北里大学
KITASATO UNIVERSITY

Sterile Neutrino Experiments at Accelerator

Takeo Kawasaki
Kitasato University

Rencontres du Vietnam, Neutrinos, Quy Nhon, July 16-22,2017

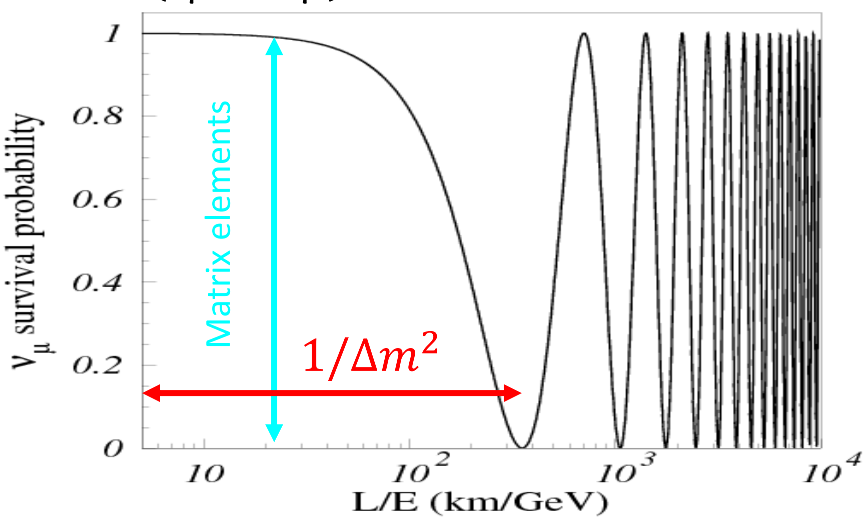
Outline

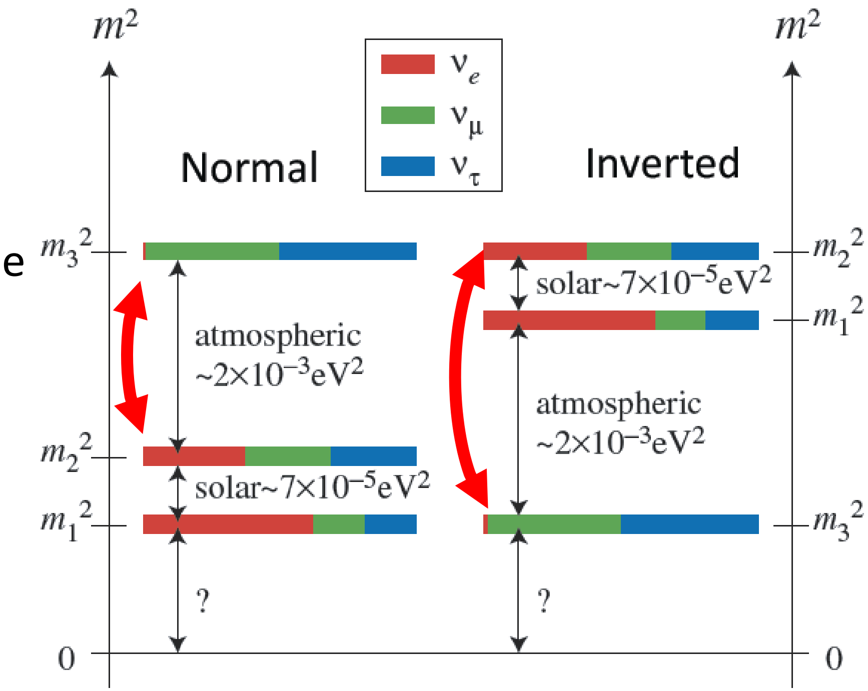
- Neutrino oscillation
  - Sterile neutrino 3+1 model
  - Neutrino oscillation experiments at accelerator
- Indication of sterile neutrino
  - LSND
  - MiniBooNE
- Sterile neutrino search at accelerator experiment
  - $JSNS^2$
  - SBN
  - NuPRISM
- Summary

Neutrino mixing matrix (3 flavors)

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu1}^* & U_{\mu2}^* & U_{\mu3}^* \\ U_{\tau1}^* & U_{\tau2}^* & U_{\tau3}^* \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Ex) $P(\nu_\mu \to \nu_\mu)$ Monochromatic energy case



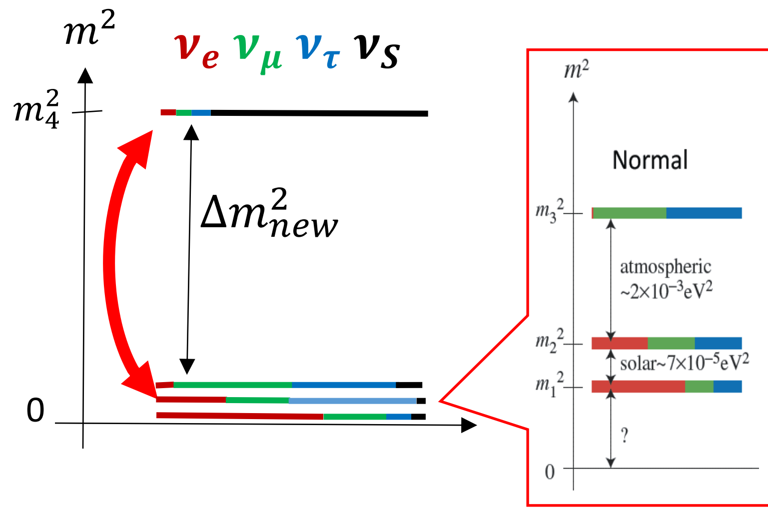


ν oscillation is explained by mixing matrix elements and mass difference.
Most Exp. Results are consistent with 3 neutrino mixing model.

Neutrino mixing matrix (4 or more flavors)

If there are more generations, it affect to the oscillation

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_s\rangle \\ \vdots \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} & U^*_{e4} & \cdots \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} & U^*_{\mu 4} & \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} & U^*_{\tau 4} & \\ U^*_{s1} & U^*_{s2} & U^*_{s3} & U^*_{s4} & \\ & \vdots & & & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \vdots \end{pmatrix}$$



For $3(\nu_\alpha) + 1(\nu_s)$ & $m_4 >> m_{1\sim 3}$ case,

$$\begin{cases} P(\nu_e \to \nu_e) \sim 1 - 4|U_{S4}|^2 |U_{e4}|^2 \sin^2\left[\dfrac{m_4^2 L}{4E_\nu}\right] & \nu_e \text{ disappearance} \\ P(\nu_\mu \to \nu_e) \sim 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2\left[\dfrac{m_4^2 L}{4E_\nu}\right] & \nu_\mu \to \nu_e \text{ appearance} \\ P(\nu_\mu \to \nu_\mu) \sim 1 - 4|U_{S4}|^2 |U_{\mu 4}|^2 \sin^2\left[\dfrac{m_4^2 L}{4E_\nu}\right] & \nu_\mu \text{ disappearance} \end{cases}$$

Reactor &source Exp. (ν_e disappearance)

Accelerator Exp. can measure ($\nu_\mu \to \nu_e$ appearance, ν_μ disappearance)

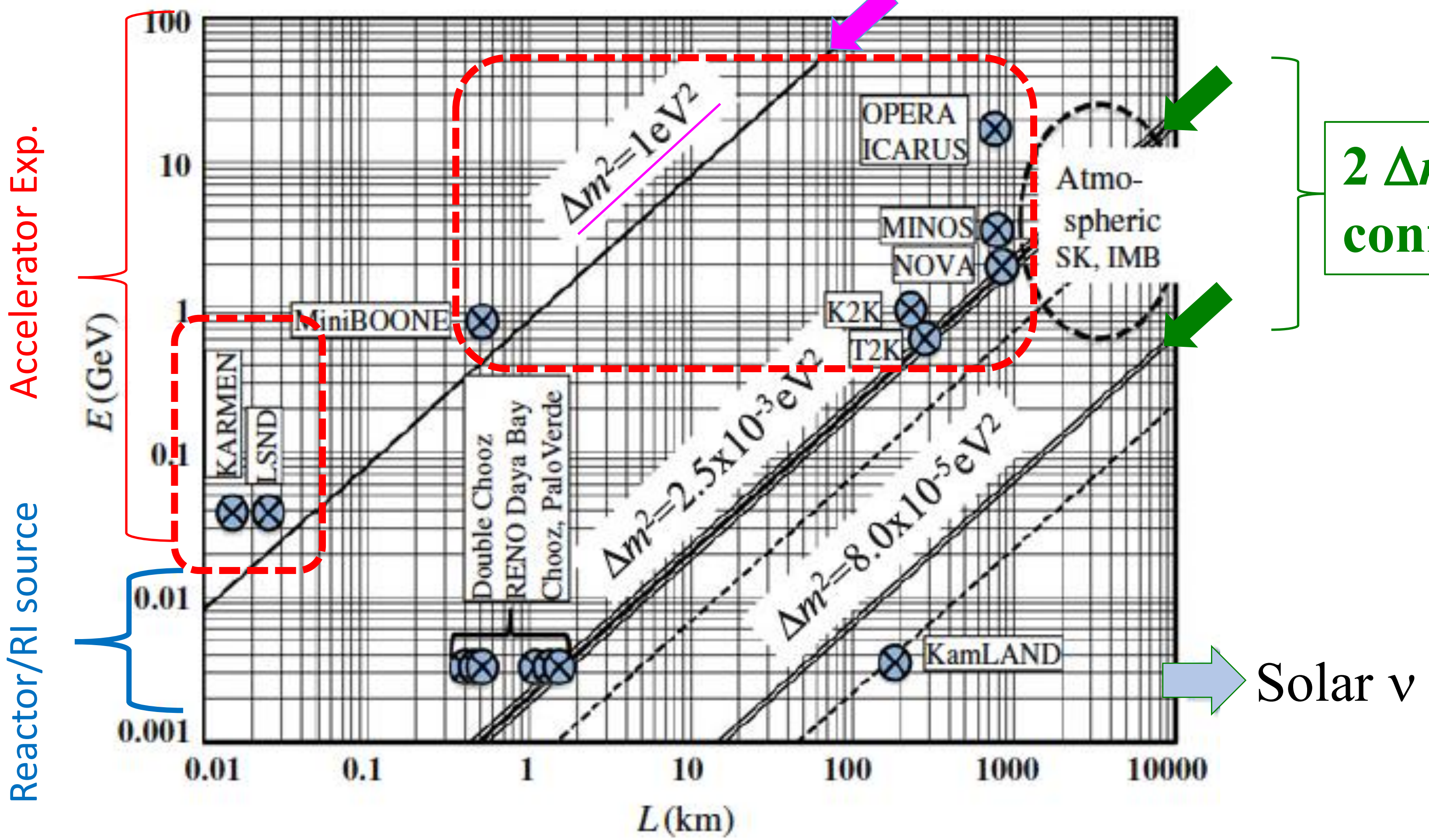
ν_s may be detected by ν oscillations

E-*L* relation of *ν* oscillation experiments

Suekane@HINT2016

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left[\frac{\Delta m_{ij}^2 L}{4E_\nu}\right]$$

There are indications of 3rd Δm^2 which requires 4 or more νs.



2 Δm^2s are confirmed

E-*L* relation of *ν* oscillation experiments

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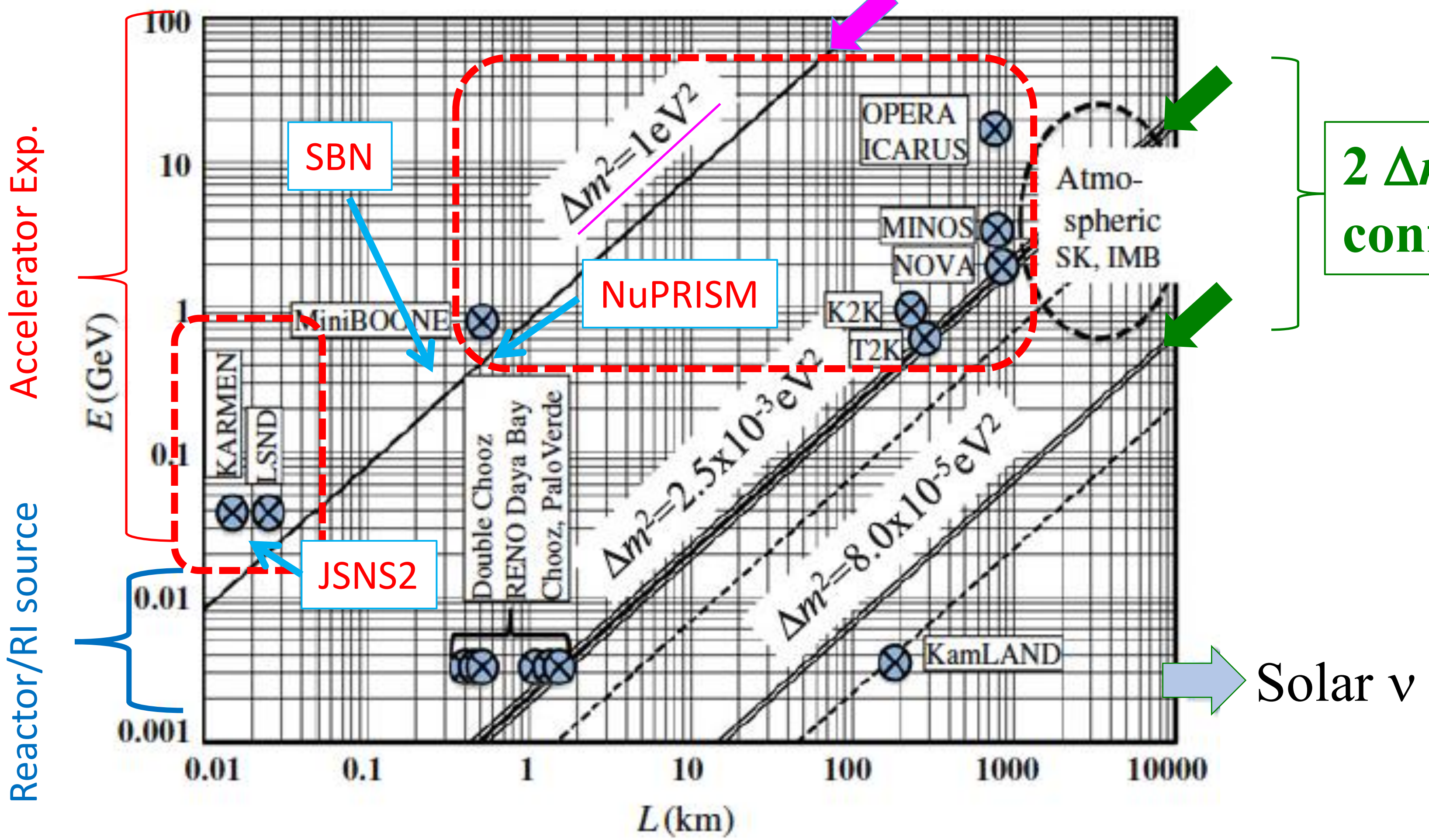
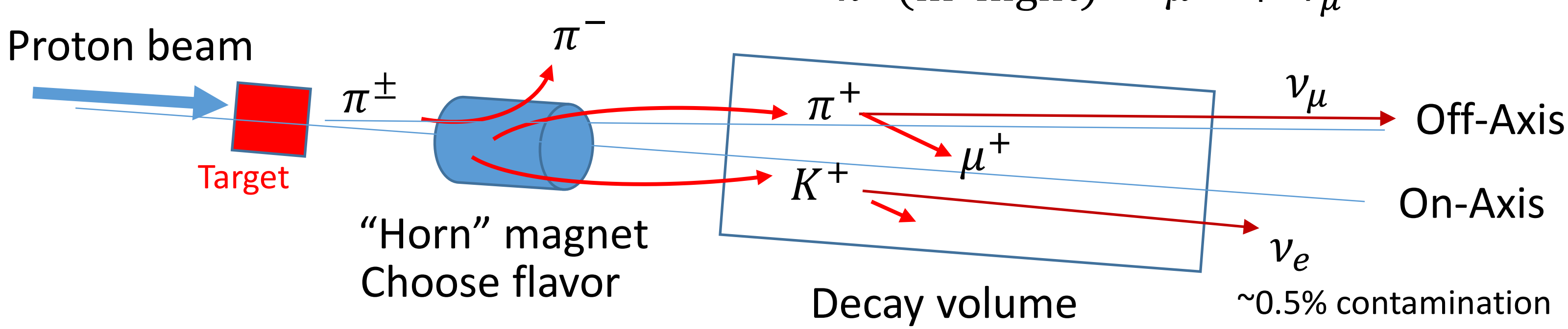


2 Δm^2s are confirmed

How to make neutrino beam

- Decay in Flight

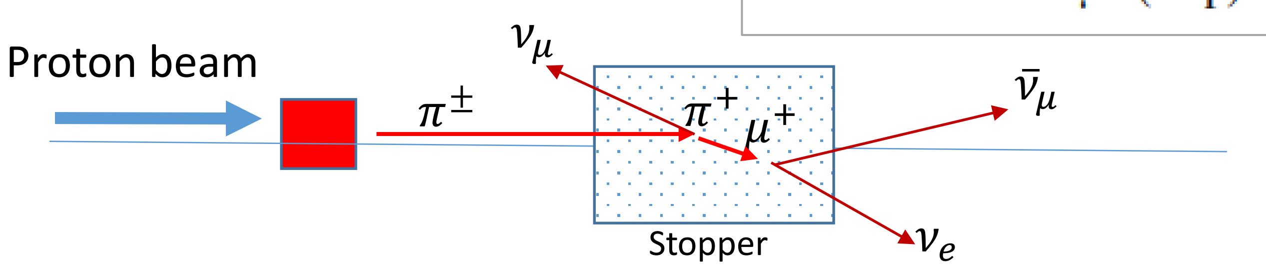
$$\pi^{\pm}(\text{in flight}) \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$



- Decay at Rest

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

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



π^{-} and μ^{-} captured in the beam stopper material

Indications of Sterile neutrinos

Experiment	ν source	Mode	Significance
LSND	Decay-At-Rest	$\nu_\mu \to \nu_e$	3.8σ
MiniBooNE	Decay-In-Flight	$\nu_\mu \to \nu_e$	3.4σ
		$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8σ
		combined	3.8σ
Ga-Solar	e capture	$\nu_e \to \nu_x$	2.7σ
Reactor	β-decay	$\bar{\nu}_e \to \nu_x$	3.0σ

Strong indication at Appearance modes at Accelerator experiment
Reactor/source experiments show indication at Disappearance mode.

However, no positive result at Dis-appearance mode at Accelerator Exp.

LSND experiment

The most significant indication of the sterile ν

$$\pi^+(\text{stop}) \to \mu^+ + \nu_\mu$$ Decay At Rest

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

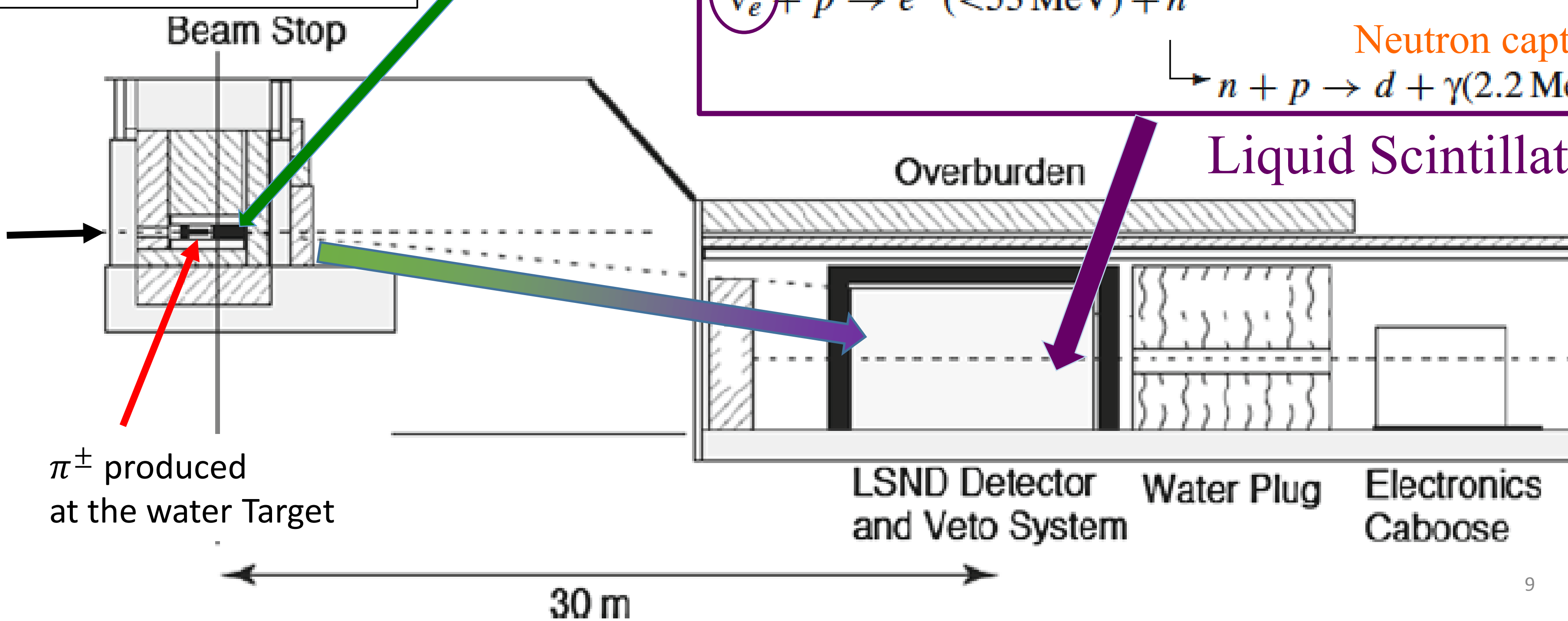
800MeV, proton beam
120Hz, 600μs
Duty factor= **6%**

Inverse β decay (**$\bar{\nu}_e$ only**)

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

Neutron capture

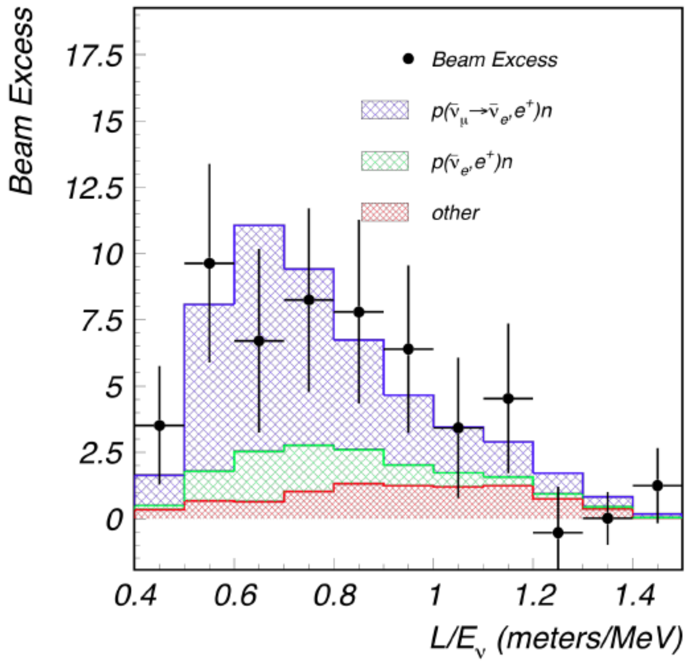
$$\hookrightarrow n + p \to d + \gamma(2.2\,\text{MeV}).$$

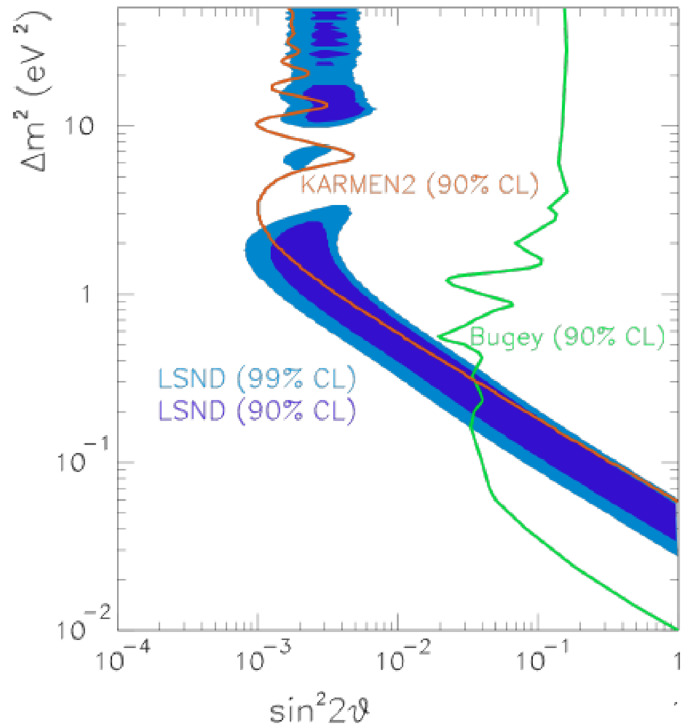


LSND Results

Phys. Rev. D64, 112007 (2001)

Oscillation Parameter





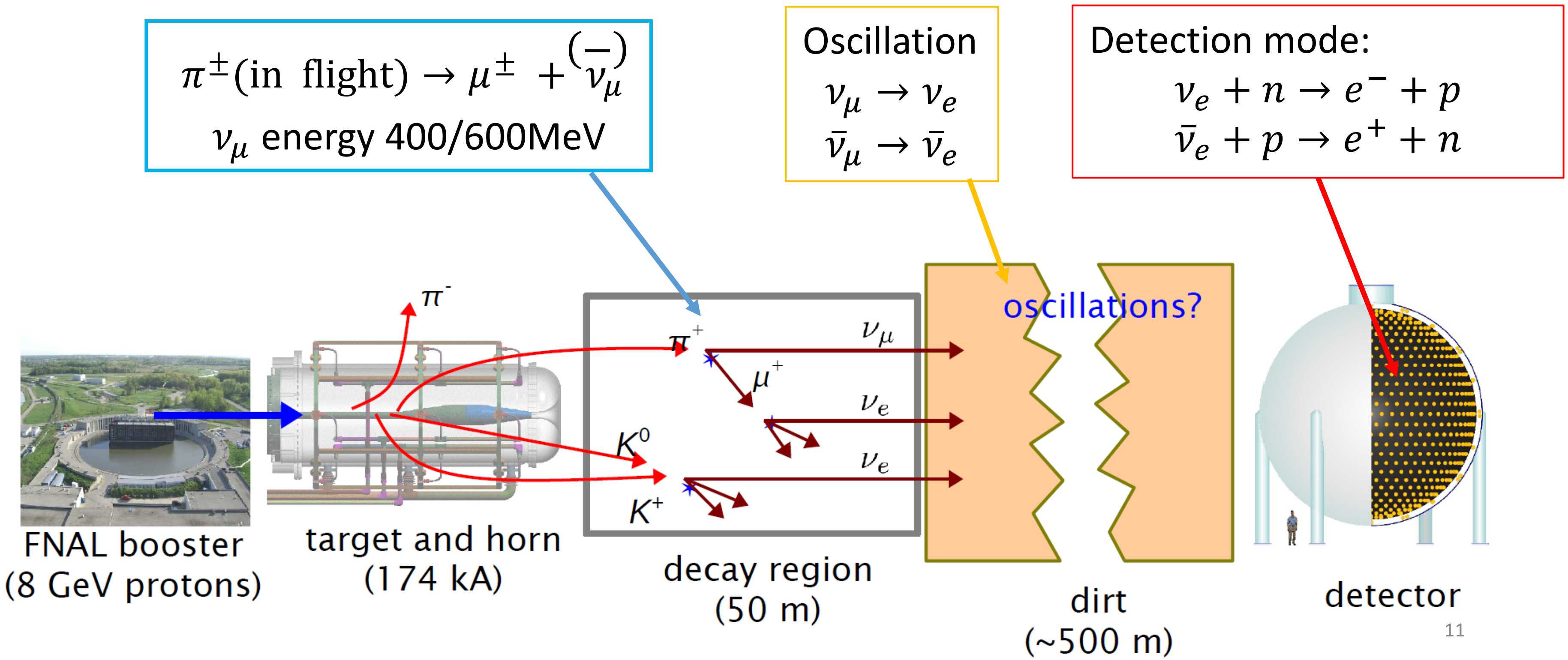
$\bar{\nu}_e$ excess $= 87.9 \pm 22.4 \pm 6.0$ events

To reject beam/cosmic related BG,
many complicated cut were applied.
Unknown systematics may have been introduced.

MiniBooNE experiment

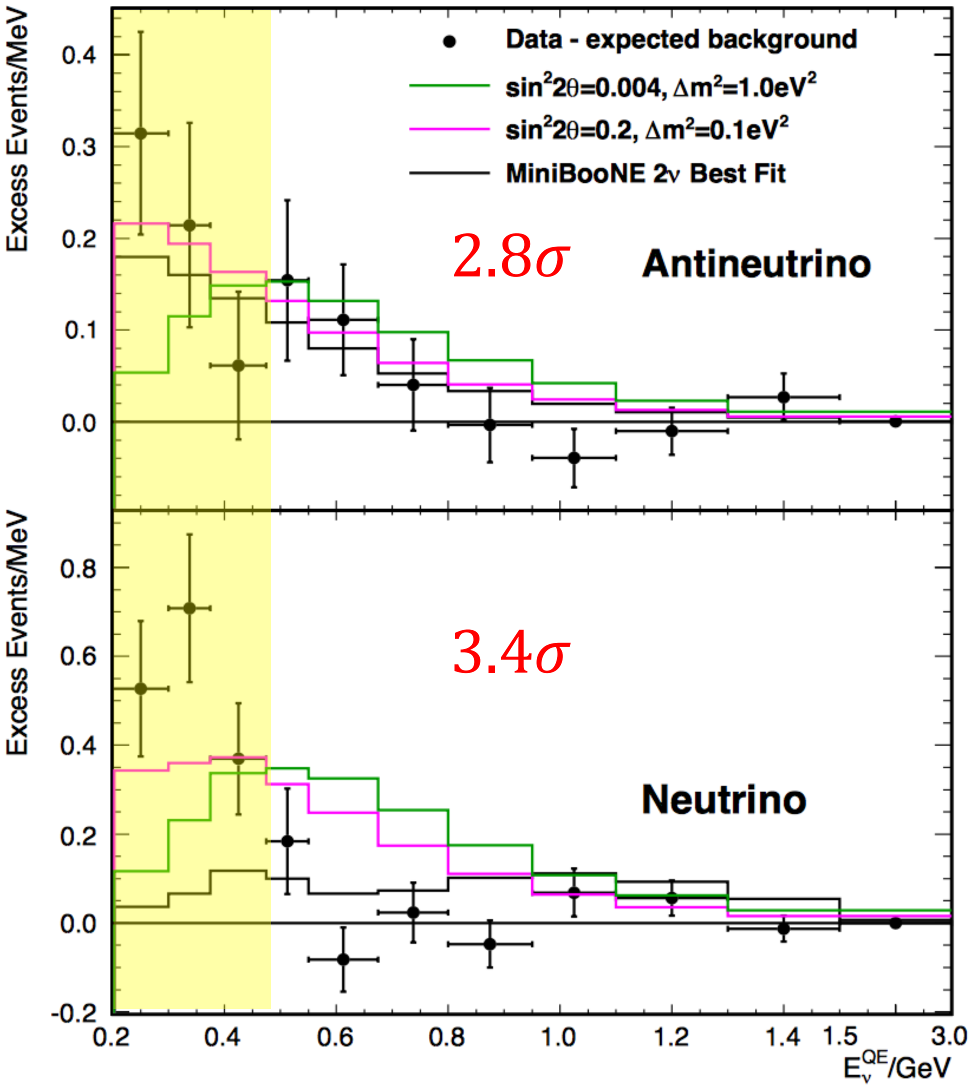
MiniBooNE Detector

- Placed at 500m to preserve LSND results with similar L/E
- 800-ton mineral oil
  - Cherenkov/Scintillation
  - Ring topology to separate e, μ and π^0
  - Can't distinguish e from γ



MiniBooNE results

Phys. Rev. Lett.110, 161801 (2013)



Event excess

$\bar{\nu}$ mode: 78.4 ± 28.5 (2.8σ)

ν mode: 162.0 ± 47.8 (3.4σ)

ν mode case;

Large excess at low energy <475MeV

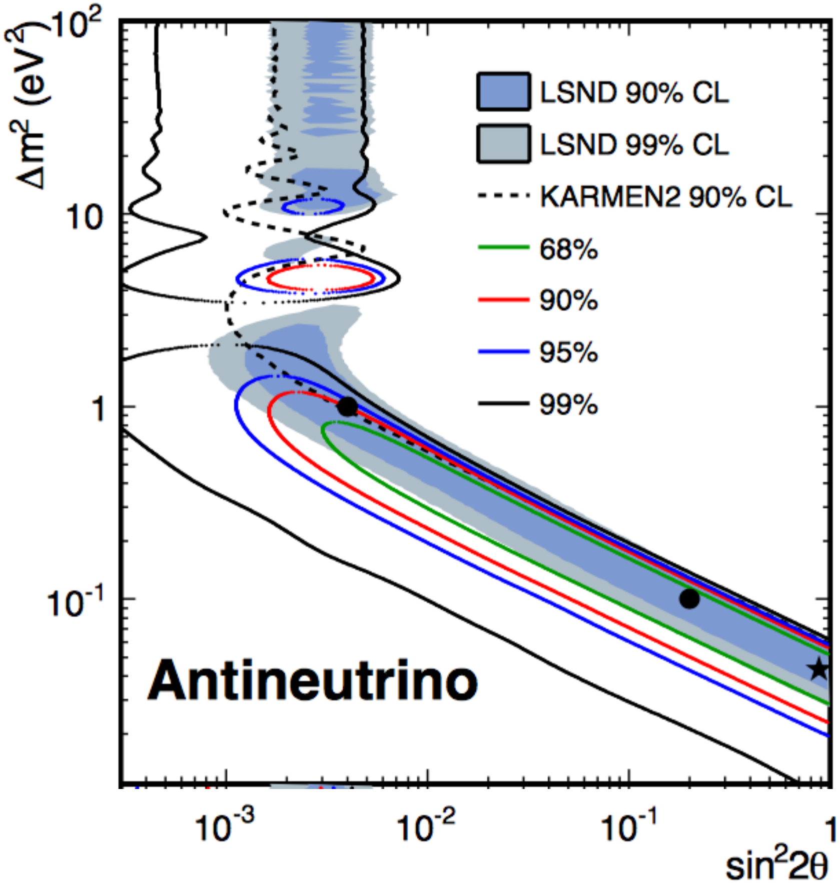
But no excess at higher energy.

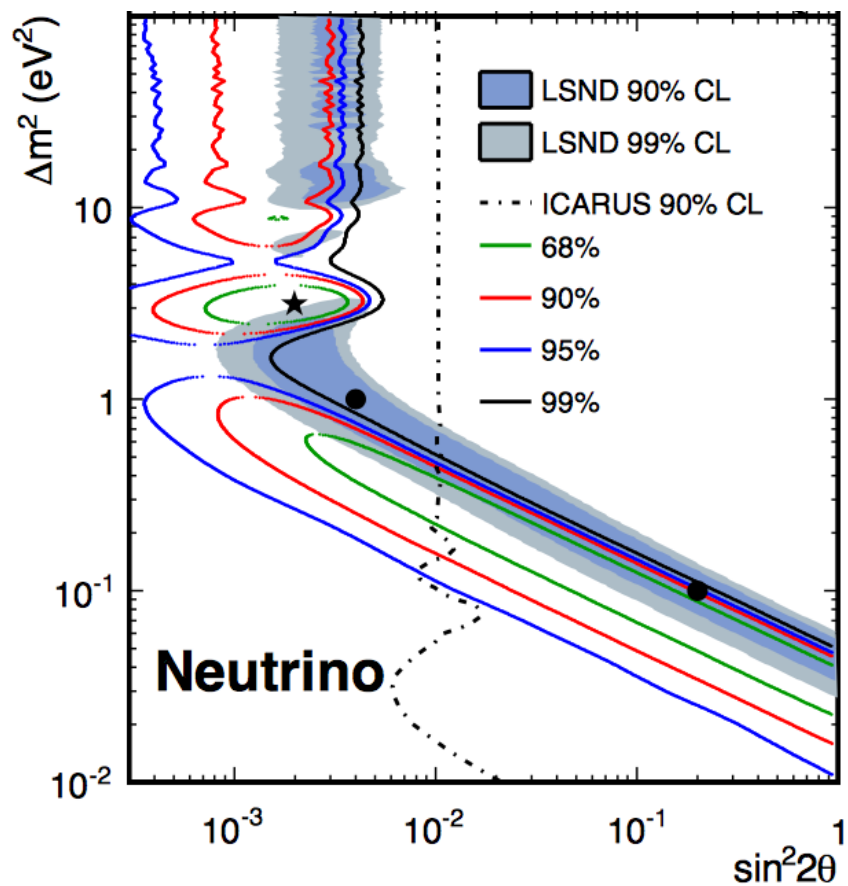
The fit result doesn't explain it?

⇒Due to miss-ID γ as electron?

MiniBooNE/LSND Results Comparison

Phys Rev. D80,073001 (2009)
Phys. Rev. Lett.110, 161801 (2013)



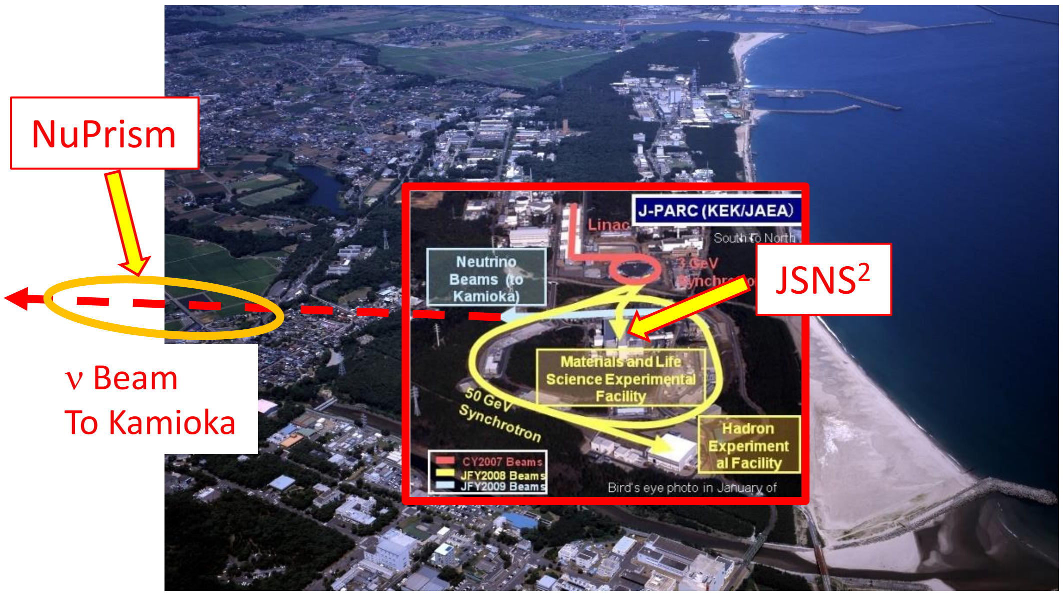


MiniBooNE $\overline{\nu}$ mode is more compatible with LSND result compared with ν mode.
How the difference is explained?

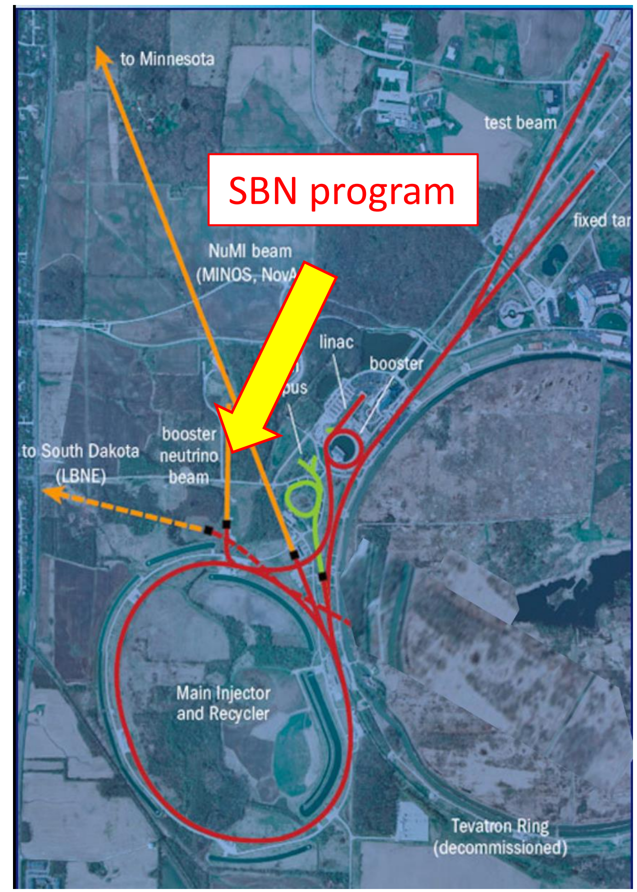
Short baseline accelerator experiments in preparation

LSND/MiniBooNE results should be checked
by accelerator experiment for Appearance/Dis-Appearance mode.

J-PARC(Japan Accelerator Research Complex)



Fermilab Booster ν beam



- **JSNS² @J-PARC/MLF** DAR/Appearance

- **SBN program@FermiLAB BNB**
- **NuPrism@J-PARC / ν -beam line**

DIF/Appearance/Dis-appearance

Direct test of LSND result

TDR released on May 2017

arXiv:1705.08629

JSNS² @J-PARC/Material Life science Facility

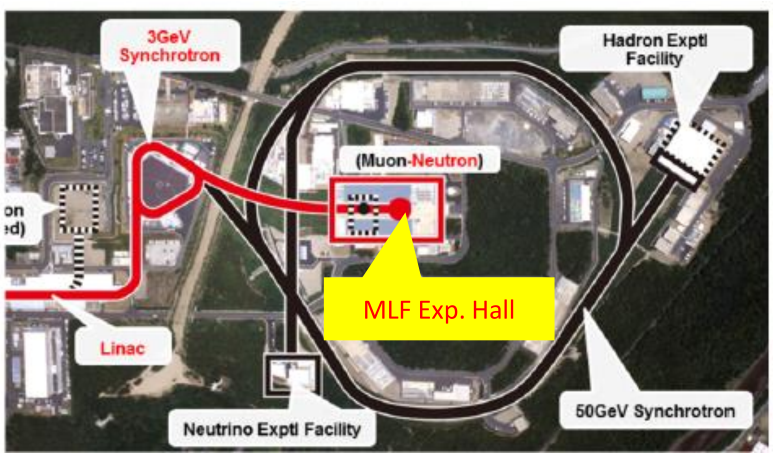
- **Stage-1 approved.**
- **Funded for 1 detector**

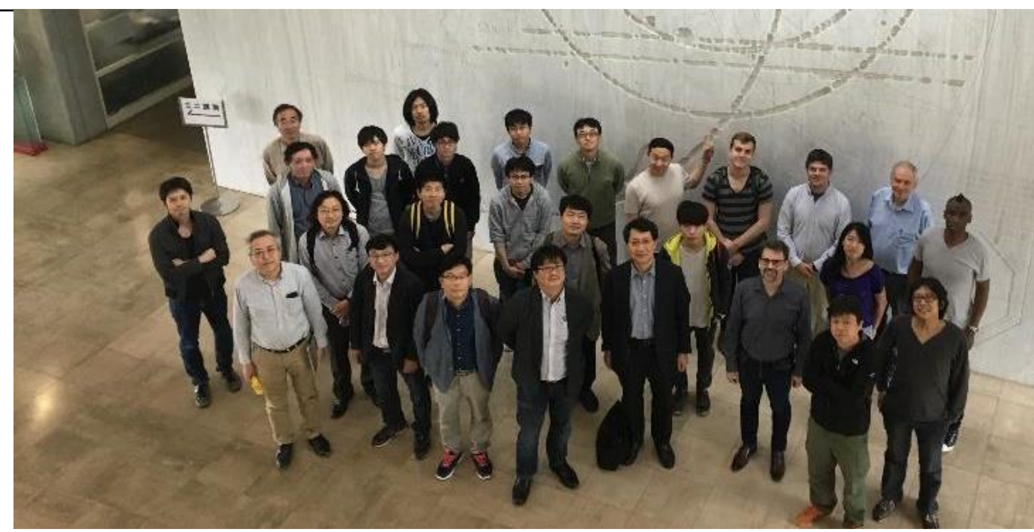
Technical Design Report (TDR):
Searching for a Sterile Neutrino at J-PARC MLF
(E56, JSNS^2)

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], T. Matsubara[4], 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], H. Ray[17], C. Rott[18], K. Sakai[5], S. Sakamoto[5], H. Seo[13], S. H. Seo[13], A. Shibata[7], T. Shima[1], J. Spitz[6], I. Stancu[19], F. Suekane[4], Y. Sugaya[1], K. Suzuya[5], M. Taira[15], W. Toki[20], T. Torizawa[7], M. Yeh[21], and I. Yu[18]

Members experienced at Reactor Exps.
(Daya-Bay, DoubleChooz,RENO)

Consists of
-21 institutes
-53 collaborators
-Japan/US/Korea

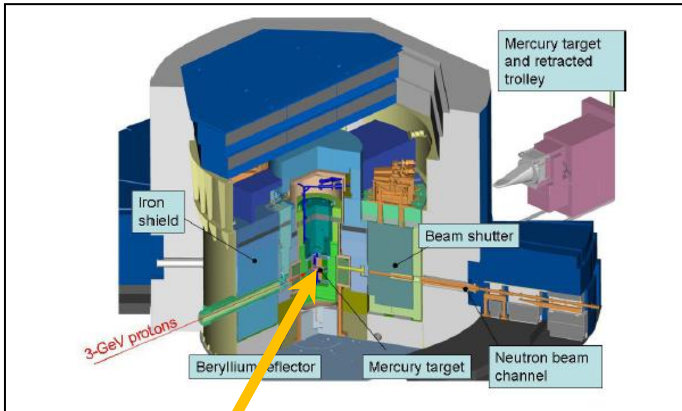




JSNS²: J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source.

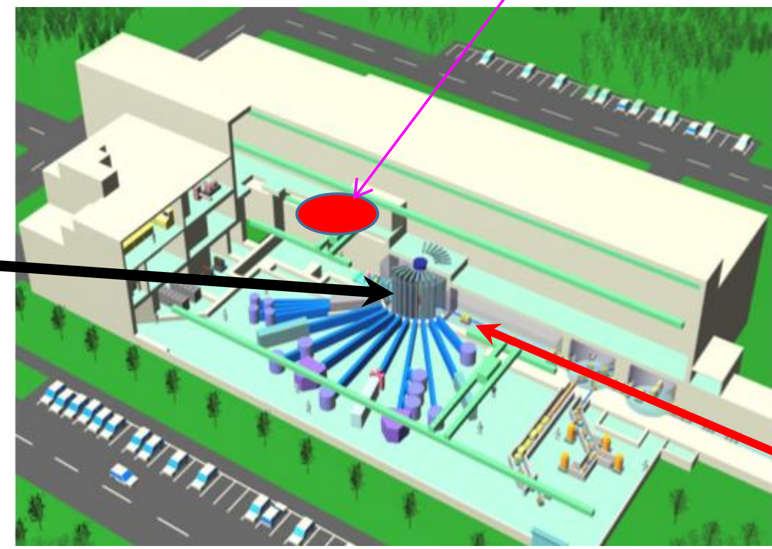
Experimental site: J-PARC MLF

Use existing building and beam facility



Mercury target
（neutron & neutrino source）

Detector positon : 3rd floor (L=24m)



3GeV, 1MW
Proton beam

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

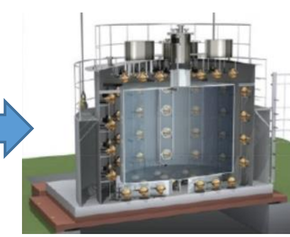
$$\pi^{+}(stop) \rightarrow \mu^{+} + \nu_{\mu}$$

(τ=2.2μs)

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

Oscillation

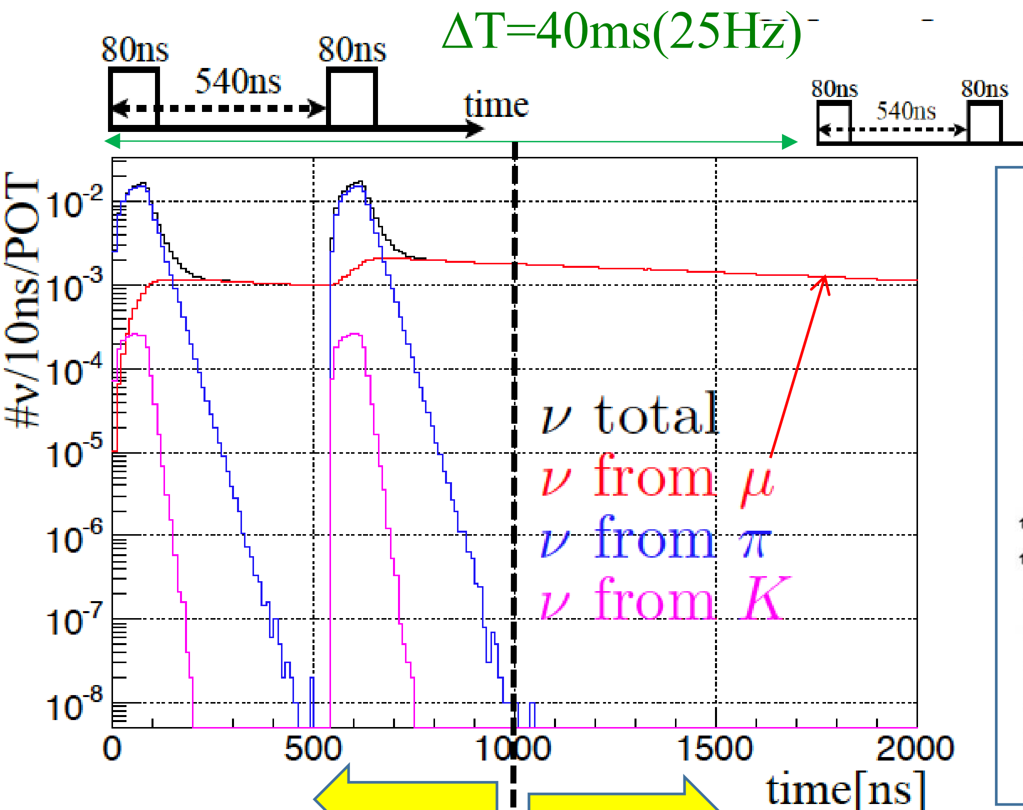
$\bar{\nu}_{e}$



ν source and oscillation mode are same as LSND

Thanks to high-*Z* of *Hg*, $\bar{\nu}_e$ from μ^- decays are suppressed to 1/1,000.

ν beam

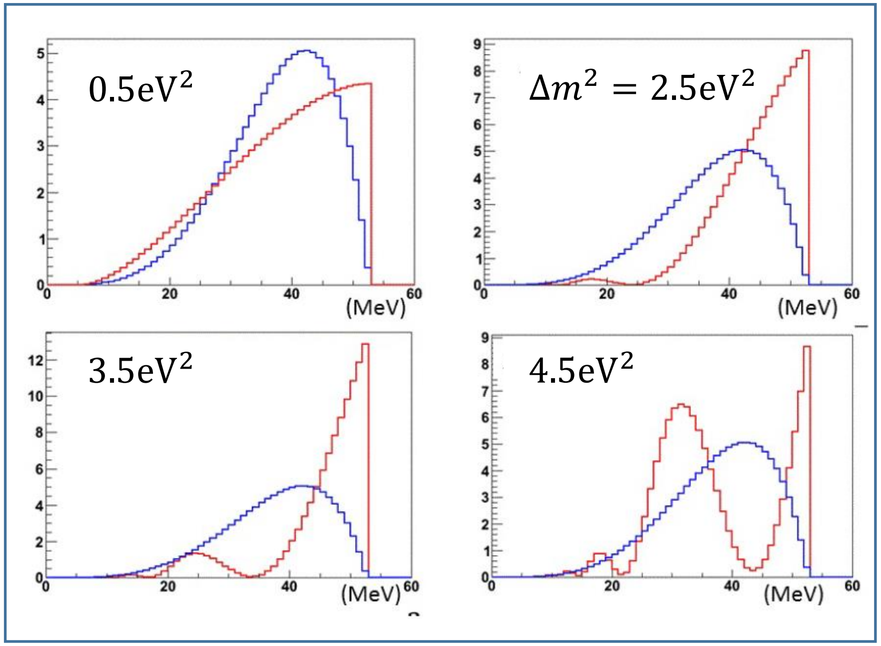


ν from π & K decays

ν from μ decay.

ν timing window =1~10μs

Expected spectrum observed for L=24m



- Signal - $\bar{\nu}_e$ from μ^- (normalized)

Pulsed beam can reduce beam BKG and accidental BKG drastically
Cosmic-ray and accidental BG: suppression factor= 9ms/40ms~2x10^{-4}

JSNS^2:Detector

Gd-loaded Liq. Scintillator 17 tons × 2 (Established for reactor Exp.)

$\bar{\nu}_e + p \rightarrow n + e^+$ (prompt)

$n + {}^{157}Gd \rightarrow {}^{158}Gd + \gamma s$ (delayed; Q~8MeV, τ_{cap}~30μs)

Depends on Gd concentration

253,000b for thermal n

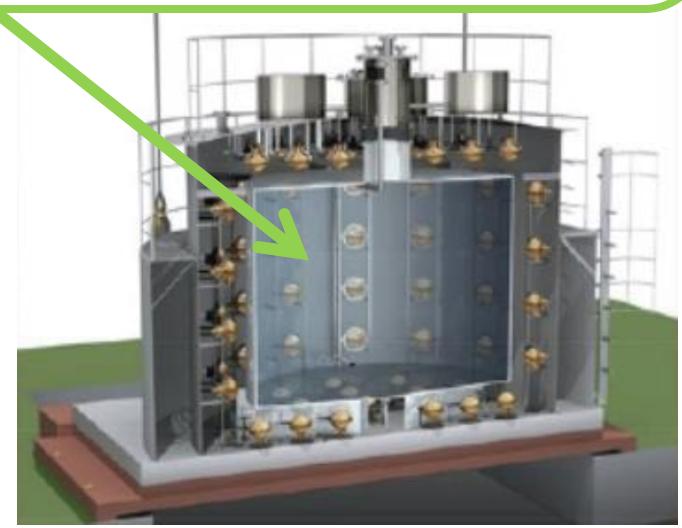
Delayed coincidence

Prompt; t_e=1~10μs, E_e=20~60MeV

Delayed; t_γ=t_p~100μs, E_γ=7~12MeV

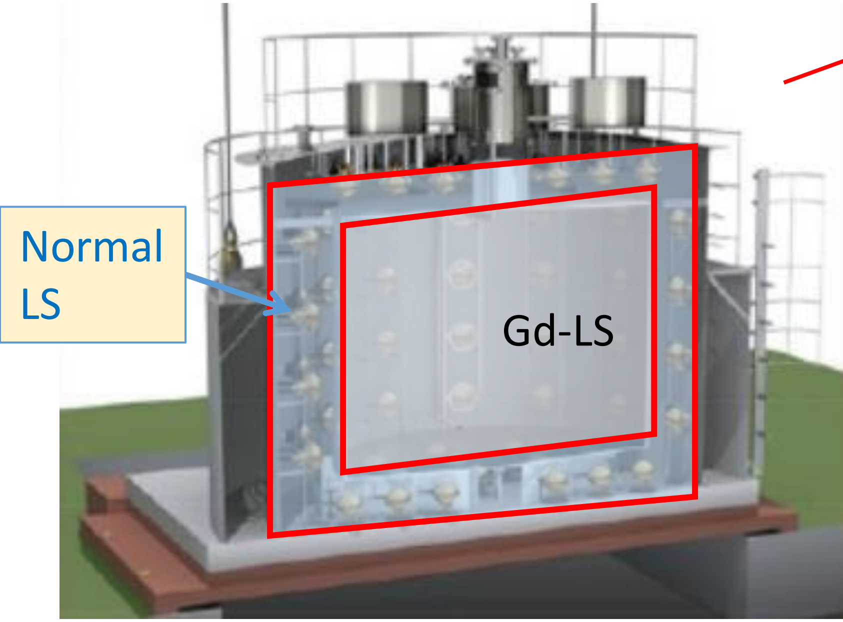
Surface level without overburden

Further BG suppression with PSD (Pulse shape discrimination)



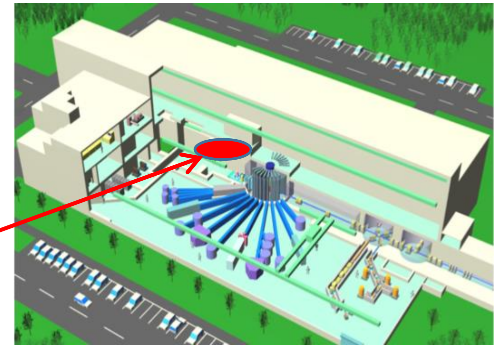
Use 2 of them. (1 detector funded)

JSNS^2:Detector



Use 2 of them. The detector size is limited by Facility requirement.

- Well established technology for reactor experiments.
    - Gd loaded LS in transparent Acrylic tank
    - Normal LS in Stainless Tank
- 200 8-inch PMTs to ensure good Energy resolution
- Huge cosmic induced BG at surface level.
    - LS region is divided to make Veto region.



3rd Floor for MLF maintenance work

Neutron beam lines

Comparison with LSND

- Neutrino beam

	Facility	Beam Pow. [MW]	Rep. Rate [Hz]	Pulse Width [ns]	Duty Factor
JSNS^2	**J-PARC/MLF**	**1**	**25**	**620**	**1.55e-5**
LSND	LANL/LAMPF	0.8	120	6e+5	0.072

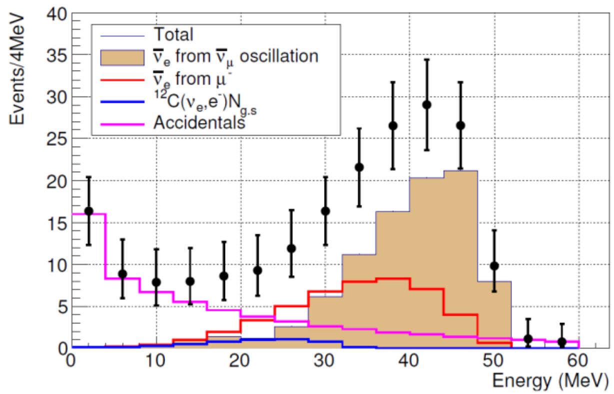
- Detector

	Type	Mass [t]	L [m]
JSNS^2	**Gd-LS with PSD**	**34**	**24**
LSND	LS	167	30

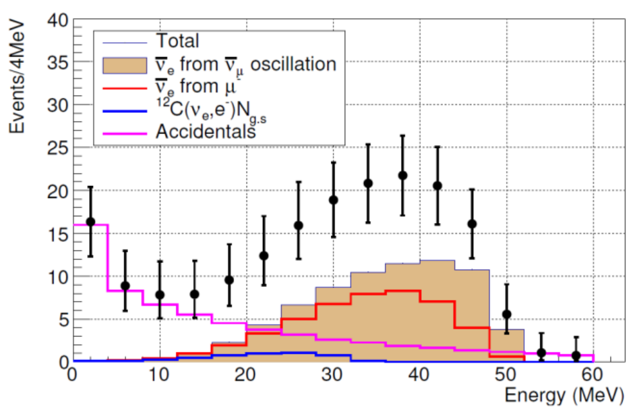
JSNS^2 : S/N > 1,000×LSND

JSNS^2 sensitivity (3y , 1 MW, 17 tons)

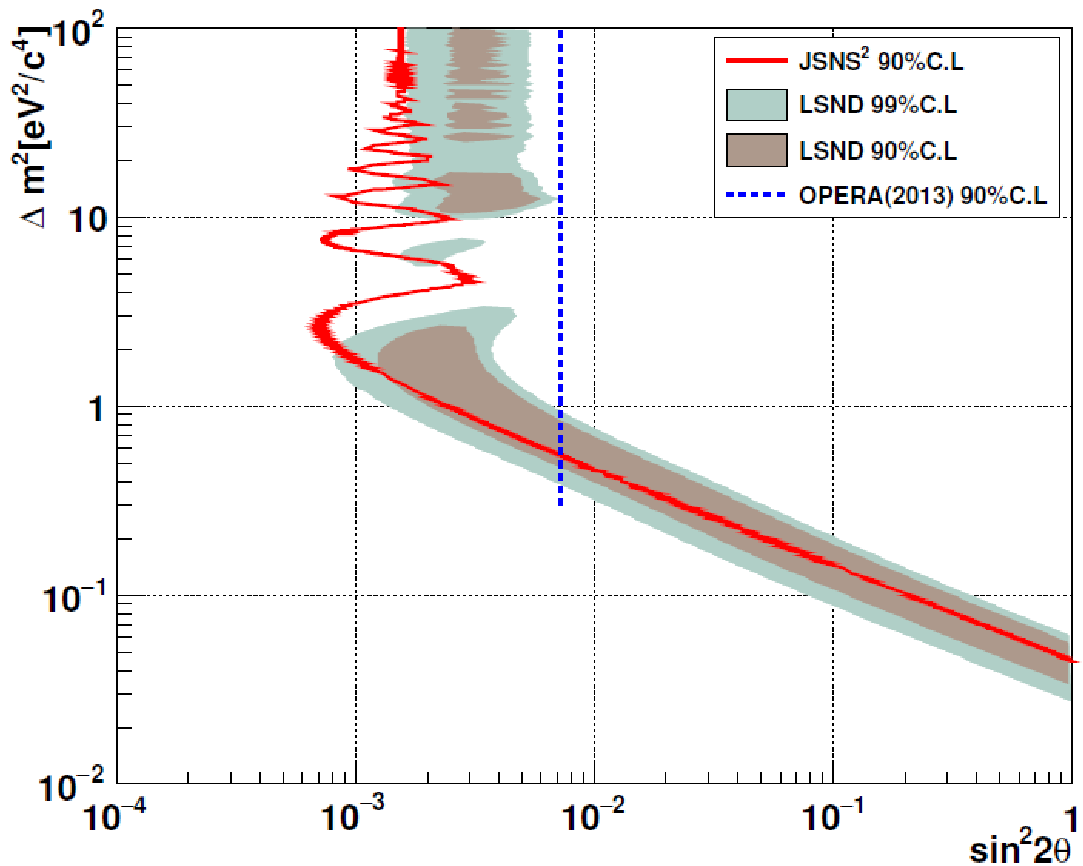
Expected spectrum



Case $\Delta m^2 = 2.5 eV^2, \sin^2 2\theta = 0.003$



Case $\Delta m^2 = 1.2 eV^2, \sin^2 2\theta = 0.003$



Schedule for the 1st Detector (17-ton)

JSNS2 group is now preparing for the 1st detector construction

Japan Fiscal Year (April – March)

Now

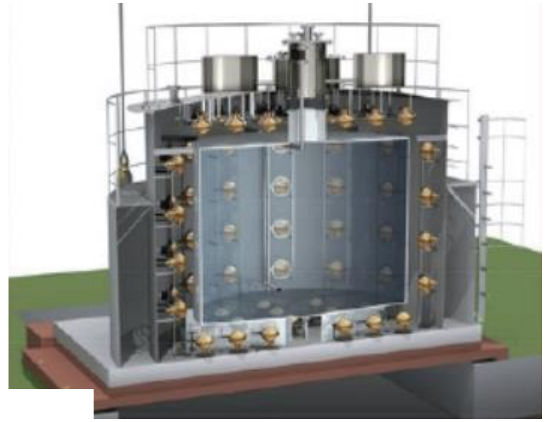
JFY	2017	2018	2019	2020	2021
S.S/Acrylic Tank					
PMT install					
LS production					
Dry run					
LS filling					
Start Exp. Run					

Continuous work for 2nd detector (17t) for increase of statistics and measurement with different baseline.

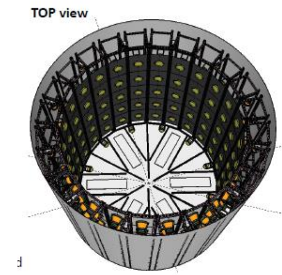
The bidding of Stainless tank was started on June, 2017 !

JSNS^2 status

Work for Detector construction
(from TDR)

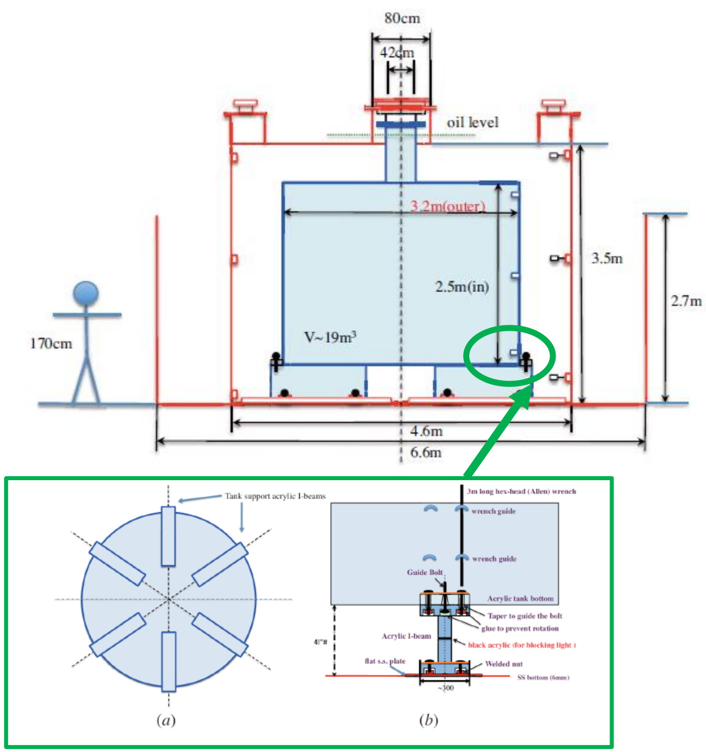


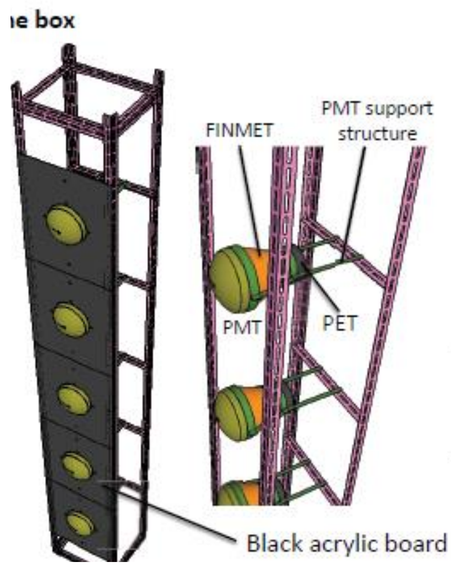
We have experiences
at reactor Expetiments

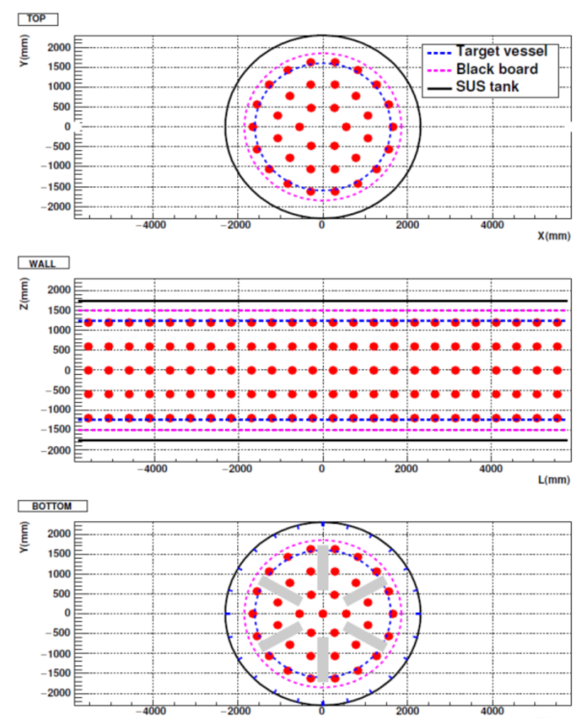


(inner)PMT location

Stainless/Acrylic Tank design







Consideration on Acrylic tank and PMTinstallation to S.S tank.

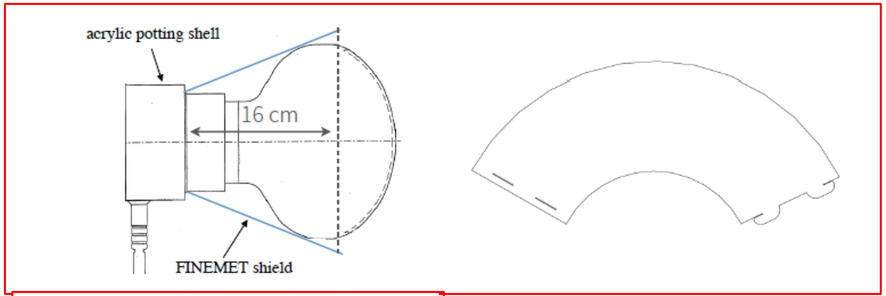
Compatibility tests of material inside Liquid Scintillators.

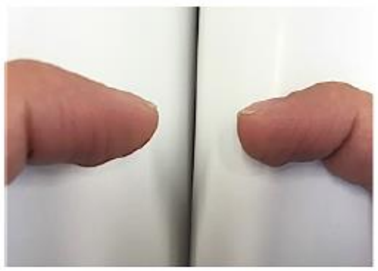
@Tohoku

It is Important to chose the material installed into LS (LAB base).

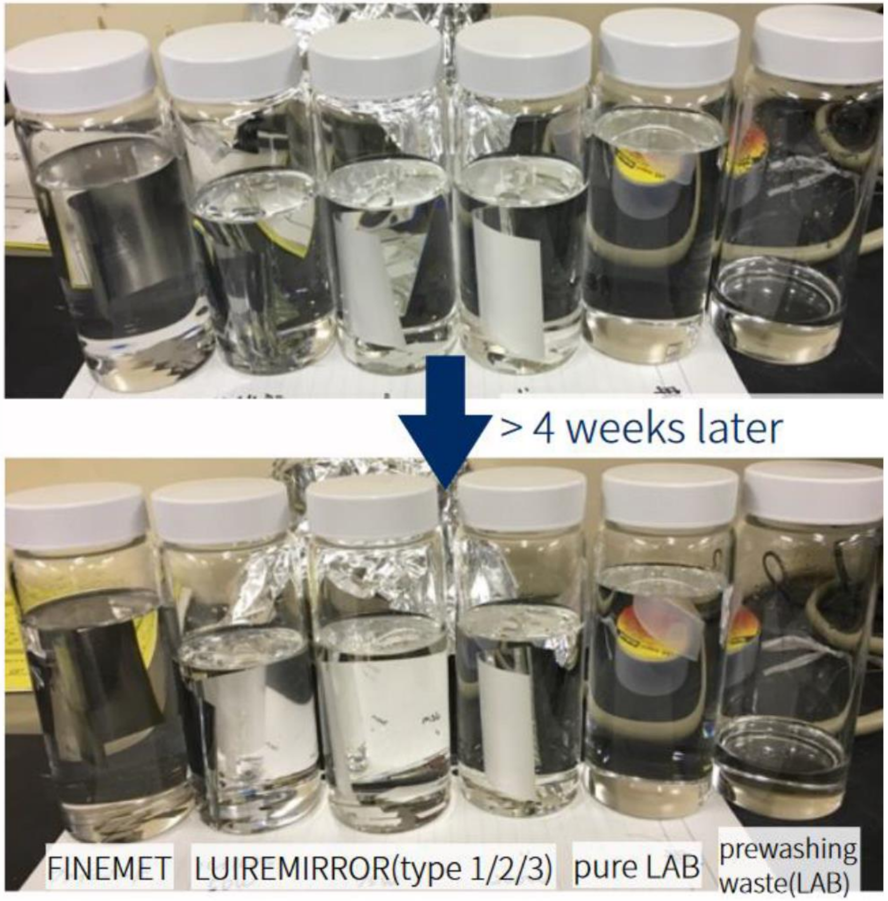
Check attenuation length of the liquids and the condition of the material surface/weight after long soak.

FINEMET for PMT magnetic shield





LUIREMIRROR
for light reflection
at veto region

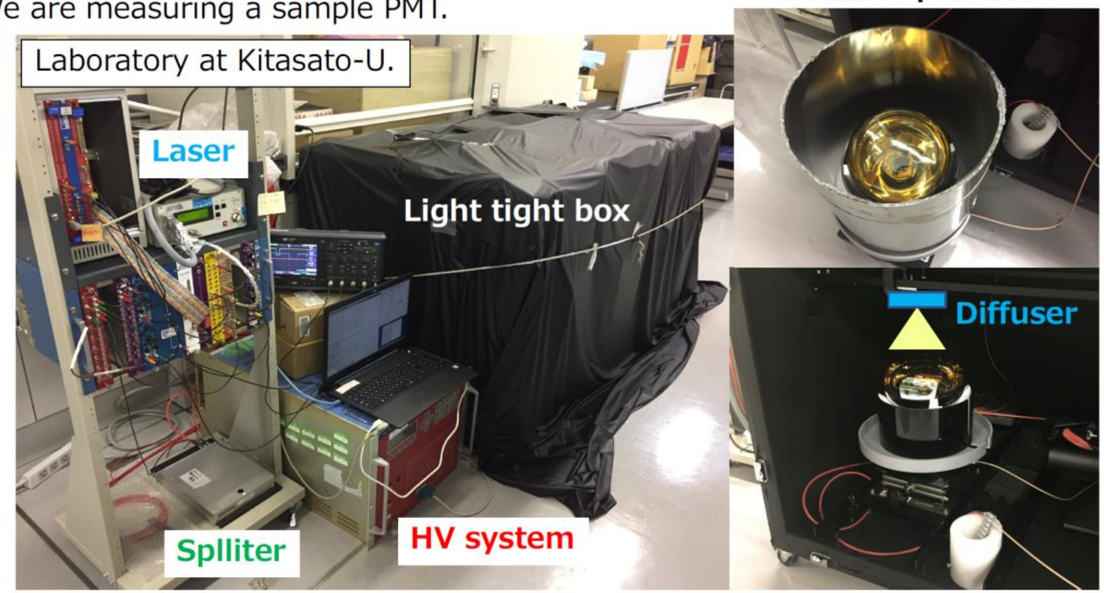


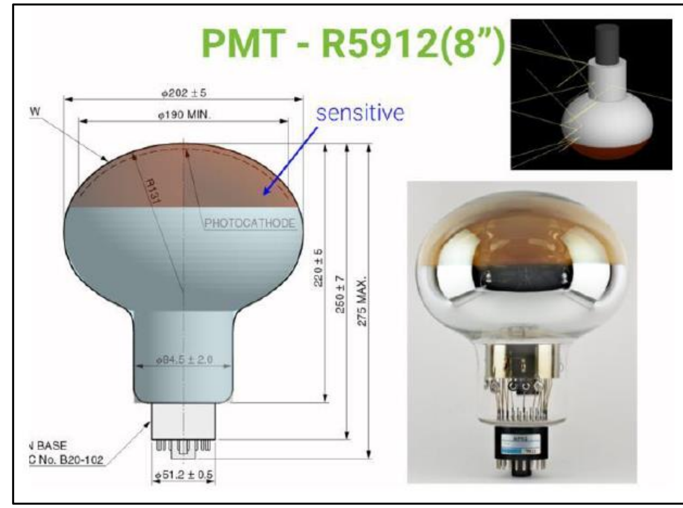
PMT Pre-Test/Calibration

@Kitasato-U

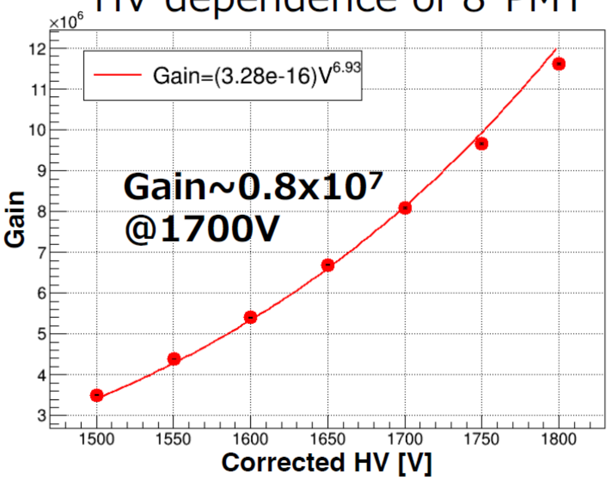
Development has been done.
We are measuring a sample PMT.

8"PMT + μ-metal

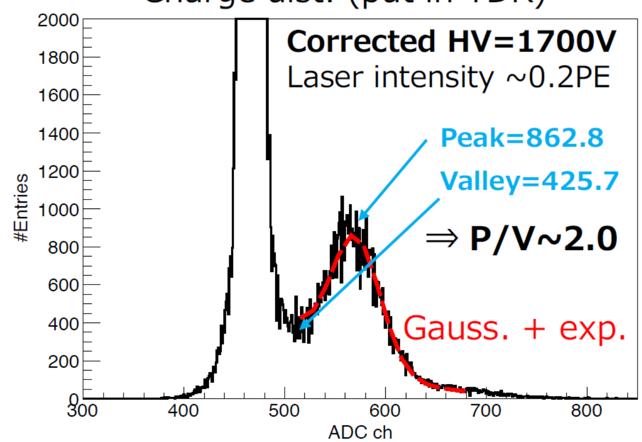




HV dependence of 8"PMT



Charge dist. (put in TDR)



Gain and P/V ratio were measured for PMT candidate.

SBN program@Fermilab

Address MiniBooNE anomaly

- Funded
- Booster neutrino Beam ~700MeV
  - L/E ~ 1km/GeV

- Use 3 Liquid Argon TPCs(100-600t)
  - Good separation e/γ
  - Study ν-LAr cross section
  - Further development for DUNE

- Sensitive to sterile oscillation
  - $\nu_\mu \rightarrow \nu_e$ appearance
  - $\nu_\mu \rightarrow \nu_\mu$ dis-appearance

I borrowed the slides from
* D.Schnitz @Neutrino2016

arXive:
1503.01520

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

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The Three LArTPC SBN Program

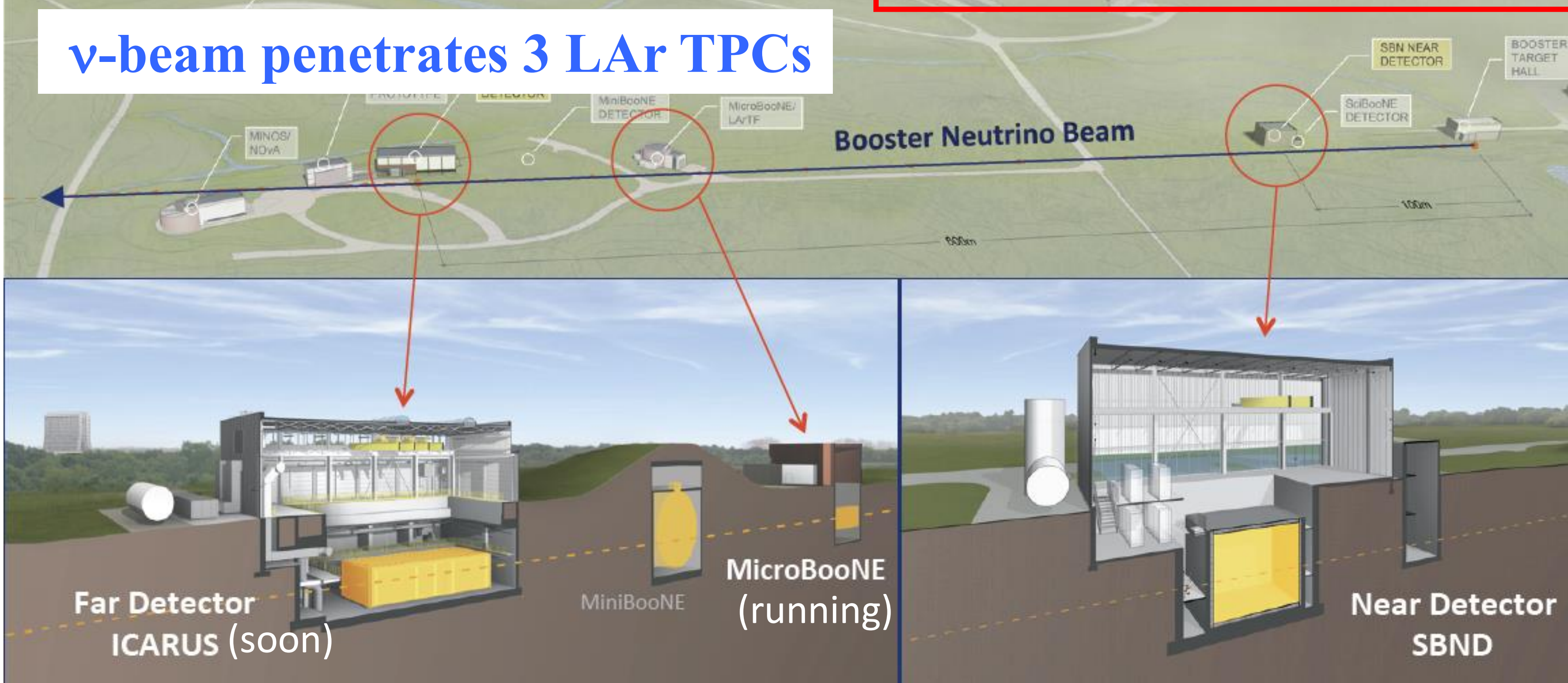
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

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
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

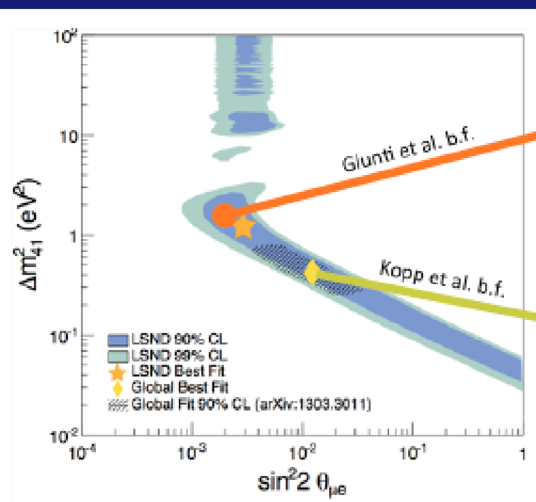
ν-beam penetrates 3 LAr TPCs

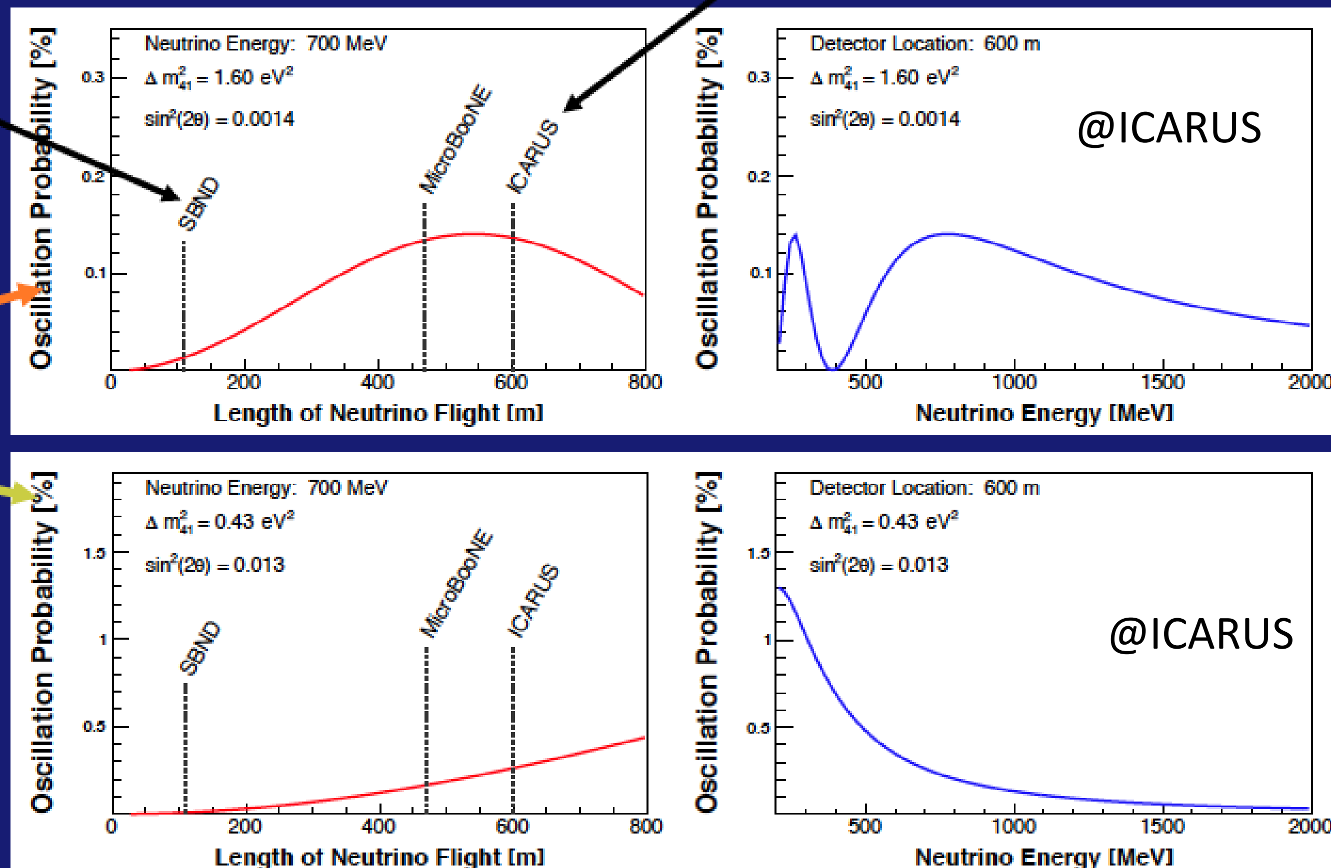


- SBN will apply the advantages of the LArTPC technology and *multiple detectors at different baselines* to the question of high-Δm^2 **sterile neutrino oscillations** to definitively test currently allowed oscillation parameter regions at ≥5σ

increase **statistics** of signal

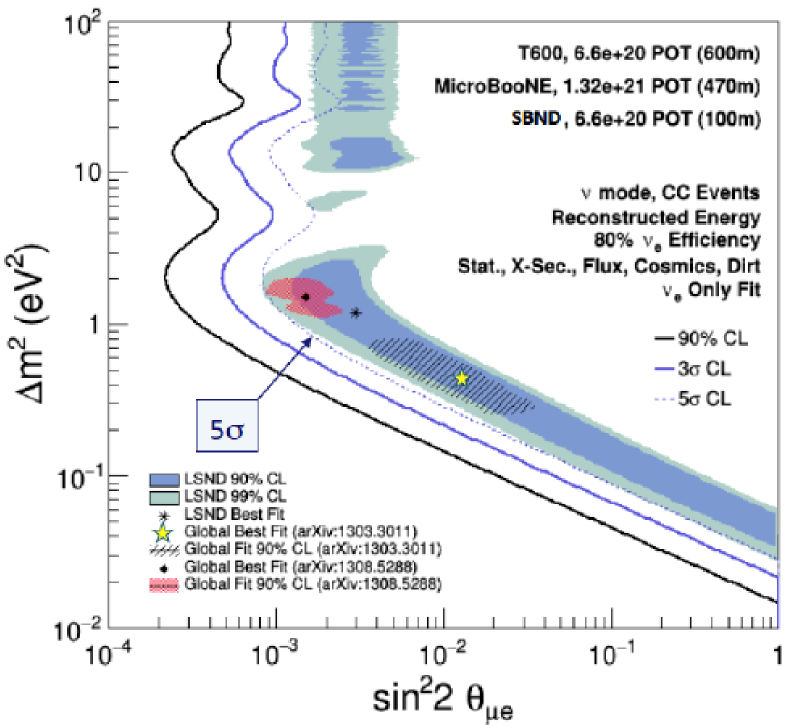
control **systematics**



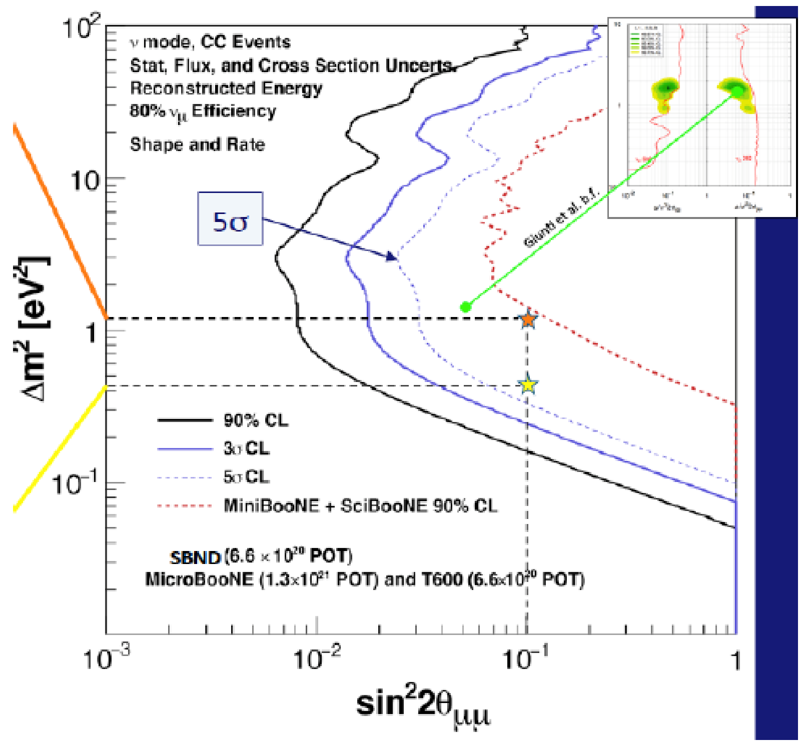


Sensitivities for sterile ν oscillations(3yrs)

$\nu_\mu \rightarrow \nu_e$ appearance



$\nu_\mu \rightarrow \nu_\mu$ disappearance



NuPrism@J-PARC neutrino beamline

Stage1 approved

Proposal for the NuPRISM Experiment in the J-PARC Neutrino Beamline

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(The NuPRISM Collaboration)

https://j-parc.jp/researcher/Hadron/en/pac_1507/pdf/P61_2015-5.pdf

- Use movable detector in a shaft hole
  - Water Cherenkov, ~1000 ton (depends on baseline)
  - Baseline :1-2km (not fixed yet)
  - Study ν – nuclear interaction with various energy
- It is sensitive to sterile ν oscillation
  - Both appearance/dis-appearance mode

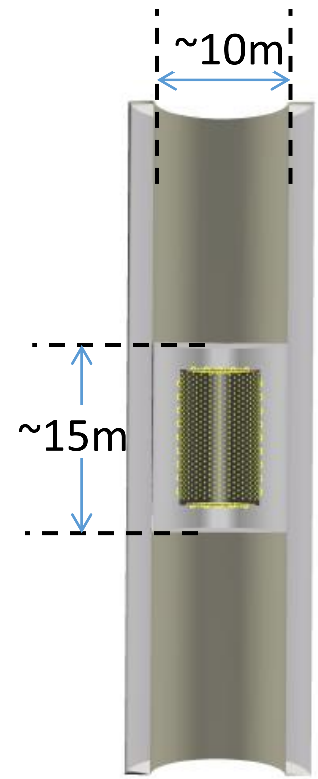


FIG. 39. The planned configuration of the nuPRISM detector within the water tank is shown. The instrumented portion of the tank moves vertically to sample different off-axis angle regions.

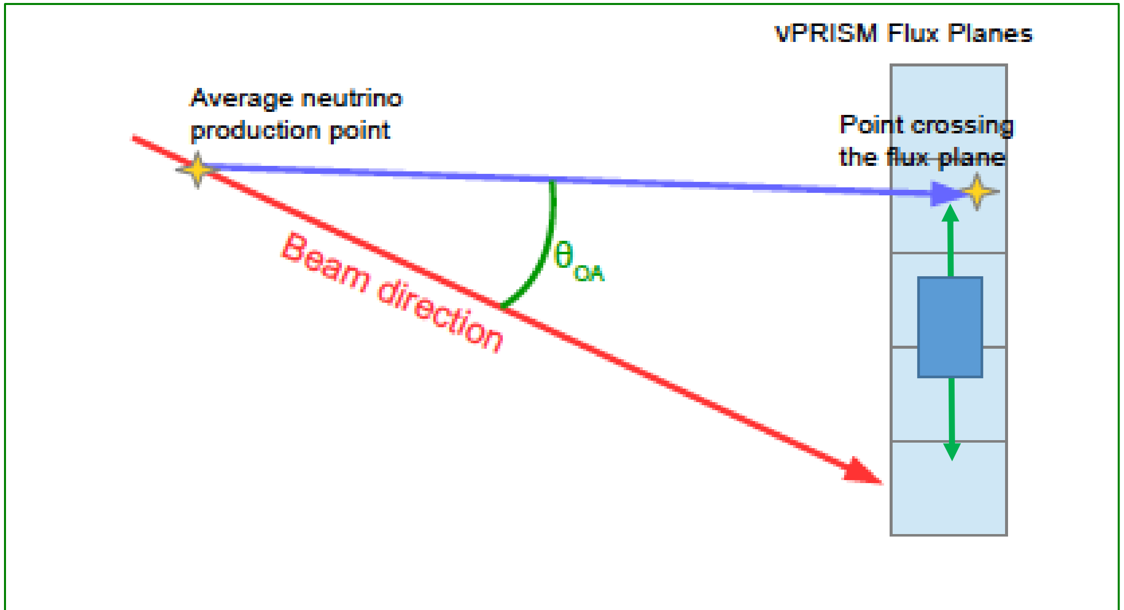
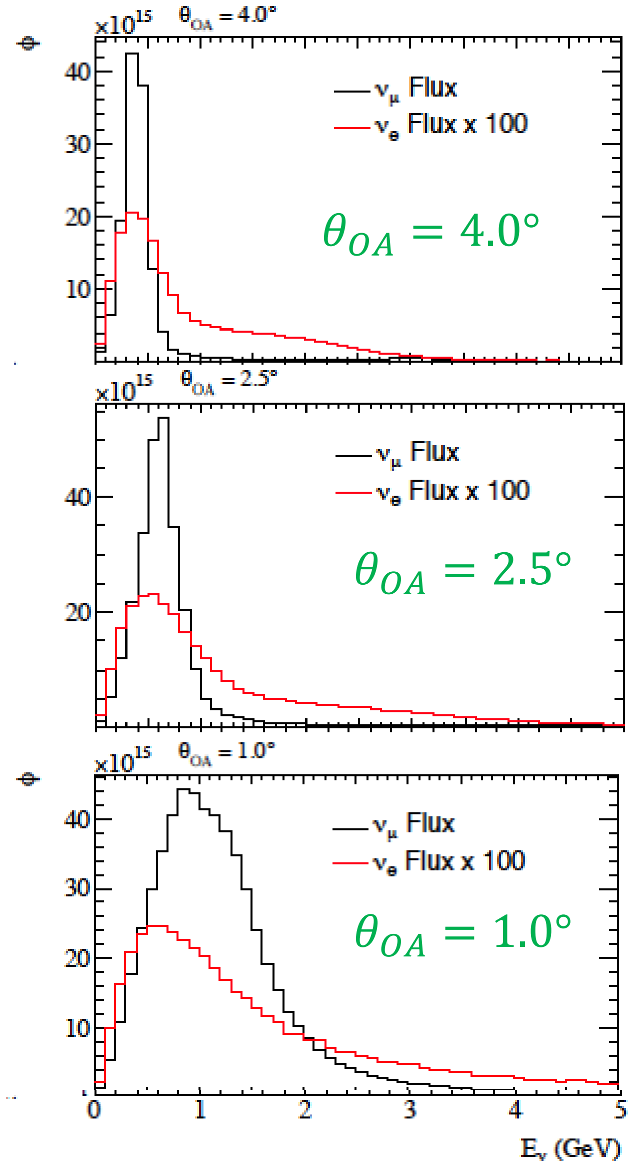


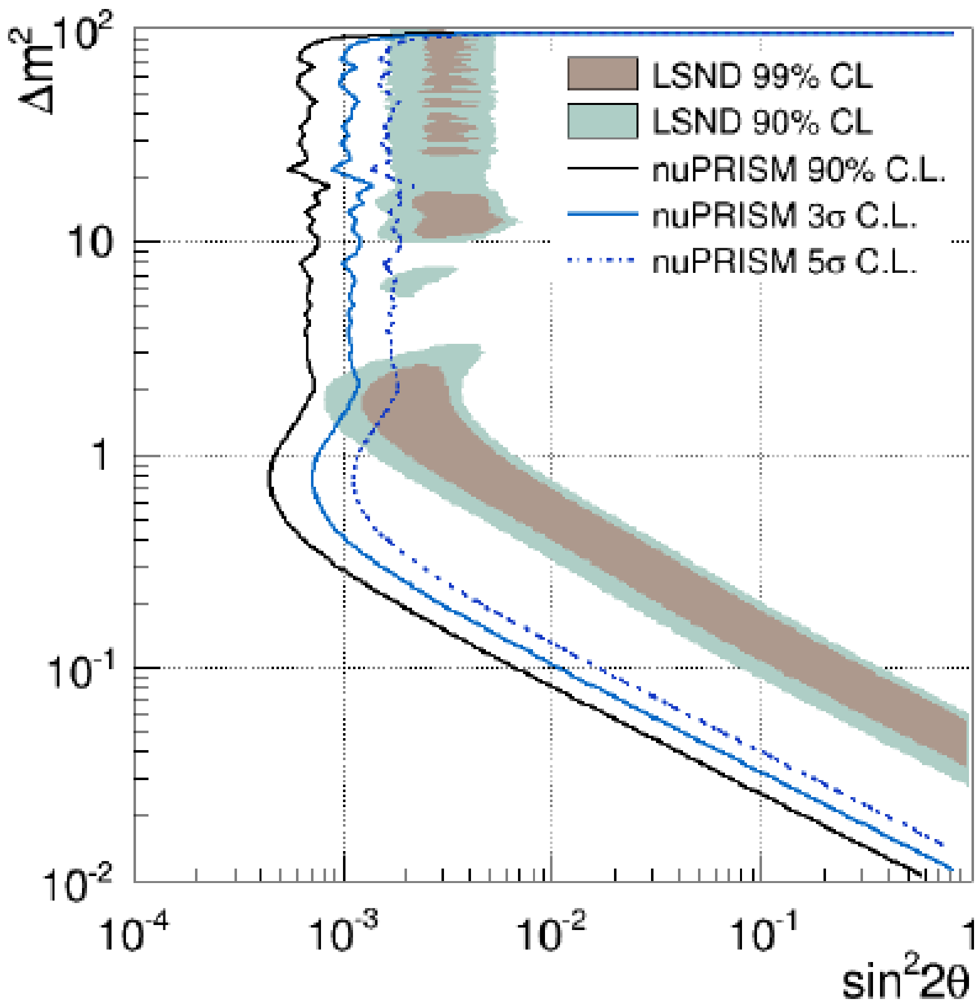
FIG. 6. The definition of the off-axis angle for individual neutrinos.



With Off-axis beam technique.
Large angle gives sharp E_ν distribution.

Change Off-Axis angle
by moving detector in a shaft,

NuPRISM: sterile ν sensitivity



T2K II exposure(2e21 POT)
ν_e appearance mode

Comparison of the future projects

	JSNS2	SBND/mBooN/ICARUS	nuPRISM
Accelerator	J-PARC/MLF	Fermilab BνB	J-PARC/ν
E_ν[MeV]	~50	~700	500~1500
ν source	μ^+ DAR	π^+ DIF	π^+ DIF
L[m]	23	110/470/600	1000~2000
Osc. mode	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\mu$	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$, $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
Detector	Gd-LS	LAr-TPC	Water Cherenkov
Fid. Mass(t)	17(phase0)	112/87/476	1000(depnds on L)
Characteristic	Direct Test of LSND	Full ν-Ar interaction reconstruction. Near/Far cancellation	Wide range semi-monochromatic ν
Status	funded for 1detector	funded	stage-1 approval
Commissioning	2018~9	2018~9/2015/2018	-
Cost	$	$$$	$$$

Summary

- There are some indications of sterile neutrinos
  - Significant at LSND/MiniBooNE: Δm^2~O(eV) at ν_e appearance mode
  - Reactor/Source Exp. also show it in ν_e dis-appearance mode

- SBL Accelerator experiments are sensitive to $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_x$
  - Experiments are in preparation
    - JSNS2@J-PARC is funded for 1 detector
    - SBN@FermiLAB is funded and will start soon
  - Those are complementary to the reactor/source experiments

- The interesting results will appear in a few years.