Review of Sterile Neutrino Searches

Takasumi Maruyama (KEK)

2018/June/21

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 and LEP experiments
  - Observed by mainly neutrino oscillations
  - Could be ν_R (Majorana) or new particle
  - Beyond PMNS matrix oscillation
  - LSND, MiniBooNE, reactors, Ga experiments indicate the existence.

- Sterile neutrino could be also one of the Dark Matter candidate?

indication of the sterile neutrino ($\Delta m^2 \sim 1eV^2$) ?

- 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	4.8σ	
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?

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

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

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 $\quad U_{e4}, U_{\mu 4} \sim 0.1 \quad U_{s4} \sim 1 \quad m_4 \sim 1\,\mathrm{eV} >> m_{1,2,3}$

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

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

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

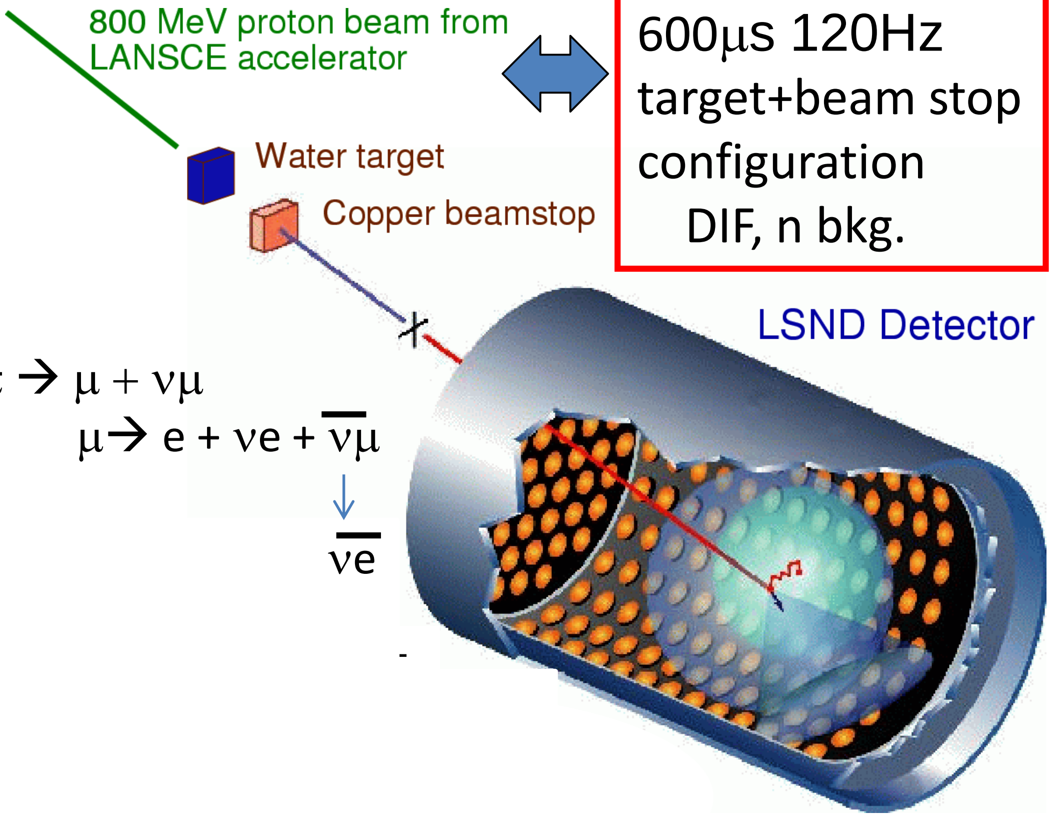
(3+1) model

Appearance

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

1998 at LANL

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

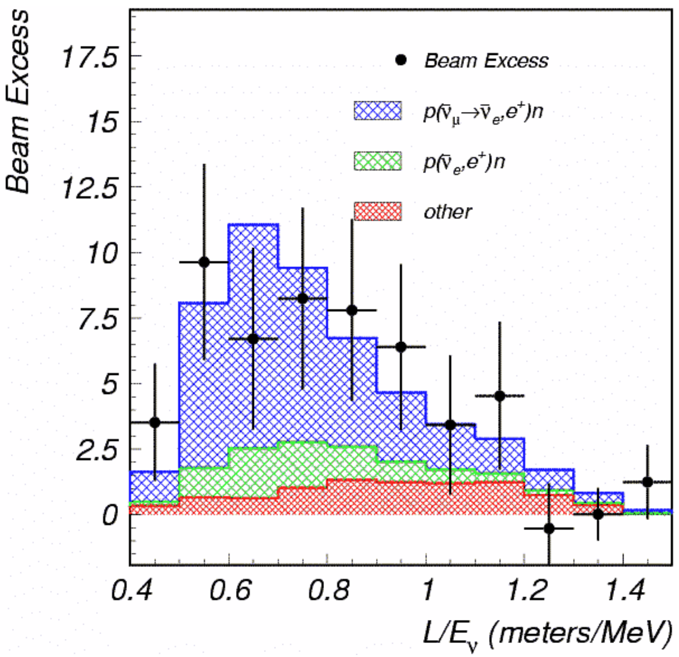


$\pi \rightarrow \mu + \nu\mu$

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

$\downarrow$

$\overline{\nu e}$



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

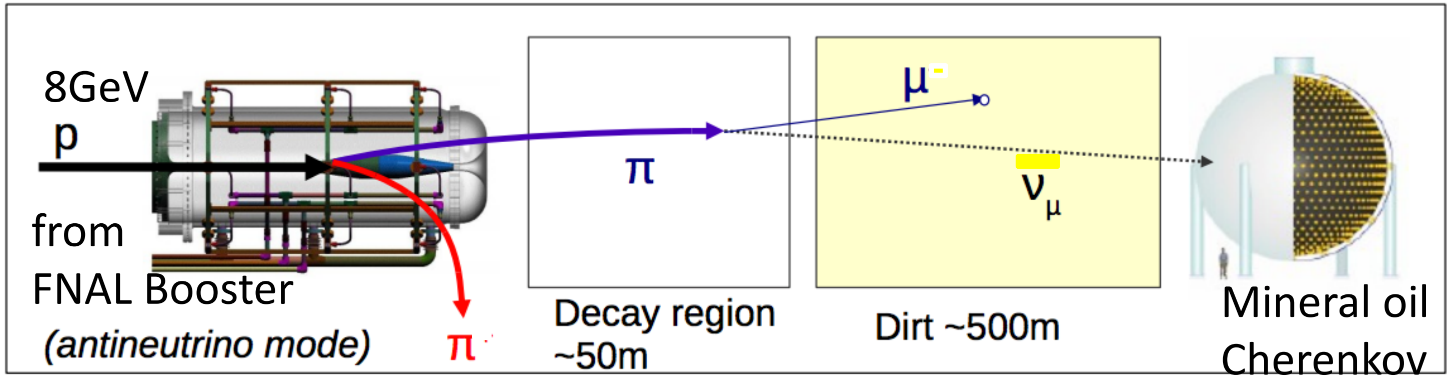
With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

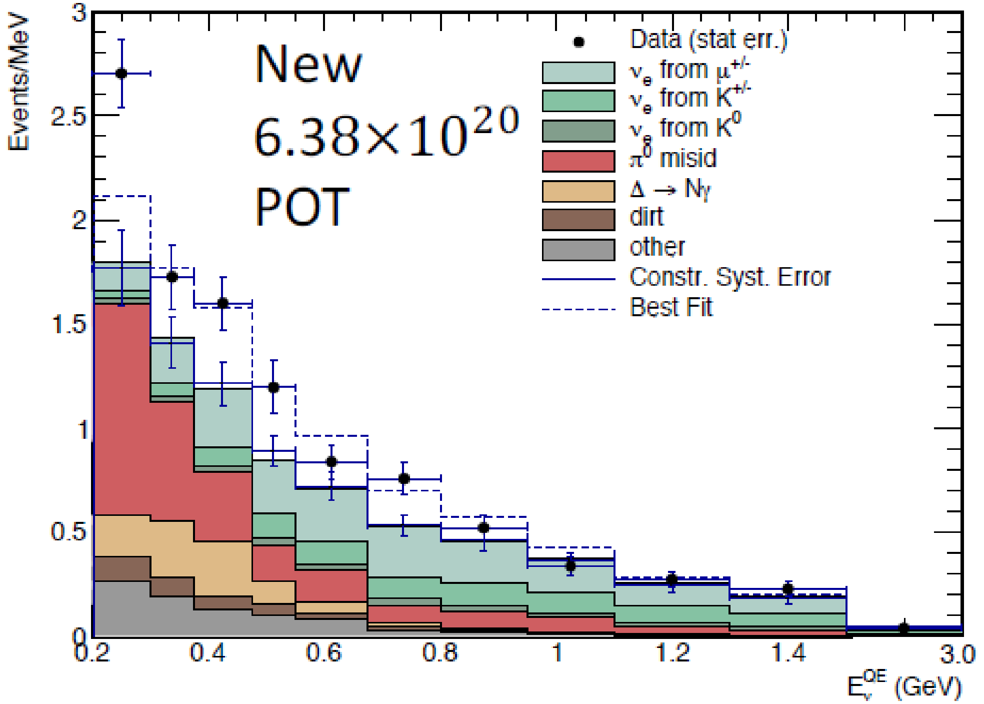
3.8 s evidence for oscillation.

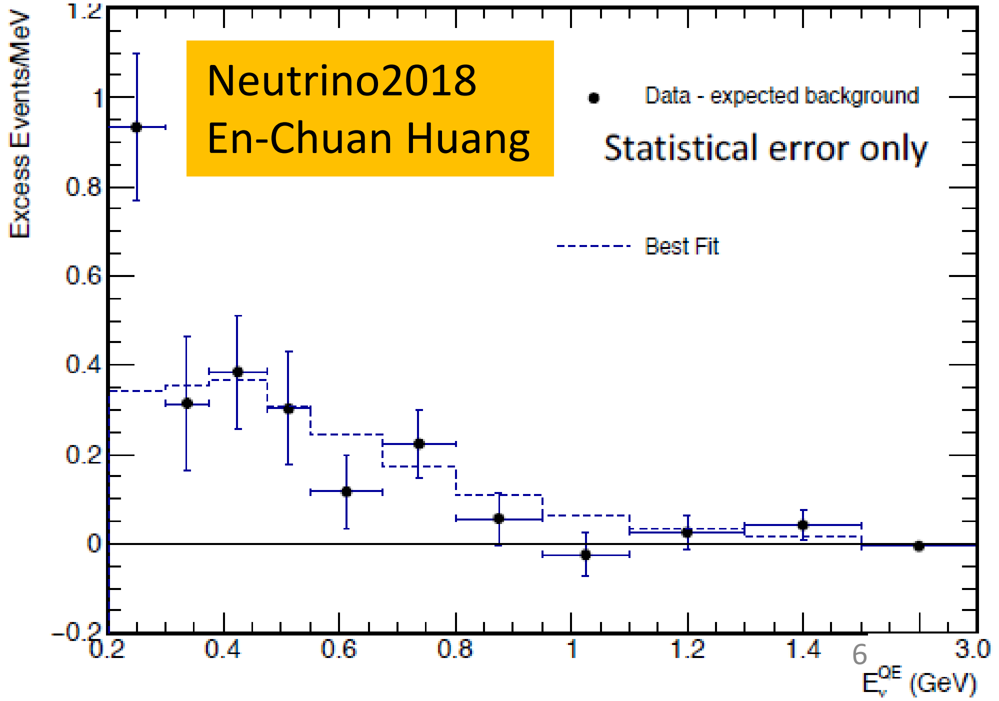
π^-, μ^- absorbed before decay into ν's
there should not be $\overline{\nu e}$ at the level of 7×10^{-4}

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

MiniBooNE latest results







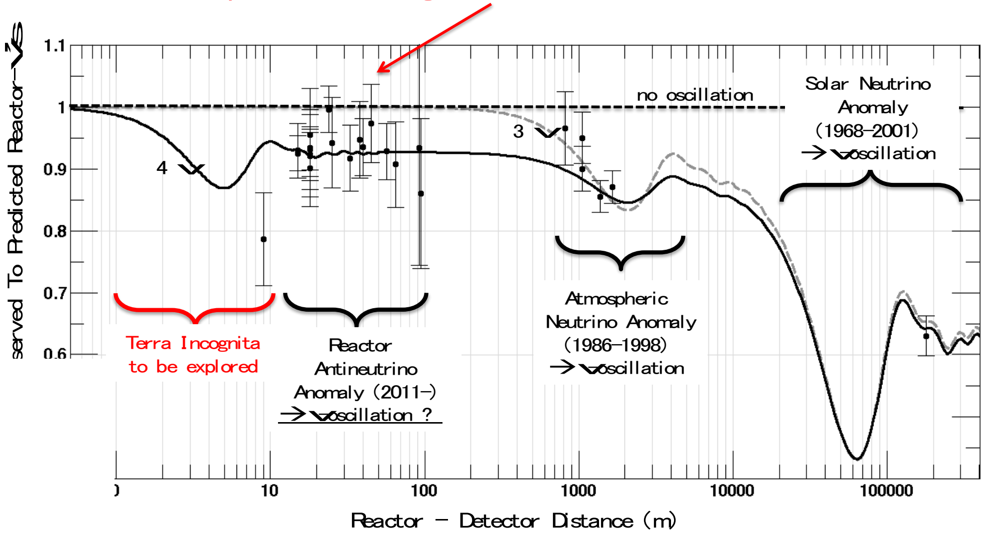
- Significant low energy events excess (4.5 σ)
- They claim that the excess is due to the same oscillation observed at the LSND.
- Concerns are
  - Systematic uncertainties (neutrino interactions, background understandings)
  - Especially, unknown single gamma production events may cause this.
- MicroBooNE can check the excess due to the gamma ray events or electron antineutrinos.

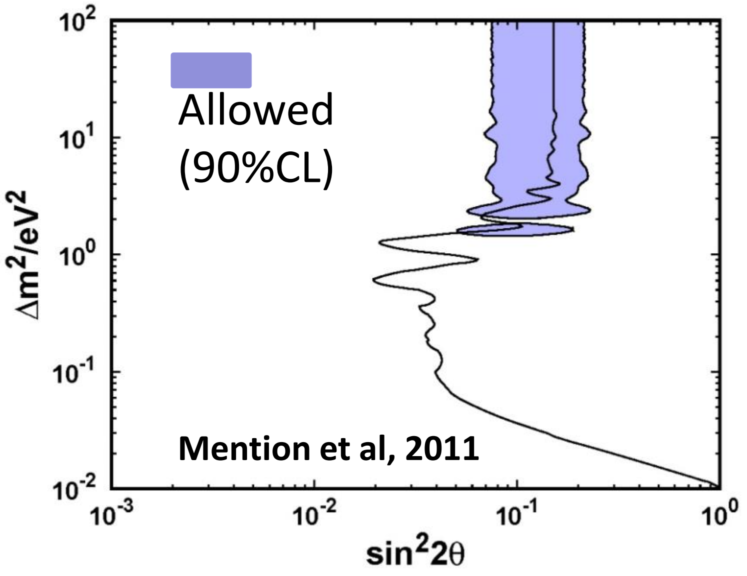
ν_e disappearance in reactor and β–source

Chris Polly, Thierry Lasserre
NEUTRINO2012

The Reactor Antineutrino Anomaly

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)

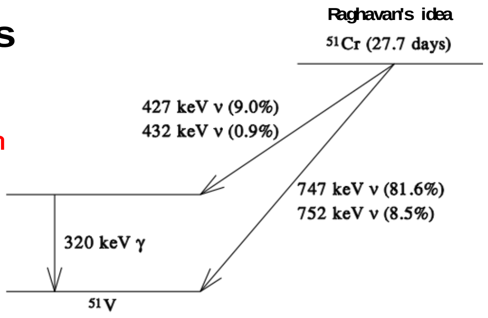


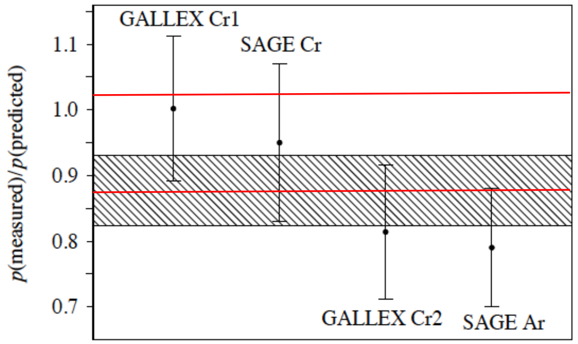


The Gallium Neutrino Anomaly

High Δm^2 ?

- Test of solar neutrino detectors GALLEX and SAGE (ν_e's)
  - E ≈ MeV, Baseline range ≈ few m
- 4 calibration runs ≈1 MCi EC ν_e emitters

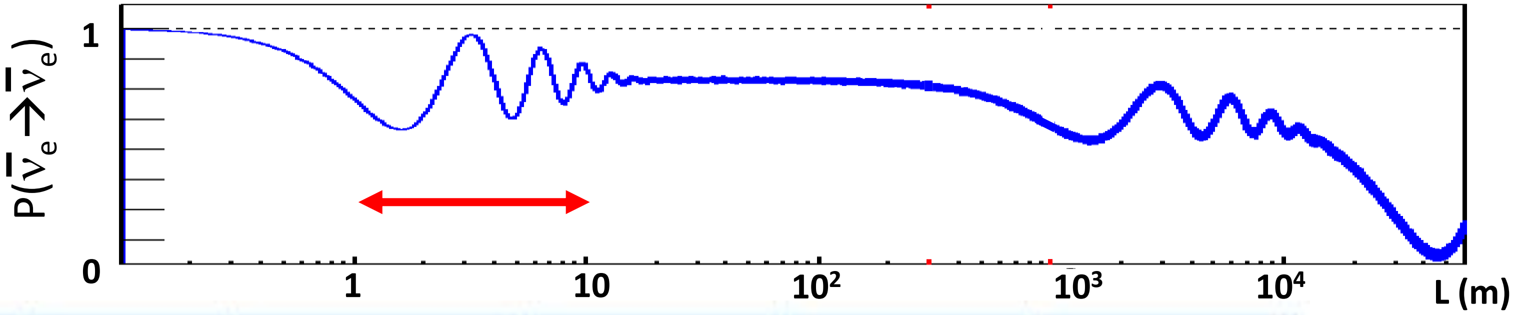


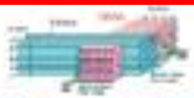


~3σ

ν_e disappearance w/ reactors

Δm^2>0.1, $\sin^2 2\theta$>0.05 → L_{osc} = [1-10] m

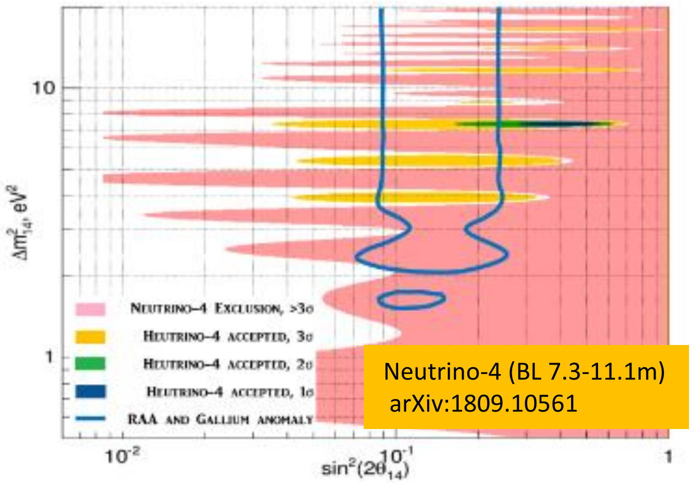


Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double 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

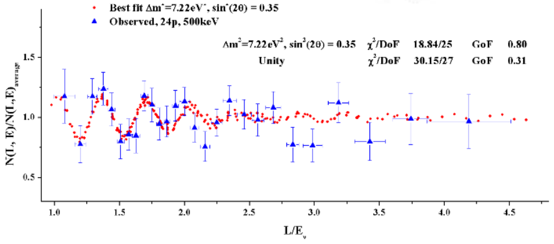
Recently, they have results.

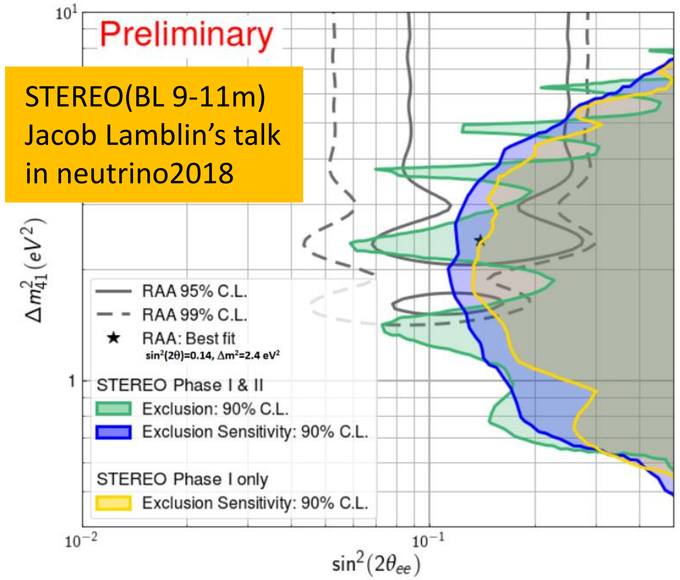
ν_e disappearance

- Summary of the recent results so far. (exciting!)

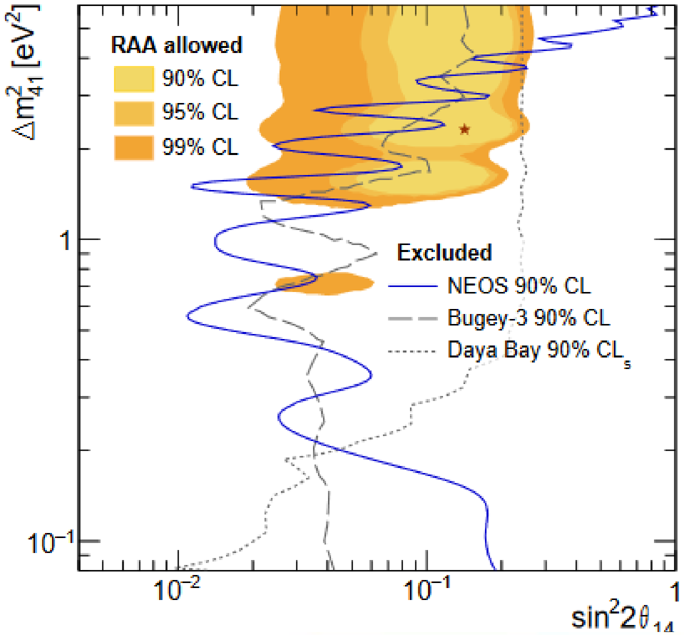


Neutrino-4 (BL 7.3-11.1m)
arXiv:1809.10561

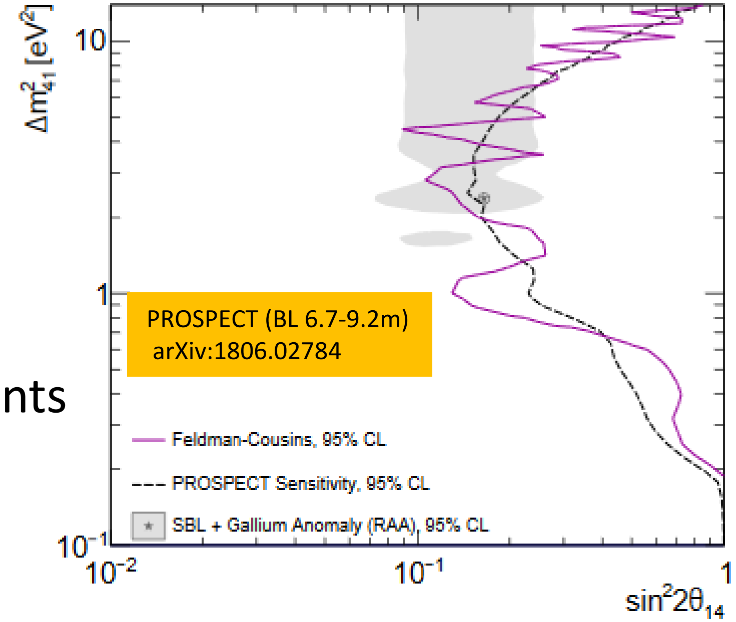




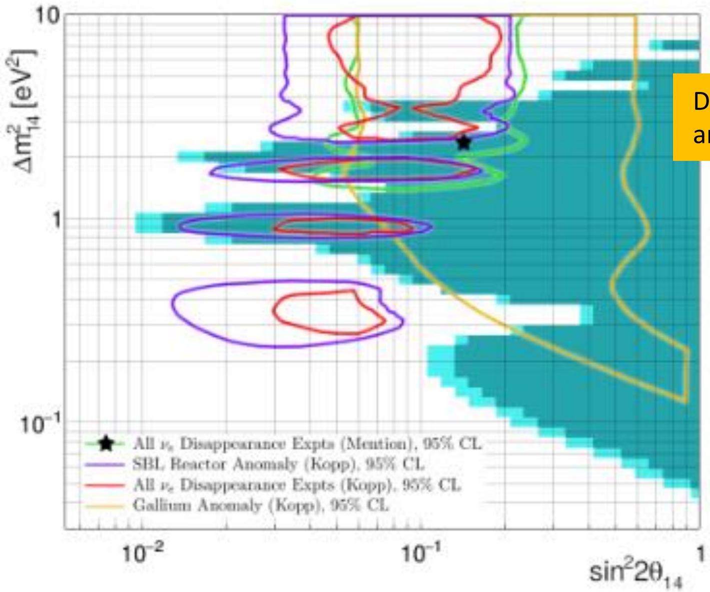
STEREO(BL 9-11m)
Jacob Lamblin's talk
in neutrino2018



NEOS (BL 24m)
PRL 118 (2017) 121802



PROSPECT (BL 6.7-9.2m)
arXiv:1806.02784



DANSS(BL 10.7→12.7m)
arXiv:1804.04046

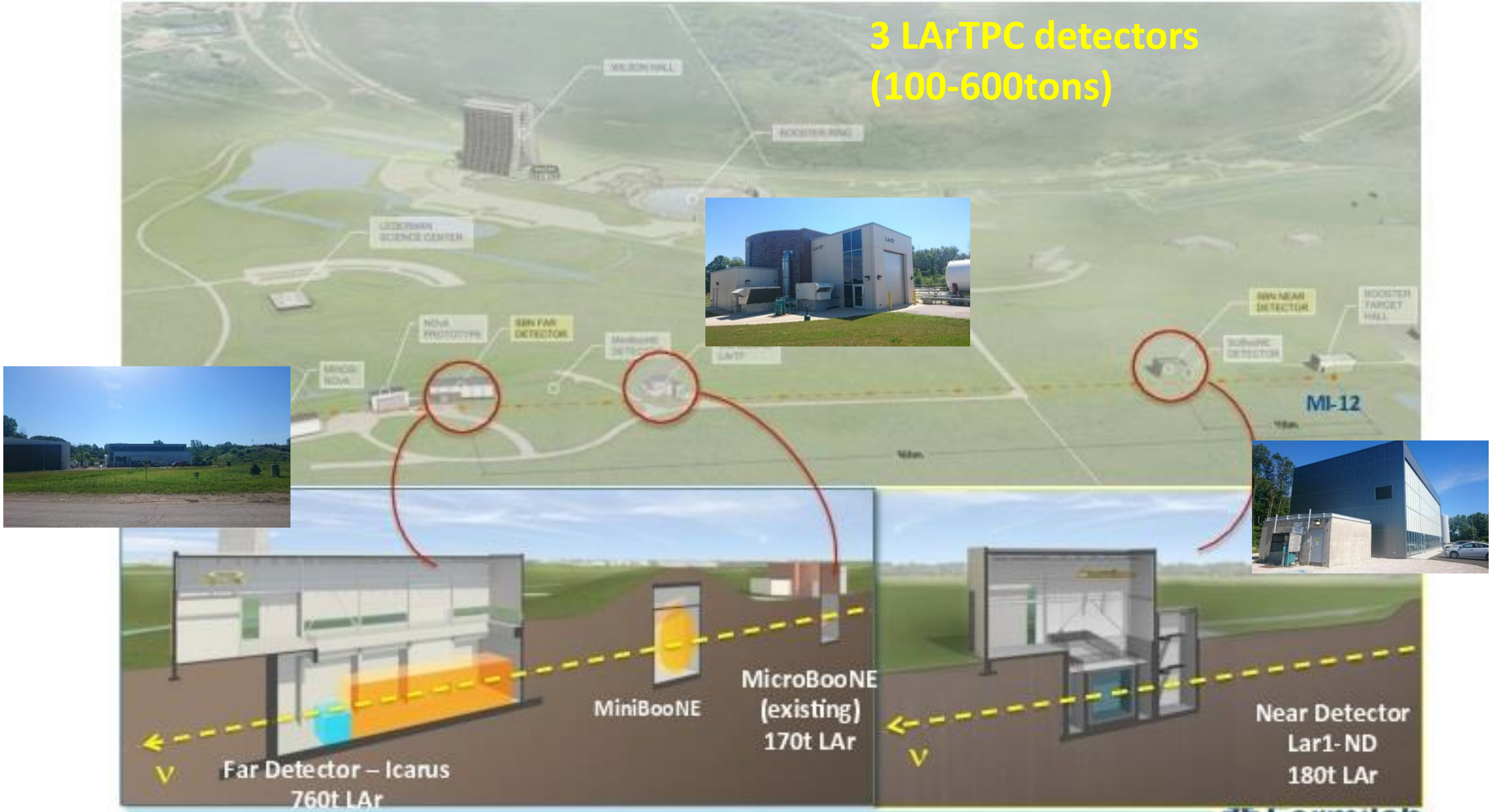
- Except for the neutrino-4 experiment, reactor experiments show the null results.

Current situation / what experimentalists should do

- 3+1 oscillation model cannot explain all phenomena from various experiments. (especially, disappearance measurements ($\nu_\mu \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_e$:except for Neutrino-4) and appearance ones have a tension.)
- If all are true, we absolutely need new physics model.
- Or experimental data is something wrong?? This part is being and will be examined by experimentalists.
  - MicroBooNE (running) / 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.

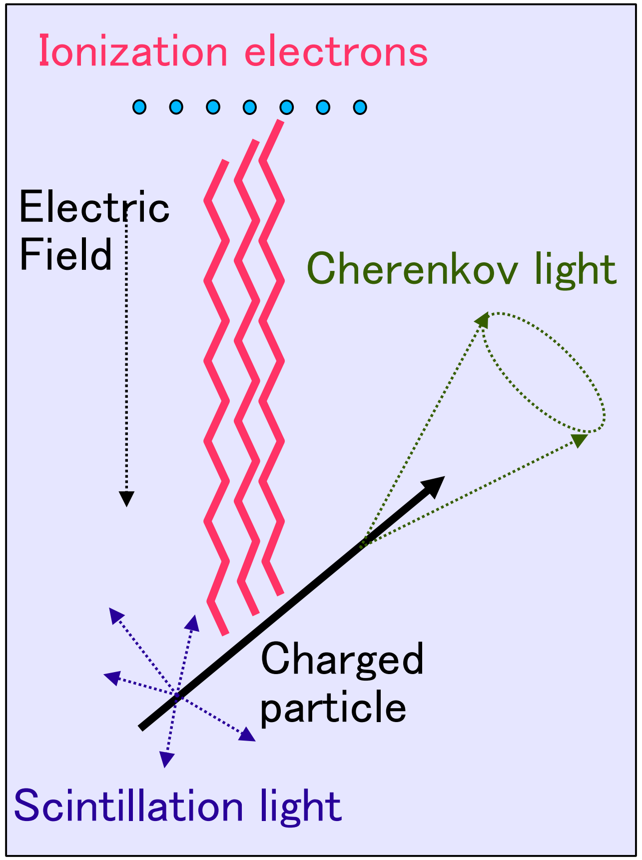
SBN Program Layout

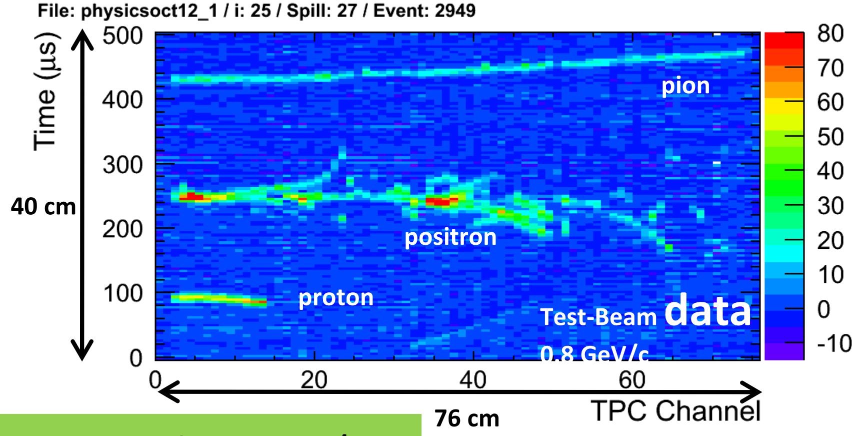
Peter Wilson's talk @ WINP workshop



Liquid Argon TPC

- Principle
  - Quasi-free electrons from ionized tracks are drifted.
    - Charge (MIP)〜1fC/mm (~5500e/mm)
    - drift velocity = 2m/ms @ 1kV/cm
  - Position information from2D (x,y) anode and timing → 3D tracking w/ 1mm resol.
  - No amplification from LAr (different from Gas Ar)
- Features
  - LAr is cheap and high density material
  - LAr TPC has high tracking efficiency
  - Low energy threshold
  - PID by local dE/dx (each wire or strip)
  - Full sampling and homogeneous calorimeter
- Advantages for physics
  - Multi-track meas. -> exclusive meas,
  - Calorimetric energy measurement. (elastic events selection is unneeded.)
  - **Good e/$\pi 0$ separation**

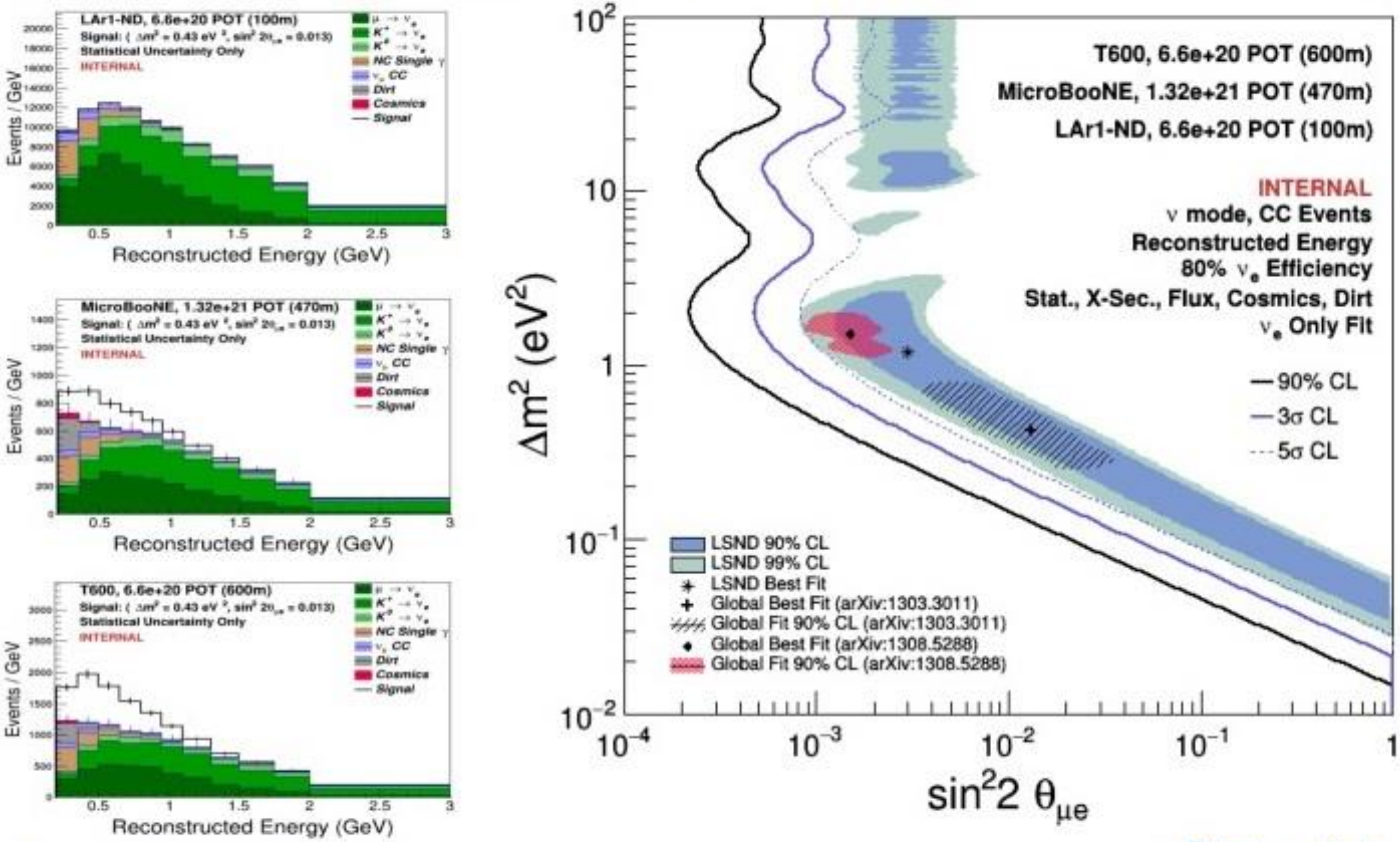




KEK LAr Group has own R&D activity independent from US/EU

SBN ν_e Appearance Sensitivity

Peter Wilson's talk @ WINP workshop

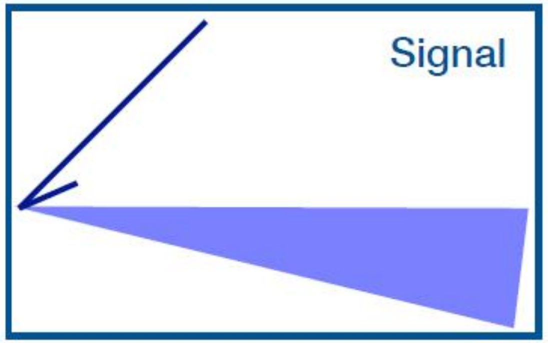


Compared to MiniBooNE, there is no $\pi0$ background events

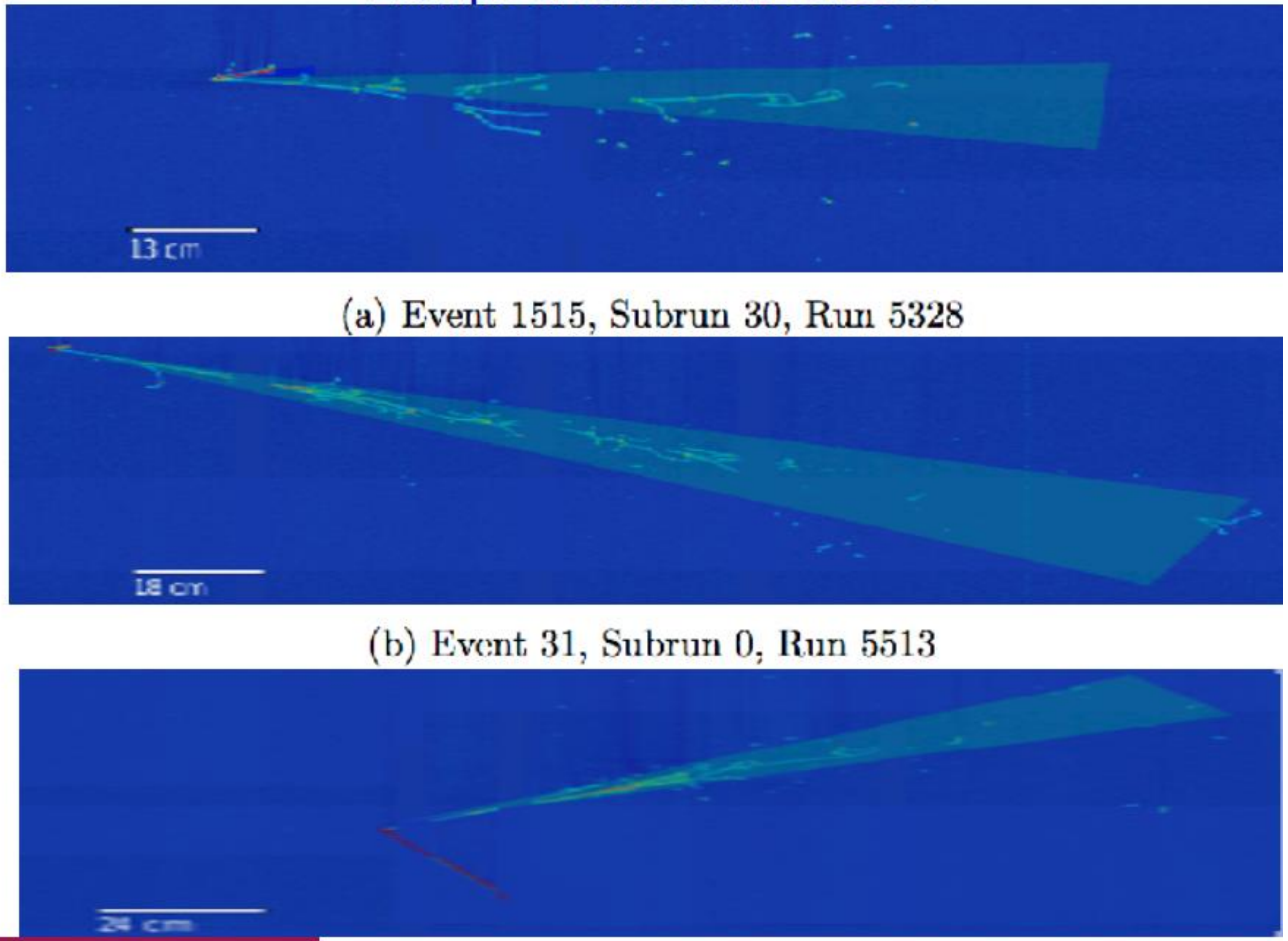
MicroBooNE is running, and ICARUS is now at FNAL. (SBN will start from 2020)

ν_e analysis

One of our first analyses focuses on the signal most similar to the MiniBooNE CC0π definition: 1 electron + N protons



Example of data events selected



(a) Event 1515, Subrun 30, Run 5328

(b) Event 31, Subrun 0, Run 5513

(c) Event 3710, Subrun 74, Run 5906

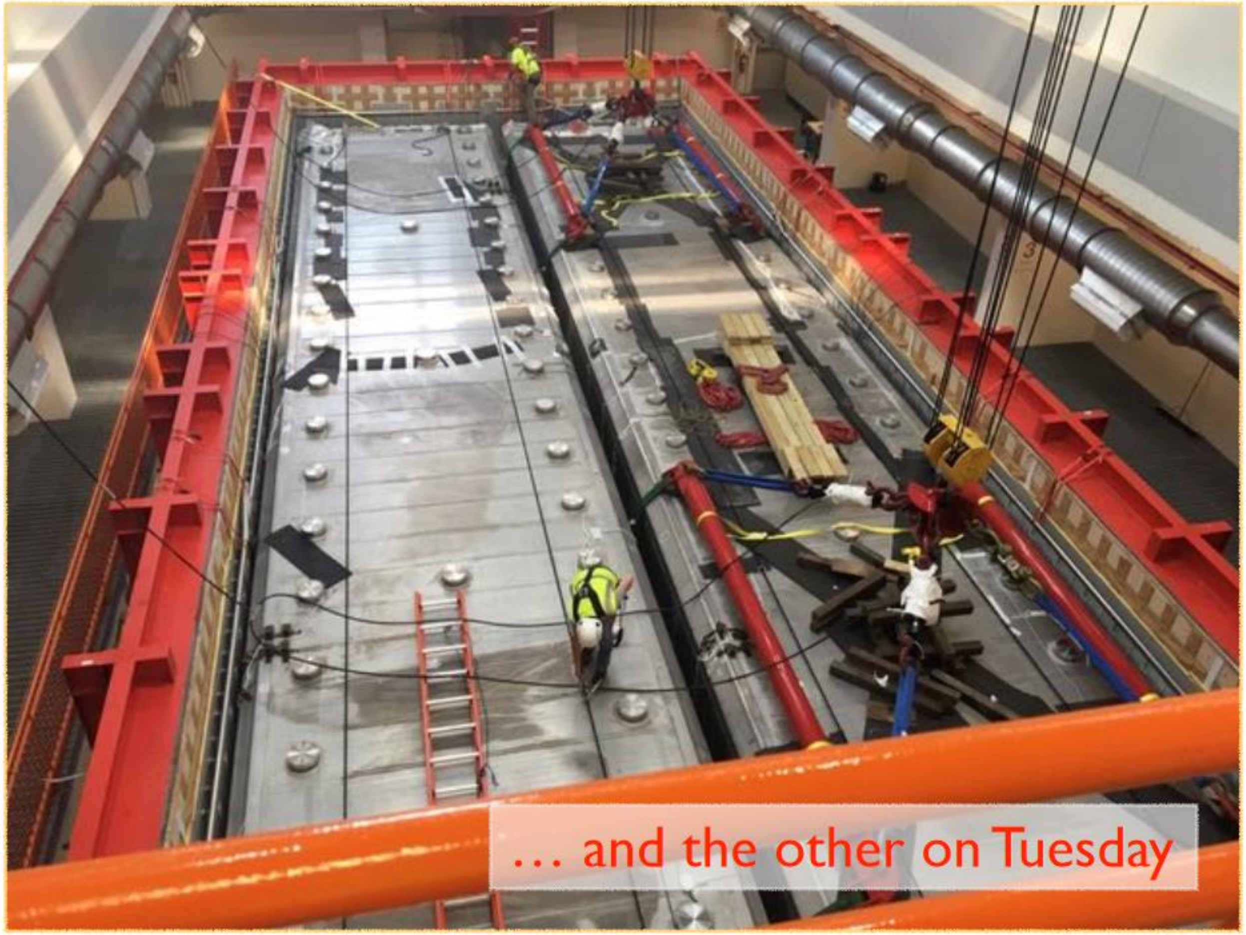
Neutrino2018
Roxanne Guenette

Selected nue data events

Poster: R. Soleti, Electron-neutrino reconstruction in MicrobooNE using the Pandora pattern reconstruction

Public Note: MICROBOONE-NOTE-1038-PUB, 2018

Status of ICARUS



Pictures from Yun-Tse Tsai's slide in NuFACT2018 conference (Aug-18)
(commissioning will be started soon, and data taking will be started by 2019-Sep)

JSNS2 (J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source)

Collaboration meeting @ J-PARC
(2018/Jul)

JSNS^2 collaboration (58 collaborators)

- 6 Japanese institutions (28 members)
- 10 Korean institutions (20 members)
- 1 UK institution (3 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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[16] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN*
[17] *Department of Physics, Kyoto University, Kyoto, JAPAN*
[18] *Department of Physics and Astronomy, University of Sussex, Brighton, UK*
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February 13, 2018

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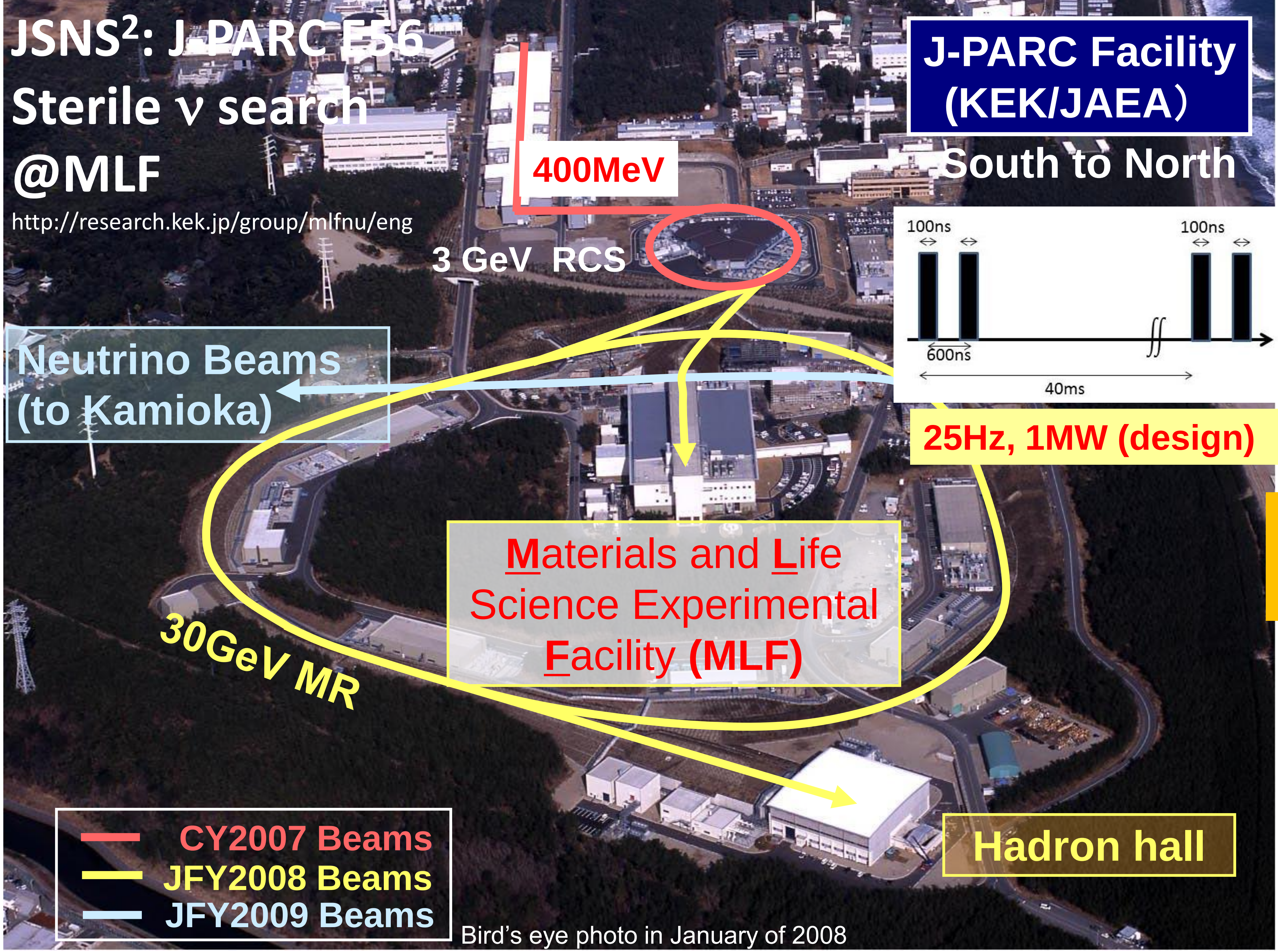
JSNS^2: J-PARC E56 Sterile ν search @MLF

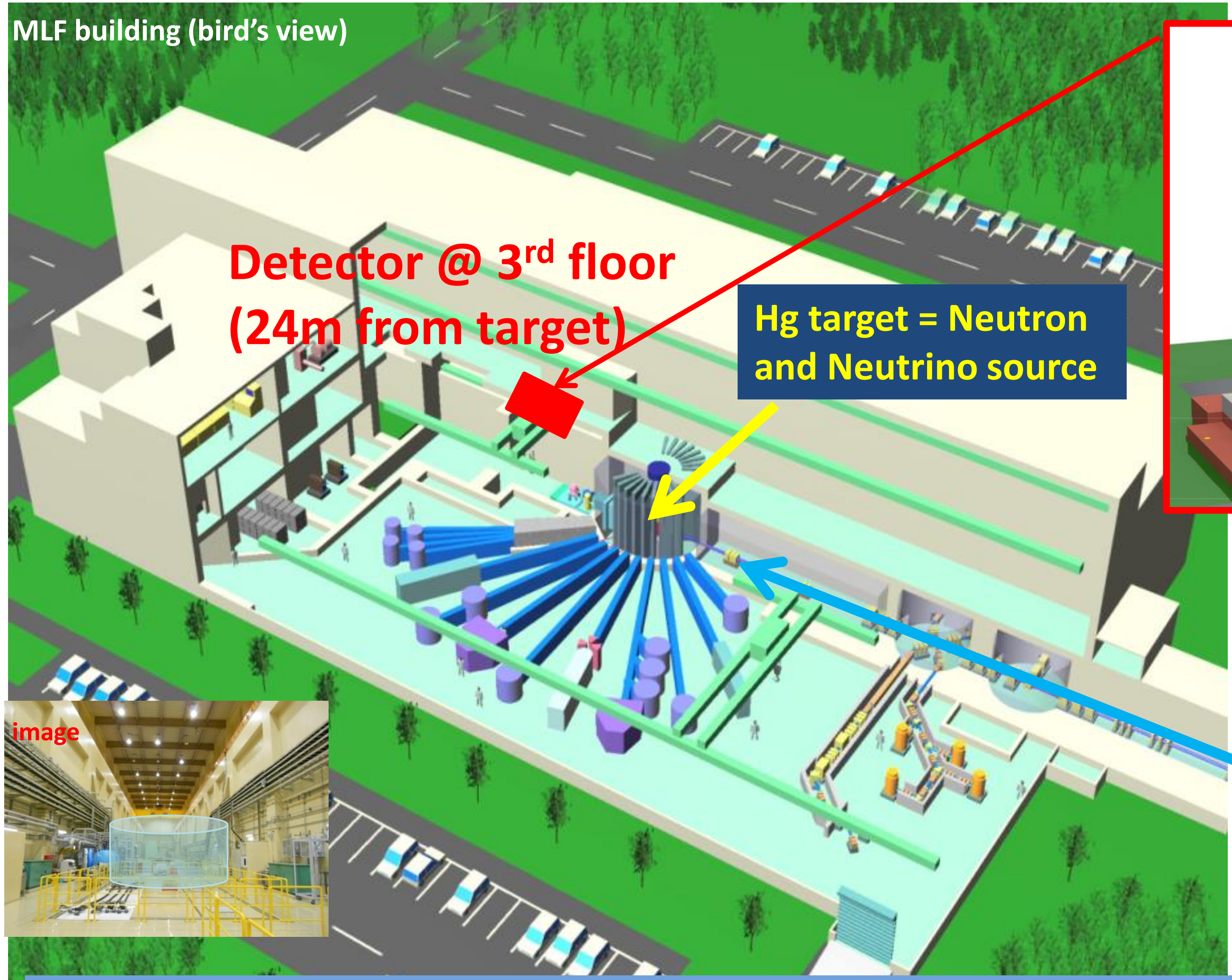
http://research.kek.jp/group/mlfnu/eng

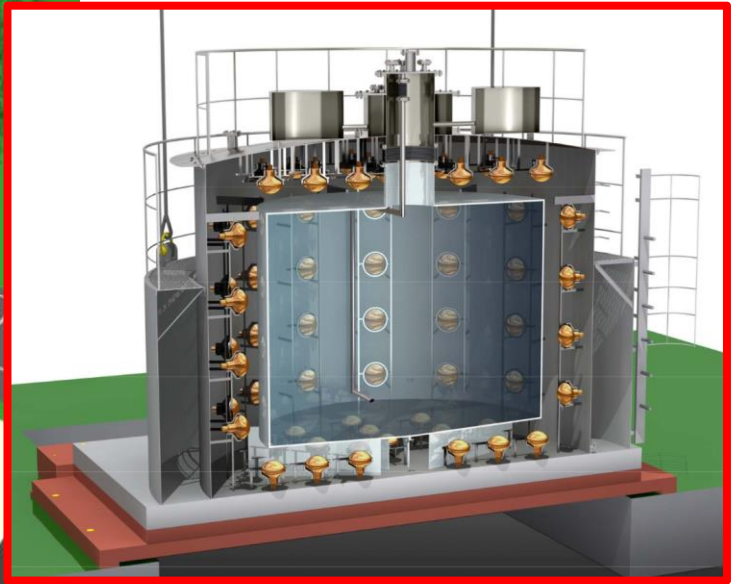


Bird's eye photo in January of 2008

1st 1MW trial was succeeded on July-3.

J-PARC MLF : World best environment





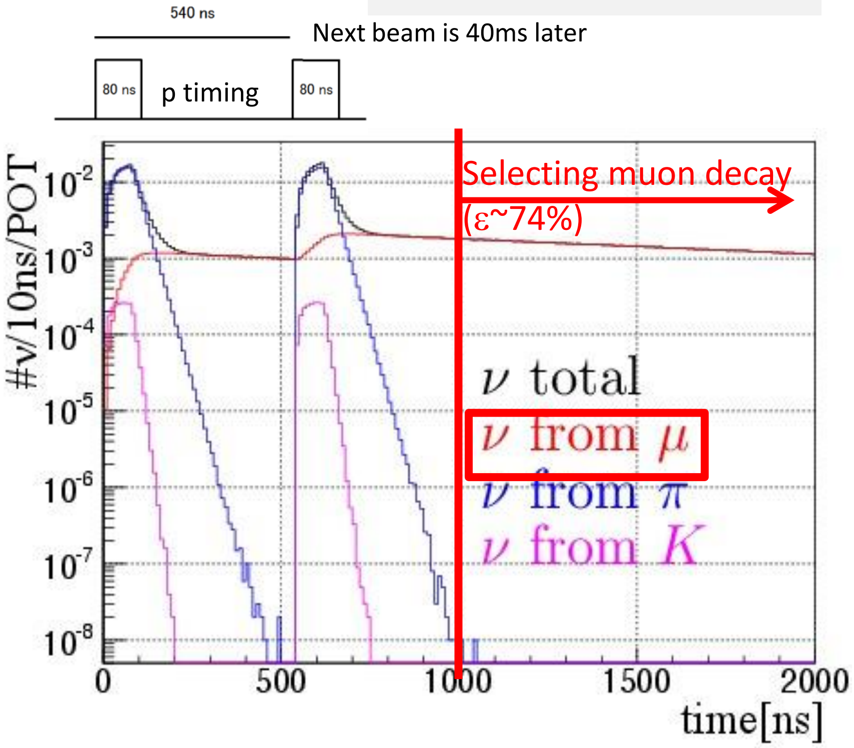
50t liquid scintillator detector (4.6m diameter x 4.0m height) 192PMTs

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

Timing and Energy

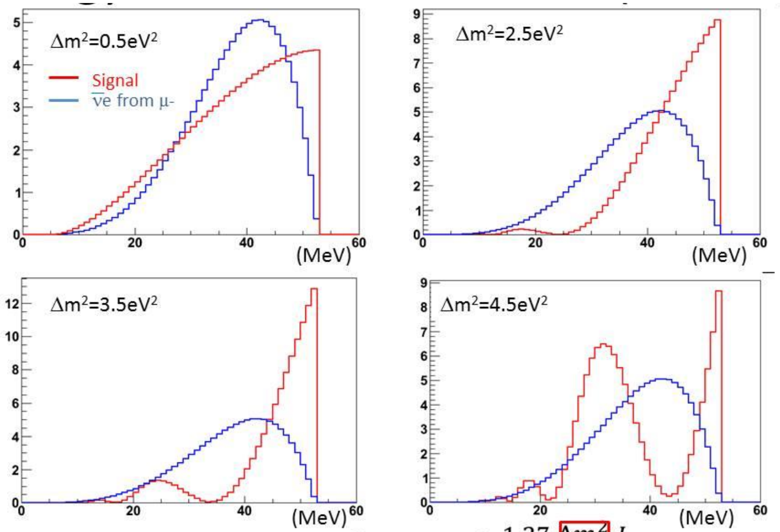
M. Harada *et al*, arXiv:1310.1437



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.

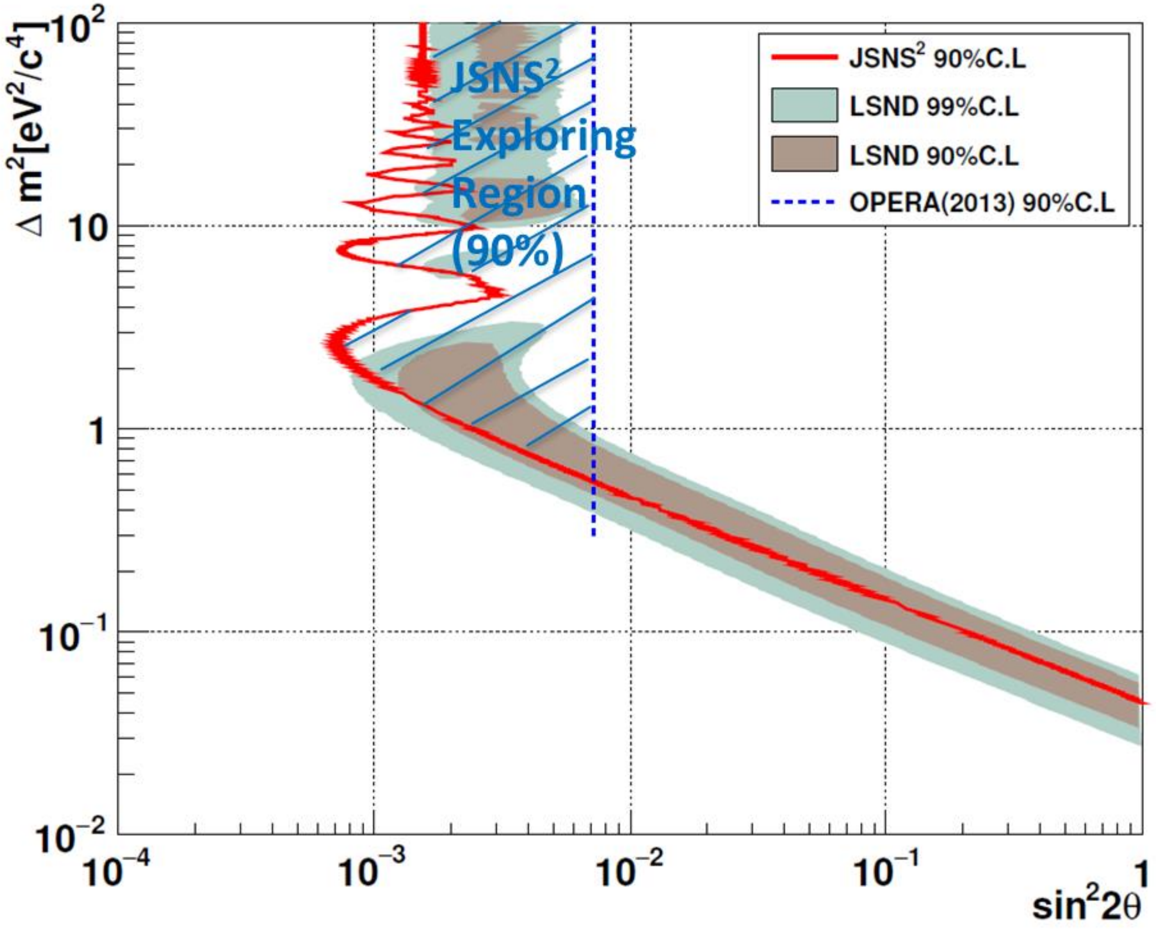
- Energy: signals / BKG separation by energy.
  - ν from μ has well-known spectrum.
  - Energy reconstruction is very easy at the IBD. (Eν ~ Evis + 0.8MeV)
  - ν from μ- is high suppressed.



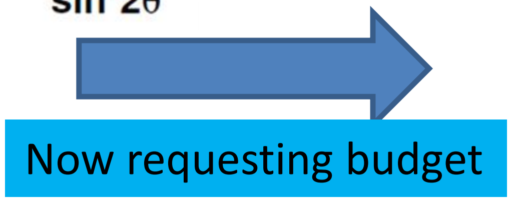
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

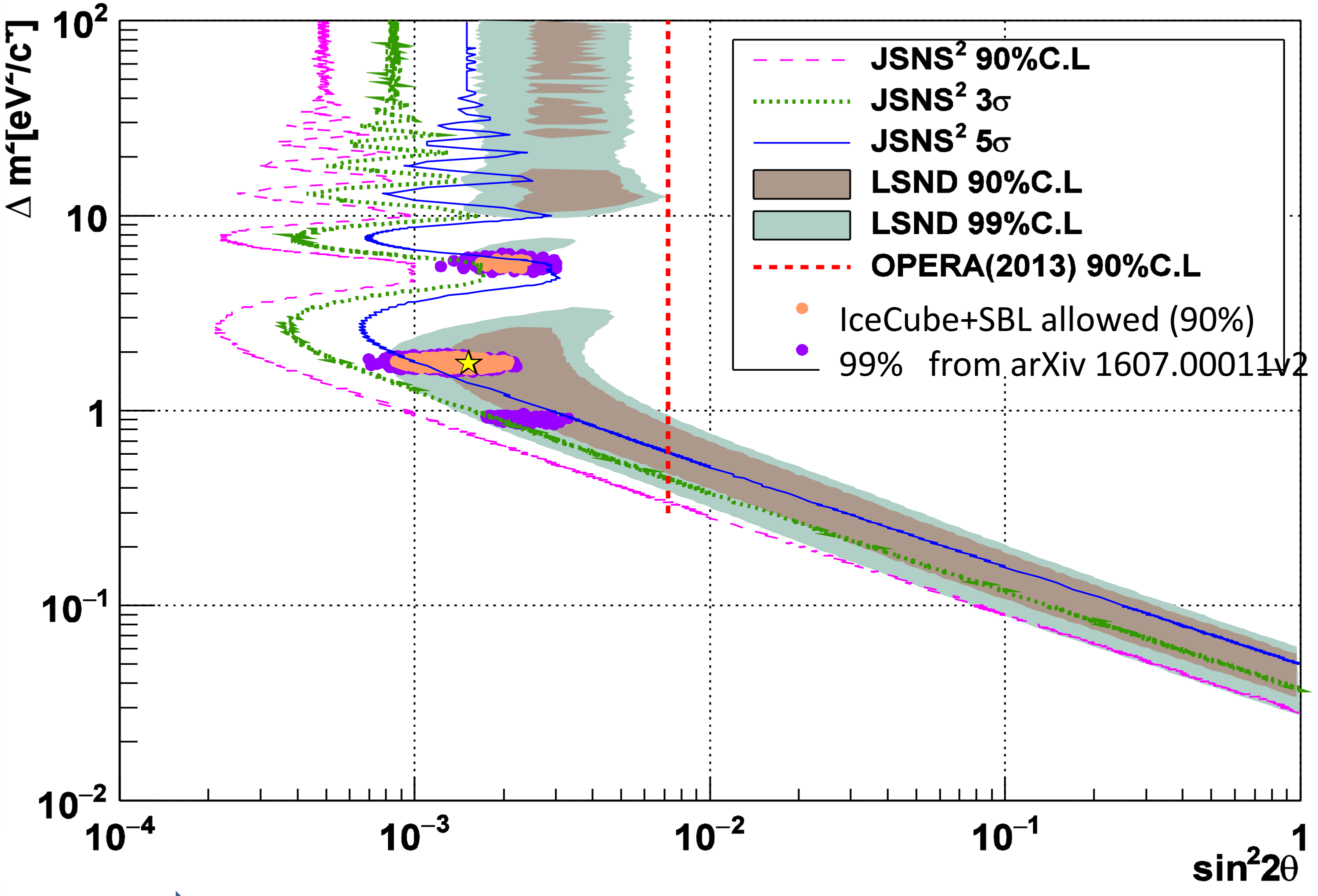
- Energy is smeared by 15%/sqrt(E) (detector E resolution)

Sensitivity of JSNS^2



One detector x 3 years



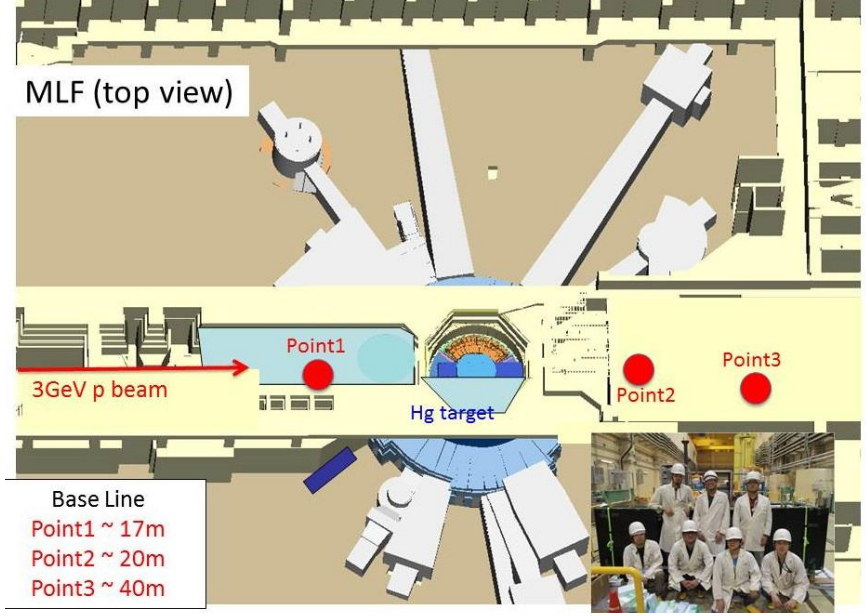


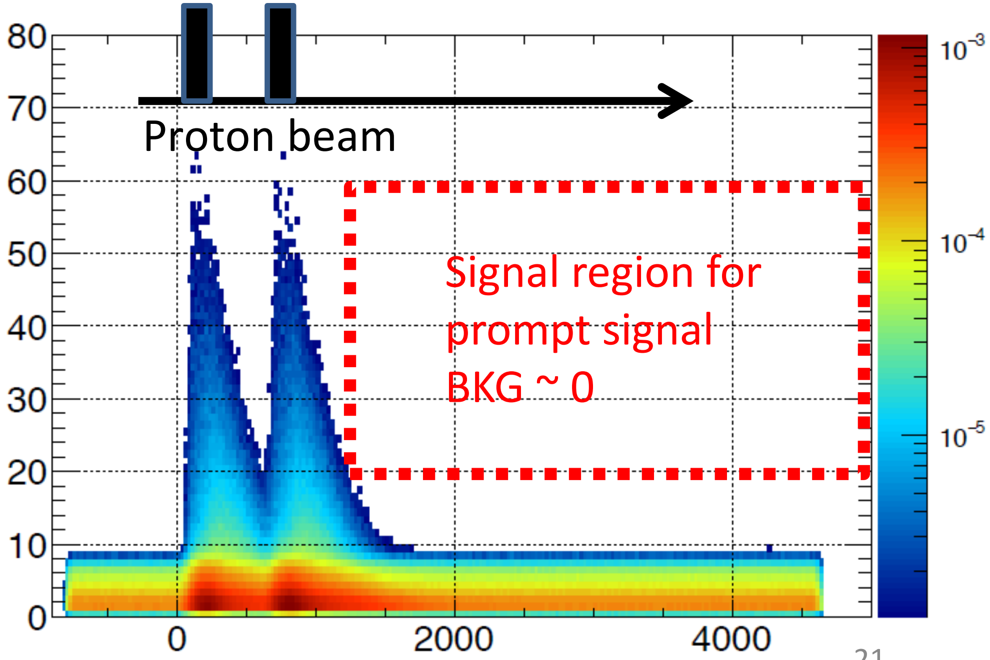
5 years x MW x 2 detectors

Achievements so far

- 2013 Sep; A proposal was submitted to the J-PARC PAC
- 2014 Apr-Jul; We measured the BKG rate on 3rd floor. -> manageable beam /cosmic BKGs to perform JSNS^2
PTEP 2015 6, 063C01 / arXiv:1502.02255
- 2014-Dec; The result was reported to J-PARC PAC. → the stage-1 status was obtained from J-PARC /KEK
- The performance check of detector and safety discussions are being performed.
- 2016-June: The grant-in-aid is 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-Sep: The stage-2 (real go-sign for experiment) was recommended by PAC.

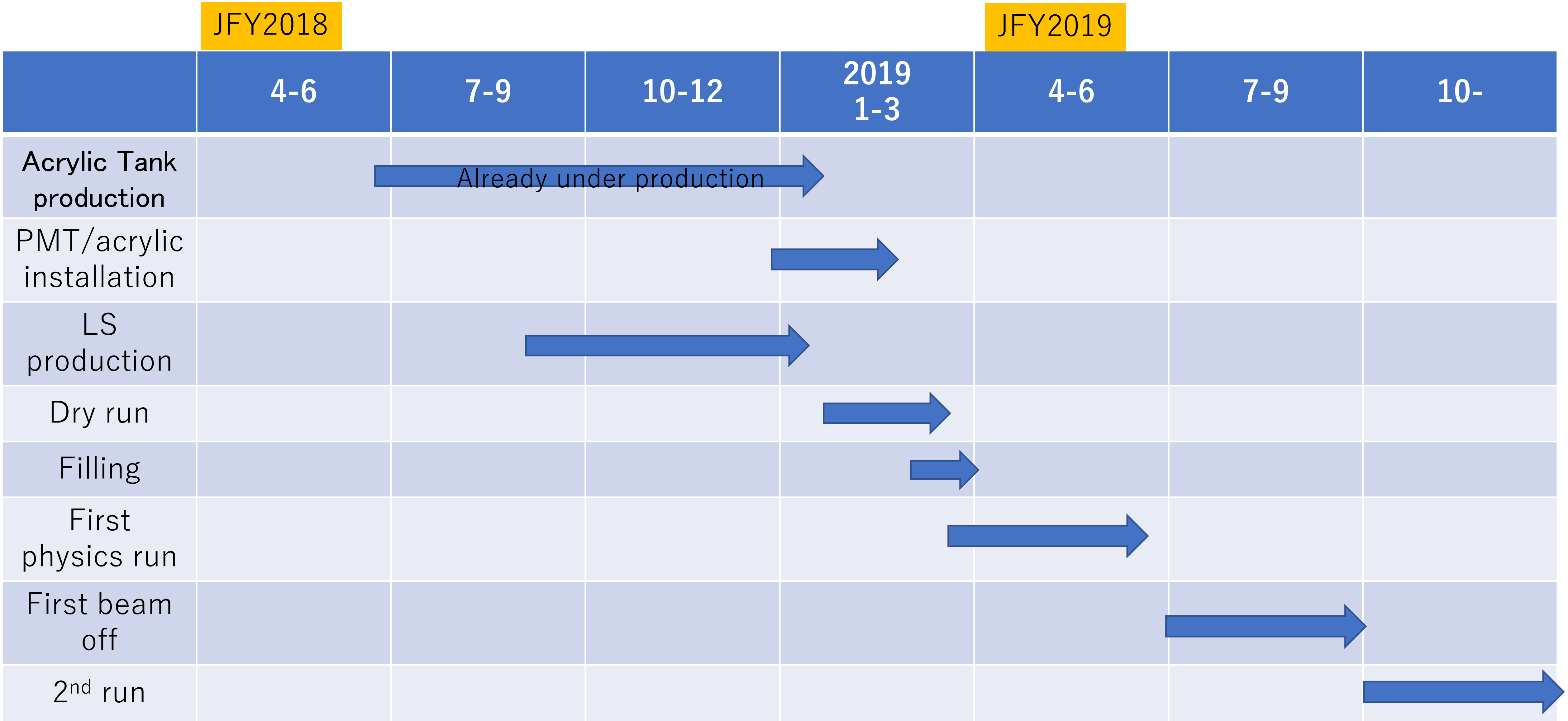
We aim to start JSNS^2 in JFY2018, the detector construction is on-going.





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

Overall schedule



We eager to start the experiment within this JFY to have good competitions, especially to SBN

Stainless tank construction

- Construction at J-PARC (2017/Dec – 2018/Jan)
- Welding, water leak test was done on 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 installation building.

Current status (1)

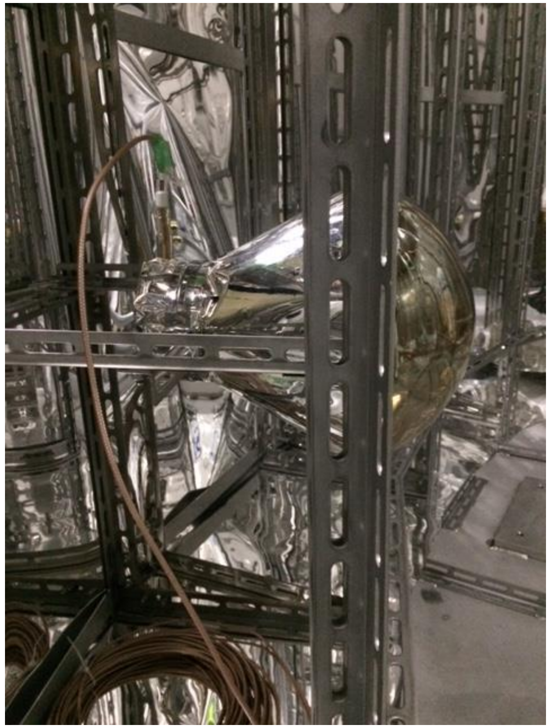
- Cleaning inside of detector was done with pure water and ethanol.
- All pieces of materials were cleaned with ultra-sonic machine with ethanol.

- Installation of PMT support structure and reflector sheet was done.
- Installation of optical separator was done.
- PMTs will be ready in the same timescale with the acrylic tank.

PMT support structure

Reflection sheet

PMT installation



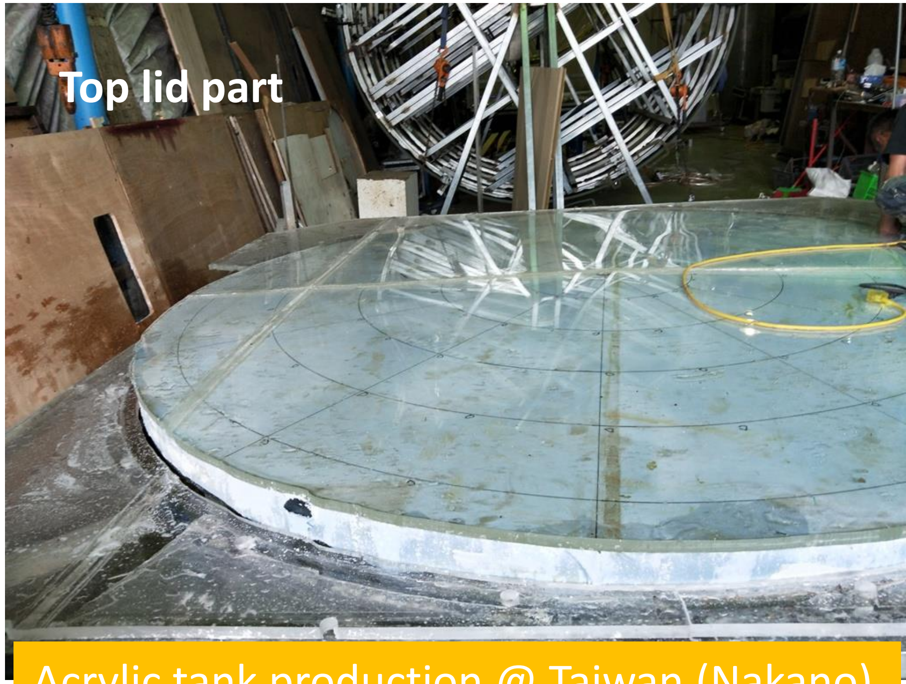
PMT

Current status

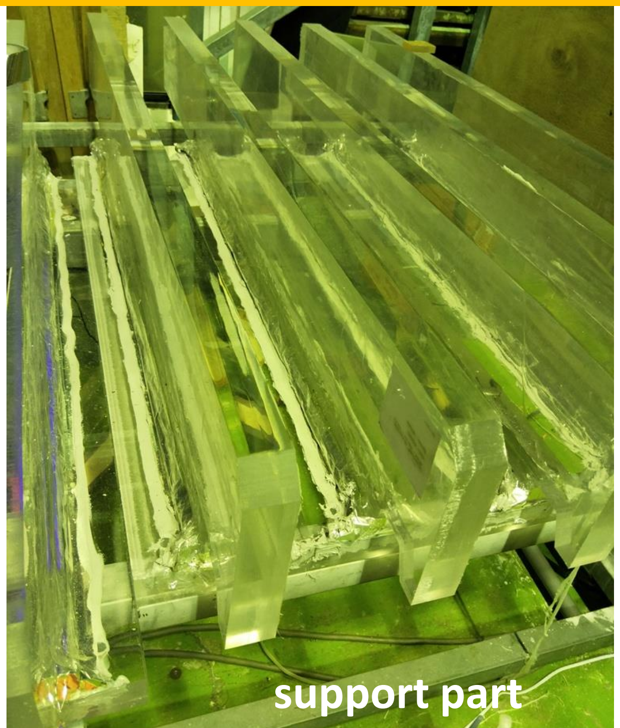
Current status (2)

- Currently, an acrylic tank and the pure-LS are being produced.
- Gd loaded LS (GdLS) will be donated by Daya-Bay experiment. (now at custom work)
- A lot of other hardware / software are in progress.

LS production @ Korea (RENO site)
21 batches in total (37000 L:)
- 4 persons / day (shift)
- 2 of ISO tanks



Acrylic tank production @ Taiwan (Nakano)



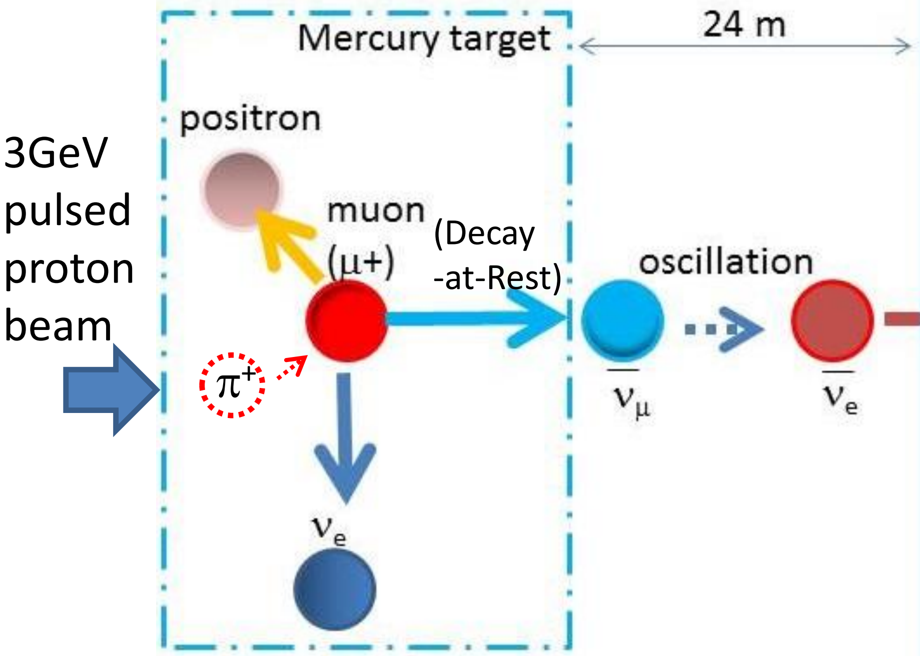
Summary

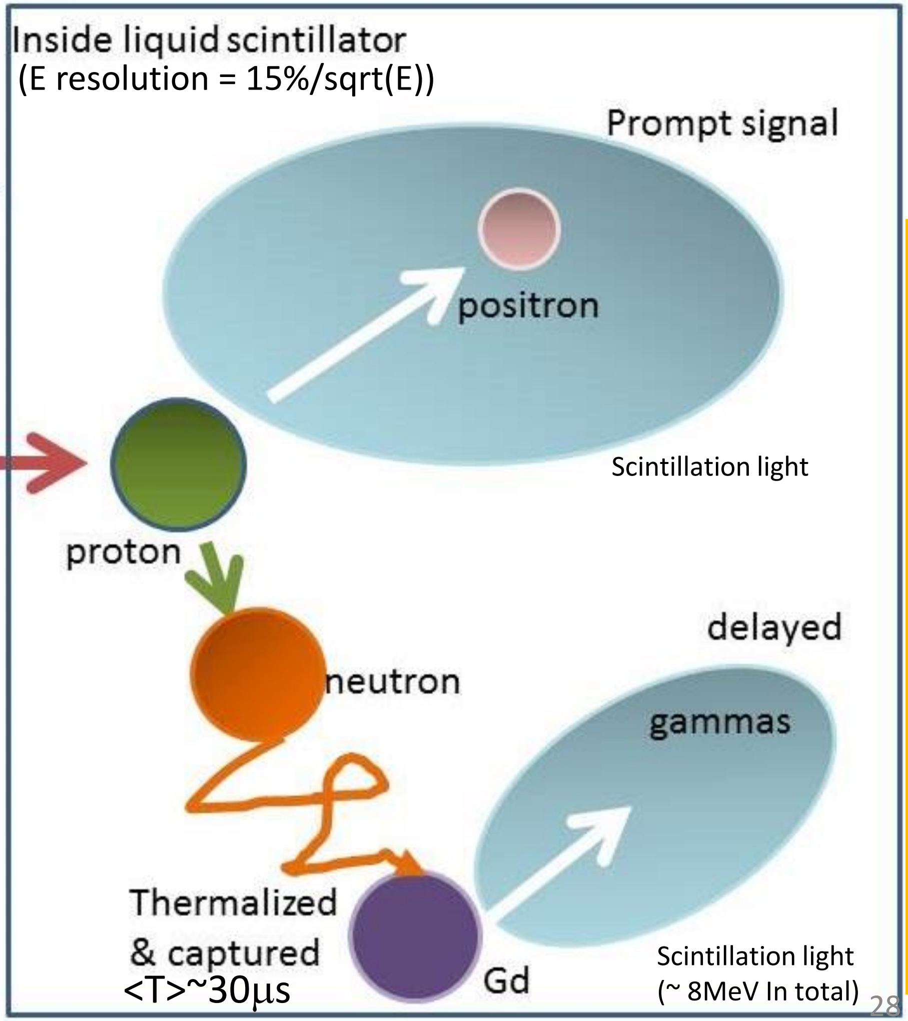
- Confirming or refuting the existence of “Sterile Neutrino” is one of hottest topics in the neutrino community in this 20 years.
- Many experiments are on-going or planned.
  - There are a lot of interesting results from reactor experiments.
  - Also ν_μ disappearance experiments.
  - Currently, results from disappearance experiments (except for Neutrino-4) and results from LSND / MiniBooNE have a tension.
- SBN will start taking data soon. (including the running μBooNE experiment)
- JSNS2 experiment aims to start the experiment from JFY2018. This experiment is a direct ultimate test for the LSND anomaly without any excuses. (same neutrino source and neutrino target but improve S/N by more than 100 and systematics)
- New appearance experiments will have results soon. Enjoy!!

backup

Production / Detection

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

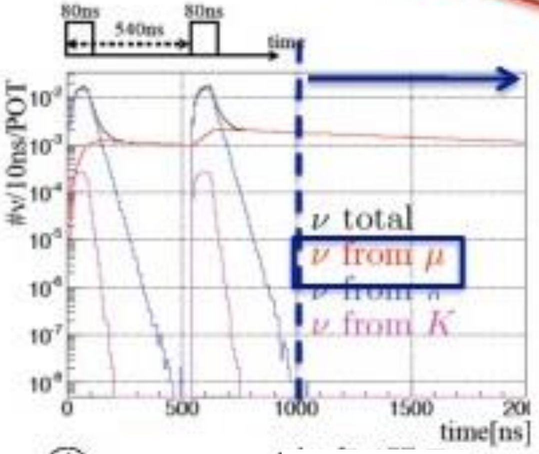
But use much better beam and Gd loaded LS.
→ Much better S/N
→ Much better systematics

IBD event selection

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

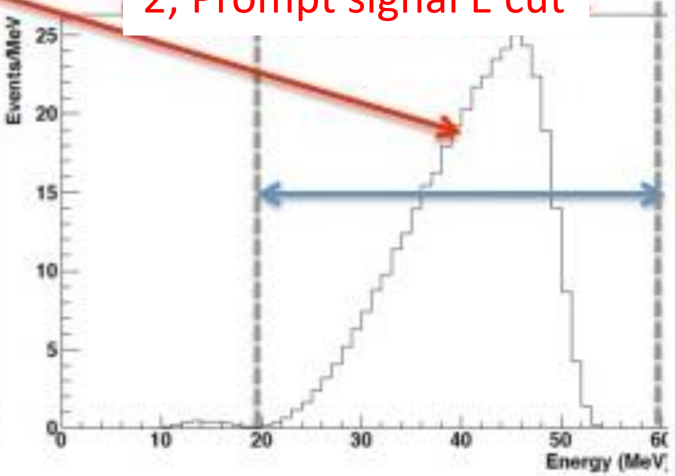
$\bar{\nu}_e + p \rightarrow e^+ + n$ -> n capture ->2(H) or 8MeV(Gd)

Δ m²=3eV², sin²2θ=3e⁻³ case

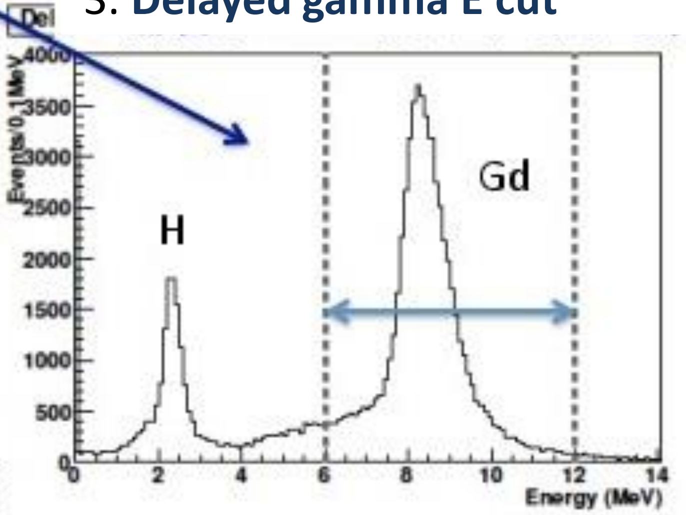


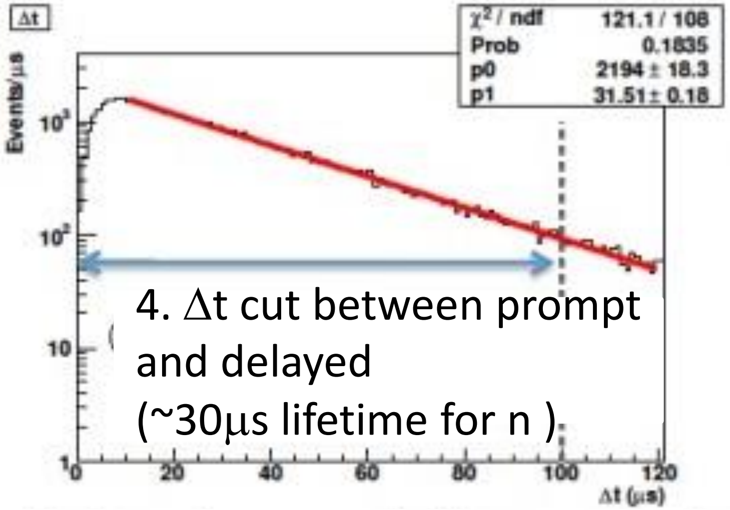
①off bunch

2; Prompt signal E cut

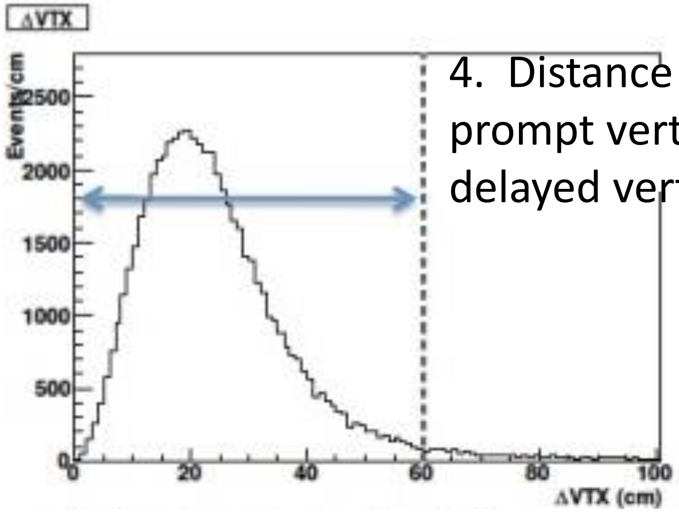


3. **Delayed gamma E cut**





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



4. Distance cut between prompt vertex and delayed vertex

Selection ε ~ 38%

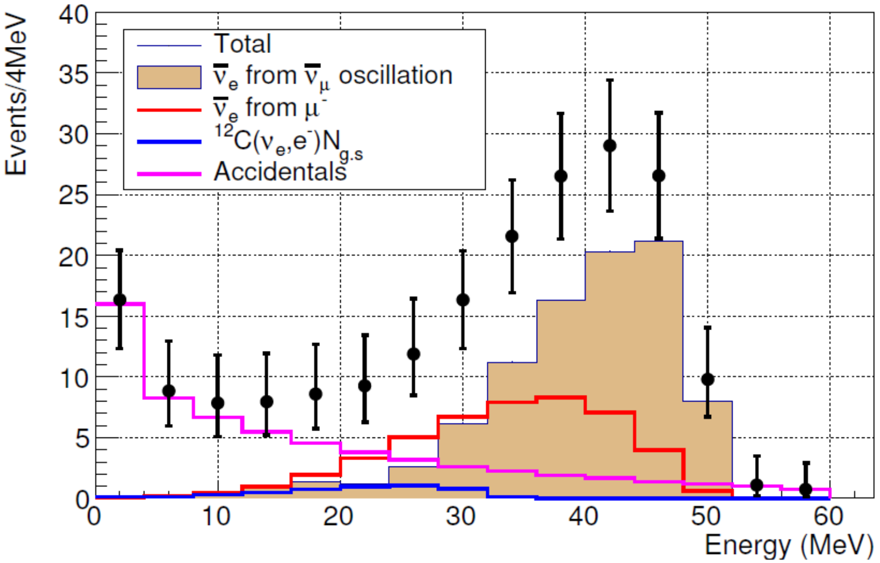
#events (1MW x 3 years x 1 detector (17tons))

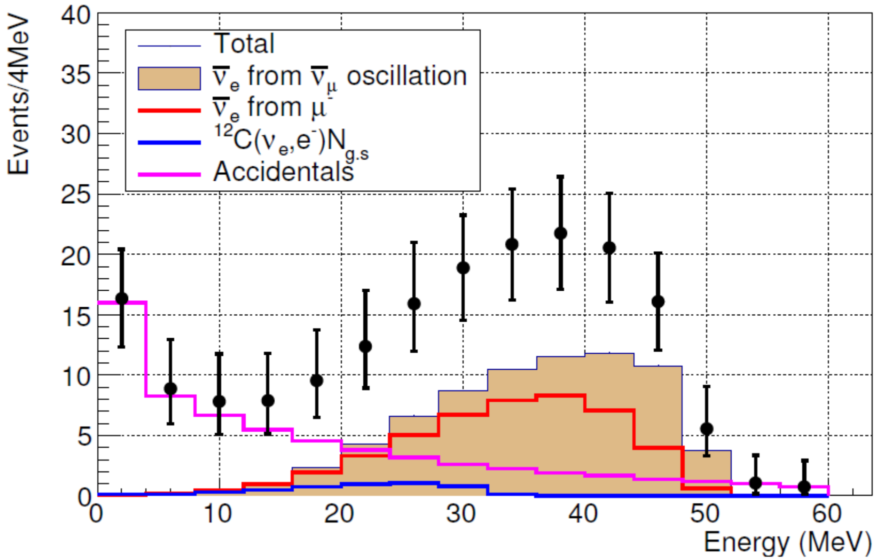
Source	contents	#ev.(17tons x 3years)	Reference : SR2014 (50tons x 5 years)	comments
background	ν_e from μ-	43	237	Dominant BKG
	$^{12}C(\nu_e,e-)^{12}N_{g.s.}$	3	16	
	Beam fast neutrons	**Consistent with 0** **< 2 (90%CL UL)**	**<13**	**Based on real data**
	Fast neutrons (cosmic)	~0	37	
	Accidental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

Accidental BKG is calculated by;R acc = $\Sigma R_{prompt} \times \Sigma R_{delay} \times \Delta_{VTX} \times N_{spill}$

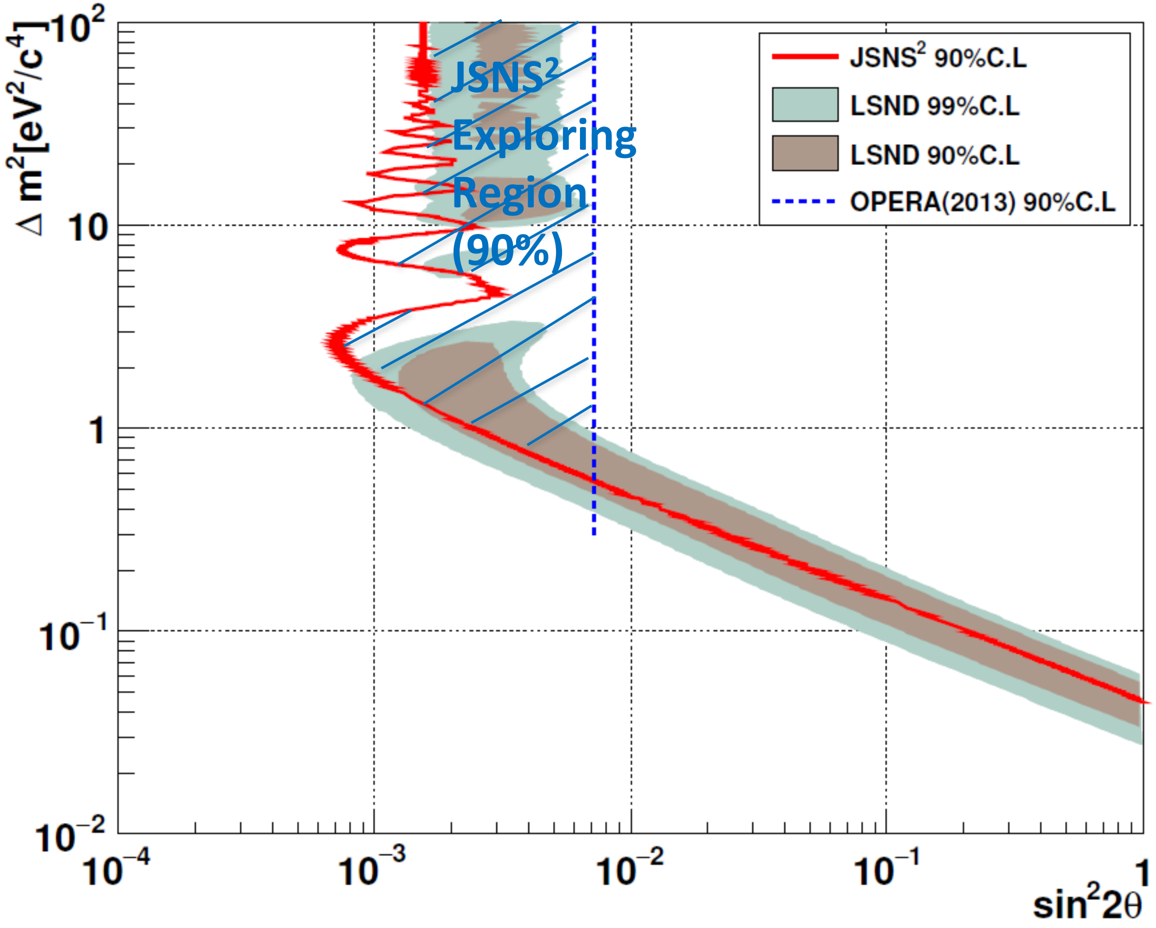
- ΣR_{prompt}, ΣR_{delay} are probability of accidental BKG for prompt and delayed.
- Δ_{VTX} ; BKG rejection factor of **50**.
- N_{spill}(#spills / 5 years) = 1.9×10^9

Energy Spectrum and Sensitivity





- Left: Energy spectrum; （Top: $\Delta m2=2.5eV^2$, Bottom; $1.2eV^2$ $\sin^2 2\theta = 0.003$)
- Right: Sensitivity of 3 years physics running of JSNS2 with **one detector.**
- We aim to start the one detector running from the end of JFY2018, and meanwhile we also try to obtain budget for the second detector.



Movement to assembly building（2018/Mar/14)


Crane work


Tank was put on the low bed Trailer


Around accelerator control building


Around Assembly building

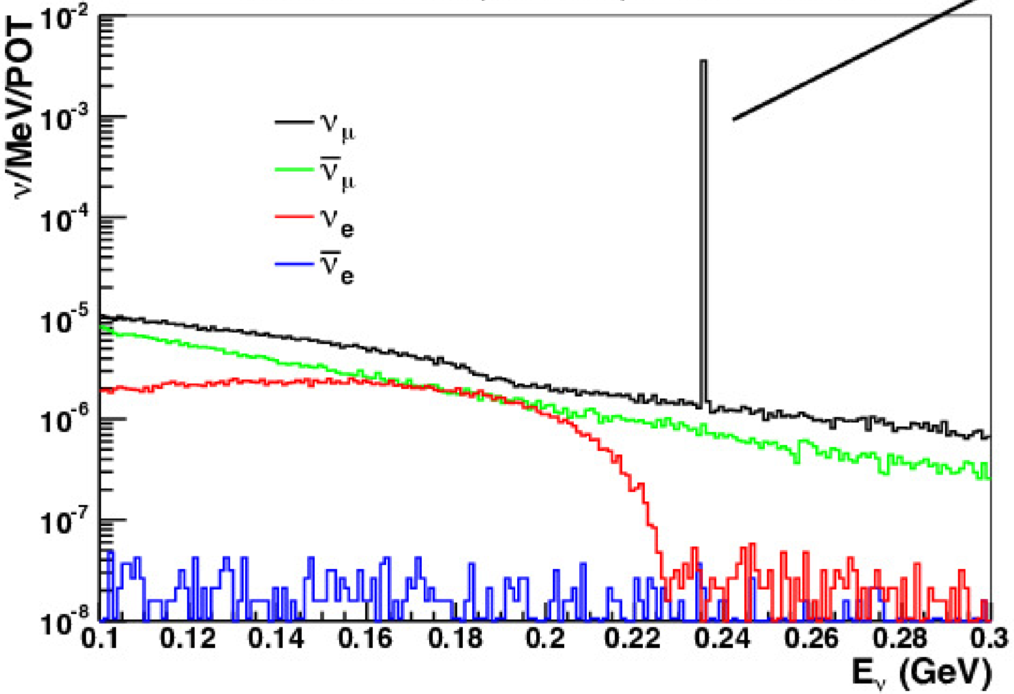

Shutter of Assembly building

The tank was moved for almost 2.2km.


Assembly building

Other physics in $JSNS^2$

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



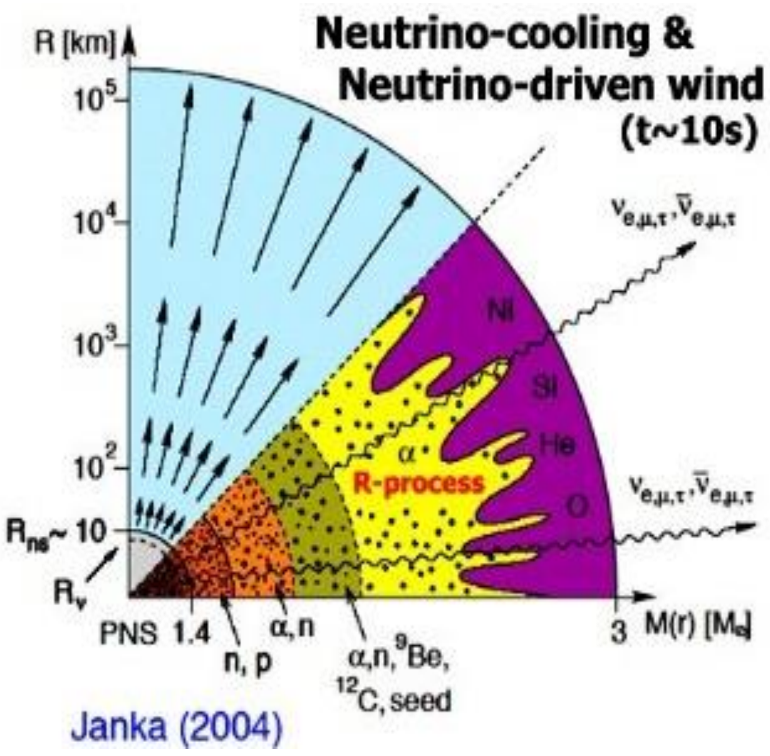
- Use this neutrino as a probe of the nucleus and as a standard candle for xsec and energy reconstruction near 236 MeV.

- 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.

Event rate expectation

Detector (source)	Target (mass)	Exposure	Distance from source	236 MeV ν_μ CC events
JSNS^2 (JPARC-MLF)	Gd-LS (50 ton)	1.875×10^{23} POT (5 years)	24 m	152000

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)