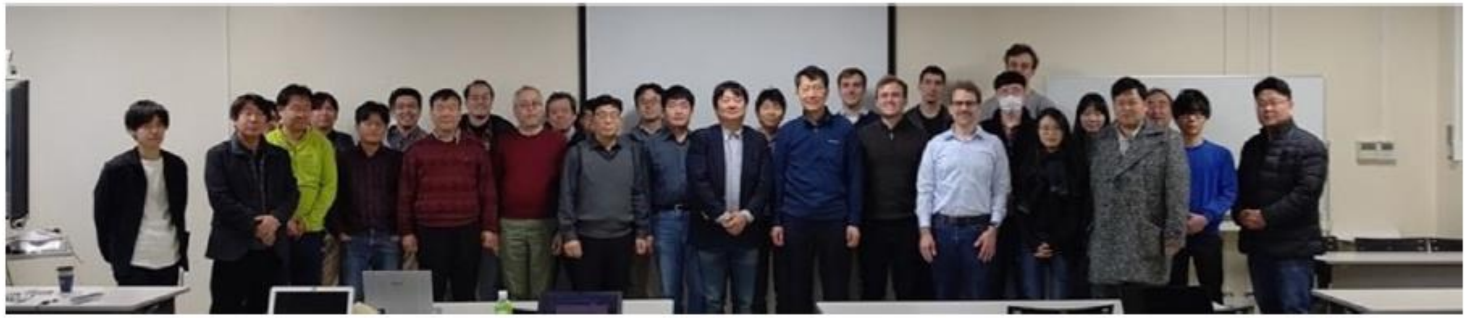
Status of the JSNS^2-I / II

ChangDong Shin (KEK)
On behalf of the JSNS^2 I / II collaboration

JSNS² / JSNS²-II Collaboration

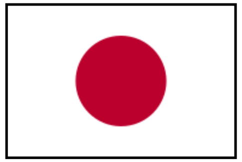
(J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source)

Collaboration meeting @ J-PARC (2020/Feb)



JSNS² collaboration (61 collaborators)

- 10 Korean institutions (24 members)
- 6 Japanese institutions (29 members)
- 4 US institutions (7 members)
- 1 UK institution (1 member)



JAEA
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Kyoto
Osaka
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Kyung Hee
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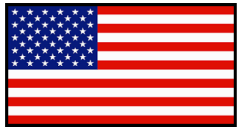


BNL
Florida
Michigan
Utah

Sussex

Indication of a sterile neutrino ($\Delta m^2 \sim 1 eV^2$)

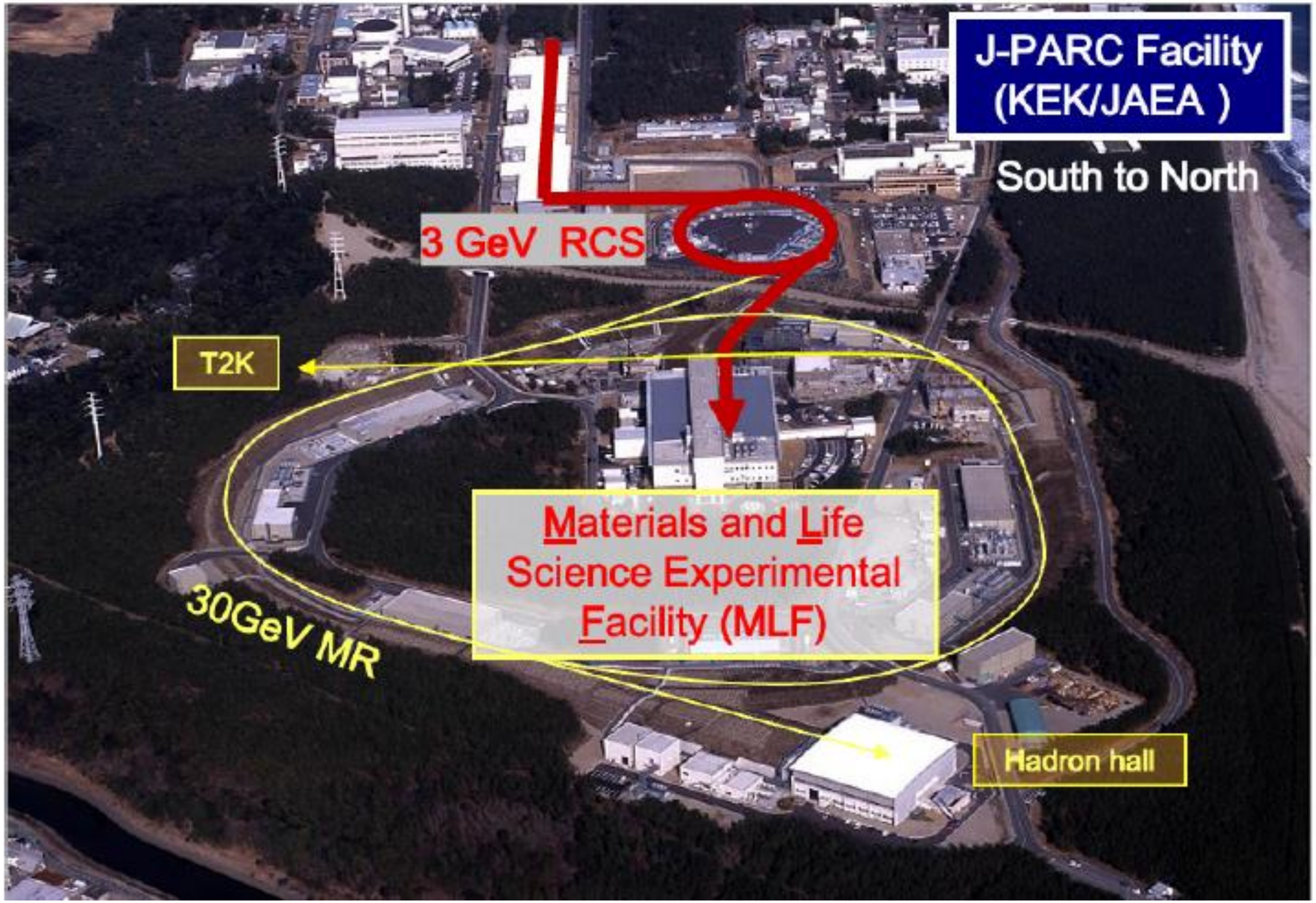
- Anomalies, which cannot be explained by standard neutrino oscillations for ~20 years are shown

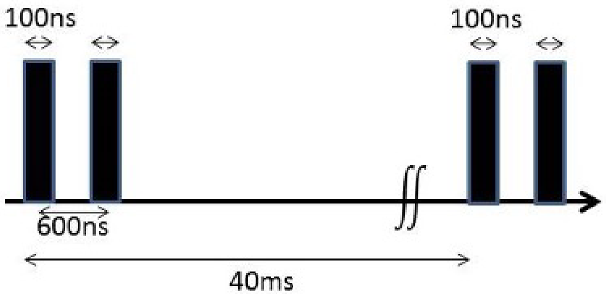
Experiments	Neutrino source	Signal	Significance	E(MeV)	L(m)
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ	40	30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	4.8σ	800	600
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$			
BEST	e capture	$\nu_e \rightarrow \nu_x$	4.2σ	<3	10
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ	3	10-100

- JSNS^2 uses the same neutrino source (μ), target (H), and detection principle (IBD) as the **LSND**

  - Even if the excess is not due to the oscillation, JSNS^2 can catch this directly
  - two advantages : short-pulsed beam and used the gadolinium(Gd)-loaded liquid scintillator(GdLS)

J-PARC facility





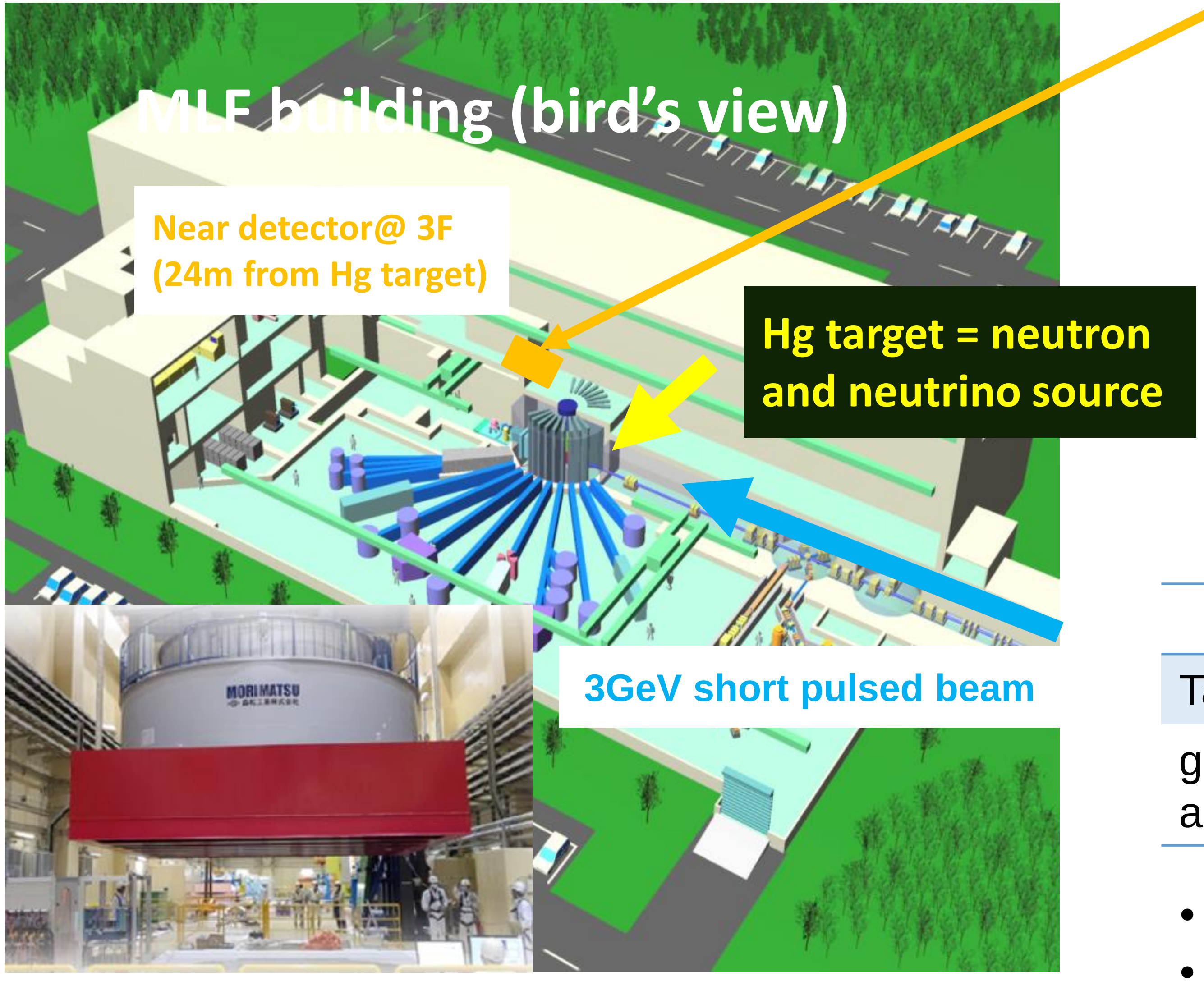
Low duty factor beam
(short-pulses + low repetition rate)
Gives an excellent signal to noise ratio

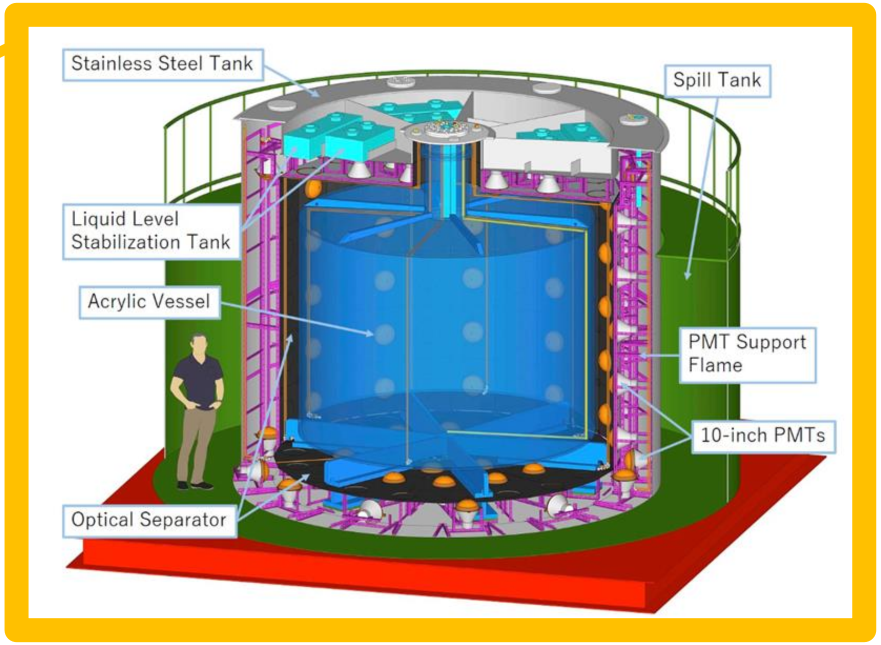
1 MW (design)

0.6MW (2021 Jan - Apr/5)
0.7MW (2021 Apr/5 - June/22)
0.7MW (2022 Jan/28 - Apr/6)
0.8MW (2022 Apr/7 - Jun/3)
0.8MW (2023 Apr/15 - Jun/2)

JSNS^2 detector

Nucl. Instrum. Methods A 1014 165742 (2021)





	Liquid	Volume
Target	GdLS + DIN (10%)	17 tons
gamma-catcher and veto	Pure LS	31 tons

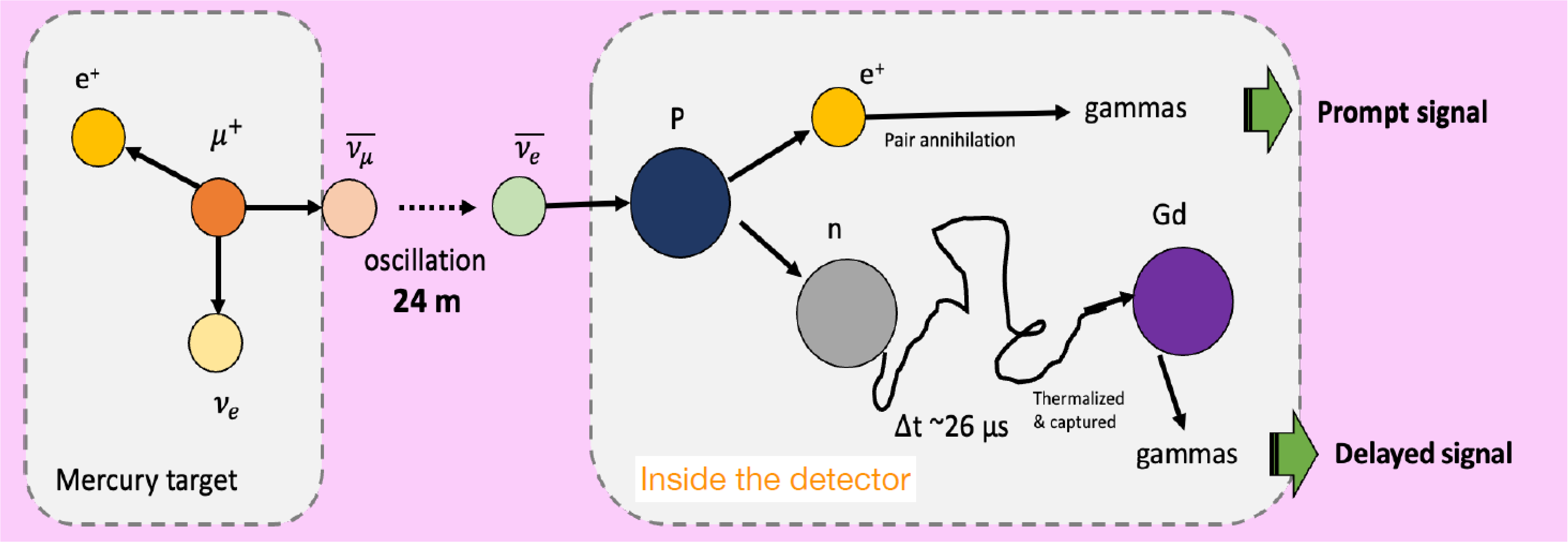
- 96, 10-inch PMTs for the inner detector
- 24, 10 inch PMTs for the veto

Production and detection

- If sterile ν exist, $\bar{\nu}_\mu$ → $\bar{\nu}_e$ oscillation occurs with 24m.

- Coincidence of Inverse Beta Decay (IBD)
  - Positron annihilation
  - Neutron capture on Gd

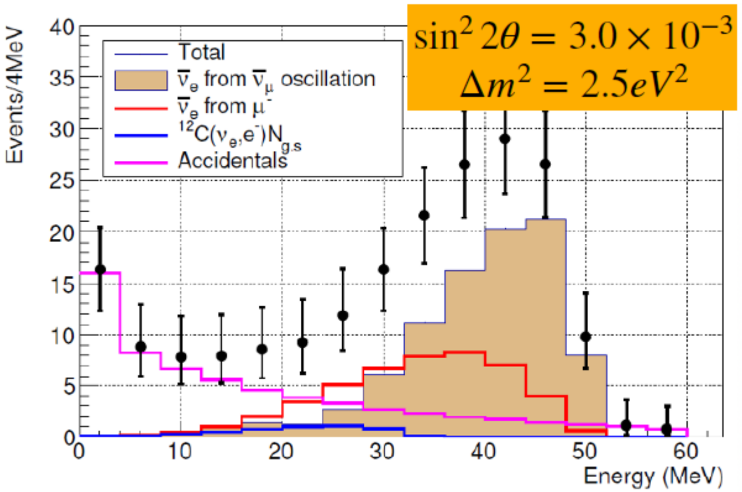
	Timing	Energy
Prompt	$1.5 < T_p < 10\ \mu s$	$20 < E < 60$ MeV
Delayed	$\Delta T_{p-d} < 100\ \mu s$	$7 < E < 12\ MeV$

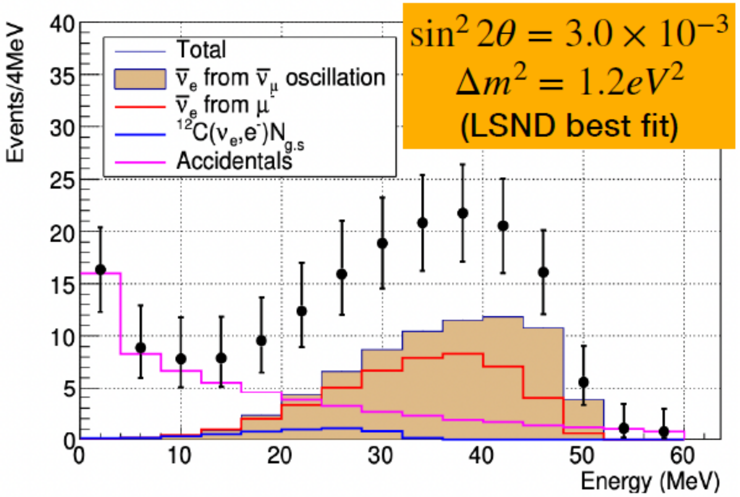


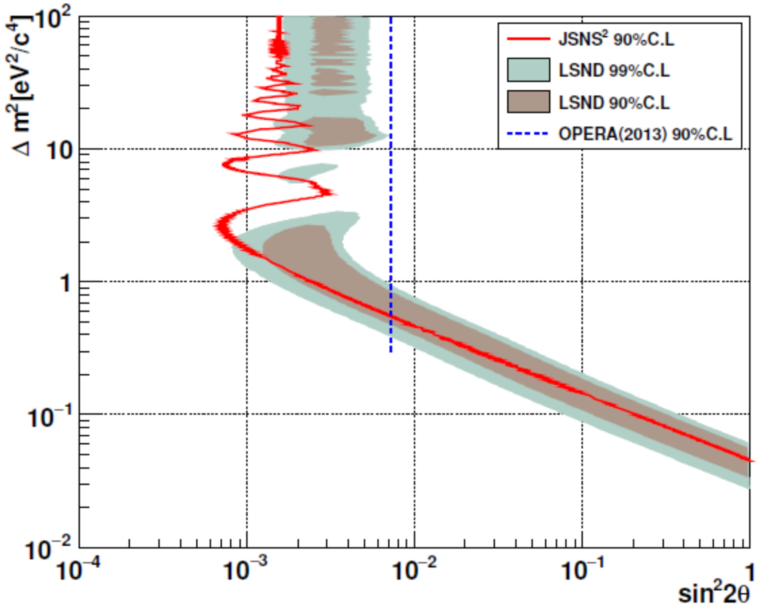
Expected energy spectrum and sensitivity

- $\bar{\nu}_e$ follows decay-at-rest $\bar{\nu}_\mu$ energy distribution
- Prompt single rate: $\sim 3.9 \times 10^{-4}$ per spill
- Delayed single rate: $\sim 4.8 \times 10^{-3}$ per spill
- Spectral fit is sensitive to the difference of energy spectrum

Signal	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 2.5 eV^2$ (Best fit values of MLF)	87
	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 1.2 eV^2$ (Best fit values of LSND)	62
background	$\bar{\nu}_e$ from μ^-	43
	$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	3
	beam-associated fast n	≤2
	Cosmic-induced fast n	negligible
	Total accidental events	20

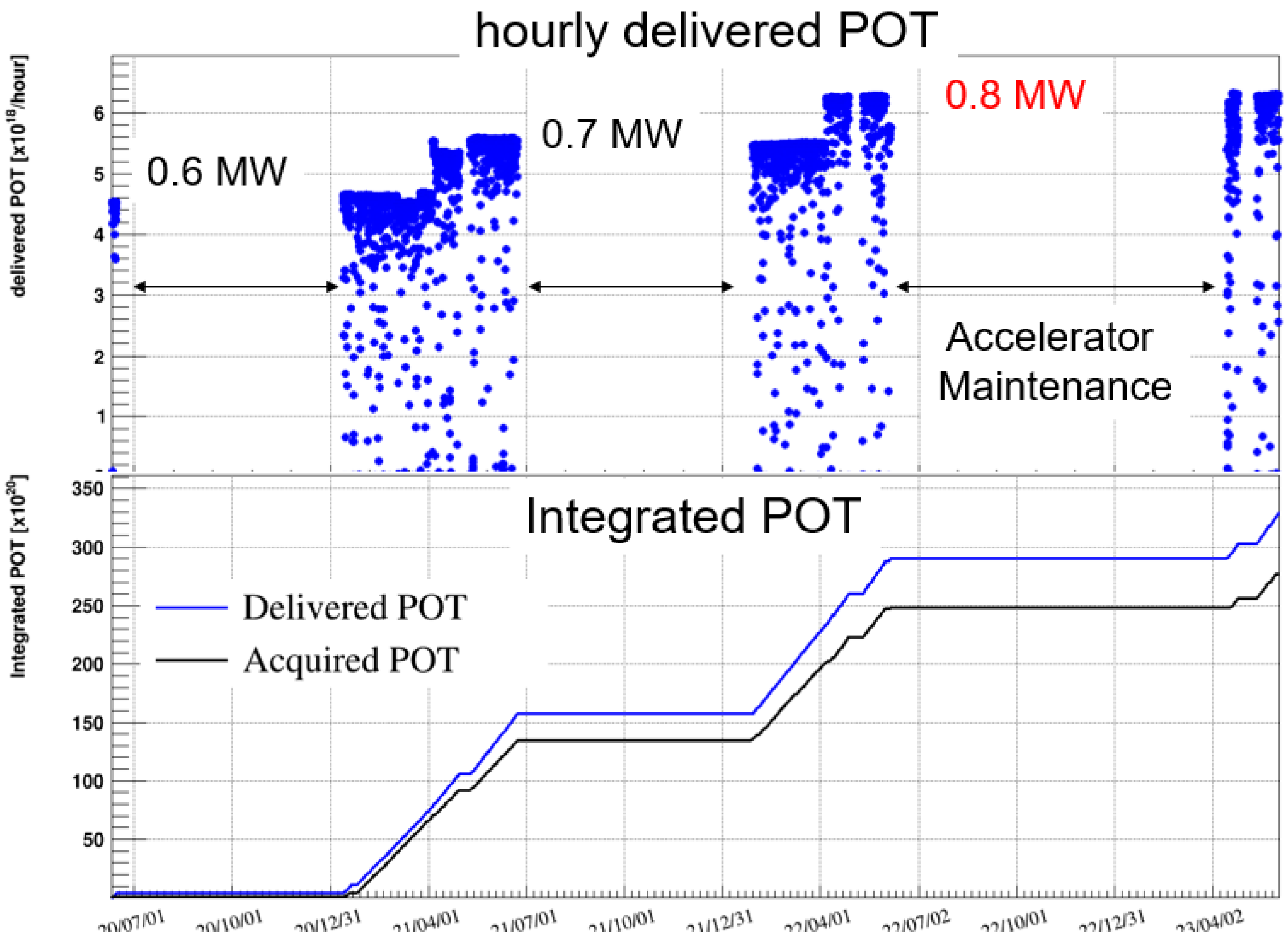






Operation

- Now beam power is very close to the design (1MW).
  - 0.95MW at RCS
- There is an accelerator maintenance period every year.
- 3.28×10^{22} POT has been delivered. (28.7% of the approved POT of JSNS[2])

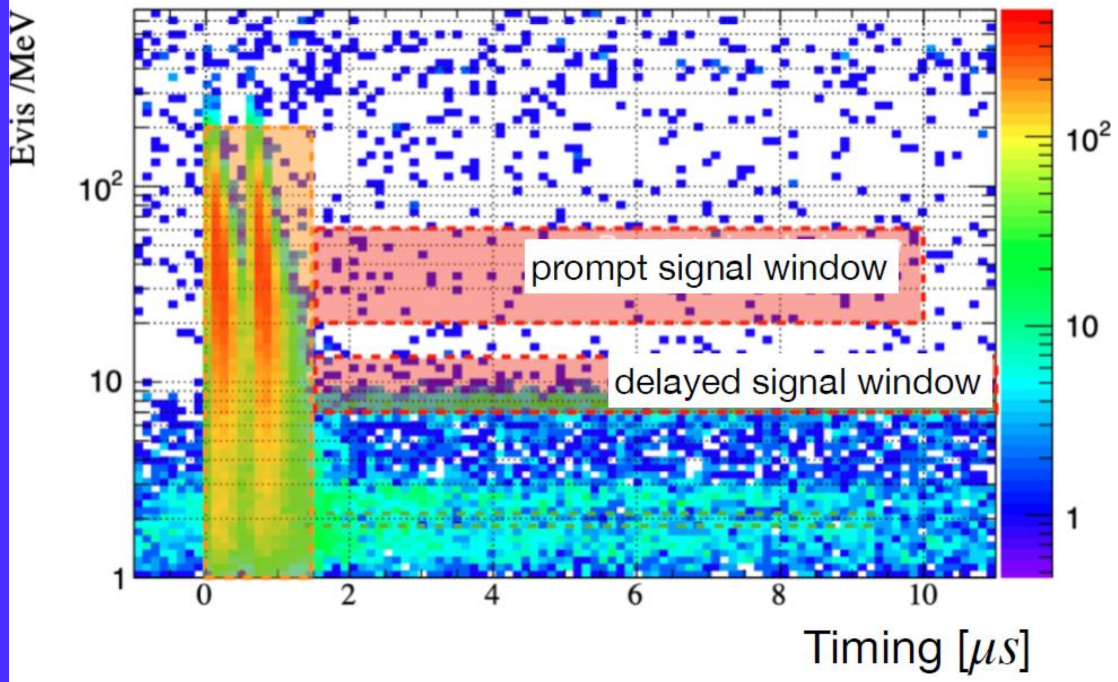


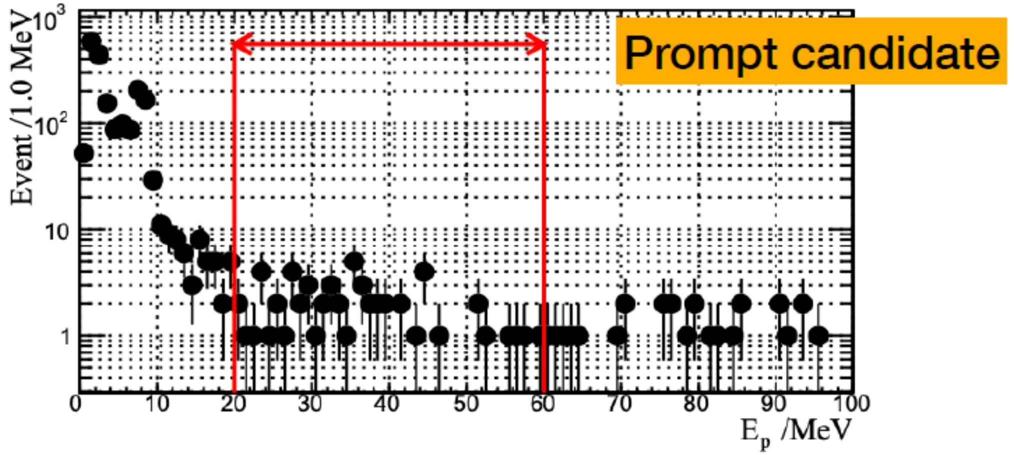
Commissioning run

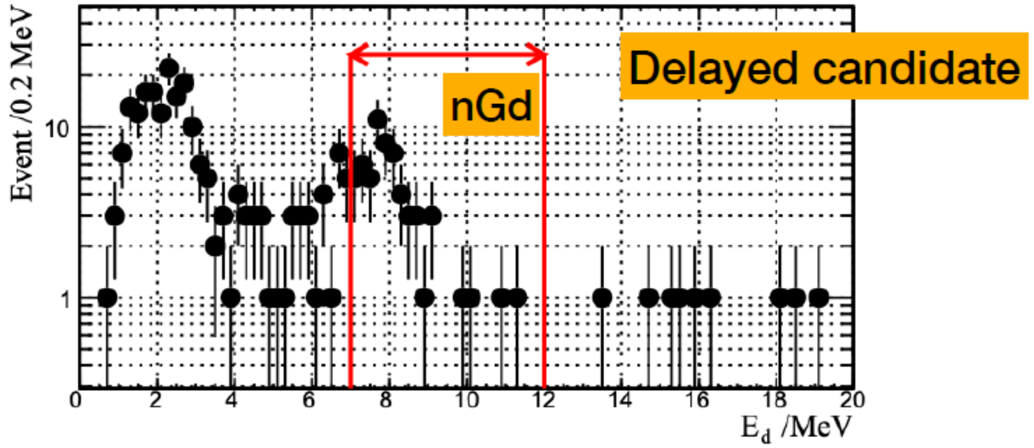
(Eur, Phys. J.C (2022) 82:331)

- Integrated POT : 8.9×10^{20}
  - expected IBD << 1 event

- Beam trigger with 25μs width







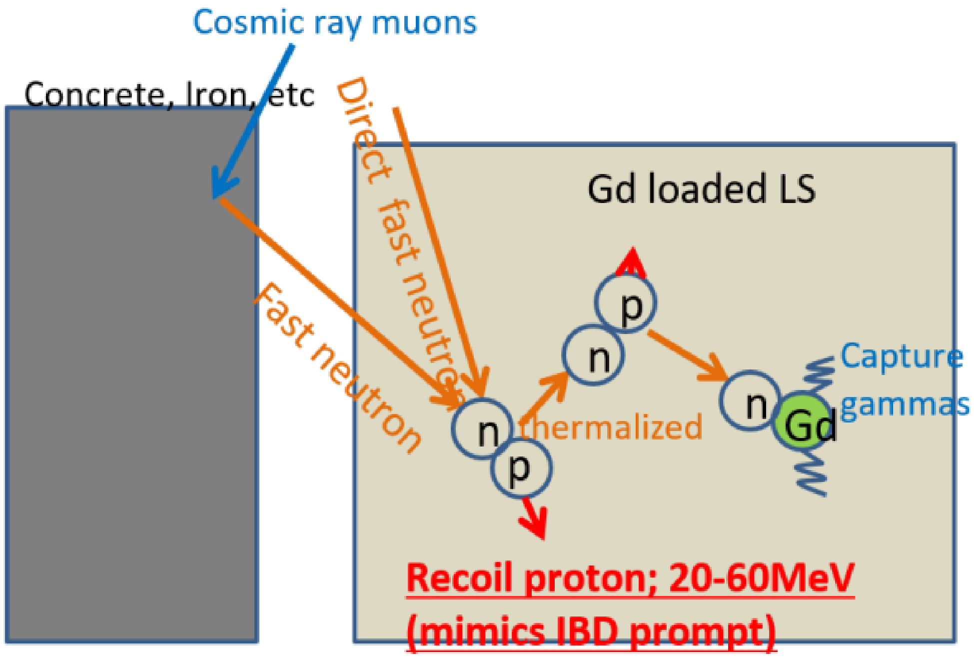
Observed correlated event candidates

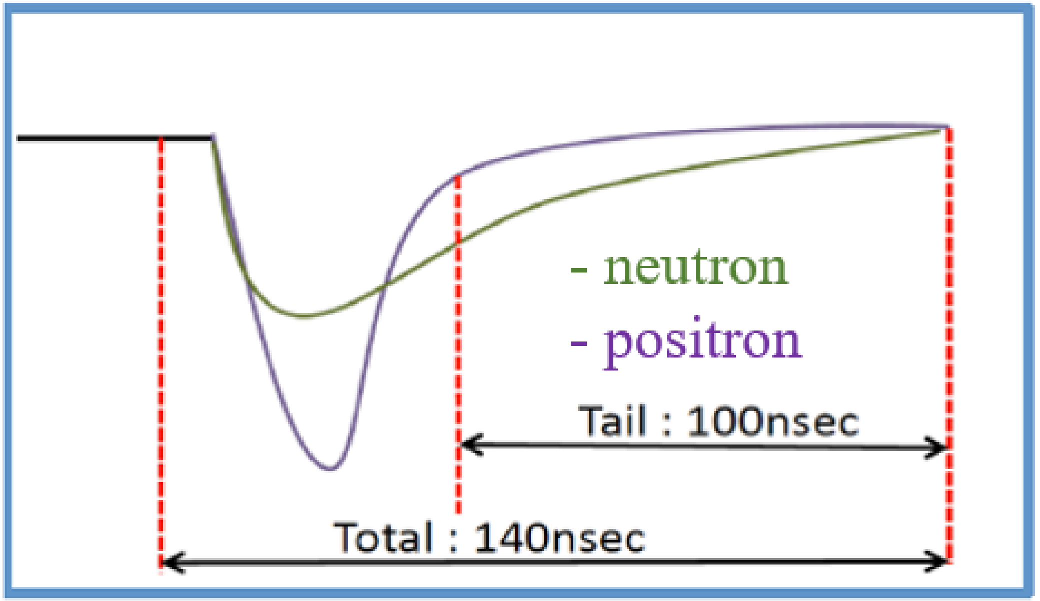
- 59±8 events / 8M spills
- Cosmic-induced fast neutrons are the dominant background
  - expected cosmic-induced fast neutron is 55.9 ±4.3 events
  - Pulse shape discrimination (PSD) would reject them.

Pulse Shape Discrimination (PSD)

- Fast neutrons can mimic IBD signals from electron anti-neutrino.
  - correlated background

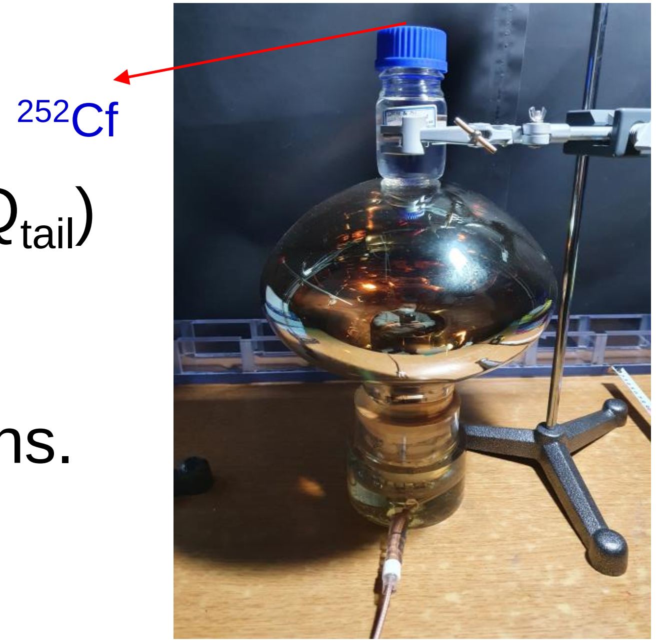
- PSD can separate the IBD signals and fast neutrons.
  - the goal is to remove 99% of fast neutrons.



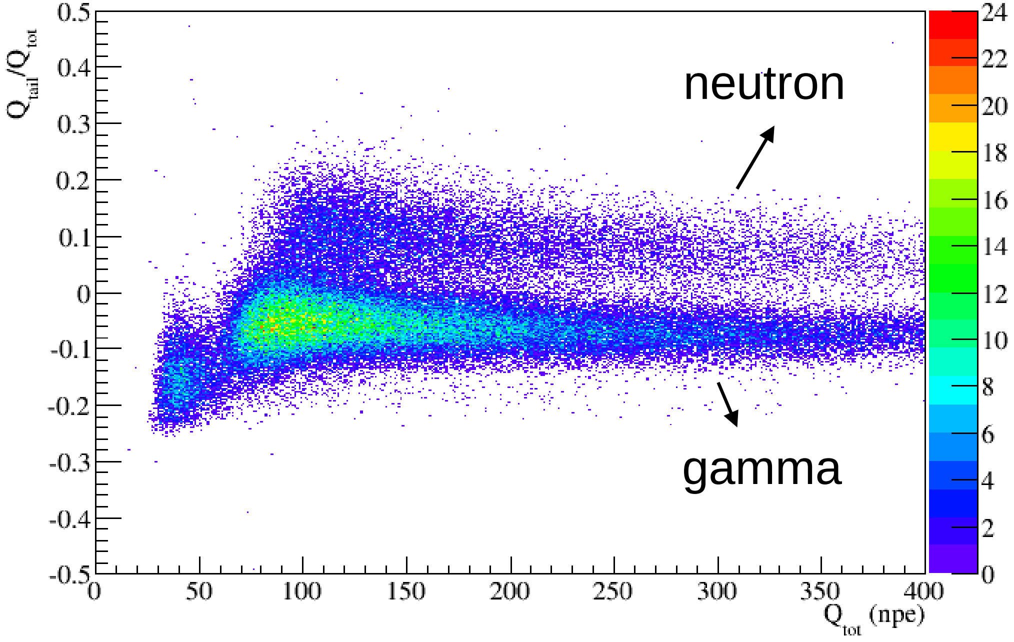


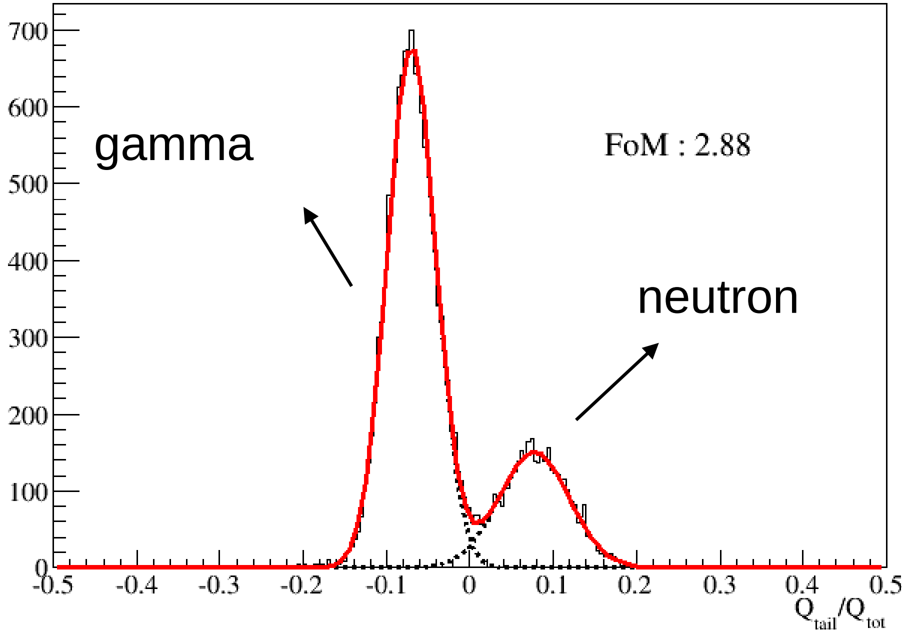
The conventional PSD method

- The conventional PSD method uses the charge of the tail (Q_{tail}) and total region (Q_{total}) in the waveform.
- Generally, neutrons have large Q_{tail}/Q_{total} compared to leptons.



^{252}Cf source with a 10inch PMT

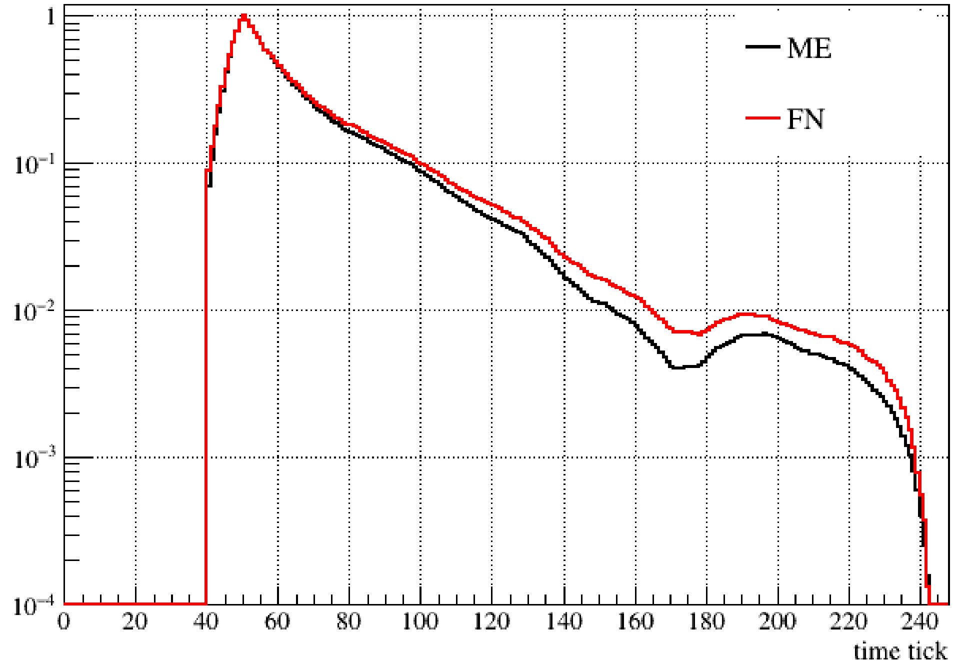




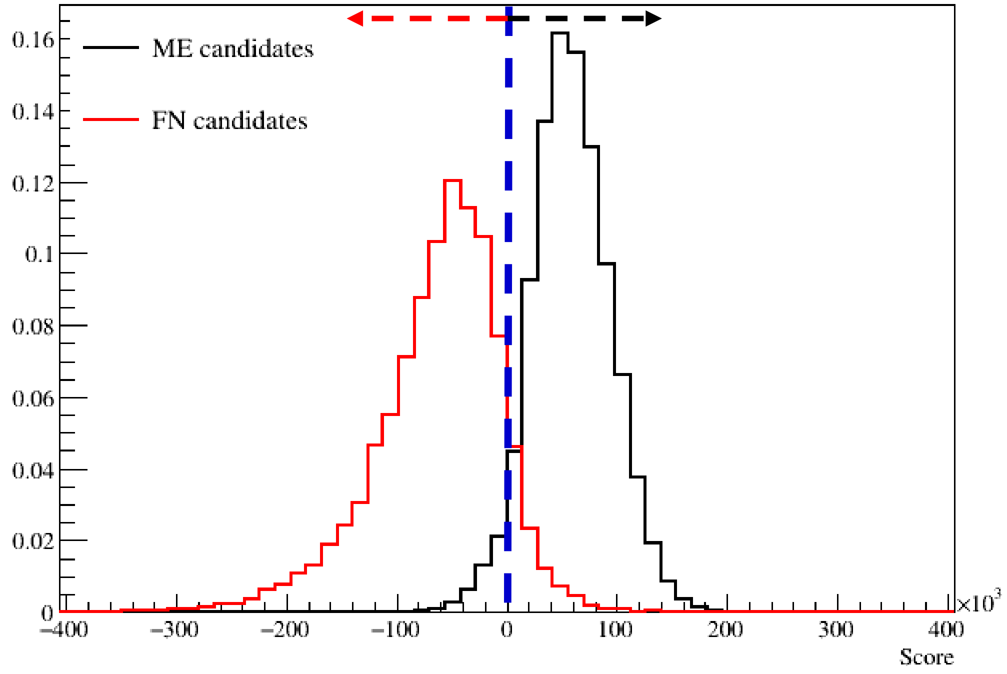
Likelihood method

- The DAQ of JSNS^2 can measure a waveform every 2ns (500MHz sampling).
- The likelihood judges that all other points look like “neutron” or “electron” after peak normalization as 1.

average waveform



neutron like electron like

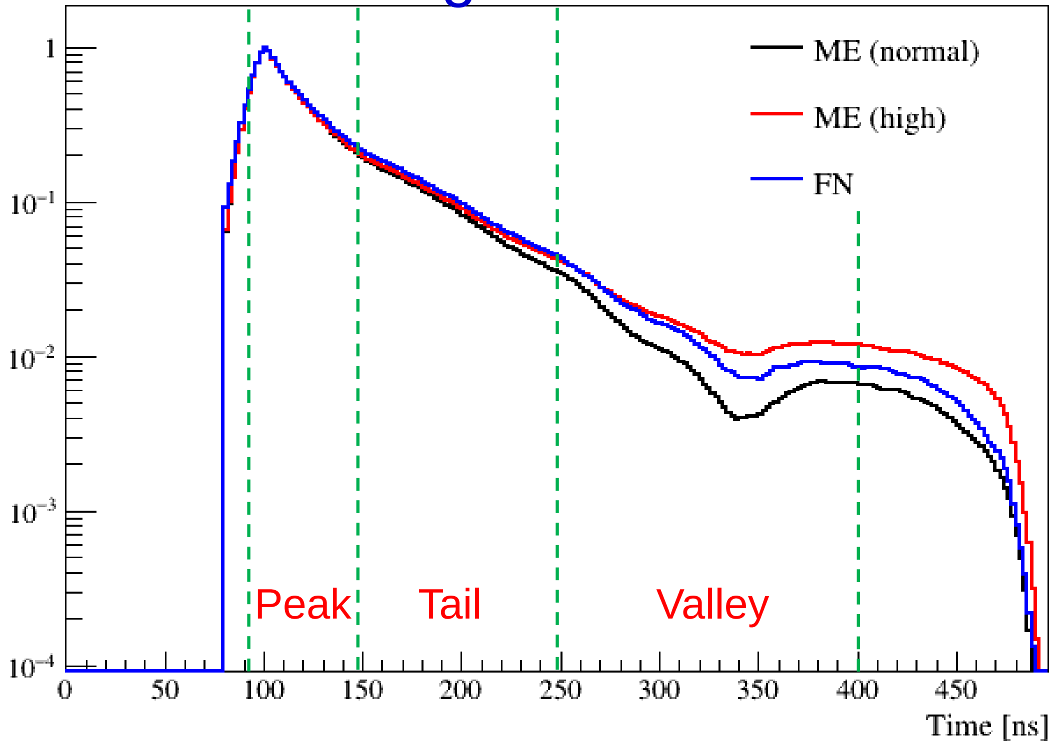


2-Dimensional likelihood method

- More improvement of PSD capability is needed to get better sensitivity for sterile neutrino search.

- There are two types of waveforms in the ME control sample.
  - 2 dimensional likelihood is developed to separate them

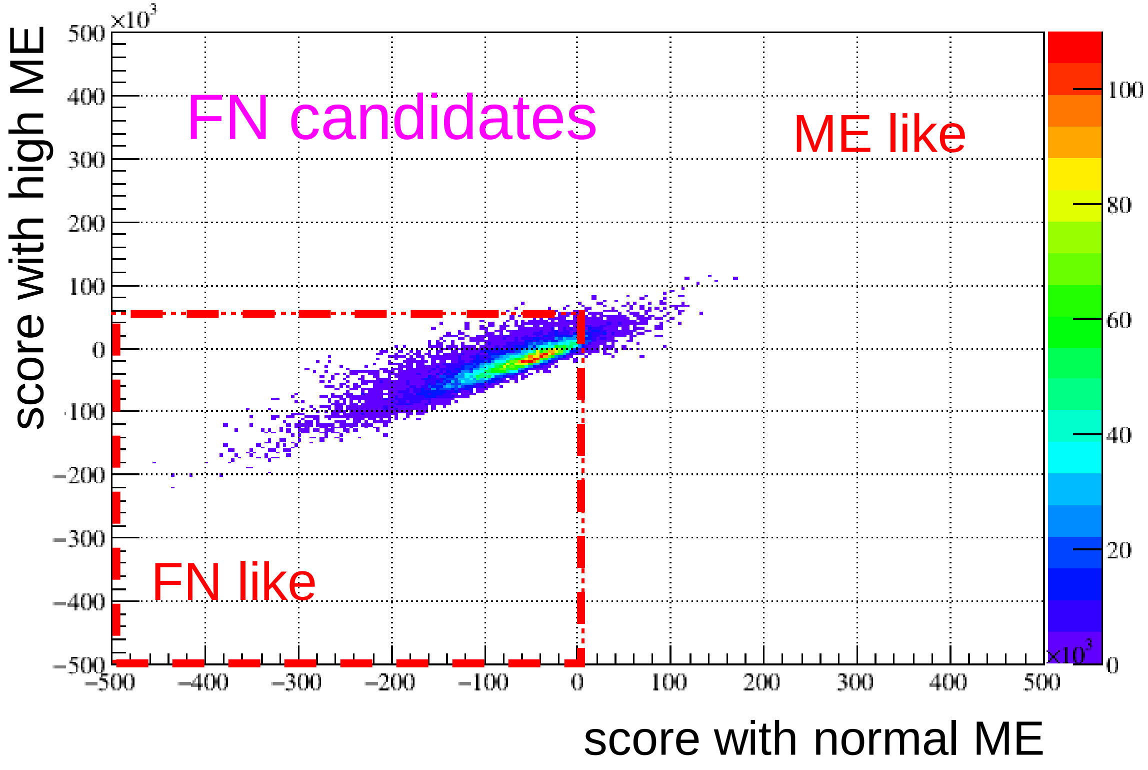
average waveform



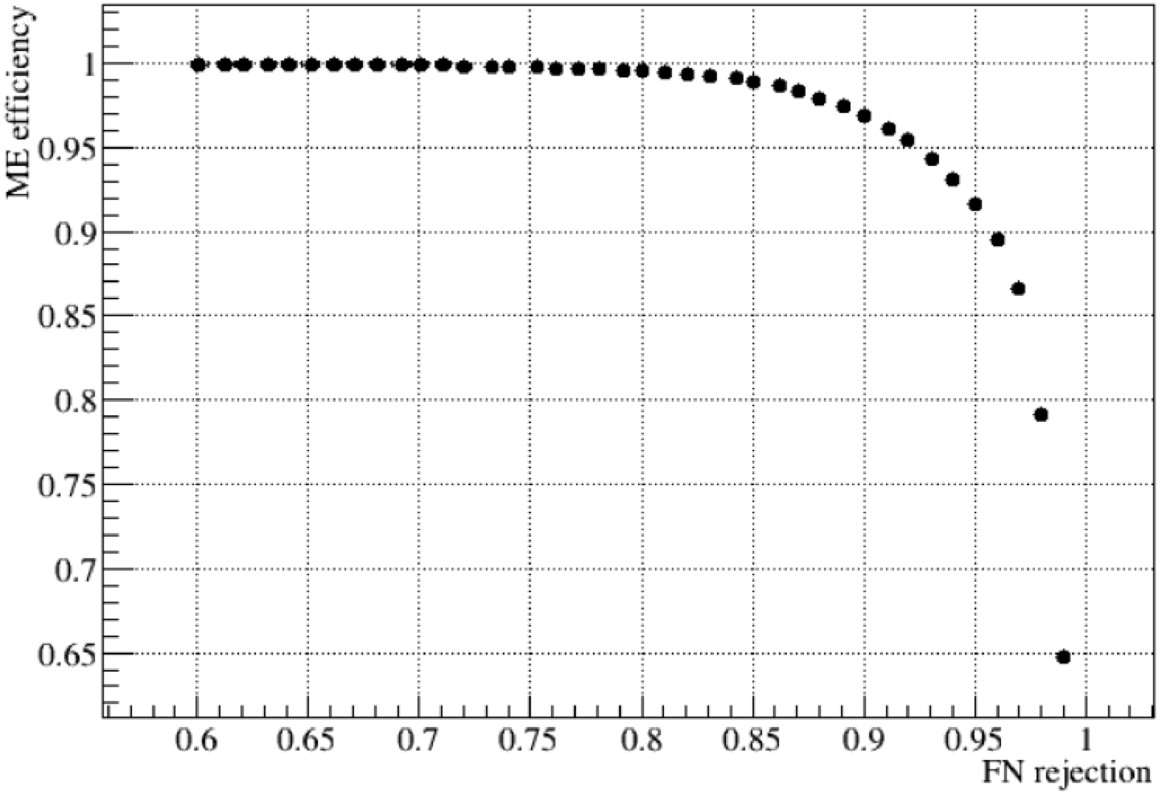
- The after-pulse from the parent muon affects the waveform of the following ME event.

PSD results with 2D likelihood method

- The ME efficiency with 95% of the FN rejection is 90.98 +/- 0.05%.
- Both ME efficiency and FN rejection depend on a reference point.



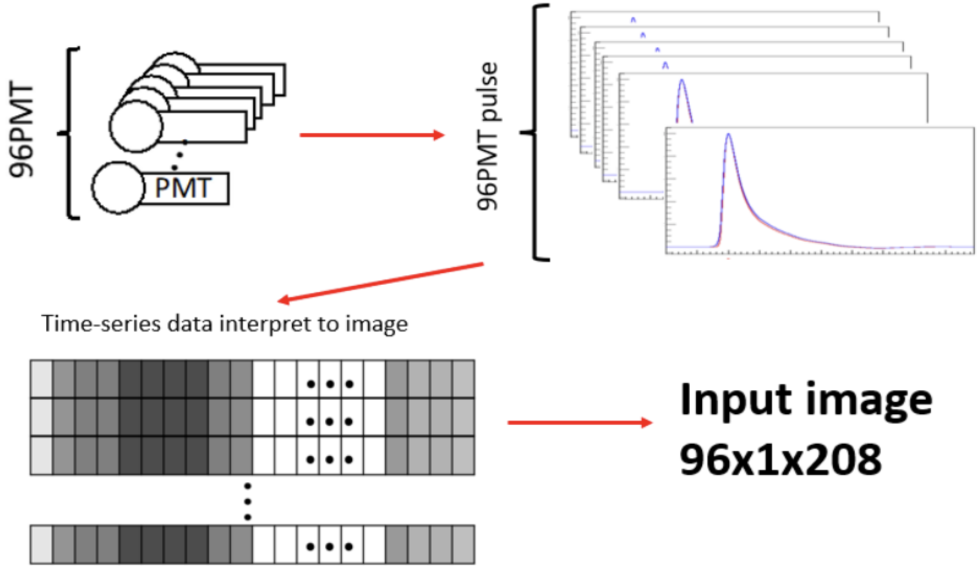
FN rejection vs ME efficiency

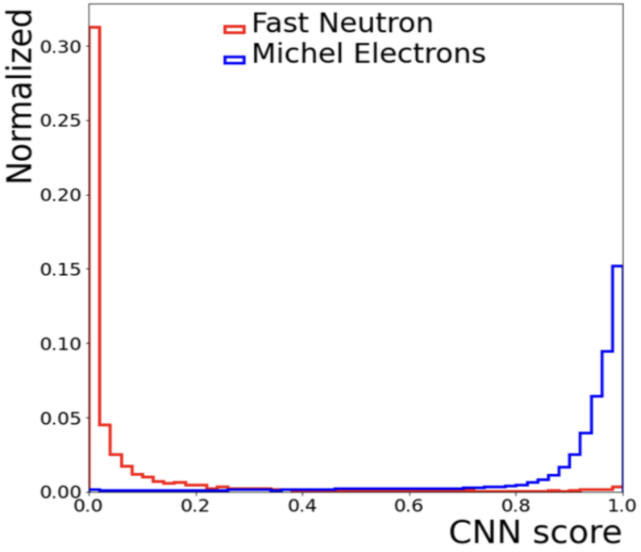


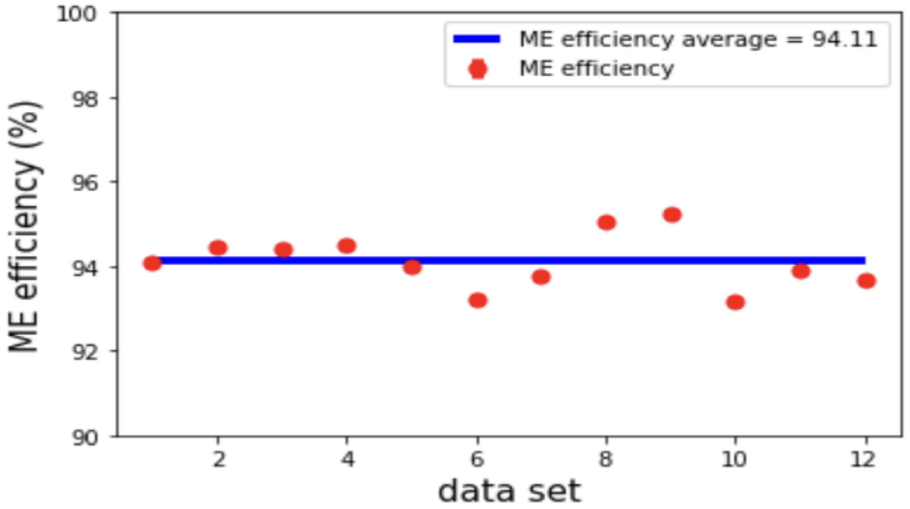
Convolutional Neural Network (CNN)

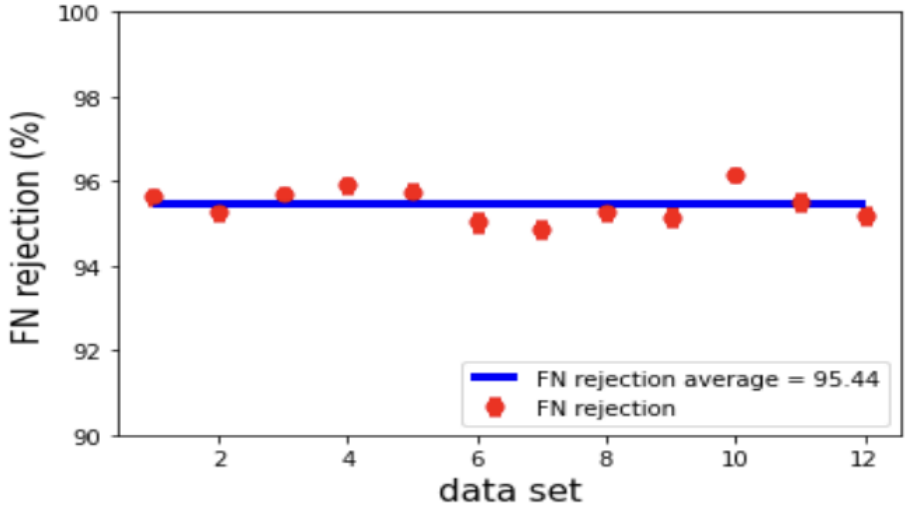
- Treated time-series data from a PMT with image data.

- Two independent efforts show consistent FN rejection results.

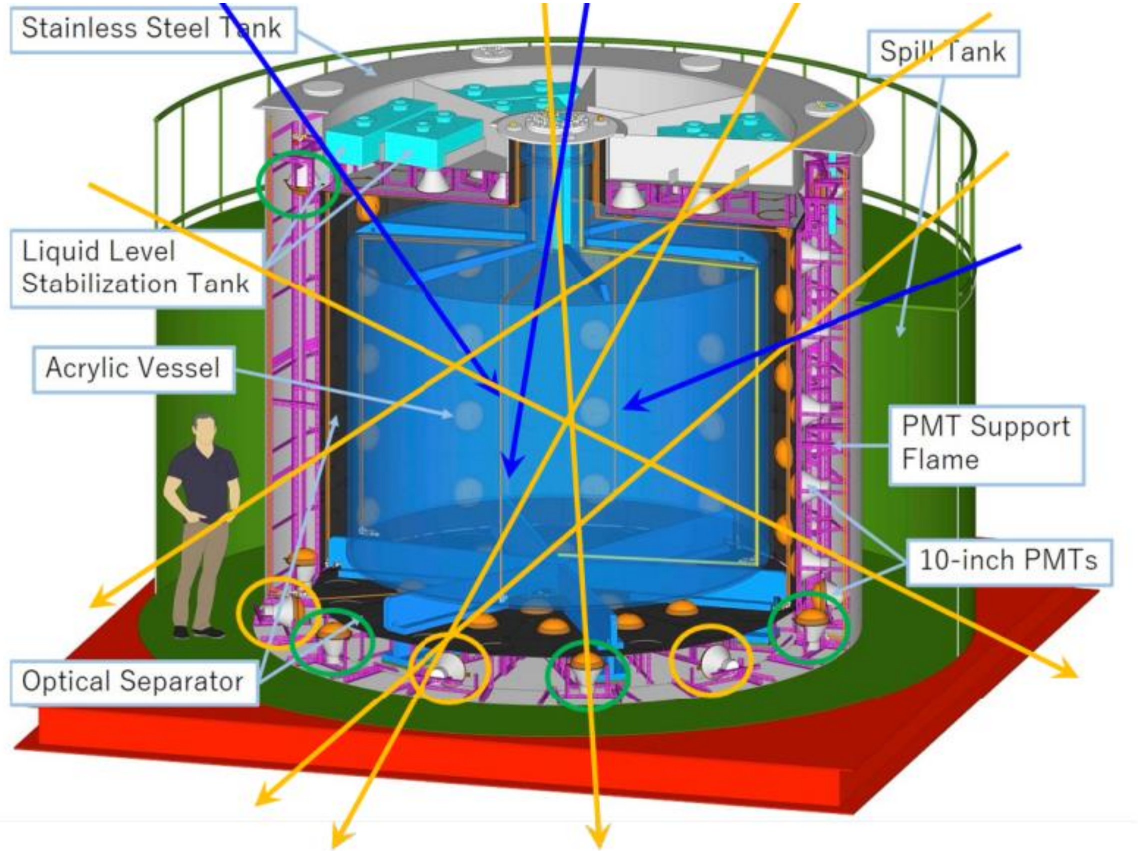








Cosmic muon identification



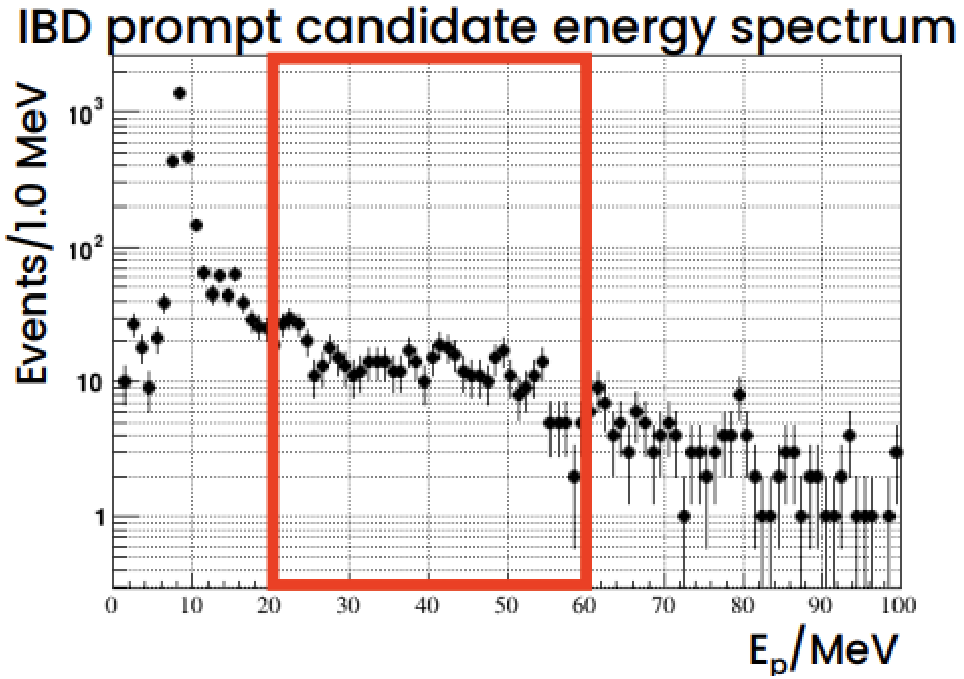
Stopping muon(blue)
Through-going muon (yellow)

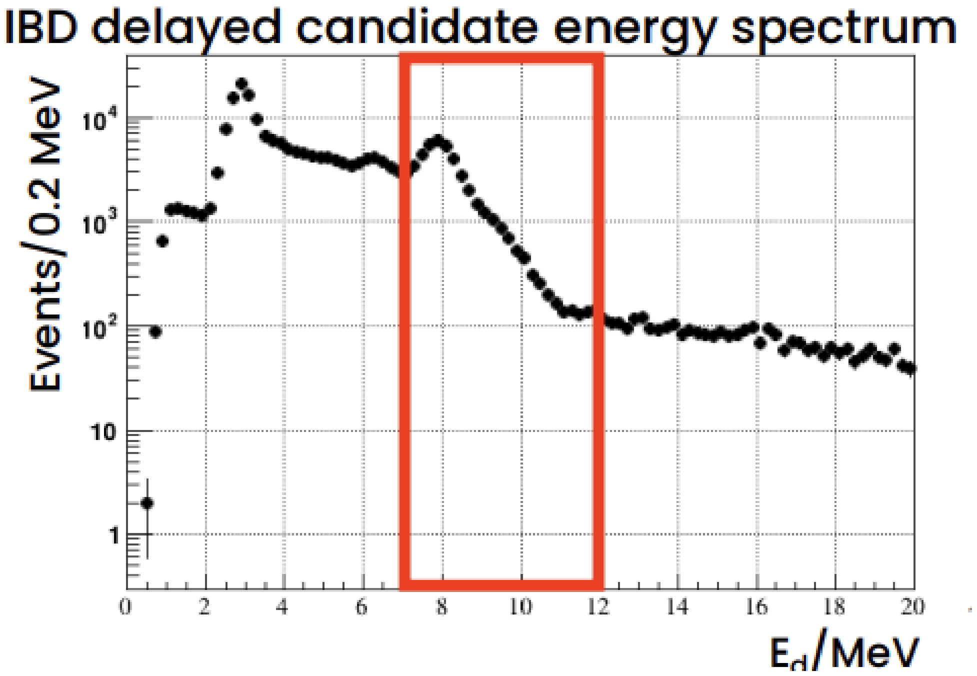
- Michel electron induced by cosmic muon and muon itself are one of backgrounds.
- Cosmic muon can be tagged by Top/Bottom Veto PMTs.
  - 12 PMTs on Top
  - 12 PMTs on Bottom
- Stopping muon candidates rate : 1487.8±0.5 Hz
- Through-going muon candidates rate : 605.4±0.4 Hz
- Michel candidates rate : 110.1±0.2 Hz (10~60 MeV)

Single rates of the prompt and delayed

- 125 μs time window from beam timing.
- External particles and the ME are rejected.

	Prompt	Delayed
Single rate	$(2.20 \pm 0.09) \times 10^{-4}$/spill	$(1.80 \pm 0.01) \times 10^{-2}$/spill



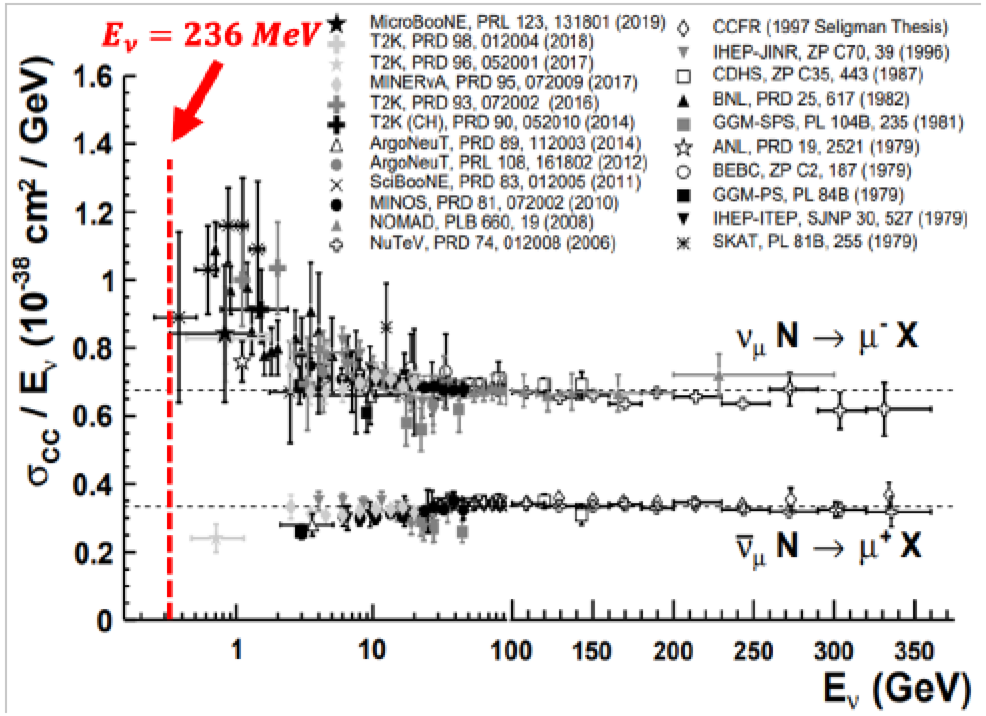


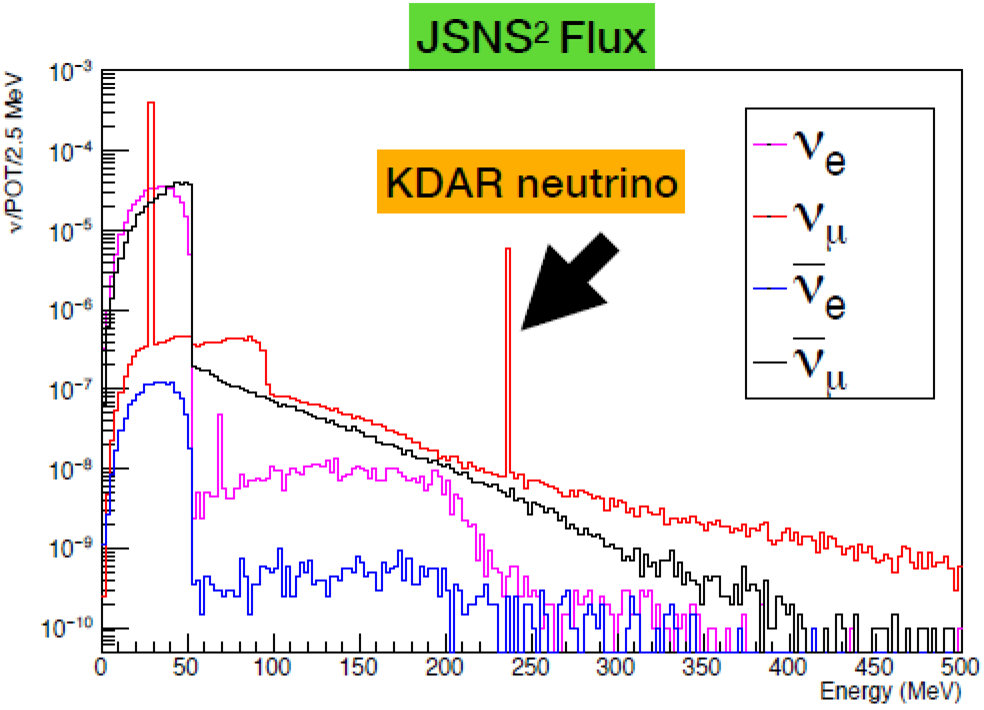
KDAR neutrino measurement

Kaon Decay-At-Rest neutrino measurement

(KDAR neutrino: 236 MeV mono-energetic)

- Neutrino interaction models are a crucial part of neutrino physics, but poorly known at low energies.
- **The JSNS² detector has the unique ability to measure the mono-energetic KDAR neutrino.**
- Note that it is hard to see a clear energy peak of KDAR neutrinos in the data of the horn focused beam.





KDAR signal measurement in JSNS²

A double coincidence between

- The initial neutrino interaction products and the subsequent muon decay.

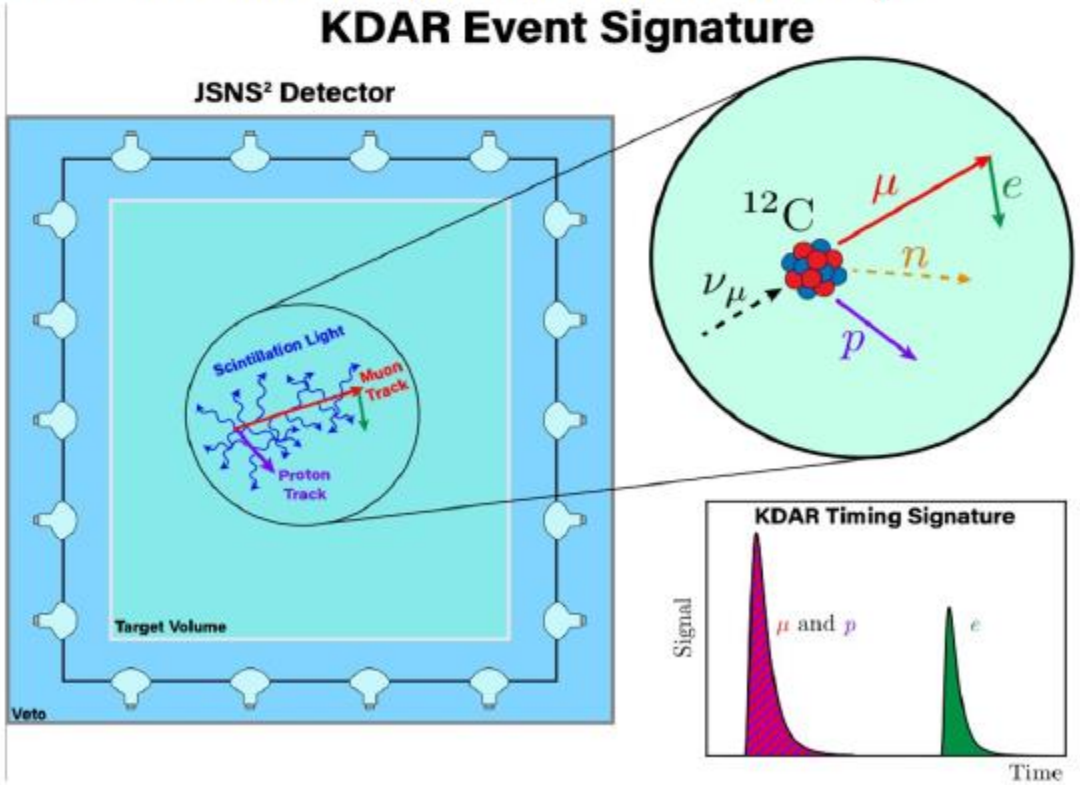
Hg target

KDAR $K^+ \rightarrow \mu^+ + \nu_\mu$

Detector

Prompt $\nu_\mu + {}^{12}C \rightarrow X + \mu^-$

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



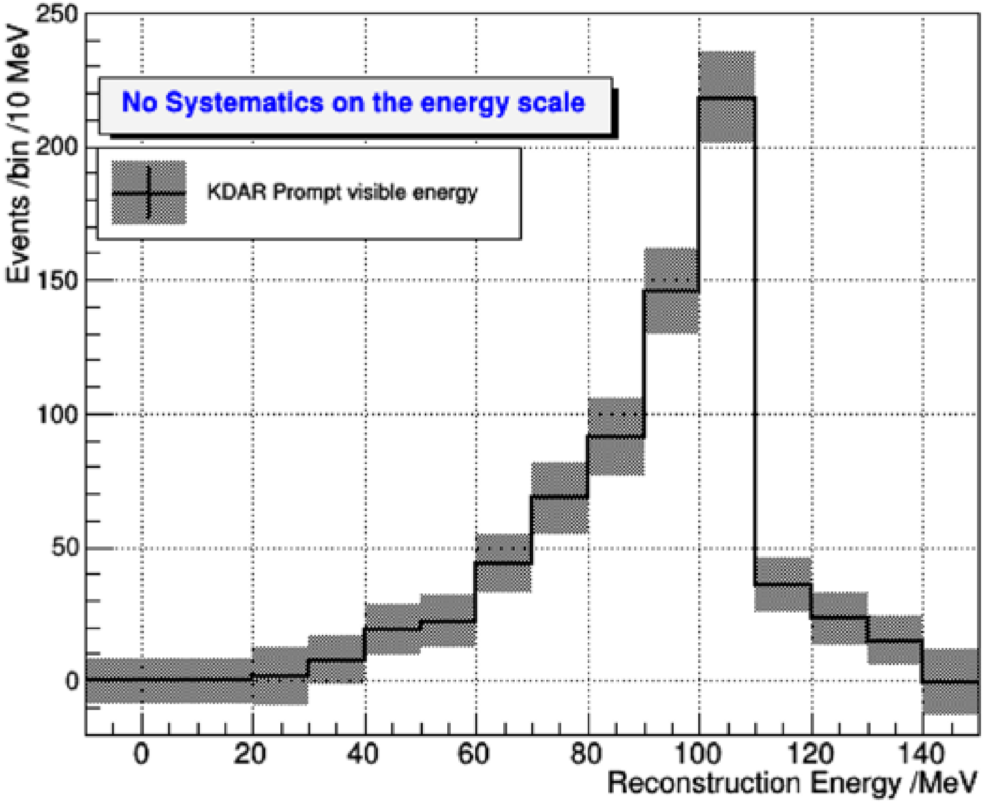
First clear KDAR signal

(Toward first precise KDAR measurement)

- **KDAR peak is clearly seen**
- **High purity (95%)** KDAR signal
  - Background: 5.2 %

- Note that **the systematics on the energy scale are not included yet**.

BKG ID	Correlated/ Accidental	BKG (# of events)	
1	Correlated	36.6 +- 34.8	5.0 +- 5.1%
2	Accidental	1.5 +- 0.1	0.2 +- 0.01%
KDAR Candidates : 730 events		38.1 +- 38.4	5.2 +- 5.3%



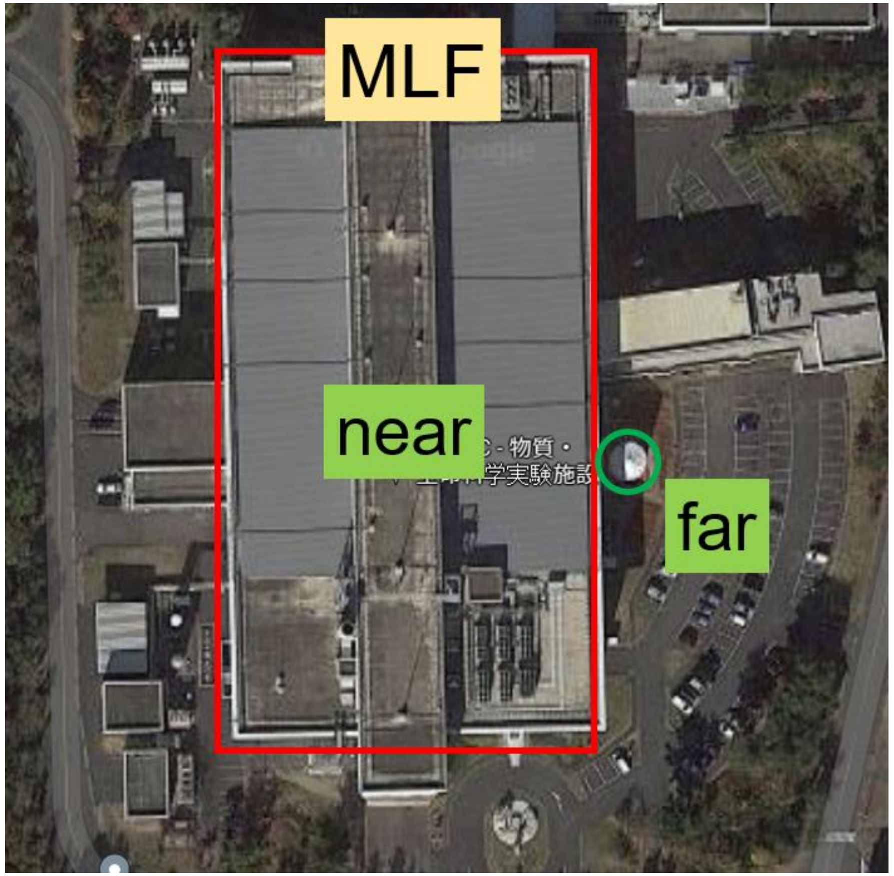
JSNS^2-II

JSNS^2-II (Second phase of JSNS^2)

- New far detector
  - fiducial 32 tonnes and 48 m location

- Two detectors with two different baseline
  - a solid conclusion on LSND anomaly

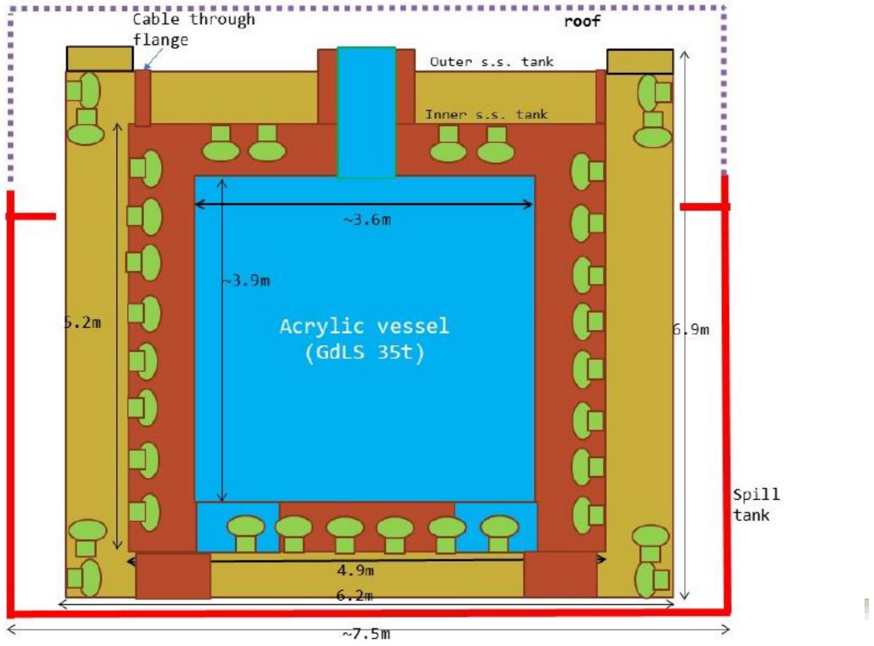
- The construction is being progressed rapidly.

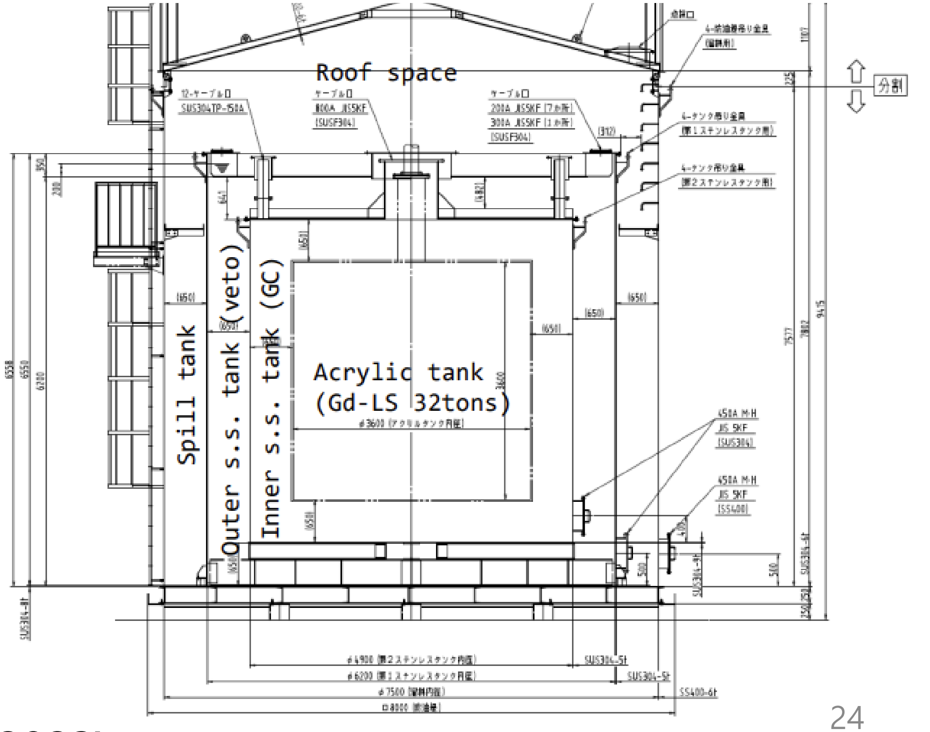


New far detector

- Almost identical to the existing near detector
  - 37m^3 Gd-LS for the neutrino target
  - 150m^3 no Gd-loaded LS for the veto and gamma catcher.
  - 228 PMTs will be used

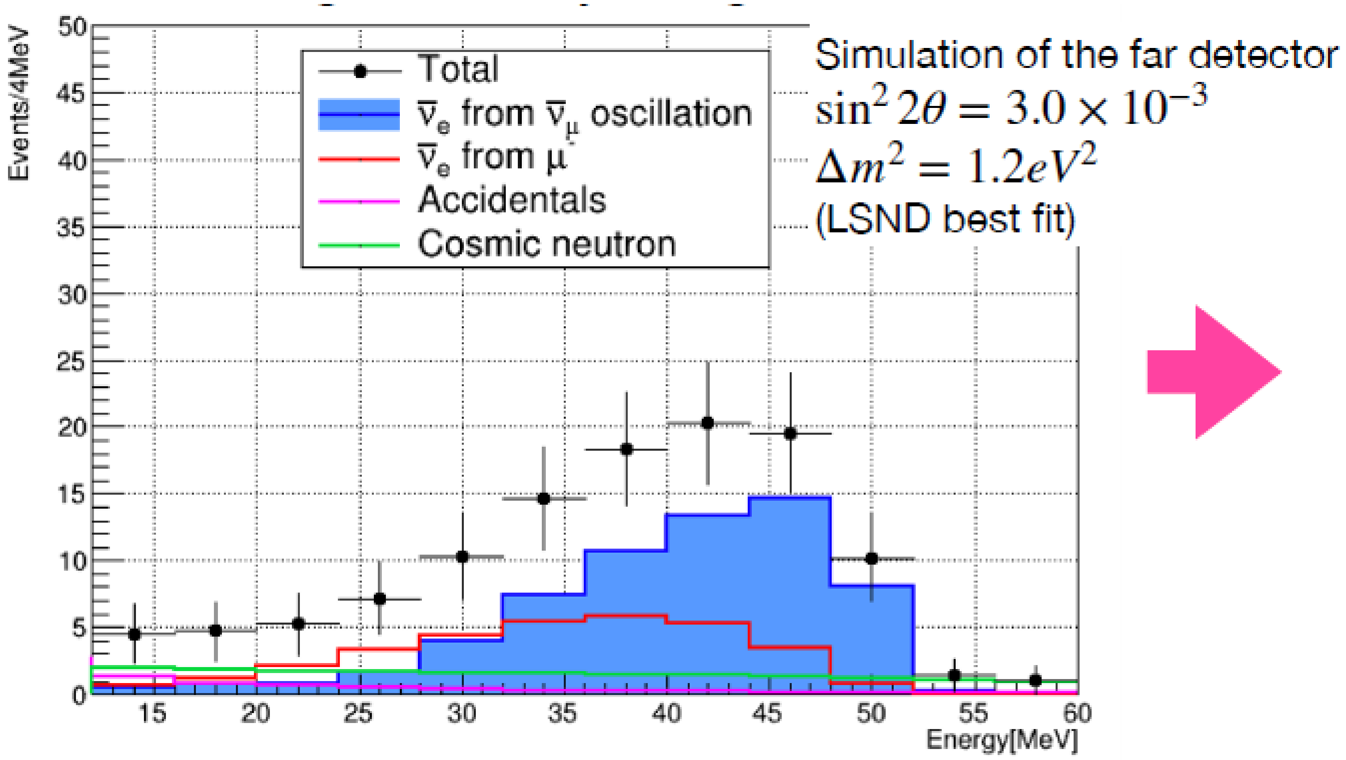
- The detector is placed outside of building
  ➔ Electronics in the “roof space”

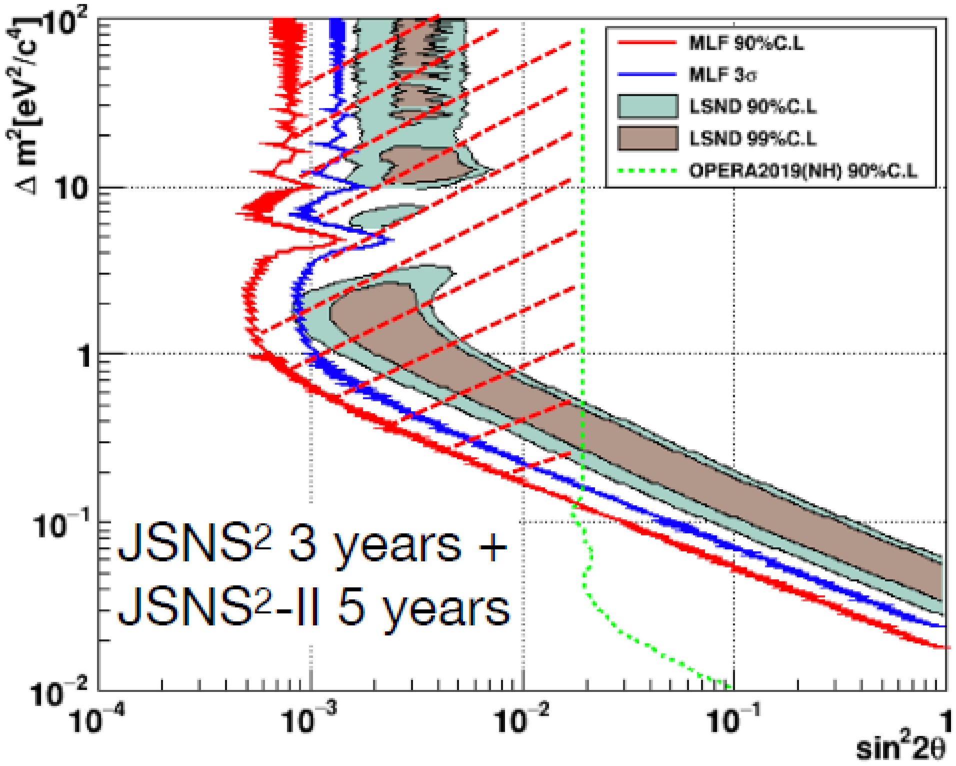




Sensitivity of JSNS^2-II

- Each background simulation was done based on the JSNS^2 data.
- The sensitivity becomes better in the low Δm^2 region.





Construction of Stainless Steel Tanks

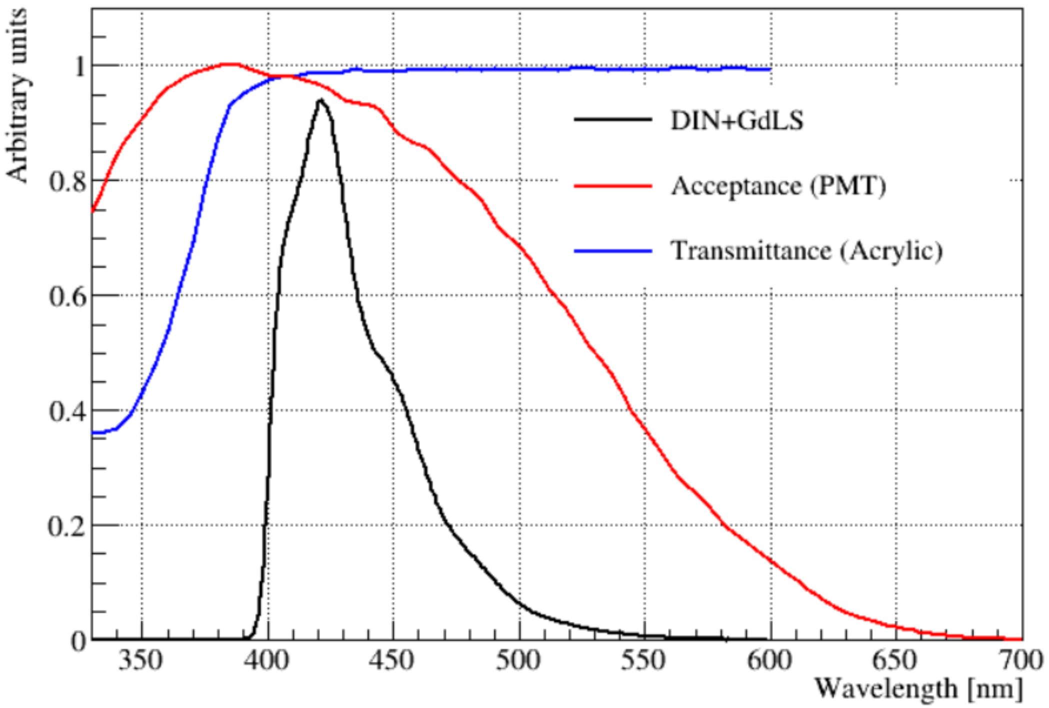
- The stainless steel tanks has been constructed.
- The S.S tank was placed at east side of the MLF building.

Acrylic Tank

- Acrylic tank for the detector target was made by Taiwan company.

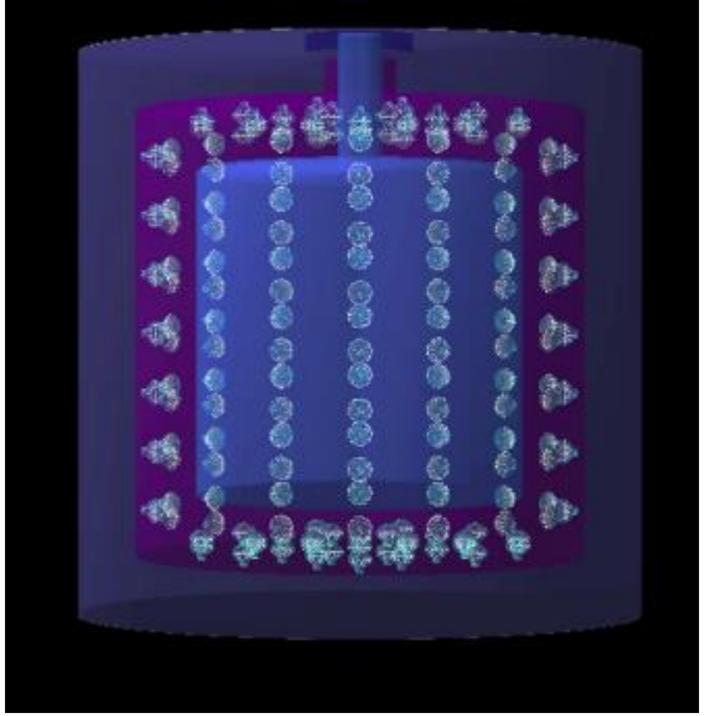
- The transmittance of the acrylic well covers the wavelength region of scintillation light.
  ➔ ~93% @ 400~600nm

- The acrylic tank will be installed to the inner S.S tank.



PMT preparation

- 190 PMTs were donated from Double-Chooz
- Dead PMT check was done.
- Our jigs for the far detector were assembled.



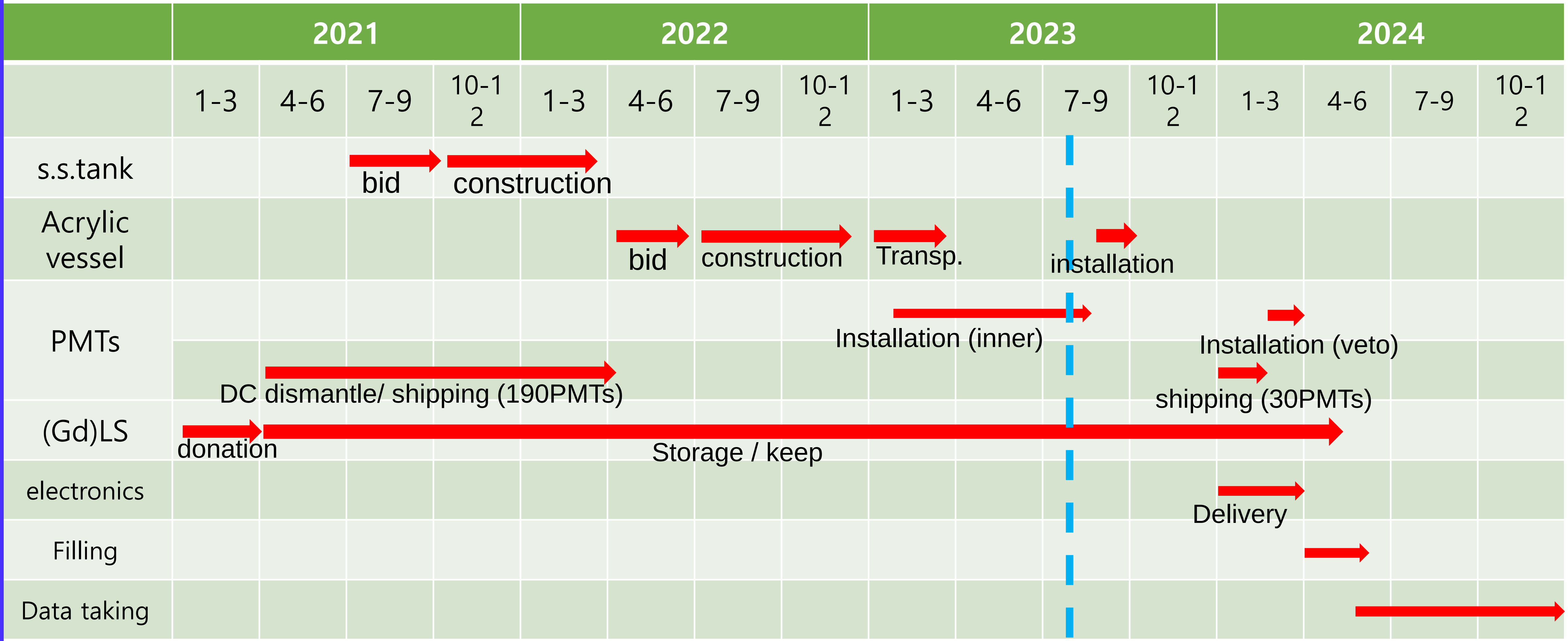
PMT installation

- 142 PMTs were installed.
  - barrel and top lid of the inner detector

- Bottom PMTs will be installed soon

- Calibration system was installed
  - LED
  - temperature sensors

Construction schedule of JSNS^2-II



Summary

- There have been 1st (2021), 2nd (2022) and 3rd (2023) long physics runs in JSNS^2.

- Analyses are ongoing with the data.
  - Has been developing PSD tools
  - Single rates in both prompt and delayed time window were measured
  - Background study is ongoing

- JSNS^2 is working toward the first precise KDAR measurement.
  - clearly see the high purity KDAR signal

- The JSNS^2-II detector is under construction.
  - first data taking on next year

Thank you for your attention

acknowledgements:
- MEXT, JSPS (Japan)
- Korea Ministry of Science, NRF (Korea)
- DOE, Heising-Simons Foundataion (US)
- Royal Society (UK)

MEXT

NRF

HEISING-SIMONS FOUNDATION

THE ROYAL SOCIETY