Sterile ν and Non-Standard Interactions of ν

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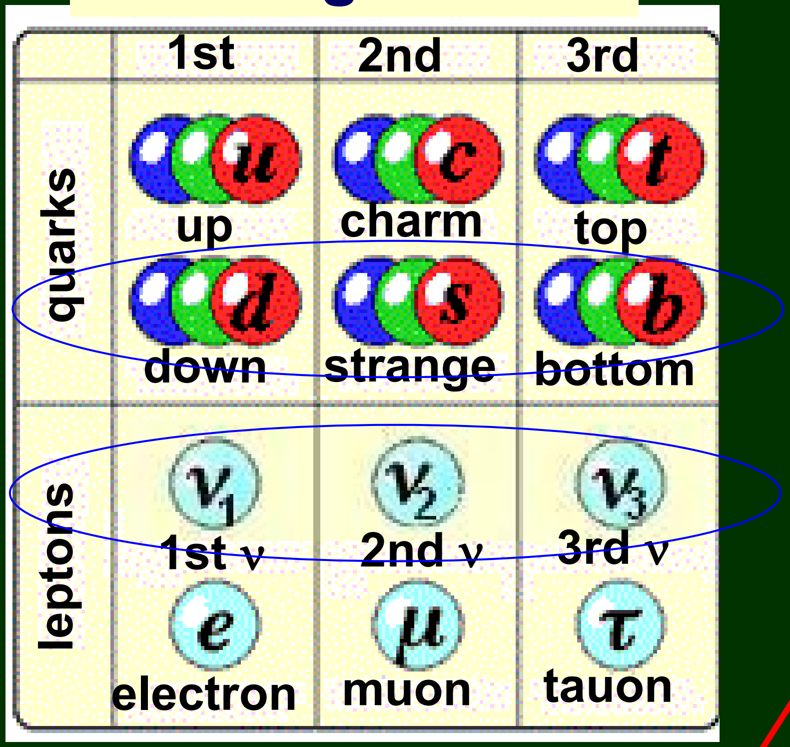
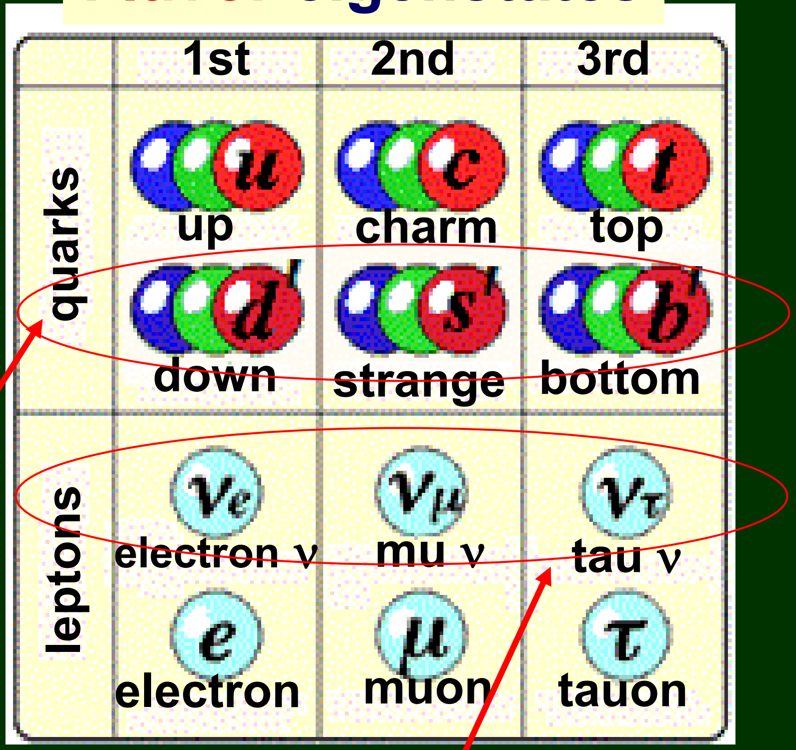
1. Introduction

Flavor and mass eigenstates in massive ν SM

Mass eigenstates



Flavor eigenstates



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CMK} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν oscillation

● 2 flavor case in vacuum

$$E_j = \sqrt{\vec{p}^2 + m_j^2}$$

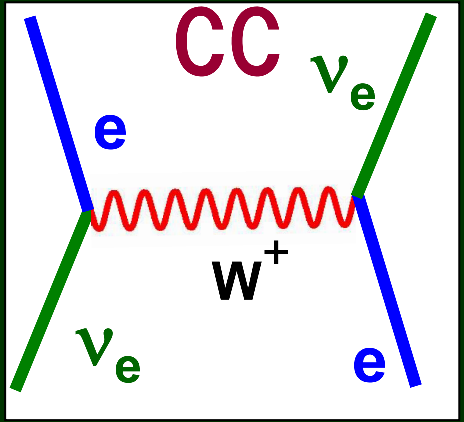
$$\Delta E = E_2 - E_1 \cong \frac{m_2^2 - m_1^2}{2E} = \frac{\Delta m^2}{2E}$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_\mu(t)\\ \nu_\tau(t)\end{pmatrix} = U\begin{pmatrix}E_2 & 0\\ 0 & E_3\end{pmatrix}U^{-1}\begin{pmatrix}\nu_\mu(t)\\ \nu_\tau(t)\end{pmatrix}$$

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta E L}{2}\right)$$

● 2 flavor case in matter

$$i\frac{d}{dt}\begin{pmatrix}\nu_e(t)\\ \nu_\mu(t)\end{pmatrix} = \left[U\begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}U^{-1} + \begin{pmatrix}A & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e(t)\\ \nu_\mu(t)\end{pmatrix}$$



$$P(\nu_\mu \to \nu_e) = \sin^2 2\tilde{\theta} \, \sin^2\left(\frac{\Delta \tilde{E} L}{2}\right)$$

$$\tan 2\tilde{\theta} \equiv \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta - A}$$

$$\Delta\tilde{E} \equiv \left[(\Delta E \cos 2\theta - A)^2 + (\Delta E \sin 2\theta)^2\right]^{1/2}$$

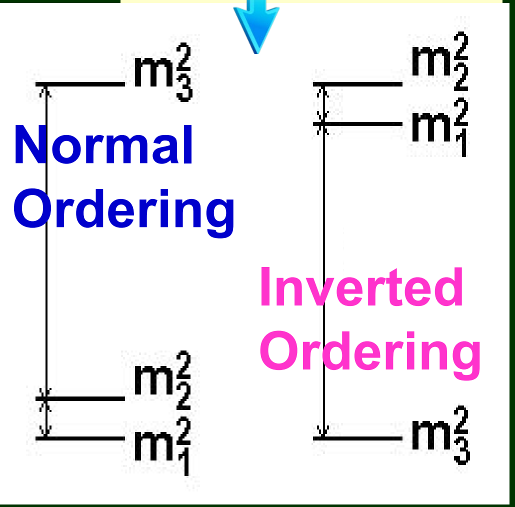
2. The standard 3 flavor scenario

3 flavor ν oscillation

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

Mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

Both mass orderings are allowed



All 3 mixing angles have been measured:

- ν_{solar}, KamLAND → $\theta_{12} \cong \frac{\pi}{6}$, $\Delta m_{21}^2 \cong 8 \times 10^{-5}\, eV^2$
- ν_{atm}, T2K, MINOS, NOvA → $\theta_{23} \cong \frac{\pi}{4}$, $|\Delta m_{32}^2| \cong 2.5 \times 10^{-3}\, eV^2$
- D-CHOOZ, Daya Bay, Reno, T2K, NOvA, etc. → $\theta_{13} \cong \pi / 20$

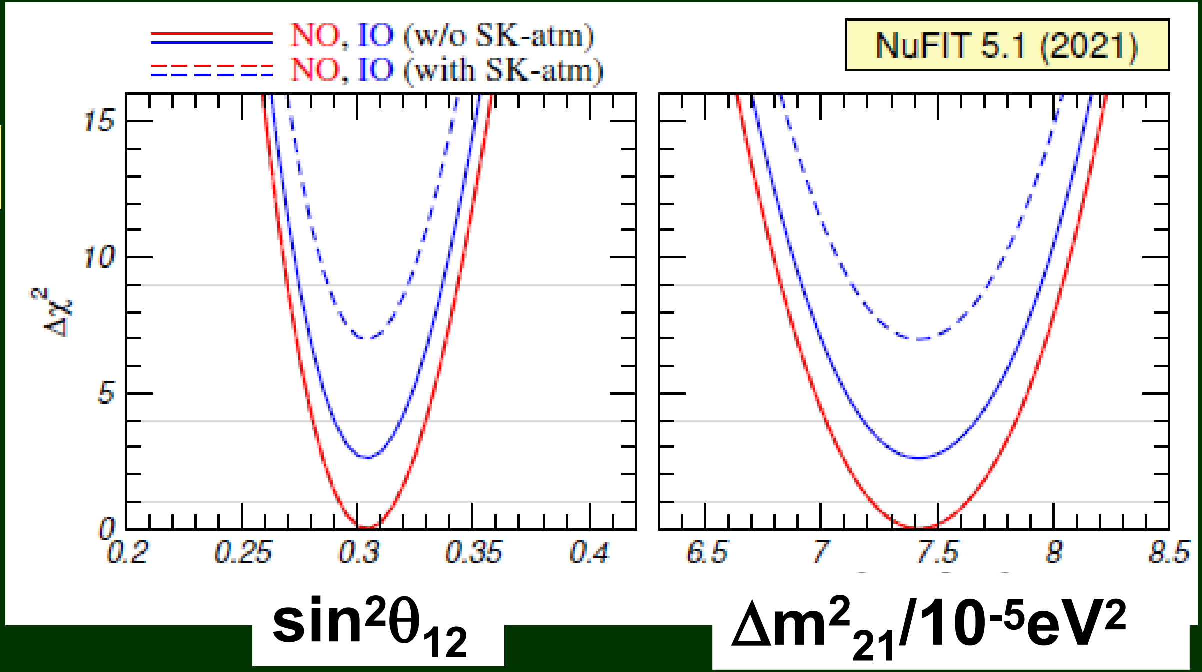
Status of 3ν fit

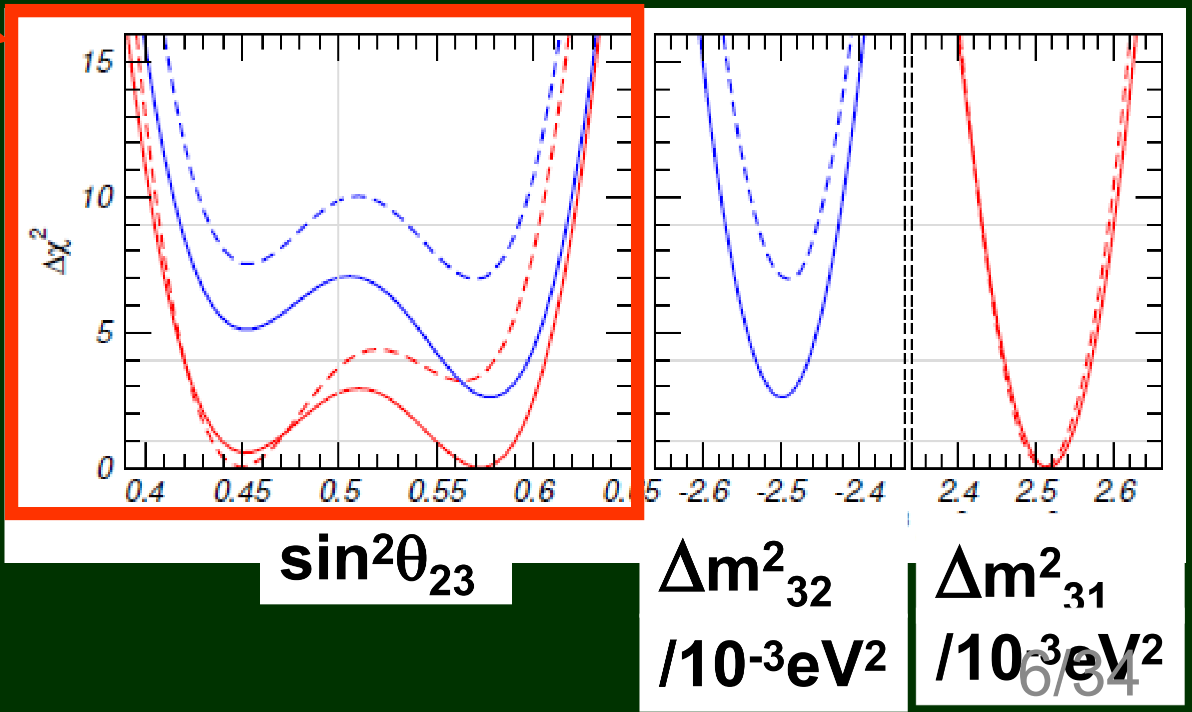
Schwetz @Neutrino2022

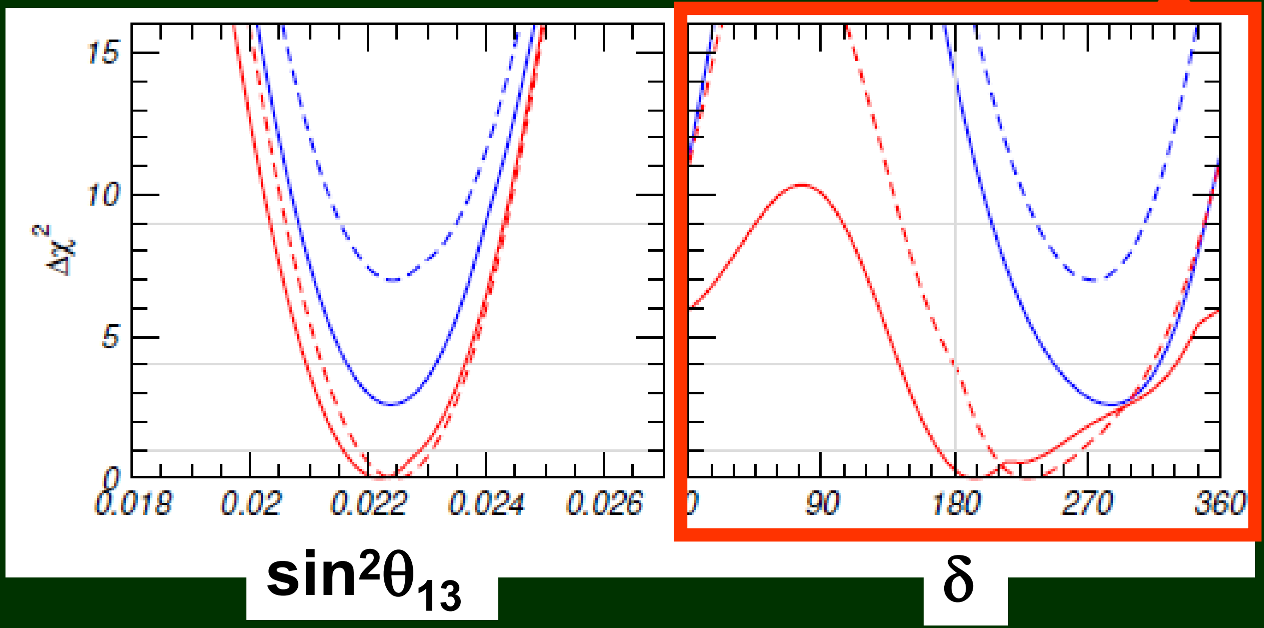
NO, δ~π seems to be preferred over IO, δ~3π/2

NO, IO (w/o SK-atm)
NO, IO (with SK-atm)

θ_{23} and δ have large errors







3ν fit appears to be OK, but if we look at each data, then there seem to be several tensions…

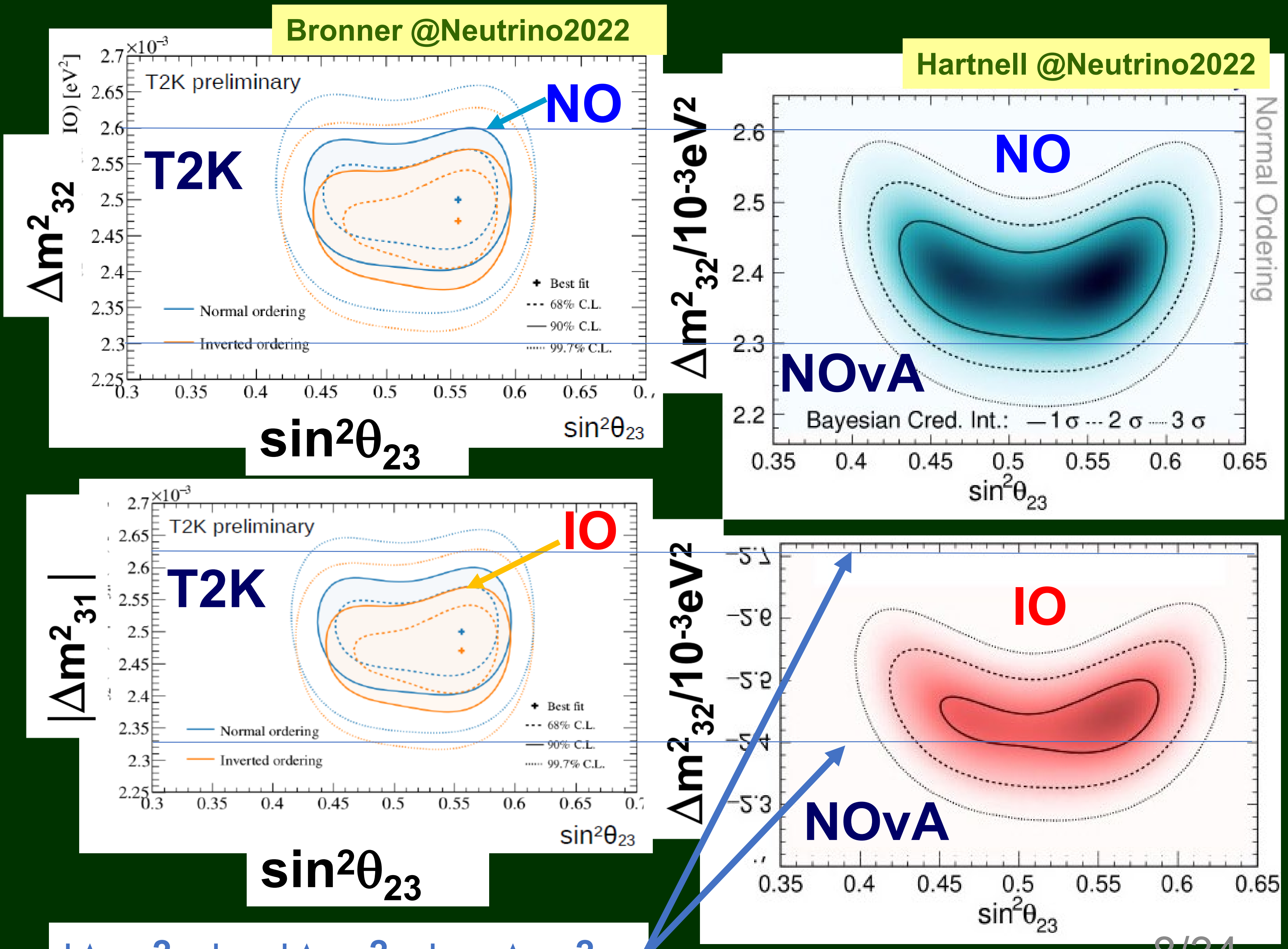
Results on ν_μ disappearance by T2K & NOvA

- **Allowed region for T2K is higher in $|\Delta m^2_{32}|$ than that of NOvA:**

  $\Delta m^2_{\text{T2K best-fit}}$

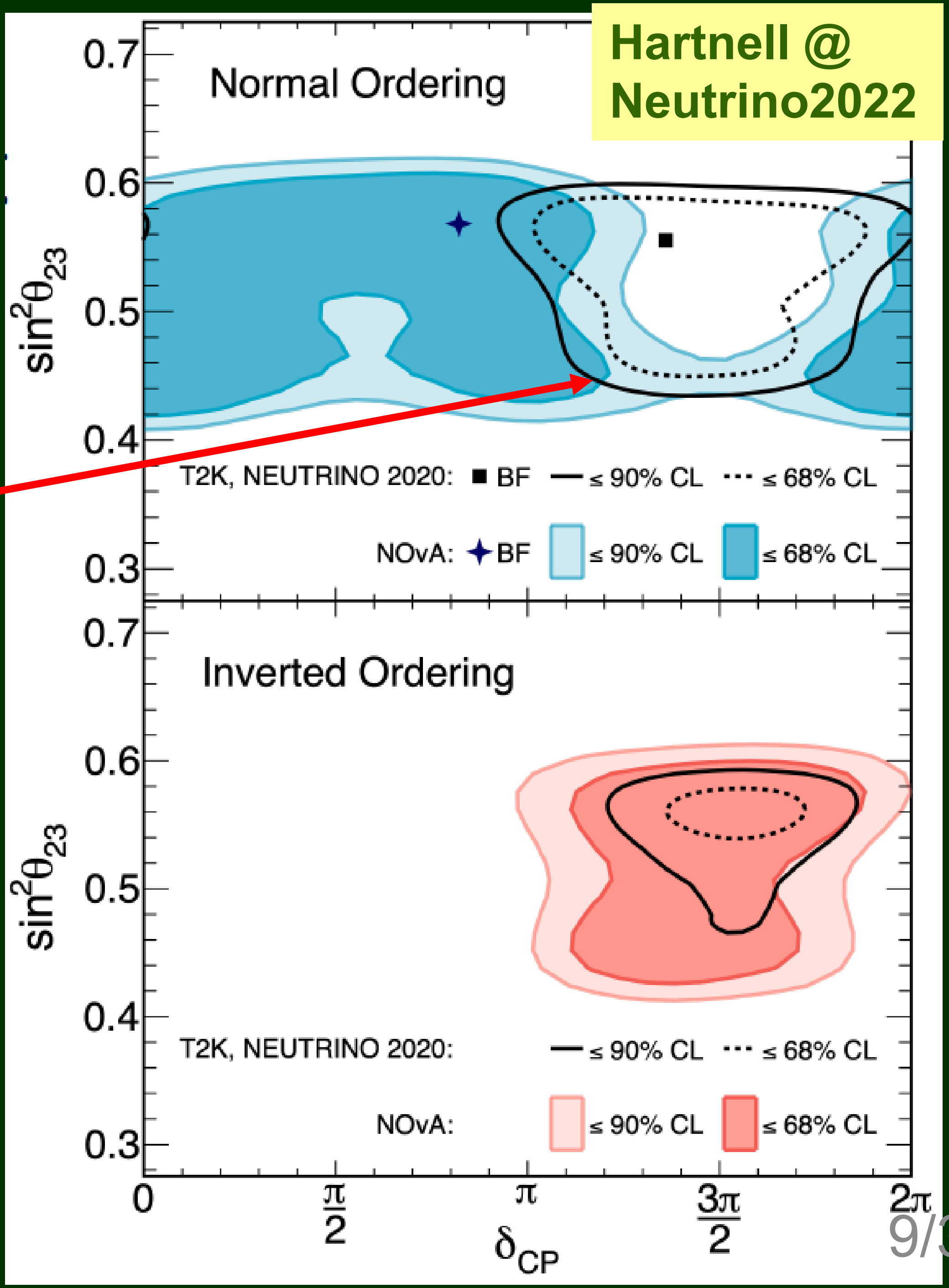
  $- \Delta m^2_{\text{NOvA best-fit}}$

  $\sim O(\Delta m^2_{21})$



$|\Delta m^2_{32}| = |\Delta m^2_{31}| + \Delta m^2_{21}$

Results on ν_e appearance by T2K & NOvA

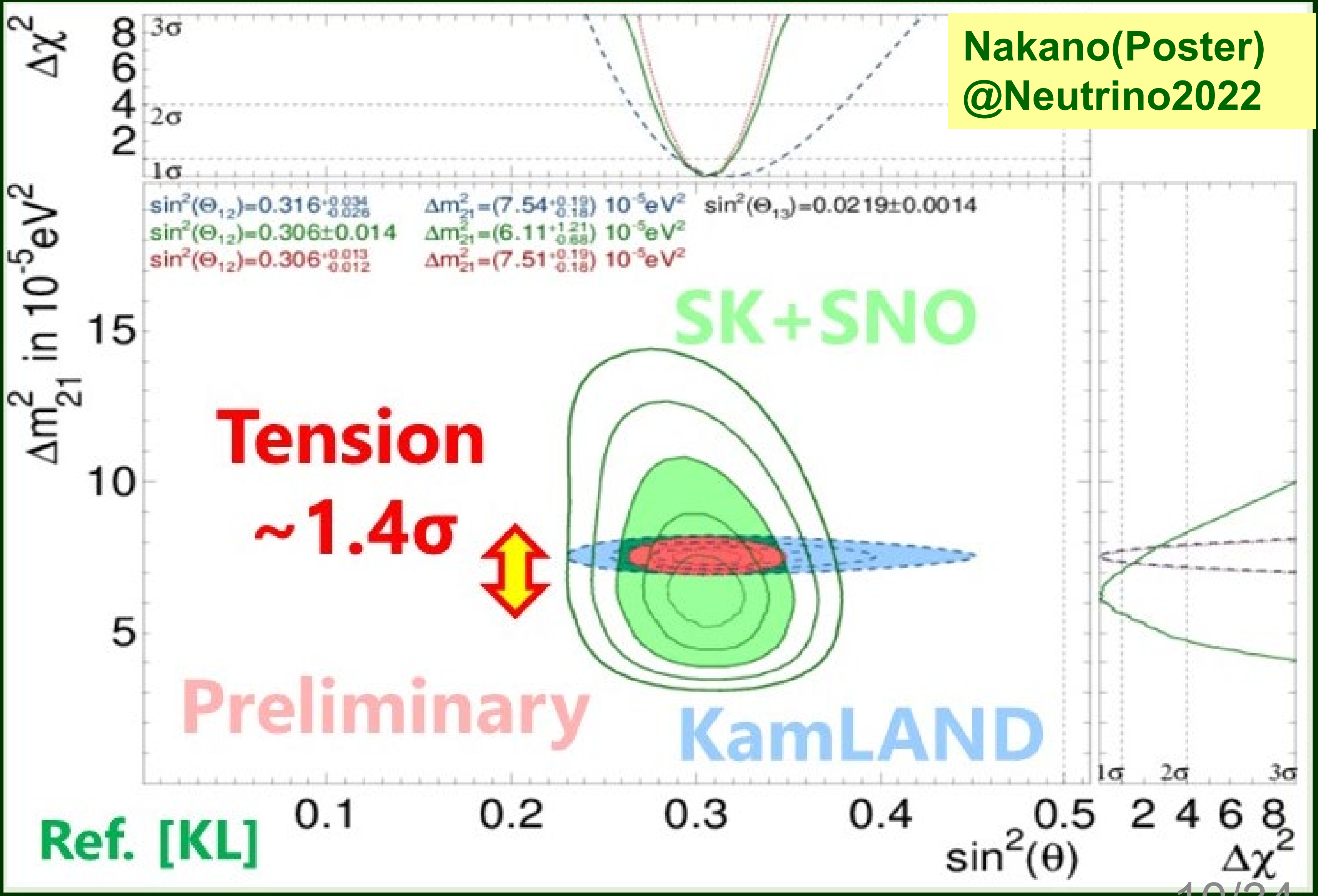


There is clear tension between T2K's and NOvA's regions for NO

Will discuss this tension later with Non-Standard Interaction.

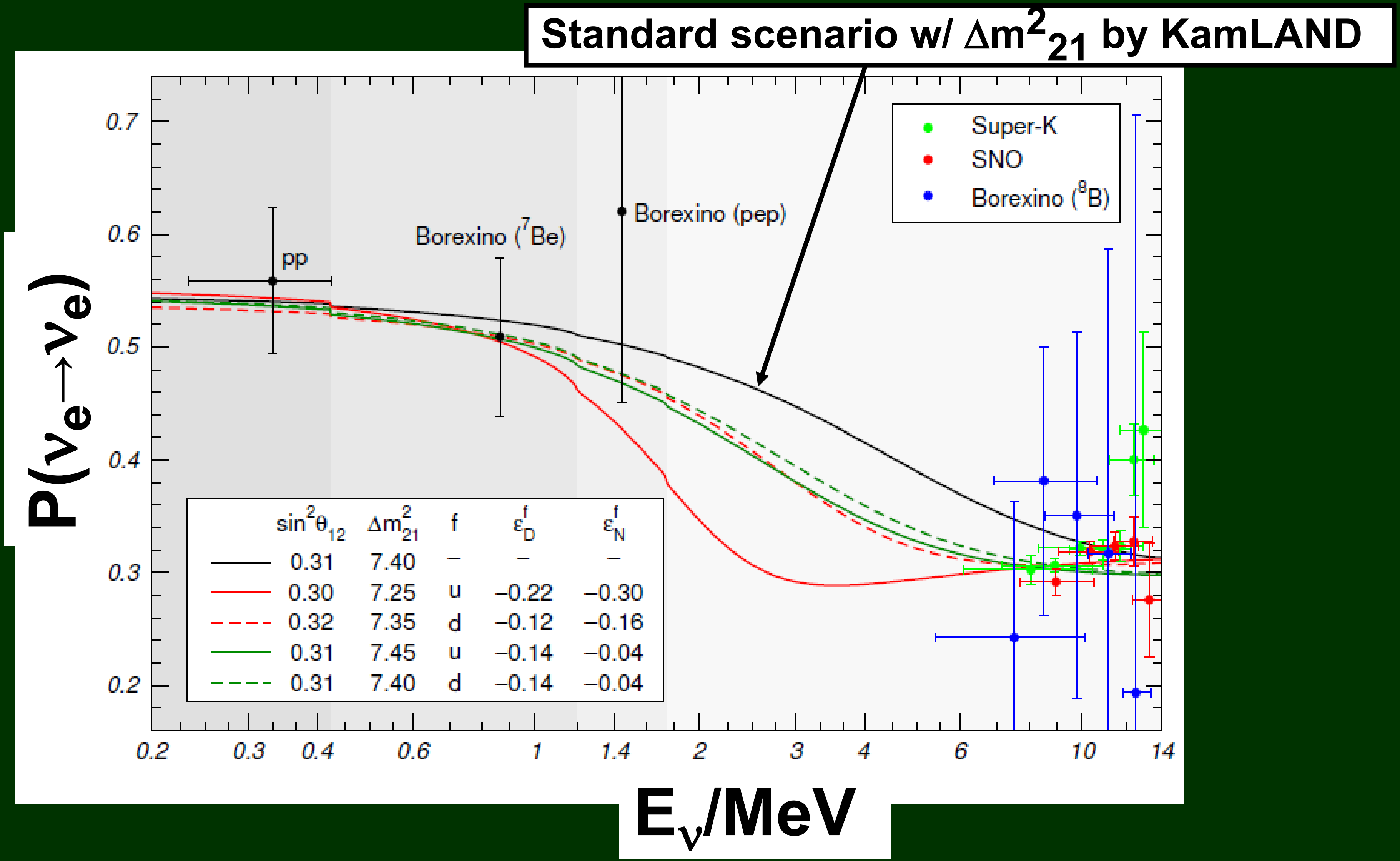
Tension between Δm^2_{21}(solar) & Δm^2_{21}(KamLAND)

Will discuss this tension later with Non-Standard Interaction.



- **Tension between solar ν & KamLAND data.**
  --> NSI may be a solution for the tension

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152



3. Beyond the standard 3 flavor framework

3.1 Light sterile neutrinos (ν_s)

Light sterile neutrinos have been phenomenologically motivated by:
- LSND/MiniBooNE anomaly
- Reactor anomaly
- Gallium anomaly

3.2 Flavor dependent Non-Standard Interaction in propagation

NSI has been phenomenologically motivated by:
- Tension between Δm^2_{21}(solar) & Δm^2_{21}(KamLAND)

3.1.1 LSND/ MiniBooNE anomaly

- LNSD experiment @LANL $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

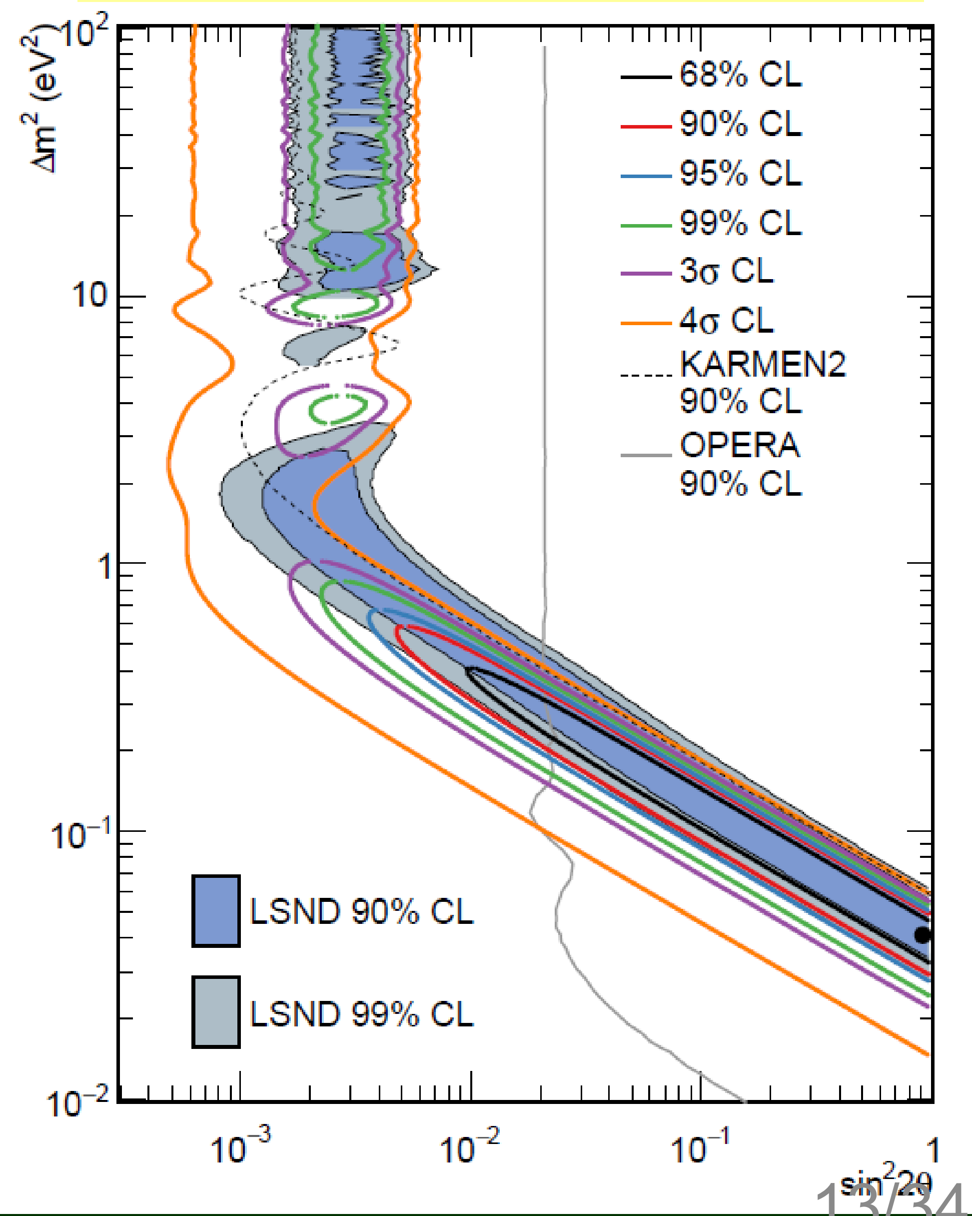
  E～50MeV, L～30m

- MiniBooNE @FNAL $\nu_\mu \rightarrow \nu_e + \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

  E～1GeV, L～500m $(L/E)_{MB}=(L/E)_{LSND}$

$\Delta m^2 \cong O(1)eV^2, \sin^2 2\theta \cong O(10^{-2})$??

MiniBooNE Collaboration, 1805.12028



3.1.2 Reactor ν anomaly

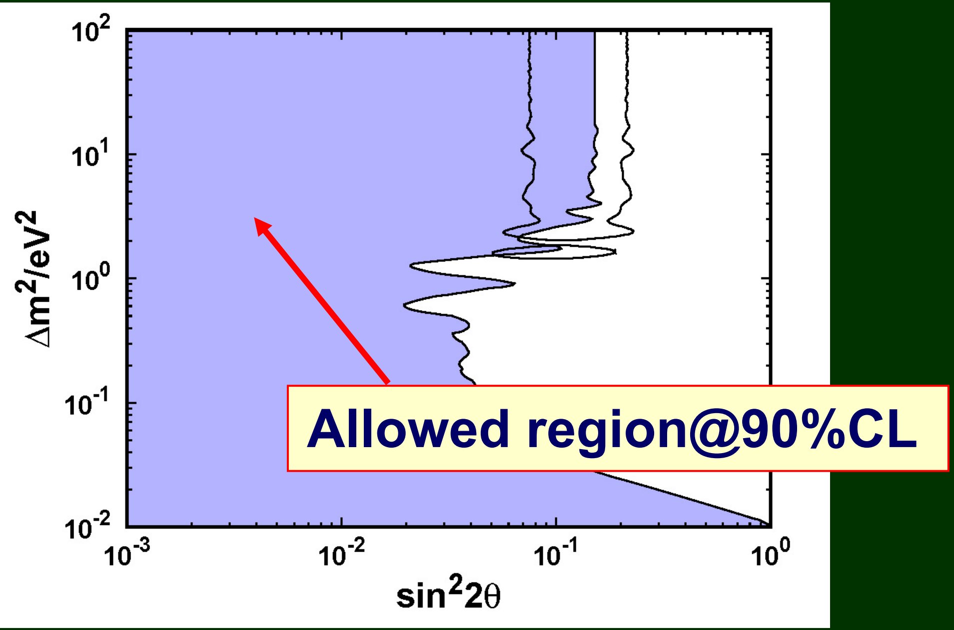
Mention et al (2011); Huber (2011)

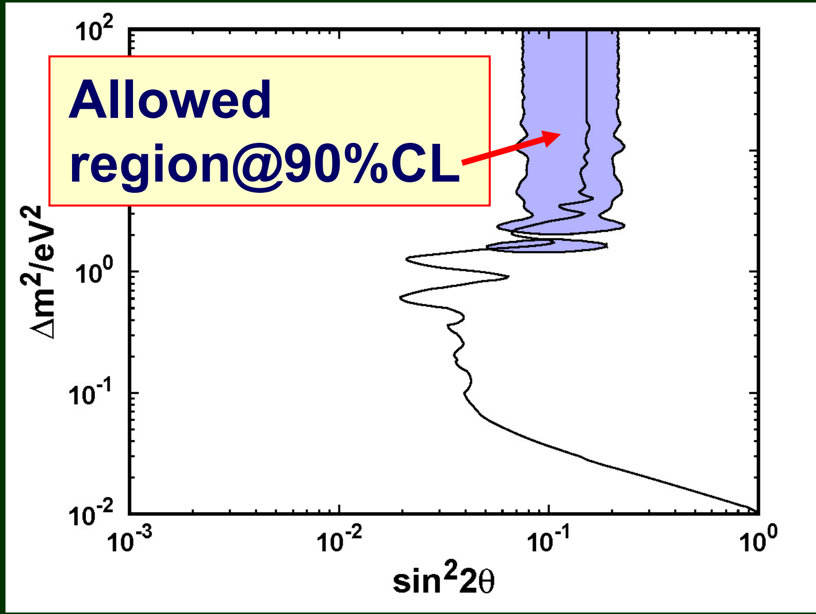
Reevaluation of reactor ν flux suggests affirmative interpretation of $\bar{\nu}_e \to \bar{\nu}_e$ oscillation at short distances

(new flux)= (old flux) x 1.03

Bugey(reactor $\bar{\nu}_e \to \bar{\nu}_e$):
Negative w/ old flux

Bugey(reactor)+etc:
Affirmative w/ new flux?

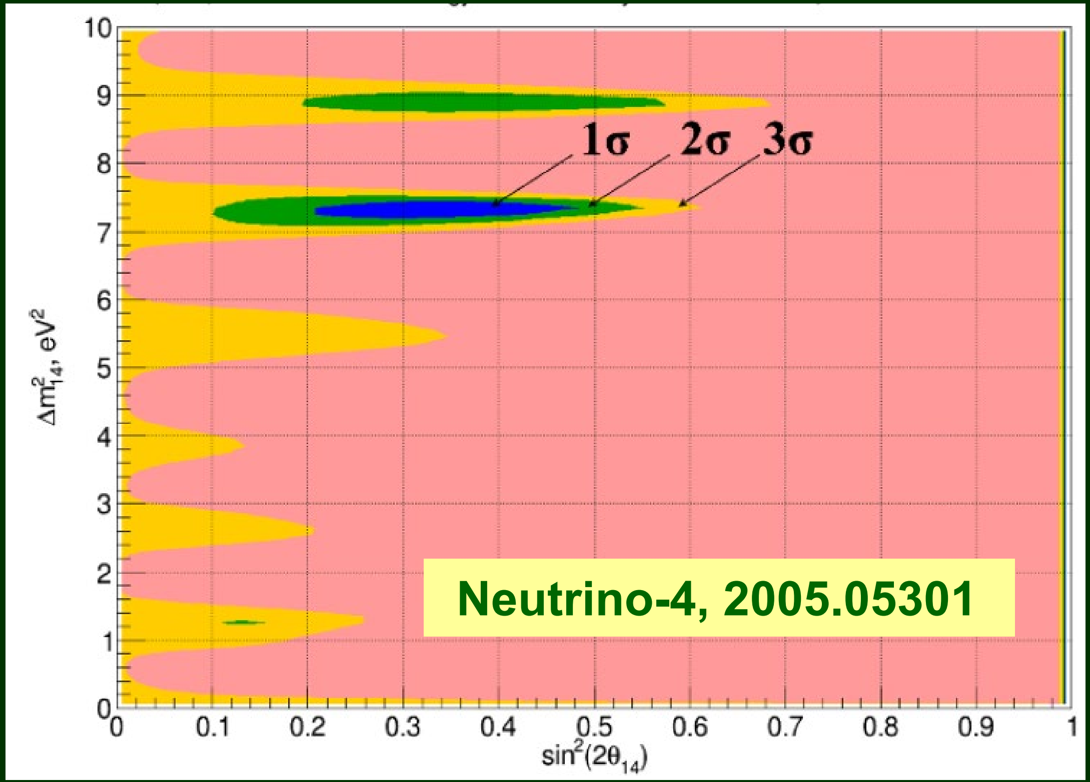


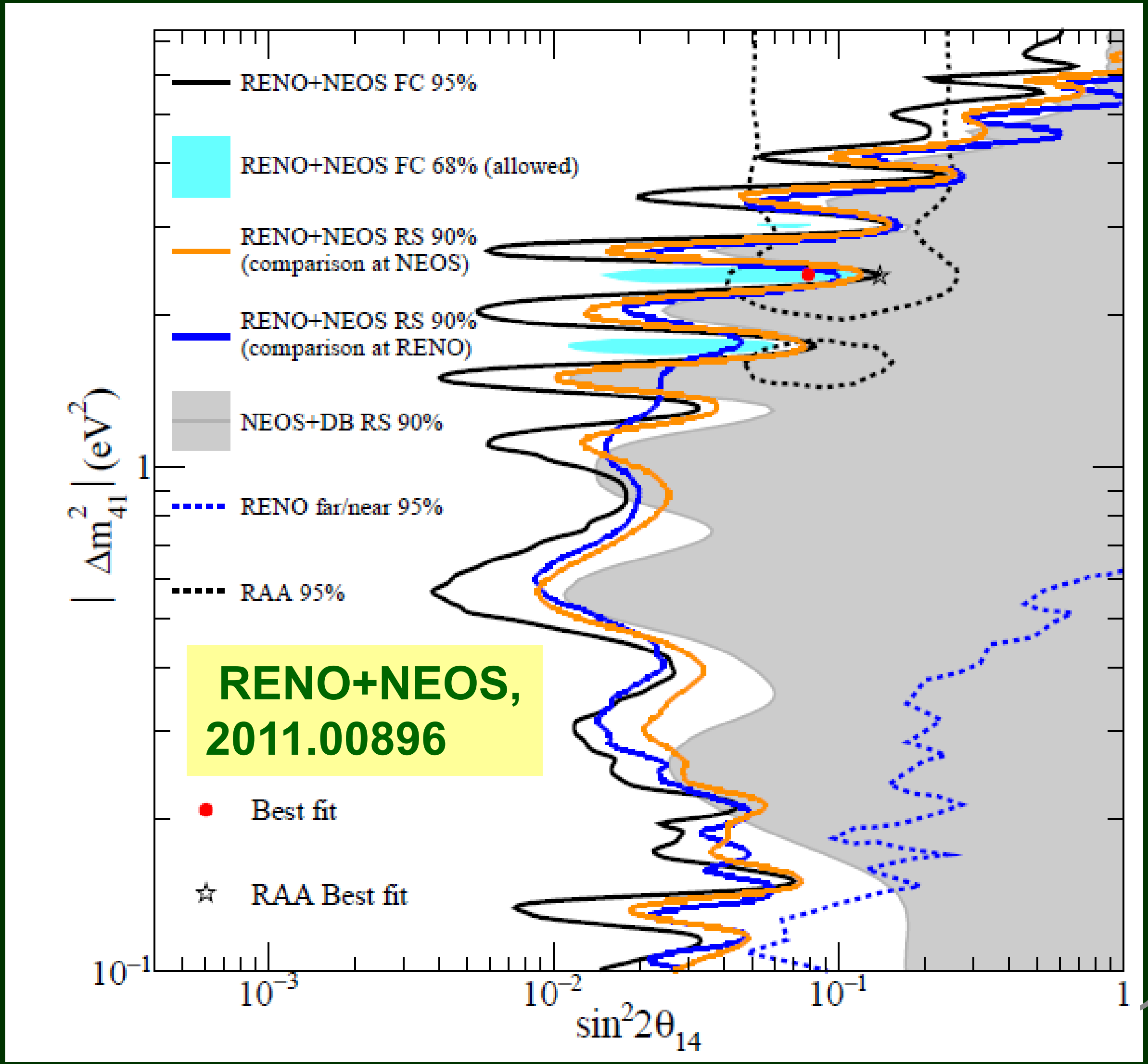


No ν oscillation for $\Delta m^2_{41} = O(1)\,eV^2$

ν oscillation may exist for $\Delta m^2_{41} = O(1)\,eV^2$

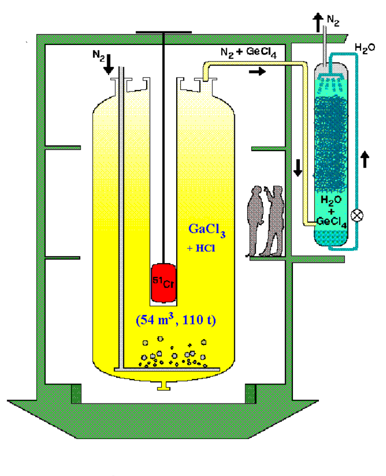
Two recent reactor ν experiments gave results consistent with affirmative interpretation of oscillation at short distances, though significance may be either weak or controversial.



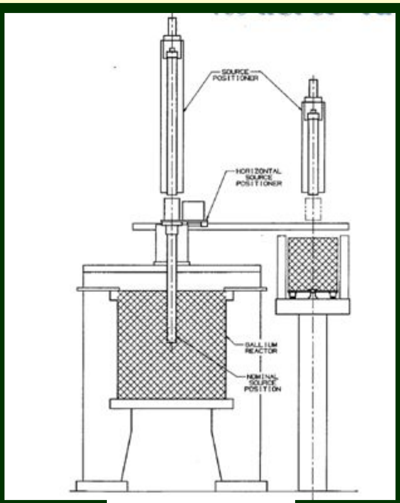


3.1.3 Gallium anomaly

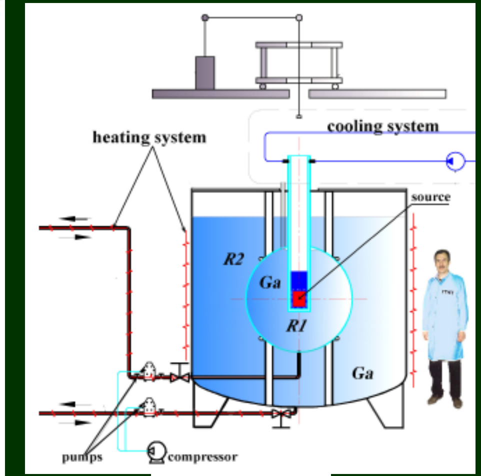
Gallium radioactive source experiments



Gallex



SAGE

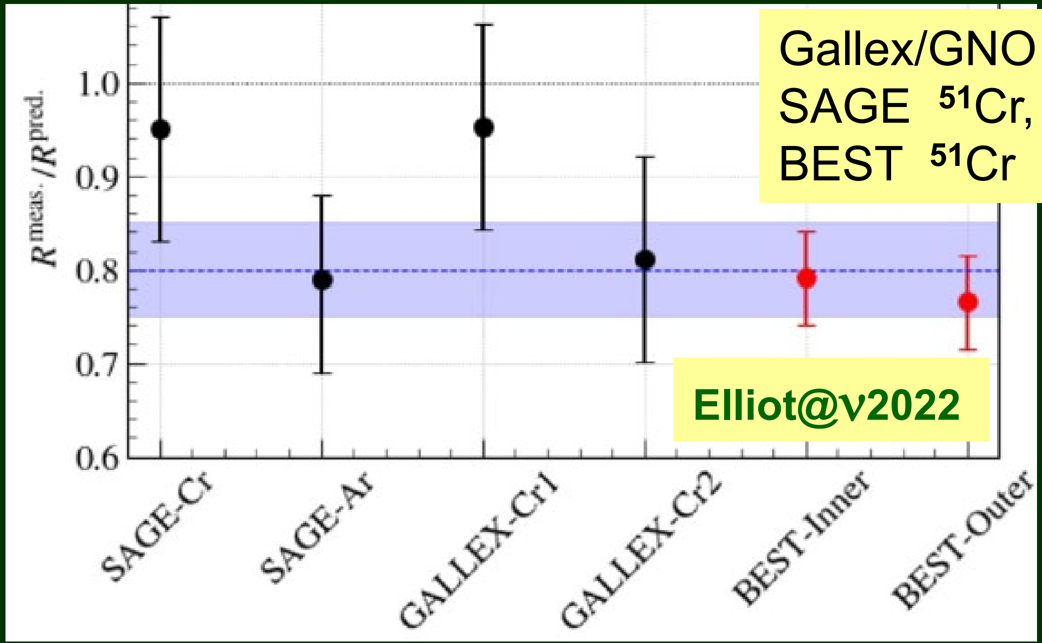


BEST

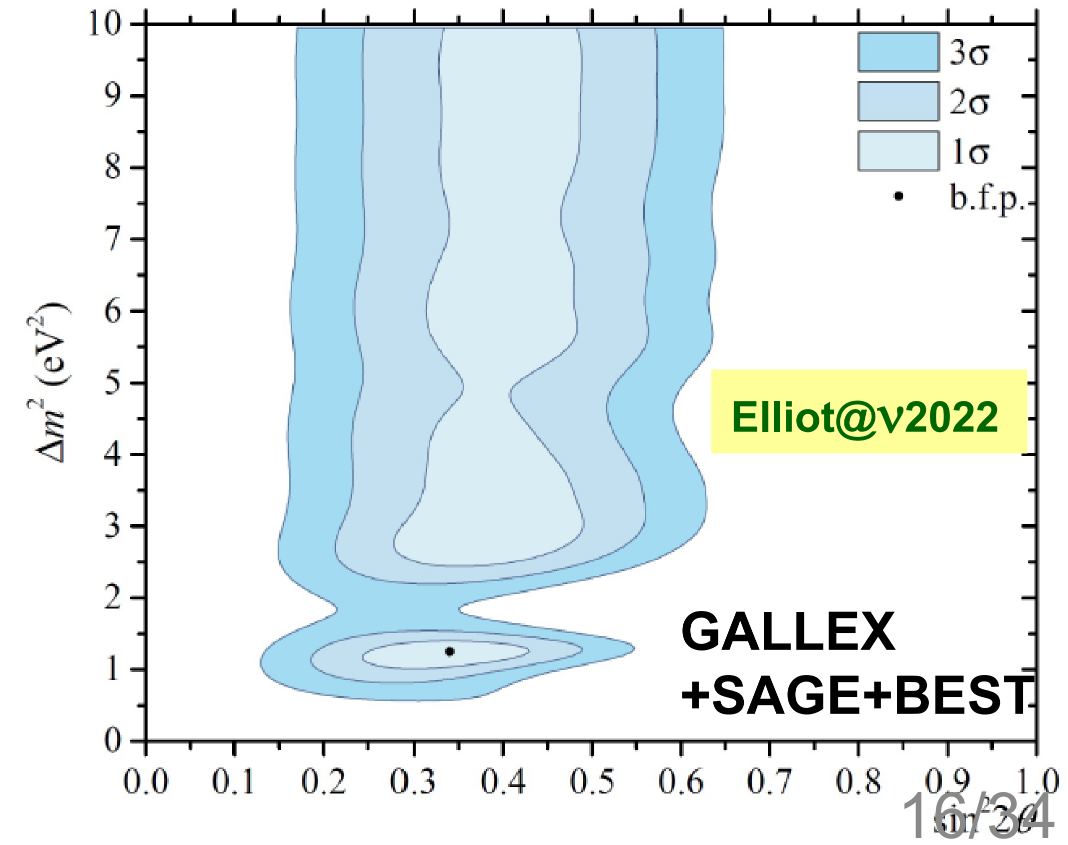
Results of the Ga radioactive source calibration experiments may be interpreted as an indication of the disappearance of ν_e due to active-sterile oscillations.

Combined result:

$R_0 = 0.80 \pm 0.05$

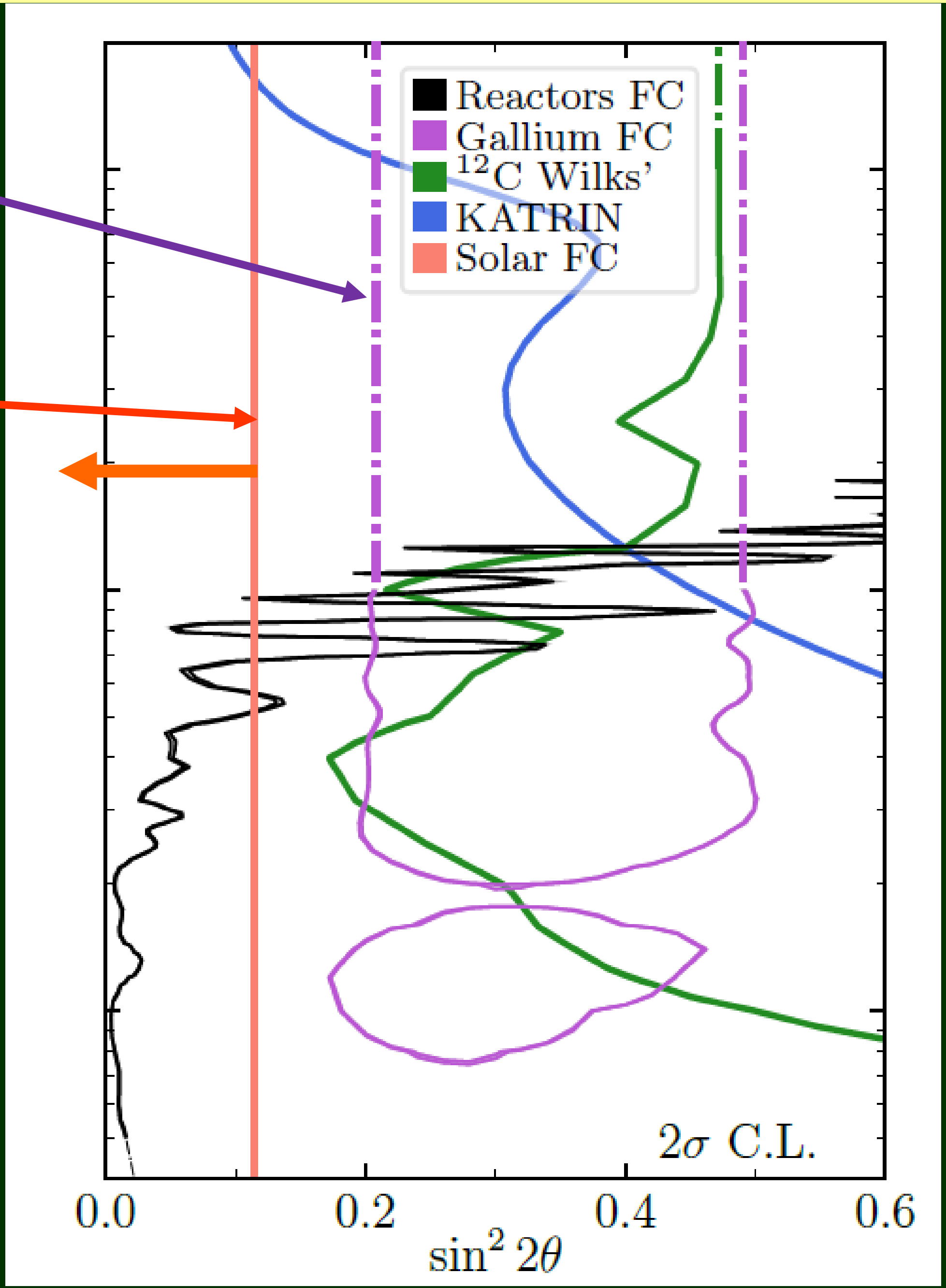


Gallex/GNO ^{51}Cr
SAGE ^{51}Cr, ^{37}Ar
BEST ^{51}Cr



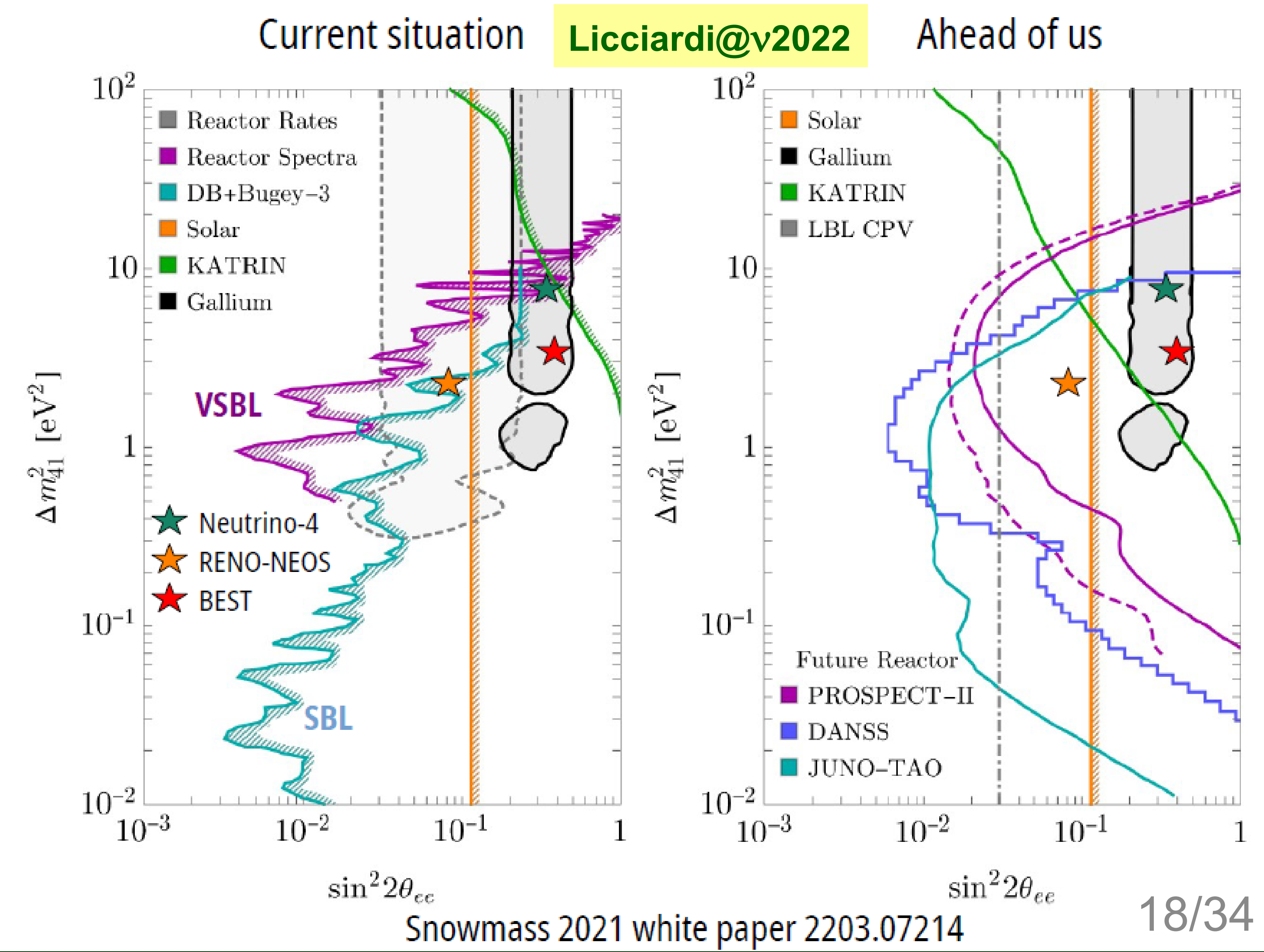
Berryman-Coloma-Huber-Schwetz-Zhou, 2111.12530

However, allowed region of the combined Ga experiments is in significant tension (~3σ) with solar ν constraint



3.1.4 Summary on ν_e disappearance

Among best-fit points of Neutrino-4, RENO-NEOS and BEST, the only one consistent with solar ν is RENO-NEOS, but it also has tension with other very short baseline reactor ν experiments.

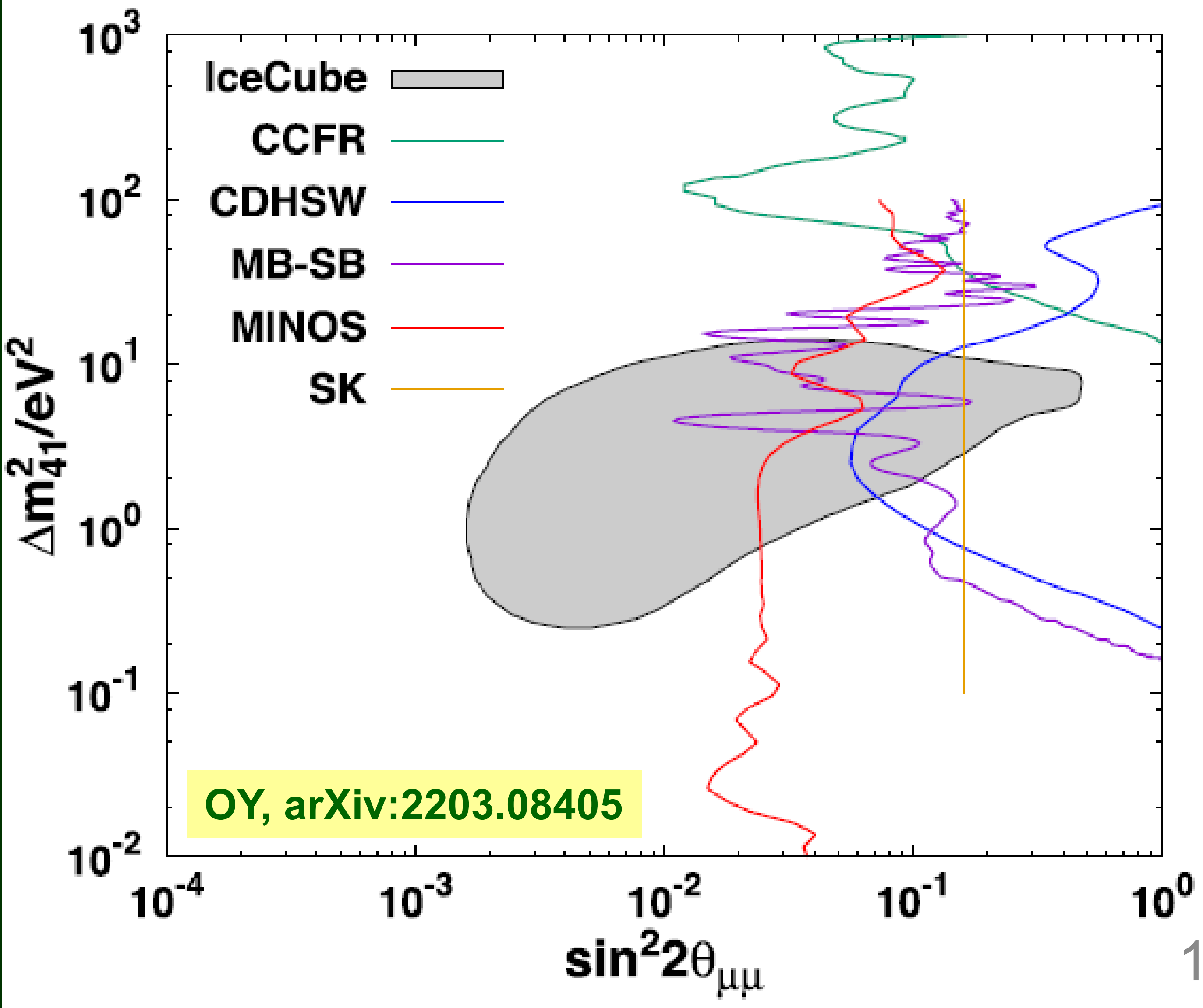


3.1.5 Results on ν_μ disappearance

$\nu_\mu \to \nu_\mu$

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

All the results except IceCube are negative. Significance of IceCube is weak (~1.6σ).



3.1.6 Oscillation with N_ν=4 schemes

Because of the hierarchy: $\Delta m^2_{sol} << \Delta m^2_{atm} << \Delta m^2_{LSND}$

Anomalies cannot be explained by N_ν=3 oscillation

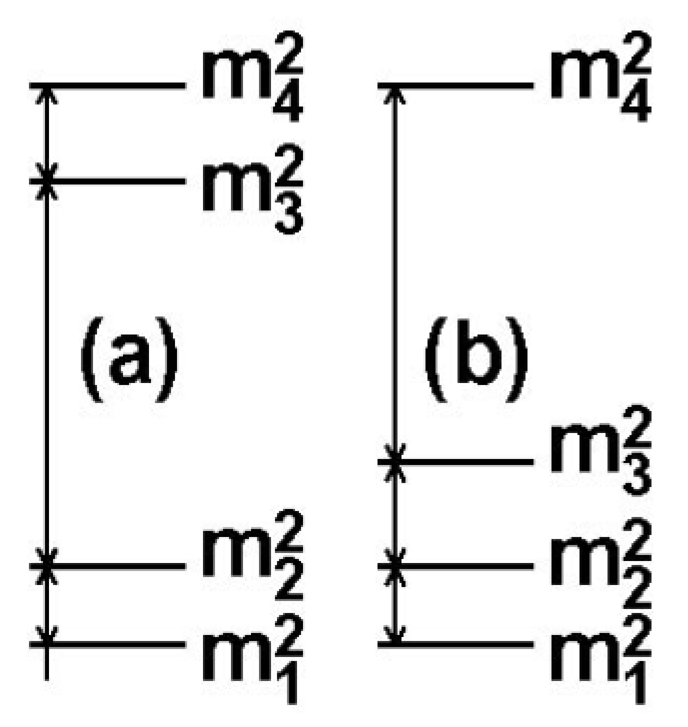
LEP data

→ N_ν=3 active light ν

→ 4th ν must be sterile

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

Two possible N_ν=4 schemes:
(a) (2+2)-scheme
(b) (3+1)-scheme



3.1.7.1 (2+2)-scheme: tension between ν_{solar} & ν_{atm}

$$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \to 0$$

$$\nu_{atm} : \nu_\mu \to \nu_s (100\%)$$

Excluded by SK ν_{atm} data

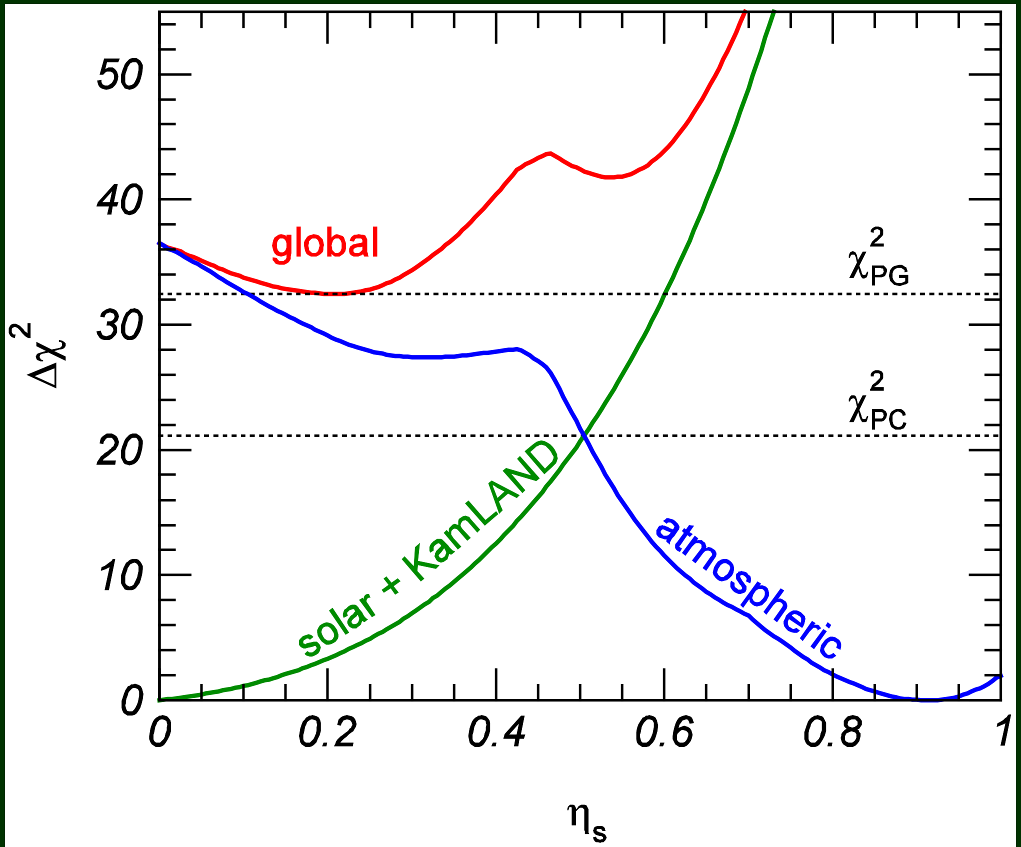
$$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \to 1$$

$$\nu_{sol} : \nu_e \to \nu_s (100\%)$$

Excluded by SNO ν_{sol} data

For any value of $|U_{s1}|^2 + |U_{s2}|^2$, fit to sol+atm data is bad.

Maltoni et al., hep-ph/0405172



PC: parameter consistency test
PG: parameter goodness-of-fit test

Reason why ν_{atm} cannot be described by $\nu_\mu \Leftrightarrow \nu_s$

$\nu_\mu \Leftrightarrow \nu_\tau$: osc in vacuum

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \, \sin^2 \left(\frac{\Delta E L}{2} \right)$$

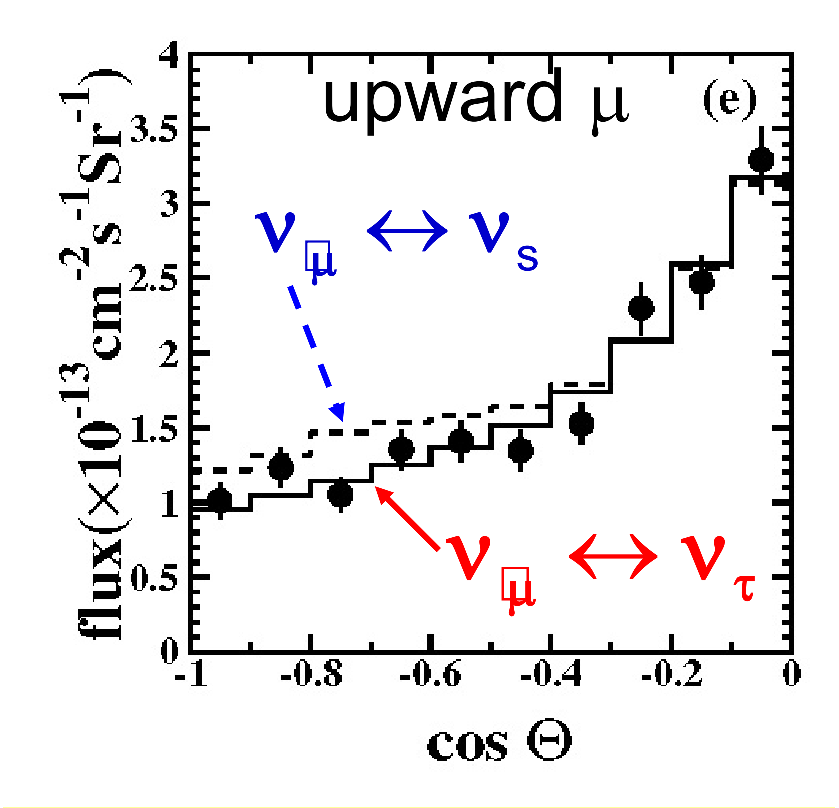
$$\Delta E = E_2 - E_1 \cong \frac{m_2^2 - m_1^2}{2E} = \frac{\Delta m^2}{2E}$$

$\nu_\mu \Leftrightarrow \nu_s$: osc in matter

$$P(\nu_\mu \to \nu_s) = \sin^2 2\tilde{\theta} \, \sin^2 \left(\frac{\Delta \tilde{E} L}{2} \right)$$

$$\Delta \tilde{E} \equiv \left[(\Delta E \cos 2\theta + V_{NC})^2 + (\Delta E \sin 2\theta)^2 \right]^{1/2}$$

$$\tan 2\tilde{\theta} = \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta + V_{NC}}$$



SK collaboration, PRL 85('00)3999

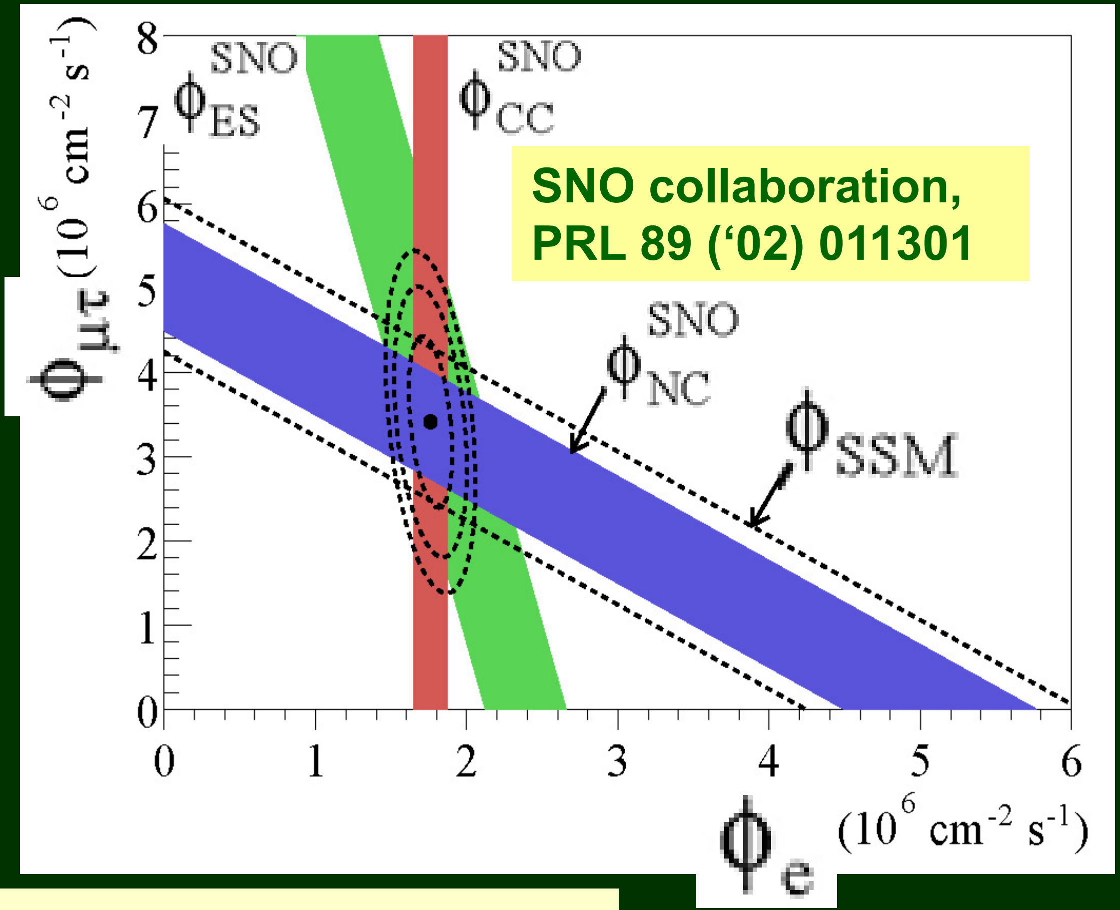
If $\theta=\pi/4$, then $\tilde{\theta}=\pi/4$ cannot be satisfied

Reason why ν_{solar} cannot be described by $\nu_e \Leftrightarrow \nu_s$

SNO can measure the sum of the flux $\nu_e + \nu_\mu + \nu_\tau$ through Neutral Current interaction

$$\nu_x + d \rightarrow p + n + \nu_x$$

x = e, μ, τ



$$[\phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau)]_{data} = 5.09\times10^6 cm^{-2}s^{-1}$$

$$[\phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau)]_{SSM} = 5.05\times10^6 cm^{-2}s^{-1}$$

3.1.7.2 (3+1)-scheme: tension between disapp. & app.

ν_e disappearance (reactor): negative

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2(\Delta m^2_{41} L/4E)$$

$$\sin^2 2\theta_{ee} > 4|U_{e4}|^2\left(1-|U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

ν_μ disappearance (accelerator): negative

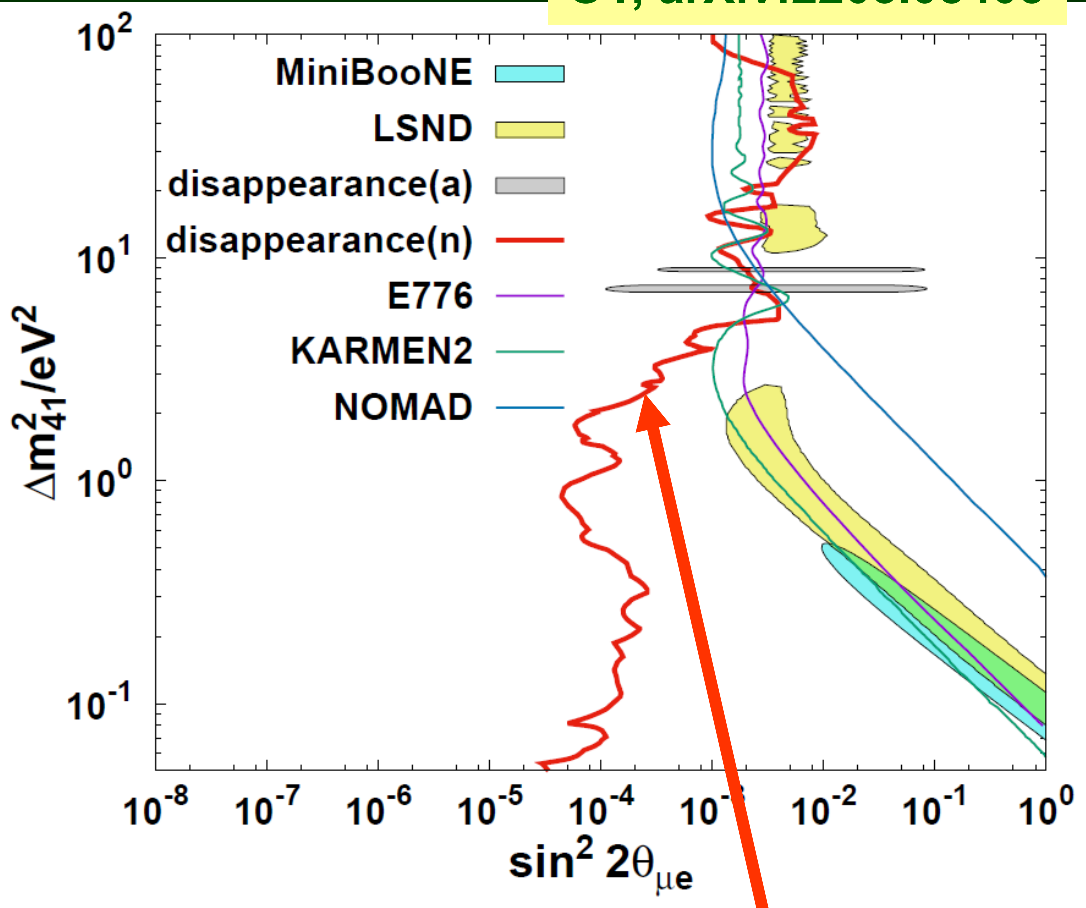
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2(\Delta m^2_{41} L/4E)$$

$$\sin^2 2\theta_{\mu\mu} > 4|U_{\mu 4}|^2\left(1-|U_{\mu 4}|^2\right) \simeq 4|U_{\mu 4}|^2$$

LSND (accelerator): affirmaive

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

OY, arXiv:2203.08405



$$\sin^2 2\theta_{\mu e}\left(\Delta m^2\right) < \frac{1}{4}\sin^2 2\theta_{ee}\left(\Delta m^2\right)\cdot \sin^2 2\theta_{\mu\mu}\left(\Delta m^2\right)$$

must be satisfied but there is no overlap between the left side of disappearance(n) and the inside of LSND or MiniBooNE

Ways out for (3+1)-scheme: tension between SBL appearance & disappearance

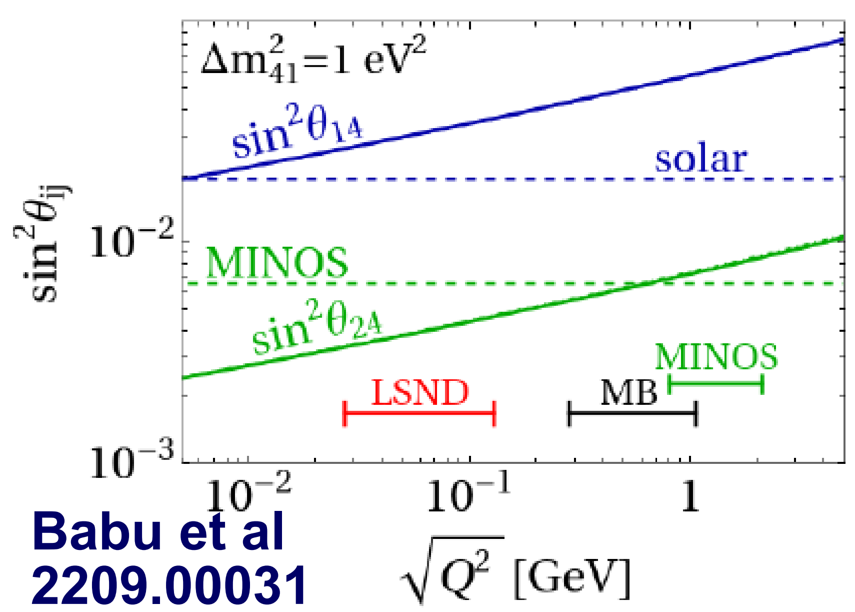
Ref. Argüelles@Neutrino2022

A) Interpretation of $\nu_\mu \to \nu_e$ as oscillation

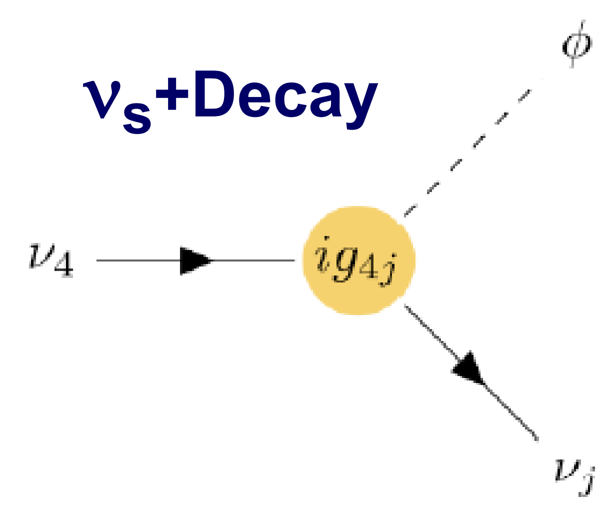
- **Sterile neutrino+NSI (may not work)**
  - Liao et al 1602.08766
  - Liao et al 1810.01000 p3 FIG.3 p4 FIG.4
  - Esmaili et al 1810.11940 (criticism against 1810.01000)
  - P. Denton et al 1811.01310

- **Energy-Dependent Mixing Parameters**
  - Babu et al 2209.00031

- **Sterile Neutrino + Decay**
  - Palomares-Ruiz et al hep-ph/0505216
  - Moss et al 1711.05921
  - Moulai et al 1910.13456
  - IceCube 2204.00612



Babu et al 2209.00031

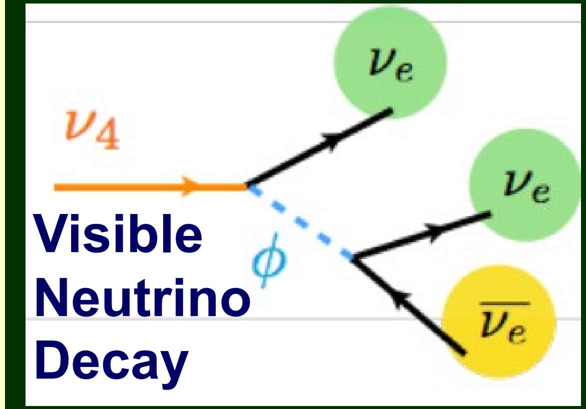


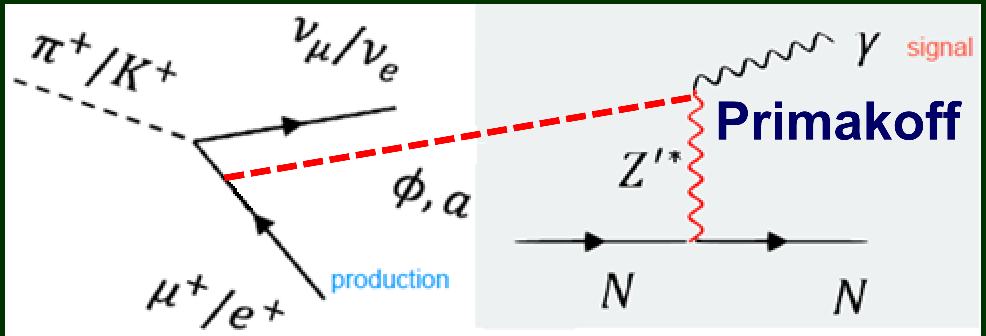
Ways out for (3+1)-scheme: tension between SBL appearance & disappearance

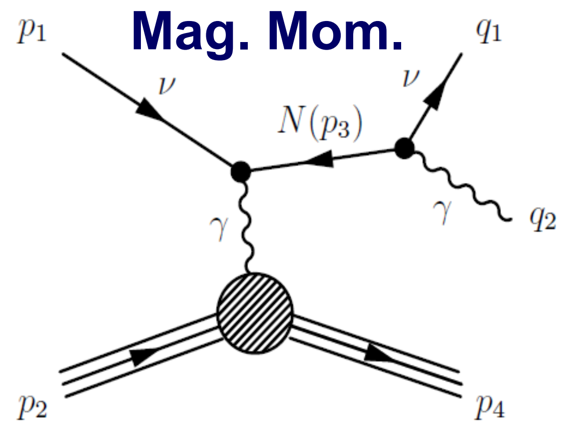
Ref. Argüelles@Neutrino2022

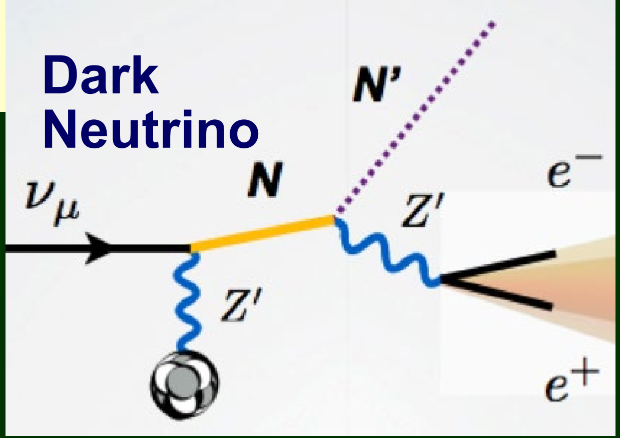
B) Interpretation of $\nu_\mu \rightarrow \nu_e$ as non-oscillation

- Visible Neutrino Decay in Beam
  Dentler et al 1911.01427;de Gouvea et al 1911.01447;
- Scalar With "Primakoff" Upscattering
  Dutta et al. 2110.11944; Abdallah et al 2202.09373
- Heavy Neutrino With Trans. Mag. Mom.
  Vergani et al 2105.06470; Magill et al 1803.03262; Kamp et al 2206.07100
- Dark Neutrino
  Bertuzzo et al. 1807.09877;Ballett et al 1808.02915; Abdullahi et al 2007.11813; Abdallah et al 2202.09373; Arguelles et al 2205.12273

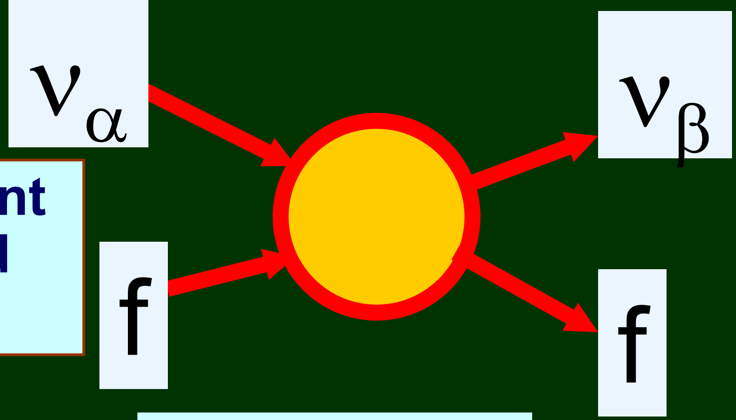








3.2 Nonstandard Interaction in propagation



Phenomenological New Physics considered here: 4-fermi Non Standard Interactions:

$$\mathcal{L}_{eff} = G_{NP}^{\alpha\beta}\,\bar{\nu}_\alpha\gamma^\mu\nu_\beta\,\bar{f}\gamma_\mu f'$$

neutral current non-standard interaction

f = e, u or d

Modification of matter effect

$A \equiv \sqrt{2}G_F N_e$ $\quad N_e \equiv$ electron density

$$\mathcal{A} \equiv \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + A\sum_{f=e,u,d}\frac{N_f}{N_e}\begin{pmatrix} \epsilon_{ee}^f & \epsilon_{e\mu}^f & \epsilon_{e\tau}^f \\ \epsilon_{\mu e}^f & \epsilon_{\mu\mu}^f & \epsilon_{\mu\tau}^f \\ \epsilon_{\tau e}^f & \epsilon_{\tau\mu}^f & \epsilon_{\tau\tau}^f \end{pmatrix}$$

NP

Solar ν basis

$$\mathcal{H} = R_{23}\,\tilde{R}_{13}\,\mathcal{H}^{\text{eff}}\,\tilde{R}_{13}^{-1}\,R_{23}^{-1}$$

$$\mathcal{A}^{\text{eff}}\Big|_{2\times 2} = \begin{pmatrix} Ac_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + A\sum_{f=e,u,d}\frac{N_f}{N_e}\begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix}$$

Ways out for tension between T2K and NOvA ν_e appearance

Ref. Rahaman@Nufact2022

Extra phases are important to fit both T2K and NOvA appearance data

- Sterile neutrino [δ_{14}, δ_{24}]
  - Chatterjee et al, 2005.10338
  - de Gouva et al, 2204.09130
- NSI [$\arg(\varepsilon_{e\mu})$, $\arg(\varepsilon_{e\tau})$]
  - Denton et al, 2008.01110
  - Chatterjee et al, 2008.04161
  - Rahaman et al 2201.03250
- Non-unitarity [$\arg(\alpha_{10})$]
  - Miranda et al, 1911.09398
  - Forero et al, 2103.01998

Non-unitarity

$$N = N_{NP} U_{3\times 3} = \begin{bmatrix} \alpha_{00} & 0 & 0 \\ \alpha_{10} & \alpha_{11} & 0 \\ \alpha_{20} & \alpha_{21} & \alpha_{22} \end{bmatrix} U_{\mathrm{PMNS}}$$

Ways out for tension between solar ν & KamLAND data

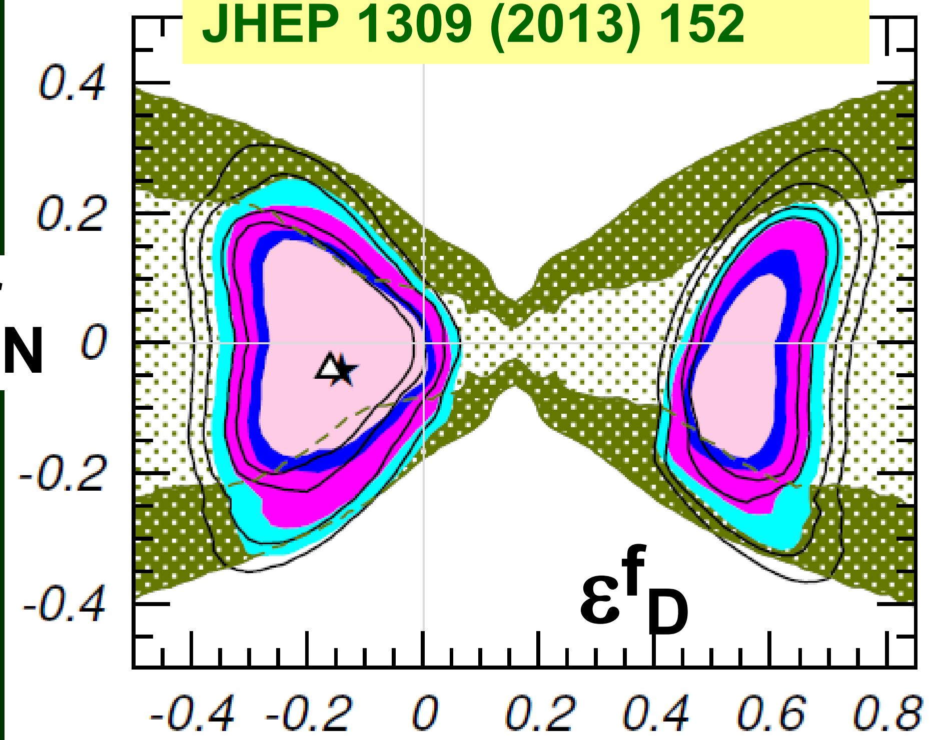
- **NSI**

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152

- **sterile neutrino with $\Delta m^2_{41} \sim O(10^{-5} eV^2)$**

Maltoni, Smirnov, arXiv:1507.05287v2 [hep-ph]

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152



ε^f_N

ε^f_D

$$\epsilon_D^f = c_{13}s_{13}\mathrm{Re}\left[e^{i\delta_{\rm CP}}\left(s_{23}\epsilon^f_{e\mu}+c_{23}\epsilon^f_{e\tau}\right)\right]-\left(1+s_{13}^2\right)c_{23}s_{23}\mathrm{Re}\left[\epsilon^f_{\mu\tau}\right] -\frac{c_{13}^2}{2}\left(\epsilon^f_{ee}-\epsilon^f_{\mu\mu}\right)+\frac{s_{23}^2-s_{13}^2c_{23}^2}{2}\left(\epsilon^f_{\tau\tau}-\epsilon^f_{\mu\mu}\right)$$

$$\epsilon_N^f = c_{13}\left(c_{23}\epsilon^f_{e\mu}-s_{23}\epsilon^f_{e\tau}\right)+s_{13}e^{-i\delta_{\rm CP}}\left[s_{23}^2\epsilon^f_{\mu\tau}-c_{23}^2\epsilon^{f*}_{\mu\tau}+c_{23}s_{23}\left(\epsilon^f_{\tau\tau}-\epsilon^f_{\mu\mu}\right)\right]$$

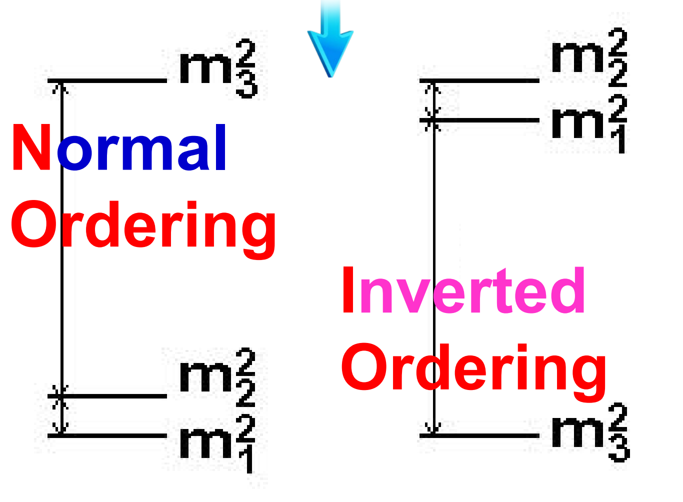
f = e, u or d

4. Future experiments

● Future long baseline experiments

Goal of the two near future experiments is to measure sign(Δm^2_{31}) , $\pi/4-\theta_{23}$ and δ

Both ordering patterns are allowed

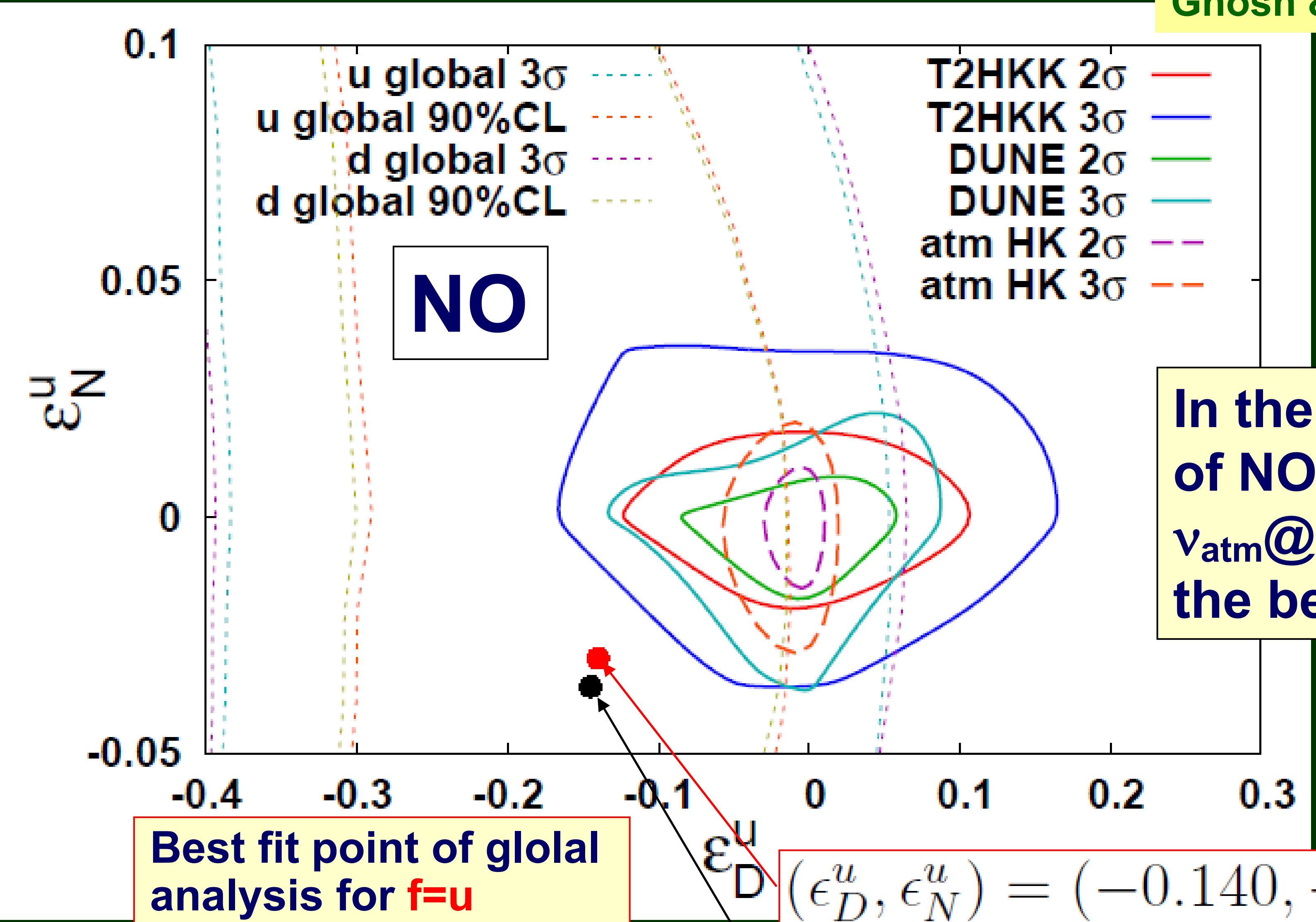


Proposed experiments

- T2HK (JP, JPARC-->HK)
  E~0.6GeV, L=295km
- DUNE (US, FNAL-->Homestake, SD)
  0GeV < E < 5GeV, L=1300km
- T2HKK (JP, JPARC-->Korea)
  E~1GeV, L=1100km

Comparison of sensitivity T2HKK, DUNE, ν_{atm}@HK

Ghosh & OY, arXiv:1709.08264



In the case of NO, ν_{atm}@HK is the best

Best fit point of glolal analysis for f=u

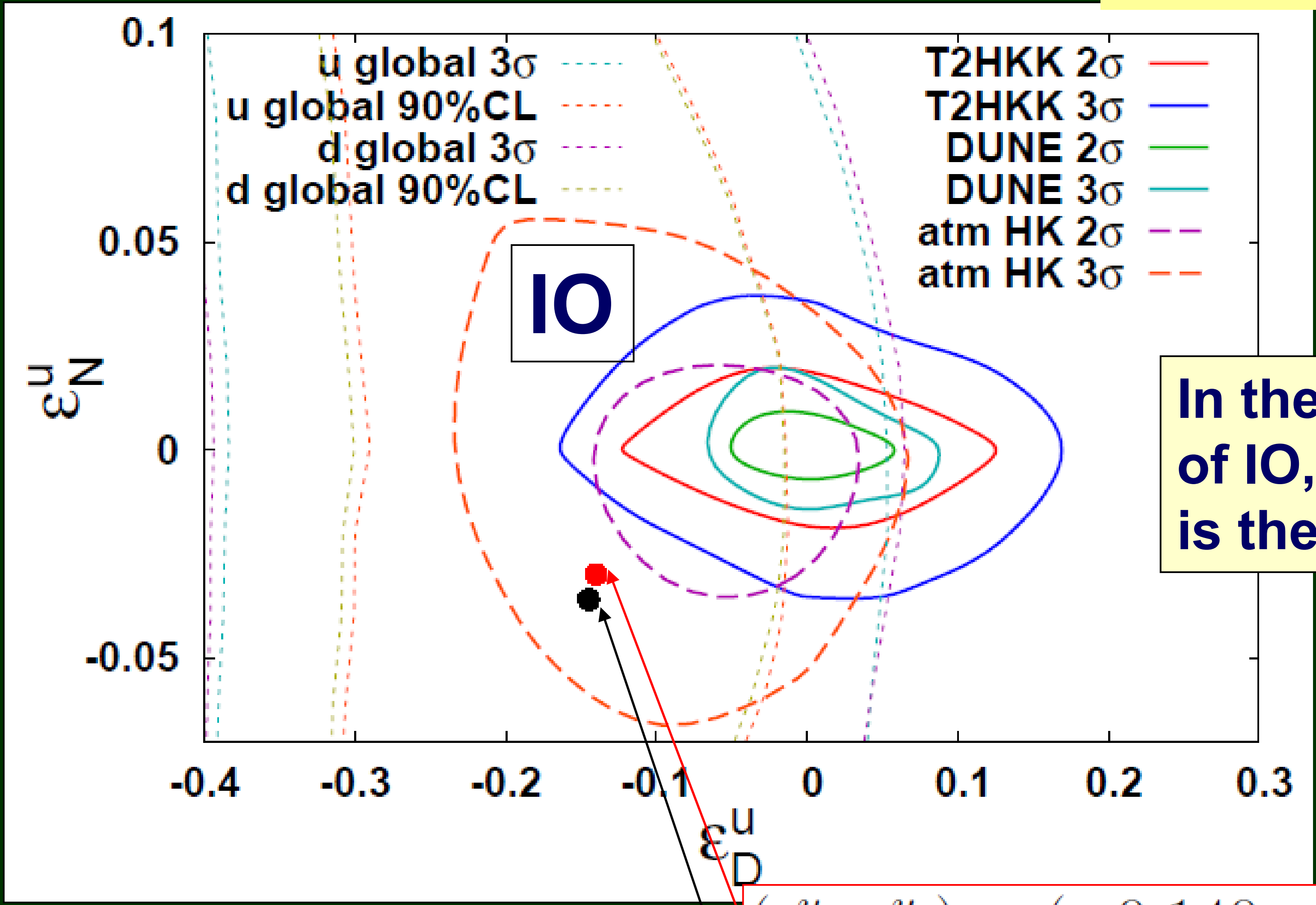
$$(\epsilon^u_D, \epsilon^u_N) = (-0.140, -0.030)$$

Best fit point of glolal analysis for f=d

$$(\epsilon^d_D, \epsilon^d_N) = (-0.145, -0.036)$$

Comparison of sensitivity T2HKK, DUNE, ν_{atm}@HK

Ghosh & OY, arXiv:1709.08264



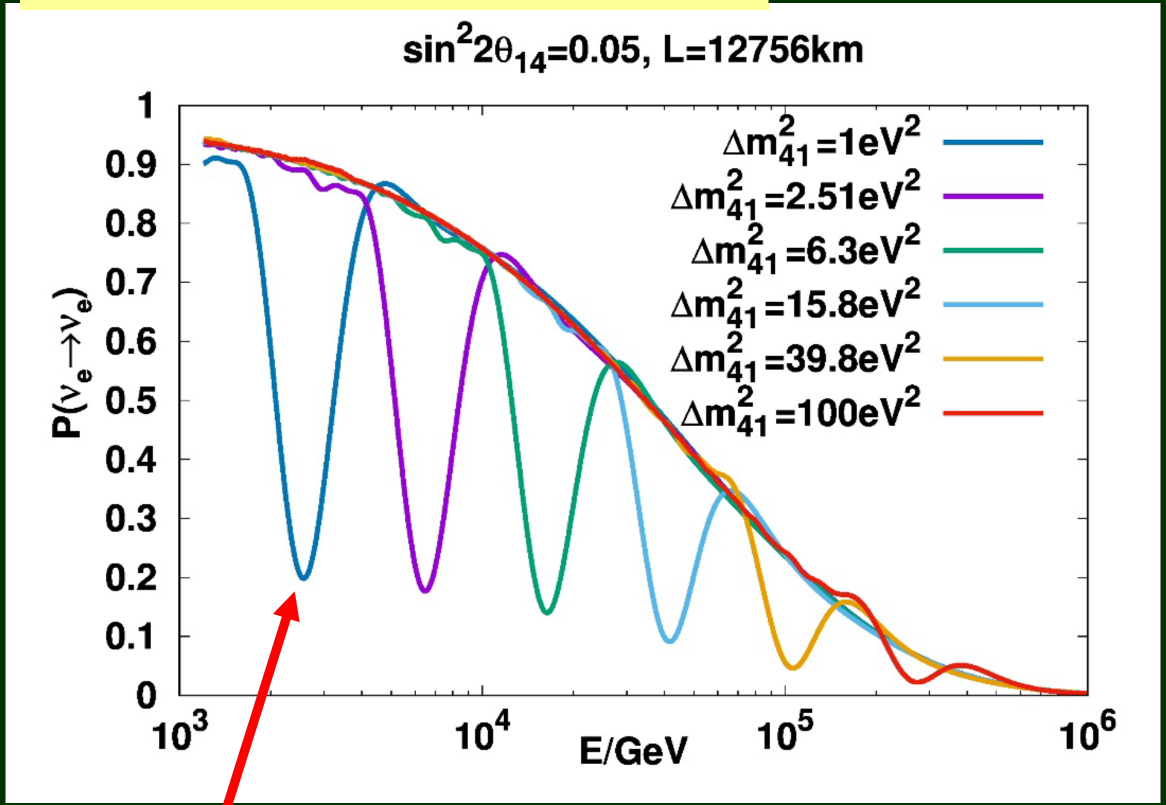
$(\epsilon^u_D, \epsilon^u_N) = (-0.140, -0.030)$

$(\epsilon^d_D, \epsilon^d_N) = (-0.145, -0.036)$

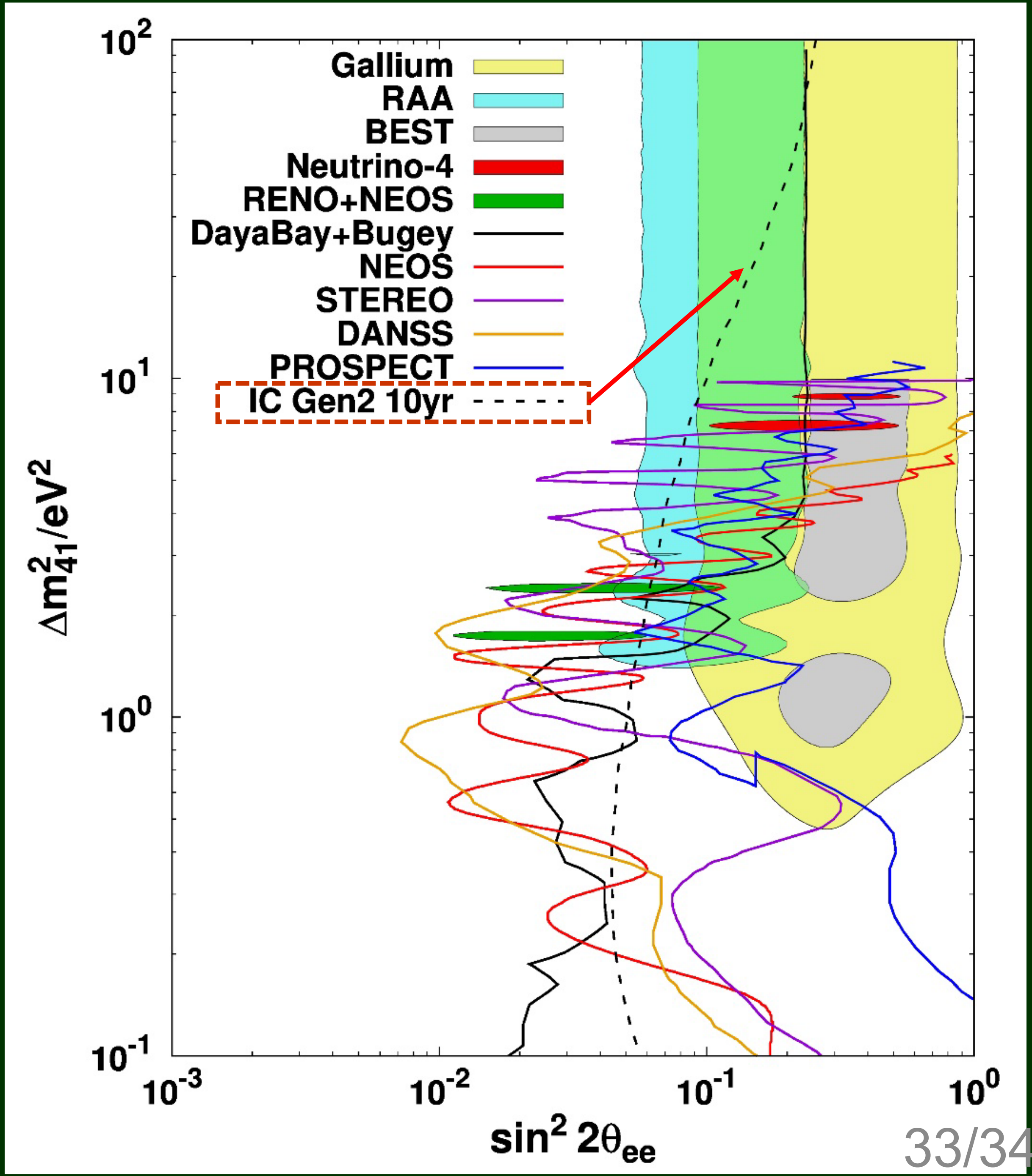
In the case of IO, DUNE is the best

●Future extension of the IceCube experiment (Gen2)

Wang & OY, arXiv:2110.12655



For 1eV^2<Δm^2<100 eV^2, ν_s can be probed by looking for a dip in atmospheric ν_e



5. Summary

1. The standard 3 flavor scenario explains most of the ν experiments, but there are several indications for deviation from the standard 3 flavor scenario:

- Tension between Δm^2 of solar and Δm^2 of KamLAND -> NSI, ν_s?
- LSND/MiniBooNE anomaly -> ν_s?
- Reactor ν anomaly -> ν_s?
- Gallium anomaly -> ν_s?

2. Among ν_s scenarios, (2+2)-scheme is dead, while (3+1)-scheme is in tension. -> Each channel $\nu_e \to \nu_e$, $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$ should be checked experimentally and phenomenologically.
3. NSI may be probed in future experiments.

Backup slides

Tiny neutrino mass

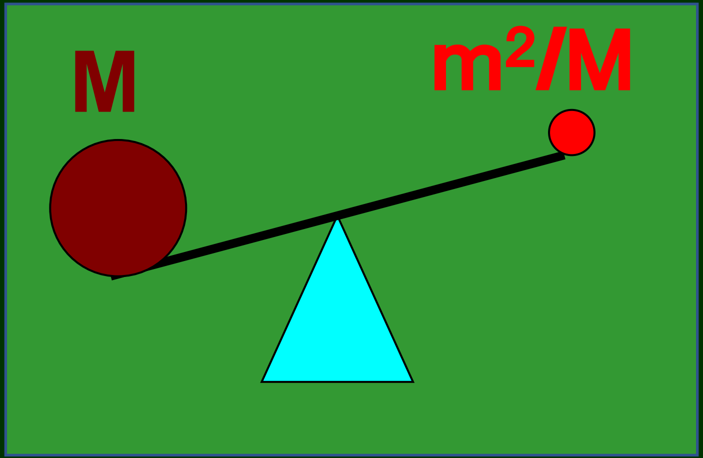
Seesaw mechanism

1977 Minkowski; 1979 Yanagida; 1979 Gell-Mann, Ramond, Slansky

$$\left(\overline{(\nu_L)^c},\ \bar{\nu}_R\right)\underbrace{\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}}_{\simeq\, U\,\mathrm{diag}(-m^2/M,\, M)\, U^{-1}}\begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix} + h.c.$$

$$U \simeq \begin{pmatrix} 1 & m/M \\ -m/M & 1 \end{pmatrix}$$

If m=1GeV and m^2/M gives m_ν,
then $m_\nu = m^2/M \sim 0.05$ eV
$\rightarrow$ $M \sim 10^{10}$GeV



Tiny ν mass may be a hint for new physics at high energy

The results of 3ν fit by 3 groups more or less seem to agree with each other

arXiv	2111.03086 (NuFIT)		2107.00532 (Bari)		2006.11237 (Valencia)	
NO	Best Fit Ordering		Best Fit Ordering		Best Fit Ordering	
Param	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}/10^{-1}$	$3.04^{+0.12}_{-0.12}$	$2.69 \to 3.43$	$3.03^{+0.13}_{-0.13}$	$2.63 \to 3.45$	$3.18^{+0.16}_{-0.16}$	$2.71 \to 3.69$
$\theta_{12}/^\circ$	$33.5^{+0.8}_{-0.8}$	$31.3 \to 35.9$	$33.4^{+0.8}_{-0.8}$	$30.9 \to 36.0$	$34.3^{+1.0}_{-1.0}$	$31.4 \to 37.4$
$\sin^2\theta_{23}/10^{-1}$	$4.50^{+0.19}_{-0.16}$	$4.08 \to 6.03$	$4.55^{+0.18}_{-0.15}$	$4.16 \to 5.99$	$5.74^{+0.14}_{-0.14}$	$4.34 \to 6.10$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$42.4^{+1.0}_{-0.9}$	$40.2 \to 50.7$	$49.3^{+0.8}_{-0.8}$	$41.2 \to 51.3$
$\sin^2\theta_{13}/10^{-2}$	$2.25^{+0.06}_{-0.06}$	$2.06 \to 2.44$	$2.23^{+0.07}_{-0.06}$	$2.04 \to 2.44$	$2.20^{+0.07}_{-0.06}$	$2.00 \to 2.41$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.59^{+0.13}_{-0.12}$	$8.21 \to 8.99$	$8.53^{+0.13}_{-0.12}$	$8.13 \to 8.92$
$\delta/^\circ$	230^{+36}_{-25}	$144 \to 350$	274^{+25}_{-27}	$139 \to 355$	194^{+24}_{-22}	$128 \to 359$
$\Delta m^2_{21}/10^{-5}$ eV^2	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.36^{+0.16}_{-0.15}$	$6.93 \to 7.93$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\Delta m^2_{\rm atm}/10^{-3}$ eV^2	$2.51^{+0.03}_{-0.03}$	$2.43 \to 2.59$	$2.49^{+0.02}_{-0.03}$	$2.40 \to 2.57$	$2.55^{+0.02}_{-0.03}$	$2.47 \to 2.63$

PDG2022, ν in cosmology

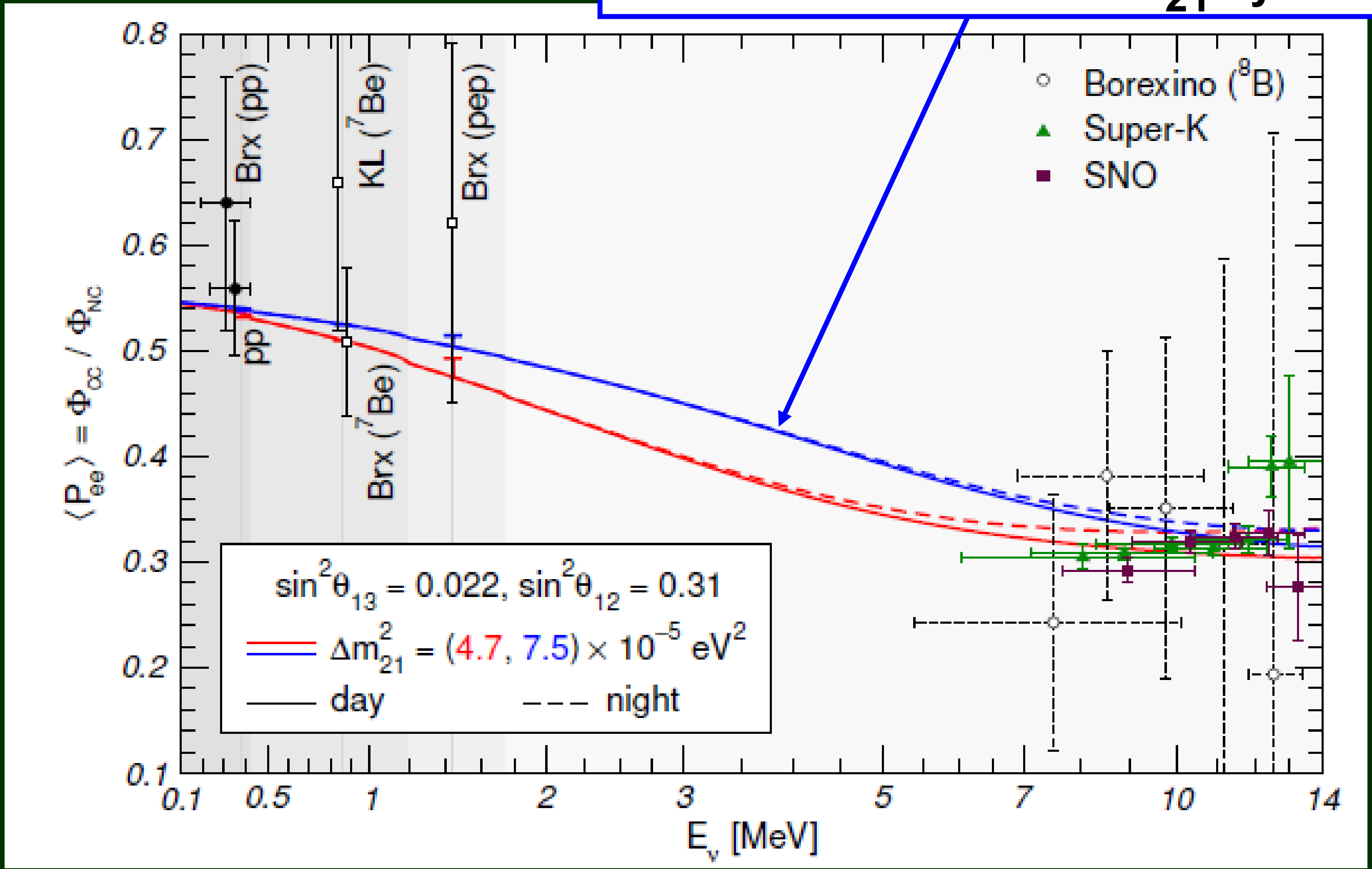
Table 26.2: Summary of $\sum m_\nu$ constraints.

	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[22]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[22]
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[43]
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	[23]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[22]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[22]
CMB + probes of background evolution + LSS			
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10	[43]
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087	[44]
Pl18[TT,TE,EE+lowE] + BAO + RSD + Pantheon + DES	ΛCDM+$\sum m_\nu$	< 0.13	[45]

- **Tension between solar ν & KamLAND data.**
  --> ν_s may be a solution for the tension

Maltoni, Smirnov, arXiv:1507.05287v2 [hep-ph]

Standard scenario w/ Δm^2_{21} by KamLAND



Terrestrial ν basis

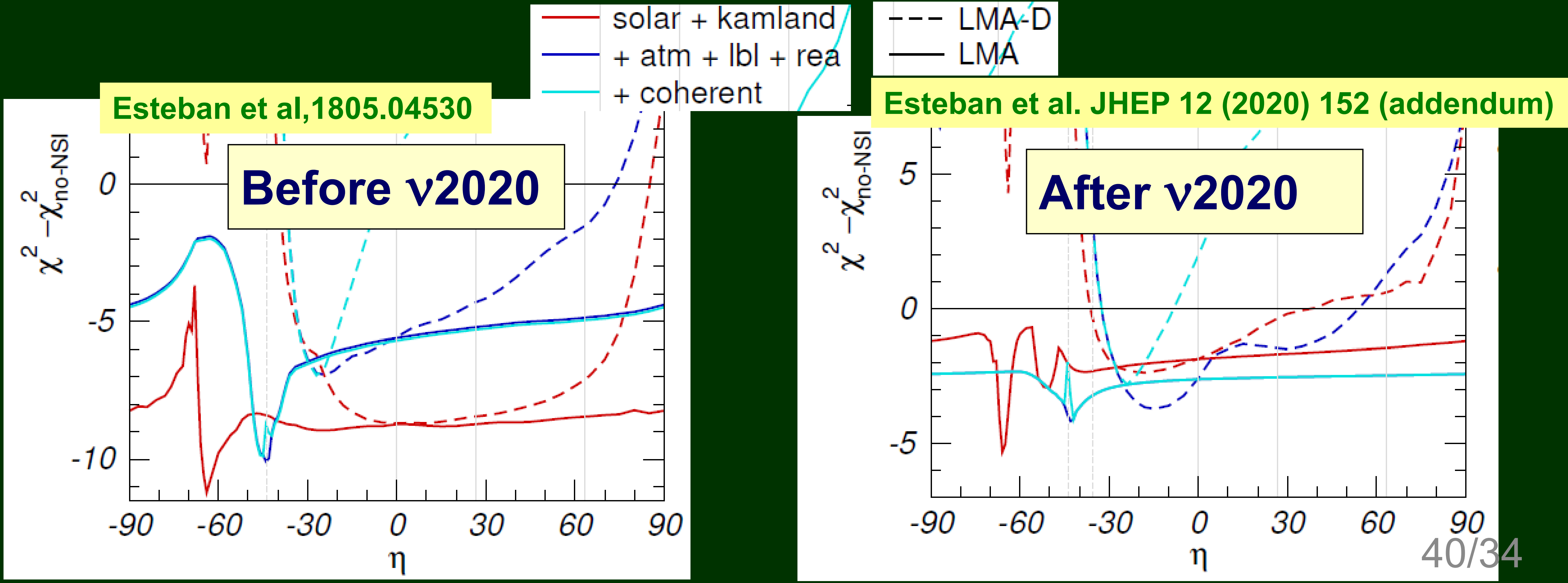
$$\varepsilon^{f}_{\alpha\beta} \equiv \varepsilon^{f,L}_{\alpha\beta} + \varepsilon^{f,R}_{\alpha\beta} = \varepsilon^{\eta}_{\alpha\beta}\,\xi^{f}$$

=0 is assumed

$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^{e}_{\alpha\beta} + \left(2+Y^{\oplus}_{n}\right)\varepsilon^{u}_{\alpha\beta} + \left(1+2Y^{\oplus}_{n}\right)\varepsilon^{d}_{\alpha\beta} = \left(\varepsilon^{e}_{\alpha\beta} + \varepsilon^{p}_{\alpha\beta}\right) + Y^{\oplus}_{n}\varepsilon^{n}_{\alpha\beta}$$

$$= \sqrt{5}\left(\cos\eta + Y^{\oplus}_{n}\sin\eta\right)\varepsilon^{\eta}_{\alpha\beta}$$

$$\xi^{u} = \frac{\sqrt{5}}{3}(2\cos\eta - \sin\eta) \qquad \xi^{d} = \frac{\sqrt{5}}{3}(2\sin\eta - \cos\eta)$$



3. Oscillation vs non-oscillation experiments

- **neutrino oscillation**

  $\Delta m^2_{jk} = m^2_j - m^2_k$

- **neutrinoless double beta decay**

  $m_{ee} = |\Sigma (U_{ej})^2 m_j \exp(i\phi_j)|$

  Majorana phases

  Only when ν has Majorana mass

- **direct measurement**

  $m_\beta = (\Sigma |U_{ej}|^2 m^2_j)^{1/2}$

- **cosmology**

  Σm_j

ν mass terms

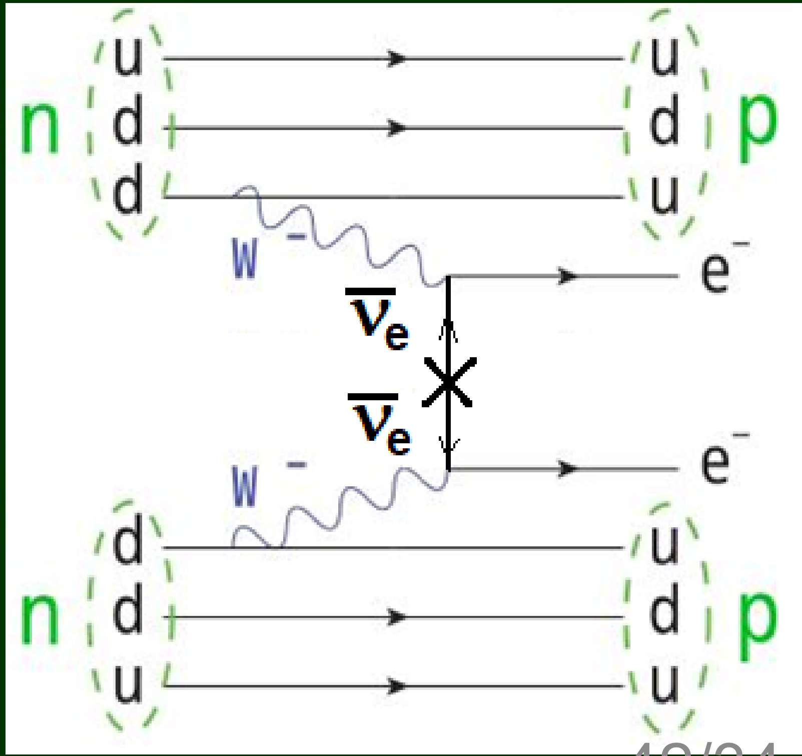
- **Dirac mass** $\mathcal{L}_D = m\,\bar{\nu}_R\,\nu_L + h.c.$
- **Majorana mass** $\mathcal{L}_M = m\,\overline{(\nu_L)^c}\,\nu_L + h.c. = m\,\bar{\nu}_M\,\nu_M$

$(\nu_L)^c \equiv C\bar{\nu}^T$ $\quad \nu_M \equiv \nu_L + (\nu_L)^c = (\nu_M)^c$

At present it is unknown whether ν mass is of Dirac or Majorana type

→ ν oscillation experiments cannot tell the difference

→ Discovery of neutrinoless double beta decay (lepton number violating process) would prove that ν mass is of Majorana type



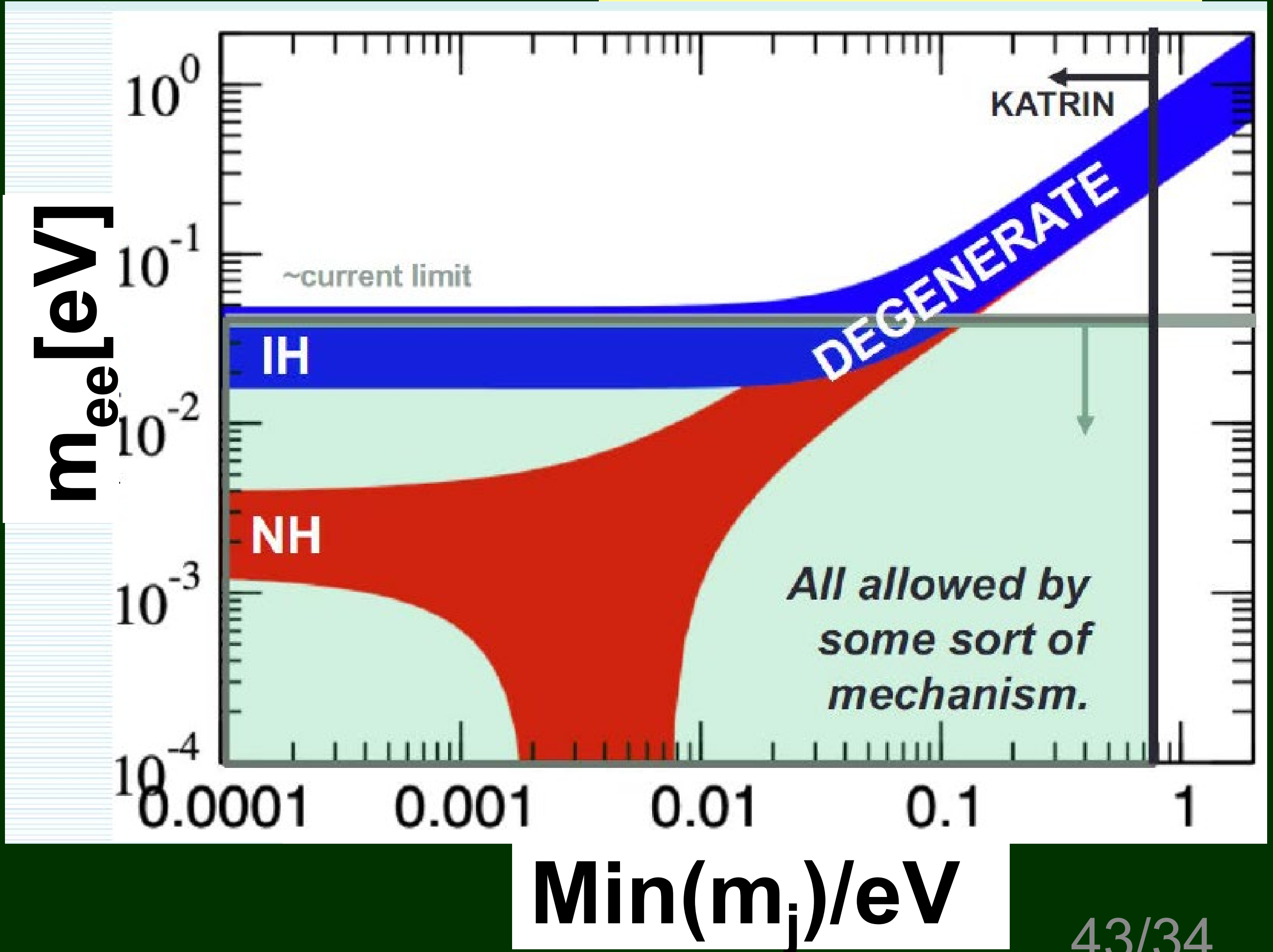
● Neutrinoless double beta decay

$m_{ee}=|\Sigma(U_{ej})^2 m_j \exp(i\phi_j)|$

Experiment	Isotope	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	79-180
Majorana	^{76}Ge	200-433
CUPID-0	^{82}Se	276-570
NEMO3	^{100}Mo	620-1000
CUPID-Mo	^{100}Mo	280-490
Amore	^{100}Mo	1200-2100
CUORE	^{130}Te	90-305
EXO-200	^{136}Xe	93-286
KamLAND-Zen	^{136}Xe	36-156

Future experiments	isotope	$m_{\beta\beta}$ [meV] 90% excl. sensitivity	$m_{\beta\beta}$ [meV] 3 σ discovery potential
Legend	^{76}Se	8.2	11.1
CUPID	^{100}Mo	11.1	12.0
nEXO	^{136}Xe	12.9	15.0

Simkovic@Neutrino2022



● Direct measurement

$m_\nu = (\Sigma |U_{ej}|^2 m^2_j)^{1/2}$

Lasserre@Neutrino2022

KATRIN

First campaign (spring 2019):

✓ total statistics: 2 million events

✓ best fit: $m_\nu^2 = (-1.0^{+0.9}_{-1.1})$ eV² (stat. dom.)

✓ limit: $m_\nu < 1.1$ eV (90% CL)

Second campaign (autumn 2019):

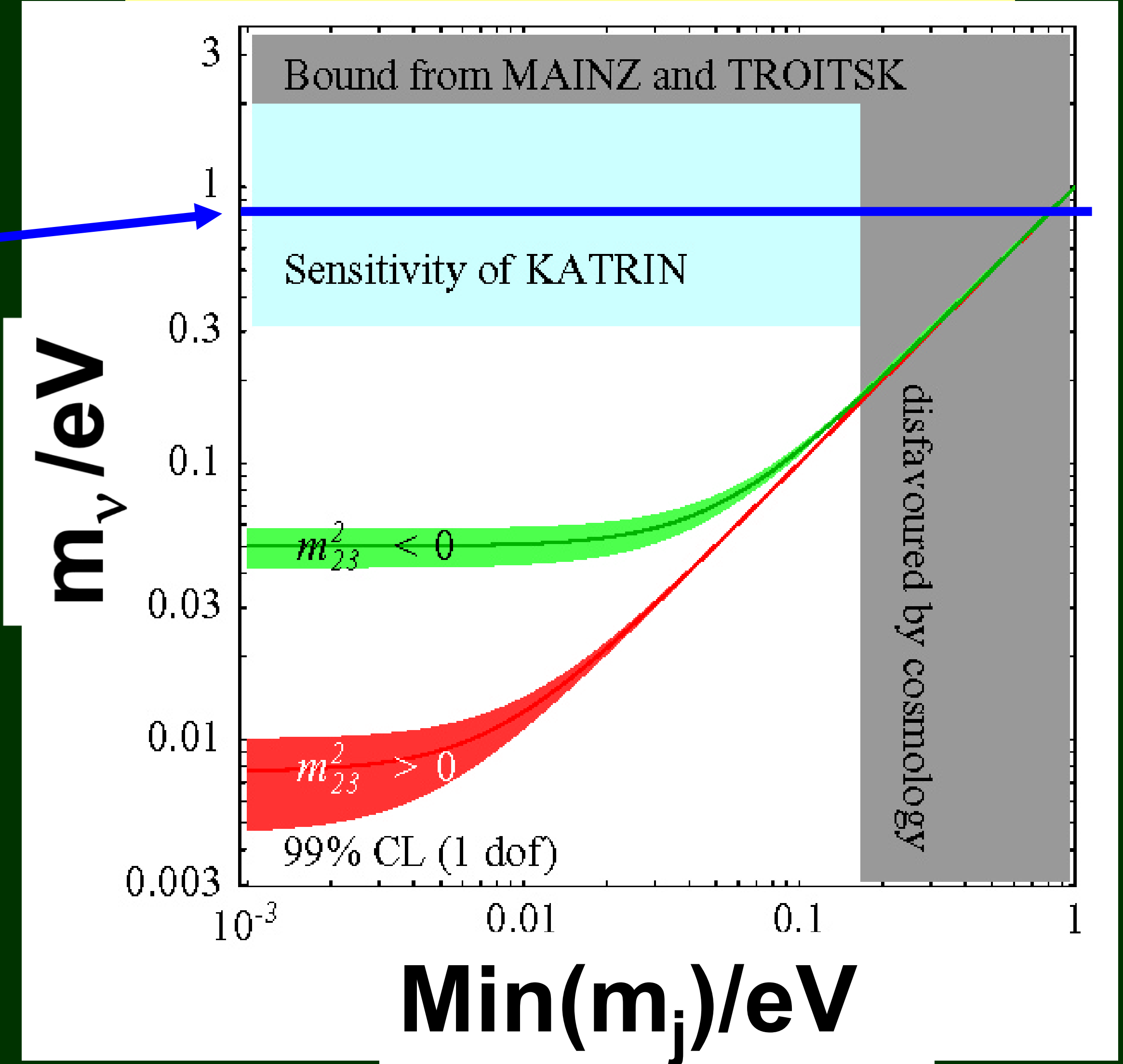
✓ total statistics: 4.3 million events

✓ best fit: $m_\nu^2 = (0.26^{+0.34}_{-0.34})$ eV² (stat. dom.)

✓ limit: $m_\nu < 0.9$ eV (90% CL)

Combined result: $m_\nu < 0.8$ eV (90% CL)

Strumia-Vissani: hep-ph/0606054



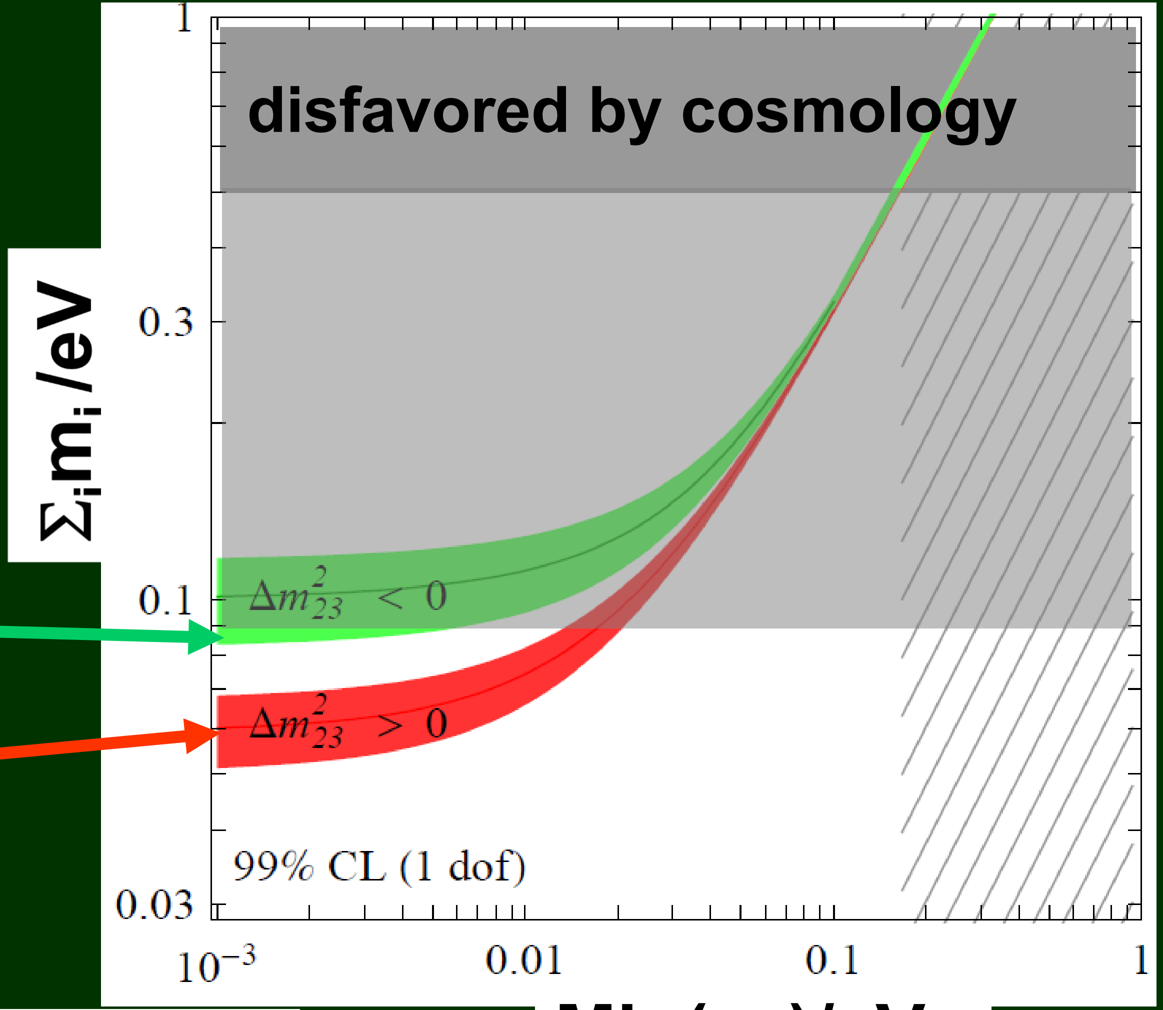
● Cosmology

Σm_j

Σm_j <0.1eV (PDG22)

$$\sum_j m_j(IO) = \sqrt{m_3^2 + |\Delta m_{31}^2|} + \sqrt{m_3^2 + |\Delta m_{31}^2| + \Delta m_{21}^2} + m_3$$

$$\sum_j m_j(NO) = m_1 + \sqrt{m_1^2 + \Delta m_{21}^2} + \sqrt{m_1^2 + \Delta m_{31}^2}$$



PDG2022, ν in cosmology

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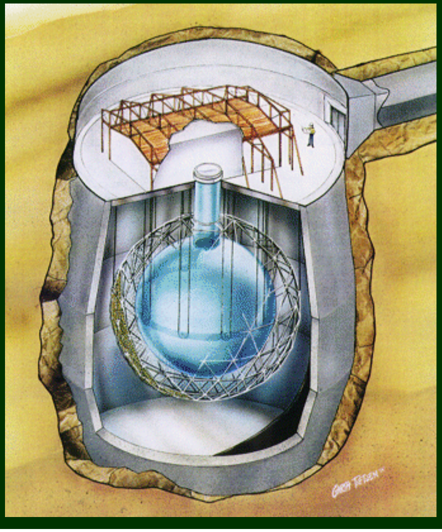
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087	[44]
Pl18[TT,TE,EE+lowE] + BAO + RSD + Pantheon + DES	ΛCDM+$\sum m_\nu$	< 0.13	[45]

SNO (Sudbury Neutrino Observatory, 1999-2006)



- Detector w/ heavy water(1kt)

D_2O, d=(pn), deutron

- Underground laboratory (〜2km) (To reduce BackGround)

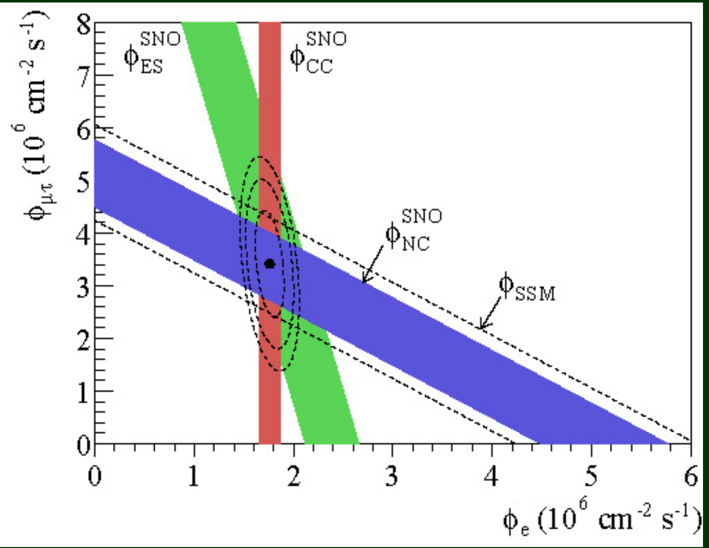
- Direct proof for solar ν deficit

SNO can detect the both reactions:

$\nu_e + d \rightarrow p + p + e^-$ ➡ only for ν_e

$\nu_x + d \rightarrow p + n + \nu_x$ ➡ for all ν_x

x=e,μ,τ



From the data of these 2 reactions, it was concluded that $\nu_e + \nu_\mu + \nu_\tau$ agrees w/ theory, but ν_e is less than theory

ν_{atm} (upward going μ): $\nu_\mu \rightarrow \nu_\tau$ vs $\nu_\mu \rightarrow \nu_s$

SK, hep-ex/0009001