# LIGHT STERILE NEUTRINO
# AND
# MASS OBSERVABLES

Based on $Phys.Rev.D$ 110 (2024)1,015028

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భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
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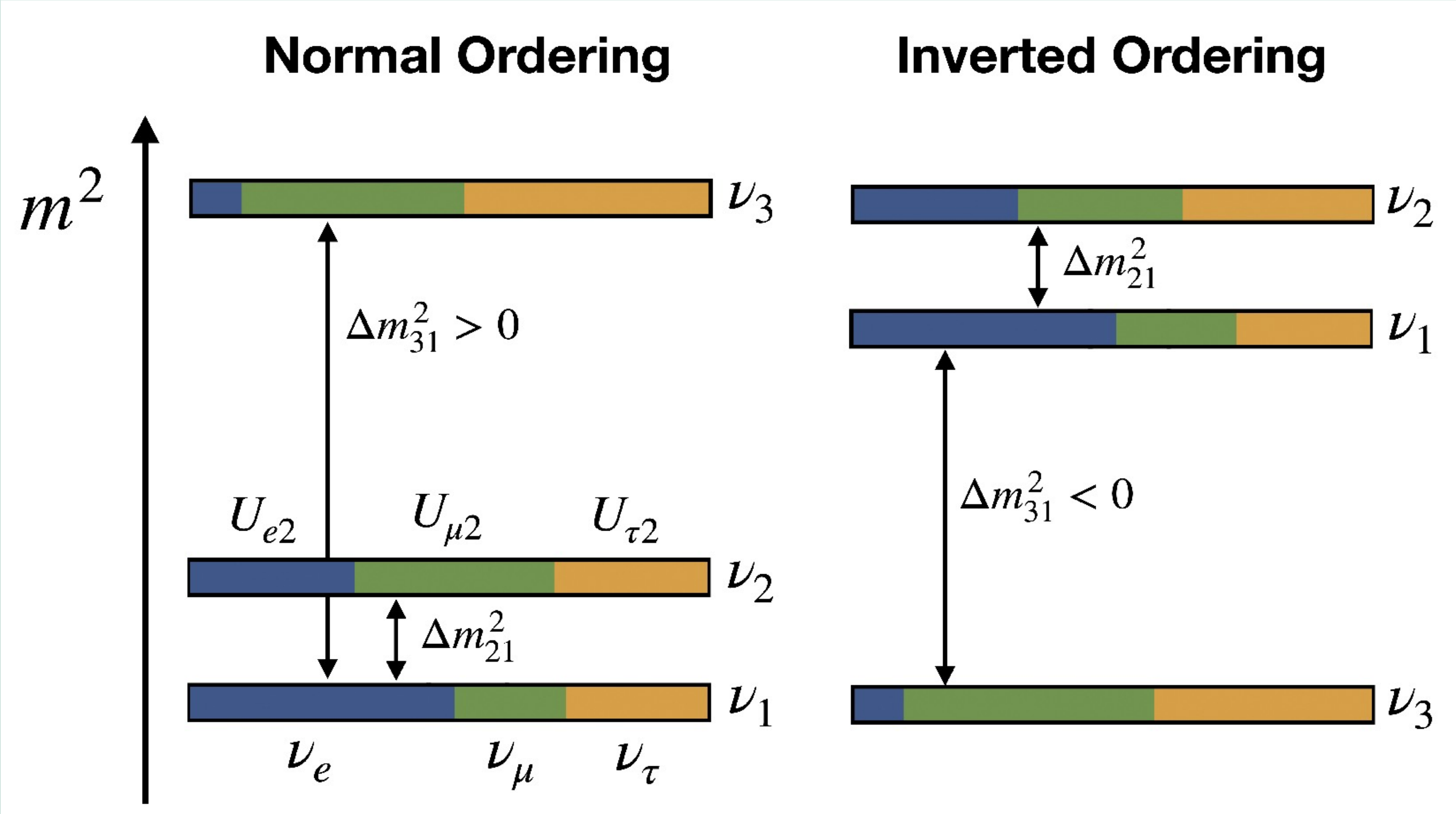
# Outline

- Introduction
- Motivation
- Possible mass spectra for 3+1 scenario
- Effect of an extra light sterile state on mass-related observables
- Conclusion

# 3 flavor Framework

$$|\nu_i\rangle = U_{i\alpha}\,|\nu_\alpha\rangle$$



- The mixing matrix is described by three angles $(\theta_{12}, \theta_{13}, \theta_{23})$ , one Dirac phase $(\delta_{13})$ and two Majorana phases $(\alpha, \beta)$

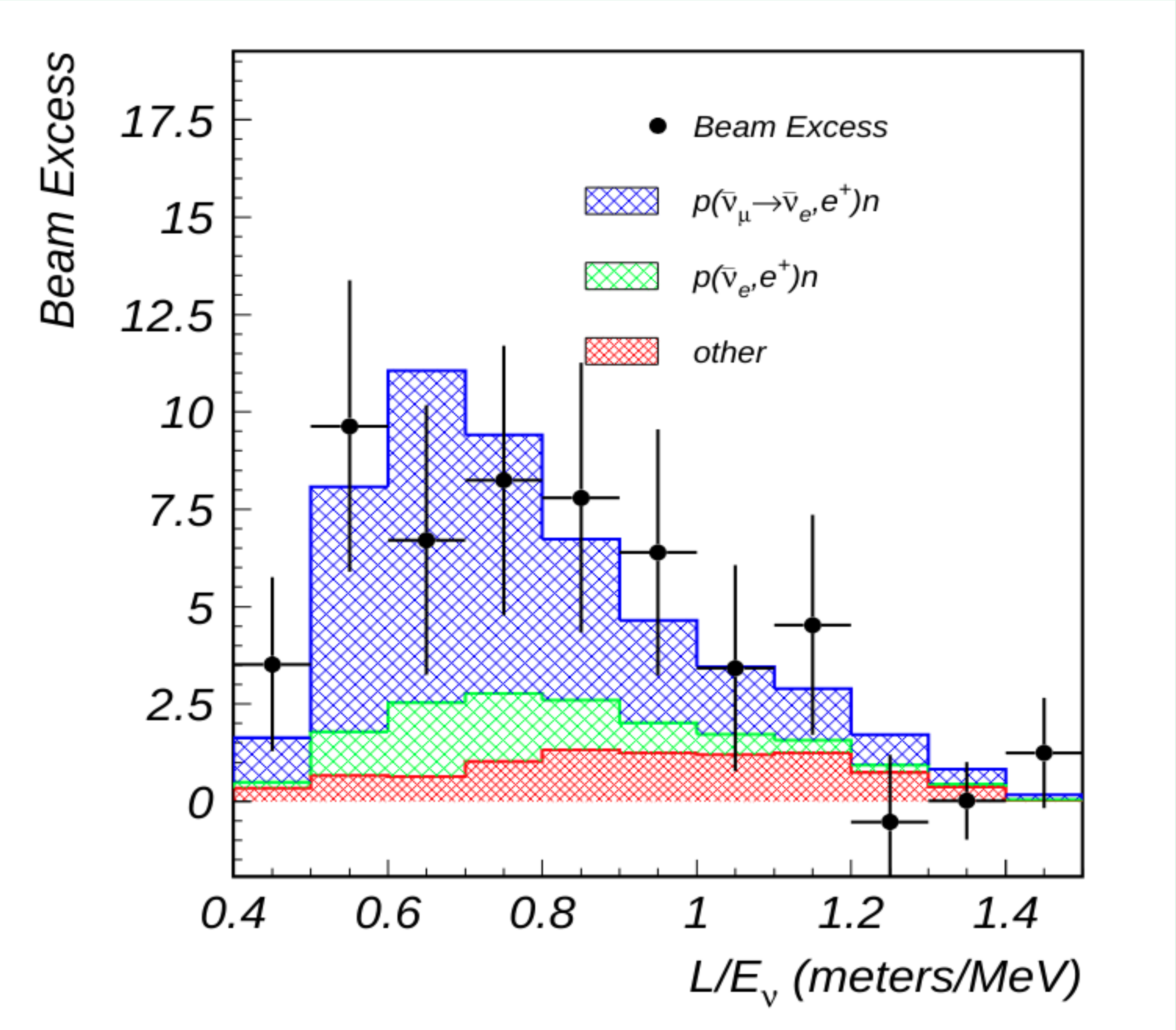
$$\boxed{U_{PMNS} = \mathbb{R}_{23}(\theta_{23})\,\mathbb{S}_{13}(\theta_{13}, \delta_{13})\,\mathbb{R}_{12}(\theta_{12})\;\mathbb{P}} \longrightarrow \mathbb{P} = \mathrm{diag}(1, e^{i\alpha}, e^{i\beta})$$

- Known in Standard Picture (Nufit 5.3, 2024)
- $\Delta m^2_{21} = (6.82 - 8.04) \times 10^{-5}\, eV^2$
- $|\Delta m^2_{3l}| = (2.42 - 2.59) \times 10^{-2}\, eV^2$
- $\sin^2\theta_{12} = (0.275 - 0.344)$
- $\sin^2\theta_{13} = (0.023 - 0.024)$
- $\sin^2\theta_{23} = (0.407 - 0.620)$

- Unknown in Standard Picture
- $\theta_{23}$ octant : $\theta_{23} > 45^\circ$ / $\theta_{23} < 45^\circ$
- Mass ordering : $\Delta m^2_{31} > 0$ / $\Delta m^2_{31} < 0$
- Value of CP phase $(\delta_{CP}) = \delta_{13}$
- Absolute mass scale
- Dirac/Majorana

# (light) sterile neutrino

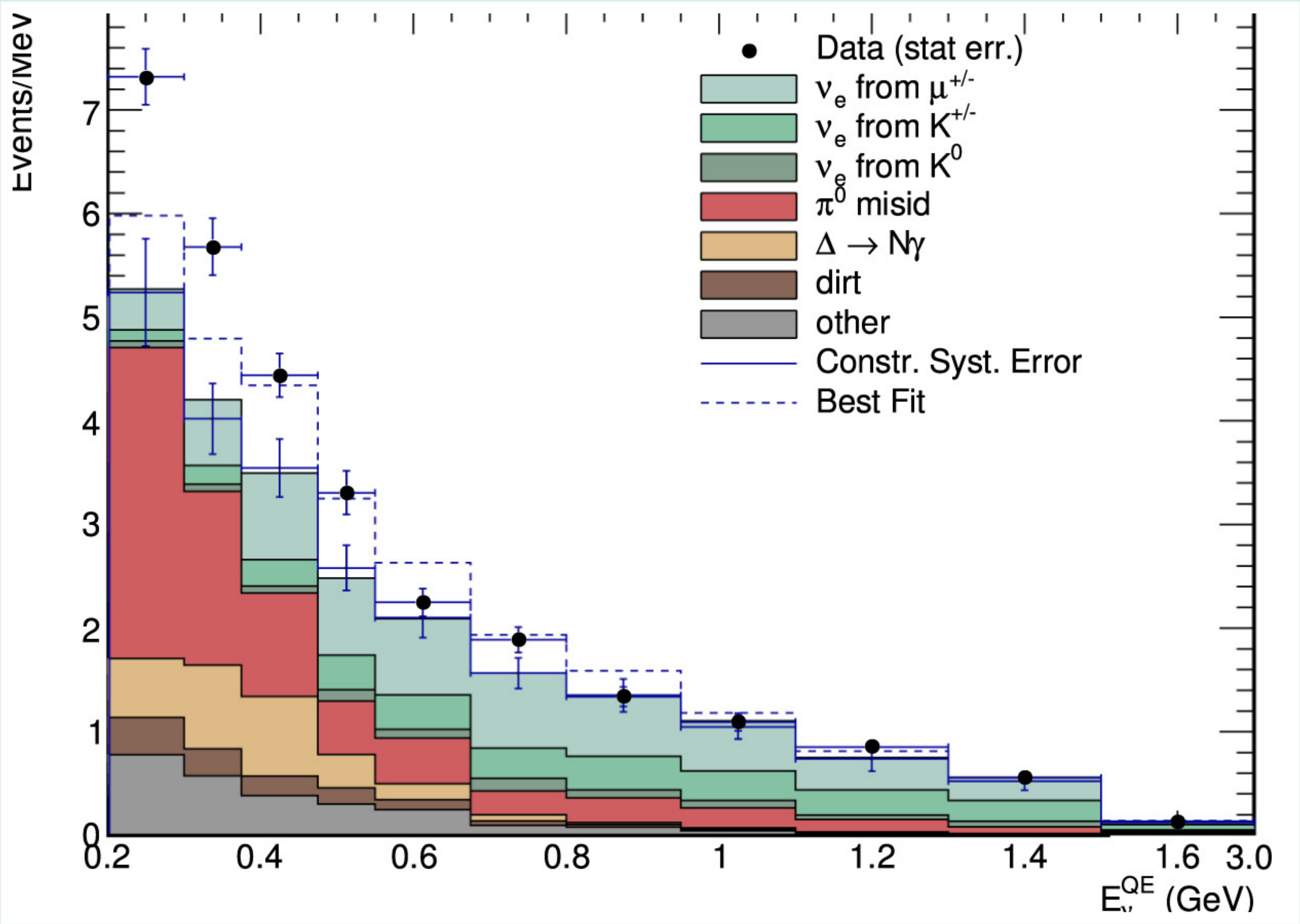
## LSND



$\bar{\nu}_\mu \to \bar{\nu}_e$ at 3.8$\sigma$ (C. Athanassopoulos et al , PRL 1995)

L: 30 m; 20 MeV< E < 52.8 MeV

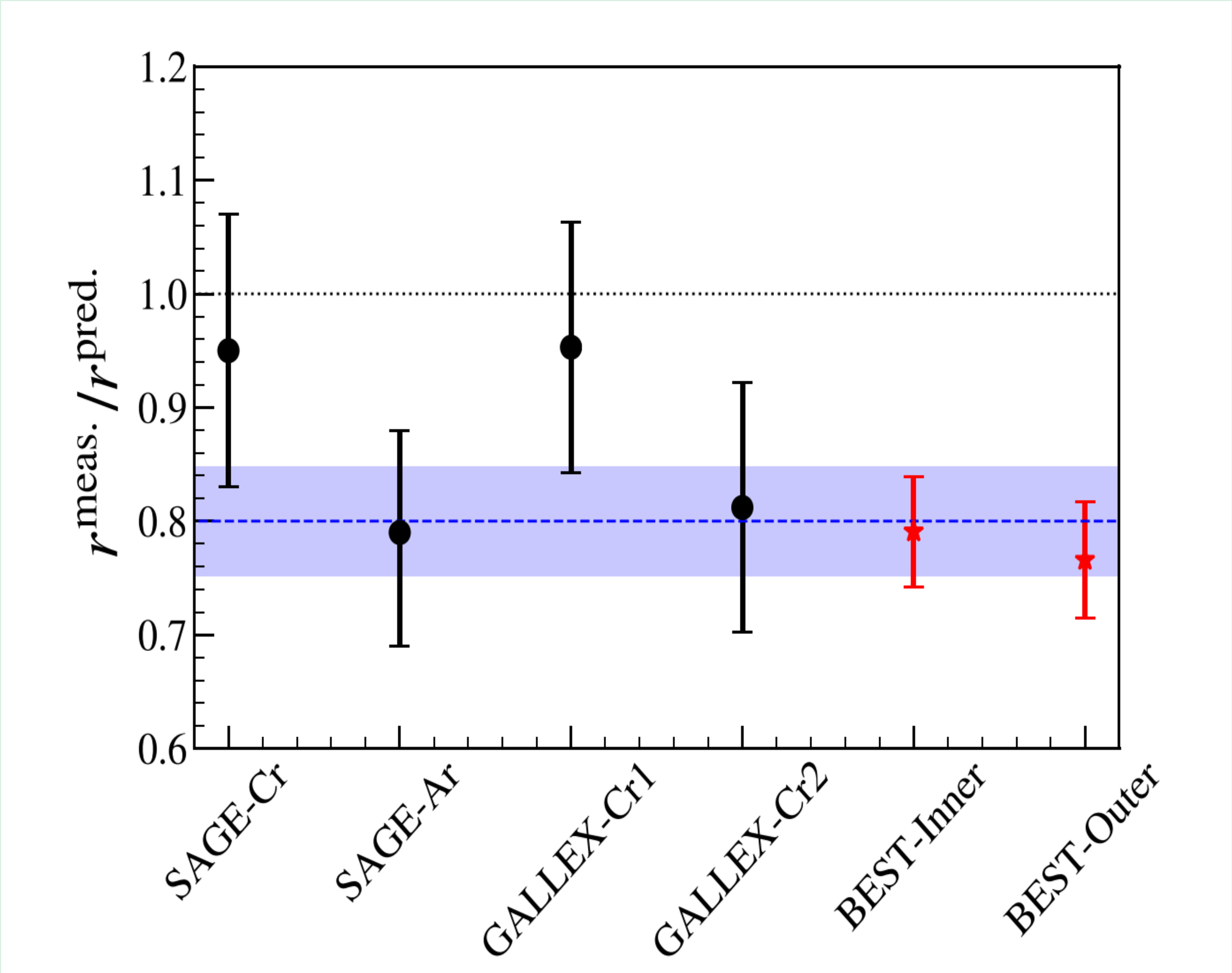
## MiniBooNE



$\nu_\mu \to \nu_e$ at 4.8$\sigma$ (Aguilar-Arevalo et al.,PRL,2009)

L:540 m; 200 MeV< E <3 GeV

## Gallium Anomaly



Deficit in $\nu_e$ at GALLEX, SAGE, BEST (Barinov et al.,2021)

L/E $\sim$ 1 suggests $\Delta m^2 \sim 1\text{eV}^2$

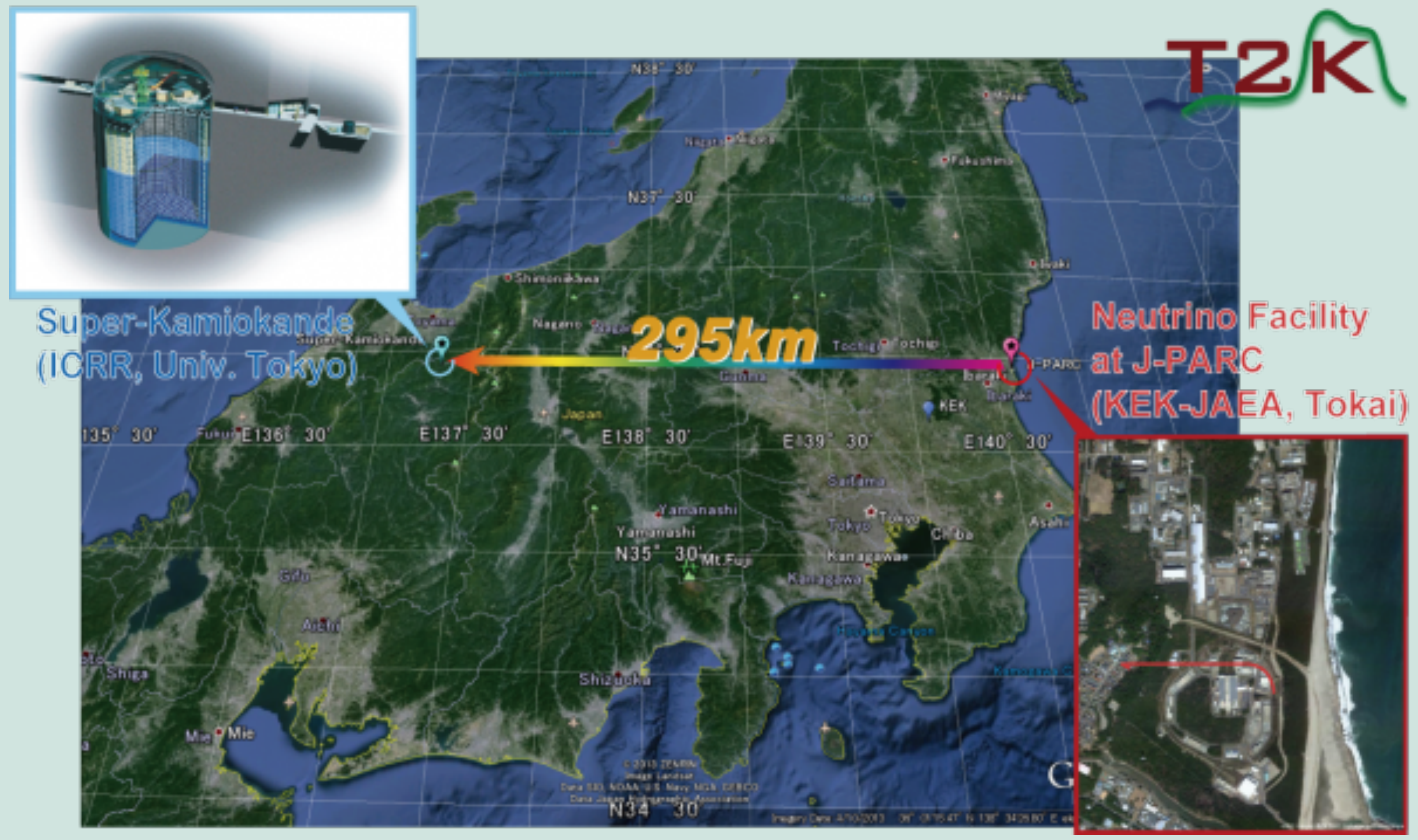
Presence of a sterile neutrino with $\Delta m^2 \sim$ eV$^2$ can explain these.

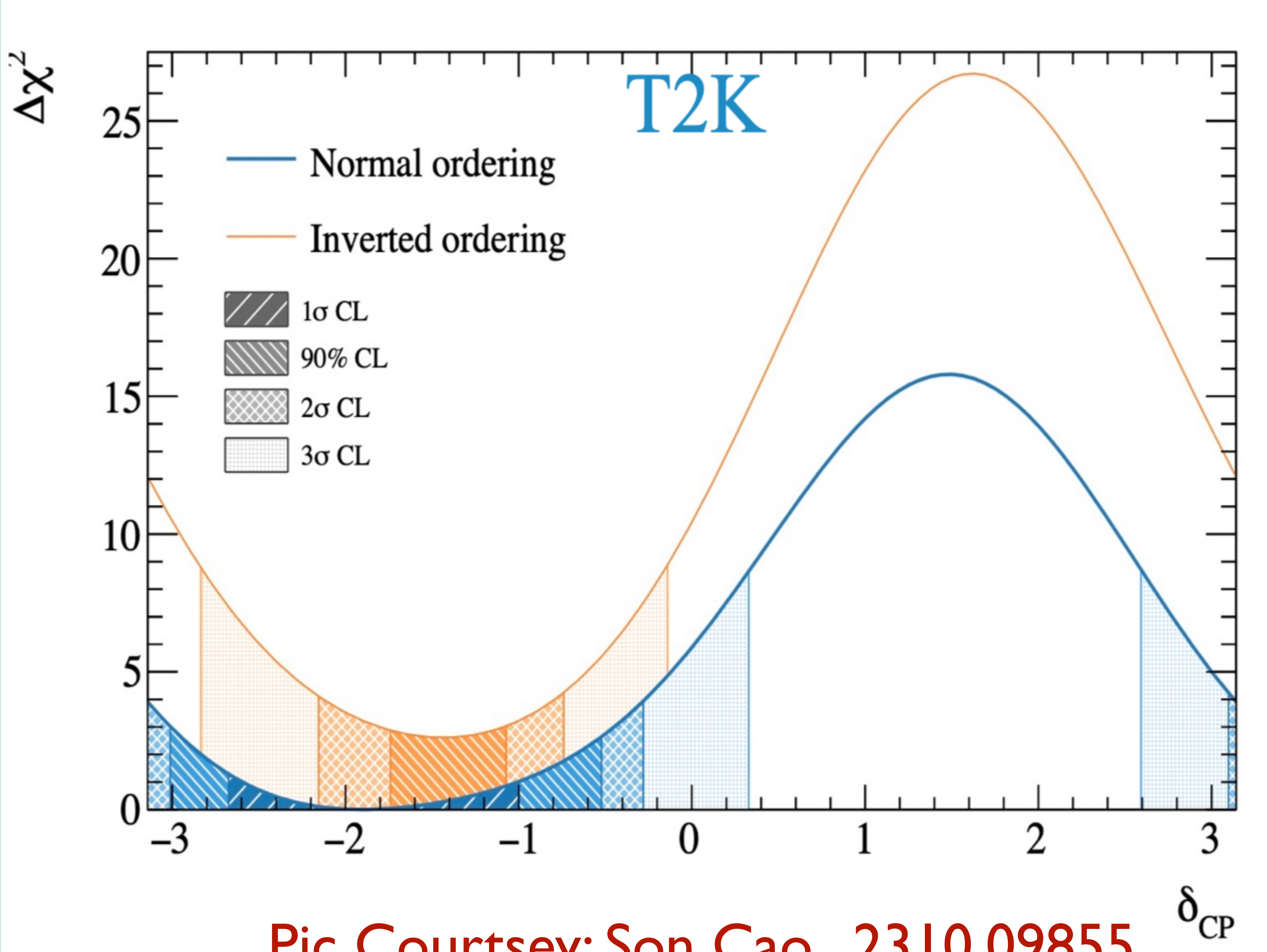
# (very light) sterile neutrino

- Long Baseline Experiments :

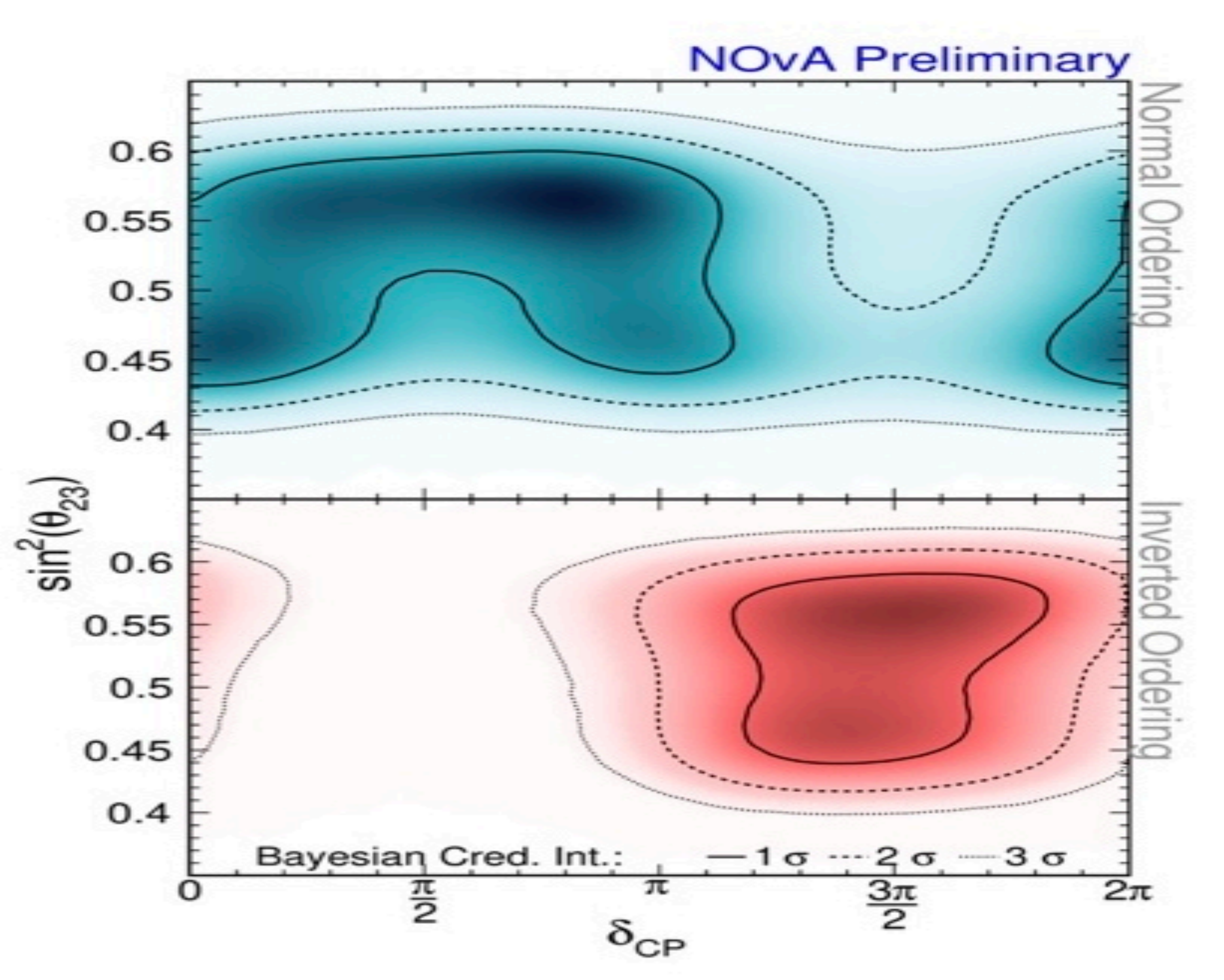
  T2K : L=295 KM , E=0.7 GeV

  NO$\nu$A: L=810 KM, E=2.0 GeV





Pic Courtsey: Son Cao , 2310.09855



- T2K, NO$\nu$A tension can be improved with introduction of $\Delta m^2_{41} = 10^{-2} eV^2$ sterile neutrino

( de Gouvea et al. , PRD, 2022)

# (Ultra-light) sterile neutrino

- Borexino is a solar neutrino experiment in Gran Sasso, Italy

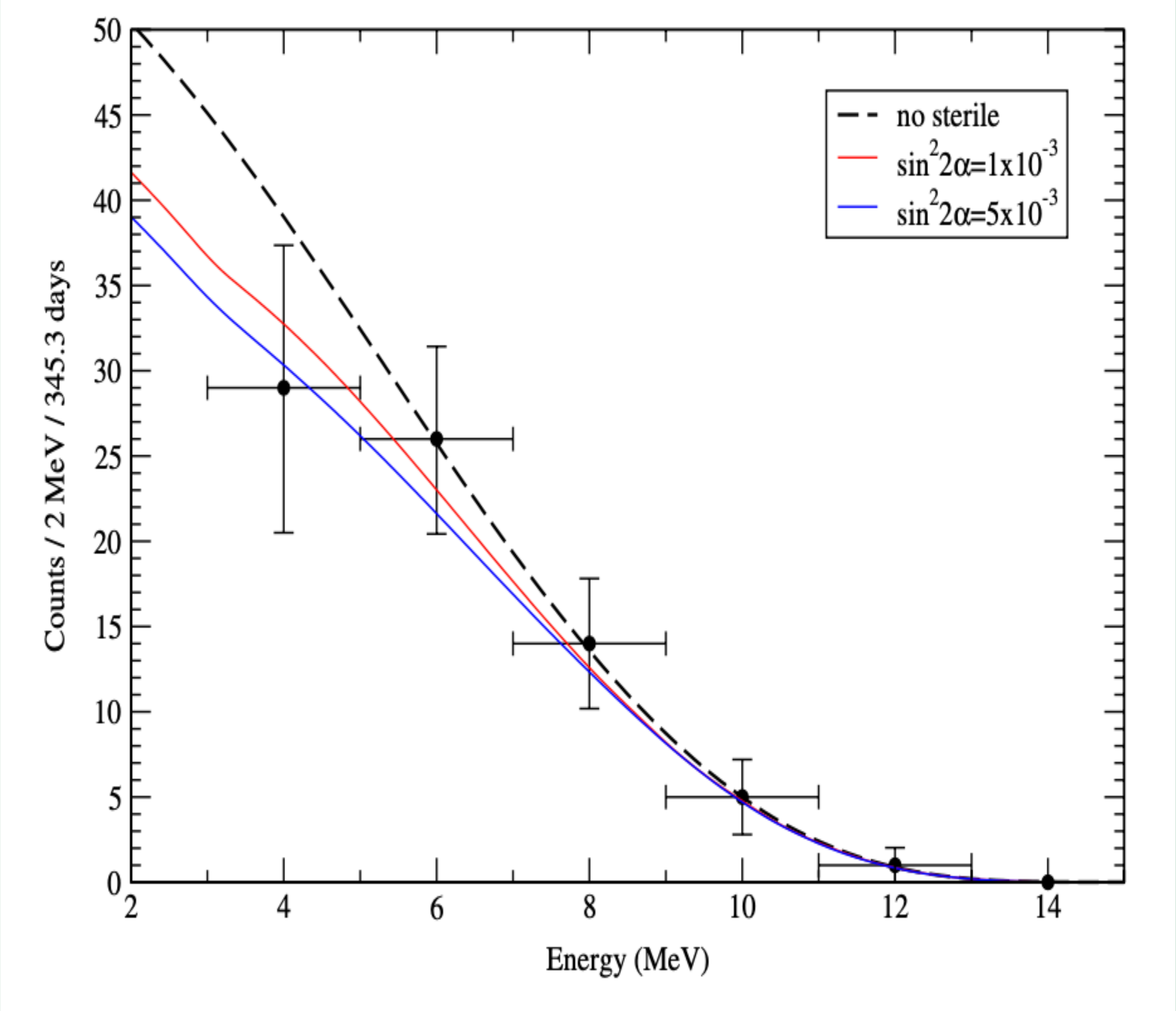
- Results from Borexino doesn't show signatures of upturn of energy spectrum below 8 MeV expected from MSW solution to the Solar Neutrino Problem. [Phys. Rev. C 81, 055504; Phys. Rev. D 82, 033006; Phys.Rev.D 83, 052010]

✓ Possible solution is extra sterile neutrino:

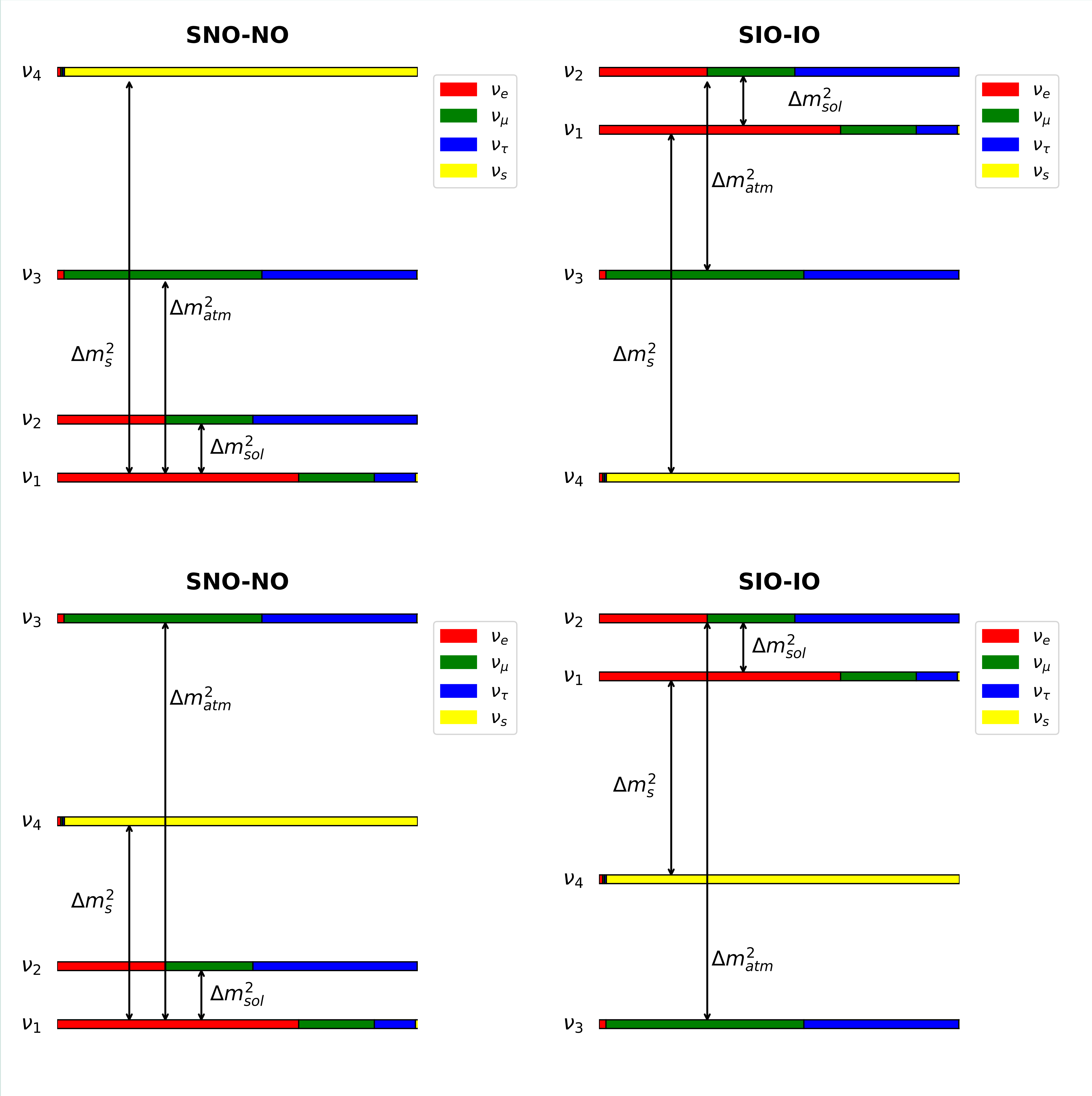
✓ $\Delta m_s^2 \sim 10^{-5}\,\mathrm{eV}^2$

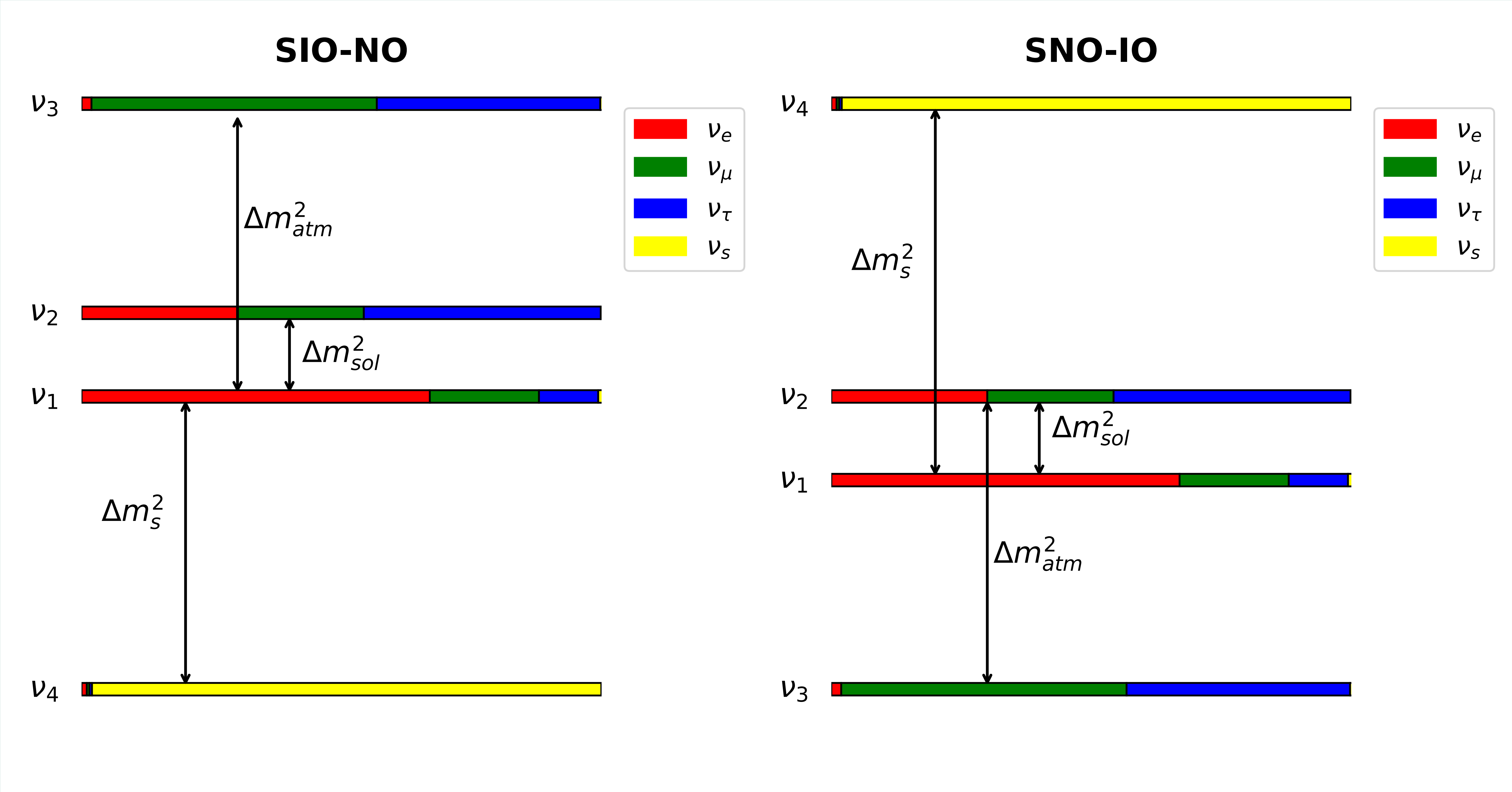
✓ Mixing with active states $\sin^2 2\alpha \sim 10^{-5} : 10^{-3}$

[PhysRevD. 83,113011]



# Mass Spectra of 3+1 framework





$$\Delta m^2_{sol} \simeq 7\times 10^{-5} eV^2\,,\quad \Delta m^2_{atm} \simeq 2.5\times 10^{-3} eV^2$$

$$\Delta m^2_s = 10^{-4}\mathrm{eV}^2, 0.01\,\mathrm{eV}^2\,, 1.3\,\mathrm{eV}^2$$

- SNO-NO and SIO-IO mass spectrum is different for $\Delta m^2_s > \Delta m^2_{atm}$ (left-above) and $\Delta m^2_{sol} < \Delta m^2_s < \Delta m^2_{atm}$ (left-below)
- SNO-IO and SIO-NO (right) spectrum is similar for both the cases

# 3+1 Framework

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \begin{pmatrix} u_{e1} & u_{e2} & u_{e3} & u_{e4}\\ u_{\mu1} & u_{\mu2} & u_{\mu3} & u_{\mu4}\\ u_{\tau1} & u_{\tau2} & u_{\tau3} & u_{\tau4}\\ u_{s1} & u_{s2} & u_{s3} & u_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

- 4×4 unitary matrix
- Parametrised by 6 angles, 3 Dirac phase and 4 Majorana Phase

$$U = \mathbb{R}_{34}(\theta_{34})\,\mathbb{S}_{24}(\theta_{24},\delta_{24})\,\mathbb{S}_{14}(\theta_{14},\delta_{14})\,\mathbb{R}_{23}(\theta_{23})\,\mathbb{S}_{13}(\theta_{13},\delta_{13})\,\mathbb{R}_{12}(\theta_{12})\,\mathbb{P}\ ,$$

$$u_{e1} = c_{12}^2\, c_{13}^2\, c_{14}^2$$

$$u_{e2} = s_{12}^2\, c_{13}^2\, c_{14}^2 e^{i\alpha}$$

$$u_{e3} = s_{13}^2\, c_{14}^2\, e^{i\beta}$$

$$u_{e4} = s_{14}^2\, e^{i\gamma}$$

## Mass Observable

**Cosmology:**

$\Sigma m_i < 0.12\, eV$ Plank Collaboration (2018)

**Direct Measurement**

$$m_\beta^2 = \sum_i \left|U_{ei}\right|^2 m_i^2 \qquad m_\beta \leq 0.8\,\mathrm{eV}$$

KATRIN Exp.
(Nat. Phys. 18,160-166 (2022)

**Neutrinoless Double Beta Decay**

$$m_{\beta\beta} = \sum U_{ei}^2 m_i \qquad m_{\beta\beta} \leq (28 - 122)\,\mathrm{meV}$$

arXiv : 2406.11438

# STERILE NEUTRINO AND COSMOLOGY

- Massless sterile neutrinos contribute to $N_{\rm eff}$
- Massive sterile neutrinos affect $N_{eff}$ and $\Sigma m_i$

$$\Delta N_{eff} = N_{eff} - \boxed{N_{eff}^{SM}} \rightarrow 3.044 \pm 0.002$$

- These parameter are bounded from cosmological observations like CMB, LSS, BBN etc

2203.07323

- 10 Parameter Cosmological Model

$$N_{\rm eff} = 3.11^{+0.37}_{-0.36}$$

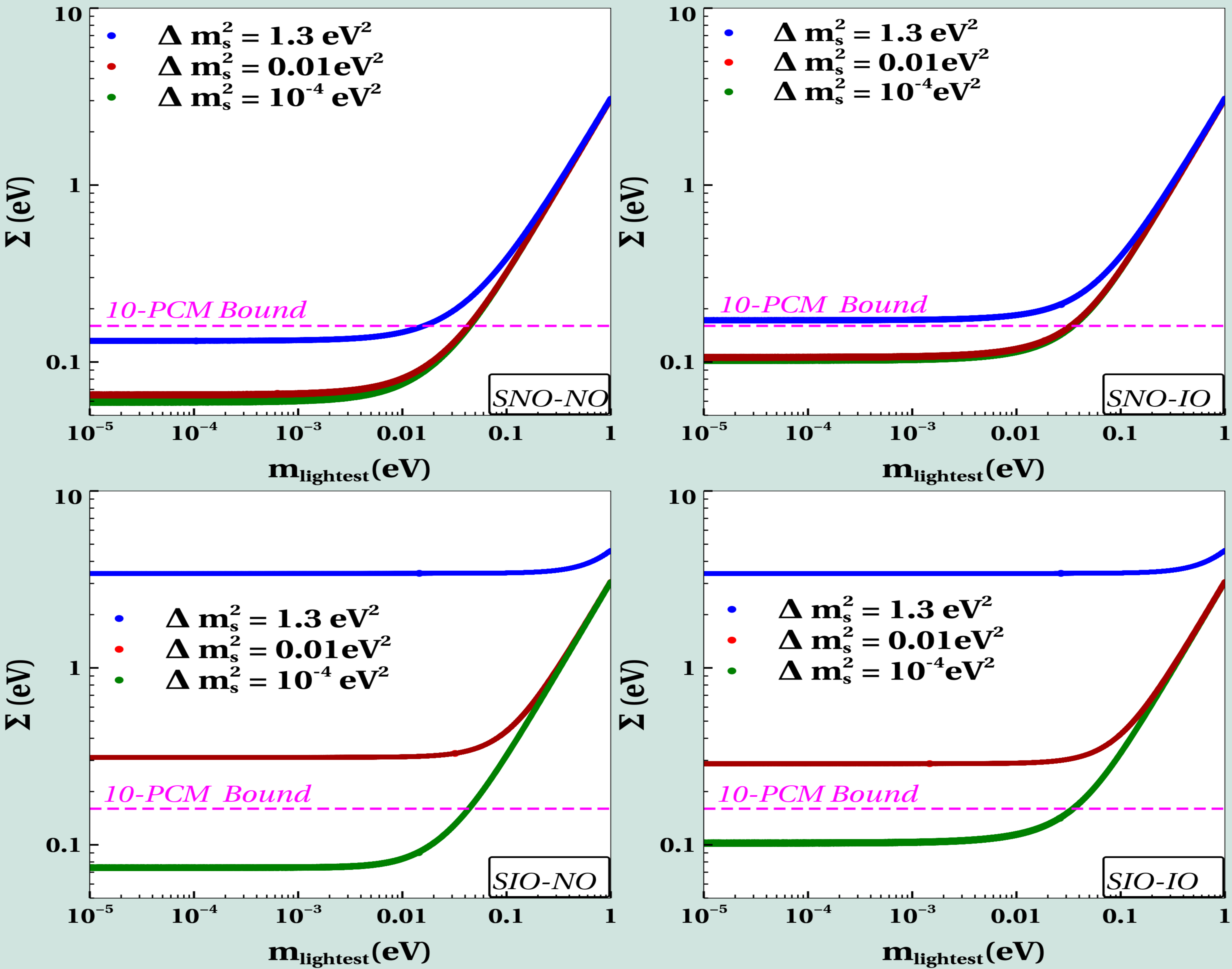
$$\Sigma m_i < 0.16\,{\rm eV}$$

- Fully thermalised neutrino $\Delta N_{\rm eff} \approx 1$ , ruled out by cosmological observations

- Can be evaded with secret interaction, low reheating temperature etc.

- Sterile state should have to be partially thermalized Hagstotz et al. , PRD , 2021

$$\Sigma m_i = m_1 + m_2 + m_3 + \left(m_4 \times \Delta N_{eff}\right)$$



- For SNO-NO

$$lightest \rightarrow m_1$$

$$m_2 = \sqrt{m_1^2 + \Delta m_{sol}{}^2}$$

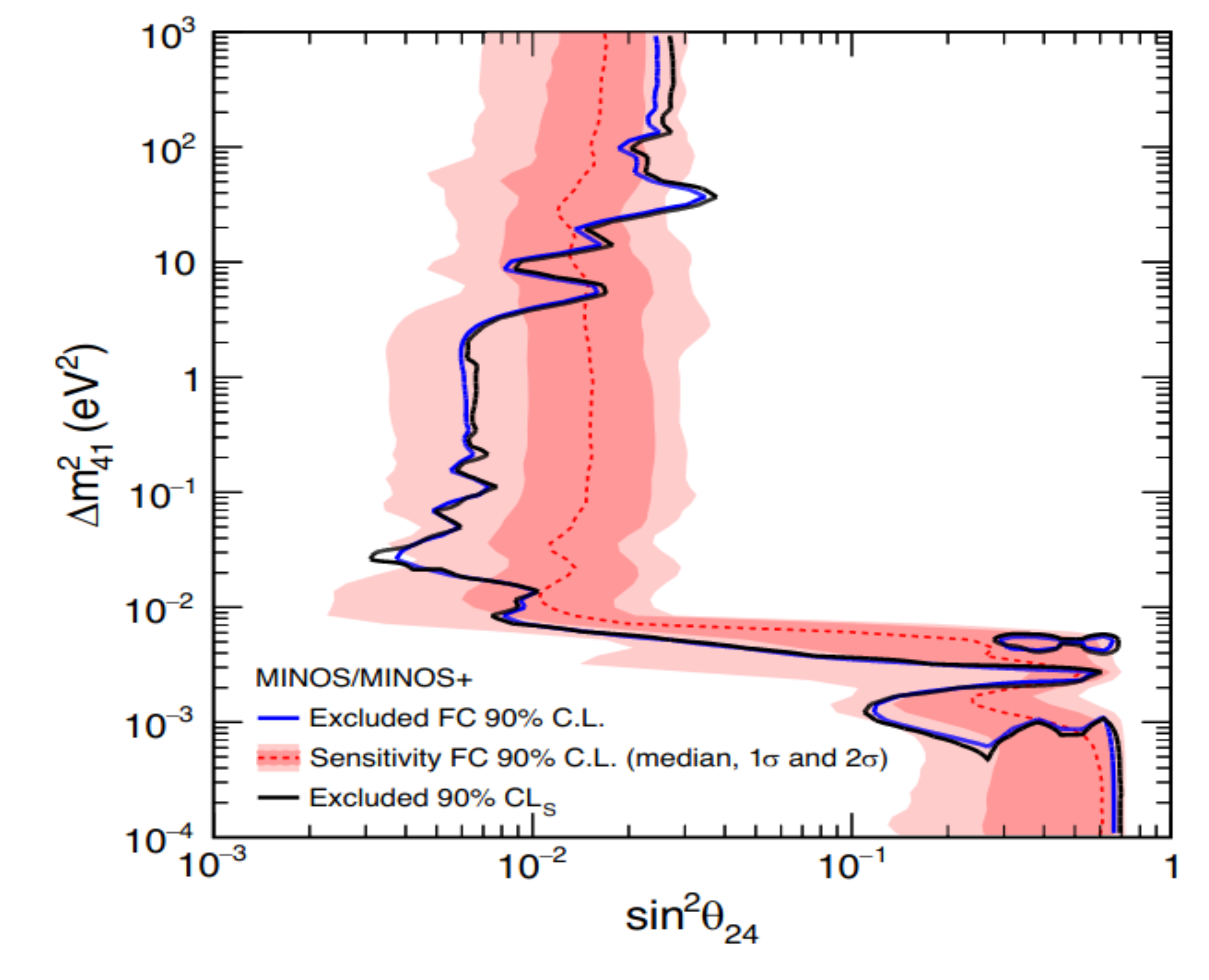
$$m_3 = \sqrt{m_1^2 + \Delta m_{atm}^2}$$

$$m_4 = \sqrt{m_1^2 + \Delta m_s^2}$$

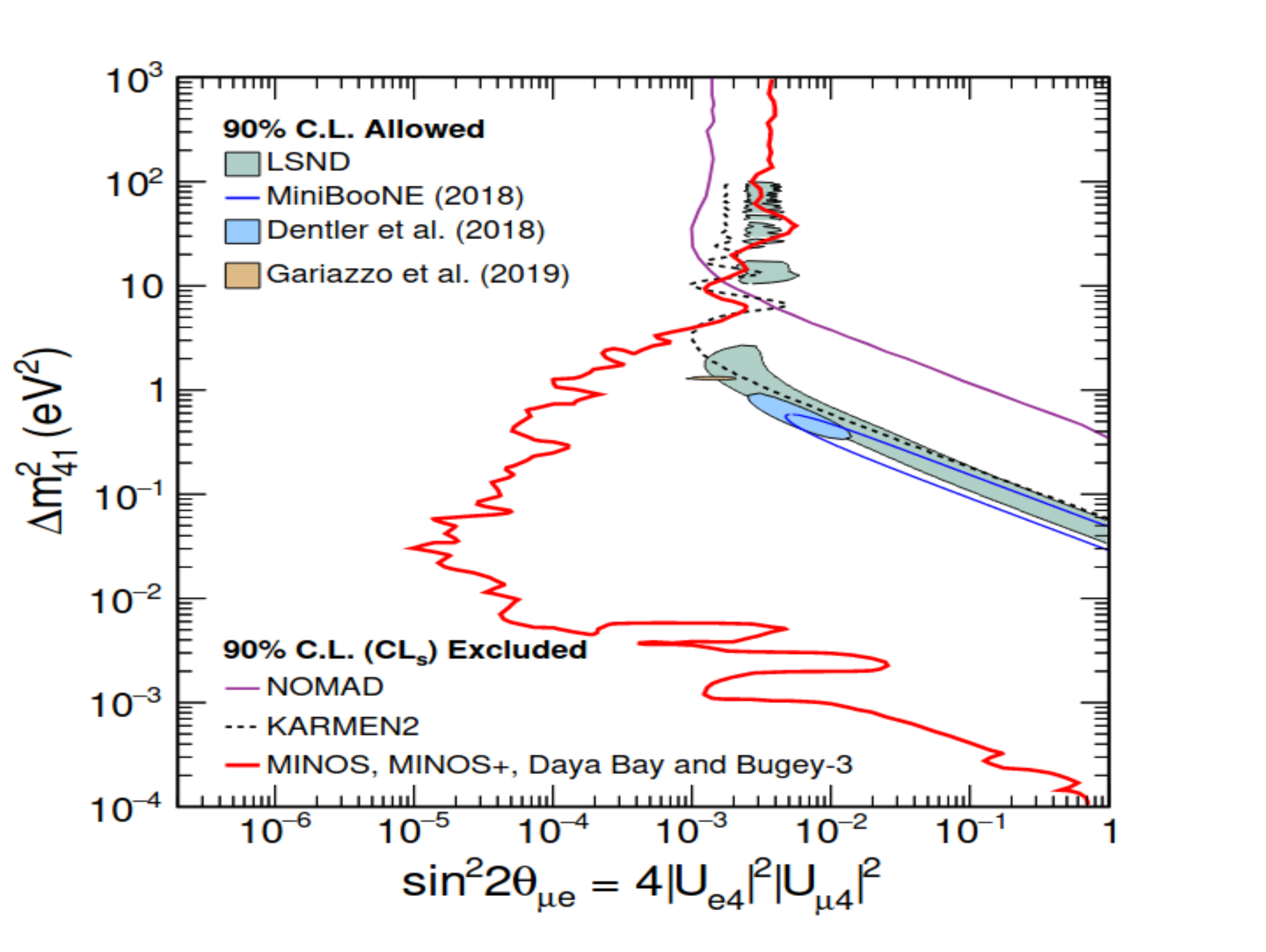
- For $\Delta m_s^2 = 1.3\,\text{eV}^2$ , SIO scenarios are disfavoured.

- Cosmology tends to favour SNO scenarios for sterile neutrino.

# Allowed $\theta_{14}$ From Oscillation Experiment



P.Adamson et al., PRL ,2020



P.Adamson et al., PRL ,2020

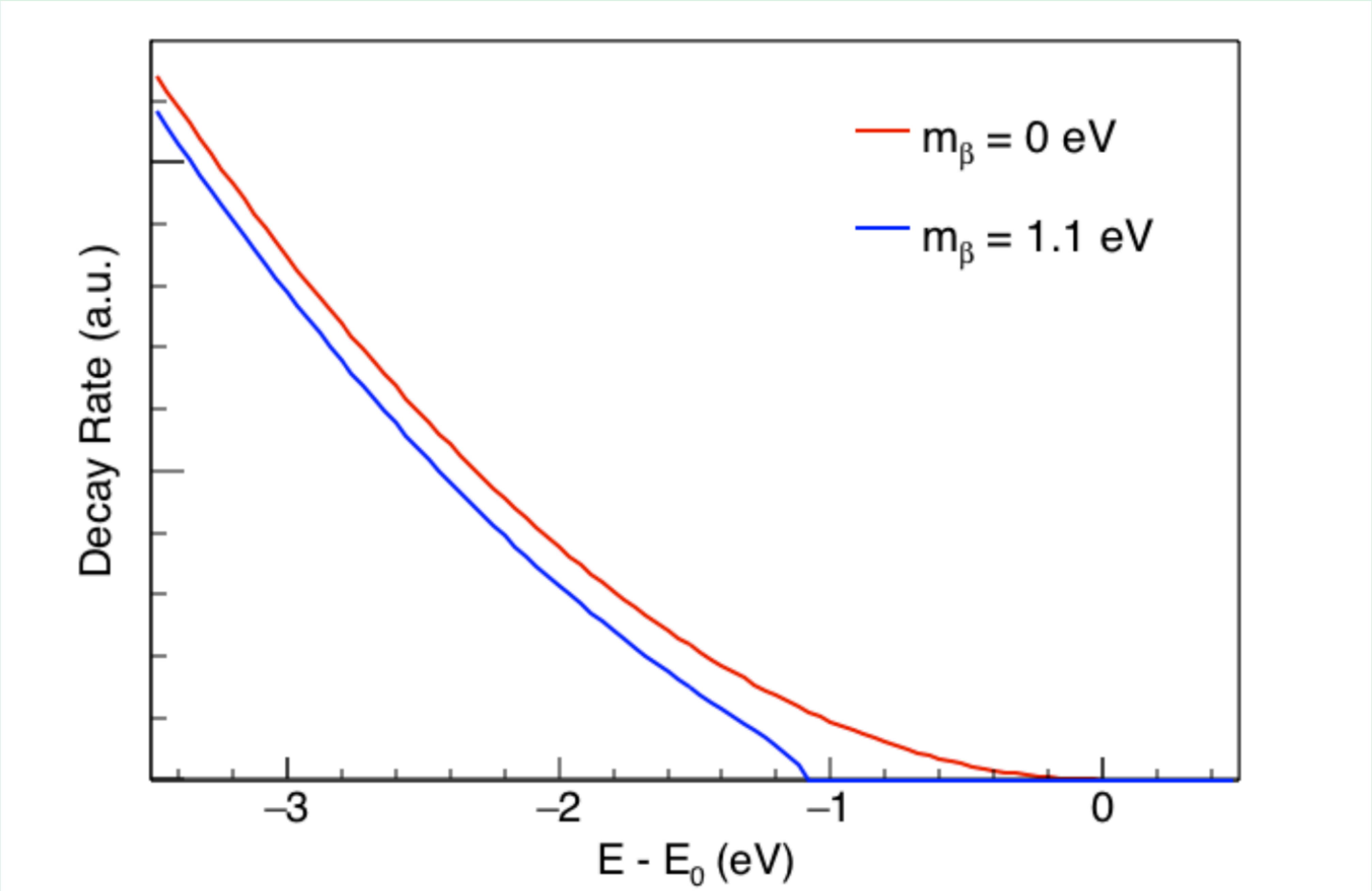
| $\Delta m_s^2$ | $10^{-4}\,\mathrm{eV}^2$ | $0.01\,\mathrm{eV}^2$ | $1.3\,\mathrm{eV}^2$ |
|---|---|---|---|
| $\sin^2\theta_{14}$ | 0.1-0.2 | 0.0005-0.005 | 0.001-0.01 |

# Tritium $\beta$ decay and sterile neutrino

$$^3H \rightarrow ^3He^+ + e^- + \bar{\nu}_e$$

$$m_\beta^2 = \sum_{i=1,4} |U_{ei}|^2 m_i^2$$

Esfahani et al, snowmass ,2021



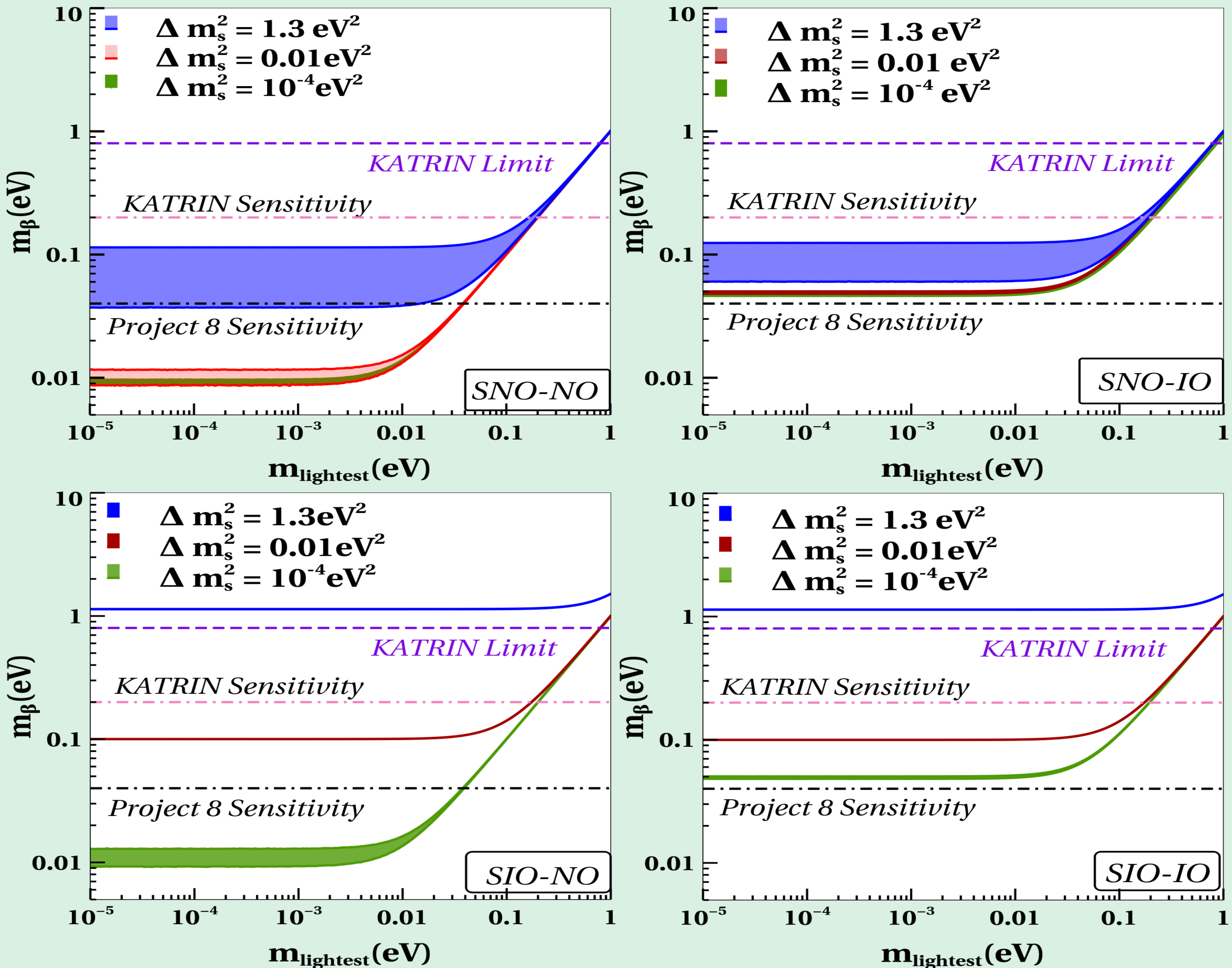
Tritium end-point energy spectrum for different $m_\beta$ scenario

## KATRIN Experiment

- Measures $\beta$ decay spectrum from Tritium Isotope
- Current limit $m_\beta \lesssim 0.8\,\mathrm{eV}$
- Projected Sensitivity $m_\beta \lesssim\ 0.2\,\mathrm{eV}$

## PROJECT 8 Experiment

- Used Cyclotron Radiation Emission Spectroscopy (CRES) for energy measurement
- $f = \dfrac{f_0}{m_e + (E/c^2)}$
- Projected sensitivity is $m_\beta \lesssim 0.04\,\mathrm{eV}$



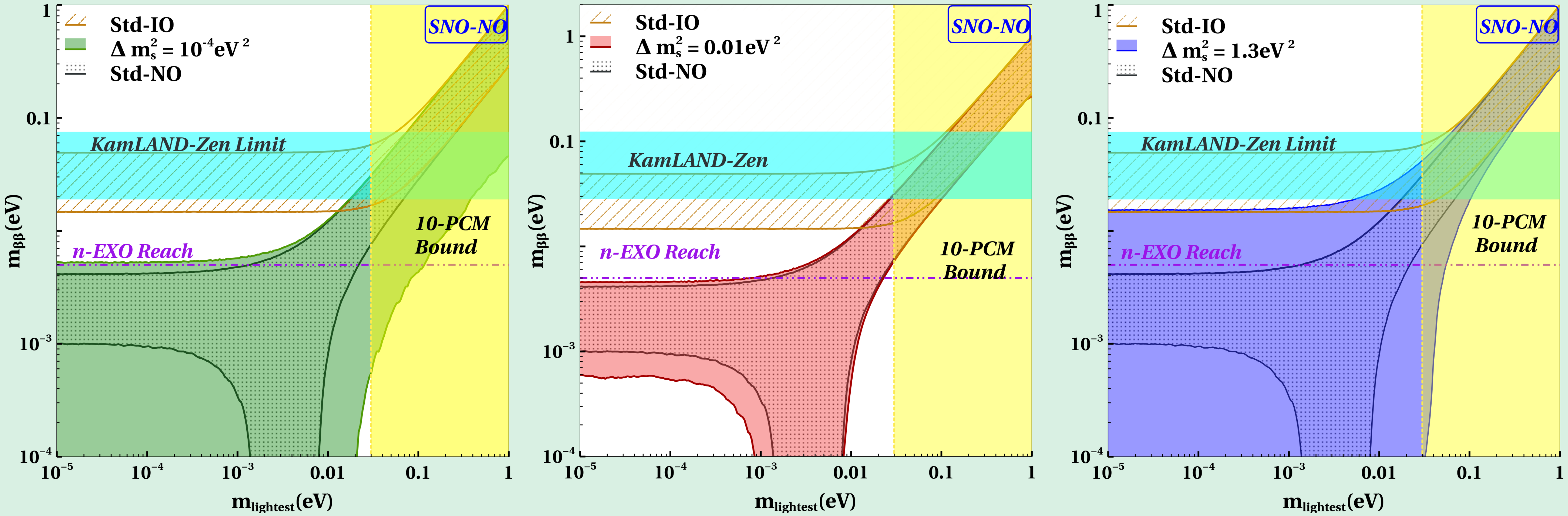
- KATRIN rules out SIO-NO and SIO-IO scenario for $\Delta m_s^2 = 1.3\,\mathrm{eV}^2$

- Future experiments will be important to probe other scenarios

$$m_{\beta\beta} \rightarrow \left| c_{14}^2\, c_{12}^2\, c_{13}^3\, m_1 + c_{14}^2\, s_{12}^2\, c_{13}^2\, m_2\, e^{i\alpha} + c_{14}^2\, s_{13}^2\, m_3\, e^{i\beta} + s_{14}^2\, m_4\, e^{i\gamma} \right|$$

$lightest \rightarrow m_1$

## SNO-NO

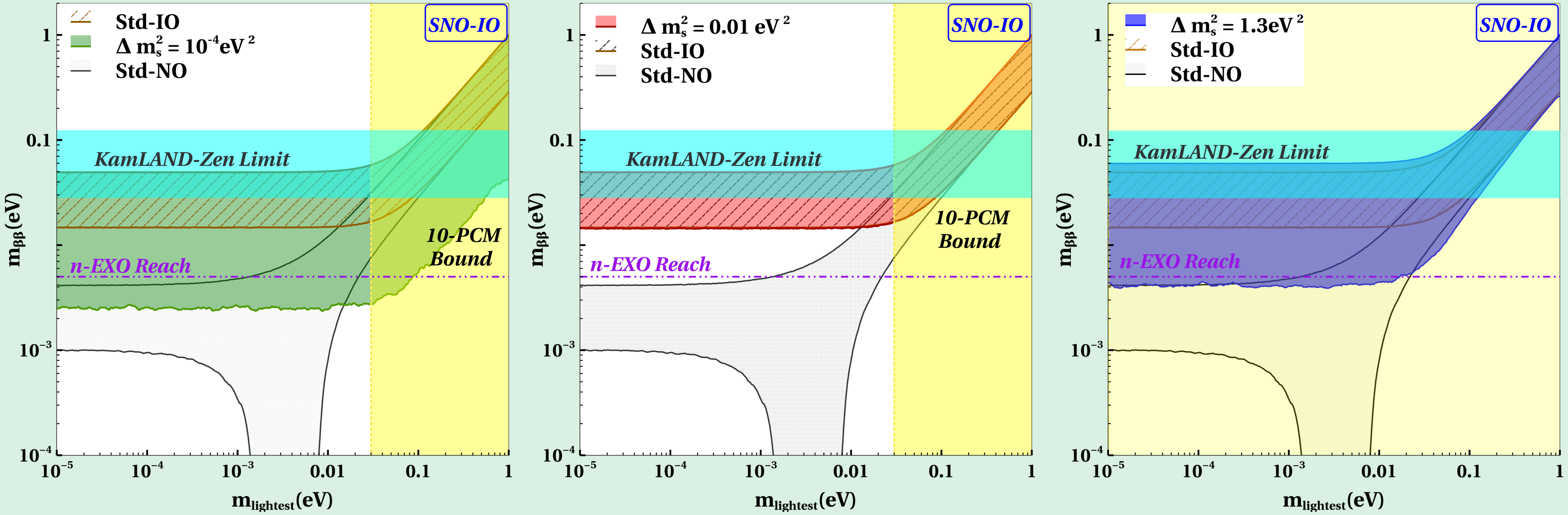


$$m_4 = \sqrt{m_1^2 + \Delta m_s^2}$$

- For $10^{-4}\text{eV}^2$ and $1.3\text{eV}^2$ , cancellation region increase
- For $0.01\ \text{eV}^2$ ,cancellation shifts on the left

## SNO-IO

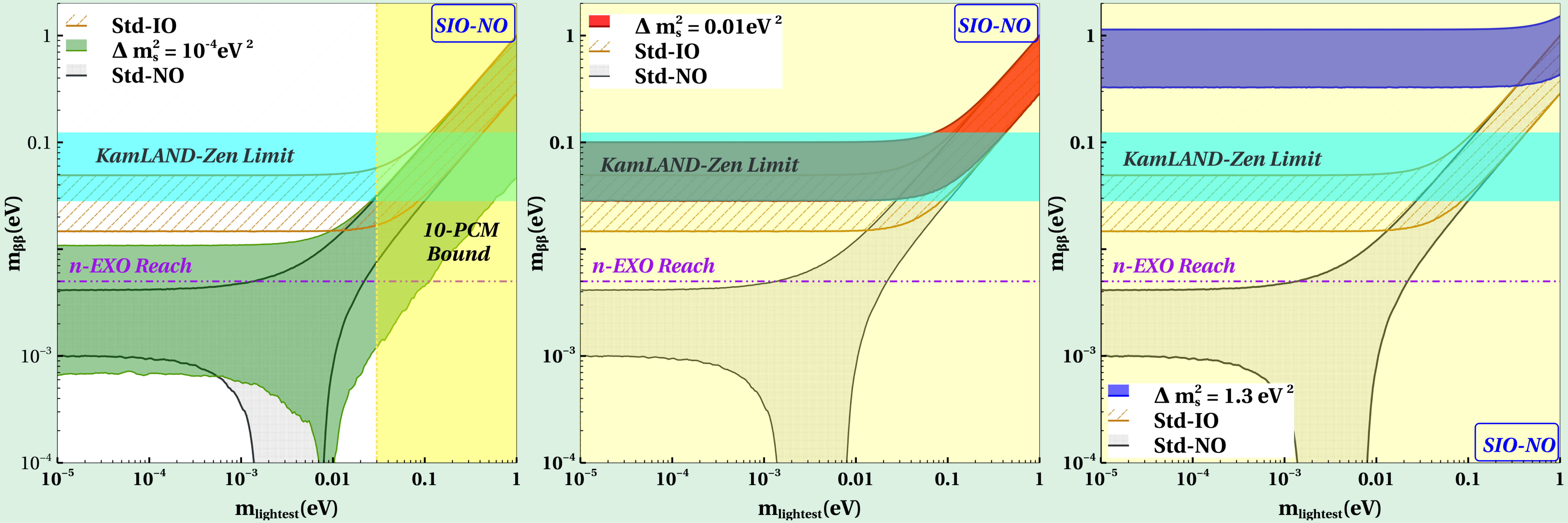
$lightest \rightarrow m_3$



$$m_4 = \sqrt{m_3^2 + \Delta m_{atm}^2 + \Delta m_s^2}$$

- For $10^{-4}\text{eV}^2$ and $1.3\ \text{eV}^2$, contribution is less than std-IO, greater than std-NO
- For $0.01\ \text{eV}^2$ , negligible effect due to small mixing angle

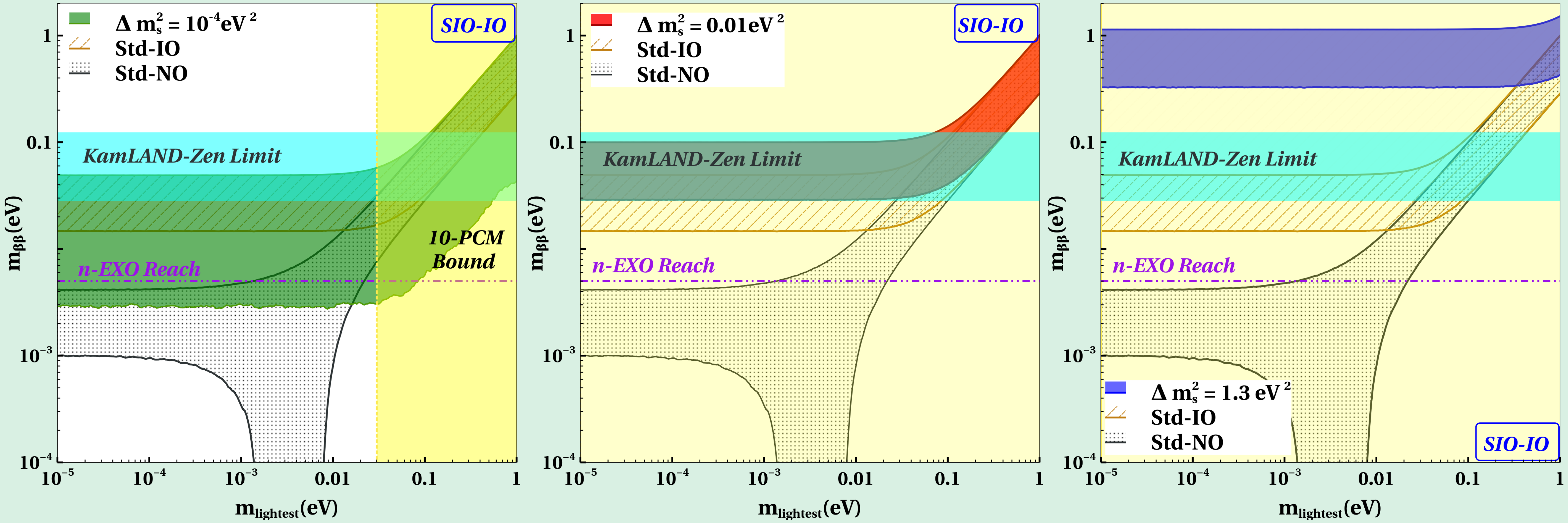
## SIO-NO



$$lightest \rightarrow m_4$$

- Narrow cancellation region is possible for $10^{-4}\,\mathrm{eV}^2$
- For $0.01\,\mathrm{eV}^2$ , maximum parameter space is ruled by KamLAND-Zen
- SIO-NO scenario for $1.3\,\mathrm{eV}^2$ is ruled out from $0\nu\beta\beta$ experiments

## SIO-IO



$$lightest \rightarrow m_4/m_3$$

- For $10^{-4}\mathrm{eV}^2$ , contribution is less than std-IO, greater than std-NO
- SIO-IO scenario for $1.3\,\mathrm{eV}^2$ is also ruled out from $0\nu\beta\beta$ experiments

# SUMMARY

- Addition of one sterile state implies four mass spectra
- We study the implications of the mass spectra on mass-related observables
- Current cosmology allows SNO-NO , SNO-IO for 0.01 $eV^2$ and smaller , SIO-NO and SIO-IO for $\Delta m_s^2 = 10^{-4}\, eV^2$
- KATRIN experiment completely ruled out the SIO-NO and SIO-IO scenario for $\Delta m_s^2 = 1.3\,\mathrm{eV}^2$
- Future experiments like Project 8 will be able to probe SNO-IO and SIO-IO completely
- $0\nu\beta\beta$ experiments like KamLAND-Zen also rules out SIO scenarios for additional sterile state with $1.3\,\mathrm{eV}^2$ mass-squared difference
- KamLAND Zen experiment almost rules out the SIO-IO scenario $\Delta m_s^2 = 0.01 eV^2$

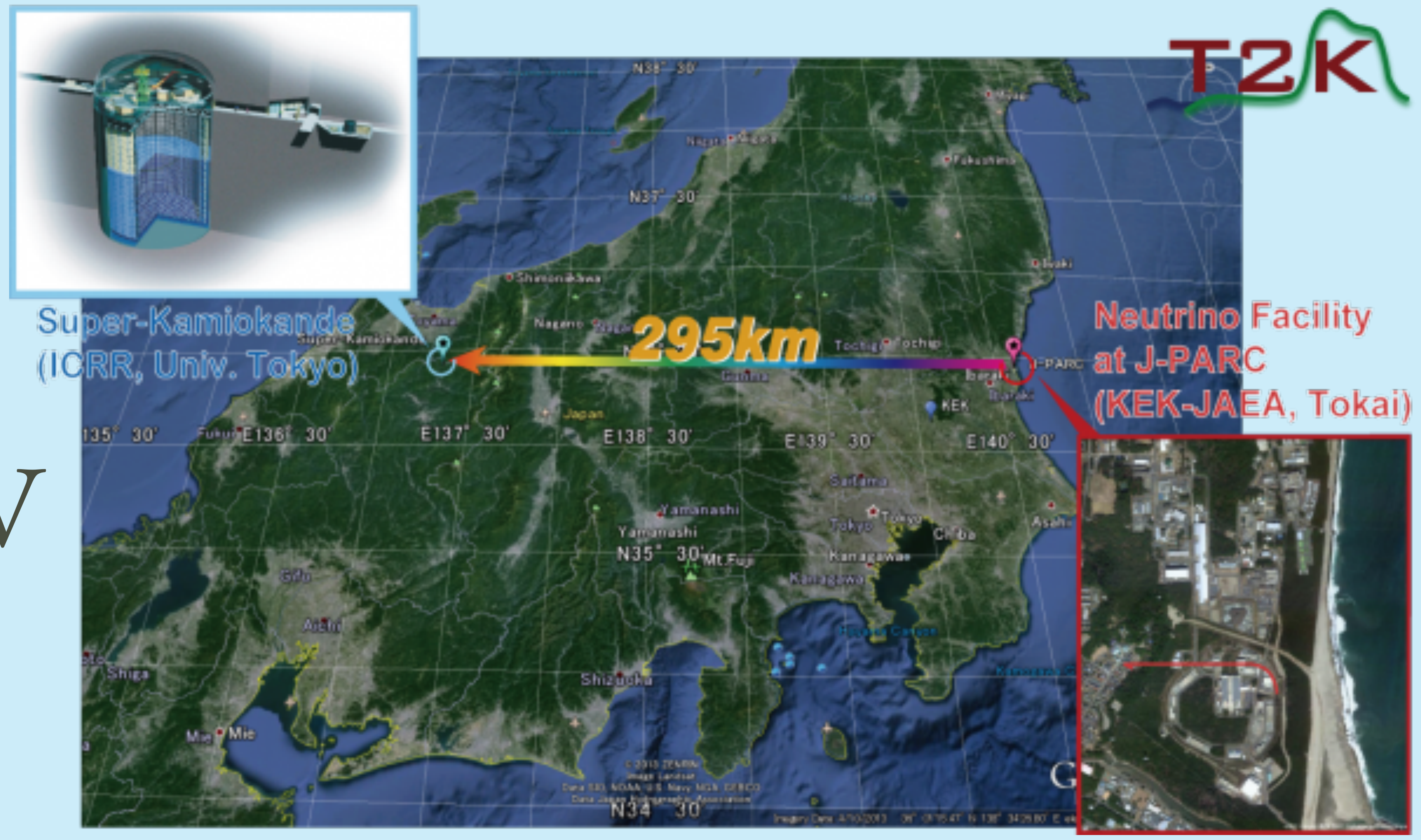
# THANK YOU

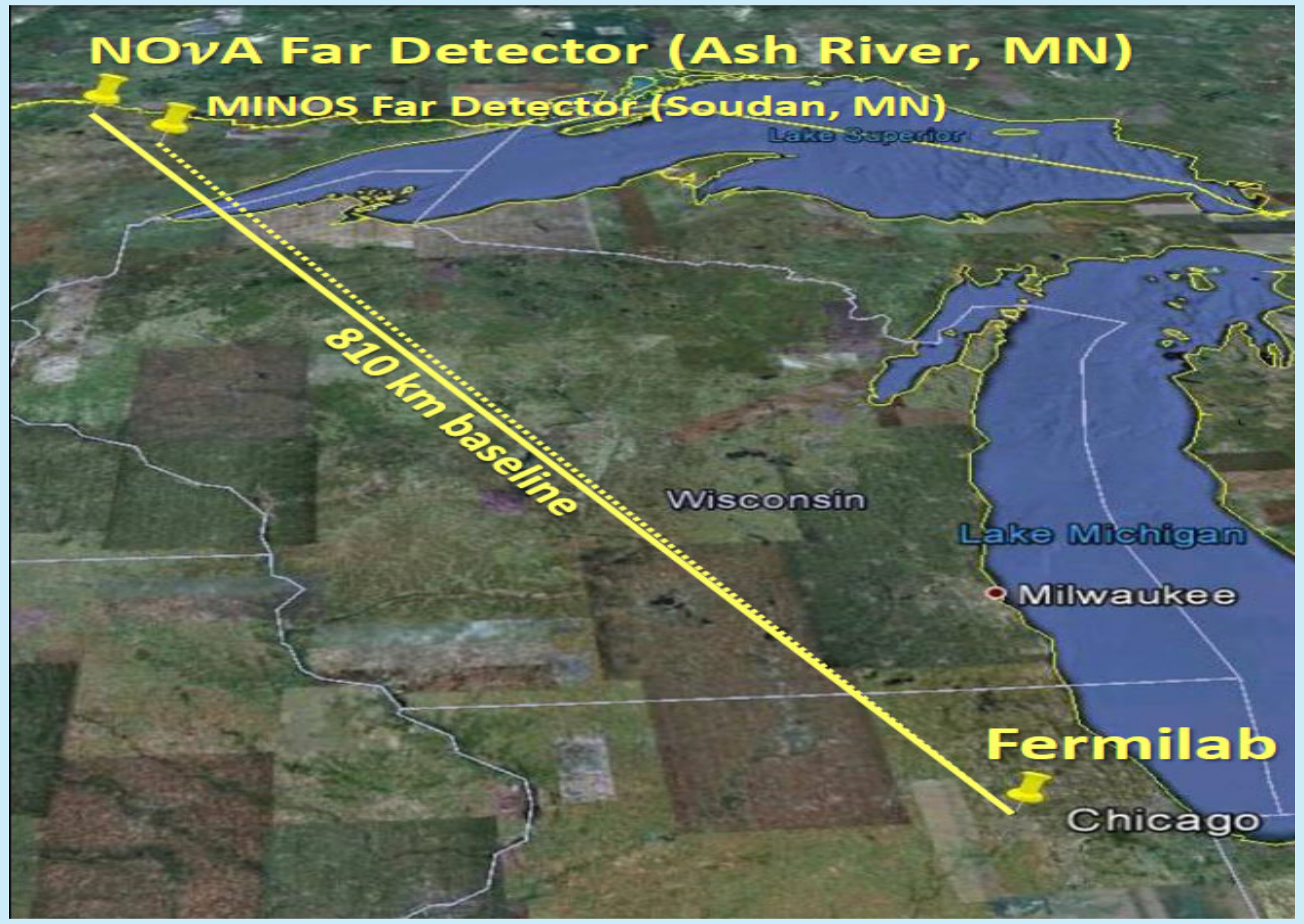
# BACK UP SLIDES

- Long Baseline Experiments :

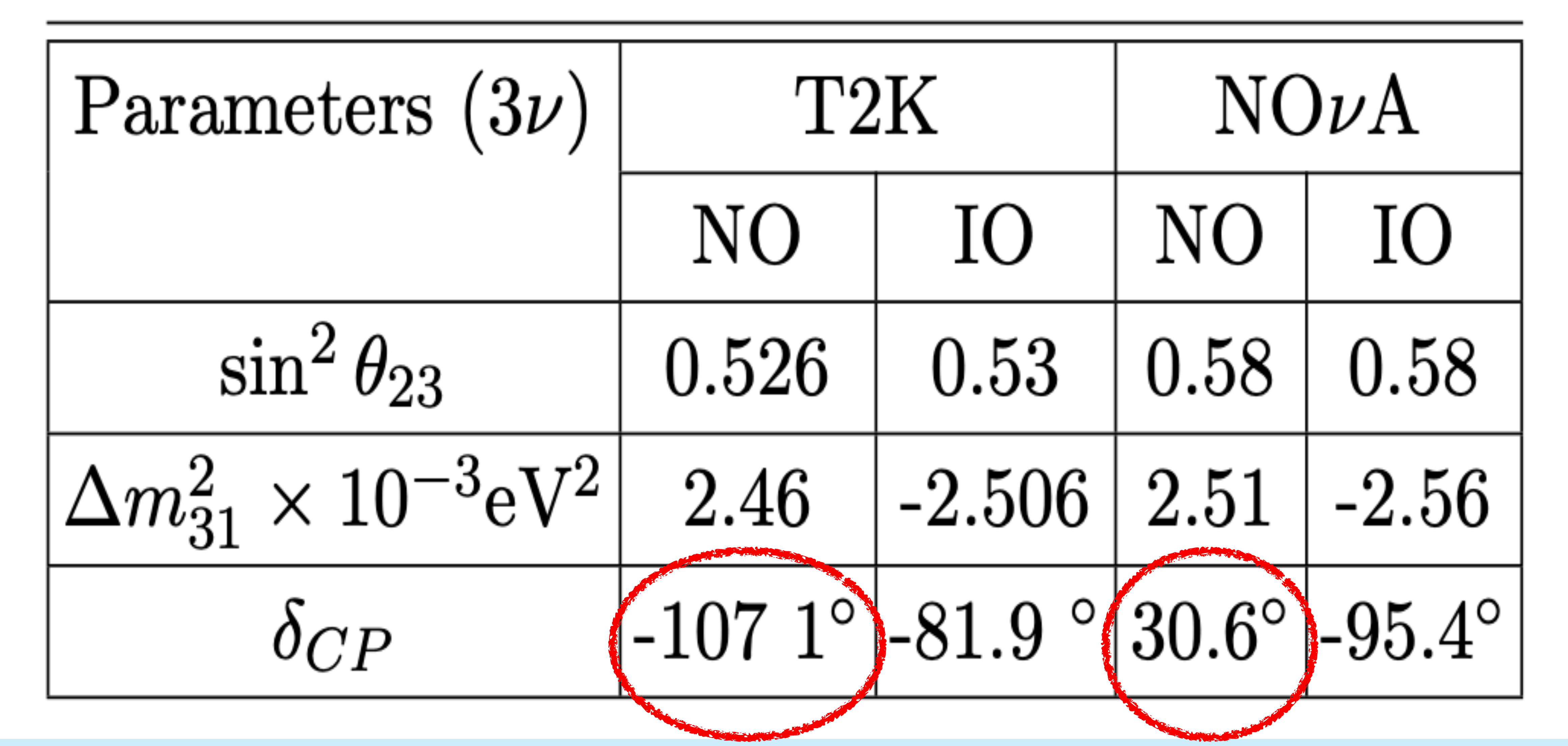
T2K : L=295 KM , E=0.7 GeV

NO$\nu$A: L=810 KM, E=2.0 GeV



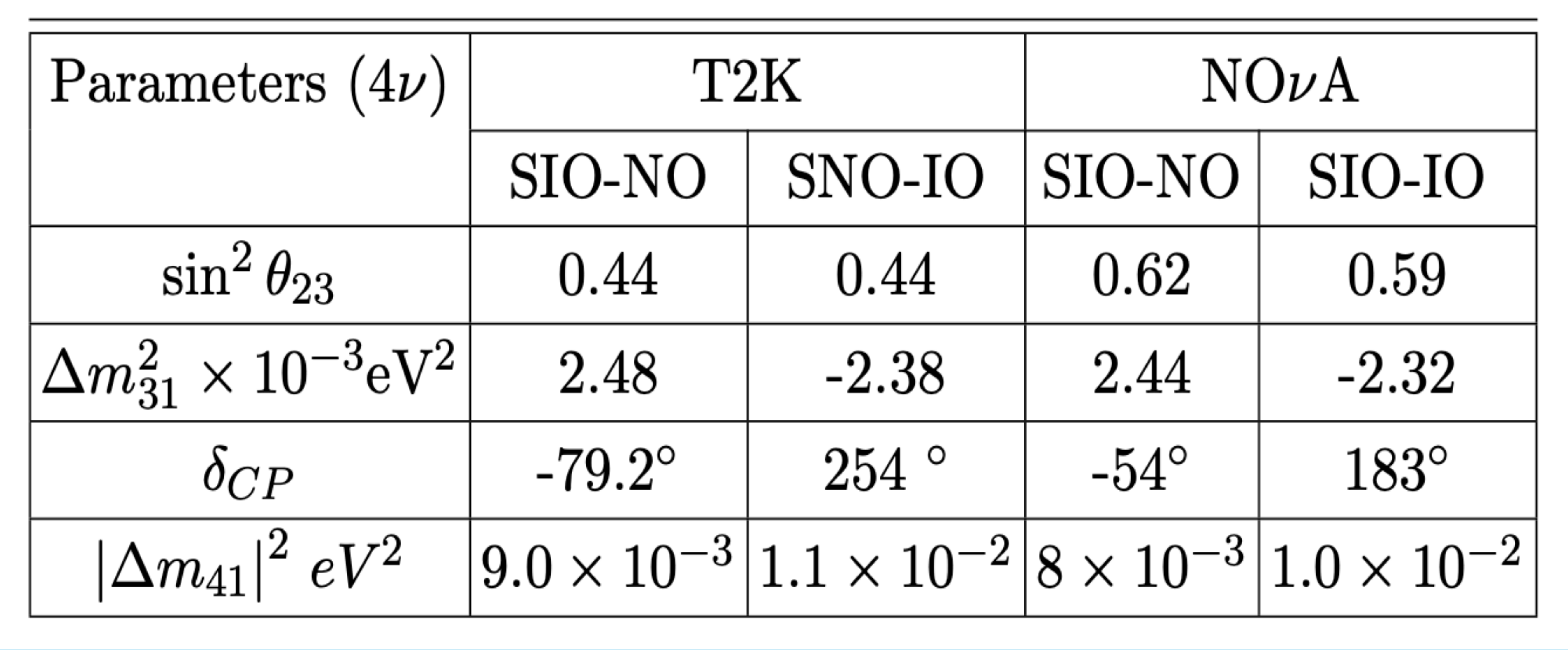


(Nizam et al. ,Mod. Phys Lett. A, 2018 )



| Parameters (3$\nu$) | T2K | | NO$\nu$A | |
|---|---|---|---|---|
| | NO | IO | NO | IO |
| $\sin^2\theta_{23}$ | 0.526 | 0.53 | 0.58 | 0.58 |
| $\Delta m^2_{31} \times 10^{-3}\mathrm{eV}^2$ | 2.46 | -2.506 | 2.51 | -2.56 |
| $\delta_{CP}$ | -107 1° | -81.9 ° | 30.6° | -95.4° |

( de Gouvea et al. , PRD, 2022)



| Parameters (4$\nu$) | T2K | | NO$\nu$A | |
|---|---|---|---|---|
| | SIO-NO | SNO-IO | SIO-NO | SIO-IO |
| $\sin^2\theta_{23}$ | 0.44 | 0.44 | 0.62 | 0.59 |
| $\Delta m^2_{31} \times 10^{-3}\mathrm{eV}^2$ | 2.48 | -2.38 | 2.44 | -2.32 |
| $\delta_{CP}$ | -79.2° | 254 ° | -54° | 183° |
| $\lvert\Delta m_{41}\rvert^2\ eV^2$ | $9.0 \times 10^{-3}$ | $1.1 \times 10^{-2}$ | $8 \times 10^{-3}$ | $1.0 \times 10^{-2}$ |

- T2k, NO$\nu$A Tension can be improved with introduction of $\Delta m^2_{41} = 10^{-2} eV^2$ sterile neutrino

# Cosmological Model Parameters

e$\Lambda_{CDM}$ Model

$\Lambda_{CDM}$ Model

1. $H_0$ = Hubble parameter
2. $\Omega_h h^2$ = Baryin Density
3. $\Omega_{CDM} h^2$ = Dark matter Density
4. $n_s$ = Scalar spectral index
5. $\tau$ = Reionization Optical depth
6. $A_s$ = Primodial amplitude of scalar perturbation

7. $N_{eff}$ = Relativistic d.o.f
8. $\sum m_\nu$ = Total neutrino mass
9. $\omega$ = Dark energy equation
10. $\frac{dn_s}{d\ln k}$ = running of spectra index
11. $A_{lens}$ = CMB angular spectrum
12. $r$ = scalar to tensor ratio

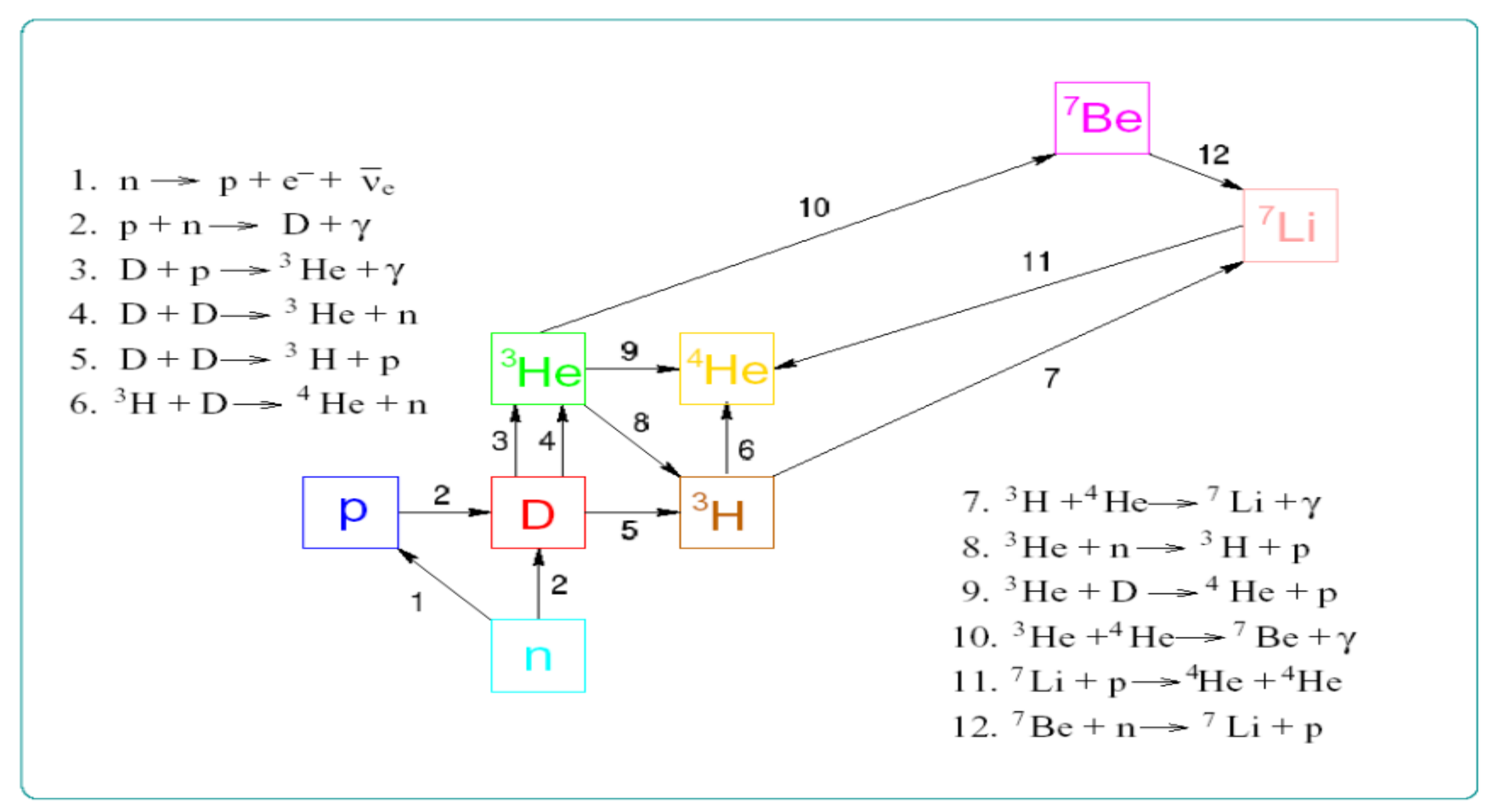
# BOUND FROM COSMOLOGY

- Sterile neutrinos contributes to $N_{\text{eff}}$

A. Hubble Parameter

$$H^2(a) = \frac{8\pi G}{3}(\rho_\gamma + \rho_\nu)$$

$$\rho_\nu = N_{\text{eff}}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$



B. Big Bang Nucleosynthesis

- $N_{\text{eff}}$ is directly affects the production of light elements abundances in BBN.

- Increase in $N_{\text{eff}}$, increase $^4He$ abundance