# A Search for Sterile Neutrinos at J-PARC Materials and Life science experimental Facility

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for MLF nu working group

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Contents

**preliminary**

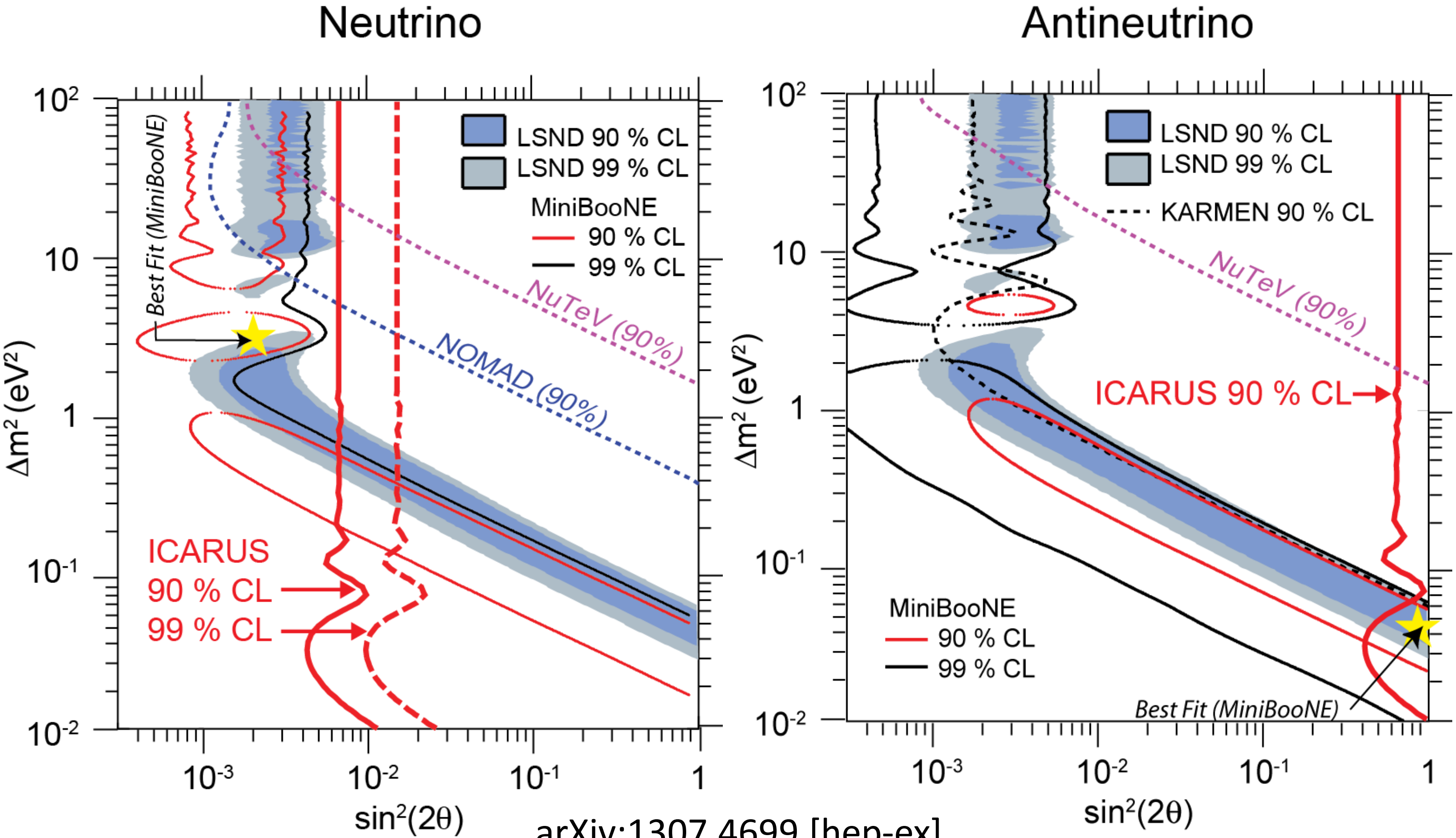
# PMNS matrix; standard model of neutrino oscillation

- Now neutrino oscillation via PMNS matrix become one of the standard model of the recent particle physics. → undiscovered parameter is only delta CP.
- The search for the physics beyond the standard model is important as well as completing the PMNS standard model.
  - One way is to check the unitarity of PMNS matrix with high precision measurements of each parameters. (but this is difficult)
  - The alternative way is to check the 4th or more generation neutrinos which are related to neutrino oscillation. (but not weak interactive ones because of LEP measurements.)

# Sterile neutrinos

- LEP experiments proved that there are three active (weak interactive) neutrinos from Z boson decays. (< Mz/2)
- However there are some hints from experiments (LSND, MiniBooNE, Solar neutrino exp. calibration, Reactor exp.) to have other neutrino(s) via neutrino oscillations, which cannot be explained by normal PMNS matrix.
- Sterile neutrinos provide wide view of physics;
  - Direct evidence beyond the standard model if exists.
  - There could be one or two or more sterile neutrinos
  - One may be Majorana neutrino, and in charge of See-saw mechanism?
  - Dark matter candidate?
- Sterile neutrinos can be proved by only neutrino oscillation phenomena.

# Status of excess of $\overline{\nu\mu} \rightarrow \overline{\nu e}$ or $\nu\mu \rightarrow \nu e$



arXiv:1307.4699 [hep-ex].

- LSND and MiniBooNE see the excess of the events. (Also see presentation by Dr. Carlo Giunti (INFN) on Thursday, summary of the status)
- 3 generation model cannot explain oscillation with $\Delta m^2 \sim 1.0 \mathrm{eV}^2$ region.
- Z measurements conclude 3 active ν → sterile

# Considering sterile neutrinos

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \bullet \end{bmatrix} = \left[\begin{array}{|ccc|cc} \hline U_{e1} & U_{e2} & U_{e3} & U_{e4} & \bullet \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \bullet \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \bullet \\ \hline \multicolumn{1}{c}{U_{s1}} & U_{s2} & \multicolumn{1}{c}{U_{s3}} & U_{s4} & \bullet \\ \multicolumn{1}{c}{\bullet} & \bullet & \multicolumn{1}{c}{\bullet} & \bullet & \bullet \end{array}\right] \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \bullet \end{bmatrix}$$

Currently, the red square part is mainly considered .

$\beta-$decay (KATRIN...)

$$m_\beta = \left| |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2 + |U_{e4}|^2 m_4^2 \right|^{1/2}$$

$0\nu 2\beta-$decay

$$m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\alpha} + |U_{e3}|^2 m_3 e^{i\beta} + |U_{e4}|^2 m_4 e^{i\gamma} \right|$$

Cosmology (with many assumptions)

$\Sigma = m_1 + m_2 + m_3 \Rightarrow$

< 0.66eV (95% CL)[Planck+WP+highL]

< 0.85 eVthe addition of the lensing

$N_{eff}$ no need for >3 (PLANCK)

Multiple sterile ν's

νMSM Dark matter Baryon >> anti-B

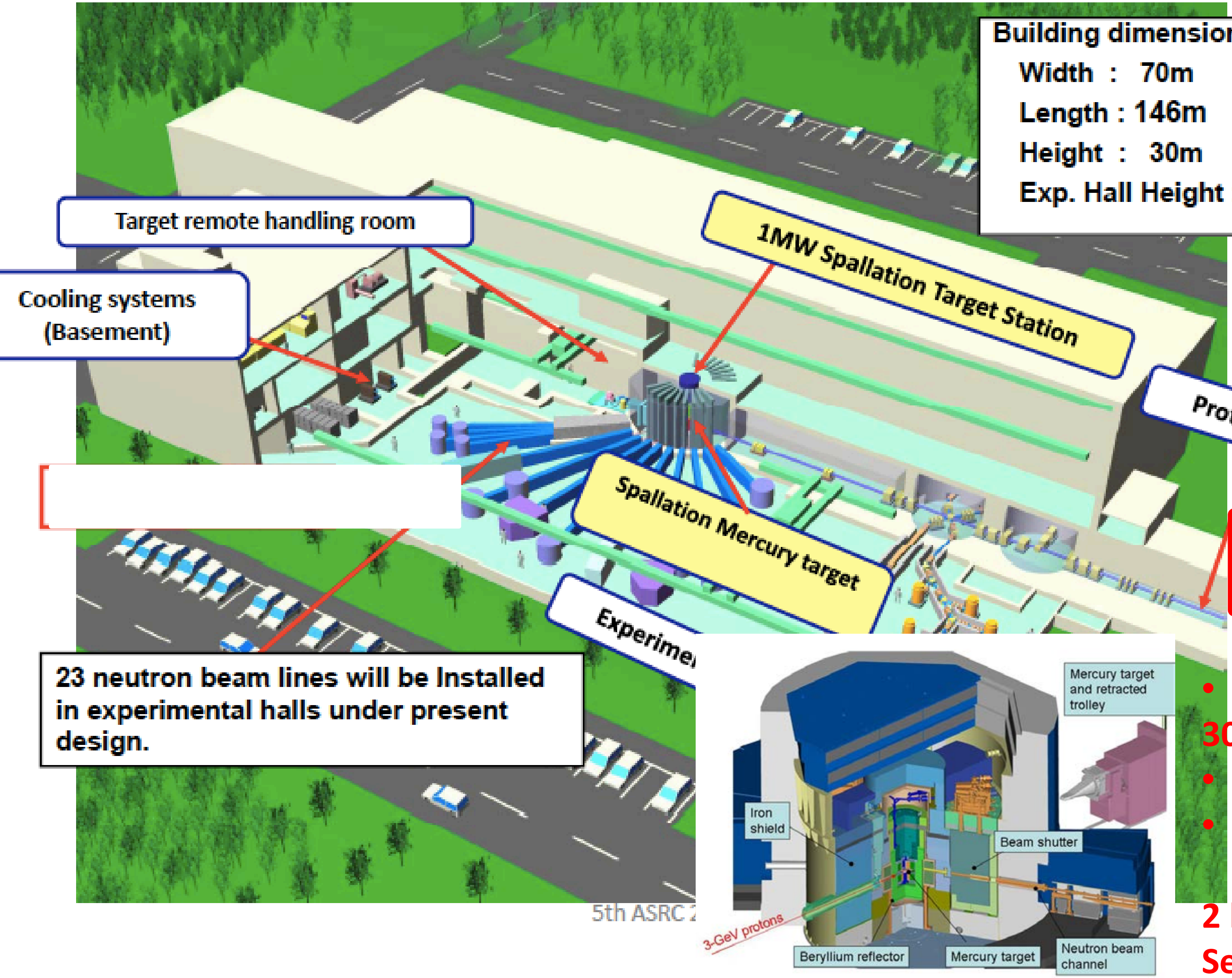
T. Asaka, S. Blanchet, and M. Shaposhnikov,
Phys. Lett. **B631,** 151 (2005)

A. Boyarsky, O. Ruchayskiy, and M. Shaposhnikov,
Ann.Rev.Nucl.Part.Sci. **59,** 191 (2009)

# New experiment using J-PARC Materials and Life science experimental Facility (MLF)

# J-PARC Materials and Life Science Experimental Facility

In this slide, baseline of the detector is 60m and 20m are assumed.



**Building dimension :**
Width : 70m
Length : 146m
Height : 30m
Exp. Hall Height : 22m

Target remote handling room

Cooling systems (Basement)

1MW Spallation Target Station

Proton beam line

Spallation Mercury target

Experime

23 neutron beam lines will be Installed in experimental halls under present design.

**3GeV, 1MW proton beam**

- 1MW (design)

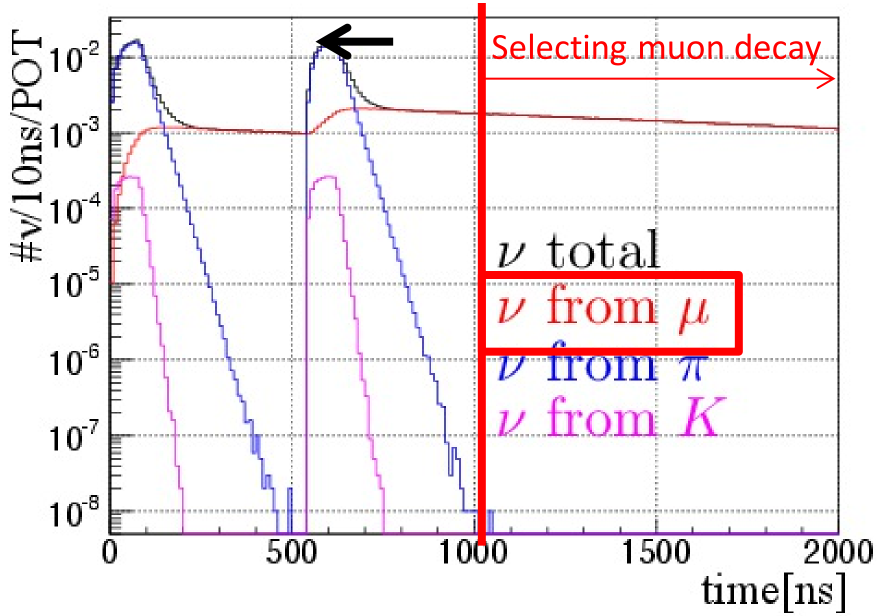
300kW (current)

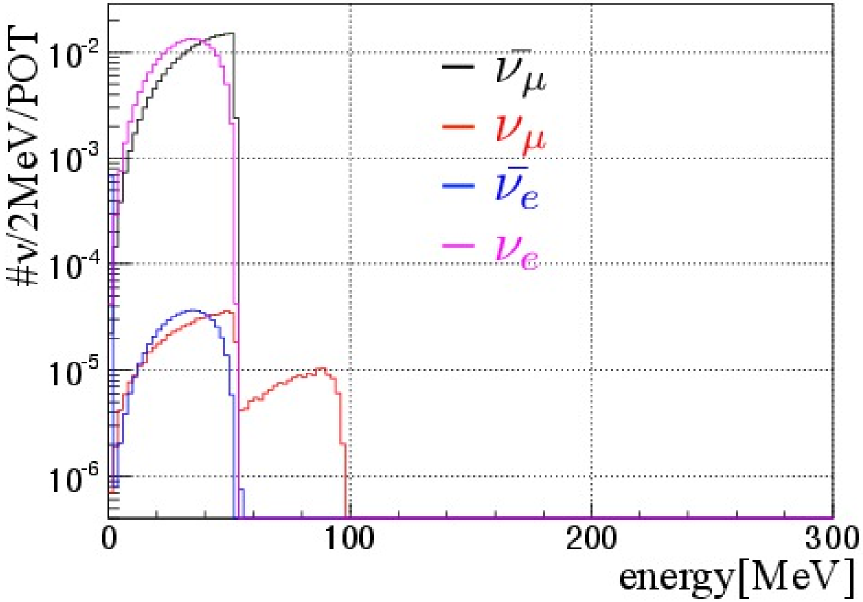
- 25Hz operation
- 2 bunches (80ns) in 1 spill.

2 bunches are Separated by 540ns

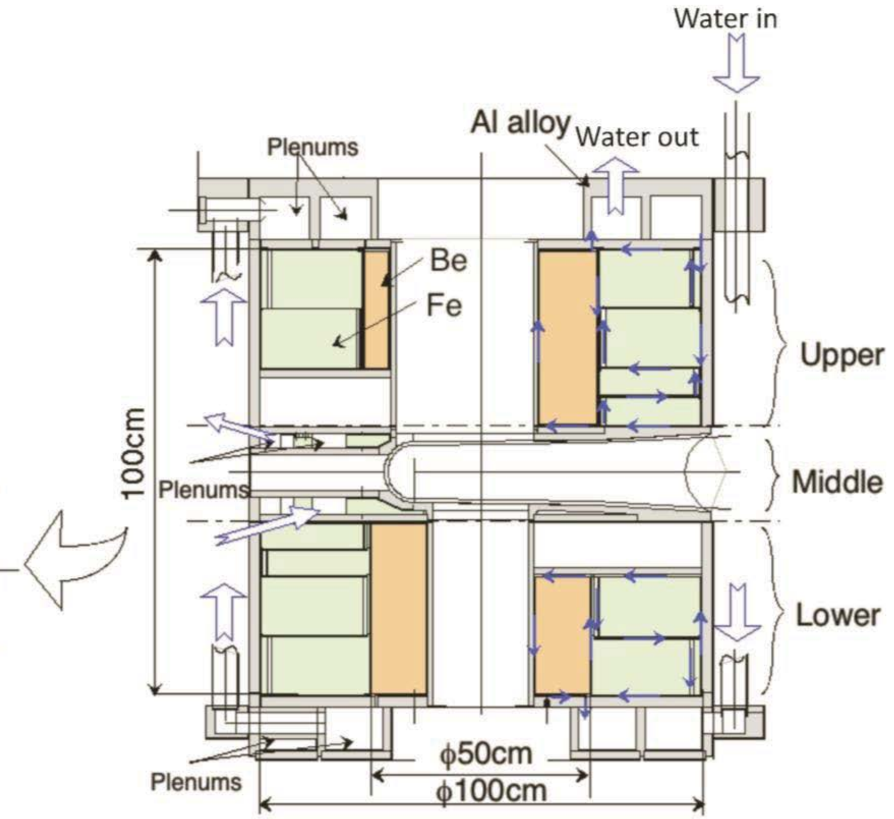
# Using neutrinos from only $\mu^+$ decay at rest

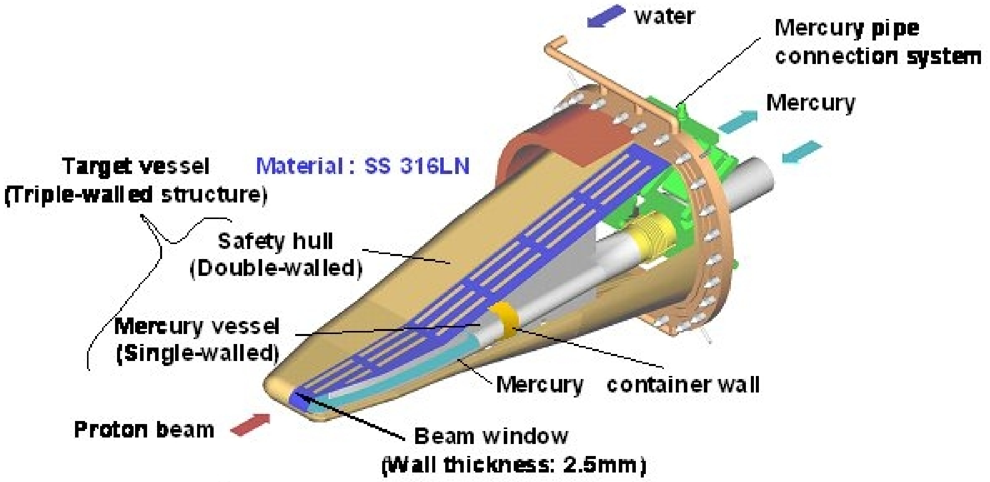
- We can choose neutrinos from only μ decays using their long life time. (top-right plot)
- Energy spectrum of $\mu^+ \rightarrow e^+ \nu\mu$ $\overline{\nu e}$ decay is well known
  - $\overline{\nu\mu} \rightarrow \overline{\nu e}$ oscillation is searched. (appearance)
  - (νe oscillation is also searched. (disappearance))
- π- → μ- decay chain is highly suppressed due to the nuclear absorption. ($10^{-3}$ compared to $\mu^+$ due to Hg neutron target)
- Fast neutrons are died out immediately after the beam bunches.





# Intrinsic $\overline{\nu}_e$ BKG (dominant BKG) estimation in J-PARC MLF target





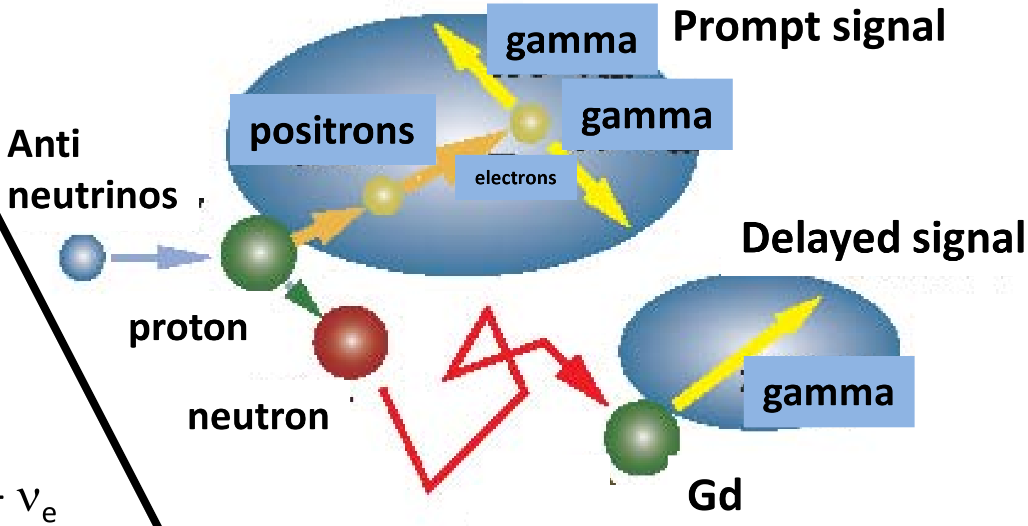
|  | Target | $\pi^-$ absorb | $\mu^-$ capture | suppression | x | $\pi^-/\pi^+$ |
|---|---|---|---|---|---|---|
| KARMEN | Ta+D2O | 98.8% | 93% | $8.4\times10^{-4}$ | x | 0.56 |
| LSND | H2O | 96% | 88% | $5\times10^{-3}$ | x | 0.13 |
| J-PARC | Hg | 99% | 94% | $6\times10^{-4}$ | x | 1. |

We will assume ~ $10^{-3}$ Intrinsic bkg (to be obtained from data)

# Detector; Liquid scintillator

- Superb performance to detect anti-neutrino detection
- Powerful coincidence between positron and gamma can be used to distinguish the signal ($\overline{\nu}_e + p \rightarrow e^+ + n$; Inverse Beta Decay; IBD) from background. Neutrons are captured by Gd, and emit the gammas, whose total energy is 8MeV and lifetime is a few 10 $\mu$s.

- Positrons create “prompt” signal
  Easy to rec. ($E\nu = Evis + 0.8MeV$)
- Neutrons create “delayed” signal



Detection of electron neutrino

- $\nu_e + {}^{12}C \rightarrow \underline{e} + {}^{12}N_{gs}$

prompt

$\hookrightarrow C + \underline{e^+} + \nu_e$

t=15.9ms

Eend = 17MeV

e- create “prompt” signal
($E\nu = Ee^+ + 17.3MeV$)
Ngs create “delayed” signal

is used for monitor signal (and disappearance analysis).

# Event selection for IBD events

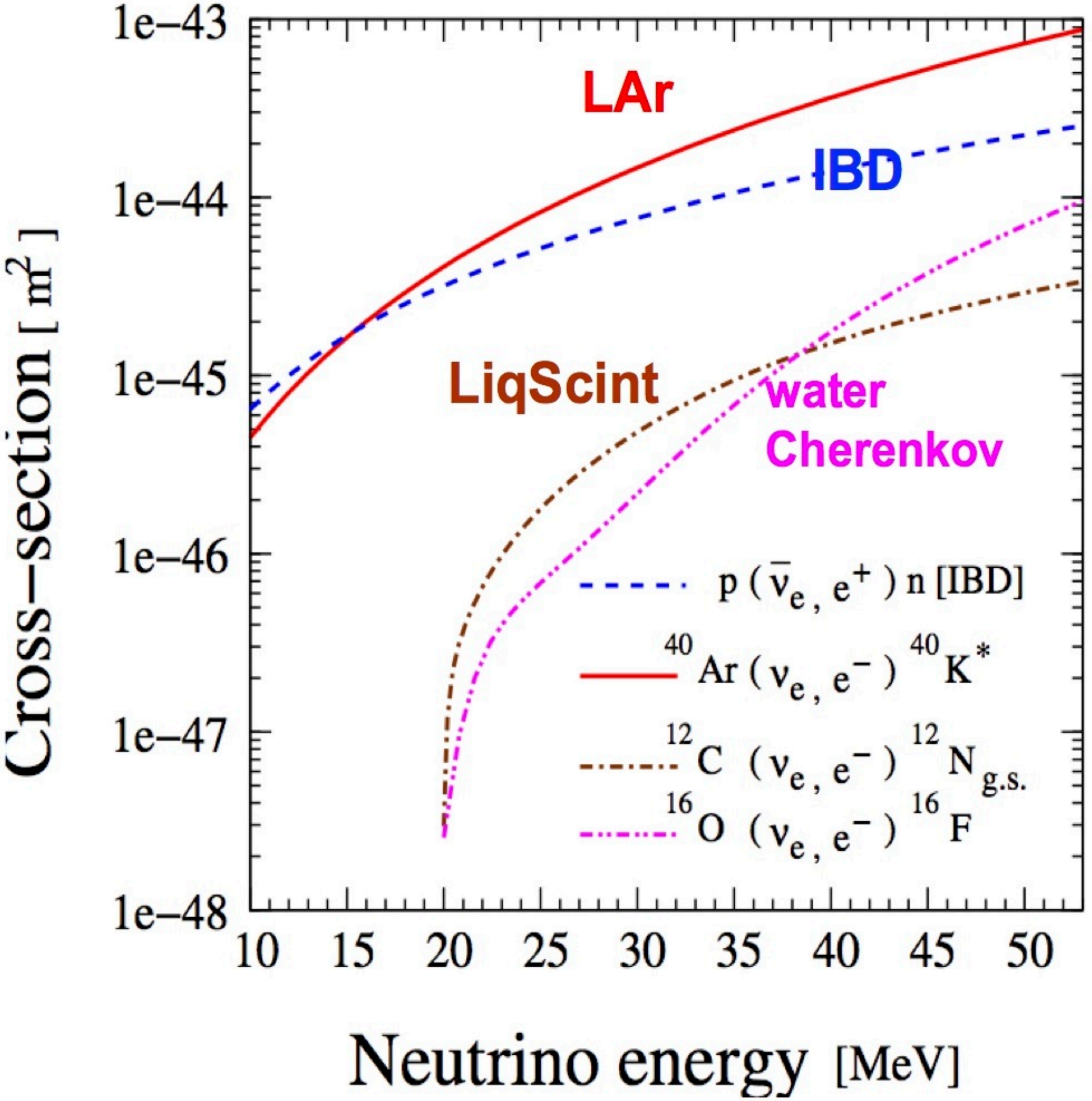
- IBD event selection;
  - Prompt signal
    - Time window after the 1st beam bunch from 1.0 to 10 μs (stopped μ is decayed with 2.2 μs lifetime)
    - Energy is cut with 20MeV (to avoid long-lived cosmic ray spallation and C(νe,e)Ngs. )
  - Delayed signal
    - Time window; from 10μs to 100μs
    - Energy; $6 < E_{gamma} < 12$ MeV
    - $\Delta VTX_{prompt\text{-}delayed} <$ 60cm
- Detection efficiency for high $\Delta m^2$ is expected to be ~50% from MC simulation.

# Pros of the MLF experiment

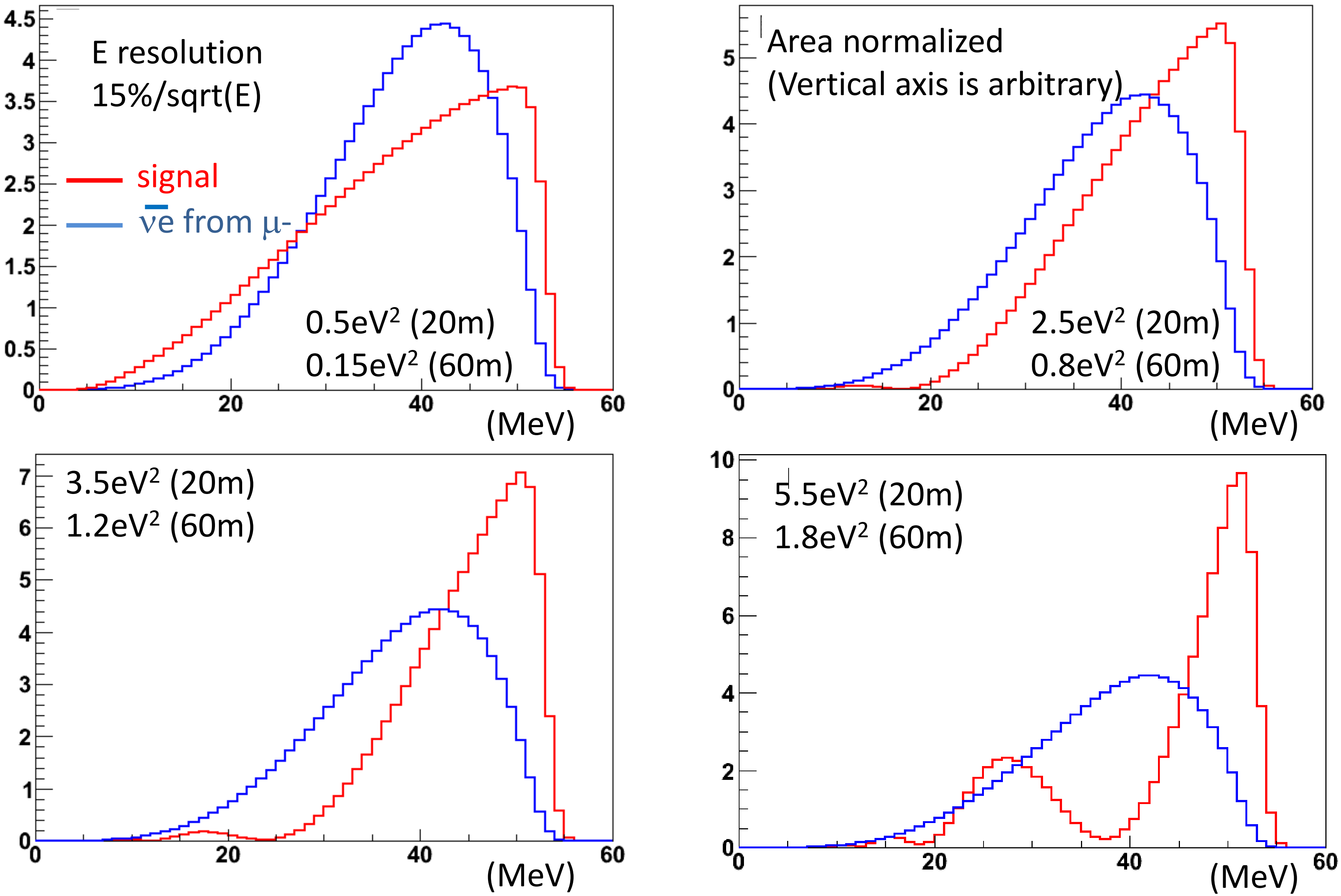
- Beam part; Intense beam
  - MLF has more intense beam than LANSCE (LSND) and ISIS (KARMEN). 0.33mA, 1MW operation after the relevant Linac upgrades. POT is more than twice of KARMEN2 experiment.
  - Proton energy of the MLF is 3GeV. #pions/proton is ~6 times more than that KARMEN.
  - Clear bunch structure due to low duty factor.
  - (SNS has 1.4MW+1GeV proton beam, #$\nu$ is comparable. J-PARC has better duty factor though)
- Detector; Gd loaded liquid scintillator will be used.
  - Delayed coincidence signal has larger energy (8 MeV) than H capture (2.2MeV), and shorter time window (~30 $\mu$s) for coincidence than H capture (220 $\mu$s).
  - High detector efficiency compared to old experiments.
- Detector; Possibility to perform PID with Cherenkov light will be pursued. (PID -> proton recoil from fast neutron from cosmic rays are one of most serious background)

# Cross section and event rate

- Xs of IBD is well known
  ($\sigma = 9.3 \times E_{\nu}^{2} \times 10^{-44}$ cm$^2$)
- $\nu$ Energy spectrum from stopped $\mu^+$ is also well known.
- Event rate of IBD at 60 (20) m ($\bar{\nu}_e$ from $\mu$-) is ~150 events / year assuming 1000 (100) tons and 100% detection $\varepsilon$.
  - 3.0x$10^{22}$ protons on target
  - $\pi$ / p ratio = 0.258
  - 8.6x$10^{28}$ free proton / ton
- #Events of oscillated signal ($\Delta m^2$=2.0eV$^2$, $\sin^2 2\theta$=0.002) is ~260.



# Typical energy distortion (L=20,60m)



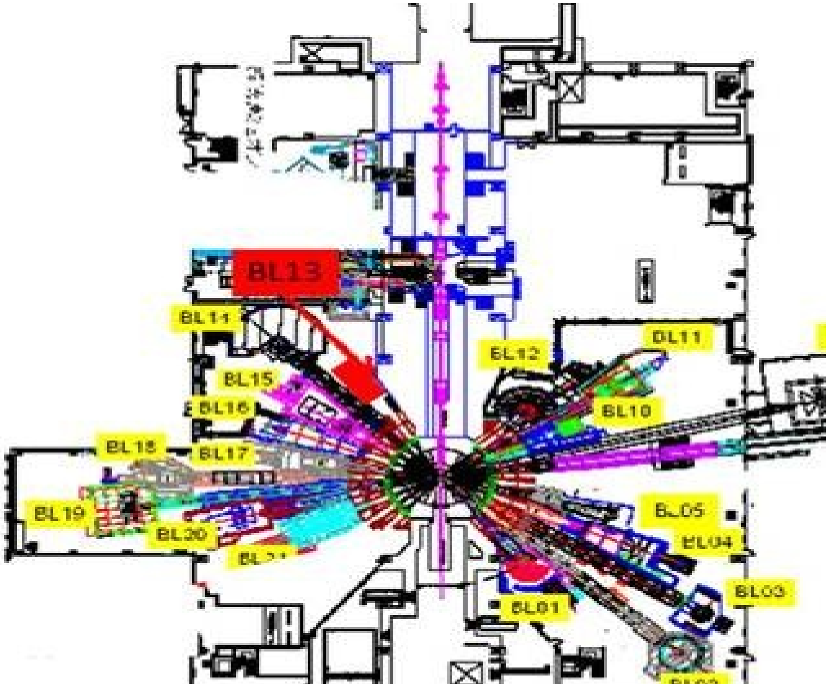
- This energy shape difference is used to distinguish oscillation signal and dominant BKG.
- Experiments with 60m can aim low $\Delta m^2$, but needs a large detector (~1kt) due to stat ($1/L^2$).

# Other backgrounds for IBD events

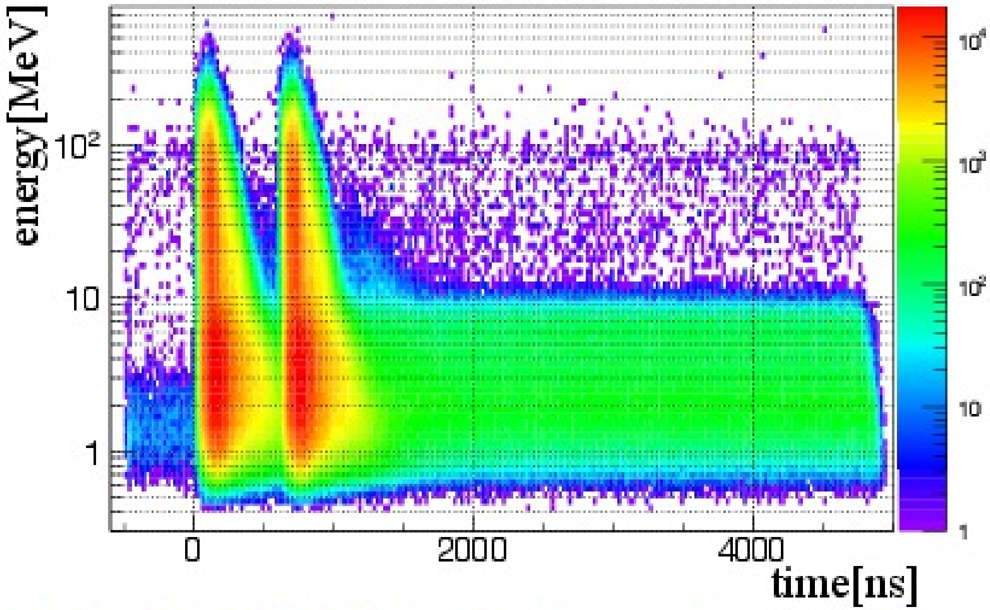
- Possible backgrounds for Inverse Beta Decay
  - Beam neutrons, which mimics prompt signals and/or delayed signal (background for delayed signal = thermal neutron captured gammas in the detector)
  - Beam related gammas from neutron captured gammas around the detector by iron and concrete (BKG for delayed signal)
  - Fast neutrons induced by cosmic rays (this mimics both prompt and delayed.)
  - Environmental gammas (up to 2.6 MeV), which can be avoided by Gd-load scintillator.
  - Spallation induced by cosmic rays
  - Neutrino interaction (primary) + accidental (delayed)
- Items highlighted by red characters are checked with our measurement recently.

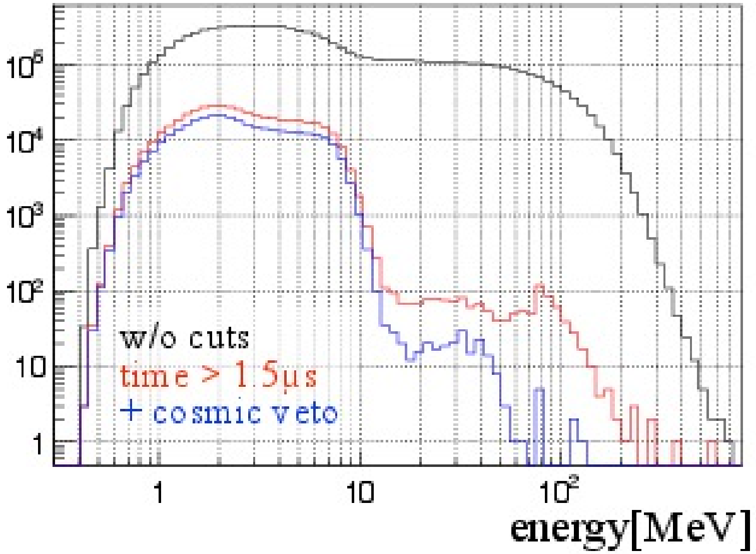
# BKG measurement with 1 ton plastic scintillator

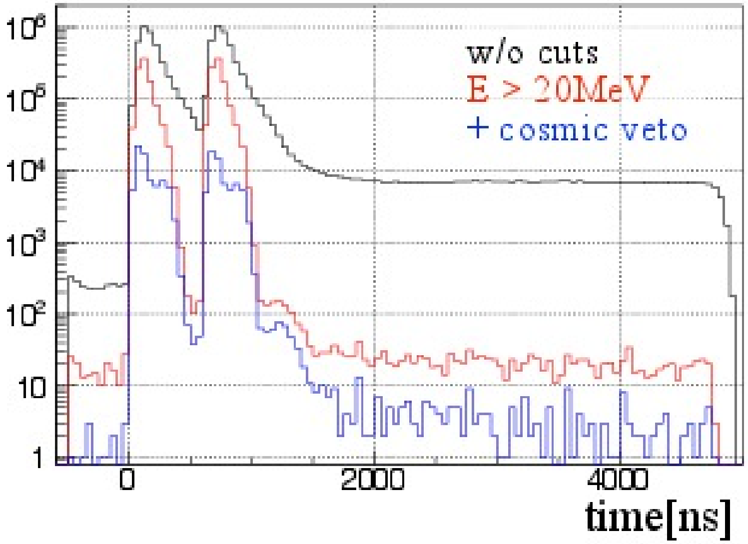
- ~$50 \times 50 \times 450 \text{cm}^3$ scintillator (about 1 ton) is made from 10.5 (or 21) x 4(t) x $450 \text{cm}^3$ (l) plastic scintillators
- We have measured the accidental backgrounds created by neutrons for prompt and delayed signal.



# Observation from 1 ton scintillator





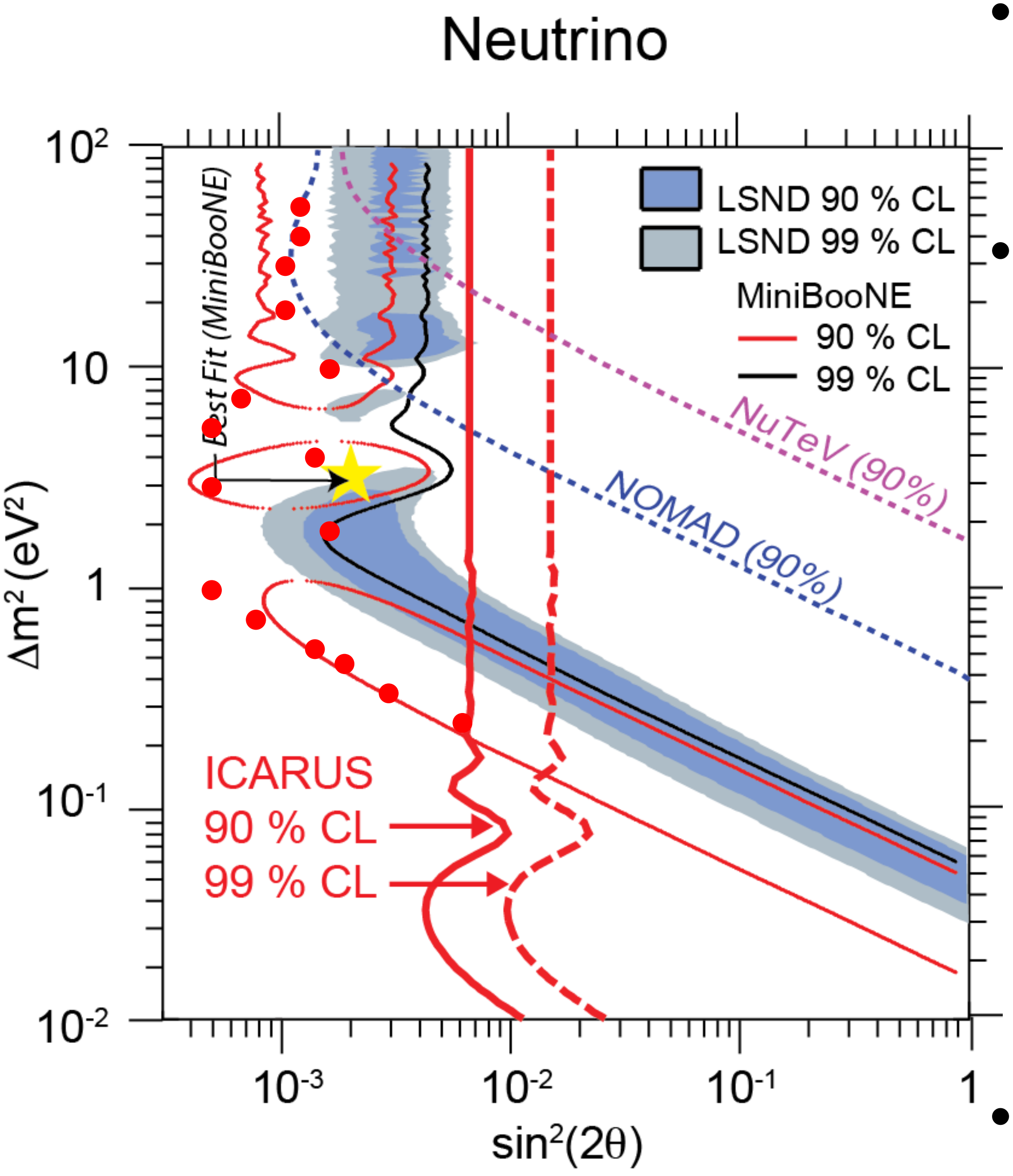


Most of 20-60 MeV activities are from cosmic rays.

# Event selection for monitor signal ($\nu_e + {}^{12}C \rightarrow e + {}^{12}N_{gs}$)

- Event rate is ~100 times higher than IBD since this monitors amount and energy of $\nu_e$ from $\mu$+
- Almost background free. (if background level is similar to LSND and KARMEN at the end)
  - Selection criteria for prompt signal is same as IBD.
  - Delayed signal
    - Time window; allowed until next beam spill (since $\tau$ of Ngs is 16 ms)
    - $E_{delay}$ < 16 MeV (end point of beta decay spectrum)
    - $\Delta$VTX ; possibly tightened than IBD. -> under study.
- This signal is also important for rate estimation for IBD background. (and maybe disappearance analysis)

# Sensitivity (60m 1kt case)



- Red circles show 5 $\sigma$ sensitivity. -> definite conclusion from the configuration.
- Assuming
  - a 1 kt detector is put at 60 m distance from Hg target.
  - 1MW x 2 years (4000 hours / year) operation
  - Detector efficiency is 50%.
  - Dominant background is $\bar{\nu}e$ from $\mu$- , 150 events $10^{-3}$ compared to $\bar{\nu}\mu$ from $\mu$+
  - Uncertainty of the BKG normalization factor is 100%, while that of signal is 10%
- Experimental setup is being designed.

# Summary

- Sterile neutrino is one of most serious and interesting puzzle driven by experiments in the particle physics. Experimentalists have to conclude the existence or non-existence.
- J-PARC MLF facility provides unique opportunity to search for sterile neutrinos with well-known neutrino energy spectrum, and their cross sections .

- A proposal of the experiment will be submitted in this summer.

# backup