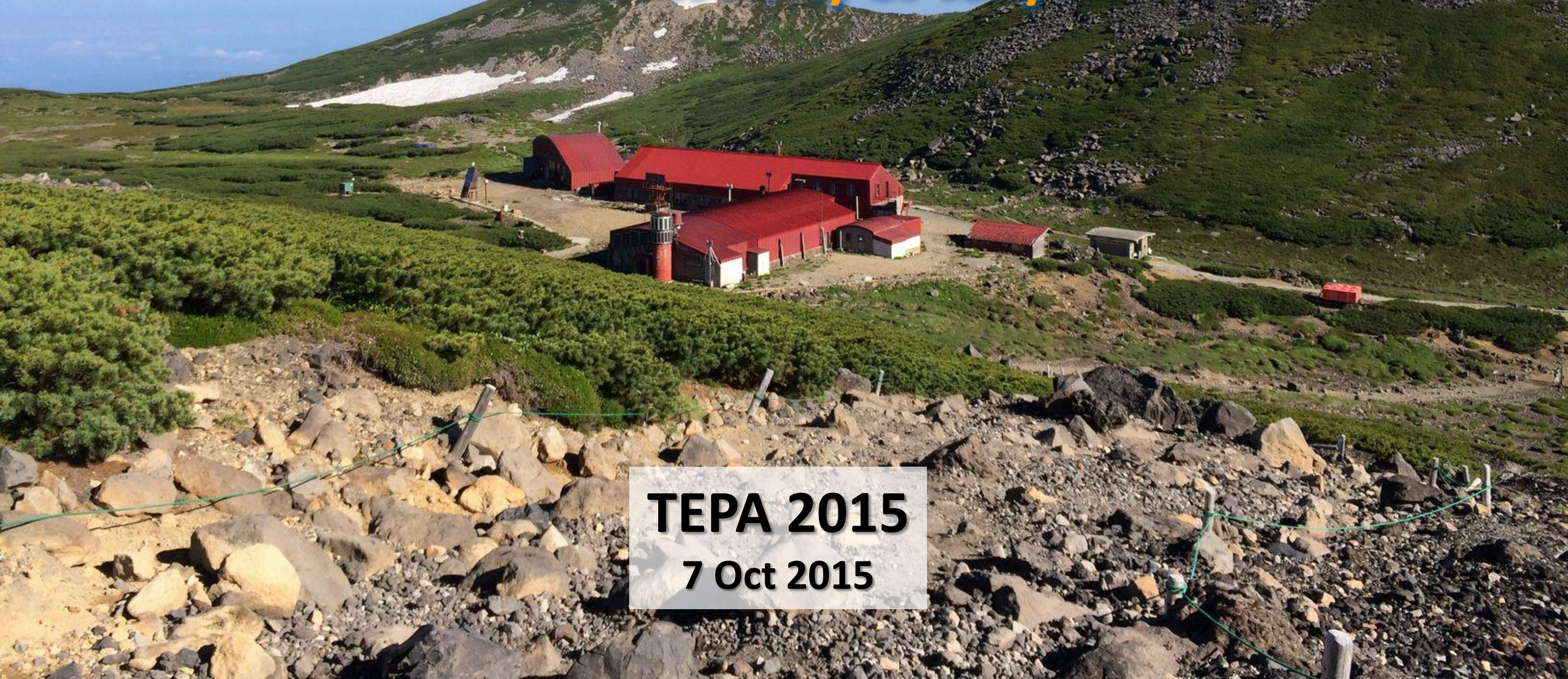
Thundercloud-related radiation bursts observed at a coastal area and a mountaintop using segmented organic scintillators

Yo KATO

The University of Tokyo



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Outline

1. Detector

- Antineutrino detector for reactor monitoring and PANDA project

2. Long bursts from thunderclouds

- Electron acceleration in thunderclouds and RREA model

3. Observation at two locations

- Ohi Power Station (coastal area) and Norikura Observatory (mountain area)

4. Observed bursts (Ohi) - 3 bursts

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- Thunder information, electric field, arrival direction and neutron component

7. Runaway electron source

- Estimation of energy and flux by Monte Carlo simulation

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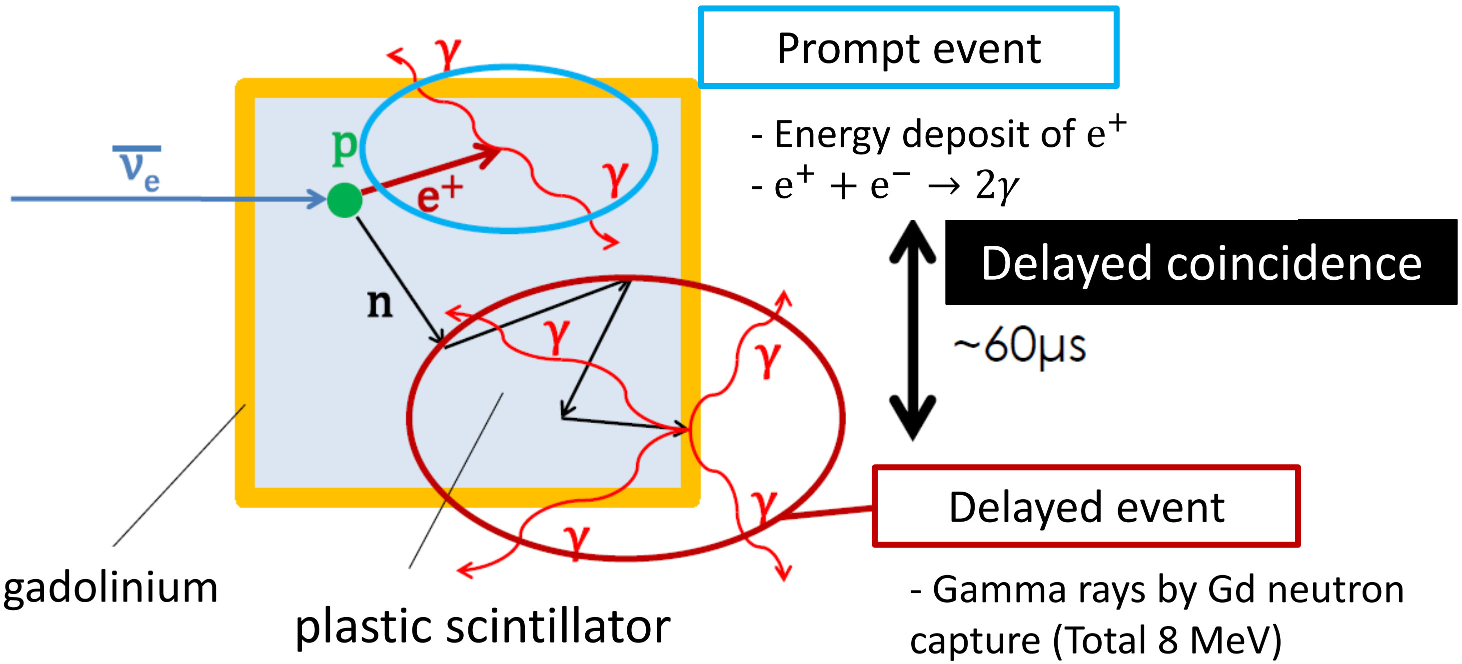
Antineutrino detector for reactor monitoring

IAEA's proposal :

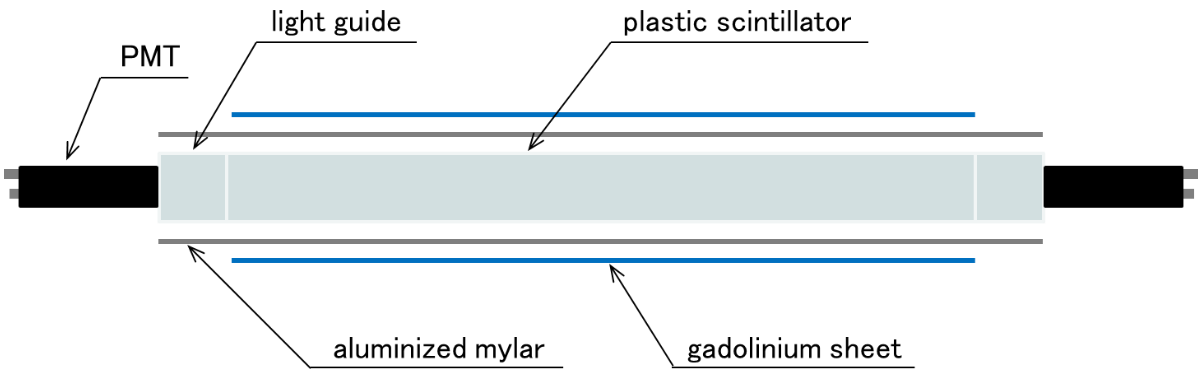
"Non-intrusive" inspection tool by antineutrino detection

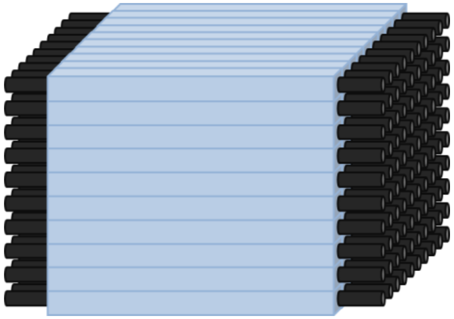
- Neutrinos cannot be shielded
- There's no alternative source of antineutrino

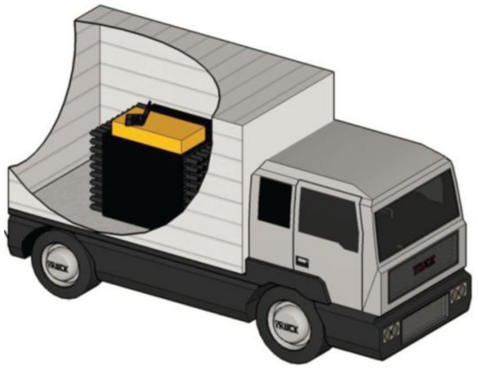


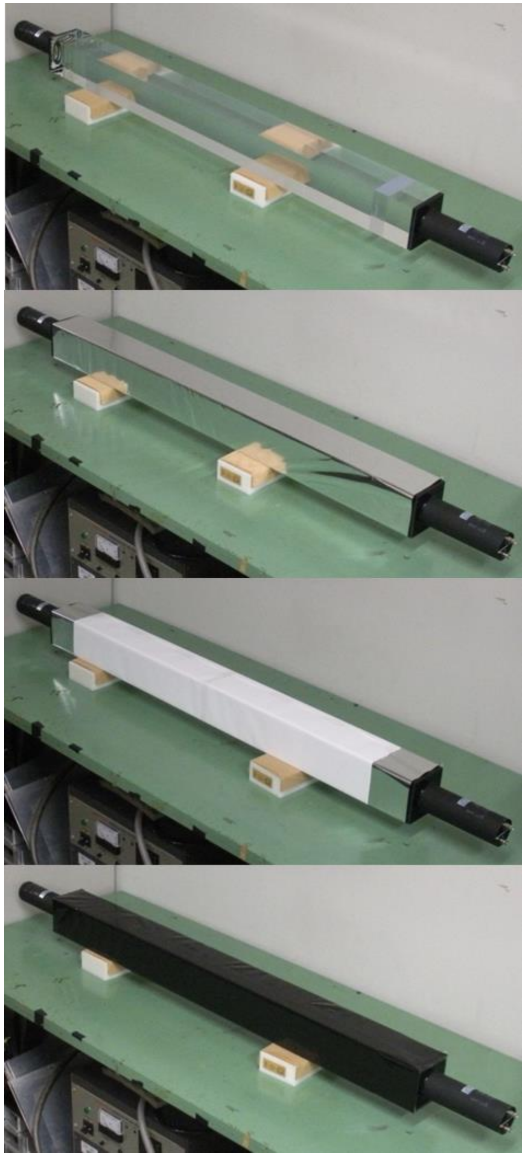
-> Monitor flux and spectrum of reactor antineutrino

PANDA (Plastic Anti-Neutrino Detector Array)





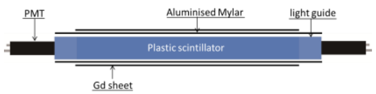


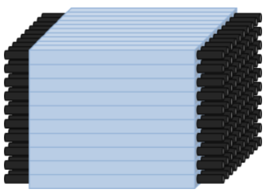


- Plastic scintillator bars wrapped with Gd film
- 2 inch PMT attached on both ends
- 10 × 10 segmented structure
- Measurement loaded on a 2-ton van

PANDA Project

Start of PANDA Project





1st prototype PANDA16

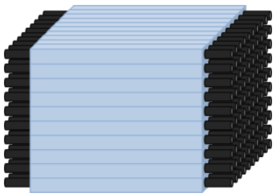
2nd prototype PANDA36

Deployed at a coastal area

3rd prototype PANDA64

Deployed at a mountaintop

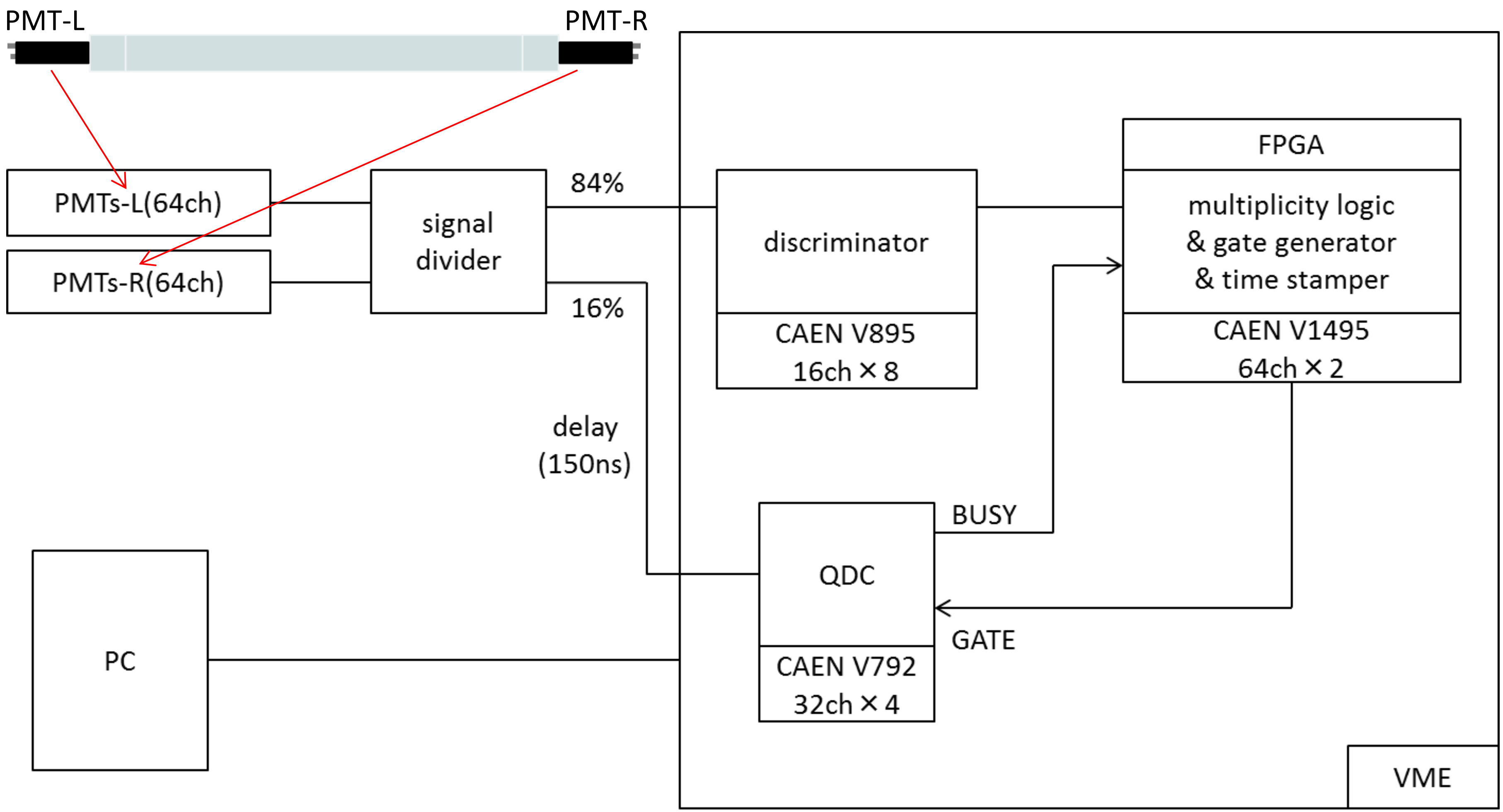
Full size PANDA100



Under development

2006 2007 2008 2009 2010 2011 2012 2013 2014 2015

Data acquisition system (PANDA64)



Calibration

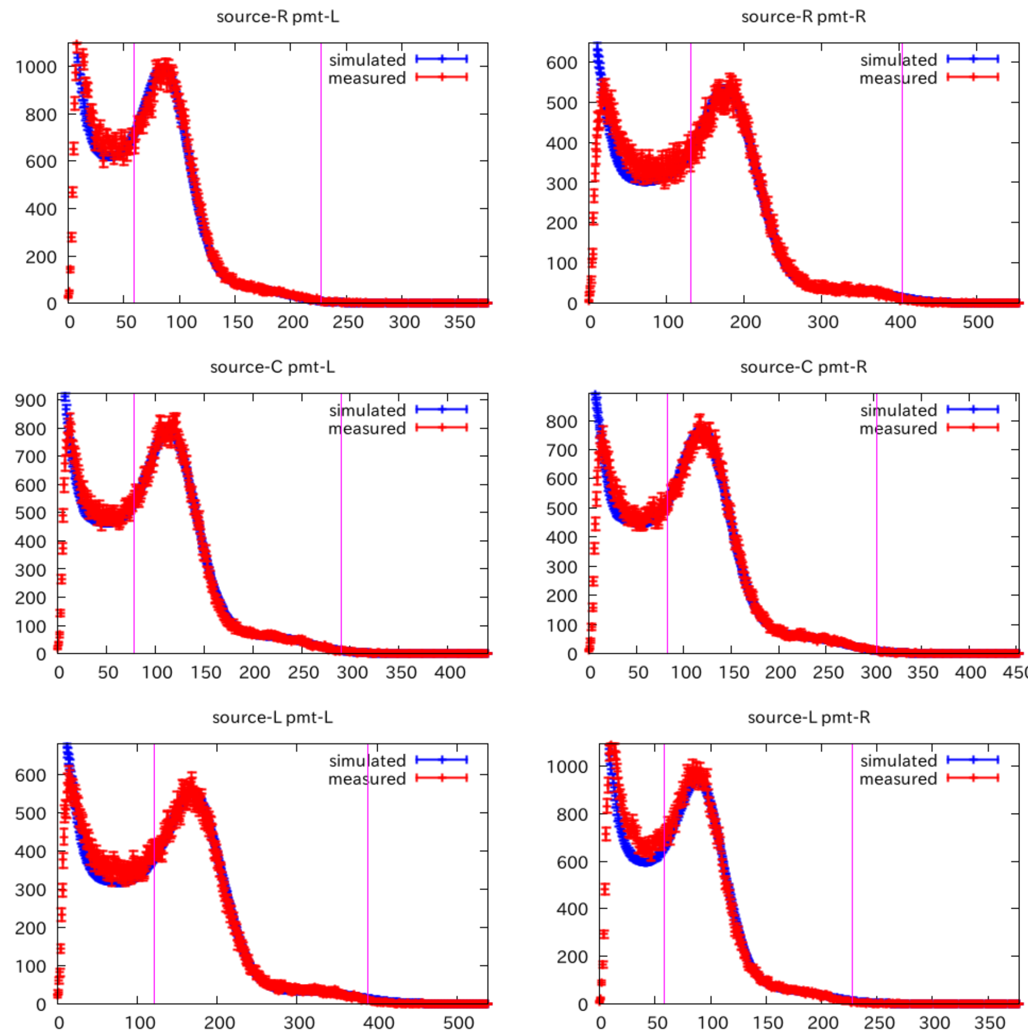
- ^{60}Co source
- 3 slits on every modules (Left / Center / Right)

-> Reconstruction of
- energy deposit
- position

module-1 : chi2/dof:0.924412

width$_{left}$:4.59278 ,a$_{left}$:3.02529 ,b$_{left}$:11.4291 : width$_{right}$:4.40957 ,a$_{right}$:3.06285 ,b$_{right}$:8.10224 : d:0.695578 l:589.274

heights(source:L):5.52887 ,heights(source:C):5.63373 ,heights(source:R):5.52083



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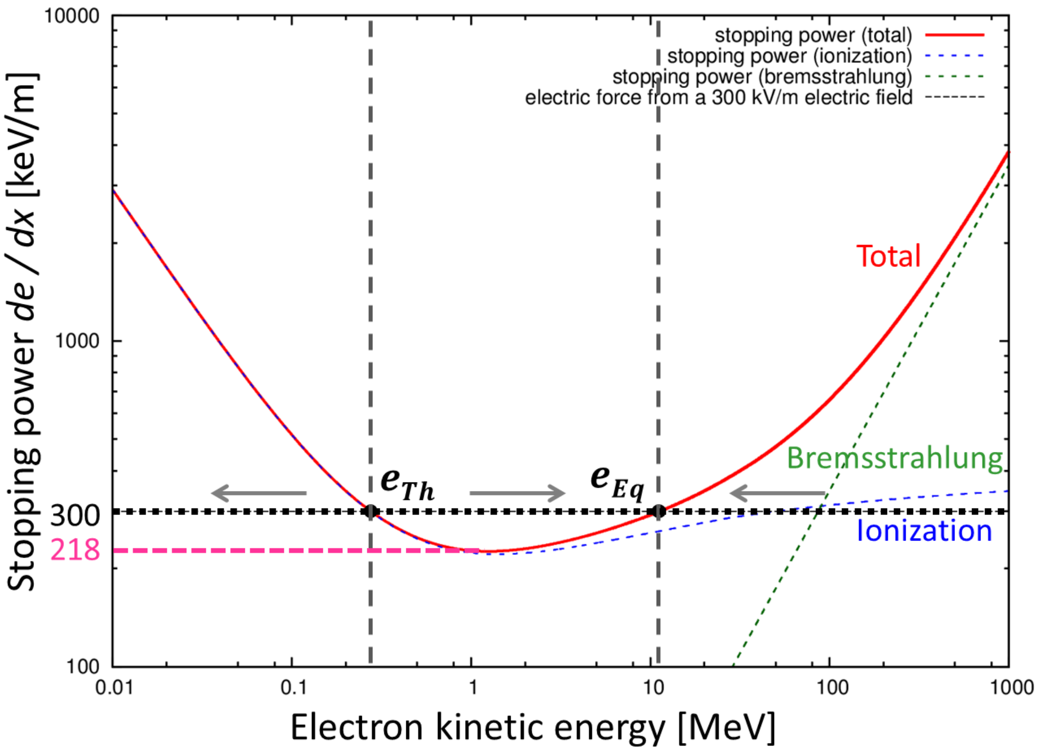
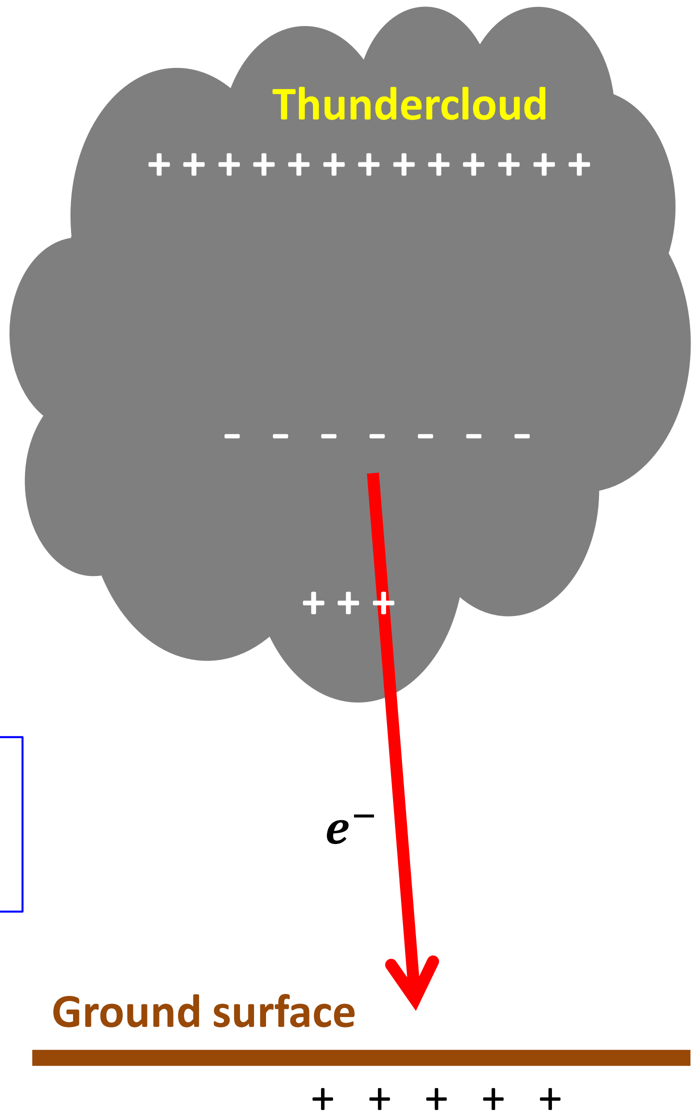
Electron acceleration in thunderclouds





Relativistic Runaway Electron Avalanche
(RREA model)

Seed electron -> Acceleration (+ γ-rays)
-> Knock-on electron -> Acceleration (+ γ-rays)
-> Knock-on electron -> ......

Radiation bursts related to thunder activity

Short bursts : below milliseconds

- known as TGFs (Terrestrial Gamma-ray Flash) from satellites
- also observed at the ground surface by natural lightning or rocket-triggered lightning
- correlated to lightning discharges

Long bursts : a few seconds to more than 10 minutes

- known as TGEs or gamma-ray glows
- frequently observed at mountain areas, occasionally at coastal areas
- correlated to thunderclouds

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PANDA36 at coastal area (2011)

- 2nd prototype (36 modules)
- Ohi Power Station (coast of Sea of Japan, ~10 m above sea level)
- Nov 2011 to Jan 2012 (winter, 2 months)
- Measurement for reactor monitoring

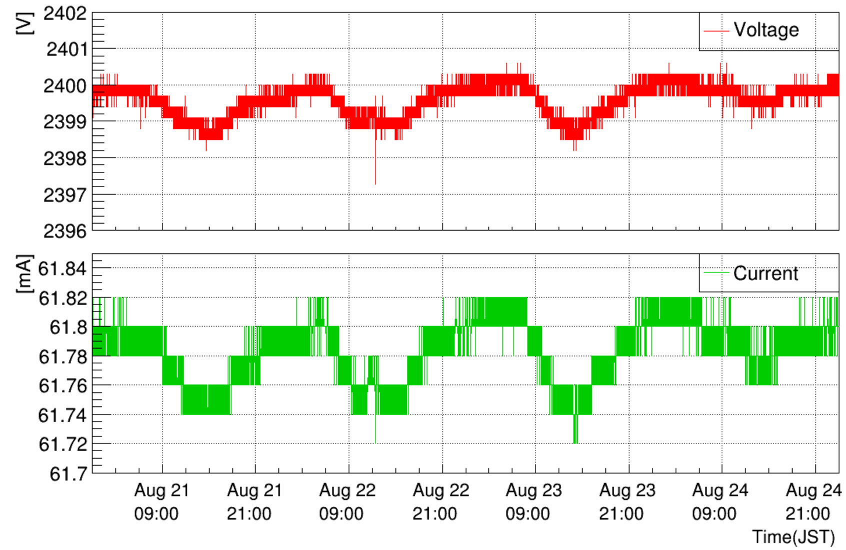
PANDA64 at mountain area (2014)

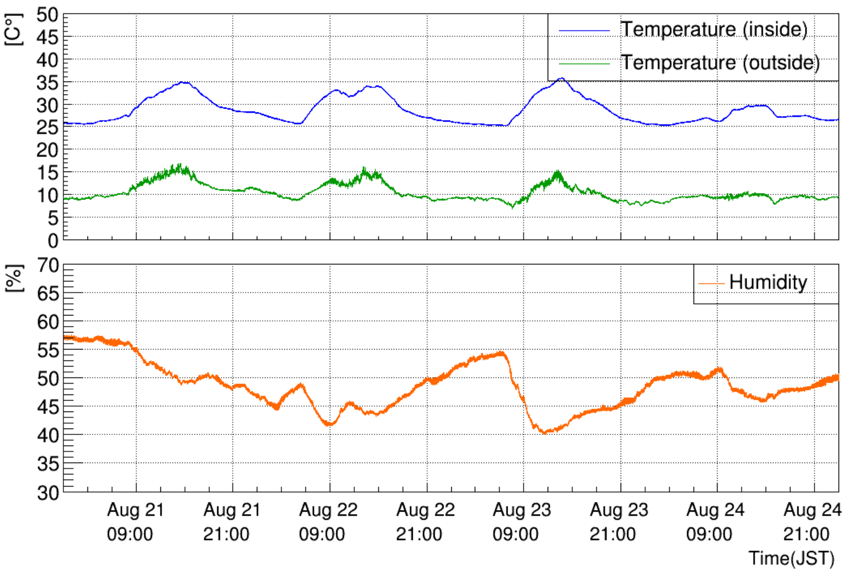
- 3rd prototype (64 modules)
- Norikura Observatory (mountaintop, 2770 m above sea level)
- Jul 2014 to Sep 2014 (summer, 2 months)
- Measurement for burst observation

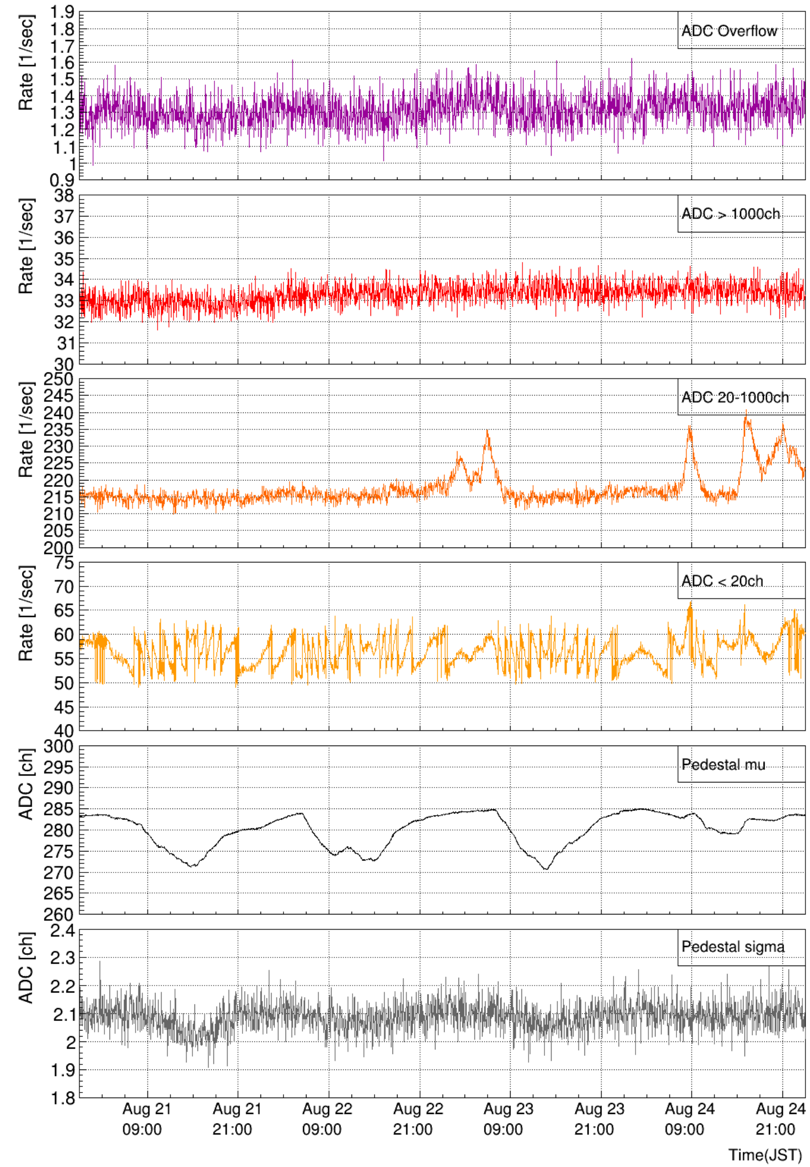
Observation 2011 & 2014

	Observation 2011	Observation 2014
Detector	PANDA36 (36 modules)	PANDA64 (64 modules)
Location	Ohi Power Station (sea level, 10m)	Norikura Observatory (high altitude, 2770m)
Season	2 months in winter	2 months in summer
Motivation	Reactor monitoring	Burst observation
Trigger	2 of inside 16 modules	1 of 64 modules

Detector monitoring







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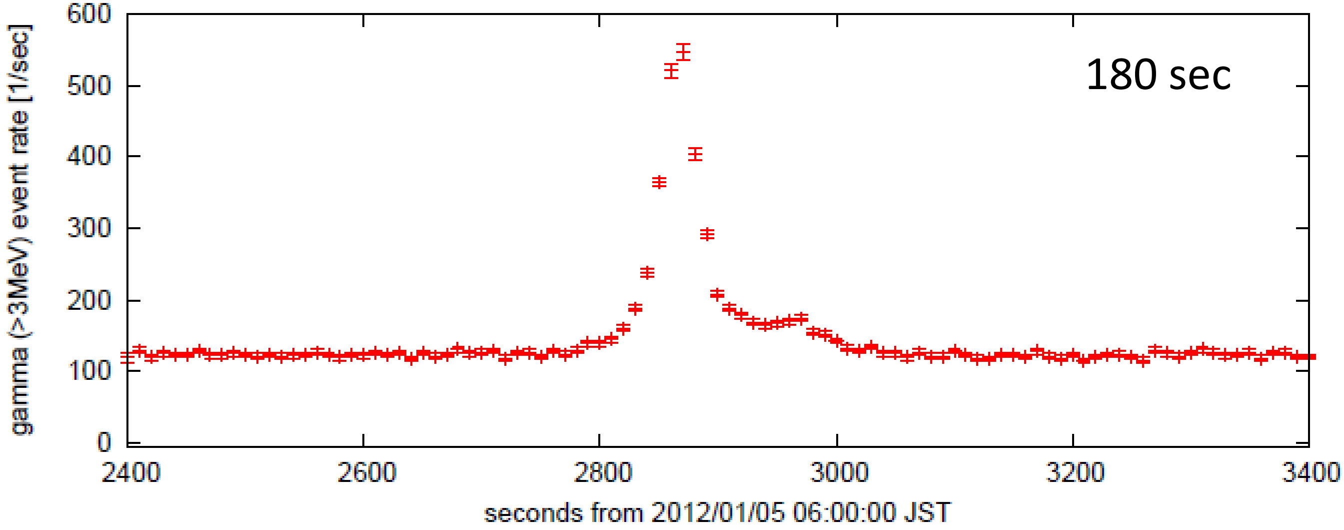
Search for burst candidates (Ohi/10m)

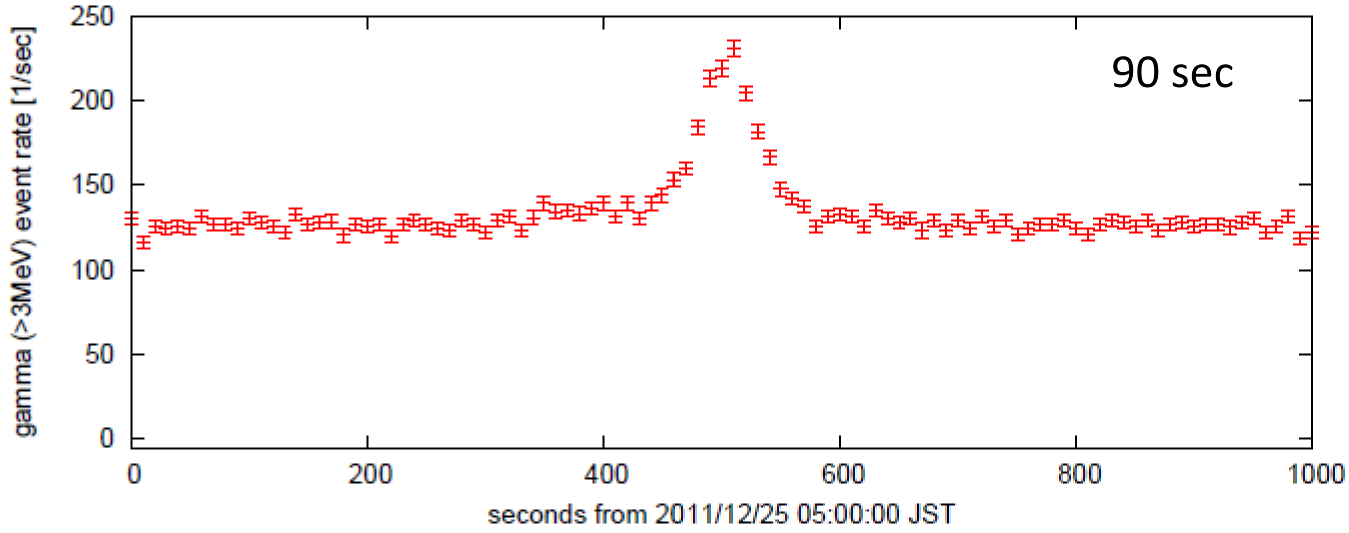
- Count rate (> 4 MeV) of 10-second time blocks
- 5σ excess for > 20 sec against average count rate

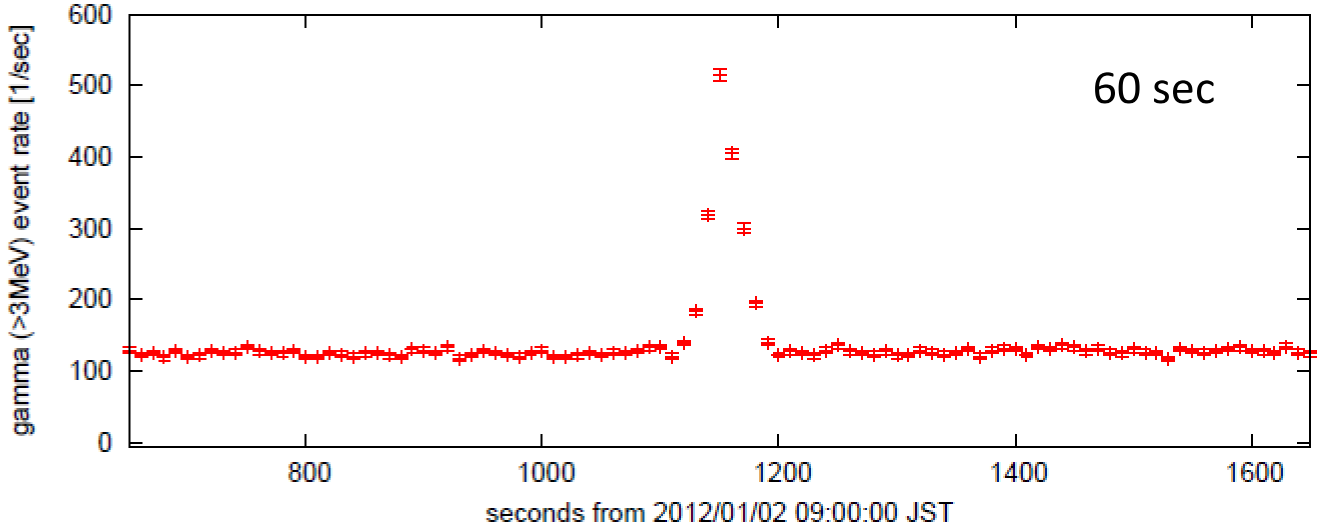


detector	date and time of the burst	peak event rate ($E_{tot} > 3\,\mathrm{MeV}$) [1/sec]
PANDA36	2011 12/25 05:07 JST	$(2.3 \pm 0.1) \times 10^2$
PANDA36	2012 01/02 09:19 JST	$(5.1 \pm 0.1) \times 10^2$
PANDA36	2012 01/05 06:46 JST	$(5.5 \pm 0.1) \times 10^2$

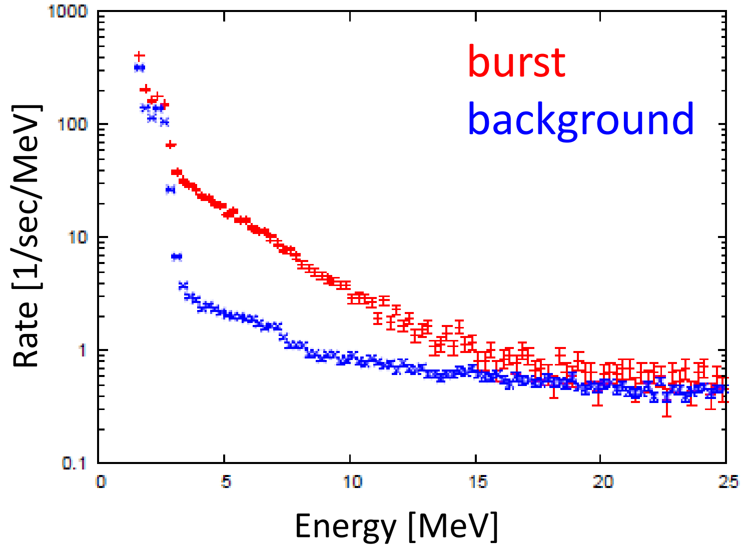
3 burst candidates were detected in 62 days

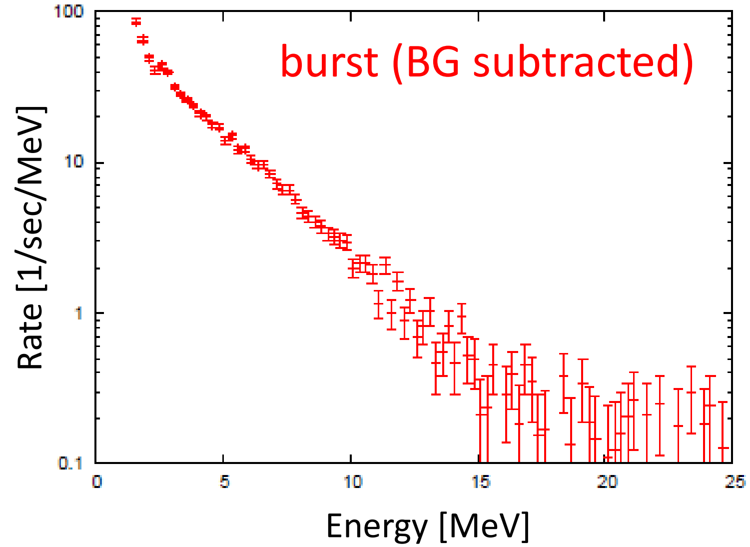
Search for burst candidates (Ohi/10m)

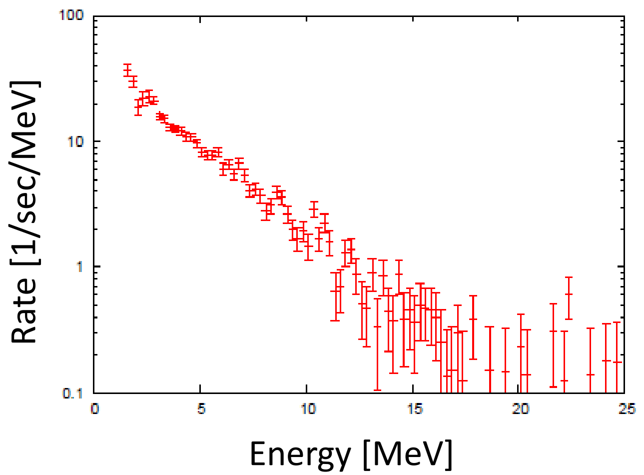


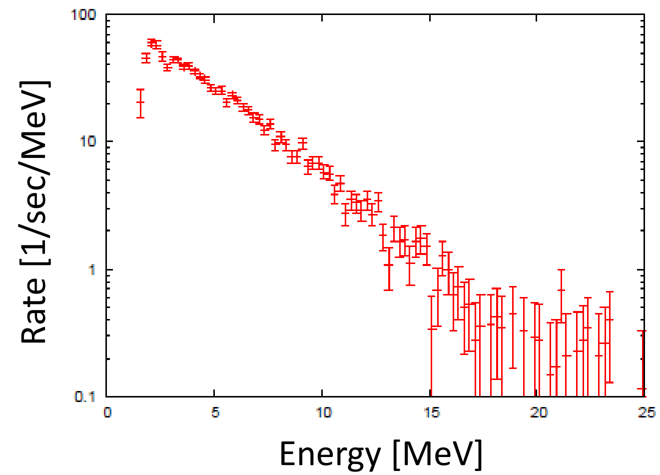


Energy spectrum (Ohi/10m)









Energy spectra extended up to ~15 MeV

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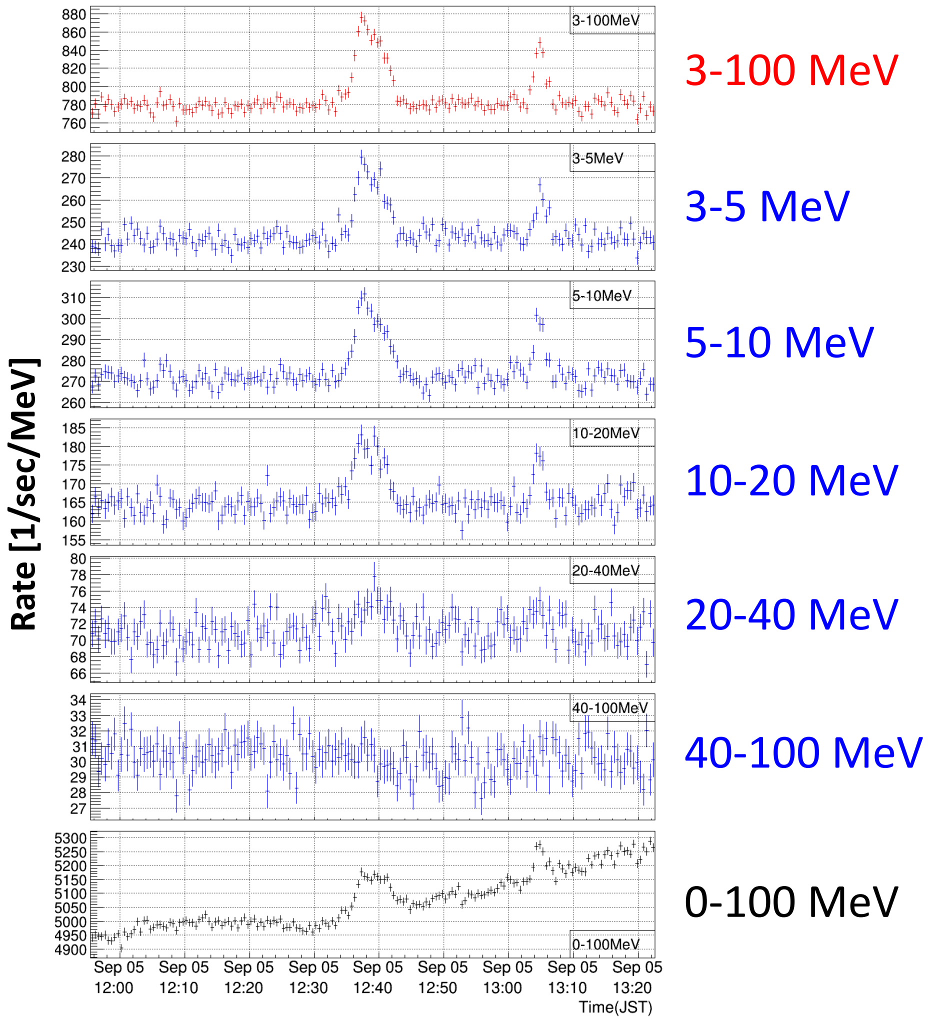
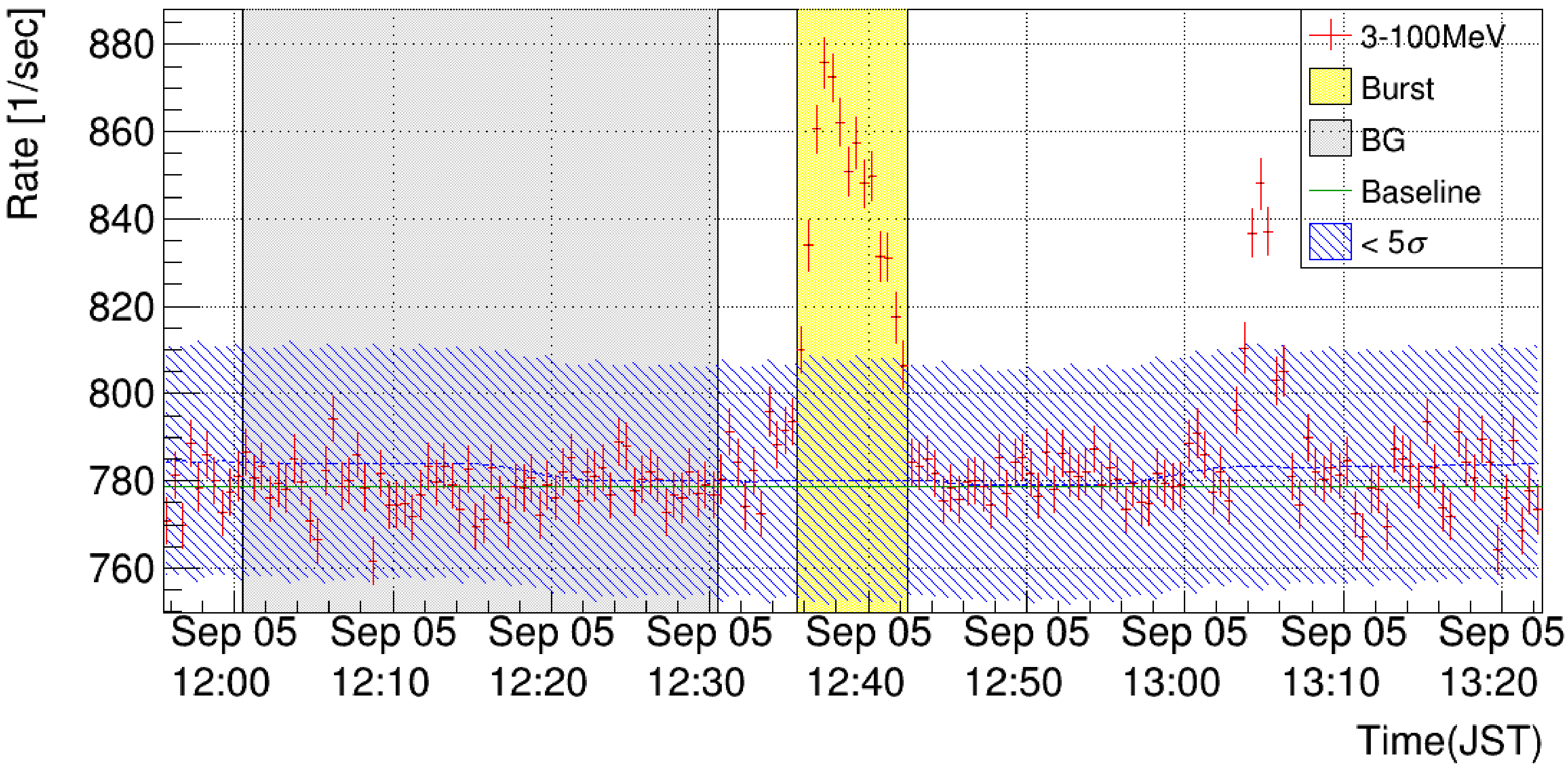
Count rate of multiple energy ranges



Count rate enhancements were seen in > 10 MeV range

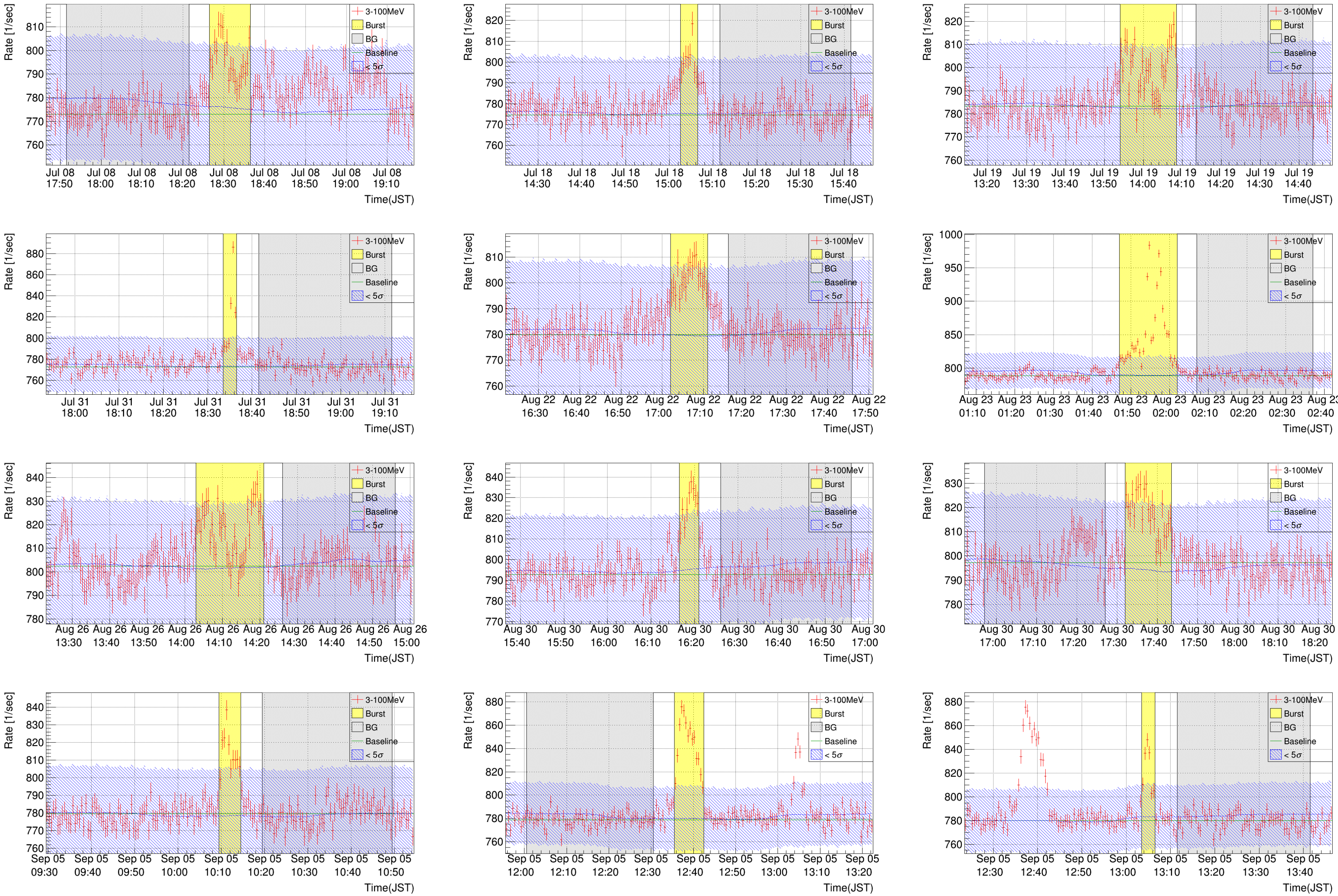
Search for burst candidates (Norikura/2770m)

- 3-100 MeV count rate of 30-second time blocks
- 5σ excess for > 1 min against 2-hour reference count rate



12 burst candidates were detected in 54 days

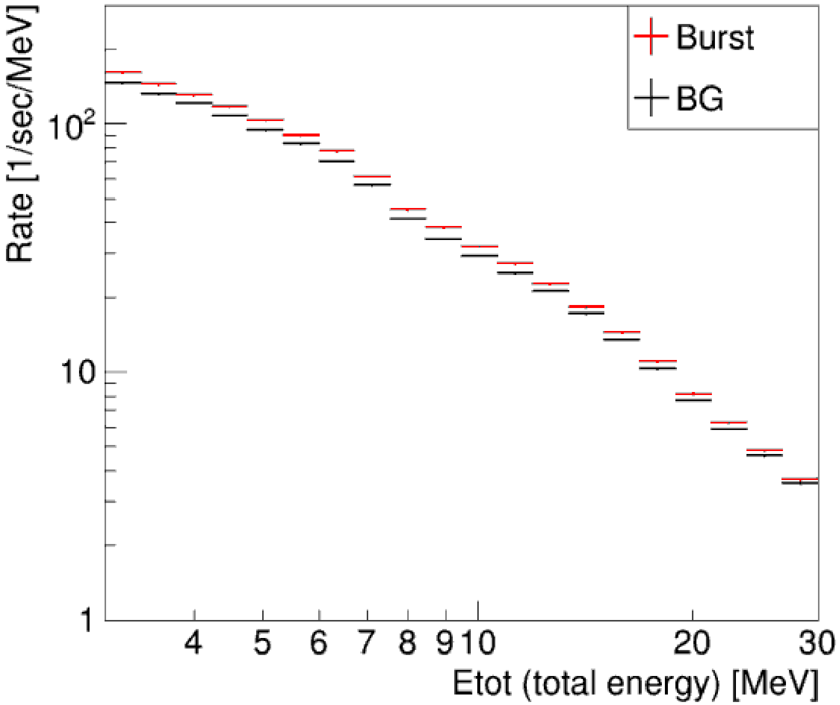
Search for burst candidates (Norikura/2770m)

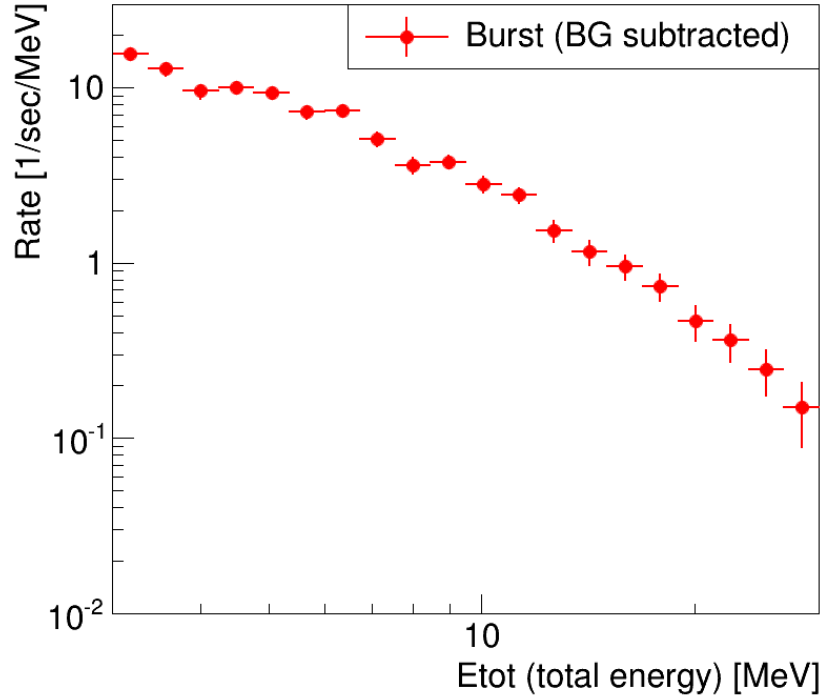


Search for burst candidates (Norikura/2770m)

Burst	Duration	Energy	Peak rate [/sec]	Mean rate [/sec]	Total count ($\times 10^3$)
burst20140708-1	10.0 min	15 MeV	38.0 ± 5.4	23.1 ± 1.4	12.95 ± 0.77
burst20140718-1	4.0 min	10 MeV	43.9 ± 5.8	26.3 ± 2.0	5.79 ± 0.45
burst20140719-1	14.5 min	10 MeV	35.3 ± 5.6	15.8 ± 1.2	12.42 ± 0.96
burst20140731-1	3.0 min	15 MeV	113.4 ± 5.6	48.0 ± 2.3	7.94 ± 0.39
burst20140822-1	9.0 min	15 MeV	31.0 ± 5.4	22.1 ± 1.4	11.10 ± 0.72
burst20140823-1	15.0 min	25 MeV	195.3 ± 6.3	62.2 ± 1.2	51.65 ± 1.02
burst20140826-1	18.0 min	10 MeV	34.8 ± 5.8	15.2 ± 1.2	14.54 ± 1.12
burst20140830-1	4.5 min	20 MeV	45.0 ± 5.5	33.7 ± 2.0	8.22 ± 0.48
burst20140830-2	11.5 min	15 MeV	32.5 ± 5.6	20.6 ± 1.4	12.65 ± 0.83
burst20140905-1	5.0 min	15 MeV	58.9 ± 5.6	34.7 ± 1.9	9.49 ± 0.51
burst20140905-2	7.0 min	25 MeV	97.0 ± 5.9	64.8 ± 1.6	24.70 ± 0.62
burst20140905-3	3.0 min	15 MeV	68.2 ± 5.7	43.9 ± 2.4	7.02 ± 0.38

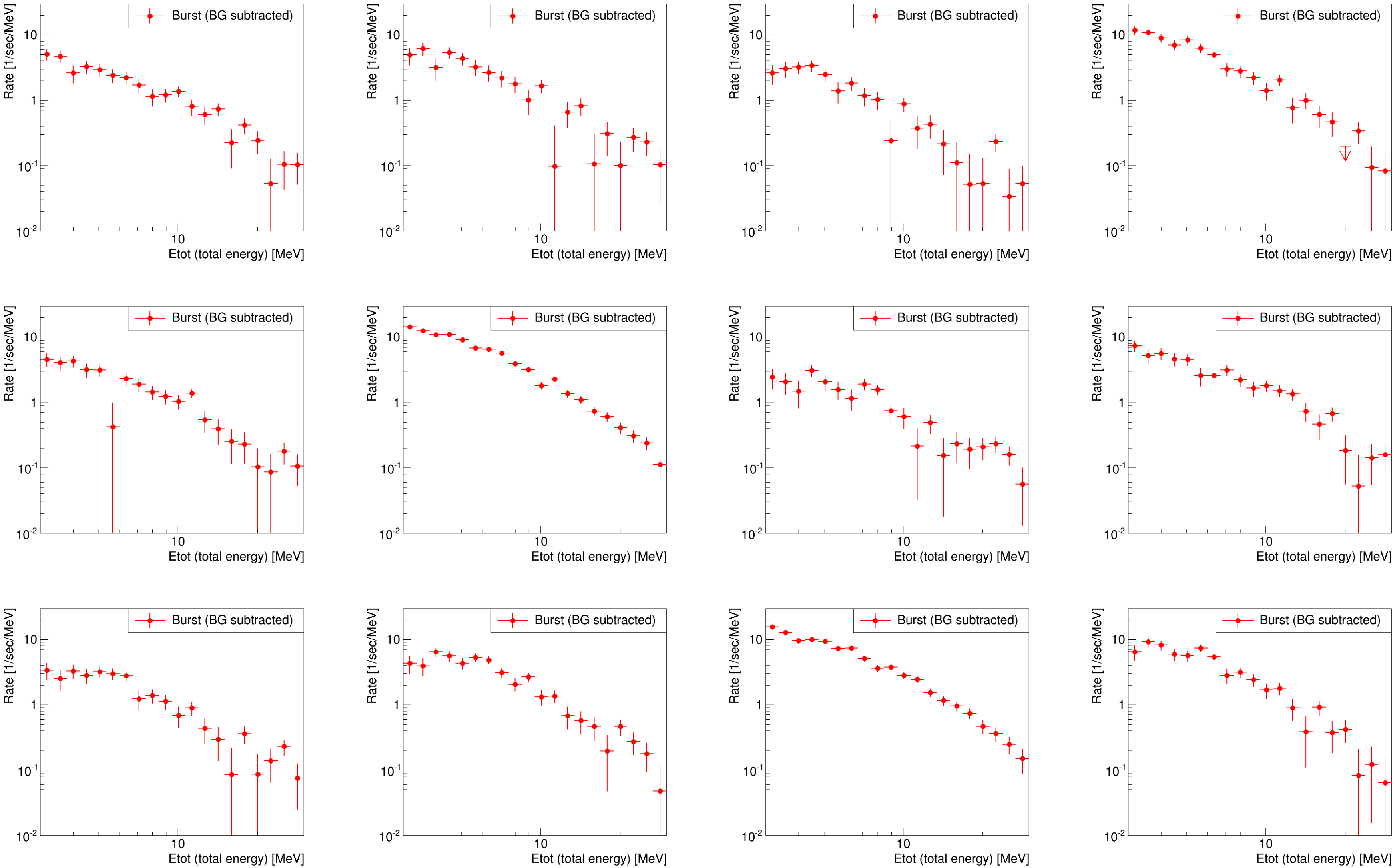
Energy spectrum (Norikura/2770m)





Energy spectra extended up to ~30 MeV

Energy spectrum (Norikura/2770m)



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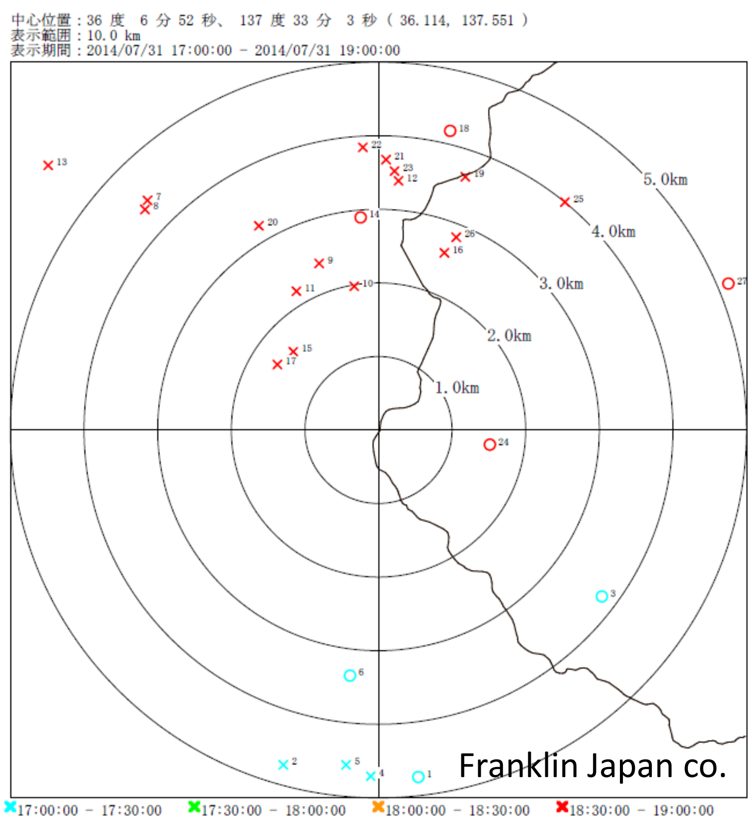
Thunder information

JLDN

(Franklin Japan co.)

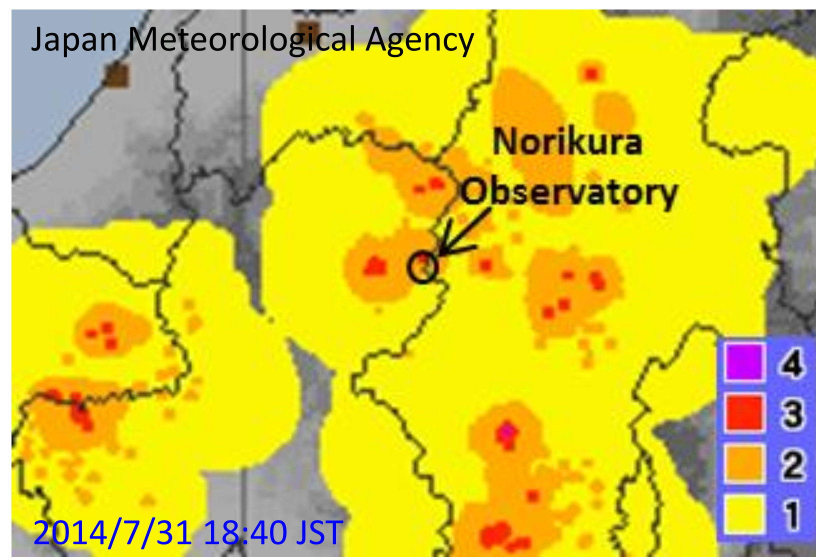
- Lightning detection system
- Time and location of lightning



Thunder Nowcast

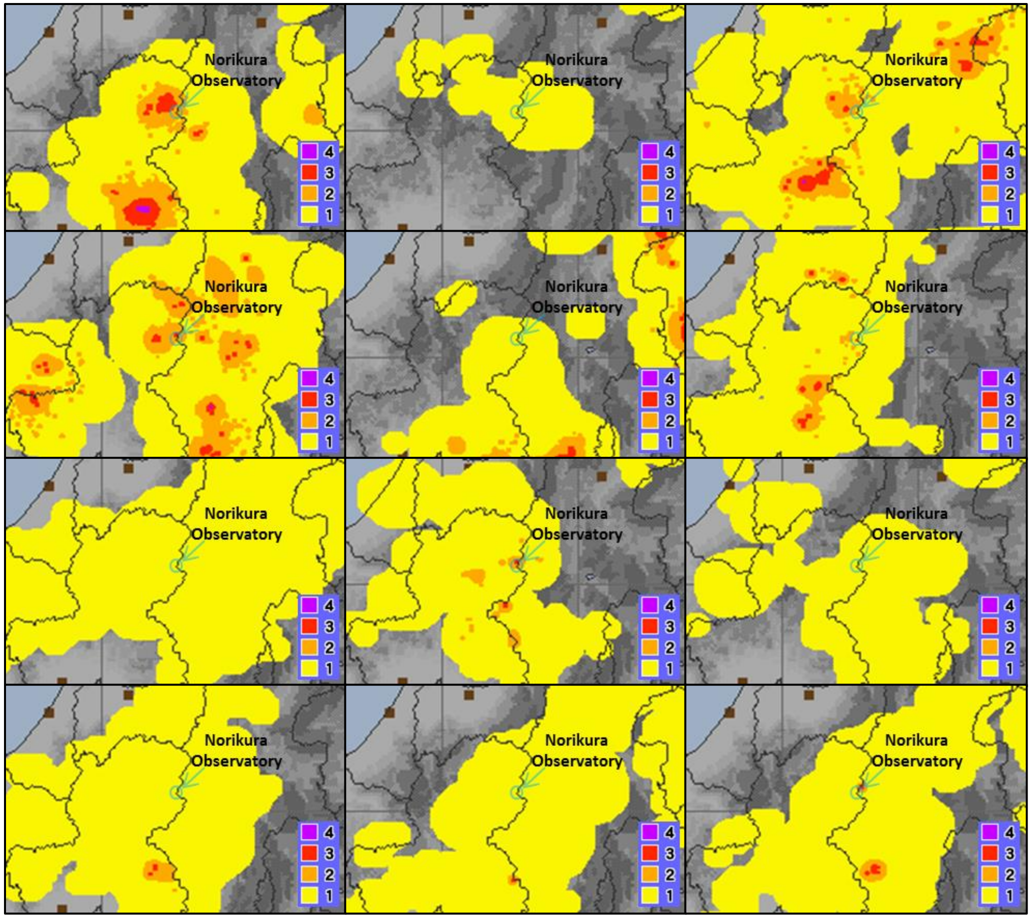
(Japan Meteorological Agency)

- Lightning detection system
- Meteorological radars
- Thunder activity in 4 levels
- 1 km grid
- every 10 minutes



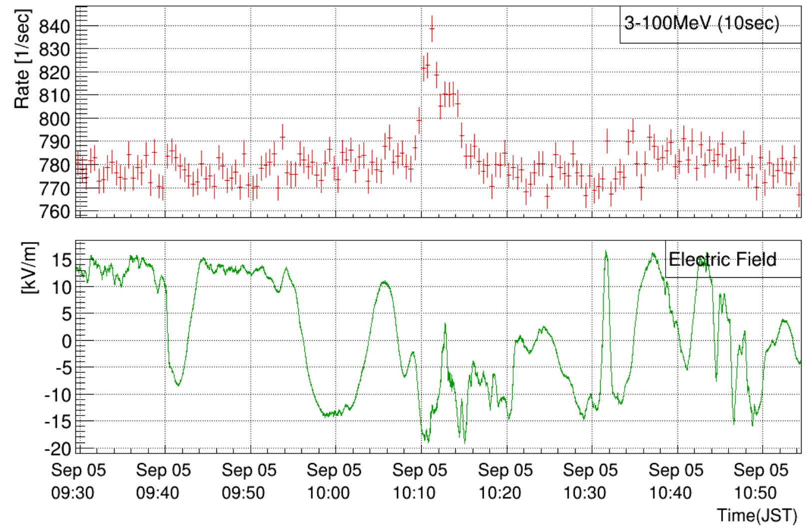
Thunder information

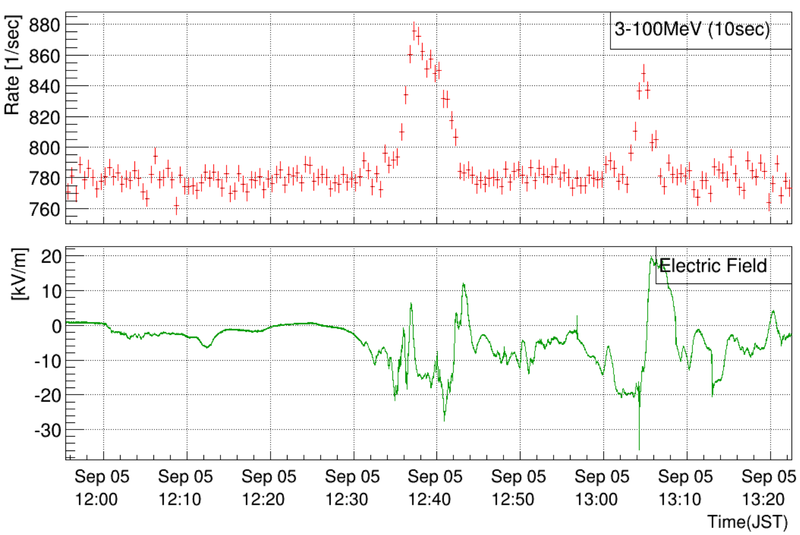
Burst	Nowcast (20 min)	JLDN (20 min)
20140708-1	Level 3	105
20140718-1	Level 1	0
20140719-1	Level 2	2
20140731-1	Level 3	21
20140822-1	Level 1	0
20140823-1	Level 2	1
20140826-1	Level 2	0
20140830-1	Level 3	2
20140830-2	Level 1	0
20140905-1	Level 1	0
20140905-2	Level 2	4
20140905-3	Level 2	4

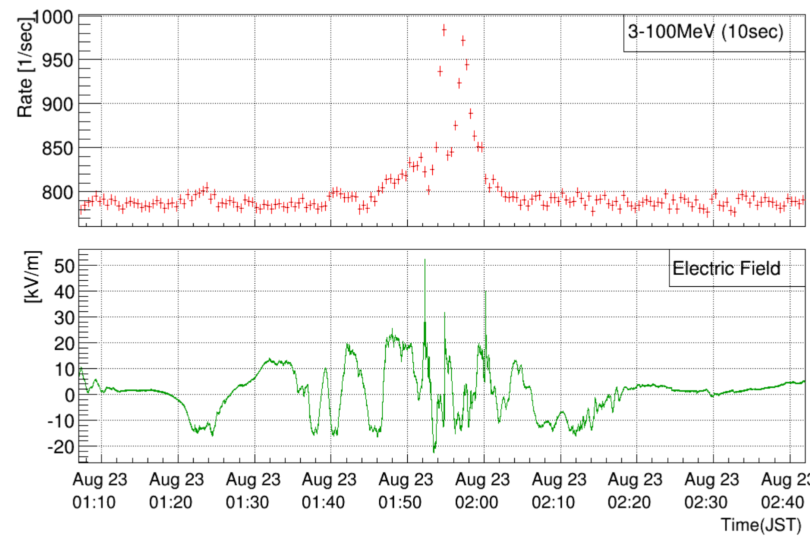


7 of 12 bursts : JLDN lightning and Nowcast level 2-3
5 of 12 bursts : Nowcast level 1-2

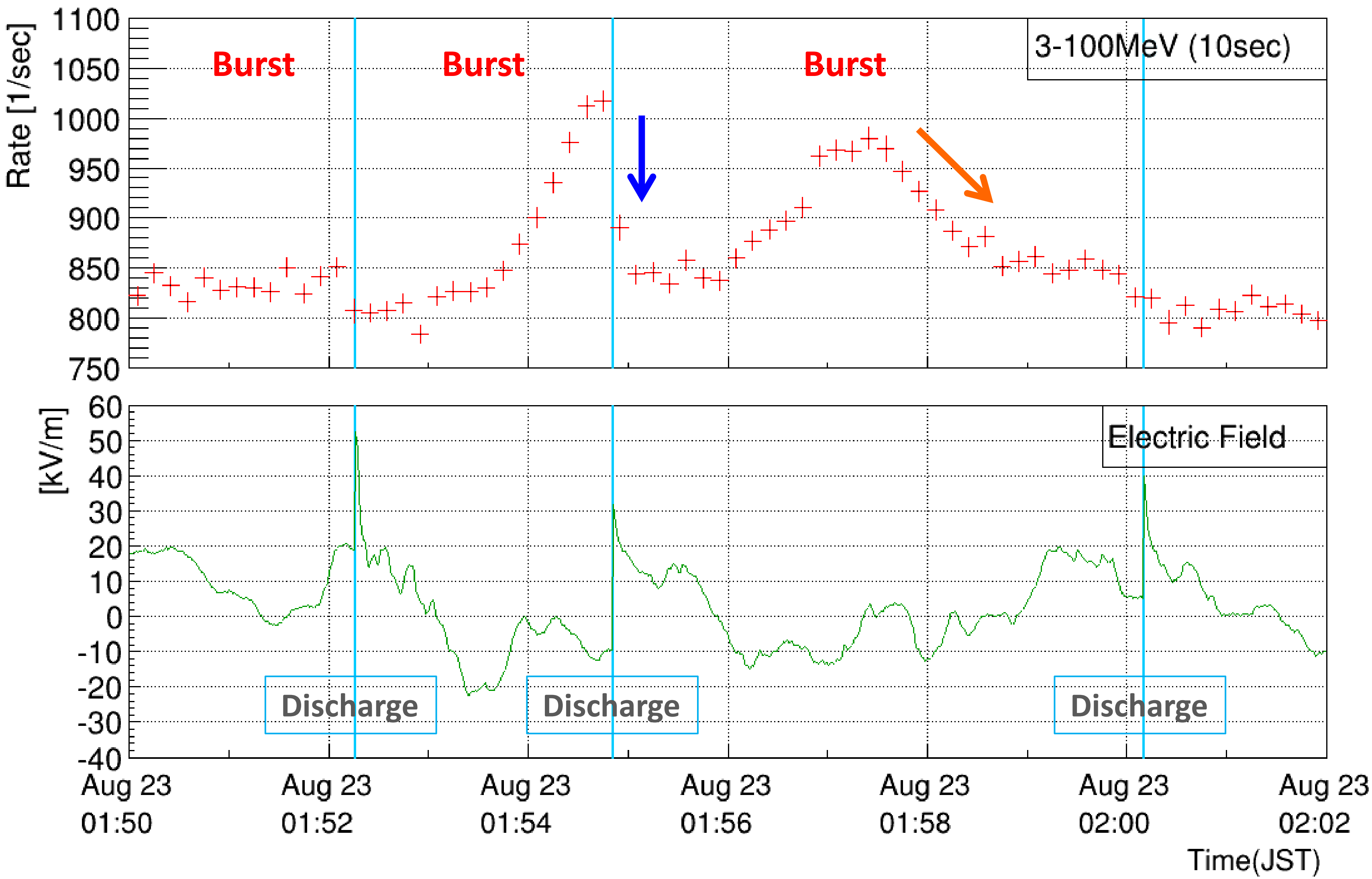
Electric field







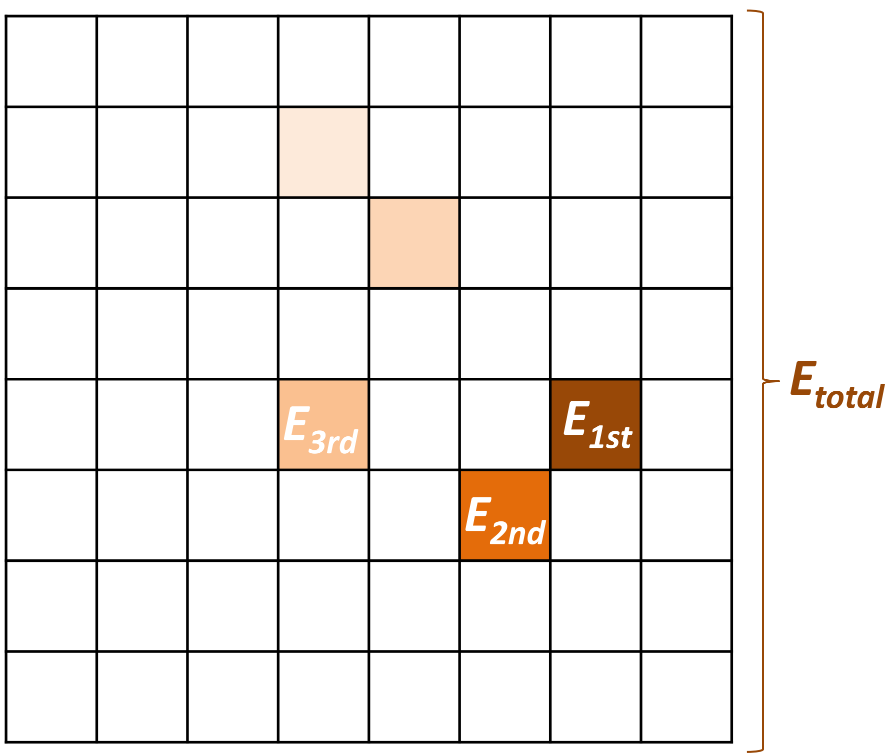
Electric field

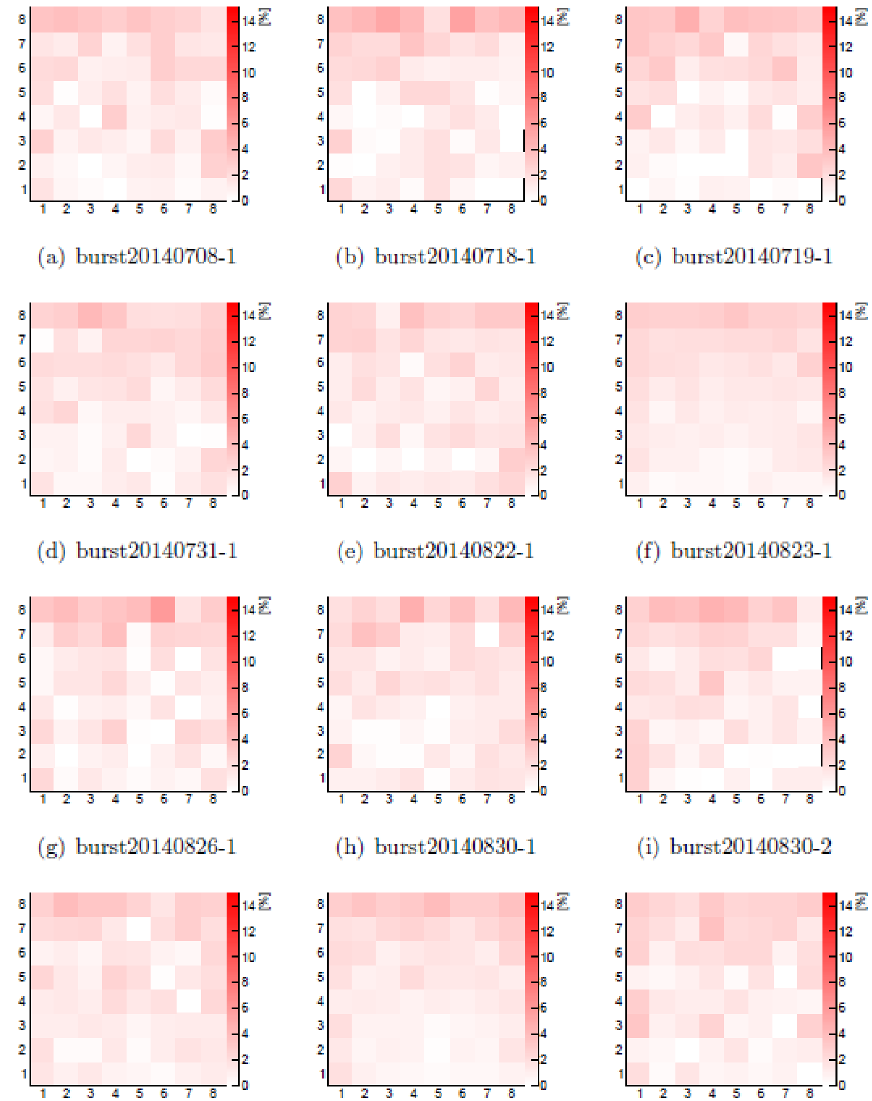


Arrival direction of bursts

- PANDA's segmented structure
- E_{1st} distribution of bursts (BG periods subtracted)

-> From upward direction



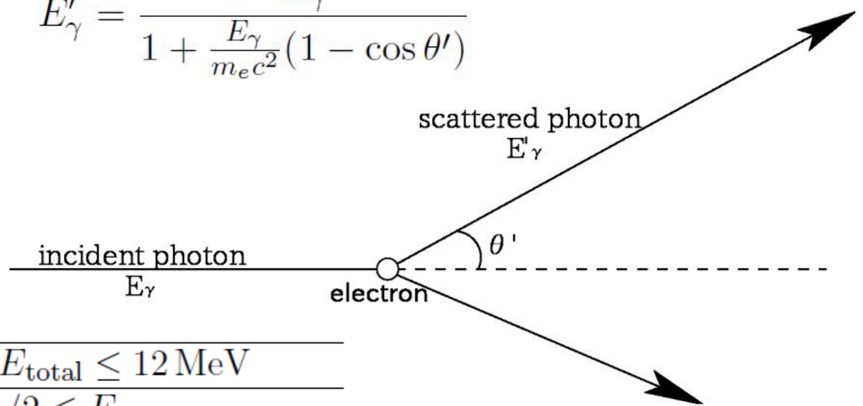


(a) burst20140708-1
(b) burst20140718-1
(c) burst20140719-1
(d) burst20140731-1
(e) burst20140822-1
(f) burst20140823-1
(g) burst20140826-1
(h) burst20140830-1
(i) burst20140830-2
(j) burst20140905-1
(k) burst20140905-2
(l) burst20140905-3

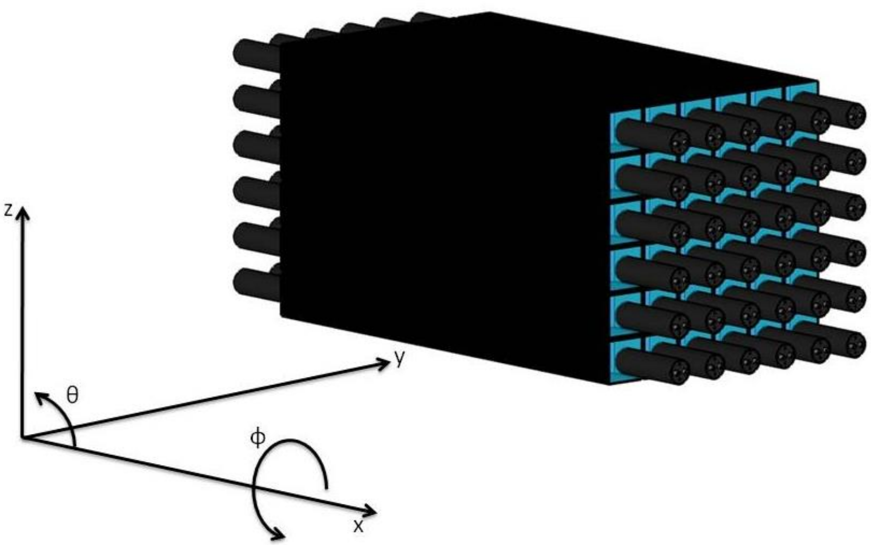
Arrival direction of bursts (PANDA36)

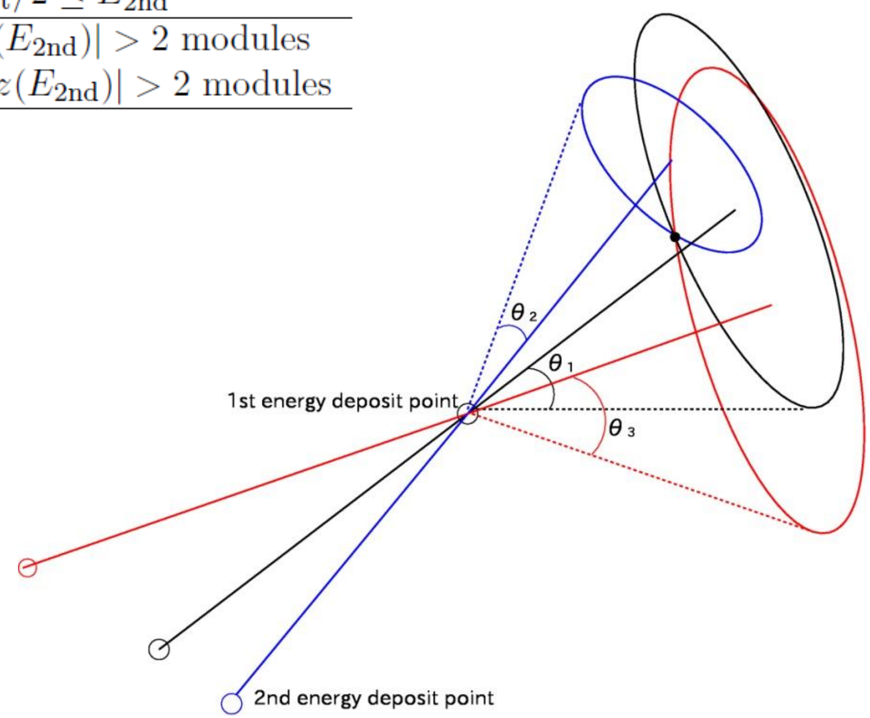
- PANDA's segmented structure
- Angle of Compton scattering
  (Obtain cone-shape restriction)

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta')}$$



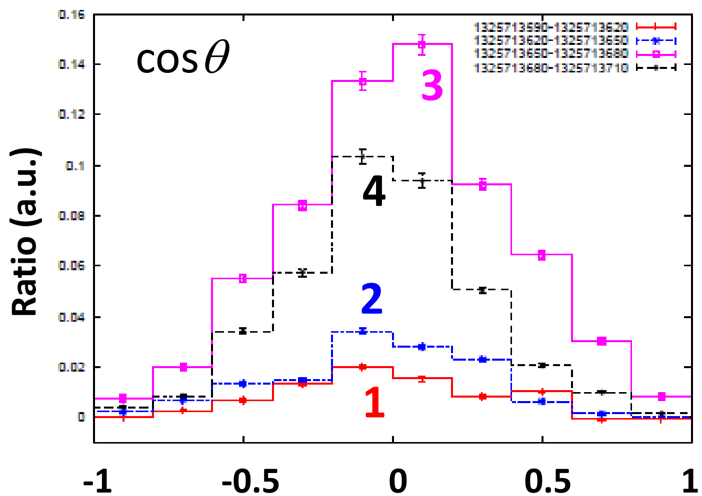
E_{total} selection to cut the noisy region	$5\,\mathrm{MeV} \leq E_{\mathrm{total}} \leq 12\,\mathrm{MeV}$
$E_{\mathrm{1st}}, E_{\mathrm{2nd}}$ ratio selection	$E_{\mathrm{1st}}/2 \leq E_{\mathrm{2nd}}$
distance selection	$\lvert y(E_{\mathrm{1st}}) - y(E_{\mathrm{2nd}})\rvert > 2$ modules or $\lvert z(E_{\mathrm{1st}}) - z(E_{\mathrm{2nd}})\rvert > 2$ modules



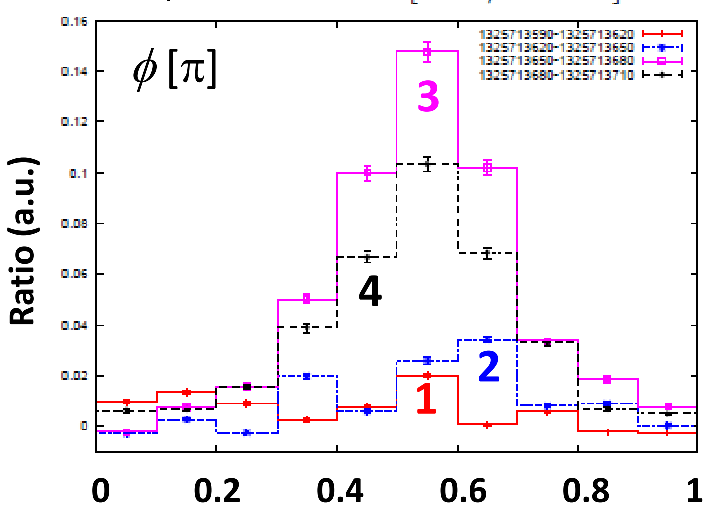


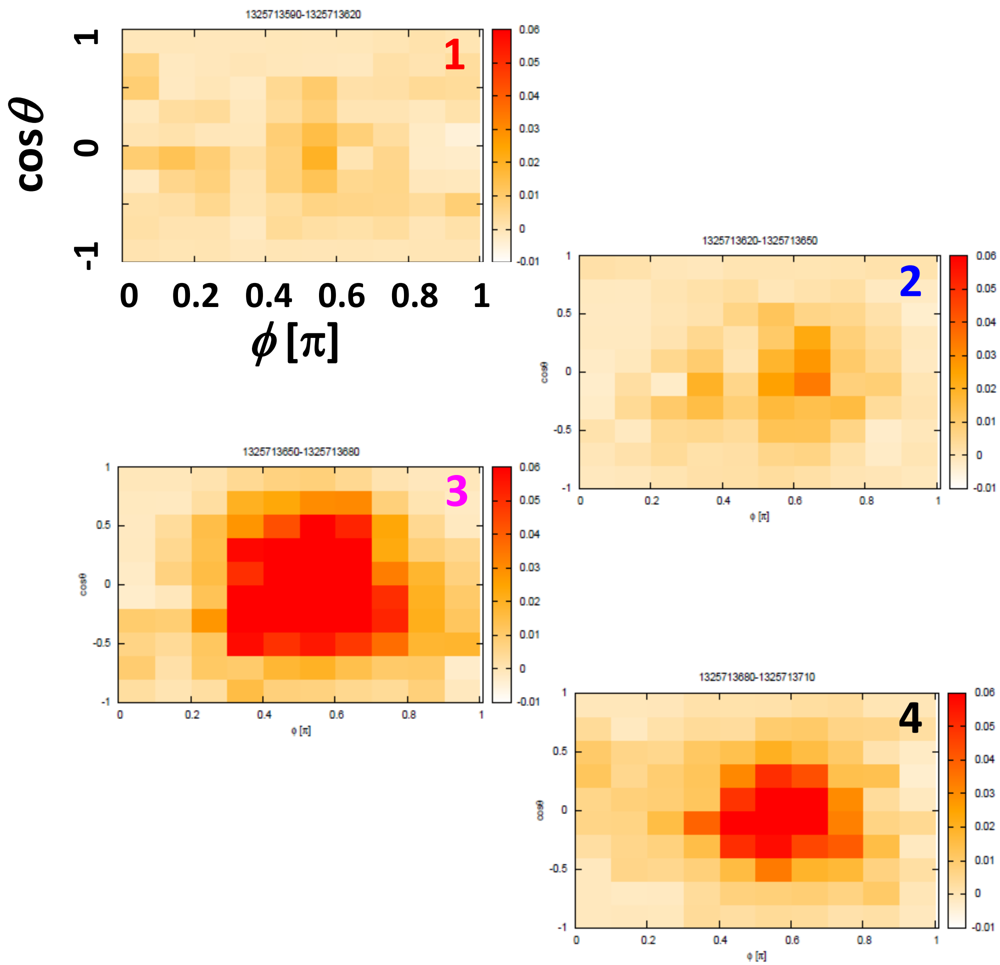
Arrival direction of bursts (PANDA36)

$\cos\theta: 0.08 \pm 0.5[/30\mathrm{sec}]$



$\phi: 0.2 \pm 0.9[\mathrm{rad}/30\mathrm{sec}]$





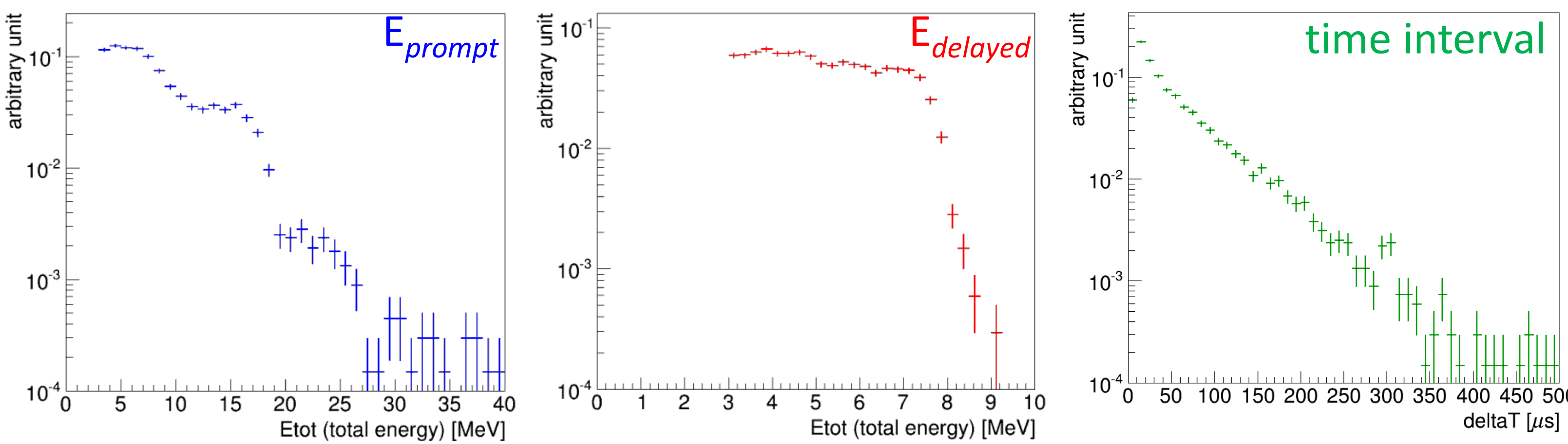
Arrival direction stayed constant during burst periods

Neutron component in bursts

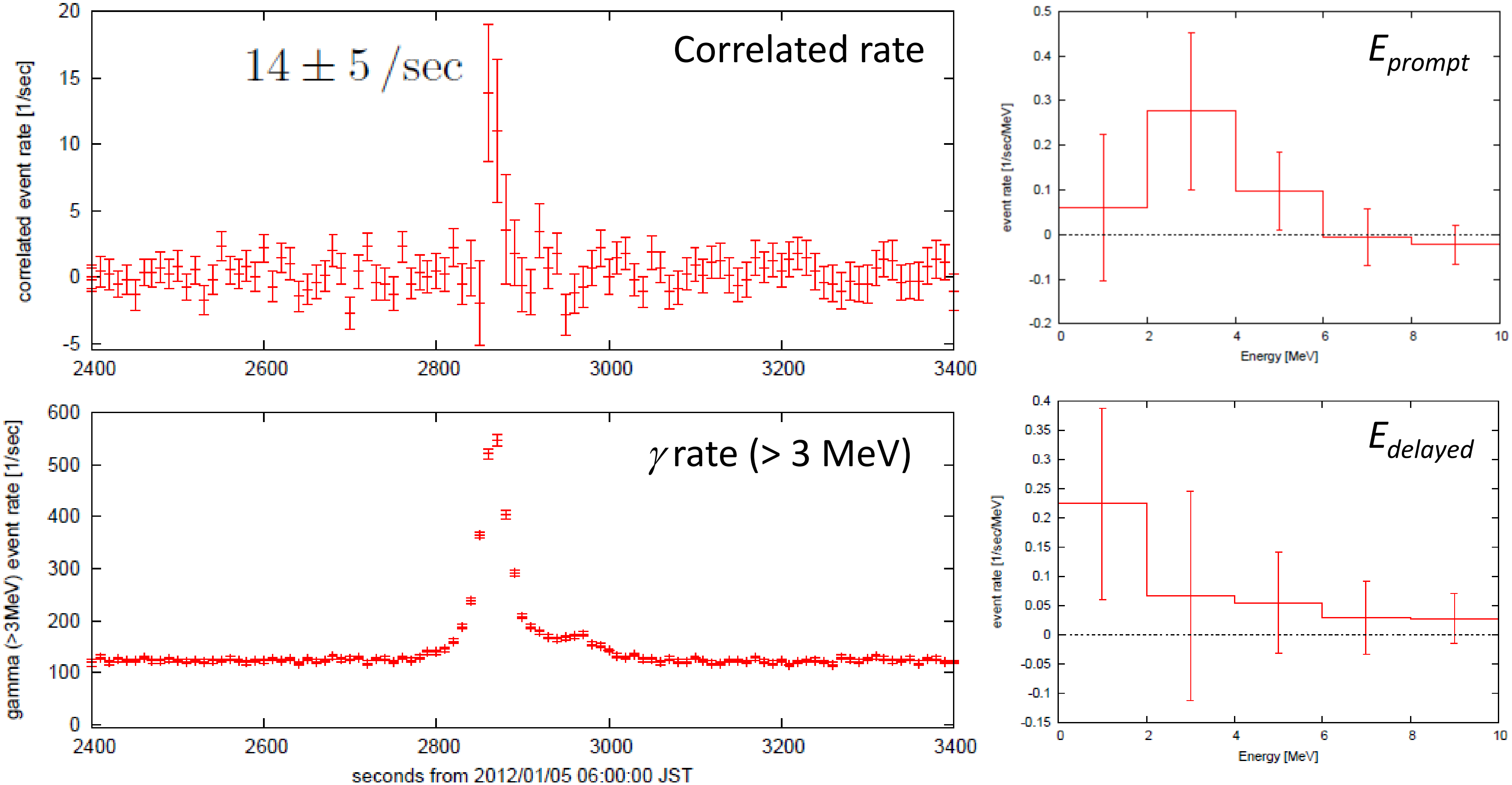
- Delayed coincidence method (similar to anti-electron neutrino)
- Prompt event : Proton recoil by collision
- Delayed event : Neutron capture by gadolinium nuclei
- Accidental event rate subtracted

	correlated	accidental
prompt event	$1.5\,\mathrm{MeV} \leq E_{\mathrm{total}} \leq 10.0\,\mathrm{MeV}$	
delayed event	$1.5\,\mathrm{MeV} \leq E_{\mathrm{total}} \leq 10.0\,\mathrm{MeV}$	
time window	$8\mu\mathrm{sec} - 150\mu\mathrm{sec}$	$1008\mu\mathrm{sec} - 1150\mu\mathrm{sec}$

50 MeV neutrons on PANDA64 (simulation)



Neutron component in bursts



Neutron signal enhancement was detected by delayed coincidence method (Ohi/10m)

Outline

1. Detector

- Antineutrino detector for reactor monitoring and PANDA project

2. Long bursts from thunderclouds

- Electron acceleration in thunderclouds and RREA model

3. Observation at two locations

- Ohi Power Station (coastal area) and Norikura Observatory (mountain area)

4. Observed bursts (Ohi) - 3 bursts

5. Observed bursts (Norikura) - 12 bursts

6. Data analysis

- Thunder information, electric field, arrival direction and neutron component

7. Runaway electron source

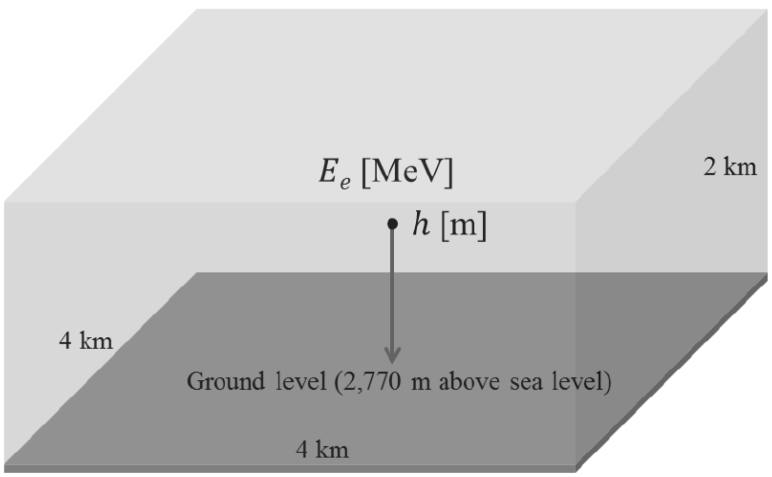
- Estimation of energy and flux by Monte Carlo simulation

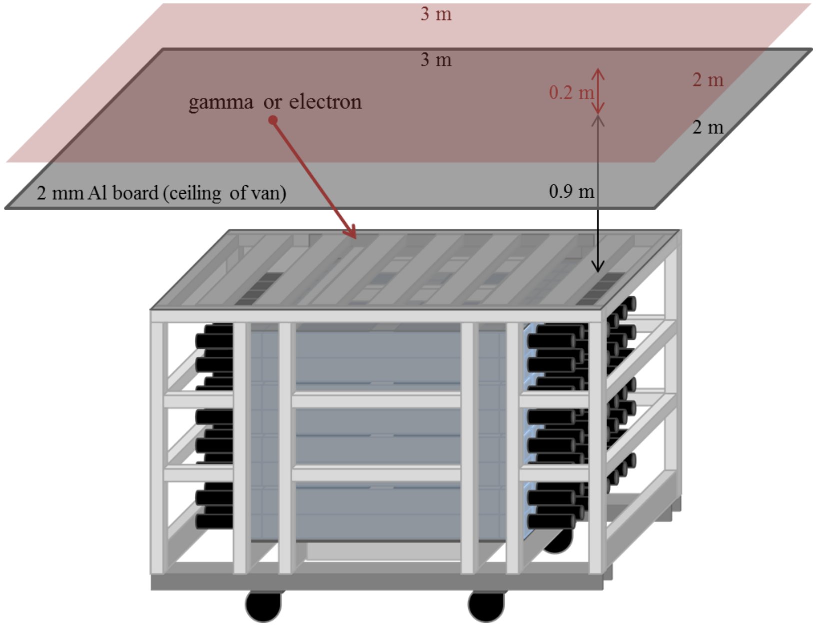
Estimation of electron source

Estimate height and energy of electron source using energy spectrum.

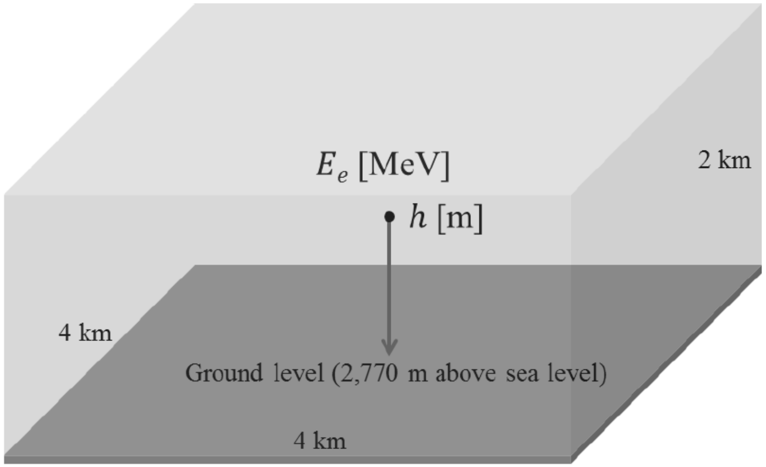
1: Simulation of Electron propagation in atmosphere

2: Simulation of Detector response

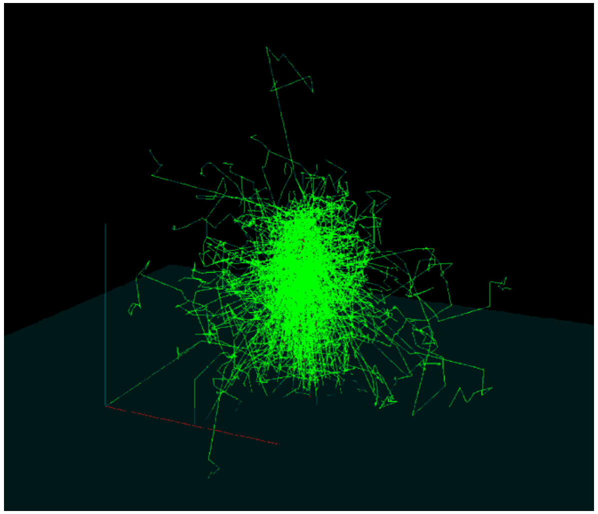


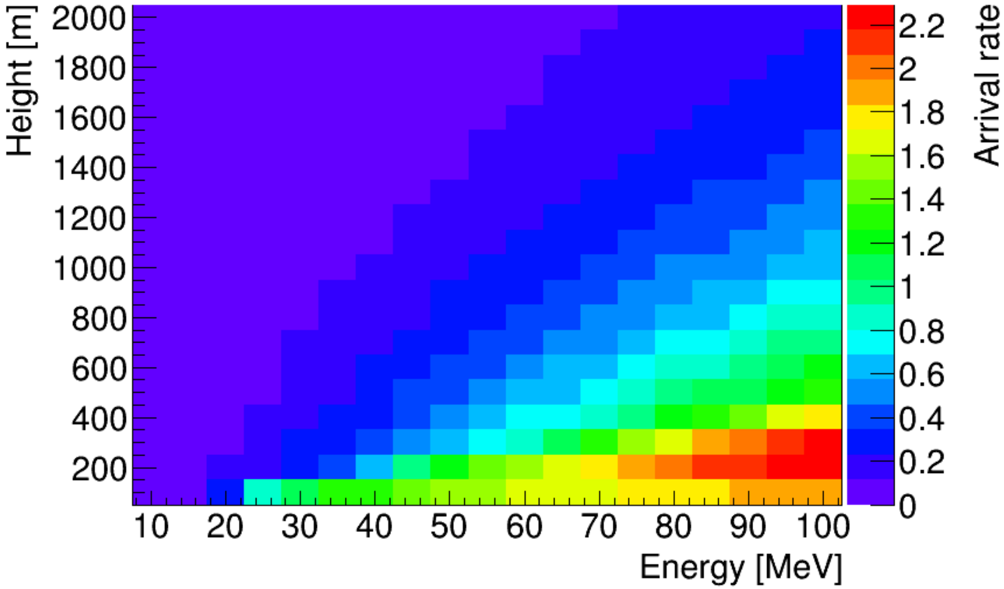


Simulation of Electron propagation in atmosphere

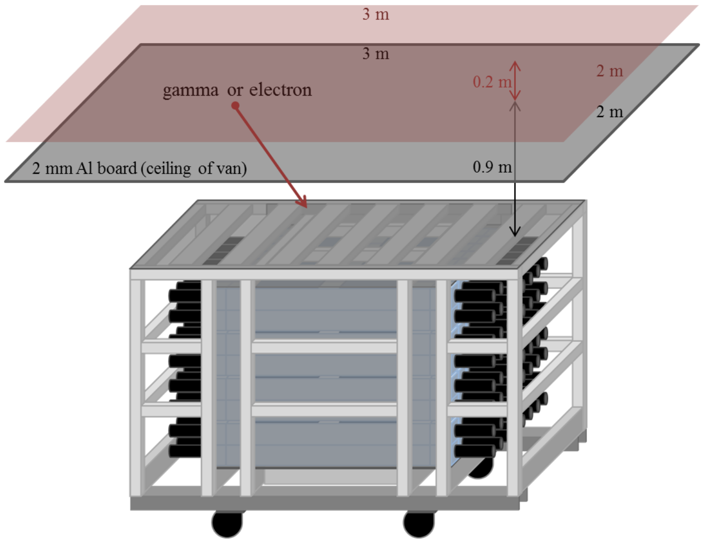


- Monochromatic electron assumed
- Vertically downward to the ground
- Height : 100 - 2000m (20 heights)
- Energy: 10 - 100MeV (19 energies)
- Total 380 combinations
- Obtain e^- and γ at the ground

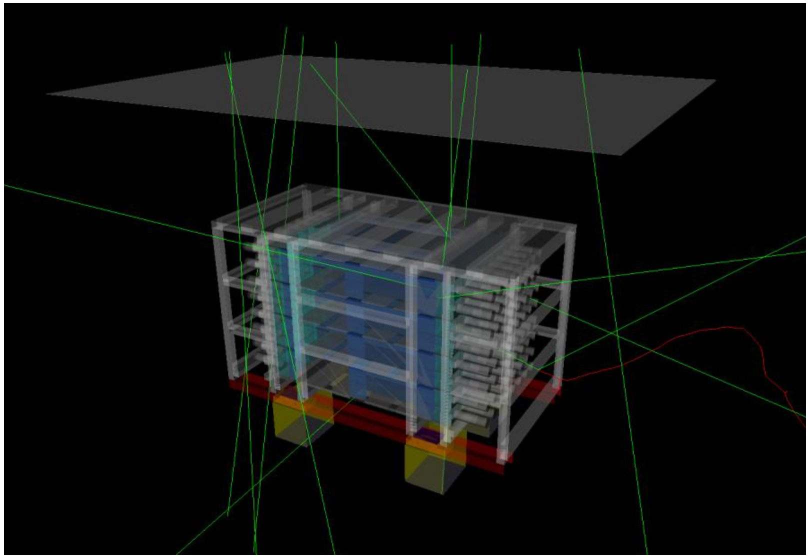


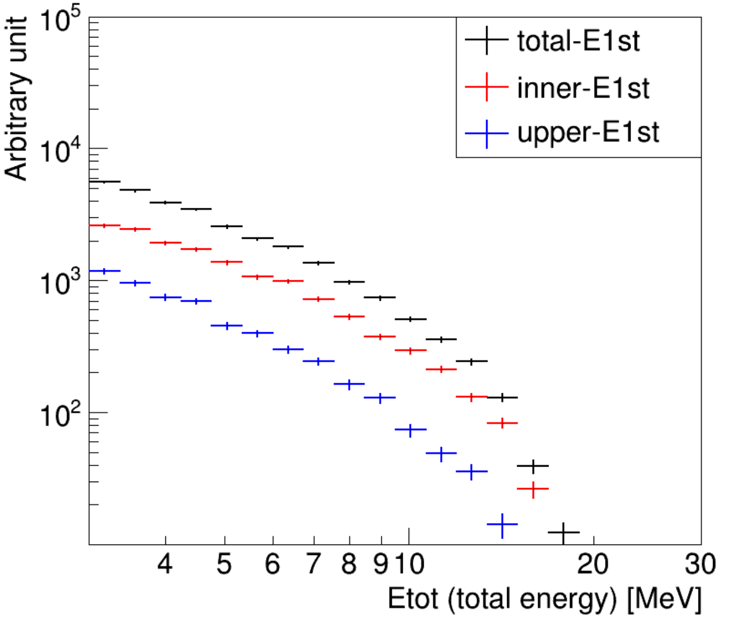


Simulation of Detector response

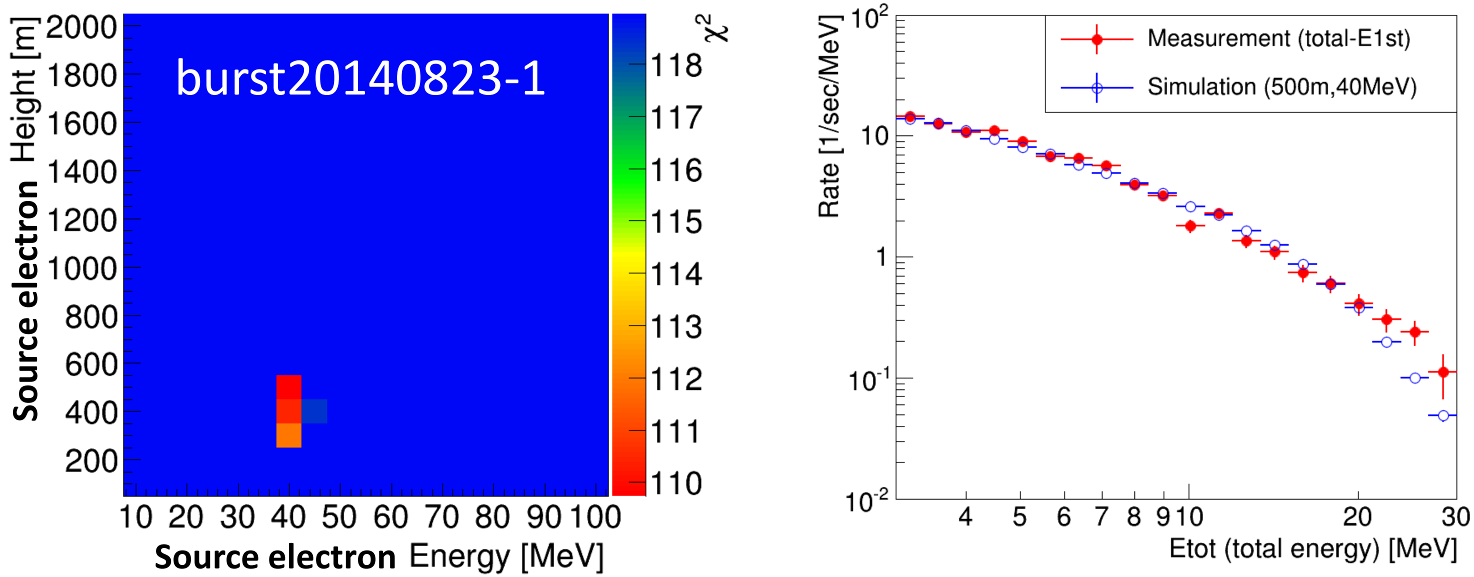


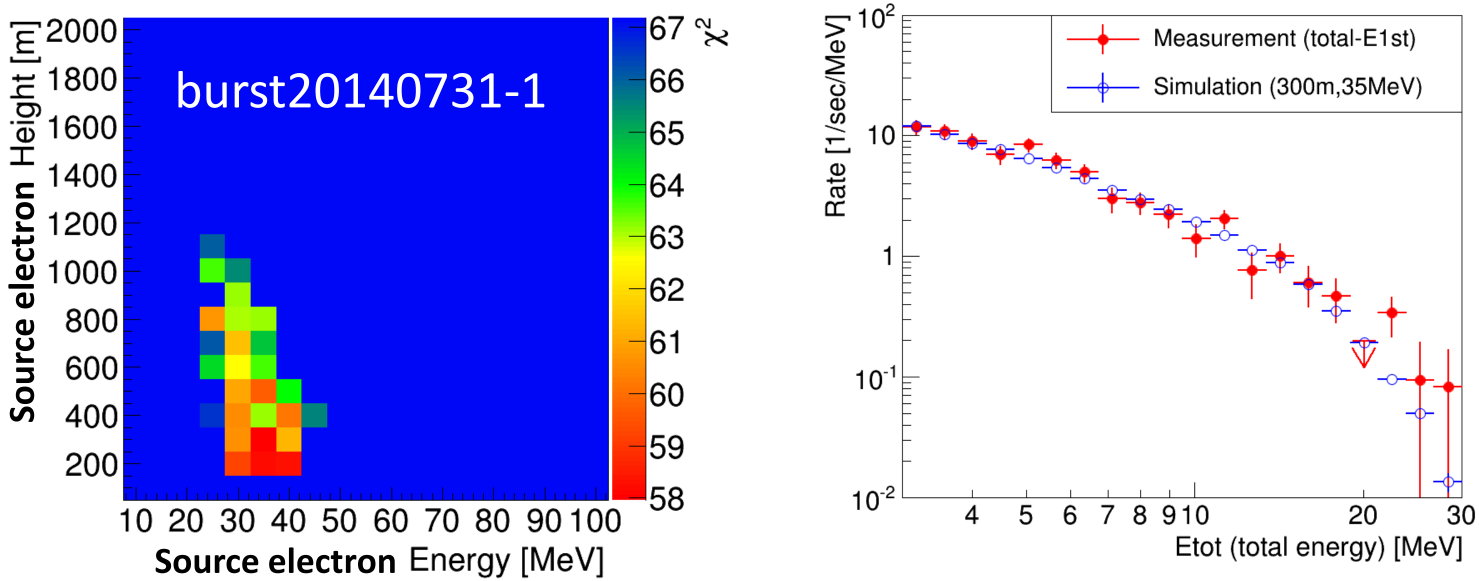
- Obtained e^- and γ at the ground
- Shot to PANDA64 through Al ceiling
- Angular distribution considered
- Total 380 combinations
- Obtain simulated energy spectra
- Spectra fitted to measurement data





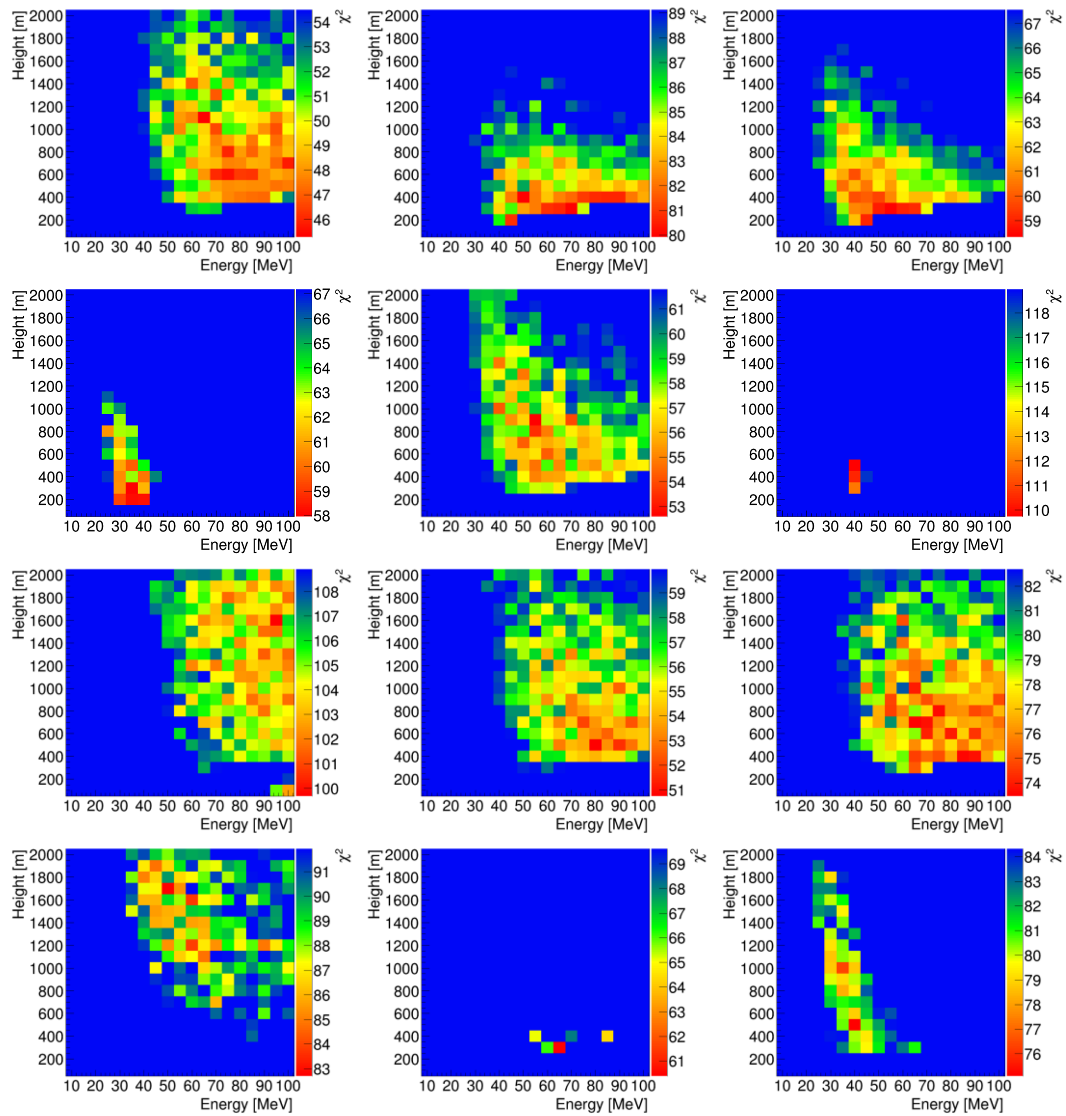
Fitting of energy spectrum



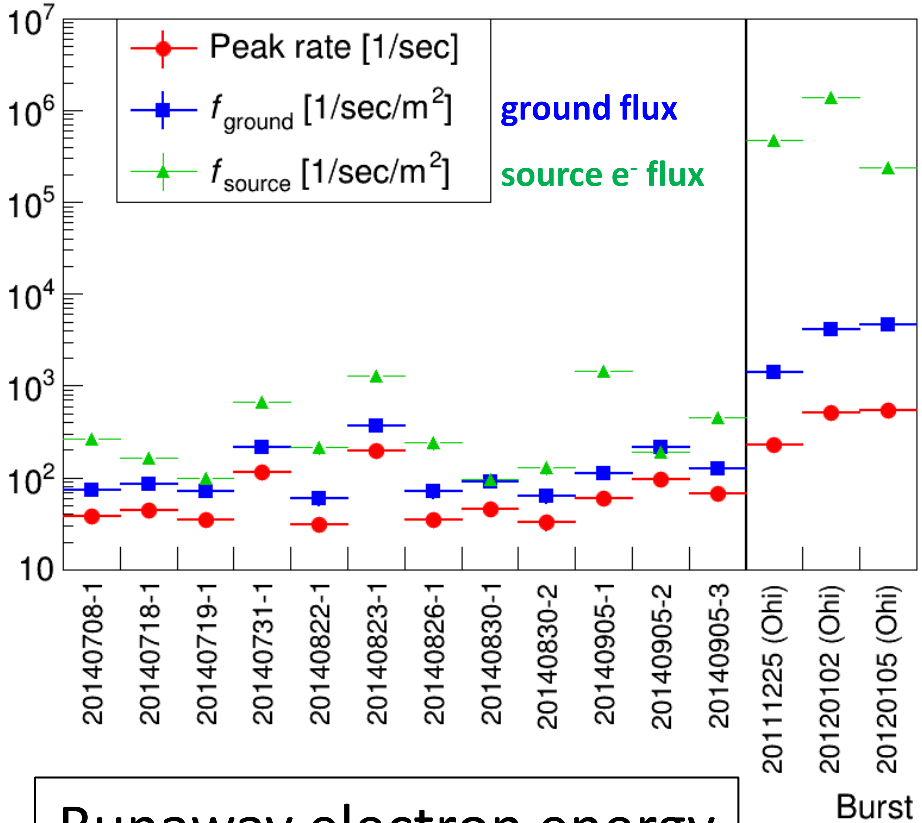


Best fit electron source

Burst	Height [m]	Energy [MeV]
20140708-1	1100	65
20140718-1	400	50
20140719-1	300	55
20140731-1	300	35
20140822-1	900	55
20140823-1	500	40
20140826-1	1600	95
20140830-1	500	80
20140830-2	700	65
20140905-1	1700	50
20140905-2	300	65
20140905-3	500	40
20111225(Ohi)	1100	16
20120102(Ohi)	1100	16
20120105(Ohi)	400	16



Estimation of source electron flux



Burst	f_{source} [/sec/m^2]
20140708-1	$(2.62 \pm 0.37) \times 10^2$
20140718-1	$(1.66 \pm 0.22) \times 10^2$
20140719-1	$(0.98 \pm 0.15) \times 10^2$
20140731-1	$(6.78 \pm 0.34) \times 10^2$
20140822-1	$(2.16 \pm 0.37) \times 10^2$
20140823-1	$(1.28 \pm 0.04) \times 10^3$
20140826-1	$(2.40 \pm 0.40) \times 10^2$
20140830-1	$(0.95 \pm 0.12) \times 10^2$
20140830-2	$(1.29 \pm 0.22) \times 10^2$
20140905-1	$(1.45 \pm 0.14) \times 10^3$
20140905-2	$(1.90 \pm 0.12) \times 10^2$
20140905-3	$(4.48 \pm 0.38) \times 10^2$
20111225(Ohi)	$(4.7 \pm 0.3) \times 10^5$
20120102(Ohi)	$(1.4 \pm 0.0) \times 10^6$
20120105(Ohi)	$(2.4 \pm 0.1) \times 10^5$

Runaway electron energy
Norikura > Ohi

Runaway electron flux
Norikura << Ohi

Summary

Observation by two PANDA prototypes at two locations

- 3 bursts detected at Ohi Power Station (coast, 10 m)
- 12 bursts detected at Norikura Observatory (mountain, 2770 m)

Data analysis by various approaches

- Correlation with thunder information (JLDN and Thunder Nowcast)
- Correlation with electric field
- Arrival direction analyzed taking advantage of segmented structure
- Neutron enhancement detected using delayed coincidence method

Estimation of electron source in thunderclouds

- Electron source (height and energy) estimated by simulation
- Difference of energy and flux of electron source between two locations