Neutrino Oscillation & Sterile Neutrino Experiment JSNS^2

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Flow of this Seminar

Part-I

*** Neutrino Oscillation**

*** Oscillation parameter measurements**

- **Status**
- **Future**

Part-II

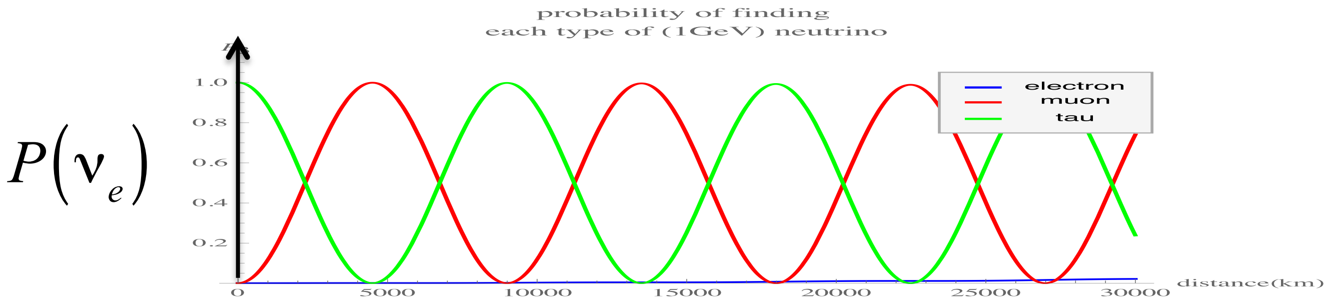
*** Sterile Neutrino experiments at $JSNS^2$**

- **Introduction**
- **Plan**

What is Neutrino Oscillation?

Electron stays as electron while it travels in space.

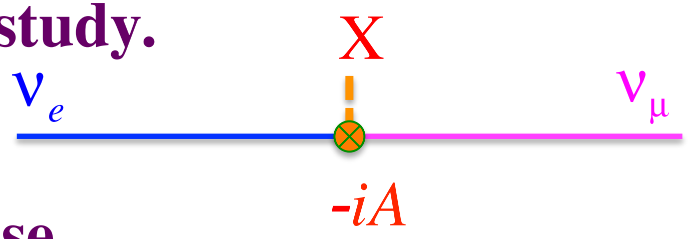
However, neutrinos change their flavors periodically.



This phenomenon is called neutrino oscillation

What causes the neutrino to oscillate?

We do not know yet.
In order for N.O. to happen, something(X) has to change the neutrino flavor. To know what is X is the important purpose of N.O. study.



"*A*" indicates the strength of the transition (amplitude).

In this case

*** State equation:**
(flavor transition rate)

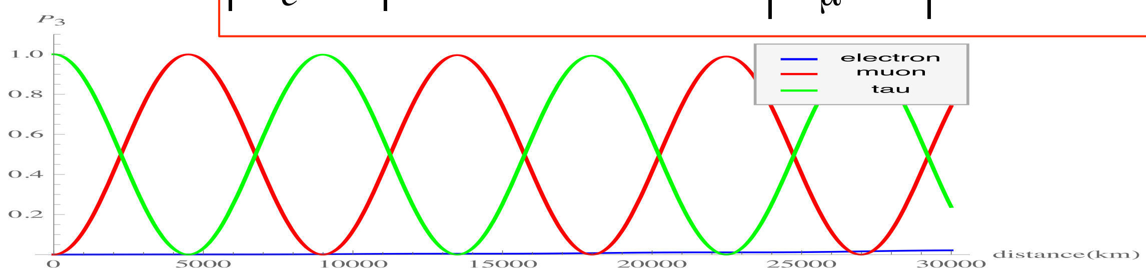
$$\frac{d}{dt}\nu_e = -iA\nu_\mu, \quad \frac{d}{dt}\nu_\mu = -iA\nu_e$$

*** Initial condition:**
(if started as ν_e)

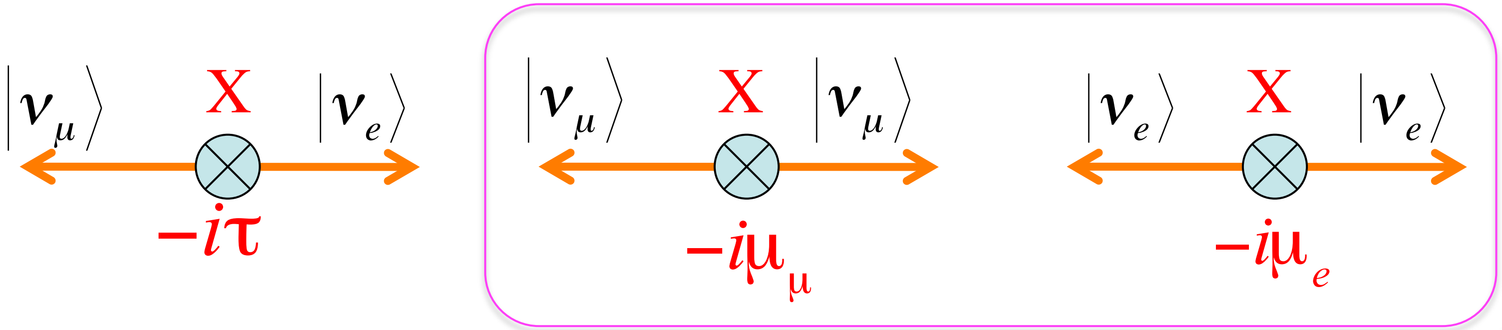
$$\nu_e[t=0]=1, \quad \nu_\mu[t=0]=0$$

*** Oscillation:**

$$\left|\nu_e[t]\right|^2 = \cos^2 At, \quad \left|\nu_\mu[t]\right|^2 = \sin^2 At$$



General transition amplitudes & mass eigenstates

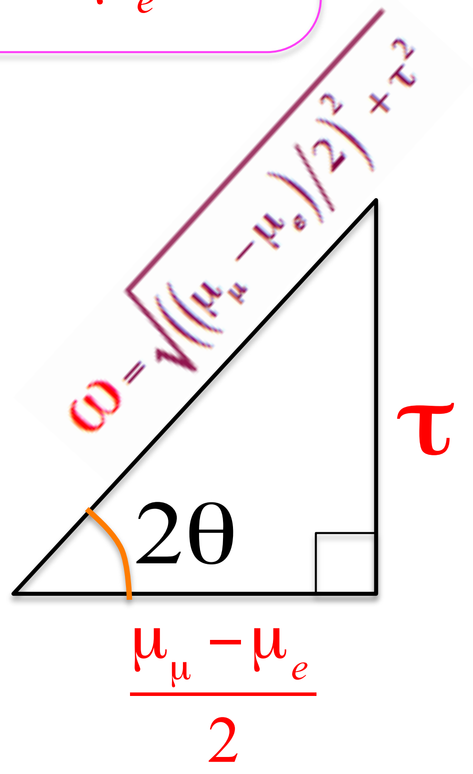


If there are self-transitions,
The mass eigenstate becomes

$$\begin{cases} \nu_1[t] = \left(\cos\theta|\nu_e\rangle - \sin\theta|\nu_\mu\rangle\right)\exp[-im_1 t] \\ \nu_2[t] = \left(\sin\theta|\nu_e\rangle + \cos\theta|\nu_\mu\rangle\right)\exp[-im_2 t] \end{cases}$$

The neutrino masses are

$$m_1 = \frac{\mu_\mu + \mu_e}{2} - \omega, \quad m_2 = \frac{\mu_\mu + \mu_e}{2} + \omega$$

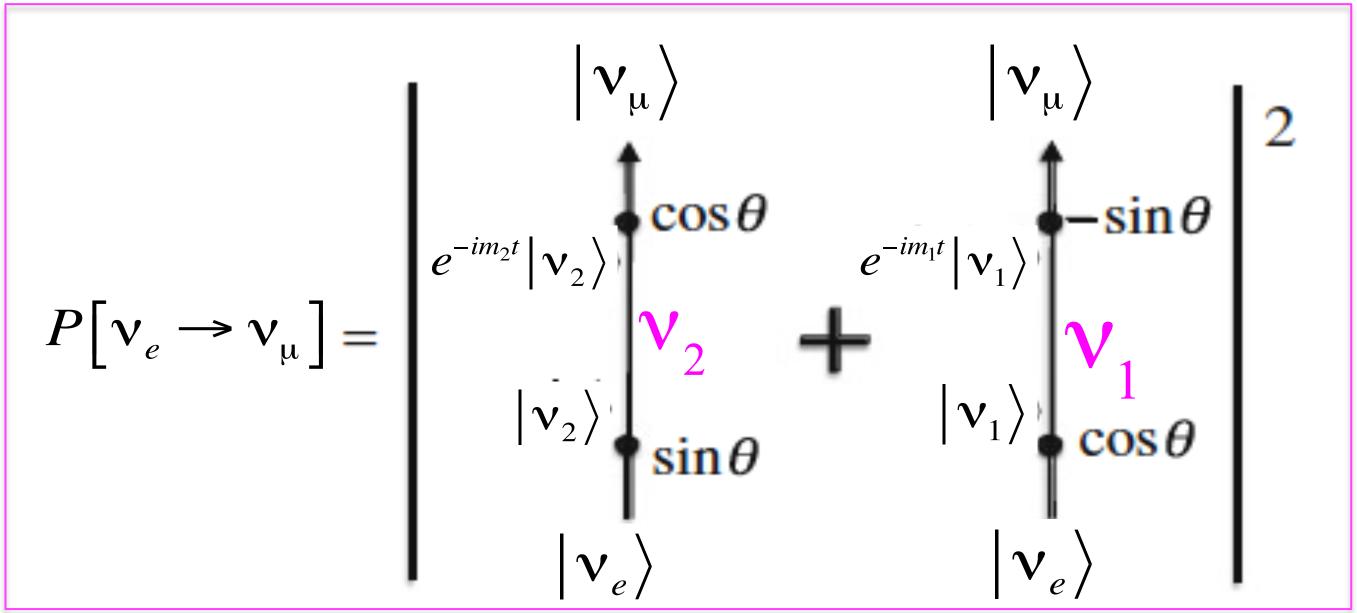


Mixing triangle

ν oscillation

A Q.M. principle: Probability for something to happen is the absolute square of the sum of amplitudes of all possible diagrams.

The probability of $\nu_e \to \nu_\mu$



$$= \left| \sin\theta\cos\theta e^{-im_2t} - \sin\theta\cos\theta e^{-im_1t} \right|^2$$

$$= \sin^2 2\theta \sin^2 \frac{m_2 - m_1}{2} t$$

Oscillation in time

Relativistic Neutrino Oscillation

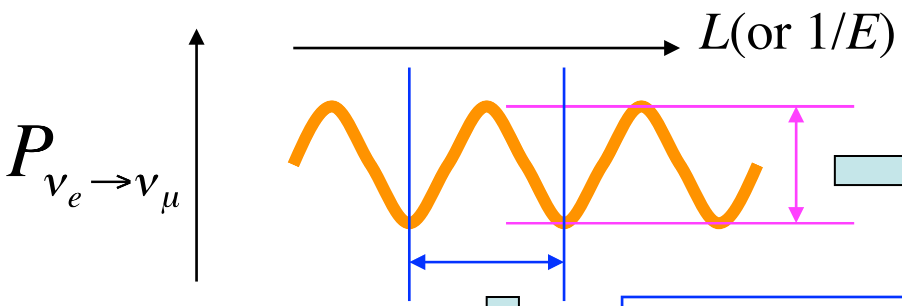
In experimental condition, neutrino is traveling relativistic

Lorentz Boost $(\gamma = E/m)$

$$mt \to m\frac{t}{\gamma} = \frac{m^2}{E}t = \frac{m^2 L}{E}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$

What we can measure,



Amplitude ==>$\sin^2 2\theta = (\tau/\omega)^2$

Frequency => $\Delta m^2 = |m_2^2 - m_1^2| = 4\bar{\mu}\omega$

Why we measure ν oscillations?

There are many oscillations (irrespective to it is observable or not).

* $K^0 \Leftrightarrow \overline{K^0}$ oscillation. ➔ CP violation
* $|u\bar{u}\rangle \Leftrightarrow |d\bar{d}\rangle$ oscillation in π^0, ρ, etc. ➔ Hadron mass pattern
* Cabbibo angle, quark mass ← $d \Leftrightarrow s$ oscillation
* Weinberg angle, W, Z^0 mass ← $B \Leftrightarrow W_3$ oscillation

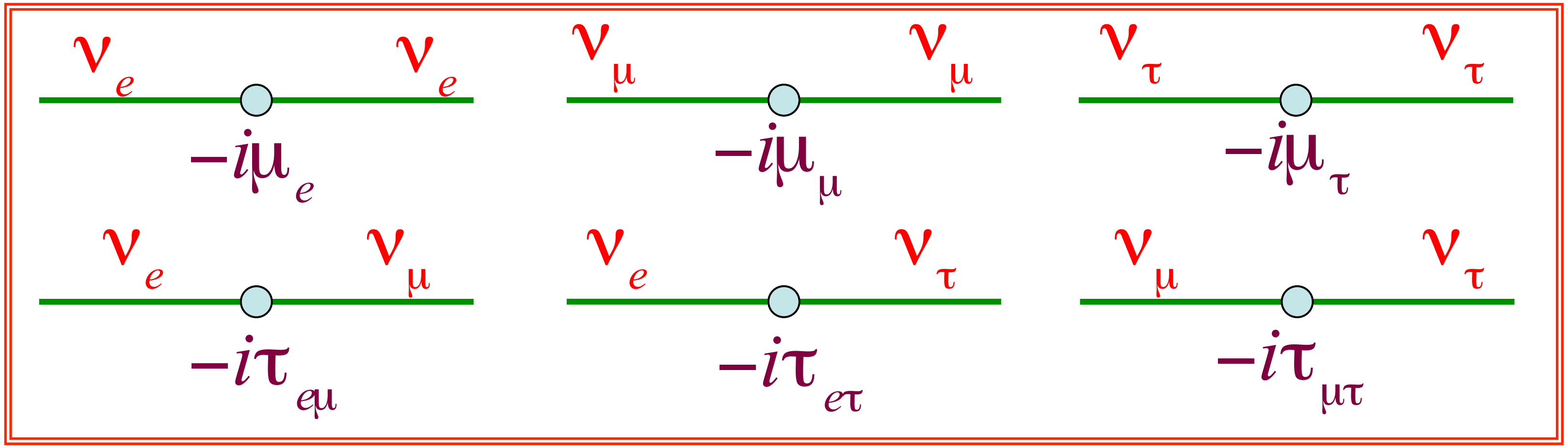
←We have learned a lot from these "Oscillations"

We can expect to learn more from ν oscillations;

$$\nu_\alpha \Leftrightarrow \nu_\beta$$

What is X??

3 Flavor Neutrino Oscillation



➔ **The mixing matrix becomes 3x3 & there are 3 mass eigenstates**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

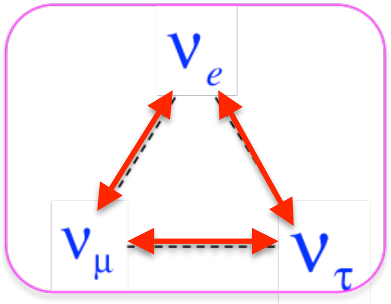
$$m_1, m_2, m_3 = \ldots$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Oscillation Experiments

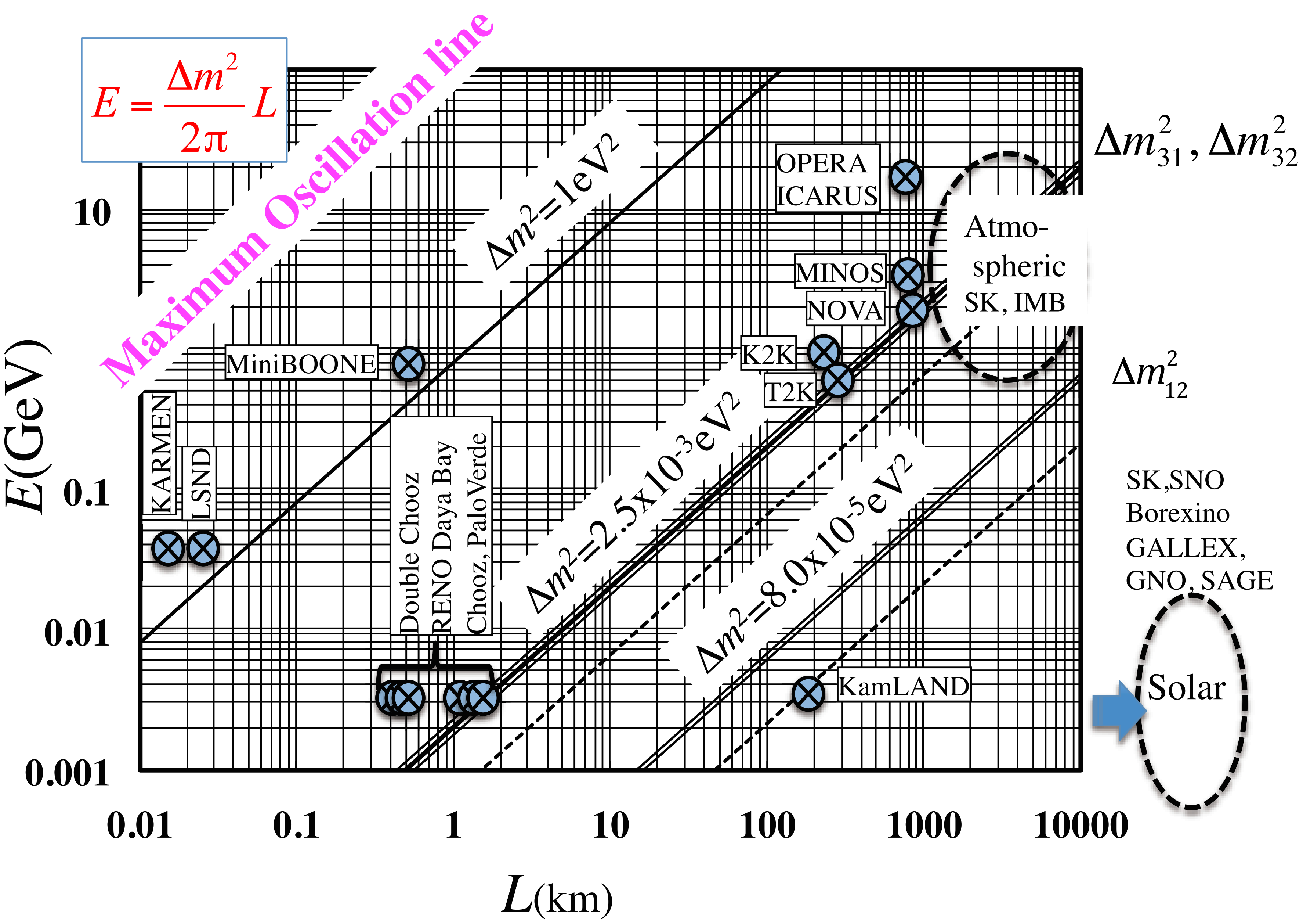
Parameters to measure

- **Mixing angles:** $\theta_{12}, \theta_{23}, \theta_{13}$
- **Square mass differences:** $\Delta m^2_{12}, \Delta m^2_{23} \left(, \Delta m^2_{13}\right)$
- **CP violation phase:** δ_{CP}



It is a long history with labors, efforts, brilliant ideas, severe competitions and sometimes errors.
But allow me to make it short .....

E-L relation of N.O. experiments

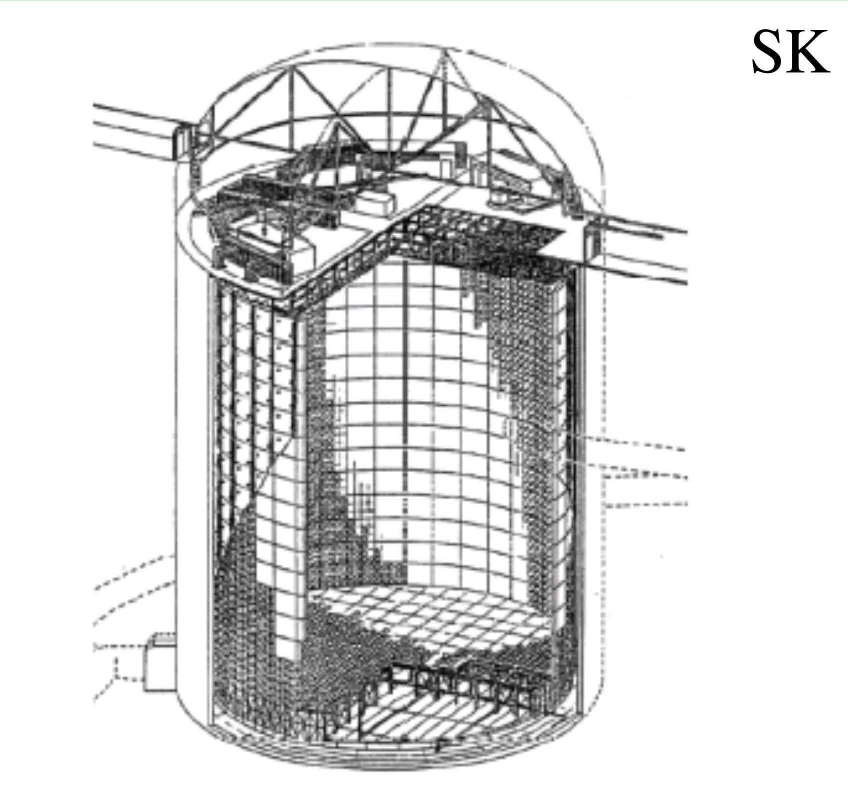


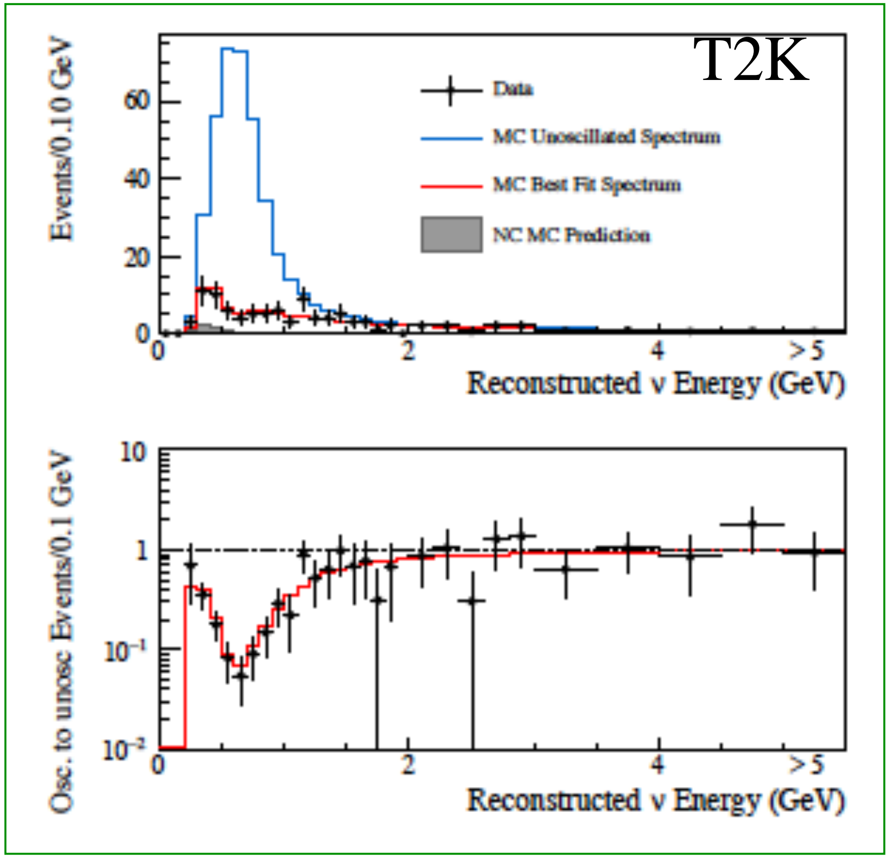
$\theta_{23}, \quad \Delta m^2_{32}$

Atmospheric (SK. etc.), T2K, MINOS, NOVA ....

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{32}}{4E} L$$

arXiv:1502.01550v1

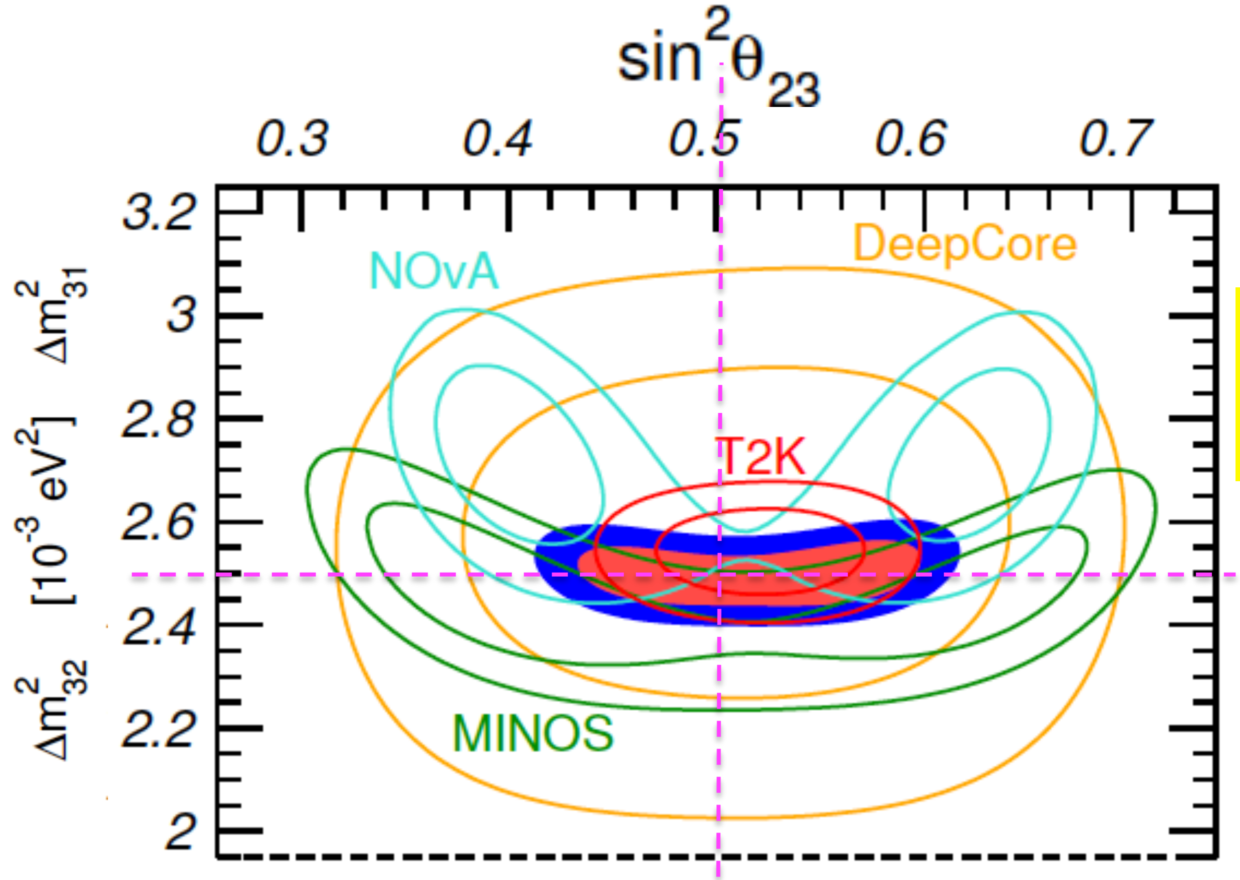




➔ Discovery of N.O. : Nobel prize in 2015 (T.Kajita)

$\theta_{23}, \quad \Delta m_{32}^2$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{32}^2}{4E} L$$



Normal Hierarchy (m_3>m_2) case

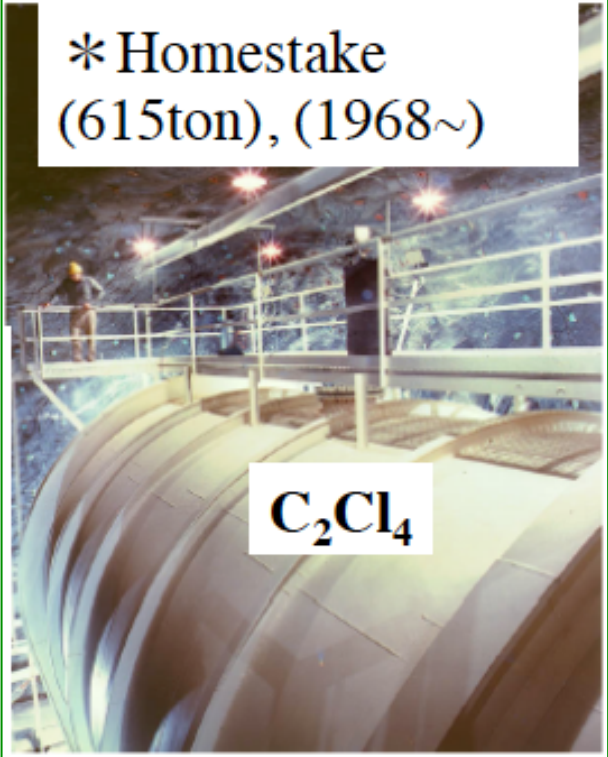
NuFIT 3.1(2017), www.nu-fit.org, JHEP01(2017)087,

$$\sin^2 2\theta_{23} \sim 1, \quad \Delta m_{32}^2 \sim 2.5 \times 10^{-3} [eV^2]$$

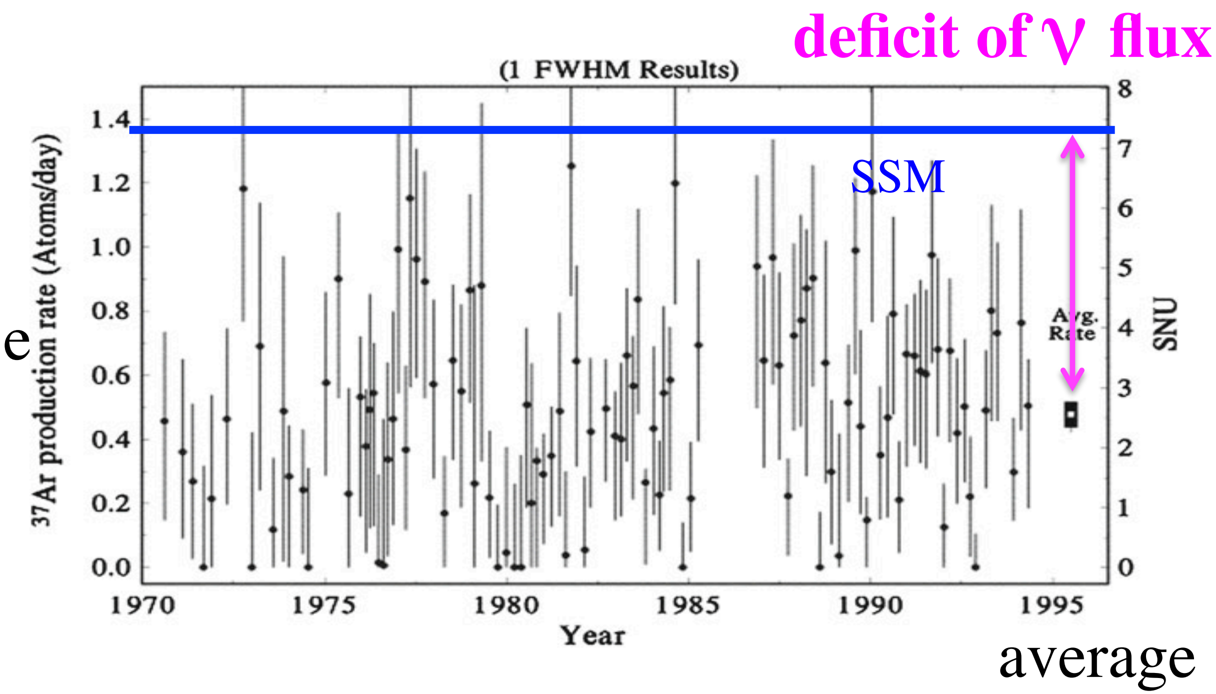
$\theta_{12}, \quad \Delta m^2_{12}$

Solar Neutrino Experiments
(Homestake, SuperK, SAGE, GALLEX, BNO, Borexino, SNO, etc.)

$$P\left(\nu_e \to \nu_e; @\Delta m^2_{21}\right) \sim 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12}}{4E} L$$



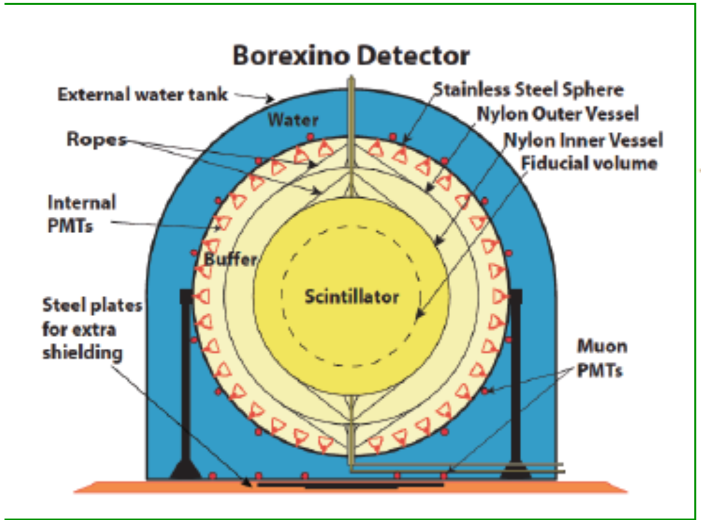
$^{37}Cl + \nu_e \to {}^{37}Ar + e^-$



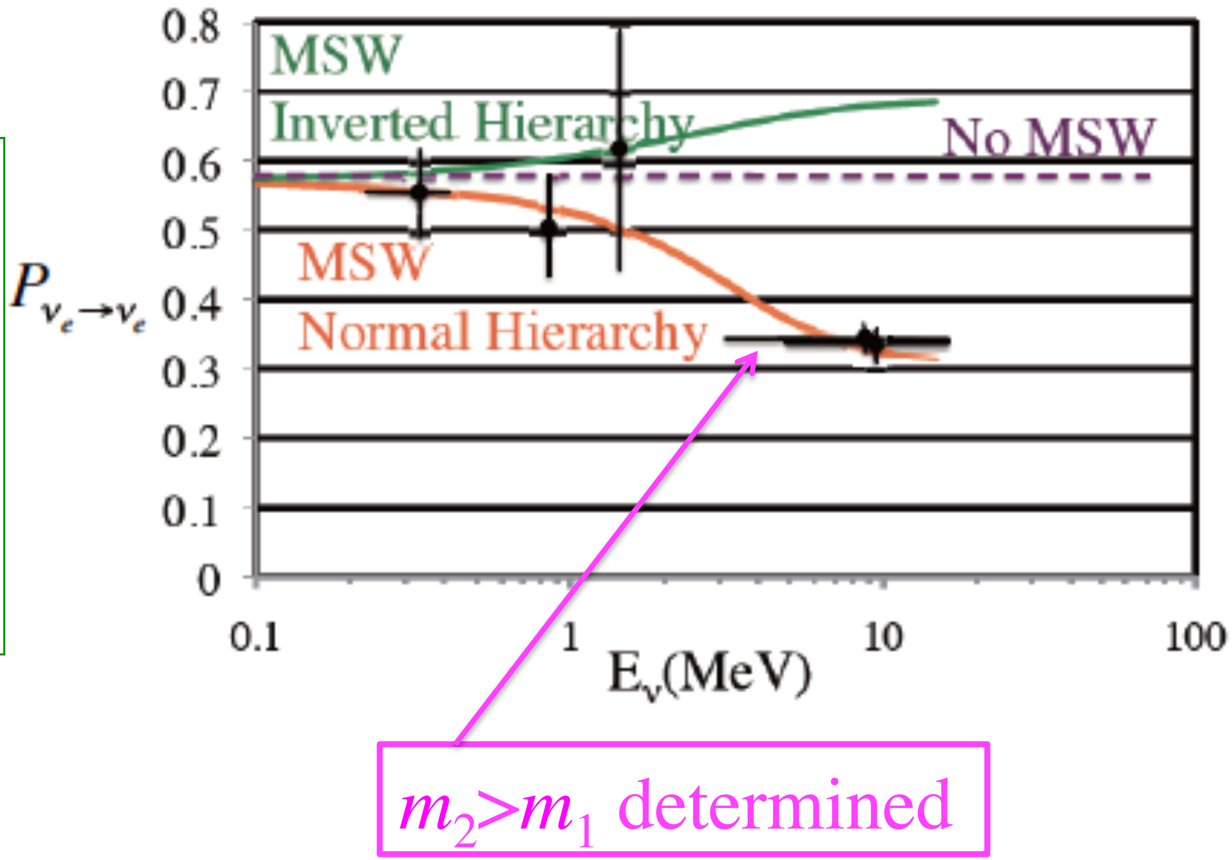
➔ **Nobel prize in 2002 (R.Davis)**

Δm_{21}^2 **mass hierarchy (m_2>m_1 or m_2<m_1)**

Genuine N.O. can not resolve it but
Matter Effect depends on M.H. and it can be used.

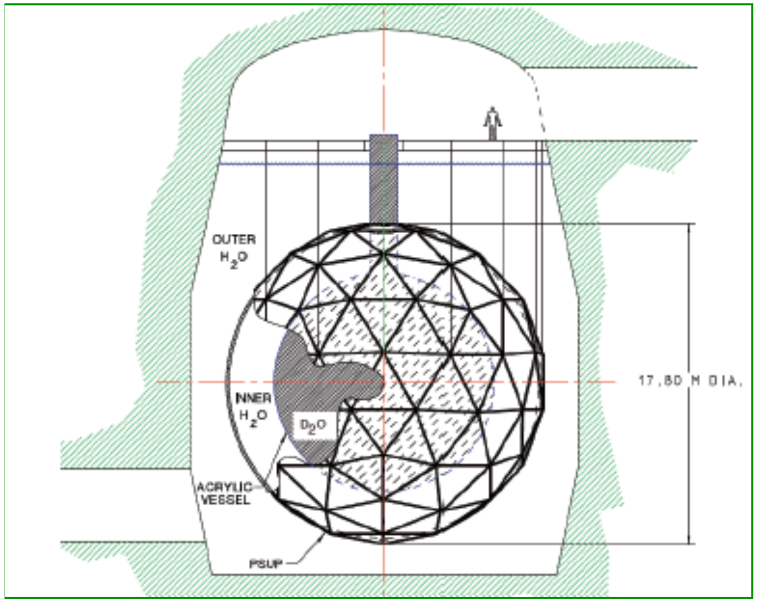


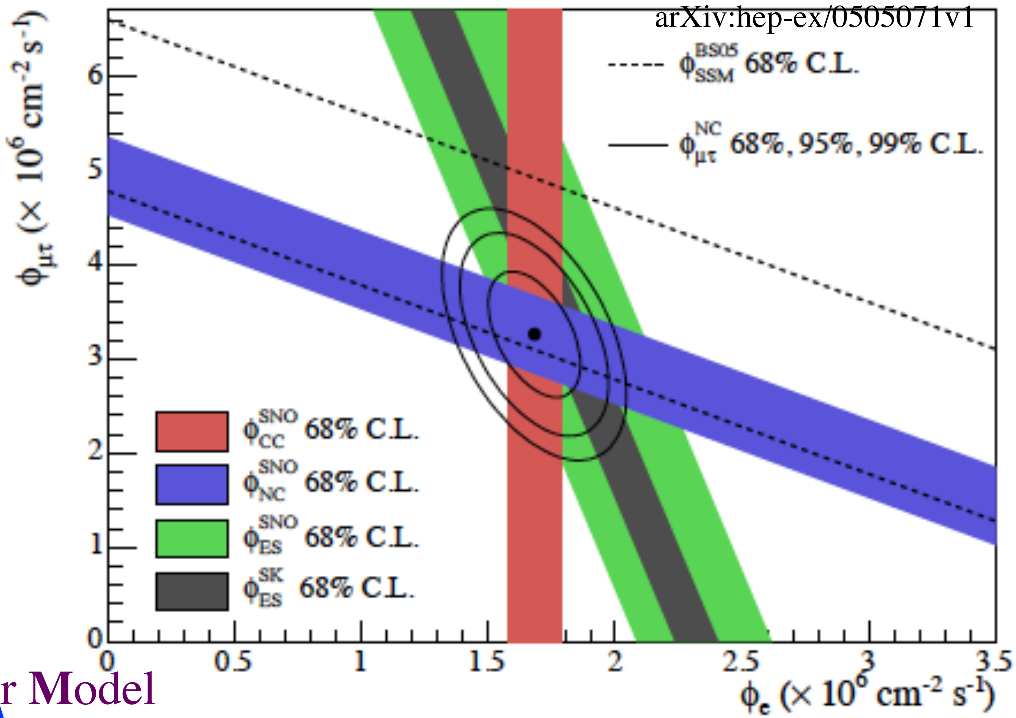
etc.



Flavor Transmutation: SNO experiment

$\nu_x + D \rightarrow \nu_x + p + n$ **NC interaction: possible to count all flavors**





Standard Solar Model

Although $\Phi(\nu_e) < \Phi(SSM)$, $\Phi(\nu_e) + \Phi(\nu_\mu) + \Phi(\nu_\tau) = \Phi(SSM)$

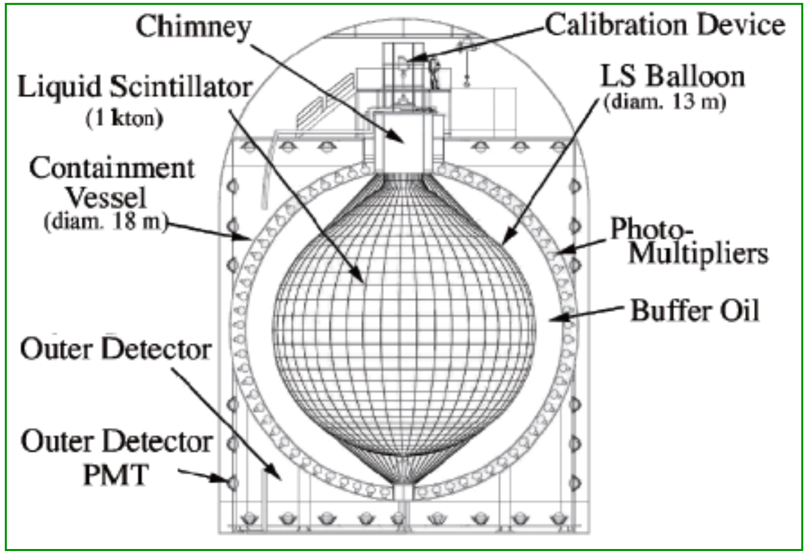
➔ Total # of ν does not change. ν_e changed to other neutrinos.

➔ Nobel prize in 2015 (A.McDonald)

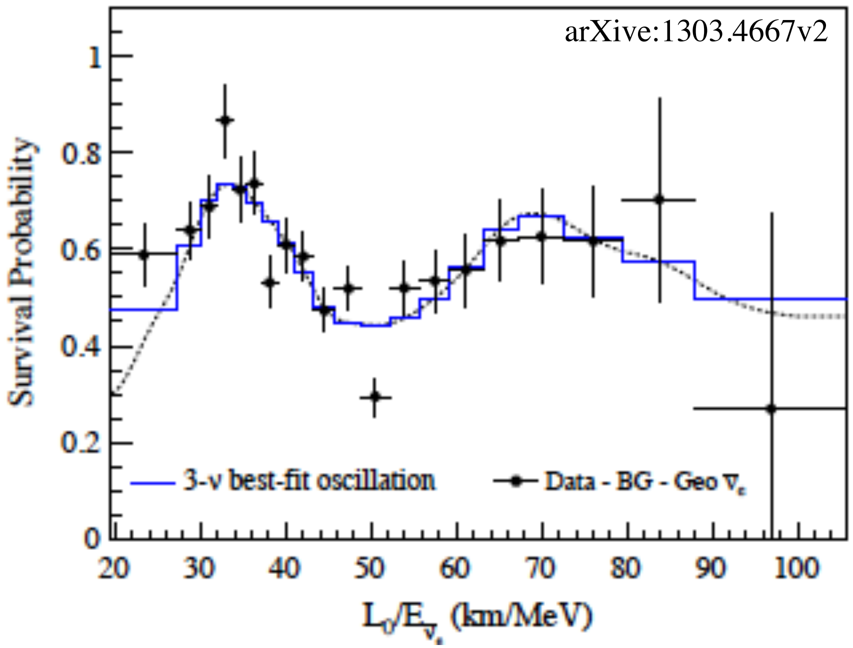
$\theta_{12}, \quad \Delta m^2_{12}$

KamLAND Reactor Neutrino Oscillation

$$P\left(\bar{\nu}_e \to \bar{\nu}_e ; @\Delta m^2_{21}\right) \sim 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12}}{4E} L$$



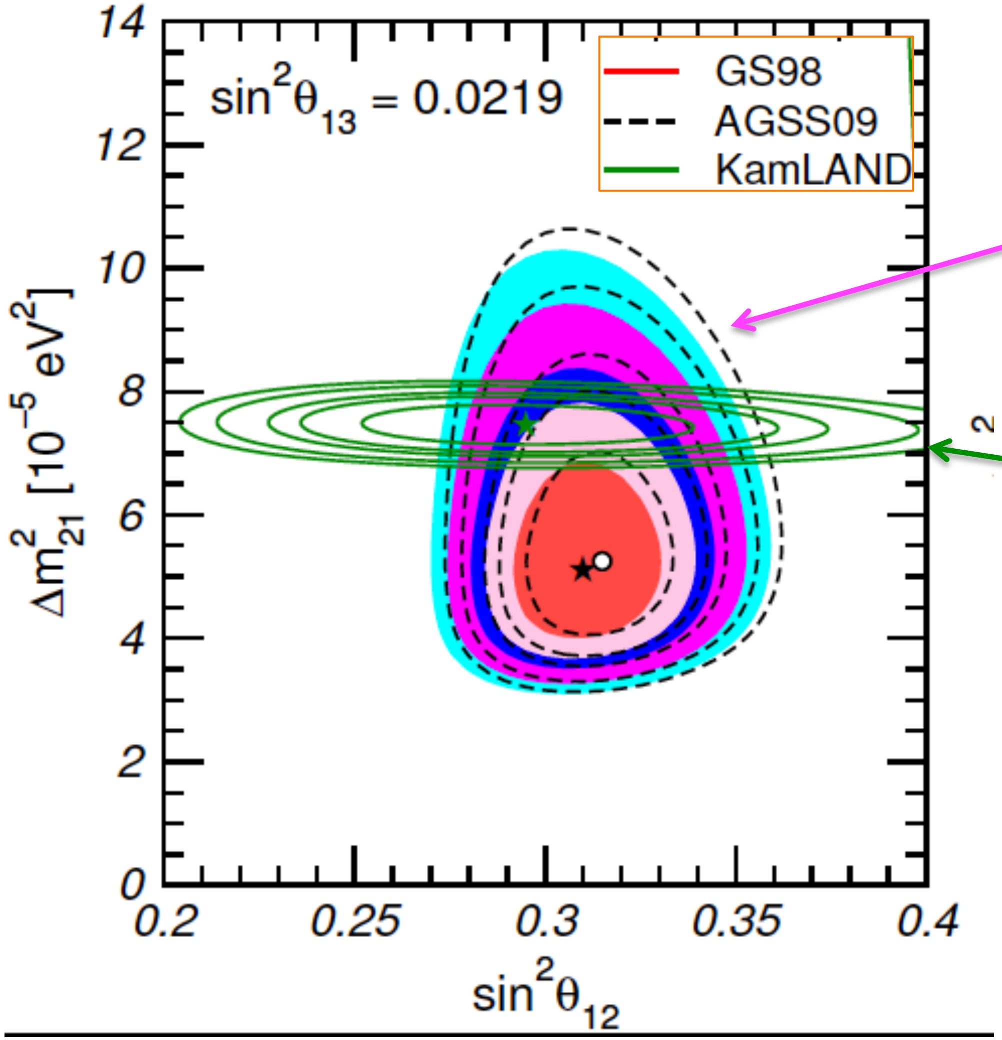
L~180km



$$\text{KamLAND}: \quad \tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}, \quad \left|\Delta m^2_{21}\right| = 7.53^{+0.18}_{-0.18} \times 10^{-5}\, eV^2$$

$\theta_{12}, \quad \Delta m^2_{12}$

NuFIT 3.1(2017), www.nu-fit.org,
JHEP01(2017)087,



Solar Exps.

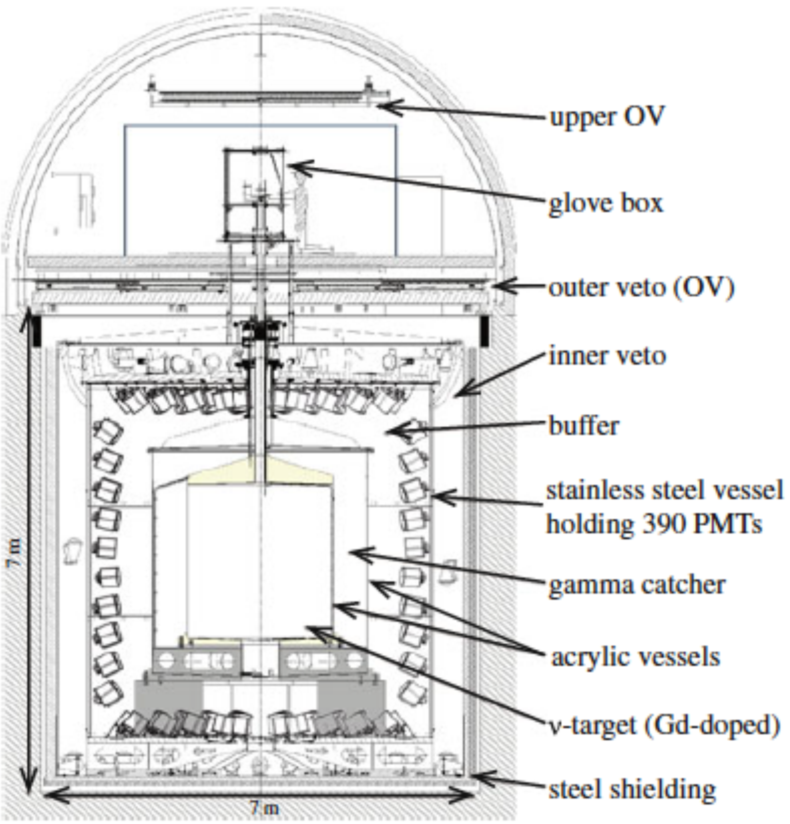
KamLAND
Reactor Exp.

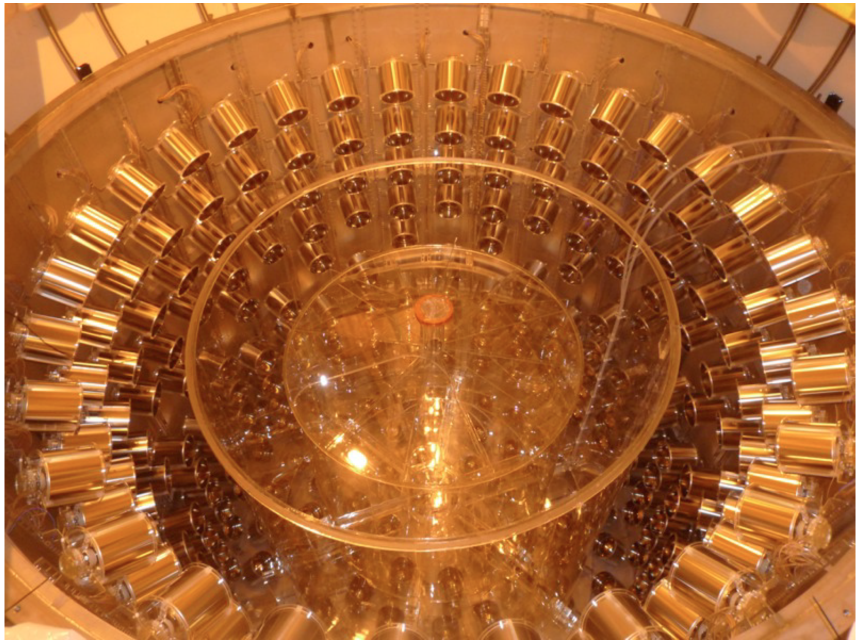
➔ There is slight tension

$\theta_{13}, \quad \Delta m^2_{31}$:

Our experiment: Double Chooz

Most of the ideas of the reactor θ_{13} experiment/detector were proposed first by the DC group members.

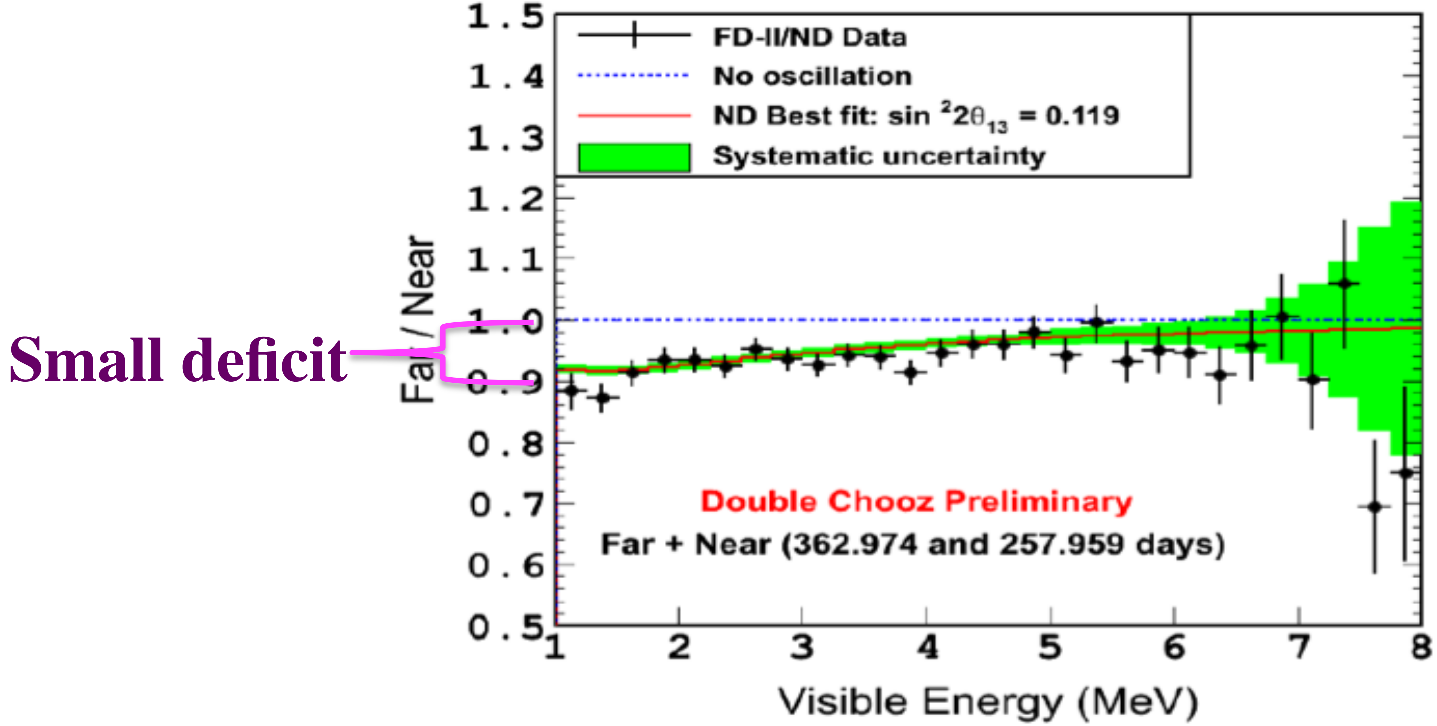




Double Chooz Oscillation fit result

Far detector/Near detector concept to cancel most of the systematics.

Far/Near ratio

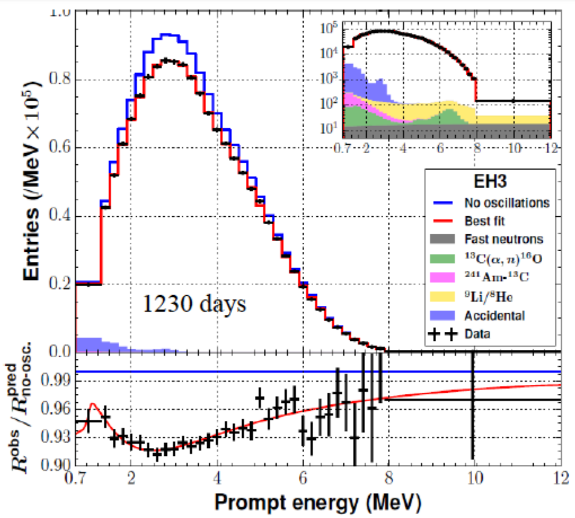


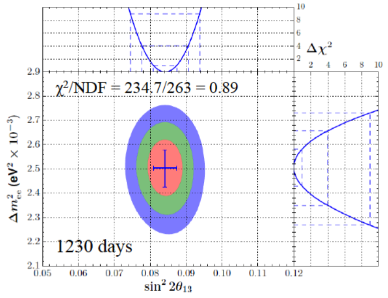
$\sin^2 2\theta_{13} = 0.119 \pm 0.016$ with $\chi^2/\mathrm{ndf} = 236.2/114$ (preliminary)

Daya Bay Result

Logan Lebanowski @ 2016.11 NNN16

Oscillation analysis result





$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$

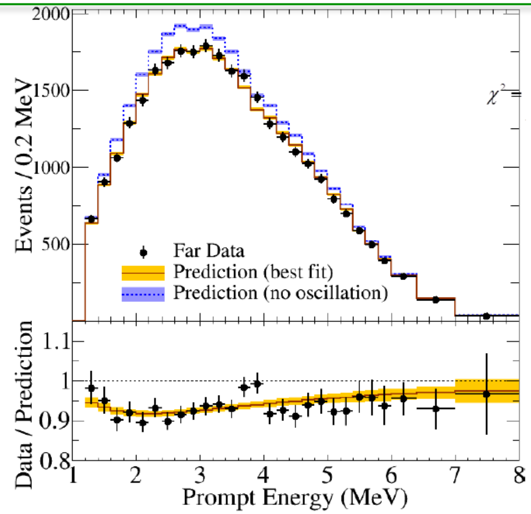
$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3} eV^2$

Multiple analyses yield consistent results.

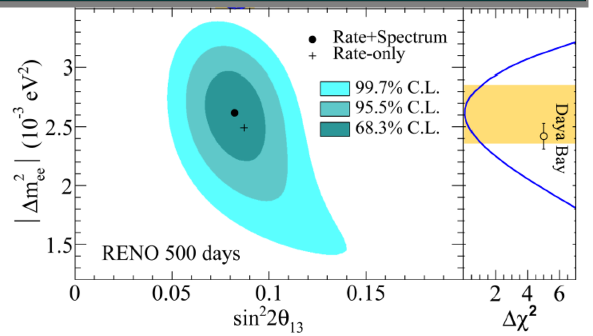
[arXiv:1610.04802]

RENO result

Hyunkwan Seo @ 2016.11 NNN16



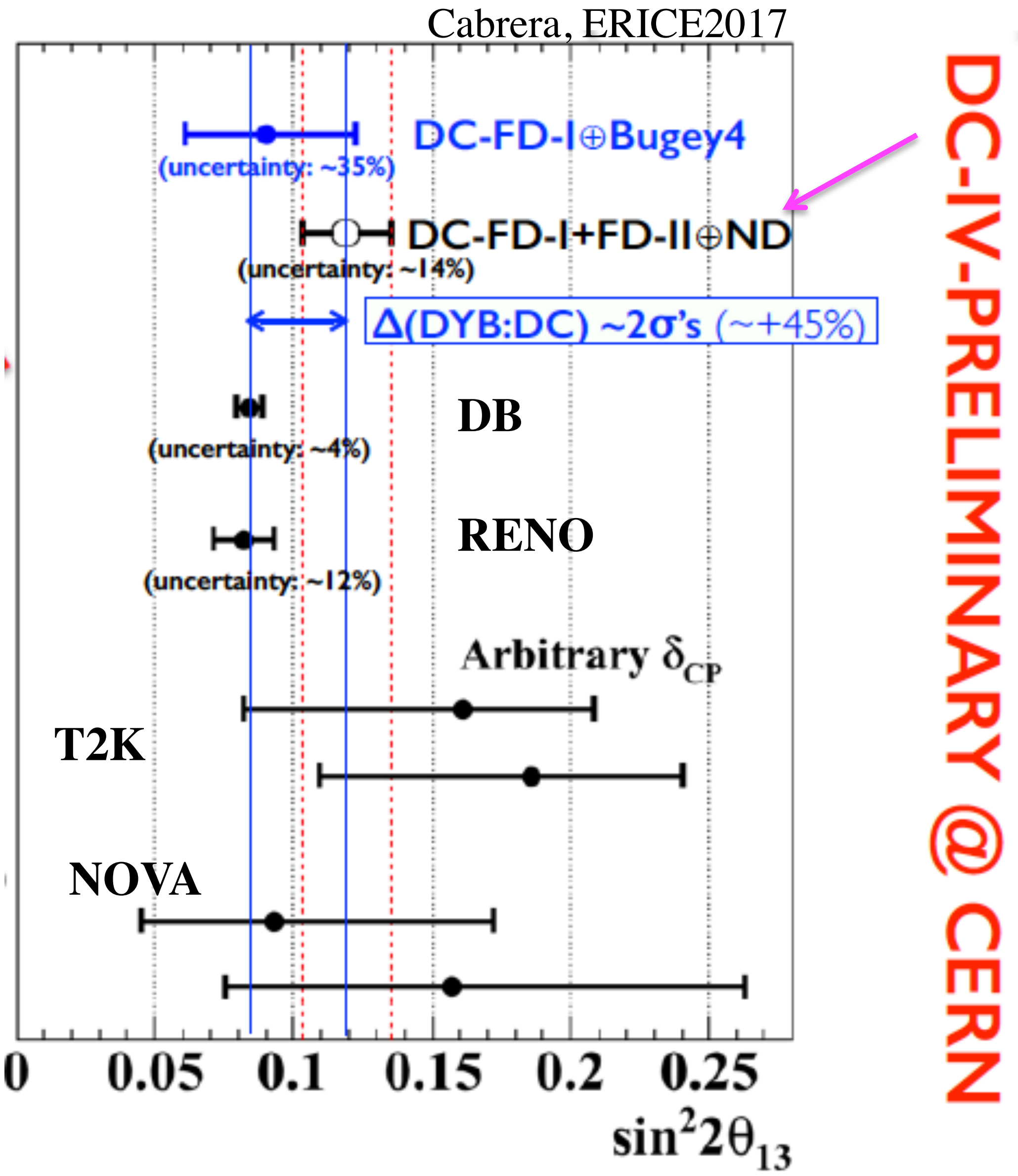
Results from Spectral Fit



Rate+shape new results

$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$

$|\Delta m^2_{ee}| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})\ (10^{-3} eV^2)$

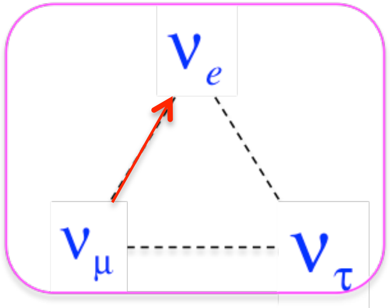


Cabrera, ERICE2017
DC-FD-I⊕Bugey4
(uncertainty: ~35%)
DC-FD-I+FD-II⊕ND
(uncertainty: ~14%)
Δ(DYB:DC) ~2σ's (~+45%)
DB
(uncertainty: ~4%)
RENO
(uncertainty: ~12%)
Arbitrary δ_{CP}
T2K
NOVA
0
0.05
0.1
0.15
0.2
0.25
$\sin^2 2\theta_{13}$
DC-IV-PRELIMINARY @ CERN

CP violation δ

T2K and NOVA measure

$$\left(\nu_\mu \to \nu_e\right), \left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$$



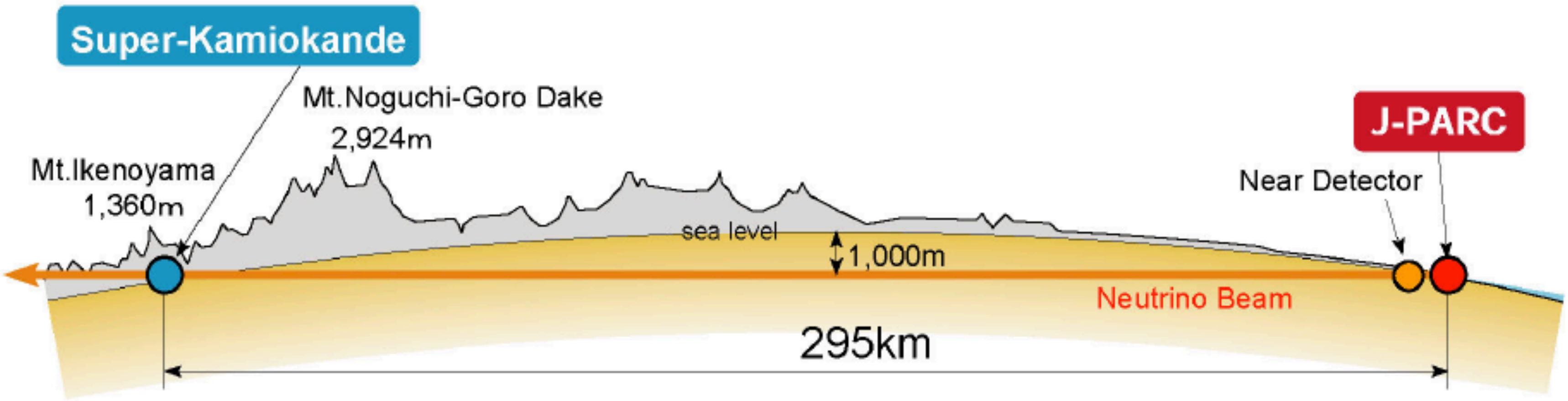
$\nu_\mu \to \nu_e$ $\quad P_A \sim 0.5\sin^2 2\theta_{13} - 0.043\sin 2\theta_{13}\,\underline{\sin\delta}$

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad \bar{P}_A \sim 0.5\sin^2 2\theta_{13} + 0.043\sin 2\theta_{13}\,\underline{\sin\delta}$

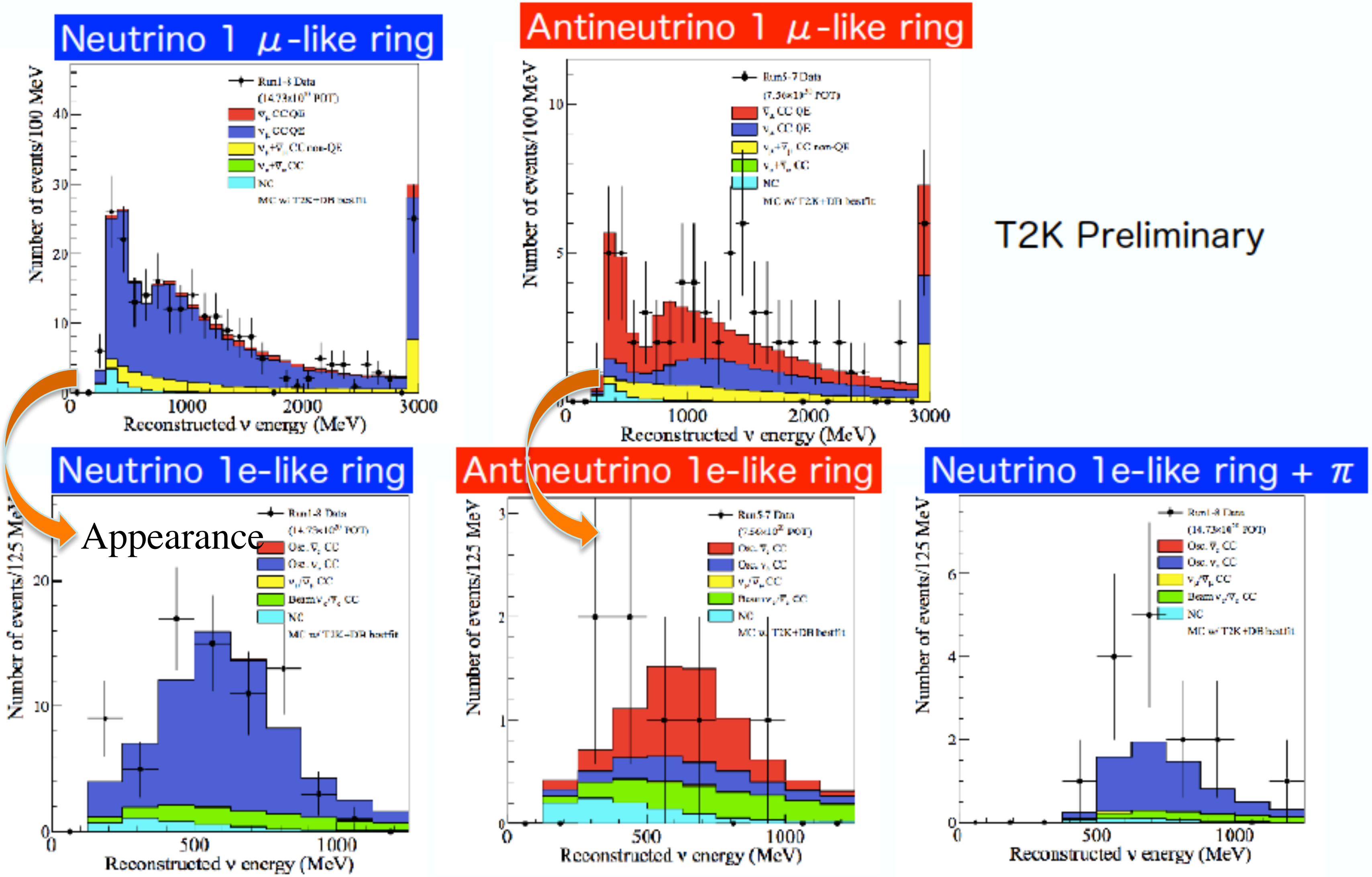
$$A_{CP} = \frac{P_A - \bar{P}_A}{P_A + \bar{P}_A} \sim 0.3\sin\delta$$

T2K Experiment

K.Iwamoto@ICHEP16



Observation at Super-K



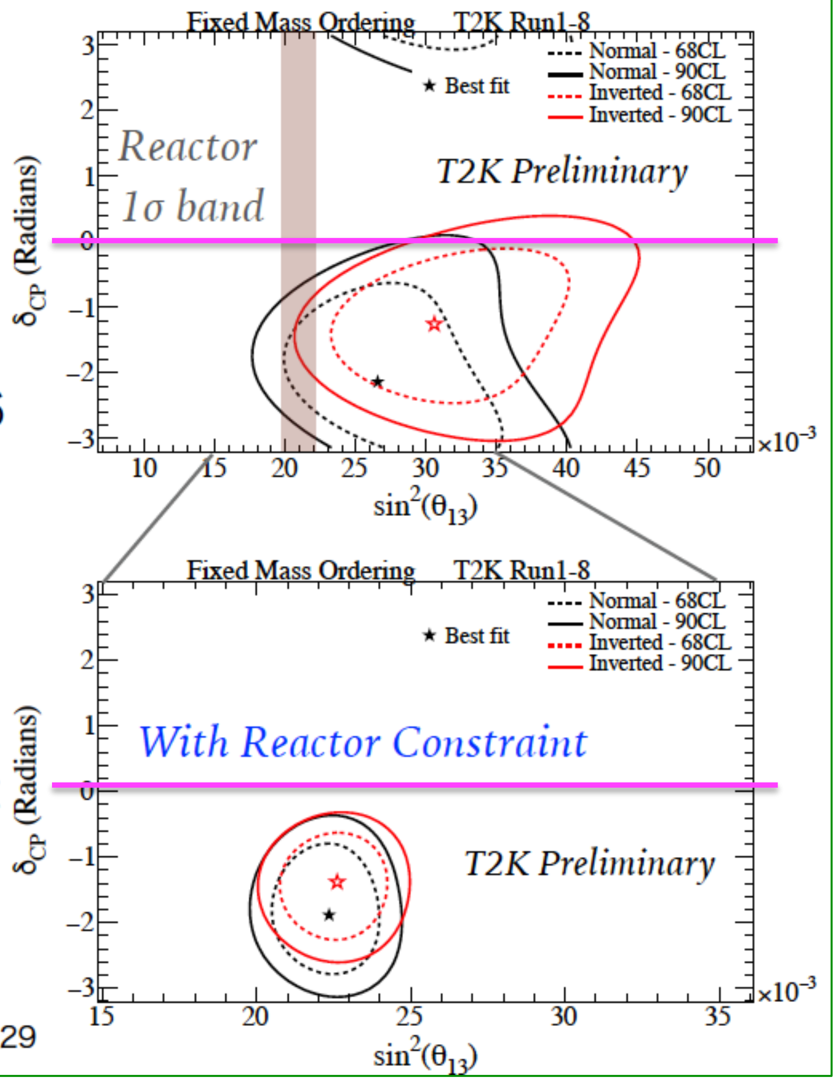
θ_{13} and δ_{CP}

- Fit without the reactor constraint: closed contours in δ_{cp} at 90% CL
- The T2K value for $\sin^2\theta_{13}$ is consistent with the PDG 2016

T2K Best Fit:
$\sin^2\theta_{13} = 0.0277^{+0.0054}_{-0.0047}$ (NH)

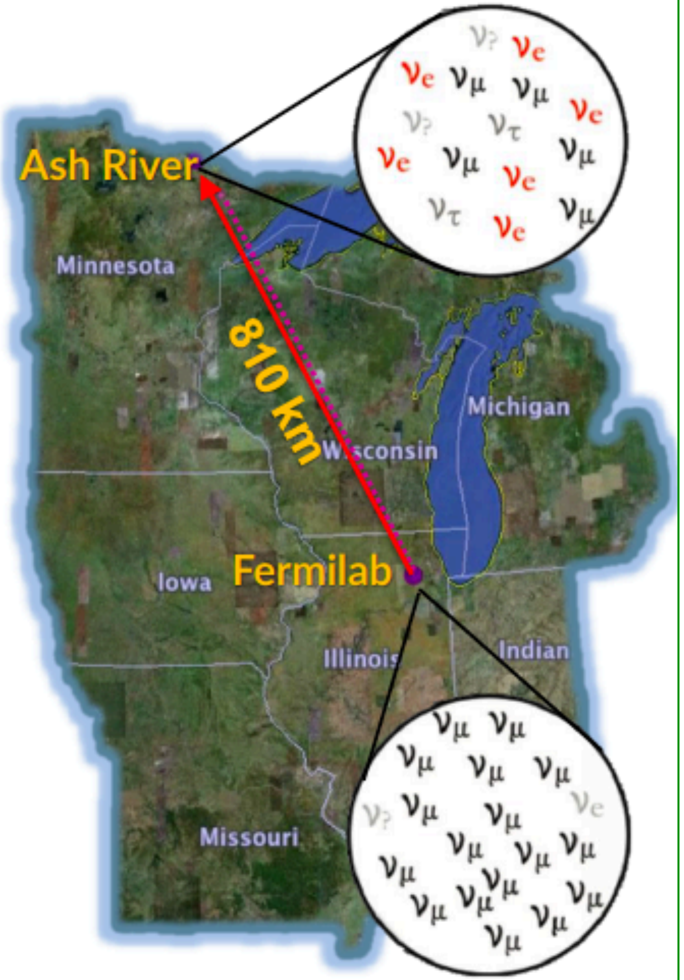
PDG 2016:
$\sin^2\theta_{13} = 0.0210 \pm 0.0011$

- Adding the reactor constraint improves the constraint on δ_{cp} average:



NuMI Off-axis ν_e Appearance Experiment

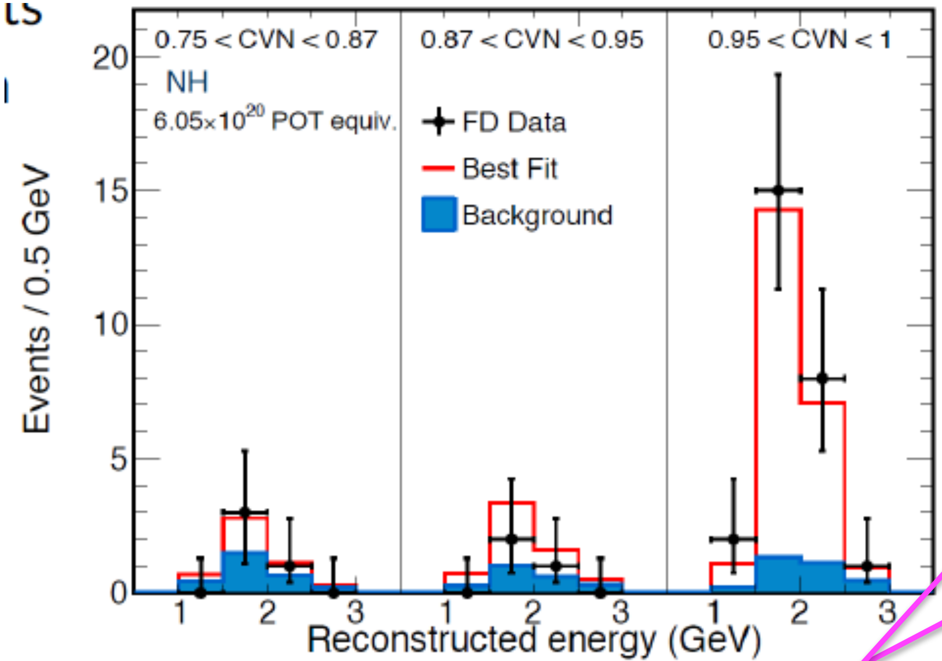
- Long-baseline, two-detector ν oscillation experiment
- Looks for ν_e in ν_μ NuMI beam
- 14 mrad off-axis
- 2 liquid scintillator detectors
- FD (14 kton), ND (0.3 kton)
- Cooled APD readout (live)
- Appearance & disappearance
- Exotics, non-beam…

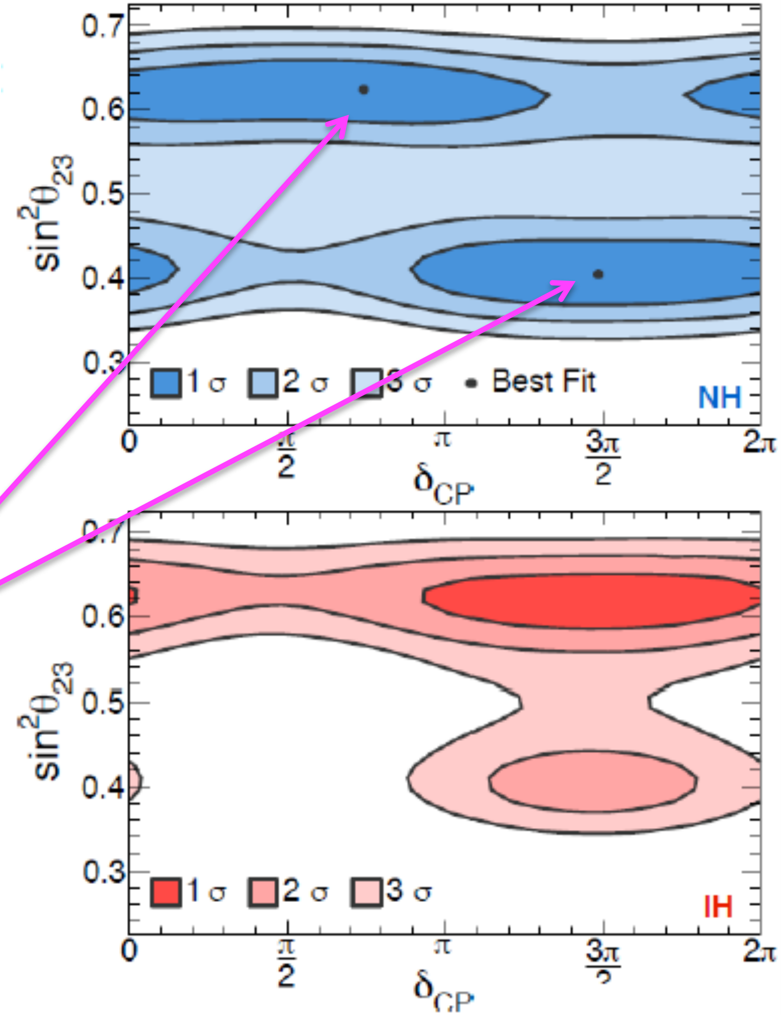


ν_e appearance results

NOvA

- Observe 33 events on a background of 8.2 ± 0.8





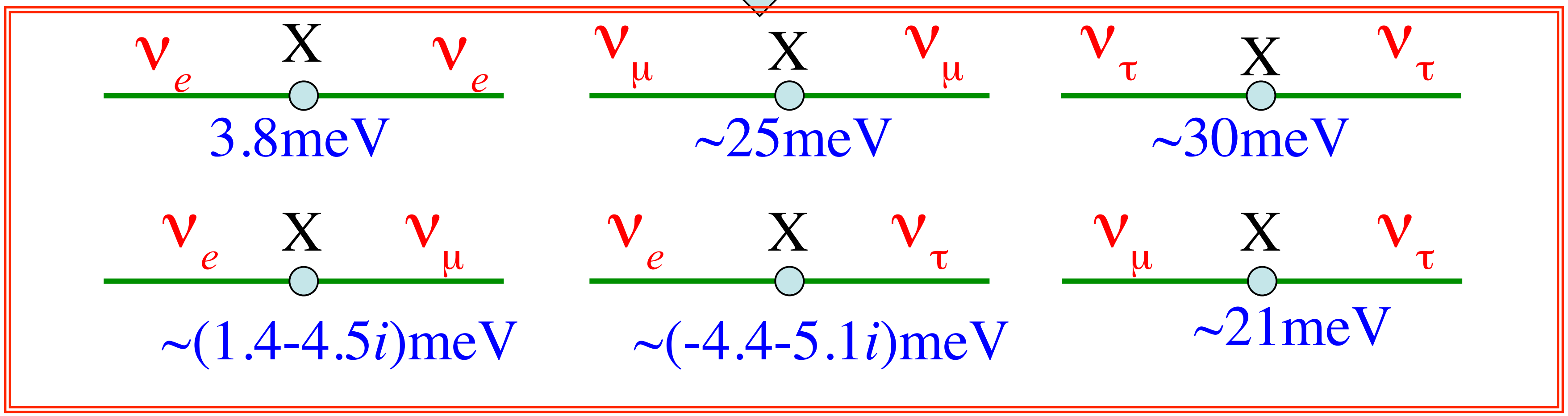
- 2 degenerate best fit points:
  - NH, $\delta_{CP} = 1.48\pi$, $\sin^2\theta_{23} = 0.404$
  - NH, $\delta_{CP} = 0.74\pi$, $\sin^2\theta_{23} = 0.623$

Our Current Knowledge of Neutrino Transition Amplitude

For Example: If NH and $\delta_{CP} = -\pi/2$

$$U_{NH} \sim \begin{pmatrix} 0.82 & 0.55 & -0.09+0.13i \\ -0.36+0.07i & 0.65+0.05i & 0.67 \\ 0.43+0.08i & -0.53+0.05i & 0.73 \end{pmatrix}$$

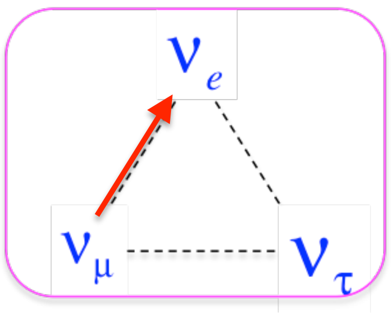
Assumption: $m_1 \sim 0$, ➔ $m_2 = 8.7\,\mathrm{meV}$, $m_3 = 50\,\mathrm{meV}$

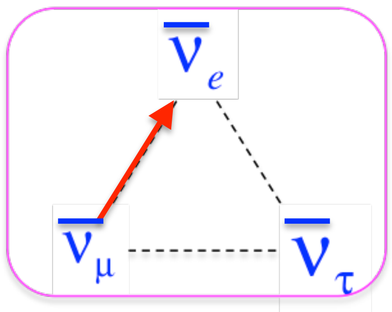


180227 **What is X and how this pattern can be explained??**

Future

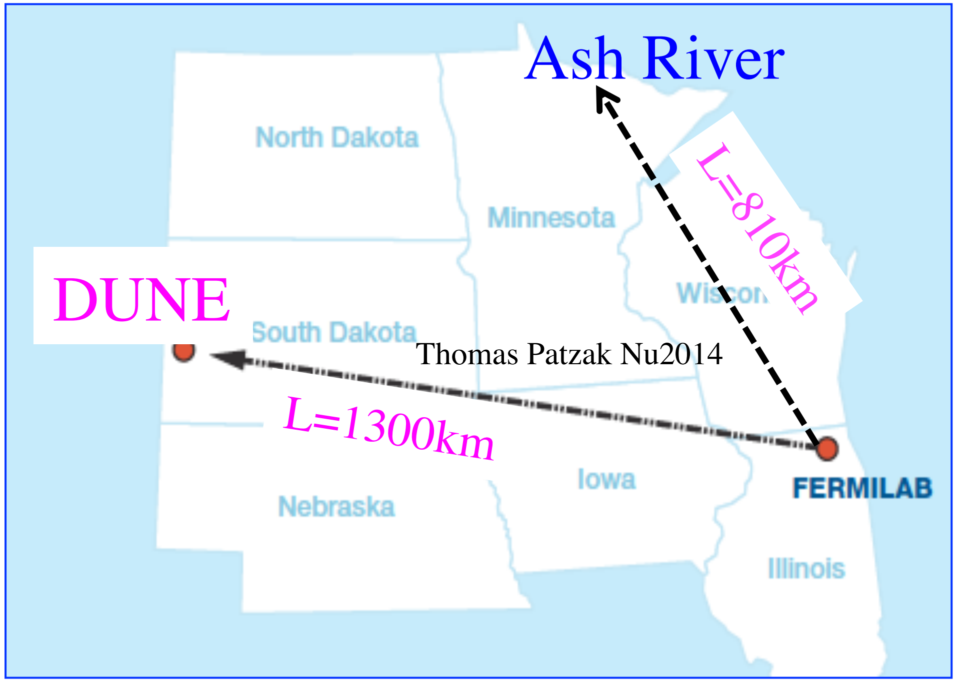
More precise CP Asymmetry
Mass Hierarchy determination
:





CP asymmetry by Future Long baseline experiments

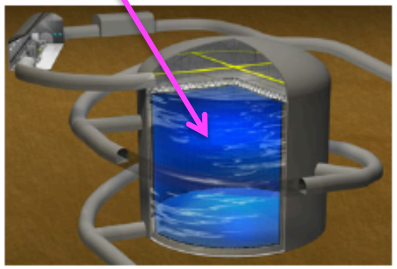
NOVA



Hyper Kamiokande:

516kt W.C.

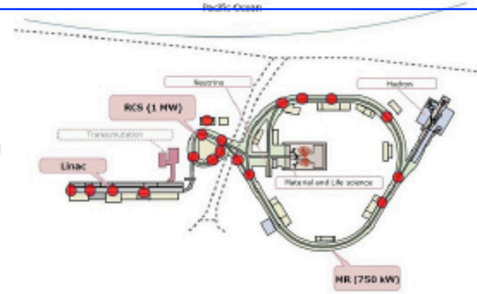
T2HK



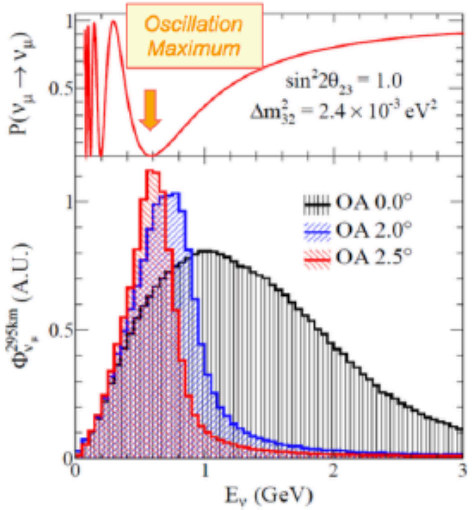
Hyper-K detector (Kamioka)

295 km

T2K→
*Larger target
*Larger acc. power



J-PARC neutrino Beam (Tokai)

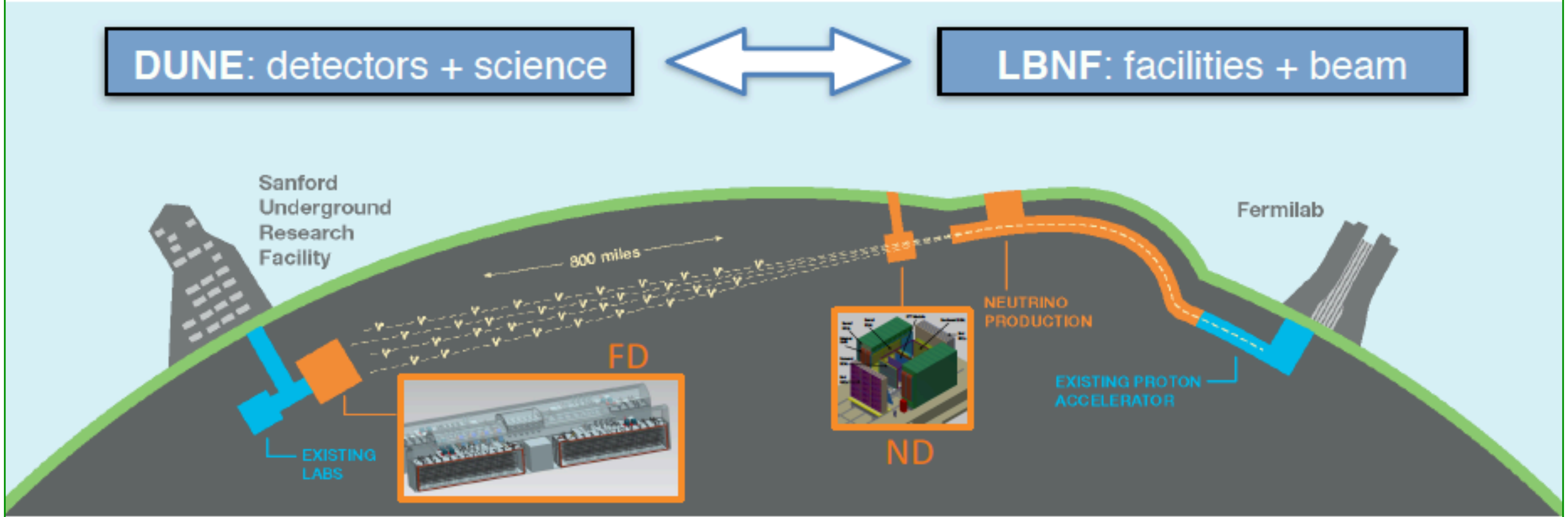


Building off the successful T2K program, Hyper-K also plans to measure neutrinos from the J-PARC neutrino beam

Data taking expected in 2026

DUNE at LBNF

Deep Underground Neutrino Experiment at the Long Baseline Neutrino Facility

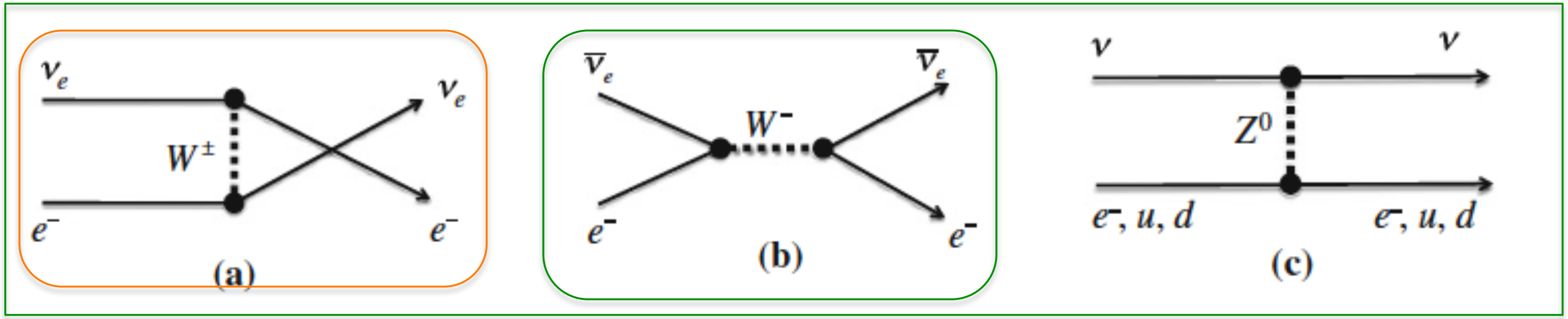


- High intensity, wide-band, neutrino beam from Fermilab
- Highly capable neutrino near detector at Fermilab
- 40-kt fiducial mass far detector at SURF based on LAr-TPCs

2026, Neutrino Beam available

IFIC DUNE

CP asymmetry with the matter effect



Difference of ν_e and $\bar{\nu}_e$ interactions with Earth matter

$$A_{CP}\left(@\Phi_{13}\right) \sim -0.3\sin\delta_{CP} \pm 2\left(L/L_0\right)$$

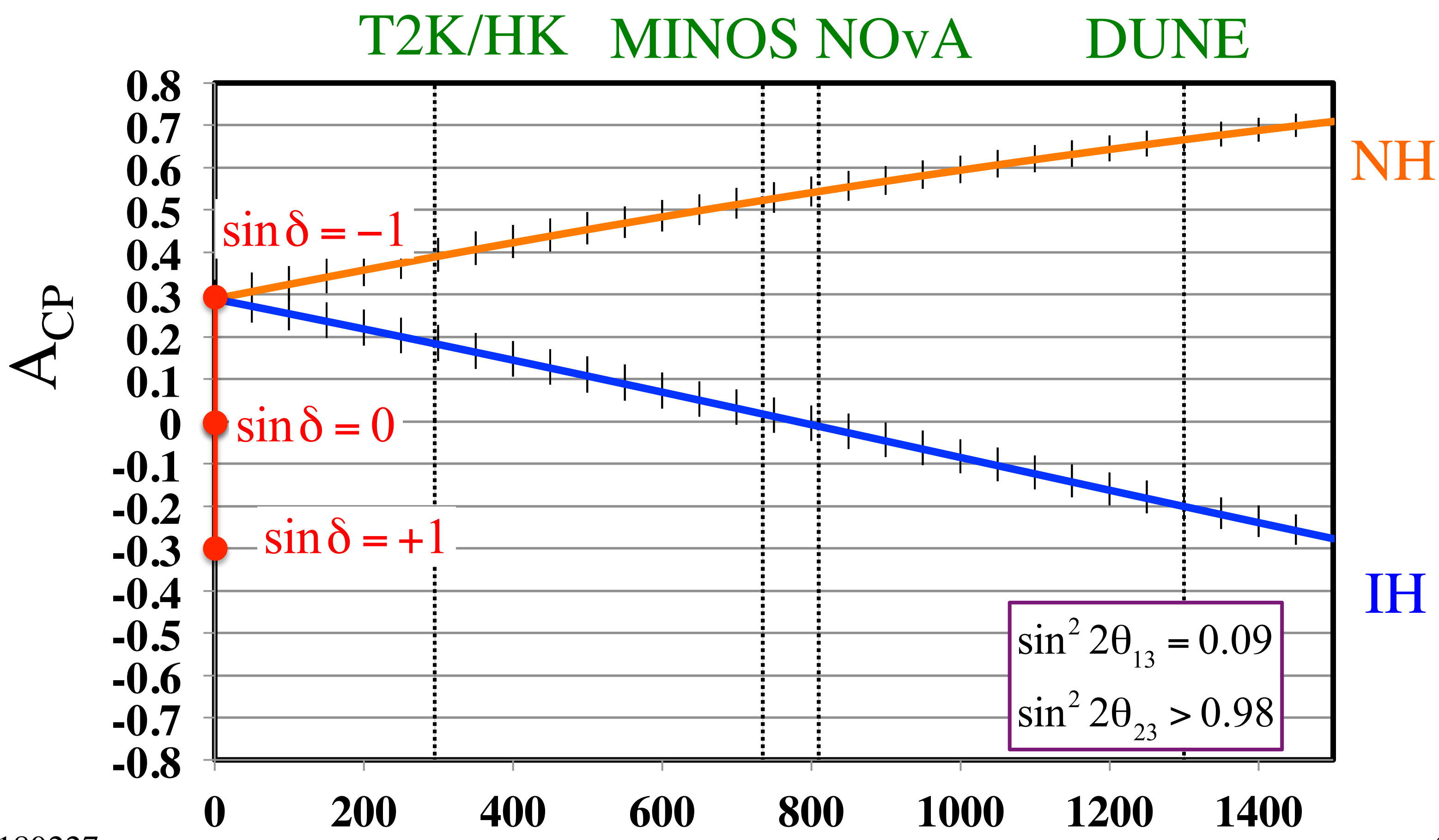
fake CP asymmetry

	L[km]	$A_{FK}=2(L/L_0)$
T2K/HK	295	±0.11
NOVA	810	±0.30
DUNE	1,300	±0.48

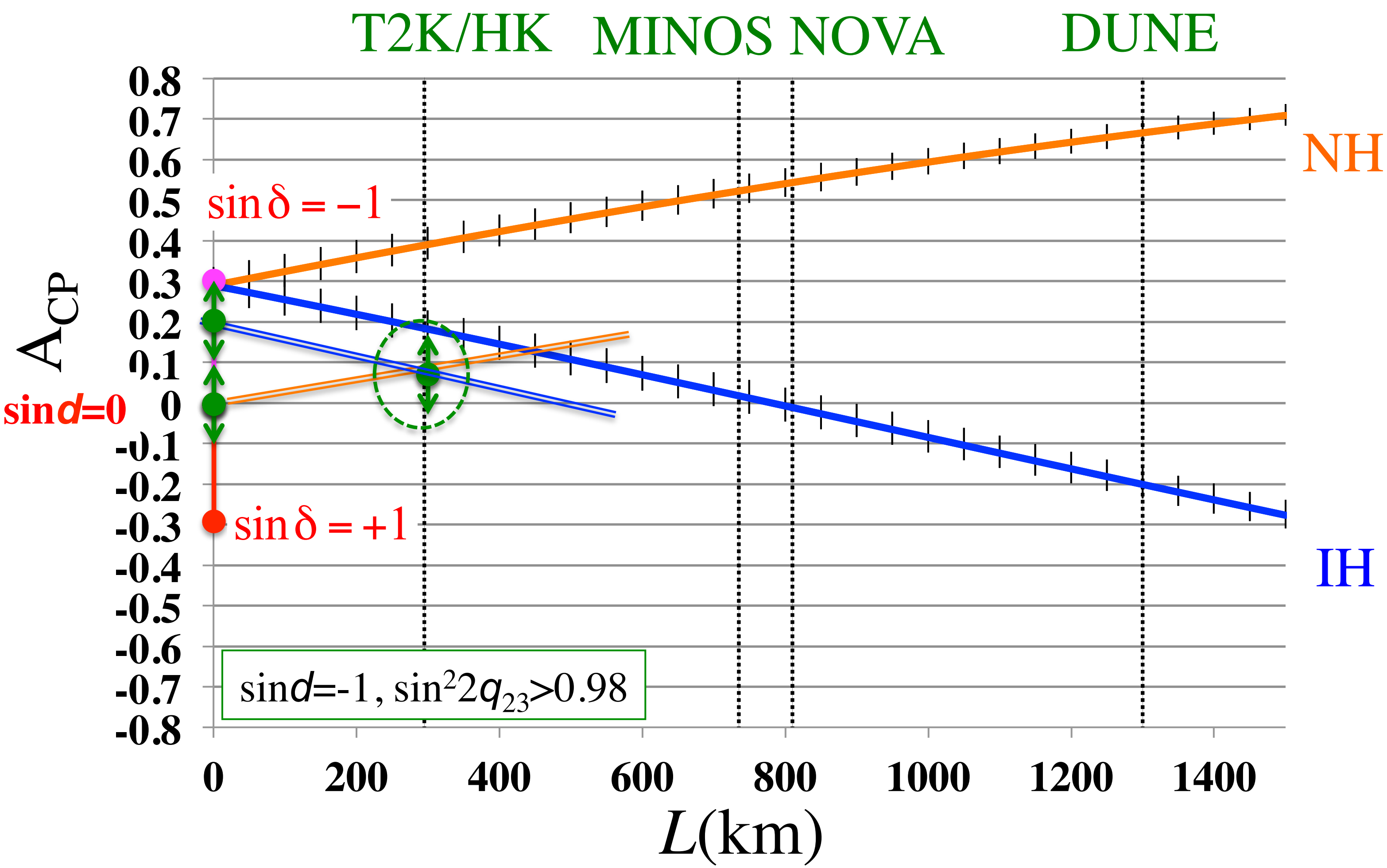
The sign depends on m_1-m_3 mass hierarchy

Baseline Dependence of Matter effect

$$A_{CP} \sim -0.29\sin\delta \pm 2\left(\frac{L}{L_0}\right)$$



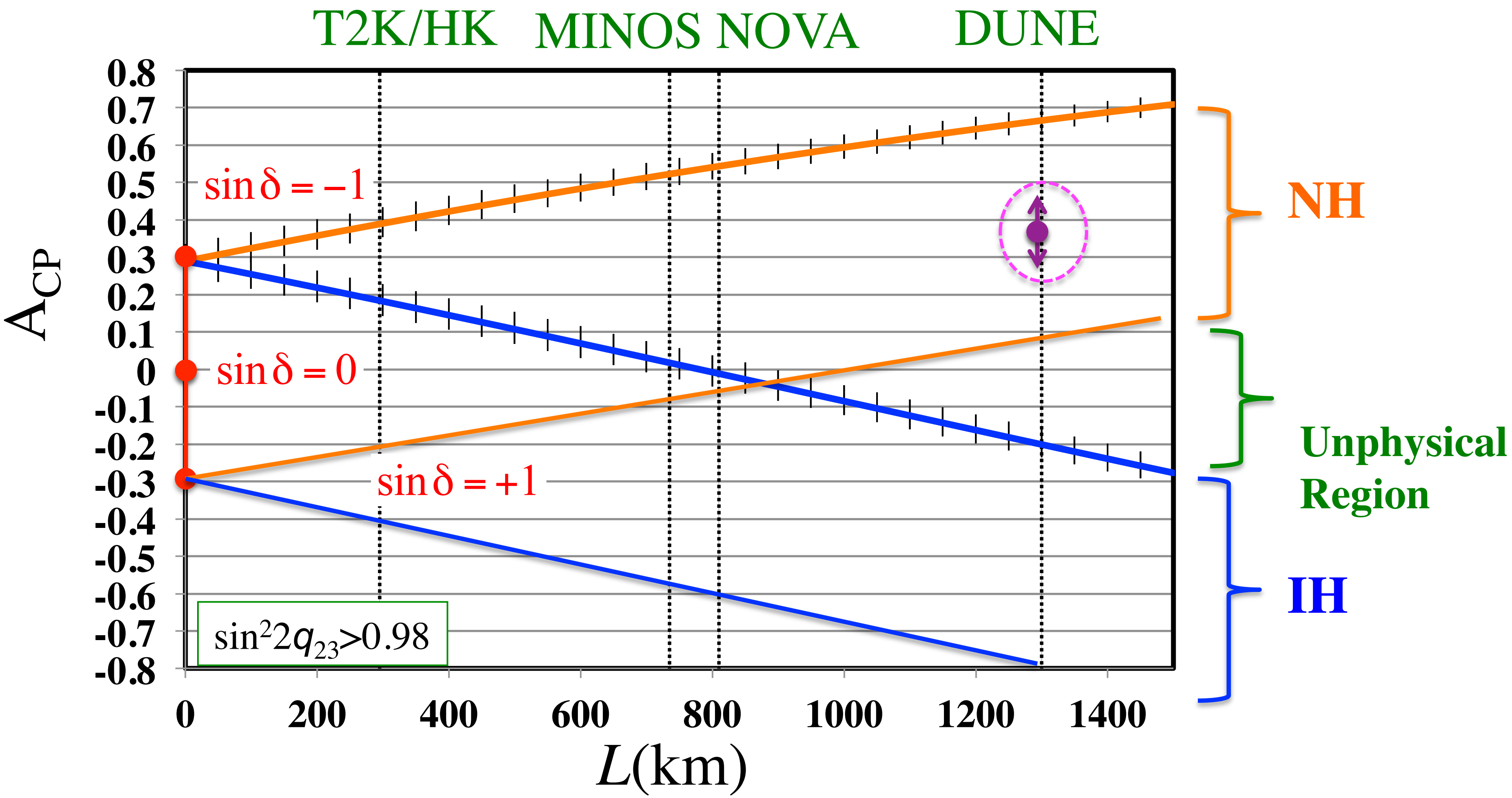
HK only case



If M.H. is not known, there are two solutions.

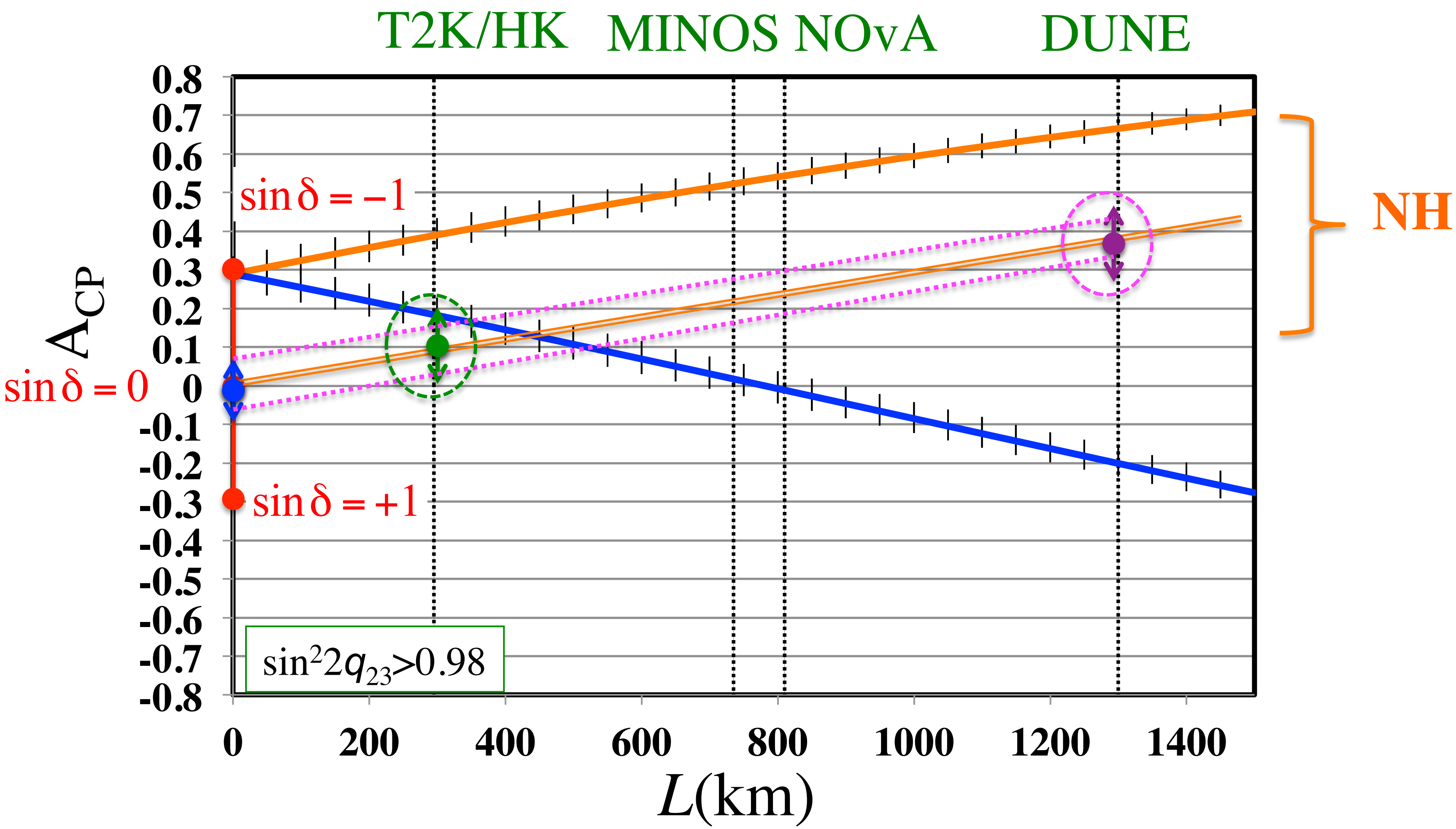
➔ M.H. is necessary.

DUNE only case



This case, M.H. is determined to be N.H.
But measurement is somewhat model dependent.

HK+DUNE



* **Matter effect independent measurement is possible.**

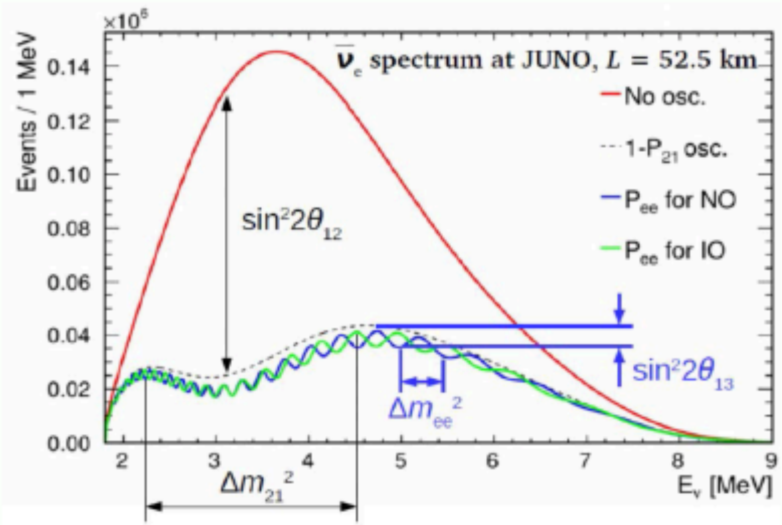
➔ **good to have both experiments.**

Δm^2_{23} mass hierarchy:

JUNO

- The **J**iangmen **U**nderground **N**eutrino **O**bservatory (JUNO) is a multipurpose experiment under construction in China:
  - Rich physics program: neutrino mass hierarchy, sub-% measurement of oscillation parameters, astrophysical neutrinos, geo-neutrinos, atmospheric neutrinos, search for exotic physics… etc.

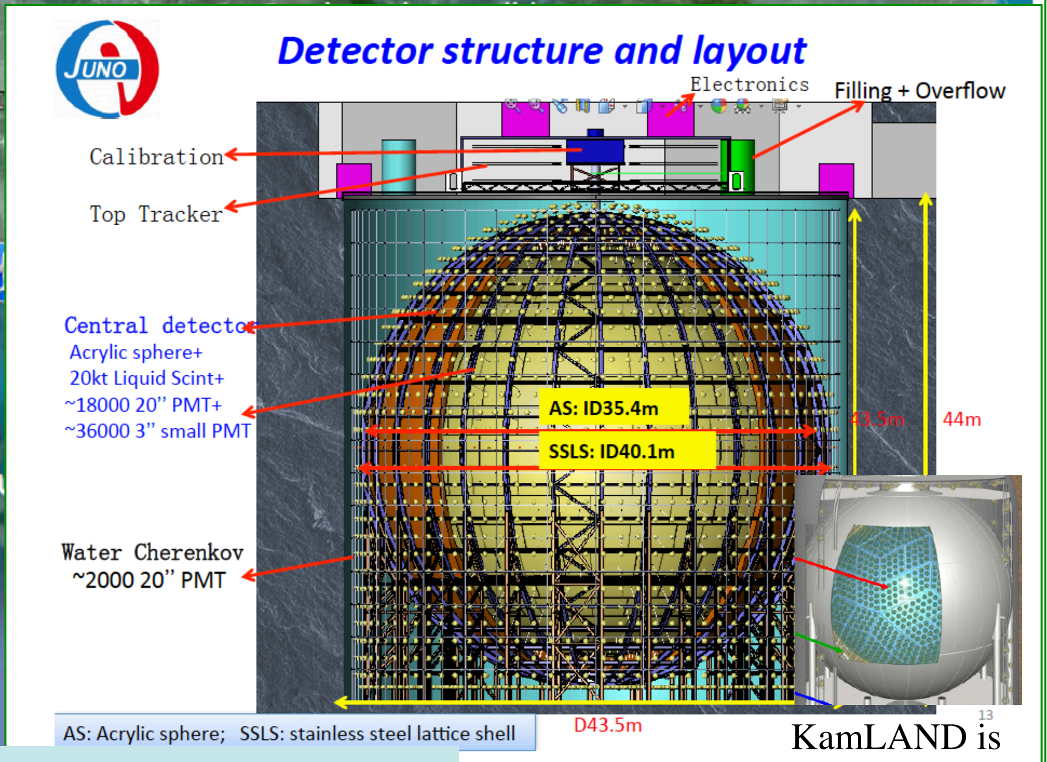
- Main keys to accomplishing the physics goals:
  - **Optimal baseline**
  - **High statistics**
  - **Superb energy resolution (3% @ 1 MeV)**
  - **Excellent control of energy response systematics**
  - **Background reduction**



Yee Bob Hsiung @ 2016.11 NNN16

Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



KamLAND is this size

Filling and data taking 2020

Summary: Part-I

* Thanks to the huge experimental efforts, $\theta_{12}, \theta_{23}, \theta_{13}$
  $\Delta m^2_{12}, \quad |\Delta \tilde{m}^2_{32}|, \quad |\Delta \tilde{m}^2_{31}|$ have been measured.
* Decisive measurements of δ, M.H. are planned
* There are several tensions.
  ➔ Redundant experiments to check each other are important.
  ➔ New physics might be behind them.

II. Sterile Neutrino Experiment JSNS^2

Standard Model Particles

Fermion(spin=1/2)

Name	Charge	1^{st} generation	2^{nd} generation	3^{rd} generation
Lepton	-1	e	μ	τ
	0	ν_e	ν_μ	ν_τ
Quark	+2/3	u	c	t
	-1/3	d	s	b

In the standard model, # of neutrino flavor is 3, not more.

Gauge boson(spin=1)

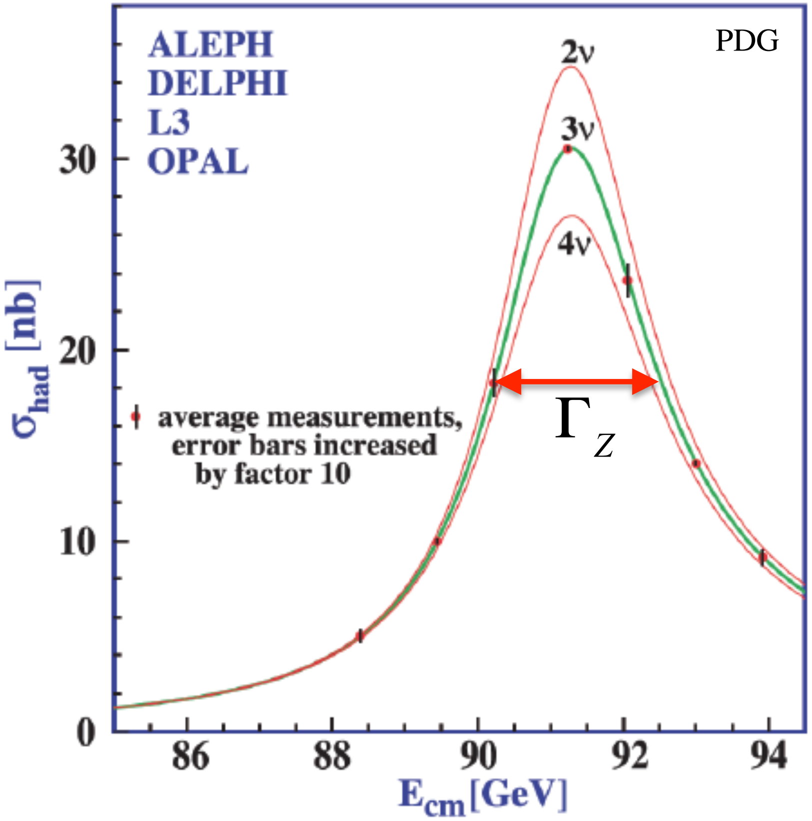
charge	EM	W	S
0	γ	Z^0	G
±1		$W^{\pm}$	

Higgs boson(spin=0)

charge	
0	H^0

Our Current Understanding of Neutrino:
of ν flavors

$$e^+ + e^- \to Z^0 \to q\bar{q} \to hadrons$$



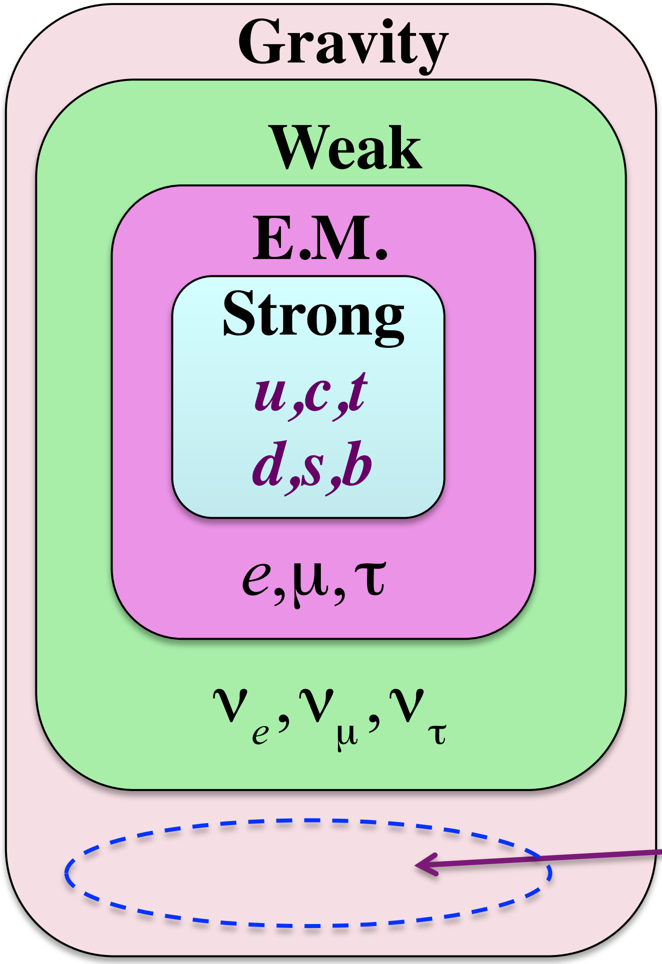
$$\Gamma_Z = n_\nu \Gamma_\nu + 3\Gamma_l + 9\Gamma_D + 6\Gamma_U$$

$$n_\nu = 3.00 \pm 0.08$$

If there is $Z^0 \to \nu_4 \bar{\nu}_4$ decay,
Z^0 lifetime → shorter, &
Z^0 width → wider

However, if
(1) $m_4 > m_Z/2 \sim 45$GeV
or
(2) ν_4 does not couple to Z^0,
it is OK such ν_4 to exist.

An idea of sterile neutrino



The interactions form a nesting structure

(For example, there is no neutral quark)

We call:

Strongly interacting fermion ➔ *quark*,

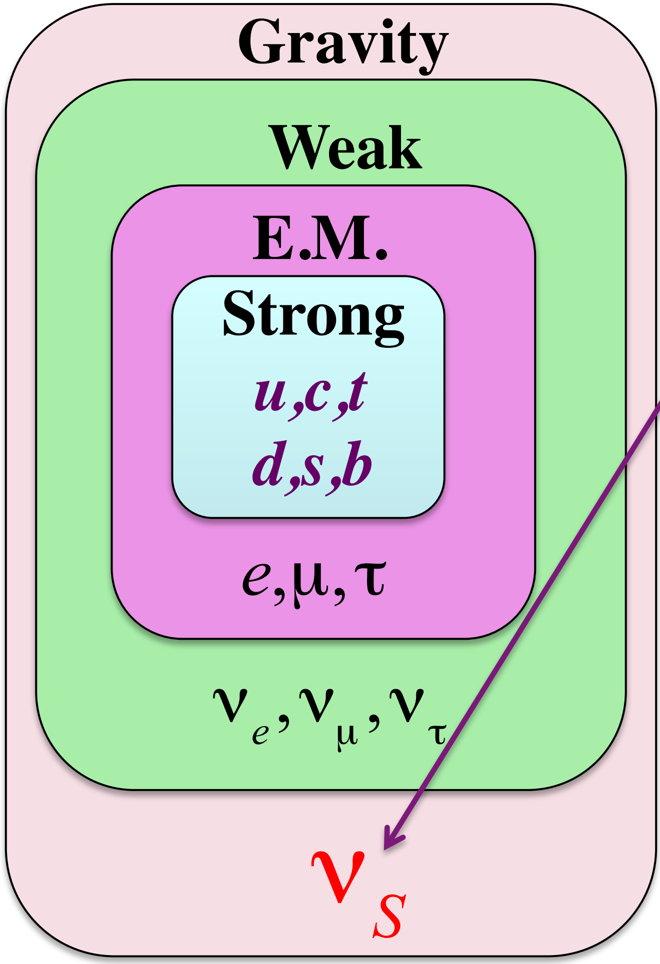
Non-Strongly " " " " ➔ *lepton*,

E.M. interacting lepton ➔ *charged lepton*,

Non-E.M. " " " " ➔ *neutrino*,

Gravity-only area is vacant.

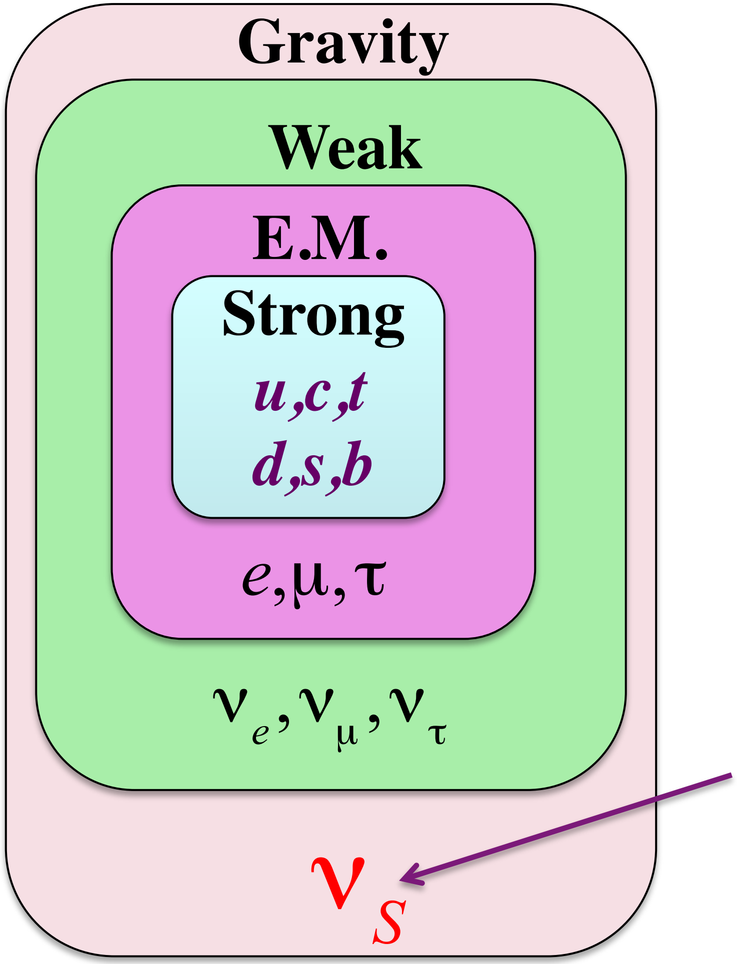
An idea of sterile neutrino



If fermions exist here, they do not affect the Z^0 width and it is OK to exists.

We call them "*Sterile Neutrino*"

An idea of sterile neutrino



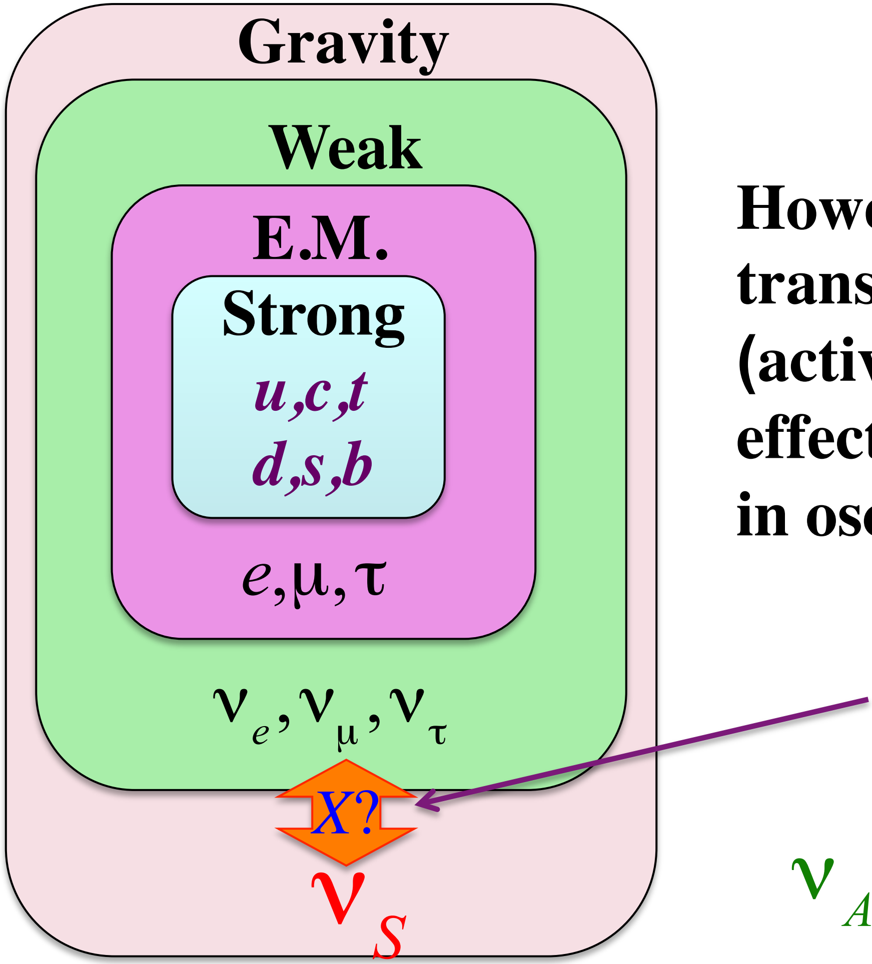
If fermions exist here, they do not affect the Z^0 width and it is OK to exists.

We call them "*Sterile Neutrino*"

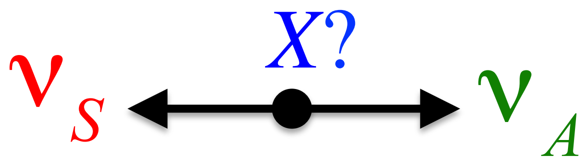
However, even if the sterile neutrino exists, we can not detect it through particle experiments because it does not perform the three standard model interactions.

(There is possibility to detect it through gravity (= mass) by space observation)

An idea of sterile neutrino



However, if there is some kind of transition between our neutrinos (active neutrino) and sterile neutrinos, effects of sterile neutrino may appear in oscillation of active neutrinos.

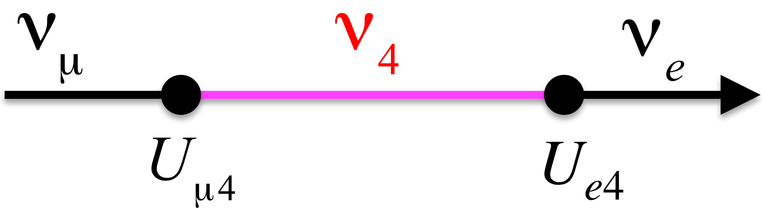


ν_A: **Active neutrino** (ν_e, ν_μ, ν_τ)

Extension of ν mixing matrix: $3\nu_A + 1\nu_S$ case

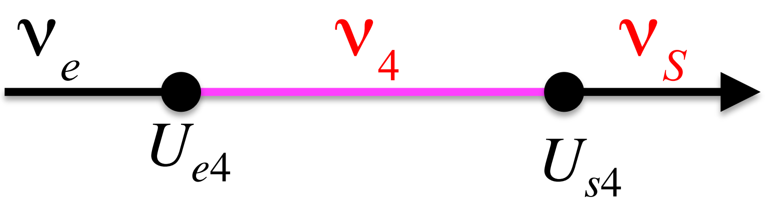
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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

For $m_4 >> m_{1\sim 3}$ case, at $E/L \sim m_4^2/4\pi$



Appearance

$$P(\nu_\mu \to \nu_e) \sim |U_{\mu 4} U_{e4}|^2 \sin^2 \frac{m_4^2}{4E} L$$



Disappearance

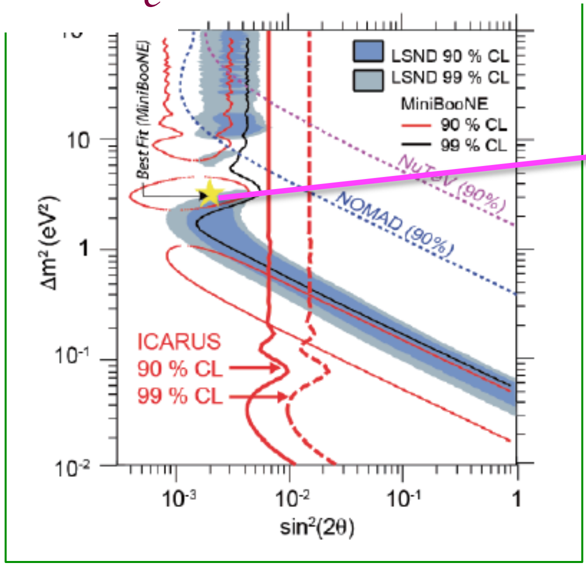
$$P(\nu_e \to \nu_e) \sim 1 - |U_{s4} U_{e4}|^2 \sin^2 \frac{m_4^2}{4E} L$$

Indications of Sterile Neutrino

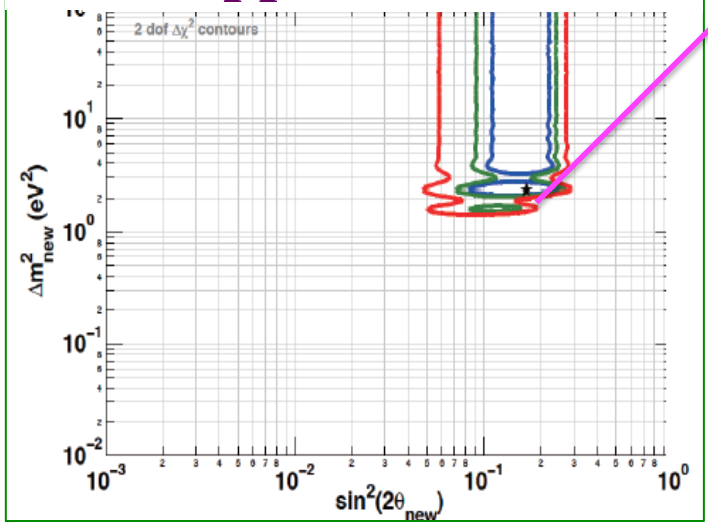
There are some indications of existence of sterile neutrino

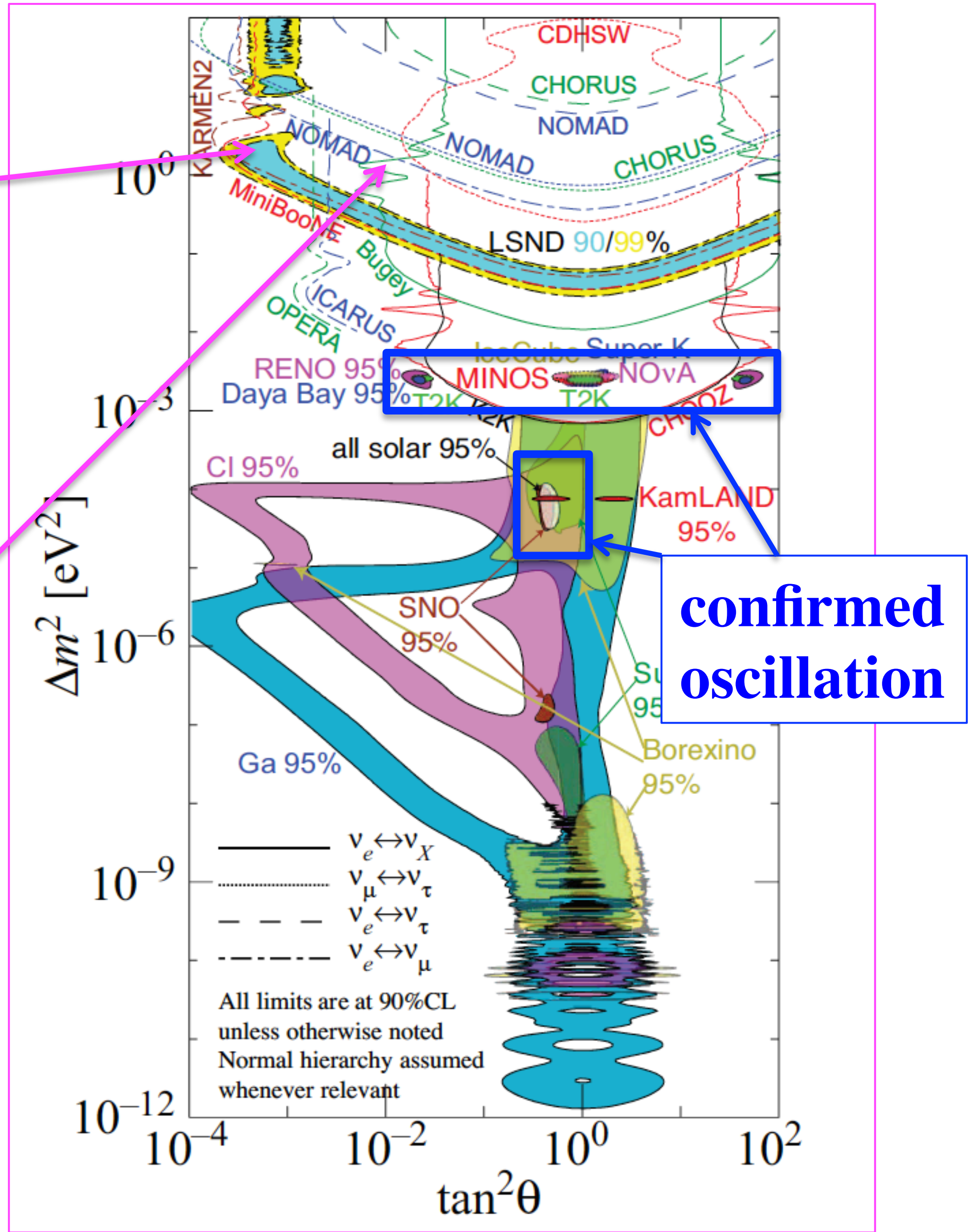
Experiment	ν source	Mode	Significance
LSND	Decay-At-Rest	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8σ
MiniBooNE	Decay-In-Flight	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.4σ
		$\nu_\mu \to \nu_e$	2.8σ
Ga-Solar	e capture	$\nu_e \to \nu_x$	2.7σ
Reactor	beta-decay	$\bar{\nu}_e \to \nu_x$	3.0σ

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance mode

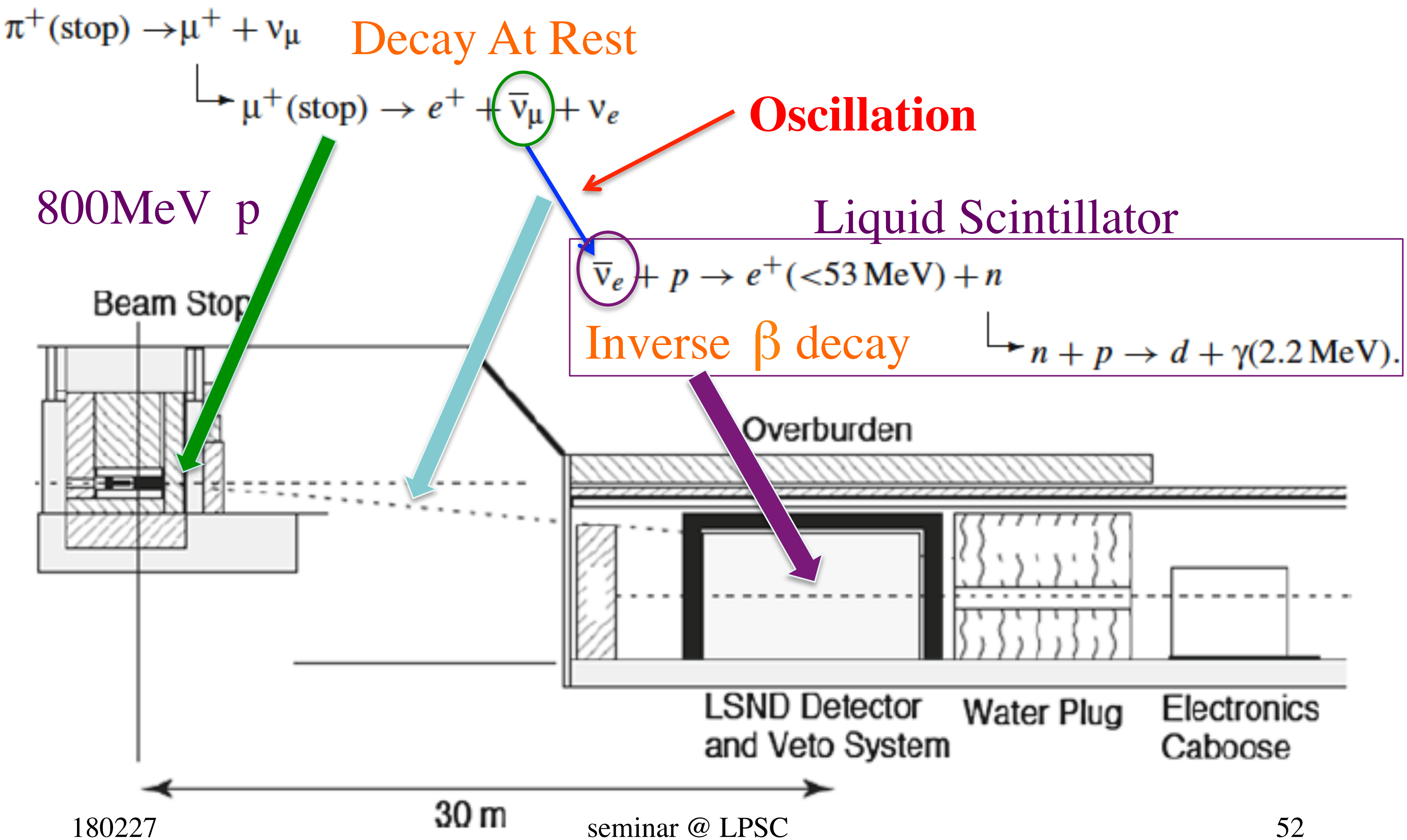


ν_e Disappearance mode



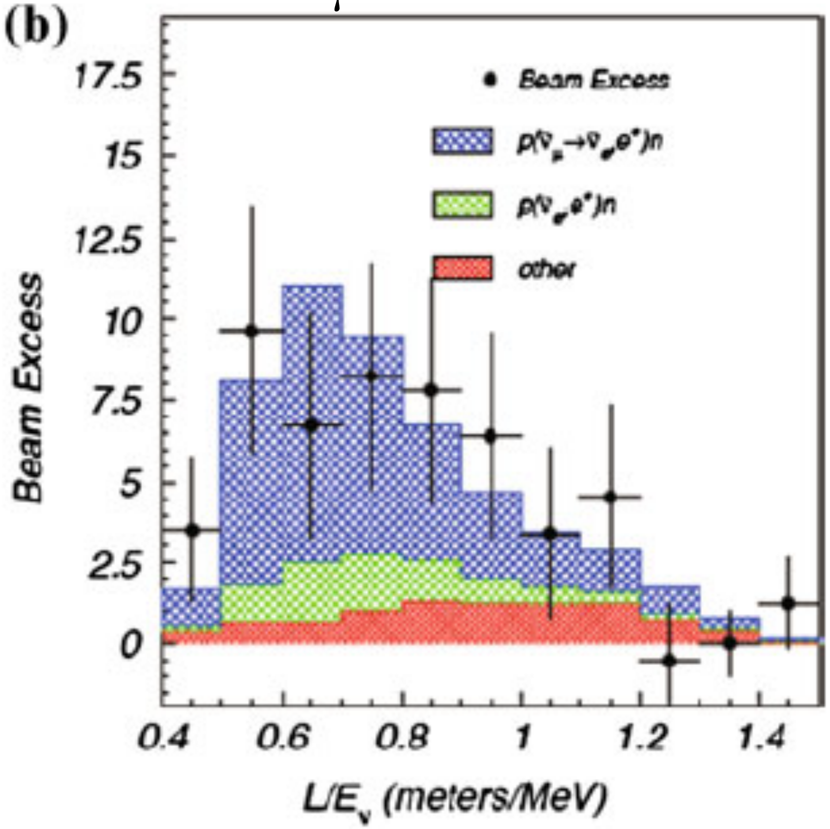


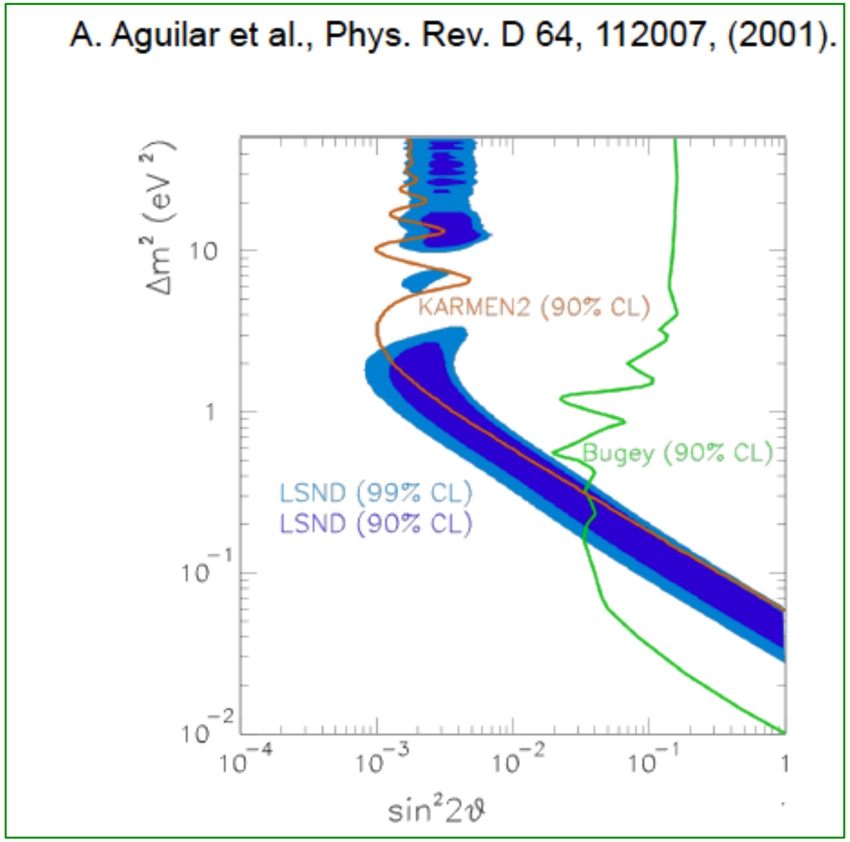
LSND experiment



LSND data: excess of $\bar{\nu}_e$ signal

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$





$\Delta m^2 > 0.03 eV^2$ ➔ **Contradict to known ν oscillations ➔ Sterile Neutrino**

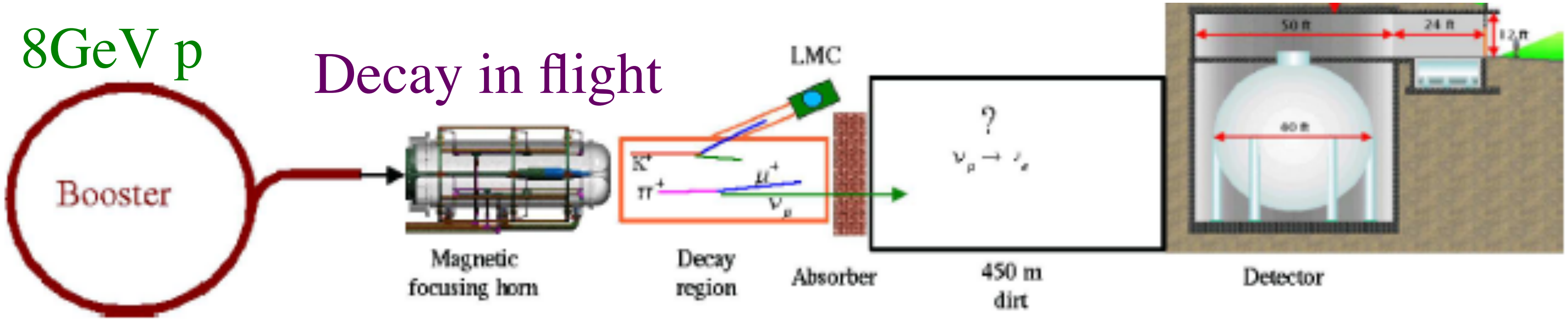
However, background were huge and analysis was complicate.
➔ Confirmation is necessary

MiniBooNE

Fermilab
8GeV p

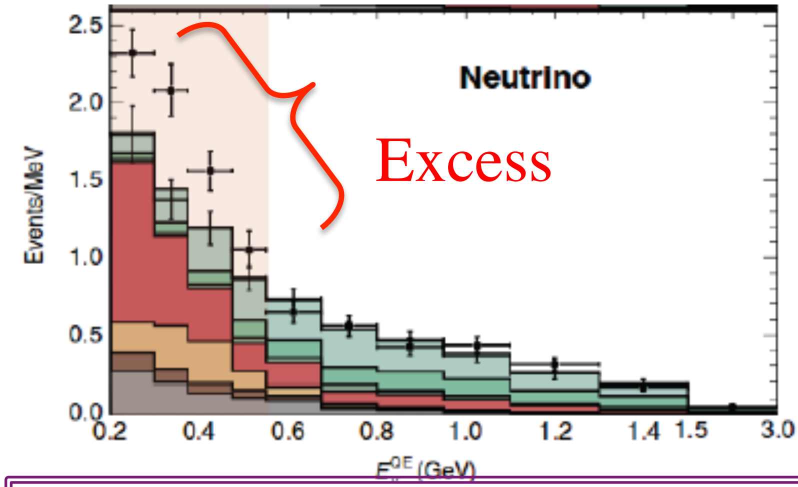
Decay in flight

Mineral oil Cherenkov

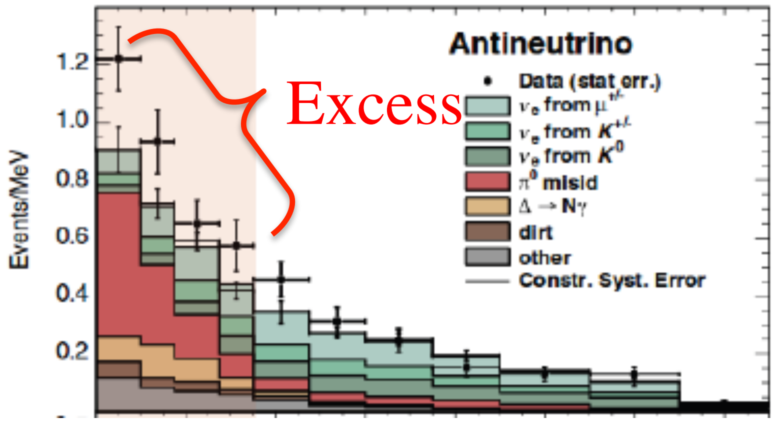


$$\pi^+ \rightarrow \mu^+ + \nu_\mu \xrightarrow{Oscillation} \nu_e \qquad \nu_e + p, C \rightarrow e^- + X$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \xrightarrow{Oscillation} \bar{\nu}_e \qquad \bar{\nu}_e + p, C \rightarrow e^+ + X$$



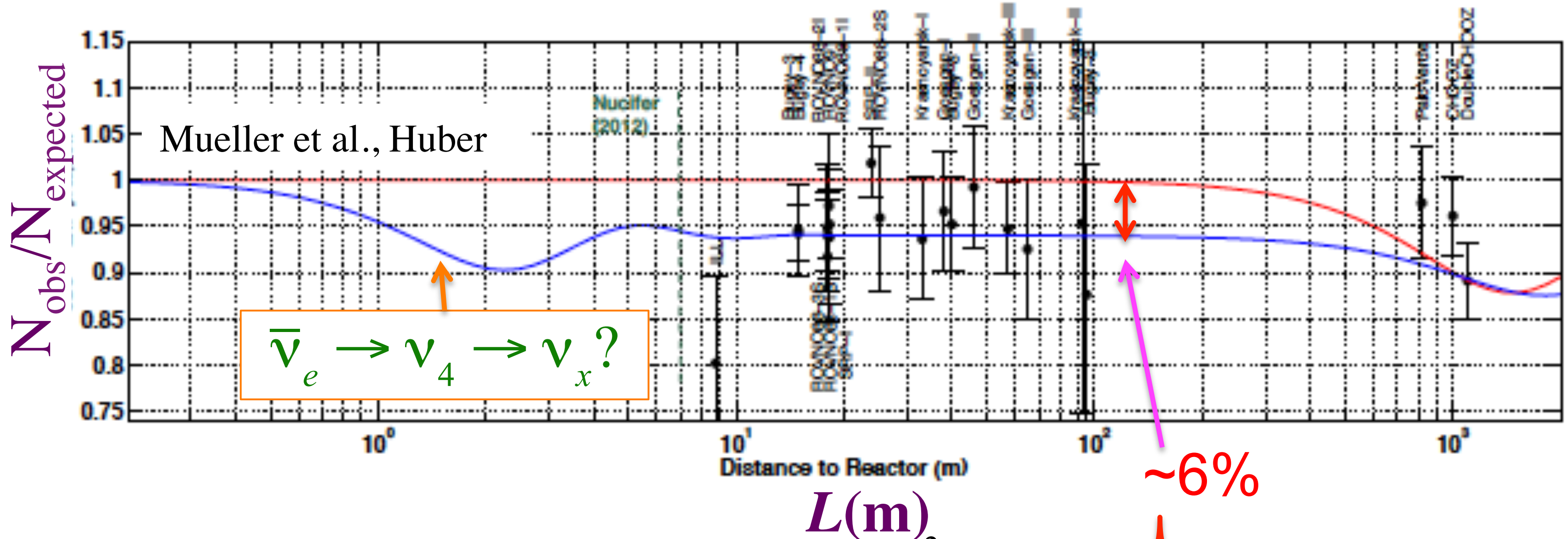
Phys. Rev. Lett. 110, 161801 (2013)



However, the electron signal might be mis-ID of N.C. γ signal
➔ Confirmation is necessary.

Reactor Neutrino Anomaly

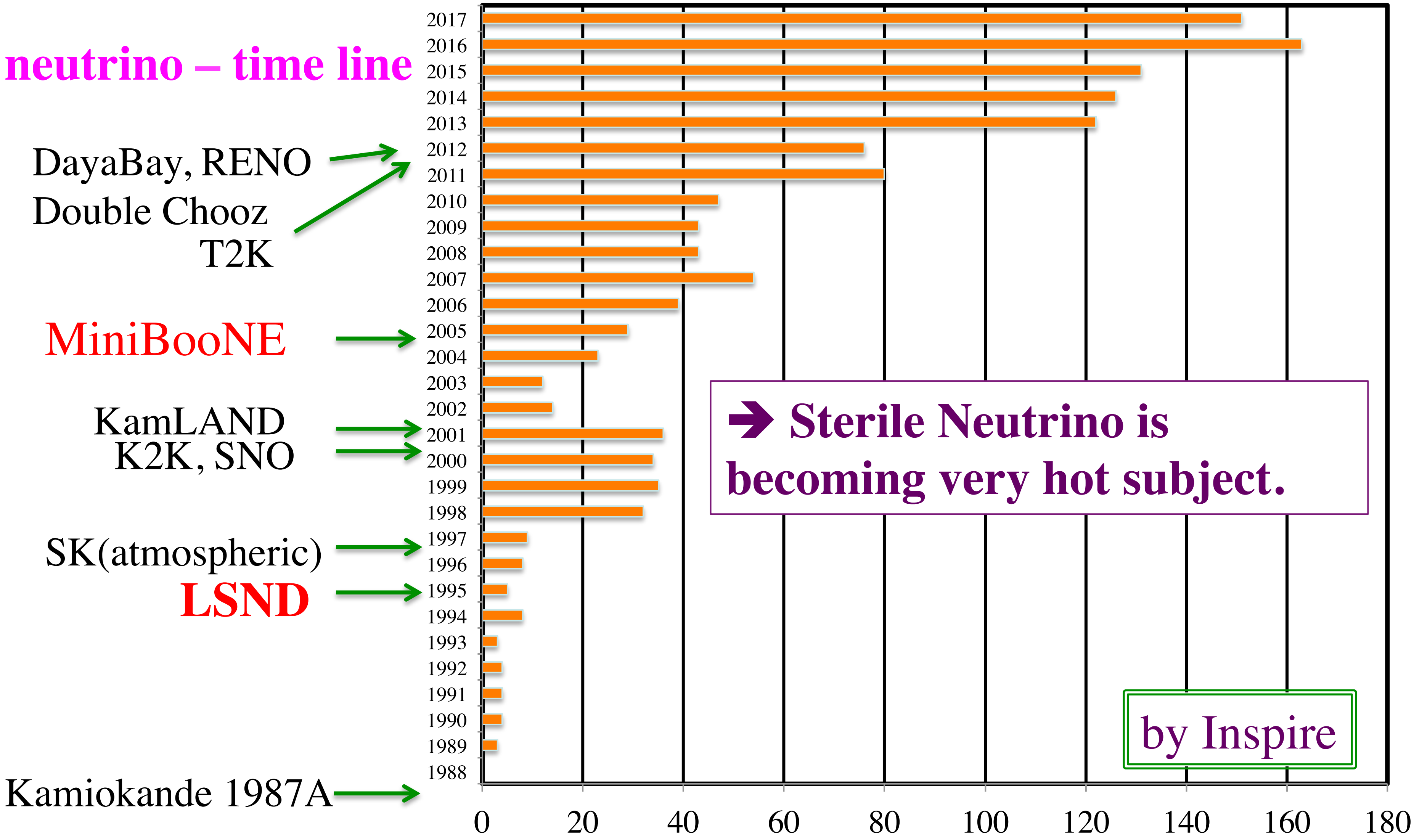
Observed reactor neutrino flux is ~6% less than expected.
It can be explained if there is $\bar{\nu}_e \to \nu_4 \to \nu_x$? oscillation at
$\Delta m^2 > 0.1\mathrm{eV}^2,\ L < 10\mathrm{m}$.



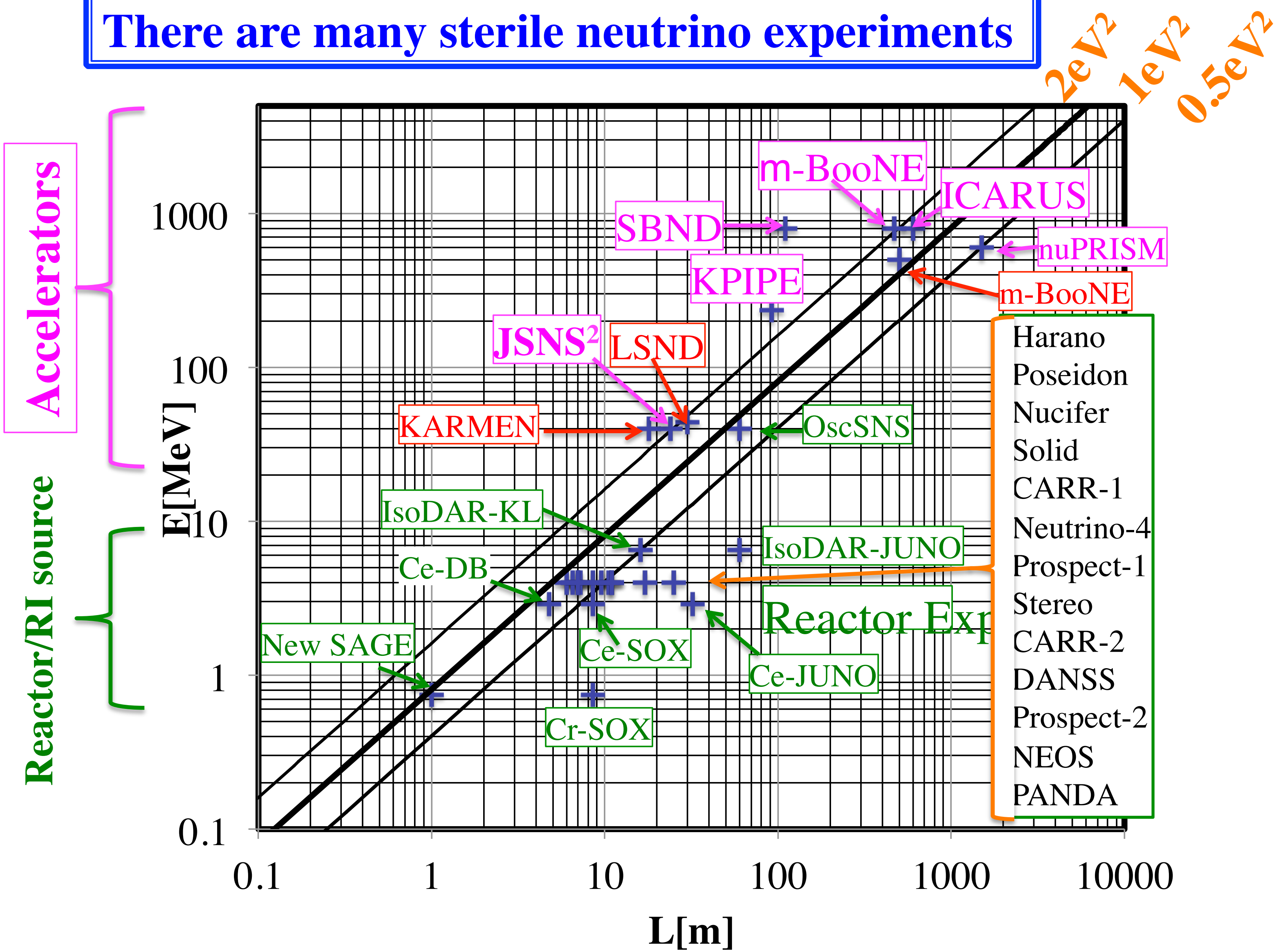
$$P(\bar{\nu}_e \to \bar{\nu}_e) \sim 1 - \sin^2 2\theta \sin^2 \frac{m_4^2}{4E} \sim 1 - \frac{1}{2}\sin^2 2\theta$$

However, it is difficult to predict yields of fission products.
➔ need to check the oscillation pattern.

yearly # of papers with title "sterile neutrino"



There are many sterile neutrino experiments

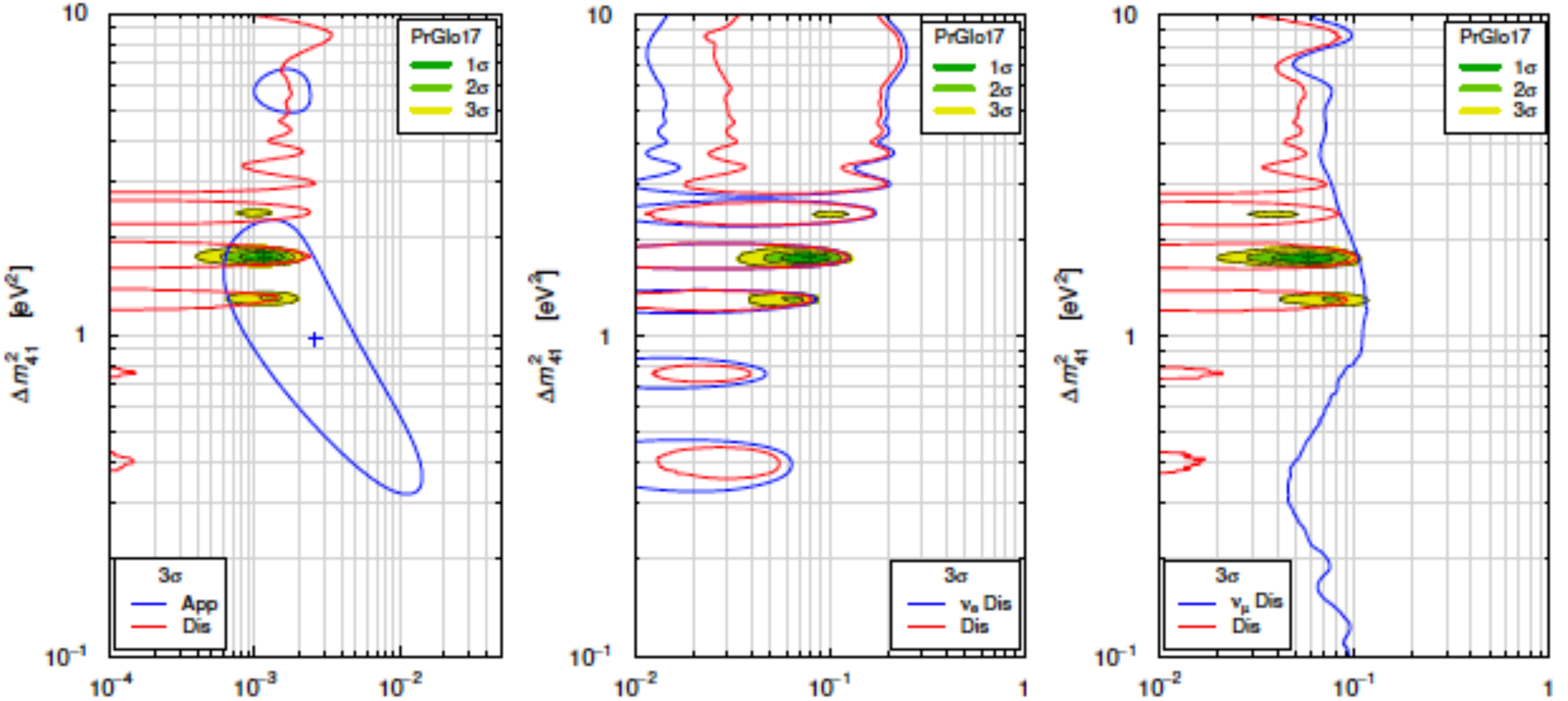


There have been a lot of negative results.

KARMEN, ICARUS, DayaBay, MINOS+, NEOS, IceCube etc. etc.

$3\nu_A + 1\nu_S$ analysis

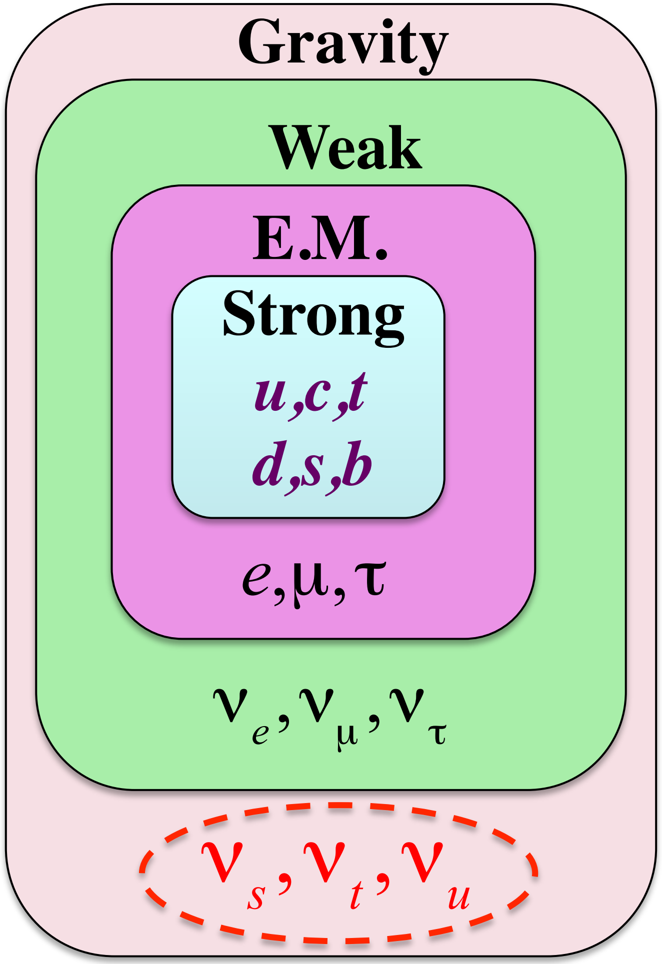
S.Gariazzo *et al*. (arXiv:1703.00860v3)



$\sin^2 2\theta_{e\mu}$ $\sin^2 2\theta_{ee}$ $\sin^2 2\theta_{\mu\mu}$

➔ **only small parameter regions remain.**

However, for $3\nu_A + 3\nu_S$ case



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_t \\ \nu_u \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & U_{e6} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & U_{\mu5} & U_{\mu6} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & U_{\tau5} & U_{\tau6} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & U_{s6} \\ U_{t1} & U_{t2} & U_{t3} & U_{t4} & U_{t5} & U_{t6} \\ U_{u1} & U_{u2} & U_{u3} & U_{u4} & U_{u5} & U_{u6} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \nu_6 \end{pmatrix}$$

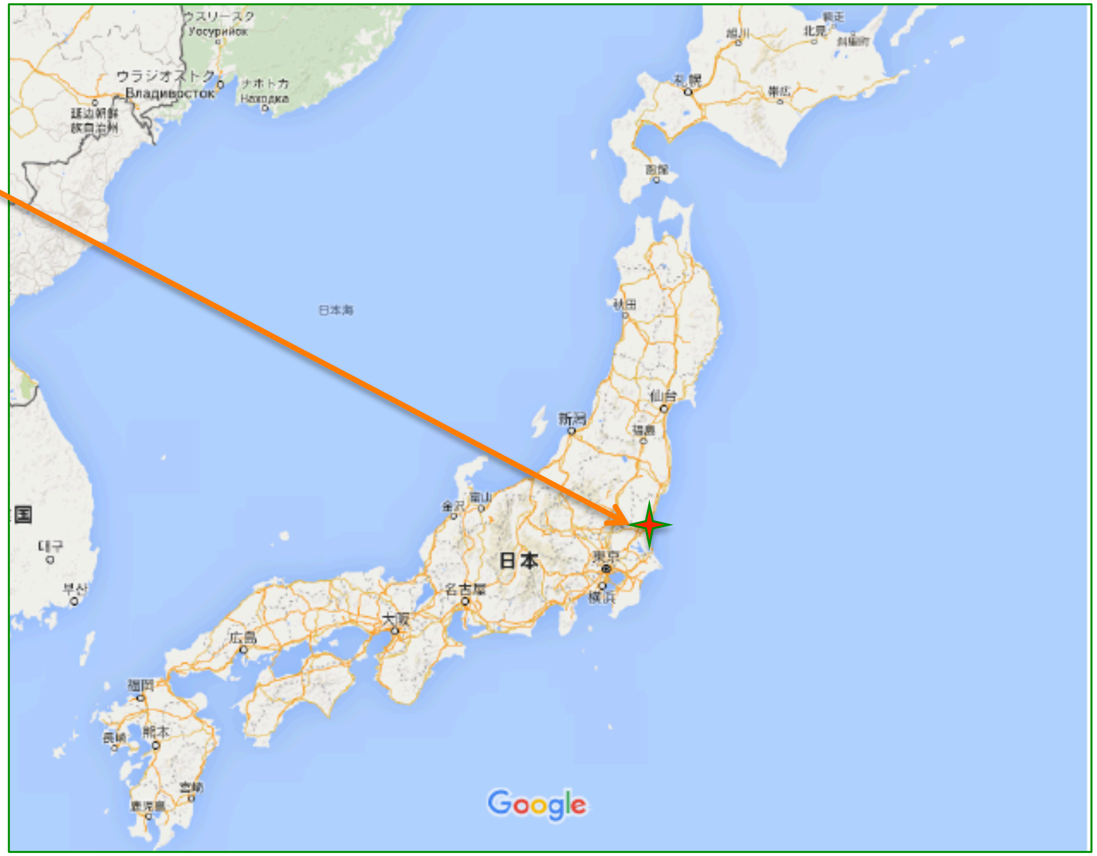
$$m_1, m_2, m_3, m_4, m_5, m_6$$

There are many free parameters and it is difficult to reject appearance results by disappearance experiments.

➔ Direct test of the LSND result is indispensable to solve the sterile neutrino anomaly.

JSNS^2 Sterile Neutrino experiments at J-PARC MLF

JSNS^2



JSNS² (J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source)

Direct ultimate tests for LSND.

JSNS² collaboration (53 collaborators)

- 10 Korean institutions (18 members)
- 6 Japanese institutions (28 members)
- 5 US institutions (7 members)

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[13], 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]

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[4] Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi, JAPAN
[5] J-PARC Center, JAEA, Tokai, Ibaraki JAPAN
[6] University of Michigan, Ann Arbor, MI, 48109, USA
[7] Department of Physics, Kitasato University, Sagamihara 252-0373, Kanagawa, JAPAN
[8] Gwangju Institute of Science and Technology, Gwangju, 61005, KOREA
[9] Department of Fire Safety, Seoyeong University, Gwangju 61268, KOREA
[10] Department of Physics, Chonnam National University, Gwangju, 61186, KOREA
[11] School of Liberal Arts, Seoul National University of Science and Technology, Seoul, 139-743, KOREA
[12] Division of Science Education, Physics major, Chonbuk National University, Jeonju, 54896, KOREA
[13] Department of Physics and Astronomy, Seoul National University, Seoul 08826, KOREA
[14] Department of Physics, Kyungpook National University, Daegu 41566, KOREA
[15] High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN
[16] Department of Physics, Kyoto University, Kyoto, JAPAN
[17] University of Florida, Gainesville, FL, 32611, USA
[18] Department of Physics, Sungkyunkwan University, Gyeong Gi-do, KOREA
[19] University of Alabama, Tuscaloosa, AL, 35487, USA
[20] Colorado State University, Tuscaloosa, AL, 35487, USA
[21] Brookhaven National Laboratory, Upton, NY, 11973-5000, USA

May 23, 2017

Review of the points of the LSND experiment

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

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

Decay At Rest

$\bar{\nu}_\mu$ from μ^+ Decay at Rest
& Inverse β decay detection
@ L=30m

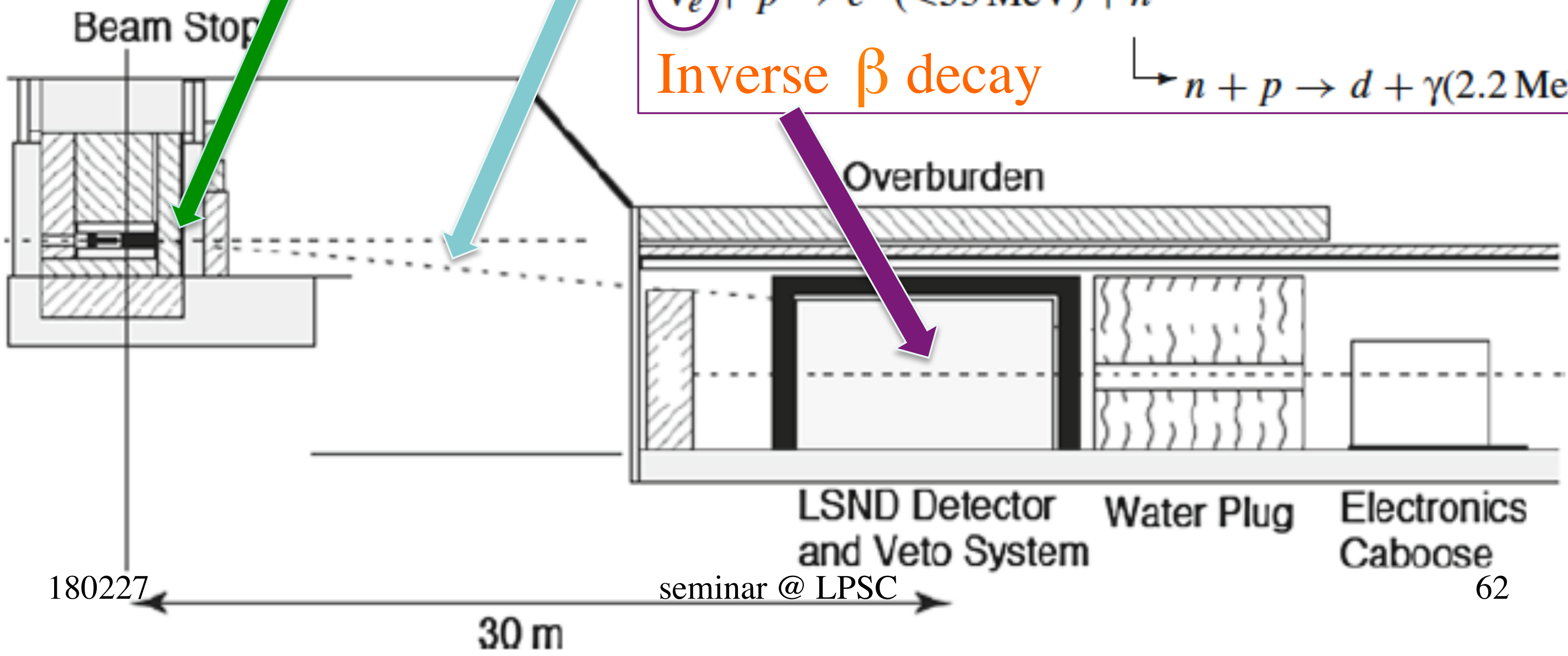
800MeV p

Liquid Scintillator

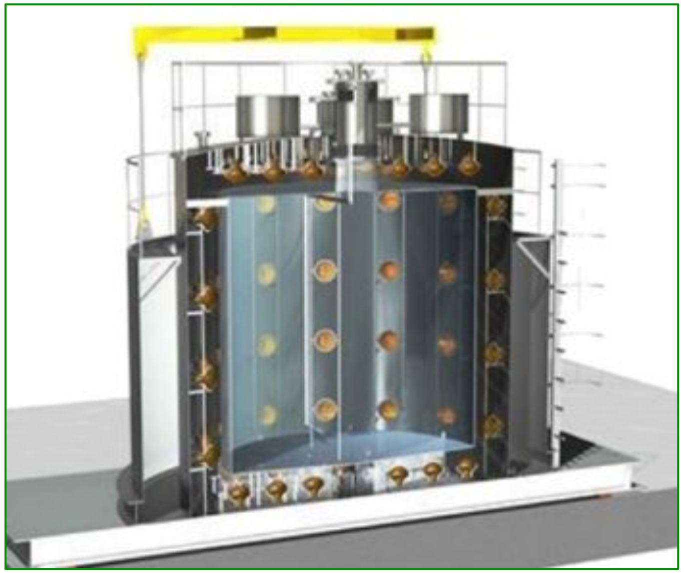
$\bar{\nu}_e + p \to e^+(<53\,\text{MeV}) + n$

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

Inverse β decay

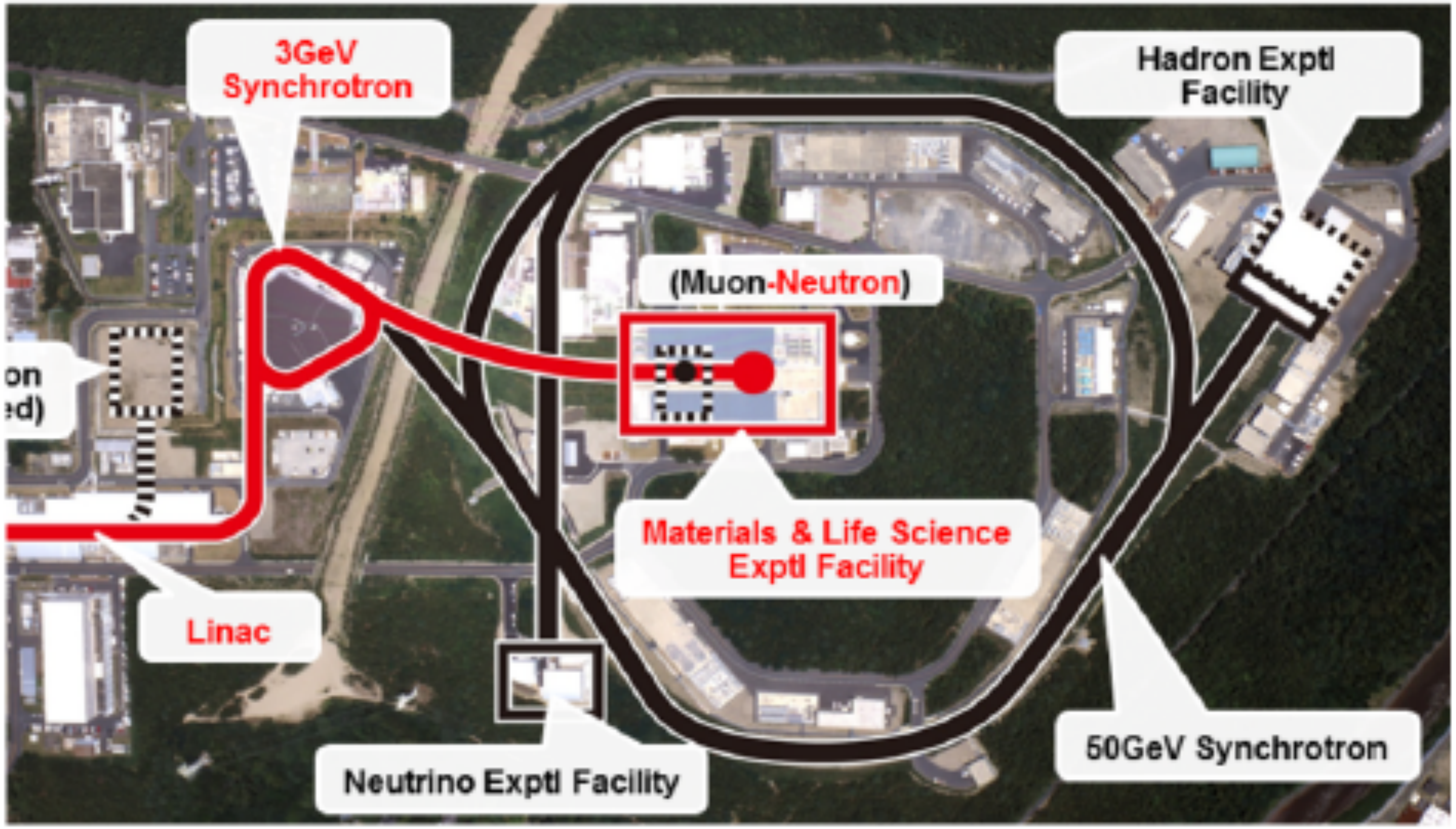


Motivation of JSNS^2 experiment

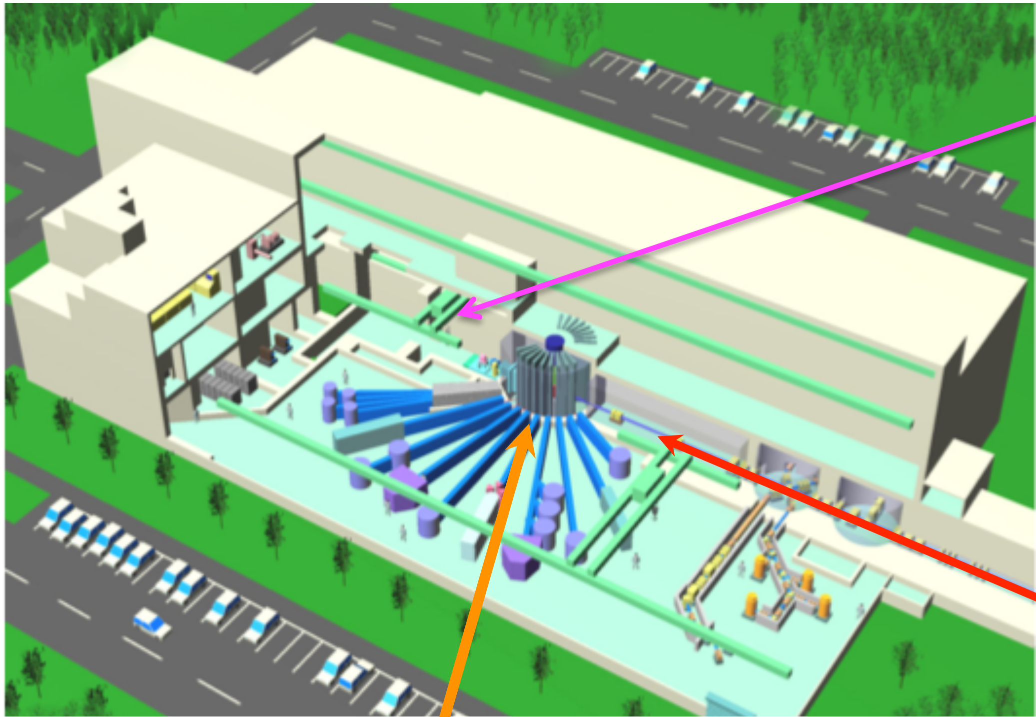


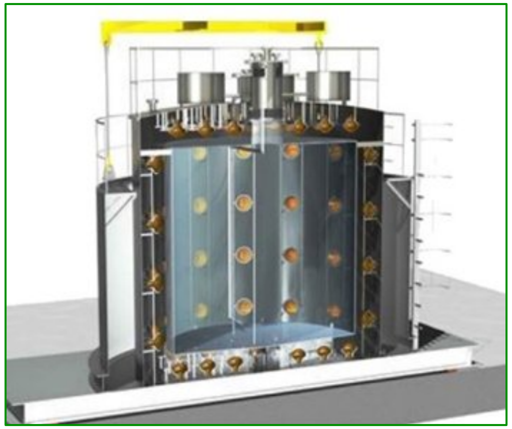
➔ **Direct test of the LSND result, using the same neutrino (from μ^+ decay at rest), the same ν detection mechanism (inverse β-decay with *p*), a similar baseline (24m vs 30m), much better S/N (pulsed beam, Gd-Liquid Scinti.), better energy resolution. (➔ scintillator vs Ch.-level light) higher statistics. (Event rate: x2 in phase-1, x6 in phase-2)**

Facility : J-PARC
Material & Life Science Experimental Facility



↓ ν to T2K





JSNS^2 Detector:
3rd floor (L=24m)

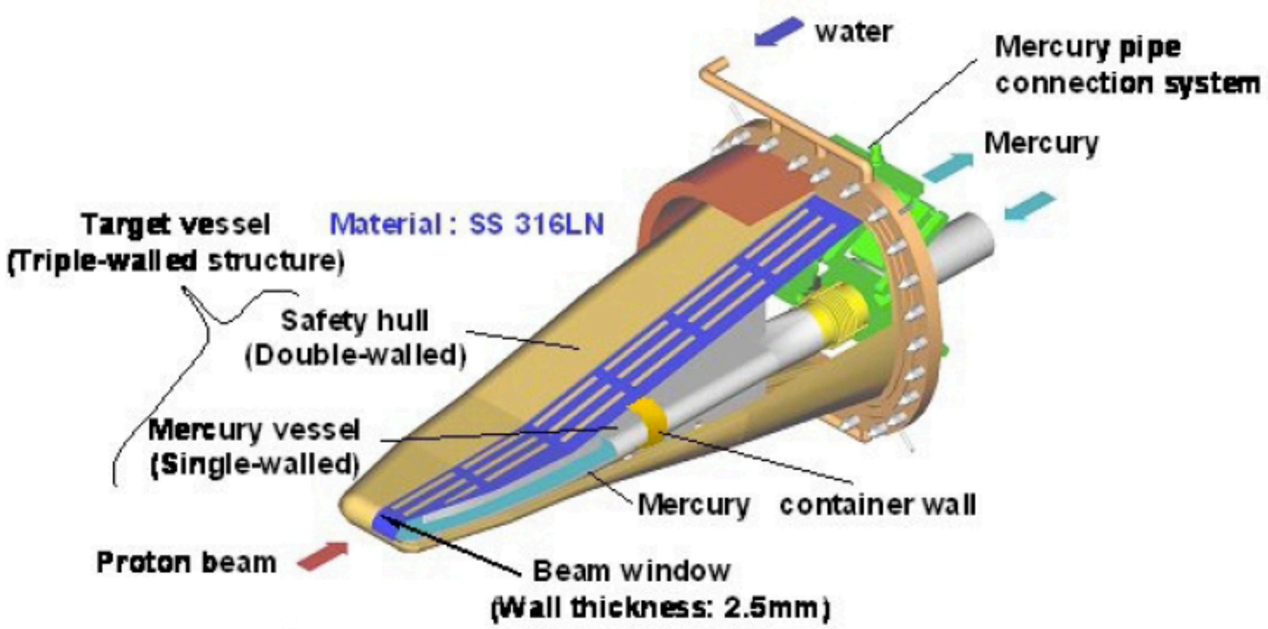
17ton detector
(1st phase)

Hg target (neutron & neutrino source)

3GeV
proton beam

- World-class high intensity neutron source driven by high power proton beam
  - beam energy: 3GeV
  - design beam power: 1MW

Neutrino source: Hg target

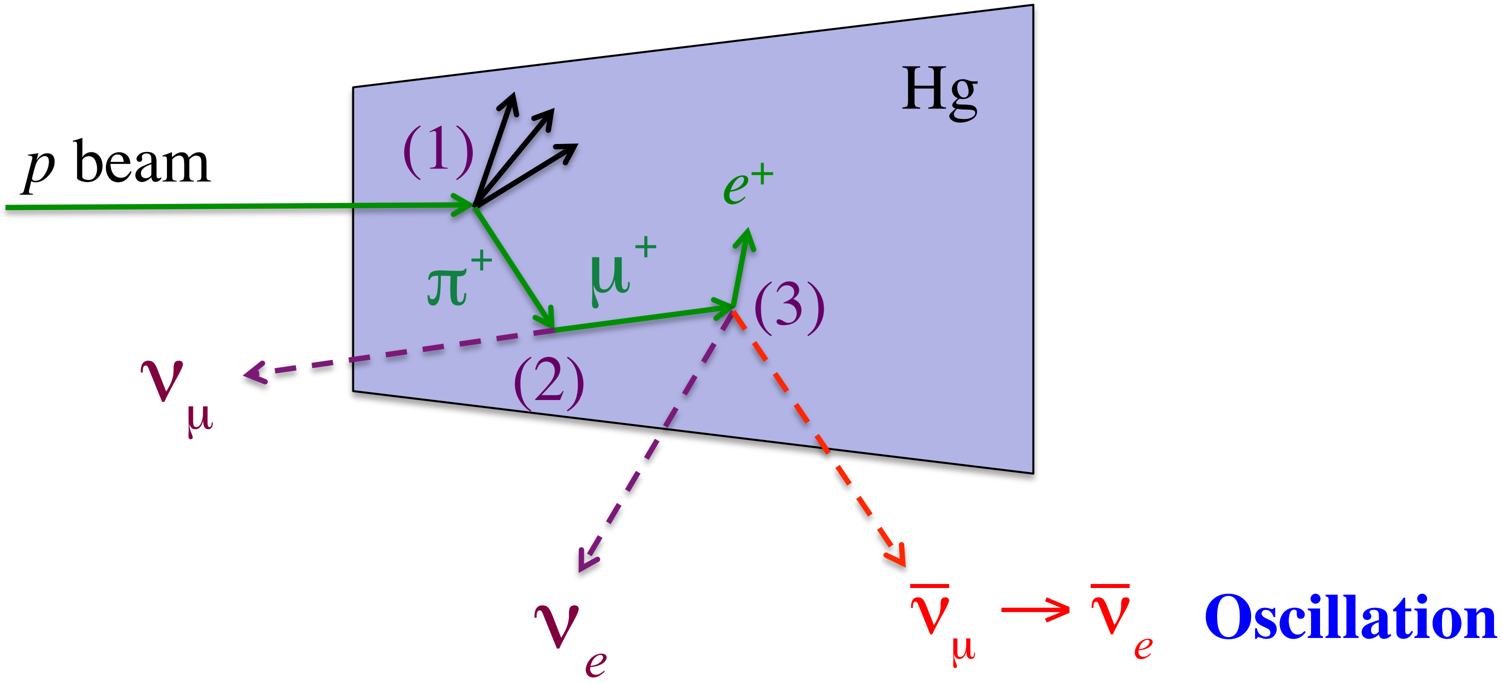


$$p + Hg \rightarrow \pi^{\pm} + X$$

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

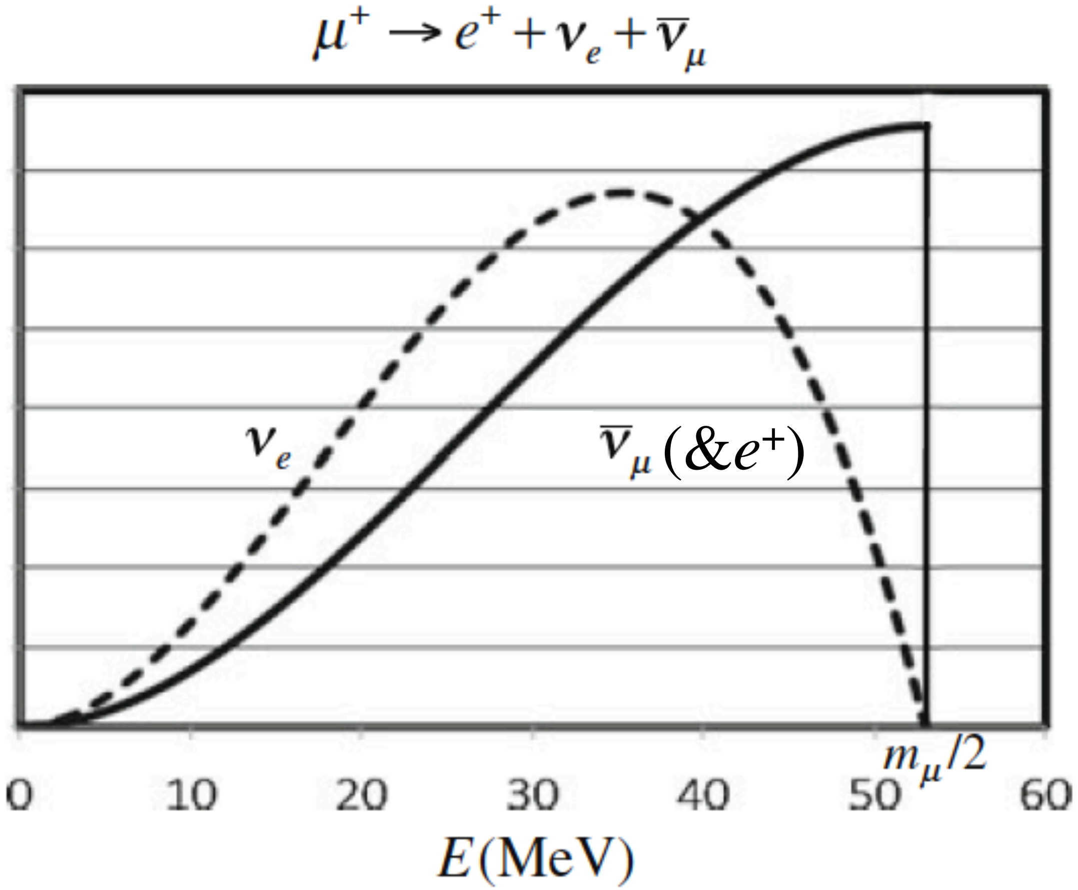
$$\hookrightarrow \mu^{+}(stop) \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

Properties of DAR neutrino with pulsed beam



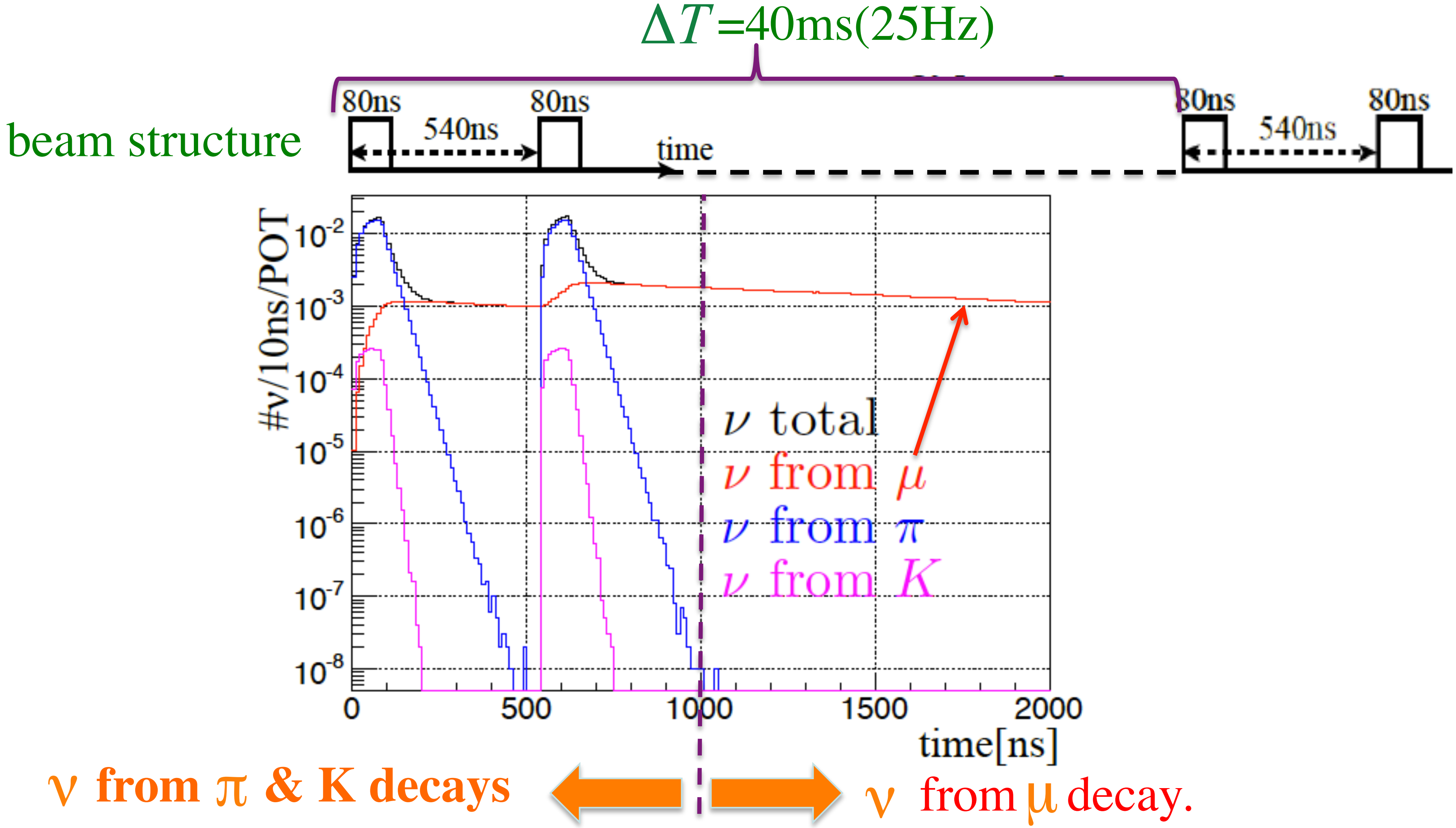
* The energy spectra of the neutrinos are perfectly known.
* The neutrino–proton IBD cross section is known to a few%
* The time structure of the neutrino is perfectly known.
* π^- & μ^- are absorbed by nucleus before they decay.
* π^+ & K^+ -origin ν can be removed by timing

Energy Spectra of ν from μ⁺ decay at rest

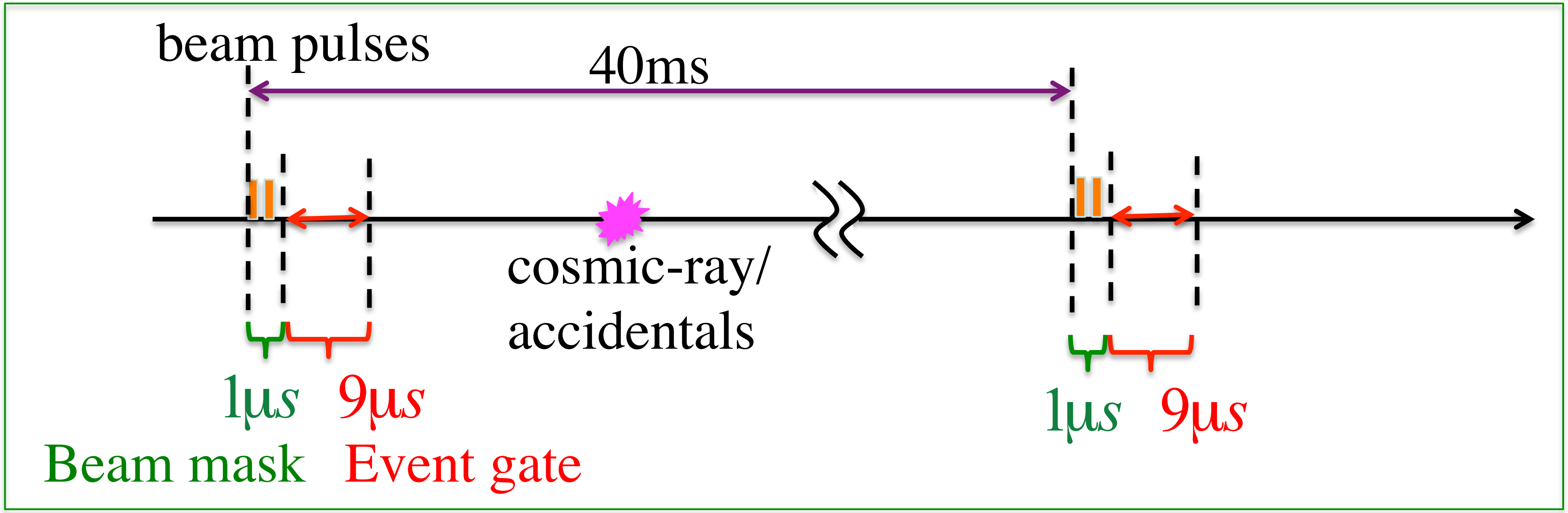


This energy spectra are the same for LSND and JSNS².

MLF Pulsed beam can reduce beam BKG and physics BKG (ν from π, K decay) drastically.



Cosmic-ray and accidental BKG can also be suppressed strongly by the pulsed beam

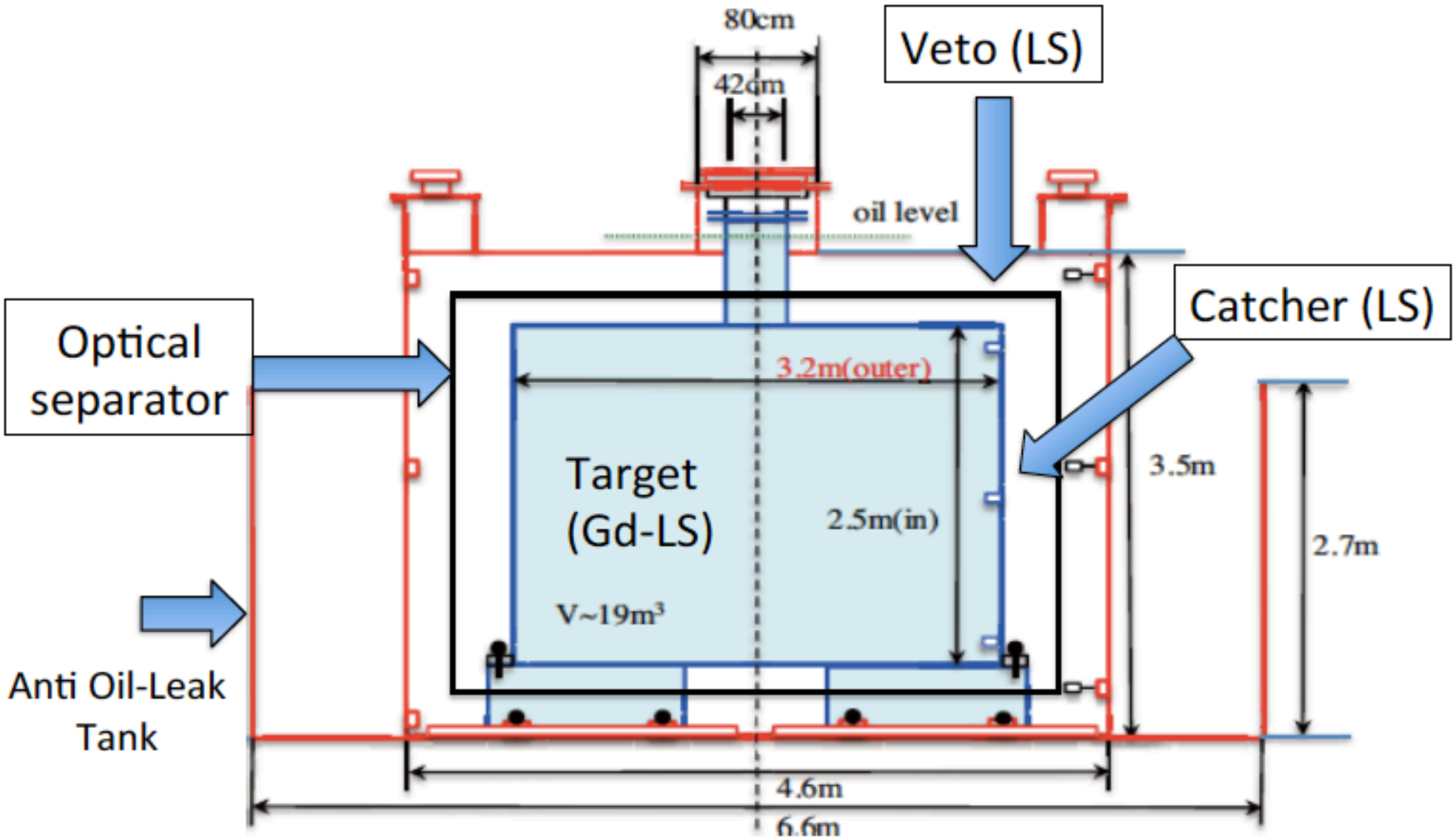


Open 9μs event gate for every 40ms of beam interval

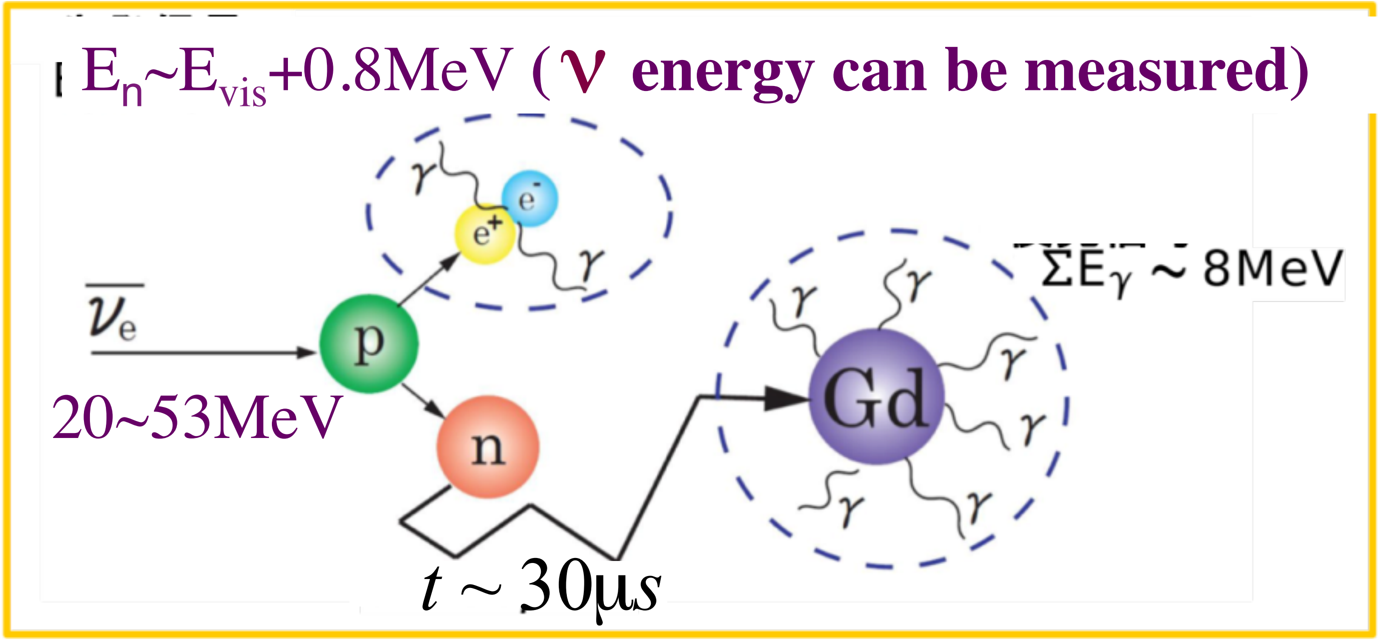
➔ beam-uncorrelated BKGs are suppressed to 1/4,400.

➔ Background level can be measured precisely by off timing events

Concept of the JSNS² Detector



$\bar{\nu}_e$ Detection: Gd-Loaded Liquid Scintillator



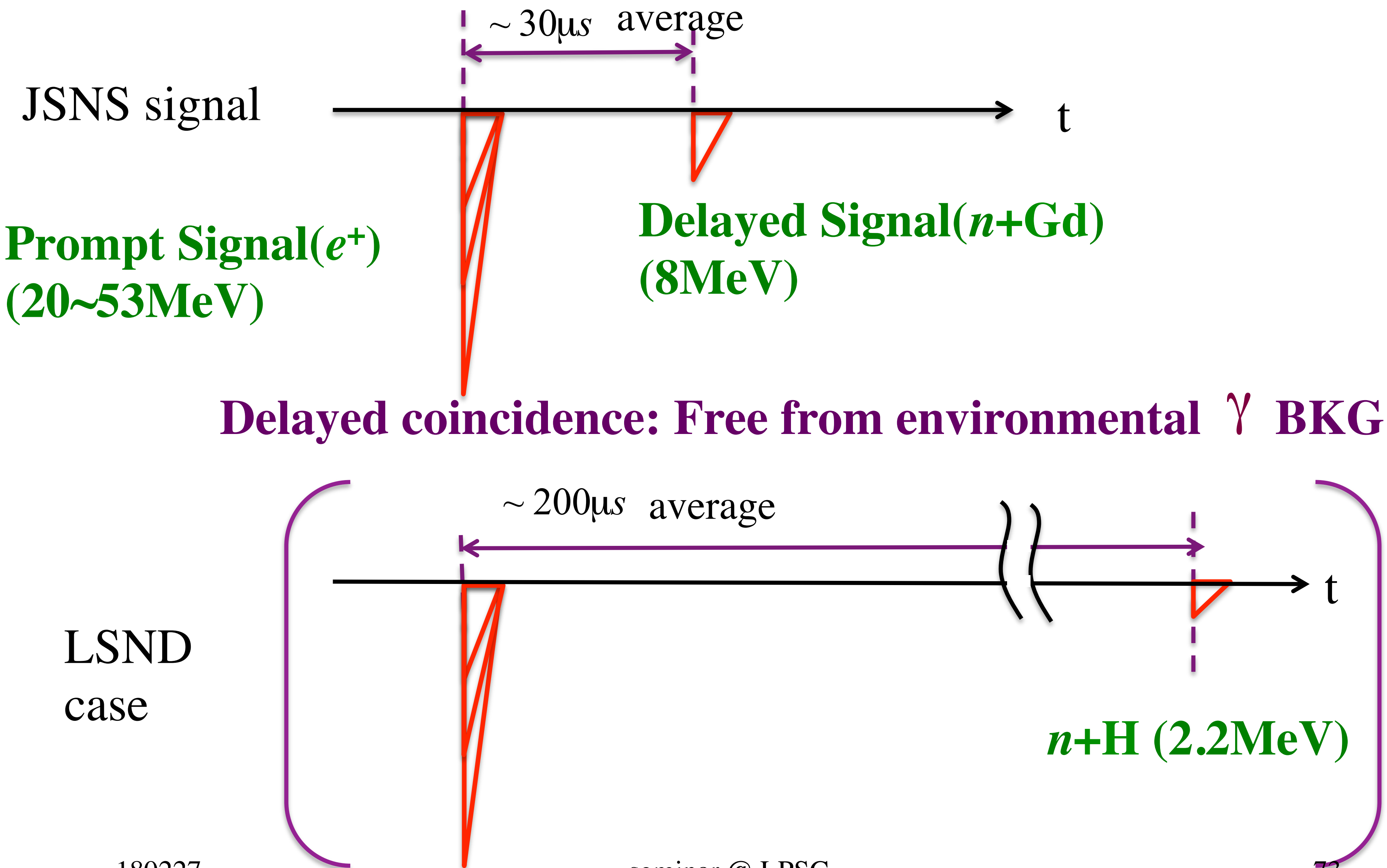
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e + p \rightarrow e^+ + n$

oscillation

n+Gd → Gd' +γs ($\sum E_\gamma$ =8MeV)

Similar to the reactor neutrino experiments but the neutrino energy is much higher (up to 53MeV)

$\bar{\nu}_e$ Detection: Gd-Loaded Liquid Scintillator



Energy Reference

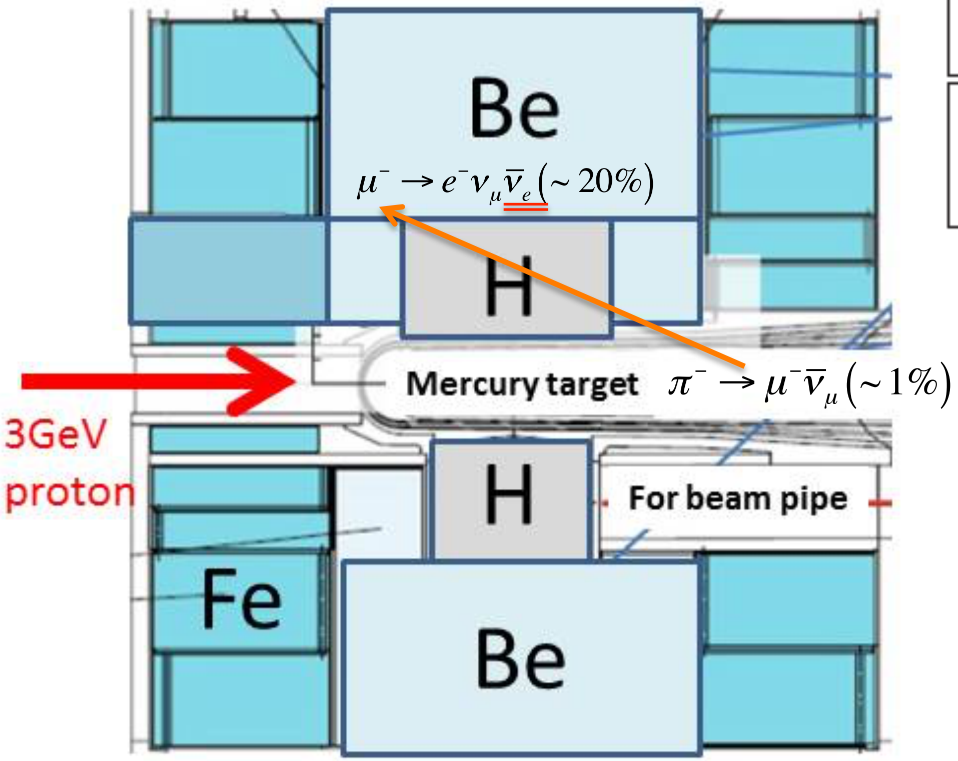
Signal: $\bar{\nu}_e(D@R) + p \rightarrow e^+ + n$

Cosmic ray Michel e: $\mu^+(stop) \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

***These positrons have the same energy distribution after corrected by the IBD cross section.**
*** The position dependence of the energy responses are the same.**

➔ Michel e^+ from stopping cosmic ray can be used as very good energy reference spectrum.

MLF mercury target and Intrinsic $\overline{\nu}_e$ BKG estimation



Material	Lifetime, ns (experiment)
Be	2162.1 ± 2.0
Fe	206.0 ± 1.0
Hg	76.2 ± 1.5

T.Suzuki et al.
PRC35,2212(1987)

	Target	π^- absorb	μ^- capture	suppression	x	π^-/π^+	
LSND	H2O	96%	88%	$5\text{x}10^{-3}$	x	0.13	$= 6.5\text{x}10^{-4}$
J-PARC	Hg(+Fe+Be)	99%	~80%	$1.7\text{x}10^{-3}$	x	1.	$= 1.7\text{x}10^{-3}$

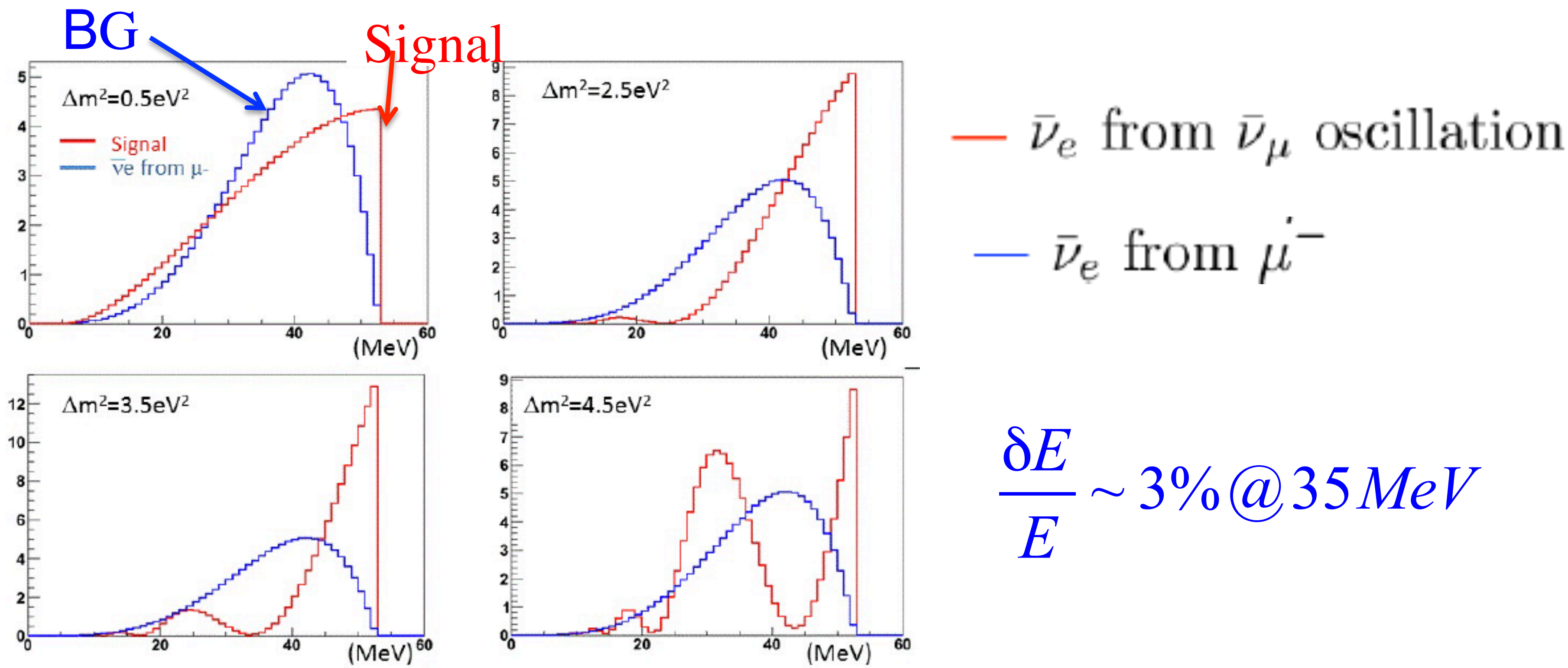
Suppression of $\mu^- \to \bar{\nu}_e$ Physics Background

π^- (stop) $\to \mu^- + \bar{\nu}_\mu$

$\quad\hookrightarrow \mu^-$ (stop) $\to e^- + \nu_\mu + \bar{\nu}_e$ (background)

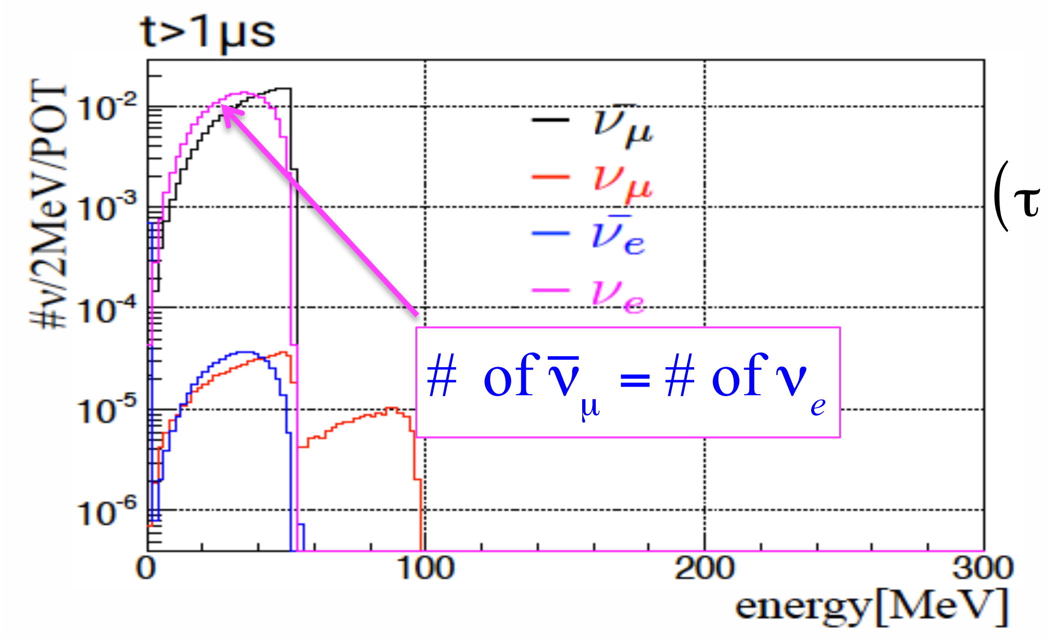
$$\bar{\nu}_e / \bar{\nu}_\mu \sim 1.7 \times 10^{-3}$$

Can be separated by the spectrum analysis



$$\frac{\delta E}{E} \sim 3\% @ 35 MeV$$

$\bar{\nu}_\mu$ flux normalization by $\nu_e + {}^{12}C$ reaction



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

$$\left(\tau = 11ms, Q = 17.3MeV\right) \searrow {}^{12}C + e^+ + \nu_e$$

$$\frac{\delta\sigma_{\nu C}}{\sigma_{\nu C}} \sim 10\%$$

	primary timing	primary energy	delayed timing	delayed energy
$\bar{\nu}_\mu \to \bar{\nu}_e$	1-10 μs	0-53 MeV	10-100 μs	8 MeV
$\nu_e C \to e N_{gs}$, $N_{gs} \to C e^+ \nu_e$	1-10 μs	0-37 MeV	100 μs-10 ms	0-16 MeV

$JSNS^2$ (1^{st} phase) vs LSND

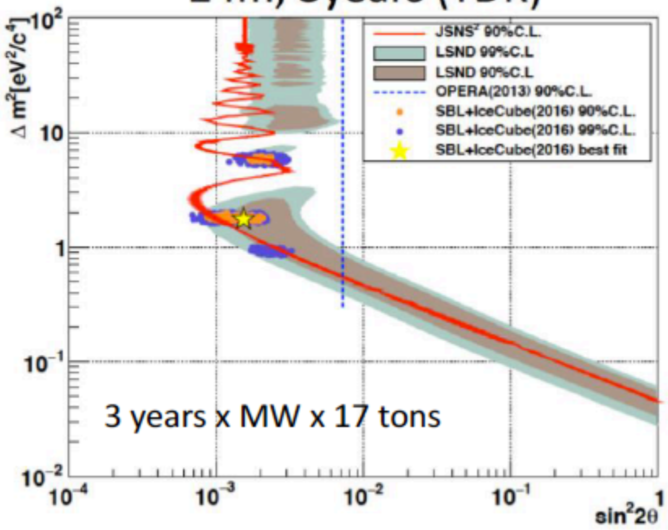
	$JSNS^2$(1st phase)	LSND
Target Mass.	17t	167t
Baseline	24m	30m
Beam energy	3GeV	0.8GeV
Beam power	1MW	--
Beam Duty Factor	1/8,800	1/14
Stopping μ^- / μ^+	$1.7\text{x}10^{-3}$	$6.5\text{x}10^{-4}$
Delayed signal	8MeV, $\Delta t \sim 30\mu s$	2.2MeV, $\Delta t \sim 200\mu s$
Liquid Scintillator	Gd Loaded	Cherenkov + Low LO Scinti.
Cosmic fast n rejection	Pulse Shape Discri.	Cherenkov
$\bar{\nu}_e$ signal events rate	29/year $(\sin^2 2\theta = 0.003)$	15/year
$\Delta E / E$	3%@35MeV	7%@45MeV
Cost	$	$$$

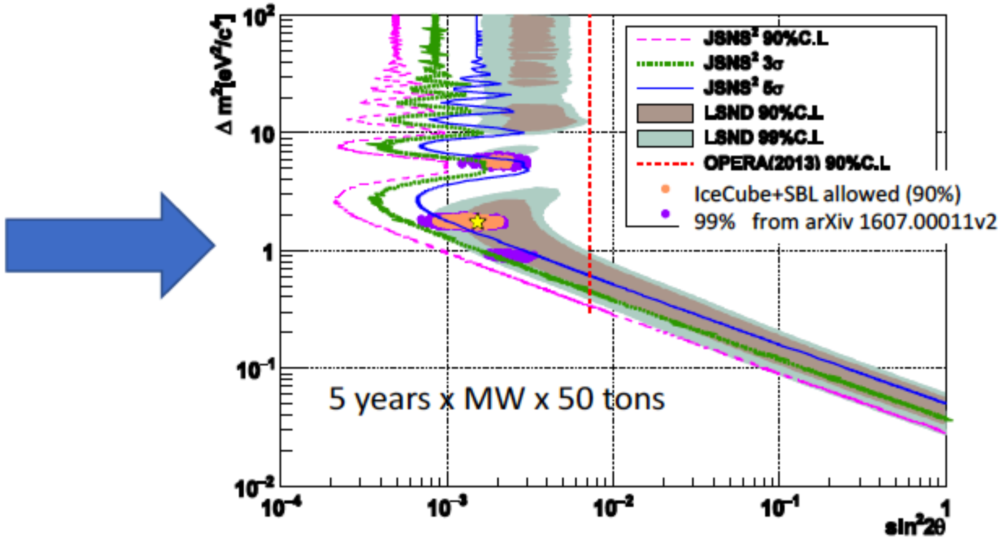
180227

Sensitivity / Upgrade

- To have a good international competition capability, we start the experiment with one detector (17tons fiducial volume).
- Even with one detector, we have a good 90% C.L constraints for the best fit point of global fit (of sterile neutrino searches) 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 5σ significance test for the best fit point of the global fit.

24m, 3years (TDR)

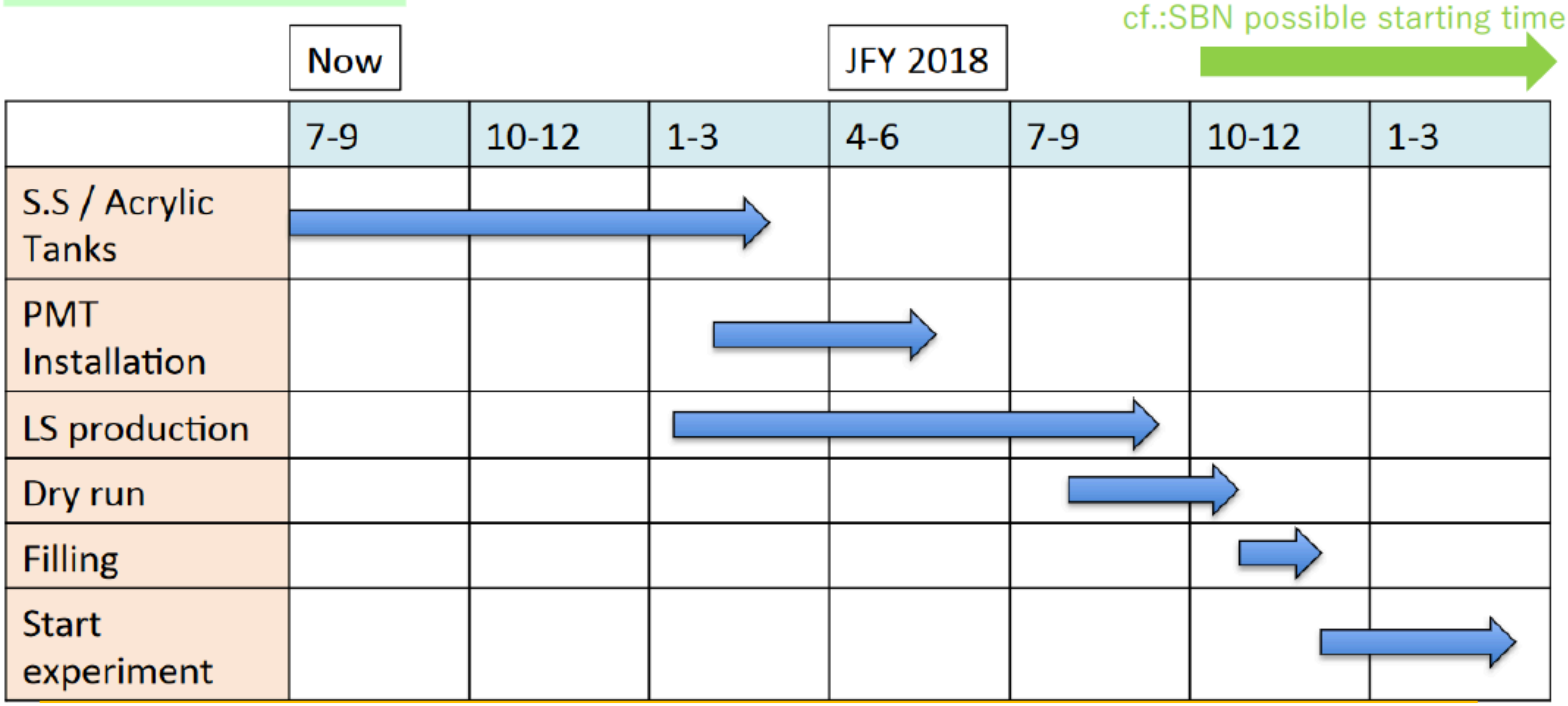




Maruyama, Erice2017

Schedule & Status

Overall schedule



Summary

* There are indications of sterile neutrinos at $m \sim O$(eV)
* Disappearance experiments can not rule out the LSND appearance indication if >1 sterile neutrino exist.
* JSNS^2 experiment performs direct test for LSND anomaly.
* The first phase (1 of 2 detectors) of JSNS^2 is funded and aiming to start data taking in 2019.
* In the 1st phase, the best fit point can be tested with 90%CL and in the 2nd phase, with 5σ CL.
* The funding for second phase (2 detectors) is being requested.