LIGHT STERILE NEUTRINO AND MASS-RELATED OBSERVABLES

Based on arXiv 2405.04176

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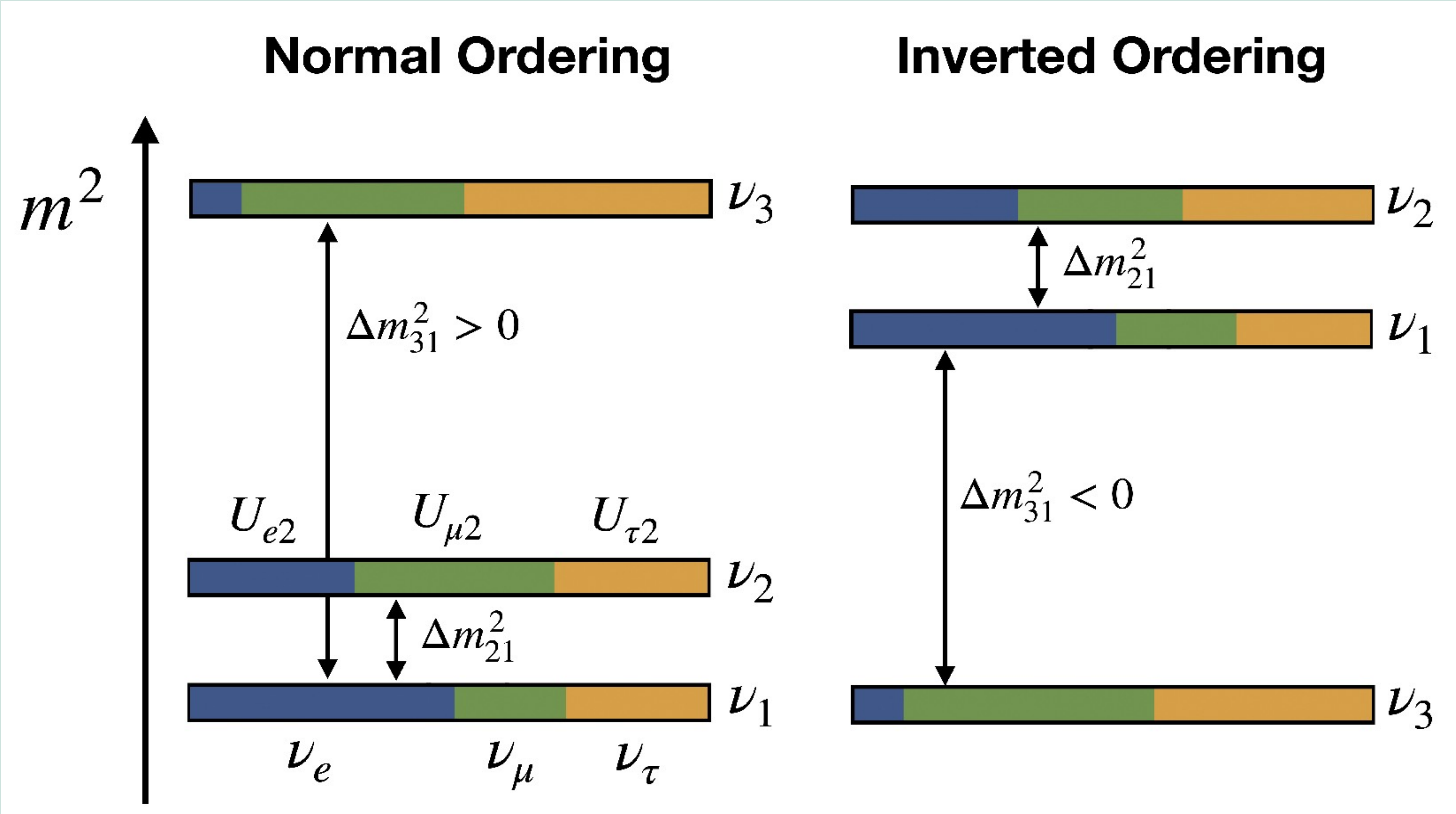
Outline

- 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 (δ_{13}) and two Majorana phases (α, β)

$$U_{PMNS} = \mathbb{R}_{23}(\theta_{23})\,\mathbb{S}_{13}(\theta_{13}, \delta_{13})\,\mathbb{R}_{12}(\theta_{12})\;\mathbb{P}$$

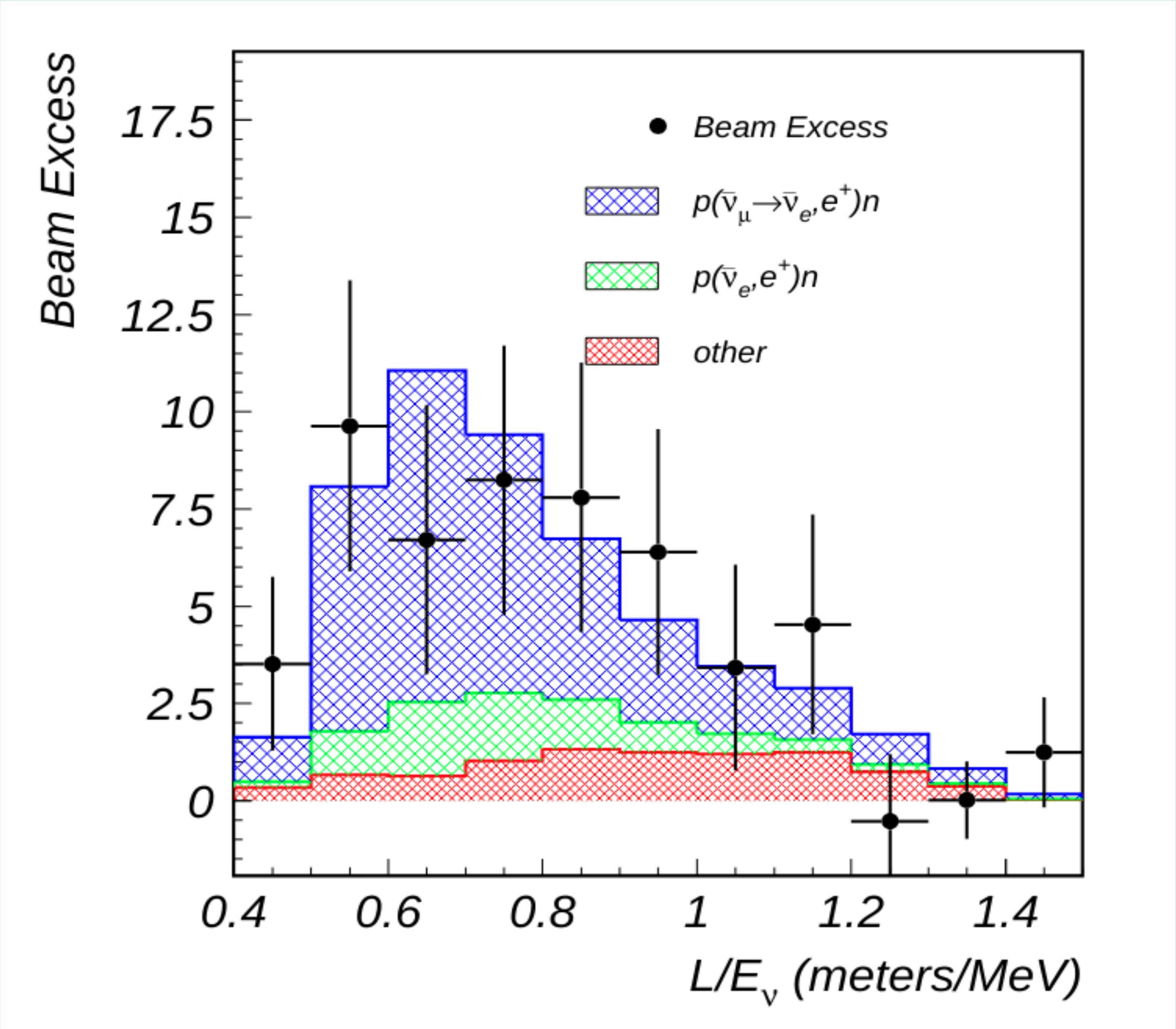
$$\mathbb{P} = \text{diag}(1, e^{i\alpha}, e^{i\beta})$$

- 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
- θ_{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

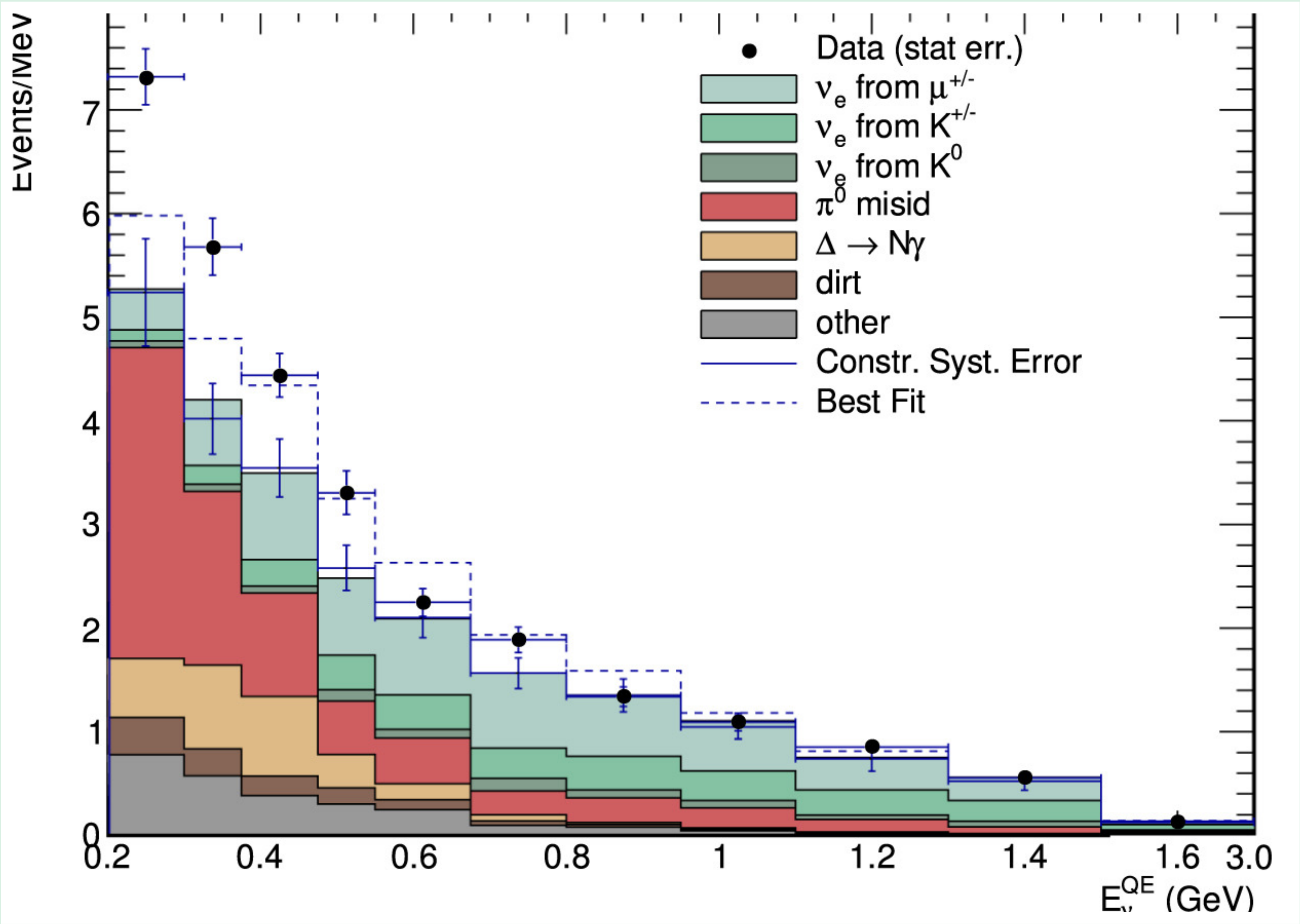
LSND



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

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

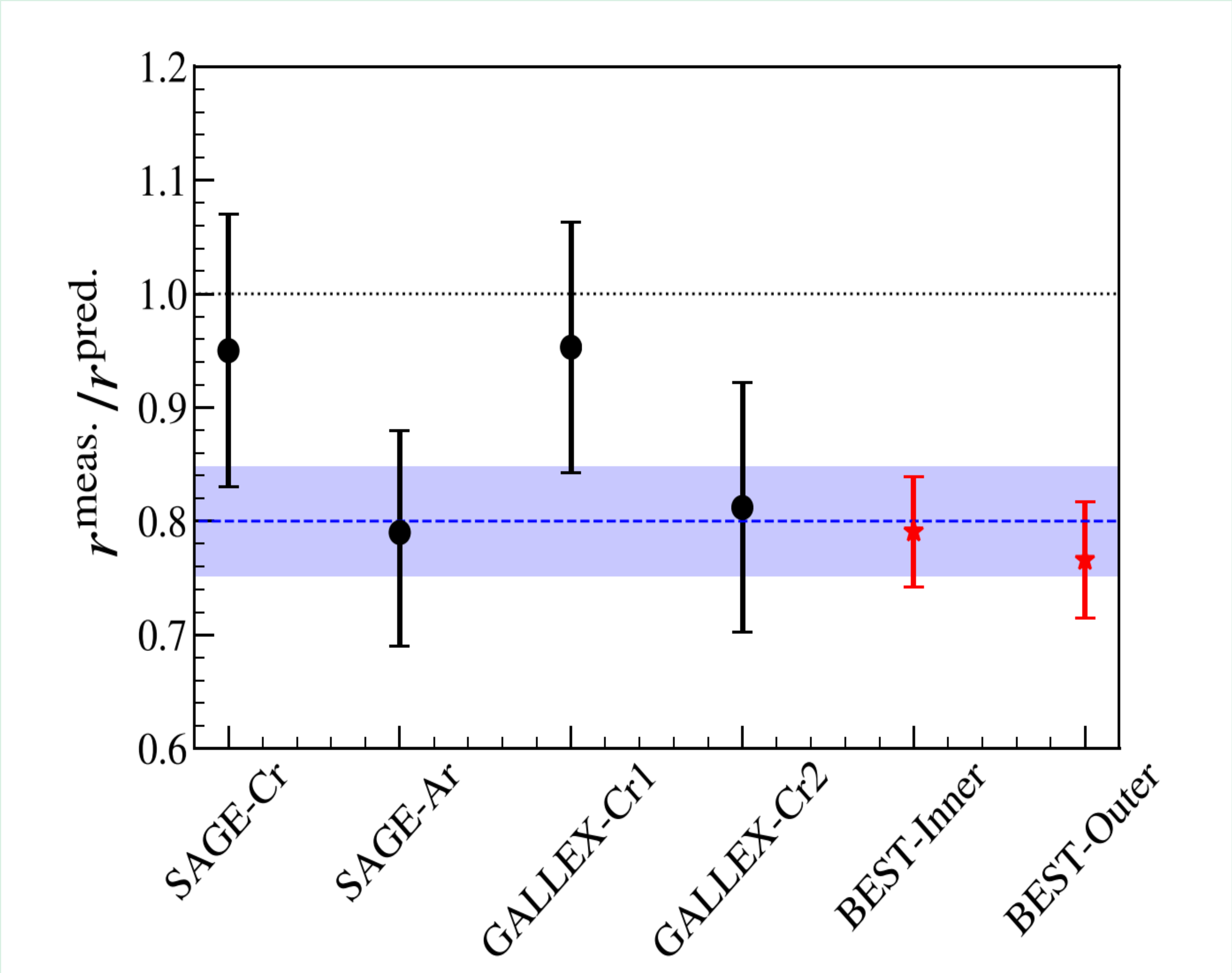
MiniBooNE



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

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

Gallium Anomaly



Deficit in ν_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.

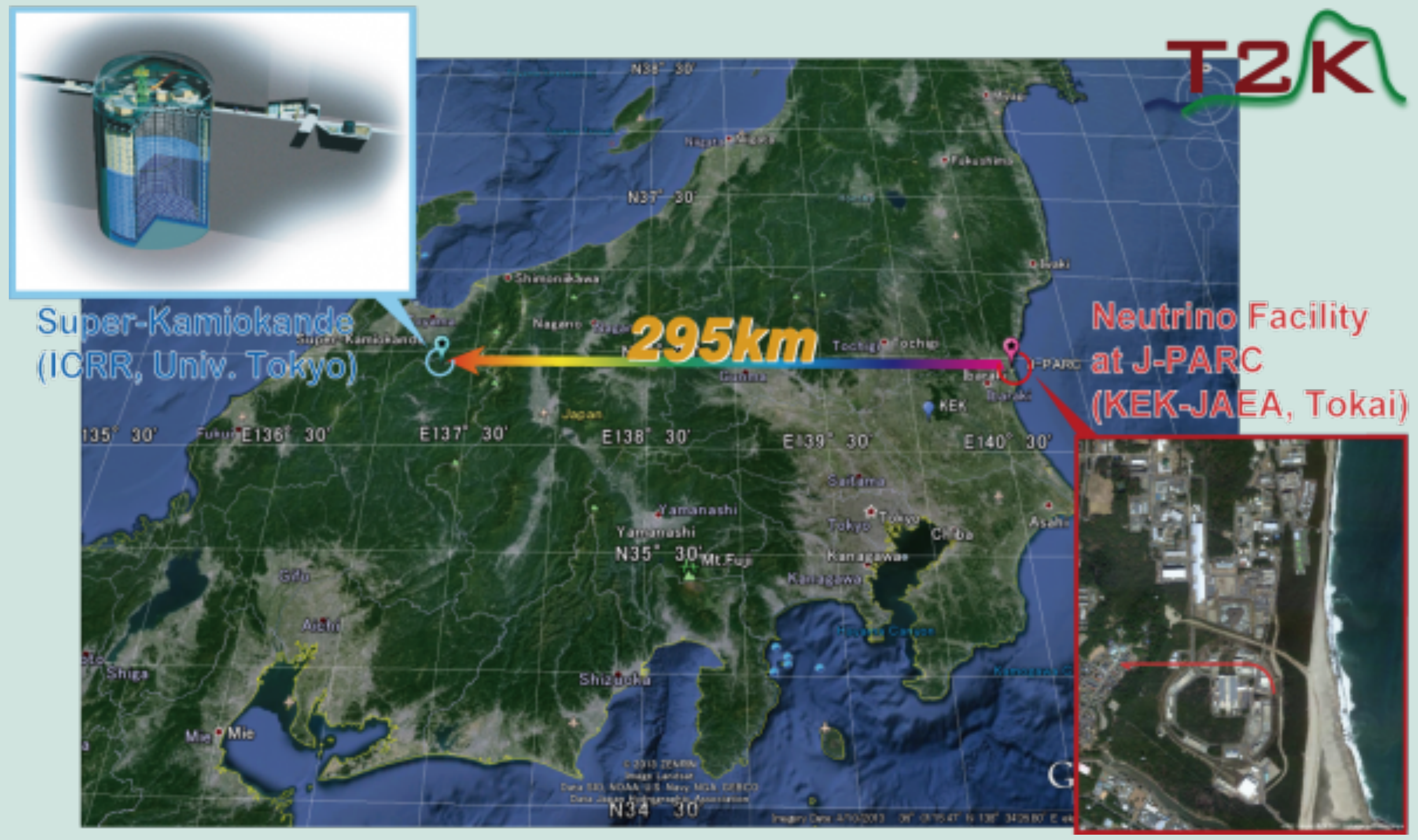
(very light) sterile neutrino

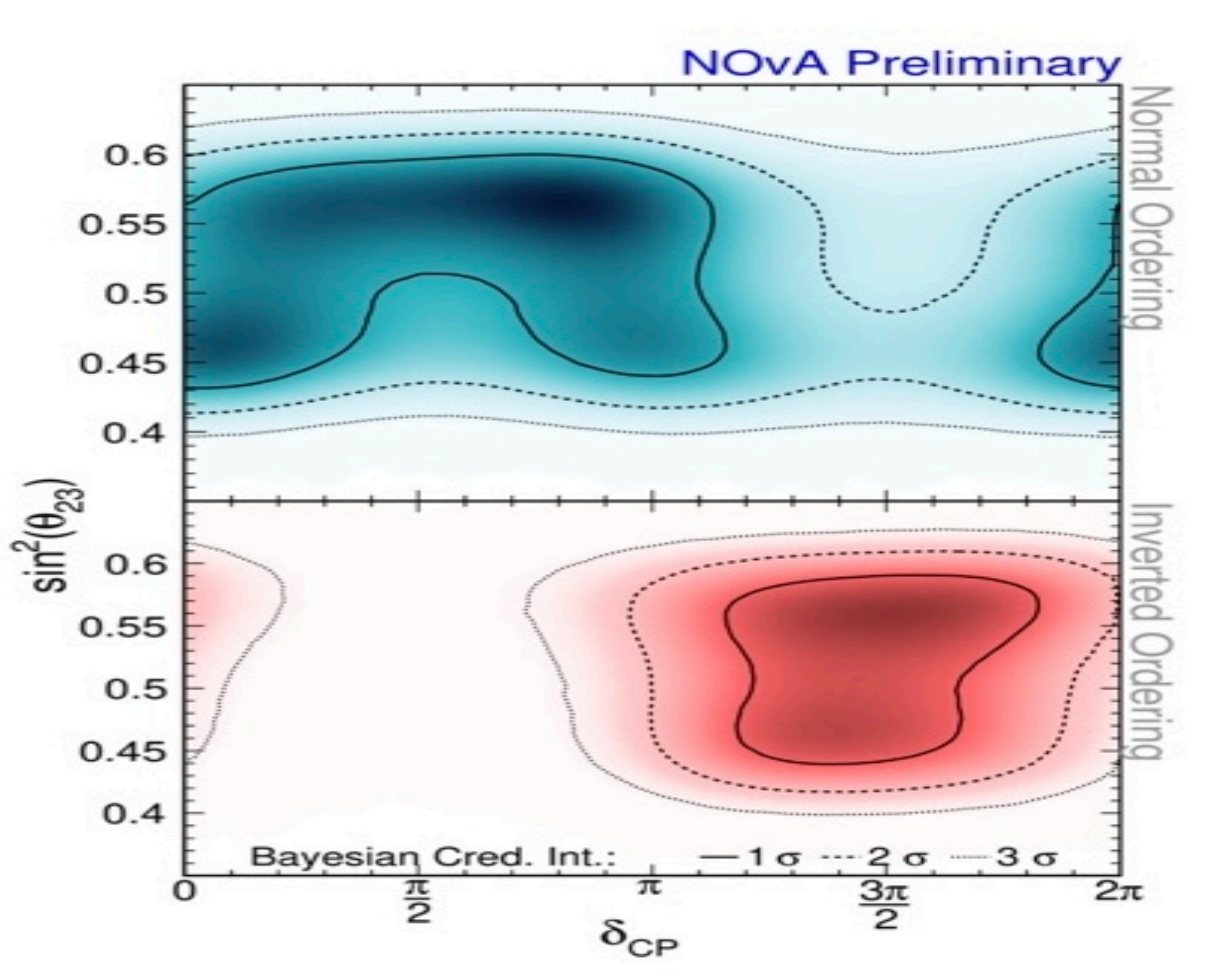
- Long Baseline Experiments :

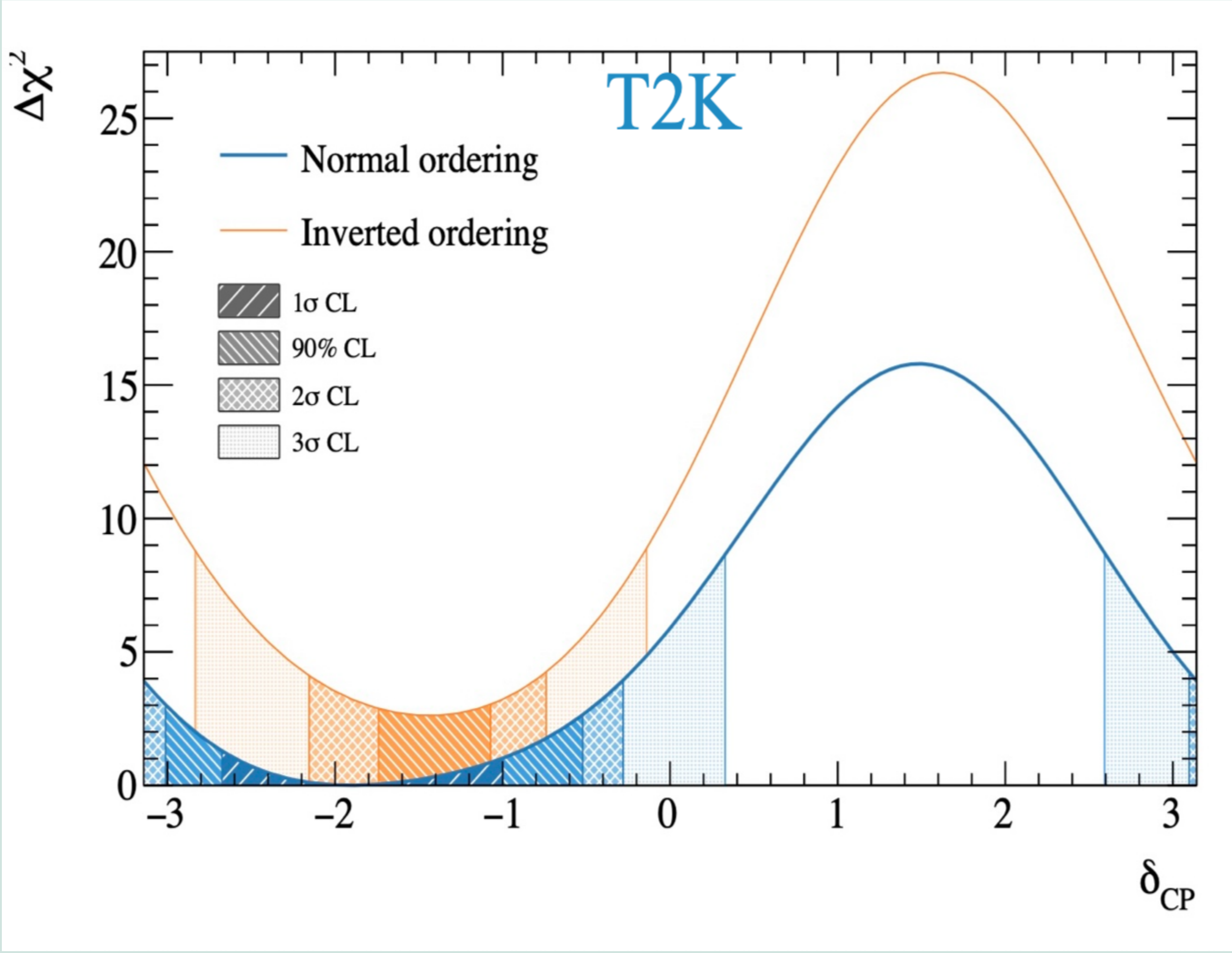
  T2K : L=295 KM , E=0.7 GeV

  NOνA: L=810 KM, E=2.0 GeV

Son Cao , 2310.09855







- T2K, NOνA 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

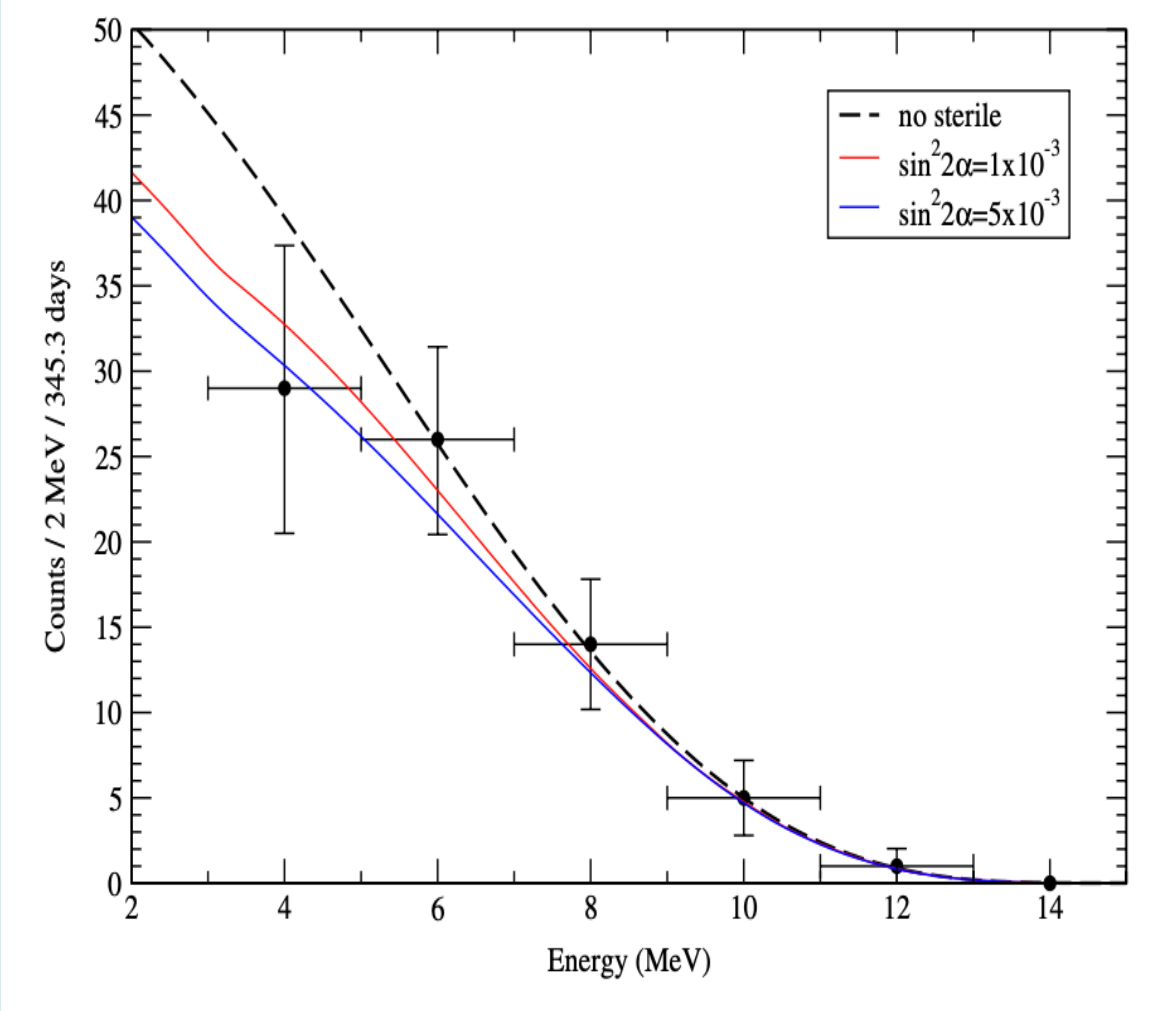
- Results from Borexino doesn't show signatures of upturn of energy spectrum below 8 MeV expected from MSW solution to the Solar Neutrino Problem. [Phys. Rev. C 81, 055504; Phys. Rev. D 82, 033006; Phys.Rev.D 83, 052010]

✓ Possible solution is extra sterile neutrino:

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

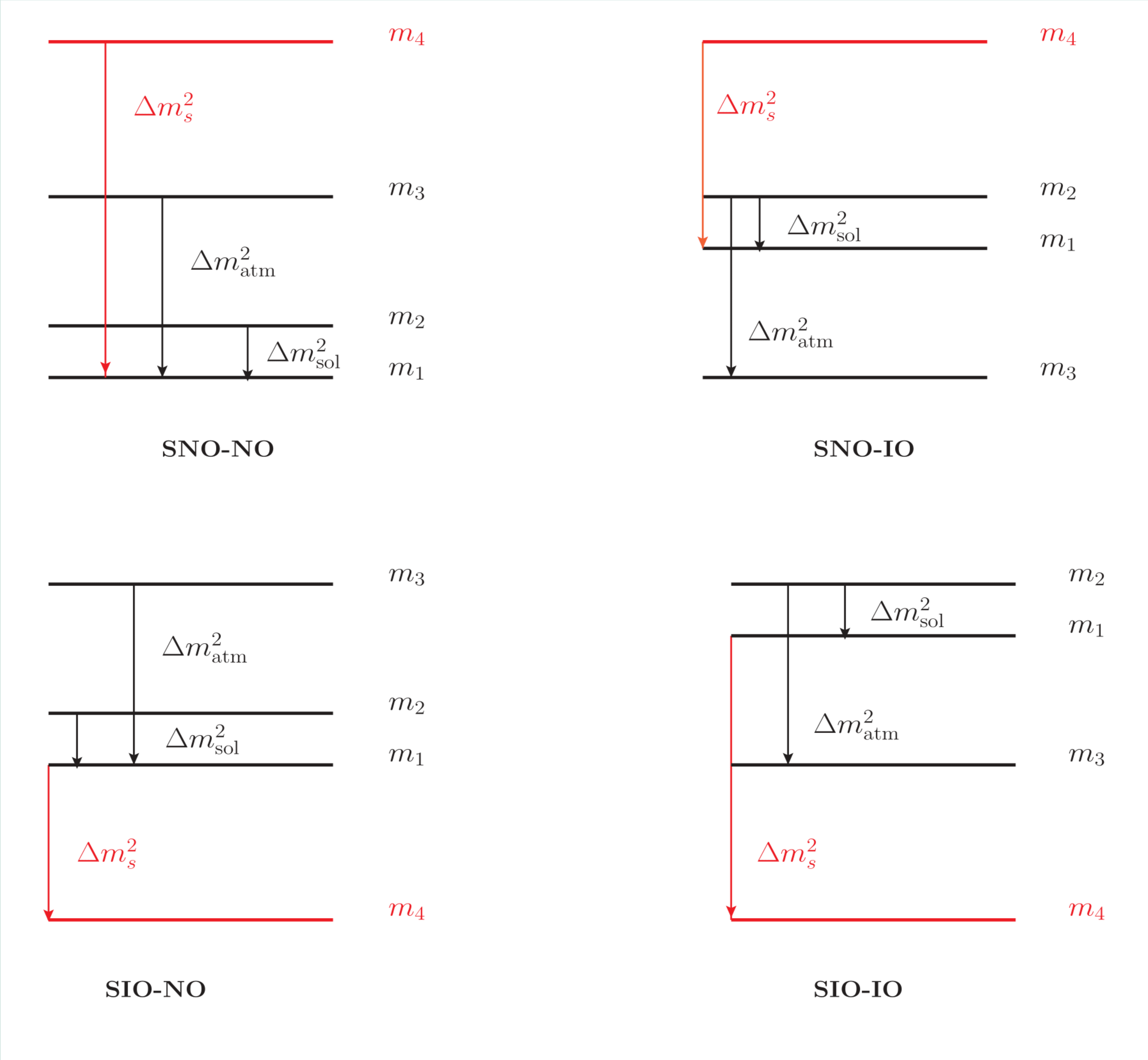
✓ Mixing with active states $\sin^2 2\alpha \sim 10^{-5} : 10^{-3}$

[PhysRevD. 83,113011]



$\Delta m^2_{sol} \simeq 7 \times 10^{-5} eV^2$, $\Delta m^2_{atm} \simeq 2.5 \times 10^{-3} eV^2$ $\Delta m^2_s = 10^{-4} \mathrm{eV}^2, 0.01\ \mathrm{eV}^2, 1.3\ \mathrm{eV}^2$

$\Delta m^2_s \gtrsim \Delta m^2_{atm}$



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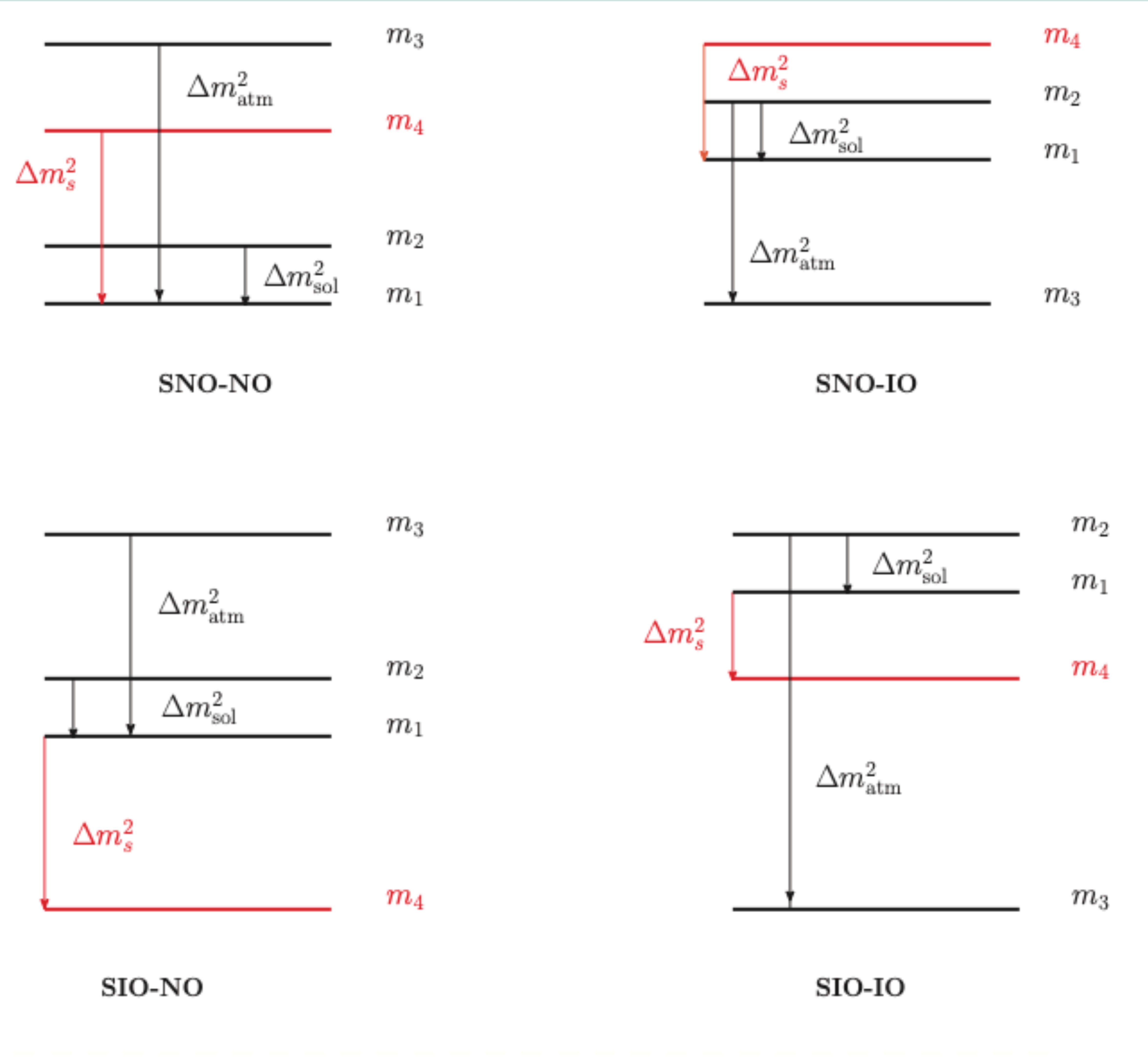


Mass Spectrum of 3+1 framework

3+1 Framework

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

- 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

$$m_\beta^2 = \sum_i \left|U_{ei}\right|^2 m_i^2$$

$m_\beta \leq 0.8\,\text{eV}$ — KATRIN Exp. (Nat. Phys. 18,160-166 (2022)

Neutrinoless Double Beta Decay

$$m_{\beta\beta} = \sum U_{ei}^2 m_i$$

$m_{\beta\beta} \leq (36 - 156)\,\text{meV}$ — Phys. Rev. Lett. 130.051801

STERILE NEUTRINO AND COSMOLOGY

- Massless sterile neutrinos contribute to N_{eff}
- Massive sterile neutrinos affect N_{eff} and Σm_i

$$\Delta N_{eff} = N_{eff} - N_{eff}^{SM}$$

N_{eff}^{SM}: 3.044 ± 0.002

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

2203.07323

- 10 Parameter Cosmological Model

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

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

Di Valentino, PRD, 2015

- Extended Cosmological Model

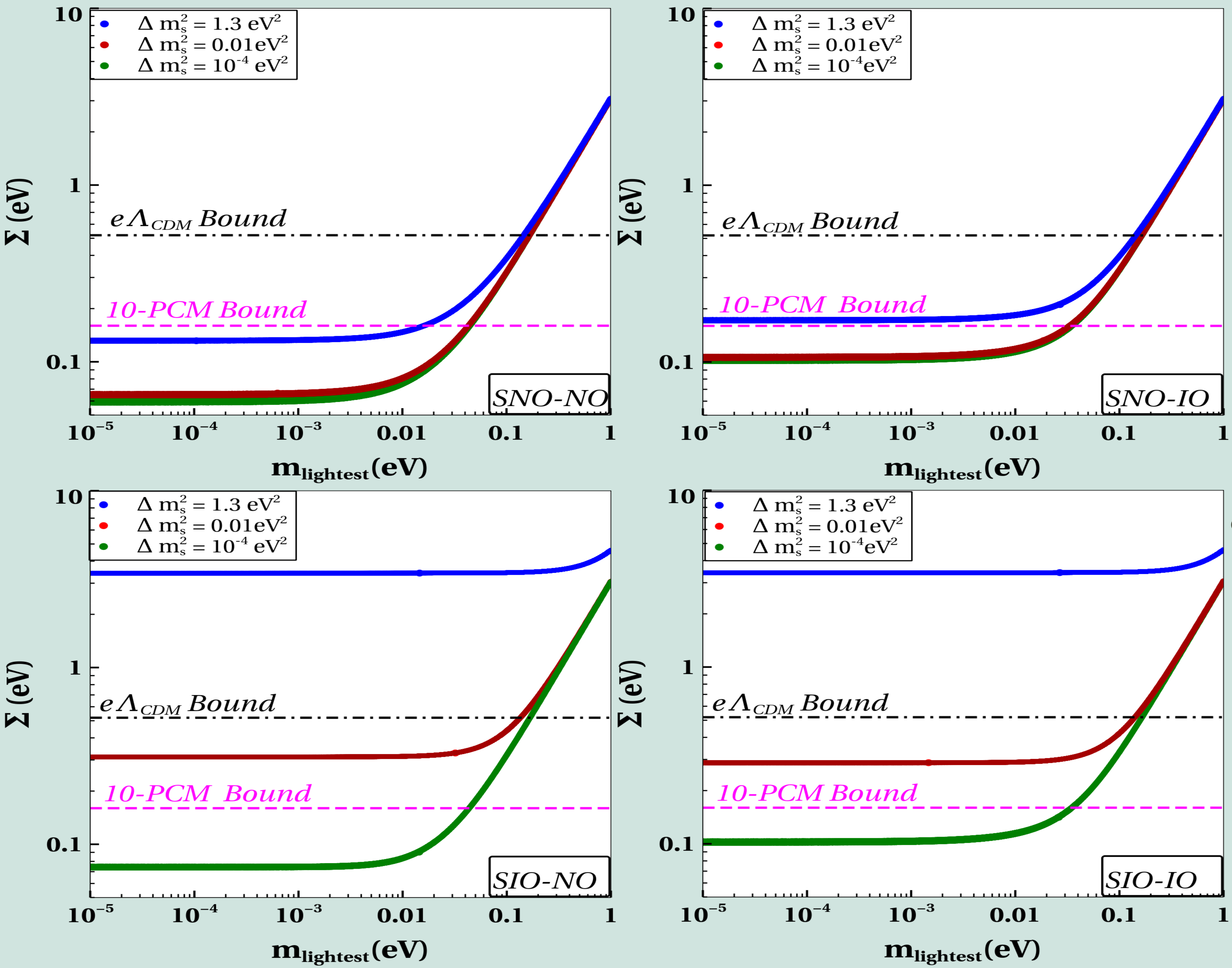
$$N_{\text{eff}} = 3.11^{+0.52}_{-0.48}$$

$$\Sigma m_i < 0.54\,\text{eV}$$

- Fully thermalised neutrino $\Delta N_{\text{eff}} \approx 1$, ruled out by cosmological observations
- Can be evaded with secret interaction, low reheating temperature etc.

Hagstotz et al. , PRD , 2021

- Can be produced through non-resonant oscillation $\Sigma m_i = m_1 + m_2 + m_3 + \left(m_4 \times \Delta N_{eff}\right)$



- For SNO-NO

$$lightest \rightarrow m_1$$

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

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

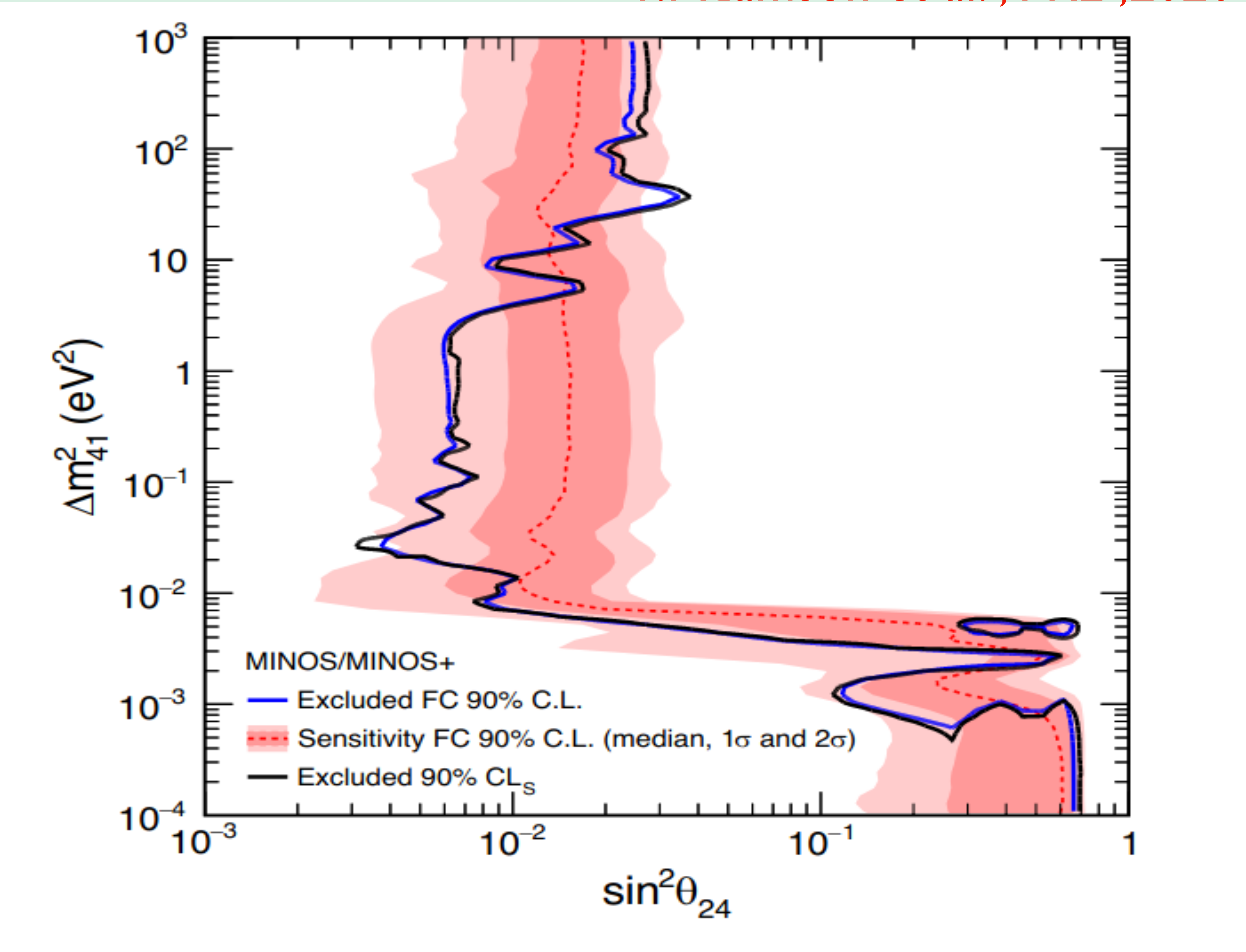
$$m_4 = \sqrt{m_1^2 + \Delta m_s^2}$$

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

- Cosmology tends to favour SNO scenarios for sterile neutrino.

Allowed θ_{14} From Oscillation Experiment

P. Adamson et al. , PRL ,2020



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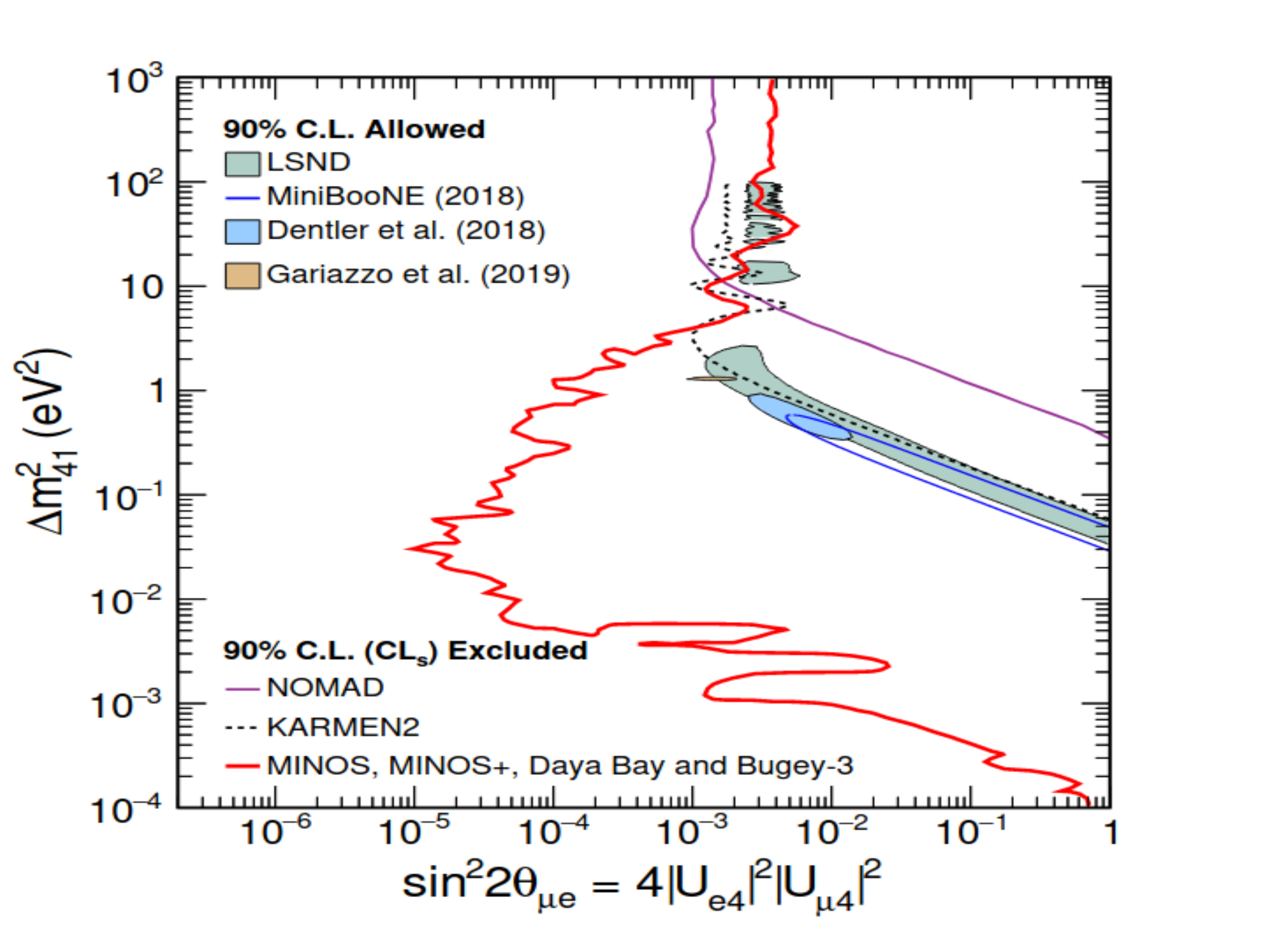


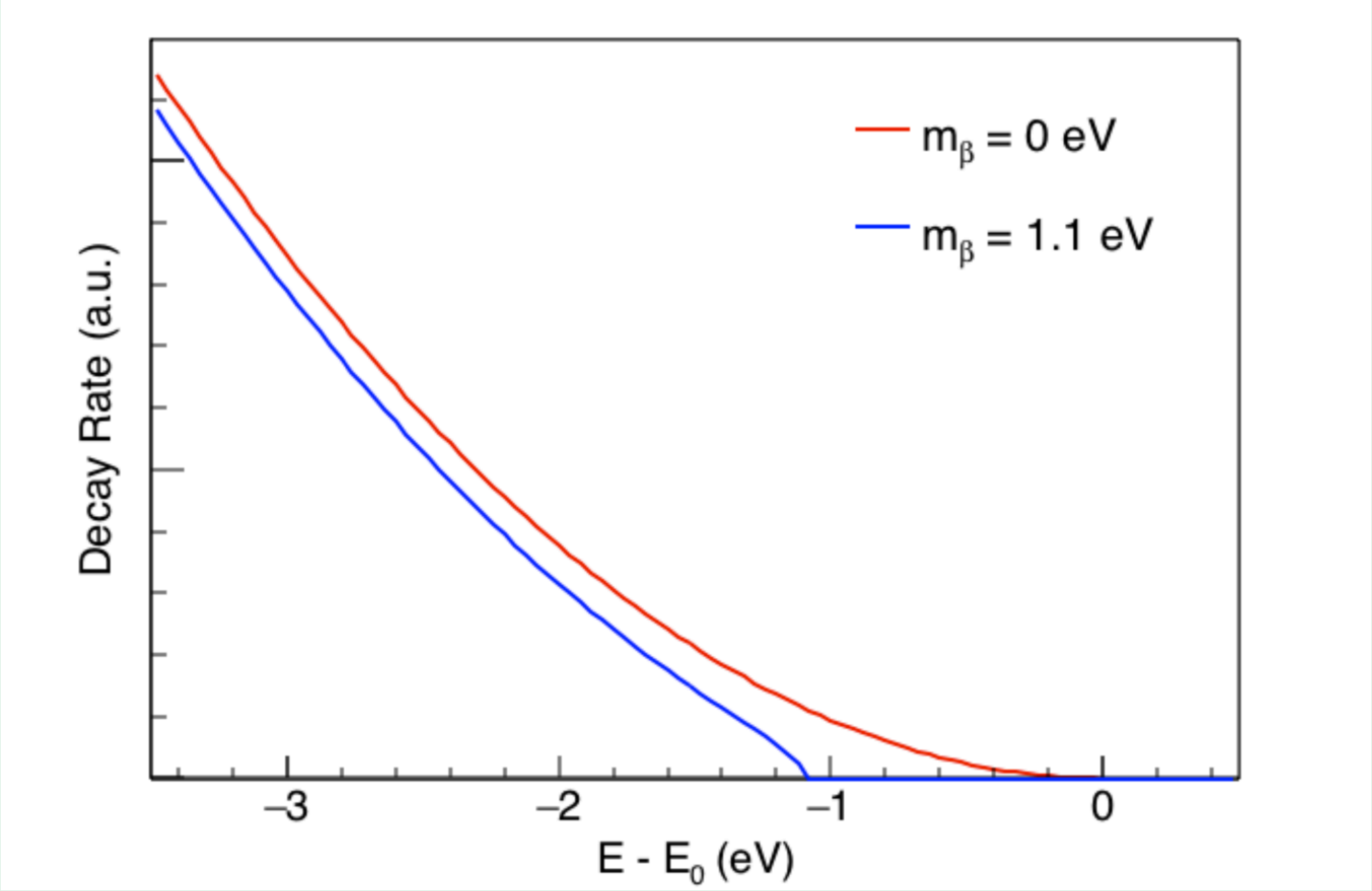
Δm_s^2	$10^{-4}\,\mathrm{eV}^2$	$0.01\,\mathrm{eV}^2$	$1.3\,\mathrm{eV}^2$
$\sin^2\theta_{14}$	0.1-0.2	0.0005-0.005	0.001-0.01

Tritium β 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



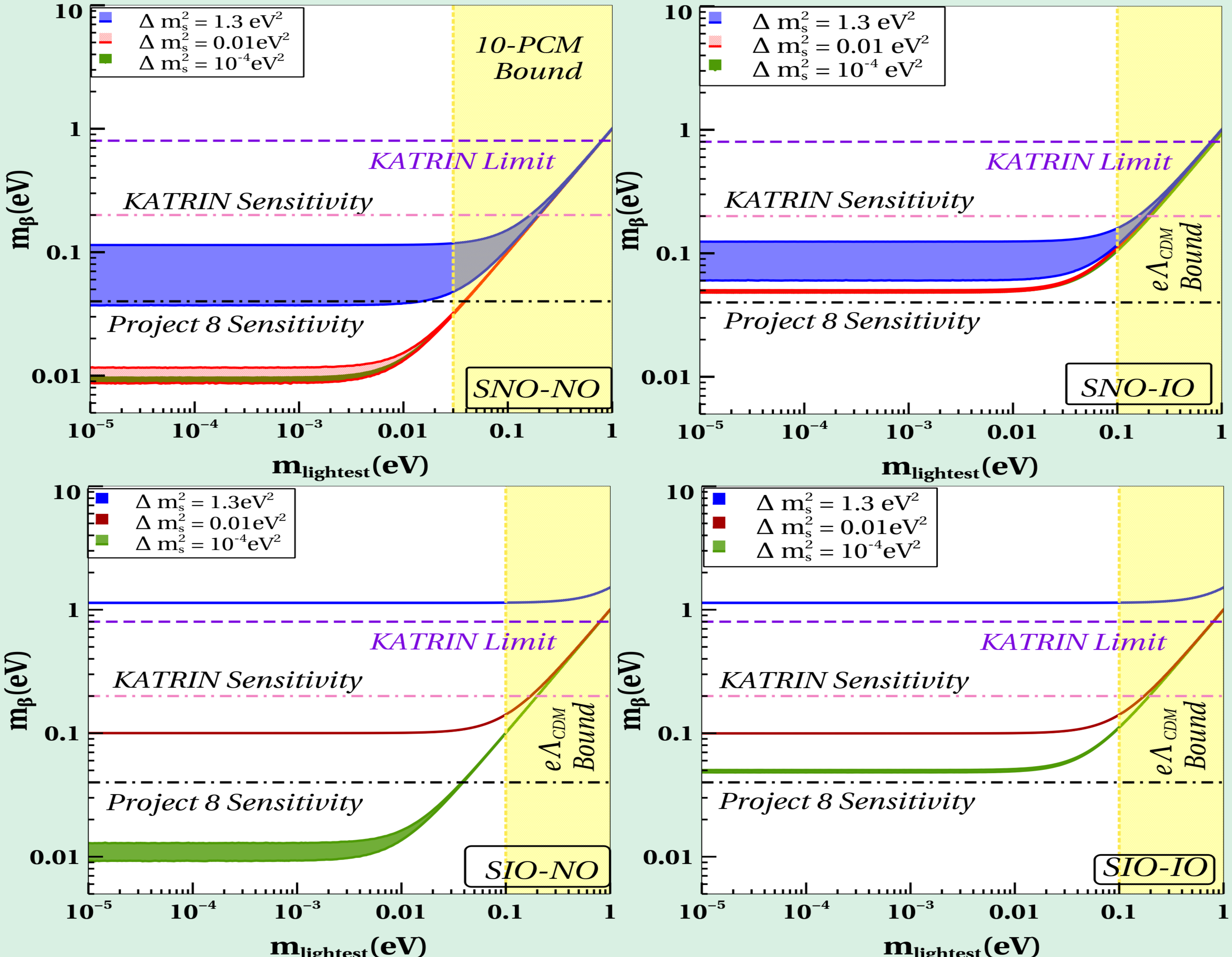
Tritium end-point energy spectrum for different m_β scenario

KATRIN Experiment

- Measures β decay spectrum from Tritium Isotope
- Current limit $m_\beta \lesssim 0.8$ eV
- Projected Sensitivity $m_\beta \lesssim 0.2$ 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 $m_\beta \lesssim 0.04$ eV



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

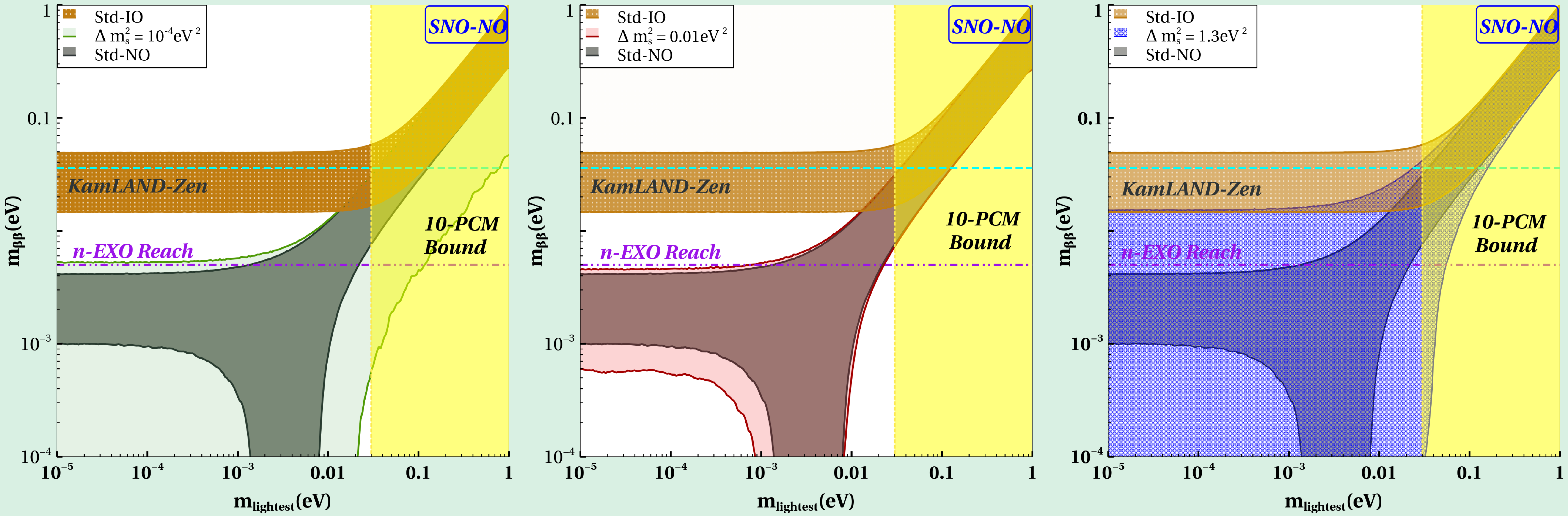
- Future experiments will be important to probe other scenarios

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

SNO-NO

lightest $\rightarrow m_1$

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

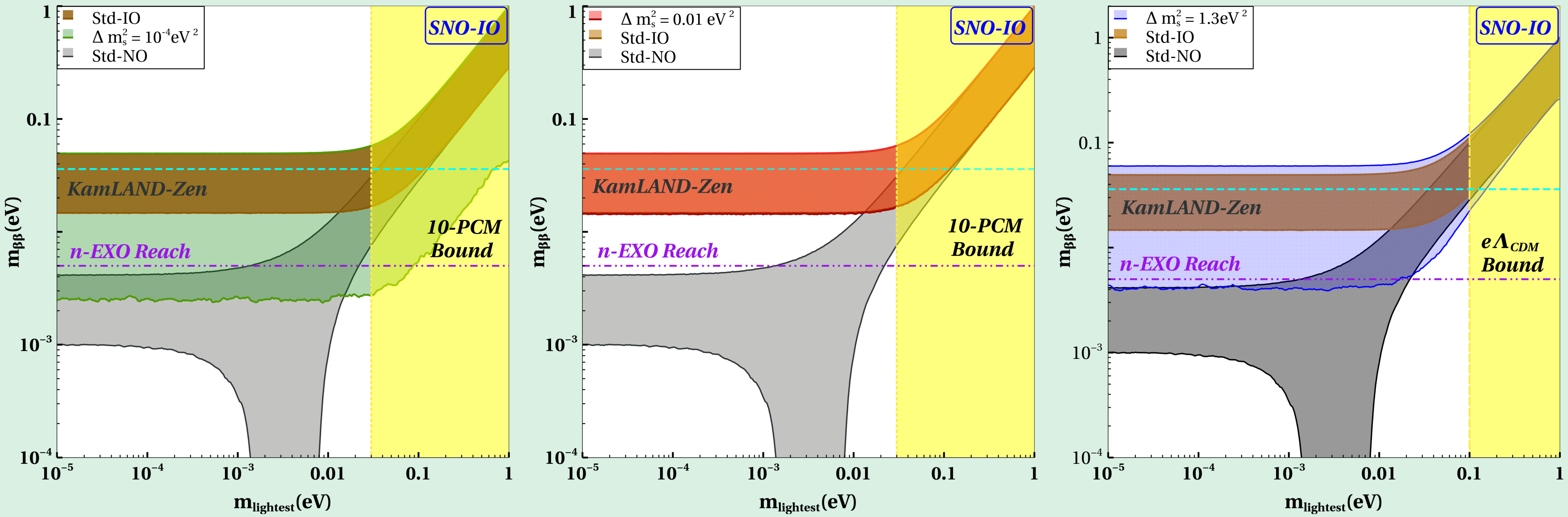


- For 10^{-4}eV^2 and 1.3eV^2 , cancellation region increase
- For $0.01\ \text{eV}^2$,cancellation shifts on the left

SNO-IO

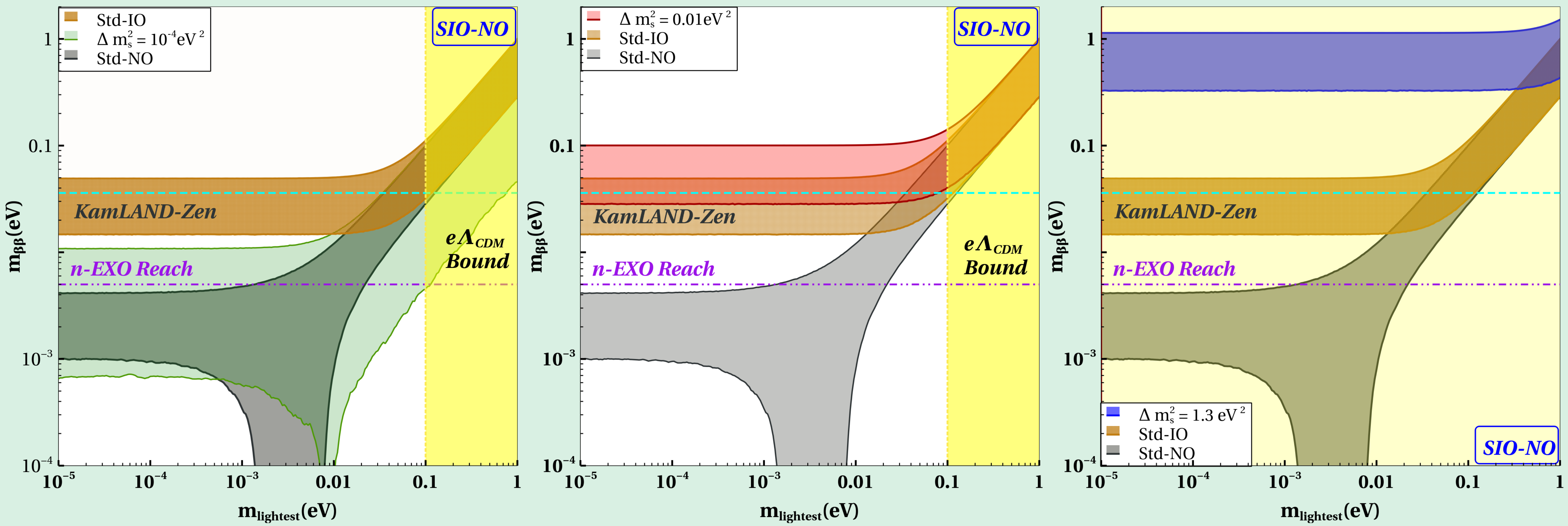
lightest $\rightarrow m_3$

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



- For 10^{-4}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

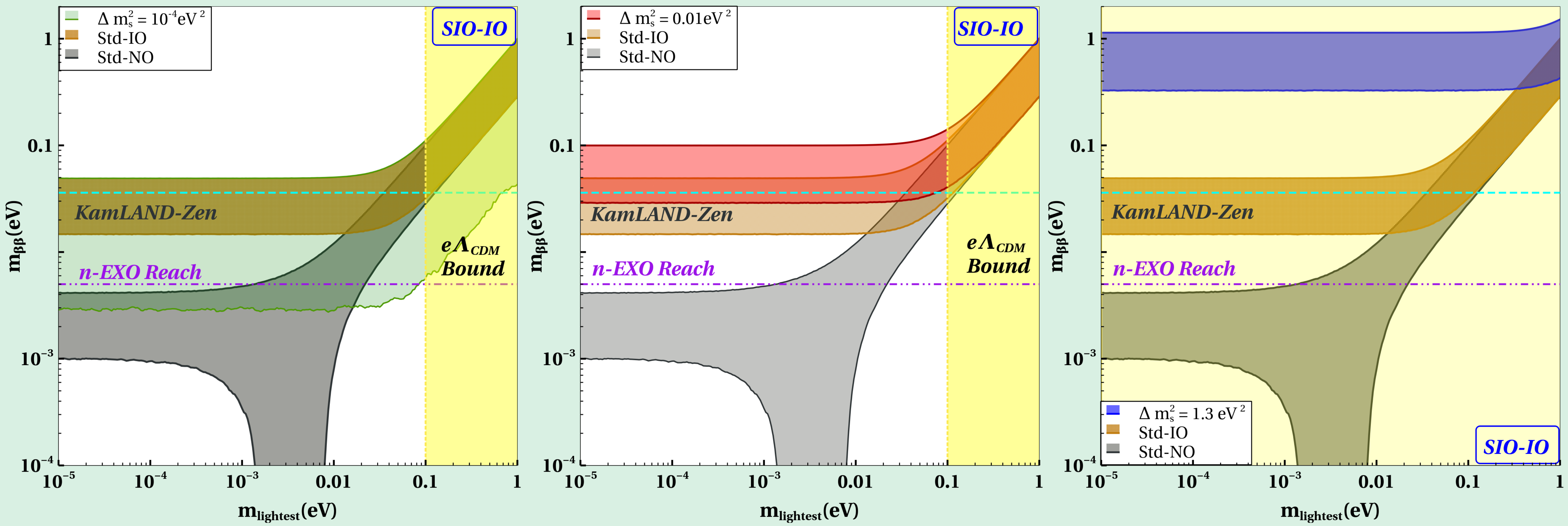
SIO-NO



lightest $\rightarrow m_4$

- Narrow region of cancellation 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