Neutrino physics opportunities at the $C\nu B$

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Outline

- Motivation
- Detection
- Neutrino physics
- Some results
- Conclusions

A New Probe of Relic Neutrino Clustering using Cosmogenic Neutrinos

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The detection of the cosmic neutrino background (CνB) is an extremely important problem in fundamental physics [1]. So far, there has been only indirect evidence for CνB from precise measurements of the primordial elemental abundances in big bang nucleosynthesis (BBN) [2], cosmic microwave background (CMB) [3], and large-scale structure (LSS) [4, 5]. However, the direct detection of CνB remains an open challenge, which is often dubbed as the "Holy Grail" of neutrino physics.

Motivation

✓ Early universe

✓ Non-relativistic neutrinos

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✗ Non-relativistic neutrinos

$$\sigma \sim G_F^2 m_\nu^2 \sim 10^{-56} \left(\frac{m_\nu}{1\,\mathrm{eV}}\right)^2 \mathrm{cm}^2$$

Neutrino mass hierarchy
[1, 7-8]

Sterile neutrinos
[1,9,11,17,19]

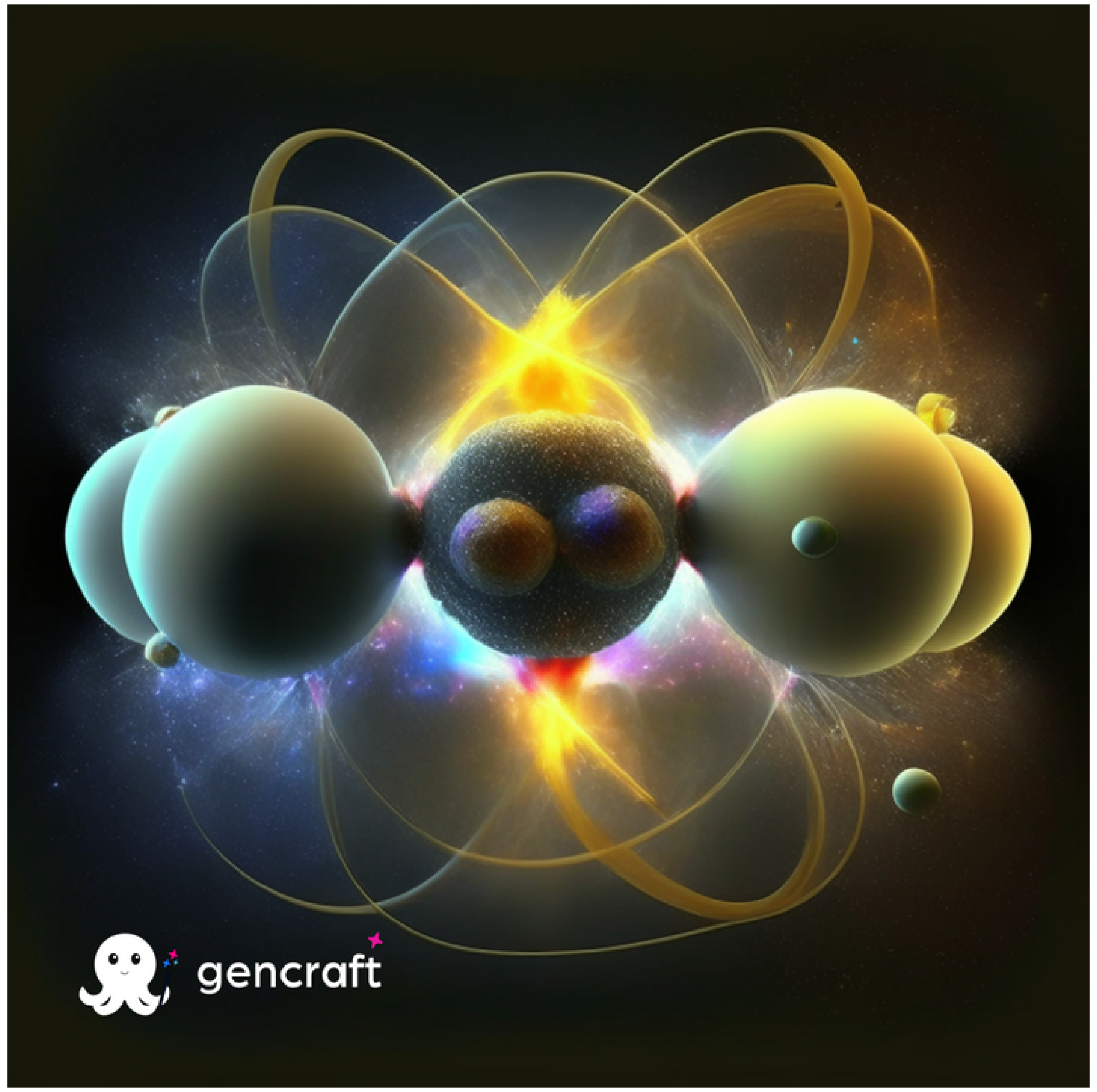
Dirac / Majorana
[1, 9-10]

Cosmological models
[11-14]

Neutrino Non-standard Interactions
[15-16]

Neutrino decay
[17-19]

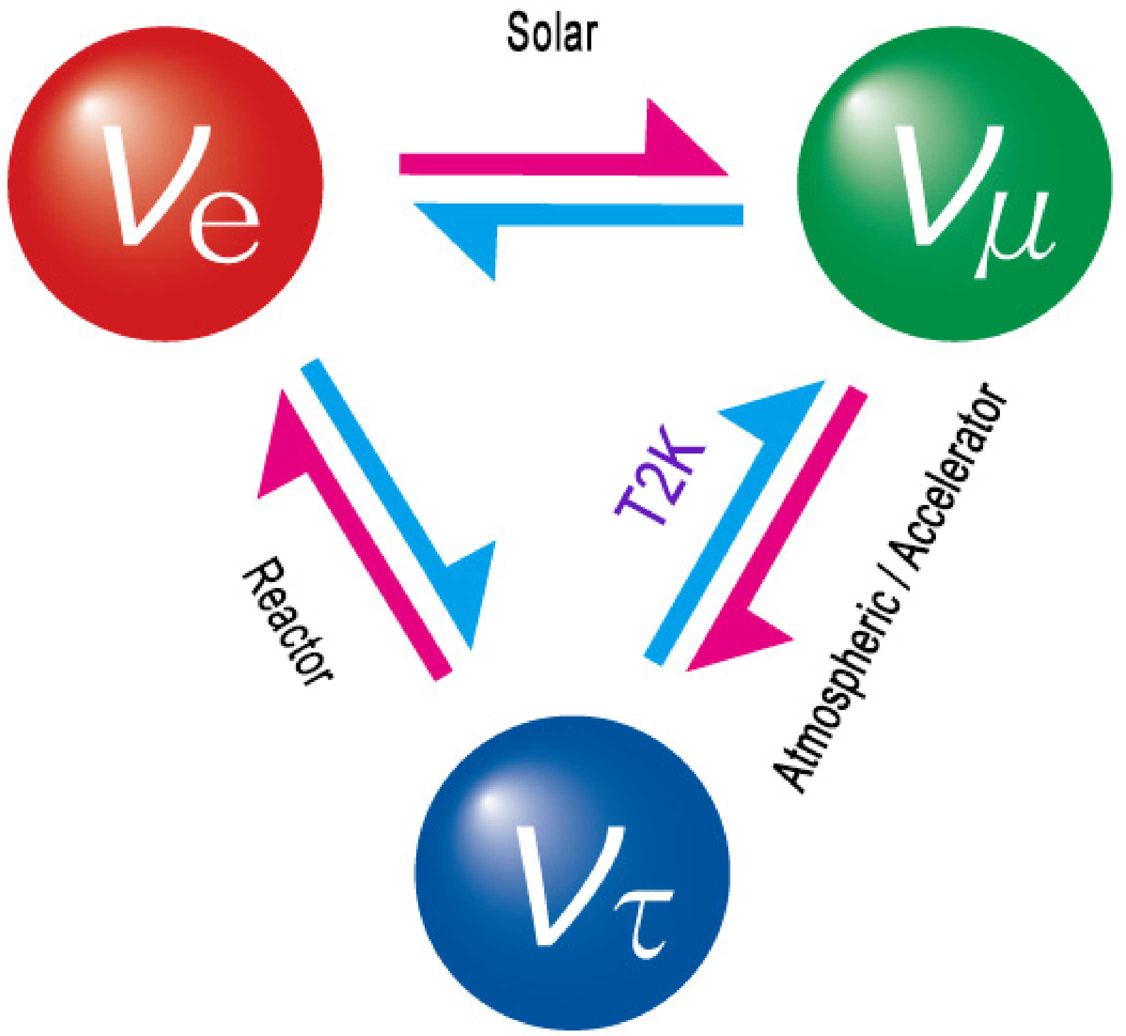
Neutrino oscillation and Mixing



Neutrino oscillation and Mixing

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

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$



Neutrino oscillation between three generations

Credit: J-PART

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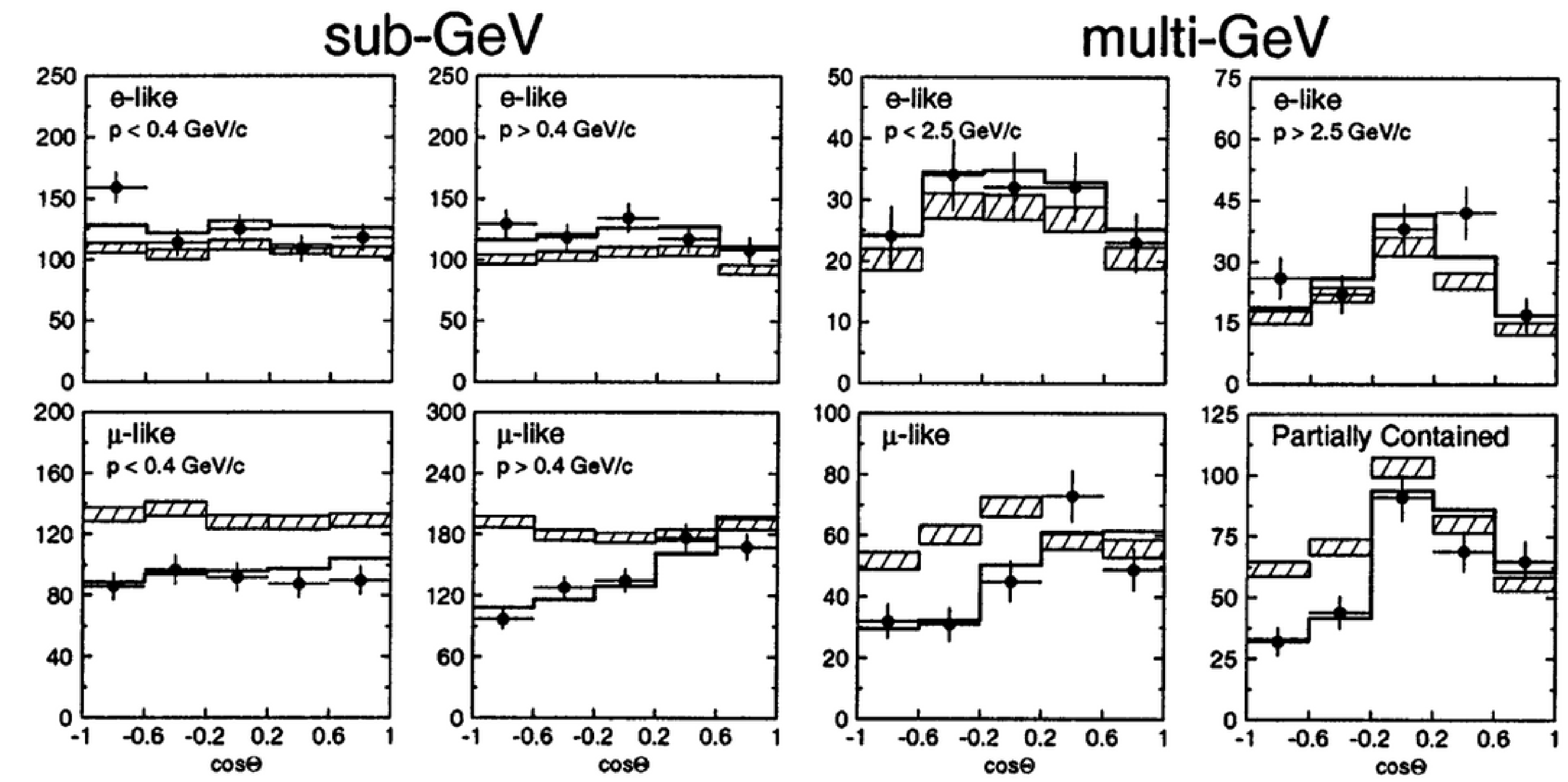
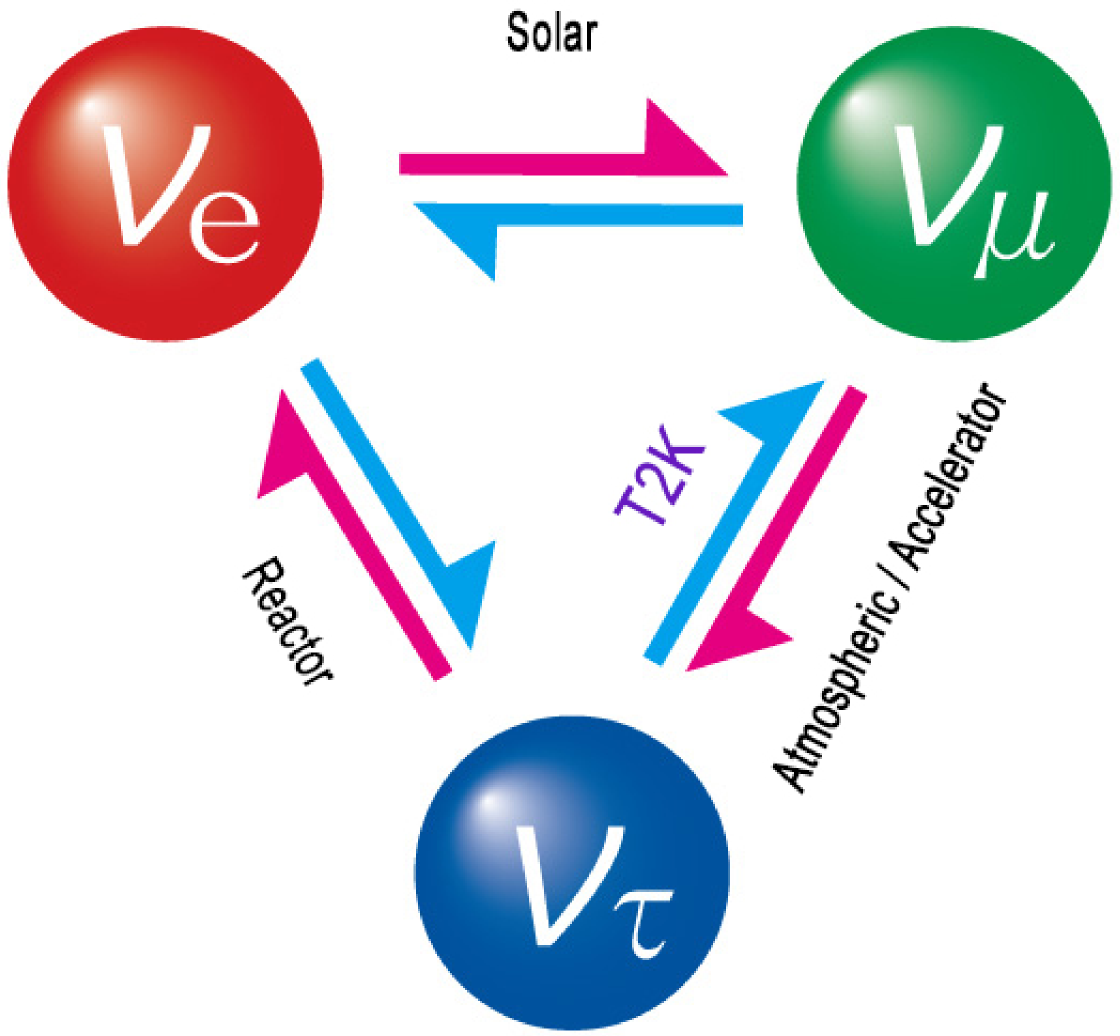


Super-Kamiokande Collaboration, Y. Fukuda et al., Evidence for oscillation of atmospheric neutrinos, Phys. Rev. Lett. 81 (Aug, 1998) 1562–1567.



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Neutrino oscillation parameters

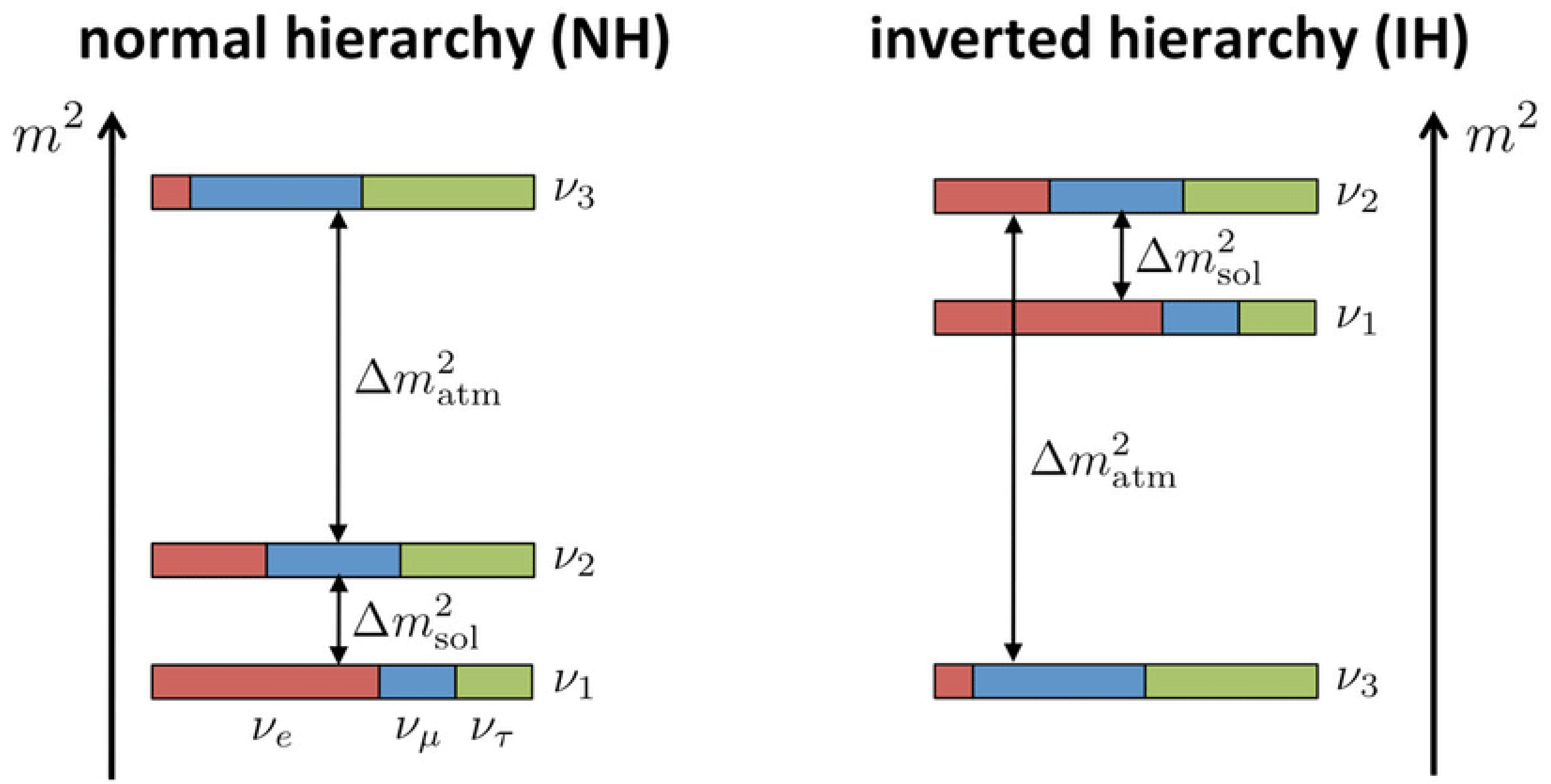
PMNS elements

$$|U| = \begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{bmatrix}$$

$$= \begin{bmatrix} 0.803 \sim 0.845 & 0.514 \sim 0.578 & 0.142 \sim 0.155 \\ 0.233 \sim 0.505 & 0.460 \sim 0.693 & 0.630 \sim 0.779 \\ 0.262 \sim 0.525 & 0.473 \sim 0.702 & 0.610 \sim 0.762 \end{bmatrix}$$

Intervals of 3σ C.L.
PDG 2022 - Global fits

Mass square difference



Credits: JUNO Collaboration,
S. Vagnozzi, Weigh them all! - Cosmological searches for the neutrino mass scale and mass ordering.
PhD thesis, 06, 2019.

CνB detection

- Neutrino Capture

$$^3\mathrm{H} + \nu_e \rightarrow {}^3\mathrm{He} + e^-$$

- Tritium β-decay

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

[1] PTOLEMY Collaboration, M. G. Betti et al., Neutrino physics with the PTOLEMY project: active neutrino properties and the light sterile case, JCAP 07 (2019) 047, [1902.05508].

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Capture rate

$$\Gamma_i = N_T |U_{ei}|^2 \bar{\sigma} v_\nu f_{c,i} n_0$$

$$\bar{\sigma} = \frac{G_F^2}{2\pi v_\nu} F(Z, E_e) \frac{m_{^3\mathrm{He}}}{m_{^3\mathrm{H}}} E_e p_e (|F|^2 + g_A^2 |GT|^2),$$

$$\frac{d\widetilde{\Gamma}_{\mathrm{CNB}}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}(\Delta/\sqrt{8\ln 2})} \sum_{i=1}^{N_\nu} \Gamma_i \times \exp\left\{ -\frac{[E_e - (E_{\mathrm{end}} + m_i + m_{\mathrm{lightest}})]^2}{2(\Delta/\sqrt{8\ln 2})^2} \right\}$$

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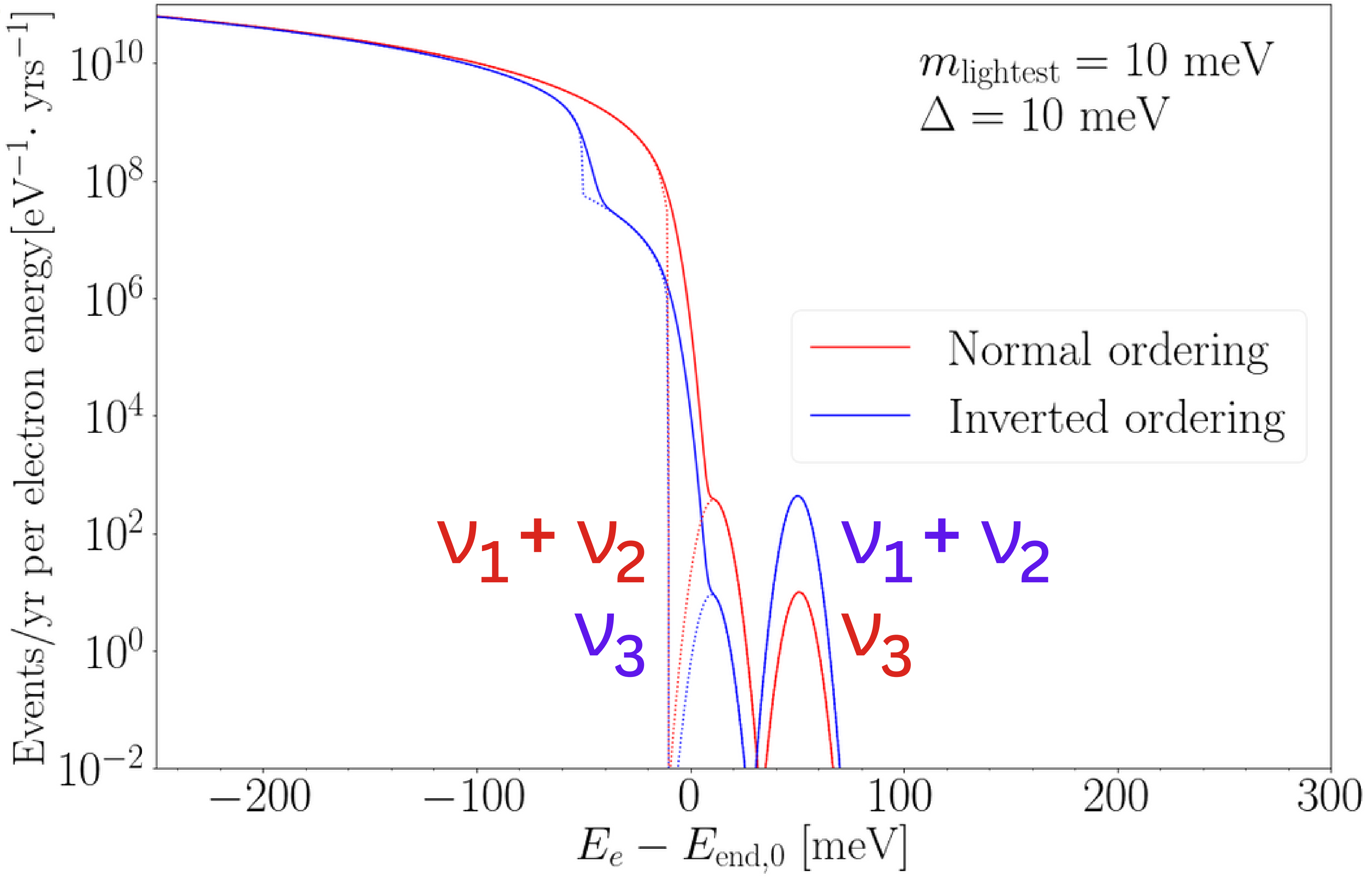

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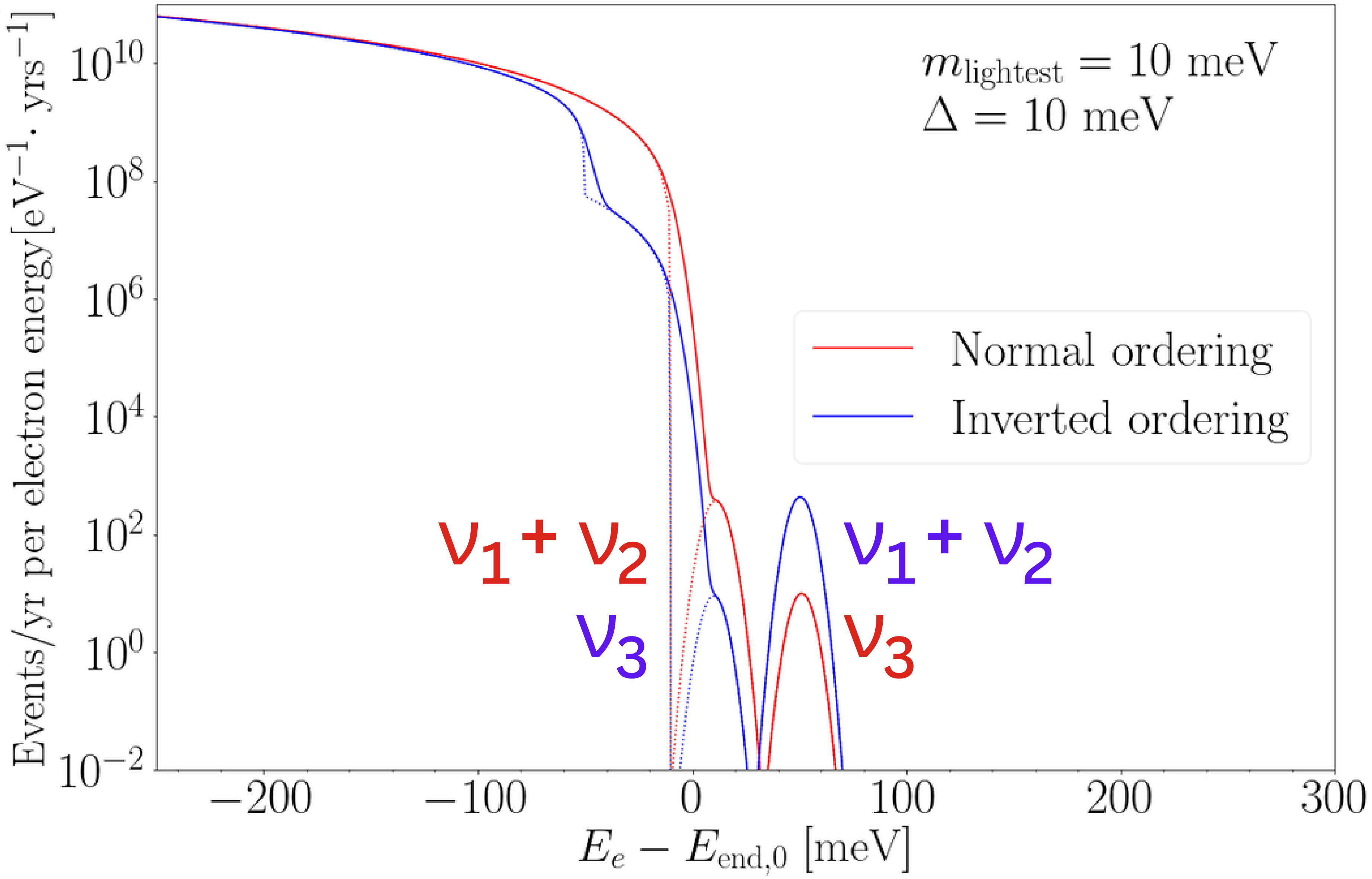
Neutrino gravitational clustering factor [2-6]

$$f_{c,i} = 76.5 \left(\frac{m_i}{\mathrm{eV}}\right)^{2.21},$$



[2] J. Zhang and X. Zhang, Gravitational clustering of cosmic relic neutrinos in the Milky Way, Nature Commun. 9 (2018) 1833, [1712.01153].
[3] A. Ringwald and Y. Y. Y. Wong, Gravitational clustering of relic neutrinos and implications for their detection, JCAP 12 (2004) 005, [hep-ph/0408241].
[4] P. F. de Salas, S. Gariazzo, J. Lesgourgues, and S. Pastor, Calculation of the local density of relic neutrinos, JCAP 09 (2017) 034, [1706.09850].
[5] E. B. Holm, I. M. Oldengott, and S. Zentarra, Local clustering of relic neutrinos with kinetic field theory (2023), 2305.13379.
[6] V. Brdar, P. S. B. Dev, R. Plestid, and A. Soni, A new probe of relic neutrino clustering using cosmogenic neutrinos, Phys. Lett. B 833 (2022) 137358, [2207.02860].

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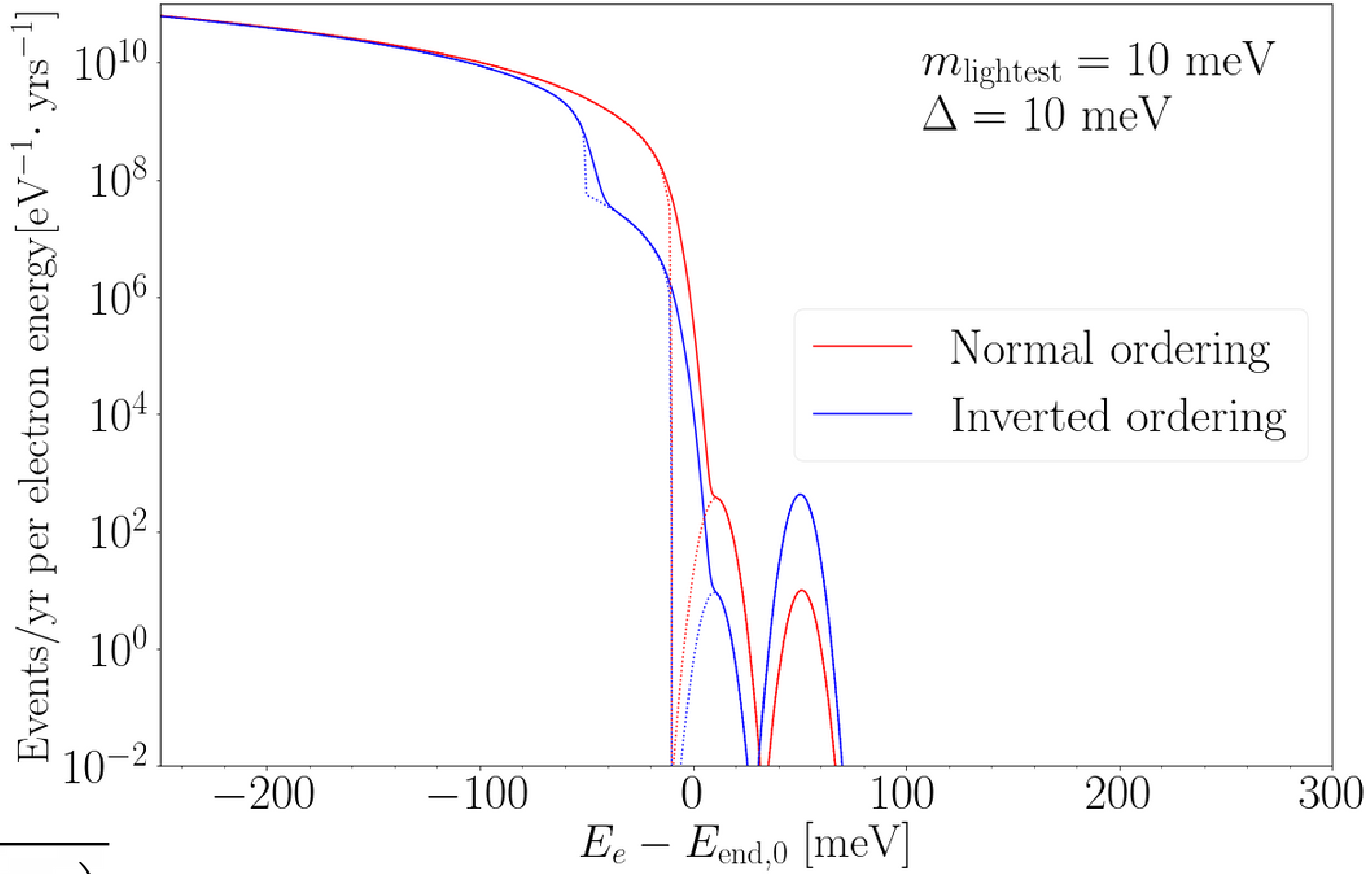
Tritium β-decay rate [7]

$$\frac{d\Gamma_\beta}{dE_e} = \frac{\bar{\sigma}}{\pi^2} N_T \sum_{i=1}^{N_\nu} |U_{ei}|^2 H(E_e, m_i),$$

$$H(E_e, m_i) = \frac{1 - m_e^2/E_e m_{^3H}}{(1 - 2E_e/m_{^3H}^2 + m_e^2/m_{^3H}^2)^2} \sqrt{y\left(y + \frac{2m_i m_{^3He}}{m_{^3H}}\right)} \times \left[y + \frac{m_i}{m_{^3H}}(m_{^3He} + m_i)\right],$$



[7] S. S. Masood, S. Nasri, J. Schechter, M. Tórtola, J. W. F. Valle, and C. Weinheimer, Exact relativistic beta decay endpoint spectrum, Phys. Rev. .C 76 (2007) 045501, [arXiv:0706.0897].
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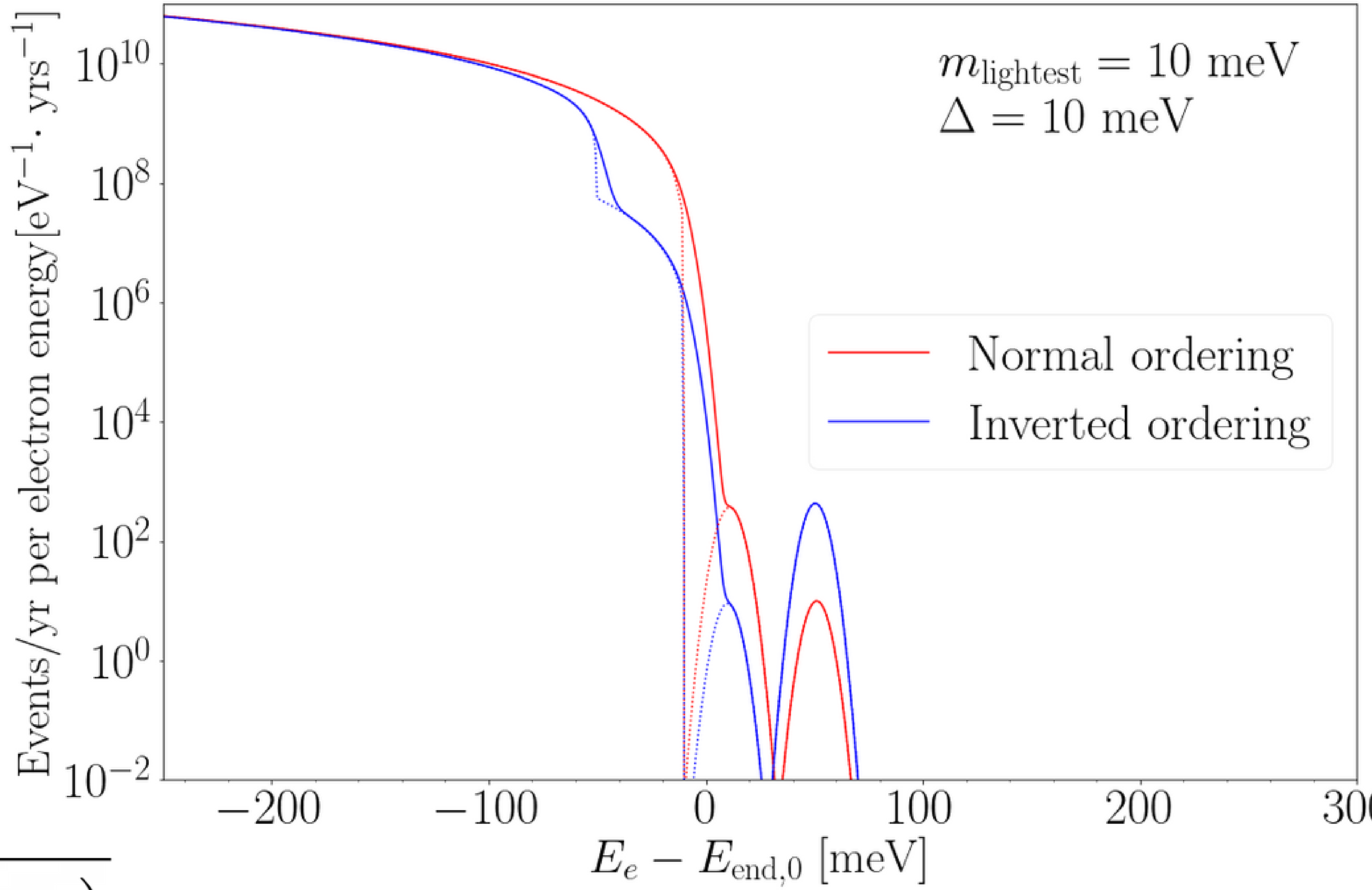

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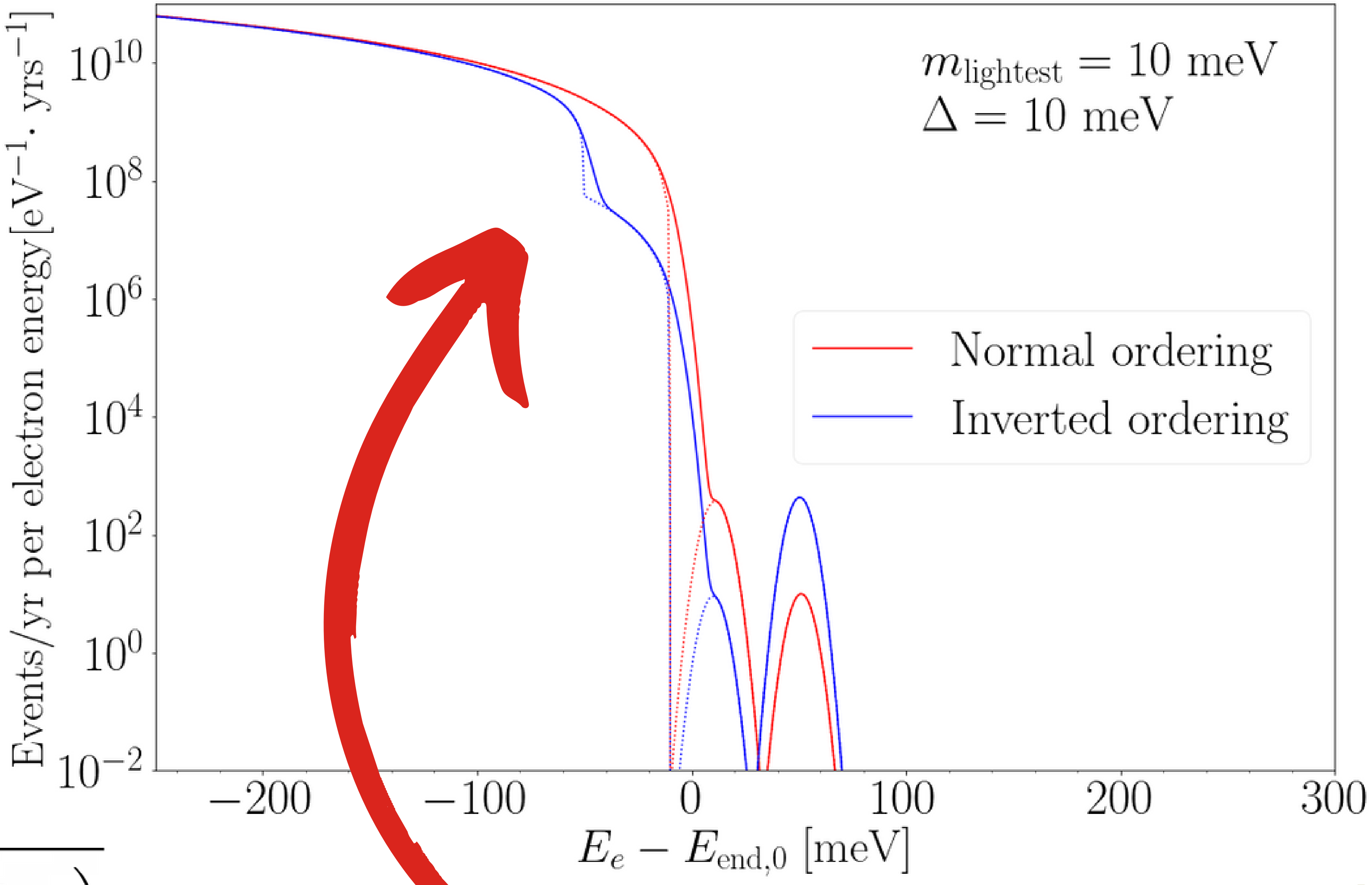

$$|U_{e1}|^2 \simeq 0.681, \quad |U_{e2}|^2 \simeq 0.297, \quad |U_{e3}|^2 \simeq 0.0222.$$
$$\Delta m_{21}^2 = 7.4 \times 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m_{3\ell}|^2 \approx 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

[7] S. S. Masood, S. Nasri, J. Schechter, M. Tórtola, J. W. F. Valle, and C. Weinheimer, Exact relativistic beta decay endpoint spectrum, Phys. Rev. .C 76 (2007) 045501, [arXiv:0706.0897].
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Dirac vs. Majorana

We expect for each degree of freedom...

$$n_0 \approx 56 \text{ cm}^{-3}$$

$$\nu_L \quad h = -1$$

$$\nu_R(\nu_L^C) \quad h = +1$$

[9] A. J. Long, C. Lunardini, and E. Sabancilar, Detecting non-relativistic cosmic neutrinos by capture on
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$$\mathcal{L}_{\mathrm{Maj}} = m_M\, \overline{\nu_L^C} \nu_L$$
$$\mathcal{L}_{\mathrm{Dirac}} = m_D\, \overline{\nu_R} \nu_L$$

...but CνB neutrinos today are non-relativistic

$\nu_L \quad h = -1 \longrightarrow \nu_L + \nu_R(\nu_L + \nu_L^C)$

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Majorana condition: $\nu_L^C \propto \nu_L$

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Majorana condition: $\nu_L^C \propto \nu_L$

$$\Gamma_{\mathrm{C}\nu\mathrm{B}} = \sum_{j=1}^{3} |U_{ej}|^2\, \bar{\sigma}\, [n_j(\nu_{h_R}) + n_j(\nu_{h_L})]\, N_{\mathrm{T}} = \bar{\sigma} \left[n(\nu_{h_R}) + n(\nu_{h_L})\right] N_{\mathrm{T}}$$

Therefore

$$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} = 2\,\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}}$$

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Cosmological models

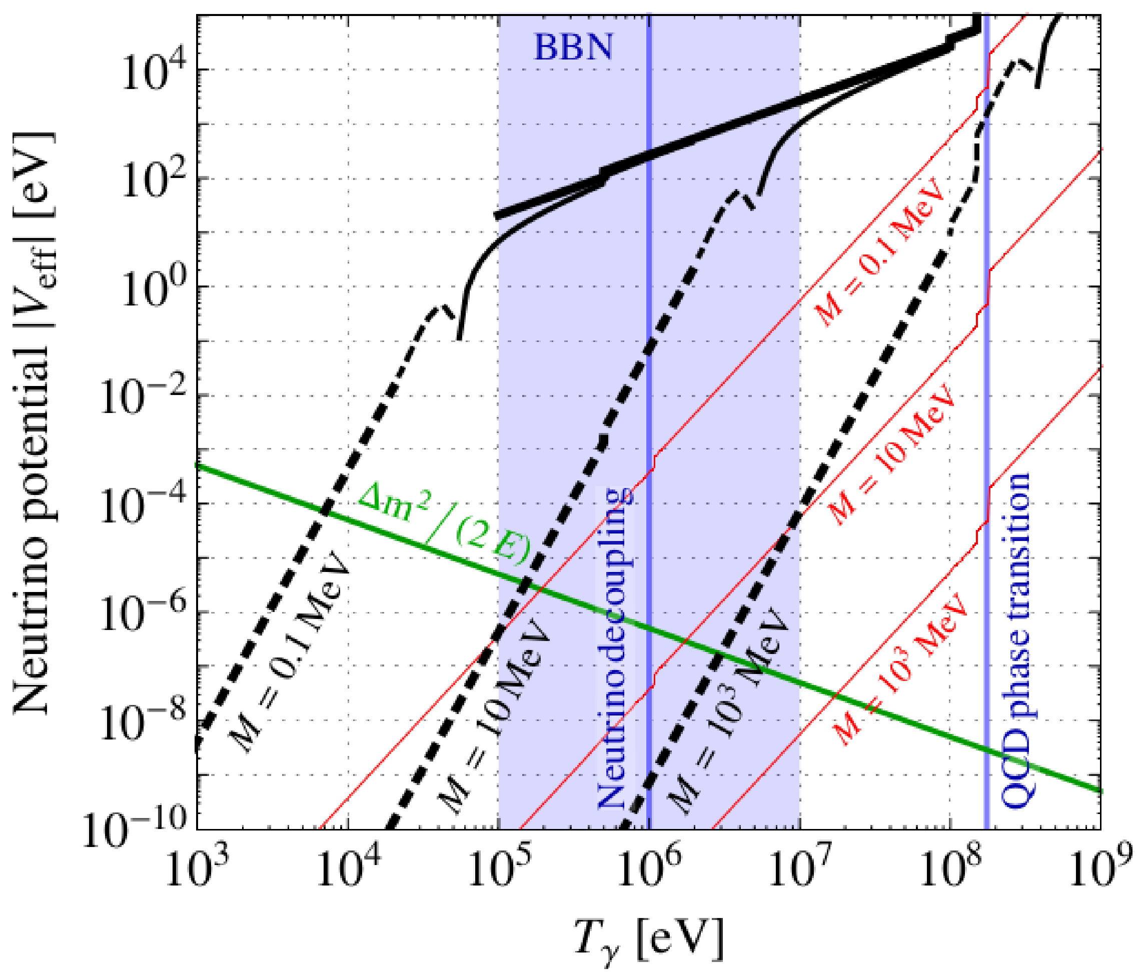

Figure taken from Ref. [11]

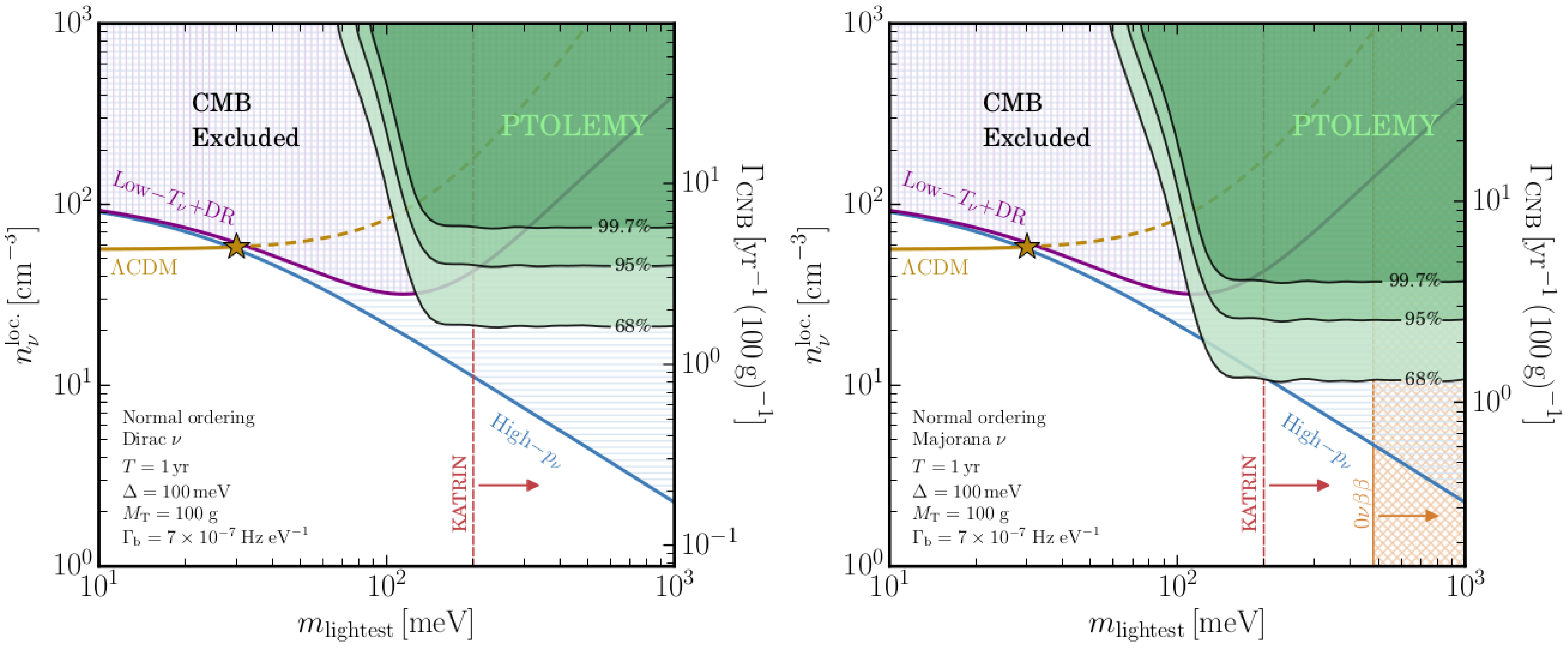

Figure taken from Ref. [14]

[11] B. Dasgupta and J. Kopp, Cosmologically Safe eV-Scale Sterile Neutrinos and Improved Dark Matter Structure, Phys. Rev. Lett. 112 (2014), no. 3 031803, [1310.6337].

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NSI in CνB

$$\mathscr{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{ud} U_{ej} \left\{ [\bar{e}\gamma^\mu(1-\gamma^5)\nu_j][\bar{u}\gamma_\mu(1-\gamma^5)d] + \sum_{l,q} \epsilon_{lq} [\bar{e}\mathcal{O}_l \nu_j][\bar{u}\mathcal{O}_q d] \right\} + \text{h.c.} \, ,$$

ϵ_{lq}	$\mathcal{O}_l$	$\mathcal{O}_q$
ϵ_{LL}	$\gamma^\mu(1-\gamma^5)$	$\gamma_\mu(1-\gamma^5)$
ϵ_{LR}	$\gamma^\mu(1-\gamma^5)$	$\gamma_\mu(1+\gamma^5)$
ϵ_{LS}	$1-\gamma^5$	1
ϵ_{LT}	$\sigma^{\mu\nu}(1-\gamma^5)$	$\sigma_{\mu\nu}(1-\gamma^5)$

[15] I. K. Banerjee, U. K. Dey, N. Nath, and S. S. Shariff, Testing generalized neutrino interactions with PTOLEMY (2023), 2304.02505.

[16] M. Arteaga, E. Bertuzzo, Y. F. Perez-Gonzalez, and R. Zukanovich Funchal, Impact of Beyond the Standard Model Physics in the Detection of the Cosmic Neutrino Background, JHEP 09 (2017) 124, [1708.07841].

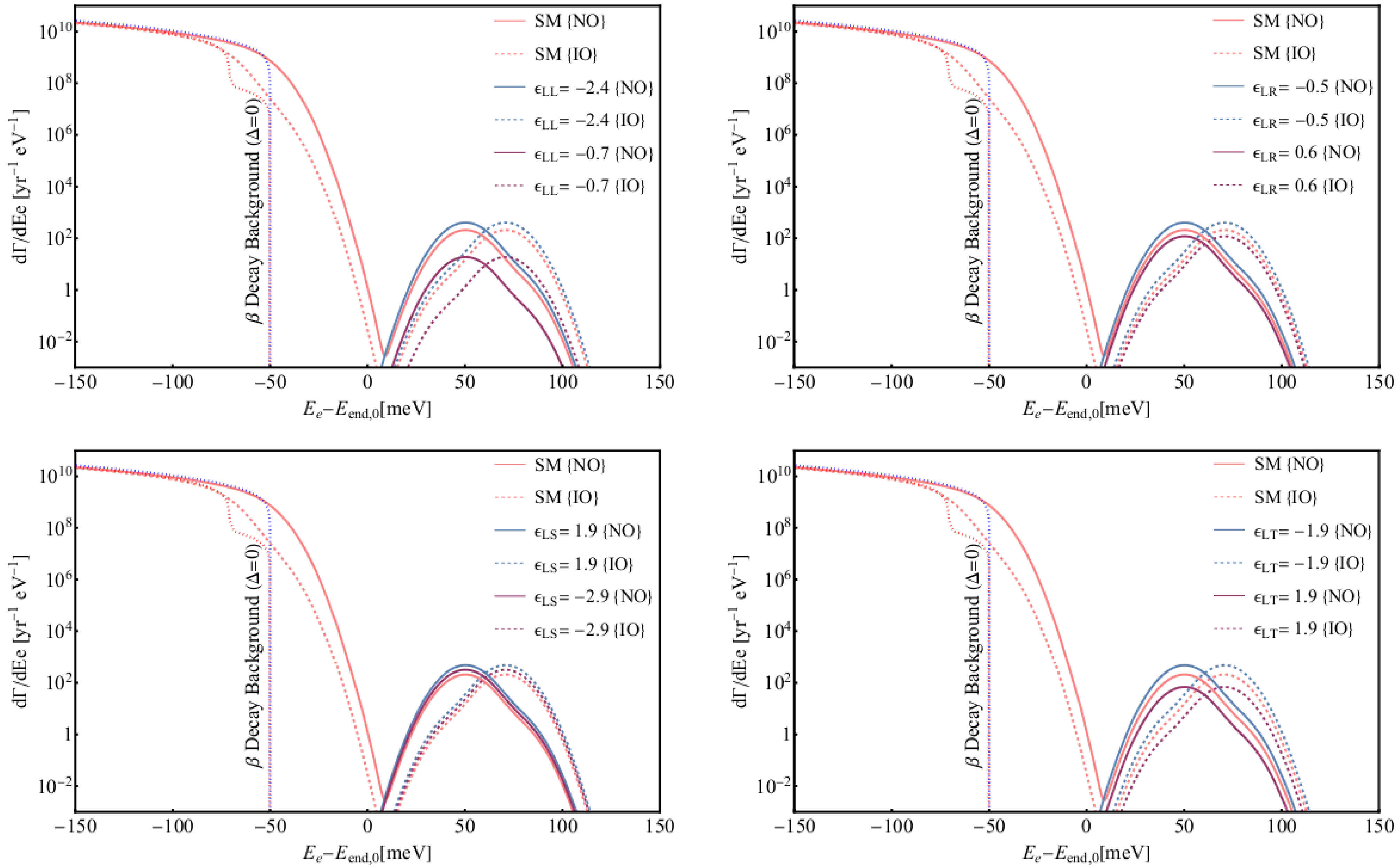

Figure taken from Ref. [15]

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Work in progress: Impact of Neutrino Decay on the Cosmic Neutrino Background

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Joachim Kopp
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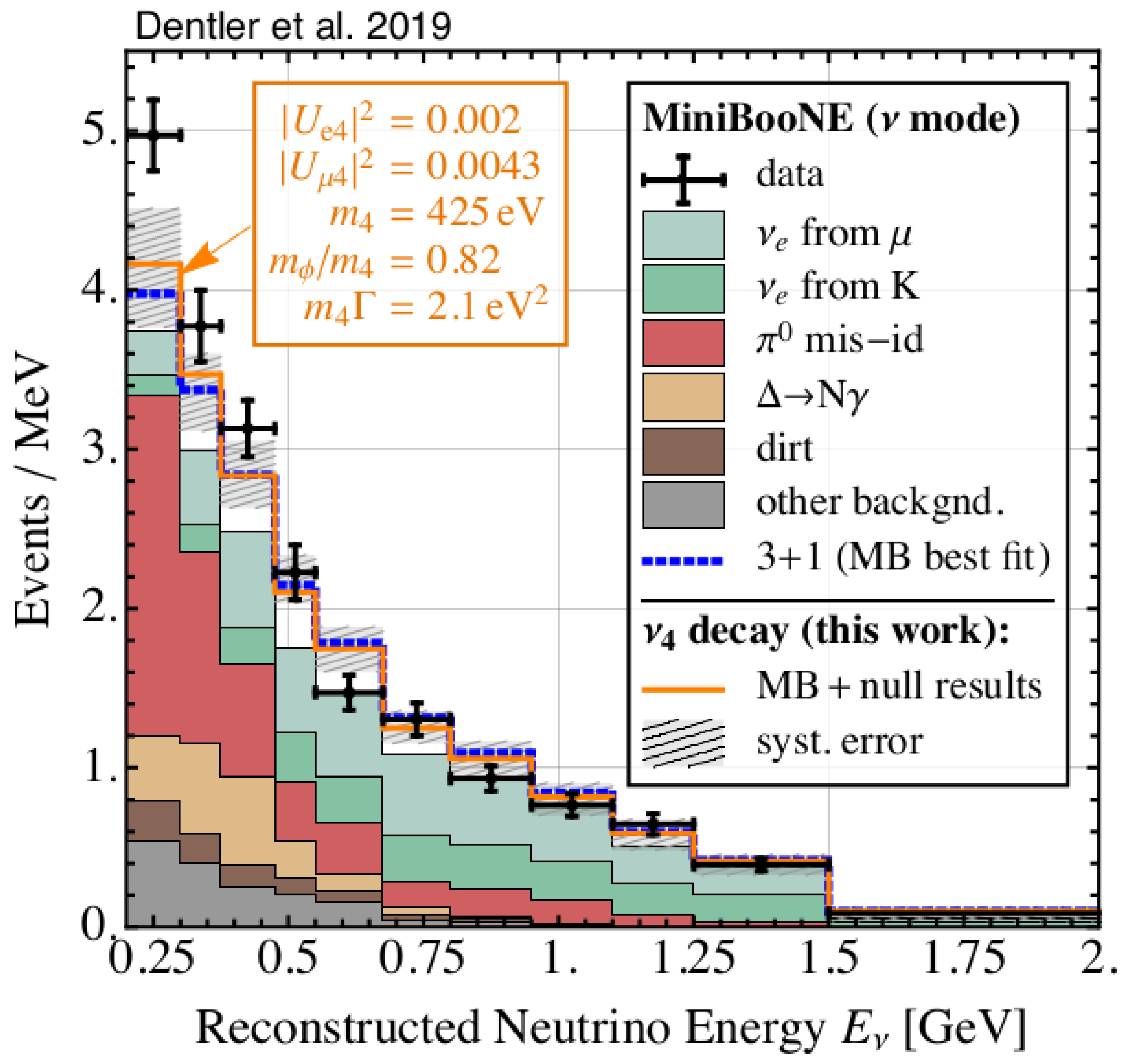
Short-Baseline Anomalies



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[21] M. Hostert and M. Pospelov, Constraints on decaying sterile neutrinos from solar antineutrinos, Phys. Rev. D 104 (2021)

Non-Standard scenario

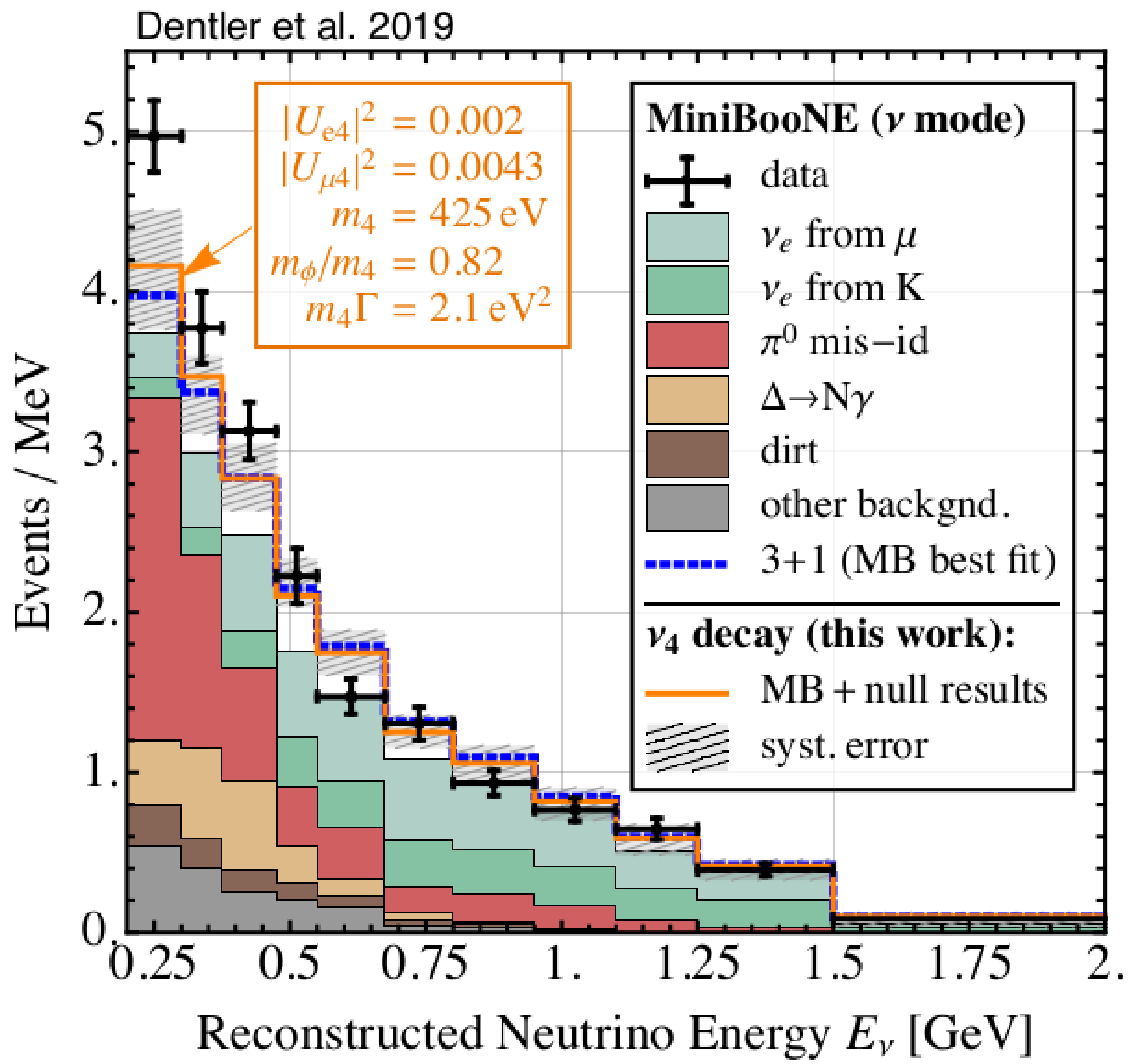
- Neutral scalar
- Sterile neutrino

$$-\mathcal{L} = g_\phi \overline{\nu_s}\nu_s\phi + \sum_{\alpha,\beta} m_{\alpha,\beta}\overline{\nu_\alpha}\nu_\beta$$

$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i$$

$$\alpha,\beta = e,\mu,\tau,s$$

Short-Baseline Anomalies



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- Neutral scalar $$-\mathcal{L} = g_\phi \overline{\nu_s}\nu_s\phi + \sum_{\alpha,\beta} m_{\alpha,\beta}\overline{\nu_\alpha}\nu_\beta$$
- Sterile neutrino $$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i \qquad \alpha,\beta = e,\mu,\tau,s$$

Induces neutrino decay

Two-body decays ➜ $\nu_i \to \nu_j\phi \to \nu_j\nu_k\bar{\nu}_l$

$$\Gamma_i(\nu_i \to \nu_j\phi) = \frac{g_\phi^2}{16\pi} m_i \left(1 - \frac{m_\phi^2}{m_i^2}\right)^2 |U_{si}^* U_{sj}|^2$$

$$\Gamma_\phi(\phi \to \nu_i\overline{\nu_j}) = \frac{g_\phi^2}{8\pi} m_\phi |U_{si}^* U_{sj}|^2$$

Three-body decays ➜ $\nu_i \to \nu_j\nu_k\bar{\nu}_l$

$$\Gamma(\nu_i \to \nu_j\bar{\nu}_k\nu_l) = \frac{1}{(2\pi)^3}\frac{g_\phi^4}{32 m_i^3}|U_{si}^* U_{sj} U_{sk}^* U_{sl}| \int |\mathcal{M}|^2 dm_{jk}^2 dm_{kl}^2$$

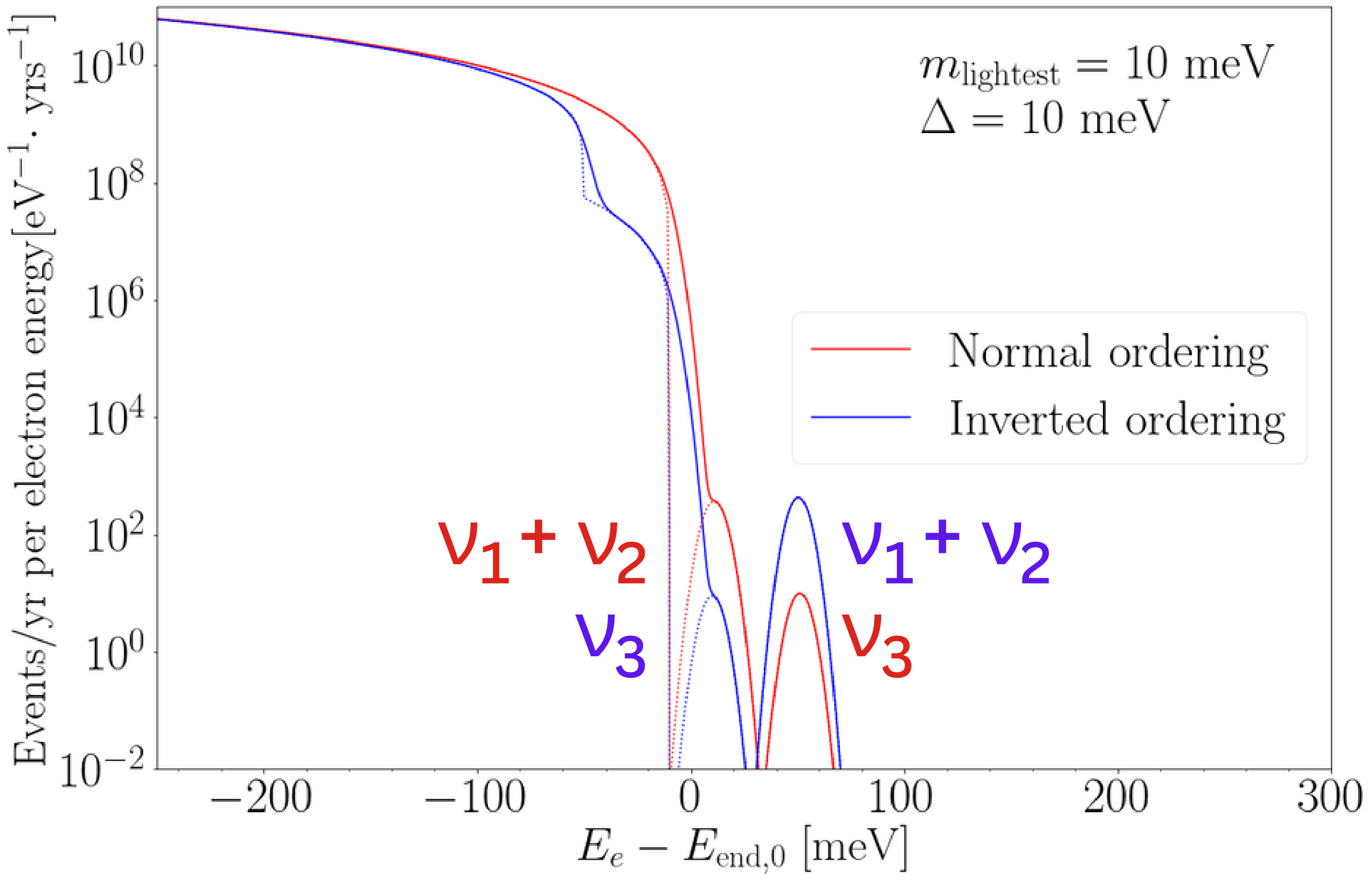
CνB detection

- Neutrino Capture

$$^3\mathrm{H} + \nu_e \rightarrow {}^3\mathrm{He} + e^-$$

- Tritium β-decay

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



Non-Standard scenario

- Neutral scalar

$$-\mathcal{L} = g_\phi \overline{\nu_s}\nu_s\phi + \sum_{\alpha,\beta} m_{\alpha,\beta}\overline{\nu_\alpha}\nu_\beta$$

- Sterile neutrino

$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i$$

$$\alpha, \beta = e, \mu, \tau, s$$

Induces neutrino decay

Two-body decays ➜ $\nu_i \rightarrow \nu_j\phi \rightarrow \nu_j\nu_k\bar{\nu}_l$

$$\Gamma_i(\nu_i \rightarrow \nu_j\phi) = \frac{g_\phi^2}{16\pi} m_i \left(1 - \frac{m_\phi^2}{m_i^2}\right)^2 |U_{si}^* U_{sj}|^2$$

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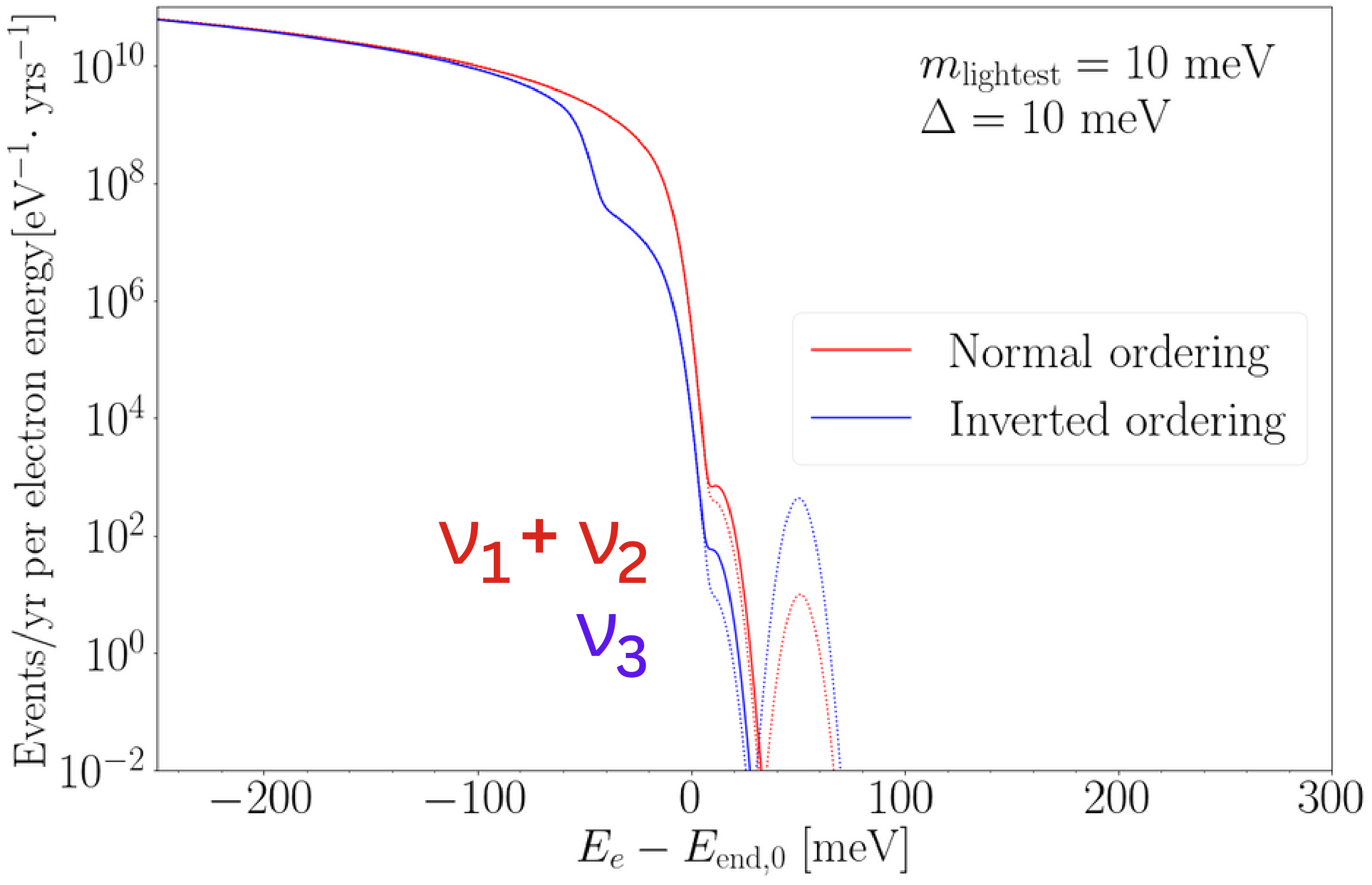

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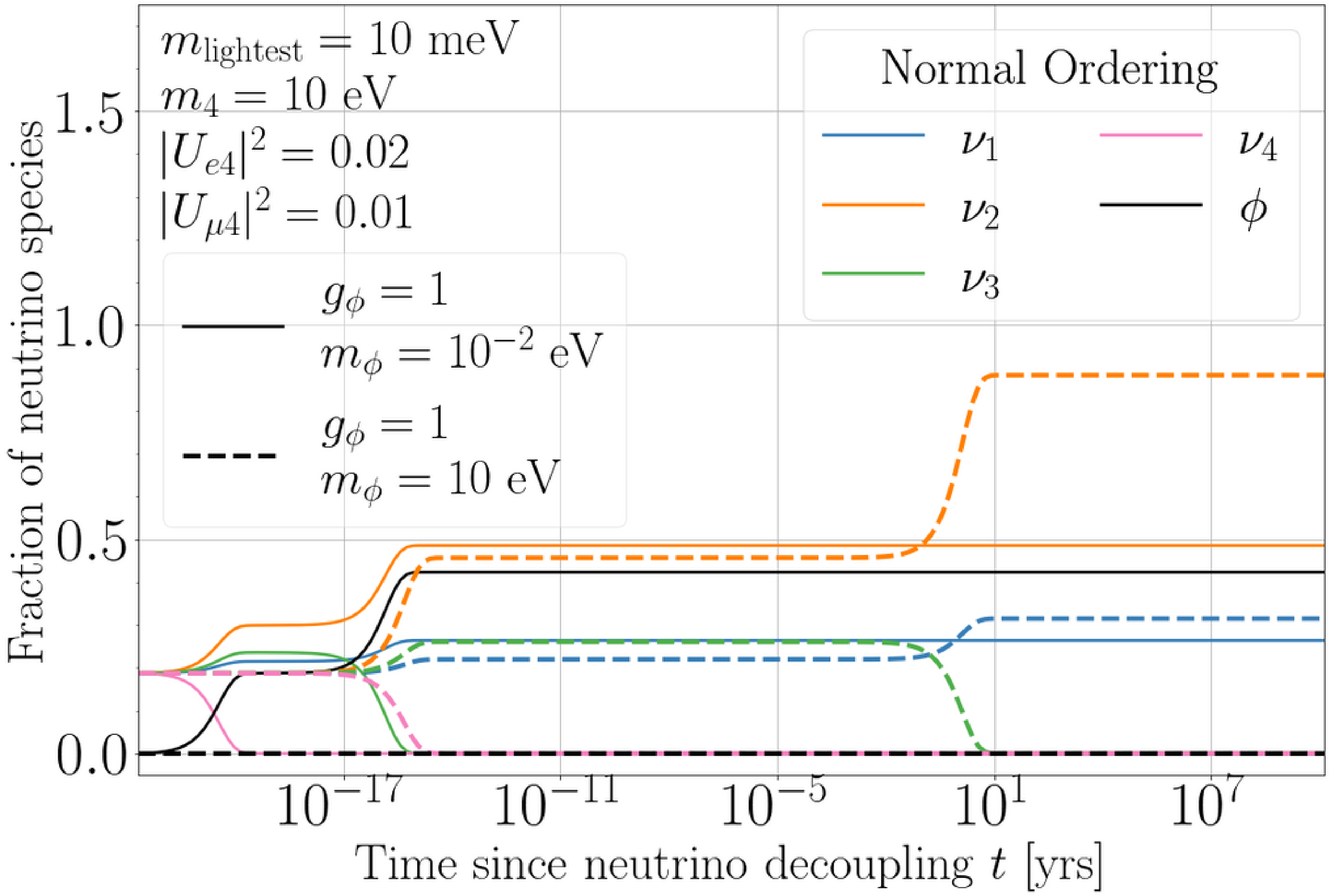
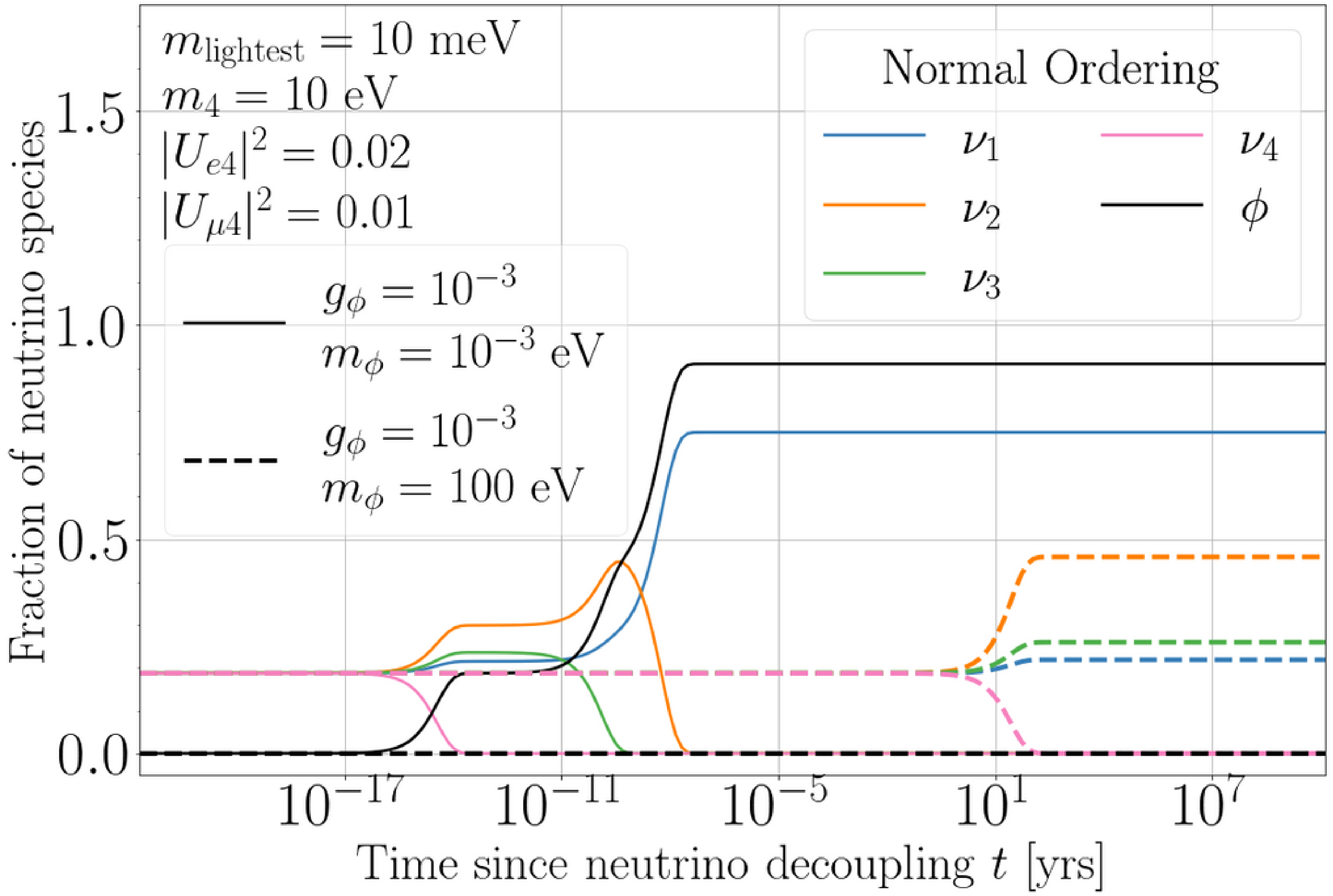
1. Proportion of neutrino mass states at present times

Solving the differential equation for the neutrino evolution with decay:





METHOD

1. Proportion of neutrino mass states at present times

2. Binned/smeared spectrum

- Bin width 10 meV in [-5, 10] eV range.

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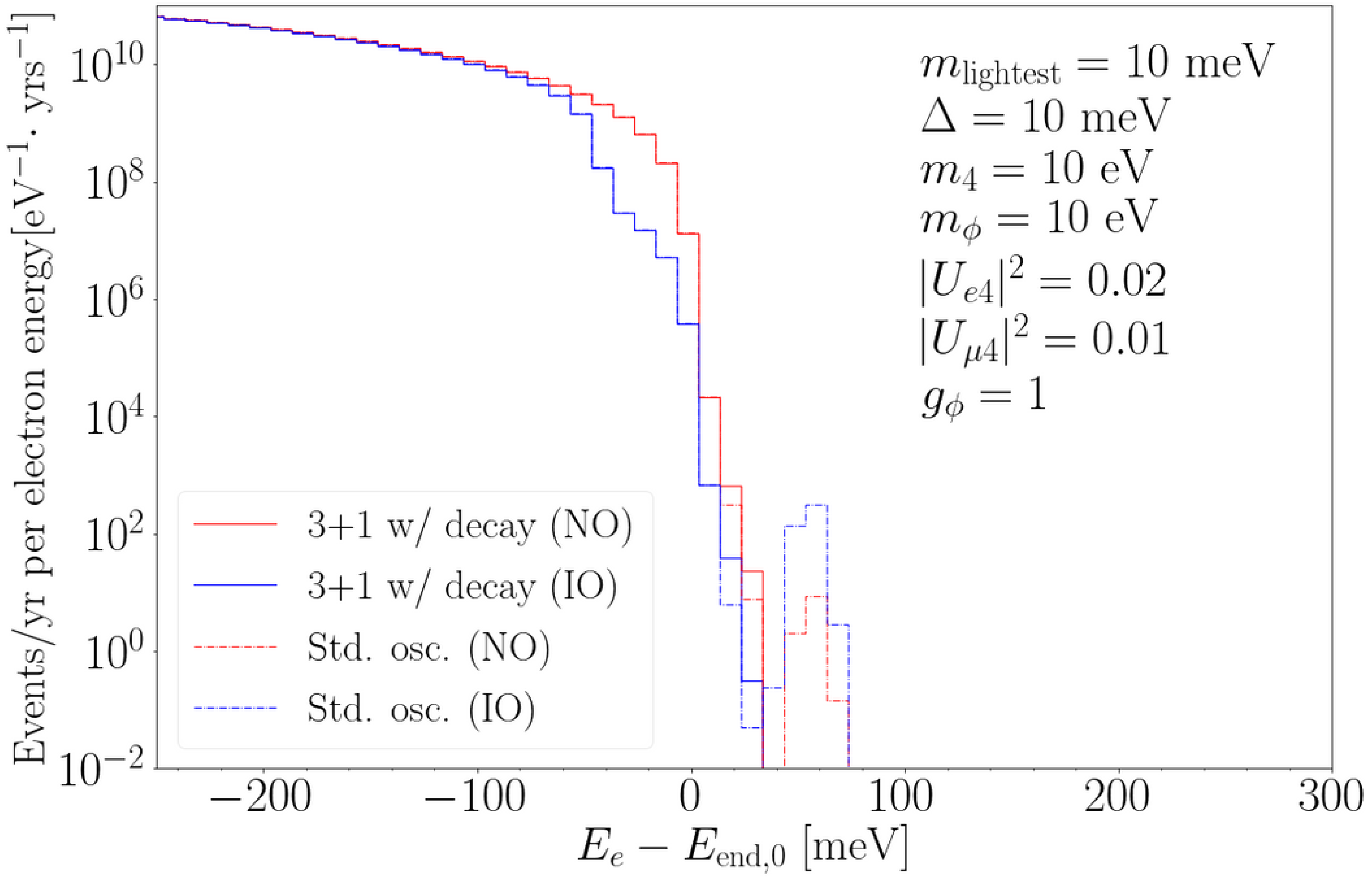


Method

1. Proportion of neutrino mass states at present times

2. Binned/smeared spectrum

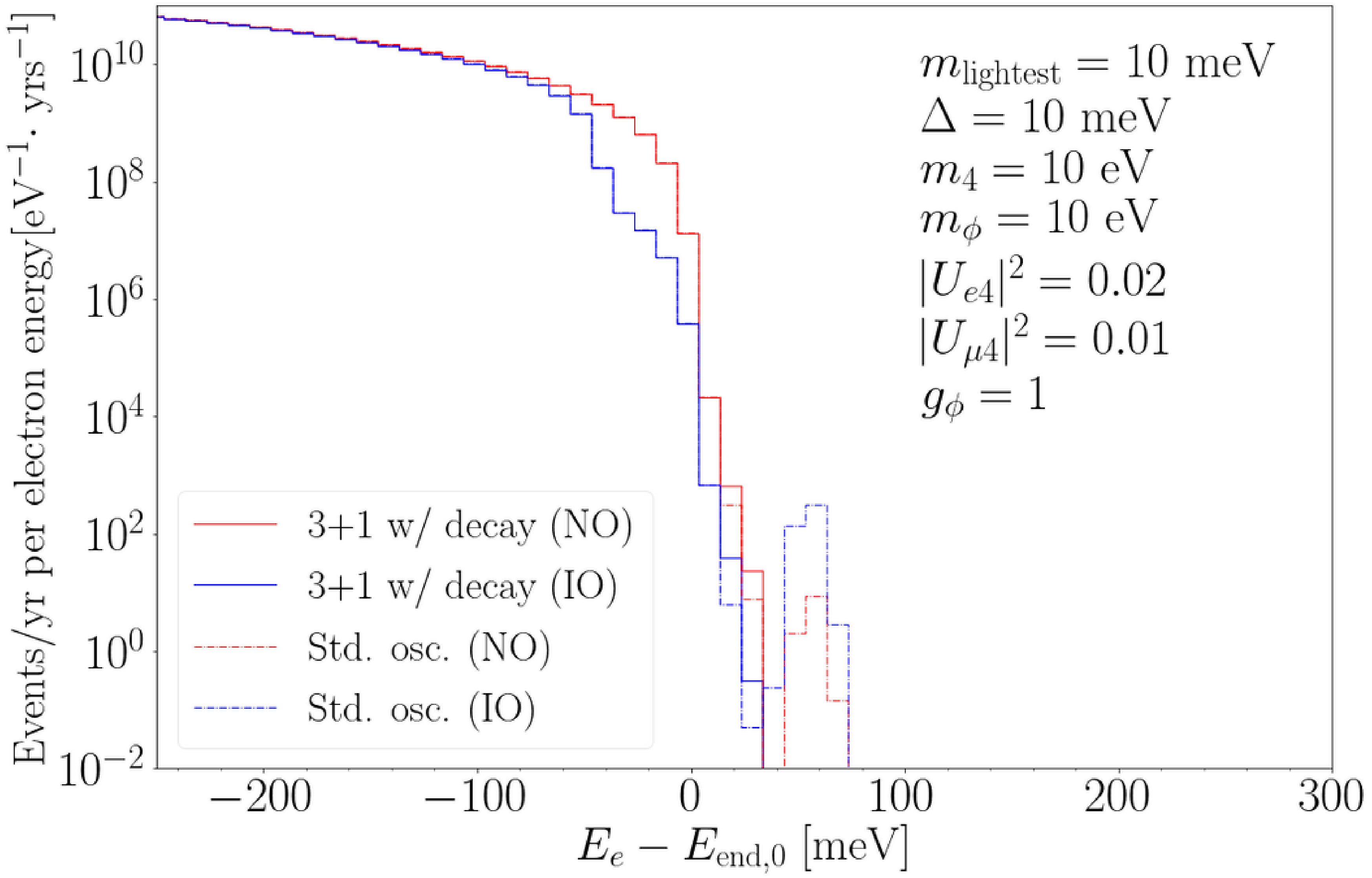
- Bin width 10 meV in [-5, 10] eV range.

3. Chi-square test

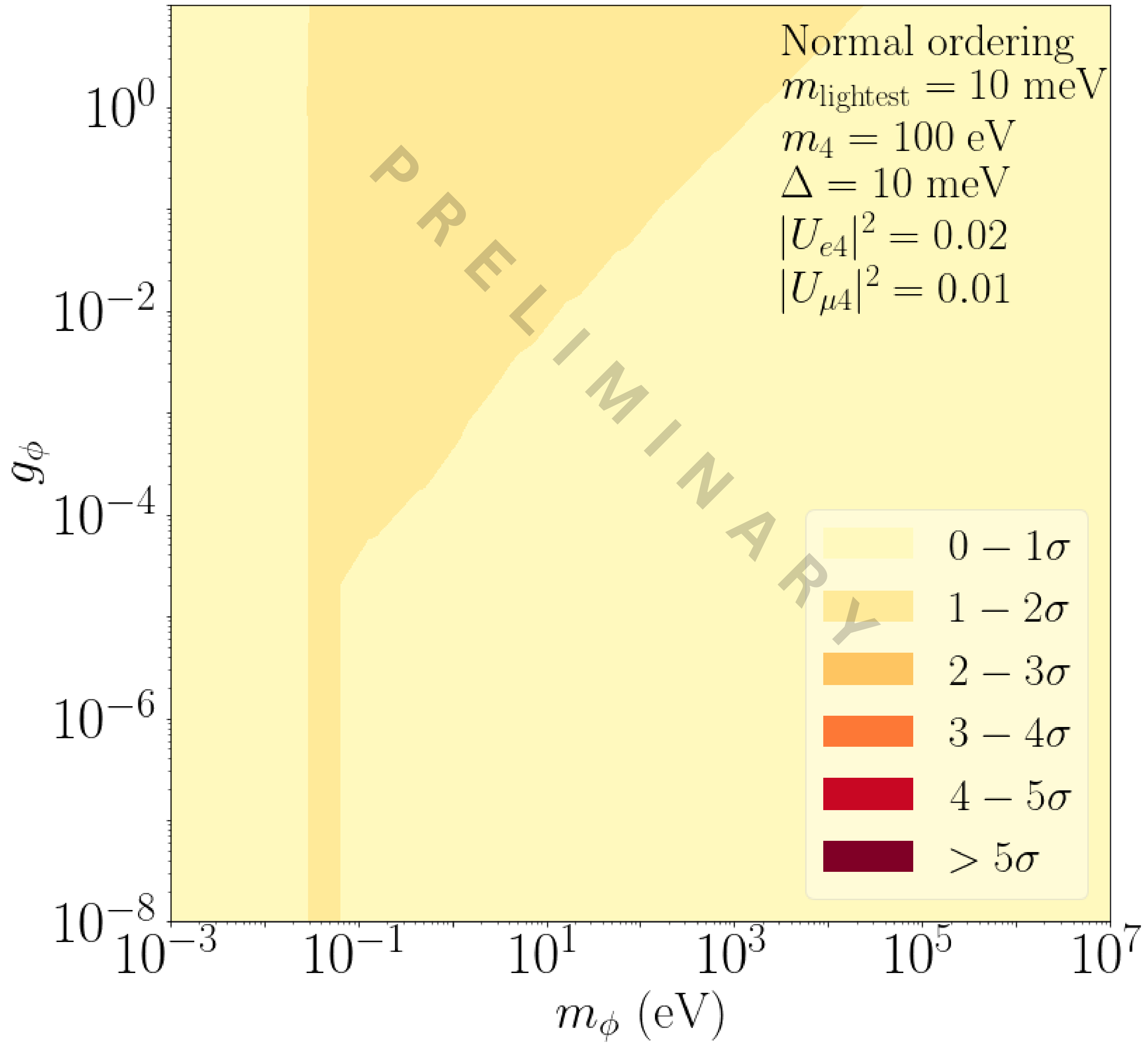
$$\chi^2 = \sum_i 2|E_i^{(3+1)}(g_\phi, m_\phi, m_4) - E_i^{SO}| + 2E_i^{SO} \ln \frac{E_i^{(3+1)}(g_\phi, m_\phi, m_4)}{E_i^{SO}} + \left(\frac{\delta E_{end,0}}{\sigma_{E_{end,0}}}\right)^2 + \left(\frac{\delta A_e}{\sigma_{A_e}}\right)^2$$

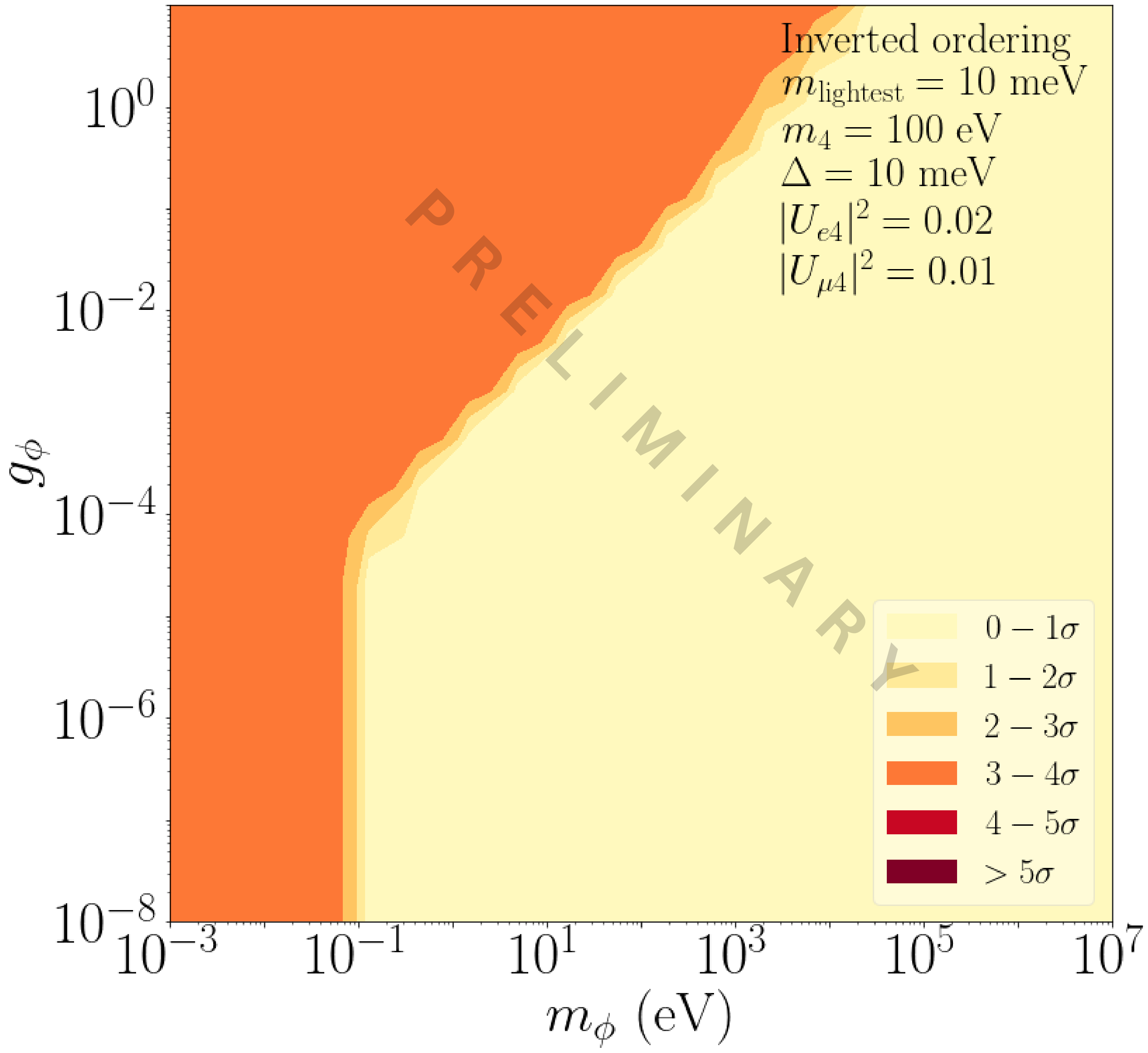
Systematic uncertainties:

$$\sigma_{E_{end,0}} = 0.1 \text{ eV}$$
$$\sigma_{A_e} = 0.1$$



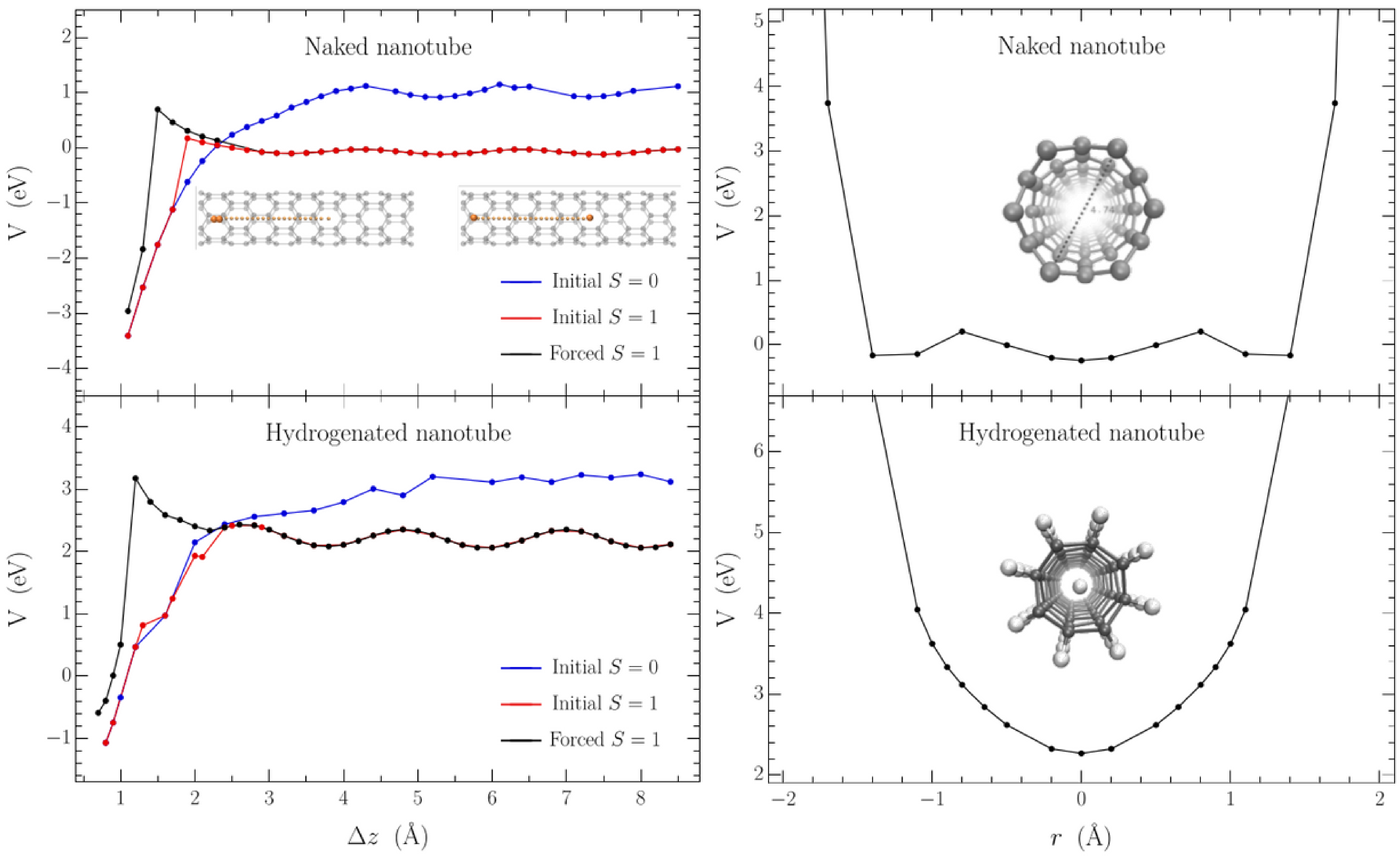
Results


Normal ordering
$m_{\text{lightest}} = 10$ meV
$m_4 = 100$ eV
$\Delta = 10$ meV
$|U_{e4}|^2 = 0.02$
$|U_{\mu 4}|^2 = 0.01$
$0 - 1\sigma$
$1 - 2\sigma$
$2 - 3\sigma$
$3 - 4\sigma$
$4 - 5\sigma$
$> 5\sigma$
PRELIMINARY
g_ϕ
m_ϕ (eV)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-3}
10^{-1}
10^1
10^3
10^5
10^7


Inverted ordering
$m_{\text{lightest}} = 10$ meV
$m_4 = 100$ eV
$\Delta = 10$ meV
$|U_{e4}|^2 = 0.02$
$|U_{\mu 4}|^2 = 0.01$
$0 - 1\sigma$
$1 - 2\sigma$
$2 - 3\sigma$
$3 - 4\sigma$
$4 - 5\sigma$
$> 5\sigma$
PRELIMINARY
g_ϕ
m_ϕ (eV)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-3}
10^{-1}
10^1
10^3
10^5
10^7

Caveats

- Low statistics
- Disambiguation required
- Optimistic perspectives
- Quantum mechanics uncertainty



[22] Y. Cheipesh, V. Cheianov, and A. Boyarsky, Navigating the pitfalls of relic neutrino detection, Phys.Rev. D 104 (2021), no. 11 116004, [2101.10069].
[23] PTOLEMY Collaboration, A. Apponi et al., Heisenberg's uncertainty principle in the PTOLEMY project: A theory update, Phys. Rev. D 106 (2022), no. 5 053002, [2203.11228].

Summary

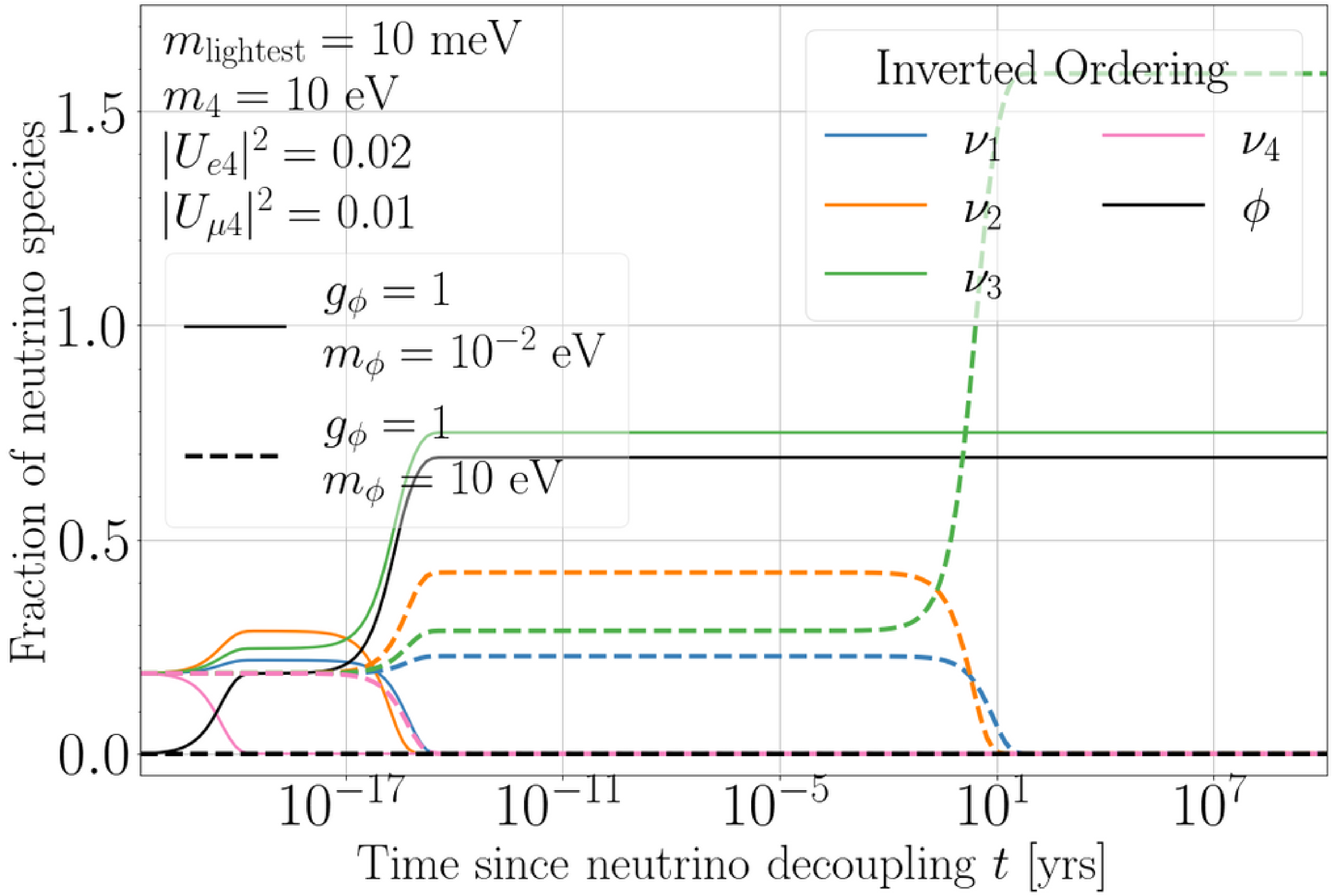
- CνB measurements can be good probes of new physics,
- Couplings as low as 10^{-8} could be probed by CνB,
- Novel and exciting perspectives!

Future

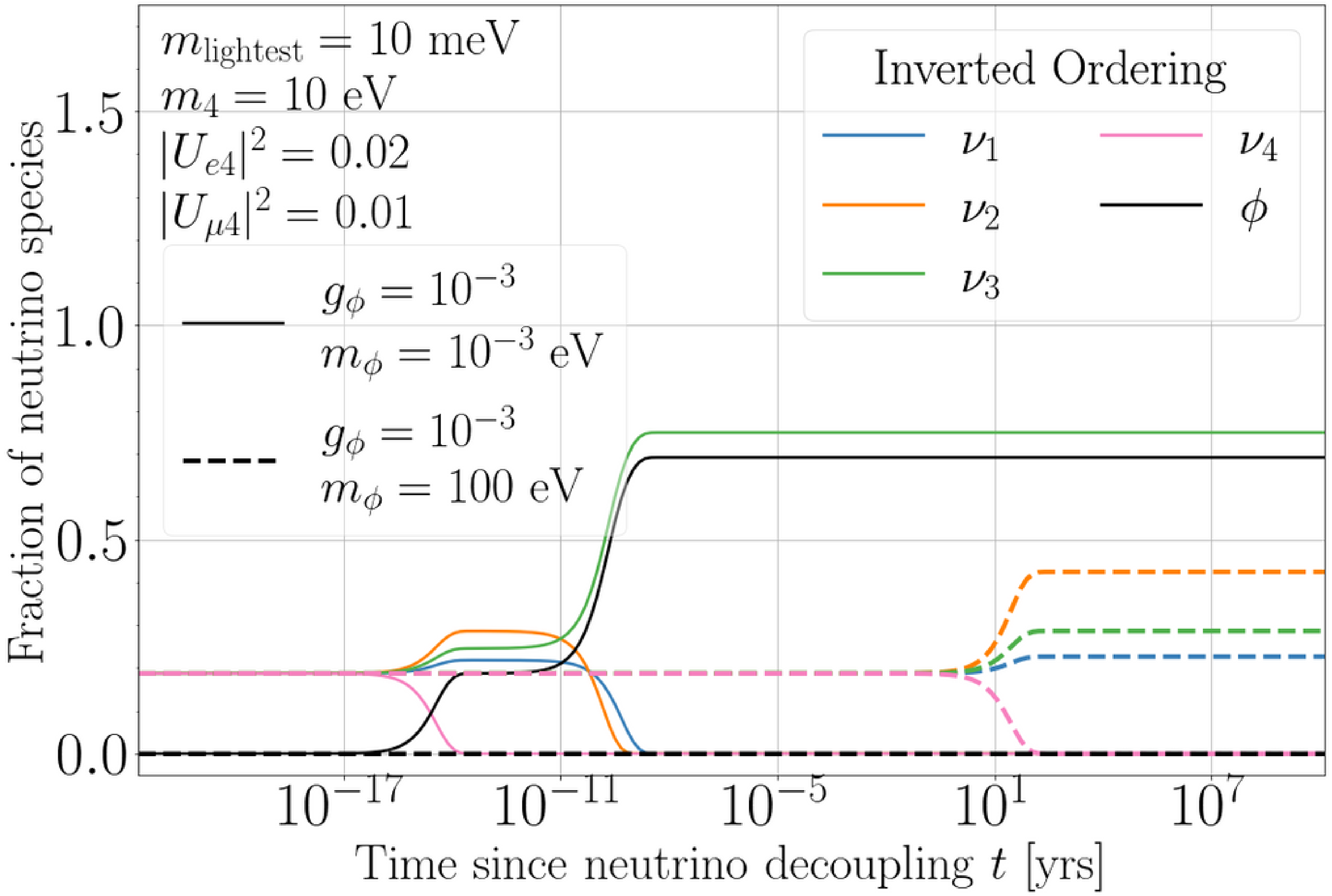
- Sensitivity in the sterile neutrino parameter space (m_4, U_{e4}),
- Constraints coming from other astrophysical sources.


So long and...
Thanks
...for all the fish!

Backup



$m_{\rm lightest} = 10$ meV
$m_4 = 10$ eV
$|U_{e4}|^2 = 0.02$
$|U_{\mu4}|^2 = 0.01$
$g_\phi = 1$
$m_\phi = 10^{-2}$ eV
$g_\phi = 1$
$m_\phi = 10$ eV
Inverted Ordering
ν_1
ν_2
ν_3
ν_4
ϕ
Fraction of neutrino species
0.0
0.5
1.0
1.5
10^{-17}
10^{-11}
10^{-5}
10^{1}
10^{7}
Time since neutrino decoupling t [yrs]



$m_{\rm lightest} = 10$ meV
$m_4 = 10$ eV
$|U_{e4}|^2 = 0.02$
$|U_{\mu4}|^2 = 0.01$
$g_\phi = 10^{-3}$
$m_\phi = 10^{-3}$ eV
$g_\phi = 10^{-3}$
$m_\phi = 100$ eV
Inverted Ordering
ν_1
ν_2
ν_3
ν_4
ϕ
Fraction of neutrino species
0.0
0.5
1.0
1.5
10^{-17}
10^{-11}
10^{-5}
10^{1}
10^{7}
Time since neutrino decoupling t [yrs]

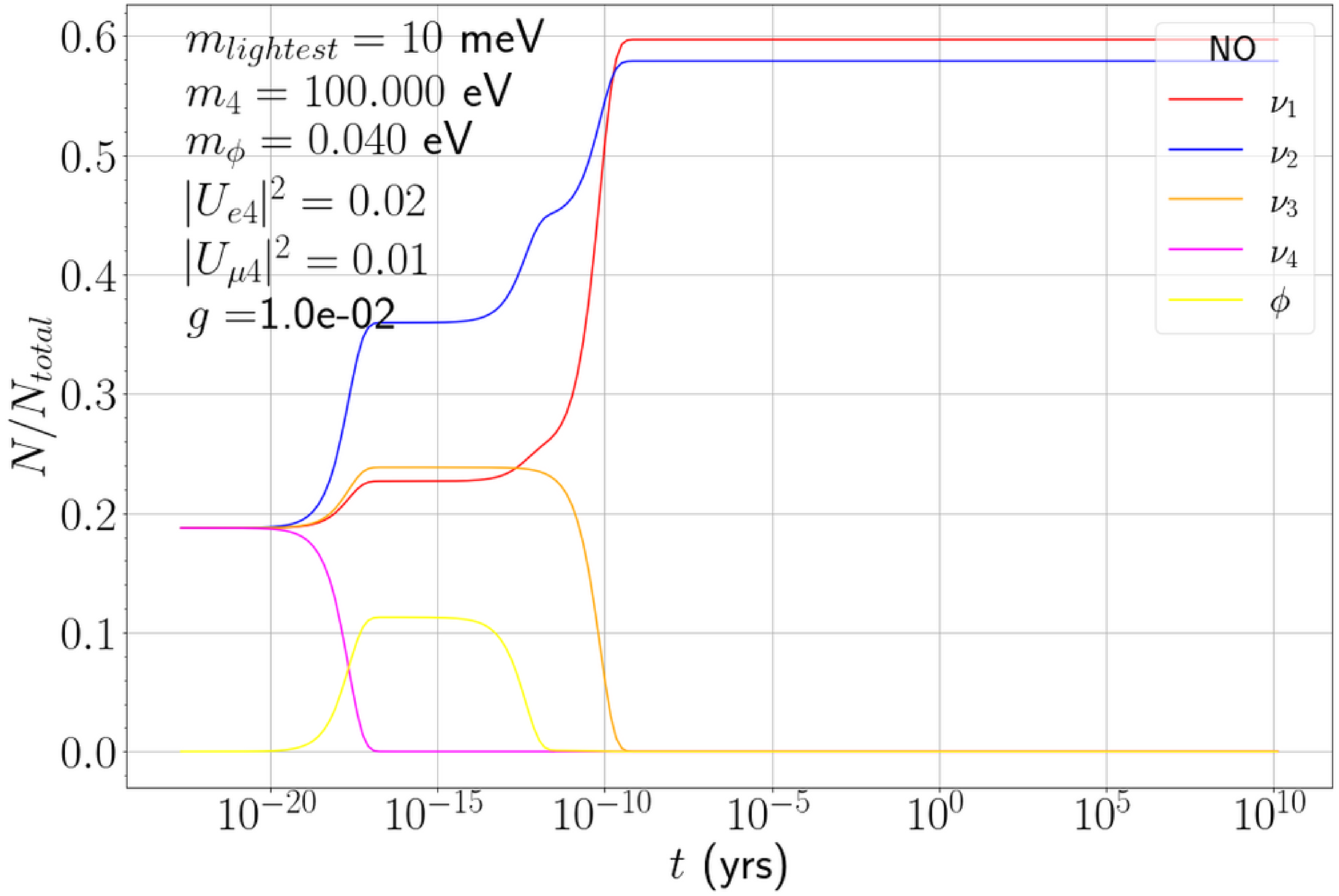
Backup

Neutrino decoherence

$$P(\alpha \to \beta; \boldsymbol{L}) = \sum_{ij} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j} \exp\left[-2\pi \mathrm{i} \frac{L}{L^{osc}_{ij}} - 2\pi^2 \left(1 - \frac{\boldsymbol{L}\cdot\boldsymbol{\xi}}{L}\right)^2 \left(\frac{\sigma_x}{L^{osc}_{ij}}\right)^2 - \left(\frac{L}{L^{coh}_{ij}}\right)^2\right]$$

[24] E. K. Akhmedov and A. Y. Smirnov, “Paradoxes of neutrino oscillations,” Phys. Atom. Nucl. 72 (2009), 1363-1381 [arXiv:0905.1903 [hep-ph]].
[25] C. Giunti and C. W. Kim, “Coherence of neutrino oscillations in the wave packet approach,” Phys. Rev. D 58 (1998), 017301 [arXiv:hep-ph/9711363 [hep-ph]].

Backup



$m_{lightest} = 10$ meV
$m_4 = 100.000$ eV
$m_\phi = 0.040$ eV
$|U_{e4}|^2 = 0.02$
$|U_{\mu 4}|^2 = 0.01$
g =1.0e-02
NO
ν_1
ν_2
ν_3
ν_4
ϕ
N/N_{total}
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
t (yrs)

Backup

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 + \frac{2E}{\Delta m^2} V_{\rm eff}\right)^2 + \sin^2 2\theta_0} \,,$$

$$|V_{\rm eff}| \gg \left|\frac{\Delta m^2}{2E}\right| ,$$

$$V_{\rm eff}^{\rm bubble} \simeq \begin{cases} -\dfrac{28\pi^3 \alpha_\chi E T_s^4}{45 M^4} & \text{for } T_s, E \ll M \\[2ex] +\dfrac{\pi \alpha_\chi T_s^2}{2E} & \text{for } T_s, E \gg M \end{cases}$$