Sterile Neutrino Search at JSNS^2

입자물리분과 전략미팅 **(2019. 9.20 – 21)**

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(Seoul National University)
Sep. 20, 2019

Sterile Neutrino

Sterile neutrino : insight for the questions beyond the SM
(e.g. PLB 631, 151 (2005))

- No strong, EM and weak interactions
- Introduced to explain both results of LSND and LEP
- Maybe recognized by neutrino oscillations
- Could be right-handed neutrino or new particle
- Beyond the PMNS standard oscillation
- Indicated by LSND, MiniBooNE, reactor anomaly, and Ga experiment

Sterile neutrino can be also one of the Dark Matter candidate?

Hints for Sterile Neutrino ($\Delta m^2 \sim 1$ eV^2)

- Anomalies that cannot be explained by standard neutrino oscillations for ~20 years

Experiments	Neutrino source	signal	significance	E(MeV),L(m)
LSND	μ Decay-At-Rest	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	3.8σ	40,30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	4.5σ	800,600
		$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	2.8σ	
		combined	4.8σ	
Ga (calibration)	e capture	$\nu_e \rightarrow \nu_x$	2.7σ	<3,10
Reactors	Beta decay	$\overline{\nu}_e \rightarrow \overline{\nu}_x$	3.0σ	3,10-100

→ Excess or deficit does really exist?

→ A new oscillation between active and inactive (sterile) neutrinos?

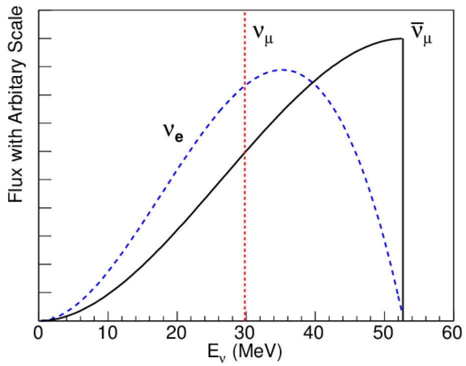
→ However, no indication for $\nu_\mu \rightarrow \nu_\mu$ and negative results from recent reactor measurements using energy spectra

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

LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Signal

1998 at LANL

($\bar{\nu}_e$ appearance)



$\pi^+(\text{stop}) \rightarrow \mu^+ + \nu_\mu$ DAR

$\quad \hookrightarrow \mu^+(\text{stop}) \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

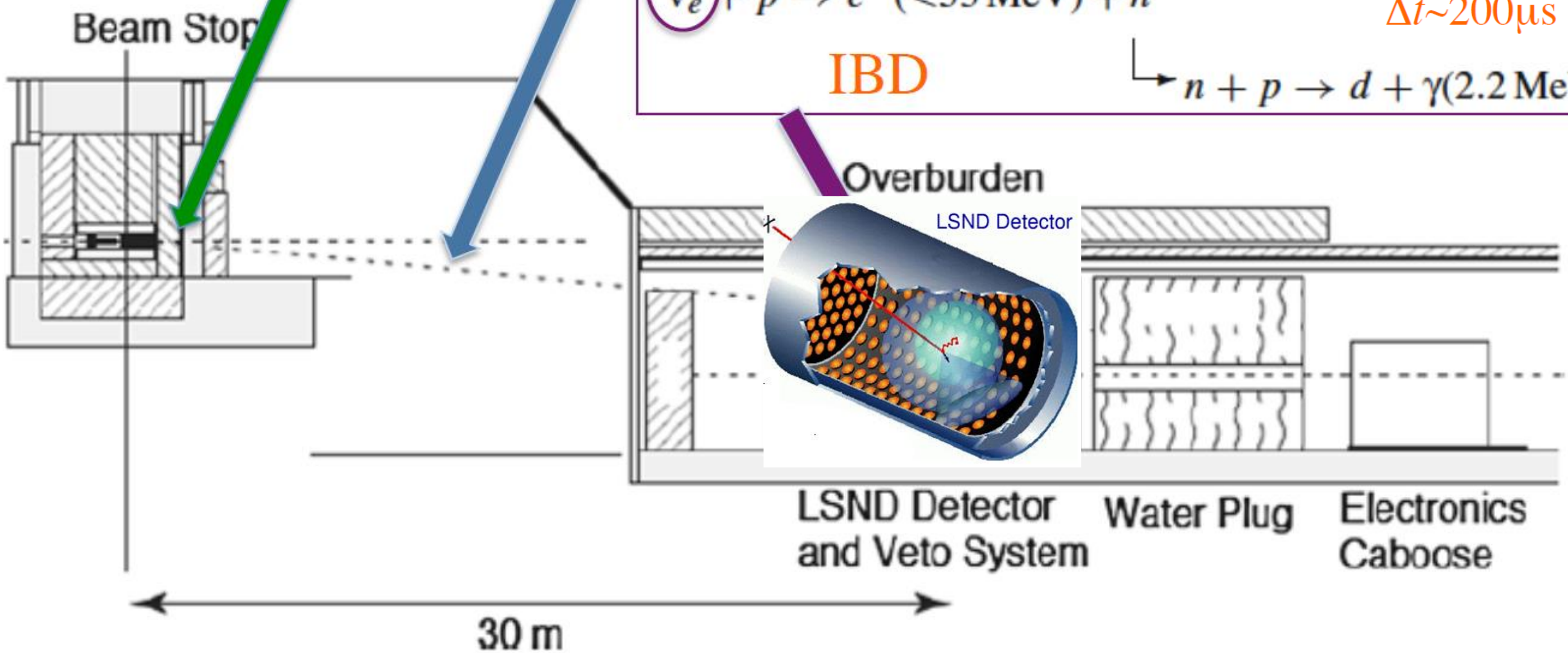
800MeV p

Liquid Scintillator

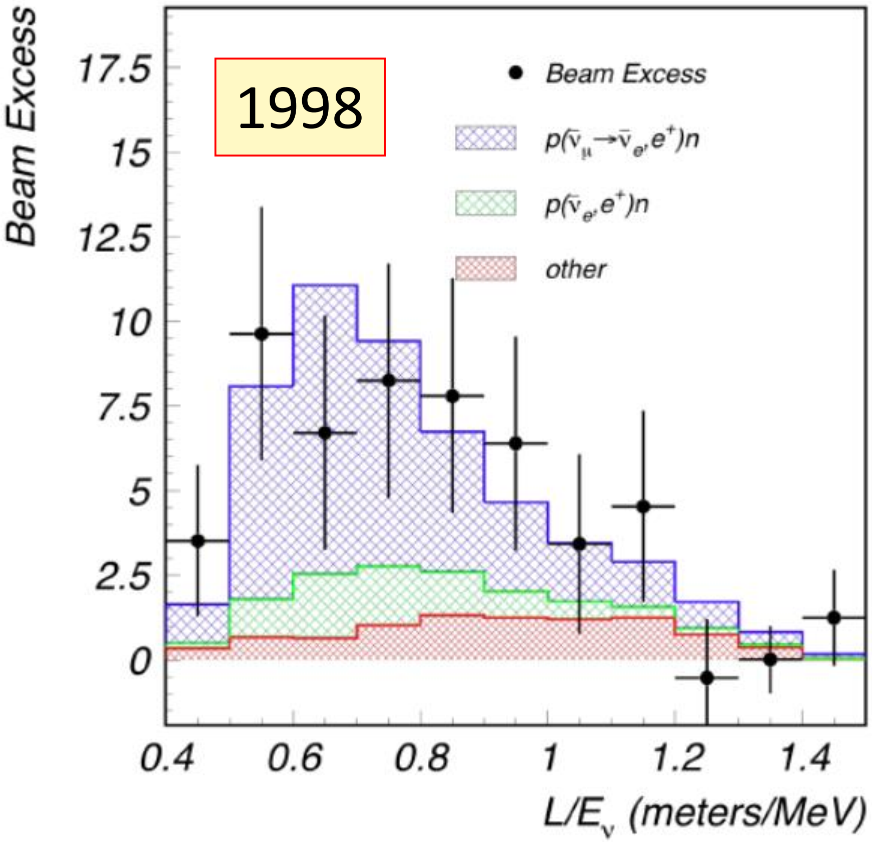
$\bar{\nu}_e + p \rightarrow e^+(<53\,\text{MeV}) + n$ IBD

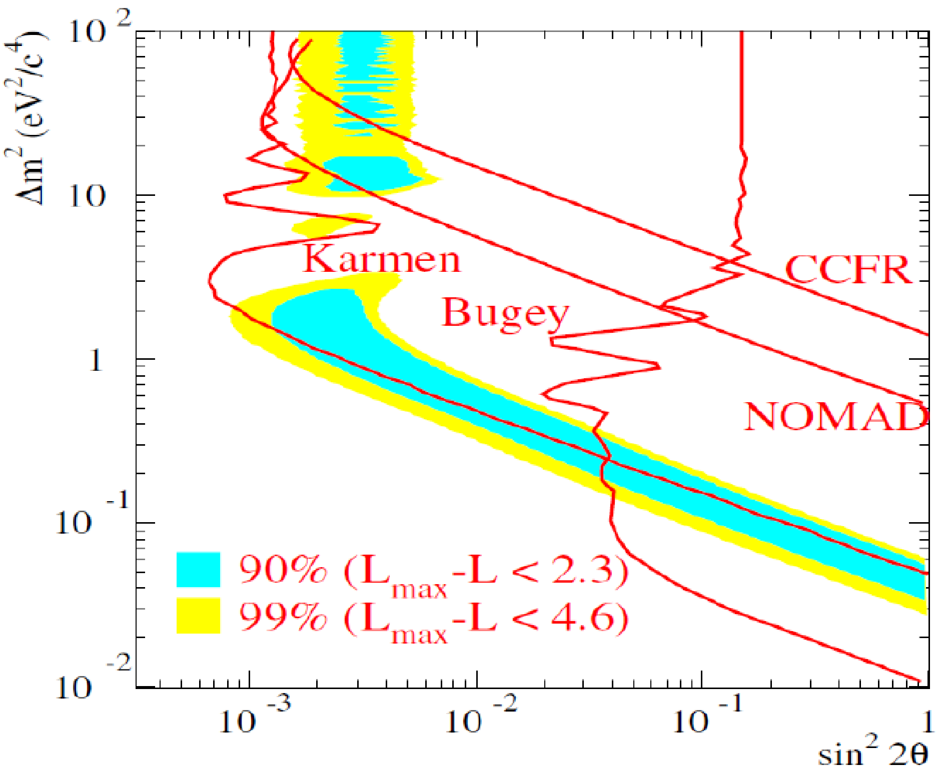
$\quad \hookrightarrow n + p \rightarrow d + \gamma(2.2\,\text{MeV}).$

Delayed Coincidence $\Delta t \sim 200\mu s$



LSND Results and Allowed Region





$$\Delta m^2_{SBL} \gtrsim 0.1\,eV^2 \gg \Delta m^2_{ATM}$$

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

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

3.8 σ evidence for oscillation.

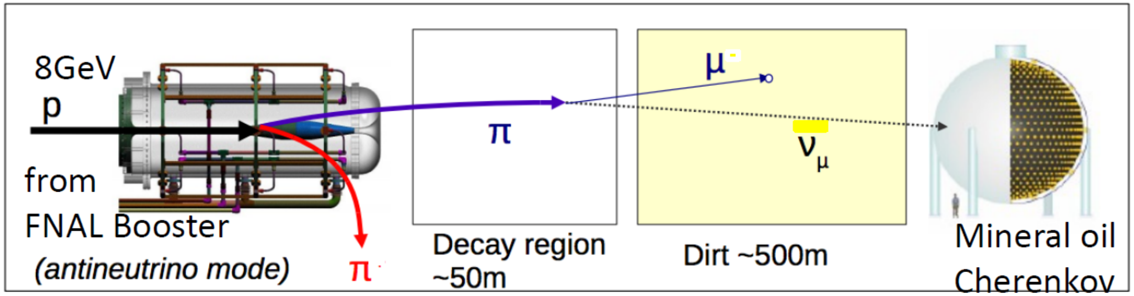
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

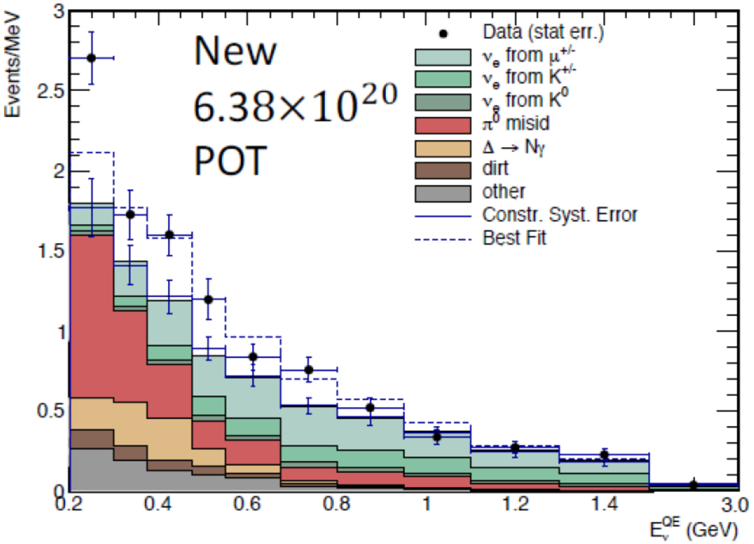
(1990-1995, 1997-1999)

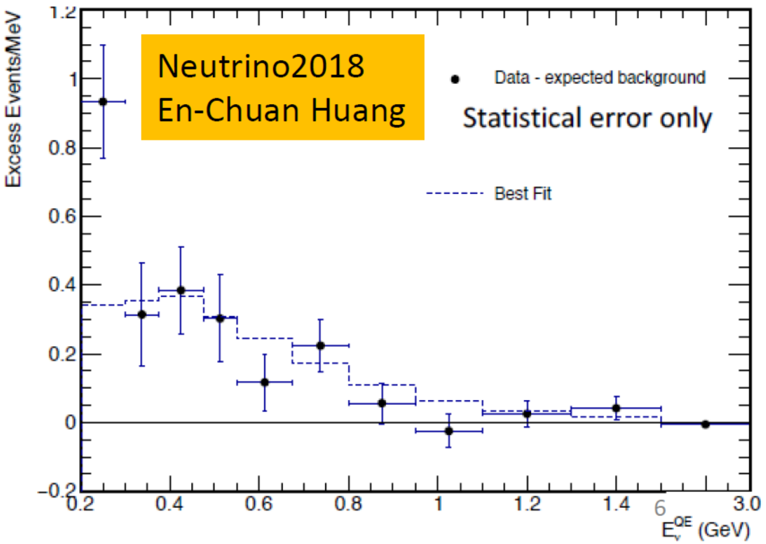
But signal not seen by KARMEN at $L \simeq 18\,m$ with the same method

[PRD 65 (2002) 112001]

MiniBooNE Latest Results







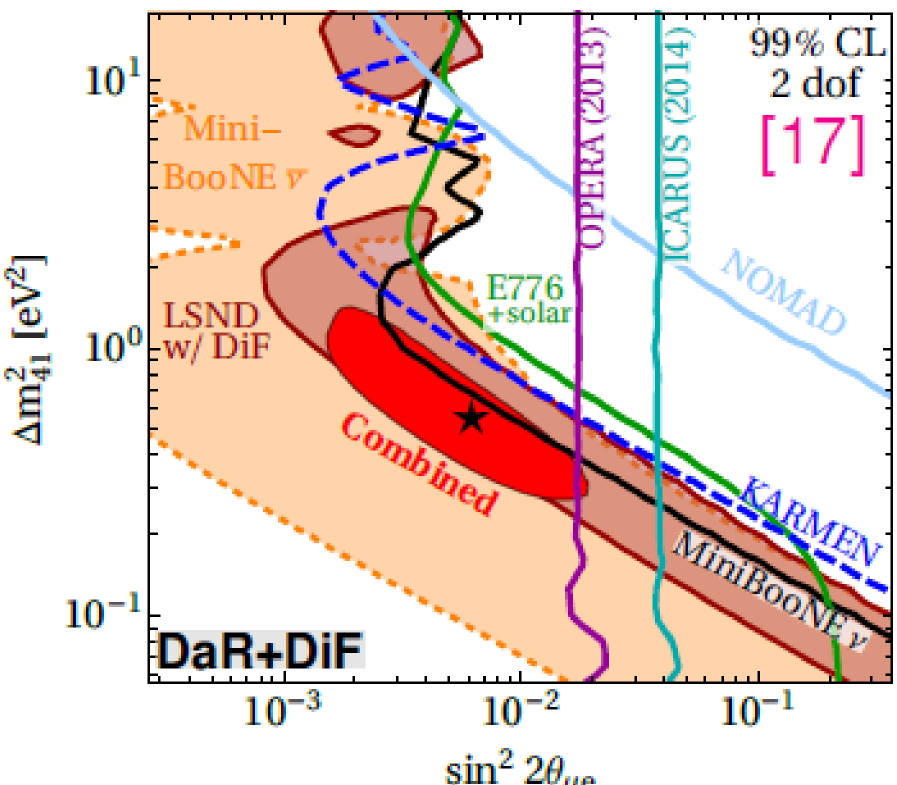
- Significant excess of low energy events : 4.5 σ
- The excess is claimed due to the same oscillation observed by the LSND.
- Concerns on systematic uncertainties of neutrino interactions and background understanding
- MicroBooNE can check the excess due to the gamma rays or electron antineutrinos

Sterile Neutrino Oscillation

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

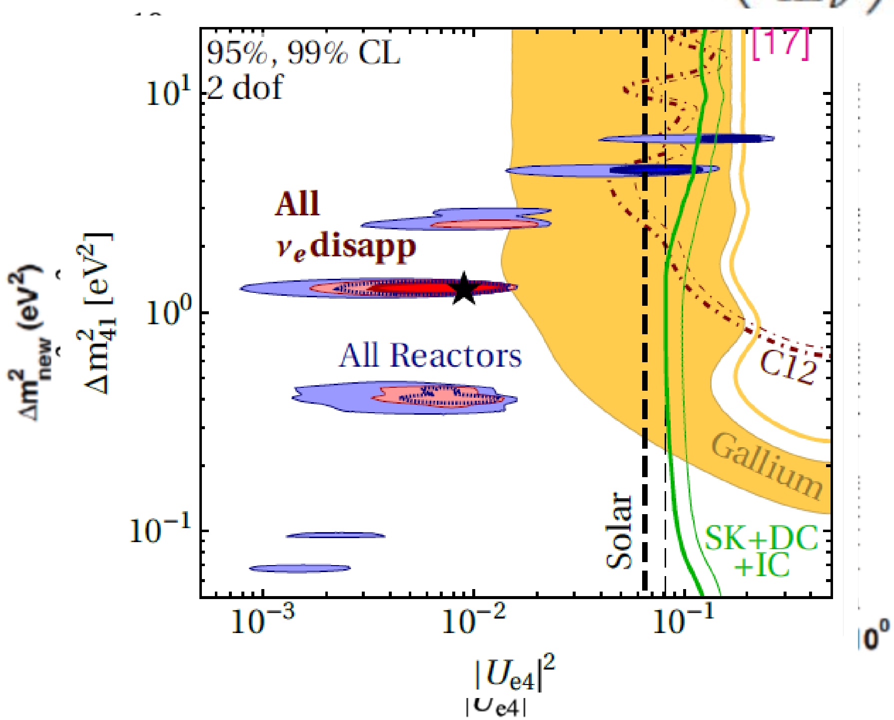
$$|U_{s4}|^2 \sim 0.9, \quad |U_{e4}|^2 \sim 0.1, \quad |U_{\mu 4}|^2 \sim 0.01$$
$$m_4 > 1eV$$

ν_e Appearance



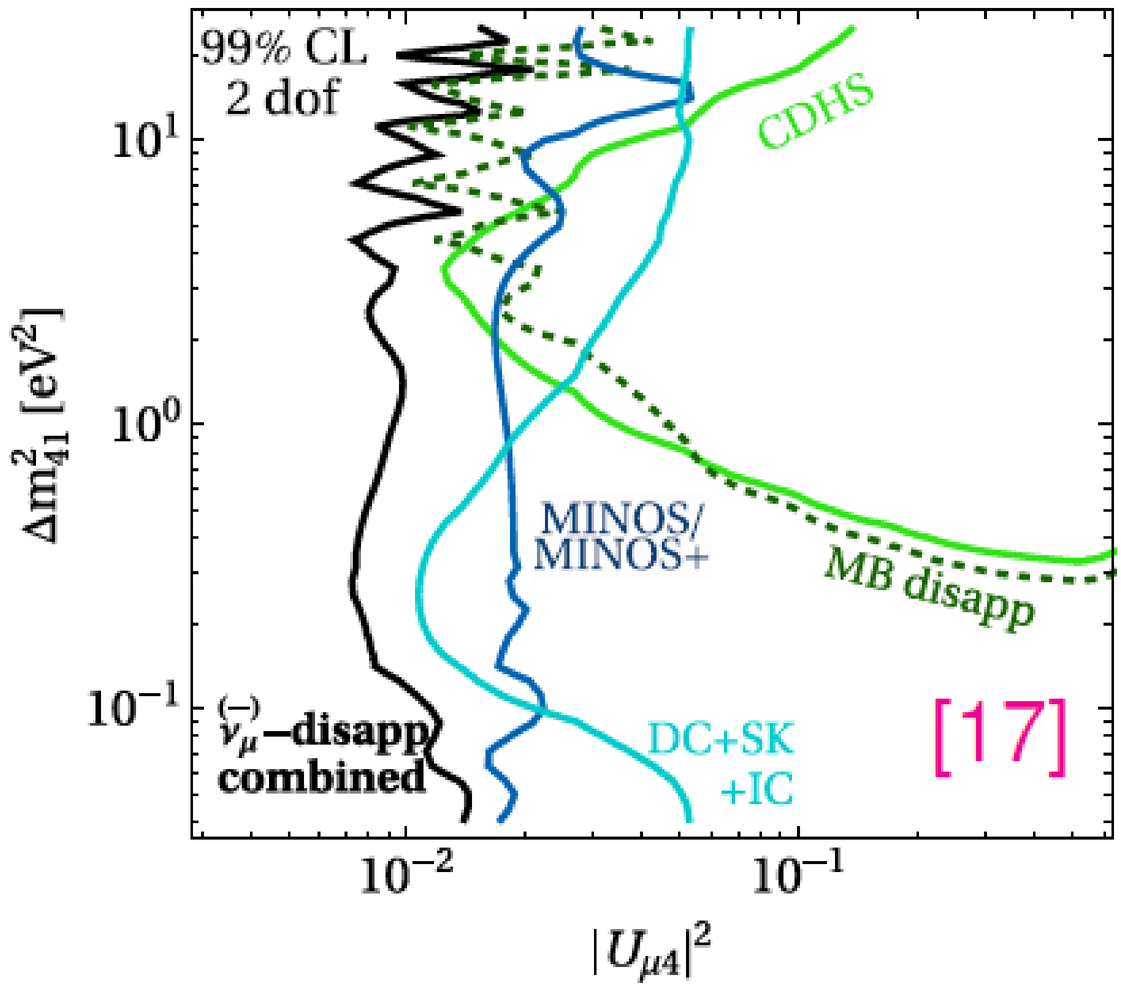
ν_e Disappearance

$$P_{\nu_e \to \nu_e} \sim 1 - 4|U_{s4}|^2|U_{e4}|^2 \sin^2\left(\frac{m_4^2 L}{4E_\nu}\right)$$



Sterile Neutrino Oscillation

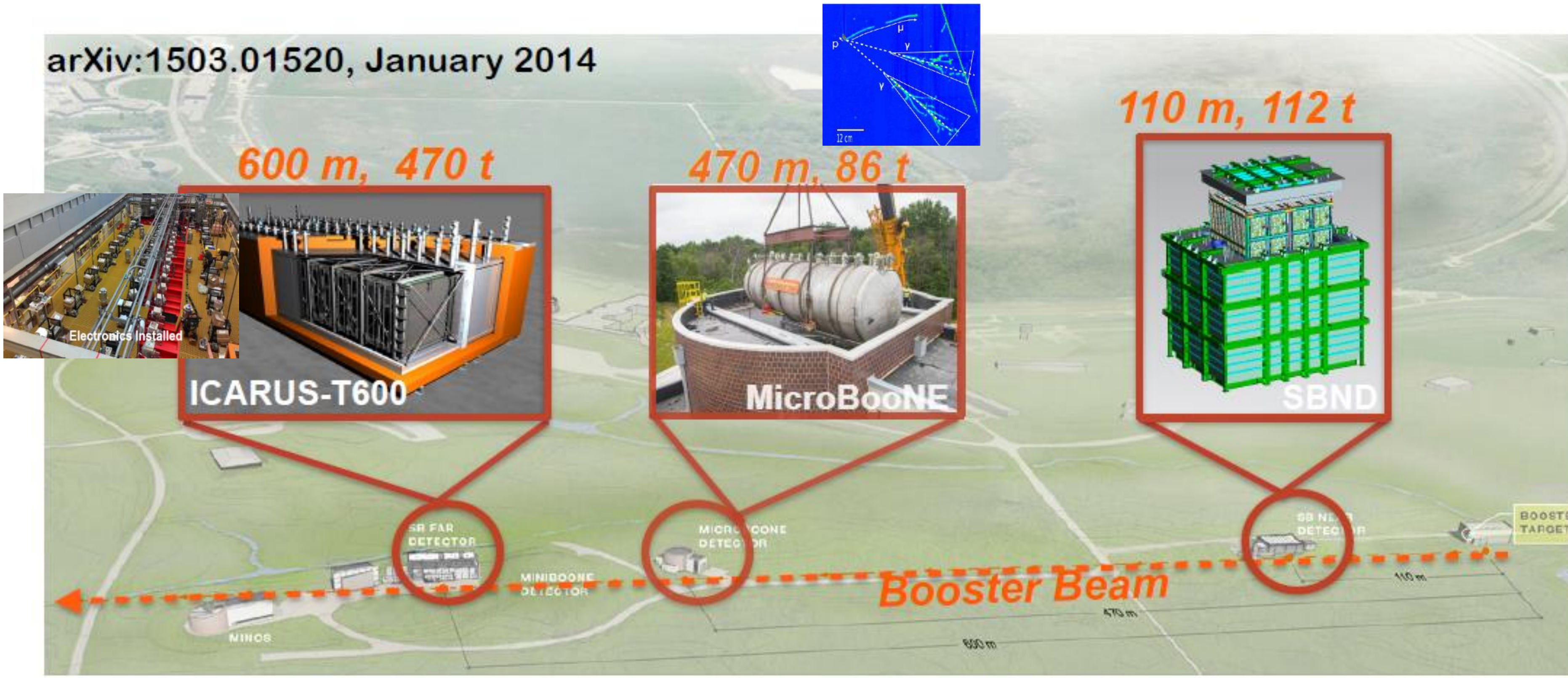
Null results of ν_μ disappearance



[17] Dentler, Hernández-Cabezudo, Kopp, Machado, MM, Martinez-Soler, Schwetz, arXiv:1803.10661.

SBN Program at Fermilab

3 LArTPCs in the Booster Neutrino Beamline

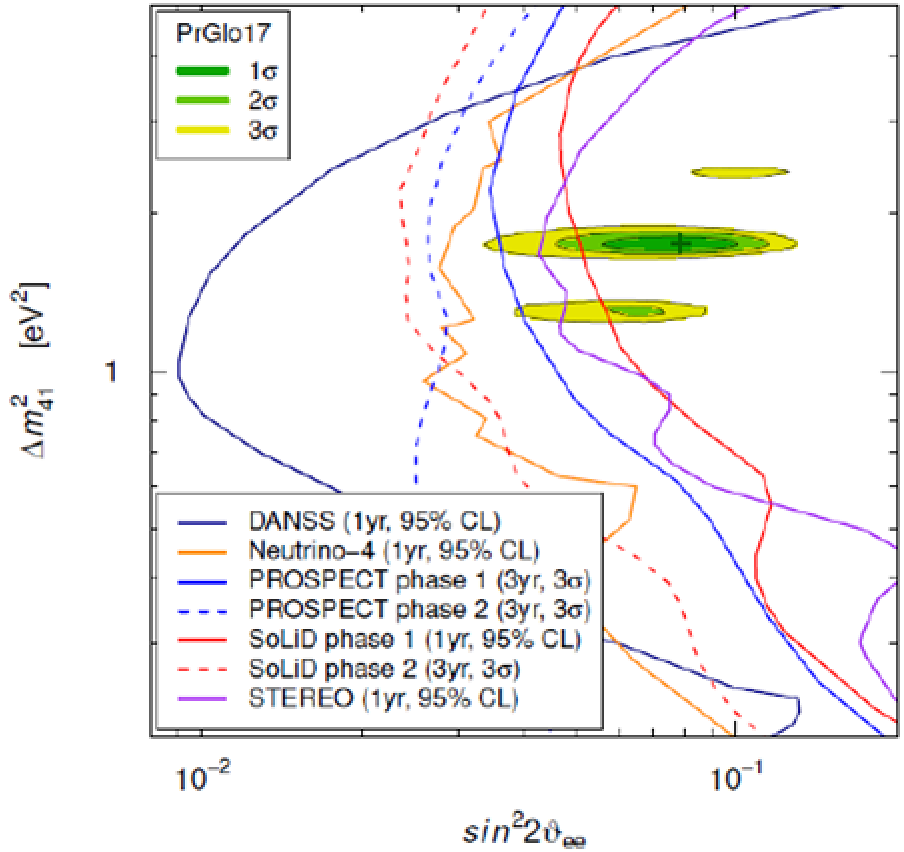


Direct test for MiniBooNE Anomaly.

SBND (first data in ~~2019~~) 2021
MicroBooNE (first data in late-2015)
ICARUS (first data in ~~2018~~) 2020

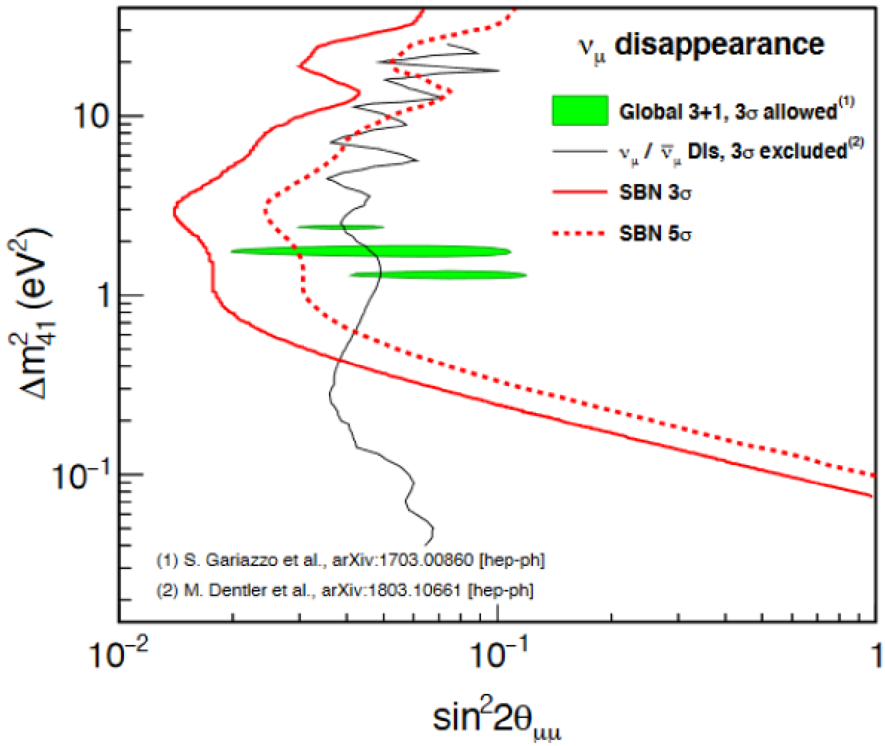
Future Sterile Neutrino Search

$\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_e$ **(Reactor disappearance)**



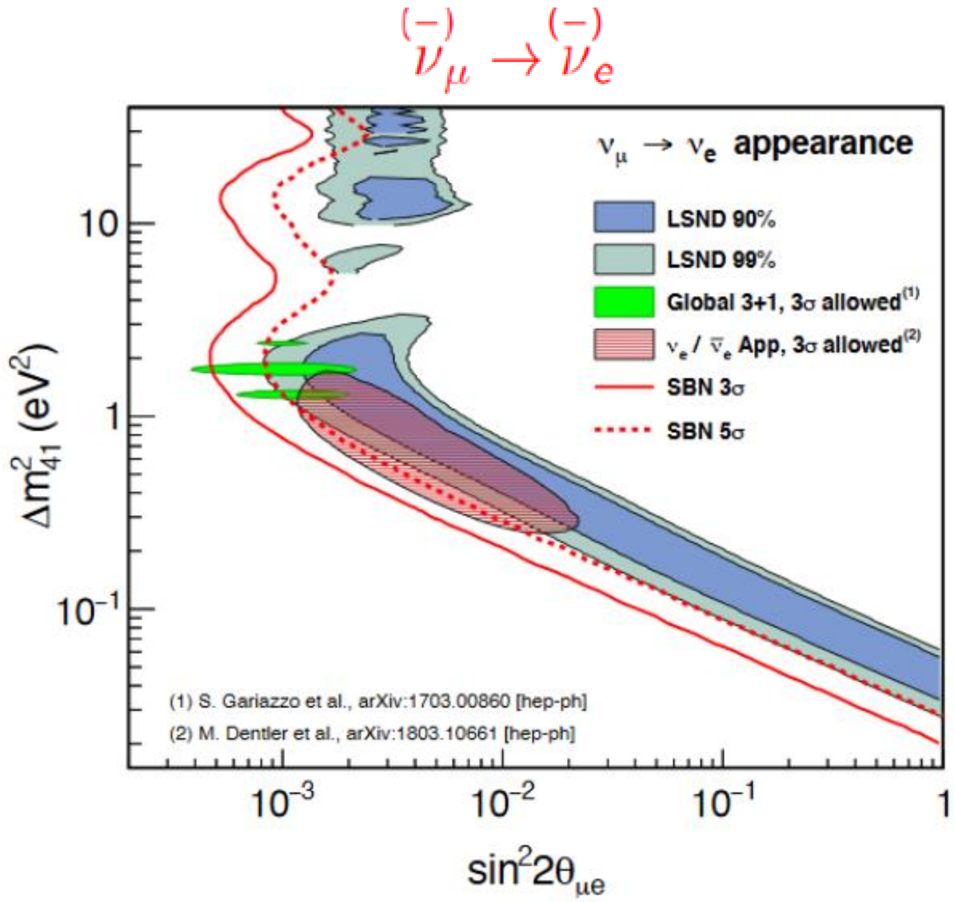
Yufeng Li

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$ **3 yrs**



J.Spitz's talk in NuFact2019

Future Sterile Neutrino Search



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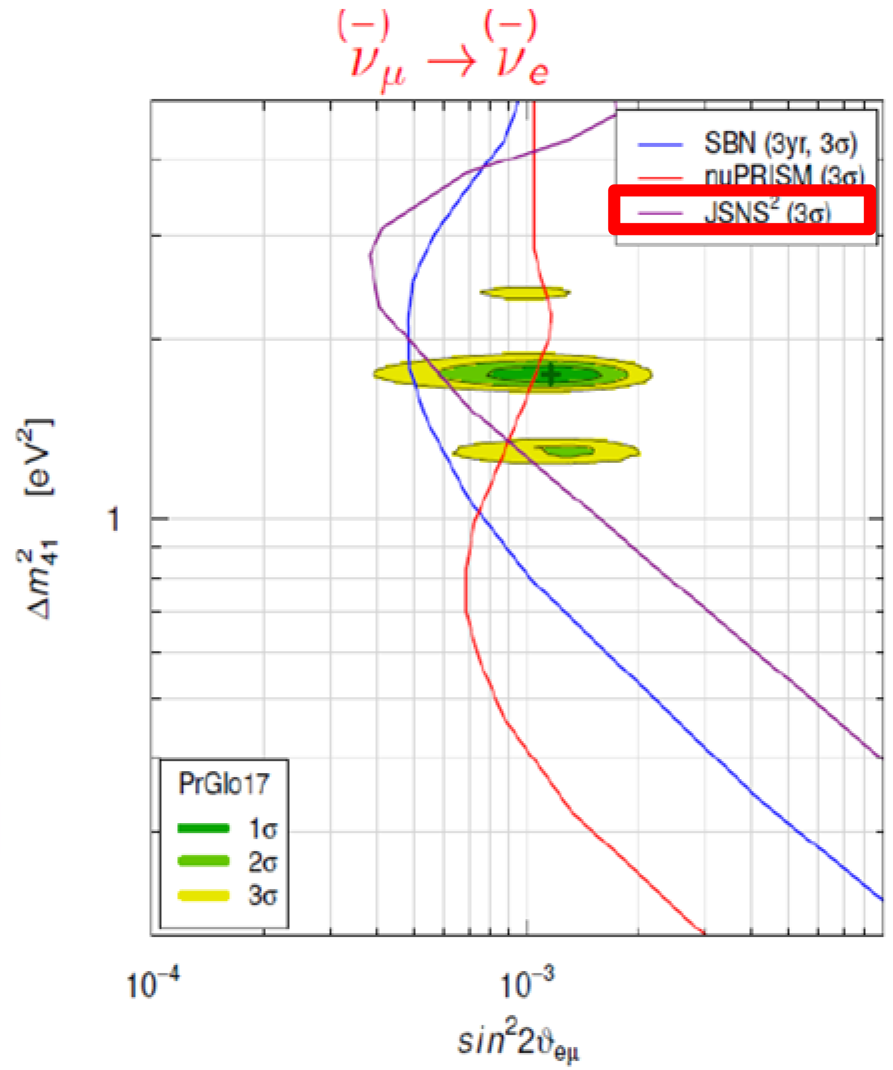


Yufeng Li

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

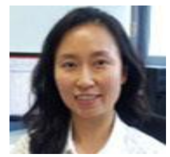

J-PARC
J-PARC
JSNS^2 Collaboration
JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku
Soongsil
Dongshin
GIST
Seoyeong
Chonnam
Seoul
Chonbuk
Kyungpook
Sungkyunkwan
Seoul Sci Tech
Alabama
BNL
Florida
Michigan
Sussex

Korean JSNS^2 Group

- *Chonnam National University:*
  K.K. Joo, J.Y. Kim, I.T. Lim and D.H. Moon

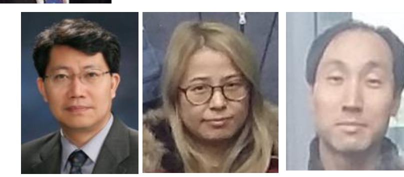
- *Dongshin University*:
  J.H. Choi and M.Y. Pac

- *GIST:*
  J.S. Jang



- *Kyungpook National University:*
  W. Kim

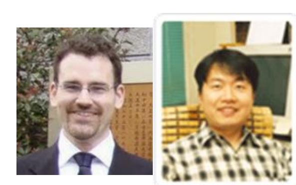
- *Seoul National University:*
  S.B. Kim, E.H. Kwon, D.H. Lee and H. Seo



- *Seoyeong University:*
- H.I. Jang

- *Soongsil University:*
  M.K. Cheoun

- *Sungkyunkwan University:*
  C. Rott and I. Yu



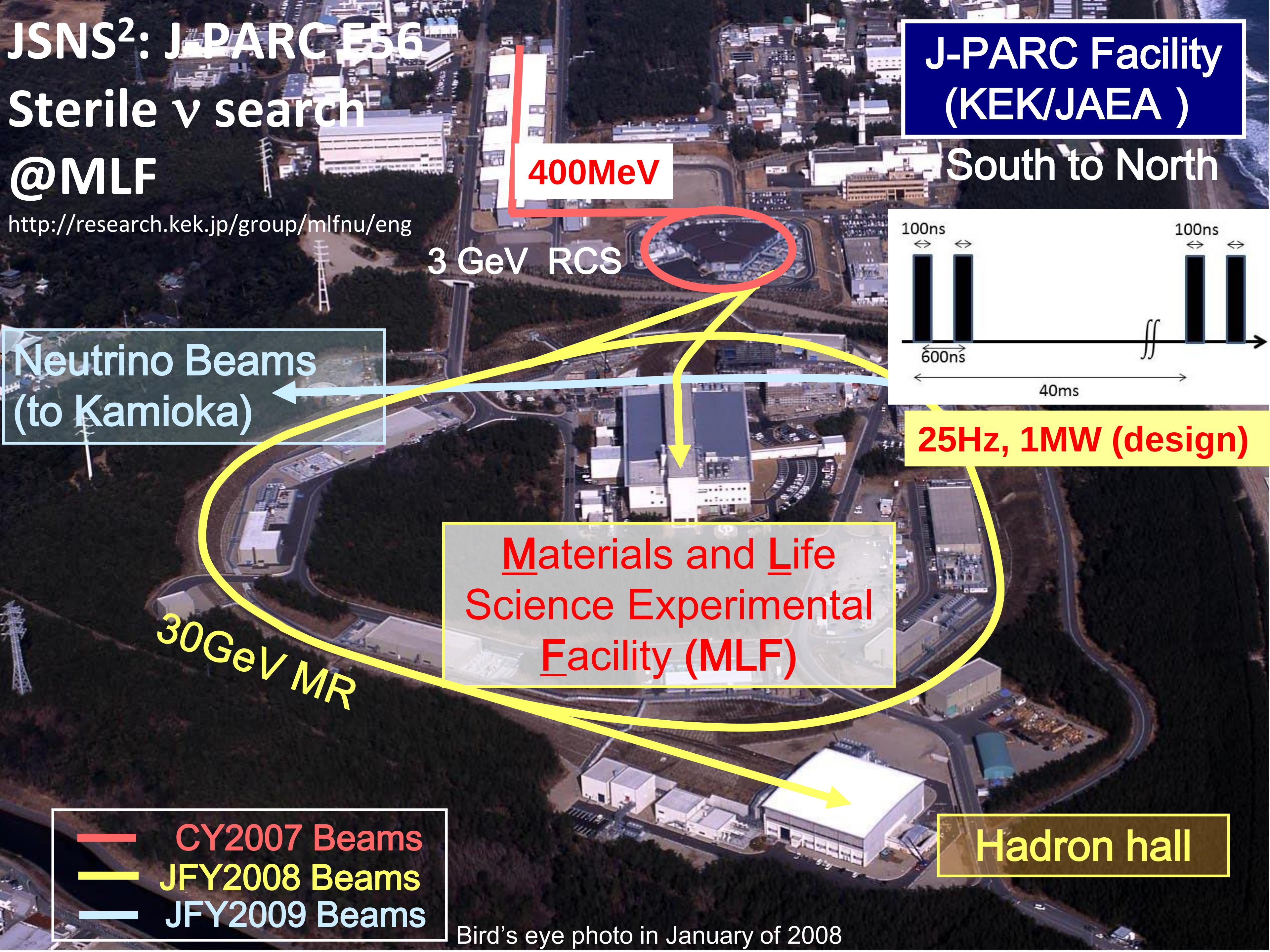
+ ~5 Ph.D. candidate students

Improved Search at JSNS^2

- **Direct test of the LSND with better sensitivity**
  - Muon antineutrino beam from muon Decay At Rest (DAR)

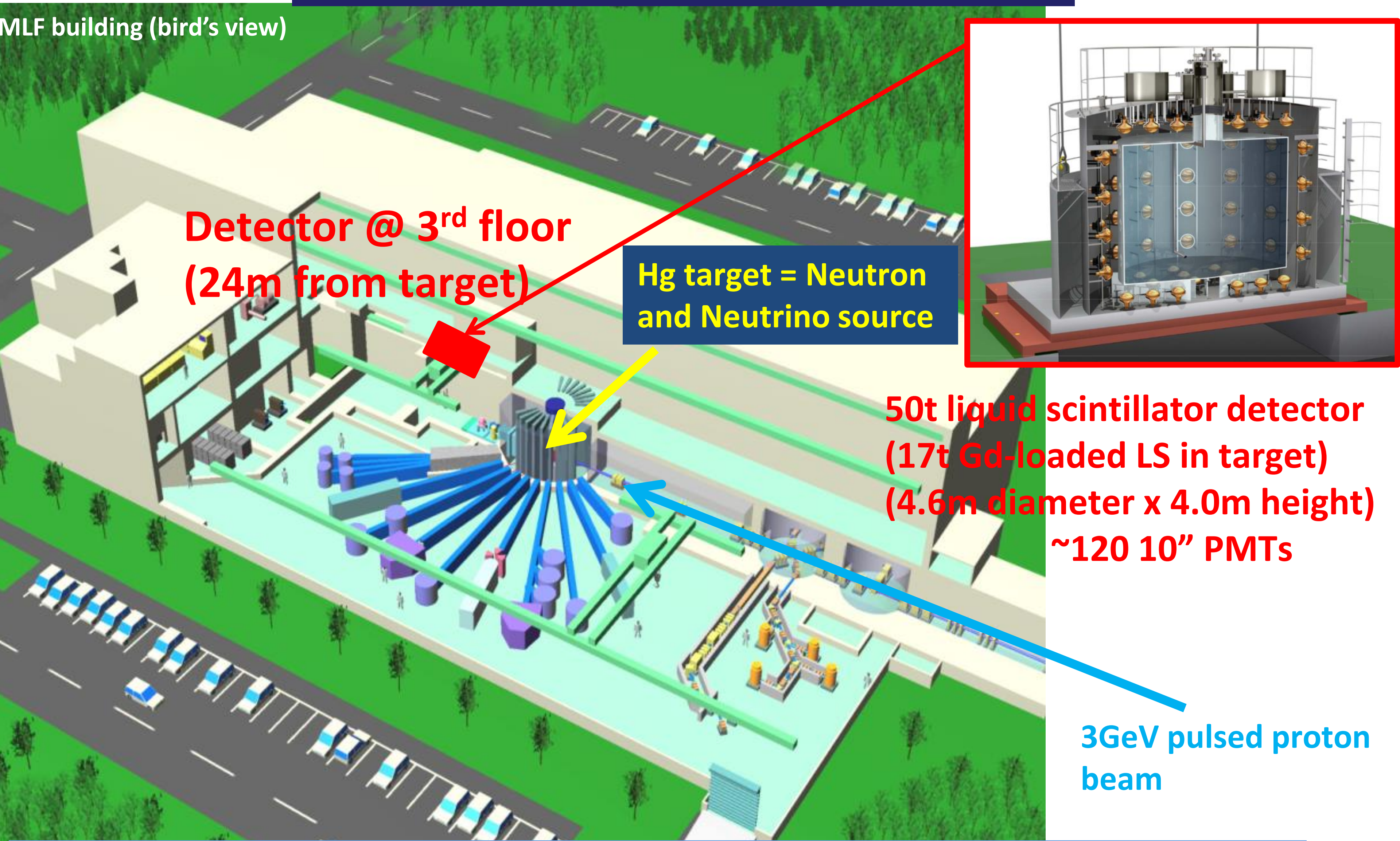
- ***Narrow (~9 μs) pulsed (every 40 ms) neutrino beam*** **at J-PARC MLF : (vs. continuous beam used by LSND)**
  - Pure muon decay at rest
  - Narrow timing window for cosmic ray rejection
  - No decay-in-flight source
  - No beam induced fast neutrons
  - The neutrino energy spectrum is perfectly known
  - The neutrino beam already available

- **Improved detector :**
  - *Gd doped LS*
  → significant reduction of backgrounds by a tighter (~1/6) time coincidence and a higher (2.2 → 8 MeV) delayed energy + well-known cross section of IBD



Bird's eye photo in January of 2008

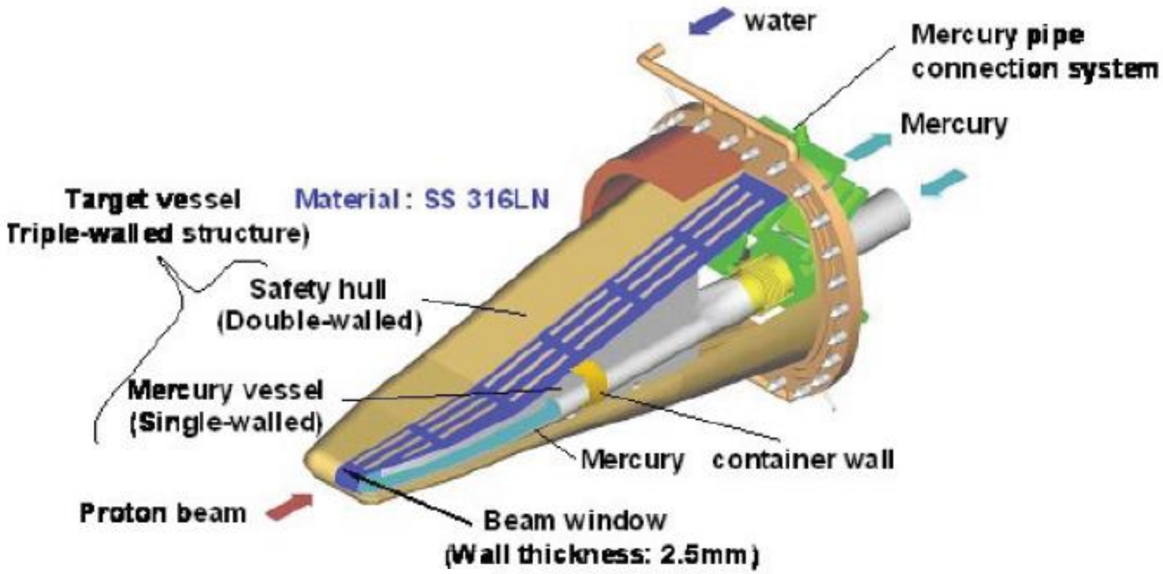
JSNS^2 at J-PARC MLF

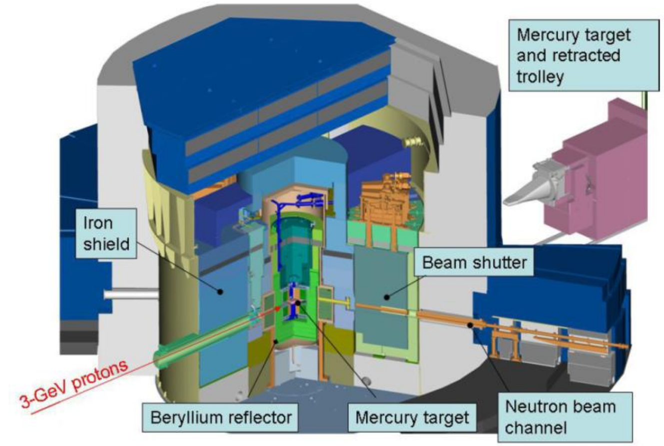


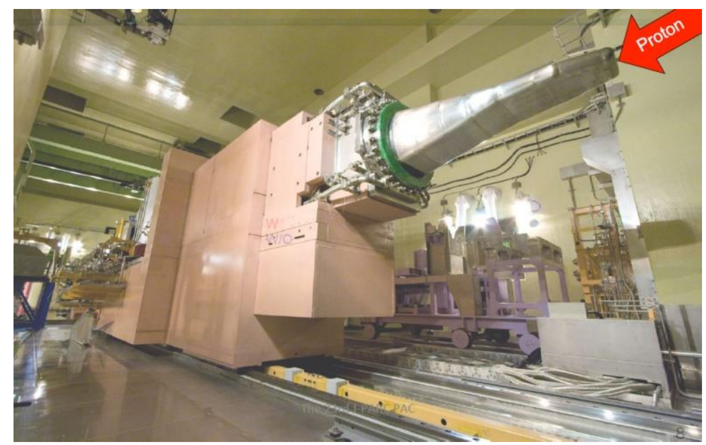
Searching for neutrino oscillation : $\overline{\nu_{\mu}} \rightarrow \overline{\nu_{e}}$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up

Neutrino Source: Mercury Target at MLF

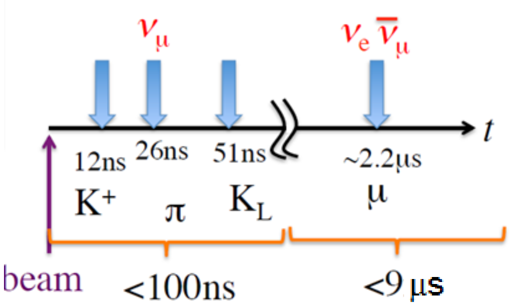
- **World-class high intensity neutron source driven by high power proton beam**
  - beam energy: 3 GeV
  - design beam power: 1 MW







Timing of the ν production



$$p + Hg \rightarrow \pi^{\pm} + X$$

$$\pi^{\pm}(stop) \rightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{+}(stop) \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

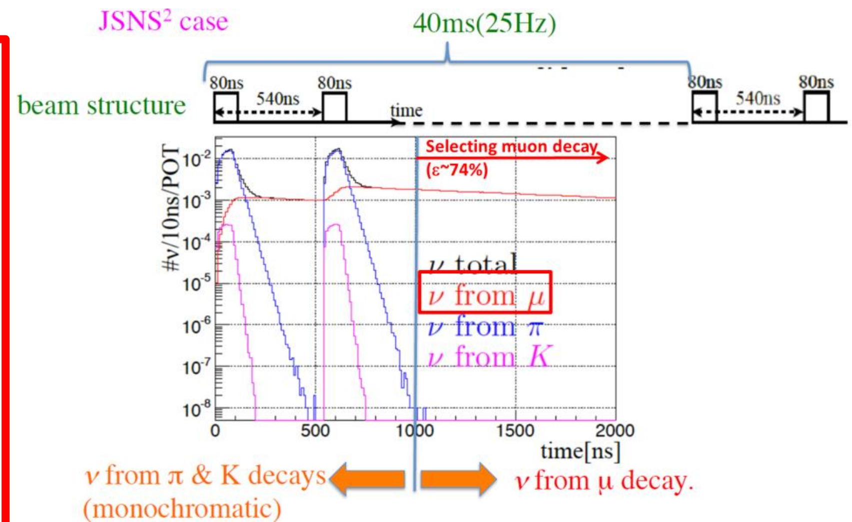
$$\bar{\nu}_e / \bar{\nu}_\mu \sim 1.7 \times 10^{-3}$$

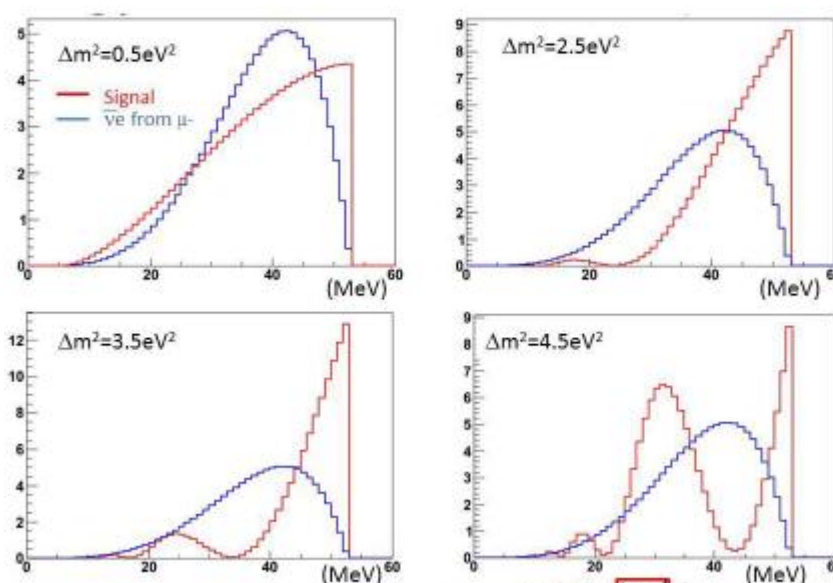
Timing and Energy of Neutrino Beam

- **Timing**: Ultra-pure ν from μ^+ Decay-at-Rest by a pulsed neutrino beam
  - ➢ Removal of ν from π and K with beam timing
  - ➢ Removal of beam fast neutrons w/ time
  - ➢ Reduction of cosmic BKG by 9μs time window.

➢ **Energy**: Good for signal BKG separation
  - ➢ Well-known spectrum of ν from μ
  - ➢ Easy energy reconstruction of IBD. (Eν ~ Evis + 0.8MeV)
  - ➢ Highly suppressed ν from μ-

$$\overline{\nu}_e / \overline{\nu}_\mu \sim 1.7 \times 10^{-3}$$





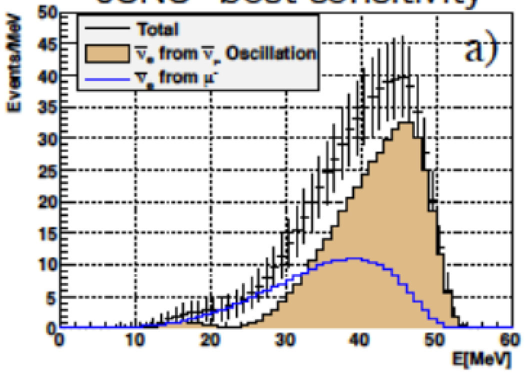
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

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

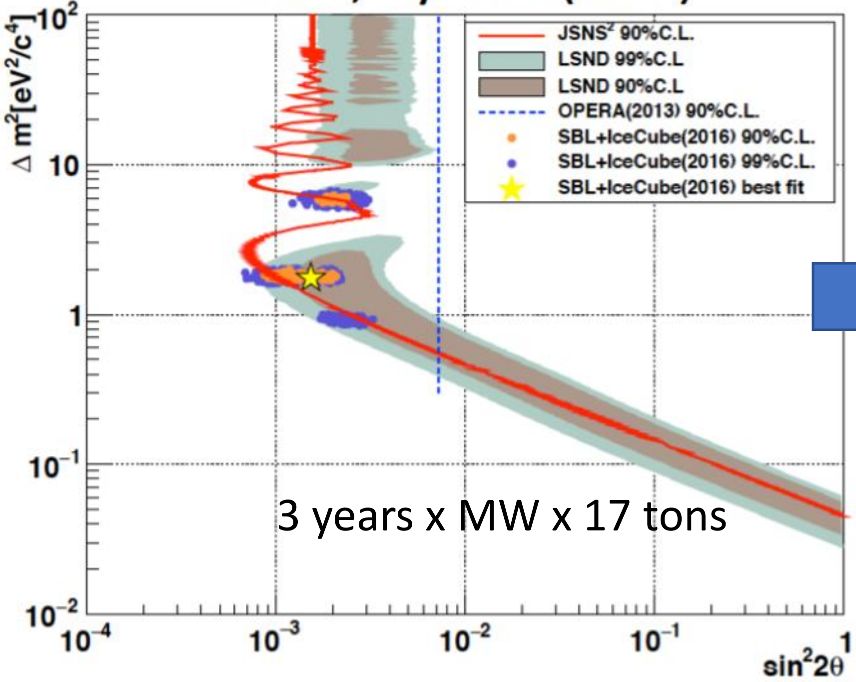
Signal Extraction & Sensitivity

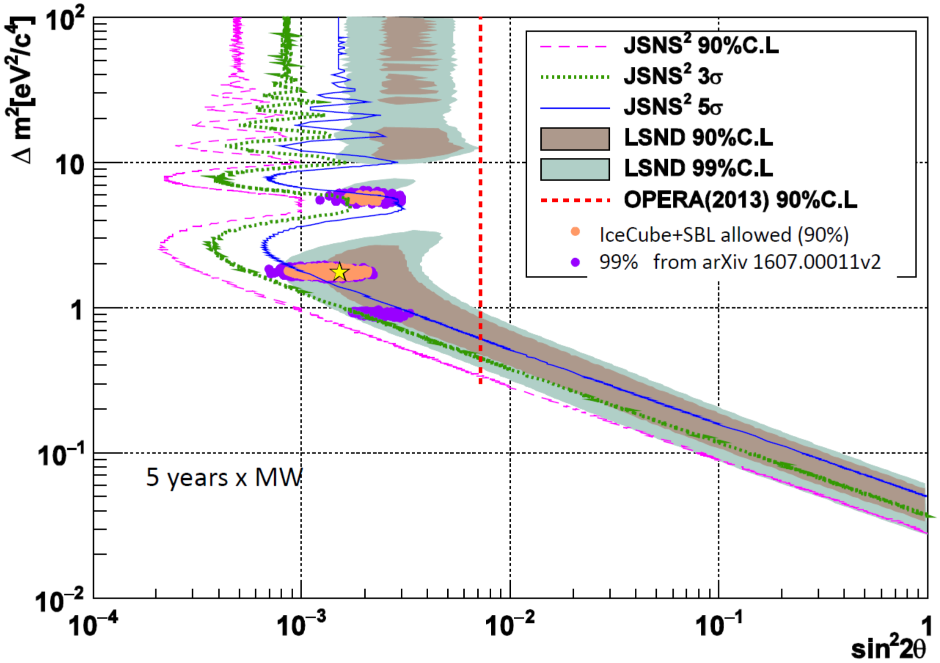
- Signal events can be distinguished from the dominant background (from another neutrino process) by using the difference of energy distributions
- Most of the parameter region indicated by LSND exp. can be explored with more than 5σ significance in 5 years with 1MW beam power

JSNS² best sensitivity

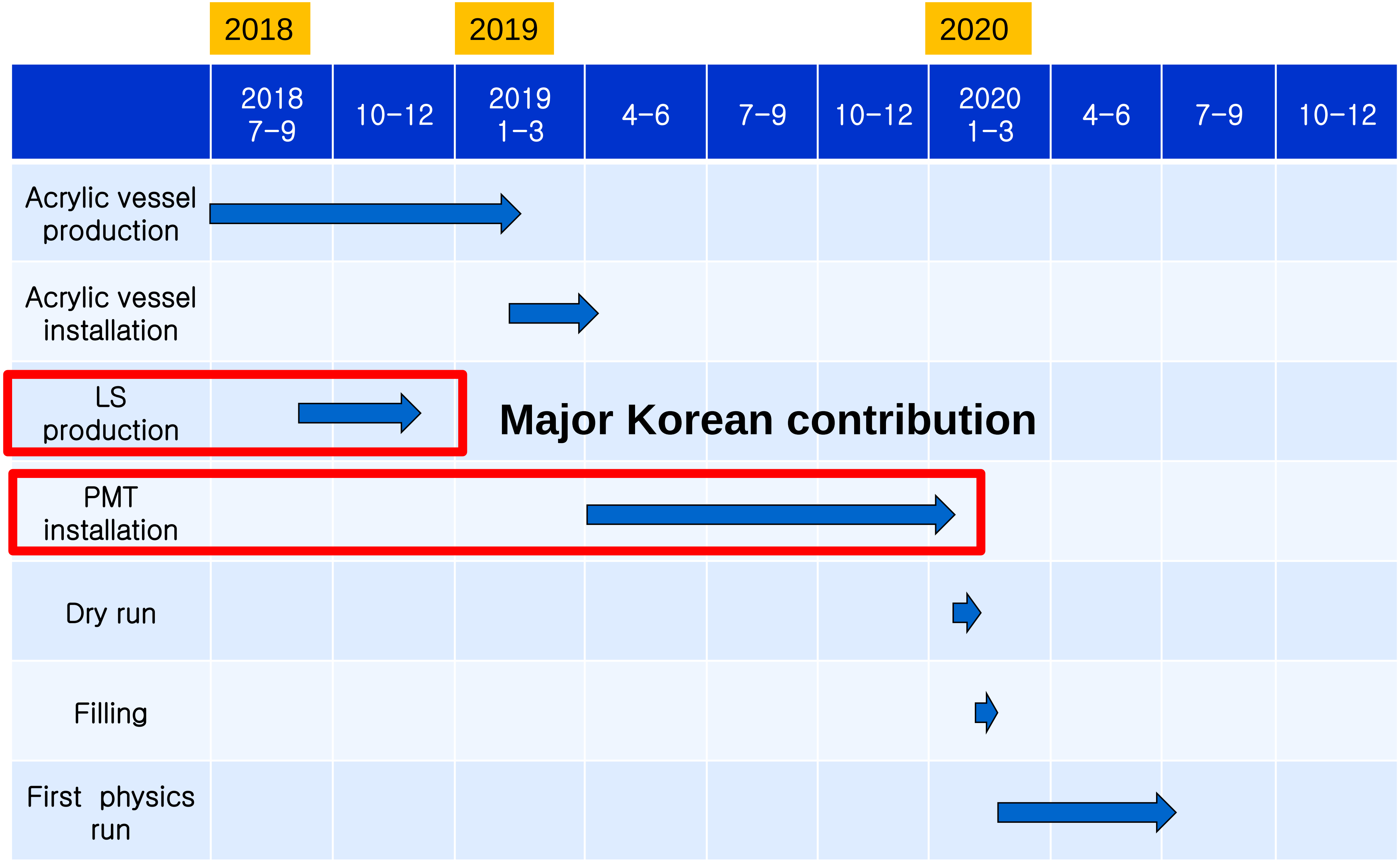


24m, 3years (TDR)

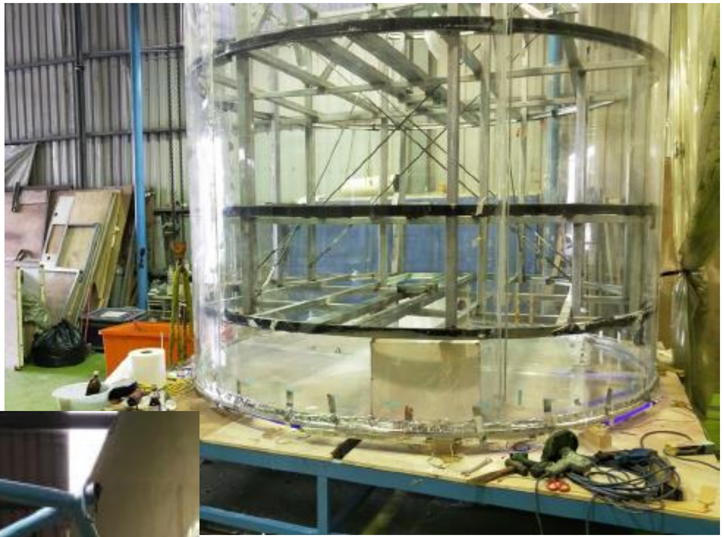


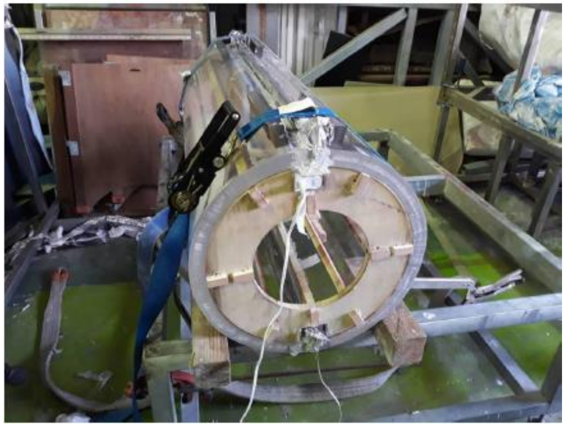


Schedule for Detector Construction



Construction of Acrylic Vessel

Relocated SUS Tank (Mar. 14, 2018)

There were no big issues.

SUS Tank and Acrylic Vessel at J-PARC

- The stainless steel tank and the acrylic vessel are ready to perform the experiment.
- On 2019-Feb, we already had rehearsal of the installation of the acrylic vessel. → succeeded.
- They are waiting for completion of PMT installation.

PMT Installation

PMT support structure

Reflection sheet

- 105 PMTs from RENO, Korea
  23 PMTs from DC, Japan
- 33 PMTs installed and ~40 will be installed till Oct. 2019.
- 50 more PMTs will arrive before Dec. 2019.

PMT installation

PMT

Current status

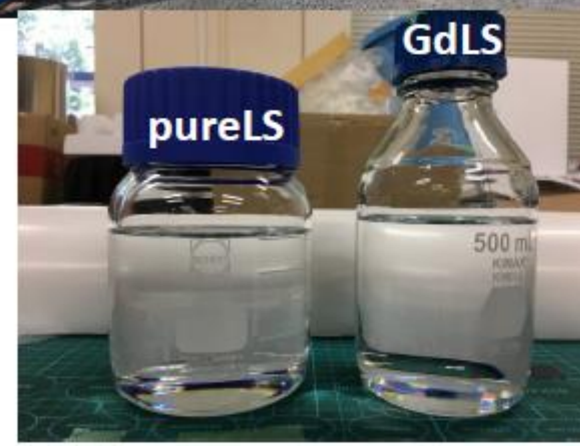
Liquid Scintillator by Ko

35 tons of LS was produced at RENO site and delivered t

Date (2018)	J
Sep. 12 - 18	R
Sep. 28	I
Oct. 1 - 22	L

21 batches in t
- 4 peoples pe
- 2 of ISO tank

LS and GdLS storage in Japan



-- **Daya-Bay experiment kindly donated 20 tons of GdLS.**

-- arrived at Japan on 2019-Aug-1.

-- Now both GdLS and LS are stored at Kawasaki in Japan.

-- quality is OK.

Schedule for Next 10 years

- Will take data for 3 years to obtain 3σ sensitivity test for the LSND allowed region [2020-2022]

- An enlarged 2nd detector and 5 year data-taking to obtain 5σ sensitivity test for the LSND allowed region [2023-2030]

- Estimated budget : ~2M USD
  (2nd detector construction, operational cost, travel expense, etc.)

Summary

- Confirming or refuting existence of “sterile neutrino oscillation” results has been one of the hottest topics in the neutrino physics in the last two decades.

- The JSNS^2 experiment will begin data taking in early 2020 and provide an ultimate test of the LSND anomaly without any ambiguity.

- If sterile neutrino oscillation is indeed found, it will be a big discovery of a dark matter candidate.

- The Korean group has been actively participating in the detector construction including delivering 36 tons of liquid scintillator and ~100 10-inch PMTs. We expect to play an important role in obtaining results.

Thanks for your attention!

Summary on Sterile Neutrino Oscillation

- Anomalies in $\nu_e \to \nu_e$ disappearance and $\nu_\mu \to \nu_e$ appearance experiments point towards conversion mechanisms beyond the well-established 3ν oscillation paradigm;
- each of these anomalies can be **individually** explained by sterile neutrinos;
- sterile neutrinos still succeed in simultaneously explaining groups of anomalies **sharing the same oscillation channel**. However some problem arises:
  - $\nu_e \to \nu_e$ disappearance data face issues with flux normalization and the 5 MeV bump, as well as small tensions in reactor vs gallium and "rates" vs DANSS/NEOS;
  - $\nu_\mu \to \nu_e$ appearance data show an excess in low-E neutrino data, which is not so manifest in antineutrino data.
- in contrast, no anomaly is found in any $\nu_\mu \to \nu_\mu$ disappearance data set;

$\Rightarrow$ sterile neutrino models **fail to simultaneously account** for **all** the $\nu_e \to \nu_e$ data, the $\nu_\mu \to \nu_e$ data and the $\nu_\mu \to \nu_\mu$ data. This conclusion is robust;

- if the $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$ anomalies are confirmed, and the $\nu_\mu \to \nu_\mu$ bounds are not refuted, new physics will be needed. Such new physics may well involve extra sterile neutrinos, but together with something else (or some "unusual" neutrino property).

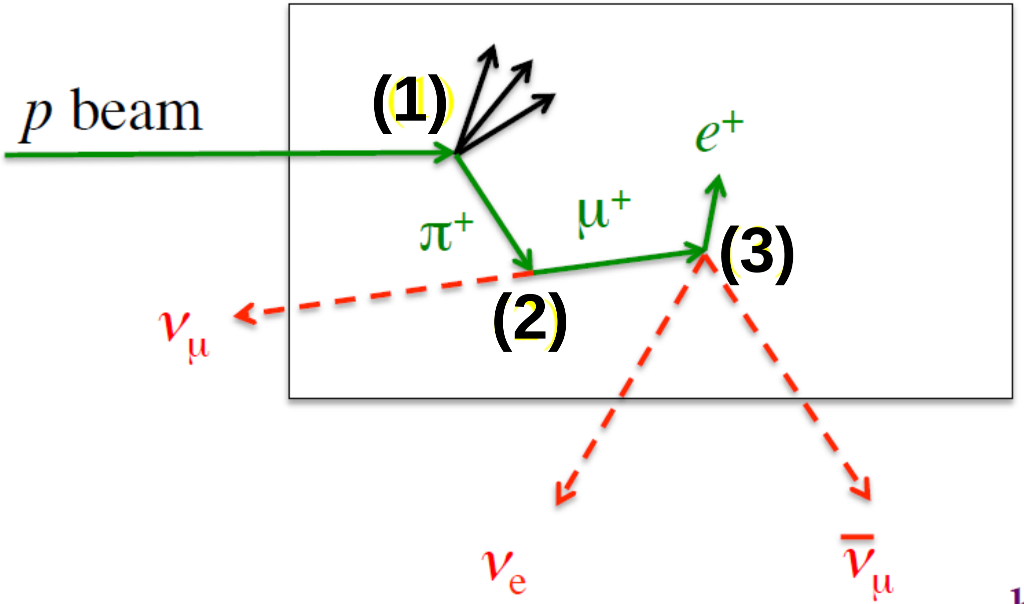
Neutrinos from Muon Decay At Rest (DAR)

(1) High energy (~GeV) protons hit a dense target material and produce π^+.

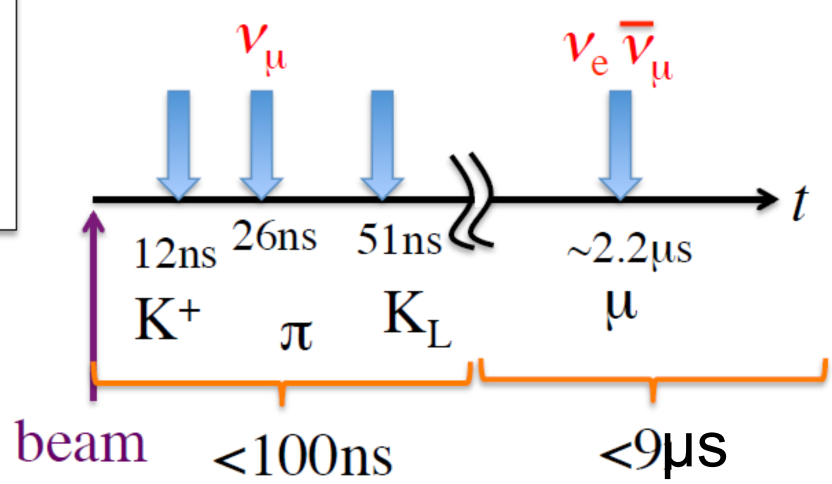
(2) π^+ stops in the material and decays producing ν_μ and μ^+.

(3) μ^+ stops in the material and decays producing ν_e and $\bar{\nu}_\mu$.

(4) ν's from π^- and μ^- are highly suppressed. $\bar{\nu}_e / \bar{\nu}_\mu \sim 1.7 \times 10^{-3}$

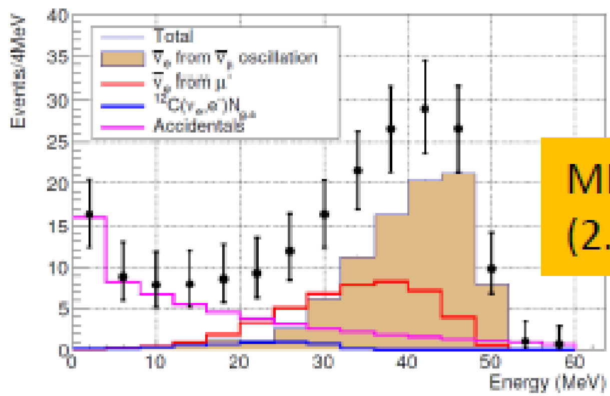


Timing of the ν production



Expected Signal and Background

Source	contents	#ev.(17tons x 3years)	Reference : SR2014 (50tons x 5 years)	comments
background	$\overline{\nu}_e$ from μ-	43	237	Dominant BKG
	$^{12}C(\nu_e,e-)^{12}N_{g.s.}$	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	$\Delta m^2=1.2$, $\sin^2 2\theta=0.003$



MLF best Δm^2 (2.5eV^2)