# Status of JSNS$^2$

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

Takasumi Maruyama (KEK) for the JSNS$^2$ collaboration

# JSNS$^2$ collaboration

JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku

Soongsil
Dongshin
GIST
Seoyeong
Chonnam Nati'
Seoul Nati'

Chonbuk Nat'
Kyungpook
Sungkyunkwan
Seoul Nat' of sci and tech

Alabama
BNL
Florida
Michigan

Sussex

21 institutions
54 members

# indication of the sterile neutrino ($\Delta m^2$~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 | $\mu$ Decay-At-Rest | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | 3.8$\sigma$ | 40,30 |
| MiniBooNE | $\pi$ Decay-In-Flight | $\nu_\mu \rightarrow \nu_e$ | 3.4$\sigma$ | 800,600 |
| | | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | 2.8$\sigma$ | |
| | | combined | 3.8$\sigma$ | |
| Ga (calibration) | e capture | $\nu_e \rightarrow \nu_x$ | 2.7$\sigma$ | <3,10 |
| Reactors | Beta decay | $\bar{\nu}_e \rightarrow \bar{\nu}_x$ | 3.0$\sigma$ | 3,10-100 |

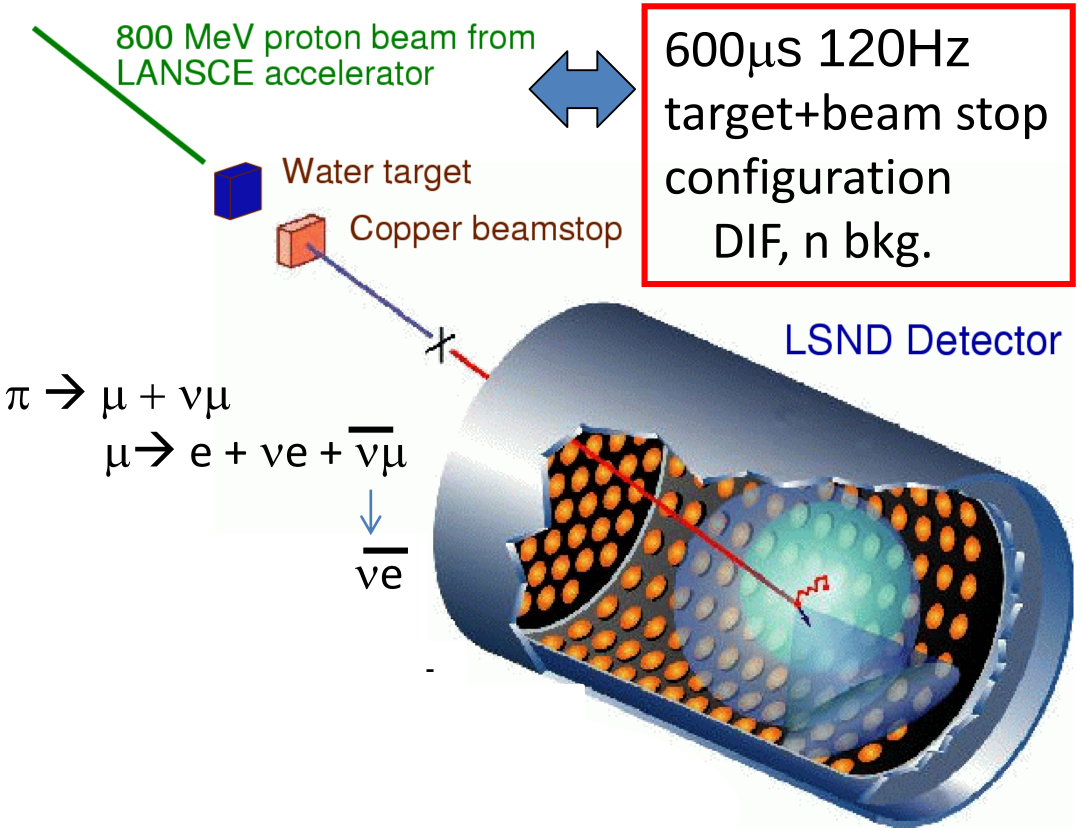
Now it is time to recheck LSND results directly

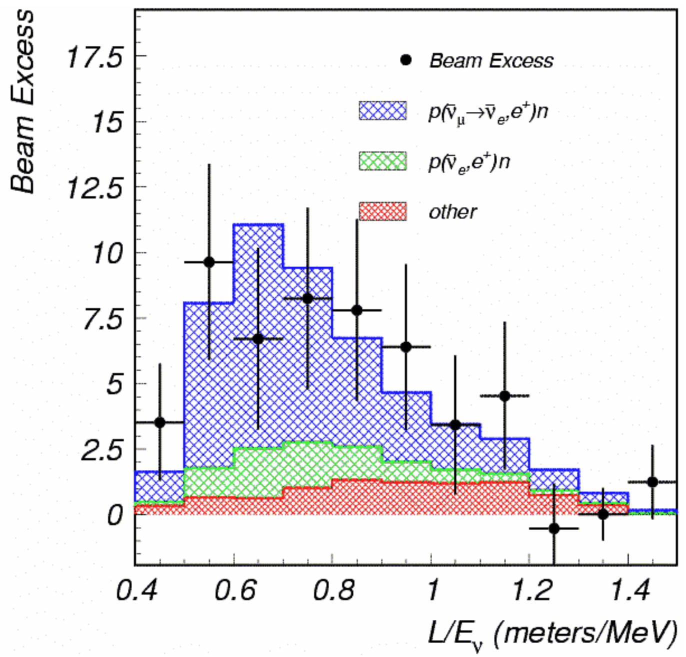
- Excess or deficit does really exist?
- The new oscillation between active and inactive (sterile) neutrinos?

# Appearance

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

1998




**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.**

$\pi^-, \mu^-$ absorbed before decay into ν's
there should not be $\overline{\nu e}$ at the level of $7\times10^{-4}$

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

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

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

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

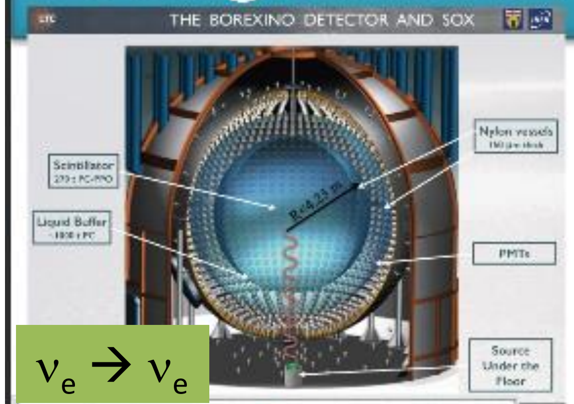
$$P_{e\mu} = -4 \sum_{i=1,3} (U^*_{e4} U_{\mu 4} U_{ei} U^*_{\mu i}) \sin^2 \frac{(m_4^2 - m_i^2)L}{4E_\nu} \sim 4 \boxed{|U_{e4}|^2 |U_{\mu 4}|^2} \sin^2 \frac{\Delta m_4^2}{4} \frac{L}{E}$$

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

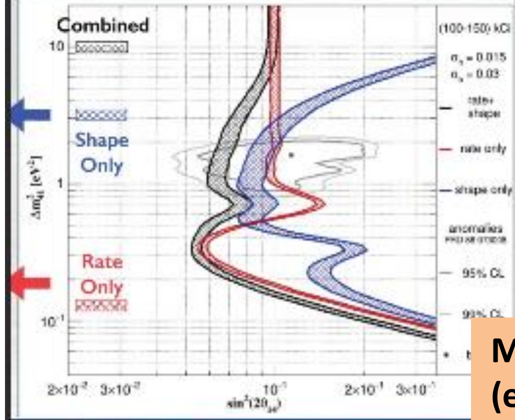
$$\boxed{P(\nu_\mu \to \nu_e) = \sin^2 2\Theta \cdot \sin^2(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu})}$$

(3+1) model

# Next generation sterile experiments are almost ready



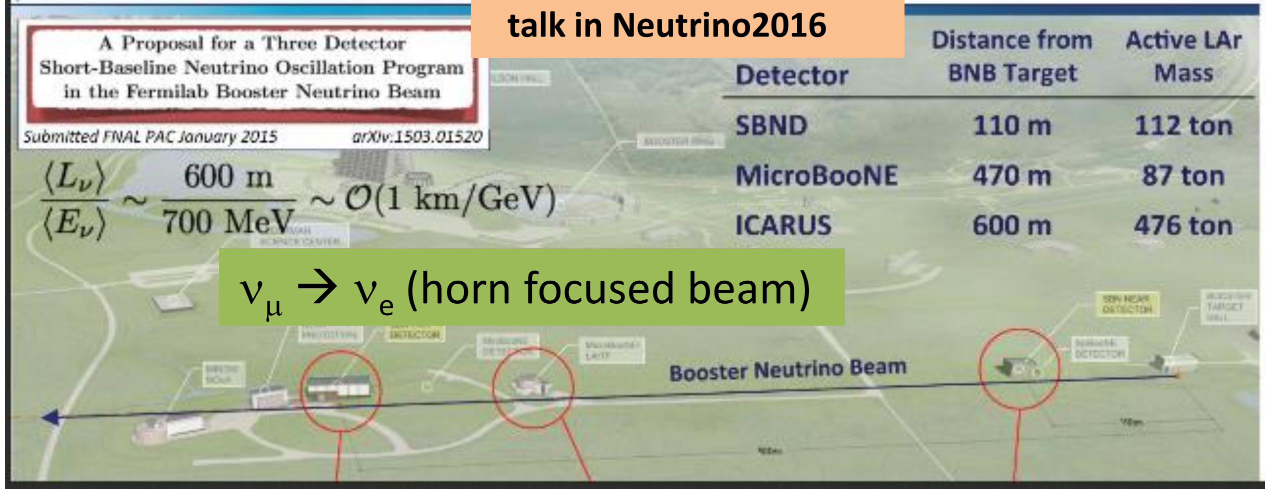

$\nu_e \rightarrow \nu_e$




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

| 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 |

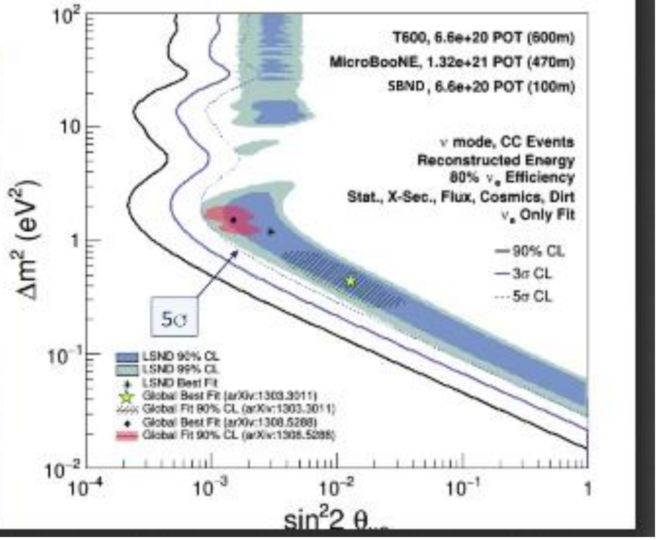
**Mauro Mezzetto's (experimental summary) talk in Neutrino2016**



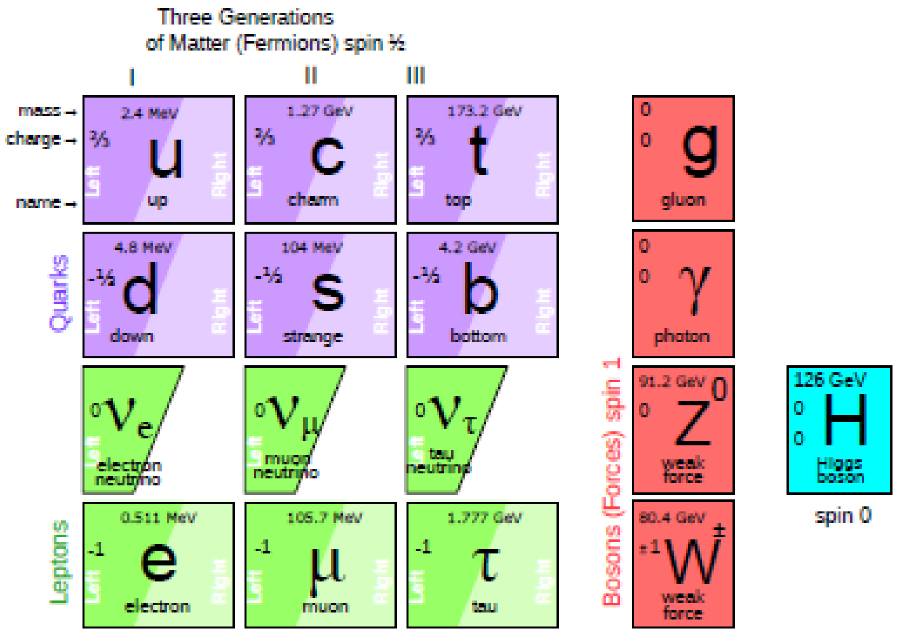

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

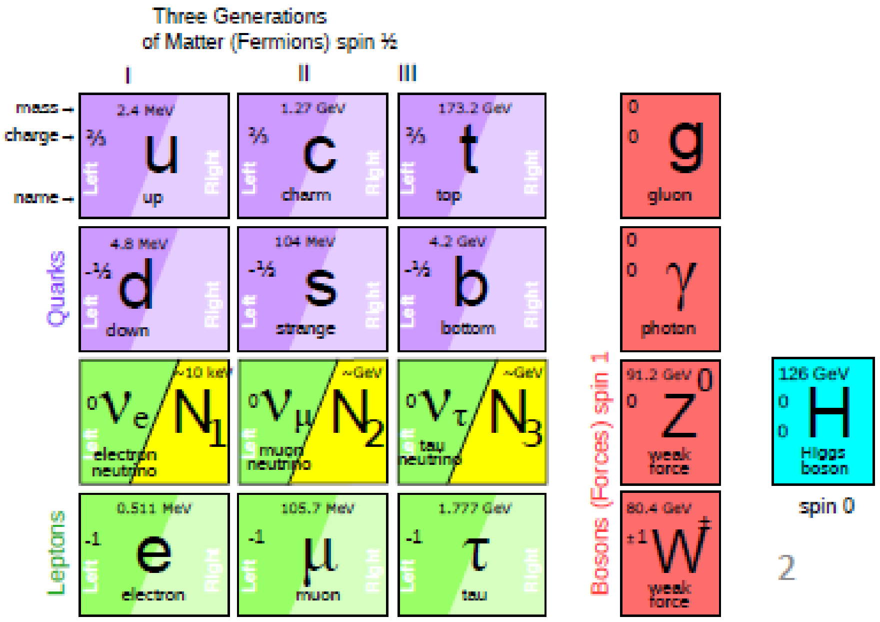
| Detector | Distance from BNB Target | Active LAr Mass |
|---|---|---|
| SBND | 110 m | 112 ton |
| MicroBooNE | 470 m | 87 ton |
| ICARUS | 600 m | 476 ton |

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



# Steile: creates SeeSaw/Dark matter ?



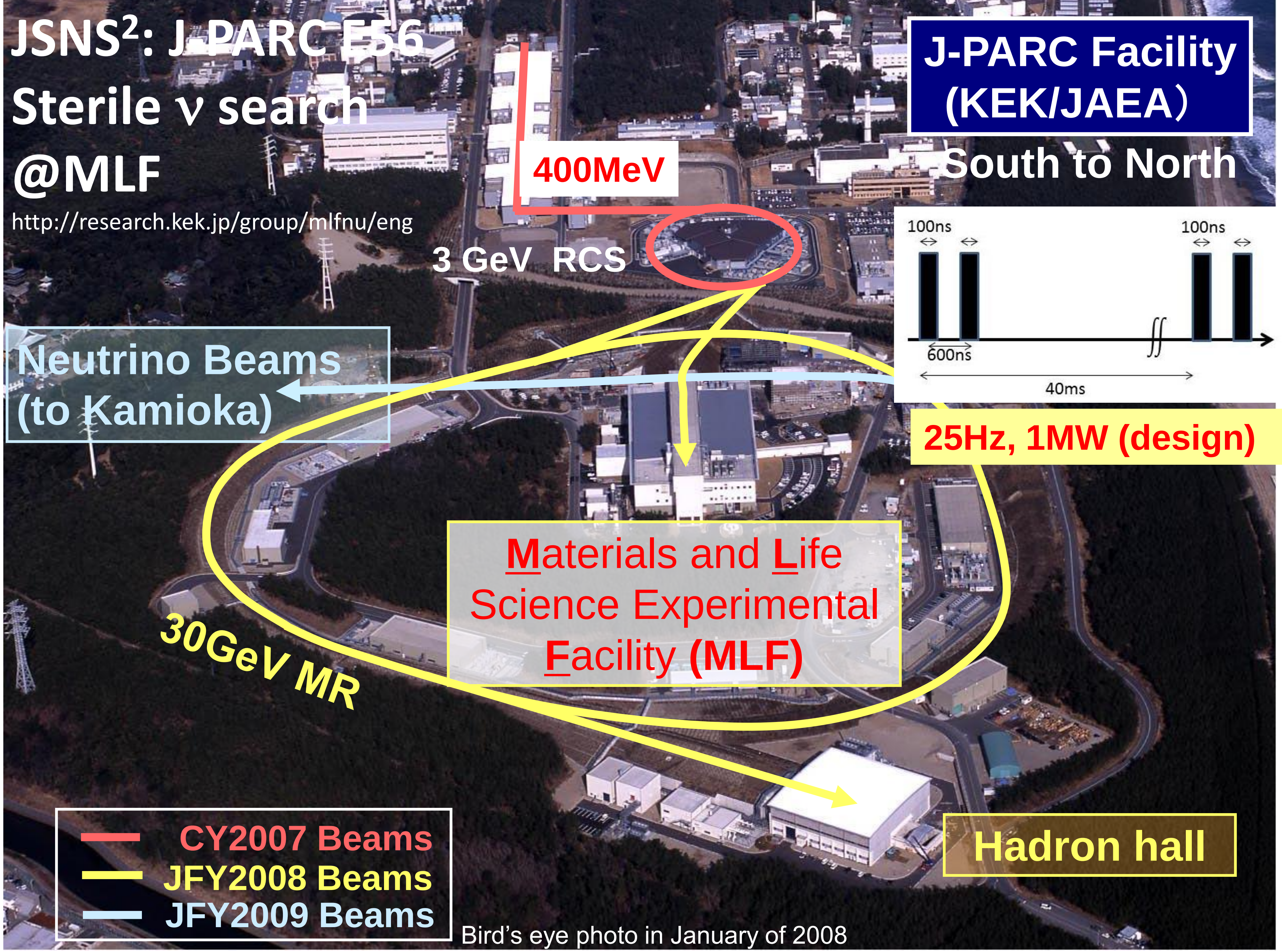




2

Since 1998 it is established that neutrinos have mass
and this very probably implies new degrees of freedom
➔ «sterile», very small coupling to known particles
completely unknown masses (eV to ZeV), nearly impossile to find.
.... but could perhaps explain all: DM, BAU,ν-masses

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

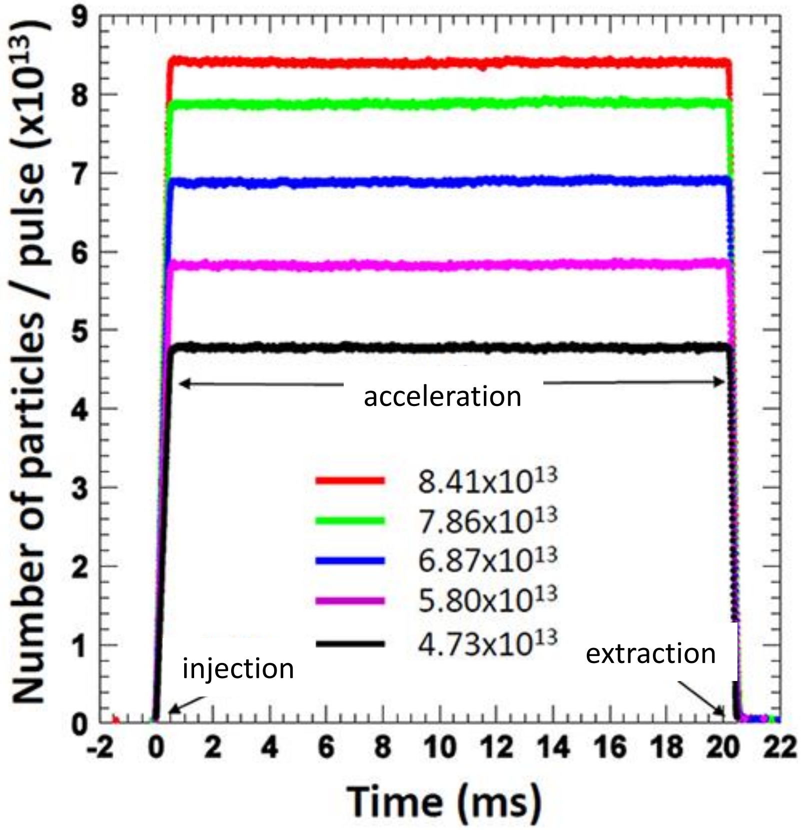
http://research.kek.jp/group/mlfnu/eng




Bird's eye photo in January of 2008

# RCS/MLF beam

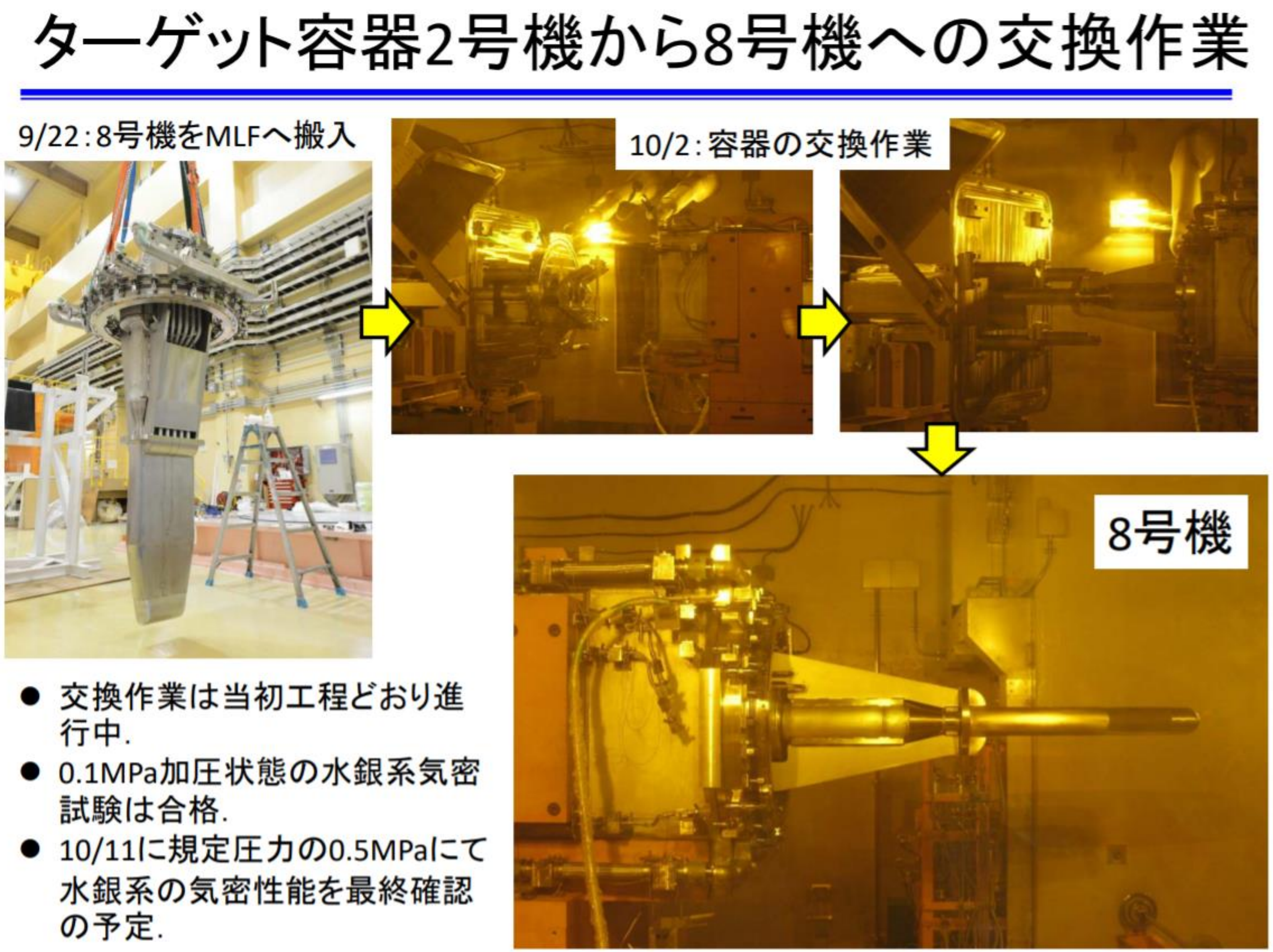
- Current best beam power so far is 500kW.
- 1MW trial during the very short period was succeeded. (bottom plot) http://j-parc.jp/ja/topics/2015/Pulse150206.html
- The mercury target had trouble in 2015, but a new mercury target which has small # of welding was installed in this summer.



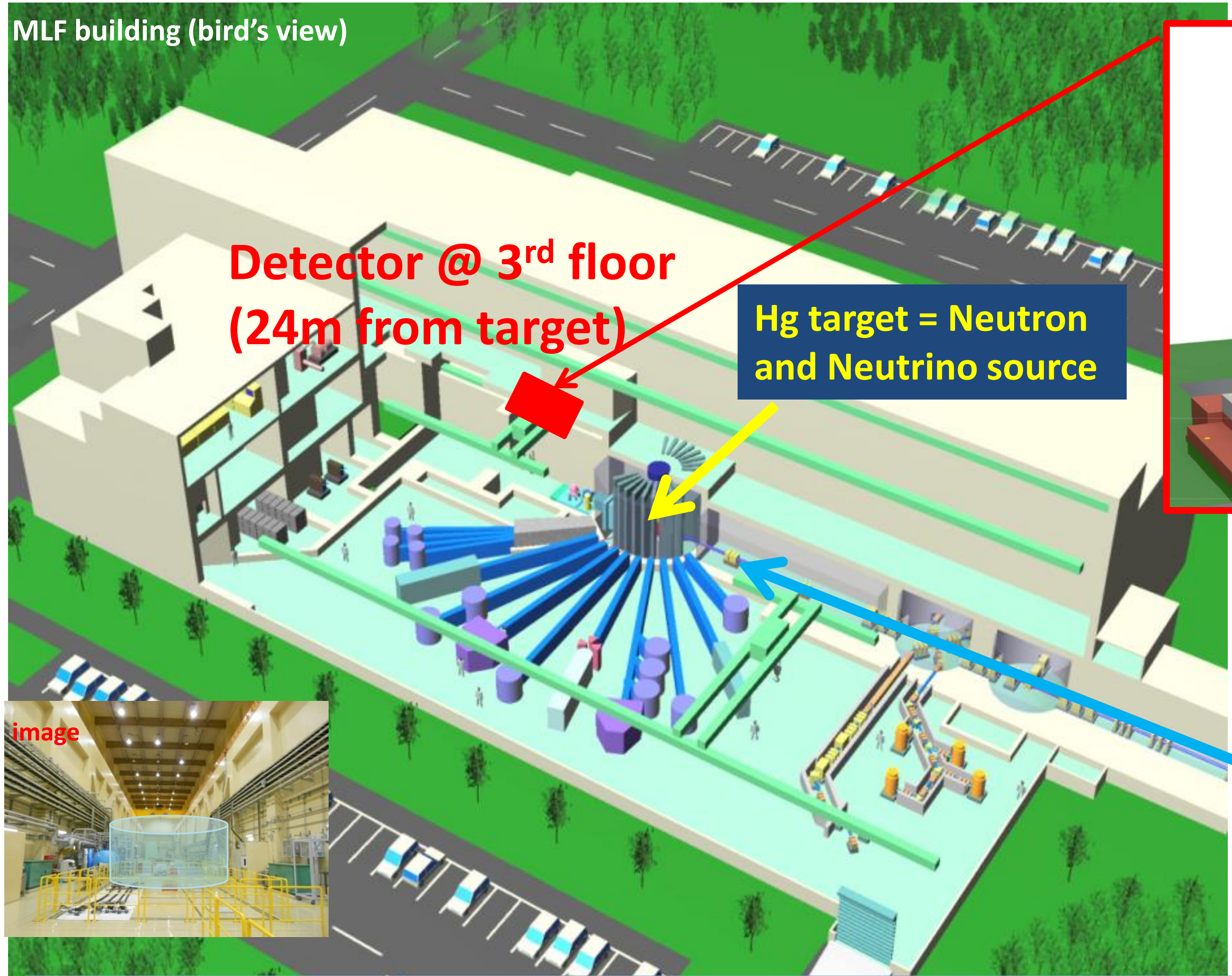

| | Number of Particles / pulse | Corresponding Power in 25 Hz |
|---|---|---|
| (red) | $8.41\times10^{13}$ | 1010 kW |
| (green) | $7.86\times10^{13}$ | 944 kW |
| (blue) | $6.87\times10^{13}$ | 825 kW |
| (magenta) | $5.80\times10^{13}$ | 696 kW |
| (black) | $4.73\times10^{13}$ | 568 kW |

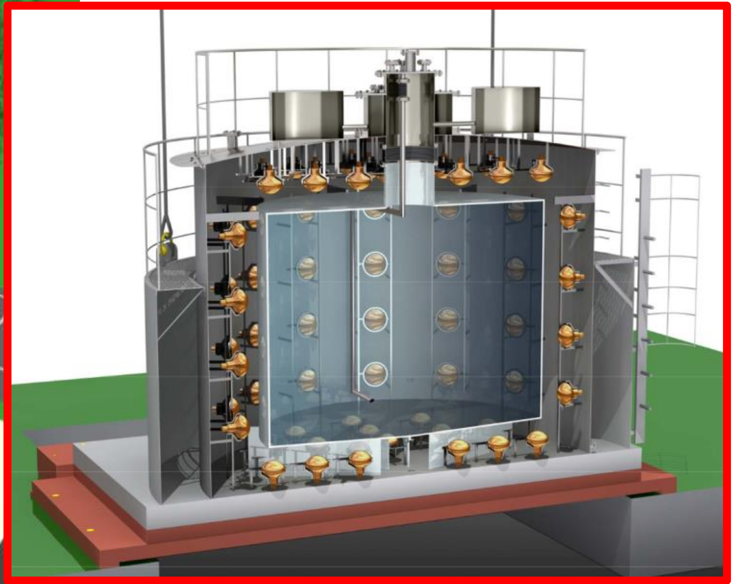
# Mercury target / beam intensity plan

- New mercury target (#8) is exchanged from old one (#2) on Oct-2.
- This is the recovery from the trouble which is occurred in 2015 Fall. (small # of welding / bolt-buts scheme)
- This #8 target is stood up to 700kW in principle.
- Target #10 which stands up to (or more than 1MW due to no weldings) will be placed in near future.



# Sterile Neutrino Search at J-PARC MLF (JSNS$^2$)



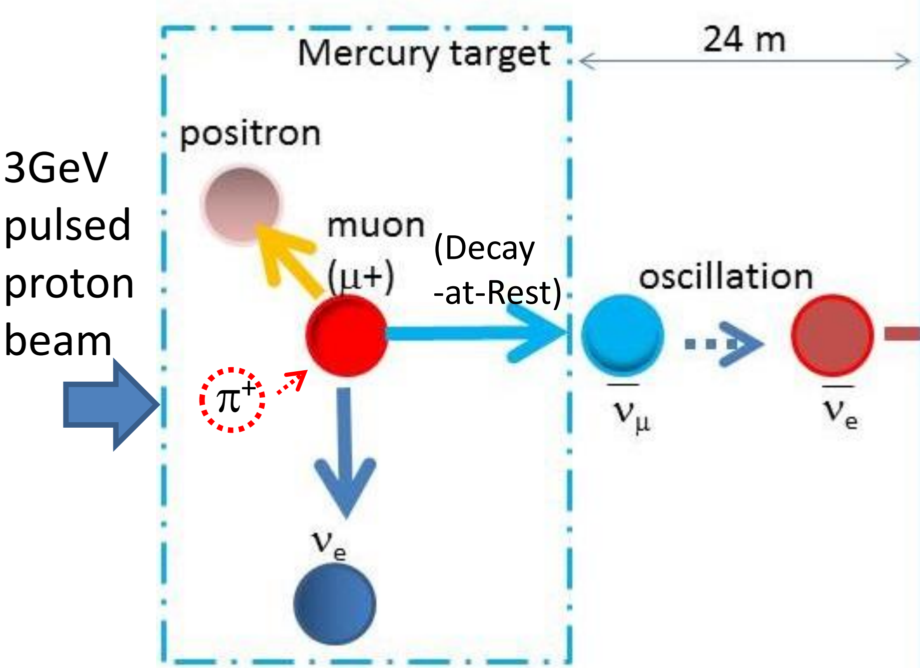
17t Gd-loaded liquid scintillator / detector (total 50tons/detector)
(4.5m diameter x 4.0m height)
193PMTs

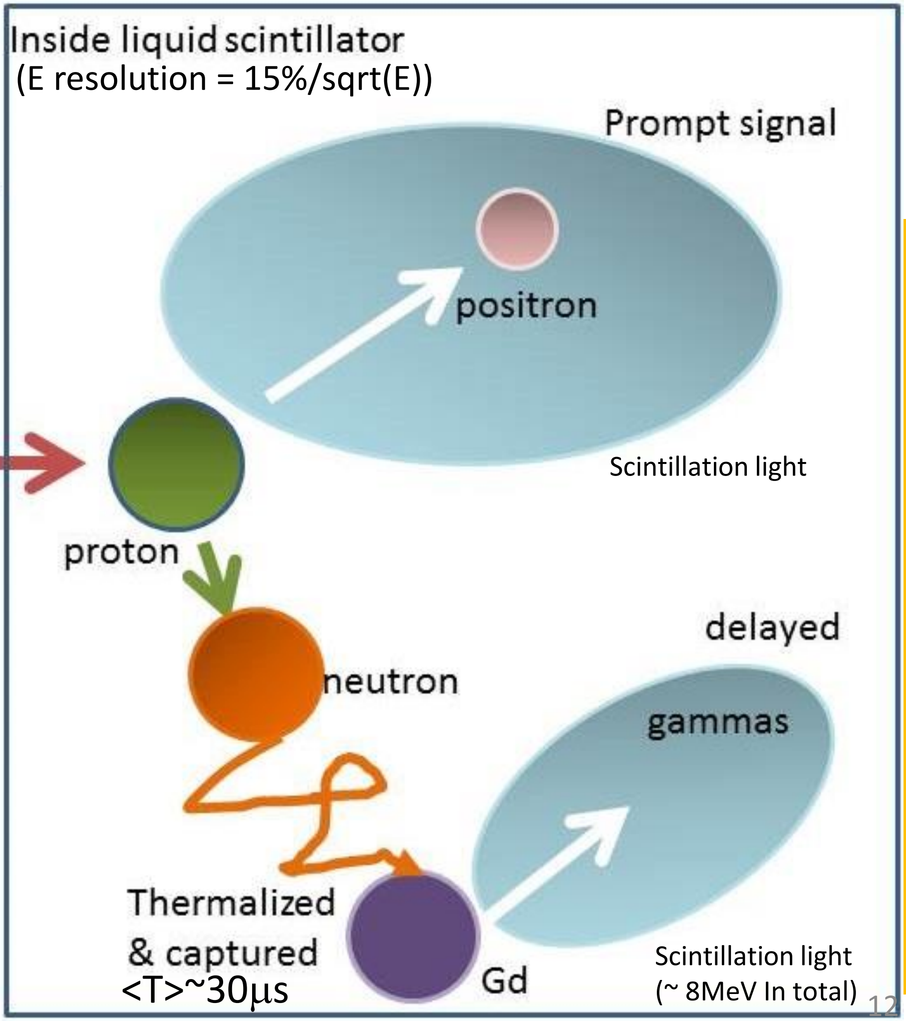
3GeV pulsed proton beam

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

# Production / Detection

- Large amount of parent $\mu$+ in Hg target → $\bar{\nu}_\mu$ are produced.
- If sterile $\nu$ exist, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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 we use much better beam and Gd loaded LS.
→ Much better S/N
→ Much better systematics

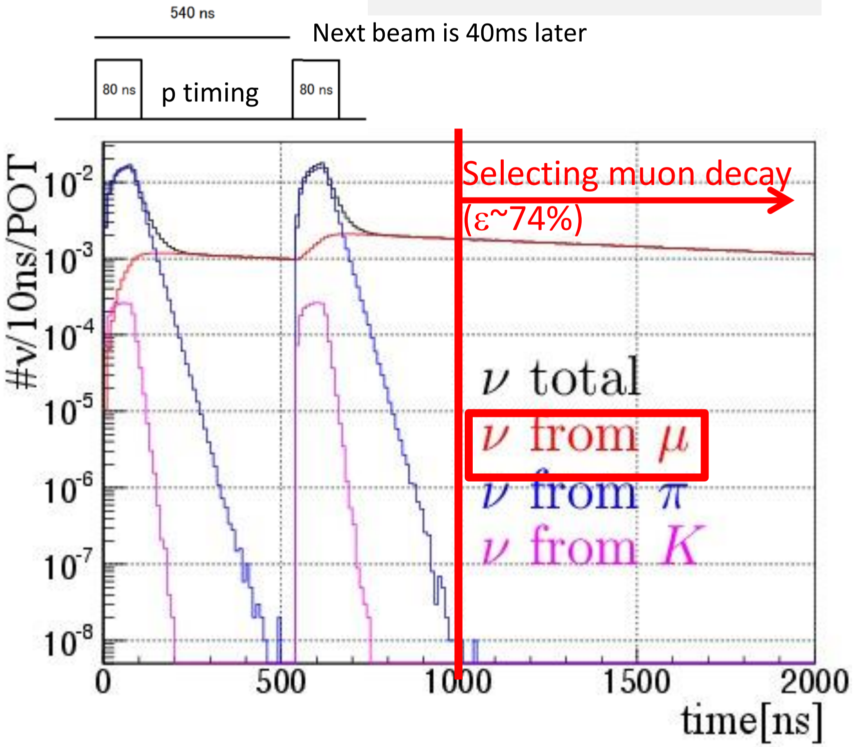
# Timing and Energy

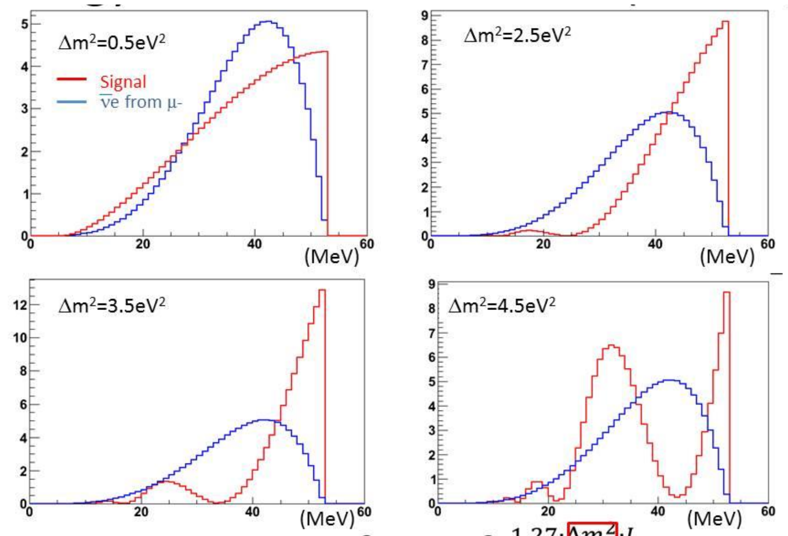
**Timing and Energy are good friends of JSNS²**

- 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.

M. Harada *et al*, arXiv:1310.1437



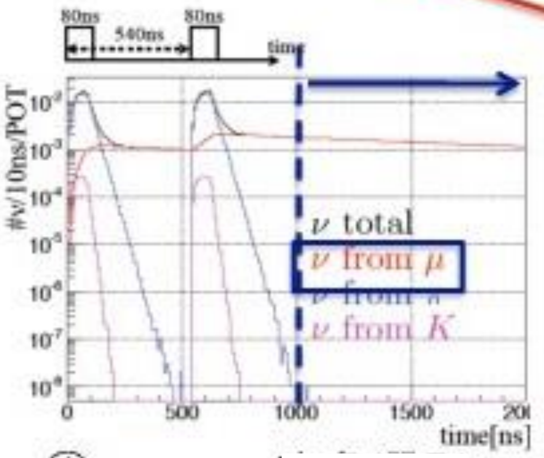

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \boxed{\Delta m^2} \cdot L}{E_\nu}\right)$$

# IBD event selection

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

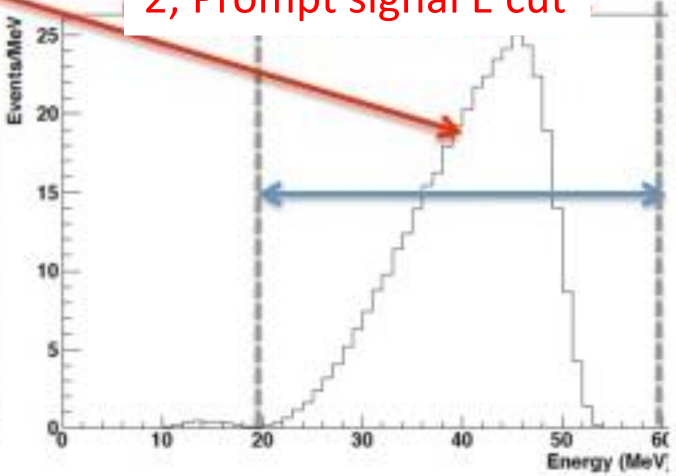
$\bar{\nu}_e + p \rightarrow e^+ + n$ -> n capture ->2(H) or 8MeV(Gd)

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

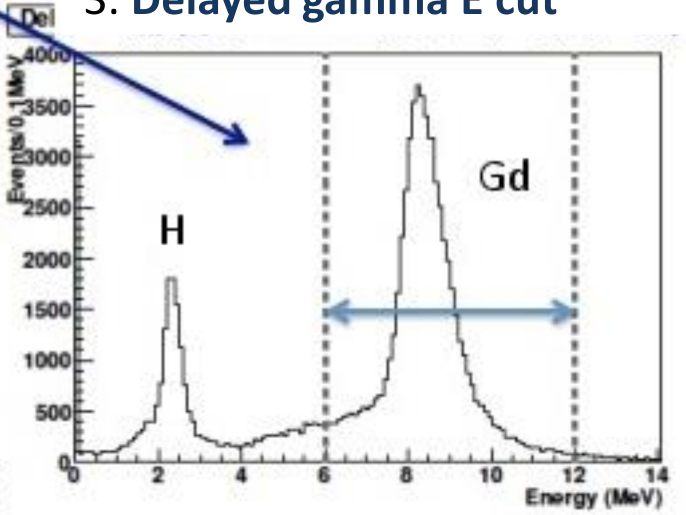


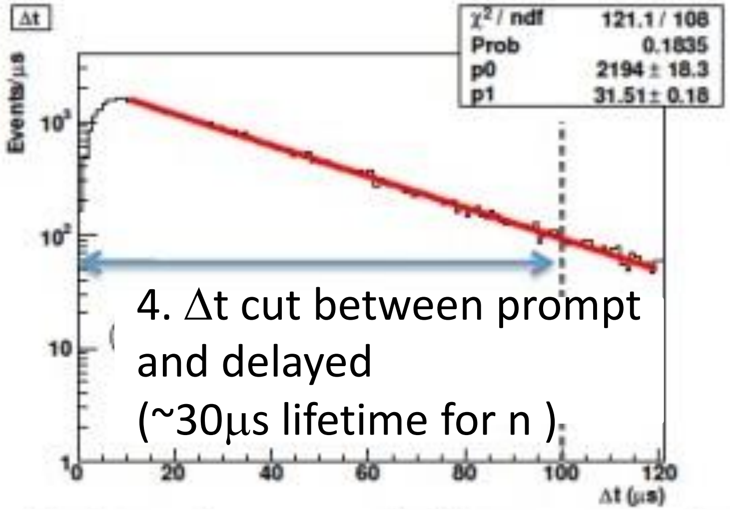

①off bunch

2; Prompt signal E cut

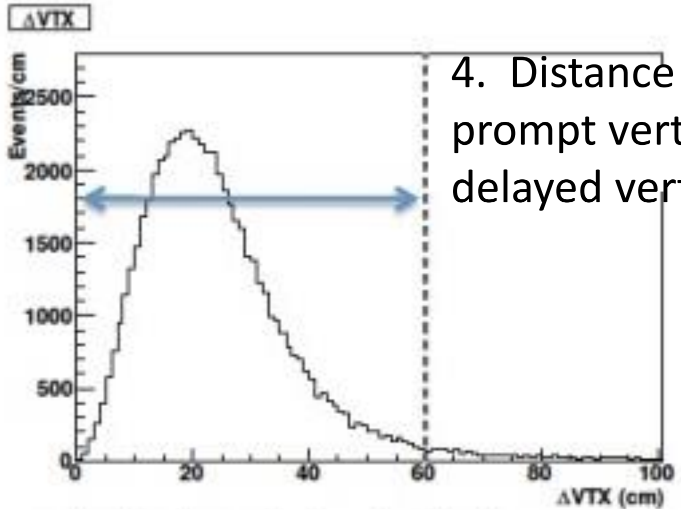



3. **Delayed gamma E cut**




4. $\Delta$t cut between prompt and delayed (~30$\mu$s lifetime for n )

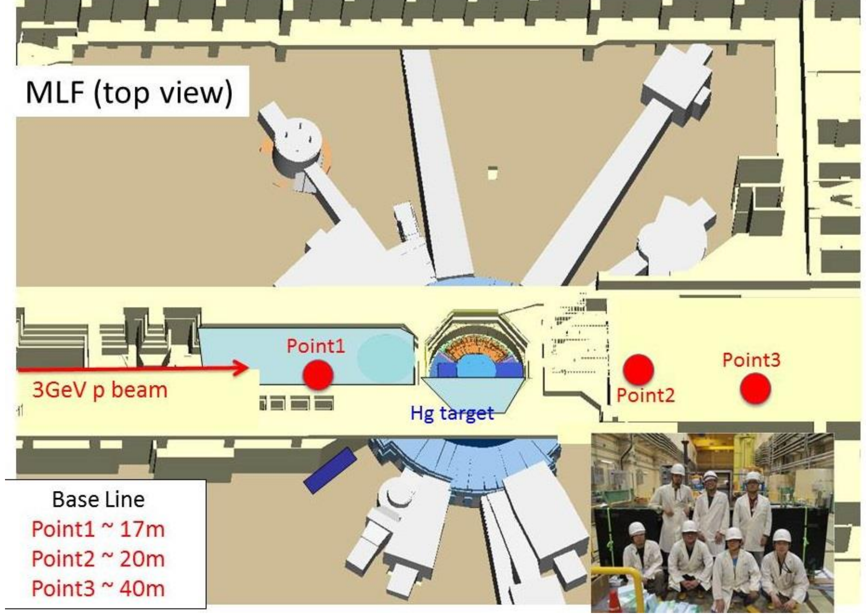


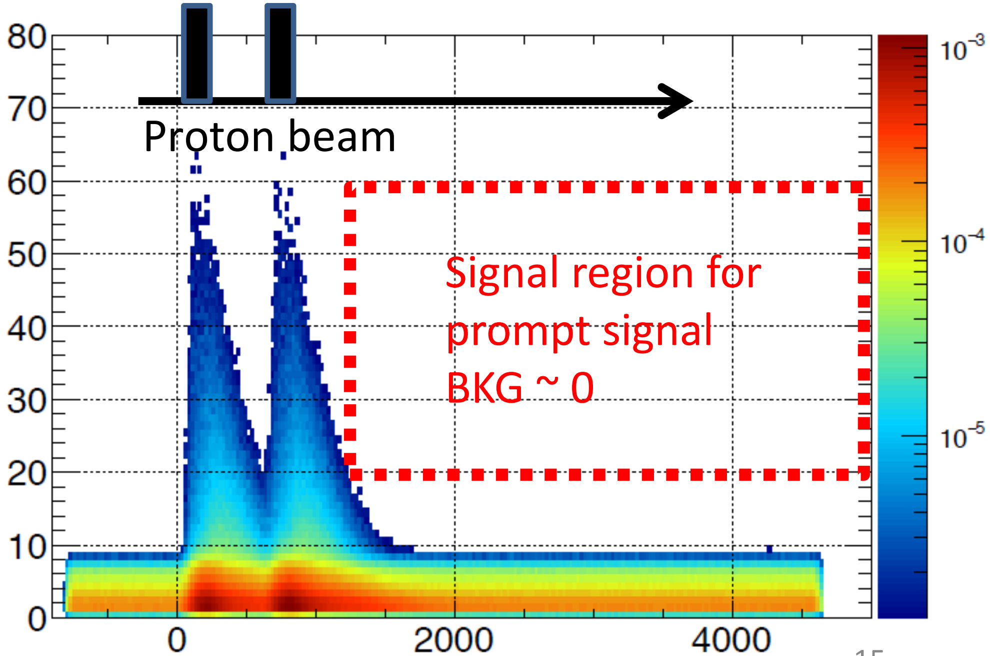

4. Distance cut between prompt vertex and delayed vertex

**Selection ε ~ 38%**

# 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 granted from J-PARC /KEK
- The performance check of detector and safety discussions are being performed.
- **2016-June: The grant-in-aid 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] )**
- **We aim to start JSNS$^2$ in JFY2018**

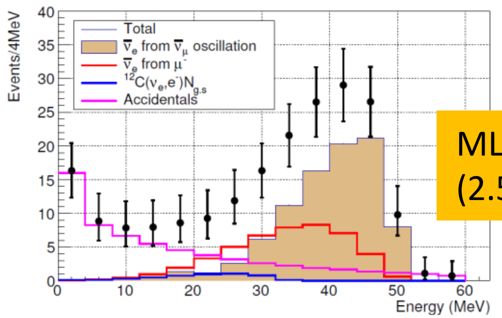



Energy (MeV, vertical) vs timing (ns, horizontal)

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

| Source | contents | #ev.(17tons x 3years) TDR | Reference : SR2014 (50tons x 5 years) | comments |
|---|---|---|---|---|
| background | $\overline{\nu}_e$ from $\mu$- | 43 | 237 | Dominant BKG |
| | $^{12}C(\nu_e,e-)^{12}N_{g.s.}$ | 3 | 16 | |
| | Beam fast neutrons | Consistent with 0<br>< 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 |



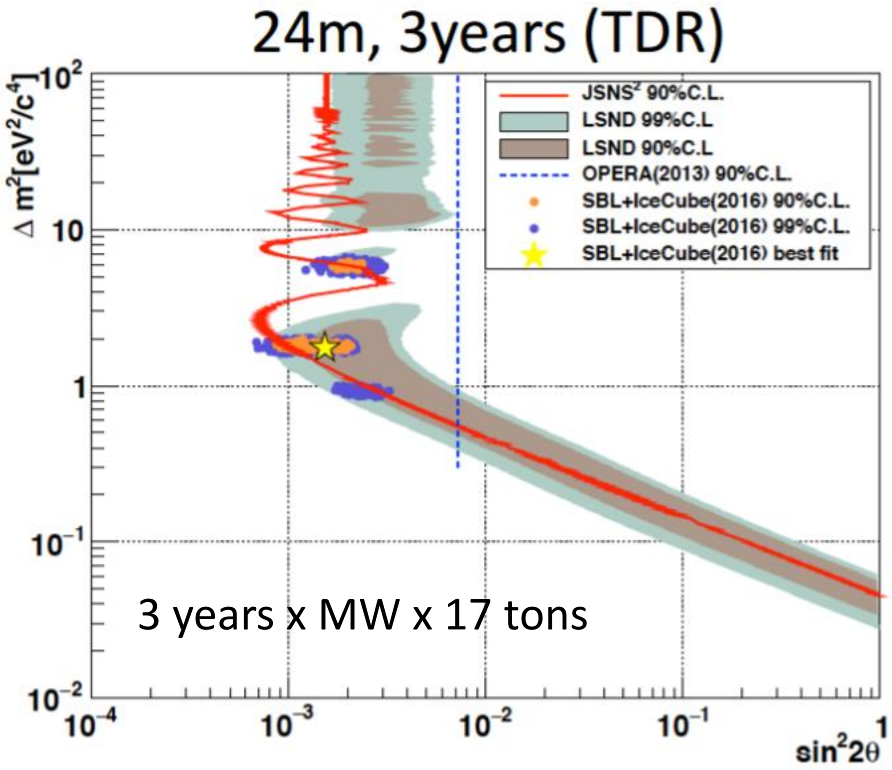

MLF best $\Delta m^2$ (2.5eV$^2$)

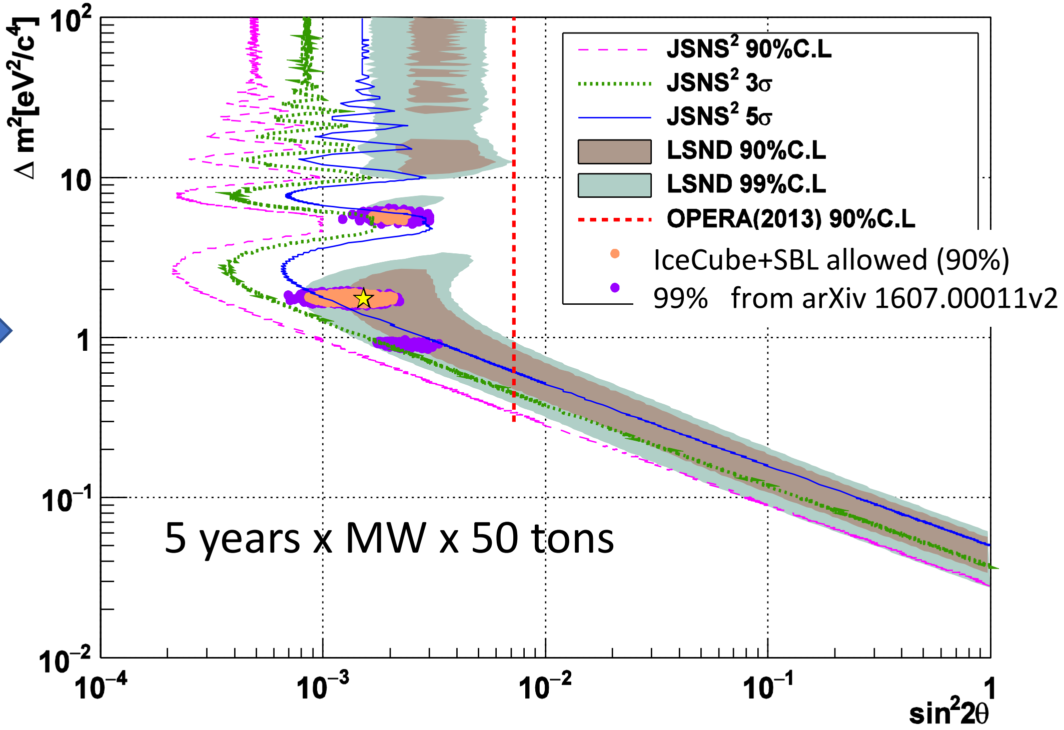
Accidental BKG is calculated by;R acc = $\Sigma R_{prompt}$ x $\Sigma R_{delay}$ x $\Delta_{VTX}$ x N $_{spill}$

- $\Sigma R_{prompt}$, $\Sigma R_{delay}$ are probability of accidental BKG for prompt and delayed.
- $\Delta_{VTX}$ ; BKG rejection factor of **50**.
- $N_{spill}$(#spills / 5 years) = 1.9x10$^9$

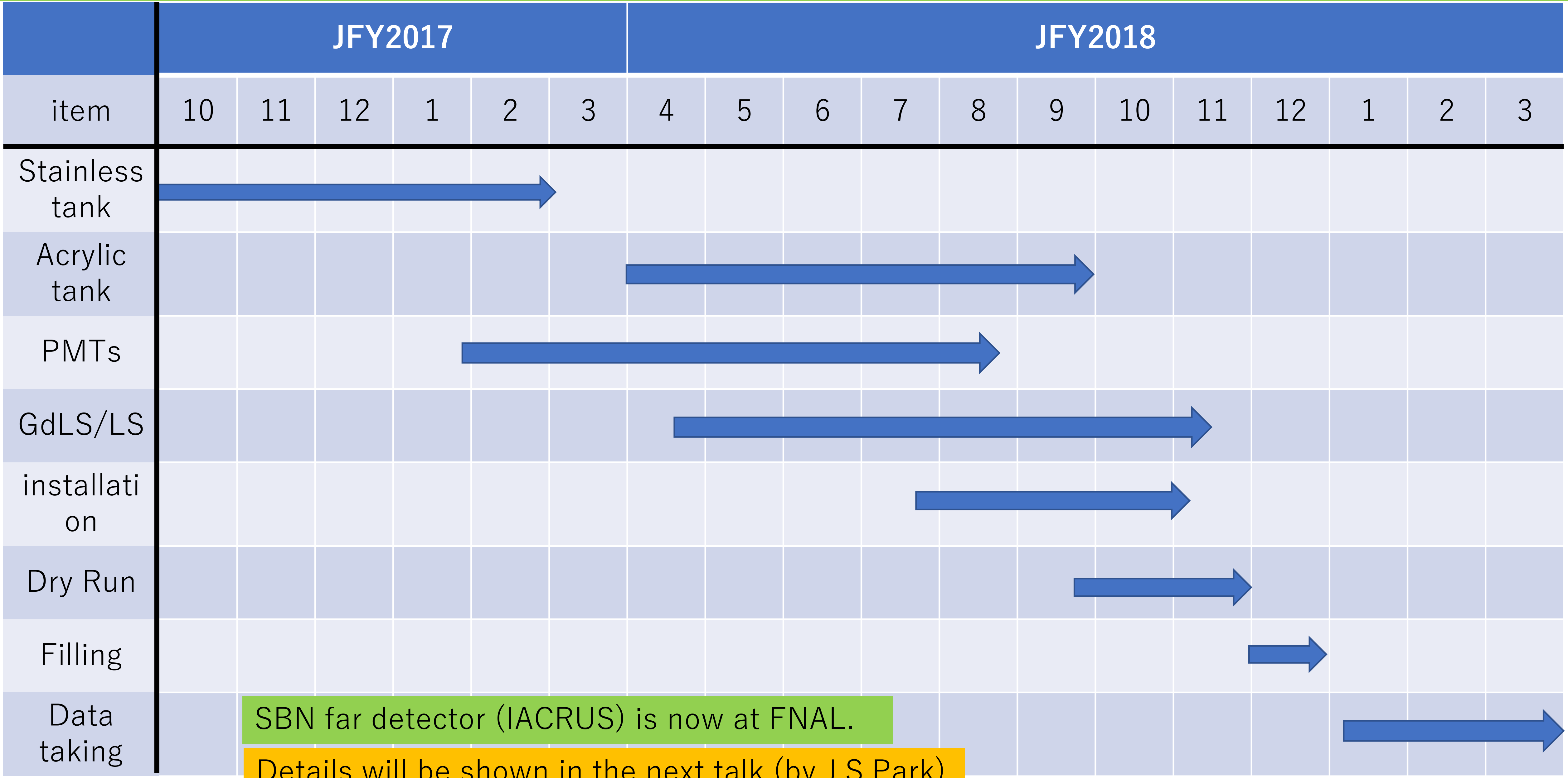
# Sensitivity / Upgrade

- To have a good international competition capability, we want to start the experiment with one detector (17tons fiducial volume).
- Even with one detector, we have a good 90% C.L constraints for 3 years. Left plot
- Meanwhile, we are making effort to obtain the budget to build the 2nd detector. (and enlarged acrylic tanks). This upgrade can make 5$\sigma$ significance test for LSND region.



# Schedule for 1st detector construction




SBN far detector (IACRUS) is now at FNAL.

Details will be shown in the next talk (by J.S.Park)

# Approval Process (J-PARC PAC, etc)

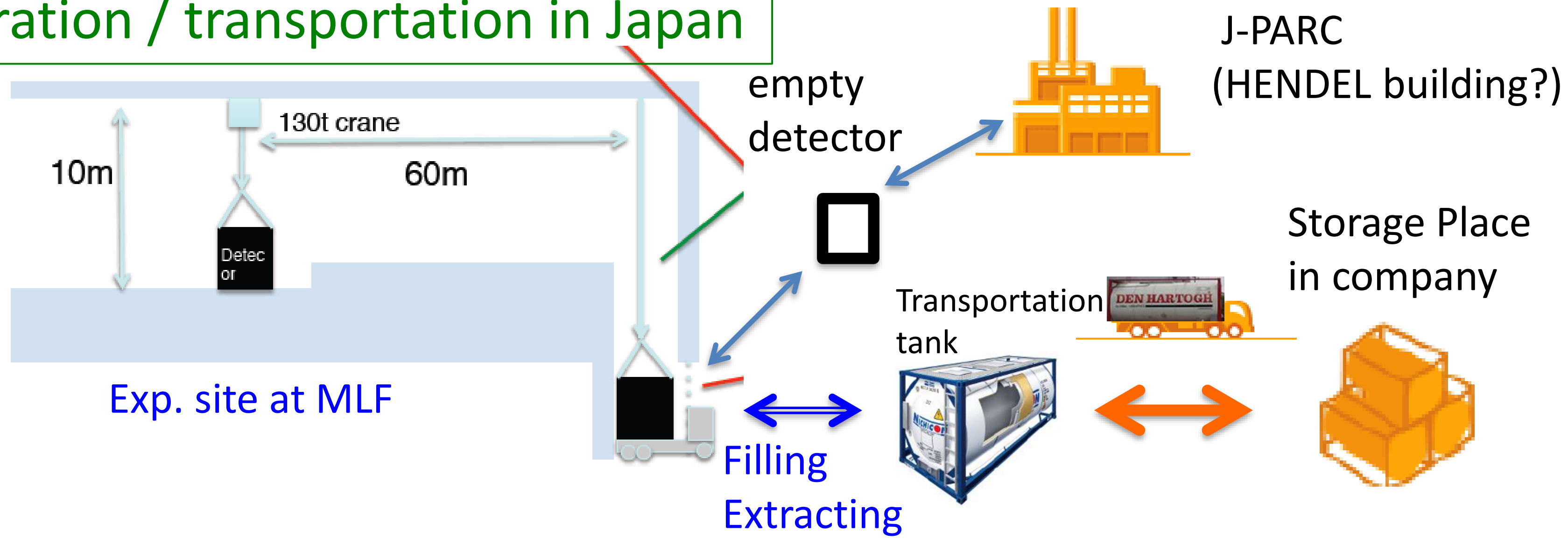
- Based on the TDR, J-PARC PAC discussed the feasibility of the JSNS$^2$ experiment. (TDR contents will be described by Jungsic)
- J-PARC PAC has two stages of the approvals (stage-1 status: motivation of physics is recognized, and real approval (stage-2))
- Lots of discussions are on-going to grant the stage-2:
  - Safety issues at J-PARC MLF (including a big earthquake).
  - Detector movement during the maintenance period (July-Oct). Note the 3rd floor is the maintenance space of the MLF
    - We have to bring the detector to outside of MLF at that time to avoid the interference.
    - Effects of quality of GdLS/LS degrade, PMT tilting during the movement were checked.
  - Calibration (Michel e + Gd captured gammas + radio-active sources)
  - Possible systematic uncertainties.
- Revised TDR including these discussions will be submitted on the middle of Nov-2017, and contents will be discussed at the next PAC.

# LS transportation / operation



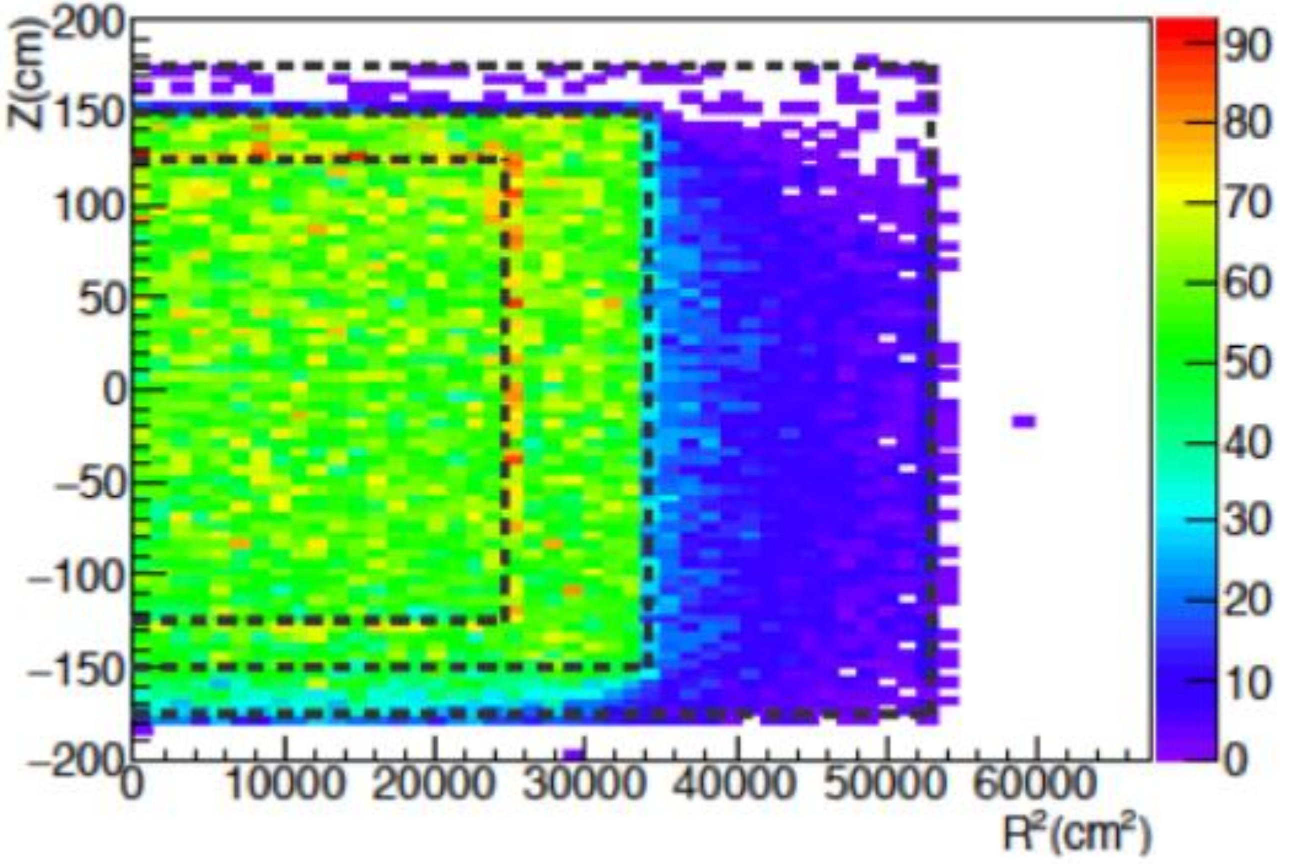
- We will use iso-tank for the transportation and the storage.
- Cost estimation to purchase iso-tanks and LS storage was already done.

## LS operation / transportation in Japan



# Michel e calibration

- One of most important calibration sources is to use Michel electrons from stopped cosmic ray muons.
  - Energy range / shape are almost same as interested samples finally.
- MC simulation said O(a few 100) Hz of stopped muon events are available because our detector is over the ground.
  - Good statistics to check the stability and position dependence of light yield.
  - Pre-scale is needed.
- Right plot shows the relative event rate of stopped muons vertex points. A rate in $R^2$-Z is flat.



# Beauty of JSNS$^2$: Small systematic uncertainties

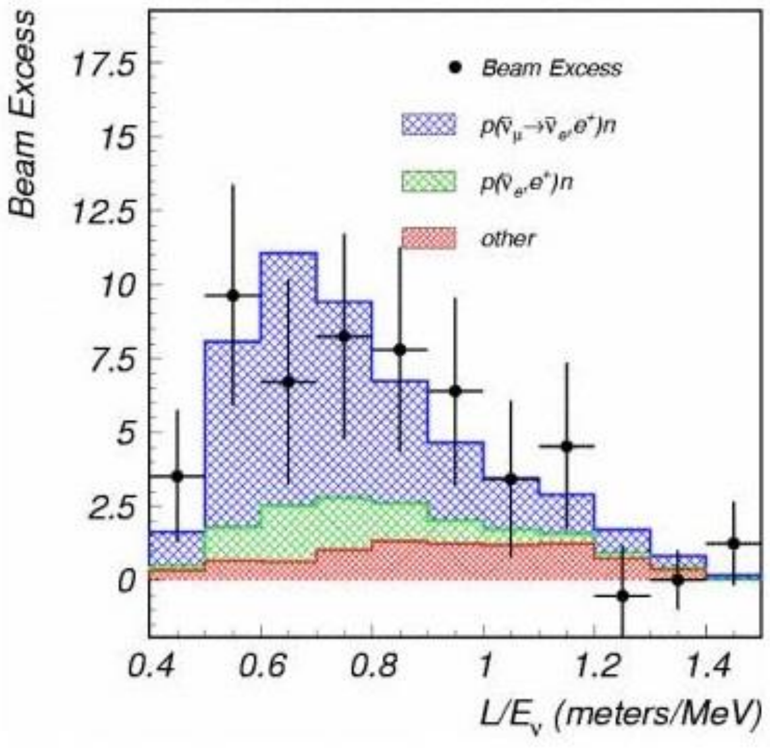
- The systematic uncertainties of the JSNS$^2$'s are small in principle.
  - Uncertainties from energy spectrum.
    - Energy spectrum of neutrinos from decay-at-rest muon is quite well understood. (gives negligible error)
    - IBD cross section is also very well known. (both for energy dependence and for absolute number. → provides negligible uncertainties).
    - Expected uncertainty on the detector energy scale is ~1% level because we have a good calibration sources including Michel e. (stability, position dependence, quenching effects are source of error)
  - Uncertainties from normalization
    - We fit the number of intrinsic $\nu$e bar background (profile fitting)
    - Number of $\mu^+$ at the mercury target can be estimated by number of C12($\nu_e$,e)Ngs reactions. → number of $\nu\mu$bar (before oscillation) can be known within 10%.
    - Accidental background will be estimated by no beam data period.

# Pros compared to LSND

- vs LSND; → direct test without any excuses (e.g.: ν type, Eν, detector target material) w/ better S/N
  - Narrow pulsed beam at MLF → timing
    - LSND has no beam timing cut (Linac → large duty factor)
    - Pure muon decay at rest at MLF.
    - No Decay-In-Flight source in MLF
    - No beam fast neutrons BKG at MLF.
    - Tighter timing window (~9μs) for cosmic ray rejection at MLF.

As mentioned before

  - Detector has many improvements;
    - Gd-LS improves S/N ratio at MLF → time window of coincidence (factor 6) and delayed Energy. (2.2 → 8MeV)
    - Faster sampling rate of electronics and improved LS make PID easy at MLF.



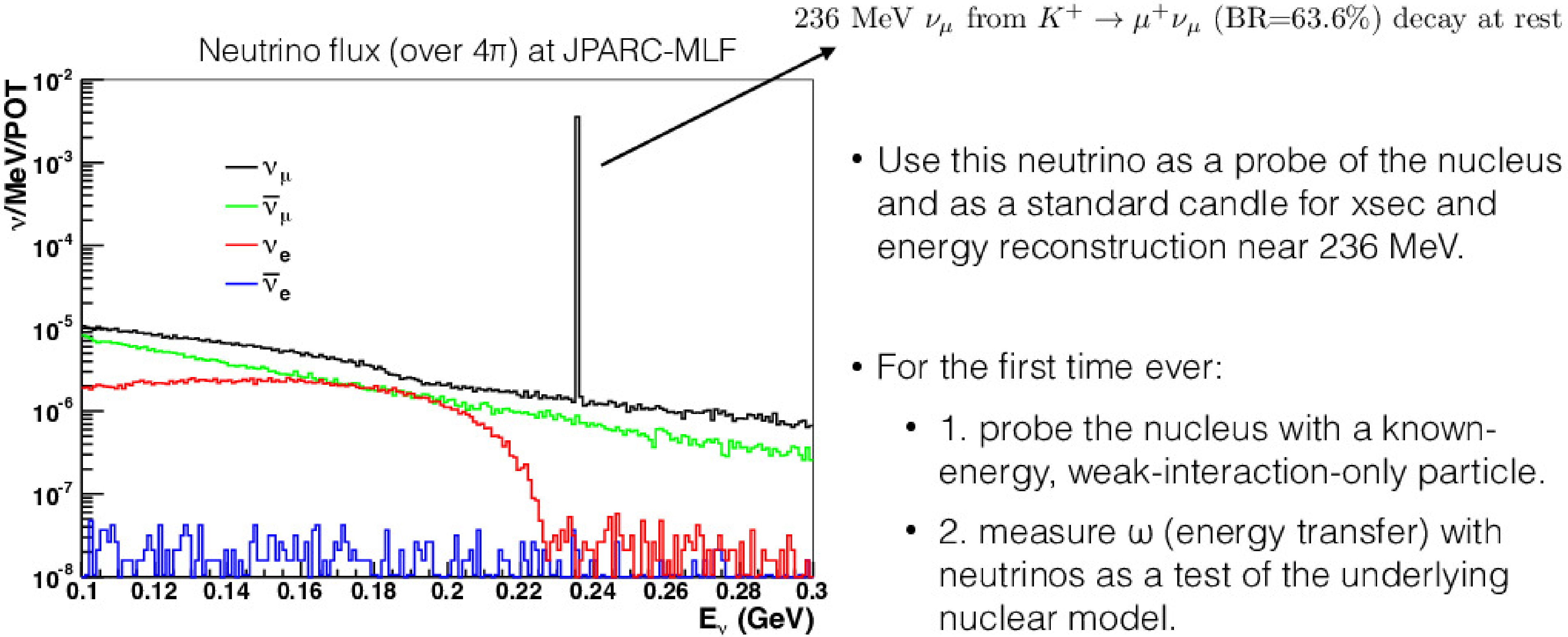

- vs KARMEN → JSNS$^2$ has more intense ν flux by >10 times + Gd-LS

# Complementarity

- to reactor / radiation source experiments
  - Disappearance measurement vs appearance (JSNS$^2$)
- to $\nu_\mu$ disappearance
  - Disappearance vs appearance
- to FNAL SBN programs (LAr TPCs + horn focused beam)
  - $\nu_\mu \rightarrow \nu_e$ oscillation vs $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation (JSNS$^2$)
  - JSNS$^2$ aims a complete test for the LSND anomaly with much better S/N and without any excuses.
  - Intrinsic background rate is smaller and energy reconstruction is much cleaner. ($E\nu$ ~ Evis + 0.8MeV in IBD)

# Other physics at JSNS$^2$

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

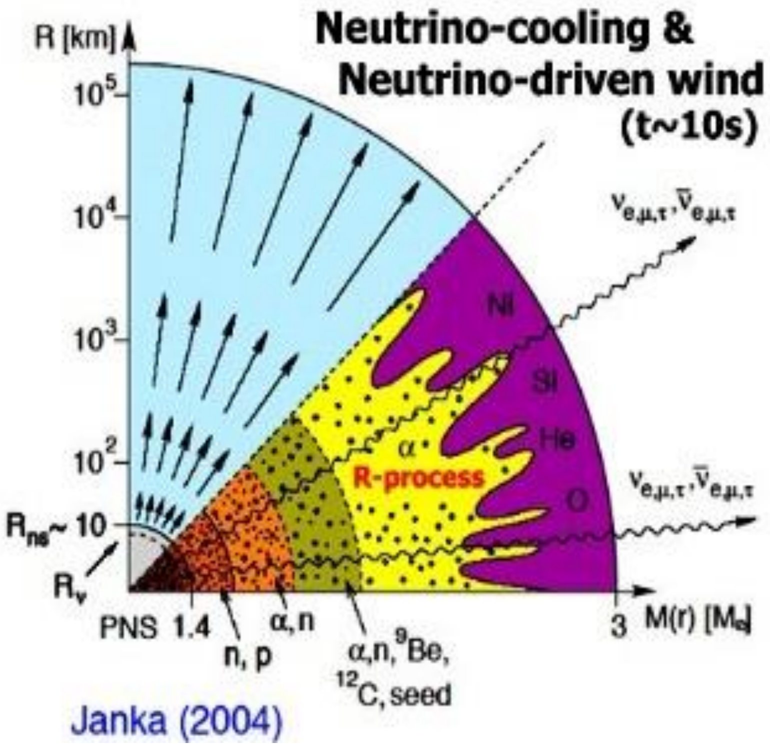



- Use this neutrino as a probe of the nucleus and as a standard candle for xsec and energy reconstruction near 236 MeV.
- For the first time ever:
  - 1. probe the nucleus with a known-energy, weak-interaction-only particle.
  - 2. measure ω (energy transfer) with neutrinos as a test of the underlying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

Event rate expectation

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

# Summary

- Sterile neutrino: One of most exciting topics in neutrino community (for 20 years!)
- JSNS$^2$ stands at a good position to confirm or refute the existence:
  - Direct test (w/o excuses) for the LSND results.
  - MLF and their short pulsed beam gives the best environment.
  - GdLS reduces the accidental background by order of magnitudes compared to the LSND.
- At the end of JFY2018, we aim to start data taking.
- Toward the data taking, the collaboration is making best effort on both approvals and construction.