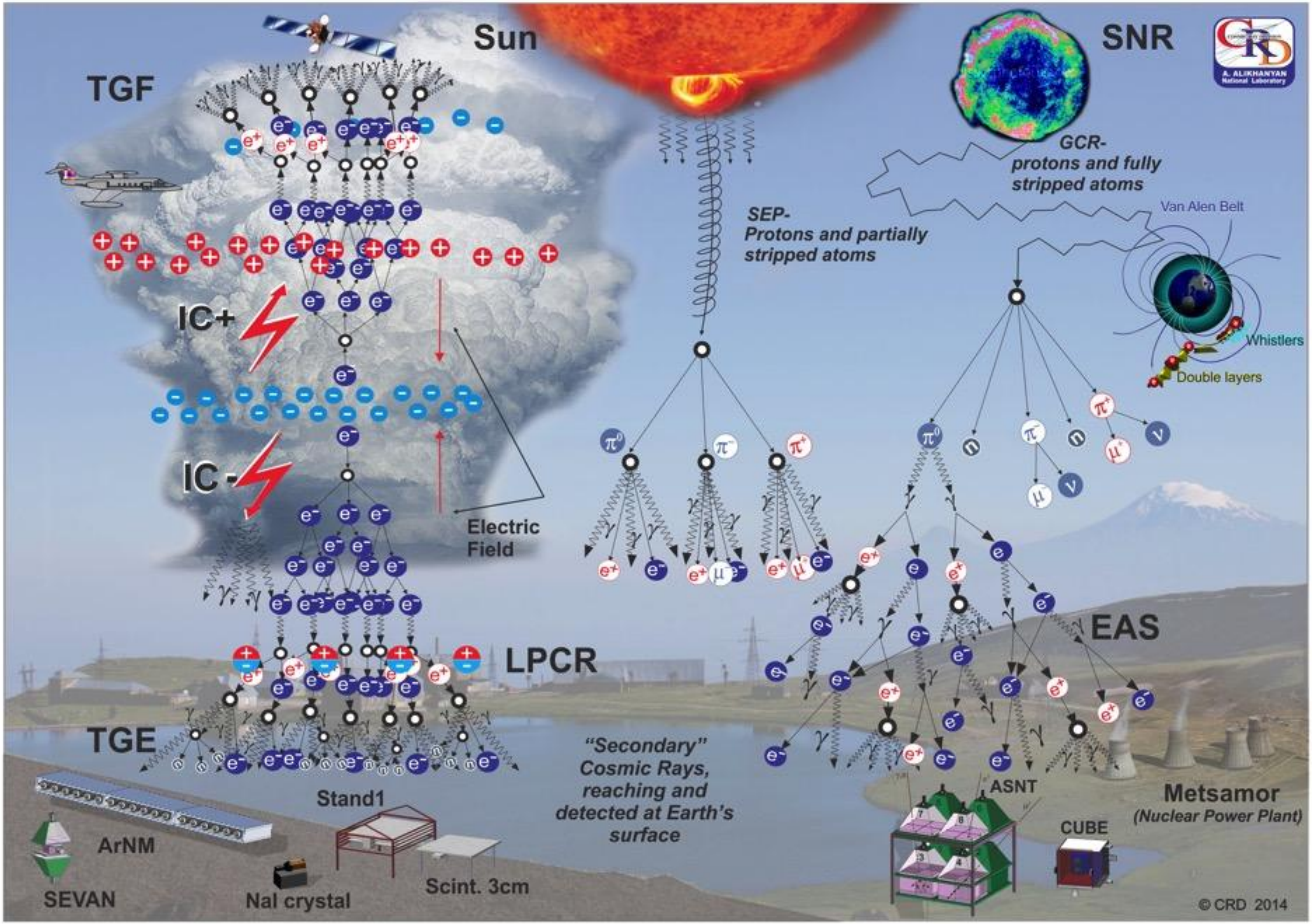
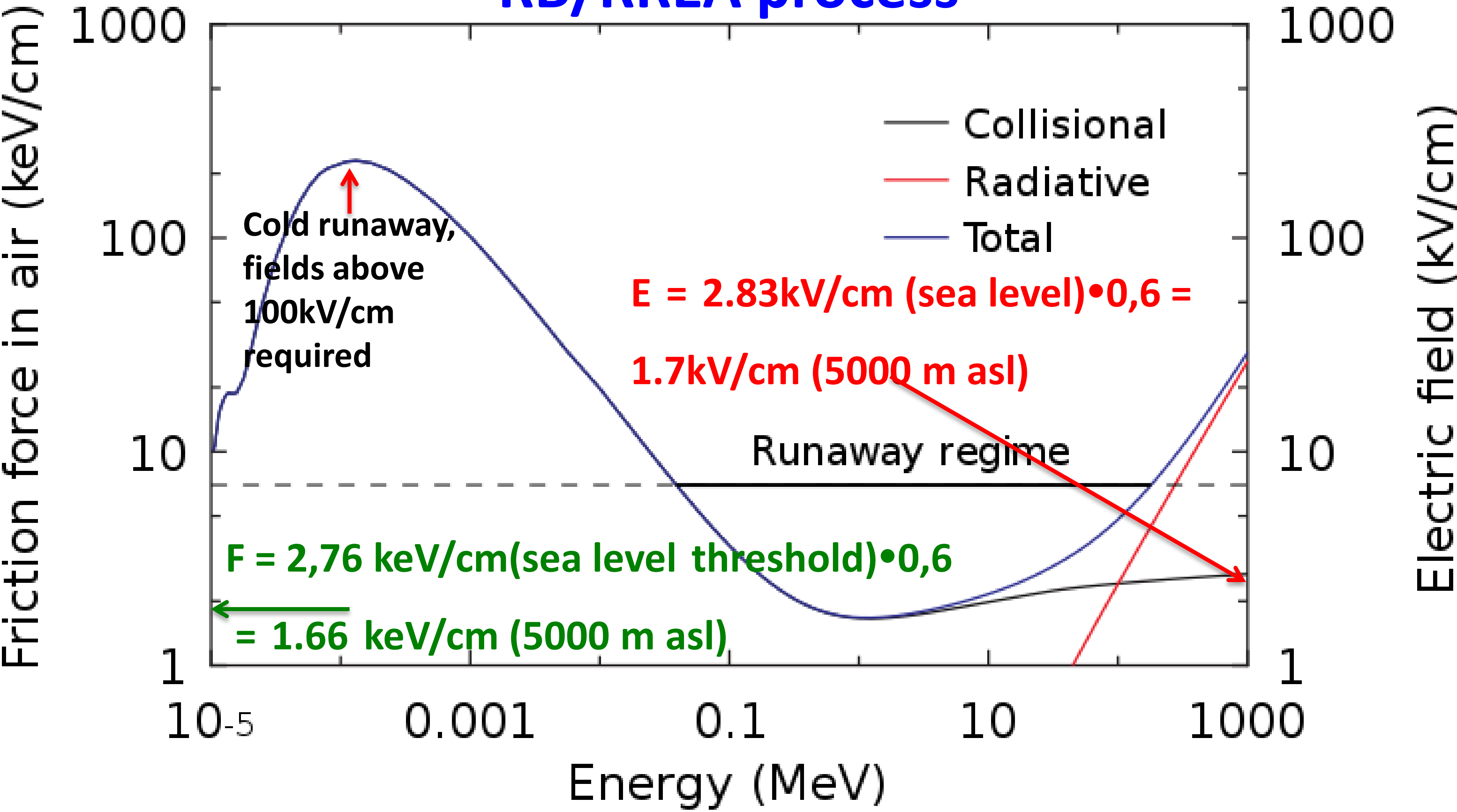
High Energy Physics in Atmosphere (HEPA): origin of particle fluxes

A.Chilingarian,Yerevan Physics Institute

Origin of Secondary Cosmic Rays

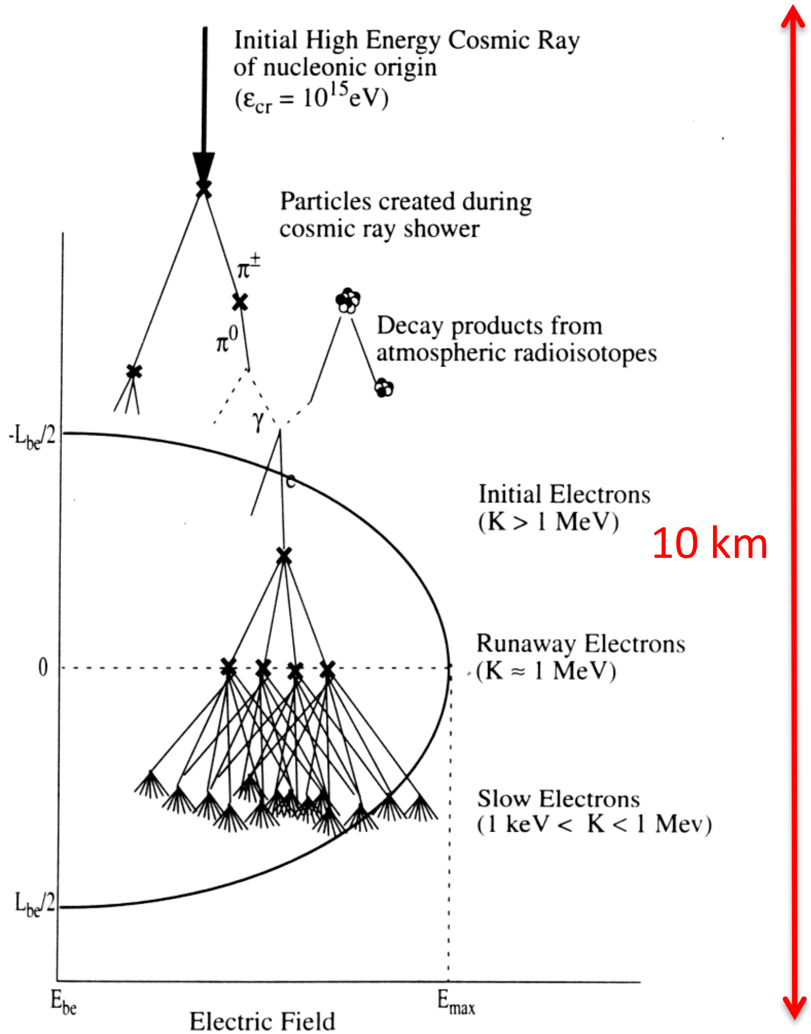


Electron energy losses in the atmosphere and energy gain from the intracloud electric field: RB/RREA process

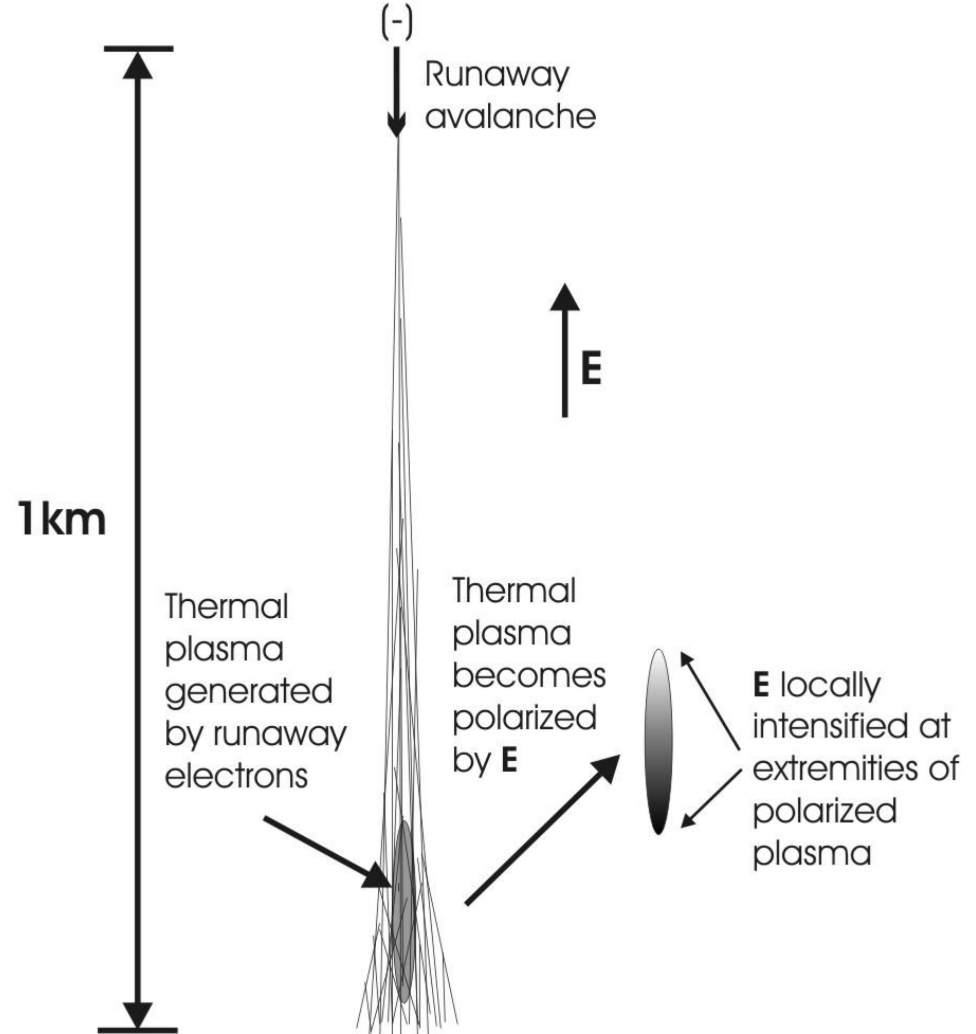


Gurevich et al., (1992), Symbalisty et al. (1998), Babich et al. (1998), Dwyer (2003), Chilingarian (2014)

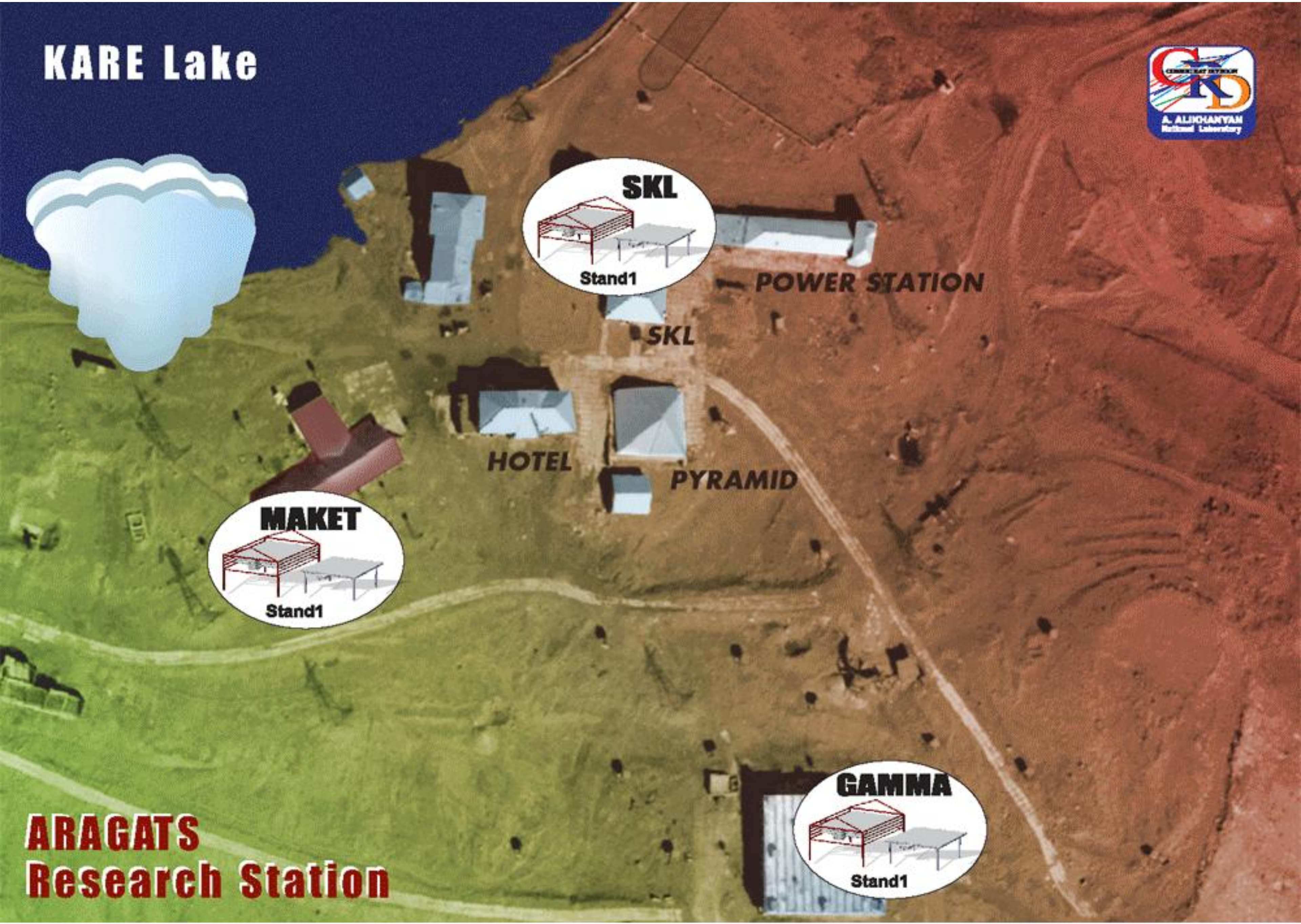
ECS and EAS



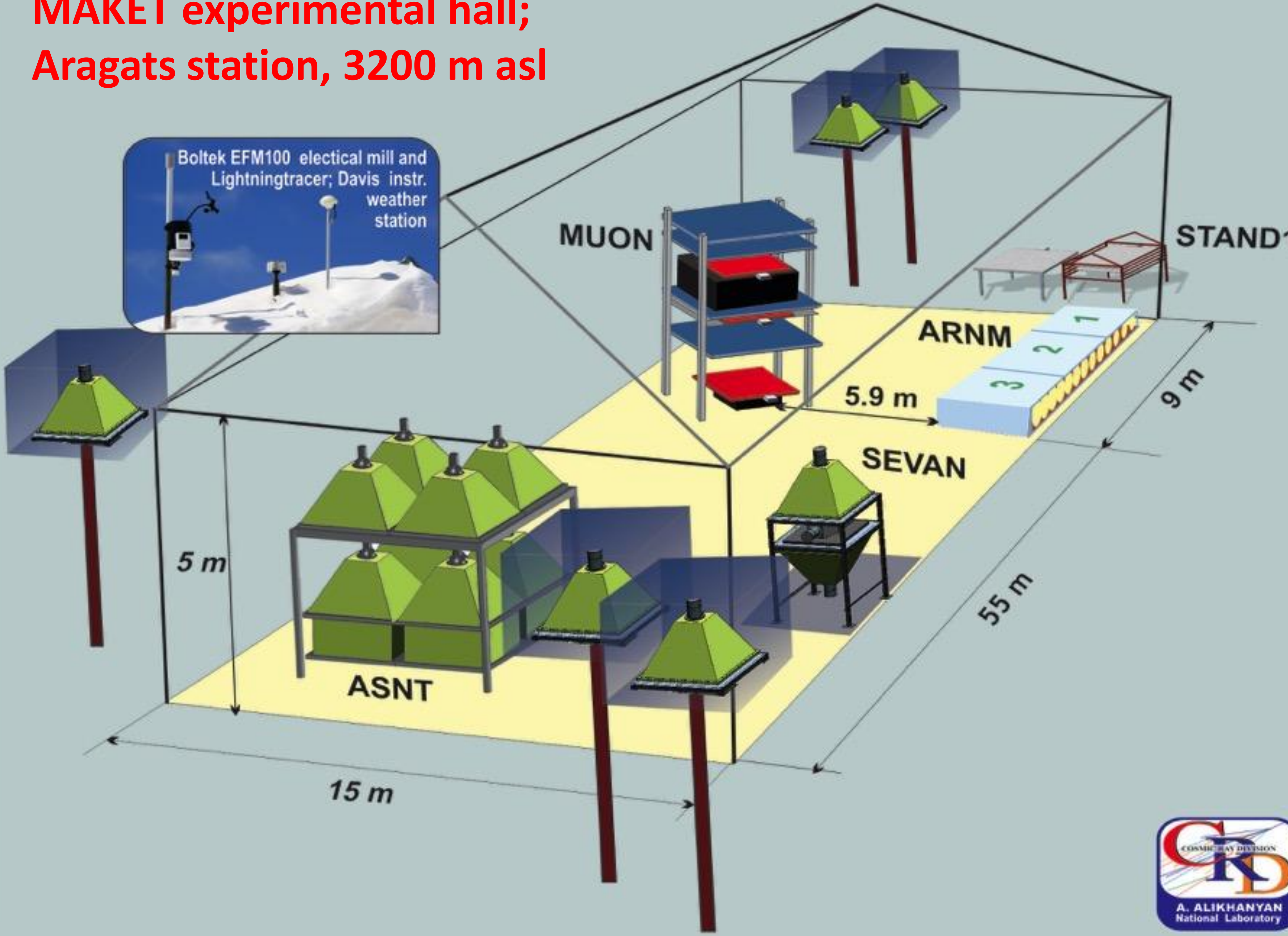
Initial High Energy Cosmic Ray
of nucleonic origin
($\varepsilon_{cr} = 10^{15}$eV)
Particles created during
cosmic ray shower
$\pi^{\pm}$
π^{0}
Decay products from
atmospheric radioisotopes
γ
$-L_{be}/2$
Initial Electrons
(K > 1 MeV)
0
Runaway Electrons
(K ≈ 1 MeV)
Slow Electrons
(1 keV < K < 1 Mev)
$L_{be}/2$
E_{be}
Electric Field
E_{max}
10 km

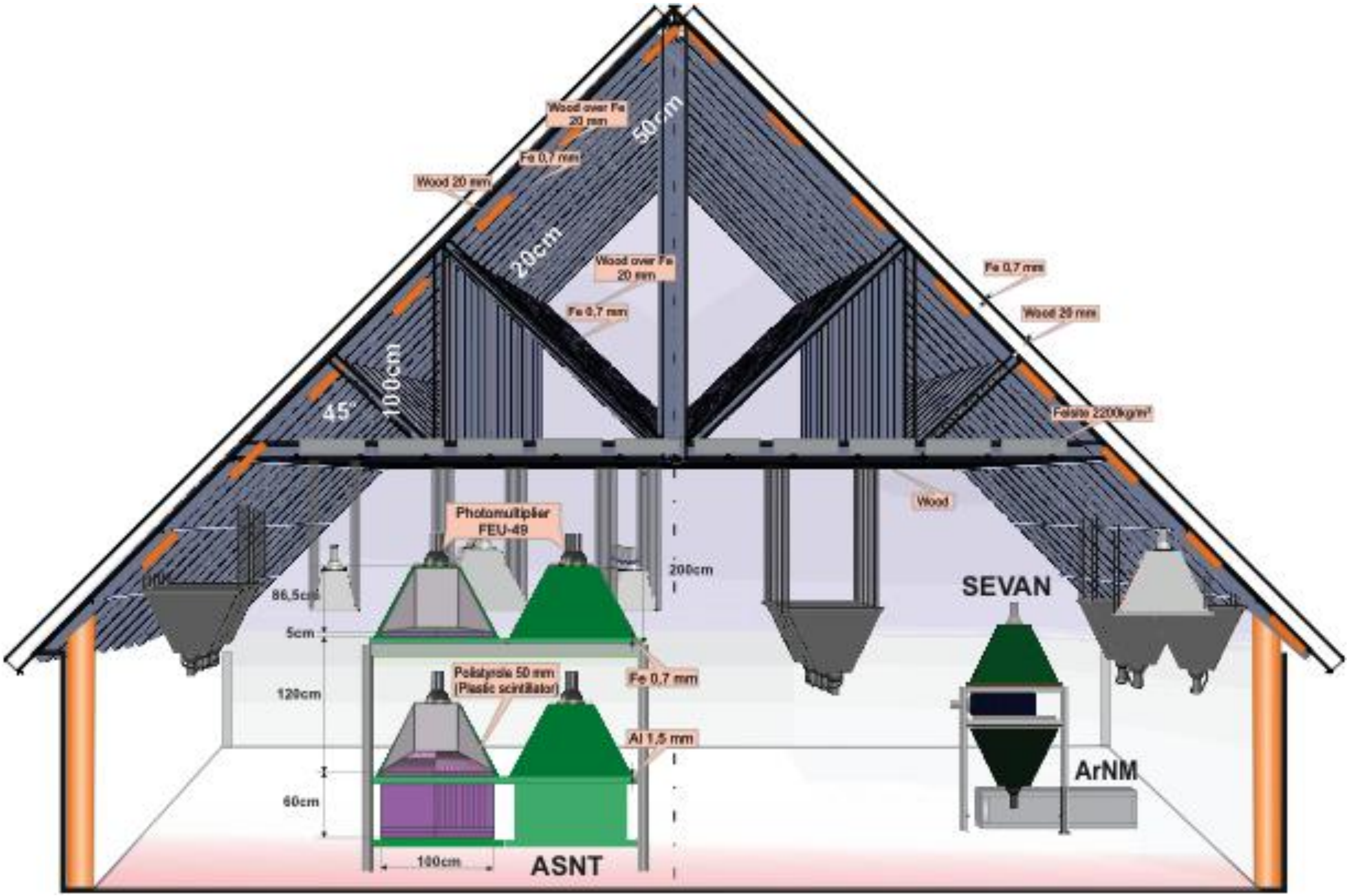


1km
(-)
Runaway
avalanche
E
Thermal
plasma
generated
by runaway
electrons
Thermal
plasma
becomes
polarized
by E
E locally
intensified at
extremities of
polarized
plasma

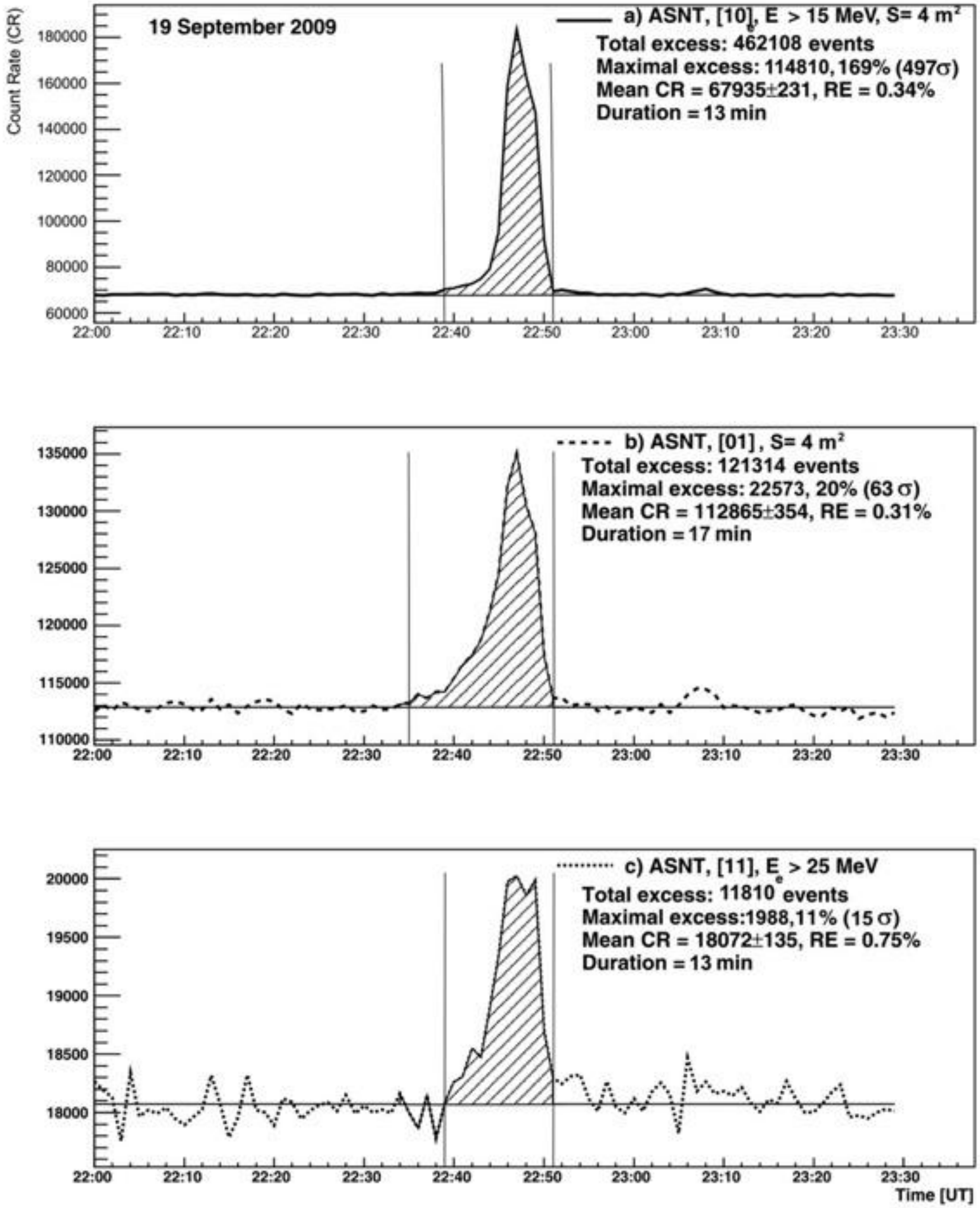

KARE Lake
SKL
Stand1
POWER STATION
SKL
HOTEL
PYRAMID
MAKET
Stand1
GAMMA
Stand1
ARAGATS
Research Station
A. ALIKHANYAN
National Laboratory

MAKET experimental hall; Aragats station, 3200 m asl

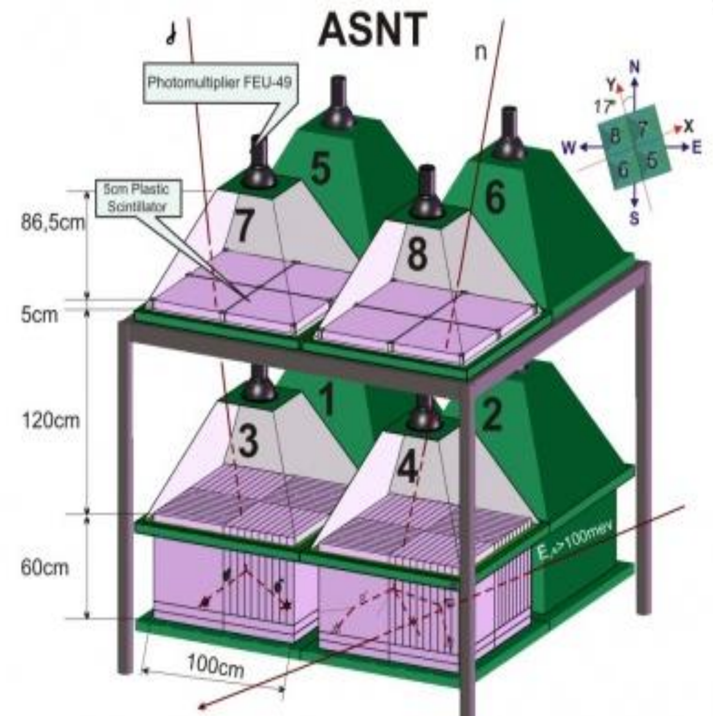




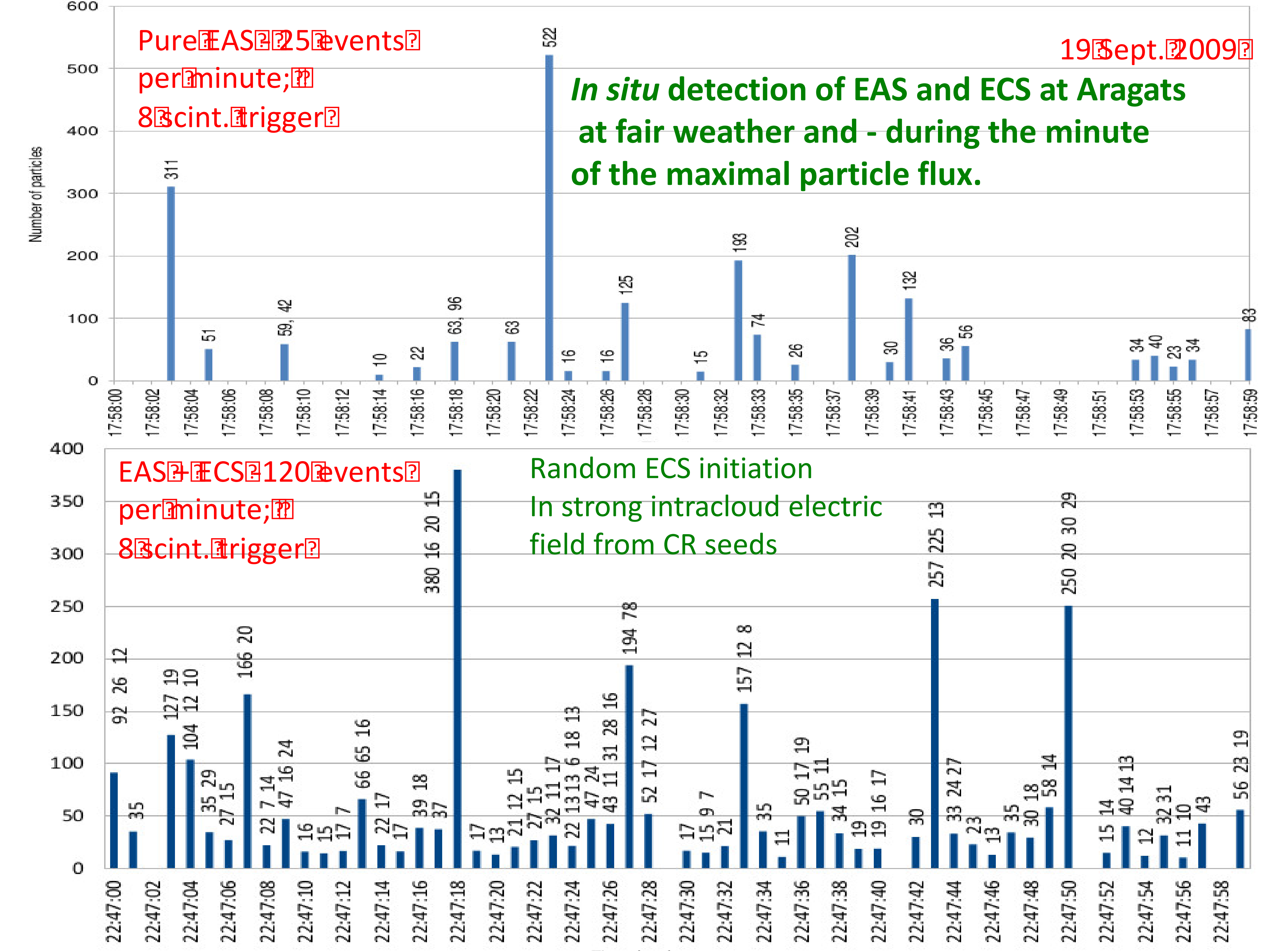
Wood over Fe
20 mm
50cm
Fe 0,7 mm
Wood 20 mm
20cm
Wood over Fe
20 mm
Fe 0,7 mm
Fe 0,7 mm
Wood 20 mm
100cm
45°
Felsite 2200kg/m³
Wood
Photomultiplier
FEU-49
200cm
86,5cm
SEVAN
5cm
120cm
Polistyrole 50 mm
(Plastic scintillator)
Fe 0,7 mm
Al 1,5 mm
ArNM
60cm
100cm
ASNT



Huge TGE of 19 September, 2009 was detected by all ASEC monitors :
ASNT (10) – > 5cm (1) and 60 (0)cm thick;
ASNT (01) – 5cm (0) and 60 (1)cm thick;
ASNT (11) – electrons E>25 MeV - 19 September event is only event with high energy

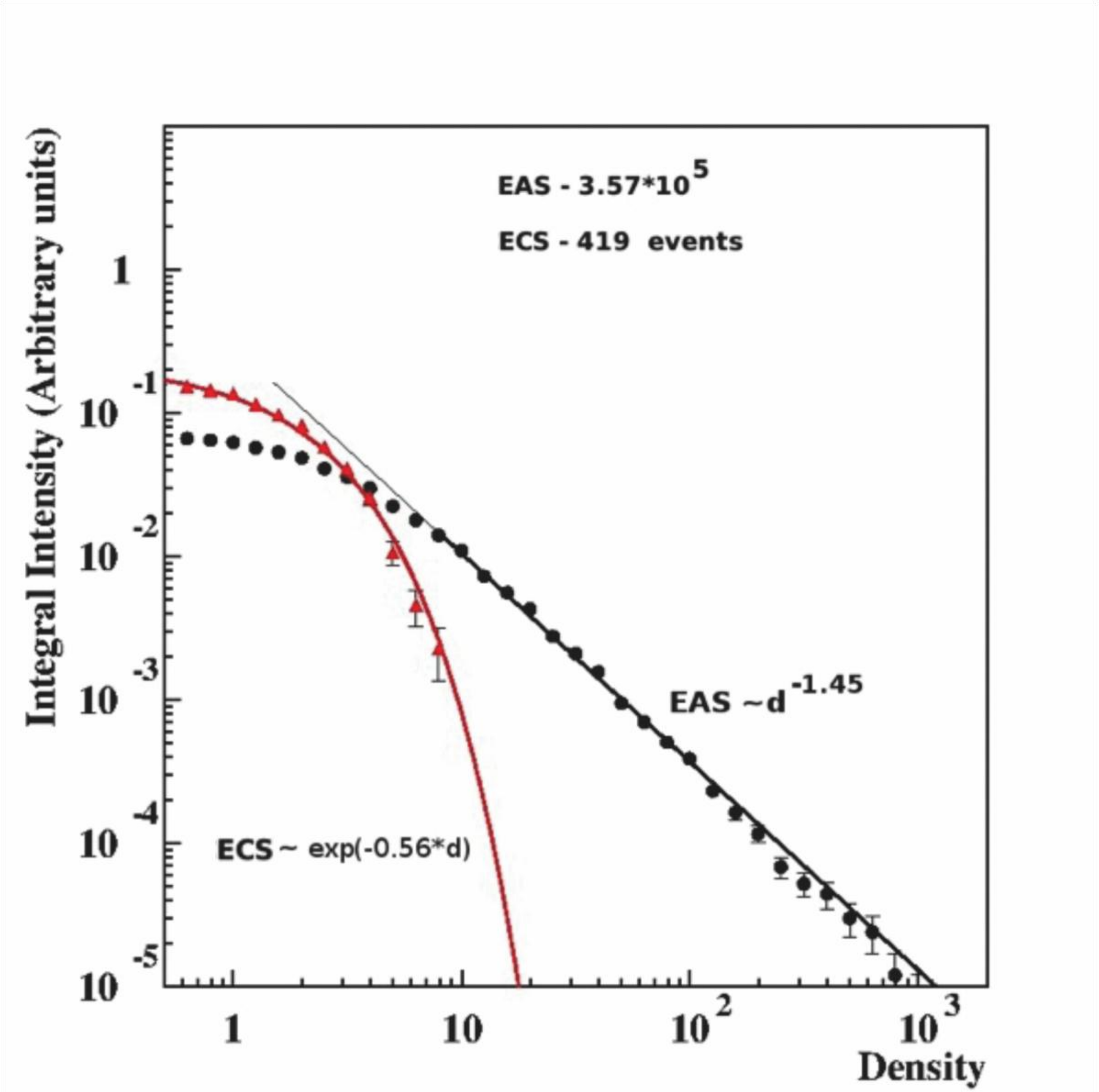


A. Chilingarian, A.Daryan, K.Arakelyan, et al., Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons, Phys.Rev. D., 82, 043009, 2010

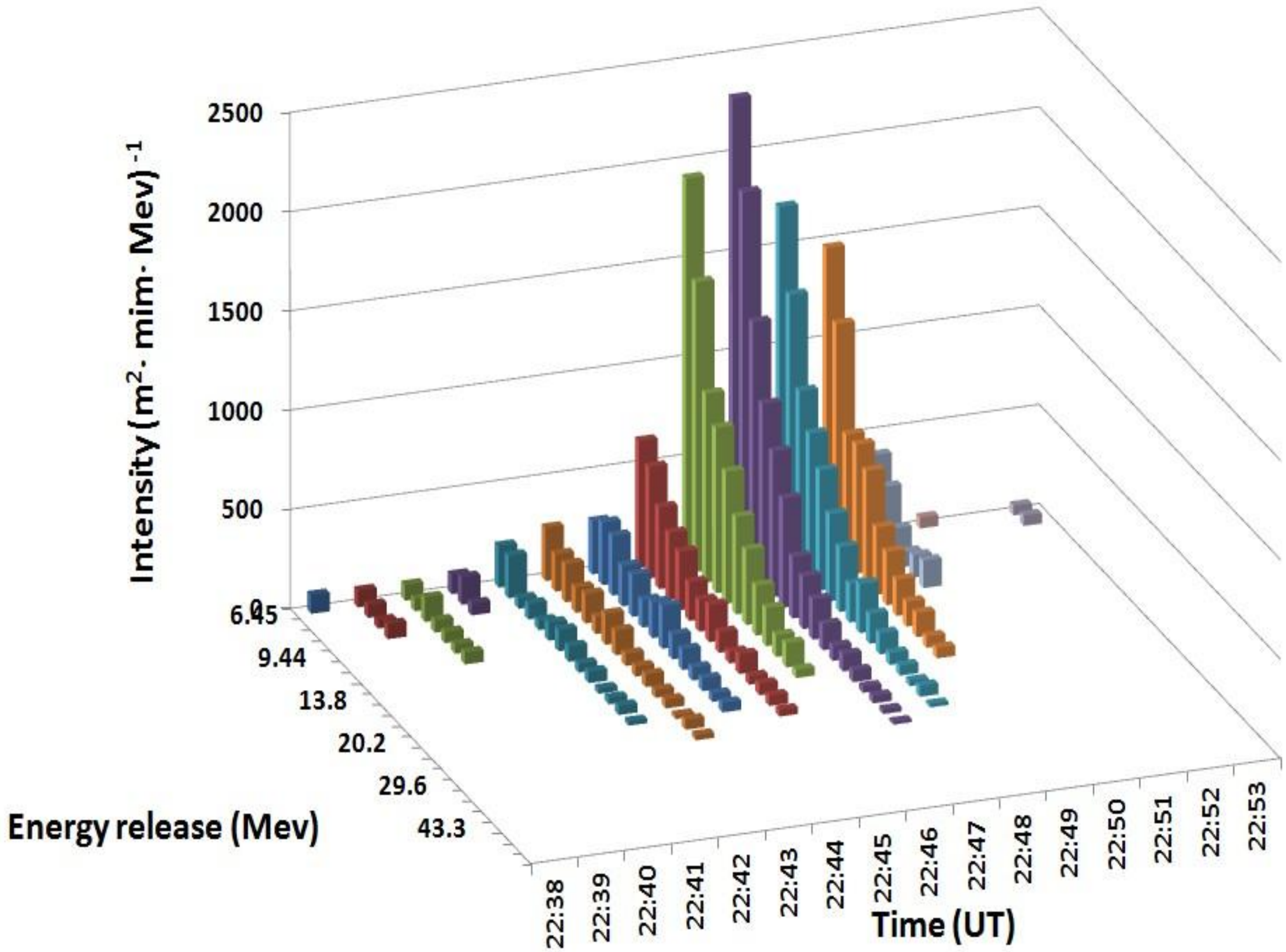


Pure EAS 25 events
per minute;
8 scint. trigger
19 Sept. 2009
In situ detection of EAS and ECS at Aragats
at fair weather and - during the minute
of the maximal particle flux.
Number of particles
EAS + ECS 120 events
per minute;
8 scint. trigger
Random ECS initiation
In strong intracloud electric
field from CR seeds

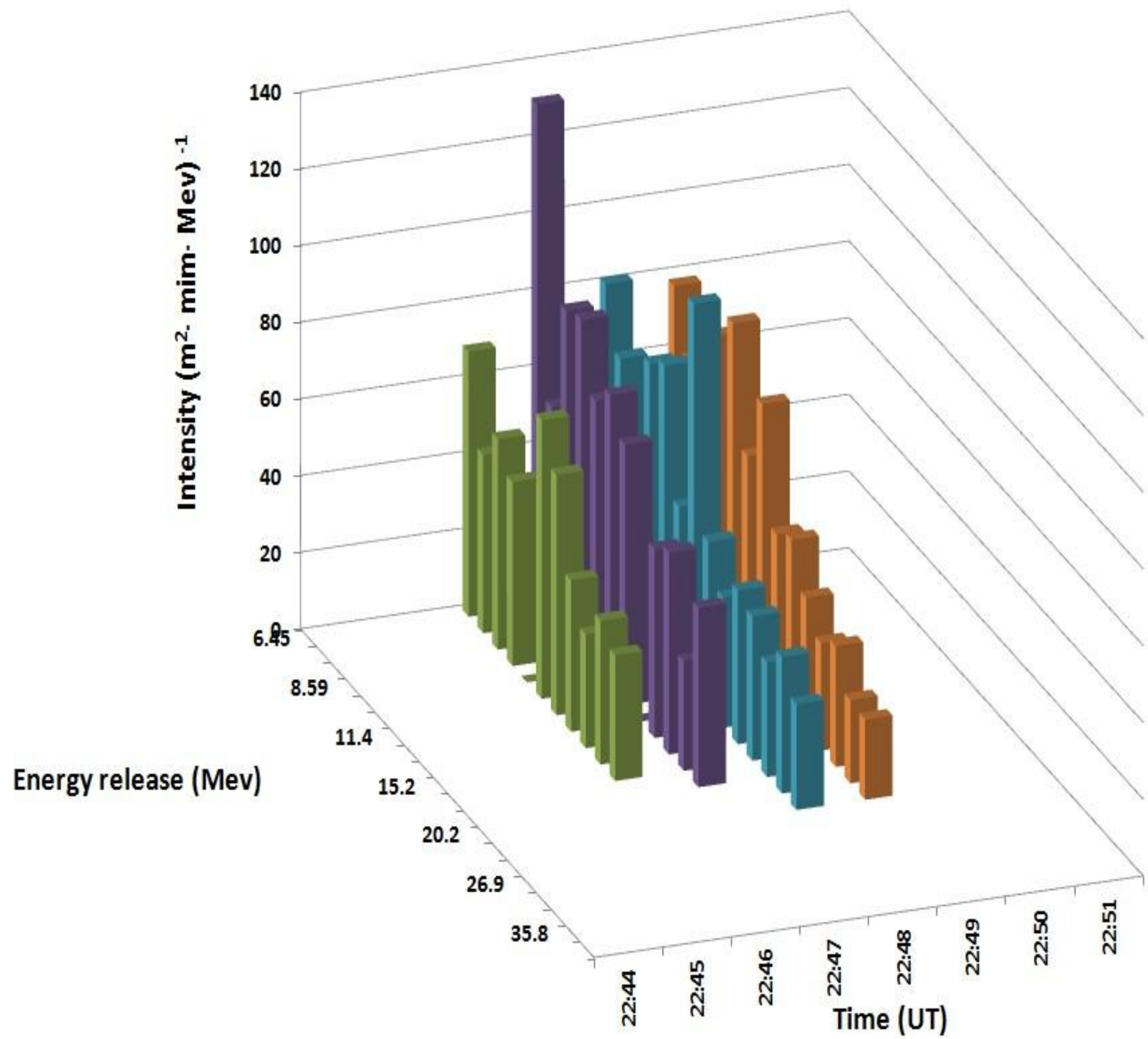
Extensive cloud showers (ECSs) are systematically different from Extensive air showers (EASs). Density spectra of 2 classes: ECS (with ~20% EAS contamination) and pure EAS



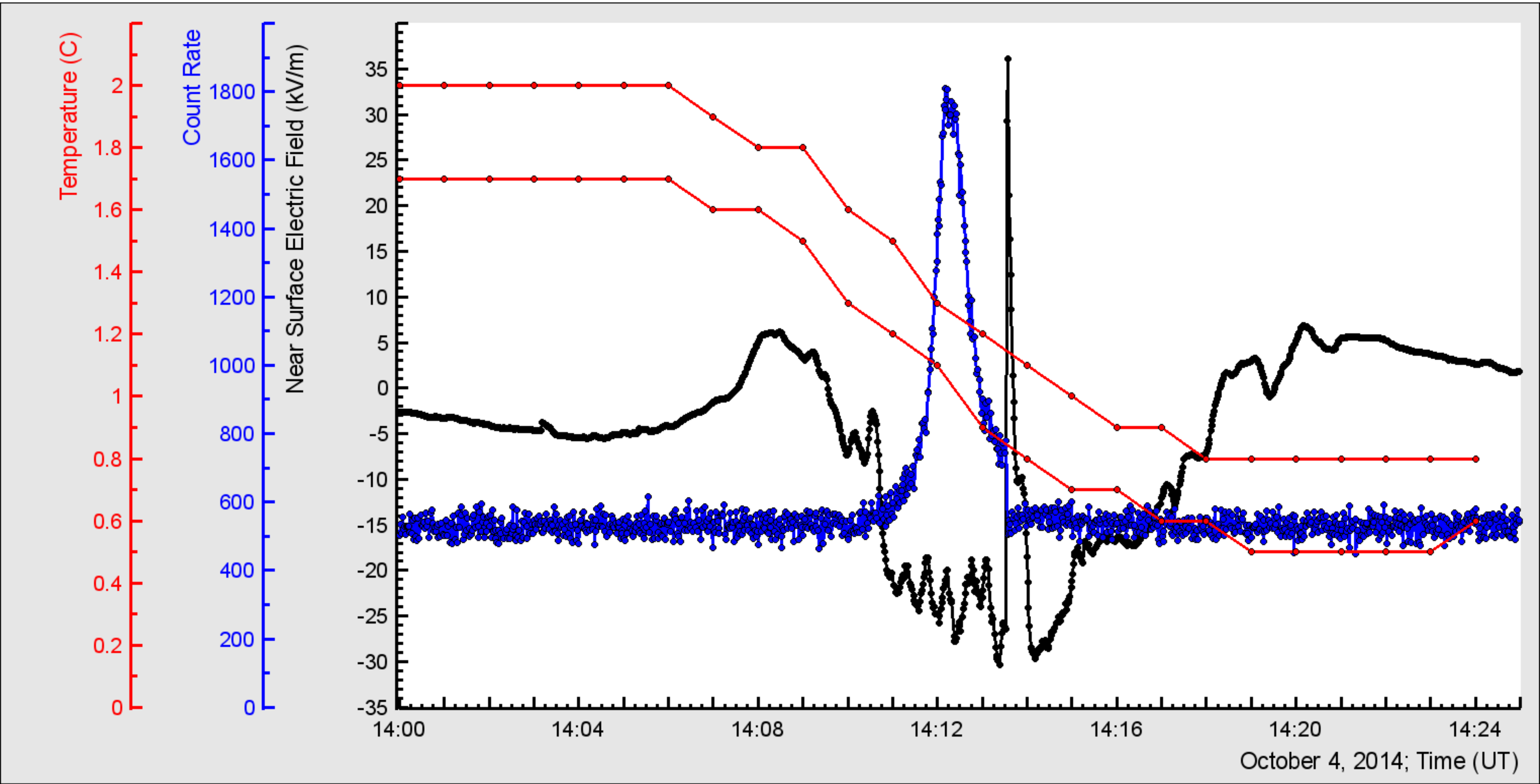
Differential energy release histogram of the TGE gamma rays obtained in 60 cm. thick scintillators of the ASNT array.

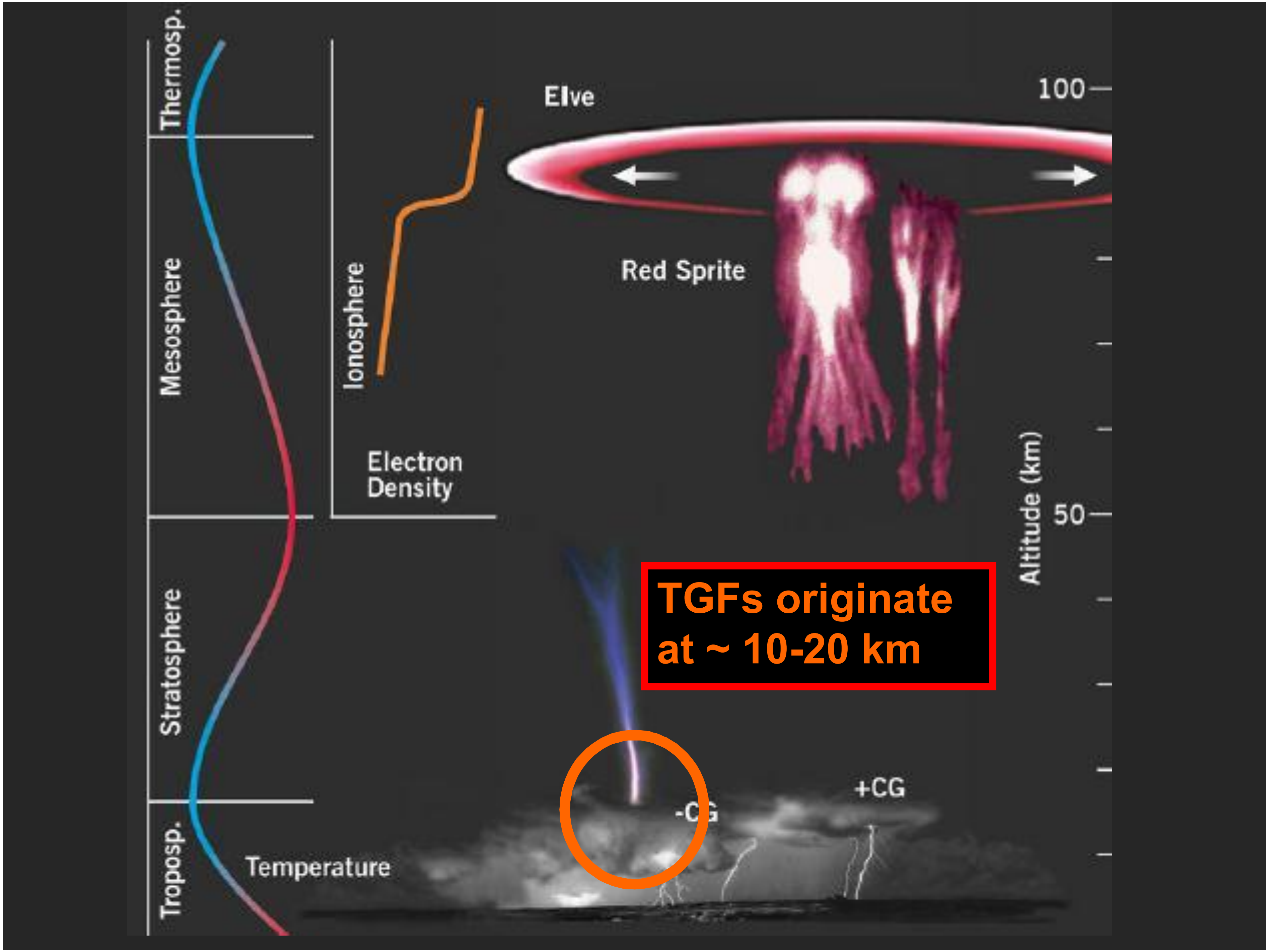


Differential energy release histogram of the TGE electrons obtained in 60 cm. thick scintillators of the ASNT detector.

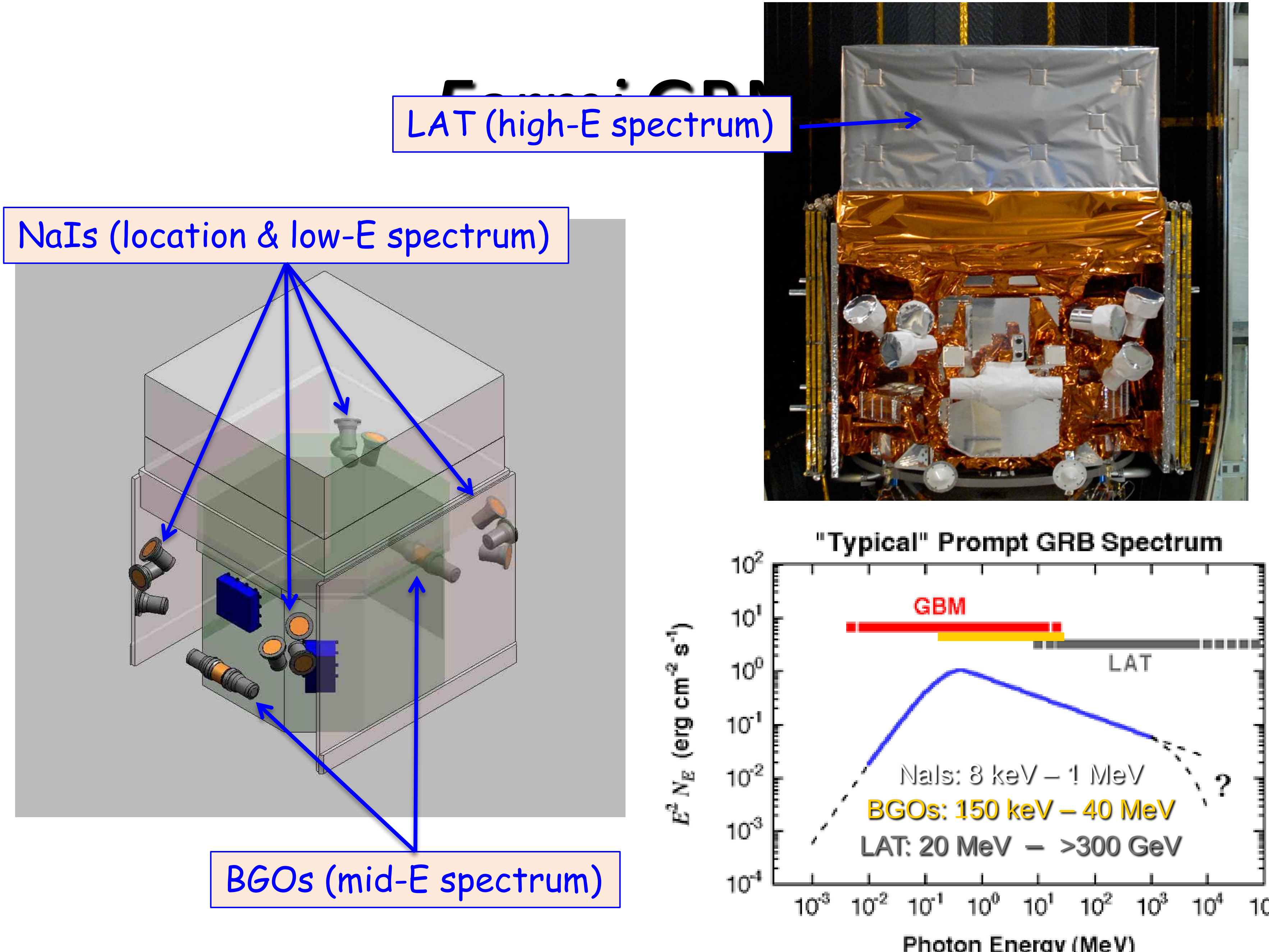


1-sec time series of count rate of 3 cm thick plastic scintillator (blue), near surface electric field (black); temperature (~1.3 C°) and dew point (~1.1 C°) used for the spread calculation (red). Strong lightning flash abruptly terminates TGE on14:13:38. Distance to cloud base 0.2 x 122 m ~ 25 m. Maximal energy of electrons: 20+20+5 MeV ~ 45 MeV



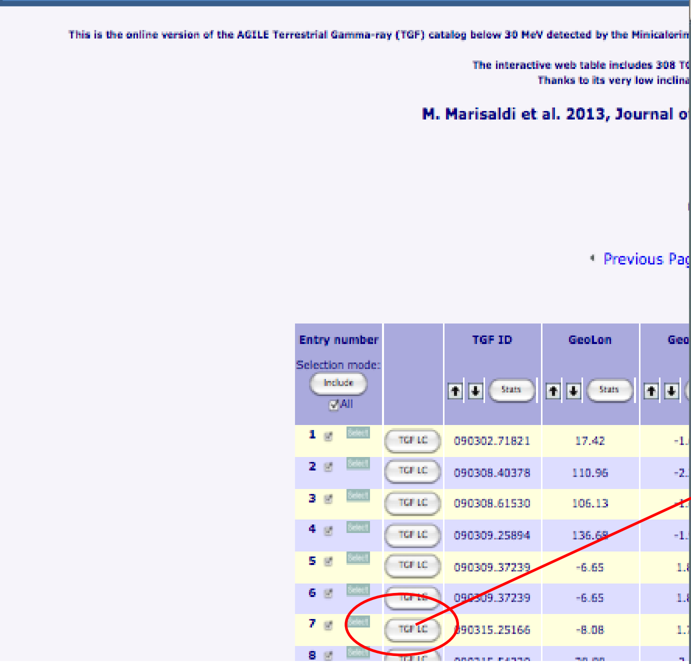


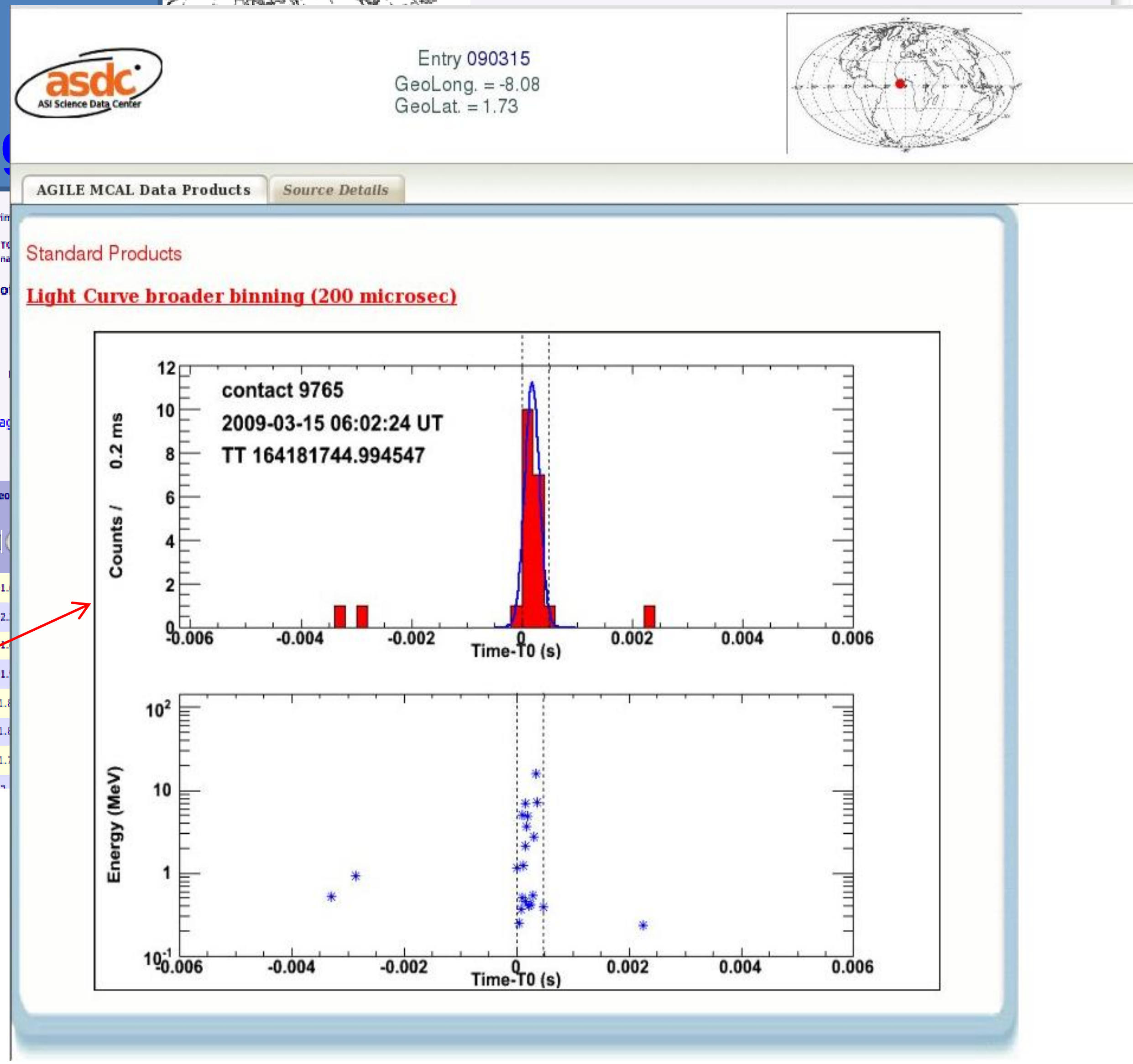
Thermosp.
Mesosphere
Stratosphere
Troposp.
Temperature
Ionosphere
Electron Density
Elve
Red Sprite
100
50
Altitude (km)
TGFs originate at ~ 10-20 km
-CG
+CG



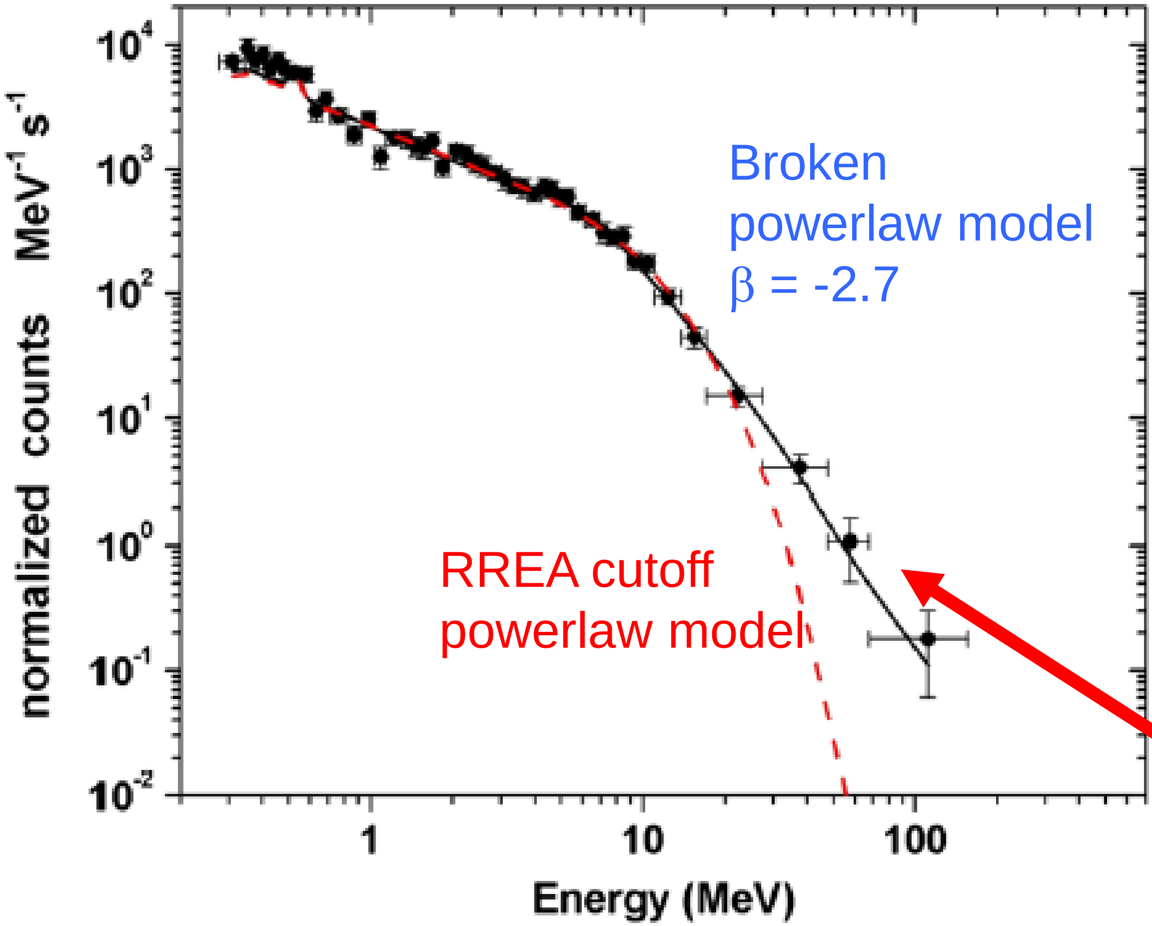
LAT (high-E spectrum)
NaIs (location & low-E spectrum)
BGOs (mid-E spectrum)
"Typical" Prompt GRB Spectrum
GBM
LAT
NaIs: 8 keV – 1 MeV
BGOs: 150 keV – 40 MeV
LAT: 20 MeV – >300 GeV
?
$E^2 N_E$ (erg cm^{-2} s^{-1})
Photon Energy (MeV)

MCAL TGF Catalogs ASDC interactive webpages: www.asdc.asi.it/mcaltg





TGF Cumulative spectrum

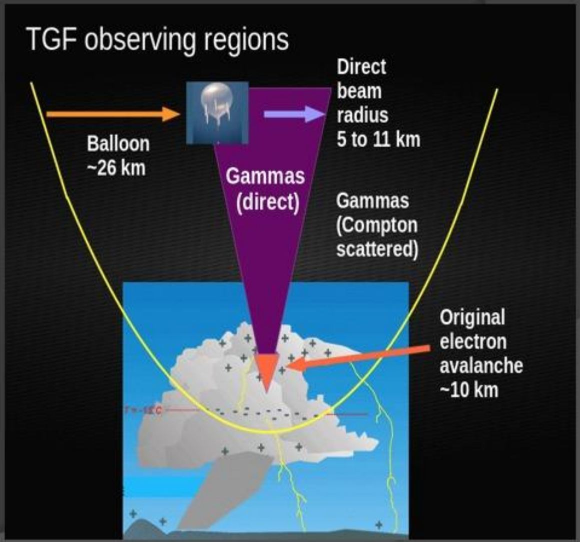


AGILE-MCAL crucial spectral contribution up to 100 MeV!!

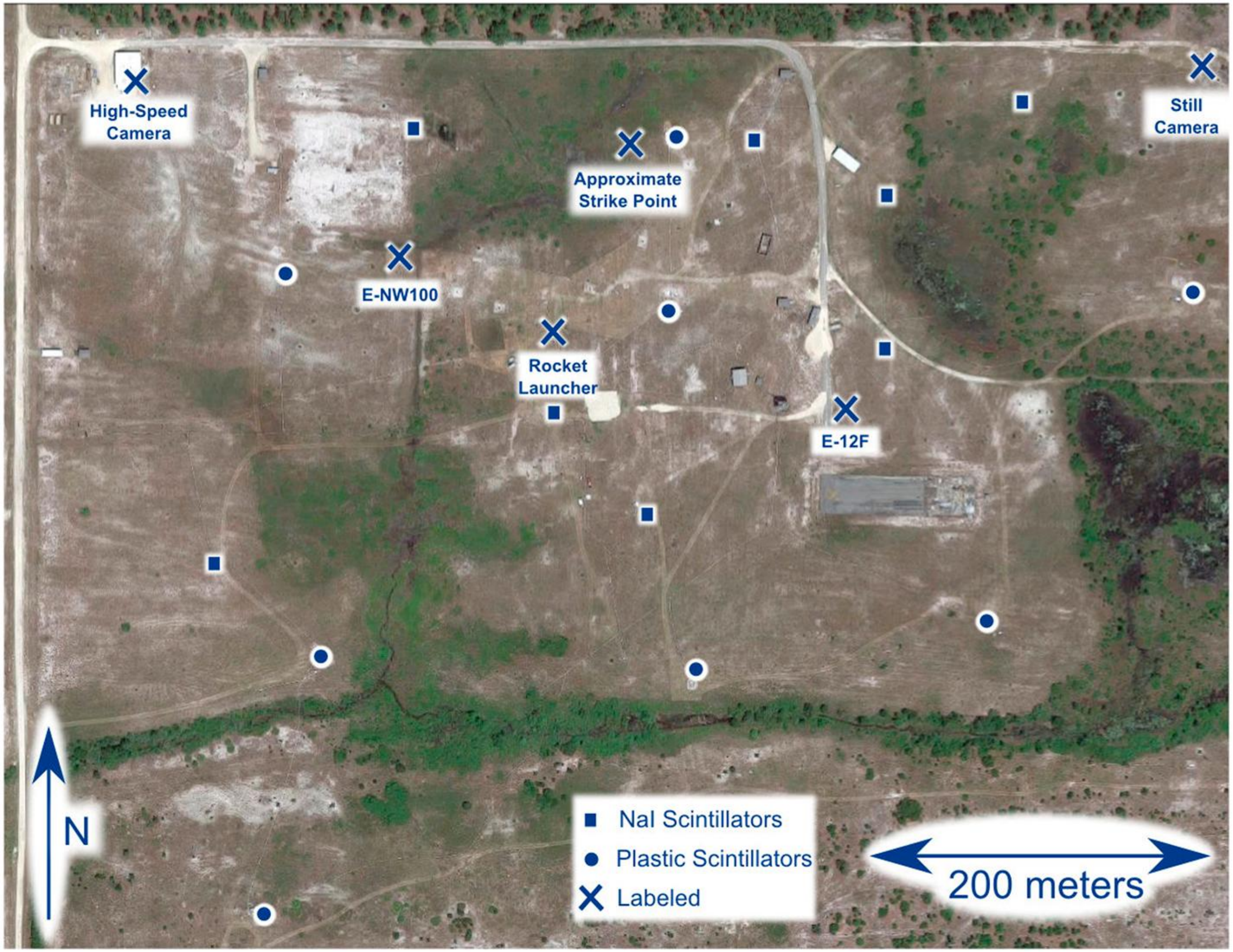
Tavani et al., Phys. Rev. Letters 106, 018501 (2011)

LAFTR has advantages over previous detectors

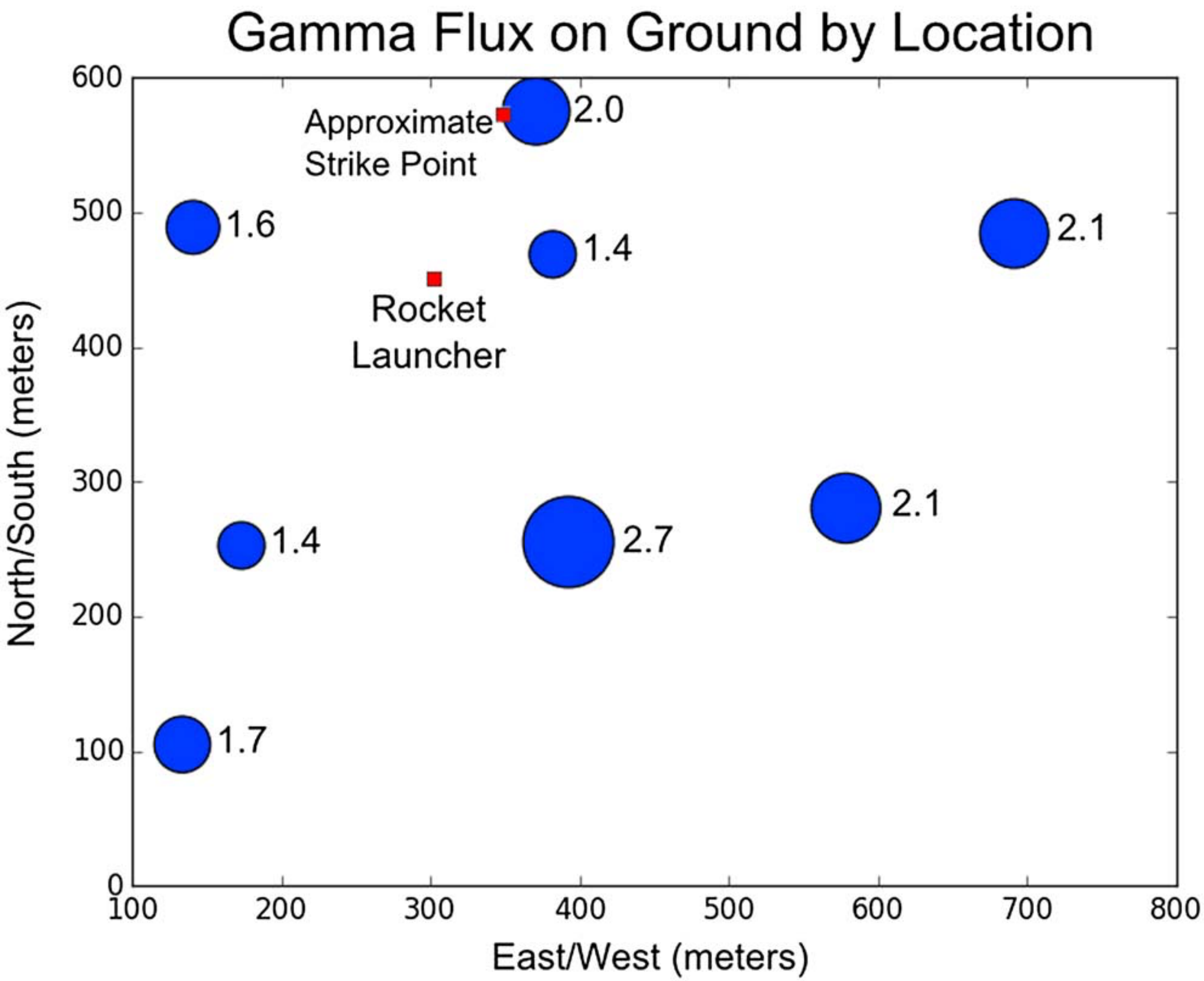
- Get closer to the thunderstorm
  - Gain signal according to $1/r^2$
  - Some atmospheric absorption is eliminated as compared to satellites
- Lightweight, micro payload design allows for wide deployment
- High time resolution



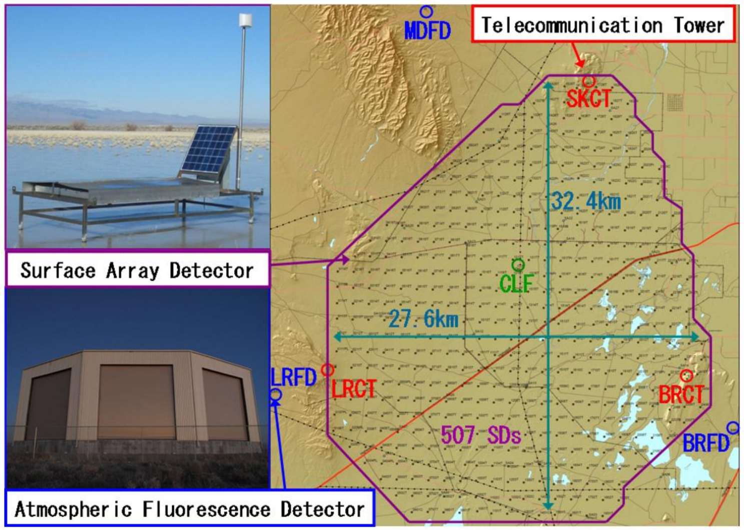
Map of the International Center for Lightning Research (ICLRT, Florida Univ.) with the 2014 trigger strike point, the rocket launcher, and instrument locations associated with measurements in this paper identified. E-NW100 and E-12F are electric field antennas.

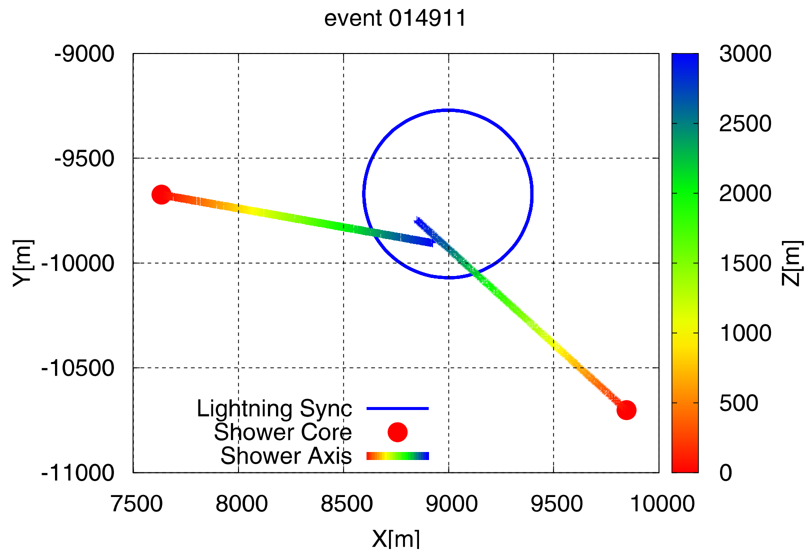


Relative count flux of the TGF on the ground versus location during a 47.8 μs period prior to the saturation of any detector. Each blue circle represents a plastic scintillator, where the radius of the circle is proportional to the flux received by that detector. The red square indicates the location of the rocket launcher used to trigger the lightning flash. This measured flux value for each detector is next to the appropriate circle in units of counts per square meter per microsecond.



The Telescope Array (TA) experiment, located in Midwest Utah, USA(39.3N, 112.9W)

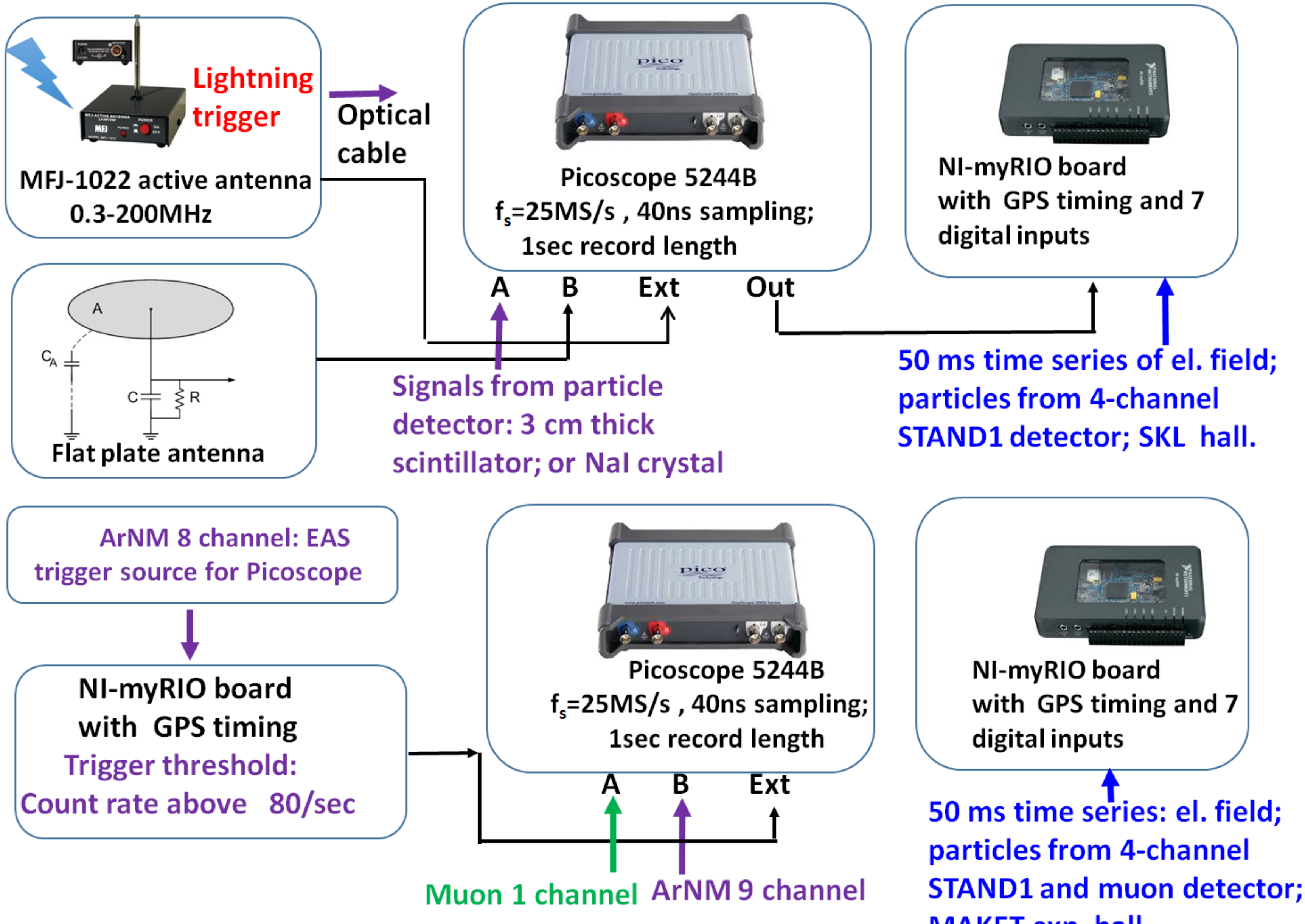




TA operates Surface Detector (SD) comprised from 507 plastic scintillation counters with equivalent energy for trigger threshold ~ 0.7 MeV. The counters are deployed as a square grid array with 1.2 km spacing, and covers 680 km^2 altogether. When three adjacent detectors detect a signal, each of which corresponds to more than three particle equivalent in 8 μs, judges that their signals are from an air shower, causing signal waveforms to be digitized from all detectors within ±32 μs of the trigger time. In the trigger data collected from May 11, 2008 to May 04, 2013 the authors of (Abassi et al., 2017) found ten cases in which at least three air shower triggers were recorded within 1 ms, called bursts. The reconstructed air shower directions for individual bursts appear to point to small regions at altitudes lower than the expected first interaction depth of cosmic ray air showers of comparable size. These bursts were checked against the Vaisala lightning database from U.S. National Lightning Detection Network (NLDN, Nag et al., 2011). The number of the detected lightning was 10,073. All 10 selected shower burst events were under thunderstorm, though only 4 of them were clearly synchronized with negative intracloud lightning. The peak current of the synchronized lightning is very large for the currents observed for negative intracloud lightning. Synchronized burst shower events occur nearly at the same time of lightning or earlier than lightning.

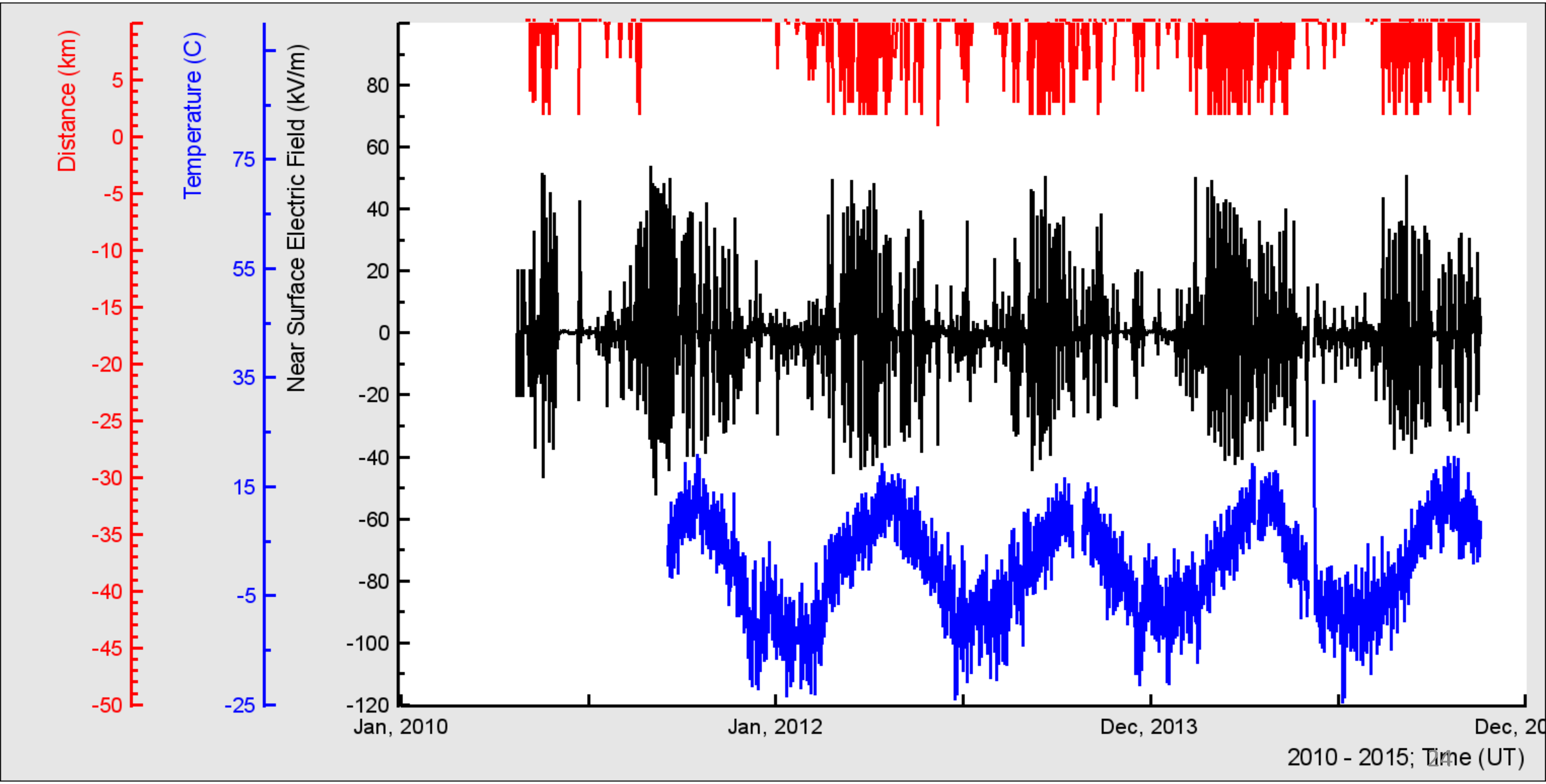
Modeling of X-ray images and energy spectra produced by stepping lightning leaders, Wei Xu, Robert A. Marshall Sebastien Celestin, and Victor P. Pasko submitted to Journal of Geophysical Research.

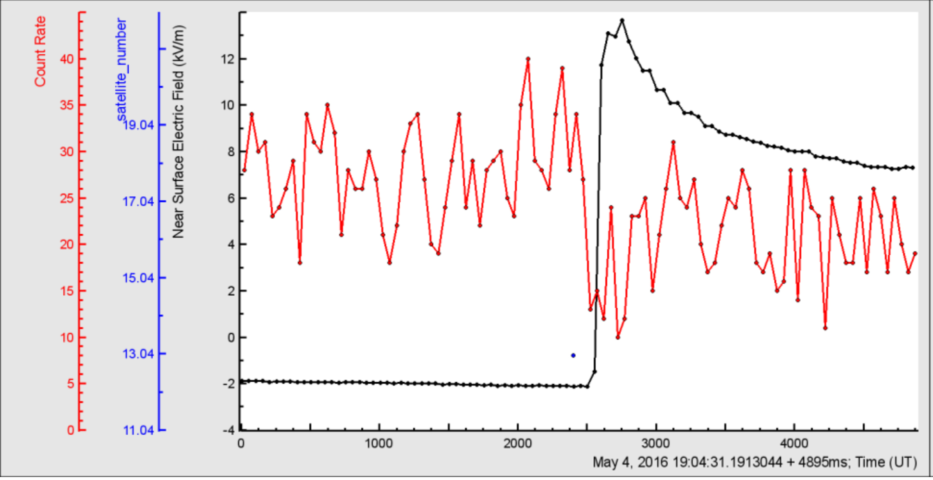
- 1. The exponential growth of the potential differences in streamer tips helps to overcome the friction force of low-energy cold electrons and brings them to a regime where they continuously accelerate. Electrons are accelerated up to characteristic energies of ∼65 keV and runaway. The number of thermal runaway electrons is proportional to the number of streamers in the streamer zone.
- 2. Following acceleration of this “seed” electrons took place in the vicinity of lightning leader tips. The electric potential of the lightning leader tip with respect to the ambient potential is approximately V0 = E0l/2, where E0 is the ambient large-scale thunderstorm electric field and l is the length of the unbranched leader channel. For the 10 MV leader, E0 is taken to be 0.2 kV/cm [e.g., Marshall et al., 2001], the length l is chosen as 1 km, and the radius of the leader channel is 1 cm.
- 3. The initial location of thermal runaway electrons is set at 15 cm from the leader tip in order to avoid the acceleration of electrons in the “unphysical high electric fields”. The electric potential that is available in the leader tip region for thermal runaway electrons is ~2 MV; thermal runaway electrons would only accelerate in a small region of the leader field, i.e., within a few meters from the tip. The beaming of thermal runaway electrons is mainly determined by the configuration of the inhomogeneous electric field near the tip region of the lightning leader.
- 4. Authors mainly investigate lightning leaders with an electric potential of 10 MV because to their opinion it is representative for the stepped leaders in the –CG flashes. The leader potential defined in the paper represents the difference between the electric potential in the leader and the ambient potential at the location of the leader tip which is a fraction of the potential difference between the leader tip and the ground. The lightning leaders propagate vertically downward towards the ground in a series of discrete steps; the length of leader steps is chosen to be 10 meters (previously 50); total length is assumed to be 1 km.
- 5. The source of isotropic-beamed bremsstrahlung photons is the streamer zone in front of the newly formed leader during the negative corona flash stage (a hemisphere with a radius of 4 m centered at the leader tip); ~10^{10} photons with energies above 10 keV are produced during each step.

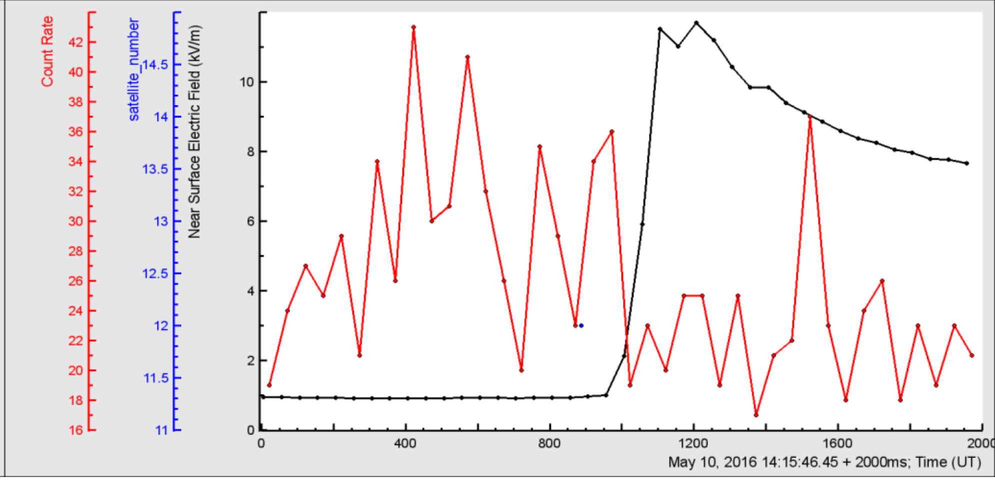


Lightning trigger
MFJ-1022 active antenna 0.3-200MHz
Optical cable
Picoscope 5244B
f_s=25MS/s , 40ns sampling;
1sec record length
NI-myRIO board with GPS timing and 7 digital inputs
A
B
Ext
Out
Flat plate antenna
Signals from particle detector: 3 cm thick scintillator; or NaI crystal
50 ms time series of el. field; particles from 4-channel STAND1 detector; SKL hall.
ArNM 8 channel: EAS trigger source for Picoscope
NI-myRIO board with GPS timing
Trigger threshold: Count rate above 80/sec
Picoscope 5244B
f_s=25MS/s , 40ns sampling;
1sec record length
NI-myRIO board with GPS timing and 7 digital inputs
A
B
Ext
Muon 1 channel
ArNM 9 channel
50 ms time series: el. field; particles from 4-channel STAND1 and muon detector; MAKET exp. hall

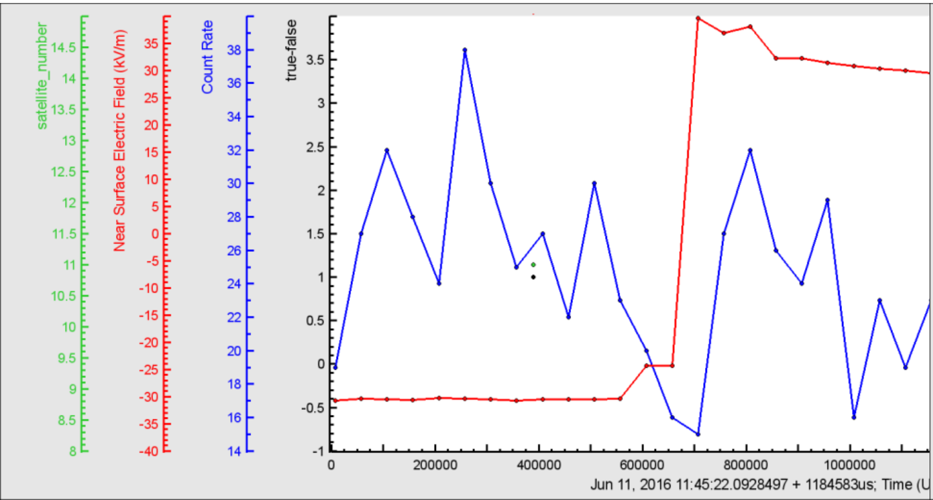
Lightnings are common on Aragats

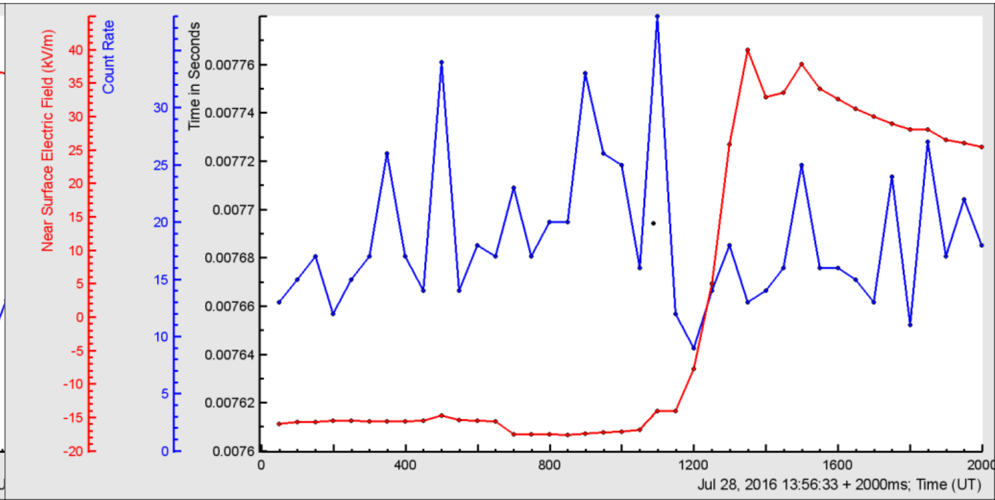



Count Rate
satellite_number
Near Surface Electric Field (kV/m)
May 4, 2016 19:04:31.1913044 + 4895ms; Time (UT)

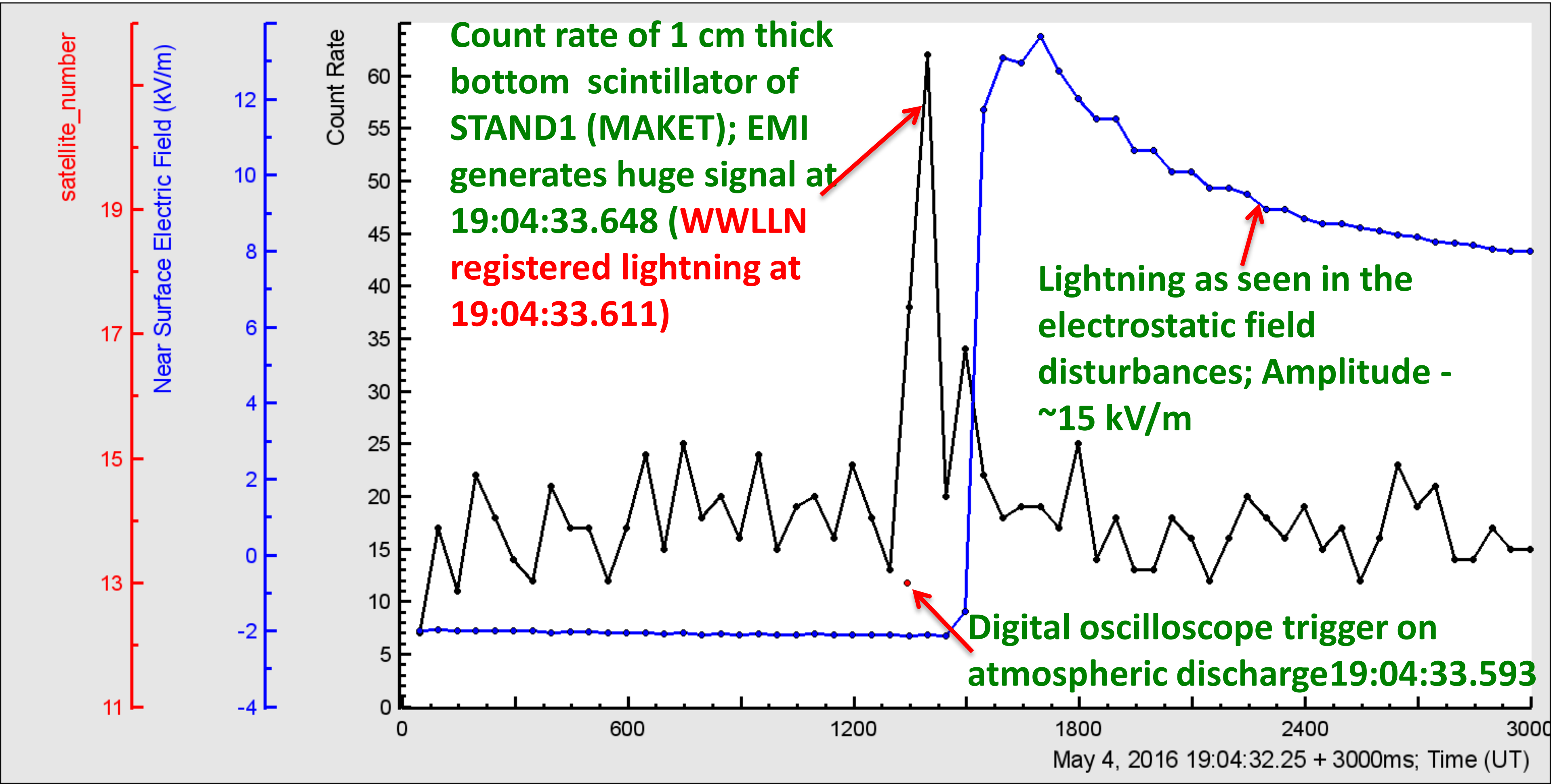

Count Rate
satellite_number
Near Surface Electric Field (kV/m)
May 10, 2016 14:15:46.45 + 2000ms; Time (UT)


2016-07-28
13:56:34-03

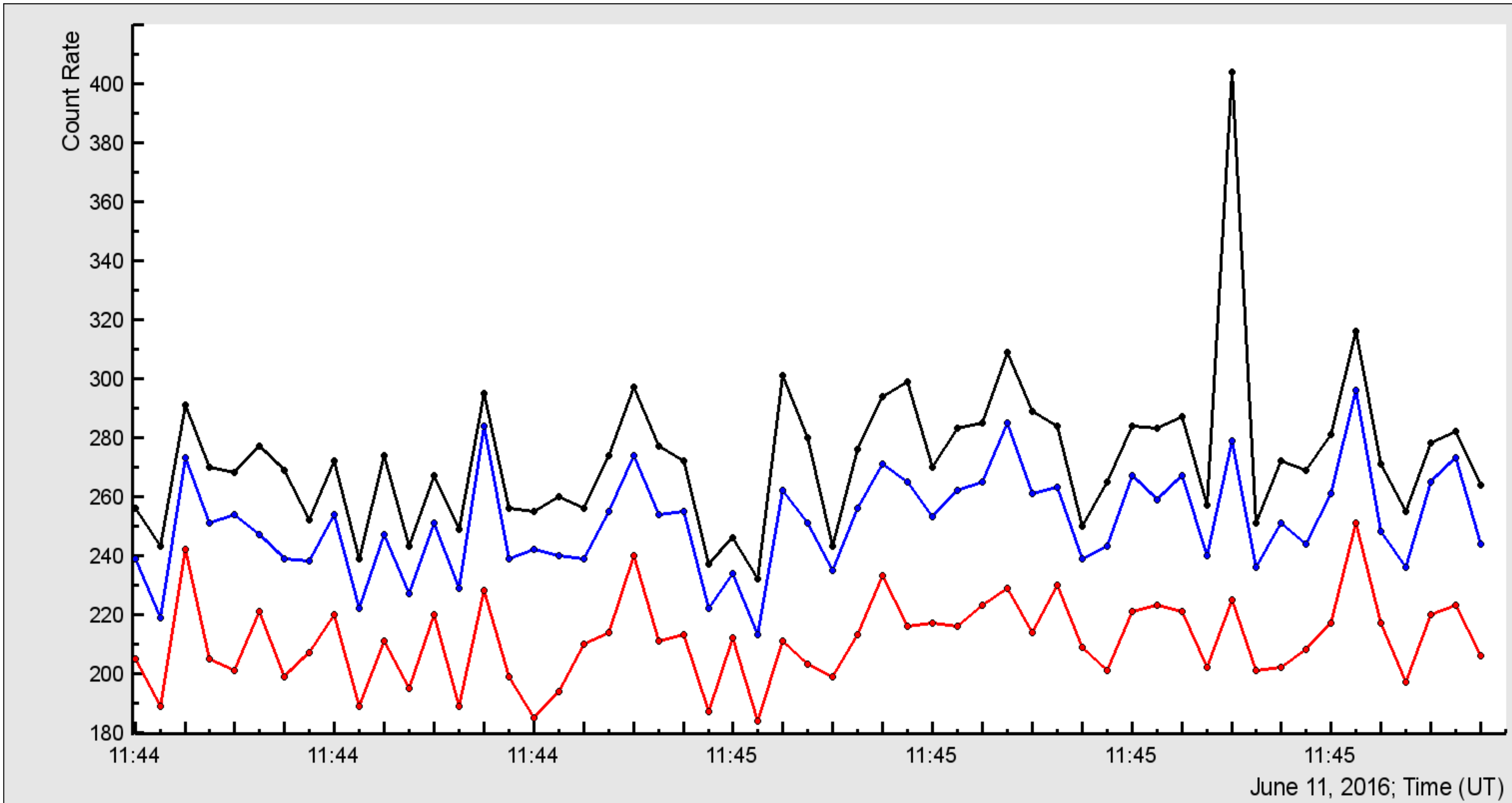

satellite_number
Near Surface Electric Field (kV/m)
Count Rate
true-false
Jun 11, 2016 11:45:22.0928497 + 1184583us; Time (U


Near Surface Electric Field (kV/m)
Count Rate
Time in Seconds
Jul 28, 2016 13:56:33 + 2000ms; Time (UT)

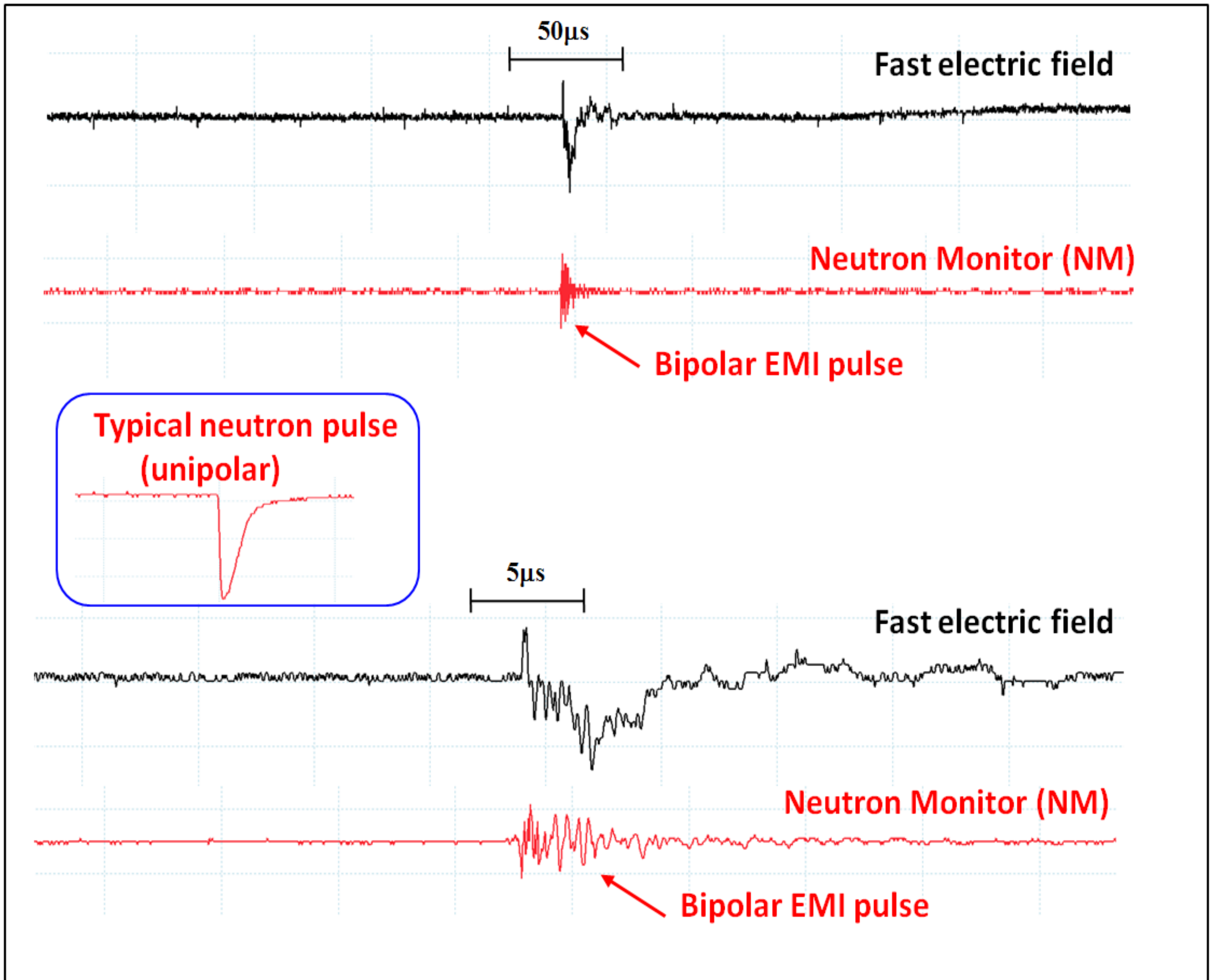
3 seconds of 50 ms particle time series including lightning occurrence and electrostatic field disturbances



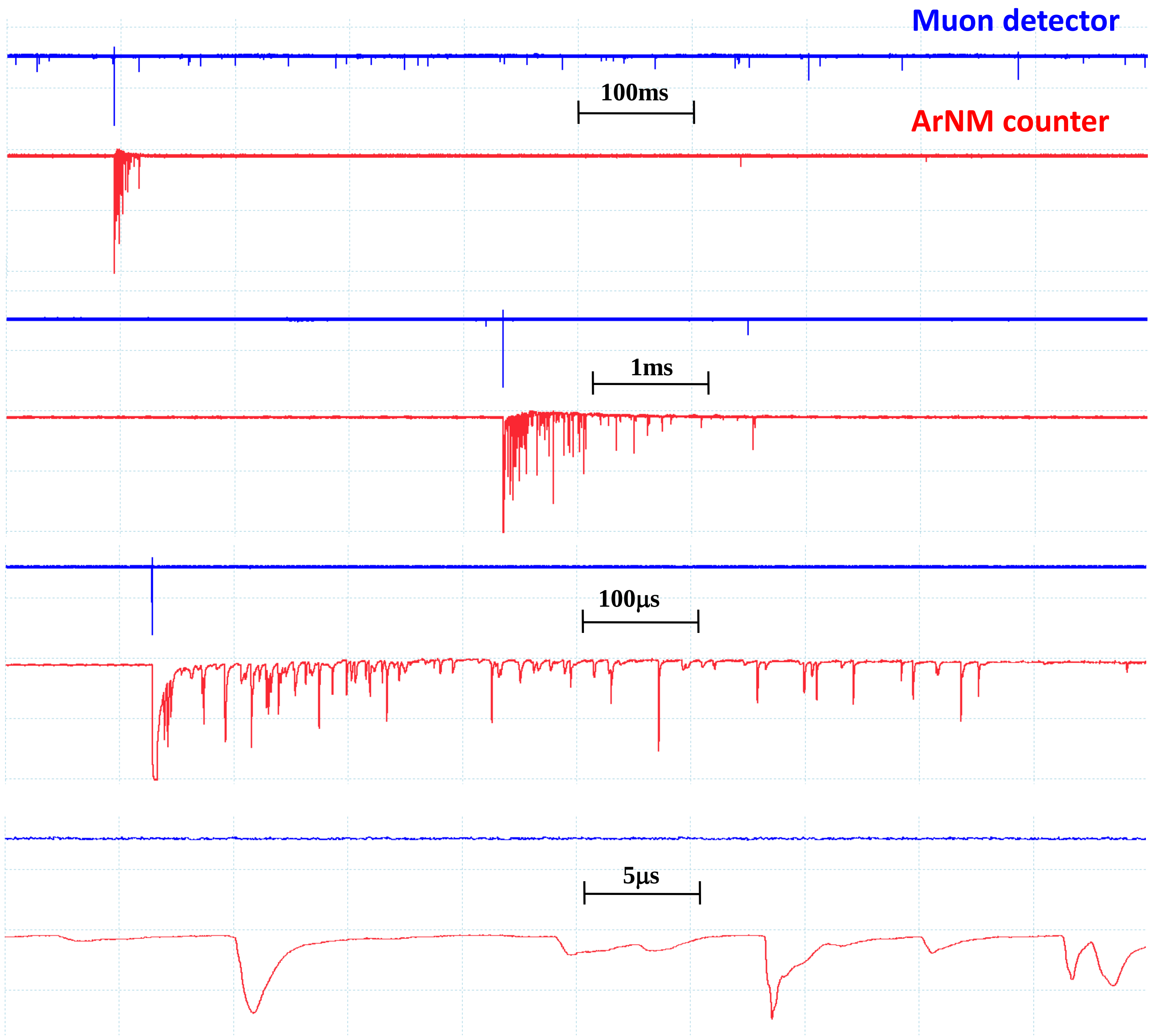
The one-second time series of ArNM. Only time series corresponding to 0.4 µs dead time (upper curve) demonstrates large peak due to counting multiple secondary neutrons coming within time span ~ 1ms; the time series corresponding to 750 and 1200 µs dead time demonstrate no peak.



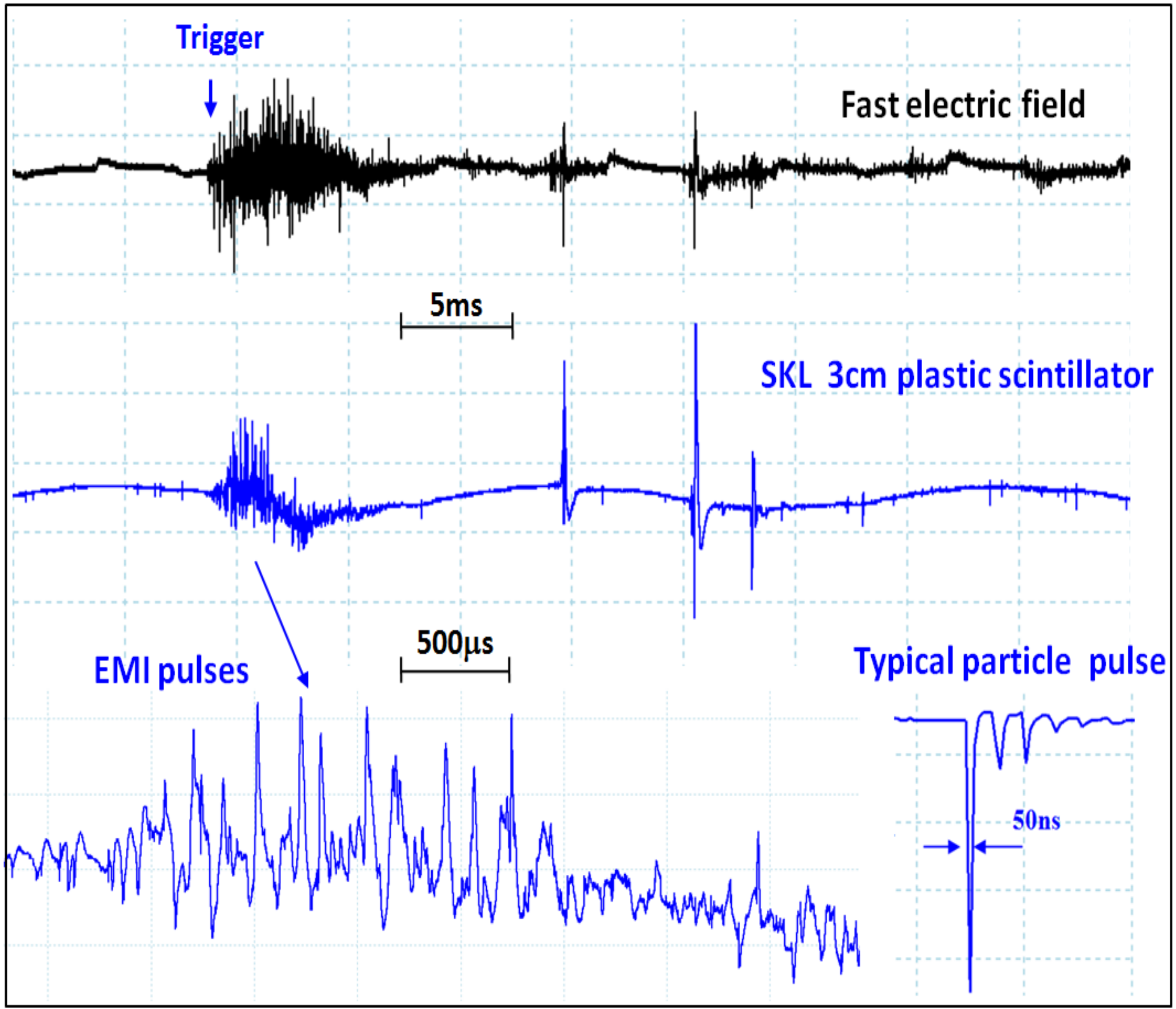
Synchronized waveforms of fast electric field and neutron monitor shown in different time scales along with a typical waveform of neutron signal from the proportional counter of NM.



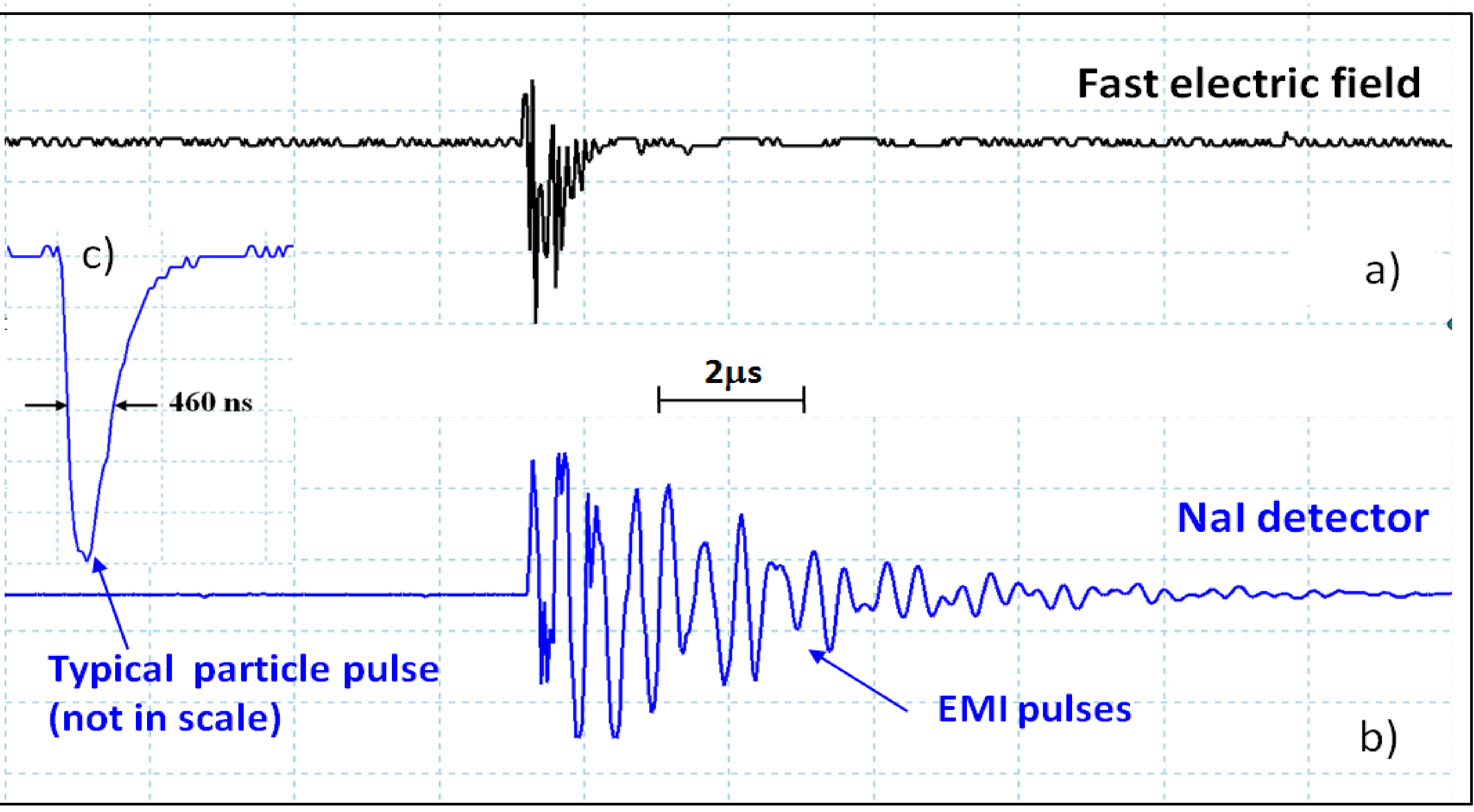
EAS registration by Neutron Monitor on November 26,2016 04:08:05



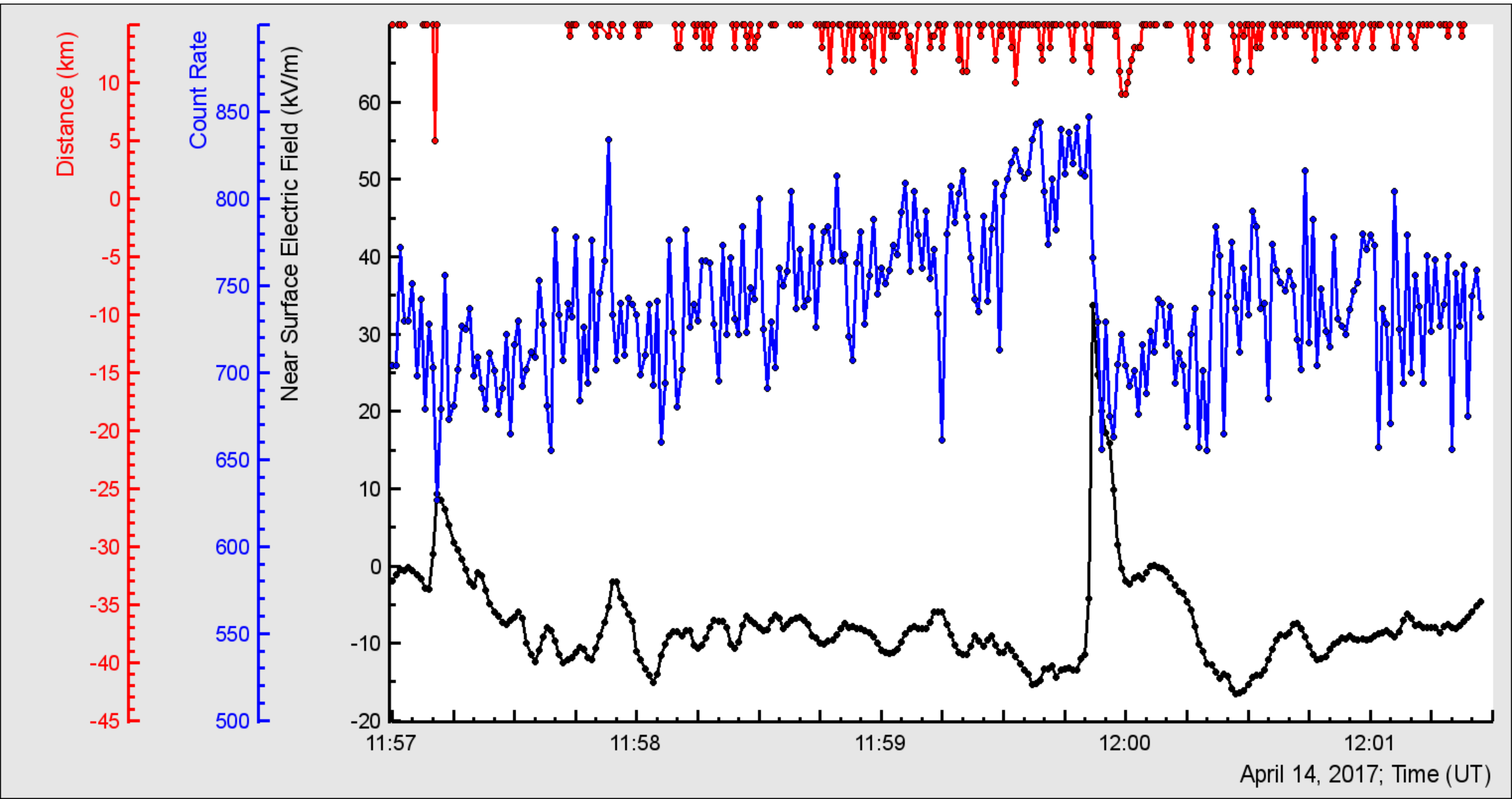
EMI activity. Typical EMI signature from atmospheric discharges in the particle detector waveform. Synchronised time-series of the pulses of fast electric field and signals from plastic scintillator. SKL trigger occurred at 14:32:34.205



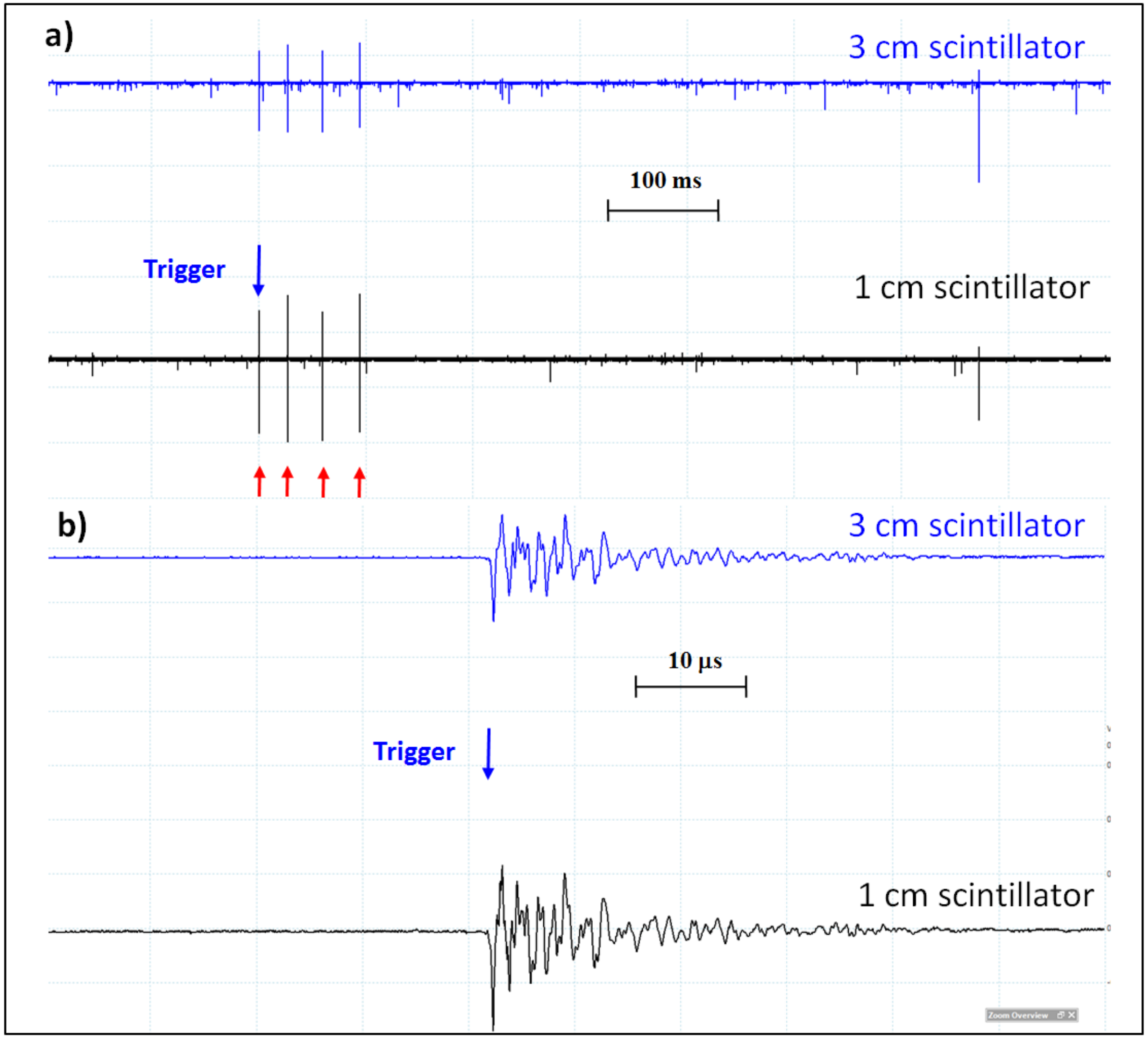
Registration of the lightning occurred on May 15, 2016, 12:48:25; Waveforms of fast electric field a); NaI detector output b); in the insert c) is shown a typical shape of NaI detector response to incident particle.



TGE abruptly terminated by the lightning flash at 11:59:51.82; trigger was registered in MAKET and SKL hall at 11: 59:51.75, surge of electrostatic field started at 11:59:51.94, decline of particle flux started 11:59:51.83



The “Shower Burst” event detected on 14 April 2014 by 1 sm thick and 3-cm thick 1 m area plastic scintillators located in the experimental hall MAKET. The signal shapes were synchronized with lightning flash (atmospheric discharge trigger was detected at 11: 59:51.75). The “burst” are denoted by 4 small arrows in the bottom of Fig. 9.a. The zoomed version of the first burst is shown in the zoomed Fig. 9b.



“The balloon passed through a region of high electric field on which time increase in X ray intensity of 2 orders of magnitude occurred, lasting for approximately 1 min. The X ray intensity returned to background level at the time of a lightning flash that reduced the electric field strength measured at the balloon”, near Norman, Oklahoma in the spring of 1995.

X-rays in Thunderstorms

interval, from one of the 1984 flights, in Figure 1. The passive channel shows only a thermal noise count rate with no statistically significant deviations during this same time period. In this instance, there is no evidence of electromagnetic interference in the passive detector and we conclude that the count rate increase in the active

The left- most peak precedes an observed flash near aircraft. Center peak precedes a strike to the aircraft. Rightmost "'hump” is not associated with any observed lightning

McCarthy, M.P., Parks, G.K. 1985. Further observations of X-rays inside thunderstorms. *Geophys. Res. Lett.* **97**, 5857–5864

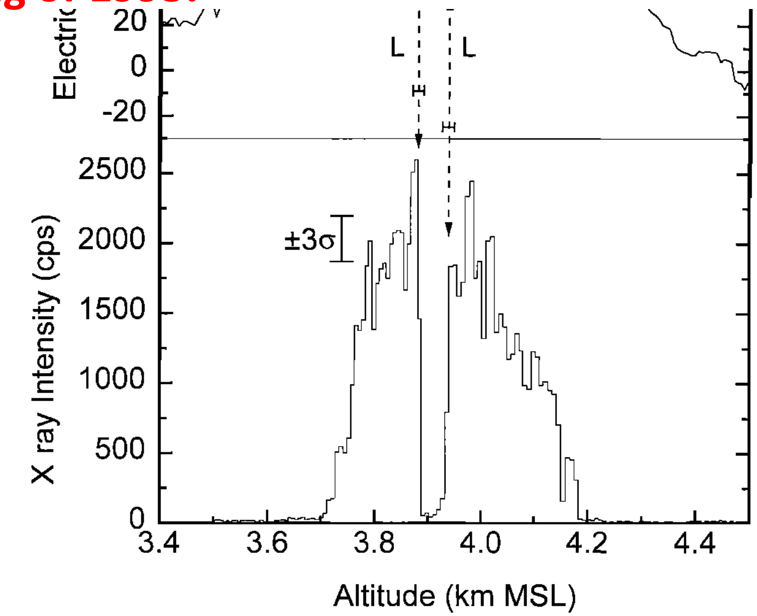
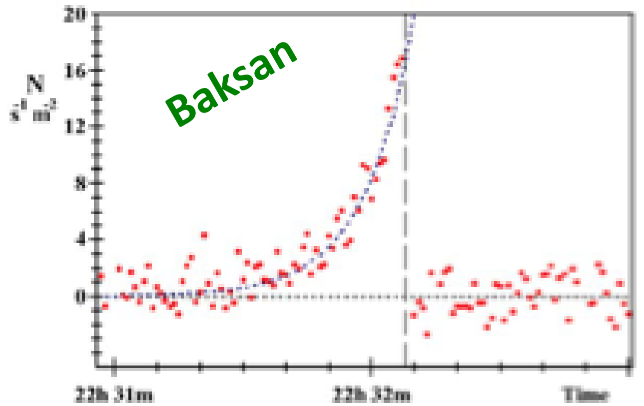


Figure 3. Detail of X ray and electric field sounding near 4 km msl. Electric field measured at the balloon and the breakeven field strength (E_{BE}) are plotted in the top panel. Electric field transients due to lightning are marked by an “L” and vertical dashed lines. The horizontal error bars (±1 s) depict the timing error between the two plots. X ray intensity for X rays between 30 and 120 keV is plotted in the bottom panel. The vertical error bar represents 3 standard deviations in the count rate.

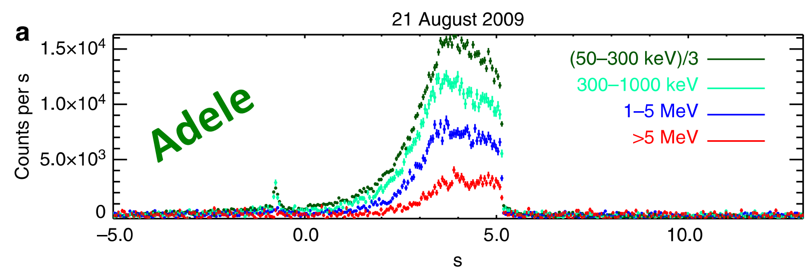
Eack, K.B, W.H. Beasley, W.D. Rust, T.C. Marshall, M.Stolzenburg, Initial results from simultaneous observations of x rays and electric fields in a thunderstorm, J.Geophys. Res., 101, 29637-29640, 1996.

Lightning terminates particle fluxes on Earth's surface and in aircraft



The large distance to lightning channels probably means that the above enhancements are not directly related to the lightning activity. We can rather suppose that the lightning serves in our case as a switch-off for the electric field.

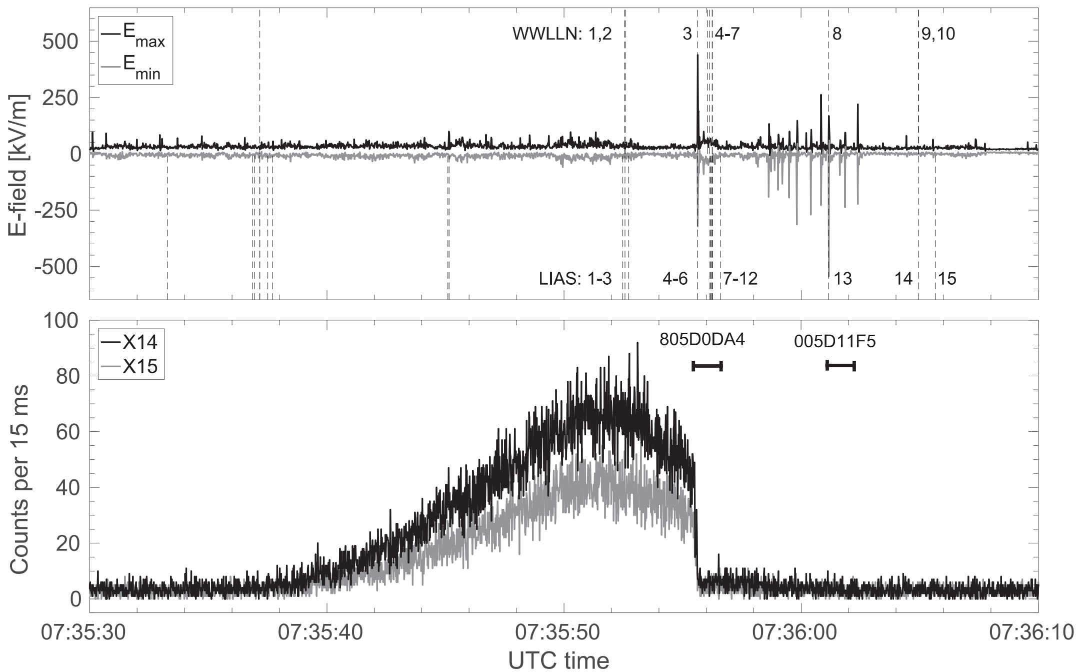
Alexeenko V.V., Khaerdinov N.S., LidvanskyA.S., and PetkovV.B., 2002. Transient Variations of Secondary Cosmic Rays due to Atmospheric Electric Field and Evidence for Pre-Lightning Particle Acceleration, *Physics Letters A*, 301, 299-306.



Examining the strongest glow measured by the airborne detector for energetic emissions, we show that this glow is measured near the end of a downward RREA, consistent with occurring between the upper positive charge layer and the negative screening layer above it.

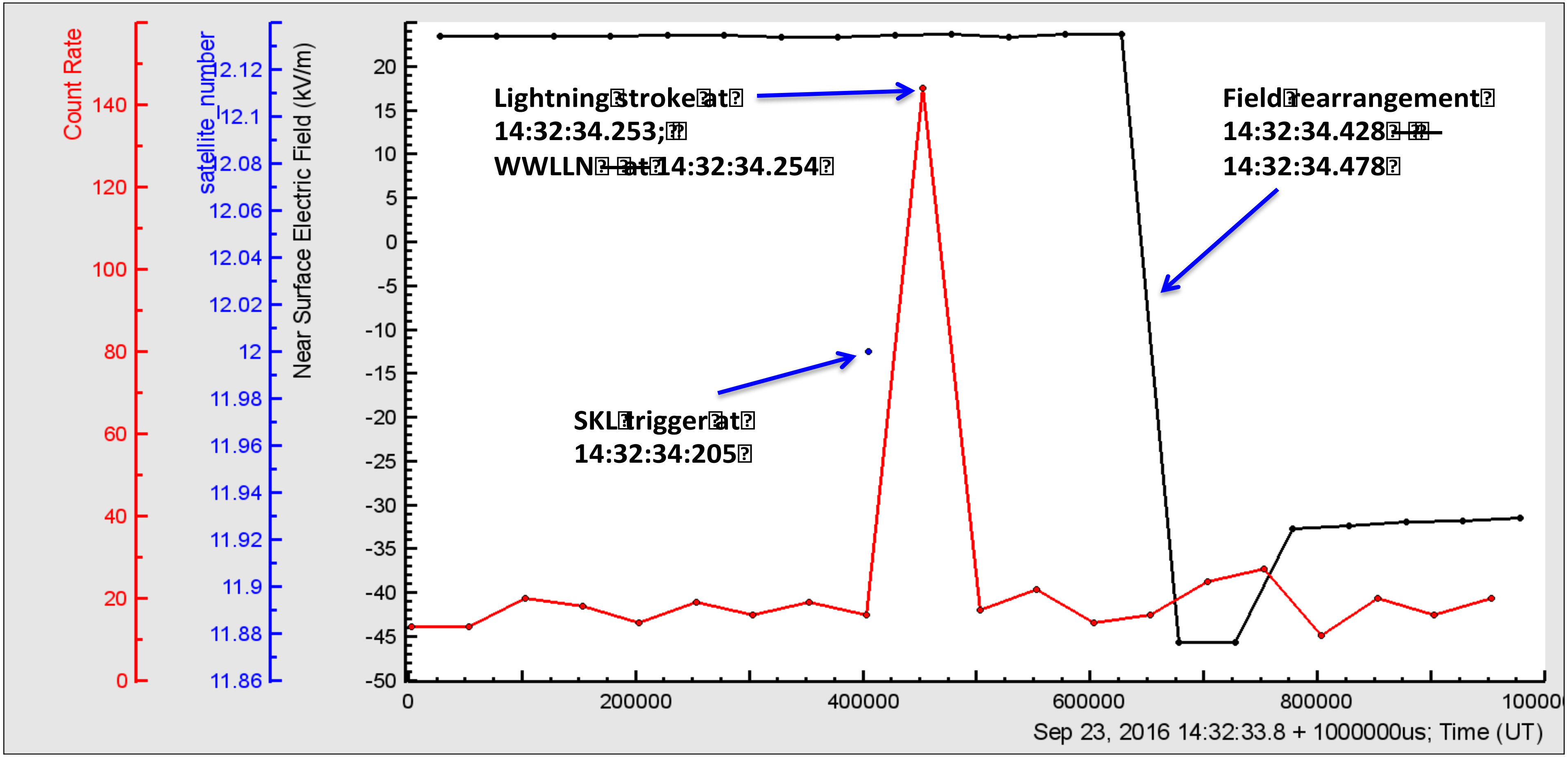
N. A. Kelley, D. M. Smith, and J. R. Dwyer et al., Relativistic electron avalanches as a thunderstorm discharge competing with lightning, Nat. Commun. 6, 7845 (2015).

An Airbus A340 aircraft flew over Northern Australia with ILDAS system installed on-board: The most intense emission was observed at 12 km altitude and lasted for 20 s. Its intensity was 20 times the background counts and it was abruptly terminated by a distant lightning flash.

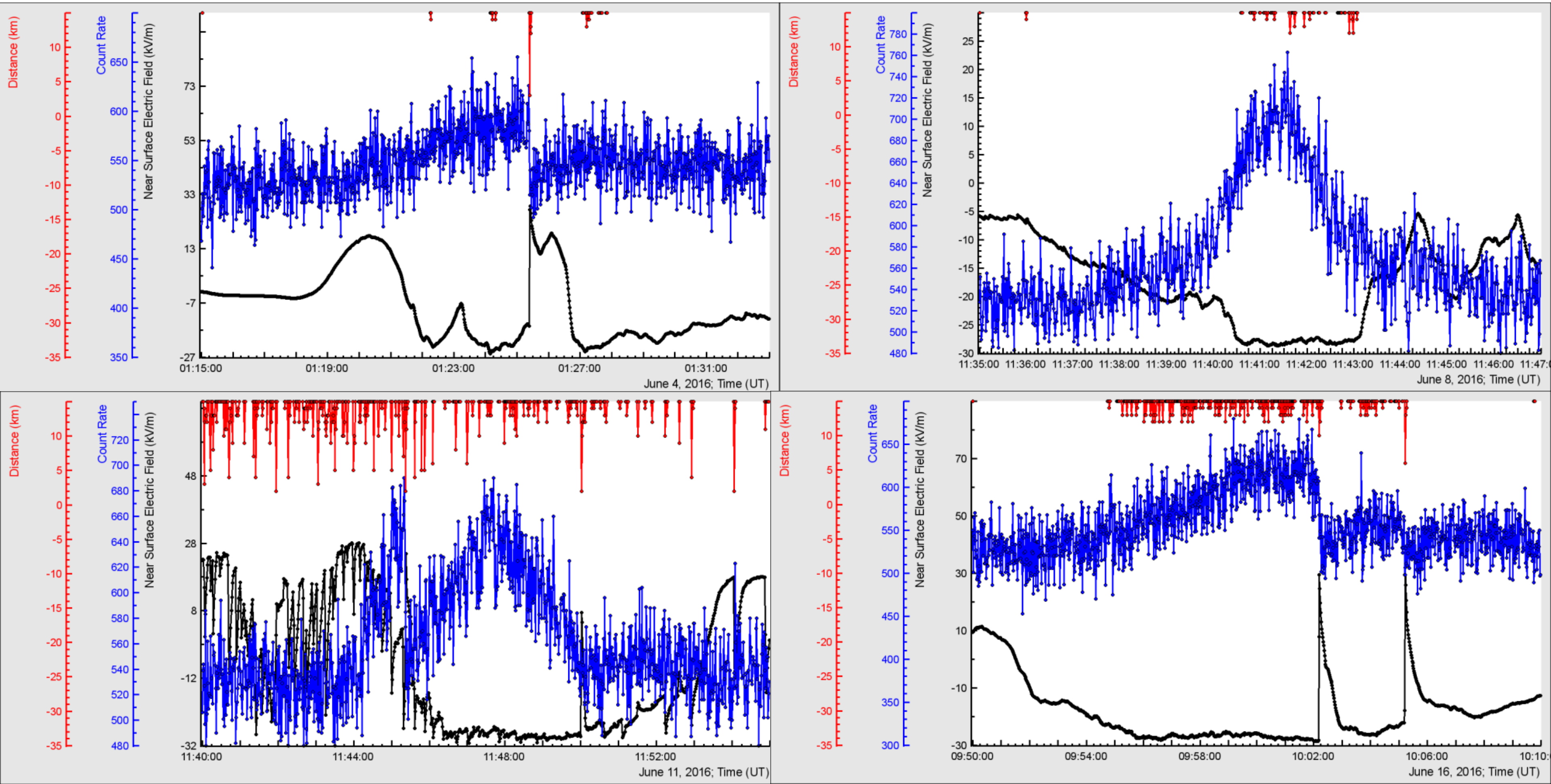


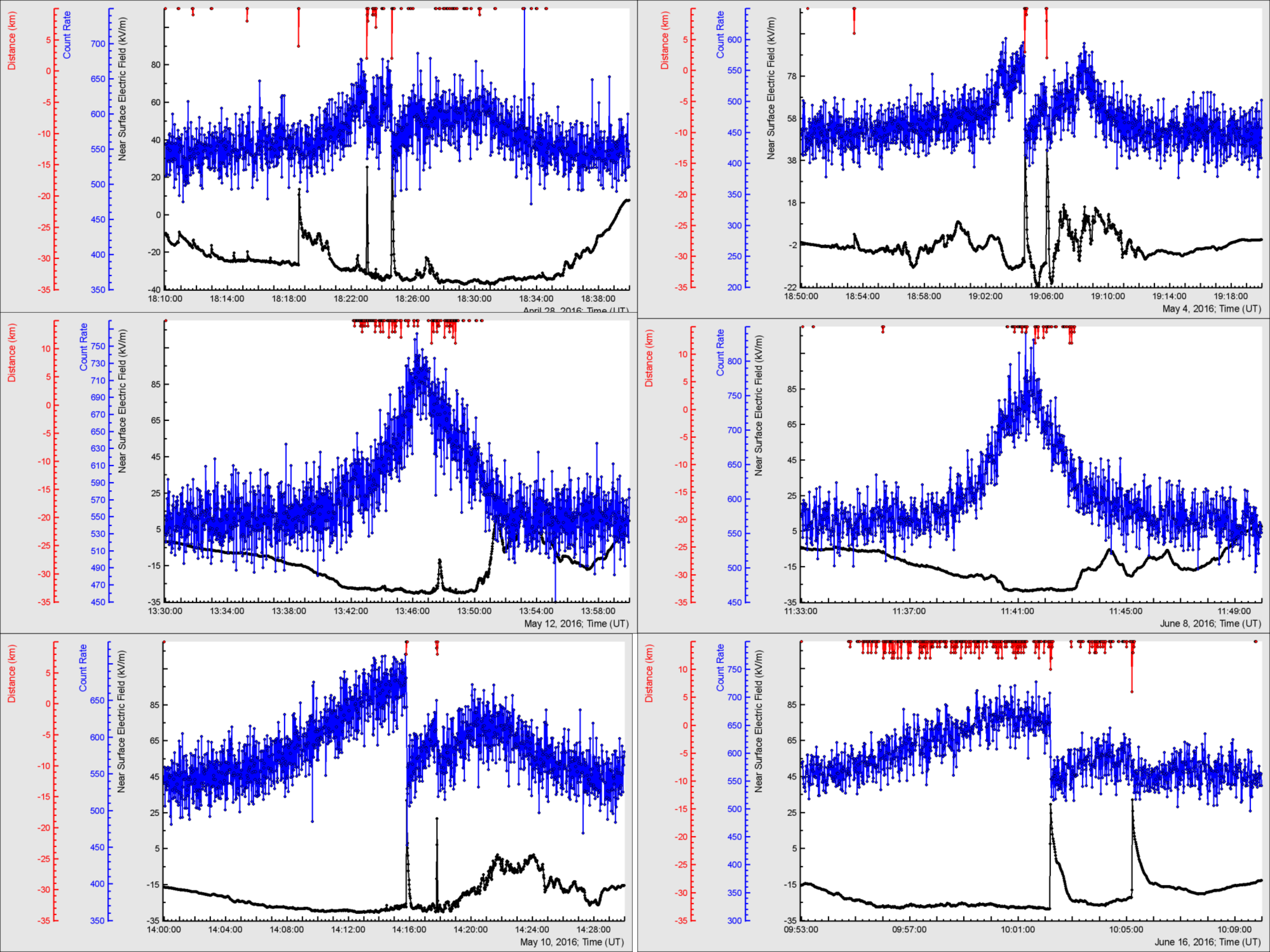
The gamma glow was abruptly terminated by a distant lightning flash. This is consistent with previously formulated assumption that glows are created by high E-filed regions inside thunderclouds.

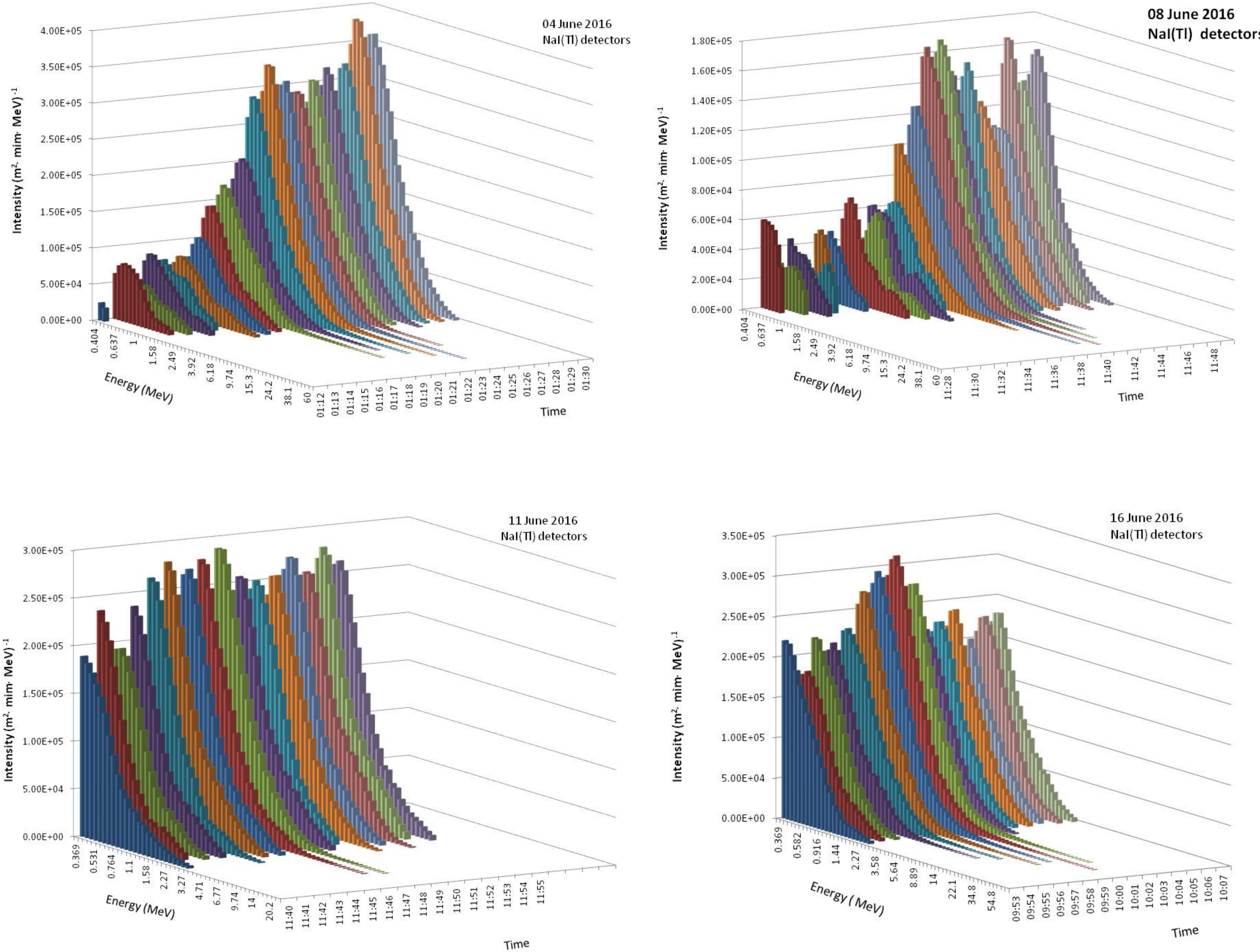
50 ms time series of the bottoms scintillator of STAND1 detector and electrostatic field disturbances (positive lightning with amplitude 69.3 kV/m).



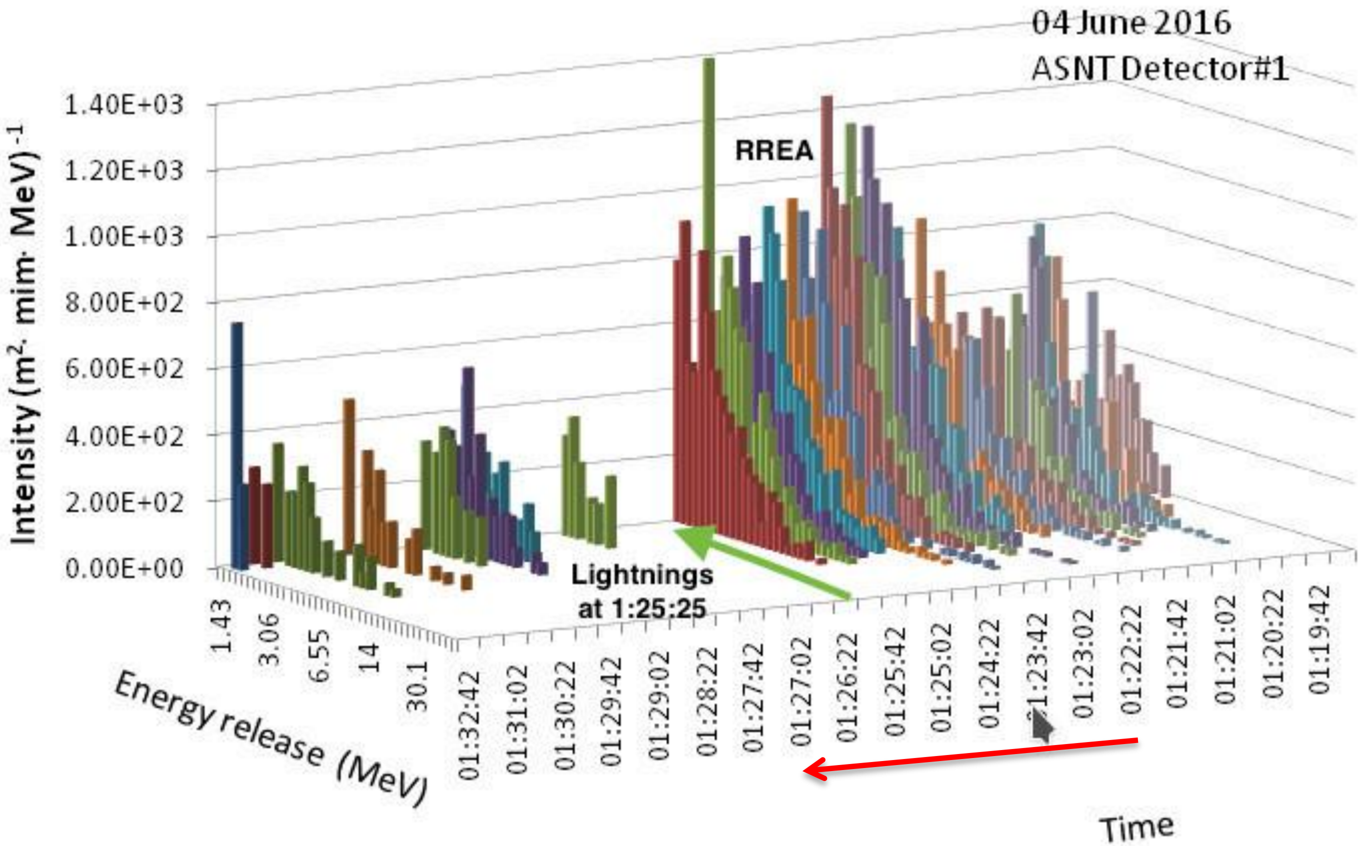
2016 TGEs occurs at prolonged (3-7 min)deep negative electrostatic field(~ -30 kV/m); lightning abruptly terminates TGE; largest TGEs occurred when there is no nearby lightnings.



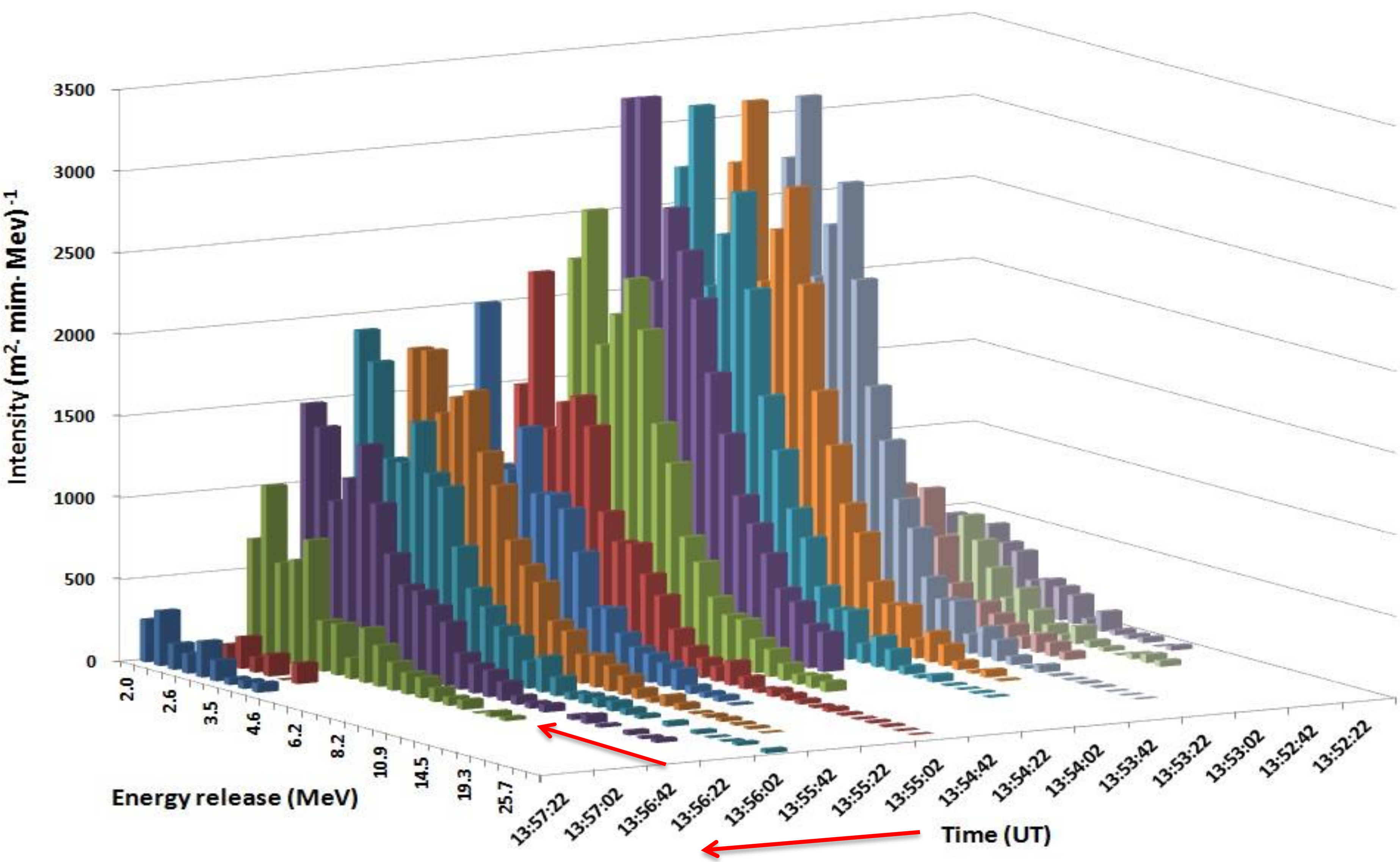

Distance (km)
Count Rate
Near Surface Electric Field (kV/m)
18:10:00 18:14:00 18:18:00 18:22:00 18:26:00 18:30:00 18:34:00 18:38:00
April 28, 2016; Time (UT)
Distance (km)
Count Rate
Near Surface Electric Field (kV/m)
18:50:00 18:54:00 18:58:00 19:02:00 19:06:00 19:10:00 19:14:00 19:18:00
May 4, 2016; Time (UT)
Distance (km)
Count Rate
Near Surface Electric Field (kV/m)
13:30:00 13:34:00 13:38:00 13:42:00 13:46:00 13:50:00 13:54:00 13:58:00
May 12, 2016; Time (UT)
Distance (km)
Count Rate
Near Surface Electric Field (kV/m)
11:33:00 11:37:00 11:41:00 11:45:00 11:49:00
June 8, 2016; Time (UT)
Distance (km)
Count Rate
Near Surface Electric Field (kV/m)
14:00:00 14:04:00 14:08:00 14:12:00 14:16:00 14:20:00 14:24:00 14:28:00
May 10, 2016; Time (UT)
Distance (km)
Count Rate
Near Surface Electric Field (kV/m)
09:53:00 09:57:00 10:01:00 10:05:00 10:09:00
June 16, 2016; Time (UT)



04 June 2016
NaI(Tl) detectors
Intensity (m2· mim· MeV)-1
Energy (MeV)
Time
08 June 2016
NaI(Tl) detectors
Intensity (m2· mim· MeV)-1
Energy (MeV)
Time
11 June 2016
NaI(Tl) detectors
Intensity (m2· mim· MeV)-1
Energy (MeV)
Time
16 June 2016
NaI(Tl) detectors
Intensity (m2· mim· MeV)-1
Energy (MeV)
Time


04 June 2016
ASNT Detector#1
RREA
Lightnings
at 1:25:25
Intensity (m². mim· MeV) -1
1.40E+03
1.20E+03
1.00E+03
8.00E+02
6.00E+02
4.00E+02
2.00E+02
0.00E+00
1.43
3.06
6.55
14
30.1
Energy release (MeV)
01:32:42
01:31:02
01:30:22
01:29:42
01:29:02
01:28:22
01:27:42
01:27:02
01:26:22
01:25:42
01:25:02
01:24:22
01:23:42
01:23:02
01:22:22
01:21:42
01:21:02
01:20:22
01:19:42
Time

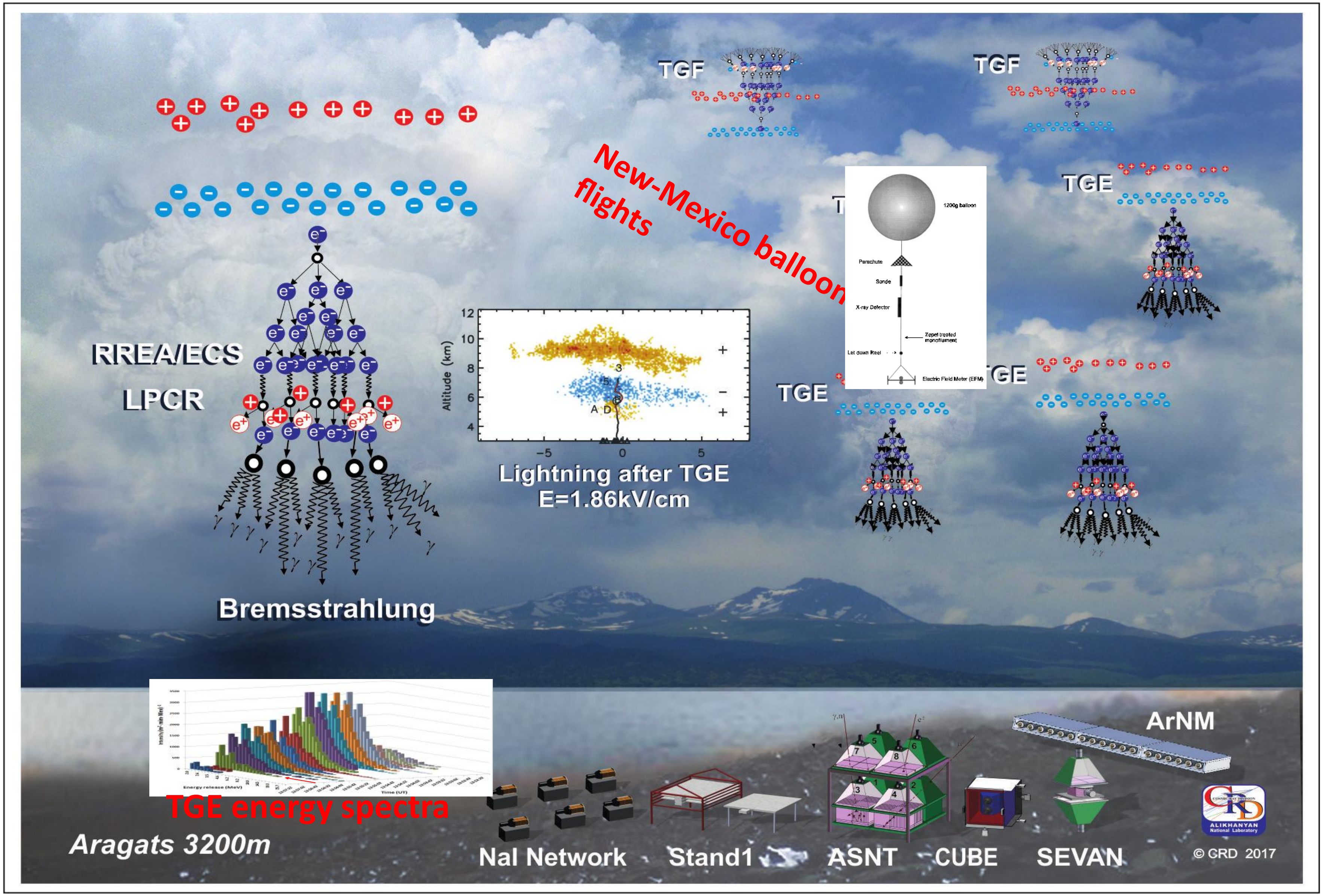
Differential Energy release spectrum of TGE (20 sec) by ASNT: red arrow – lightning flash on 28 July 2016 at 13:56:34



RB/TGE model universality!
TGE, TGF, “Inverse TGF”, “bursts”, MRB

- RB/TGE: -Electrons from the ambient population of CR accelerated in the strong electric field in the lower part of cloud, runaway, generate bremsstrahlung gamma rays and the gamma rays produce neutrons via photonuclear reactions;
- Possibly the lightning leaders supply additional seed electrons to RB process;
- Energy spectra – power law. Electron maximal energy reach 40-50 MEV; Gamma ray – 35=45MeV;
- Duration: tens of seconds (balloons, aircraft) – up to 10 minutes (surface);
- Intensity can outperform background 10-fold;
- MOS: - High energy electrons from the ambient population of CR get energy from field and their energy spectra modified getting additional energy from electric field. Consequently their live time enhanced and probability of emitting bremstrahlung gamma ray get a bust;
- Energy spectra – exponential, maximal energy of gamma rays – 100 MeV;
- Duration – hours (for energies 0.4 – 3 MeV);
- Intensity – tens of percent of background, few percent at high energy tail;

One from numerous randomly emerging TGEs in the thundercloud open path to the lightning leader!



TEPA 2016

THUNDERSTORMS & ELEMENTARY PARTICLE ACCELERATION

Published

A. Chilingarian

3-7 October 2016

Yerevan Physics Institute

TEPA 2017

ORGANIZERS:
Cosmic Ray Division of Yerevan Physics Institute, Armenia
Skobeltsyn Institute of Nuclear Physics of Moscow State University, Russia

THUNDERSTORMS AND ELEMENTARY PARTICLE ACCELERATION

Internationanl symposium

From March 2017 Registration open!!!

STRUCTURE OF THE SYMPOSIUM:

We anticipate the following sessions:

1. Models of high-energy emissions in thunderclouds;
2. Multivariate observations of thunderstorms from the Earth's surface and from space;
3. Particle fluxes and lightnings – any causal relations?
4. Research of the Thunderstorm ground enhancements (TGEs);
5. Research of the Terrestrial gamma-ray flashes (TGF);
6. Extensive air showers, lightning and RB/RREA process;
7. Atmospheric High-energy phenomena observations by space-born facilities
8. Instrumentation

Topics to be covered during oral and poster sessions:

- Research of the Thunderstorm ground enhancements (TGEs), measurements of electrons, gamma rays and neutrons by networks of particle detectors located on Earth's surface;
- Research of the Terrestrial gamma-ray flashes (TGFs) observed by the orbiting gamma-ray observatories;
- Radio emissions produced by atmospheric discharges and particle fluxes;
- Lightning initiation and its relation to particle fluxes originated in thundercloud;
- Neutron production during thunderstorms;
- Ultraviolet and infrared emissions during thunderstorms;
- Monitoring of thunderclouds and particle emission from orbit;
- Monitoring of the thunderstorms by high speed cameras e;
- Methods of the remote sensing of the thundercloud structure and electric field;
- X-ray emissions from the lightning;
- Abrupt termination of the particle flux by the lightning flash;
- Precise electronics for the high-energy atmospheric research;
- Relations to the climate and space weather issues;
- Possibility of joint observations by space-born and ground-based facilities.
- The global electrical circuit.

October 2 - 6

Nor Amberd International Conference Centre
Yerevan Physics Institute,
Byurakan, Aragatsotn Province, Armenia

BACKGROUND:

New emerging field of high-energy atmospheric physics (HEAP) is still lacking firmly established concepts and theories. The relationship of lightning and elementary particle fluxes in the thunderclouds is not fully understood to date. HEAP presently includes 2 main physical phenomena: Terrestrial Gamma Flashes (TGFs) - brief burst of gamma radiation (sometimes also electrons and positrons) registered by the orbiting gamma ray observatories in the space and Thunderstorm ground enhancements (TGEs) -the prolonged particle fluxes registered on the ground level|. Both TGFs and TGEs are related to the thunderstorms and lightning flashes: TGEs - by directly detecting electric field and lightning occurrences above the detector site; TGFs by making rather complicated synchronization with worldwide lightning detecting networks. The central engine initiated TGE is believed to be the Relativistic Runaway Electron avalanches (RREA) accelerated seed electrons from ambient population of cosmic rays (CR) in the large-scale thundercloud electric field up to 40-50 MeV. Observation of numerous TGEs by the Japanese, Russian, Armenian, Chines, Slovakian groups prove that RREA is a robust and realistic mechanism for electron acceleration and multiplication leaving no doubts about correctness of the RREA model for the TGE initiation. Models using CERN origin GEANT4 code support in situ measurements of electron and gamma ray energy spectra at Aragats. Another model of the gamma glow initiation was used for explaining gamma ray detections by TERA array in Florida. The main idea of the model is thermal electron acceleration in the streamer tips up to energies of □65 keV; thereafter these electrons runaway and accelerate further by the extreme electric field in the streamer zone in vicinity of negative lightning leader. This 2-stage model includes development of very strong electric fields in very short times. Correspondingly, the model includes compatible theories and models with several parameters which values are very difficult to measure or estimate (for instance the electric field of 260 kV/cm in the lightning leader tip, or- field strength and elongation in the streamer zone where runaway electrons suppose to reach MeV energies). Thus, 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 a complete and common accepted explanation yet. One of the most important problems "do lightning flashes produce relativistic particles or not?" is still open. TEPA meeting is great opportunity for scientist to meet, discuss, invent new ideas and make new bridges for collaborative works.

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