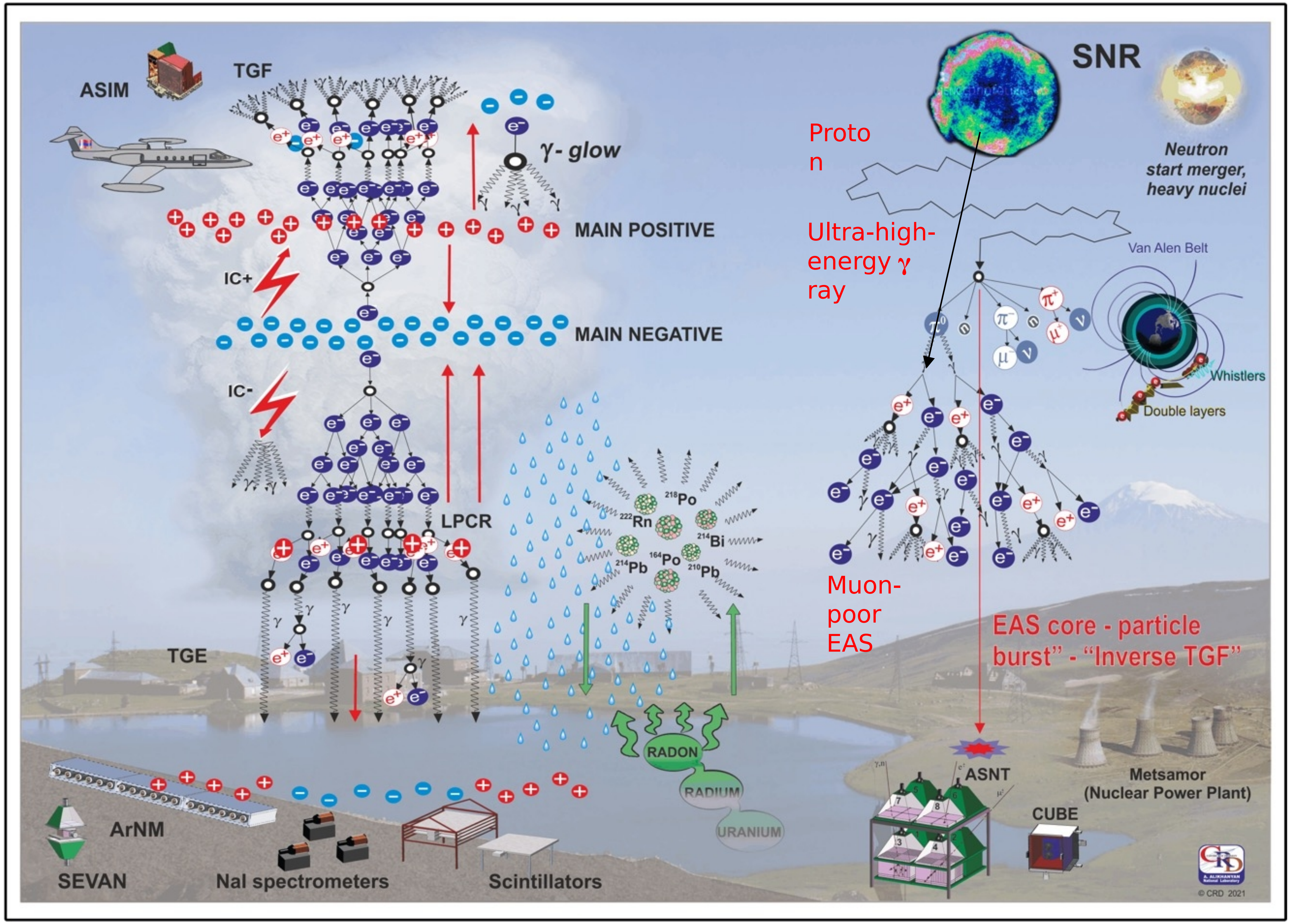
On the vertical and horizontal profiles of the atmospheric electric field during thunderstorms

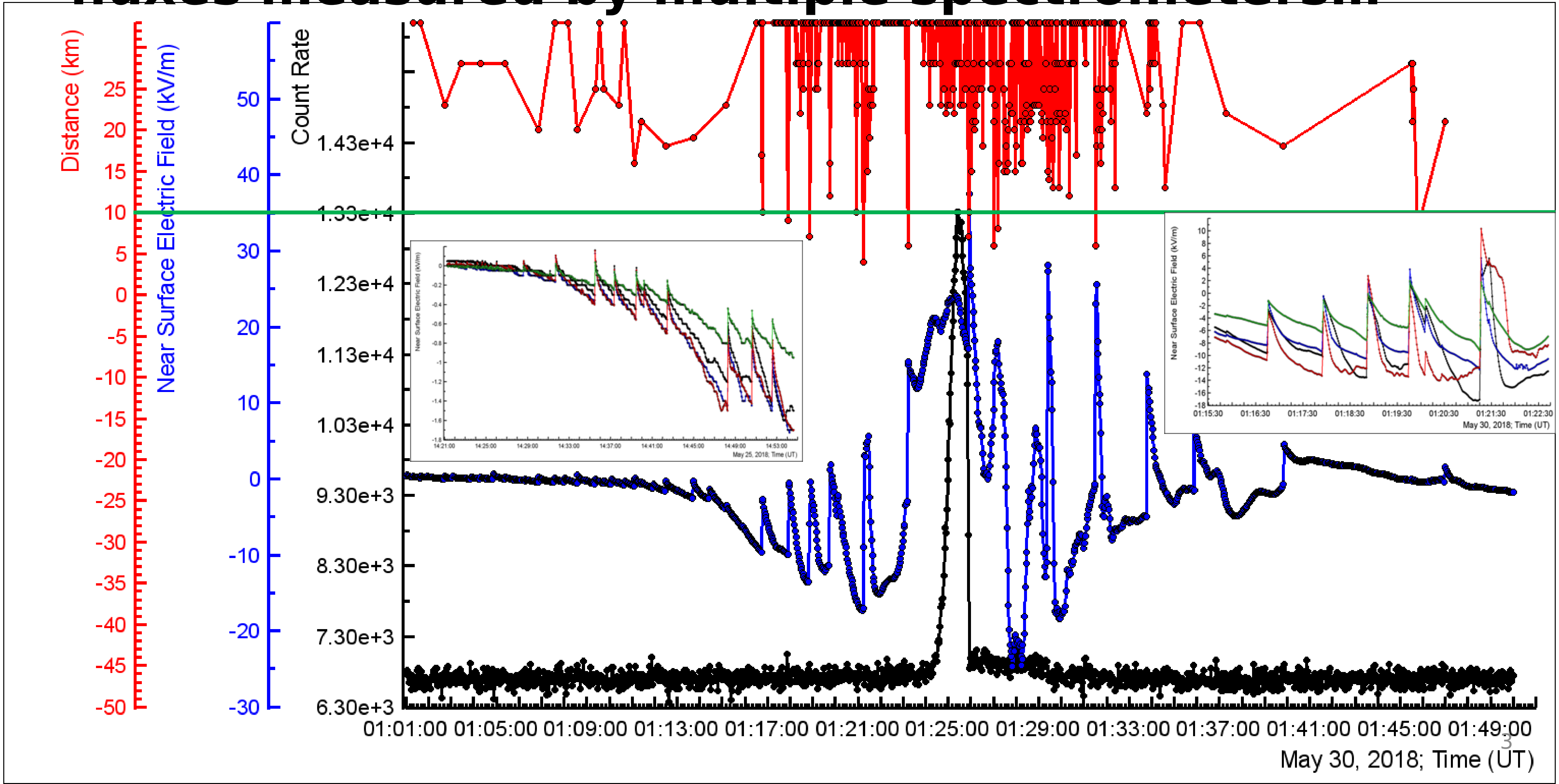
A Chilingarian, G Hovsepyan, **T Karapetyan, and B Sargsyan**
Yerevan Physics Institute, Alikhanyan brothers 2, Yerevan, Armenia 0036

Kare lake nearby the station and Sougth and Western peaks of

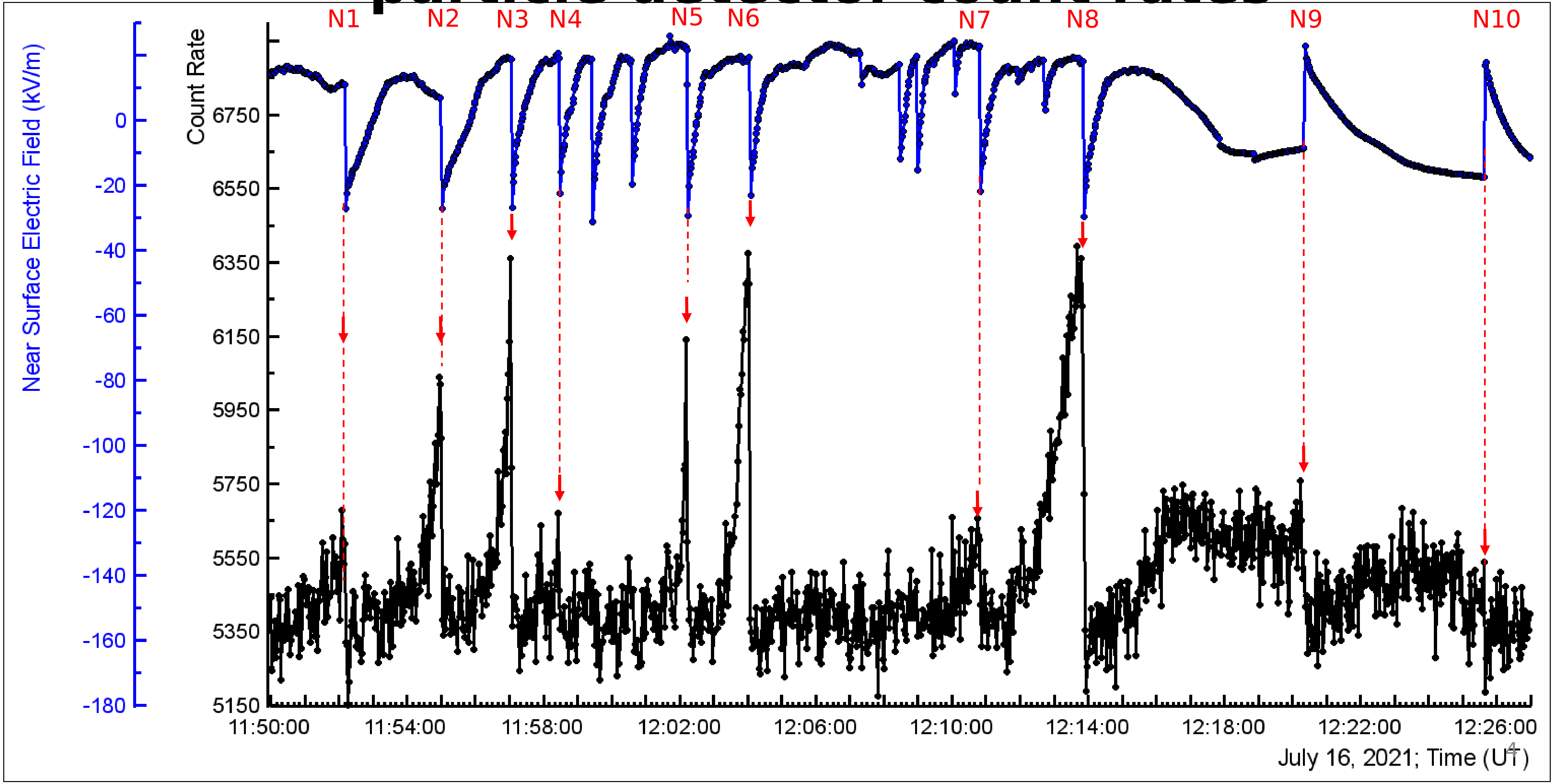


Aragats Cosmic Ray station: research of planetary, solar and galactic particle accelerators. Year-round operation from 1943. Coordinates: [40.47N, 44.18E](), 3200m a.s.l. Located on highland near Kare lake in the vicinity of Aragats south peak ≈(3700m), the highest North peak is ≈4000 m.

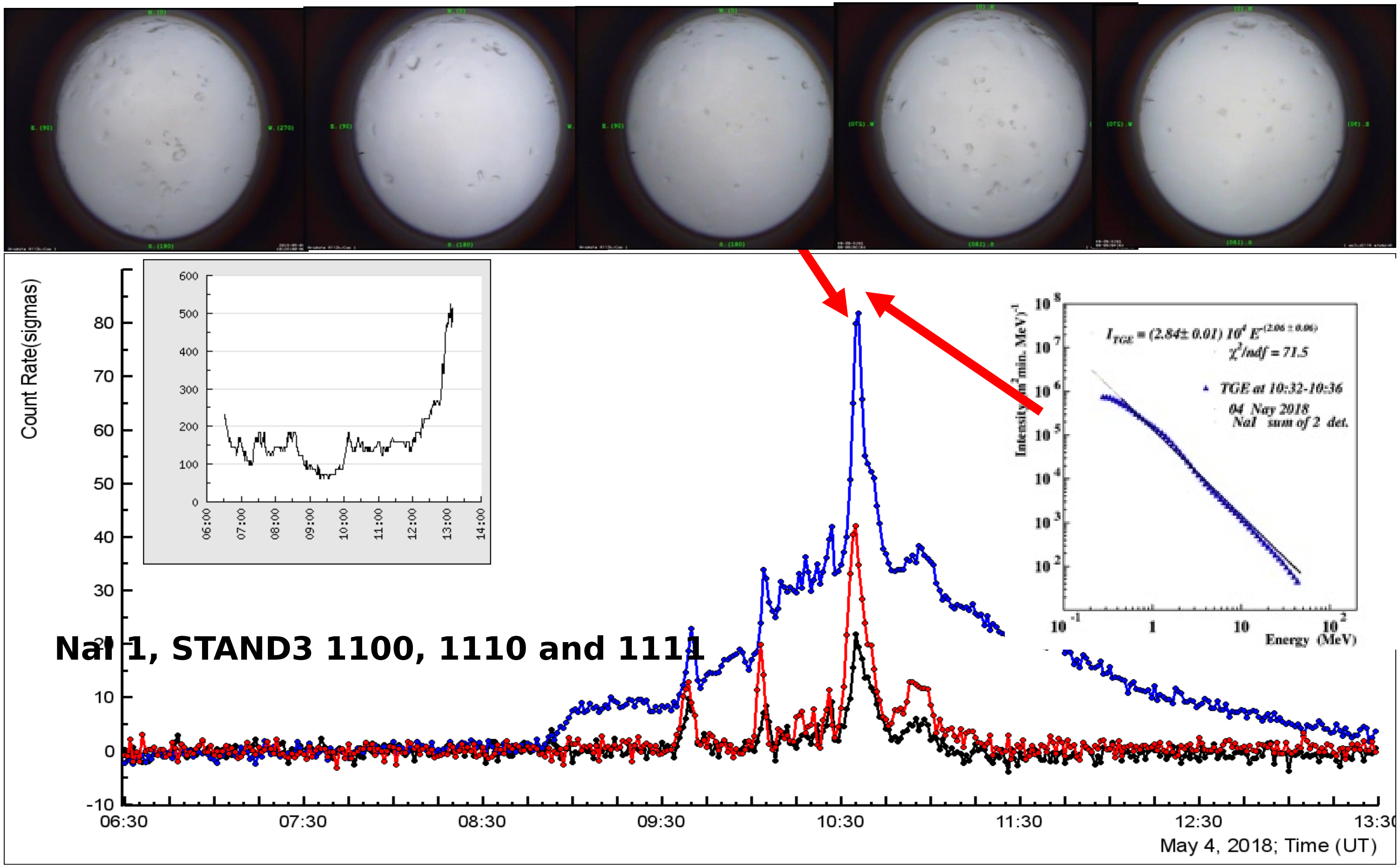
15 years of monitoring of Lightning location, Near-surface electric field (NSEF) and particle fluxes measured by multiple spectrometers…



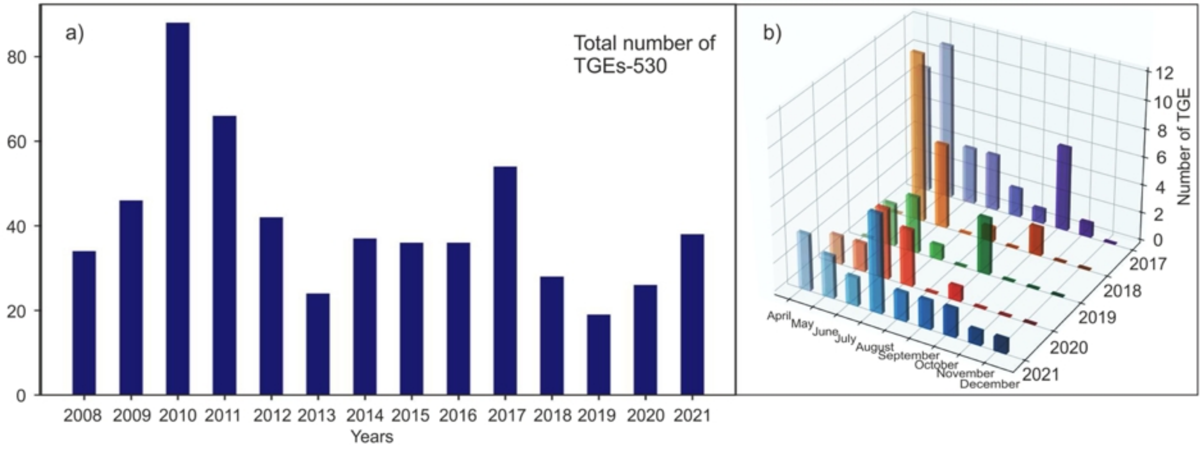
TGE terminations by nearby (distance <10 km) lightning flashes: NSEF disturbances and particle detector count rates



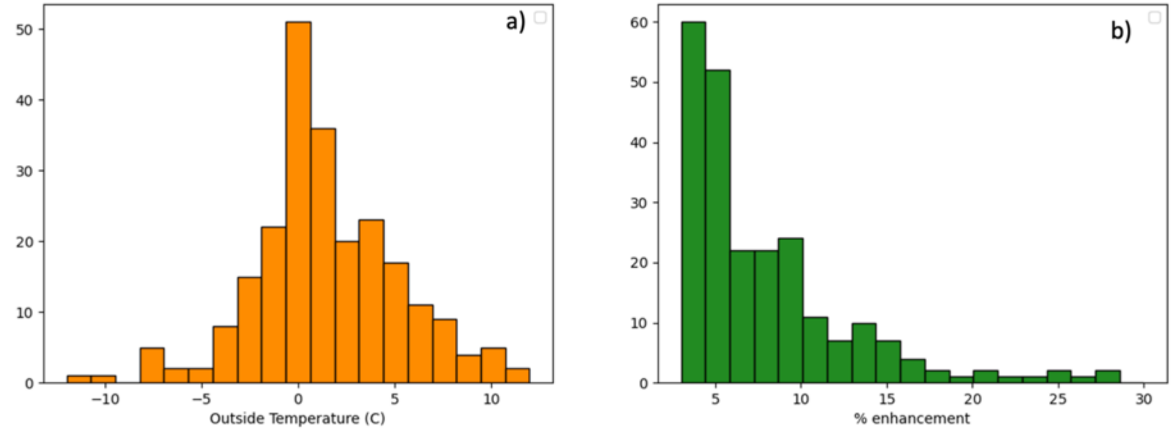
Long duration TGEs observed by spectrometers with low energy threshold (≈0.3 MeV). Radon progeny gamma radiation: mostly 214Pb and 214Bi: Radon isotopes circulation. Graupel detection.



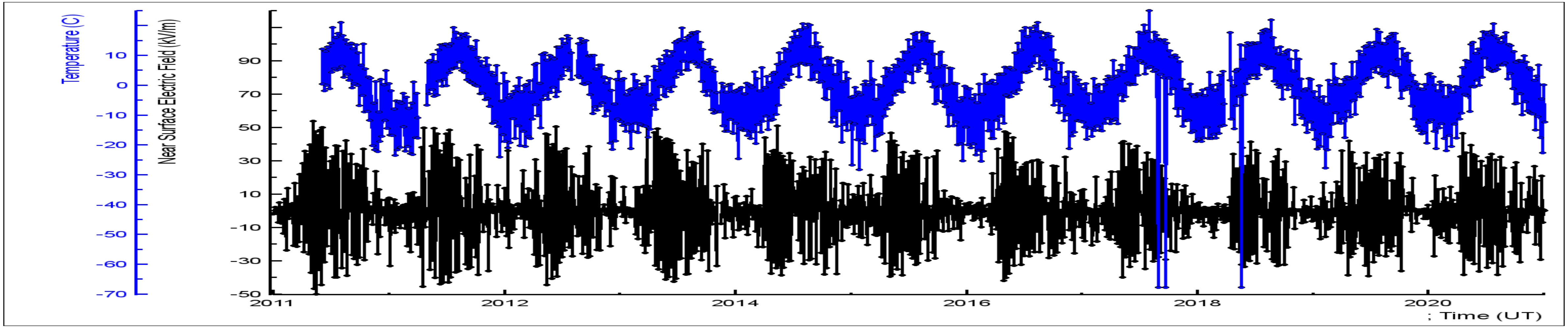
TGE statistics ≈550 TGEs registered in 2009-2021



TGE yearly and monthly statistics.



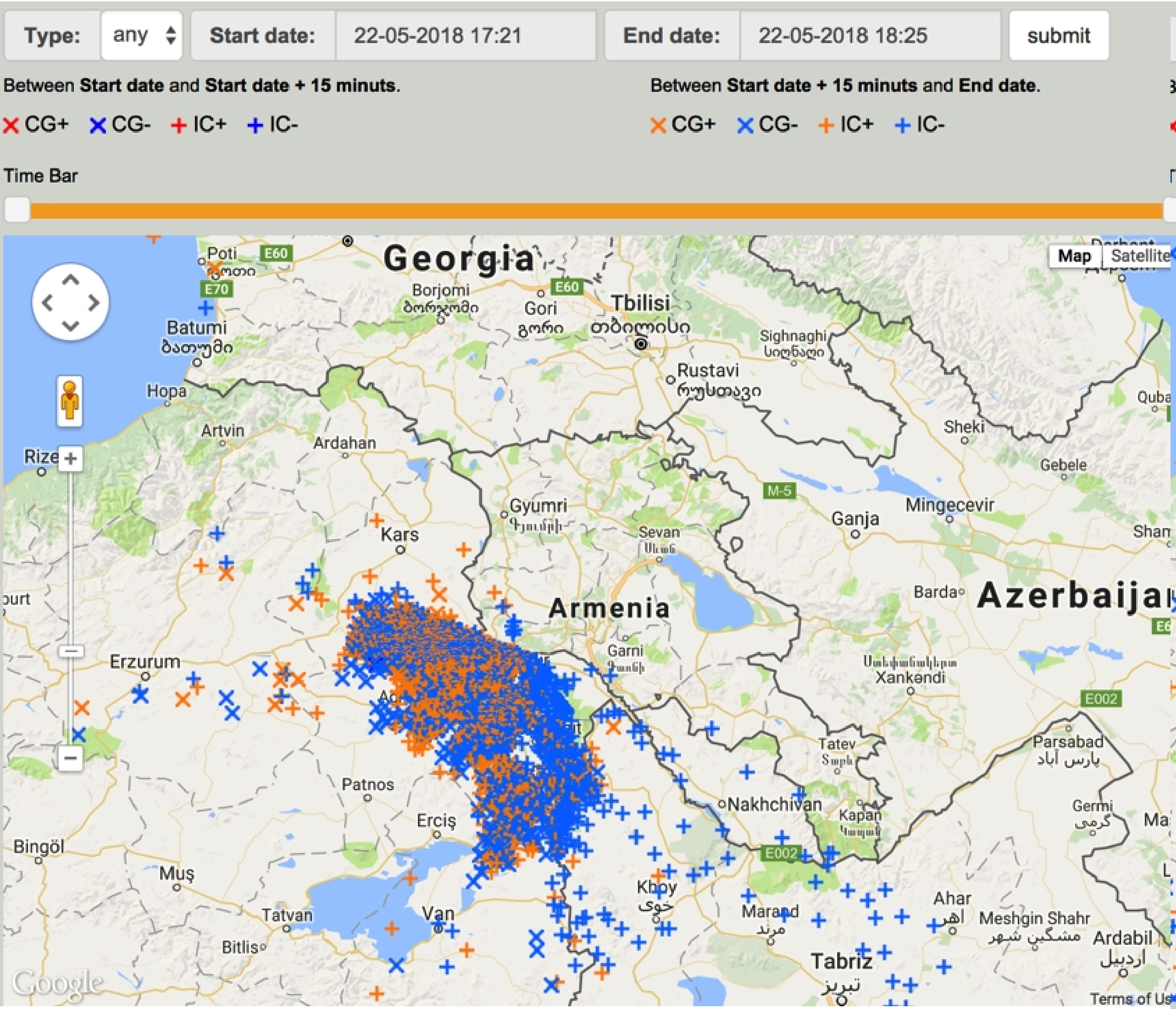
a)The distribution of outside temperatures during TGEs;
b) distribution of TGE significances by 3 cm thick plastic scintillator of STAND3 detector

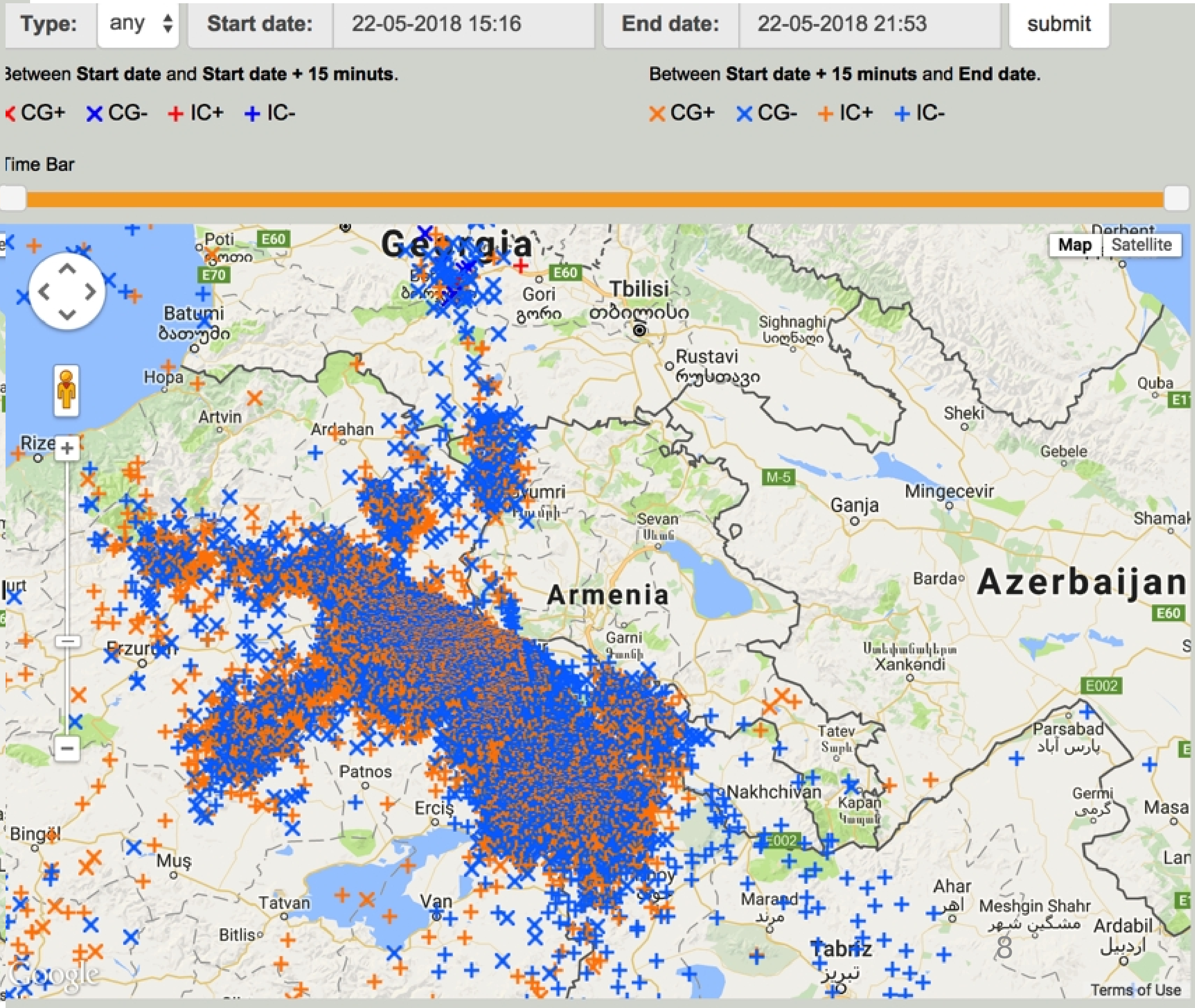


Time series of the NSEF (electric mill EFM-100 by BOLTEK firm, black), and outside temperature (DAVIS weather station, blue)


Thundeclouds above
Aragats highland

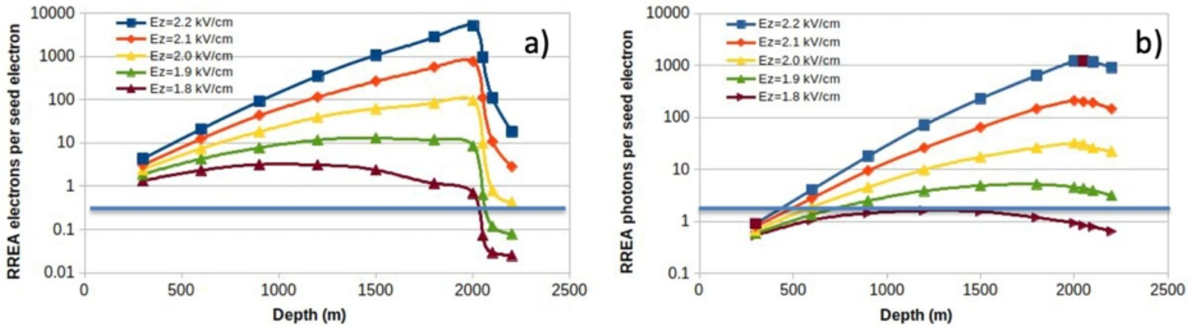
Huge thunderstorms with hundreds of lightning flashes are usual on Aragats.





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.



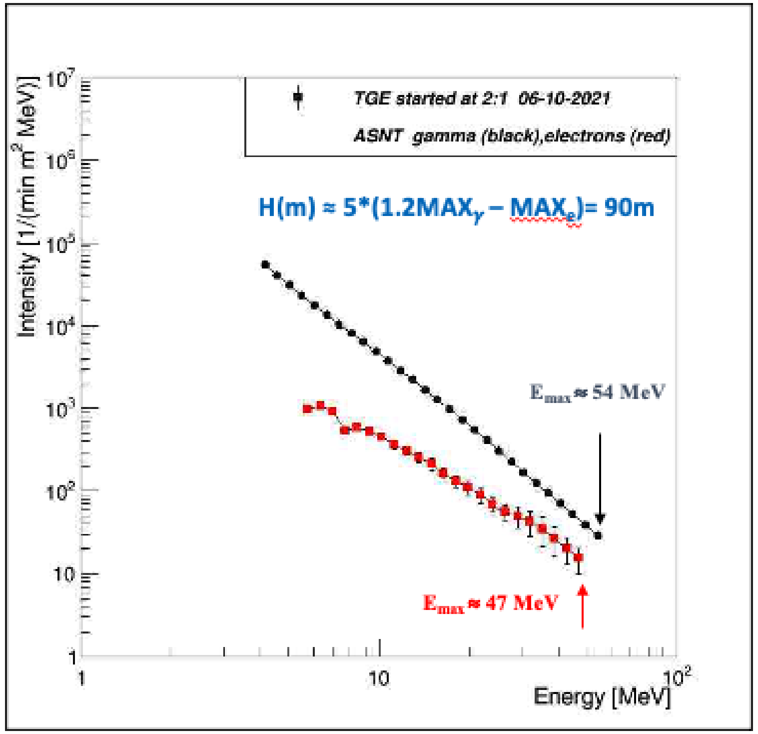
RRE avalanche in the atmosphere a) – electrons, b) gamma rays. Avalanche started at 5400 m a.s.l. (0 depth), that is 2200 m above the Aragats station. The number of avalanche particles is calculated each 300 m. After exiting from the electric field propagation of avalanche particles is followed additionally 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.

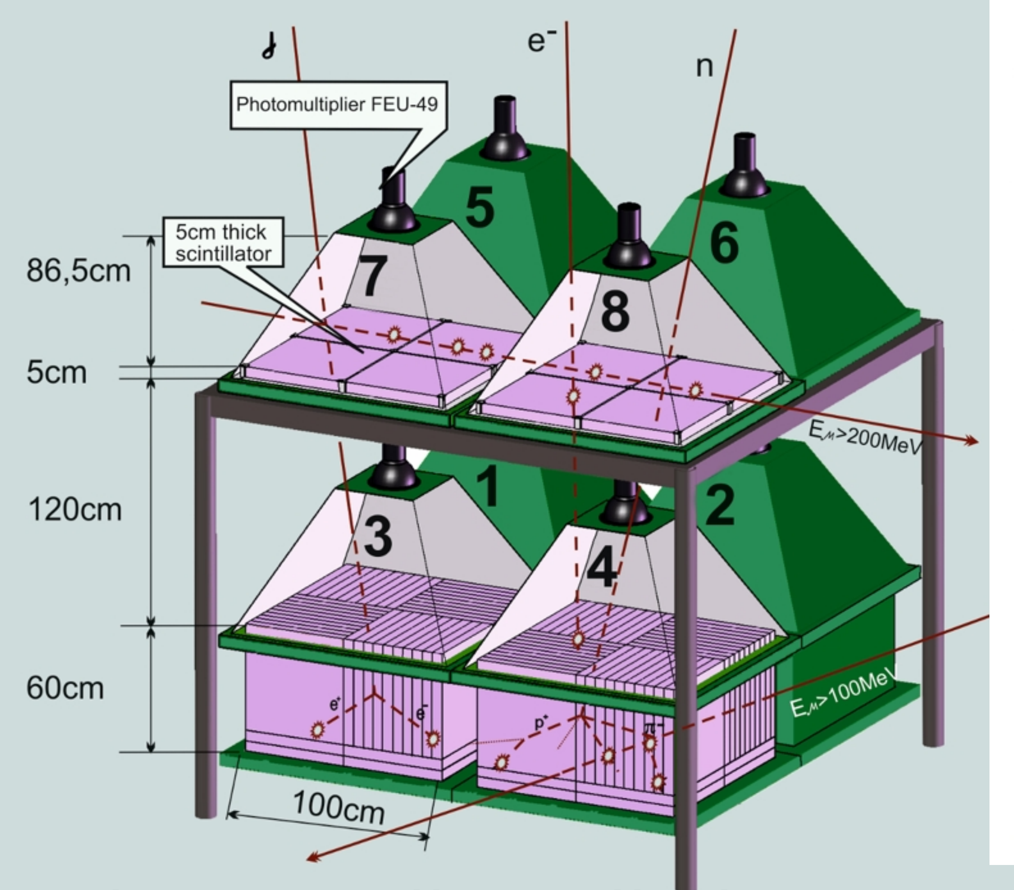
The difference of attenuation of gamma ray and electron fluxes allows estimation of the height where both fluxes leave the electron acceleration region

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!

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



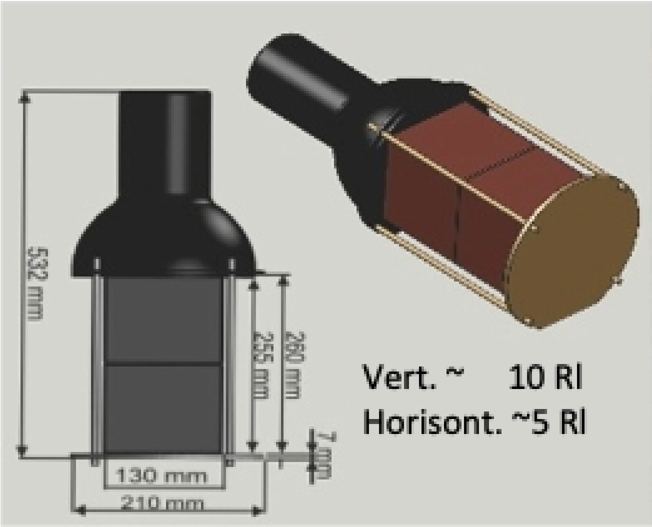
TGE electrons are registered by upper and lower layers; gamma rays and neutrons – by invoking the veto option (no signals from the upper scintillators), horizontal muons – by the condition of operation of 2 upper scintillators from 4 and no signal in the lower scintillators (to prevent registration of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

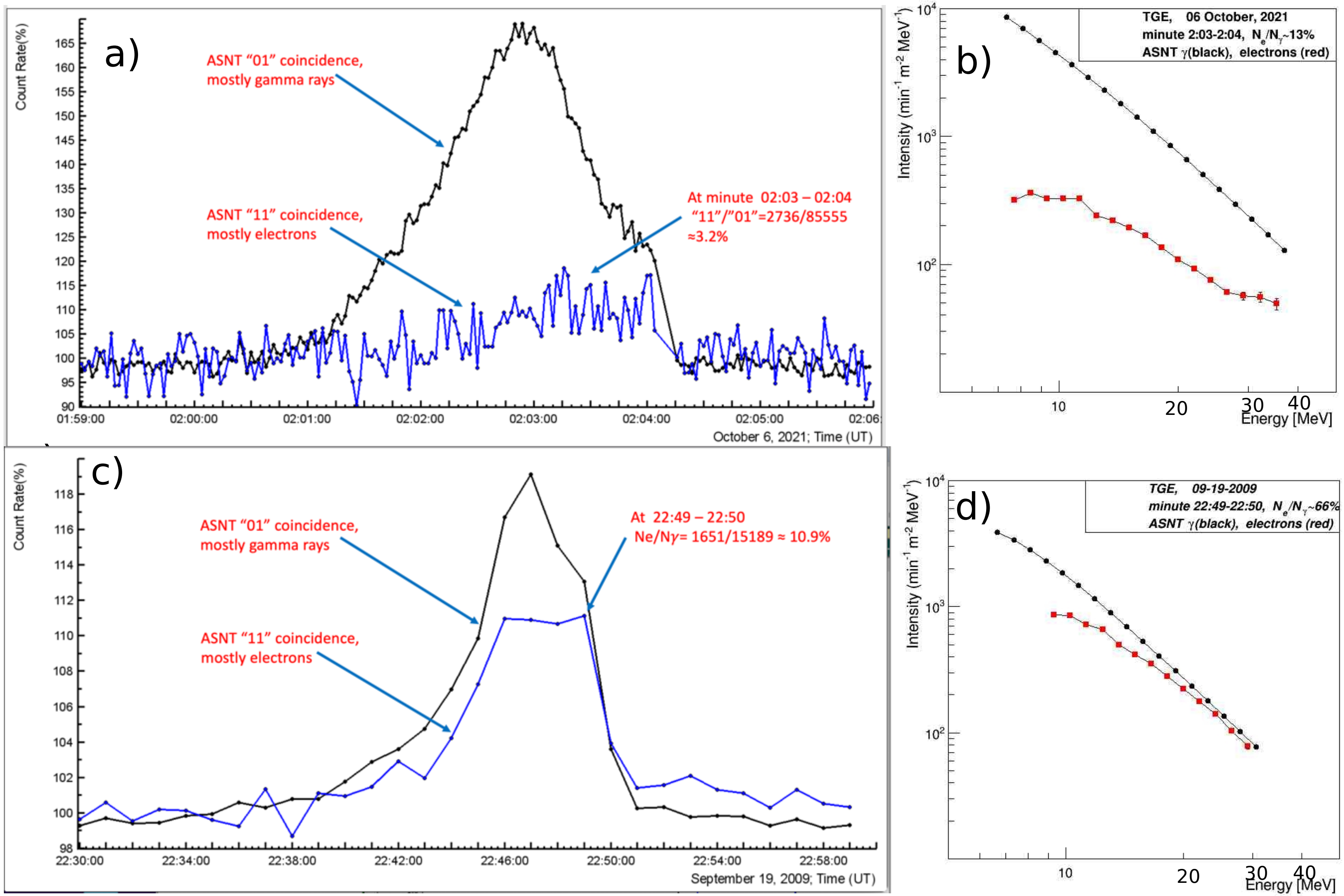
Material	Radiation length		Density
	g/cm2	cm	g/cm3
Polystyr. scint.	43.72	42.4	1.032
Cesium iodide (CzI)	8.39	1.85	4.53
Sodium iodide (NaI)	9.49	2.59	3.67

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.




a)
ASNT "01" coincidence,
mostly gamma rays
ASNT "11" coincidence,
mostly electrons
At minute 02:03 – 02:04
"11"/"01"=2736/85555
≈3.2%
Count Rate(%)
October 6, 2021; Time (UT)
b)
TGE, 06 October, 2021
minute 2:03-2:04, Ne/Nγ~13%
ASNT γ(black), electrons (red)
Intensity (min-1 m-2 MeV-1)
Energy [MeV]
c)
ASNT "01" coincidence,
mostly gamma rays
ASNT "11" coincidence,
mostly electrons
At 22:49 – 22:50
Ne/Nγ= 1651/15189 ≈ 10.9%
Count Rate(%)
September 19, 2009; Time (UT)
d)
TGE, 09-19-2009
minute 22:49-22:50, Ne/Nγ~66%
ASNT γ(black), electrons (red)
Intensity (min-1 m-2 MeV-1)
Energy [MeV]

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

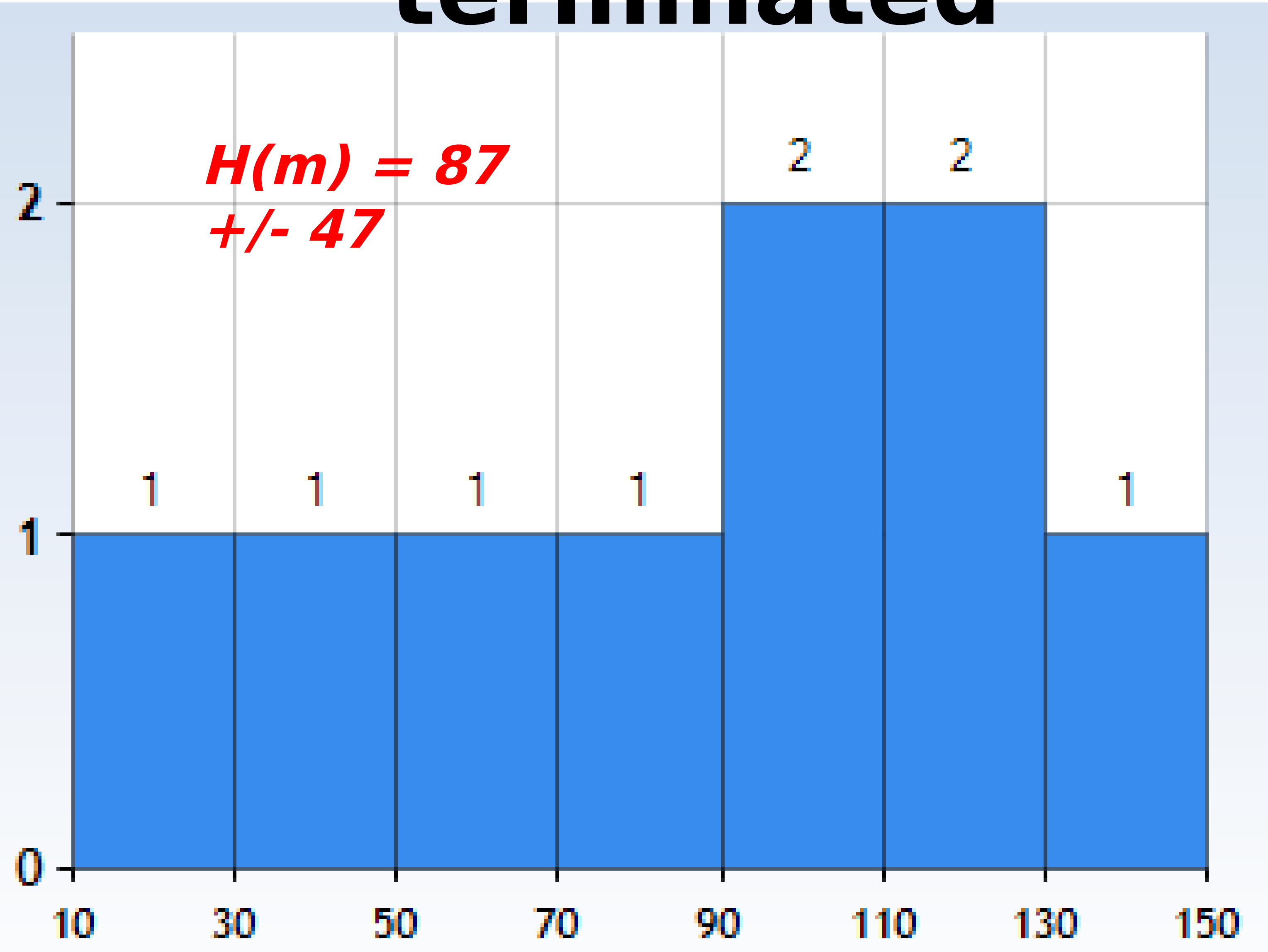
Date, (month. day. year)	Power law Index el.	Power law index γ-rays	Int. Spectra el.	Int. Spectra γ-rays	Max energy el. (MeV)	Max energy γ-rays (MeV)	TGE significance (%)	El.Field height (m)	TGE duration (min)	Ne/Nɣ	Outside T C°	Cloud height (m)	Dist. to lightning flash (km)	Max. positive NS el. field + (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
[illegible].23.20	2.35	2.86	7570	39070	32	32	20	30	5	0.10	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

ndeley Data, V3, doi: 10.17632/tvbn6wdf85.3

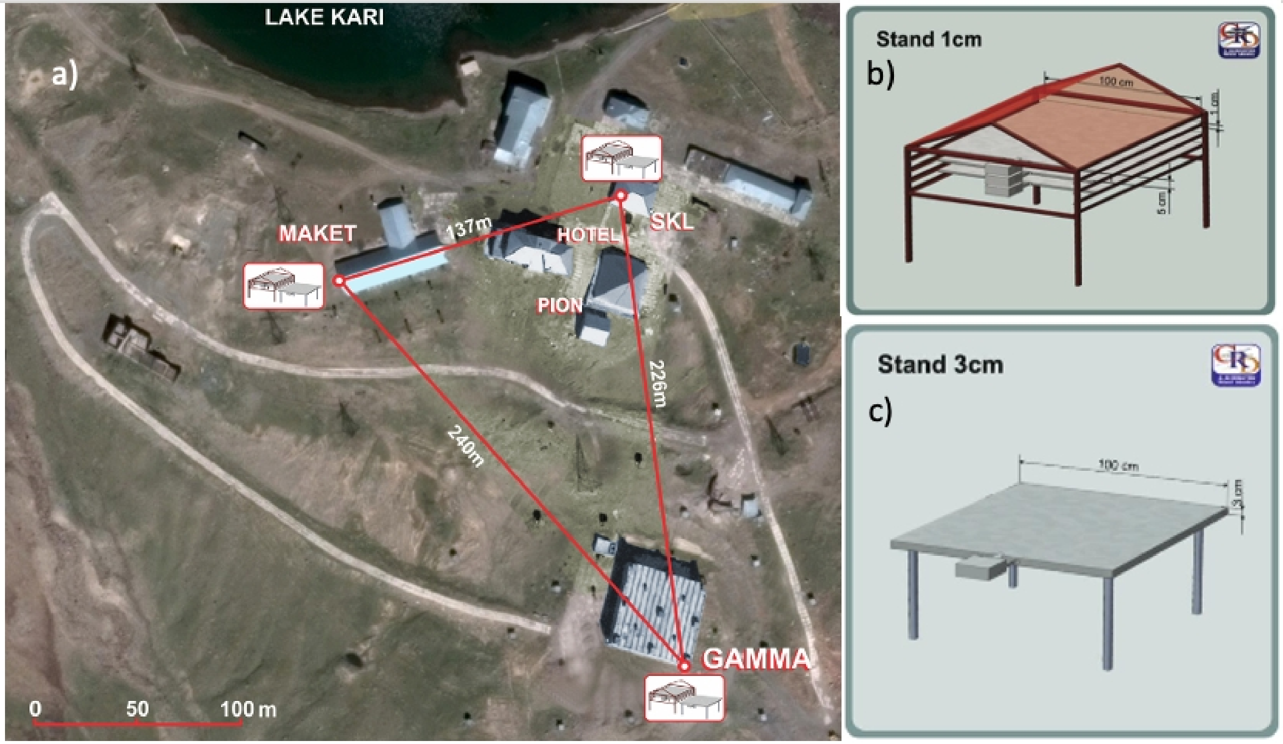
tron and gamma ray energy spectra are recovered

n energy release histograms s, cloud height is recovered by outside temperature and dew poin

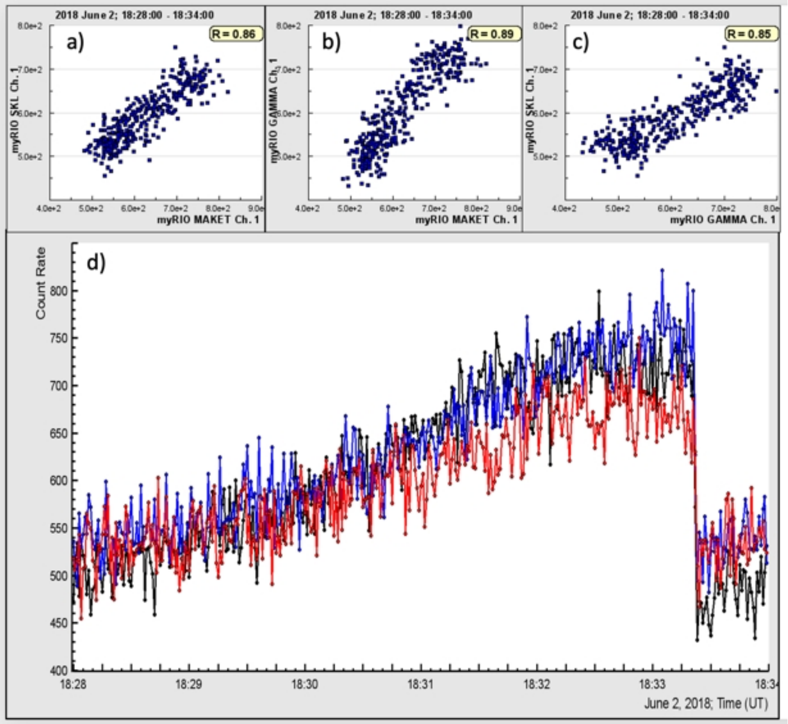
Height above ground where strong accelerated electric field terminated



STAND1 network on Aragats station: research uniformity of TGE flux, high-energy particles, and lightning-TGE relation on 50 microsecond time scale



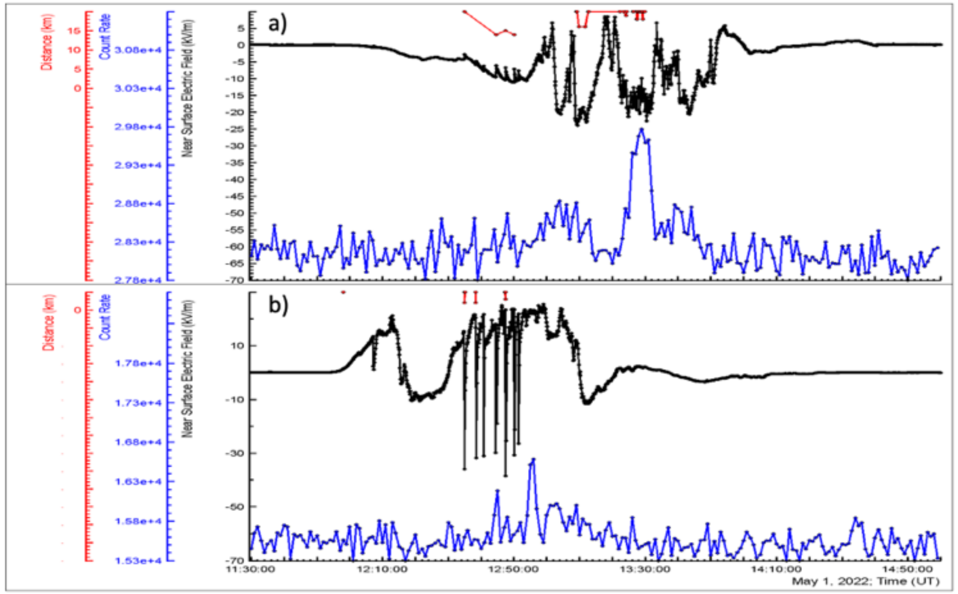
The map of Aragats station with STAND1 network; b) Stand1 unit: vertically stacked 1 cm thick, and 1 m^2 area plastic scintillators; c) Stand1 unit: stand-alone 3 cm thick plastic scintillator with the same area.



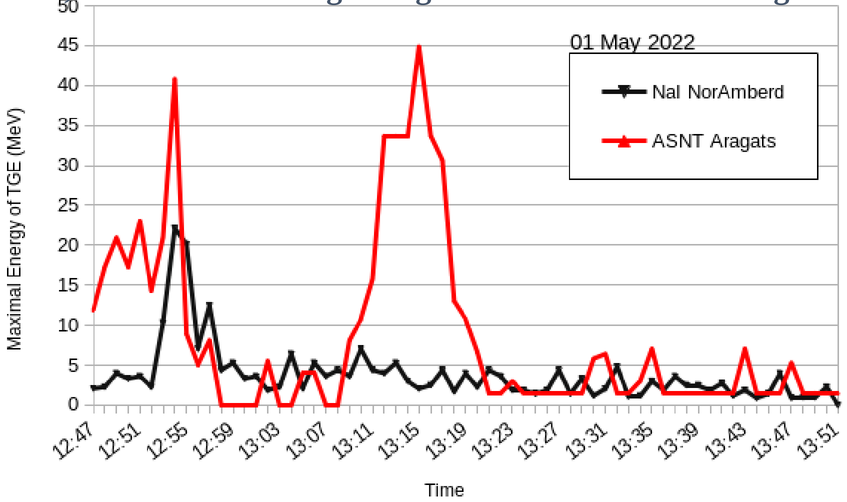
1-s time series registered by the STAND1 network: in the upper panel we show scatter plots of 1s count rates of STAND1 modules; in the bottom panel - 1-s time series of the upper scintillators of the STAND1 network.

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.

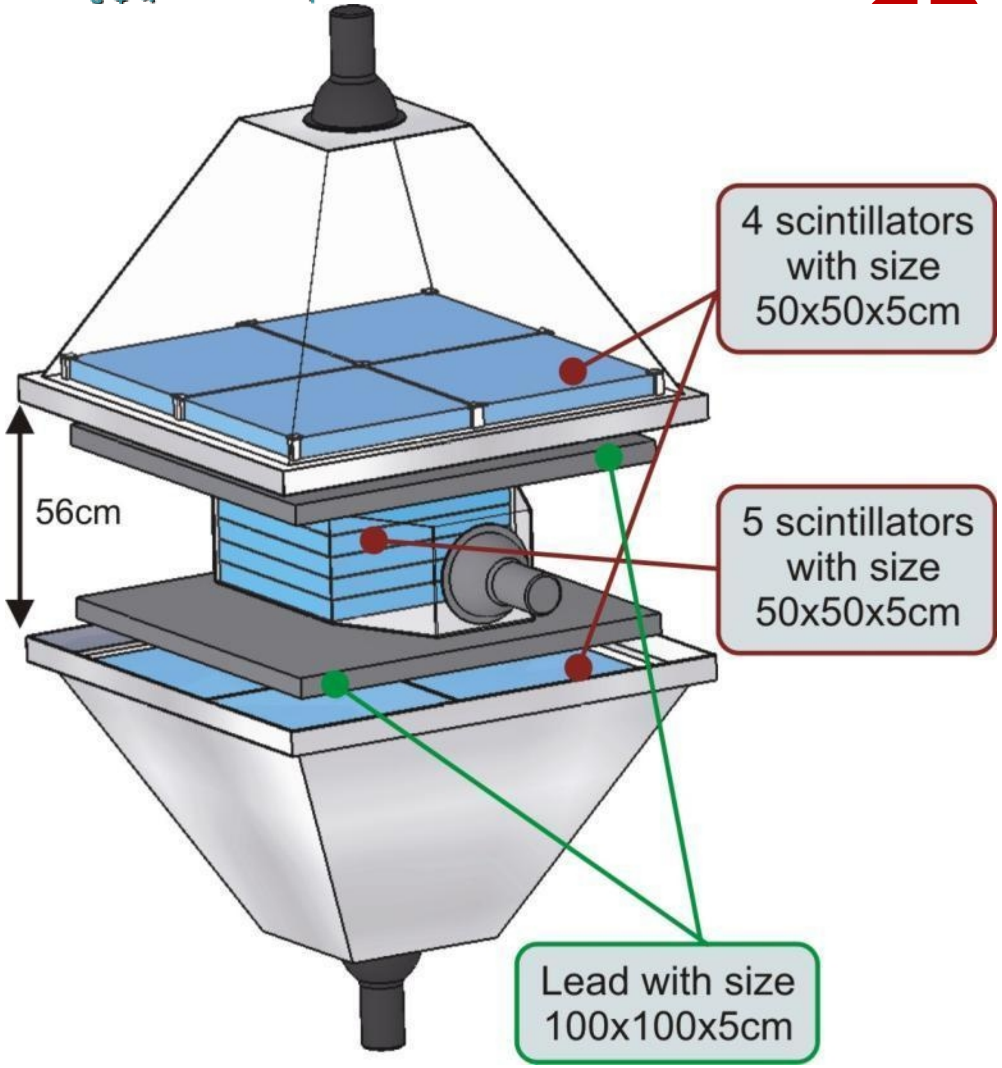


The disturbances of the NSEF; 1-minute count rates of 5 cm thick and 1 m² area plastic scintillators; and distances to lightning flashes measured on Aragats and in Nor Amberd



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

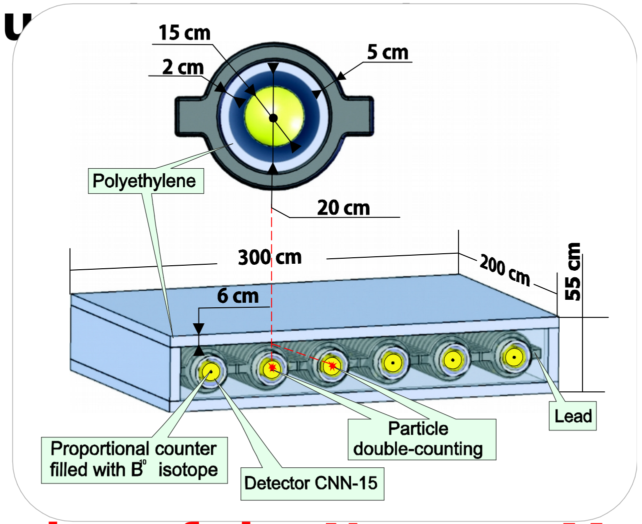
monitoring
3 species of secondary



100 – low energy charged particle;

010 – neutral particle (gamma ray or neutron;

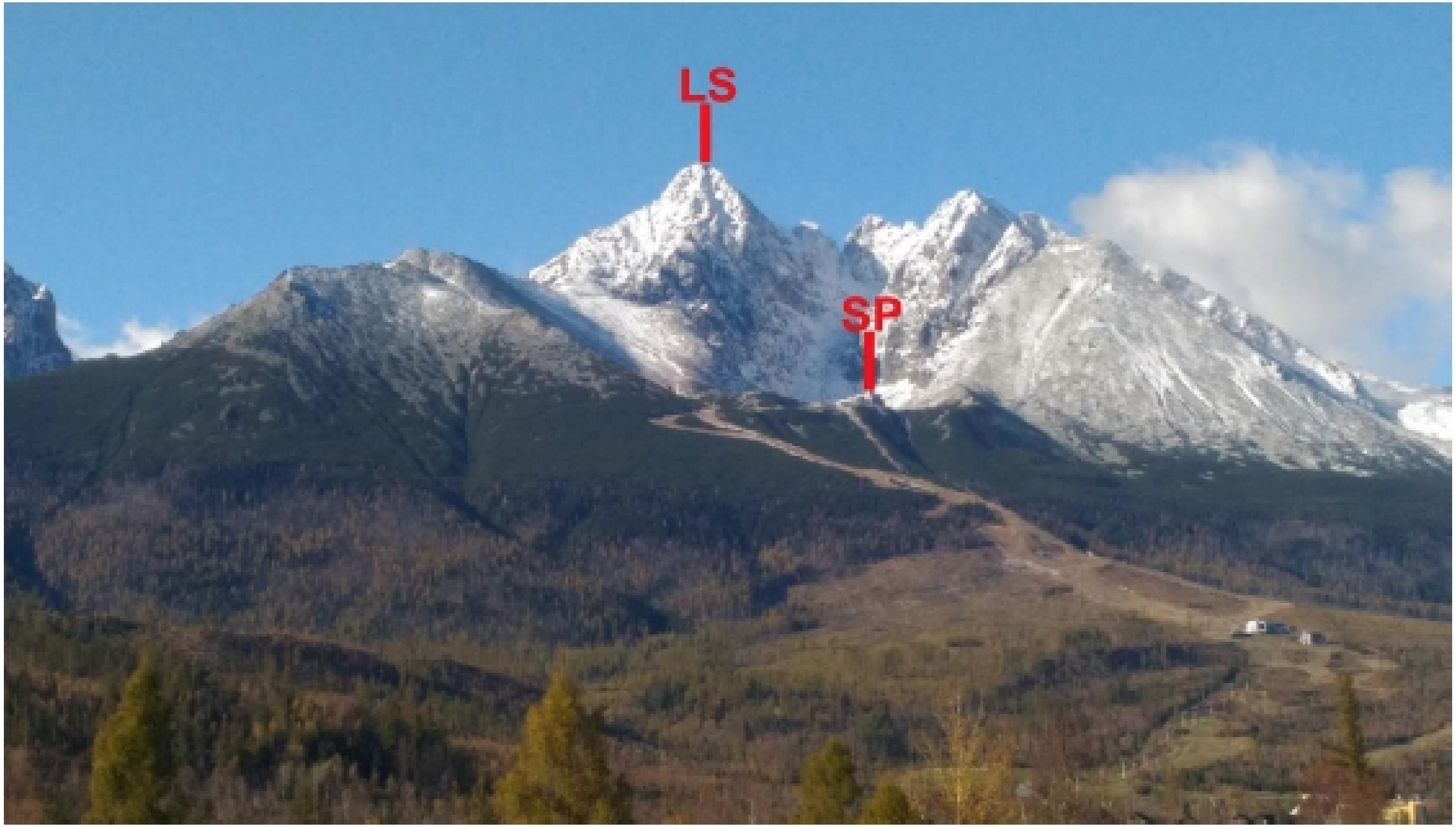
111 & 101 – high energy mu

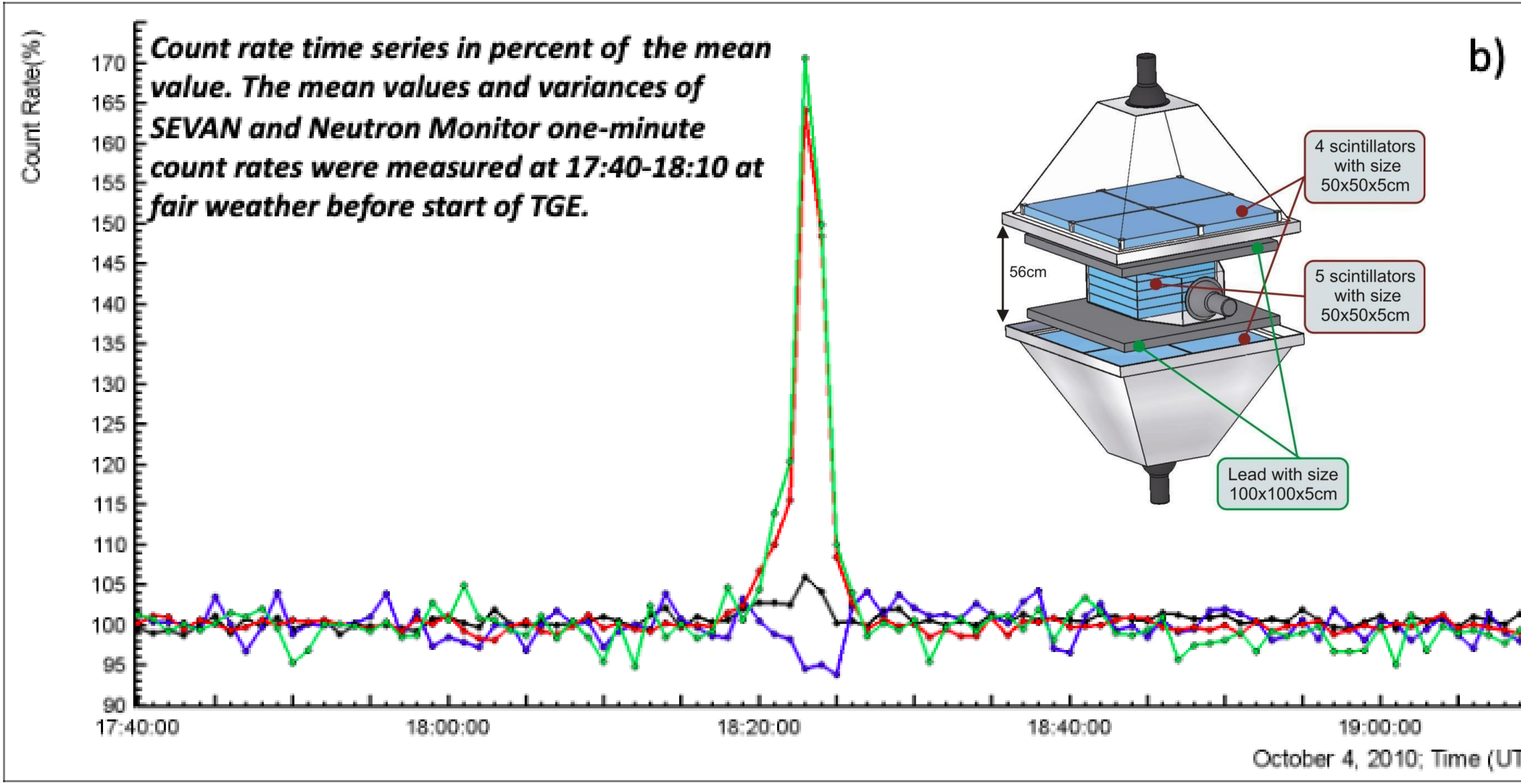


Section of the Neutron Monitor

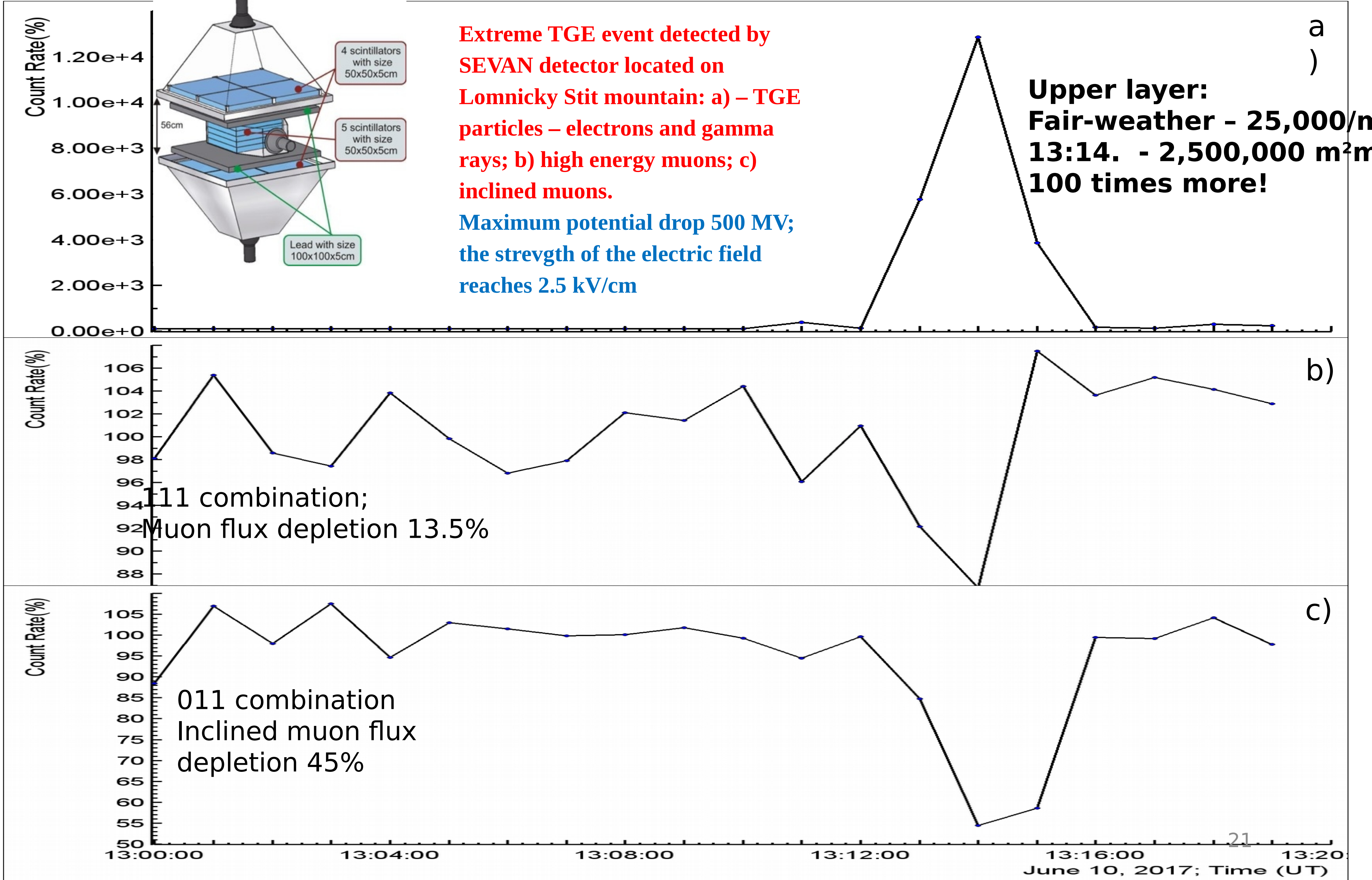
MUSALA Latitude - 42º11’N, 23º35’ E 2925 m,

Lomnický štít (LS) 49.1952 N 20.2131 E 2634 m

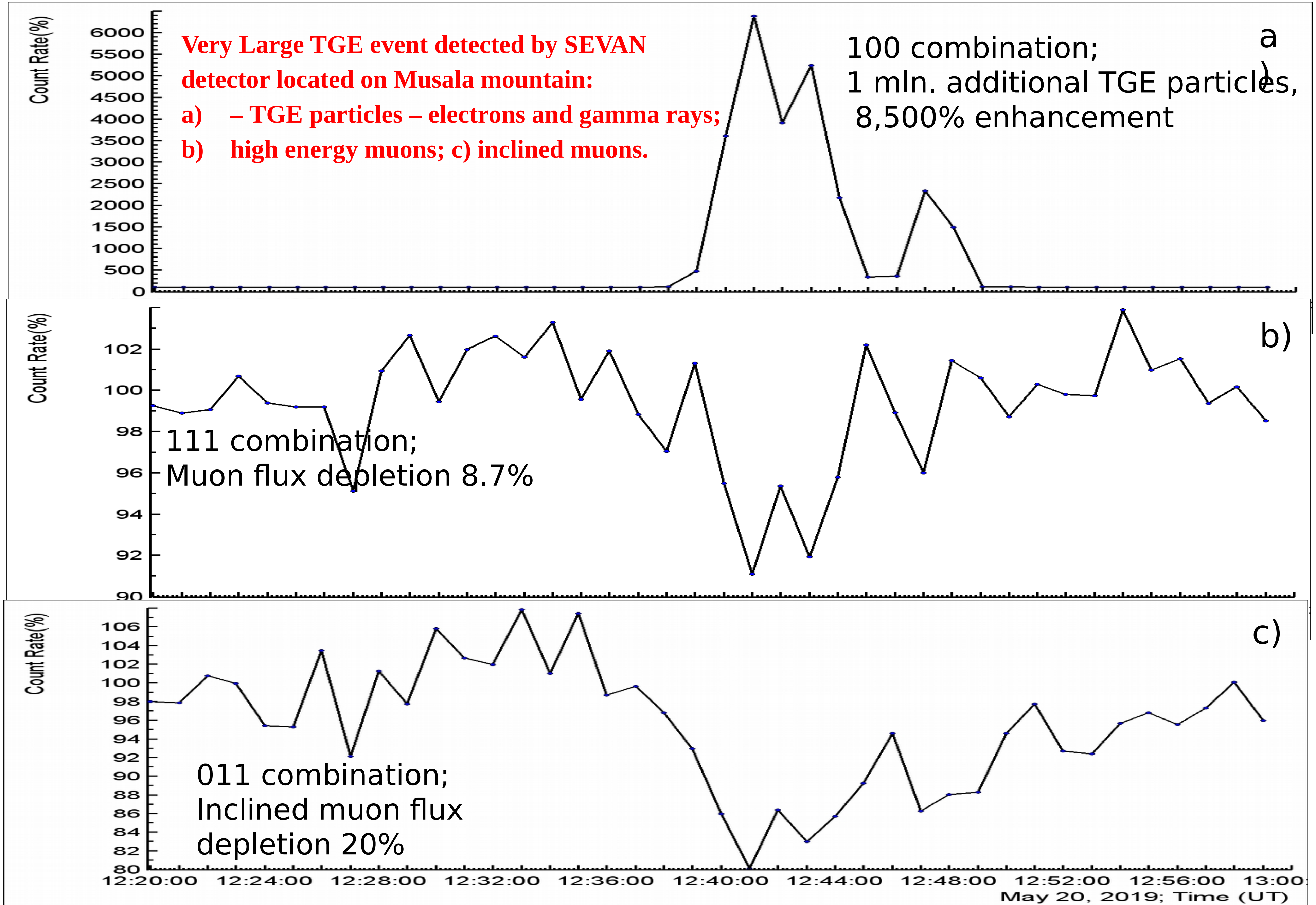




Count rate time series in percent of the mean value. The mean values and variances of SEVAN and Neutron Monitor one-minute count rates were measured at 17:40-18:10 at fair weather before start of TGE.



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/m
13:14. - 2,500,000 m²m
100 times more!
4 scintillators with size 50x50x5cm
5 scintillators with size 50x50x5cm
Lead with size 100x100x5cm
56cm
Count Rate(%)
a)
b)
c)
111 combination;
Muon flux depletion 13.5%
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)
Count Rate(%)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
b)
111 combination;
Muon flux depletion 8.7%
Count Rate(%)
102
100
98
96
94
92
90
c)
011 combination;
Inclined muon flux
depletion 20%
Count Rate(%)
106
104
102
100
98
96
94
92
90
88
86
84
82
80
12:20:00
12:24:00
12:28:00
12:32:00
12:36:00
12:40:00
12:44:00
12:48:00
12:52:00
12:56:00
13:00
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.

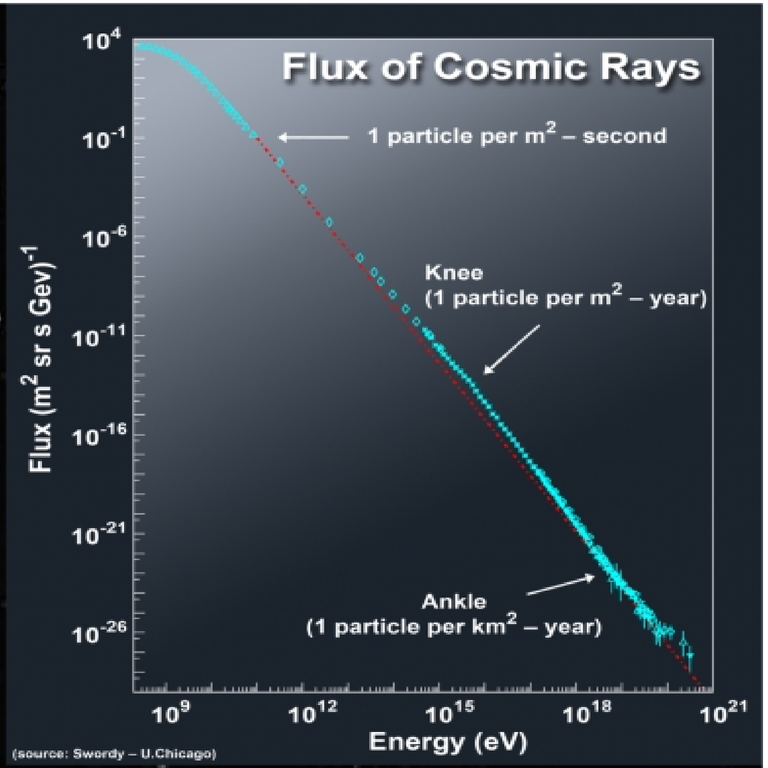
Time series of particle fluxes measured by hundreds of particle detectors. Data on NSEF, geomagnetic field, weather conditions, shots of panoramic cameras. Data are available in numerical and graphical formats for 20 years of operation **http://adei.crd.yerphi.am/**

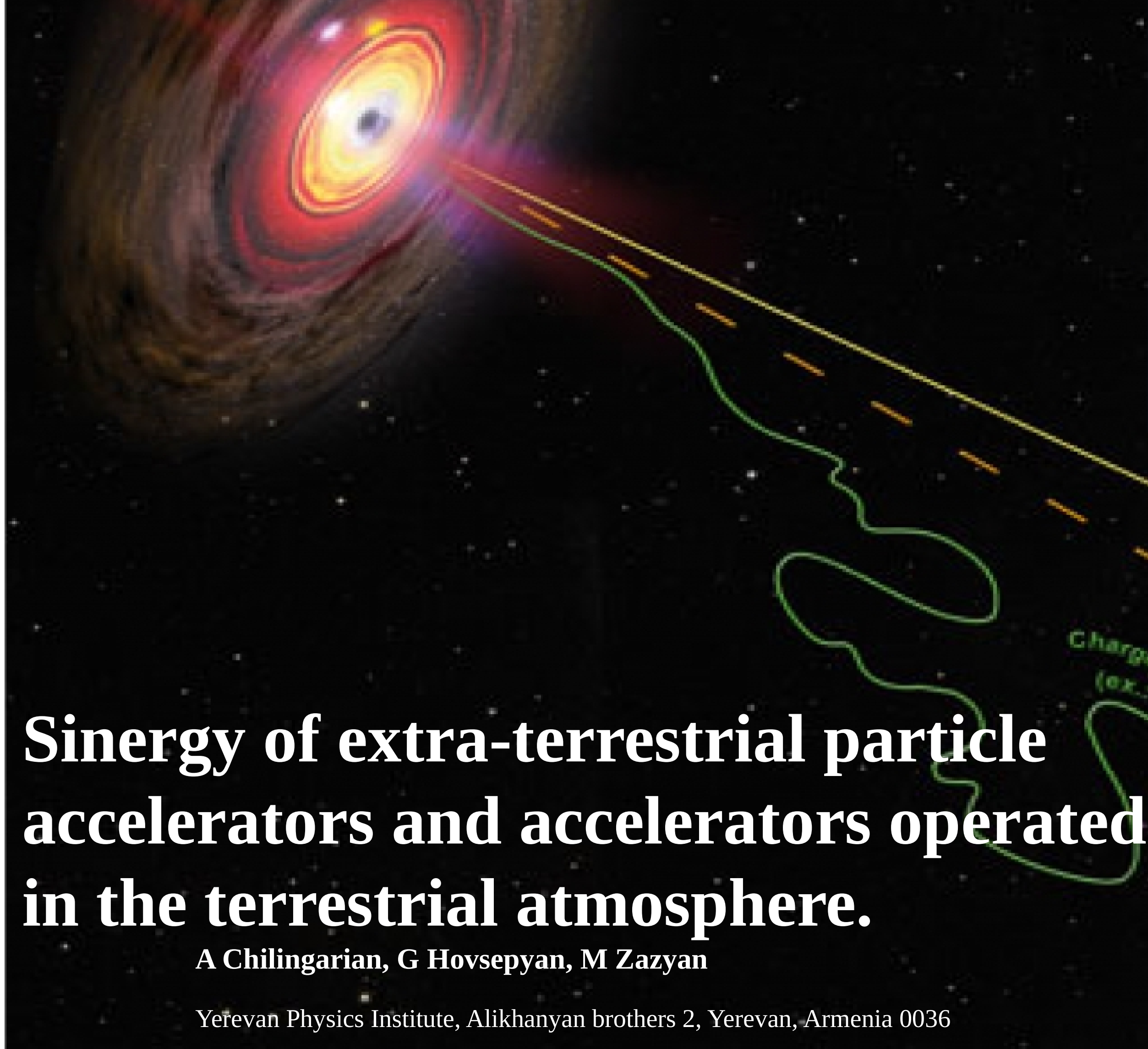
Mendeley datasets with selected data on different research topics:

- "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
- "Thunderstorm ground enhancements abruptly terminated by a lightning flash registered both by WWLLN and local network of EFM-100 electric mills.", Mendeley Data, V1, doi: 10.17632/ygvjzdx3w3.1
- "Extensive Air Shower (EAS) registration by the measurements of the multiplicity of neutron monitor signals", Mendeley Data, V1, doi: 10.17632/43ndcktj3z.1

The main results made by 24/7 monitoring of particle fluxes in Armenia and Eastern Europe (SEVAN network)

- **Thunderstorm ground enhancements are a universal physical phenomena sending ≈10^{18} particles to the earth's surface each second.**
- **Strong accelerating electric field of 1.8-2.2 kV/cm can extend 2 km vertically till the earth's surface and several kilometers horizontally.**
- **The potential drop in thunderous atmosphere can reach 350-500 MV.**
- **Near-surface electrical field lift the Radon progeny to the atmosphere providing additional gamma radiation.**
- **The majority of TGEs, which produce large electron fluxes produce also yet unknown optical emissions of different shapes.**

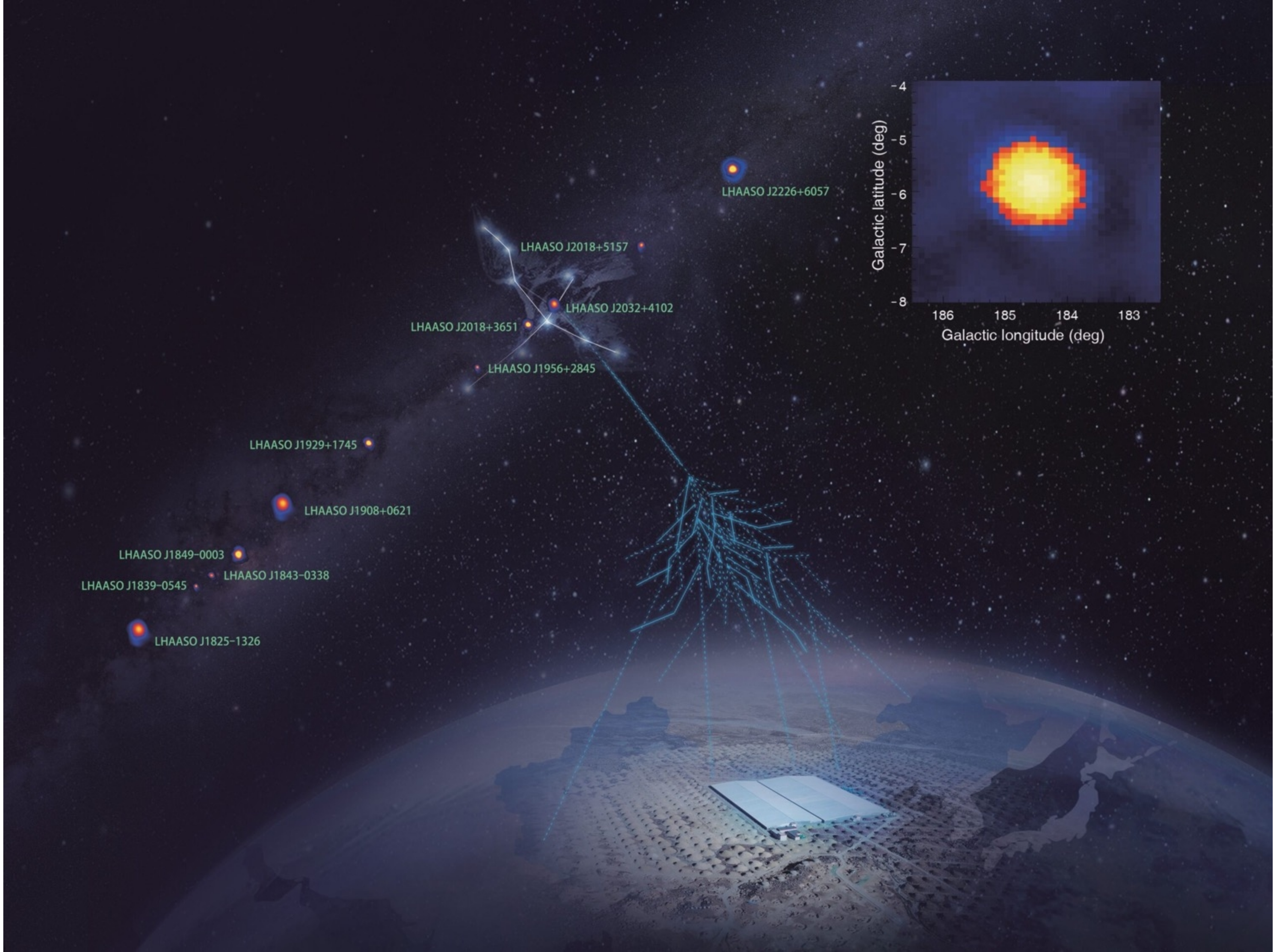




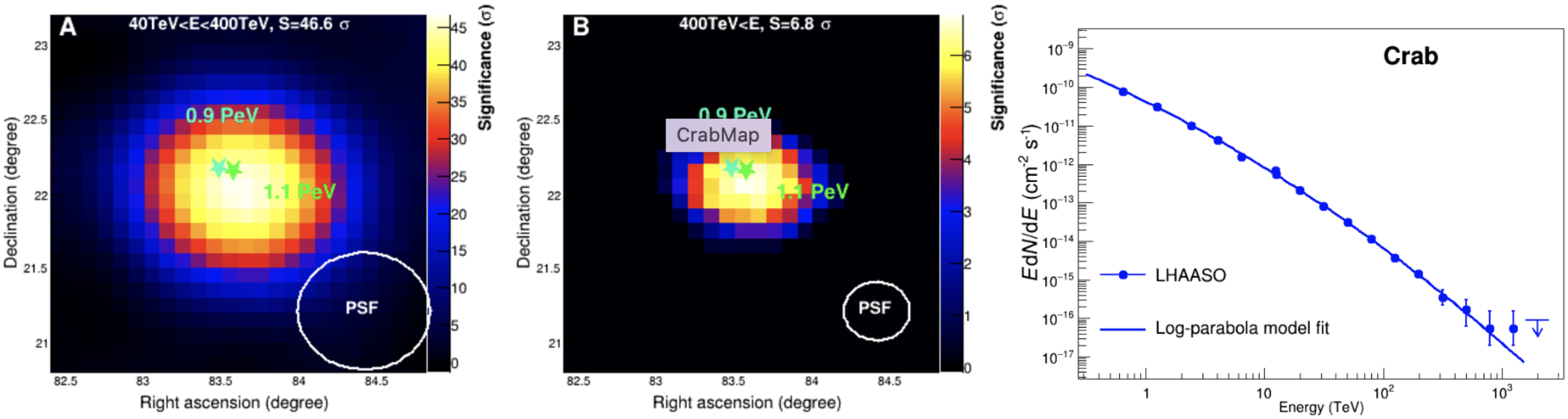
Sinergy of extra-terrestrial particle accelerators and accelerators operated in the terrestrial atmosphere.

A Chilingarian, G Hovsepyan, M Zazyan

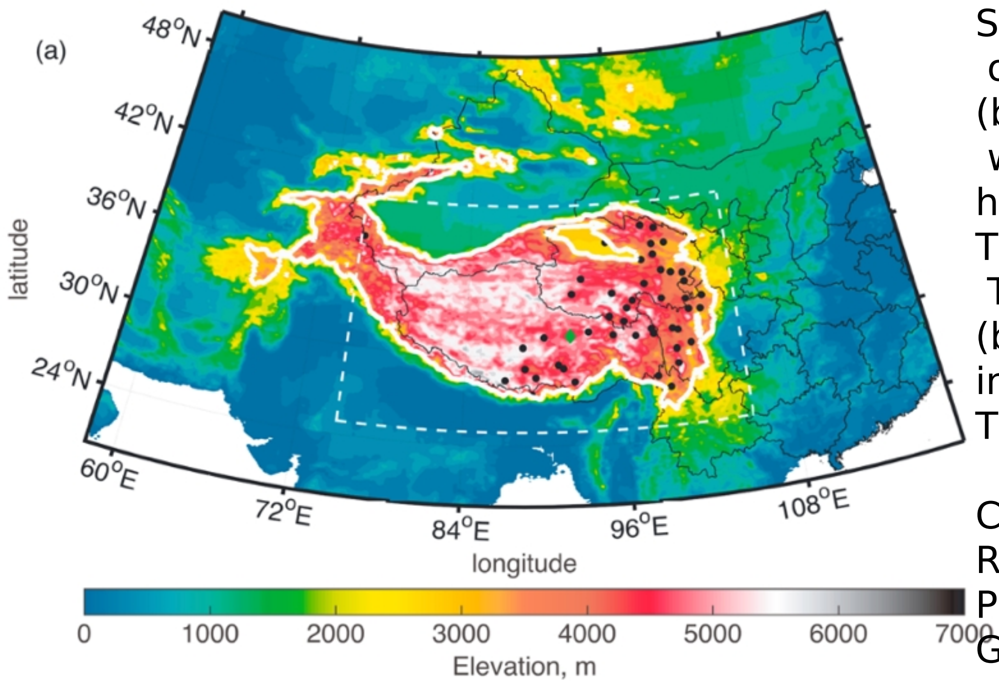
Yerevan Physics Institute, Alikhanyan brothers 2, Yerevan, Armenia 0036


LHAASO J2226+6057
LHAASO J2018+5157
LHAASO J2032+4102
LHAASO J2018+3651
LHAASO J1956+2845
LHAASO J1929+1745
LHAASO J1908+0621
LHAASO J1849-0003
LHAASO J1843-0338
LHAASO J1839-0545
LHAASO J1825-1326
Galactic latitude (deg)
-4
-5
-6
-7
-8
186
185
184
183
Galactic longitude (deg)

PeV gamma-ray emission from the Crab Nebula

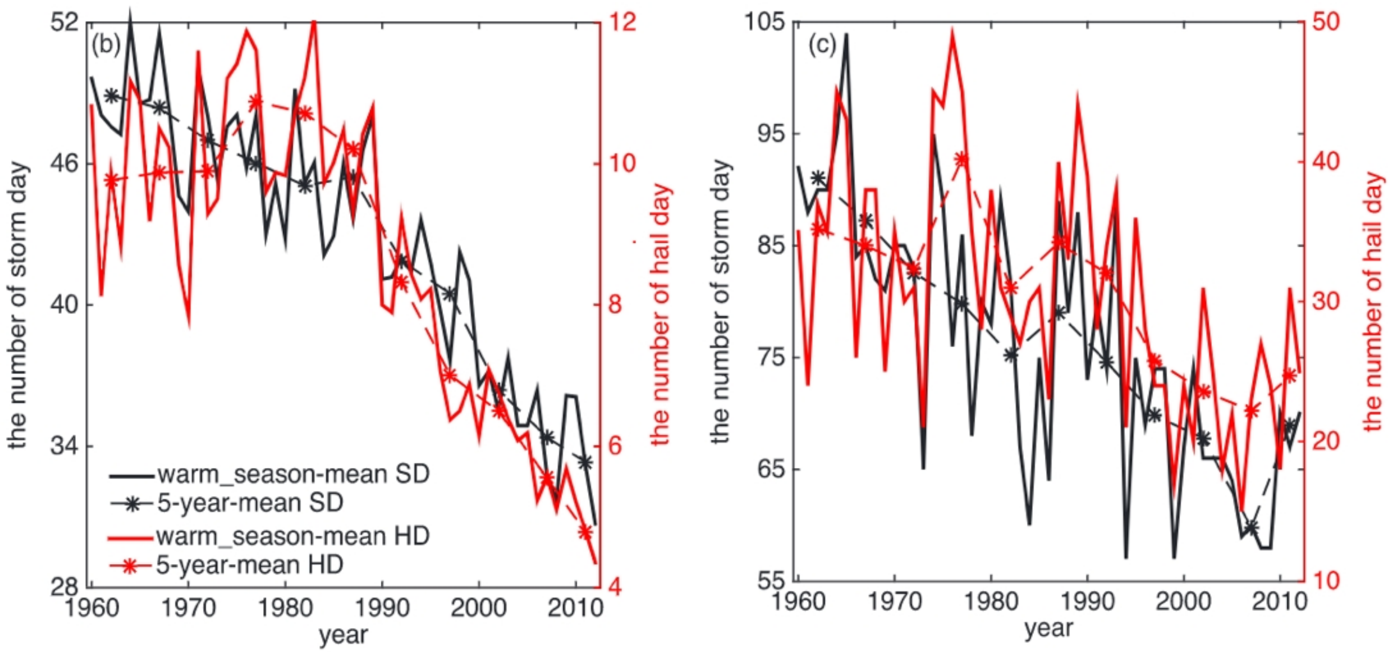


Very good rejection of the proton initiated EASs by selection of muon-poor events enabled detection of 1.1 and 1.4 PeV events from point sourses in the Milkyway



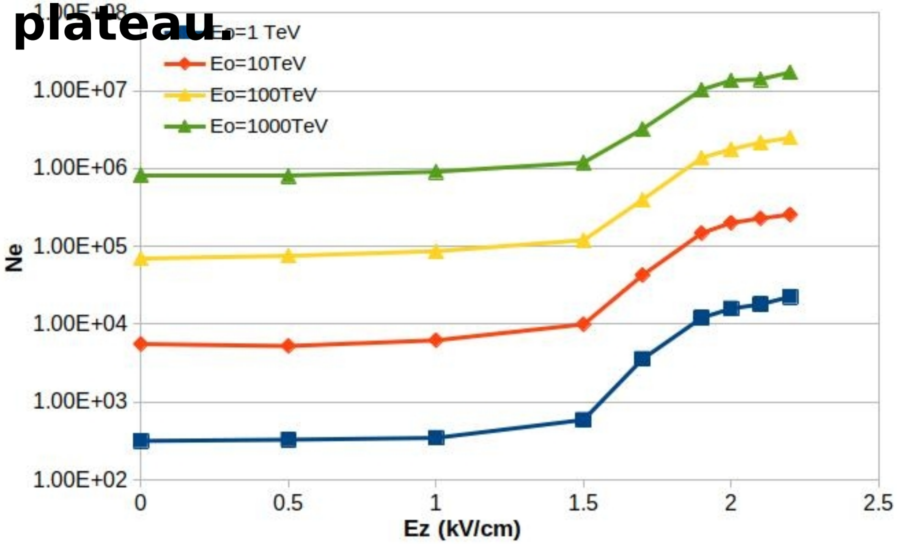
Station distribution in the Tibetan Plateau (TP) and the variations
of storm day (SD) and hail day (HD). (a)Meteorological stations
(black dots)
within the study region (dashed box), and the white contour
highlights the 3,000-m-elevation line.
The green diamond indicates Nagqu station (31.29°N, 92.04°E).
Time series of warm season mean HD (redlines) and SD (black l
(b) averaged over TP, and (c)
in Nagqu during 1960 to 2012.
The dash lines present the 5-yearaverage values.

Credit:Zou, T., Zhang, Q., Li, W., & Li, J. (2018).
Responses of hail and storm days toclimate change in the Tibeta
Plateau.
Geophysical Research Letters,45



LHASSO detects PEV gamma ra
from direction of SNR G106.3+
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

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
• Ashot Chilingarian, Yerevan Physics Institute, Armenia (Chair)
• Ondrej Ploc, CRREAT head, Nuclear Physics Institute of the CAS, Czechia (Co-chair)
• Eric Benton, Oklahoma University, USA
• Lev Dorman, Israel Cosmic Ray Center and Emilio Segré Observatory, Israel
• Joseph Dwyer, Department of Physics University of New Hampshire, USA
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• Marco Tavani, INAF and University of Rome "Tor Vergata", Italy
• Tatsuo Torii, Japan Atomic Energy Agency, Tsuruga, Japan
• Harufumi Tsuchiya, Cosmic Radiation Laboratory, Riken, Japan.
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A. ALIKHANYAN National Laboratory
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Miscelaneous


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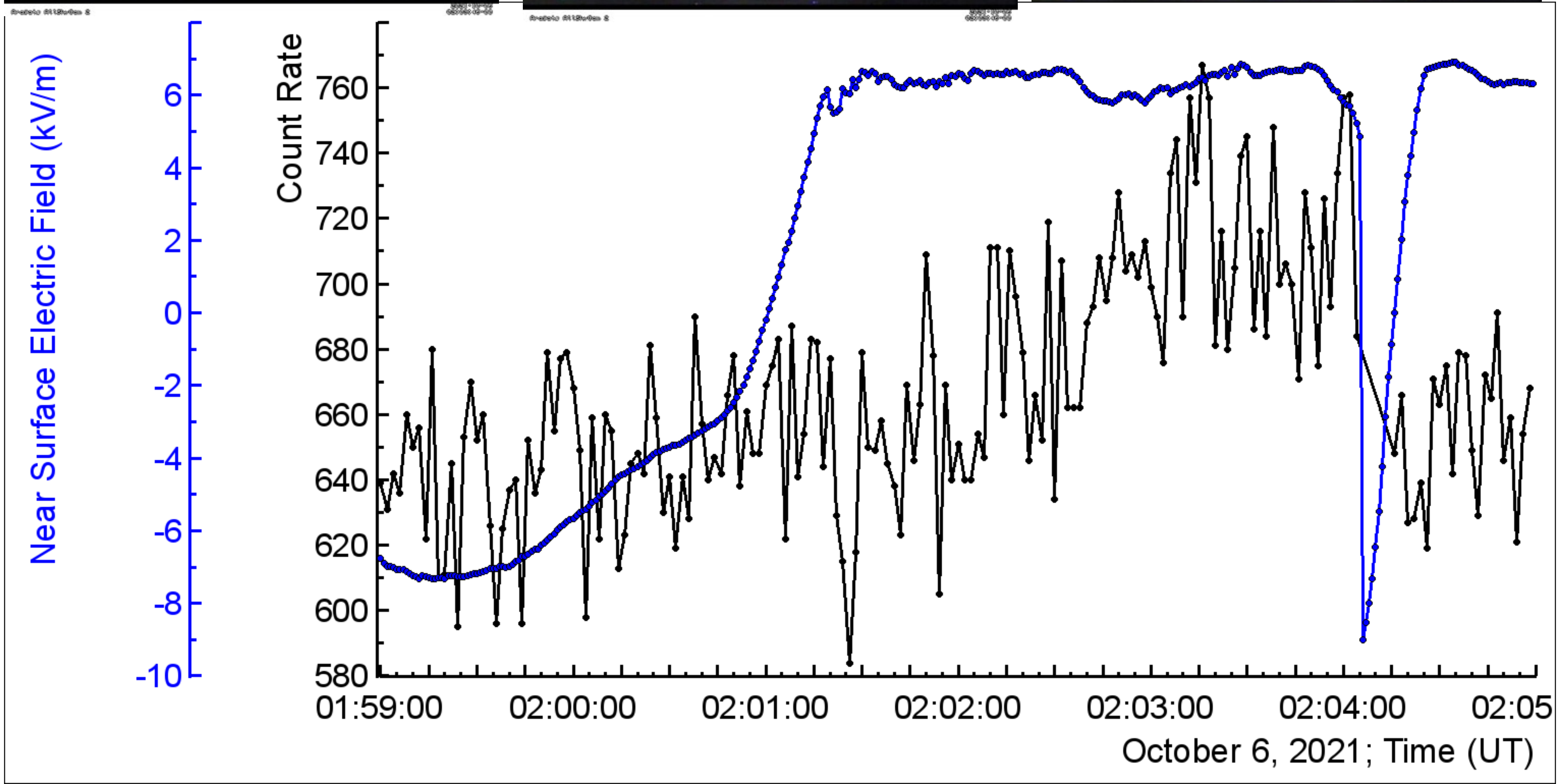
E. (90)
W. (270)


Near Surface Electric Field (kV/m)
6
4
2
0
-2
-4
-6
-8
-10
Count Rate
760
740
720
700
680
660
640
620
600
580
01:59:00
02:00:00
02:01:00
02:02:00
02:03:00
02:04:00
02:05
October 6, 2021; Time (UT)