Sterile Neutrino Search at J-PARC MLF

Takasumi Maruyama (KEK) for JSNS^2 collaboration

Sterile neutrinos

- Sterile neutrinos could give an insight for the questions beyond the standard model; (E.g.; PLB 631, 151 (2005))
  - No strong, electro-magnetic, weak interactions.
  - Introduced to explain both results of LSND (later we show) and LEP (:there are only 3 weak interactive neutrinos below 45GeV) experiments
  - Observed by mainly neutrino oscillations (?)
    - Beyond PMNS matrix oscillation
  - Could be ν_R (Majorana) or new particle
  - LSND, MiniBooNE, reactors, Ga experiments indicate the existence.

- sterile neutrino could be a dark matter candidate ?

Indication of the 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	$\nu_\mu \rightarrow \nu_e$	4.5σ	800,600
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ	
		combined	4.7σ	
Ga (calibration)	e capture	$\nu_e \rightarrow \nu_x$	2.7σ	<3,10
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ	3,10-100

- Excess or deficit does really exist?
- The new oscillation between active and inactive (sterile) neutrinos?
- (Note: no indications in $\nu_\mu \rightarrow \nu_\mu$, recent reactor experiments using energy spectrum have negative results)

Please also see M.Dentler et al JHEP 08, 010 (2018) for recent reviews

Neutrino oscillations with $\Delta m^2 \sim 1eV^2$ region

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \bullet \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \bullet \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \bullet \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \bullet \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \bullet \end{bmatrix}$$

Matrix elements, which are considered in 3x3 mixing framework.

$$\sum_{j=1,3} U^*_{ej} U_{\mu j} = -U^*_{e4} U_{\mu 4}$$

Small mixiture with active ν's $U_{e4}, U_{\mu 4} \sim 0.1$ $U_{s4} \sim 1$ $m_4 \sim 1\,eV >> m_{1,2,3}$

$$P_{e\mu} = -4 \sum_{i=1,3} (U^*_{e4} U_{\mu 4} U_{ei} U^*_{\mu i}) \sin^2 \frac{(m_4^2 - m_i^2)L}{4E_\nu} \sim 4 |U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \frac{\Delta m_4^2}{4} \frac{L}{E}$$

$$P_{es} = -4 \sum_{i=1,3} (U^*_{e4} U_{s4} U_{ei} U^*_{si}) \sin^2 \frac{(m_4^2 - m_i^2)L}{4E_\nu} \sim 4 |U_{e4}|^2 |U_{s4}|^2 \sin^2 \frac{\Delta m_4^2}{4} \frac{L}{E}$$

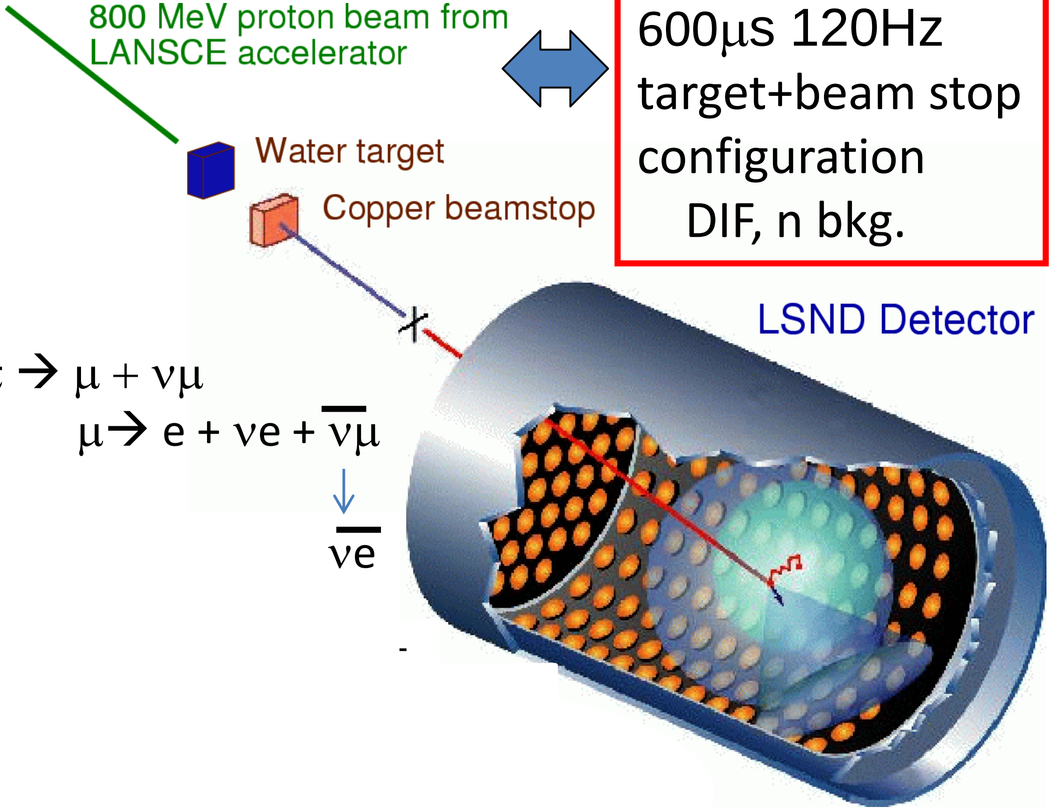
$$P(\nu_\mu \to \nu_e) = \sin^2 2\Theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

(3+1) model case

Appearance (LSND)

LSND $\bar{\nu}_m \to \bar{\nu}_e$ Signal

1998 at LANL



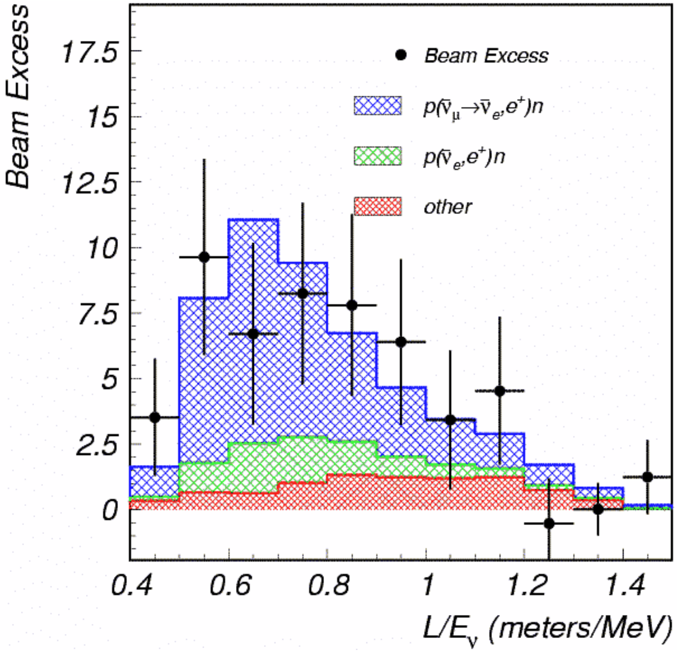
600μs 120Hz
target+beam stop
configuration
DIF, n bkg.

$\pi \to \mu + \nu\mu$

$\mu \to e + \nu e + \overline{\nu\mu}$

$\downarrow$

$\overline{\nu e}$



Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

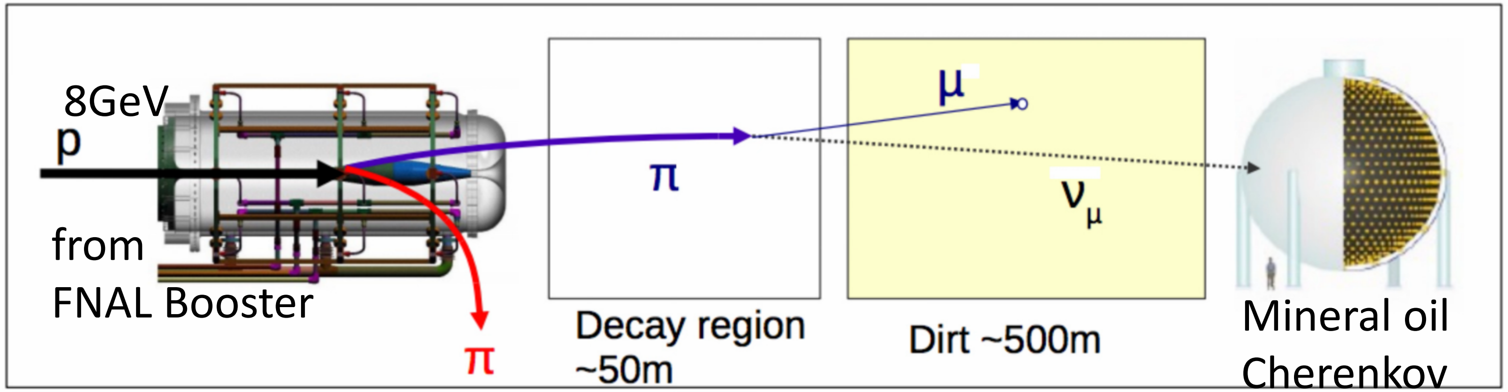
With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 s evidence for oscillation.

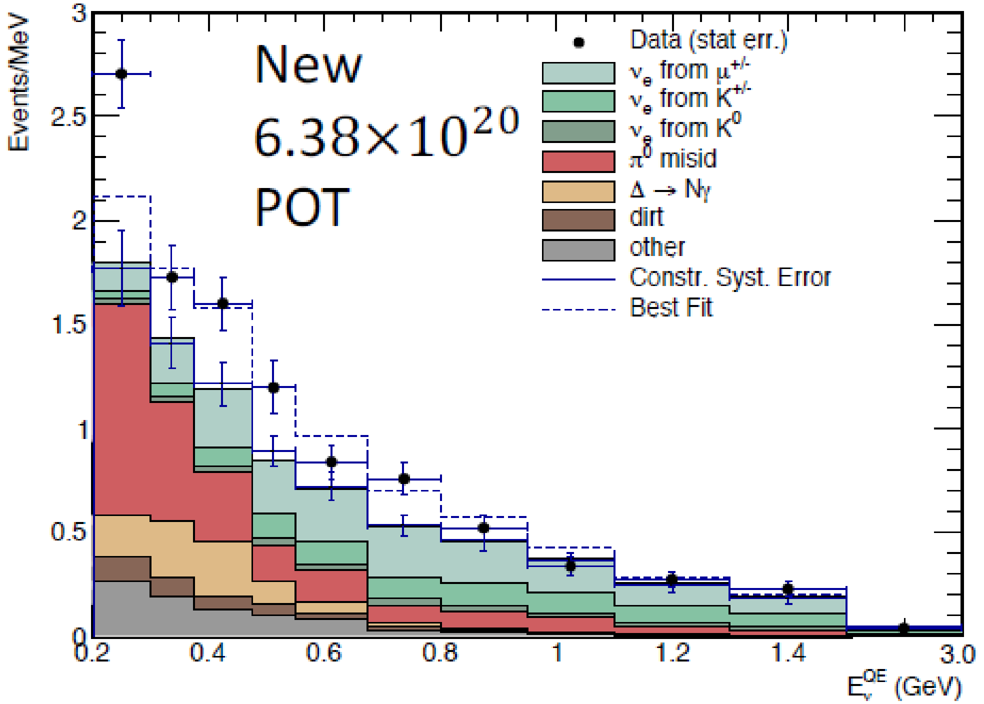
π^-, μ^- absorbed before decay into ν's
there should not be $\overline{\nu e}$ at the level of 7×10^{-4}

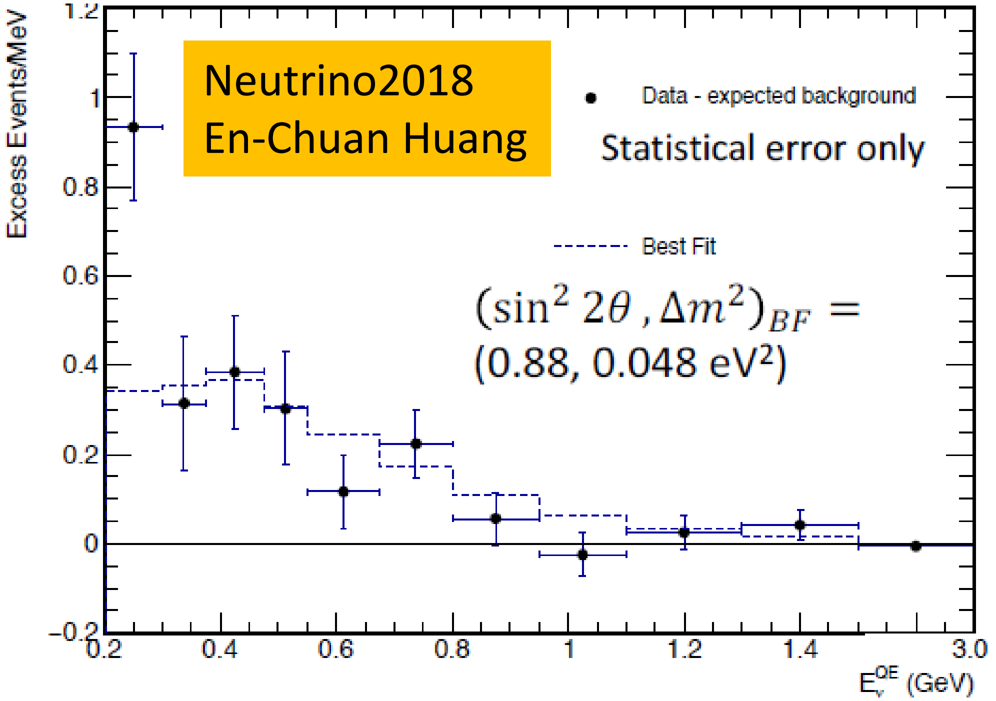
Signal : $\overline{\nu e}\ p \to e^+ n \quad np \to d\ \gamma(2.2\text{MeV})$

MiniBooNE results (2018)



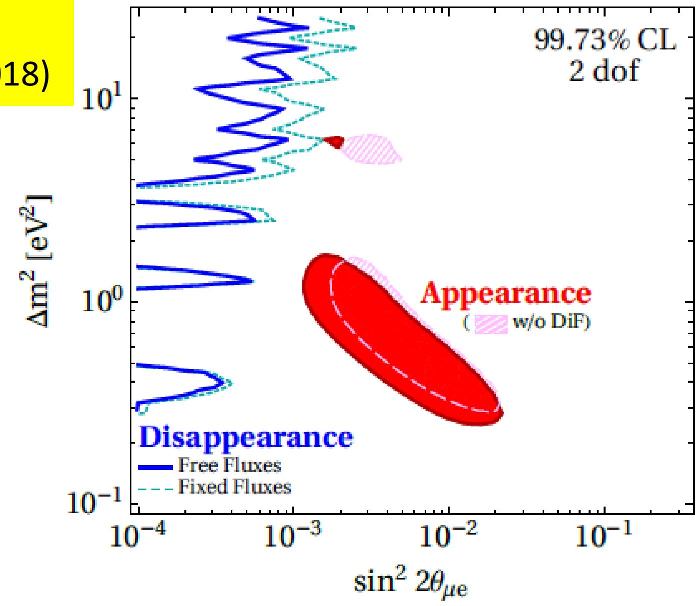
- Significant low energy events excess is observed. (4.5 σ)
- They claimed that this excess is due to the same phenomena as LSND experiment.
- Concerns are
  - Systematic uncertainties (neutrino interactions, background understandings)
  - Especially, unknown single gamma production events may cause this.
- MicroBooNE (Large Liquid Ar TPC detector) is checking the neutrino interaction mode.





Current situation / what experimentalists should do

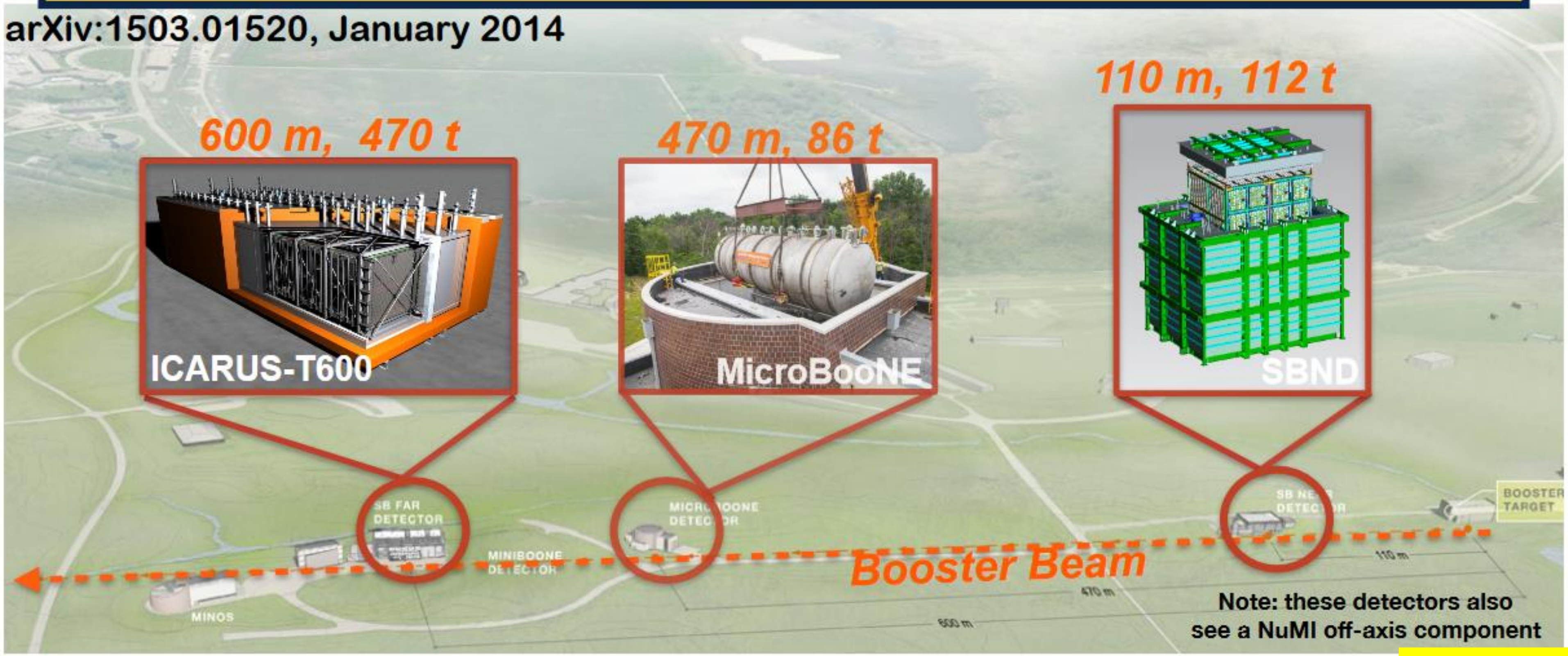
M.Dentler et al
JHEP 08, 010 (2018)



- 3+1 oscillation model cannot explain all phenomena from various experiments.
- If $\nu_\mu \rightarrow \nu_e$ anomalies are confirmed (high significance but maybe not the issue of level of σ) but the $\nu_\mu \rightarrow \nu_\mu$ (and $\nu_e \rightarrow \nu_e$) bounds are not refuted, we absolutely need new physics model.
- Or experimental data is something wrong?? This part is being and will be examined by experimentalists extensively.
  - MicroBooNE (running) / FNAL SBN (SBND+MicroBooNE+ICARUS) for Mini-BooNE anomaly
  - JSNS^2 for the LSND experiment
  - Many reactor experiments are on-going, thus they can check further.

SBN Program at Fermilab

3 LArTPCs in the Booster Neutrino Beamline, looking for (among other things) muon->electron flavor oscillations as a function of L/E



J.Spitz's talk in NuFact2019

SBND (first data in 2021)
MicroBooNE (running since late-2015)
ICARUS (fill in late-2019; first data in 2020)

Direct test for MiniBooNE Anomaly.

JSNS^2 (J-PARC Sterile Neutrino Search at J-PARC Neutron Spallation Source)

Collaboration meeting @ J-PARC
(2019/July-Aug)

JSNS^2 collaboration (55 collaborators)

- 6 Japanese institutions (27 members)
- 10 Korean institutions (20 members)
- 1 UK institution (1 members)
- 5 US institutions (7 members)

Direct tests for LSND.

Technical Design Report (TDR):
Searching for a Sterile Neutrino at J-PARC MLF
(E56, JSNS^2)

S. Ajimura[1], M. K. Cheoun[2], J. H. Choi[3], H. Furuta[4], M. Harada[5], S. Hasegawa[5], Y. Hino[4], T. Hiraiwa[1], E. Iwai[6], S. Iwata[7], J. S. Jang[8], H. I. Jang[9], H. K. Jeon[10], S. H. Jeon[10], K. K. Joo[11], J. R. Jordan[6], S. K. Kang[12], T. Kawasaki[7], Y. Kasugai[5], E. J. Kim[13], J. Y. Kim[10], S. B. Kim[14], W. Kim[15], K. Kuwata[4], E. Kwon[14], I. T. Lim[11], T. Maruyama*[16], S. Meigo[5], S. Monjushiro[16], D. H. Moon[11], T. Nakano[1], M. Niiyama[17], K. Nishikawa[16], M. Nomachi[1], M. Y. Pac[3], J. S. Park[16], S.J.M. Peeters[18], H. Ray[19], C. Rott[10], K. Sakai[5], S. Sakamoto[5], H. Seo[14], S. H. Seo[14], A. Shibata[7], T. Shima[1], J. Spitz[6], I. Stancu[20], F. Suekane[4], Y. Sugaya[1], K. Suzuya[5], M. Taira[16], T. Torizawa[7], J. Waterfield[18], R. White[18], M. Yeh[21], and I. Yu[10]

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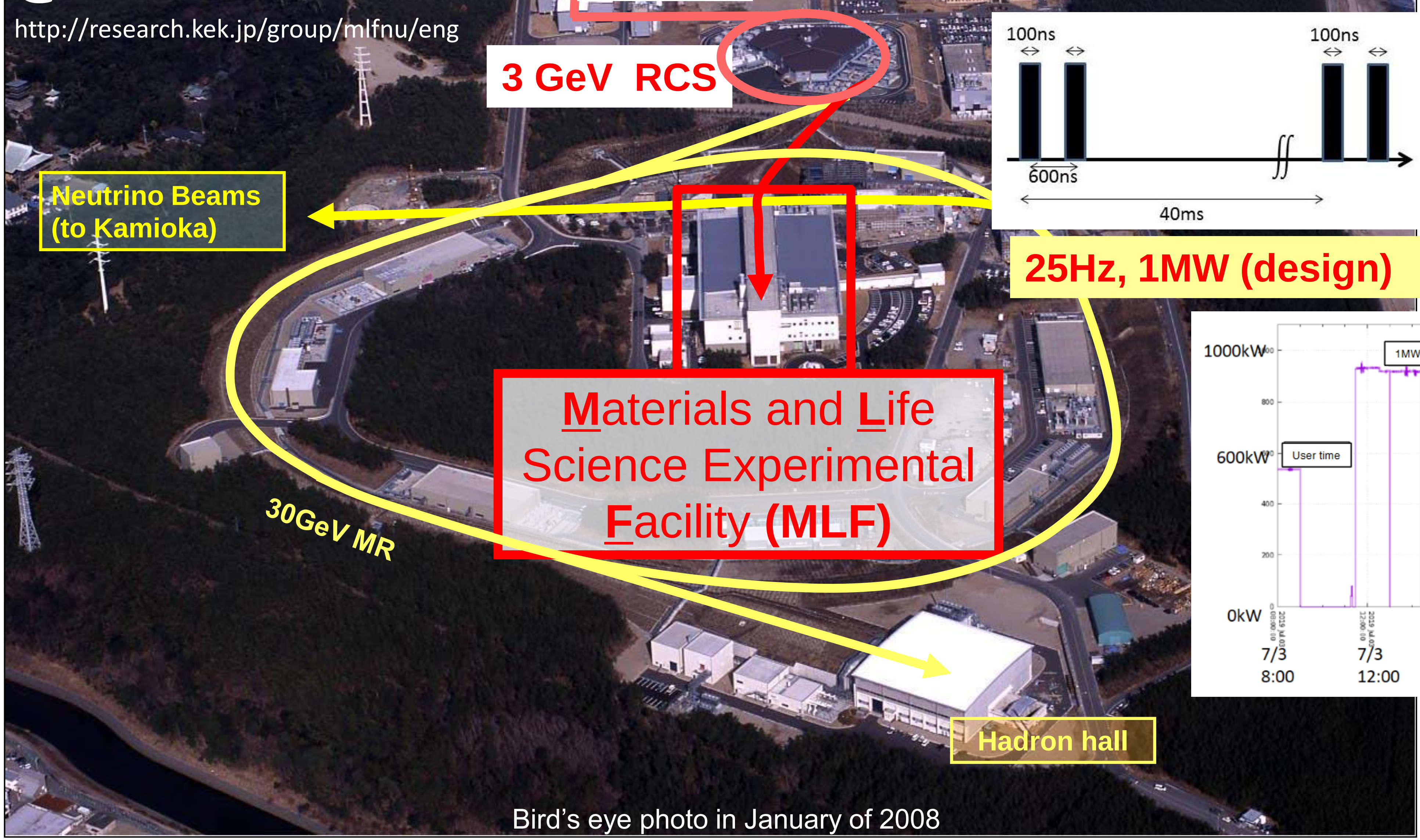
February 13, 2018

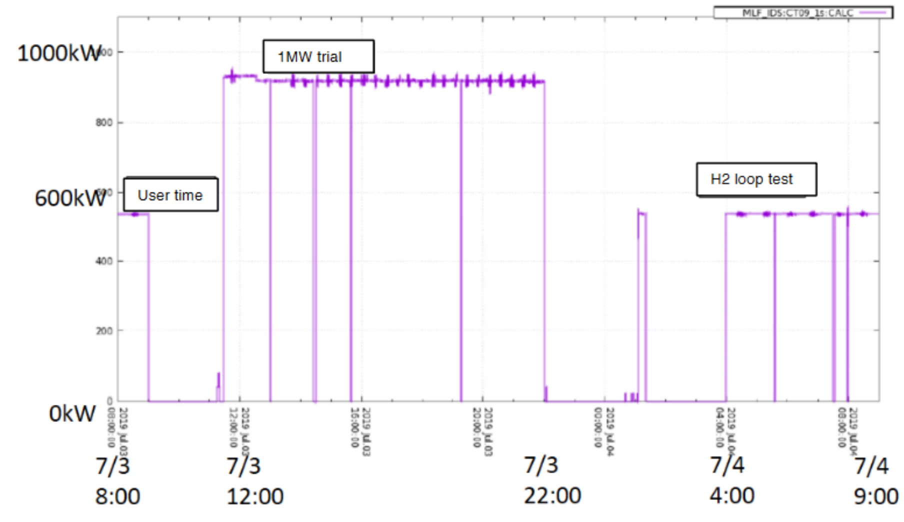
JSNS^2: J-PARC E56
Sterile ν search @MLF

http://research.kek.jp/group/mlfnu/eng

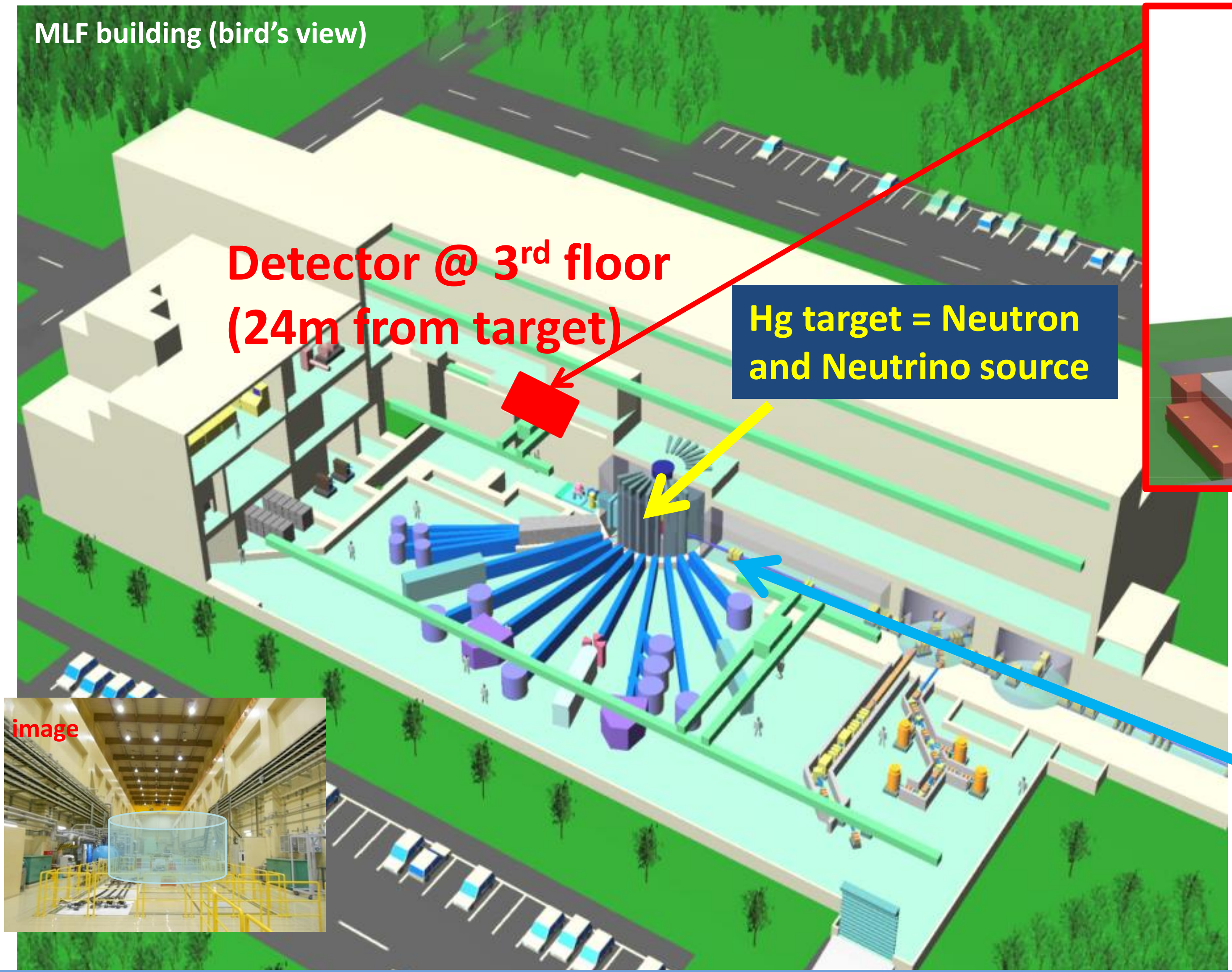


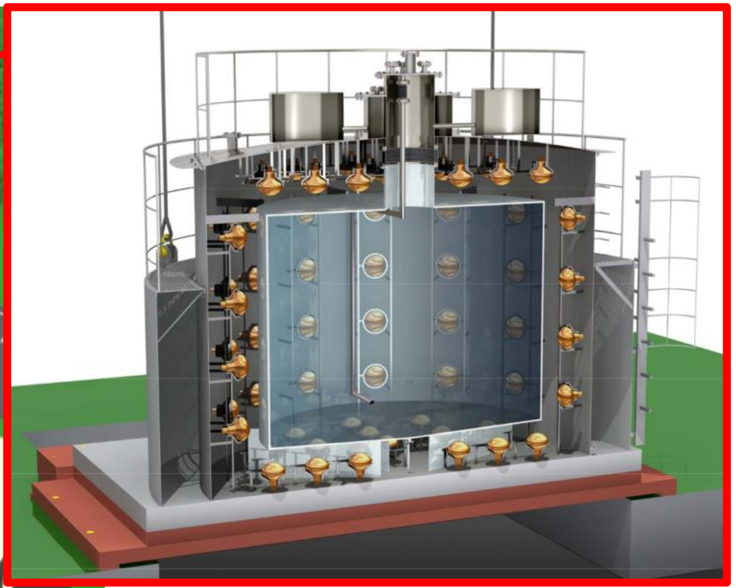
Bird's eye photo in January of 2008

Successful 10.5 hours 1MW trial performed on 2019-July-3



JSNS^2 setup at J-PARC MLF





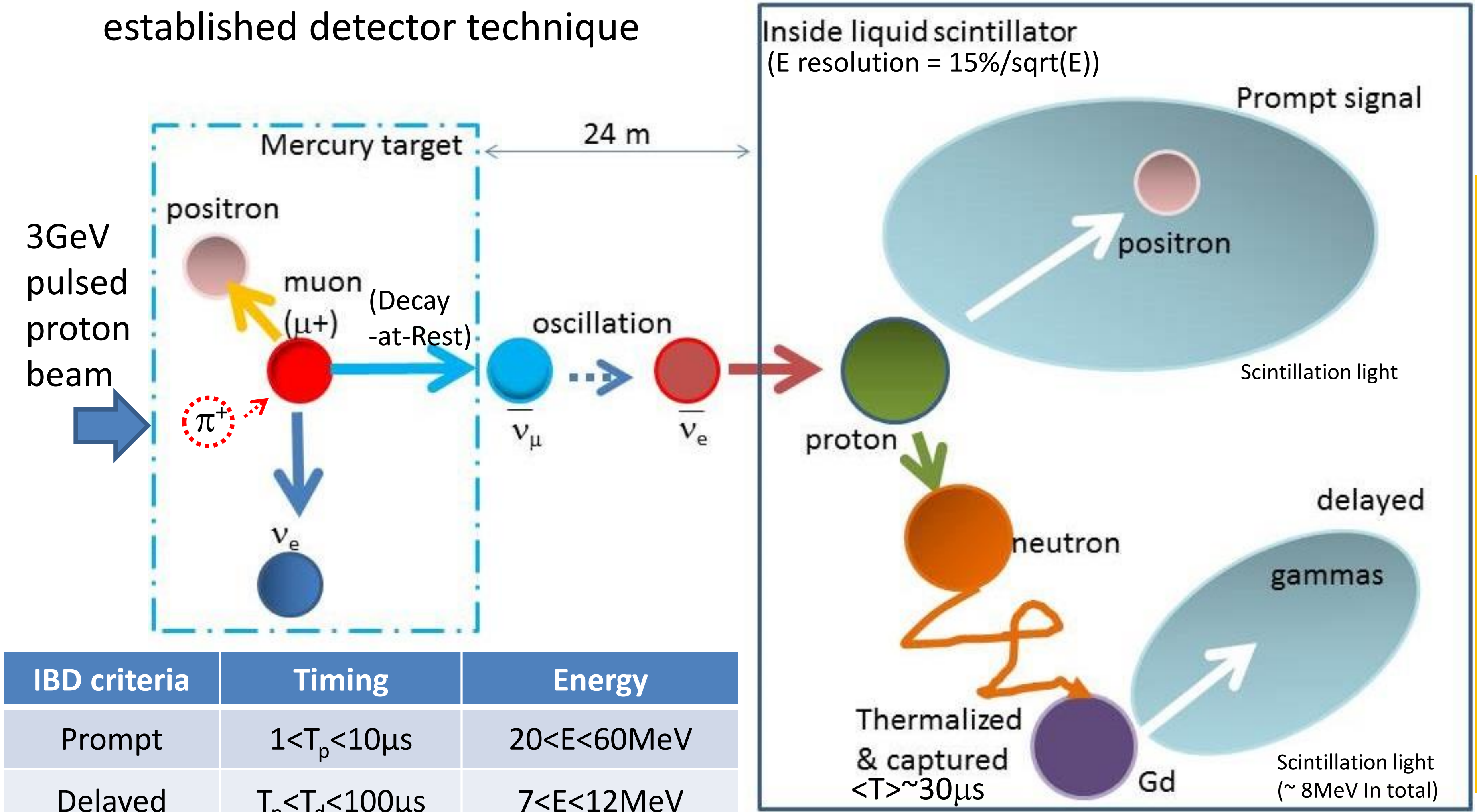
50t liquid scintillator detector
(17t Gd-loaded LS in target)
(4.6mϕ x 3.5m h)
~120 10" PMTs

3GeV pulsed
proton beam

Searching for neutrino oscillation : $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up

Neutrinos Production and Detection

- Large amount of parent μ+ in Hg target → $\overline{\nu}_\mu$ are produced.
- If sterile ν exist, $\overline{\nu}_\mu$ → $\overline{\nu}_e$ oscillation is happened with 24m.
- Oscillated $\overline{\nu}_e$ is detected by Inverse Beta Decay (IBD): $\overline{\nu}_e + p \rightarrow e^+ + n$ w/ well established detector technique



IBD criteria	Timing	Energy
Prompt	$1<T_p<10\mu s$	20<E<60MeV
Delayed	$T_p<T_d<100\mu s$	7<E<12MeV

Most of them are same as The LSND.
→ Direct ultimate tests for LSND.

But use much better beam and Gd loaded LS.
→ Much better S/N
→ Much better systematics

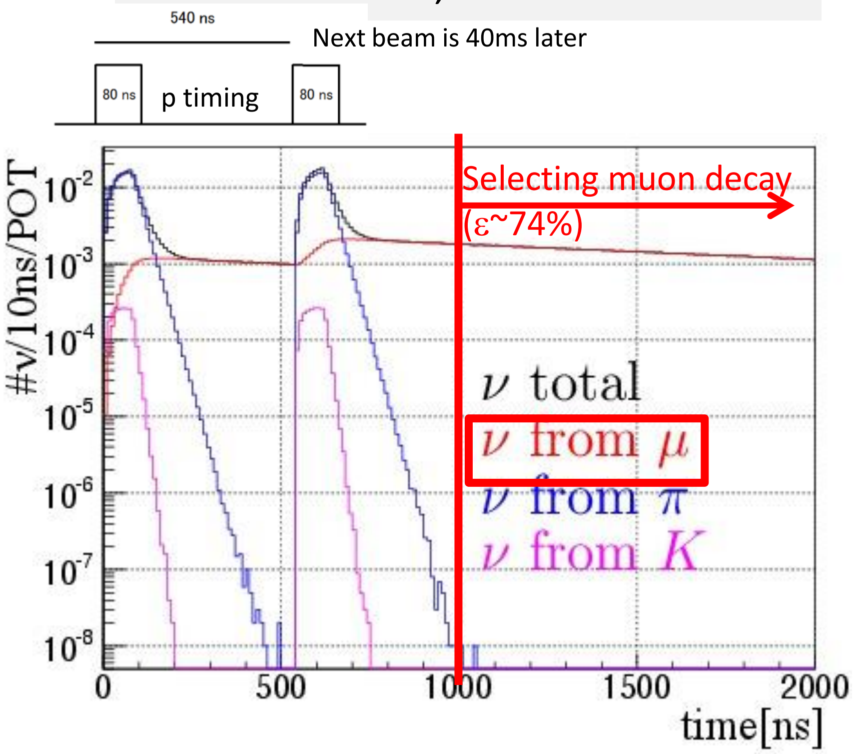
Timing and Energy

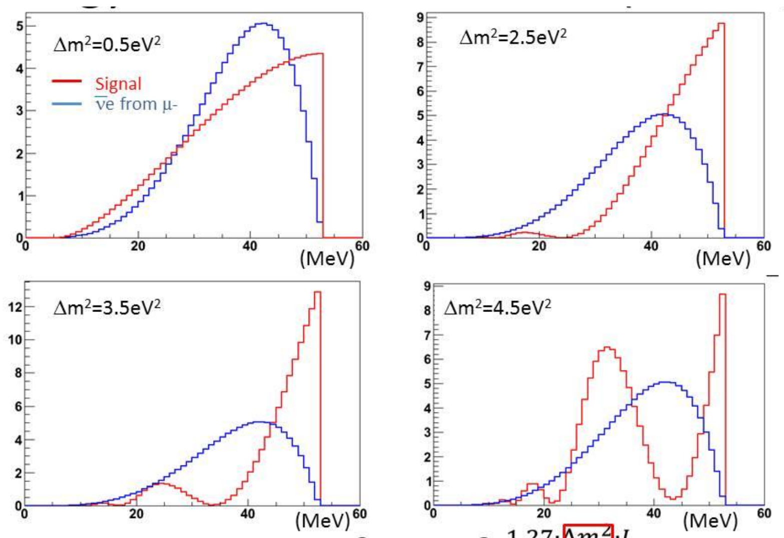
Timing and Energy are friends of JSNS²

- Timing: Ultra-pure ν from μ^+ Decay-at-Rest
  - ν from π and K -> removed with timing
  - Beam Fast neutrons -> removed w/ time
  - Cosmic ray BKG -> reduced by 9μs time window.

- Energy: signals / BKG separation by energy.
  - ν from μ has well-known spectrum.
  - Energy reconstruction is very easy at the IBD. (Eν ~ Evis + 0.8MeV)
  - ν from μ- is high suppressed.

M. Harada *et al*, arXiv:1310.1437





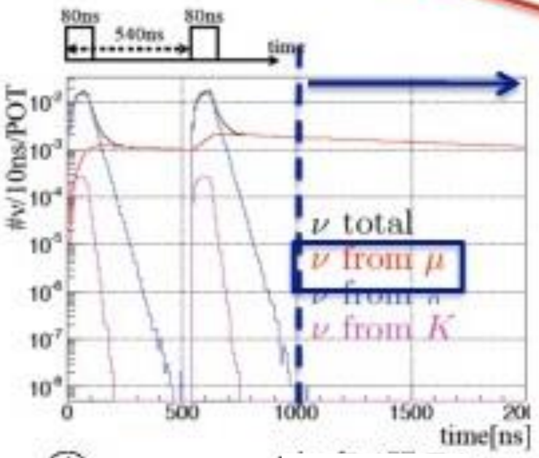
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

IBD event selection

$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$ *appearance*

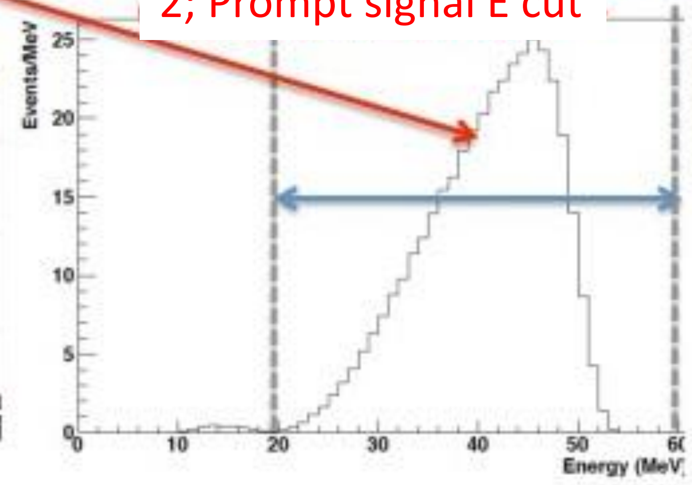
$\bar{\nu}_e + p \to e^+ + n$ -> n capture ->2(H) or 8MeV(Gd)

$\Delta m^2 = 3 eV^2$, $\sin^2 2\theta = 3e^{-3}$ case

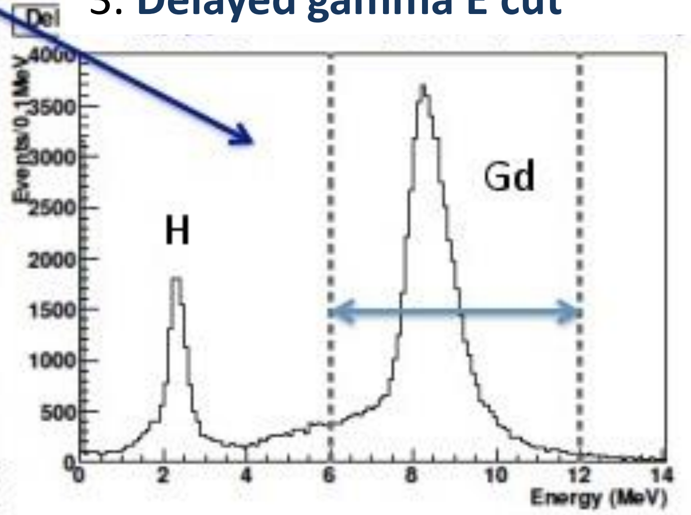


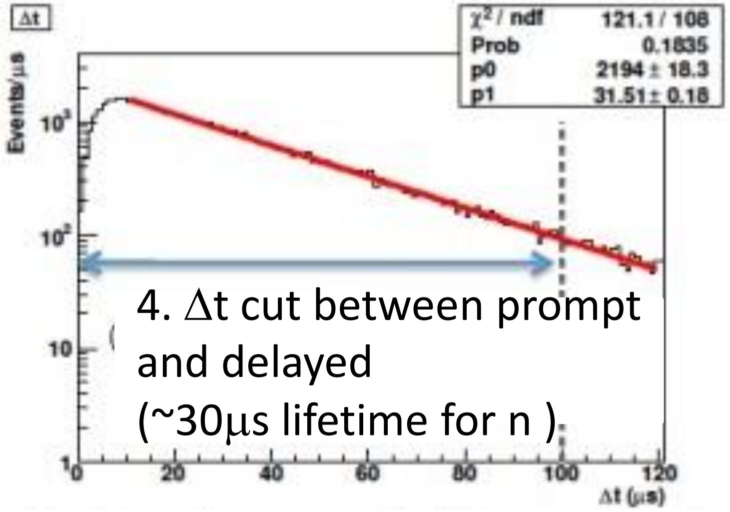
①off bunch

2; Prompt signal E cut

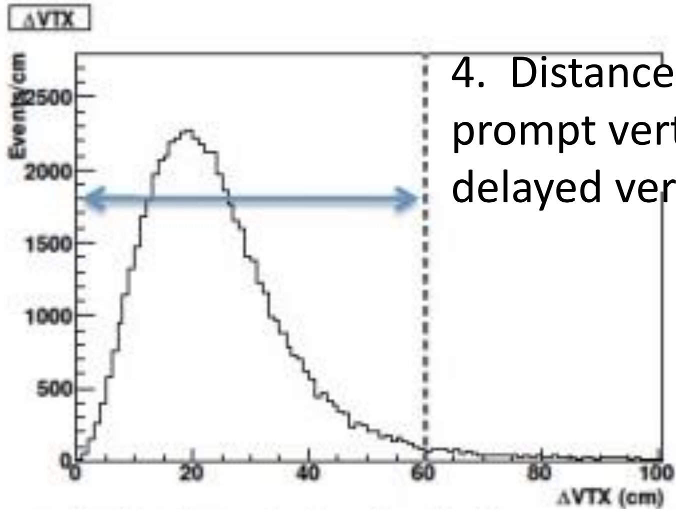


3. **Delayed gamma E cut**





4. Δt cut between prompt and delayed (~30μs lifetime for n)

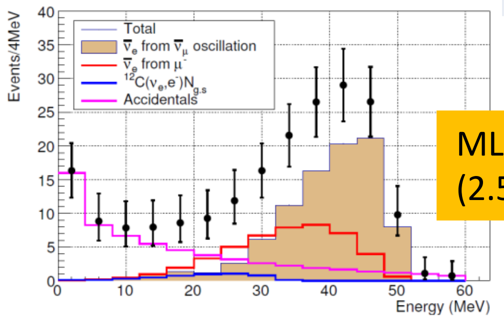


4. Distance cut between prompt vertex and delayed vertex

Selection ε ~ 38%

#events (1MW x 3 years x 1 detector (17tons))

Source	contents	#ev.(17tons x 3years)	Reference : SR2014 (50tons x 5 years)	comments
background	$\overline{\nu}_e$ from μ-	43	237	Dominant BKG
	$^{12}C(\nu_e,e\text{-})^{12}N_{g.s.}$	3	16	
	Beam fast neutrons	Consistent with 0 < 2 (90%CL UL)	<13	Based on real data
	Fast neutrons (cosmic)	~0	37	
	Accidental	20	32	Based on real data
signal		87	480	Δm^2=2.5, $\sin^2 2\theta$=0.003
		62	342	Δm^2=1.2, $\sin^2 2\theta$=0.003



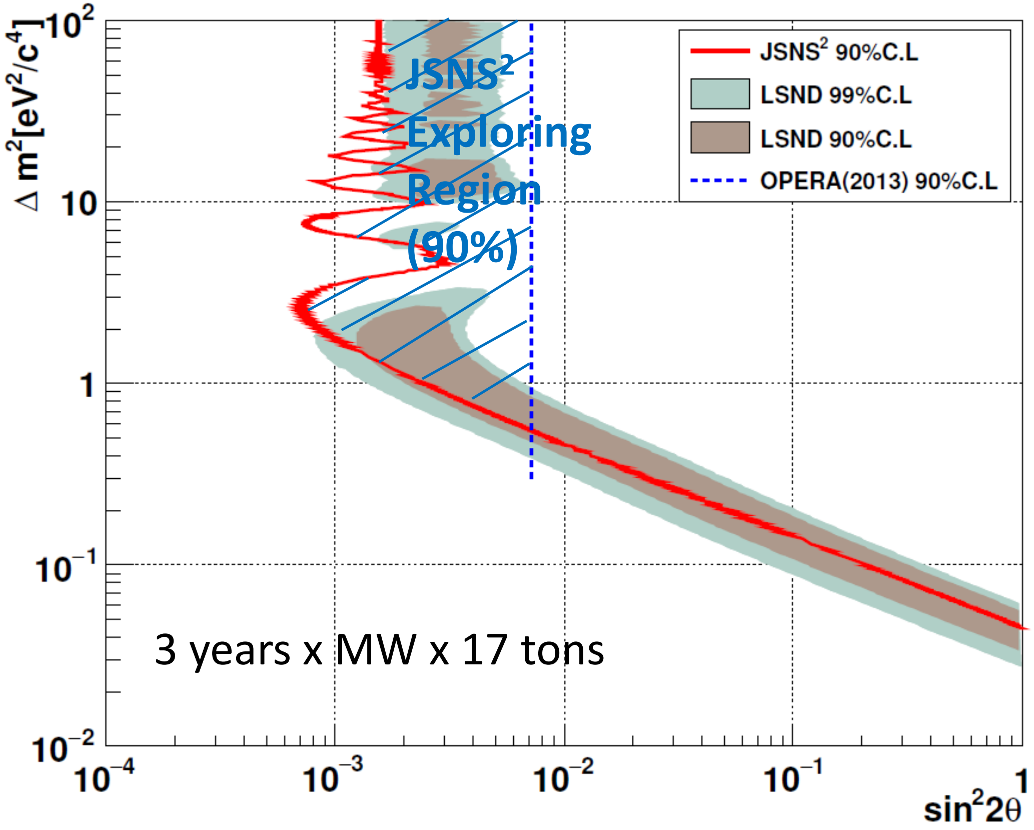
MLF best Δm^2 (2.5eV^2)

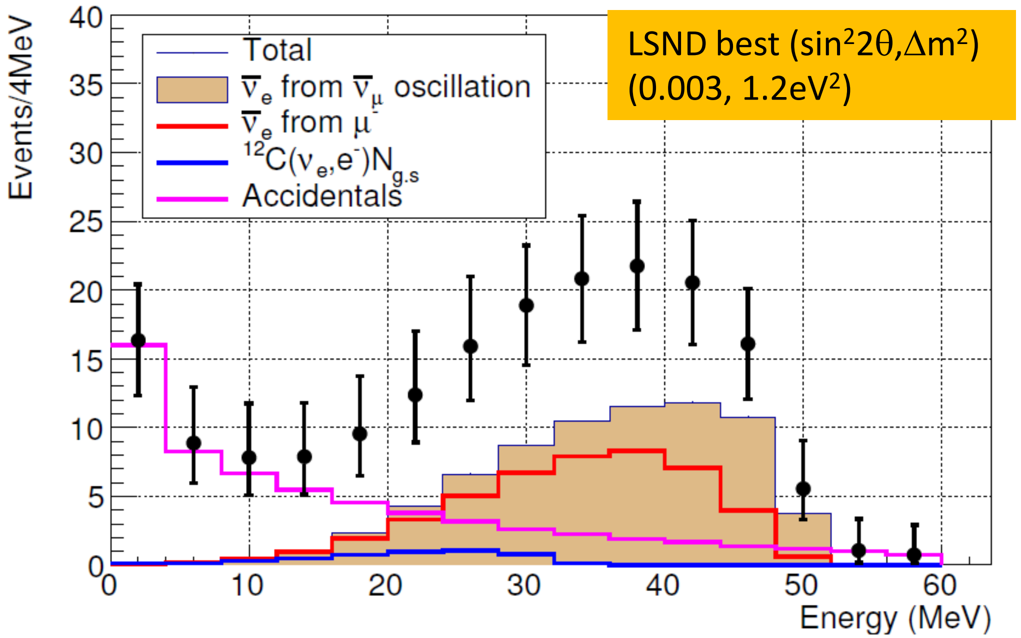
Accidental BKG is calculated by;R acc = ΣR_{prompt} x ΣR_{delay} x Δ_{VTX} x N_{spill}

- ΣR_{prompt}, ΣR_{delay} are probability of accidental BKG for prompt and delayed.
- Δ_{VTX} ; BKG rejection factor of **50**.
- N_{spill}(#spills / 5 years) = 1.9×10^9

Sensitivity / Upgrade

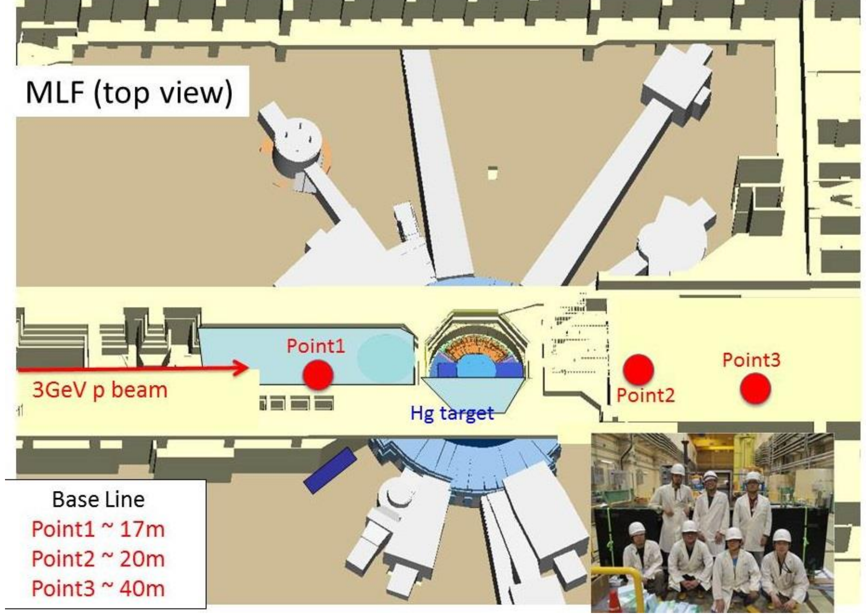
- To have a good international competition capability, we start the experiment with one detector (17tons fiducial volume).
- Even with one detector, we have a good 90% C.L constraints for LSND results for 3 years. Left plot
- Meanwhile, we are making effort to obtain the budget to build the 2nd detector.

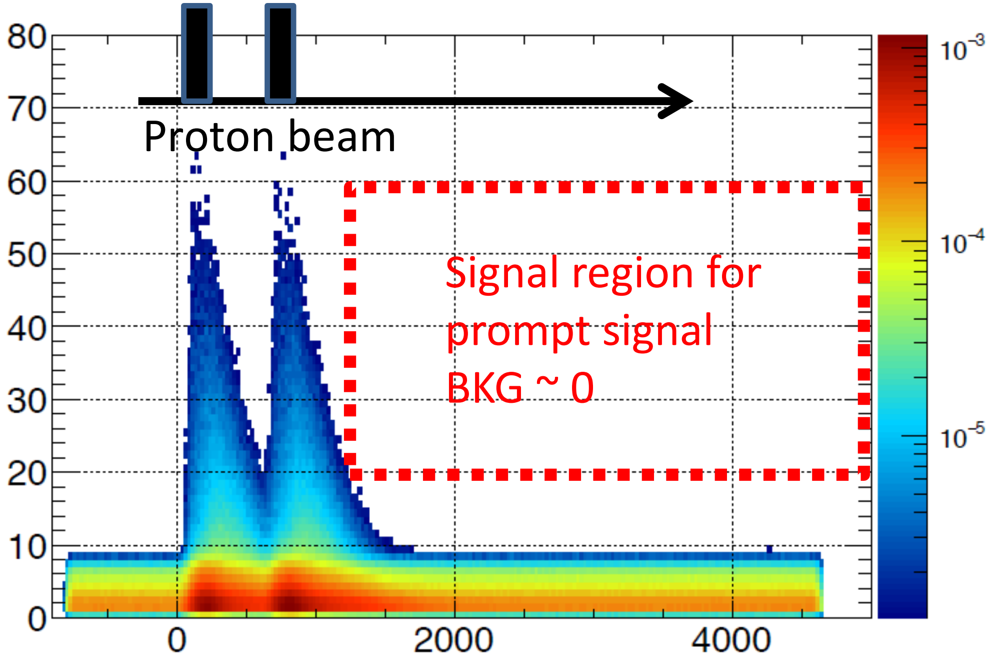




Achievements so far

- 2013 Sep; A proposal was submitted to the PAC
- 2014 Apr-Jul; We measured the BKG rate on 3rd floor. -> manageable beam /cosmic BKGs to perform JSNS^2 **(PTEP 2015 6, 063C01)**
- 2014-Dec; The result was reported to J-PARC PAC. → the stage-1 status was obtained.
- 2016-June: The grant was approved for one detector construction
- 2017-May: Technical Design Report was submitted to J-PARC PAC and arXiv (arXiv:1705.08629 [physics.ins-det])
- 2018-Nov: The stage-2 ("go-sign" of starting the experiment) from KEK/J-PARC was granted.
- **We aim to start JSNS^2 in JFY2019, the detector construction will be completed soon.**





Energy (MeV, vertical) vs timing (ns, horizontal)

Stainless tank construction

- Construction at J-PARC (2017/Dec – 2018/Feb)
- Water leak test was done on 2018/Feb.
- L-type angles, stainless plates were welded to the tank to install PMTs and acrylic tank. (bottom-right picture)
- This tank was moved from the construction place to assembly building.

Acrylic vessel installation rehearsal (2019/Feb)

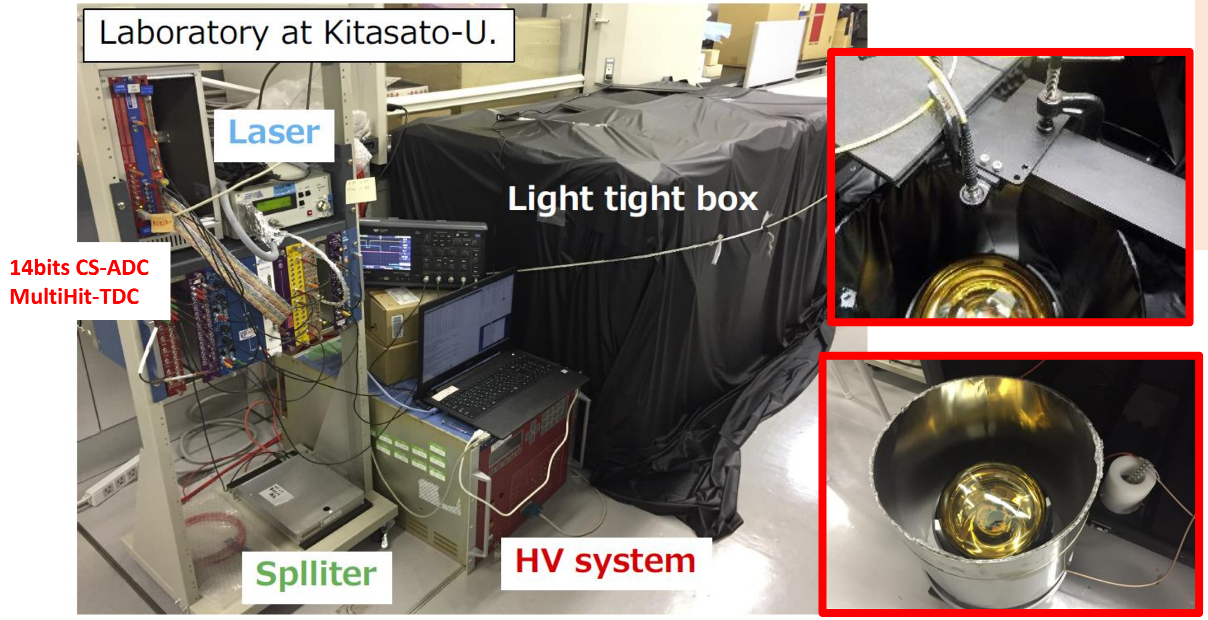
- Feb-18: the acrylic vessel arrived from Taiwan.
- Immediately after the arrivals, we had rehearsal to install the acrylic tank. → succeeded.
- Currently, the acrylic tank was out of detector to install PMTs.

10” PMTs

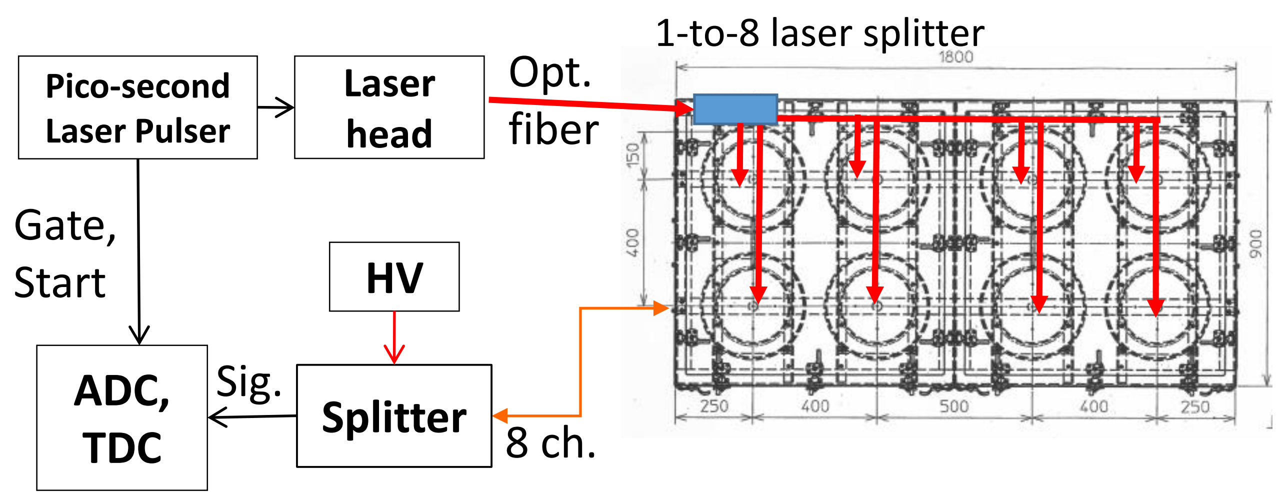
- 67 RENO experiment spare PMTs were rental to JSNS[2].
- 13 Double-Chooz spare PMTs were also borrowed.
- 80 PMTs are now at J-PARC. Most of them were pre-calibrated and installed to the detector.

- ~50 more PMTs will come to J-PARC from 2019 Sep to Dec.
- Soon after the installation of these ~50 PMTs, we will start data taking.

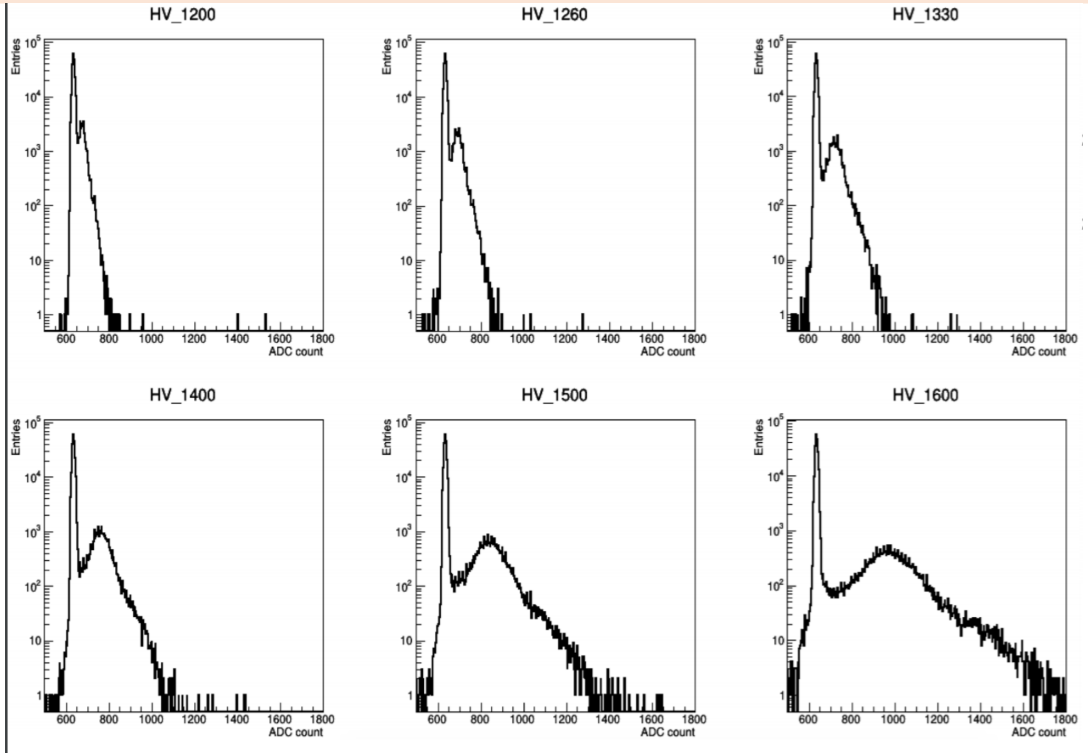
PMT pre-calibration



- Gain, P/V ratios, Dark rate (@ 10^7 gain) measurements for 8 PMTs at once
- 8 PMTs/day can be pre-calibrated.
- charge info. is much more important than timing for JSNS2's reconstruction because of several 10 MeV.



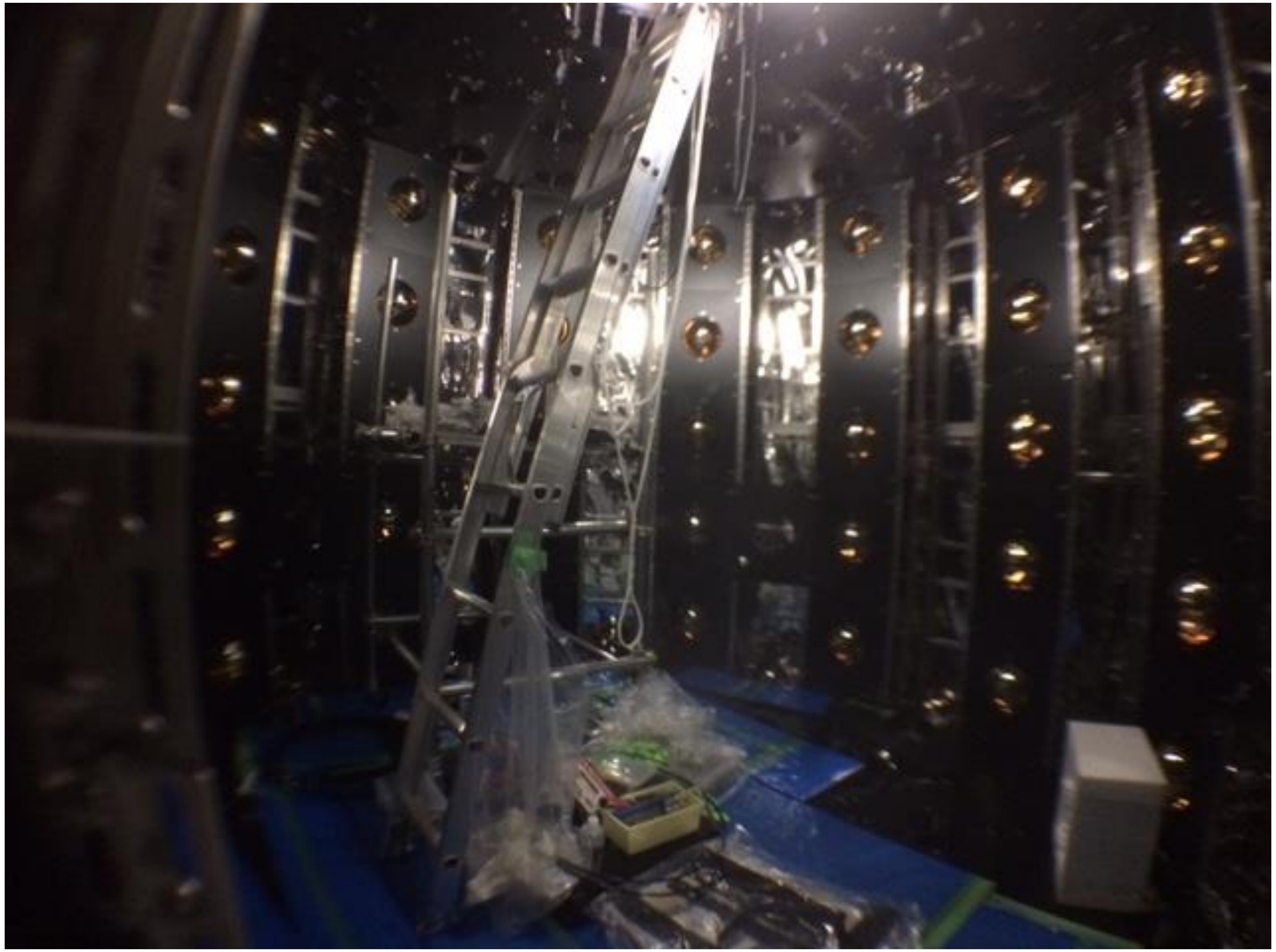
The system has been launched at J-PARC



- Typical 1 p.e. dist. with various HVs.
- Currently most of arrived PMTs were pre-calibrated.
- A few PMTs have troubles. → rejected to use.

PMT Installation status

- Immediately after the pre-calibration (and the results are OK), we can install the PMTs in parallel to the pre-calibration works.
- We already installed 67 PMTs to barrel and veto parts. (remaining PMTs will be installed soon)
- After the installation works, one by one checks of PMTs signal were and will be done. → so far, installed PMTs have no problems to see the signal.

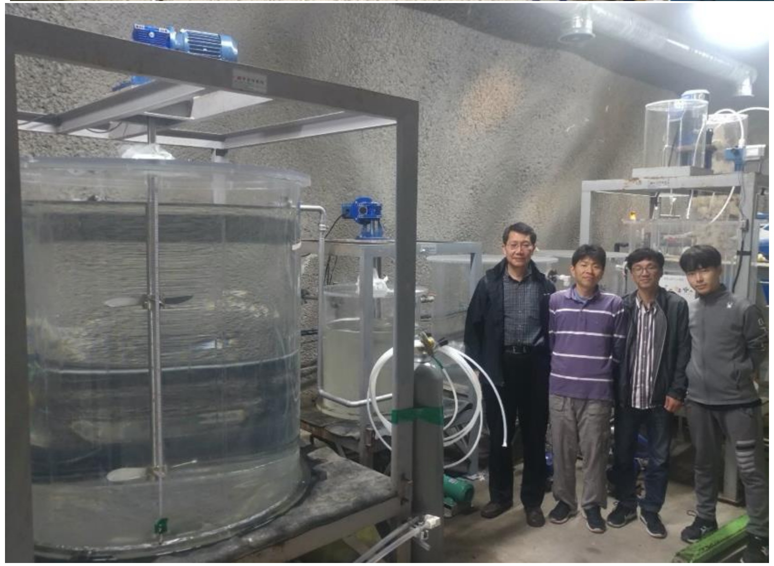


Liquid Scintillator (LS) Production in Korea (2018)

35 tons of LS was produced at RENO site and delivered to Japan with two iso-tanks.

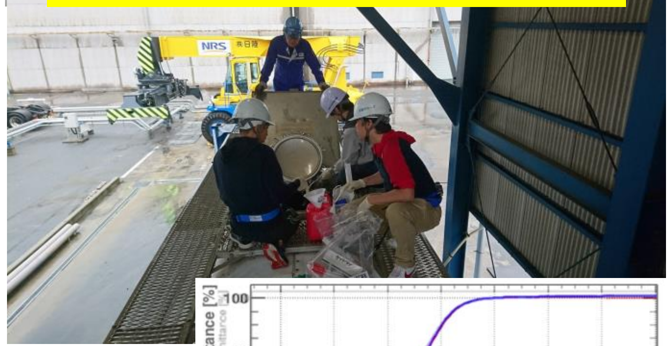
Date	Job description
Sep. 12 - 18	Refurbishment and cleaning
Sep. 28	ISO tank arrived at RENO site
Oct. 1 - 22	LS production (6 shift periods)

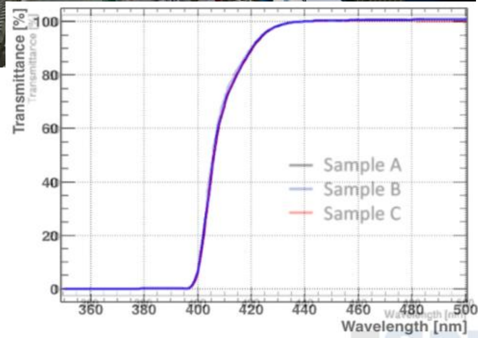
21 batches in total (37000 L)
- 4 peoples per day
- 2 of ISO tanks



LS storage in Japan

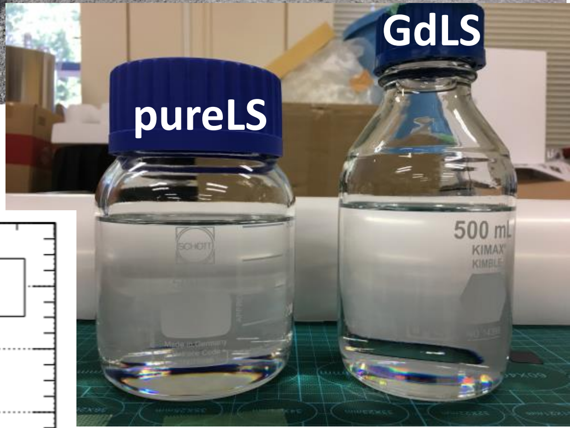
First sampling test in Japan

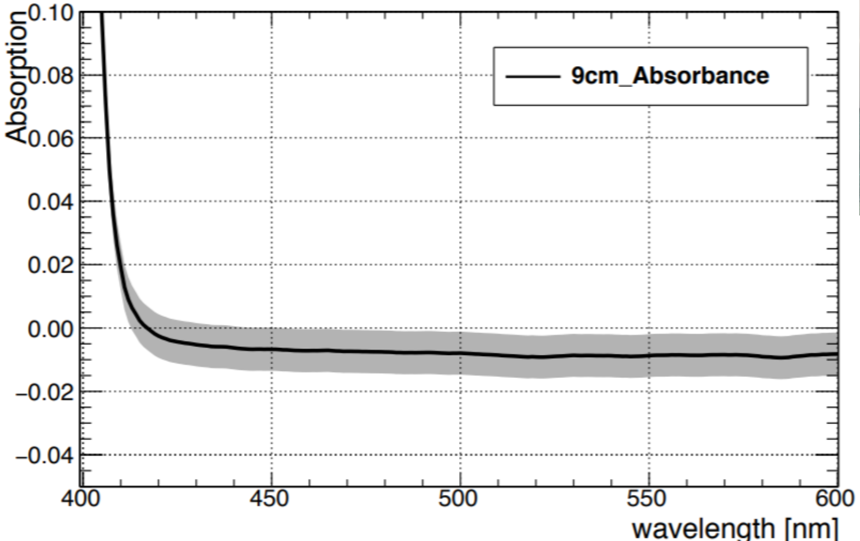




Gd-loaded Liquid Scintillator is donated from Daya-Bay

- Daya-Bay experiment kindly donated the 20 tons of Gd-loaded Liquid Scintillator (GdLS).
  → $JSNS^2$ would express deep appreciatiation for this.
- On 2019 August-1, the GdLS passed Japanese custom.
- We visited the GdLS/LS storage area and obtained samples on Aug-6.
- We did measure the optical properties at Tohoku Univ.. They look nice.

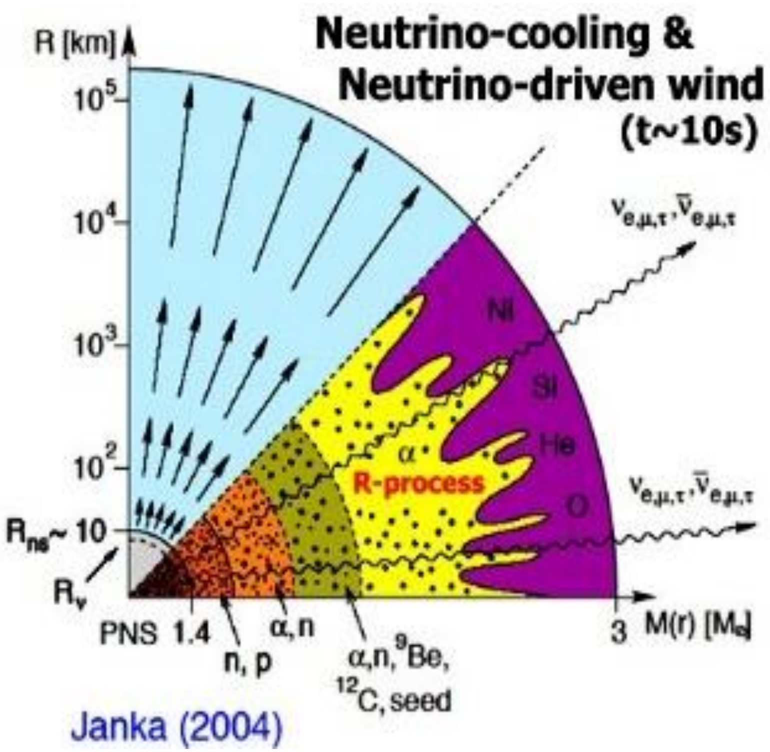




Absorbance Spectra

	Values	Method
Absorbance	See right plot	UV-Vis spectrometer
Light yield	11.7 photon/keV	Back scattered g of 137Cs
Gd concentration	0.096+-0.002 w%	EDTA Titration

Neutrino-nucleus interaction in Type-II SN



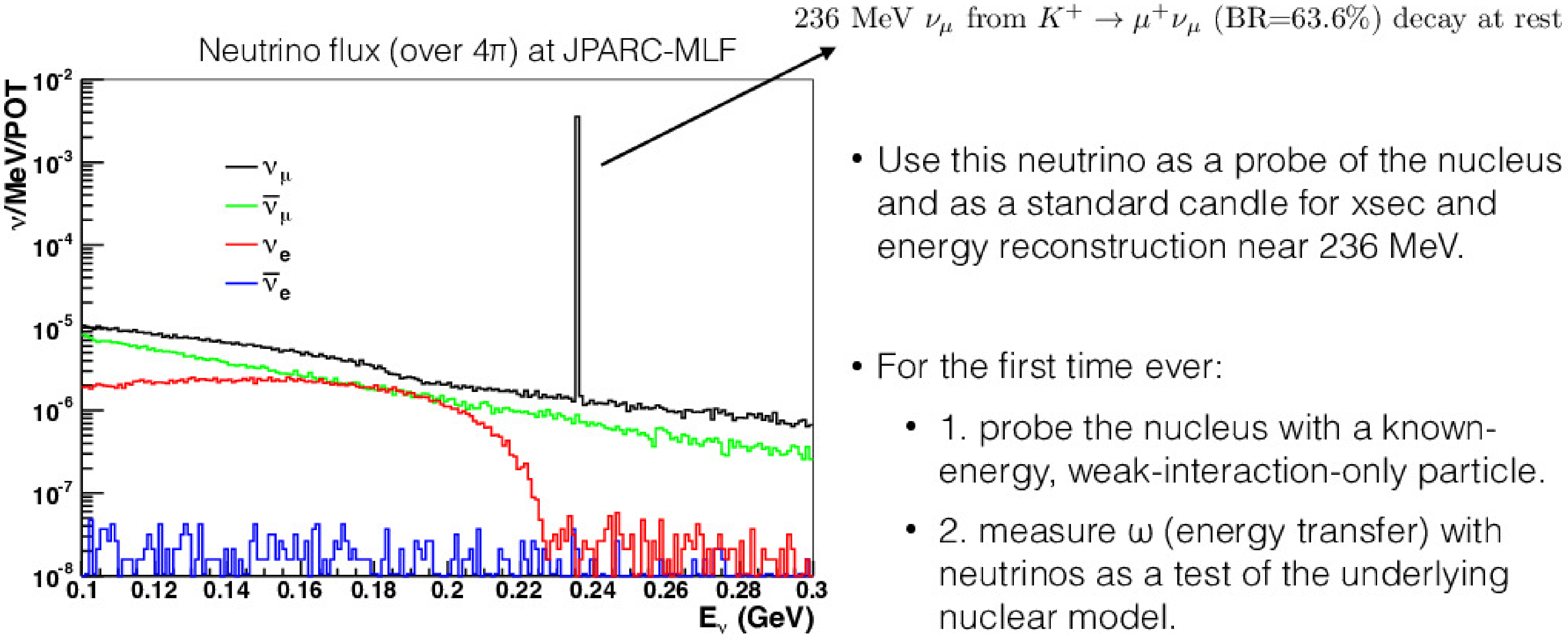
ν-A interactions are important in

- core-cooling by ν-emission
- ν-heating on shock wave
- ν-process of nucleosynthesis
- efficiency of neutrino detectors

Reaction rates are to be known with accuracy better than ~10%!

Experiment	$\sigma(^{12}C(\nu_e,e^-)^{12}N_{g.s.})$ (10^{-42} cm^2)
KARMEN (PLB332, 251 (1994))	9.1±0.5±0.8 (10.4%)
LSND (PRC64, 065501 (2001))	8.9±0.3±0.9 (10.7%)
JSNS^2 (arXiv:1601.01046)	(~3%(stat.) expected in 5yrs)

JSNS^2 physics: Cross section measurements with monoenergetic muon neutrinos



- Use this neutrino as a probe of the nucleus and as a standard candle for xsec and energy reconstruction near 236 MeV.

- For the first time ever:
  - 1. probe the nucleus with a known-energy, weak-interaction-only particle.
  - 2. measure ω (energy transfer) with neutrinos as a test of the underlying nuclear model.

50-100 events / day with 1MW beam

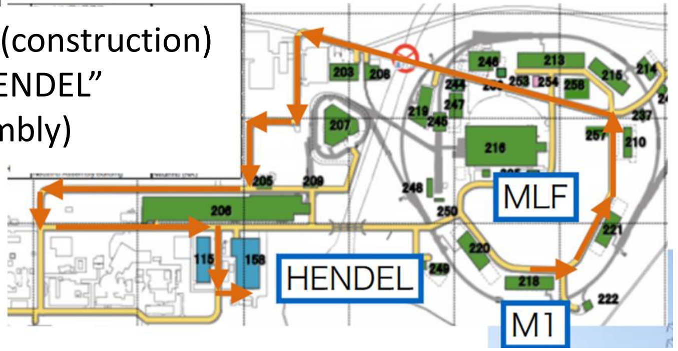
Summary

- If sterile neutrinos exist, it opens the era of new physics.
- There are a lot of experiments on going to search eV scale sterile neutrinos. Recently, direct confirmation or refuting of LSND and MiniBooNE experiments are getting crucial.
- For the direct test for LSND experiment, the $JSNS^2$ experiment will start data taking very soon.
  - Same neutrino sources (energy, flavor), neutrino target and interaction are used.
  - But using much better quality of beam (on duty factor) and Gd-loaded liquid scintillator. → can improve signal-to-noise ratio (~100 for accidental BKG)
  - We will complete the detector construction soon.
  - First physics run for 3 years, but meanwhile requesting budget for the 2nd detector.
- Other physics topics are also interesting! You can see the results soon !!

backup

Detector moving to assembly building (2018/Mar)

"M1" (construction)
To "HENDEL"
(assembly)



This work was successful w/o problems!