Neutrino Decay scenarios on the Cosmic Neutrino Background

Leonardo J. Ferreira Leite
(State University of Campinas / CERN)

In collaboration with:

Joachim Kopp
(Johannes Gutenberg University Mainz / CERN)

UNICAMP CERN

NBIA Summer School - Copenhagen
July 17, 2023

PrInt

Outline

- Detection
- Neutrino decay
- Preliminary results
- Conclusions

CνB detection

- Neutrino Capture

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

- Tritium β-decay

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

[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].

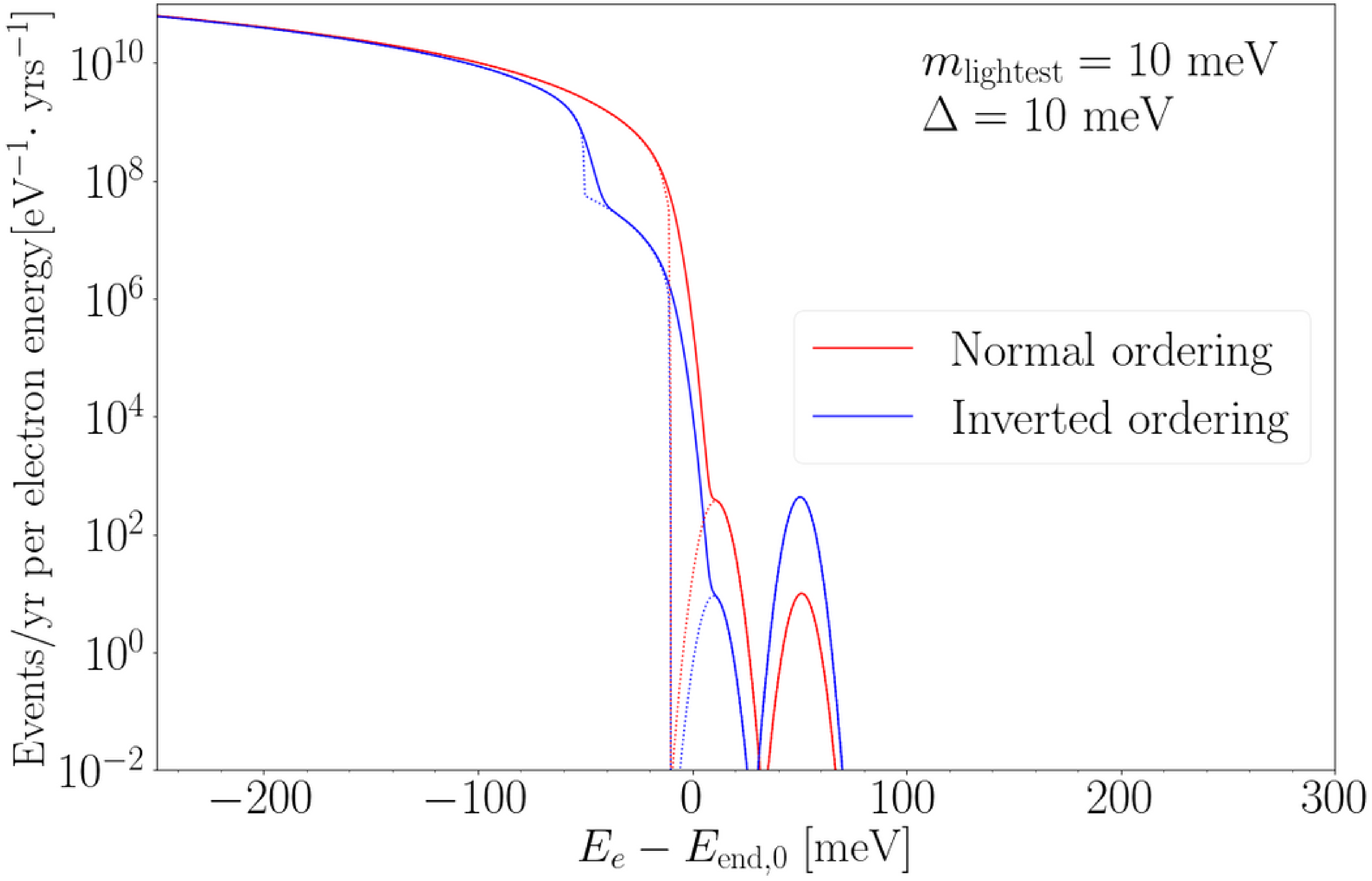
CνB detection

- 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].

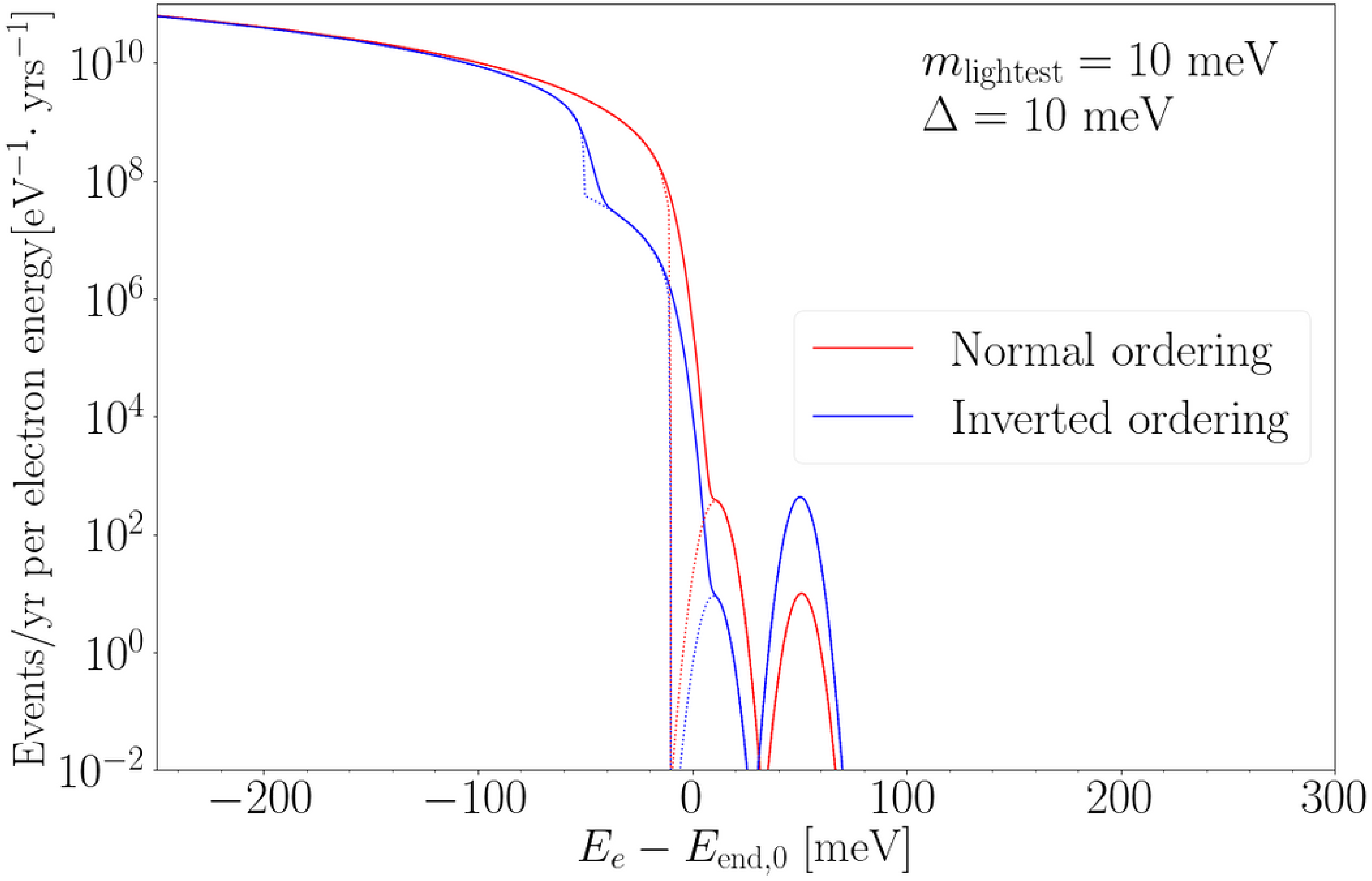
CνB detection

- <u>Neutrino Capture</u>

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

- 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].

CvB detection

- Neutrino Capture

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

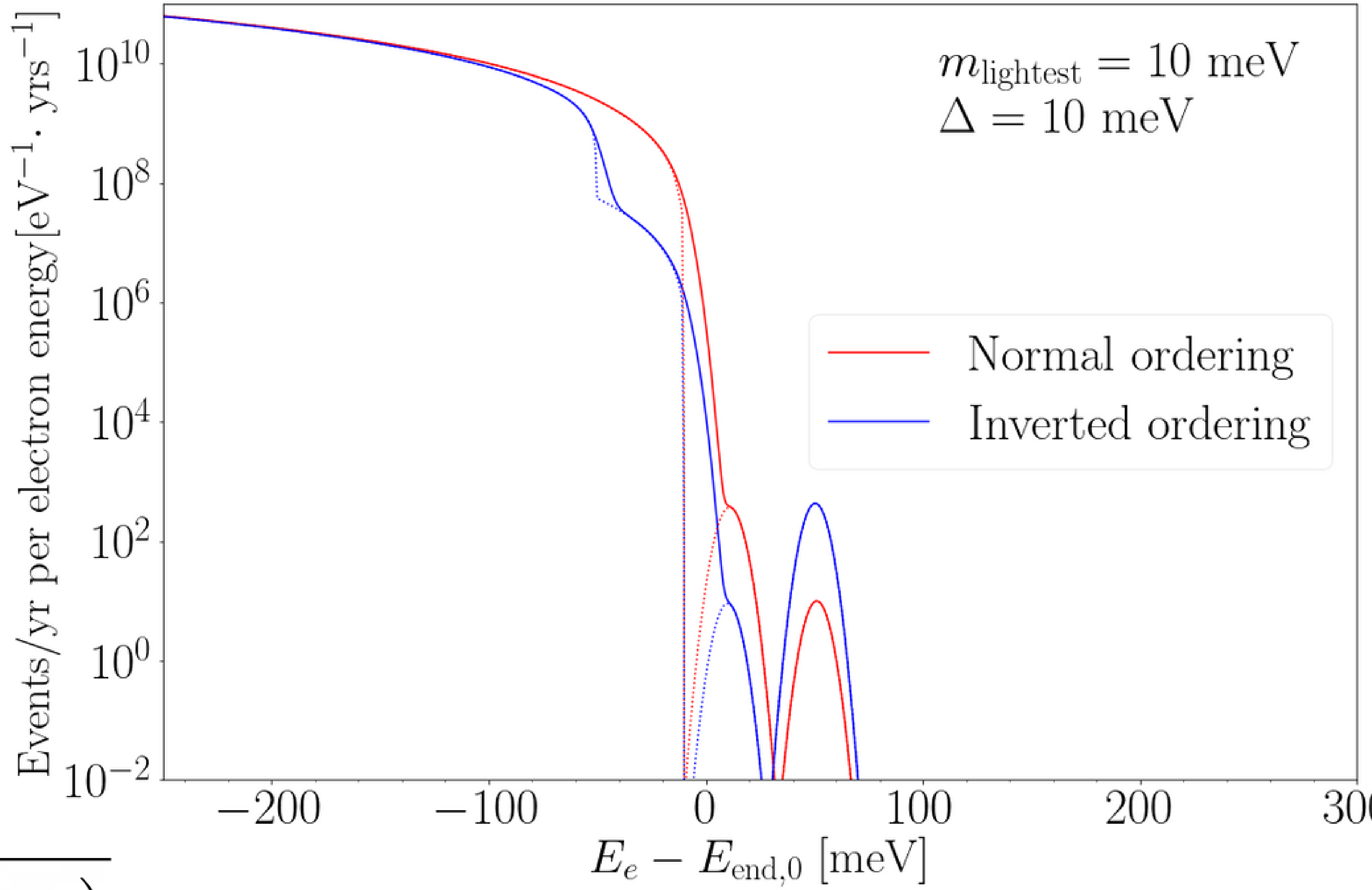
- Tritium β-decay

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

Tritium β-decay rate [7]

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

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



[2] 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].

[3] KATRIN Collaboration, A. Osipowicz et al., KATRIN: A Next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass. Letter of intent, hep-ex/0109033.

CvB detection

- Neutrino Capture

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

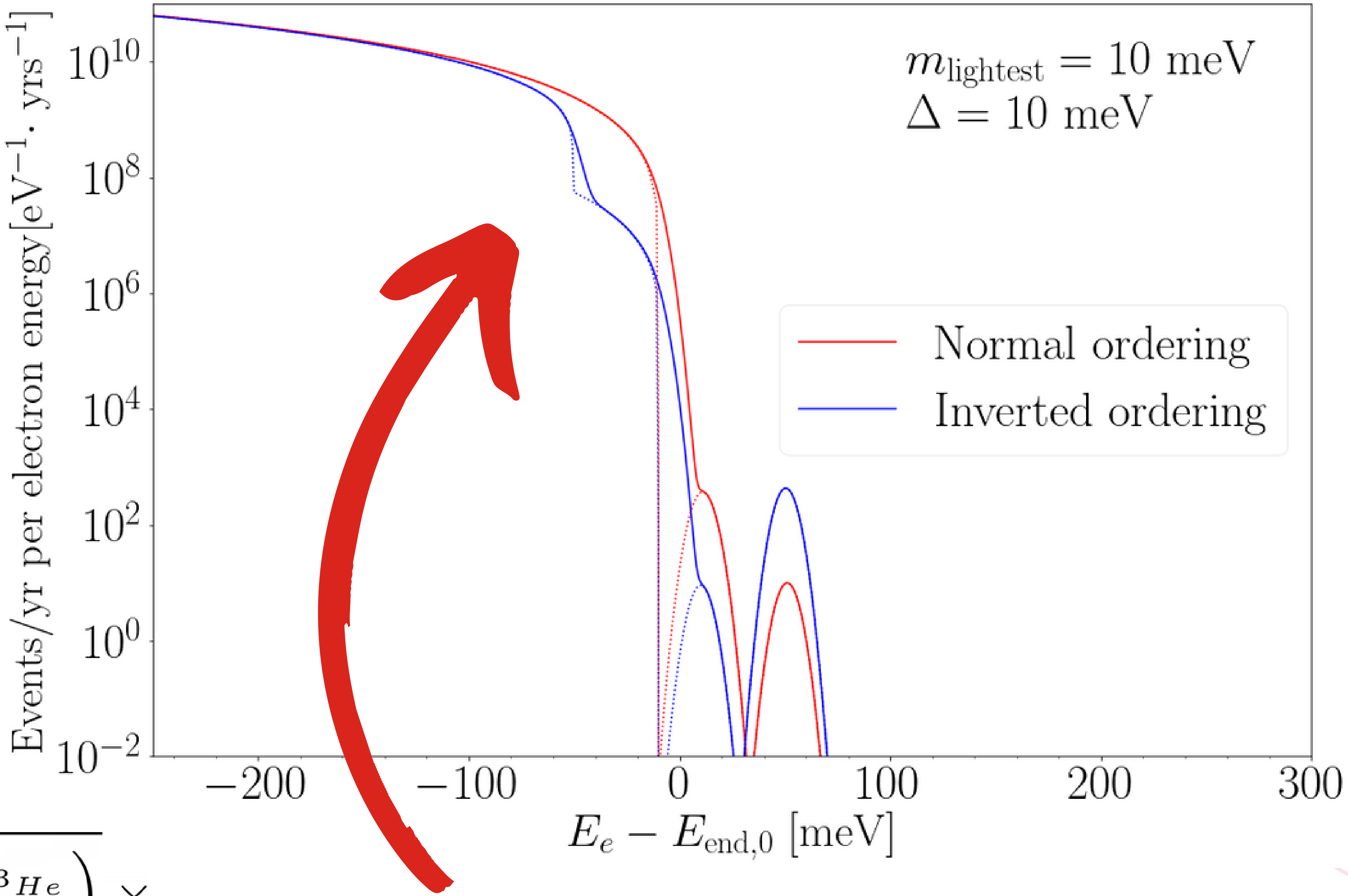
- Tritium β-decay

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

Tritium β-decay rate [7]

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

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



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

[2] 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].
[3] KATRIN Collaboration, A. Osipowicz et al., KATRIN: A Next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass. Letter of intent, hep-ex/0109033.

CνB detection

- Neutrino Capture

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

- Tritium β-decay

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

[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].

CνB detection

- Neutrino Capture

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

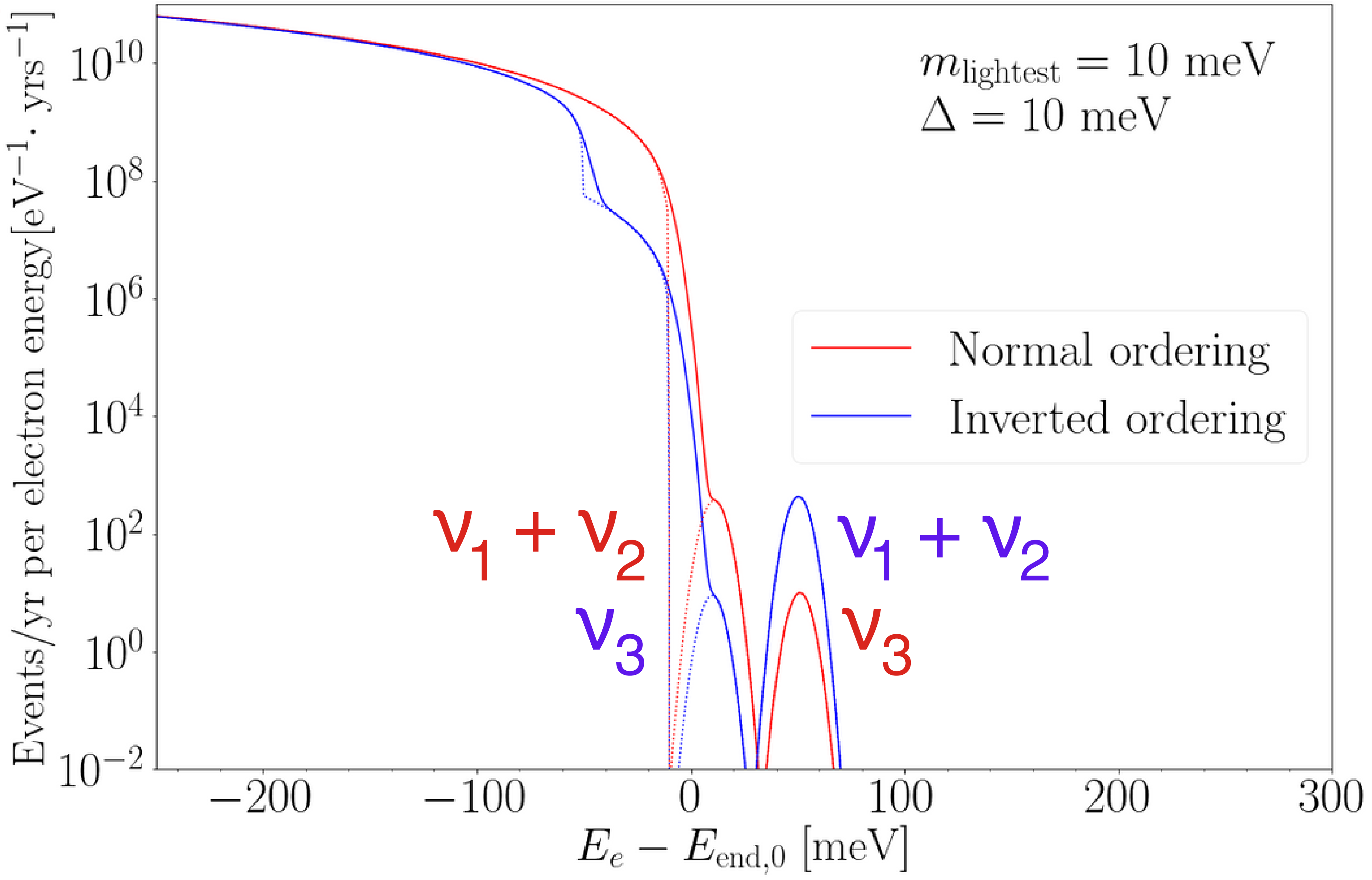
- Tritium β-decay

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

Capture rate

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

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



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

[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].

CνB detection

- Neutrino Capture

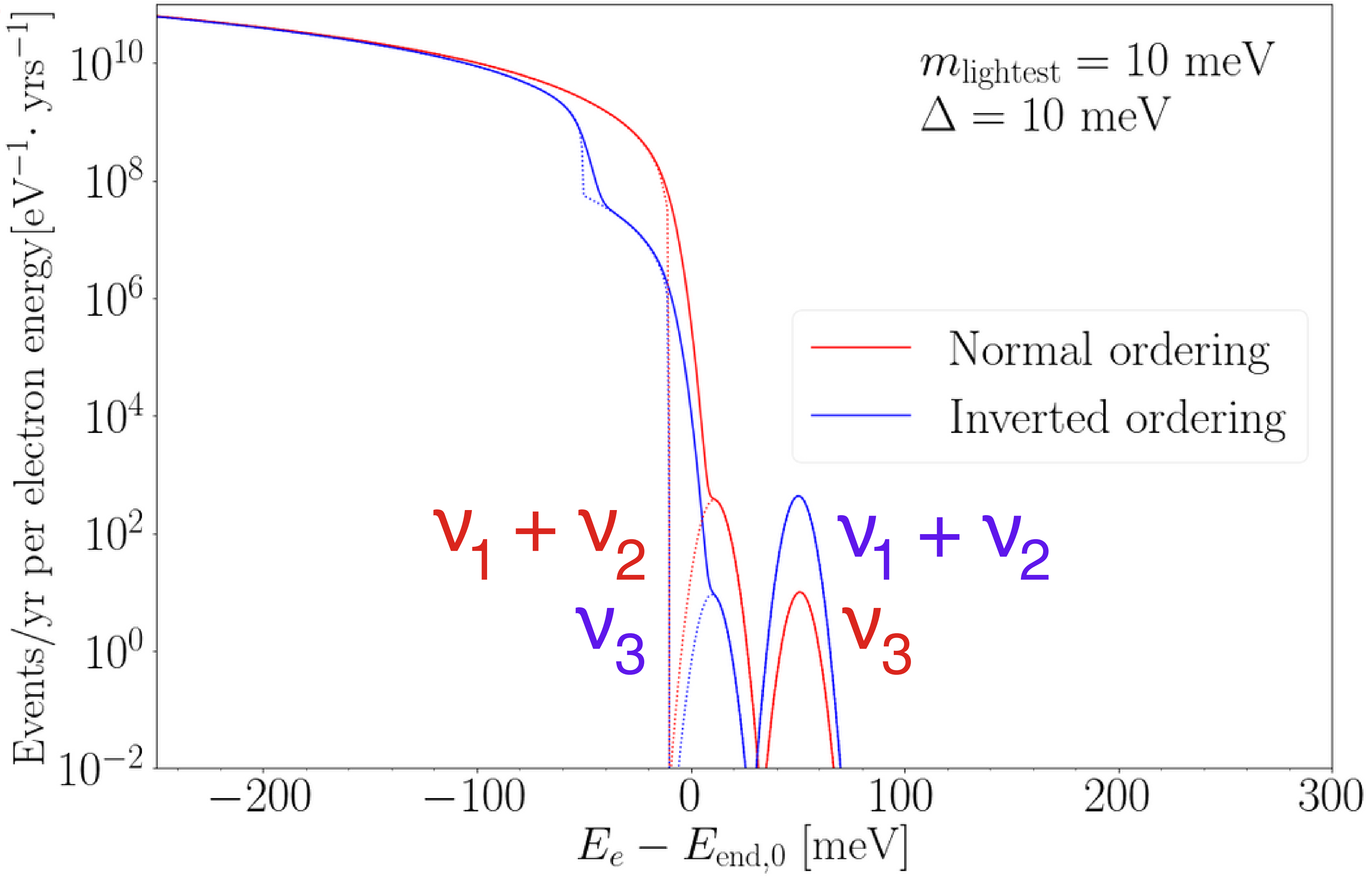
$$^3\mathrm{H} + \nu_e \rightarrow {}^3\mathrm{He} + e^-$$

- Tritium β-decay

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

Neutrino gravitational clustering factor [2-6]

$$f_{c,i} = 1 + 76.5 \left(\frac{m_i}{\mathrm{eV}}\right)^{2.21},$$



[4] J. Zhang and X. Zhang, Gravitational clustering of cosmic relic neutrinos in the Milky Way, Nature Commun. 9 (2018) 1833, [1712.01153].

[5] A. Ringwald and Y. Y. Y. Wong, Gravitational clustering of relic neutrinos and implications for their detection, JCAP 12 (2004) 005, [hep-ph/0408241].

[6] 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].

[7] E. B. Holm, I. M. Oldengott, and S. Zentarra, Local clustering of relic neutrinos with kinetic field theory (2023), 2305.13379.

[8] 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].

CνB detection

- Neutrino Capture

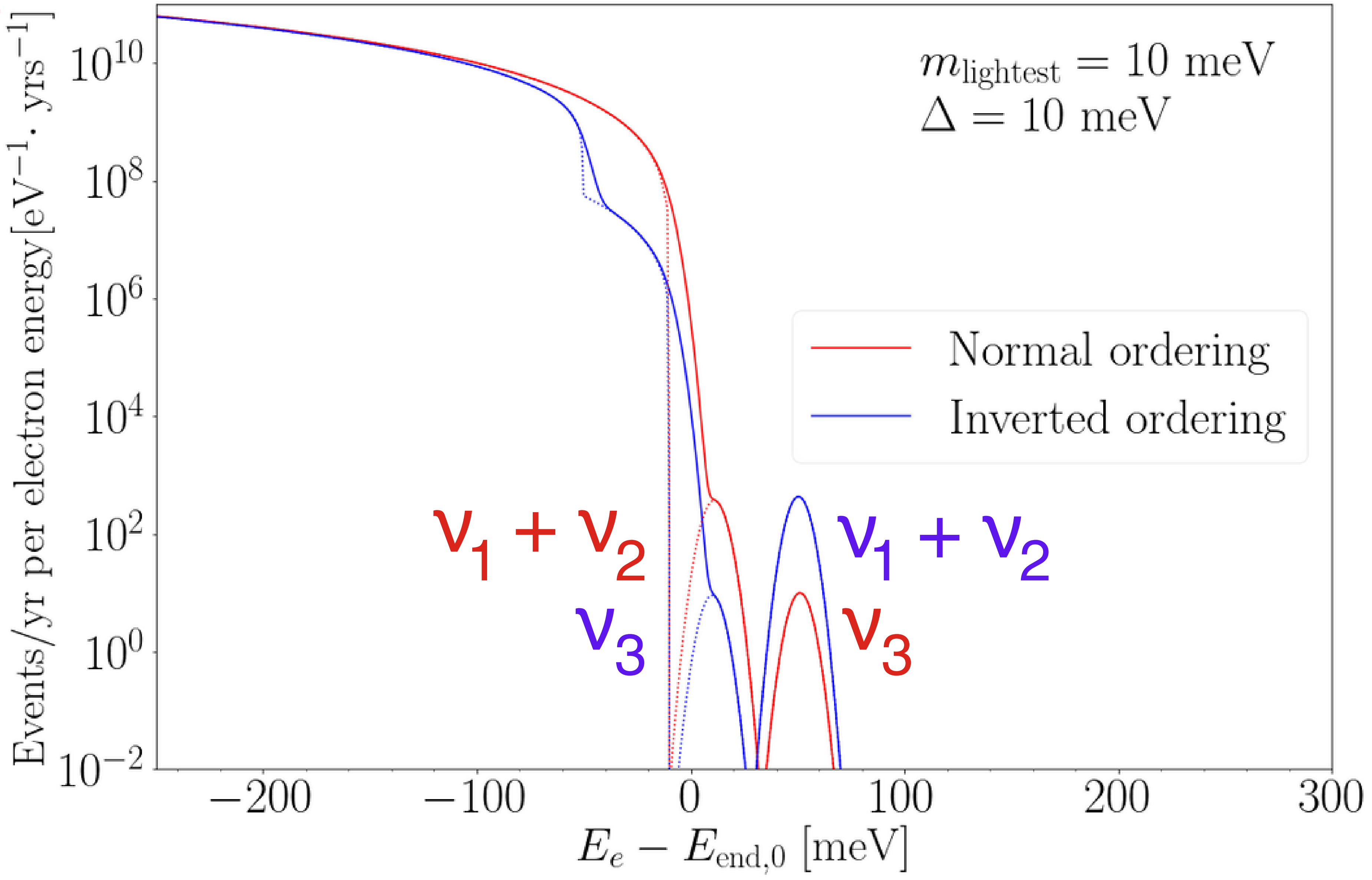
$$^{3}\mathrm{H} + \nu_e \rightarrow {}^{3}\mathrm{He} + e^-$$

- Tritium β-decay

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

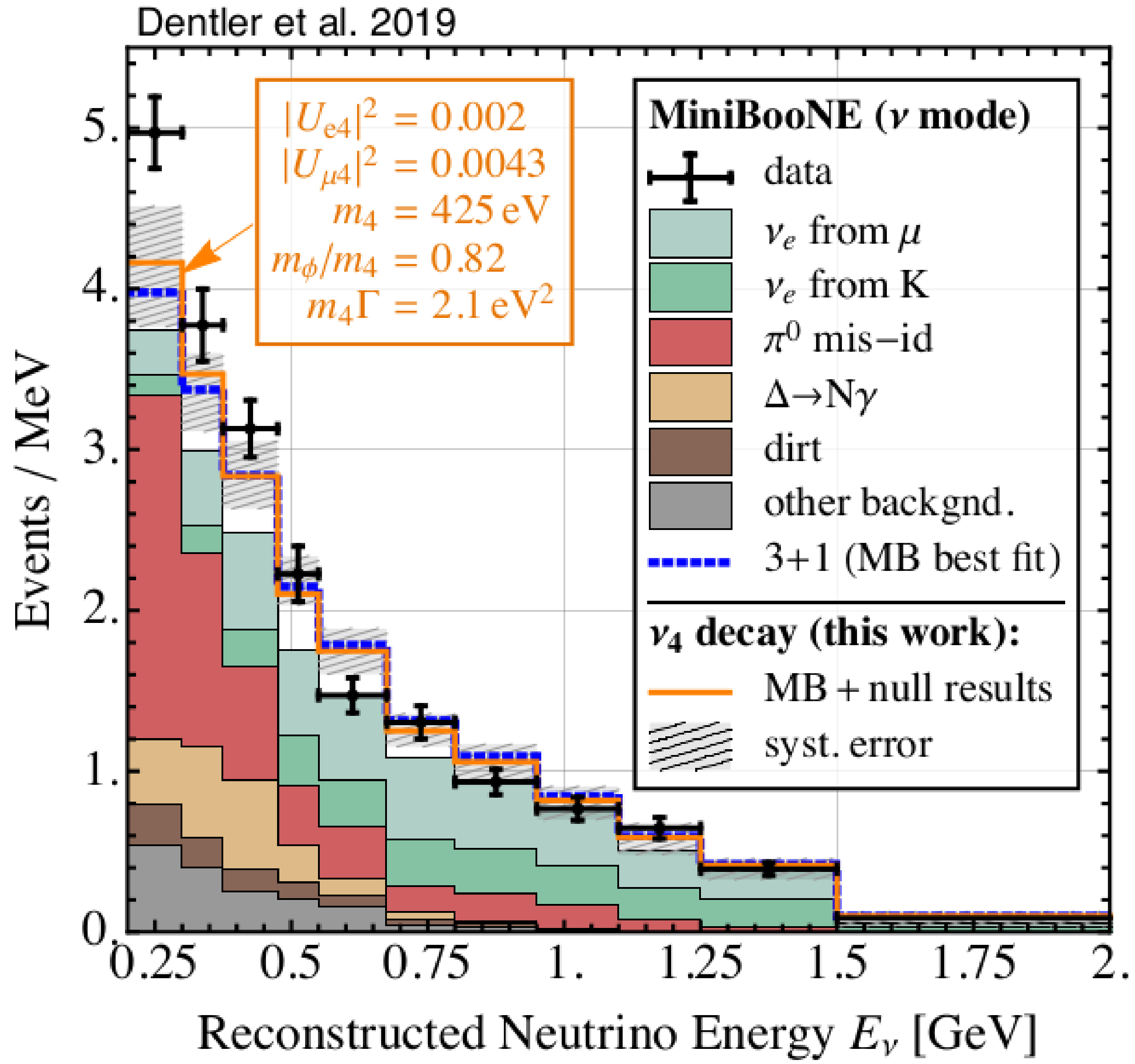
Neutrino gravitational clustering factor [7]

$$f_{c,i} = 1 + f_{c,\mathrm{DM}} \left[1 + \left(a \frac{\mathrm{keV}}{m_i} \right)^{b} \right]^{-c/b} ,$$



[9] K.-Y. Choi, E. Lkhagvadorj, and S. M. Yoo, Probing sterile neutrino dark matter in the PTOLEMY-like experiment, JCAP 06 (2023) 021, [2212.14192].

Short-Baseline Anomalies



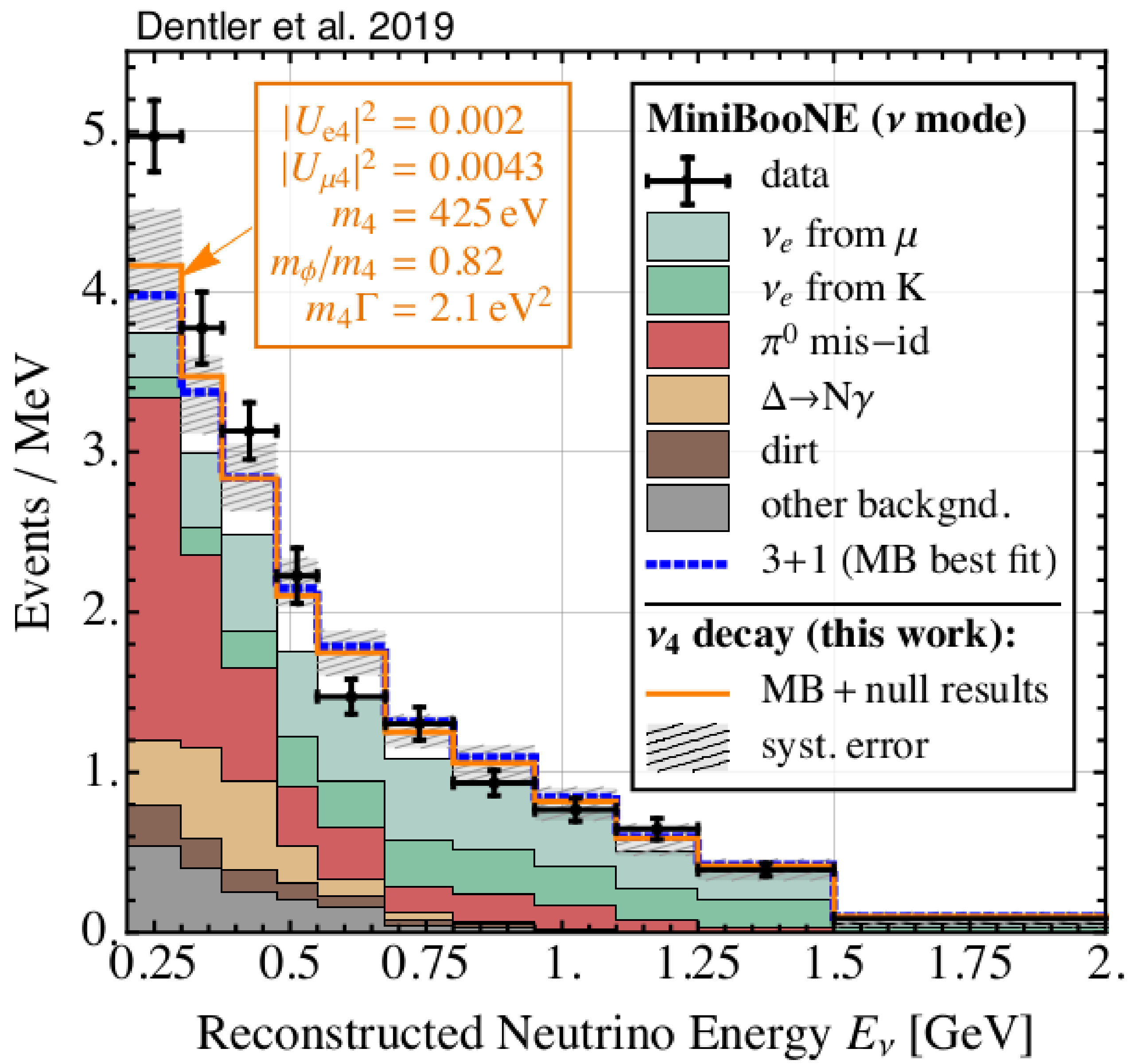
[14] M. Dentler, I. Esteban, J. Kopp, and P. Machado, Decaying Sterile Neutrinos and the Short Baseline Oscillation Anomalies, Phys. Rev. D 101 (2020).
[15] M. Hostert and M. Pospelov, Constraints on decaying sterile neutrinos from solar antineutrinos, Phys. Rev. D 104 (2021)

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

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

Short-Baseline Anomalies



[14] M. Dentler, I. Esteban, J. Kopp, and P. Machado, Decaying Sterile Neutrinos and the Short Baseline Oscillation Anomalies, Phys. Rev. D 101 (2020).
[15] M. Hostert and M. Pospelov, Constraints on decaying sterile neutrinos from solar antineutrinos, Phys. Rev. D 104 (2021).

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 ➡ $\nu_i \to \nu_j\phi \to \nu_j\nu_k\bar{\nu}_l$

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

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

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

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

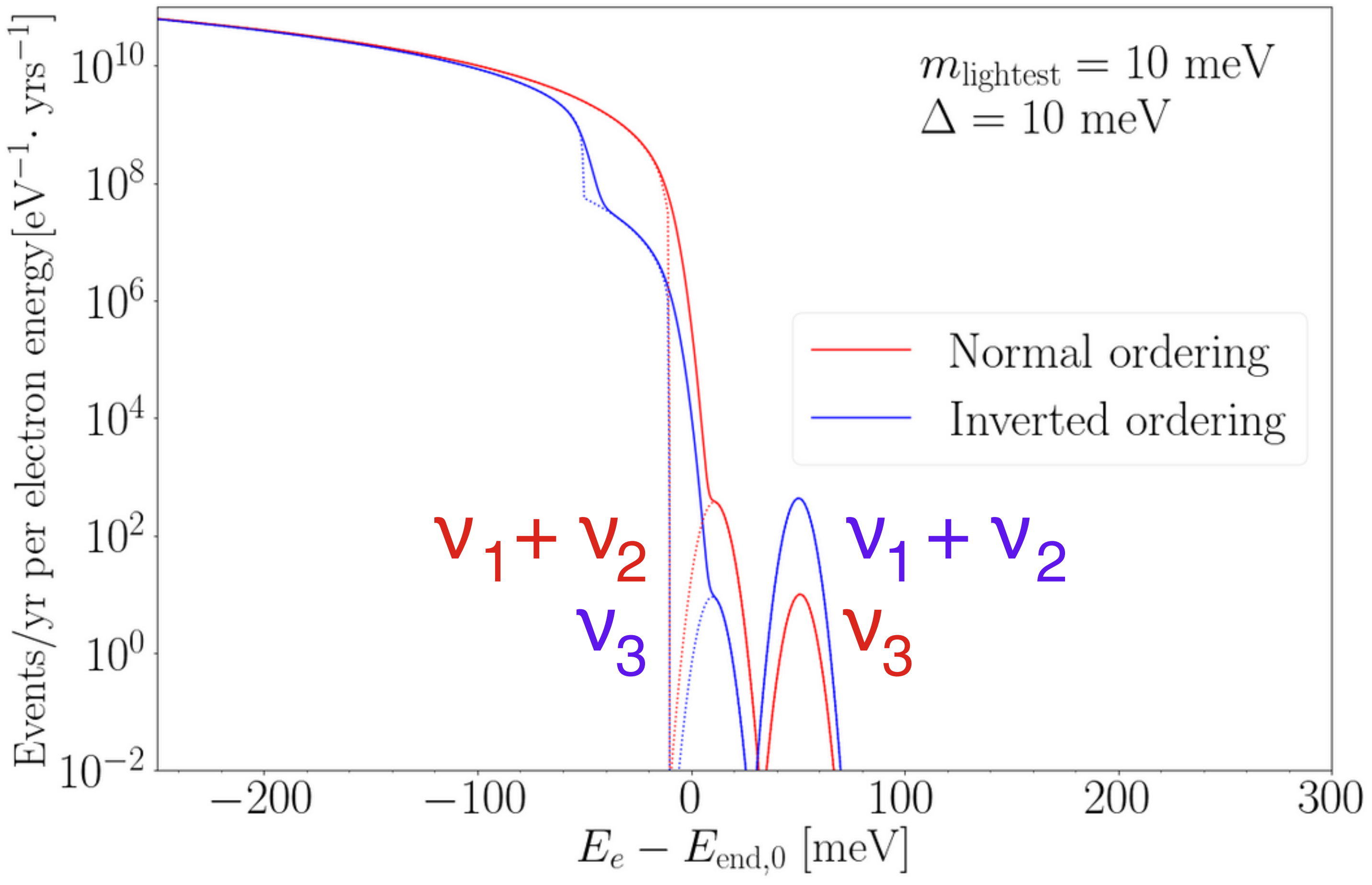
CνB detection

- 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 $\quad -\mathcal{L} = g_\phi \overline{\nu_s}\nu_s\phi + \sum_{\alpha,\beta} m_{\alpha,\beta}\overline{\nu_\alpha}\nu_\beta$
- Sterile neutrino $\quad \nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i$

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

Induces neutrino decay

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

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

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

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

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

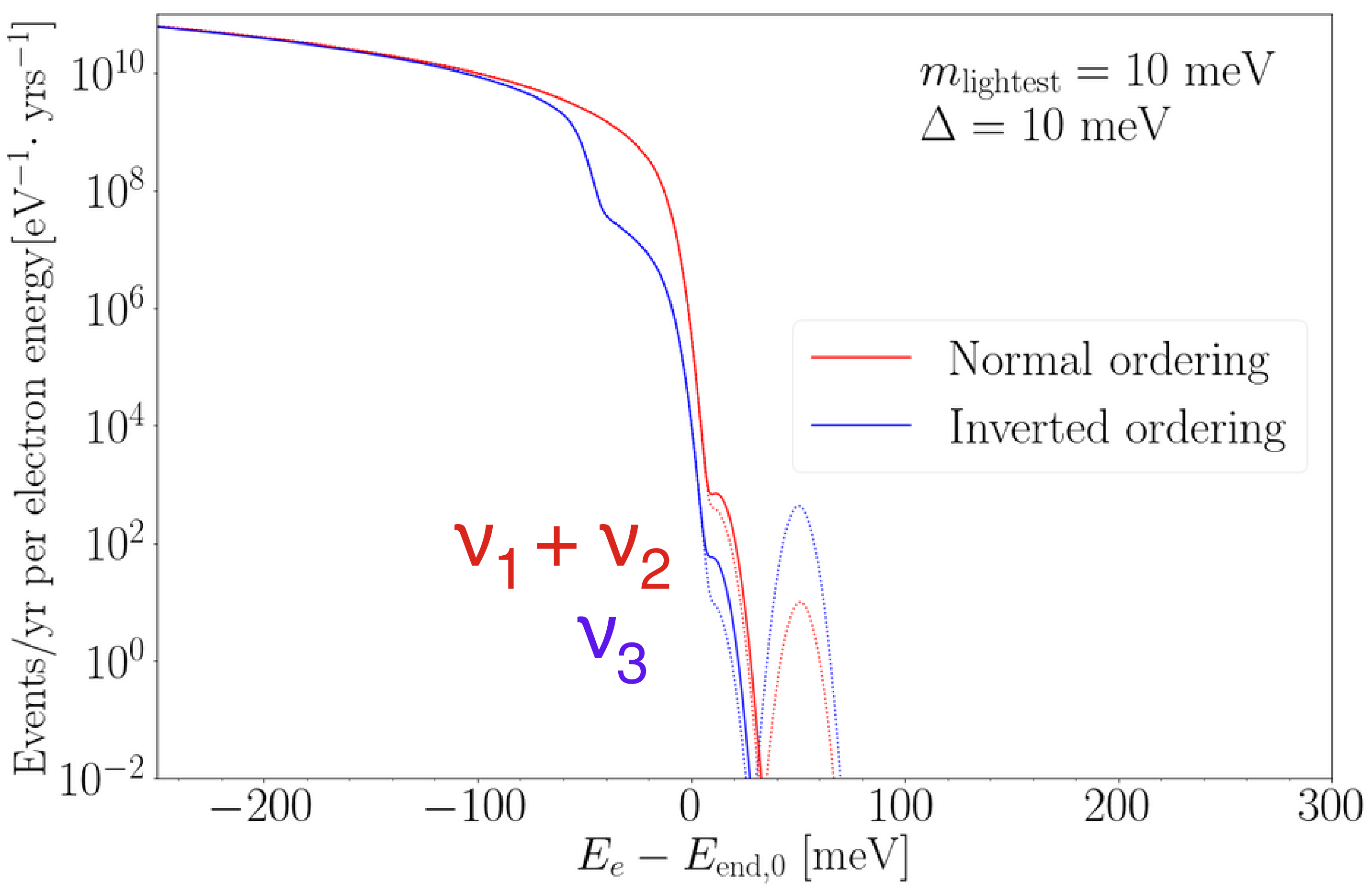
CvB detection

- Neutrino Capture

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

- Tritium β-decay

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



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

$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i \qquad \alpha, \beta = e, \mu, \tau, s$$

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 ➜ $\nu_i \to \nu_j\nu_k\bar{\nu}_l$

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

Method

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

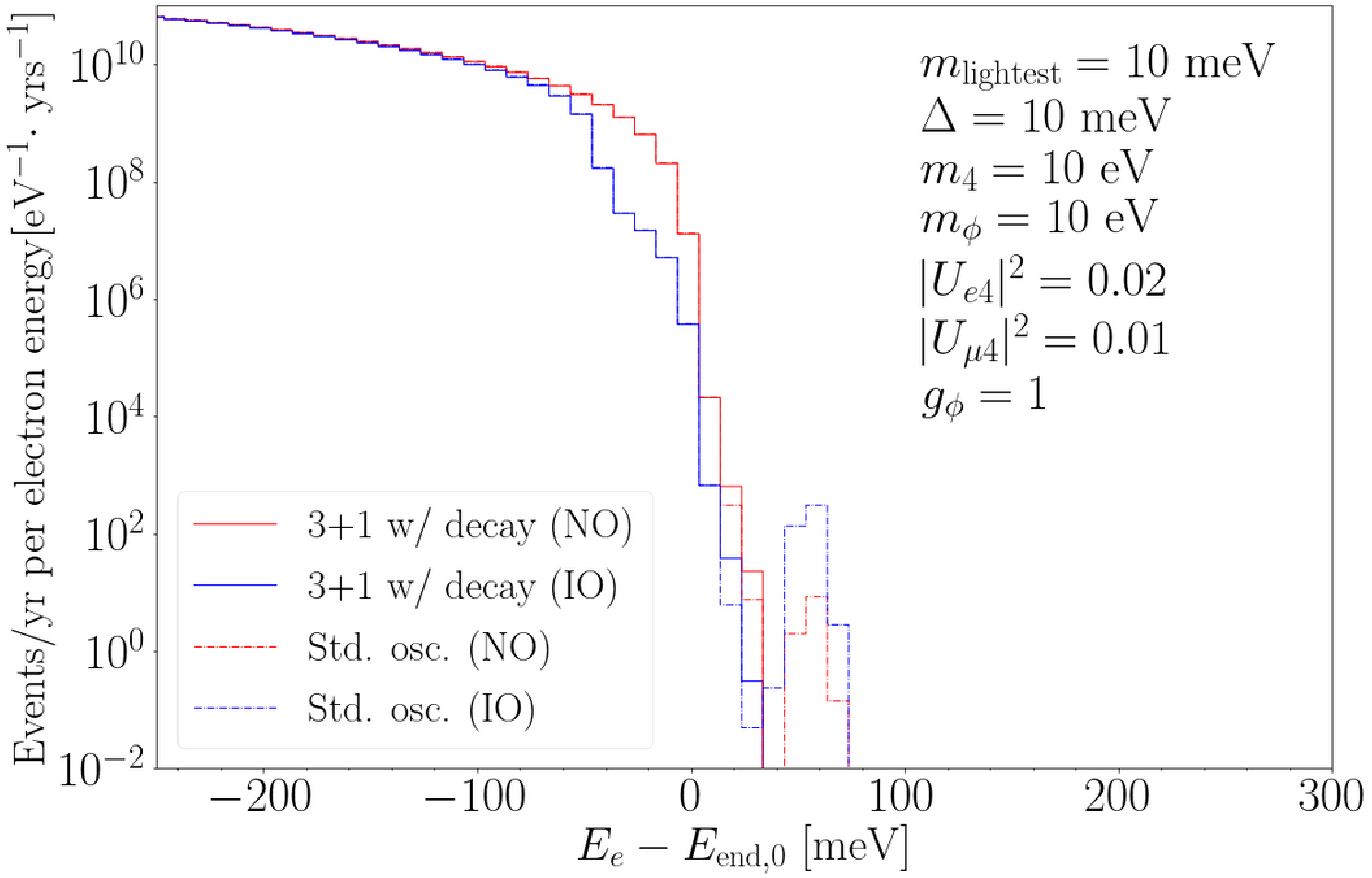
- Bin width 10 meV in [-5, 10] eV range.

Method

1. Proportion of neutrino mass states at present times

2. Binned/smeared spectrum

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



Method

1. Proportion of neutrino mass states at present times

2. Binned/smeared spectrum

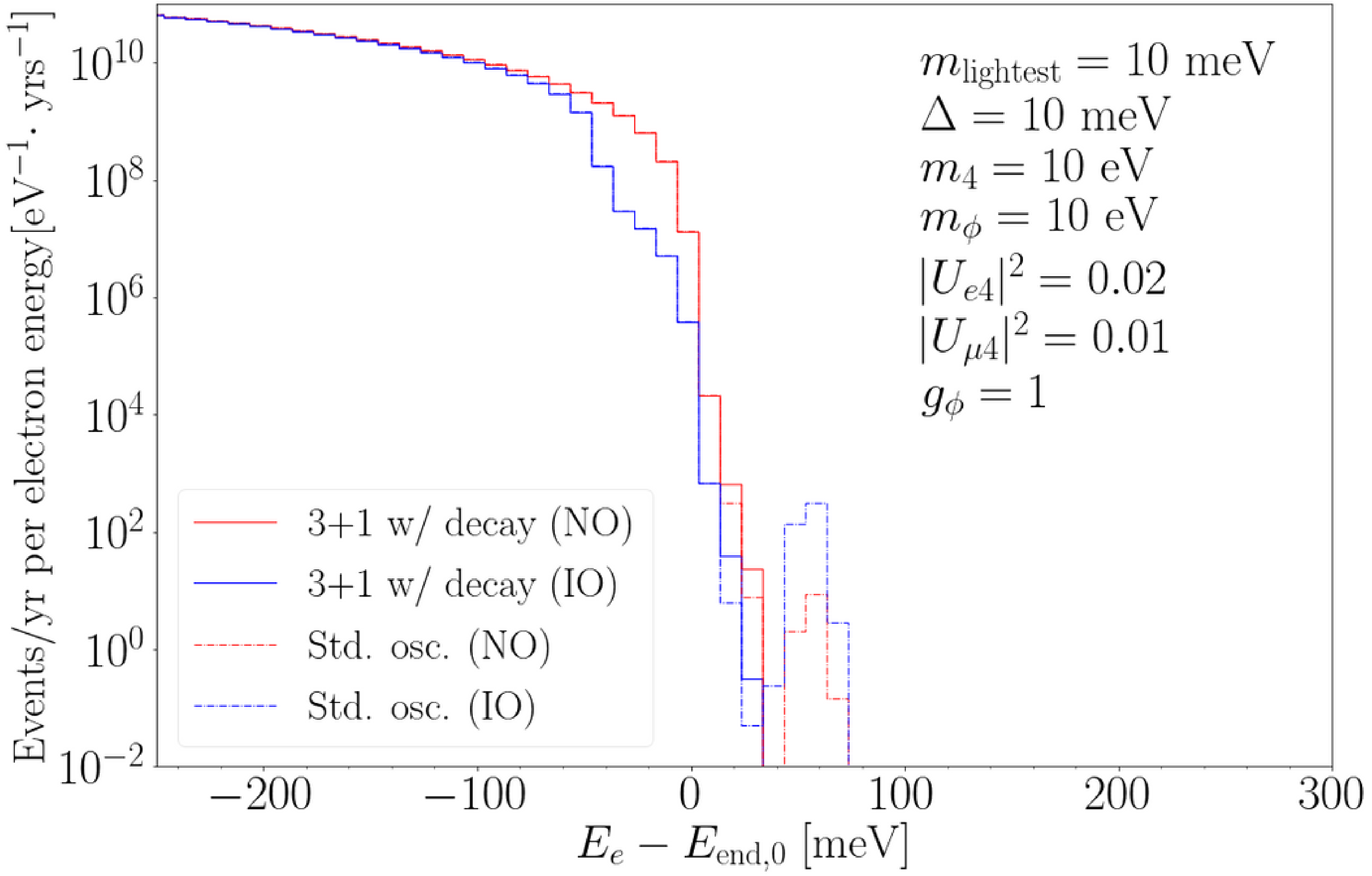
- Bin width 10 meV in [-5, 10] eV range.

3. Chi-square test

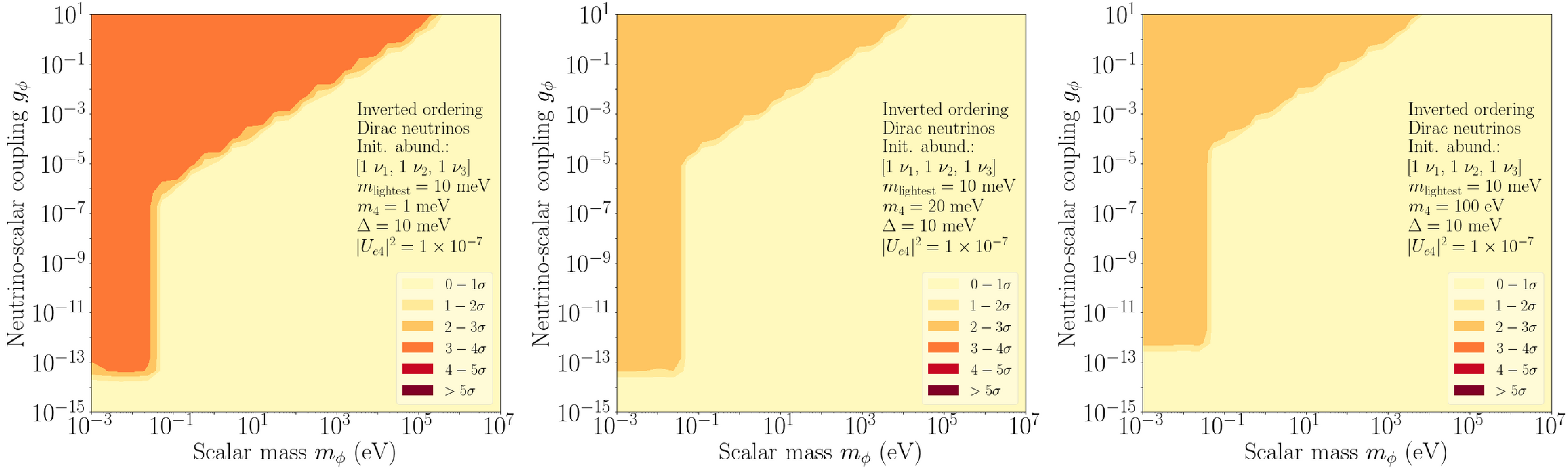
$$\chi^2 = \sum_i 2|(1+\delta A_x)E_i^{(3+1)}(g_\phi, m_\phi, m_4, U_{e4}) - E_i^{\rm SO}| + +2E_i^{\rm SO}\ln\frac{(1+\delta A_x)E_i^{(3+1)}(g_\phi, m_\phi, m_4, U_{e4})}{E_i^{\rm SO}} + + \left(\frac{\delta E_{\rm end,0}}{\sigma_{E_{\rm end,0}}}\right)^2 + \left(\frac{\delta A_\beta}{\sigma_{A_\beta}}\right)^2 + \left(\frac{\delta A_{\rm C\nu B}}{\sigma_{A_{\rm C\nu B}}}\right)^2.$$

Systematic uncertainties:

$$\sigma_{E_{\rm end,0}} = 2\ {\rm eV}$$
$$\sigma_{A_\beta} = 2A_\beta$$
$$\sigma_{A_{\rm C\nu B}} = 0.2A_{\rm C\nu B}$$

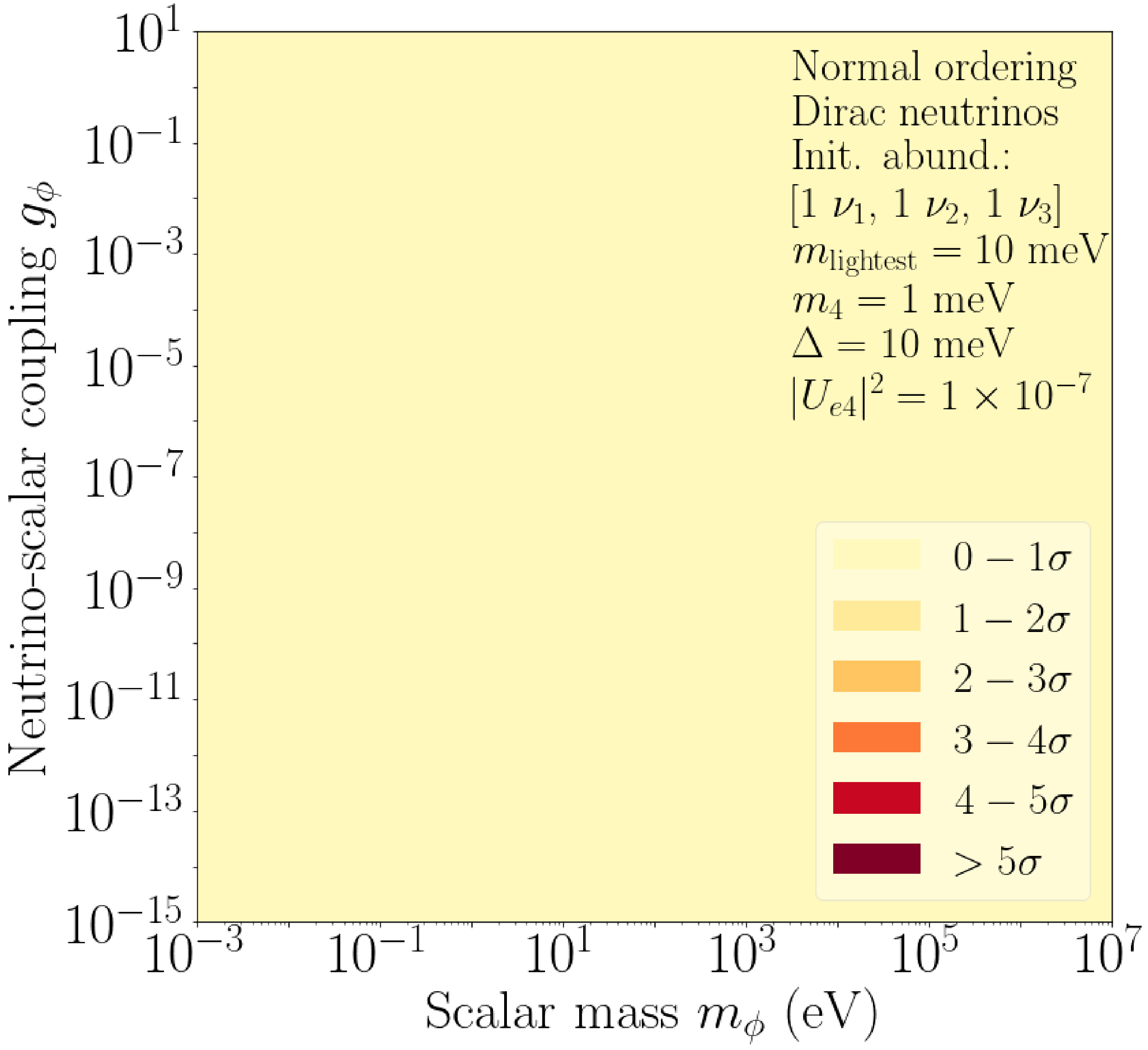


Results



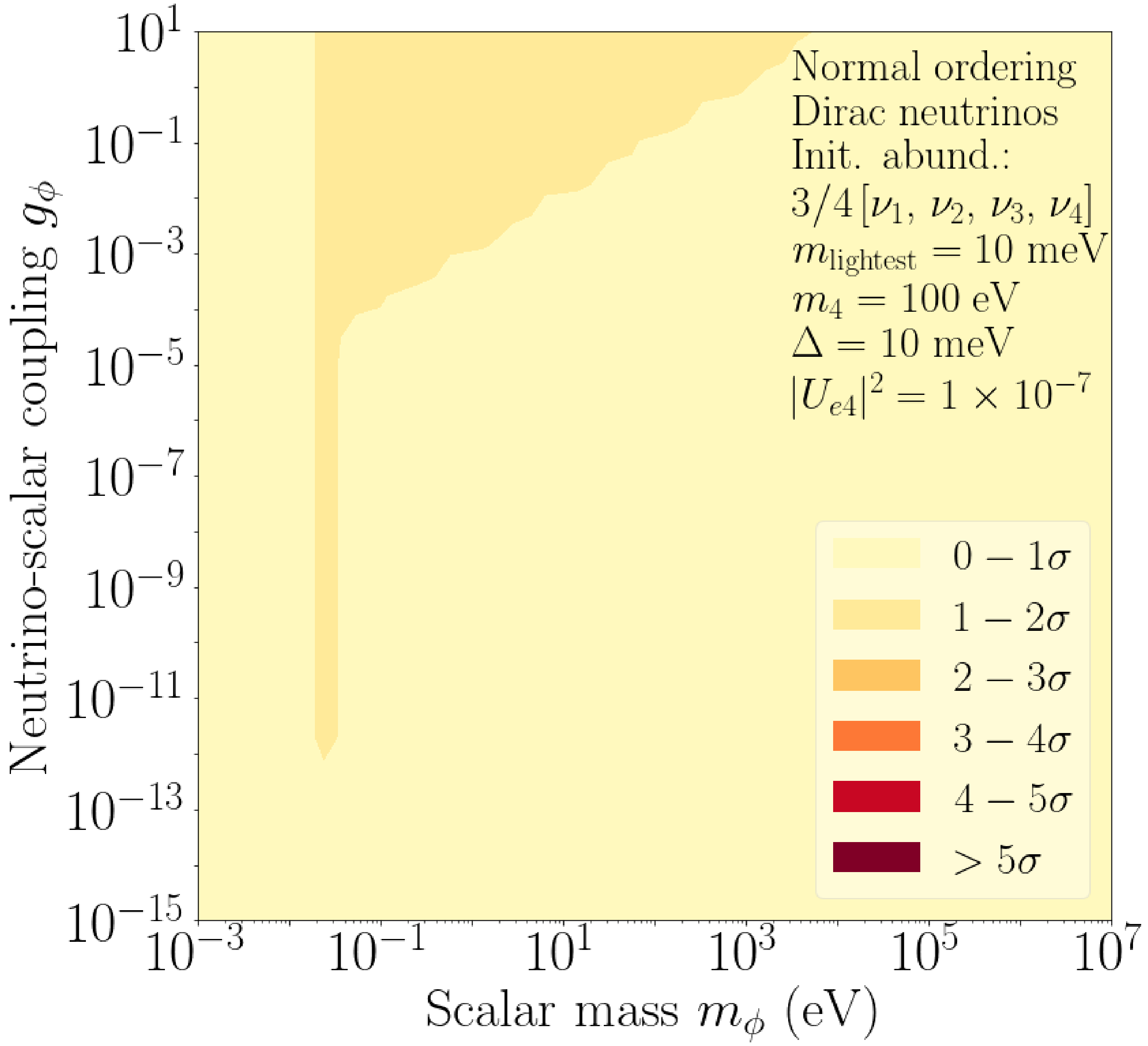
Considering inverted ordering, an exposure of 100 g yr, Dirac neutrinos, an initial population of only active neutrinos, and non-relativistic capture.

Results



For an exposure of 100 g yr, Dirac neutrinos, initial active neutrino population and light sterile mass.

Results

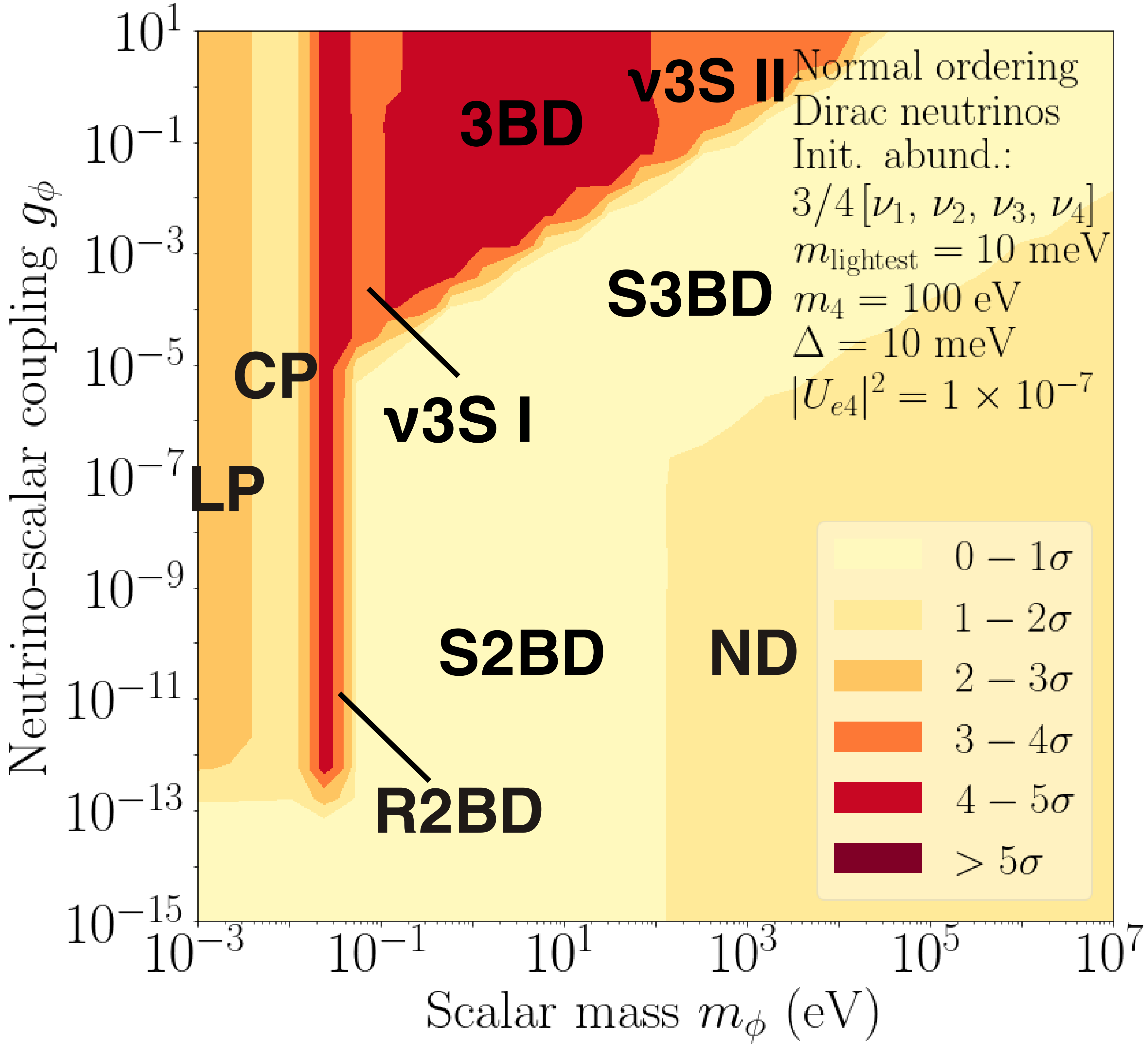


Considering normal ordering, an exposure of 100 g yr, Dirac neutrinos, an initial population of 3 active neutrinos + 1 sterile (<u>normalized to 3 species</u>), and non-relativistic capture.

Results

Additional exposure
(1000 g yr)

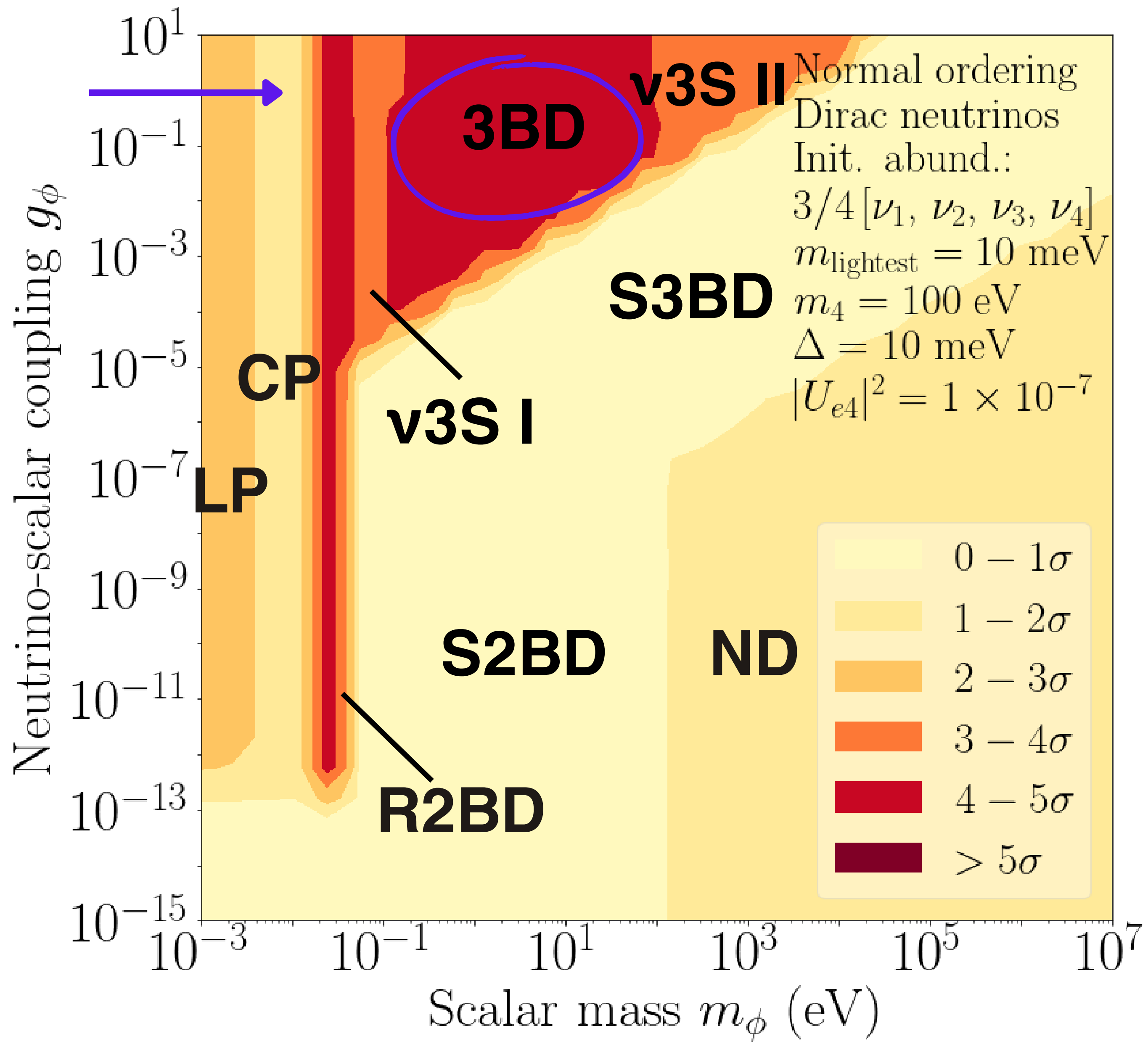
- Lightest neutrino peak (**LP**)
- Combined Peak (**CP**)
- Resonant Two-Body Decay (**R2BD**)
- v3 Suppression I (**v3S I**)
- Three-Body Decay (**3BD**)
- Sterile Two-Body Decay (**S2BD**)
- v3 Suppression II (**v3S II**)
- Sterile Three-body decay (**S3BD**)
- No Decay (**ND**)

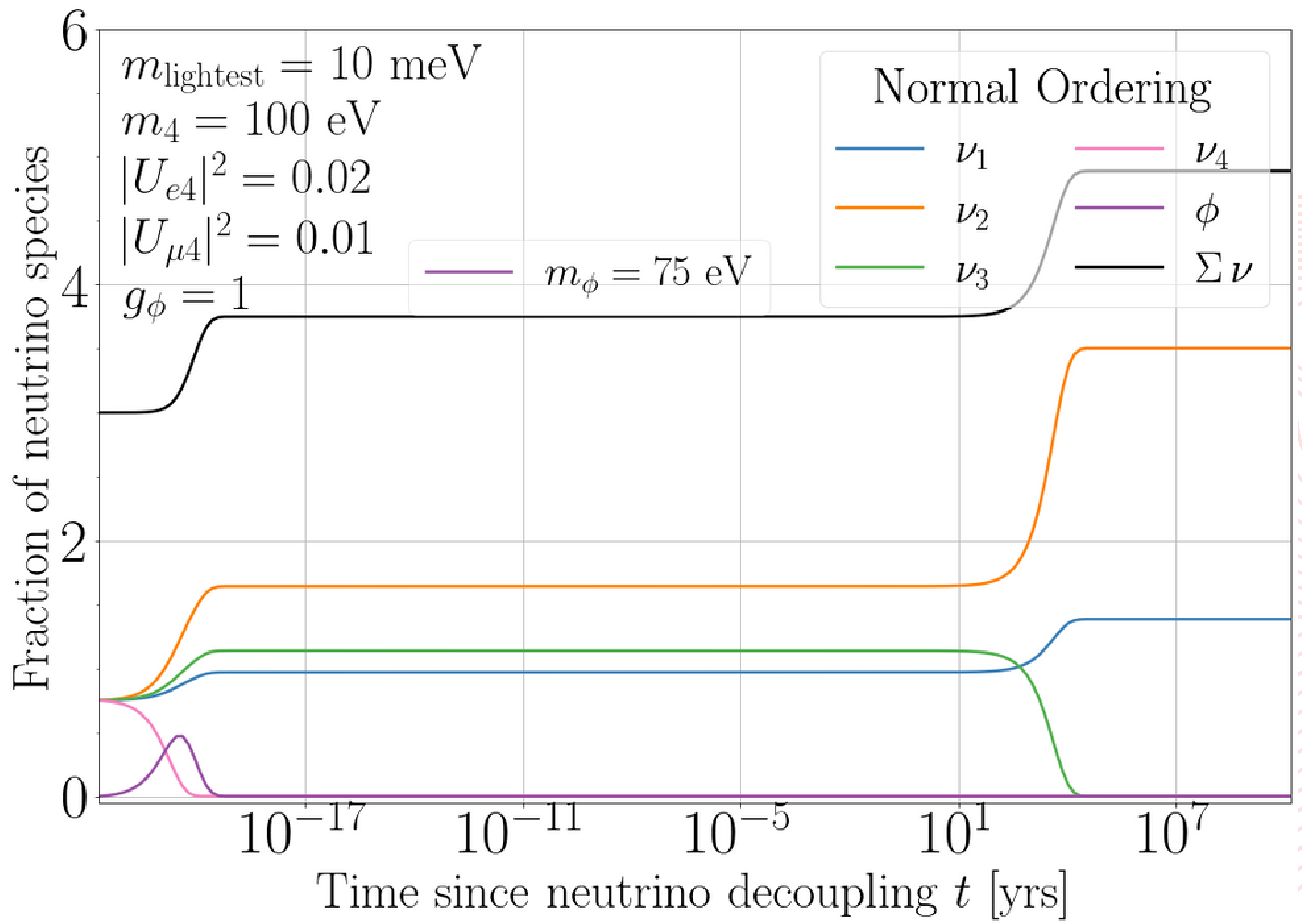


Results

- v3 Suppression I/II (**v3S I / II**)
- Three-Body Decay (**3BD**)

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

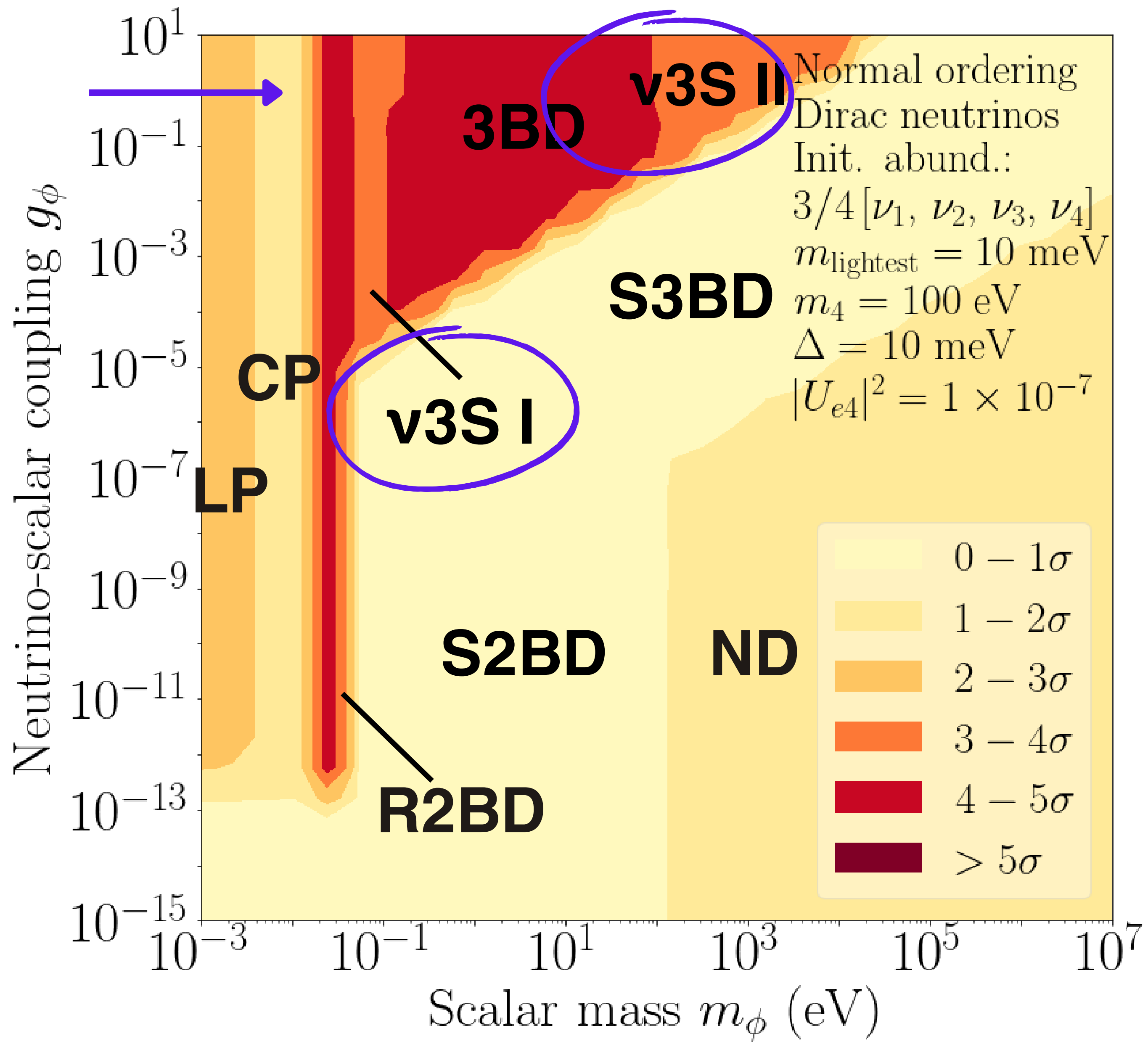


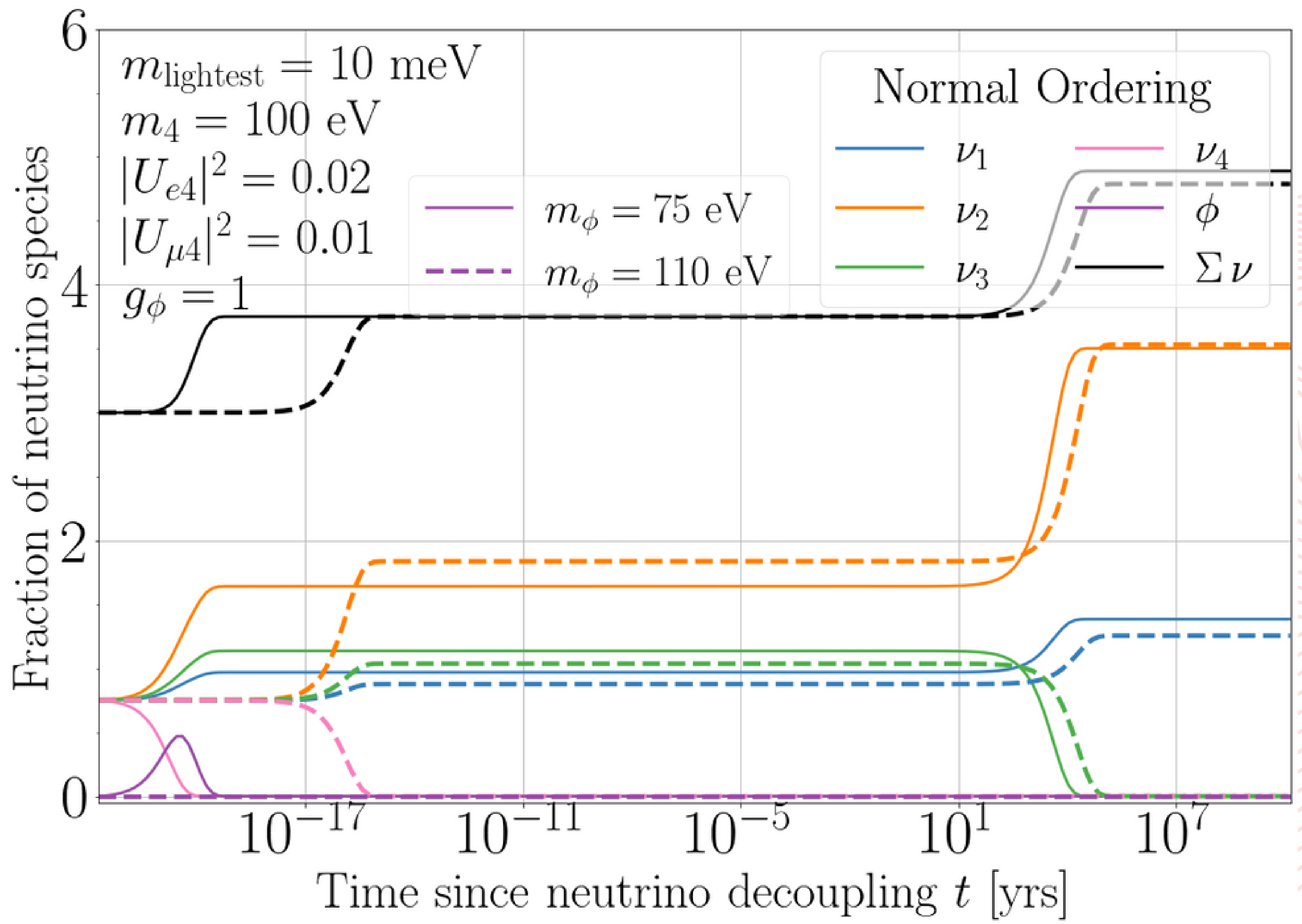


Results

- v3 Suppression I/II (**v3S I / II**)
- Three-Body Decay (**3BD**)

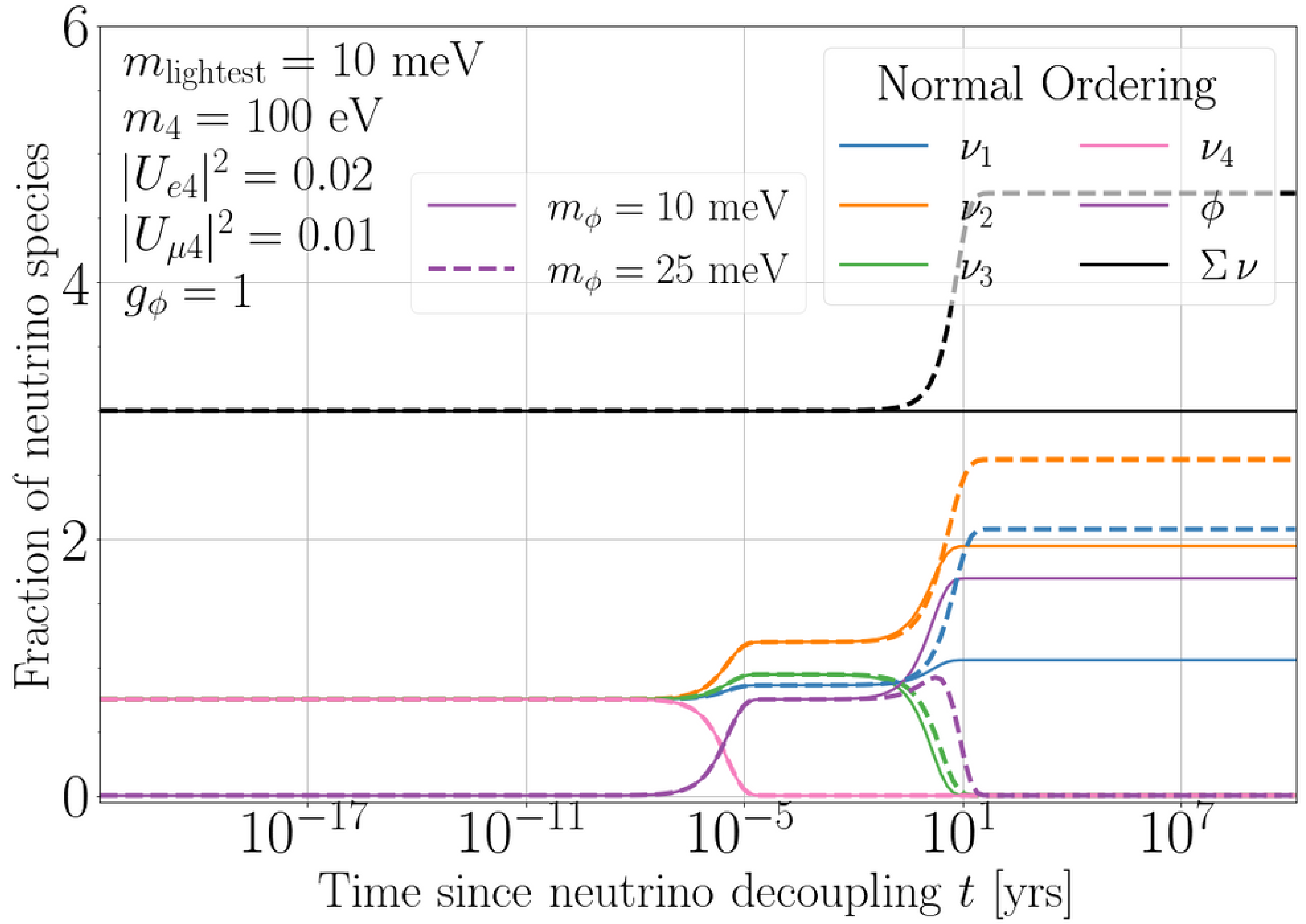
Three-body decays ➜ $\nu_i \to \nu_j \nu_k \bar{\nu}_l$

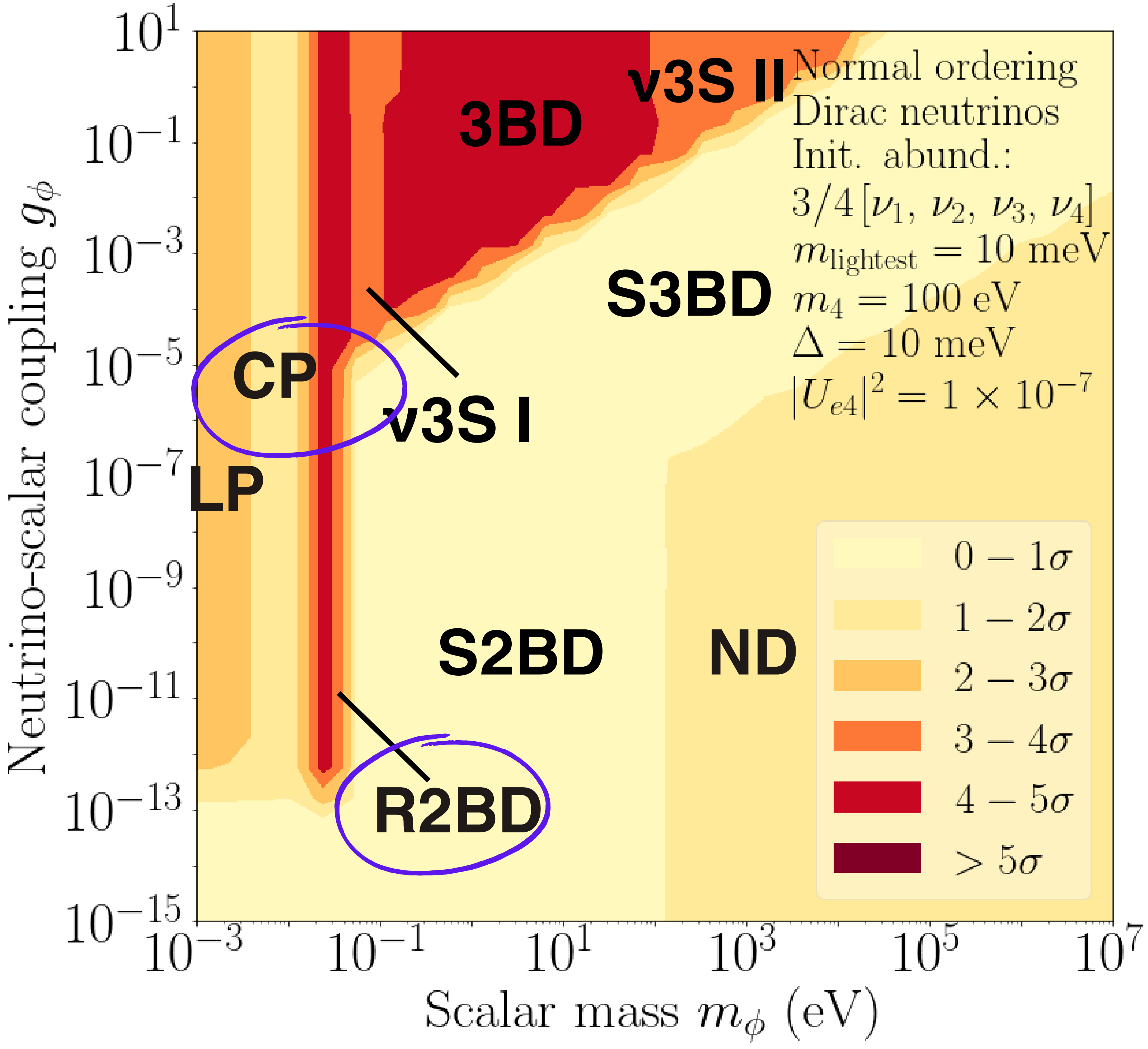




Results

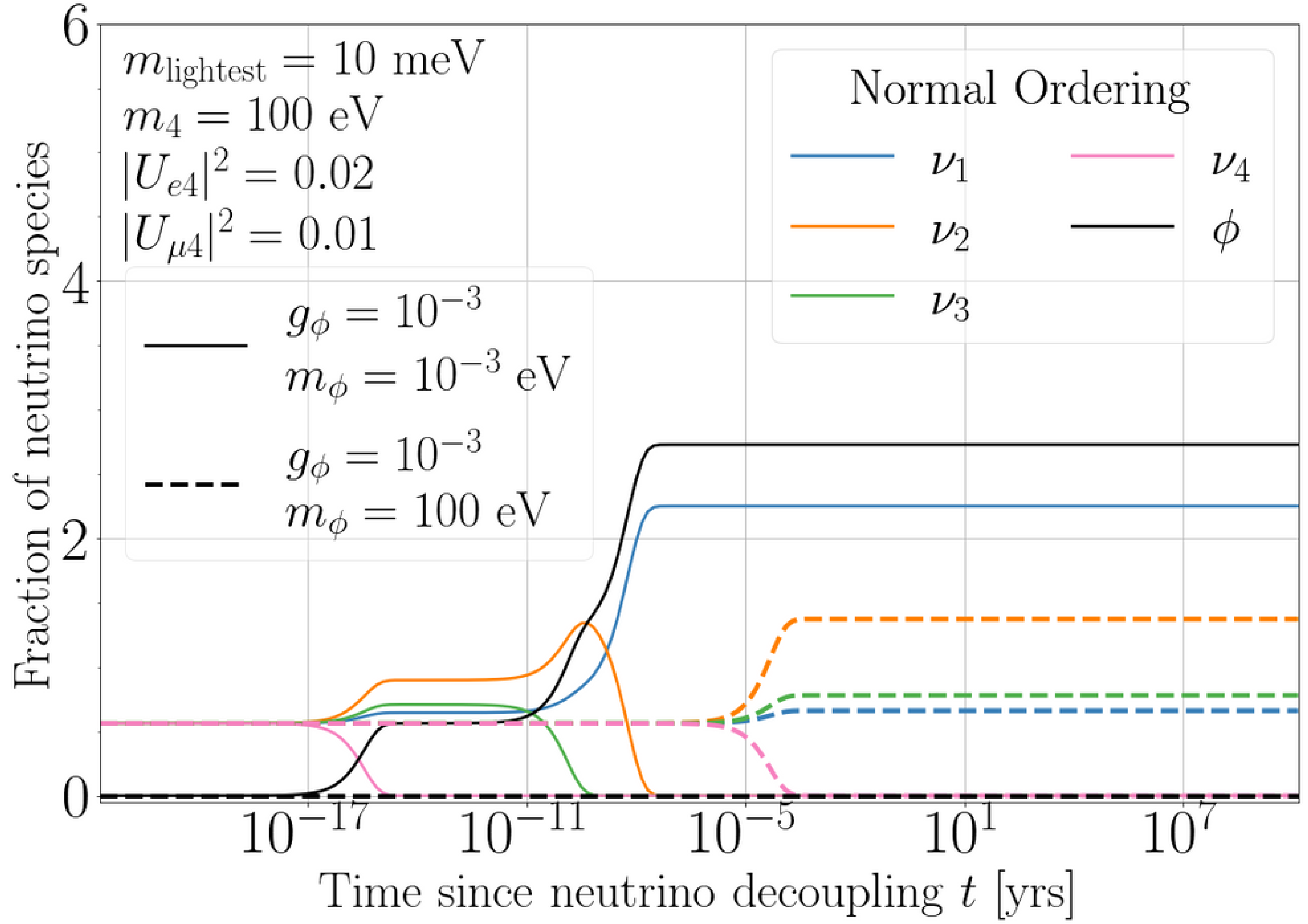
- Combined Peak (**CP**)
- Resonant Two-Body Decay (**R2BD**)

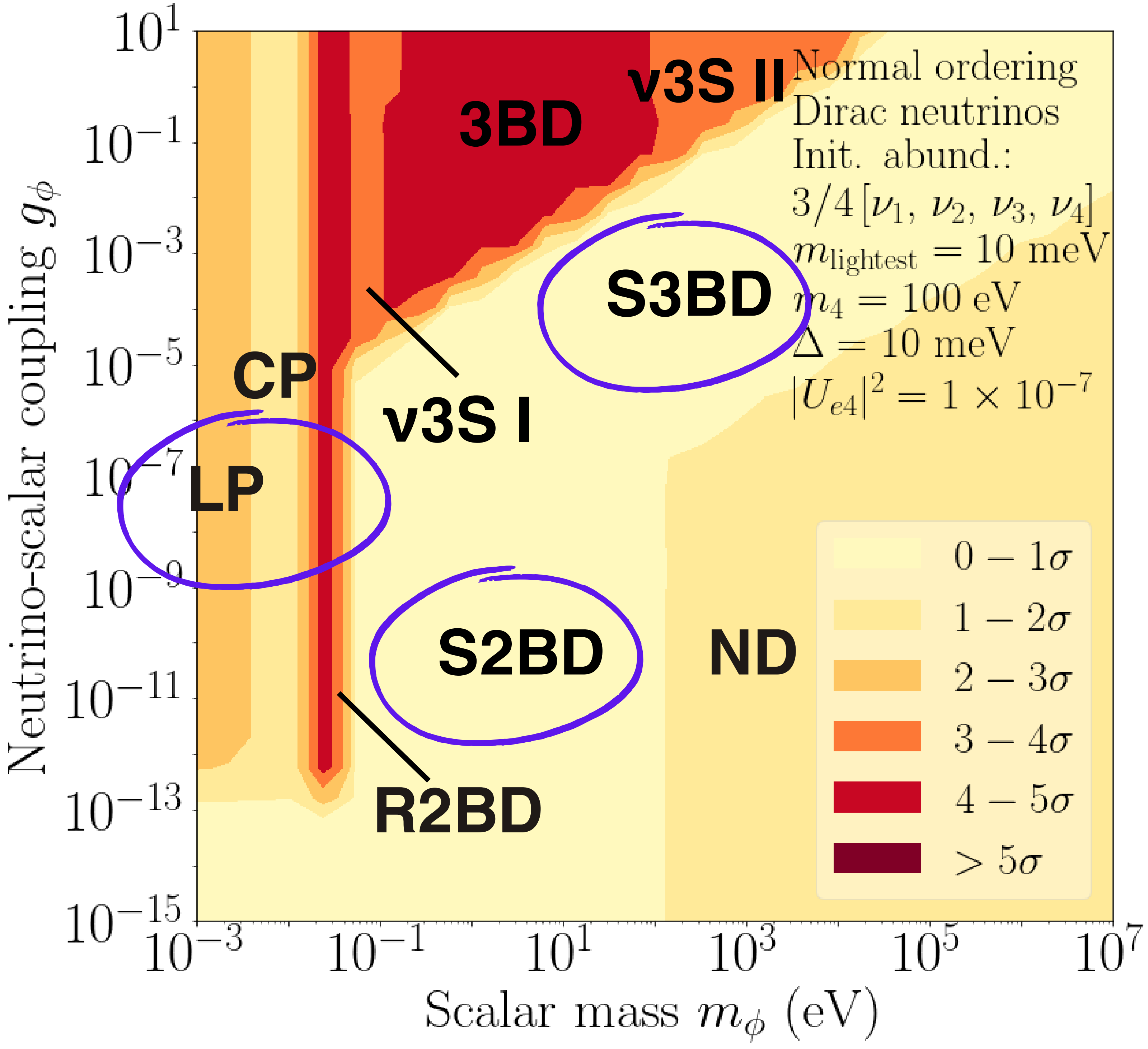




Results

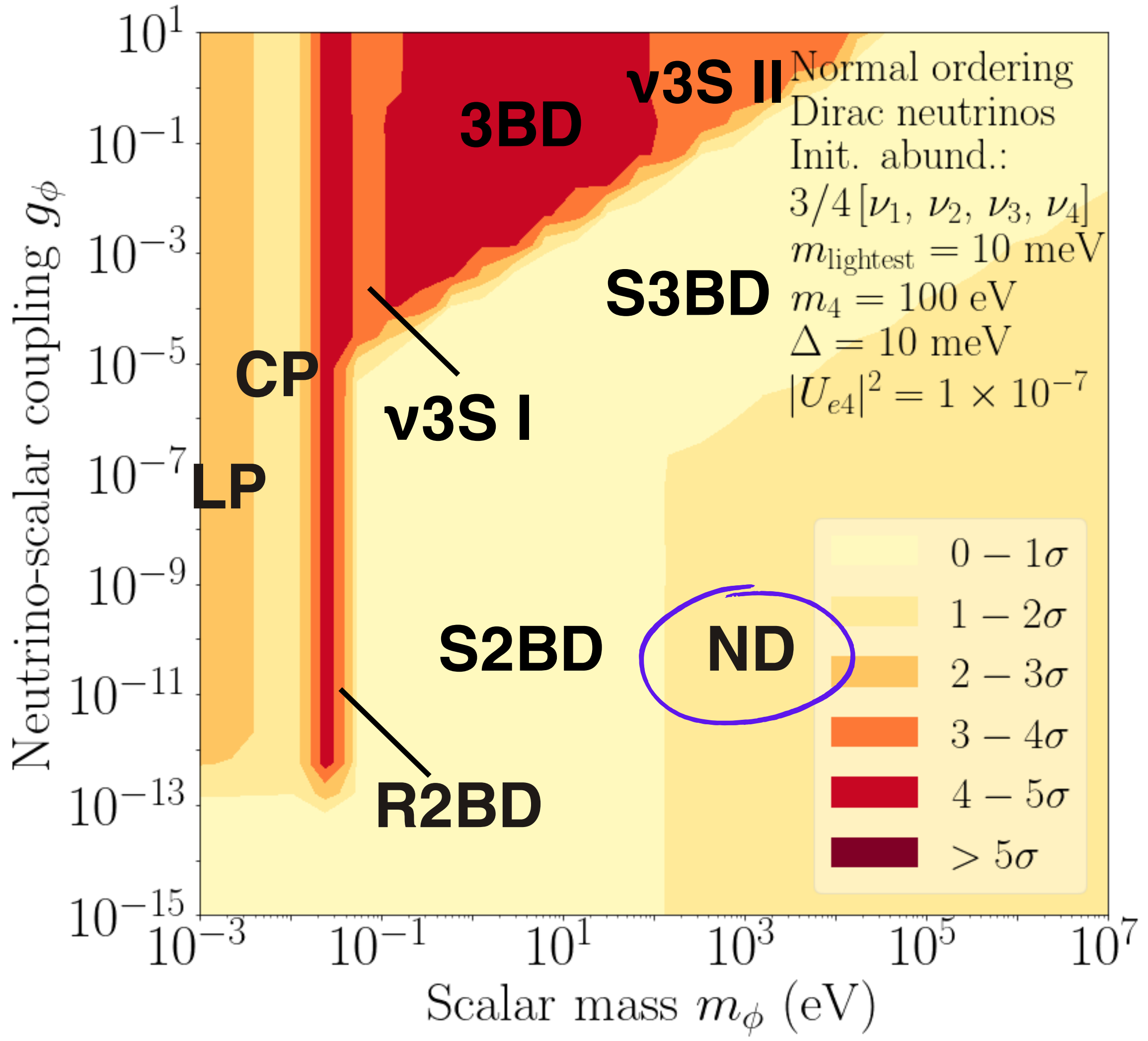
- Lightest neutrino peak (**LP**)
- Sterile Two(Three)-Body Decay (**S2BD/S3BD**)

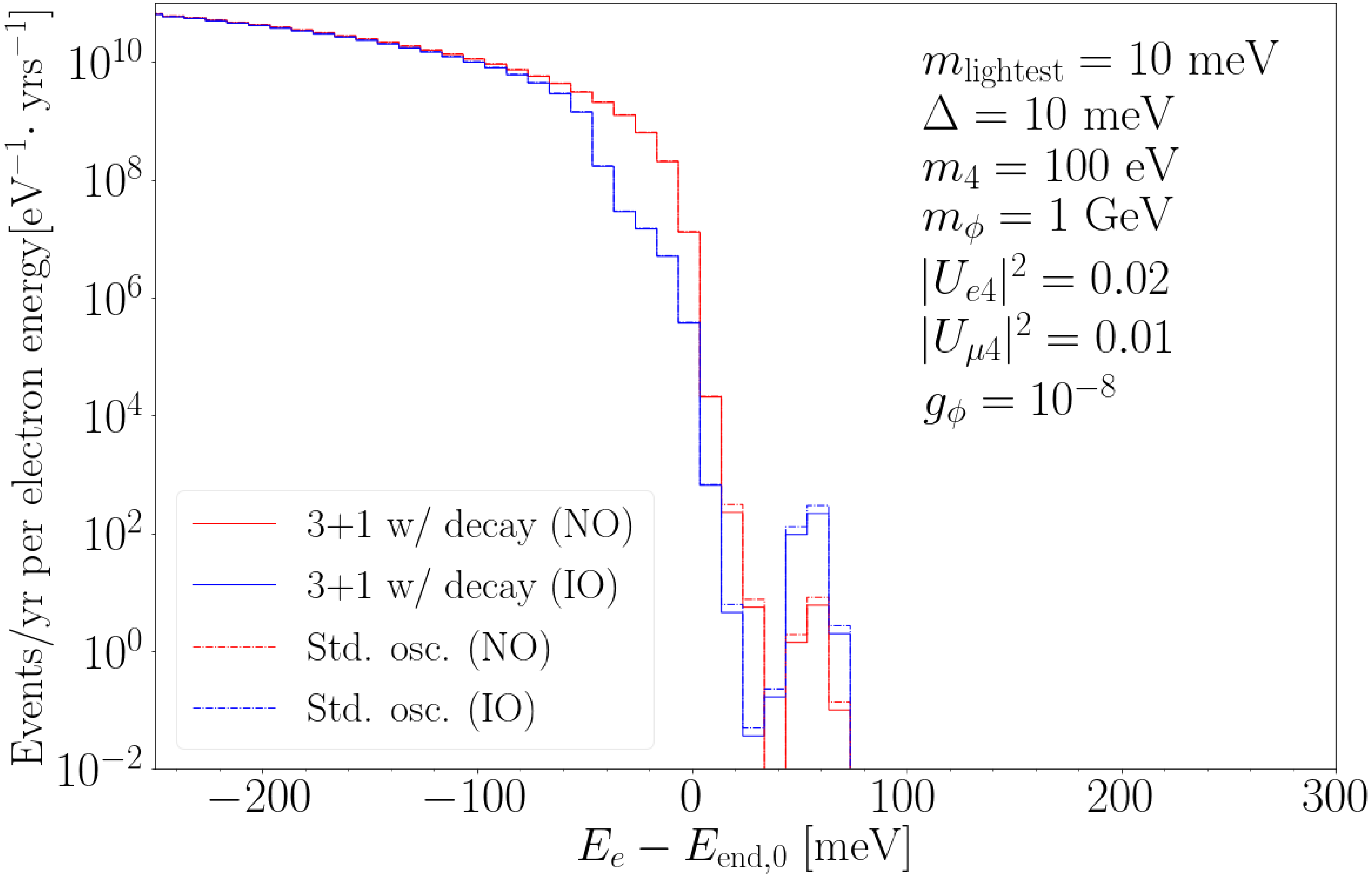




Results

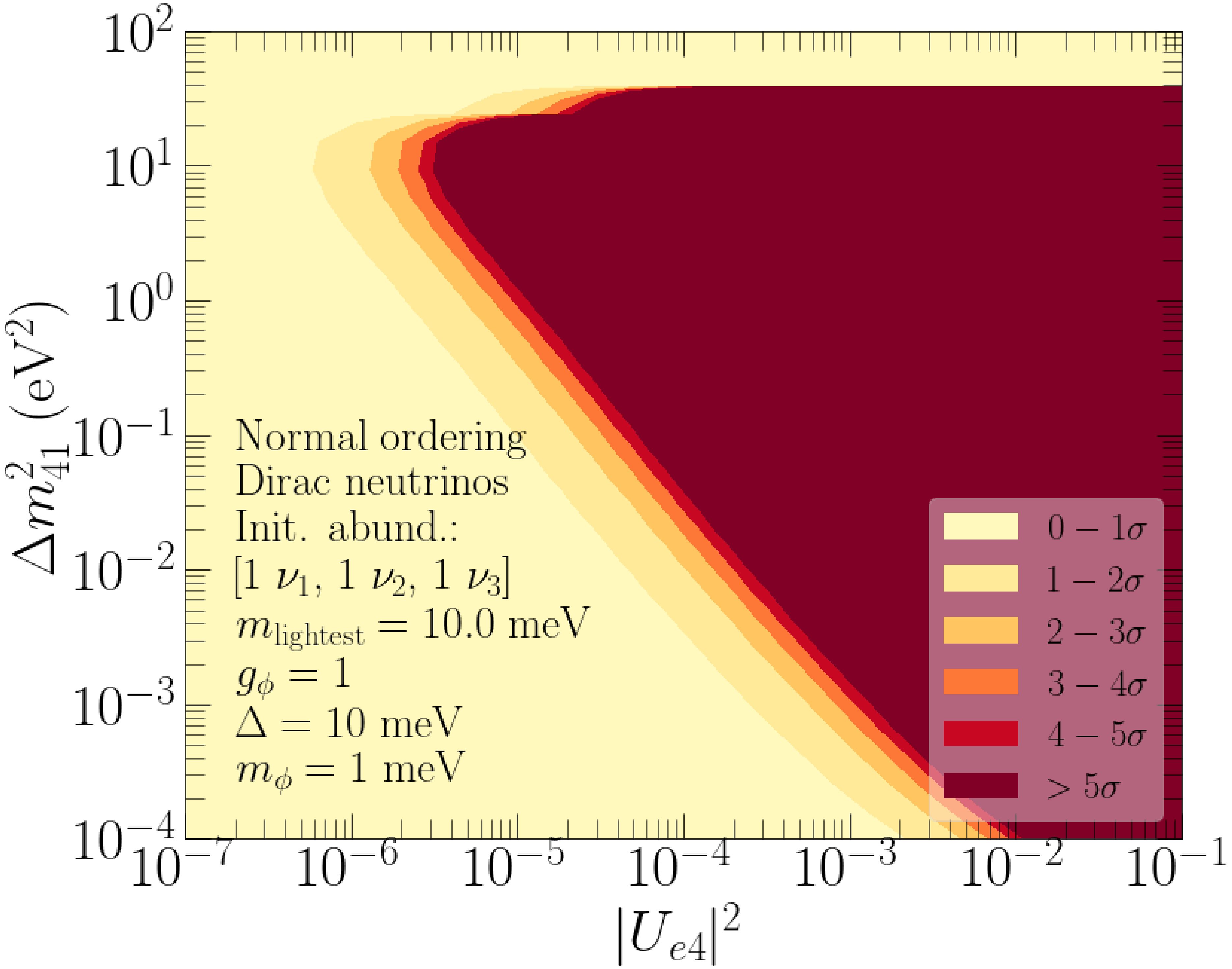
- No Decay (**ND**)





Results

- New limits on sterile neutrino parameter space (?)



Summary

- The disappearance or appearance of neutrinos leaves an imprint in the spectrum,
- CvB measurements can be good probes of new physics,
- Couplings as low as 10^{-14} could be probed by CvB,
- Very rich parameter space,
- Novel and exciting perspectives!

Summary

- The disappearance or appearance of neutrinos leaves an imprint in the spectrum,
- CνB measurements can be good probes of new physics,
- Couplings as low as 10^{-14} could be probed by CνB,
- Very rich parameter space
- Novel and exciting perspectives!

Thank You!

Works in Neutrino decay

[10] K. Akita, G. Lambiase, and M. Yamaguchi, Unstable cosmic neutrino capture, JHEP 2022, 132, arXiv:2109.02900 [hep-ph].

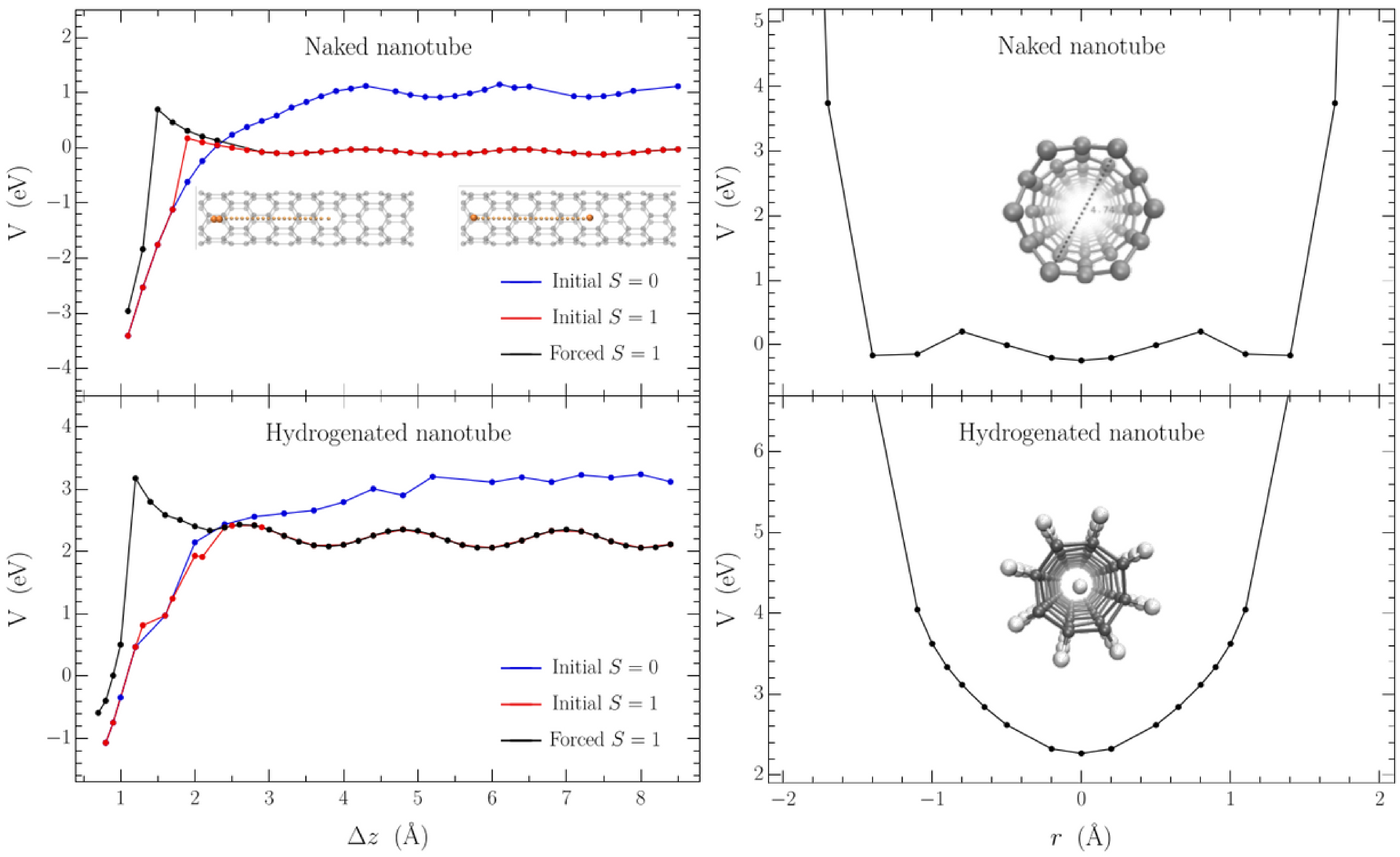
[11] Z. Chacko, A. Dev, P. Du, V. Poulin, and Y. Tsai, Determining the Neutrino Lifetime from Cosmology, Phys. Rev. D 103, 043519 (2021), arXiv:2002.08401 [astro-ph.CO].

[12] M. Escudero, J. Lopez-Pavon, N. Rius, and S. Sandner, Relaxing Cosmological Neutrino Mass Bounds with Unstable Neutrinos, JHEP 12 (2020), no. 119 [2007.04994].

[13] J. Alvey, M. Escudero, N. Sabti, and T. Schwetz, Cosmic neutrino background detection in large-neutrino-mass cosmologies, Phys. Rev. D 105 (Mar, 2022) 063501.

Backup

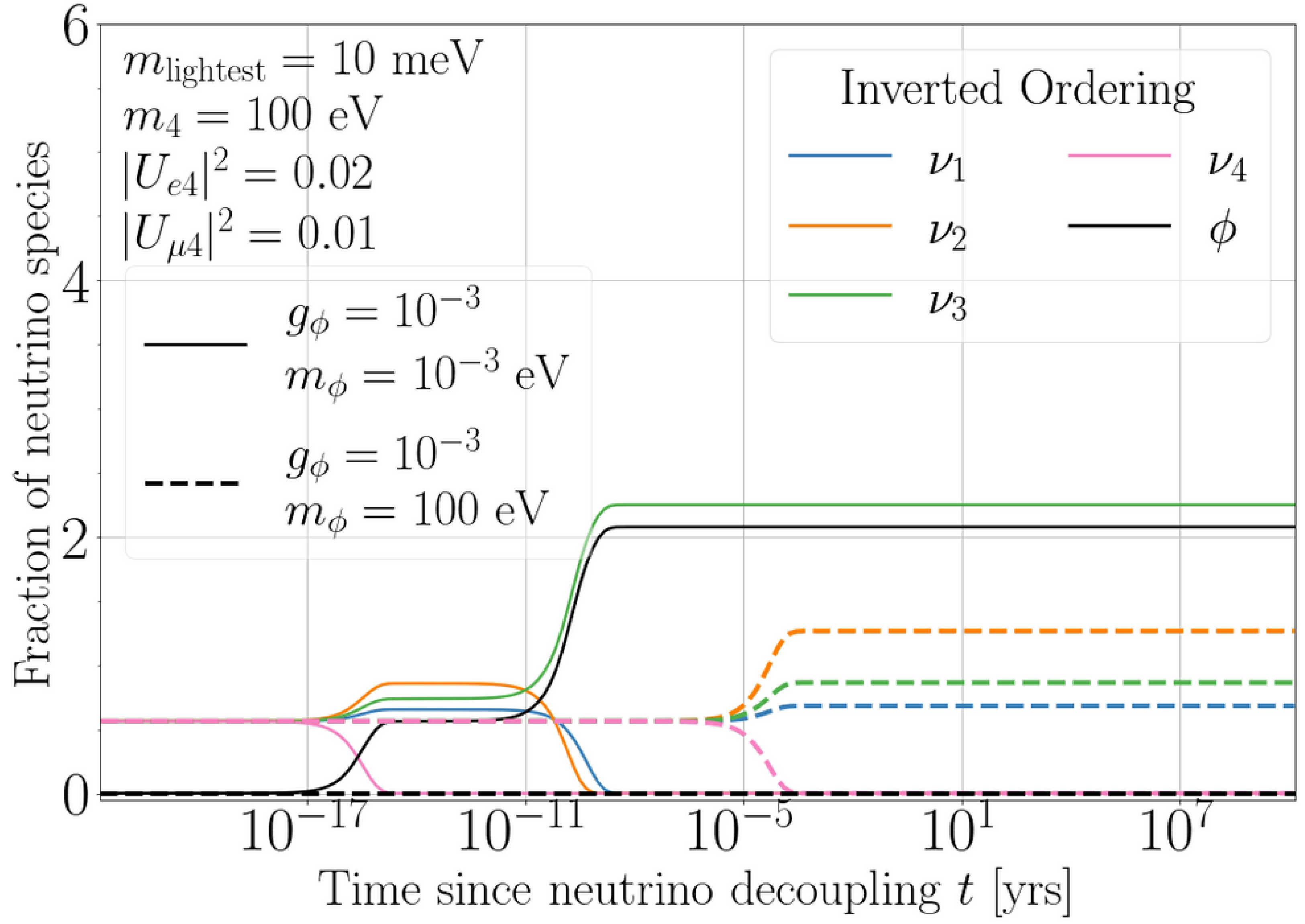
- Low statistics
- Different effects have the same signal
- High sensitivity required
- Quantum mechanics uncertainty



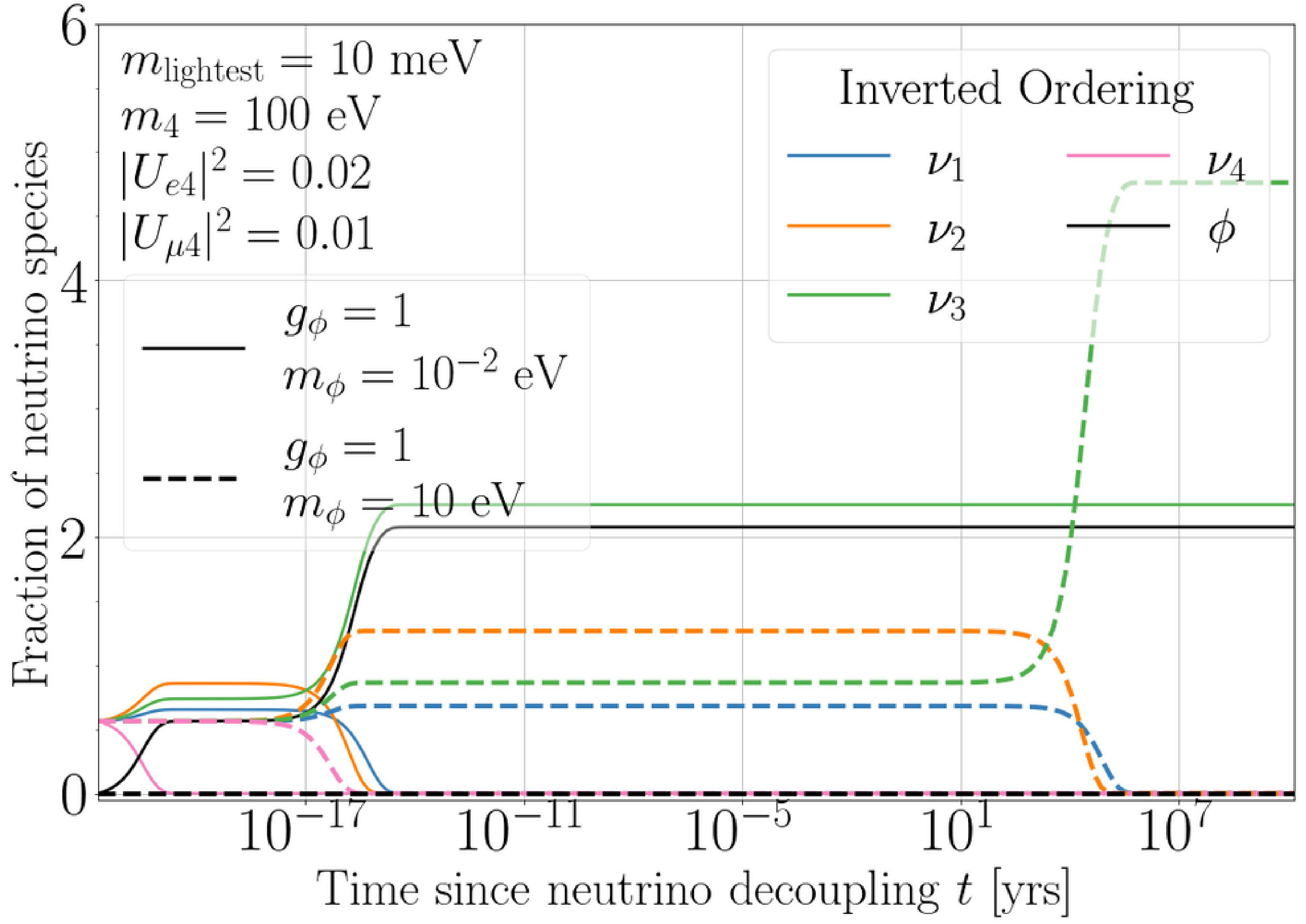
[16] Y. Cheipesh, V. Cheianov, and A. Boyarsky, Navigating the pitfalls of relic neutrino detection, Phys.Rev. D 104 (2021), no. 11 116004, [2101.10069].

[17] 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].

Backup

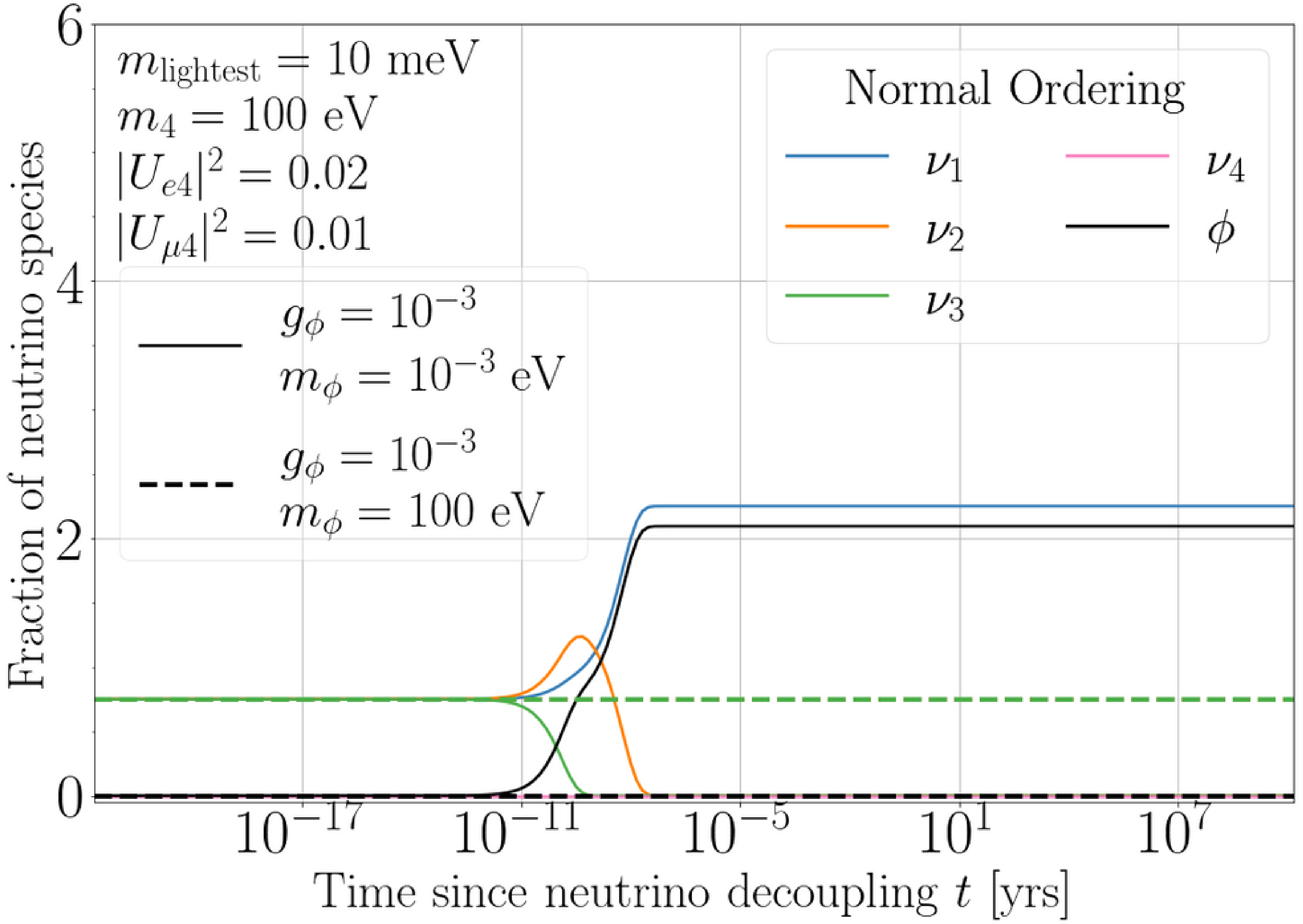


$m_{\text{lightest}} = 10$ meV
$m_4 = 100$ eV
$|U_{e4}|^2 = 0.02$
$|U_{\mu 4}|^2 = 0.01$
Inverted Ordering
ν_1
ν_2
ν_3
ν_4
ϕ
$g_\phi = 10^{-3}$
$m_\phi = 10^{-3}$ eV
$g_\phi = 10^{-3}$
$m_\phi = 100$ eV
Fraction of neutrino species
Time since neutrino decoupling t [yrs]

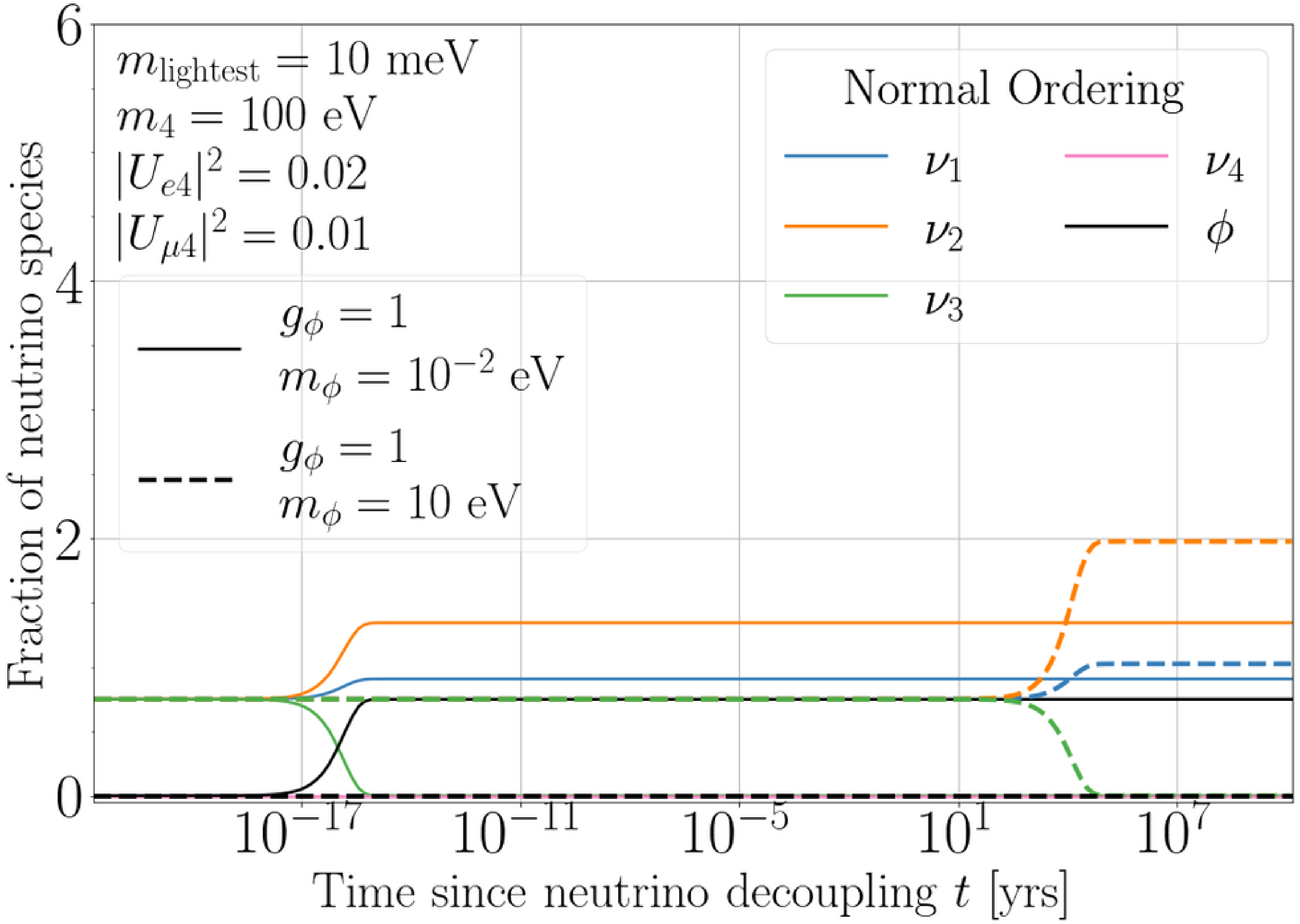


$m_{\text{lightest}} = 10$ meV
$m_4 = 100$ eV
$|U_{e4}|^2 = 0.02$
$|U_{\mu 4}|^2 = 0.01$
Inverted Ordering
ν_1
ν_2
ν_3
ν_4
ϕ
$g_\phi = 1$
$m_\phi = 10^{-2}$ eV
$g_\phi = 1$
$m_\phi = 10$ eV
Fraction of neutrino species
Time since neutrino decoupling t [yrs]

Backup

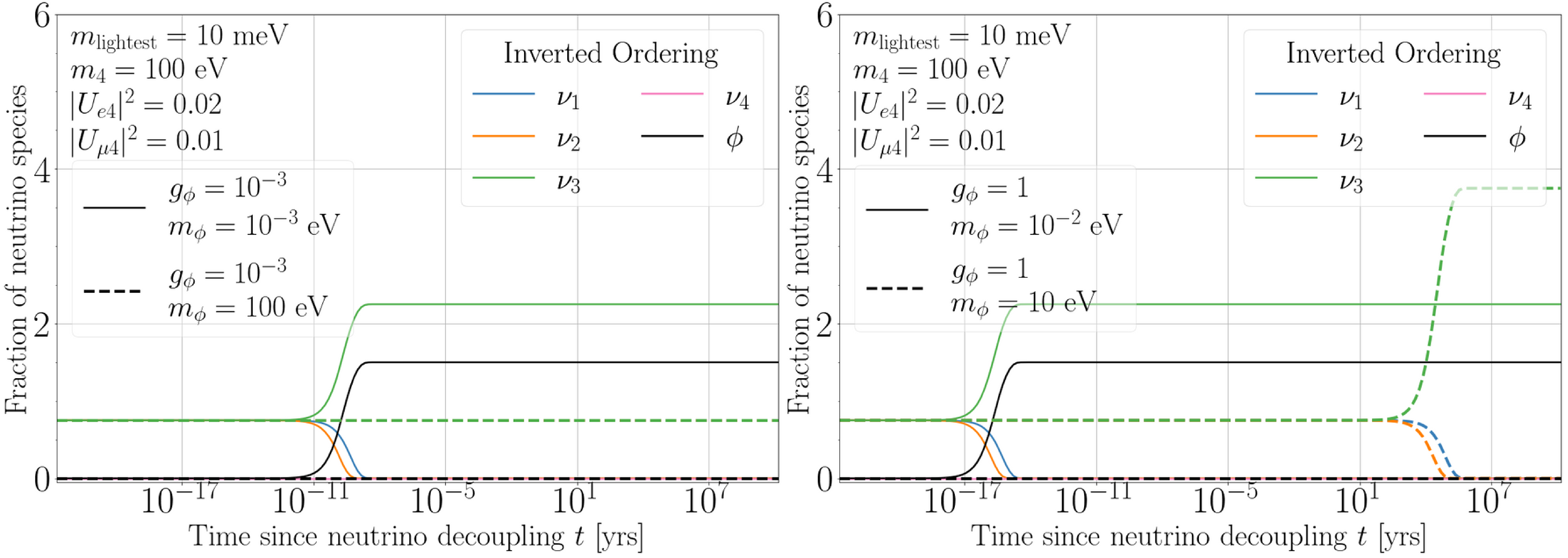


$m_{\text{lightest}} = 10$ meV
$m_4 = 100$ eV
$|U_{e4}|^2 = 0.02$
$|U_{\mu4}|^2 = 0.01$
$g_\phi = 10^{-3}$
$m_\phi = 10^{-3}$ eV
$g_\phi = 10^{-3}$
$m_\phi = 100$ eV
Normal Ordering
ν_1
ν_2
ν_3
ν_4
ϕ
Fraction of neutrino species
Time since neutrino decoupling t [yrs]



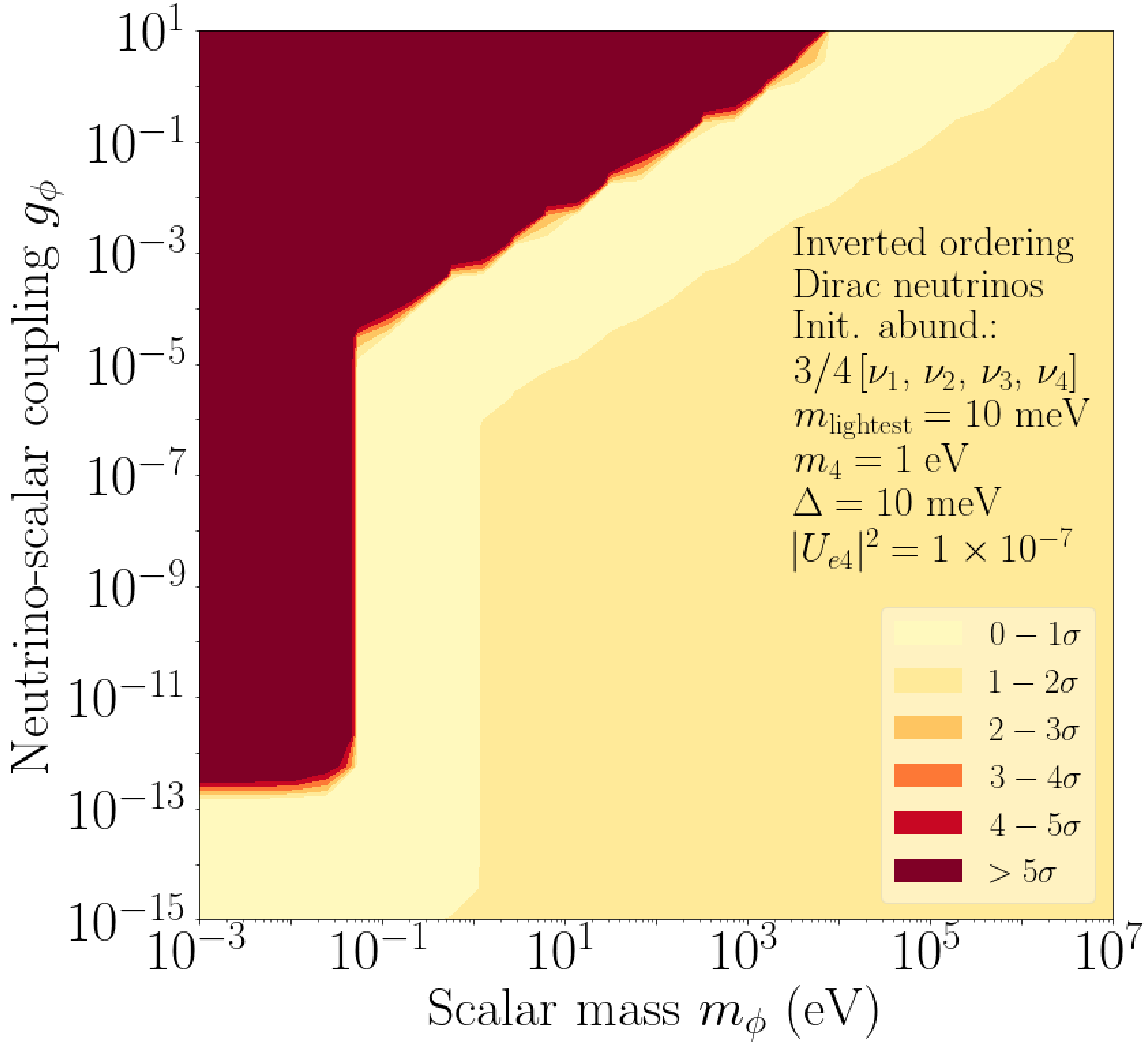
$m_{\text{lightest}} = 10$ meV
$m_4 = 100$ eV
$|U_{e4}|^2 = 0.02$
$|U_{\mu4}|^2 = 0.01$
$g_\phi = 1$
$m_\phi = 10^{-2}$ eV
$g_\phi = 1$
$m_\phi = 10$ eV
Normal Ordering
ν_1
ν_2
ν_3
ν_4
ϕ
Fraction of neutrino species
Time since neutrino decoupling t [yrs]

Backup



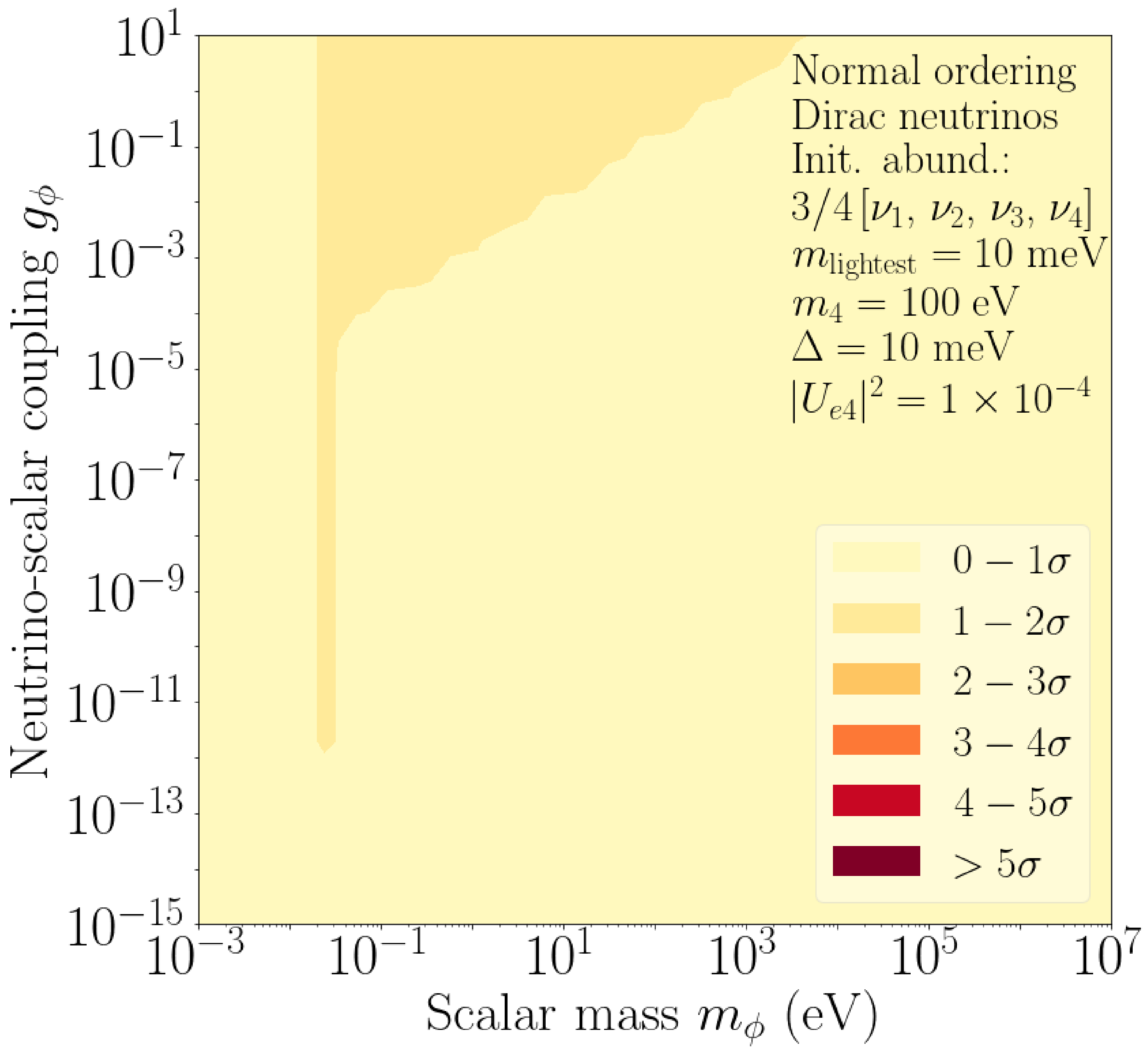
$m_{\text{lightest}} = 10$ meV
$m_4 = 100$ eV
$|U_{e4}|^2 = 0.02$
$|U_{\mu4}|^2 = 0.01$
$g_\phi = 10^{-3}$
$m_\phi = 10^{-3}$ eV
$g_\phi = 10^{-3}$
$m_\phi = 100$ eV
Inverted Ordering
ν_1
ν_2
ν_3
ν_4
ϕ
Fraction of neutrino species
Time since neutrino decoupling t [yrs]
$m_{\text{lightest}} = 10$ meV
$m_4 = 100$ 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
Time since neutrino decoupling t [yrs]

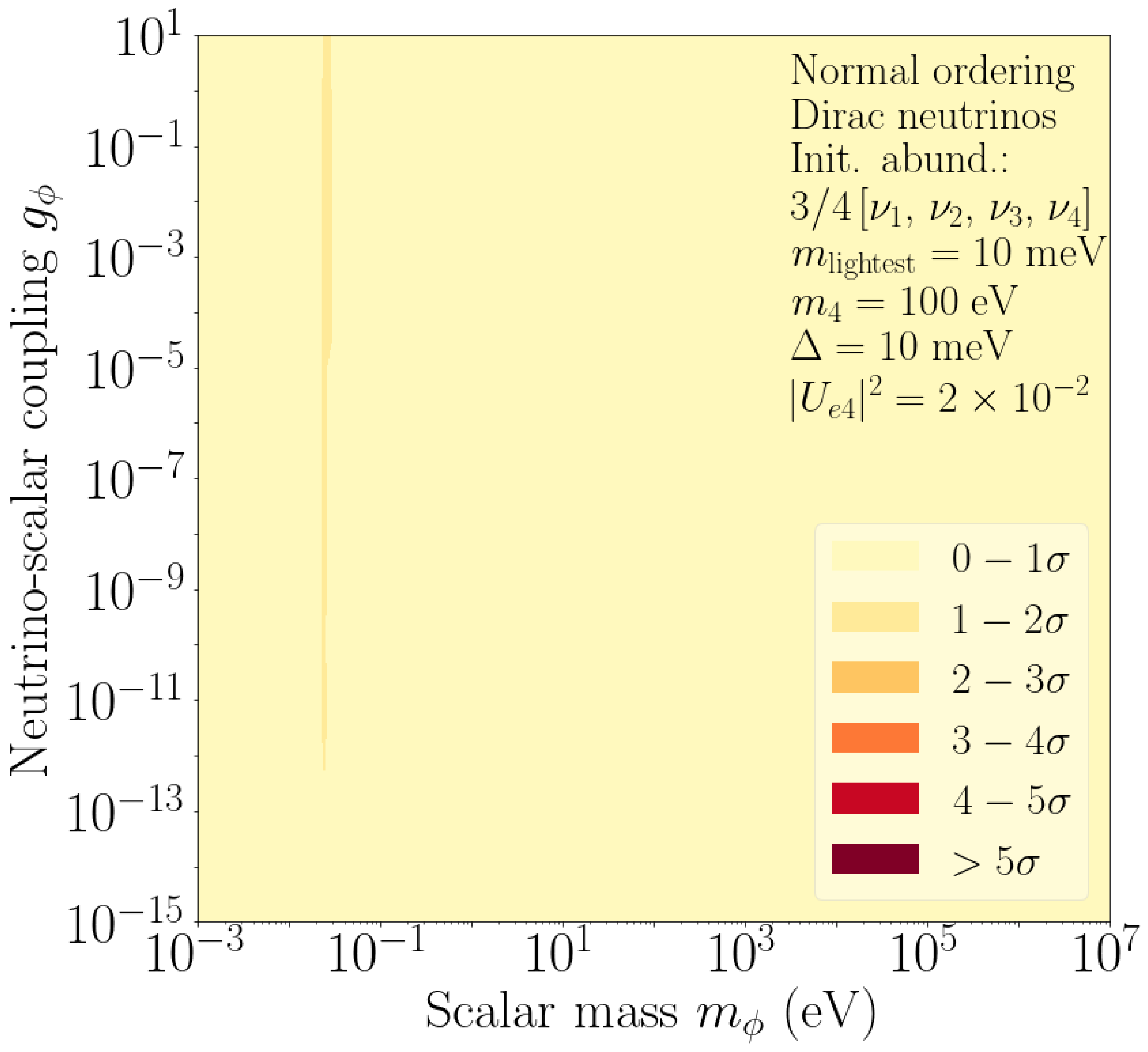
Backup



Inverted ordering
Dirac neutrinos
Init. abund.:
$3/4\,[\nu_1,\,\nu_2,\,\nu_3,\,\nu_4]$
$m_{\rm lightest} = 10$ meV
$m_4 = 1$ eV
$\Delta = 10$ meV
$|U_{e4}|^2 = 1 \times 10^{-7}$
$0-1\sigma$
$1-2\sigma$
$2-3\sigma$
$3-4\sigma$
$4-5\sigma$
$>5\sigma$
Neutrino-scalar coupling g_ϕ
Scalar mass m_ϕ (eV)
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}

Backup


Normal ordering
Dirac neutrinos
Init. abund.:
$3/4\,[\nu_1,\,\nu_2,\,\nu_3,\,\nu_4]$
$m_{\rm lightest} = 10$ meV
$m_4 = 100$ eV
$\Delta = 10$ meV
$|U_{e4}|^2 = 1 \times 10^{-4}$
$0-1\sigma$
$1-2\sigma$
$2-3\sigma$
$3-4\sigma$
$4-5\sigma$
$>5\sigma$
Neutrino-scalar coupling g_ϕ
Scalar mass m_ϕ (eV)


Normal ordering
Dirac neutrinos
Init. abund.:
$3/4\,[\nu_1,\,\nu_2,\,\nu_3,\,\nu_4]$
$m_{\rm lightest} = 10$ meV
$m_4 = 100$ eV
$\Delta = 10$ meV
$|U_{e4}|^2 = 2 \times 10^{-2}$
$0-1\sigma$
$1-2\sigma$
$2-3\sigma$
$3-4\sigma$
$4-5\sigma$
$>5\sigma$
Neutrino-scalar coupling g_ϕ
Scalar mass m_ϕ (eV)