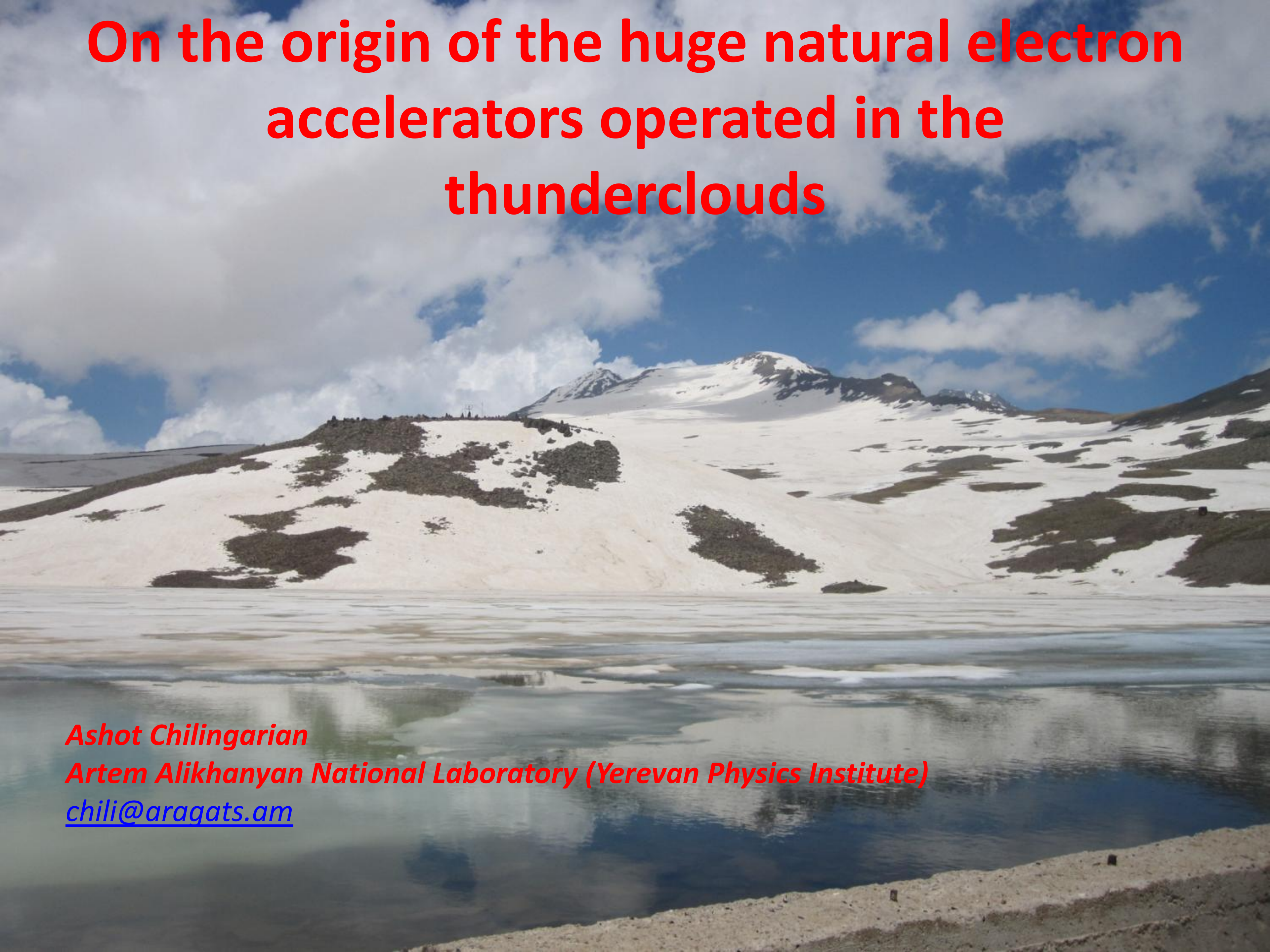


On the origin of the huge natural electron accelerators operated in the thunderclouds

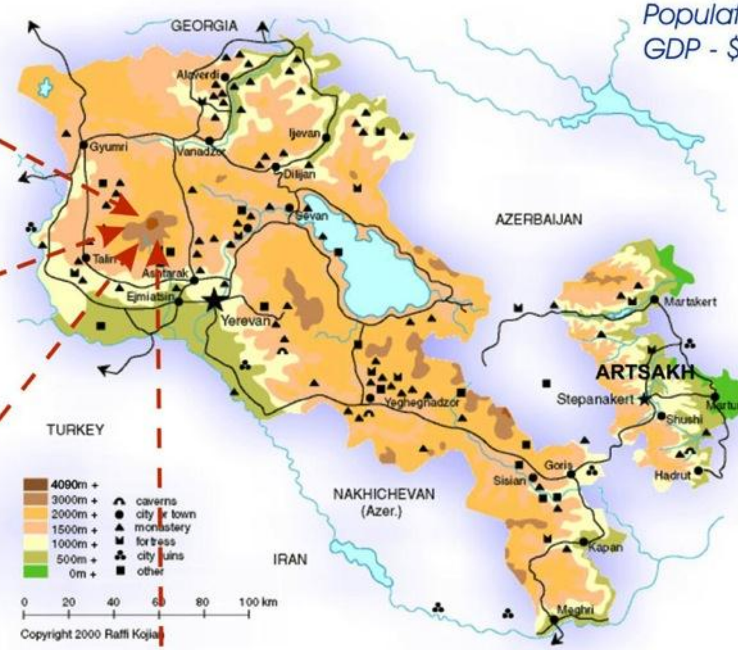
Ashot Chilingarian
Artem Alikhanyan National Laboratory (Yerevan Physics Institute)
chili@aragats.am

Physics with Particle Detectors on Earth surface: Detecting and counting Cosmic rays and its energies

Map of Armenia

Area:
total: 29,800 sq km
land: 28,400 sq km
water: 1,400 sq km

Population - 3.000.000
GDP - $9.2 billion



Mt. Aragats

CRD Research Profile

- Cosmic Ray Astrophysics – Research of Cosmic Ray Sources and Acceleration Mechanisms by ground based surface detectors.
- Solar Physics – Detection on Earth by neutron monitors and muon telescopes of Solar Energetic Particles.
- Monitoring and Forecasting of the Space Weather.
- High energy phenomena in thunderclouds;
- Scientific instrumentation: networks of particle detectors;
- Multivariate Data Analysis - Monte Carlo Statistical Inference.

Abram Alikhanov and Artem Alikhanyan

Aragats, June

Aragats, August

Aragats Research Station

Nor Amberd Research Station

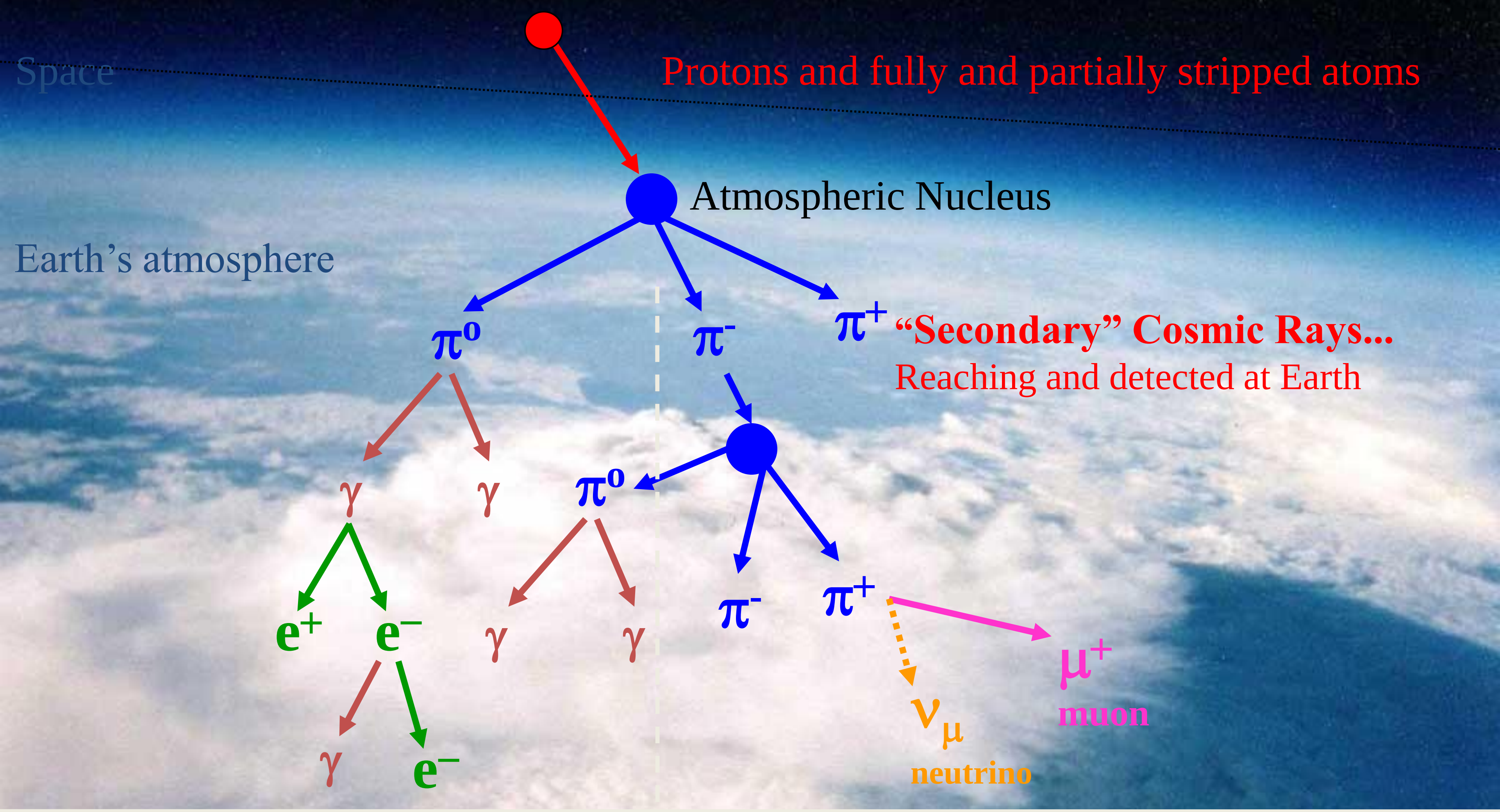
Most Important Achievements 1942-1992

- **1942 – First expedition to Aragats**
- **1943 – Establishment of the Physical-mathematical Institute of Yerevan State University; then Yerevan Physics Institute after Artem Alikanyan, now A.Alikhanyan national lab;**
- **1945-1955 – Foundation of Aragats high-mountain research station. Experiments at Aragats with Mass-spectrometer of Alikhanyan-Alikhanov: investigations of the composition of secondary CR (energies <100 GeV); exploration of the “third” component in CR; observation of particles with masses between μ-meson and proton;**
- **1957 –construction of the first Ionization calorimeter, detection of particles with energies up to 10 TeV;**
- **1960 – Foundation of the Nor Amberd high-mountain research station;**
- **1970 – Lenin prize for the Wide-gap Spark Chambers;**
- **1975 –Experiment MUON: energy spectrum and charge ratio of the horizontal muon flux;**
- **1975 – Neutron supermonitors 18NM64 at Aragats and Nor Amberd research stations;**
- **1977 – Experiment PION: measuring pion and proton energy spectra and phenomenological parameters of CR hadron interactions;**
- **1981-1989 –ANI Experiment: Commence of MAKET-ANI and GAMMA surface detector arrays for measuring cosmic ray spectra in the “knee” region (10^{14} – 10^{16} eV);**
- **1989-1992 –Introduction of multivariate methods for signal detection from γ-ray point sources, prove of the detection of Crab nebula by Whipple collaboration;**

Most Important Achievements 1993 - 2008

- **1993-1996 – Development of new methodology of multivariate, correlation analysis of data from Extensive Air Shower detectors, event-by-event analysis of shower data from KASCADE experiment; classification of primary nucleus;**
- **1996-1997 – Renewal of Cosmic ray variation studies at Aragats: installation of the Solar Neutron Telescope and resumption of Nor Amberd Neutron Monitor;**
- **2000 – Foundation of Aragats Space Environmental Center (ASEC) – for Solar Physics and Space Weather research; measurements of the various secondary fluxes of cosmic rays; inclusion of the large surface arrays in monitoring of the changing fluxes of secondary cosmic rays ;**
- **2003 – Detection of the intensive solar modulation effects in September – November in the low energy charged particle, neutron and high energy muon fluxes;**
- **2004 – Measurement of the spectra of heavy and light components of GCR, observation of very sharp "knee" in light nuclei spectra and absence of "knee" in heavy" nuclei spectra, confirmed in 2007 by spectra published by GAMMA detector;**
- **2005 - Measurements of highest energy protons in Solar Cosmic Rays (GLE 69 at 20 January; detection of Solar protons with E>20GeV);**
- **2007 - Starting of SEVAN (Space Environmental Viewing and Analysis Network - a new type of world-wide network of particle detectors for monitoring of geophysical parameters**
- **2008 - Multivariate analysis and classification of the solar transient events (Ground level enhancements, Geomagnetic effects, Forbush decreases) detected by ASEC monitors during 23rd solar activity cycle.**

“Primary "Cosmic Rays from Galaxy and from the Sun

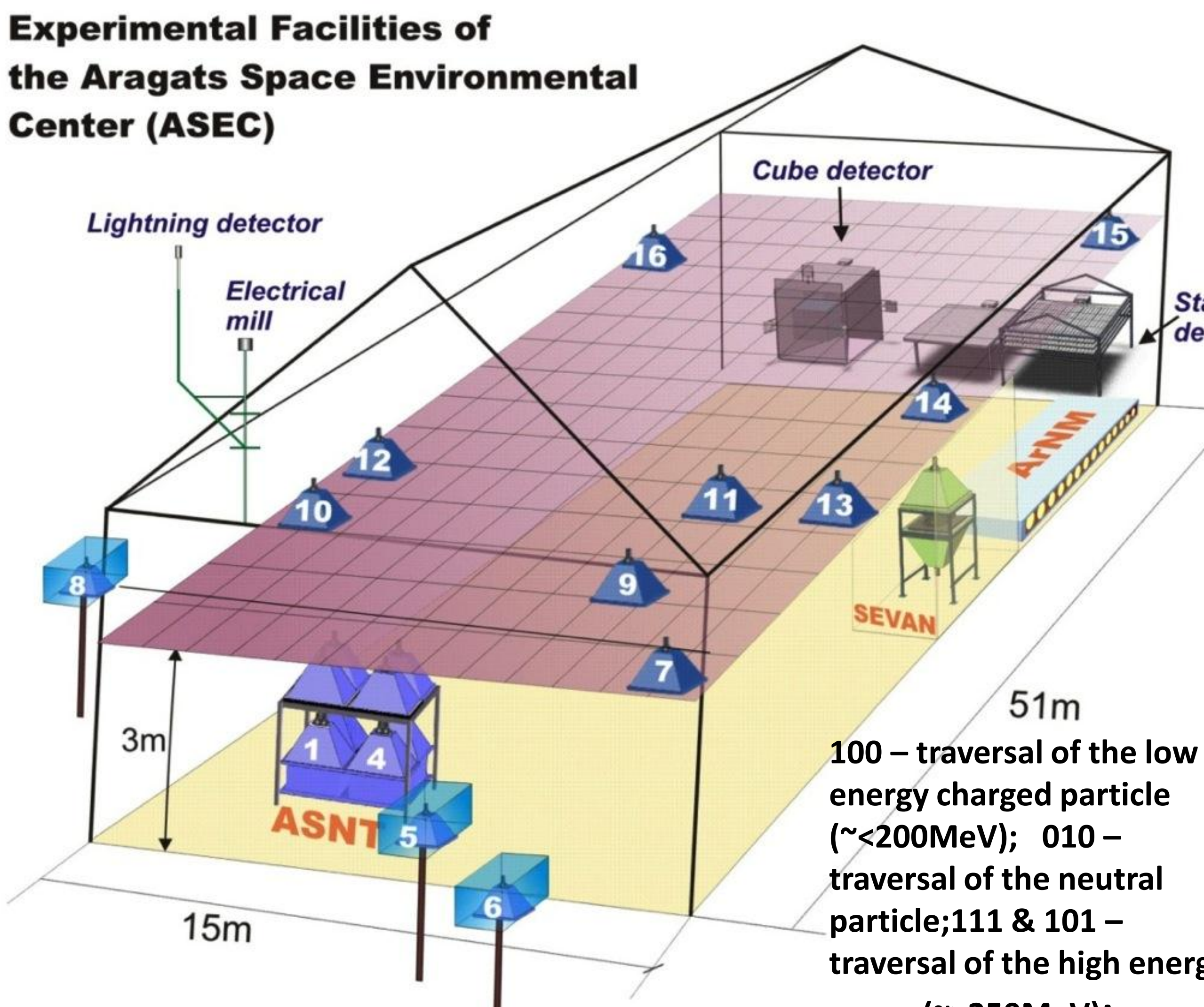


Electromagnetic Shower
electrons and γ-rays

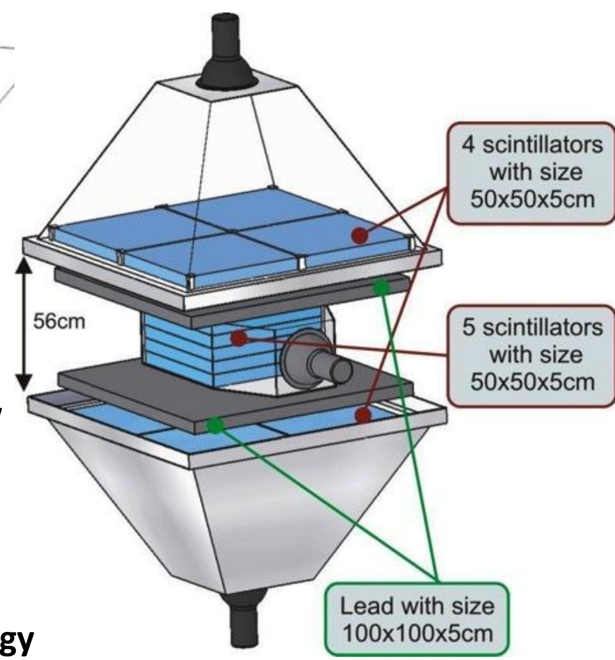
Hadronic Shower
muons, neutrons and neutrinos reach earth

Plus : Powerful Natural Accelerator in atmosphere: electrons, gammas, neutrons

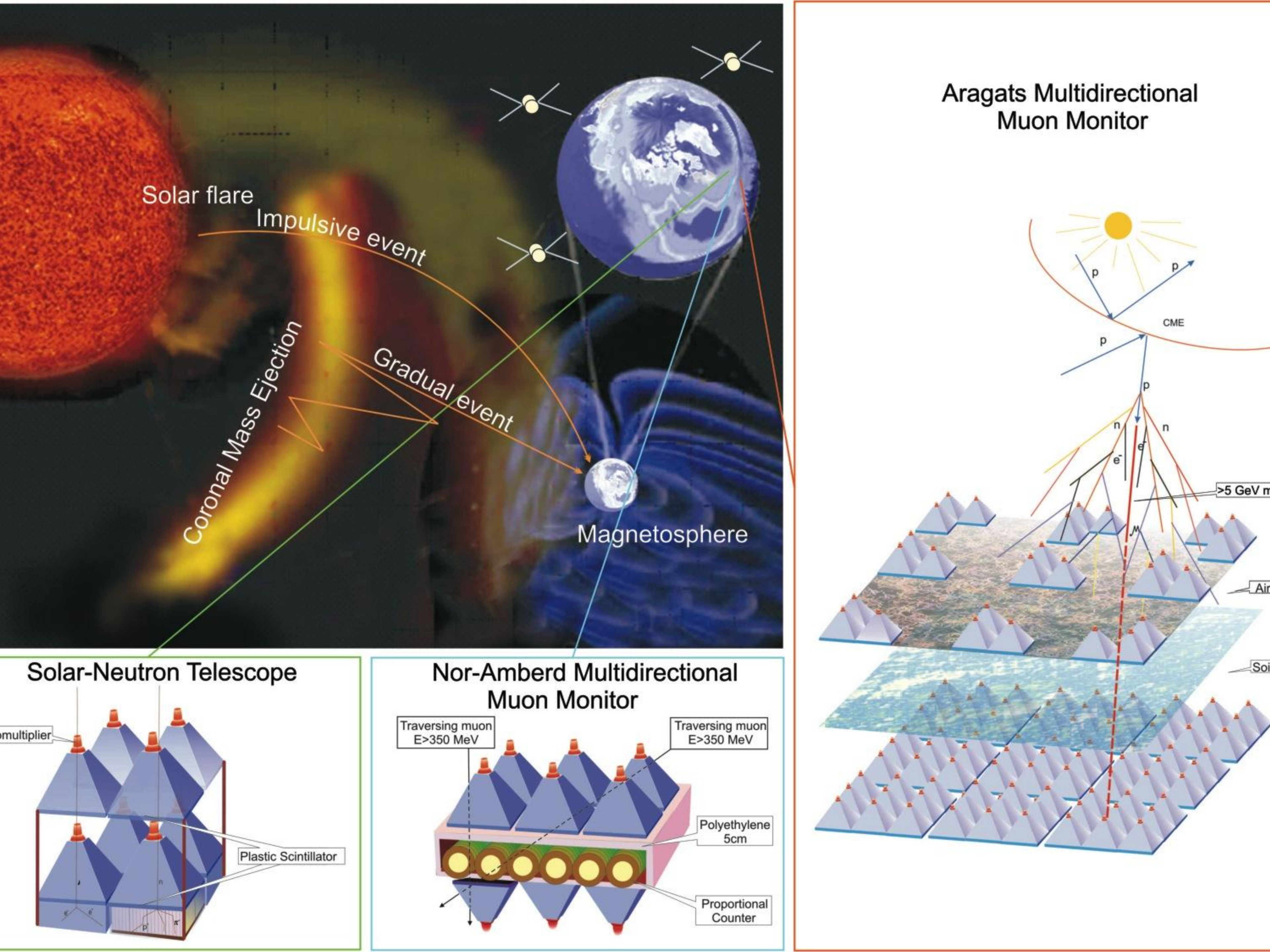
Simultaneous monitoring of fluxes and fields and meteorological conditions



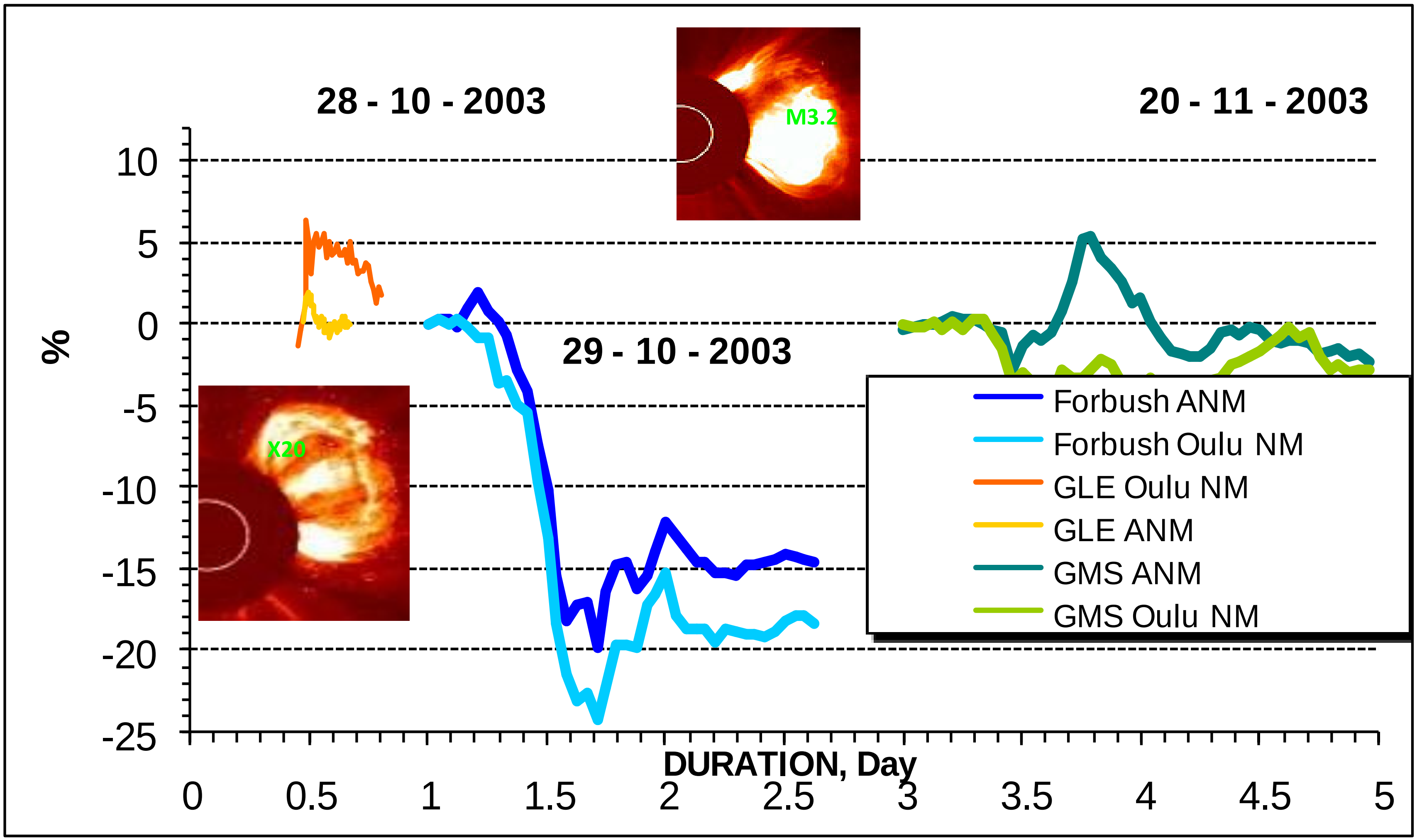
Boltec electrical mill and LD; Davis instr. weather station



100 – traversal of the low energy charged particle (~<200MeV); 010 – traversal of the neutral particle;111 & 101 – traversal of the high energy


Solar flare
Impulsive event
Coronal Mass Ejection
Gradual event
Magnetosphere
Solar-Neutron Telescope
multiplier
Plastic Scintillator
Nor-Amberd Multidirectional
Muon Monitor
Traversing muon
E>350 MeV
Traversing muon
E>350 MeV
Polyethylene
5cm
Proportional
Counter
Aragats Multidirectional
Muon Monitor
CME
>5 GeV m
Air
Soi

Aragats Space Environmental Center (ASEC) aims to detect the Solar Modulation effects: Ground Level Enhancements, Forbush decreases, Geomagnetic effects; At quit Sun (2007-2011) ASEC measure hundreds of Thunderstorm ground enhancements (TGEs)



The 24-th Solar Activity Cycle Produce the First Violent Blast: Now Ramping up Toward a Solar Maximum in 2013.

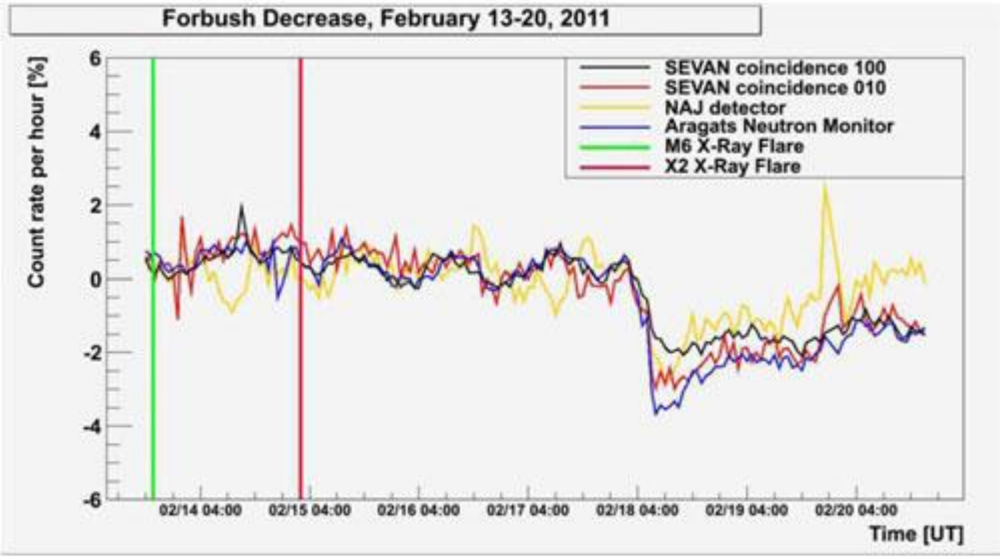
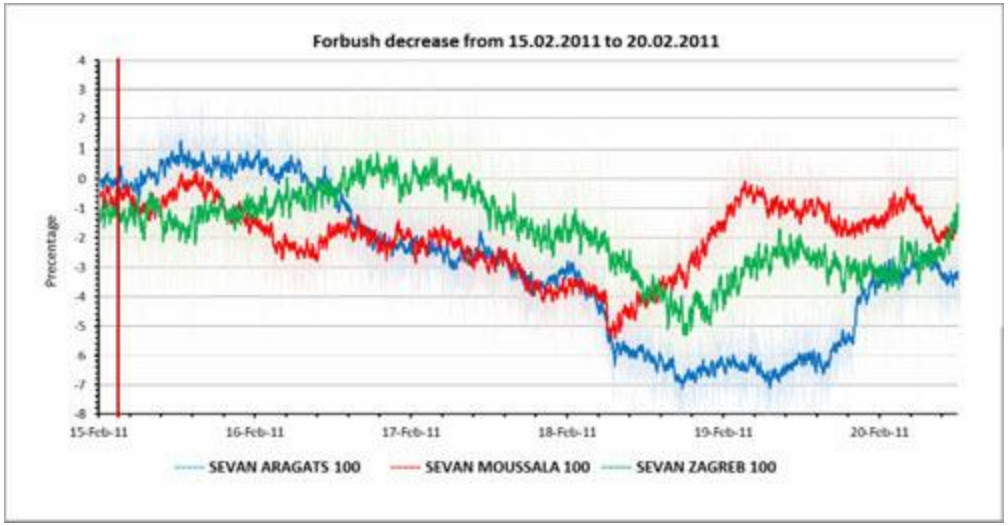
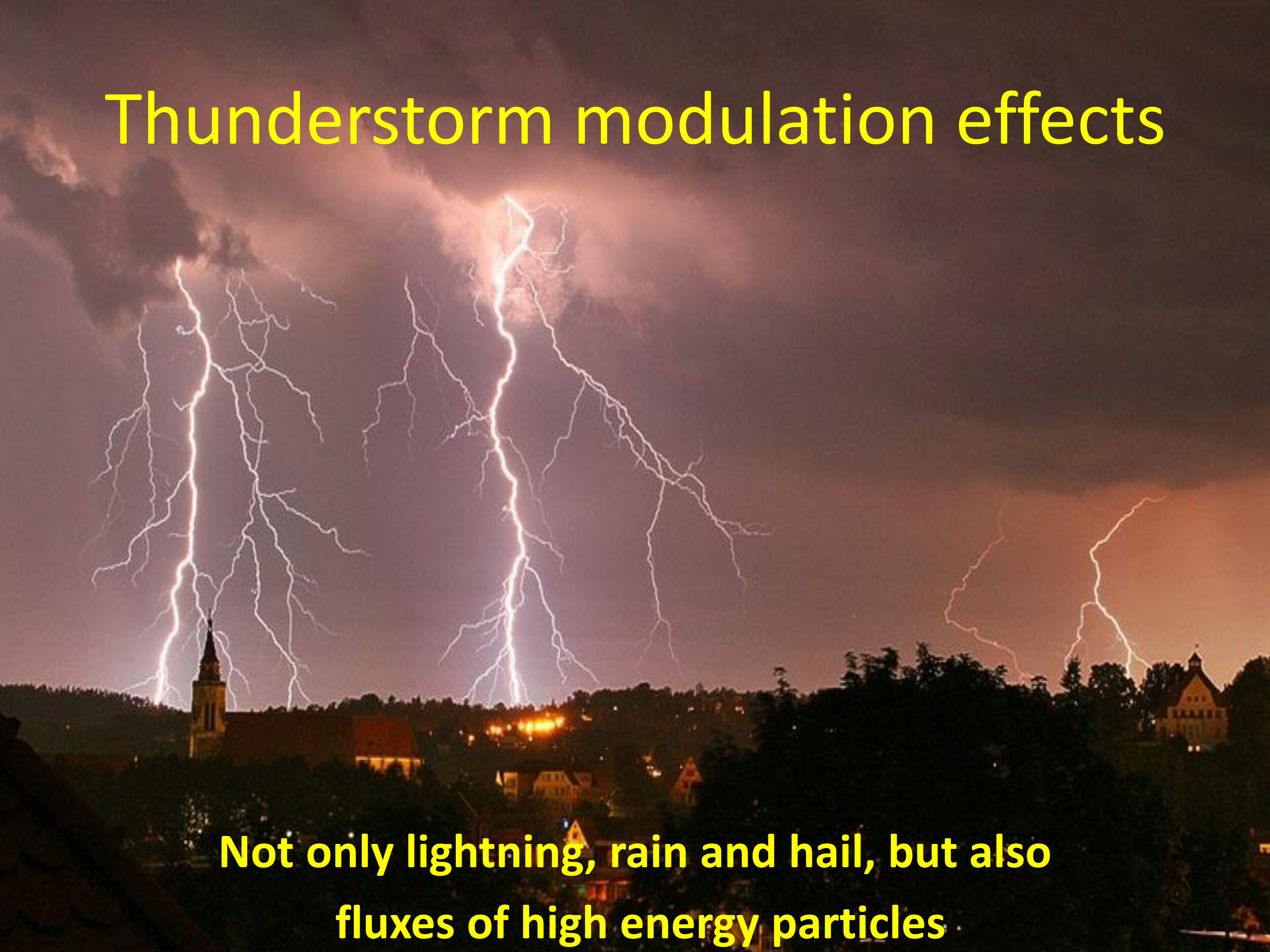


Figure 1. *Pressure corrected time series of ASEC particle monitors*

Figure 2*. Pressure corrected time series of SEVAN particle monitors*



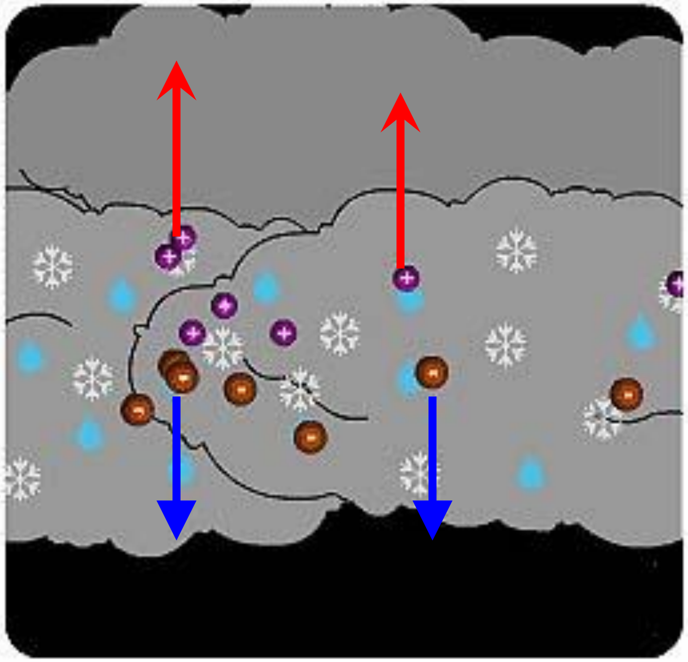
Thunderstorm modulation effects



Not only lightning, rain and hail, but also fluxes of high energy particles

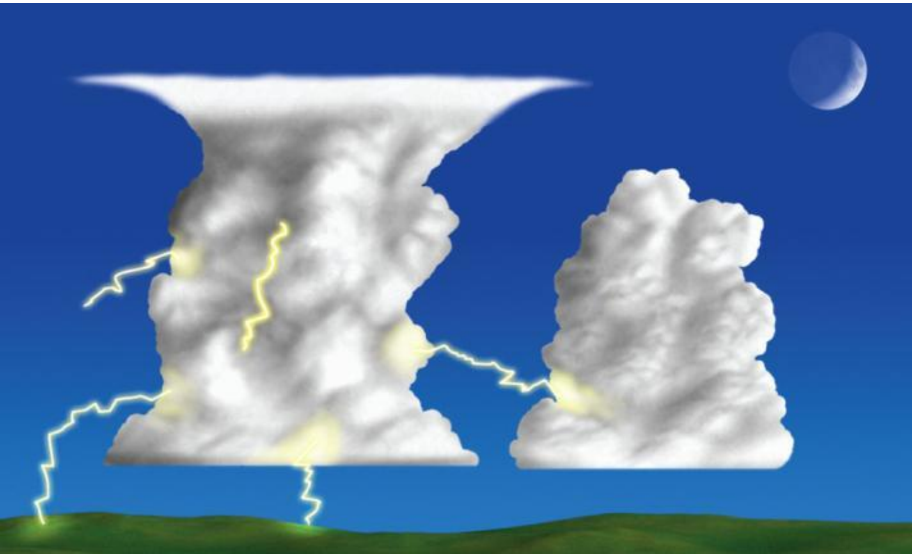
Charging a Thundercloud

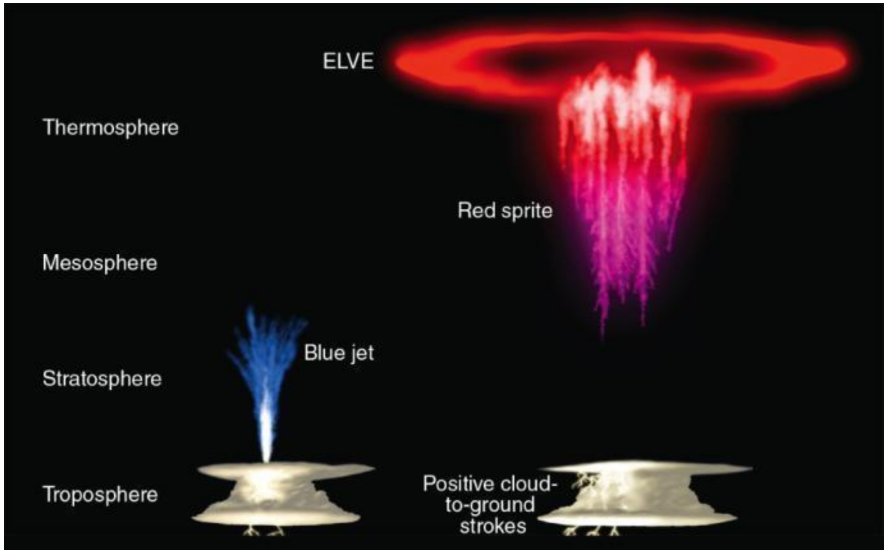
- Raindrops, snow crystals and hail stones collide inside the cloud. During these collisions they may exchange electrons and ions.
- The exact mechanism is not well understood, but the bottom line is:
  - Larger particles become negatively charged.
  - Smaller particles become positively charged.
- Larger particles settle down to the bottom of the cloud.
- Smaller particles are lifted to the top of the cloud by strong updrafts.



Type of Discharges

- Cloud-to-ground
  - 90% of the time: IC- negative cloud to positive ground (electrons moving from cloud to the ground)
  - 10% of the time: IC+ positive cloud to negative ground (electrons moving upward from ground to the cloud))
- Cloud-to-cloud: IC- (negative above positive, electrons moving downwards)
- and IC+ (positive above negative, electrons moving upward)
- Cloud-to-atmosphere Elves, red sprites, **blue jets**





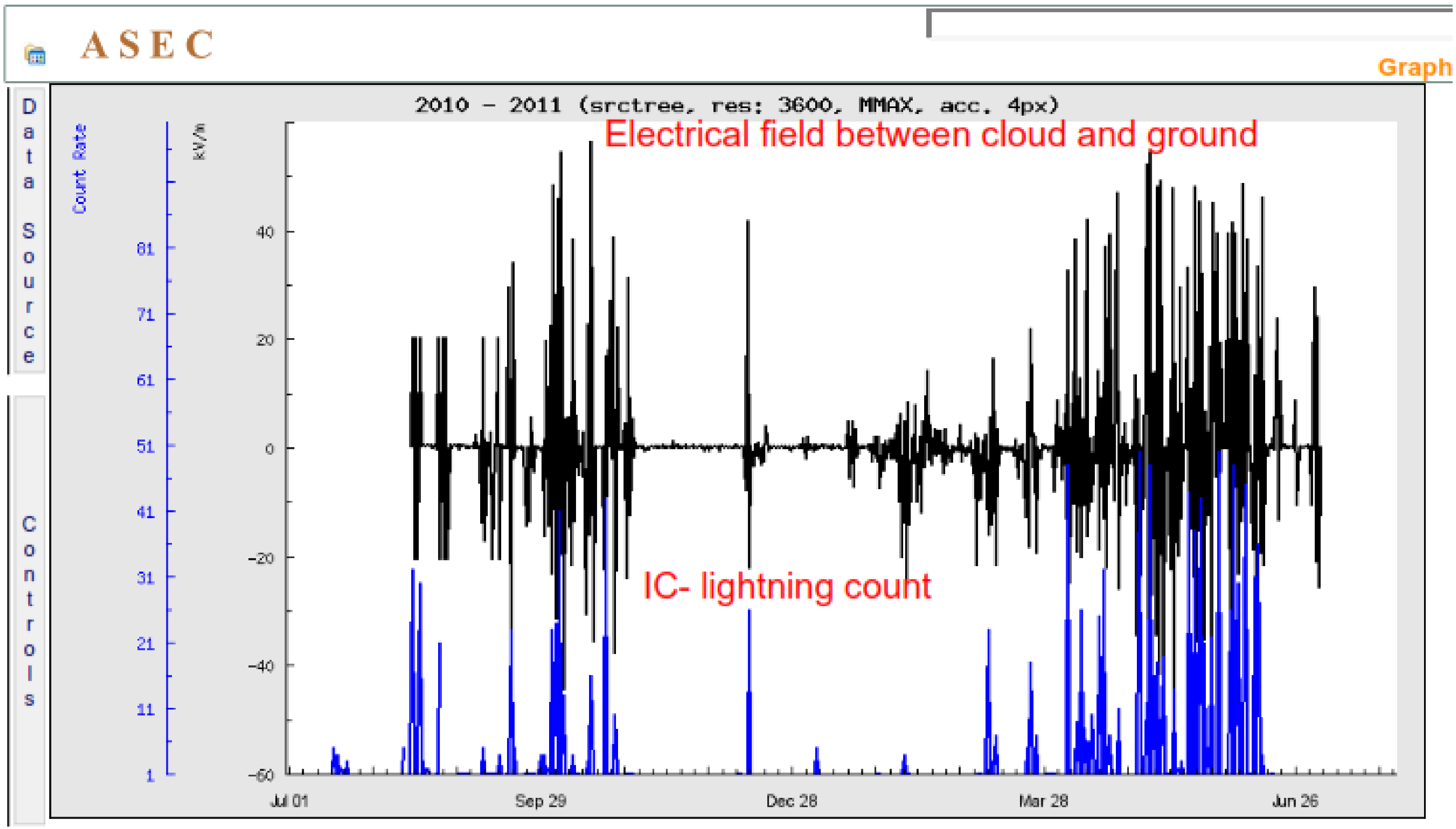
CRT Wilson: discovery of high-energy phenomena in atmosphere

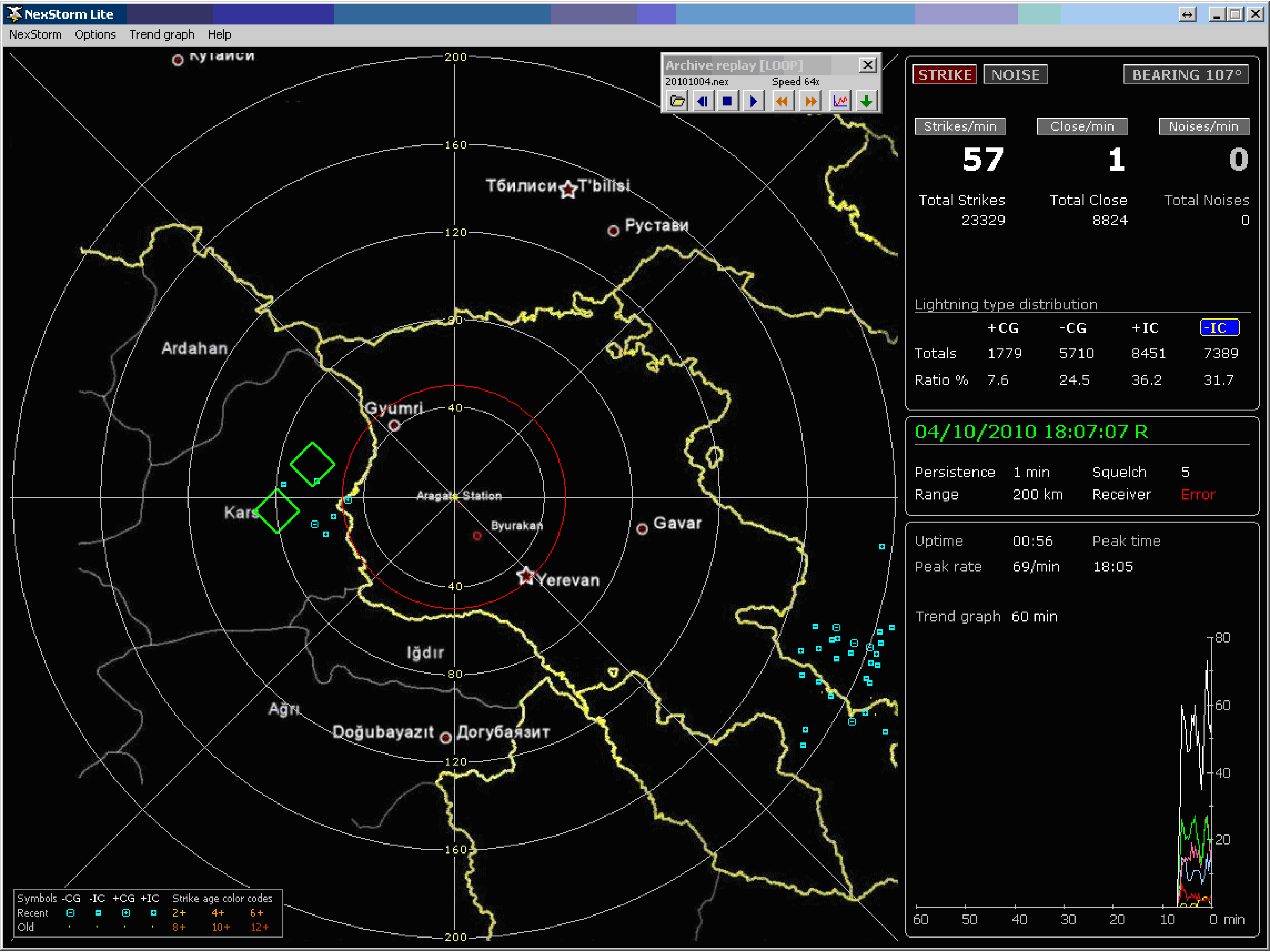
"In a field of 20 kV/cm the energy supplied to β-particle will exceed the average loss; so that particle will be continuously accelerated until some accident occurs"
"There is, as well known, some evidence of the existence of penetrating radiation in the atmosphere; possibly some portion of it may originate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

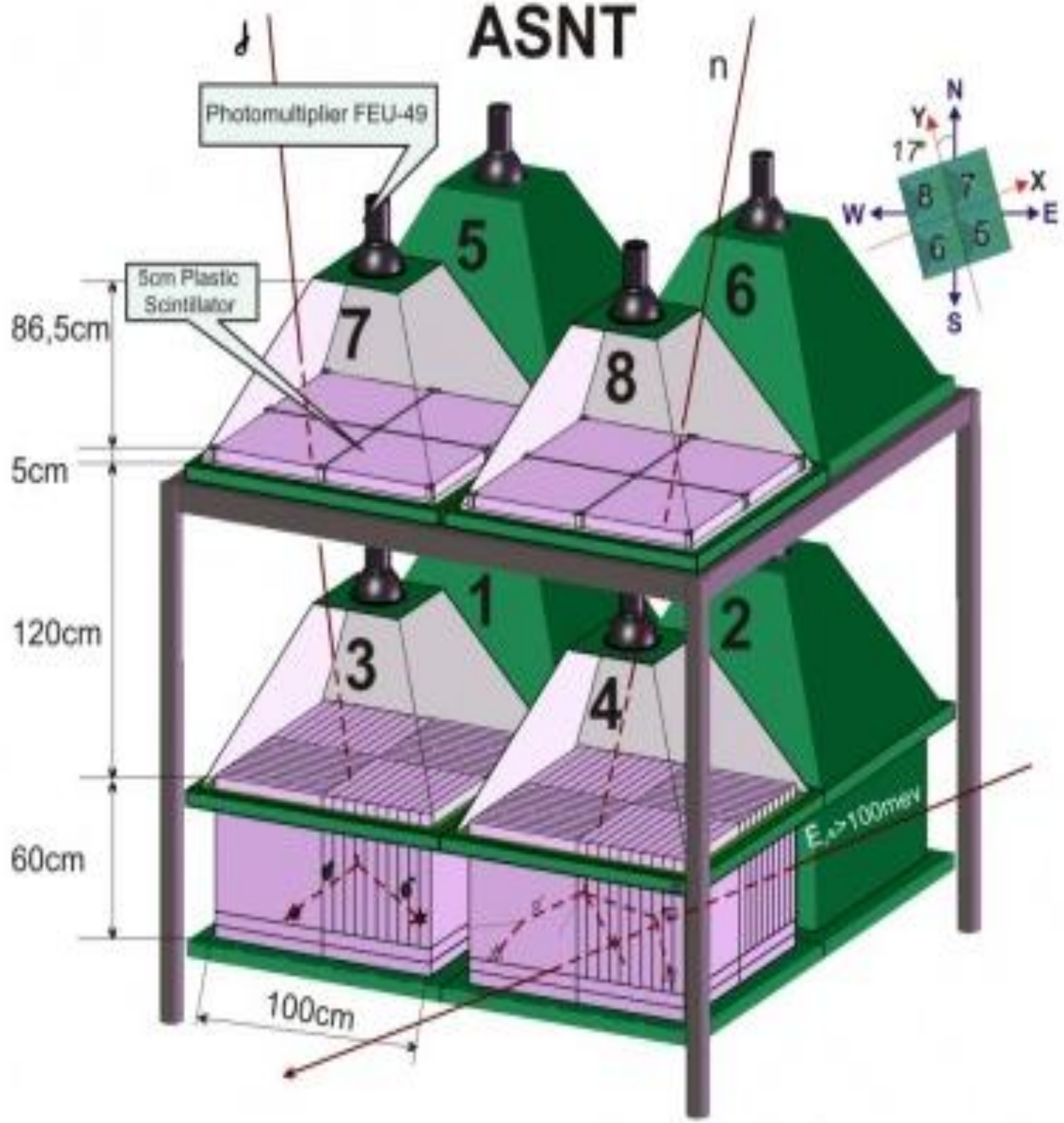
C. T. R. Wilson, the acceleration of β-particle in strong electrical fields of thunderclouds, Proc. Cambridge Philos. Soc. 22, 534, (1925).
E.R.Williams, Origin and context of C.R.T. Wilson's ideas on electron runaway in thunderclouds, JGR, 115, A00E50, 2010.

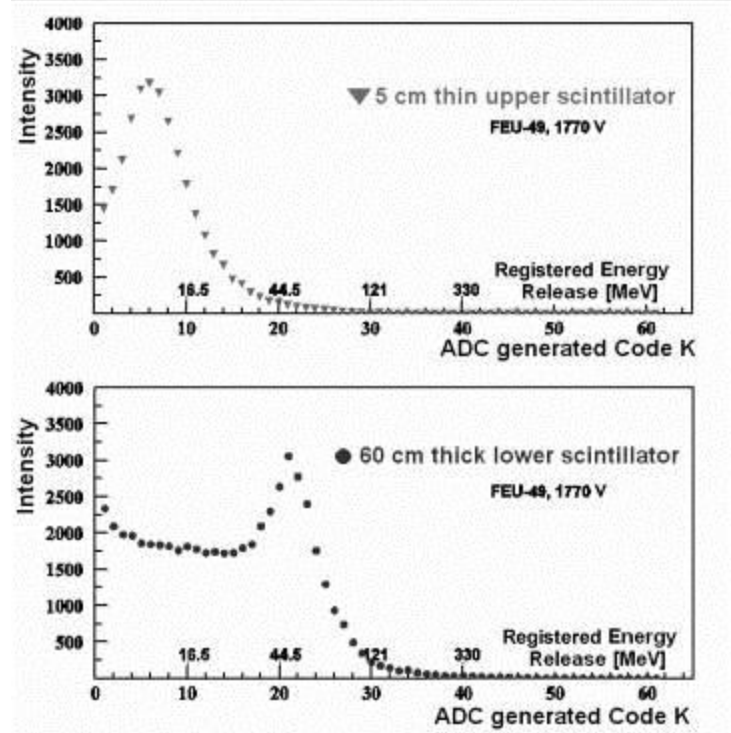
Field and lightning monitoring at Aragats (Boltec FM100 and LD) – July 2010- July 2011 (~100 TGE)



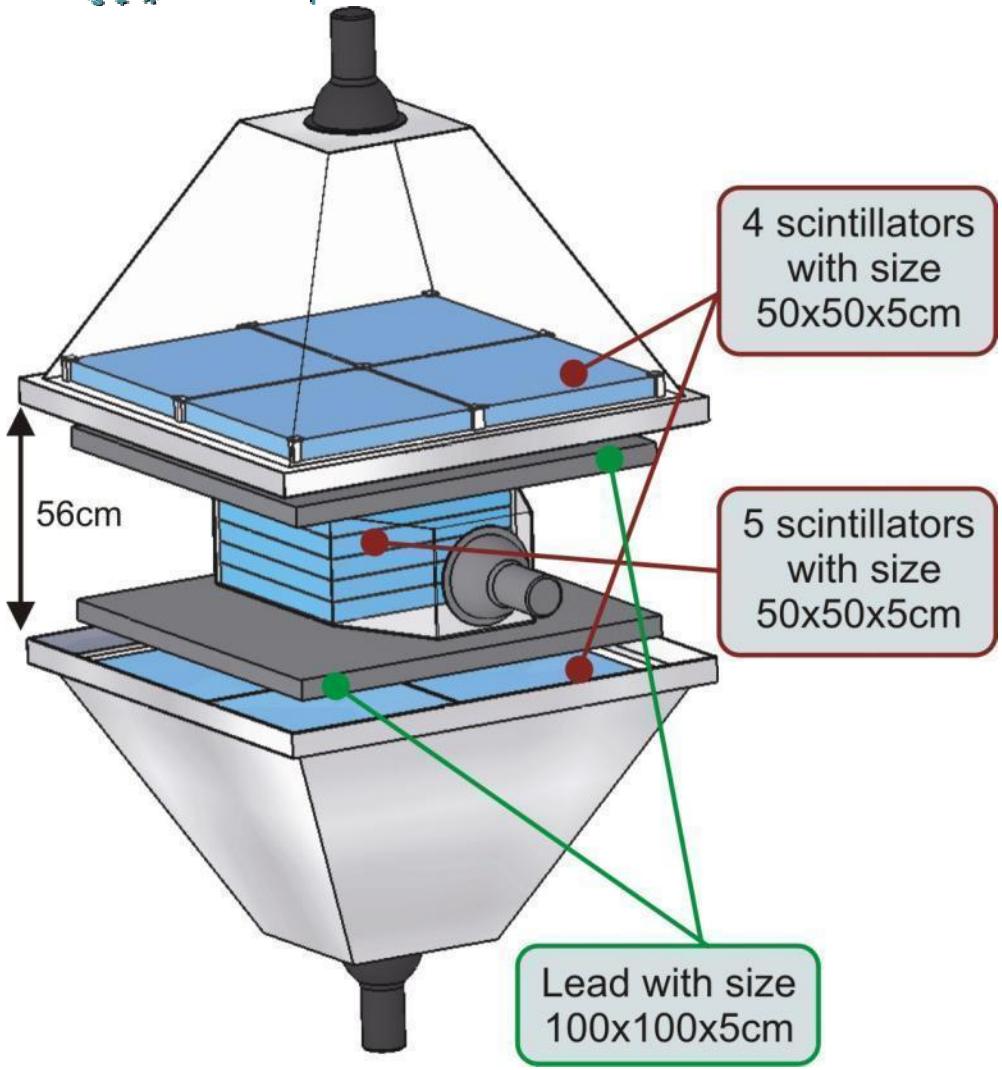

NexStorm Lite
NexStorm
Options
Trend graph
Help
Archive replay [LOOP]
20101004.nex
Speed 64x
STRIKE
NOISE
BEARING 107°
Strikes/min
Close/min
Noises/min
57
1
0
Total Strikes
23329
Total Close
8824
Total Noises
0
Lightning type distribution
+CG
-CG
+IC
-IC
Totals
1779
5710
8451
7389
Ratio %
7.6
24.5
36.2
31.7
04/10/2010 18:07:07 R
Persistence
1 min
Squelch
5
Range
200 km
Receiver
Error
Uptime
00:56
Peak time
Peak rate
69/min
18:05
Trend graph
60 min
80
60
40
20
60
50
40
30
20
10
0 min
Кутаиси
Тбилиси
T'bilisi
Рустави
Ardahan
Gyumri
Kars
Aragats Station
Byurakan
Gavar
Yerevan
Iğdır
Ağrı
Doğubayazıt
Догубаязит
200
160
120
80
40
Symbols -CG -IC +CG +IC
Strike age color codes
Recent
Old
2+
4+
6+
8+
10+
12+

Aragast Solar Neutron Telescope("deep" calorimeter for 10-120 MeV particles)





SEVAN basic unit: monitoring 3 species of secondary CR

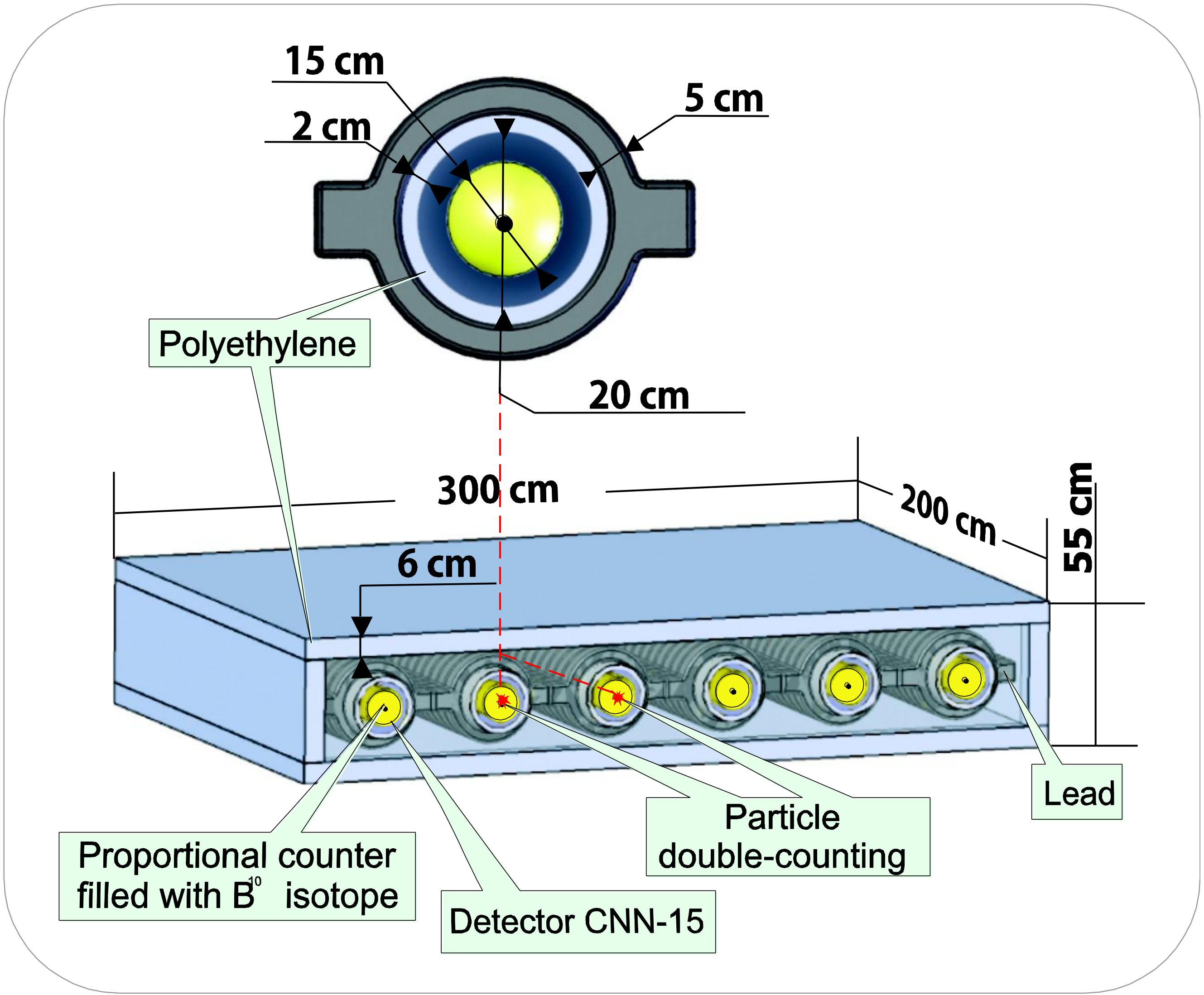


100 – traversal of the low energy charged particle (~<200MeV);

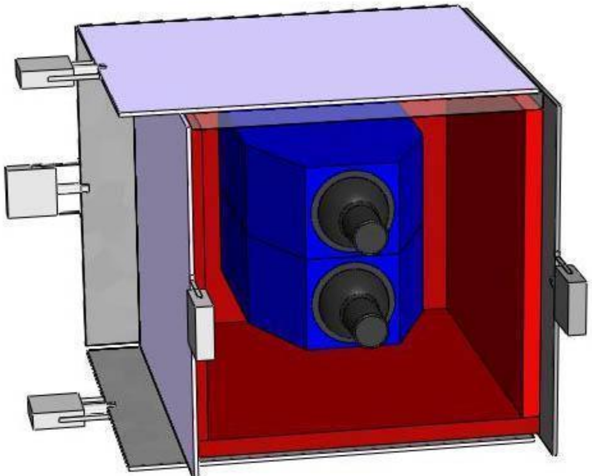
010 – traversal of the neutral particle;

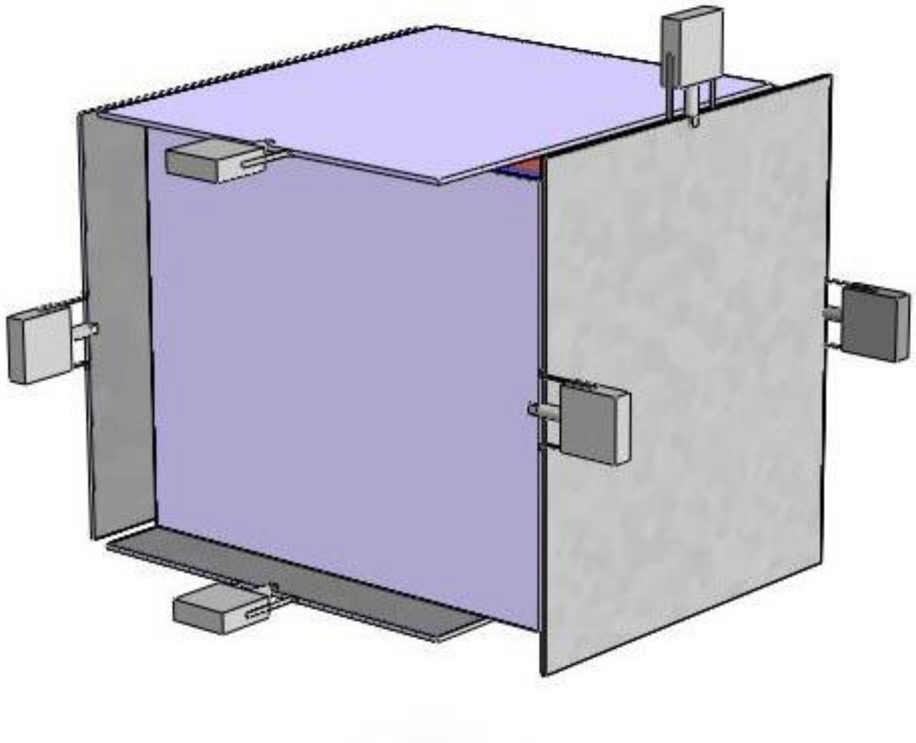
111 & 101 – traversal of the high energy muon (~>250MeV);

Section of the Neutron Monitor

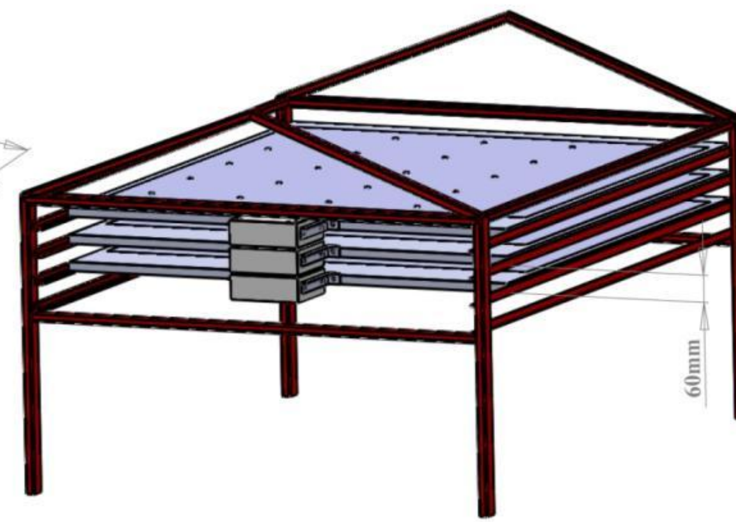


Cube gamma-electron Detector

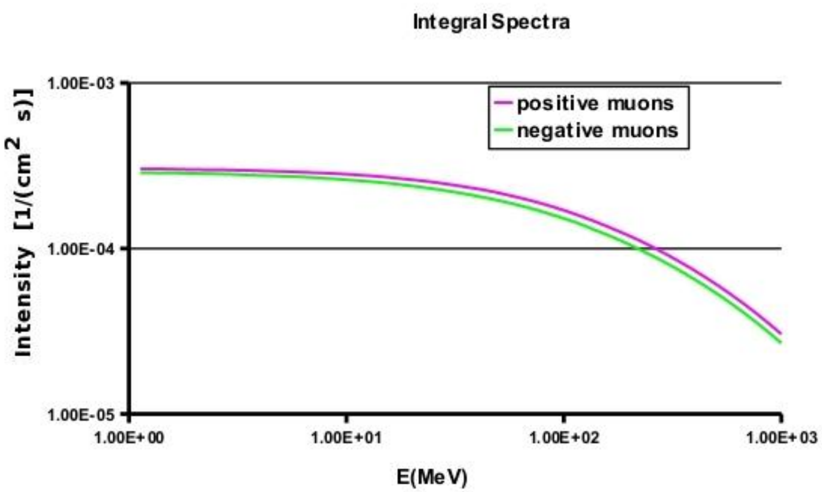


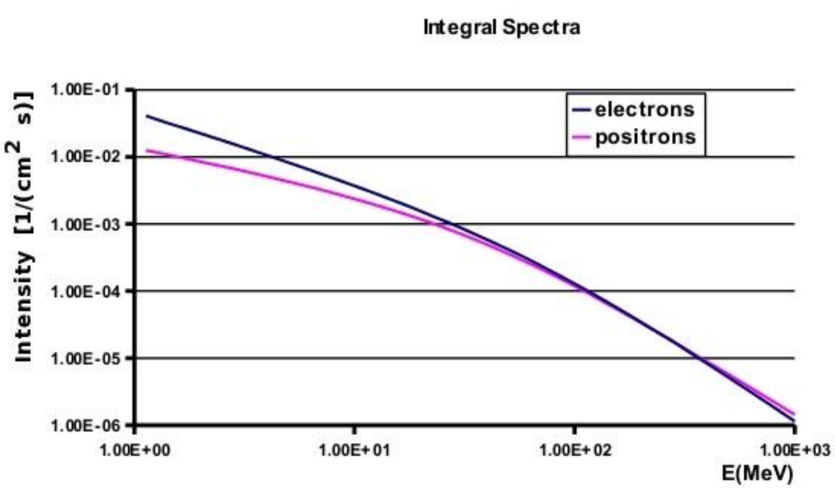


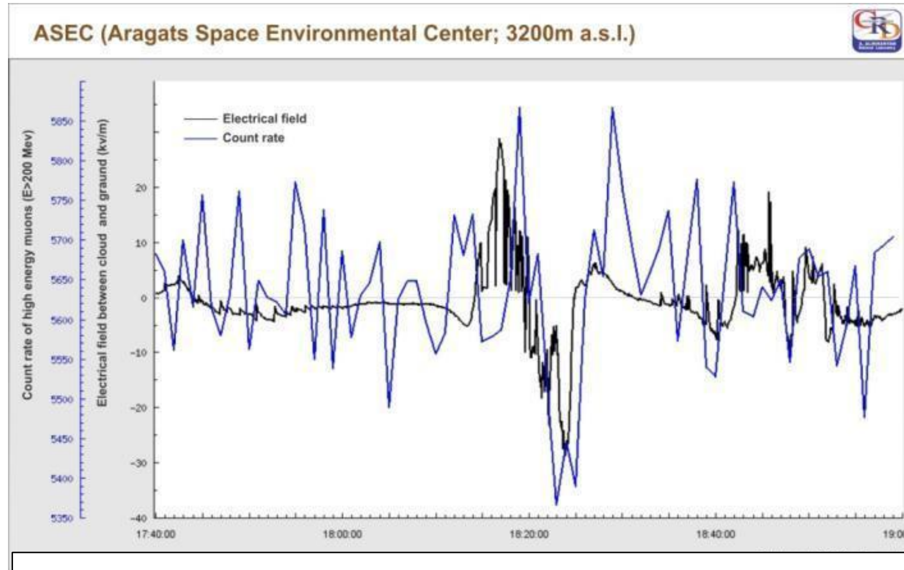
STAND Detector

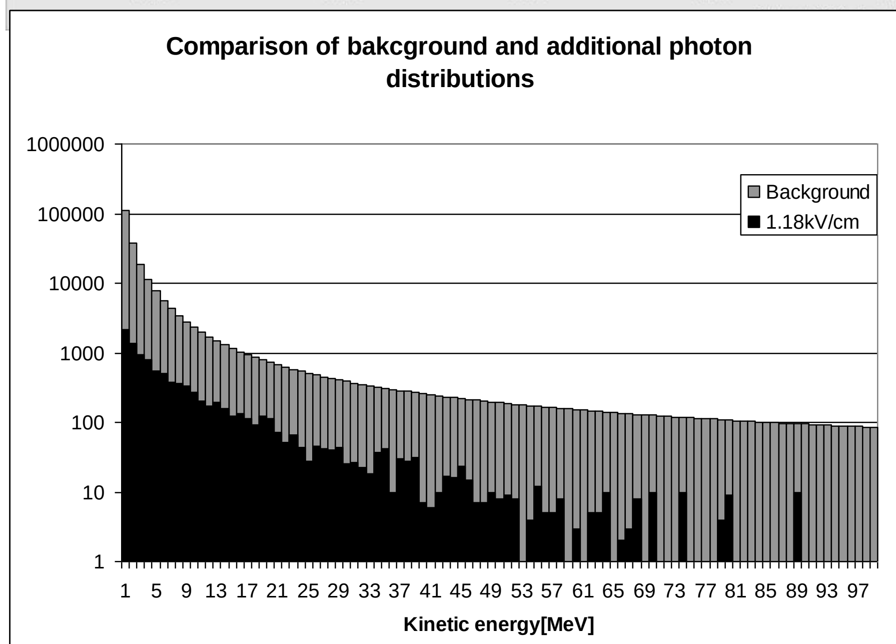


TGE of up to 20% magnitude (peaks and deeps) can be explained by the energy spectra modification

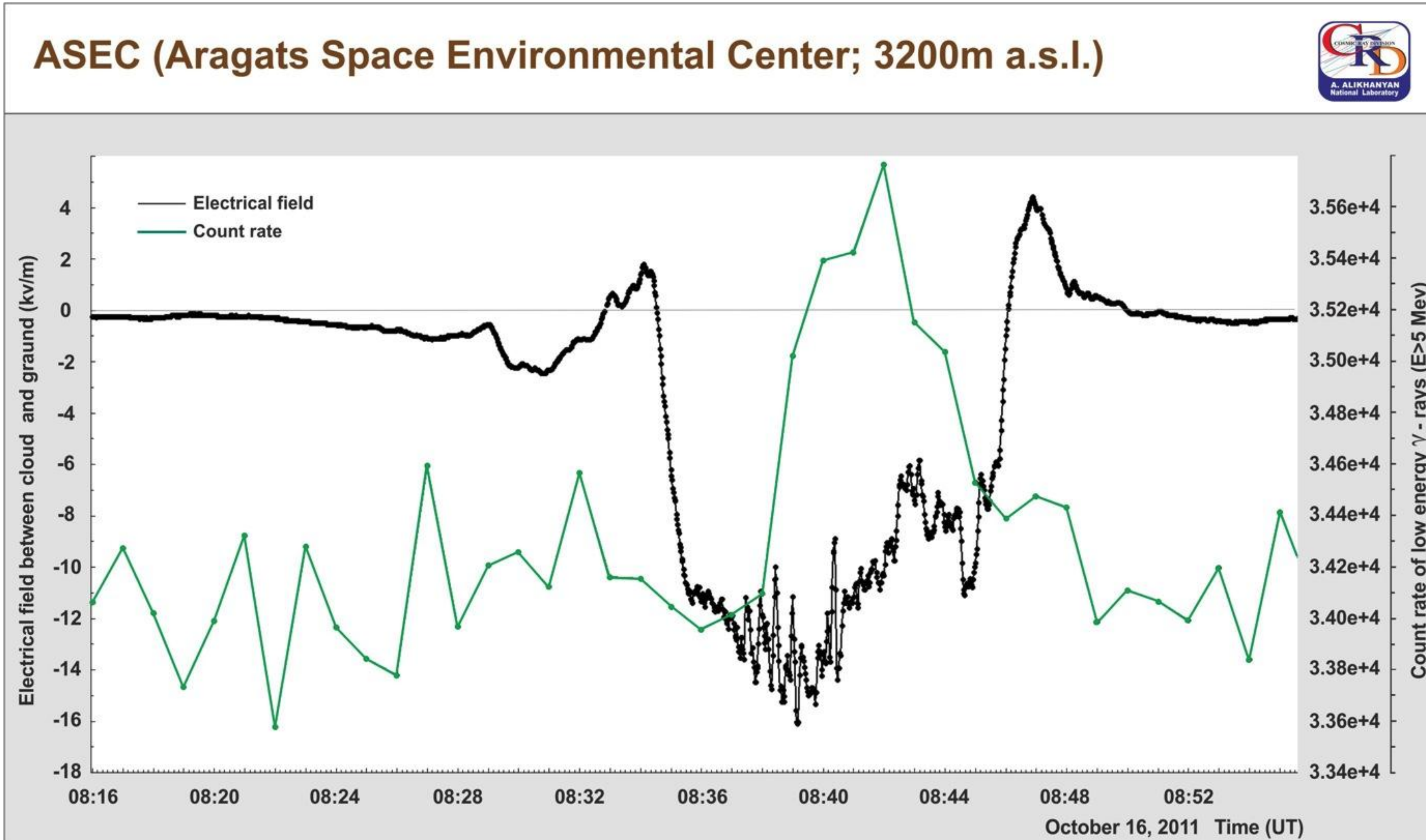




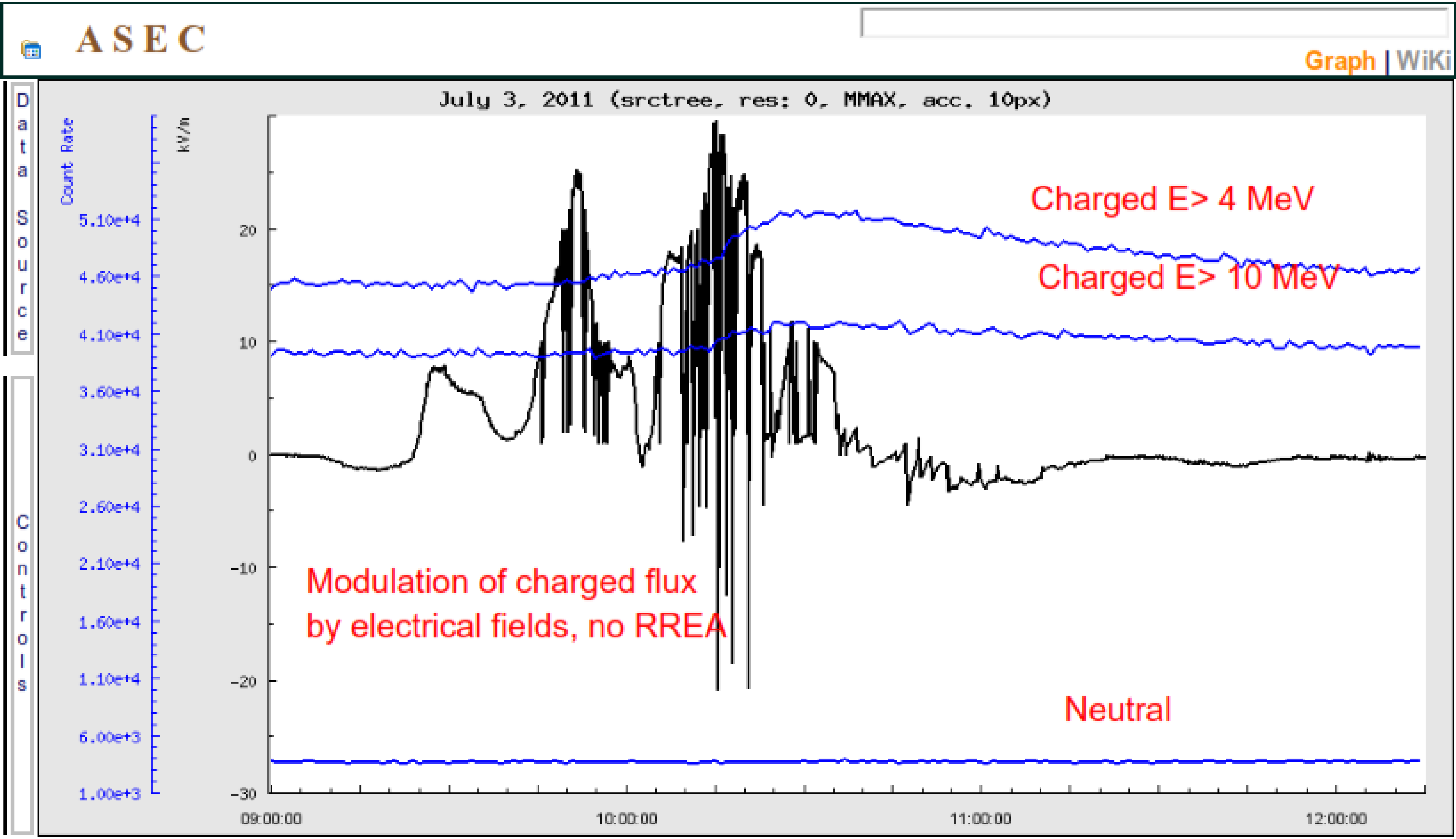


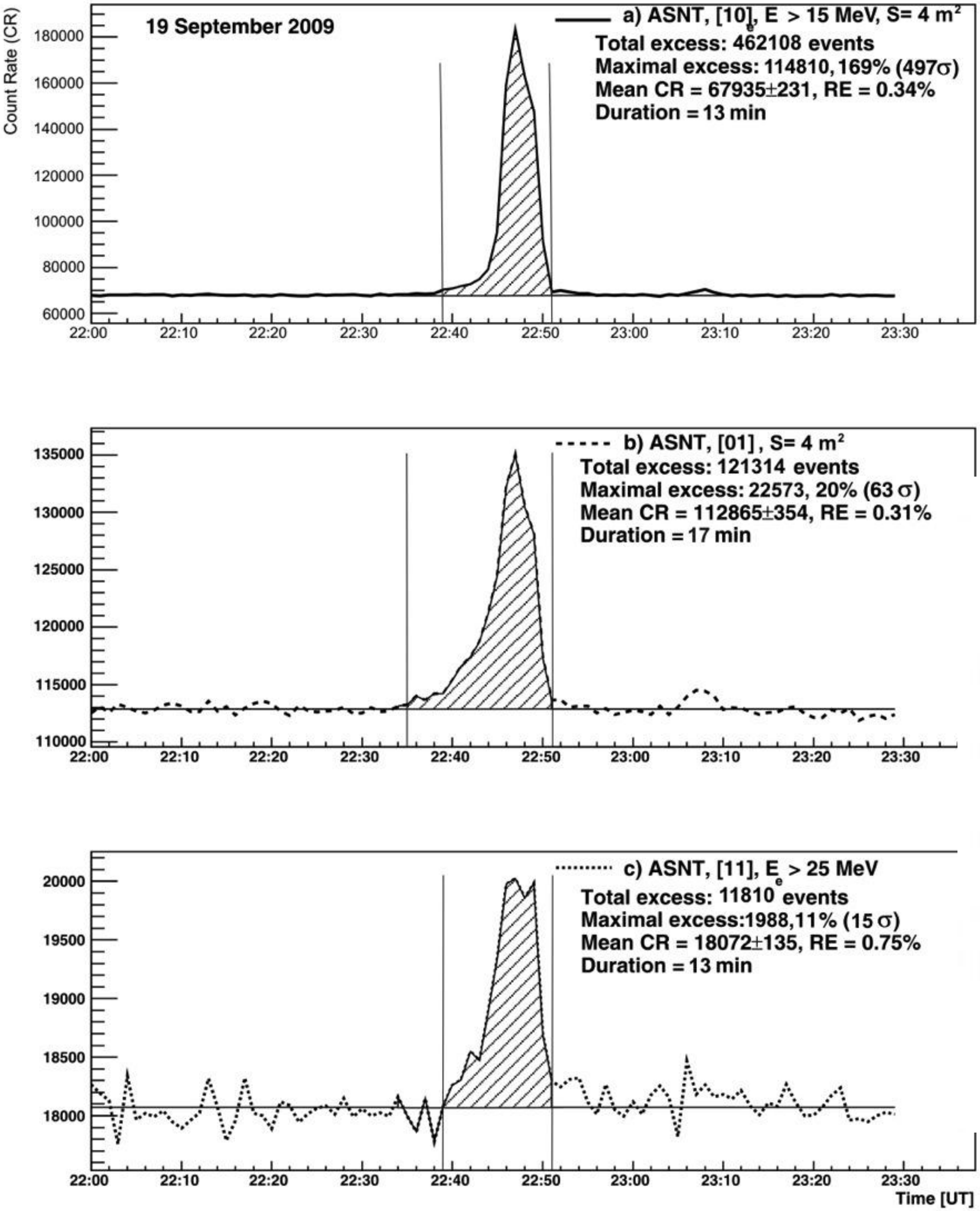


Thunderstorm ground enhancement – TGE – small effects (transformation of the energy spectra)

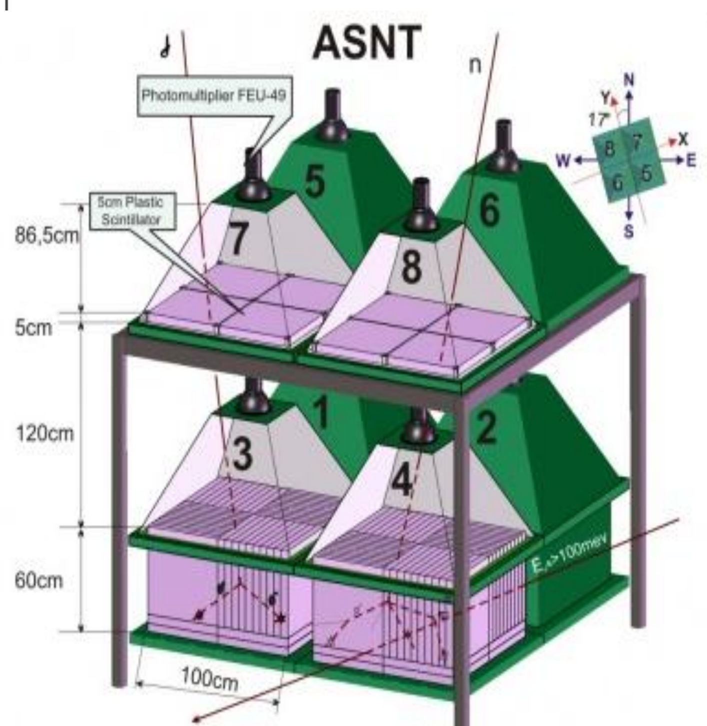


Modulation of charged flux by electrical the atmospheric radiation

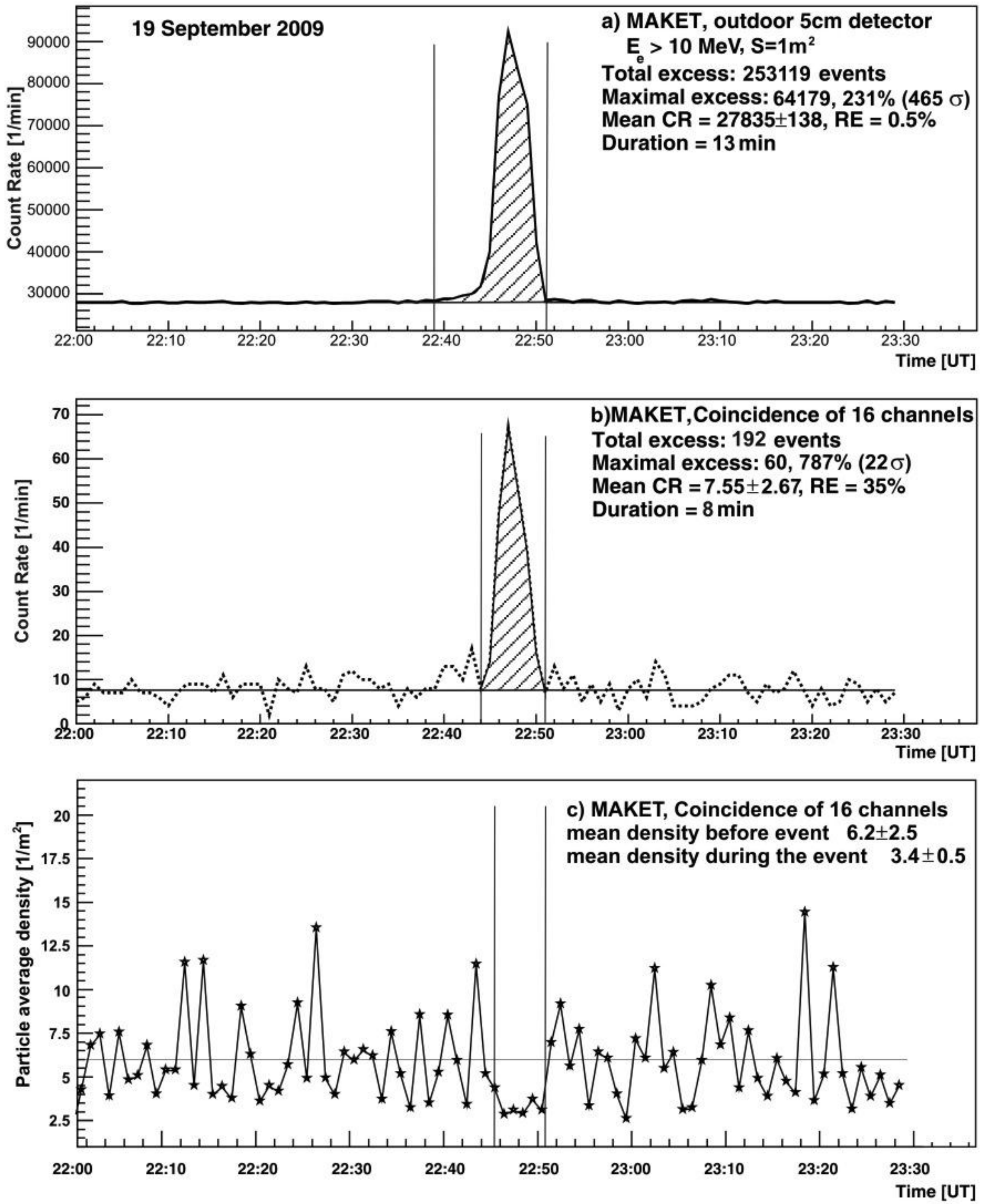




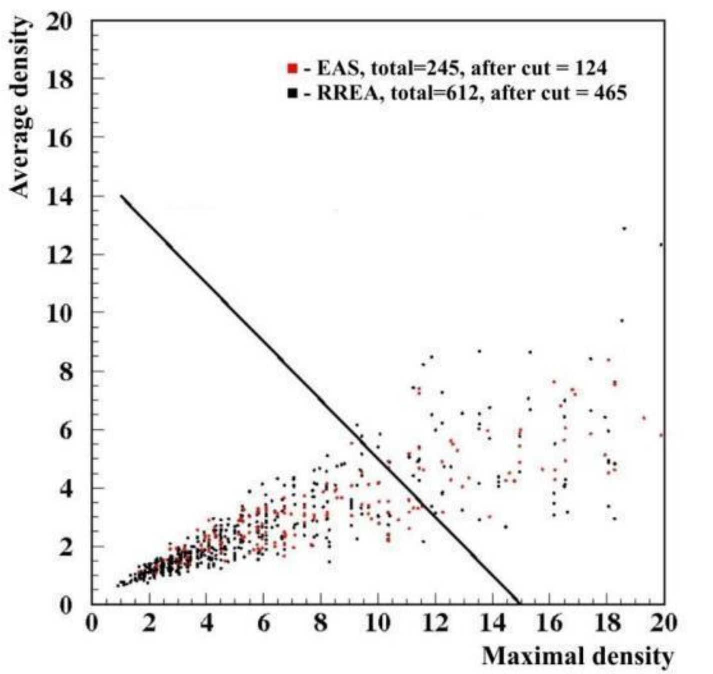
Huge TGE of 19 September, 2009 was detected by all ASEC monitors :
ASNT (10) – >10 MeV electrons;
ASNT (01) - gamma rays;
ASNT (11) – electrons E>25 MeV -
19 September event is only event with high energy electrons and one of two with short particle bursts.



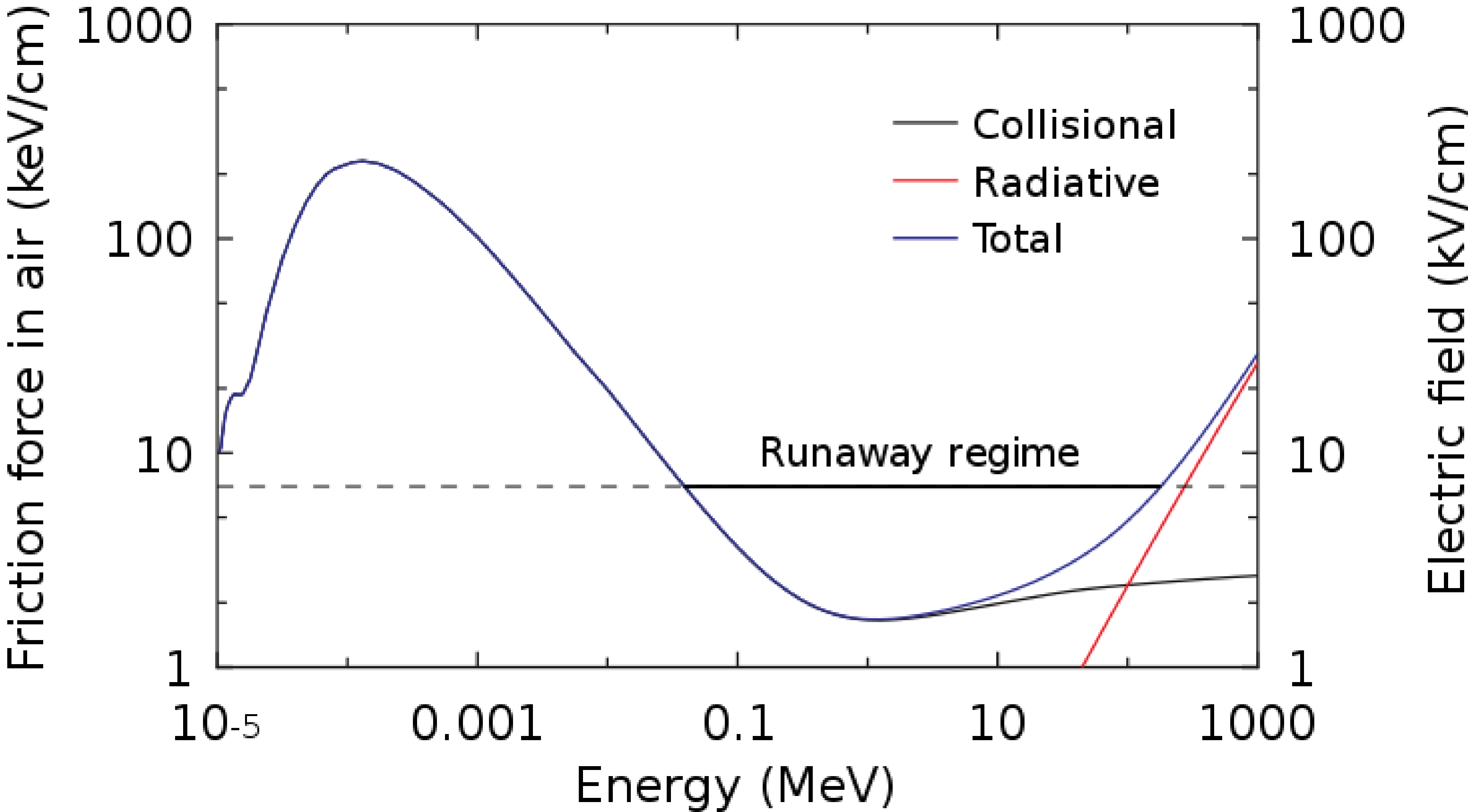
A. Chilingarian, A.Daryan, K.Arakelyan, et al., **Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons,** Phys.Rev. D., **82,** 043009, 2010

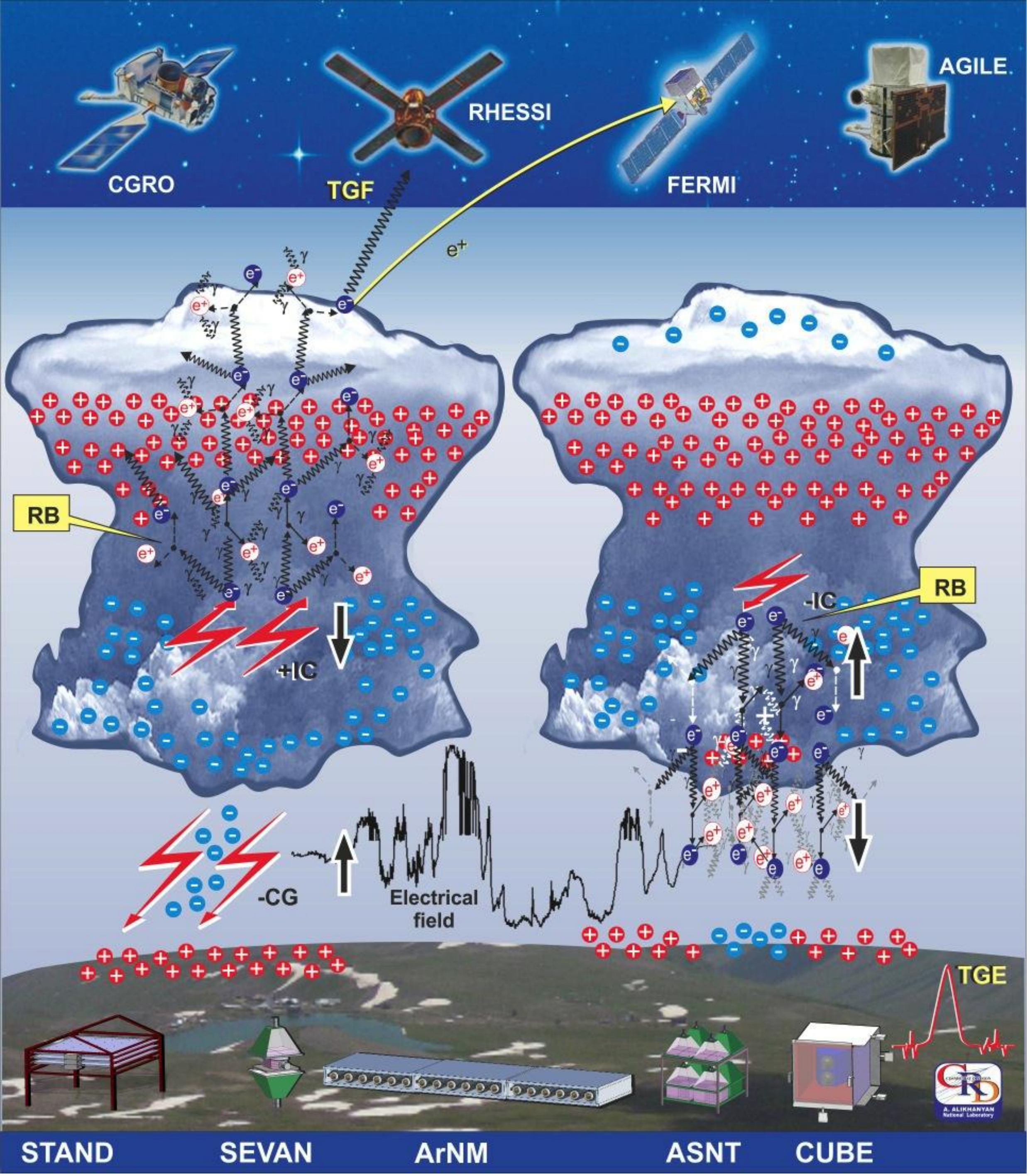


Outdoor and indoor stand alone scintillators detect huge peaks lasting ~10 minutes
MAKET – a surface array with 16 scintillators (1000 m.sq.) detect short coherent bursts of electrons (within 1 μsec); duration less than 50 μsec;
Short TGEs have small densities – can be distinguished from EAS events



Runaway Breakdown (RB, RREA): when and how



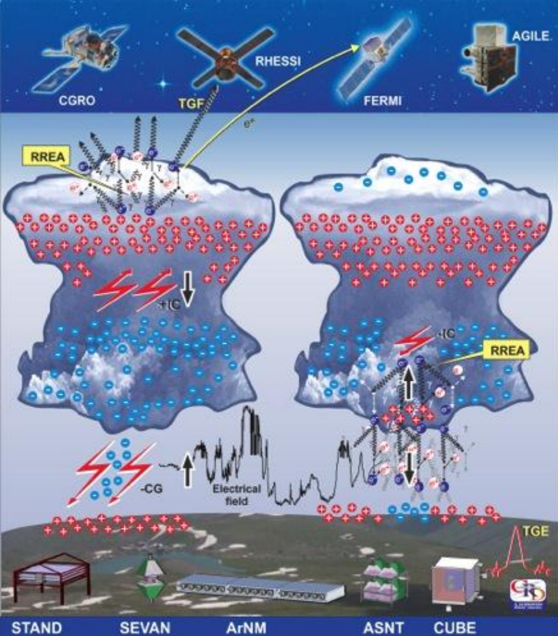


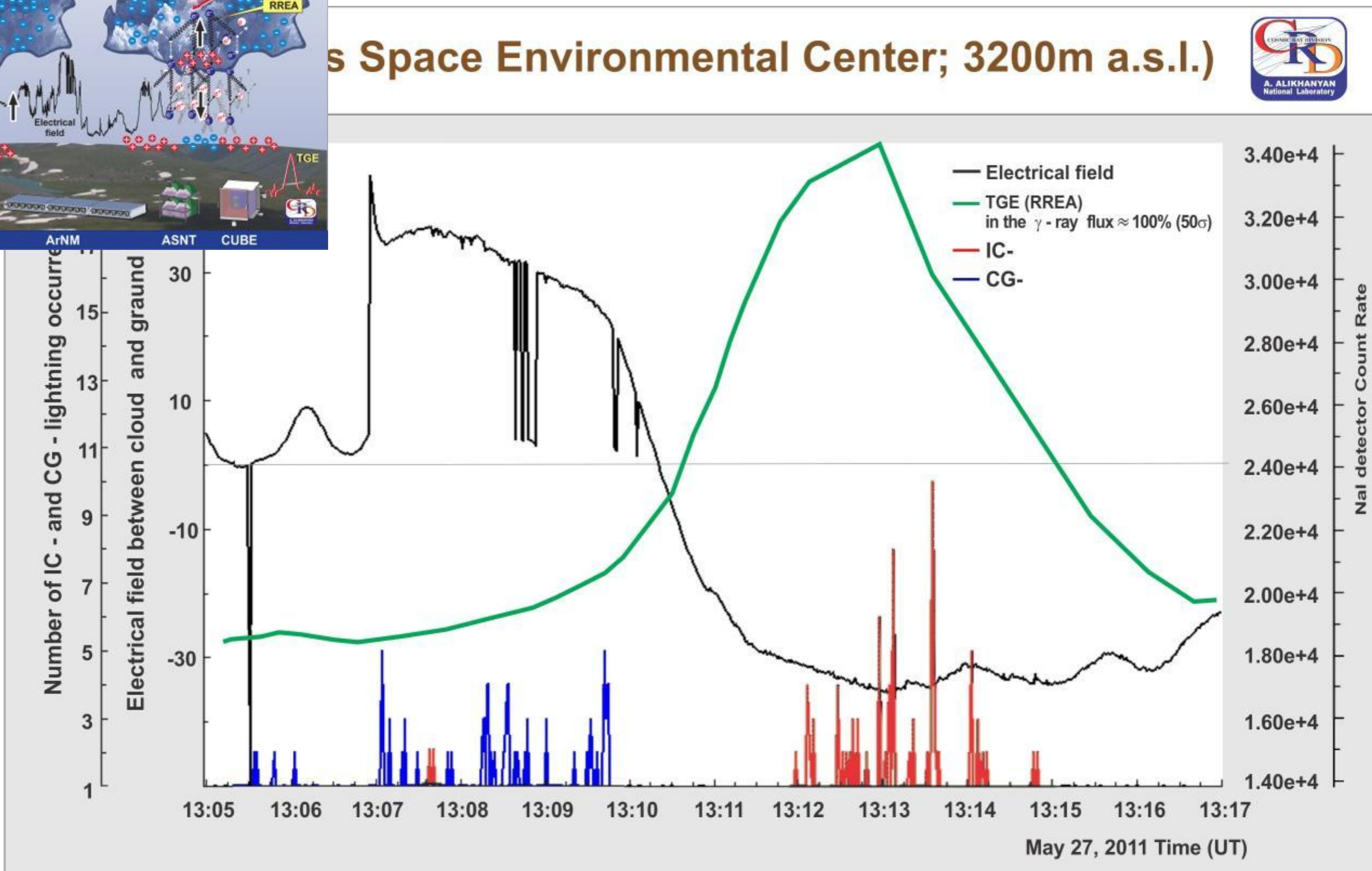
TGE-TGF model

Huge fluxes of the gamma are detected by orbiting telescopes and surface networks of particle detectors.
The physical mechanism is the same – runaway electron-gamma avalanches developing in atmosphere using as seeds both ambient population of MeV cosmic ray electrons and current pulses of lightning stepped leaders

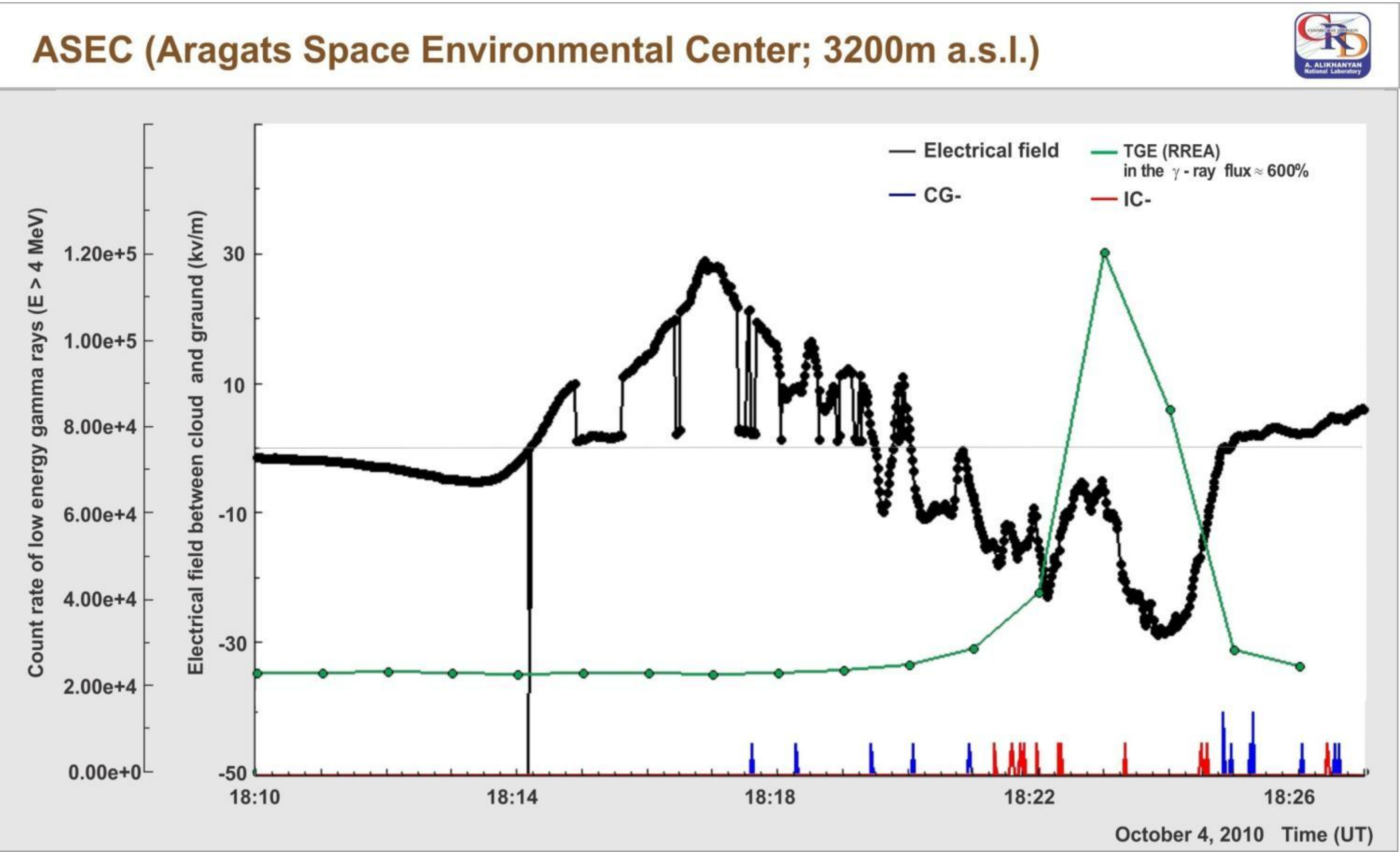
RB - Runaway breakdown;
RREA – Relativistic Runaway electron avalanche

The dynamic of a TGE event

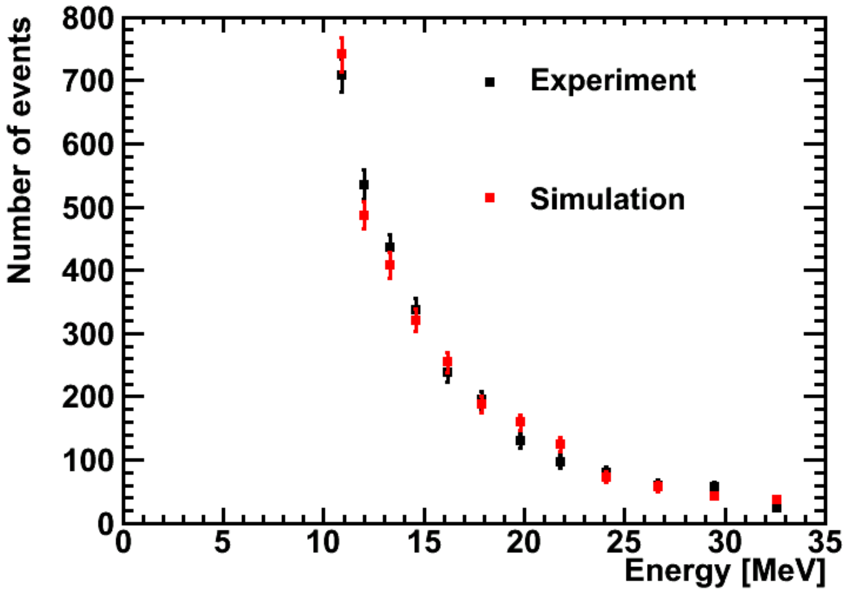




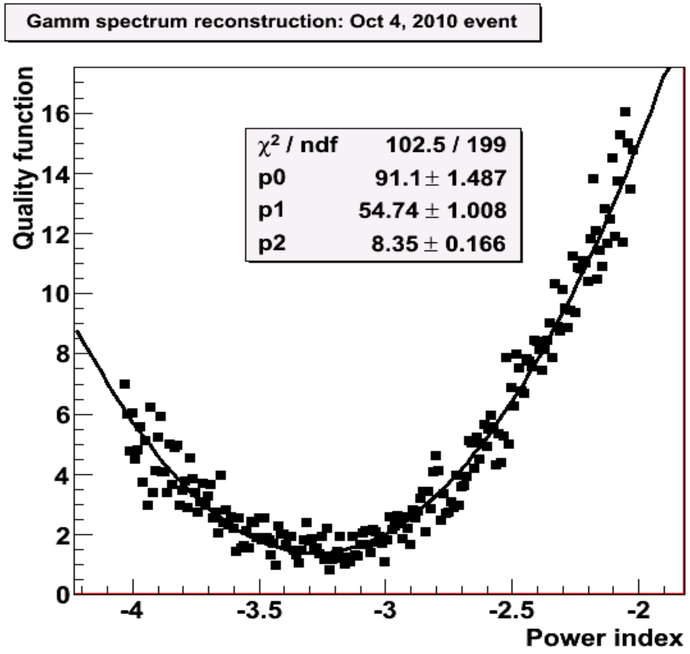
Huge TGE on 4 October 2010



Inverse problem solving: incident Gamma spectra recovery by the measured energy deposit spectra

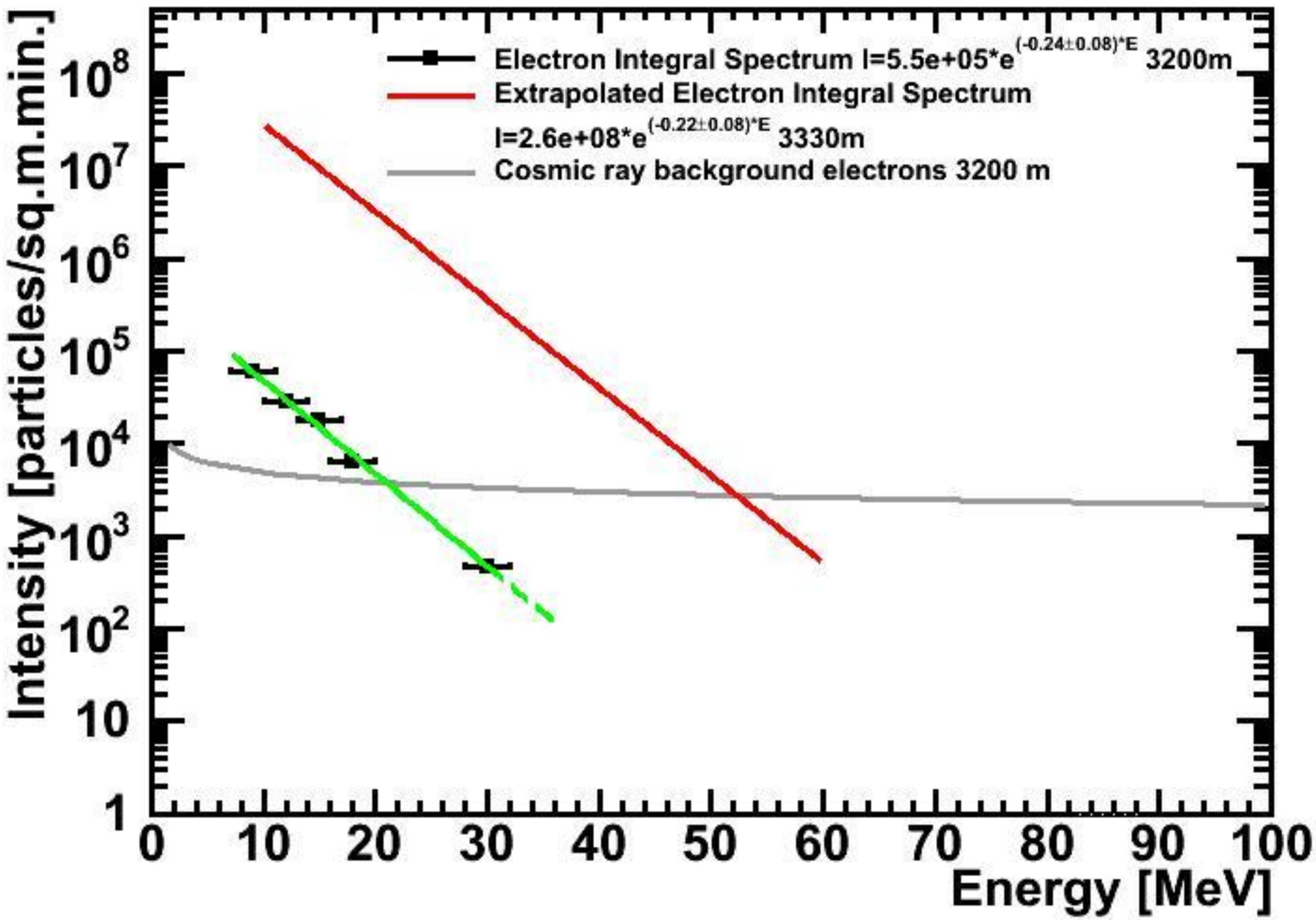


Measured and simulated energy deposit spectra of Cube upper scintillator at 18:23, 4 October, 2010

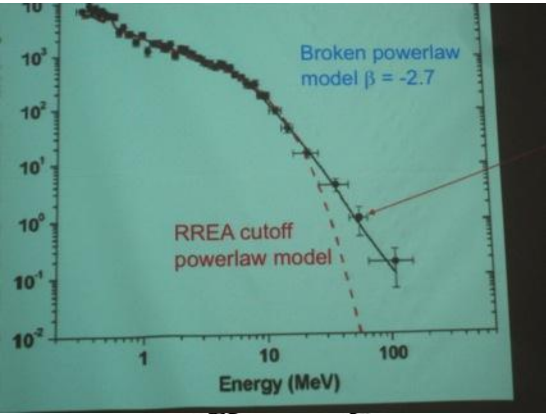


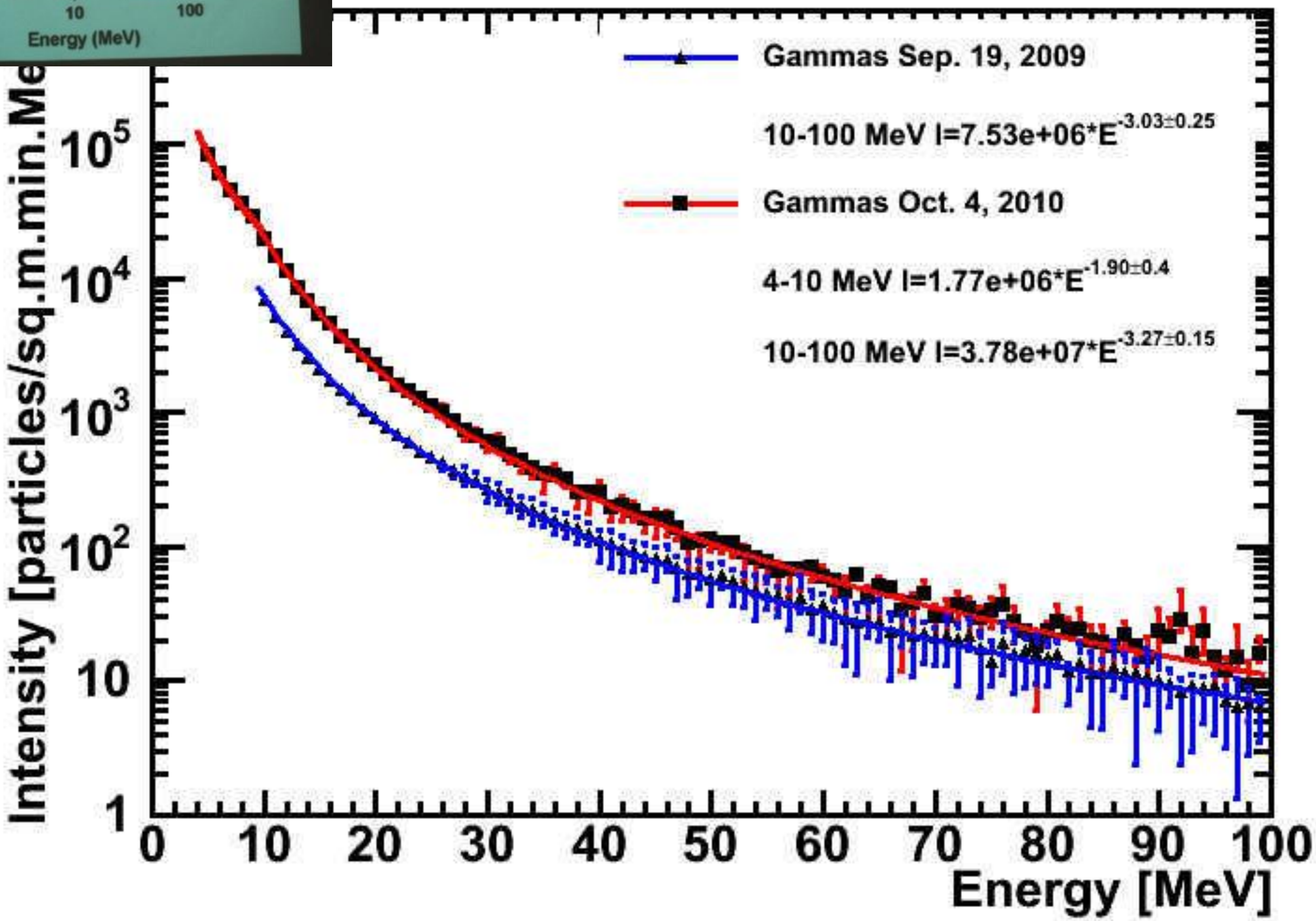
Fitting the power spectra index by multiple CR direct problem (Cube detector data on 18:23, 4 October, 2010).

TGE 19.09.09: Electron Integral Energy spectra

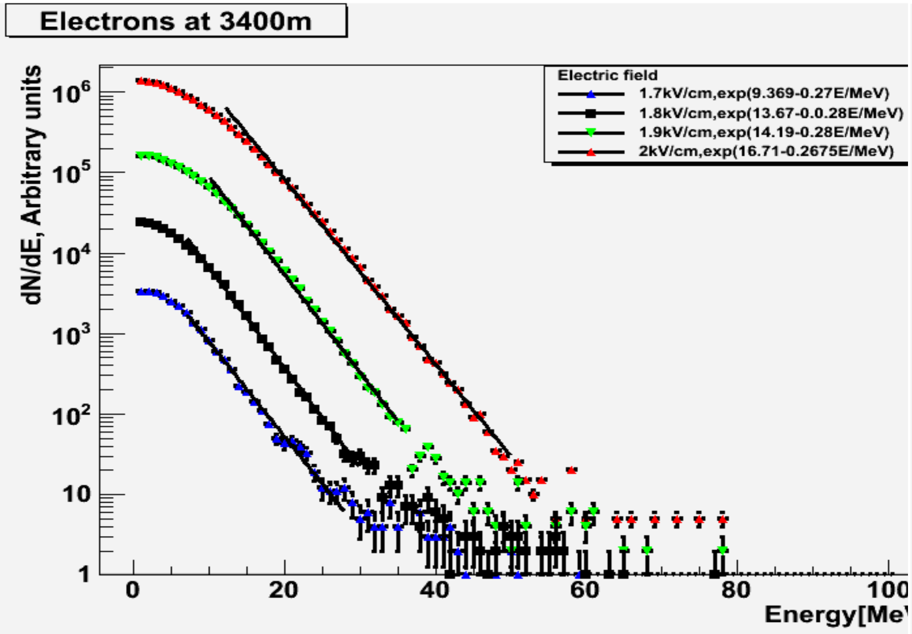


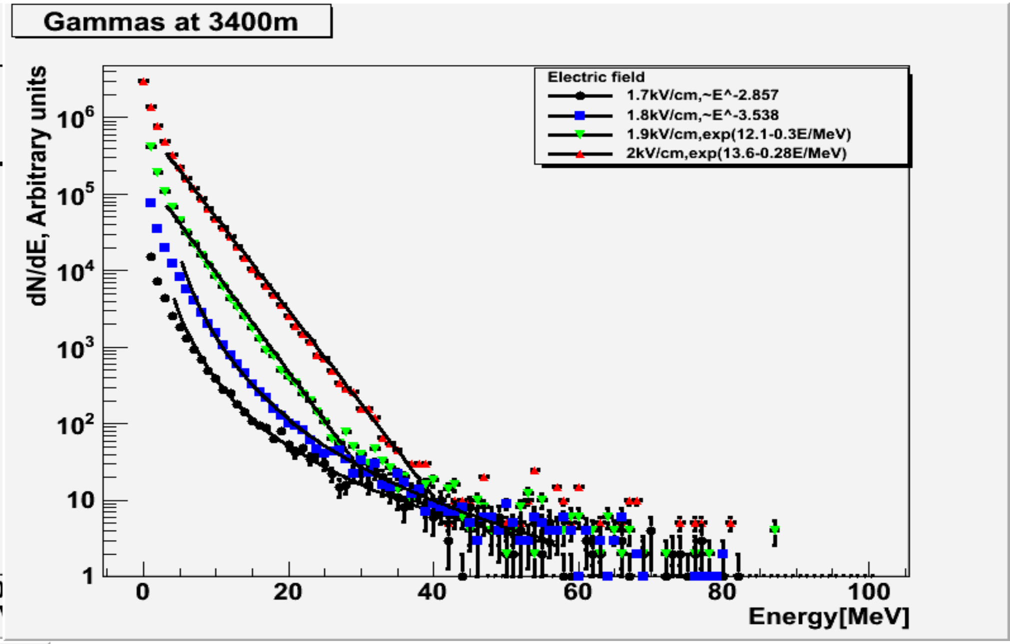
Energy Spectra of the RREA gamma rays

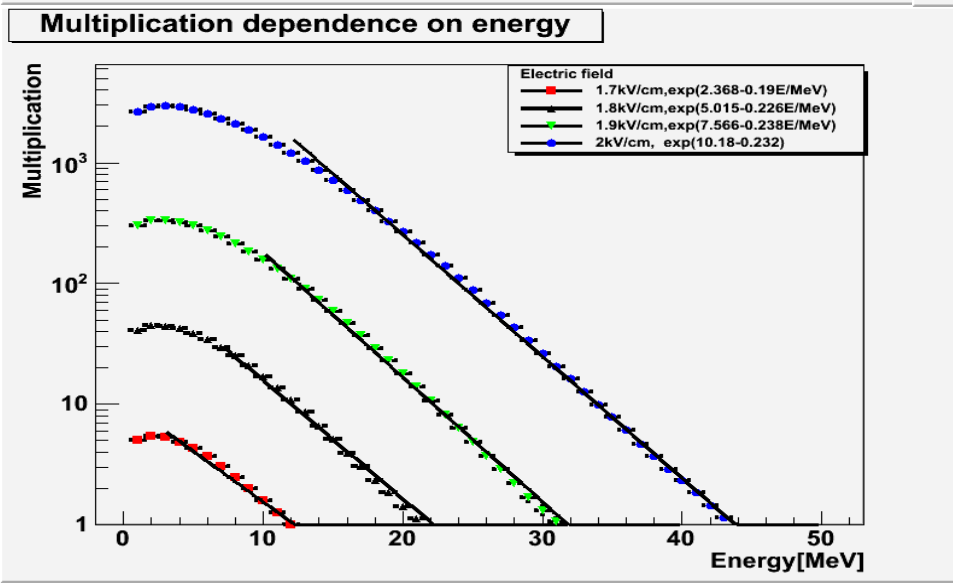




Simulation of the RB from 5000 till 3400 m

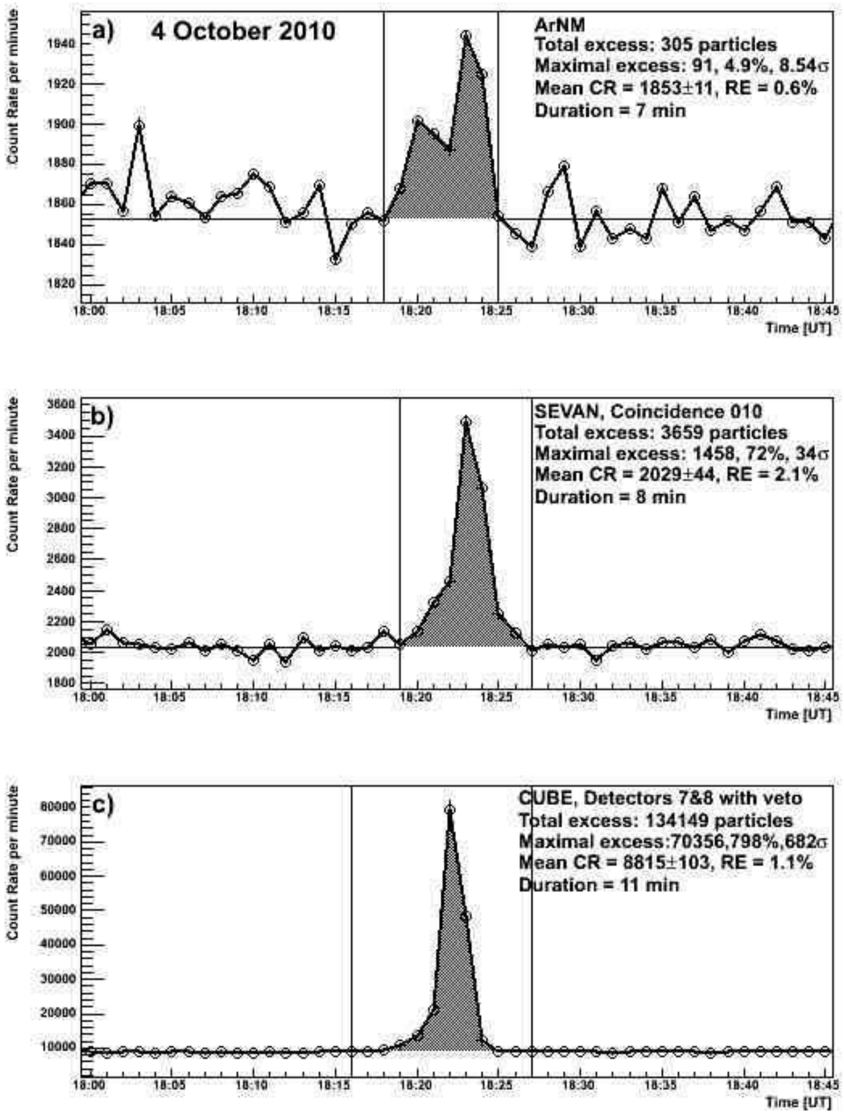


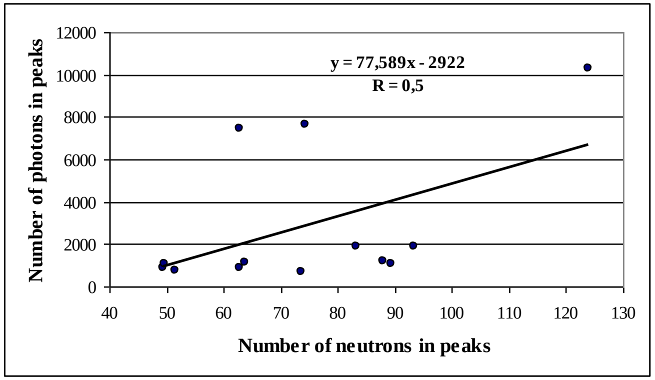


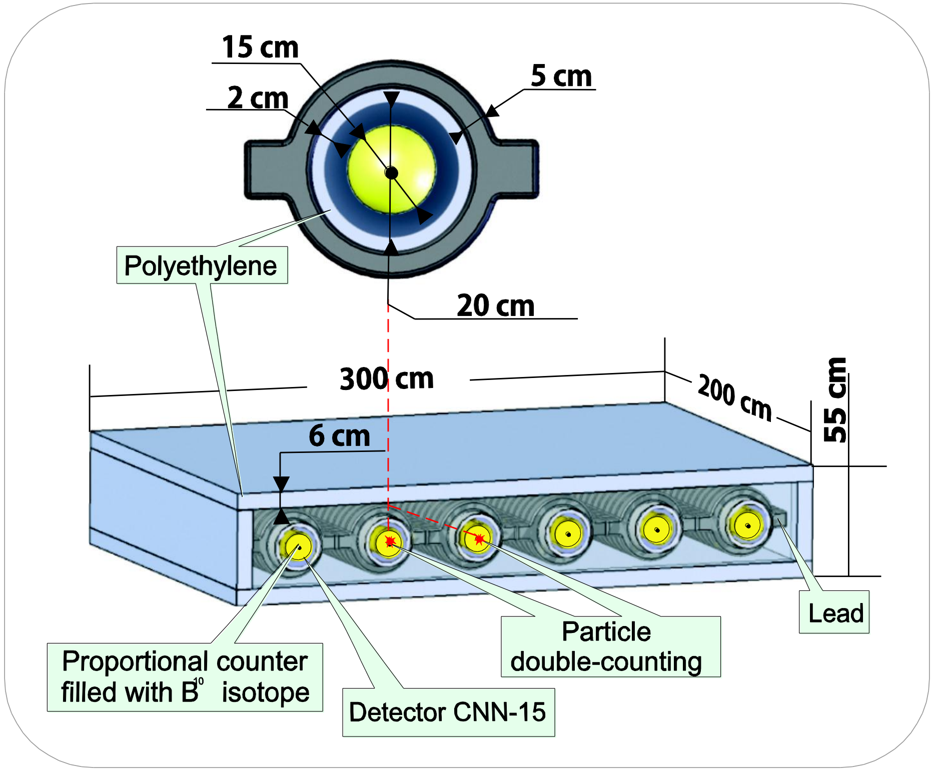


Maximal energy of electrons on the ground (ASNT 11) ~30 MeV(on exit from cloud ~50 MeV) ; Height of cloud - 130 m;; elongation of electrical field 1600 m, the needed strength of field ~1.8 kV/m .
The multiplication rate M ~ 2000, corresponds to ~7 e-folding lengths of ~200m;Total number of electrons > 10 MeV – 3.8*10^12 in radii 0.5 km; Maximal energy of gamma rays – much higher than electrons.

Origin of the peaks in the Neutron Monitor: photonuclear reaction? Additional negative muons? Not enough gamma rays to explain neutron monitor counts







Prove of natural accelerator in thunderclouds

- Largest TGE events allows to estimate energy spectra and avalanche multiplication rate prove the existence of the Runway breakdown (RB, or RREA, electron avalanche) suggested by Wilson and Gurevich.
- Majority of TGEs (also small enhancements reported previously by other groups) are not connected with RB (RREA) process – it is only modification of the energy spectra of charged secondary cosmic rays in the electrical fields of the thunderclouds.
- Discovery of the “short” TGEs put the TGE and TGF phenomena on the same scale and point on the alternative source of seed particles (current pulses along developing lightning step leaders).
- Measured for the first time energy spectra of electrons and gamma rays (it is not possible to estimate energy spectra from TGFs due to scarcity of gammas) pose several restrictions on the structure and strength of the electrical field within thunderclouds.
- Lightning phenomena: TGE and CG-, IC- lightning occurrences are interconnected: Avalanche enables only when p-layer is above the detectors; p-layer prevent CG- lightning occurrence; maybe p-layer is intensified by CG- lightning during positive field period by the CG- lightning. Particles and lightning are also competing: at largest TGEs there are very few IC- lightning.

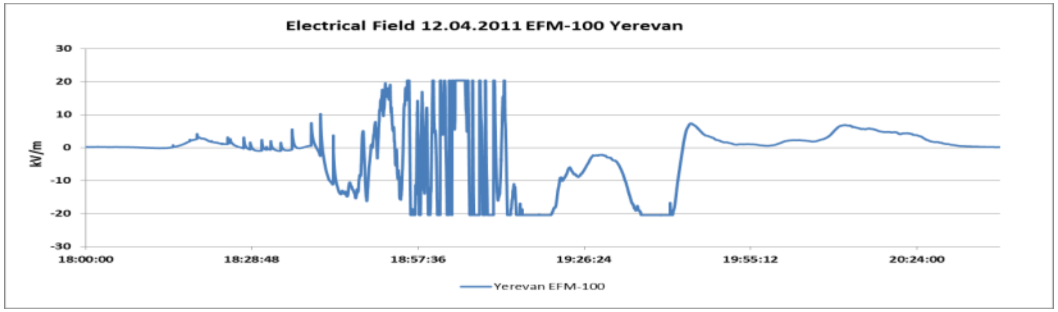
University of Alabama in Huntsville (UAH)

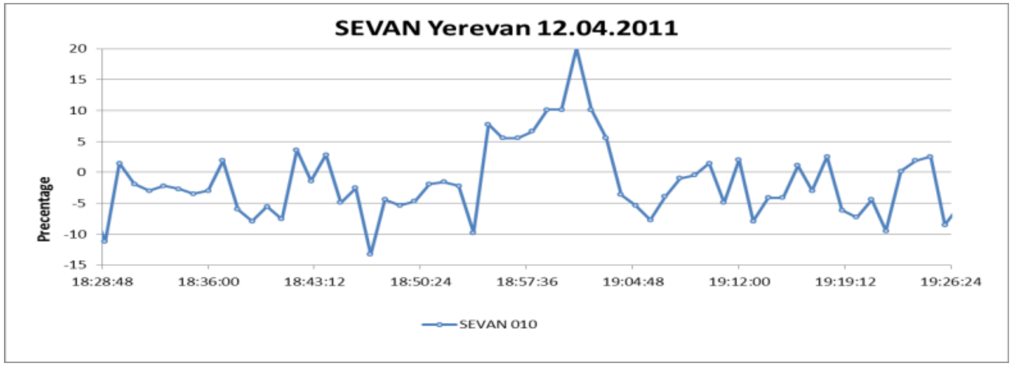
Miscellaneous

Why Is Lightning Mapping Important?

- Severe storm detection and warning.
- Convective rainfall estimation.
- Storm tracking, hailing forecasting.
- Aviation hazards.
- Warnings: Power companies, fuel depots, golf courses, etc.
- Forest fire forecasting.
- Indicator of cyclone development.
- Understanding of high energy phenomena in atmosphere.
- Understanding of the physics of the Global Electric Circuit.
- Understanding the magnetosphere and the ionosphere.
- NOx generation studies.
- Studies of whistler and other wave propagation phenomena.
- Magnetospheric-ionospheric research.
- Solar-tropospheric studies.

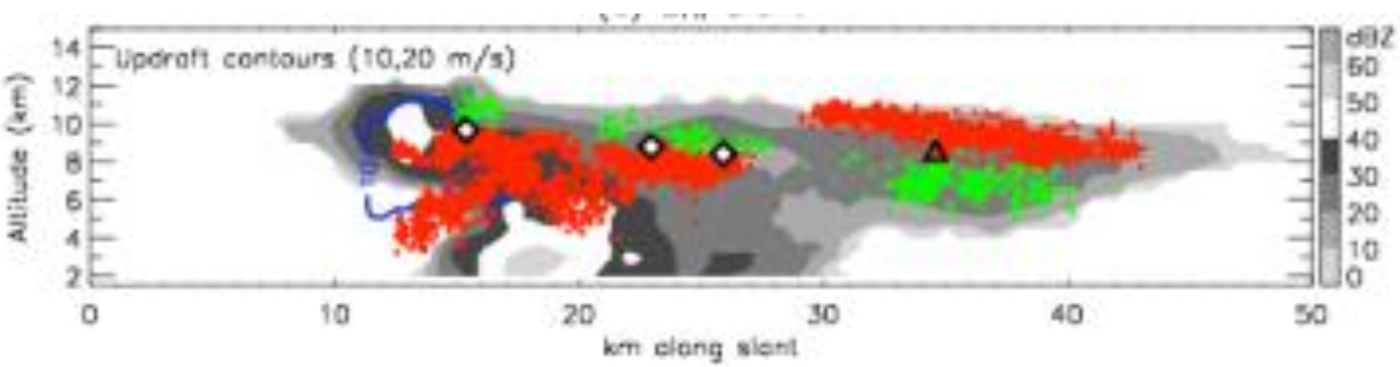
TGE in Yerevan 12 April, 2011 at 800 m asl: on-line data from all ~ 200 channels of the ASEC monitors is available from http://adei.crd.yerphi.am/adei/





Sarah A. Tessendorf, Kyle C. Wiens, and Steven A. Rutledge Radar and lightning observations of the 3 June 2000 electrically inverted storm from STEPS

Until recently, hypotheses offered to explain positive CG-dominated storms and positive CG lightning in general (e.g., the tilted dipole or inverted dipole outlined in detail in Williams 2001) do not discuss the role of a lower negative charge layer below the lowest positive charge region. The charge structure typically associated with negative CG-producing storms is often referred to as a 'normal' tripole, consisting of a main midlevel negative charge region below an upper-level positive charge layer, with a small lower positive charge layer situated below the3 negative region (Simpson and Scrase 1937, Krehbiel 1986, Williams 1989, Stolzenburg et al. 1998). Several studies (e.g., Jacobson and Krider 1976, Williams et al. 1989) suggest that, in these normal tripole storms, the lower positive charge region is required to produce negative CG lightning. The model simulations of storm electrification by Mansell et al. (2002, 2005) also suggest that lower negative charge regions may be necessary for positive CG flashes, consistent with the observations of Wiens et al. (2005). Hence, lower negative charge may play a role in the production of positive CG flashes similar to the role played by lower positive charge in the production of negative CG flashes.



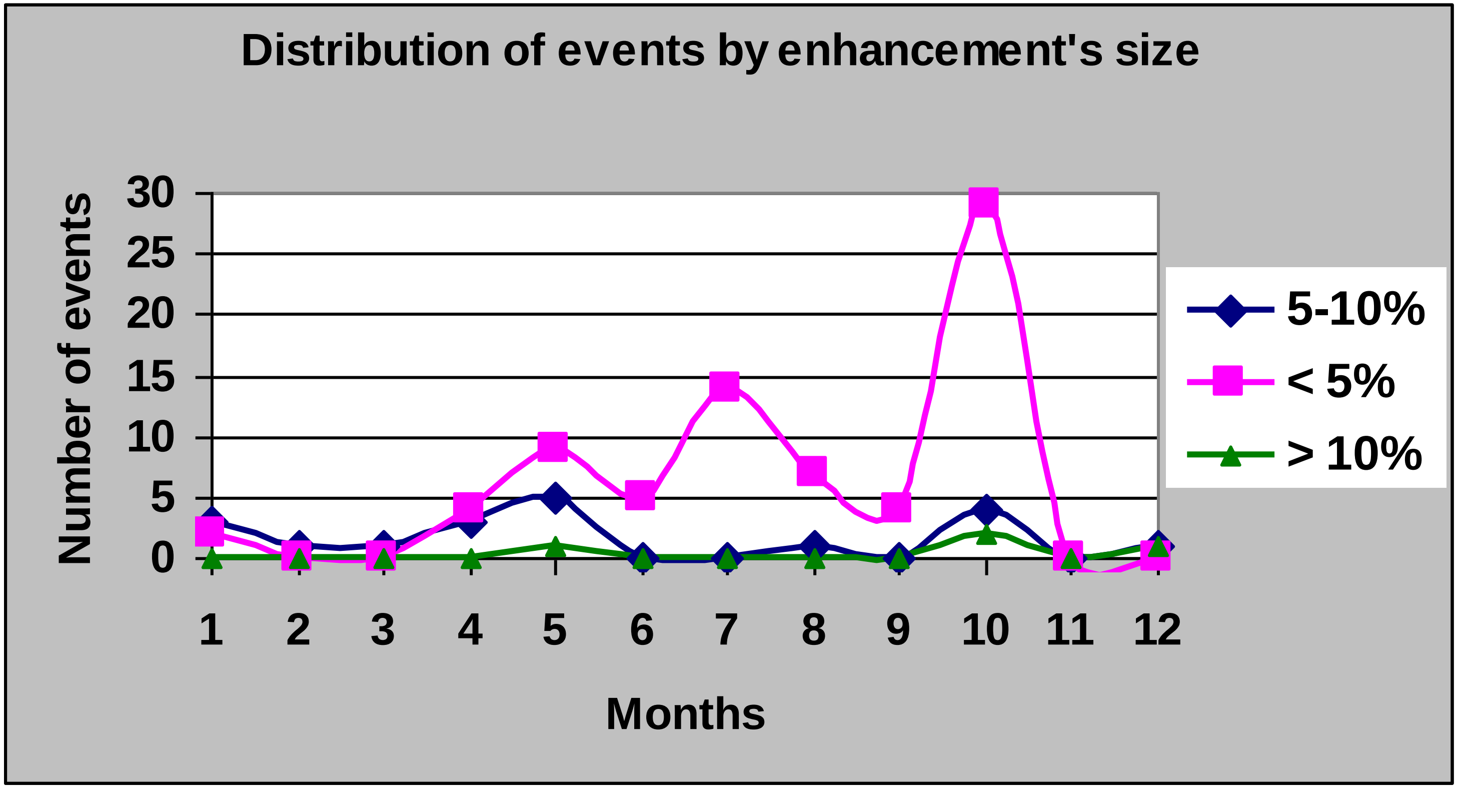
P-layer:

One explanation for lower positive charge is that it results from non-inductive collisions between graupel and ice below the charge reversal level, such that the graupel attains positive charge at the warmer temperatures and falls to the lowest part of the cloud, while the negatively charged ice is carried higher and into the main negative region (Williams 1989, Stolzenburg et al. 1998c).
Though most studies show that non-inductive processes are primarily responsible for this tripole charge structure, it has also been suggested that inductive charging processes do play a secondary role in thunderstorm charging and could contribute to the lower positive charge layer, and that screening layer processes create additional charge layers along the cloud edge (Ziegler et al. 1991, Brooks and Saunders 1994, Stolzenburg et al. 1998c, Mansell et al. 2005).

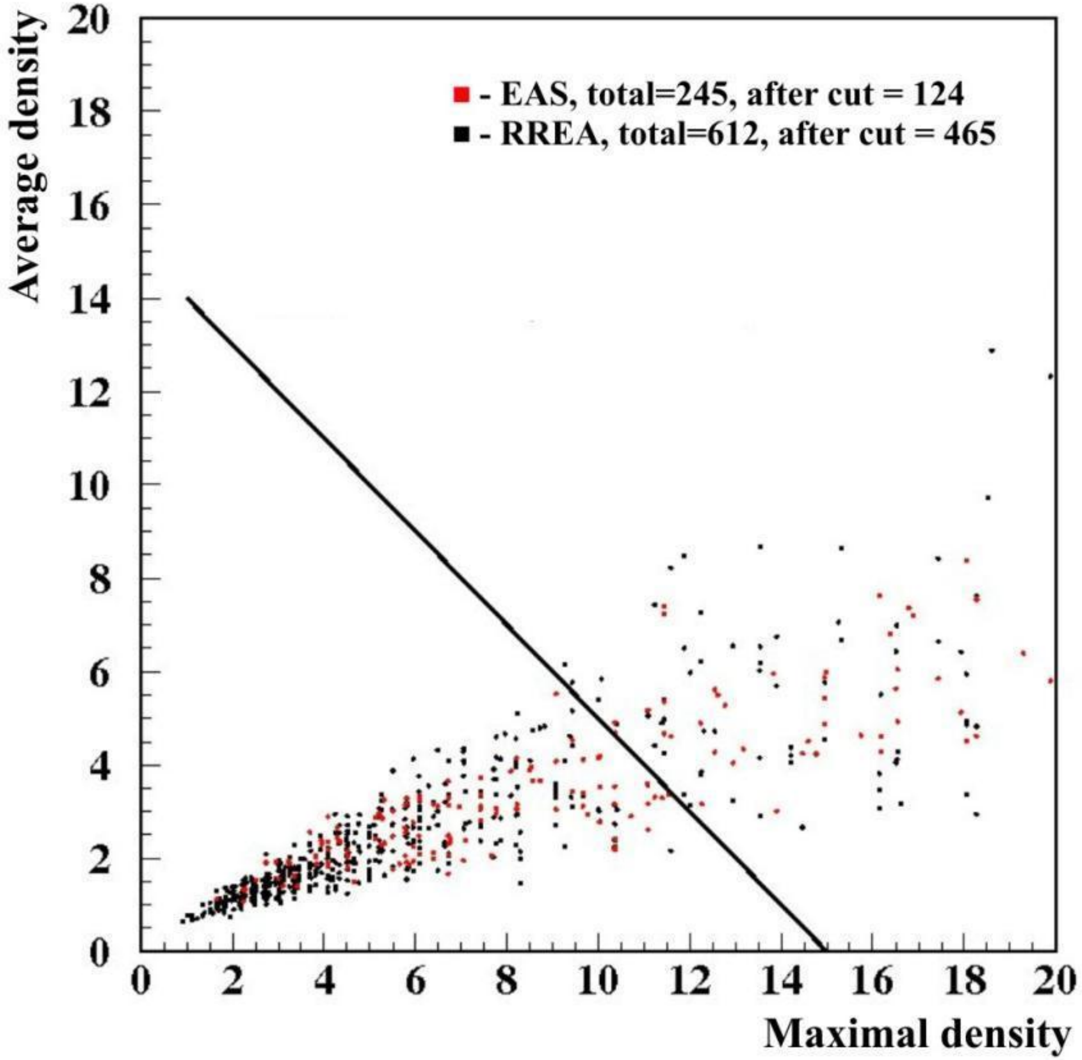
This hypothesis suggests that the presence of the lower positive charge locally enhances the electric field below the main negative charge region, and thus provides a bias for the negative charge transfer to go to ground, whereas it is less energetically favorable to transfer negative charge to ground otherwise (Williams et al. 1989). The behavior of modeled lightning discharges (Williams et al. 1985, Solomon and Baker 1998, Mansell et al. 2002) also supports this idea.

With the advent of cloud-to-ground lightning detection networks, mobile electric field balloon facilities, and three dimensional lightning mapping systems, more information on lightning properties of thunderstorms has been collected, occasionally within supercell storms.

Aragats TGE of 2010

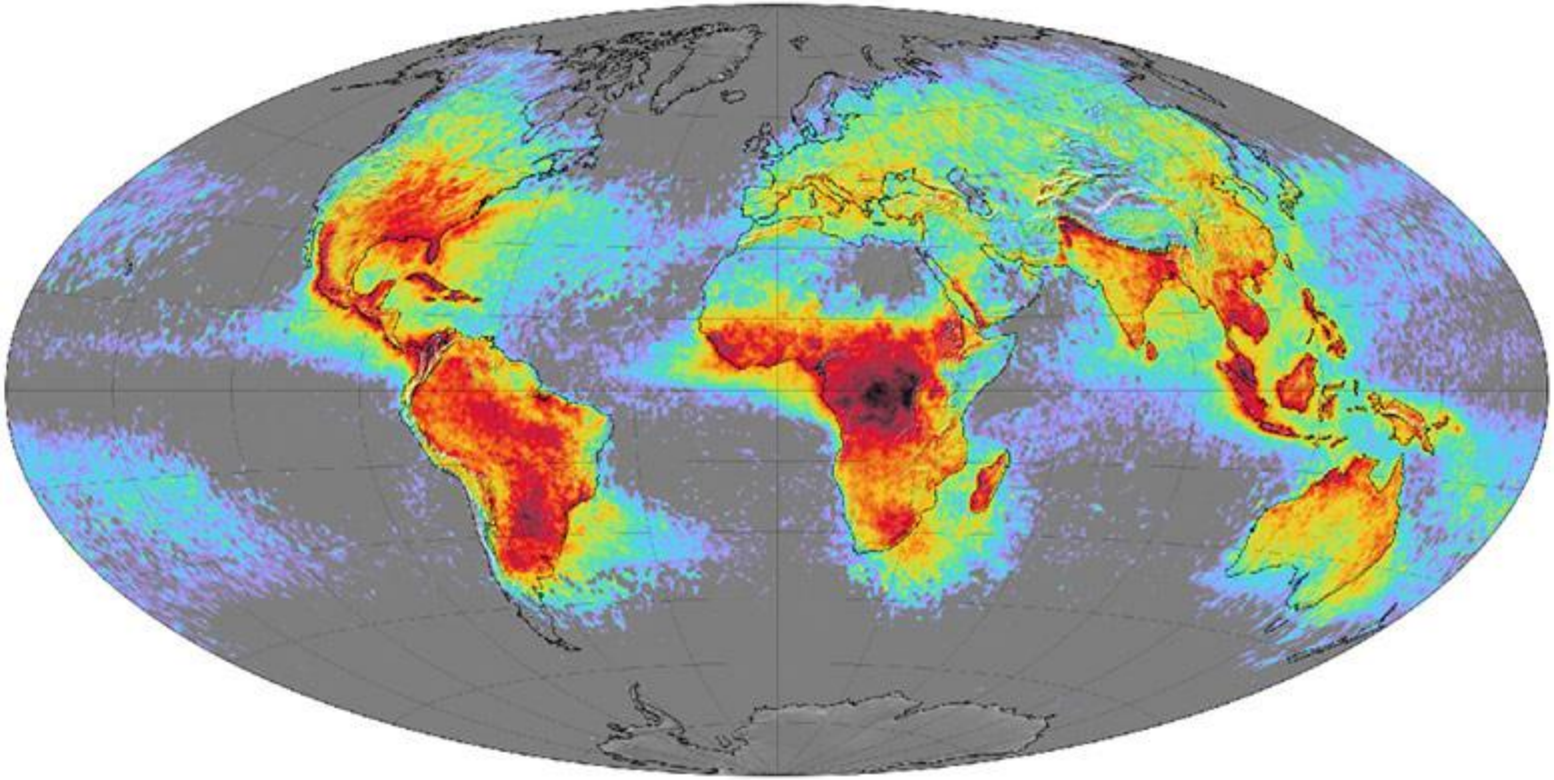


2-way classification of the MAKET triggers – discovery of the short TGE events (particle bursts of duration less than 50 μsec)



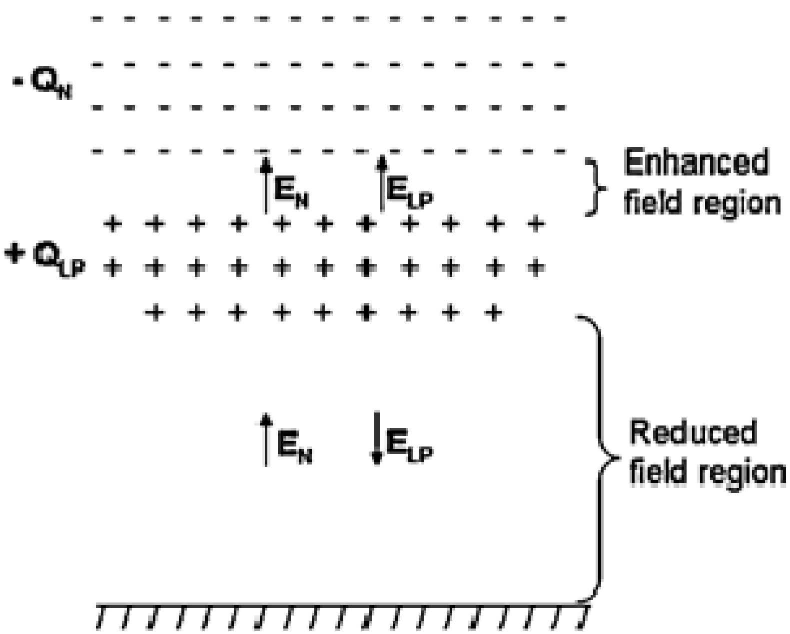
A.Chilingarian, et.al., Particle bursts from thunderclouds: Natural particle accelerators above our heads, Physical review D 83, 062001 (2011)

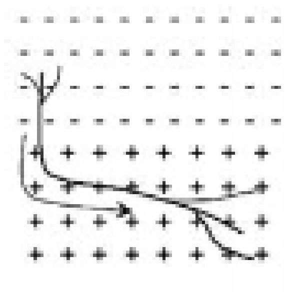
Much more lightning occurs over land than ocean because daily sunshine heats up the land surface faster than the ocean.

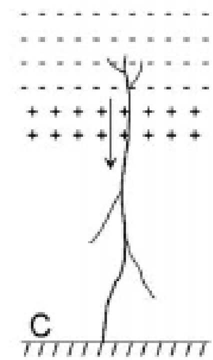


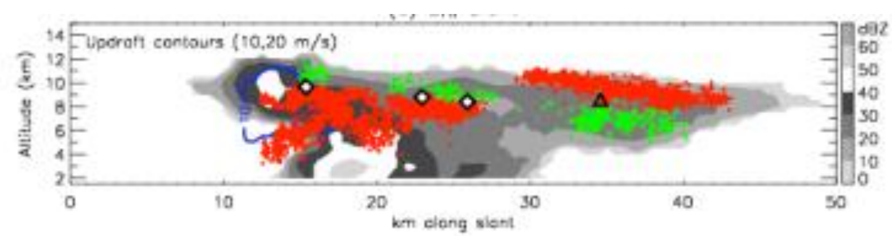
The area on earth with the highest lightning activity is located over the Democratic Republic of the Congo in Central Africa. This area has thunderstorms all year round as a result of moisture-laden air masses from the Atlantic Ocean encountering mountains.

Role of lower positive charge region (LPCR) in facilitating different types of lightning



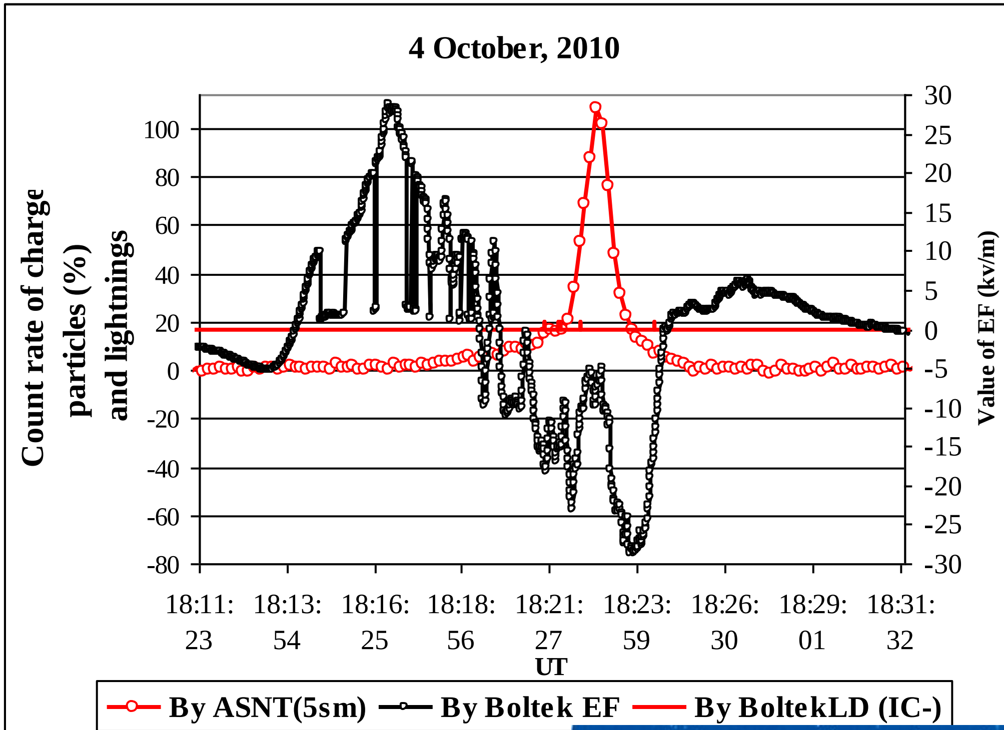


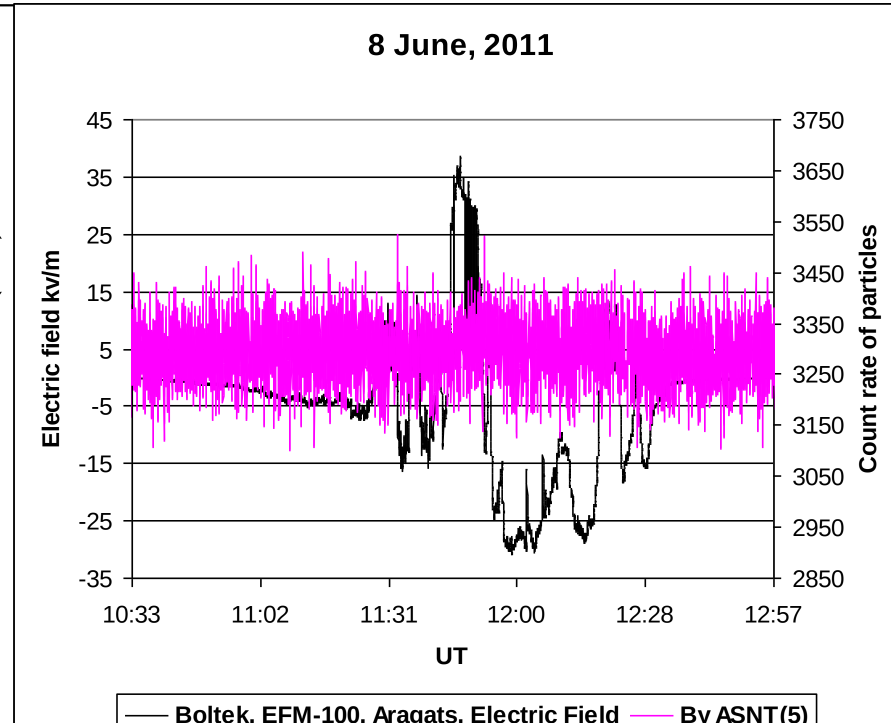


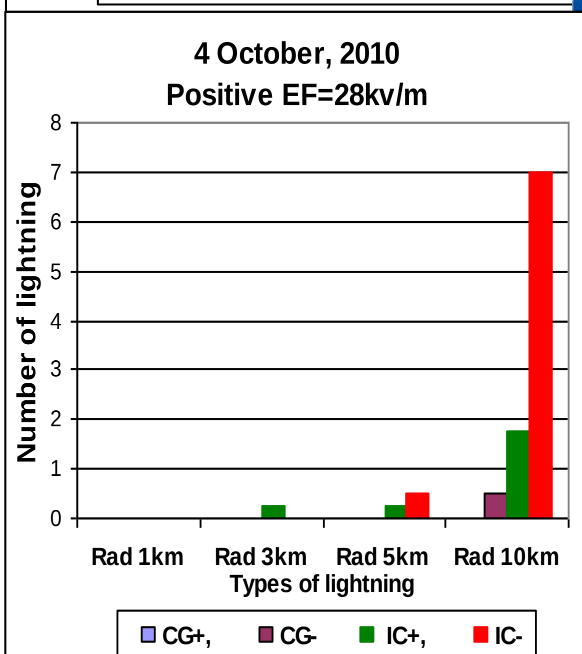


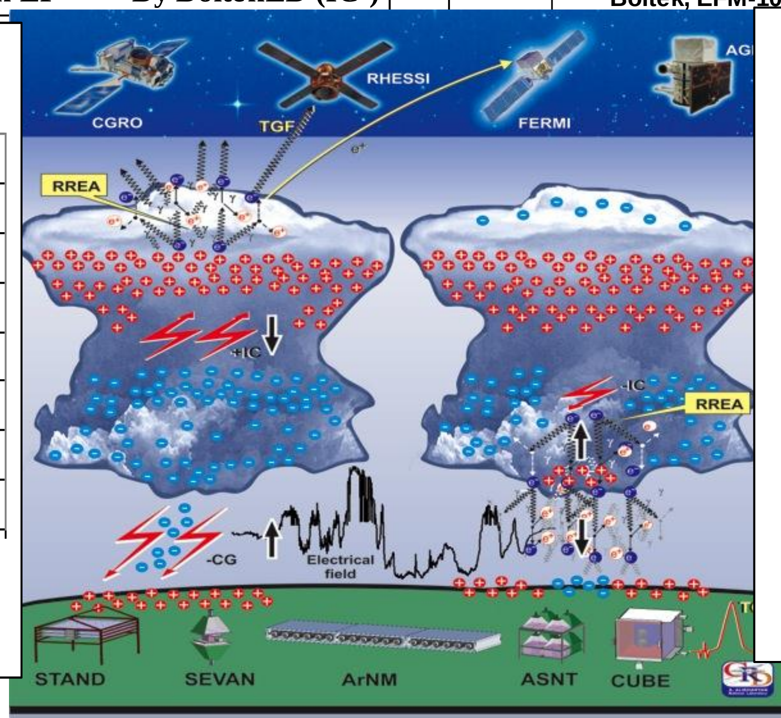
Vertical components of electric field vectors, E_n and E_lp, due to the main negative and lower positive cloud charge regions, respectively. Between the negative and positive charge regions, E_n and E_lp are in the same direction and hence electric field is enhanced due to the presence of the LPCR. On the other hand, in the region below the LPCR E_n and E_lp are in opposite directions and hence the field is reduced. After originating at the lower boundary of main negative charge region the step leader would be initially accelerated and then (after traversing the LPCR) decelerated due to the presence of the LPCR.

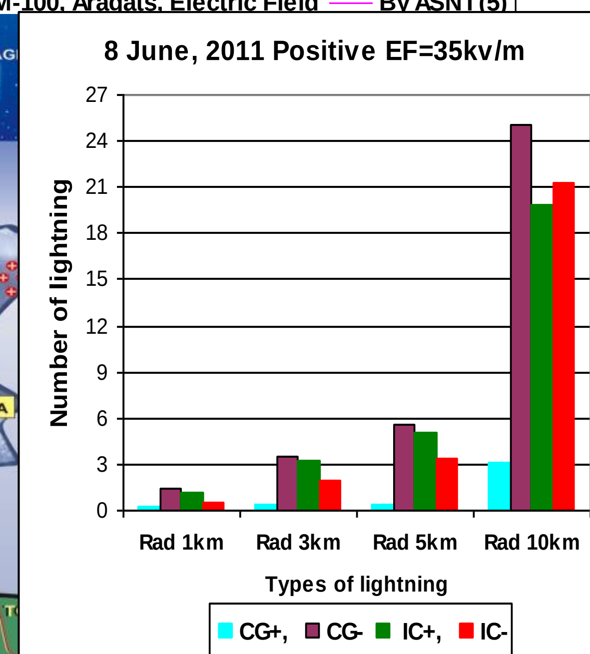
Amitabh Nagand Vladimir A. Rakov ,
GRL, VOL. 36, L05815, doi:10.1029/2008GL036783, 2009







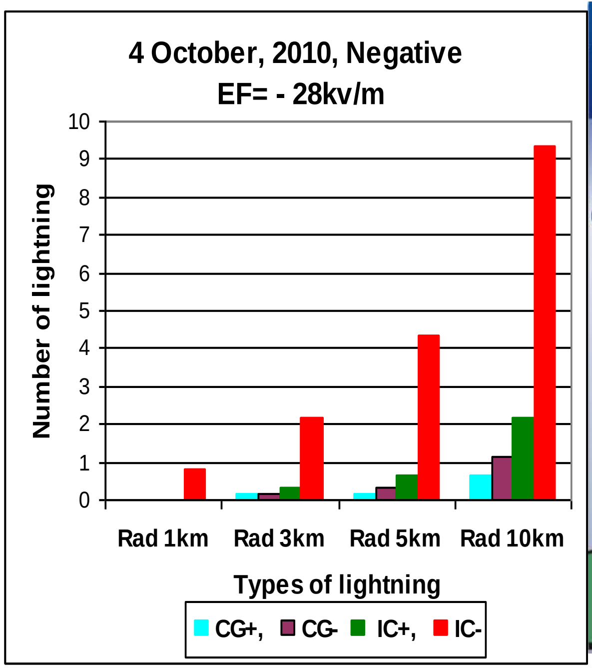


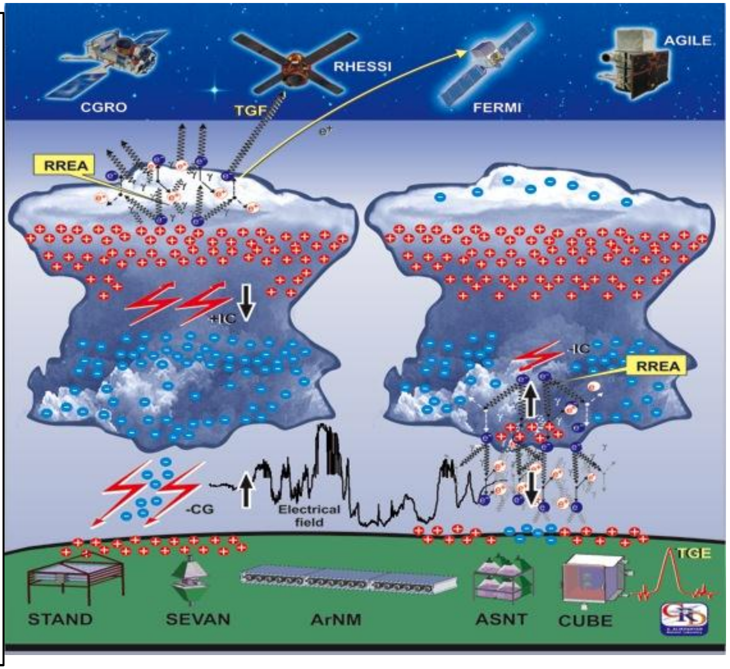


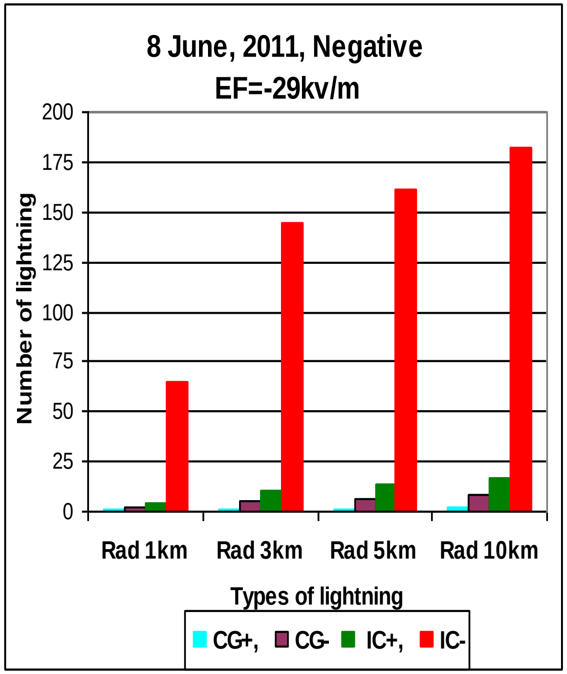
Mean in (18:14 - 18:18)

Mean in (11:44 - 11:53)

Negative Field IC- lightning occurrences; CG- - suppresed



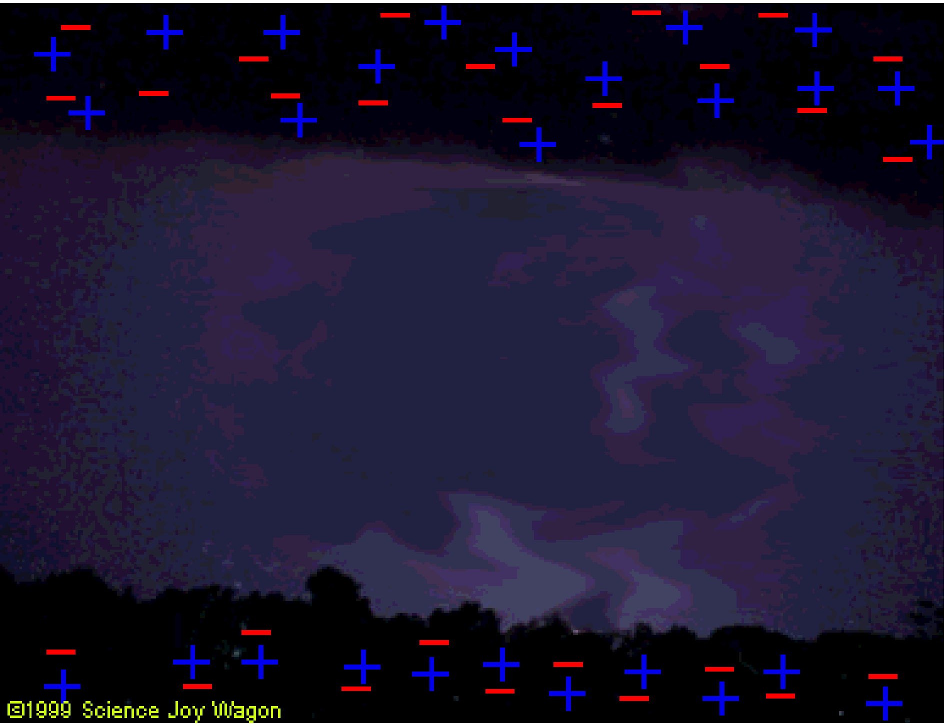


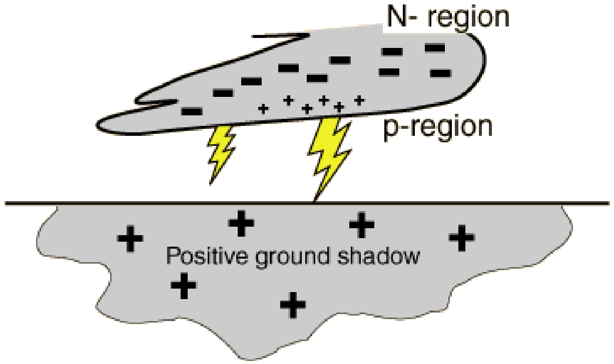


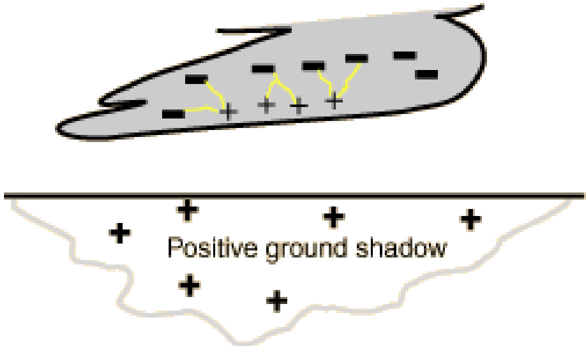
Lightning number: 18:19 - 18:25

Lightning number:11:54 - 12:10

Charge layered structure

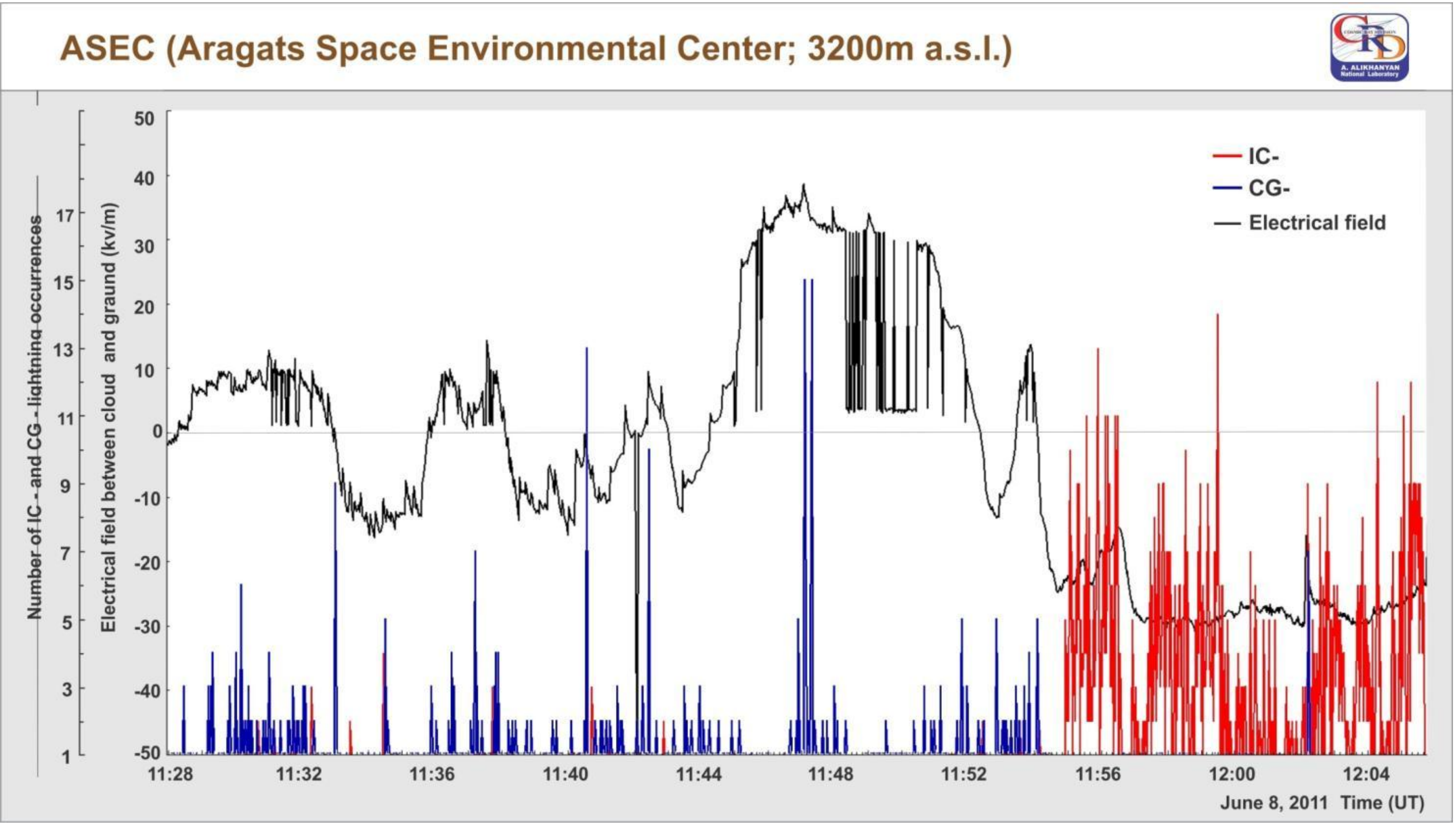




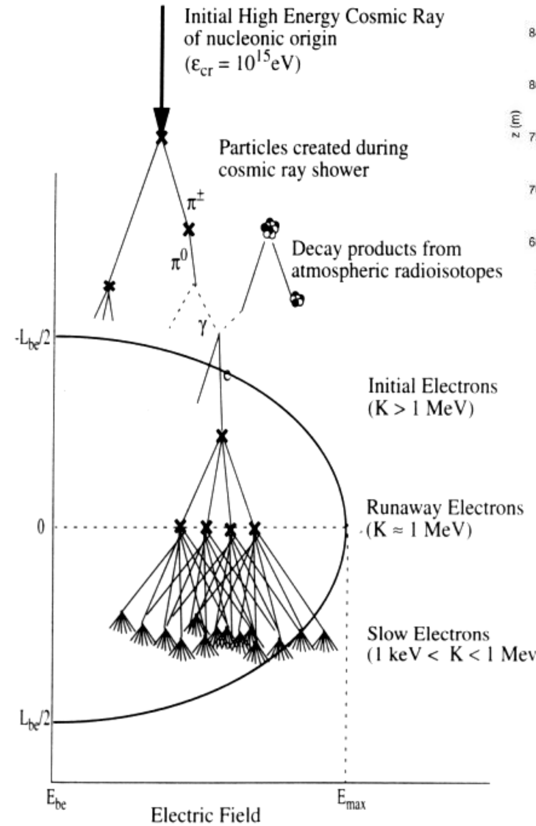


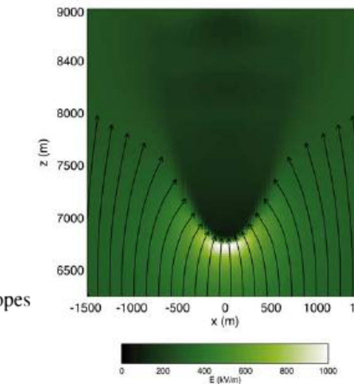
In addition to the positive region at the top of a thundercloud and the main negative N-region near the bottom, a smaller positive region called the p-region has been observed at the bottom of the cloud. This positive region is thought to be important in the triggering of the most common cloud-to-ground discharges. Uman :"The usual cloud-to- ground discharge probably begins as a local discharge between the small pocket of positive charge at the base of the cloud and the primary region of negative charge (the N region) above it. This local discharge frees electrons in the N-region that previously had been attached to water or ice particles. These electrons overrun the p-region, neutralize its small positive charge, and then continue on their trip to the ground. " This description is based upon the tripolar model of charge buildup.

More lightning occurrence – less particles



Relation of the electron-gamma avalanche and lightning



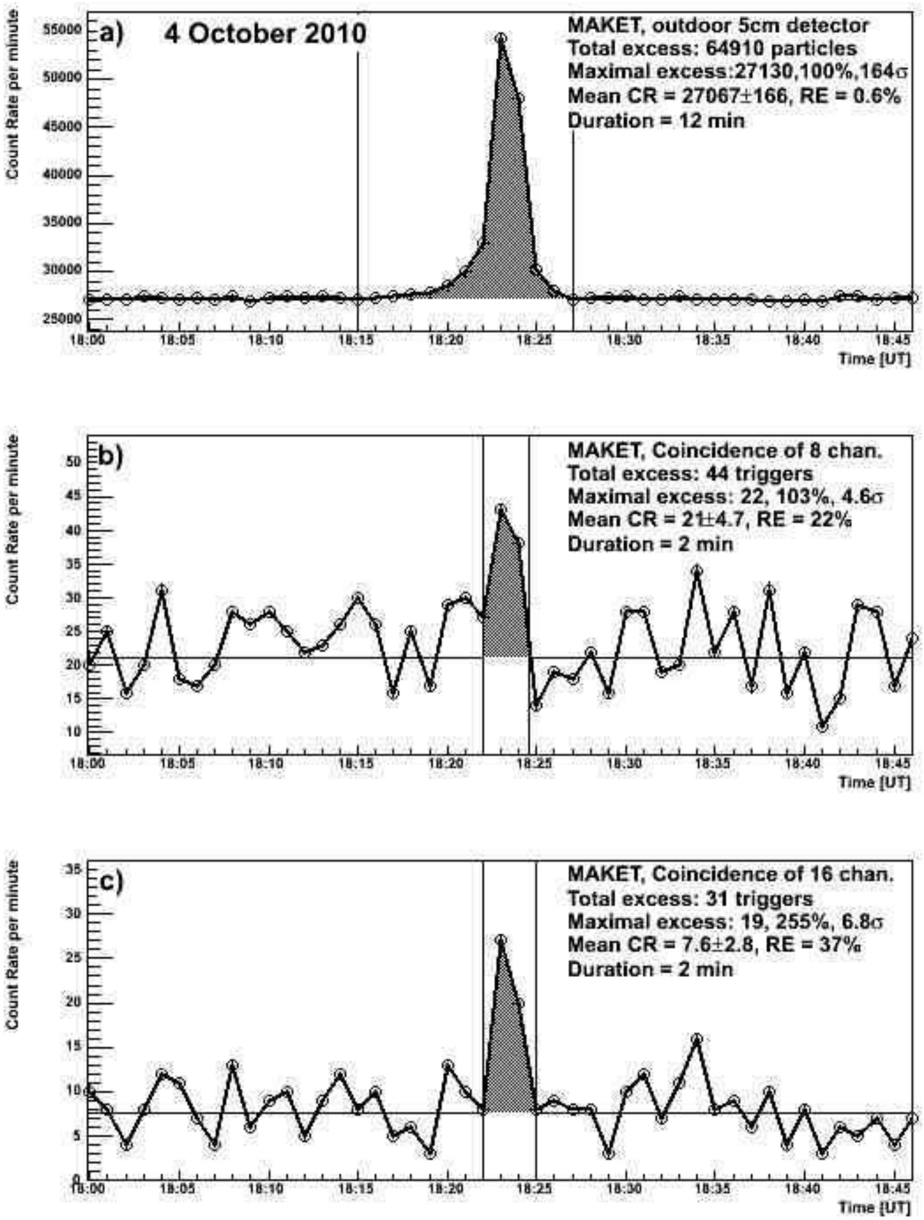


Observation: Maximum observed thundercloud electric fields are 1/10th the dielectric strength of air

Relativistic Runaway Electron avalanche (RREA) generate numerous low energy electrons and gamma rays (conductive channel) followed by positive streamer systems; This provide the required field intensification allowing positive streamer system start step leader process.

Particles, fields and strokes are interconnected!

Short TGE, evidence for the step leader seeds



Short TGEs occur during large negative electrical field accompanied by negative intracloud lightning (IC-). The generation mechanisms of the TGFs and short TGEs are close to each other and symmetric: *RREA using as seeds the electrons from the current pulses along the step leaders (+/- IC) and developing in consequent negative and positive electrical fields.* Short TGEs are very rare events (detected at Aragats about once a year); the MAKET array observes the sky just above the detector (~10^6 m^2).

Fermi and AGILE are observing huge areas reaching ~10^{12} m^2, therefore, the number of detected TGFs is much larger reaching hundreds per year.

TGE develops in rather dense atmosphere; only close location of the thundercloud to ground and rather large elongation of the strong electrical field can provide unique possibilities of detection TGE electrons and gamma rays. The duration of the TGE is more than an order of magnitude shorter than the ones of TGF. Gamma-rays arriving at satellite altitude are covering at least 3 order of magnitude longer path length comparing with TGEs and arrive spread over a pulse of ~500 µs. TGEs come from thunderclouds just above our heads and cover less than 500 m, therefore, they come in pulses with duration less than 50 µs.

Chilingarian, A., G. Hovsepyan and A. Hovhannisyan, Particle bursts from thunderclouds: Natural particle accelerators above our heads Phys. rev. D, 83, 062001, (2011).

100 MeV Electron accelerator in the thundercloud

2011 plans

- **Calibrate energy spectra by 3 independent networks of particle detectors: NaI, outdoor Cube and indoor ASNT;**
- **Measure electron energy spectrum by 3 cm 4 layered STAND up to 30 MeV;**
- **Multivariate inference: analyze electron and gamma ray fluxes simultaneously with lightning occurrence, magnetometer, weather and electrometers data;**
- **Get more information about thundercloud formation at Aragats;**
- **Understand field reversal: small p-layers comes above due to moving cloud or due to CG- lightning?**
- **Start measurements of the PMT height spectra on the µsec scale (150 MHz flash ADCS);**
- **Perform precise lightning mapping with network of Boltec detectors;**