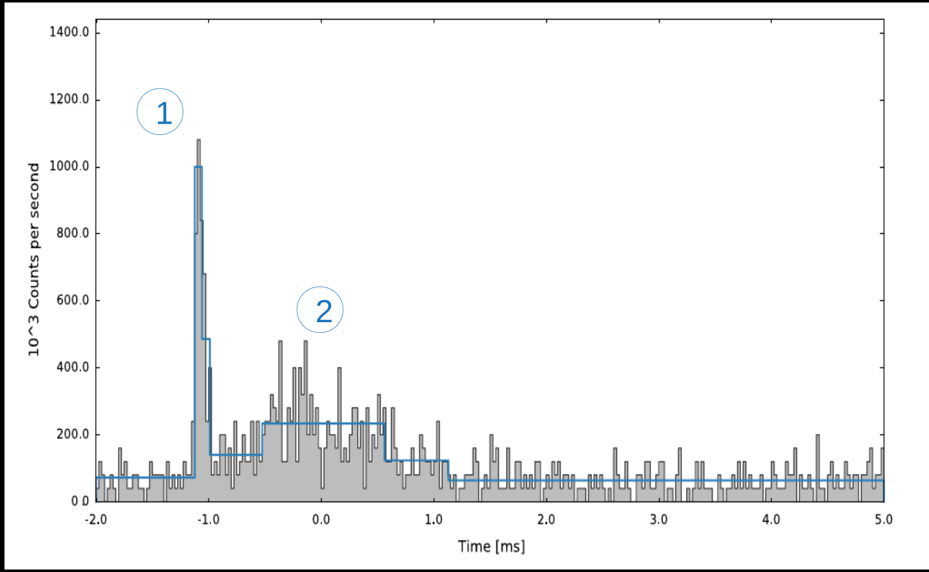
The 1st GBM TGF catalog: contains 4144 TGFs detected between 2008 July 11 and 2016 July 31
→ TGFs bright enough to trigger on board
→ TGFs recovered in an offline search for weaker events (>80%).
→ It also includes an associations table containing results for 1544 TGFs for which temporally-coincident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

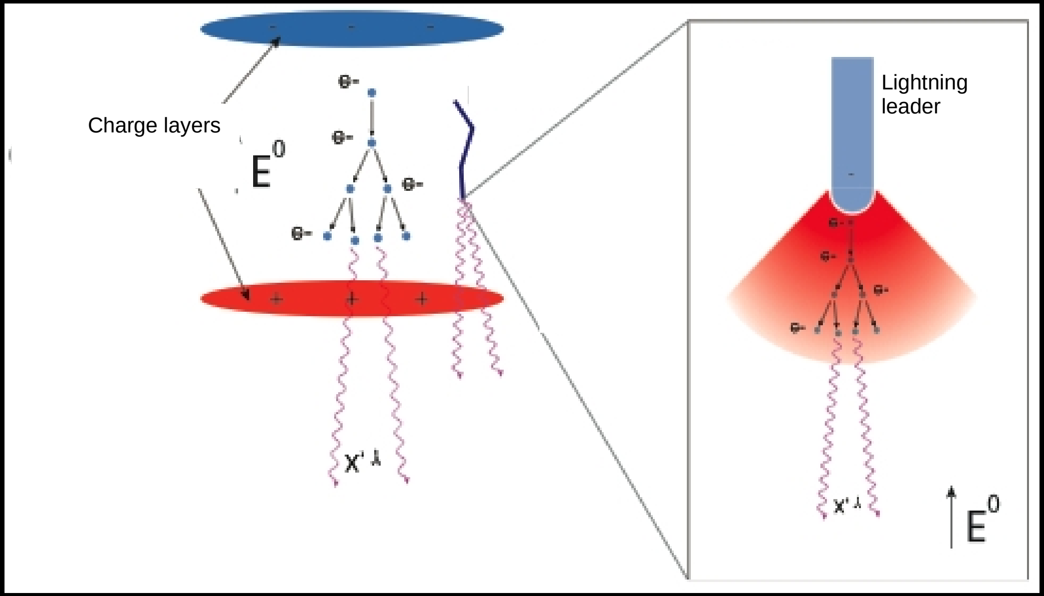
TGFs from ground

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



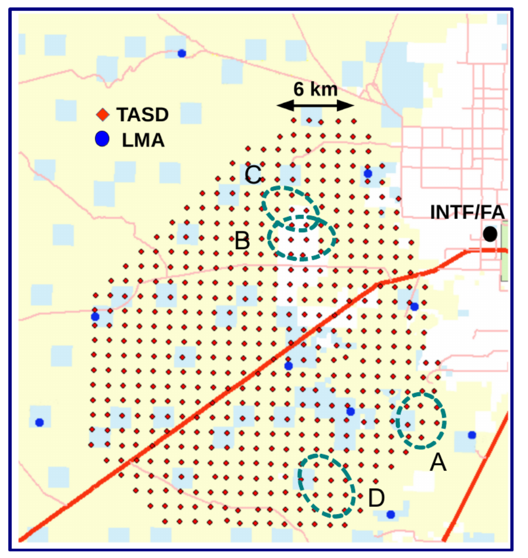
More recent indication of downward TGFs, occurring during strong initial breakdown pulses in the first few milliseconds of negative cloud-to-ground and low-altitude intra-cloud flashes
(J. W. Belz for Telescope Array Collaboration, https://doi.org/10.1029/2019JD031940
→ first high-resolution observations 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)

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.

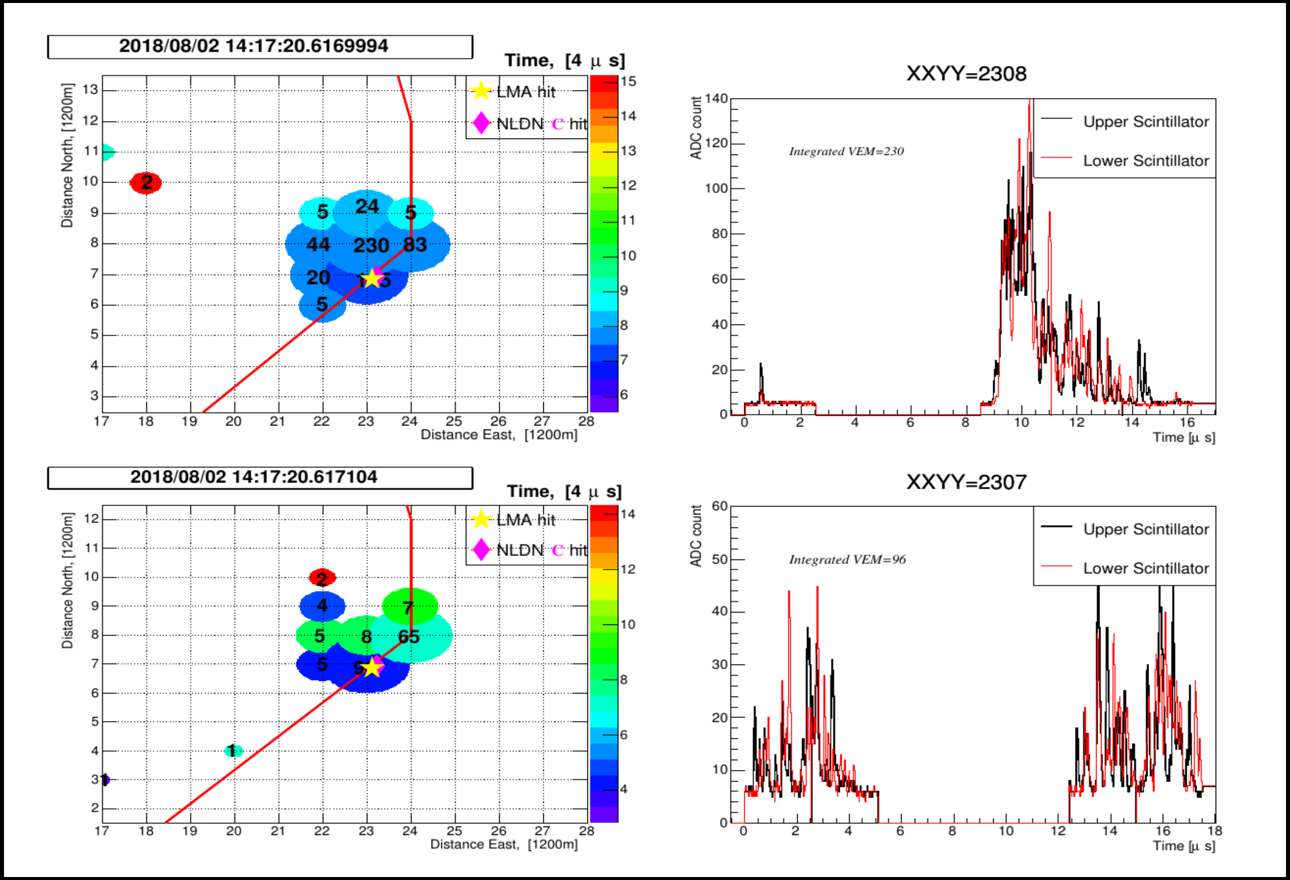


The combined use of all these instruments
+ dedicated simulations
led to an advanced understanding of events initially detected by the only TASD

TGFs @ Telescope Array

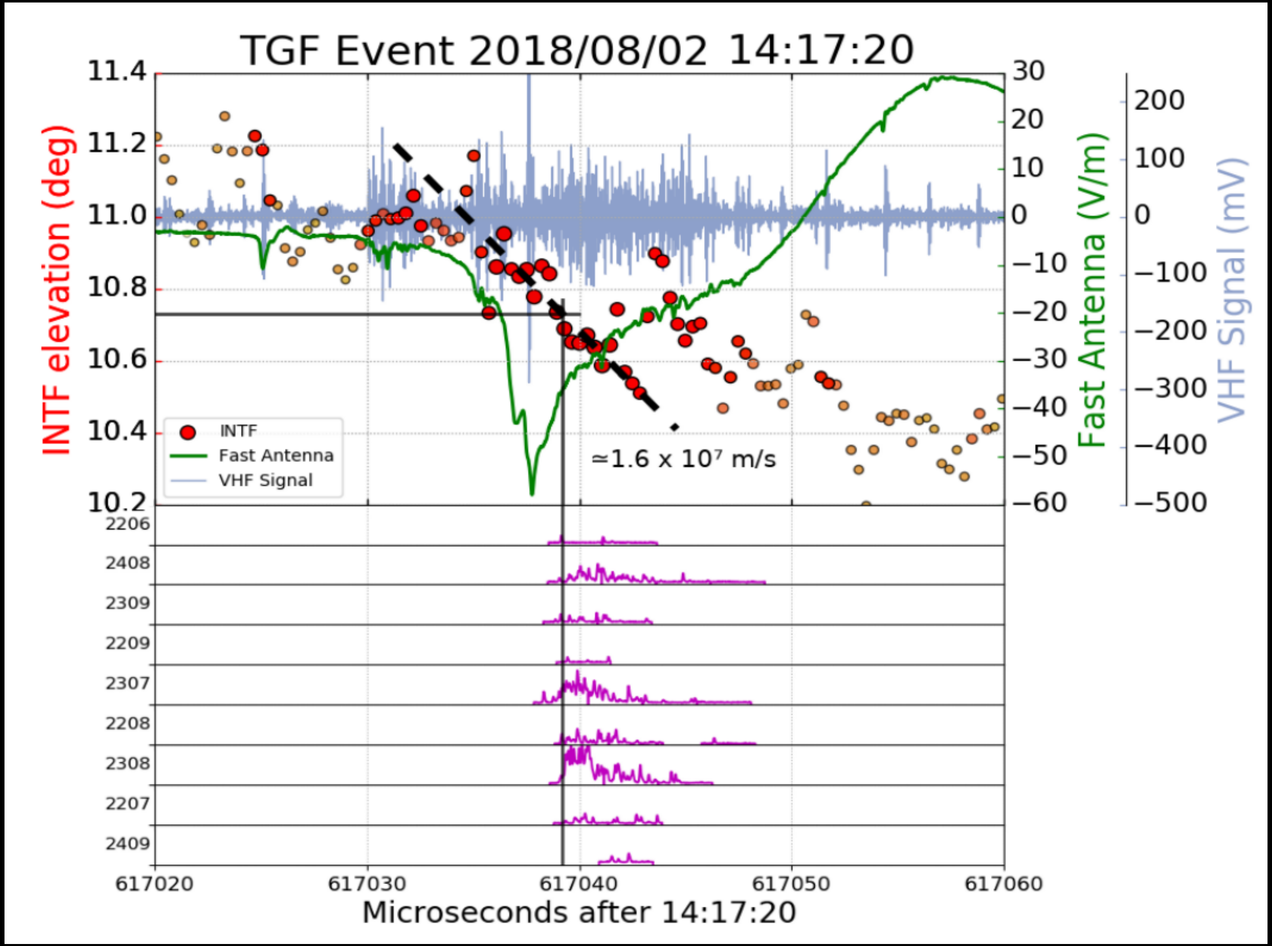
2 triggers occurred within about 100 μs of each other, in the S-E corner of the TASD → they are signatures of the same TGF

Footprint of the two events: TASD stations with signal



TASD station recording the strongest energy deposit during each trigger

TGFs @ Telescope Array

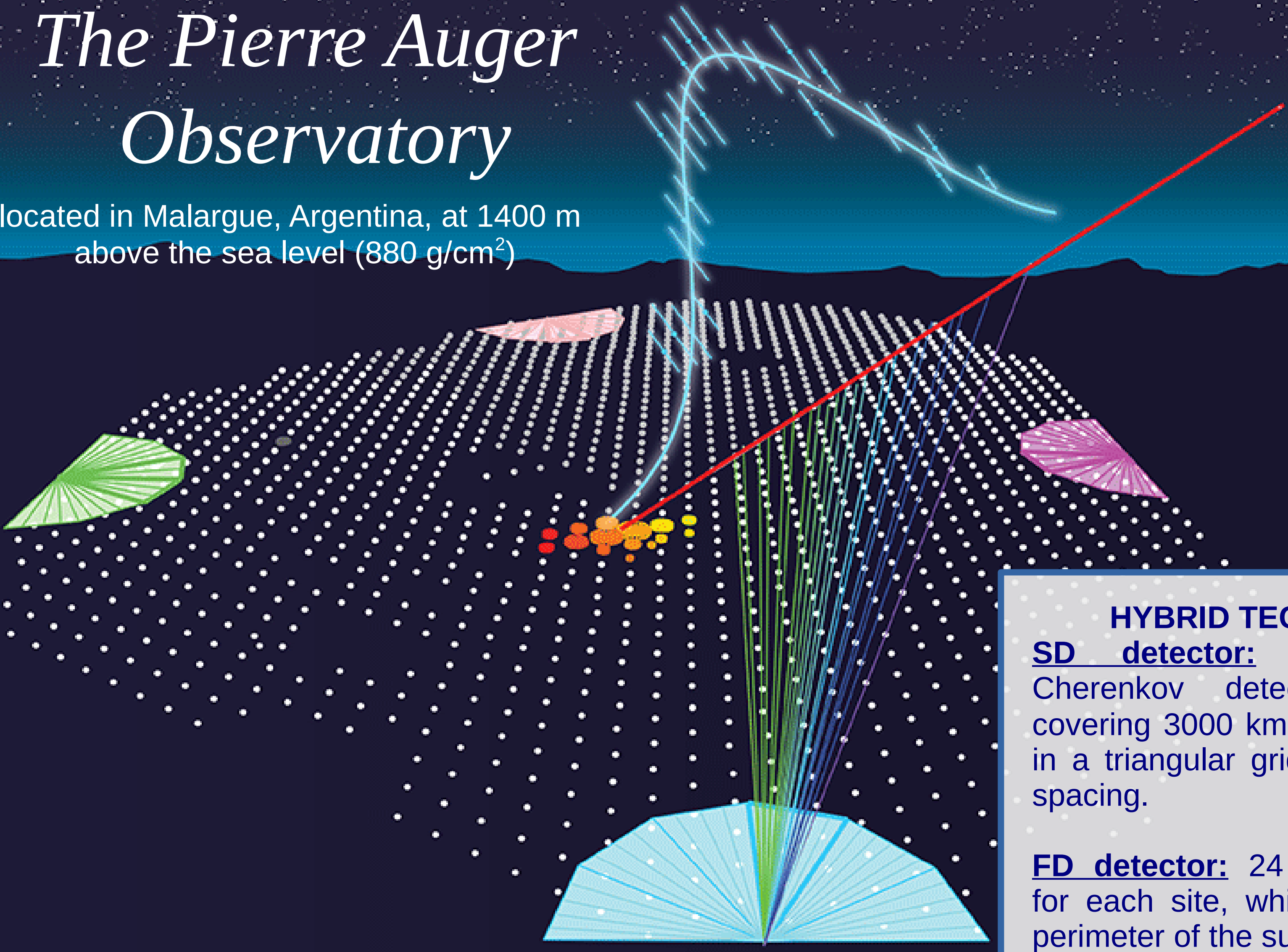


The black vertical line shows the median onset time of the TGF relative to the INTF and fast antenna data. Purple traces in the lower panels are particle detector responses.

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.

The Pierre Auger Observatory

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

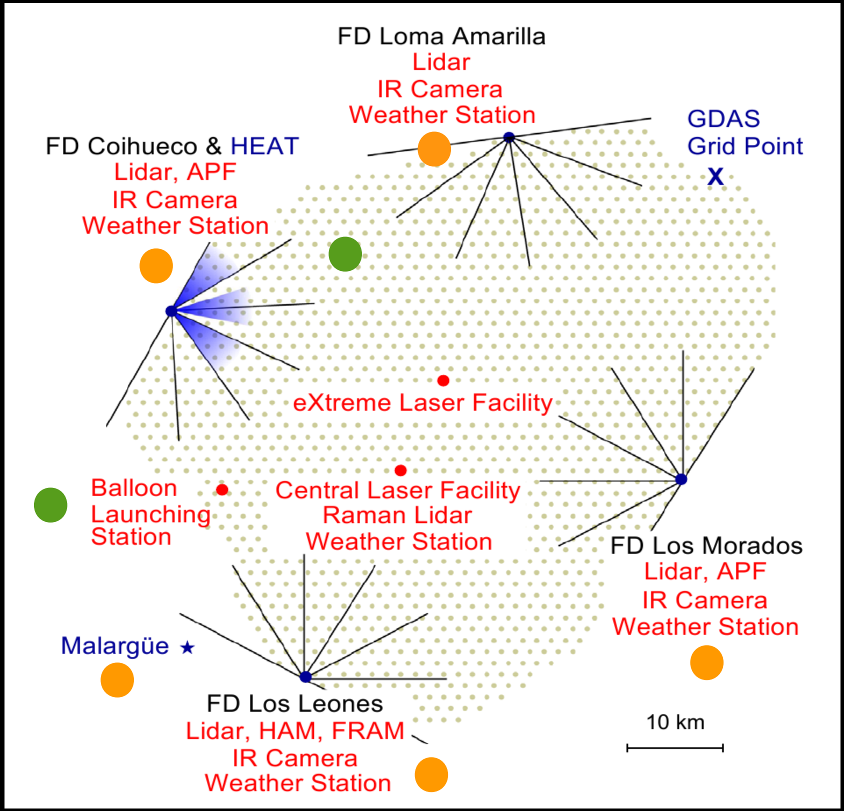


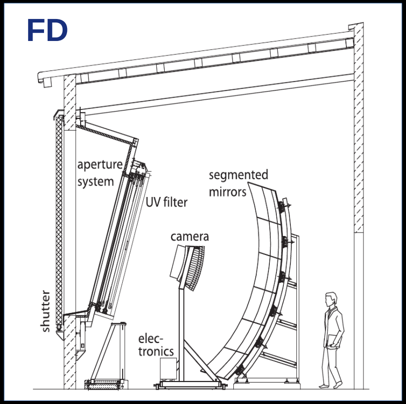
HYBRID TECHNIQUE

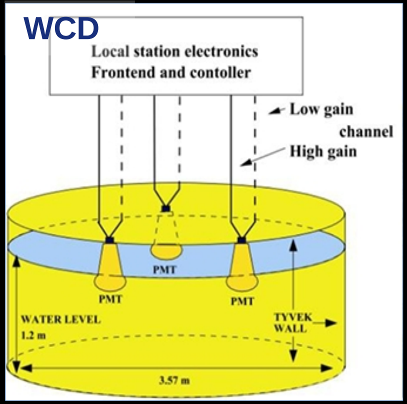
<u>SD detector:</u> 1600 Water Cherenkov detectors (WCD), covering 3000 km^2 and arranged in a triangular grid with 1500 m spacing.

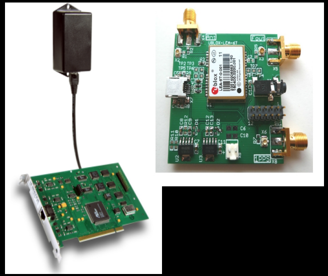
<u>FD detector:</u> 24 telescopes, 6 for each site, which are on the perimeter of the surface array.

The Auger detectors + atmospheric monitoring

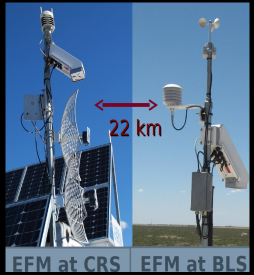






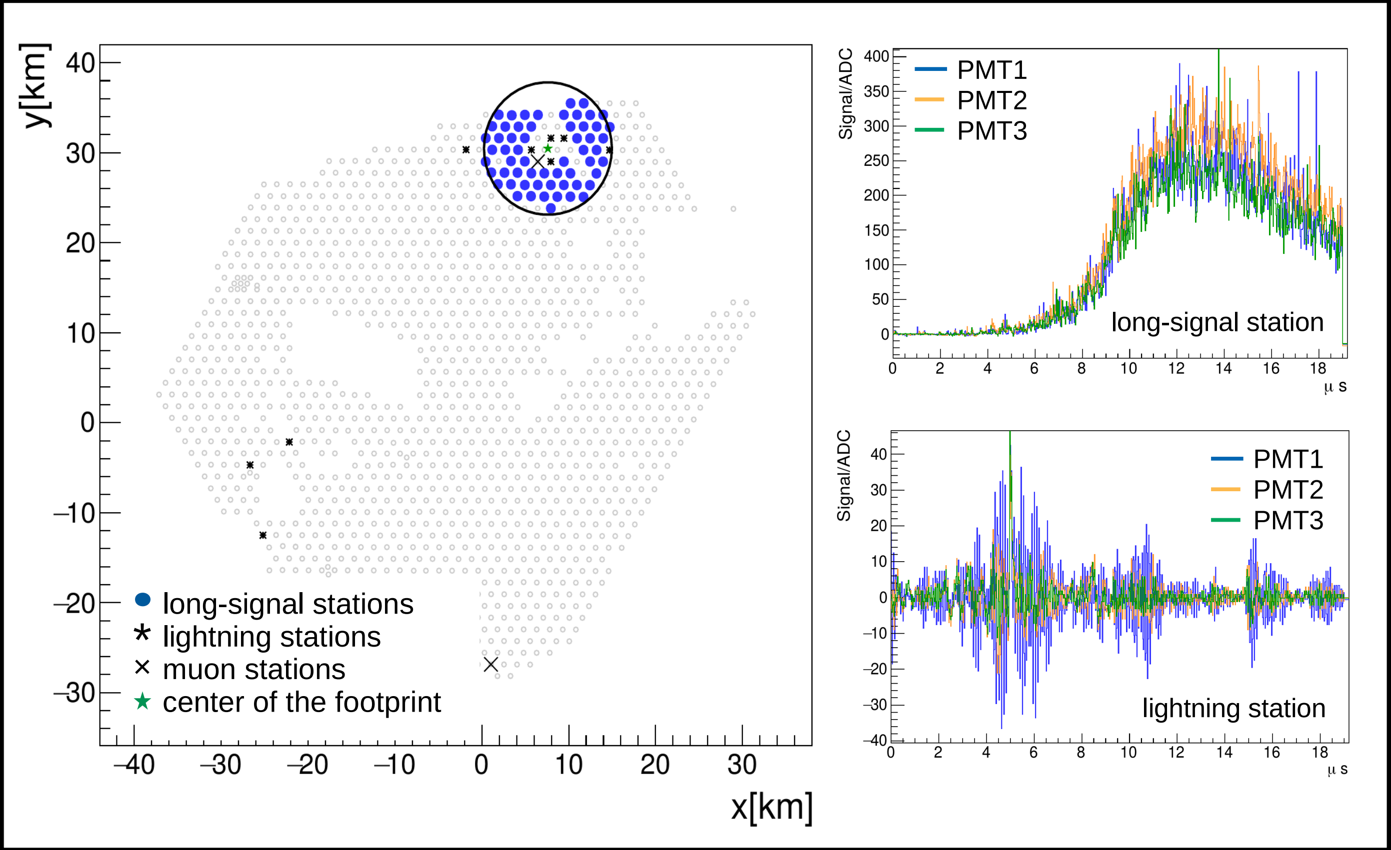


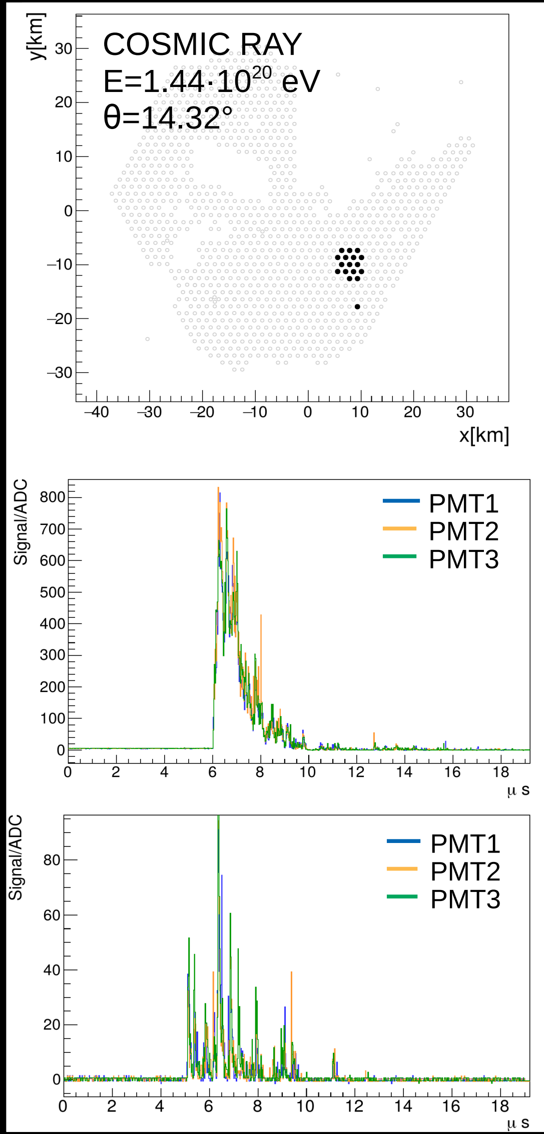
5 Boltek Storm trackers with
GPS antenna (30ns resolution)
Range: up to 500 km



2 E-field mills
Campbell Scientific CS110

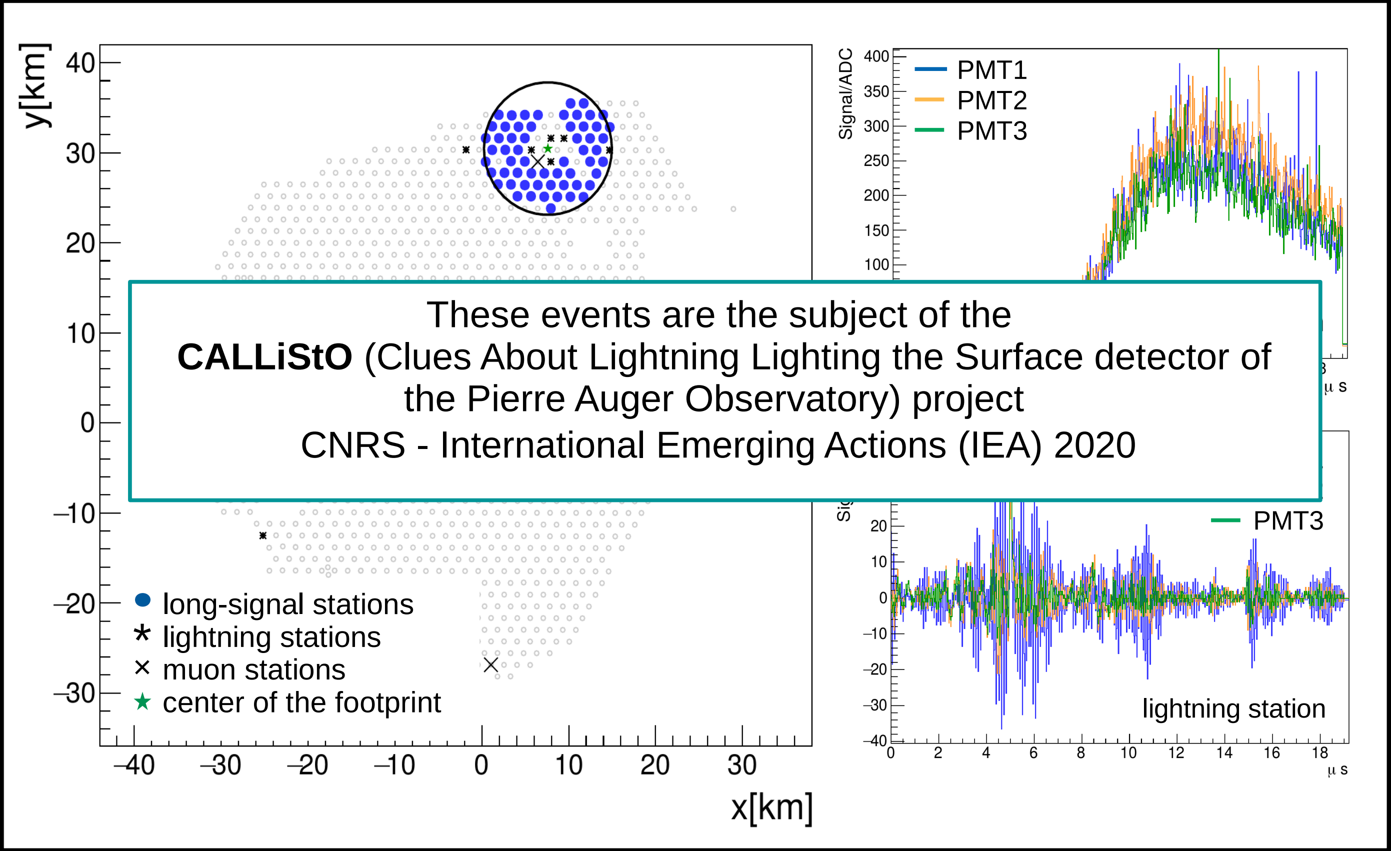
“SD-ring” events: comparison with cosmic-ray events



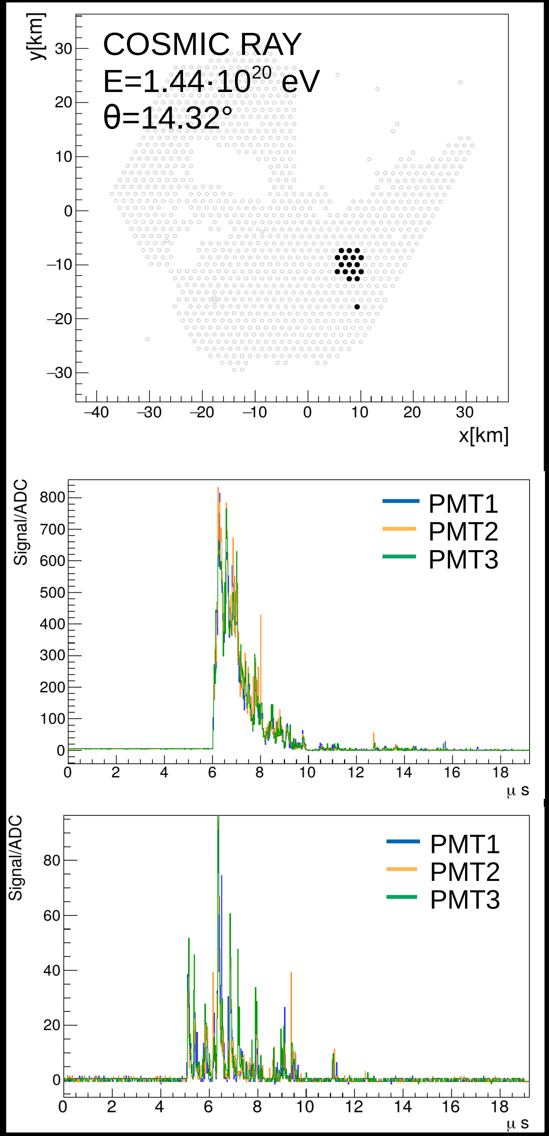


23 peculiar events collected.

“SD-ring”events: comparison with cosmic-ray events



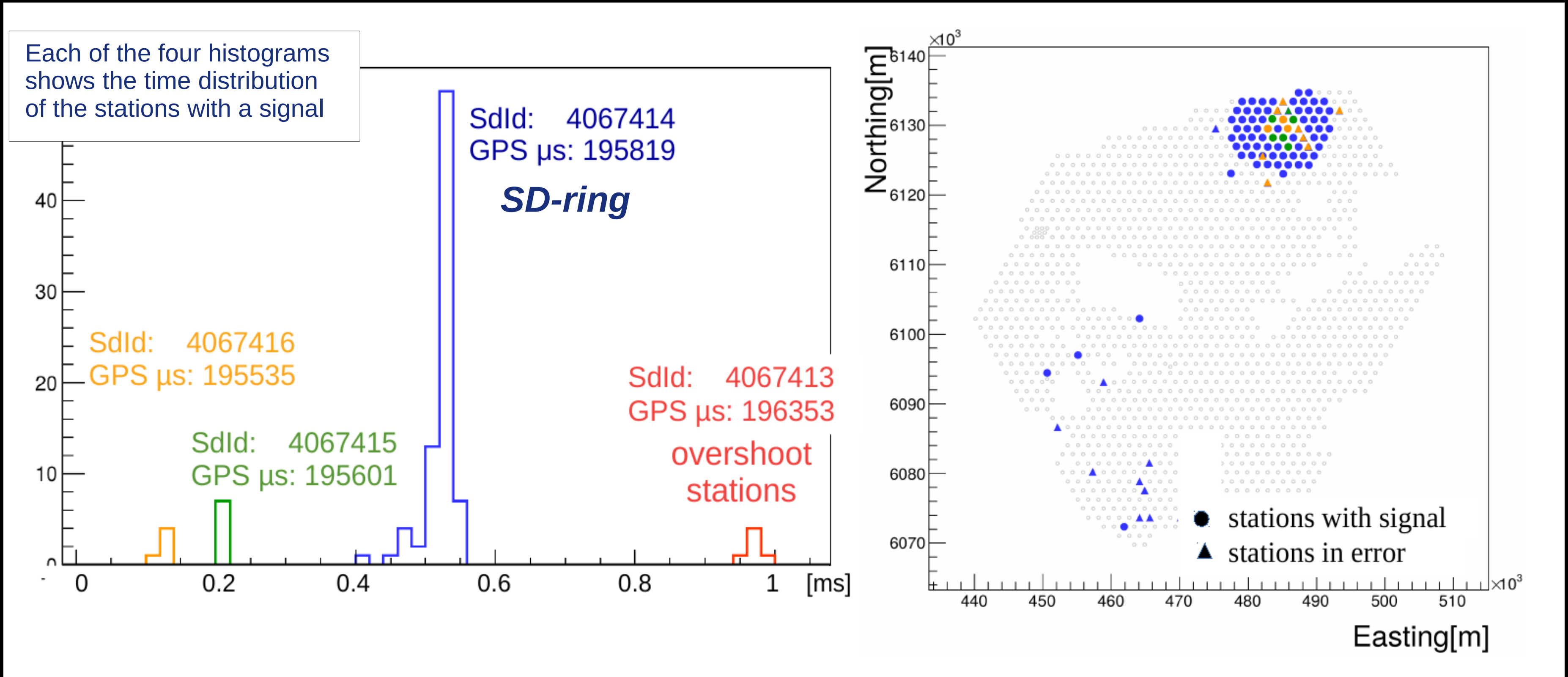
These events are the subject of the
CALLiStO (Clues About Lightning Lighting the Surface detector of the Pierre Auger Observatory) project
CNRS - International Emerging Actions (IEA) 2020



23 peculiar events collected.

"SD-ring" events

→ We searched for additional triggers in a time interval of ±2.5 ms with respect to the SD-ring time
→ we found accompanying events for all the identified SD-rings



“SD-rings”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:

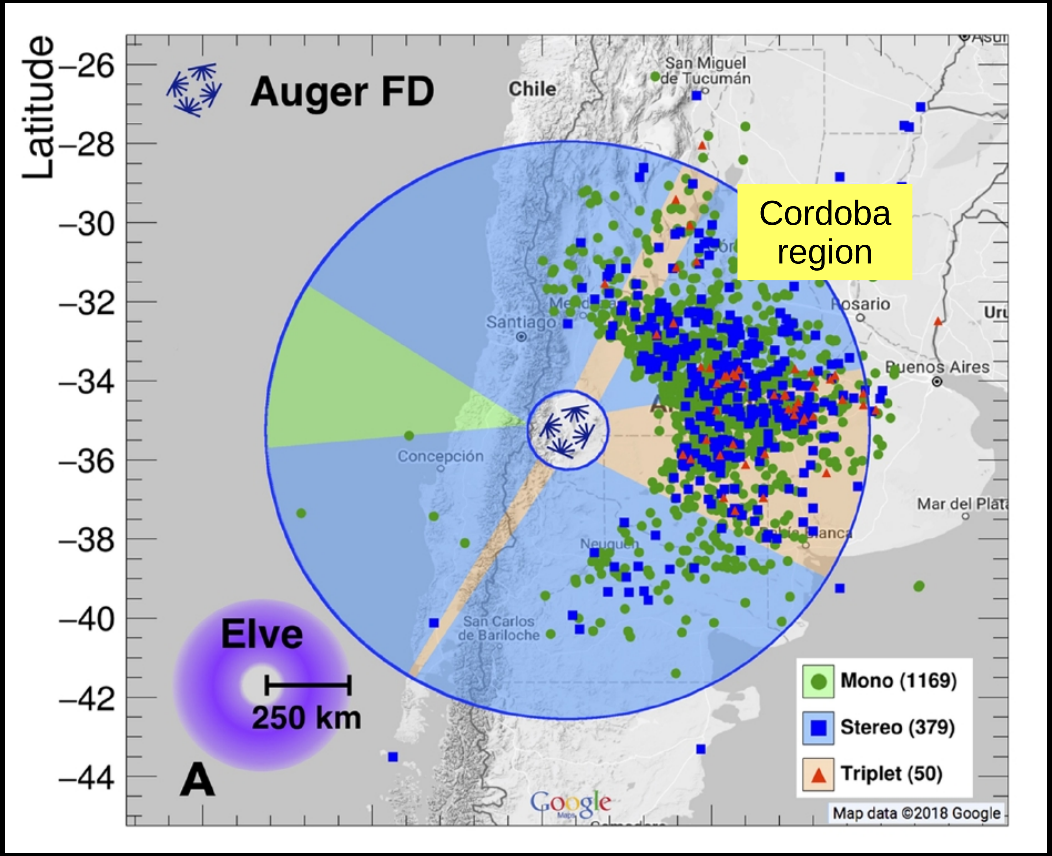
→ comparison with data from instruments recently installed at the observatory that can monitor lightning and electric field at the ground;
→ comparison with data from AERA antennas;
→ comparison with simulations.

ELVES @ the Pierre Auger Observatory

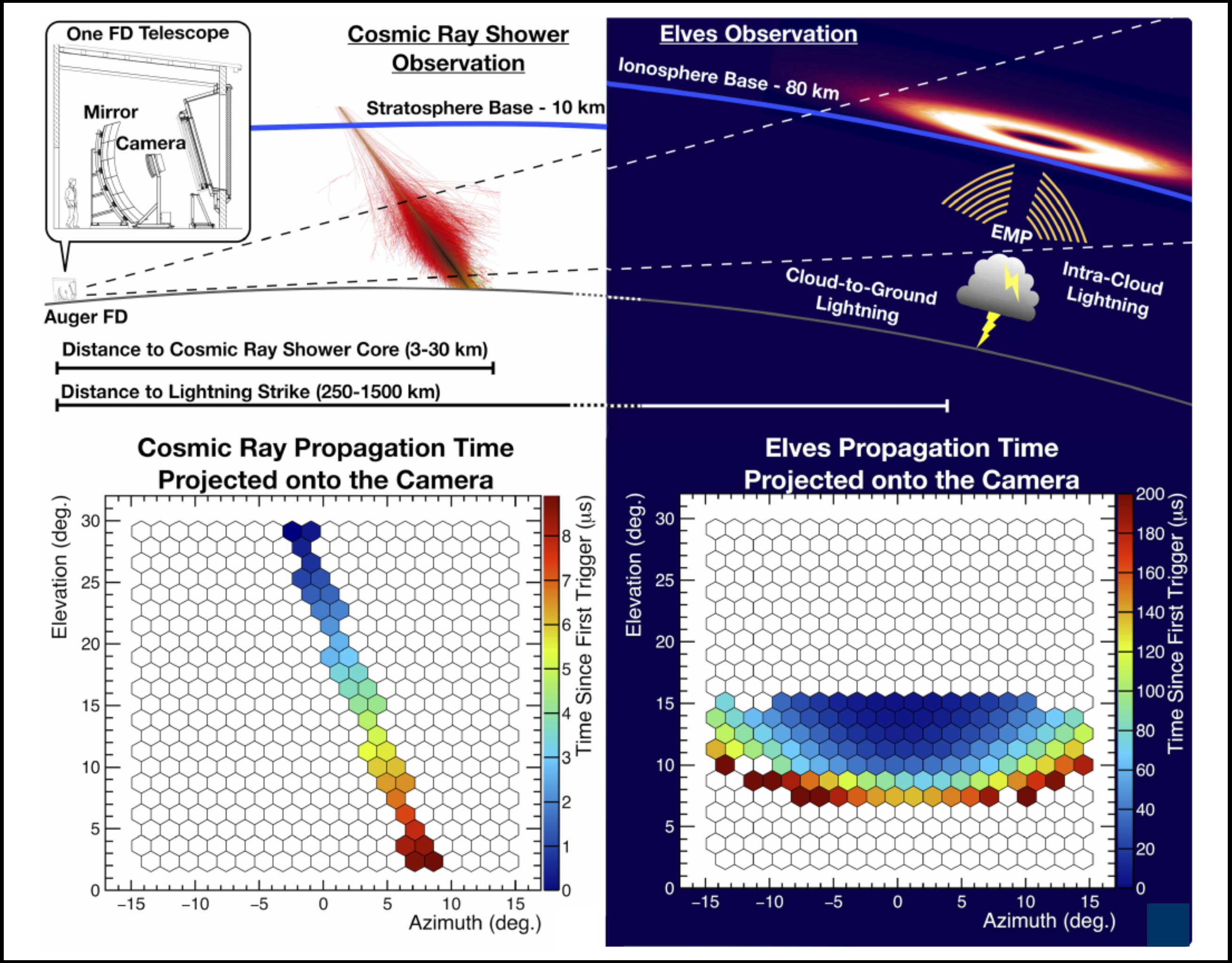
More than 95% of the observed elves are 250-1000 km away, where the FoV of a telescope crosses the ionosphere and direct light from lightning is blocked by the limb of the Earth
→ the observatory acceptance for elves extends over $3 \cdot 10^6$ km^2, the largest ground-based area ever used for detecting 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.

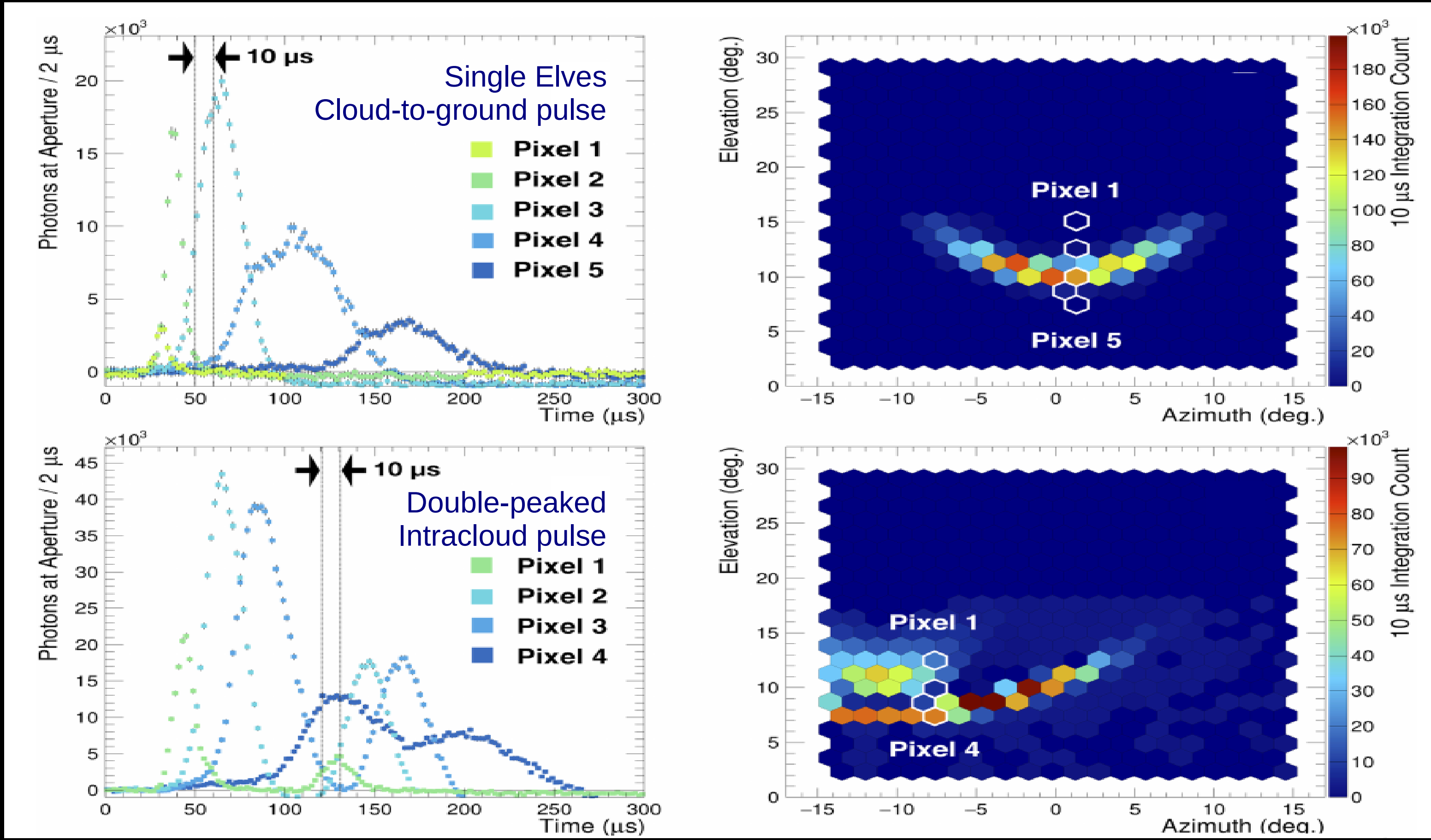
Thanks to HEAT (High Elevation Auger Telescopes), we can reduce the lower limit of the acceptance and observe other events very close to the array.



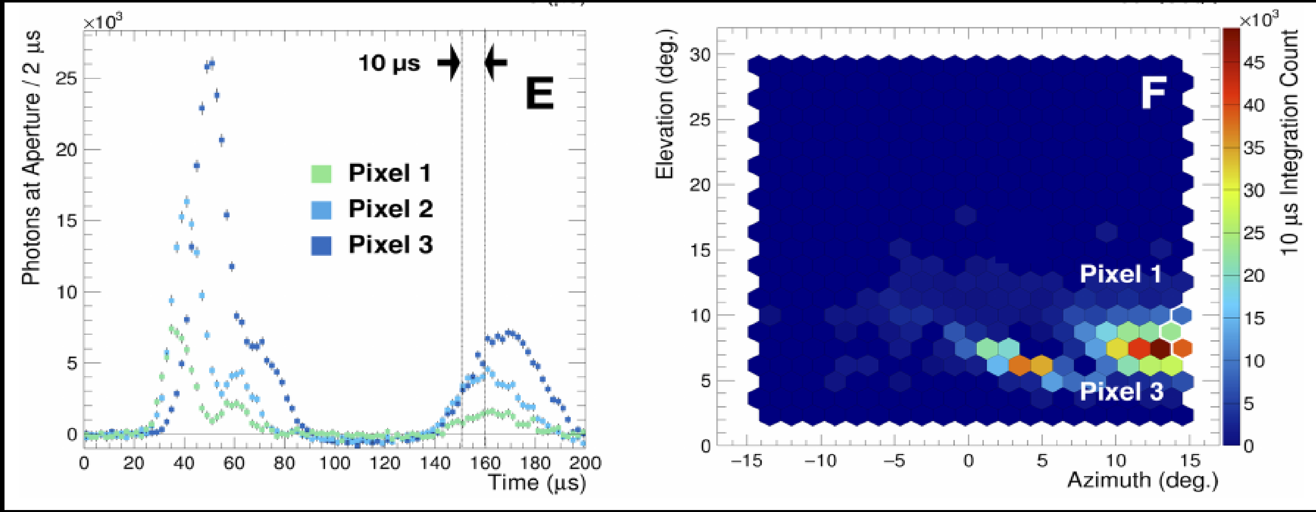
ELVES @ the Pierre Auger Observatory



ELVES @ the Pierre Auger Observatory → zoology



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?

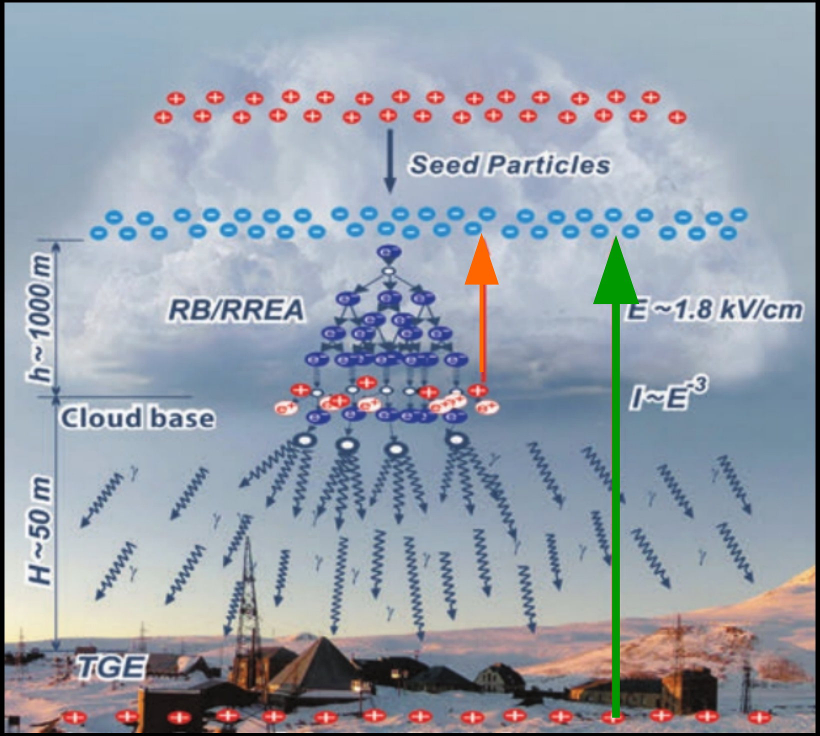
Variations in cosmic-ray flux at the ground

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.

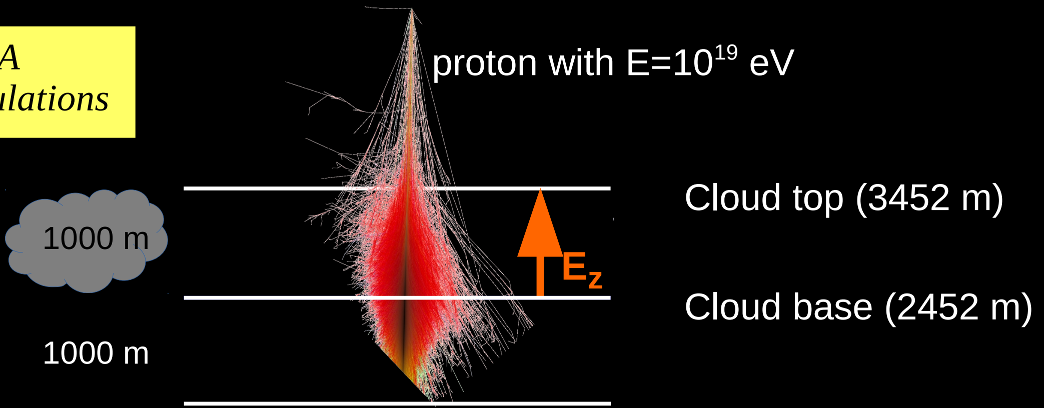
Main field:
bottom dipole between the main negative charge layer and the positively charged region at the base of the cloud.

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.

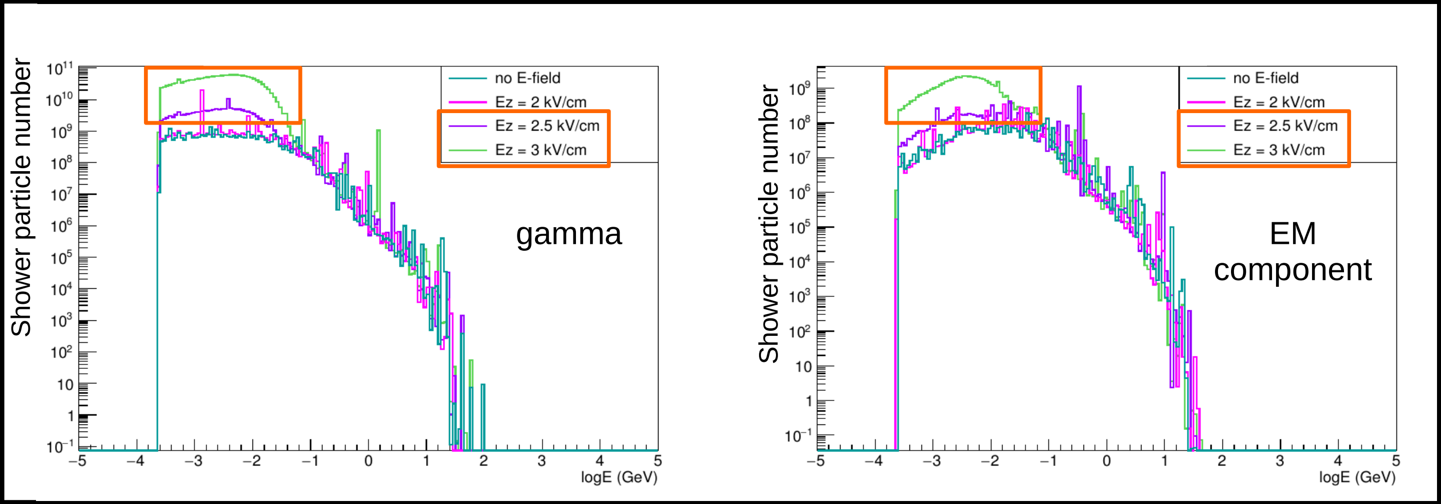


Variations @ Auger observation level

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.

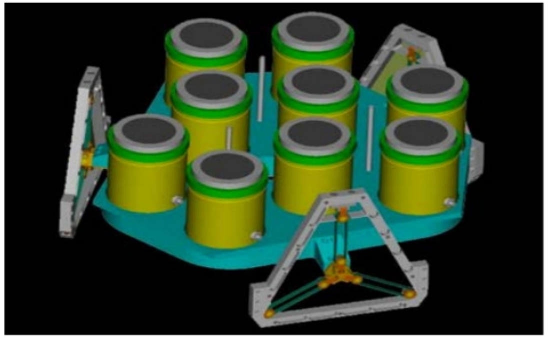
Finally, we need to investigate the possible effects that thunderstorms can have on the cosmic-ray measurements.

Thank you for your attention

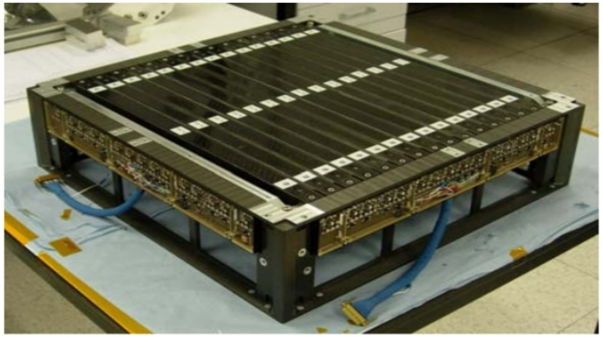
Backup

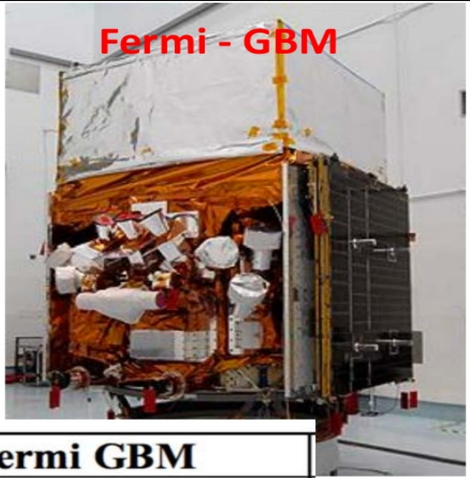
TGF detectors

RHESSI - GeD



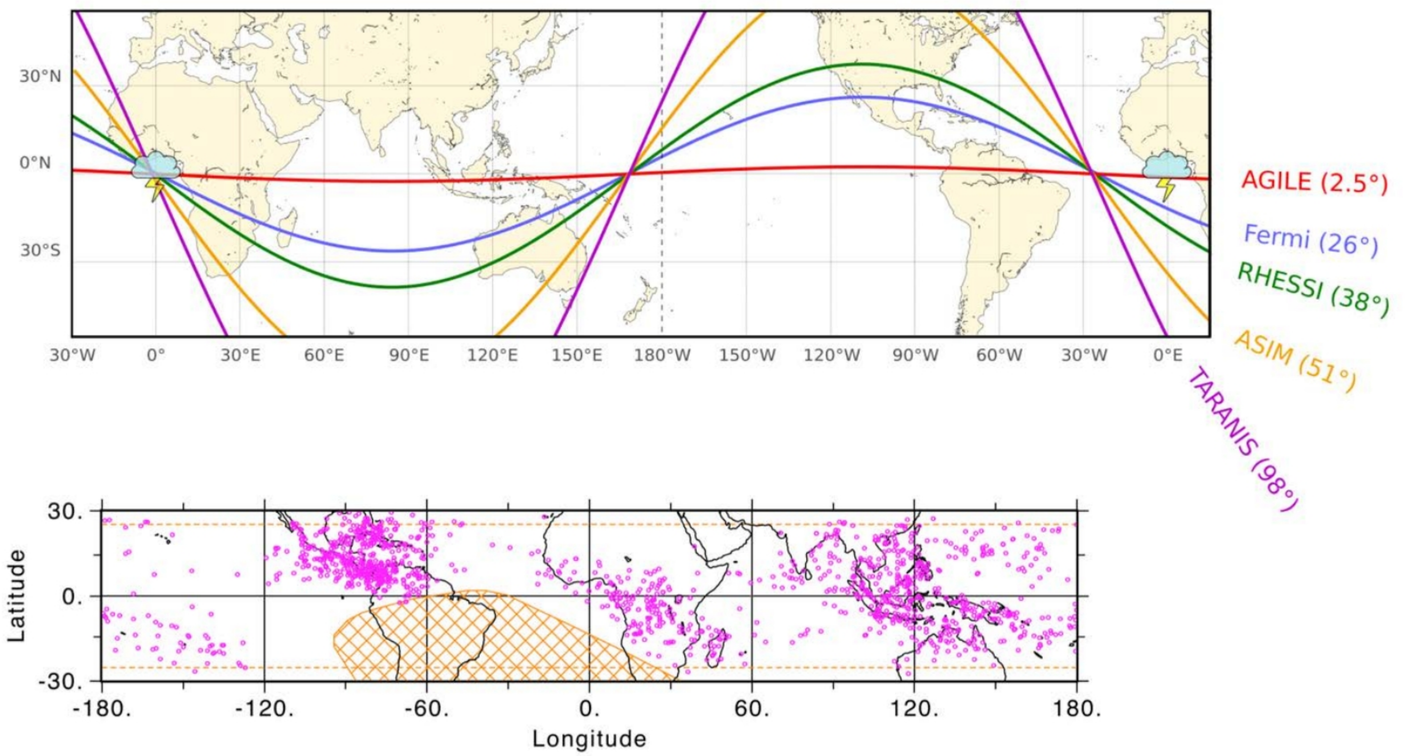
AGILE - MCAL





	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

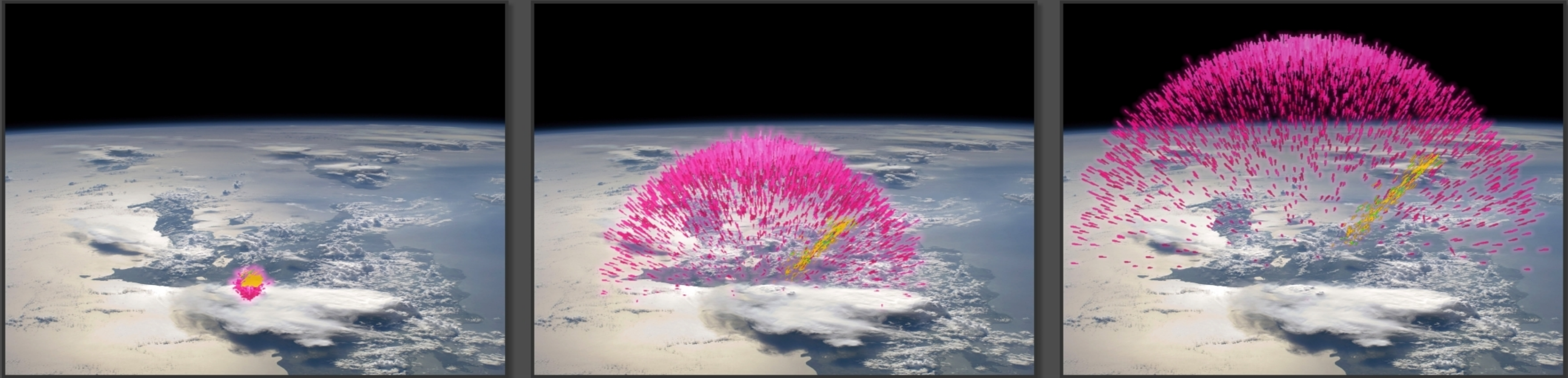
TBE & Magnetic mirroring

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).

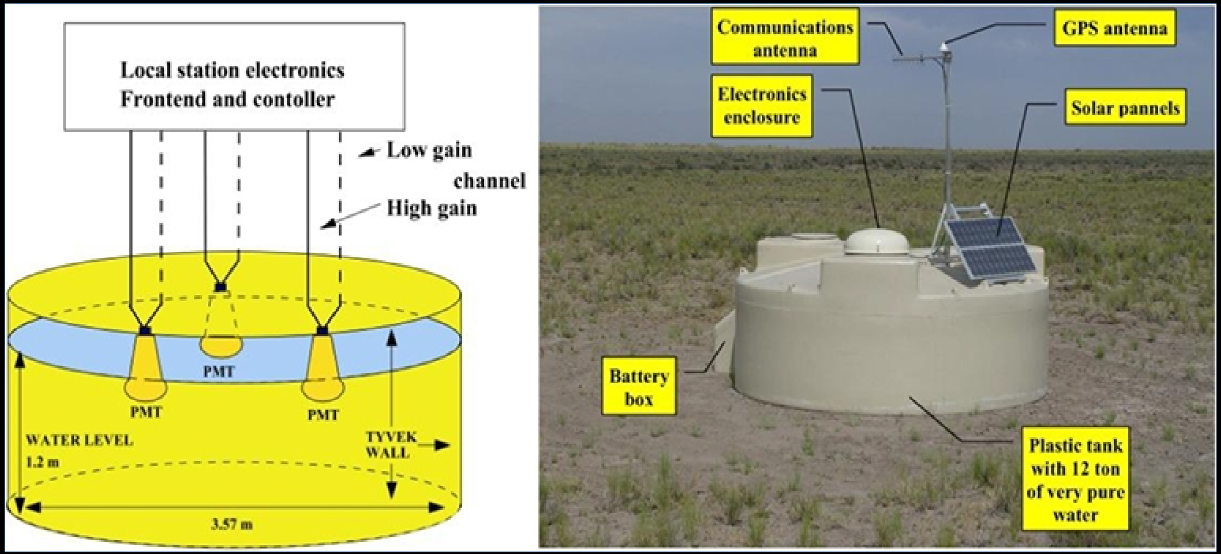
2. When gamma-ray energy collides with electrons, they accelerate to near the speed of light. Some gamma rays pass near the nuclei of atoms. When this happens, the gamma ray transforms into an electron and its antiparticle, a positron.

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.

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.