Sterile Neutrino Search at JSNS^2 experiment

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20/11/2017

Flow of the talk

* ν which we know.
* What is Sterile Neutirno
* Indications of Sterile Neutrino
* JSNS^2 experiment
* K-Pipe experiment
* SBN experiment
* Summary

Standard Model Particles

Fermion(spin=1/2)

Name	Charge	1st generation	2nd generation	3rd 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, The # of neutrino flavor is 3, not more.

Gauge boson(spin=1)

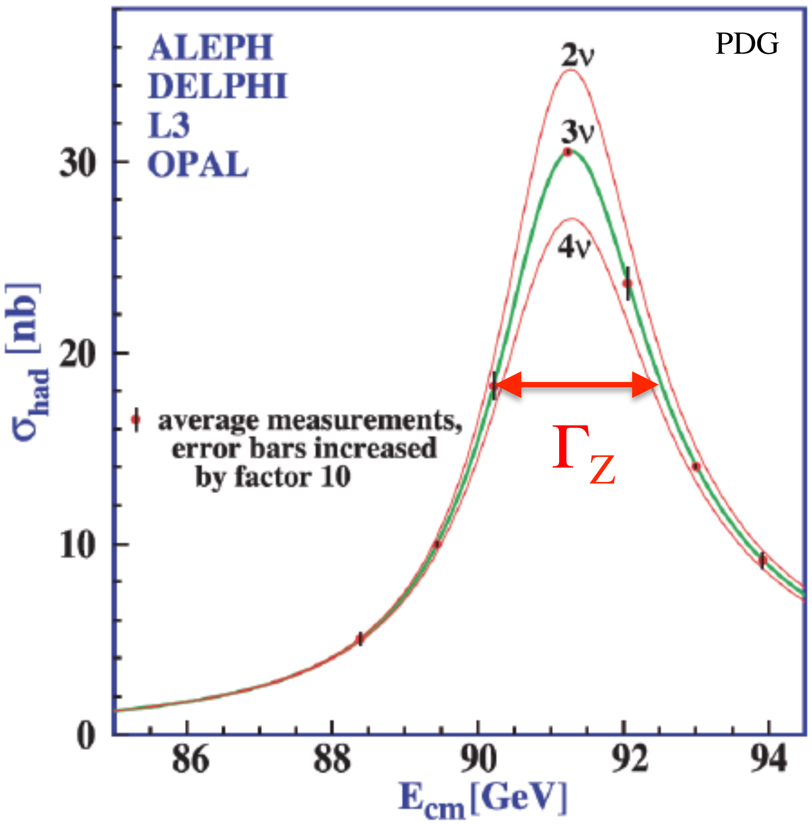
charge	EM	W	S
0	γ	Z^0	G
±1		$W^\pm$	

Higgs boson(spin=0)

charge	
0	H^0

Our Current Understanding of Neutrino:
of ν flavors

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



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

n_ν=3.00+/- 0.08

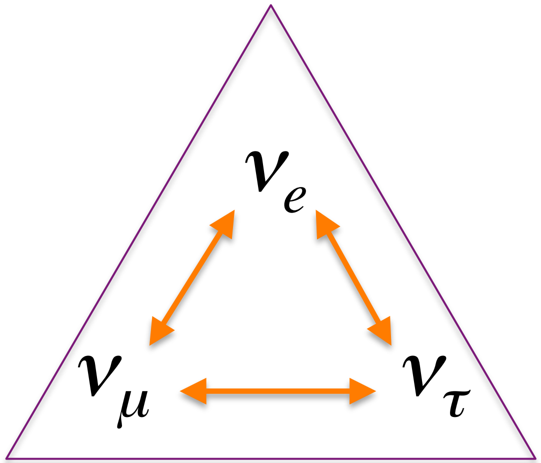
If there is $Z^0 \rightarrow \nu_4 \bar{\nu}_4$ decay,
Z^0 lifetime → shorter, &
Z^0 width → wider

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

Our Current Understanding of Neutrino:

Neutrino Oscillation exists

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4\sum_{k>j} \Re[\Lambda_{kj}^{\alpha\beta}] \sin^2 \Phi_{kj} - 2\sum_{k>j} \Im[\Lambda_{kj}^{\alpha\beta}] \sin 2\Phi_{kj}$$



$$\Lambda_{kj}^{\alpha\beta} = U_{\alpha k} U_{\alpha j}^{*} U_{\beta j} U_{\beta k}^{*}, \quad \Phi_{ij} = \frac{\Delta m_{ij}^2}{4E} L$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \sim \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.37 & 0.51 & 0.70 \\ 0.39 & 0.59 & 0.68 \end{pmatrix}$$

$$\Delta m_{12}^2 \sim 7.5 \times 10^{-5} eV^2, \quad \Delta m_{31}^2 \sim 2.5 \times 10^{-3} eV^2$$

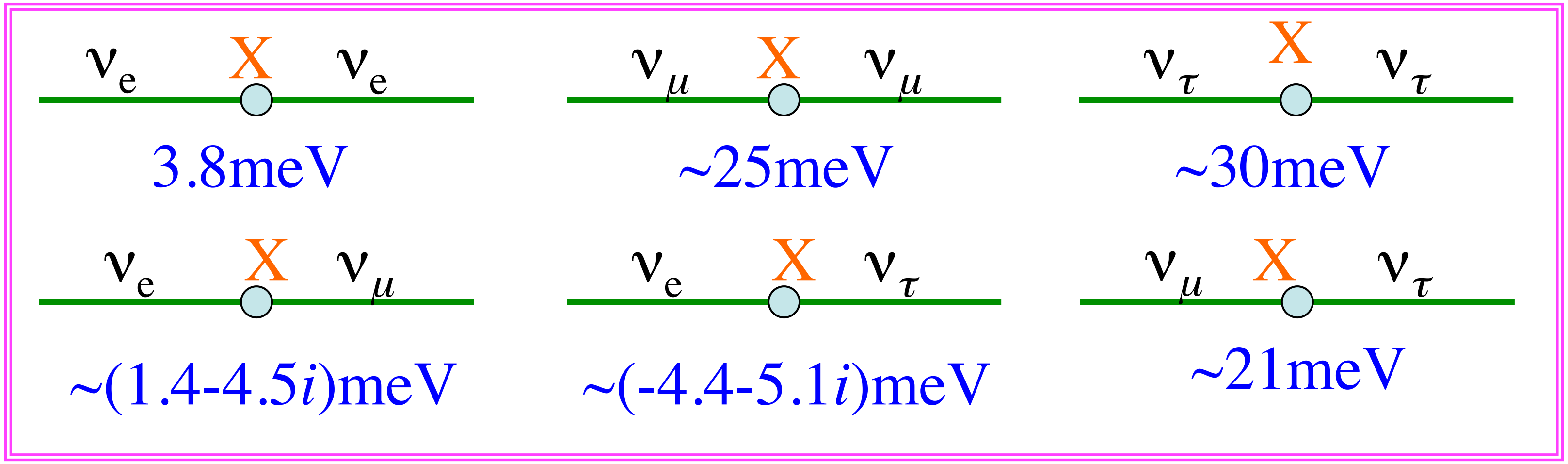
Our Current Understanding of Neutrino:
Neutrino Flavor Transitions

There is something X which transforms neutrino flavor.

An example case:

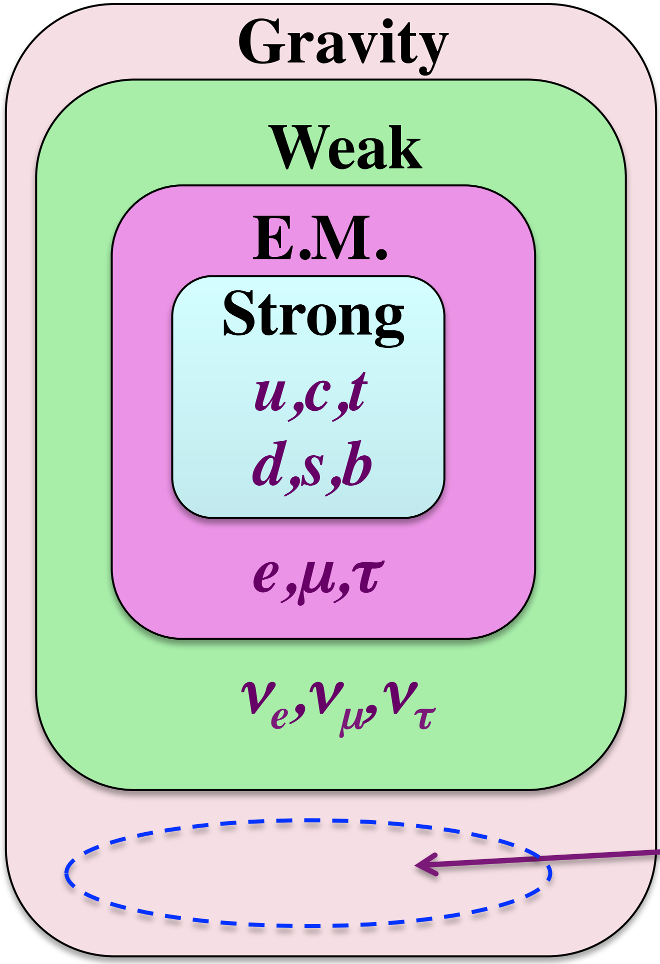
In case normal hierarchy
& minimum neutrino mass: $m_1 = 0$ → **$m_2 = 8.7$meV, $m_3 = 50$meV,**

& if $\delta_{CP} = -\pi/2$,



This transition X might be acting also to sterile neutrino oscillation

Nesting Structure of Interactions



The interactions form a nesting structure

(For example, there is no neutral quark)

We call:

Strongly interacting fermion → *quark*,

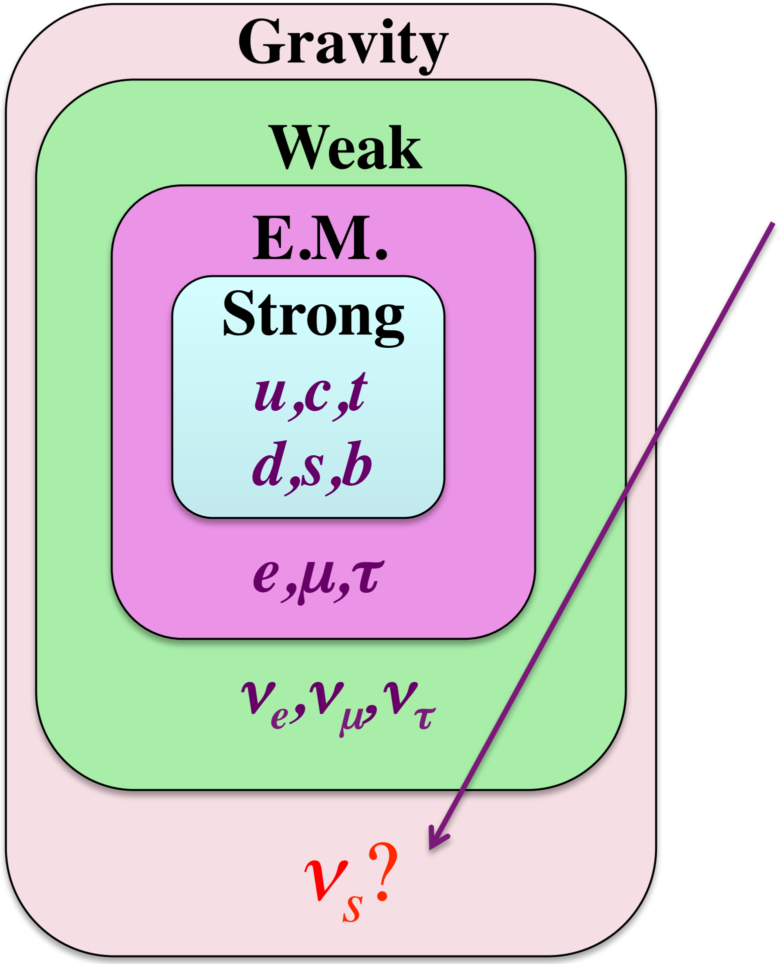
Non-Strongly " " " " → *lepton*,

E.M. interactive lepton → *charged lepton*,

Non-E.M. " " " " → *neutrino*,

Gravity-only area is vacant.

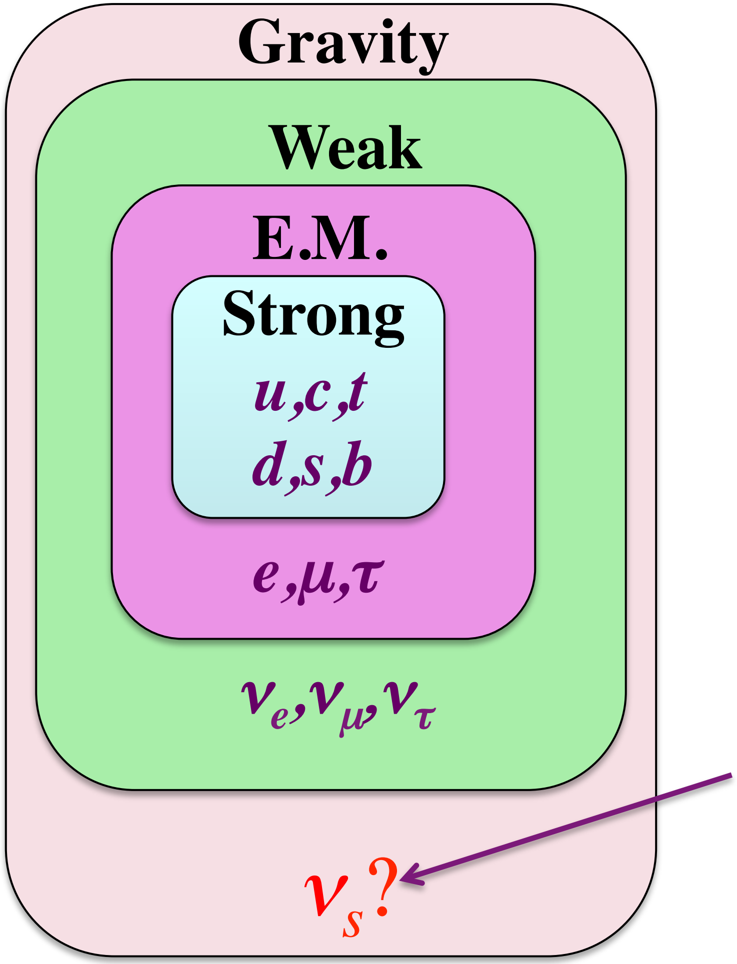
Nesting Structure of Interactions



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

We call them "*Sterile Neutrino*"

Nesting Structure of Interactions

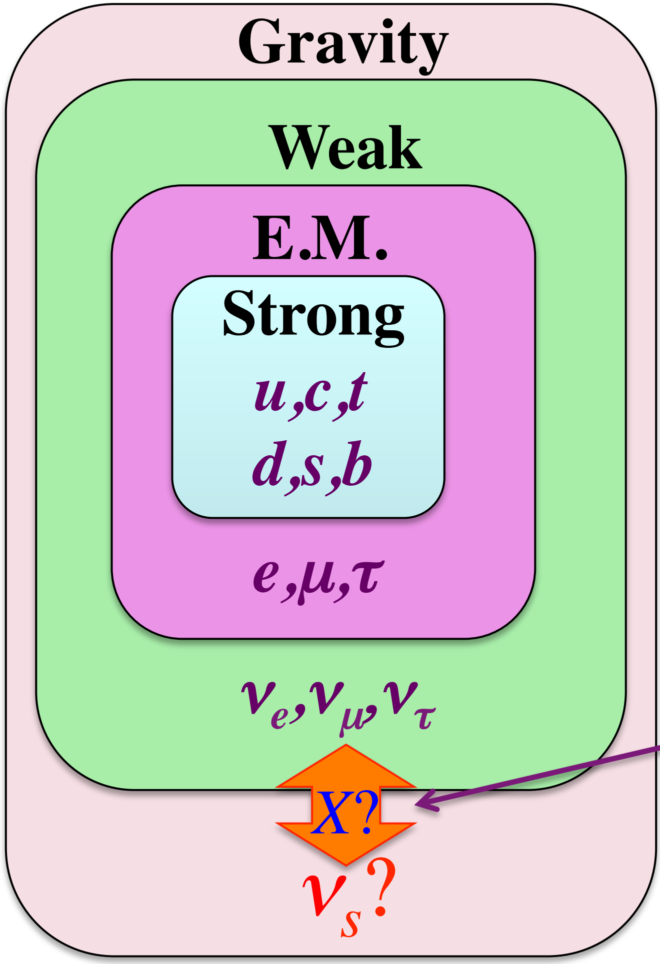


If fermions exist here, they do not affect the Z^0 width and it is OK to exists.

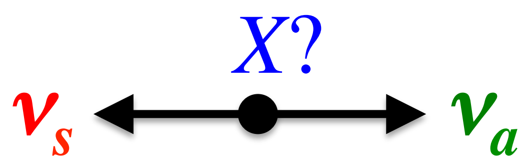
We call them "*Sterile Neutrino*"

However, even if the sterile neutrino exists, we can not detect it through experiments because it does not perform EM, Weak nor Strong interactions.

Nesting Structure of Interactions



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 our neutrinos.

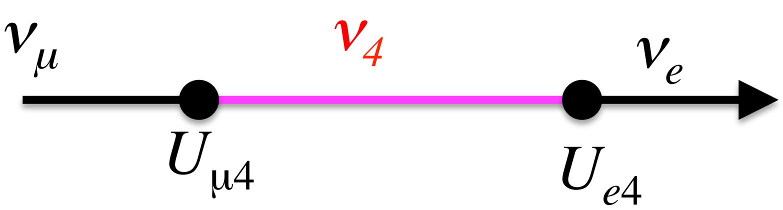


ν_a: active neutrino (ν_e,ν_μ,ν_τ)

Extension of ν mixing matrix: $3\nu_a + 1\nu_s$ case

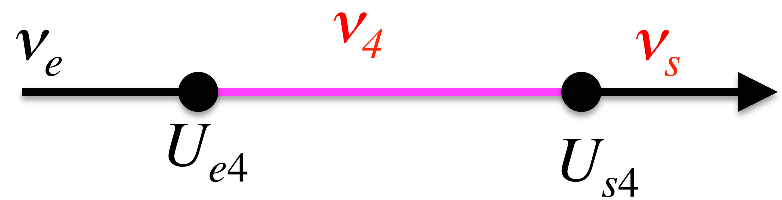
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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

For $m_4 >> m_{1\sim3}$ 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

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

LSND experiment

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

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

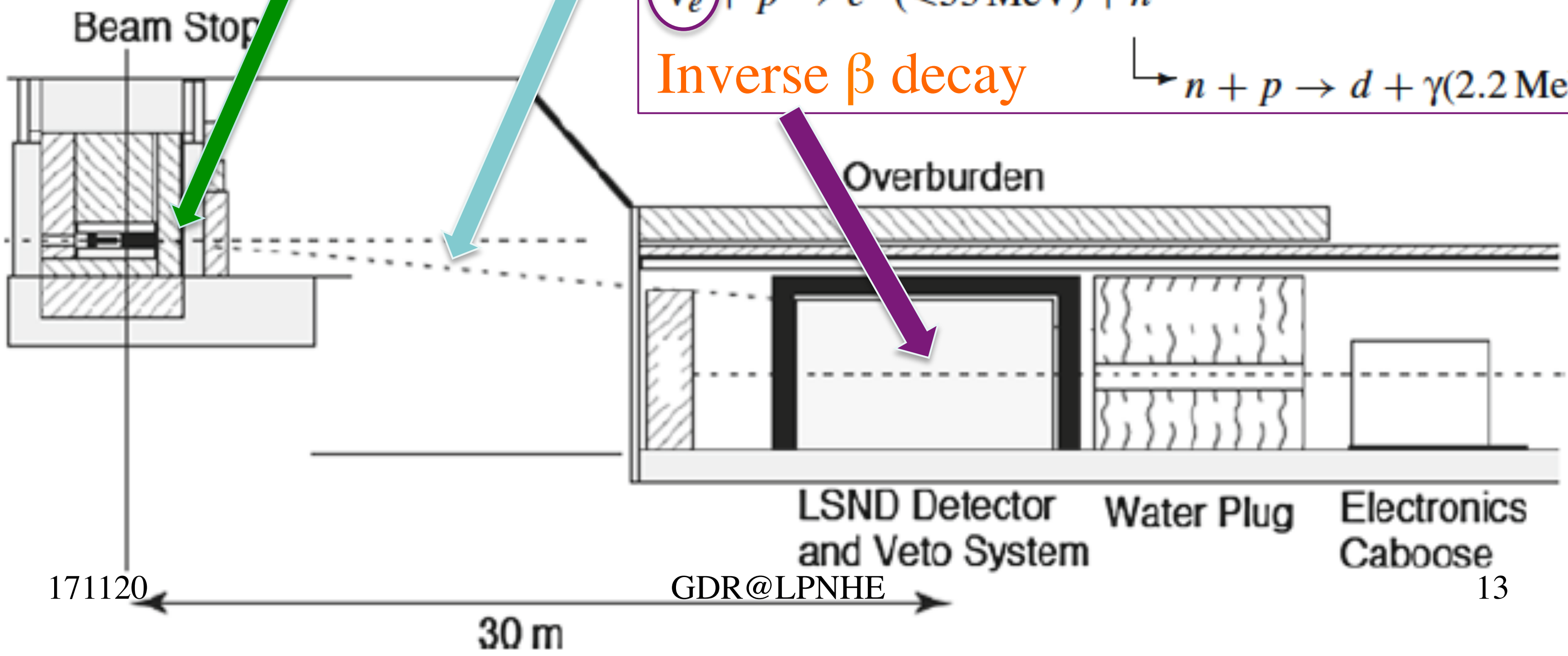
Oscillation

800MeV p

Liquid Scintillator

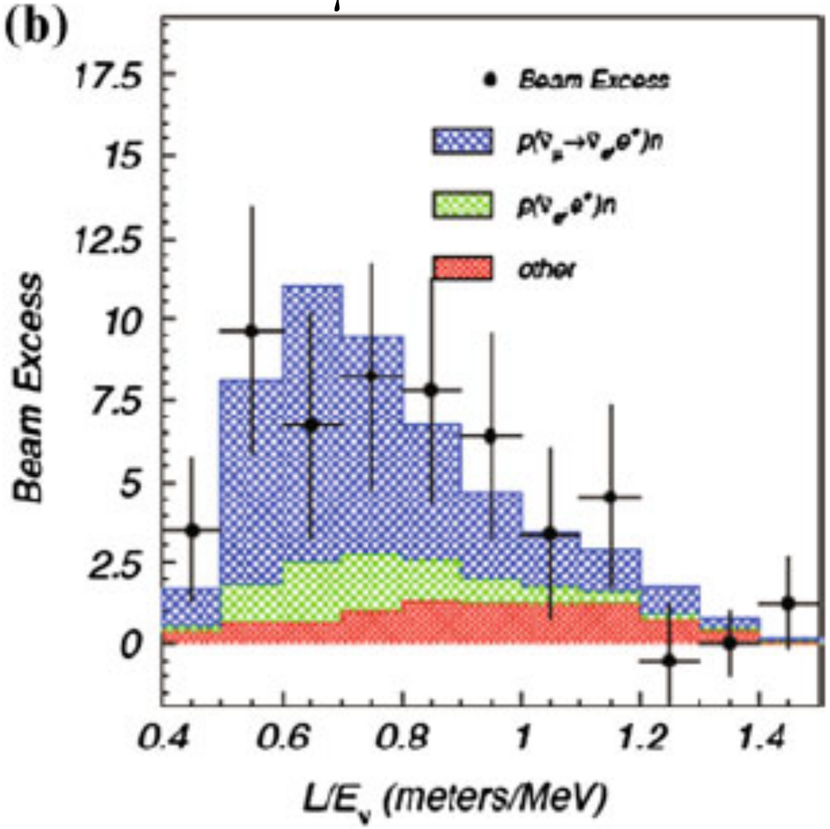
$\bar{\nu}_e + p \to e^+(<53\,\text{MeV}) + n$

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

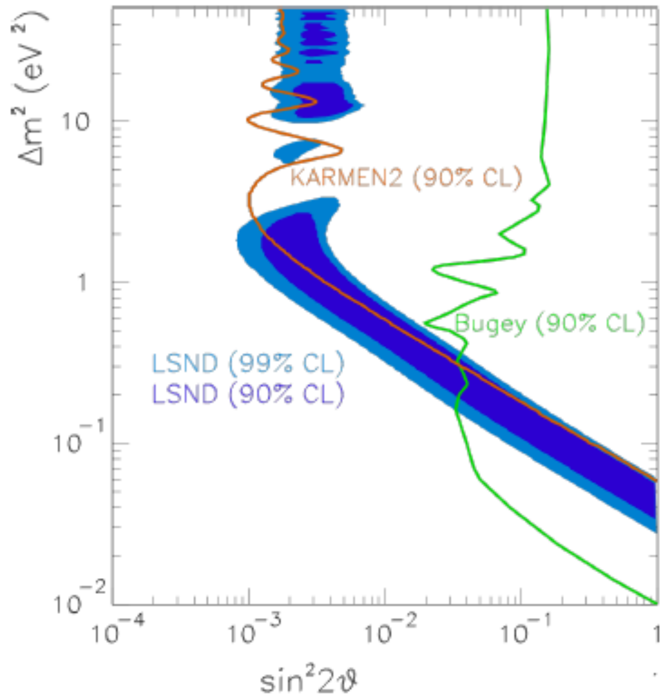


LSND data: excess of $\overline{\nu}_e$ signal

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



A. Aguilar et al., Phys. Rev. D 64, 112007, (2001).



Δm^2>0.03eV^2 ➔ Contradict known ν oscillations ➔ Sterile Neutrino

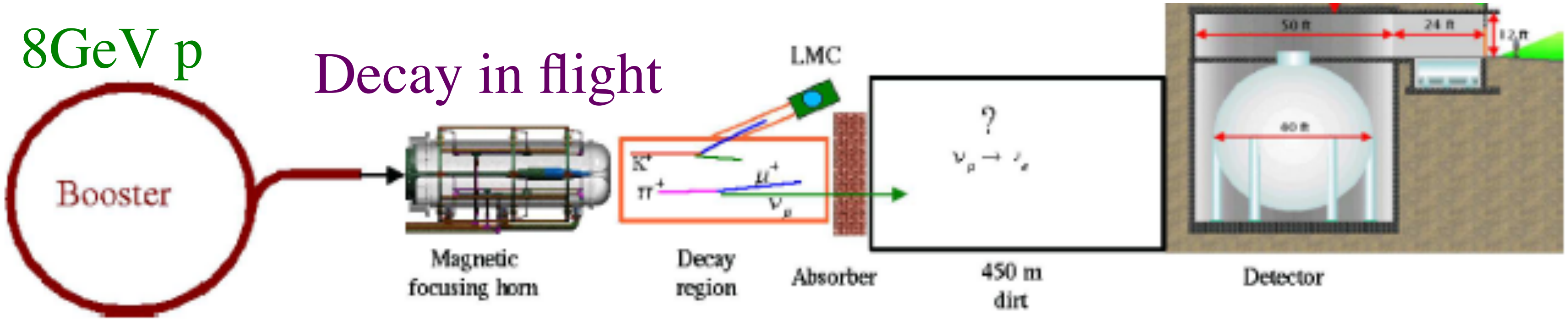
However, background were huge and analysis was complicate.
➔ Confirmation is necessary

MiniBooNE

Fermilab
8GeV p

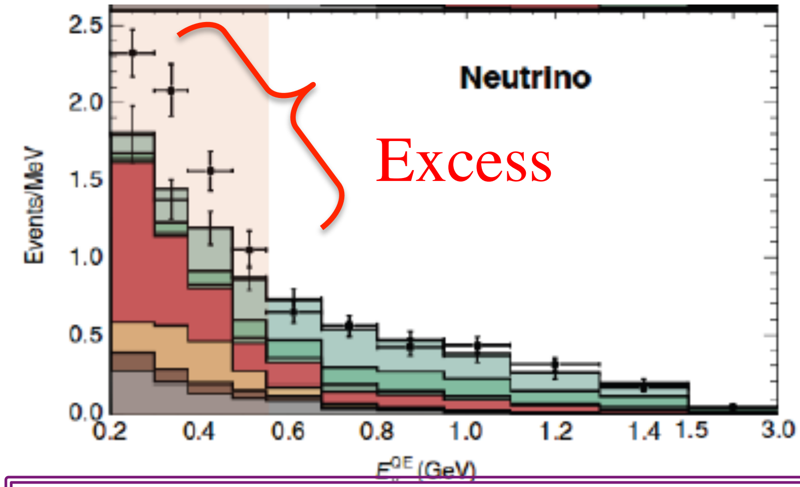
Decay in flight

Mineral oil Cherenkov

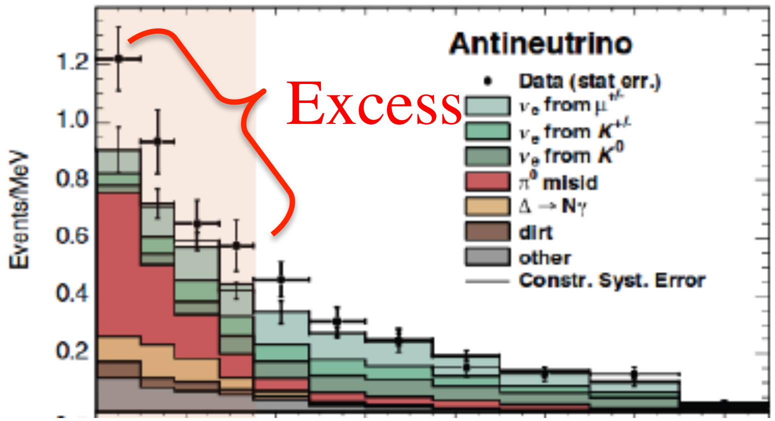


$$\pi^+ \rightarrow \mu^+ + \nu_\mu \xrightarrow{Oscillation} \nu_e \qquad \nu_e + p,C \rightarrow e^- + X$$

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



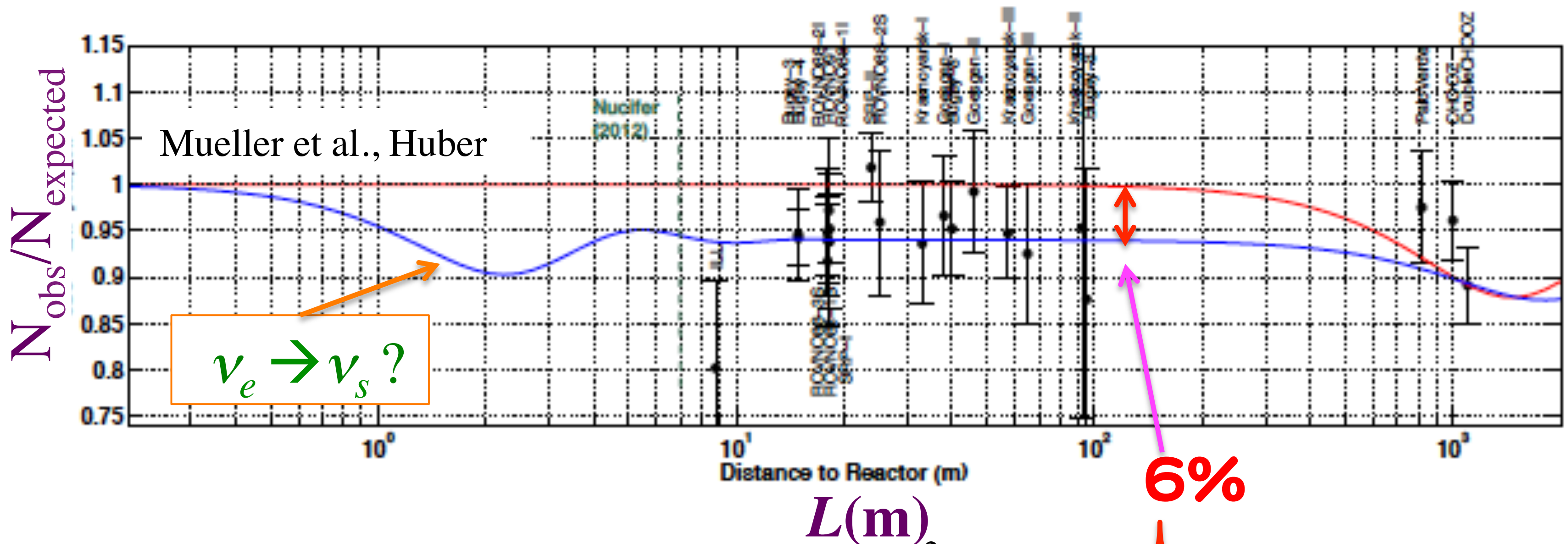
Phys. Rev. Lett. 110, 161801 (2013)



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

Reactor Neutrino Anomaly

Observed reactor neutrino flux is ~6% less than expected.
It can be explained if there is $\nu_e \rightarrow \nu_s$ oscillation at
$\Delta m^2 > 0.1\text{eV}^2$, $L < 10\text{m}$.



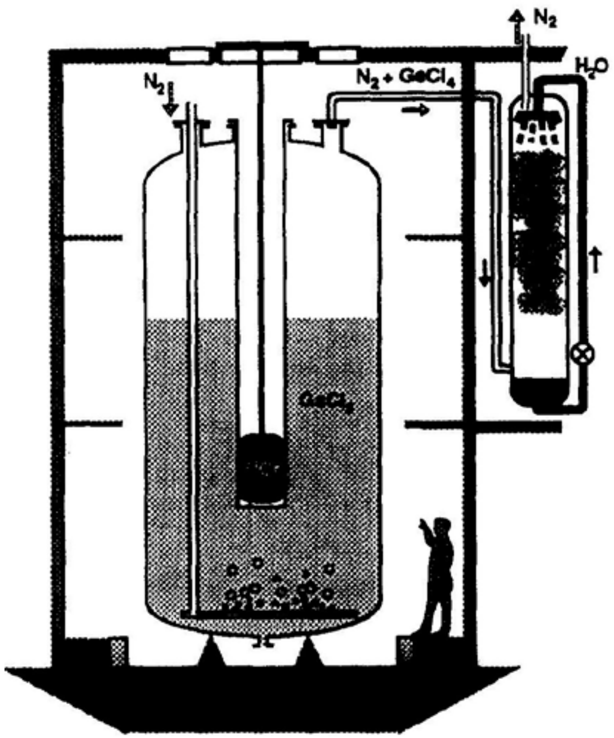
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \sin^2 2\theta \sin^2 \frac{m_4^2}{4E} \sim 1 - \frac{1}{2}\sin^2 2\theta$$

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

Gallium anomaly

The event rate for ν_e+Ga (solar ν detector) from strong neutrino sources (^{51}Cr, ^{37}Ar) is ~15% less than expected.
It can be explained if there is $\nu_e \rightarrow \nu_s$ oscillation before it is detected,

Cr: E_ν=0.82MeV
Ar: E_ν=0.90MeV

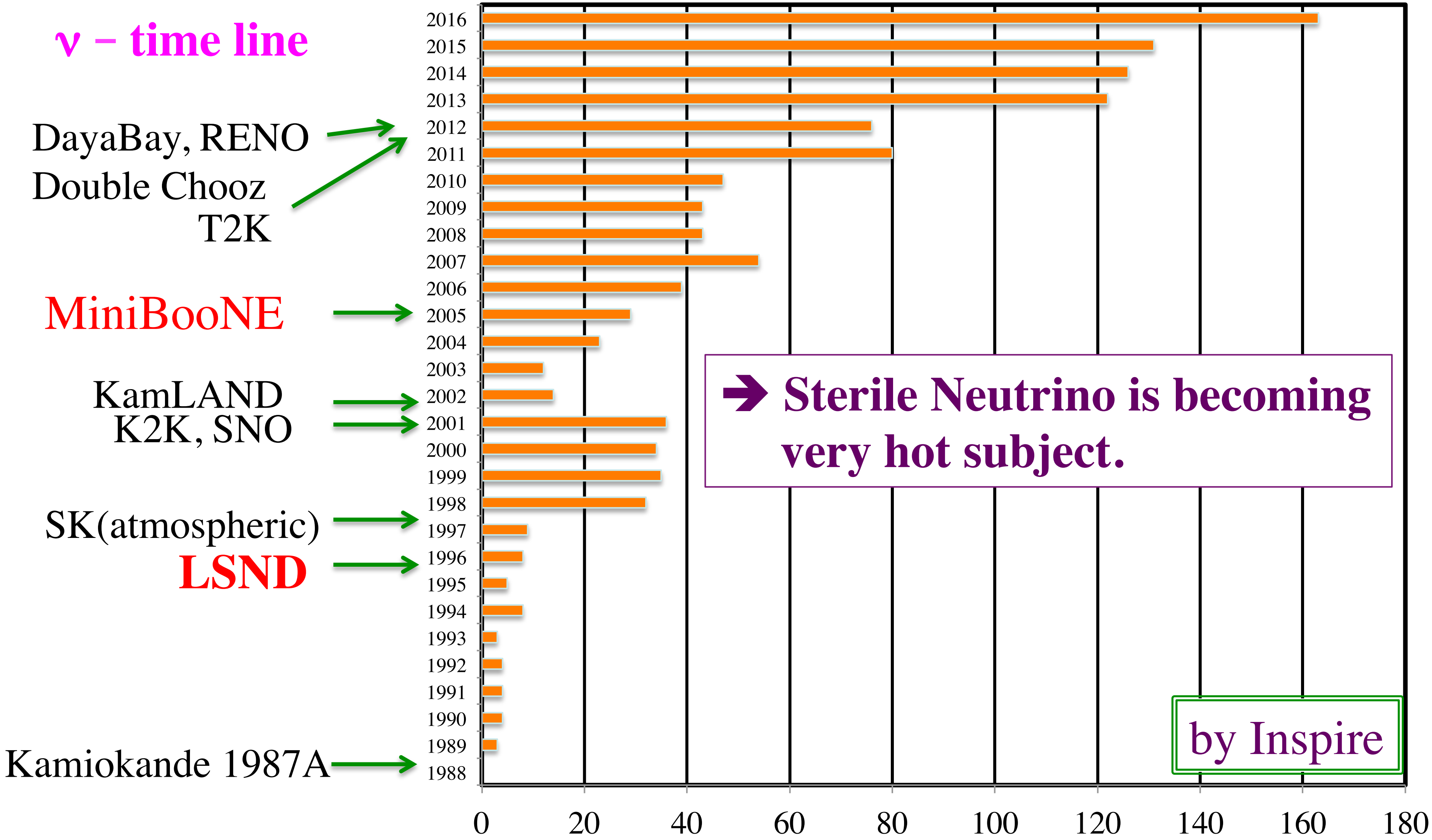


Experiment	Source	Meas./Exp.
Gallex	Cr1	0.94 +/- 0.11
	Cr2	0.80 +/- 0.10
Sage	Cr	0.93 +/- 0.12
	Ar	0.77 +/- 0.08
Average		0.84 +/- 0.05

JHEP 1305, 50 (2013)

However, ν-Ga cross section may contain unknown error.
➔ Need to check the oscillation pattern.

yearly # of papers with title "sterile neutrino"

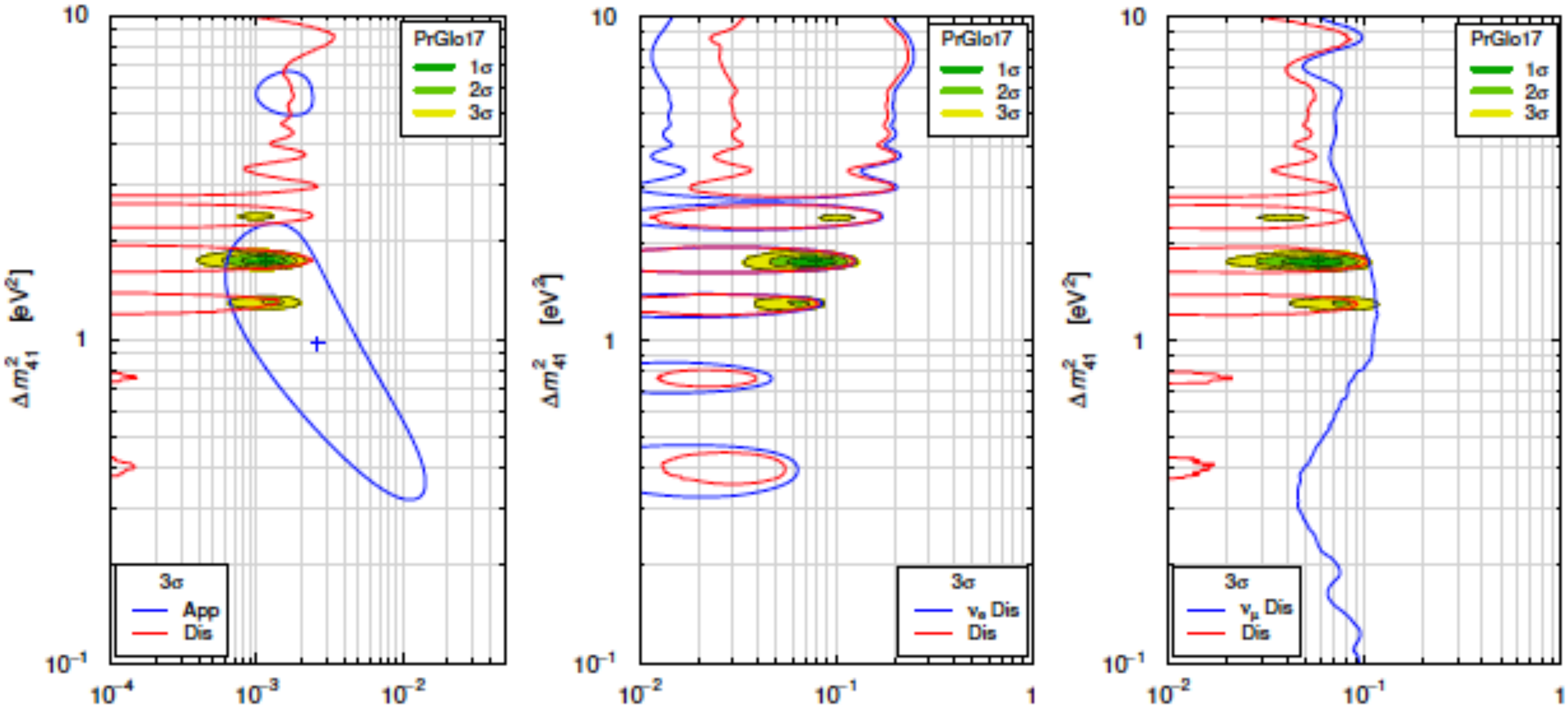


There have been a lot of negative results.

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

3 (ν_a) +1(ν_s) analysis

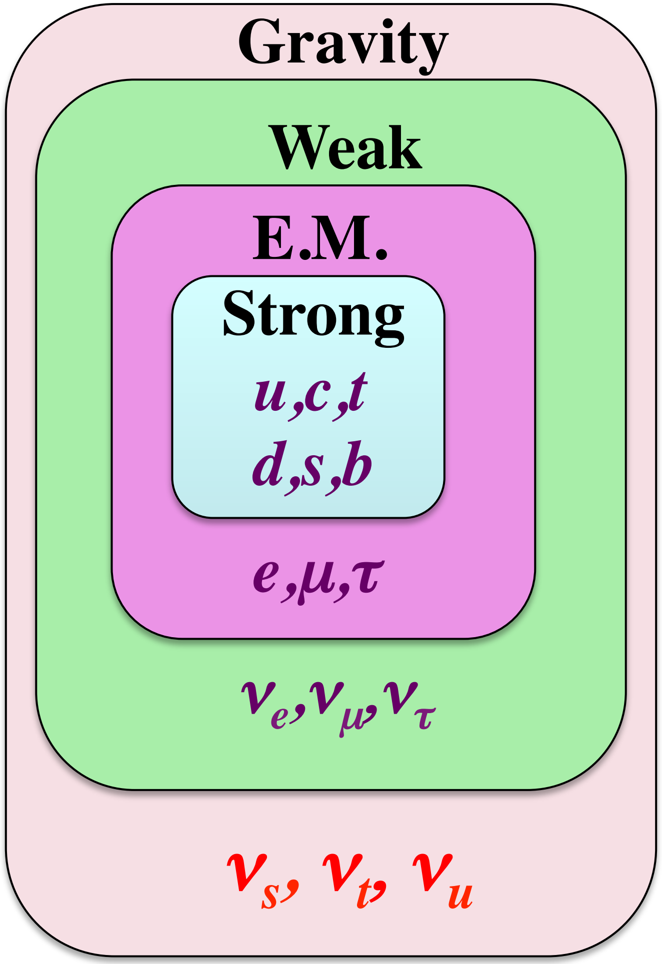
S.Gariazzo *et al*. (arXiv:1703.00860v3)



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

➔ **only small parameter regions remain.**

However, for $3\nu_a+3\nu_s$ case



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_t \\ \nu_u \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & U_{e6} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & U_{\mu 6} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & U_{\tau 6} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & U_{s6} \\ U_{t1} & U_{t2} & U_{t3} & U_{t4} & U_{t5} & U_{t6} \\ U_{u1} & U_{u2} & U_{u3} & U_{u4} & U_{u5} & U_{u6} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \nu_6 \end{pmatrix}$$

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

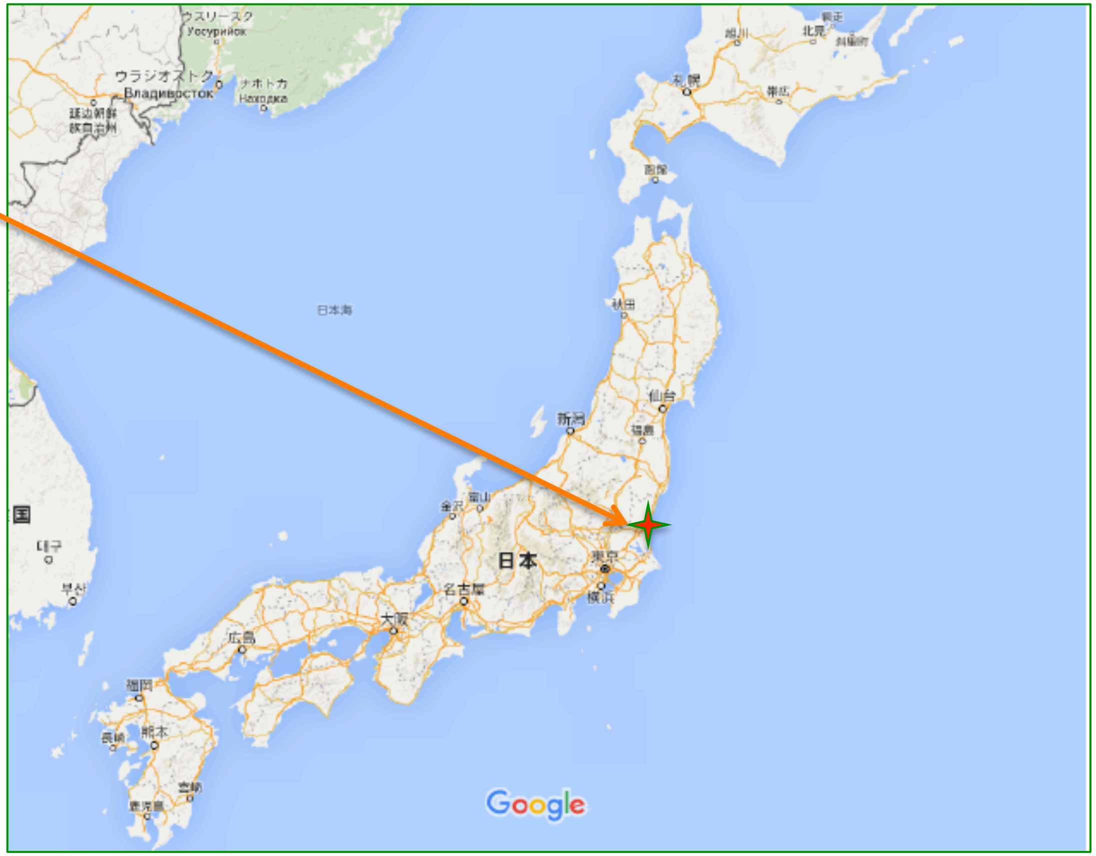
There are many parameters and it is impossible to reject appearance results by disappearance experiments.

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

Sterile Neutrino experiments at J-PARC MLF

JSNS^2

K-Pipe



JSNS^2 (J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source)

Direct ultimate tests for LSND.

JSNS^2 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[5], 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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[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

$\overline{\nu}_\mu$ from μ^+ Decay at Rest
& Inverse β decay detection

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

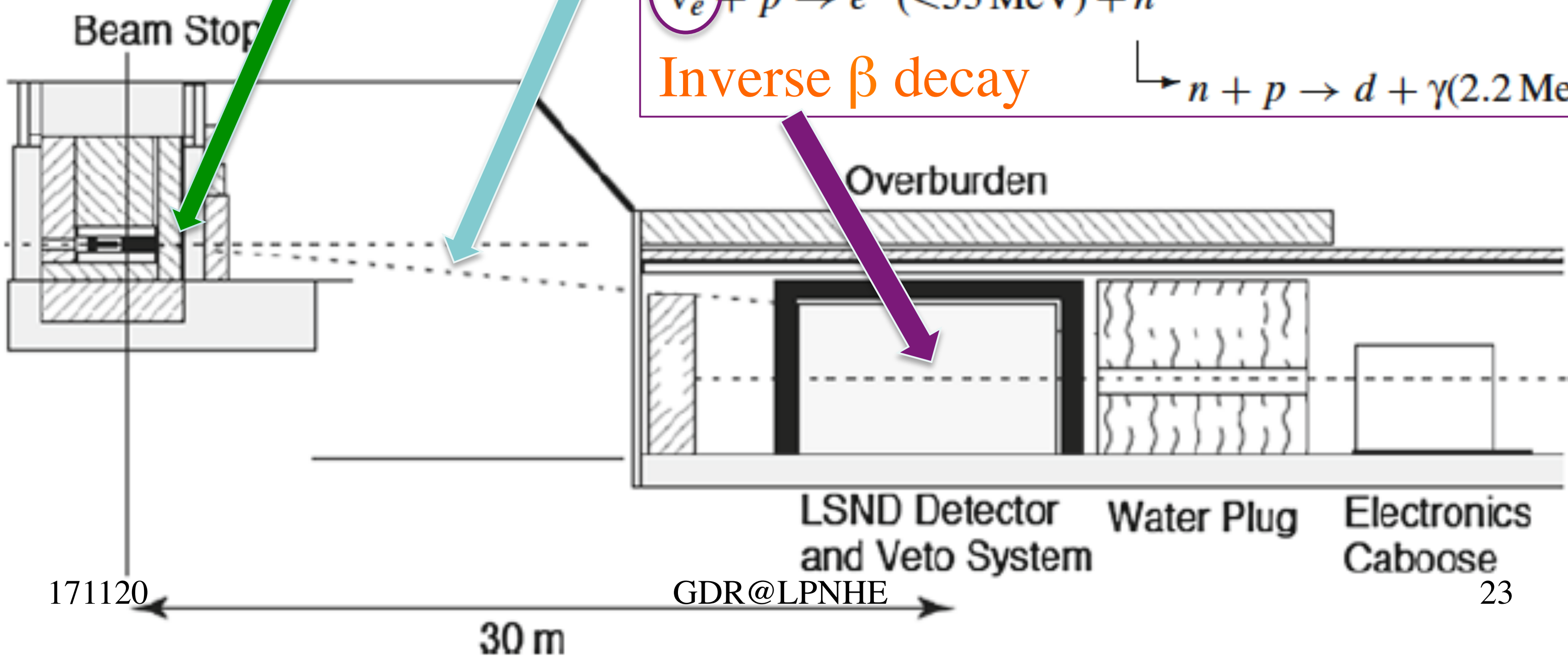
$\quad \hookrightarrow \mu^+(\text{stop}) \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$

800MeV p

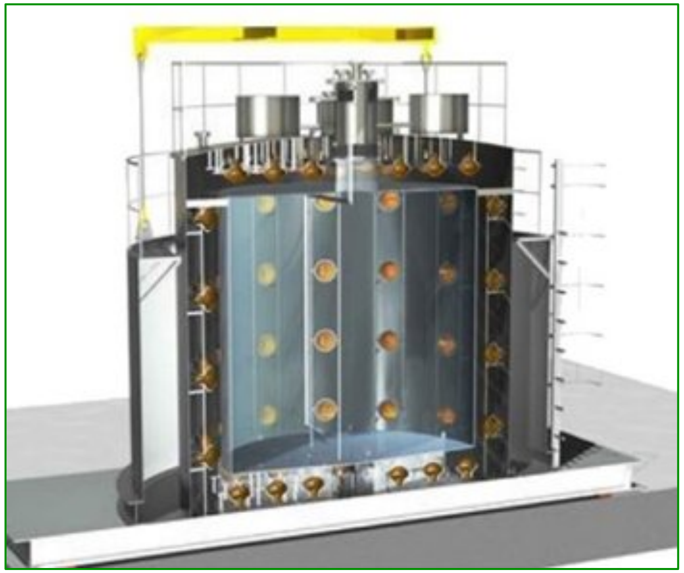
Liquid Scintillator

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

Inverse β decay $\quad \hookrightarrow n + p \rightarrow d + \gamma(2.2\,\text{MeV}).$

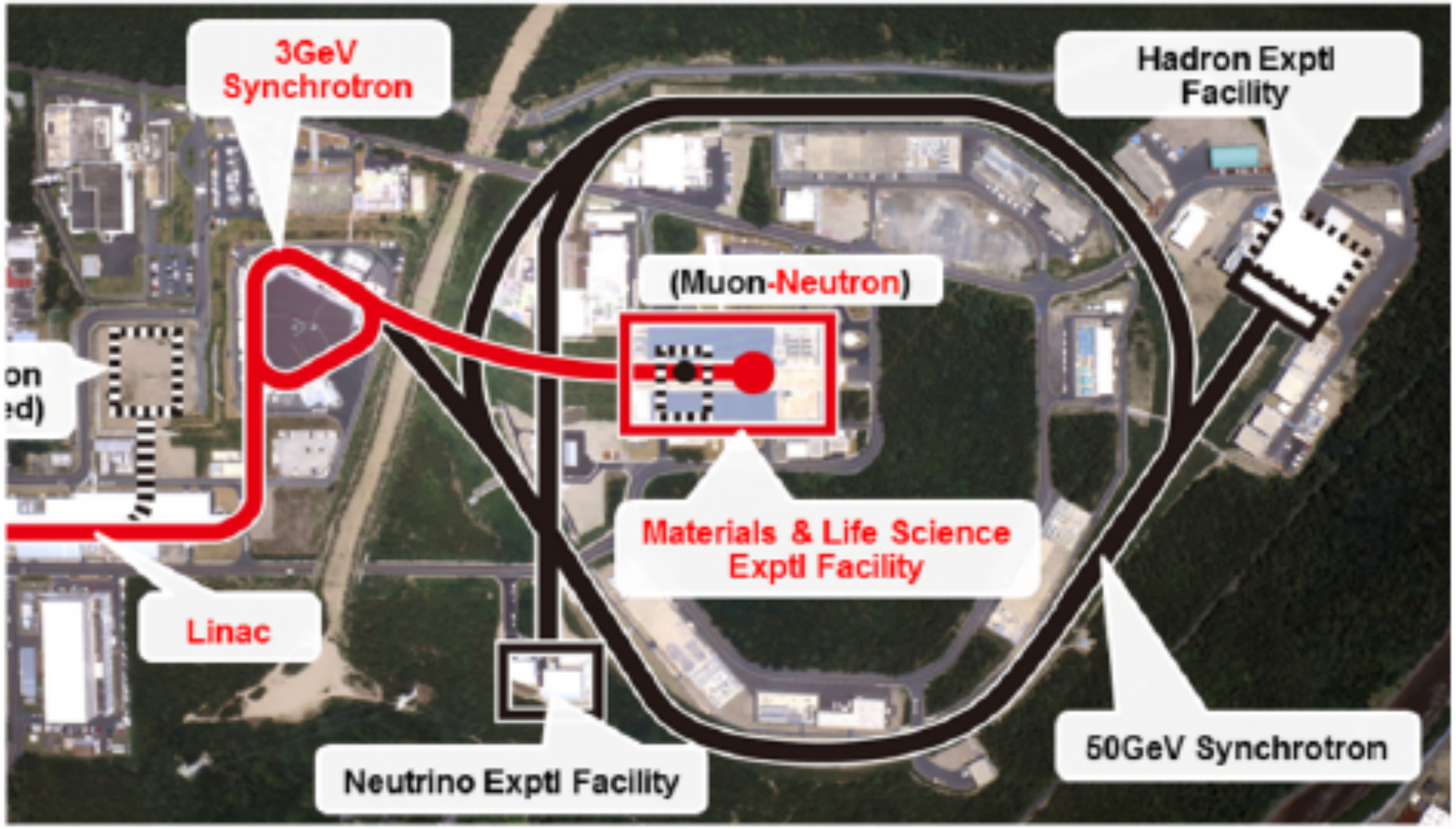


Motivation of JSNS^2 experiment

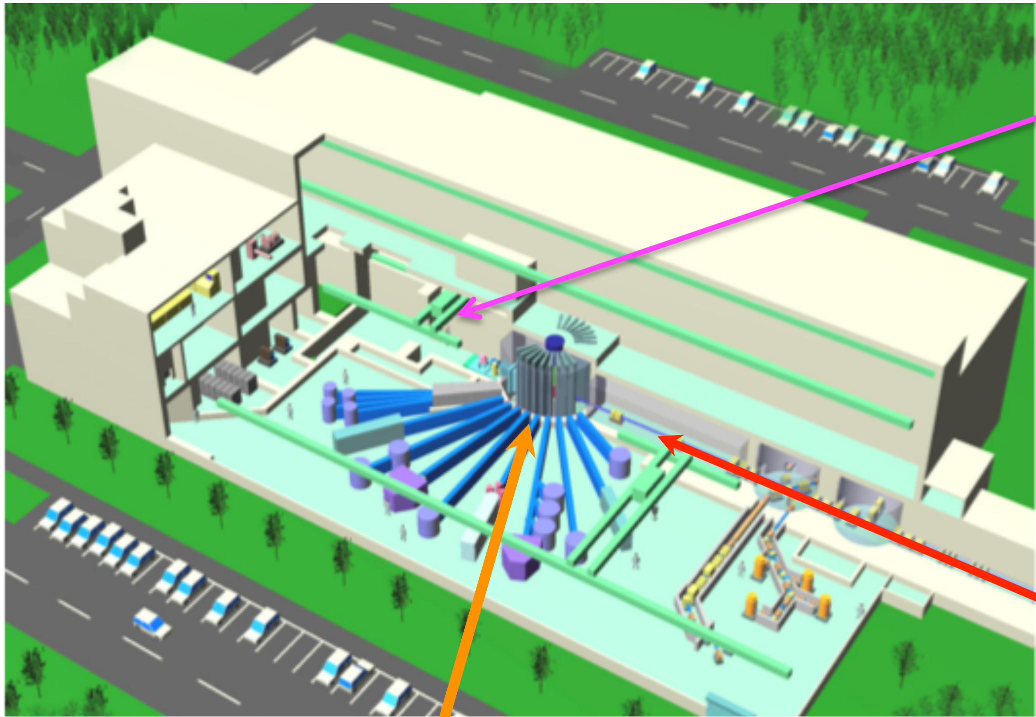


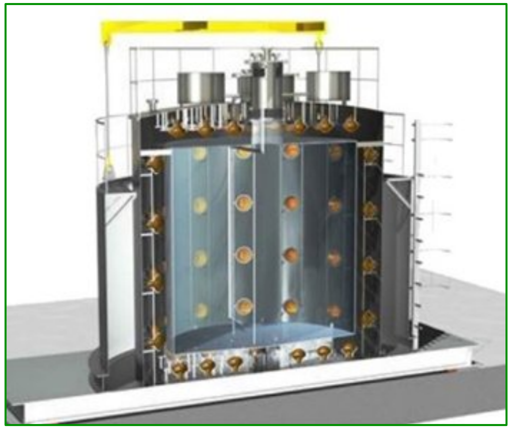
➔ **Direct test of the LSND result, using**
the same neutrino (from μ^+ decay at rest),
the same ν detection mechansm (inverse β-decay with p),
a similar baseline (24m vs 30m),
much better S/N (pulsed beam, Gd-Liquid Scinti.),
better energy resolution. (oscillation pattern)
higher statistics.

Facility : J-PARC
Material & Life Science Experimental Facility



↓ to T2K





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

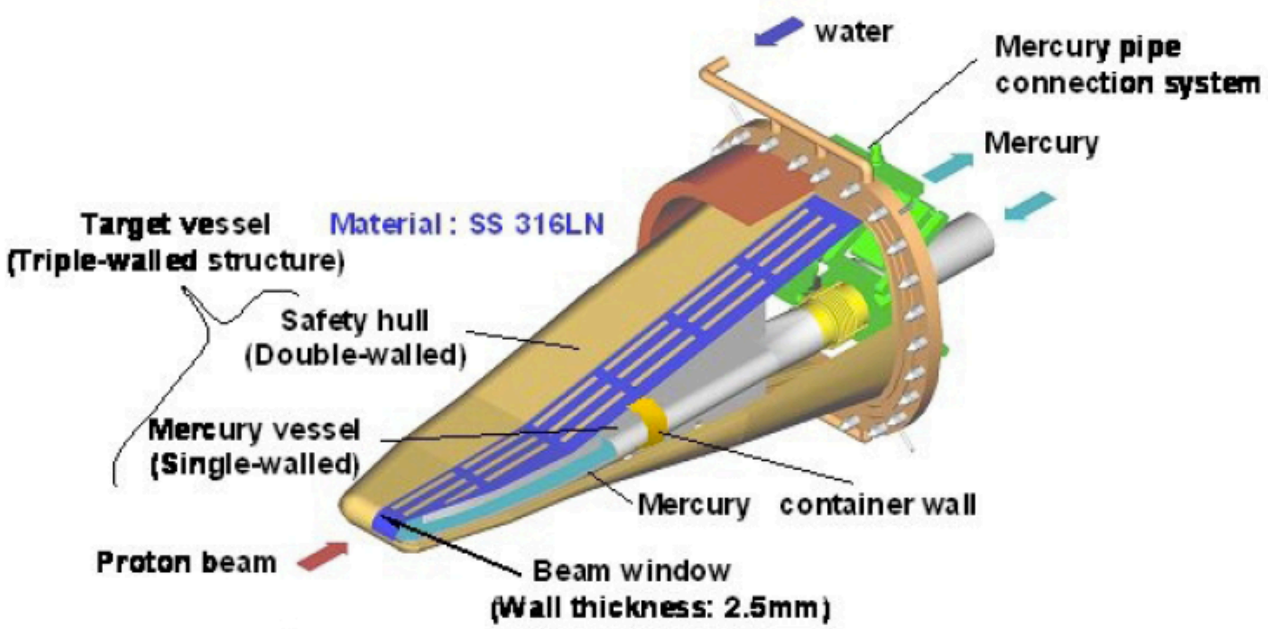
17ton detector
(1st phase)

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

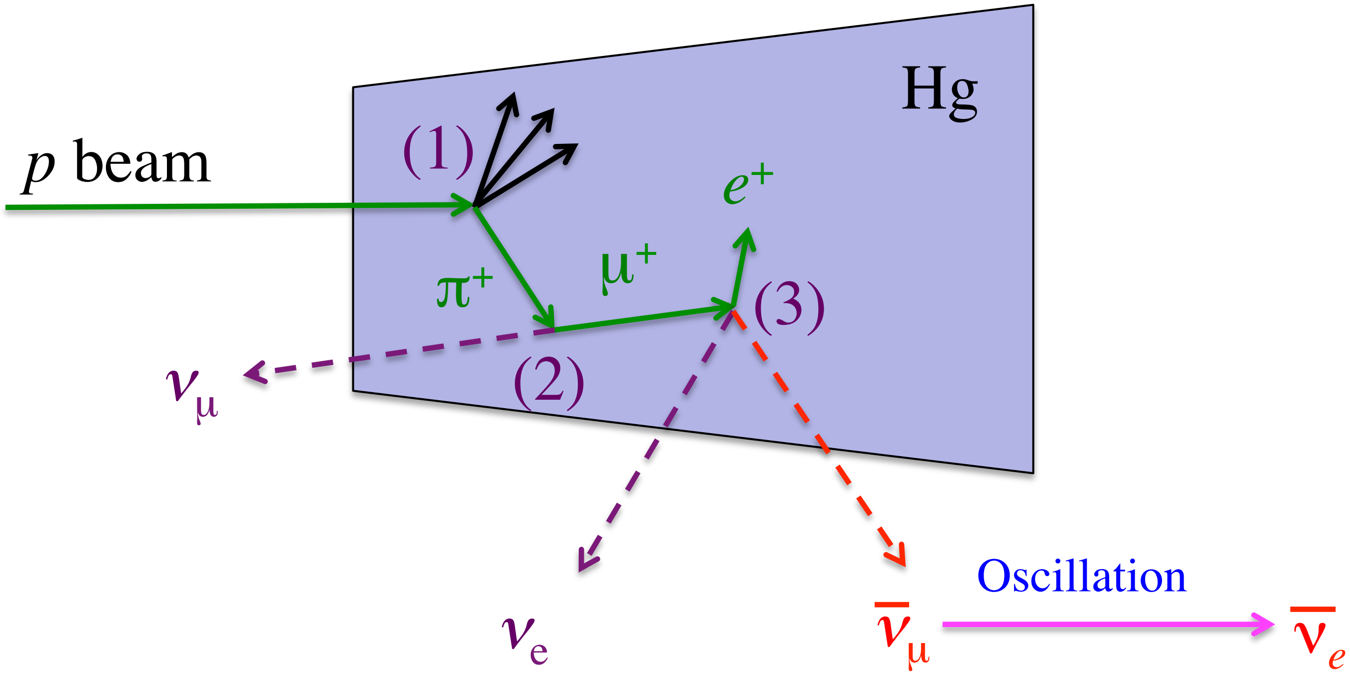


$$p + Hg \rightarrow \pi^{\pm} + X$$

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

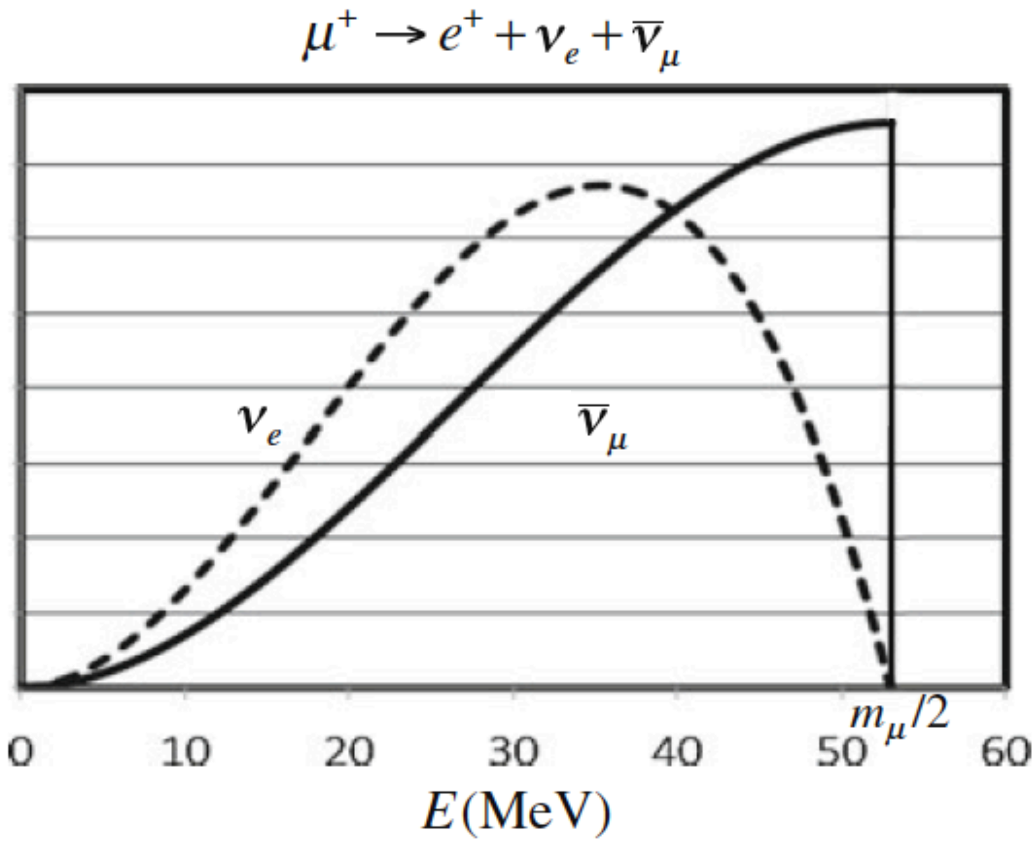
$$\hookrightarrow \mu^{+}(stop) \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

Properties of DAR neutrino



* The energy spectra of the neutrinos are perfectly known.
* The neutrino–nucleus cross section is known to a few%
* The time structure of the neutrino is perfectly known.
* π^+-origin and hadron-origin ν can be separately obtained
* Monochromatic ν_μ can be obtained

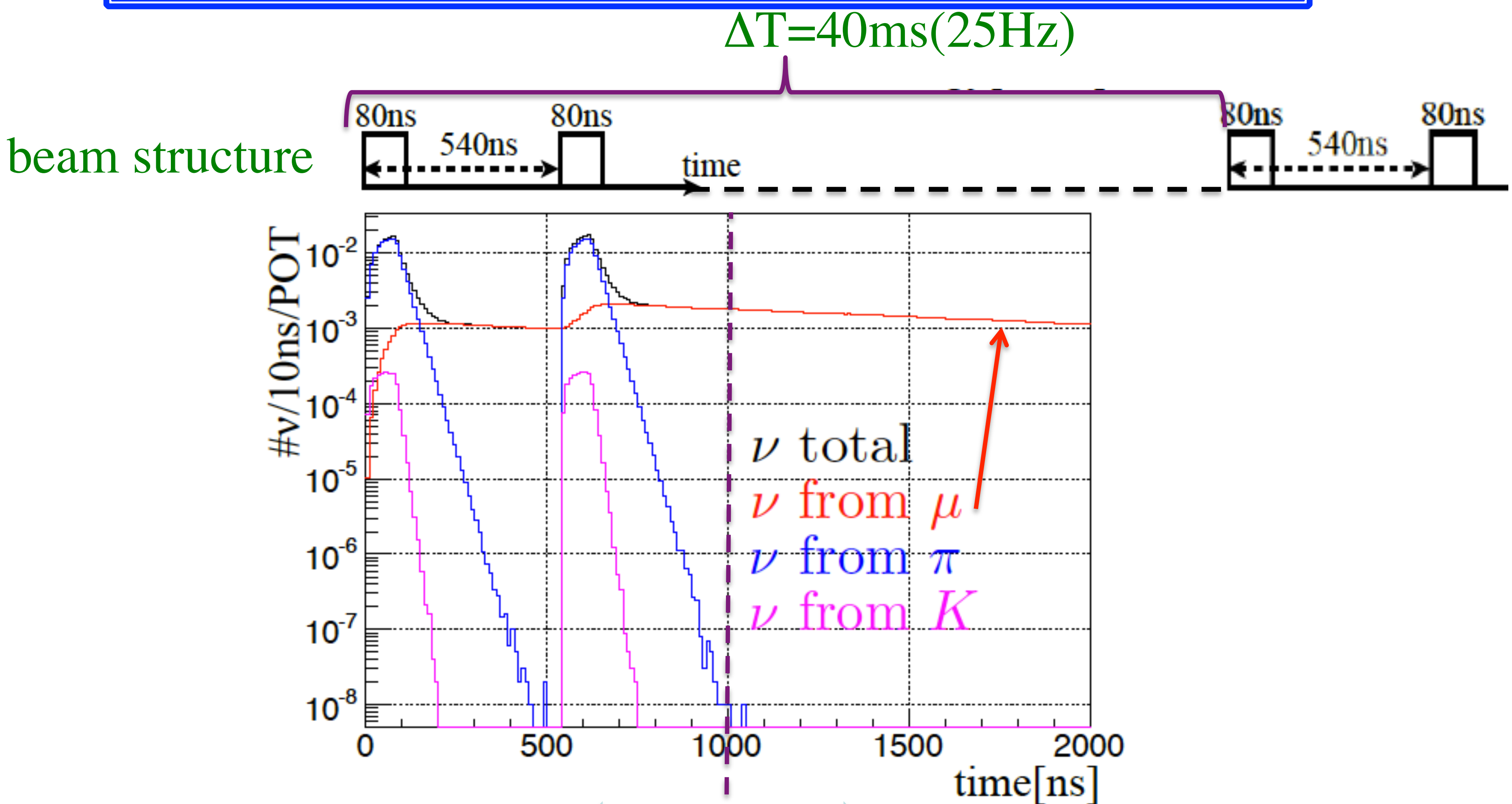
Energy Spectra of ν from μ+ decay at rest



Since the parent μ+ has no momentum, the neutrino energy spectra are well known.

This energy spectra are the same for LSND and JSNS[2].

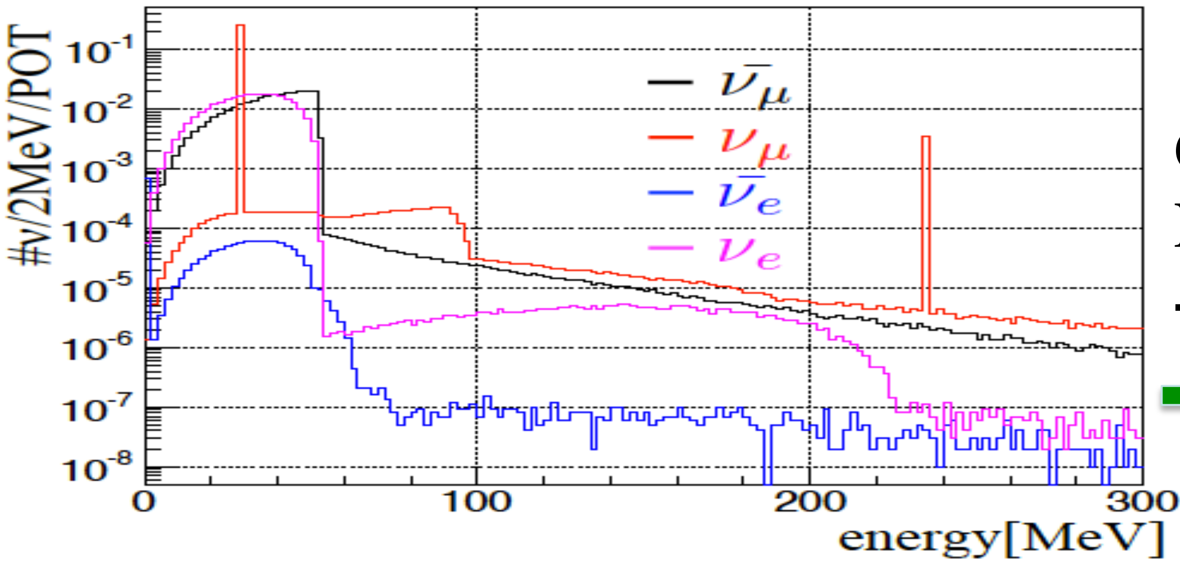
MLF Pulsed beam can reduce beam BKG and accidental BKG drastically.



ν from π & K decays (monochromatic)

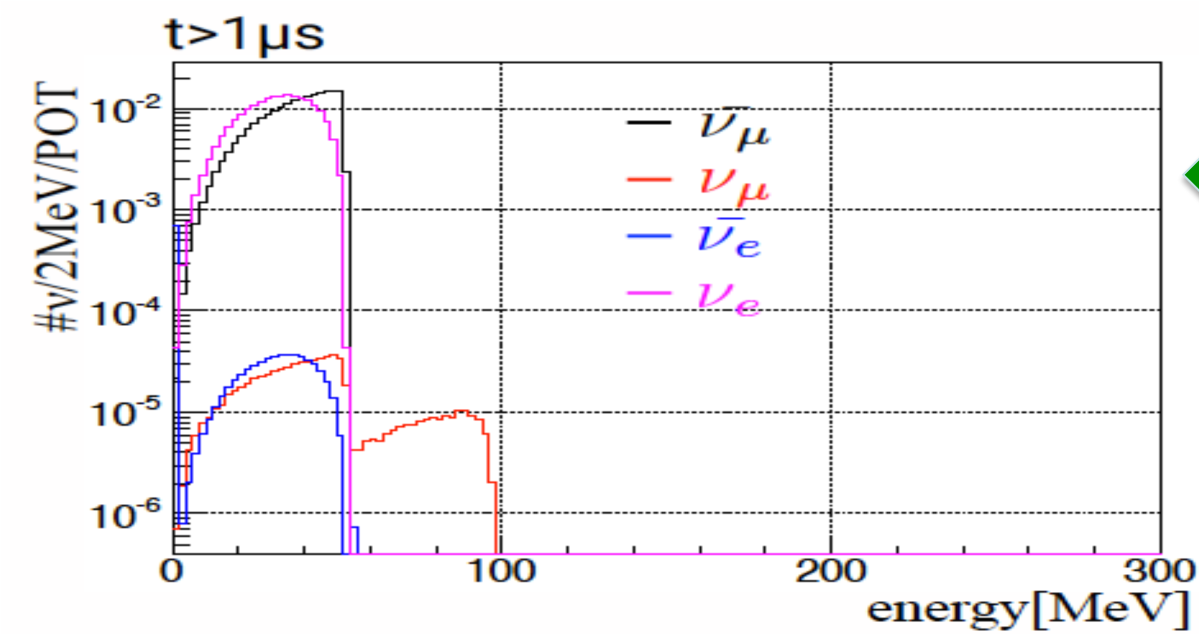
ν from μ decay.

Neutrino Spectrum after the beam gate cut



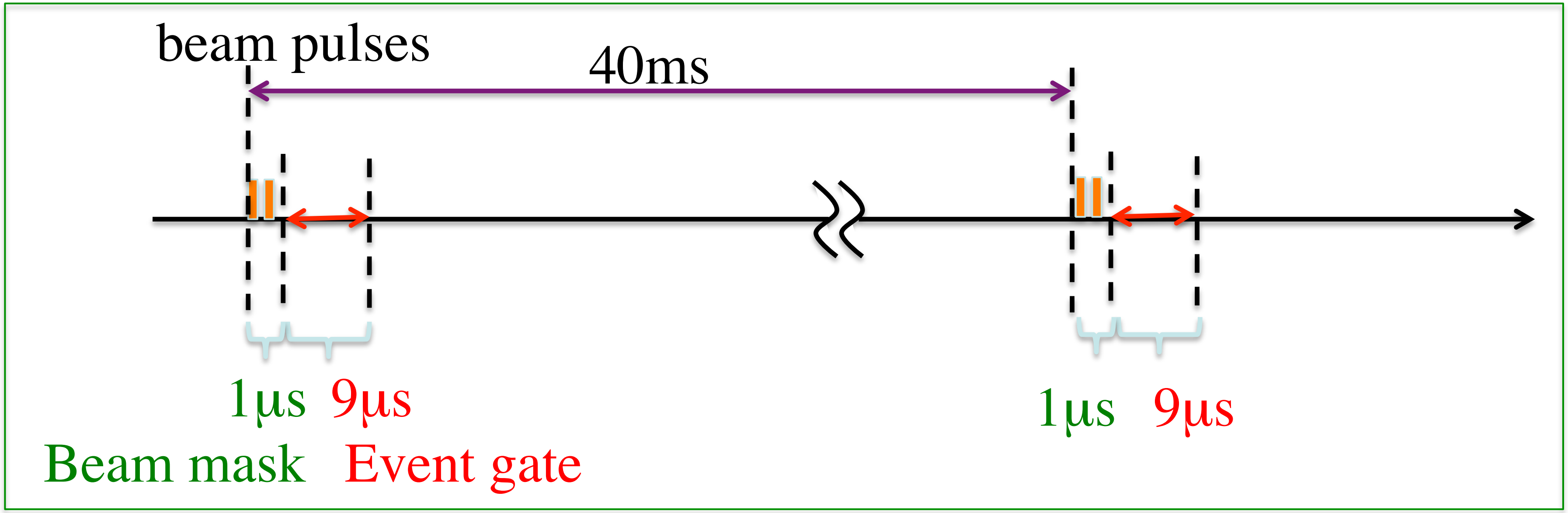
Original ν spectra
DAR + Decay in Flight
+ absorption of π, K, μ.

t >1μs



ν only from μ can be selected

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

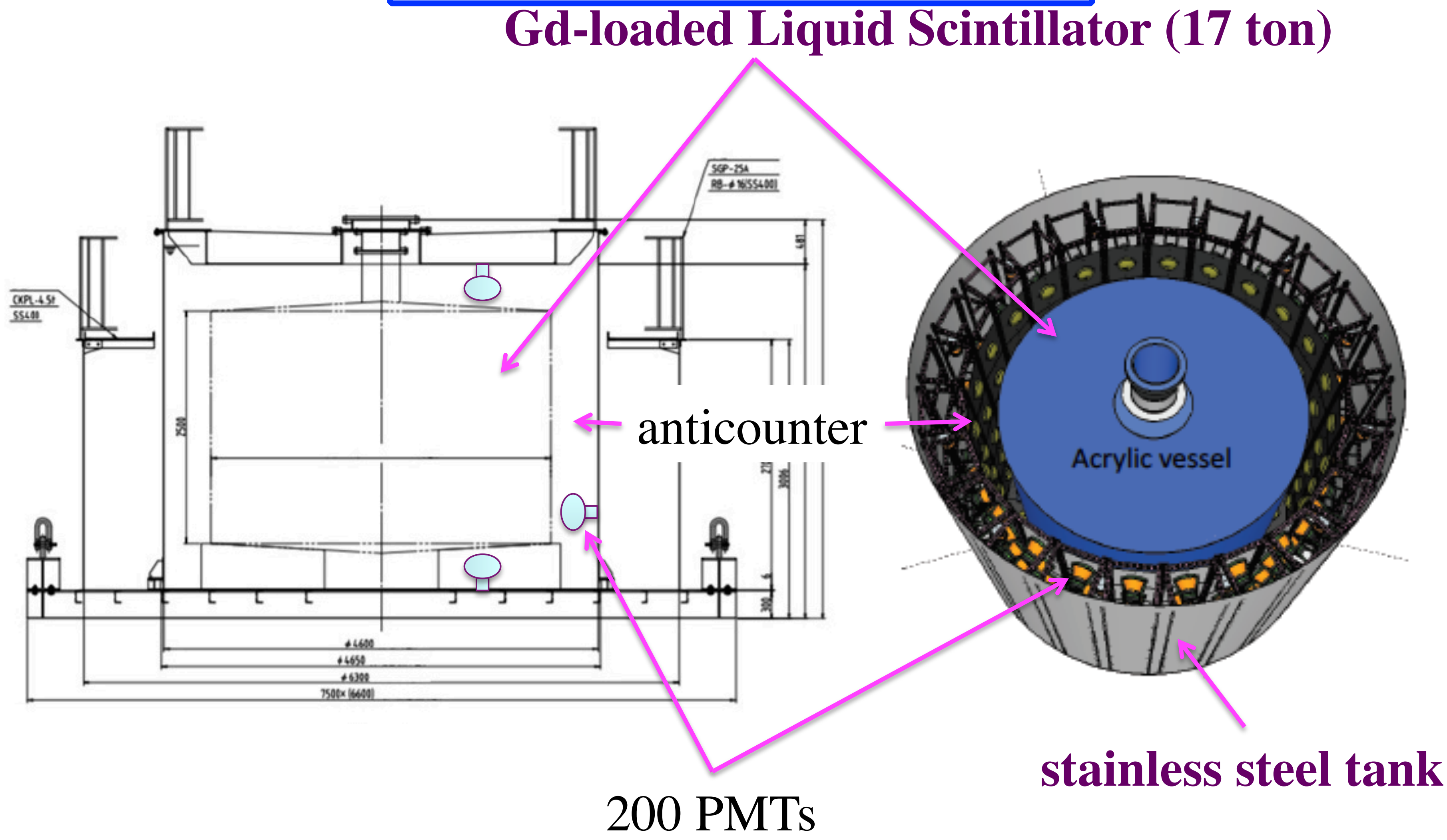


Open 9ms event gate for every 40ms of beam pulse

➔ Cosmic-ray BKG is suppressed to 1/4,400.

➔ Background level can be measured precisely by off timing events

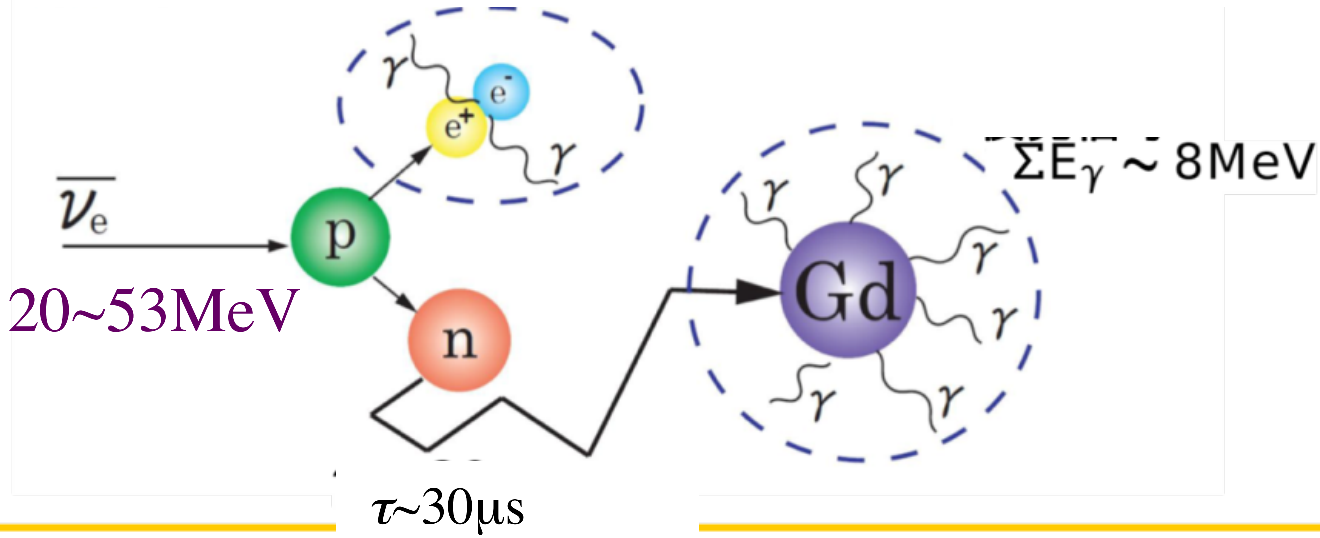
JSNS^2 Detector Structure



Much of the JSNS^2 design have been made based on the Double Chooz experience

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

$E_\nu \sim E_{vis} + 0.8MeV$ (**ν energy can be measured**)



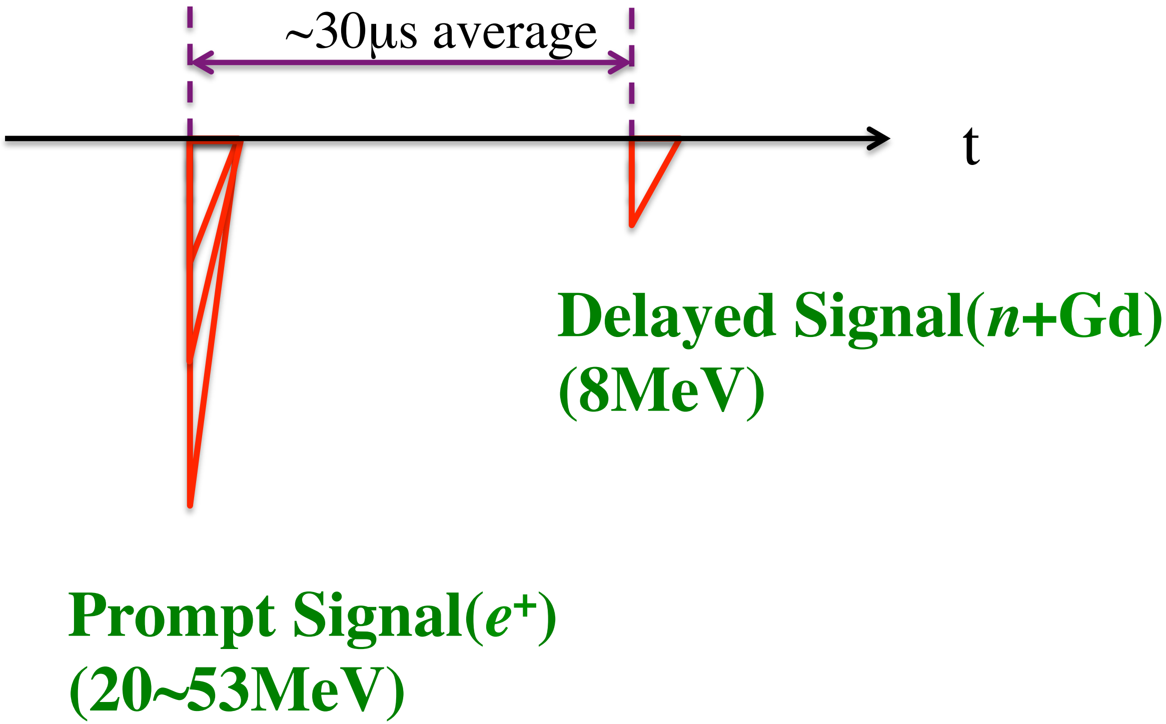
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e + p \rightarrow e^+ + n$

oscillation

n+Gd → Gd' + γs (ΣE_γ=8MeV)

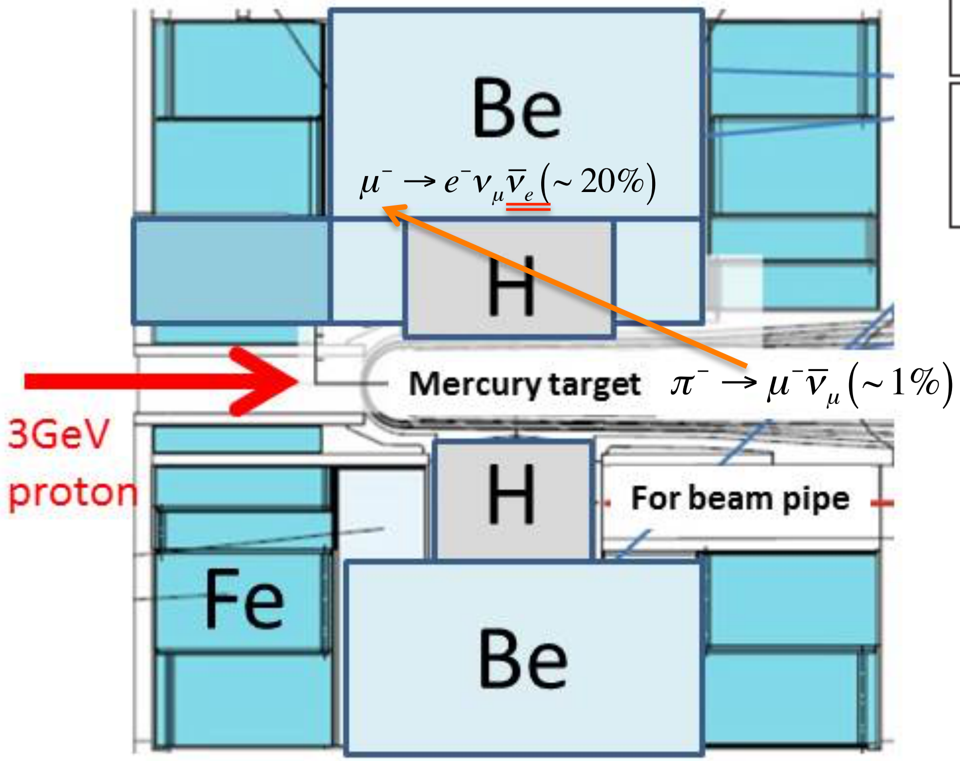
Similar to the reactor neutrino experiments but the neutrino energy is much higher (~53MeV)

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



Delayed coincidence: Free from environmental γ BKG

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%	5×10^{-3}	x	0.13	**$= 6.5\times10^{-4}$**
J-PARC	Hg(+Fe+Be)	99%	~80%	1.7×10^{-3}	x	1.	**$= 1.7\times10^{-3}$**

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

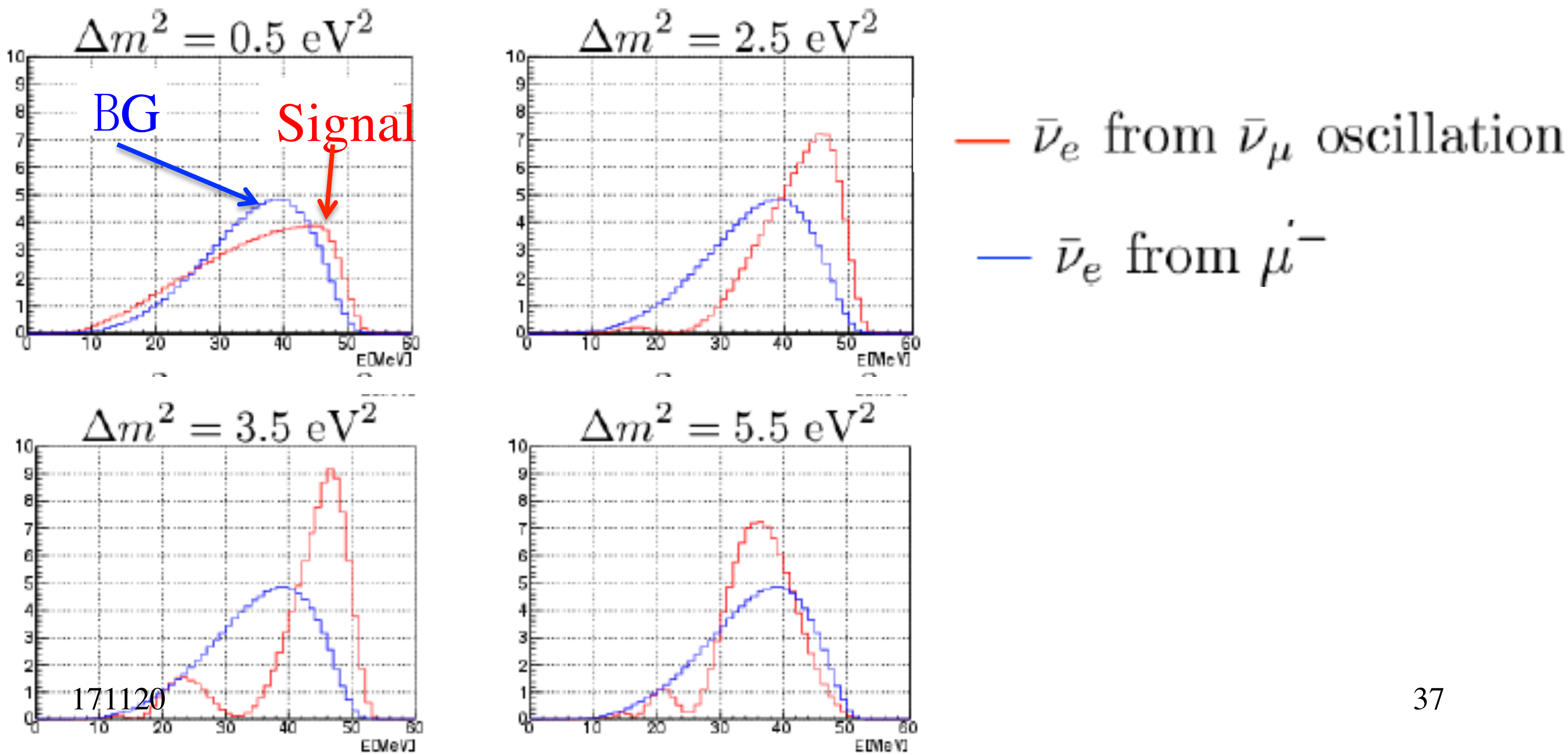
$$\pi^- \text{ (stop)} \rightarrow \mu^- + \bar{\nu}_\mu$$

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

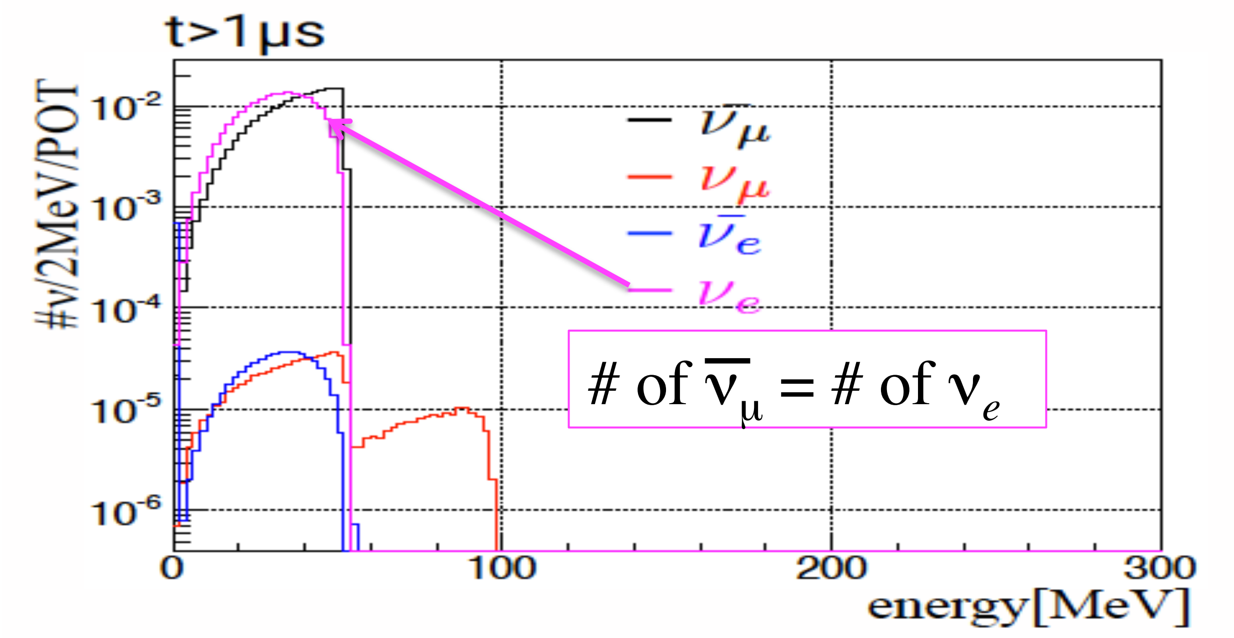
background

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

Can be separated by the spectrum analysis



ν flux normalization by $\nu_e + {}^{12}C$



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

${}^{12}N_{gs} \rightarrow {}^{12}C + e^+ + \nu$

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

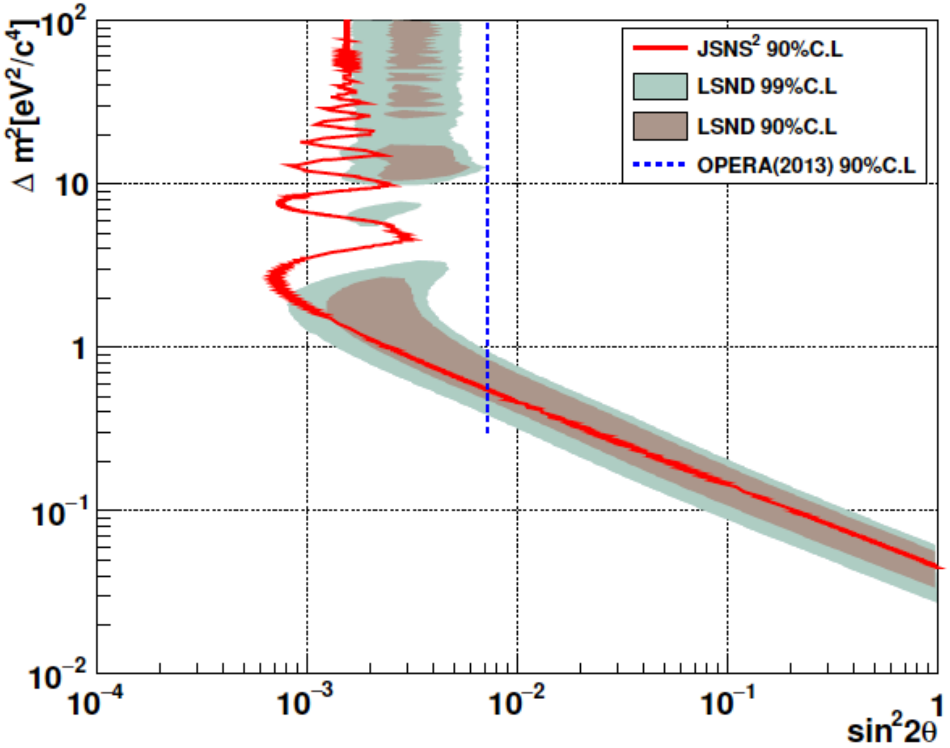
	primary timing	primary energy	delayed timing	delayed energy
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	1-10 μs	0-53 MeV	10-100 μs	8 MeV
$\nu_e C \rightarrow e N_{gs},\ N_{gs} \rightarrow C e^+ \nu_e$	1-10 μs	0-37 MeV	100 μs-10 ms	0-16 MeV

$JSNS^2$(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	--
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, Δt=30μs	2.2MeV, Δt=200μs
Liquid Scintillator	Gd Loaded	Cherenkov + Low 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

Sensitivity (1st phase)

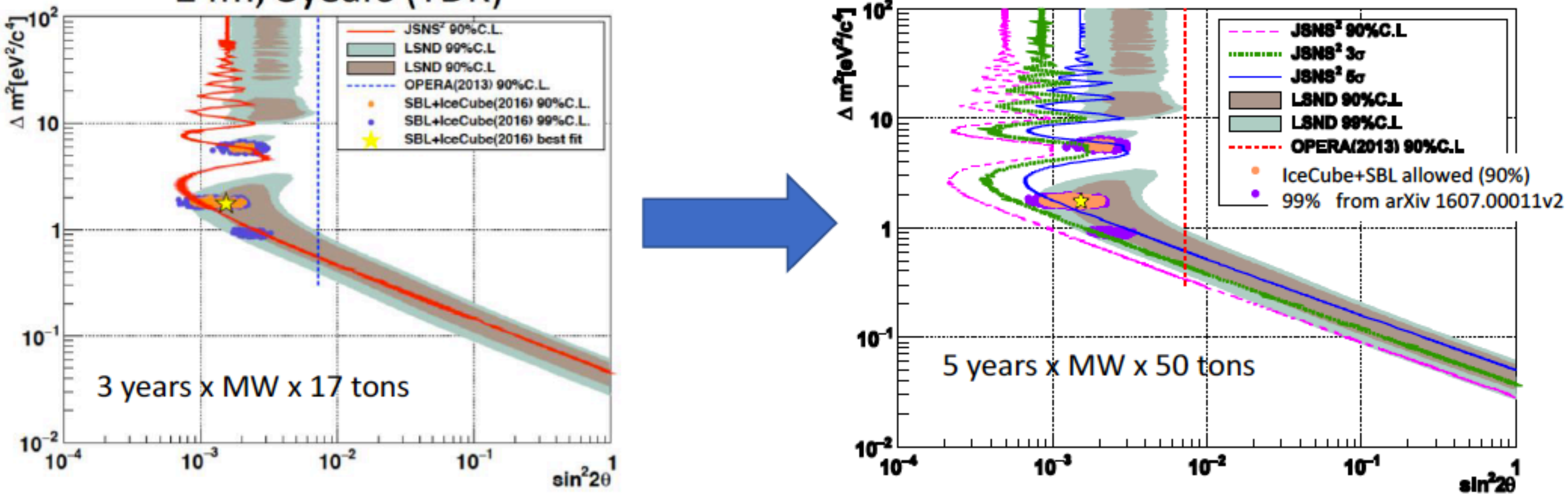
M=17ton, L=24m, T=3yrs



Sensitivity / Upgrade

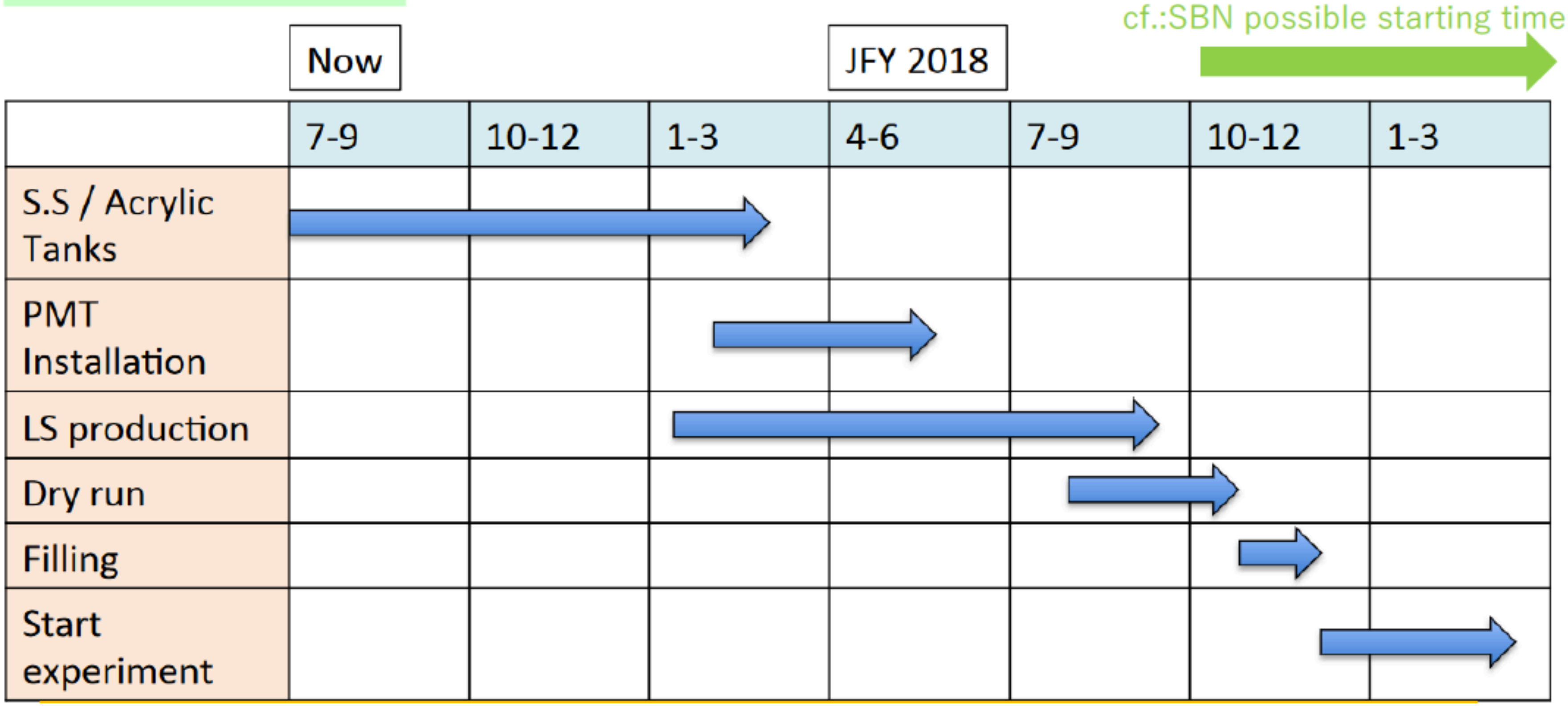
- To have a good international competition capability, we start the experiment with one detector (17tons fiducial volume).
- Even with one detector, we have a good 90% C.L constraints for the best fit point of global fit (of sterile neutrino searches) for 3 years. Left plot
- Meanwhile, we are making 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)



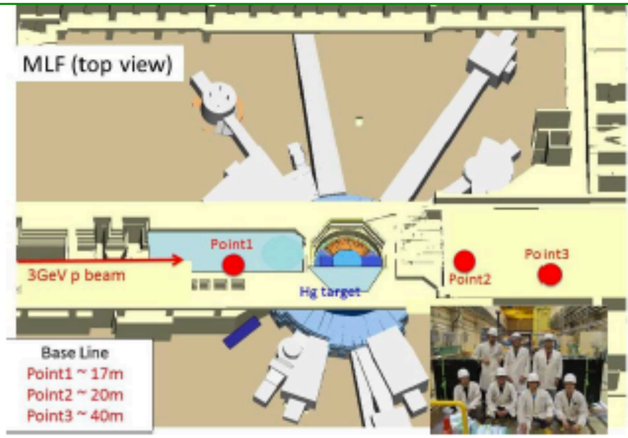
Schedule & Status

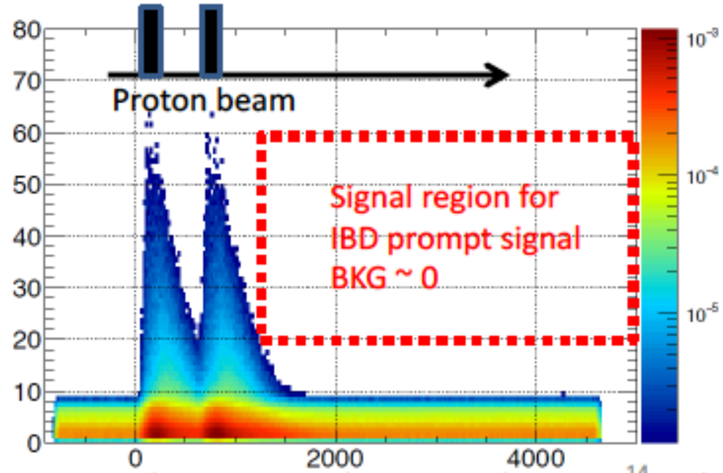
Overall schedule



Achievements so far

- 2013 Sep; A proposal was submitted to the J-PARC PAC
- 2014 Apr-Jul; We measured the BKG rate on 3rd floor. -> manageable beam /cosmic BKGs to perform JSNS^2
  PTEP 2015 6, 063C01 / arXiv:1502.02255
- 2014-Dec; The result was reported to J-PARC PAC. → the stage-1 status was obtained from J-PARC /KEK
- The performance check of detector and safety discussions are being performed.
- **2016-June: The grant-in-aid was approved for one detector construction**
- **2017-May: Technical Design Report was submitted to J-PARC PAC and arXiv (arXiv:1705.08629 [physics.ins-det])**
- **We aim to start JSNS^2 in JFY2018**



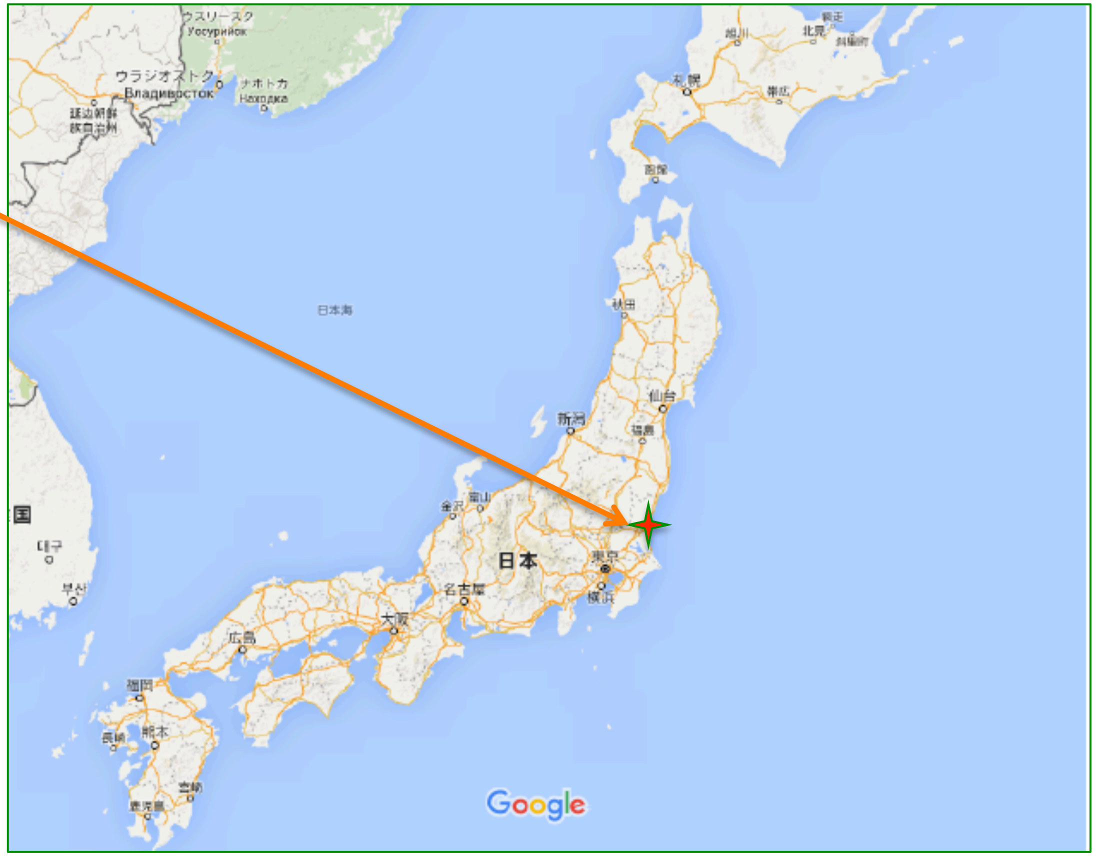


Energy (MeV, vertical) vs timing (ns, horizontal)

Sterile Neutrino experiments at J-PARC MLF

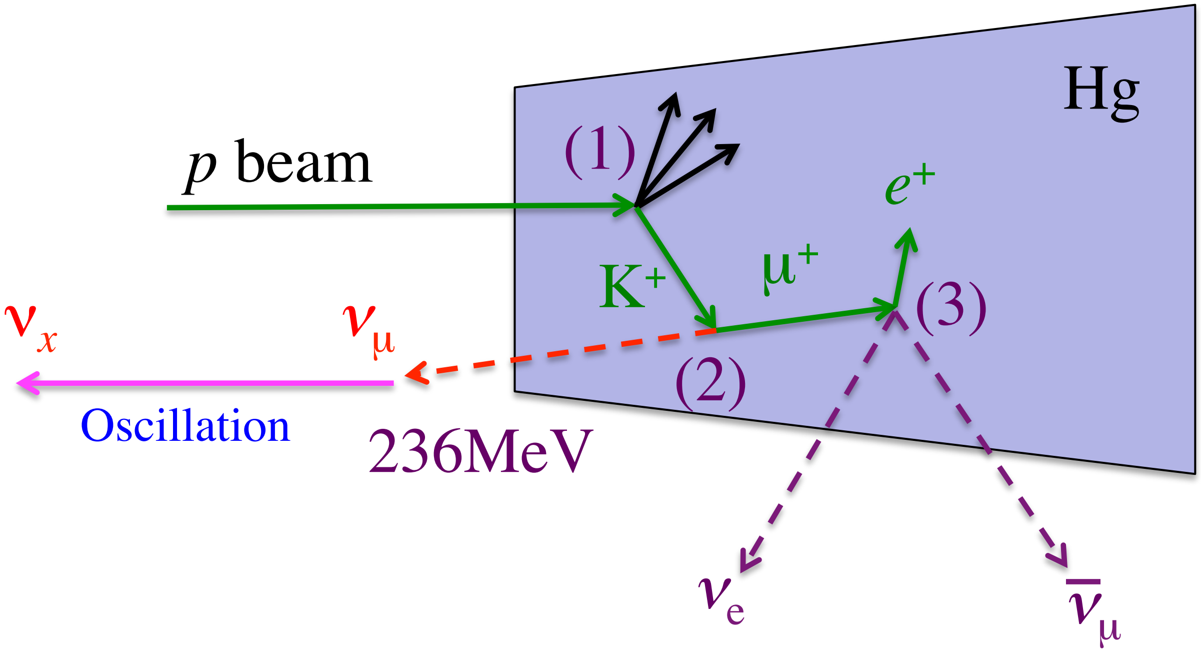
JSNS^2

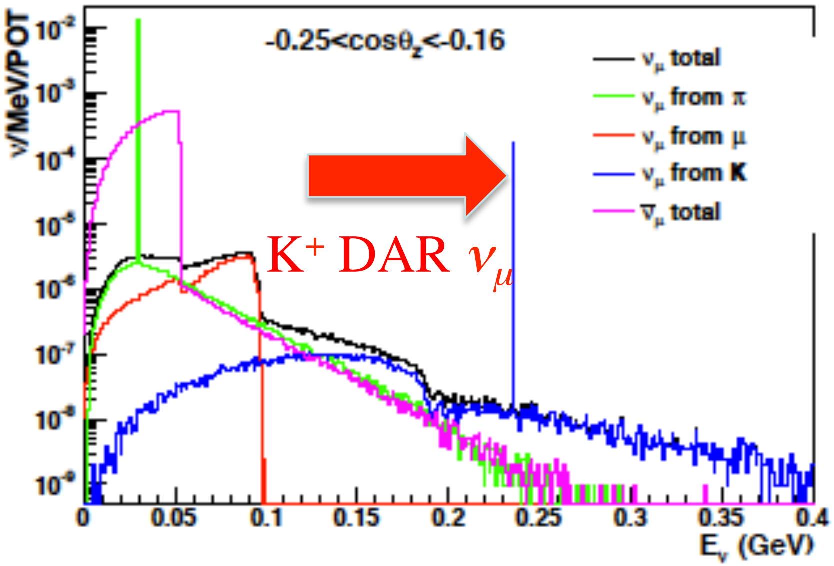
K-Pipe



$\nu_\mu \rightarrow \nu_\mu$ is also important

Monochromatic Neutrino from K^+ decay at rest





K-Pipe

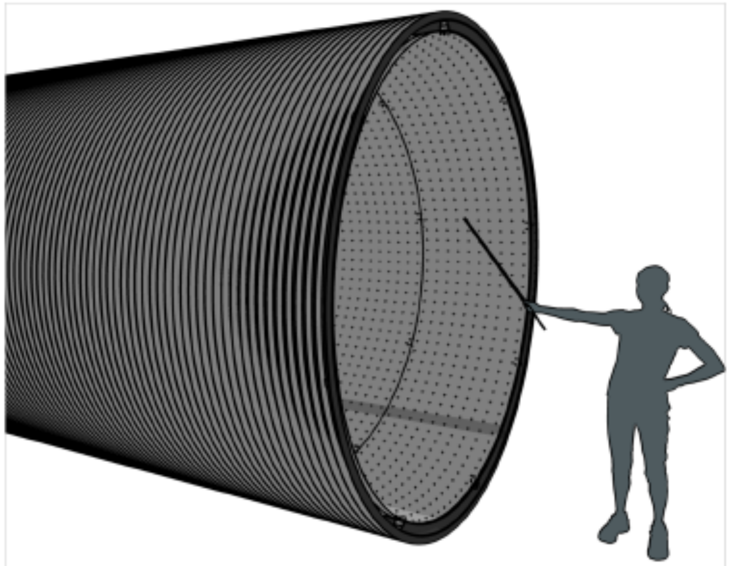
A Decisive Disappearance Search at High-Δm^2 with Monoenergetic Muon Neutrinos

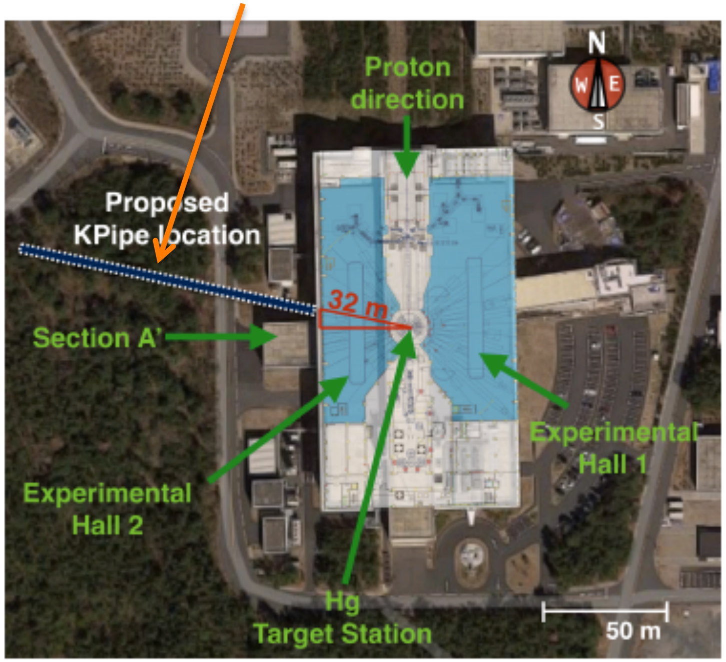
S. Axani[1], G. Collin[1], J.M. Conrad[1], M.H. Shaevitz[2], J. Spitz[1], T. Wongjirad[1]
[1] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA and*
[2] *Columbia University, New York, NY 10027, USA*

arXive:1506.0581v1

L dependence of monochromatic ν_μ disappearance

120m long liquid scintillator tank (pipe) (684 tons)



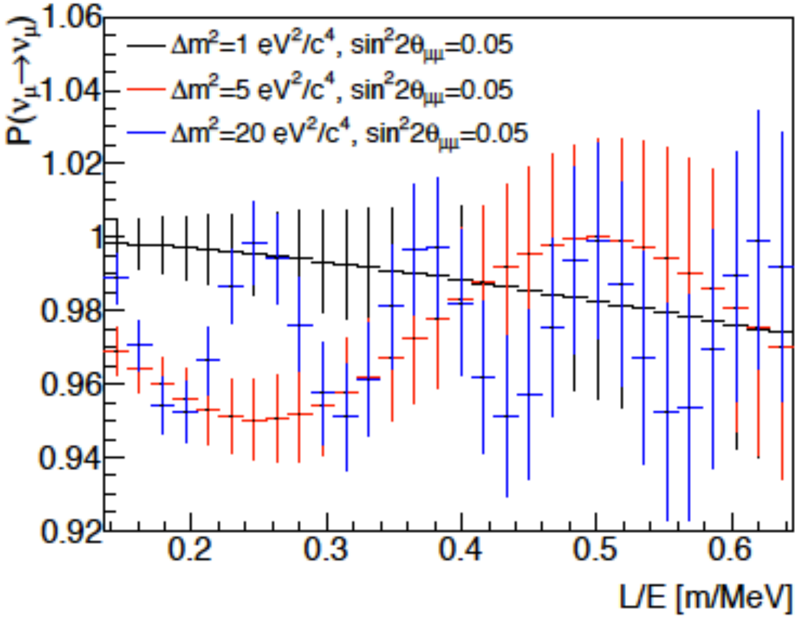


ν from K⁺:
Possible only at J-PARC MLF

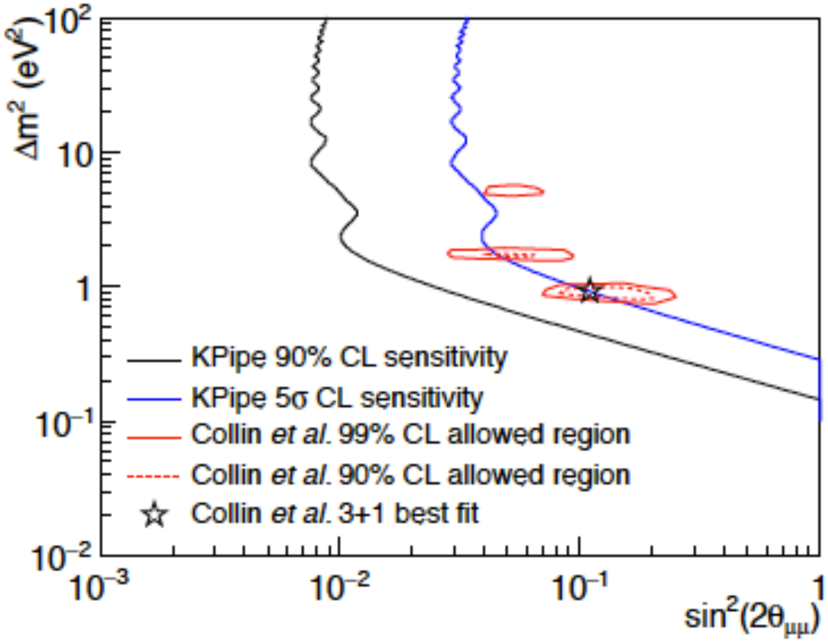
$$\nu_\mu \rightarrow \nu_S \left(\text{Deficit}\right)$$

ν detection principle

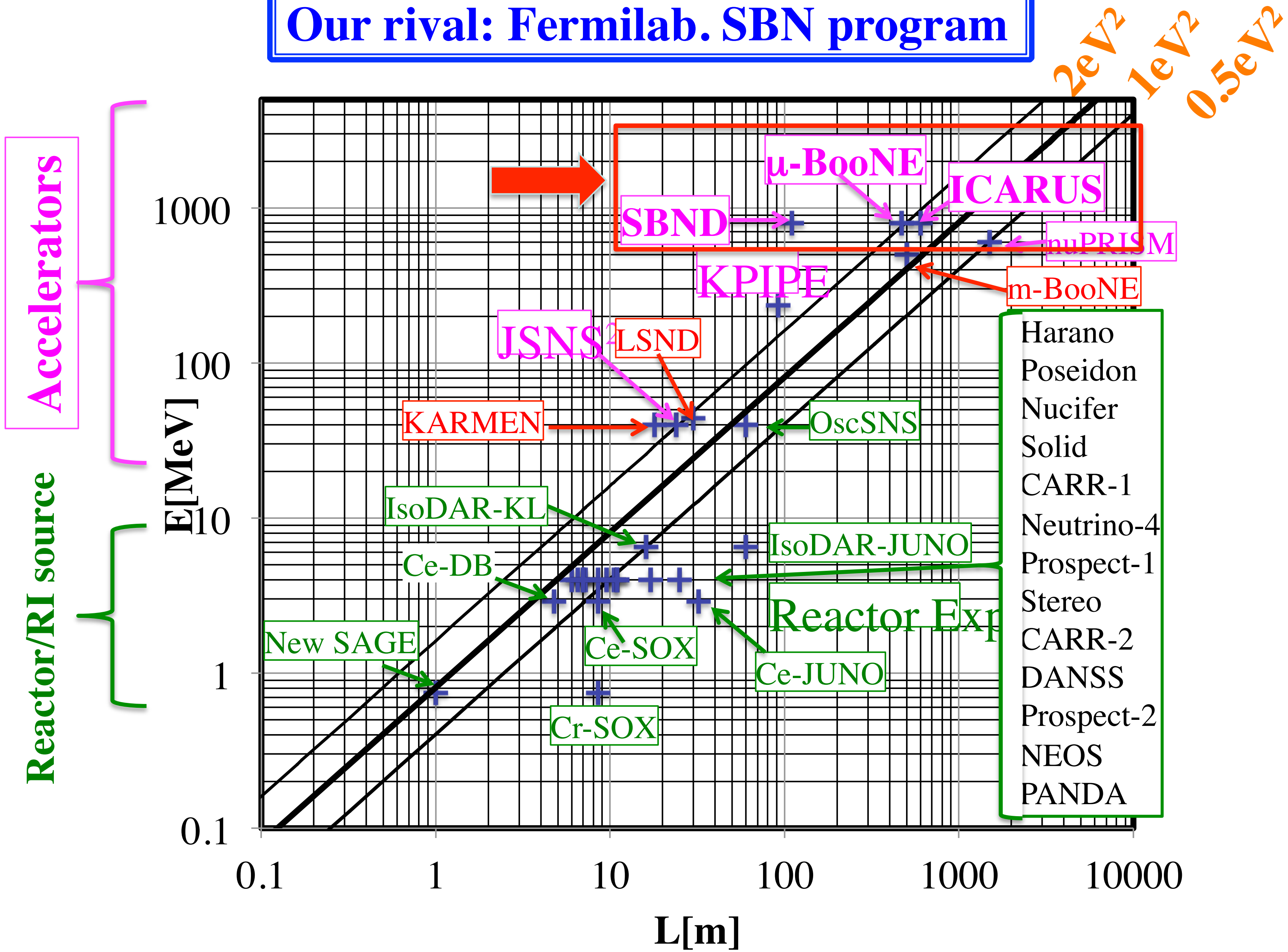
$$\nu_\mu + {}^{12}C \rightarrow \mu^- + X$$



Sensitivity (3years)



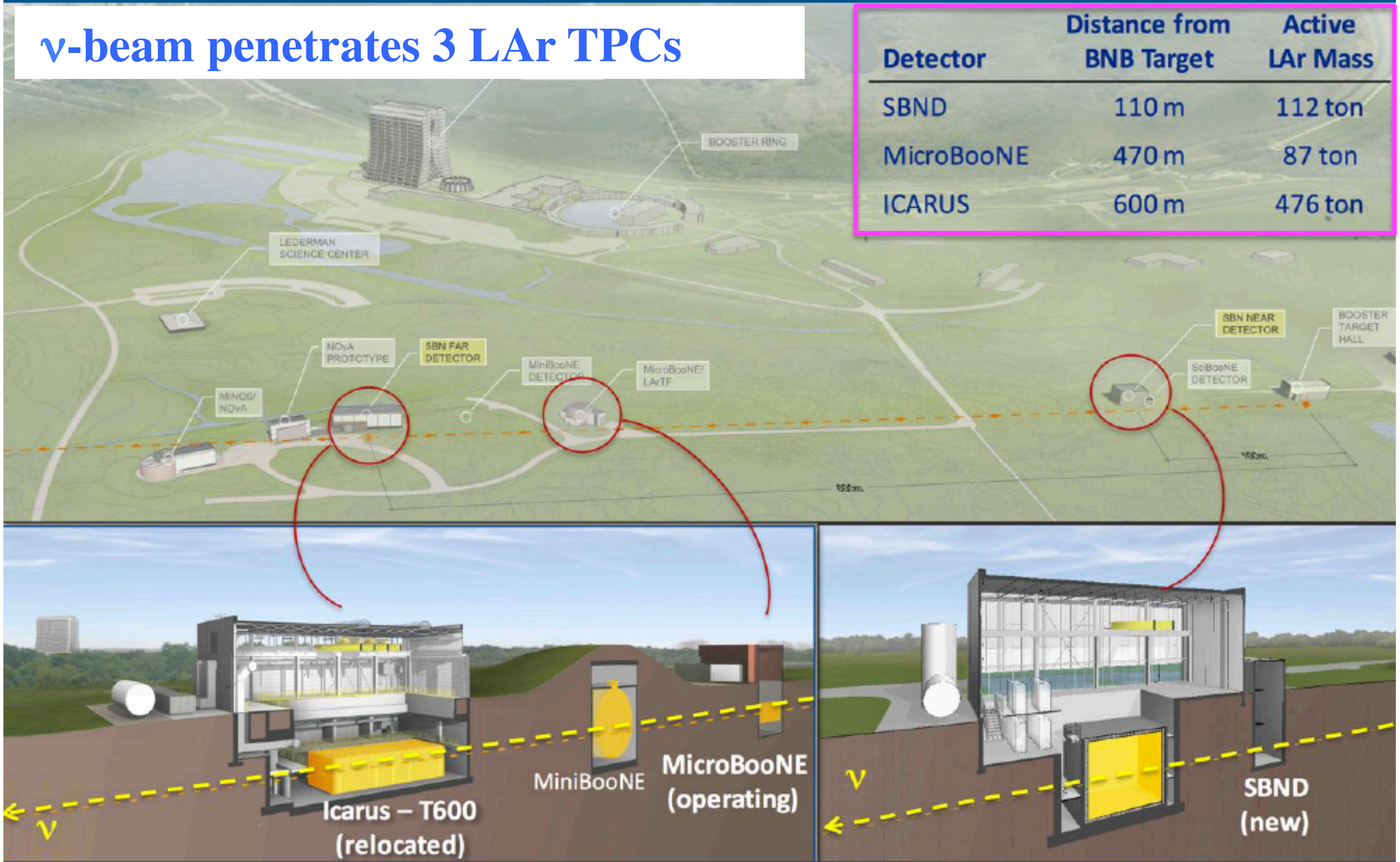
Our rival: Fermilab. SBN program



SBN project

ν-beam penetrates 3 LAr TPCs

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

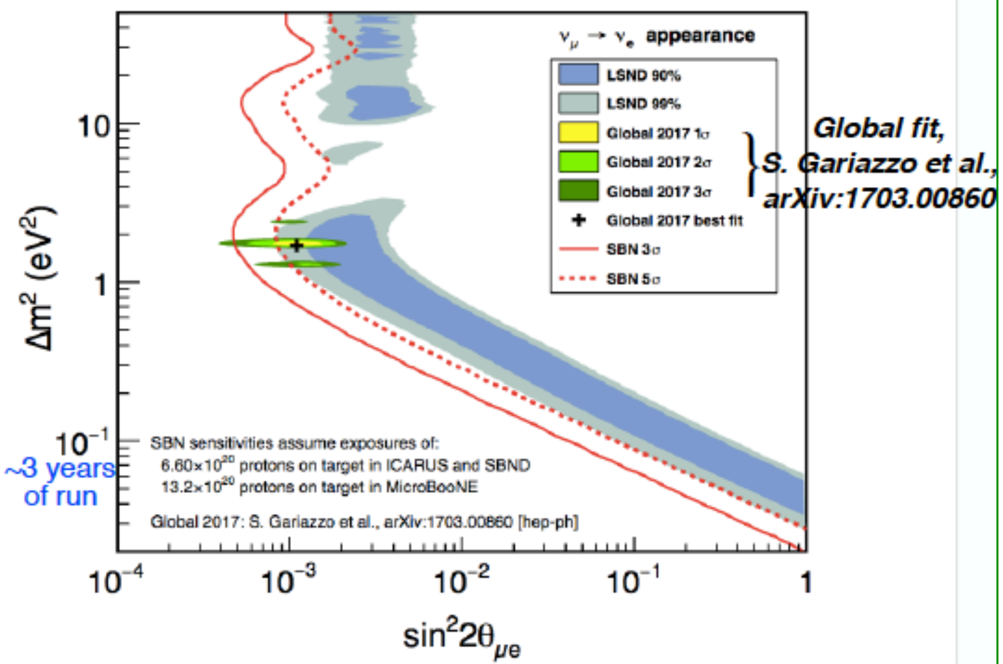


SBN Program Detectors - LAr TPCs

Physics reach of the SBN Program

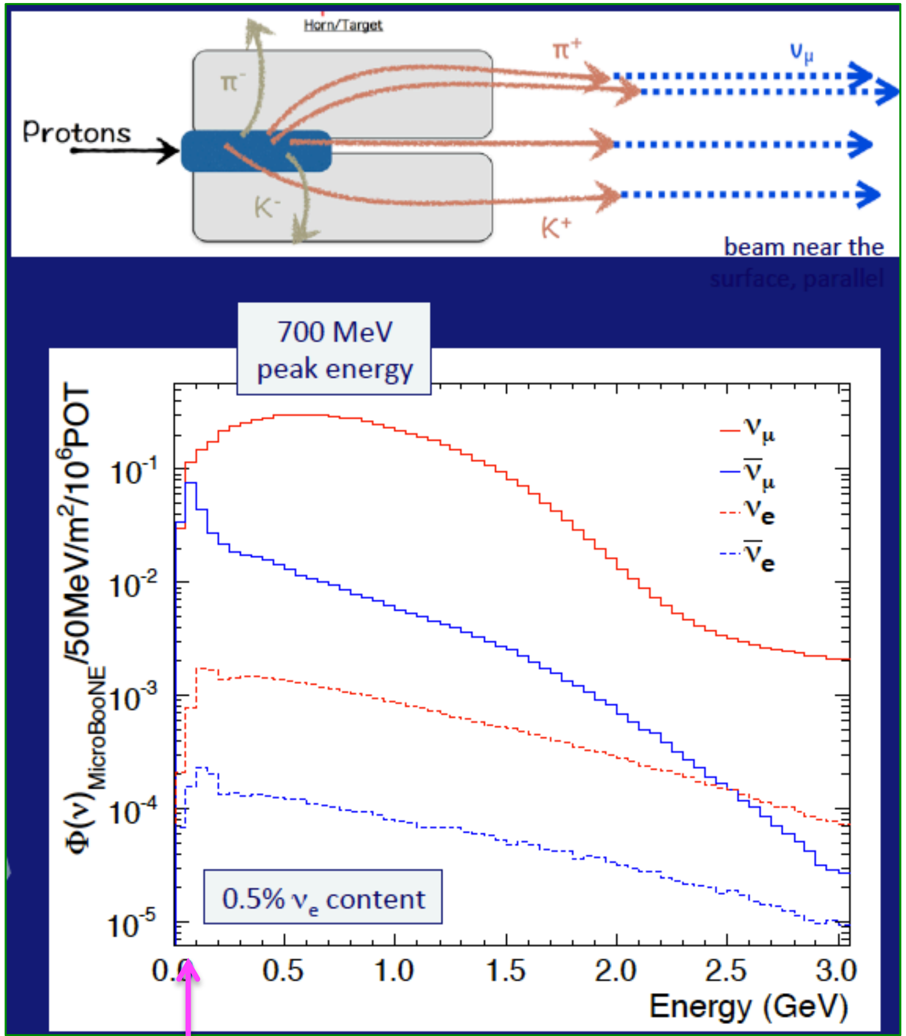
$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity

- *3+1" Analysis*
- *Multi-channel approaches, **with possible improvements in sensitivity from** exclusive topology measurements **are under study***



- The sensitivity of the SBN program is highest near the most favored values of Δm^2
- SBN will cover the LSND 99% C.L. allowed region with **≥ 5σ significance** (conclusive experiment w.r.t. LSND anomaly)

Difference from LSND/JSNS[2]:



D@R ν energy

* ν is π^+ & K^+ decay in flight
* ν energy is much higher
* ν detection mechanism is different

Different Systematics

Anyway, direct test of LSND is still important.

Summary

* There are indications of sterile neutrinos at $m \sim O$(eV)
* JSNS^2 experiment performs direct test for LSND anomaly.
* The first phase (1 of 2 detectors) of JSNS2 is funded and aiming to tart data taking in 2018.
* The funding for second phase (2 detectors) is being requested.