Sterile neutrino searches using accelerators

Takasumi Maruyama (KEK)

Thank you for useful information / discussions;

- Alan Bross (for nuSTORM)
- Bill Louis (for OscSNS)
- Sam Zeller (for microBooNE)

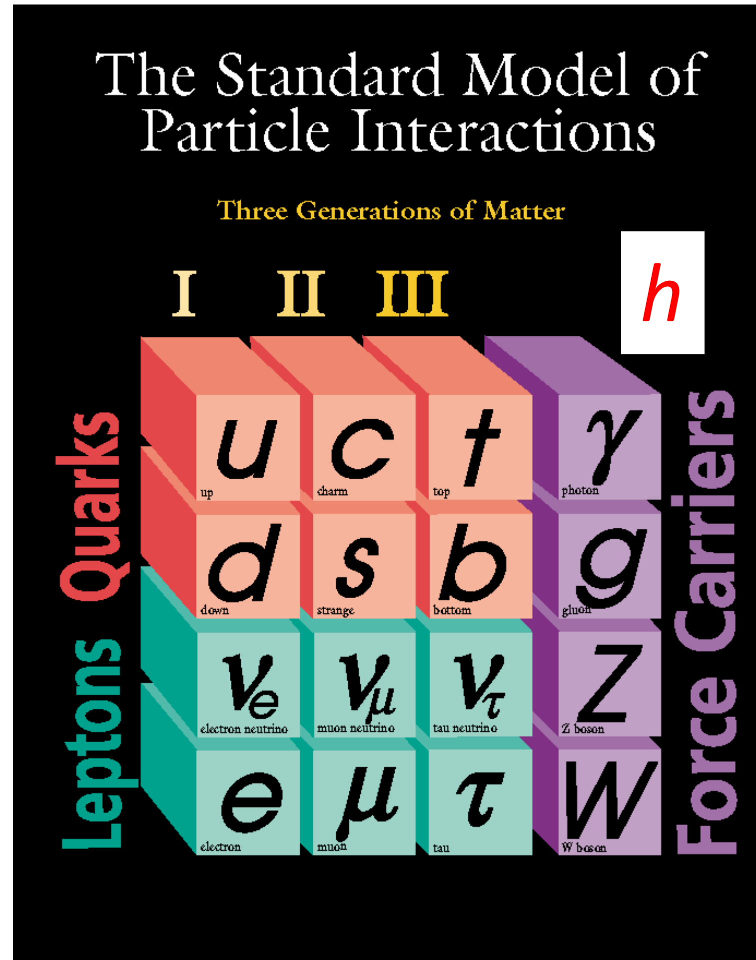
A fundamental questions in flavor physics

- How many generations exists?
  - Only 3 active (weak interactive) neutrinos existed below Mz/2.

- No more elementary fermion in three generations?

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix},\ u_{R,}\ d_R,\ \cdots$$

$$\begin{pmatrix} \nu_{e_L} \\ e_L \end{pmatrix}, e_R, \ldots$$



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
  - Observed by only neutrino oscillations (also indicated by some experiments)
  - Could be ν_R (even see-saw partner) or new particle
  - Beyond PMNS matrix

- Sterile neutrino can be one of the Dark Matter candidate.

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

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

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

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

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

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

Approximately, the oscillation is expressed by 2 flavor equation.

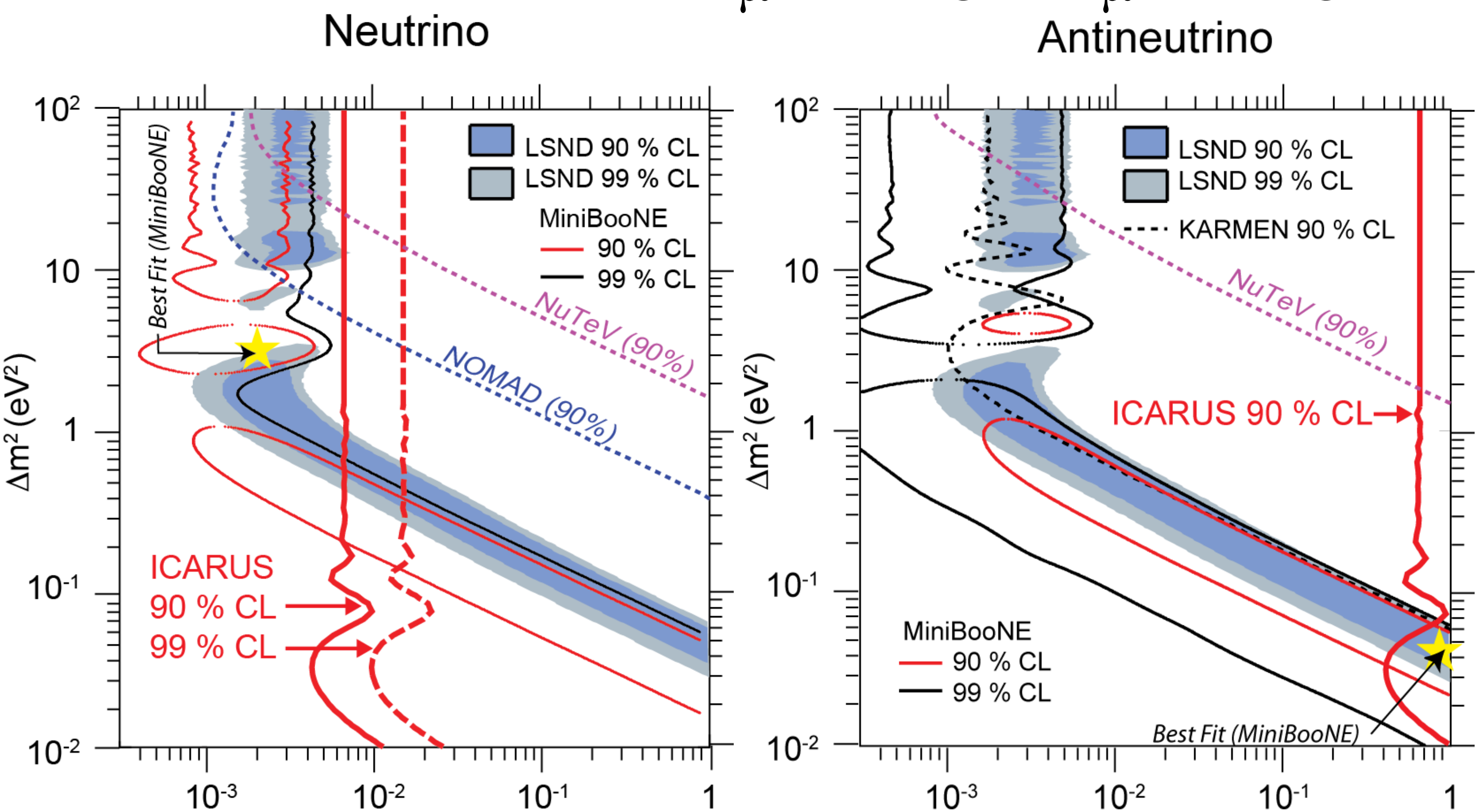
Status of the sterile neutrino search

- Anomalies, which cannot be explained by standard neutrino oscillations for 15 years are shown;

Experiments	Neutrino source	signal	significance
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	3.4σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ
		combined	3.8σ
Ga (calibration)	e capture	$\nu_e \rightarrow \nu_x$	2.7σ
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ

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

Excess are due to $\nu_\mu \rightarrow \nu_e$ / $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$?



arXiv:1307.4699 [hep-ex].

- LSND and MiniBooNE saw the excess.
- 3 generation model cannot explain oscillation with Δm^2>~1.0eV^2

  ($|m_3^2 - m_2^2|$~2.3×10^{-3} eV^2, $m_2^2 - m_1^2$~7.5×10^{-5} eV^2)
- Z measurements conclude 3 active ν → sterile

Sterile neutrino searches

- To prove or refute the existence of sterile neutrinos with various modes are important.
  - μ Decay-At-Rest source ; J-PARC P56 @MLF (proposed) and OscSNS (white paper was submitted)
    - Better pulsed beam than LSND ($\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$; $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$)
    - Better liquid scinti. detector than KARMEN / LSND (PID / Gd loaded)
  - LAr + conventional horn focused beam; ICARUS, MicroBooNE (on-going, will start) ($\pi^+ \rightarrow \mu^+ + \nu_\mu$; $\nu_\mu \rightarrow \nu_e$ / reversed horn polarity)
    - Better detector (BKG rejection, e ID, ν energy reconstruction) than MiniBooNE → reduced #BKG and systematics on BKG
  - $\nu_\mu \rightarrow \nu_\mu$ disappearance; search for new disappearance mode
    - MINOS+ (on-going)
  - New type of beam + Fe+scintillator detector; nuSTORM
    - Using neutrinos from STORed Muons. ($\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$) ; stage I (from FNAL PAC)
    - Good sensitivity with golden channel; $\nu_e \rightarrow \nu_\mu$

Picking up typical experiments.
Not covering all (sorry!)

Search mode summary

Experiments	source	$\nu_e \rightarrow \nu_x$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ($\nu_e \rightarrow \nu_\mu$)	$\nu_\mu \rightarrow \nu_x$	NC
J-PARC P56 (@MLF)	μDAR	○	◎		○
OscSNS	μDAR	○	◎	○	○
ICARUS	πDIF		◎ ($\nu_\mu \rightarrow \nu_e$)		
MicroBooNE	πDIF		◎ ($\nu_\mu \rightarrow \nu_e$)		
MINOS+	πDIF			◎	
nuSTORM	μDIF	○	◎ ($\nu_e \rightarrow \nu_\mu$)	○	○
Reactors		◎			
Radio-active sources		◎			

◎ Main search mode (golden channel)

○ possible search mode

Picking up typical experiments.
Not covering all (sorry!)

nuSTORM (neutrinos from STORed Muons)

A low-energy muon storage (P_μ=3.8 GeV/c) ring based on existing technology to:

- Address the large Δm^2 neutrino oscillations
- Provide beams for precision ν_e and ν_μ cross section measurements
- Provide an accelerator technology test bed (ν-Factory & μ-Collider)
- Provide a neutrino Detector Test Facility
  - Proposal: arXiv:1308.6822
  - Project Definition Report: arXiv:1309.1389

Technologically limited Schedule: 5-7 years

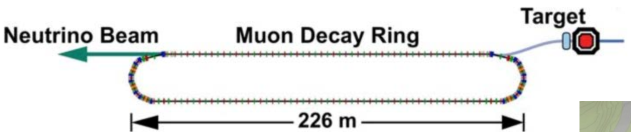
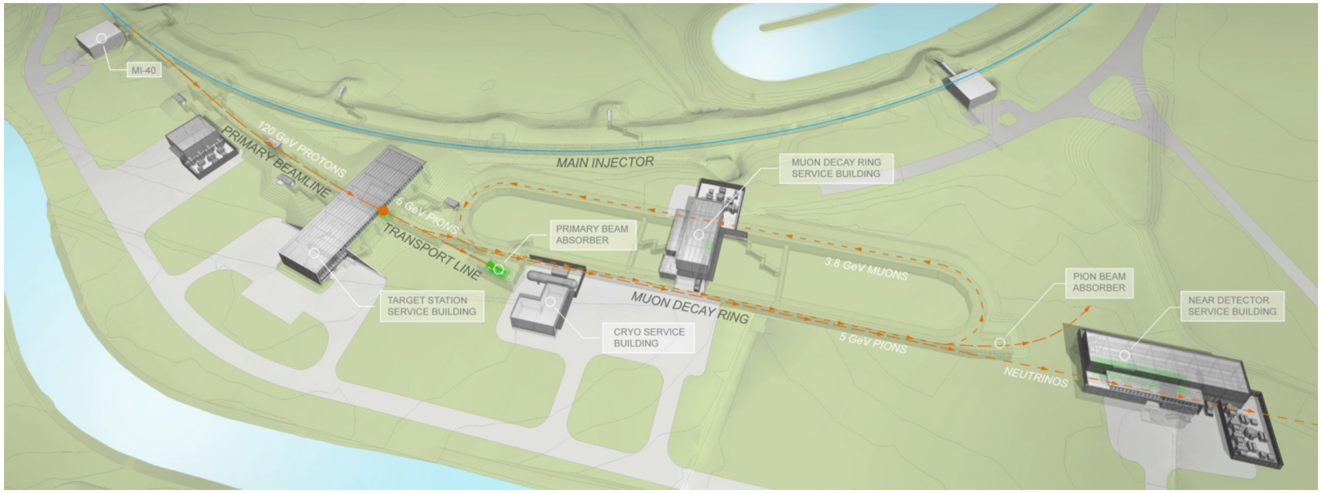


Table 1: Decay ring specifications

Parameter	Specification	Unit
Central momentum P_μ	3.8	GeV/c
Momentum acceptance	$\pm$ 10%	
Circumference	480	m
Straight length	185	m
Arc length	50	m
Arc cell	DBA	
Ring Tunes (ν_x, ν_y)	9.72, 7.87	
Number of dipoles	16	
Number of quadrupoles	128	
Number of sextupoles	12	

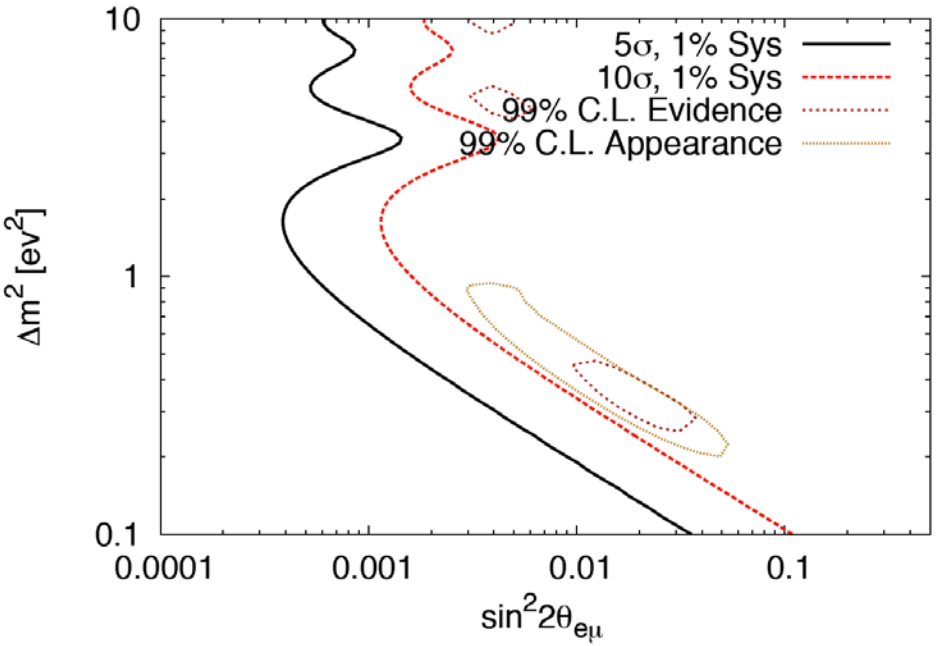
The nuSTORM facility



Sterile ν search sensitivity

- Performance for an exposure of 10^{21} proton on target (120 GeV) from Fermilab Main Injector for sterile neutrino appearance
  - 2 X 10^{18} useful muon decays
  - Can confirm or rule out LSND/MiniBooNE region at 10σ

Golden mode; $\nu_e \rightarrow \nu_\mu$



5 and 10 σ contours for a Boosted Decision Tree analysis. The 99% confidence level contours from a global fit to all experiments are also shown (from Kopp *et al.* JHEP 1305, 050 (2013).)

Conventional beam + LAr

- Topics are covered by previous session's speakers.
- Clear electron, π^0 and single γ PID can be performed.

FIGURES

ICARUS arXiv:1307.4699 [hep-ex].

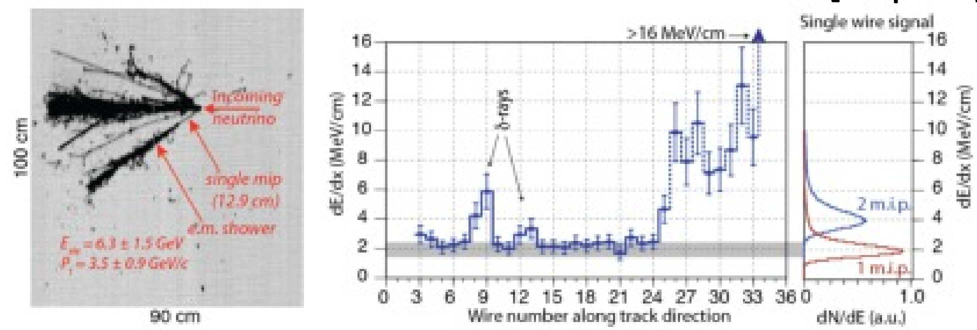
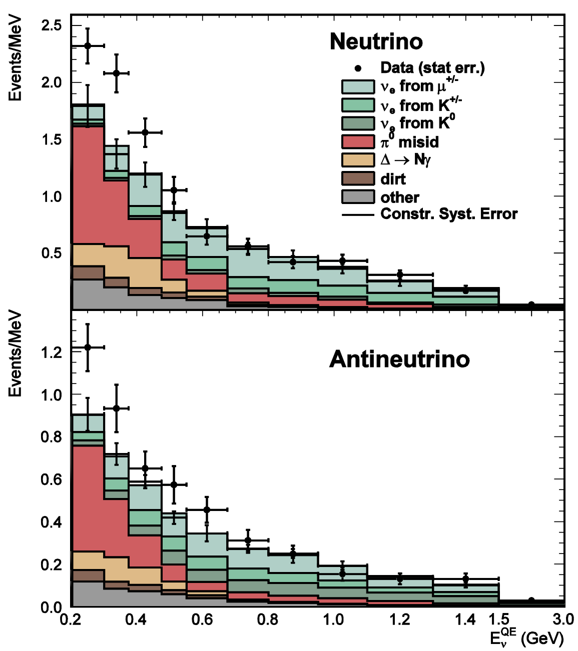


Figure 1. Experimental pictures of the first of the two events with a clear electron signature found in the additional sample of 904 neutrino interactions. The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is shown along the individual wires. The event has a total energy of ~27 GeV and an electron of 6.3 ± 1.5 GeV with a transverse momentum of 3.5 ± 0.9 GeV/c.

MiniBooNE Excess

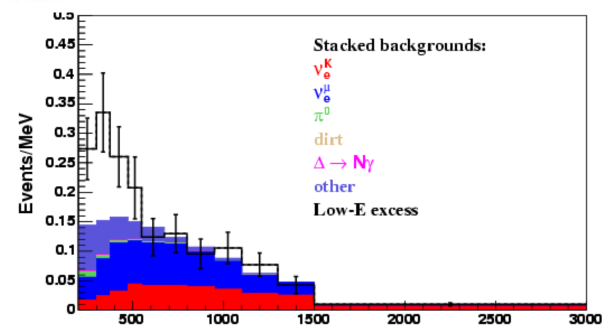
PRL 110.161801,2013.

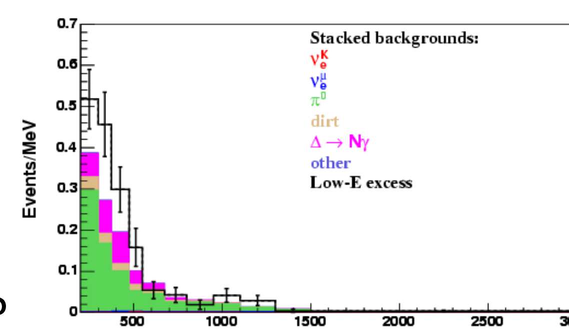


Electron excess (oscillation)?

MicroBooNE

or γ excess (uncertainty of ν cross section)?

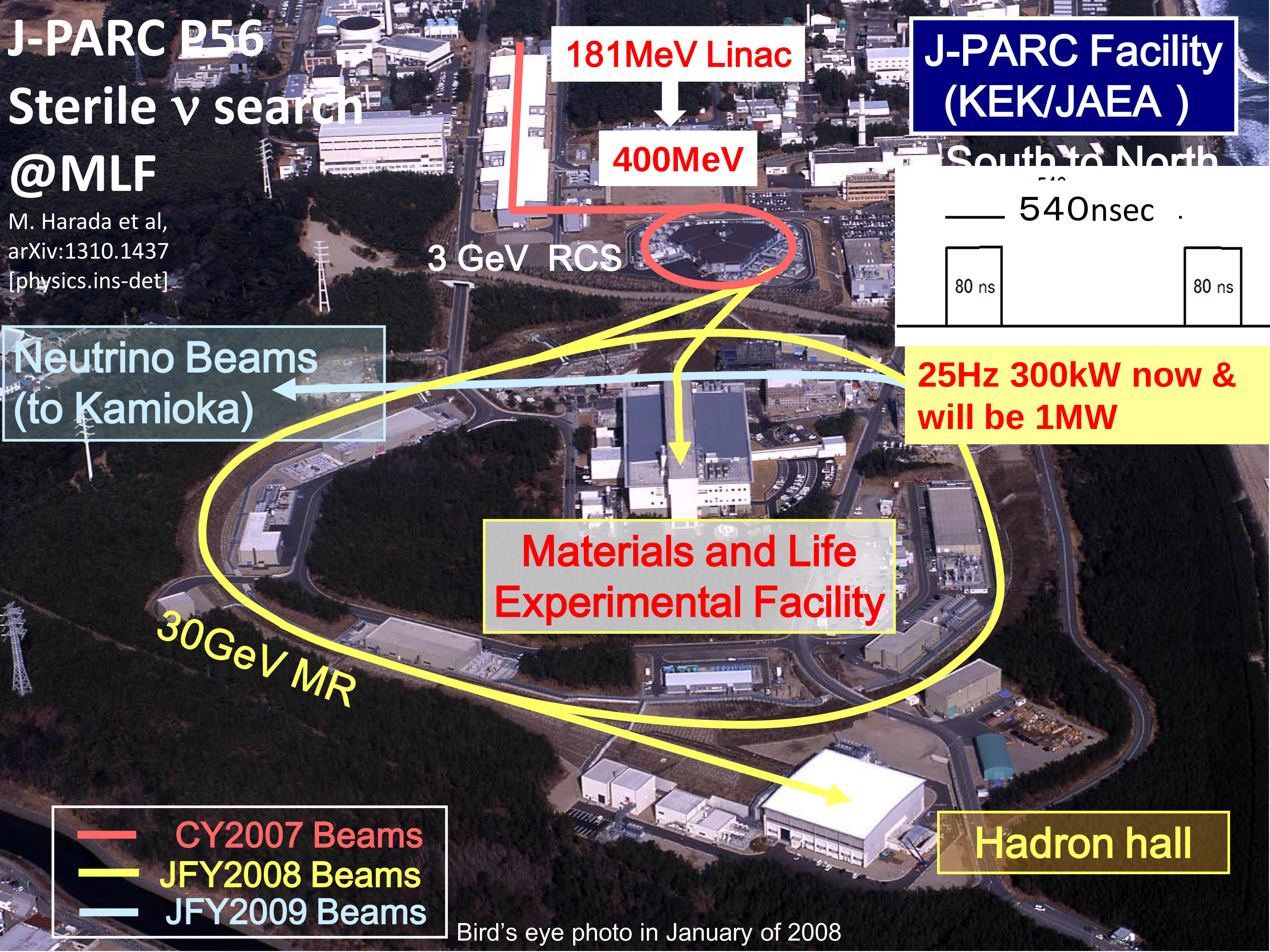




MicroBooNE

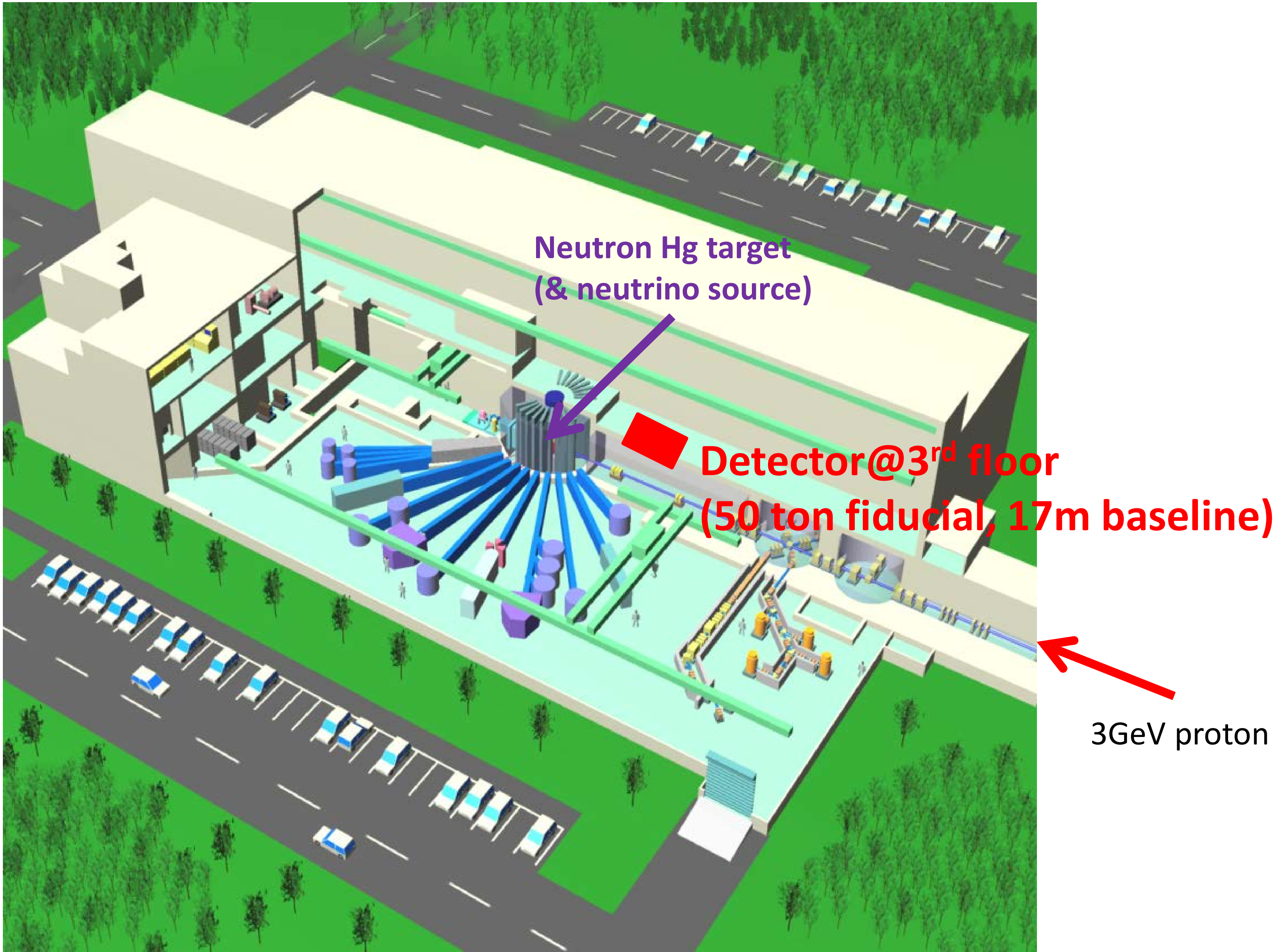
- 170 ton (total) Liquid Argon TPC will be largest LAr TPC in the U.S.
- important step towards large scale LAr TPCs for long-baseline ν physics
- **physics goals**:
  - *address MiniBooNE low energy excess*
  - *measure ν cross sections on argon*
- **R&D goals**:
  - *argon fill without evacuation*
  - *cold front-end electronics*
  - *long drift (2.5m)*
  - *near surface operation*
  - *reconstruction development (e/γ)*
- MicroBooNE just entered our last 6 months of project construction
- experiment will begin data-taking in the Fermilab Booster Neutrino beam in 2014!

microboone



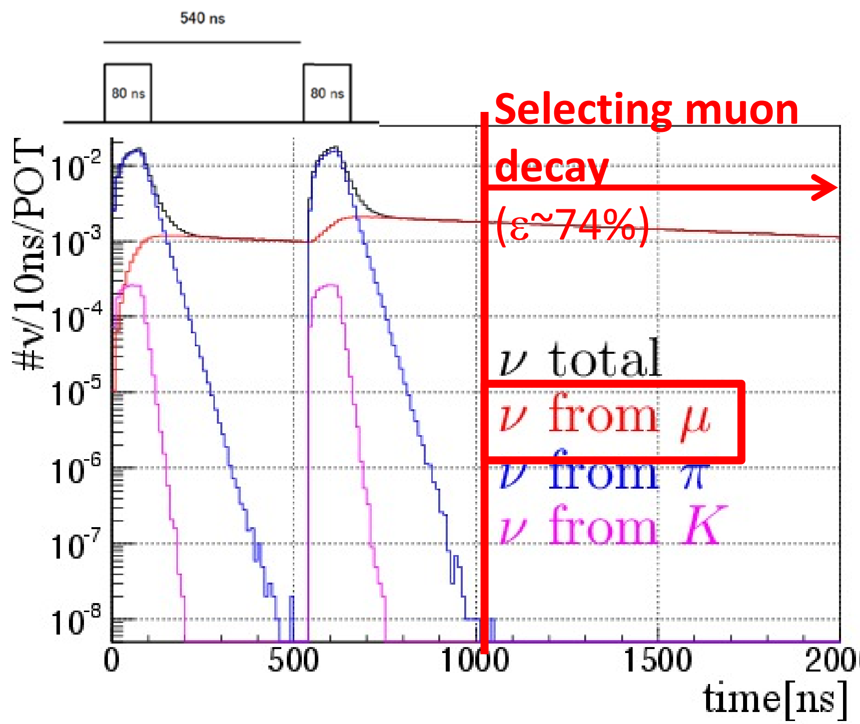
J-PARC P56
Sterile ν search
@MLF
M. Harada et al,
arXiv:1310.1437
[physics.ins-det]
181MeV Linac
400MeV
3 GeV RCS
J-PARC Facility
(KEK/JAEA)
South to North
540nsec
80 ns
80 ns
25Hz 300kW now &
will be 1MW
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
30GeV MR
Hadron hall
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

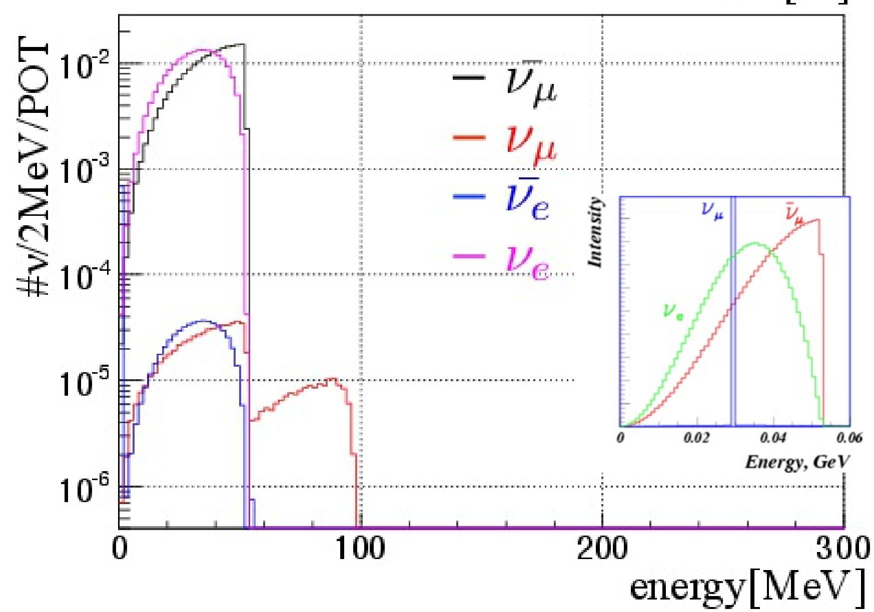
Neutrino production and detector site (3F)



Neutrinos from only μ^+ decay at rest (MLF)

- Neutrinos from only μ^+ decays are used. (μ^+ has long lifetime). (top)
- Energy spectrum of $\mu^+ \rightarrow e^+ \overline{\nu}_\mu \nu_e$ decay is well known (bottom)
  - Useful to examine the excess of $\overline{\nu}_e$.
  - $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation is searched.
- $\pi^- \rightarrow \mu^-$ decay chain is highly suppressed (10^{-3} compared to μ^+)
- Proton energy of J-PARC is 3GeV, thus π^+/p ratio is higher than LSND / KARMEN (0.8GeV) by 5-10 times

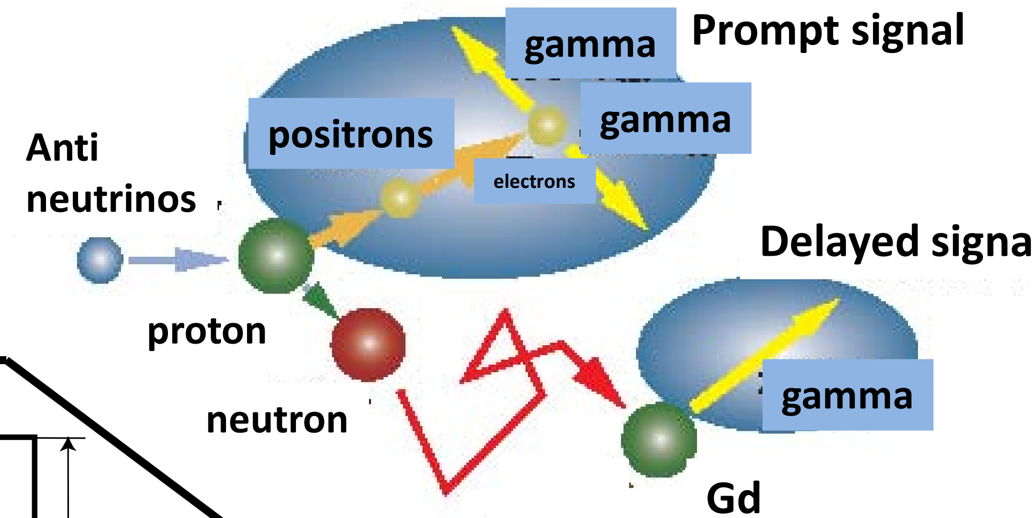


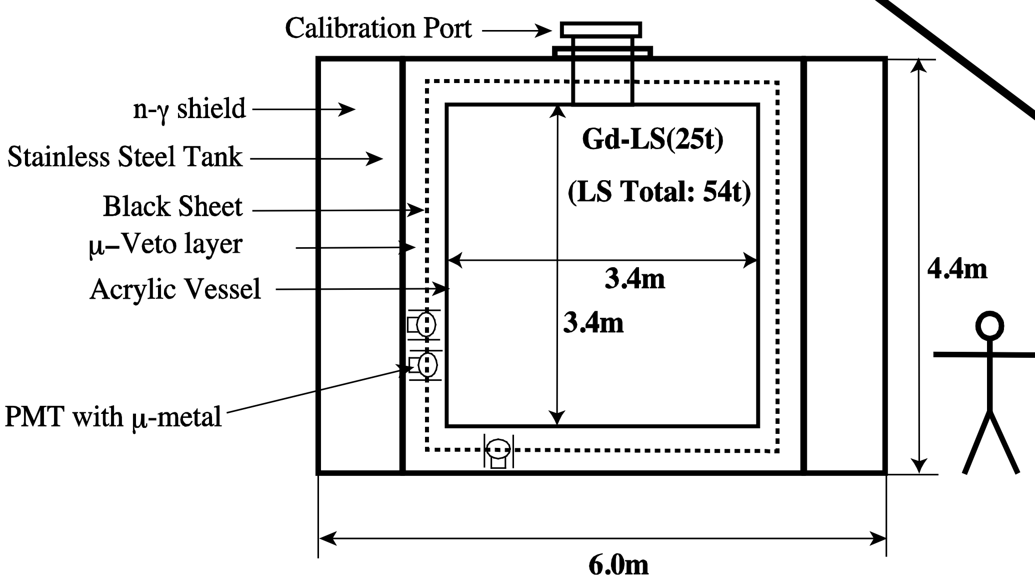


Detector; Liquid scintillator

- Coincidence between positron and neutron signal ($\overline{\nu}_e + p \rightarrow e^+ + n$; Inverse Beta Decay; IBD).
- Neutrons are captured by Gd, and emit gammas (totalE = 8MeV, lifetime; a few 10 μs.)

- Positrons → "prompt" signal ($E\nu$ = Evis+0.8MeV)
- Neutrons → "delayed" signal
- Cross section is well known (~2% level)

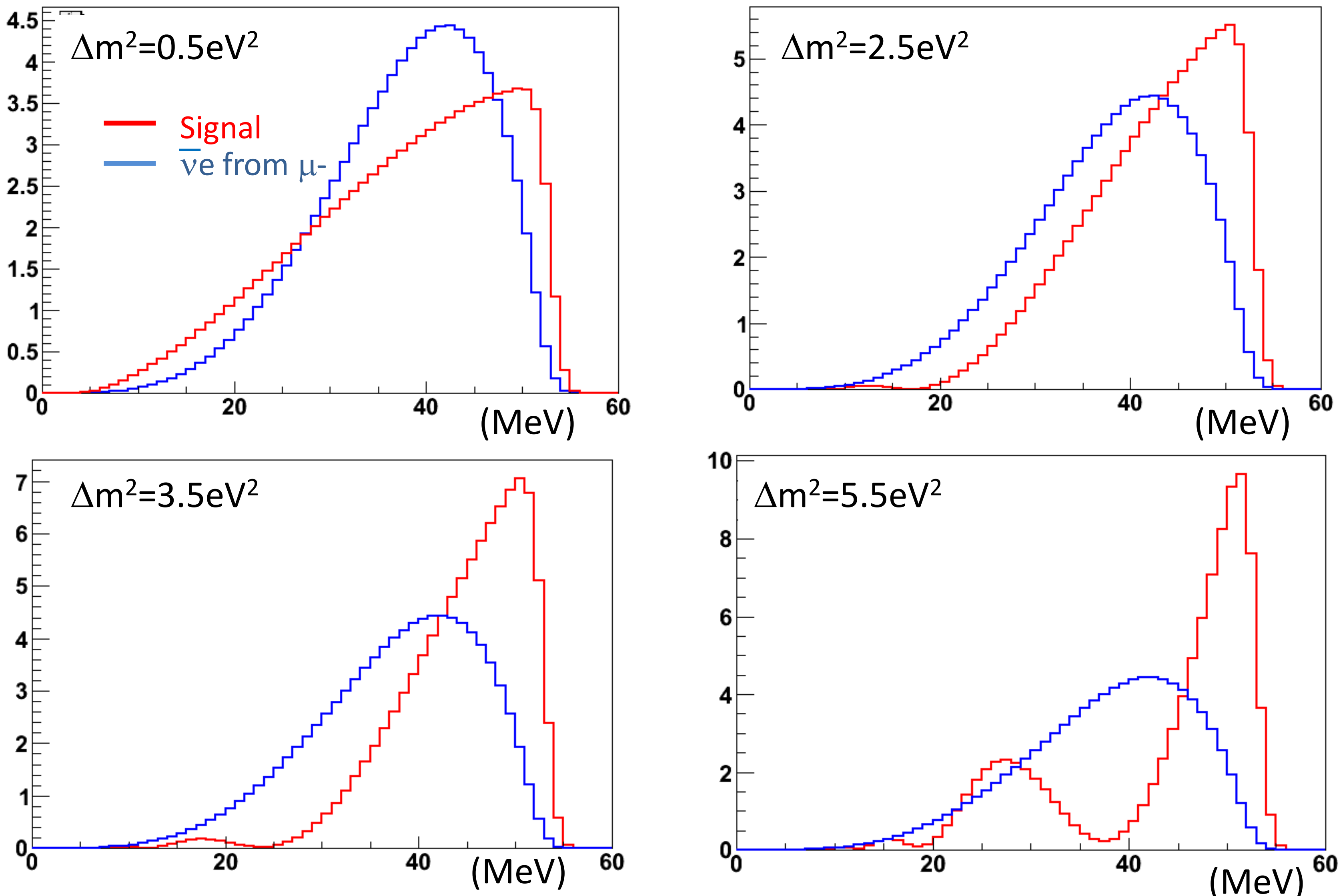




Current design of the detector

- Movable 2 identical detectors (from MLF constraints)
- 150 10" PMTs
  energy resolution < 15%/sqrt(E)
- 50cm buffer region (no Gd)
  → reject low E neutrons and gammas

Energy distribution of events (L=17m)

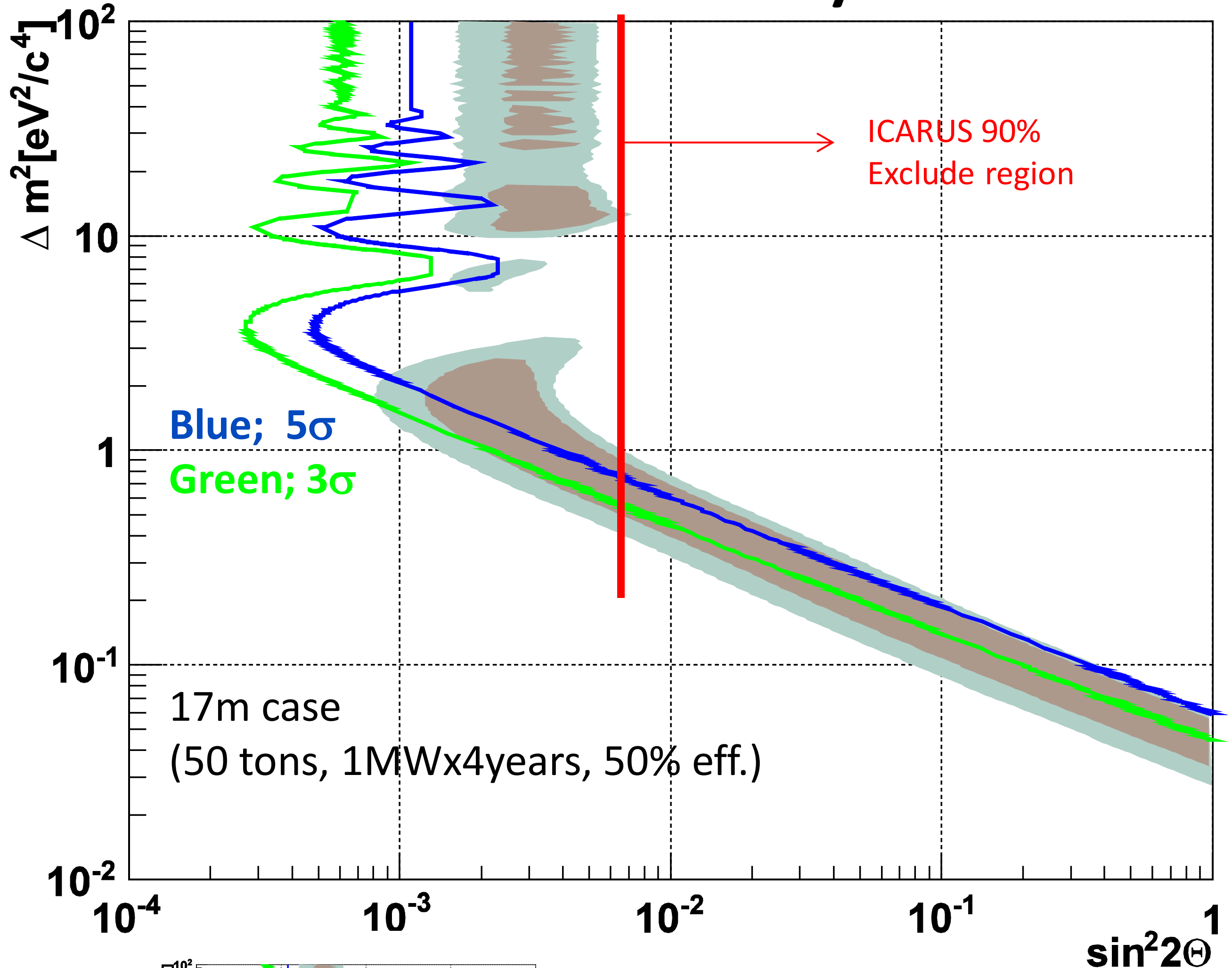


$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

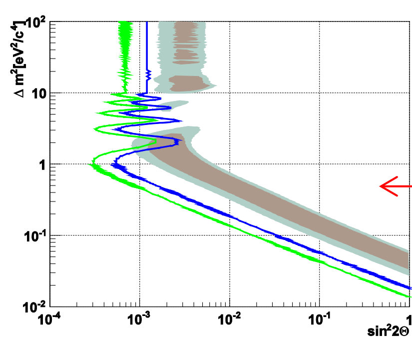
- Energy is smeared by 15%/sqrt(E) (detector E resolution)

Sensitivity

- Top plot;
  - 1MW x 4 years
  - 4000h / year
  - 50 tons fiducial
  - ~50% detection ε
- a definite conclusion above ~1eV^2 is obtained

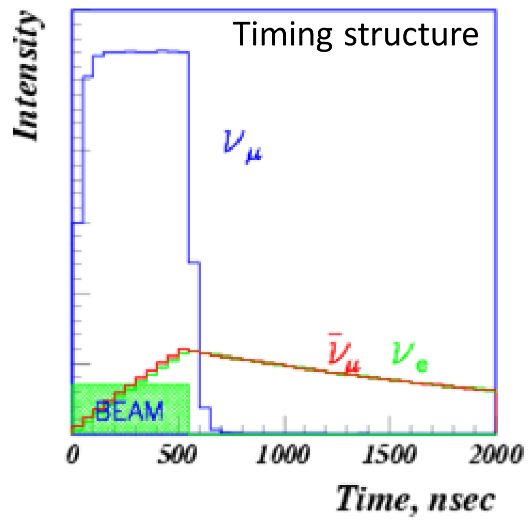


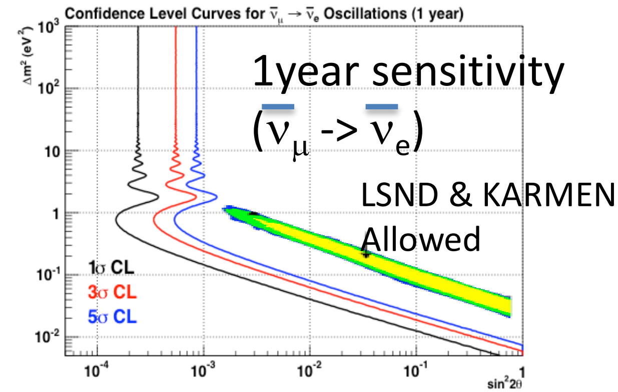
- Bottom plot;
  - If no clear result in step1, then we go to step2
  - Example configuration for future step2 is to use 1kt detector with 60 m baseline

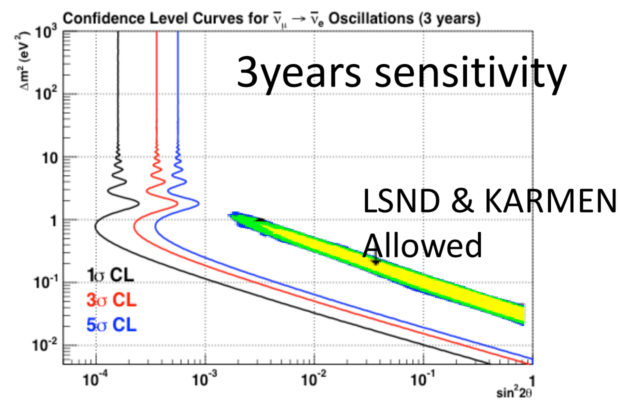


OscSNS (arXiv:1307.7097)

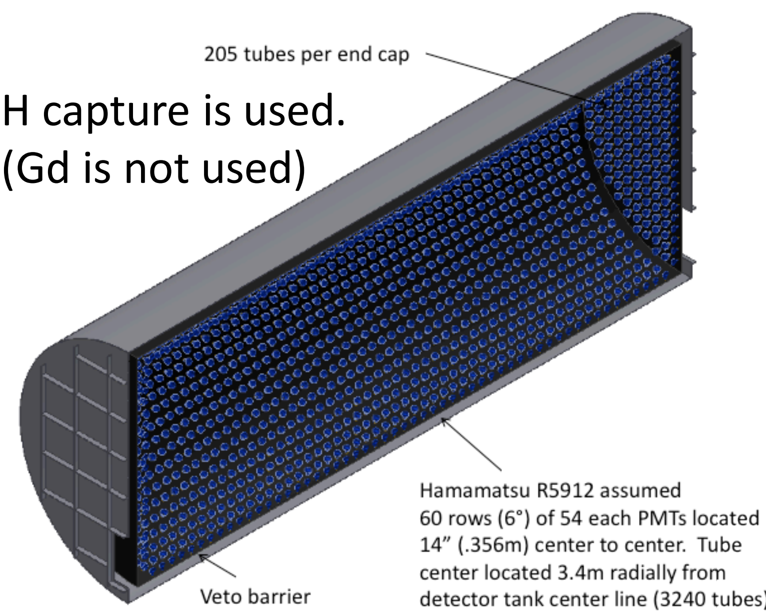
- Use Spallation Neutron Source (SNS) at ORNL
- ~1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos







H capture is used.
(Gd is not used)



Summary

- Sterile neutrino search is in a new era to check the consistencies;
  - With various search modes;
    - $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$, $\nu_\mu \rightarrow \nu_e$, $\nu_e \rightarrow \nu_\mu$
    - ν_μ disappearance
    - $\overline{\nu}_e$ or ν_e disappearance
    - NC
  - With different techniques;
    - Intense pulsed beam (μDAR) + LS
    - Horn focused beam (πDIF) + LAr (or Fe + scintillator)
    - New type of beam (Muon strage; μDIF) + Fe/scintillator
- Exciting next decade is expected.
  - To confirm or refute the results of LSND/MiniBooNE at first
  - All results from experiments above are consistent?

backup