Status of liquid scintillator based reactor monitor (Gd-loaded Liquid Scintillator)

Tohoku Univ.

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新学術領域研究「ニュートリノフロンティア」研究会２０１４ （富士Calm）

Contents

1. Introduction of R&D of a compact reactor monitor with neutrino detection.

2. Activity in Tohoku Univ.
(Development of a new detector is ongoing)

3. MC study of expected sensitivity for neutrino observation with the new detector.

1. Introduction of R&D of a compact reactor monitor with neutrino detection.

Anti-neutrino based Nuclear Safeguards and Nonproliferation Applications

Introduction

^{239}Pu is produced for burn-up in reactor core, so there is a possibility of the diversion from civil nuclear fuel cycle facilities into nuclear weapons program.
-> IAEA (safeguards agency) tracks the flow of Pu in the civil nuclear fuel cycle through item accountancy and surveillance.
(effective, but **not include direct measurements of fissile inventory, costly, time consuming..** => Could be improved)

Advantage of reactor monitoring with anti-neutrino detection.

There is feasibility of ..

- **Real time remote monitoring (non-intrusively) of the core operation status because of the high penetrating power.**
- **Monitoring of evolution of fissile inventory in the core.**

=> Anti-neutrino detection attracts IAEA's attention as one of novel technologies.

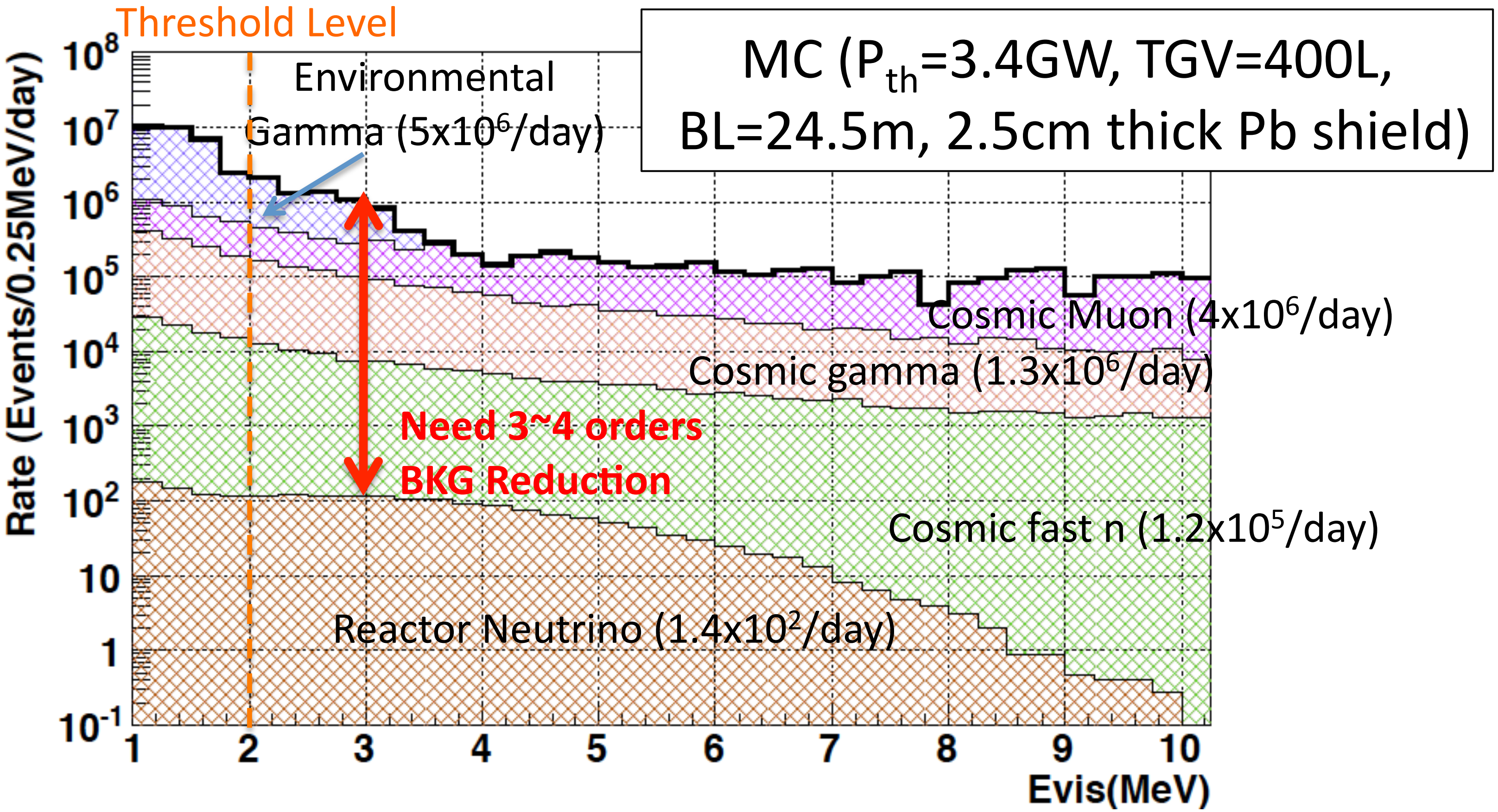
Requirement for the specification of compact reactor monitor

- **Operate non-intrusively (independent, save space)**
  → **few tens meter of the base line with about 1GWth.**
  → **1ton class detector (cubic meter class).**
- **safety**
  → use non-flammable material or use flammable material under the limitation in fire laws.
- **low cost (needed to be competitive with other technologies)**
  → **simple structure (less shield).**
  → **measurable above ground.**

However, aboveground measurement of reactor monitor meeting above conditions, is difficult, because of much amount of cosmic muon induced BKG despite of simple detector (less shield).

=> It is challenging to put the compact reactor monitor to practical use.

BKG (single events) of the aboveground measurement



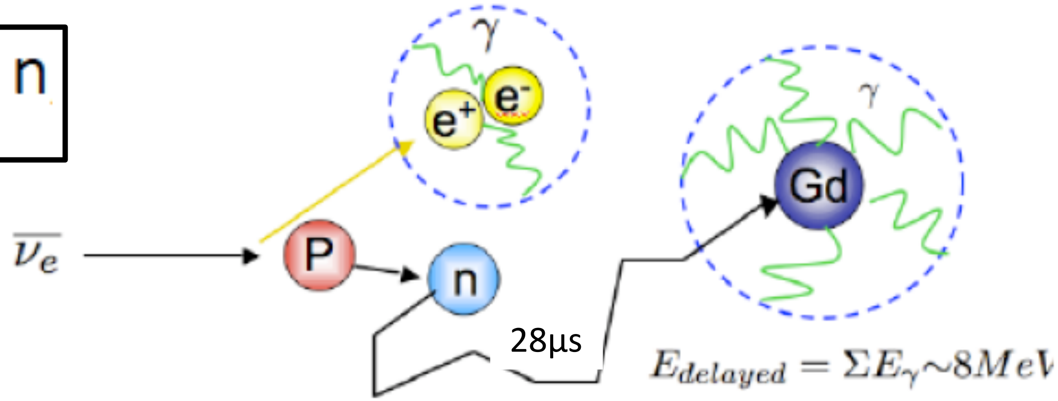
There are much amount of BKGs above ground.
(Env. Gammas, cosmic muons, gammas, fast n, etc.)
To observe the reactor neutrinos, 3~4 orders BKG reduction is needed.
⇒Use Delayed Coincidence method using IBD reaction.

Neutrino detection method

Delayed Coincidence (IBD reaction)

$$\overline{\nu}_{\mu} \Rightarrow \overline{\nu_e} + p \rightarrow e^{+} + n$$

oscillation



Anti-neutrino is Identified by detecting
e+(prompt signal) and γs from n capture on Gd(delayed signal).

=>Can reduce accidental BKG (1/100)
(Gd~8MeV γs, capture time ~ 28 μs).

=> Eν ~ 4MeV

=>Can reconstruct ν energy well (E_{prompt} + 1.8MeV).

=>IBD rate (Target) ~ 1800 events/day (400L, 24.5m, 3.4GWth)

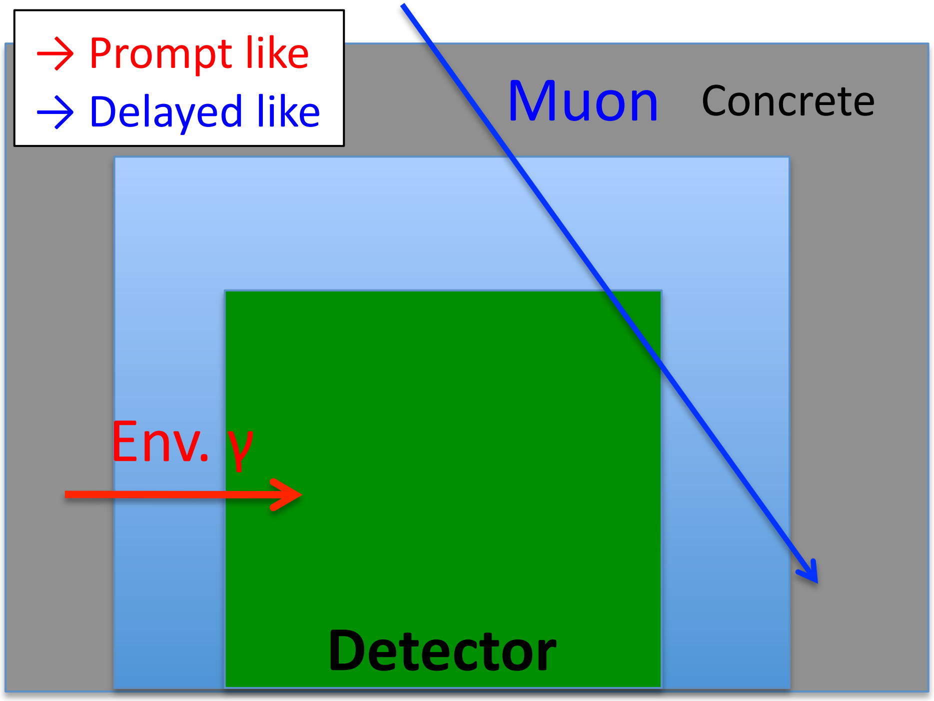
BKGs for delayed coincidence

2 types of BKG for the delayed coincidence (IBD).

1. Accidental BKG

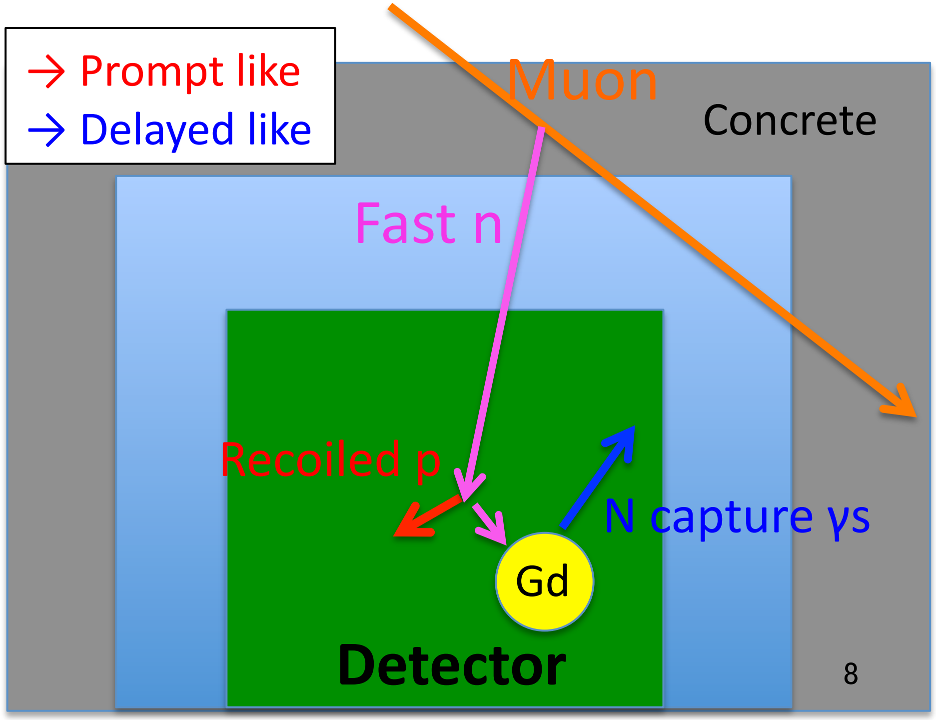
When 2 single BKG events occurs in a time window(~100us) accidentally, they makes the ACC BKG.

Main sources for ACC BKG are **Env. γ, Cosmic Muon and the muon induced γ**.



2. Correlated BKG

Muon induced Fast n enters into the detector, losses the kinetic energy by recoiling protons(prompt like). => Emits gammas via thermal n capture on Gd (delayed like).

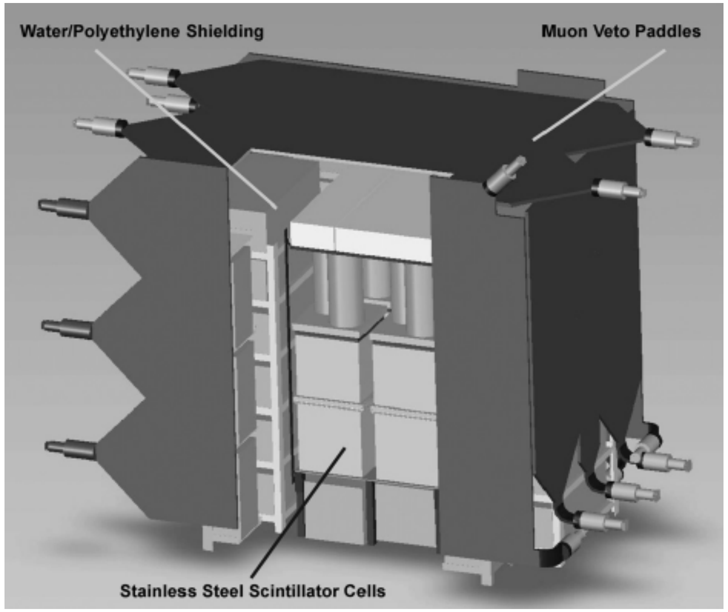


SONGS experiment (US, SanOnofre)

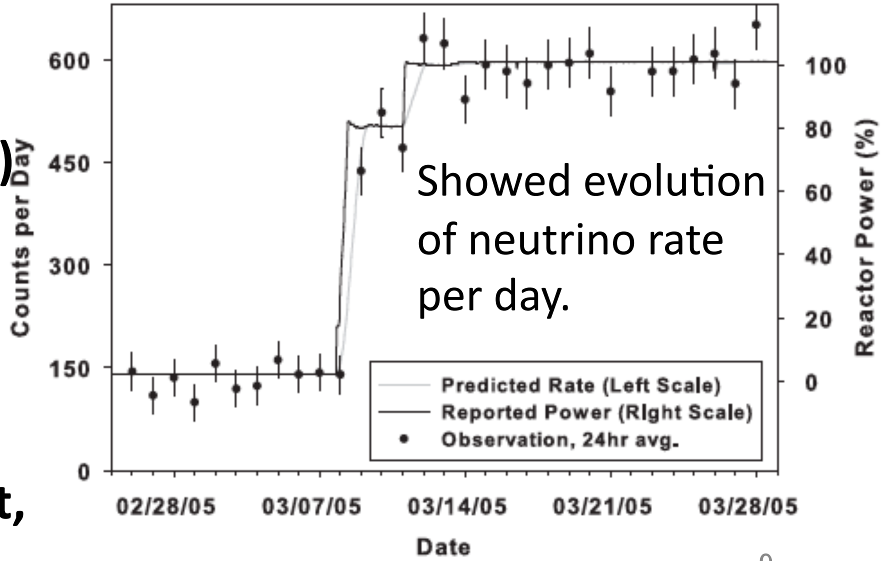
<u>SONGS experiment already shows feasibility of reactor monitoring with neutrino detection.</u>

Experimental design

Thermal Power = 3.4GW.
Base line = 24.5m.
Depth = 10m (1/7 of muon flux)
Target = Gd-LS (748L), 8 x 9inches PMTs.
Shield = 50cm thick of water/Polyethylene.



Measured ν excess = 459 ± 16/day
Expected ν rate = 407 ± 75/day (ν eff. ~ 11%)
ACC BKG = 3732 ± 25/day
Fast n BKG = 105 ± 9/day

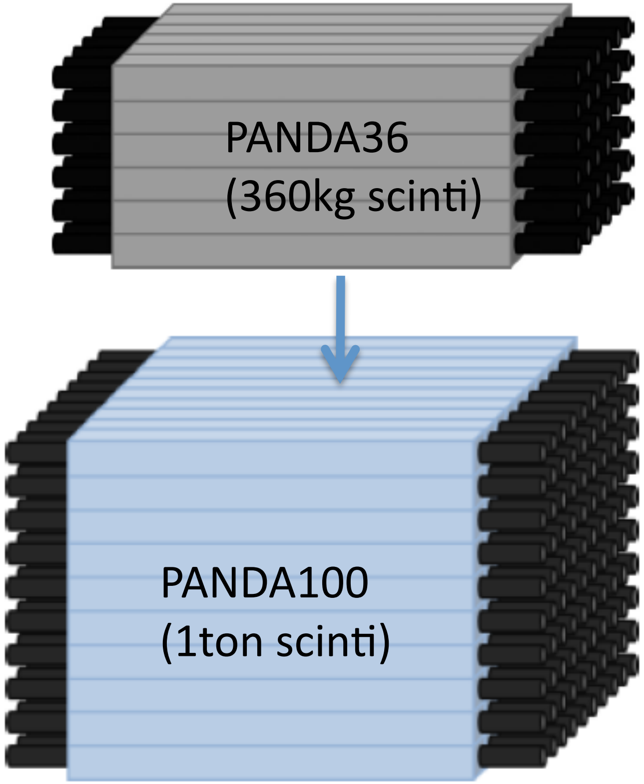


However,
<u>more improvement is needed for practical use</u>.
(**neutrino efficiency, reduction of ACC amount, keeping low fast n BKG rate in aboveground case**.)

N. S. Bowden, Nucl. Instr. Meth. A 572 (2007) 985

PANDA(A02班)

In this year, they published NIMA paper for resulting aboveground measurement with PANDA36 at Ohi Power Station.
(Pth=3.4GWt, Baseline=36m,)



They succeeded to observe neutrino excess above ground.

Observed excess	**:21.8±11.4 /day (ν eff.~3%)**
Expected rate	**:17.3±6.2 /day**

Now they are upgrading the detector to PANDA 100, and they are waiting restarting of Ohi reactor.

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Reactor antineutrino monitoring with a plastic scintillator array as a new safeguards method

CrossMark

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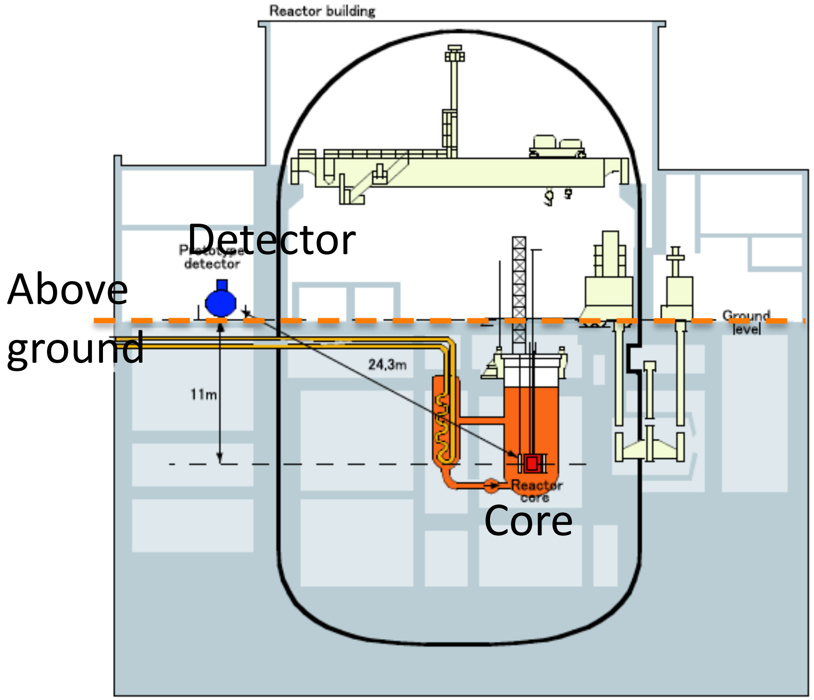
2. Activity in Tohoku Univ.
(Gd-loaded Liqud Scintillator)

Activity in Tohoku Univ.

<u>2006~2008 Joyo measurement</u>

(H. Furuta et al., NIMA 662 (2012) 90-100)

Above ground measurement with KASKA prototype(0.7tons, Gd-LS) at Joyo site (experimental fast reactor, 140MWth, baseline~24.3m)



Observed excess :1.1±1.3 /day (ν eff.~0.3%)   **Expected rate :0.5 /day**

Finally, we could not observe clear neutrino excess, because of …

- Low thermal power comparing usual commercial reactor (~3GW).
- Degradation of Gd-LS, long term. => Poor statistics.
- Poor knowledge for BKGs above ground.

=>However, we could understand BKG aboveground well.

Activity in Tohoku Univ.

2010~2012 PSD study with 200L Gd-LS

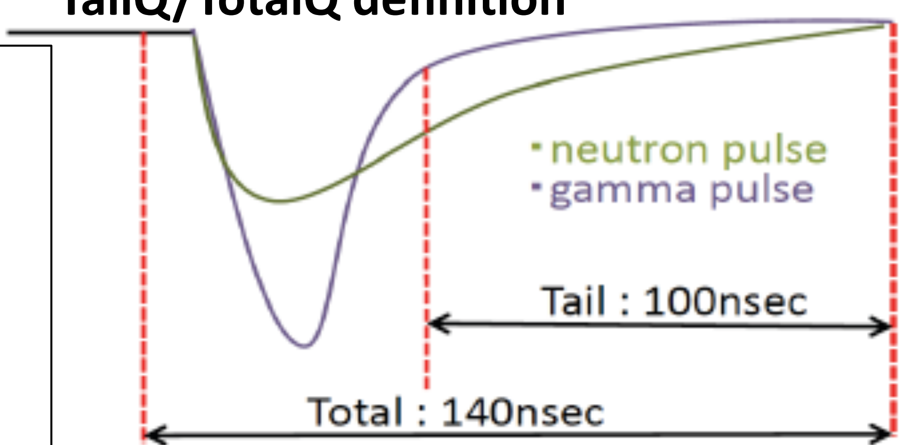
(H. Furuta et al., IEEE proceedings of the 2nd int.conf. ANIMMA 2011.)

In 2010, we remodeled KASKA prototype for PSD study for fast n BKG reduction.

PSD for fast n rejection

Pulse shape of recoiled proton is wider than one of gamma.
-> possible to distinguish neutrino prompt signal from fast n signal.
*->**TailQ/TotalQ** ratio is useful as the PSD variable, powerful for the fast n rejection.*

TailQ/TotalQ definition

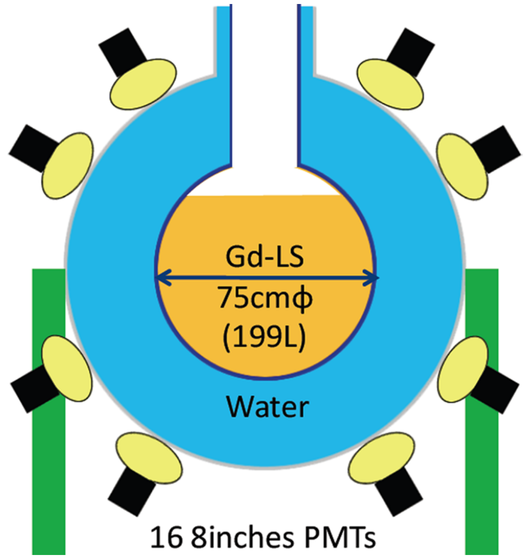


How to remodel..

Target was changed to **200L PC based Gd-LS with PSD** capability(**PC shows good PSD performance with vial**).
Target Vessel : Acrylic -> Large glass flask.
(PC attacks acrylic material)

Main purpose of the remodeling

PSD capability tends to become worse in case of larger volume.=> Checked how much it becomes worse.



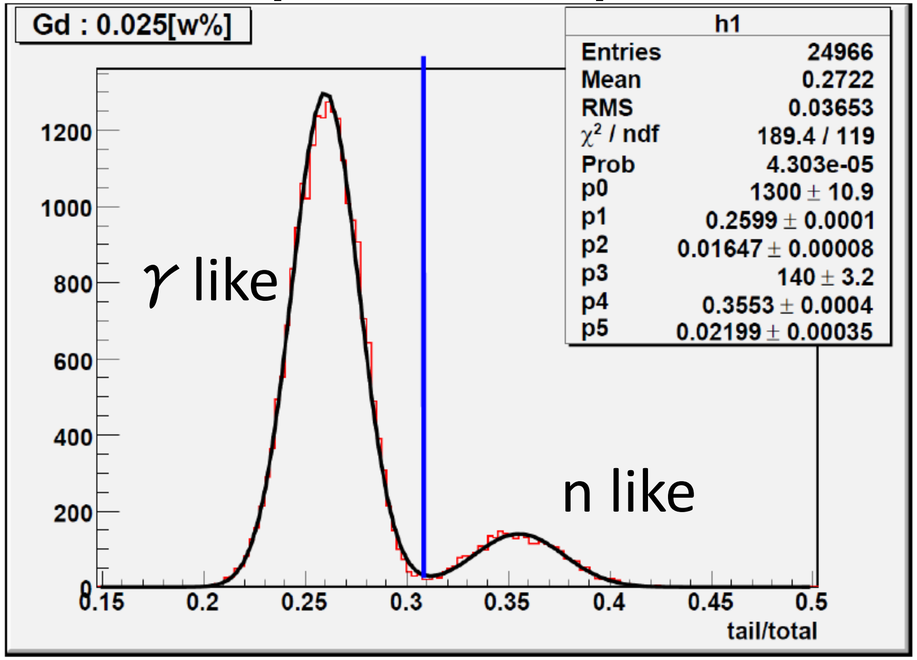
Activity in Tohoku Univ.

2010~2012 PSD study with 200L Gd-LS

(H. Furuta et al., IEEE proceedings of the 2nd int.conf. ANIMMA 2011.)

Fast n rejection power for PC based Gd-LS

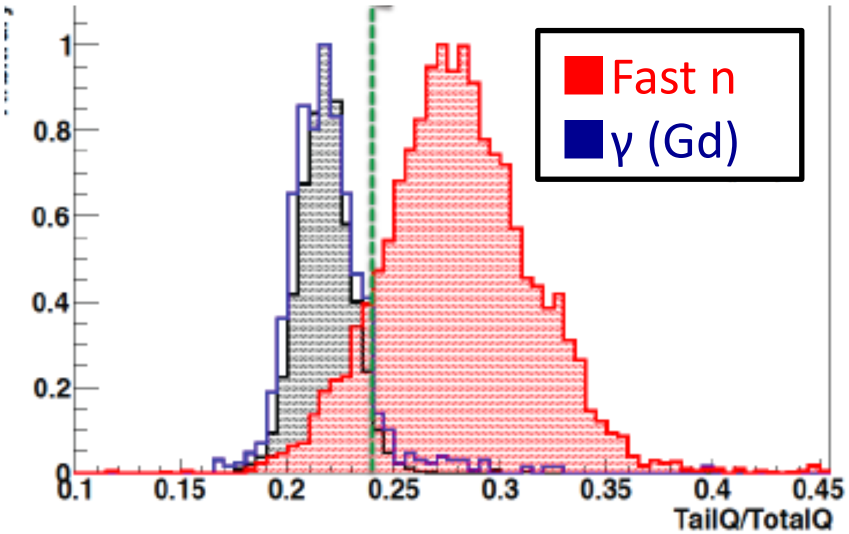
Vial size (^{252}Cf source)



Good PSD capability with Vial size.

Target volume = 200L

(Measured BKG data at Tohoku Univ.)



~90% n rejection keeping ~90% ν eff.

New cubic meter detector (2013 ~)
(development is ongoing)

Main purpose : To observe clear neutrino excess at some reactor site.

Liquid scintillators

Target volume : LAB based Gd-loaded liquid scintillator (0.1w%Gd, 400L)
with PSD capability (not fixed yet, R&D is on going).

Veto volume : Silicon oil (ShinEtsu KF50) + PPO (3g/L)

=>The detail is explained later.

Characteristic related to lights

24x10 inches PMTs(Hamamatsu R7081)

Photocathode coverage ~14.7%

(Target=300pe/MeV, Veto=50pe/MeV)

E resolution ~ 11%

Thin lead shield (2.5cm thick)

Electronics

Flash ADC (CAEN V1730),

500MS/s, 14bit for PSD

$E_{threshold}$ >2MeV

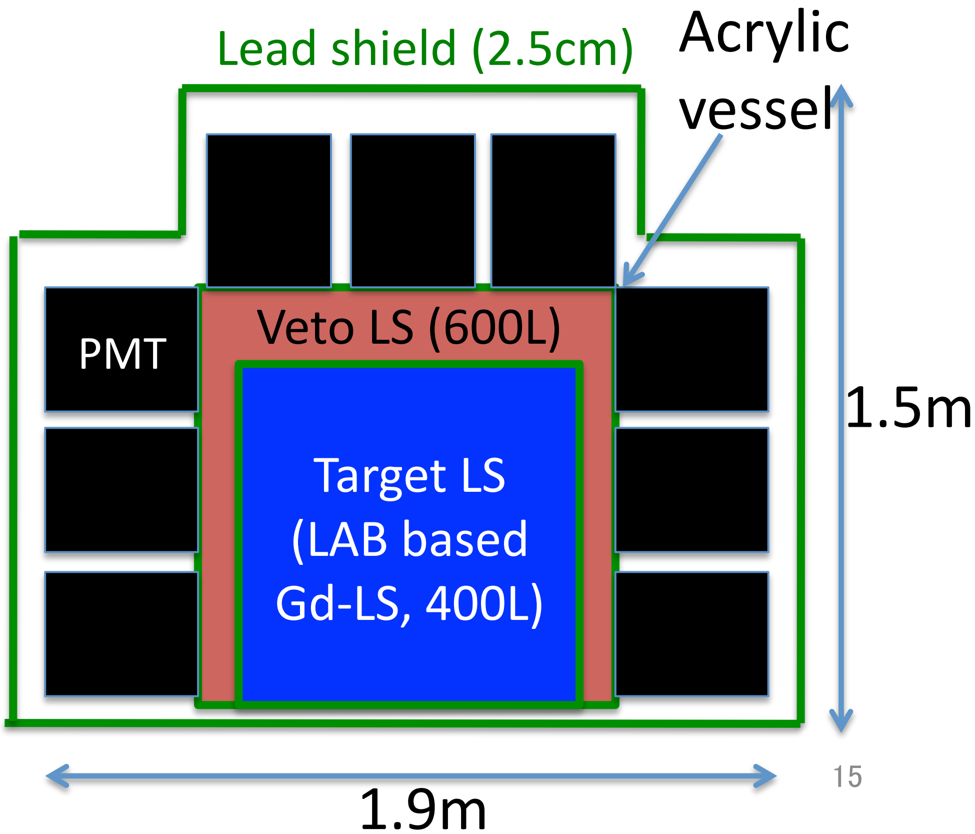


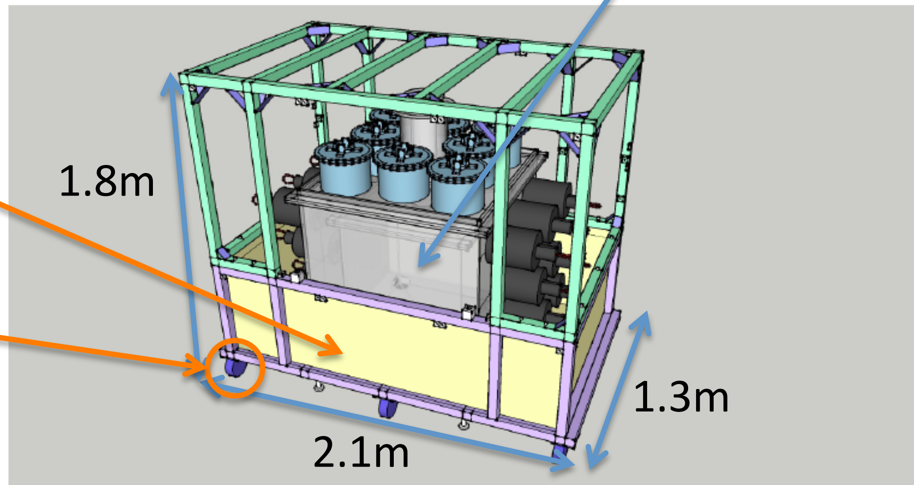
Figure of new detector

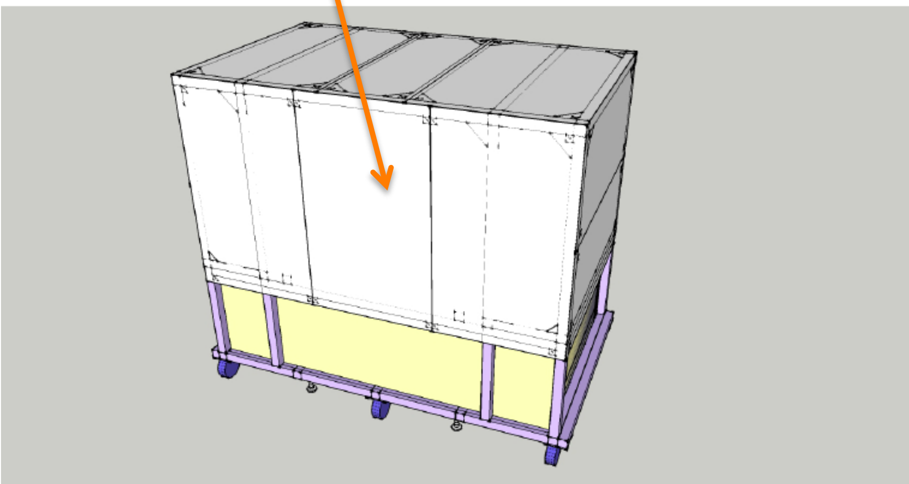
Acrylic vessel

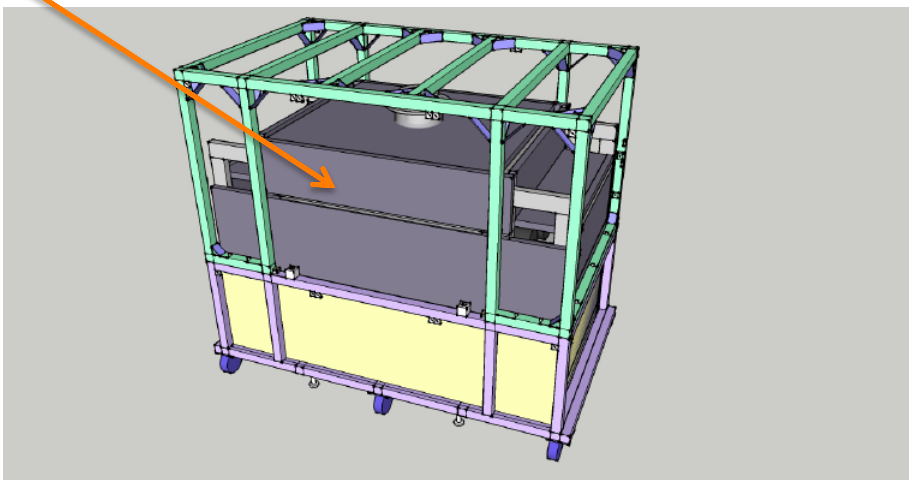
•The detector is set on **oil pan (1.5m³)**.

•**Casters** are set under the oil pan for **movable detector**.

•The detector is surrounded by **lead shields** and **Al boards** for light tightness.







Acrylic vessel and support structure were already ordered to their companies.
=> Detector construction will be completed until end of Jan. 2015.

Development of Gd-Loaded Liquid Scintillator (Development is on going)

Requirements

1. High PSD capability.

Rejection of muon induced fast n.

2. High Flash point

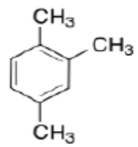
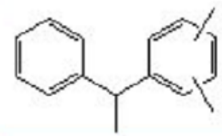
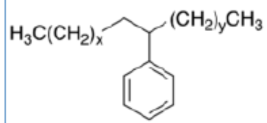
There is an usable volume limitation for hazardous material, 危険物 without any application in municipal bylaw(条例).

21<FP<70°C =>“第2石油類“ => 200L
70<FP<200°C => “第3石油類” => 400L
=> Can increase target volume.

3. Acrylic compatibility

Previous detector(PC based LS)
=> large glass flask (200L).
Acrylic vessel is better because of the strength.

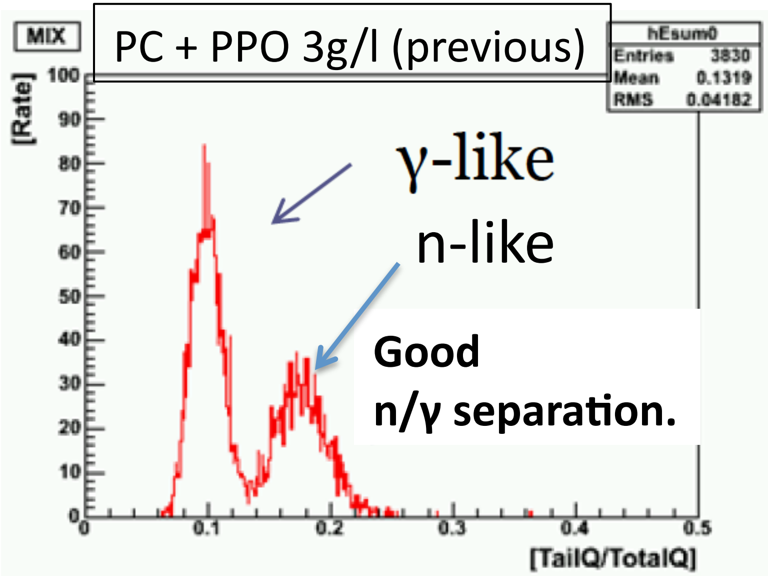
Solvent candidates for Gd-LS

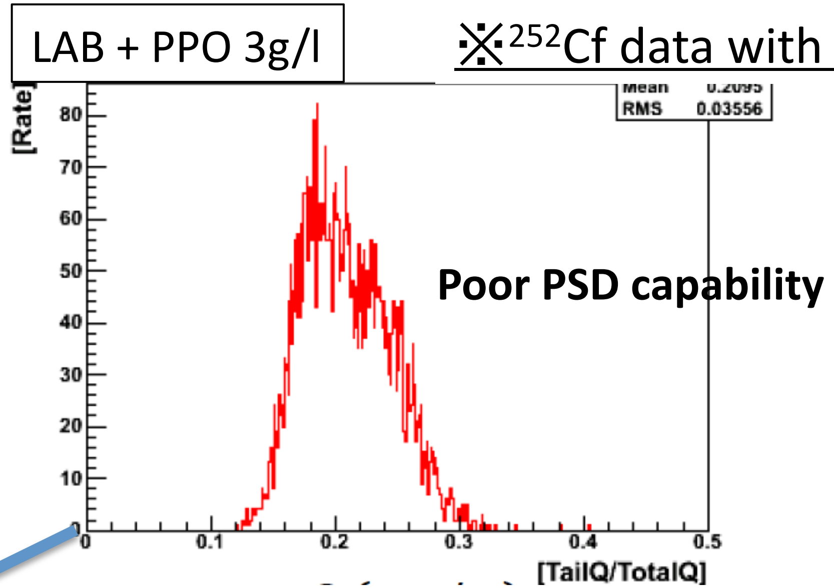
	PC (previous)	PXE	LAB (Current)
Molecular formula	C_9H_{12}	$C_{16}H_{18}$	$C_6H_5C_nH_{2n+1}$
structural formula			
Density(g/cm3)	0.89	0.99	0.86
Flash point(°C)	48	145	130
H/C ratio	1.33	1.12	1.67 (n=12)
Attenuation length at 430nm	8m	2.6~3.2m	8.5m
PSD ability	○	○	△
Acrylic compatibility	×	×	○

Current work for LAB based LS

- Improve PSD capability of LAB based LS by adding extra solute.
- Investigate how to add Gd.

Improvement of PSD capability for LAB based Gd-LS

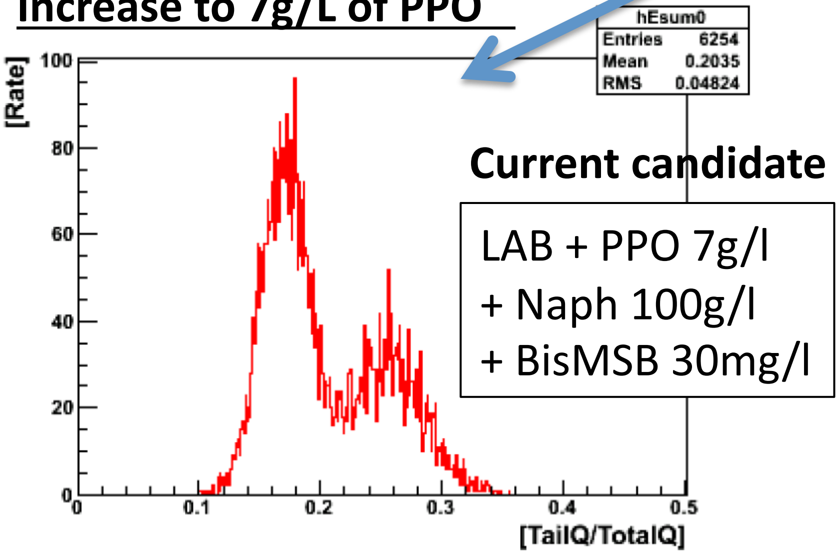




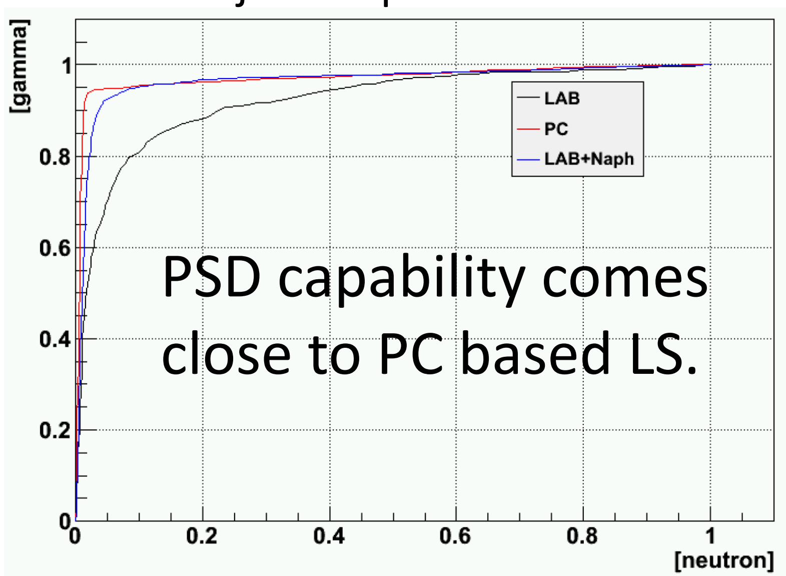
※^{252}Cf data with vial

Add Naphthalene (100g/L)

Increase to 7g/L of PPO



Fast n rejection power



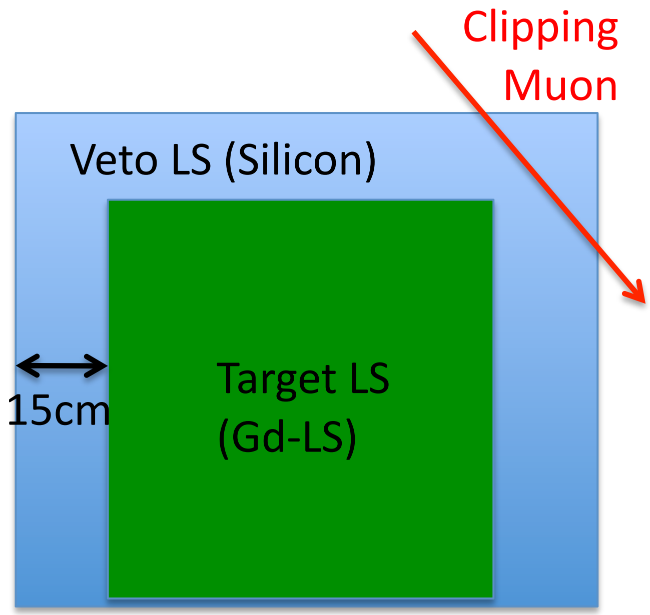
Continue the development => PSD test adding Gd (next step).

Cosmic muon veto with PSD

Concept

To develop the detector with simpler structure, PSD between Target and Veto LSs is used for muon veto replacing surrounding plastic scintillators.

Muons in the energy cut(2~10MeV) are clipping events.=> Difference of waveforms between target and Veto LSs is useful for the clipping muon veto.



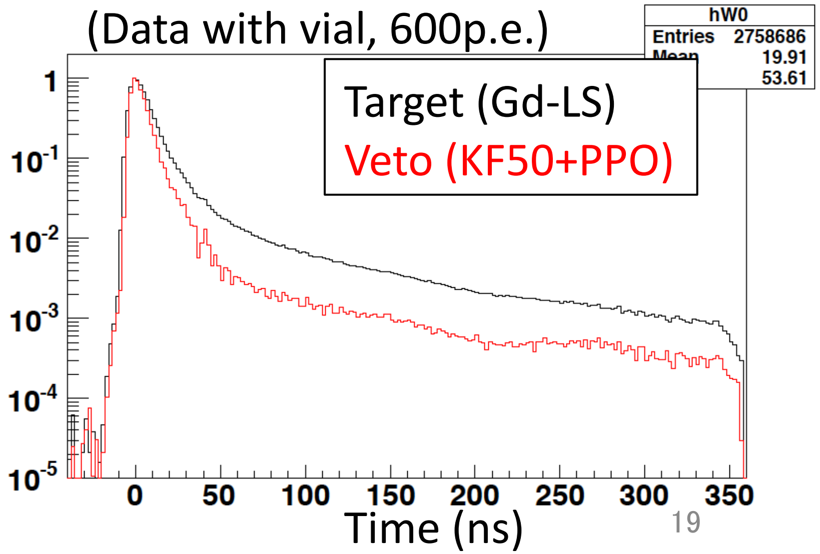
Silicon oil (ShinEtsu KF50) for Veto volume(600L)

1. The flash point is very high (above 300°C).
⇒It is not categorized as “危険物”.
(”指定可燃物”, the volume limitation increase to 2m^3)

2. KF50 has phenyl ring.
⇒Can emit scintillation lights by adding PPO (wave length shifter, 3g/L, light yield ~ 1/6 of target LS).

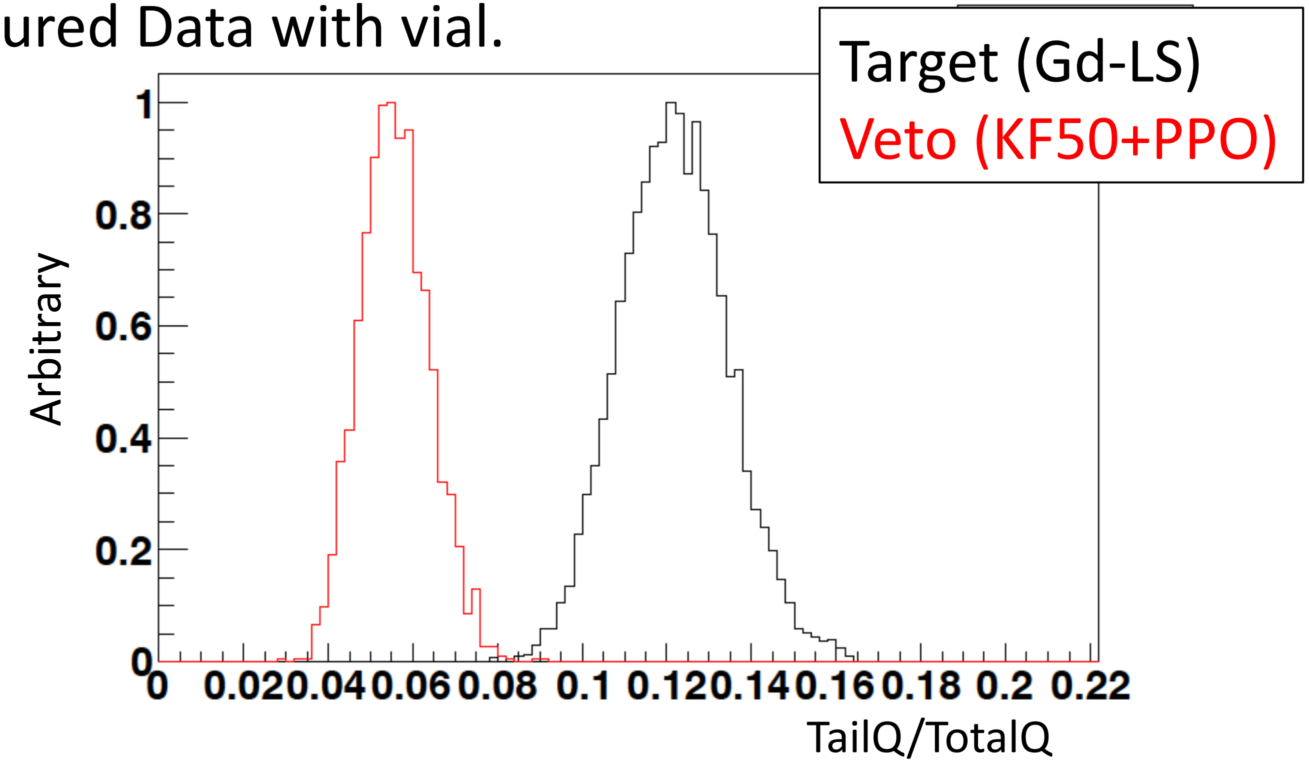
3. Waveform is narrower than one for target LS.

Mean waveform
(Data with vial, 600p.e.)



Muon veto efficiency with PSD

TailQ/TotalQ
Measured Data with vial.



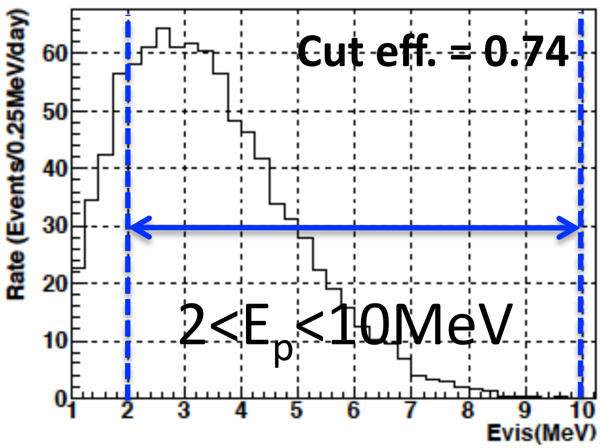
Show good separation of signals in Target and Veto volume. => Good veto efficiency of the new detector is expected.

3. MC study of sensitivity for neutrino observation with the new detector

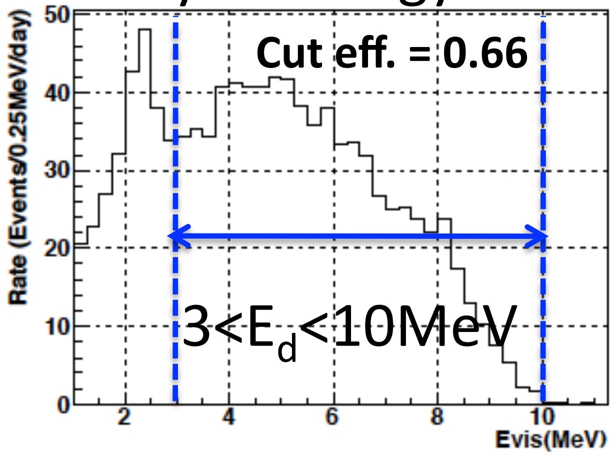
Neutrino event selection

IBD selection

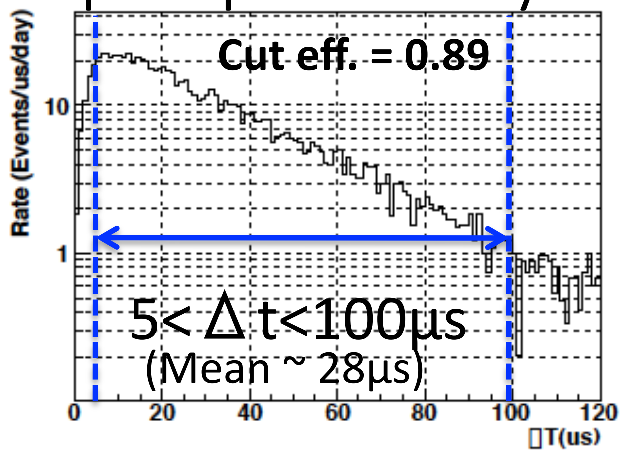
Prompt Energy



Delayed Energy



Δt between prompt and delayed



Additional powerful cuts (rejection power, cut efficiency are assumed below)

- **PSD Veto => Muon veto eff. = 1.0, ν cut eff. = 1.0** (based on vial size measurement).
- **PSD cut (n/gamma)** => **Fast n rejection = 0.9, ν cut eff. = 0.9**(same as the 200L PC based Gd-LS).
- **ΔVTXcut between prompt and delayed for ACC BKG rejection** (explain in next slide).

Assumption in this MC study

Neutrino flux (same as SONGS)

Reactor power=3.4GWth
Base line=24.5m

BKG flux for each component

Use the BKG flux above ground in our experimental room in Tohoku Univ. (Estimated by using measured data with the PC based Gd-LS and NaI(2x2inches cylinder)).

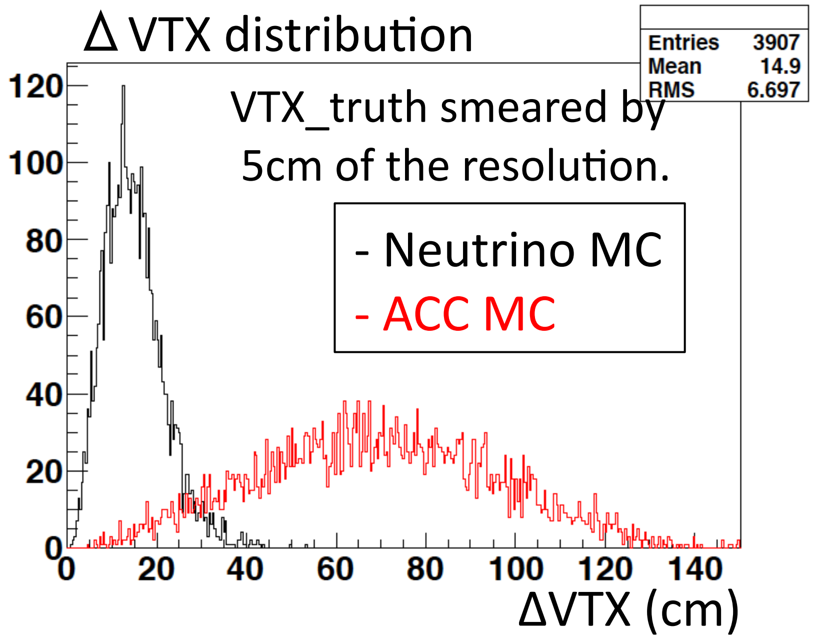
ΔVTX cut for Accidental BG reduction

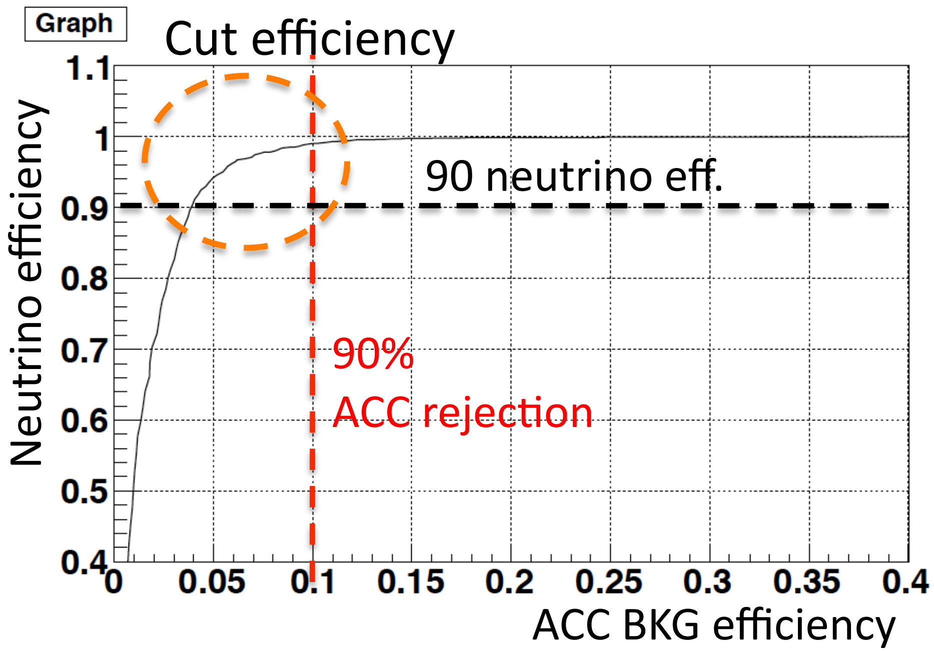
Concept

Neutrinos : Distance between prompt and delayed signals is close. => ΔVTX distribution is narrow.
ACC BKG : There is no correlation between vertices of prompt and delayed signals => broad.
=>**ΔVTX cut is very powerful variable for the accidental BKG rejection**.

Rejection power

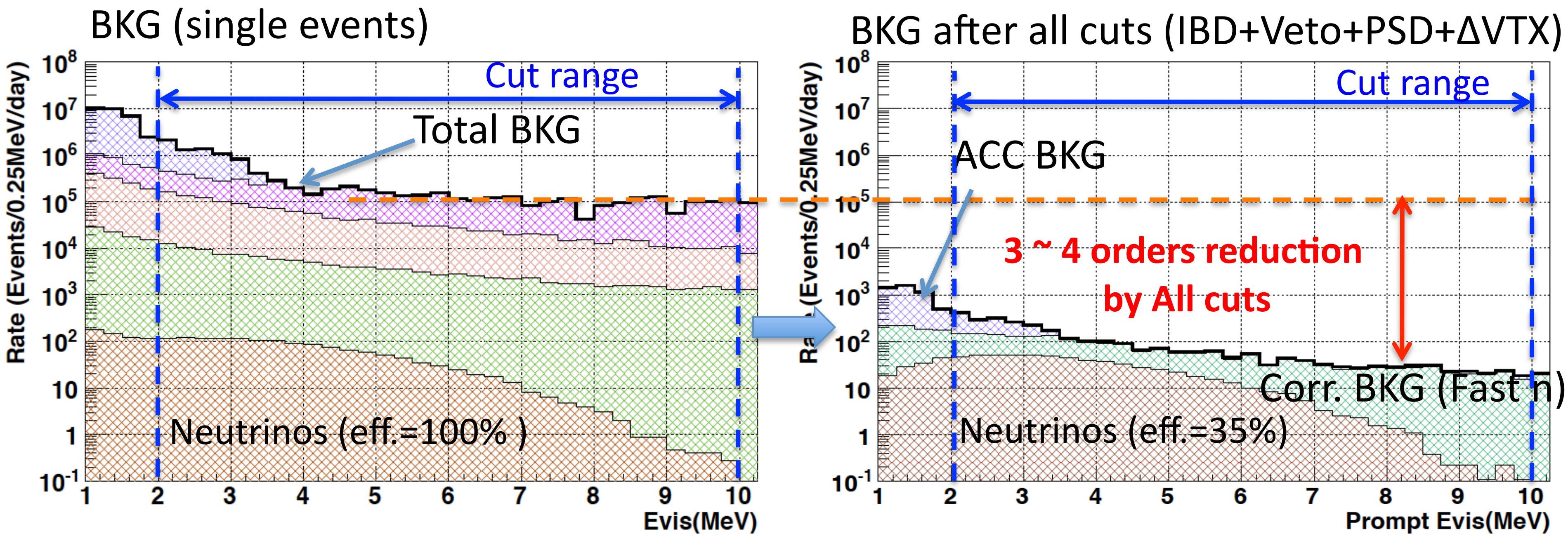
The rejection power was checked roughly with smeared distribution of truth VTX info of MC.
(Development of VTX reconstruction algorithm is on going => 5cm resolution is achievable.)





Assuming 5cm of ΔVTX resolution of Gaussian sigma,
=> 90% ACC BKG rejection is achievable keeping 90% signal eff.

Selection Summary



	Target volume	Depth	Shield	Corr. Rate (Fast n)	Acc. rate	Num of v reaction	V rate (Effciency)	S/N
SONGS	748L	10m (μ flux ~1/7)	Water/ Polyethylene (50cm)	105/day	3732/day	3800/day	459/day (12%)	1/8.4
New	400L	0m	Veto LS (15cm) Lead(2.5cm)	1390/day	960/day	1800/day	624/day (35%)	1/3.8

Despite of above ground measurement and smaller target volume, S/N ratio and neutrino rate are higher than SONGS case.

Required measurement time for observation of reactor neutrino excess (2σ C.L.)

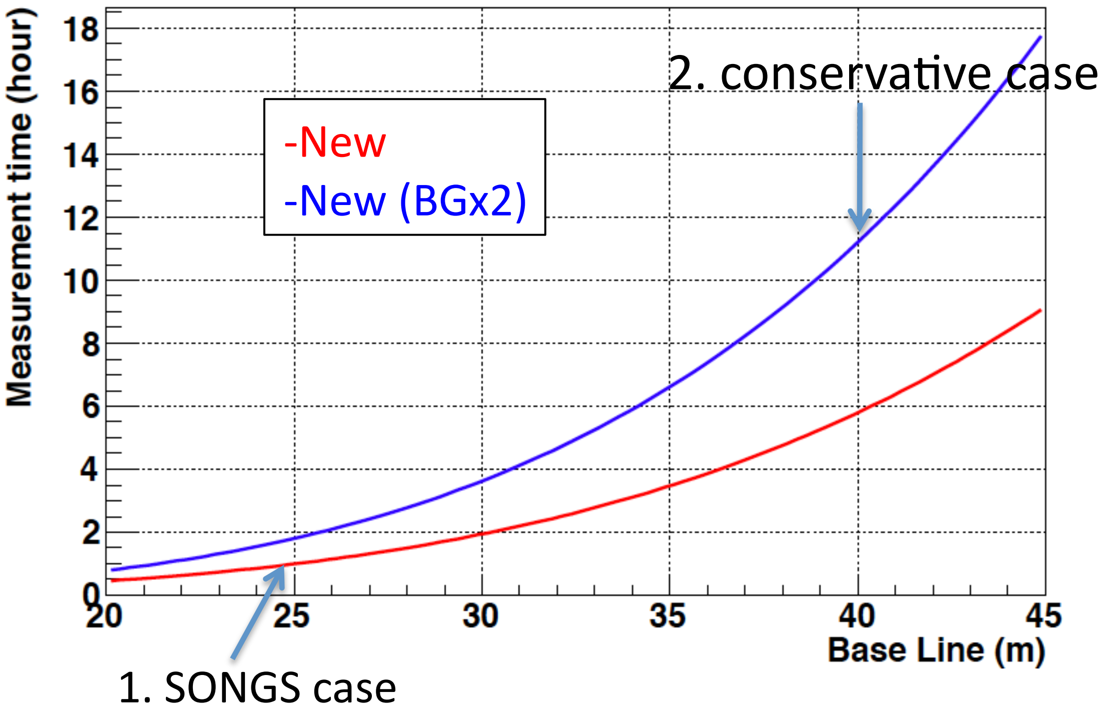
1. SONGS case (24.5m, red line)

The required time is expected to be about **1hour**.

2. More conservative case (40m, BKGx2, blue line)

The required time is expected to be about **half a day**.

Required measurement time vs Base line for observation of reactor neutrino excess (2σ C.L.) (3.4GWth, Off data for 30days are assumed)



Schedule in near future

Detector construction and the test

Acrylic vessel and support structure were already ordered on Dec. 2014.
Detector construction will be completed until end of Jan. 2015.

After the construction,

1. Test the detector performance (measure single rate, n/γ PSD, veto PSD, energy and VTX reconstruction, etc.) with **Gd-unloaded LS**.
2. Continue R&D of LAB based Gd LS to improve PSD capability more.

Measurement at reactor site

Currently **we do not have any plan** for the measurement at some reactor site, because all reactors have stopped in Japan. However, it is expected to restart some reactors (Sendai, Takahama?) before long. Then we will start to negotiate the measurement with some reactor sites.

Summary

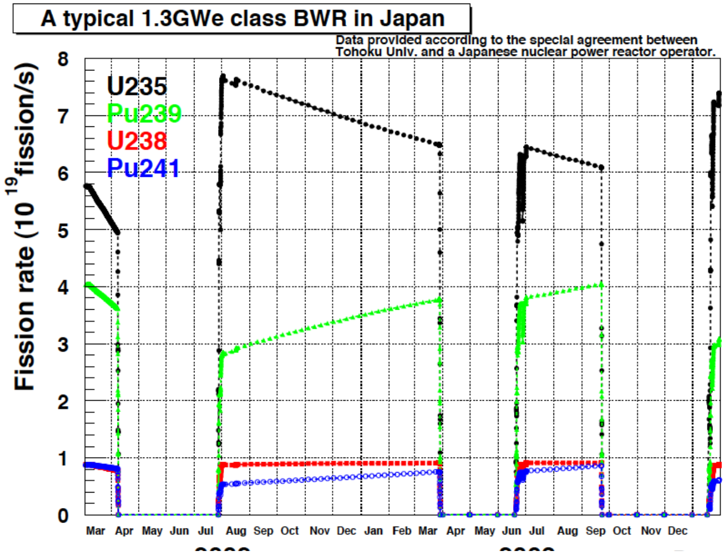
- Development of the new cubic meter detector is on going from 2013.
- LAB based Gd-LS, which is poor PSD capability, is improved by adding naphthalene.
- High PSD capability for muon veto was shown by vial measurement with silicon oil based LS (KF50).
- Acrylic vessel and support structure were ordered already, and detector construction will be completed until end of Jan. 2015.
- MC study for sensitivity of observation of neutrino excess was done. Observation of the neutrino excess is expected to be observable within one day with the new detector design.

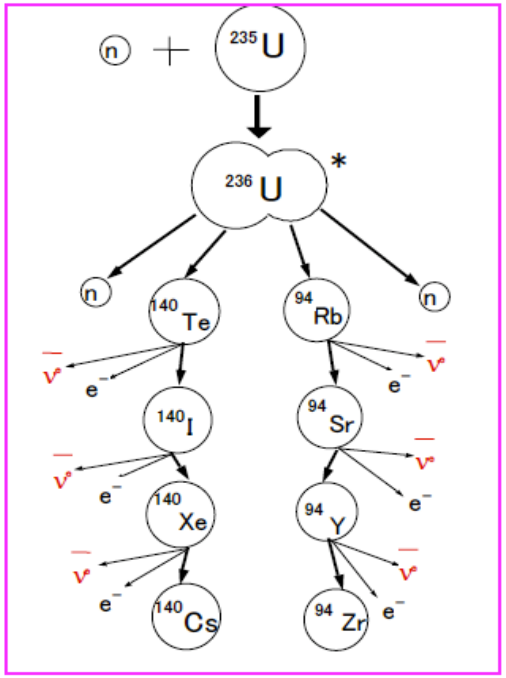
Backup

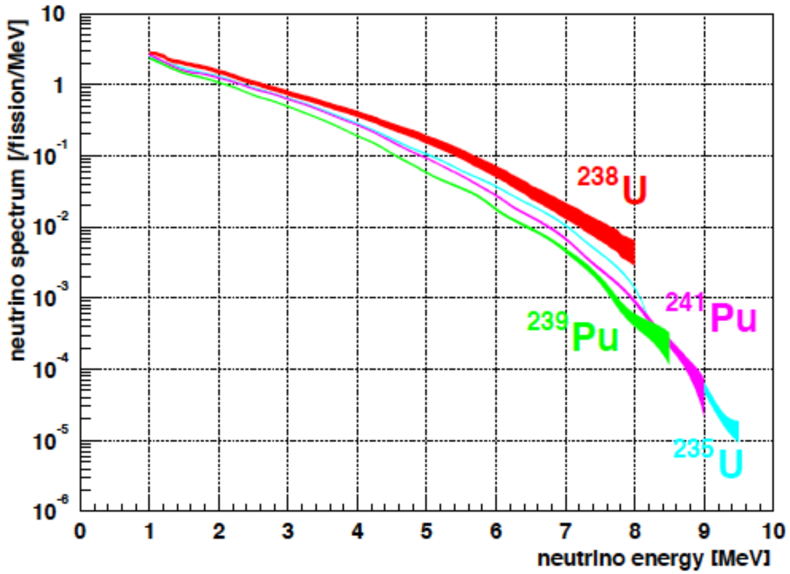
Activity in the world

Experiment	Country	Detector type	Info
SONGS	US	Gd-LS	
Nucifer	FRA	Gd-LS, PSD	Sterile search
Tohoku U.	JPN	Gd-LS, PSD	**(A02班)**
Stereo	FRA	Gd-LS, PSD	Sterile search
DANSS	(RU)	Gd-LS ,Segmented	Sterile search
Hanaro	Korea	Gd or ^{6}Li-LS, PSD	Sterile search
Prospect	US	Gd or ^{6}Li-LS, PSD	Sterile search
PANDA	JPN	Gd Plastic, Segmented	Tag anihi-gammas **(A02班)**
Niigata U.	JPN	Gd Plastic, Segmented	
Solid	UK	Li-LS, Segmented	Sterile search
Angora	BRA	Water Cherenkov	

Neutrino generator







3 x 10^{19} fissions/GWth