Development of Plastic Anti-neutrino Detector Array (PANDA) for reactor monitoring

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Kitasato University

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KITASATO UNIVERSITY

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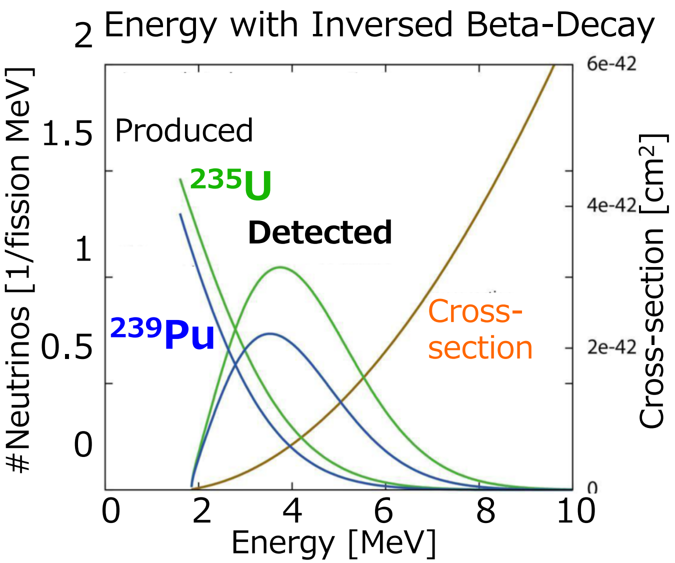
Introduction

- **The aim of reactor monitoring**
  - **Real-time monitoring** of a reactor operation
    - By measuring **energy spectrum** and **rate** of reactor neutrinos, we can infer **the nuclide and abundance of reactor fuel**.
  - Nonproliferation of nuclear technology
    - It can be applied to **the non-intrusive inspection tool** proposed by IAEA.
- Using a detection of an anti-neutrino
  - **High penetration**
    - The detector can be operated outside a reactor building.
  - **No alternative source**
    - Nobody can hide anti-neutrinos generated at a reactor operation.



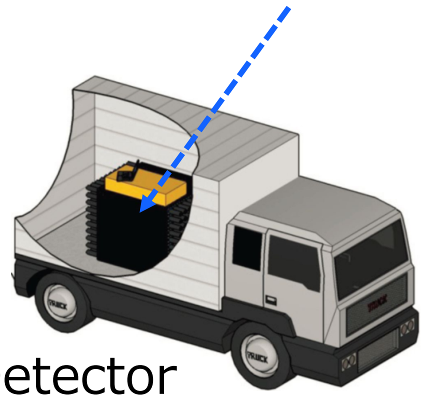
An anti-neutrino is suitable tool for a reactor monitoring.

PANDA

Plastic Anti-Neutrino Detector Array

- Requirements for the aboveground reactor monitor
  - **Portability**
    - We want to monitor any reactor/place.
    - The total weight:
      - the enough fiducial volume to detect anti-neutrinos,
      - we can load with a van to transport.
  - **Stability**
    - Qualities of detection materials do not change while a detector was monitoring.
  - **Safety**
    - The detector (materials) is required to be non-flammability.
  - **Cosmic-ray muon veto**
    - Muon and γ/neutron produced by it cause major background sources.

$\bar{\nu}_e$
from reactor core



Detector
(Distance from core
is several tens of meters.)

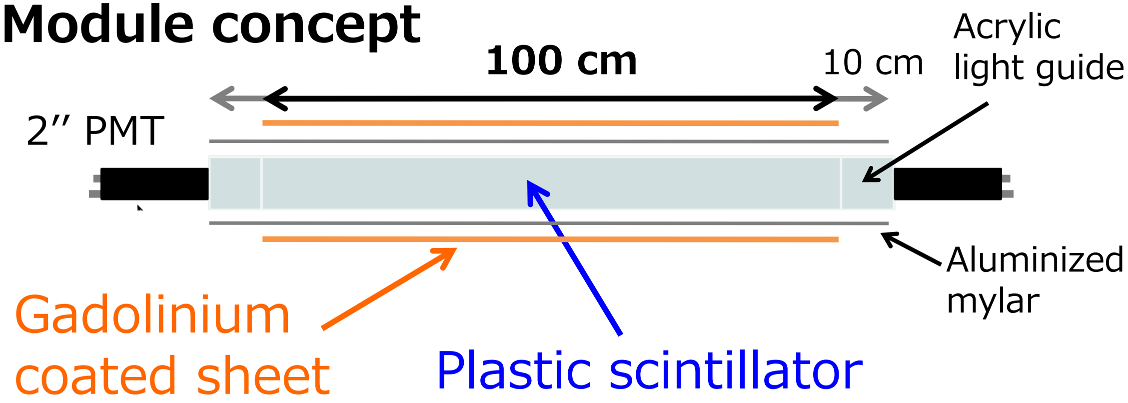
⇒ We decided to use

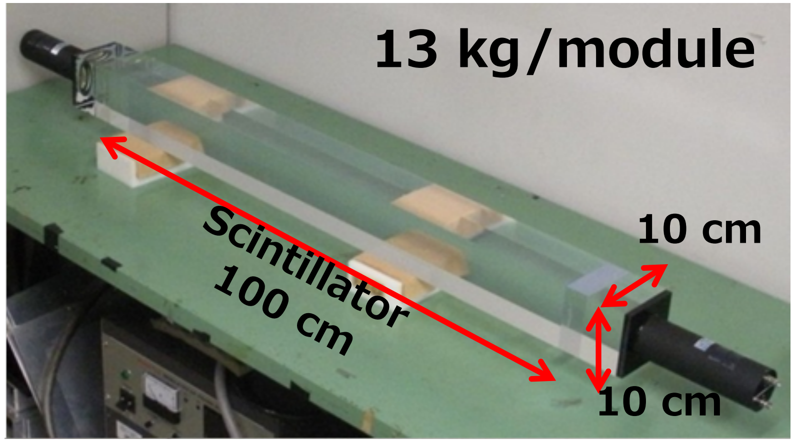
Plastic scintillator wrapped in **Gadolinium coated sheets**.

PANDA

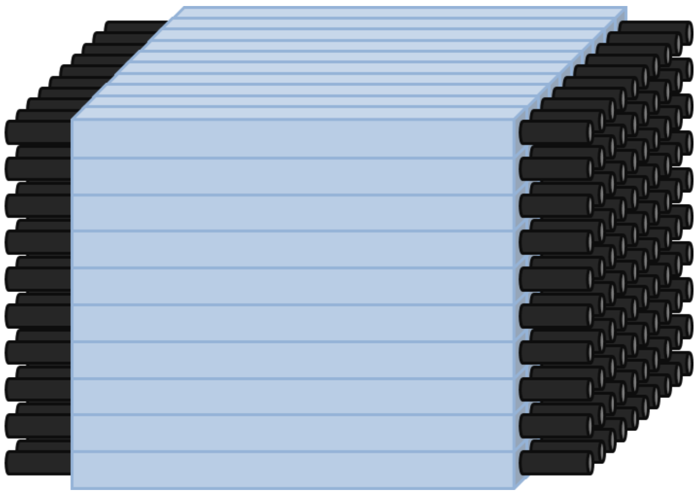
Plastic Anti-Neutrino Detector Array

Module concept



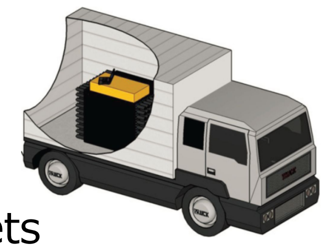


10×10=100 modules



Advantages

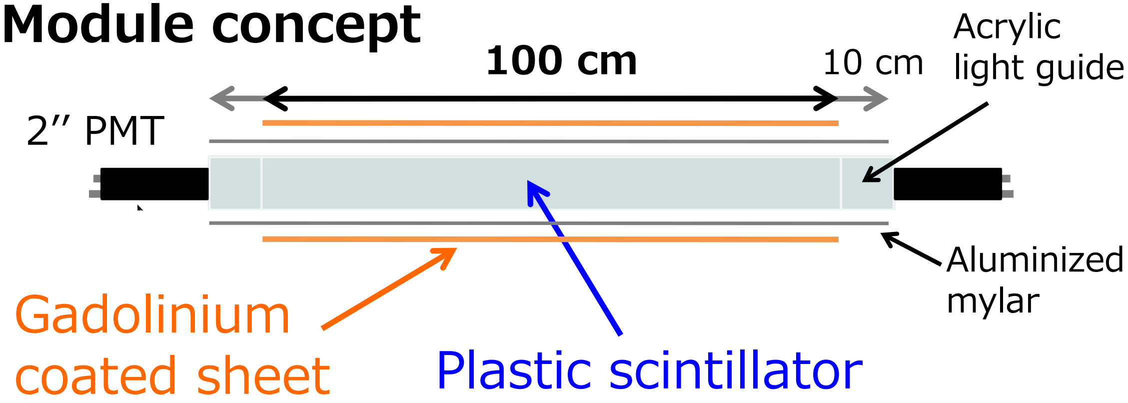
- Solid state plastic scintillator
  ⇒ Non-flammability & Safety
- Segmented structure: 100 modules
  ⇒ 1,000 kg target volume
  ⇒ Muon-veto can be given by itself without any counter.
- The detector can be loaded with a container (or a van)
  ⇒ Portability
- Gd is not dissolving, coated on sheets
  ⇒ Stability

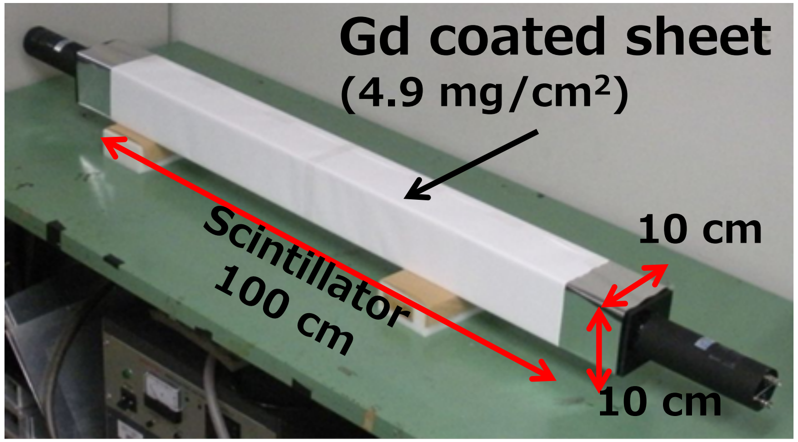


PANDA

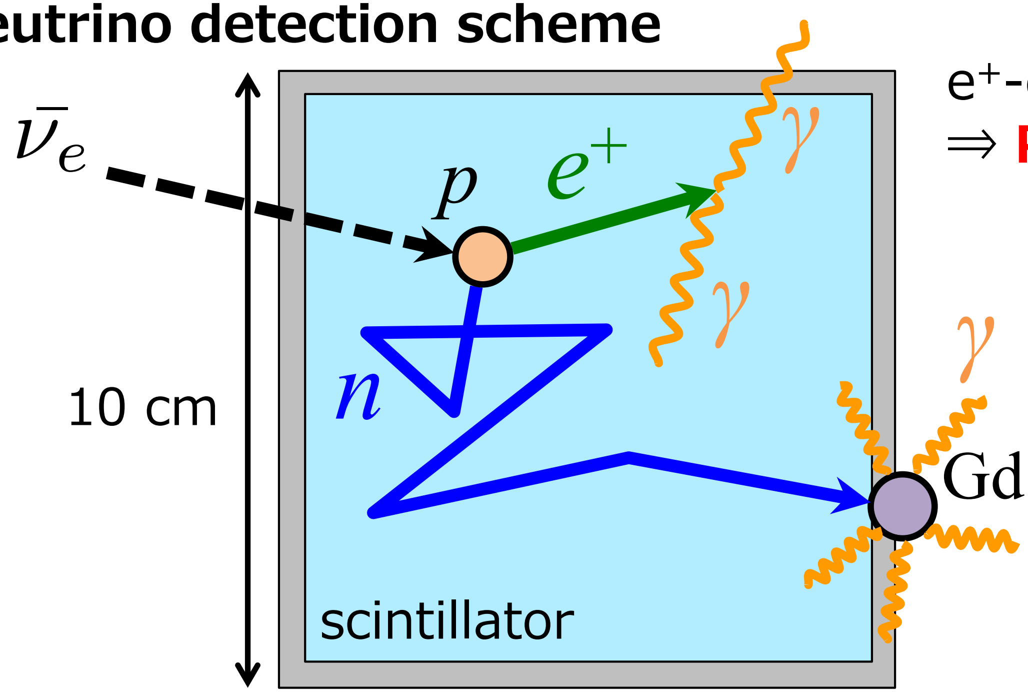
Plastic Anti-Neutrino Detector Array

Module concept





Neutrino detection scheme



e^+-e^- Annihilation event
⇒ **Prompt signal**: e^+ + 2γ(1022 keV)

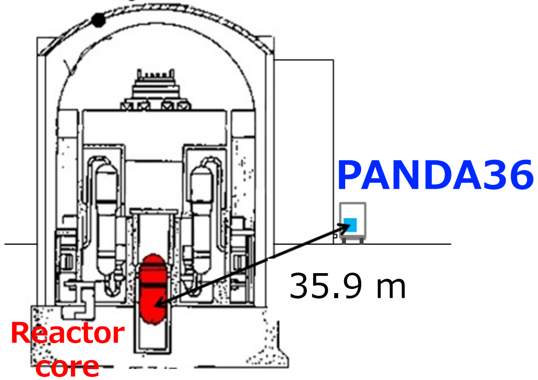
Delayed coincidence (~60 μs)

n-Gd captured event
⇒ **Delayed signal**: several γ's (~8 MeV)

Reactor monitoring test with PANDA36

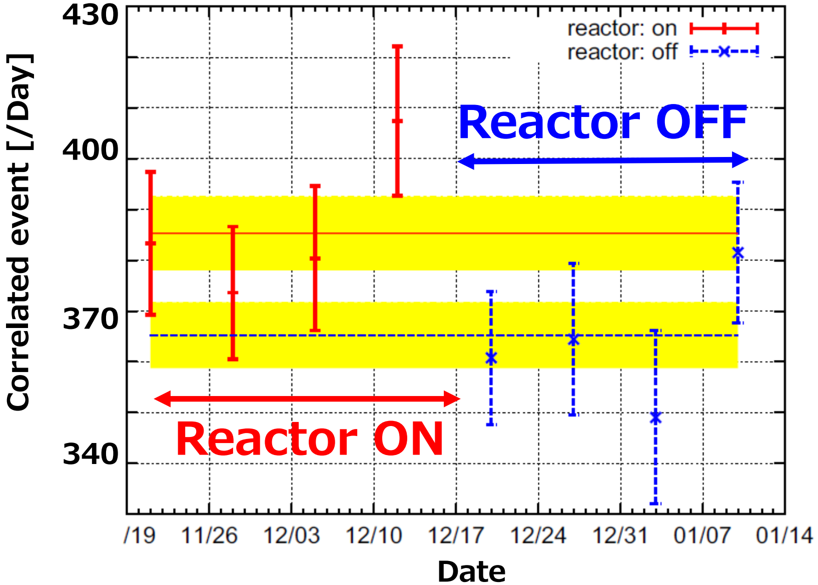
- Development had been started since 2006 at University of Tokyo.
  - 2008-2011: **PANDA16**: **4×4=16** modules
  - 2011-2013: **PANDA36**: **6×6=36** modules
  - 2013-2014: **PANDA64**: **8×8=64** modules
- 2012.Nov-2013.Jan, First measurement of ON/OFF operation of the Ohi reactor (Fukui, Japan).

PANDA36



Ohi reactor Unit 2: 3.4 GWth (PWR)
Distance form the core: 35.9 m
Duration: 30 days (ON), 34 days (OFF)
Observed neutrino event: **21.8 ± 11.4 /day**

S.Oguri *et al.* NIM A 757 (2014) 33-39



Time line of PANDA project

Development had been started since 2006 at University of Tokyo,
Since 2016, the PANDA project had been taken over to Kitasato Univ.

U. Tokyo → Kitasato U.

PANDA100: **10×10=100** modules

- 2015 Construction had been started
- 2016.Mar: Project had been taken over to Kitasato Univ.
- 2016.Jul: Construction had been completed.
- 2016.Aug-Oct: γ-bursts observation at Mt. Norikura was carried out.

Detection efficiency prospect
(at the Ohi reactor: 3.4 GWth (PWR))

	PANDA36 (～2013)	**PANDA100 (2016～)**
Target mass [kg]	360	**1000**
Efficiency† [%]	3.15	**9.24**
Expected ν rate‡ [Events/day]	18.1	**147**
Expected BG rate [Events/day]	809	**5061**

† Based on simulation

‡ Distance of 36m from a core was assumed

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U. Tokyo

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PANDA Collaborators

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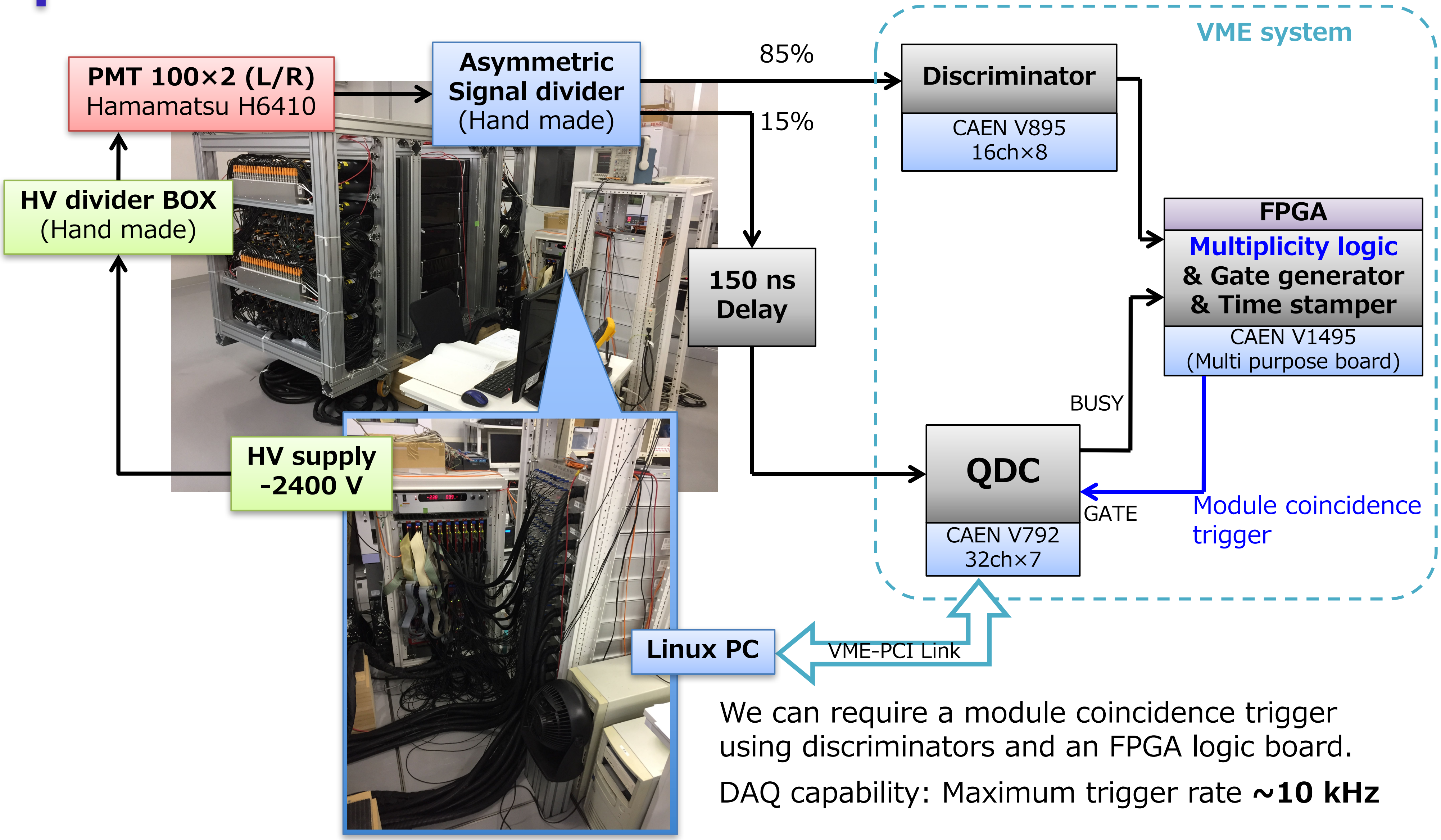
[B]ICEPP, The University of Tokyo
[C]Japan Atomic Energy Agency (JAEA)
[D]ICRR, The University of Tokyo
[E]School of Science, The University of Tokyo
[F]High Energy Accelerator Research Organization (KEK)

PANDA100 system

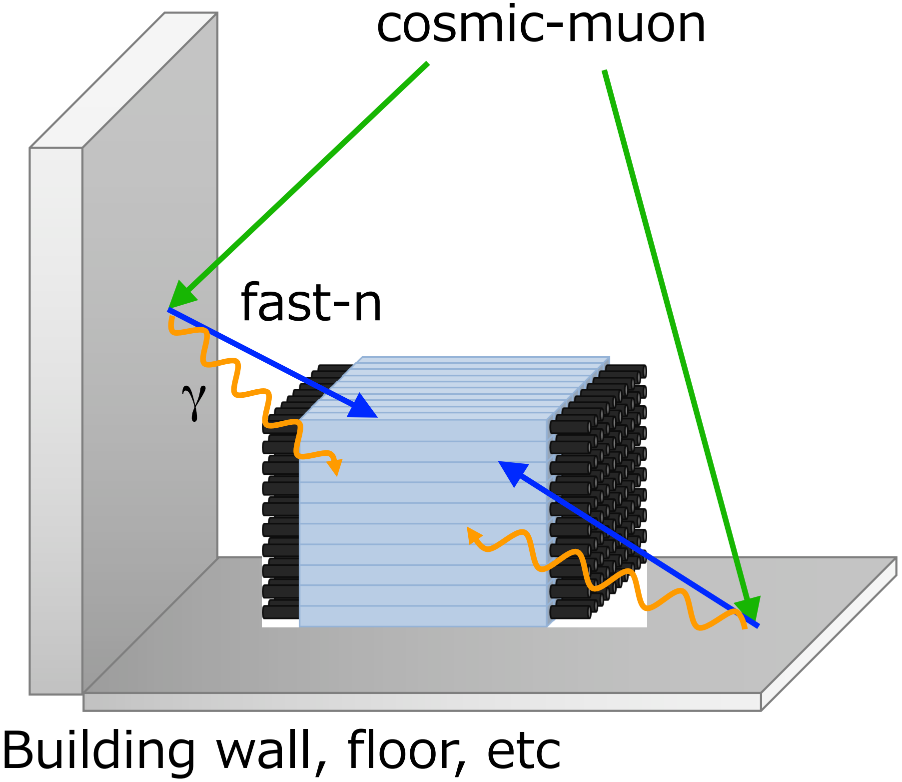


We can require a module coincidence trigger using discriminators and an FPGA logic board.

DAQ capability: Maximum trigger rate **~10 kHz**

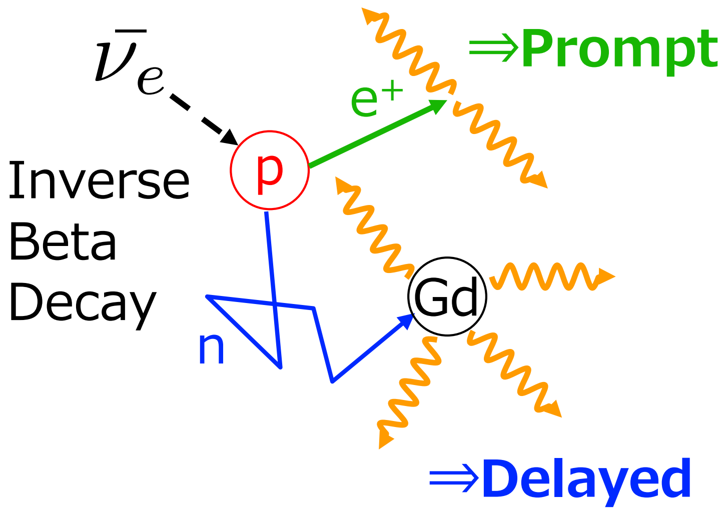
Background sources for PANDA

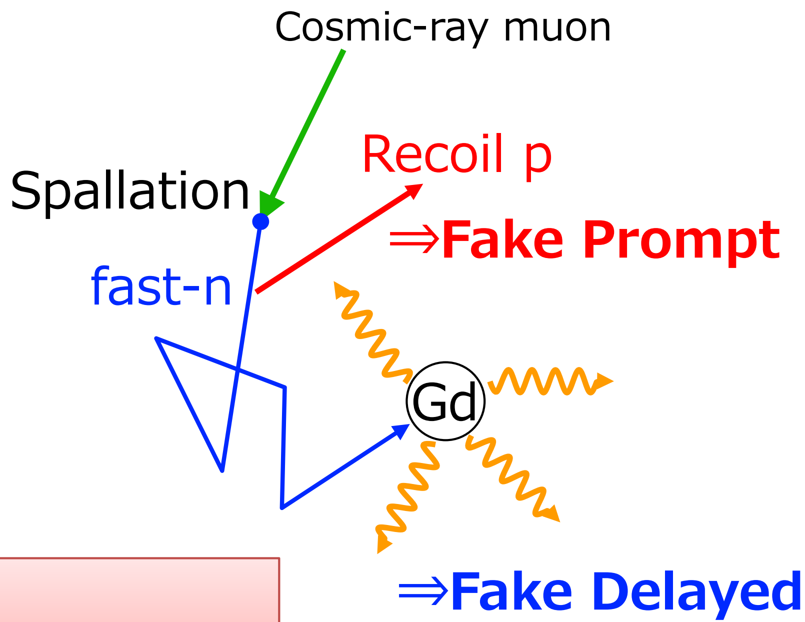
- Due to operate PANDA on the ground, a **cosmic-ray muon** causes major background sources.
  - **Cosmic-ray muon**
    - Fast-neutron by spallation
    - High energy γ-ray from radioactive isotopes produced by muon
  - Environmental γ-ray up to 2.6 MeV
    - ^{238}U and ^{232}Th series
    - ^{40}K series
  - Environmental (thermal) neutron



Background classification

	Neutrino event	Accidental BG	Correlated BG
Prompt signal	Positron dE/dx + 2γ (1,022 keV)	Environmental γ	Recoil protons caused by **fast-n**
Delayed signal	Several γ's from thermal-n capture on Gd	Cosmic-ray muon, Environmental-n/γ	Several γ's from **thermal-n** capture on Gd

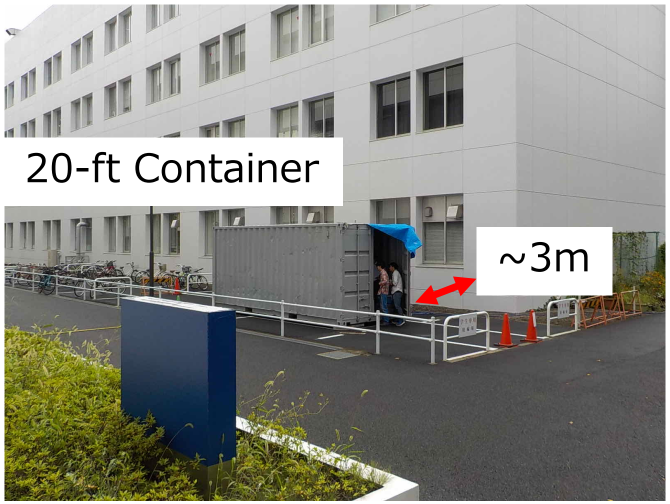




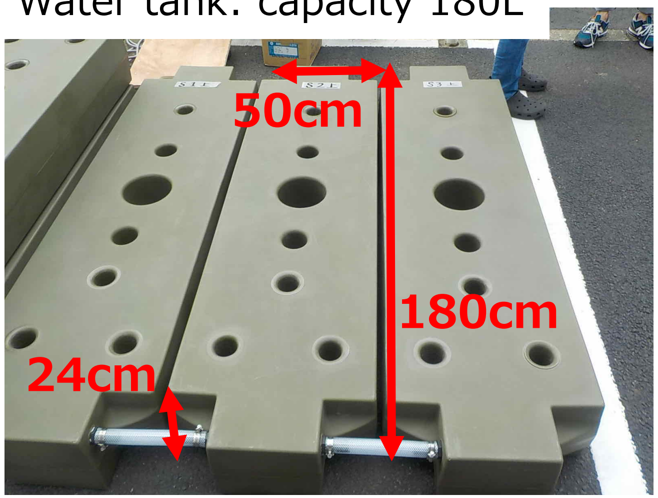
We estimate these BG rates
after requiring the Delayed-Coincidence

Background measurement

- In order to estimate the BG rate at the actual environment, we carried out the outside-measurement by PANDA100 into a 20-ft container.
  - Period: Aug.31 – Sep.8, 2017 at Kitasato-Univ.
    - This experiment was as the practice for moving of PANDA100.
- We confirmed the shield effect of **water tanks** to buffer the neutron comes from outside of detector.
    - To shield from environmental-n and fast-n produced by a muon



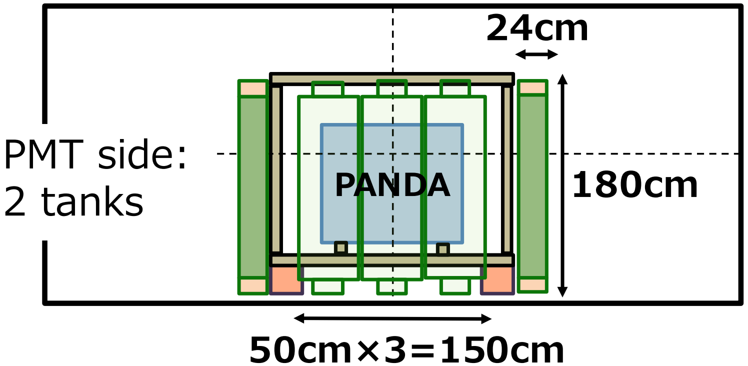
Water tank: capacity 180L



Water tank

- We measured background rates
  with four configurations of the water tank setting.

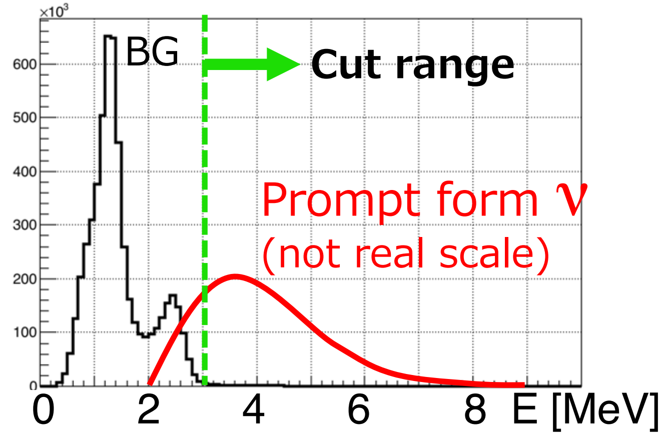
1. **No tank**
2. Only tank put at the **Bottom**.
   - To protect n/γ coming from the ground.
3. Tank-B + **4-side tanks**
   - To protect environmental n or
     γ coming from a building wall.
4. Tank-B + 4-side tanks + put on the **Top**



Trigger and selection condition

- **Trigger condition**
  - Discriminator threshold level: -60 mV
  - #Hit-modules: 2 or more
- **Event selection**
  - Prompt signal
    - 3 MeV < E_{tot} < 8 MeV
  - Delayed signal
    - #Hit-modules ≧ 4
    - 4 MeV < E_{tot} < 8 MeV
    - 1.0 MeV < E_{1st} < 8.0 MeV
    - 1.0 MeV < E_{2nd} < 8.0 MeV
    - Time window: 50 us < dT ≦ 100 us

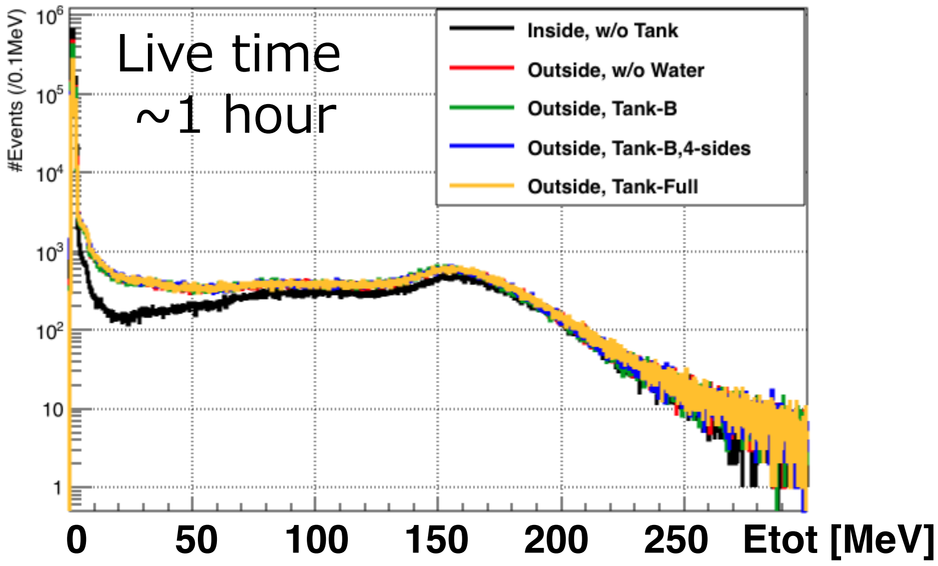
Spectra of the expected neutrino and typical low-energy BG



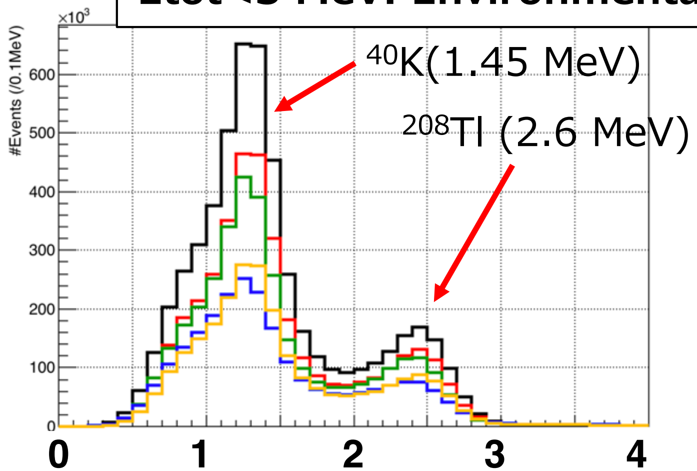
Low-energy BG (=environmental γ) is more than a amount of expected ν up to 3 MeV.

Result: Environmental γ

Single spectra from PANDA



Etot<3 MeV: Environmental γ



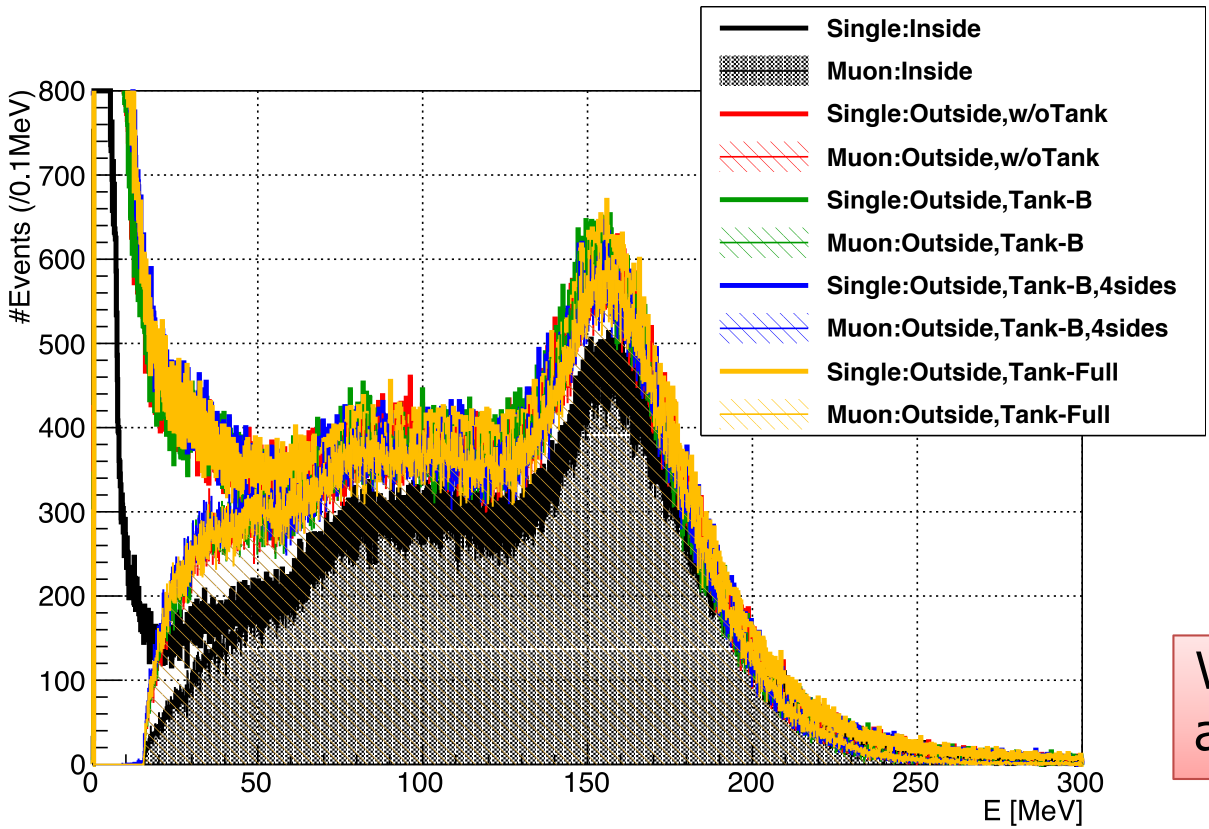
Selection:
Total deposit energy < 3 MeV

	Total	<3MeV
Inside (Reference)	1.63kHz	1.46kHz
Outside, w/o Water	1.29kHz (-20.8%)	1.04kHz (-28.7%)
Outside, Tank-B	1.19kHz (-27.0%)	0.94kHz (-35.7%)
Outside, Tank-B,4-sides	0.92kHz (-43.4%)	0.67kHz (-54.4%)
Outside, Tank-Full	0.94kHz (-42.3%)	0.68kHz (**-53.2%**)

Water tank is powerful shield
for low-energy environmental γ-ray.

Result: Cosmic-ray muon

Selection:
15 MeV < E < 25 MeV for each hit-module
(Module size: 10 cm×10 cm×100cm)

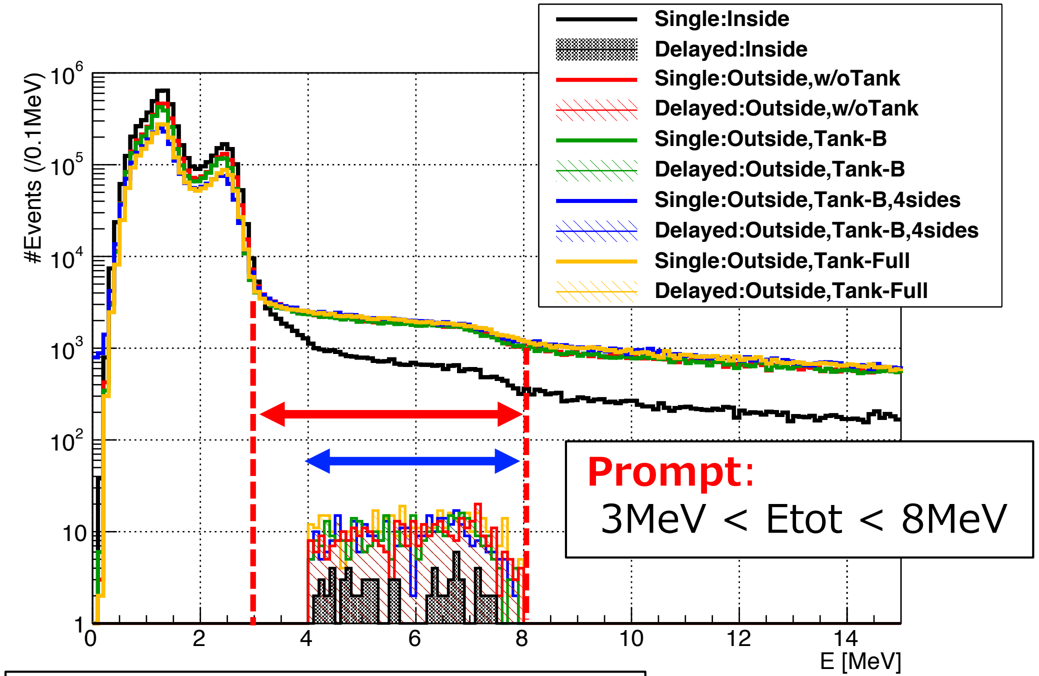


	Muon
Inside (Reference)	133.76Hz
Outside, w/o Water	176.63Hz (+32.0%)
Outside, Tank-B	177.75Hz (+32.9%)
Outside, Tank-B,4-sides	178.28Hz (+33.3%)
Outside, Tank-Full	179.52Hz (+34.2%)

Water shield is not effective against cosmic-ray muon.

Result: Delayed coincidence events

To evaluate BG events in delayed signal,
we applied the delayed coincidence method into measured data.



	Delayed Coincidence	#Events /day
Inside (Reference)	0.022 Hz	1,900
Outside, w/o Water	0.097 Hz (+345.0%)	8,380
Outside, Tank-B	0.095 Hz (+335.0%)	8,210
Outside, Tank-B,4-sides	0.095 Hz (+332.5%)	8,210
Outside, Tank-Full	0.122 Hz (**+465.0%**)	10,540

Delayed coincidence:
- #Hits ≧ 4
- 4MeV < Etot < 8MeV
- 1MeV < E1st,E2nd < 8MeV
- 50 us < dT < 100 us

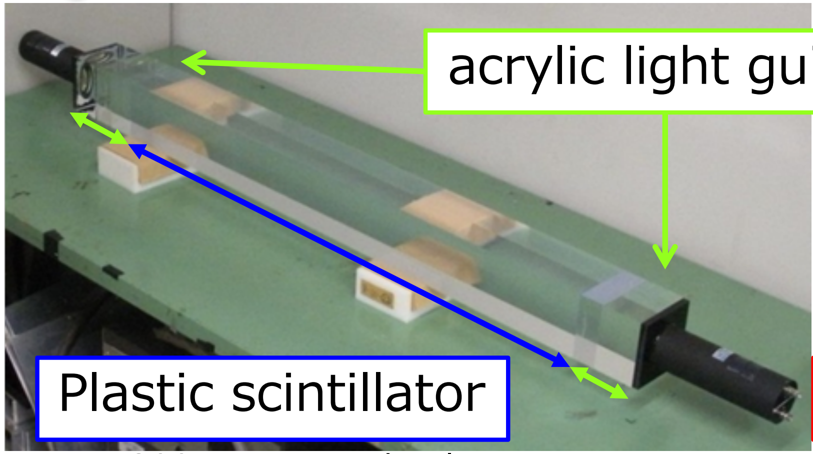
For BG events in delayed energy region,
water shield is not effective.
The top-tank may cause the increase of BG
since **cosmic muon makes spallation** there.
Configuration of the shield tanks should be considered carefully.

Summary

- Anti-neutrino detector based on scintillator with Gd are suitable tools as a reactor monitor.
- We are developing the portable and non-flammable detector using a solid scintillator; **PANDA project**
- **Construction of the PANDA100** as the final version had completed in 2016.
- Accidental background estimation is in working.
  BG rates for various conditions were measured in our University.
  - In Laboratory: **0.022 Hz** (**~1,900 /day**)
  - Outside w/o water shield: **0.097 Hz** (**~8,400 /day**)
  - Bottom+4-sides covered: **0.095 Hz** (**~8,200 /day**)
  - Full surface covered: **0.122 Hz** (**~10,500 /day**)
  - Expected neutrino flux: **0.0017 Hz** (**147 ν/day**)
- **The water shield** seems to be effective against **low-energy γ-ray**.
- Further improvement of analysis is preparing for reducing accidental BG rate. (Ex. **Event topological information**)
- We are ready to measure at a Japanese reactor and are asking about the reactor status to an electric company.

Back Up

PANDA module

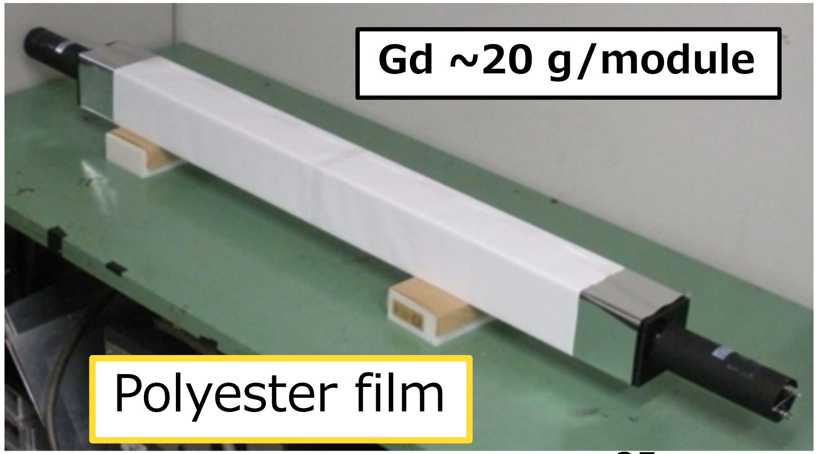


10x10x10 cm^3

EJ-200, ELJEN Technology
(RP-408, Rexon Technology)

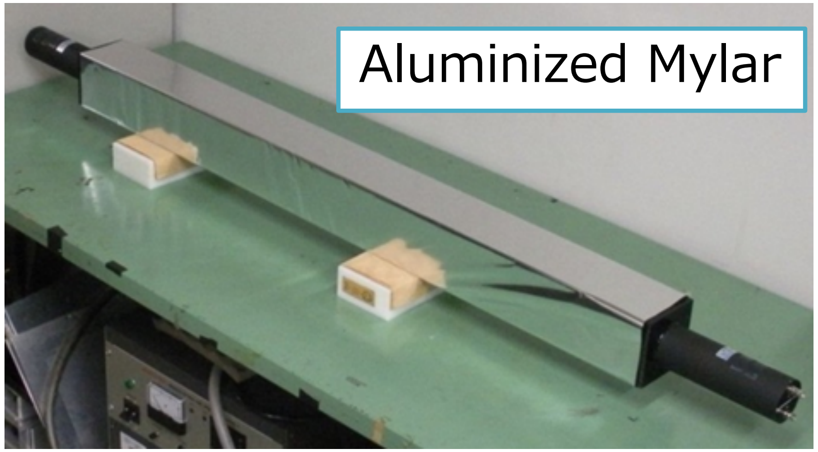
2″ PMT

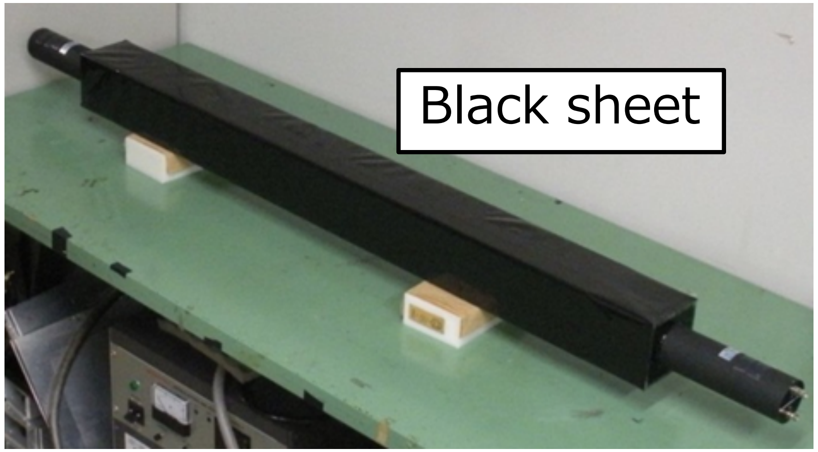
H6410, Hamamatsu



25 µm
50 µm
25 µm

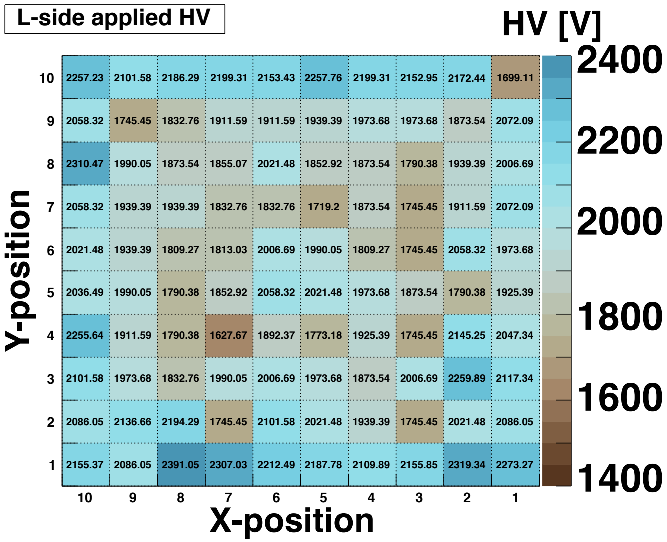
Gd (Gd_2O_3) coating
⇒ Gd density: ***4.9*** mg/cm^2
(Ask Sanshin Engineering Corp.)

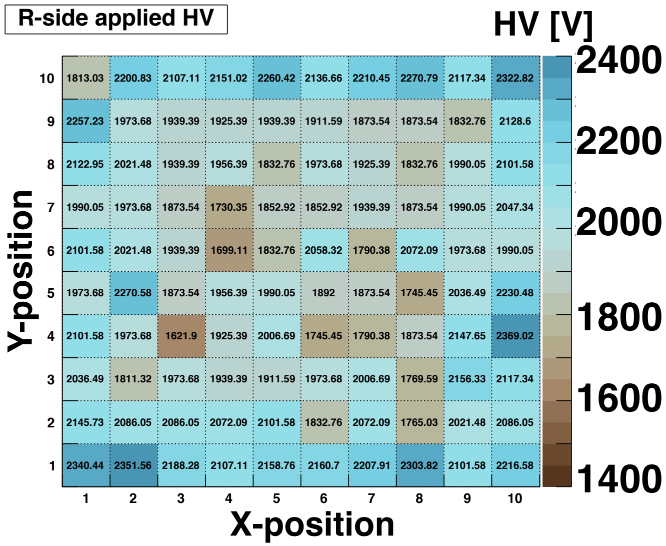




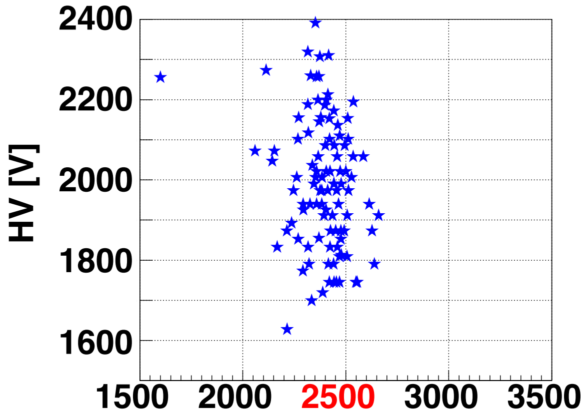
Gain adjustment

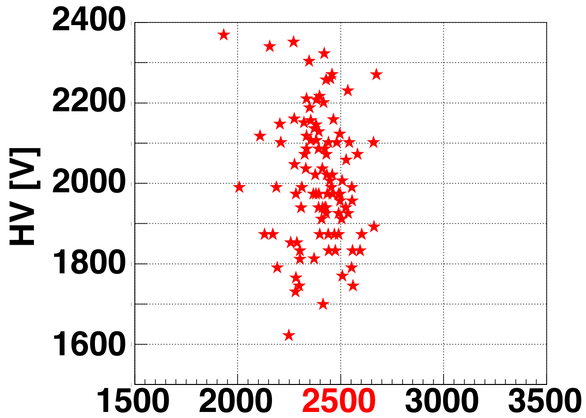
- We adjusted each PMT gain (applied HV value) by energy spectrum of cosmic-ray

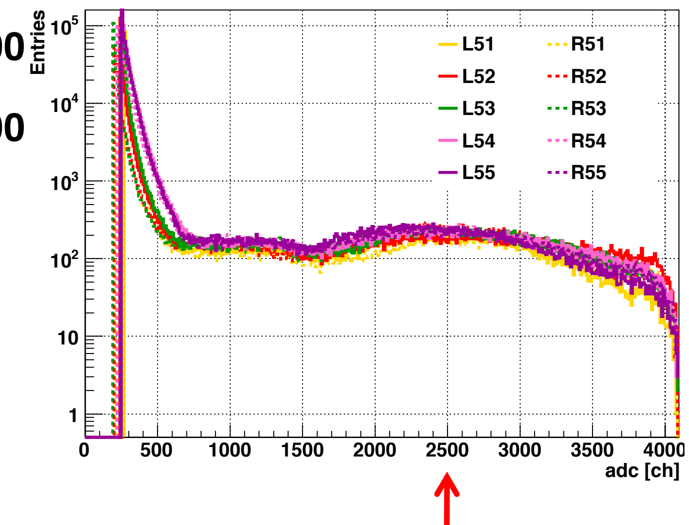




Since 64 PMTs were not able to be used to generate a trigger, PMTs with a lower gain were placed at outermost layer.





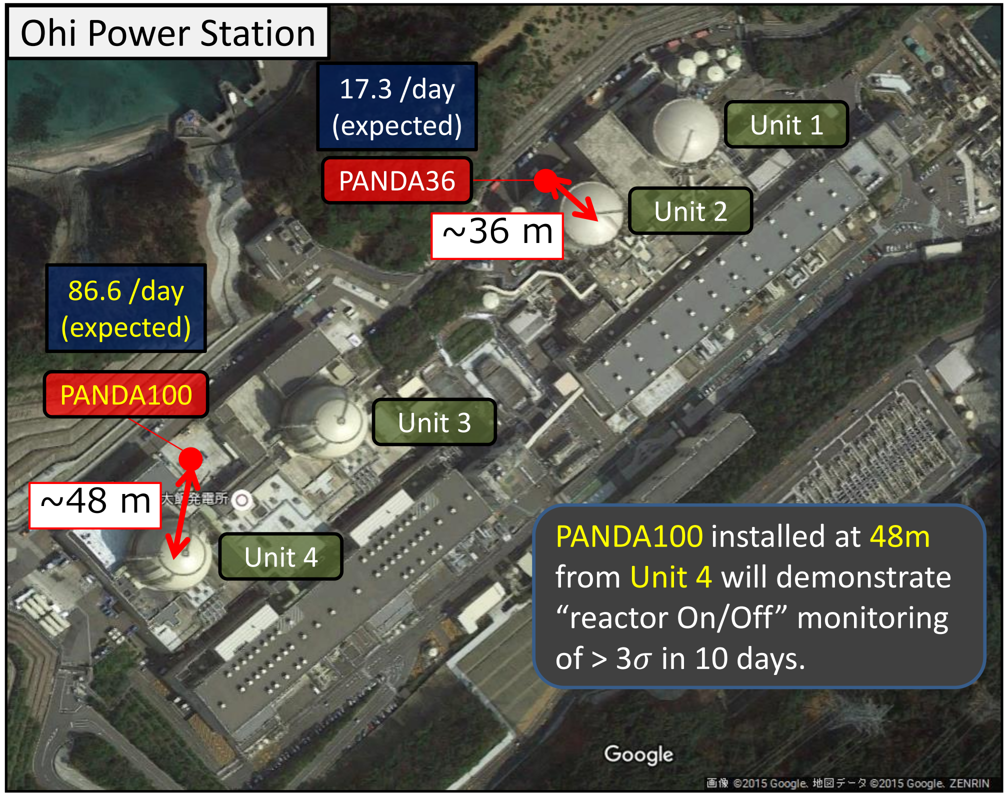


Target ADC value

Prospection of neutrino flux

【Ohi Power station case】
Thermal power: 3.4 GW
Distance from core: 48 m

Neutrino detection rate (Ave.)
1.08×10^{-5} /sec/kg



	PANDA36 (~2013)	**PANDA100 (2016~)**
Target mass [kg]	360	**1000**
Distance from core [m]	36	**48**
Efficiency※ [%]	3.15	**9.24**
Expected ν rate [Events/day]	18.8	**86.2**

※ Based on simulation

Prospects for PANDA100

Efficiency and error estimation for PANDA36

Table 7.1: Summary of the detection efficiency and the systematic error: The detection efficiency of the delayed events is estimated for the simulated events which satisfied the prompt event selection, and the one of the time window is estimated for the simulated events which satisfied the prompt and delayed event selection. The relative error consists of the uncertainties in the simulation models "relative error(model)" and the PMT gain factors "relative error(gain)". The detection efficiency of 3.15 ± 0.93 % was estimated.

		efficiency	relative error(model)	relative error(gain)
prompt	trigger	28.6%	12.1%$^{(1)}$	—
	E_{total} cut	44.2%	10.5%	—
	E_{2nd} cut	82.2%	12.1%$^{(1)}$	—
	fiducial cut	93.5%	5.0%	—
	total	9.7%	16.8%	3.4%
delayed	trigger	48.8%	19.4%$^{(2)}$	—
	E_{total} cut	79.1%	19.4%$^{(2)}$	—
	E_{3rd} cut	91.9%	19.4%$^{(2)}$	—
	total	35.5%	19.4%	1.0%
time window		91.2%	14.3%	—
Total		3.15%	29.6%	

(1) The uncertainties in the software trigger efficiency and the prompt E_{2nd} selection were estimated as a whole.

(2) The uncertainties in the three criteria for the delayed events were estimated as a whole.

Table 9.1: Anti-neutrino event selection criteria for PANDA100: It is similar to selection-1 for PANDA36 except for the software trigger.

software trigger:	Two or more modules in 100 modules deposite the energy of 150 keV or more.
prompt:	$3\text{ MeV} \leq E_{\text{total}} \leq 6\text{ MeV}$ $E_{\text{2nd}} \leq 520\,\text{keV}$
delayed:	$3\text{ MeV} \leq E_{\text{total}} \leq 8\text{ MeV}$ $\frac{E_{\text{3rd}}}{E_{\text{total}}} \geq \frac{E_{\text{1st}}/E_{\text{total}}-0.5}{5}$
time window:	$8\,\mu\text{s} \leq t \leq 150\,\mu\text{s}$
fiducial cut:	The highest energy deposit places in inside $8 \times 8 = 64$ modules.
muon veto:	There is no event with $E_{\text{total}} > 8$ MeV for 250 μs before the delayed event.

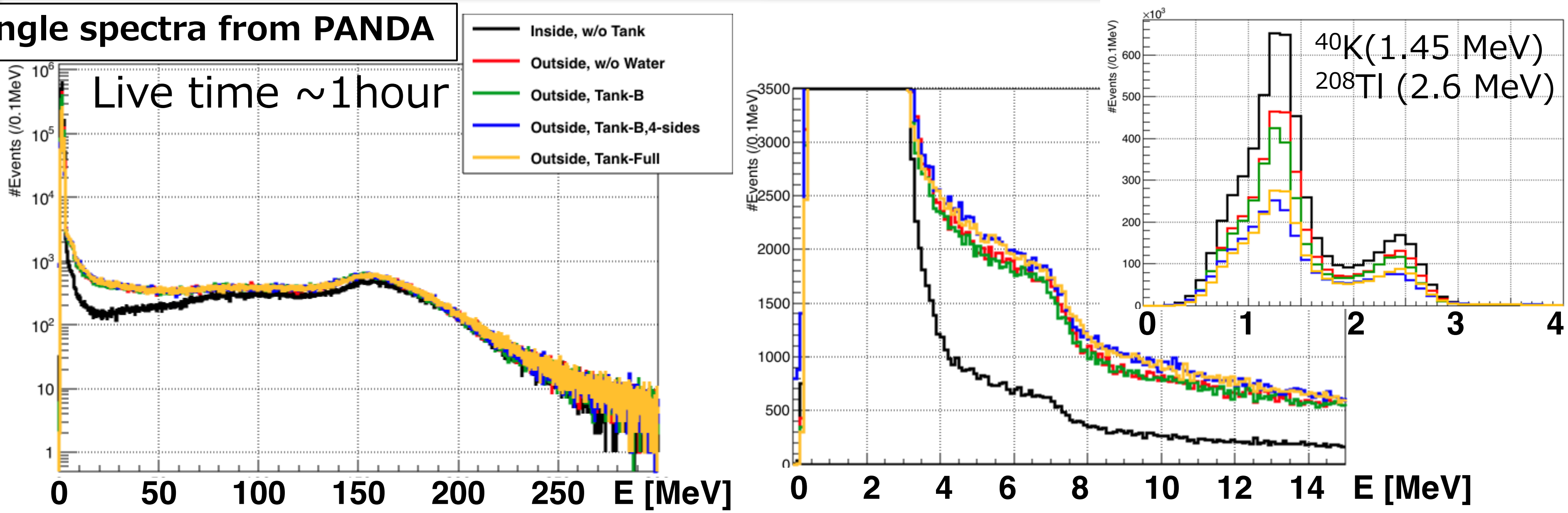
Table 9.2: Detection efficiency of PANDA100 by applying the selection of Tab.9.1: The detection efficiency of 9.24 % was estimated.

		efficiency
prompt	trigger	44.5%
	E_{total} cut	58.0%
	E_{2nd} cut	89.9%
	fiducial cut	77.1%
	total	17.9%
delayed	trigger	81.9%
	E_{total} cut	76.6%
	E_{3rd} cut	91.8%
	total	57.6%
time window		89.8%
Total		9.24%

S. Oguri Ph.D thesis, University of Tokyo, 2012

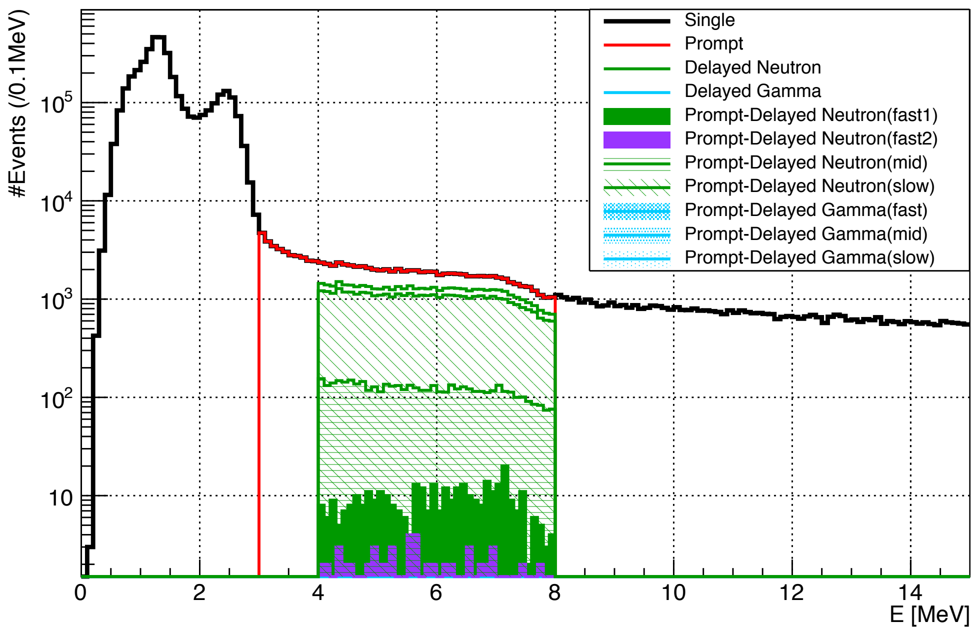
Result: Single event

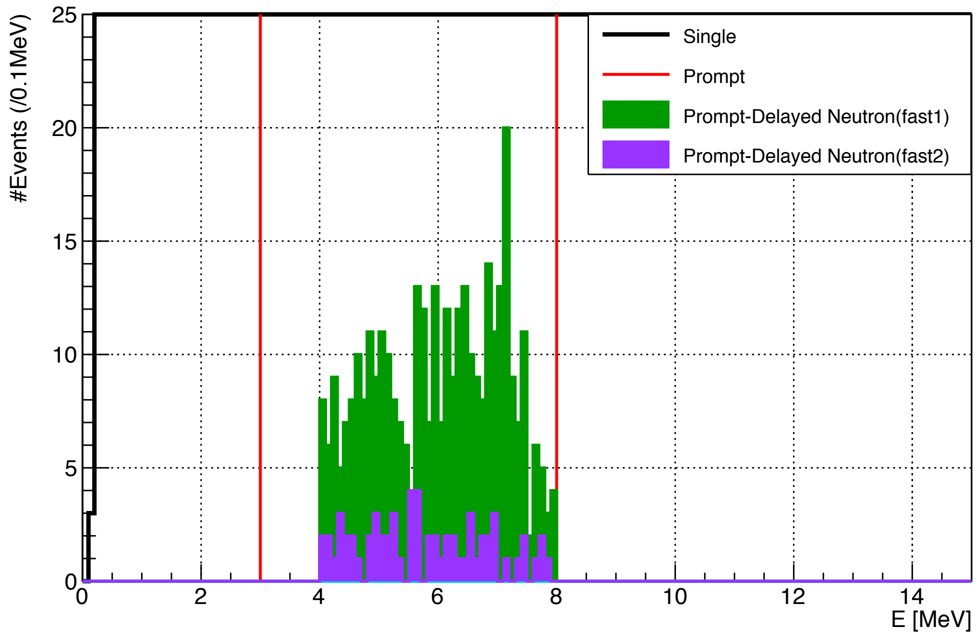
Single spectra from PANDA



	Total	0-3MeV	3-6MeV	6-10MeV	10-50MeV	>50MeV
Inside (Reference)	1.63kHz	1.46kHz	13.62Hz	4.86Hz	18.90Hz	131.87Hz
Outside, w/o Water	1.29kHz (-20.8%)	1.04kHz (-28.7%)	21.88Hz (+60.7%)	13.84Hz (+184.9%)	47.04Hz (+148.9%)	167.80Hz (+27.2%)
Outside, Tank-B	1.19kHz (-27.0%)	0.94kHz (-35.7%)	20.49Hz (+50.5%)	13.50Hz (+178.0%)	47.26Hz (+150.1%)	168.72Hz (+27.9%)
Outside, Tank-B,4-sides	0.92kHz (-43.4%)	0.67kHz (-54.4%)	22.59Hz (+65.9%)	15.22Hz (+213.2%)	50.61Hz (+167.8%)	168.29Hz (+27.6%)
Outside, Tank-Full	0.94kHz (-42.3%)	0.68kHz (-53.2%)	21.73Hz (+59.6%)	15.23Hz (+213.5%)	49.69Hz (+162.9%)	170.94Hz (+29.6%)

2017-09-01_c2_T60 (w/o tank)
Live time ~1 hour





(fast1)50us<dT<100us: 0.097 Hz
(fast2)1050<dT<1100us : 0.018 Hz
→ These events are not considered
what were correlated with the prompt events in time.

Time line of PANDA project

Development had been started since 2006 at University of Tokyo

U. Tokyo

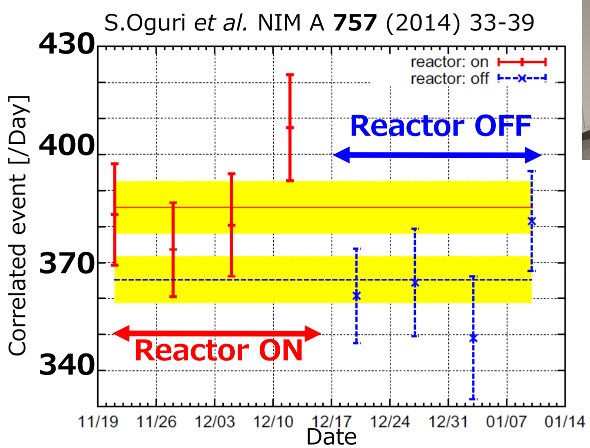
PANDA16 (Lesser PANDA): **4×4=16** modules

- 2008-2011
- Confirmation of the construction and operation
- 2011.Mar-May: First measurement at Hamaoka reactor

PANDA36: **6×6=36** modules

- 2011-2013
- DAQ system were updated
- 2012.Nov-2013.Jan:
  First measurement of ON/OFF operation of the Ohi reactor (Fukui, Japan).

Ohi reactor Unit 2: 3.4 GWth (PWR)
Distance form the core: 35.9 m
Duration: 30 days (ON), 34 days (OFF)
Observed neutrino event: **21.8 ± 11.4 /day**



PANDA64: **8×8=64** modules

- 2013-2014
- Water tanks for fast-n shield were introduced and tested
- 2014.Jul-Sep: γ-bursts from thundercloud had been observed at Mt. Norikura

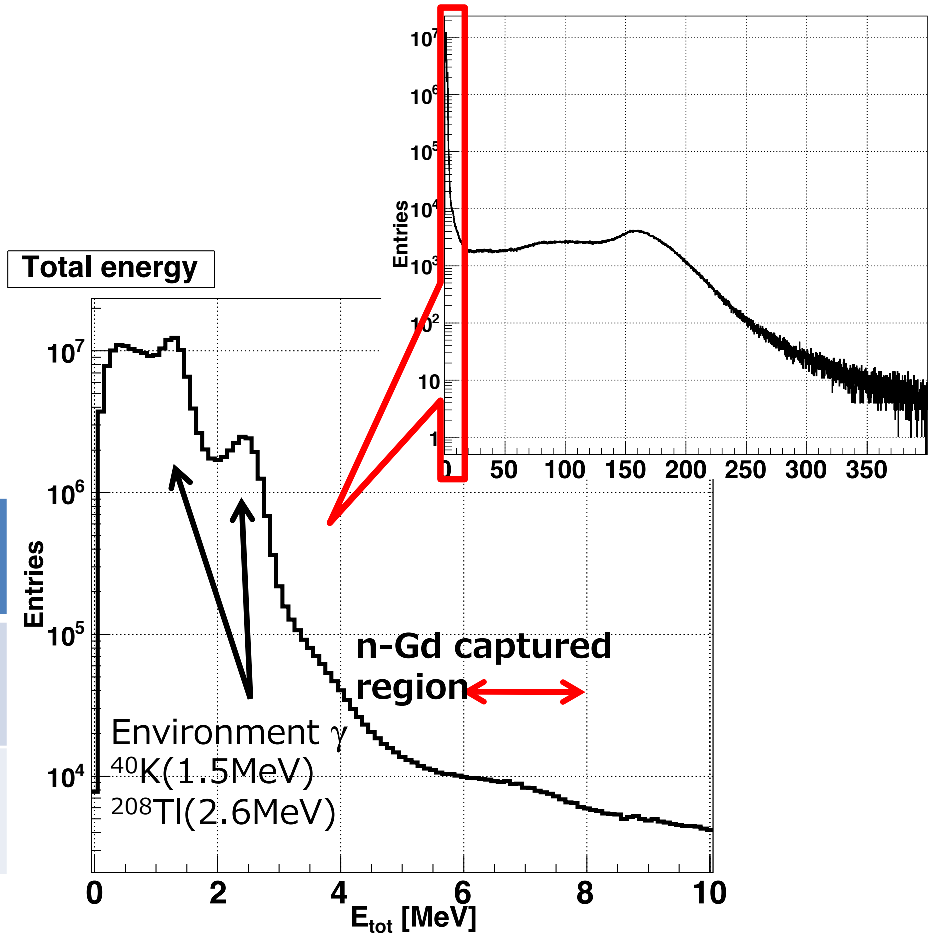
Background measurement

In order to estimate accidental background near the reactor, we performed the background measurement of the PANDA100 at Kitasato Lab (Ground floor of 3F Bldg).

Trigger condition
- Threshold of discriminator: -20 mV
- Module hit coincidence: 2 or more

Live time: 32,501 sec (~0.38 days)
- Averaged DAQ rate: 5.45 kHz

Energy spectrum of single event



Uncorrelated Background rate

Single event	Event rate
Environment γ (E_{tot}<3 MeV)	5.27 kHz
Cosmic-ray (4 hit modules with E>15 MeV)	0.09 kHz

Japanese reactor status

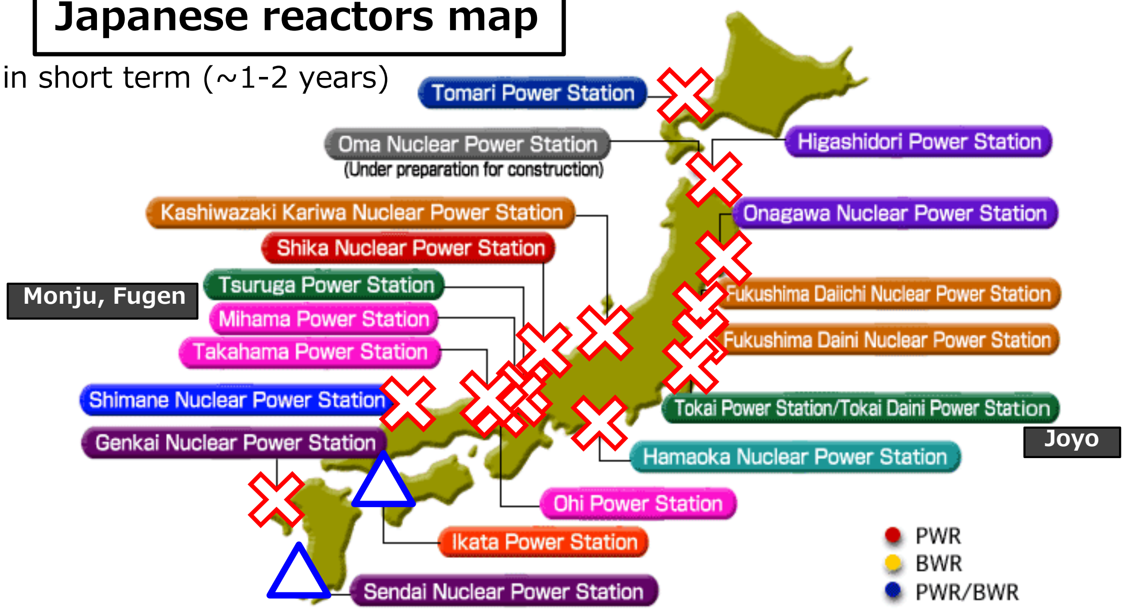
After the Great East Japan Earthquake, regulations of reactors in Japan were renewed.
Almost all reactors in Japan are shut down for inspection or decommissioning.
Restart of them is difficult so far.

Research reactors (Monju, Joyo, etc)
are also shut down by operational troubles.

A using of them soon as a neutrino facility
is not clear.

Japanese reactors map

in short term (~1-2 years)



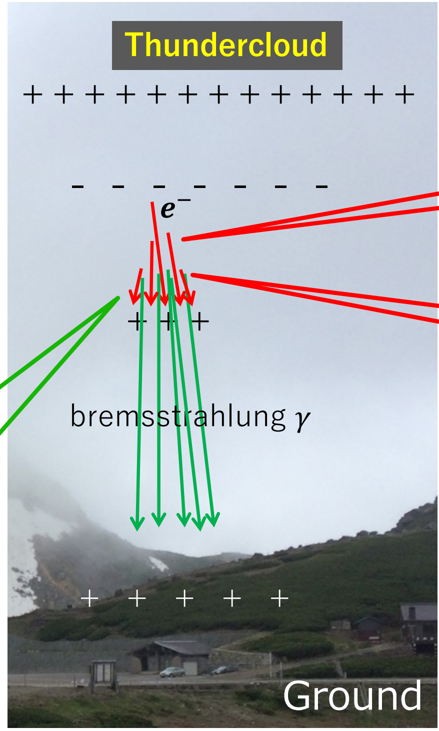
Japan Nuclear Technology Institute (http://www.gengikyo.jp)

Power Station	Thermal power [GW]	Status
Tomari	1.6(#1), 2.6(#2)	Shutdown
Higashidori	3.3	Shutdown
Onagawa	1.6(#1), 2.4(#2,3)	Shutdown
Fukushima II	3.3(#1-4)	Shutdown
Kashiwazaki-Kariwa	3.3(#1-5), 4.0(#6,7)	Shutdown
Shika	1.6(#1), 4.0(#2)	Shutdown
Tokai	3.3	Shutdown
Tsuruga	3.4	Shutdown
Hamaoka	3.3(#1,2), 4.0(#3)	Shutdown
Mihama	2.4	Shutdown
Ohi	3.4	Shutdown
Takahama	2.7(#1-4)	Shutdown
Shimane	1.4(#1), 2.4(#2)	Shutdown
Ikata	1.7 (#2) 2.7 (#3)	Shutdown Operating
Genkai	1.7(#1), 3.4(#2,3)	Shutdown
Sendai	2.7 (#1) 2.7 (#2)	Shutdown Operating

γ-ray bursts under Thundercloud

PANDA detector is also working as the large volume γ-ray detector.
We try to observe γ bursts from the thundercloud.
In the thundercloud, the natural electron acceleration is expected.

Y. Kuroda, *et al.* Phys.Lett.B **758** (2016) 286-291



Seed electron is accelerated

Knock-on e^- are produced

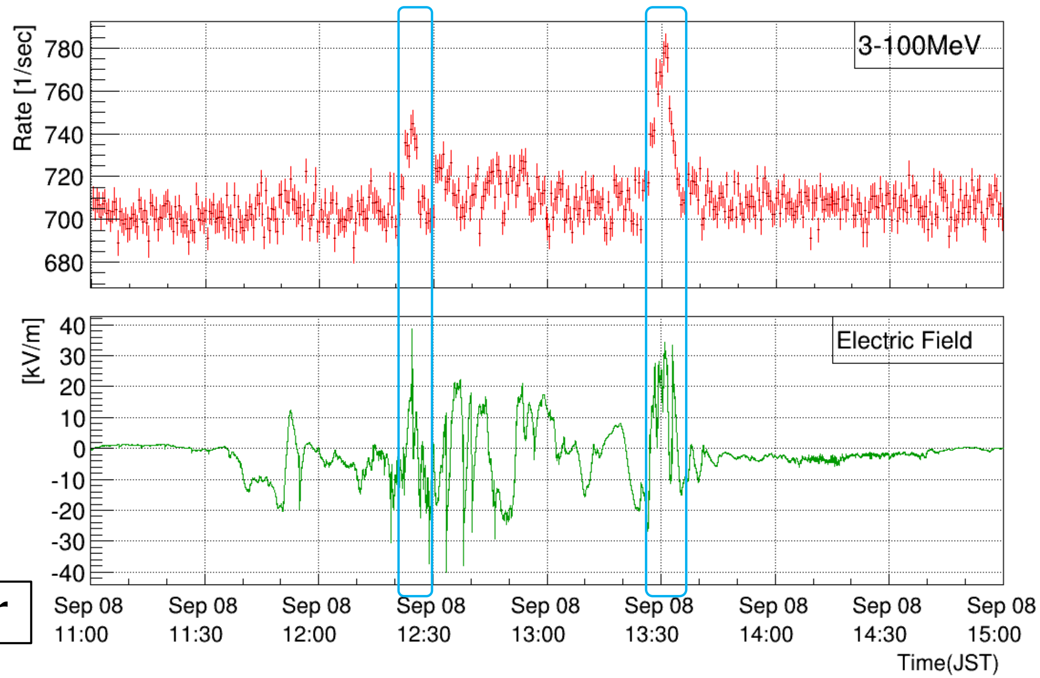
Bremsstrahlung γ are produced by electrons ⇒ γ-ray Bursts

Finally, accelerated electrons can cause an avalanche multiplication process. (*Relativistic Runaway Electron Avalanche*)
As the result, **γ-ray bursts** from electrons are observed under the thundercloud.

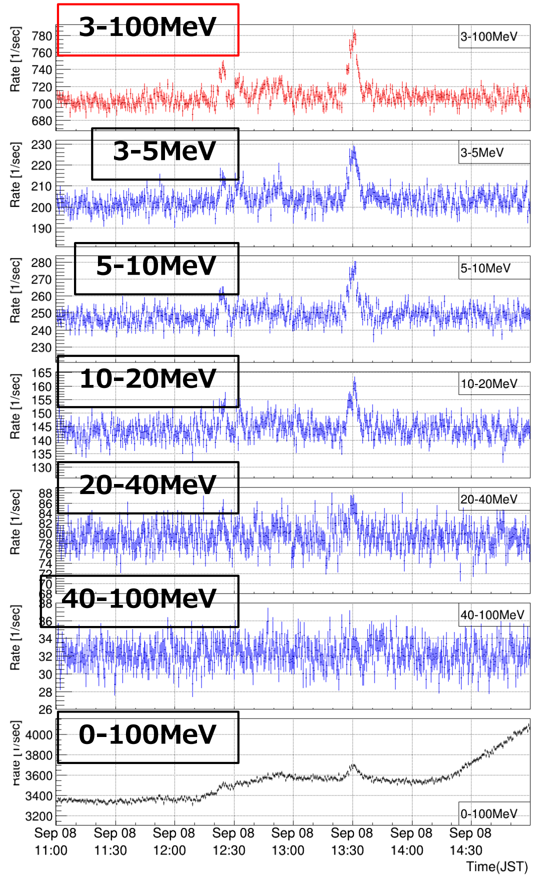
For accumulating of γ-ray burst events and the total system test of the PANDA100, we carried out the observation test using the PANDA100 at mountaintop.

Burst event candidate

A burst event is indentified using the **single event analysis**.
We found the burst event candidate on 8 Sep. 2016.



Electric field meter



We continued observing γ bursts with up to around 100 MeV.
Such burst events had been also observed at our previous test of the PANDA64.

And we are doing detail analyses of all data.