# Sterile Neutrino Search in the JSNS$^2$ Experiment


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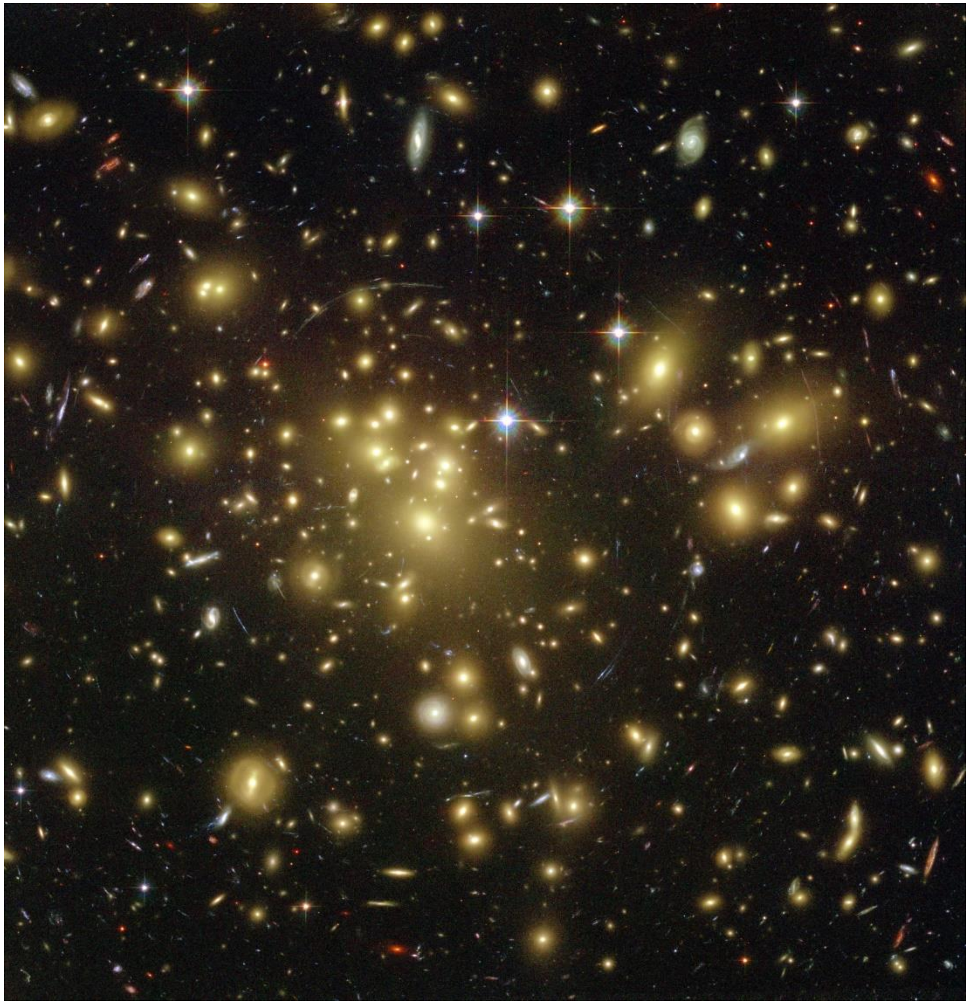
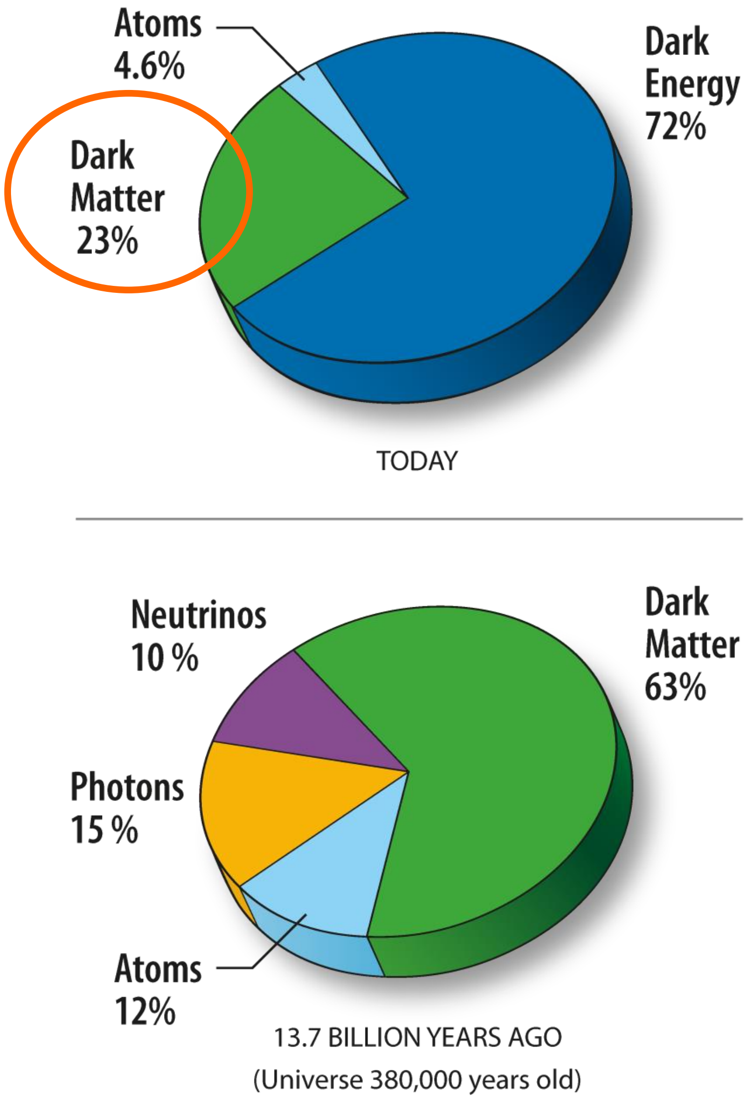
**TCHOU seminar**

**Jan. 19, 2018**

# Dark World



Strong gravitational lensing by HST in Abel 1689

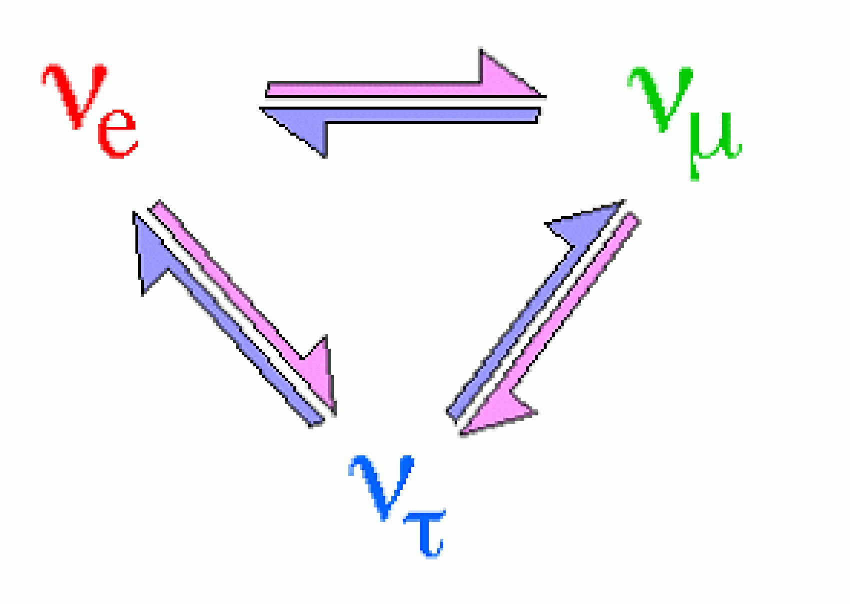



WMAP 2008

# Neutrino Oscillations and Mass

***"Established three-flavor mixing framework"***

| | |
|---|---|
| **Atmospheric Neutrino Oscillation (1998)** | $\theta_{23}$ |
| **Solar Neutrino Oscillation (2001)** | $\theta_{12}$ |
| **Reactor Neutrino Oscillation (2012)** | $\theta_{13}$ |




***"Neutrino has mass"***
***→ Right-handed sterile neutrino?***

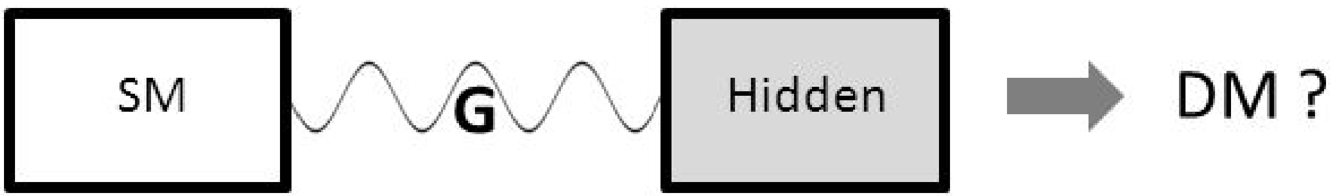
$$L^D = -\overline{\nu_R} M^D \nu_L + H.c.$$

$$L^M = -\frac{1}{2}\overline{(\nu_L)^c} M^M \nu_L + H.c.$$

# Coupling between SM and Dark Worlds

**Hidden Sector** : sterile particles as SM singlets

The particles interact to our SM world through **Gravity**.

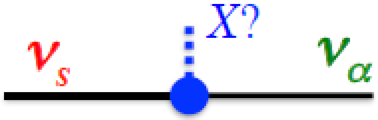



Also, they may interact through...

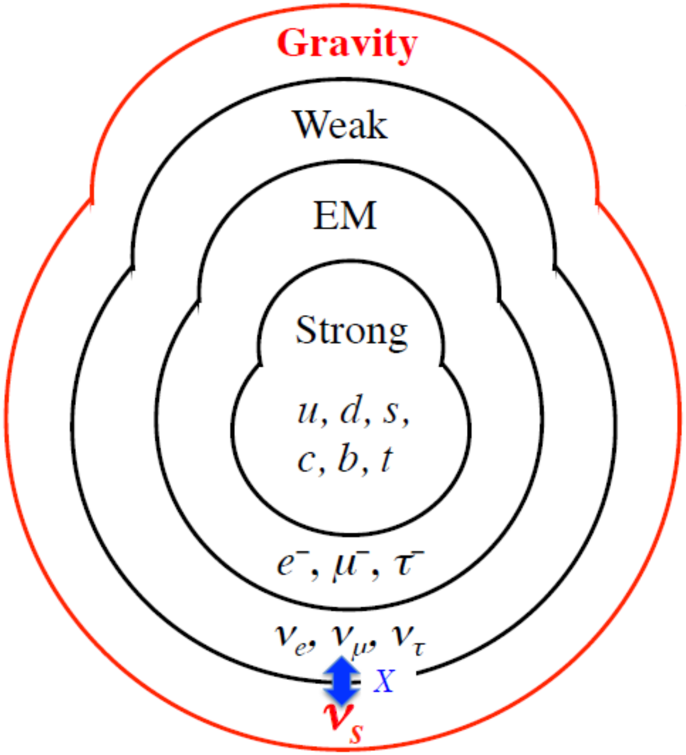
| | | |
|---|---|---|
| **Neutrino Portal** | $HL\psi$ | Sterile neutrino |
| **Vector Portal** | $F^{Y}_{\mu\nu}X^{\mu\nu}$ | Dark Photon |
| **Axion Portal** | $\frac{1}{f_S}F_{\mu\nu}\tilde{F}^{\mu\nu}S$ | Axino-like particle |
| **Higgs Portal** | $\lvert H\rvert^2 S^2$ | Higgs invisible decay |

# Mixing with Sterile Neutrinos?

- If mixing between $\nu_s$ and $\nu_\alpha$ (like $\nu_\mu$ to $\nu_e$ )
  → chance for **neutrino oscillation** with $\Delta m^2 \sim 1\ eV^2$




- Sterile neutrinos $\nu_s$ , which interact with the gravity only, may be indirectly observed by neutrino oscillation because of a possible mixing due to $X$ .




**F. Suekane**

# Hints for Sterile Neutrino Search

- Anomalies that cannot be explained by standard neutrino oscillations, but tension with null results in disappearance

| Experiments | Neutrino source | signal | significance | E(MeV),L(m) |
| --- | --- | --- | --- | --- |
| LSND | μ Decay-At-Rest | $\nu_\mu \rightarrow \nu_e$ | 3.8σ | 40,30 |
| MiniBooNE | π Decay-In-Flight | $\nu_\mu \rightarrow \nu_e$ | 3.4σ | 800,600 |
| | | $\nu_\mu \rightarrow \nu_e$ | 2.8σ | |
| | | combined | 3.8σ | |
| Ga (calibration) | e capture | $\nu_e \rightarrow \nu_x$ | 2.7σ | <3,10 |
| Reactors | Beta decay | $\nu_e \rightarrow \nu_x$ | 3.0σ | 3,10-100 |

→ Needs repeat of the LSND measurement using an identical neutrino beam (DAR) and the same detection method (IBD) with better sensitivity.

# LSND Experiment

($\bar{\nu}_e$ appearance) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **Signal**

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

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

800MeV p

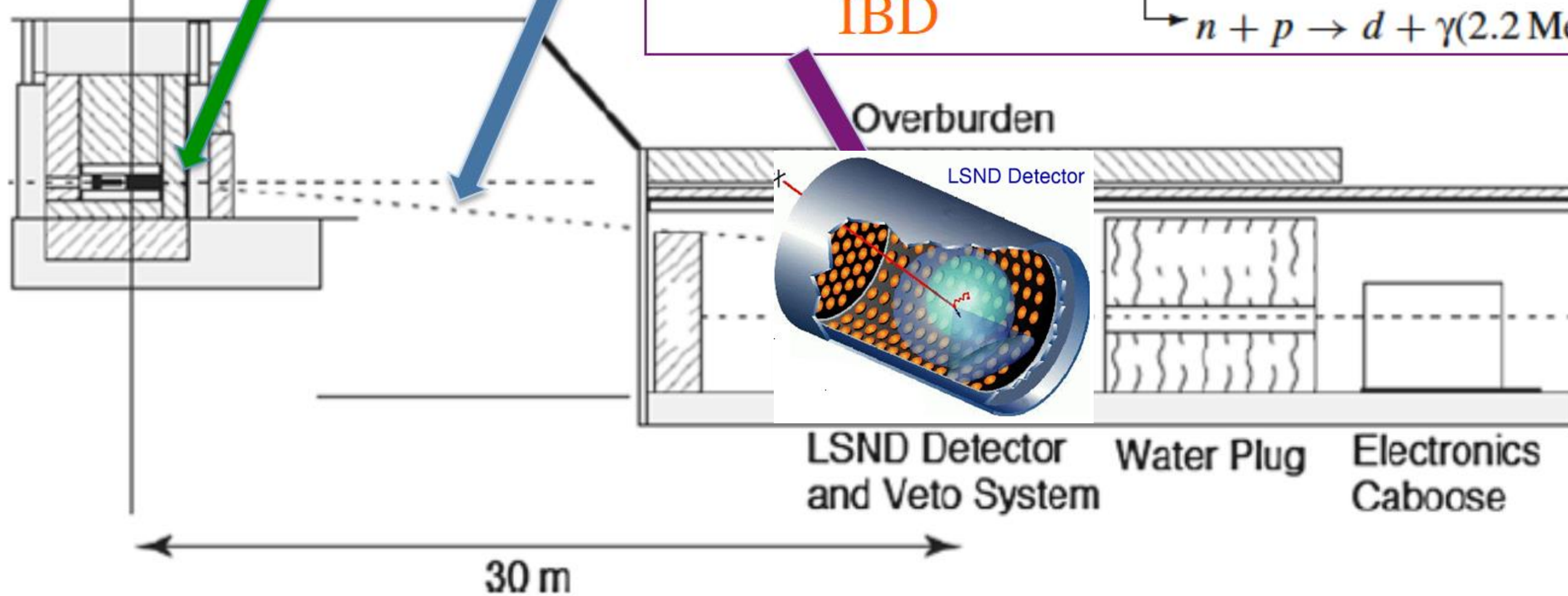
Liquid Scintillator

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

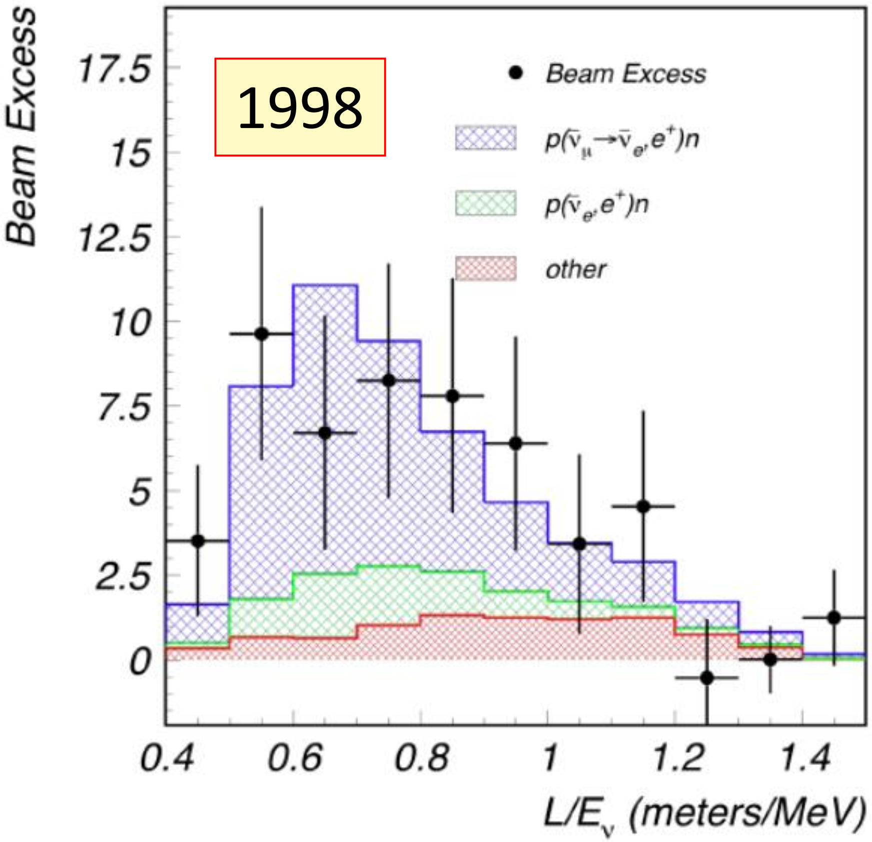
IBD

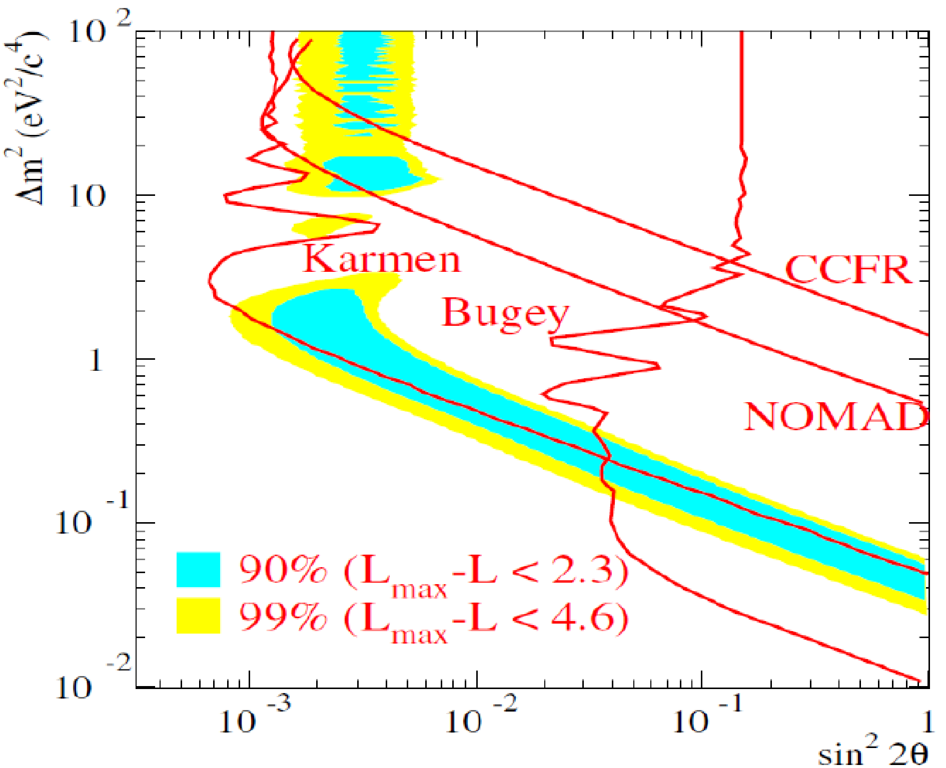
$\quad \hookrightarrow n + p \rightarrow d + \gamma(2.2\,\text{MeV}).$

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



# LSND Results




**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.**

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

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

(1990-1995, 1997-1999)

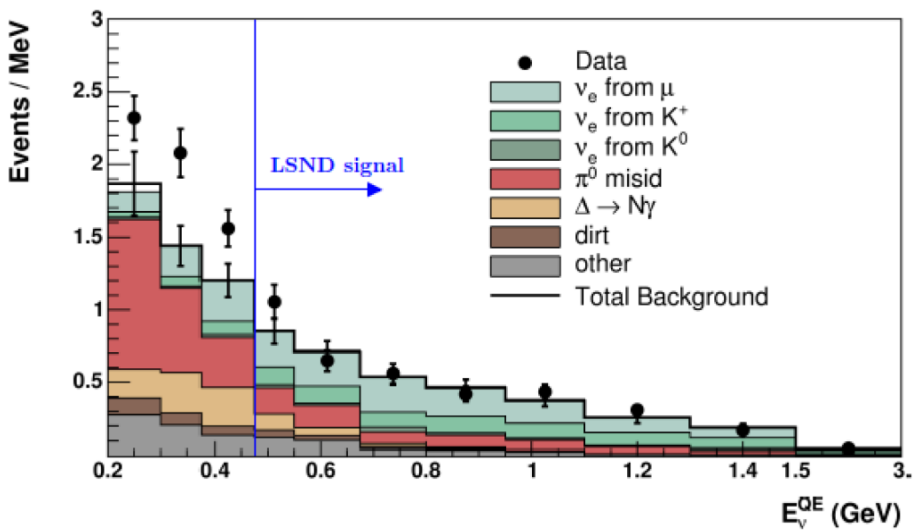
But signal not seen by KARMEN at $L \simeq 18\,{\rm m}$ with the same method

[PRD 65 (2002) 112001]

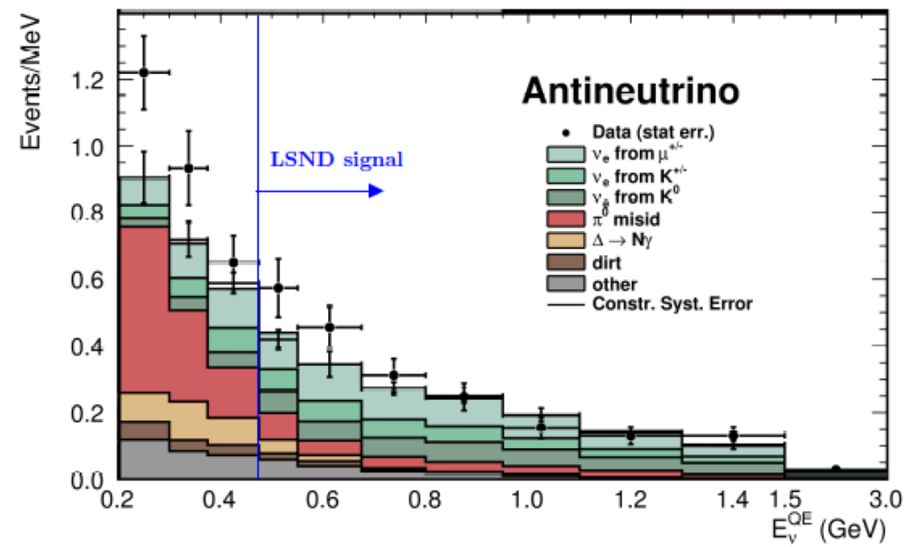
# MiniBooNE Results

$L \simeq 541\,\mathrm{m}$ $\quad$ $200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]




$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

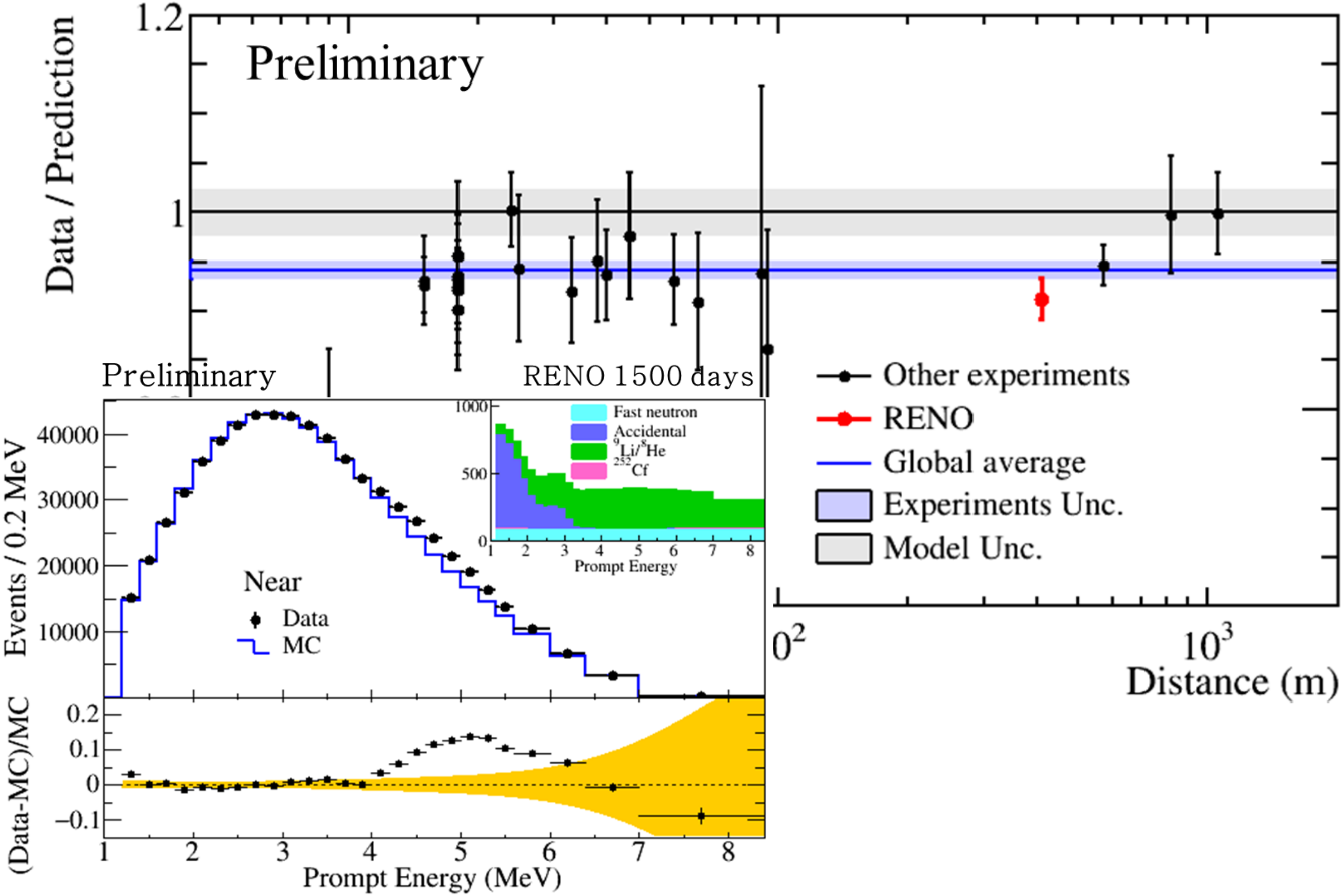



**Purpose:** check LSND signal with different L&E, but the same L/E

**~3σ excess** in the Low energy range: unidentified backgrounds?

**Oscillation search is not conclusive. → no near detector!**

# Reactor Anomaly



# Sterile Neutrino Oscillation

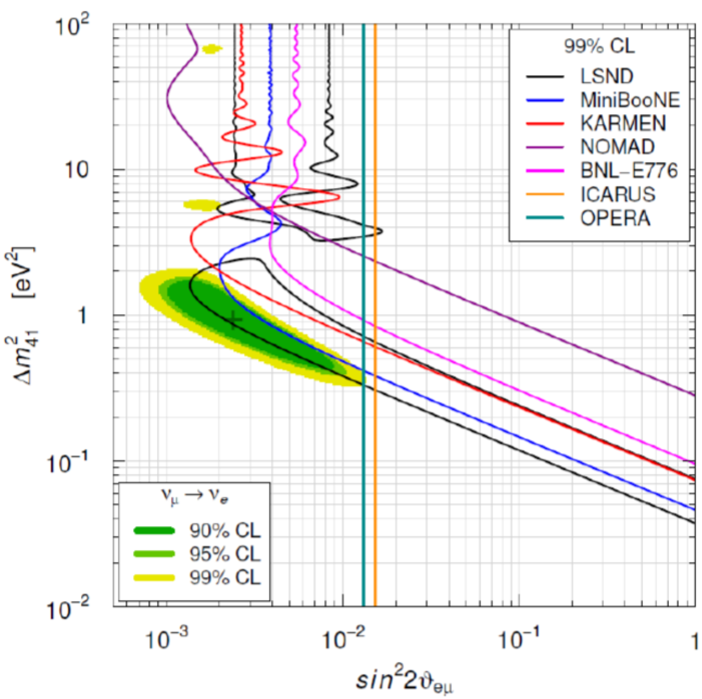
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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

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

$$m_4 > 1eV$$

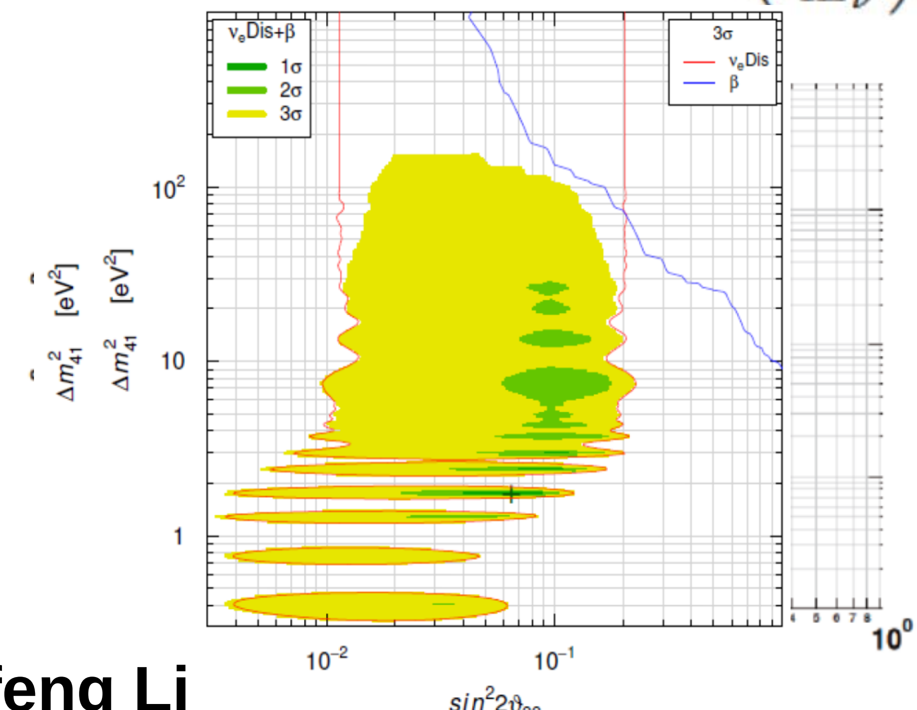
## $\nu_e$ Appearance

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




## $\nu_e$ Disappearance

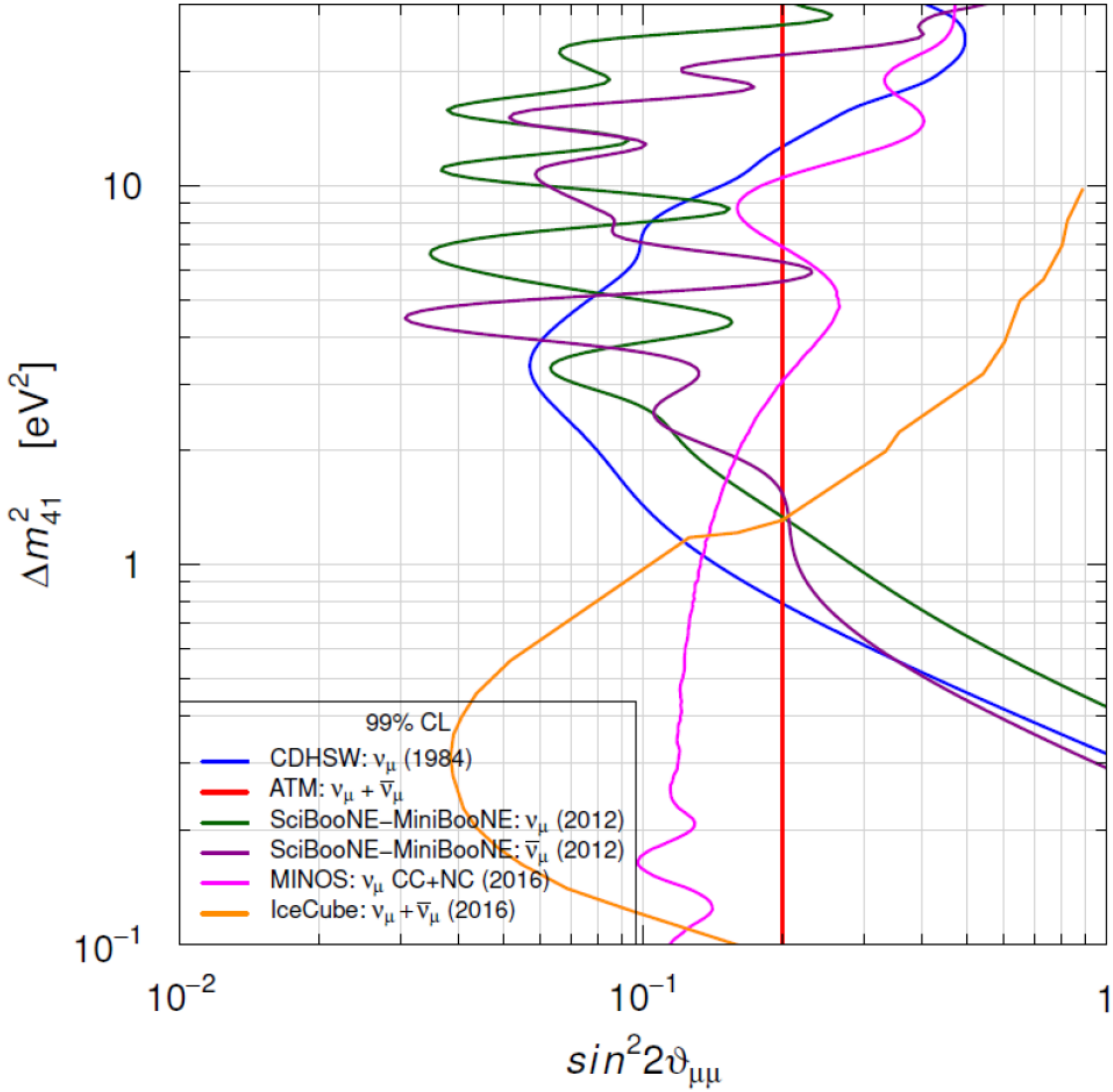
$$P_{\nu_e \to \nu_e} \sim 1 - 4|U_{s4}|^2 |U_{e4}|^2 \sin^2\left(\frac{m_4^2 L}{4E_\nu}\right)$$




Yufeng Li

# Sterile Neutrino Oscillation

## Null results on $\nu_\mu$ disappearance

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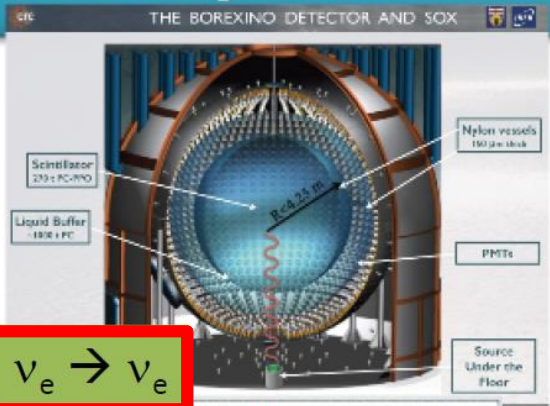
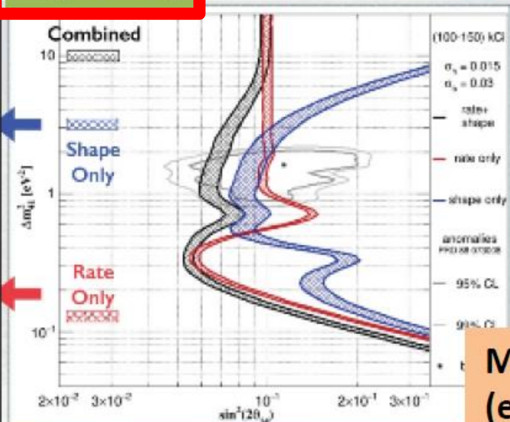
# Next generation sterile experiments are almost ready




$\nu_e \rightarrow \nu_e$

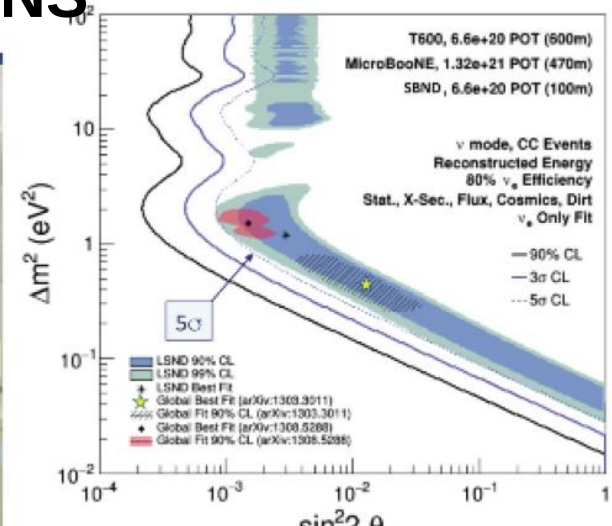



$\overline{\nu}_e \rightarrow \overline{\nu}_e$

| 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 |

**Mauro Mezzetto's (experimental summary) talk in Neutrino2016**

$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ **JSNS$^2$**




A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Submitted FNAL PAC January 2015 arXiv:1503.01520

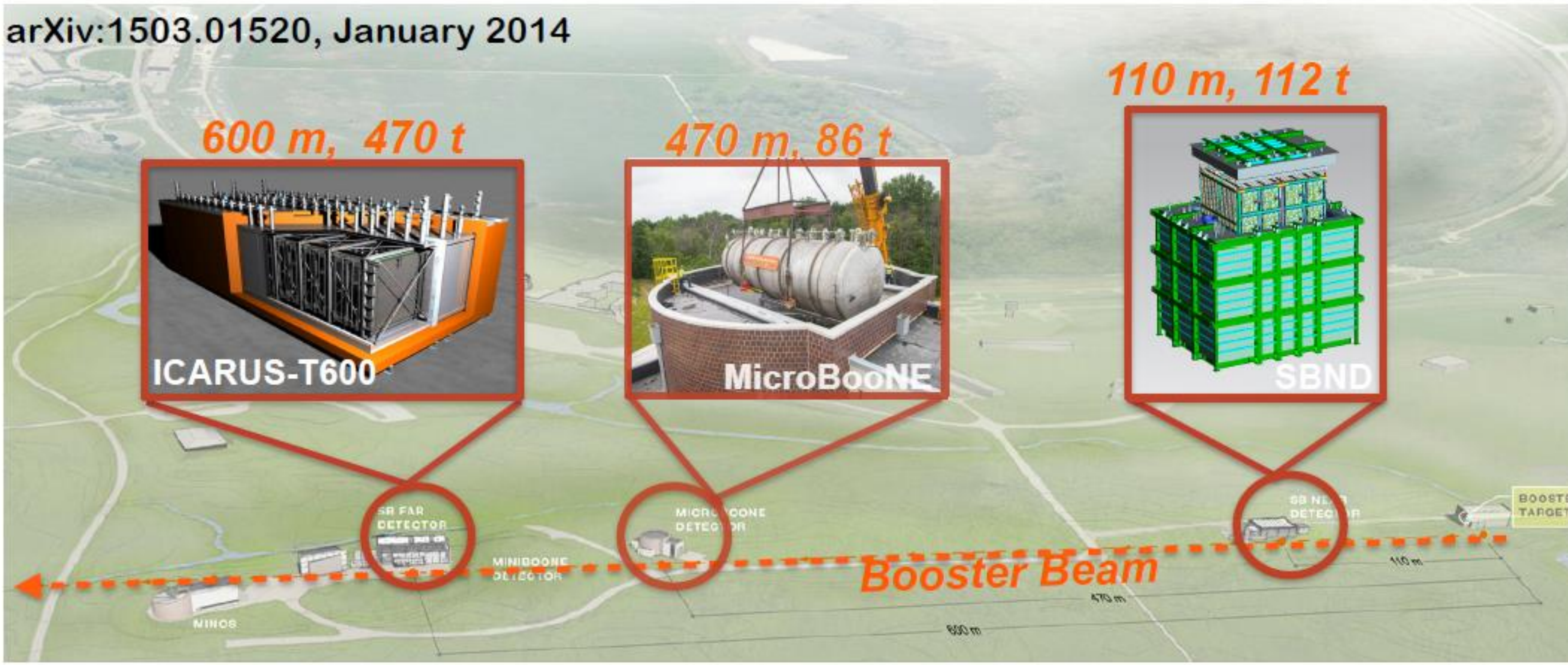
$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\text{ m}}{700\text{ MeV}} \sim \mathcal{O}(1\text{ km/GeV})$$

| | Detector | Distance from BNB Target | Active LAr Mass |
|---|---|---|---|
| (2019) | SBND | 110 m | 112 ton |
| (2015) | MicroBooNE | 470 m | 87 ton |
| (2018) | ICARUS | 600 m | 476 ton |

$\nu_\mu \rightarrow \nu_e$ (horn focused beam)

# SBN Program at Fermilab

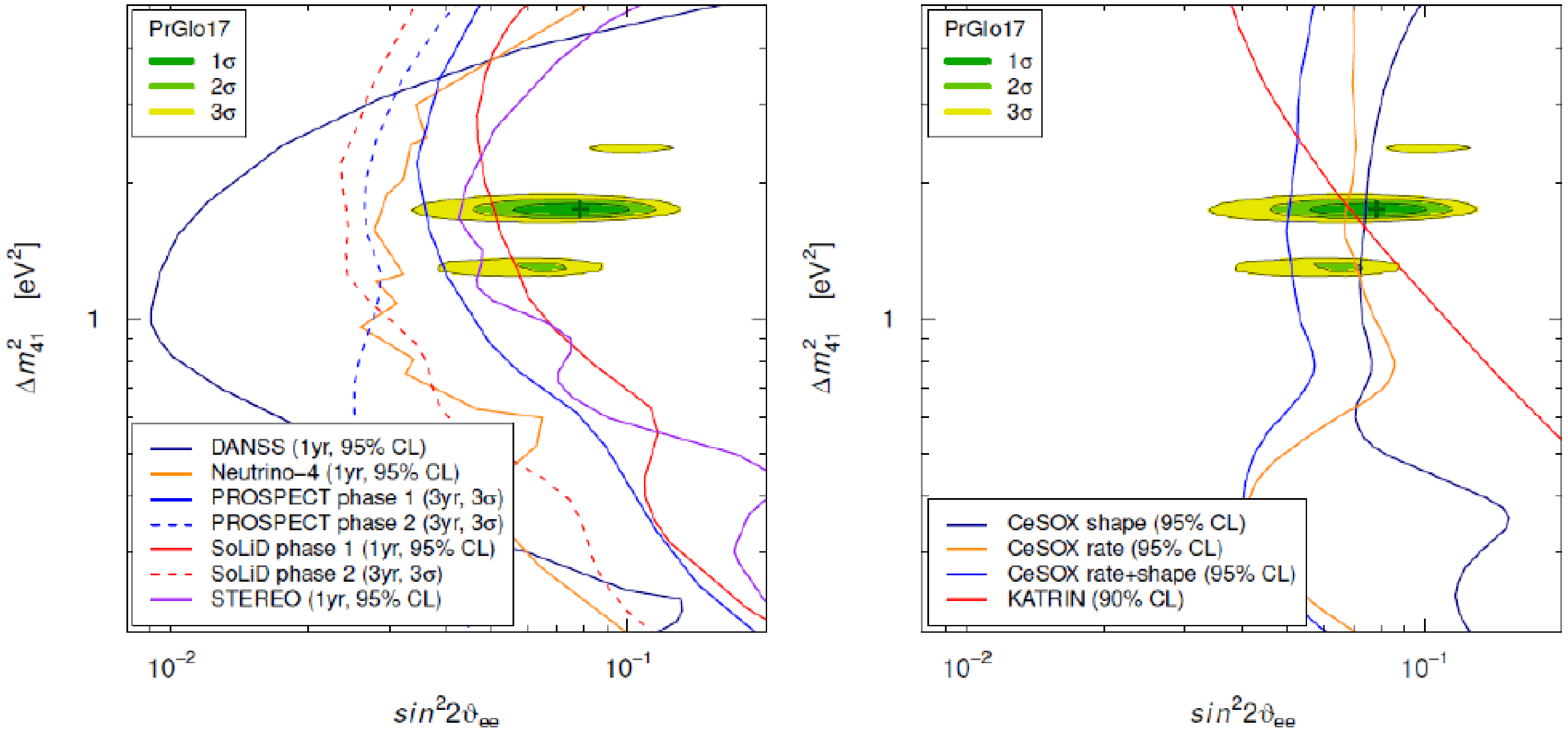
**3 LArTPCs in the Booster Neutrino Beamline**




**SBND (first data in 2019)**
**MicroBooNE (first data in late-2015)**
**ICARUS (first data in 2018)**

# Future Sterile Neutrino Search

$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ **(Reactor/β/Source Exp.)**

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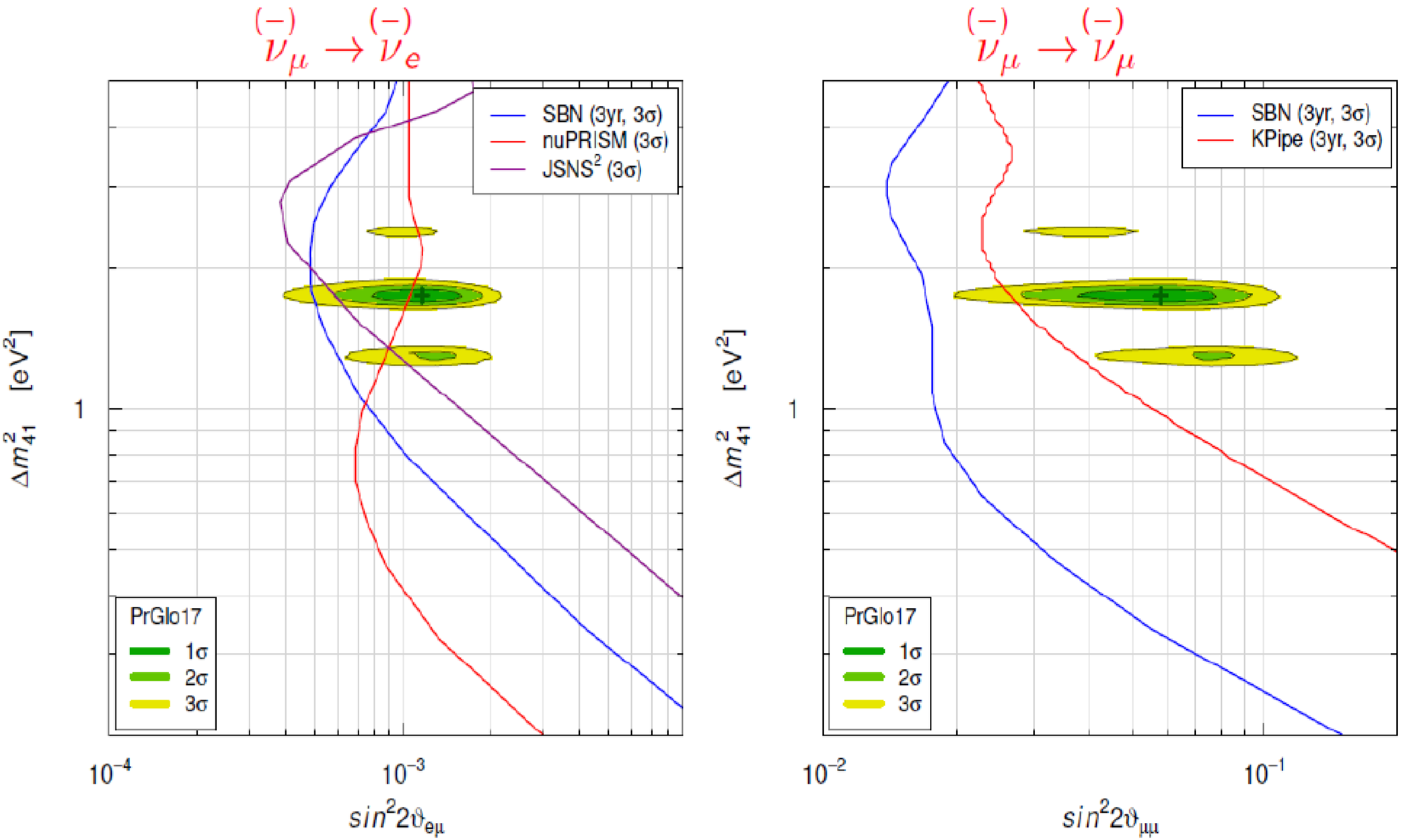
# Future Sterile Neutrino Search

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# JSNS$^2$ Experiment

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

# JSNS$^2$ Collaboration

JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku

Soongsil
Dongshin
GIST
Seoyeong
Chonnam
Seoul

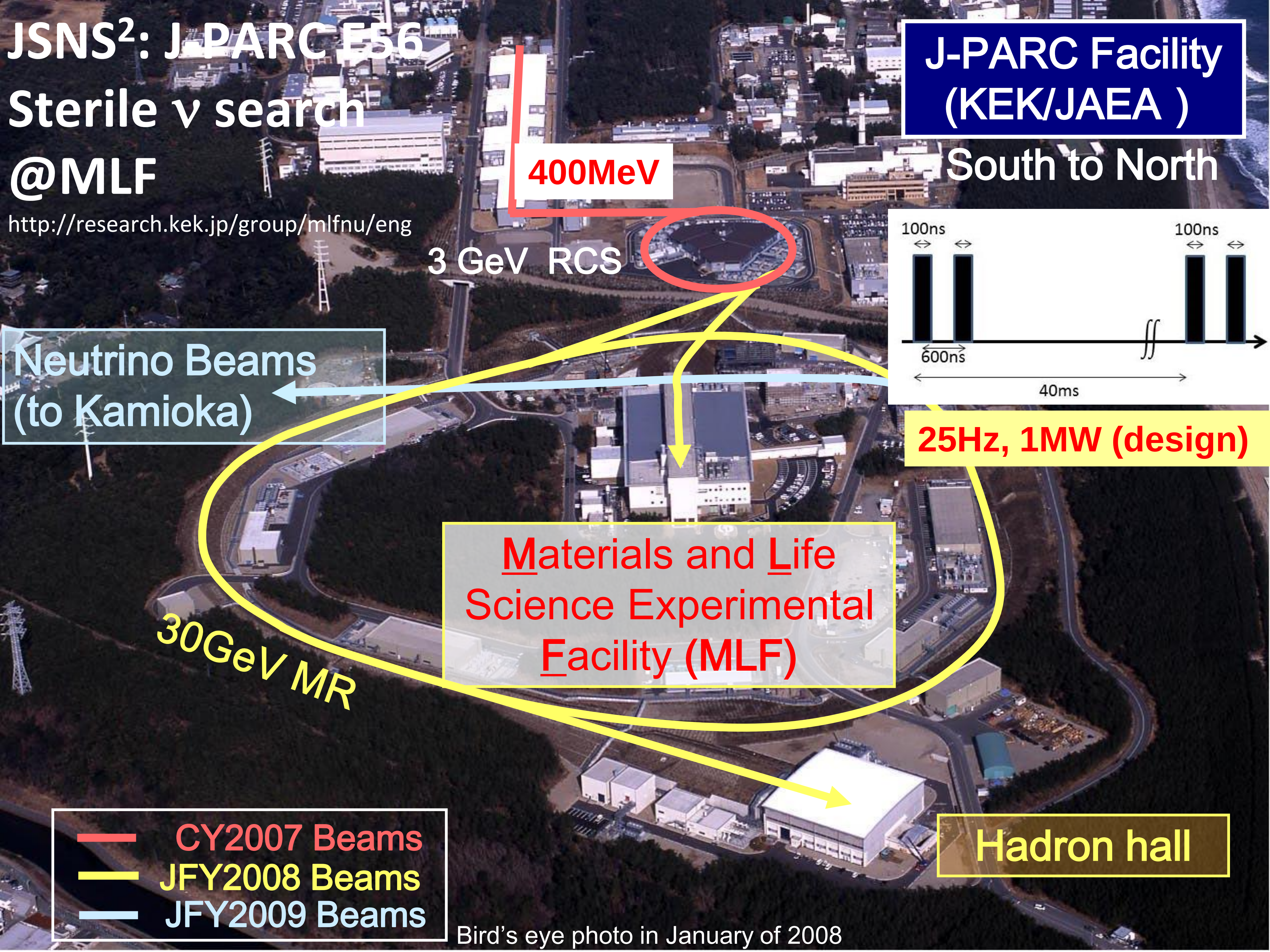
Chonbuk
Kyungpook
Sungkyunkwan
SeoulTECH

Alabama
BNL
Florida
Michigan

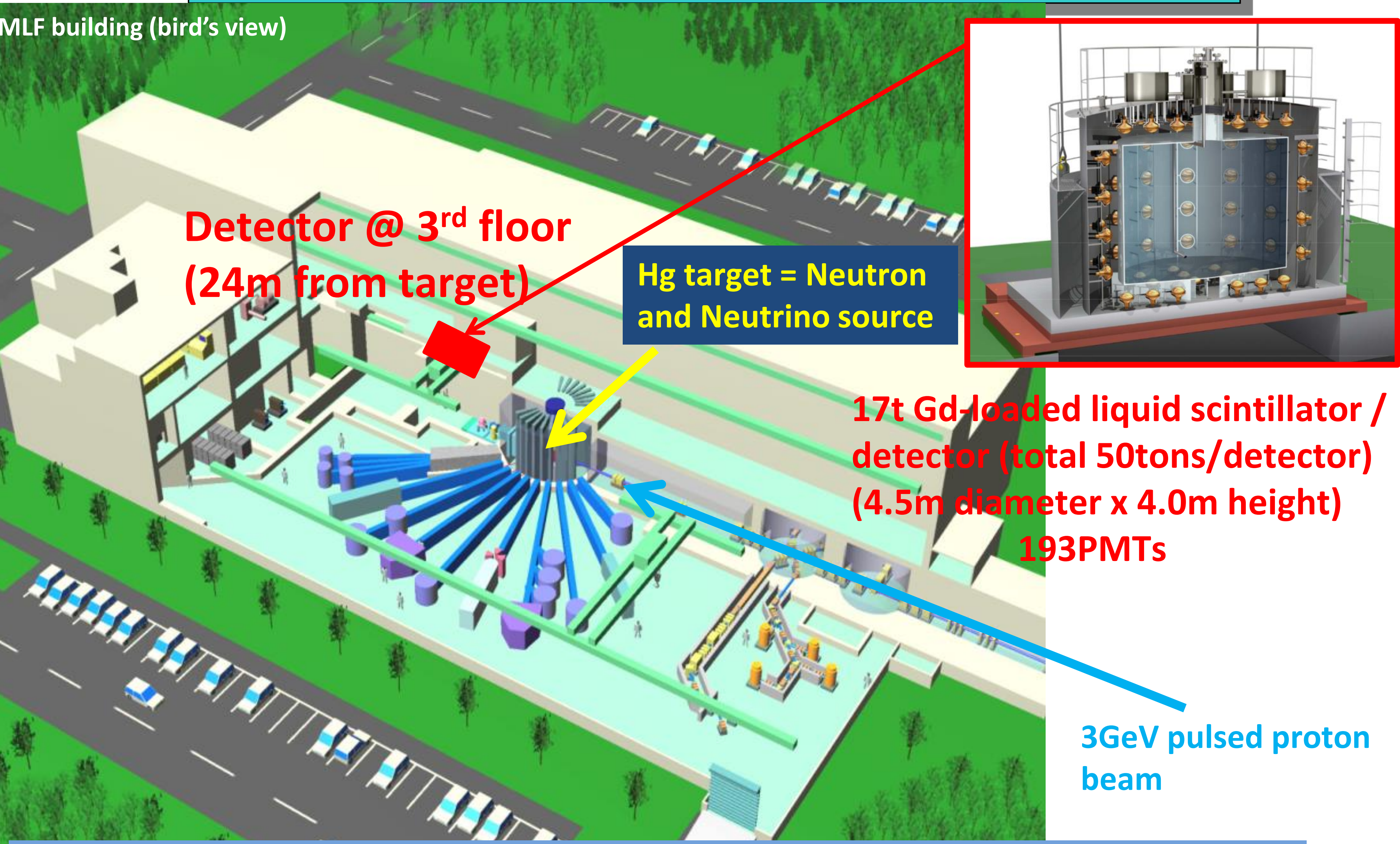
Sussex

# Why JSNS$^2$ ?

- **Direct test of the LSND with better sensitivity**
  **- Muon antineutrino beam from muon Decay At Rest (DAR)**
- ***Narrow (~9 $\mu$s) 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**
- **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**


JSNS$^2$: J-PARC E56
Sterile ν search
@MLF
http://research.kek.jp/group/mlfnu/eng
J-PARC Facility
(KEK/JAEA )
South to North
400MeV
3 GeV RCS
100ns
100ns
600ns
40ms
Neutrino Beams
(to Kamioka)
25Hz, 1MW (design)
Materials and Life
Science Experimental
Facility (MLF)
30GeV MR
Hadron hall
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

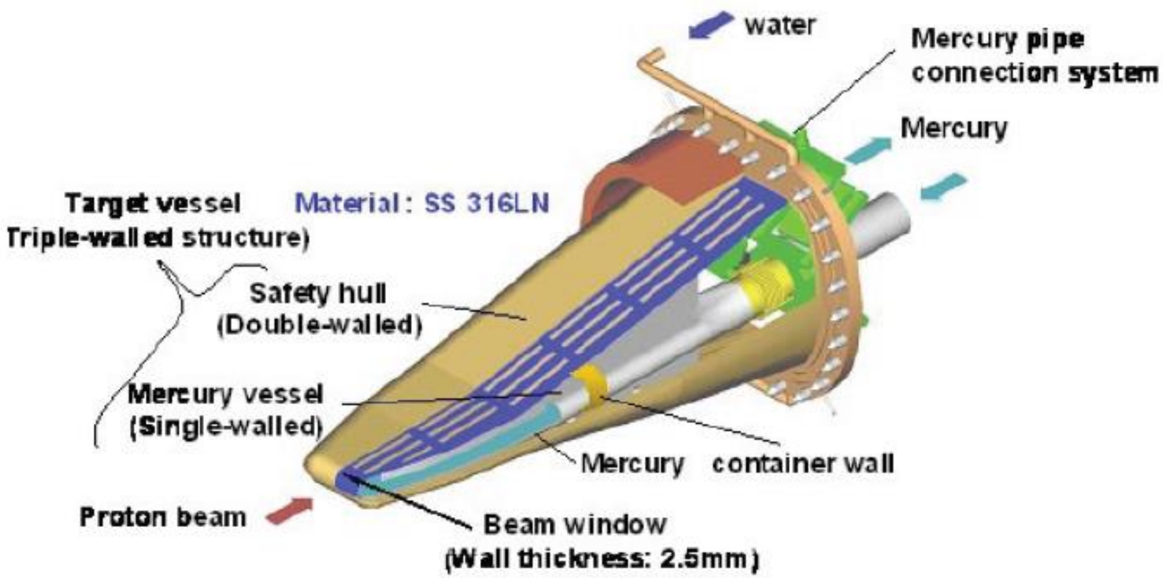
# JSNS$^2$ Experiment at J-PARC MLF

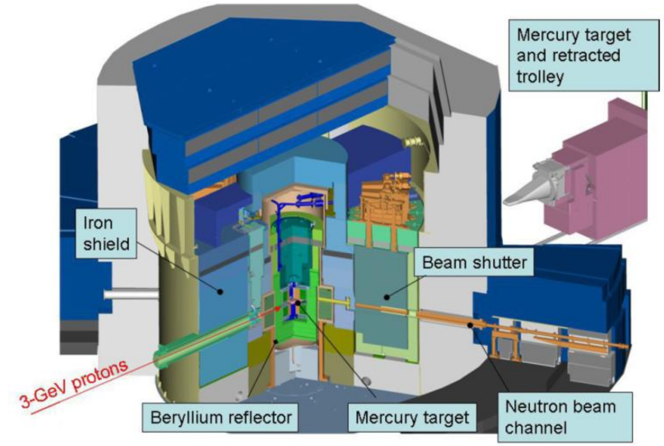


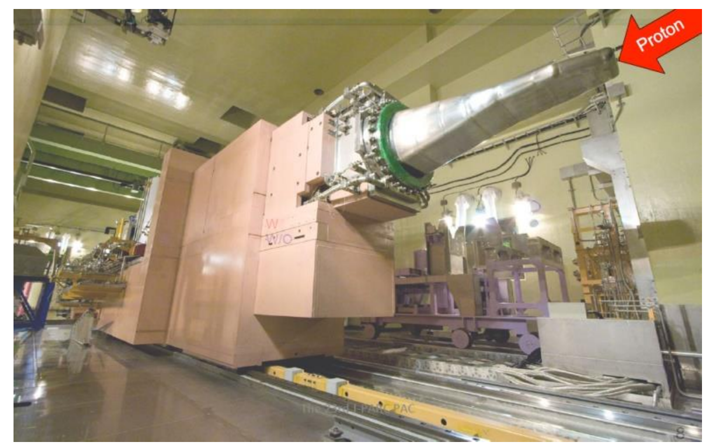

Searching for neutrino oscillation : $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up

# 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**




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

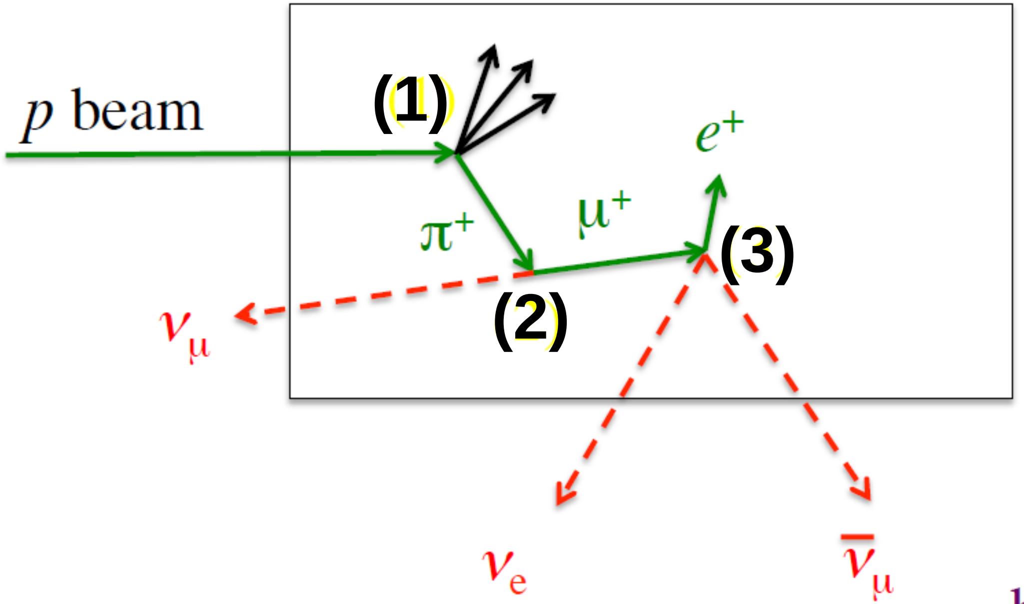
$$\hookrightarrow \pi^{\pm}(stop) \rightarrow \mu^{+} + \nu_{\mu}$$

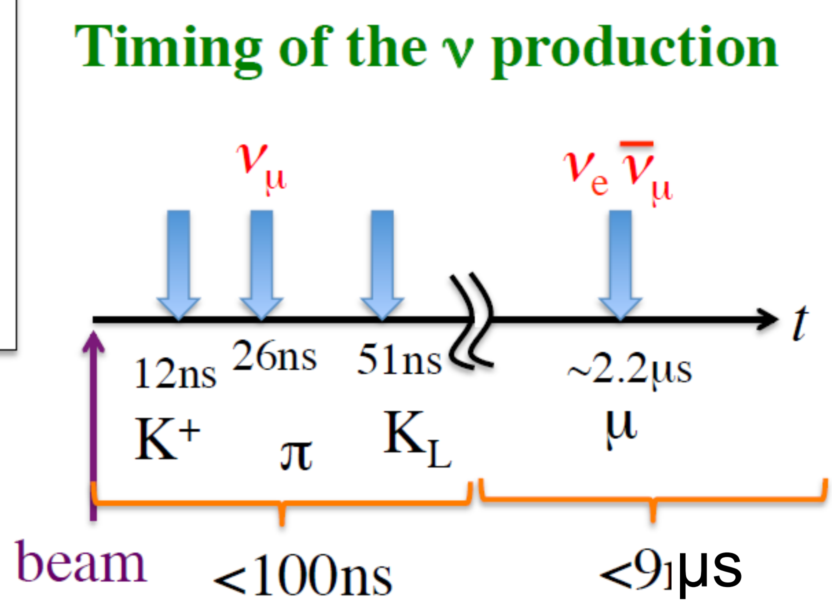
$$\hookrightarrow \mu^{+}(stop) \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

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

# Neutrinos from Muon Decay At Rest (DAR)

(1) High energy (~GeV) protons hit a dense target material and produce $\pi^+$.
(2) $\pi^+$ stops in the material and decays producing $\nu_\mu$ and $\mu^+$.
(3) $\mu^+$ stops in the material and decays producing $\nu_e$ and $\bar{\nu}_\mu$ .
(4) $\nu$'s from $\pi^-$ and $\mu^-$ are highly suppressed. $\bar{\nu}_e/\bar{\nu}_\mu \sim 1.7\times10^{-3}$



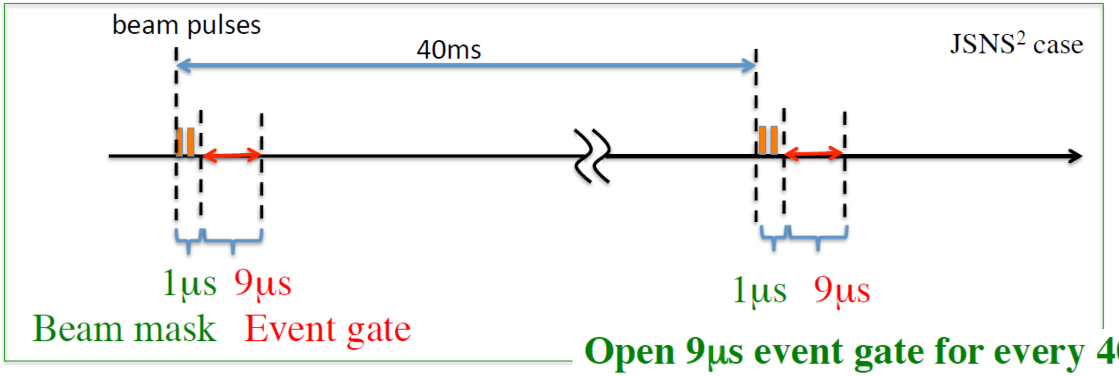
# Advantages of JSNS2 DAR Neutrino Beam

* The energy spectra of the neutrinos are perfectly known.
* The neutrino–nucleus cross section is known to a few%
* The time structure of the neutrino is perfectly known.
* $\mu^+$-origin and hadron-origin $\nu$ can be separately obtained
* Monochromatic $\nu_\mu$ can be obtained
* Neutrinos are free. Can perform experiments as parasite.

# Timing and Energy of Neutrino Beam

**Timing and Energy are good friends of JSNS²**

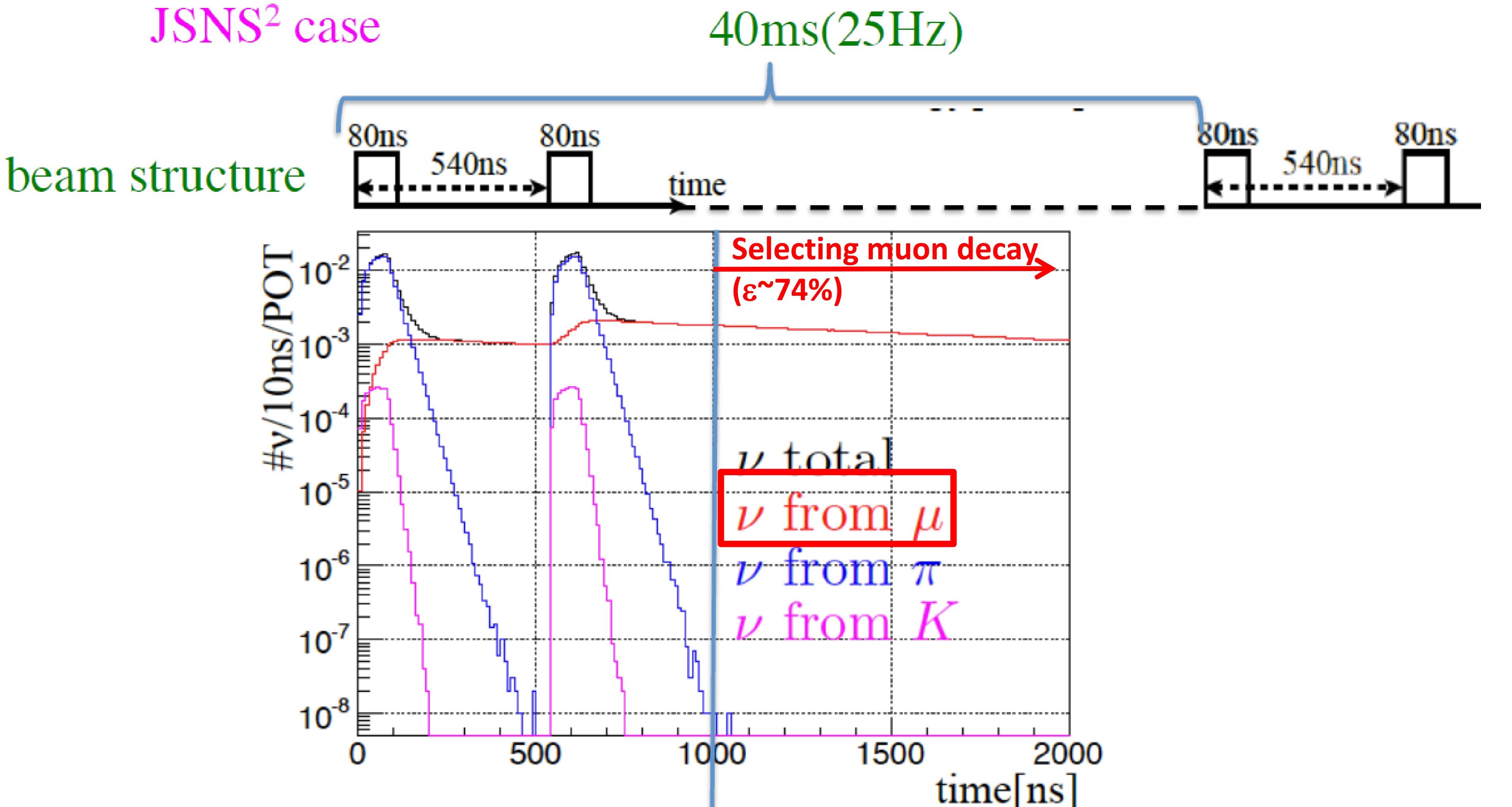
- Timing: Ultra-pure ν from $\mu^+$ Decay-at-Rest
  - ν from π and K -> removed with timing
  - Beam Fast neutrons -> removed w/ time
  - Cosmic ray BKG -> reduced by 9μs time window.
- Energy: signals / BKG separation by energy.
  - ν from μ has well-known spectrum.
  - Energy reconstruction is very easy at the IBD. (Eν ~ Evis + 0.8MeV)
  - ν from μ- is high suppressed. $\bar{\nu}_e / \bar{\nu}_\mu \sim 1.7 \times 10^{-3}$




Open 9μs event gate for every 40ms of beam pulse
➔ Cosmic-ray BKG is suppressed to 1/4,400×1/2 (by analysis)

# Pulsed Neutrino Beam

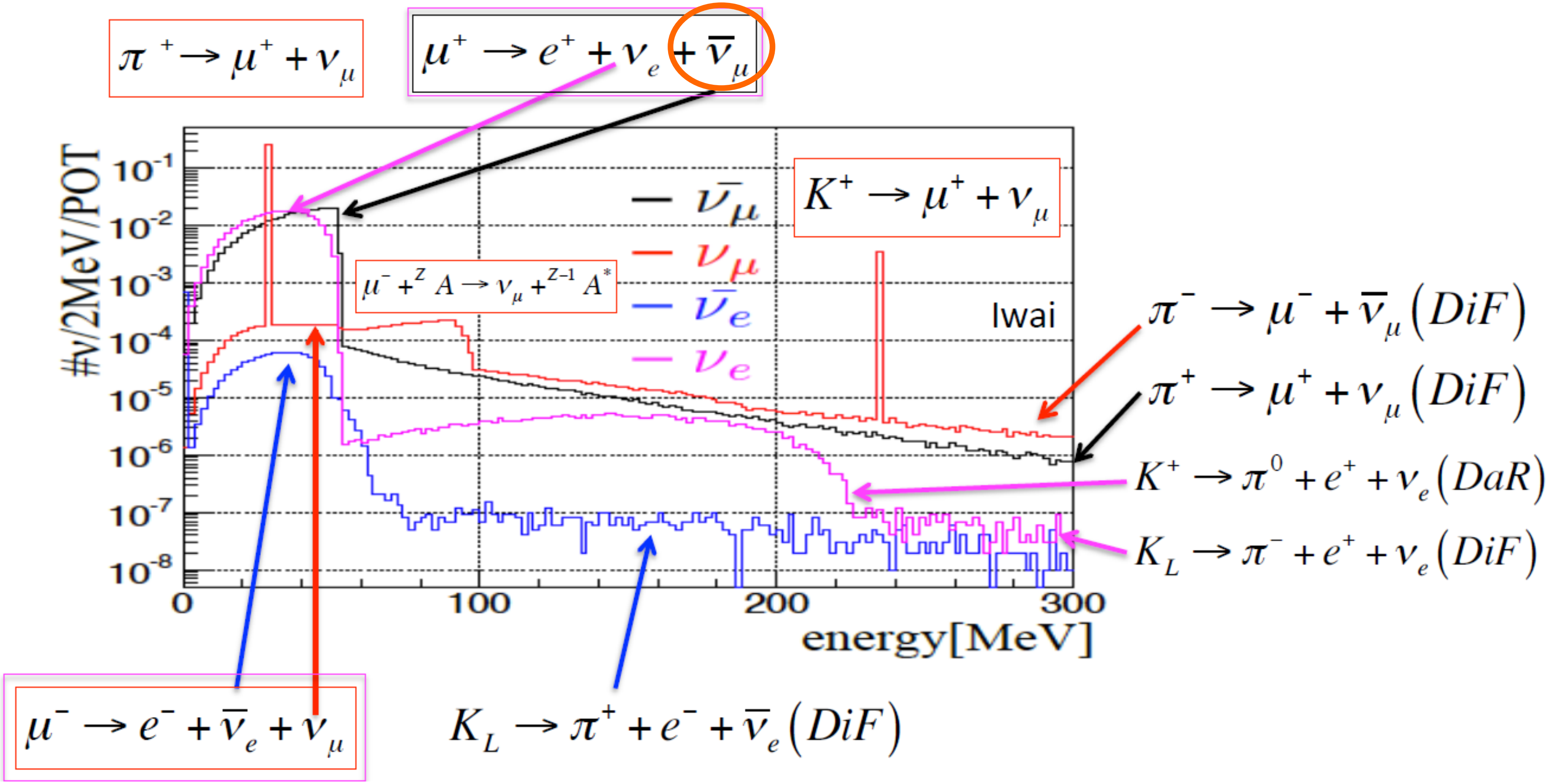
JSNS² case




ν from π & K decays (monochromatic)

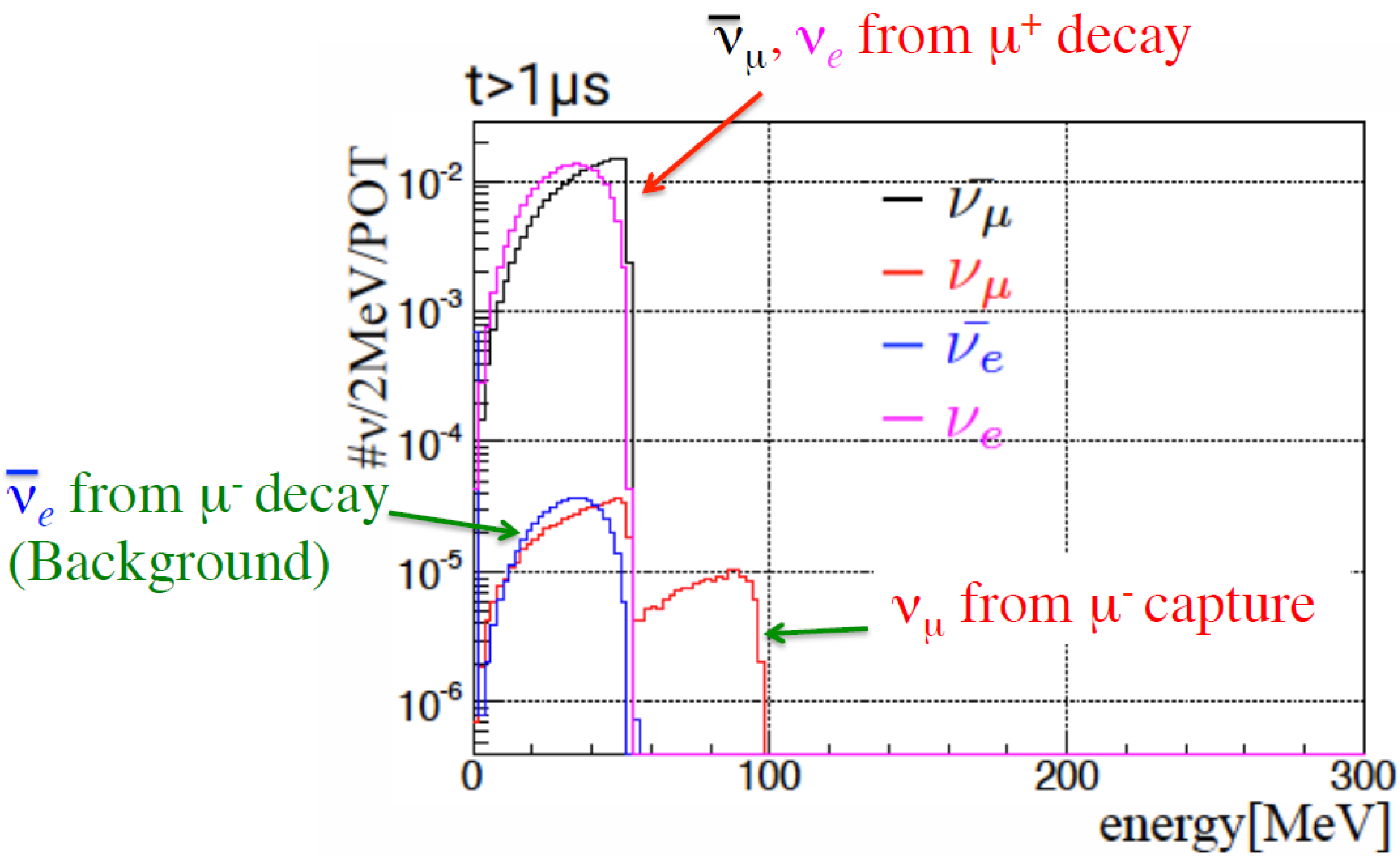
ν from μ decay.

# Neutrino Spectra from DAR+Decay in Flight

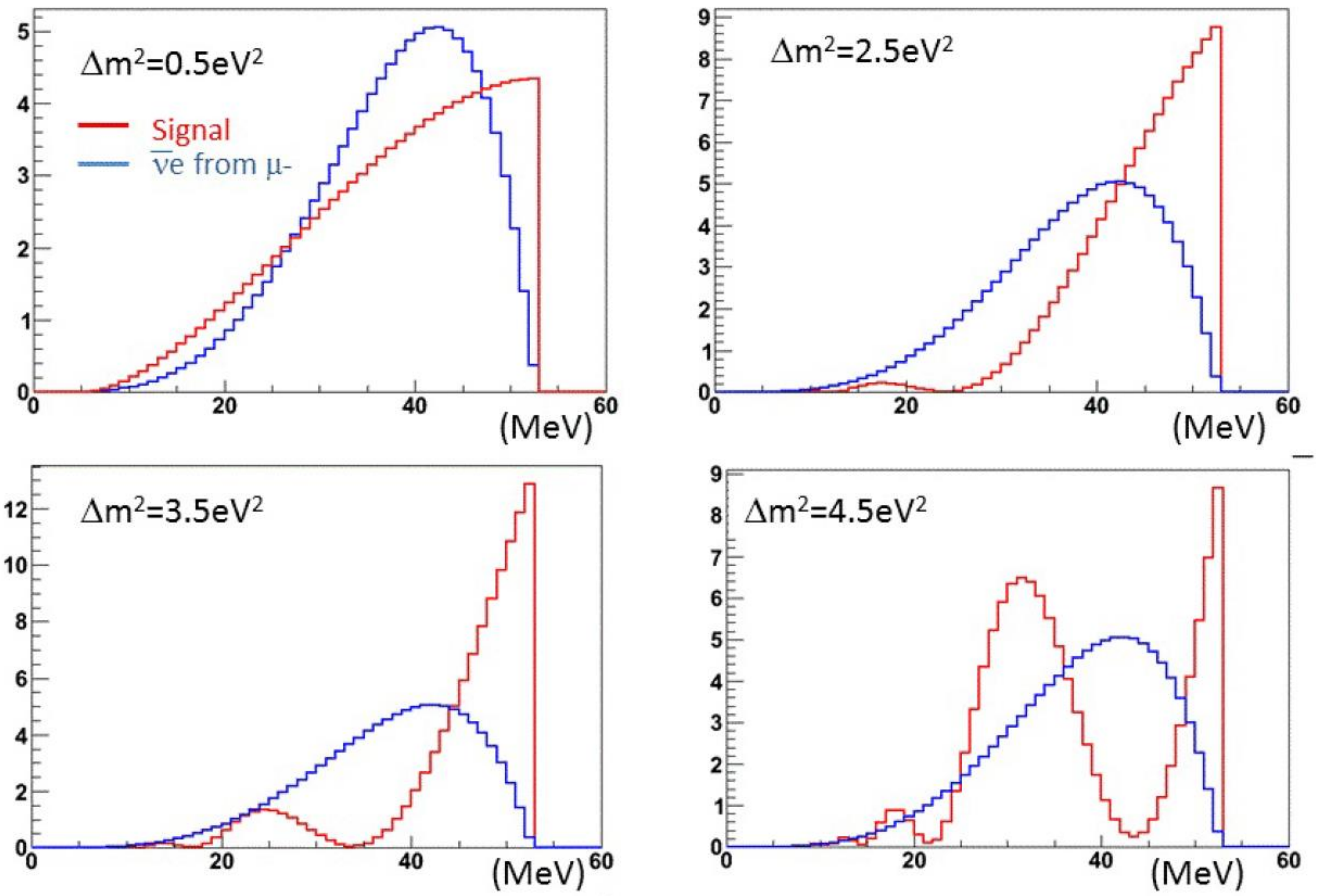


# Pure Muon Antineutrino Beam

- t > 1 μs after arrival of a beam
  → choose neutrinos from μ decay
  → suppress beam backgrounds $\bar{\nu}_e/\bar{\nu}_\mu \sim 1.7\times10^{-3}$

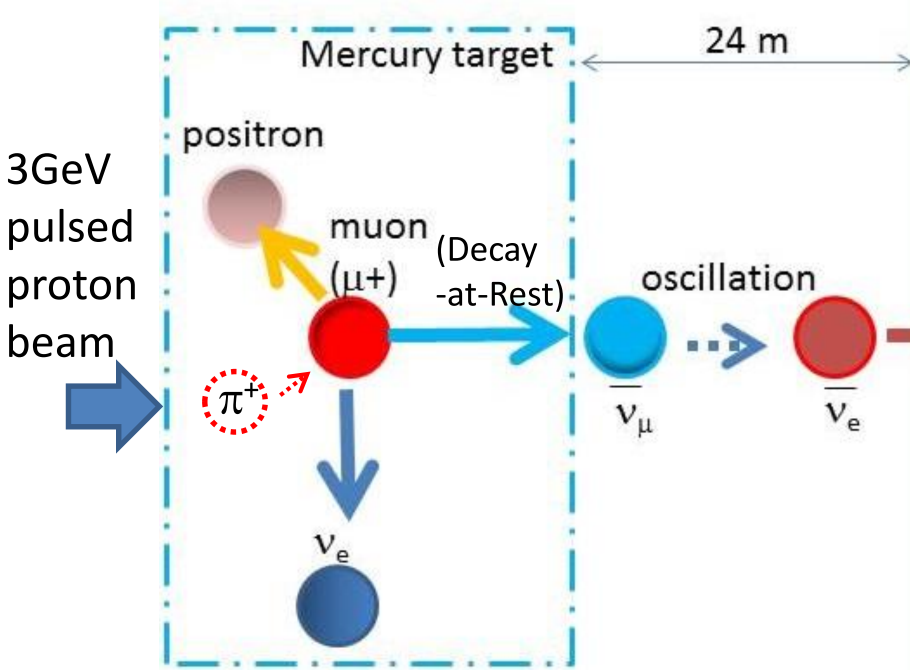


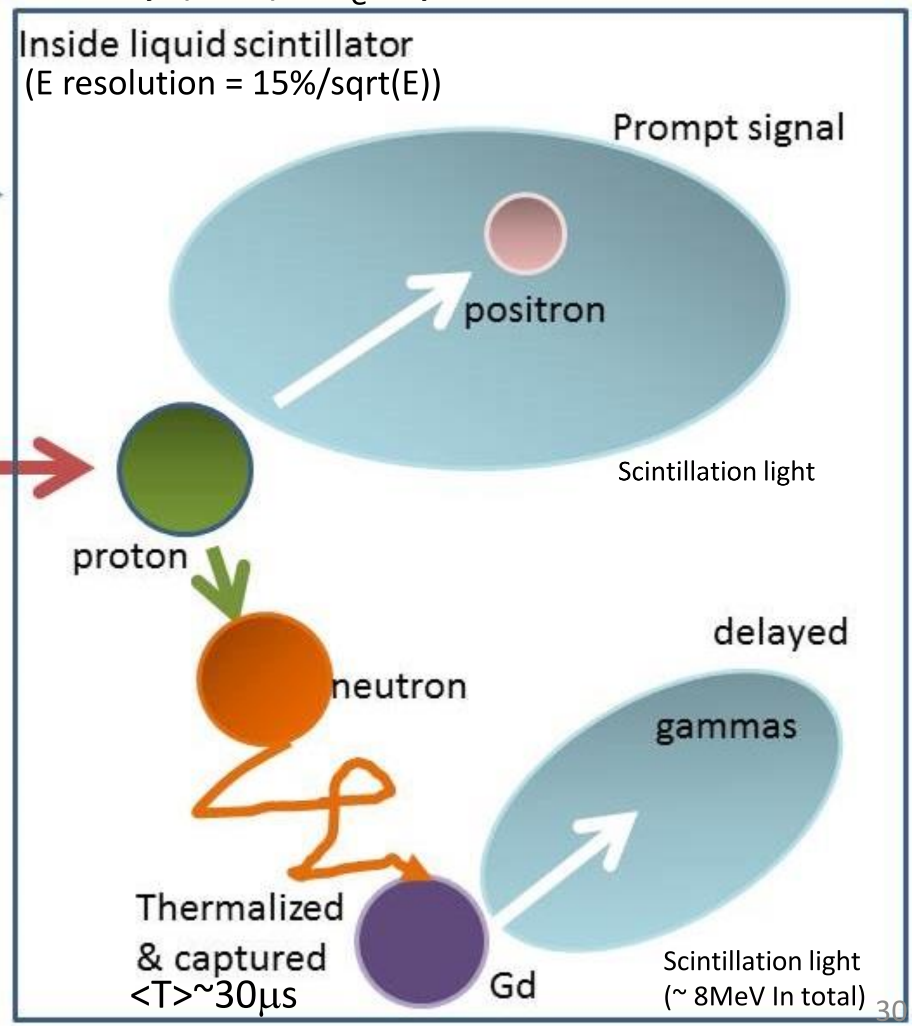
# Oscillation Signature of Muon Antineutrino



# Neutrino Production and Detection

- Large amount of parent $\mu$+ in Hg target → $\nu_\mu$ are produced.
- If sterile $\nu$ exist, $\nu_\mu$ → $\nu_e$ oscillation is happened with 24m.
- Oscillated $\nu_e$ is detected by Inverse Beta Decay (IBD): $\nu_e$ + p → $e^+$ + 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 |

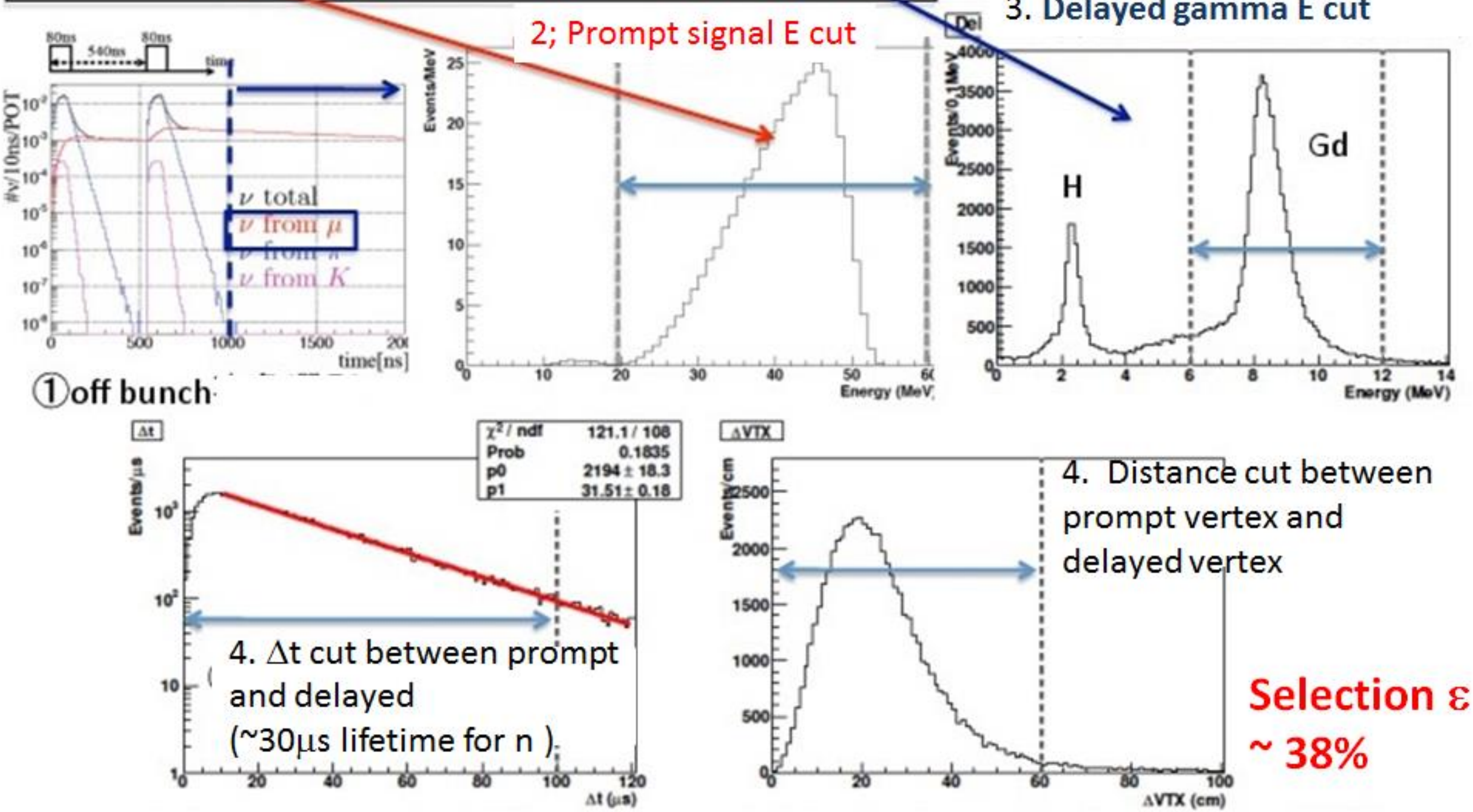
# Event Selection for Electron Antineutrinos

## IBD event selection

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

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

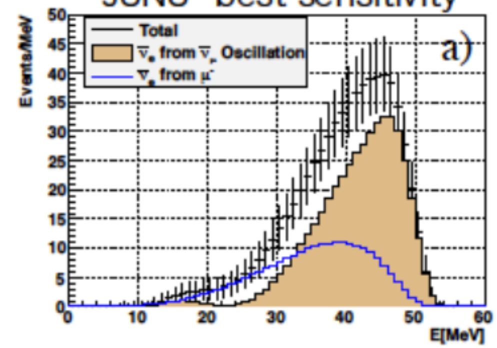
$\Delta m^2 = 3 eV^2$,
$\sin^2 2\theta = 3e^{-3}$ case



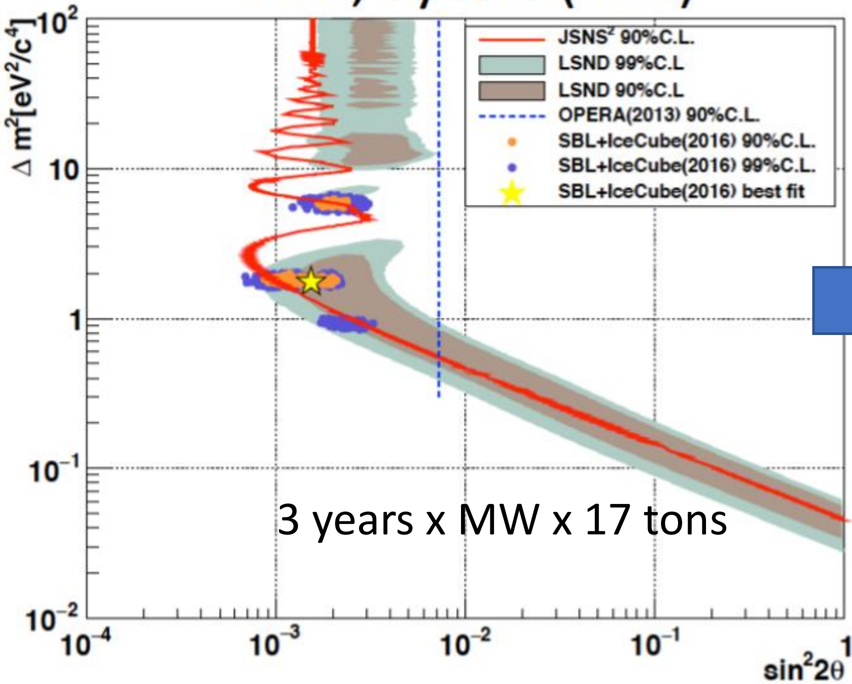
# Signal Extraction & Sensitivity

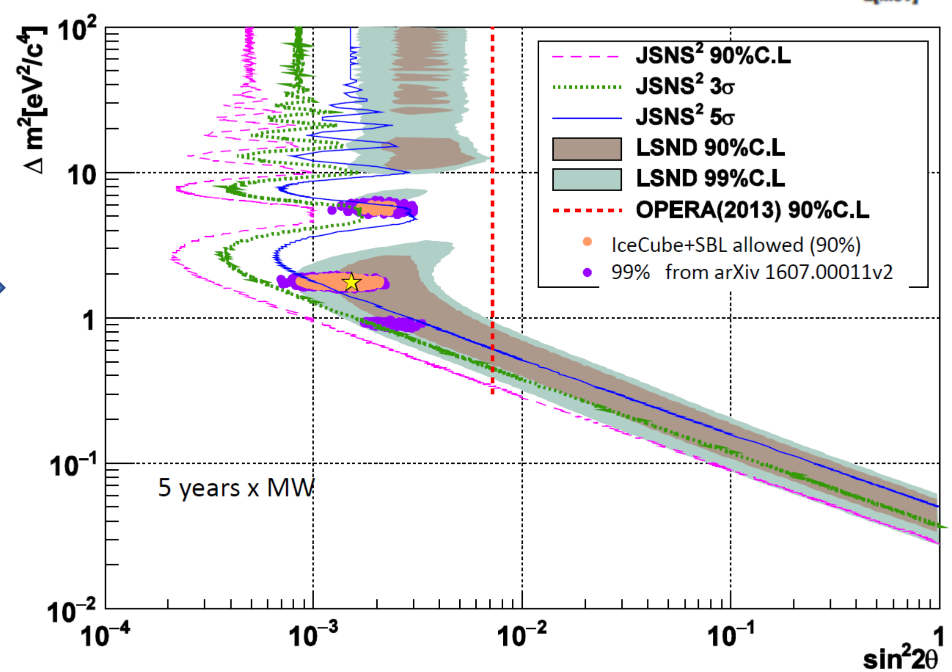
- Signal events can be distinguished from the dominant background (from another neutrino process) by using the difference of energy distributions
- Most of the parameter region indicated by LSND exp. can be explored with more than 5$\sigma$ significance in 5 years with 1MW beam power

JSNS² best sensitivity




24m, 3years (TDR)



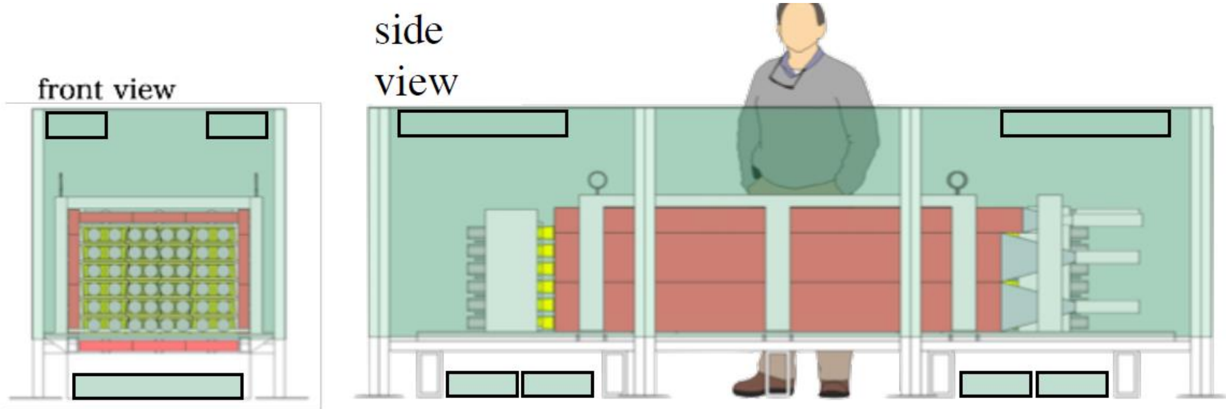



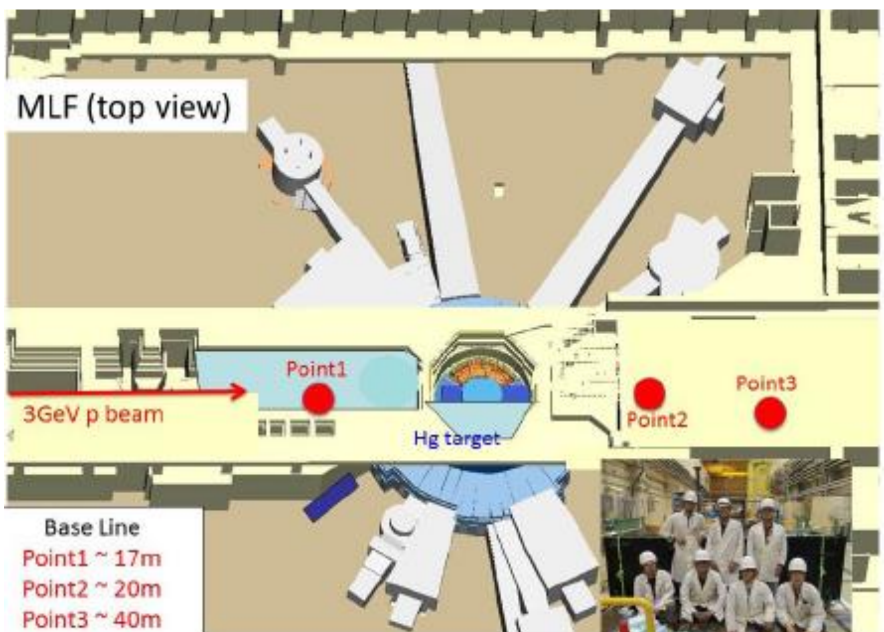
# History and Plan of JSNS$^2$

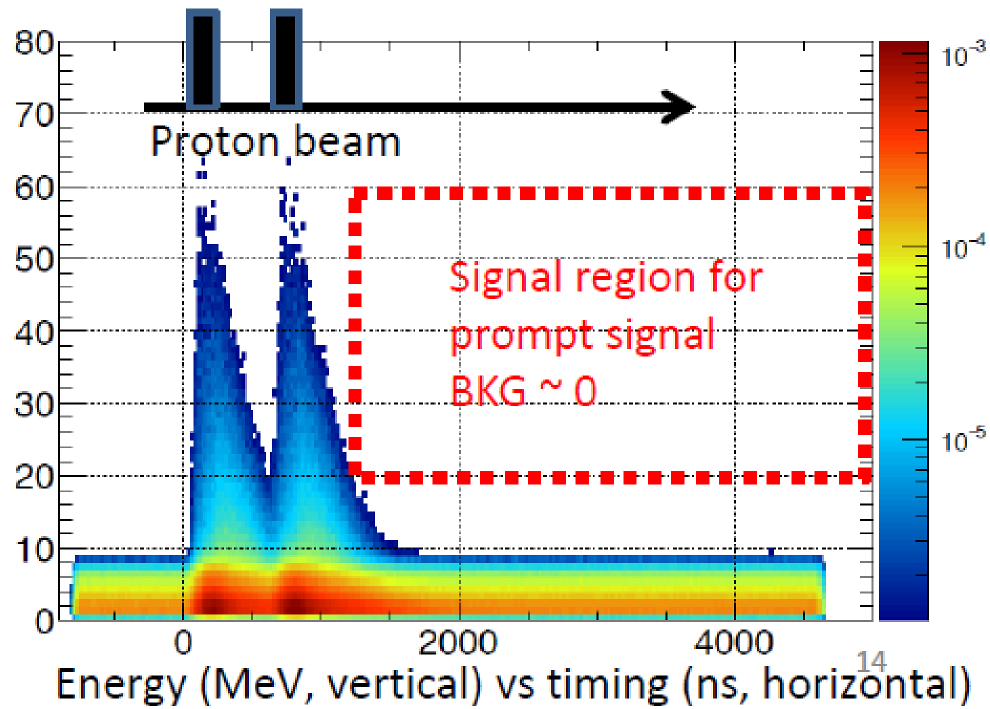
- Sep 2013: Submitted a proposal to J-PARC PAC
- Apr-Jul 2014: BG rate measurement at MLF 3$^{rd}$ floor
- Dec 2014: Submitted a status report on BG results
- Jan 2015: Stage-1 approval from J-PARC PAC
- Jun 2016: Funding approval for the first detection construction
- Jan 2017: Participation of Korean group
- May 2017: Submitted a TDR to J-PARC PAC to request stage-2 approval
- Nov 2017: Submitted a revised TDR to the PAC for stage-2 approval
- Jan 2018: SUS tank under construction
- Early 2019: Will start data-taking

# On-site Background Measurement (2014)

- **main scintillators**
  - **24 pieces, 500kg**
- **2 layers of veto scintillators**
  - **inner and outer veto**
  - **efficiency > 99.9%**



# Technical Design Report to PAC

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

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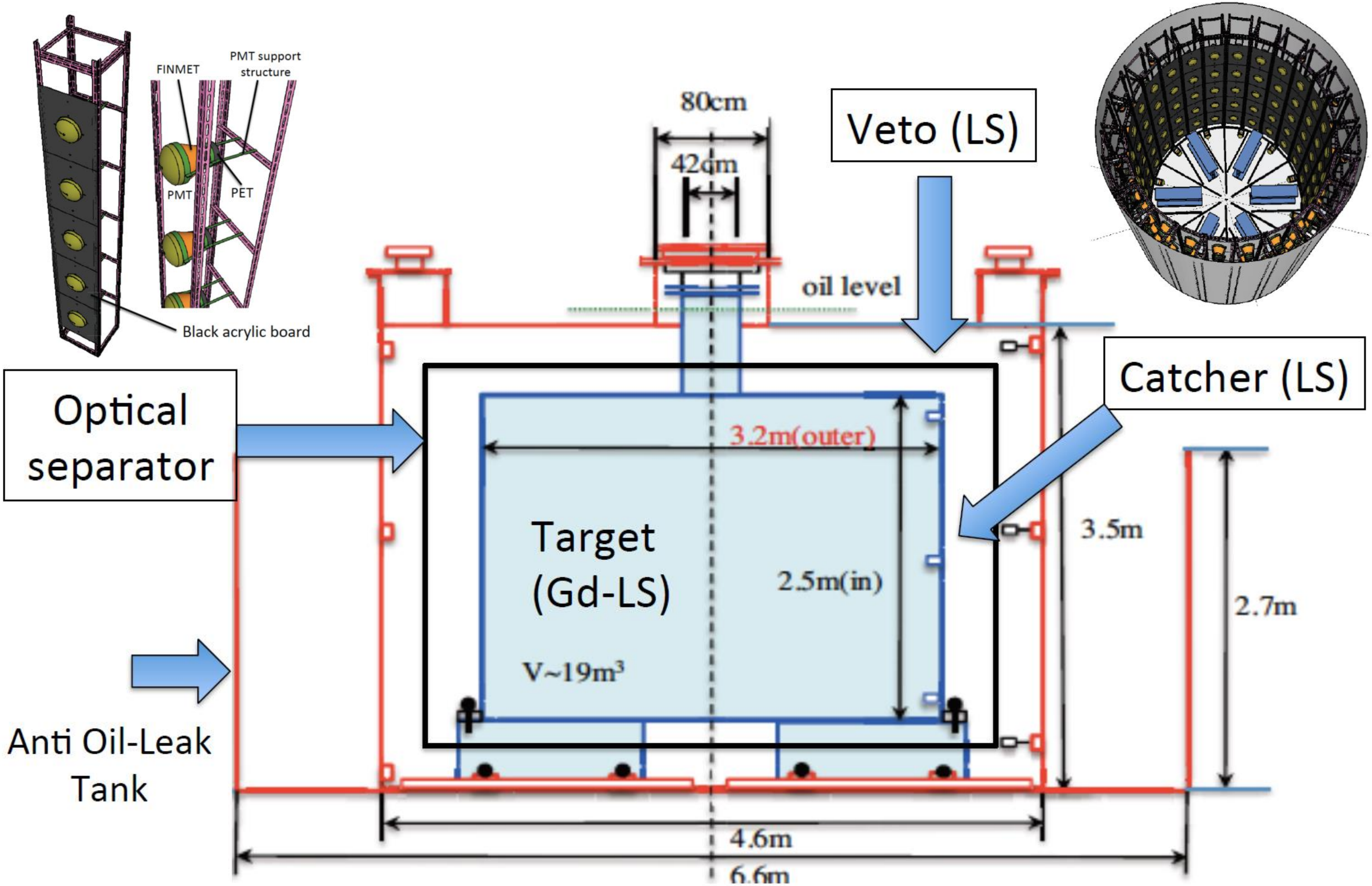
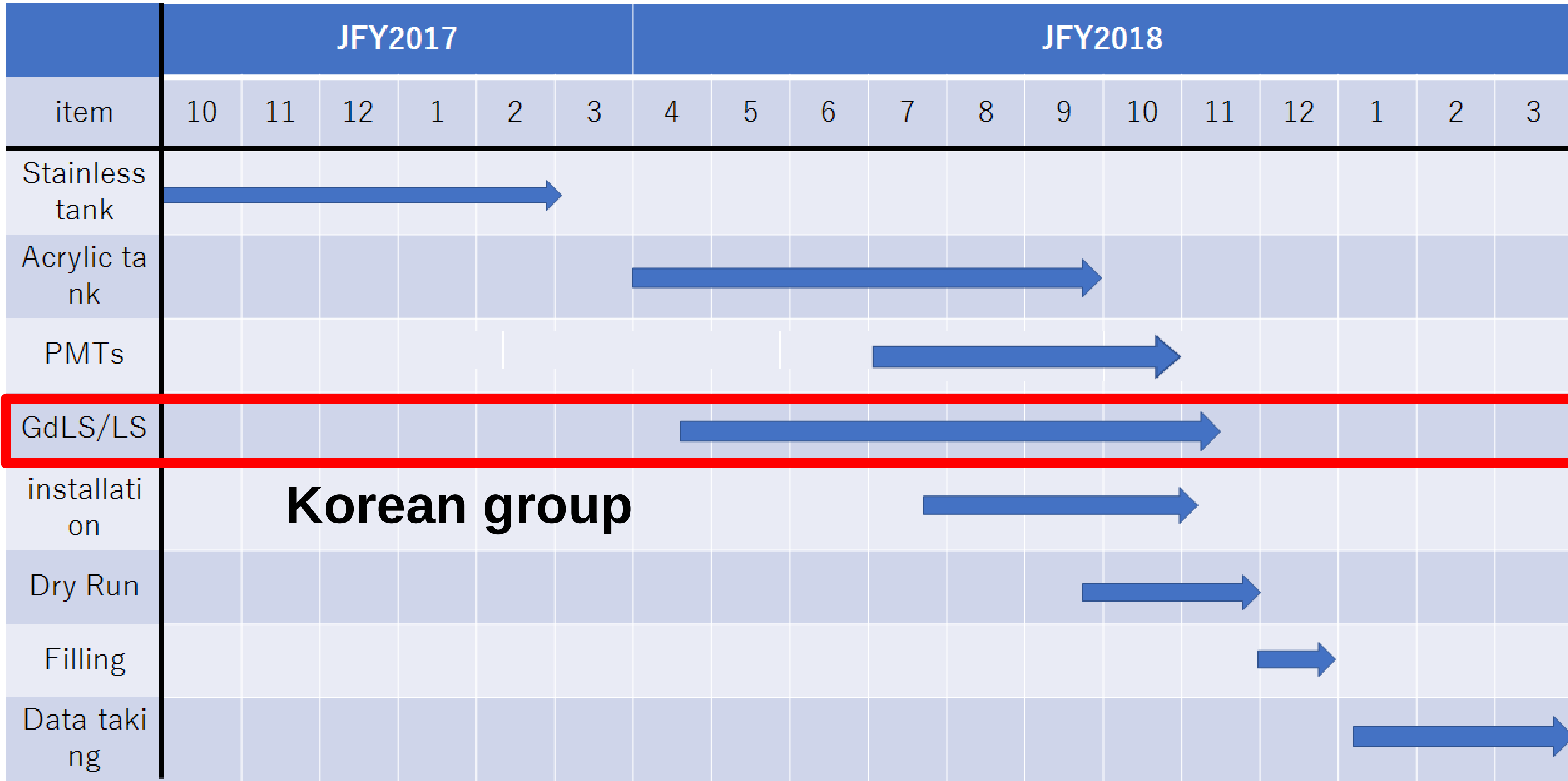
October 30, 2017

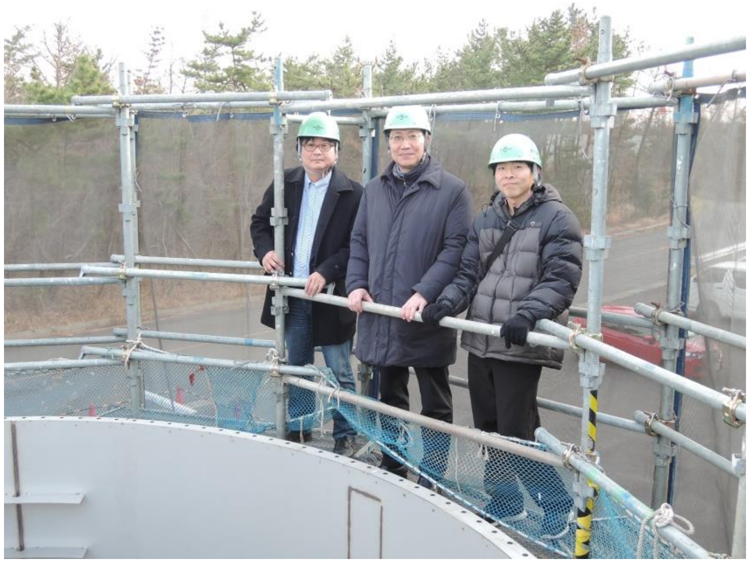
# JSNS2 Detector



# Schedule for 1st Detector Construction

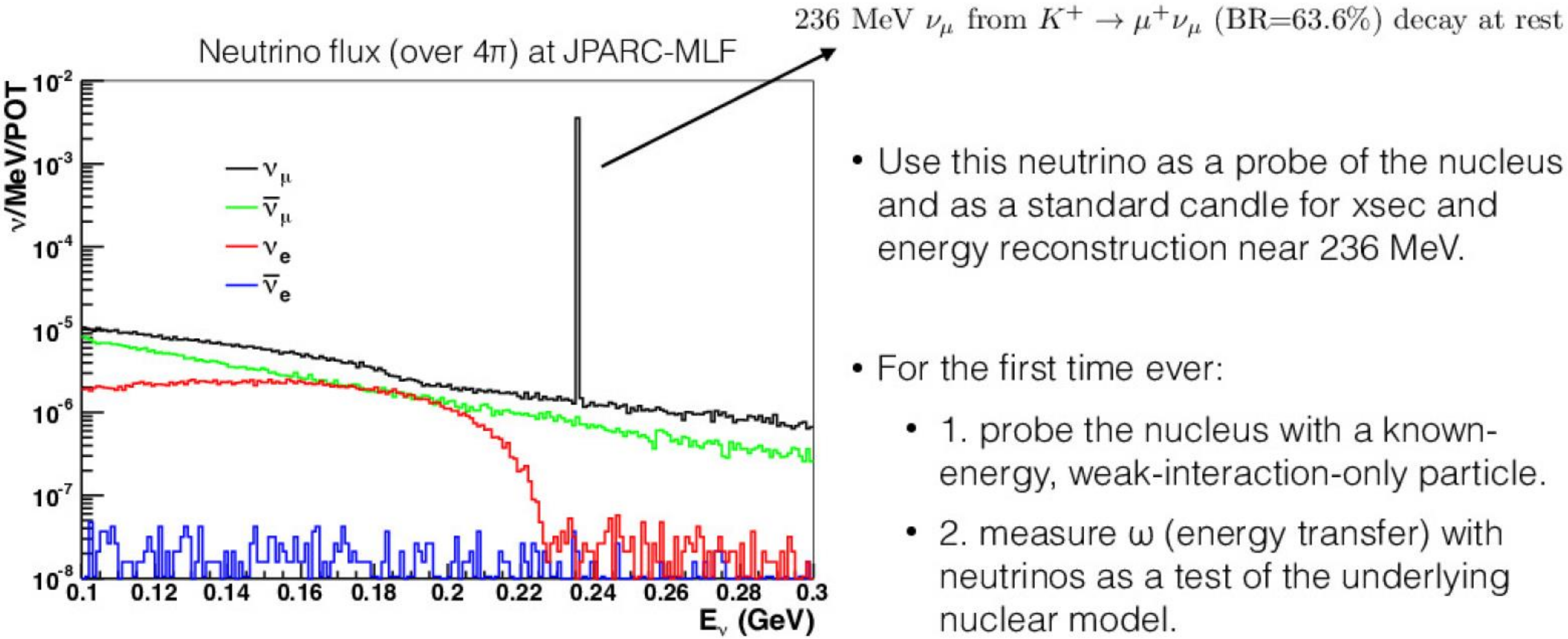


# SUS Vessel at J-PARC

# LS Production at RENO

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



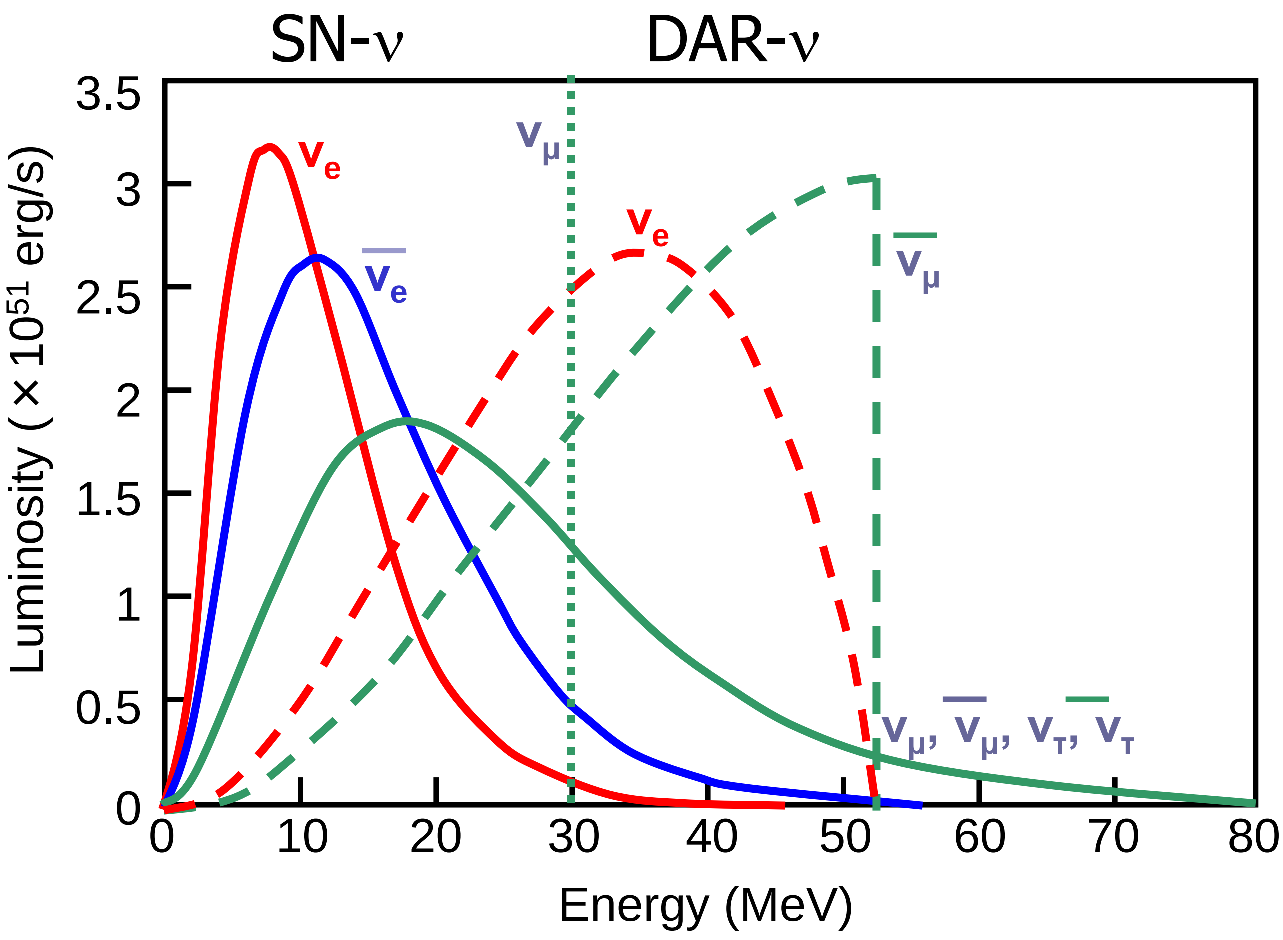

- Use this neutrino as a probe of the nucleus and as a standard candle for xsec and energy reconstruction near 236 MeV.
- For the first time ever:
  - 1. probe the nucleus with a known-energy, weak-interaction-only particle.
  - 2. measure ω (energy transfer) with neutrinos as a test of the underlying nuclear model.

## Event rate expectation

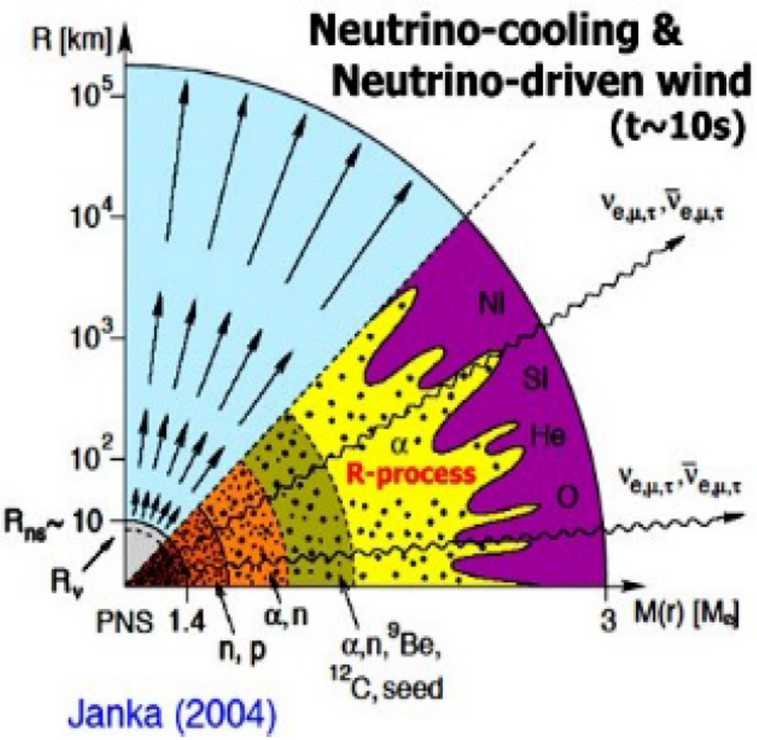
| Detector (source) | Target (mass) | Exposure | Distance from source | 236 MeV $\nu_\mu$ CC events |
|---|---|---|---|---|
| JSNS$^2$ (JPARC-MLF) | Gd-LS (50 ton) | $1.875 \times 10^{23}$ POT (5 years) | 24 m | 152000 |

# Low Energy Neutrino Beam

## Energy Spectra of Decay-At-Rest ν



# 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) |

Thanks for your attention!