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

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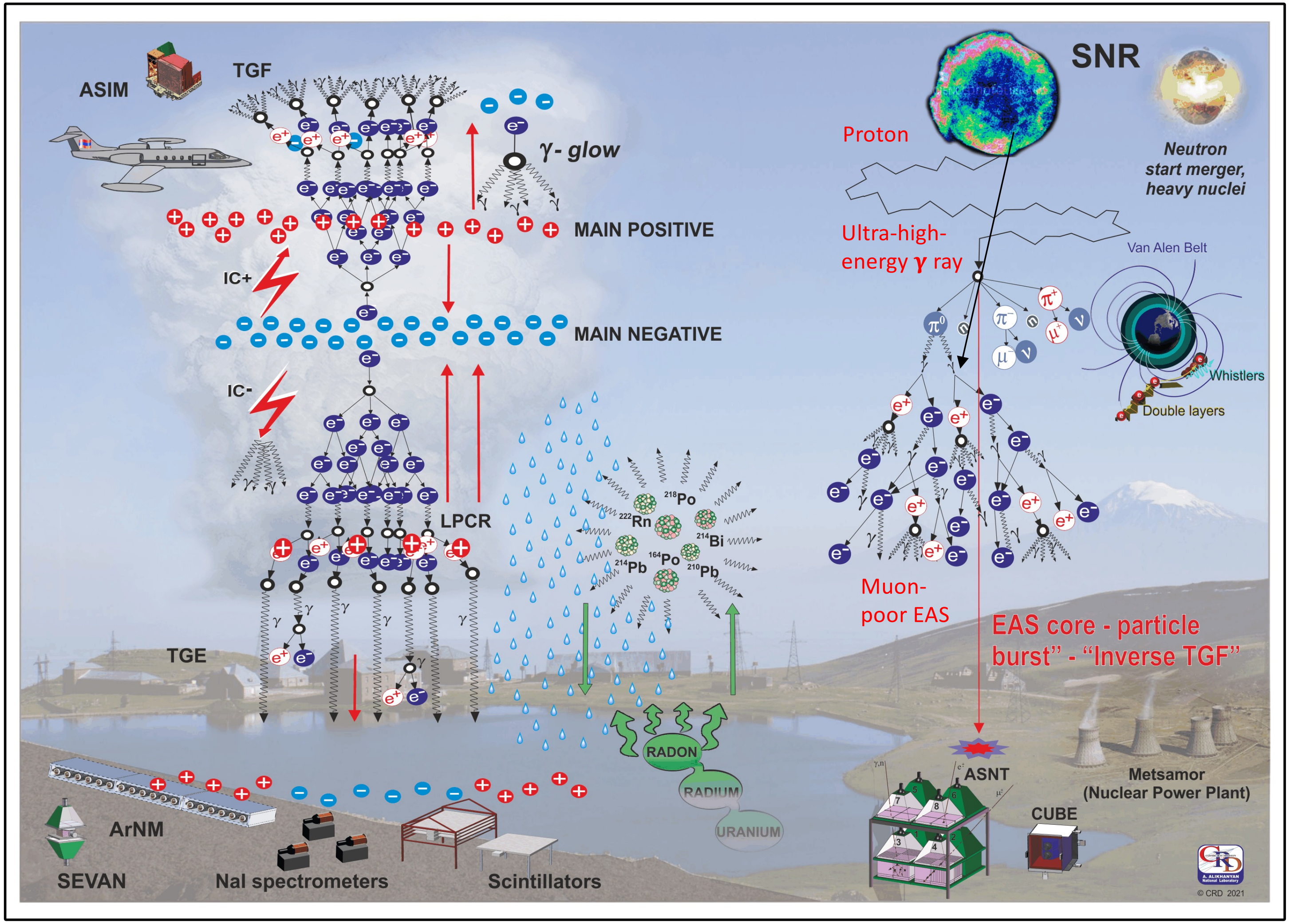
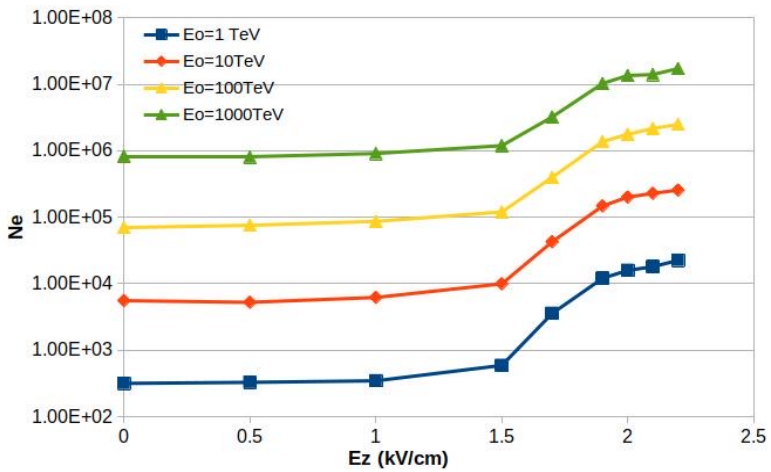
37 ВСЕРОССИЙСКАЯ КОНФЕРЕНЦИЯ ПО КОСМИЧЕСКИМ ЛУЧАМ

- Science goals and objectives
  - **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.**



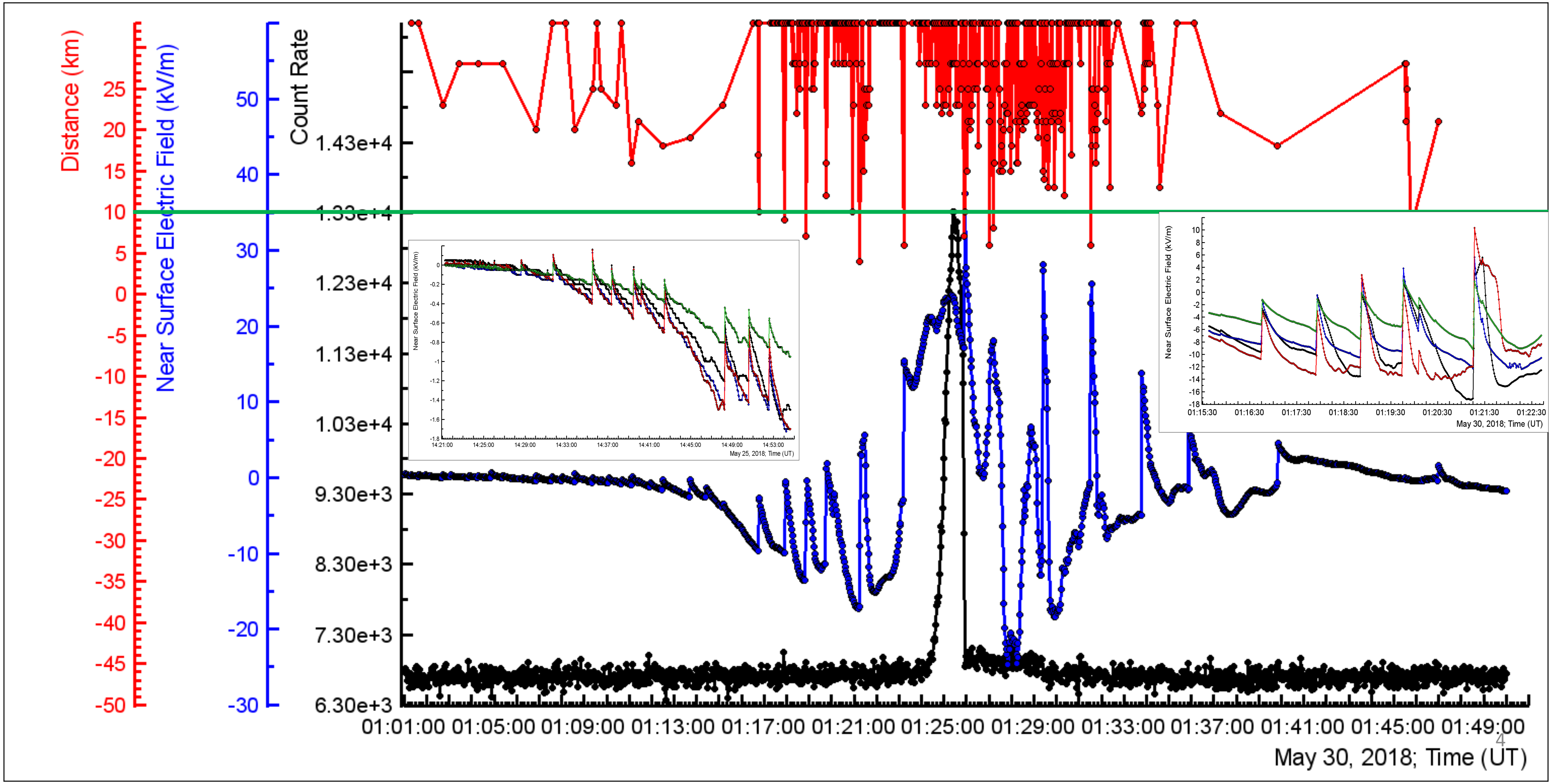
Aragats Cosmic Ray station: research of planetary, solar and galactic particle accelerators. Year-round operation from 1943. Coordinates: 40.47N, 44.18E, 3200m a.s.l. Located on highland near Kare lake in the vicinity of Aragats south peak ≈(3700m), the highest North peak is ≈4000 m.

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

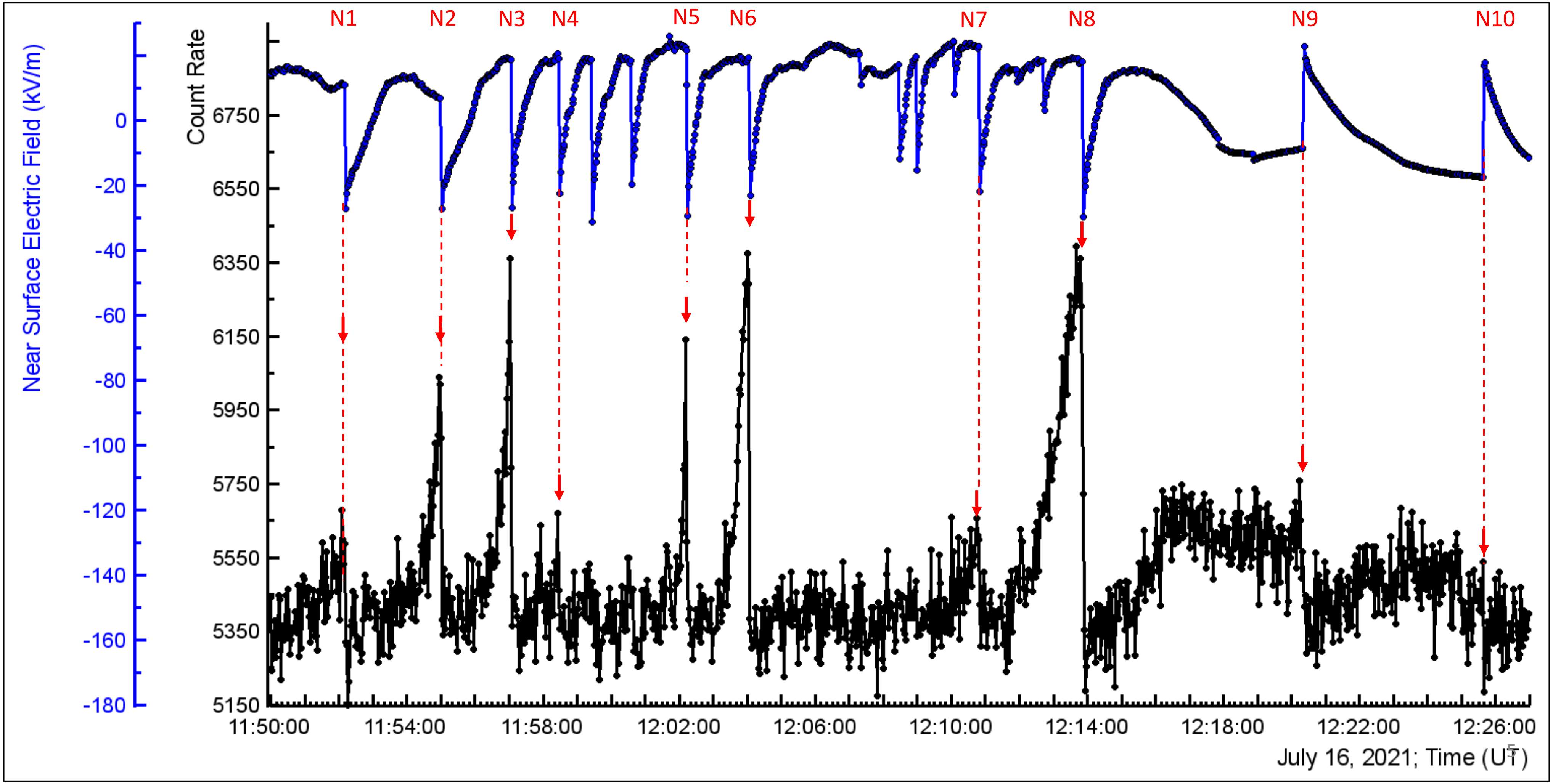


Eo (GeV)	Eest (GeV)
1.00E+03	2.23E+04
1.00E+04	1.34E+05
1.00E+05	6.50E+05
1.00E+06	2.42E+06

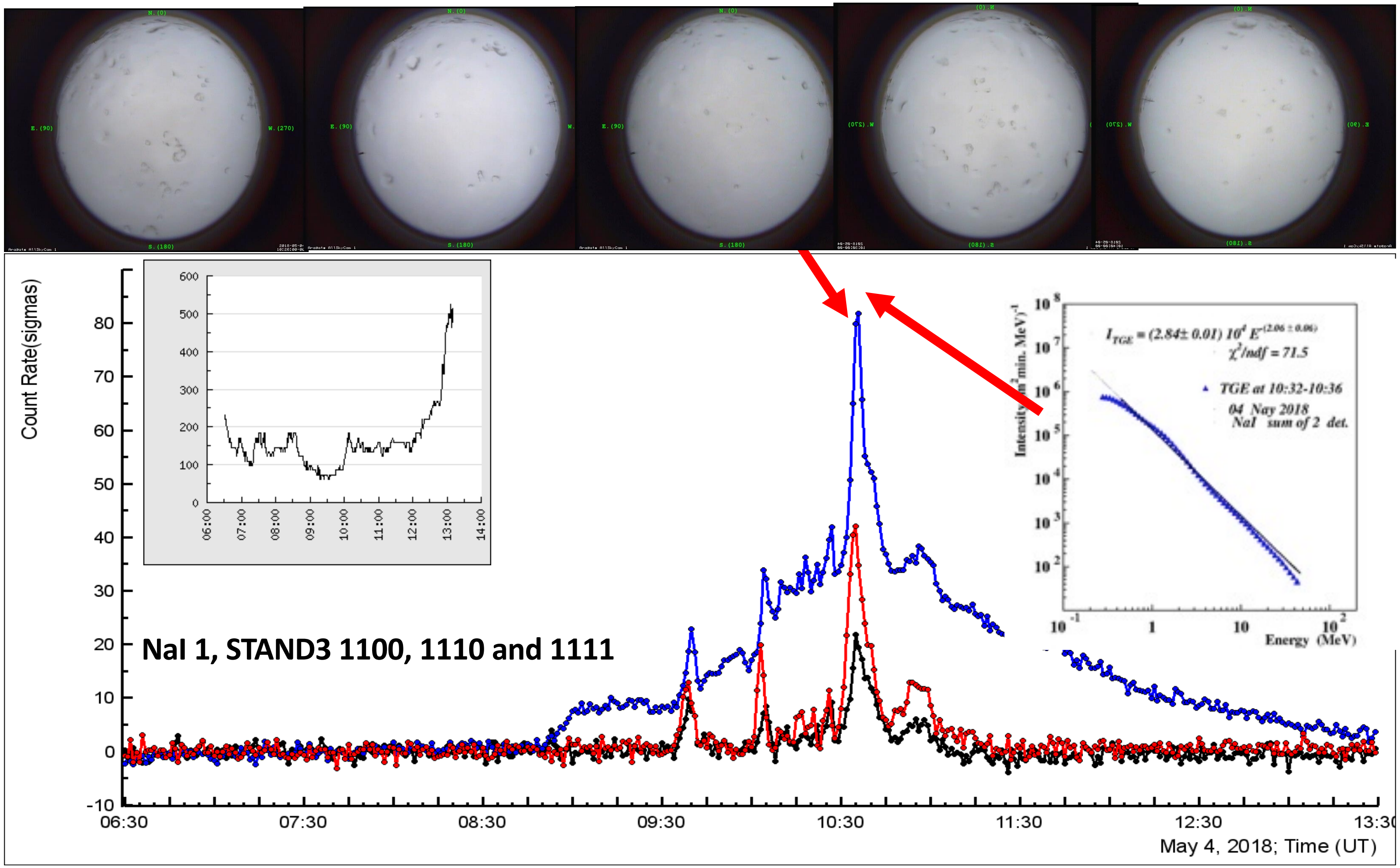
15 years of monitoring of Lightning location, Near-surface electric field (NSEF) and particle fluxes measured by multiple spectrometers…



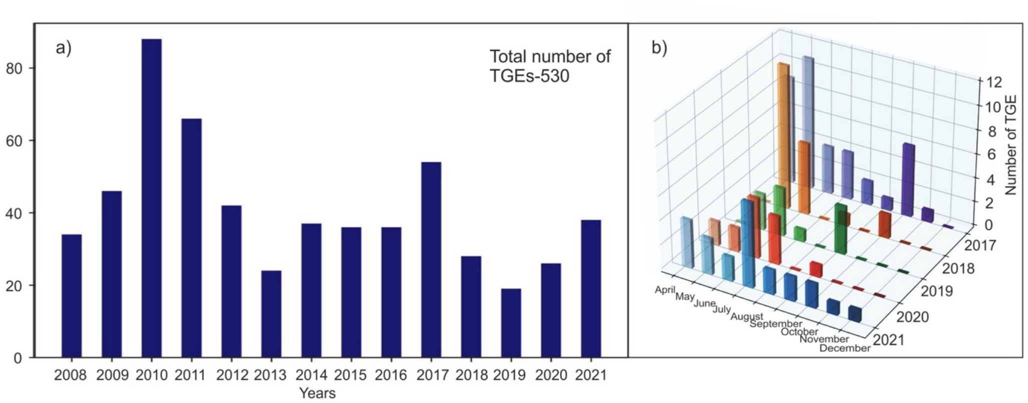
TGE terminations by nearby (distance <10 km) lightning flashes: NSEF disturbances and particle detector count rates



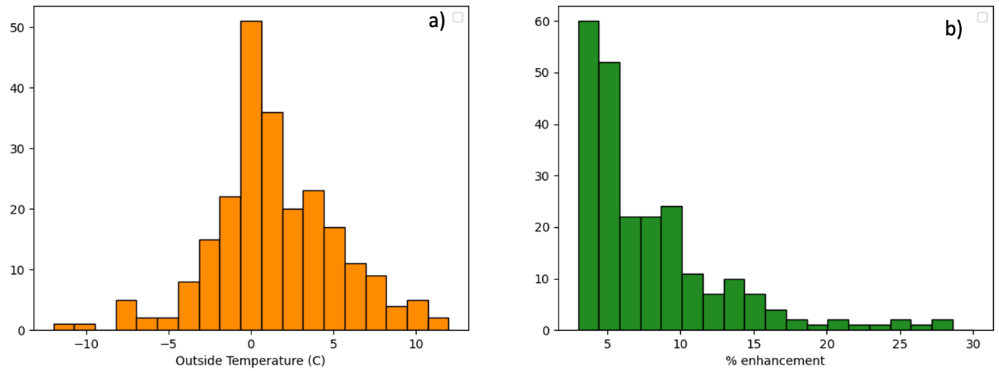
Long duration TGEs observed by spectrometers with low energy threshold (≈0.3 MeV). Radon progeny gamma radiation: mostly 214Pb and 214Bi: Radon isotopes circulation. Graupel detection.



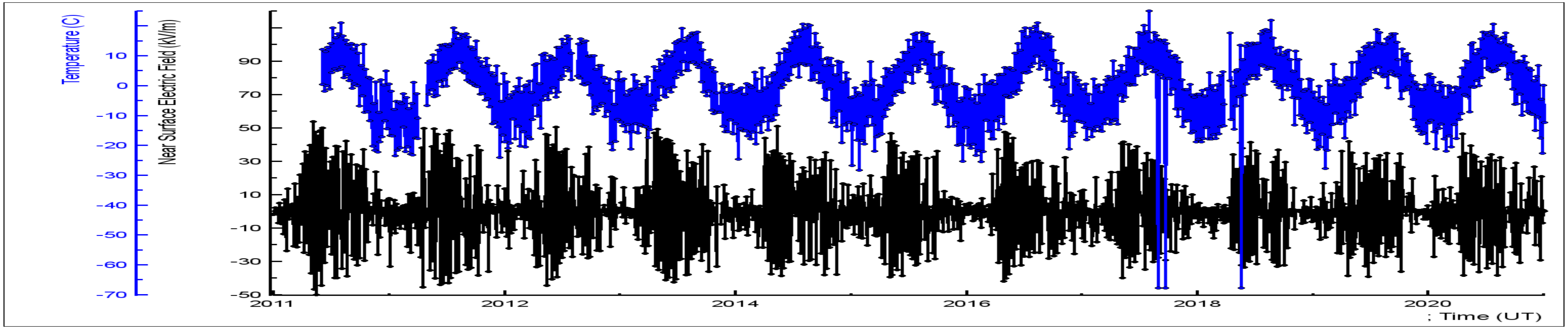
TGE statistics ≈550 TGEs registered in 2009-2021



TGE yearly and monthly statistics.

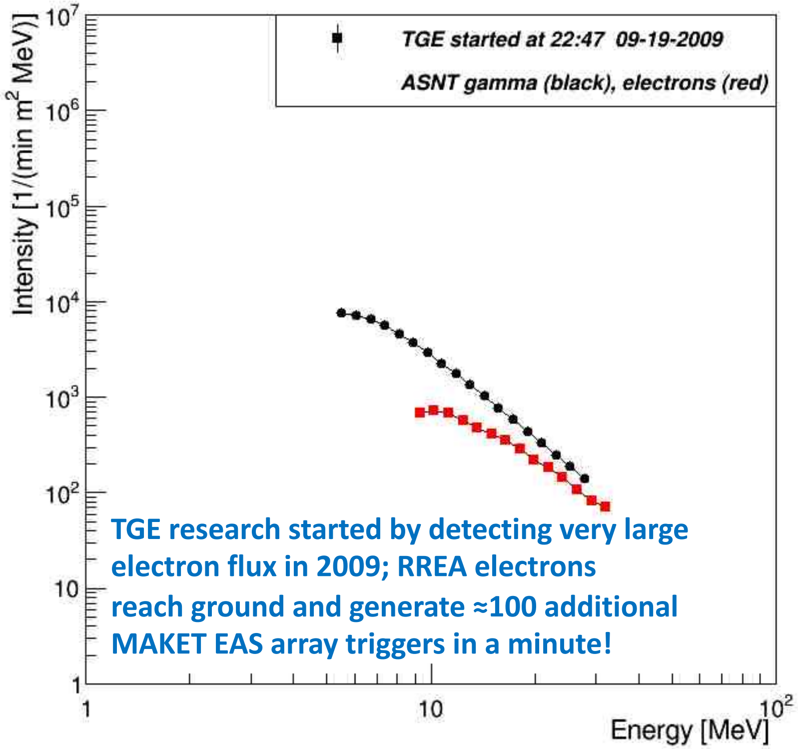


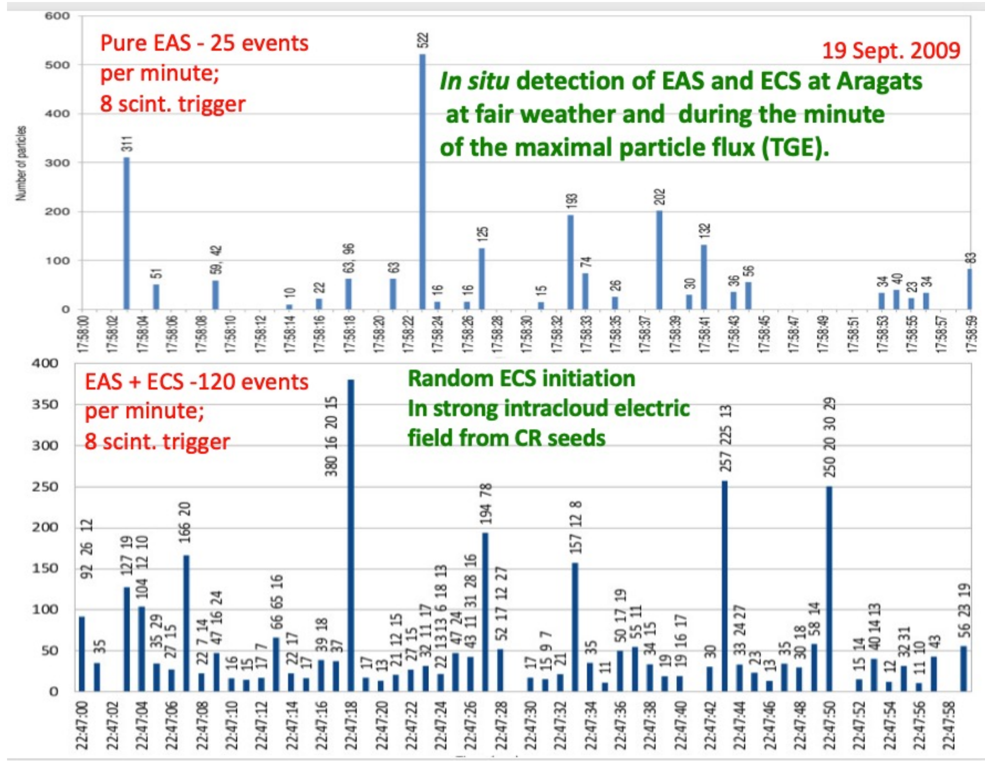
a)The distribution of outside temperatures during TGEs;
b) distribution of TGE significances by 3 cm thick plastic scintillator of STAND3 detector.



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

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

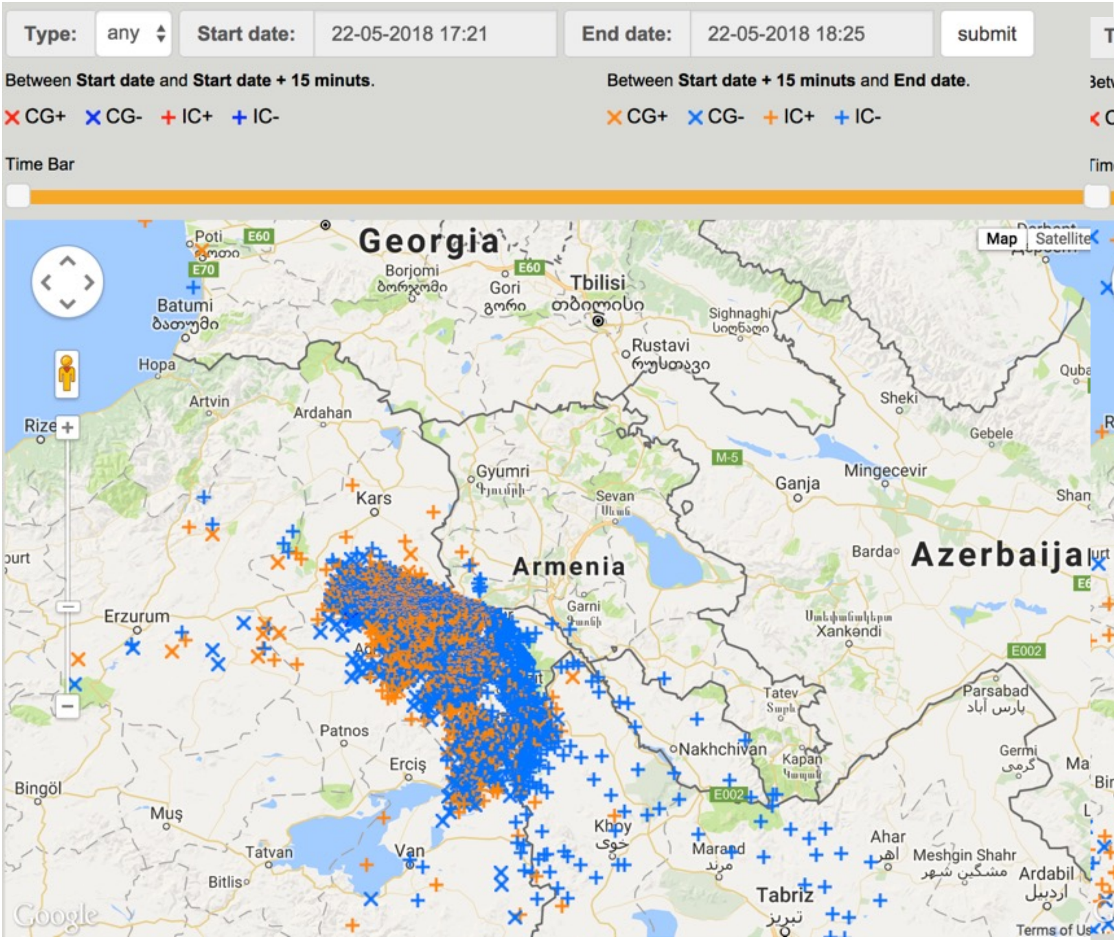


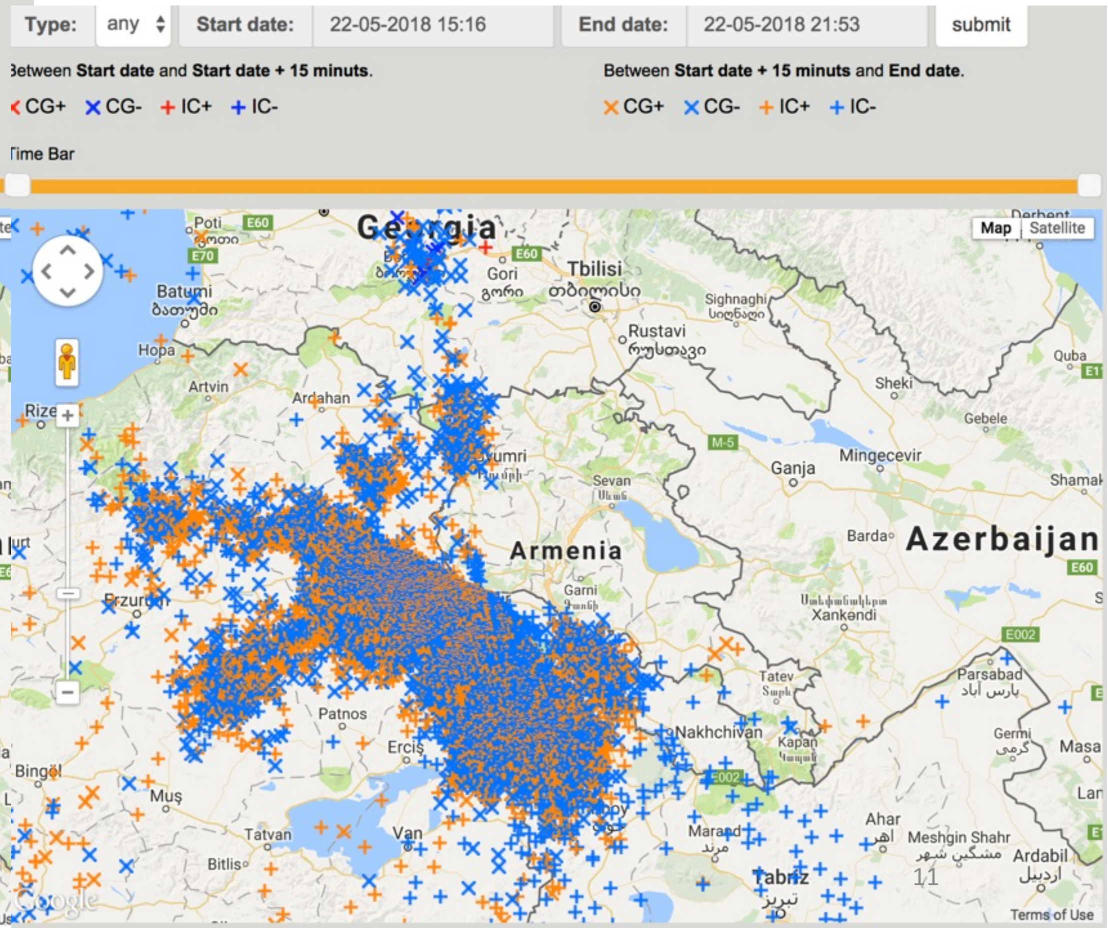



Kare lake nearby the station
and Sougth and Western peaks
of Aragats Mountain

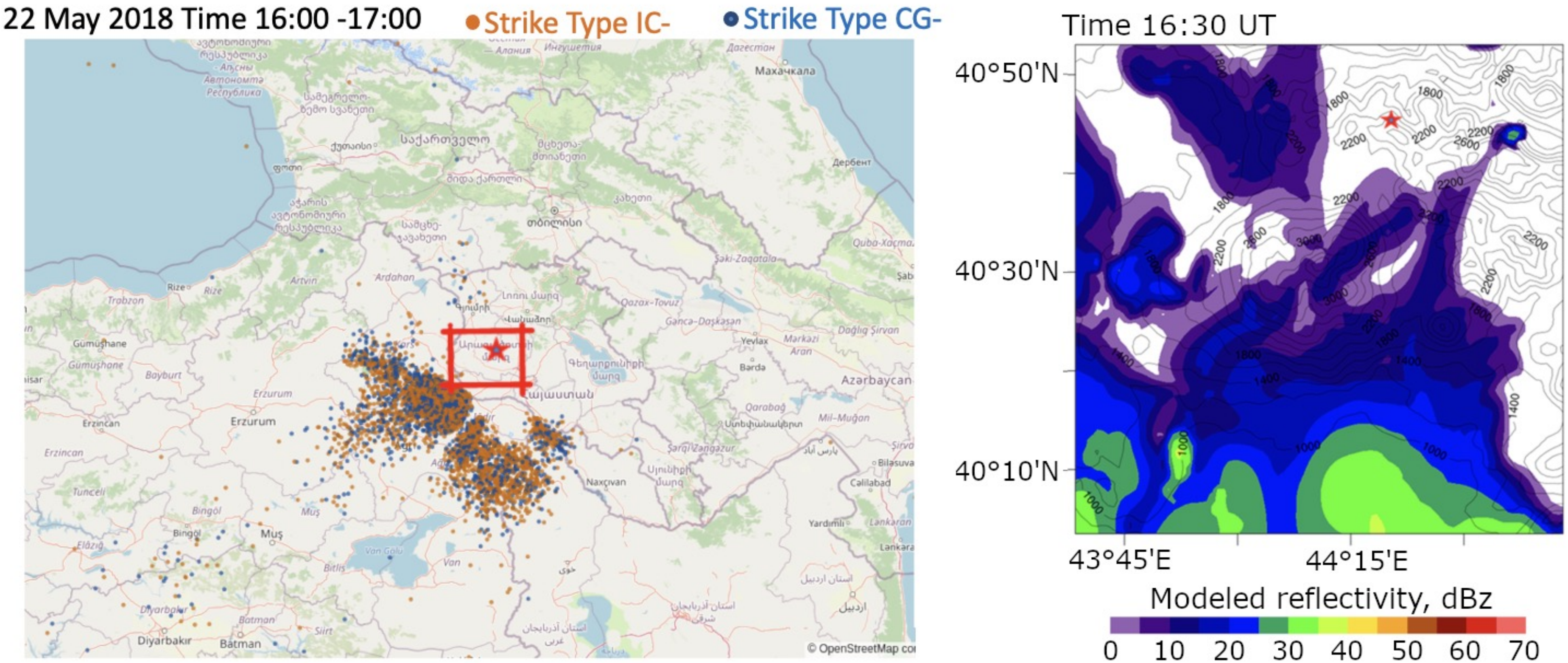

Thundeclouds above
Aragats highland

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





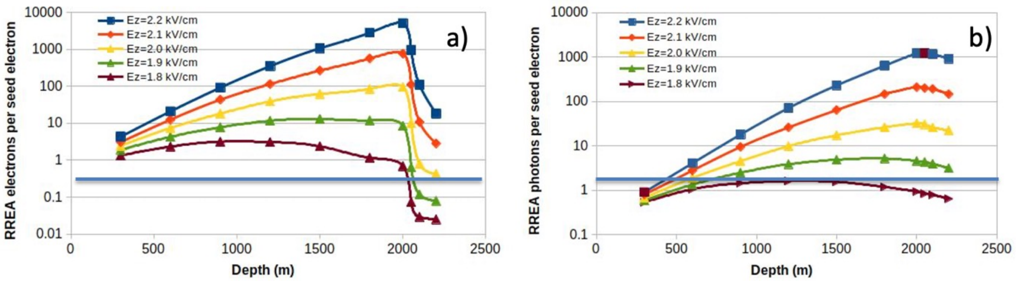
Aragats station on pherefery of a large thundestorm



Left: Projection of the thundercloud obtained by registering the lightning active zone with Boltek's storm tracker, 22 May 2018. The lightning type symbols and storm duration are shown in the upper panel, the Aragats research station location is shown by the red star, Red square mark the region in the the picture on the left. Right: the WRF modeled radar reflectivity.

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.



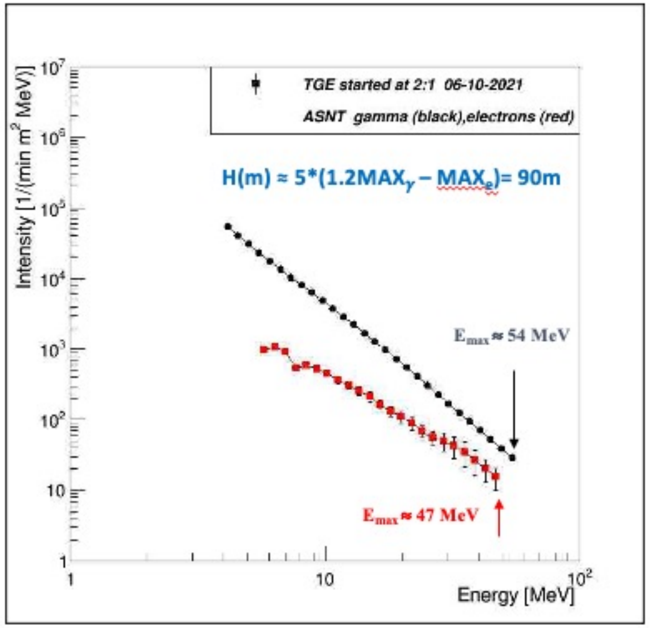
RRE avalanche in the atmosphere a) – electrons, b) gamma rays. Avalanche started at 5400 m a.s.l. (0 depth), that is 2200 m above the Aragats station. The number of avalanche particles is calculated each 300 m. After exiting from the electric field propagation of avalanche particles is followed additionally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

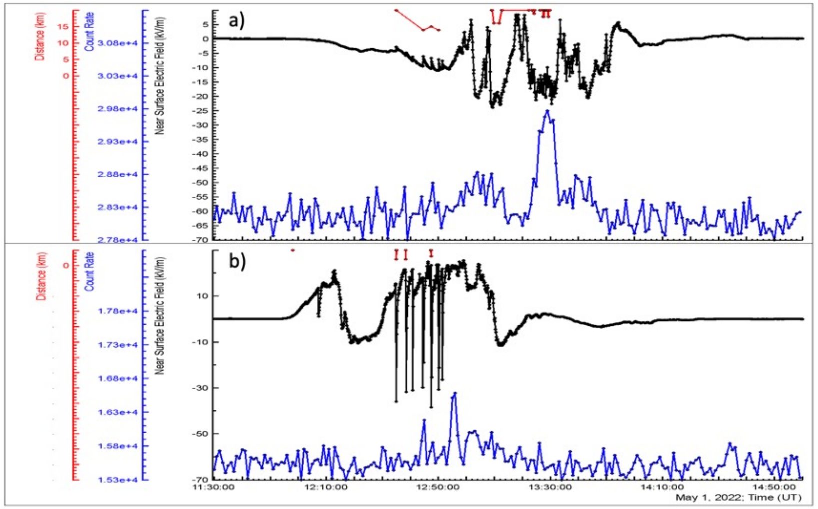
Distance from detector to the bottom edge of the field (m)	Expected gamma absorption (%) and electron ionization losses (MeV)
50	8.67
100	16.6
200	30.44
300	41.98
400	51.62
1000	83.7
10000	99.99999
50	8
100	16.1
200	32.1
300	48.23
400	64.3



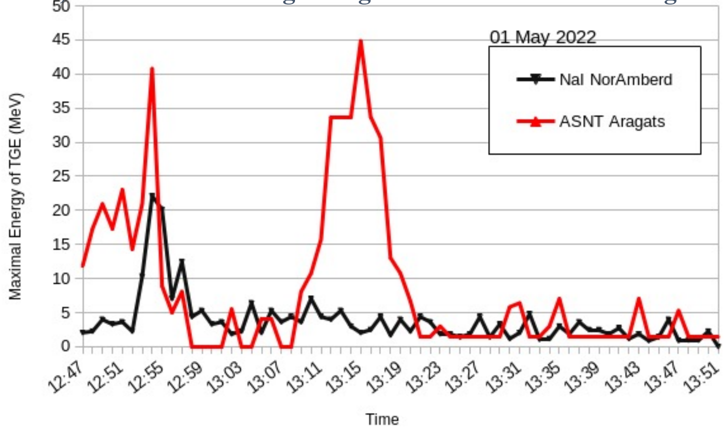
By comparing maximal energy of the recovered electron and gamma ray spectra we show that a strong accelerating field (≈2 kV/cm) can be very low above the earth's surface!

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.

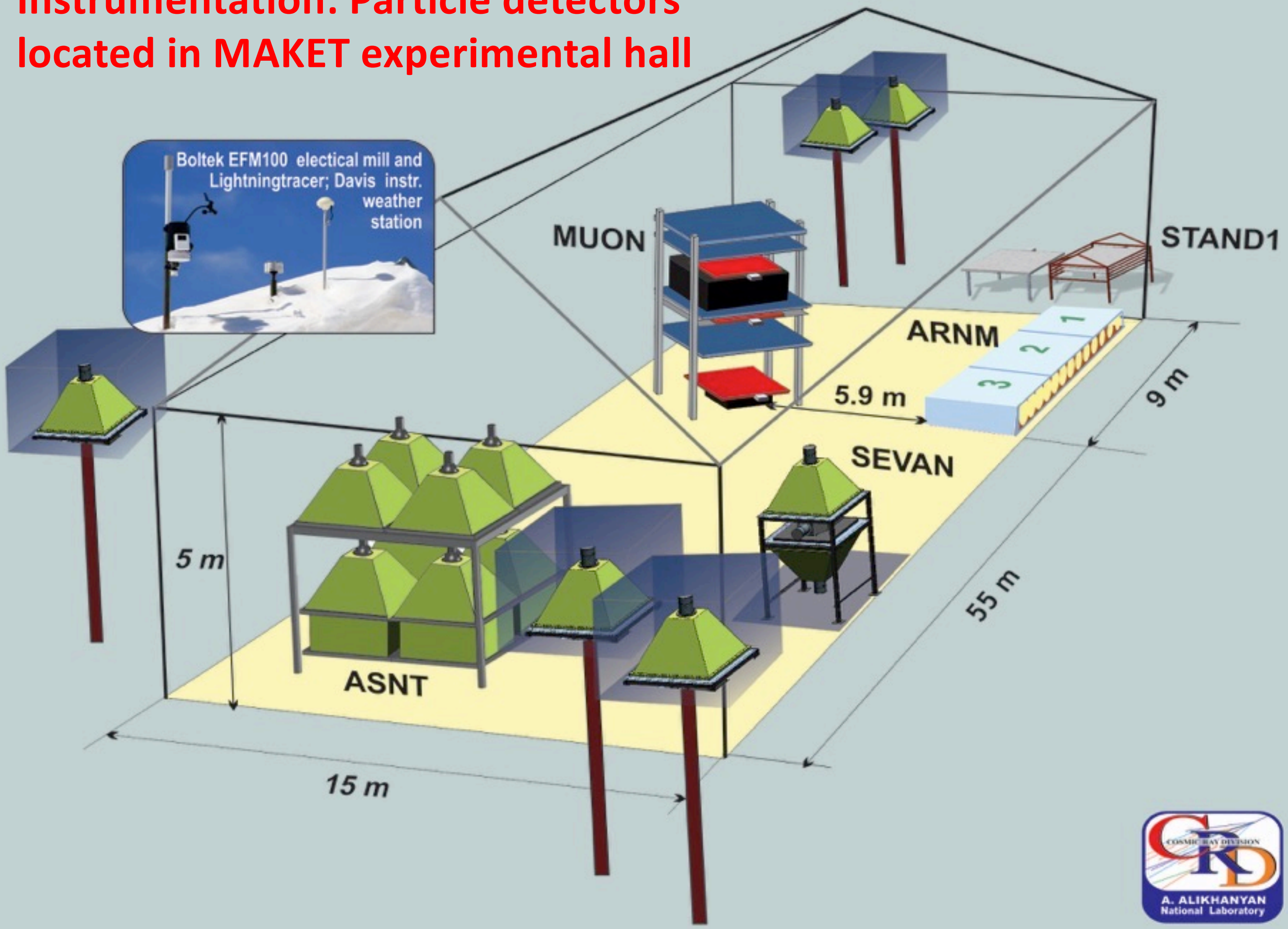


The disturbances of the NSEF; 1-minute count rates of 5 cm thick and 1 m^2 area plastic scintillators; and distances to lightning flashes measured on Aragats and in Nor Amberd

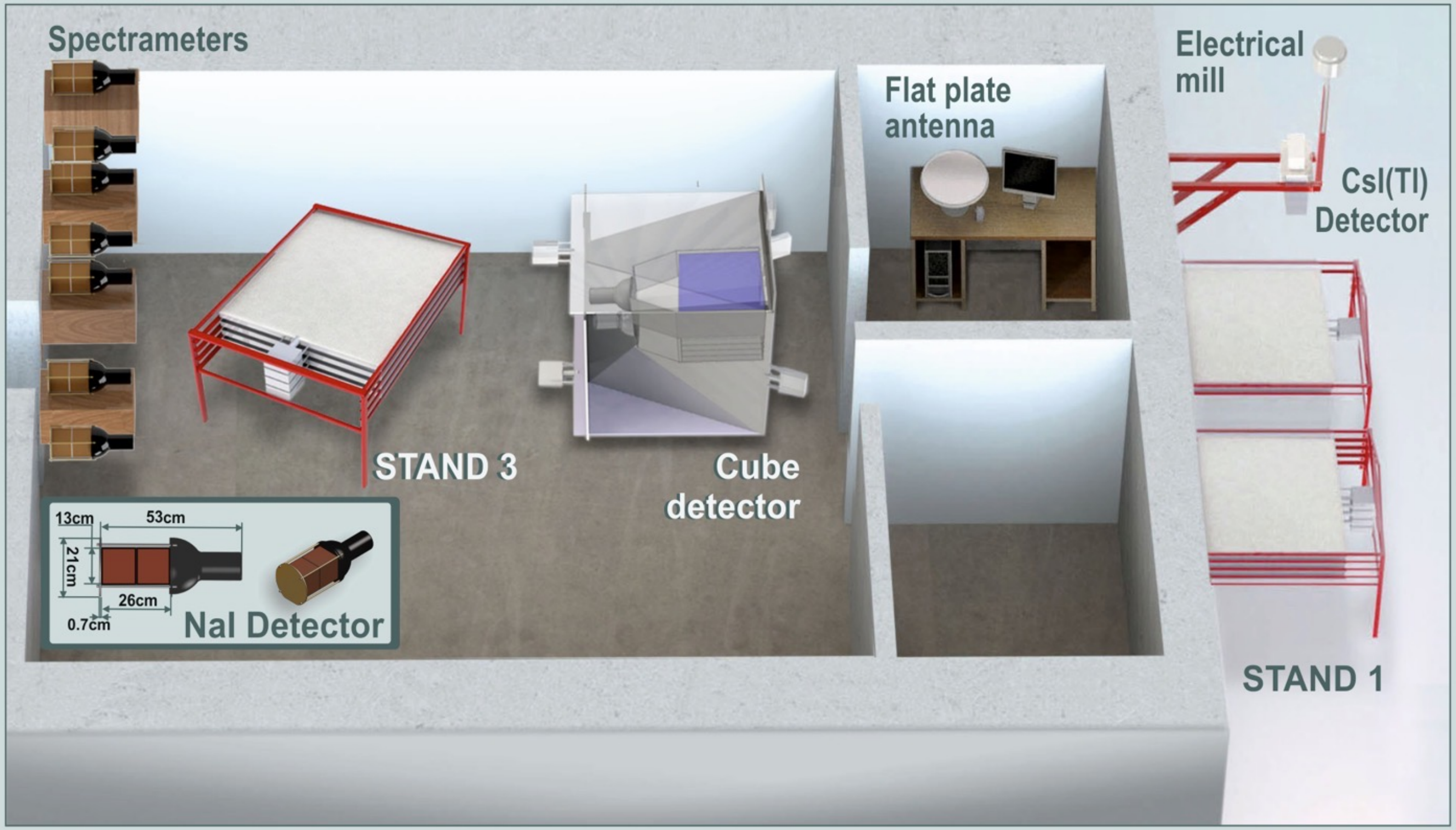


The histogram of maximum energies of energy spectra measured on Aragats with a large scintillation spectrometer ASNT, and in Nor Amberd by the NaI

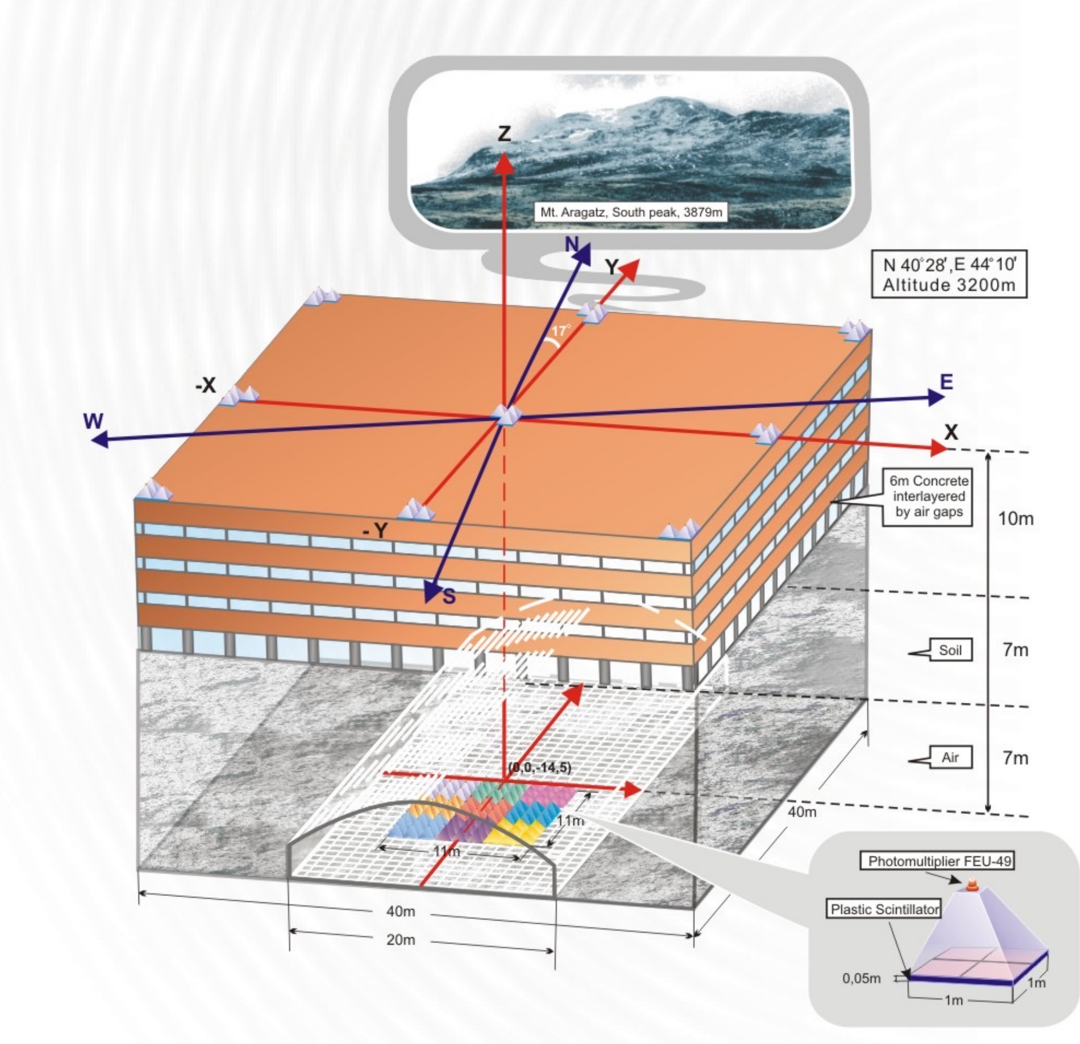
Instrumentation: Particle detectors located in MAKET experimental hall



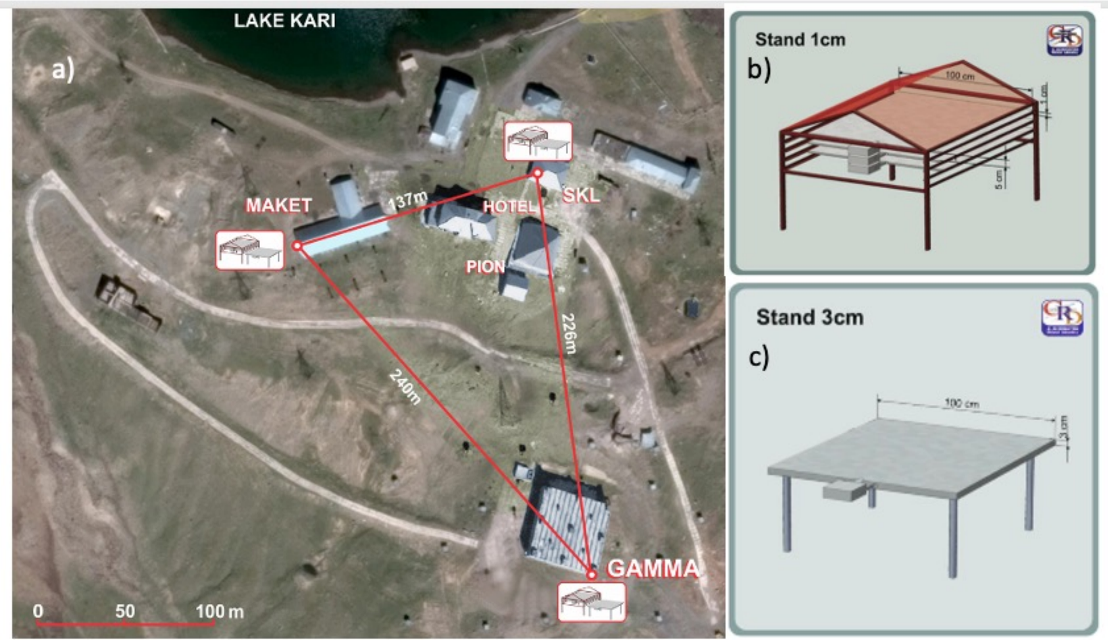
SKL EXperimental Hall



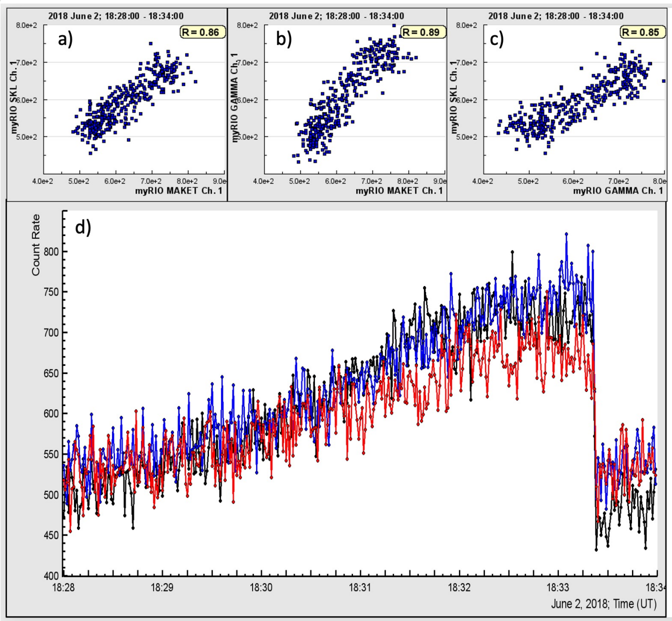
GAMMA experiment: 30 m^2 outside scintillators and 200 m^2 muon detectors (under 15 m of soil and concrete). 1s time series



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

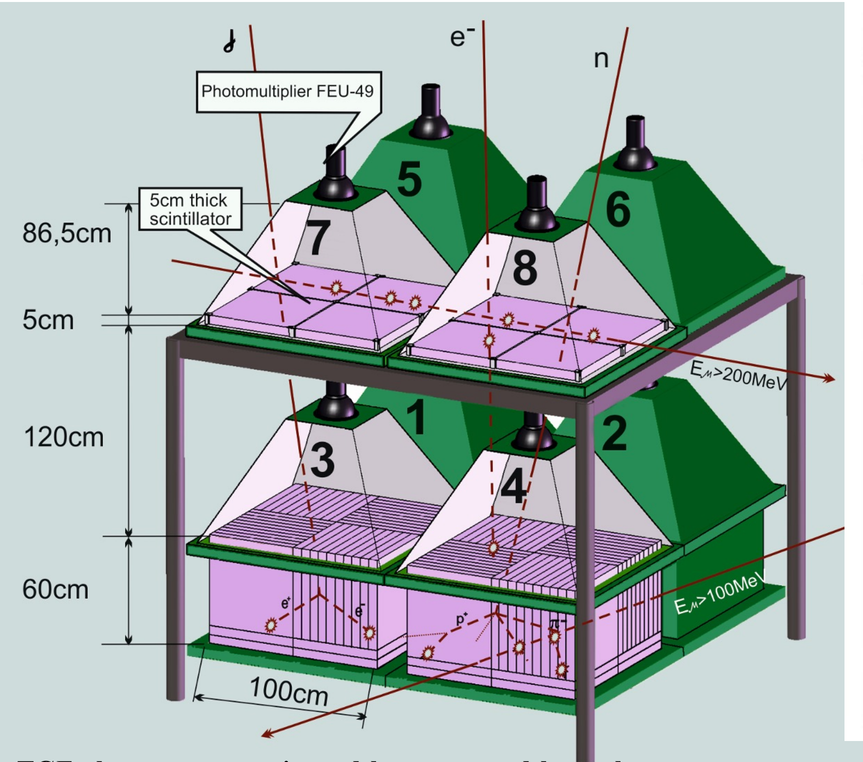


The map of Aragats station with STAND1 network; b) Stand1 unit: vertically stacked 1 cm thick, and 1 m^2 area plastic scintillators; c) Stand1 unit: stand-alone 3 cm thick plastic scintillator with the same area.



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.

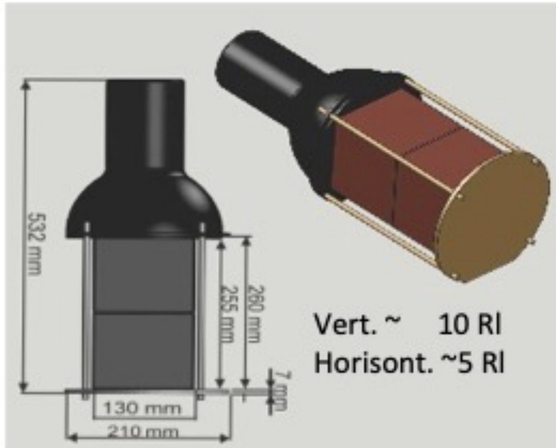
Aragats Solar Neutron Telescope (ASNT) and network of NaI(TL) spectrometers used for recovery of TGE electrons and gamma ray energy spectra



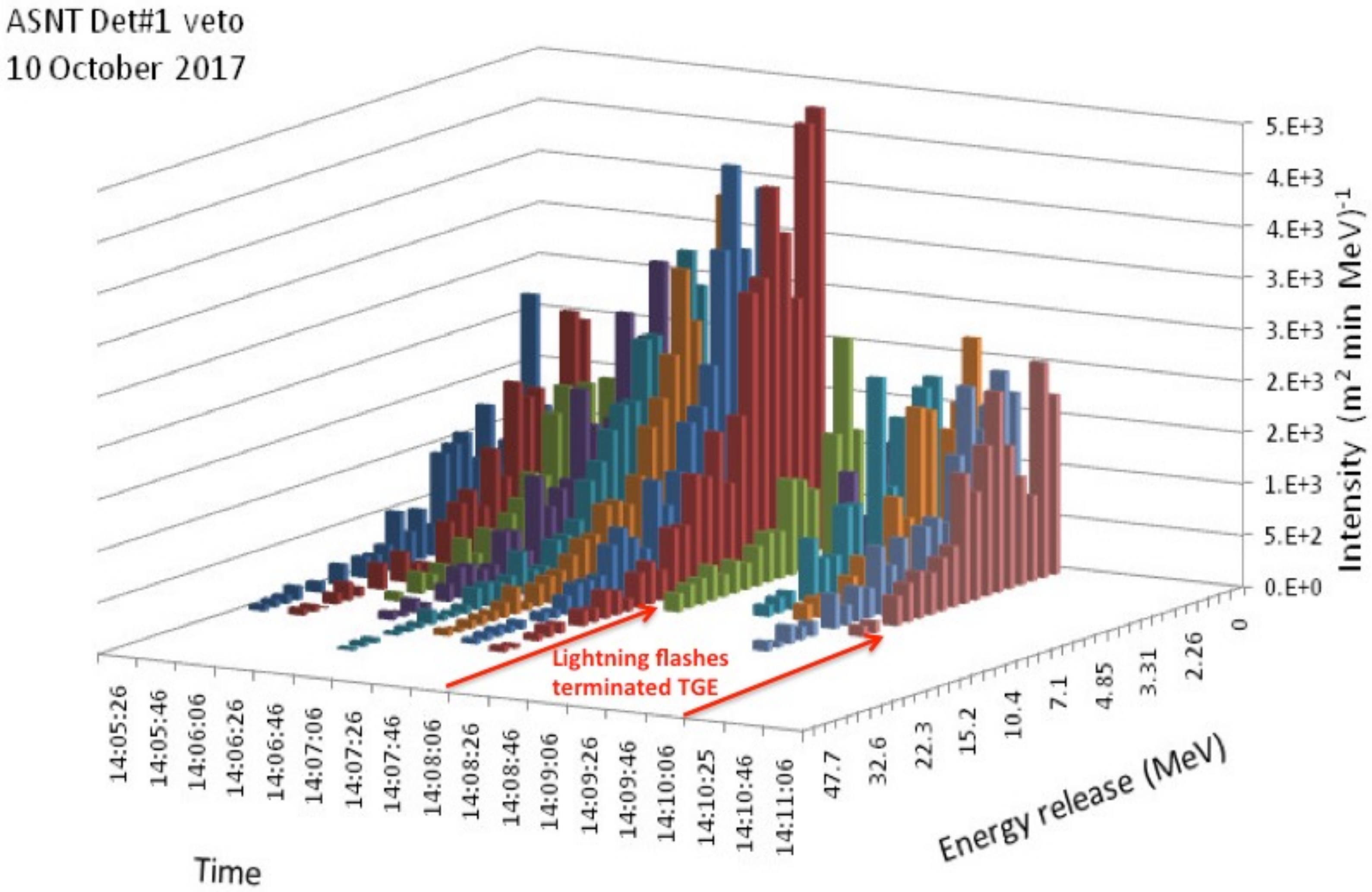
TGE electrons are registered by upper and lower layers; gamma rays and neutrons – by invoking the veto option (no signals from the upper scintillators), horizontal muons – by the condition of operation of 2 upper scintillators from 4 and no signal in the lower scintillators (to prevent registration of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

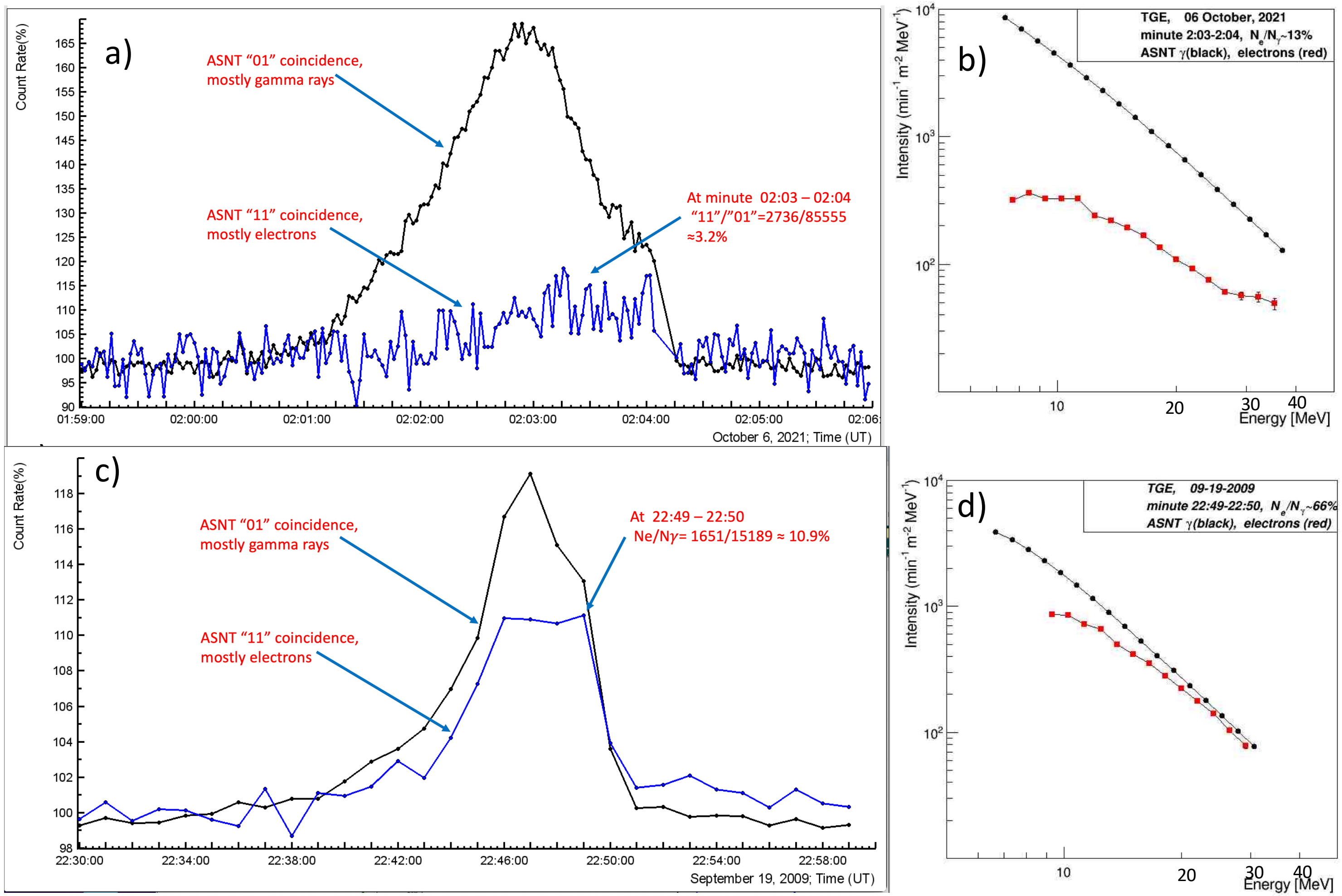
Material	Radiation length		Density
	g/cm2	cm	g/cm3
Polystyr. scint.	43.72	42.4	1.032
Cesium iodide (CzI)	8.39	1.85	4.53
Sodium iodide (NaI)	9.49	2.59	3.67

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.



The 20-sec energy release histograms measured by the 60-cm thick plastic scintillator of the ASNT detector. The lightning flashes shown by arrows abruptly terminate the high-energy particle flux.





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]

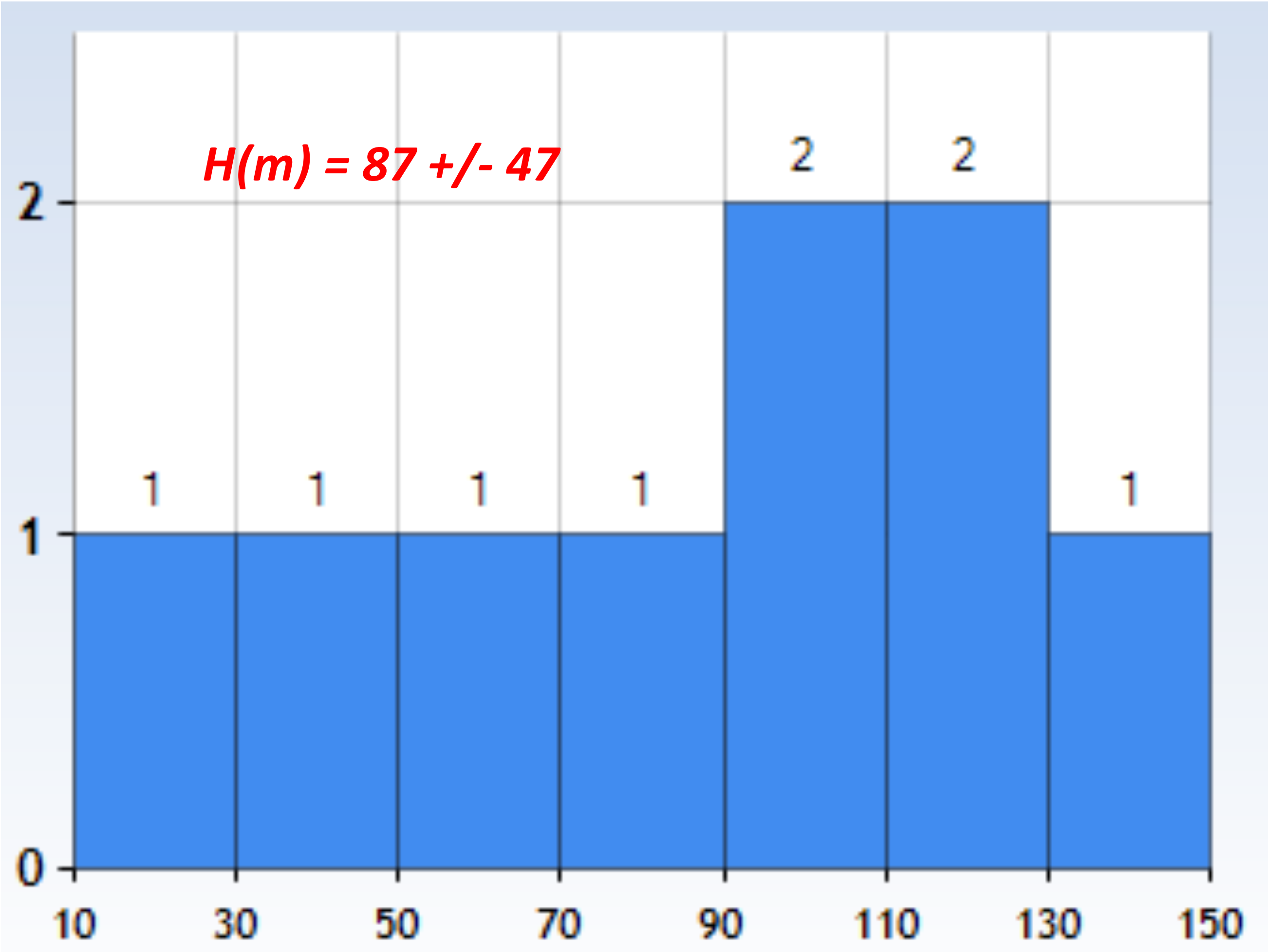
Parameters of Thunderstorm ground enhancements (TGEs) allowing recovering electron energy spectra (2019-2021)*. Selection criteria: Significance of peak enhancement – larger than 5%, Ne/Nγ > 0.06

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

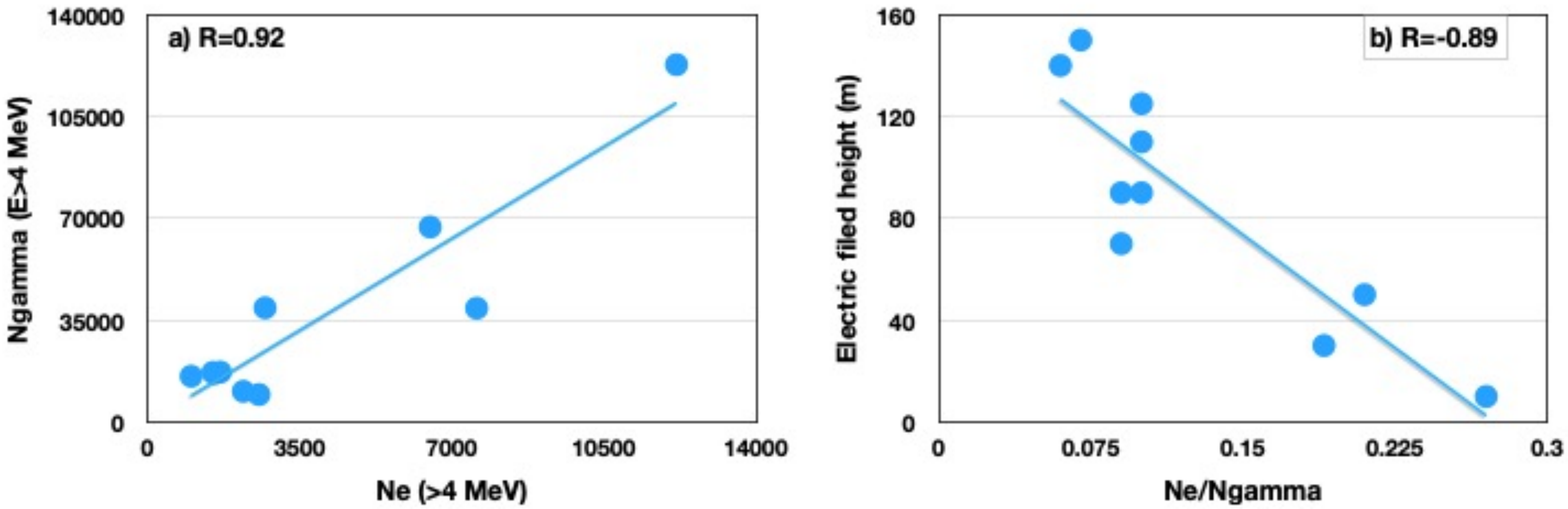
*Mendeley Data, V3, doi: 10.17632/tvbn6wdf85.3

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

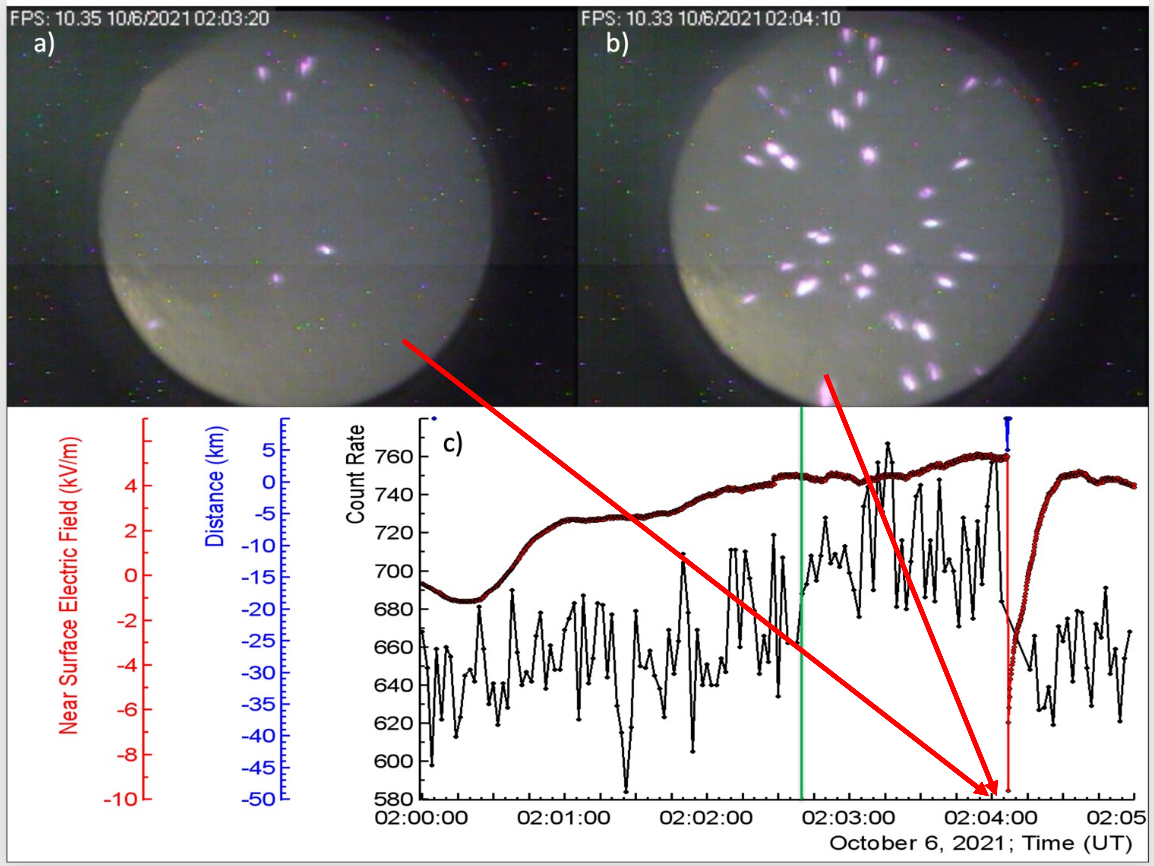
Height above ground where strong accelerated electric field terminated



Coherence of Ne - Nγ and Ne – H estimates: Larger Ne/Nγ - smaller the RREA path after going out from the strong accelerating electric filed



TGEs and TGFs are precursours of the lightning flash, and both are occompanied with optical emission: MeV particles do not originate in the lightning bolt, lightning flash abruptly terminate them!

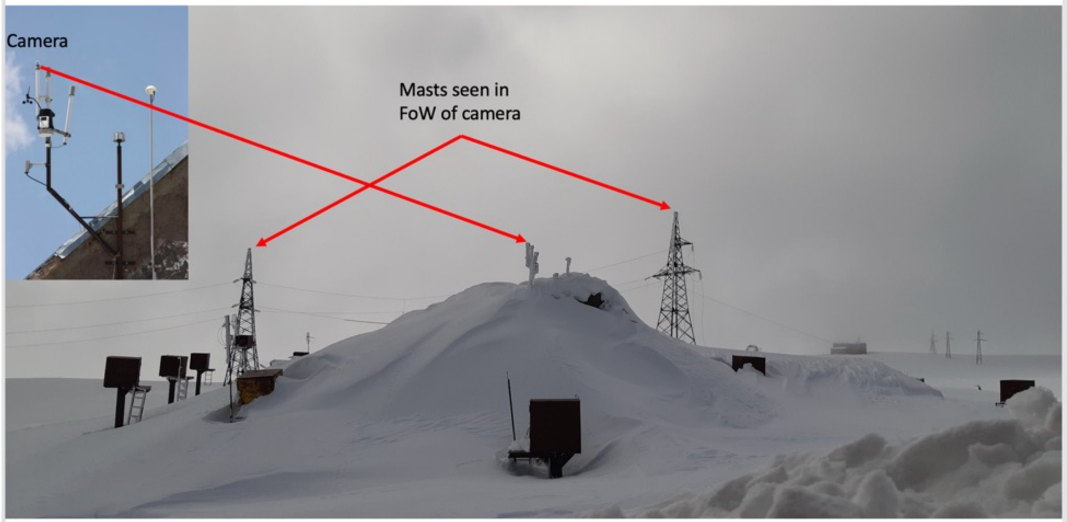


Lights were detected above research station at maximum electron flux denoted by black curve in c). By red curve is denoted the near surface electric field measured with frequency 20 Hz by EFM-100 sensor. The abrupt decrease of the electric field is due to the nearby lightning flash (1.8

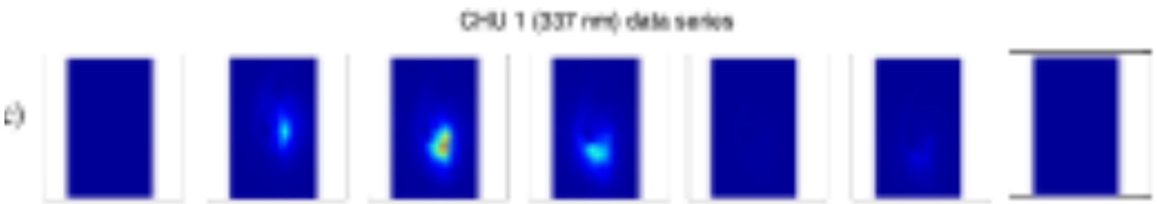
The Atmosphere-Space Interactions Monitor (**ASIM**), an ESA Earth observation facility on the outside of the space station used to study severe thunderstorms and their role in Earth's atmosphere and climate. ASIM data proves that TGFs form when powerful electric fields course through the atmosphere, just before a lightning bolt travels along the same path. **A weak pulse of light appeared, perhaps after electrically charged particles started moving along a conductive channel in the thunderstorm**. Then the TGF burst, spewing gamma rays everywhere. Within a few hundred microseconds, a huge pulse of electric current flowed along that same electrically charged path, making lightning.

Lindanger, et al. (2022) JGR: Atmospheres, 127, e2021JD036305

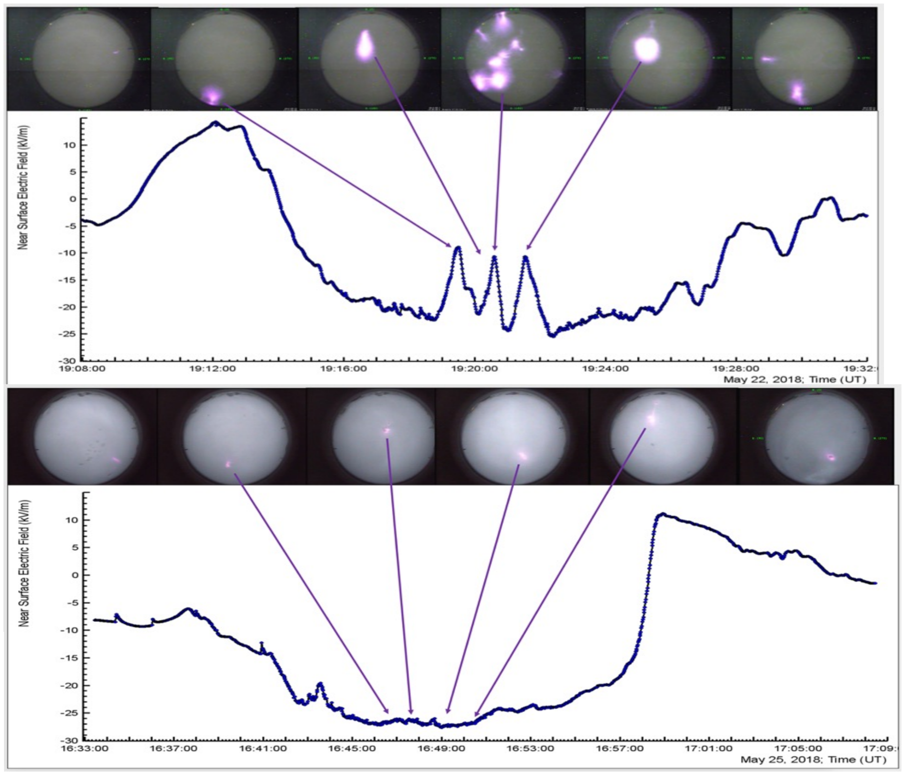
Optical emissions during TGE (Aragats) and TGF (ASIM)



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.

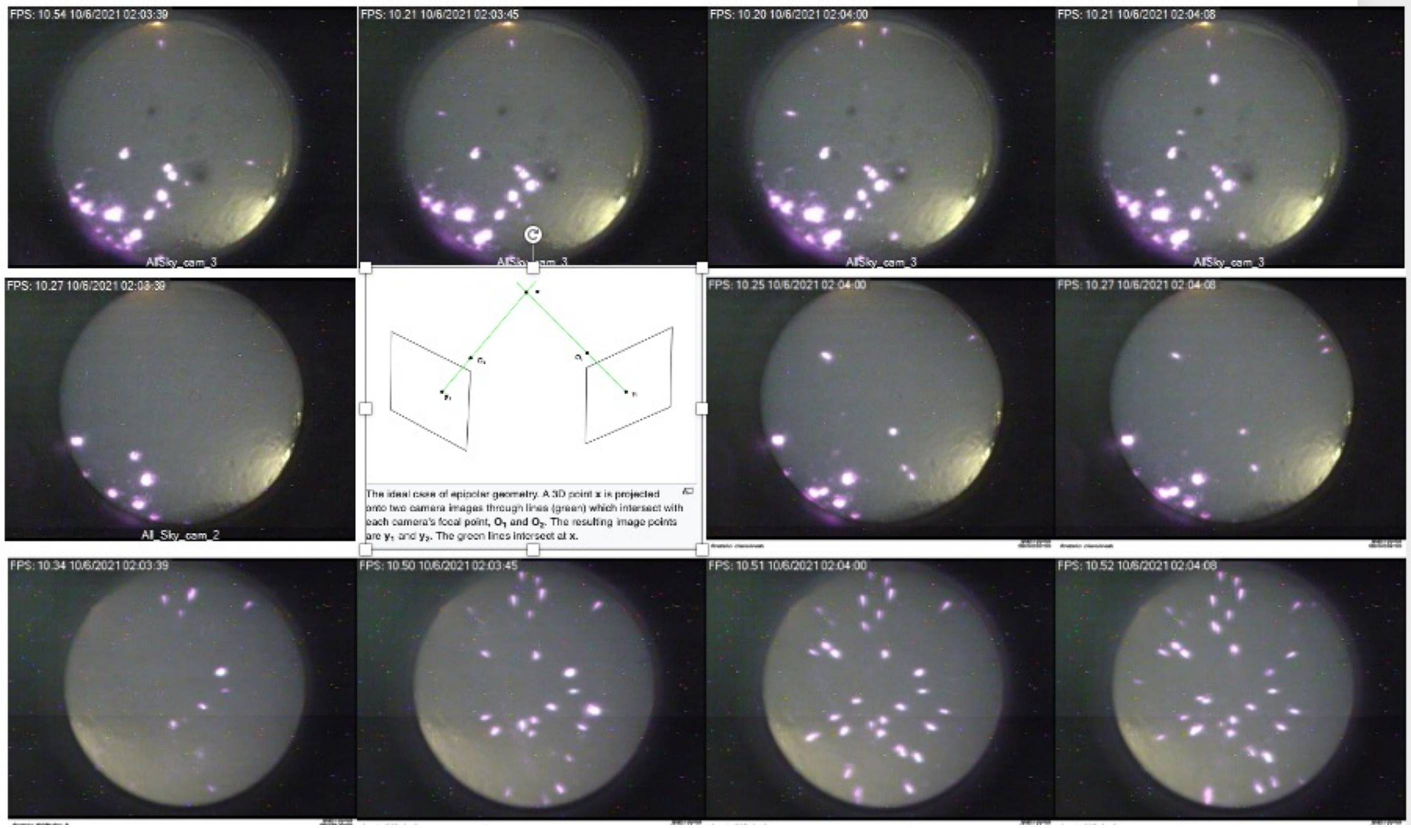


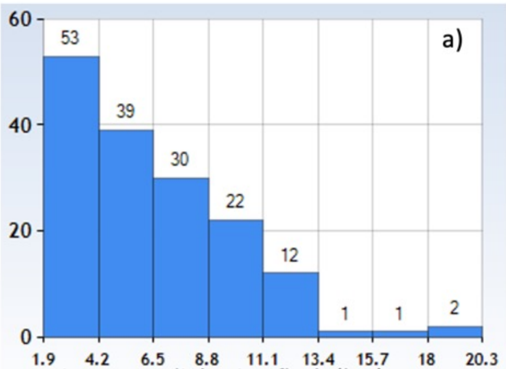
ASIM detection of TGFs, optical emission, and lightning flashes. The 337 nm photometer data with ADC units on the *y*-axis. The lights appear after TGF start and before the lightning flash



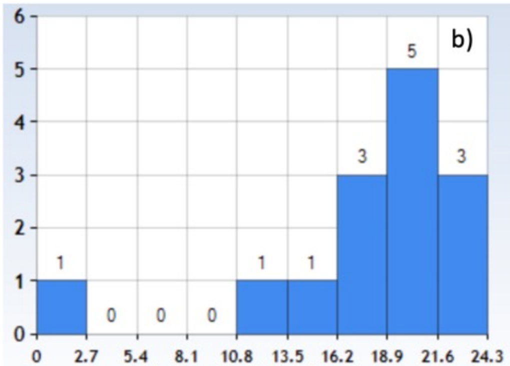
The disturbances of the NSEF during TGE, measured by an EFM-100. In the upper panel, w show the panoramic camera shots of the sky above the station; by a violet arrow, we indic the times when panoramic shots were done.

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?

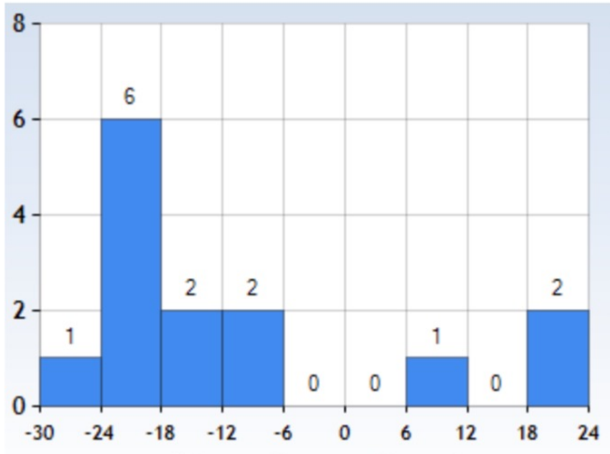




Distance to lightning flash (km).
(130 TGEs terminated by lightning flash)



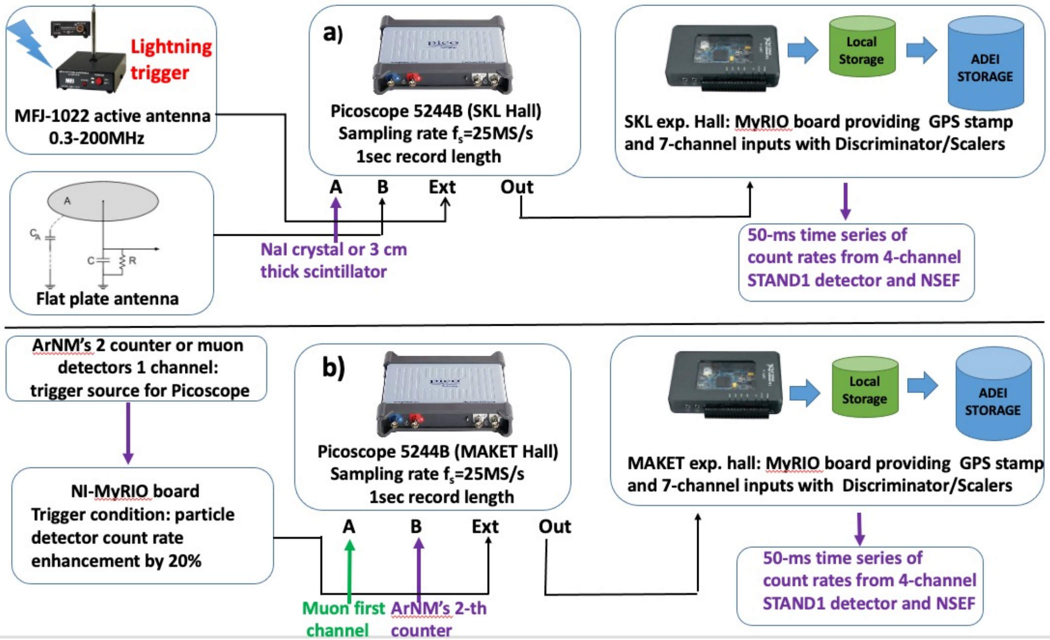
Distance to lightning flash (km).
(14 TGEs accompanied with light glows)



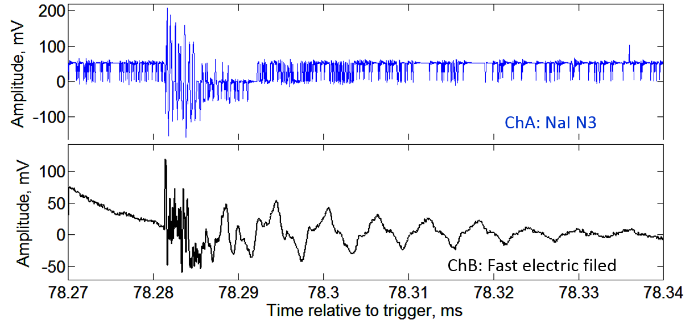
Near-surface electric field (kV/m)

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.

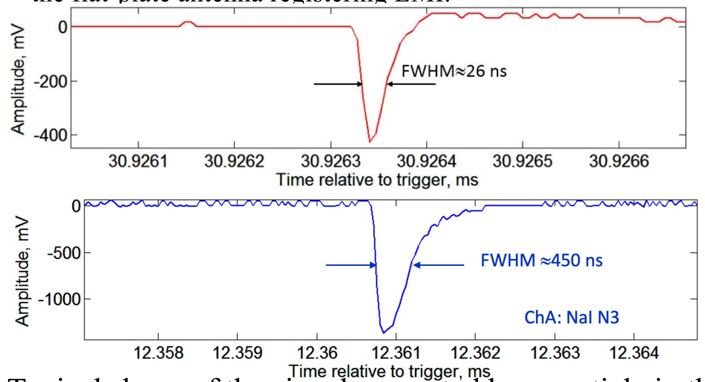
Particles do not originate in the lightning bolt: TGEs and TGFs are precoursors of lightning flashes!



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).

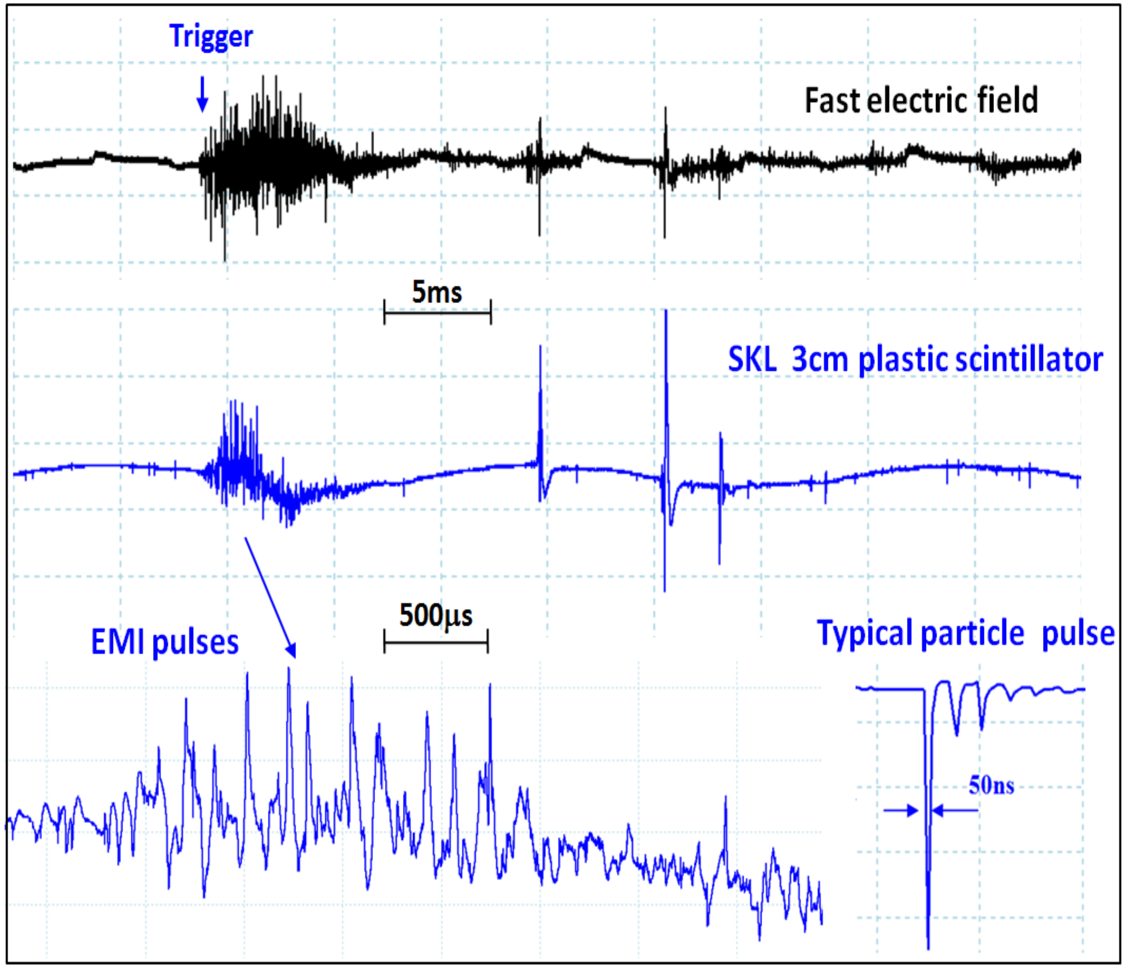


40-ns time series of NaI spectrometer, and the signals from the flat-plate antenna registering EMI.



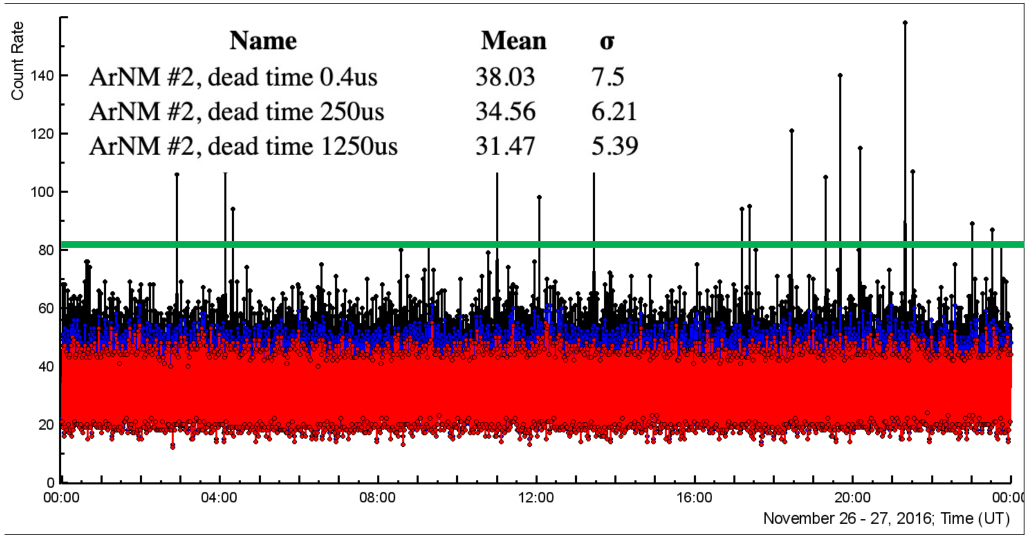
Typical shape of the signal generated by a particle in the large NaI crystal (12 x 12 x 24 cm) and in 1-cm scintillator.

Lightning flashes do not produce MeV particles, they terminate enhanced particle fluxes (TGEs).

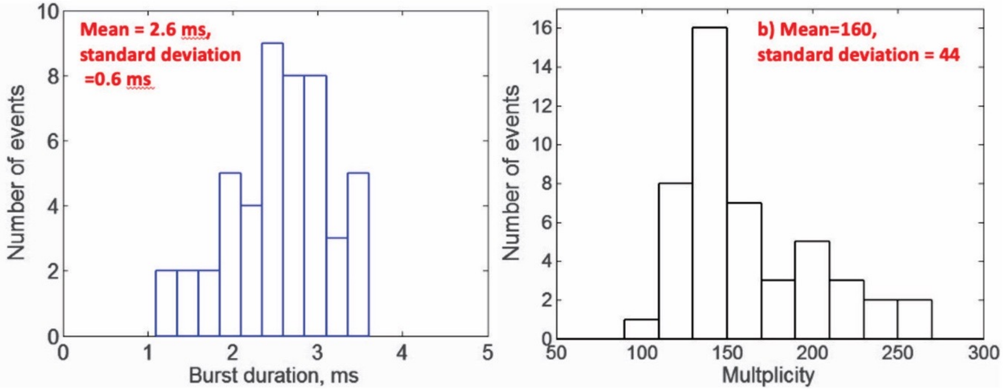


Typical EMI signature from atmospheric discharges in the particle detector waveform. Synchronized time-series of the pulses of fast electric field and signals from plastic scintillator. SKL trigger occurred at 14:32:34.205

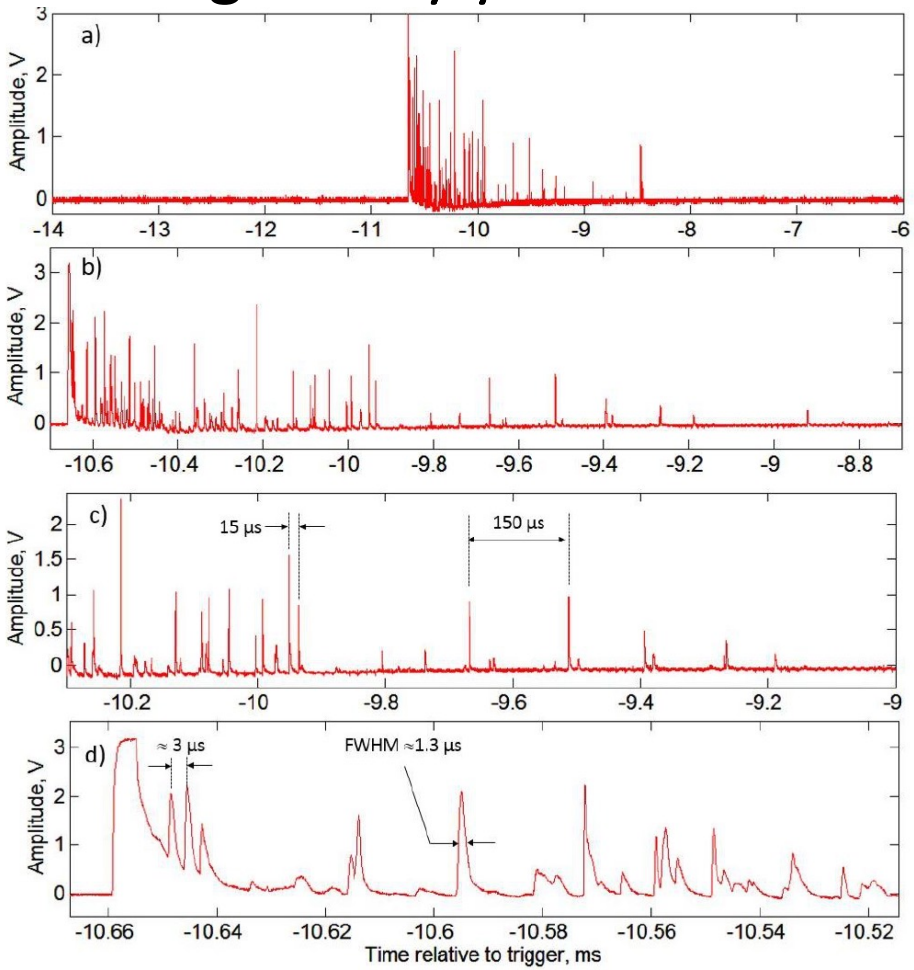
Inverse TGFs – are EAS core particles interacting in soil or lead of neutron monitor: ≈20 signals above 5 sigma dayly!



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.

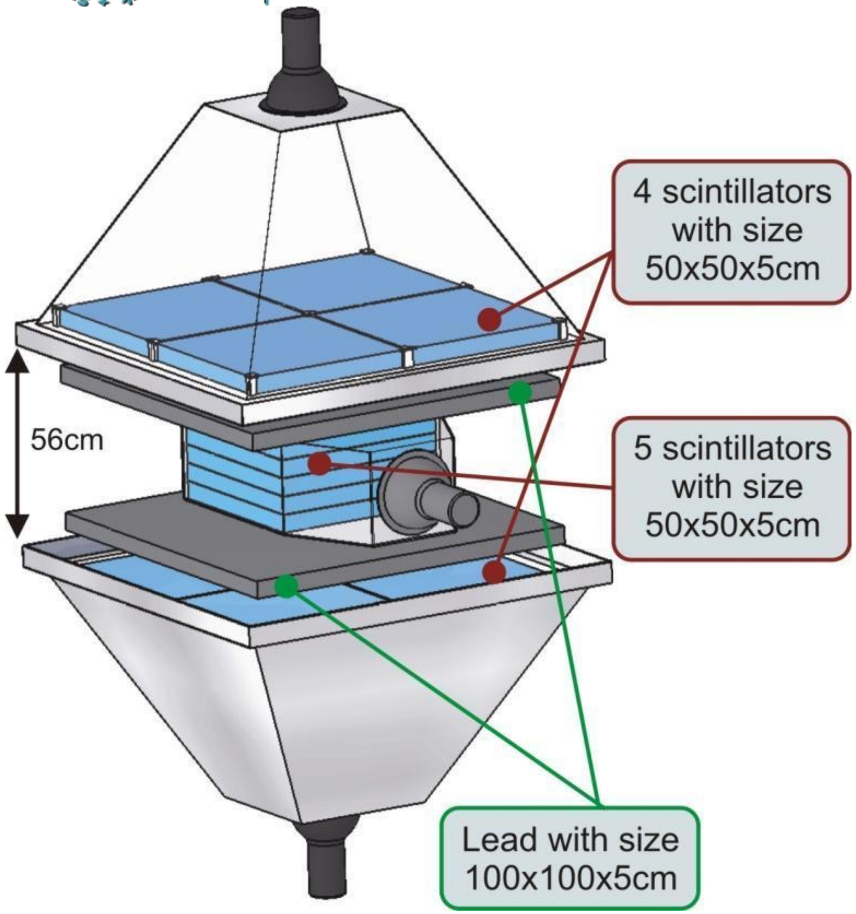


Neutron burst duration (a) and corresponding multiplicity histogram (b).



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.

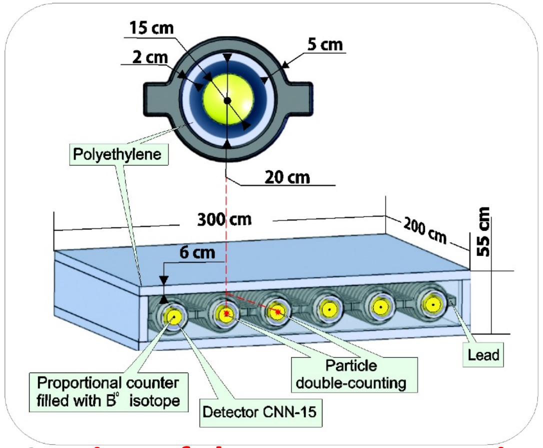
SEVAN basic unit: monitoring 3 species of secondary CR



100 – low energy charged particle;

010 – neutral particle (gamma ray or neutron;

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

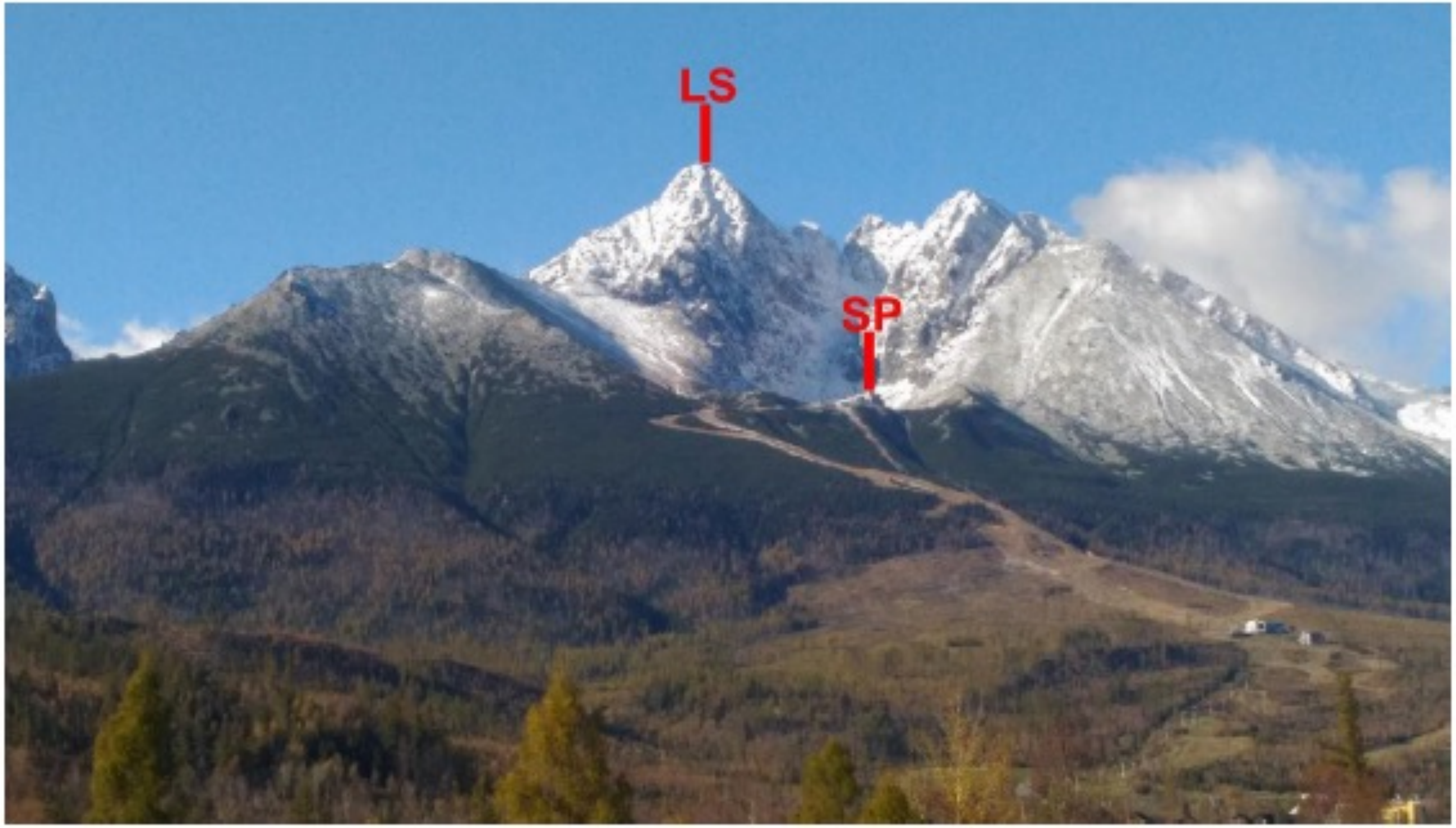


Section of the Neutron Monitor

MUSALA Latitude - 42º11’N, 23º35’ E

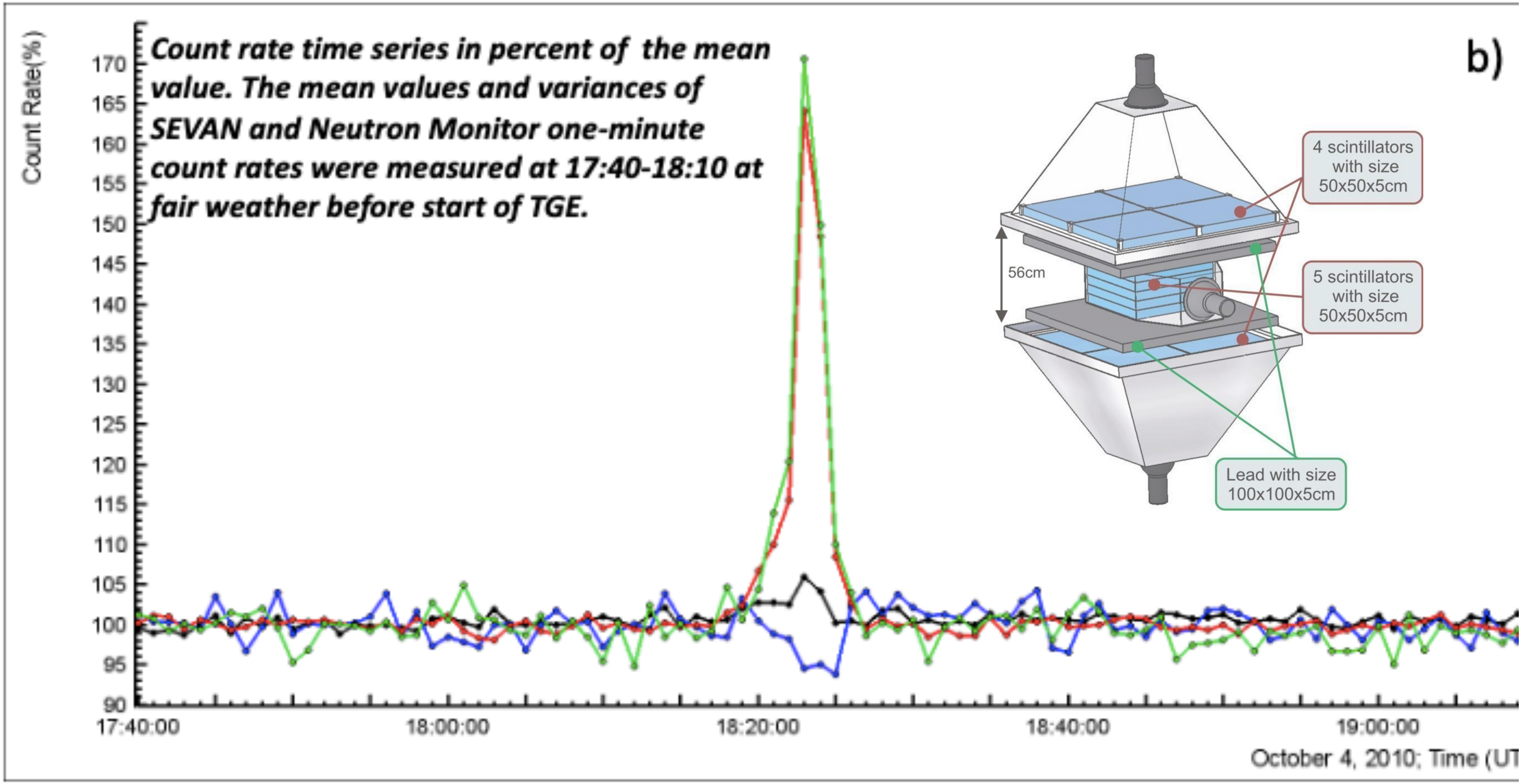
2925 m,

Lomnický štít (LS) 49.1952 N 20.2131 E 2634 m

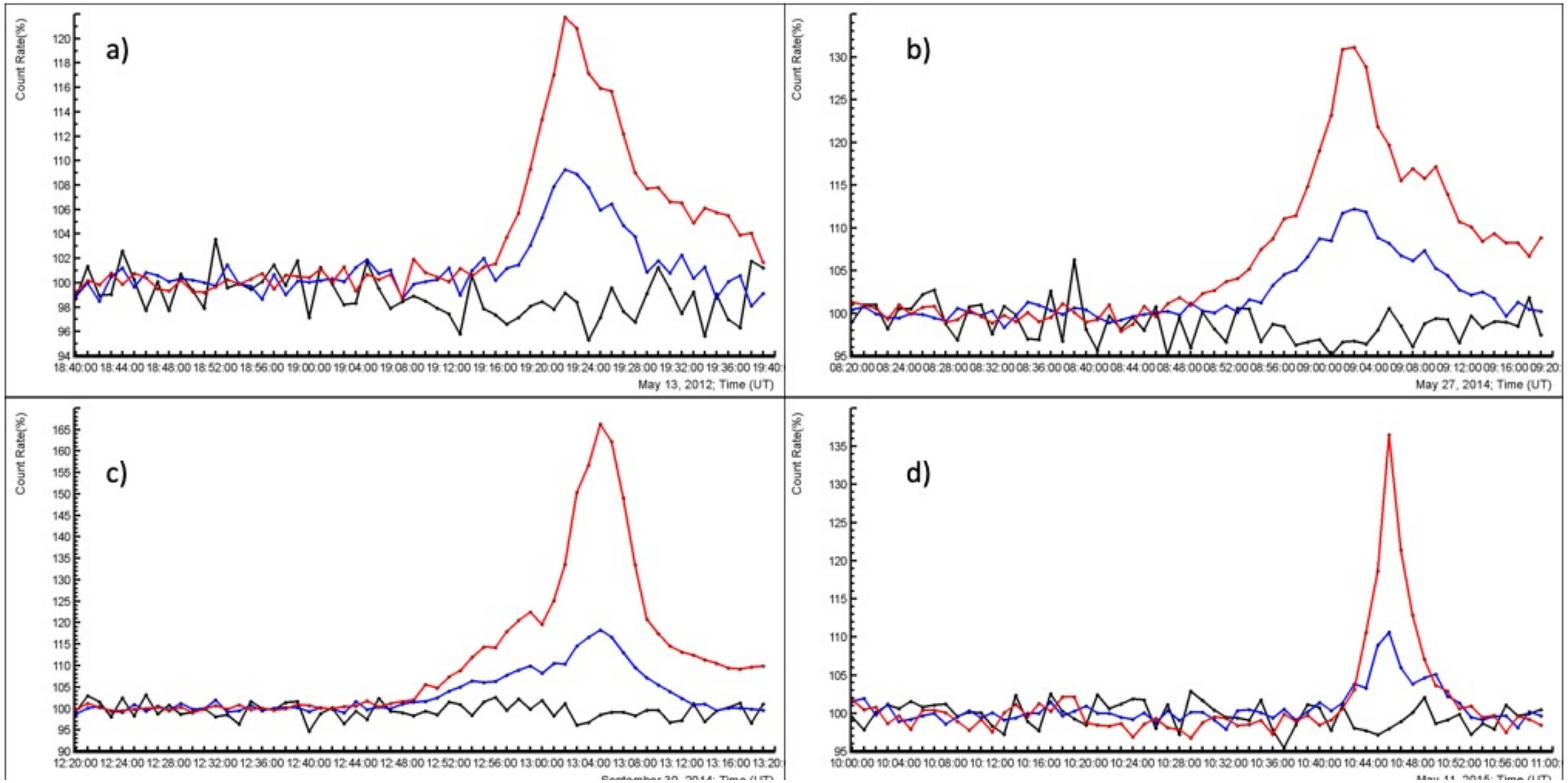


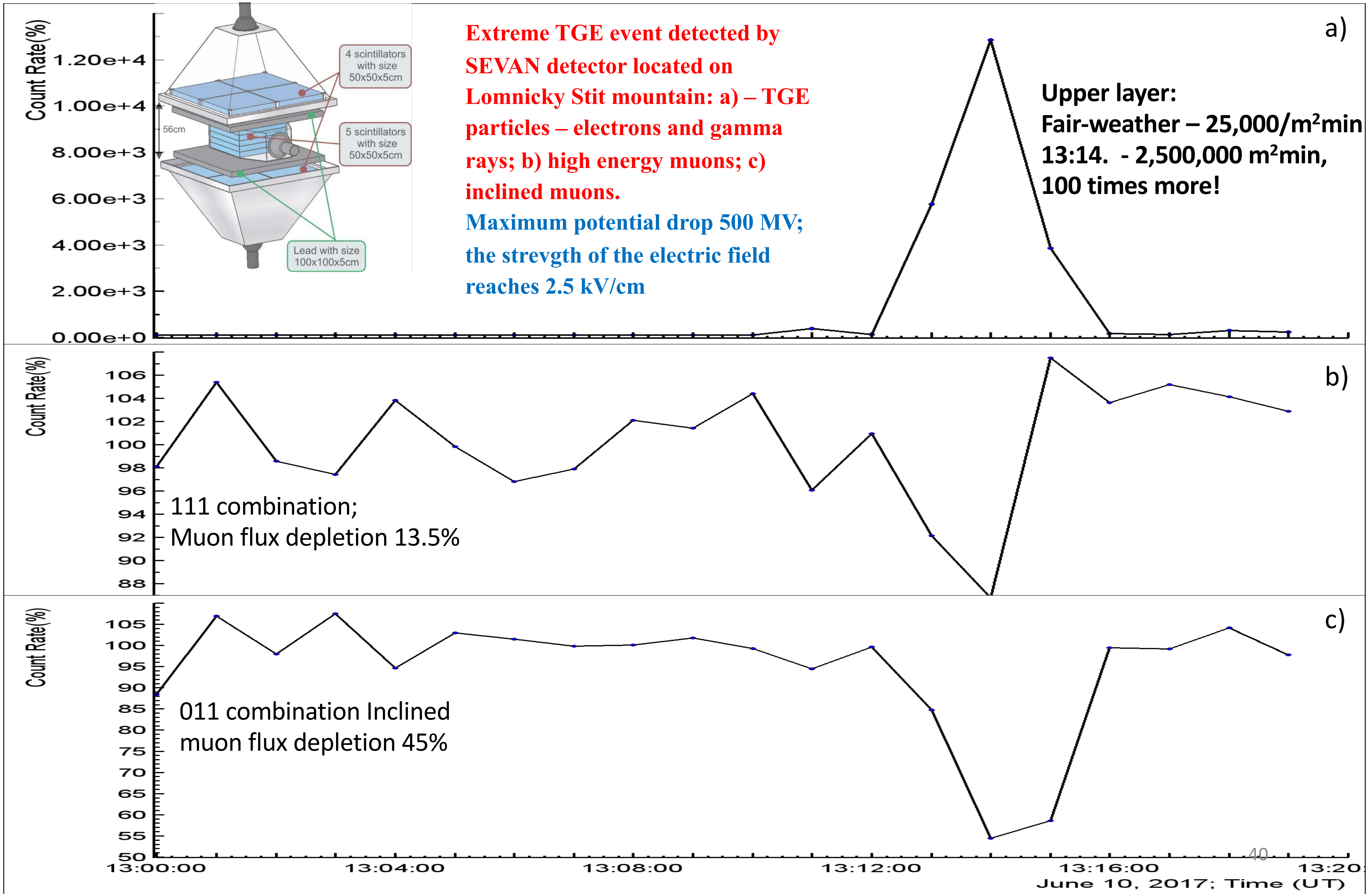
Installation of SEVAN module at entrance of DESY (Zeuthen) in 2020, also, installed in DESY-Hamburg

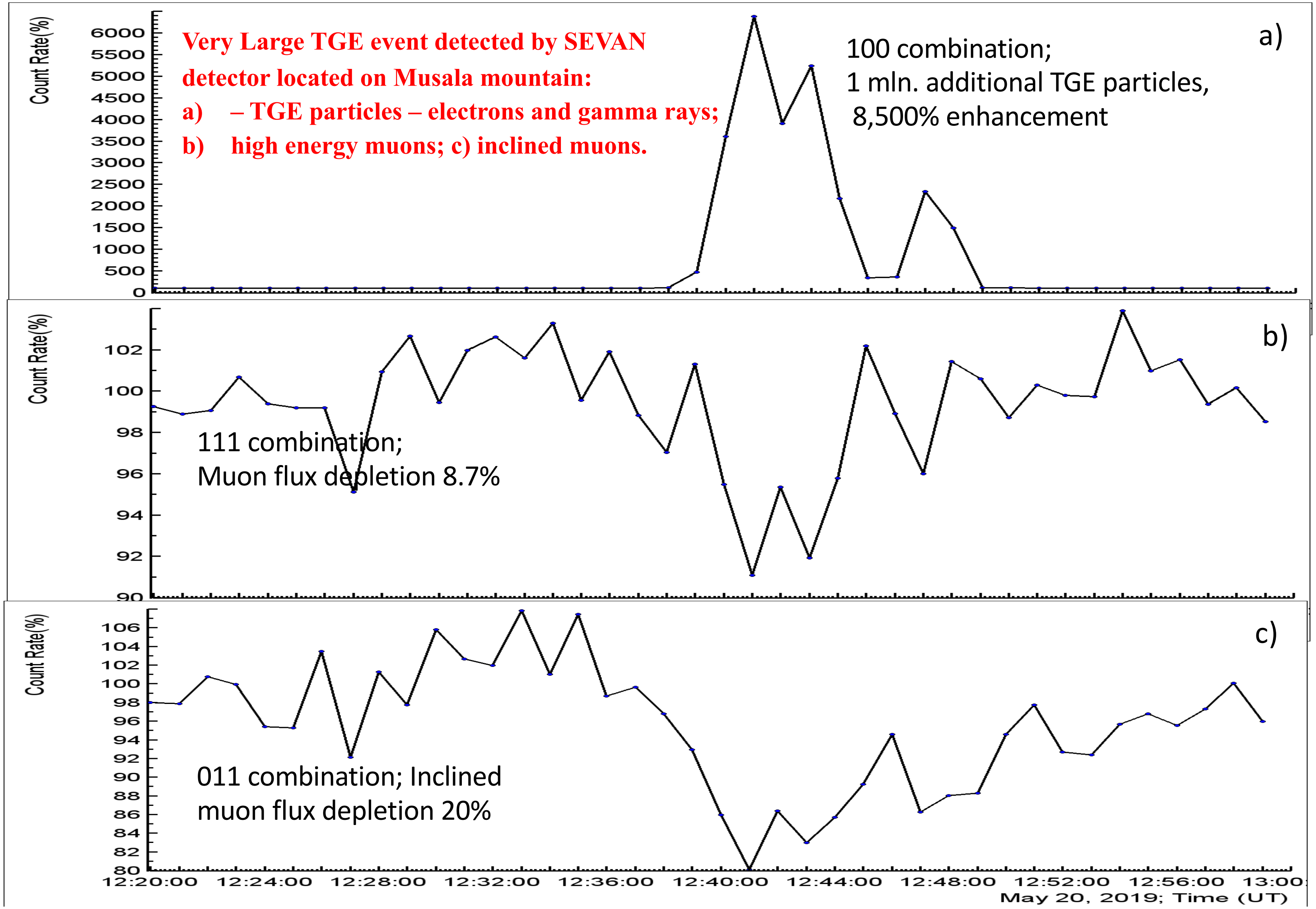

Zugspitze, 2650 a.s.l.


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
56cm
5 scintillators with size 50x50x5cm
Lead with size 100x100x5cm

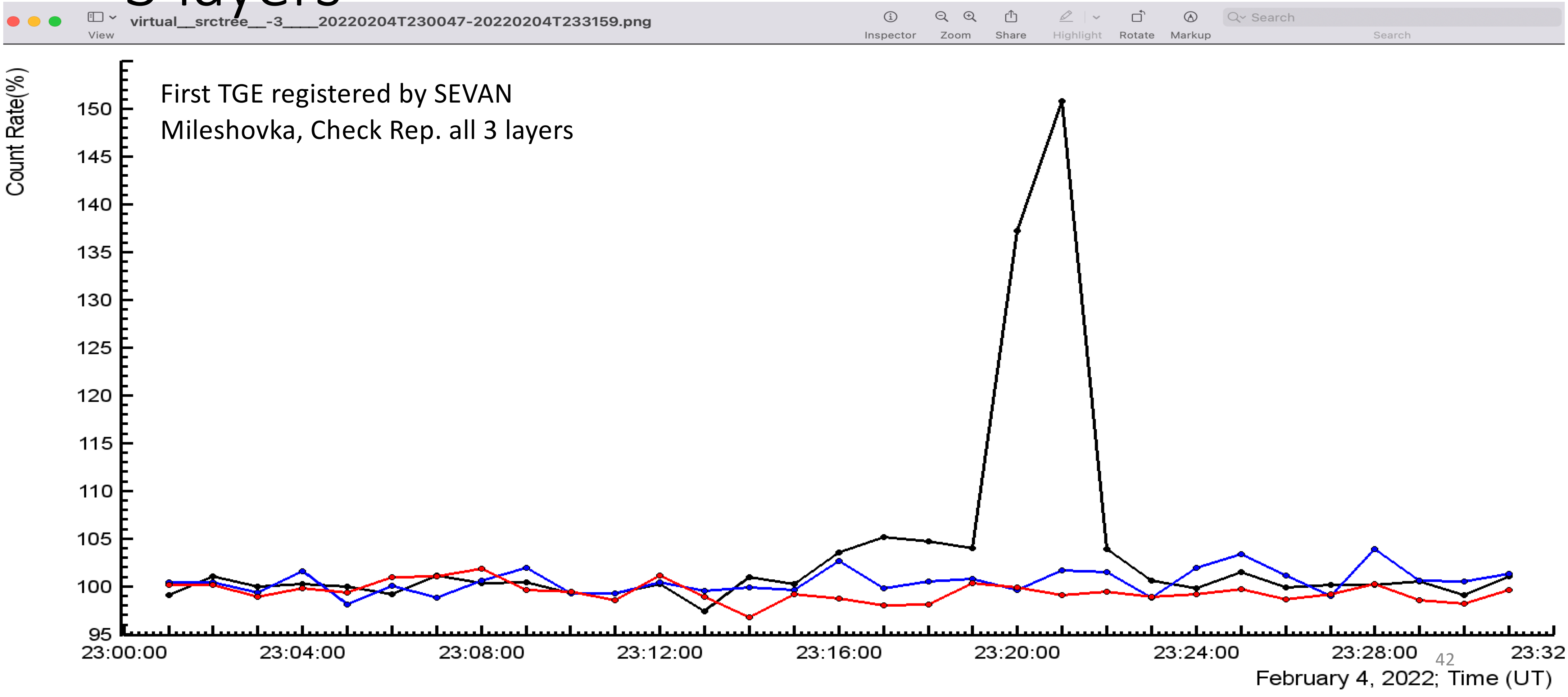
Date	Muon depletion [%]	Electron & gamma ray boost SEVAN/STAND1[%]	El. field record [kV/m]	Cloud base height [m]	Outside Temp. interval [Cº]	RH [%]
a)May 13 2012, 19:24	-4.5	9.3/22	-30 - - 16	65	0.4 - -0.5	95
b) May 27 2014, 9:02	-4.6	12.3/31	-17 - +5	60	1.9 -0.2	94
c)Sept. 30 2014, 13:02	-3.5	19/65	-11 - +5	95	1.9 – 0.4	94
d)May 11 2015 10:45	-2.5	11/36	-24 - +29	130	2.2 – 1.4	92




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(%)
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
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(%)
111 combination;
Muon flux depletion 8.7%
b)
011 combination; Inclined
muon flux depletion 20%
c)
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 13:00:00
May 20, 2019; Time (UT)

First TGE registered by SEVAN Mileshovka, all 3 layers



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

Expansion of SEVAN network: connecting atmospheric and space physics

- TGEs are detected in Armenia, Russia, Slovakia, Bulgaria, Japan, China, and other countries. However, events are rare and detectors small not allowing recovering of energy spectra. Only in Armenia was measured TGE electron spectra and reliably established origination of TGE neutrons.
- We need worldwide network for TGE registration and we propose to use SEVAN detector with NSEF sensor and panoramic camera;
- SEVAN is unique network researching both solar and atmospheric modulation of the different species of cosmic rays;
- 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).

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

- **The boost of the secondary cosmic ray flux observed during thunderstorms, is a manifestation of high-energy processes in the terrestrial atmosphere (HEPA).**
- **Origin of TGE is the strong electrical field in the thundercloud giving rise to following high-energy processes**
- **Thunderstorm ground enhancements are a universal physical phenomena sending ≈10^{18} particles 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.**
- **Muon stopping effect, decrease of muon flux during TGEs.**
- **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.**