성균관대학교
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Probing mixing of sterile-tau neutrino at SHiP experiment

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with Seong Moon Yoo and KSHiP members

[Work in progress]

12 January Pohang

Dark Matter as a portal to New Physics 2024

Motivation for sterile neutrino

- to generate neutrino mass for explaining the oscillation of the active neutrinos

- to explain possible anomalies in the neutrino oscillation in the short baseline experiments

- to explain the asymmetry of matter-antimatter in the Universe such as leptogenesis

- to explain the non-relativistic matter component in the Universe

Neutrino Mixing and Oscillation

Neutrino mixing and oscillation

ν_e, ν_μ, ν_τ $\qquad |\nu_\alpha\rangle = \sum U^*_{\alpha k} |\nu_k\rangle \,,$ $\qquad \nu_1, \nu_2, \nu_3$

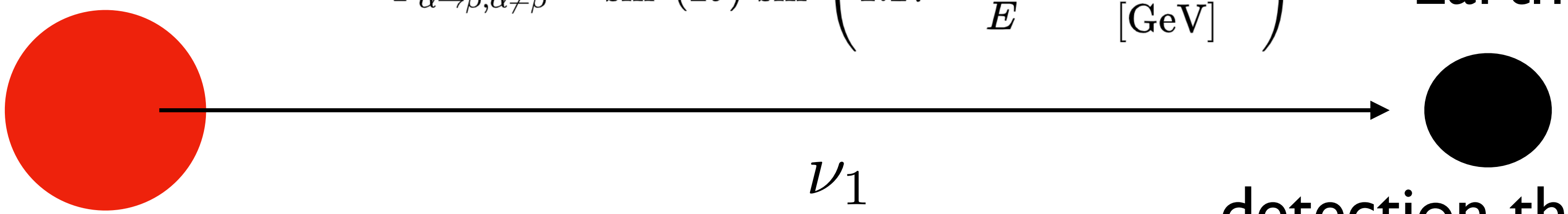
weak interaction states $\qquad$ mass states

(production, detection) $\qquad$ (propagation)

SUN

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\Delta m^2 L}{E}\,\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

Earth



ν_1

ν_2

ν_3

ν_e are produced

detection through interaction

ν_e, ν_μ, ν_τ

Oscillation Probability

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\Delta m^2 L}{E}\,\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

to make an order of O(1) inside sine-function

	Experiment		L (m)	E (MeV)	$\|\Delta m^2\|$ (eV^2)	
ν_e	Solar		10^{10}	1	10^{-10}	$\ll 10^{-5}$
$\nu_\mu, \bar{\nu}_\mu$	Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$	$\sim 10^{-3}$
$\bar{\nu}_e$	Reactor	VSBL–SBL–MBL	$10 - 10^3$	1	$1 - 10^{-3}$	
		LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$	
$\nu_\mu, \bar{\nu}_\mu$	Accelerator	SBL	10^2	10^3–10^4	> 0.1	
		LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$	

[PDG 2022]

Standard 3 neutrino oscillation

$$|\nu_\alpha\rangle = \sum U^*_{\alpha k}\, |\nu_k\rangle \,,$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \,,$$

$$= \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{\rm CP}} \\ -s_{12}\, c_{23} - c_{12}\, s_{13}\, s_{23}\, e^{i\delta_{\rm CP}} & c_{12}\, c_{23} - s_{12}\, s_{13}\, s_{23}\, e^{i\delta_{\rm CP}} & c_{13}\, s_{23} \\ s_{12}\, s_{23} - c_{12}\, s_{13}\, c_{23}\, e^{i\delta_{\rm CP}} & -c_{12}\, s_{23} - s_{12}\, s_{13}\, c_{23}\, e^{i\delta_{\rm CP}} & c_{13}\, c_{23} \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

Propagation and oscillation probability

The neutrino state after a time T and a distance L

$$|\nu_\alpha(T,L)\rangle = \sum_j e^{-iE_jT+ip_jL} U^*_{\alpha j}|\nu_j\rangle$$

with E_j and p_j for the j-th mass eigenstates

The oscillation probability

$$P_{\alpha\beta} \equiv \left|\, \langle \nu_\beta|\nu_\alpha(T,L)\rangle \,\right|^2 = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} e^{-i(E_j-E_k)T+i(p_j-p_k)L)}$$

Then the phase term is approximated as

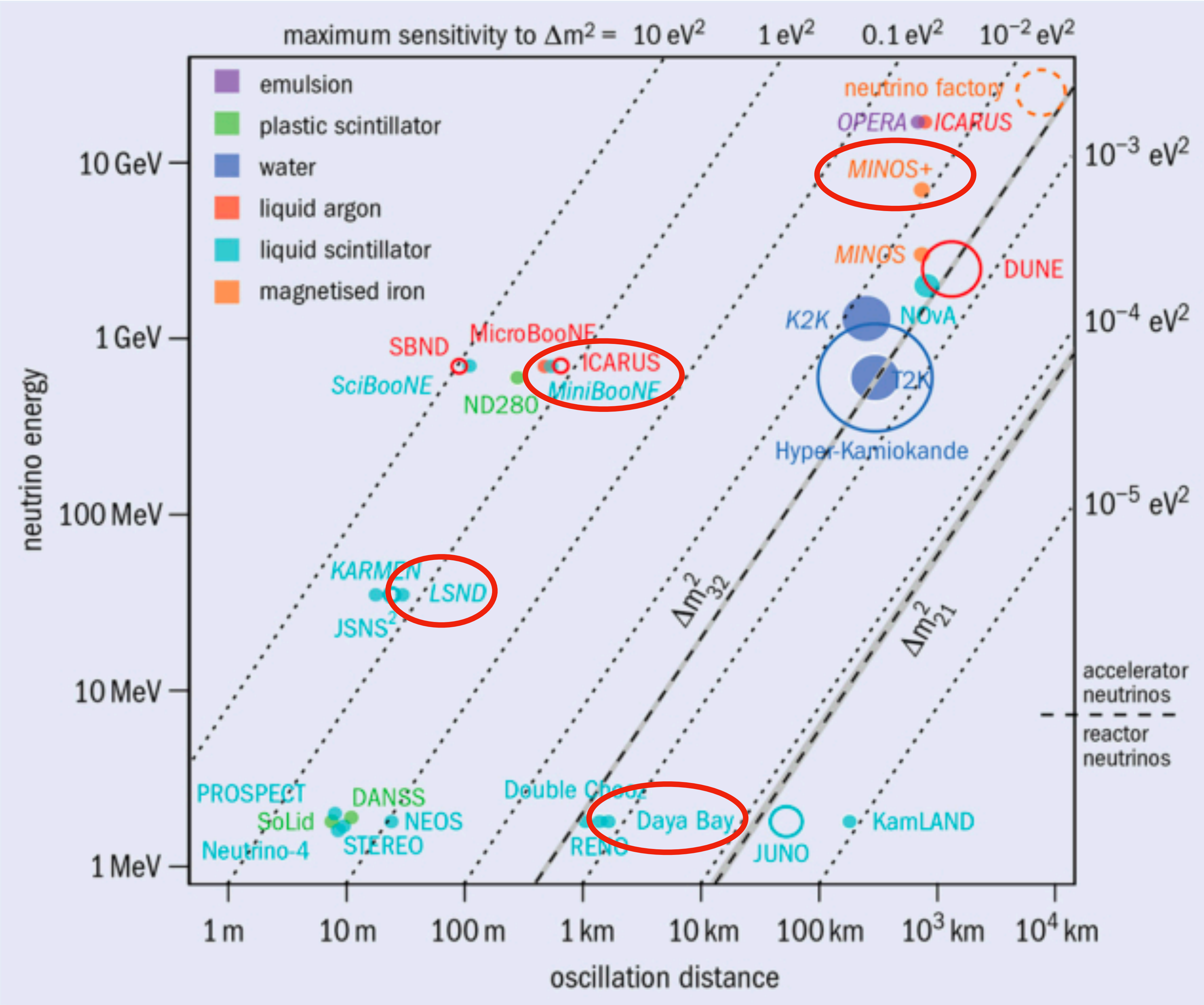
$$p_j = \sqrt{E_j^2 - m_j^2}$$

$$-i(E_j - E_k)(T-L) - i\Delta m^2_{jk}L/(2E) \sim -\, i\Delta m^2_{jk}L/(2E)$$

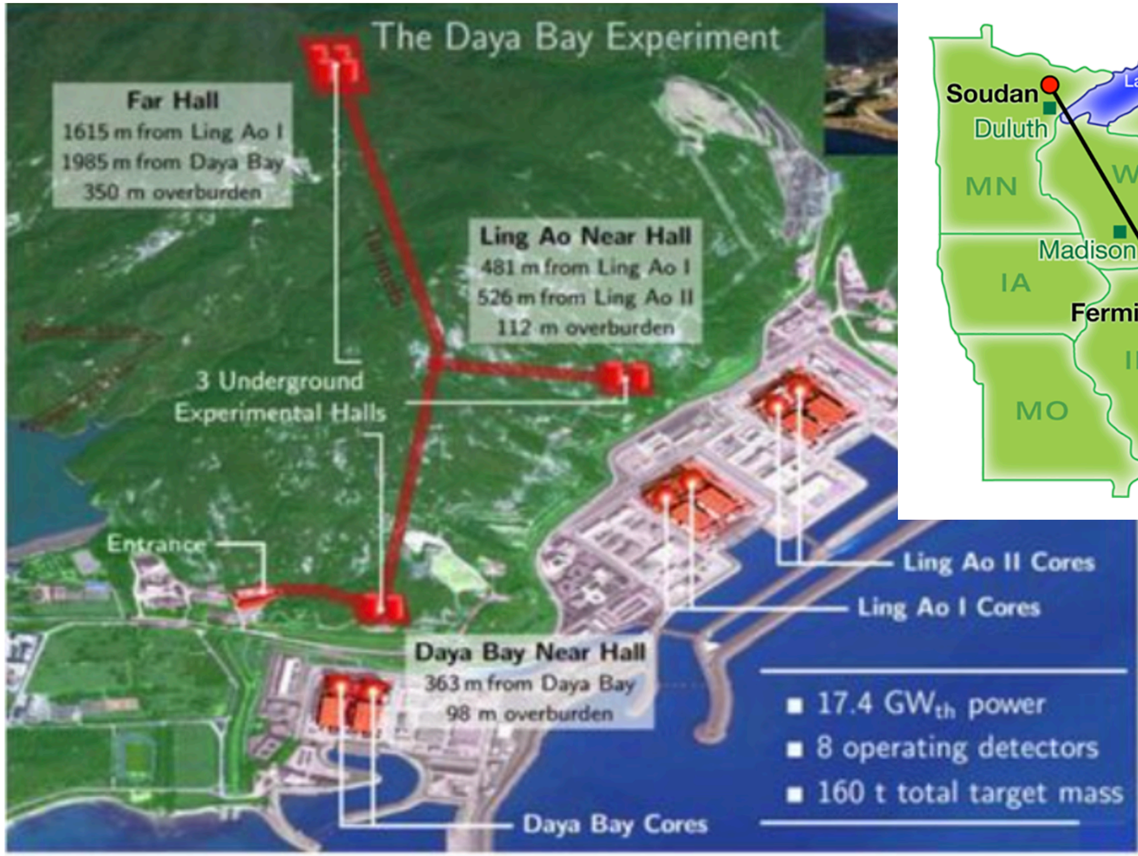
Therefore

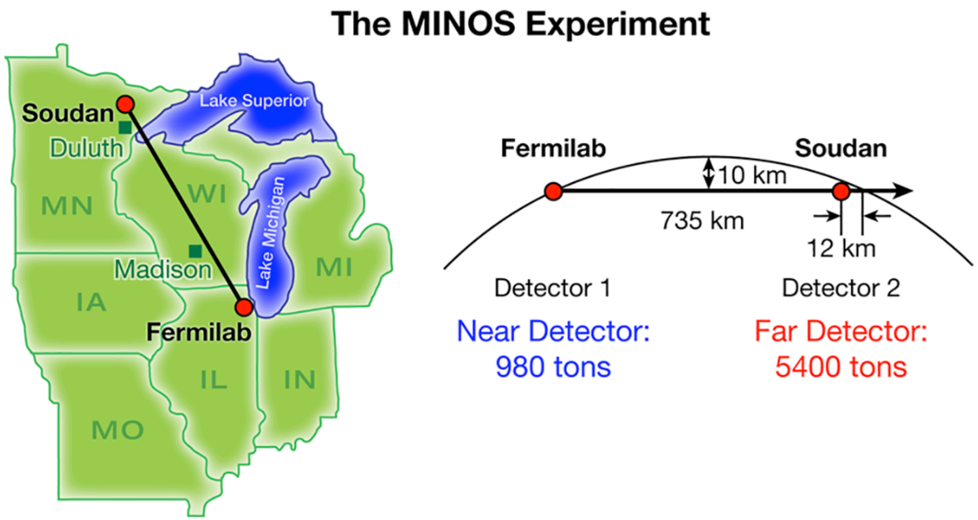
$$P_{\alpha\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} e^{-i\Delta m^2_{jk}L/(2E)}$$

	Ref. [181] w/o SK-ATM		Ref. [181] w SK-ATM		Ref. [182] w SK-ATM		Ref. [183] w SK-ATM	
NO	Best Fit Ordering		Best Fit Ordering		Best Fit Ordering		Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$	$3.03^{+0.12}_{-0.12}$	$2.70 \to 3.41$	$3.03^{+0.13}_{-0.13}$	$2.63 \to 3.45$	$3.18^{+0.16}_{-0.16}$	$2.71 \to 3.69$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.40^{+0.80}_{-0.82}$	$30.85 \to 35.97$	$34.3^{+1.0}_{-1.0}$	$31.4 \to 37.4$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.72^{+0.18}_{-0.23}$	$4.06 \to 6.20$	$4.51^{+0.19}_{-0.16}$	$4.08 \to 6.03$	$4.55^{+0.18}_{-0.15}$	$4.16 \to 5.99$	$5.74^{+0.14}_{-0.14}$	$4.34 \to 6.10$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$42.4^{+1.0}_{-0.9}$	$40.2 \to 50.7$	$49.3^{+0.8}_{-0.8}$	$41.2 \to 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.203^{+0.056}_{-0.059}$	$2.029 \to 2.391$	$2.225^{+0.056}_{-0.059}$	$2.052 \to 2.398$	$2.23^{+0.07}_{-0.06}$	$2.04 \to 2.44$	$2.200^{+0.069}_{-0.062}$	$2.00 \to 2.405$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.59^{+0.13}_{-0.12}$	$8.21 \to 8.99$	$8.53^{+0.13}_{-0.12}$	$8.13 \to 8.92$
$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	232^{+36}_{-26}	$144 \to 350$	223^{+32}_{-23}	$139 \to 355$	194^{+24}_{-22}	$128 \to 359$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.36^{+0.16}_{-0.15}$	$6.93 \to 7.93$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$	$2.437^{+0.028}_{-0.027}$	$2.354 \to 2.523$	$2.433^{+0.026}_{-0.027}$	$2.353 \to 2.516$	$2.448^{+0.023}_{-0.031}$	$2.367 \to 2.521$	$2.47^{+0.02}_{-0.03}$	$2.40 \to 2.46$
IO	$\Delta\chi^2 = 2.3$		$\Delta\chi^2 = 6.4$		$\Delta\chi^2 = 6.5$		$\Delta\chi^2 = 6.4$	
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$	$3.03^{+0.12}_{-0.11}$	$2.70 \to 3.41$	$3.03^{+0.13}_{-0.13}$	$2.63 \to 3.45$	$3.18^{+0.16}_{-0.16}$	$2.71 \to 3.69$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.40^{+0.80}_{-0.82}$	$30.85 \to 35.97$	$34.3^{+1.0}_{-1.0}$	$31.4 \to 37.4$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.78^{+0.16}_{-0.21}$	$4.12 \to 6.23$	$5.69^{+0.16}_{-0.21}$	$4.12 \to 6.13$	$5.69^{+0.13}_{-0.21}$	$4.17 \to 6.06$	$5.78^{-0.10}_{+0.17}$	$4.33 \to 6.08$
$\theta_{23}/^\circ$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$	$49.0^{+0.7}_{-1.4}$	$40.2 \to 51.1$	$49.5^{+0.6}_{-1.0}$	$41.2 \to 51.2$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.219^{+0.060}_{-0.057}$	$2.047 \to 2.396$	$2.223^{+0.058}_{-0.058}$	$2.048 \to 2.416$	$2.23^{+0.06}_{-0.06}$	$2.03 \to 2.45$	$2.225^{+0.064}_{-0.070}$	$2.02 \to 2.42$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$	$8.59^{+0.13}_{-0.12}$	$8.19 \to 9.00$	$8.58^{+0.12}_{-0.14}$	$8.17 \to 8.96$
$\delta_{CP}/^\circ$	286^{+27}_{-32}	$192 \to 360$	276^{+22}_{-29}	$194 \to 344$	274^{+25}_{-27}	$193 \to 342$	284^{+26}_{-28}	$200 \to 353$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.36^{+0.16}_{-0.15}$	$6.93 \to 7.93$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$	$-2.486^{+0.028}_{-0.025}$	$-2.570 \to -2.406$	$-2.492^{+0.025}_{-0.030}$	$-2.578 \to -2.413$	$-2.52\pm^{+0.03}_{-0.02}$	$-2.60 \to -2.44$

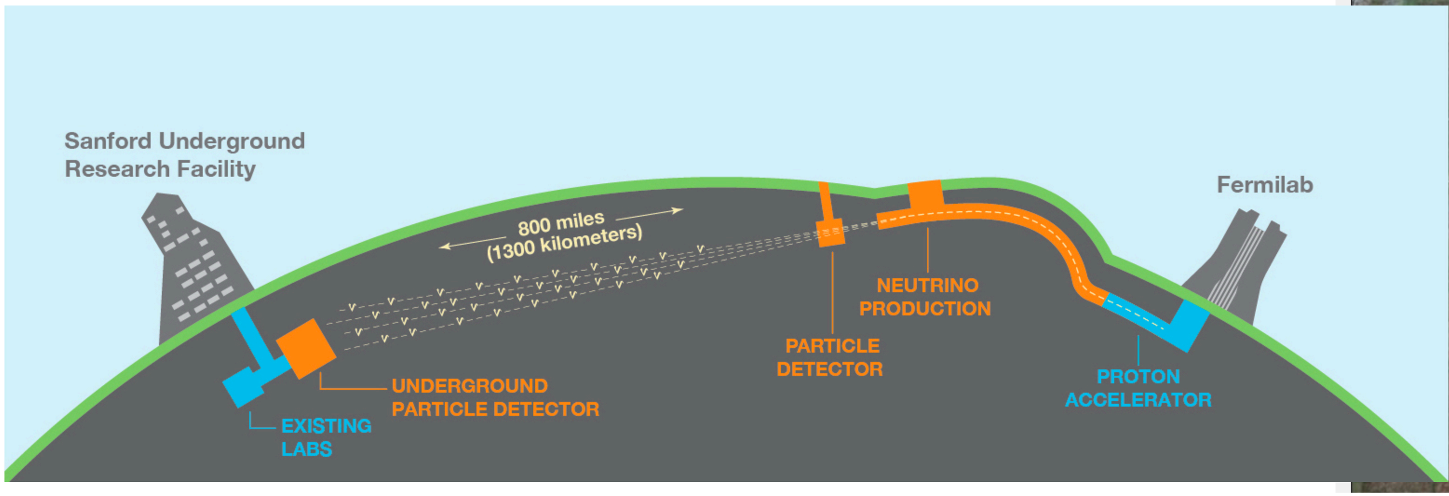


maximum sensitivity to Δm² = 10 eV² 1 eV² 0.1 eV² 10⁻² eV²
emulsion
plastic scintillator
water
liquid argon
liquid scintillator
magnetised iron
neutrino factory
OPERA
ICARUS
MINOS+
MINOS
DUNE
K2K
NOvA
T2K
Hyper-Kamiokande
SBND
MicroBooNE
ICARUS
SciBooNE
ND280
MiniBooNE
KARMEN
LSND
JSNS²
PROSPECT
DANSS
SoLid
NEOS
Neutrino-4
STEREO
Double Chooz
Daya Bay
RENO
JUNO
KamLAND
Δm²32
Δm²21
10⁻³ eV²
10⁻⁴ eV²
10⁻⁵ eV²
accelerator neutrinos
reactor neutrinos
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
neutrino energy
1 m
10 m
100 m
1 km
10 km
100 km
10³ km
10⁴ km
oscillation distance


The Daya Bay Experiment
Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden
Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden
3 Underground Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden
17.4 GW$_{th}$ power
8 operating detectors
160 t total target mass
Daya Bay Cores


The MINOS Experiment
Soudan
Duluth
Lake Superior
MN
WI
Lake Michigan
MI
IA
Madison
Fermilab
IL
IN
MO
Fermilab
Soudan
10 km
735 km
12 km
Detector 1
Detector 2
Near Detector:
980 tons
Far Detector:
5400 tons


NOνA Far Detector (Ash River, MN)
MINOS Far Detector (Soudan, MN)
Lake Superior
810 km baseline
Wisconsin
Lake Michigan
Milwaukee
Fermilab
Chicago


Sanford Underground Research Facility
Fermilab
800 miles (1300 kilometers)
NEUTRINO PRODUCTION
PARTICLE DETECTOR
PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS

LSND Anomaly

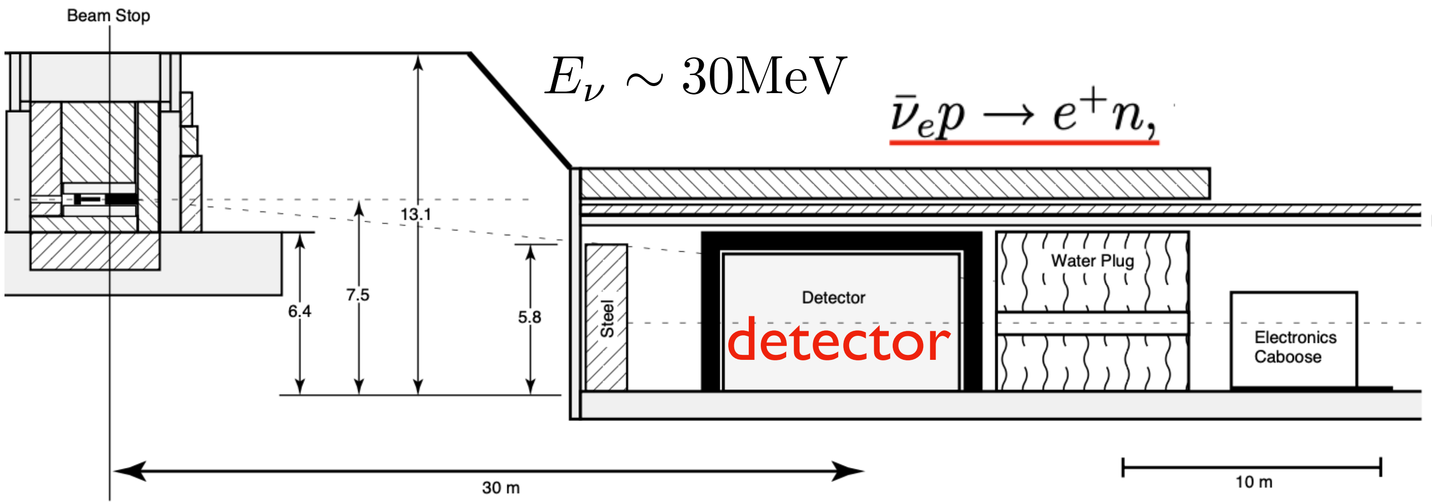
$$\pi^+ \to \nu_\mu + (\mu^+ \to e^+ \nu_e \bar{\nu}_\mu)$$

stopped pion decay

Liquid Scintillator Neutrino detector at Los Alamos National Laboratory (1993-1998)

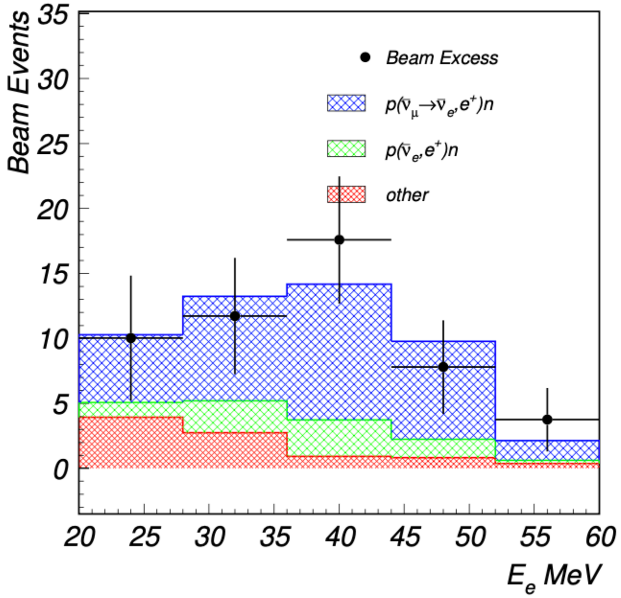
$E_\nu \sim 30\mathrm{MeV}$

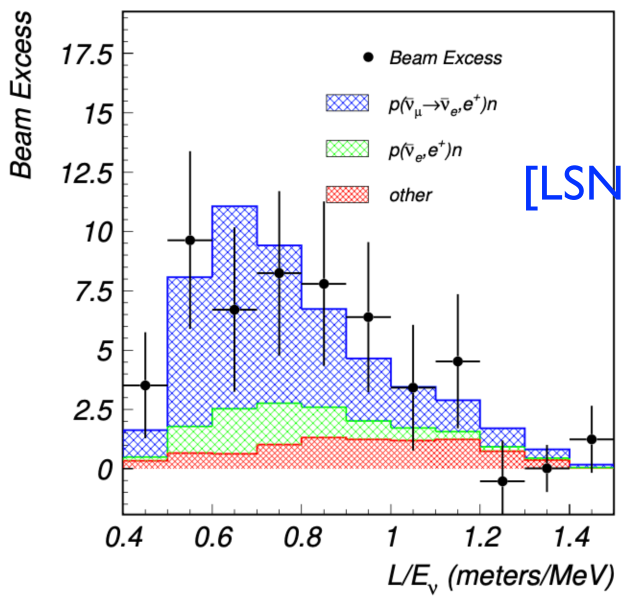
$\bar{\nu}_e p \to e^+ n,$



30 meters

$\bar{\mu}_\nu \to \bar{\nu}_e$ oscillation search : e-neutrino appearance





[LSND, PRD (2001), hep-ex/0104049]

blue: predicted signal from oscillation due to sterile neutrino

$$\bar{\nu}_\mu \to \bar{\nu}_s \to \bar{\nu}_e$$

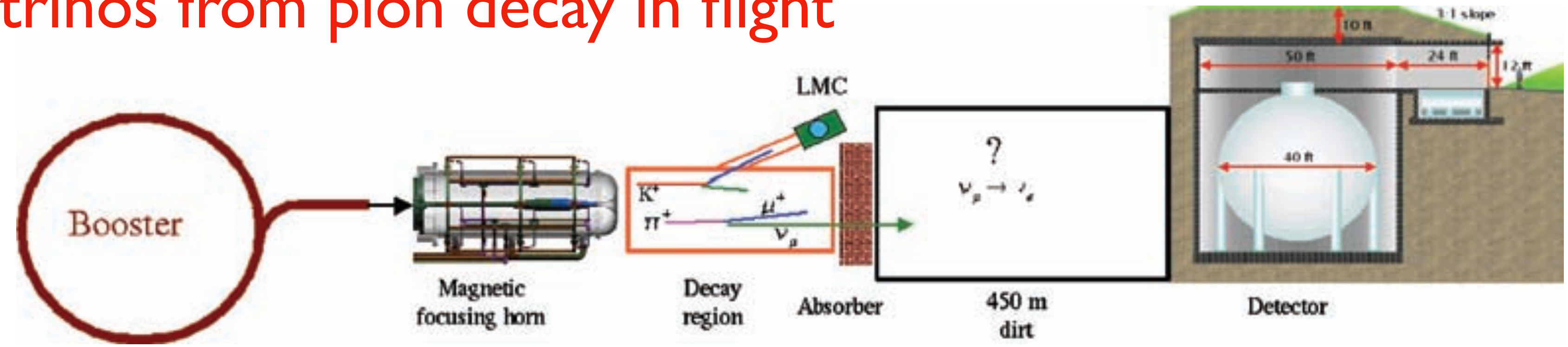
green, red: background

MiniBooNE Anomaly

at Fermilab

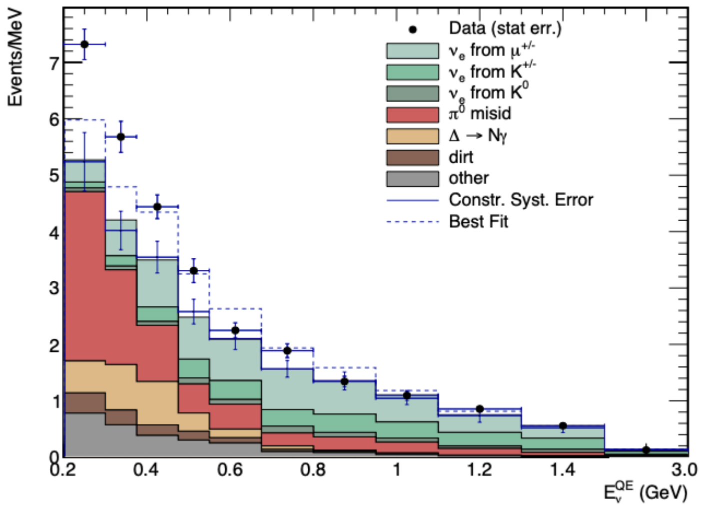
ν_μ or $\bar{\nu}_\mu$: 200 MeV ~ 1.5 GeV

neutrinos from pion decay in flight

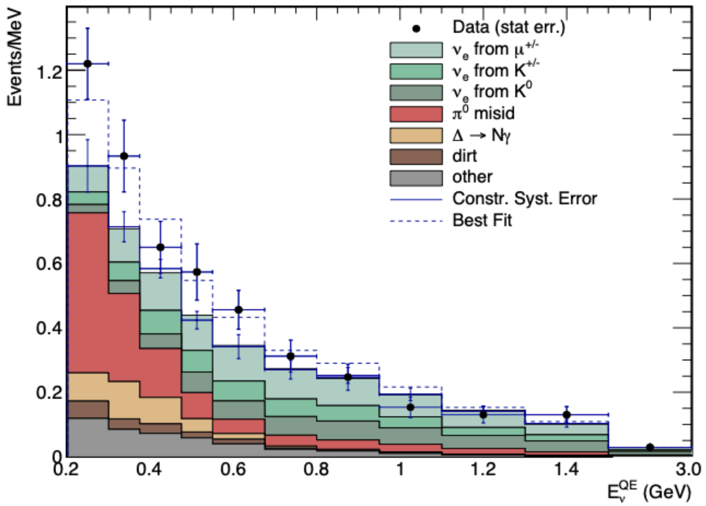


~ 500 meters

ν_μ mode : e-neutrino appearance



$\bar{\nu}_\mu$ mode



blue dashed: predicted signal from oscillation due to sterile neutrino

[MiniBoone, PRL (2018), 1805.12028]

$\nu_\mu \rightarrow \nu_e$ appearance searches

ex) LSND, MiniBoone, etc

In the short-baseline limit, $\Delta m^2_{21} L/E \ll 1,\ \Delta m^2_{31} L/E \ll 1$

: standard model oscillations have not been developed yet.

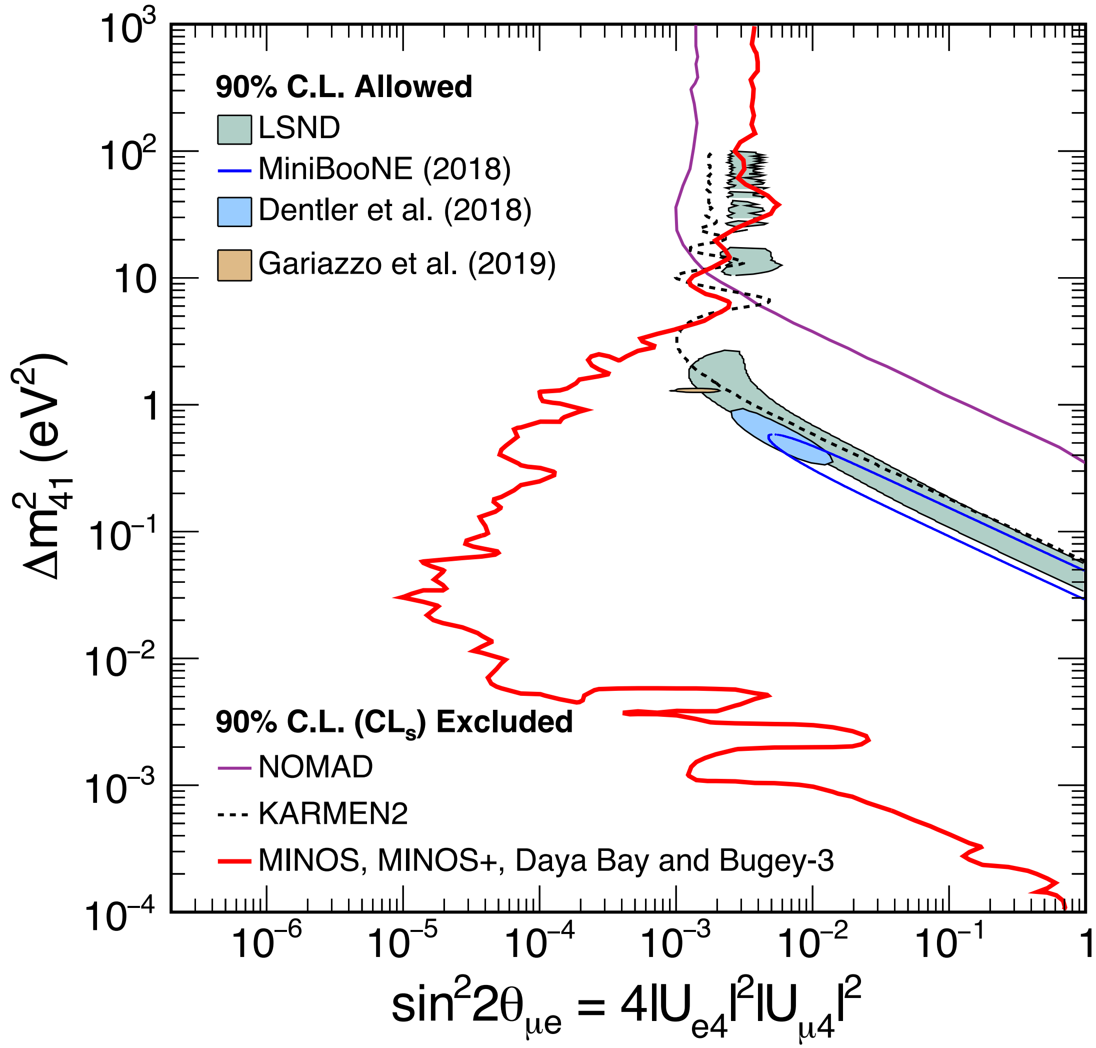
The oscillation can be solely due to sterile neutrino mixing as

$$P^{\rm sbl}_{\mu e} \simeq 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

thus, the effective mixing is defined as $\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}|^2|U_{\mu 4}|^2$

Constraints on the sterile neutrino mixing

[DAYA BAY, MINOS+ collaboration, PRL (2020), 2002.00301]



LSND, MiniBooNE 90% CL allowed region

MINOS, MINOS+, DAYA BAY, Bugey-3 combined 90% CL excluded region

disappearance of e-antineutrino, mu-neutrino, mu-antineutrino

$$|U_{e3}|^2 = \cos^2\theta_{14}\sin^2\theta_{13},$$
$$|U_{e4}|^2 = \sin^2\theta_{14},$$
$$|U_{\mu4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}.$$

3+1 model

Standard 3 neutrino + one sterile neutrino

for fields

$$|\nu_\alpha\rangle = \sum U^*_{\alpha k} |\nu_k\rangle \,, \qquad \mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

weak states mass states

$$\nu_\alpha = \sum U_{\alpha j} \nu_j$$

$$|\nu_\alpha\rangle = \nu^\dagger_\alpha |0\rangle$$

$$\mathbf{U} = \mathbf{U}_{34}\mathbf{U}_{24}\mathbf{U}_{23}\mathbf{U}_{14}\mathbf{U}_{13}\mathbf{U}_{12},$$

ν_e and $\bar{\nu}_e$ disappearance searches

In the short-baseline limit, $\Delta m^2_{21} L/E \ll 1,\ \Delta m^2_{31} L/E \ll 1$

: standard model oscillations have not been developed yet.

The oscillation is solely due to sterile neutrino mixing as

$$P^{\rm sbl}_{ee} \simeq 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m^2_{41} L}{4E}$$

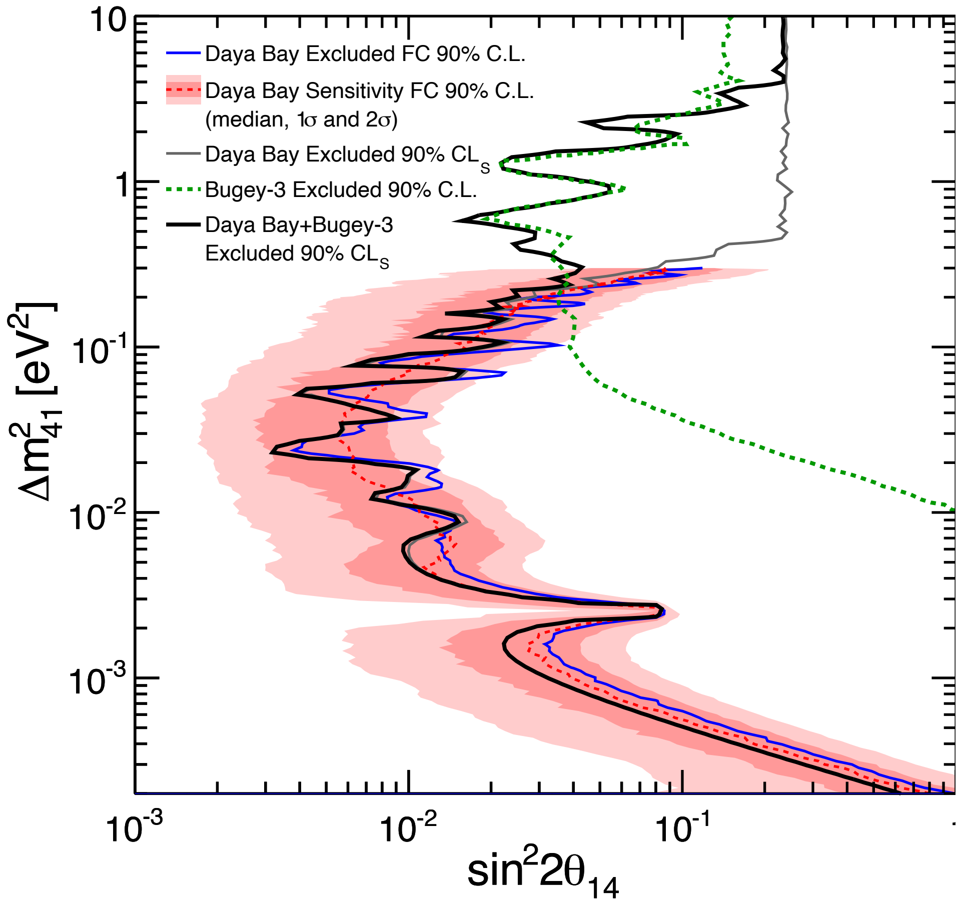
with the effective mixing angle can be define as

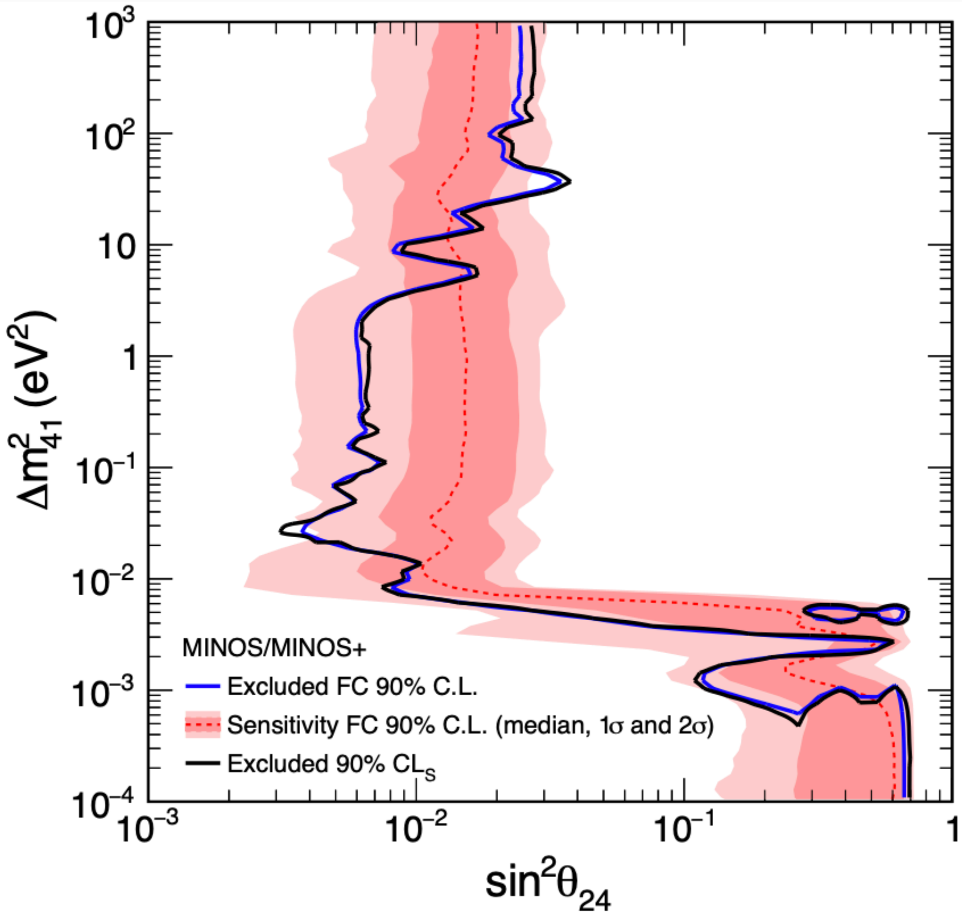
$$\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1-|U_{e4}|^2)$$

Similar to the muon neutrino disappearance searches, in the short-baseline

$$P^{\rm sbl}_{\mu\mu} \simeq 1 - 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)\sin^2\frac{\Delta m^2_{41} L}{4E}$$

[DAYA BAY, MINOS+ collaboration, PRL (2020), 2002.00301]



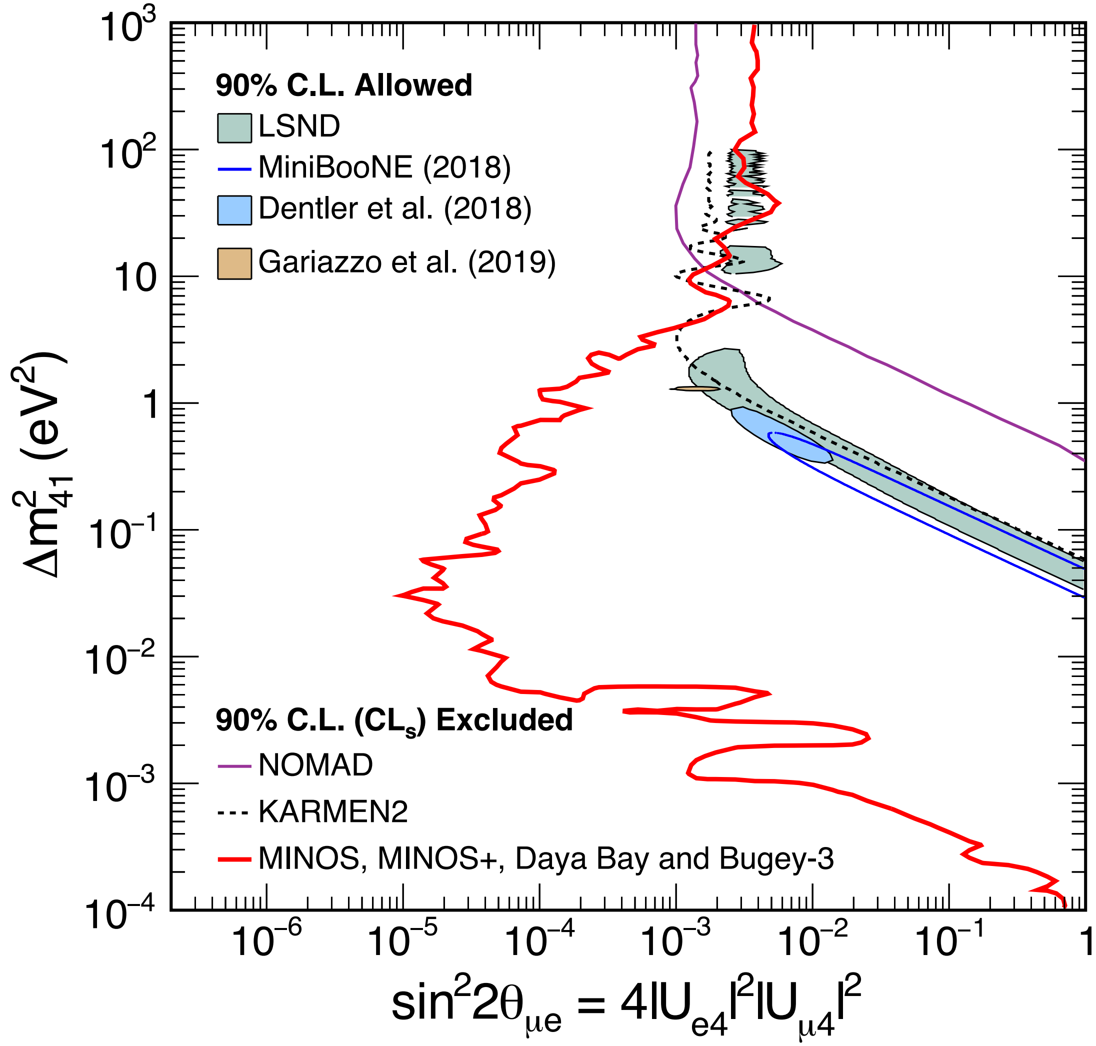


disappearance of e-antineutrino,

disappearance of mu-neutrino, mu-antineutrino

Constraints on the sterile neutrino mixing

[DAYA BAY, MINOS+ collaboration, PRL (2020), 2002.00301]



LSND, MiniBooNE 90% CL allowed region

MINOS, MINOS+, DAYA BAY, Bugey-3 combined 90% CL excluded region

disappearance of e-antineutrino, mu-neutrino, mu-antineutrino

$$|U_{e3}|^2 = \cos^2\theta_{14}\sin^2\theta_{13},$$
$$|U_{e4}|^2 = \sin^2\theta_{14},$$
$$|U_{\mu4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}.$$

reactor

disappearance of e-antineutrino

$$P_{\bar{\nu}_e\to\bar{\nu}_e} \approx 1 - 4|U_{e4}|^2\left(1-|U_{e4}|\right)^2 \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) - 4|U_{e3}|^2\left(1-|U_{e3}|^2\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right),$$

$$\approx 1 - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right).$$

Long baseline

disappearance of mu-(anti)neutrino

$$P_{\overset{(-)}{\nu}_\mu\to\overset{(-)}{\nu}_\mu} \approx 1 - \sin^2 2\theta_{23}\cos 2\theta_{24}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) - \sin^2 2\theta_{24}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right).$$

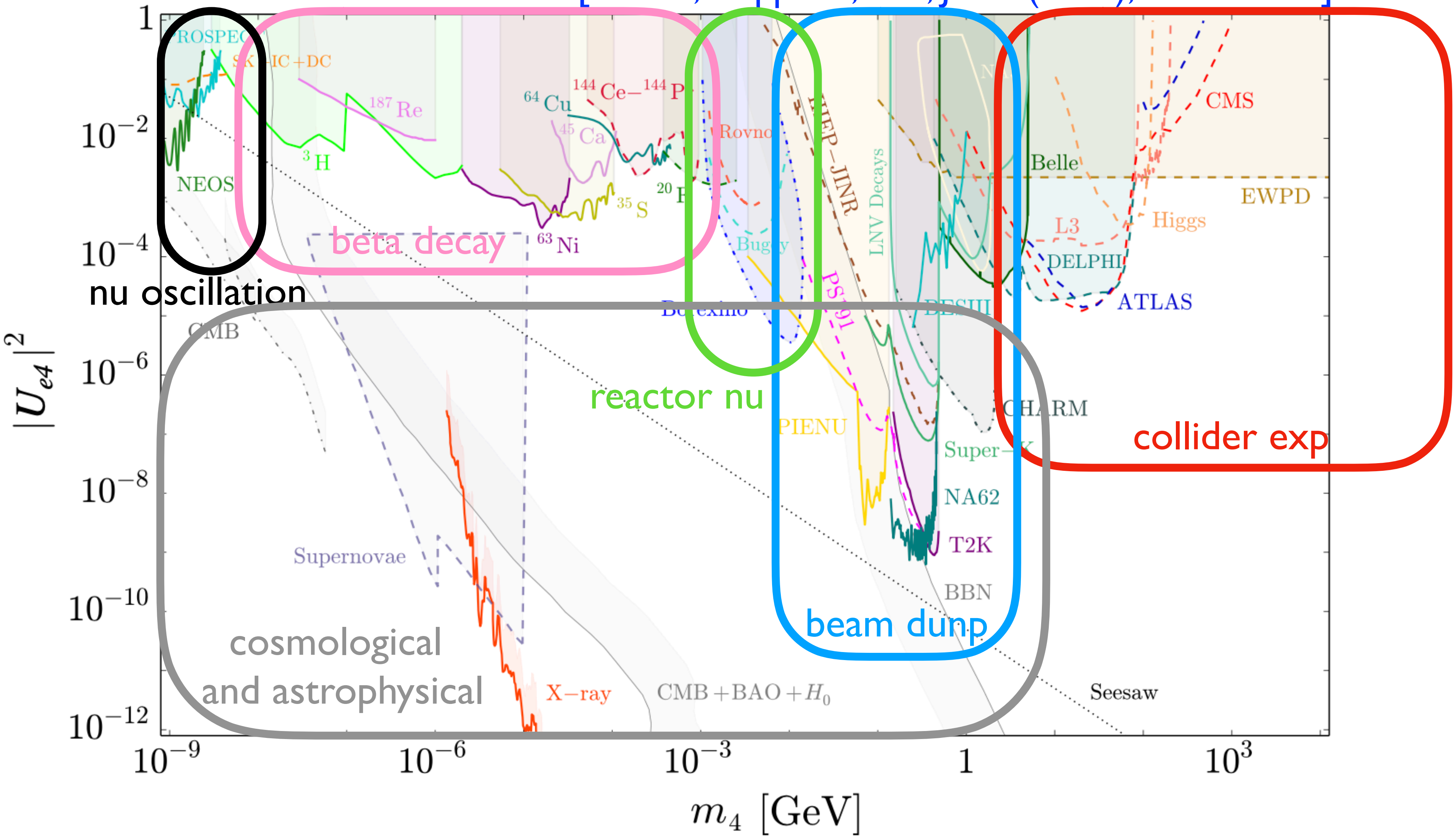
Long baseline

Deficits of neutral current neutrino interaction between near and far detector

$$\begin{aligned} P_{\rm NC} &= 1 - P\left(\nu_\mu\to\nu_s\right) \\ &\approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) \\ &\quad - \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \\ &\quad + \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin\left(\frac{\Delta m^2_{31}L}{2E}\right). \end{aligned} \qquad (5)$$

Constraints on the mixing between ν_e and ν_s

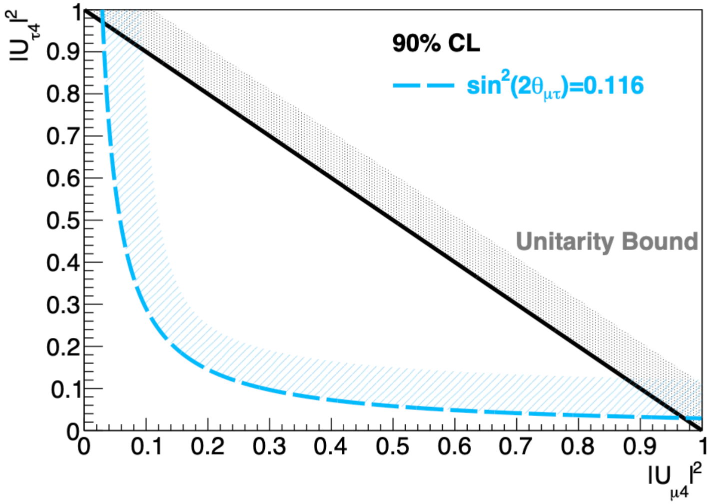
[Bolton, Deppisch, Dev, JHEP (2020), 1912.03058]



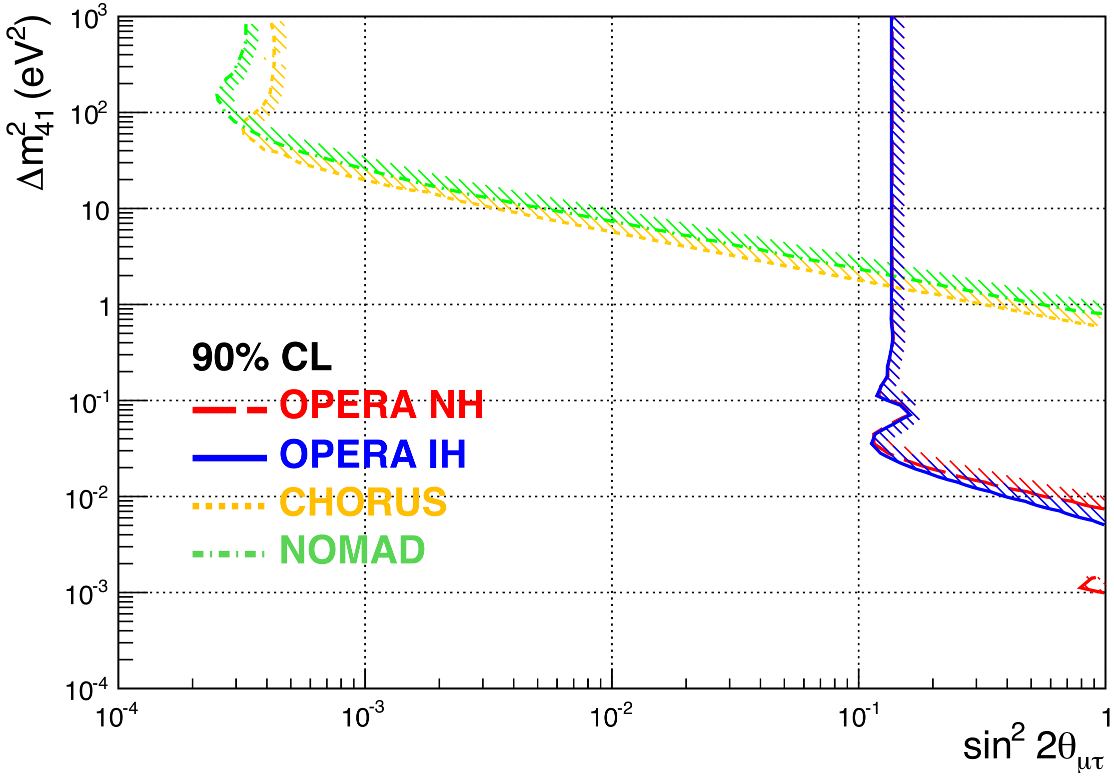
Sterile neutrino search via $\nu_\mu \to \nu_\tau$ oscillations

: tau neutrino appearance

$\Delta m^2_{41} > 1 \text{ eV}^2$



[OPERA, JHEP (2015), 1503.01876]

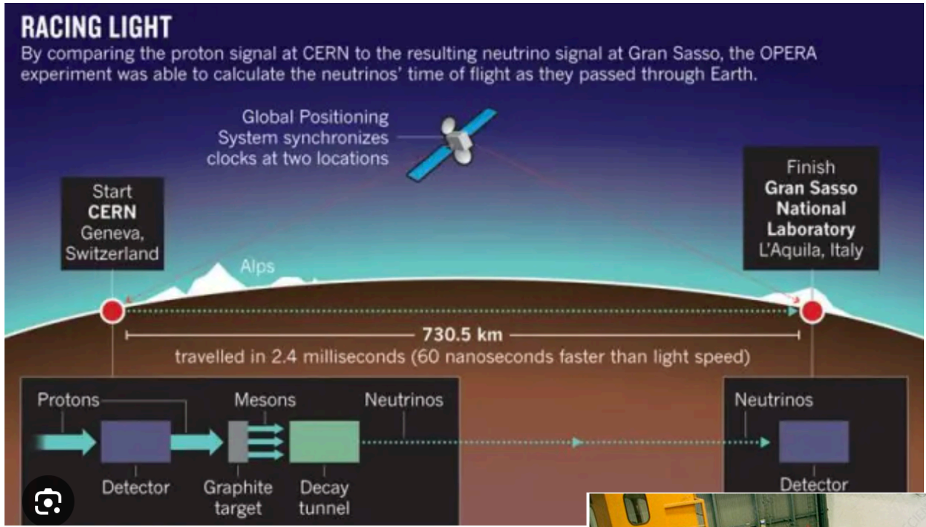


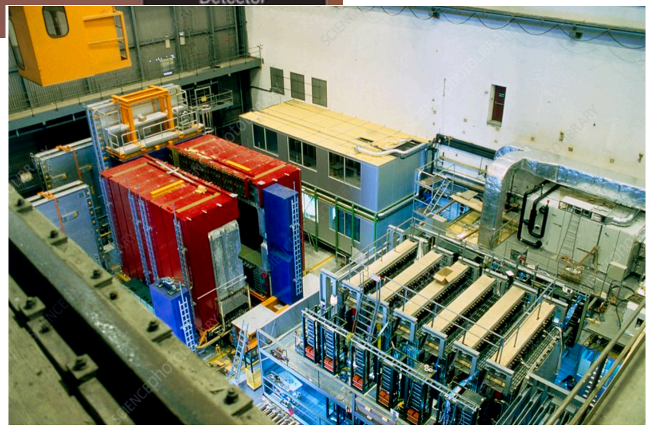
$$P(E) = C^2 \sin^2 \Delta_{31} + \frac{1}{2} \sin^2 2\theta_{\mu\tau} + C \sin 2\theta_{\mu\tau} \cos\phi_{\mu\tau} \sin^2 \Delta_{31} + \frac{1}{2} C \sin 2\theta_{\mu\tau} \sin\phi_{\mu\tau} \sin 2\Delta_{31}.$$

$$\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|,$$

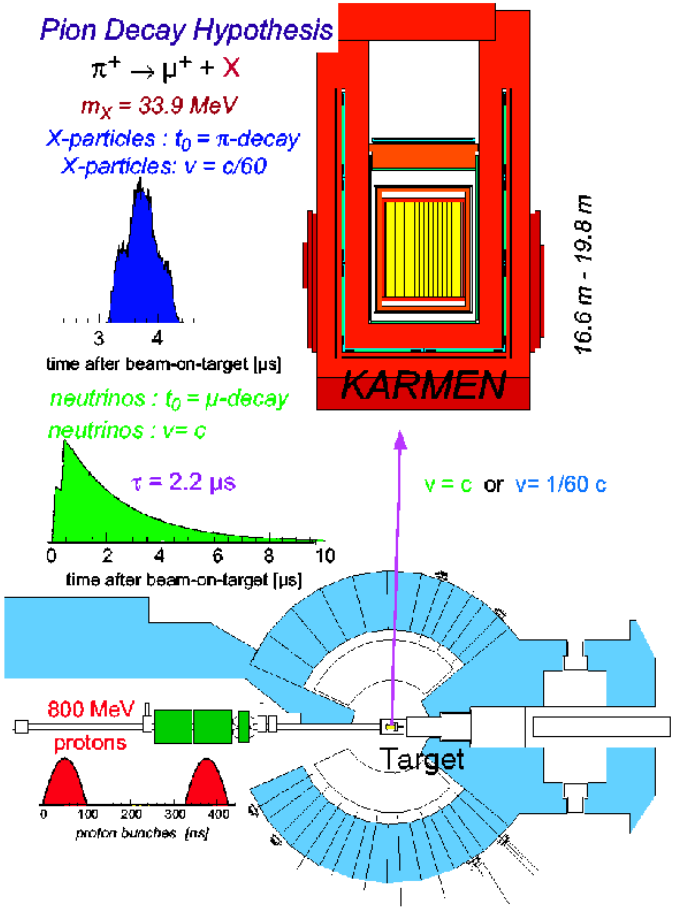
$$C = 2|U_{\mu 3}||U_{\tau 3}|,\ \Delta_{ij} = 1.27\ \Delta m^2_{ij}\ L/E\ (i,j = 1,2,3,4),\ \phi_{\mu\tau} = Arg(U_{\mu 3}U^*_{\tau 3}U^*_{\mu 4}U_{\tau 4})$$

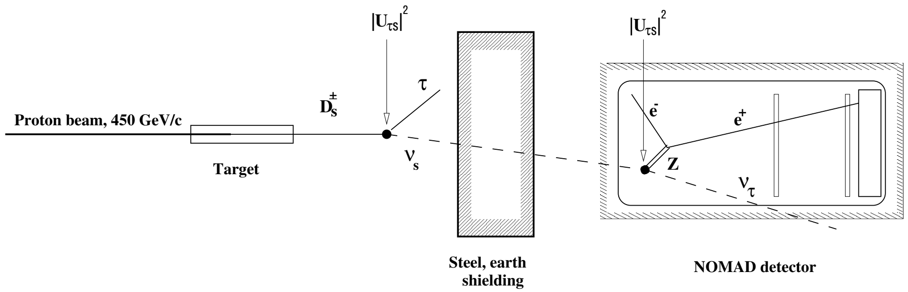
OPERA



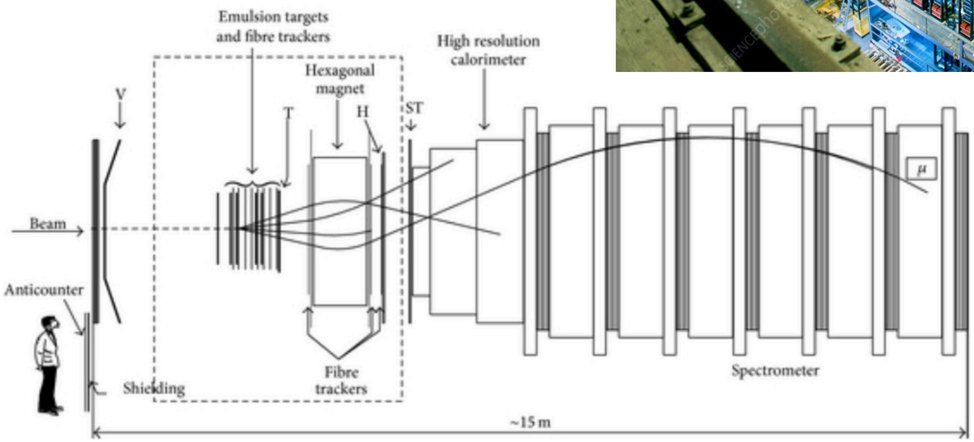


NOMAD at CERN



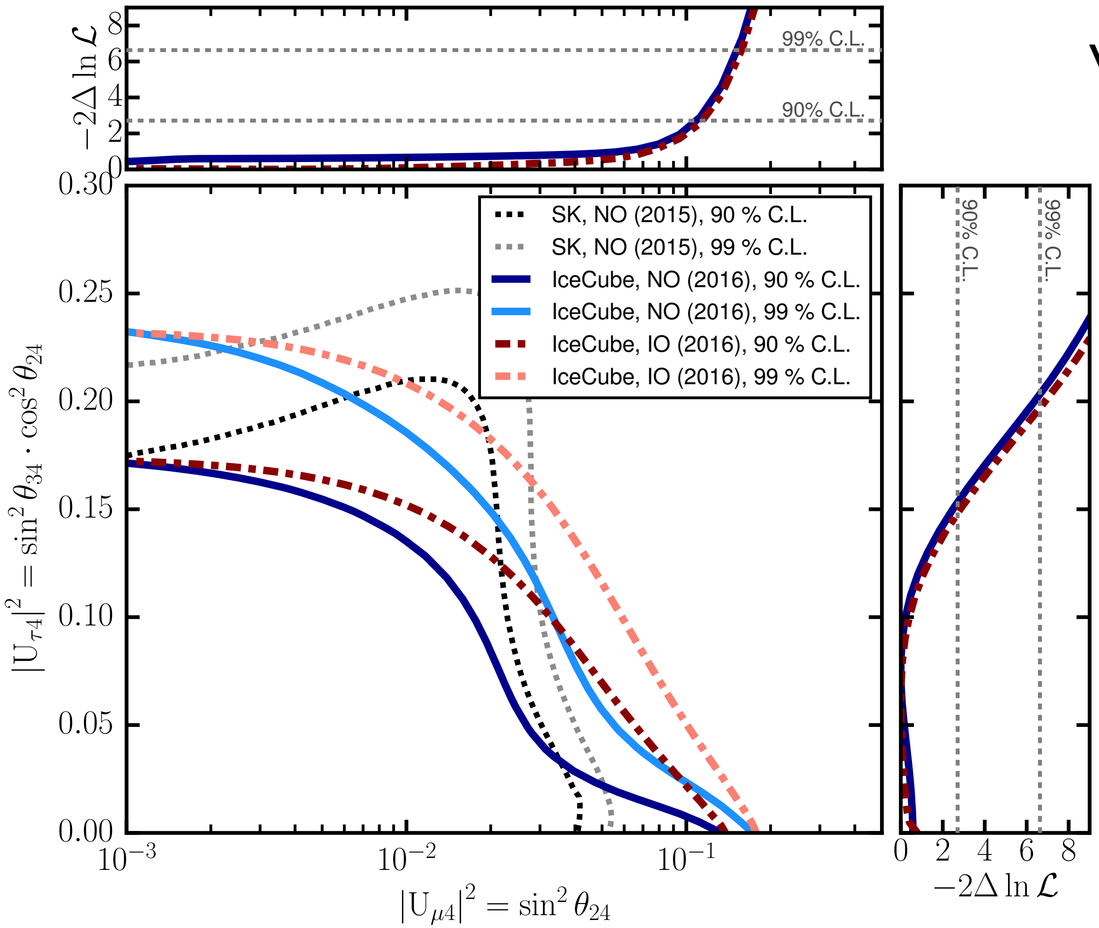


CHORUS



Search for sterile neutrino mixing using three years of IceCube DeepCore data

[IceCube, PRD (2017), 1702.05160]



atmospheric neutrino with energy around 10 - 60 GeV

the upper bound on the mixing from muon neutrino disappearance

for $\Delta m^2_{41} \sim 1\ \mathrm{eV}^2$

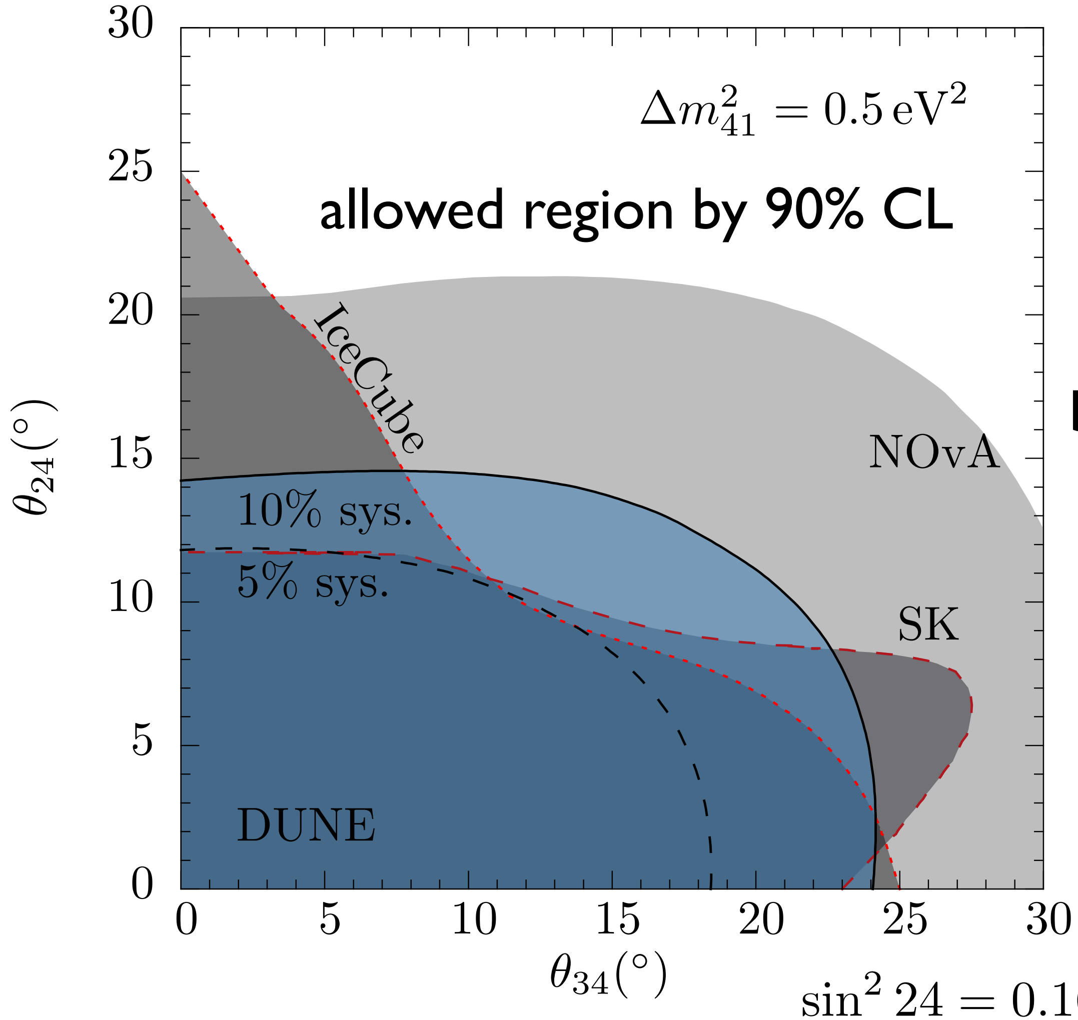
$$|U_{\mu4}|^2 < 0.11$$

$$|U_{\tau4}|^2 < 0.15\ (90\%\ \mathrm{C.L.})$$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2\left(\Delta m^2_{32}\frac{L}{4E_\nu}\right),$$ w/o sterile neutrino

Using neutral current interaction

Coloma etal (JHEP 2018, 1707.05348): DUNE expectation



$\sin^2 24 = 0.165$

neutral current interaction
:observe all 3-flavors

muon neutrino flux is suppressed
by the oscillation into sterile neutrino

$$\phi_{\nu_\mu}\,\sigma_\nu^{NC}\,\{1 - P(\nu_\mu \to \nu_s)\}$$

NOvA (PRD 2017, 1706.04592)

Probing depletion into sterile neutrino

1,300 km

Near detector ⟷ Far detector

$$\nu_\mu \to \nu_\tau, \nu_s$$

Initially muon neutrino and assume no oscillation

Oscillation to sterile neutrino as well as standard ones

Then there will be depletion in the neutral current (NC)events since sterile does not have NC interaction.

$$N_{NC} = N_{NC}^{e} + N_{NC}^{\mu} + N_{NC}^{\tau} = \phi_{\nu_\mu}\, \sigma_\nu^{NC} \left\{ P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau) \right\}$$
$$= \phi_{\nu_\mu}\, \sigma_\nu^{NC} \left\{ 1 - P(\nu_\mu \to \nu_s) \right\} \ ,$$

This is sensitive to the oscillations between muon and sterile neutrinos.

Can we constrain the mixing of sterile neutrino
and tau neutrino directly
using tau neutrinos?

Search for Hidden Particles (SHiP) at ECN3

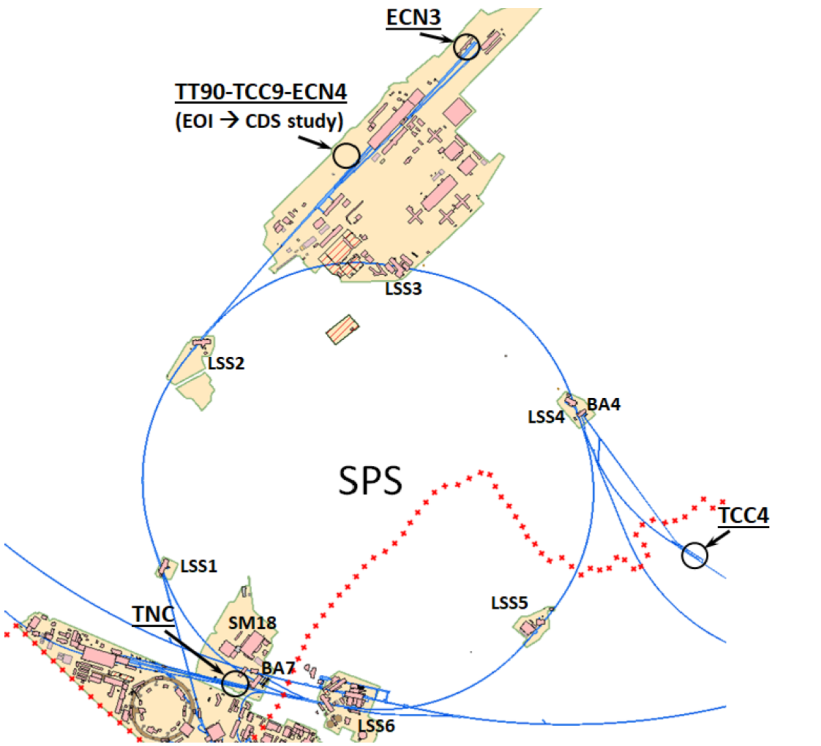
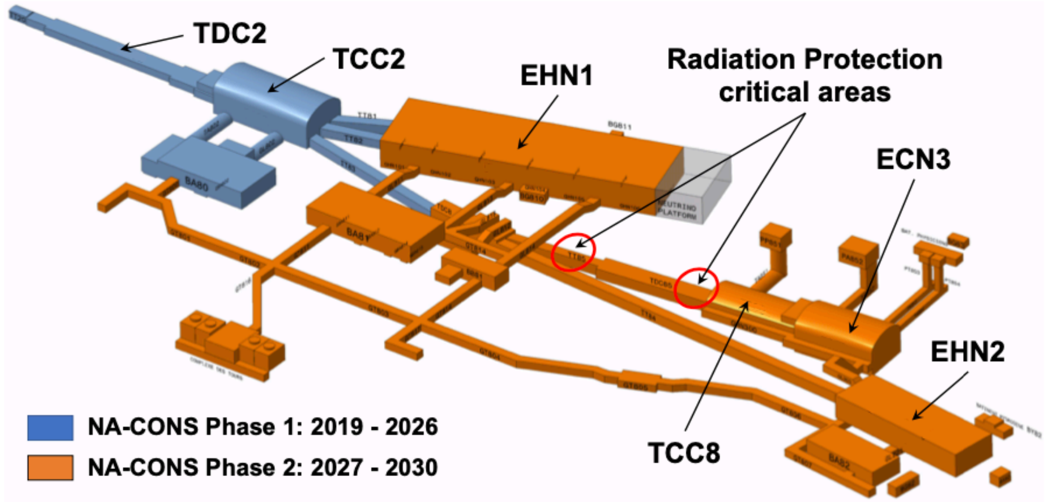


Figure 1: Overview of the locations considered for the implementation of the BD



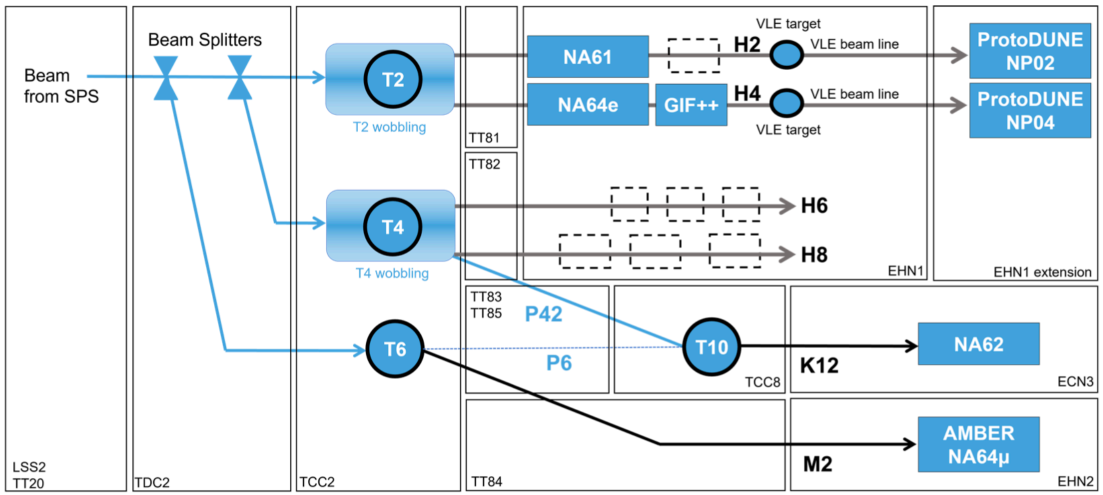
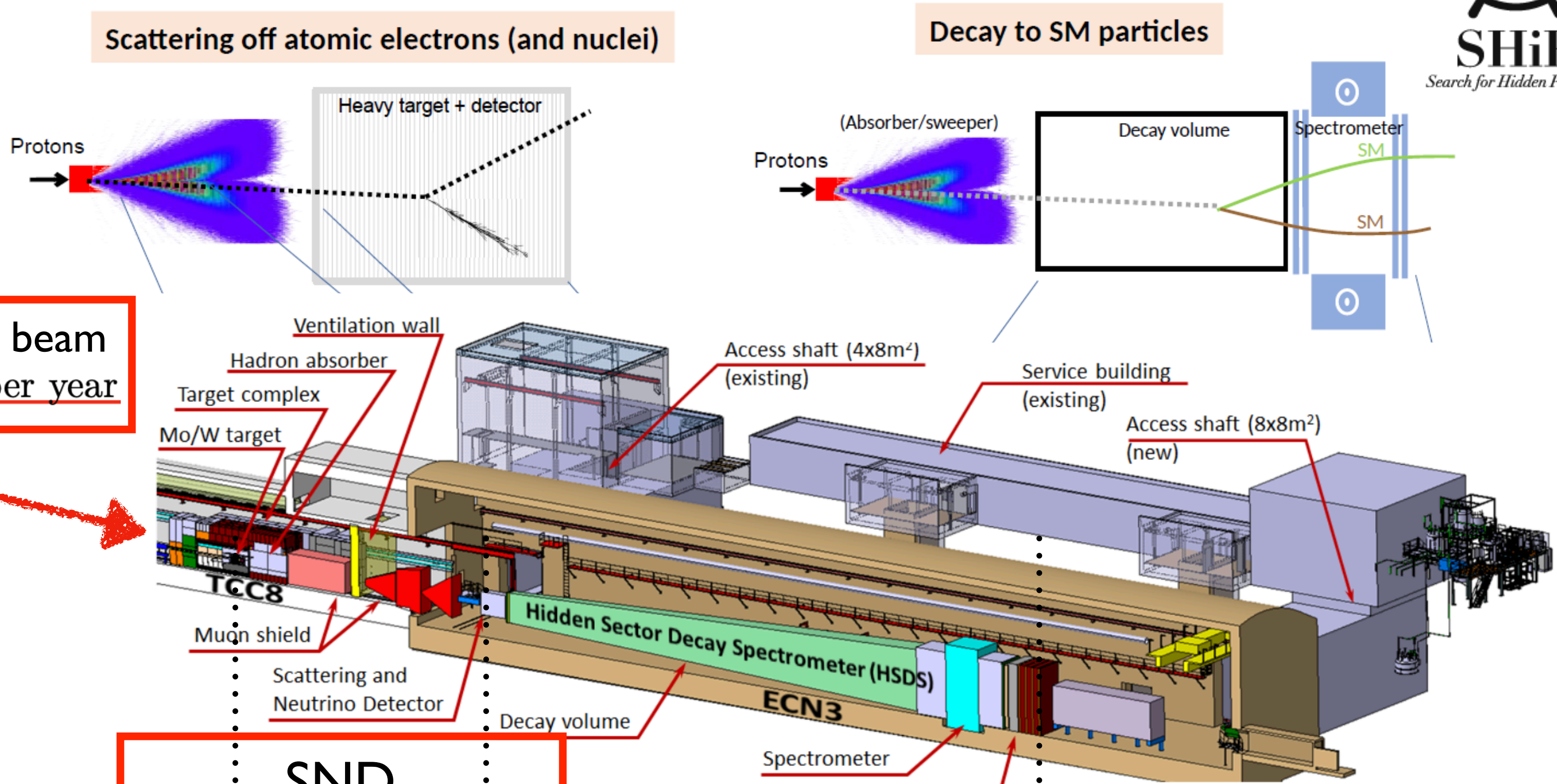


Figure 1: A schematic layout of the NA beamline and experiment complex as of 2023.

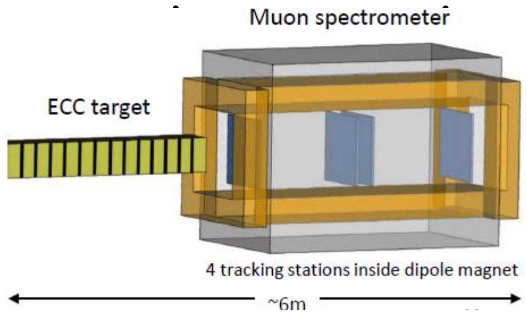
Search for Hidden Particles



400GeV proton beam
4×10^{19} protons per year

SND
:neutrino detector

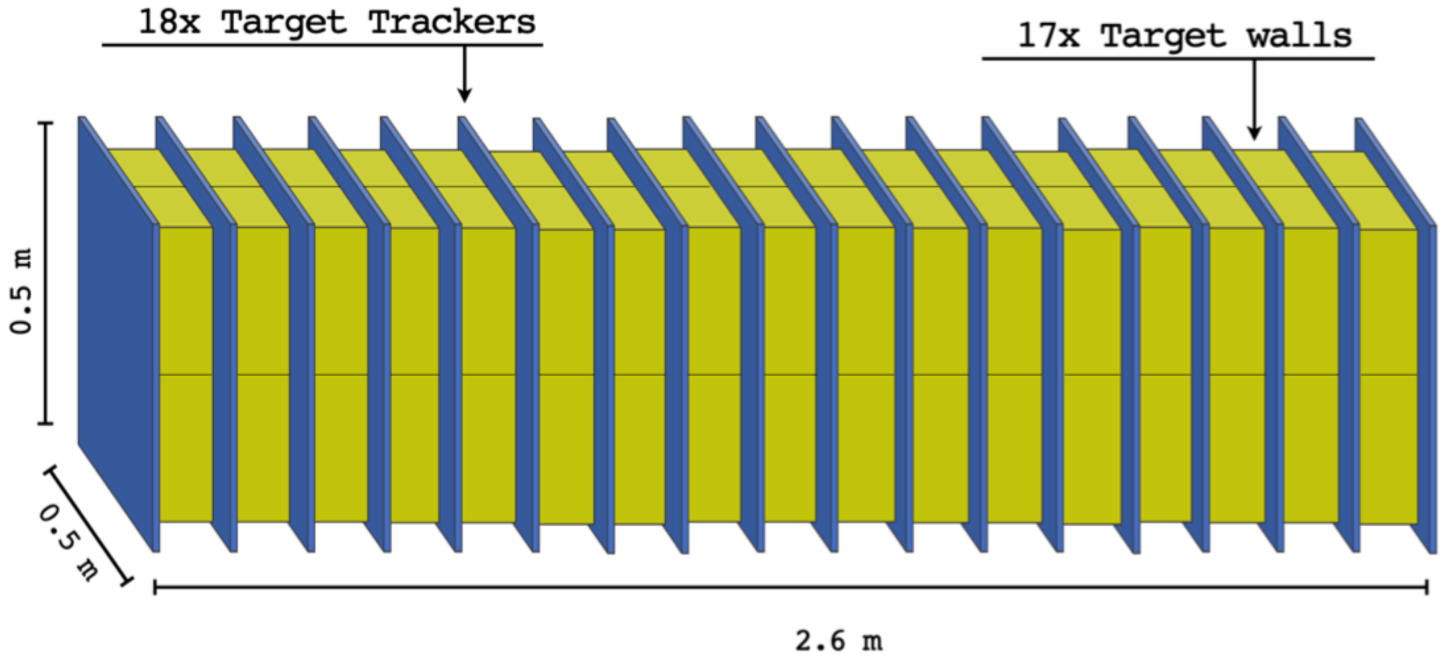
30 m

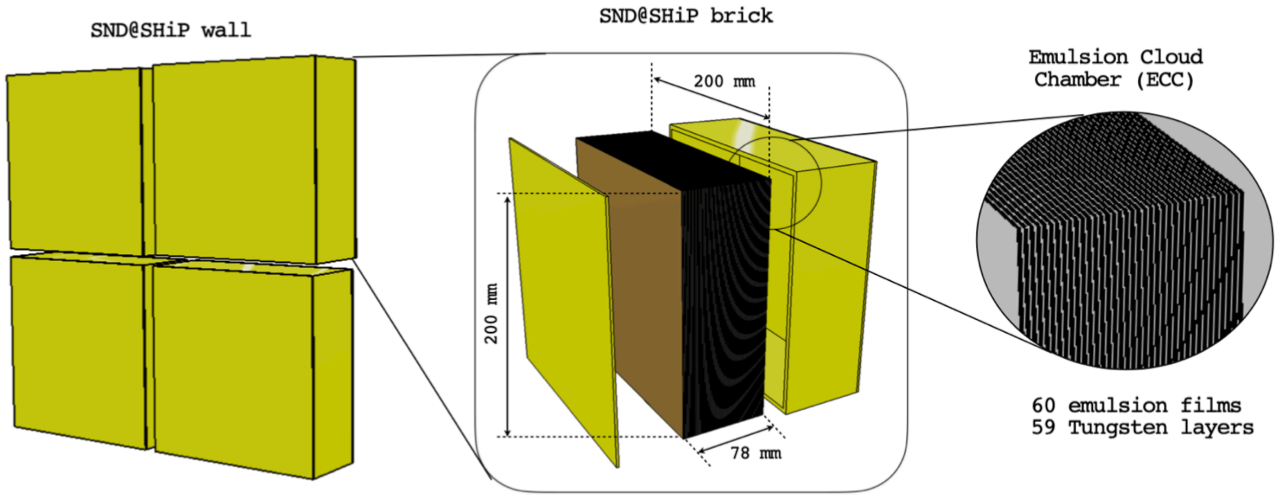


Hidden Sector detector

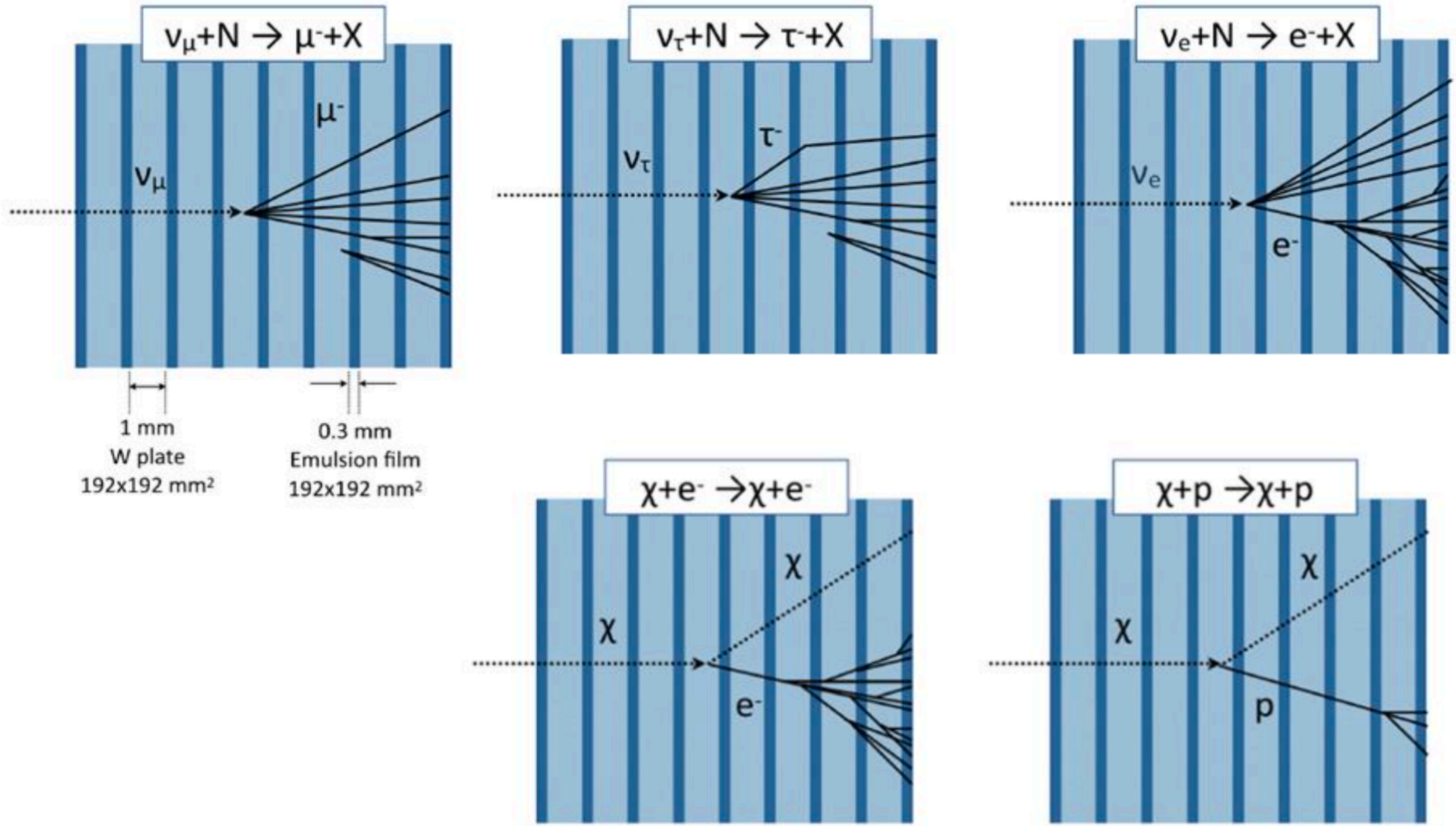
120 m

SND detector and ECC block





ECC block



ν_μ+N → μ^-+X
μ^-
ν_μ
1 mm
W plate
192x192 mm^2
0.3 mm
Emulsion film
192x192 mm^2
ν_τ+N → τ^-+X
τ^-
ν_τ
ν_e+N → e^-+X
ν_e
e^-
χ+e^- →χ+e^-
χ
χ
e^-
χ+p →χ+p
χ
χ
p

Korean Group

Gyeongsang National University (GNU)

S. H. Kim, K. Y. Lee, B. D. Park, J. Y. Sohn, C. S. Yoon

Korea University (KU)

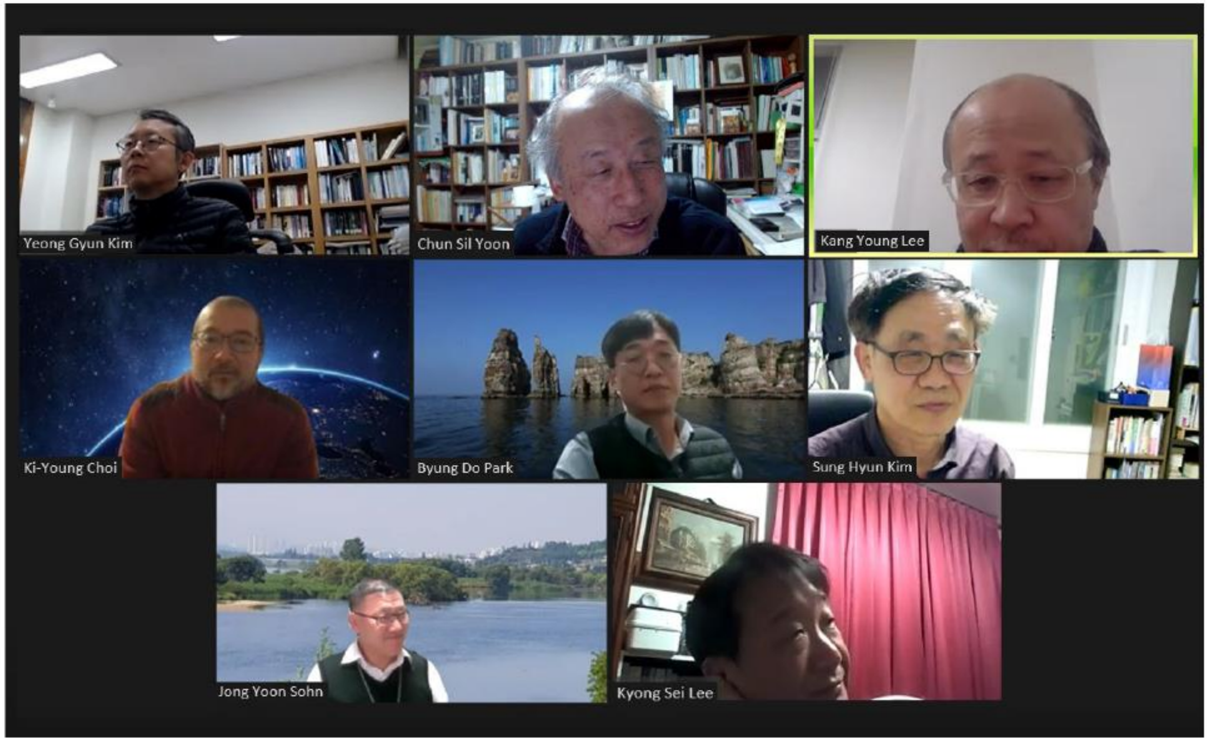
K. S. Lee

Gwangju National University of Education (GNUE)

Y. G. Kim

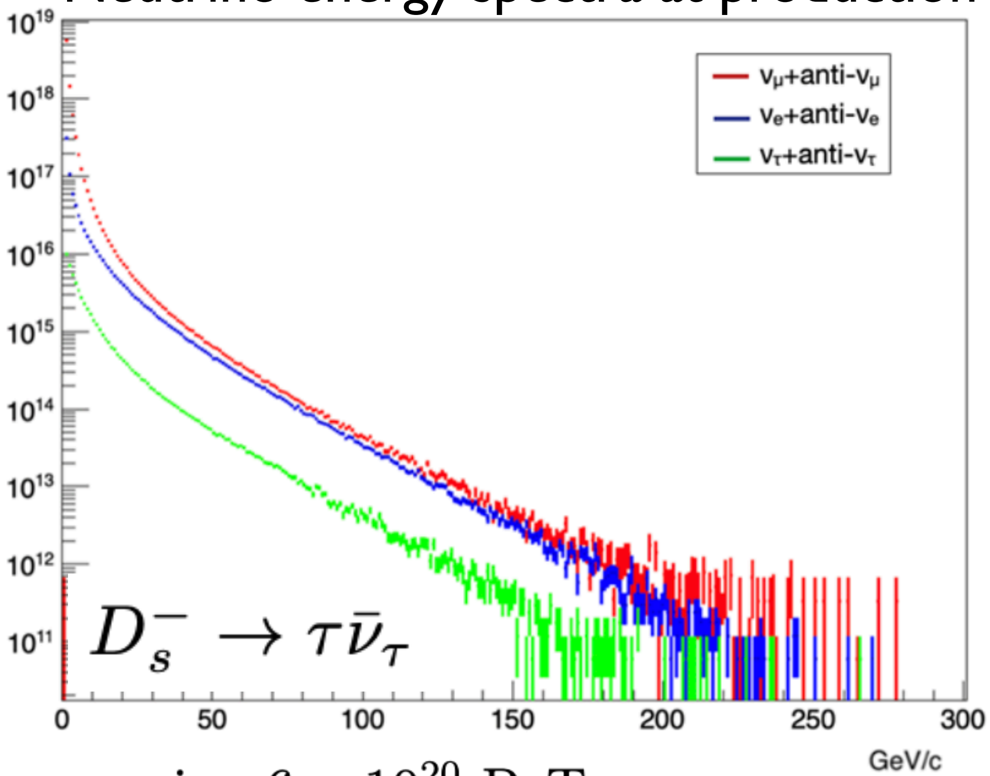
Sungkyunkwan University (SKKU)

K.-Y. Choi

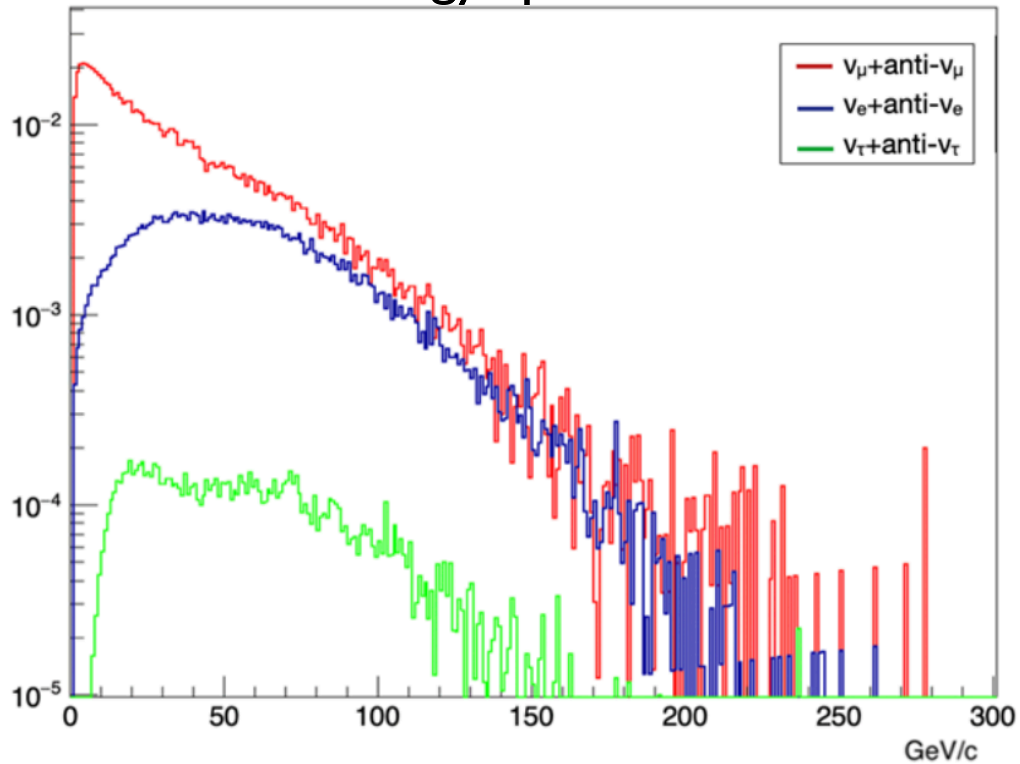


Expected Neutrino Spectrum at SHiP

Neutrino energy spectra at production



Neutrino energy spectra at detection



assuming 6×10^{20} PoT.

[SHiP collaboration, 2023]

	<E>[GeV]	Beam dump	<E>[GeV]	CC DIS interactions
N_{ν_e}	6.3	4.1×10^{17}	63	2.8×10^6
N_{ν_μ}	2.6	5.4×10^{18}	40	8.0×10^6
N_{ν_τ}	9.0	2.6×10^{16}	54	8.8×10^4
$N_{\bar{\nu}_e}$	6.6	3.6×10^{17}	49	5.9×10^5
$N_{\bar{\nu}_\mu}$	2.8	3.4×10^{18}	33	1.8×10^6
$N_{\bar{\nu}_\tau}$	9.6	2.7×10^{16}	74	6.1×10^4

Efficiency for tau decay channels

ν_τ and $\overline{\nu}_\tau$ efficiencies for different τ decay channels

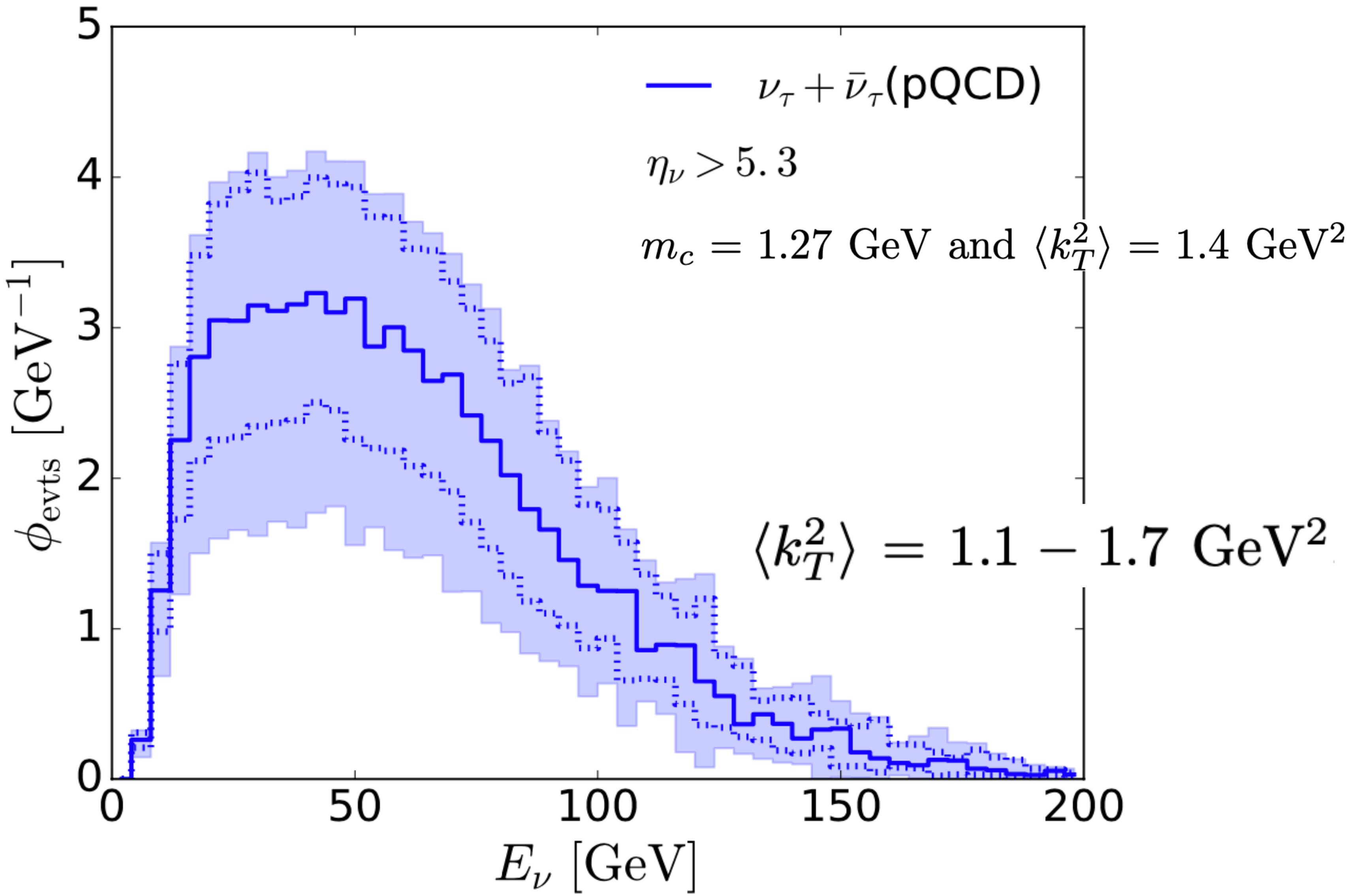
Efficiency	$\tau \to \mu$	$\tau \to h$	$\tau \to 3h$	$\tau \to e$
Geometrical	0.89			
Location	0.71			
Decay search	0.38	0.37	0.51	0.35
PID	0.32	0.37	0.51	0.31
Charge	0.30	-	-	-

[SHiP collaboration, 2023]

Expected number of ν_τ and $\overline{\nu}_\tau$ signal events observed in different τ decay channels, assuming 6×10^{20} PoT.

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

Uncertainty in the tau neutrino events



The number of events per GeV.

Neutrino Oscillation

$$\Delta_{ij} \simeq 1.27 \left(\frac{\delta_{ij} m^2}{\mathrm{eV}^2}\right)\left(\frac{L}{\mathrm{km}}\right)\left(\frac{\mathrm{GeV}}{E}\right)$$

Solar neutrinos

E ~ MeV, L ~10^8 km, $\Delta m_{12}^2 = 0.759 \times 10^{-4}\ \mathrm{eV}^2$

Atmospheric neutrinos ~ DUNE far detector

E ~ GeV, L ~10- 10,000 km, $\Delta m_{32}^2 \approx \Delta m_{13}^2 = 23.2 \times 10^{-4}\ \mathrm{eV}^2$ $\sim 1\mathrm{eV}^2$

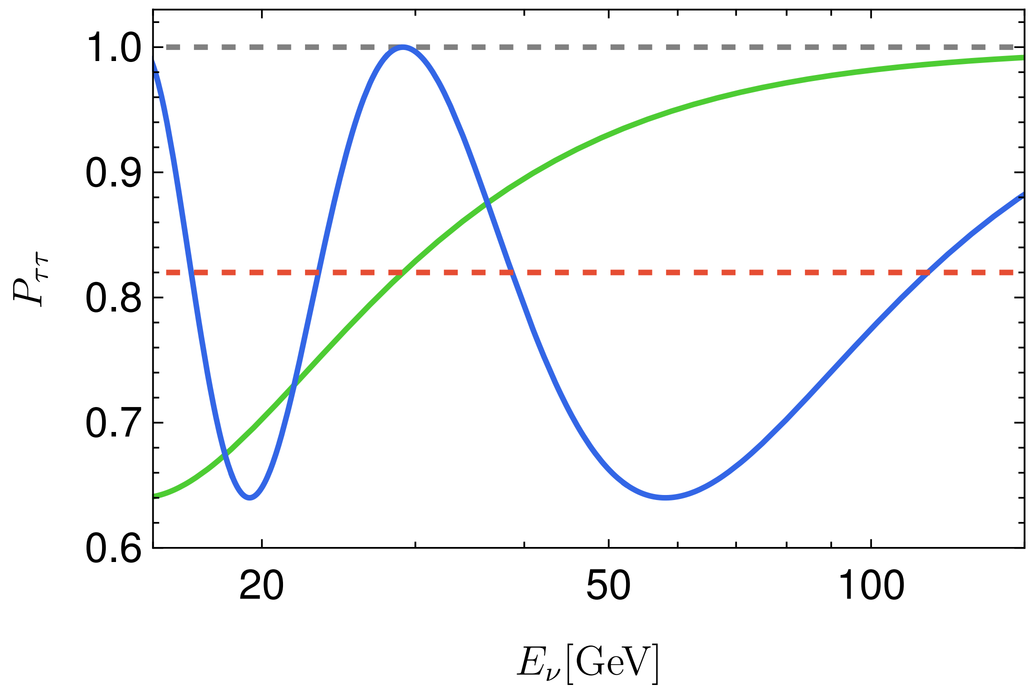
E ~ 10 GeV, L ~1,000 km, $\Delta m^2 \sim 10^{-2}\mathrm{eV}^2$

SHiP : oscillations between active neutrino are suppressed.

E ~ 100GeV, L ~ 100 m, → $\Delta m_{41}^2 \simeq 10^3\ \mathrm{eV}^2$

Active neutrinos may disappear with sterile neutirno mixing!

Survival Probability of tau neutrino at SHiP



$$|U_{\tau 4}|^2 = 0.1$$

$$L = 30\,\text{meters}$$

dashed black w/o mixing

$\Delta m^2_{41} = 600\ \text{eV}^2$

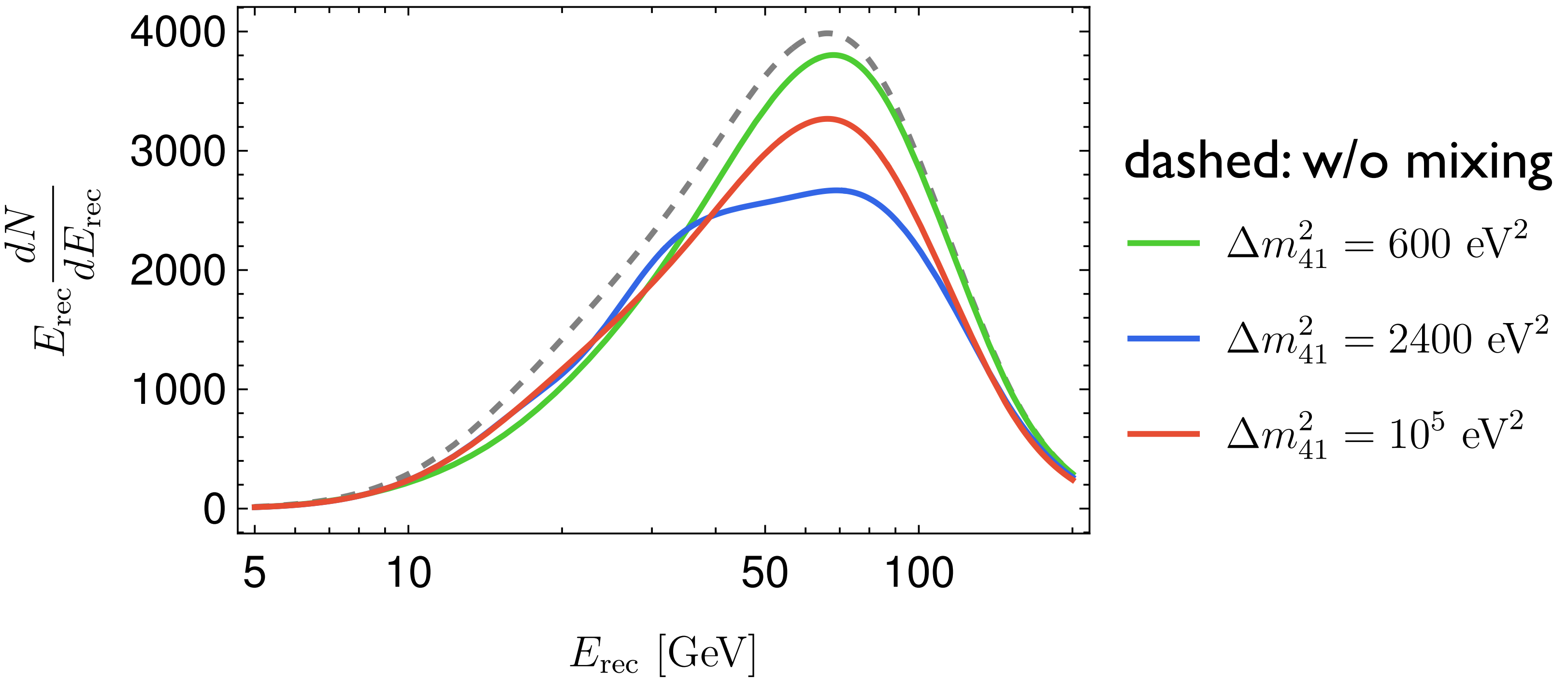
$\Delta m^2_{41} = 2400\ \text{eV}^2$

$\Delta m^2_{41} = 10^5\ \text{eV}^2$ (averaged)

$$P_{\tau\tau} = 1 - 4|U_{\tau 4}|^2(1 - |U_{\tau 4}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

* neutrino oscillation between active neutrinos are negligible.

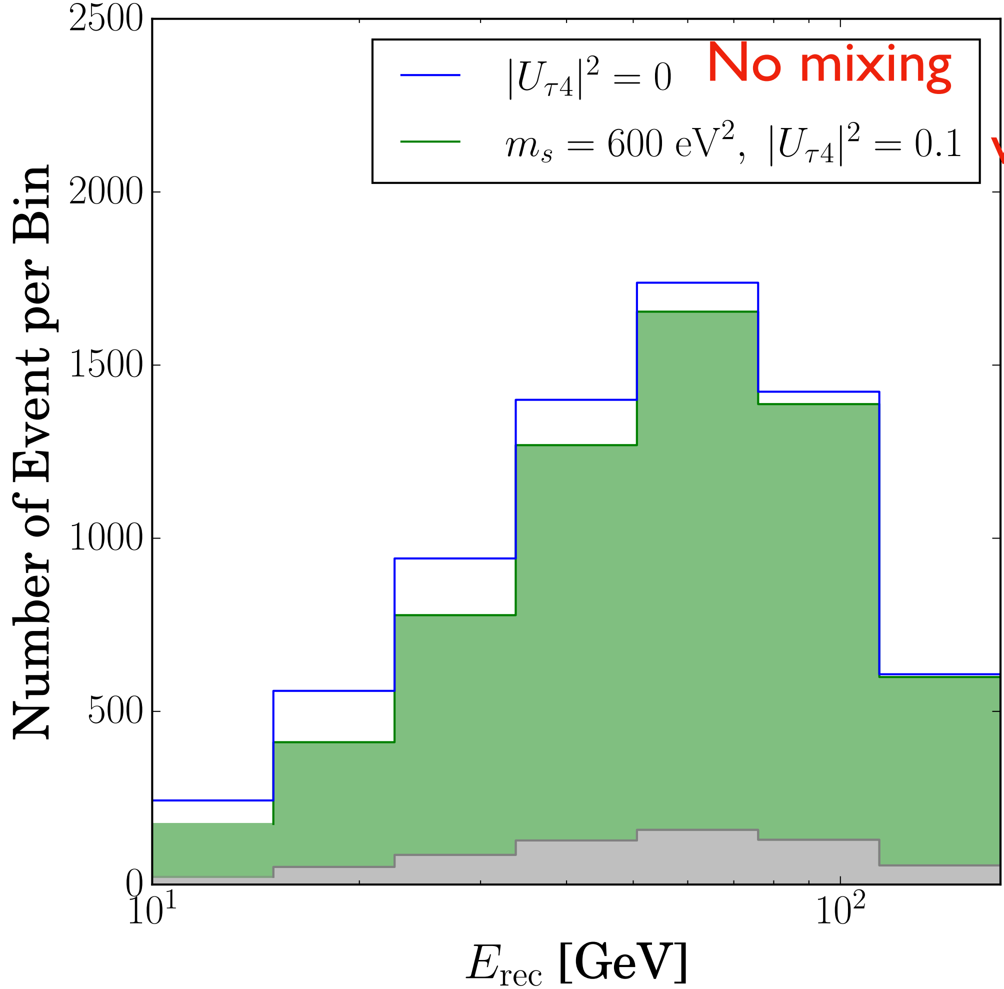
Observed Spectrum of tau neutrinos at SND



The energy spectrum can be used to observe or constrain the sterile neutrino.

Number of Events with Sterile Neutrino

with 5 years data expected



No mixing

with mixing for reference

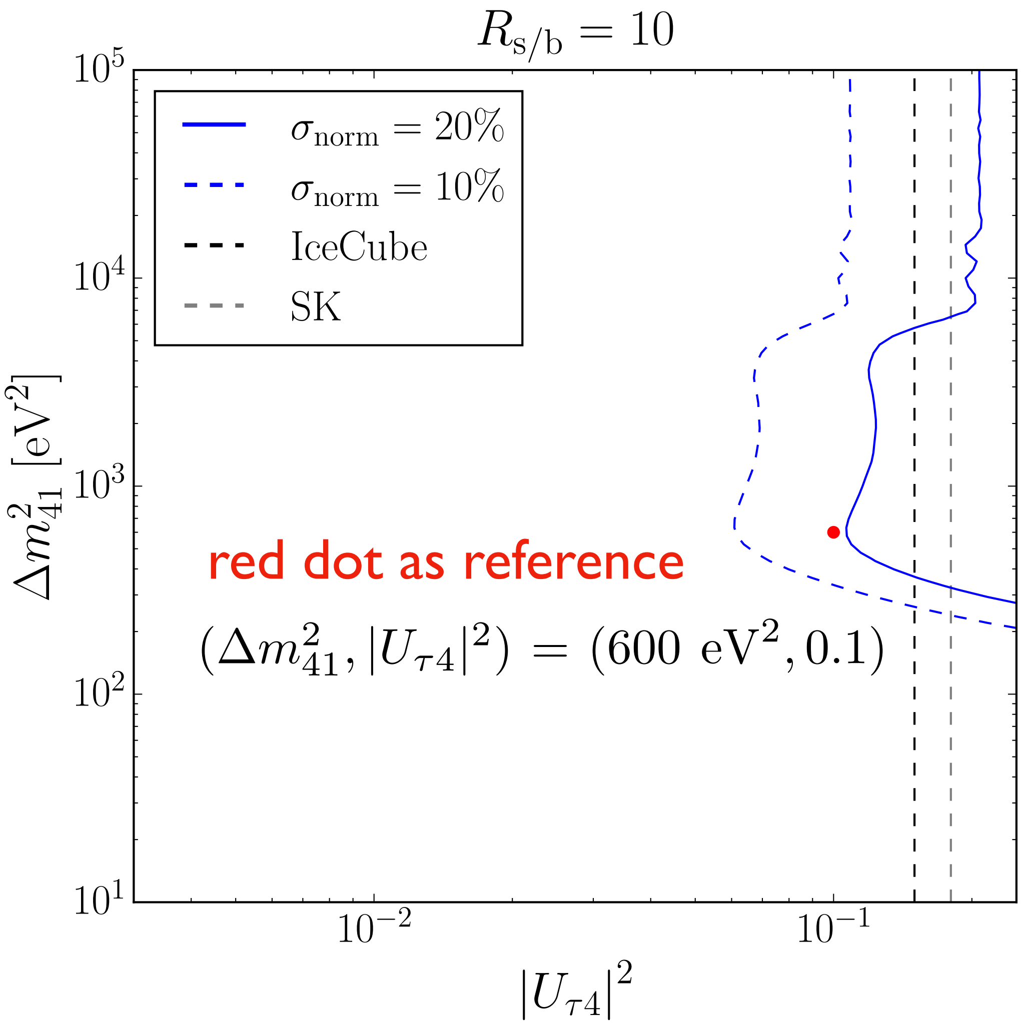
energy resolution 20%:

$\sigma_E = 0.2E$

gray: background assuming 10% from mu-neutrino CC events

Sensitivity in the plane of $(\Delta m^2_{41}, |U_{\tau 4}|^2)$

90%CL expected sensitivity with 5 years data



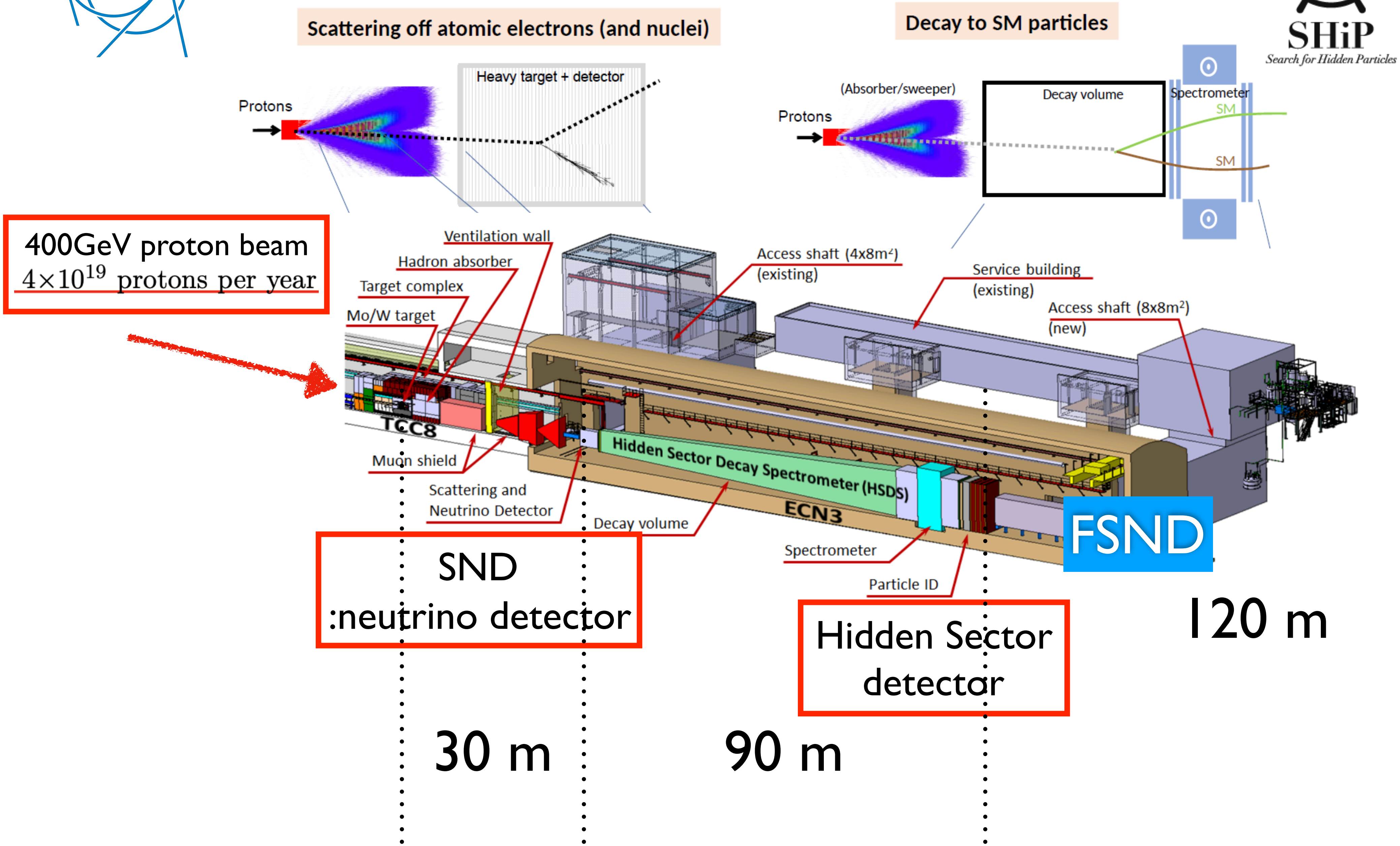
energy resolution 20%: $\sigma_E = 0.2E$

overall and shape uncertainty
in the energy spectrum: 20% or 10%

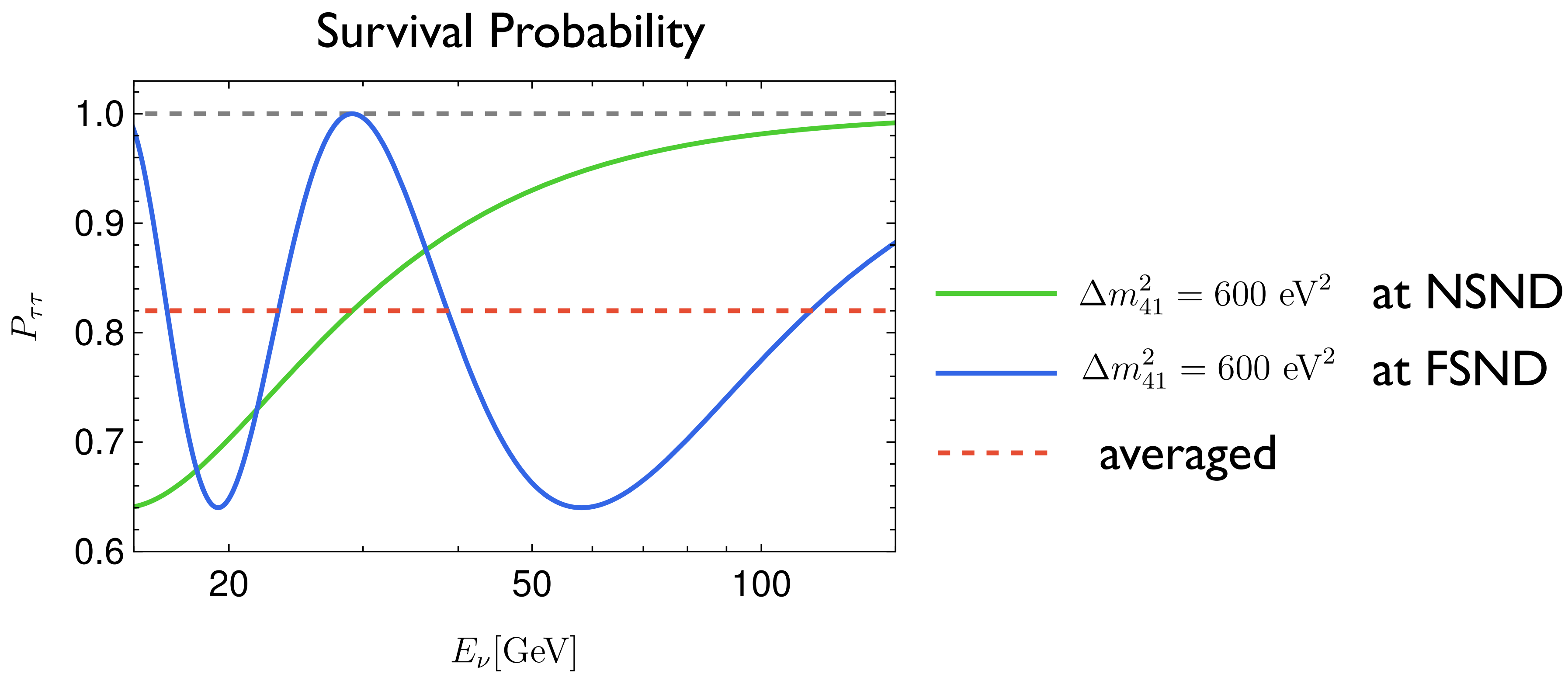
background assuming 10%

$\theta_{14} = \theta_{24} = 0$

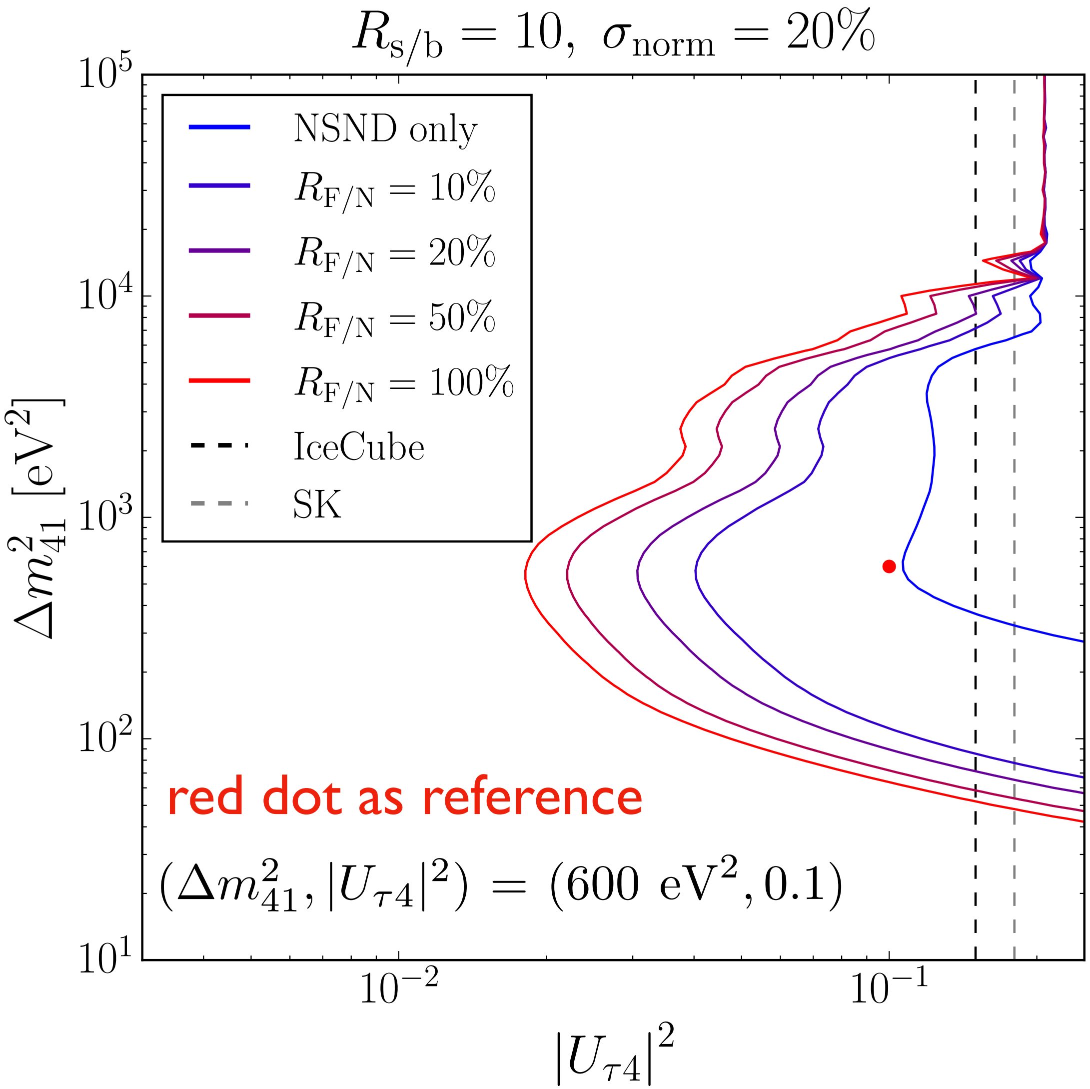
Near SND + Far SND at SHiP



Near SND + Far SND at SHiP



Sensitivity with SND + FSND



energy resolution 20%: $\sigma_E = 0.2E$

overall and shape uncertainty in the energy spectrum: 20%

background assuming 10%

$\theta_{14} = \theta_{24} = 0$

acceptance ratio of FSND to NSND

$R_{\mathrm{F/N}} = 10\%,\ 20\%,\ 50\%,\ \text{and}\ 100\%$

Summary

[Choi, Yoo, KSHiP, ongoing work]

1. It is possible to constrain the sterile-tau neutrino mixing directly at SHiP experiment.

2. With 5 years operation, SHiP has a sensitivity to

$$|U_{\tau 4}|^2 \sim 0.06 \quad \text{for} \quad \Delta m_{41}^2 \sim 10^3 \, \text{eV}$$

3. With additional FSND at the end of HS detector of SHiP

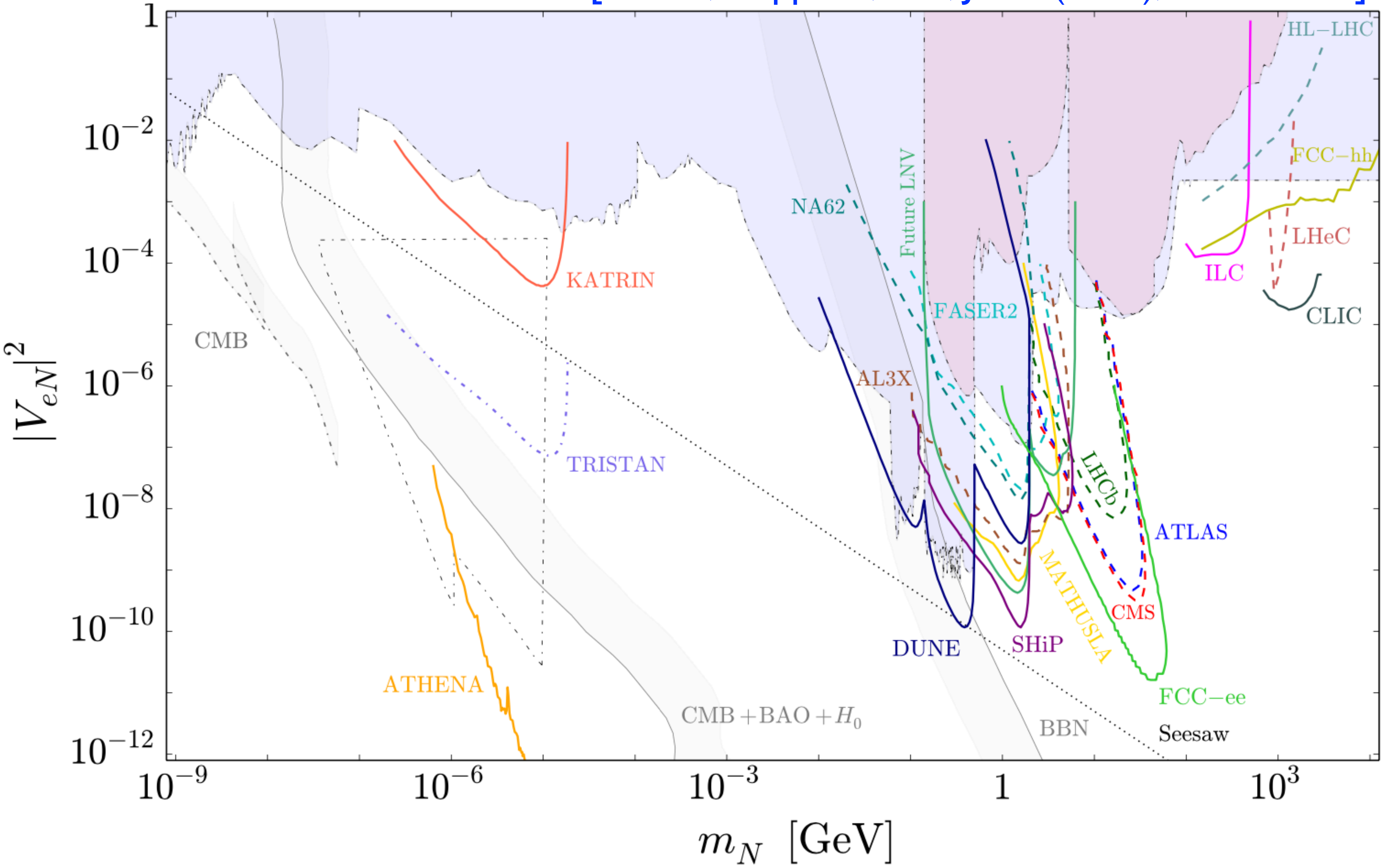
$$|U_{\tau 4}|^2 \sim 0.02 \quad \text{for} \quad \Delta m_{41}^2 \sim 10^3 \, \text{eV}$$

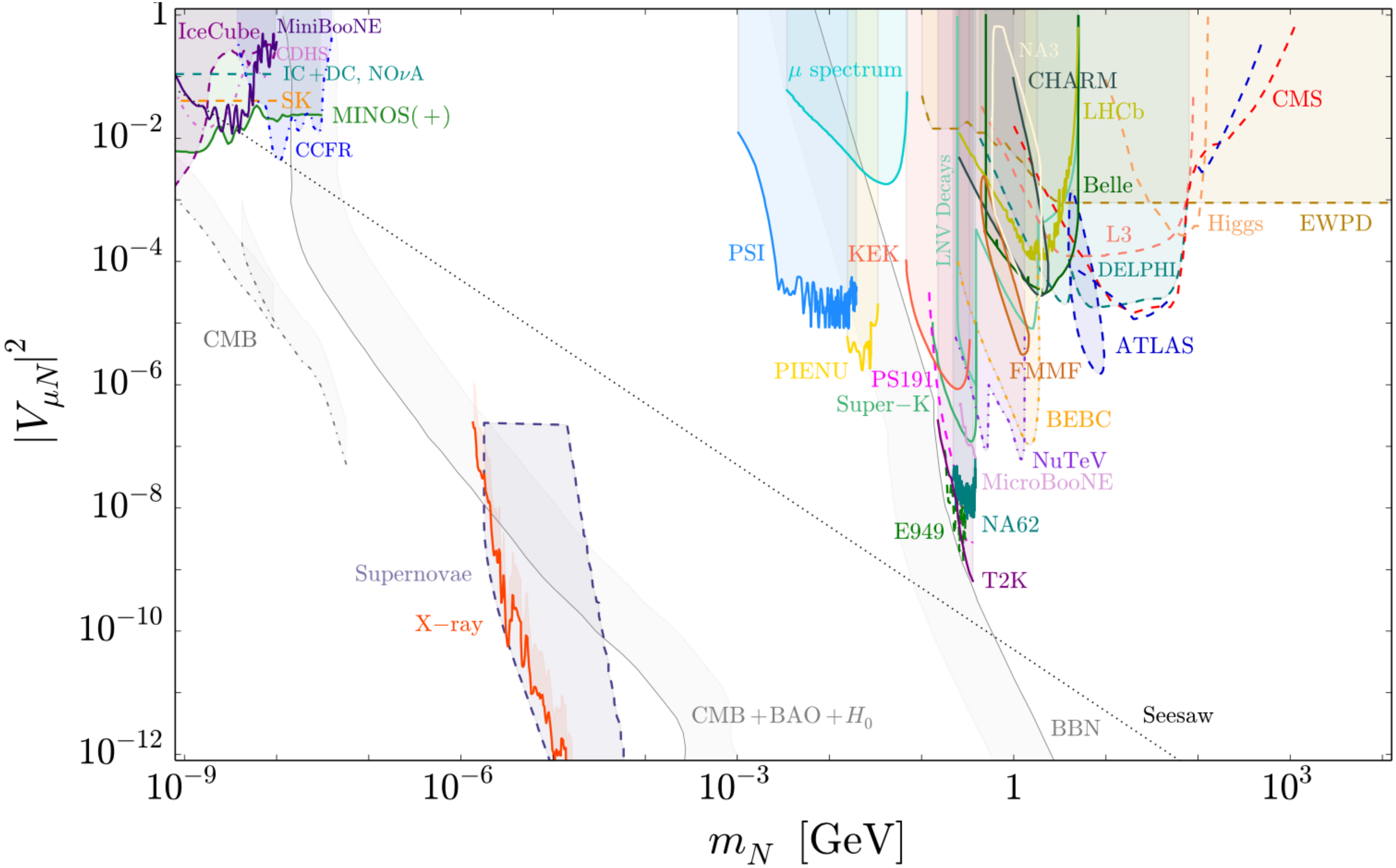
Thank You!

backup

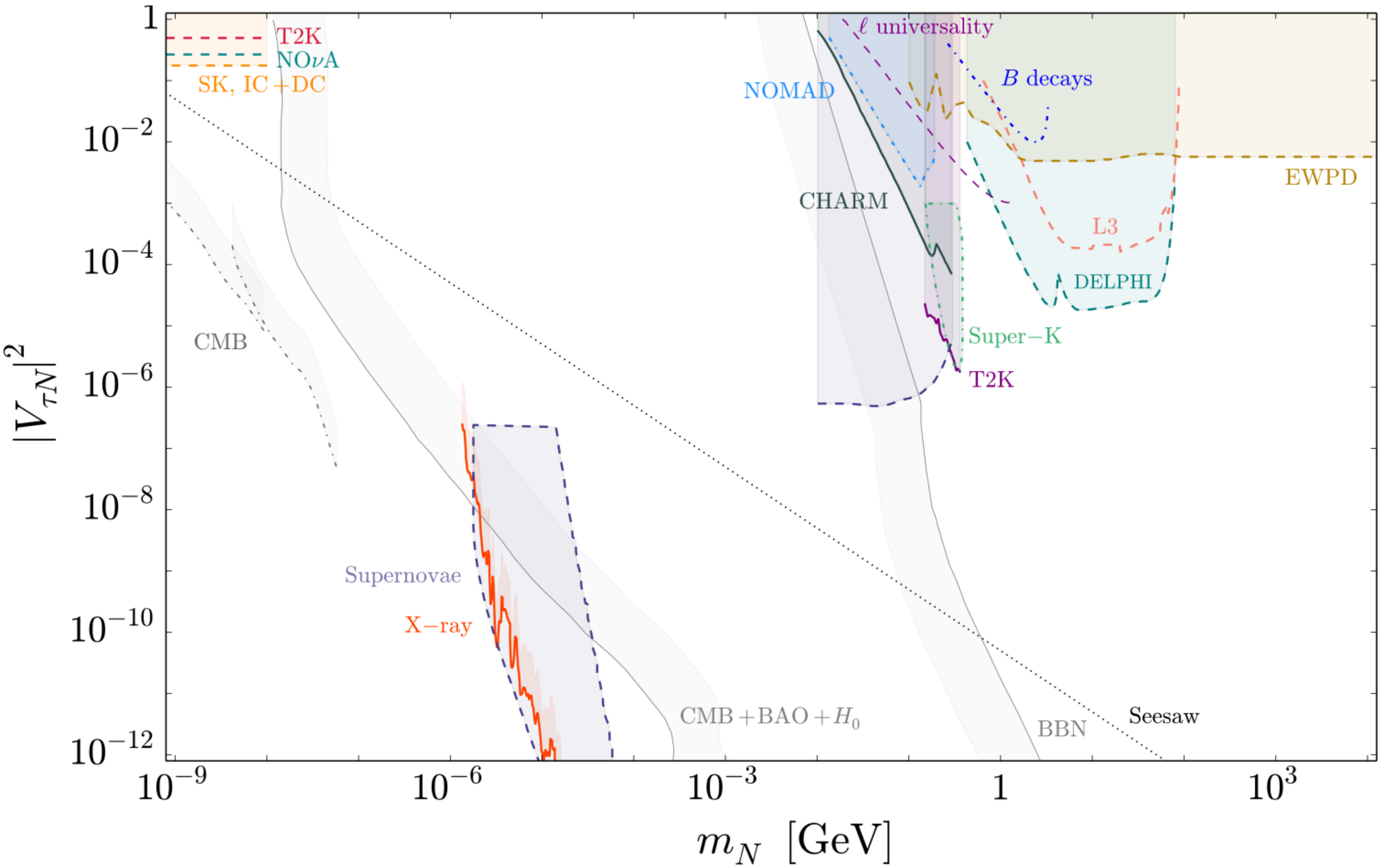
Future Prospect

[Bolton, Deppisch, Dev, JHEP (2020), 1912.03058]





IceCube
MiniBooNE
CDHS
IC+DC, NOνA
SK
MINOS(+)
CCFR
CMB
Supernovae
X−ray
CMB+BAO+H_0
μ spectrum
PSI
KEK
PIENU
PS191
Super−K
LNV Decays
NA3
CHARM
LHCb
Belle
L3
DELPHI
Higgs
EWPD
CMS
ATLAS
FMMF
BEBC
NuTeV
MicroBooNE
NA62
E949
T2K
BBN
Seesaw
$|V_{\mu N}|^2$
m_N [GeV]



T2K
NOνA
SK, IC+DC
CMB
Supernovae
X−ray
CMB+BAO+H_0
NOMAD
ℓ universality
B decays
CHARM
EWPD
L3
DELPHI
Super−K
T2K
BBN
Seesaw
$|V_{\tau N}|^2$
m_N [GeV]

Sterile Neutrino Dark Matter

Neutrino Minimal Standard Model (nuMSM)

[Asaka, Blanchet, Shaposhnikov, 2005] $(\nu_R)^c \equiv C\,\overline{\nu_R}^T$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{\nu_R}\partial\!\!\!/\nu_R - \overline{\ell_L}F\nu_R\tilde{\Phi} - \tilde{\Phi}^\dagger\overline{\nu_R}F^\dagger\ell_L - \frac{1}{2}(\overline{\nu_R^c}M_M\nu_R + \overline{\nu_R}M_M^\dagger\nu_R^c).$$

singlet RH neutrino

Majorana mass

$\ell_L = (\nu_L, e_L)^T$

Yukawa coupling: Dirac mass with non-zero Higgs VEV $\tilde{\Phi} = \epsilon\Phi^*$

Three RH neutrinos with Majorana mass and Yukawa couplings.

After electroweak symmetry breaking, the mass term

$$\frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c})\begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.,$$

The hierarchy $m_D \equiv Fv \ll M_M$ gives mass eigenvalues with

three light active neutrinos and three heavy sterile neutrinos.
(See-saw mechanism)

Sterile Neutrinos and mixing

After electroweak symmetry breaking, the mass eigenstates are

interaction eigenstates

$$
\begin{aligned}
B_\mu =& c_W A_\mu - s_W Z_\mu, \\
\nu_{L\alpha} =& U_{\alpha i}\nu_i + \Theta_{\alpha i}\nu_{si}^c, \\
\nu_{Ri}^c =& -(\Theta^\dagger U)_{ij}\nu_j + \nu_{si}^c,
\end{aligned}
$$

mass eigenstates

with PMNS matrix U

$$
U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$

and the mixing parameter

$$
\Theta = m_D M_{\nu_R}^{-1} \ll 1,
$$

and the light active neutrino mass

$$
m_\nu \simeq -m_D \frac{1}{M_{\nu_R}} m_D^T = -\Theta M_{\nu_R} \Theta^T.
$$

seesaw mechanism

Interaction of RH Neutrino

RH sterile neutrinos can interact with SM sector through

- Mass mixing after electroweak symmetry breaking

$$\Theta = m_D M_{\nu_R}^{-1} \ll 1,$$

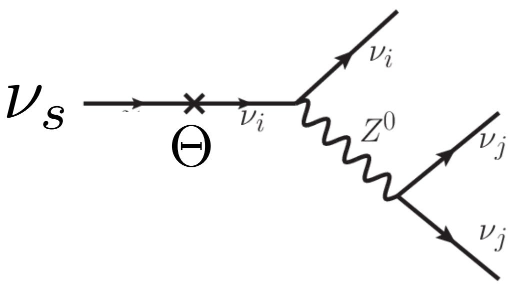
- Yukawa interaction with Higgs and LH neutrino

$$y_{\nu\alpha i}\frac{v}{\sqrt{2}} = iU(m_\nu^{\rm diag})^{1/2}\Omega(M_{\nu_R})^{1/2},$$

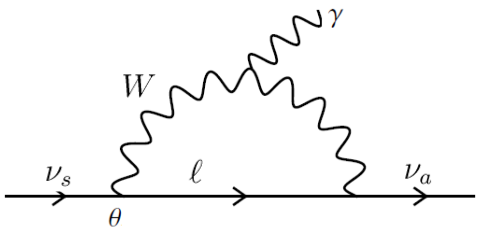
The interaction induces

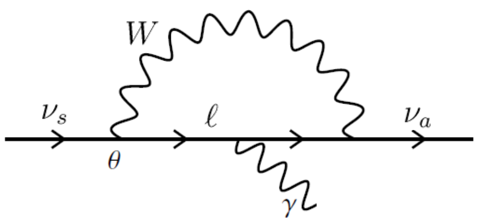
- Decay of sterile neutrinos into SM neutrino and photon (X-ray)

$$\nu_s \to 3\nu$$



$$\nu_s \to \nu + \gamma$$





Cosmic Sterile Neutrino Background

Sterile neutrino DM in nuMSM

To explain the two mass differences in the neutrino observations, two RH neutrinos are enough. The third RH neutrino, the lightest one around keV, can be DM candidate.

[Dodelson, Widrow, 1994] [Dolgov, Hansen, 2002] [Asaka, Blanchet, Shaposhnikov, 2005]

Production of DM oscillation from active neutrinos

- Dodelson-Widrow mechanism (Non-resonant production)

$$\Omega_s \sim 0.2 \left(\frac{\sin^2\theta}{3\times 10^{-9}}\right)\left(\frac{m_s}{3\,\mathrm{keV}}\right)^{1.8}$$

- Shi-Fuller (Resonant production) with lepton asymmetry

Decay rate of DM $\nu_s \to 3\nu$

$$\Gamma_\gamma(m_s, \sin^2 2\theta) \approx 1.36\times 10^{-30}\,\mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\,\mathrm{keV}}\right)^5,$$

Production of sterile neutrino

Boltzmann equation

[Dodelson, Widrow, 1993]
[Abazajian, Fuller, Pate, 2001]

$$\frac{\partial f_s(E,t)}{\partial t} - HE\frac{\partial f_s(E,t)}{\partial E} = \frac{1}{4}\sin^2(2\theta_M)\Gamma_\alpha(f_\alpha - f_s)$$

with mixing angle in the matter and the interaction rate with thermal particles

$$\sin^2(2\theta_M) = \frac{\sin^2(2\theta)}{\sin^2(2\theta) + [\cos(2\theta) - 2E\,V_T(T)/m_s^2]^2}, \qquad \Gamma_\alpha \approx 1.27 \times G_F^2 T^4 E,$$

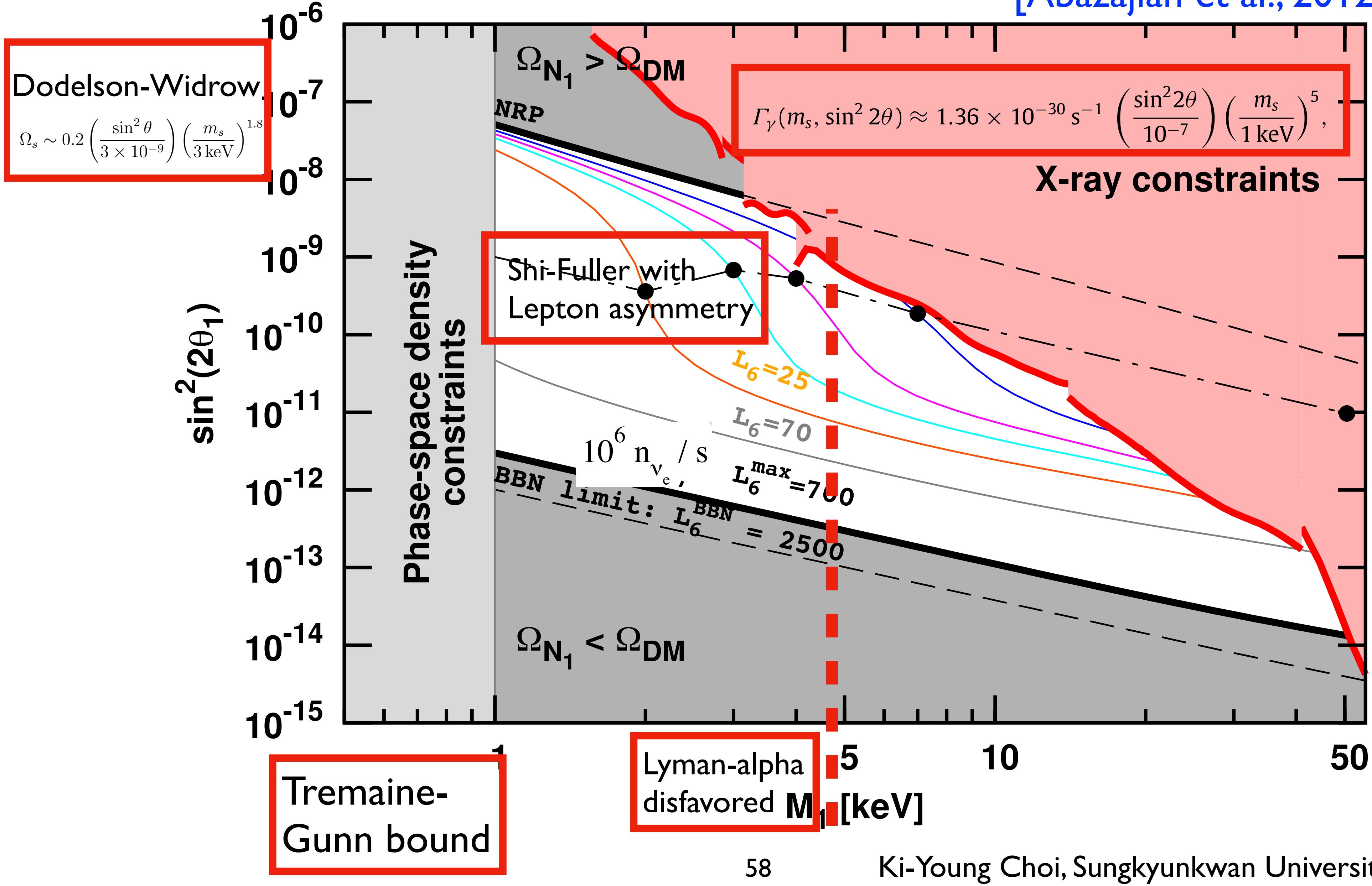
potential in matter $V_T = -BT^4E, \quad \text{and} \quad B \sim \begin{cases} 10.88 \times 10^{-9}\ \text{GeV}^{-4} & T > 2m_e \\ 3.04 \times 10^{-9}\ \text{GeV}^{-4} & T < 2m_e \end{cases}.$

The maximum production rate happens at

$$T_{\max} \simeq 108\ \text{MeV}\left(\frac{m_s}{\text{keV}}\right)^{1/3}$$

Sterile Neutrino DM in the nuMSM

[Abazajian et al., 2012]



Now, Sterile neutrino 100% DM is ruled out?

[Sicilian etal, 2208.12271]

X-ray constraints

[Dekker etal, 2111.13137]

structure formation of WDM