Thunderstorm Ground Enhancements: model and observations

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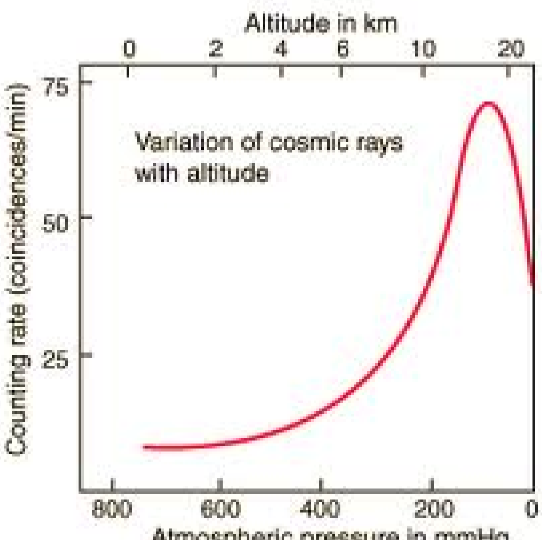
Thunder Cloud



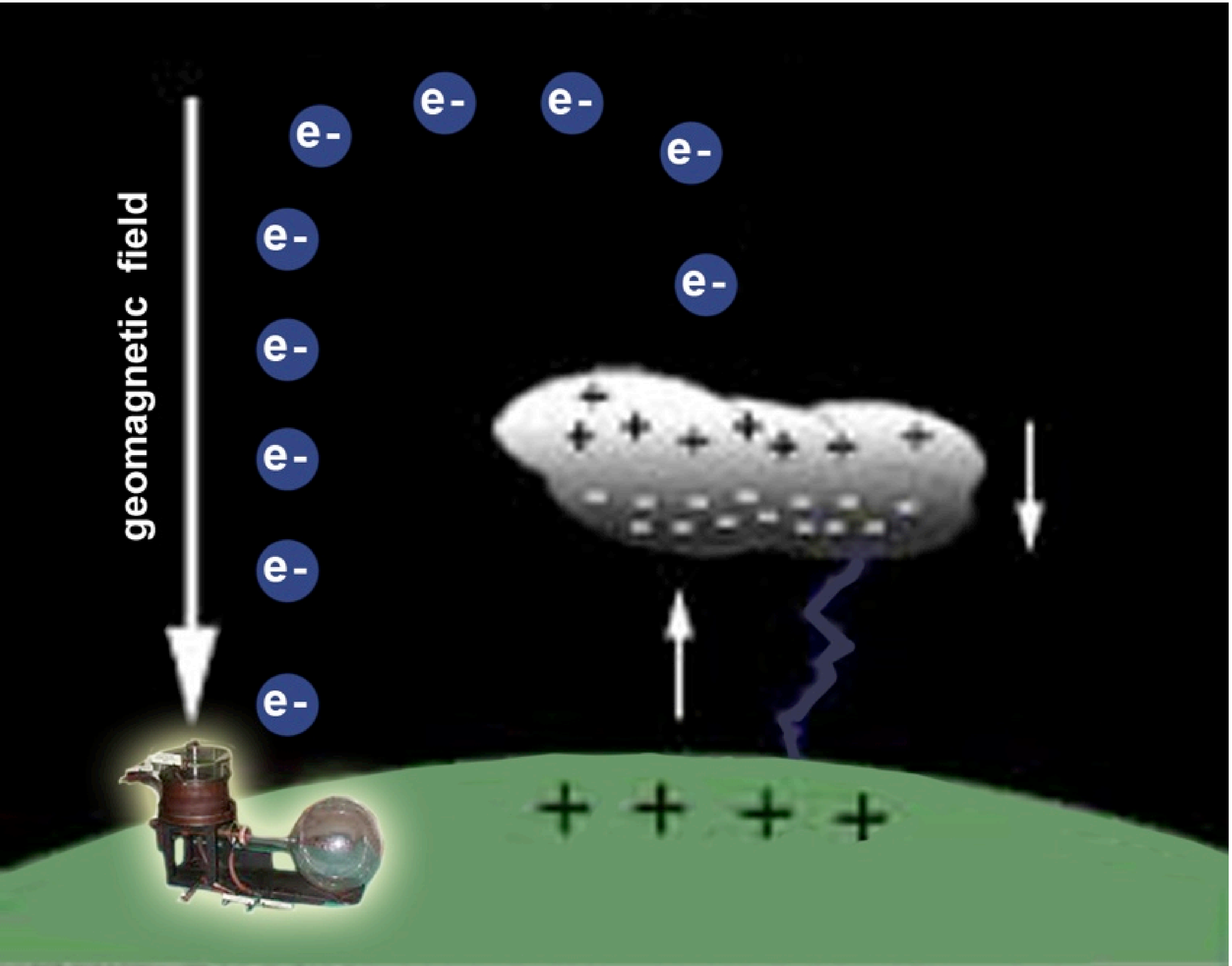
CTR Wilson, 1924: prediction of high-energy phenomena in thunderclouds

"In a field of 20 kV/cm the energy supplied to β-particle will exceed the average loss; so that particle will be continuously accelerated until some accident occurs"
"There is, as well known, some evidence of the existence of penetrating radiation in the atmosphere; possibly some portion of it may originate in the electrical fields of thunderclouds."

Despite numerous negative results by Bazil Schonland, Edward Halliday and others in searching of energetic particles from thunderclouds (as a result of using inadequate equipment) Wilson supported the idea till his last publication in 1956.

C. T. R. Wilson, the acceleration of β-particle in strong electrical fields of thunderclouds, Proc. Cambridge Philos. Soc. 22, 534, (1925).
E.R.Williams, Origin and context of C.R.T. Wilson's ideas on electron runaway in thunderclouds, JGR, 115, A00E50, 2010.

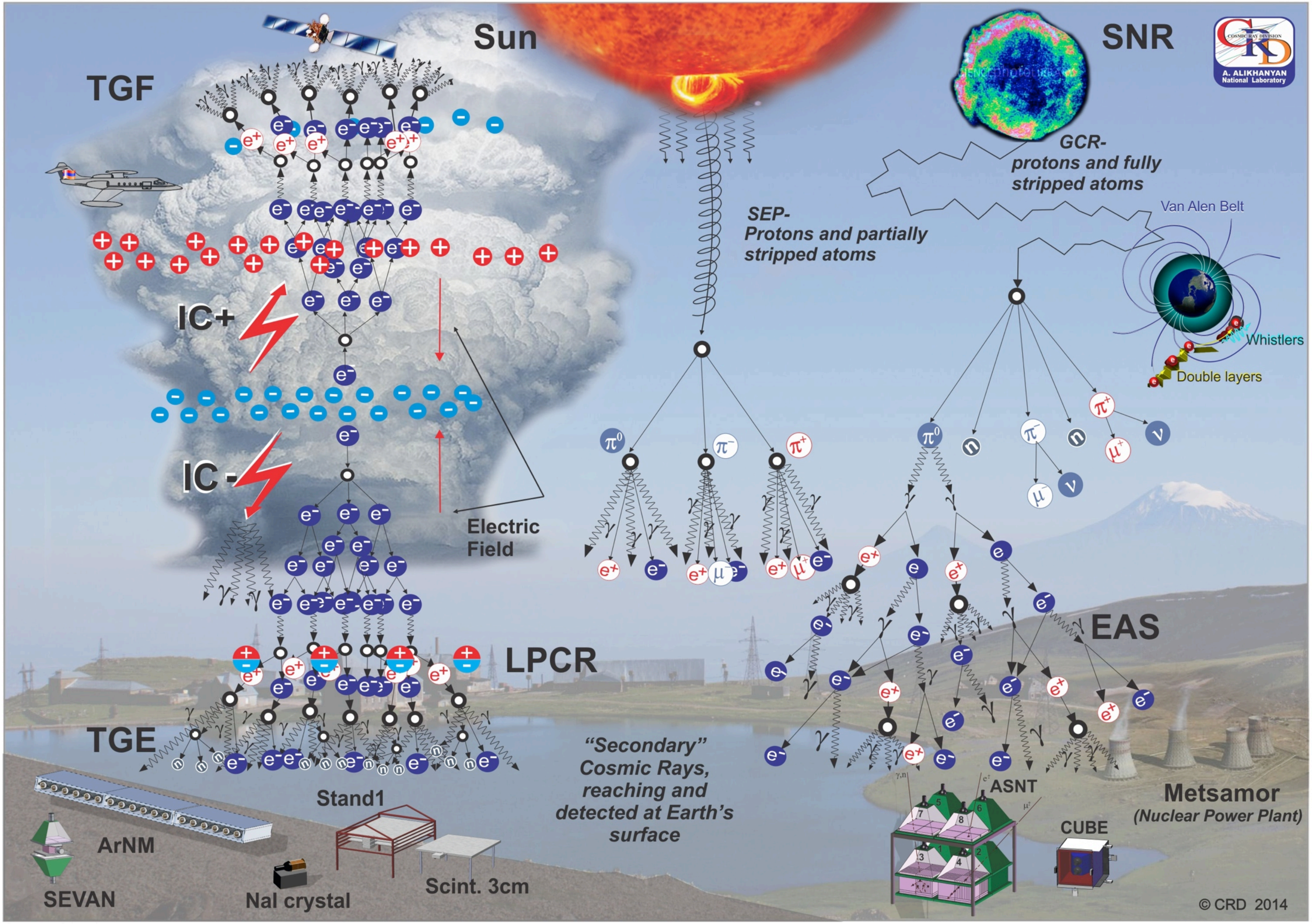
Wilson’s TGE model



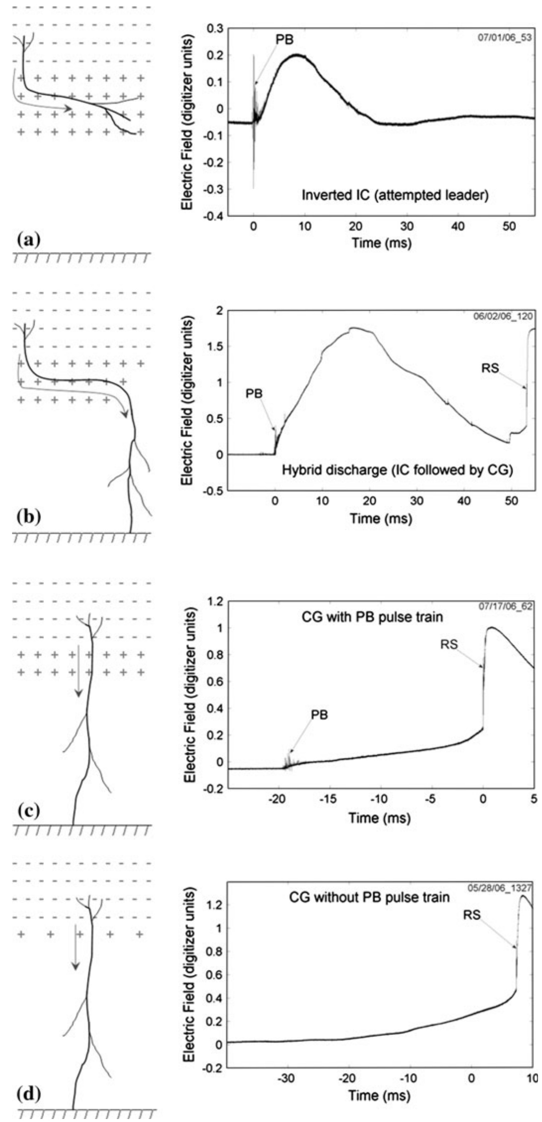
“Electrons are accelerated upwards by the field between the positive and negative charges of the cloud;
After escaping from the cloud electrons spiral round the lines of force of earth’s magnetic field, subsequently returning to the earth at great distances from the cloud which had produced them.”

Cited: Halliday E.C., The Thundercloud as a Source of Penetrating particles, Phys.Rev. 60, 101, 1941.

Origin of Secondary Cosmic Rays

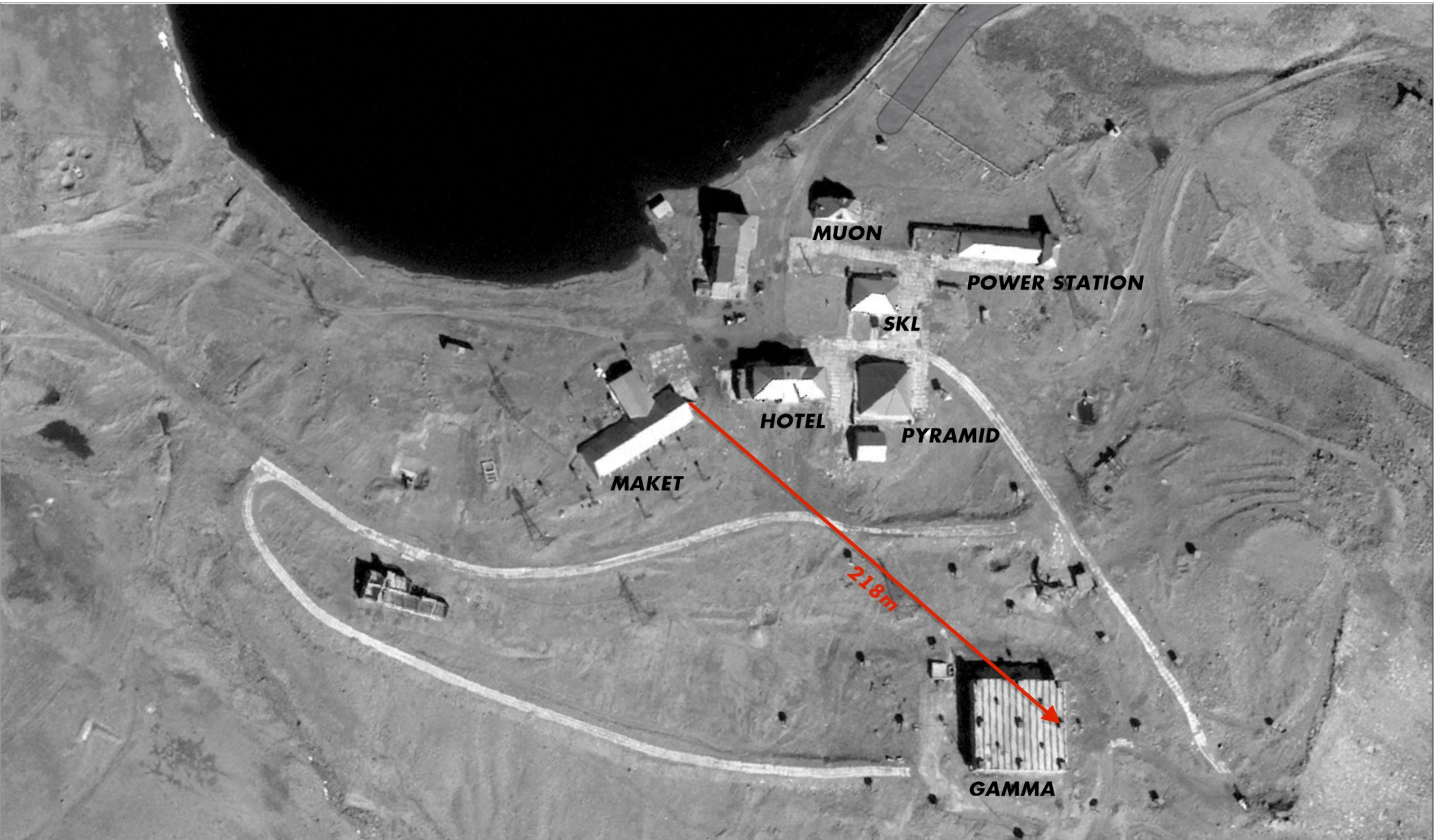


Origin of LPCR

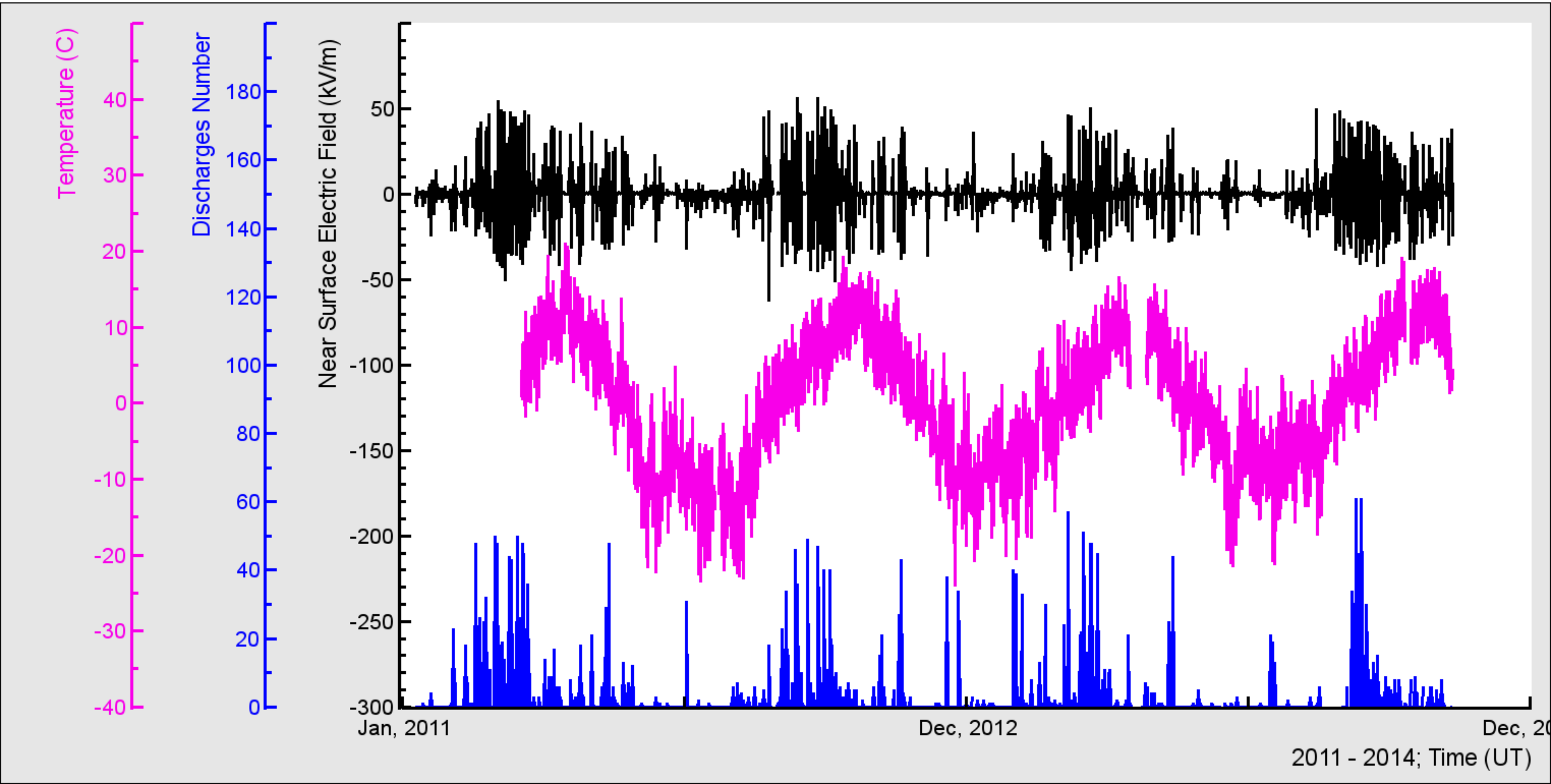


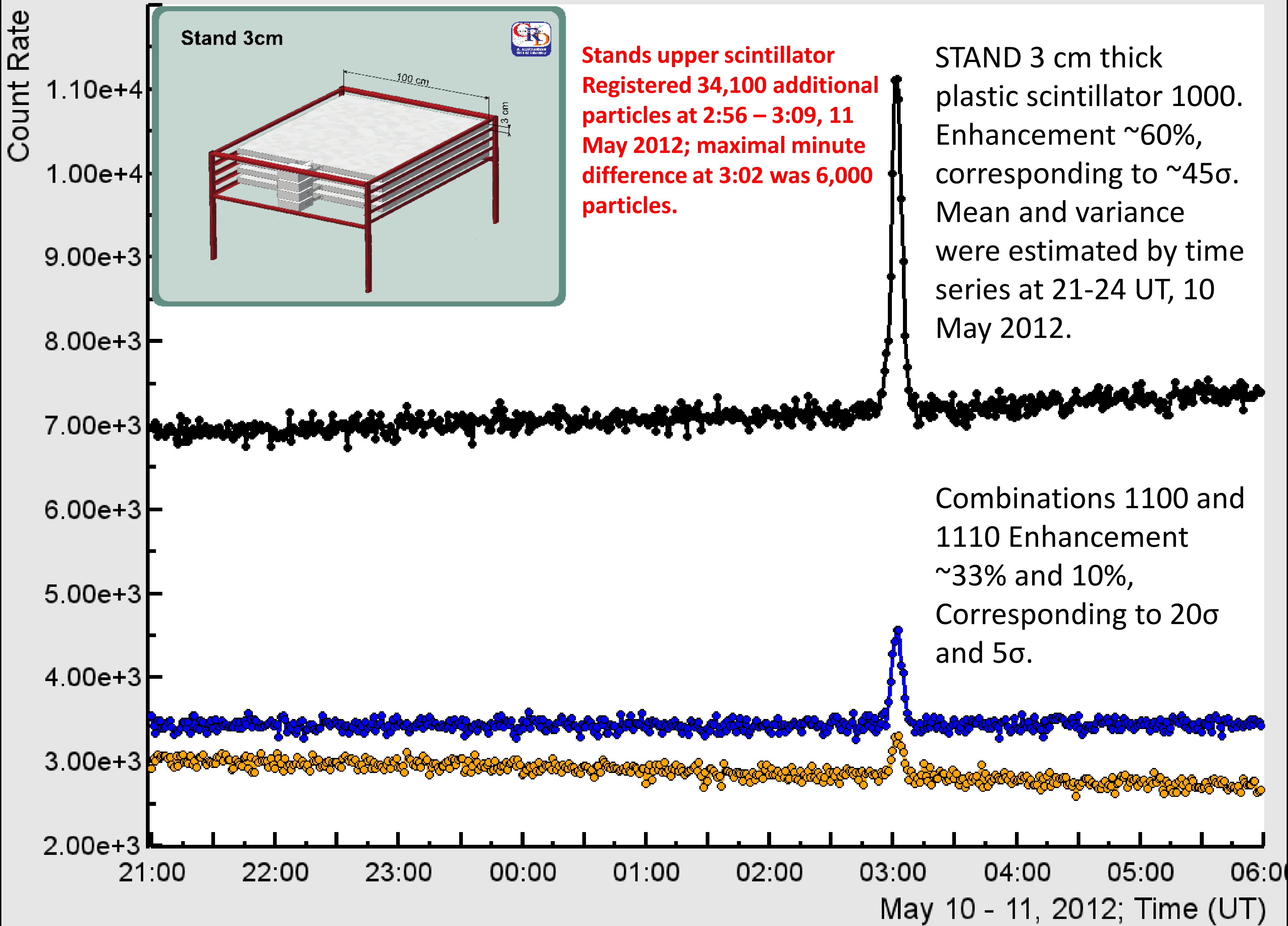
Gurevich, A.V., Karashtin A.N. (2013), Runaway Breakdown and Hydrometeors in Lightning Initiation, PRL 110, 185005.

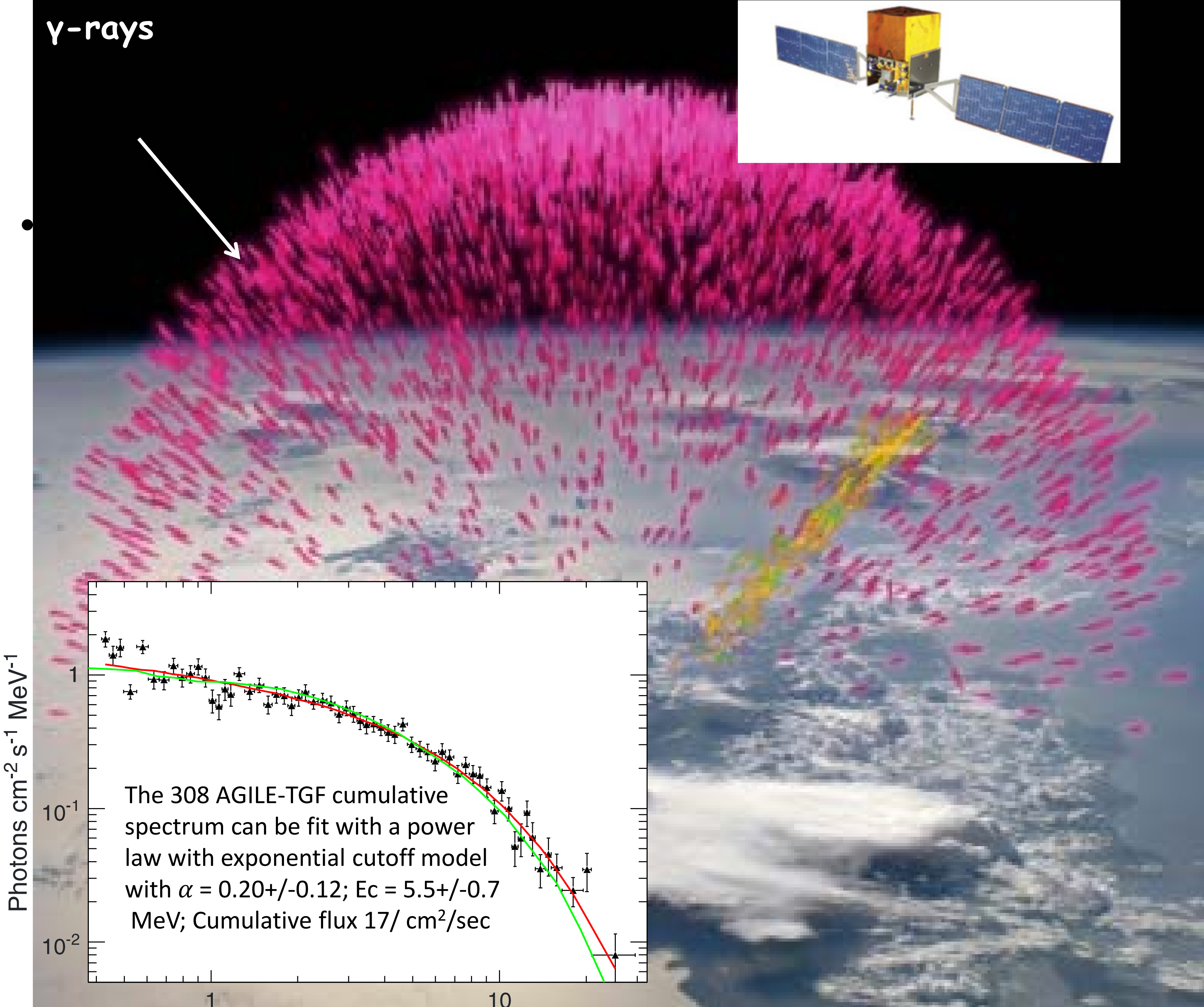
Aragats research station, Armenia



Aragats - 2011-2014 – one of the best sites in world for research of atmospheric electricity




Stand 3cm
100 cm
3 cm
Stands upper scintillator Registered 34,100 additional particles at 2:56 – 3:09, 11 May 2012; maximal minute difference at 3:02 was 6,000 particles.
STAND 3 cm thick plastic scintillator 1000. Enhancement ~60%, corresponding to ~45σ. Mean and variance were estimated by time series at 21-24 UT, 10 May 2012.
Combinations 1100 and 1110 Enhancement ~33% and 10%, Corresponding to 20σ and 5σ.
Count Rate
1.10e+4
1.00e+4
9.00e+3
8.00e+3
7.00e+3
6.00e+3
5.00e+3
4.00e+3
3.00e+3
2.00e+3
21:00
22:00
23:00
00:00
01:00
02:00
03:00
04:00
05:00
06:00
May 10 - 11, 2012; Time (UT)


γ-rays
Photons cm^{-2} s^{-1} MeV^{-1}
1
10^{-1}
10^{-2}
1
10
The 308 AGILE-TGF cumulative spectrum can be fit with a power law with exponential cutoff model with α = 0.20+/-0.12; Ec = 5.5+/-0.7 MeV; Cumulative flux 17/ cm^2/sec

Vocabulary of abbreviations

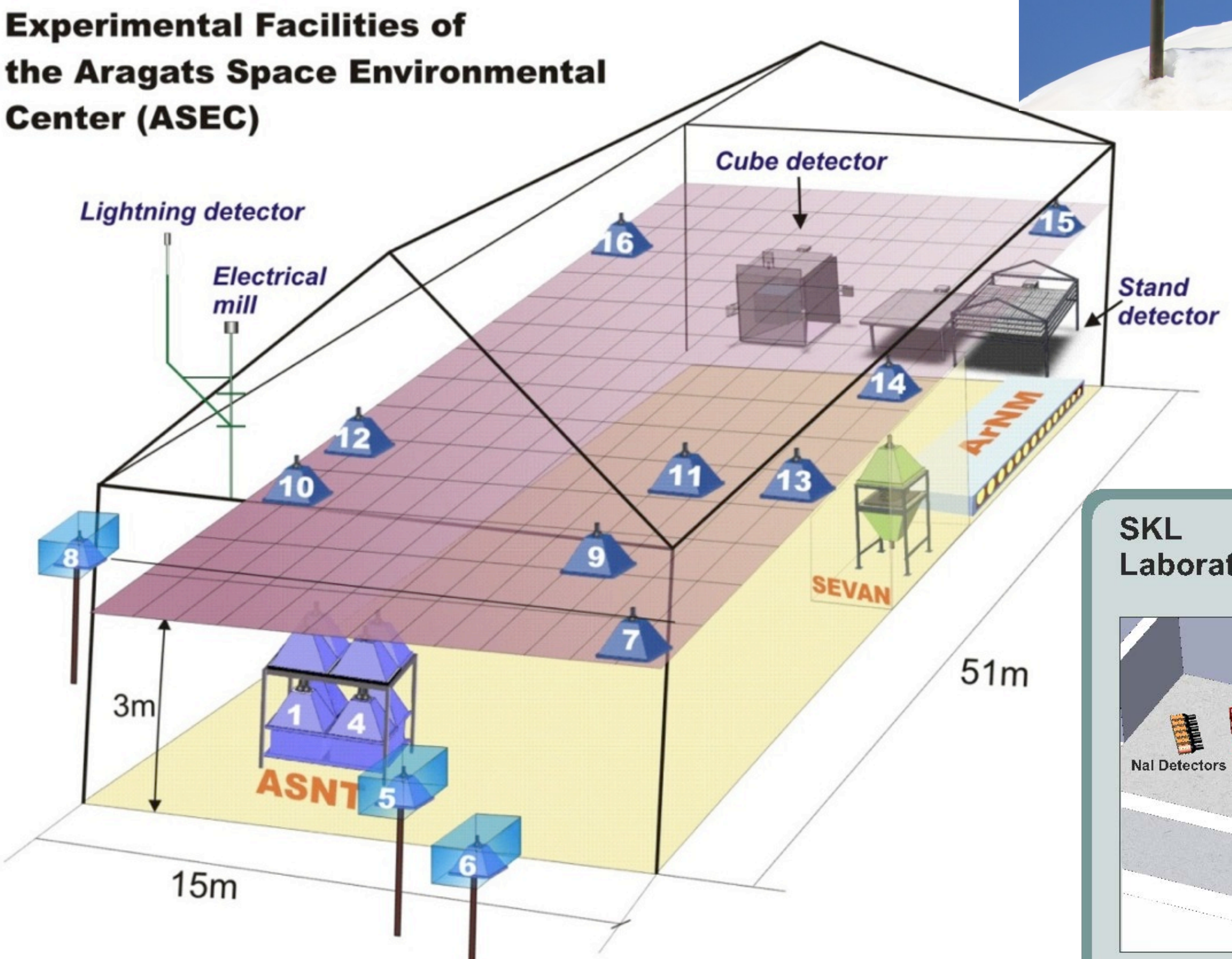
- GLE – Ground Level Enhancement solar modulation of surface CR flux;
- TGF – Terrestrial Gamma Flashes –short intense bursts of gamma radiation in space from direction of Earth;
- TGE – Thunderstorm Ground Enhancement – short and longer particle fluxes detected on Erath's surface correlated with thunderstorm ;
- TLE - Transient Luminous Events;
- RREA – Relativistic Runaway Electron Avalanches – "electromagnetic" and "short" version of EAS!
- MOS – MOdification of Energy Spectra, on of main sources of TGE;
- EAS – Extensive Air Shower;
- ECS – Extensive shower spectra or surface TGF;
- LPCR – Lower positive charge region;

Secondary Cosmic Ray Enhancements – connected with arrival of thunderclouds - TGEs

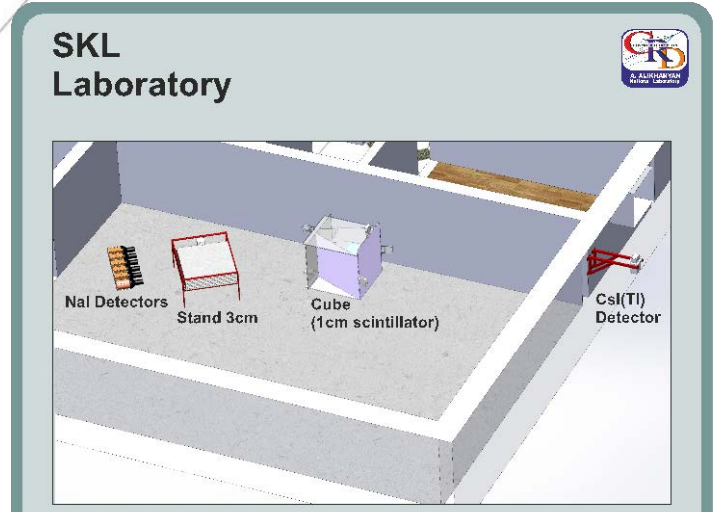
The boost of the secondary cosmic ray flux observed during thunderstorms, so-called Thunderstorm Ground Enhancements (TGEs), is the manifestation of high-energy processes in the terrestrial atmosphere. Origin of TGE is the strong electrical field in the thundercloud and lightning, giving rise to rather complicated physical phenomena, including at least 6 physical processes:

- Relativistic Runaway Electron Avalanches (RREA) – huge particle fluxes up to 40MeV with duration up to 10 minute;
- **Modification of the secondary Cosmic ray (CR - electrons, muons, protons and charged mesons) energy spectra (MOS) – modest fluxes up to 100 MeV ;**
- Photonuclear reactions of the RREA gamma rays;
- **Attenuation of the cosmic ray muon flux;**
- Short “individual” particle RRE avalanches from the lightning (Ground Level TGFs);
- γ-ray bursts from lighting tips;
- **Prolonged (2-3 hours and more) enhancement of the low energy (0.5-2 MeV) cosmic ray flux.**

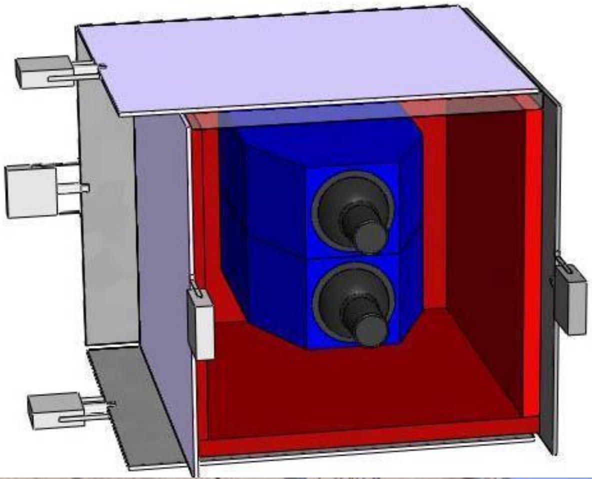
Monitoring of fluxes, fields, meteorological conditions

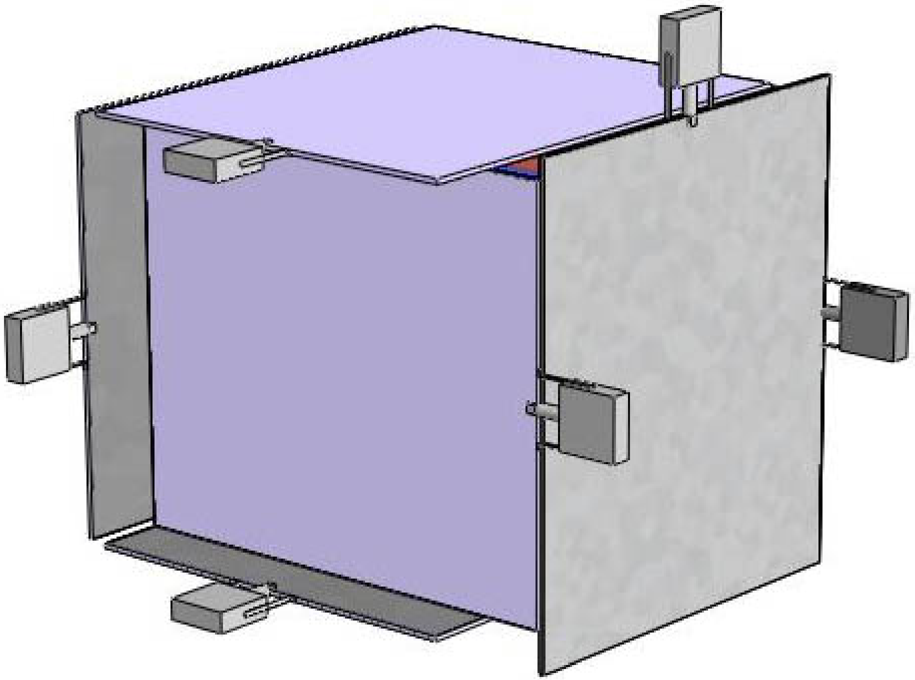


Boltek EFM 100 electrical mill and Lightning tracer; Davis instr. weather station

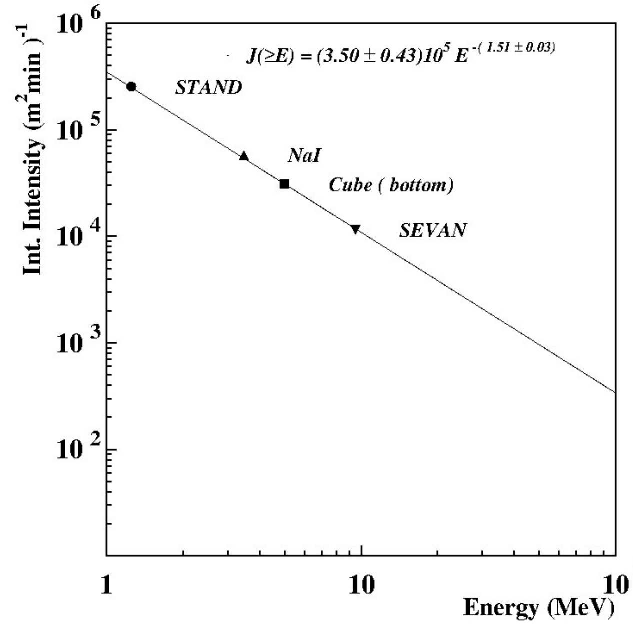


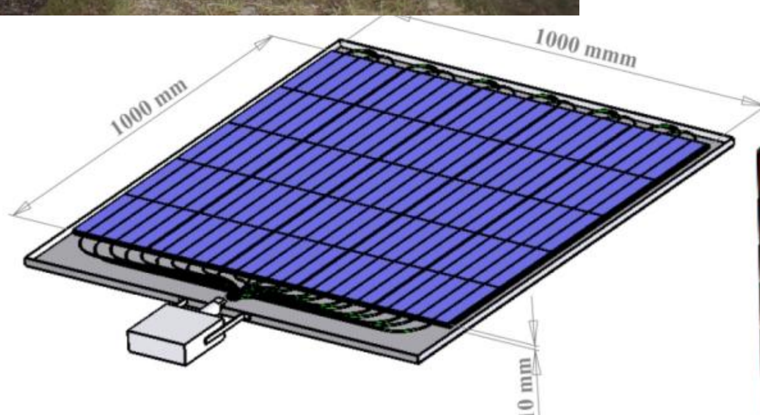
Cube Detector for detection of Neutral particle

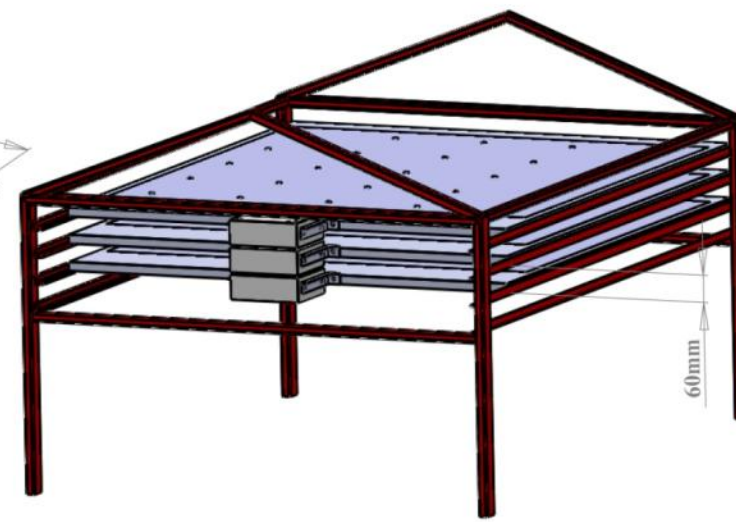




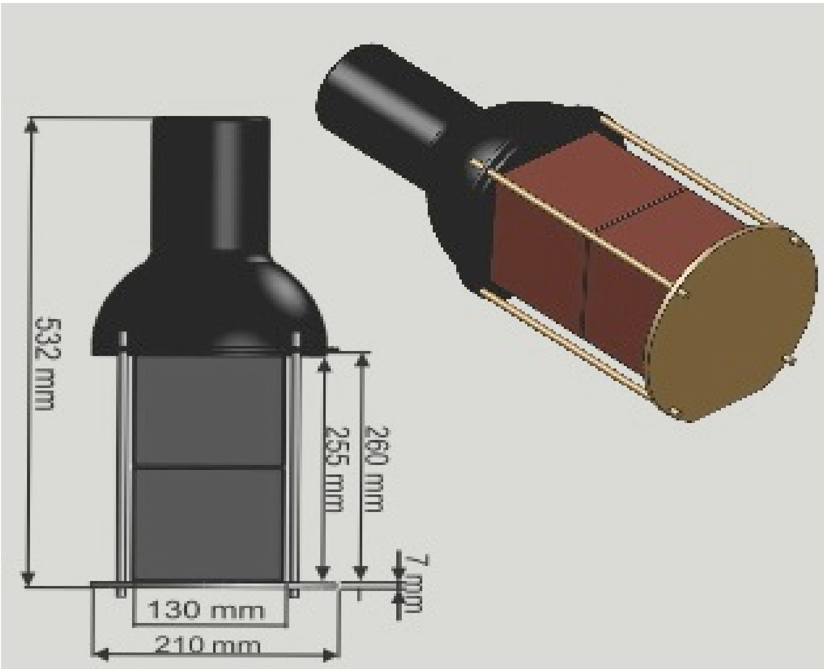
STAND multilayered Detector

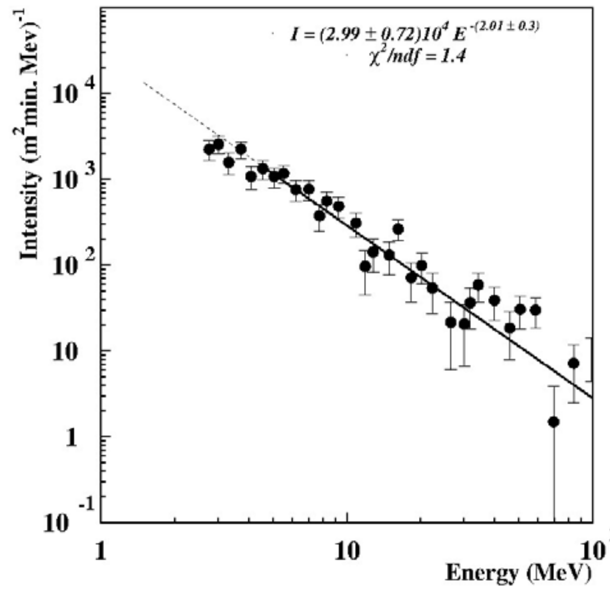


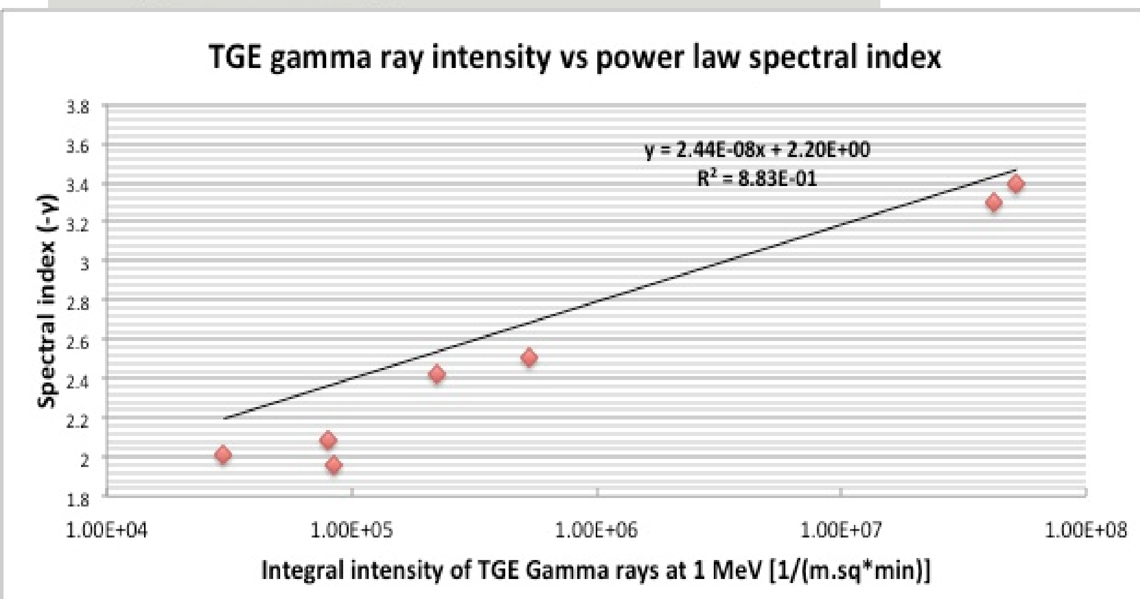


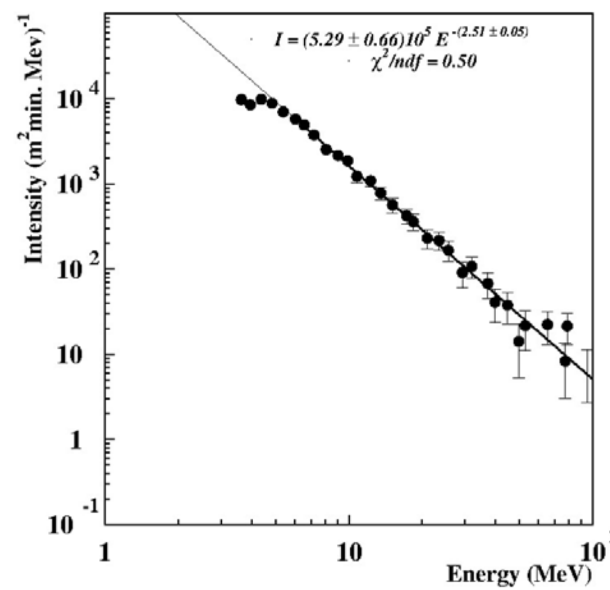


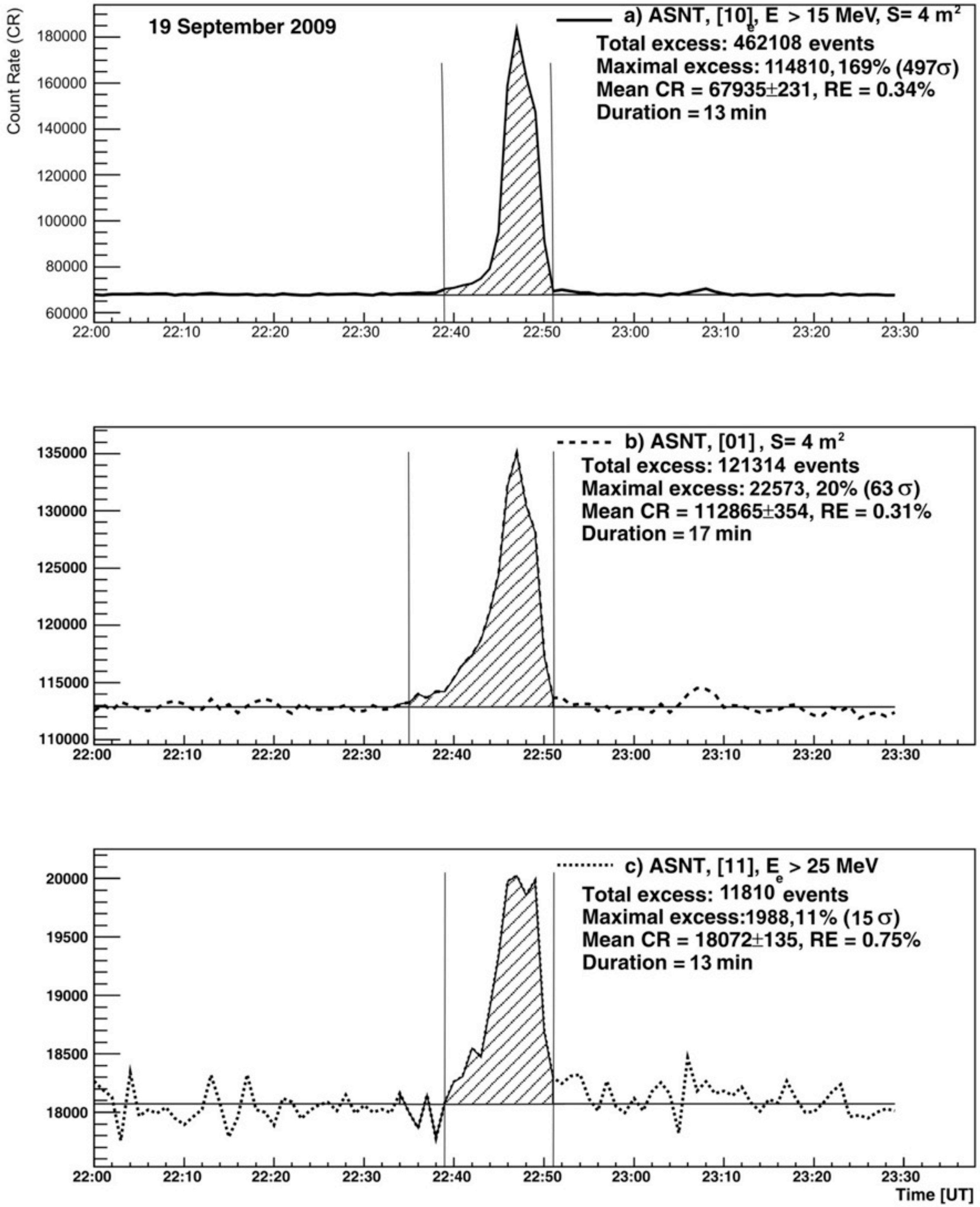
NaI network 5 detectors 12.5 x 12.5 x 25 each





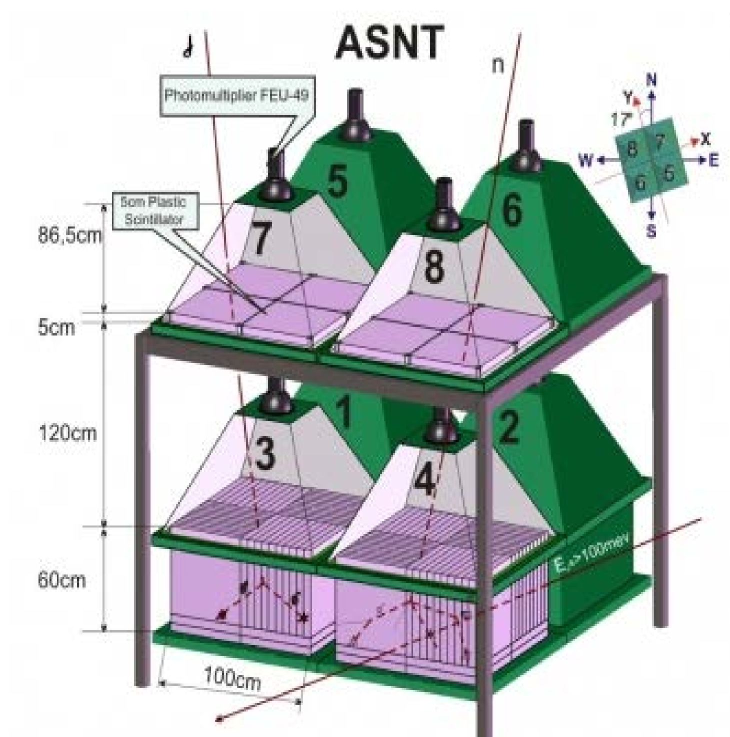




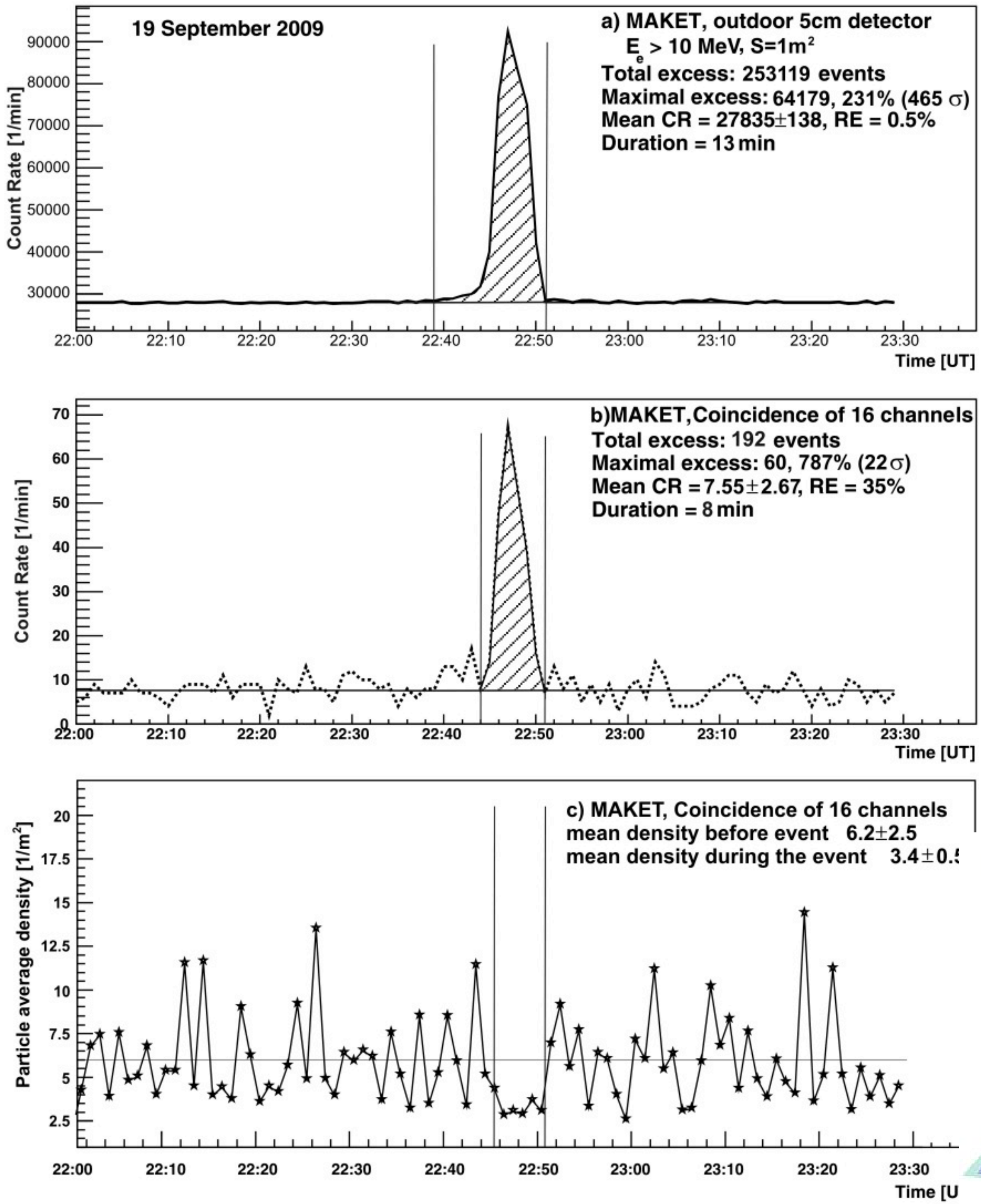


Huge TGE of 19 September, 2009 was detected by all ASEC monitors : ASNT consists of 5 cm and 60 cm thick scintillators (4 modules each 1 m.sq. area;

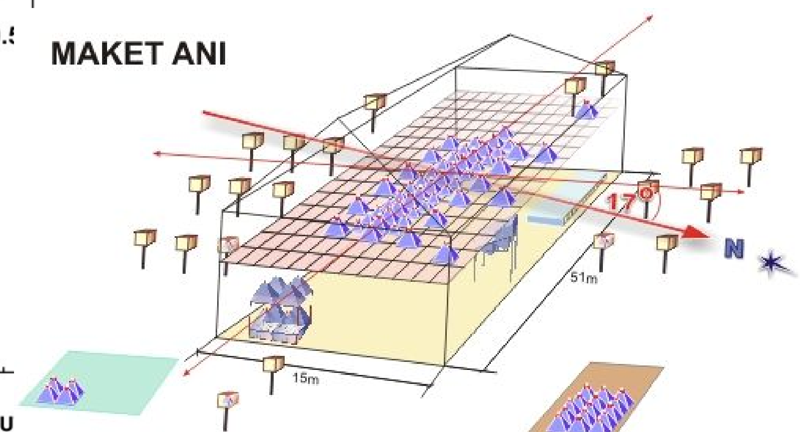
ASNT (11) – electrons E ~ 30 MeV -



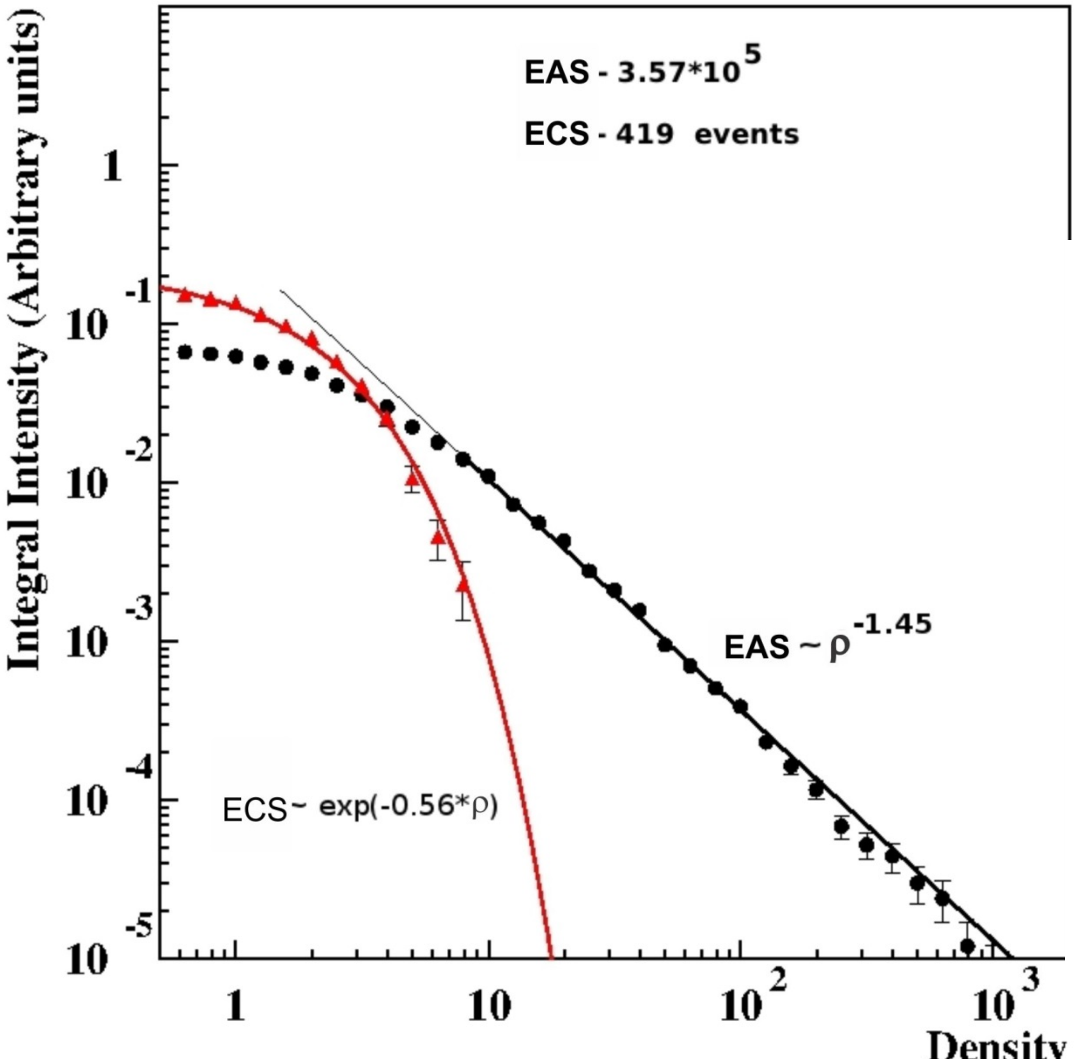
A. Chilingarian, A.Daryan, K.Arakelyan, et al., Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons, Phys.Rev. D., 82, 043009, 2010

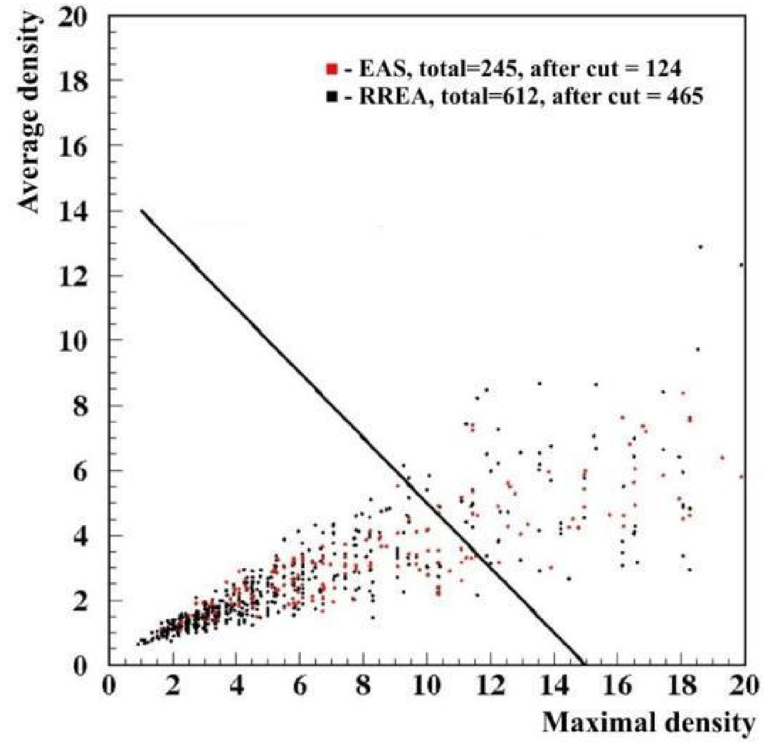


First detection of "individual" RRE avalanches - more than 400 events.
New type of particle showers – Extensive Cloud Showers (ECS surface TGFs);
MAKET detect short coherent bursts of electrons/gamma rays (within 1 µsec);
ECS counts 7 times more than EAS!
ECSs have smaller densities – can be distinguished from CR EAS.

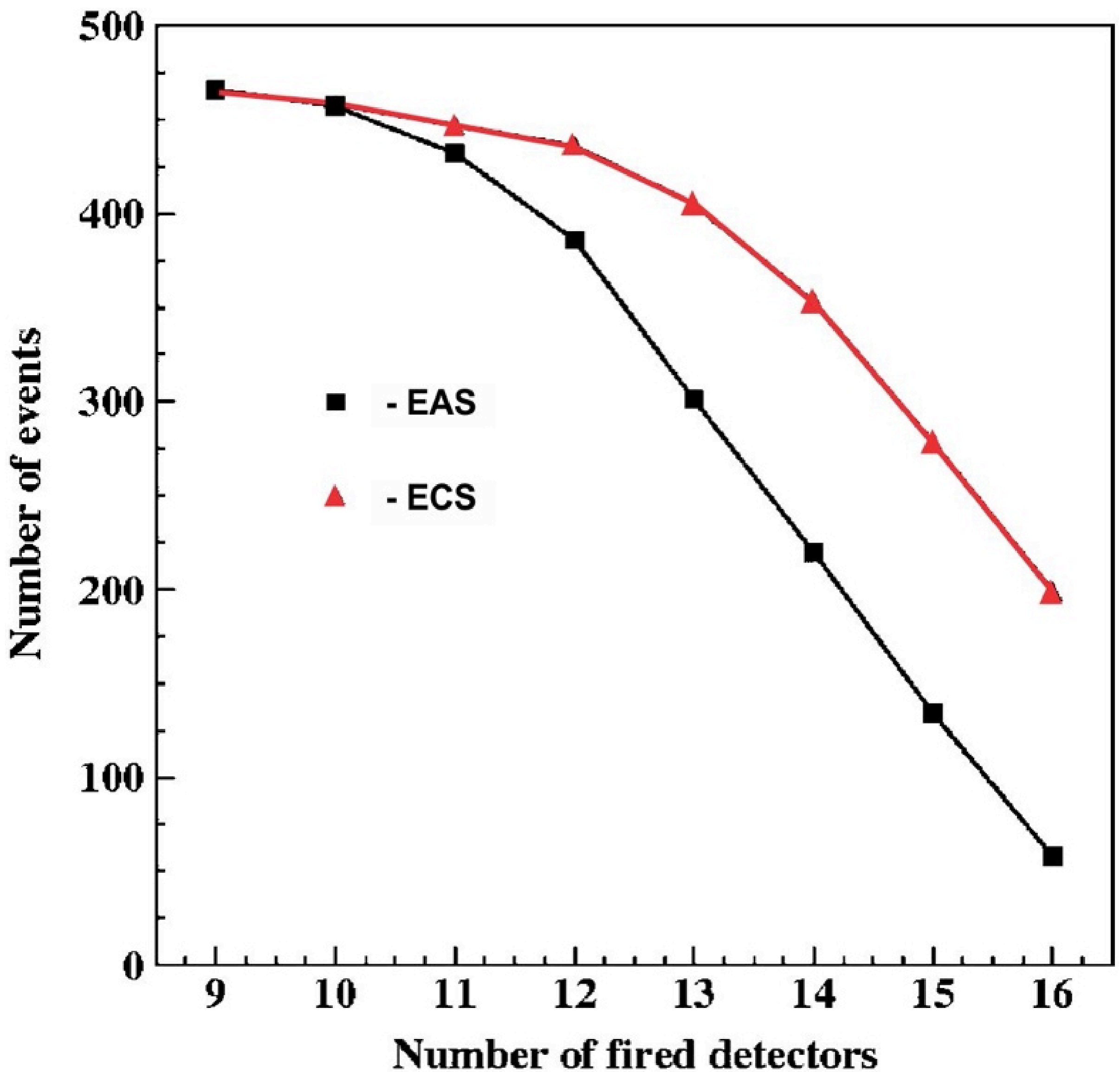


Spectra of Extensive Air Showers (EAS) and Extensive Cloud Showers (ECS)

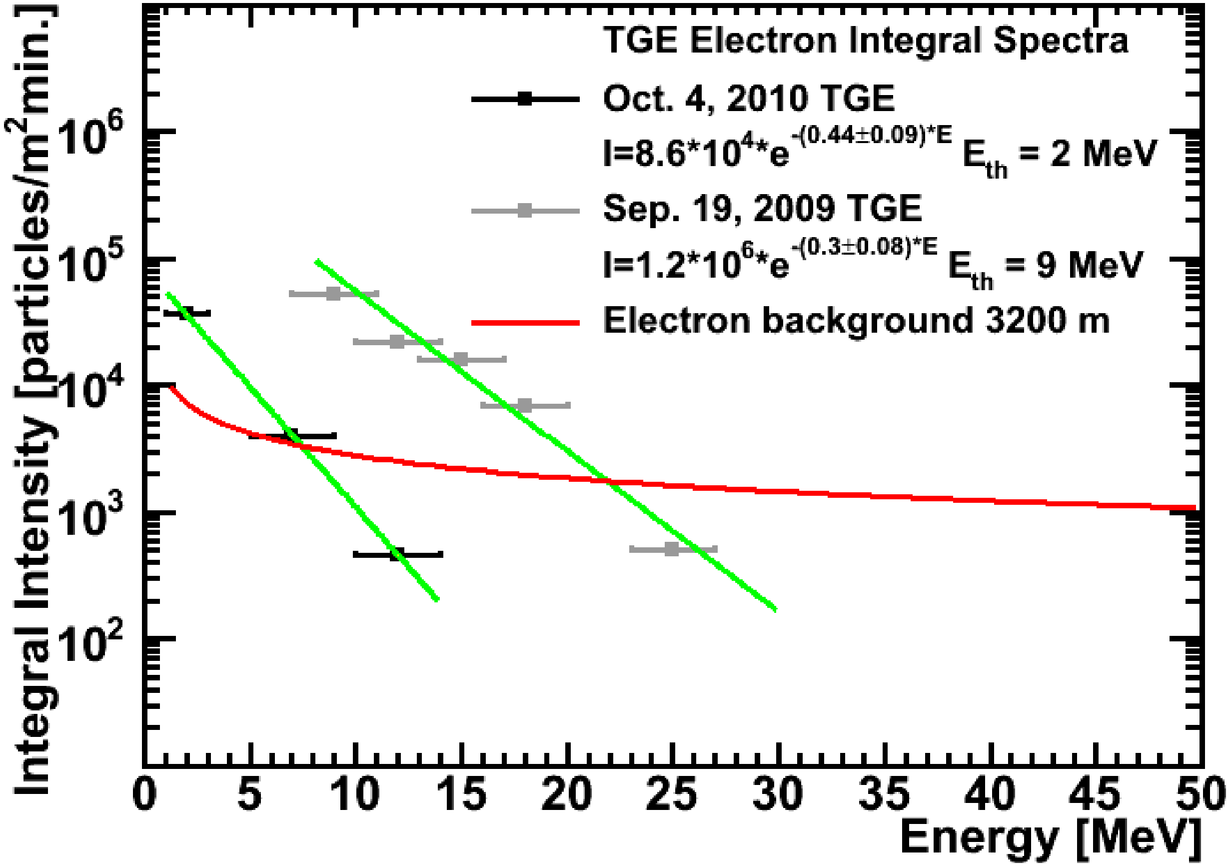




Extensive Cloud Showers (ECS) extended more than Extensive Air Showers (EAS)

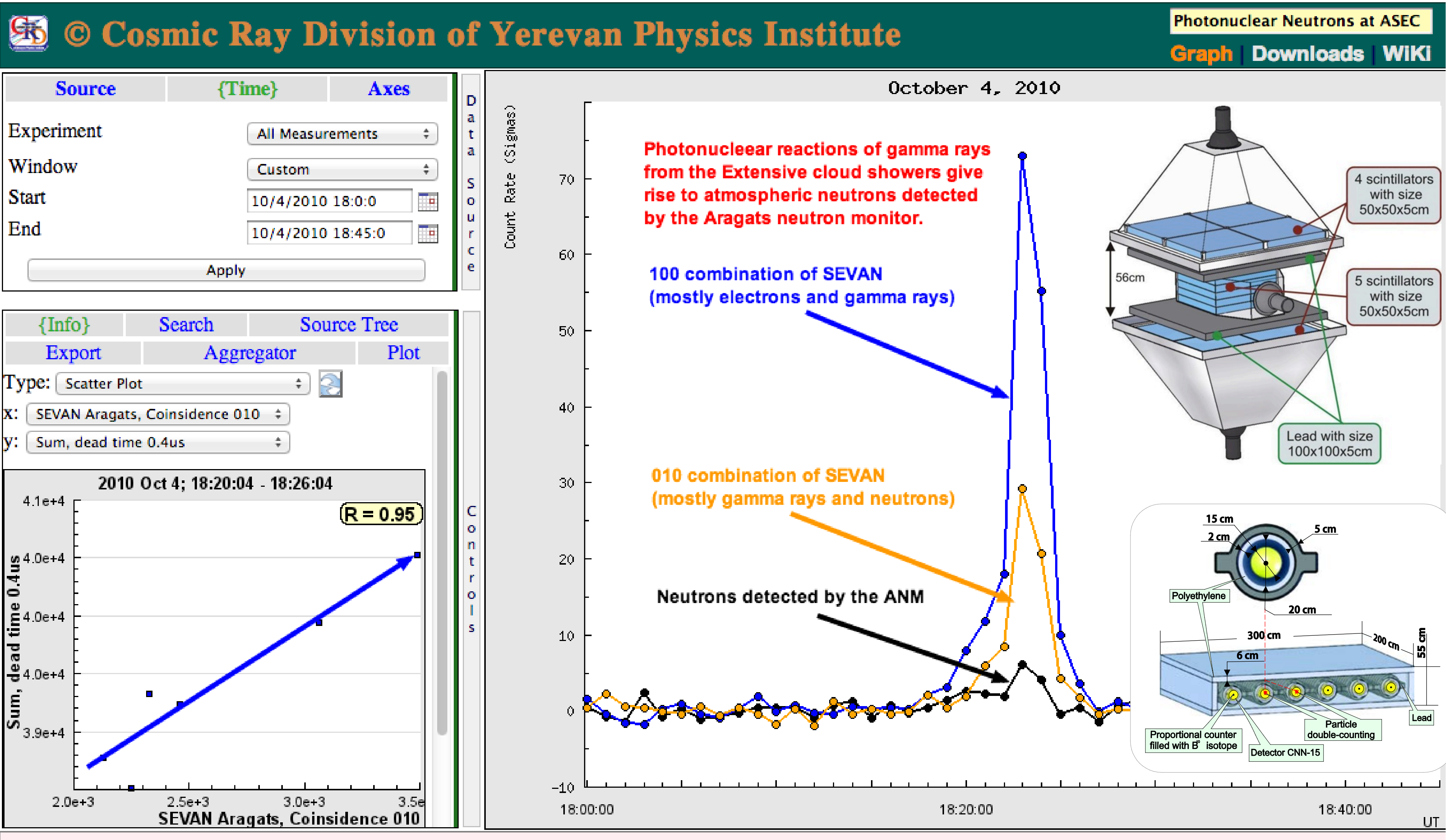


Electron Integral Energy spectra for 2 largest TGEs

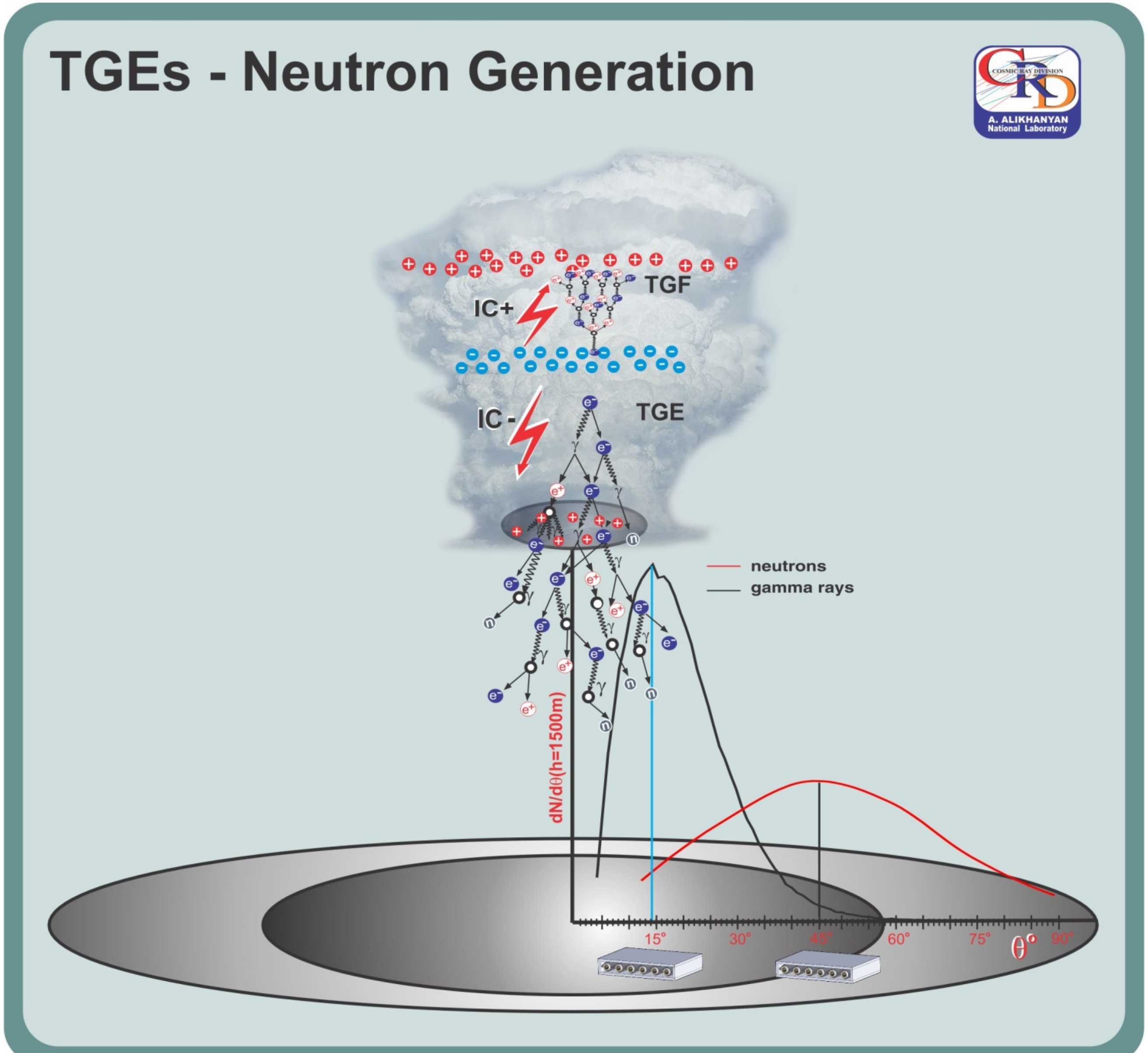


Mean energy of electrons on observation level 2.3 and 3.3 MeV, good agreed with TGE simulations with field strength 1.7-1.8 kV/m

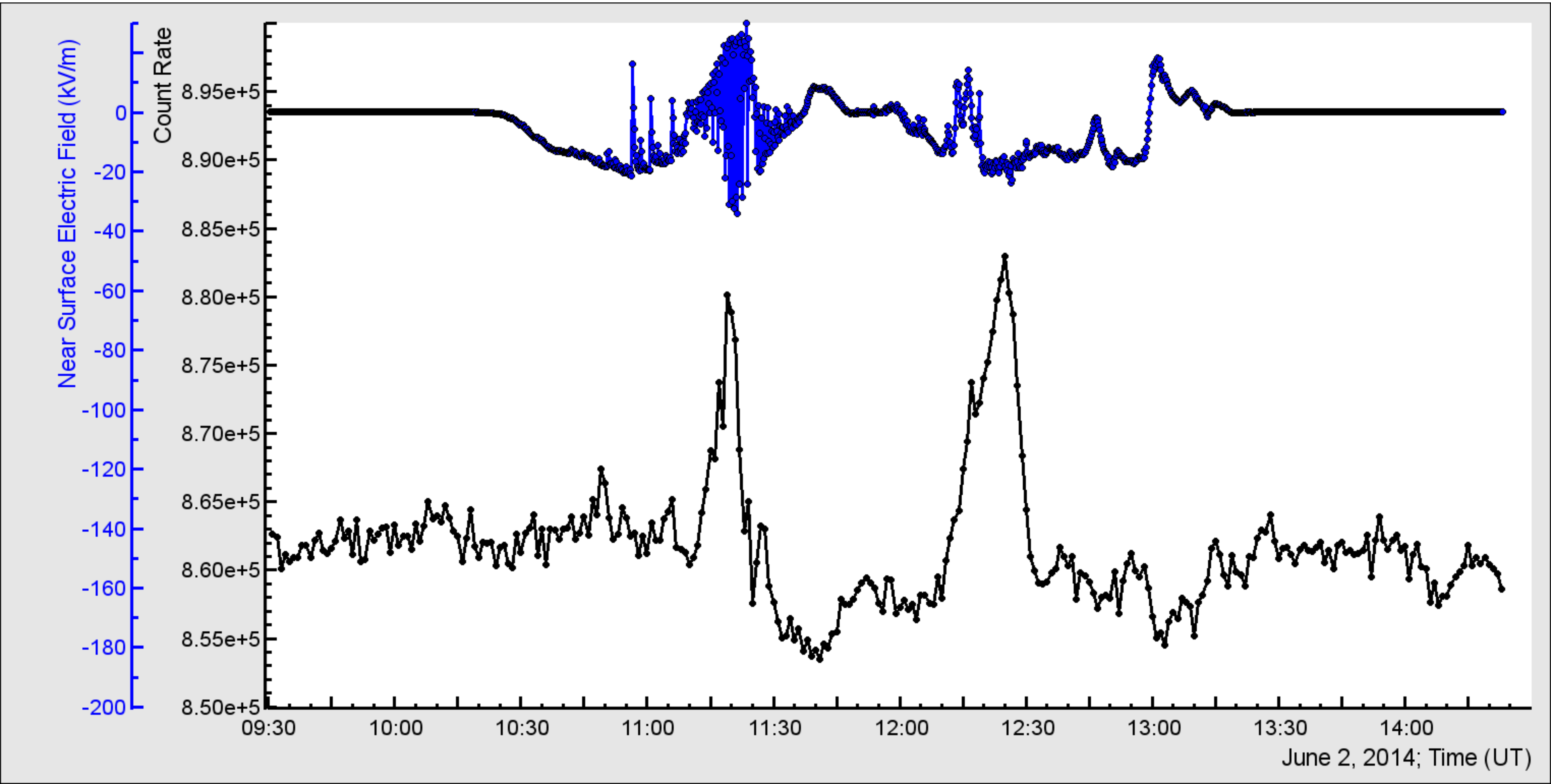
Detection of TGE neutrons



Origin of TGE neutrons (lightning bolt, photonuclear reactions: in lead or in atmosphere)



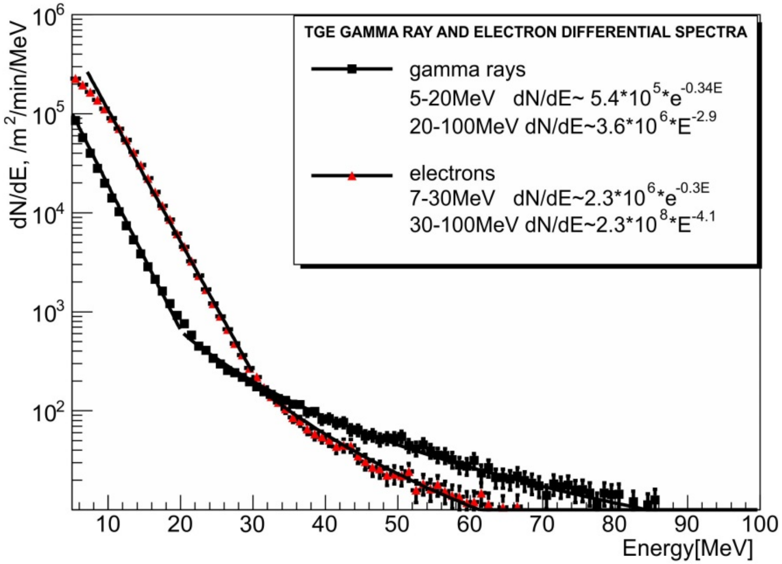
AMMM – 20 m.sq. outdoor scintillators – muon flux depletion after peaks

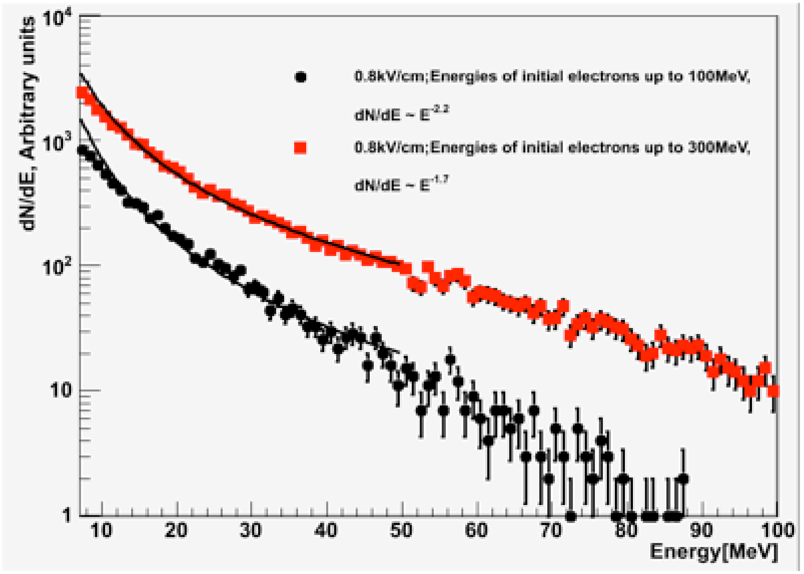


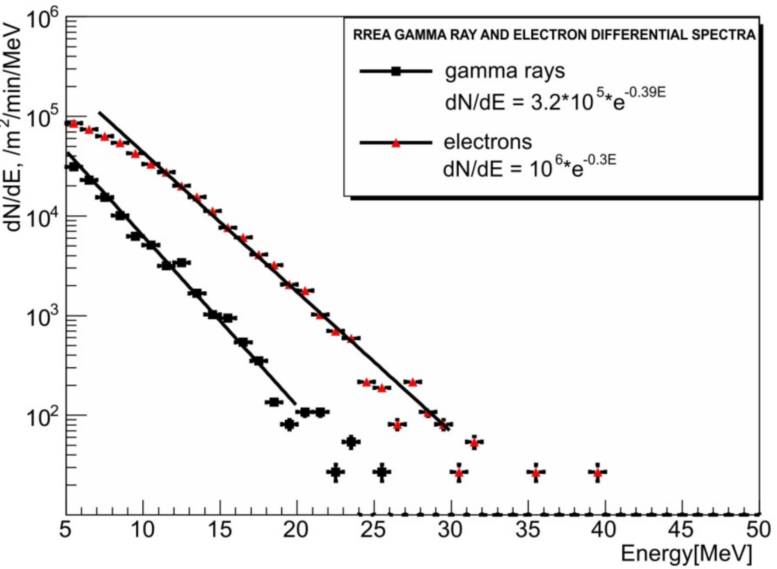
Origin of TGE: RREA or MOS (2 different populations)

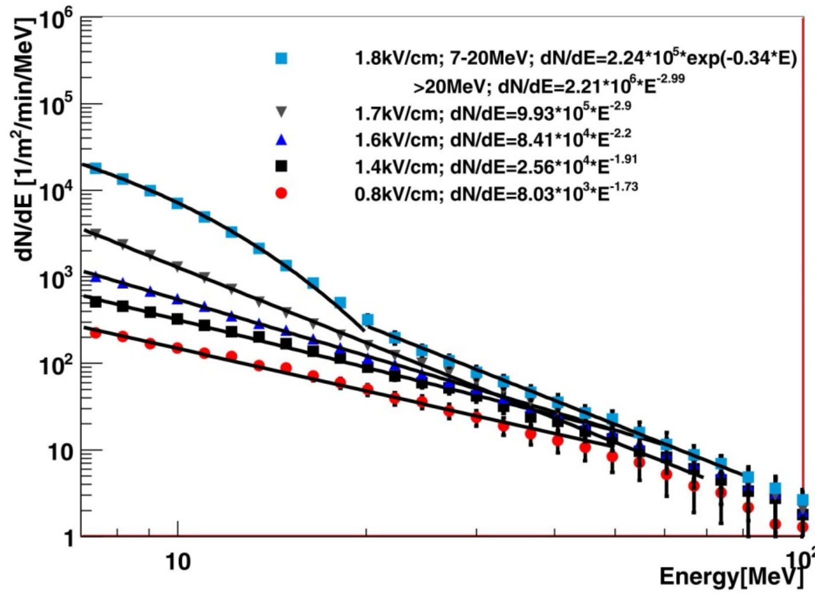
- “Any intense burst of gamma-rays in our atmosphere with energies exceeding 7 MeV, the characteristic RREA energy scale, almost certainly is produced by runaway electrons experiencing RREA multiplication” (Dwyer et. Al., 2012, J. Geophys. Res., 117, A10303);
- “The analysis performed suggests that during thunderstorms, at a moderate strength of the near-Earth field (±7 kV m^{-1} for our array), the observed variations in the intensity of the electron–photon component are in fact completely determined by the transformation of the electron–positron spectrum by the near-Earth field.” *A.S. Lidvansky, N.S. Khaerdinov, 2007, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2007, Vol. 71, No. 7, pp. 1052–1055.*

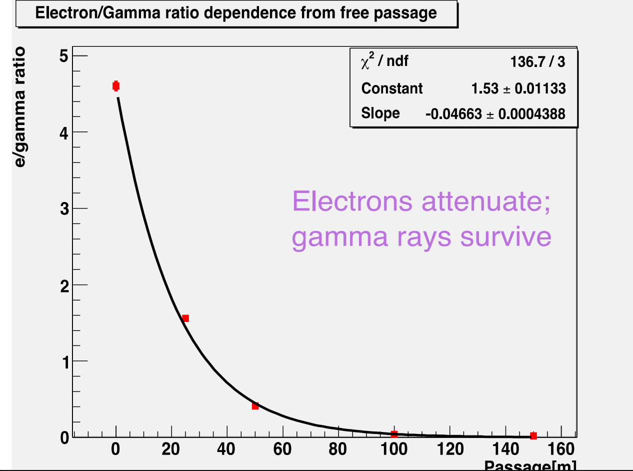
2-component model of TGE: GEANT4 simulation of TGE: Uniform Electrical fields of 0.8 – 1.8 kV/m, started from 5000 m till 3350Observation on 3200. Seeds: CR ambient electrons



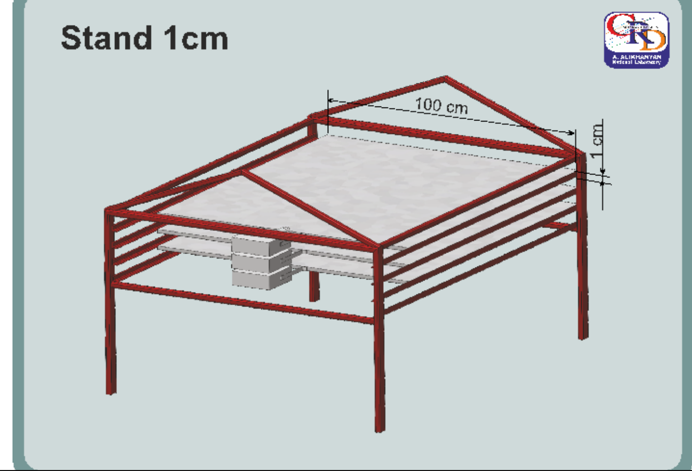


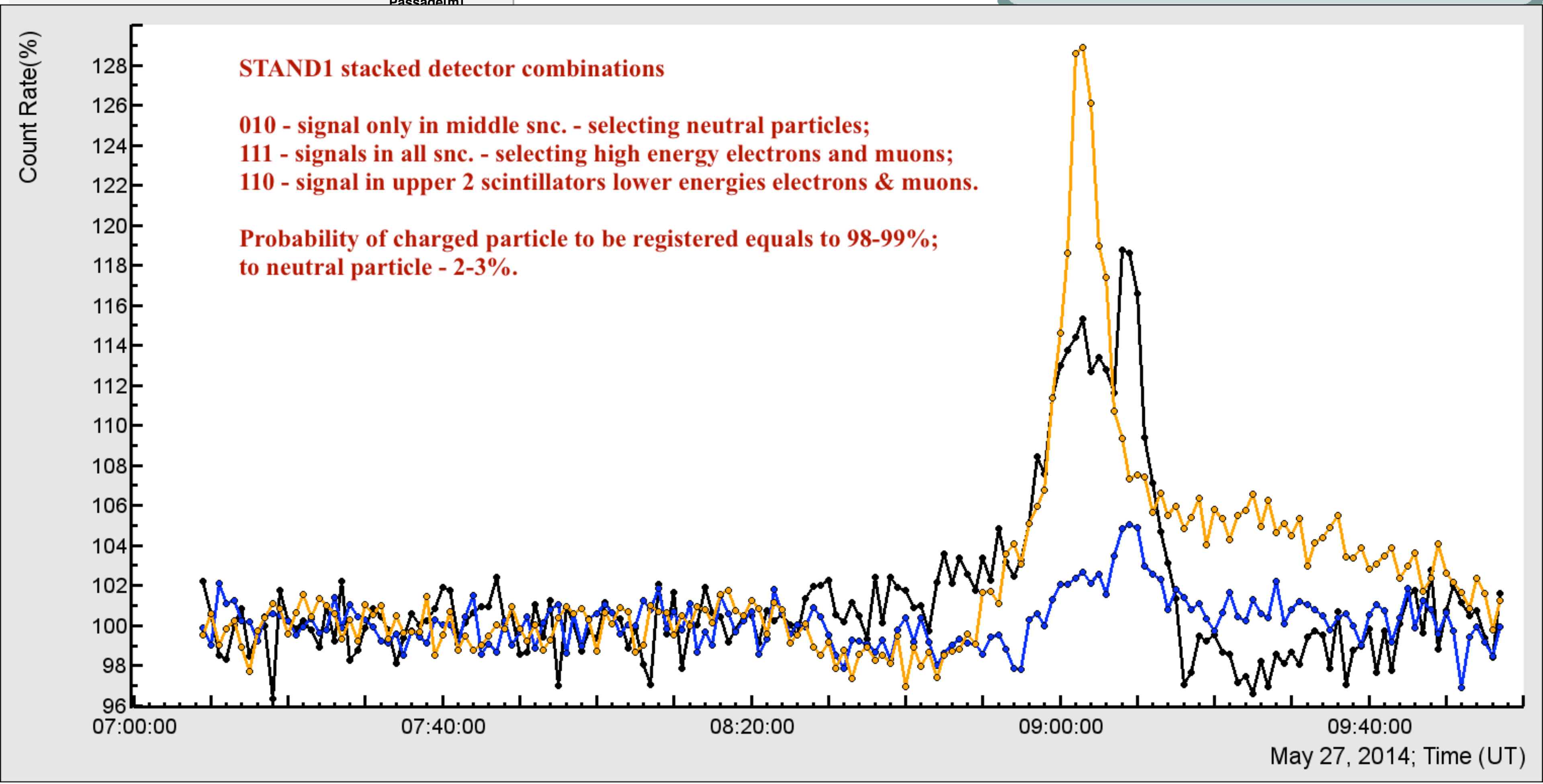


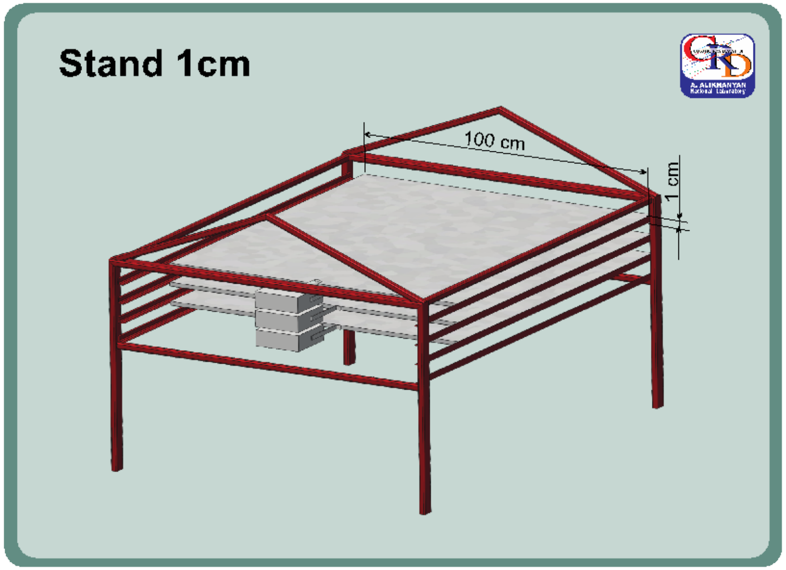




e/gamma ratio







Energy Spectra: Lower threshold

$$N(100) = N_{\mathrm{e}}\mathrm{p}(100/\mathrm{e}) + N_{\mathrm{g}}\mathrm{p}(100/\mathrm{g})$$

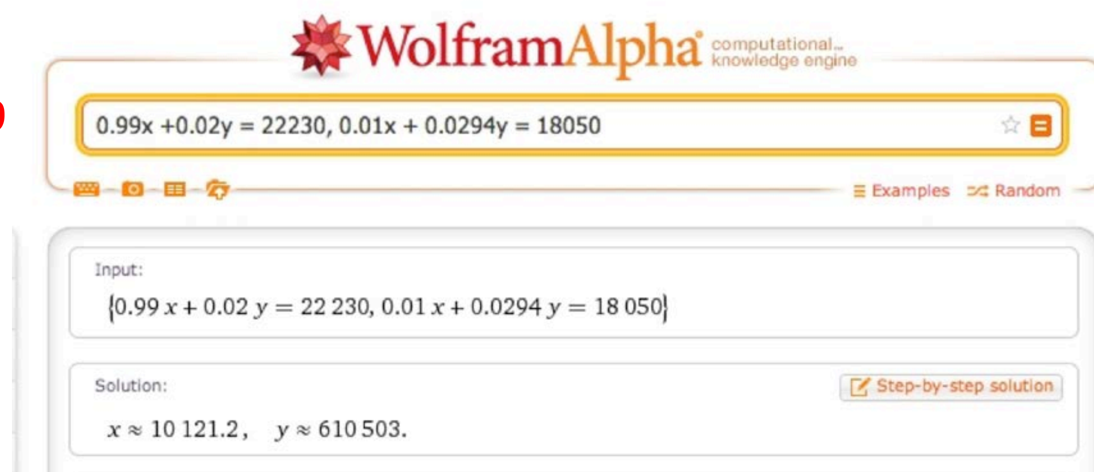
$$N(010) = N_{\mathrm{e}}\mathrm{p}(010/\mathrm{e}) + N_{\mathrm{g}}\mathrm{p}(010/\mathrm{g}).$$

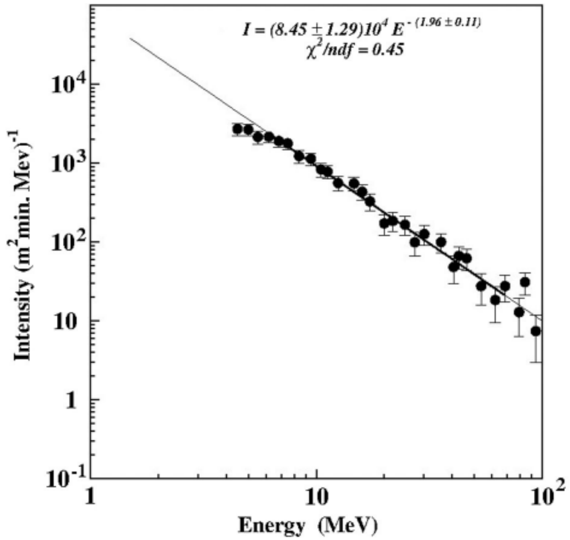
$$\mathrm{p}(100/\mathrm{e}) = 0.99 \qquad \mathrm{p}(100/\mathrm{g}) = 0.02$$

$$\mathrm{p}(010/\mathrm{e}) = (1\text{-}\mathrm{p}(100/\mathrm{e}))\mathrm{p}(100/\mathrm{e}) = 0.0099$$

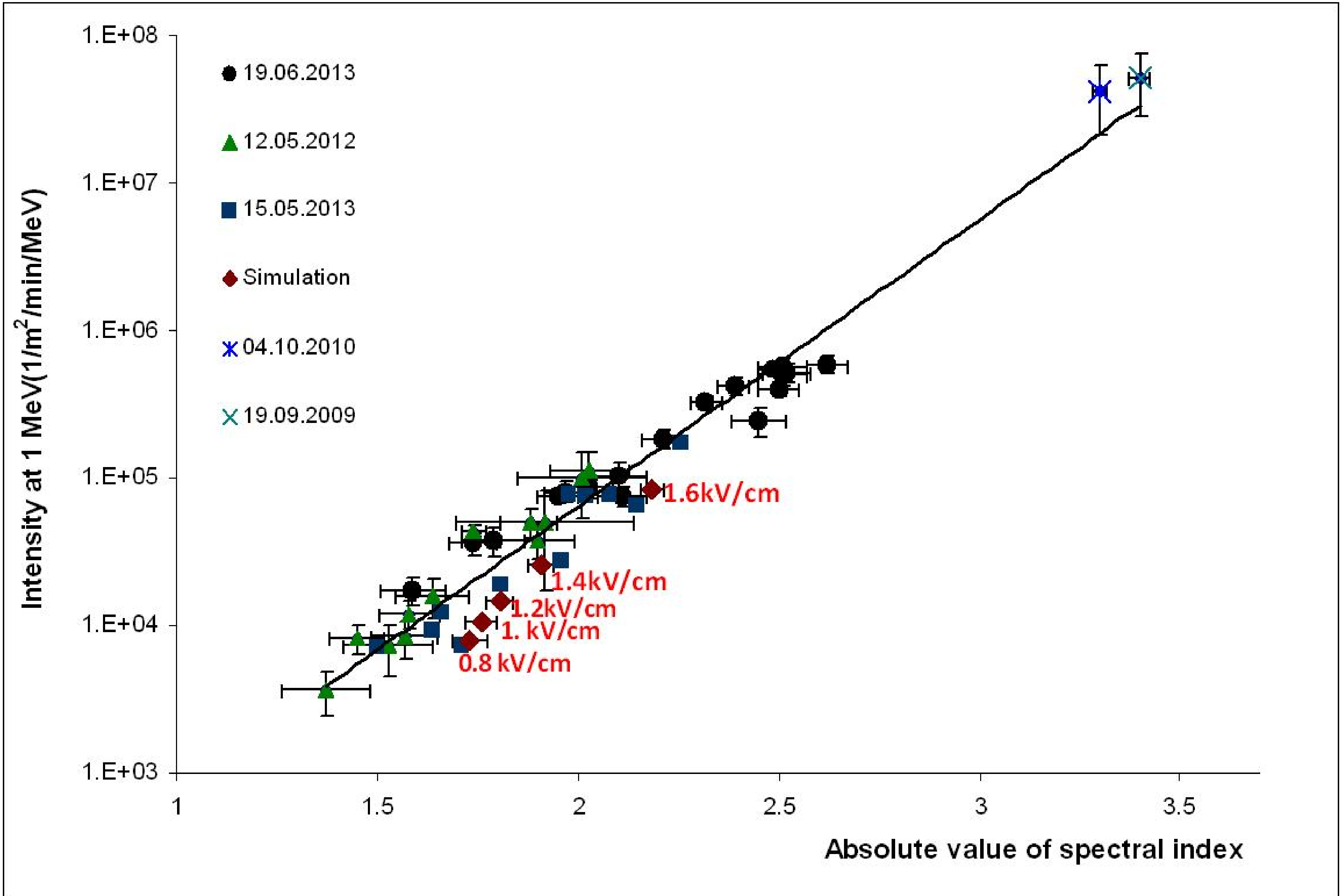
$$\mathrm{p}(010/\mathrm{g}) = (1\text{-}\mathrm{p}(100/\mathrm{g}))\mathrm{p}(010/\mathrm{g}) = 0,0294.$$

I(e)=10121/60 [1/m^{2}sec] = 169
I(γ) = 610503/60 = 10175
I(e)/I(γ) = 1,7%





individual crystals. However, as we can see in Fig. 11, the

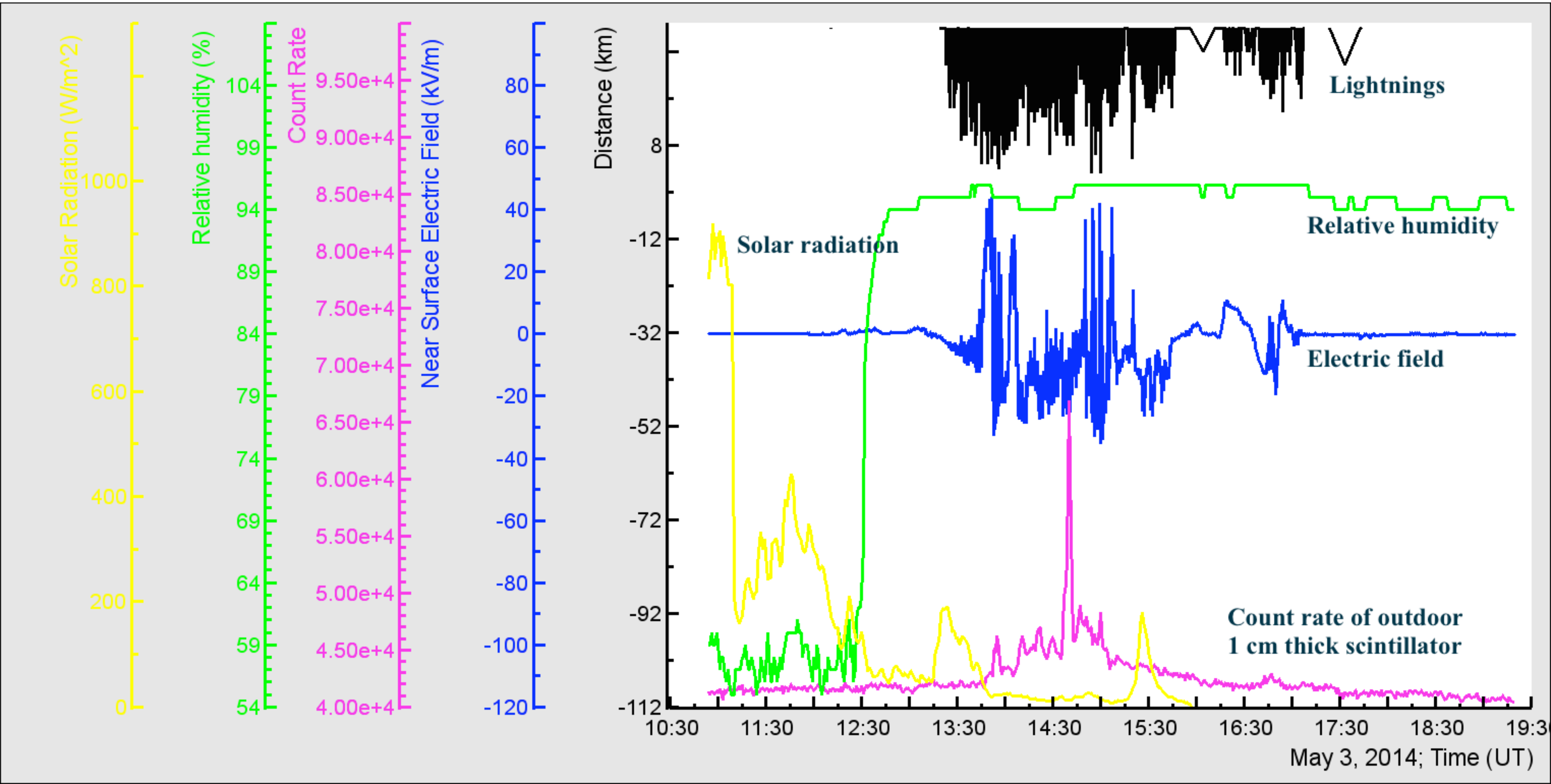


1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1
1.5
2
2.5
3
3.5
19.06.2013
12.05.2012
15.05.2013
Simulation
04.10.2010
19.09.2009
1.6kV/cm
1.4kV/cm
1.2kV/cm
1. kV/cm
0.8 kV/cm
Intensity at 1 MeV(1/m2/min/MeV)
Absolute value of spectral index

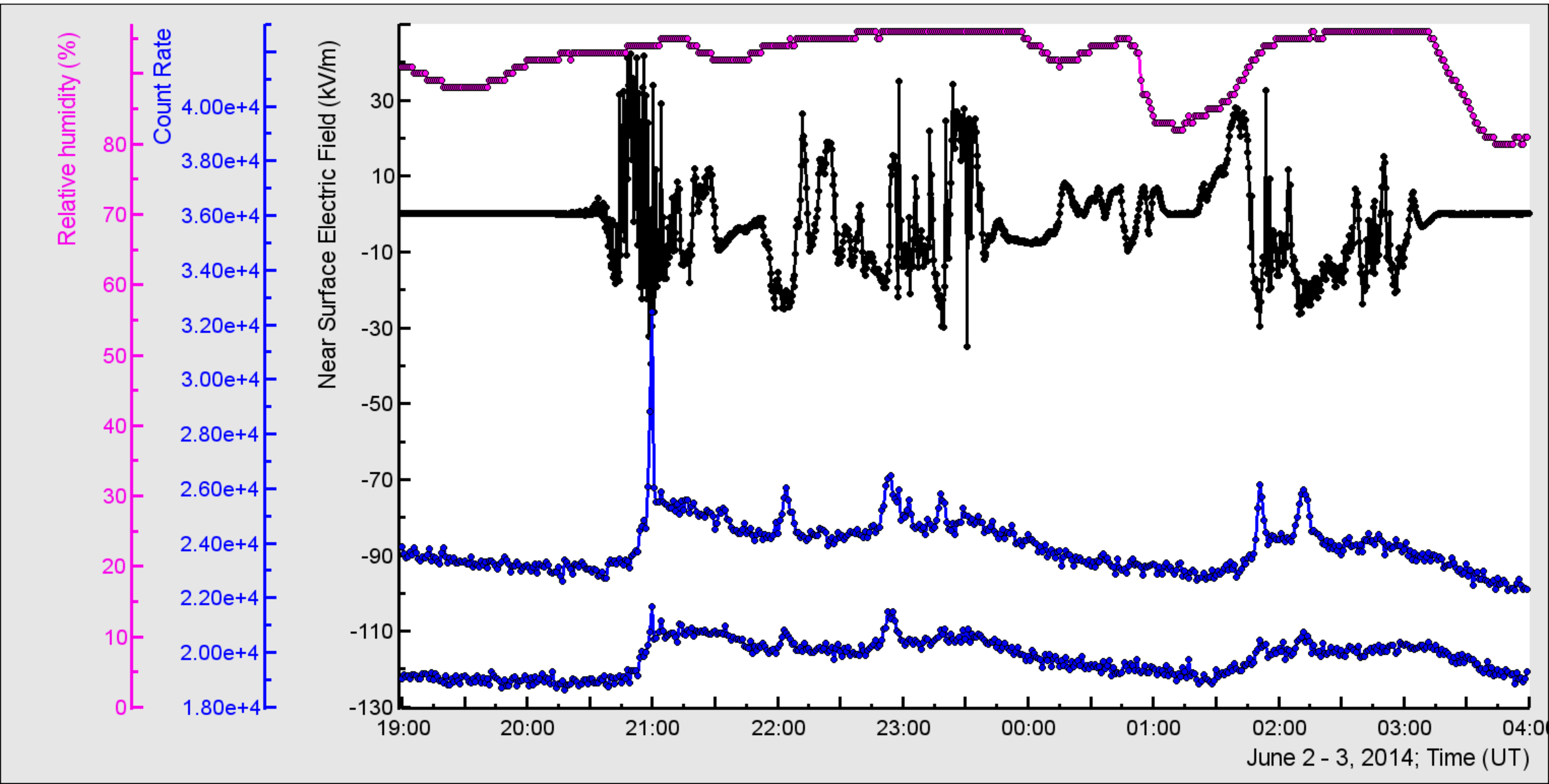
Prove of the LPCR residing on rain droplets

- At start of TGE humidity is always high > 80%;
- Rain wash out the TGE (LPCR)

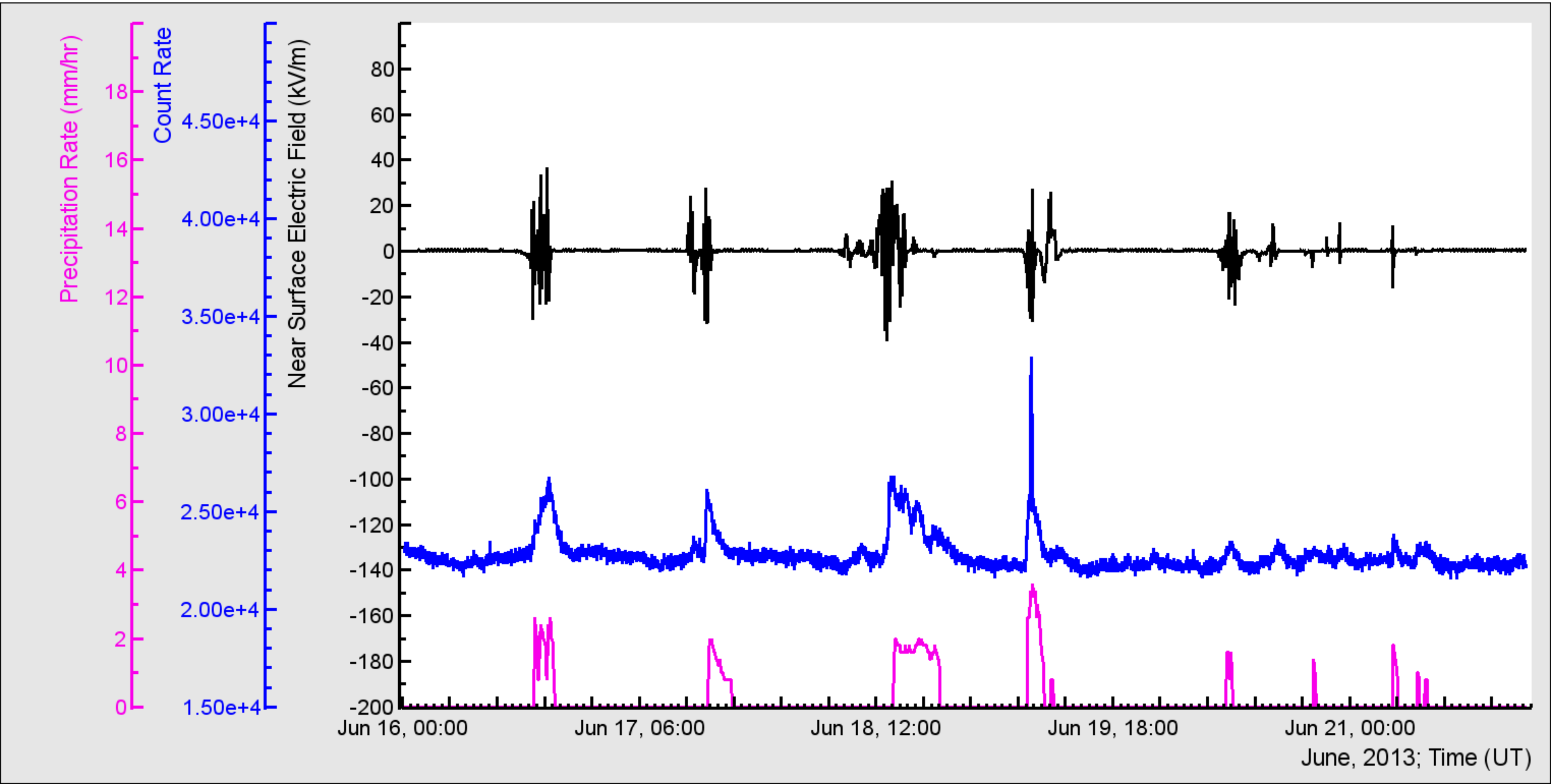
TGE is coincided with rise of Humidity – LPCR development



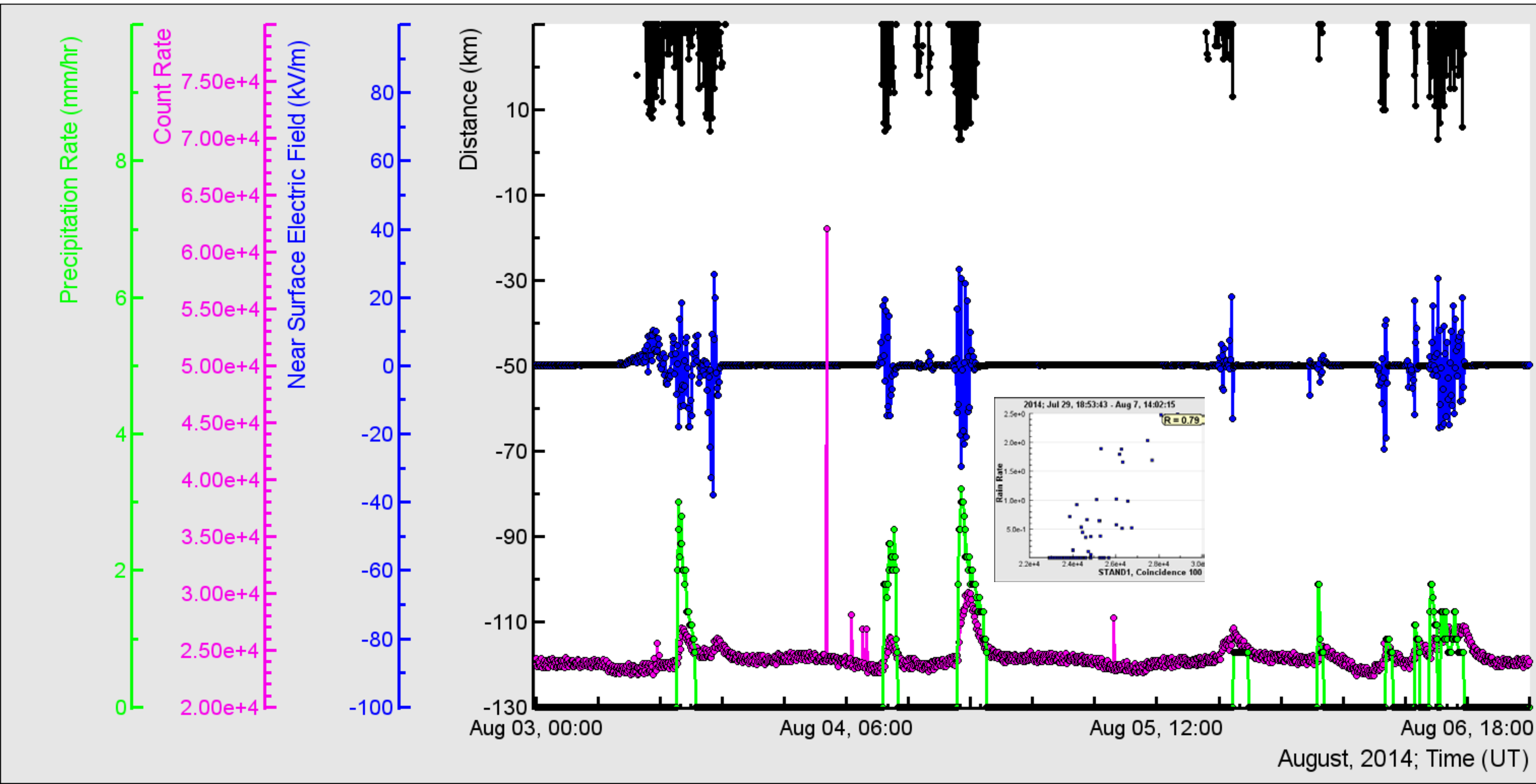
Strong storm in beginning of June, 2014- TGEs occure ast high humidities



Charge reside on rain droplets making LPCR and- lower dipole accelerated electrons downward



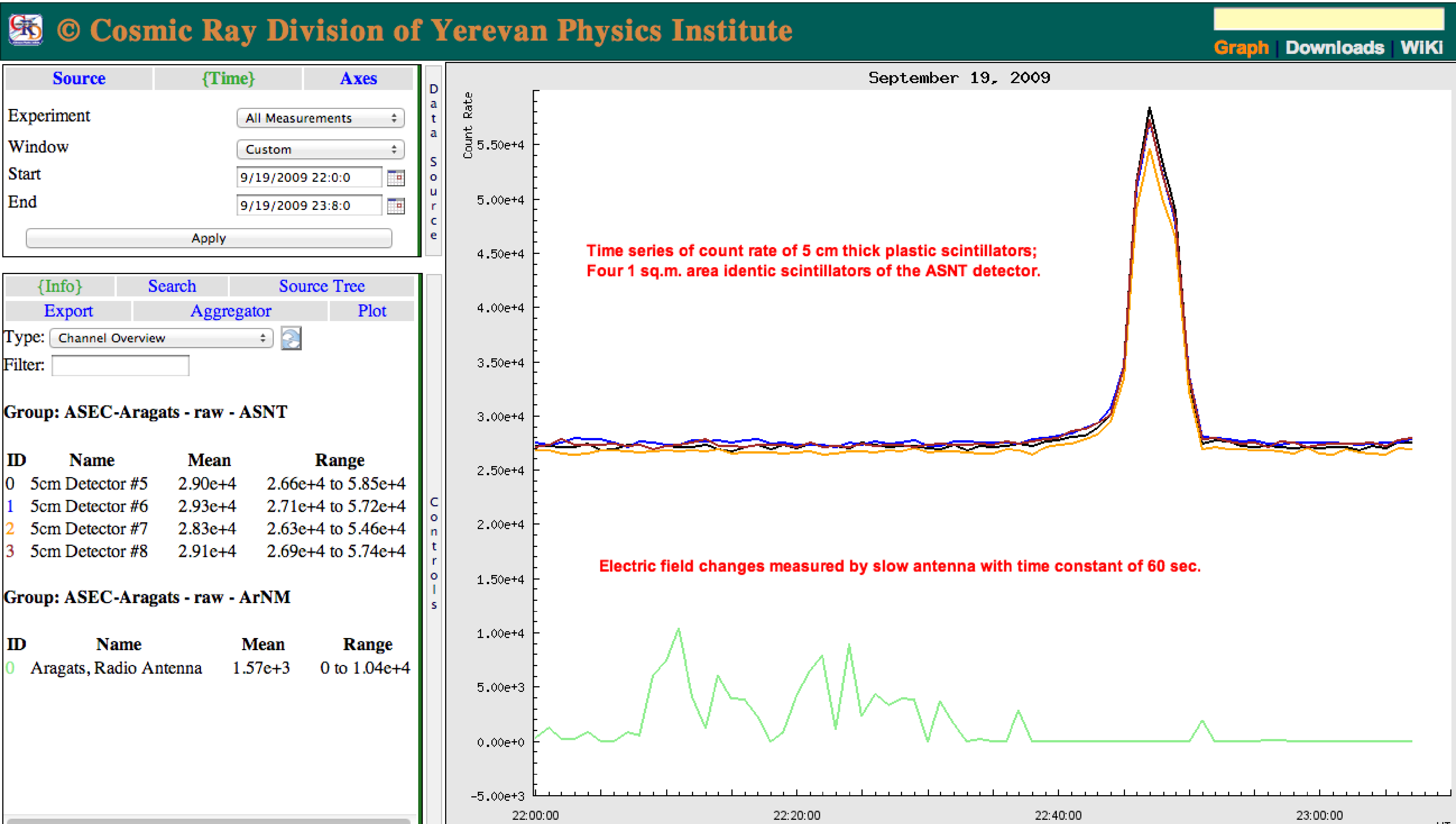
After finishing of rain TGE fast decays – rain wash down LPCR and lower dipole decays as well



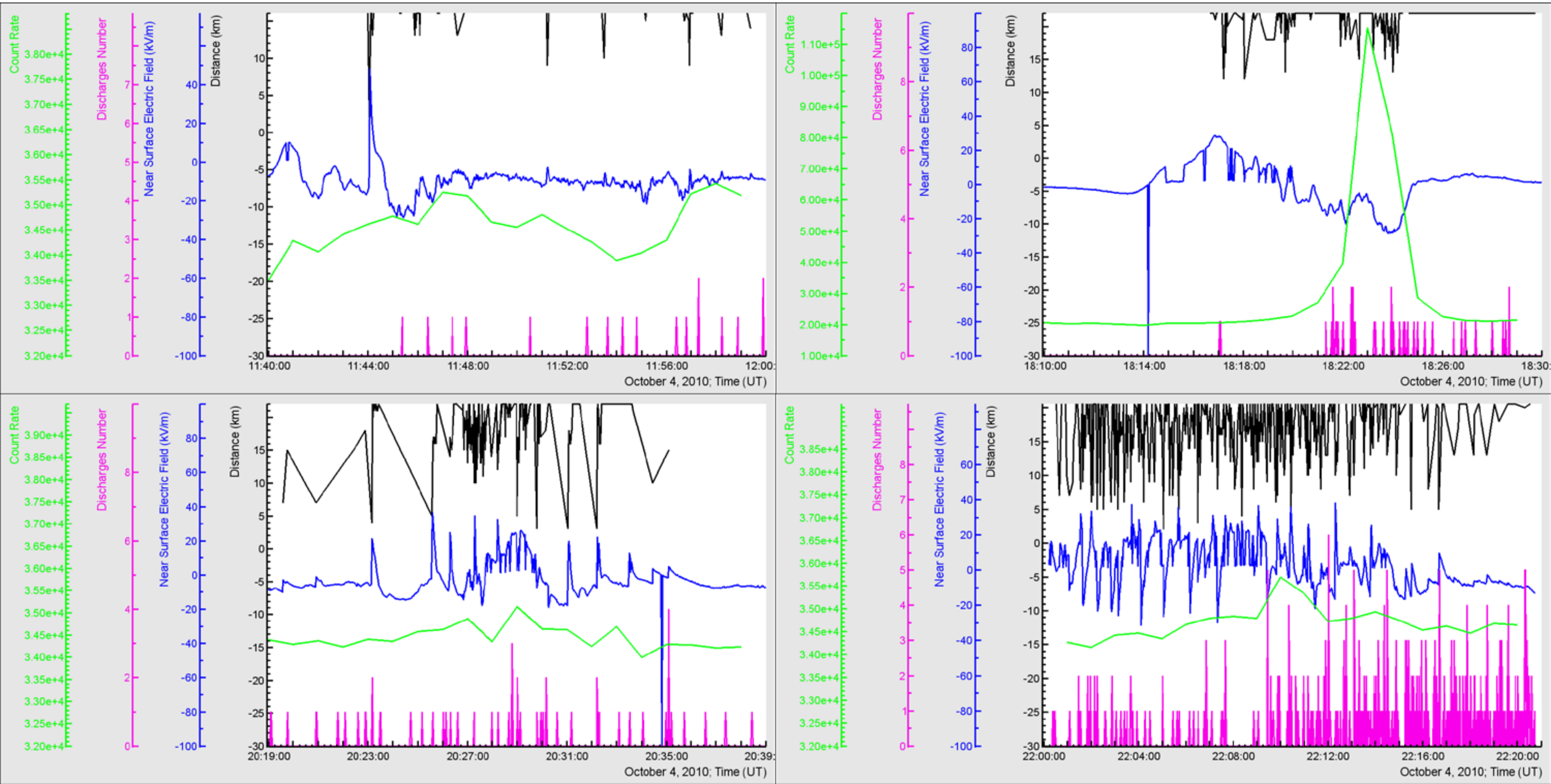
TGE & Lightning relation

- Developed LPCR blocked the negative leader;
- CG lightnings occur after (and at) decaying of LPCR (i.e. after TGE maximum)

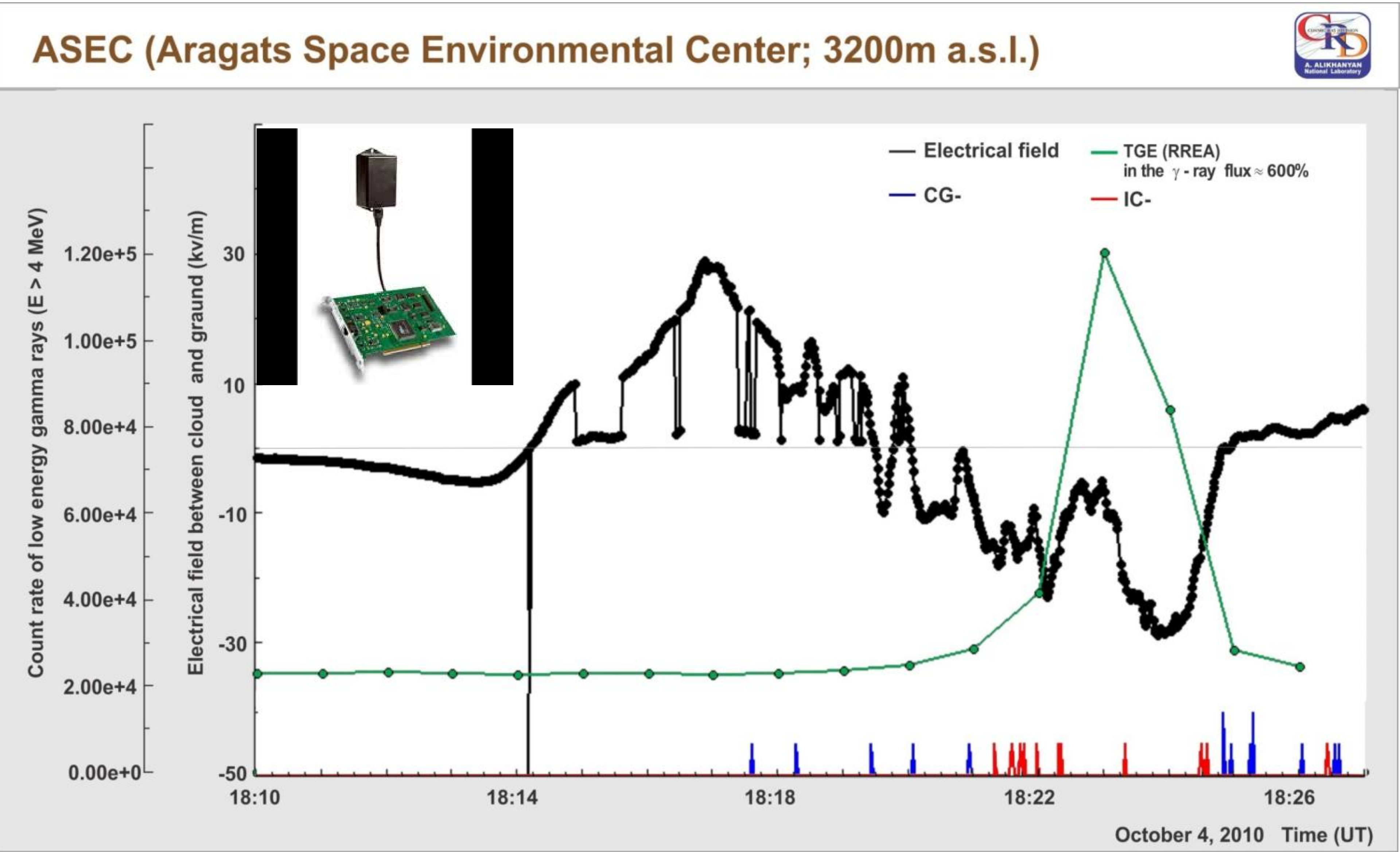
TGE — no lightning occurrences



October 4, 2010 – super storm- lightning is not cause of GLE!



TGE are detected at large negative near-surface electrical field; at the same time CG- are suppressed.



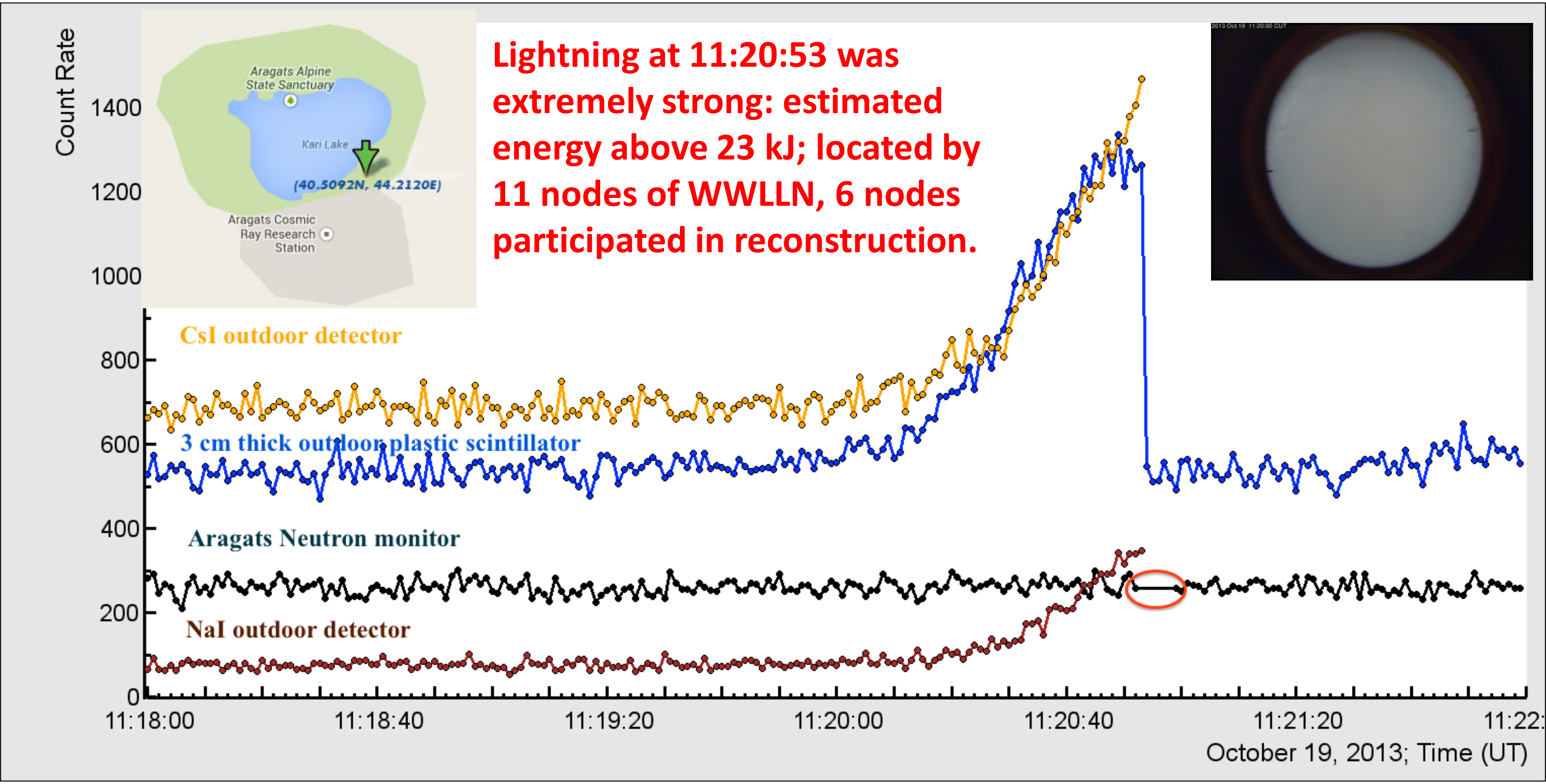
Relations between Lightning- radio signals – particle fluxes

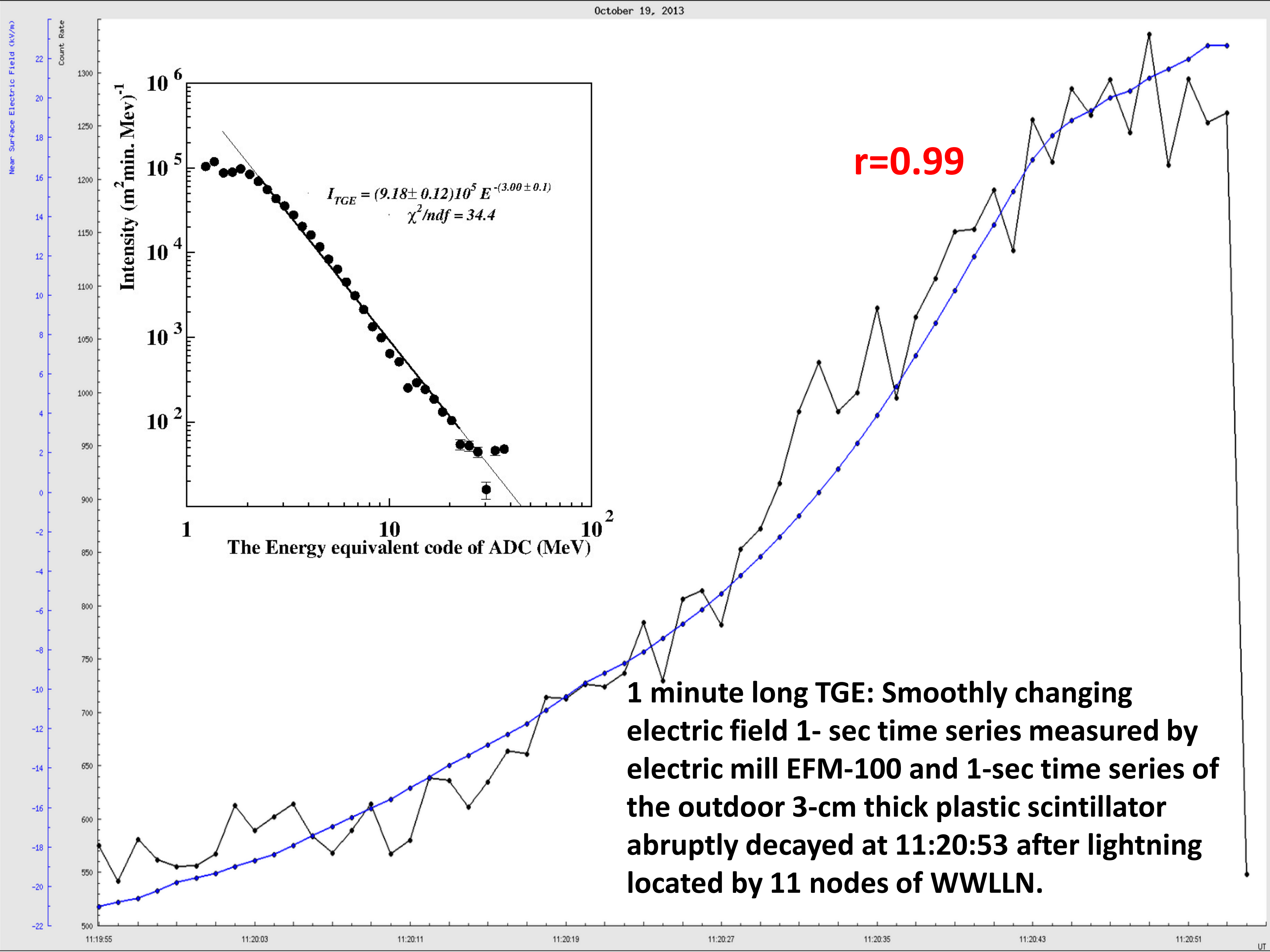
- **Particle fluxes start before lightning flashes;**
- **Lightning flashes are numerous and strong without any relation to particle fluxes;**
- **For initiation of TGE we need developed LPCR, i.e. large negatively charged layer in middle of thundercloud and high humidity for polarization of the water droplets;**
- **Development of LPCR may be accompanied by HF radio emission – coherent discharges of stretched HM with CR (RREA) electrons – measurements at Aragats started;**
- **Particle fluxes and lightnings are alternative processes – both are initiated by strong electric fields in thunderclouds and both discharge lower dipole;**

Exceptional event at 19 October 2013

- Duration – 50 seconds;
- Electric field smoothly decreased in correlation with particle flux;
- TGE flux rise at when near surface electric field rose in positive domain
- Large gamma ray flux

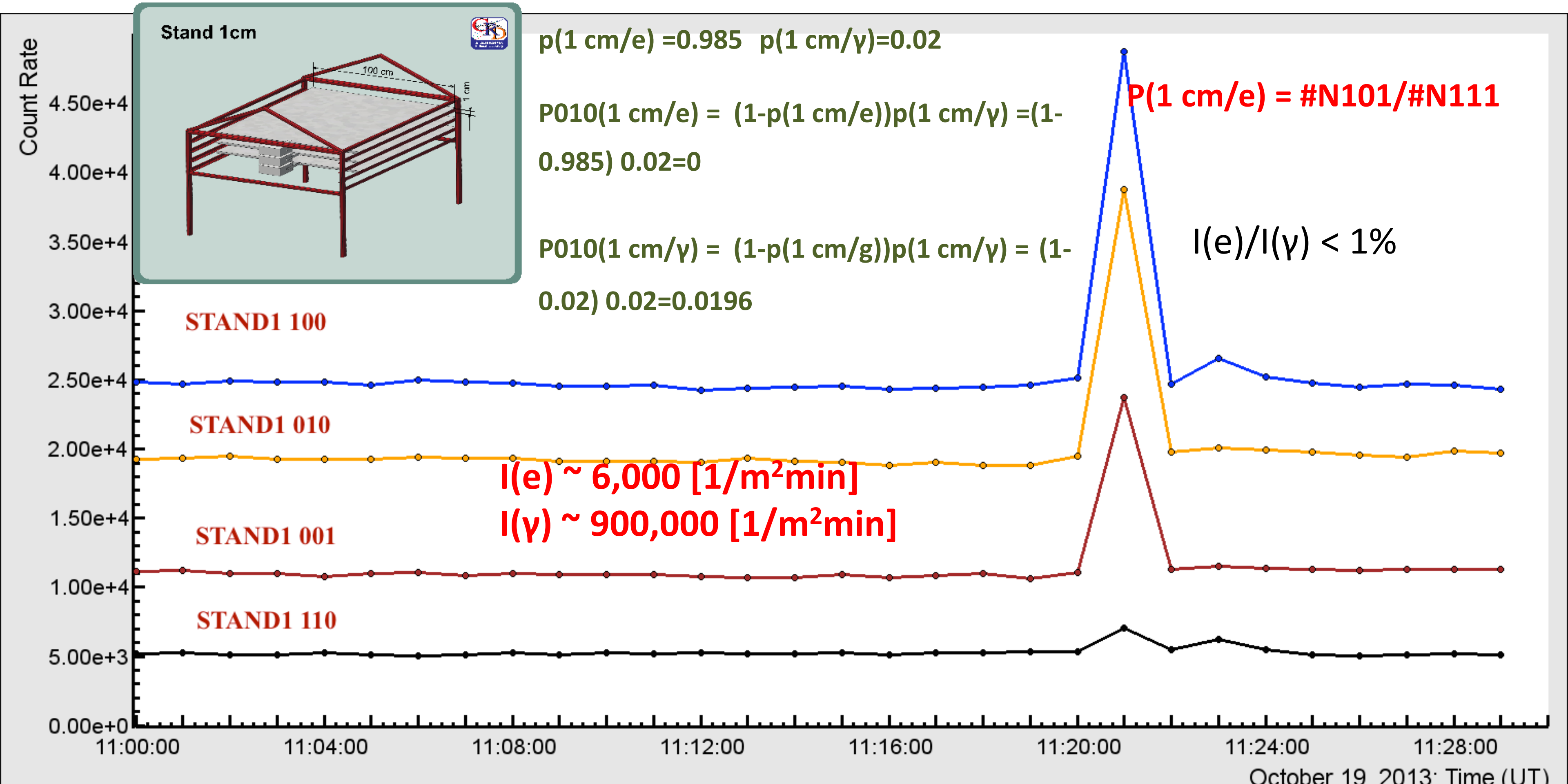
1-second time series of ASEC detectors After lightning several seconds are missing





October 19, 2013
Near Surface Electric Field (kV/m)
Count Rate
Intensity (m^{2}min. Mev)$^{-1}$
$I_{TGE} = (9.18 \pm 0.12)10^5\,E^{-(3.00 \pm 0.1)}$
$\chi^2/ndf = 34.4$
The Energy equivalent code of ADC (MeV)
r=0.99
1 minute long TGE: Smoothly changing electric field 1- sec time series measured by electric mill EFM-100 and 1-sec time series of the outdoor 3-cm thick plastic scintillator abruptly decayed at 11:20:53 after lightning located by 11 nodes of WWLLN.
11:19:55
11:20:03
11:20:11
11:20:19
11:20:27
11:20:35
11:20:43
11:20:51
UT

One-minute time series of STAND1 – contamination of electrons less than 1%; reliability – more than 100σ



19 October 2013 TGE, 1-sec fluxes at 11:20:49 – 11:20:53 – compared with commulative flux AGILE TGFs

	Mean (CR) count rate 1/sec	TGE peak	TGE flux = PEAK-CR	Detector area (m^2)	Det. eff.	TGE Flux** ($1/cm^2sec$)
ScI	689+/- 25	1450	50,000	0.0135	0.8	7
3cm thick sc.	532+/- 23	1320	532	1	0.02	4
60 cm thick sc.***	3080+/- 55	10054	3080	1	0.20	1.7
NaI	75+/- 10	345	2340	0.032	0.8	1.2
AGILE 308 TGFs						17

Marisaldi, M., et al. (2014), Properties of terrestrial gamma ray flashes detected by AGILE MCAL below 30 MeV *J. Geophys. Res. Space Physics*, *119*, 1337–1355

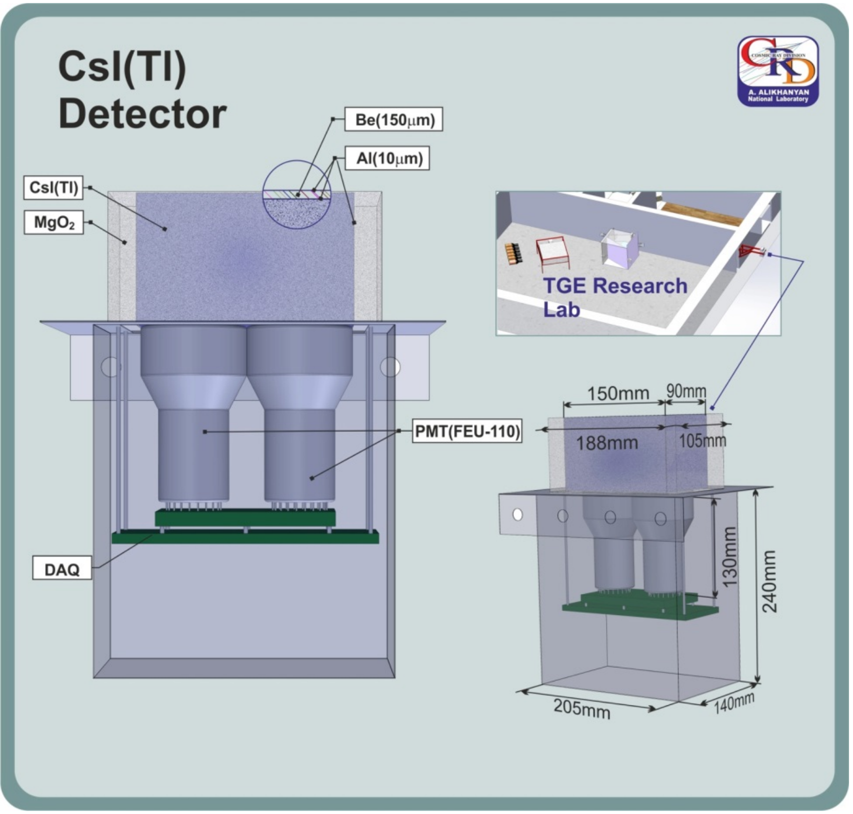
What we know about TGEs?

- Lower dipole in thunderclouds transfer effectively field energy to electrons; electrons generate gamma rays and gamma rates by photo-nuclear reactions born neutrons detected on earth's surface;
- Origin of TGE is mainly mixture of 2 processes RREA (1 -30 MeV, enhancement up to 10 times above CR flux) and modification of CR energy spectra MOS (1- 100 MeV enhancement only few % of CR flux).
- RREA generates particle bursts with duration less than 1 μsec (ECS – "downward" TGFs); overall duration of TGE is ~ 10 minutes, large amount of ECSes due to RREA (if electric field strength is larger than 1.7 kV/m) and emissions due to MOS process occurs;
- Simultaneously with boost of electrons and gamma rays high energy muon flux attenuates;
- TGEs usually occurs during negative near surface electrical field varied from -10 to -30 kV/m; TGE flux correlate with strength of electric field;
- During TGEs mostly IC- lightning occur; CG- lightning are suppressed – LCPR stops negative lightning leaders.

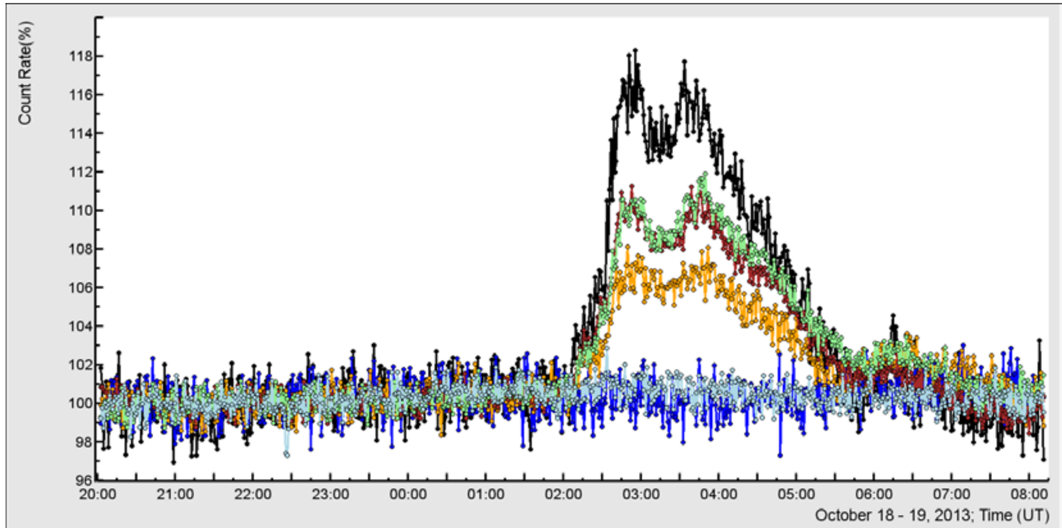
Long lasting TGE

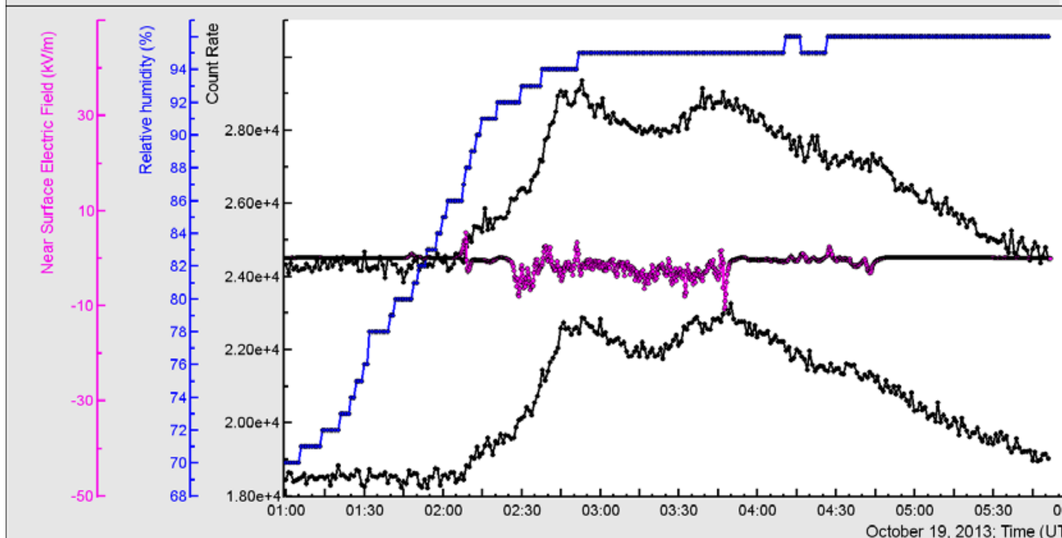
- After starting measurements with lower energy threshold (~ 1 MeV) new type of TGE events were discovered;
- Duration – many hours;
- Can be registered on non-disturbed electric field, short leaving isotopes?;
- During long TGE several short TGEs can occur;
- Energy spectrum at low energies differ from high energy spectra

New low threshold CsI spectrometer



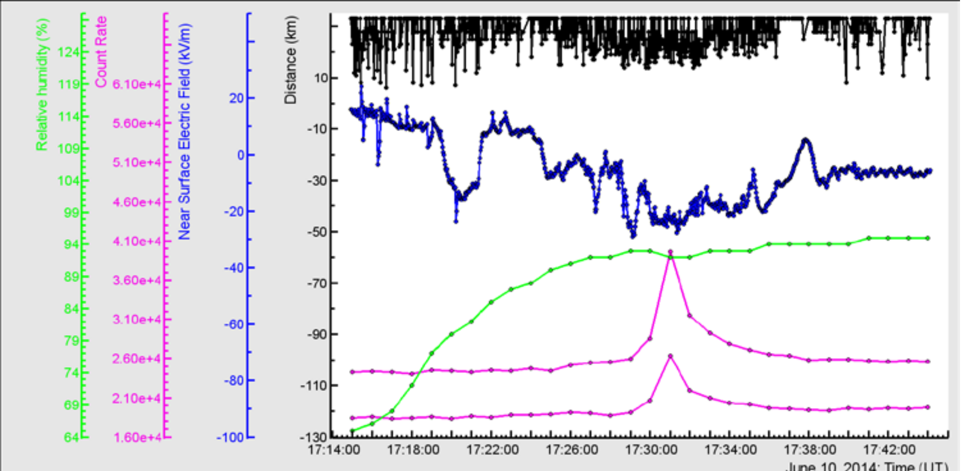
	CsI(Tl)	NaI(Tl)
Photons/MeV	60,000	40,000
Density(g/cm3)	4.53	3.67
Decay Time(ns)	1050	230
Peak emission (nm)	550	415
Hygroscopic property	modest	strong

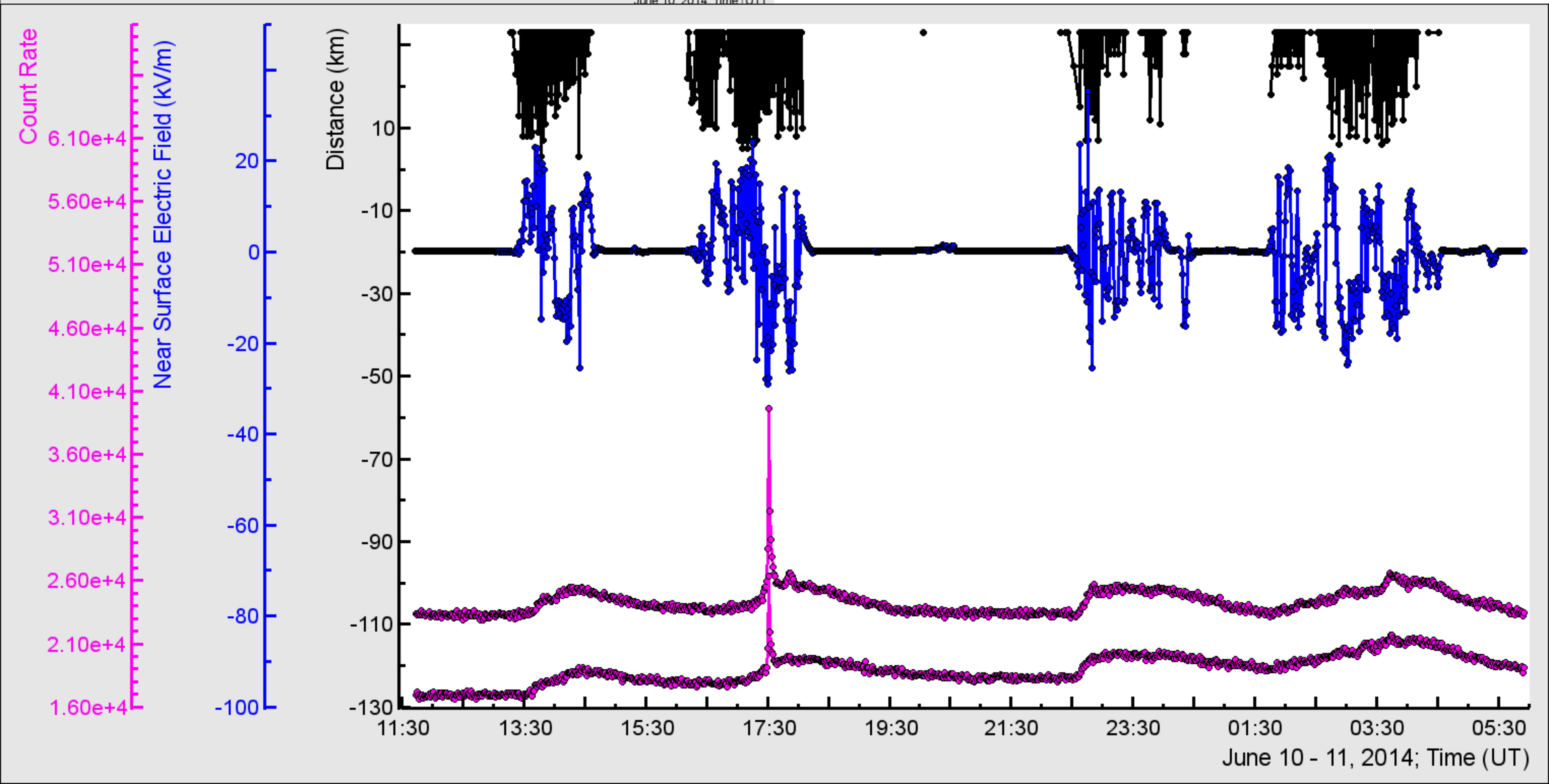




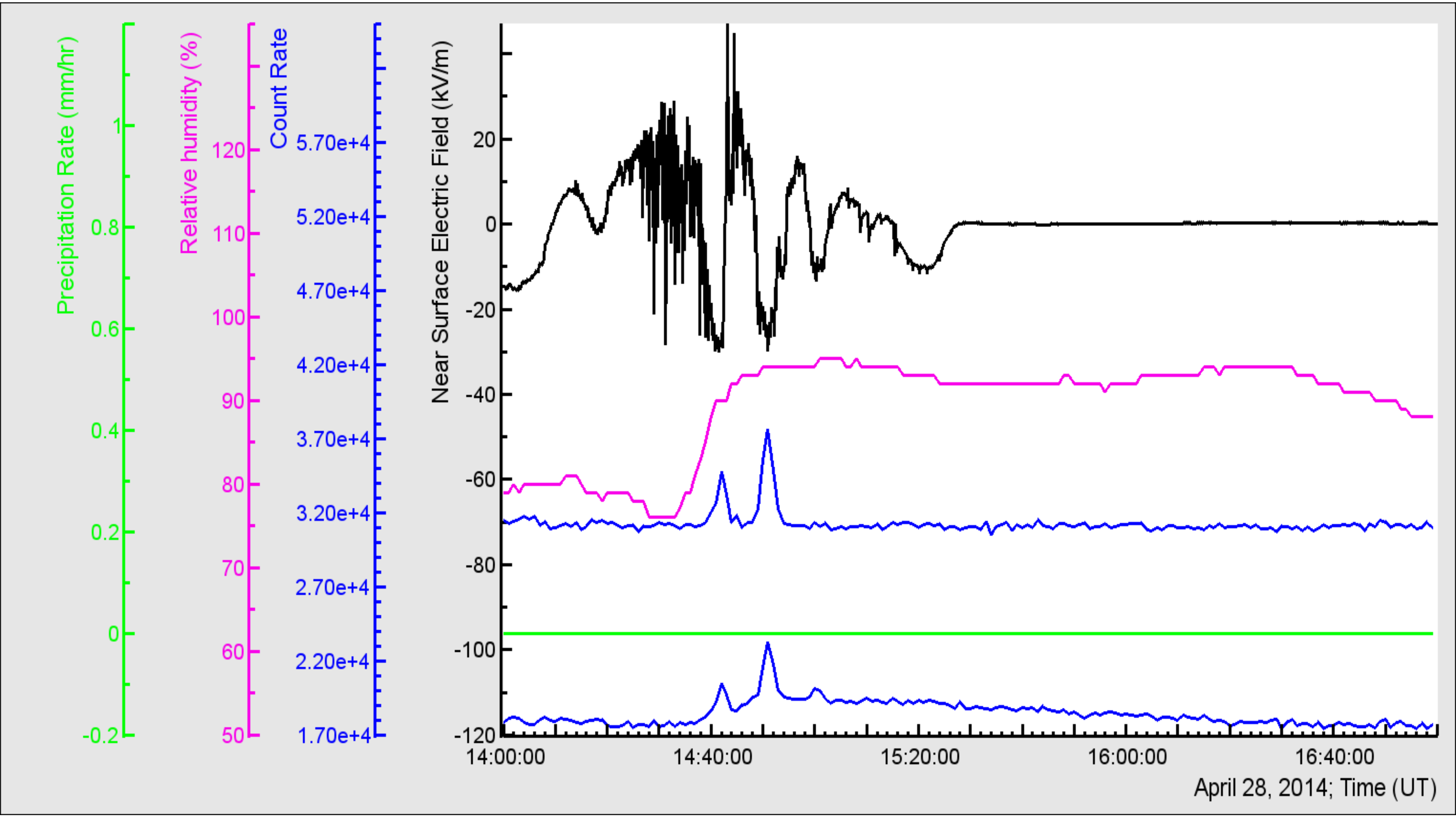
Effective Area	9 x 14.5 = 130cm^2
Geometrical Acceptance	400 cm^2*sr
Energy threshold	0,05 MeV

June 2014 seem to be very fruitful for TGEs



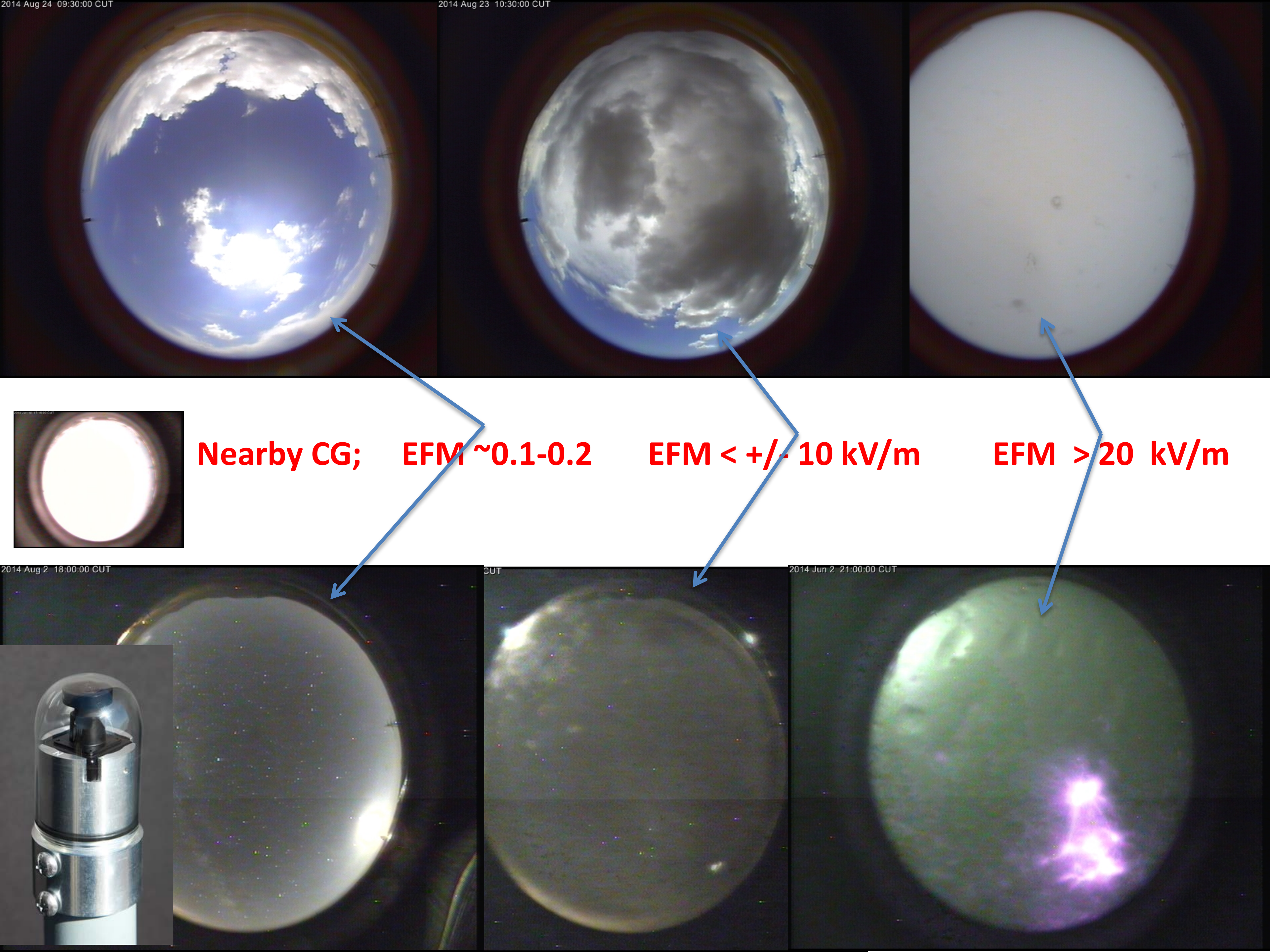


Low energy gamma rays (below 2 MeV) registered at near zero values of near surface electric field.

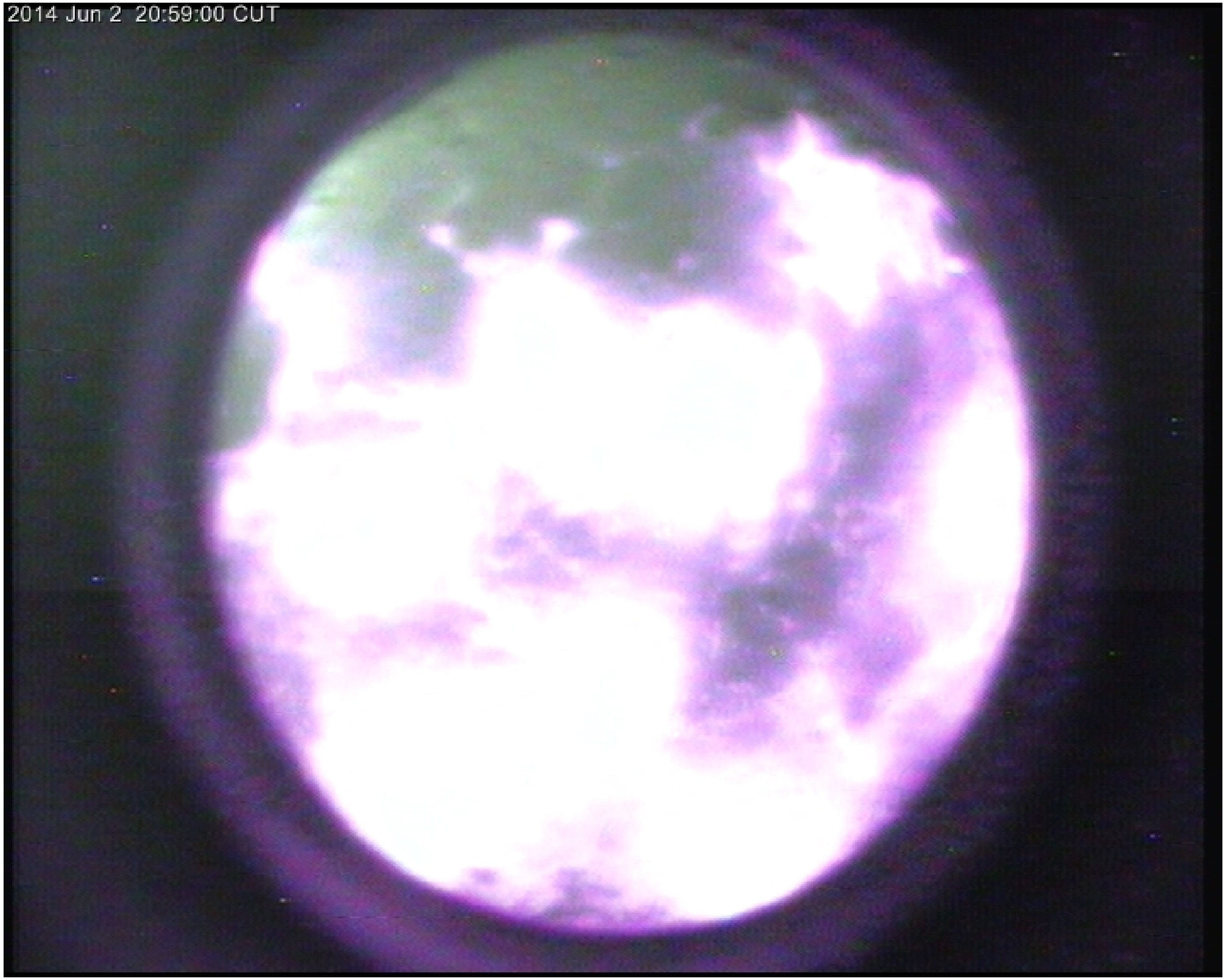


TGF - TGE(ECS) relation

- **The generation mechanisms of the space TGFs and downward TGFs (ECSes) share some common features: runaway electron avalanches *in lower dipole and in upper dipole.* TGEs happen in series – hundreds of Extensive Cloud Showers in a second. TGFs represent few RREA cascade lasting ~100 microseconds;**
- **RREA/ECSes are very rare events (detected at Aragats only twice in 2009 and 2010); number of detected TGFs detected by RHESSY, FERMI LAT and GBM is much larger - reaching hundreds per year. Nonetheless, because of closeness of the particle beam, the number of detected ECSes is comparable with number of yearly detected TGFs ~500.**
- **TGFs are believed to be produced by the RREA process only; Most of TGEs produced by MOS process – why not to check if ~ 100 MeV TGFs are also produced by MOS?**
- **We measure tens of high-statistics TGE gamma ray spectra; only cumulative spectra are available for TGFs; why not compare TGF with measured TGEs and not only with simulations?**
- **From both TGE and TGF measurements no causal relation between TGE and lightning occurrences can be derrived.**

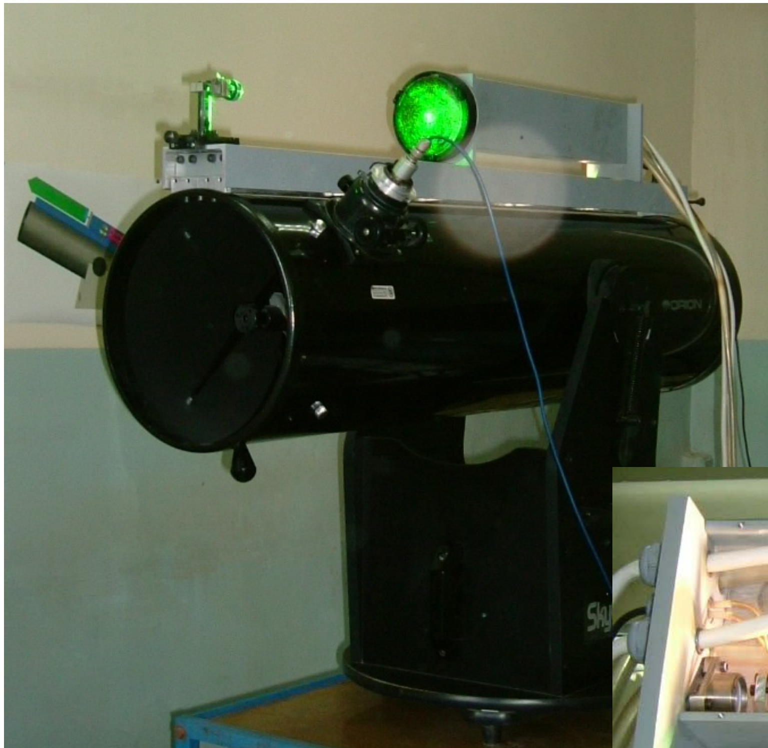

2014 Aug 24 09:30:00 CUT
2014 Aug 23 10:30:00 CUT
Nearby CG;
EFM ~0.1-0.2
EFM < +/- 10 kV/m
EFM > 20 kV/m
2014 Aug 2 18:00:00 CUT
CUT
2014 Jun 2 21:00:00 CUT

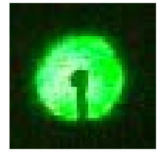
2 June, 21:00 TGE

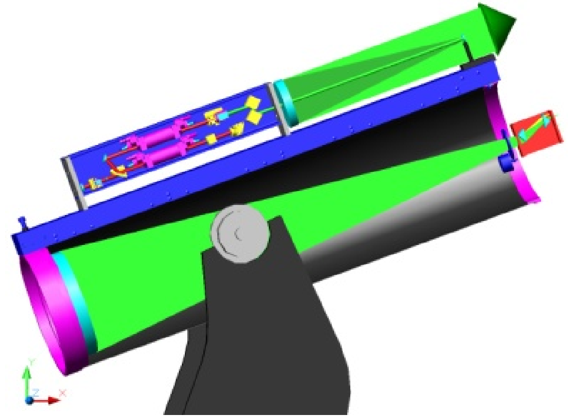


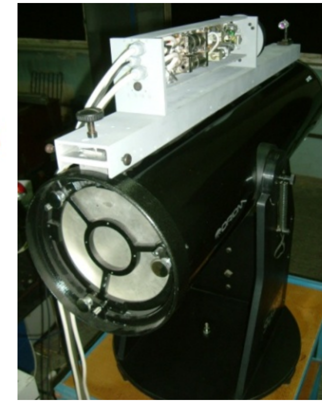
RAZ-200 – device for measuring near-surface electric field

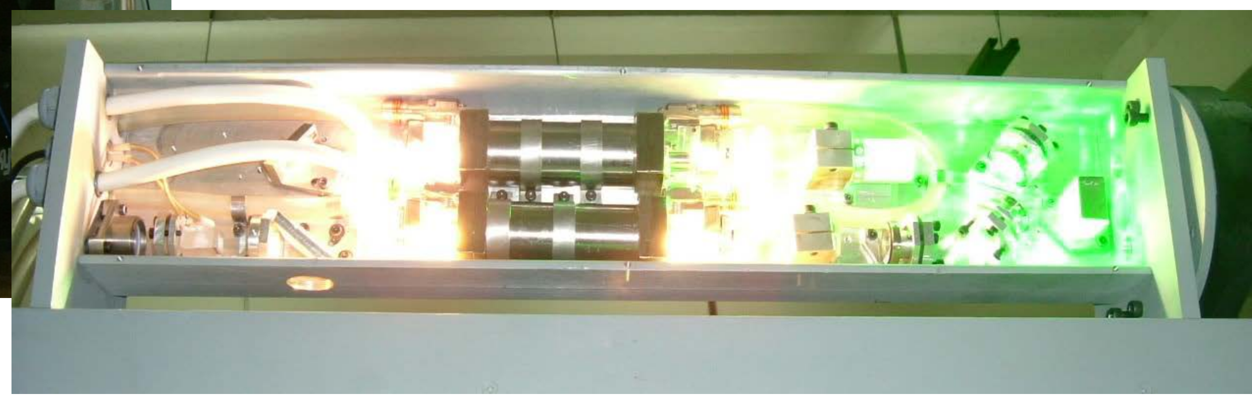
LIDAR for measurement of electric field inside thundercloud

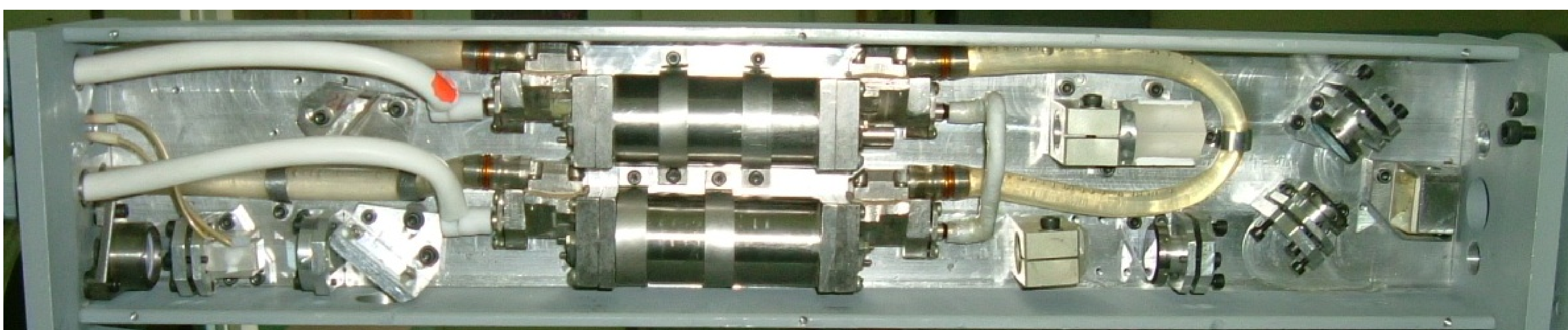












Radio measurements started at Aragats in September 2014