Ground-based facilities for the correlated study of particle bursts, lightning occurrences, and light glows

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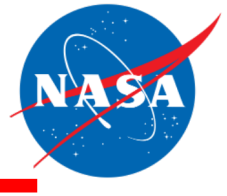
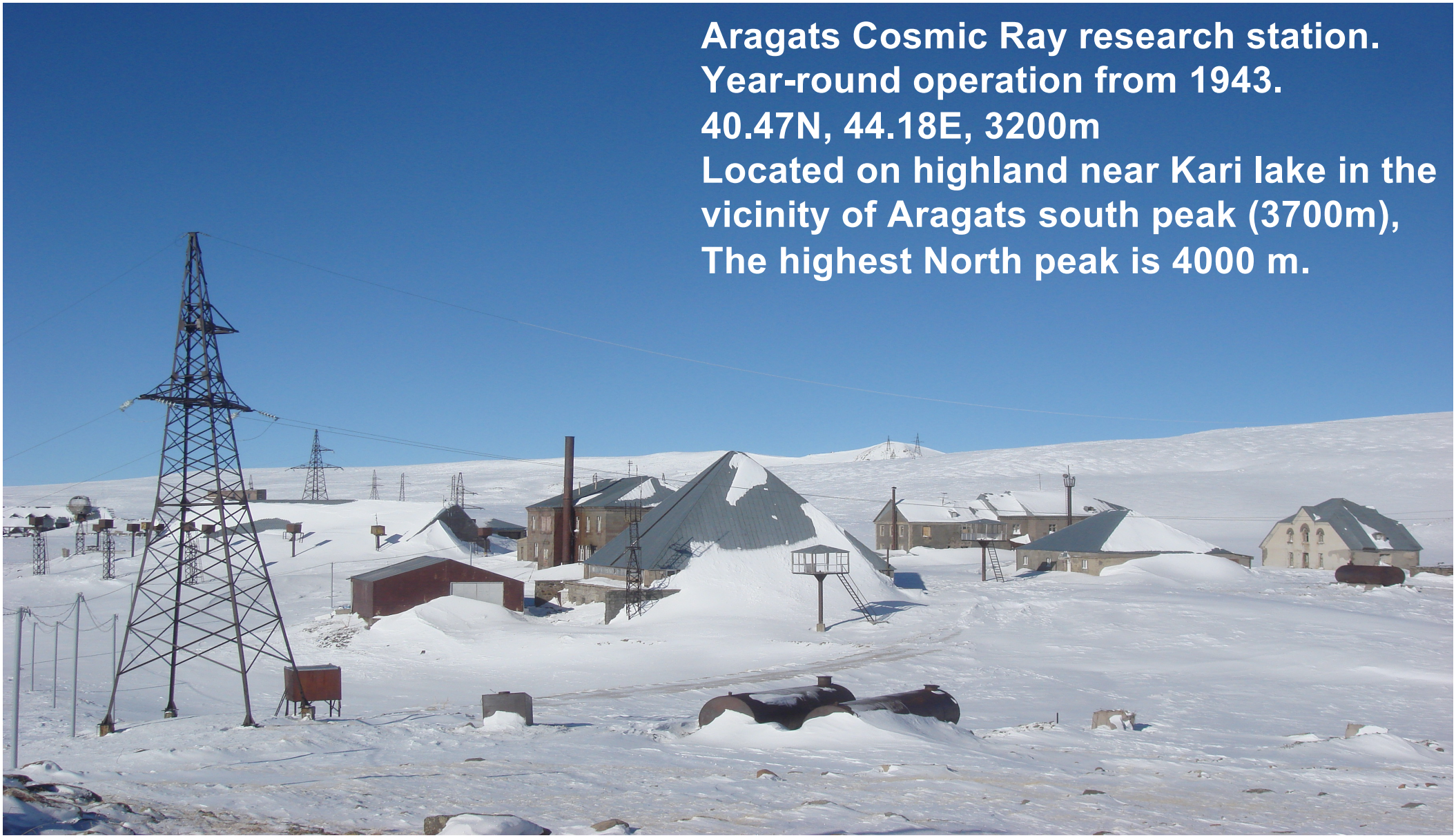
Operation of electron accelerator in thunderclouds and lightning initiation



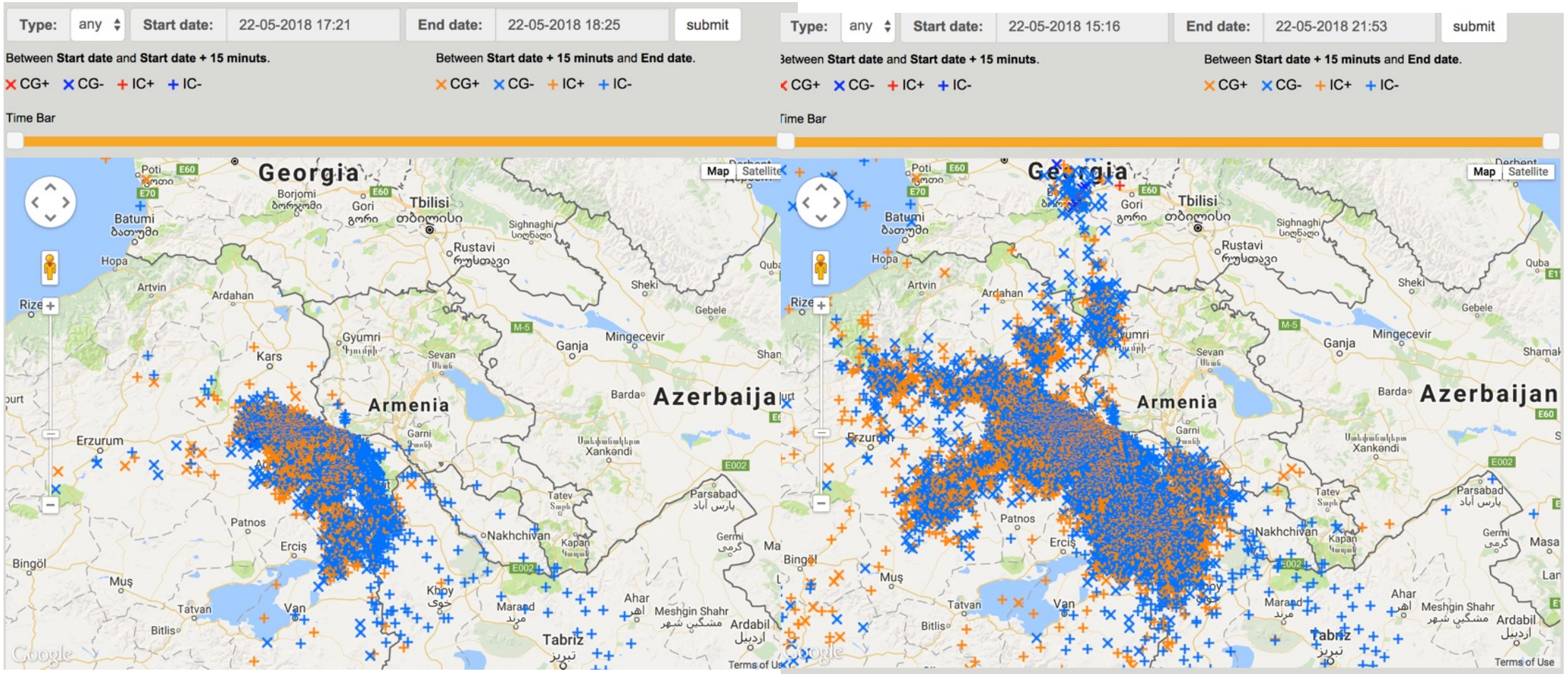
- **Science goals and objectives: Comic Ray Division (CRD) of YerPhI**
  - Secondary cosmic ray modulation by strong atmospheric electric fields;
  - Conditions of the atmosphere supporting the emergence of electron accelerators;
  - Origination of particle bursts measured on the earth's surface;
  - Vertical and horizontal profiles of the near-surface electric field;
  - Lightning flashes of different types and TLEs and their relation to particle bursts;
  - Muon tomography of the electrified atmosphere (muon stopping effect);
  - Influence of electric fields on Extensive air showers: ACTs (MAGIC, HESS, CTA) and high-altitude large particle arrays (HAWK, LHASSO).

- **Investigation strategy/techniques: The synergy of CR physics and Atmospheric physics.**

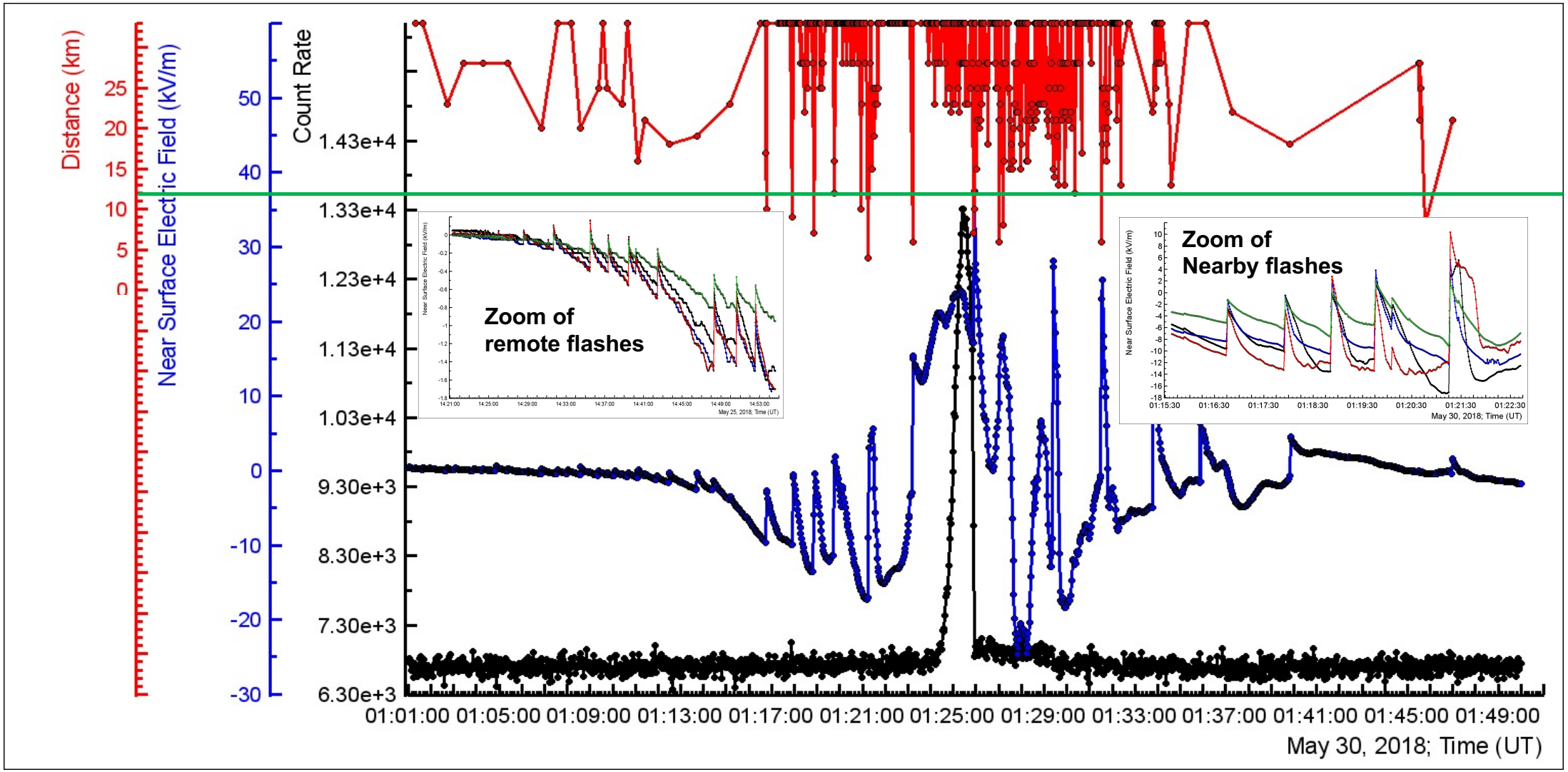
  - Continuous monitoring of different species of cosmic rays, electric and geomagnetic fields, lightning locations, meteorological parameters, and TLEs;
  - Worldwide networks of identical particle detectors and field meters allowing synchronization and mutual analysis of data (Armenian network, East European SEVAN network);
  - Possibilities of the online visualization and analysis of the stream of multivariate data by the advanced data extraction infrastructure (ADEI platform);
  - Recovering electron and gamma ray energy spectra.

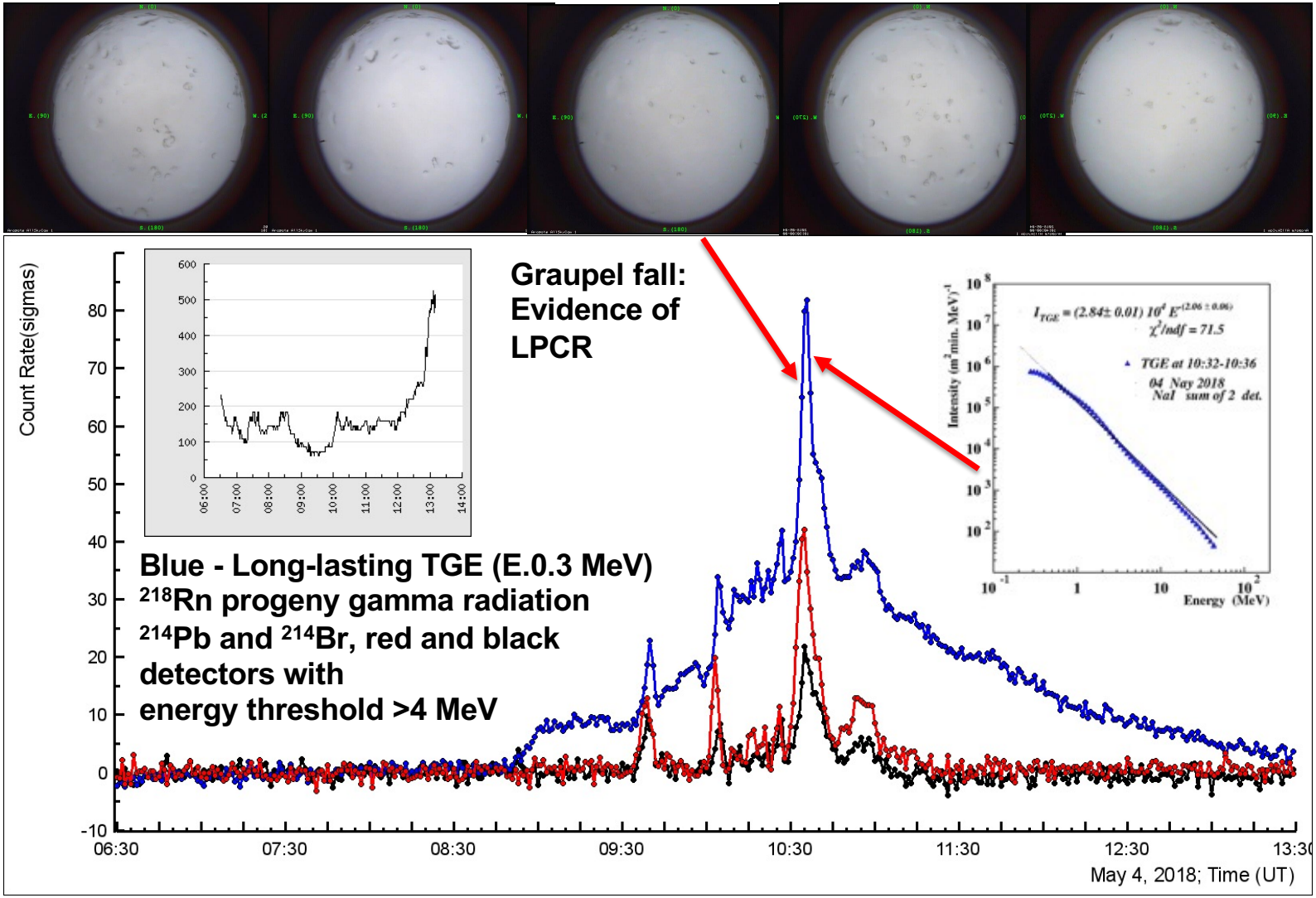

Aragats Cosmic Ray research station.
Year-round operation from 1943.
40.47N, 44.18E, 3200m
Located on highland near Kari lake in the vicinity of Aragats south peak (3700m),
The highest North peak is 4000 m.

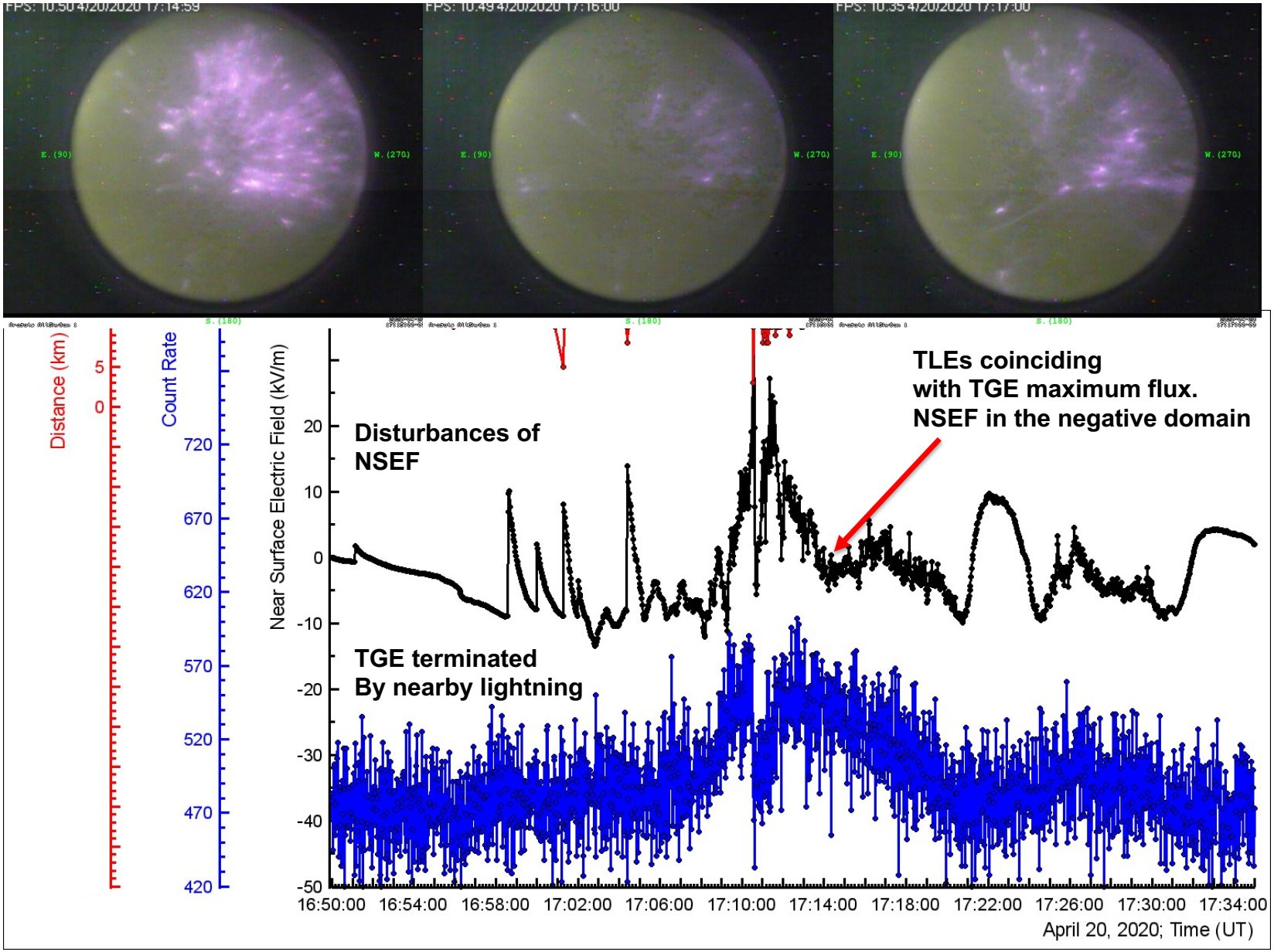
Thunderstorms with hundreds of lightning flashes are usual on Aragats.



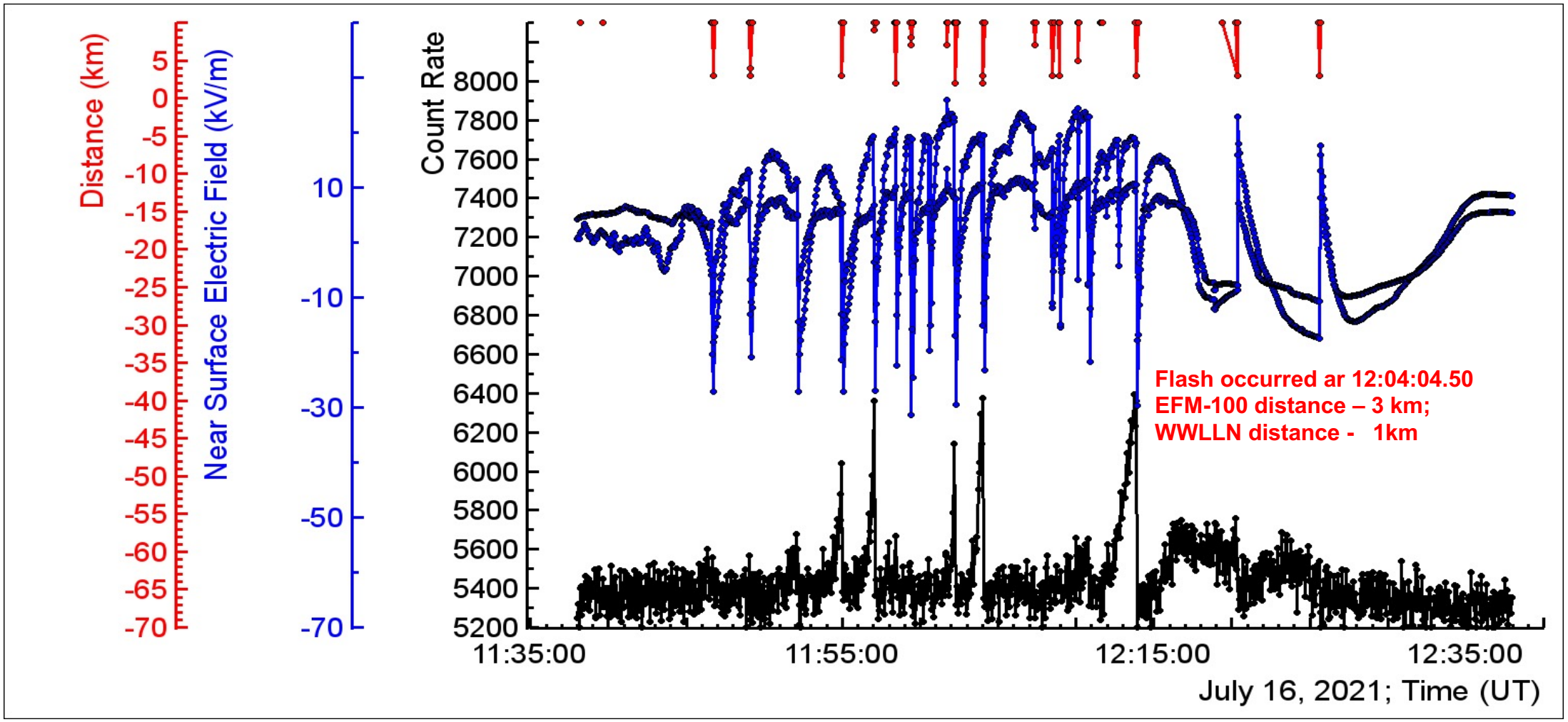
Particle burst (black) at positive NSEF (blue) during storm with multiple flashes (distance in red), green line – 10 km distance



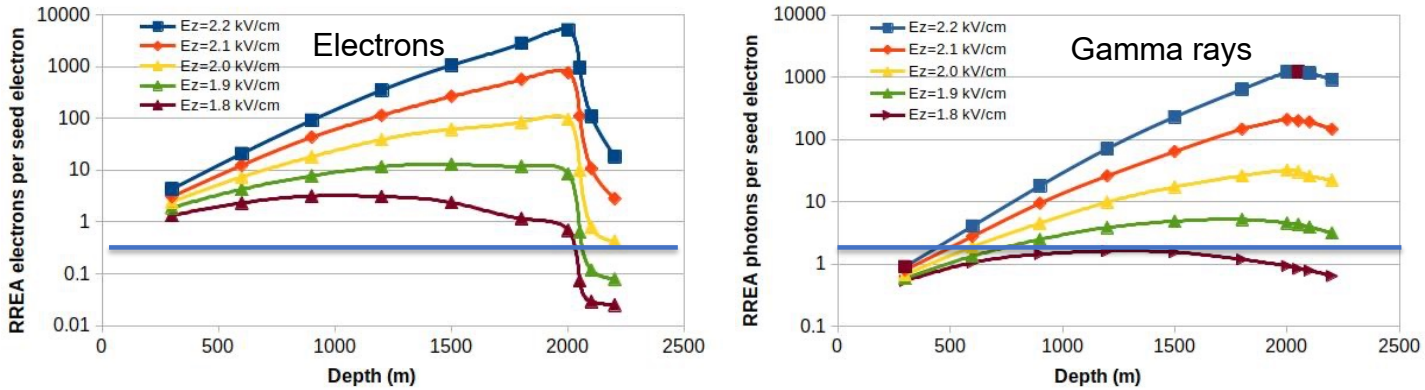

Graupel fall:
Evidence of
LPCR
Blue - Long-lasting TGE (E.0.3 MeV)
218Rn progeny gamma radiation
214Pb and 214Br, red and black
detectors with
energy threshold >4 MeV
Count Rate(sigmas)
May 4, 2018; Time (UT)
Intensity (m²min. MeV)⁻¹
Energy (MeV)
TGE at 10:32-10:36
04 May 2018
NaI sum of 2 det.


E. (90)
W. (270)
S. (180)
Distance (km)
5
0
Count Rate
720
670
620
570
520
470
420
Near Surface Electric Field (kV/m)
20
10
0
-10
-20
-30
-40
-50
Disturbances of
NSEF
TLEs coinciding
with TGE maximum flux.
NSEF in the negative domain
TGE terminated
By nearby lightning
16:50:00
16:54:00
16:58:00
17:02:00
17:06:00
17:10:00
17:14:00
17:18:00
17:22:00
17:26:00
17:30:00
17:34:00
April 20, 2020; Time (UT)

Multiple nearby lightning flashes terminate attempts to start TGE

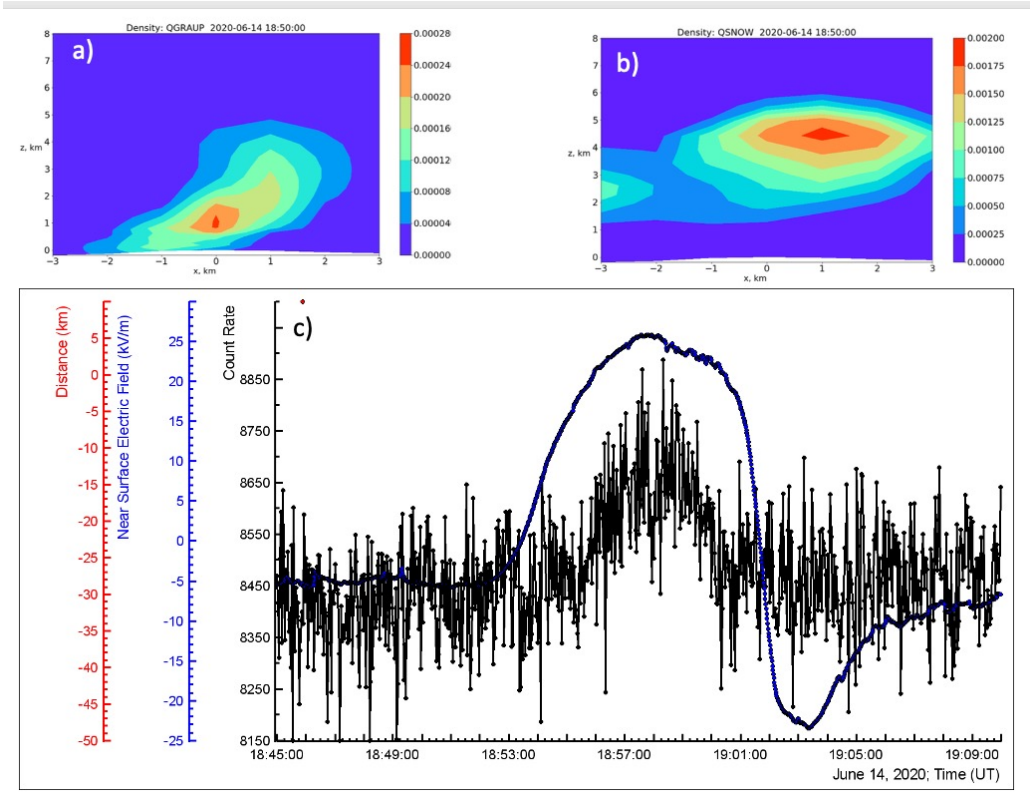


Modeling of the TGE particle energy spectra with CORSIKA and GEANT4 simulations: verifying the vertical profile of the atmospheric electric field



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.

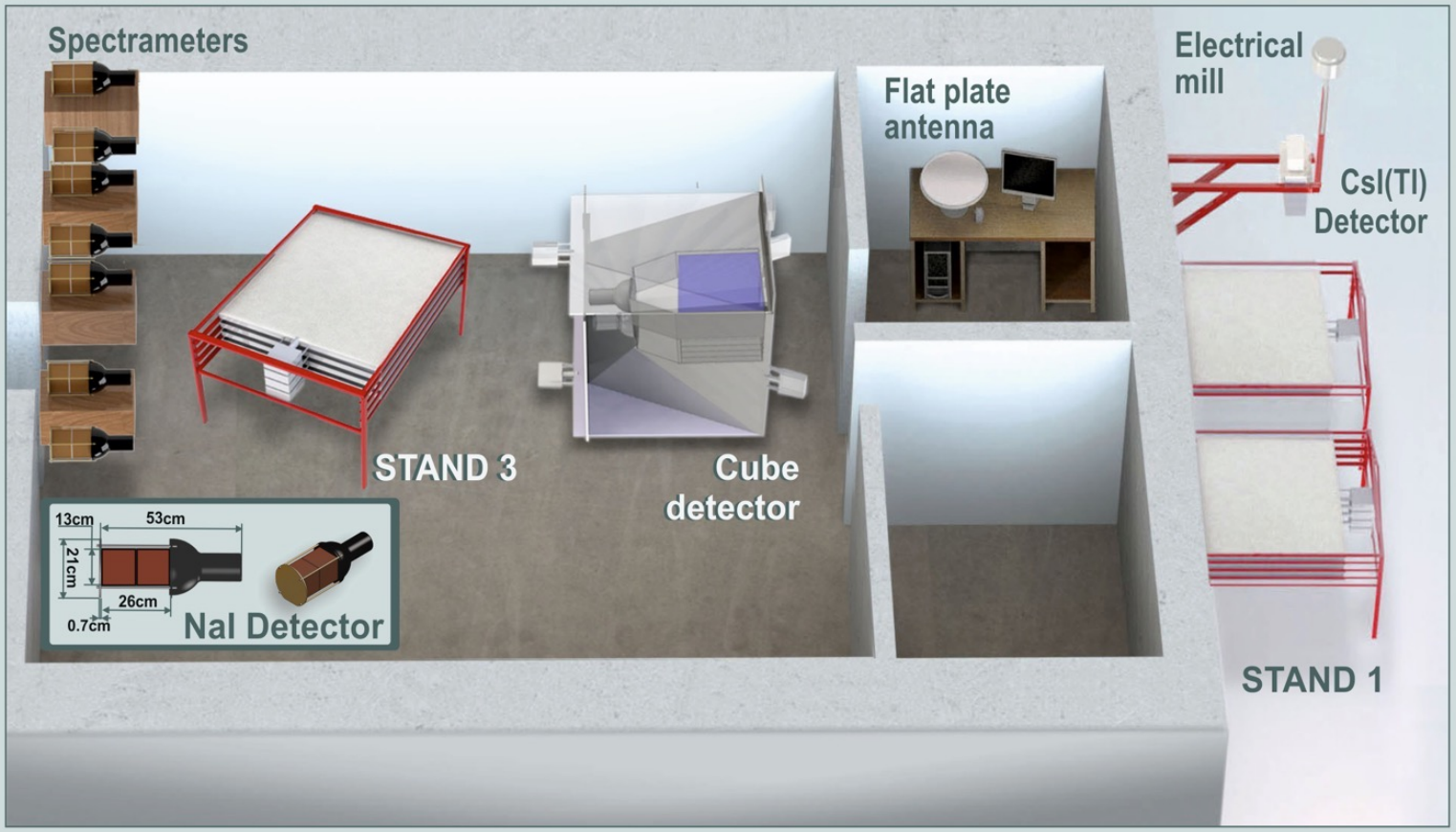
Lower dipole accelerated electrons in direction to the earth's surface: Main negative layer - LPCR



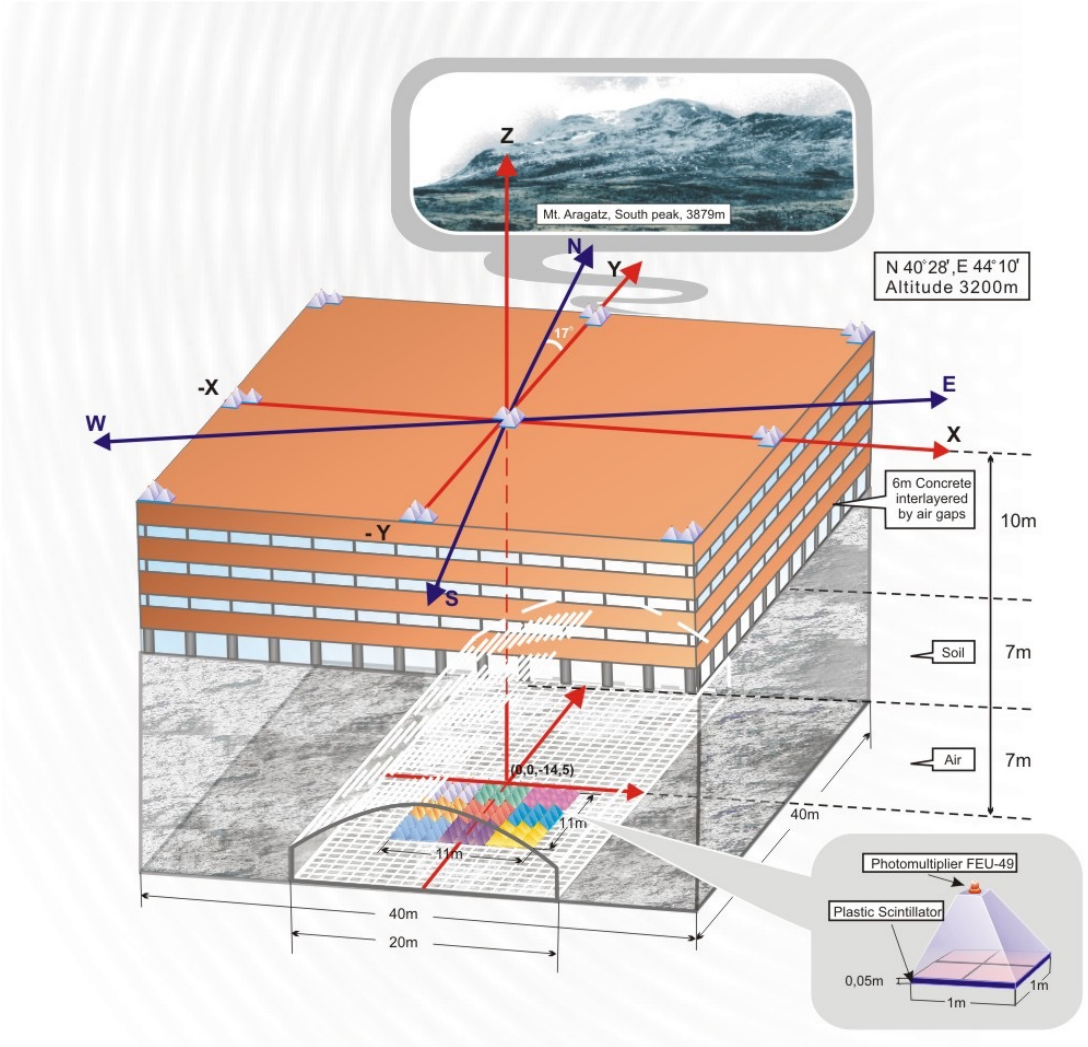
Vertical profile of the hydrometeor density (kg/m^3) obtained by WRF model (a and b) is well corresponding to the registered TGE (c black curve) and NSEF (c blue curve).

Instrumentation: Particle detectors located in MAKET experimental hall

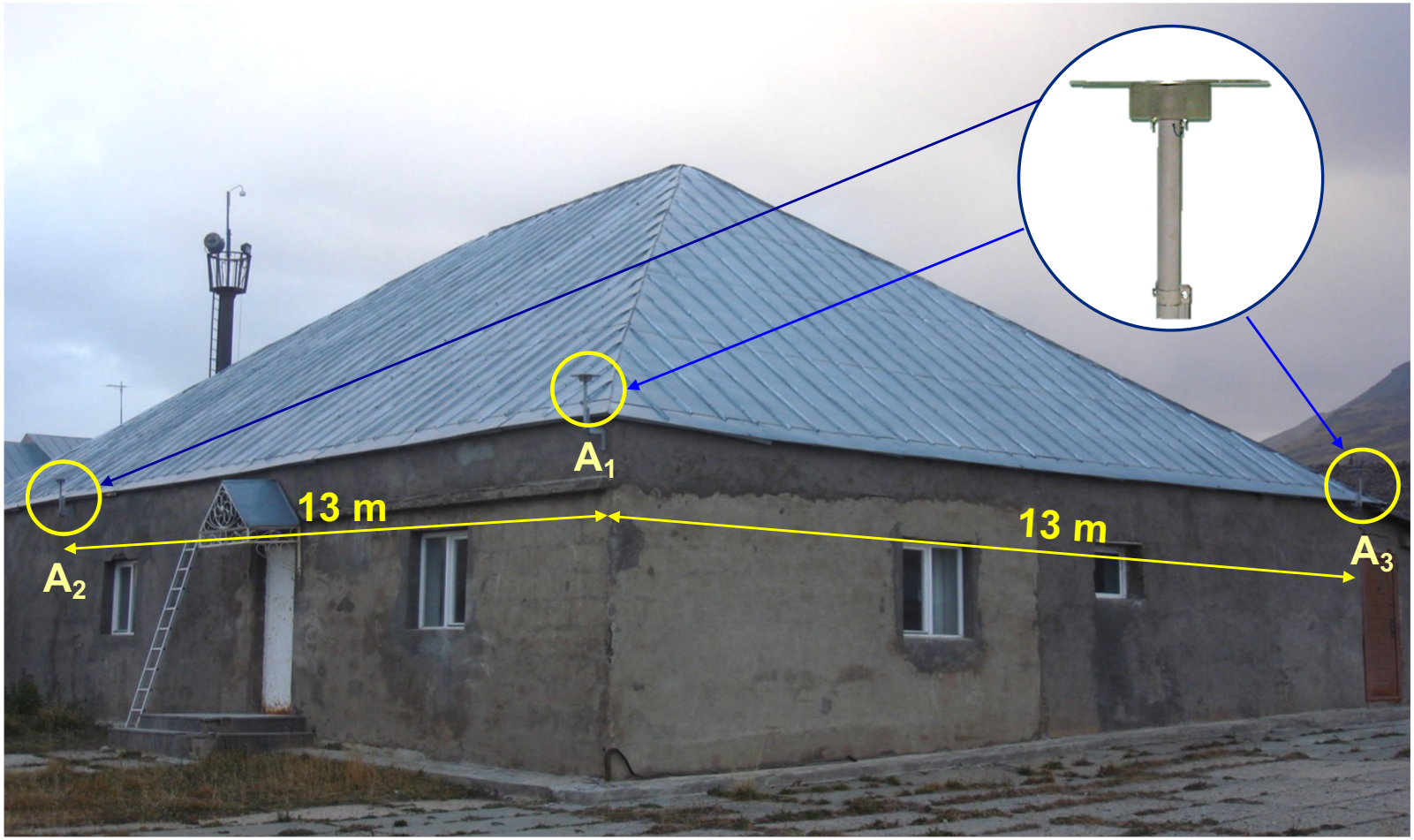
SKL EXperimental Hall



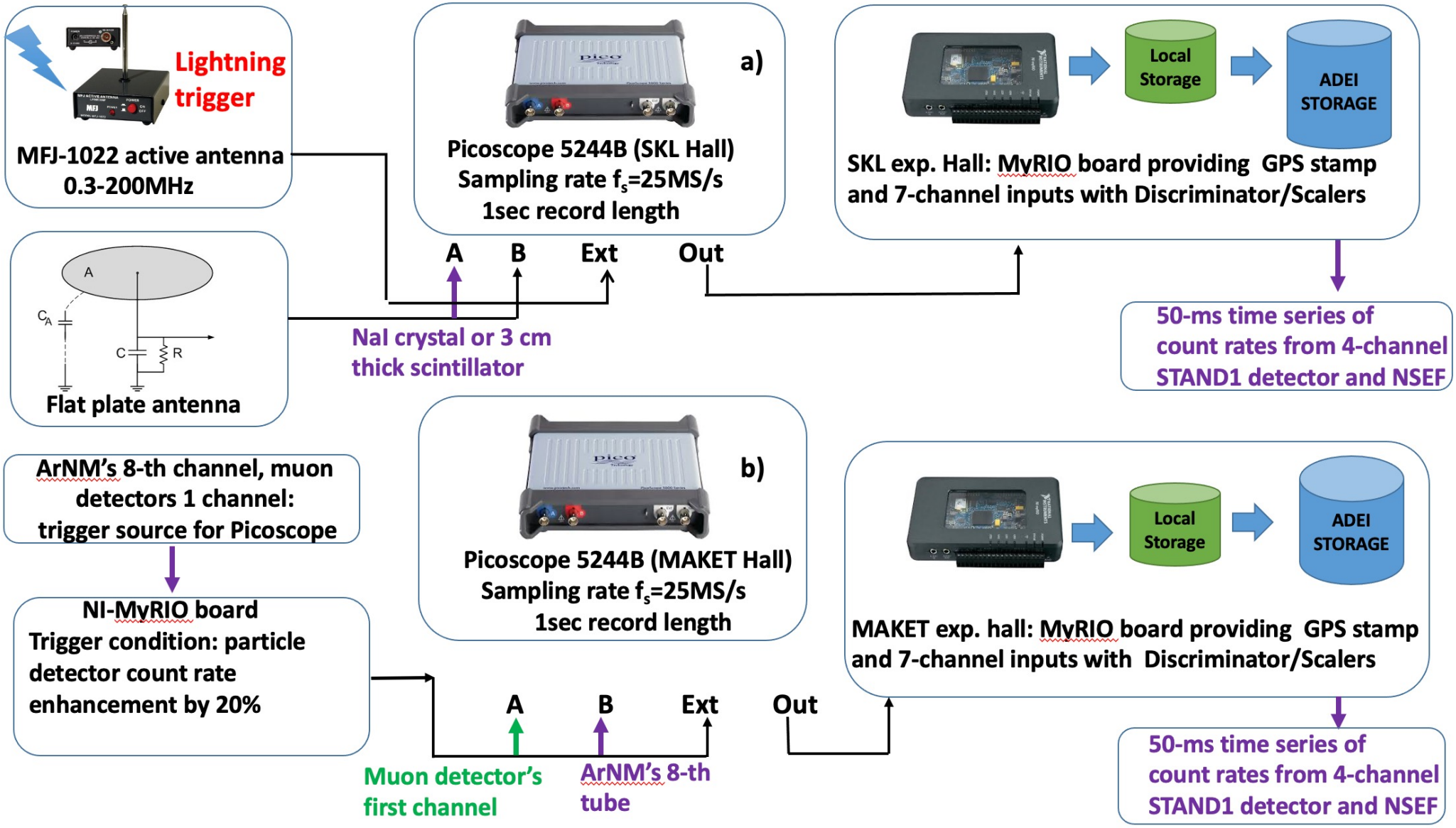
GAMMA experiment: 30 m^2 outside scintillators and 200 m^2 muon detectors (under 15 m of soil and concrete). 1s time series



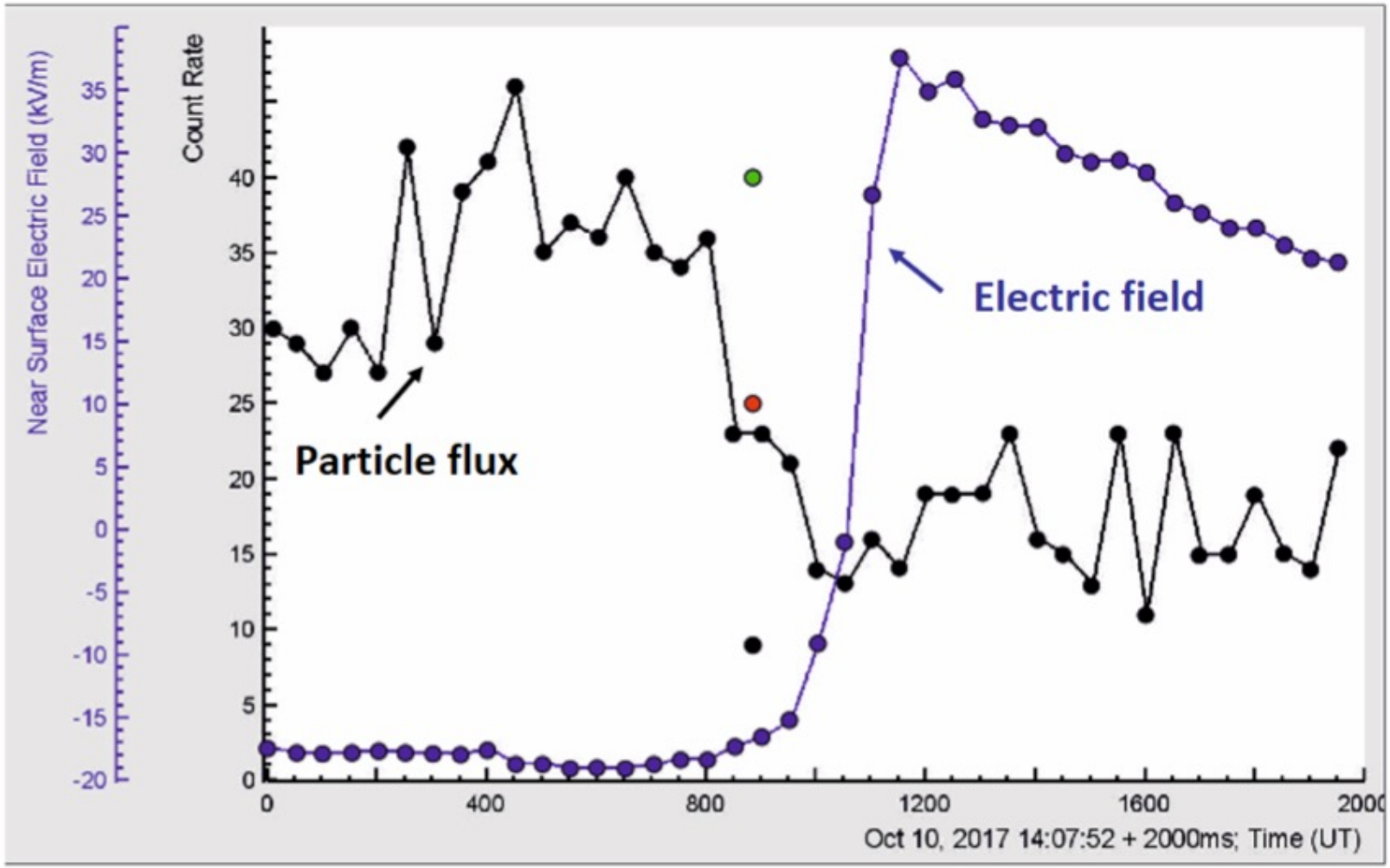
Three flat plate antennas of VHF interferometer installed at SKL hall of Aragats station

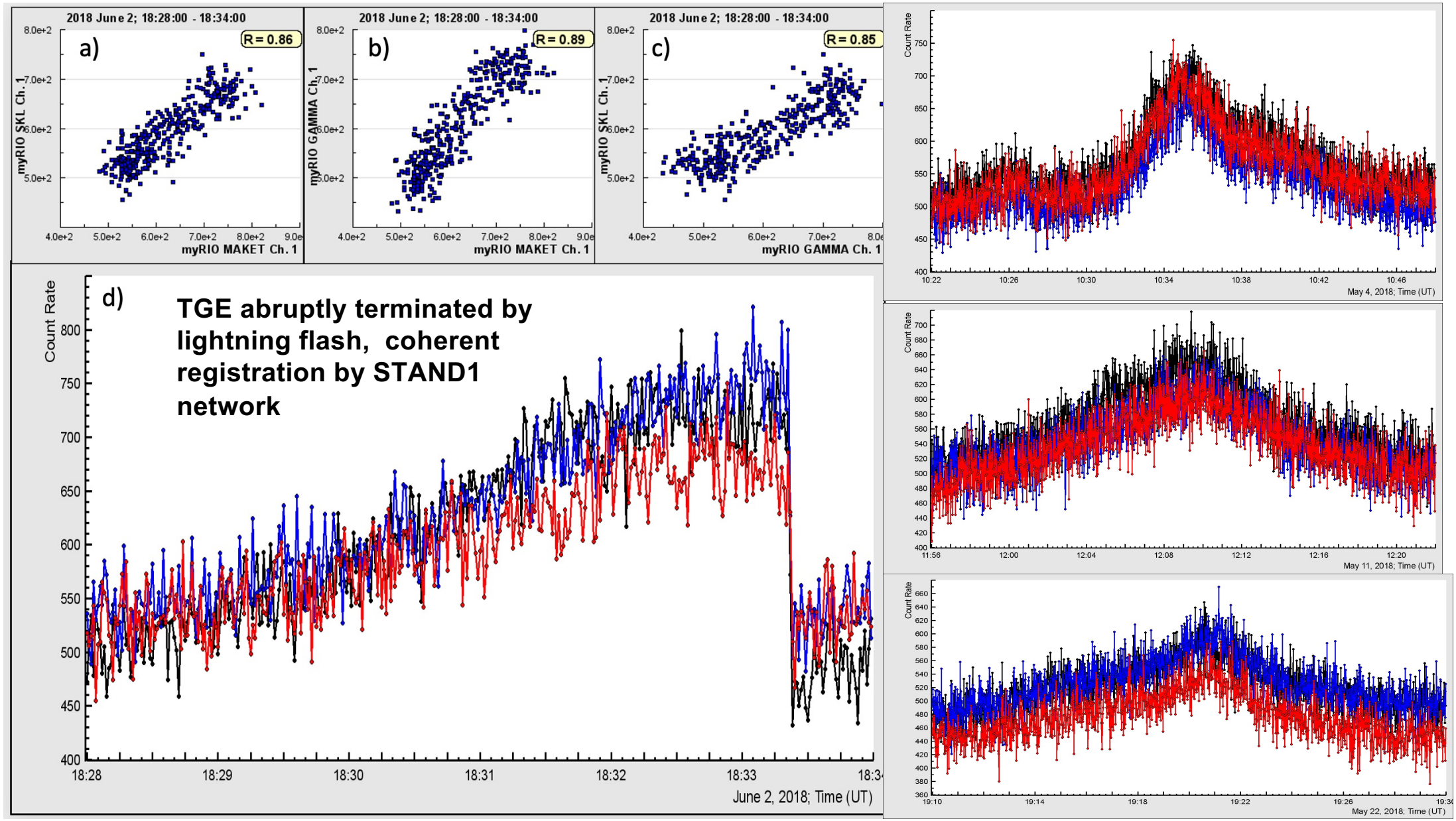


Aragats station: EFM and STAND1 networks

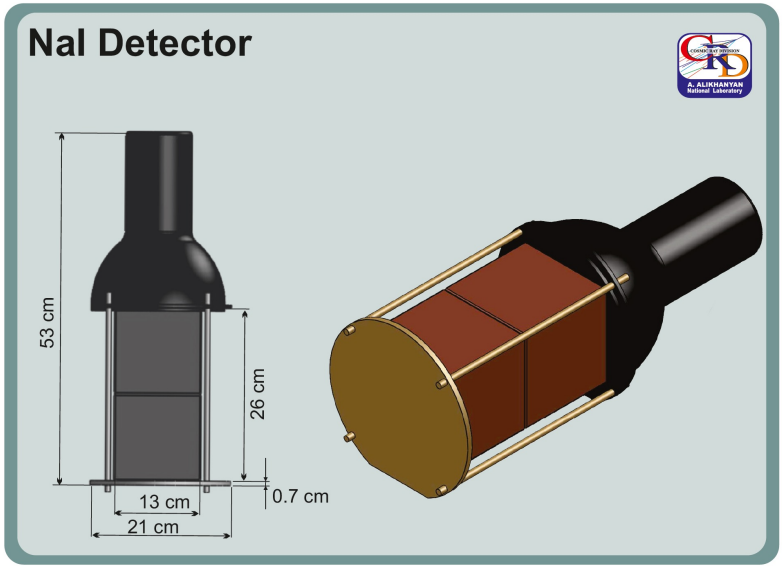

Lightning trigger
MFJ-1022 active antenna
0.3-200MHz
a)
Picoscope 5244B (SKL Hall)
Sampling rate f_s=25MS/s
1sec record length
Local Storage
ADEI STORAGE
SKL exp. Hall: MyRIO board providing GPS stamp and 7-channel inputs with Discriminator/Scalers
A
B
Ext
Out
50-ms time series of count rates from 4-channel STAND1 detector and NSEF
NaI crystal or 3 cm thick scintillator
Flat plate antenna
ArNM's 8-th channel, muon detectors 1 channel: trigger source for Picoscope
NI-MyRIO board
Trigger condition: particle detector count rate enhancement by 20%
b)
Picoscope 5244B (MAKET Hall)
Sampling rate f_s=25MS/s
1sec record length
Local Storage
ADEI STORAGE
MAKET exp. hall: MyRIO board providing GPS stamp and 7-channel inputs with Discriminator/Scalers
A
B
Ext
Out
50-ms time series of count rates from 4-channel STAND1 detector and NSEF
Muon detector's first channel
ArNM's 8-th tube

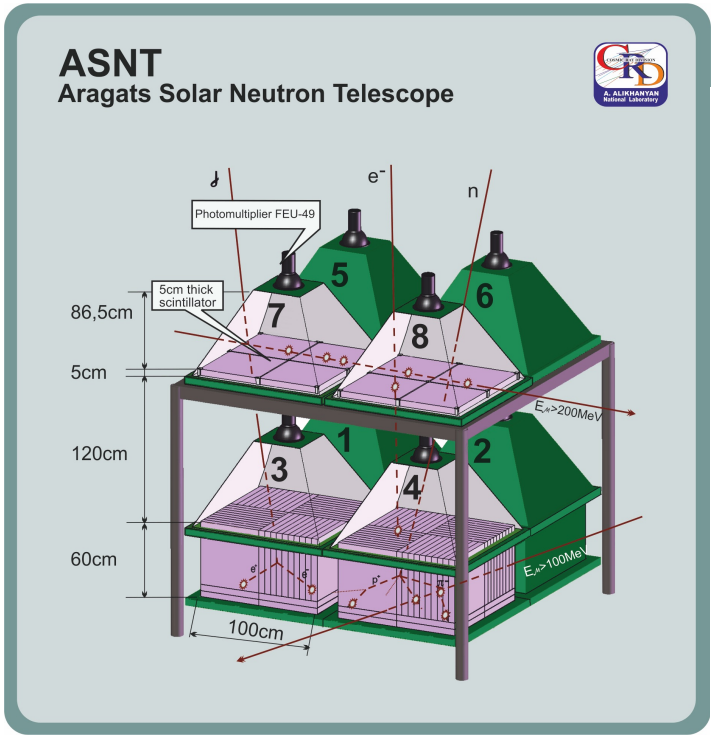
Synchronized detection of the particle fluxes and electrostatic field disturbances (50 ms time series in 3 destinations). Triggered by lightning flashes and TGEs.

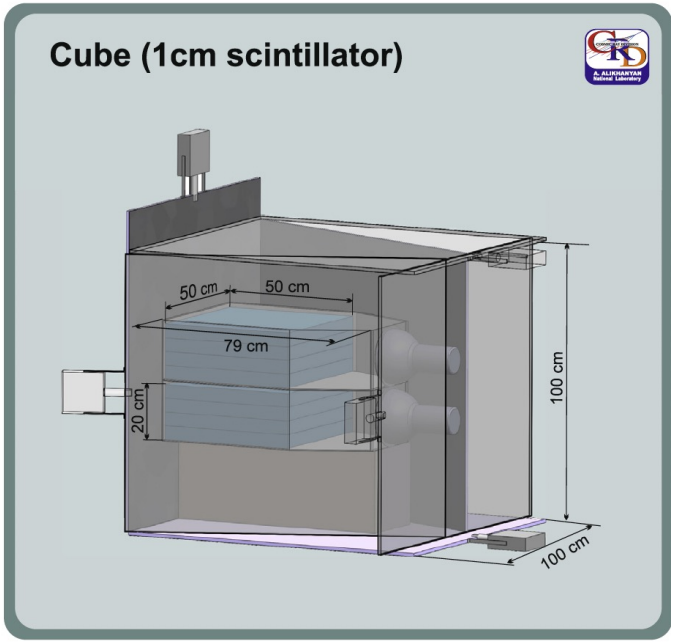



2018 June 2; 18:28:00 - 18:34:00
a)
R = 0.86
myRIO ŞKL Ch. 1
myRIO MAKET Ch. 1
2018 June 2; 18:28:00 - 18:34:00
b)
R = 0.89
myRIO GAMMA Ch. 1
myRIO MAKET Ch. 1
2018 June 2; 18:28:00 - 18:34:00
c)
R = 0.85
myRIO ŞKL Ch. 1
myRIO GAMMA Ch. 1
d)
TGE abruptly terminated by lightning flash, coherent registration by STAND1 network
Count Rate
June 2, 2018; Time (UT)
Count Rate
May 4, 2018; Time (UT)
Count Rate
May 11, 2018; Time (UT)
Count Rate
May 22, 2018; Time (UT)

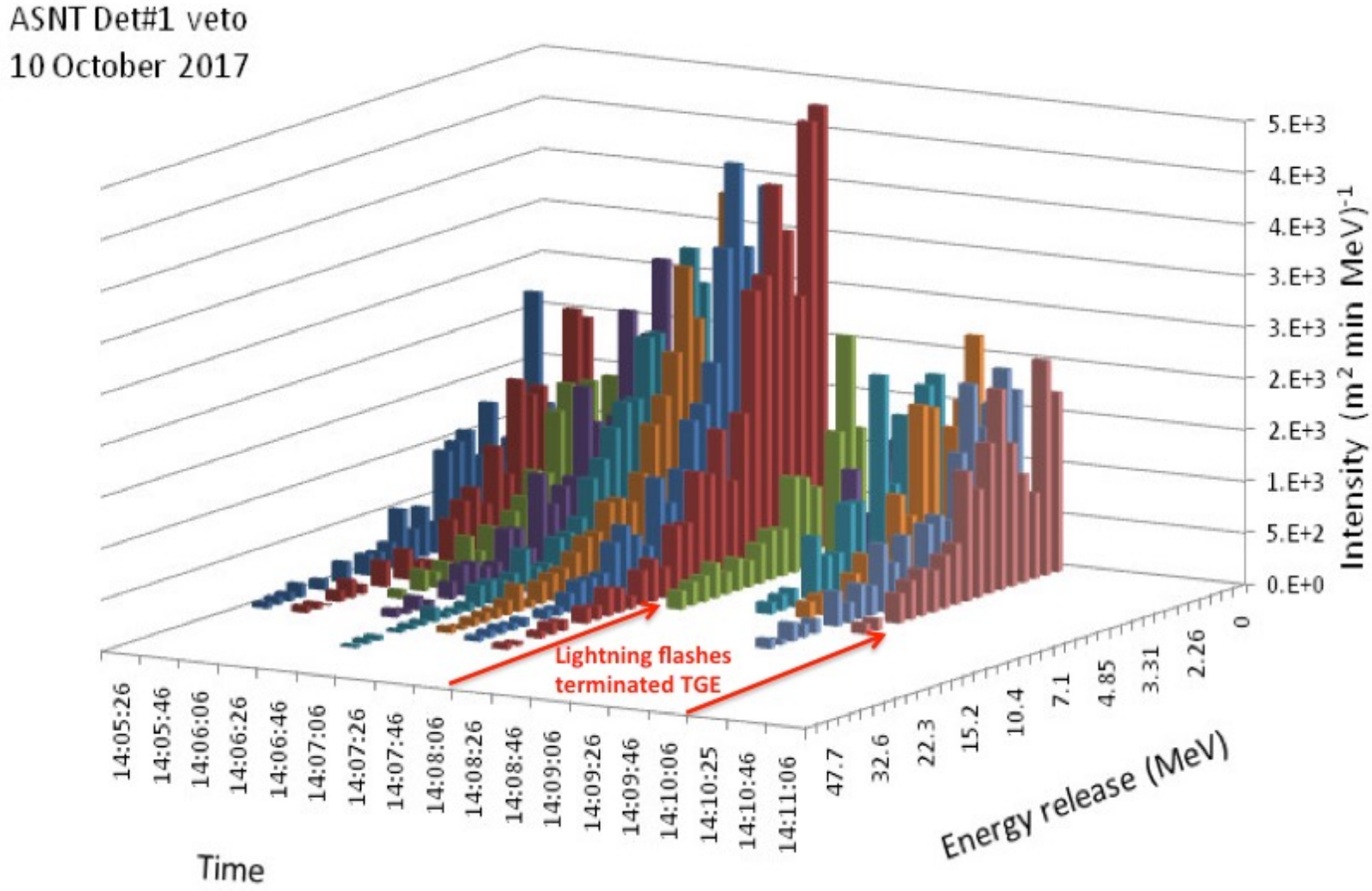
Detectors monitoring energy spectra of electron and gamma rays in the energy range from 0.3 do 100 MeV (10s and 1 minute time series – 13 years data)



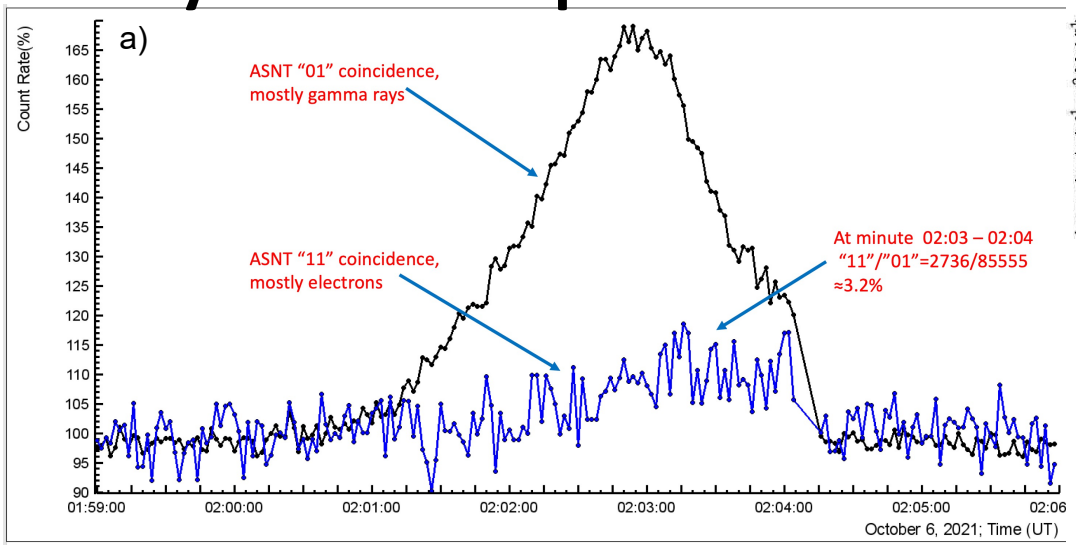


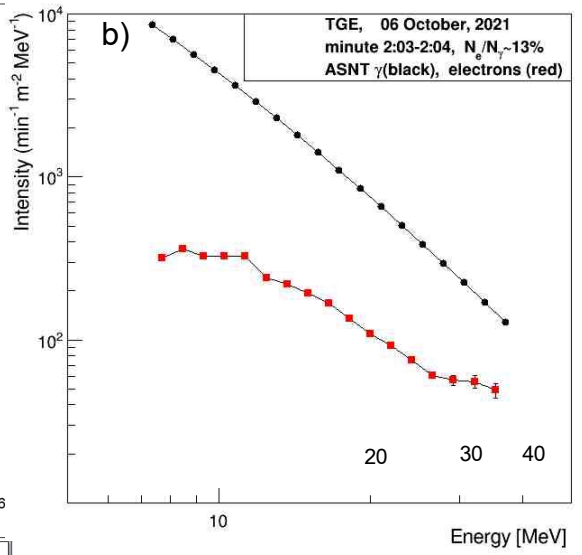


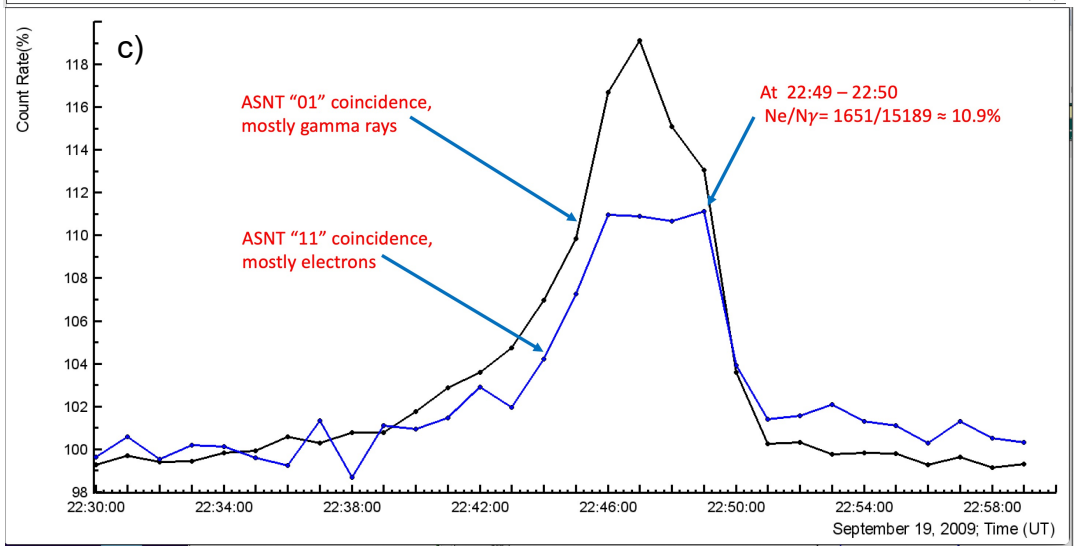
The 20-sec energy release histograms measured by the 60-cm thick plastic scintillator of the ASNT detector. The lightning flashes shown by arrows abruptly terminate the high-energy particle flux.

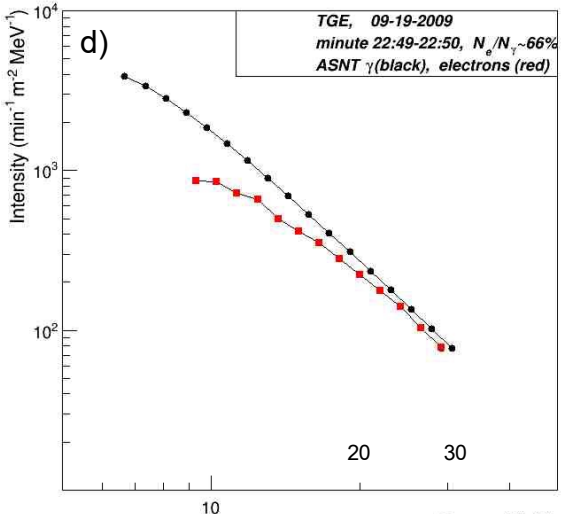


Measured count rates and estimated energy spectra of TGE particles by the ASNT spectrometer

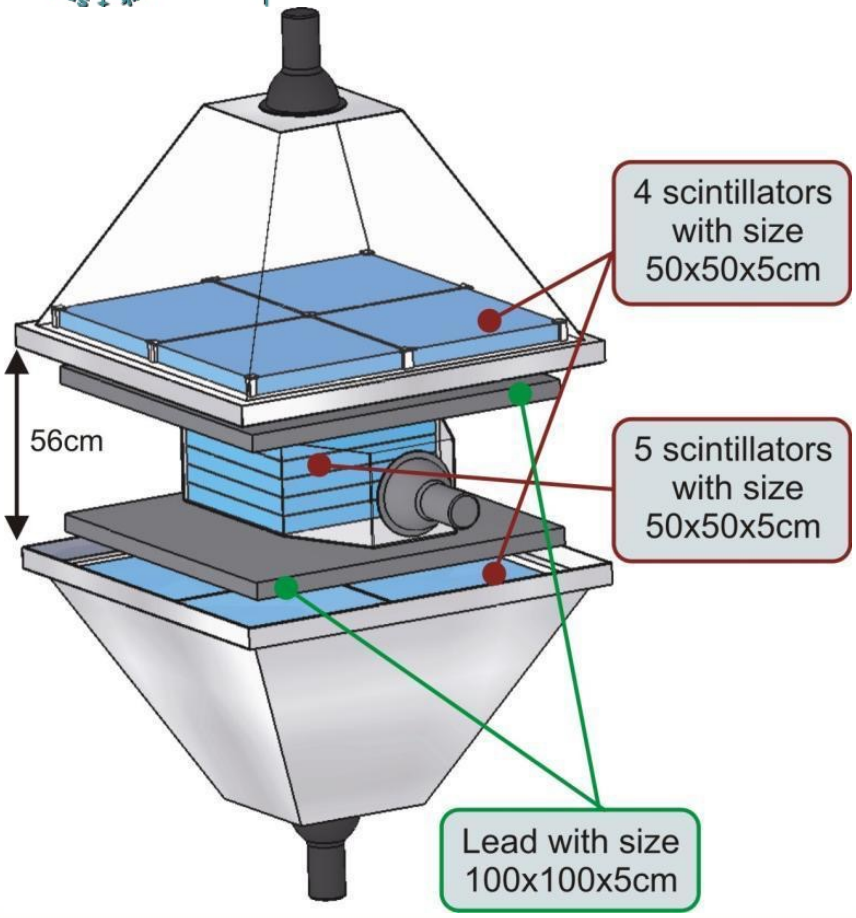








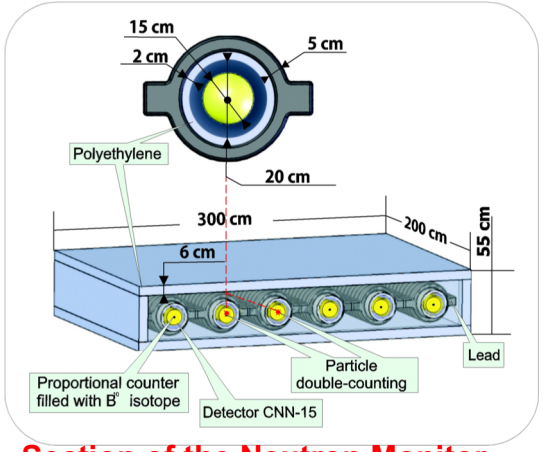
SEVAN network (9 detectors in 6 countries): 24/7 CR monitoring



100 – low energy charged particle;

010 – neutral particle (gamma ray or neutron;

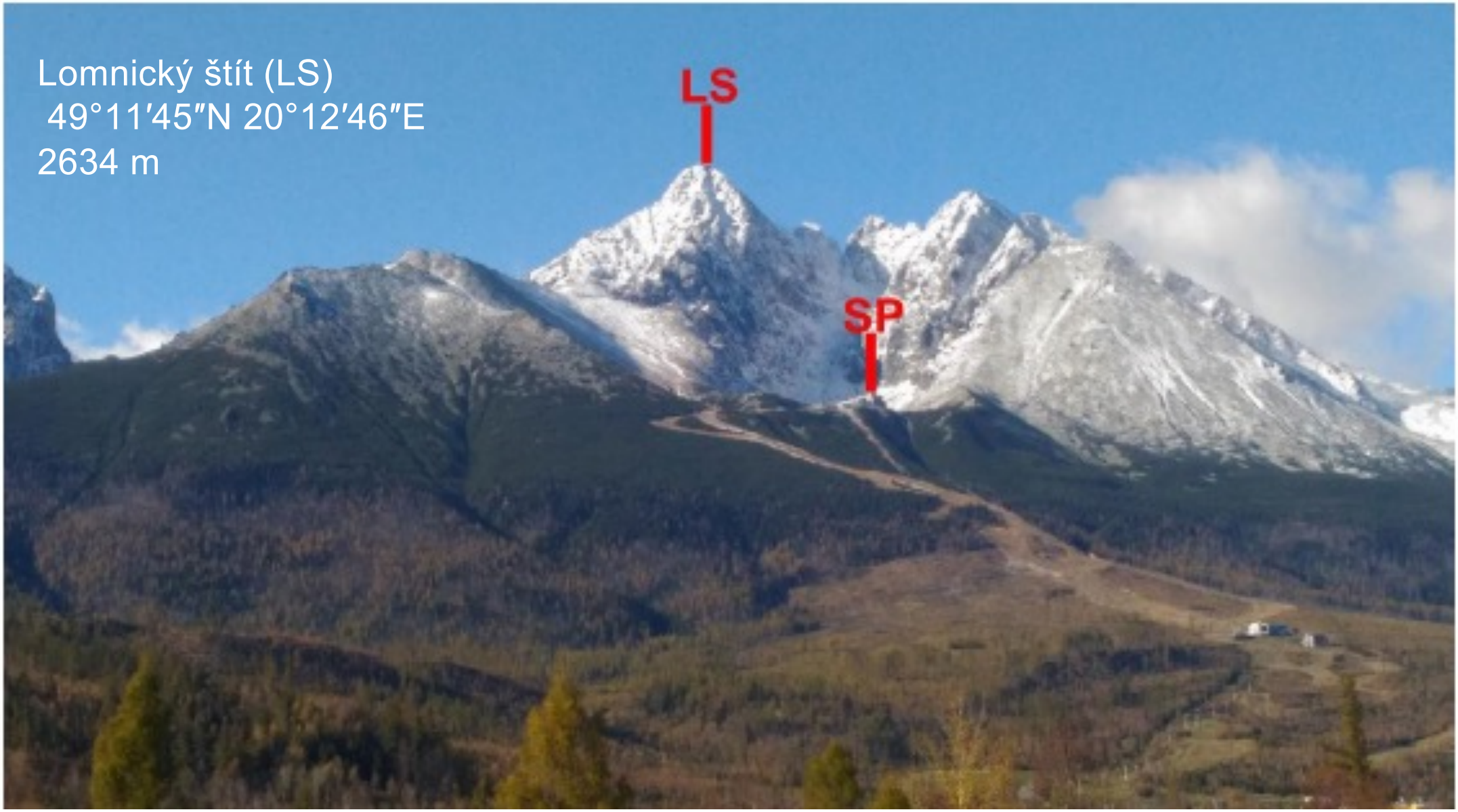
111 & 101 – high energy muon (>200MeV);



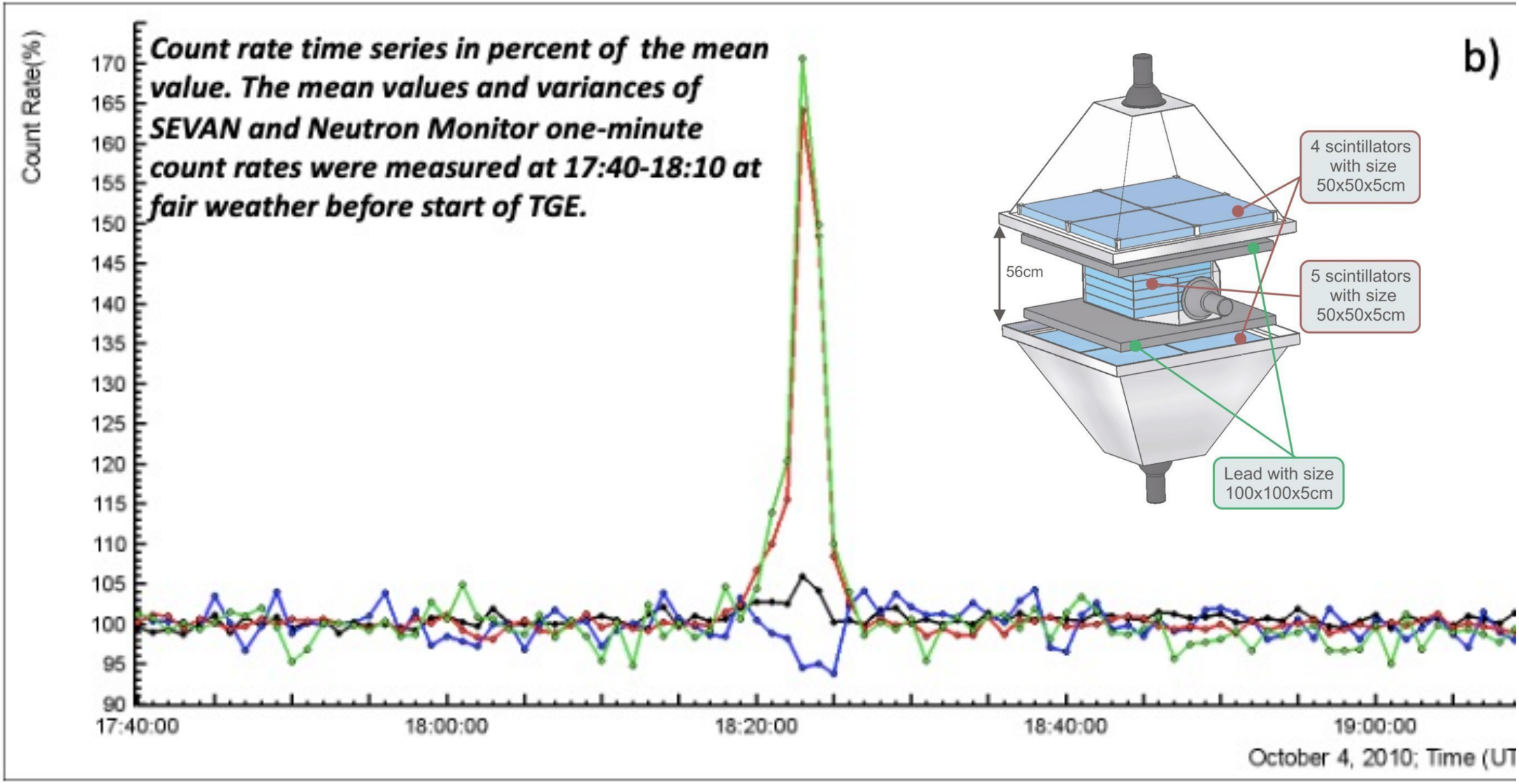
Section of the Neutron Monitor

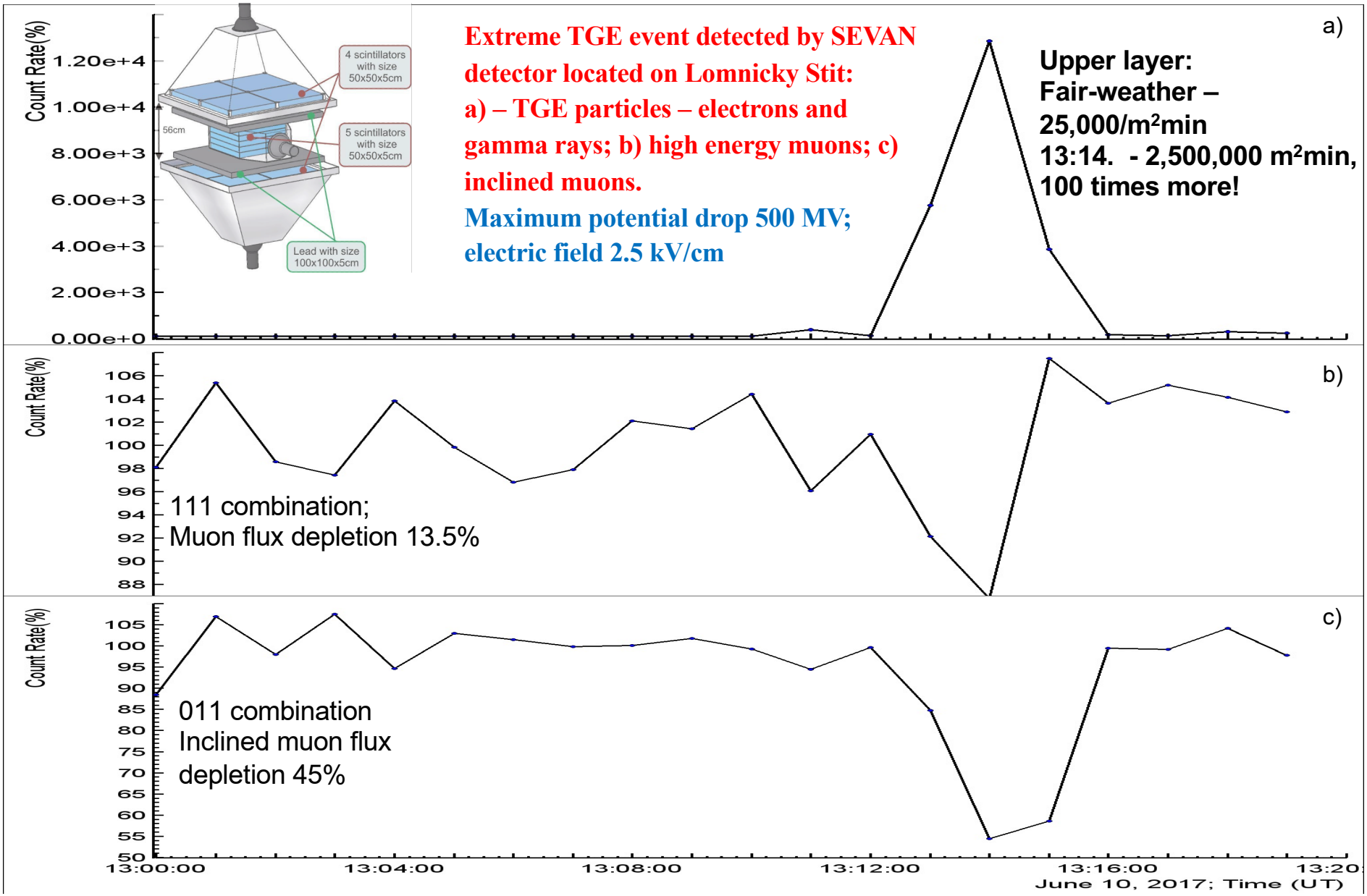
COSMIC RAY DIVISION
Alikhanyan Physics Institute,
Alikhanyan Brothers 2,
Yerevan 375036, Armenia

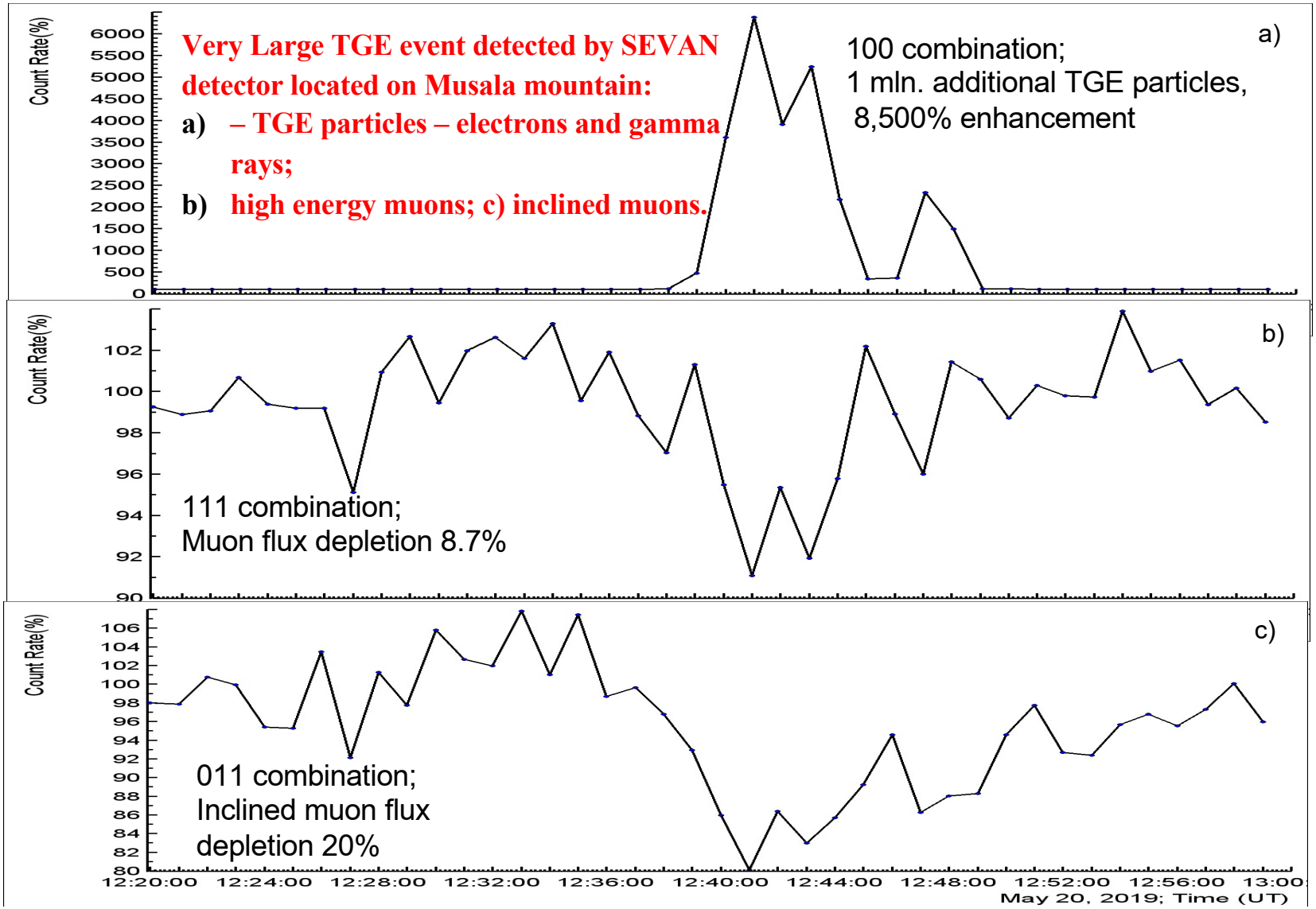

MUSALA (highest peak of Eastern Europe)
42 11' 00''N 23 34' 00''E
2925 m


Lomnický štít (LS)
49°11′45″N 20°12′46″E
2634 m
LS
SP

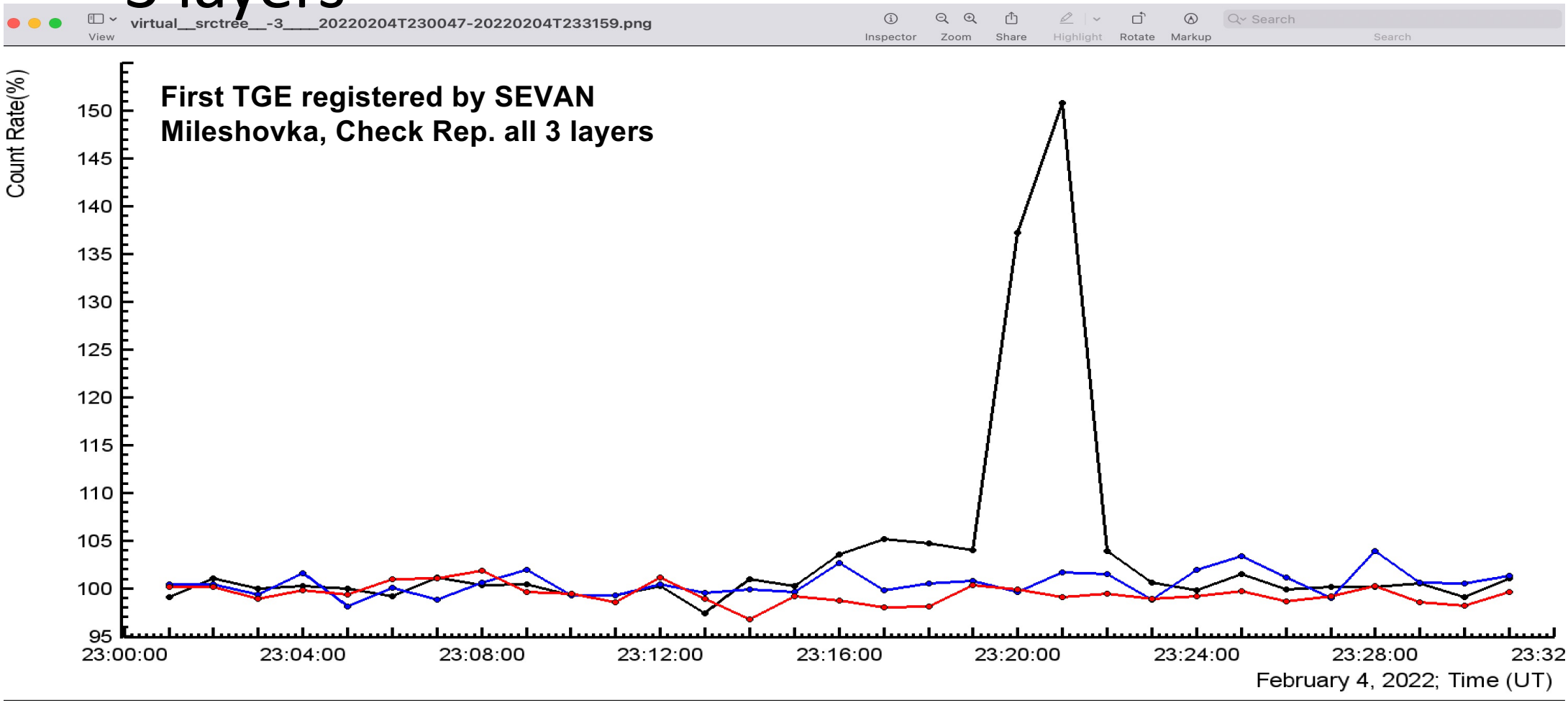

Zugspitze (Germany's **highest peak**),
47°25′16″N 10°59′07″E
2962 a.s.l.


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

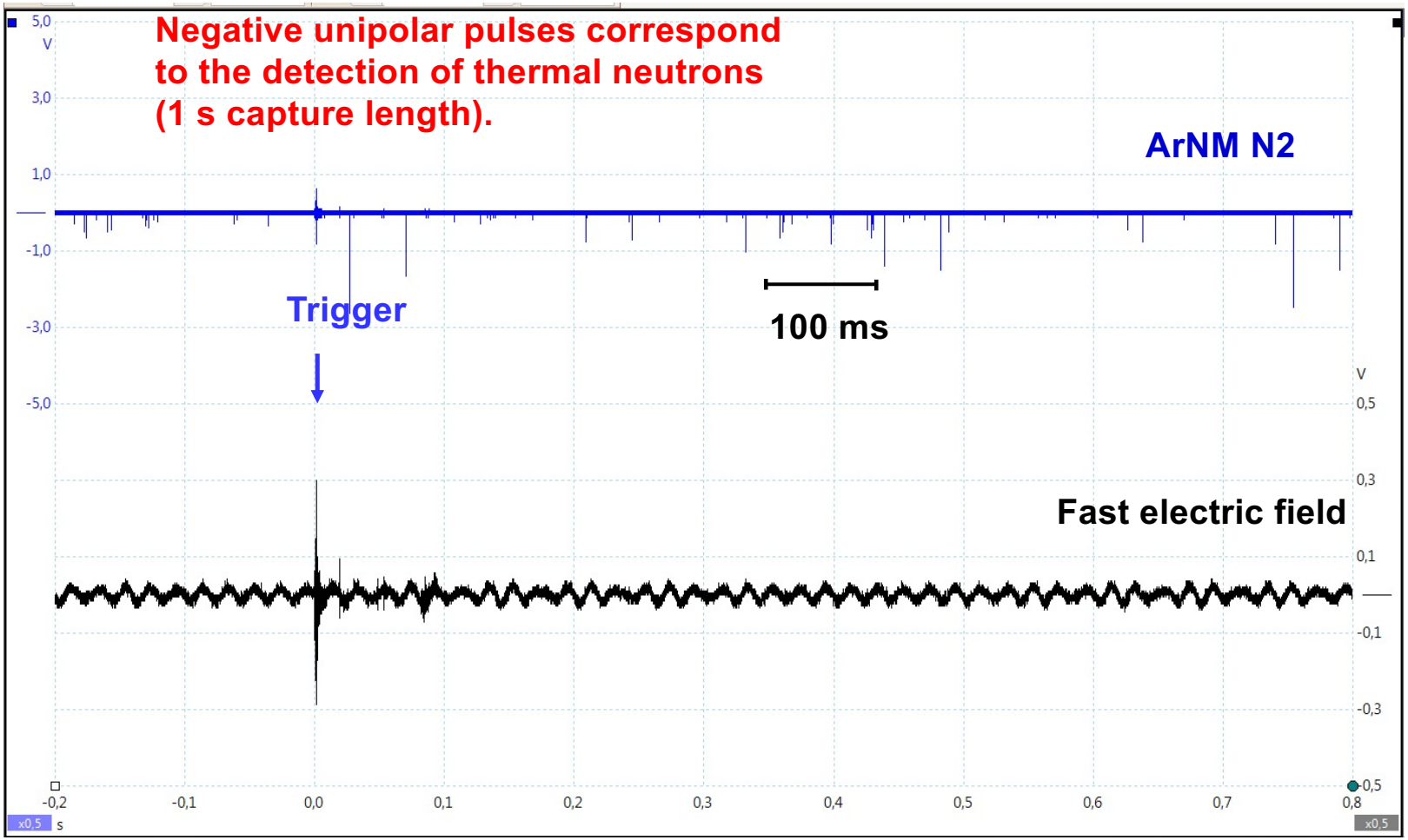

Extreme TGE event detected by SEVAN detector located on Lomnicky Stit:
a) – TGE particles – electrons and gamma rays; b) high energy muons; c) inclined muons.
Maximum potential drop 500 MV; electric field 2.5 kV/cm
4 scintillators with size 50x50x5cm
5 scintillators with size 50x50x5cm
56cm
Lead with size 100x100x5cm
a)
Upper layer:
Fair-weather – 25,000/m²min
13:14. - 2,500,000 m²min, 100 times more!
Count Rate(%)
b)
111 combination;
Muon flux depletion 13.5%
c)
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.
a)
100 combination;
1 mln. additional TGE particles,
8,500% enhancement
Count Rate(%)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
b)
111 combination;
Muon flux depletion 8.7%
102
100
98
96
94
92
90
c)
011 combination;
Inclined muon flux
depletion 20%
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)

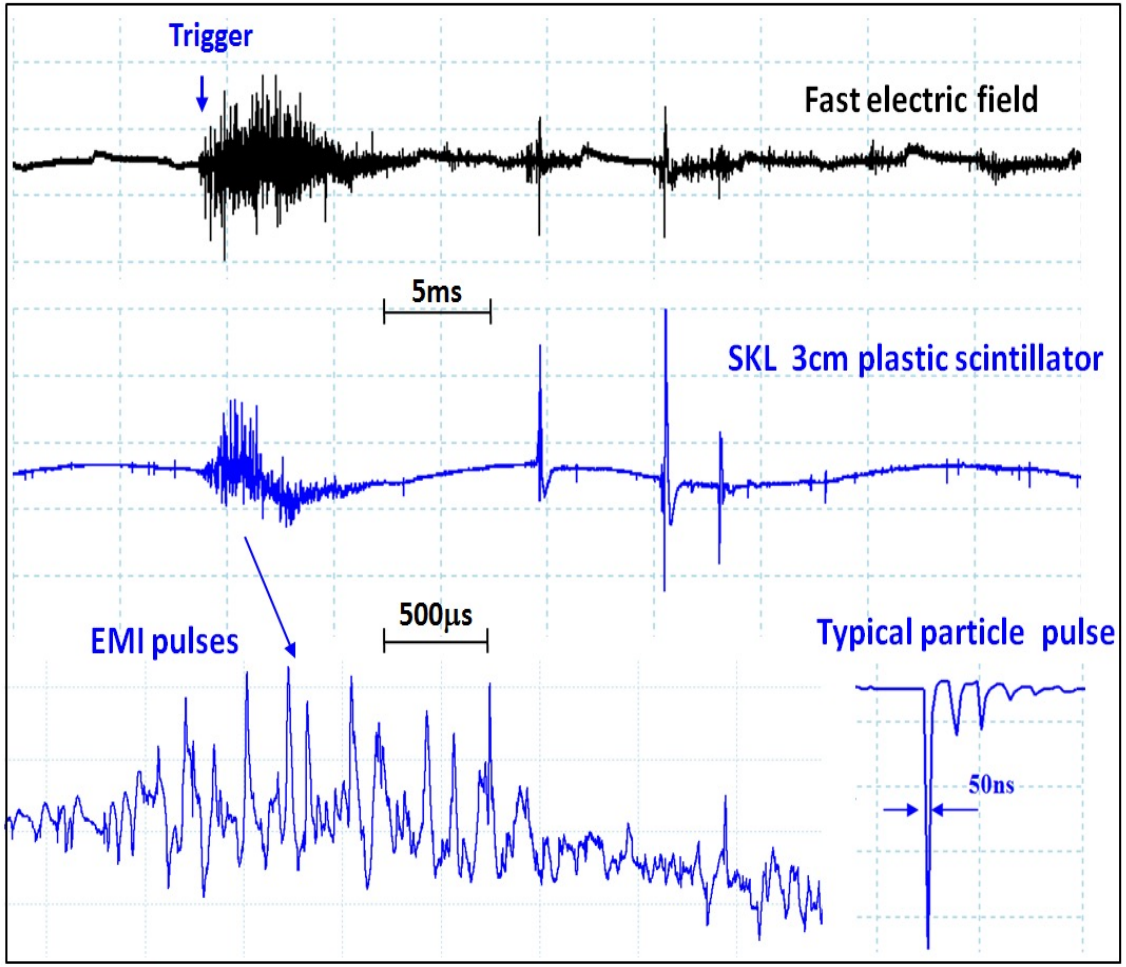
First TGE registered by SEVAN Mileshovka, all 3 layers



Origin of the particle bursts: synchronized pulses from particle detectors and from broadband antenna detected during lightning flash within 1 s capture length.

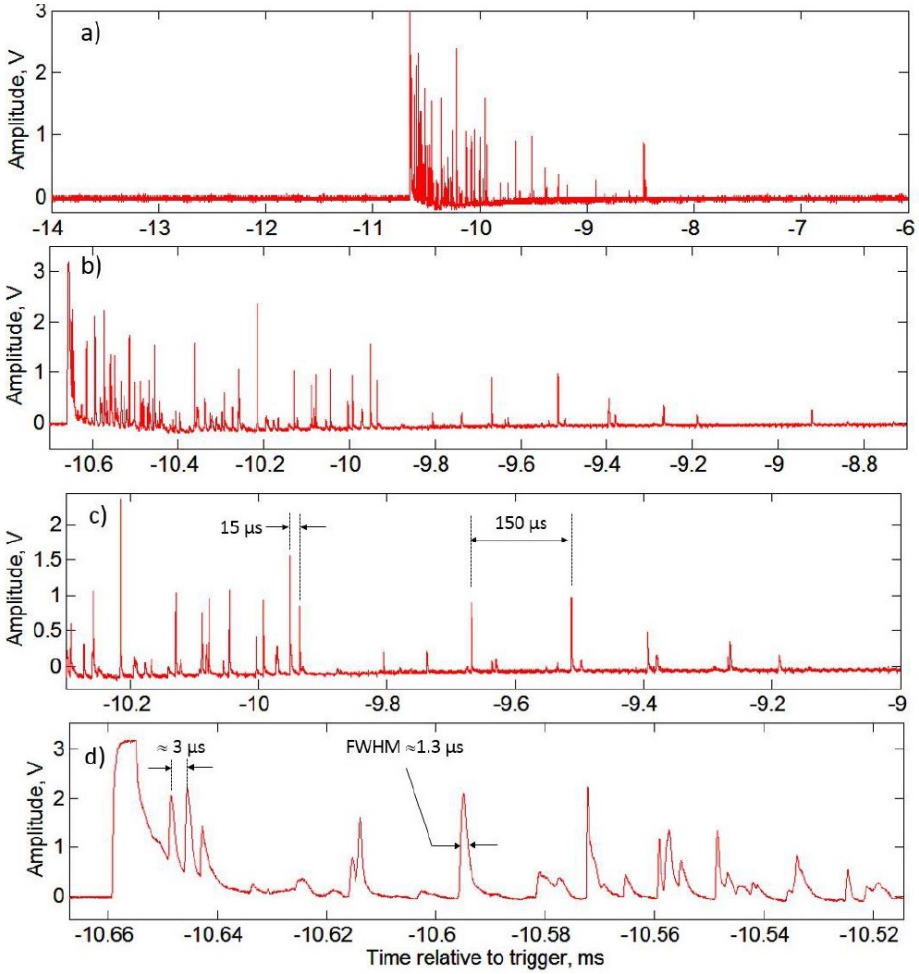


By 7 year monitoring we conclude that Lightning flashes do not produce MeV particles, they terminate TGE only.

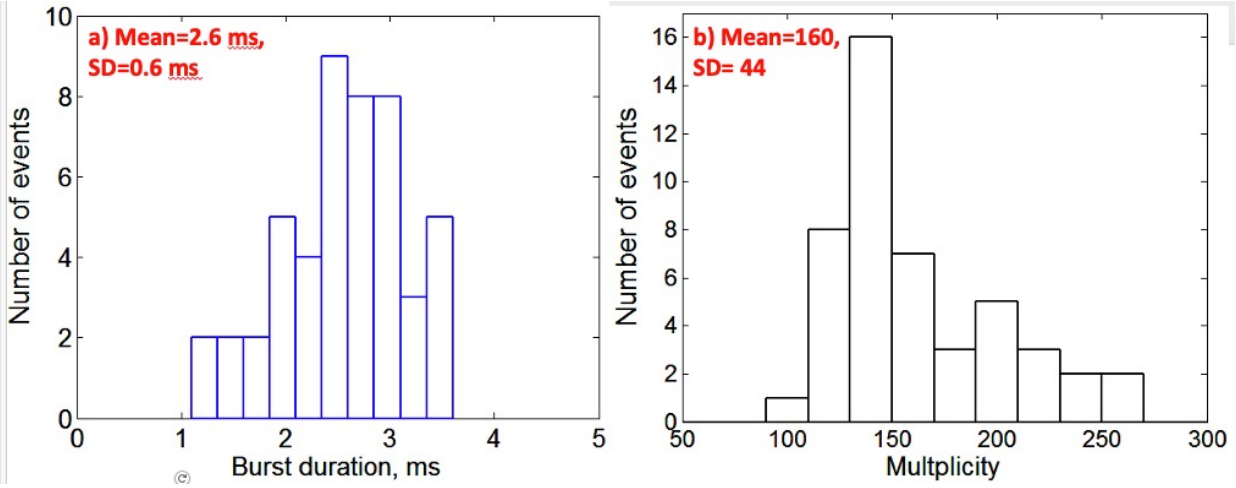


Typical EMI signatures from atmospheric discharges. Synchronized time-series of the pulses of fast electric field and signals from plastic scintillators.

Particle bursts detected on the earth's surface by Aragats Neutron Monitor

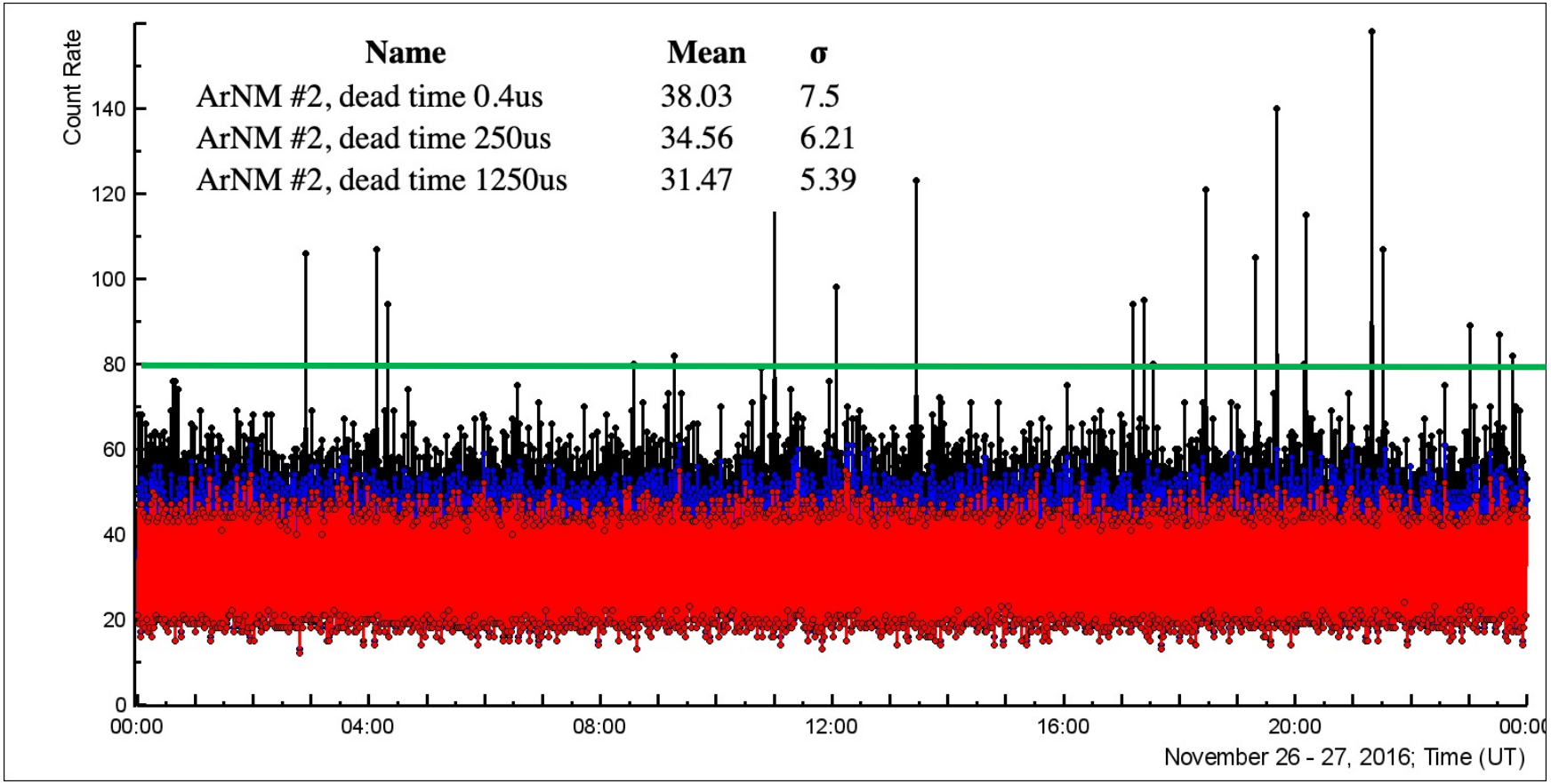


Oscilloscope records of neutron burst that occurred at 4:08:05 on November 26, 2016. Burst duration is ≈ 2.2 ms, the multiplicity is 107 per m^2. The four panels (a-c) show the records of the burst on different time scales.

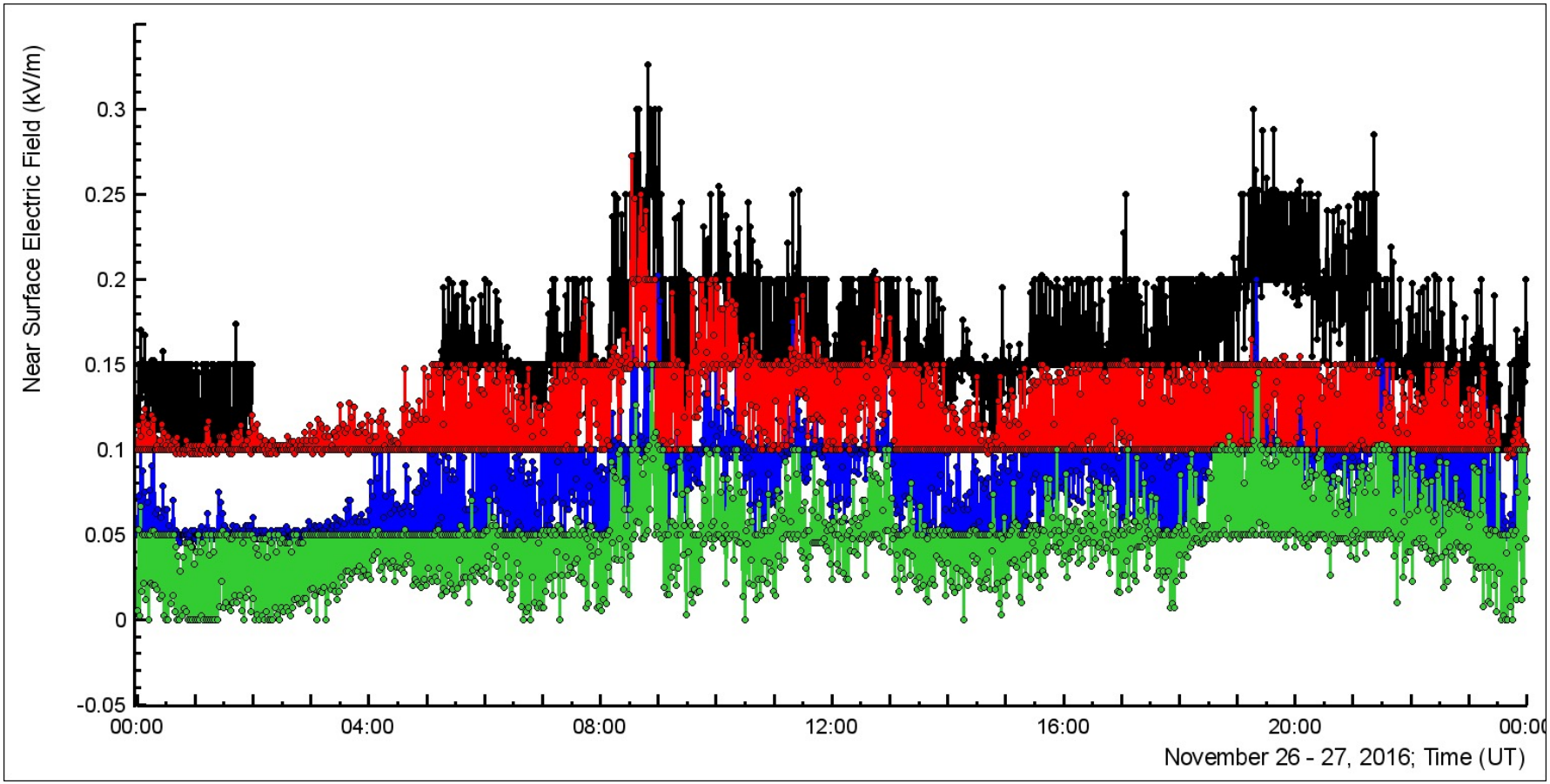


Histogram of the neutron burst duration (a) and corresponding multiplicity histogram (b).

ArNM: Proportional Chamber N 2, 20 signals above 5sigma daily!



No storms, no lightning flashes: Fair-weather electric field measured by EFM-100 network



Data sources

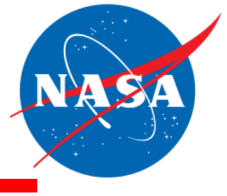
- Observations/Models needed to support research
  - **TGE energy spectra measured by particle detector networks on Aragats and on the highest peaks of Eastern Europe and Germany (SEVAN network);**
  - **Corresponding measurements of near-surface electric fields, lightning location, skies above particle 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

Avenues for Collaborations across NASA



- The lower and upper dipoles are interconnected. Placing particle detectors at sites of violent thunderstorms in Latin America (or/and measuring possible TGFs originated from thunderstorms above Aragats by space-borne facilities) will help to better understand particle-lightning and TGF - TGEs relations.
- Surface networks of particle detectors (SEVAN) lightning trackers (WWLLN, EFM-100) provide information on global processes in the ionosphere-earth electric circuit.
- Establishing a better exchange of results obtained in TGE and TGF physics;
- Comparison of models, energy spectra measured on the earth's surface and in the space;
- Research of lightning-particle burst relations in TGEs and TGFs;
- Models of lightning initiations and TLEs in the lower atmosphere and in the upper atmosphere and beyond;
- Measurements of the parameters of the atmosphere by NASA satellites for the input to WRF modeling the charged layers above Aragats;

Miscelaneous

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.**

Expansion of SEVAN network: connecting atmospheric and space physics

- TGEs are detected in Russia, 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).