MODULATION EFFECTS POSED BY STRONG ATMOSPHERIC ELECTRIC FIELDS OF THE FLUXES OF SECONDARY COSMIC RAYS

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37 ВСЕРОССИЙСКАЯ КОНФЕРЕНЦИЯ ПО КОСМИЧЕСКИМ ЛУЧАМ

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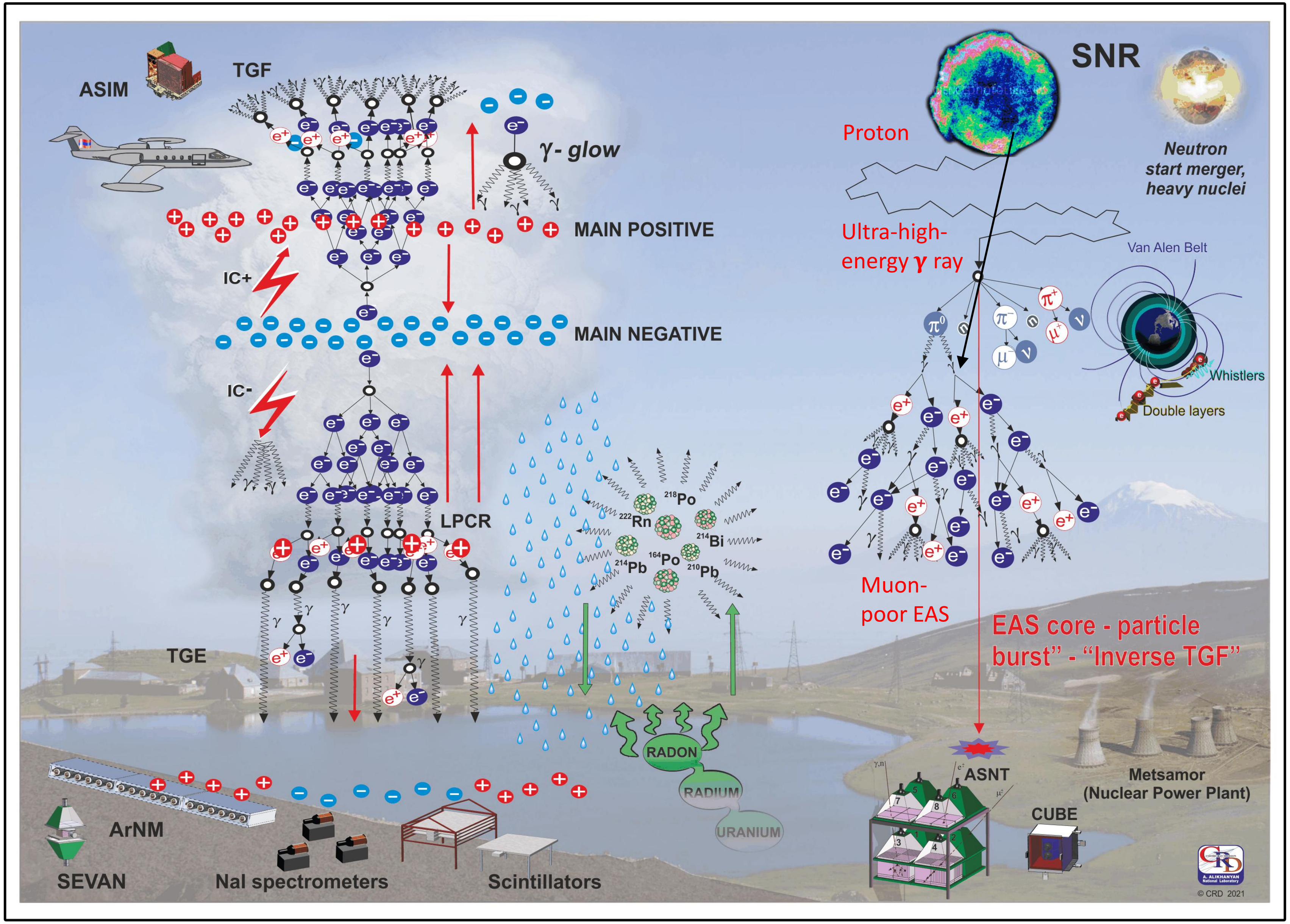
- Models of secondary cosmic ray modulation by strong atmospheric electric fields;
- Vertical and horizontal profiles of the atmospheric electric fields;
- Charge structures in atmosphere supporting the emergence of TGEs;
- Origination of particle bursts measured on the earth's surface;
- Lightning flashes of different energies and types and TLEs and their relation to TGEs;
- Muon stopping effect;
- Influence of electric fields on EASs: ACTs (MAGIC, HESS, CTA) and high-altitude large particle arrays (HAWK, LHASSO).

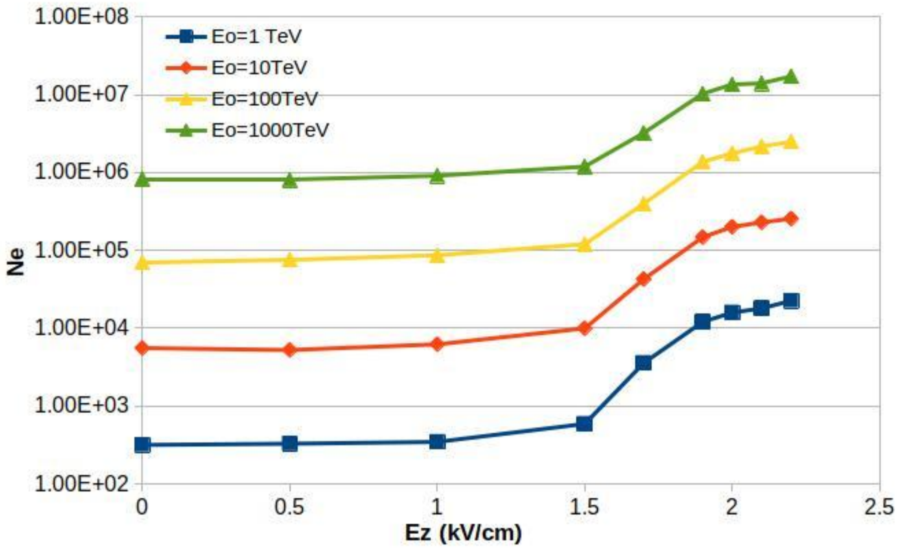
- Investigation strategy/techniques
  - The synergy of Comic Ray physics and Atmospheric physics;
  - Continuous monitoring of different species of cosmic rays, electric and geomagnetic fields, lightning locations, meteorological parameters, cloud movements, and TLEs;
  - Worldwide networks of identical particle detectors and field meters allowing precise synchronization and mutual analysis of data (Armenian network, East European SEVAN network);
  - Possibilities of the online visualization and analysis of the stream of multivariate from hundreds of measuring channels data by the advanced data extraction infrastructure (ADEI platform);
  - Electron and gamma ray energy spectra recovering by the scintillation and the NaI crystal spectrometers.



Aragats Cosmic Ray station: research of planetary, solar and galactic particle accelerators. Year-round operation from 1943. Coordinates: 40.47N, 44.18E, 3200m a.s.l. Located on highland near Kare lake in the vicinity of Aragats south peak ≈(3700m), the highest North peak is ≈4000 m.

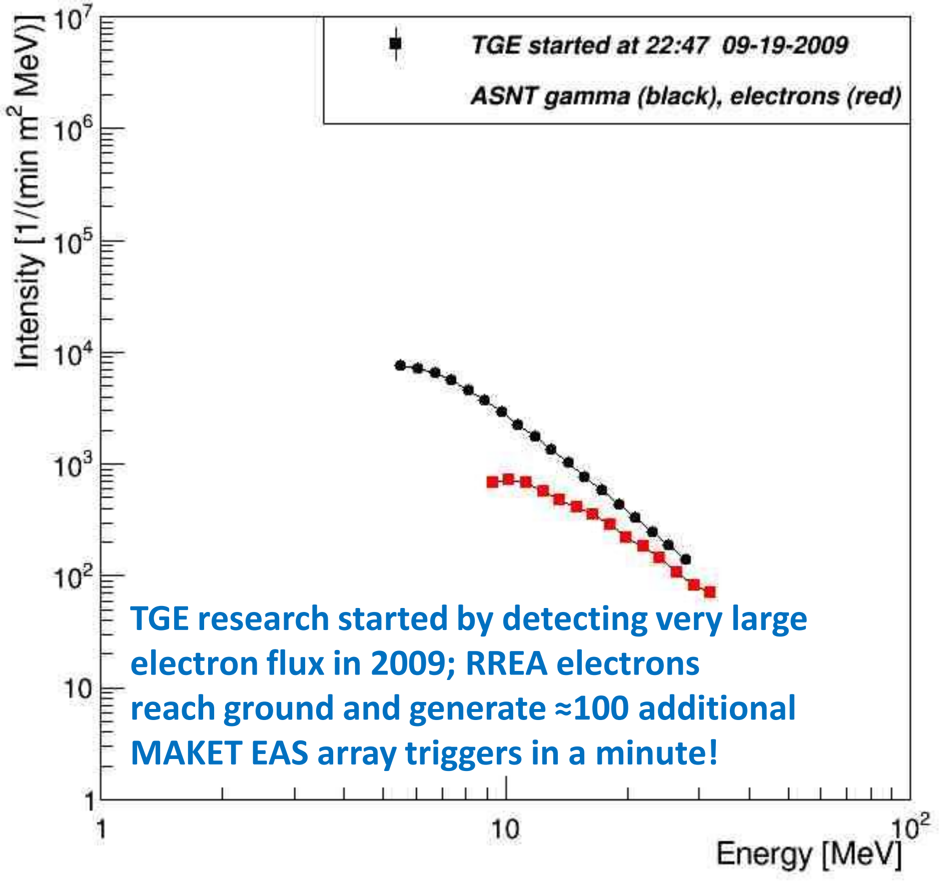
LHASSO detects PEV gamma rays from direction of SNR G106.3+2.7, PSR B0656+14 and other SNRs

PEVatron detection by LHASSO: possible overestimation of primary gamma ray energies if observations were done during thunderstorms often in Tibetan plateau.

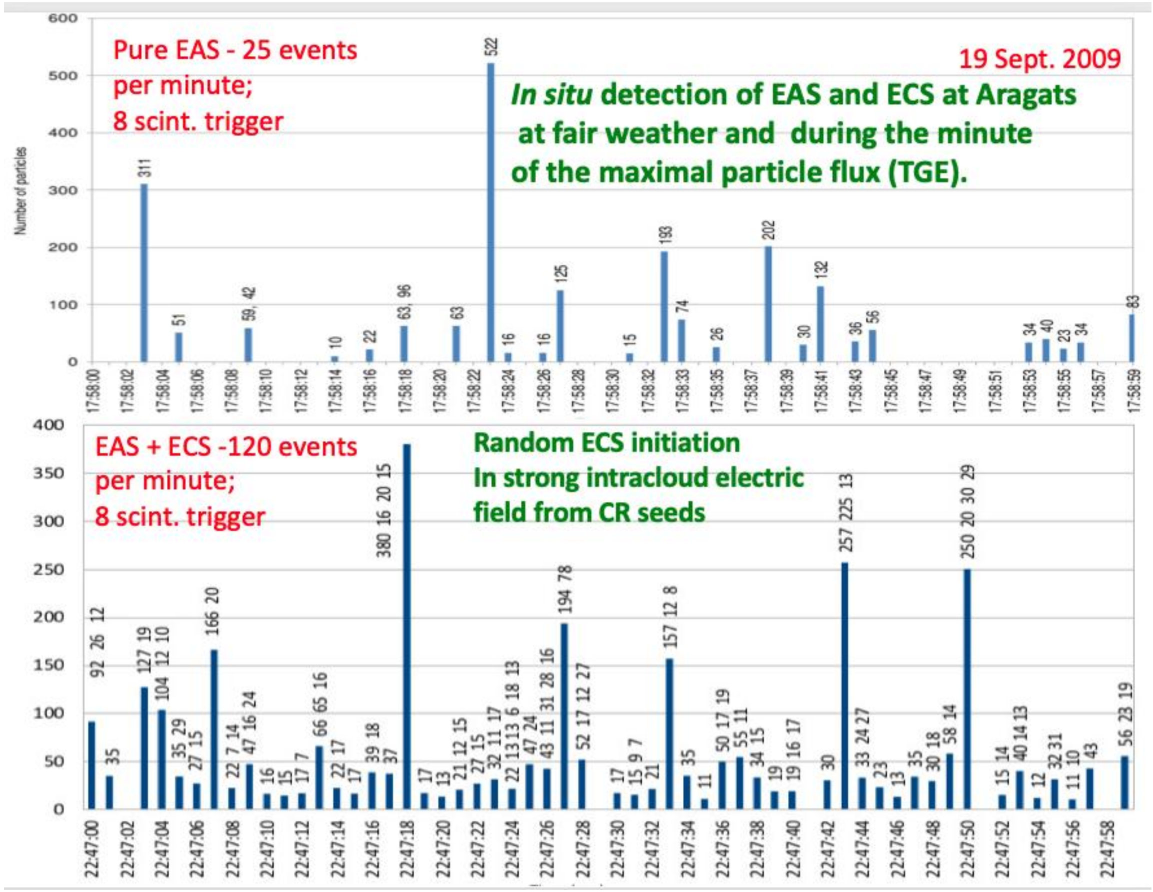


Eo (GeV)	Eest (GeV)
1.00E+03	2.23E+04
1.00E+04	1.34E+05
1.00E+05	6.50E+05
1.00E+06	2.42E+06

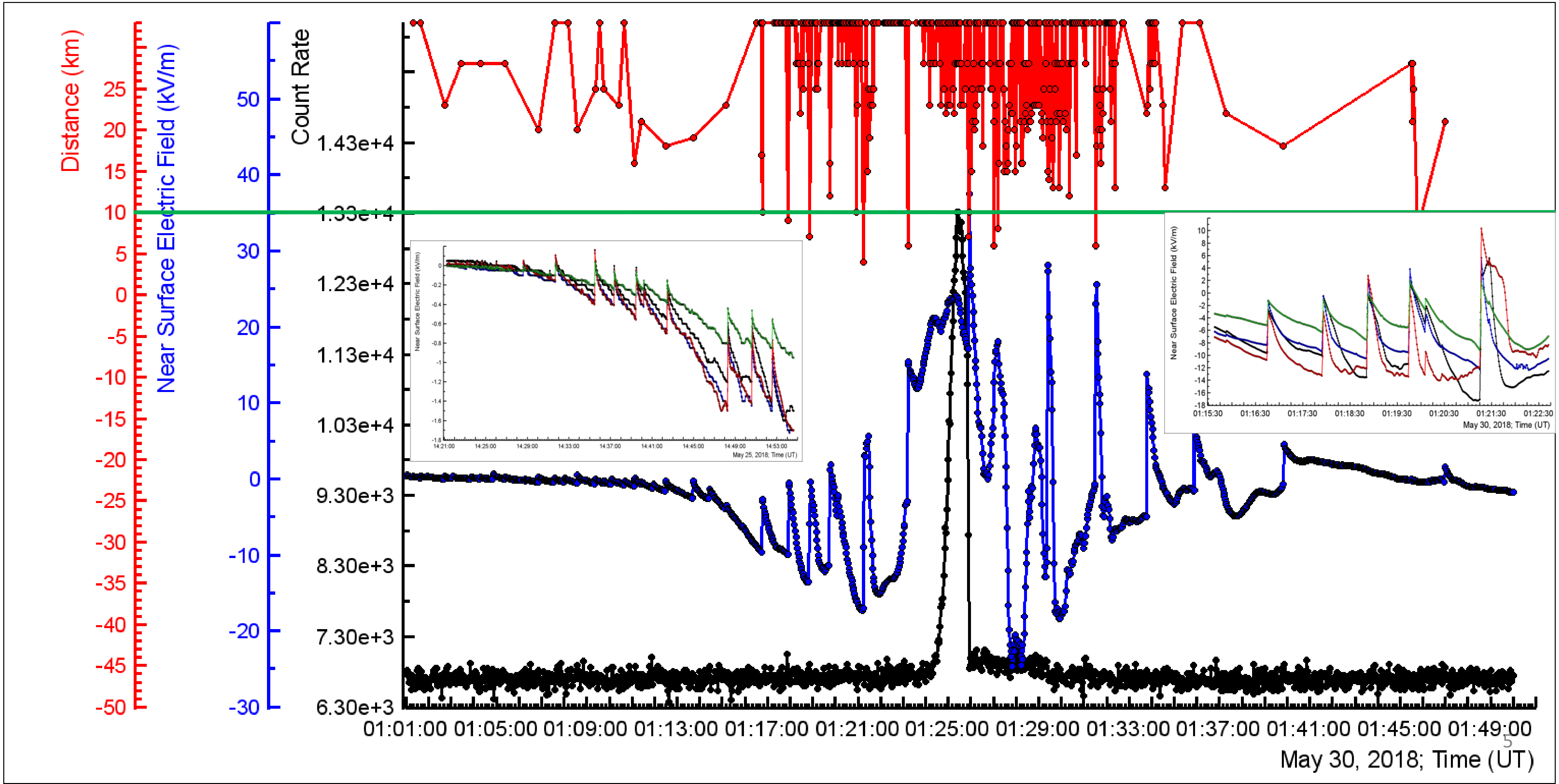
First direct detection of RREA/TGE: MAKET EAS array registered RREA electrons reaching earth’s surface



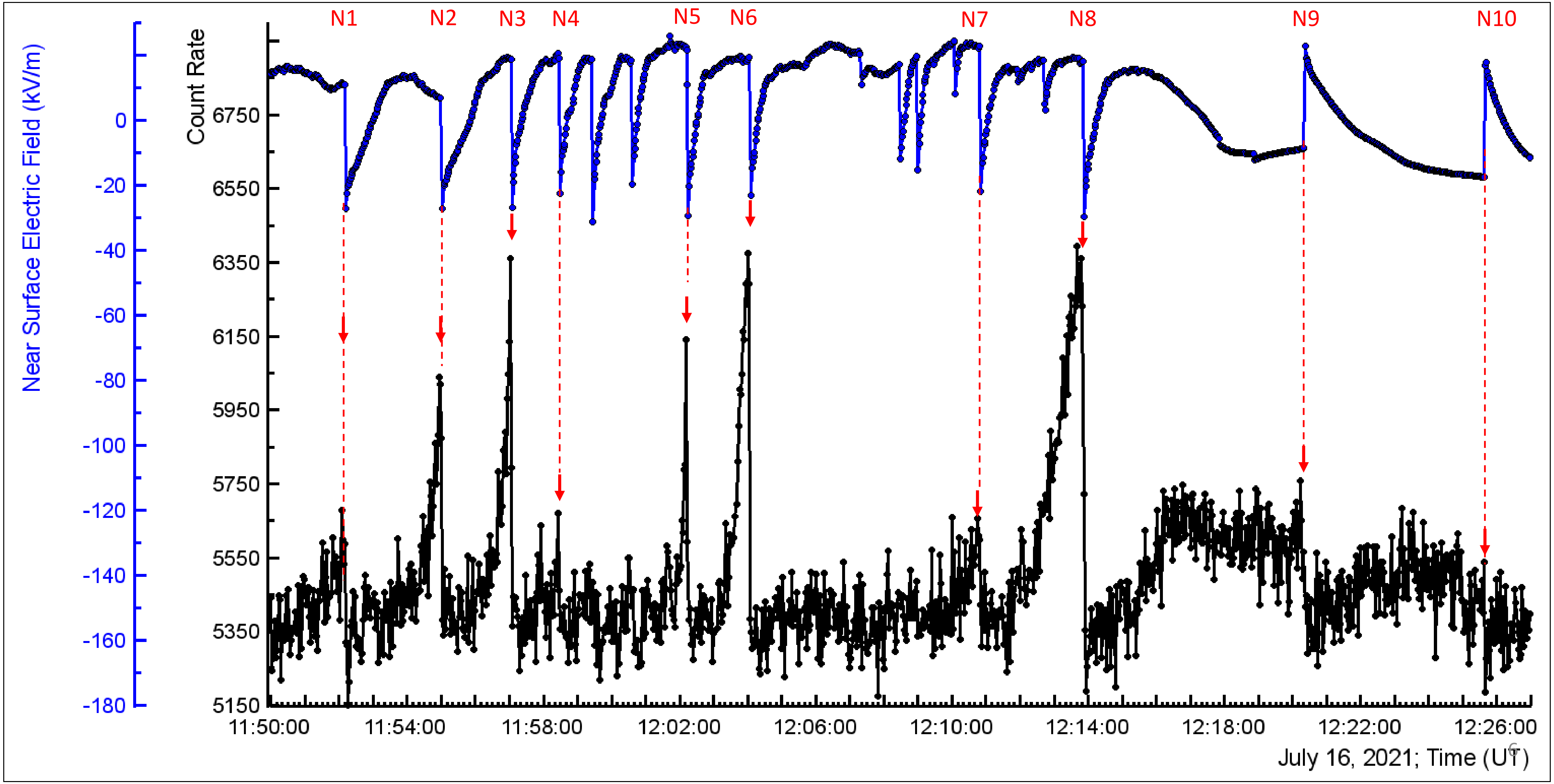
TGE research started by detecting very large electron flux in 2009; RREA electrons reach ground and generate ≈100 additional MAKET EAS array triggers in a minute!



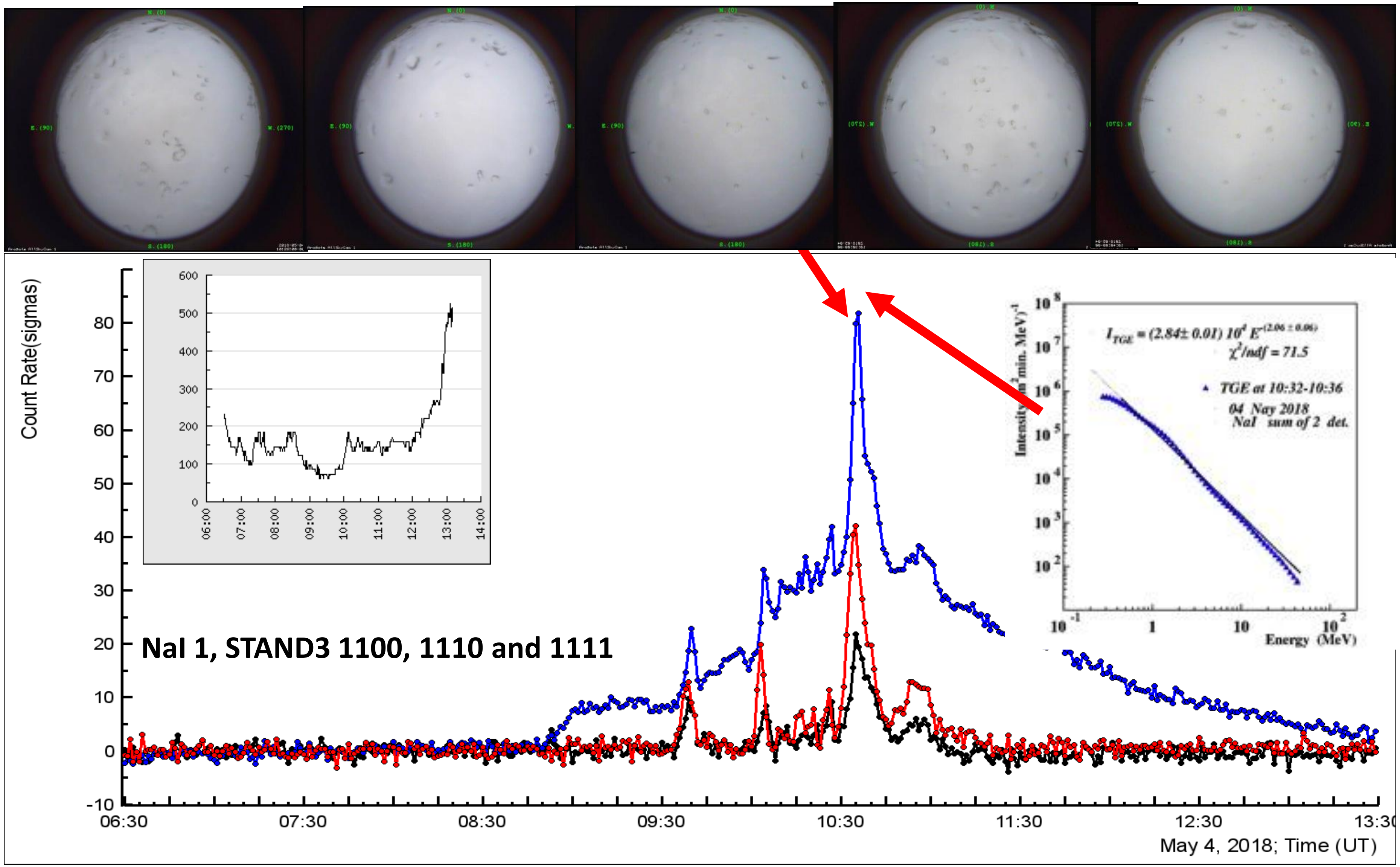
15 years of monitoring of Lightning location, Near-surface electric field (NSEF) and particle fluxes measured by multiple spectrometers…



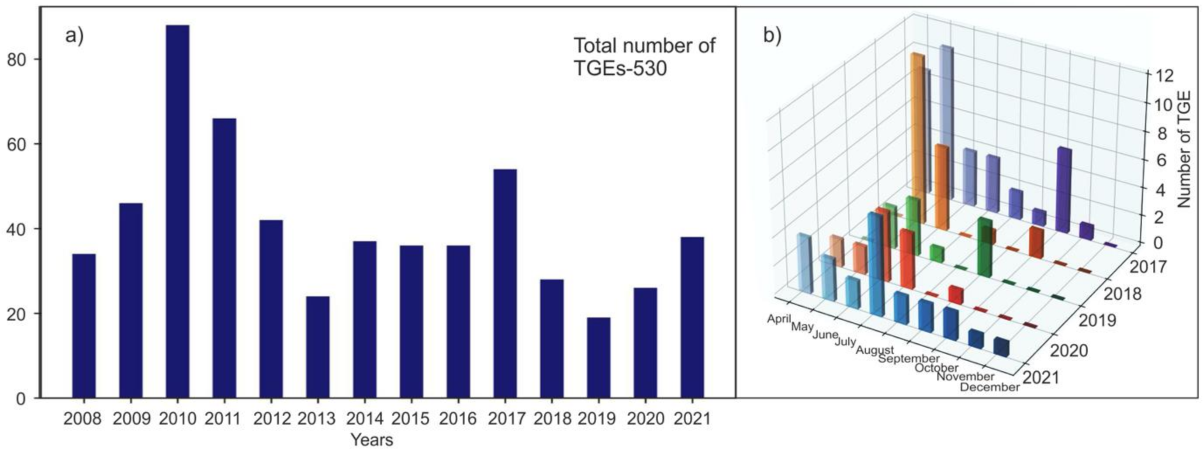
TGE terminations by nearby (distance <10 km) lightning flashes: NSEF disturbances and particle detector count rates



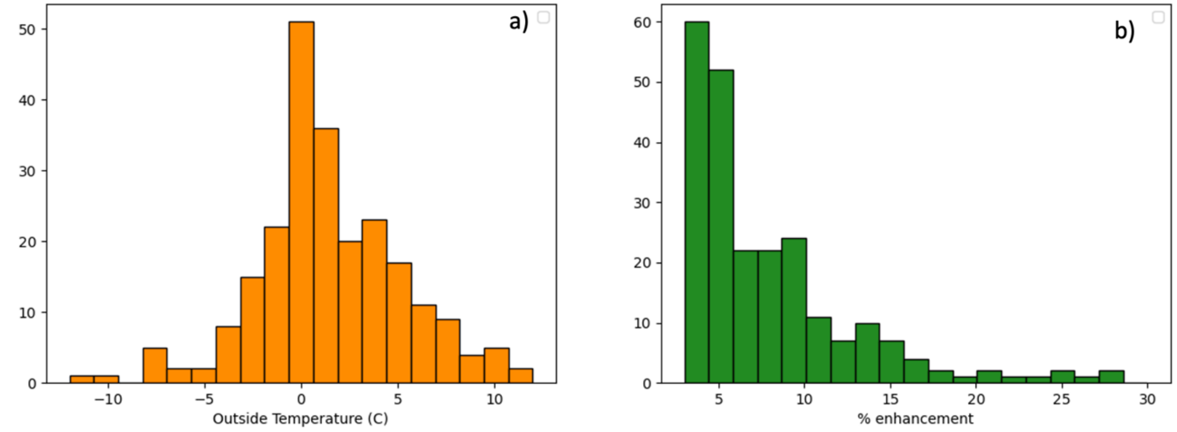
Long duration TGEs observed by spectrometers with low energy threshold (≈0.3 MeV). Radon progeny gamma radiation: mostly 214Pb and 214Bi: Radon isotopes circulation. Graupel detection.



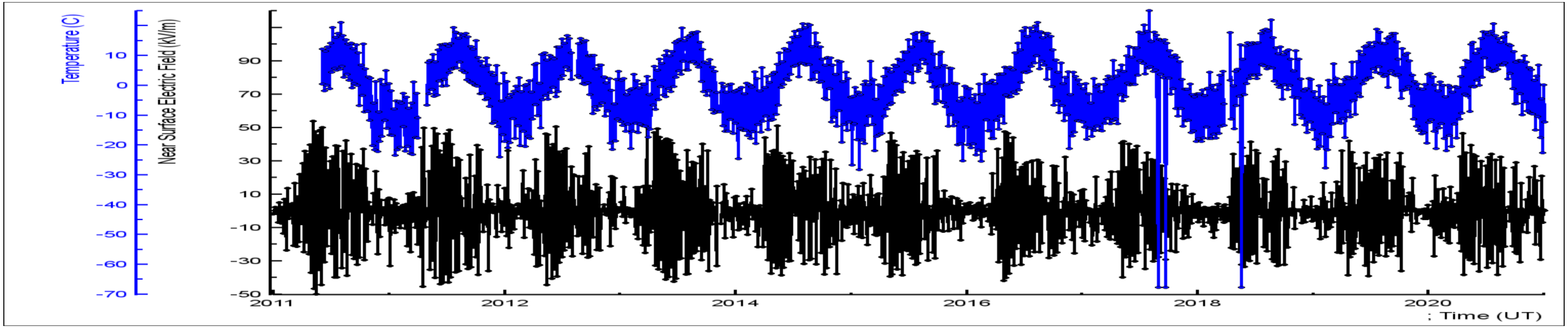
TGE statistics ≈550 TGEs registered in 2009-2021



TGE yearly and monthly statistics.



a)The distribution of outside temperatures during TGEs;
b) distribution of TGE significances by 3 cm thick plastic scintillator of STAND3 detector.

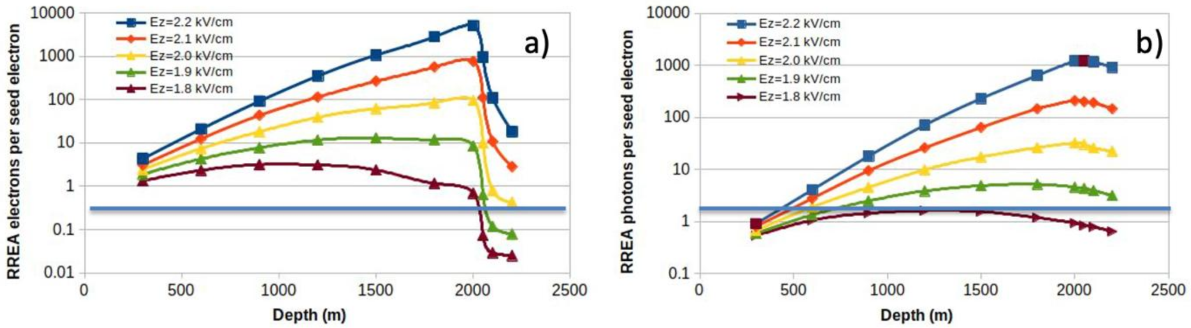


Time series of the NSEF (electric mill EFM-100 by BOLTEK firm, black), and outside temperature (DAVIS weather station, blue)

Kare lake nearby the station
and Sougth and Western peaks
of Aragats Mountain

Vertical profile of the atmospheric electric field conditioned on the registered TGE

The energy spectrum of seed electrons was adopted from the EXPACS WEB calculator following the power low with power index - 1.173 in the energy range 1-300 MeV. The number of seed electrons from the ambient population of secondary cosmic rays was obtained from the same calculator, to be 42,000 with energies above 1 MeV. The estimated distance to the cloud base during large “electron” TGE is usually 25 – 200 m, thus in our simulations presented in Table 1, the particle avalanches continued propagation in the dense air additionally 50, 100, and 200 meters before registration. Simulation trials include from 10^3 to 10^4 events for the electric field strengths of 1.8-2.2 kV/cm. The propagation of electrons and gamma rays were followed in the avalanche until their energy decreased down to 0.05 MeV.



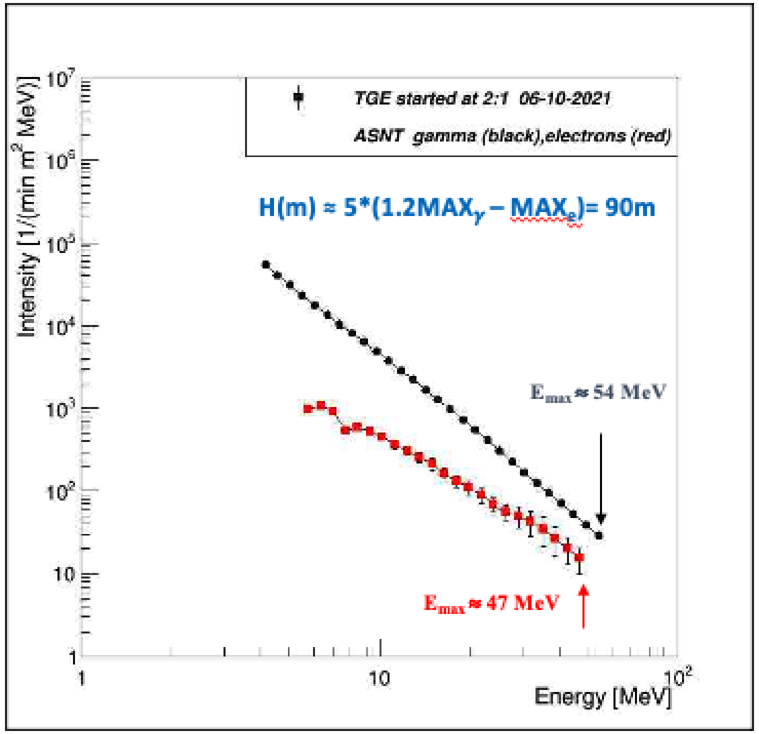
RRE avalanche in the atmosphere a) – electrons, b) gamma rays. Avalanche started at 5400 m a.s.l. (0 depth), that is 2200 m above the Aragats station. The number of avalanche particles is calculated each 300 m. After exiting from the electric field propagation of avalanche particles is followed additionally 200 m before reaching the station. By blue line, we show the electron and gamma ray number per seed electron for the TGE that occurred on 14 June 2020.

	Height of termination of el. field above detectors	N of el. E> 4 MeV per seed electron	N of γ rays E> 4 MeV per seed electron
1.8 kV/cm	100	0.03	0.78
1.9 kV/cm	100	0.12	3.9
1.9 kV/cm	200	0.08	3.1
2.0 kV/m	200	0.43	22
14/6/2020	-	0.14	1.26
27/6/2020	-	0.041	0.51
23/7/2020	-	0.059	0.49

Parameters of the simulated RREAs calculated with CORSIKA code and of 3 TGEs observed in 2020.

The difference of attenuation of gamma ray and electron fluxes allows estimation of the height where both fluxes leave the electron acceleration region

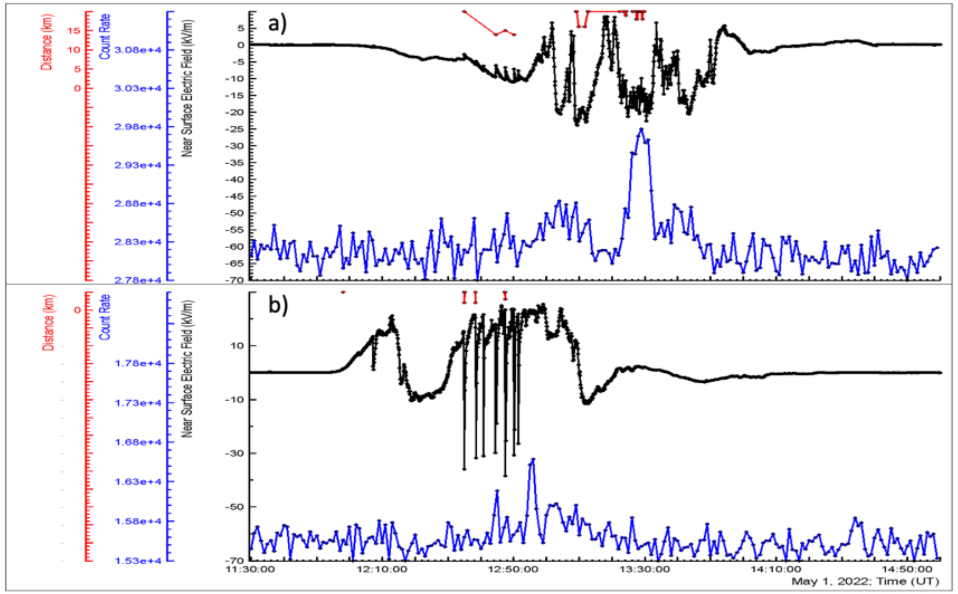
Distance from detector to the bottom edge of the field (m)	Expected gamma absorption (%) and electron ionization losses (MeV)
50	8.67
100	16.6
200	30.44
300	41.98
400	51.62
1000	83.7
10000	99.99999
50	8
100	16.1
200	32.1
300	48.23
400	64.3



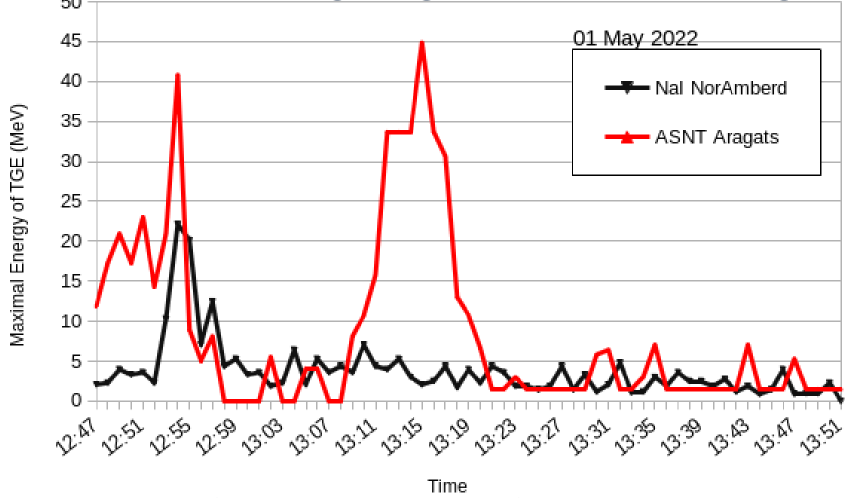
By comparing maximal energy of the recovered electron and gamma ray spectra we show that a strong accelerating field (≈2 kV/cm) can be very low above the earth’s surface!

Horizontal profile of atmospheric electric field during TGE

The map of networks of NaI spectrometer locations: five on Aragats (3200 m), one in Burakan (1700 m), and one in Nor Amberd station (2000 m). Electric mills and lightning locators are installed on Aragats (5 units) and in Nor Amberd.

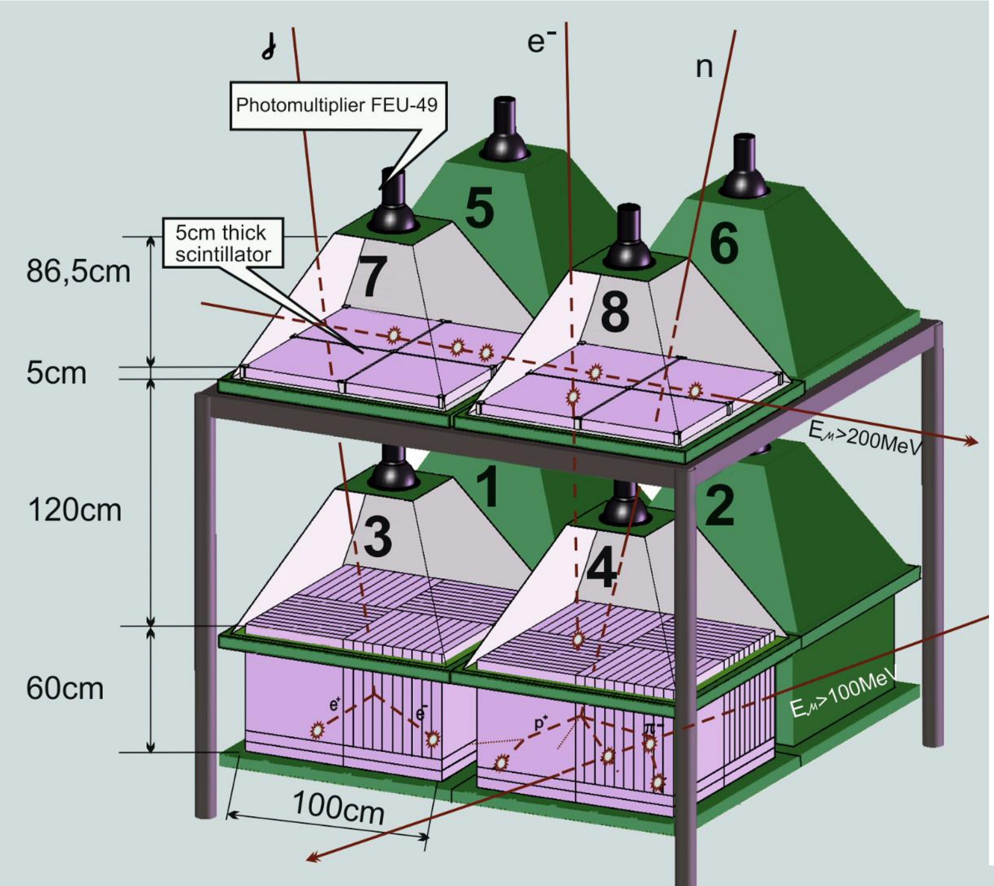


The disturbances of the NSEF; 1-minute count rates of 5 cm thick and 1 m^2 area plastic scintillators; and distances to lightning flashes measured on Aragats and in Nor Amberd



The histogram of maximum energies of energy spectra measured on Aragats with a large scintillation spectrometer ASNT, and in Nor Amberd by the NaI

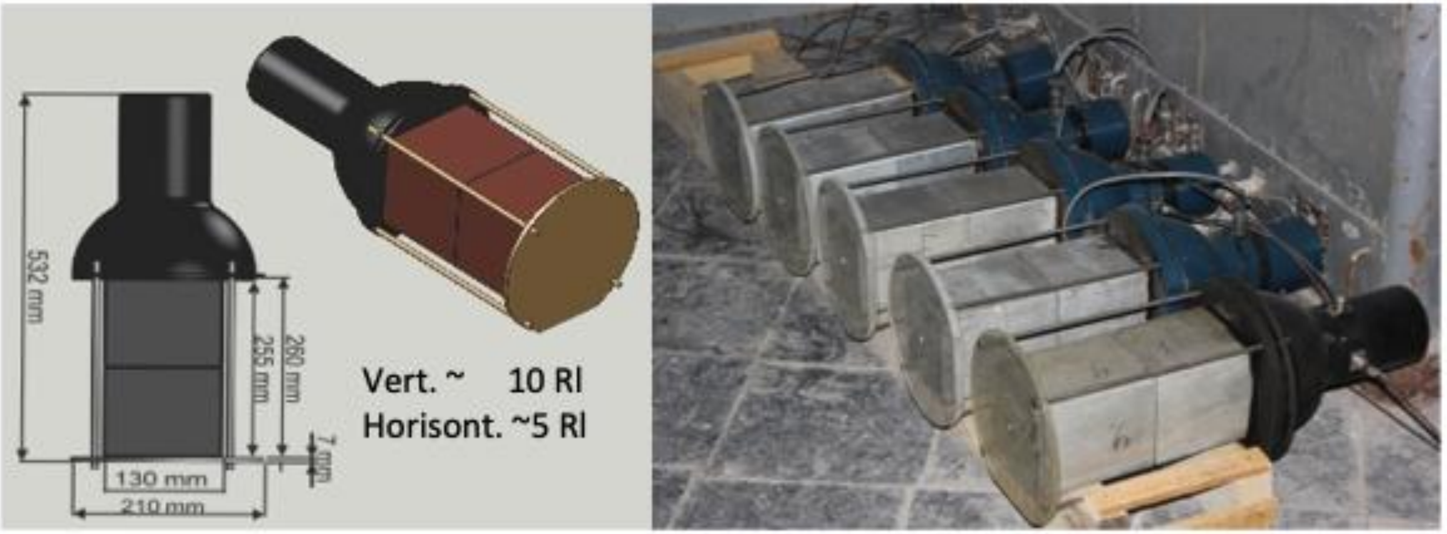
Aragats Solar Neutron Telescope (ASNT) and network of NaI(TL) spectrometers used for recovery of TGE electrons and gamma ray energy spectra



TGE electrons are registered by upper and lower layers; gamma rays and neutrons – by invoking the veto option (no signals from the upper scintillators), horizontal muons – by the condition of operation of 2 upper scintillators from 4 and no signal in the lower scintillators (to prevent registration of EAS events) and by very large energy release.

Material	Radiation length		Density
	g/cm2	cm	g/cm3
Polystyr. scint.	43.72	42.4	1.032
Cesium iodide (CzI)	8.39	1.85	4.53
Sodium iodide (NaI)	9.49	2.59	3.67

NaI – matter above NaI sensitive volume (mg/cm^2):
Al(800)+MgO(300)+Fe(400)=1500
Energy threshold for detecting TGE electrons – 3-4 MeV; Threshold to detect Gamma rays was the same, from 2015 – 0.4 MeV, from 2018 – 0.3 MeV.



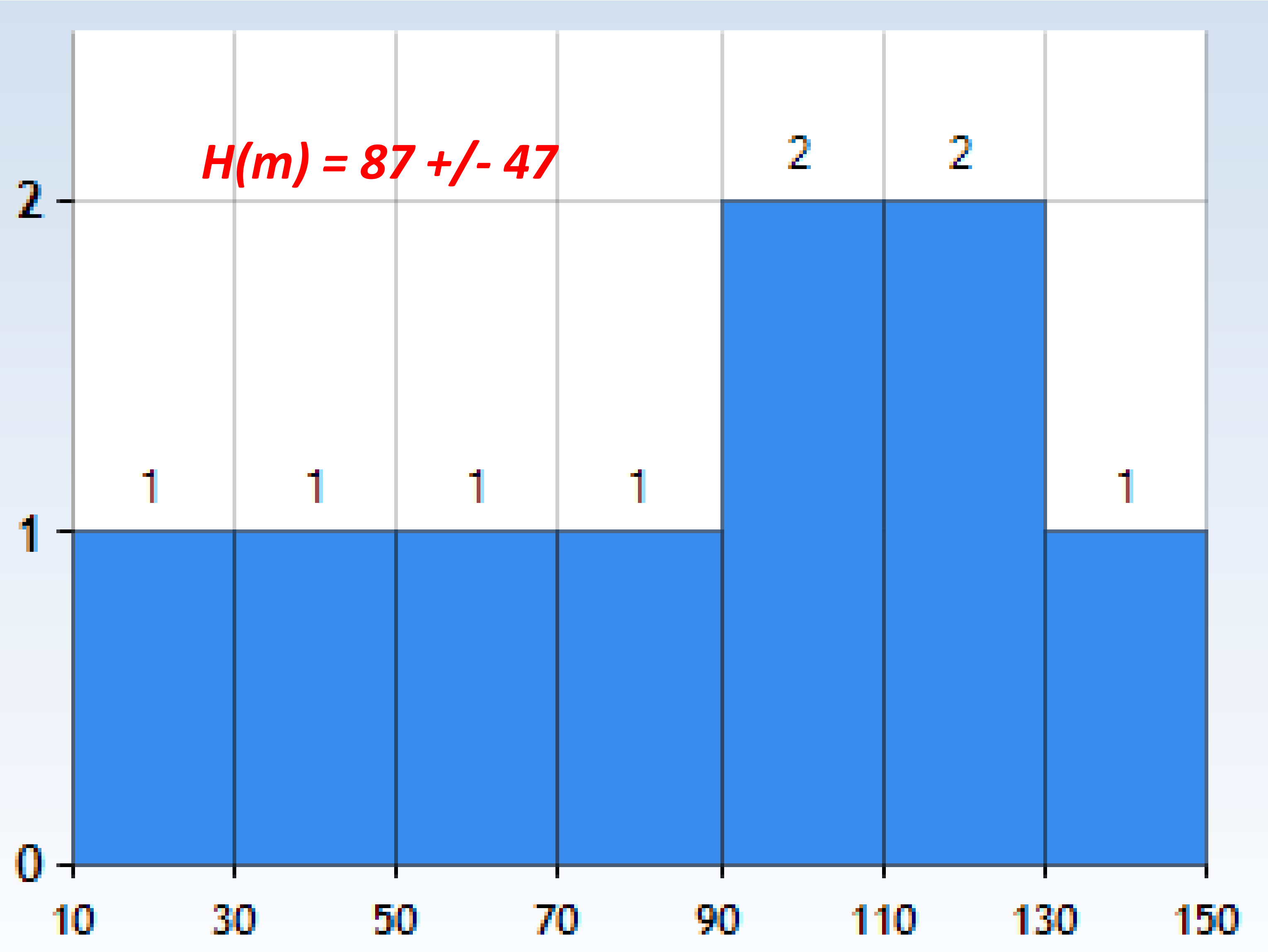
Parameters of Thunderstorm ground enhancements (TGEs) allowing recovering electron energy spectra (2019-2021)*. Selection criteria: Significance of peak enhancement – larger than 5%, Ne/Nγ > 0.06

Date, (month.day. year)	Power law Index el.	Power law index γ-rays	Int. Spectra el.	Int. Spectra γ-rays	Max energy el. (MeV)	Max energy γ-rays (MeV)	TGE significance (%)	El.Field height (m)	TGE duration (min)	Ne/Nγ	Outside T C°	Cloud height (m)	Dist. to lightning flash (km)	Max. positive NS el. field + (kV/m)	Max.negative NS el. Field - (kV/m)
06.14.19	1.64	2.41	1540	16700	16	25	6	70	3	0.09	5.5	220	1.7	20	0
06.18.19	1.65	2.67	2700	39200	25	40	13	150	6	0.07	3.7	180	2.5	23	25
07.07.19	2.16	2.48	2200	10500	24	28	5	50	4	0.21	7	180	4.2	23	0
06.14.20	2.45	2.89	6500	67000	18	39	20	110	4	0.06	2.8	250	7.5	13	16
06.27.20	1.61	2.64	1000	15700	32	43	9	140	19	0.10	4.6	110	11	0	21
07.23.20	1.63	2.16	1500	17020	24	35	10	90	8	0.09	6.9	170	11	6	15
09.25.20	2.35	2.86	7570	39070	32	32	26	30	5	0.19	7.1	400	5.4	0	26
05.24.21	2.02	2.34	1670	17120	29	45	9	125	13	0.10	1.8	200	12	0	20
10.06.21	2.16	2.8	12170	122800	47	54	46	90	3	0.10	-2.5	100	4.5	6	0
09.24.21	2.18	2.11	2560	9400	29	25	6	10	3	0.27	2.9	200	17	0	22

*Mendeley Data, V3, doi: 10.17632/tvbn6wdf85.3

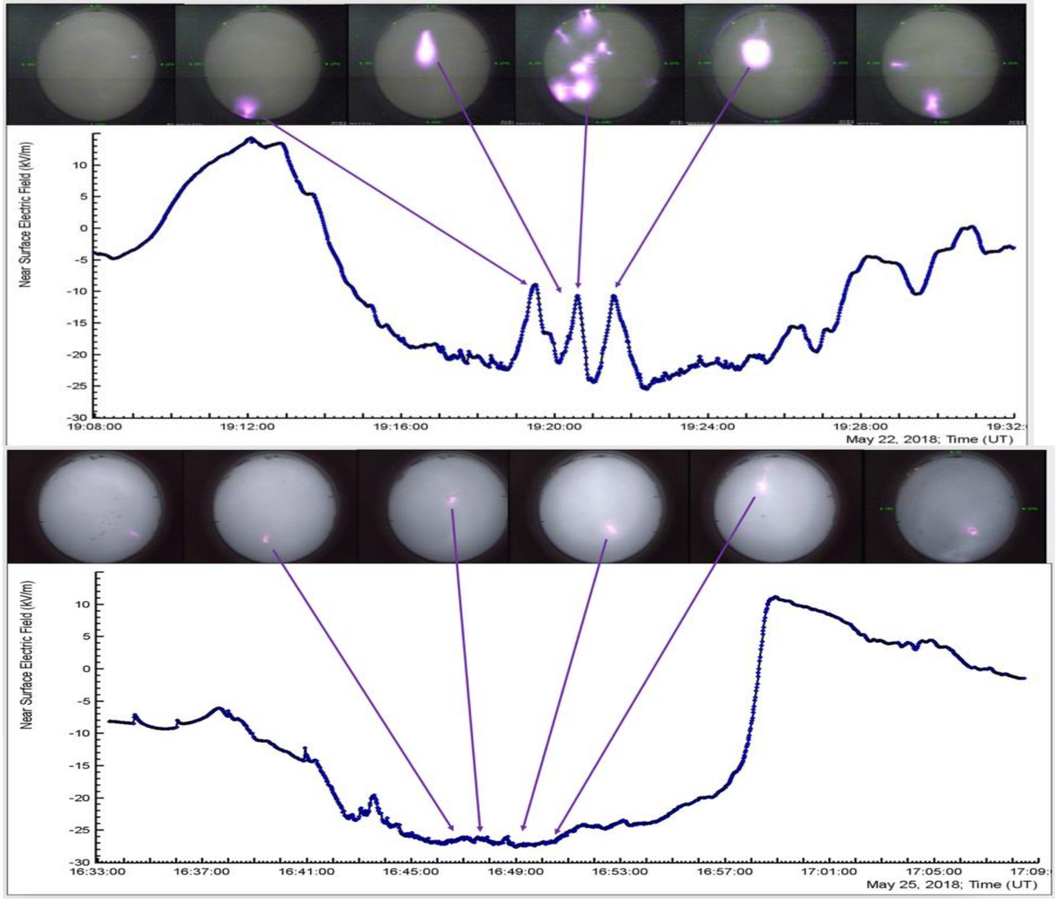
Electron and gamma ray energy spectra are recovered
from energy release histograms s, cloud height is recovered by outside temperature and dew point.

Height above ground where strong accelerated electric field terminated

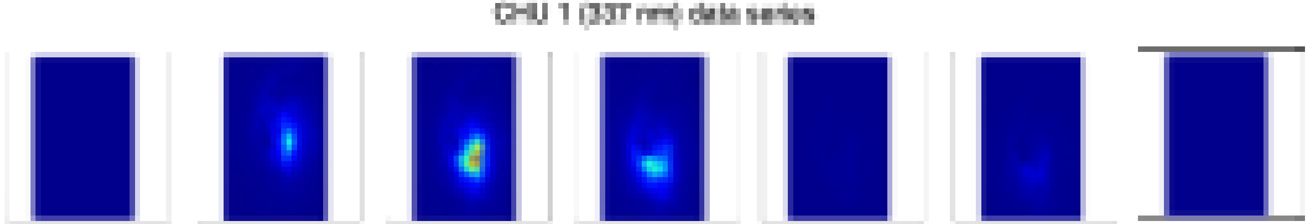


Optical emissions during TGE (Aragats) and TGF (ASIM)

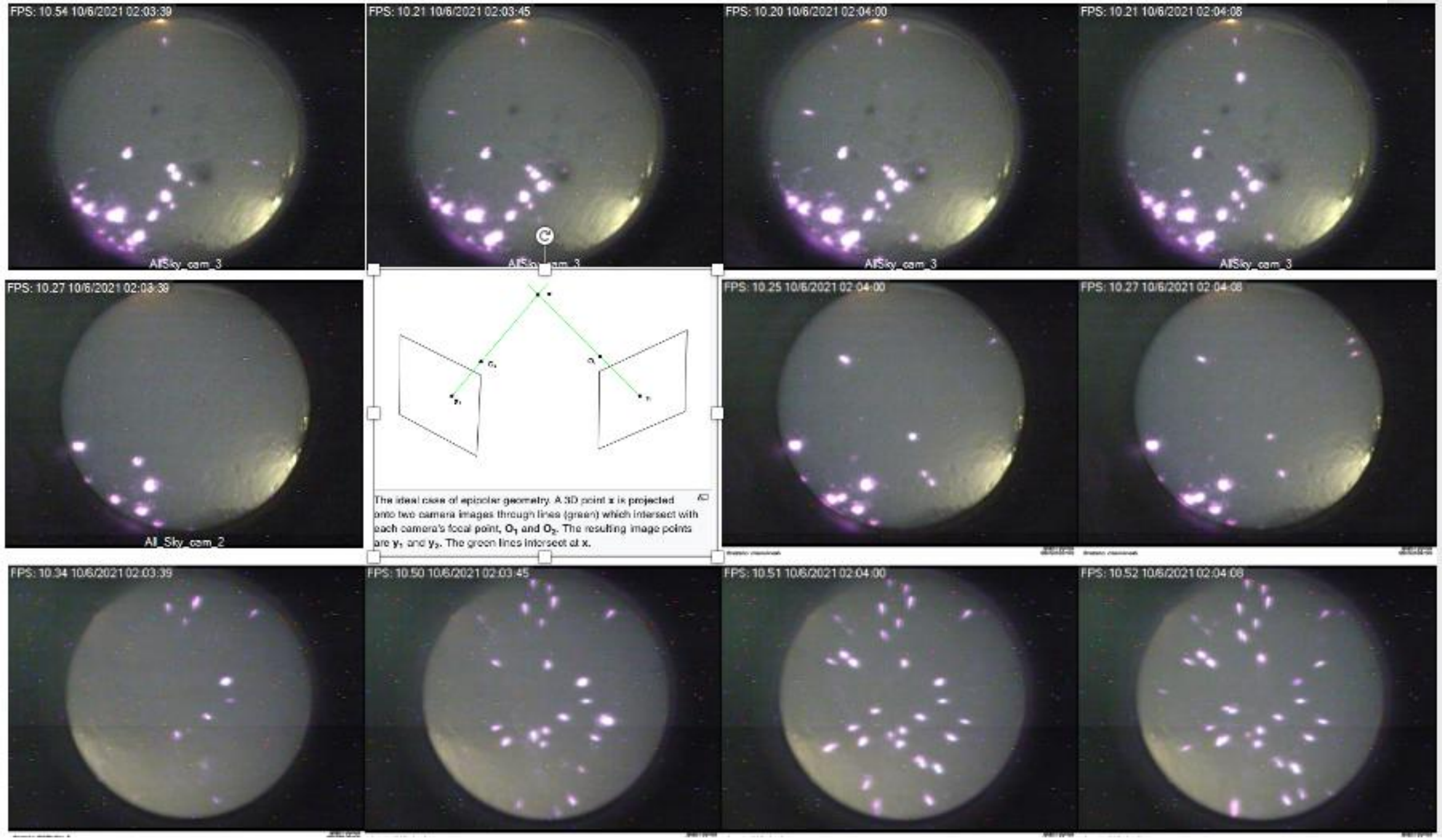
The MAKET experimental hall, in the inset the zoomed ALL SKY CAM surrounded by DAVIS weather station, BOLTEK's electric field sensor, and lightning tracker.



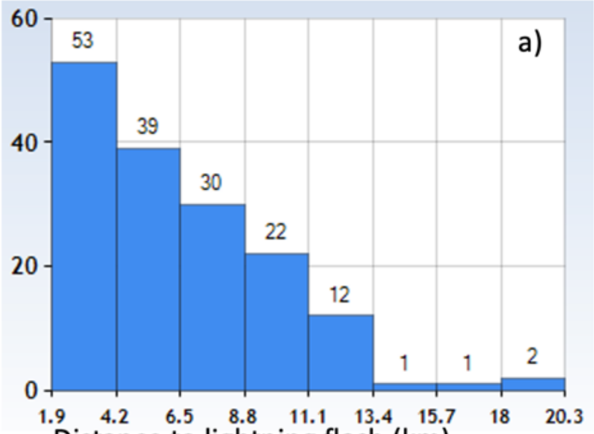
The disturbances of the NSEF during TGE, measured by an EFM-100. In the upper panel, we show the panoramic camera shots of the sky above the station; by a violet arrow, we indicate the times when panoramic shots were done.



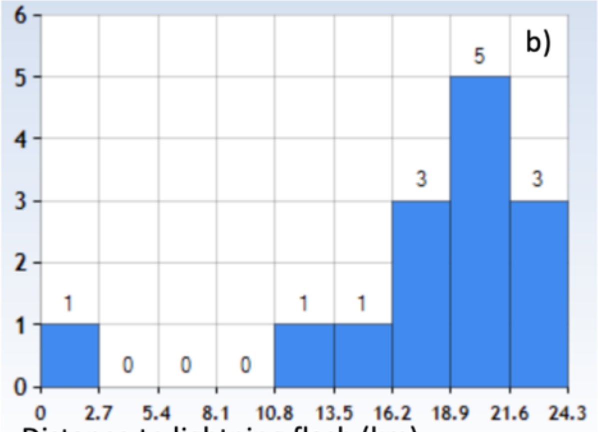
Large TGE occurred on 6 October 2021 was accompanied with intense multiple light spots remaining in skies tens of seconds. Each row represents shots of one from 3 cameras at the same second. Not blue starters not ball lightning, what it can be?



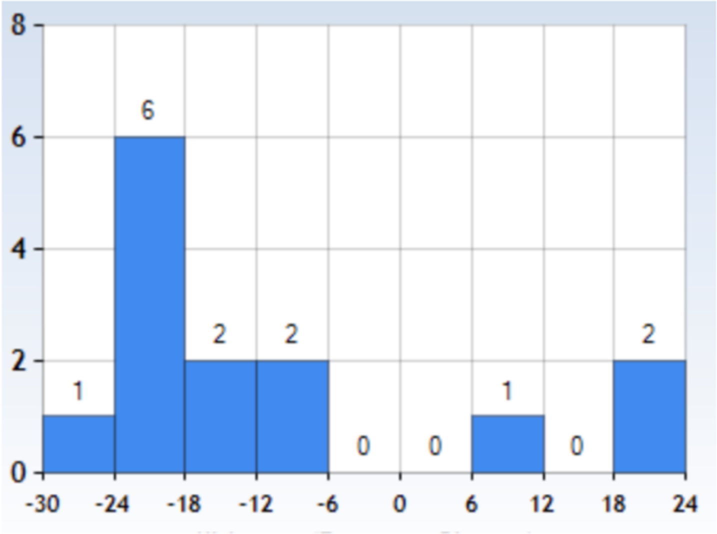
TLEs in the lower Atmosphere: charcateristics



Distance to lightning flash (km).
(130 TGEs terminated by lightning flash)



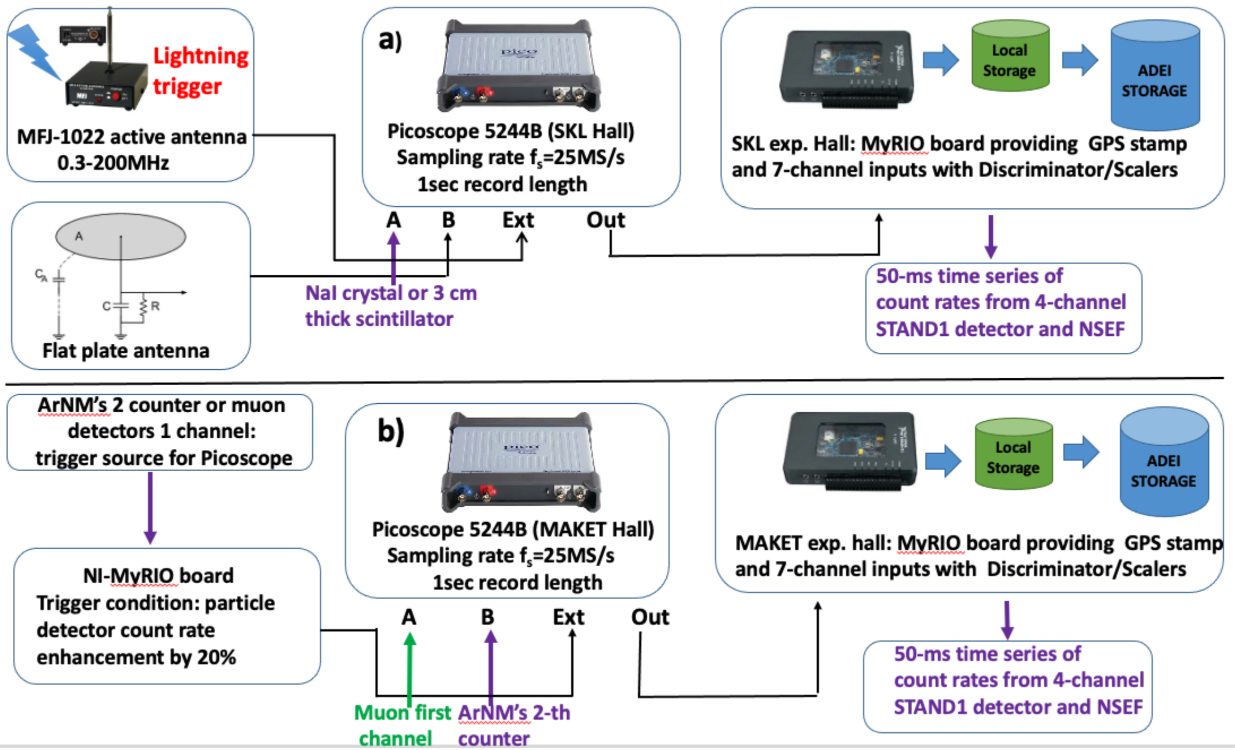
Distance to lightning flash (km).
(14 TGEs accompanied with light glows)



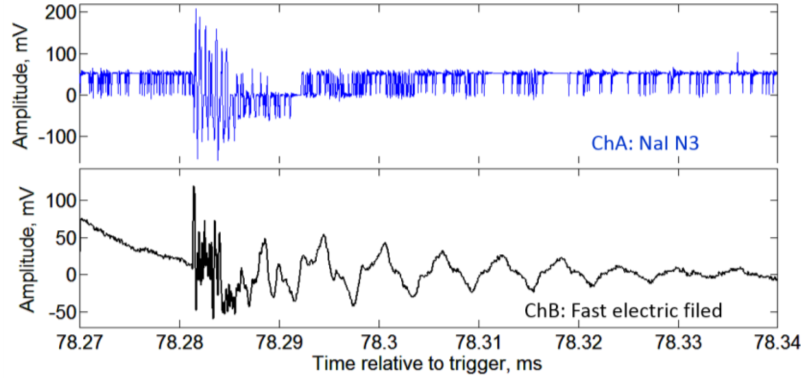
Near-surface electric field (kV/m)

The origin of light glows is under discussion, the possible explanations are intense fluxes of TGE electrons , ball lightning, St. Elmo's fires, and geomagnetic disturbances. However, after examining luminous TGE events, along with lightning location maps and NSEF time series, we think that these unusual luminous phenomena below thunderclouds are a new optical phenomenon. An electrical discharge or starting lightning leader much weaker than a lightning flash could only partially neutralize the charge above, and hence, only partially lowers the corresponding potential difference, allowing the electron accelerator to operate and send particle fluxes in the direction to the earth’s surface.

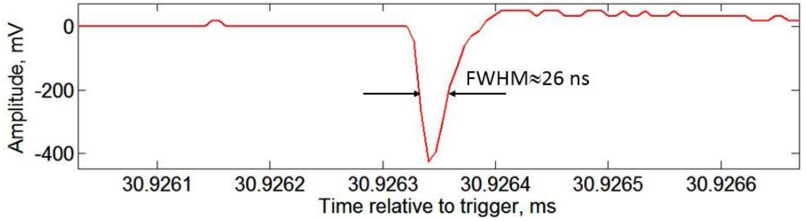
Particles do not originate in the lightning bolt: TGEs and TGFs are precoursors of lightning flashes!

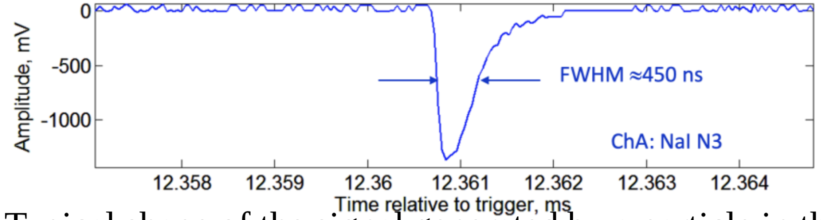


Fast synchronized data acquisition (FSDAQ) for the research of particle–lightning relations, triggered by atmospheric discharges, MAKET hall; in SKL experimental hall (triggered by TGE – 10% enhancement of count rate).



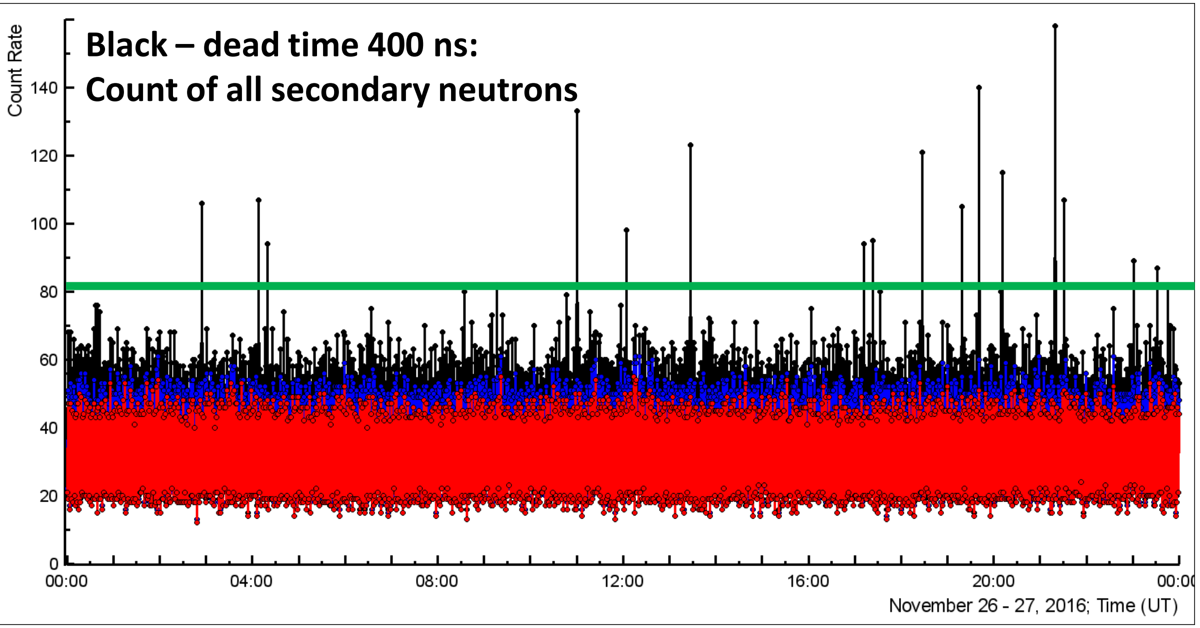
40-ns time series of NaI spectrometer, and the signals from the flat-plate antenna registering EMI.



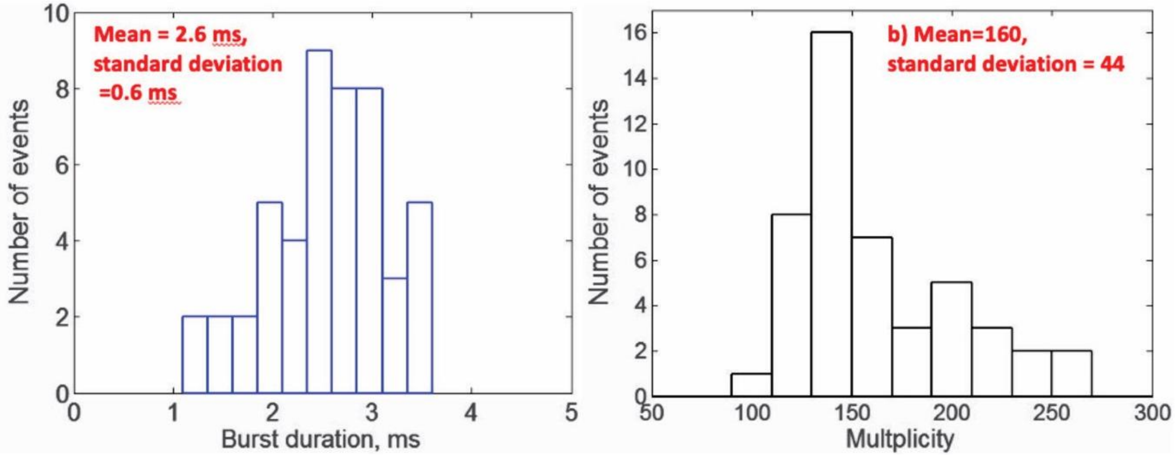


Typical shape of the signal generated by a particle in the large NaI crystal (12 x 12 x 24 cm) and in 1-cm scintillator.

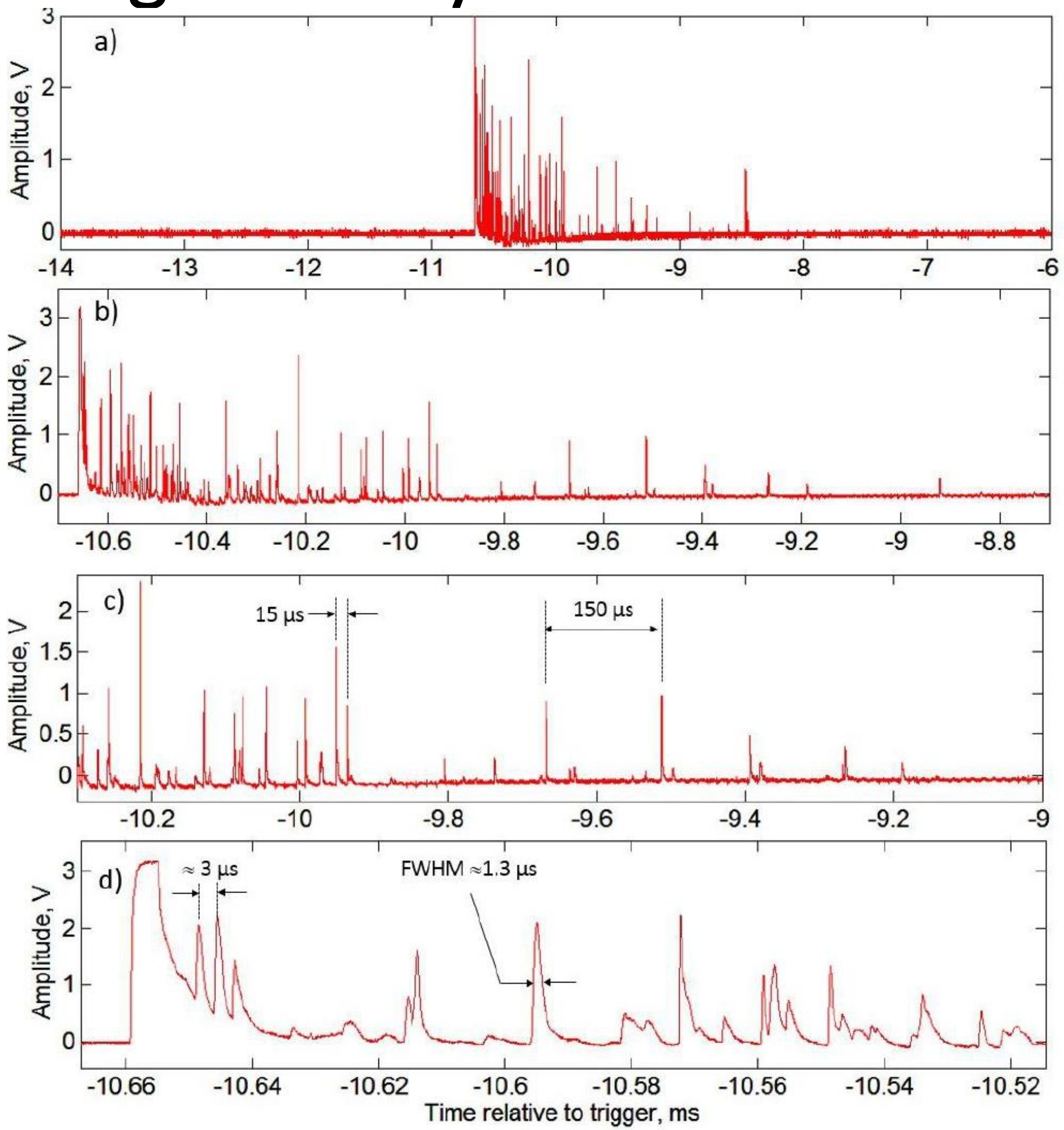
Inverse TGFs – are EAS core particles interacting in soil or lead of neutron monitor: ≈20 signals above 5 sigmas daily!



1-s time series of ArNM multiplicities (dead tine 400 ns); by the red line the multiplicities above 100 are outlined, by the red arrow – the neutron burst shown in Figure to the left.

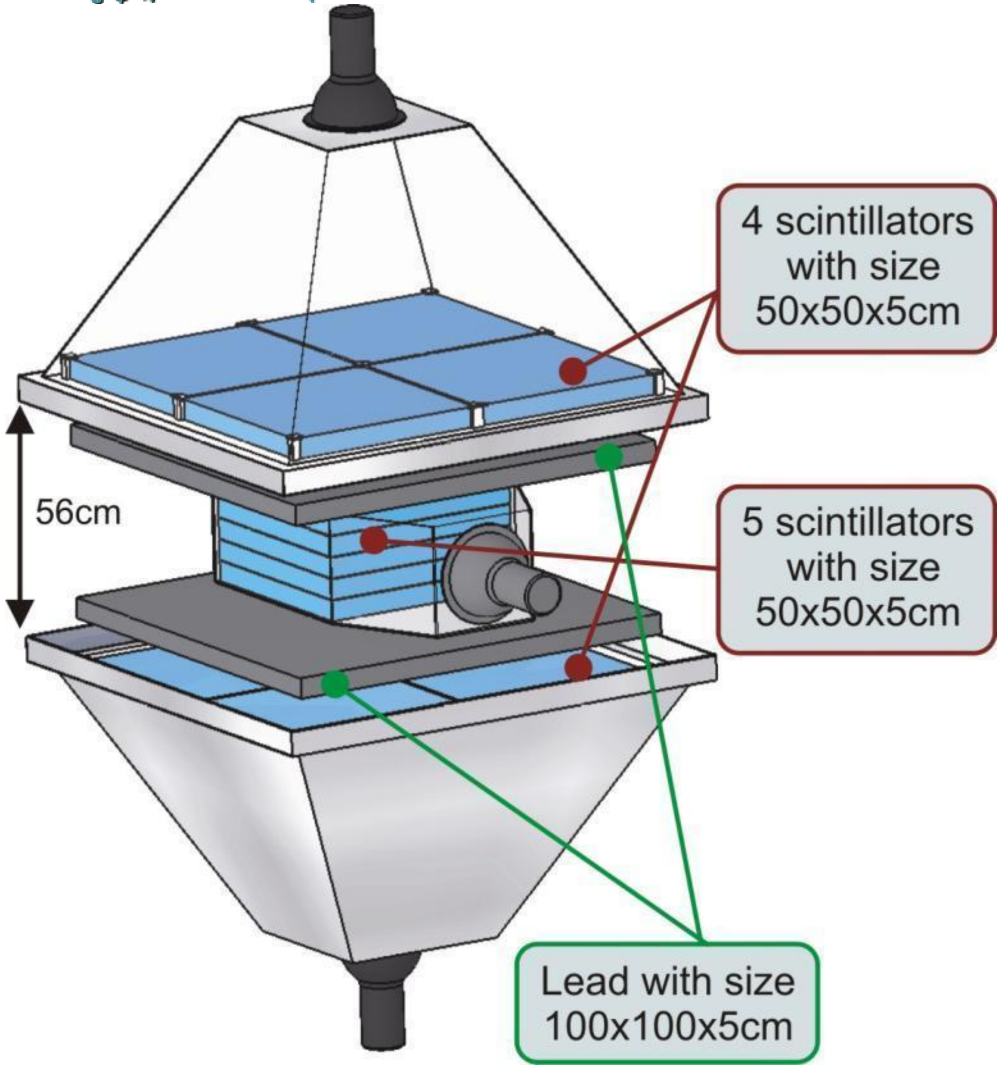


Neutron burst duration (a) and corresponding multiplicity histogram (b).



Oscilloscope records of neutron burst that occurred at 4:08:05 on 11.26, 2016. The burst duration was ≈ 2.2 milliseconds and the multiplicity is 107 per m^2. The four panels (a-c) show the records of the burst on different time scales.

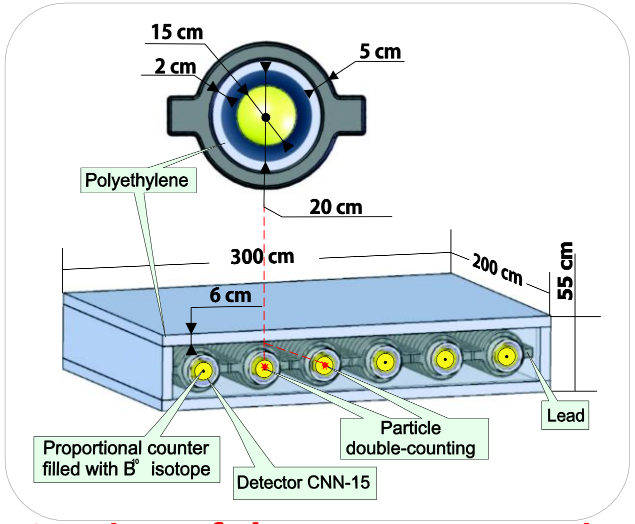
SEVAN basic unit: monitoring 3 species of secondary CR



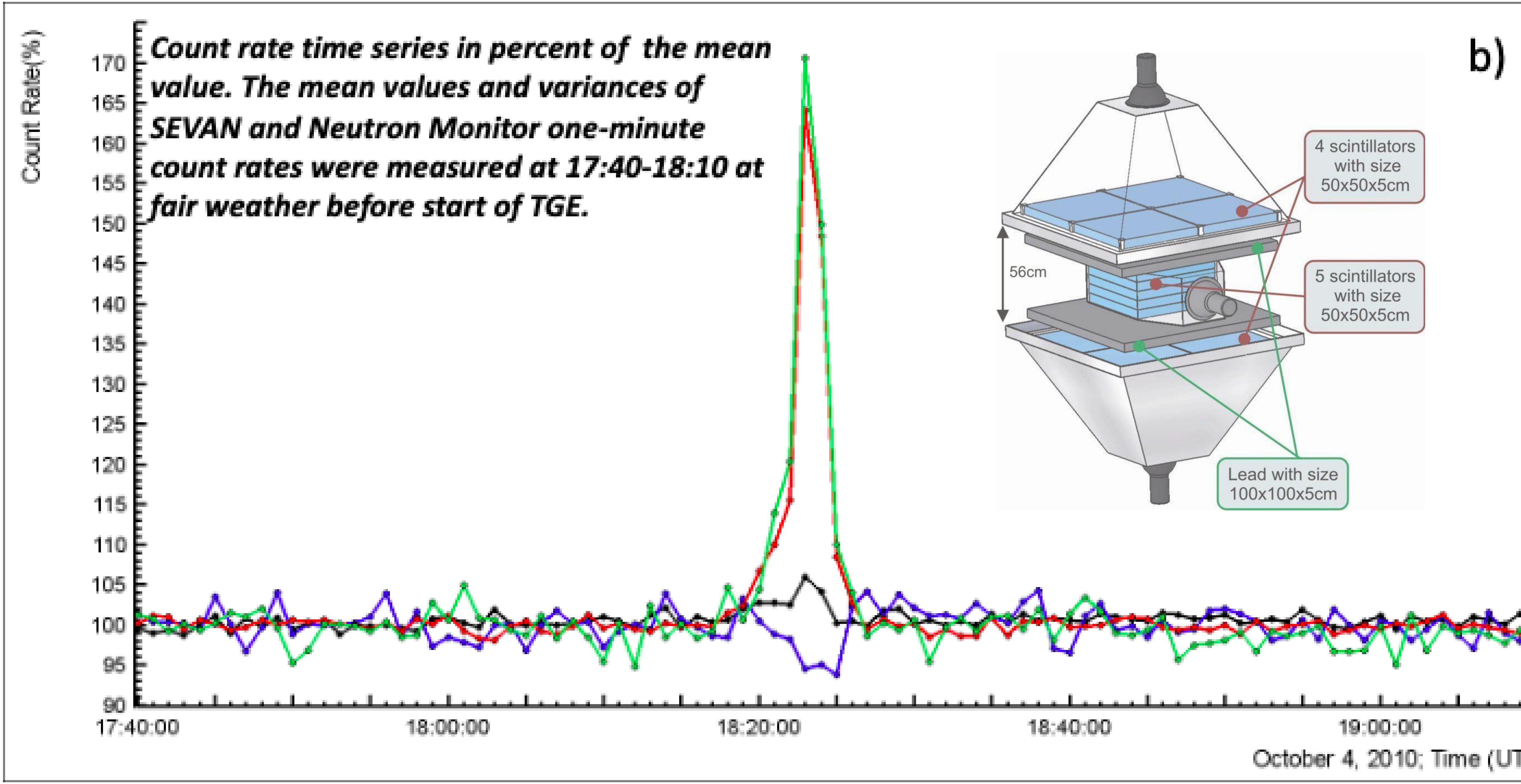
100 – low energy charged particle;

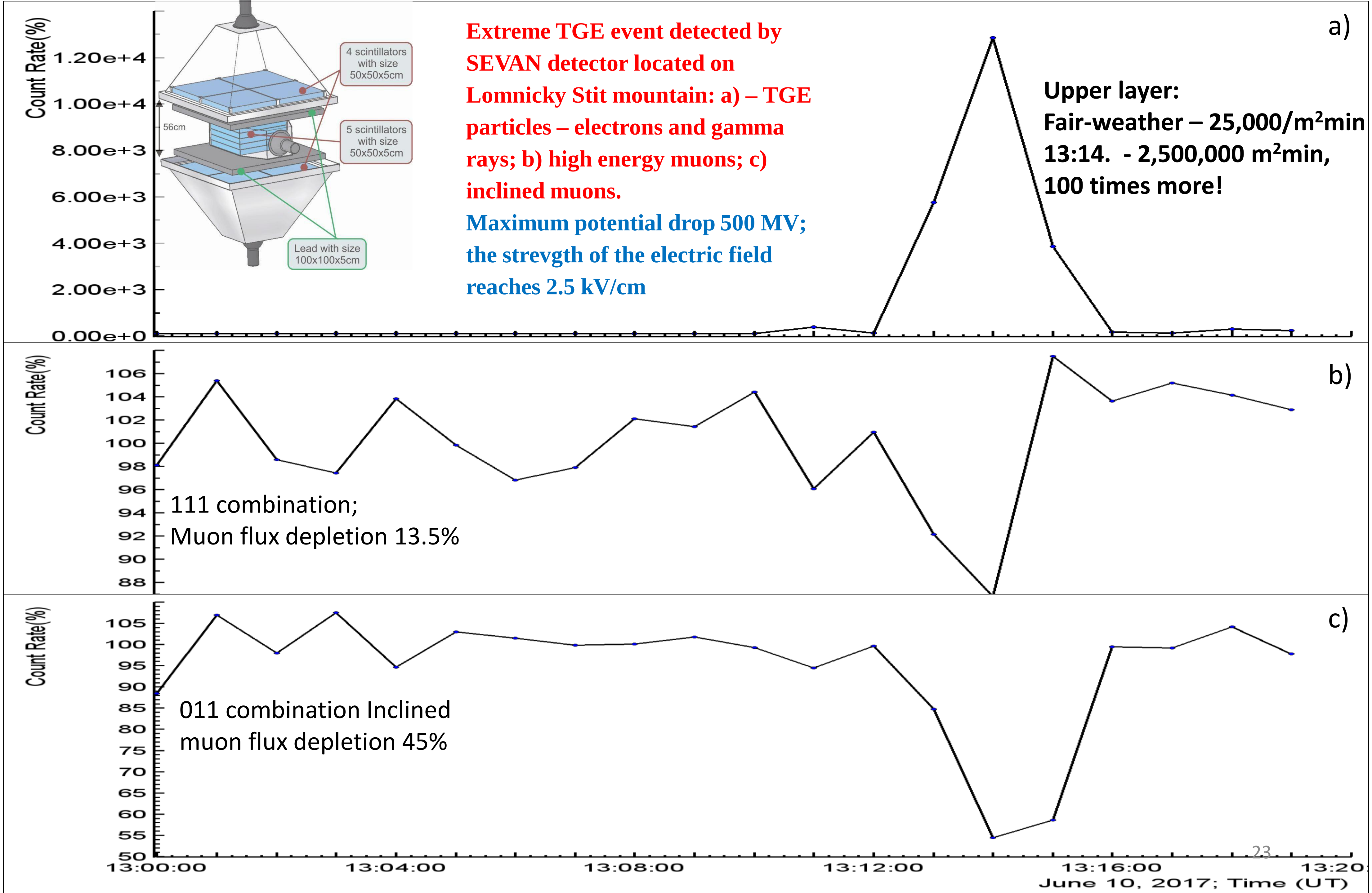
010 – neutral particle (gamma ray or neutron;

111 & 101 – high energy muon (>250MeV);

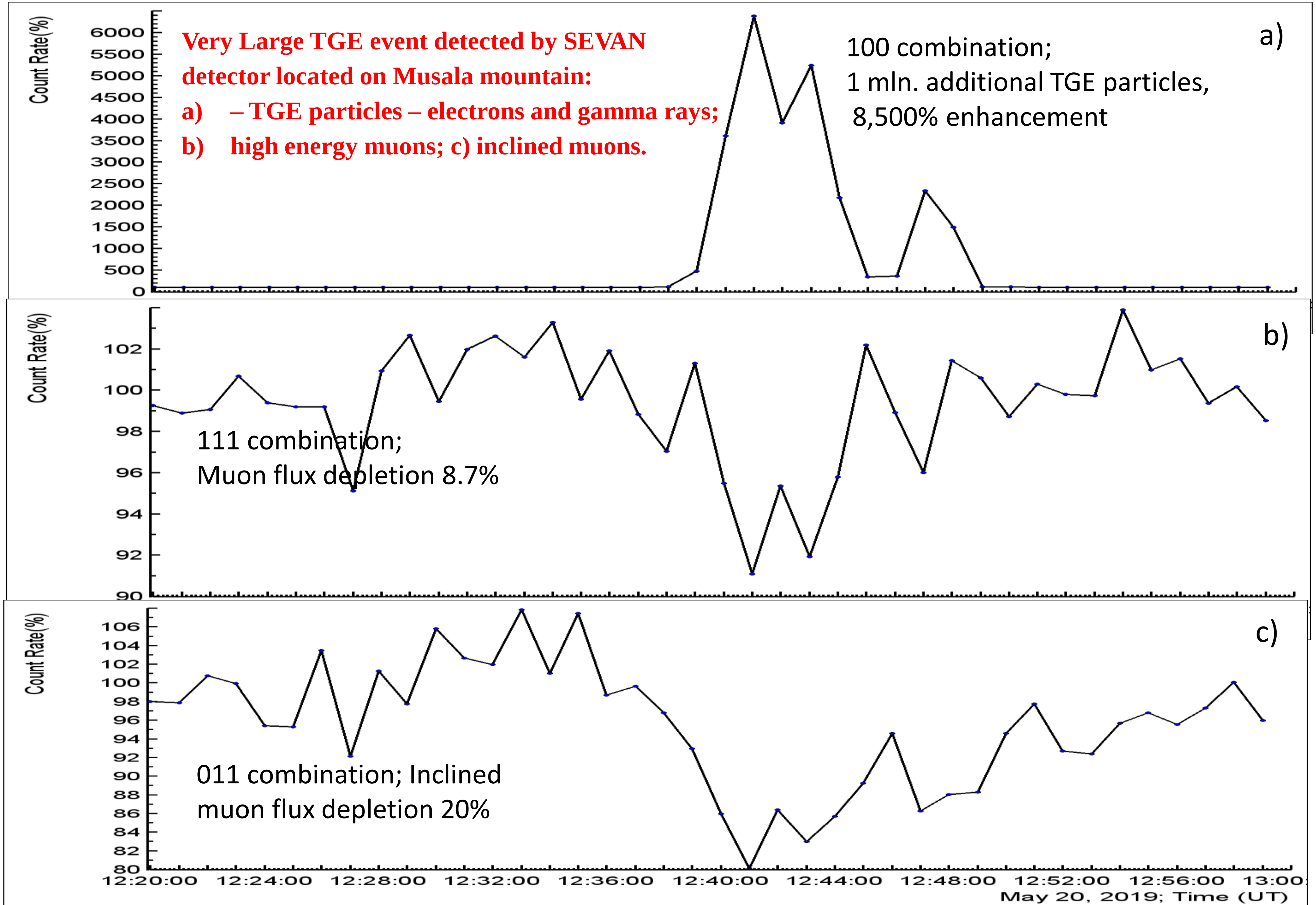


Section of the Neutron Monitor


Count rate time series in percent of the mean value. The mean values and variances of SEVAN and Neutron Monitor one-minute count rates were measured at 17:40-18:10 at fair weather before start of TGE.
b)
Count Rate(%)
170
165
160
155
150
145
140
135
130
125
120
115
110
105
100
95
90
17:40:00
18:00:00
18:20:00
18:40:00
19:00:00
October 4, 2010; Time (UT
4 scintillators with size 50x50x5cm
5 scintillators with size 50x50x5cm
56cm
Lead with size 100x100x5cm



Extreme TGE event detected by SEVAN detector located on Lomnicky Stit mountain: a) – TGE particles – electrons and gamma rays; b) high energy muons; c) inclined muons.
Maximum potential drop 500 MV; the strevgth of the electric field reaches 2.5 kV/cm
Upper layer:
Fair-weather – 25,000/m2min
13:14. - 2,500,000 m2min,
100 times more!
4 scintillators with size 50x50x5cm
5 scintillators with size 50x50x5cm
Lead with size 100x100x5cm
56cm
a)
b)
c)
Count Rate(%)
1.20e+4
1.00e+4
8.00e+3
6.00e+3
4.00e+3
2.00e+3
0.00e+0
106
104
102
100
98
96
94
92
90
88
111 combination;
Muon flux depletion 13.5%
105
100
95
90
85
80
75
70
65
60
55
50
011 combination Inclined
muon flux depletion 45%
13:00:00
13:04:00
13:08:00
13:12:00
13:16:00
13:20:
June 10, 2017; Time (UT)


Very Large TGE event detected by SEVAN
detector located on Musala mountain:
a) – TGE particles – electrons and gamma rays;
b) high energy muons; c) inclined muons.
100 combination;
1 mln. additional TGE particles,
8,500% enhancement
a)
b)
111 combination;
Muon flux depletion 8.7%
c)
011 combination; Inclined
muon flux depletion 20%
Count Rate(%)
Count Rate(%)
Count Rate(%)
May 20, 2019; Time (UT)

Data sources

- Observations/Models needed to support research
    - **TGE energy spectra measured by particle detector networks on Aragats and on the highest peaks of Eastern Europe and Germany (SEVAN network);**
    - **Corresponding measurements of near-surface electric fields, lightning location, skies above particle detectors, and weather parameters;**
    - **Models of the propagation of particle showers in the troposphere with included electric field: CORSIKA, GEANT4.**
- Available data sources and datasets : Database of the cosmic ray division (CRD) of Yerevan Physics Institute.

Time series of particle fluxes measured by hundreds of particle detectors. Data on NSEF, geomagnetic field, weather conditions, shots of panoramic cameras. Data are available in numerical and graphical formats for 20 years of operation **http://adei.crd.yerphi.am/**

Mendeley datasets with selected data on different research topics:

- "Catalog of Sky Glows above Aragats Mountain", Mendeley Data, V1, doi: 10.17632/8ygy98r99d.1
- "Dataset for Thunderstorm Ground Enhancements terminated by lightning discharges", Mendeley Data, V1, doi:10.17632/p25bb7jrfp.1
- "Dataset for 16 parameters of ten thunderstorm ground enhancements (TGEs) allowing recovery of electron energy spectra and estimation the structure of the electric field above earth's surface ", Mendeley Data, V3, doi: 10.17632/tvbn6wdf85.3
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From the 24/7 monitoring of particle fluxes in Armenia and Eastern Europe (SEVAN network) we coclude

- **Thunderstorm ground enhancements (TGEs) are a universal physical phenomena sending ≈10^{18} particles (above 100 keV) to the earth's surface each second.**
- **Strong accelerating electric field of 2.0-2.2 kV/cm can extend 2 km till the earth's surface.**
- **The potential drop in thunderous atmosphere can reach 350-500 MV.**
- **The majority of TGEs, which produce large electron fluxes produce also yet unknown optical emissions of different shapes.**
- **With SEVAN based modules it will be possible not only research TGE relation to lightning origination and modes of electron acceleration in thunderclouds but also connect both atmospheric and space physics (solar bursts, coronal mass ejections, SEP).**


TEPA 2022
International Conference, 17-20 October
Prague, Czech Republic
THUNDERSTORMS AND ELEMENTARY PARTICLE ACCELERATION
ORGANIZERS:
Cosmic Ray Division
of Yerevan Physics Institute, Armenia
Research Centre of Cosmic Rays and Radiation Events in Atmosphere (CRREAT),
Nuclear Physics Institute of the CAS, Czechia
STRUCTURE OF THE SYMPOSIUM:
We anticipate the following sessions:
1. Multivariate observations of particles from the Earth's surface, in the atmosphere, and from space (TGEs, gamma glows, and TGFs);
2. Remote sensing and modeling of the atmospheric electric field;
3. Correlated measurements of the atmospheric discharges and particle fluxes, time-space structure of particle bursts;
4. Influence of the atmospheric electric field on measurements of experiments using the atmosphere as a target (Surface Arrays and Cherenkov Imaging Telescopes)
5. Instrumentation
We plan also discussions on the most intriguing problems of high-energy physics in the atmosphere and on possible directions for the advancement of collaborative studies.
Aragats Research Station and Mt. Ararat
The new emerging field of high-energy atmospheric physics (HEAP) has been enriched recently by important observations of particle fluxes on Earth's surface, in the troposphere, and in space. HEAP presently includes 3 main types of measurements: Terrestrial Gamma Ray Flashes (TGFs) - a brief bursts of gamma radiation (sometimes also electrons and positrons) registered by orbiting gamma ray observatories in the space, Thunderstorm ground enhancements (TGEs) – short and prolonged electron and gamma ray fluxes registered on the earth's surface, and gamma glows - gamma ray bursts observed in the thunderclouds by instrumentation on balloons and aircraft. Recently to this classification scheme some authors add inverse TGFs, a millisecond duration of intense particle bursts registered on the earth's surface. The central engine initiating the TGE and TGFs is believed to be the Relativistic Runaway Electron avalanches (RREA), which accelerates seed electrons from an ambient population of cosmic rays (CR) in the large-scale thundercloud electric fields. Observation of numerous TGEs by Japanese, Russian, Armenian, Czech, Chinese, Bulgarian, and Slovakian groups proves that RREA is a robust and realistic mechanism for electron acceleration and multiplication. The origin of gamma glows can be also the MOS process, modification of electron energy spectrum in the atmospheric electric field leading to additional gamma ray radiation. The hypothesis of the "lightning origin" of inverse TGFs is still under debate. TGE electron and gamma ray energy spectra give a new clue for recovering the vertical profile of the atmospheric electric field and for testing models of electron acceleration in the atmosphere. Models using GEANT4 and CORSIKA codes support in situ measurements of electron and gamma ray energy spectra at Aragats. Numerous observations of TGEs made on Aragats during the past 13 years can be widely used for the validation of models aimed to explain TGF phenomena. CRREAT project is making good progress in establishing instrumentation for the comprehensive measurements of the particle fluxes, lightning monitoring with fast cameras and various atmospheric parameters, including radar measurements of the hydrometeor evolution during storms. Many questions about thundercloud electrification and discharge mechanisms, lightning initiation, propagation and attachment processes, the global electrical circuit, and transient luminous events do not have yet a commonly accepted explanation. The estimated horizontal profile of the atmospheric electric field, that emerges during thunderstorms is still badly understood. The estimate of the size of the particle emitting region in the thundercloud, made a decade ago by Japanese and Armenian physicists (≈1km radii) seen to be largely undervalued. Enigmatic light glows observed on Aragats during TGEs still waiting for an explanation. The new view of thunderclouds as media full of radiation can help to establish a comprehensive theory of cloud electrification and estimate the possible role of cloud radiation on climate change. The influence of the electrifying atmosphere on the fluxes of electrons and other charged particles can be important for experiments registering very-high-energy photons (Atmospheric Cherenkov telescopes) and hadrons (Surface arrays registering Extensive Air Showers). The TEPA meeting is a great opportunity for the scientists to establish synergy between Atmospheric and Cosmic ray physics, discuss new ideas, and make new bridges for collaborative works.
INTERNATIONAL ADVISORY COMMITTEE
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• Ondrej Ploc, CRREAT head, Nuclear Physics Institute of the CAS,
• Czechia (Co-chair)
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