PANDA: Neutrino Detector for Reactor Monitor

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Today's topics

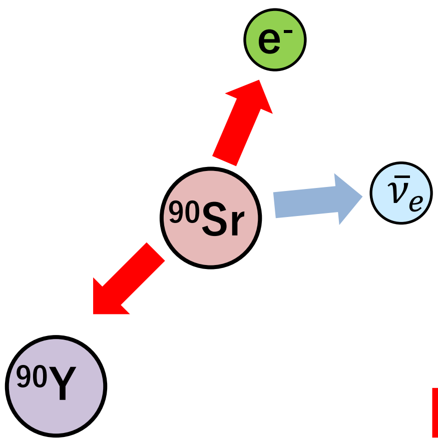
- Basics of reactor neutrino experiments
  - Properties of neutrino
  - Reactor neutrino measurements
  - Short base line experiments
- PANDA : Plastic Anti-Neutrino Detector Array
  - Concept and History
  - Neutrino measurements in 2019
  - Future

Basics of reactor neutrino experiments

Neutrino in β decay

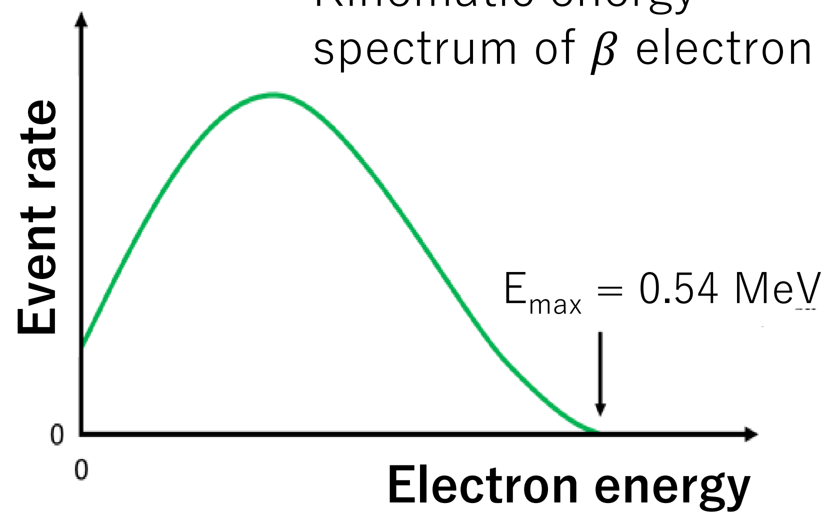
- Invisible energy in β decay
  - Continuous β spectrum

  => Not 2 body system



3 body system with invisible particle!

Kinematic energy spectrum of β electron



Prediction of neutrino existance

Invisible particle steals a part of energy
= three-body system

Confirmed by the reactor experiment

Properties of neutrino

- Very light particle
  - Zero mass in Standard Model

    --> Found nonzero mass

    by <u>neutrino oscillation</u>
  - Still effectively zero mass
- Neutral lepton particle
  - No strong and E.M. interaction

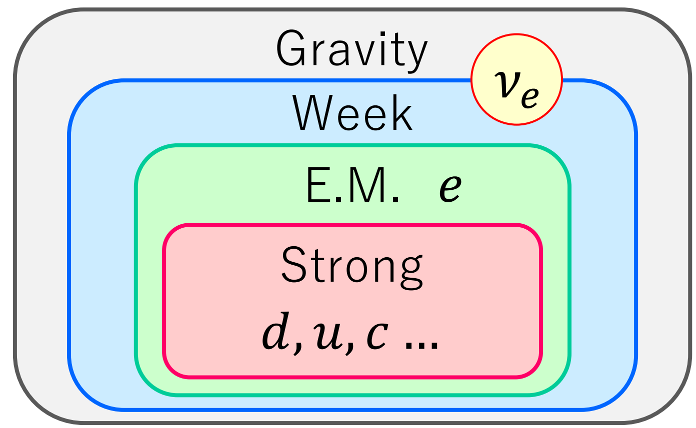
    --> Good for cosmology

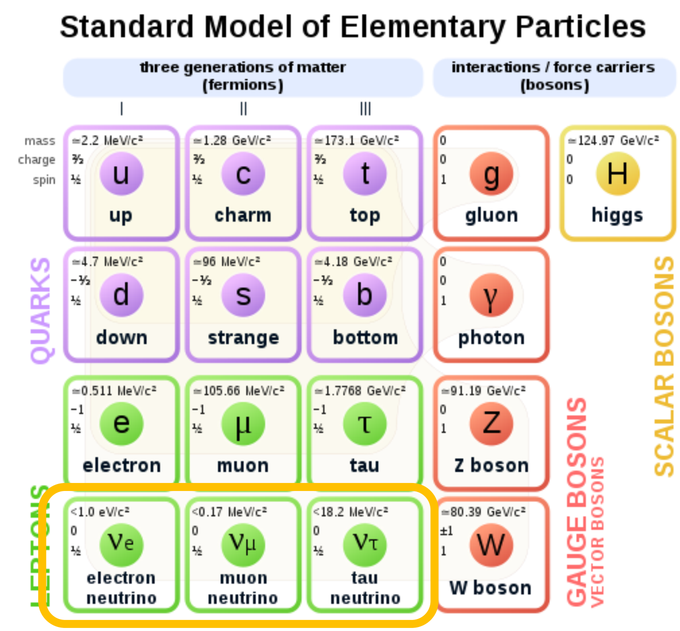
    by the higher transparency
  - Weekly interactive

    --> Good for particle physics

    --> Search for B.S.M.

Categories of interaction

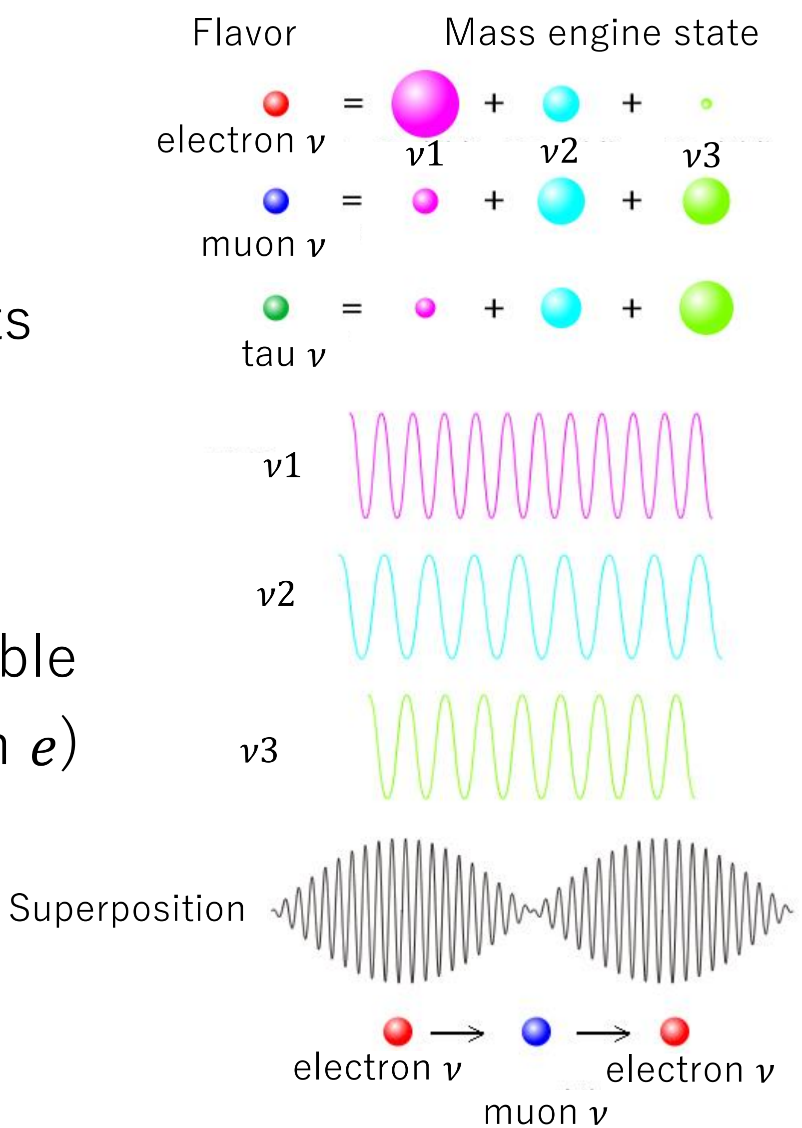




Neutrino mixing

- Flavor = engine state of interaction
  - ~ Particle generation
  - Indefinite before measurement
- Particle = Superposition of wavelets
  - Superposition changes in time

  => Flavor changes during flight
- Disappearance and appearance
  - Disappearance : to be indetectable
    - $\nu_e \longrightarrow \nu_\mu$ (less interactive with e)
  - Appearance : to be detectable
    - $\nu_\mu \longrightarrow \nu_e$ (interactive with e)



Neutrino oscillation

Neutrino oscillation ⇦ {
- Neutrino mass
- Mixing of mass eigne state

Maki-Nakagawa-Sakata (MNS) matrix

$s_{ij} = \sin\theta_{ij} \quad c_{ij} = \cos\theta_{ij}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

θ_{23}: $P(\nu_\mu \to \nu_\mu)$ by Atm. ν & ν beam

θ_{13}: $P(\bar{\nu}_e \to \bar{\nu}_e)$ by Reactor ν
θ_{13}& δ: $P(\nu_\mu \to \nu_e)$ by ν beam

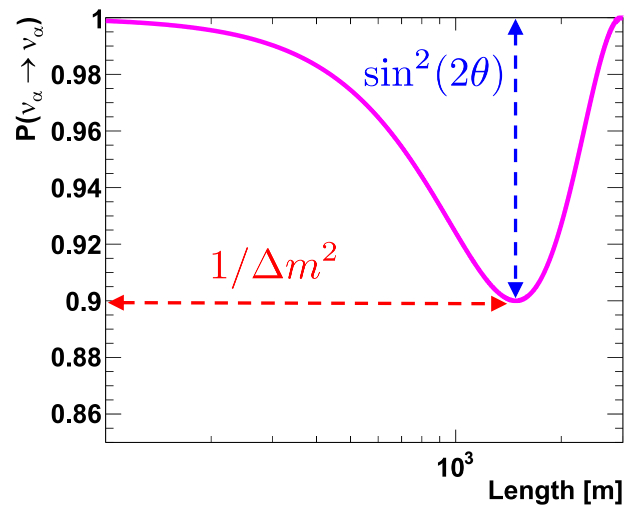
θ_{12}: $P(\nu_e \to \nu_x)$ by Reactor ν & solar ν

2 flavor system:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

⇨ Flavor can change in flight

Survival probability of reactor ν



Neutrino oscillation is the unique phenomenon beyond the standard model
--> Probe toward the new physics

Origins of neutrino

Generated in Nuclear reaction

- β decay of Nuclear fission product
- Decay chain of π and μ

Kinds of neutrino sources

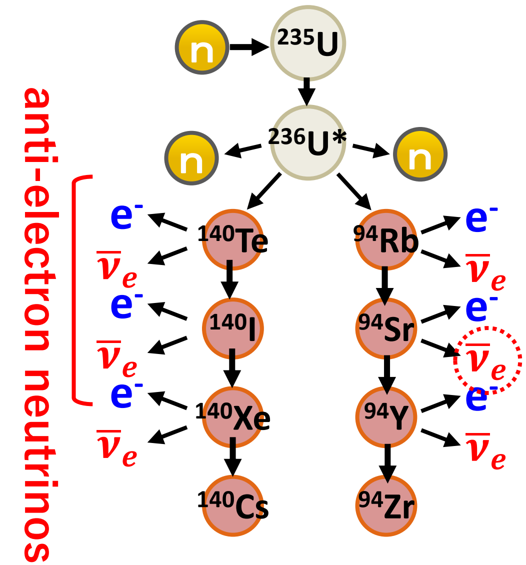
- Artificial：Mainly for Particle Physics
  - Reactor in power production
  - Accelerator
- Natural ：Cosmology or Geo Physics
  - CNO cycle in the sum
  - Supernova ν
  - Geo ν: Core of the earth
  - Atmospheric ν

Space

Geo

Neutrino is good probe toward
Nuclear and Geo and cosmology

Fission in Uran-235



Decay chain of π and μ

$$\pi^- \rightarrow \bar{\nu}_\mu + \mu^-$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Artificial neutrino sources

Generation processes are well known

- Reactor：β decays in Nuclear fission
- Decay at rest： π decay in proton beam target

⇨ Pure test of neutrino properties

Advantage

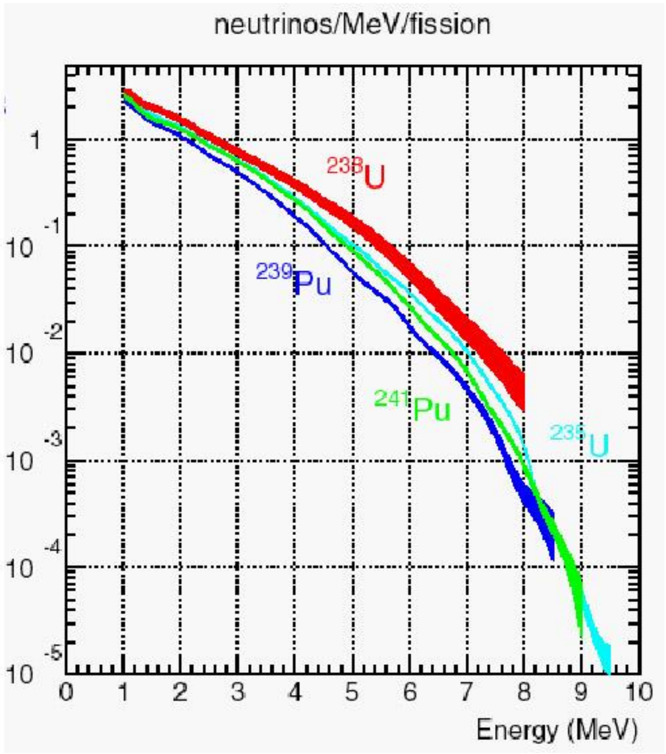
- Well known source
  - Flux & distance
- Close to source
  - High statistics
- Free neutrino
  - No operation fee

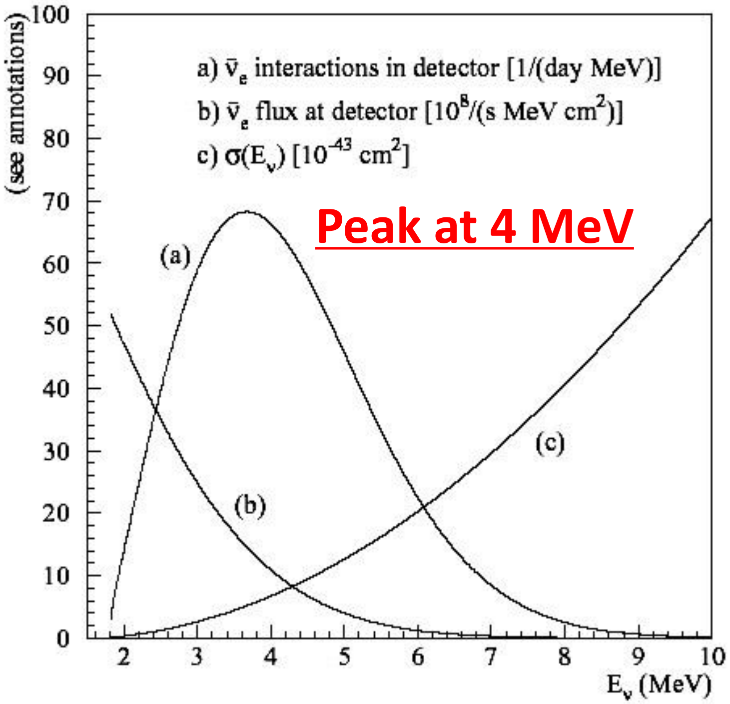
Disadvantage

- Not normal laboratory
  - Portability is important
  - Bad background condition

Reactor Neutrinos

- Most commercial reactors are PWR or BWR.
  - ^{235}U, ^{239}Pu, ^{241}Pu beta spectra measured at ILL, ^{238}U theoretically.
  - In LS: Energy 1-10 MeV, Rate : ~ 1 event/day/ton/GW @ 1km
- Power fluctuation <1%, rate and shape precision 2-3%
  - Rate and spectra were verified by Bugey, Bugey3, Bugey4

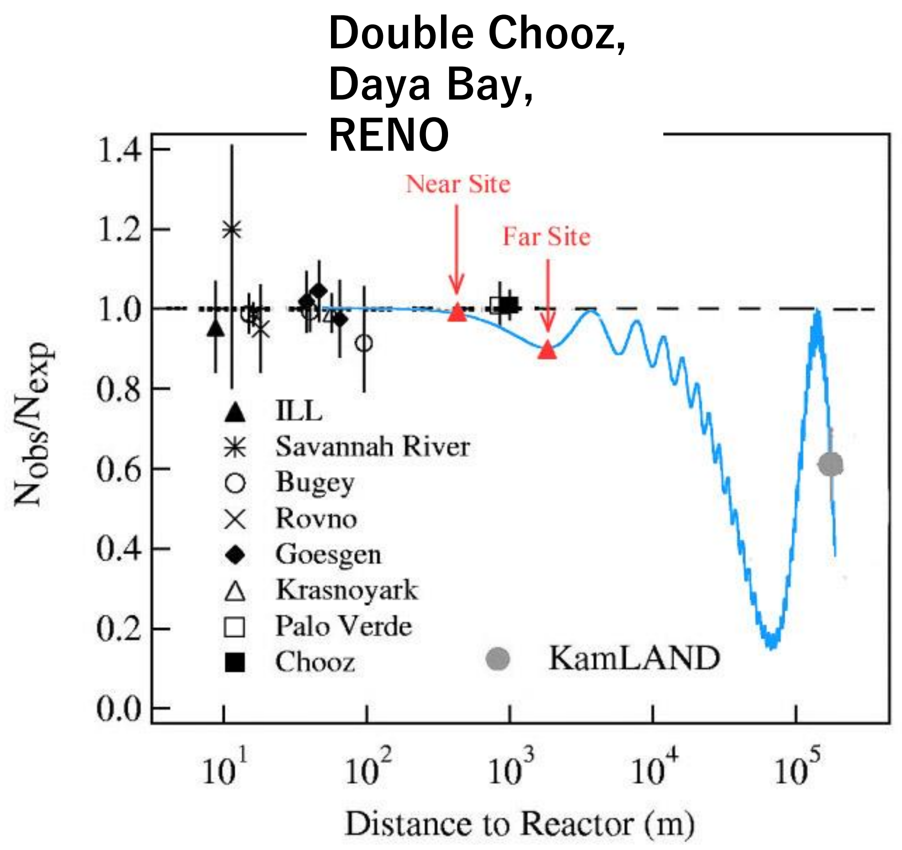




Reactor Neutrino Experiments

Reactor anti-neutrino experiments have played a critical role in the 60-year-long history of neutrinos.

- The first neutrino observation in 1956 by Reines and Cowan
- Determination of the upper limit of mixing angle θ_{13} in 90's
- The first observation of reactor anti-neutrino disappearance at KamLAND in 2002.
- Measurement of the smallest mixing angle θ_{13} at Double Chooz and other experiments in 2012.



The Cowan-Reines Reaction

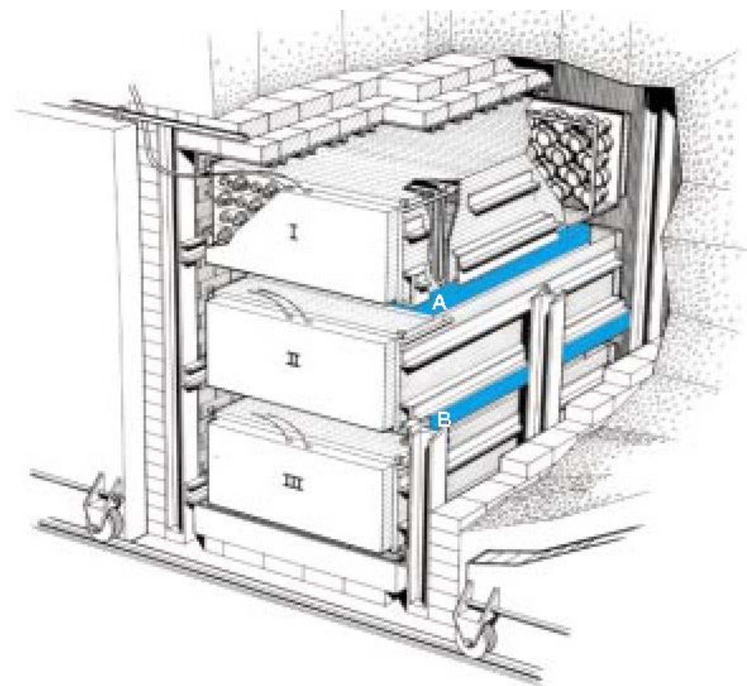
- The first observation of neutrinos in 1956 by Reines & Cowan.
  - Inverse beta decay in $CdCl_3$ water solution
    → coincidence of prompt and delayed signal
  - Liquid scintillator + PMTs
  - Underground
- Modern experiments are still quite similar, except
  - Loading Gd into liquid scintillator
  - Larger detector
  - Deeper underground, shielding

Prompt signal

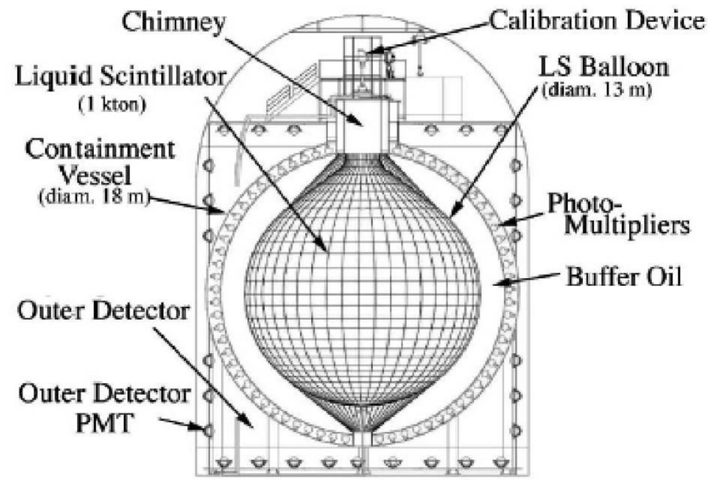
$$e^+ + e^- \rightarrow 2\gamma$$

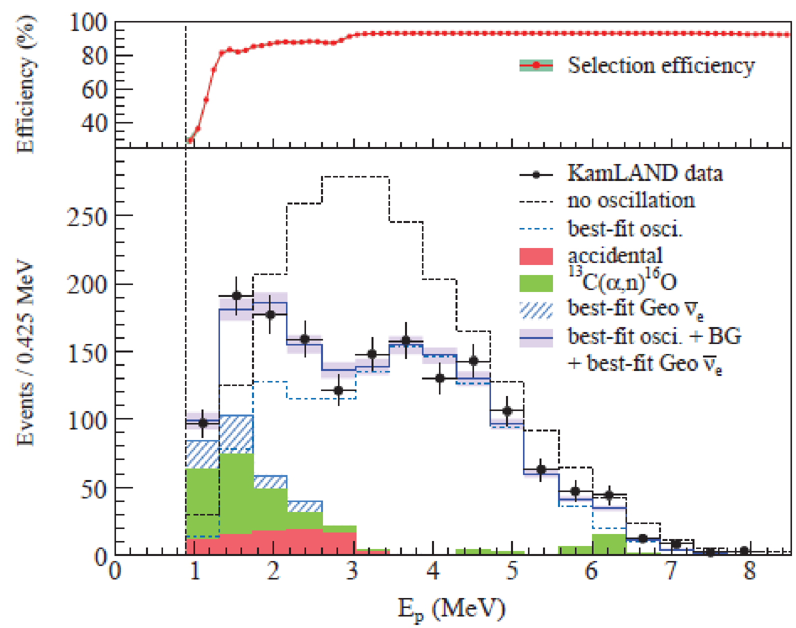
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Capture on H, or Gd, Cd, etc.
Delayed signal



KamLAND

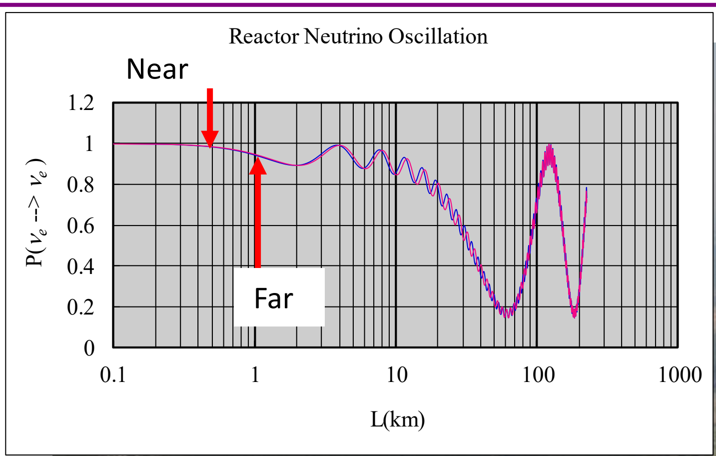


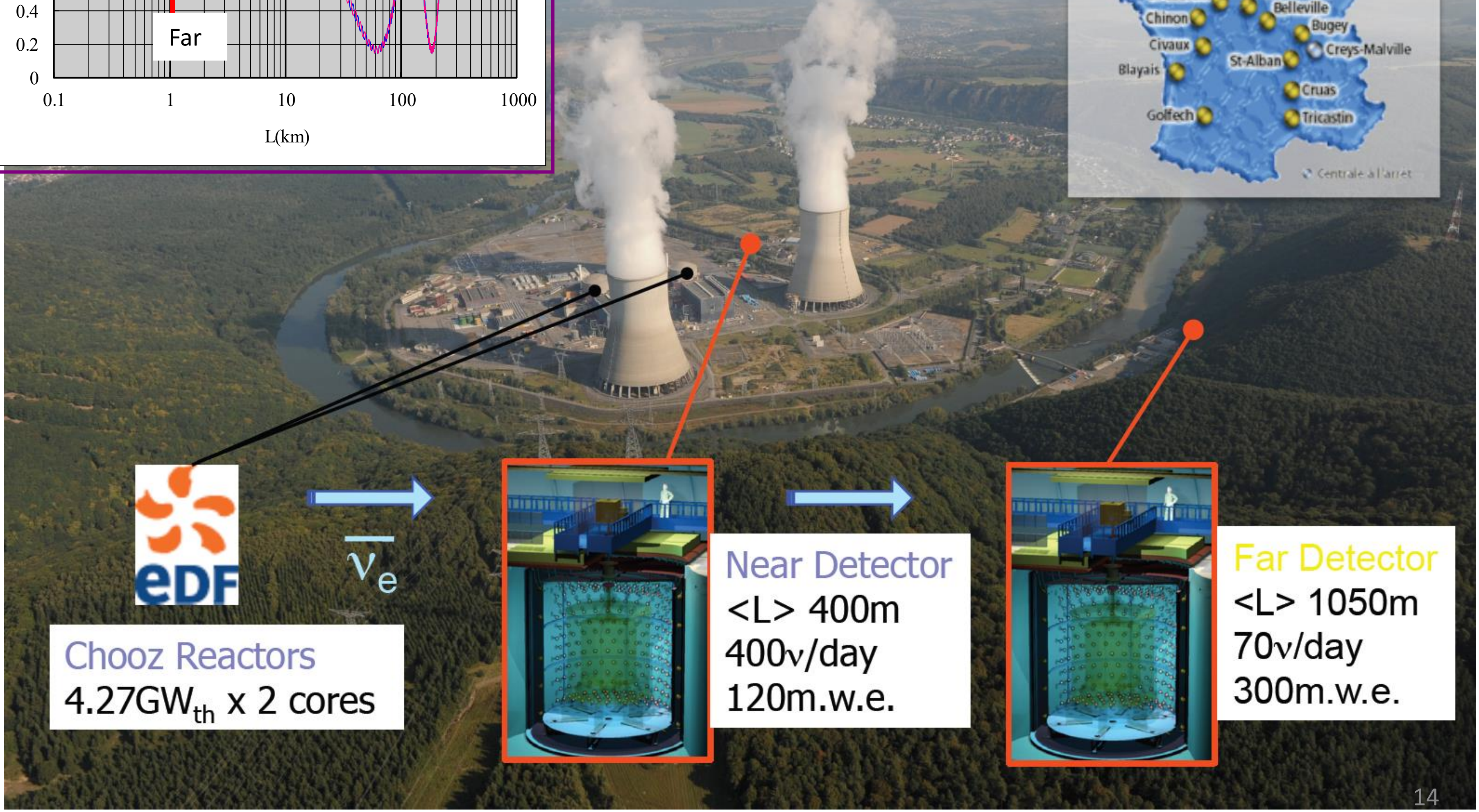


- 2002-, Kamioka, Japan
- 53 reactors, 80 GWth
- 1000-ton LS
- 2700 mwe

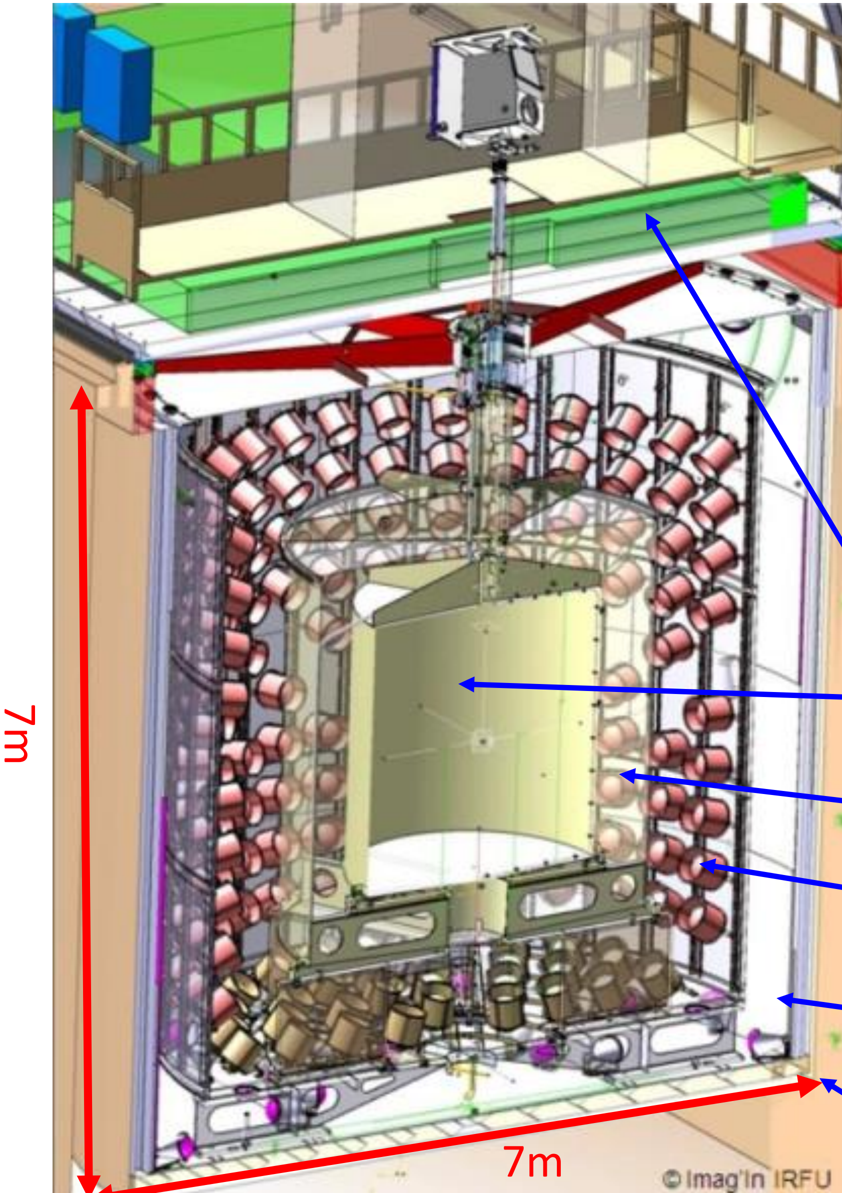
Double Chooz Experiment

Measurement of mixing angle θ_{13}





DoubleChooz detector



Outer Veto: plastic scintillator strips (400 mm-t)

ν-Target: 10.3 m^3 scintillator doped with 0.1g/l of Gd in an acrylic vessel (8 mm-t)

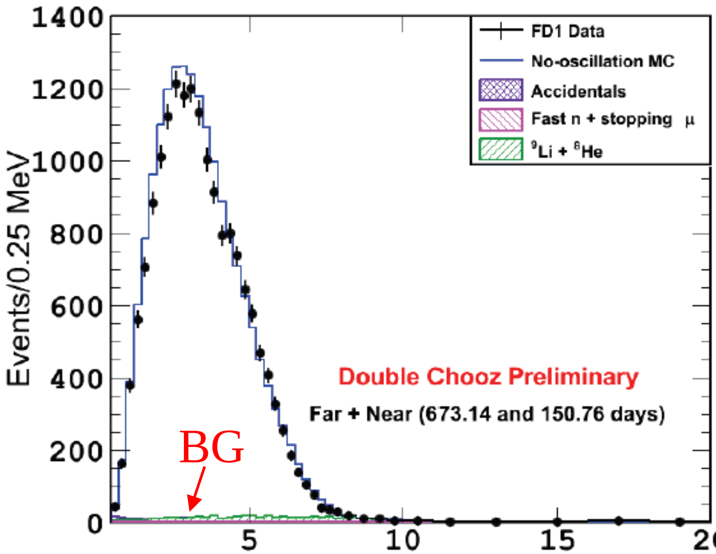
γ-Catcher: 22.3 m^3 scintillator in an acrylic vessel (12 mm-t)

Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs

Inner Veto: 90m^3 of scintillator in a steel vessel equipped with 78 PMTs

Veto Vessel (10mm) & Steel Shielding

Double Chooz results

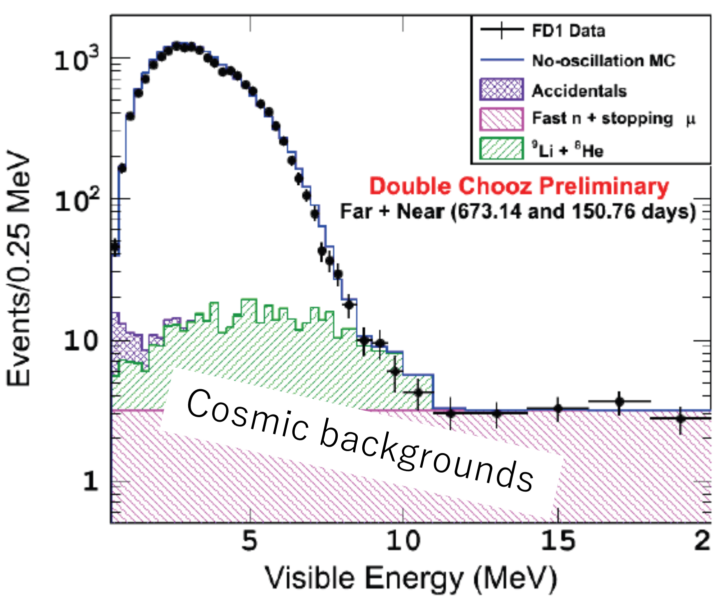


Located under ground 120/300 mwe
Distance in 400/1050m
30to Gd-loaded liquid scintillator

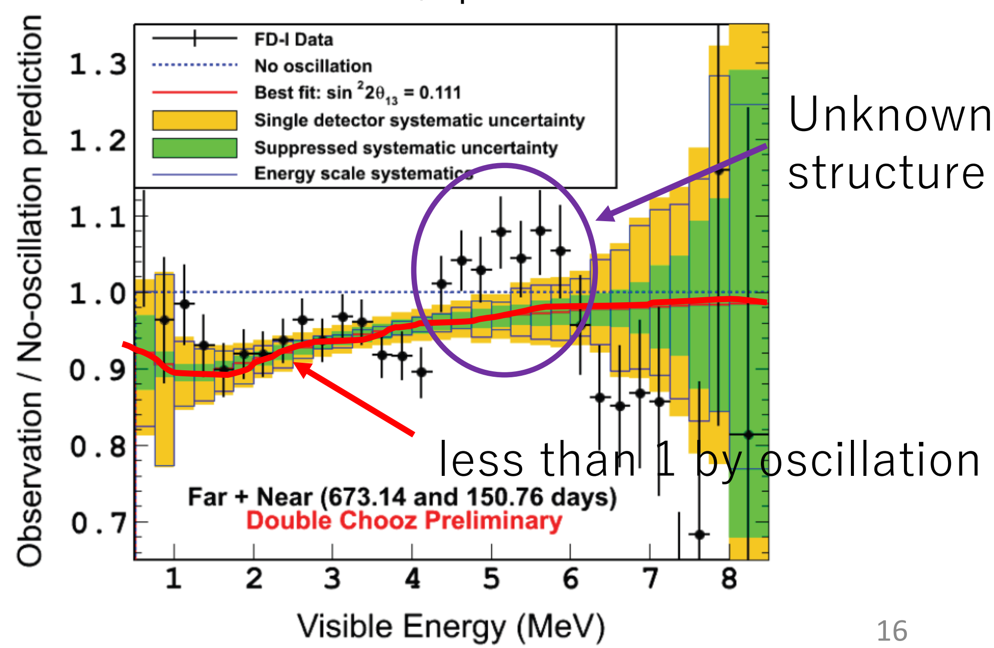
Latest results

$\sin^2 2\theta_{13} = 0.105 \pm 0.014$

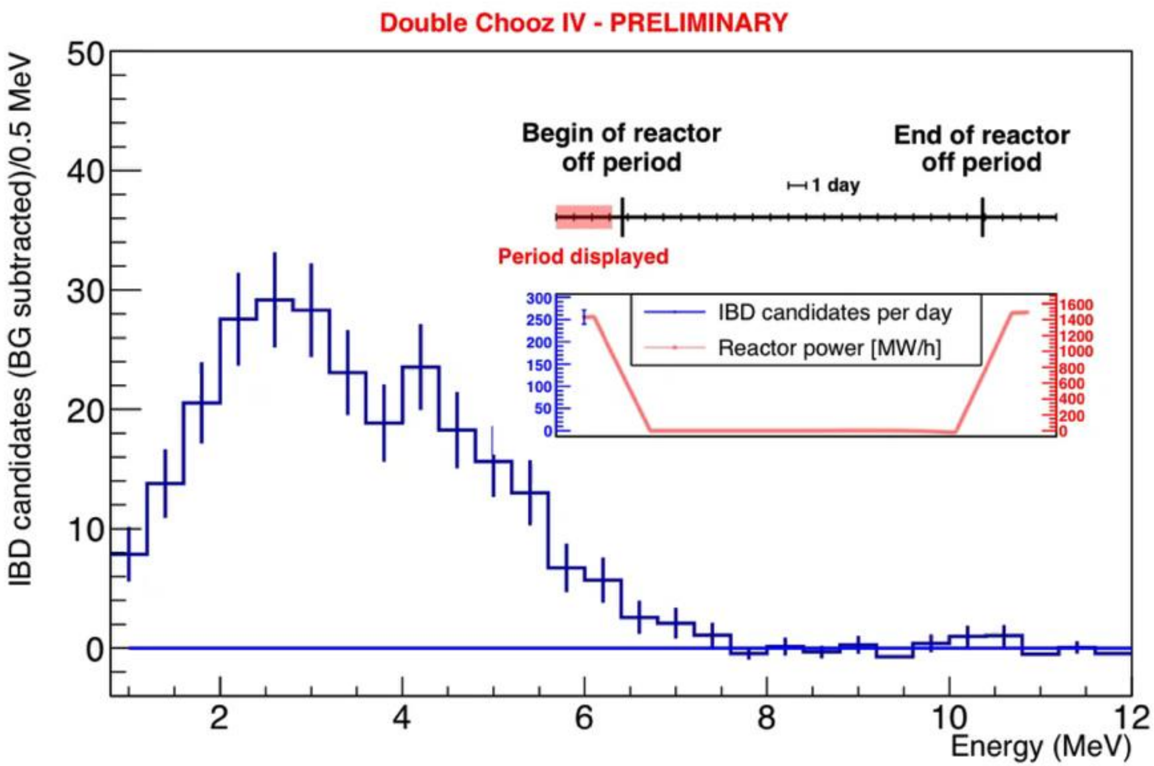
Nature Phys. 16 (2020) 5, 558-564



observed / predicted



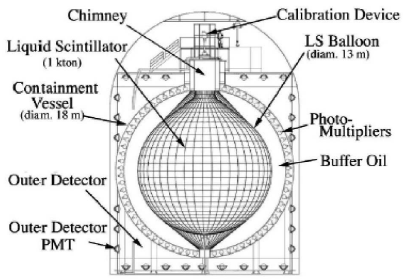
Day-by-day neutrinos around reactor off period



Near detector Data (~400m)

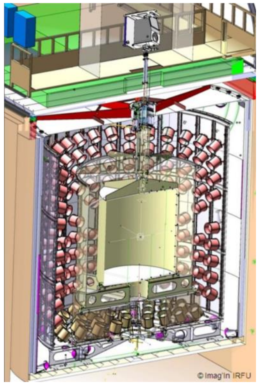
Next road of reactor ν measurments

~2000



Long baseline ~ 100km
Large scale ~ 1kton

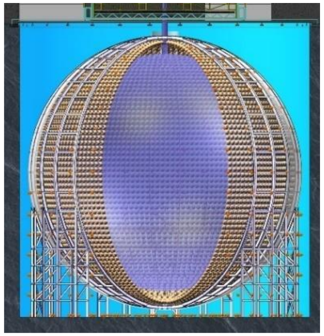
~2010



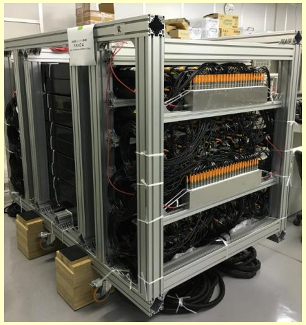
Middle baseline ~ 1km
Middle scale ~ 10ton

~2020

JUNO



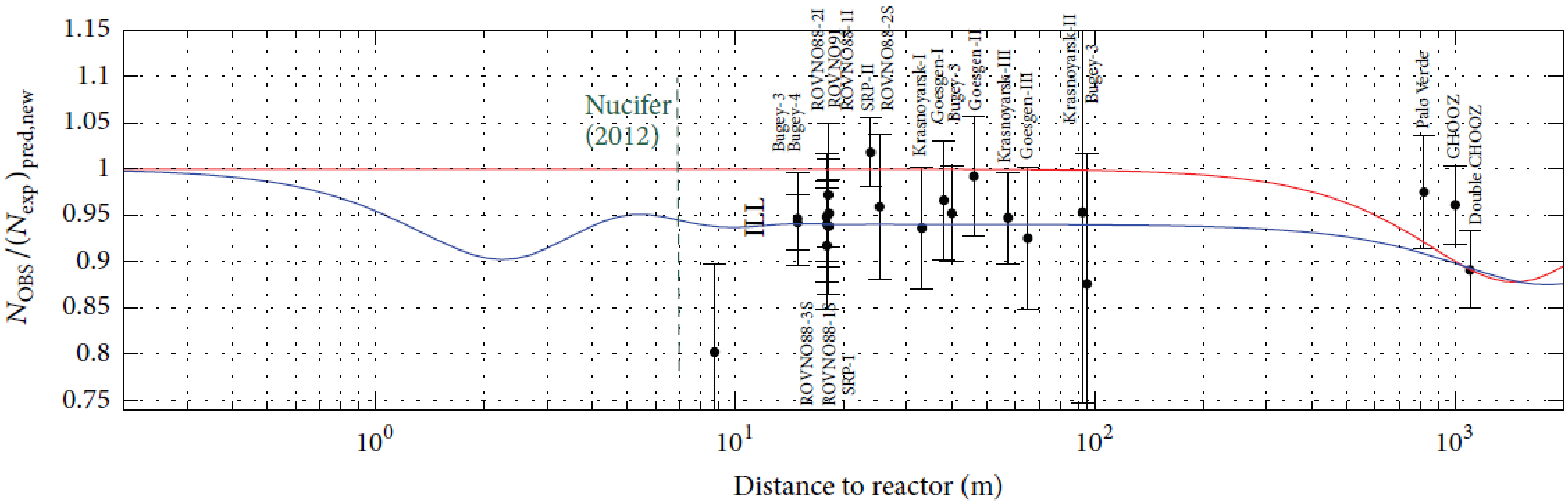
Long baseline ~ 100km
Large scale ~ 2kton



Short baseline ~ 100m
Small scale ~ 1ton

- Detector gets close to reactor core
  – Search for more fine oscillation
- Smaller detector size
  – Enough statistics can be kept

Reactor Anomaly in short baseline experiments



Reactor neutrino anomaly

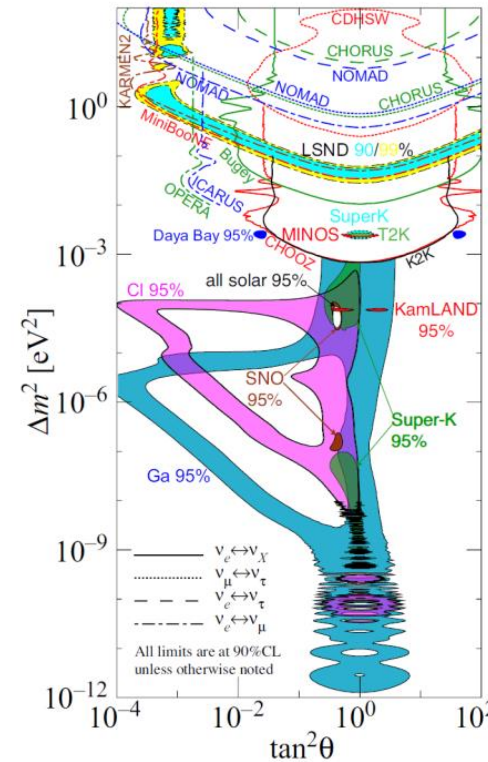
- Lack of neutrino flux in 10-100 m distance from core
  - Due to calculation of nuclear fission?
  - Hits for new particle such as sterile neutrino?

Potential of short baseline experiments

International Atomic Energy Agency

- Reactor activity monitor (Neutrino application)
  - Security for Nuclear Non-Proliferation Treaty
    --> Possible to monitor outside of reactor building
- Search for next neutrino oscillation
  - Search for unknown neutrino
- More for Nuclear physics and engineering
  - Scope to inside of the reactor core for next generation reactor
  - More ??

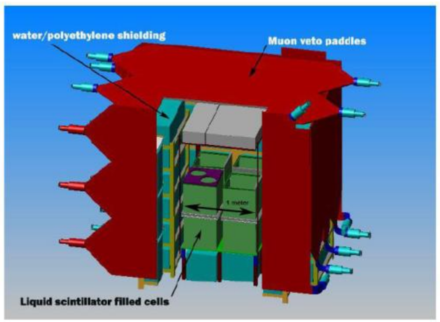
Essentials to archive
- Measurement very close to the reactor
- High efficiency and low BG detector



Oscillation parameters

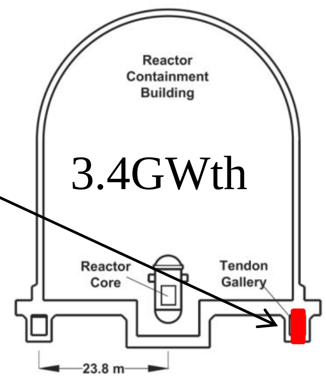
Non-proliferation Monitoring

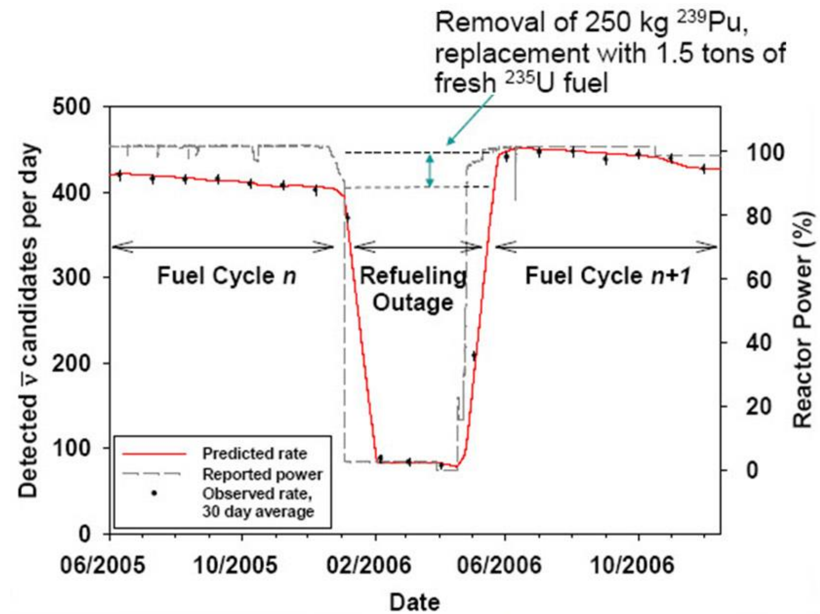
SONGS



Gd-loaded liquid scintillator

San Onofre (U.S.)

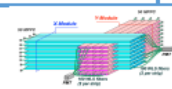
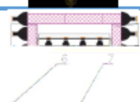
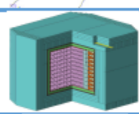
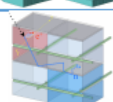




Bowden, LLNL, 2008

- Non-proliferation monitoring studies supported by IAEA (France, US, Russia, Japan, Brazil, Italy)
  - Ton-level detector
  - Very close to core < 100m

Short baseline reactor experiments

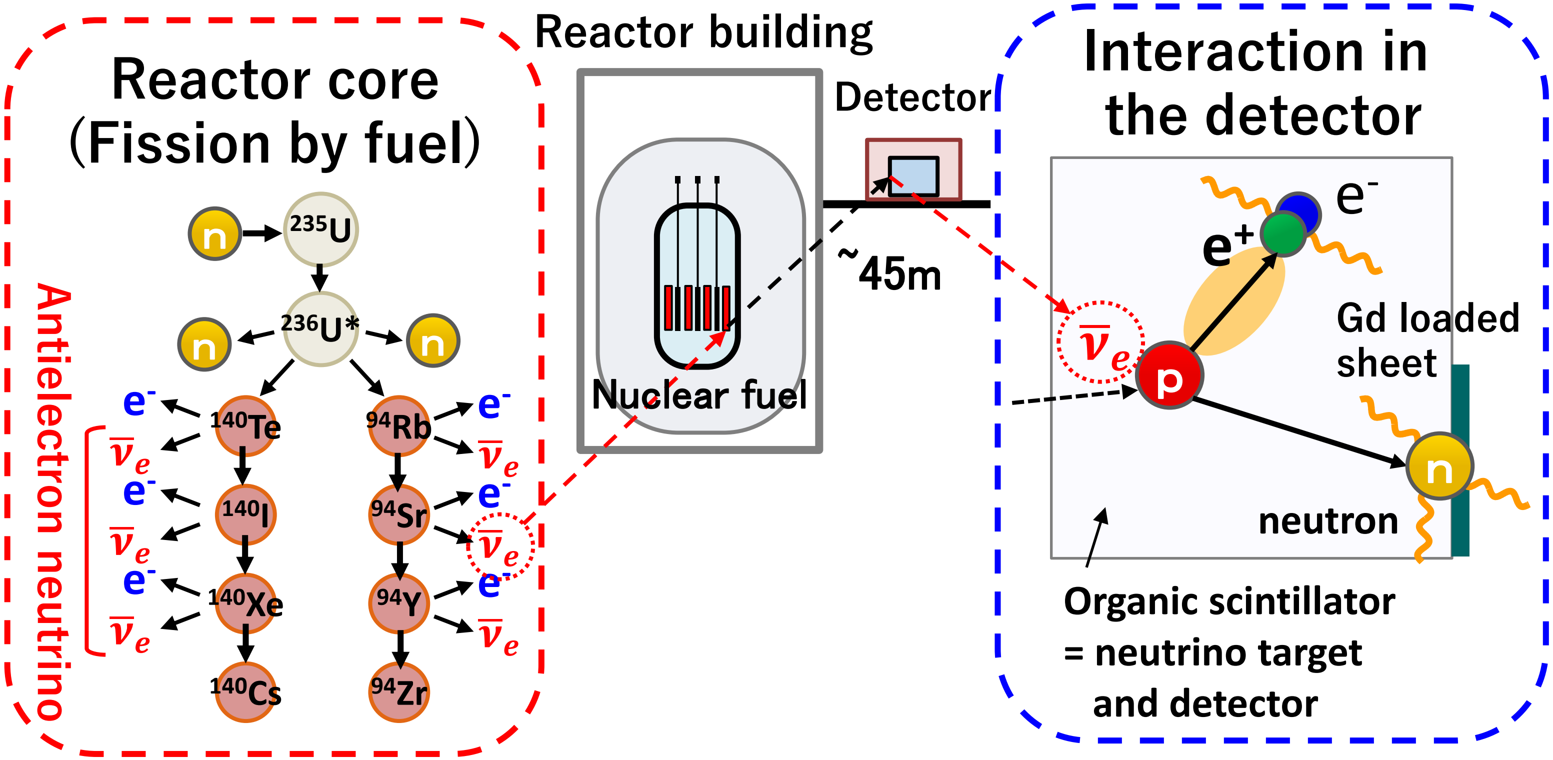
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

From Neutrino2016 N.Bowden

- 1ton size with some PID capability
- 10~100m distance from the core

PANDA:
Plastic Anti-Neutrino Detector Array

Portable reactor neutrino detection



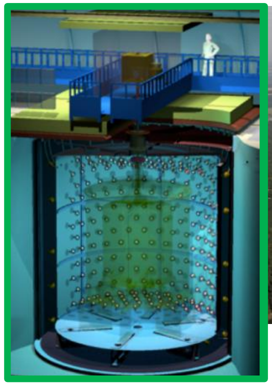
Reactor＝Powerful source of reactor neutrino

- Neutrinos / fission：$6 \times 10^{20}\ \nu$ /s (3GWth)
- Observable in outside of building (~45m)
- Detectable via Inverse beta decay

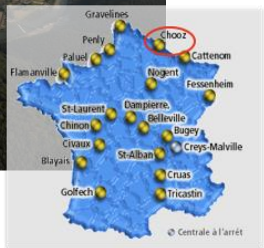
Technology change

Double Chooz (France)

- 2009 ~ 2017
- Liquid scintillator
- Volume ~ 10 t (7 x 7 x 7m)
- Under ground (300mwe)



Chooz power plant



Safety
Portability

PANDA (Japan)

- 2006 ~ 2019
- Plastic scintillator
- volume ~ 1 t (1 x 1 x 1m)
- On ground

Ohi power plant reactor 2

PANDA36

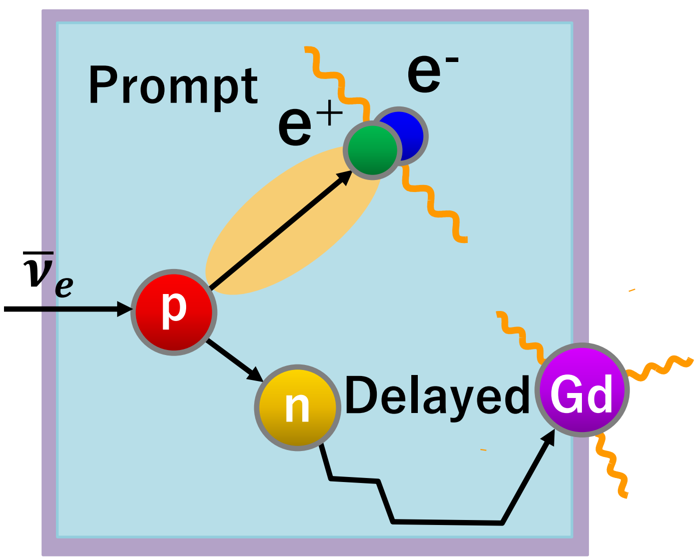
Upgrades for quick and portable neutrino measurement

- Safety : Liquid (burnable) to Solid plastic (stable)
- Portability : Less than 2 ton without shielding

$\overline{\nu}_e$ detection technique

Inverse Beta Decay (IBD) creates positron and neutron

- Positron : e^+ dE/dx + 2γs from annihilation
- Neutron : γs from neutron capture by nucleus
  - **Gd : $n + Gd^{155(157)} \rightarrow Gd^{156(158)} + \gamma s$ (~8MeV)**



Surrounding Gd-loaded sheet around a plastic scintillator

Delayed coincidence

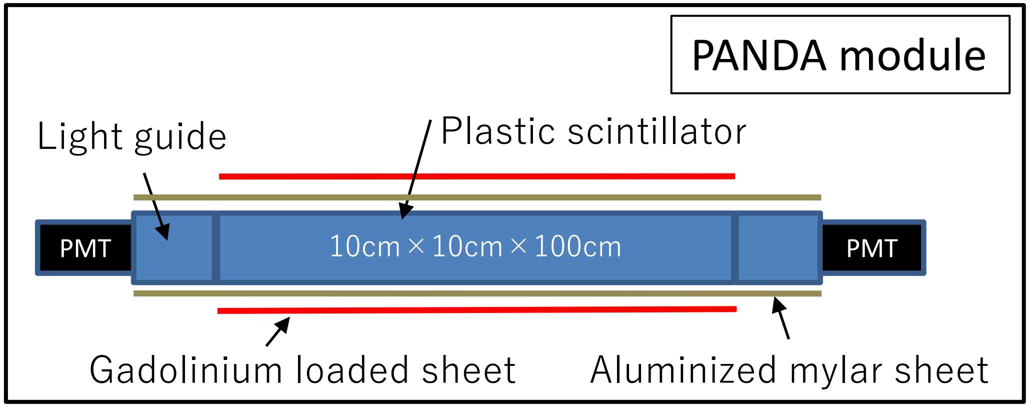
- Prompt (positron) ：1~8 MeV
- Delayed (n-Gd)：～8 MeV
- Time difference：～60 μ s

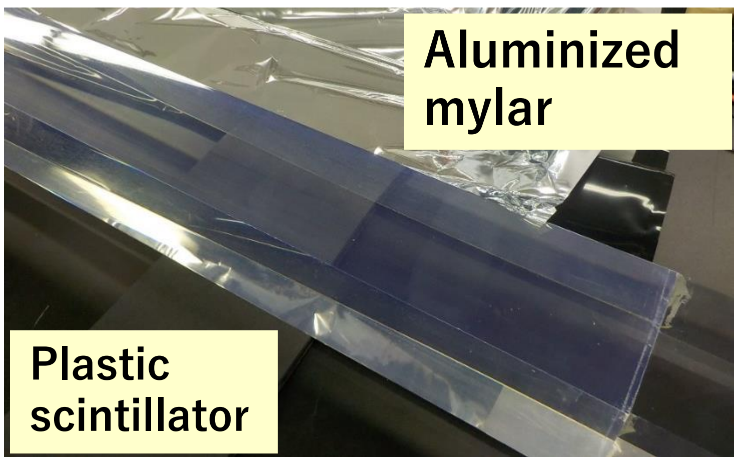
Reduces environment BG significantly but still too much BG remain..

Major backgrounds for IBD

- Accidental : Environment γ + n
- Correlated : Fast neutron

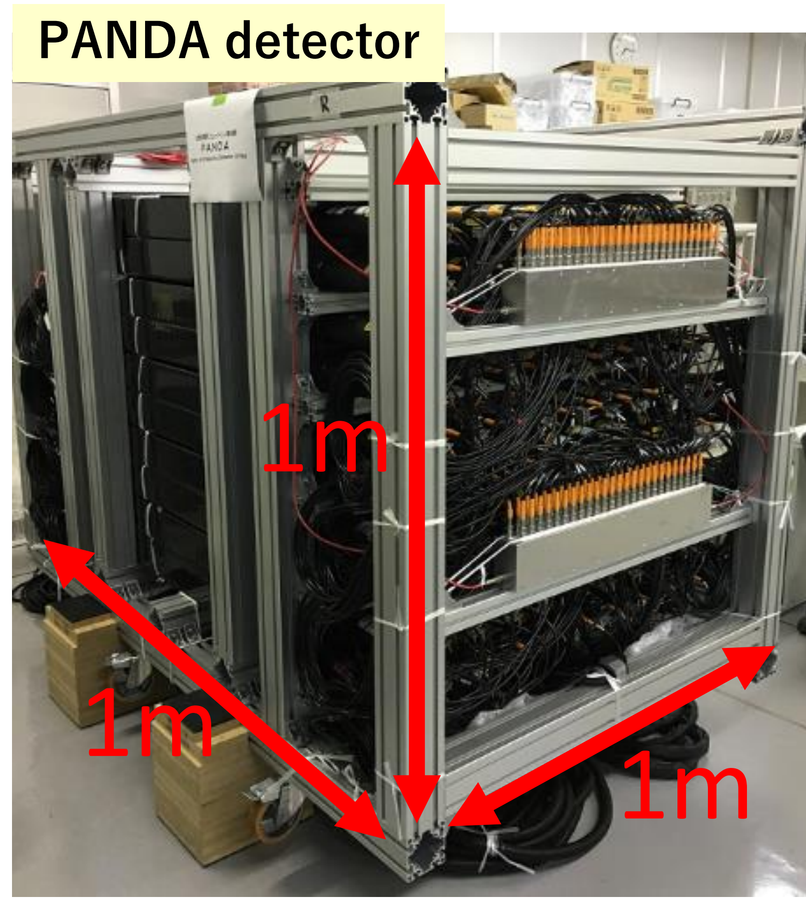
Plastic Anti-Neutrino Detector Array (PANDA)





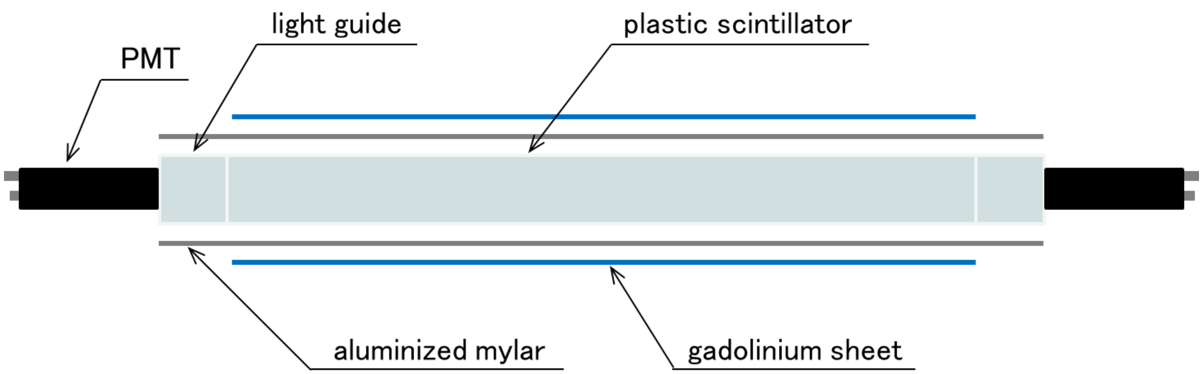
- Scintillator BC-408
- Target volume : ~1 t (1 x 1 x 1m)
- No anti-background material

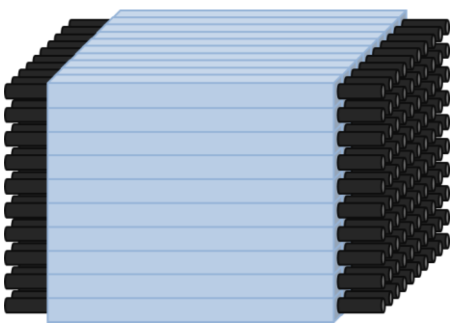
Combined 10 x 10 = 100 modules

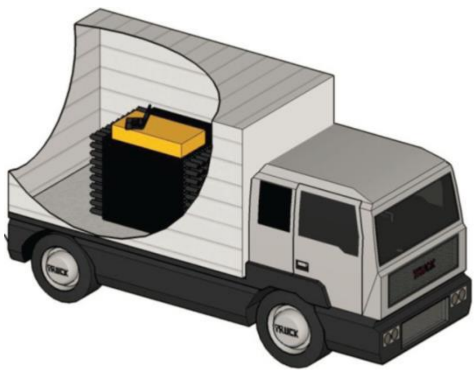


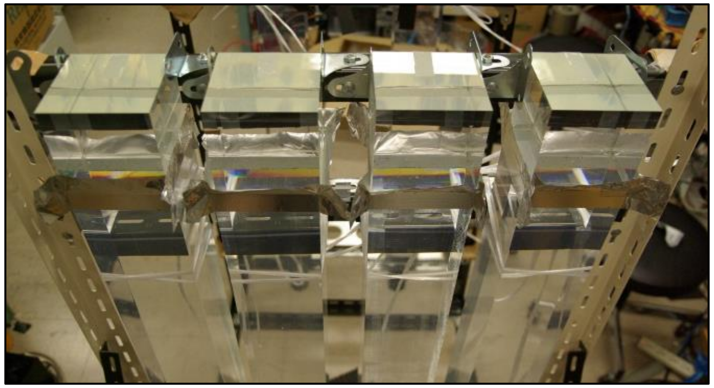
Portable on the truck

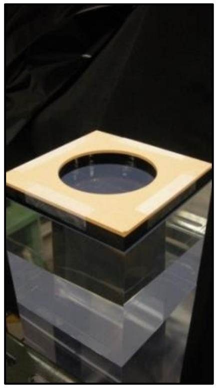
Construction of PANDA

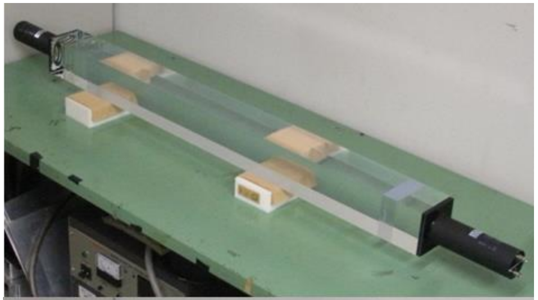


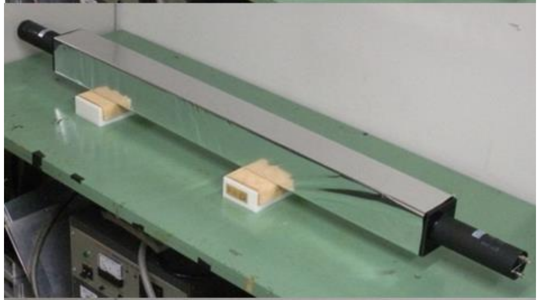


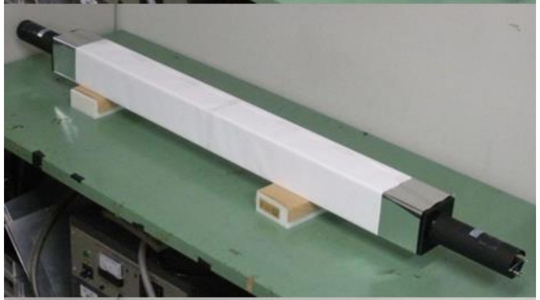


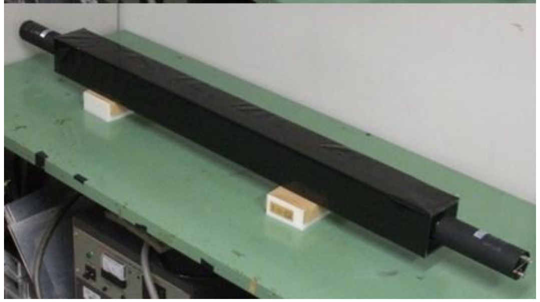




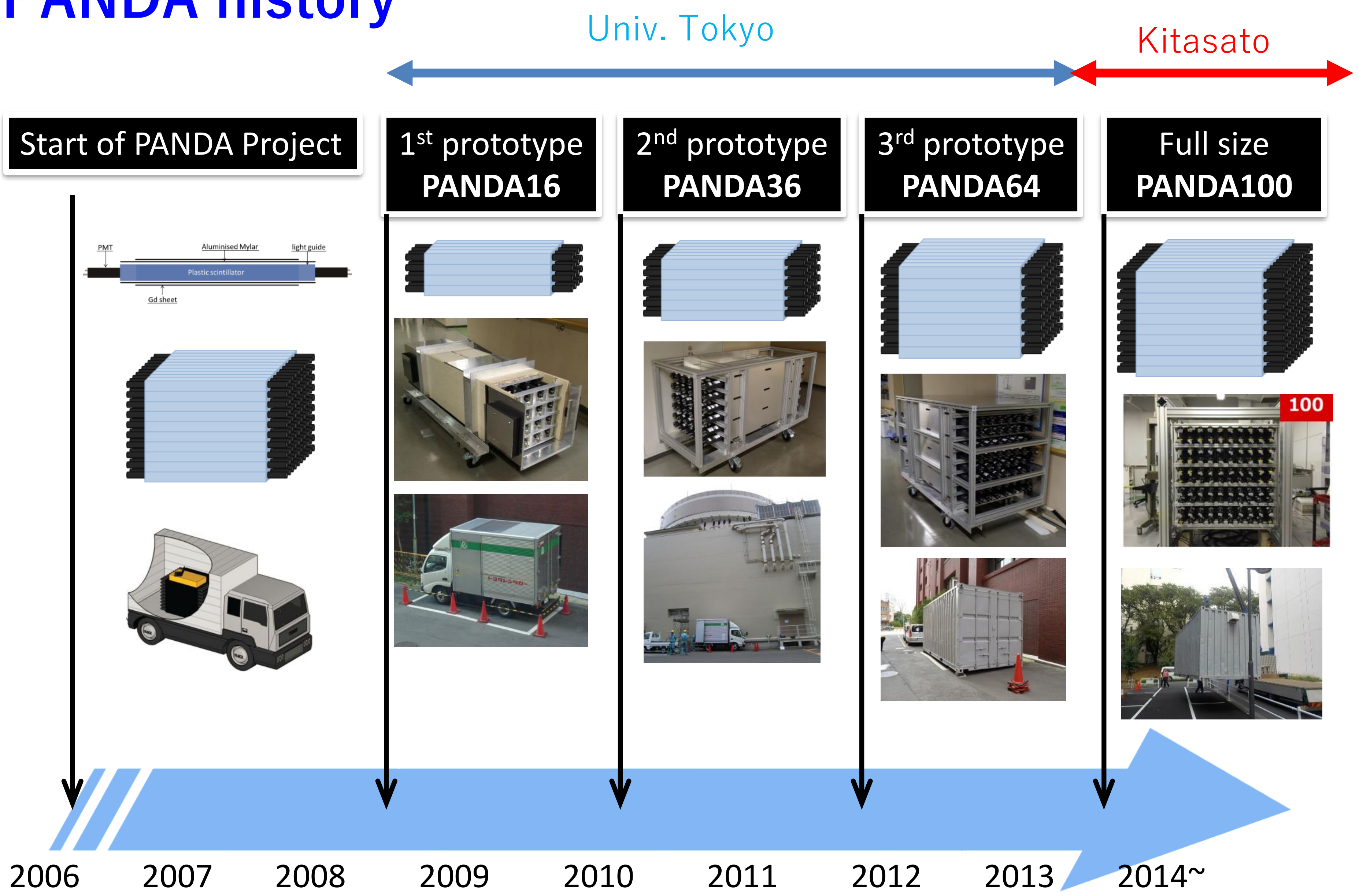








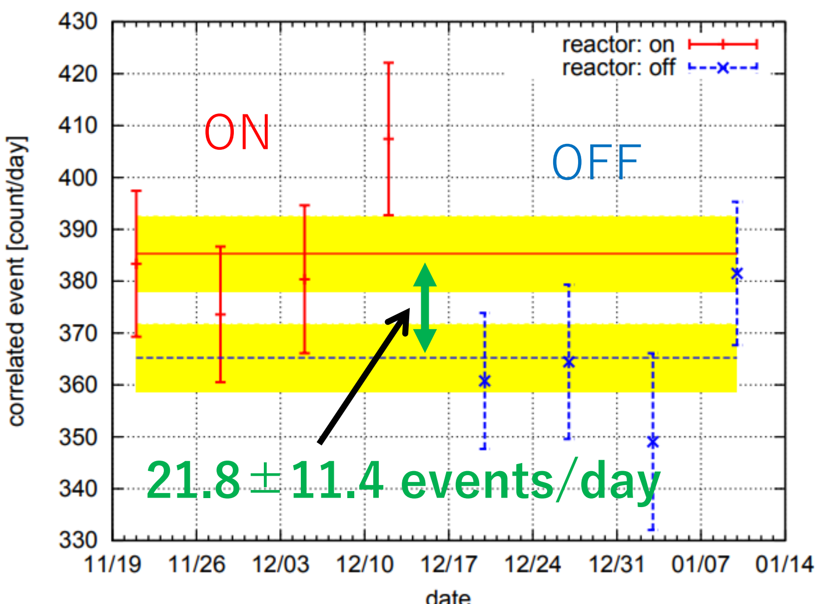
PANDA history

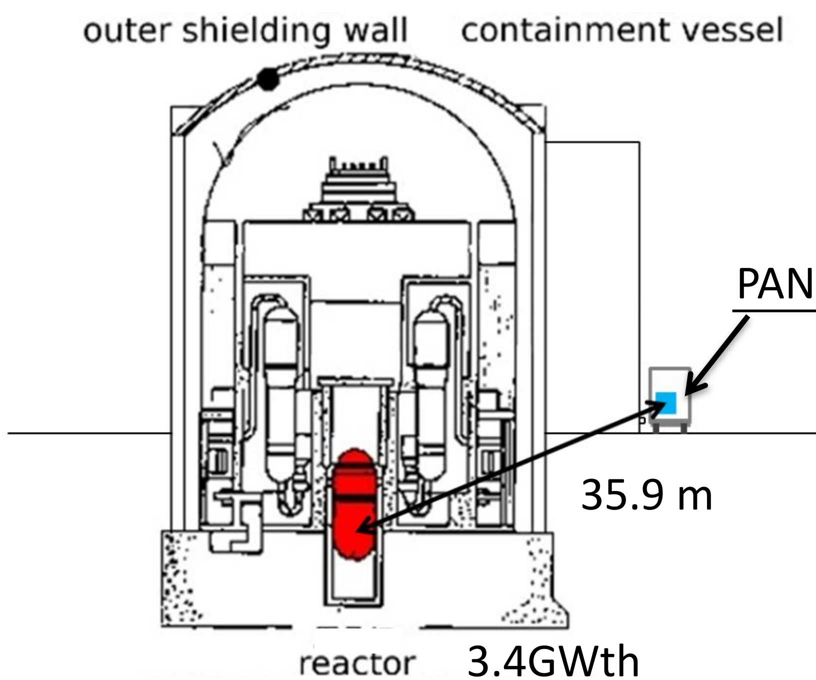


First trial for neutrino measurement

PANDA36 @Ohi plant (2012)

- By Univ. Tokyo
- Reactor 2 : 3.42 GWth (PWR)
- On ground 35.9m far from core
- Sep. 2012 – Jun. 2013
- Reactor on (30 days) - off (34 days)

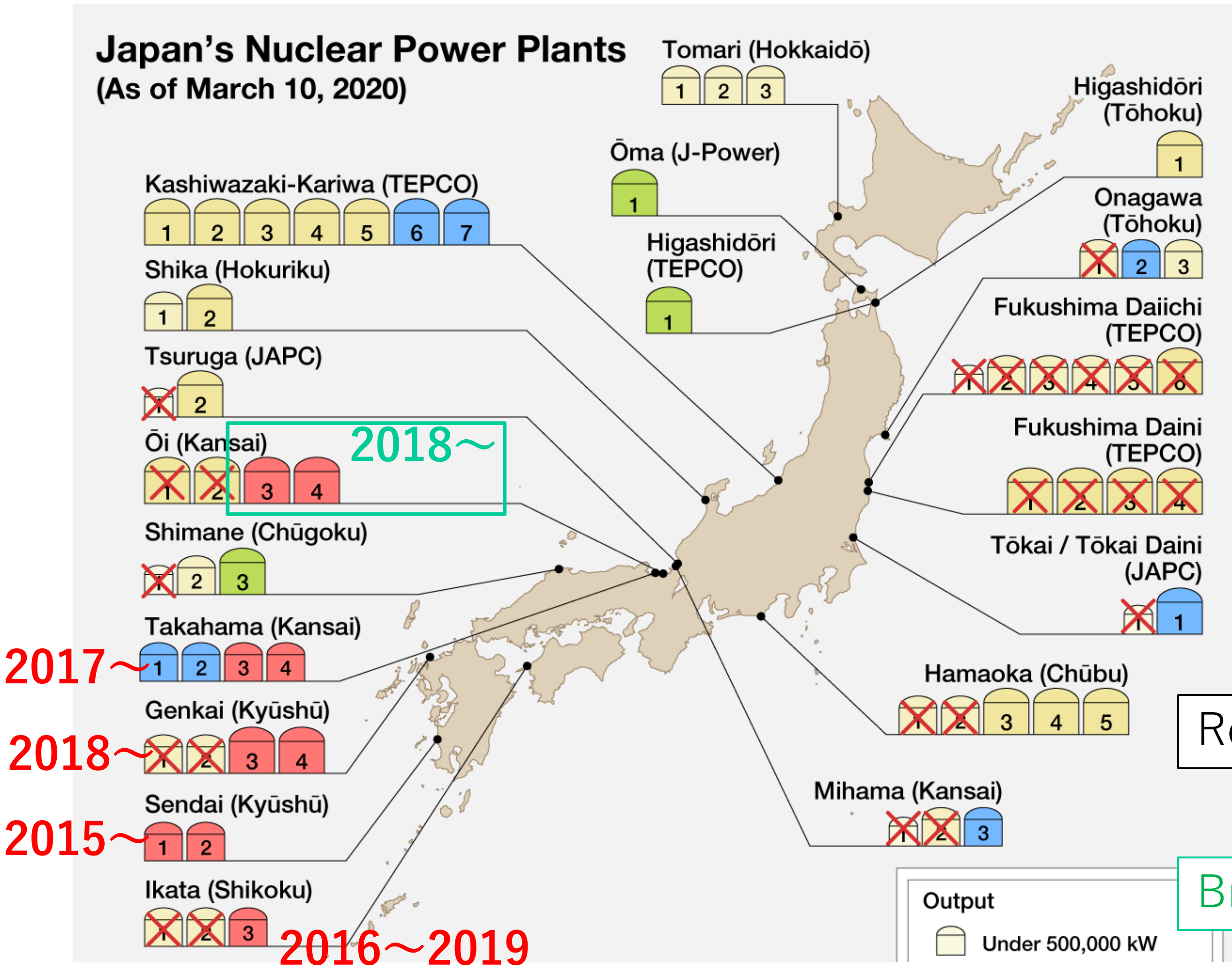


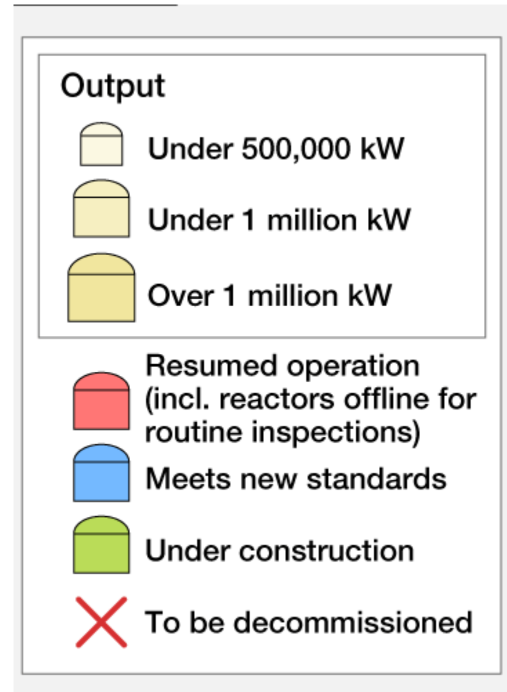


Not enough statistics and bad background subtraction

Reactors after the earthquake

Operation status（No reactor operated in 2014)





Reactors resumed in 2018

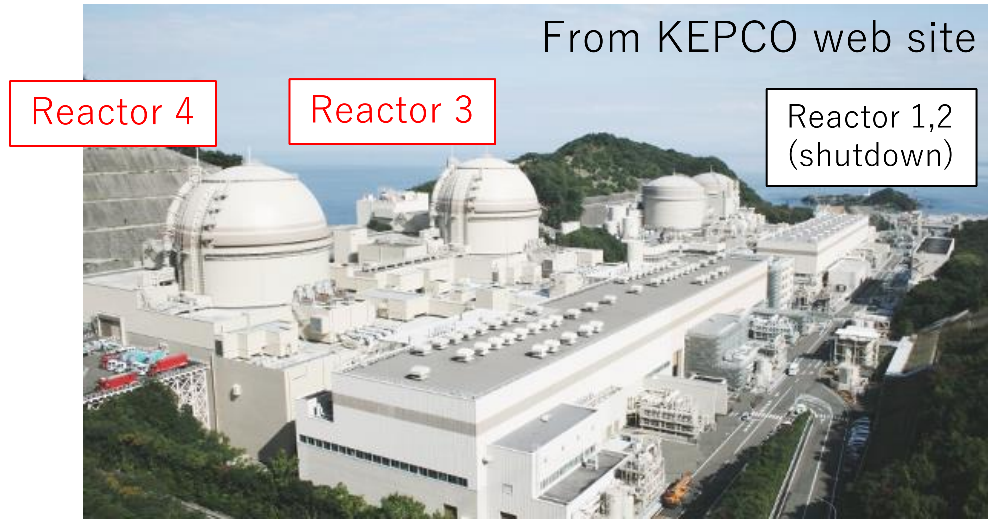
Bring detector in 2018-19

https://www.nippon.com/en/features/h00238/

Experiment site: Ohi power plant

(From google map)

- Close to Osaka and Kyoto
- 7 hours by train from Tokyo



Ohi reactor power plant in Japan

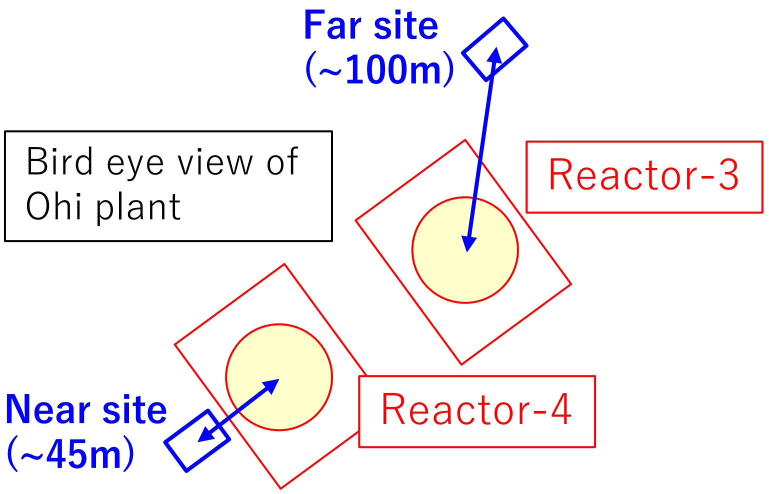
- Operated by Kansai Electric Power Company (KEPCO)
- Locates at Fukui (Hokuriku area)
- Two reactors restarted in 2018
  - Reactor 3 : 1.18MW (~3GWth)
  - Reactor 4 : 1.18MW (~3GWth)

Neutrino observation at Ohi

Premeasurement（2018）

- Detector tests at two locations
  – Near site (Reservoir 4)：18 days
  11/26 ~ 12/14
  – Far site (Reactor 3)：12 days
  12/14 ~ 12/26

Tuned DAQ configuration



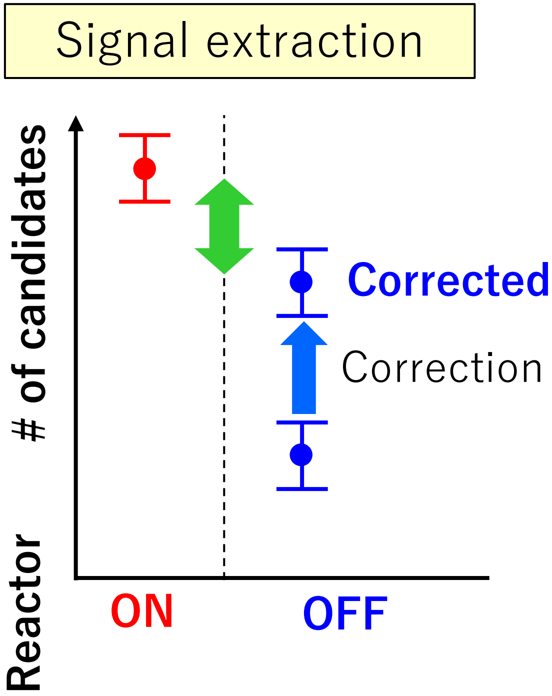
ON-OFF（2019, near site）

- ON - OFF subtraction
  – Reactor ON ：38 days
  5/28 ~ 7/4
  – Reactor OFF：33 days
  7/5 ~ 8/7

Measurement of reactor anti-neutrino energy spectrum by subtraction of Reactor ON - OFF

Reactor ON : Neutrino + BG
Reactor OFF : BG only

Goals of the Ohi measurement



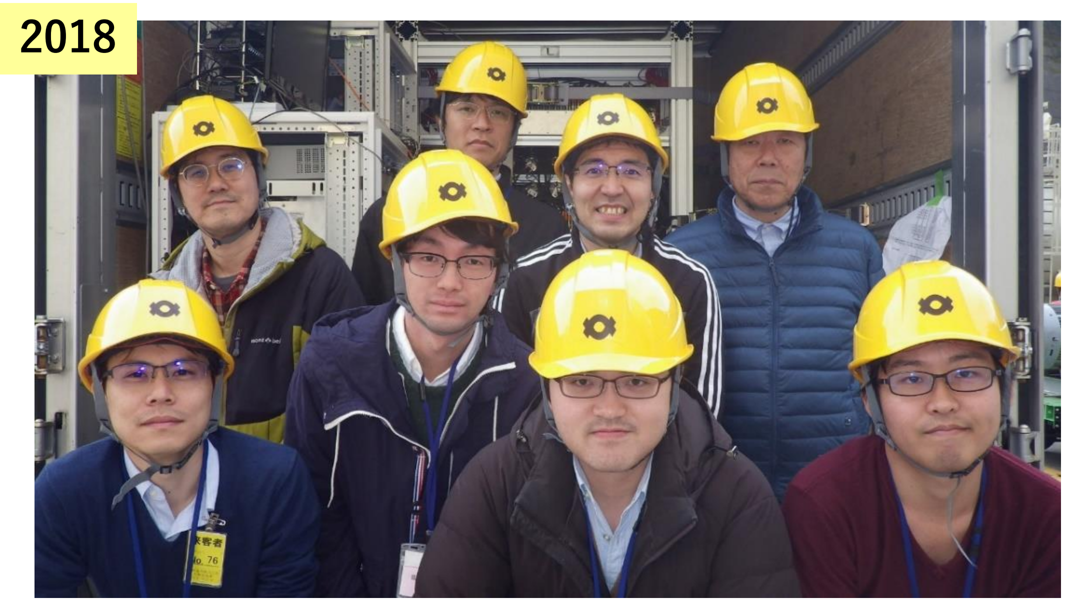
- Extraction of neutrino spectrum with amount of environmental backgrounds
  – Reactor ON: neutrino ＋BG
  – Reactor OFF: BG only

Neutrino spectrum can be obtained by subtraction of ON - OFF periods

Two operation phases

- Premeasurement (2018)
  – Confirm on-site operation
  – Background measurement
- Measurement (2019)
  – ON - OFF Subtraction

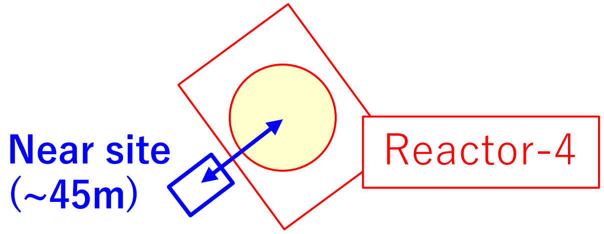
Members at the reactor site



Staff and Students from
Kitasato, Fukui, Tokyo metro etc.

PANDA detector in truck

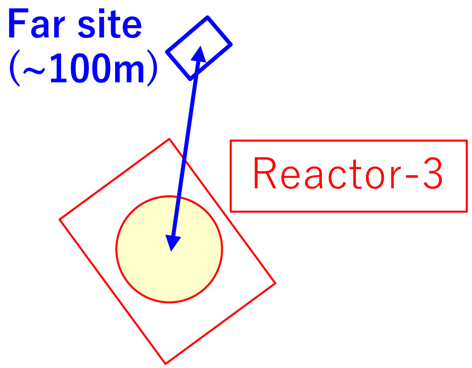
Measurement at Ohi Reactor 4



Ohi Reactor-4

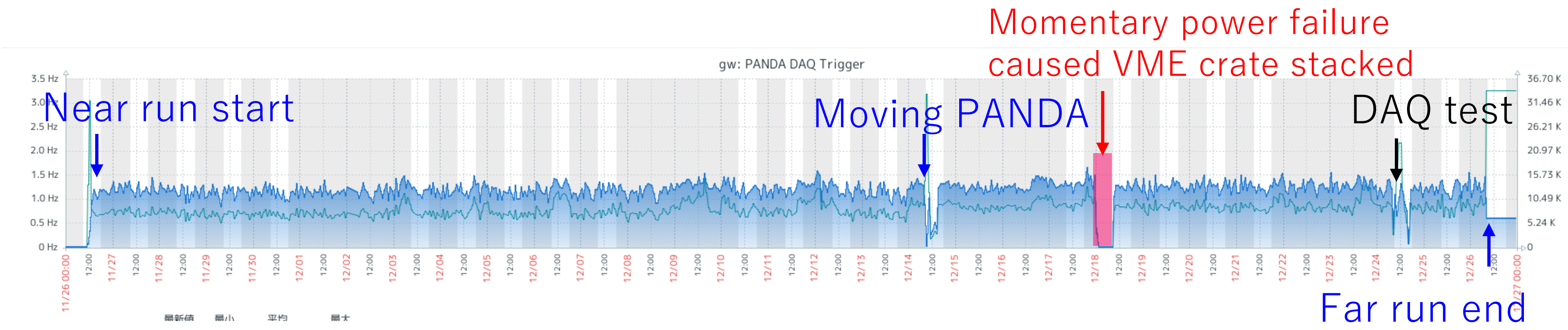
PANDA in side the truck

Measurement at Ohi Reactor 3

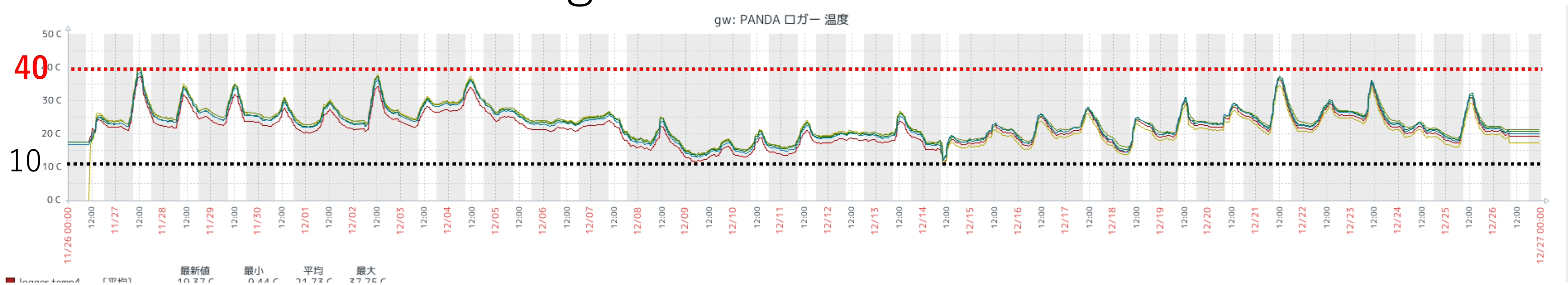


Operation status (2018)

- DAQ succeeded almost non-stop operation
  - Trigger rate ~1.1kHz

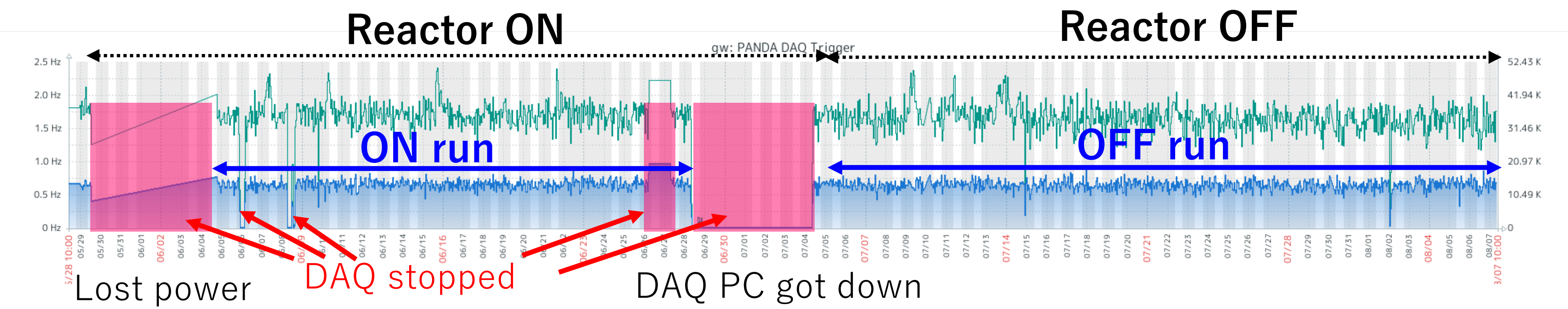


- Temperature changed in 1day (no cooler)
  - Increased ~40 degrees due to sunshine

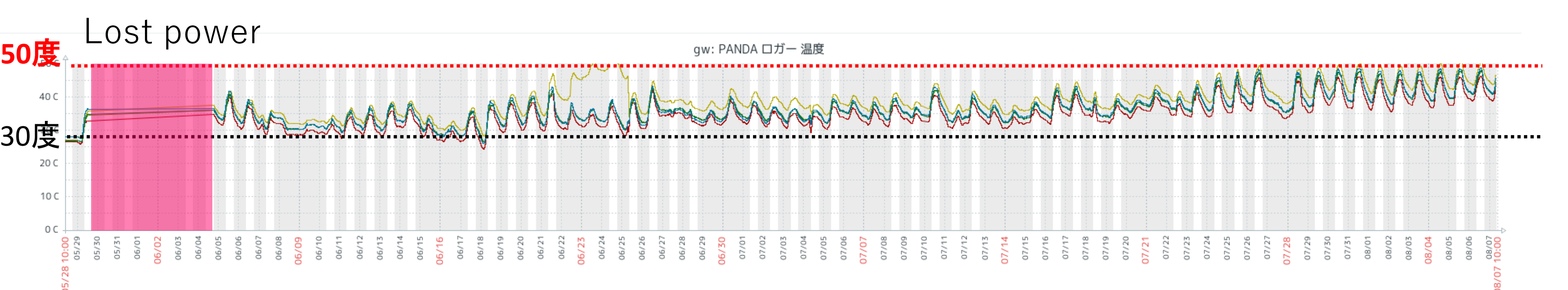


Detector status (2019)

- Unstable compared to 2018 =>High temperature in summary
  - External electronics noise : 2% of data is not available



- Increased temperature from late July to August
  - Varied in 30～50 degrees in each day



IBD selection results

Reactor near-far (2018)

- ~45m (11/26~12/14)
  - Live time：**17.0 days**
  - # candidates : 7437 [/day]
  - Accidental : 2812 [/day]
  - Correlated : 4625 [/day]
- ~100m (12/14~12/26)
  - Live time：**10.6 days**
  - # candidates : 7462 [/day]
  - Accidental : 3034 [/day]
  - Correlated : 4428 [/day]

Reactor ON-OFF (2019)

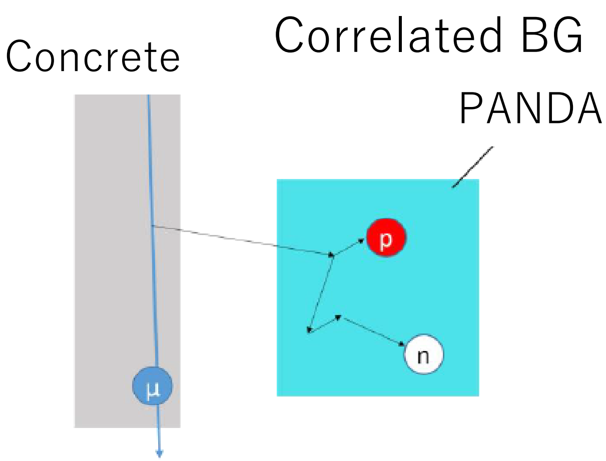
- Reactor-ON (6/4~6/28)
  - Live time：**19.6 days**
  - # candidates : 16184 [/day]
  - Accidental : 6414 [/day]
  - Correlated : 9770 [/day]
- Reactor-OFF (7/5~8/7)
  - Live time：**29.1 days**
  - # candidates : 15227 [/day]
  - Accidental : 5988 [/day]
  - Correlated : 9239 [/day]

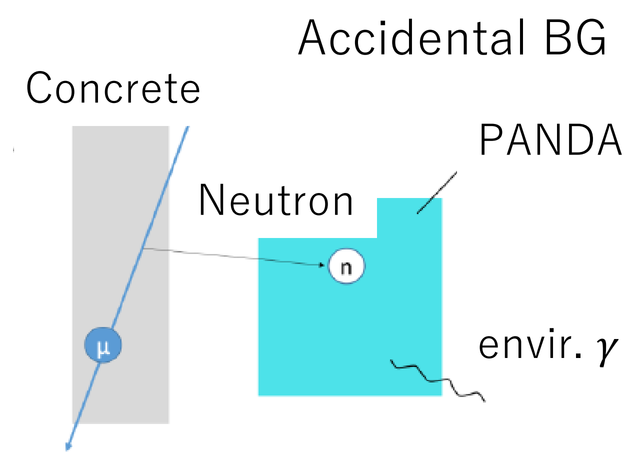
- Obtained enough data set for neutrino observation
- Threshold voltages was changed from 60mV to 30mV, causing increase of the trigger rage

Analysis strategy

Tight experiment environment for portability must be treated

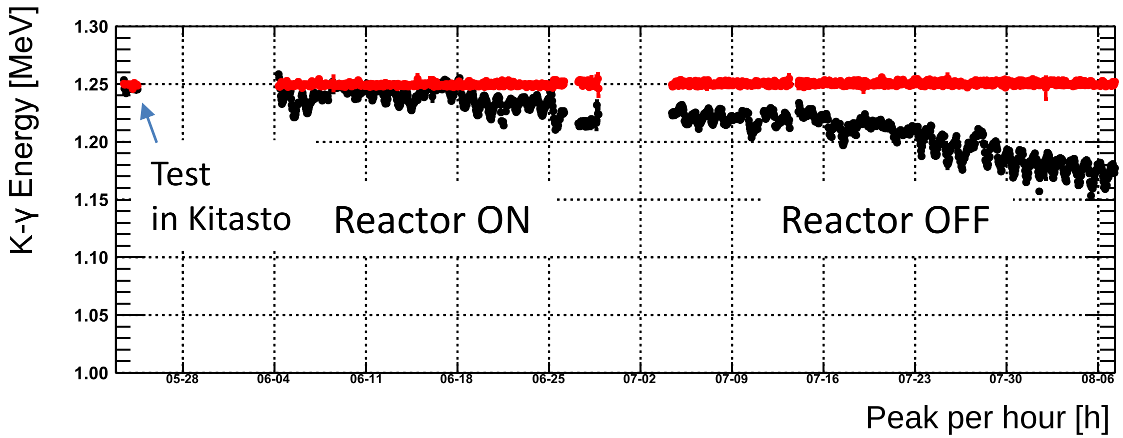
- Room & detector temperature were instable
  - Energy scale varied very much --> Requires correction
- Higher background signals on the ground
  - Correlated BG: Fast neutrons from cosmic products
  - Accidental BG: Environmental γ and neutrons
    --> Selection using event topology
- On BG level gets suppressed, we can compare ON / OFF!

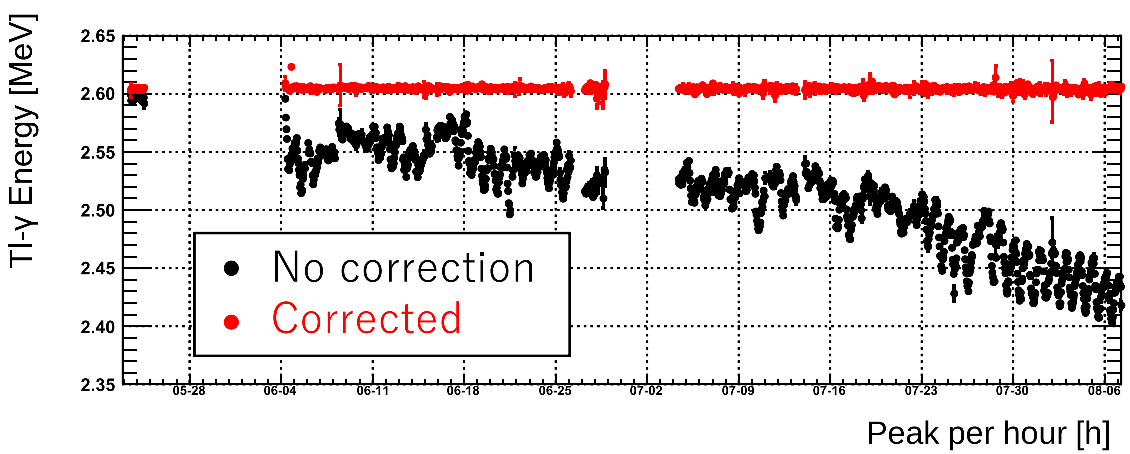


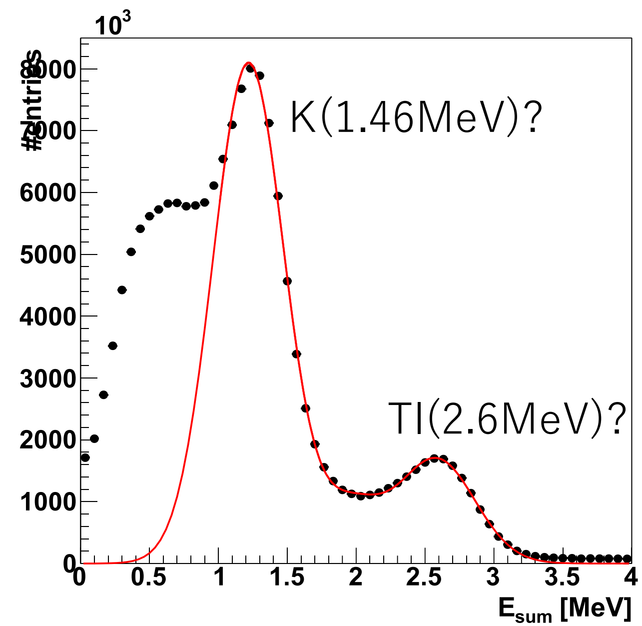


Energy scale correction

- Correction using 2 energy peaks of environmental ^{40}K and ^{202}Tl
  - $E_{cor} = (a * E_{sum} + b)/E_{sum}$ $E^{*(i)}_{mod} = E_{cor} \times E^{(i)}_{mod}$
  - $a = \frac{E_{Tl}^{room} - E_K^{room}}{E_{Tl} - E_K}$, $b = -aE_K + E_K^{room}$

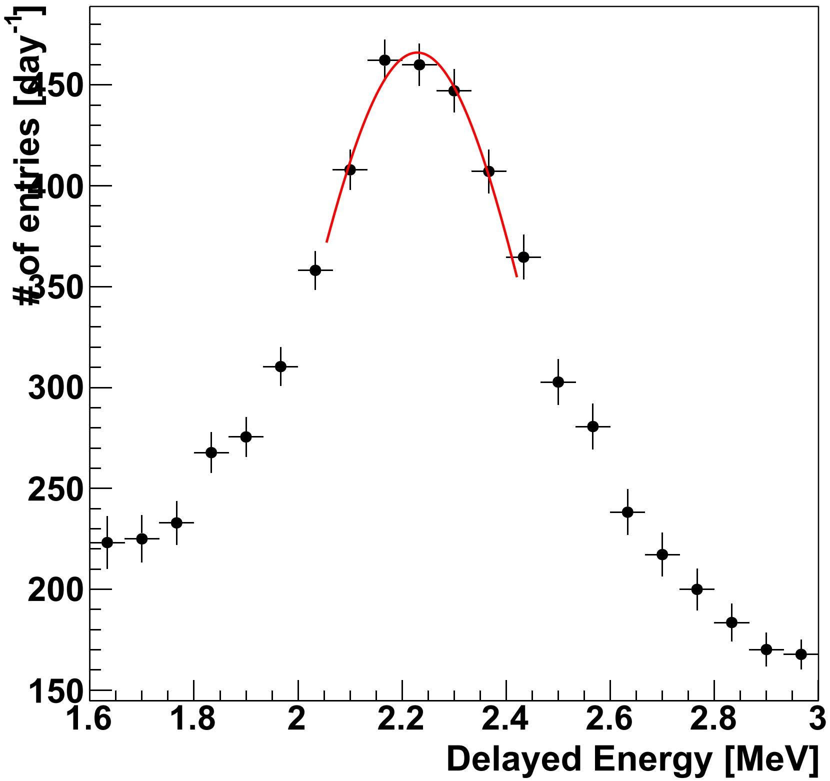




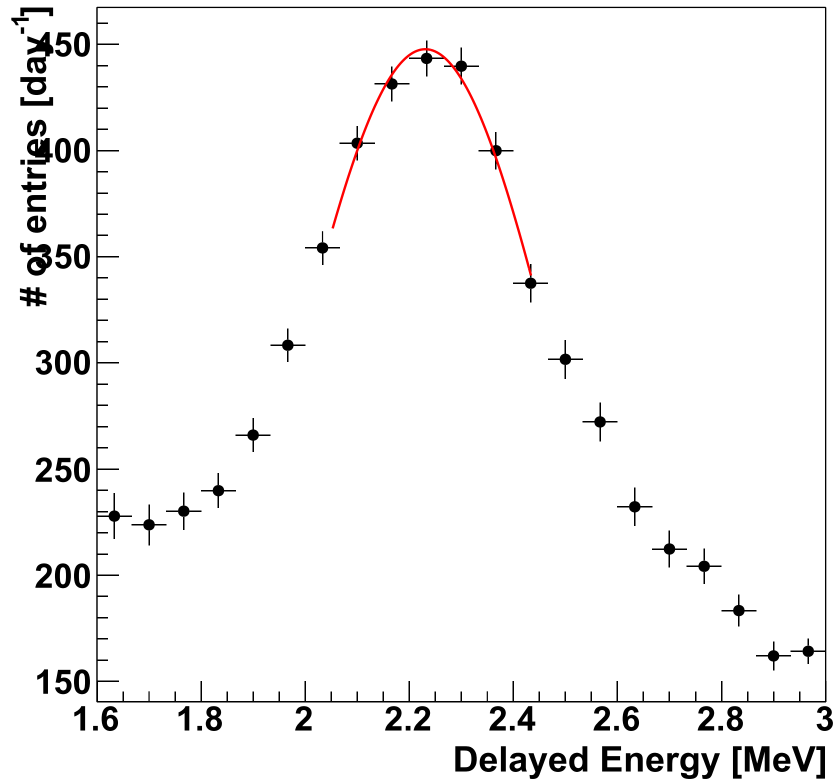


Energy scale stability (in n-H)

Reactor ON



Reactor OFF

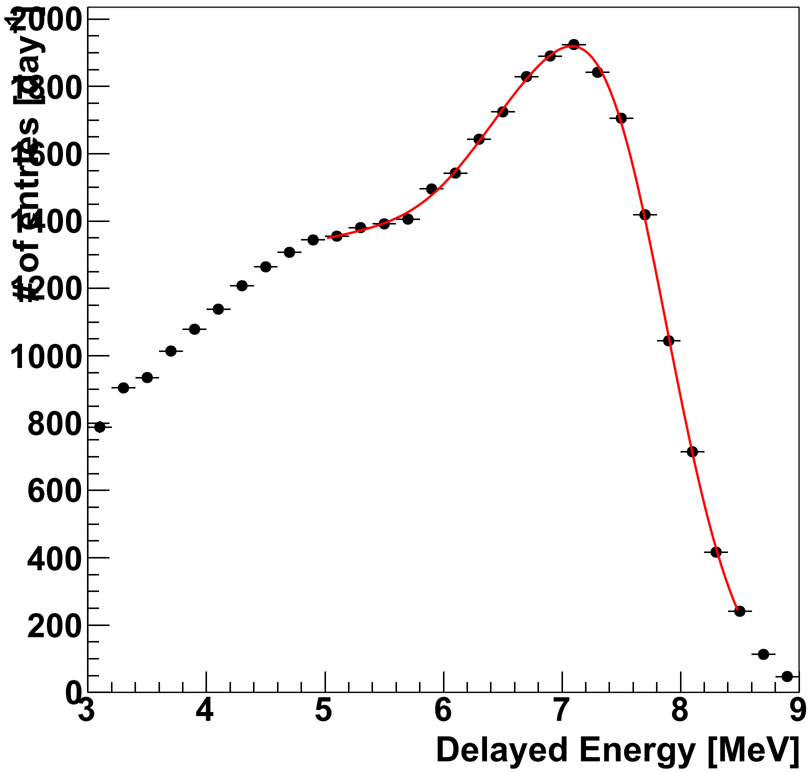


μ ：2.229 ± 0.0080 [MeV] ← μ ：2.231 ± 0.0069

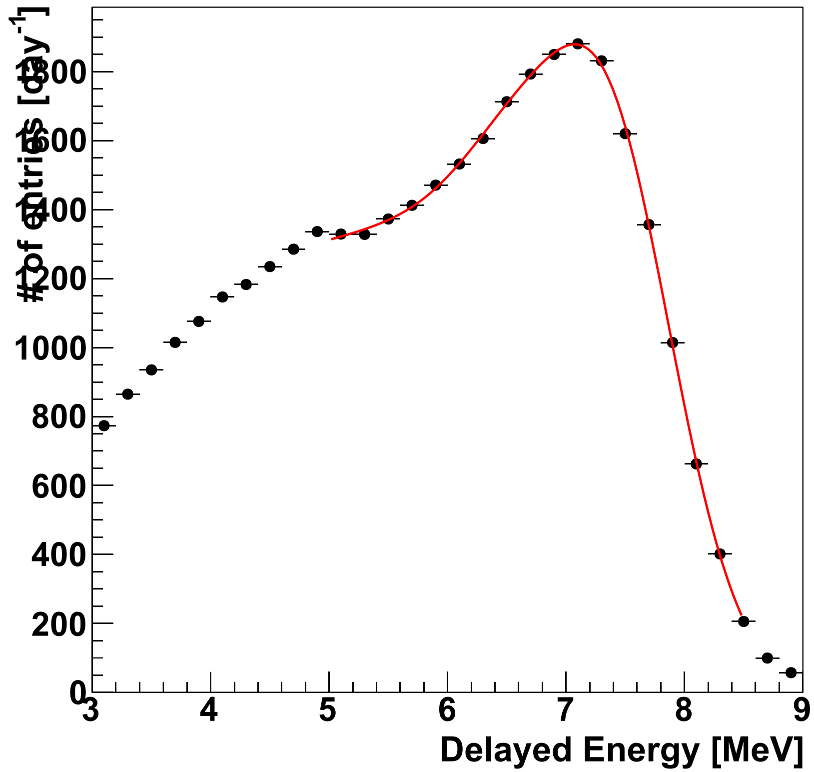
σ ：0.259 ± 0.0261 [MeV] **-0.08%** σ ：0.275 ± 0.0165 [MeV]

Energy scale stability (in n-Gd)

Reactor ON



Reactor OFF



μ ：7.686 ± 0.0539 [MeV] ← μ ：7.635 ± 0.0237 [MeV]

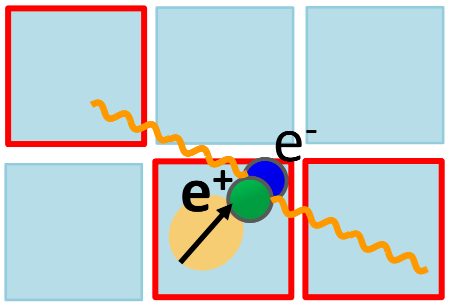
σ ：0.596 ± 0.0267 [MeV] **+0.67 %** σ ：0.607 ± 0.0132 [MeV]

Consistent between ON/OFF periods

IBD selection criteria

- **Muon veto**: dT_μ > 400 [us] (Muon ID : E_{sum} > 25 [MeV])
- **Delayed coincidence：**
  - Prompt signal: $2 < E_{sum} < 24$ [MeV]
    - $2 \leqq N_{hits} \leqq 5$
    - $E_{2nd} < 0.6$ [MeV]
    - $E_{sum} - (E_{1st} + E_{2nd}) < 0.7$ [MeV]
    - $\cos(\theta) < 0.8$
  - Delayed signal: $3 < E_{sum} < 9$ [MeV]
  - Time difference : $8 < dT < 300$ [us]
- **Further background reduction**
  - **Selection using likelihood ratio:**
    - $R = \frac{pdf(\text{correlated})}{pdf(\text{correlated}) + pdf(\text{accidental})} > 0.85$

Identification of annihilation gammas



PDF for accidental/correlated events

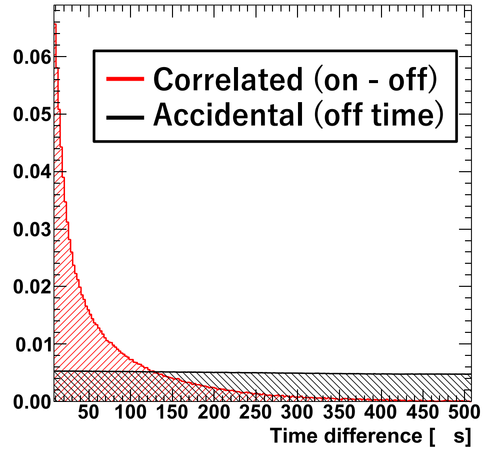
- P.D.F obtained from **fast neutron** candidates

Prompt
- – $8 < E_{sum} < 24$ [MeV]
- – $E_{2nd} > 1$ [MeV]

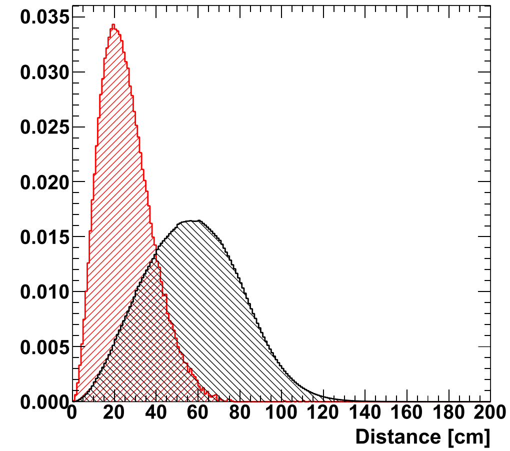
  → independent of IBD candidates by E2nd

- Accidental = off time
- Correlated = on - off time

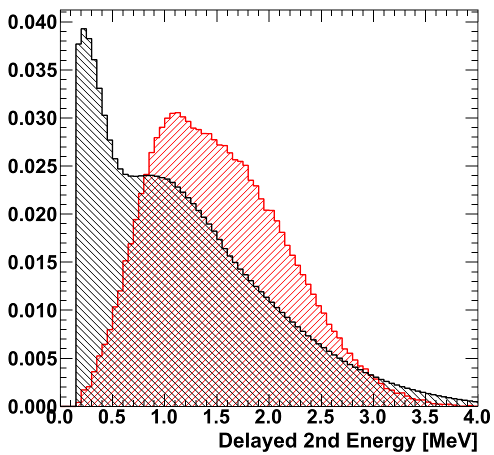
Time difference (prompt - delayed)



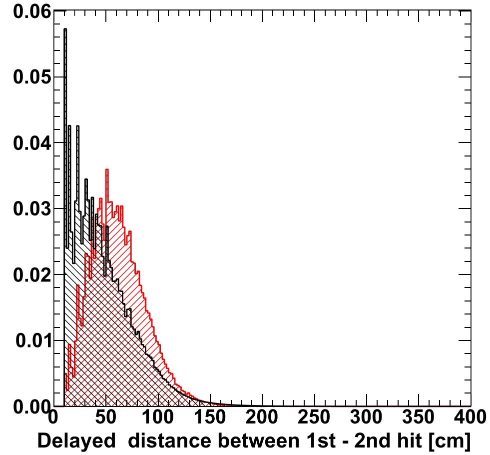
Spatial difference (prompt - delayed)



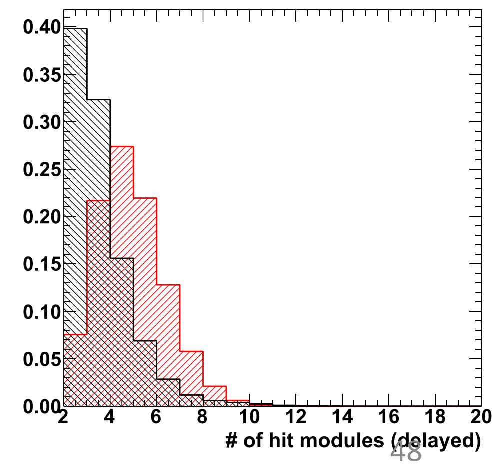
2nd Maximum energy in hit modules



Distance between delayed most distant 2 hits



 # hit delayed modules



Likelihood ratio for delayed event

- Event Likelihood is defined as multiply of P.D.F.s

$$L_{\mathrm{acc/cor}} = \prod_{v} p_{\mathrm{acc/cor}}(v)$$

v : the five parameters

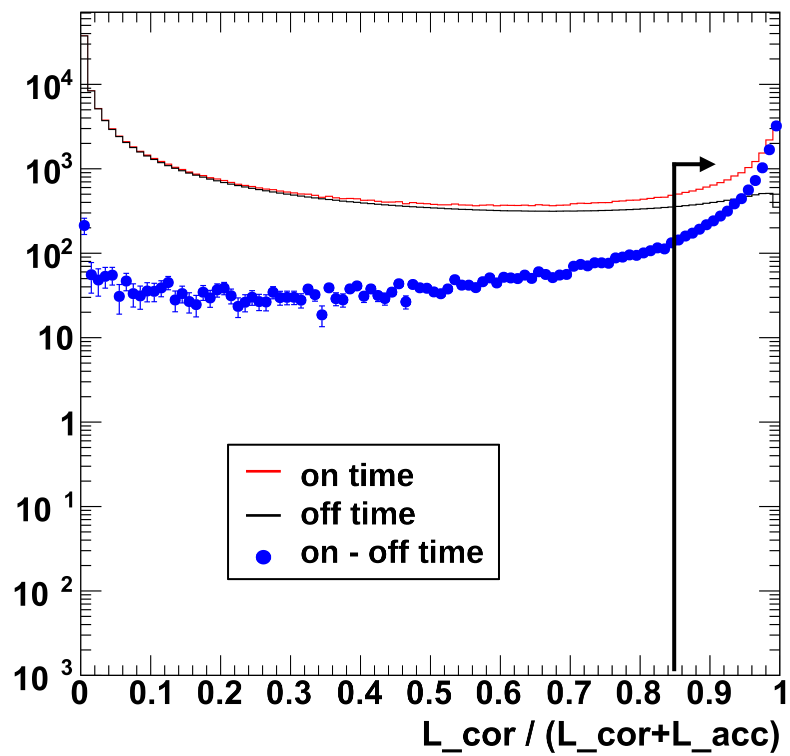
- Defined Likelihood ratio as

$$R = \frac{L_{\mathrm{cor}}}{L_{\mathrm{cor}} + L_{\mathrm{acc}}}$$

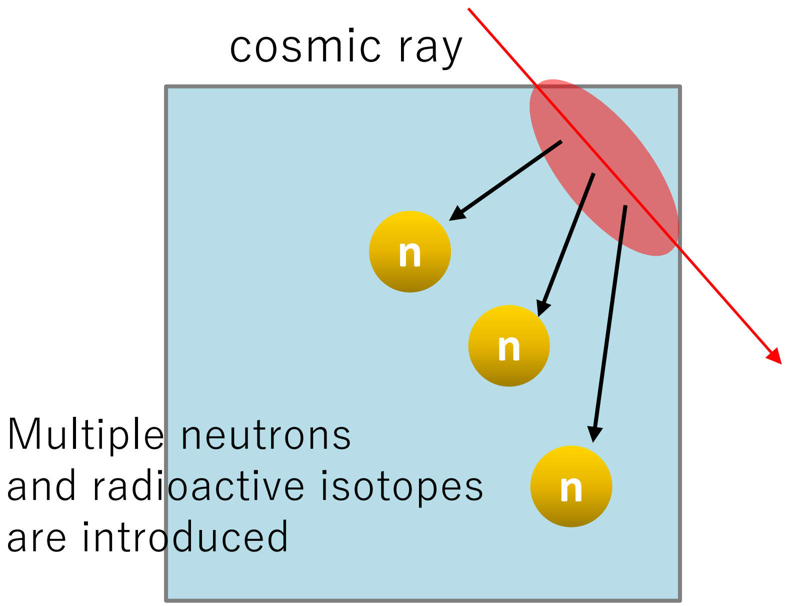
- EEfficiency for correlated :
  – Reactor ON：69.7 [%]
  – Reactor OFF：68.1 [%]

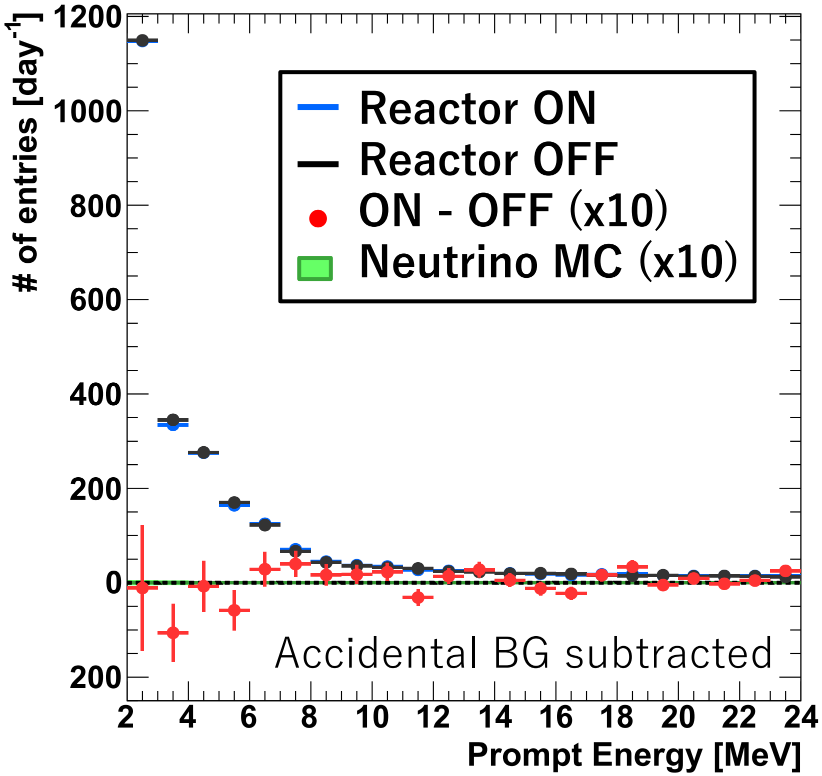
ON/OFF ratio：+2.35%

Likelihood ratio (Reactor ON)



ON / OFF comparison by cosmic induced events





Independent of reactor operation

Energy spectrum for cosmic products

- ON/OFF ratio： $+0.39 \pm 0.72$ [%]
- # neutrino signal : 0.00 ± 1.36 [day^{-1}]

=> Consistent between ON / OFF

Extraction of neutrino speactum

Comparison of ON and OFF spectra in IBD candidates

- χ^2 minimization of spectra comparison

$$\chi^2 = \sum_i \frac{\left(N_i^{ON} - (\boldsymbol{P_{OFF}} \times \widetilde{N}_i^{OFF} + \boldsymbol{P_{MC}} \times N_i^{MC})\right)^2}{\sigma_i^{ON2} + \sigma_i^{OFF2} + \boldsymbol{P_{MC}} \times N_i^{MC}}$$

  - $\boldsymbol{P_{OFF}}$: Correction factor of OFF event rate (free parameter)
  - $\boldsymbol{P_{MC}}$: # of IBD signals in MC (free parameter)

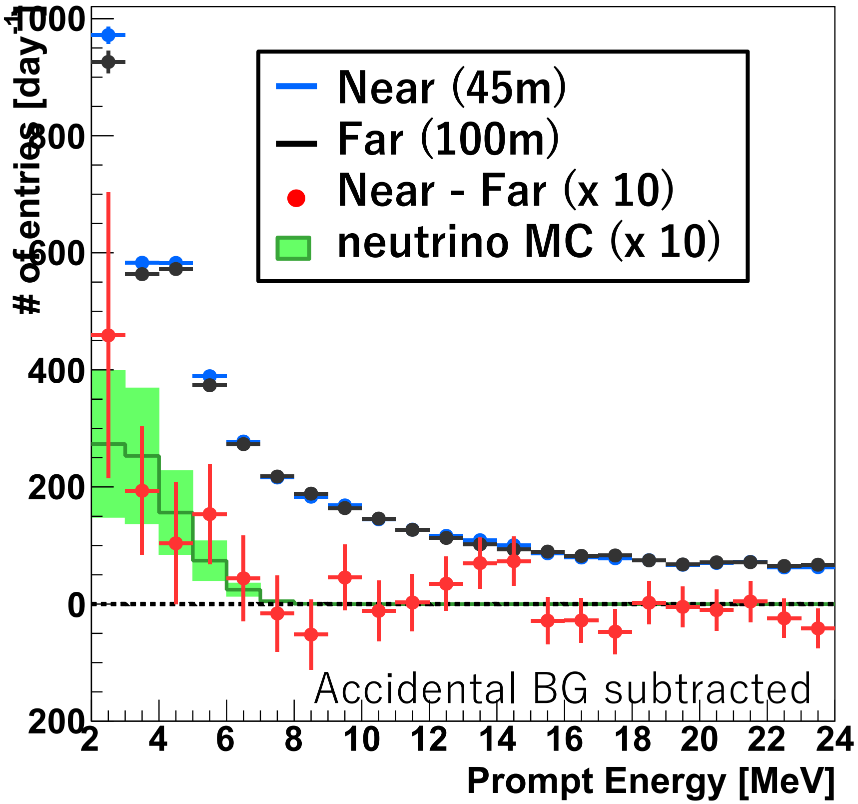
- Updates: Fit with muon product spectrum as penalty term

$$\chi^2 = \sum_i \frac{\left(N_i^{ON} - (\boldsymbol{P_{OFF}} \times \widetilde{N}_i^{OFF} + \boldsymbol{P_{MC}} \times N_i^{MC})\right)^2}{\sigma_i^{ON2} + \sigma_i^{OFF2} + \boldsymbol{P_{MC}} \times N_i^{MC}} + \sum_i \frac{\left(N_i^{ON} - \boldsymbol{P_{OFF}} \times \widetilde{N}_i^{OFF}\right)^2}{\sigma_i^{ON2} + \sigma_i^{OFF2}}$$

IBD candidate spectrum — muon product spectrum

- Minimized by MINUT

Neutrino extraction (Near/Far comparison, 2018)



- Near, Far: Accidental subtracted
- Error of Near - Far from Near and Far stat
- MC shows 1σ range

Compared Near－Far to MC simulation

- # IBD signal： **78.7±36.0 [/day]**

Non-Zero：2.18σ(>95%C.L.)

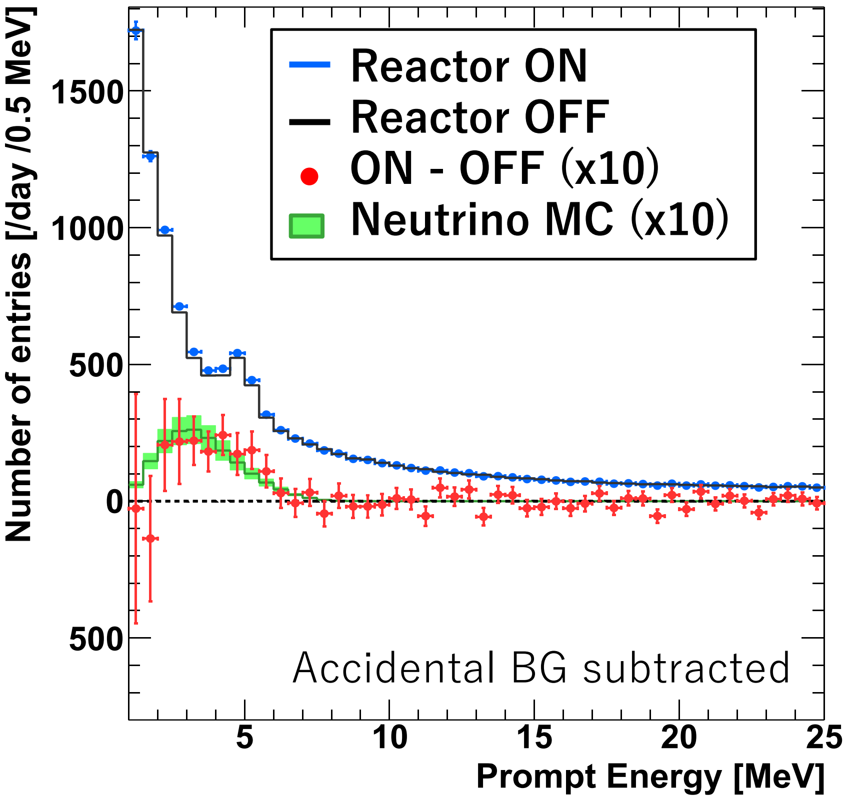
- Expected from 2019 ~ 77.8[/day]
  - Far also included neutrinos
  - Higher threshold voltage
  - Narrower Prompt energy range

=> ~ 60 % decreased

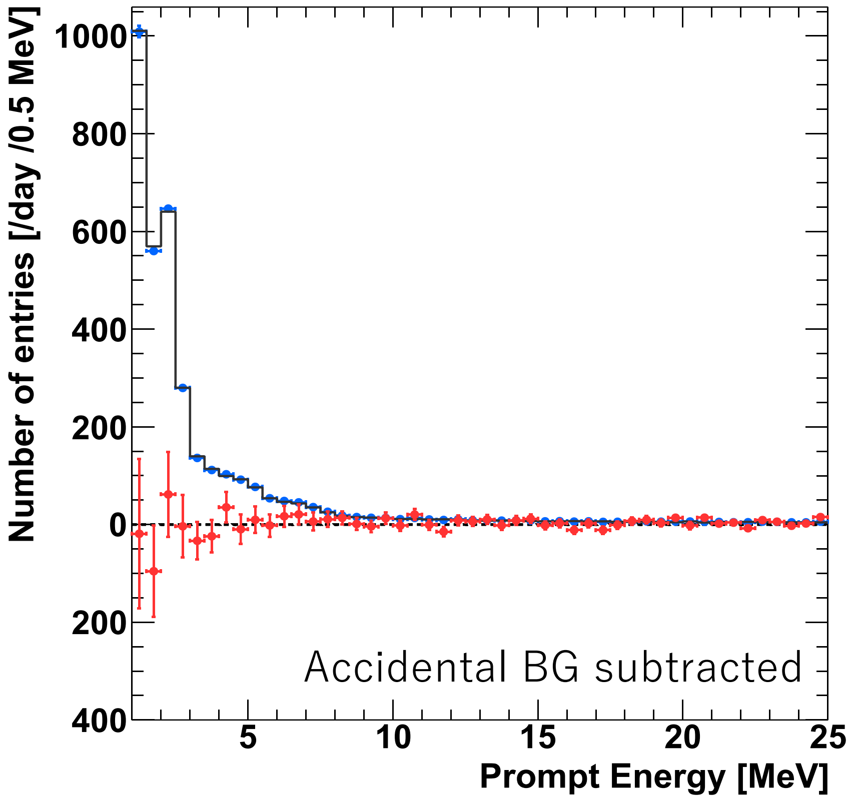
Consistent with ON/OFF measurement in 2019

Extraction of neutrino spectrum

Spectrum of IBD candidates



Spectrum of cosmic products



- # of observed neutrinos : 175.8 ± 34.4[day^{-1}] (5.10 σ)
- OFF/ON ratio : 103.1 ± 0.41 [%]
- Reactor ON : 8858.6 ± 44.3 [day^{-1}]
- Reactor OFF : 8722.4 ± 36.4 [day^{-1}]

First observation after the big earthquake

Success and tasks

Success: completed neutrino observation at Ohi plant

- No critical trouble among 2018-2019 operations
  - No critical point in PANDA for safety
  - No troubles in high voltage supplies
- Observed reactor neutrino spectrum with 5.2σ
  - Comparison of reactor ON - OFF periods
  - Correction temperature difference

Tasks: Improvement of reactor neutrino sensitivity

- Background
- Detection efficiency
- Temperature control
- Electronics noise

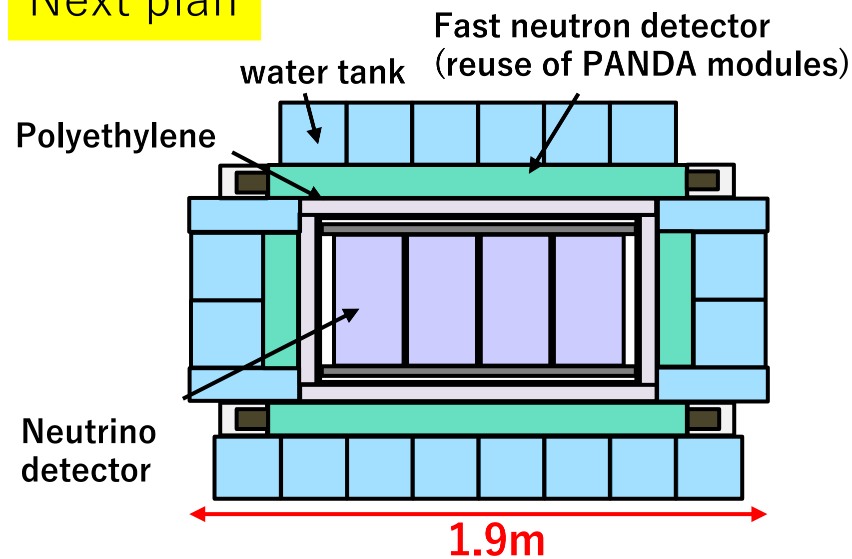
Background, Detection efficiency → Development of new detector

Prospect for next detector

Development was started

- New detection methods
  - ^{6}Li sheet for n-capture
  - More channel from PMT -> MPPCs
- Capability of event topology
  - Fine segmentation Less than 5 cm
- Anti-BG materials
  - Water tank ：~1.7t
  - Fast neutron detector by reuse of PANDA

Next plan



- Size：1.9 x 1.2 x 1.2 m
- Mass：1.4t (no water)
  3.1t (total)

New detector development continues for coming 2-3 years

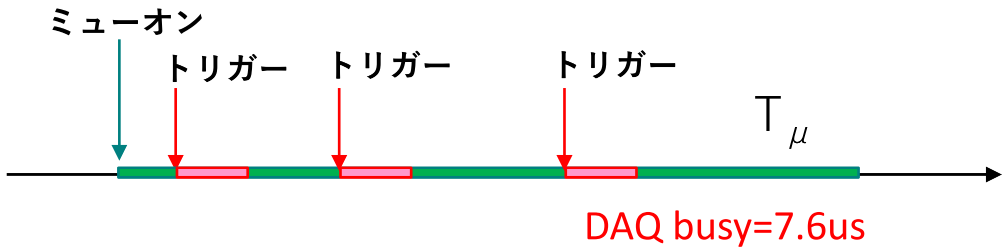
Summary

- Reactor neutrino is essential tools for both particle physics and reactor safety
  - Measurement on the ground is a key
- Japanese group developed PANDA (plastic anti neutrino detector array) as 1t volume detector
- Measurement at KEPCO Ohi reactor power plant during reactor ON and OFF in 2018 and 2019
  - 2018：45m → 100m for 3 weeks
  - 2019：ON (1month) → OFF (1month) for 2 months
- Obtained neutrino spectrum for both 2018 and 2019
  - Background level is still higher than 100 times
- New detector development is already started

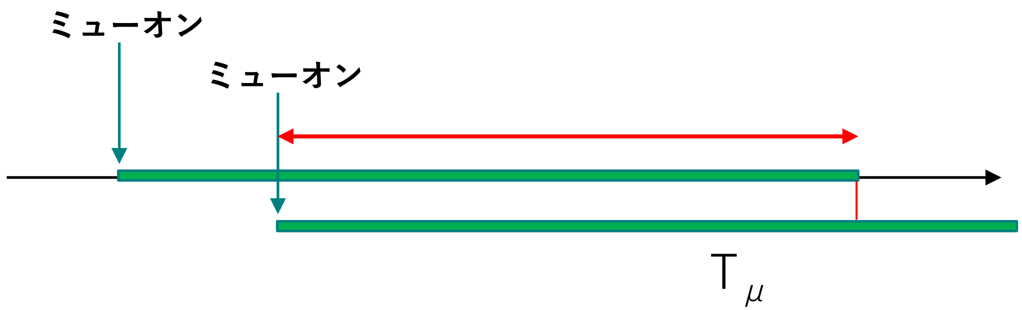
This work was supported by JSPS KAKENHI Grant Number JP19K03891

Live timeの計算

- Run time : DAQ section開始から終了までの経過時間の合計
  - 最後と最初のイベントのタイムスタンプの差
- DAQ live time : Run timeからDAQ busyを差し引いたもの
  - BUSY時間はFPGAロジックボードが記録
- Live time : DAQ live timeからmuon veto timeを差し引いたもの
  - **Veto time は N_μ x T_μ (=400us)ではない**



Veto window 内のイベント数を数え上げてVeto timeから差し引く

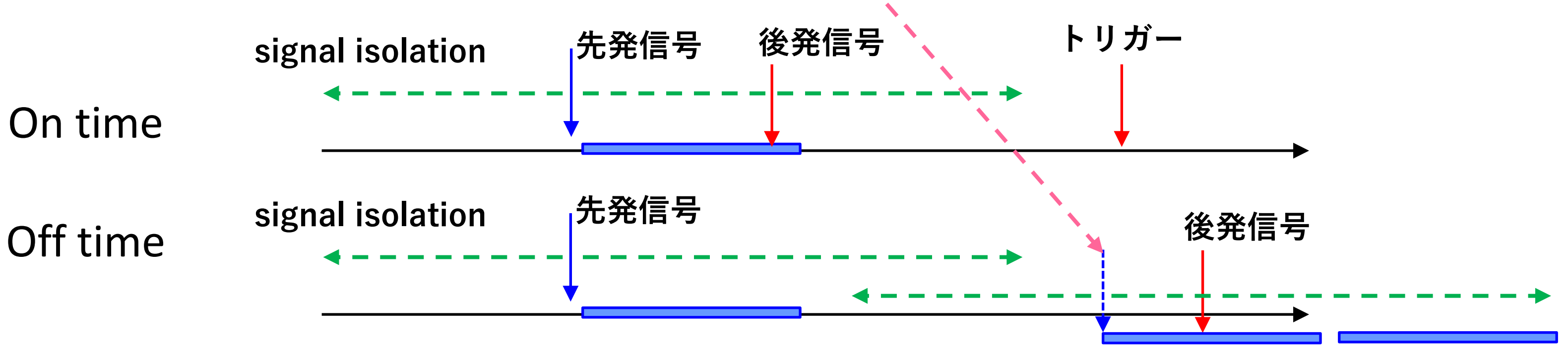


重なり合うVeto windowの重複分を差し引く

Off timing法(Accidentalの見積もり)

Promptからわざと時間的に離れたDelayed用のTime windowを作り、
時間相関のない事象の組み合わせ(Accidental)を作る

- **On time** ：Correlated（ニュートリノ信号含む)＋Accidental
  - 時間相関 : 8 < dT < 300 [us]
  - 連続信号の除去: -200 < dT < 300 [us]
- **Off time** : 1つのPrompt候補に**最大100個のtime window (i=1..100)**
  - 時間相関 : 8 < dT - (1s + 2000us x i) < 300 [us]
  - 連続信号の除去: -200 < dT < 300 [us]かつ
    Delayed window 周辺: -200 < dT - (1s + 2000us x i) < 300 [us]
  - 偽Prompt (T+ (1s + 2000us x i))がμ veto にかかる場合は
    ウィンドウ自体を作らない



Off timingのレート補正

Off timeのDelayed信号のinefficiencyはOn timeと異なる

=> Off timingのTime window 補正 : f_{iso} x x f_{win}

- Signal Isolation : Off timeだけdelayedに二重にかかる
  - Isolation cutのefficiency: $e_{iso} = \exp(- R_{iso} \times T_{iso})$
  - R_{iso} : 前後-200 < dT < 300 us にイベントがないDelayed候補(ミューオンベトー後のイベントのみ)のイベントレート
  - 補正項: $f_{iso} = 1. / e_{iso}$ (e_{iso} : isolation cut のefficiency)
- Prompt候補数(N_{pwin})とDelayed window数(N_{dwin})を数えて比を取る
  - 補正項： $f_{win} = N_{pwin} / N_{dwin}$