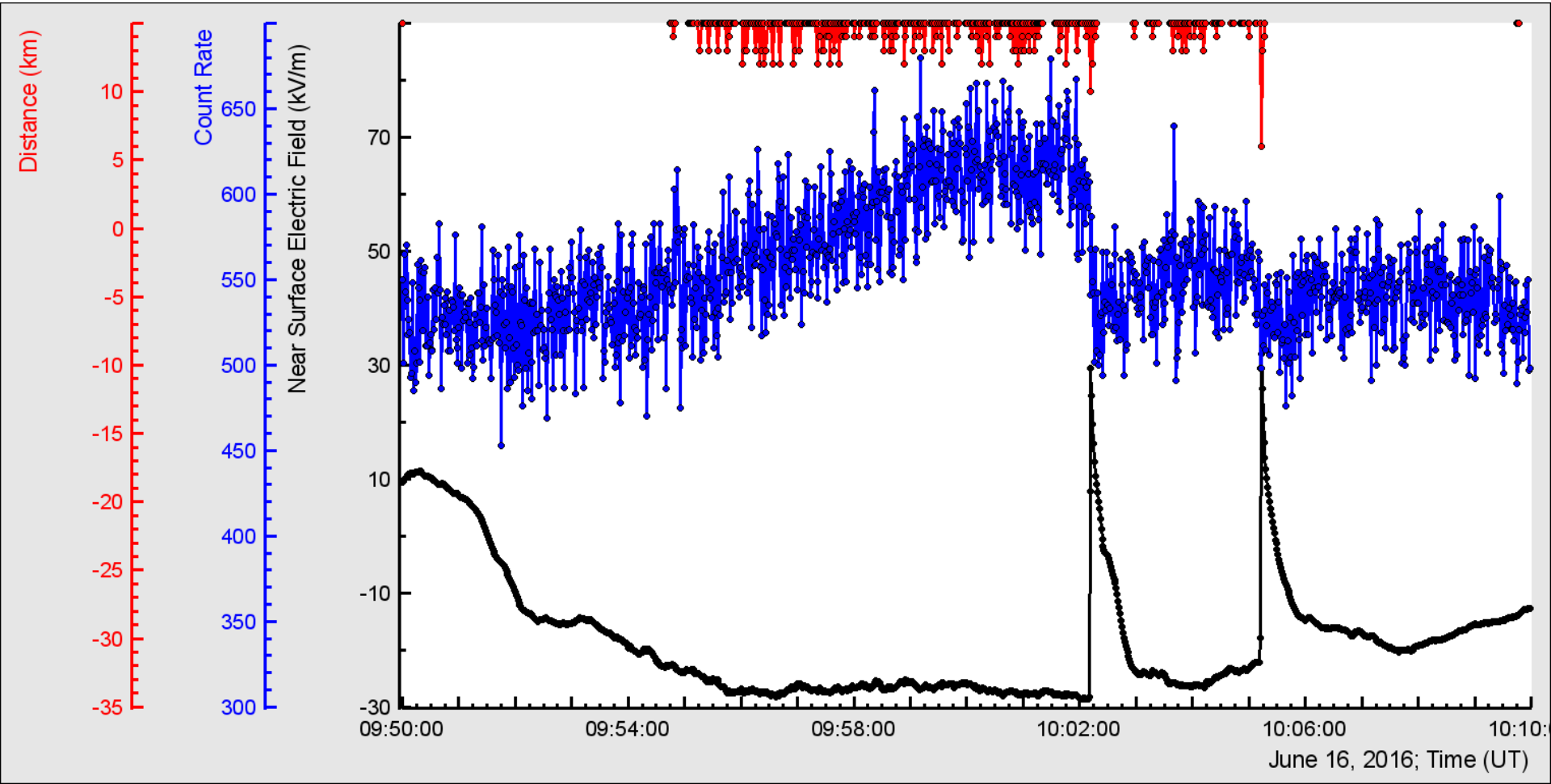
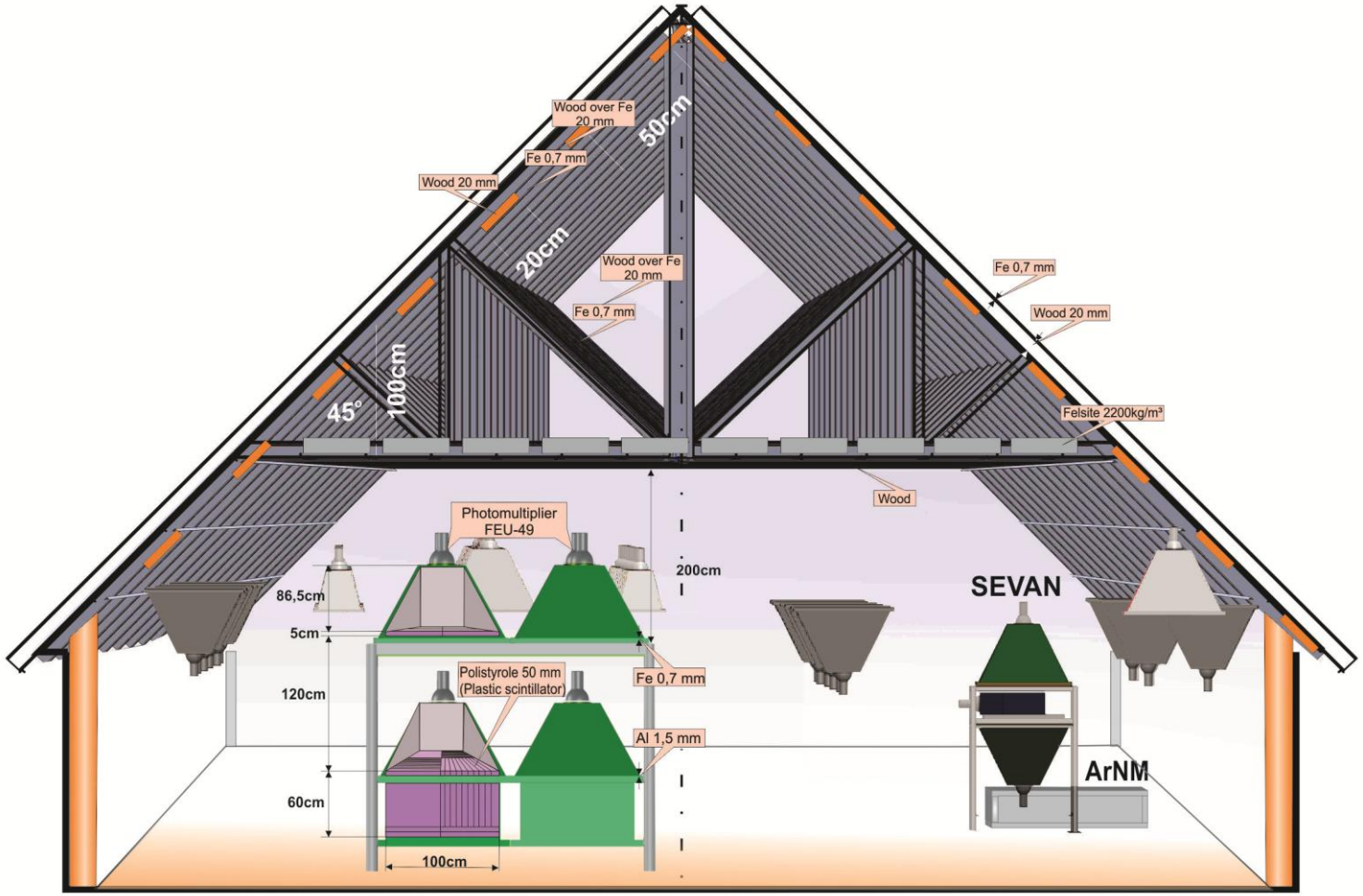
THE RUNAWAY BREAKDOWN (RB) PARTICLES SPECTRA OBTAINED BEFORE AND AFTER THE LIGHTNING STROKE

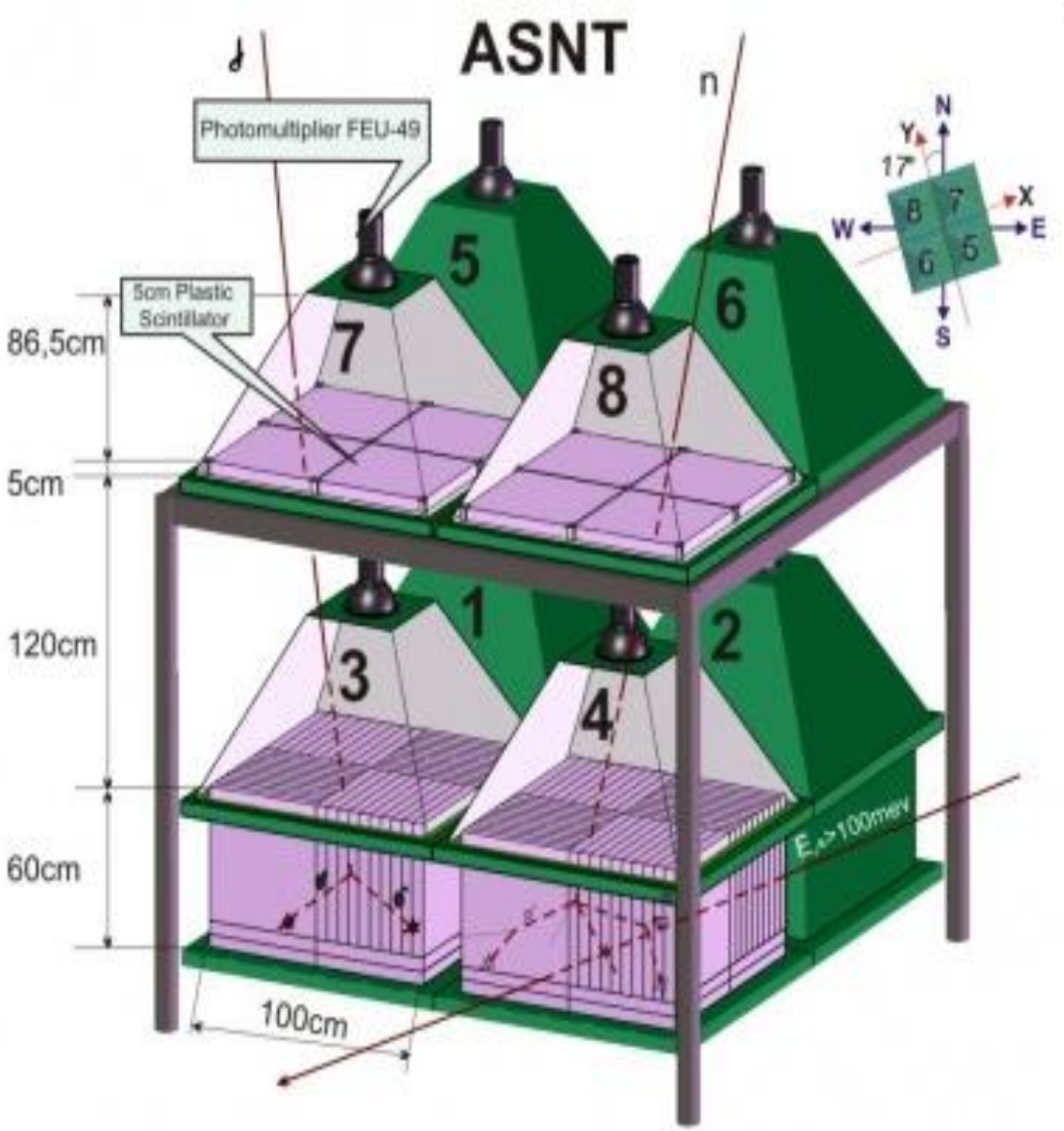
2016 TGEs occurs at prolonged (3-10 min) negative electrostatic field; lightning abruptly terminates TGE; largest TGEs occurred when there is no nearby lightnings.

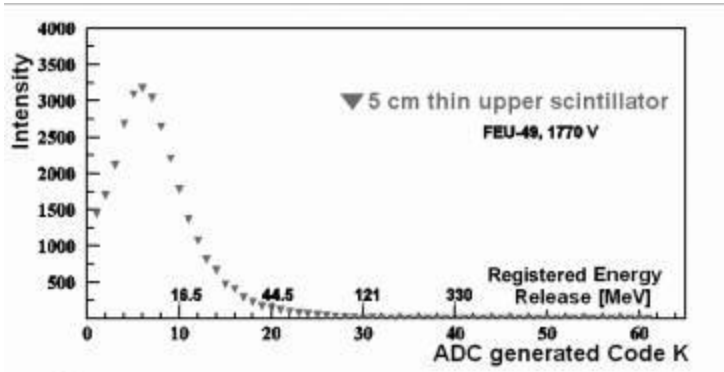


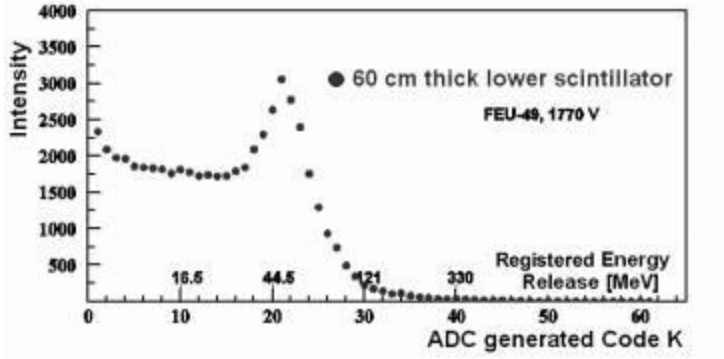
MAKET Experimental hall (electron lost by ionization ~ 20 MeV in the construction matter)



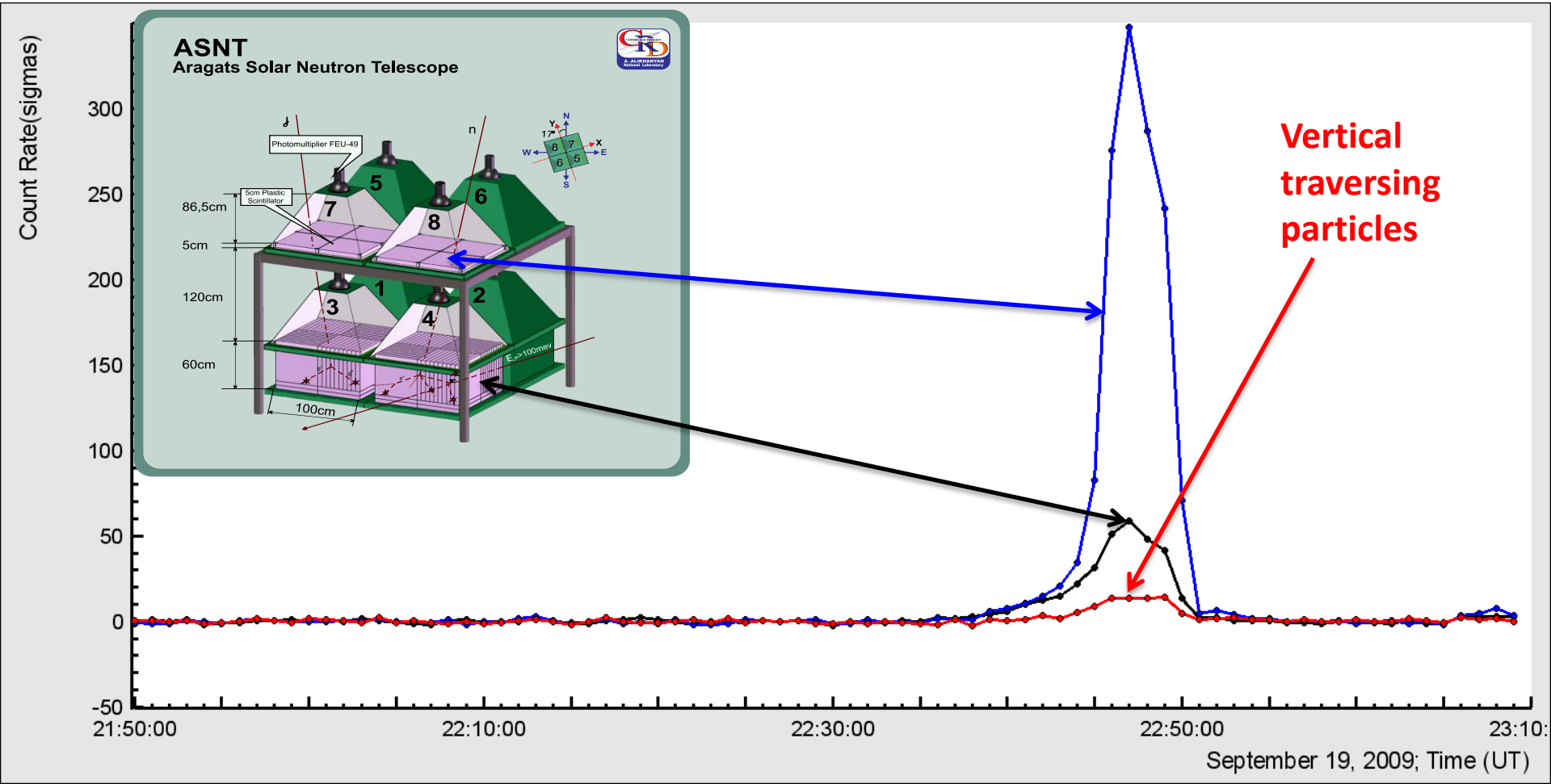
Aragast Solar Neutron Telescope (calorimeter for 10-120 MeV particles)



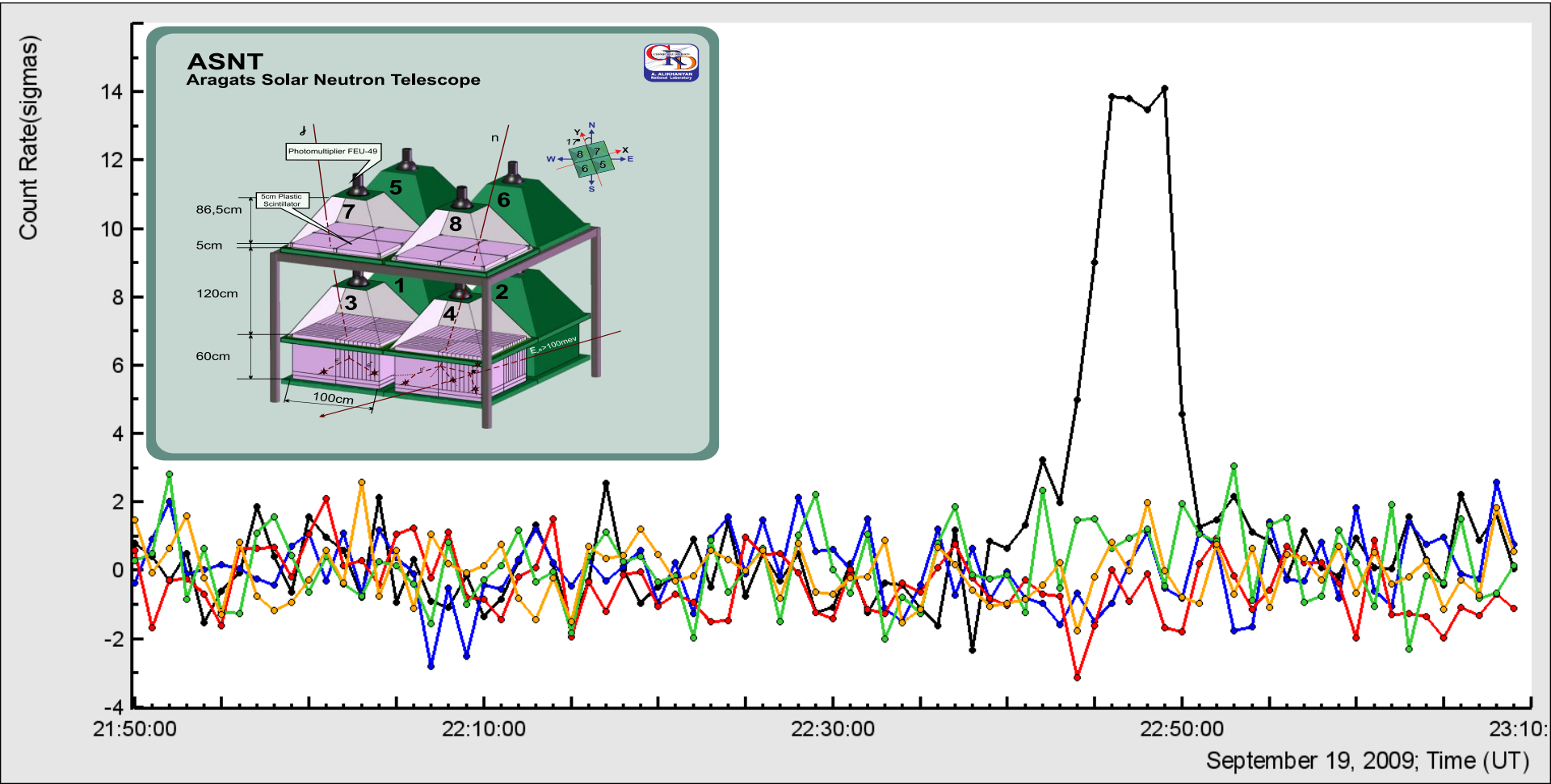




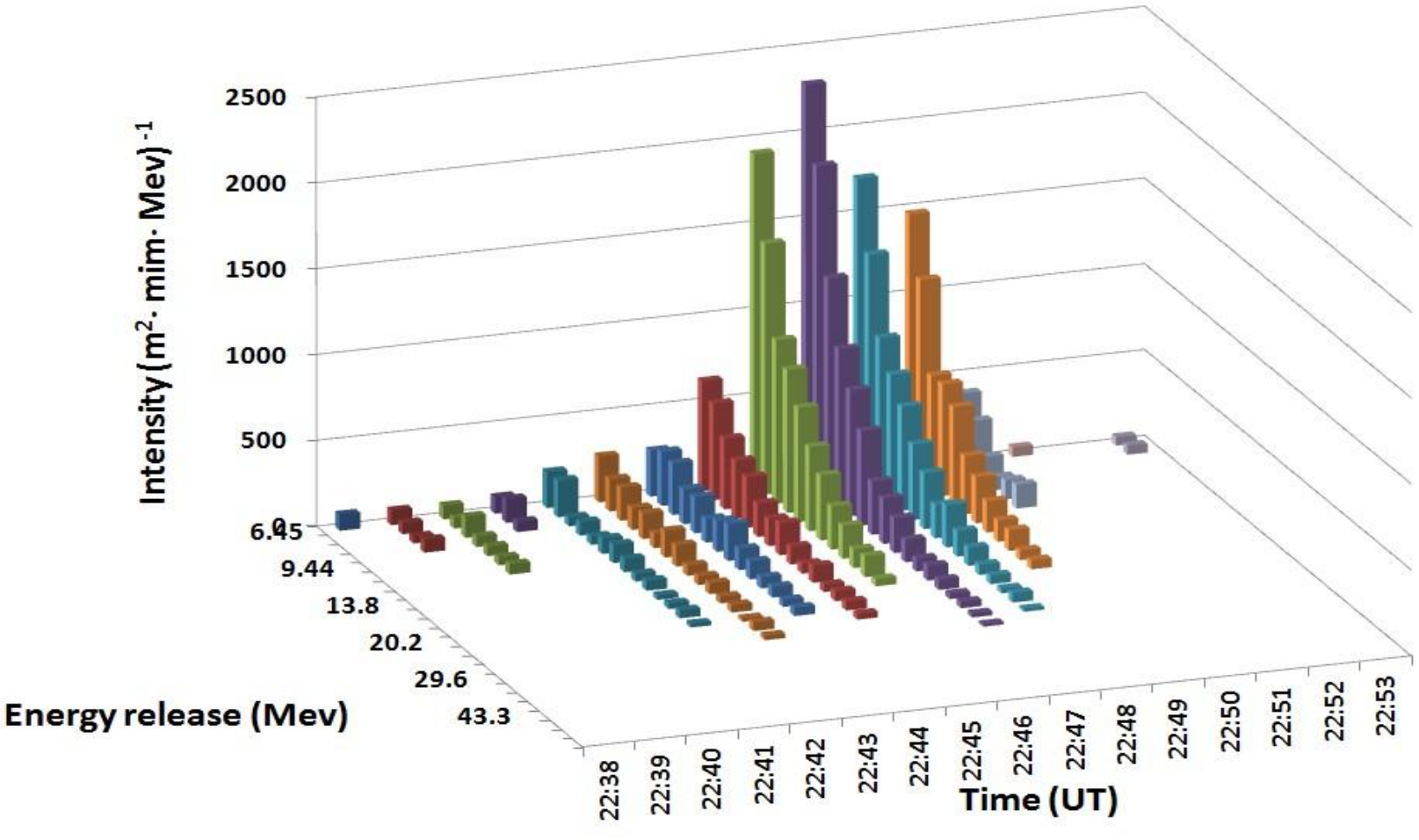
1-minute count rate of 5 cm thick, 60 cm thick scintillators and vertical traversing particles.



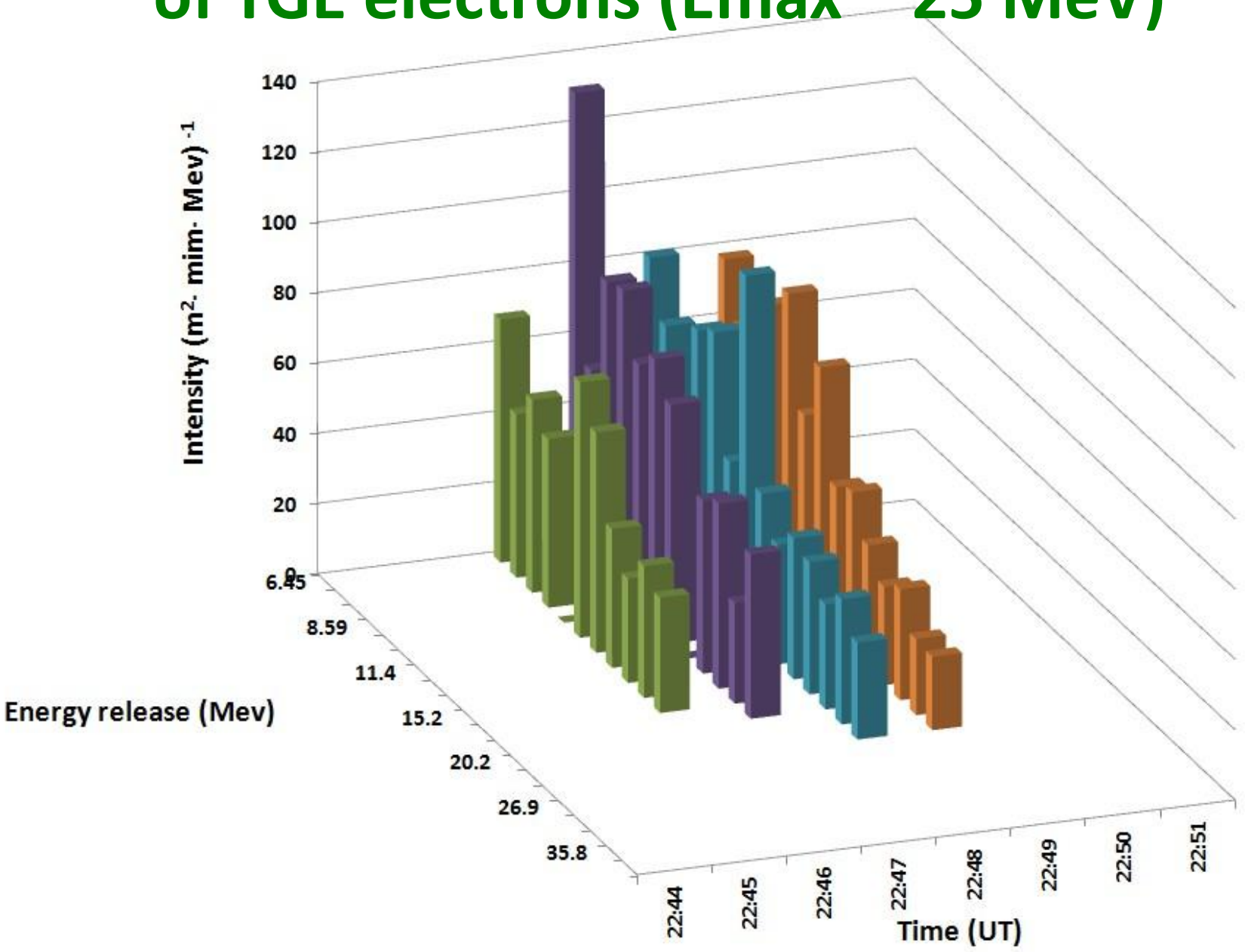
Particle fluxes come from near-vertical direction



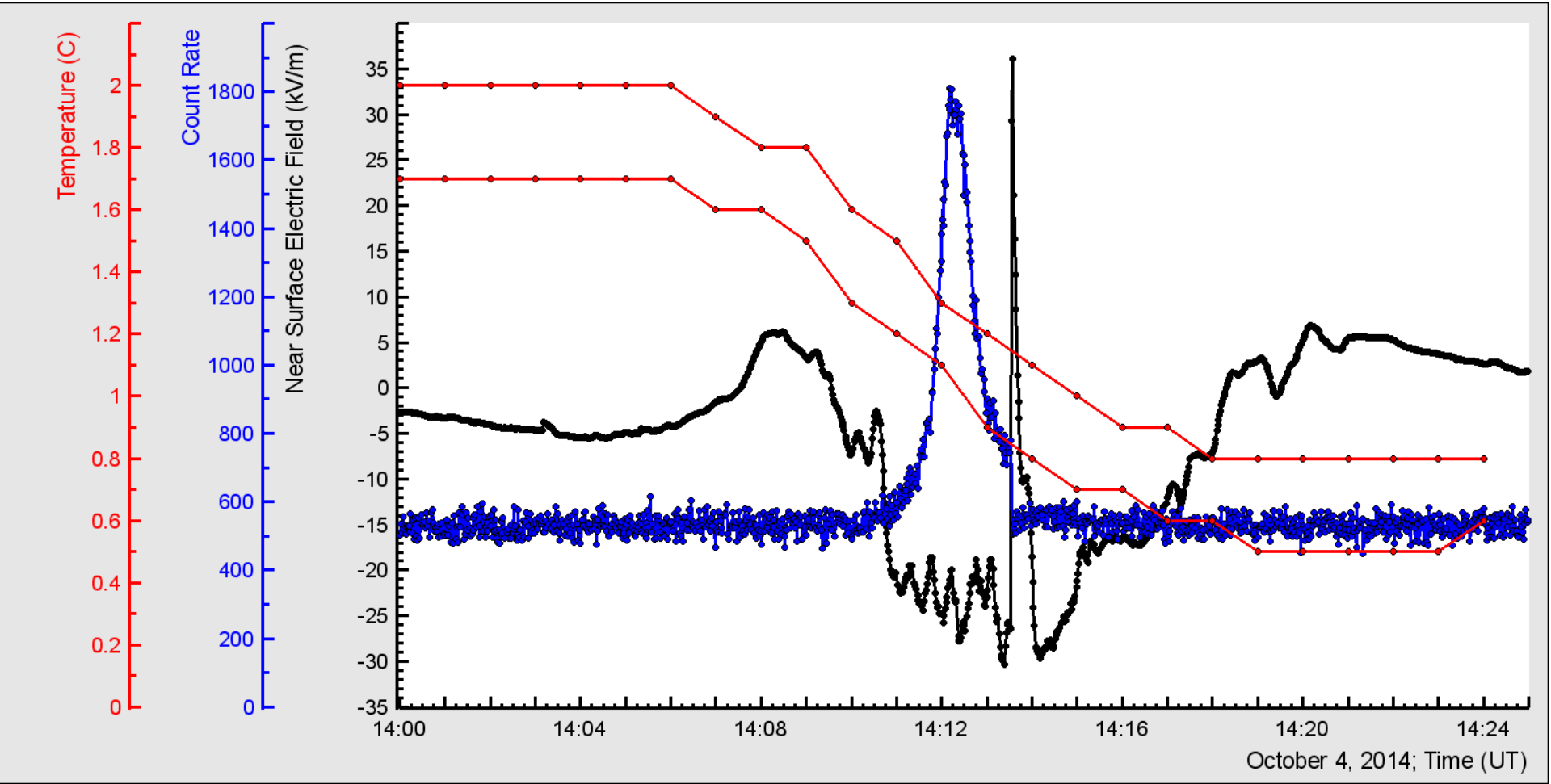
19 September 2009: Energy release spectrum of TGE gamma rays (Emax ~ 30 MeV)



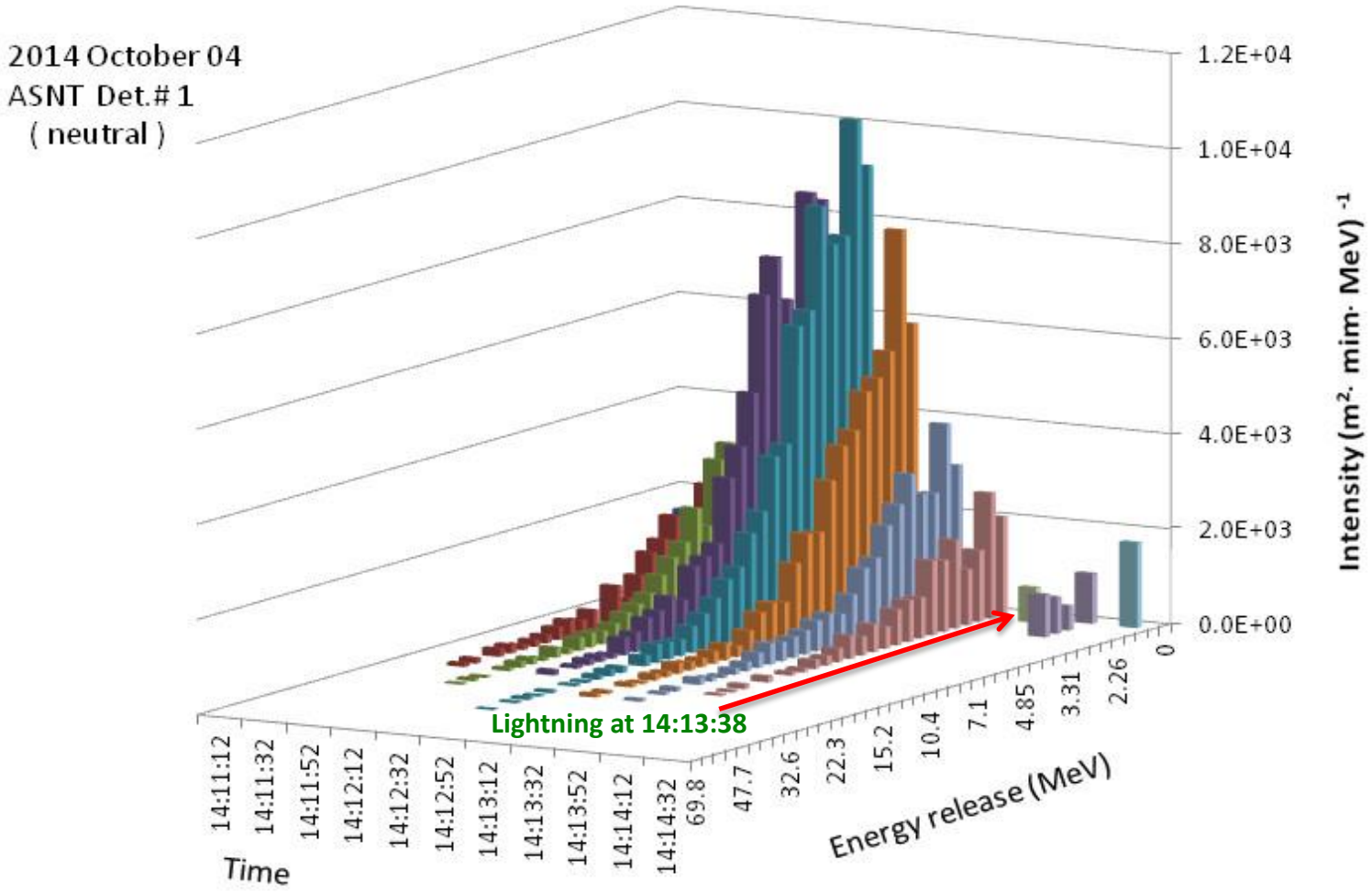
19 September 2009: Energy release spectrum of TGE electrons (Emax ~ 25 MeV)



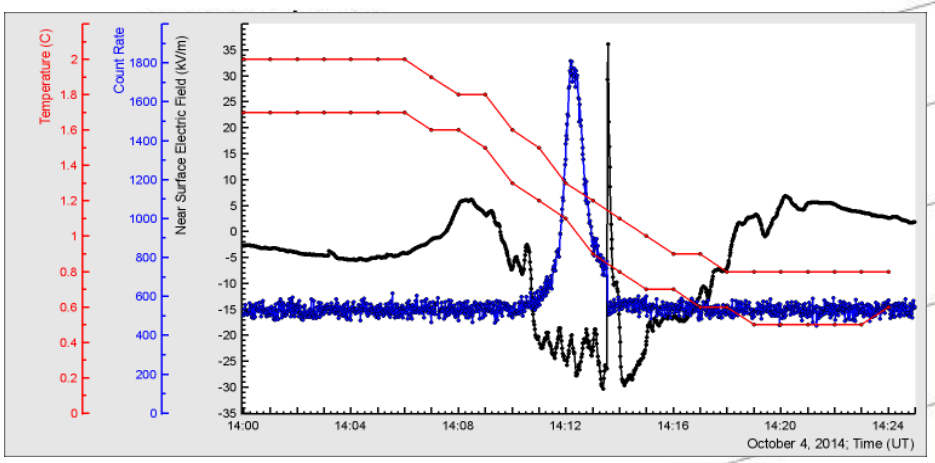
4 October 2014: insert 1-sec time series of count rate of 3 cm thick plastic scintillator (blue), near surface electric field (black) and temperature and dew point used for the spread calculation (red). Spread = 1.3-1.1; Cloud height ~25 m, electron energy losses ~ 5 MeV.



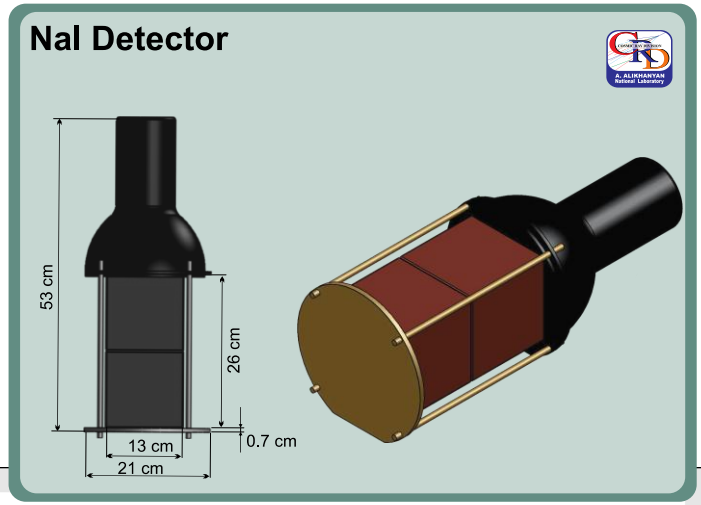
TGE gamma ray diff. energy spectra on 4 October 2014 Maximal gamma ray energy 25 MeV, cloud height ~25 m

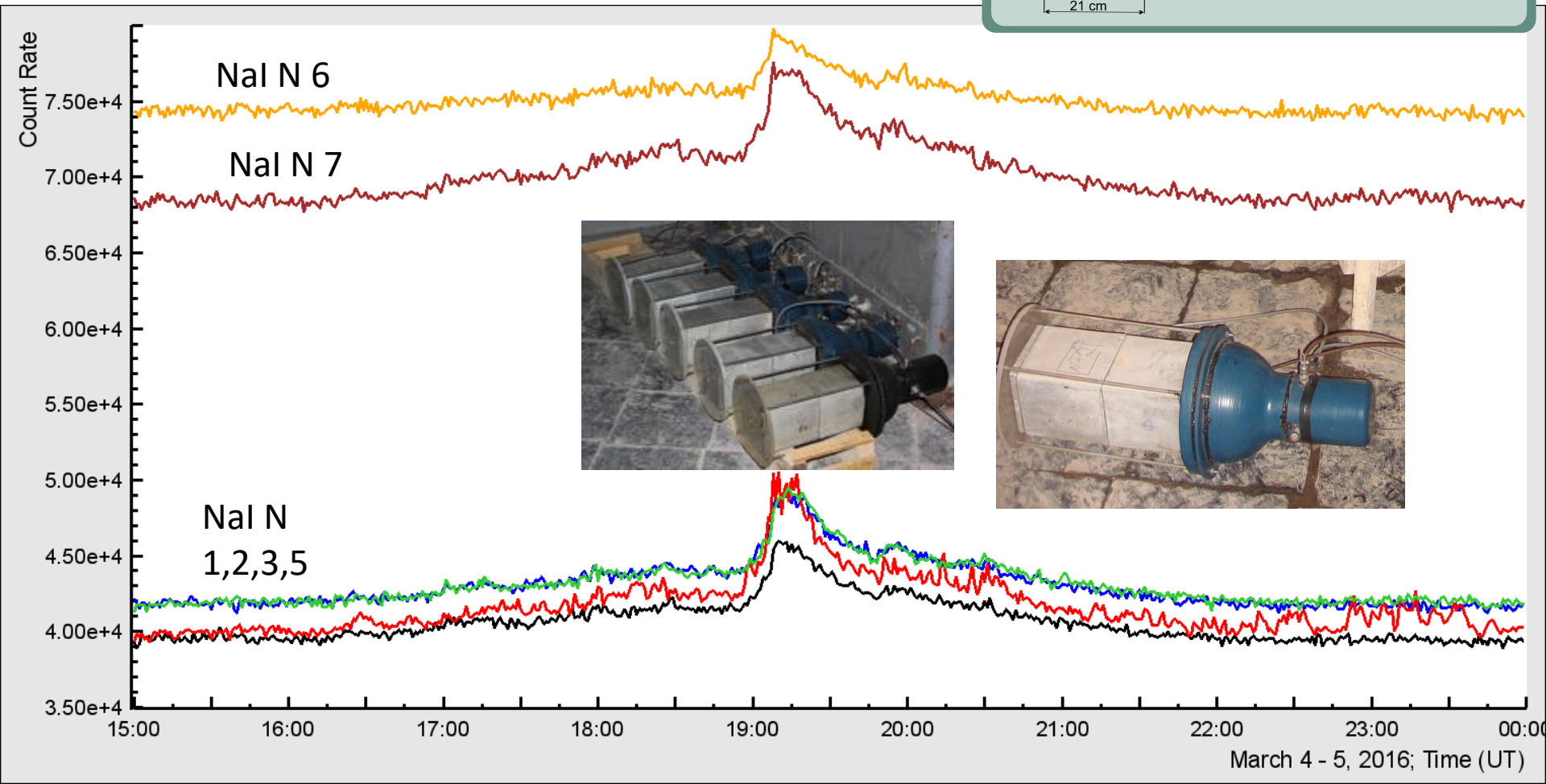


Differential Energy spectra of RB electrons. Emax ~ 20 MeV, declined after lightning; Maximal energy of electrons on the entrance from cloud 20+20+5 = 45MeV

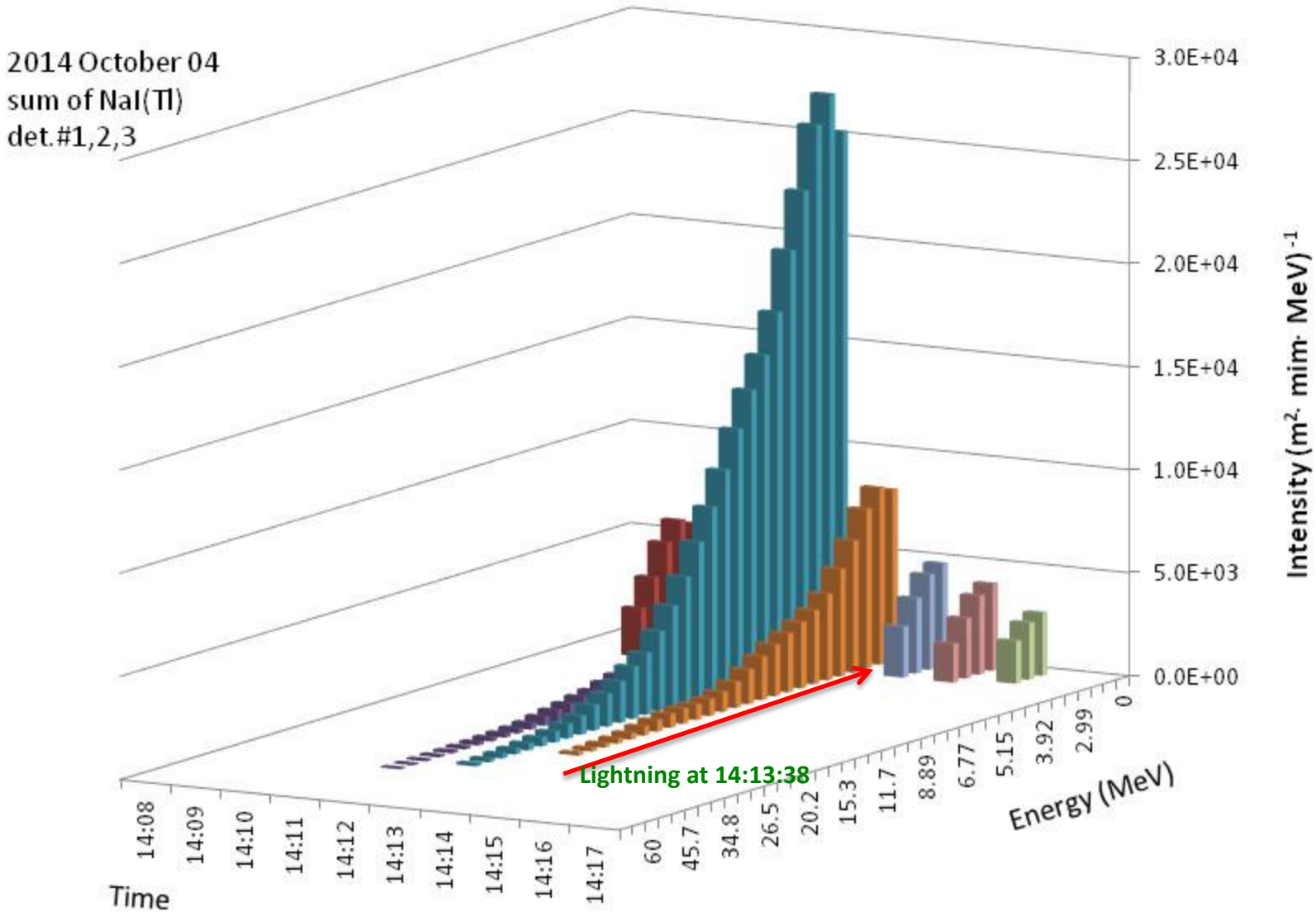


NaI spectrometers network

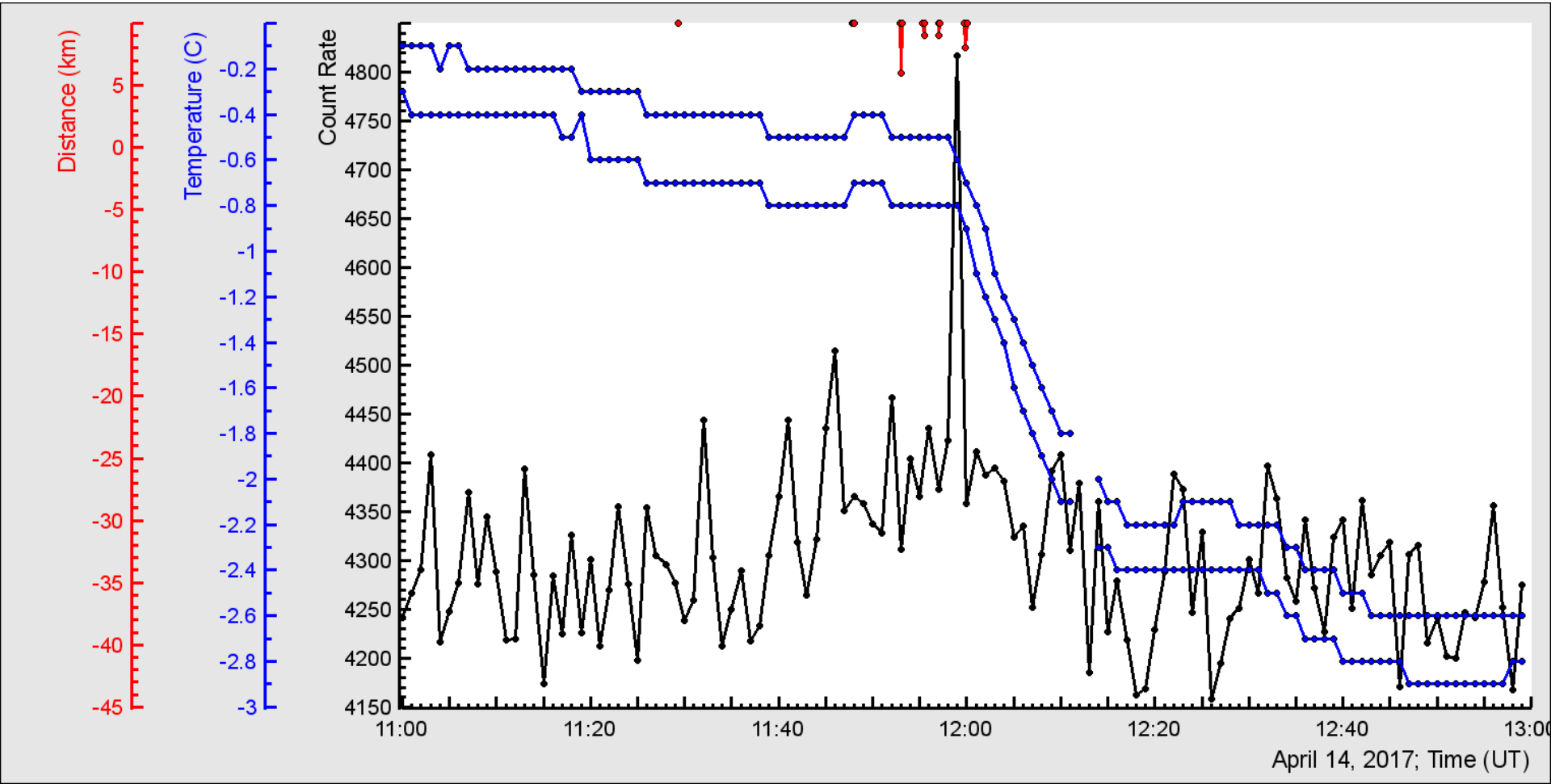




Energy spectra of the TGE particles (gamma rays with small contamination of high-energy electrons) measured with NaI spectrometers



NaI network N 5, energy threshold 3-4 MeV; Spread at particle peak equals -0.6 - (0.8) = 0.2; Cloud base heigth – 122 m * 0.2 ~ 25 m



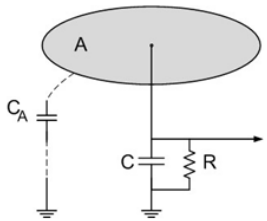
Lightning trigger

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



Flat plate antenna

A B Ext Out

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

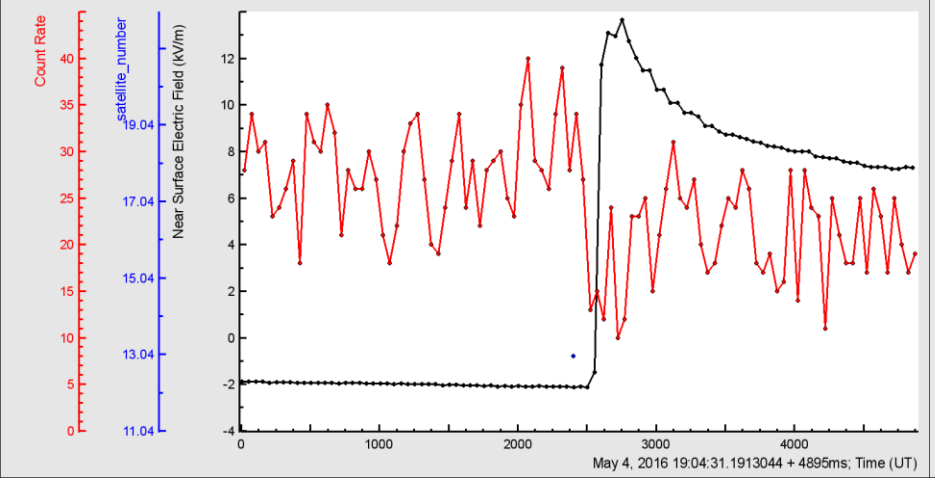
Picoscope 5244B
f_s=25MS/s , 40ns sampling;
1sec record length

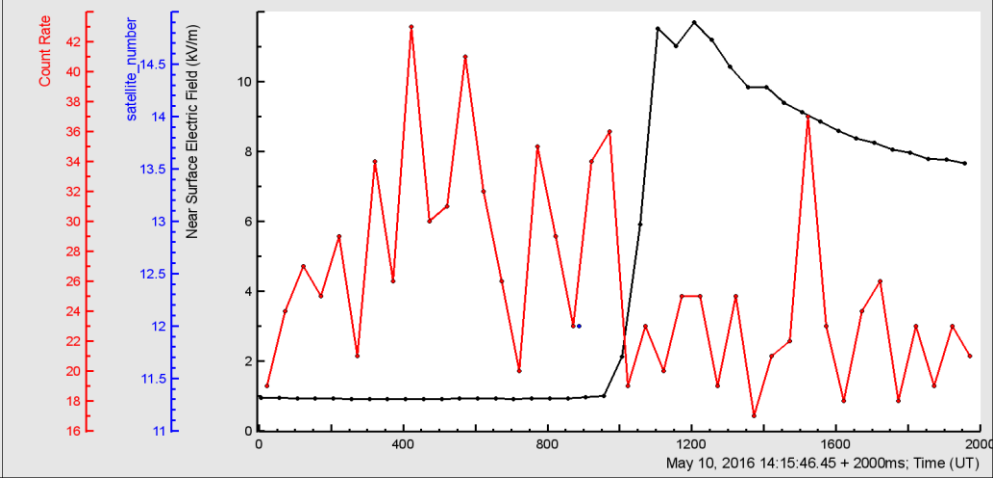
A B Ext

Muon 1 channel ArNM 9 channel

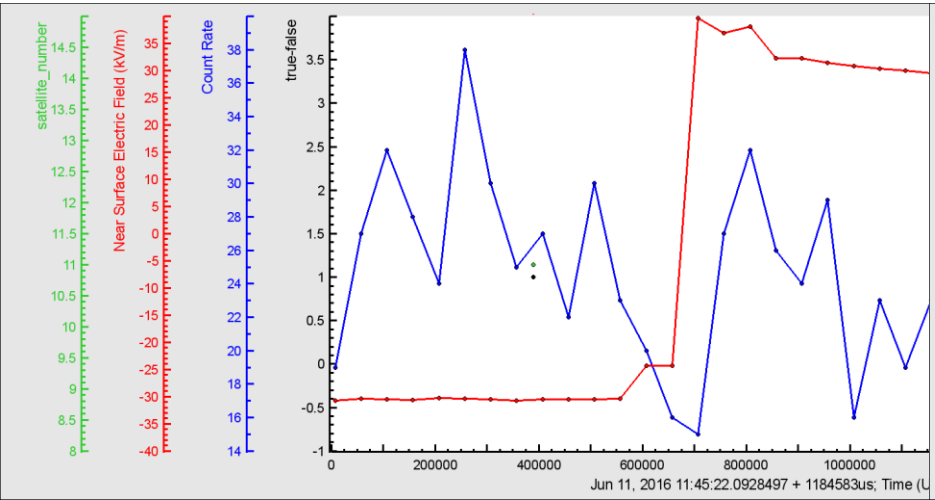
NI-myRIO board
with GPS timing and 7 digital inputs

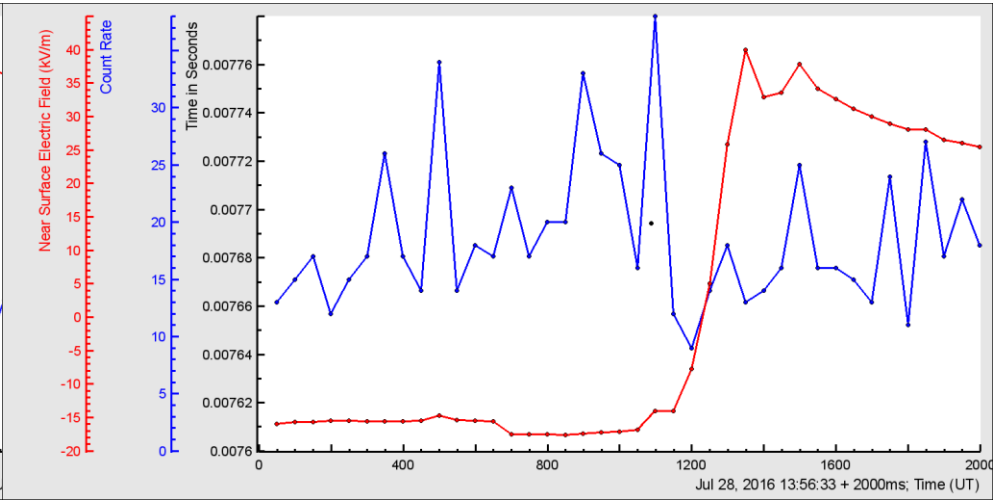
50 ms time series: el. field; particles from 4-channel STAND1 and muon detector; MAKET exp. hall


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

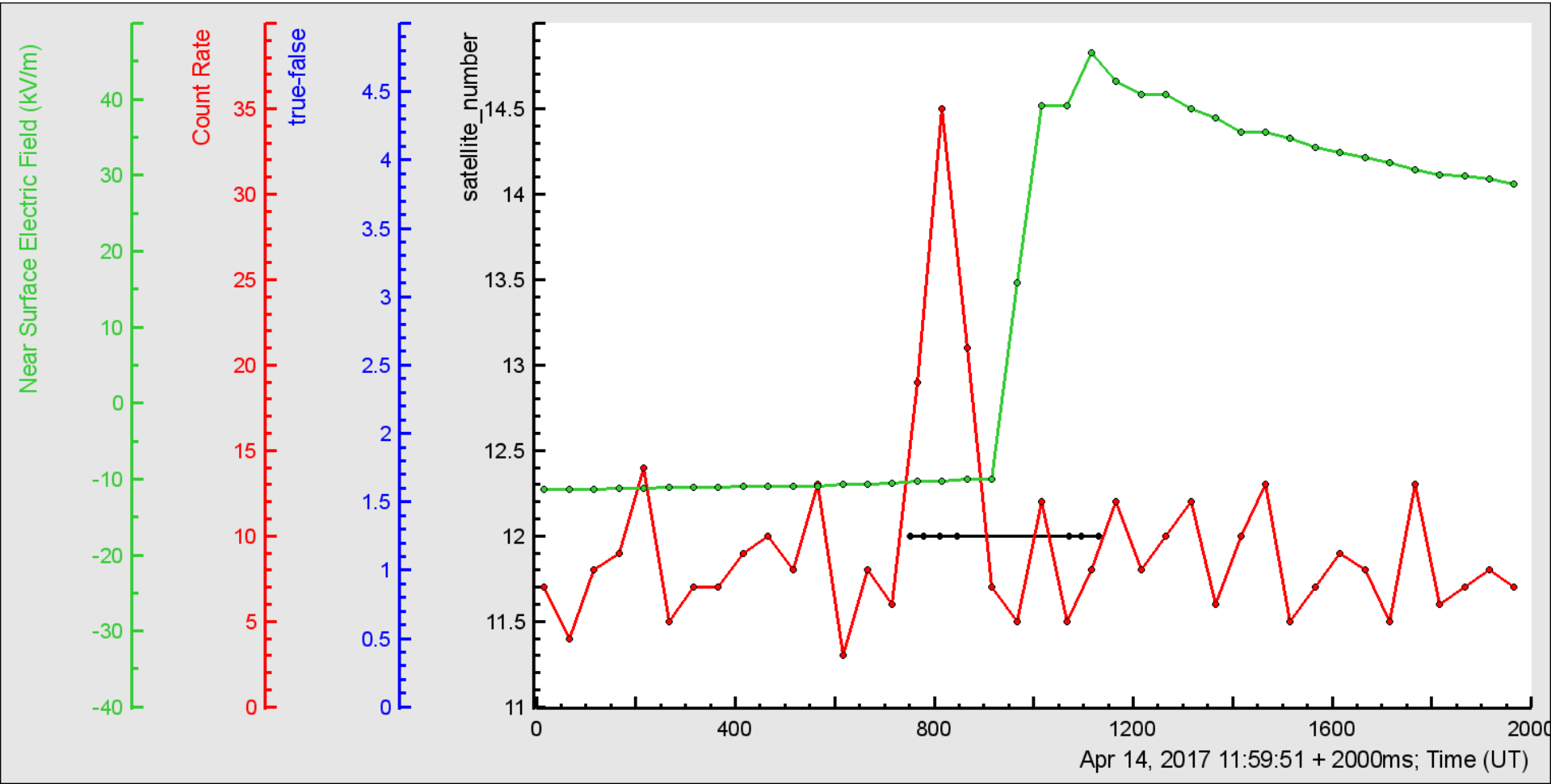

Count Rate
satellite_number
Near Surface Electric Field (kV/m)
May 10, 2016 14:15:46.45 + 2000ms; Time (UT)


2016-07-26
13:56:34-03

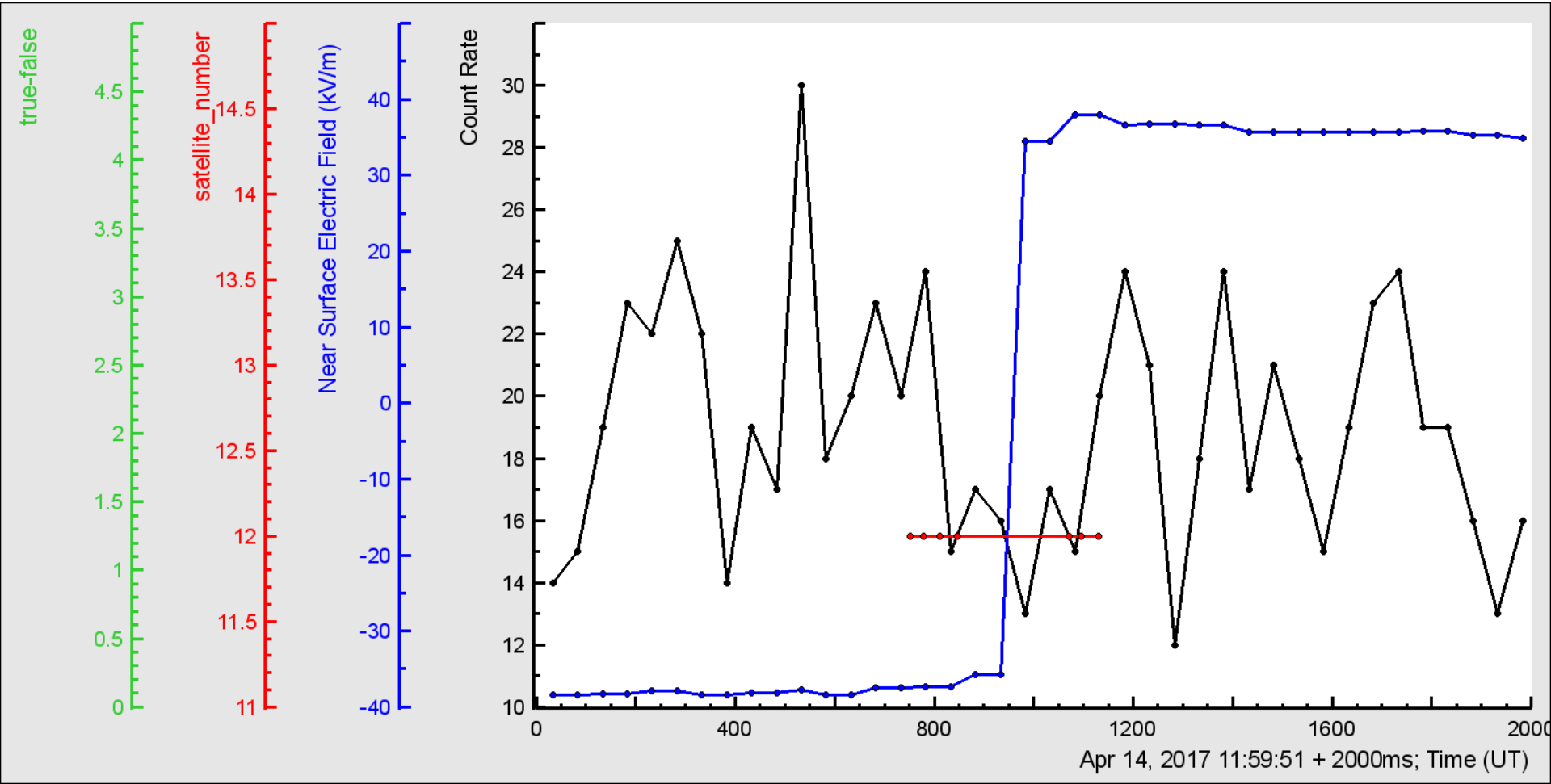

satellite_number
Near Surface Electric Field (kV/m)
Count Rate
true-false
Jun 11, 2016 11:45:22.0928497 + 1184583us; Time (U

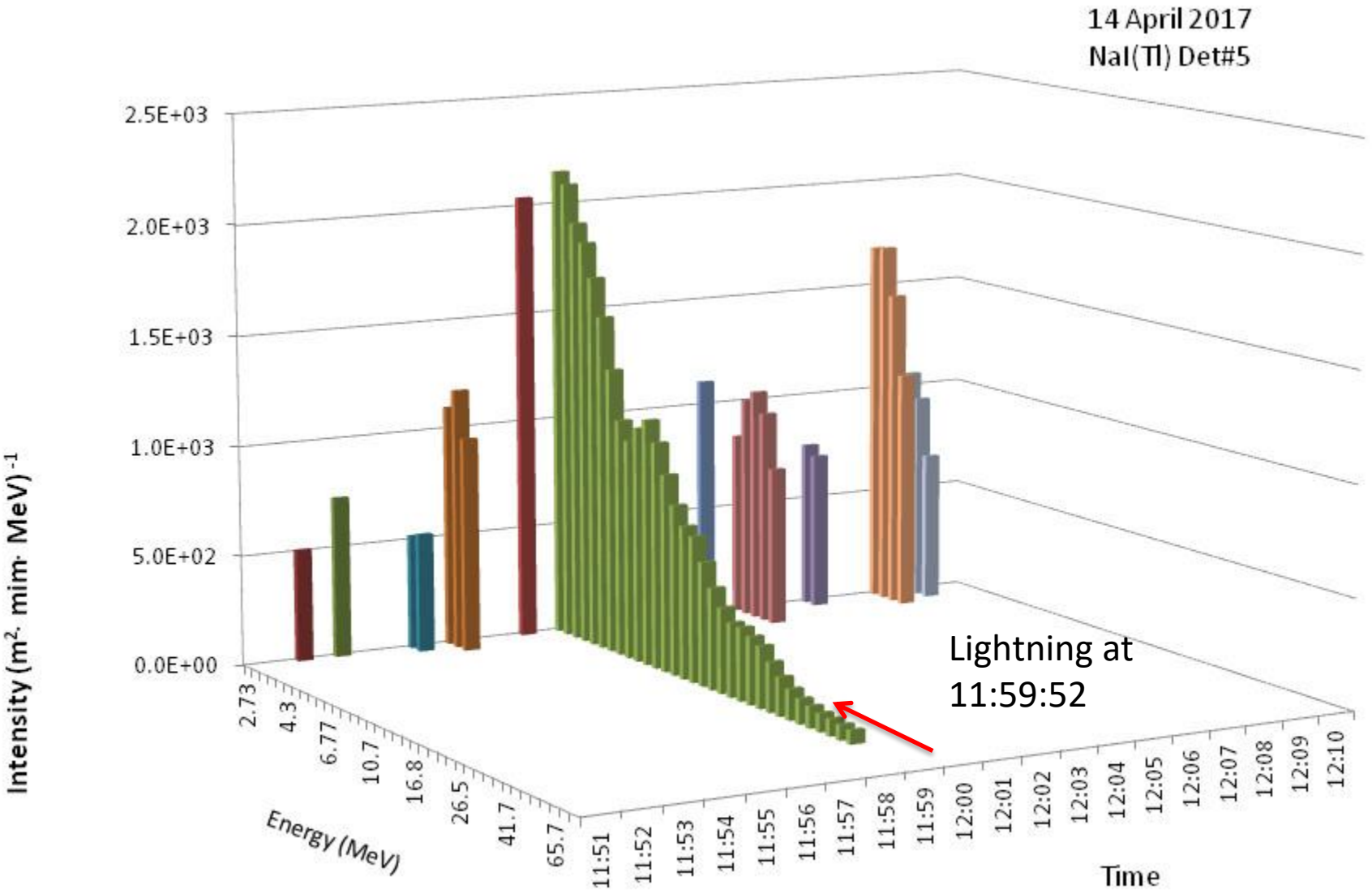

Near Surface Electric Field (kV/m)
Count Rate
Time in Seconds
Jul 28, 2016 13:56:33 + 2000ms; Time (UT)

Electric field from SKL EFM-100: 100 ms surge from 59:51.92 (-9.7 kV/m) until 59:52.02 (38.7 kV/m); MAKET and SKL FDAQ at 59:51.75. Particle flux observed –SKL STAND1 3 cm thick scintillator. Lightning stroke occurred at 11:59:51.82 (detected by EMI)

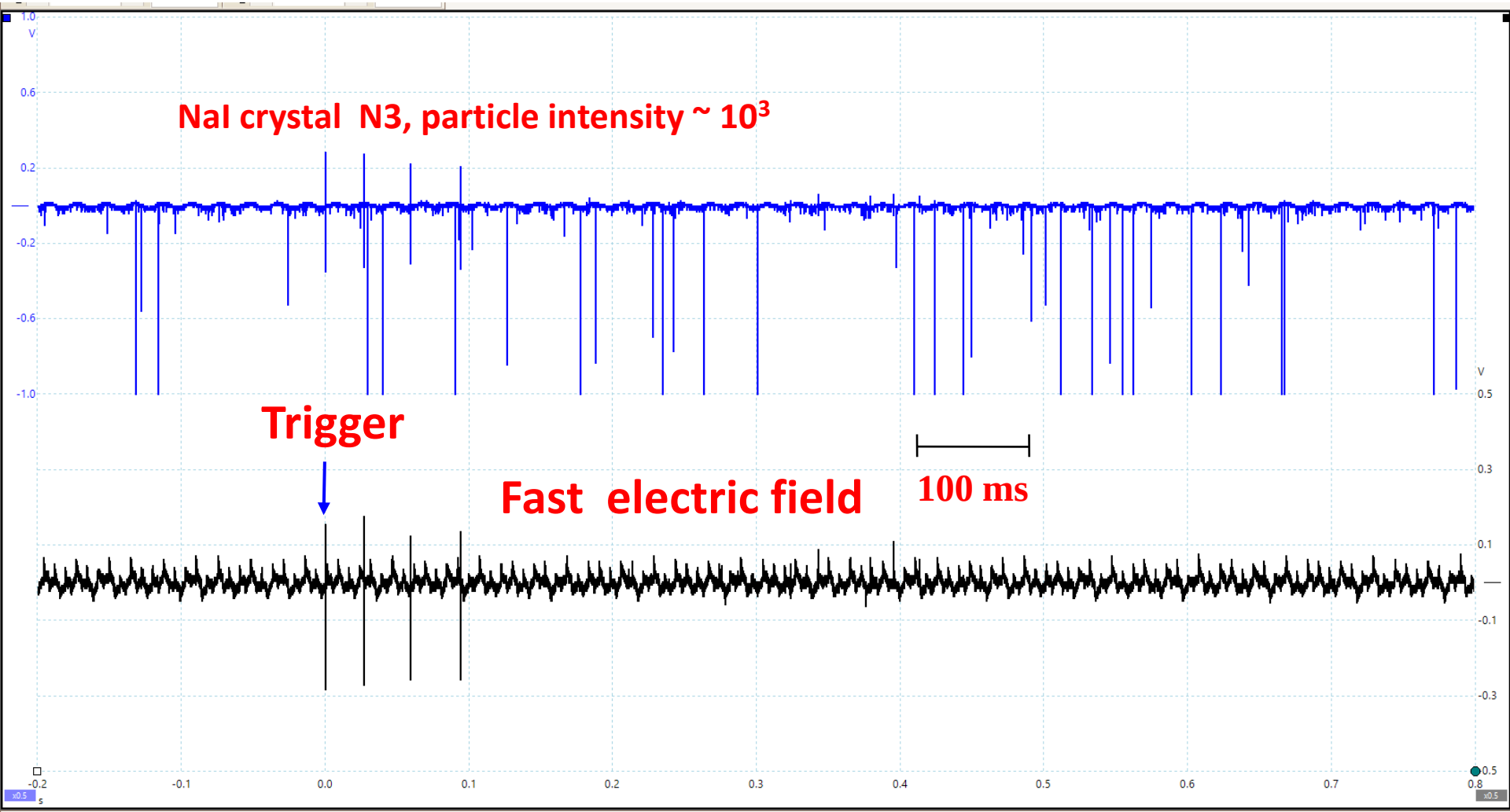


Electric field from GAMMA EFM-100: 50 ms surge from 59:51.94 (-35 kV/m) until 59:51.99 (35 kV/m); MAKET and SKL FDAQ trigger coincides at 59:51:75. Particle flux observed – GAMMA STAND1 1 cm thick scintillator: decline during rearrangement of electric field after lightning.

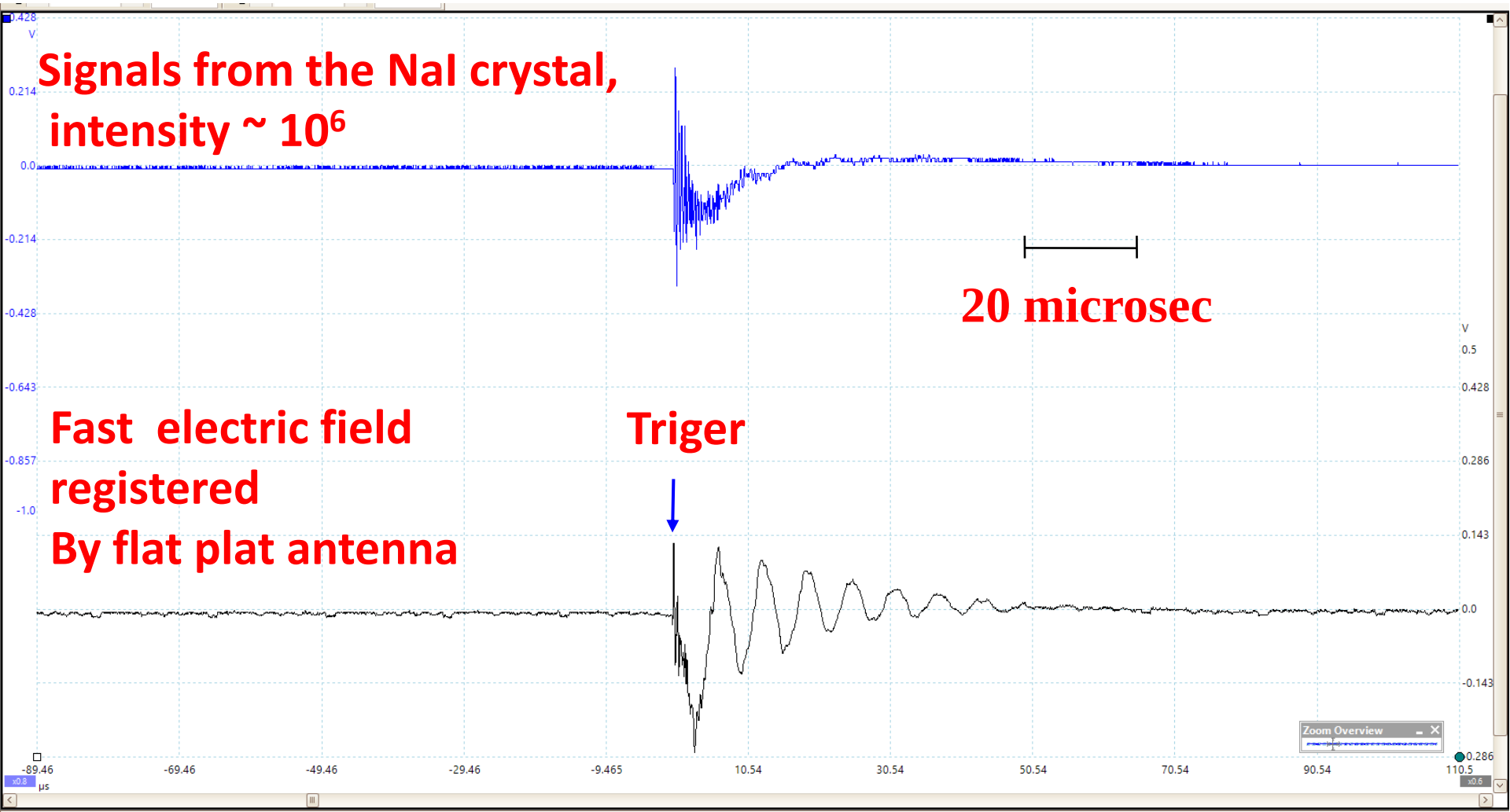



14 April 2017
NaI(Tl) Det#5
2.5E+03
2.0E+03
1.5E+03
1.0E+03
5.0E+02
0.0E+00
Intensity (m-2 min- MeV)-1
2.73
4.3
6.77
10.7
16.8
26.5
41.7
65.7
Energy (MeV)
11:51
11:52
11:53
11:54
11:55
11:56
11:57
11:58
11:59
12:00
12:01
12:02
12:03
12:04
12:05
12:06
12:07
12:08
12:09
12:10
Time
Lightning at
11:59:52

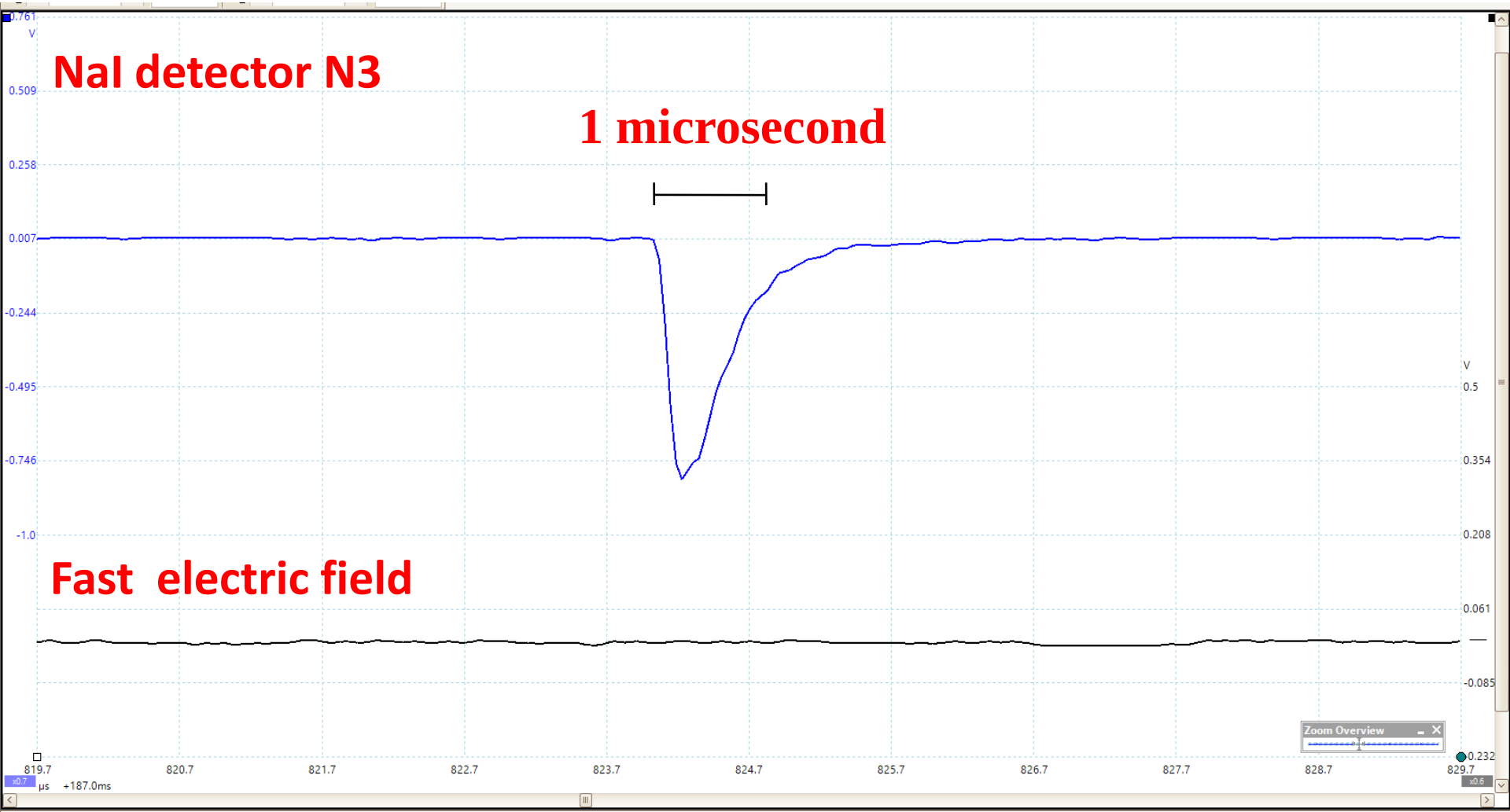
40 ns time series captured by digital oscilloscope located in the SKL experimental hall on Aragats. April 14, 2017 11:59:52
Fast electric field and NaI detector N3. Note 4 bipolar pulses in NaI outputs coinciding with fast bipolar pulses after trigger in fast forms !



“Particle” burst detected by NaI crystal – EMI!



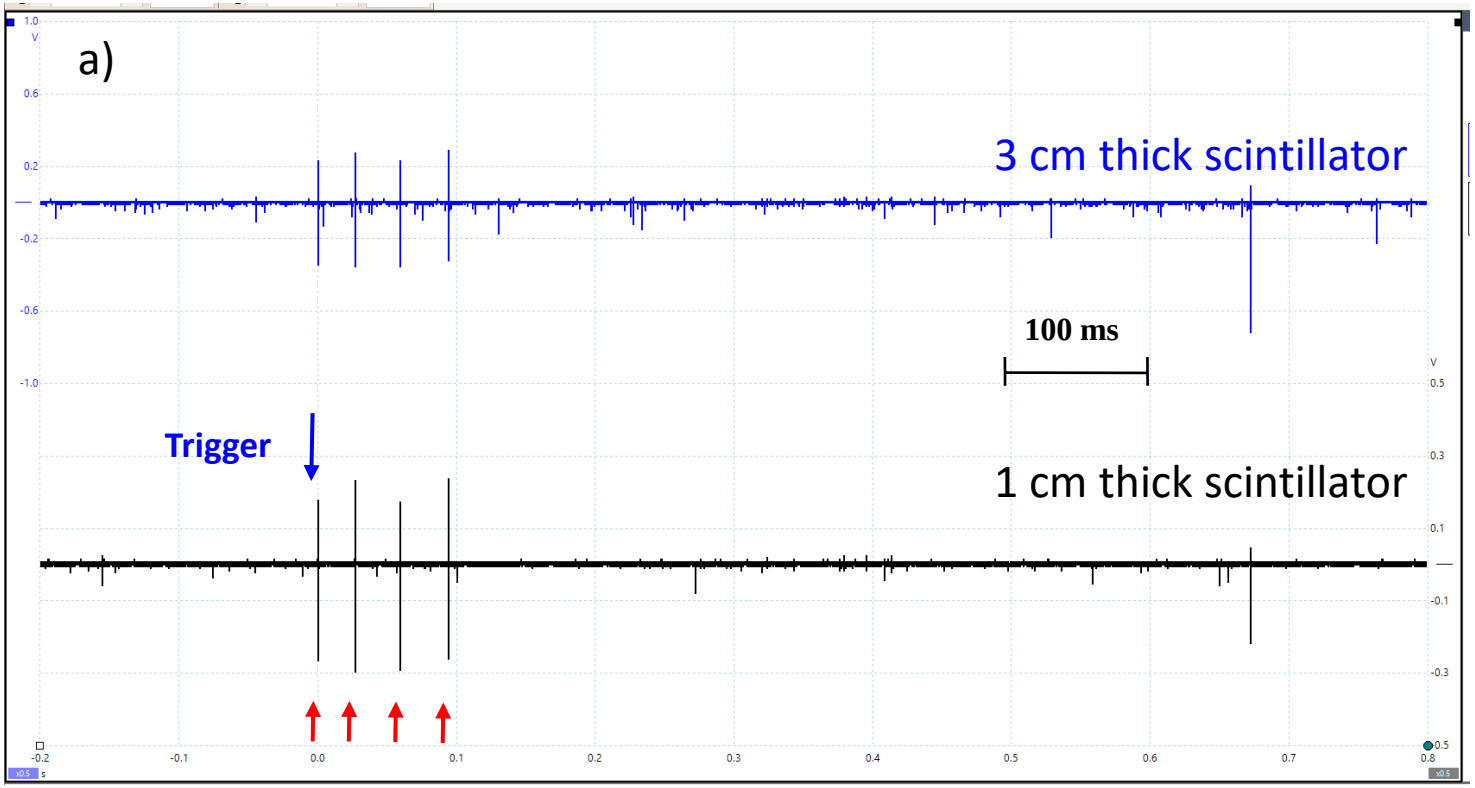
Typical shape of the signal from particle detected by the NaI detector



Picoscope N3 MAKET April 14, 2017 11:59:52

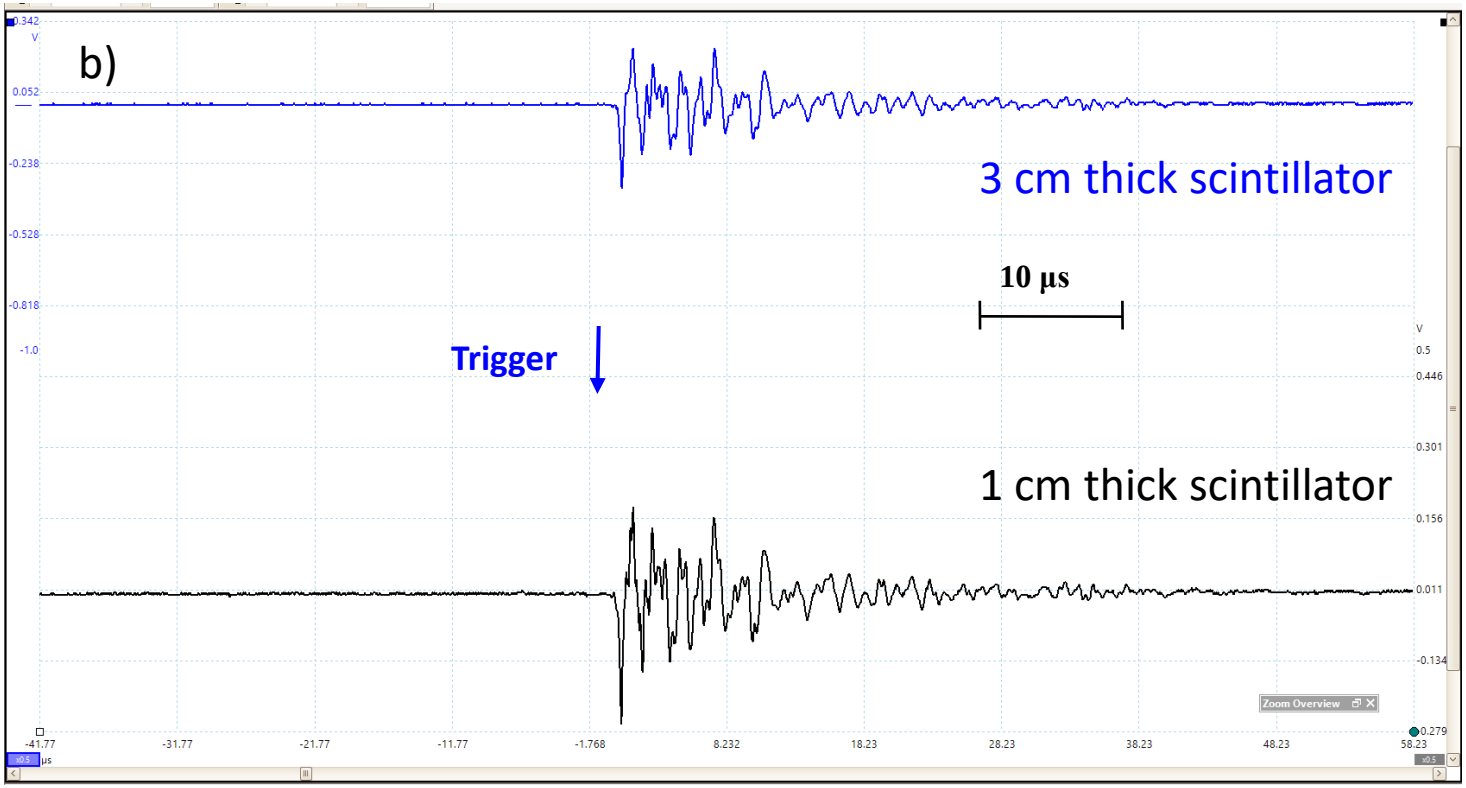
Ch A - One sec 3 cm; Ch B – One sec 1 cm

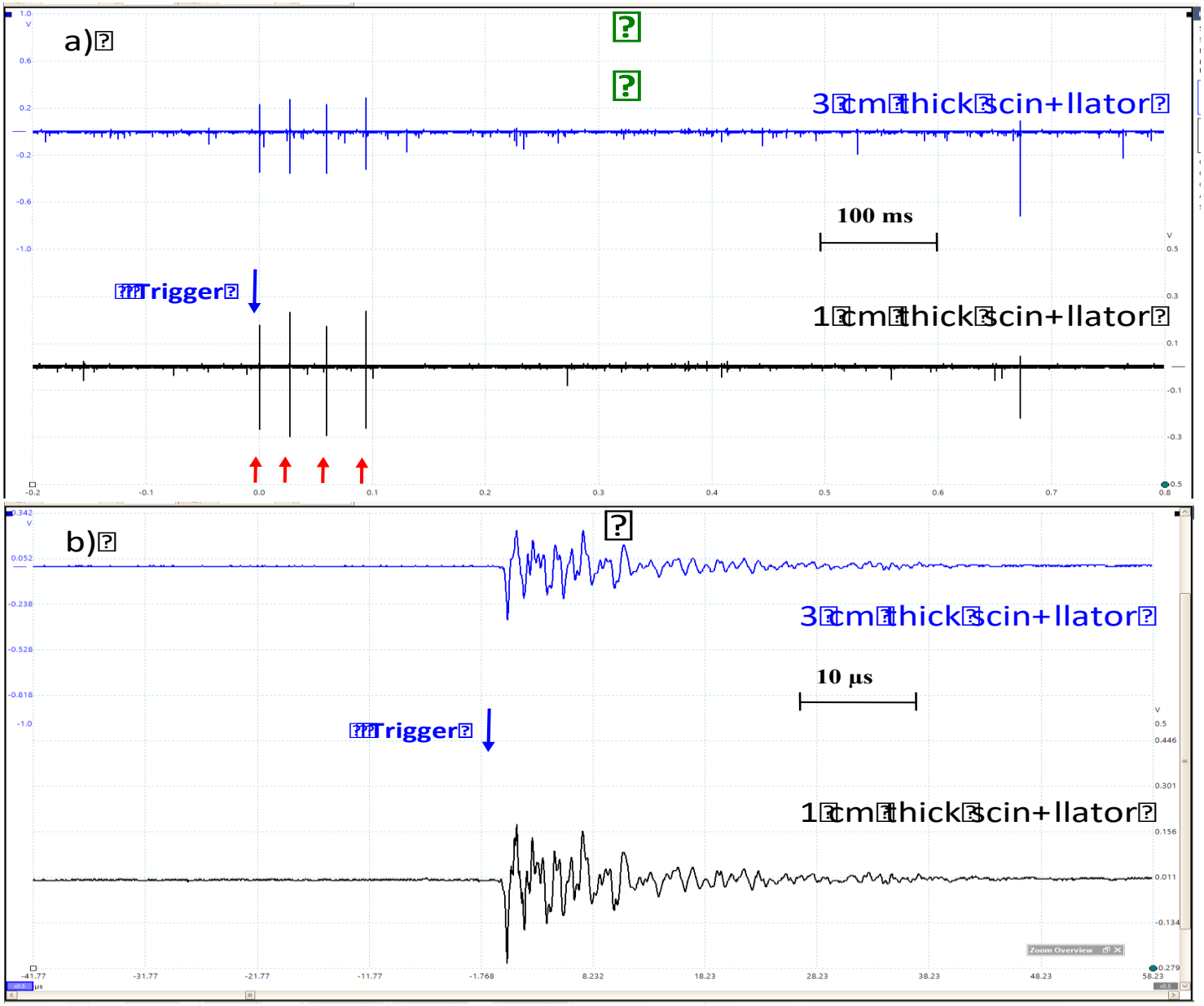
Again EMIs in plastic scintillators!

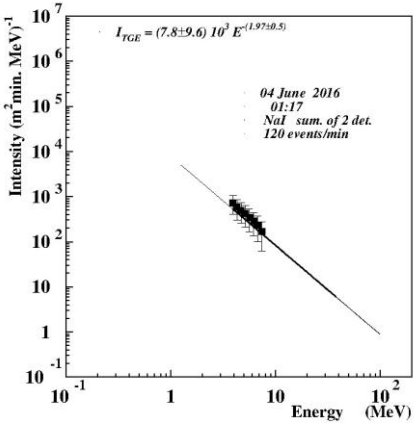


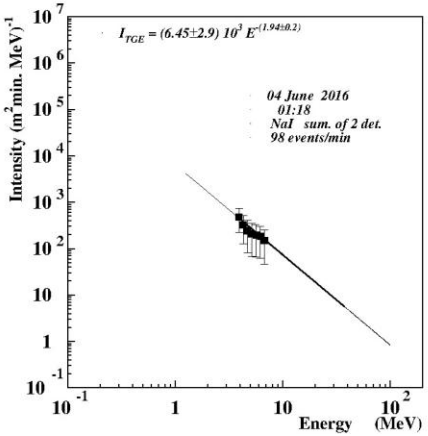
Four pulses with similar shape. Zoom of first pulse is shown in next slide

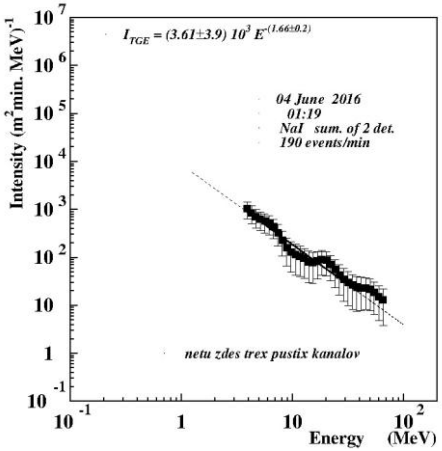
Picoscope N3 MAKET April 14, 2017 11:59:52
Ch A - One sec 3 cm; Ch B – One sec 1 cm

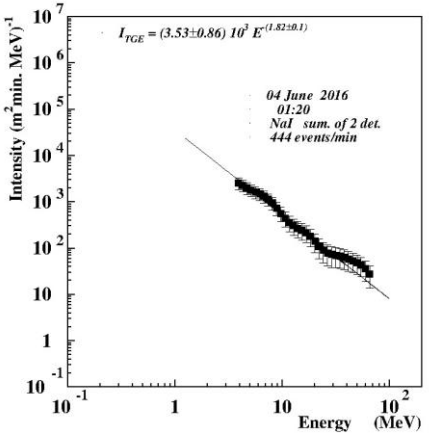


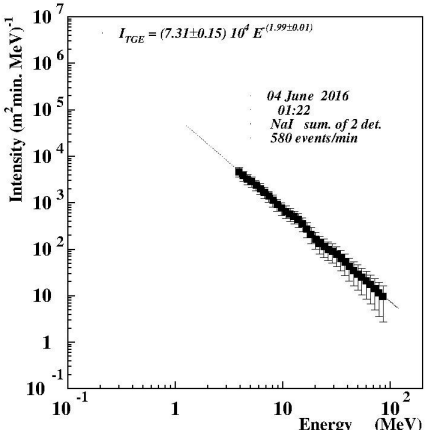

a)
3 cm thick scin+llator
100 ms
Trigger
1 cm thick scin+llator
b)
3 cm thick scin+llator
10 µs
Trigger
1 cm thick scin+llator

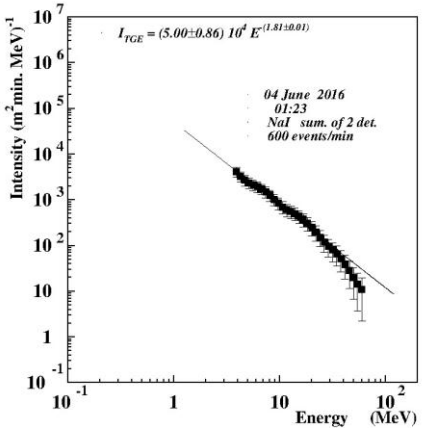

$I_{TGE} = (7.8 \pm 9.6)\ 10^{3}\ E^{-(1.97 \pm 0.5)}$
04 June 2016
01:17
NaI sum. of 2 det.
120 events/min
Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)

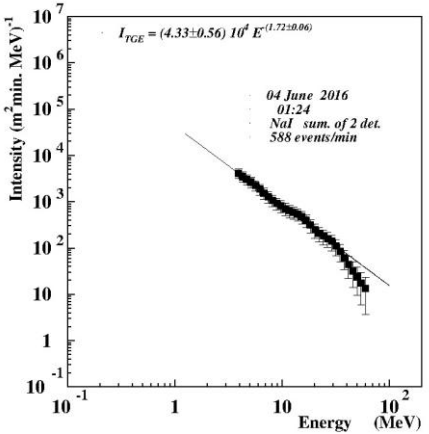

$I_{TGE} = (6.45 \pm 2.9)\ 10^{3}\ E^{-(1.94 \pm 0.2)}$
04 June 2016
01:18
NaI sum. of 2 det.
98 events/min
Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)

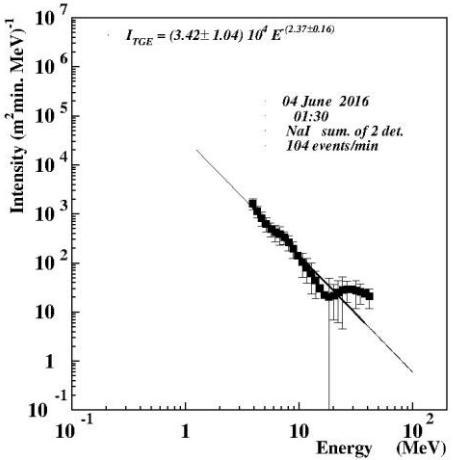

$I_{TGE} = (3.61 \pm 3.9)\ 10^{3}\ E^{-(1.66 \pm 0.2)}$
04 June 2016
01:19
NaI sum. of 2 det.
190 events/min
netu zdes trex pustix kanalov
Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)

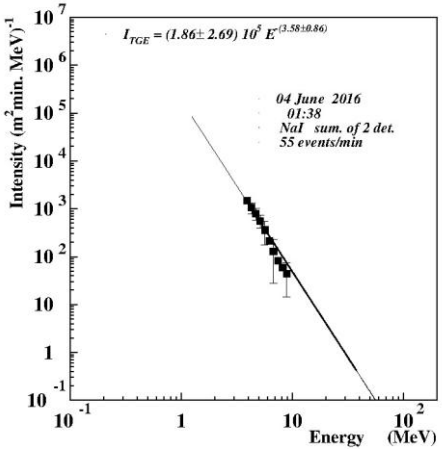

$I_{TGE} = (3.53 \pm 0.86)\ 10^{3}\ E^{-(1.82 \pm 0.1)}$
04 June 2016
01:20
NaI sum. of 2 det.
444 events/min
Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)

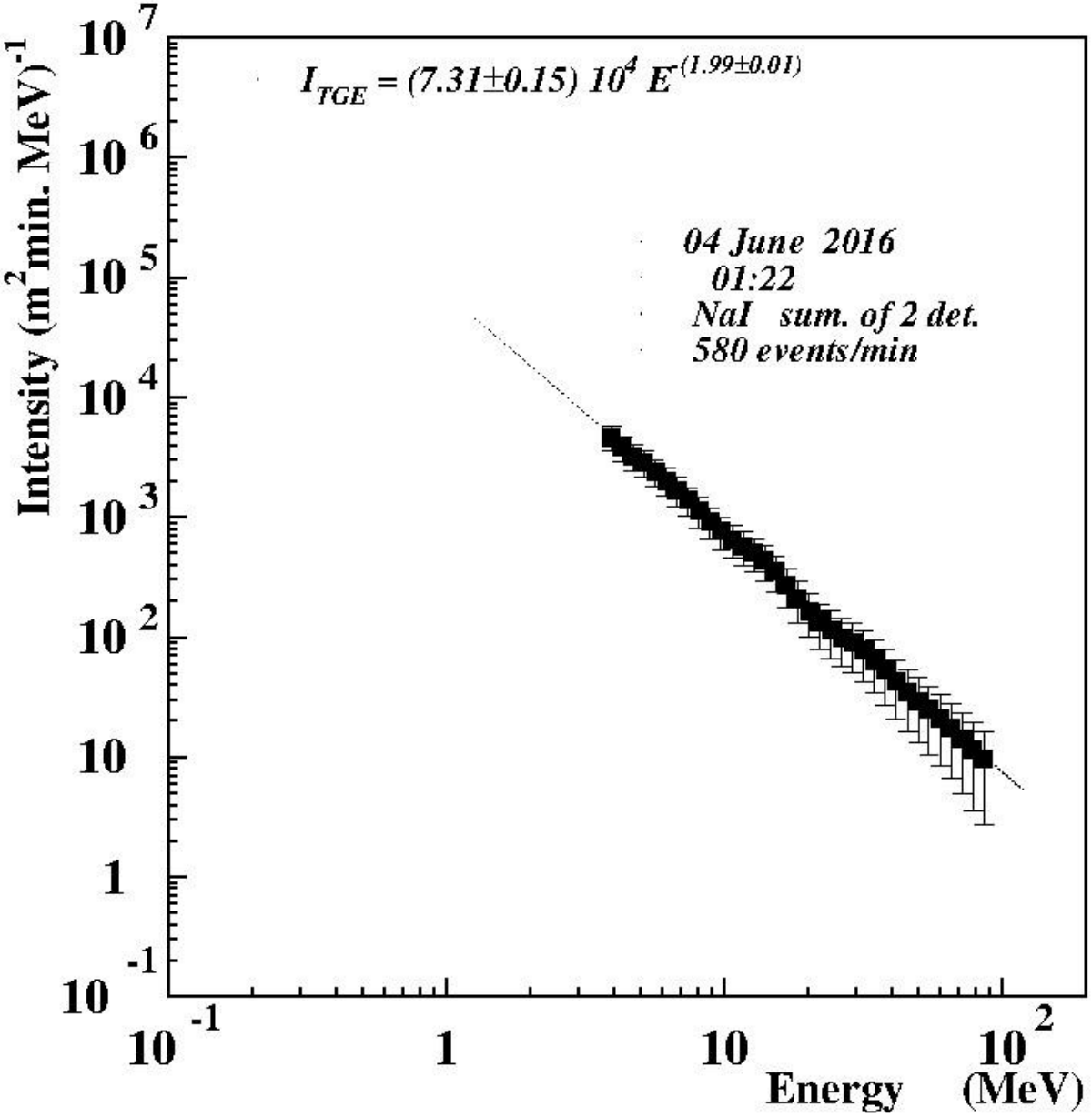

$I_{TGE} = (7.31 \pm 0.15)\ 10^{4}\ E^{-(1.99 \pm 0.01)}$
04 June 2016
01:22
NaI sum. of 2 det.
580 events/min
Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)

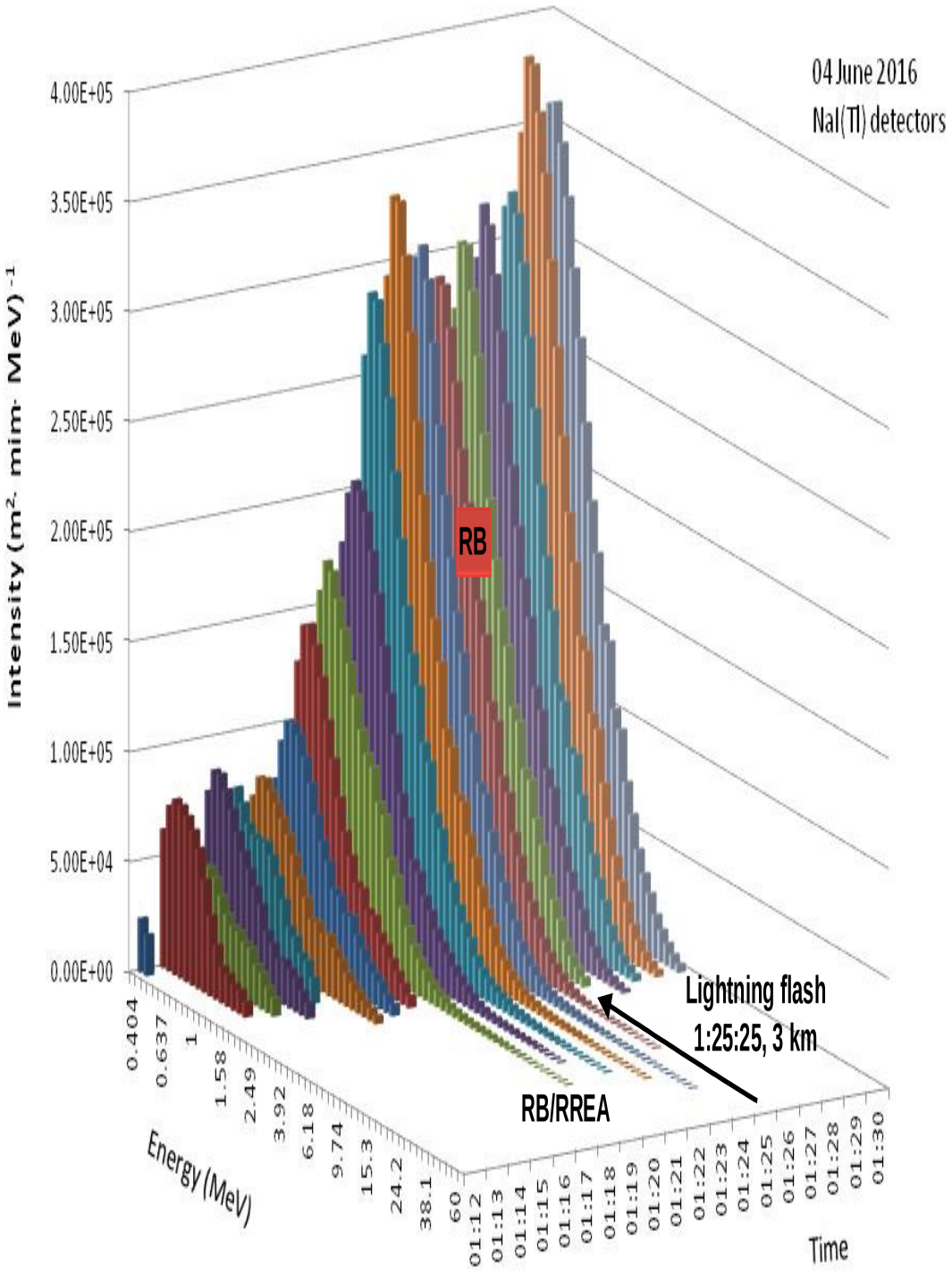

$I_{TGE} = (5.00 \pm 0.86)\ 10^{4}\ E^{-(1.81 \pm 0.01)}$
04 June 2016
01:23
NaI sum. of 2 det.
600 events/min
Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)

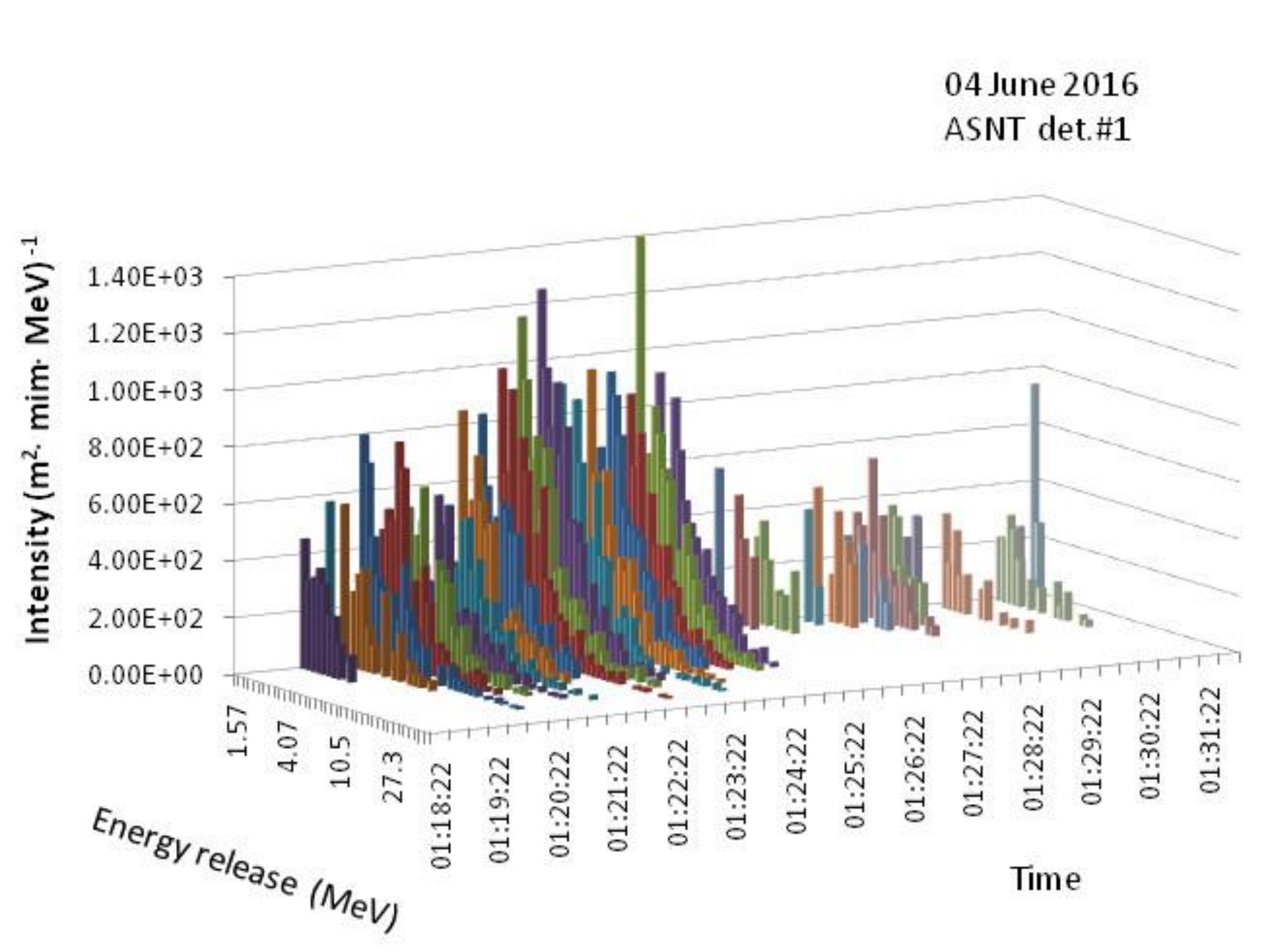

$I_{TGE} = (4.33 \pm 0.56)\ 10^{4}\ E^{-(1.72 \pm 0.06)}$
04 June 2016
01:24
NaI sum. of 2 det.
588 events/min
Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)


$I_{TGE} = (3.42 \pm 1.04)\ 10^{4}\ E^{-(2.37 \pm 0.16)}$
04 June 2016
01:30
NaI sum. of 2 det.
104 events/min
Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)

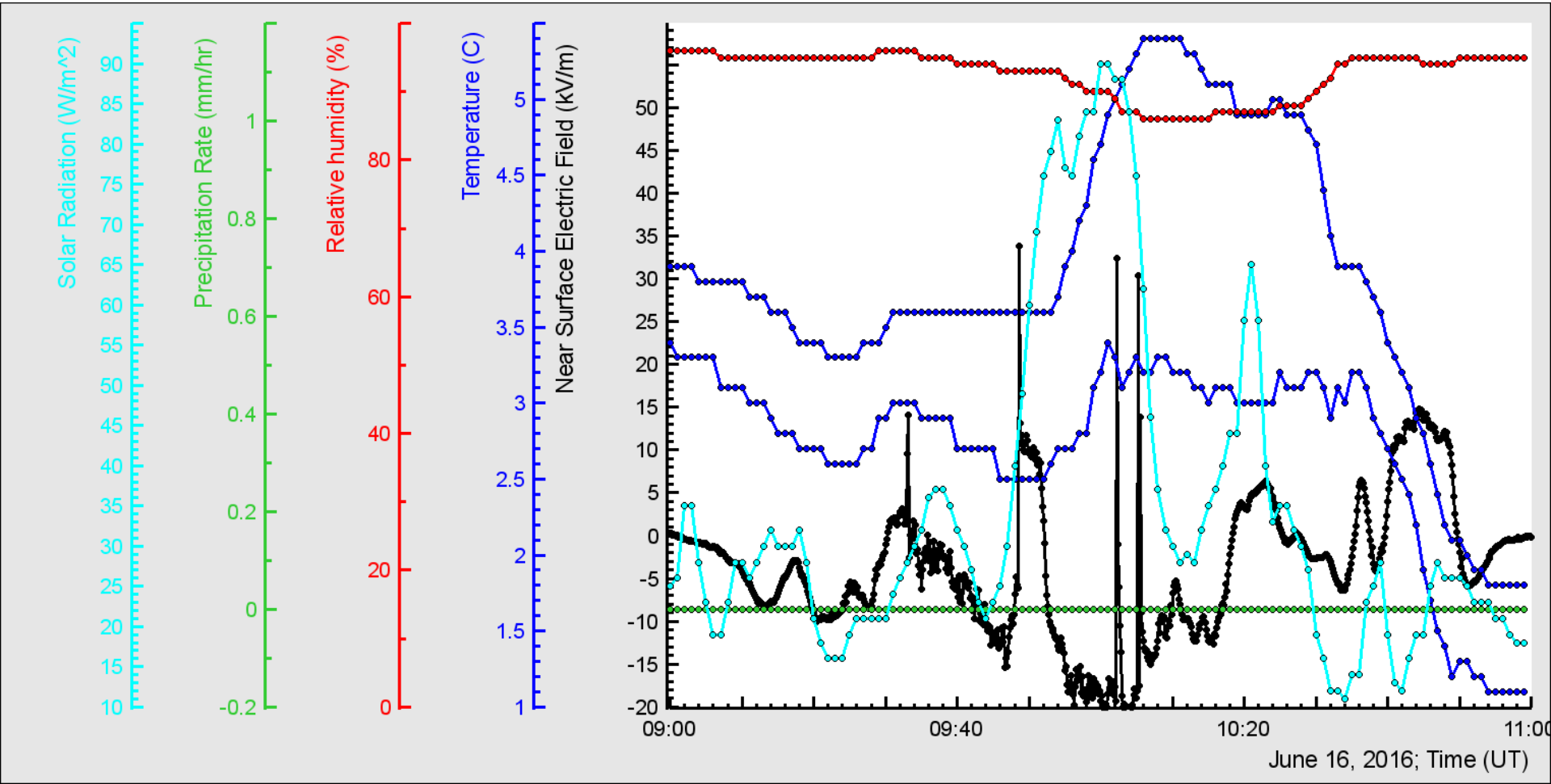

$I_{TGE} = (1.86 \pm 2.69)\ 10^{5}\ E^{-(3.58 \pm 0.86)}$
04 June 2016
01:38
NaI sum. of 2 det.
55 events/min
Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)


$I_{TGE} = (7.31 \pm 0.15)\ 10^{4}\ E^{(1.99 \pm 0.01)}$
04 June 2016
01:22
NaI sum. of 2 det.
580 events/min
Intensity (m^2min. MeV)$^{-1}$
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-1}
1
10
10^{2}
Energy (MeV)

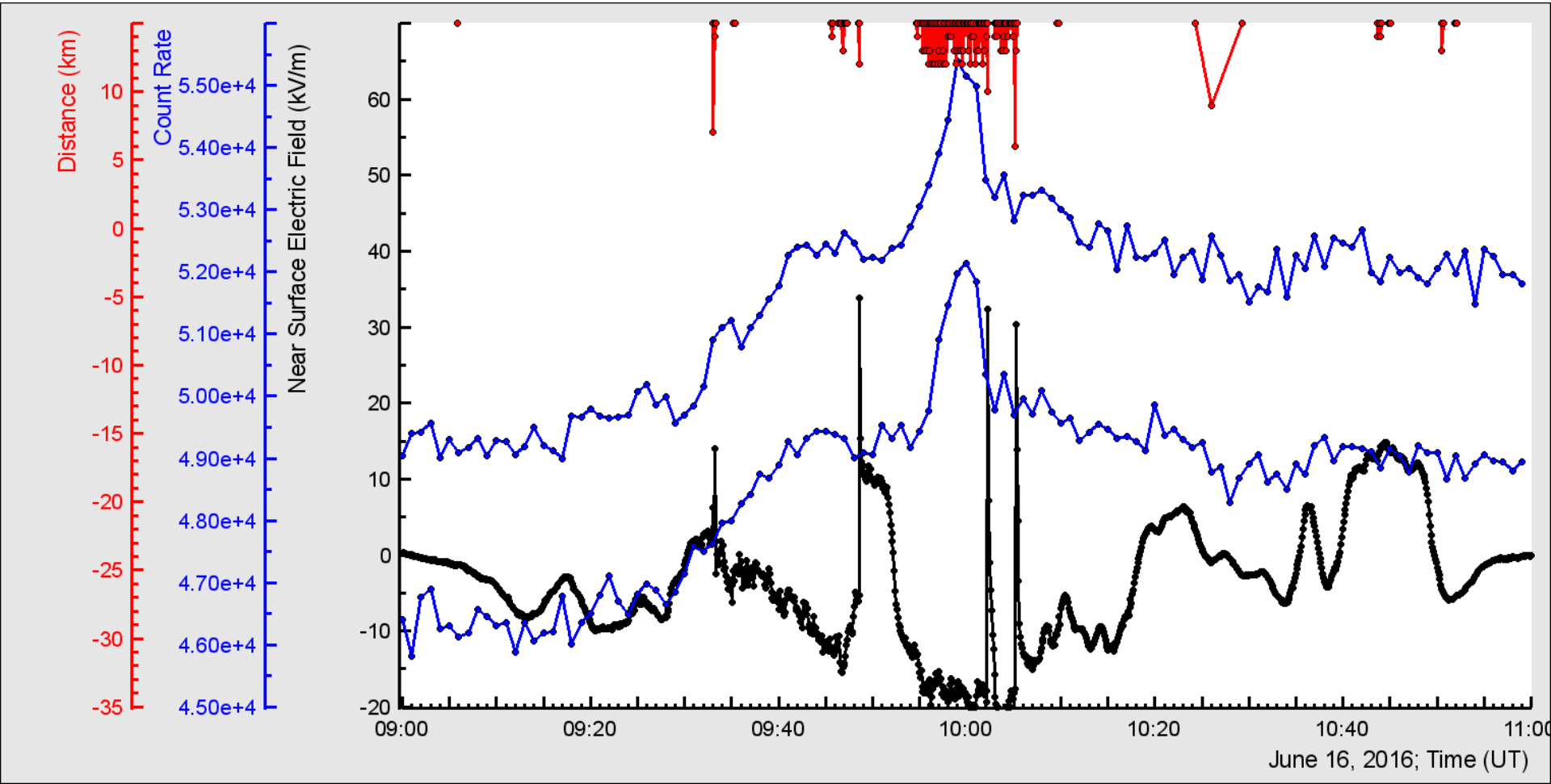

04 June 2016
NaI(Tl) detectors
Intensity (m-2 mim MeV) -1
4.00E+05
3.50E+05
3.00E+05
2.50E+05
2.00E+05
1.50E+05
1.00E+05
5.00E+04
0.00E+00
RB
RB/RREA
Lightning flash
1:25:25, 3 km
Energy (MeV)
0.404
0.637
1
1.58
2.49
3.92
6.18
9.74
15.3
24.2
38.1
60
Time
01:12
01:13
01:14
01:15
01:16
01:17
01:18
01:19
01:20
01:21
01:22
01:23
01:24
01:25
01:26
01:27
01:28
01:29
01:30

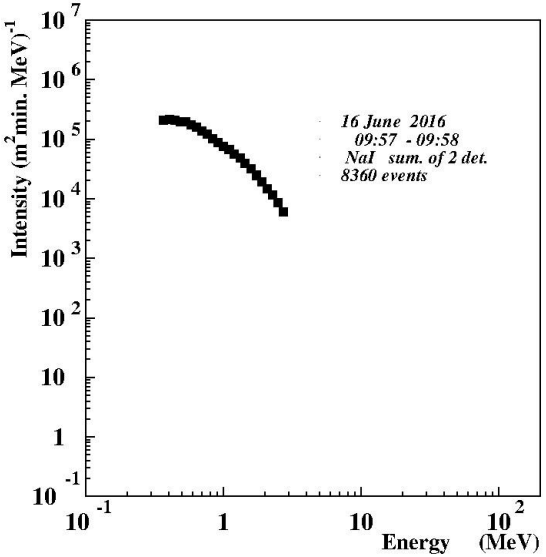

04 June 2016
ASNT det.#1
Intensity (m2· mim· MeV)-1
1.40E+03
1.20E+03
1.00E+03
8.00E+02
6.00E+02
4.00E+02
2.00E+02
0.00E+00
1.57
4.07
10.5
27.3
Energy release (MeV)
01:18:22
01:19:22
01:20:22
01:21:22
01:22:22
01:23:22
01:24:22
01:25:22
01:26:22
01:27:22
01:28:22
01:29:22
01:30:22
01:31:22
Time

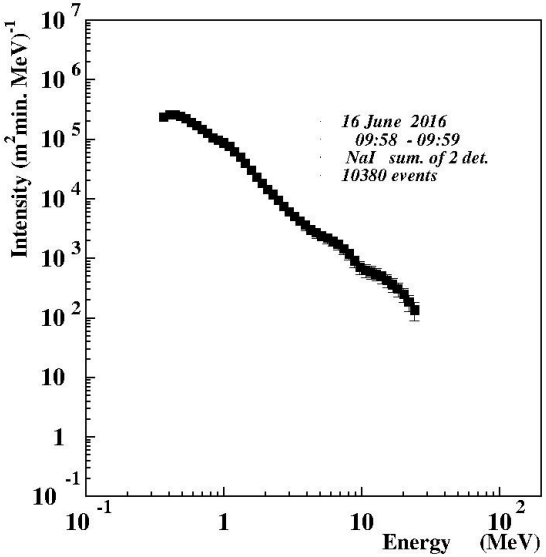
June 16, 2016: Height of the cloud 100-120 m

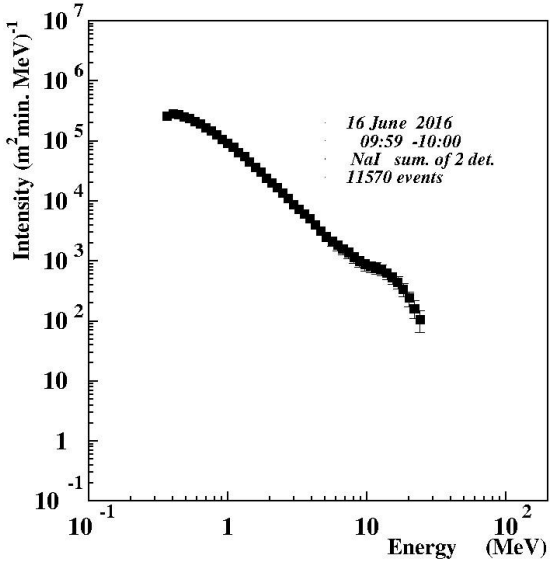


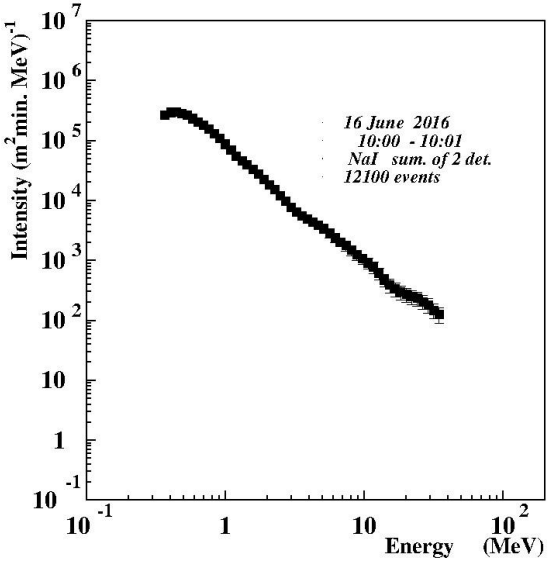
NaI 1 and 2

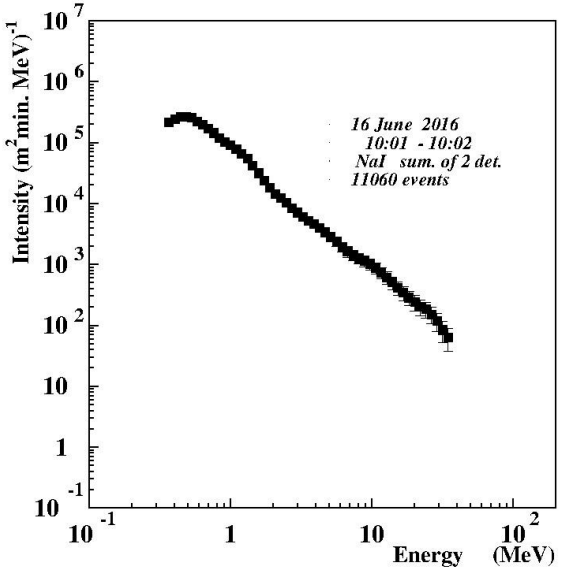

Distance (km)
10
5
0
-5
-10
-15
-20
-25
-30
-35
Count Rate
5.50e+4
5.40e+4
5.30e+4
5.20e+4
5.10e+4
5.00e+4
4.90e+4
4.80e+4
4.70e+4
4.60e+4
4.50e+4
Near Surface Electric Field (kV/m)
60
50
40
30
20
10
0
-10
-20
09:00
09:20
09:40
10:00
10:20
10:40
11:00
June 16, 2016; Time (UT)

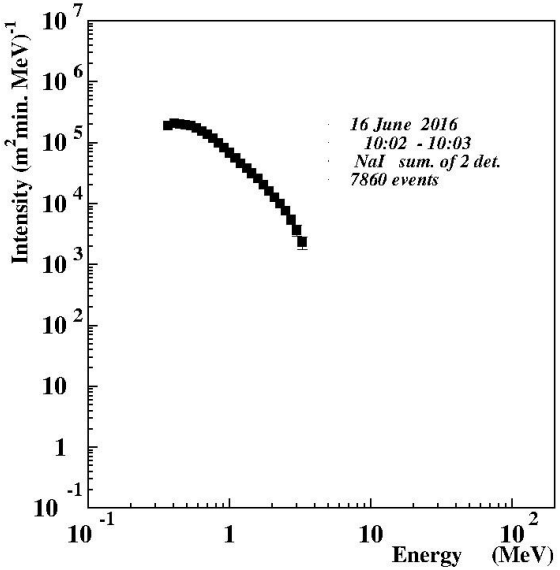

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
09:57 - 09:58
NaI sum. of 2 det.
8360 events

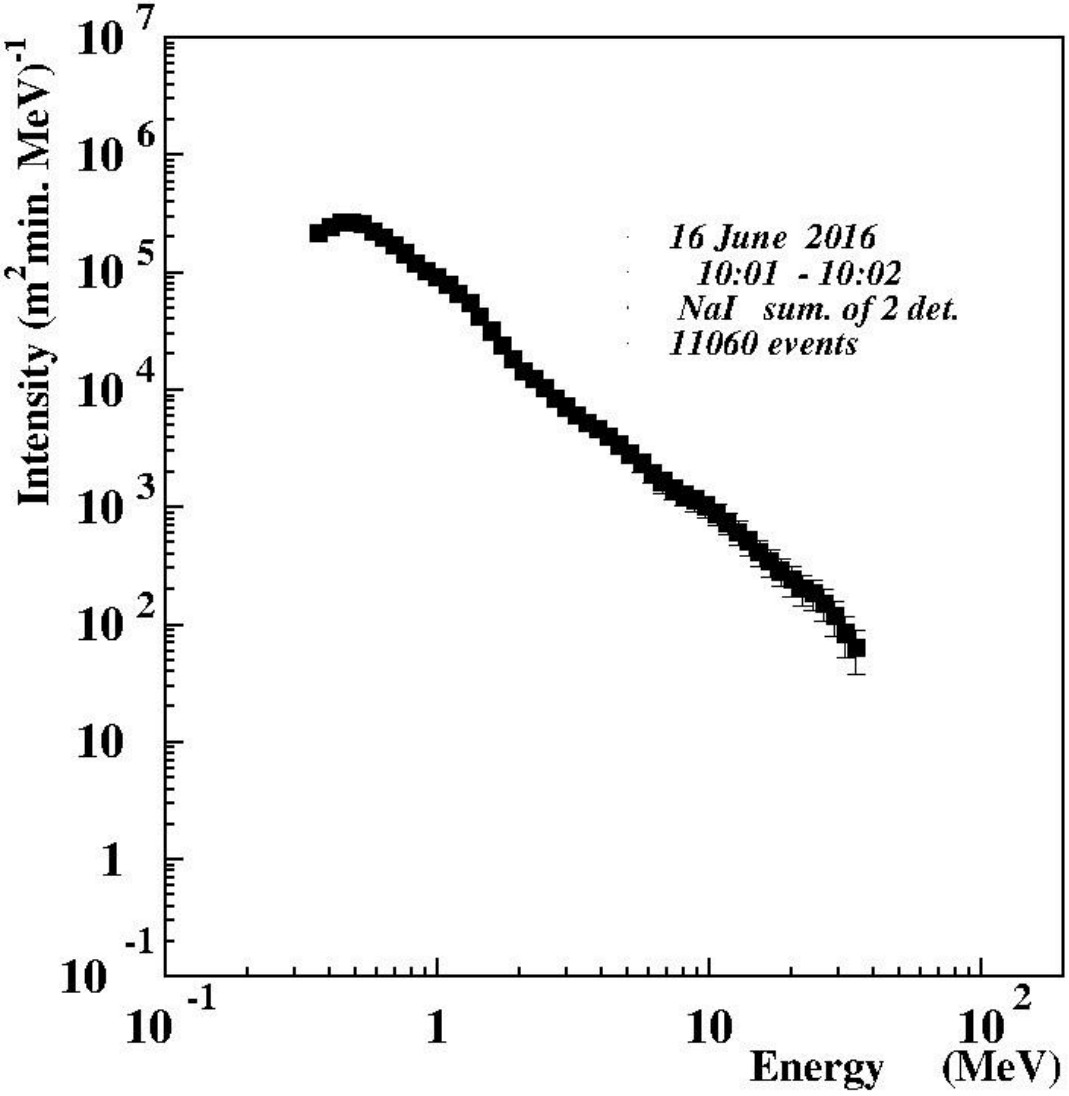

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
09:58 - 09:59
NaI sum. of 2 det.
10380 events


Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
09:59 -10:00
NaI sum. of 2 det.
11570 events

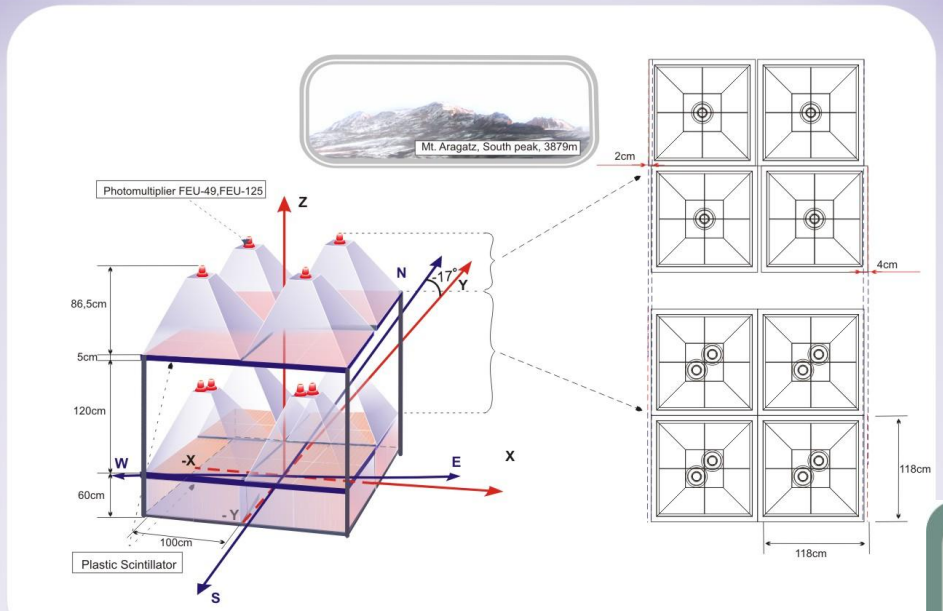

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
10:00 - 10:01
NaI sum. of 2 det.
12100 events

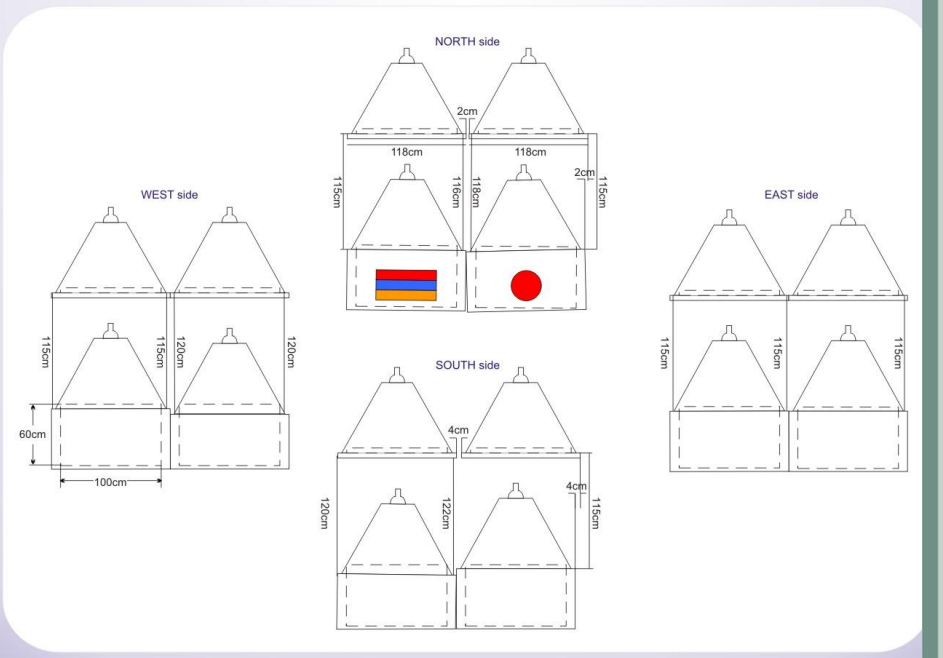

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
10:01 - 10:02
NaI sum. of 2 det.
11060 events

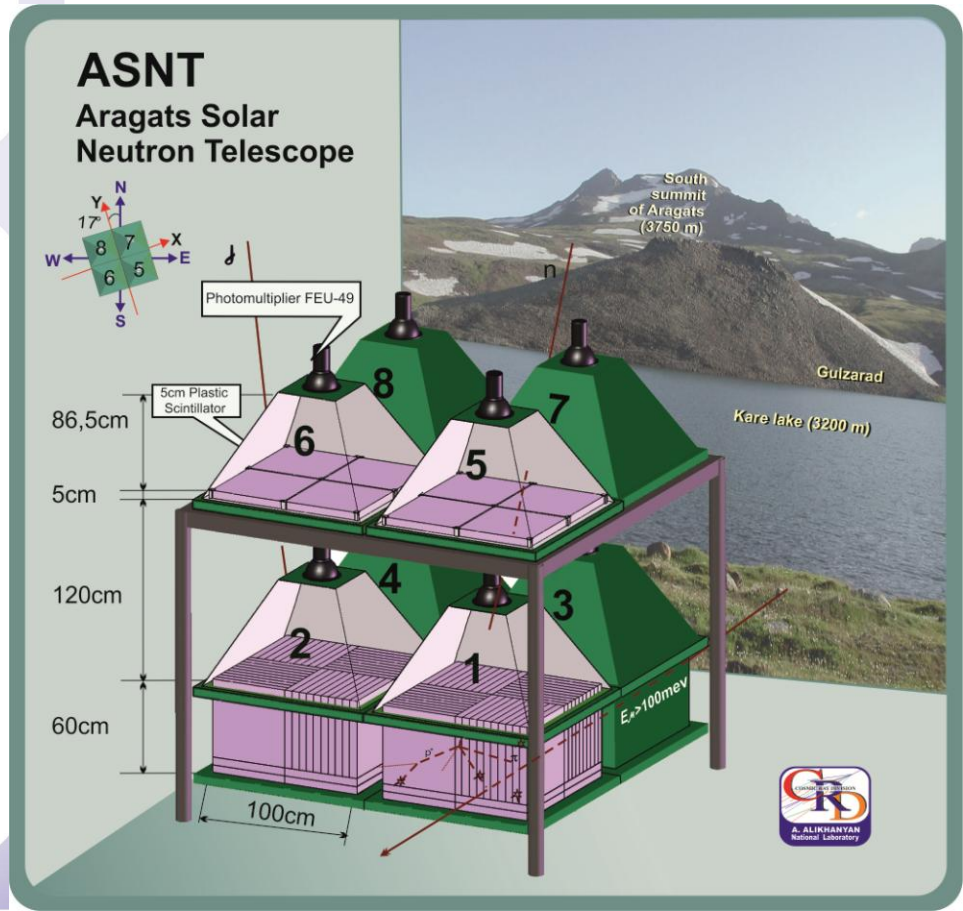

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
10:02 - 10:03
NaI sum. of 2 det.
7860 events

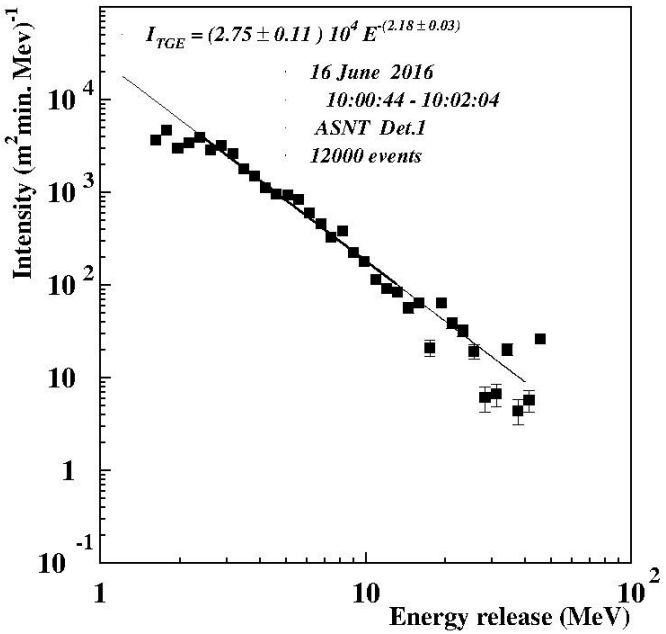

Intensity (m^{2}min. MeV)$^{-1}$
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-1}
1
10
10^2
Energy (MeV)
16 June 2016
10:01 - 10:02
NaI sum. of 2 det.
11060 events

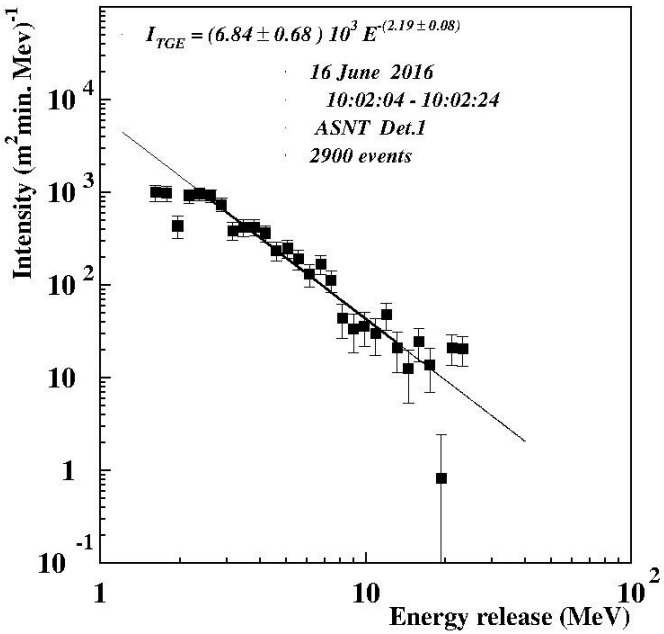
ASNT – universal CR detector

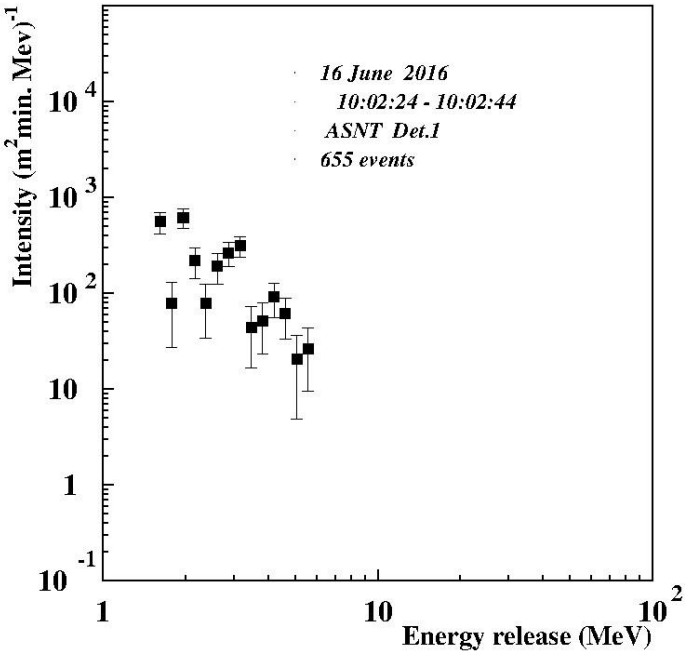


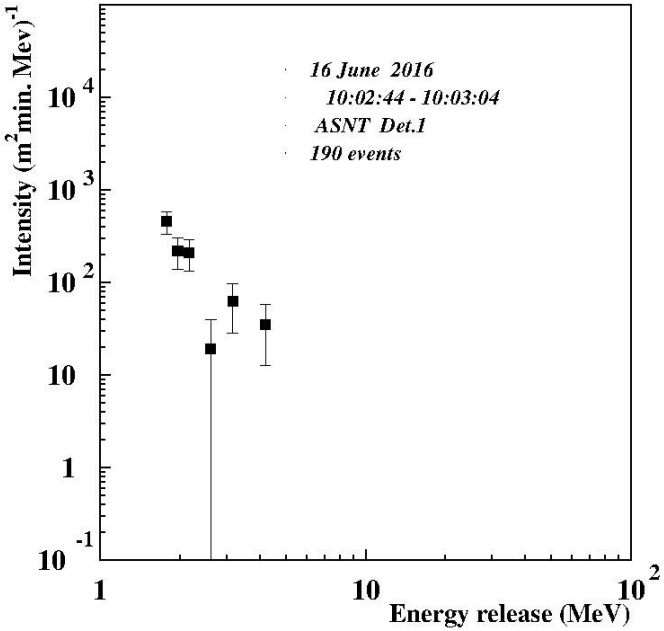





$I_{TGE} = (2.75 \pm 0.11)\ 10^4\ E^{-(2.18 \pm 0.03)}$
16 June 2016
10:00:44 - 10:02:04
ASNT Det.1
12000 events
Intensity (m^2min. Mev)$^{-1}$
Energy release (MeV)


$I_{TGE} = (6.84 \pm 0.68)\ 10^3\ E^{-(2.19 \pm 0.08)}$
16 June 2016
10:02:04 - 10:02:24
ASNT Det.1
2900 events
Intensity (m^2min. Mev)$^{-1}$
Energy release (MeV)

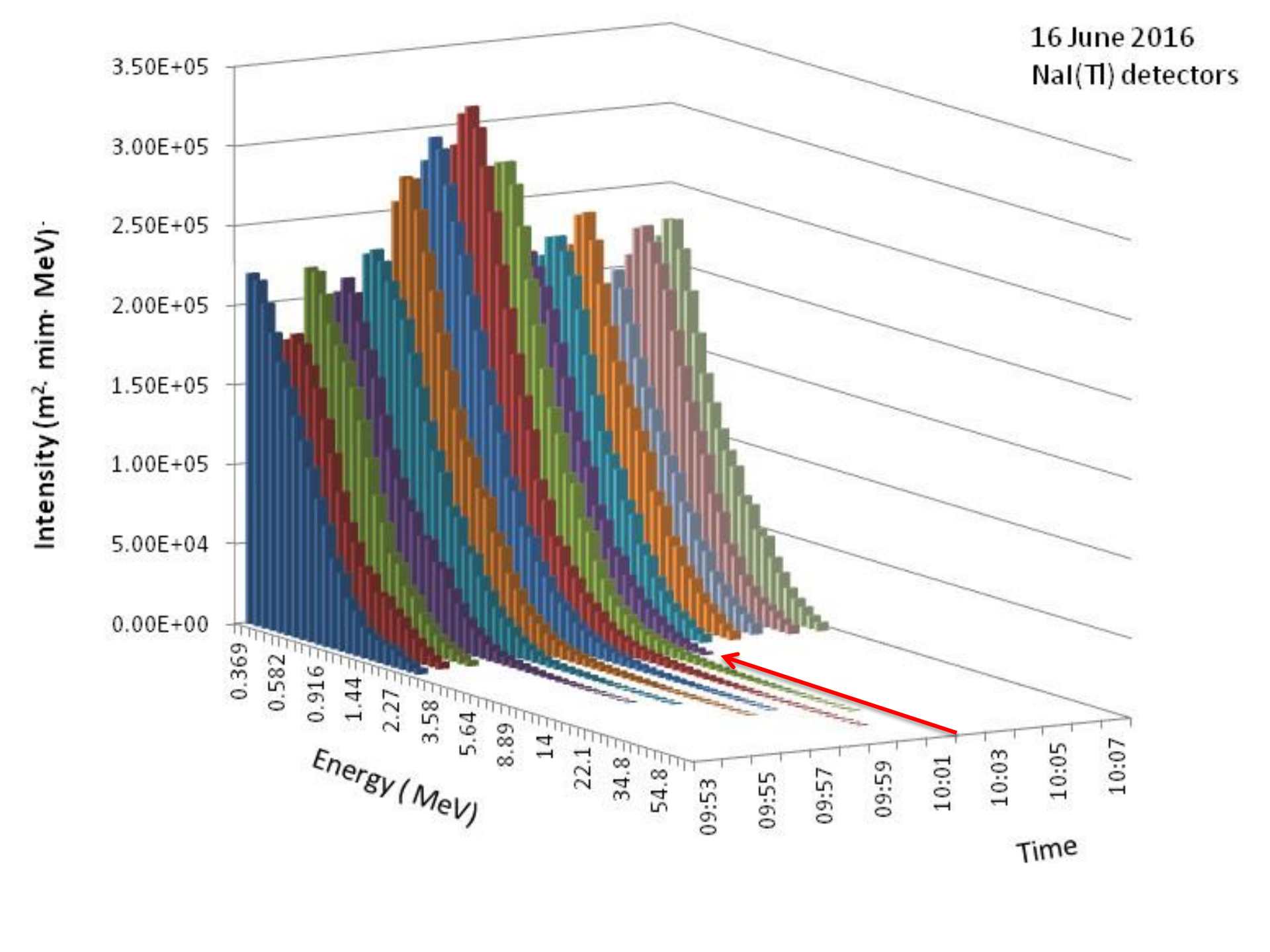

16 June 2016
10:02:24 - 10:02:44
ASNT Det.1
655 events
Intensity (m^2min. Mev)$^{-1}$
Energy release (MeV)

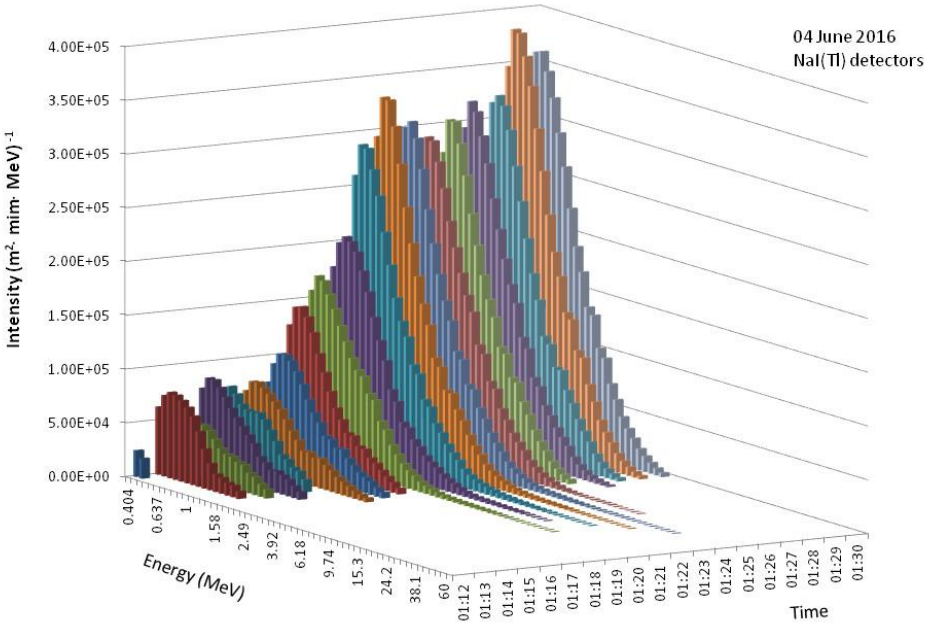

16 June 2016
10:02:44 - 10:03:04
ASNT Det.1
190 events
Intensity (m^2min. Mev)$^{-1}$
Energy release (MeV)

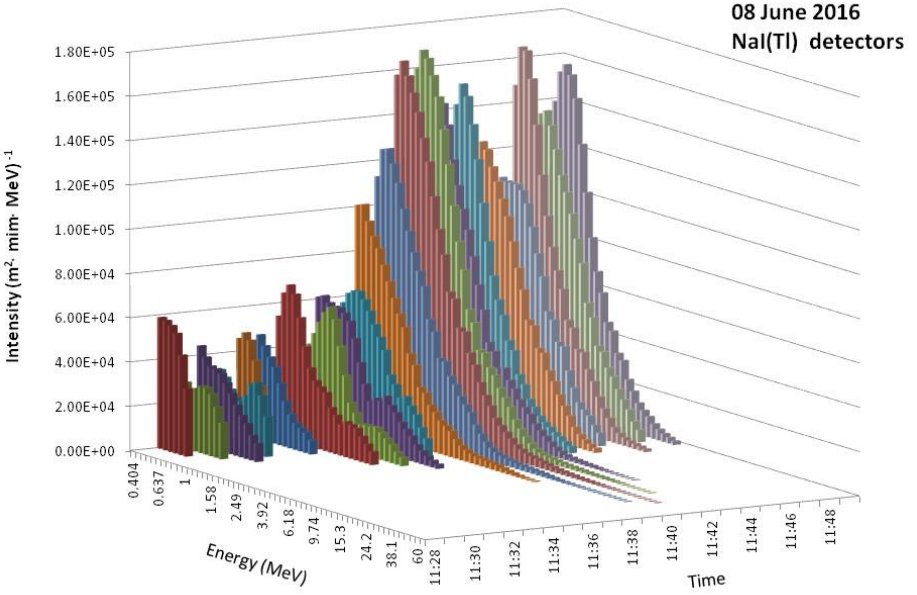
16 June, 20-second energy release spectra in 60 cm thick plastic scintillator before the lightning occurred at 10:02:11; the enhancement of count rate in the 22 ADC channels (1.62- 15.9 MeV) to be compared with CR MSE (red); lightning at 10:02:11

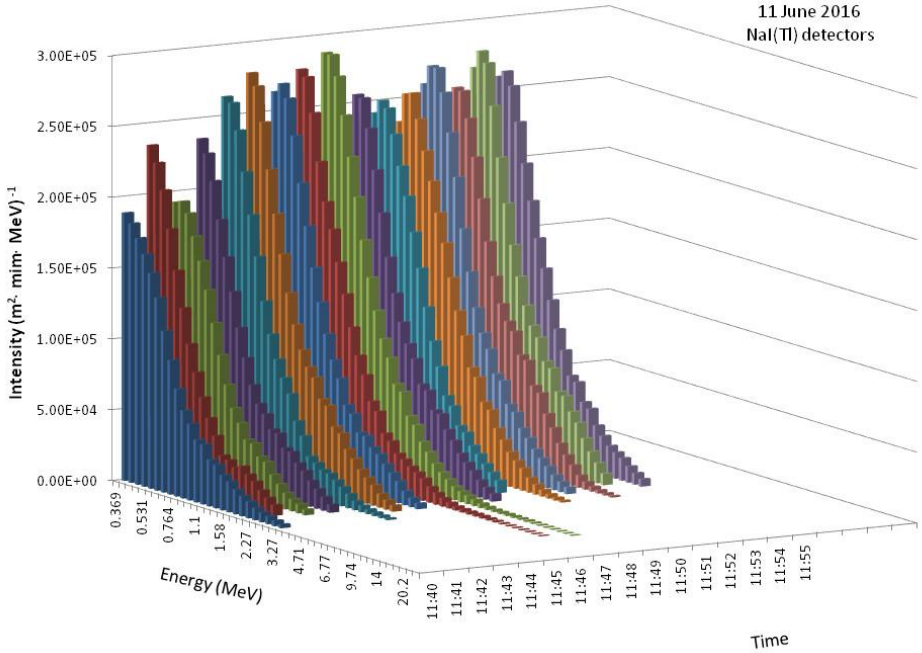
Code of ADC	1	2	3	4	5	6	7	8	9	10	11
Energy(MeV)	1.6	1.8	2.0	2.2	2.4	2.6	2.9	3.2	3.5	3.8	4.2
CR background	952.0	1112.0	735.0	892.0	1013.0	941.0	867.0	808.0	754.0	708.0	664.0
CR variance	30.9	33.3	27.1	29.9	31.8	30.7	29.4	28.4	27.5	26.6	25.8
10:02:04 -10:02:23	161.2	175.0	85.4	196.3	227.6	239.0	212.7	122.0	144.4	161.6	152.8
10:02:24 -10:02:43	**90.2**	**14.0**	**121.4**	**47.3**	**18.6**	**50.0**	**75.7**	**99.0**	**15.4**	**19.6**	**38.8**
10:02:44 -10:03:03	**-5.8**	**81.0**	**43.4**	**45.3**	**-50.4**	**5.0**	**-1.3**	**20.0**	**-20.6**	**-0.4**	**14.8**
Code of ADC	15	16	17	18	19	20	21	22	23	24	25
Energy(MeV)	6.2	6.8	7.4	8.2	0.9	10.0	10.9	12.0	13.2	14.5	15.9
CR background	526.6	510.9	492.3	479.7	474.1	462.1	455.0	449.3	446.2	435.7	429.9
CR variance	22.9	22.6	22.2	21.9	21.8	21.5	21.3	21.2	21.1	20.9	20.7
10:02:04 -10:02:23	80.4	114.1	83.7	36.3	29.9	35.9	33.0	57.7	27.8	18.3	39.1
10:02:24 -10:02:43	**12.4**	**-6.9**	**52.7**	**3.3**	**-1.1**	**38.9**	**0.0**	**1.7**	**23.8**	**31.3**	**26.1**
10:02:44 -10:03:03	**-9.6**	**3.1**	**12.7**	**-16.7**	**19.9**	**-1.1**	**7.0**	**-0.3**	**15.8**	**33.3**	**6.1**

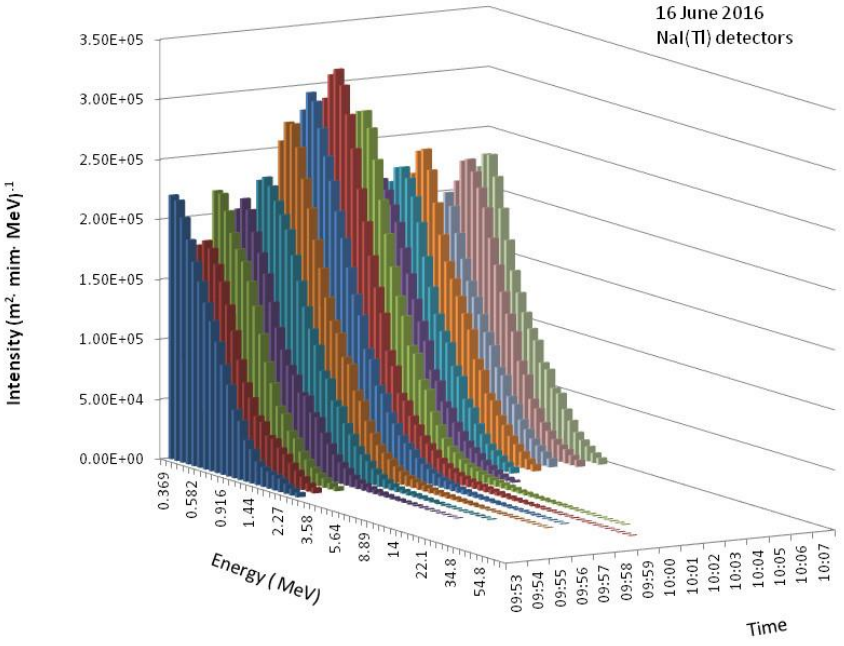
□

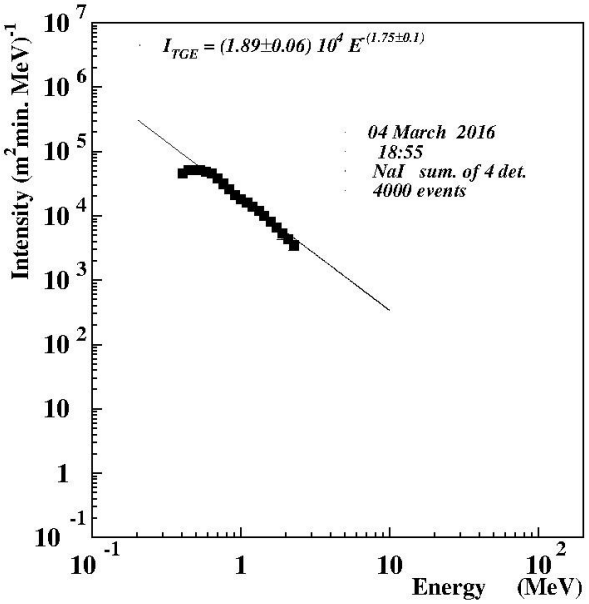

16 June 2016
NaI(Tl) detectors
Intensity (m² mim MeV)
3.50E+05
3.00E+05
2.50E+05
2.00E+05
1.50E+05
1.00E+05
5.00E+04
0.00E+00
0.369
0.582
0.916
1.44
2.27
3.58
5.64
8.89
14
22.1
34.8
54.8
Energy (MeV)
09:53
09:55
09:57
09:59
10:01
10:03
10:05
10:07
Time

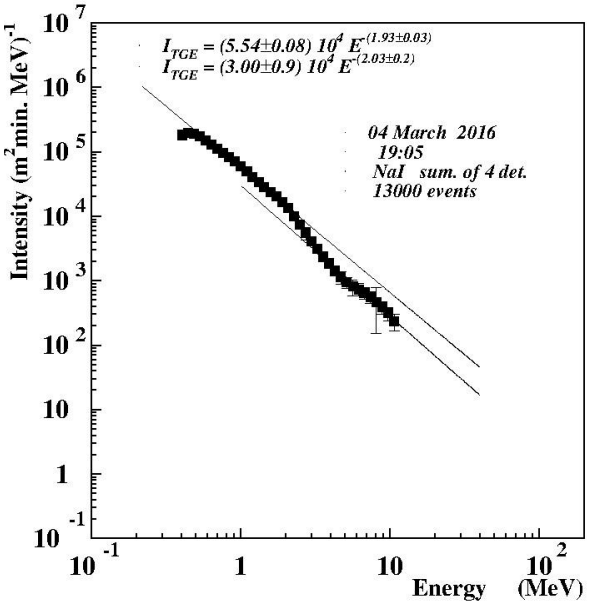

04 June 2016
NaI(Tl) detectors
Intensity (m-2· mim· MeV)-1
4.00E+05
3.50E+05
3.00E+05
2.50E+05
2.00E+05
1.50E+05
1.00E+05
5.00E+04
0.00E+00
0.404
0.637
1
1.58
2.49
3.92
6.18
9.74
15.3
24.2
38.1
60
Energy (MeV)
01:12
01:13
01:14
01:15
01:16
01:17
01:18
01:19
01:20
01:21
01:22
01:23
01:24
01:25
01:26
01:27
01:28
01:29
01:30
Time

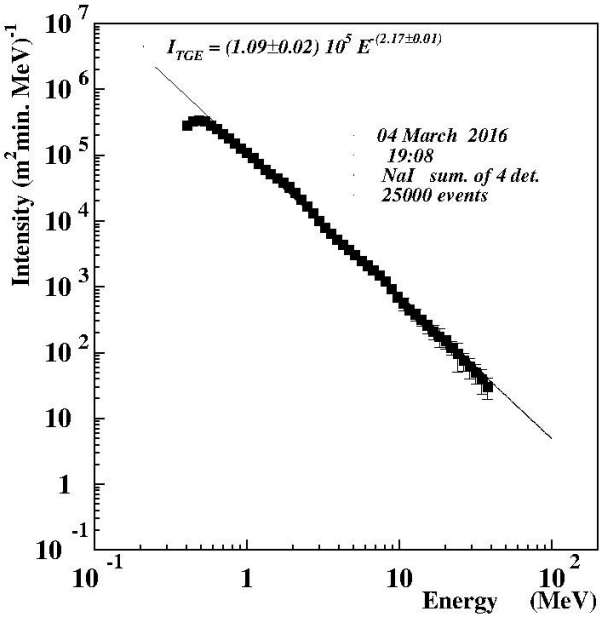

08 June 2016
NaI(Tl) detectors
Intensity (m-2· mim· MeV)-1
1.80E+05
1.60E+05
1.40E+05
1.20E+05
1.00E+05
8.00E+04
6.00E+04
4.00E+04
2.00E+04
0.00E+00
0.404
0.637
1
1.58
2.49
3.92
6.18
9.74
15.3
24.2
38.1
60
Energy (MeV)
11:28
11:30
11:32
11:34
11:36
11:38
11:40
11:42
11:44
11:46
11:48
Time


11 June 2016
NaI(Tl) detectors
Intensity (m-2· mim· MeV)-1
3.00E+05
2.50E+05
2.00E+05
1.50E+05
1.00E+05
5.00E+04
0.00E+00
0.369
0.531
0.764
1.1
1.58
2.27
3.27
4.71
6.77
9.74
14
20.2
Energy (MeV)
11:40
11:41
11:42
11:43
11:44
11:45
11:46
11:47
11:48
11:49
11:50
11:51
11:52
11:53
11:54
11:55
Time

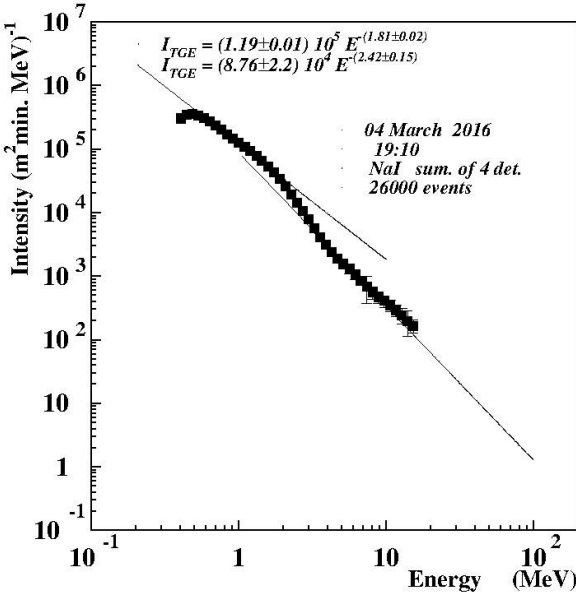

16 June 2016
NaI(Tl) detectors
Intensity (m-2· mim· MeV)-1
3.50E+05
3.00E+05
2.50E+05
2.00E+05
1.50E+05
1.00E+05
5.00E+04
0.00E+00
0.369
0.582
0.916
1.44
2.27
3.58
5.64
8.89
14
22.1
34.8
54.8
Energy (MeV)
09:53
09:54
09:55
09:56
09:57
09:58
09:59
10:00
10:01
10:02
10:03
10:04
10:05
10:06
10:07
Time

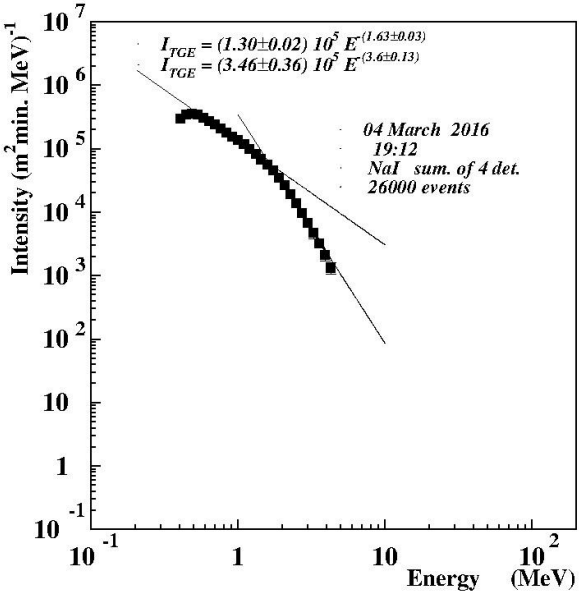


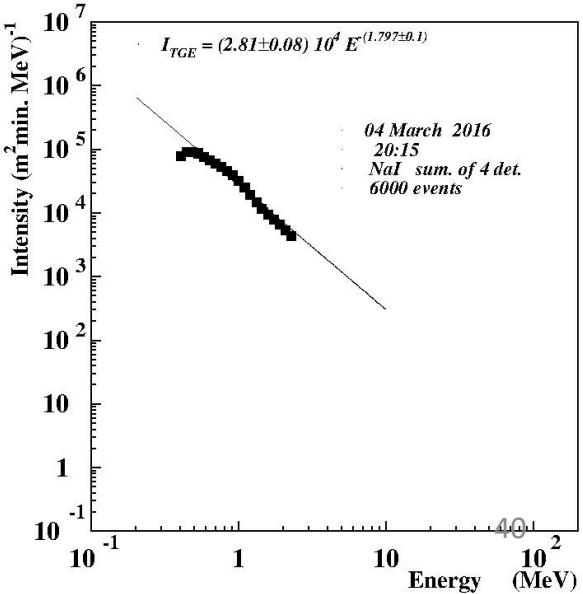


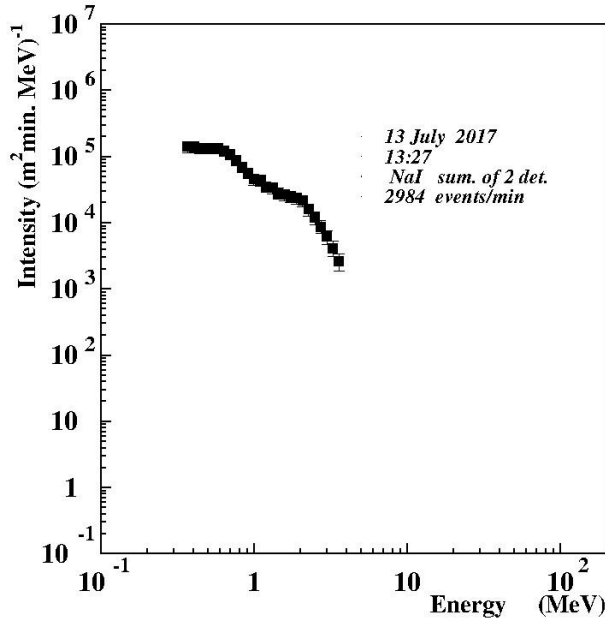


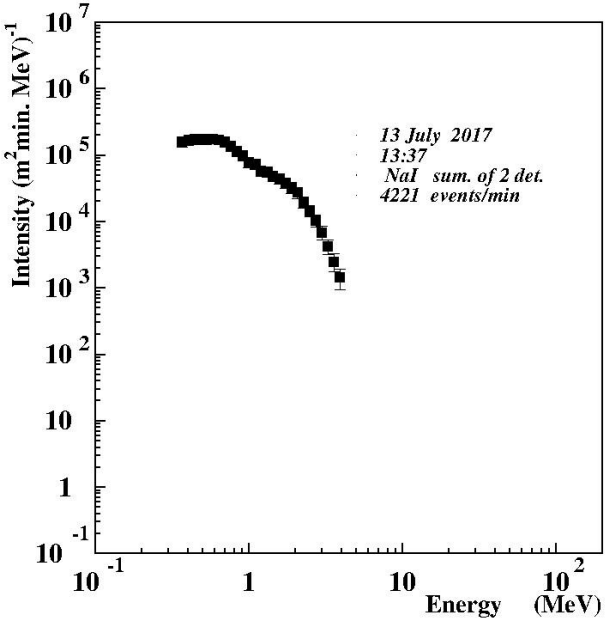
Dynamics of TGE on March 4, note the symmetry of start and decay!

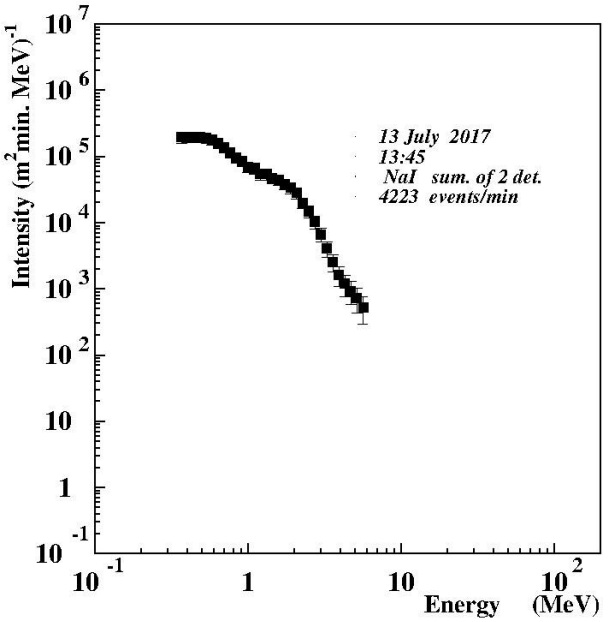


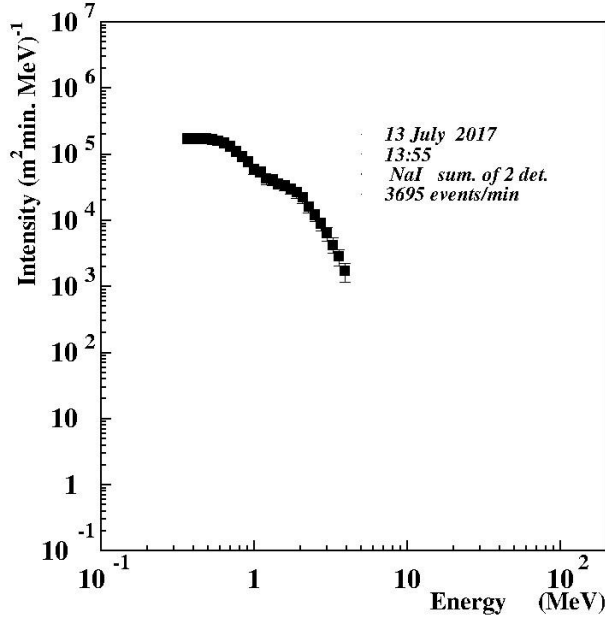


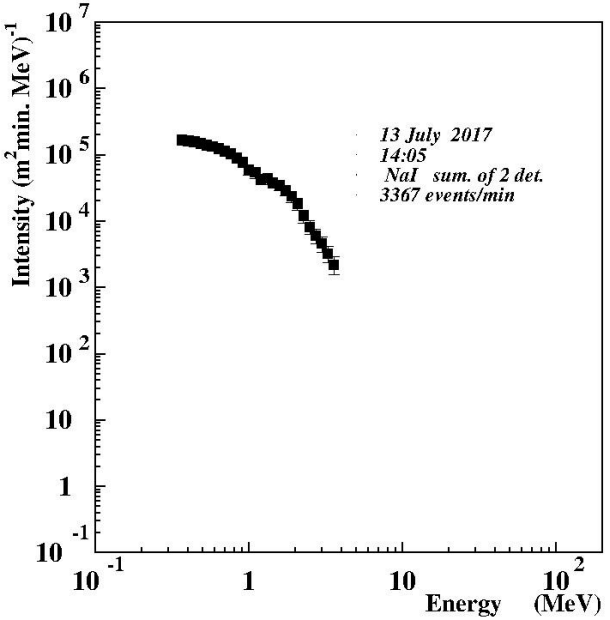


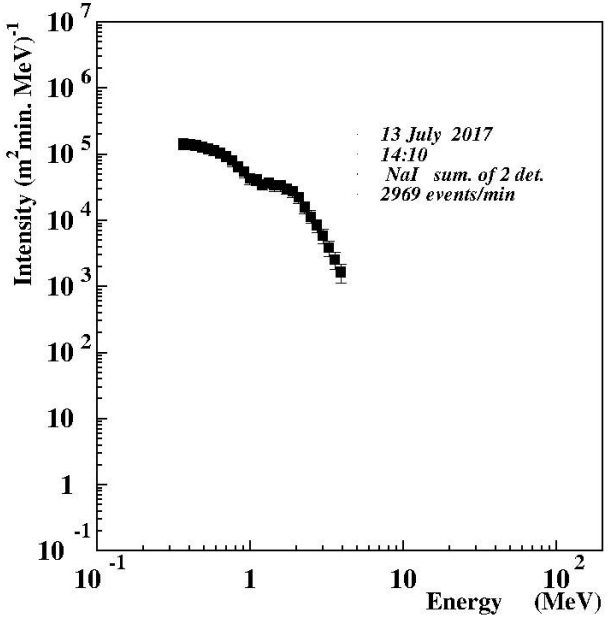

13 July 2017
13:27
NaI sum. of 2 det.
2984 events/min
Intensity (m2min. MeV)-1
Energy (MeV)

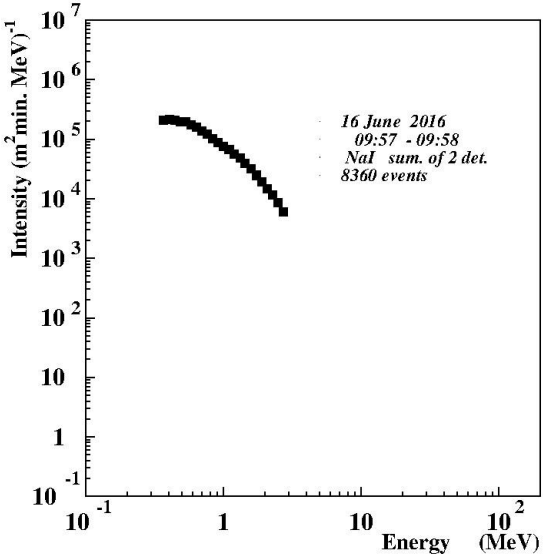

13 July 2017
13:37
NaI sum. of 2 det.
4221 events/min
Intensity (m2min. MeV)-1
Energy (MeV)

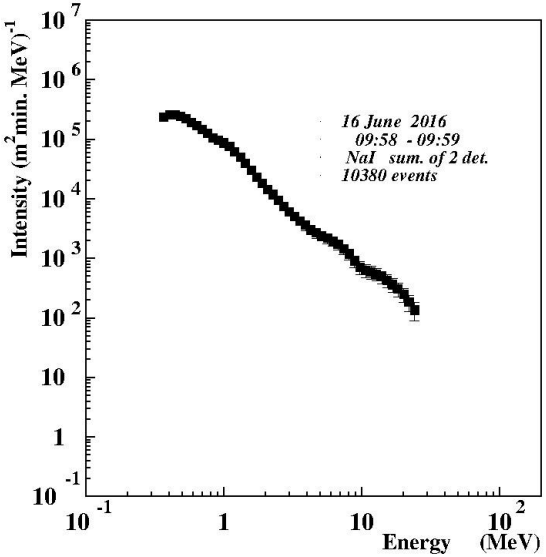

13 July 2017
13:45
NaI sum. of 2 det.
4223 events/min
Intensity (m2min. MeV)-1
Energy (MeV)

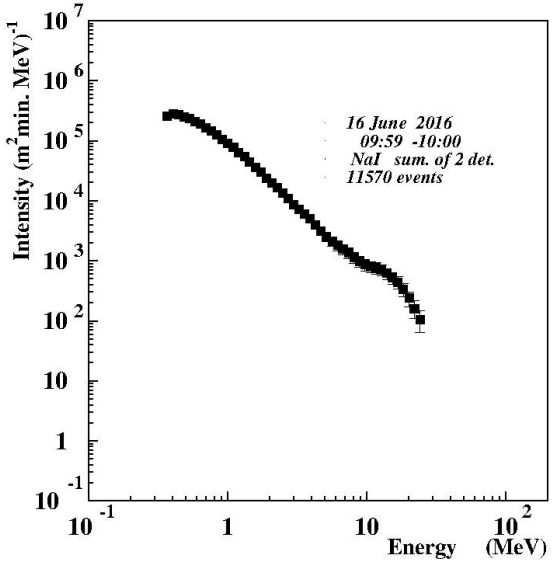

13 July 2017
13:55
NaI sum. of 2 det.
3695 events/min
Intensity (m2min. MeV)-1
Energy (MeV)

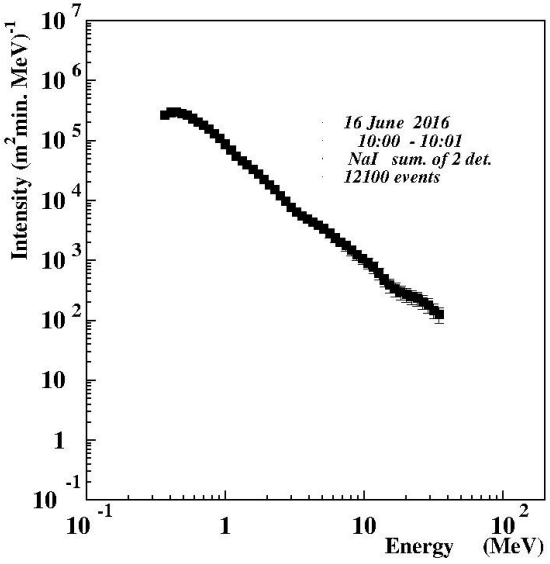

13 July 2017
14:05
NaI sum. of 2 det.
3367 events/min
Intensity (m2min. MeV)-1
Energy (MeV)

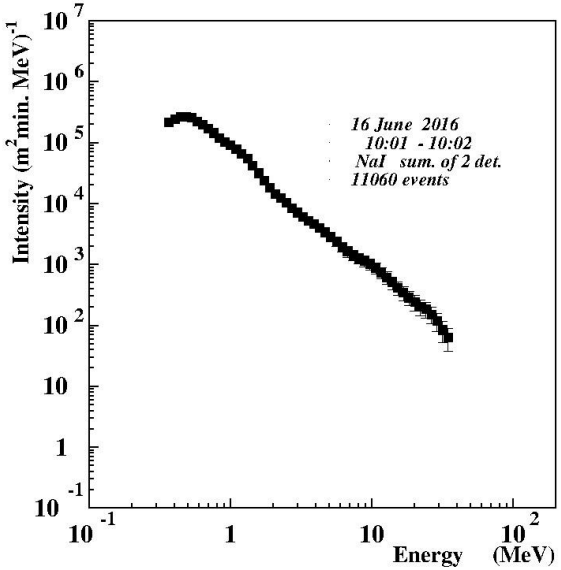

13 July 2017
14:10
NaI sum. of 2 det.
2969 events/min
Intensity (m2min. MeV)-1
Energy (MeV)

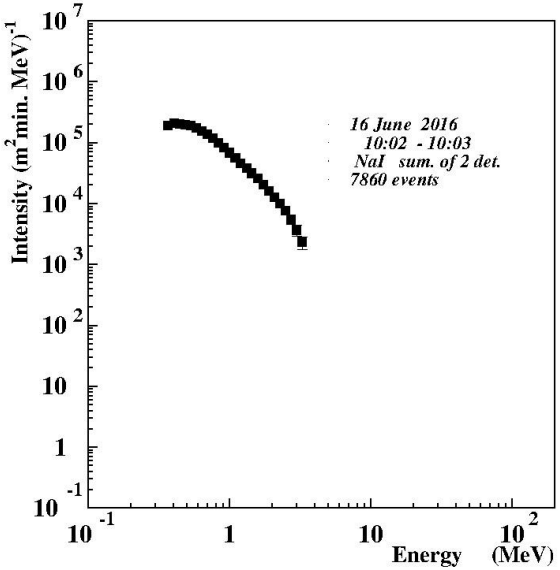

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
09:57 - 09:58
NaI sum. of 2 det.
8360 events


Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
09:58 - 09:59
NaI sum. of 2 det.
10380 events

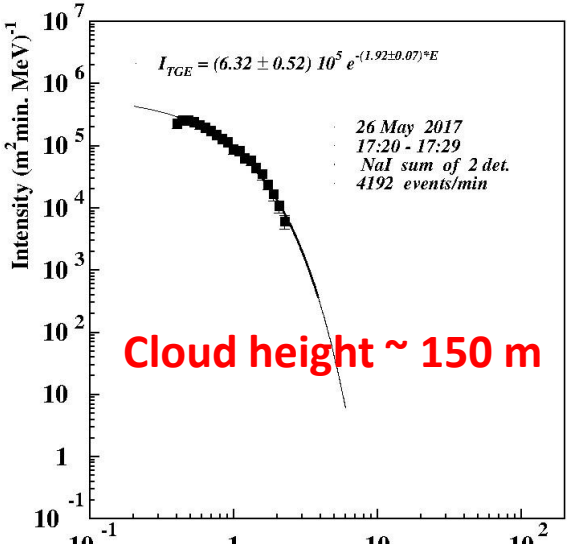

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
09:59 -10:00
NaI sum. of 2 det.
11570 events

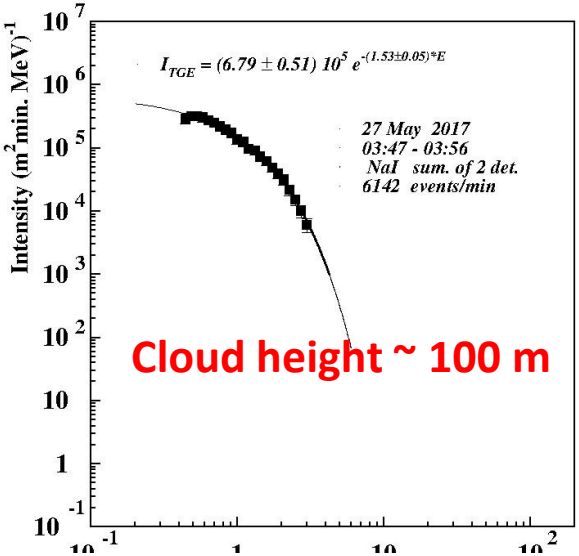

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
10:00 - 10:01
NaI sum. of 2 det.
12100 events

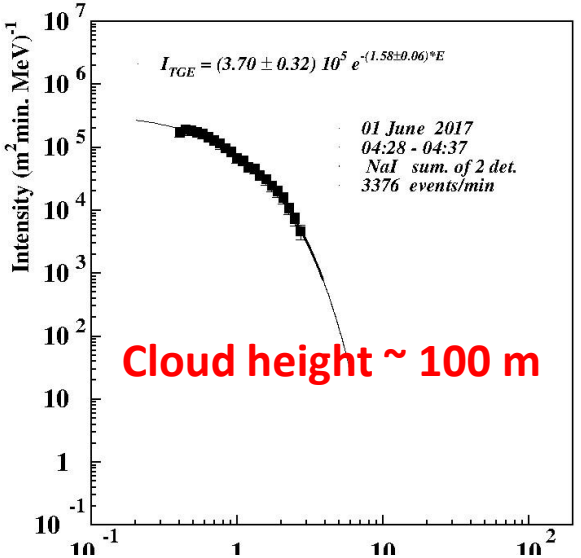

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
10:01 - 10:02
NaI sum. of 2 det.
11060 events

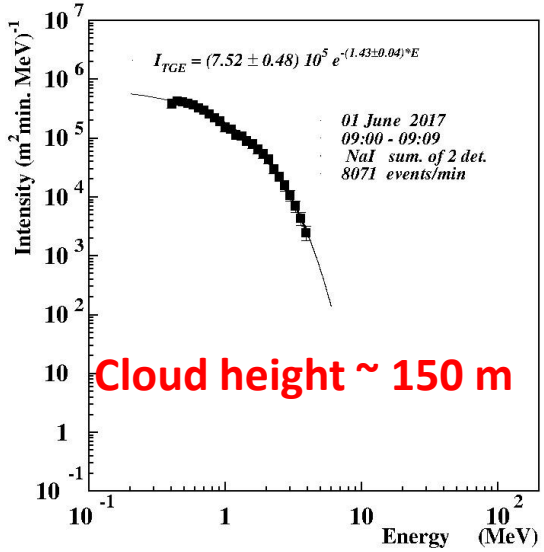

Intensity (m^{2}min. MeV)$^{-1}$
Energy (MeV)
16 June 2016
10:02 - 10:03
NaI sum. of 2 det.
7860 events

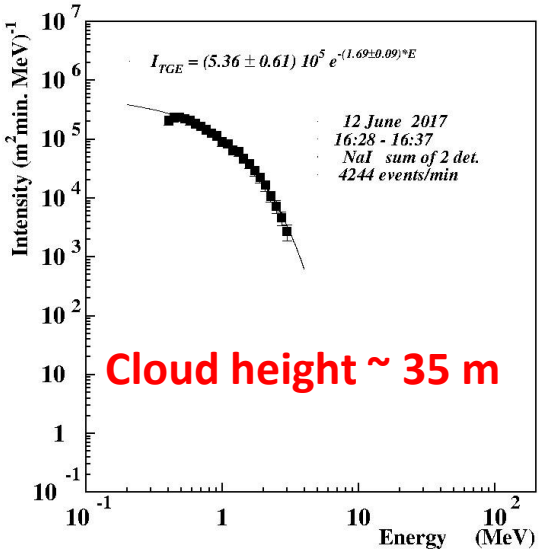
Intensity of TGE should be inversely proportional to cloud height and proportional to electrostatic field (a proxy of field in the cloud); however we need electromagnetic cascade simulations in the electrified atmosphere for firm inference!

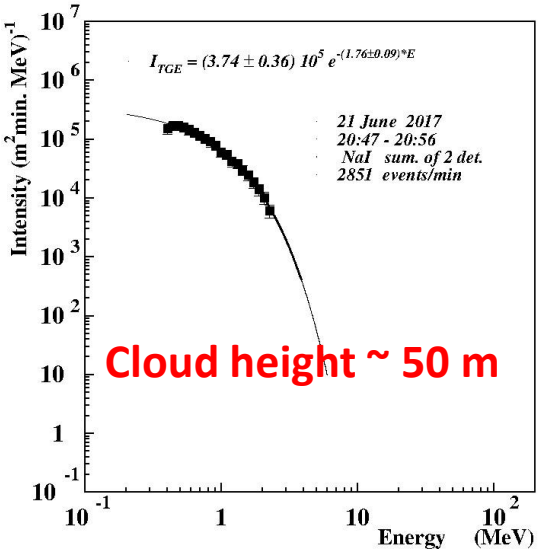












RB/TGE and MOS processes in thunderclouds

- TGE started with gamma ray flux having exponential energy spectrum up to 4 MeV;
- In few minutes the RB process started just above the detectors and maximal energy of gamma rays/electrons can reach tens of MeV;
- After lightning and rearranging of intracloud electric field the high energy part of spectra (RB) vanished very fast, however low energy gamma ray (below 4 MeV) still can come from distances above 1 km;
- Rather few highest energy gamma rays (up to 100 MeV) form the “tails” of TGE due to enhanced probability of the bremsstrahlung process of high energy electrons (100-300 MeV) in the strong electric field.
- Thundercloud is full of radiations the RB process started and ended in several places and keep low energy gamma ray flux sustainable at least in a part of cloud for a limited time.