Karlsruher Institut für Technologie

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

# Neutrino mass from heaven and earth

## Portoroz 2023, 12 April 2023

Thomas Schwetz
Karlsruhe Institute of Technology, Institute for Astroparticle Physics

# Outline

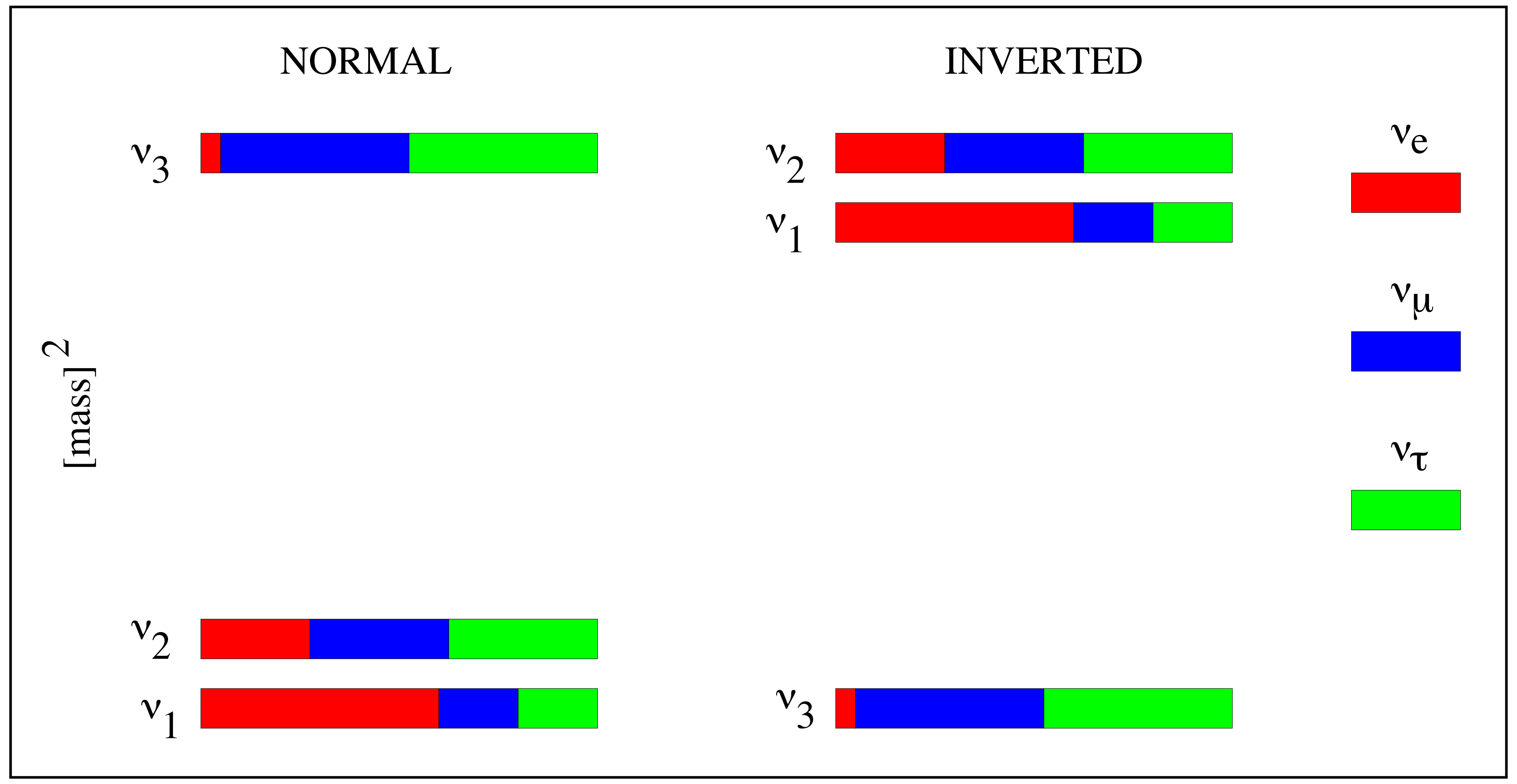
- Tension between terrestrial and cosmological neutrino mass determinations?

  w. Stefano Gariazzo, Olga Mena, 2302.14159 (Phys. Dark Univ.)

- A seesaw model for „large“ neutrino masses consistent with cosmology

  w. Miguel Escudero, Jorge Terol-Calvo, 2211.01729 (JHEP)

# Neutrino masses




## Neutrino oscillations:

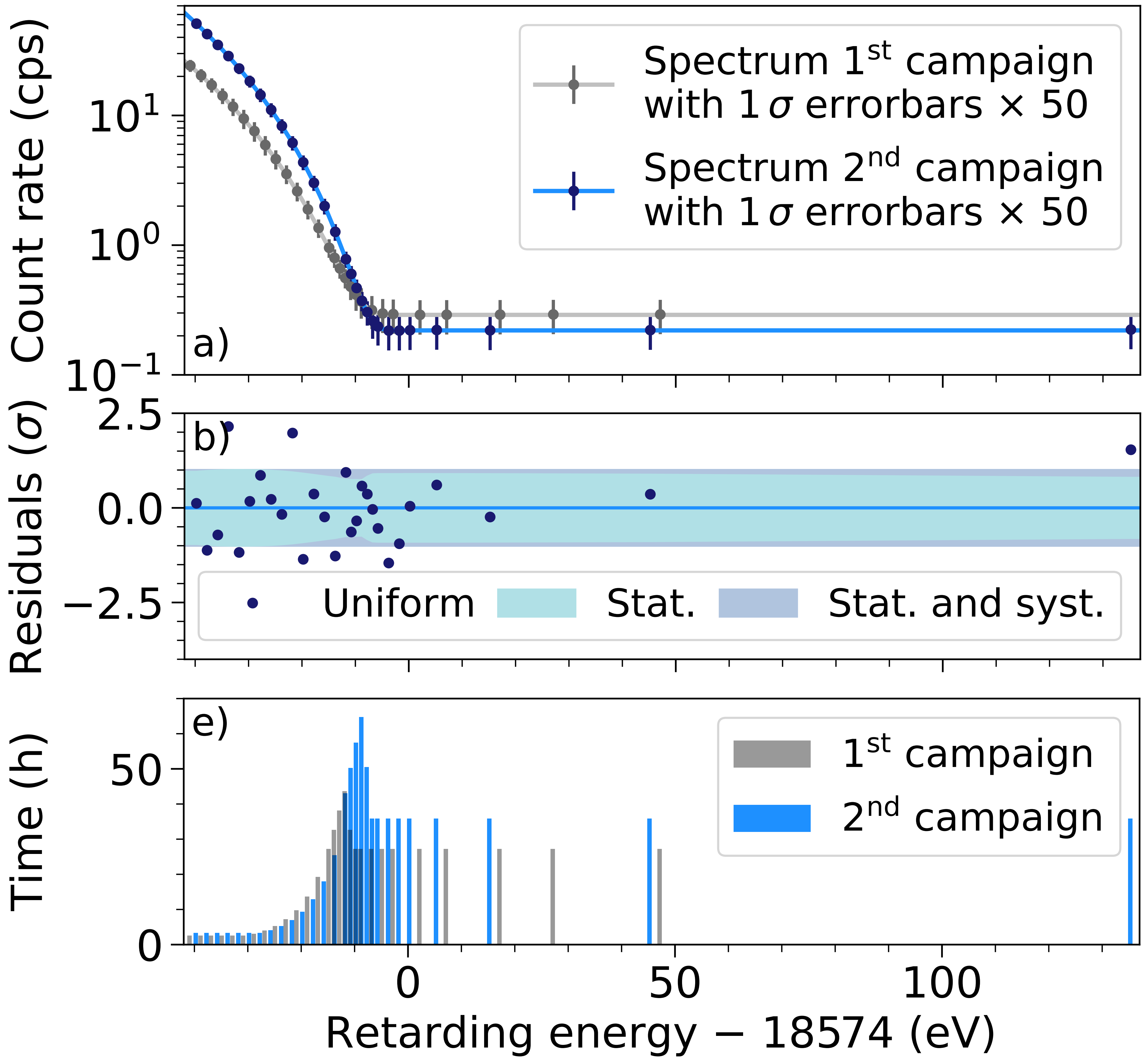
- $|m_3^2 - m_1^2| \approx (2.5 \pm 0.03) \times 10^{-3}\,\mathrm{eV}^2$
- $m_2^2 - m_1^2 = (7.42 \pm 0.21) \times 10^{-5}\,\mathrm{eV}^2$

## Absolute mass determinations:

- beta-decay spectrum(KATRIN) $m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 0.8\,\mathrm{eV}$
- neutrinoless double-beta decay (assuming Majorana neutrinos) $m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| \lesssim 0.07\,\mathrm{eV}$
- cosmology $\sum_i m_i \lesssim 0.1\,\mathrm{eV}$

# Beta decay spectrum — KATRIN

KATRIN, Nature Phys. 18 (2022) 160 [2105.08533]

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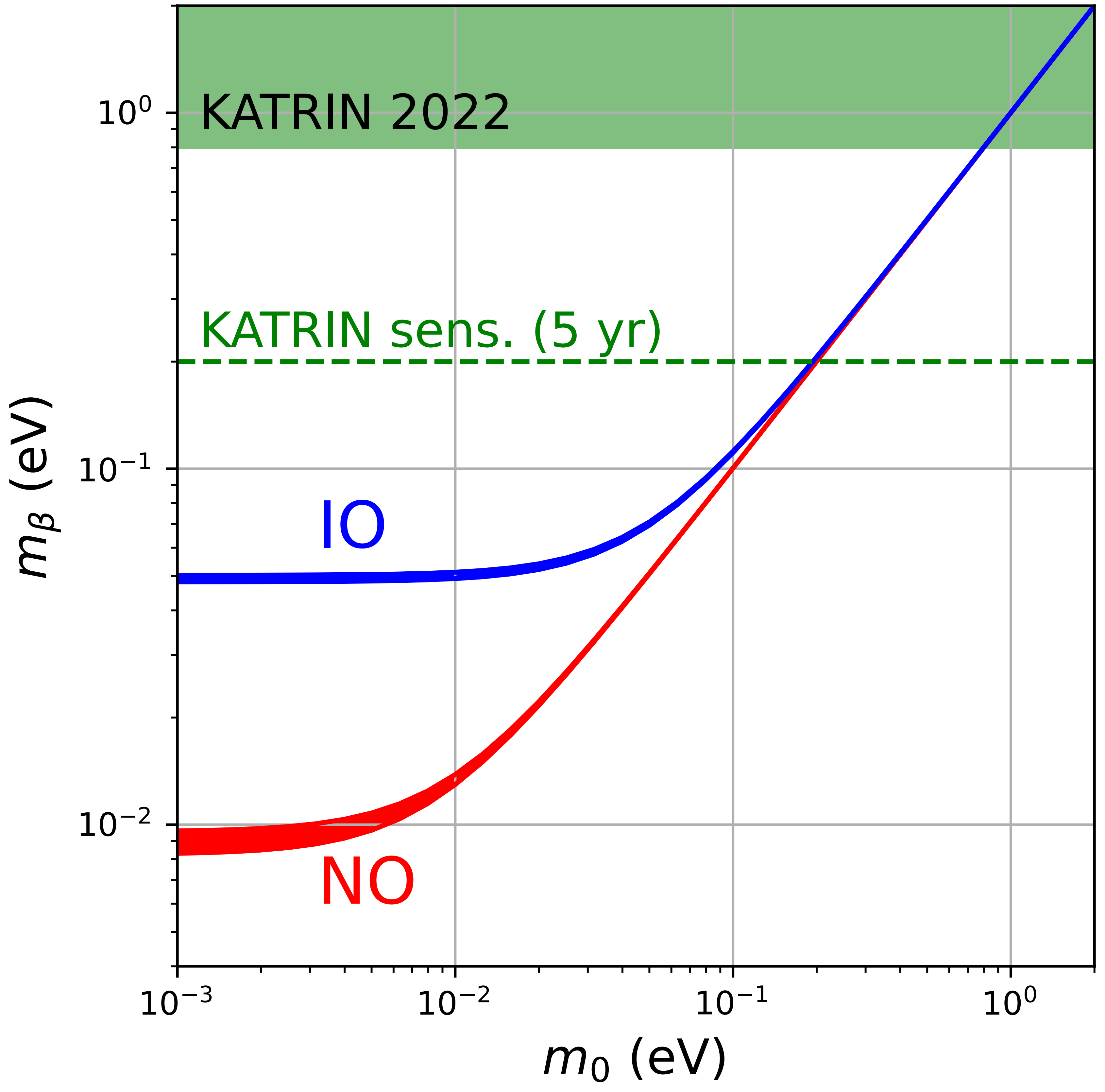




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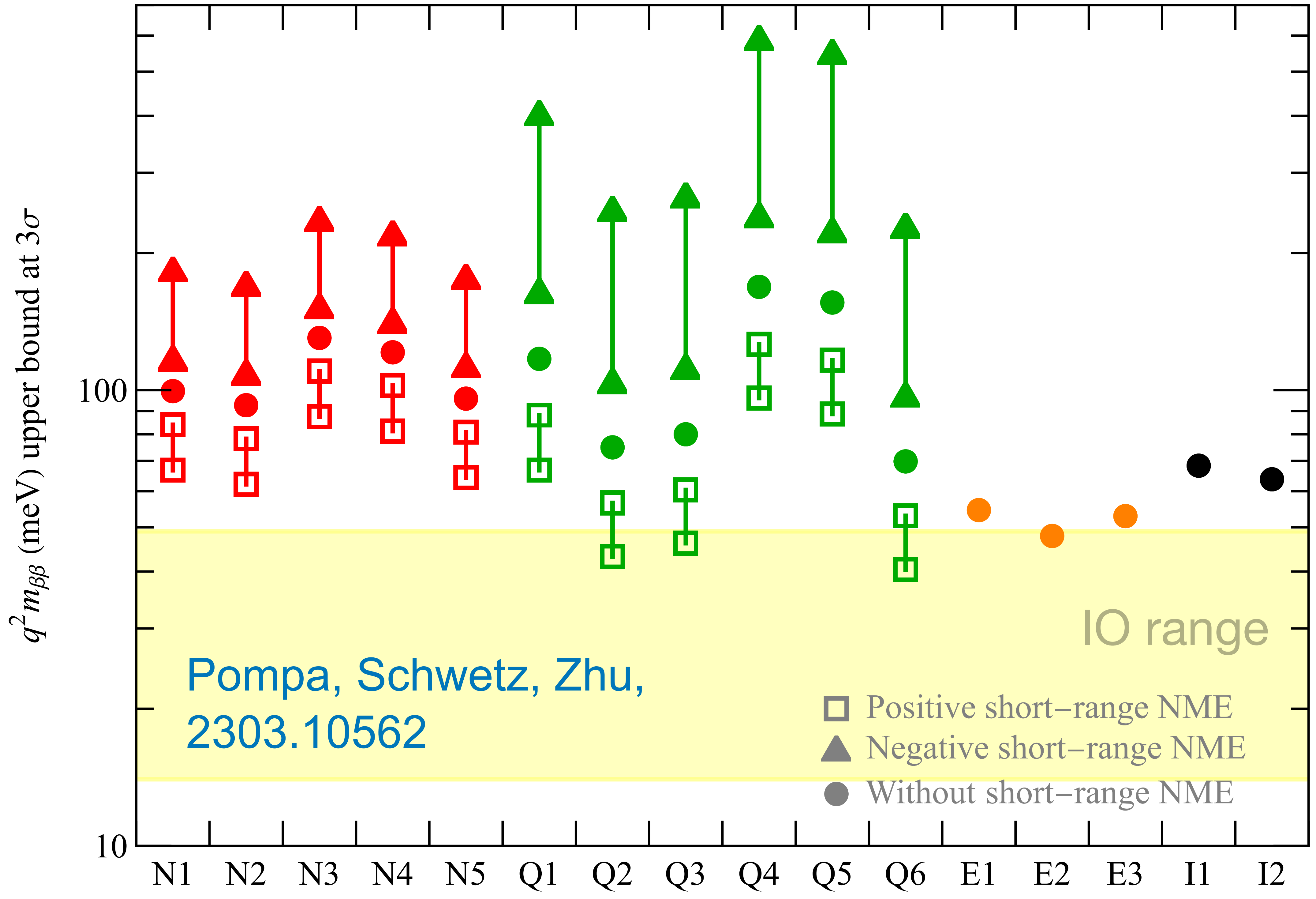
# Neutrinoless double-beta decay ⇒ lepton number violation

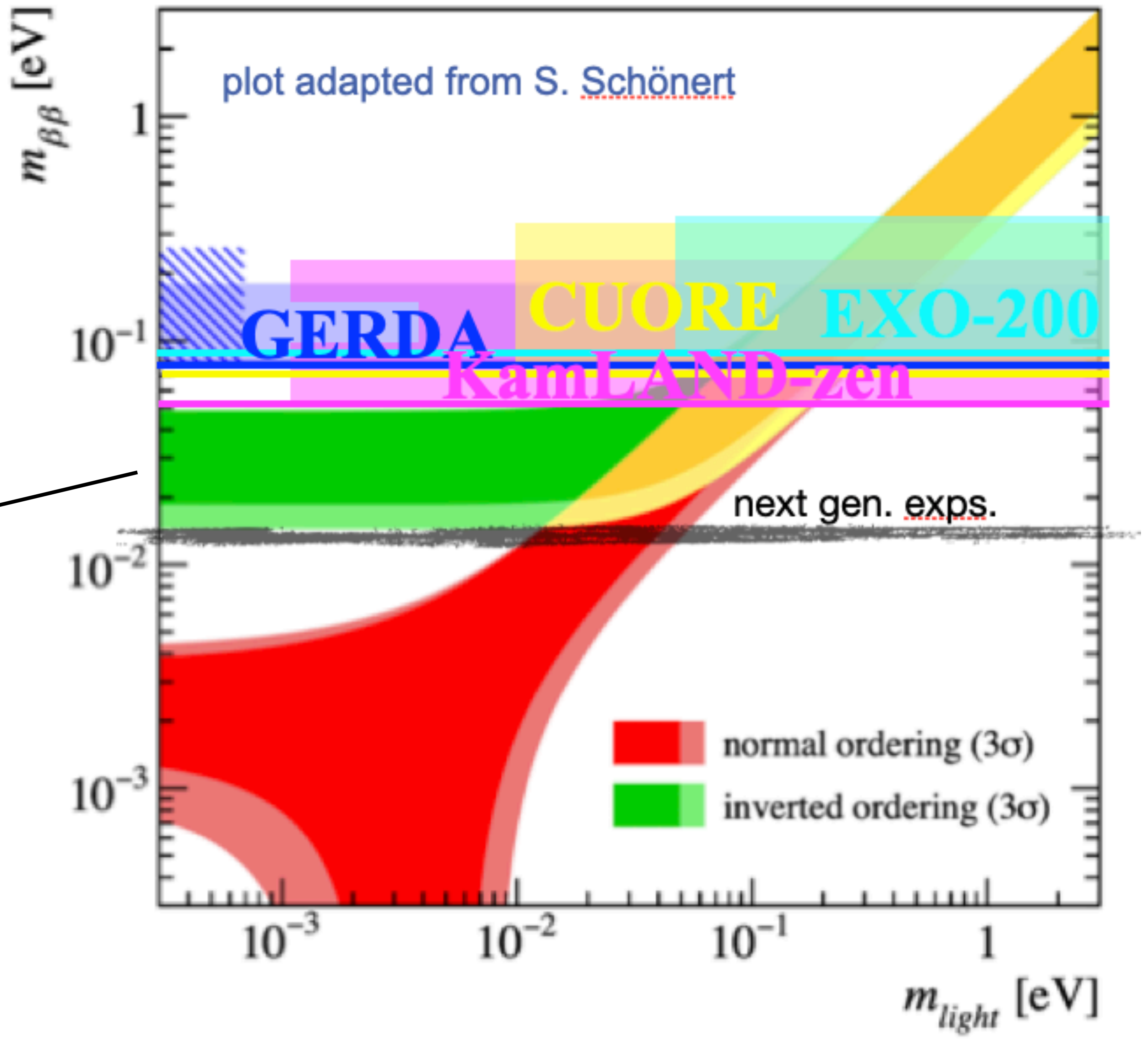
Combined 3$\sigma$ upper bound from CUORE, EXO, GERDA, KamLLAND-Zen, MAJORANA




selection of nucl. matrix element calculations

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

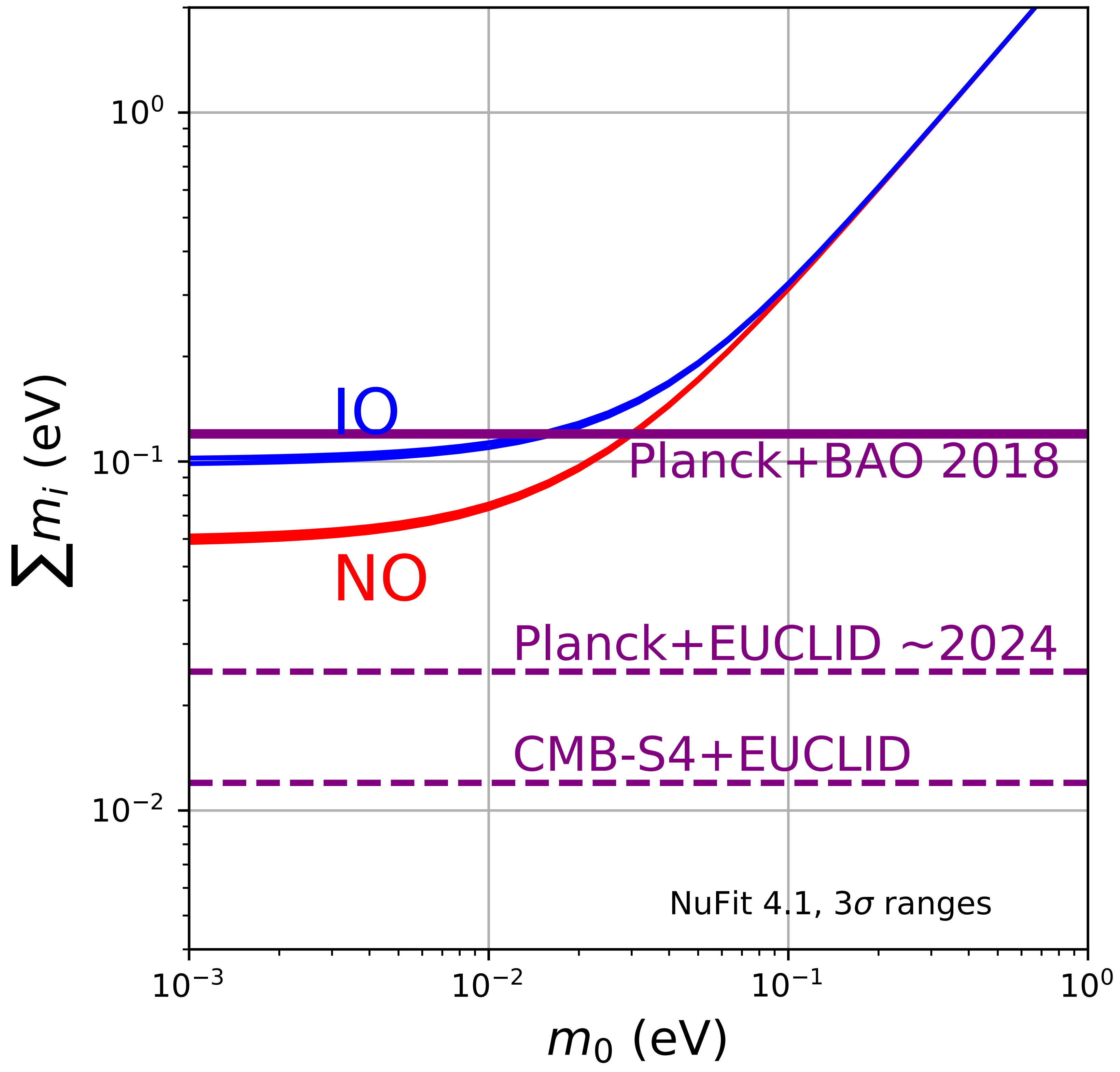
neutrino mass interpretation affected by nuclear matrix elements and Majorana phases




new short-range contribution to NME Cirigliano et al., 1802.10097

# Neutrino mass from cosmology

$$\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} & \text{(NO)} \\ m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} & \text{(IO)} \end{cases}$$



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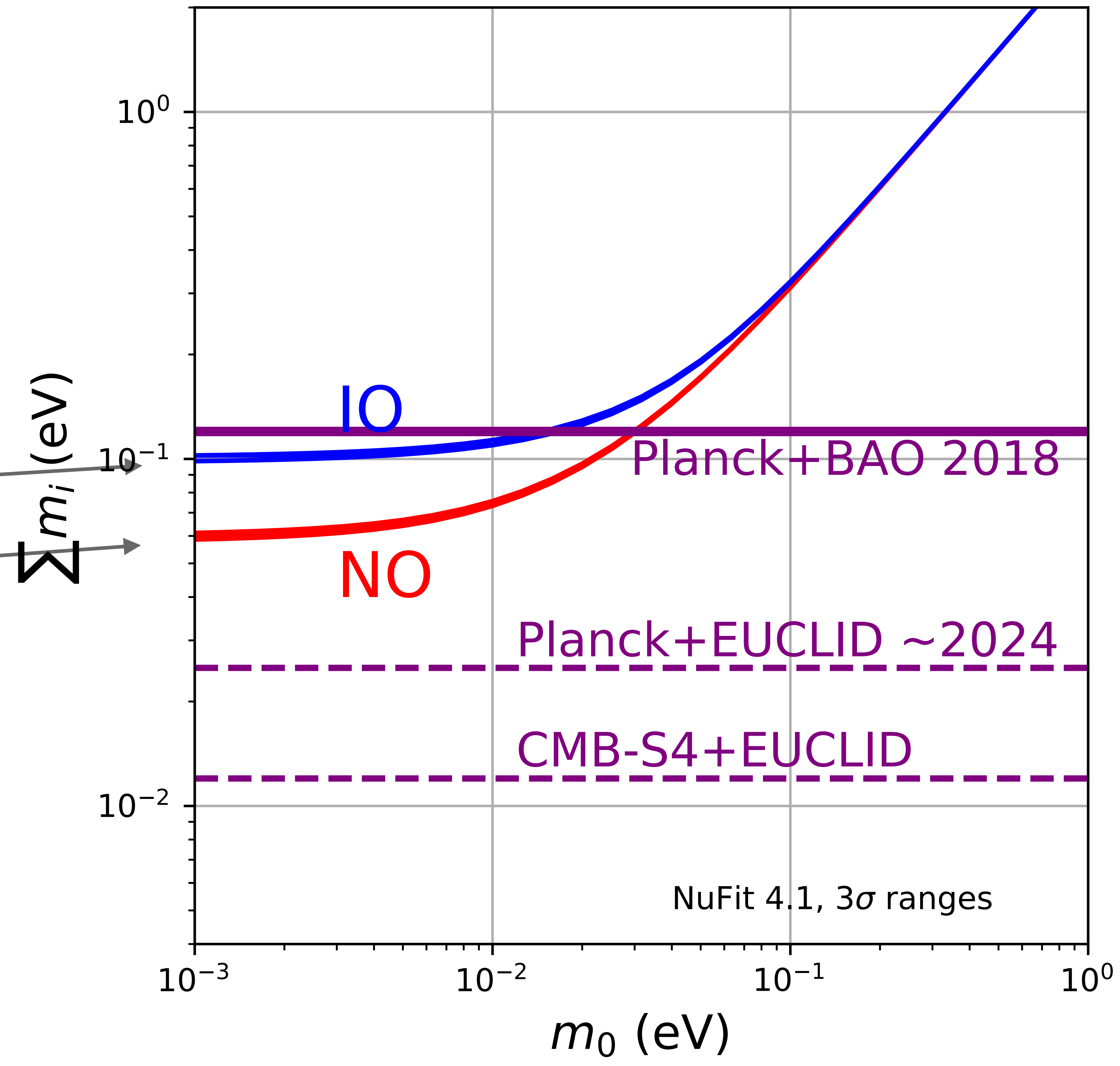
- minimal values predicted from oscillation data for $m_0 = 0$:

$$\Sigma_{\min} = \begin{cases} 98.6 \pm 0.85\,\text{meV} & \text{(IO)} \\ 58.5 \pm 0.48\,\text{meV} & \text{(NO)} \end{cases}$$



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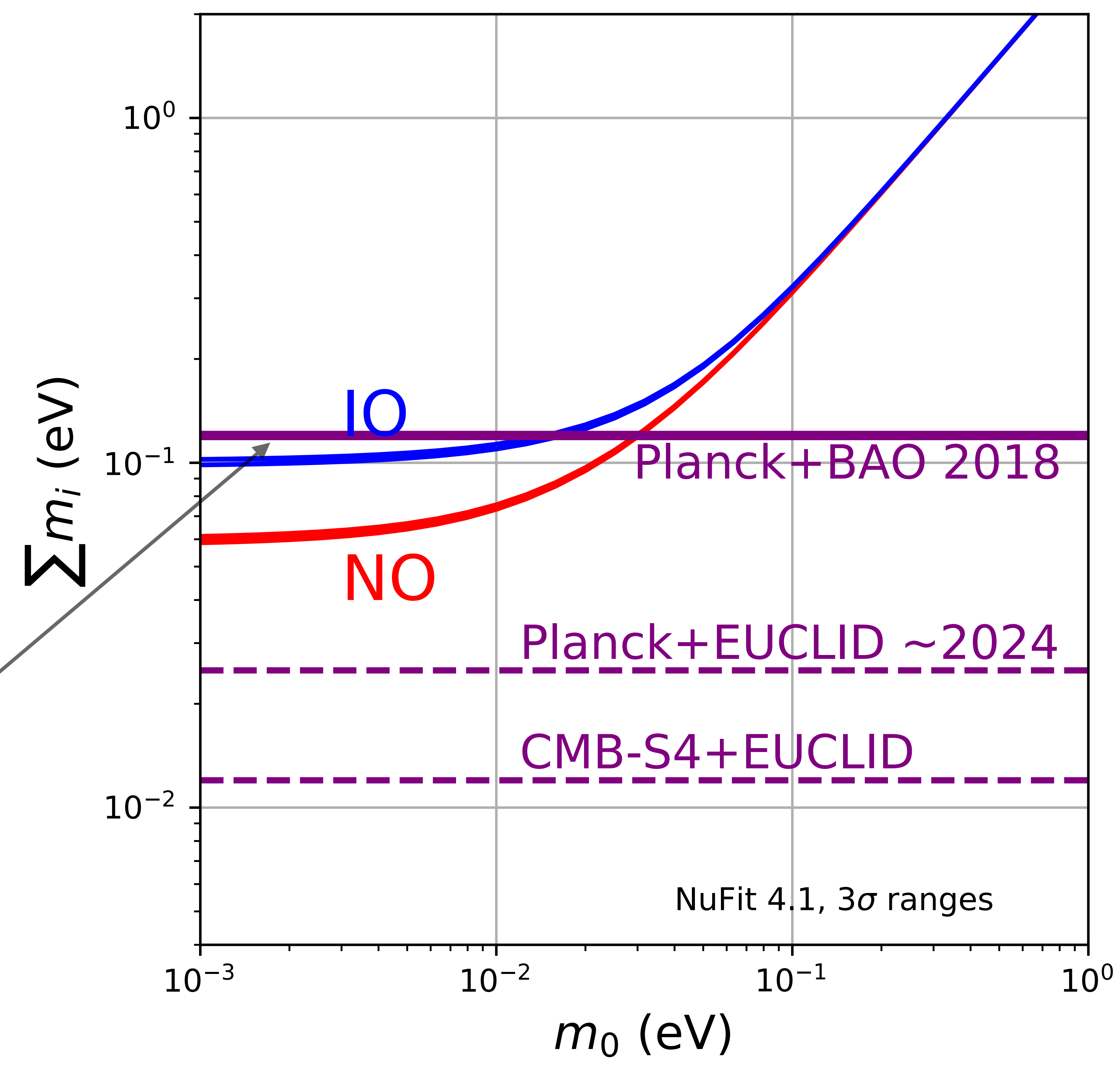
- **Upper bounds from current data:**
  - $\Sigma m_\nu < 0.12\,\text{eV}\ (95\,\%\ \text{CL})$ Planck CMB+BAO
  - $\Sigma m_\nu < 0.09\,\text{eV}\ (95\,\%\ \text{CL})$
    DiValentino, Gariazzo, Mena, 21; many papers



# Excluding inverted ordering with cosmology?

- **Strong Bayesian Evidence for the Normal Neutrino Hierarchy** Simpson et al., 1703.03425; Jimenez et al., 2203.14247

- **No conclusive evidence for normal ordering:** TS et al. 1703.04585; Vagnozzi et al., 1701.08172; Gariazzo et al., 1801.04946; Heavens, Sellentin, 1802.09450; deSalas et al., 1806.11051; Mahony et al., 1907.04331; Hannestad, Roy Choudhury, 1907.12598; Gariazzo et al., 2205.02195

## Bayesian model comparison:

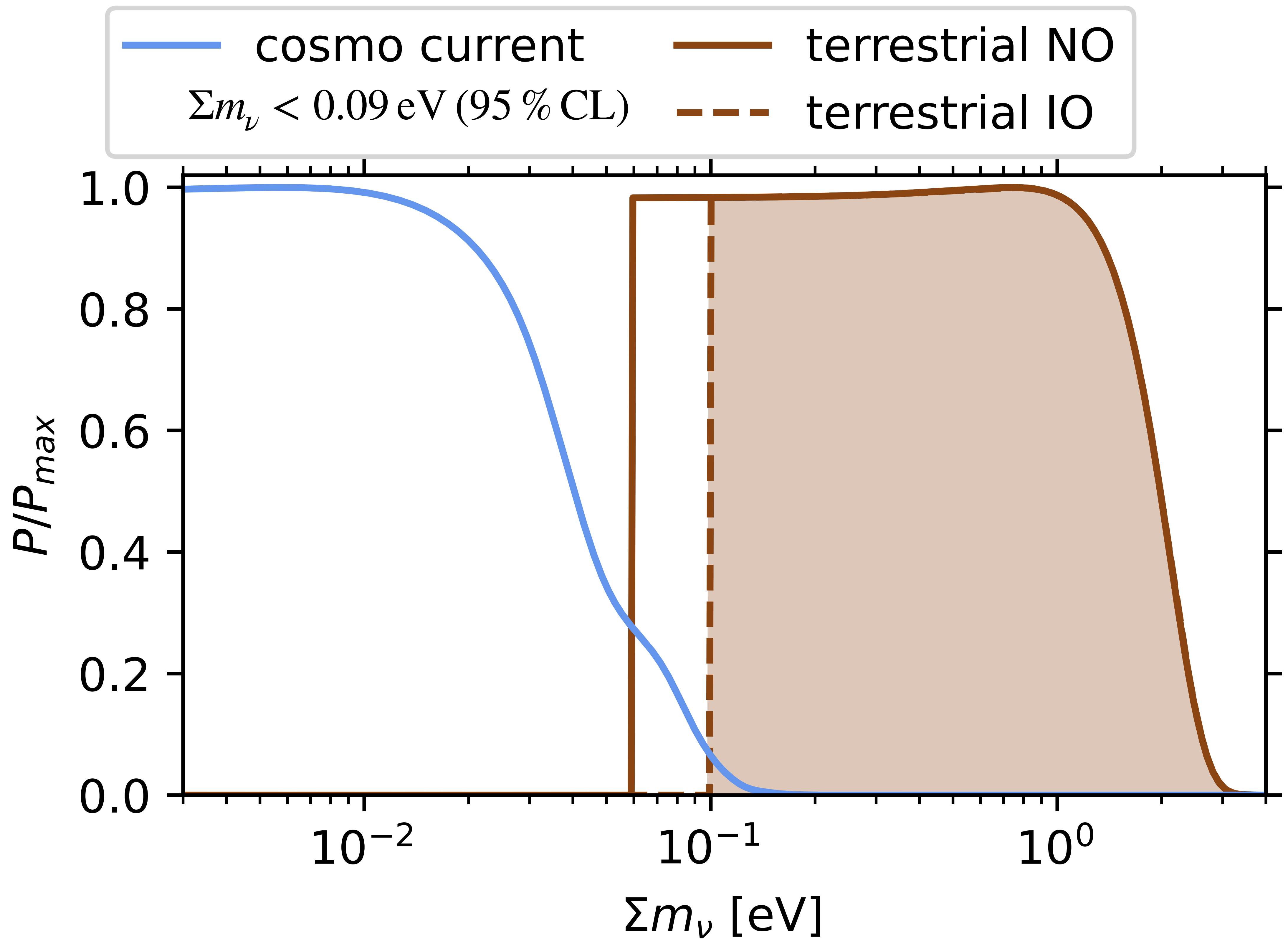
$$B_{\mathrm{NO,IO}} \equiv \frac{\mathcal{Z}_{\mathrm{NO}}}{\mathcal{Z}_{\mathrm{IO}}}$$

$$\mathcal{Z}_D = P(D|M) = \int \mathrm{d}\theta \, \mathcal{L}_D(\theta) \, \Pi(\theta)$$

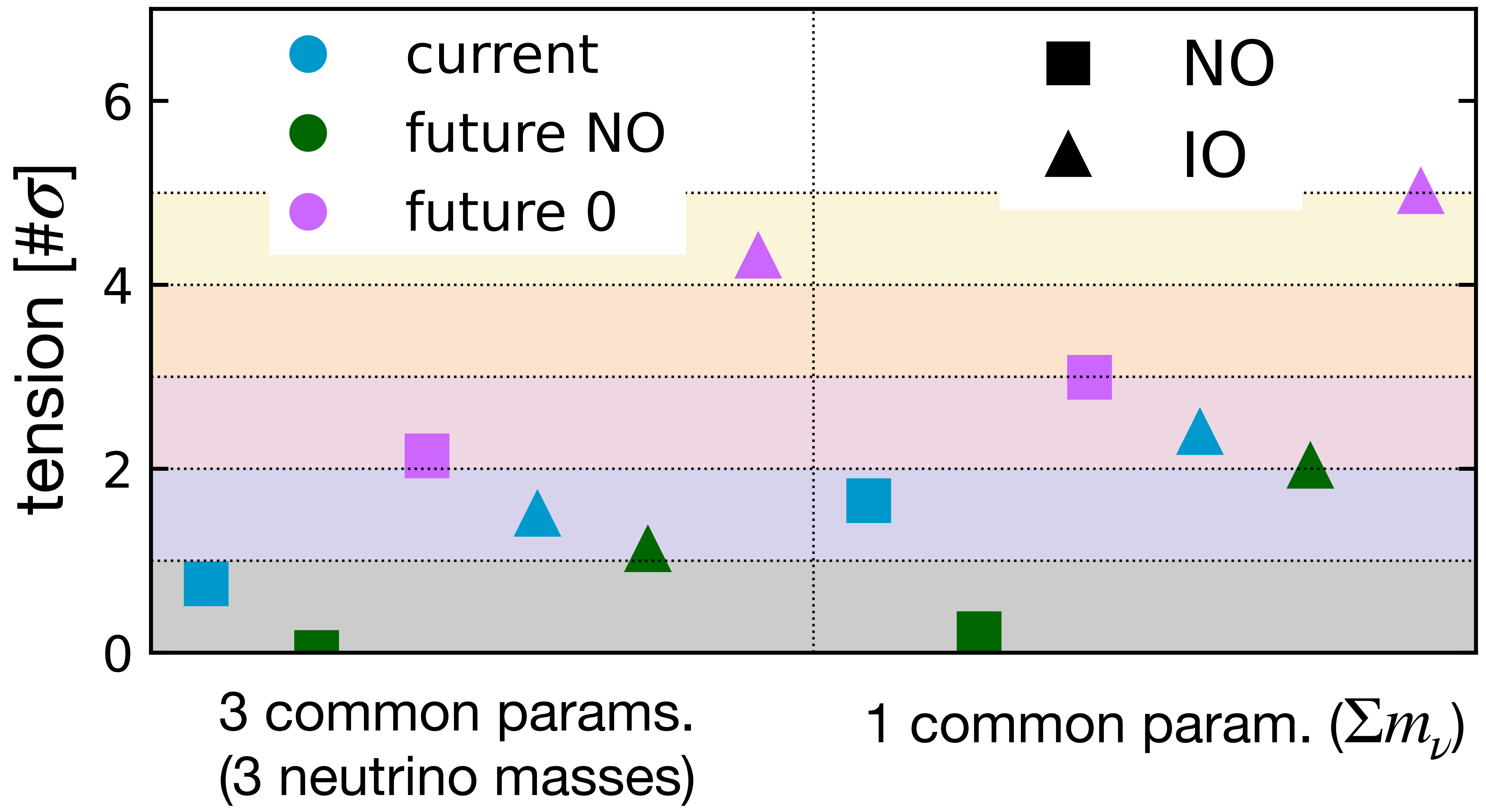
- current preference for NO from cosmology is **prior driven** (not data driven)

Gariazzo et al., 2205.02195

# Tension between cosmology and terrestrial data




Gariazzo, Mena, Schwetz, 2302.14159



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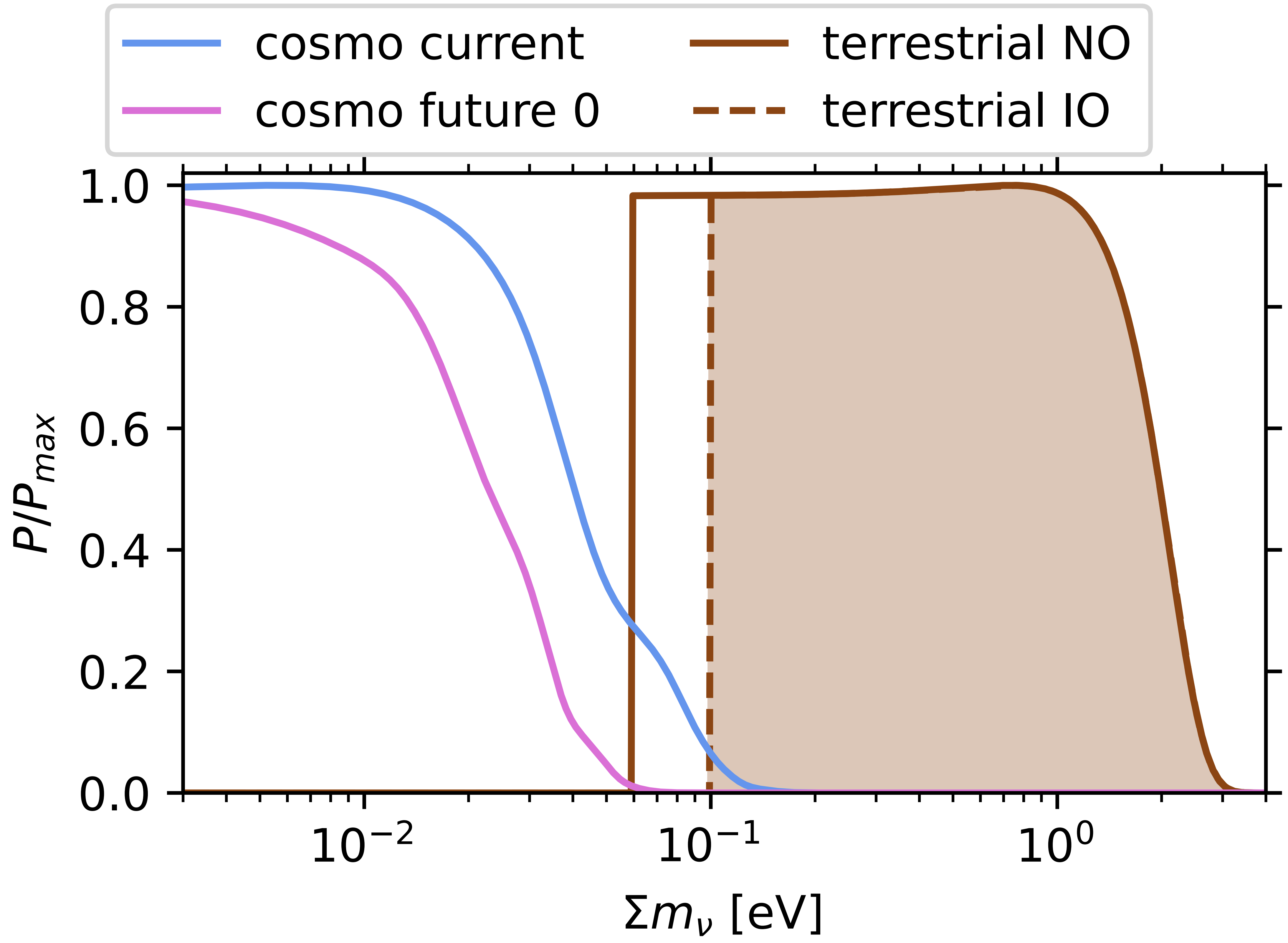


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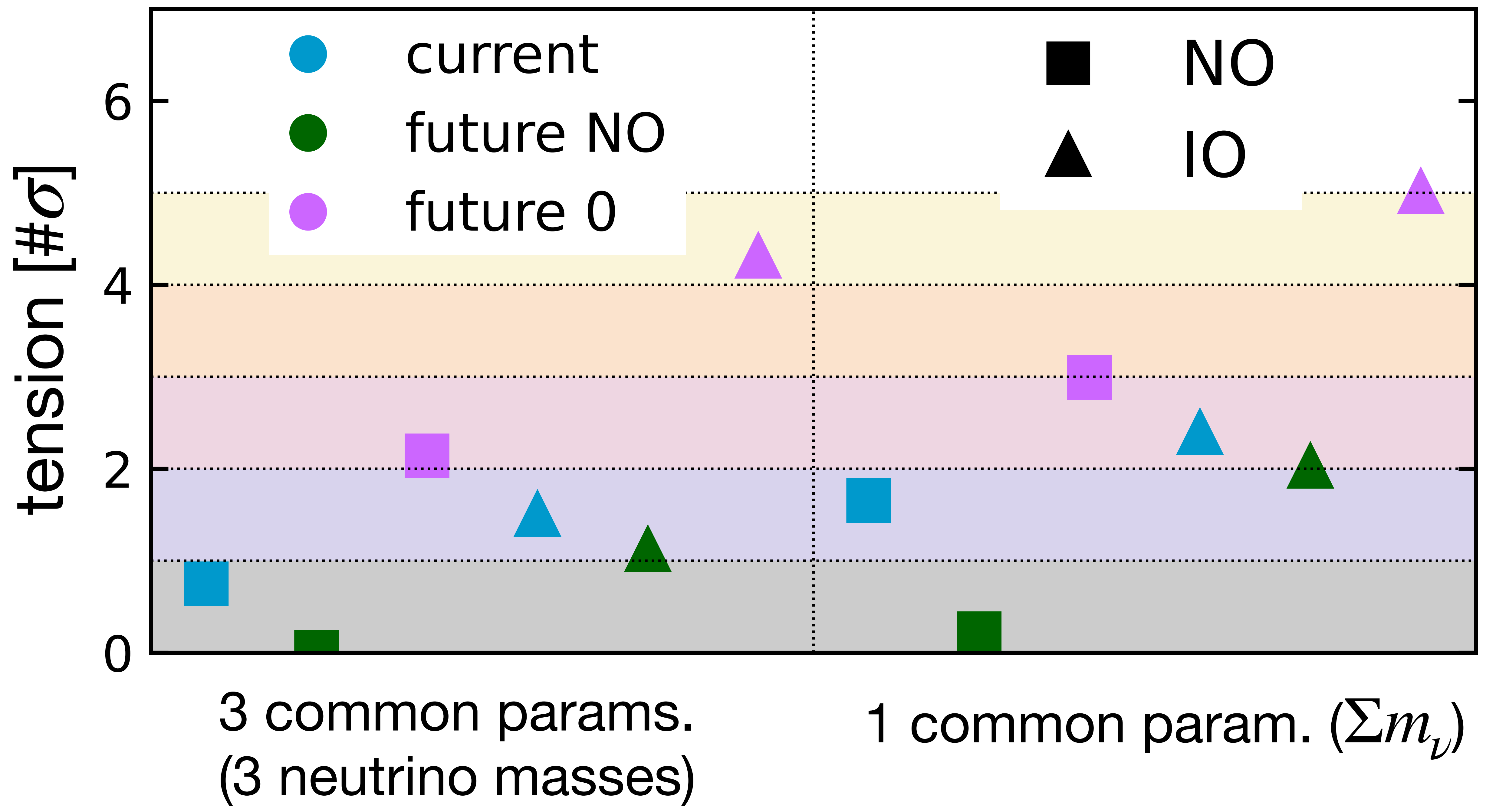


future 0: $\Sigma m_\nu < 0.02\,\mathrm{eV}(1\sigma)$

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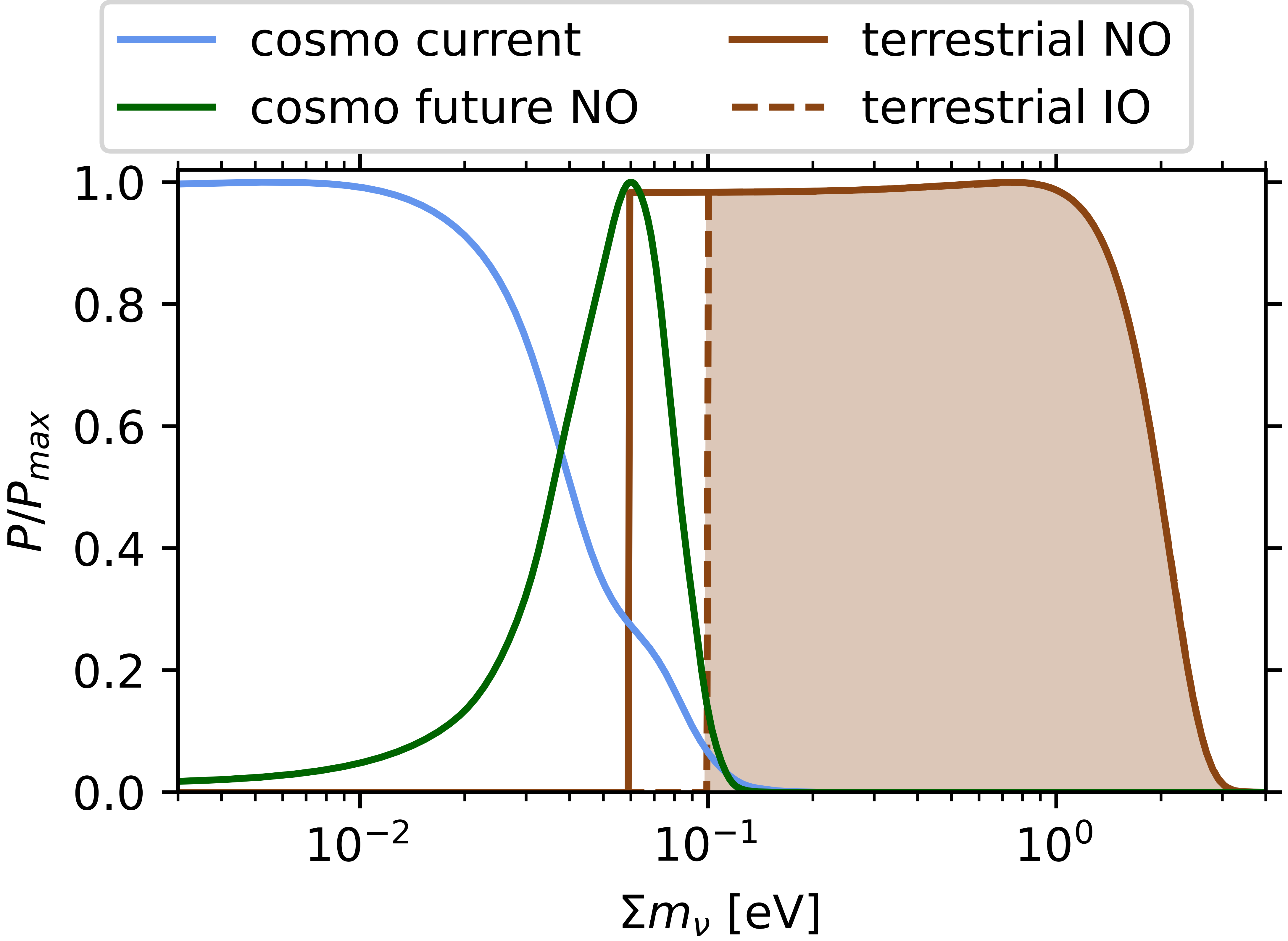
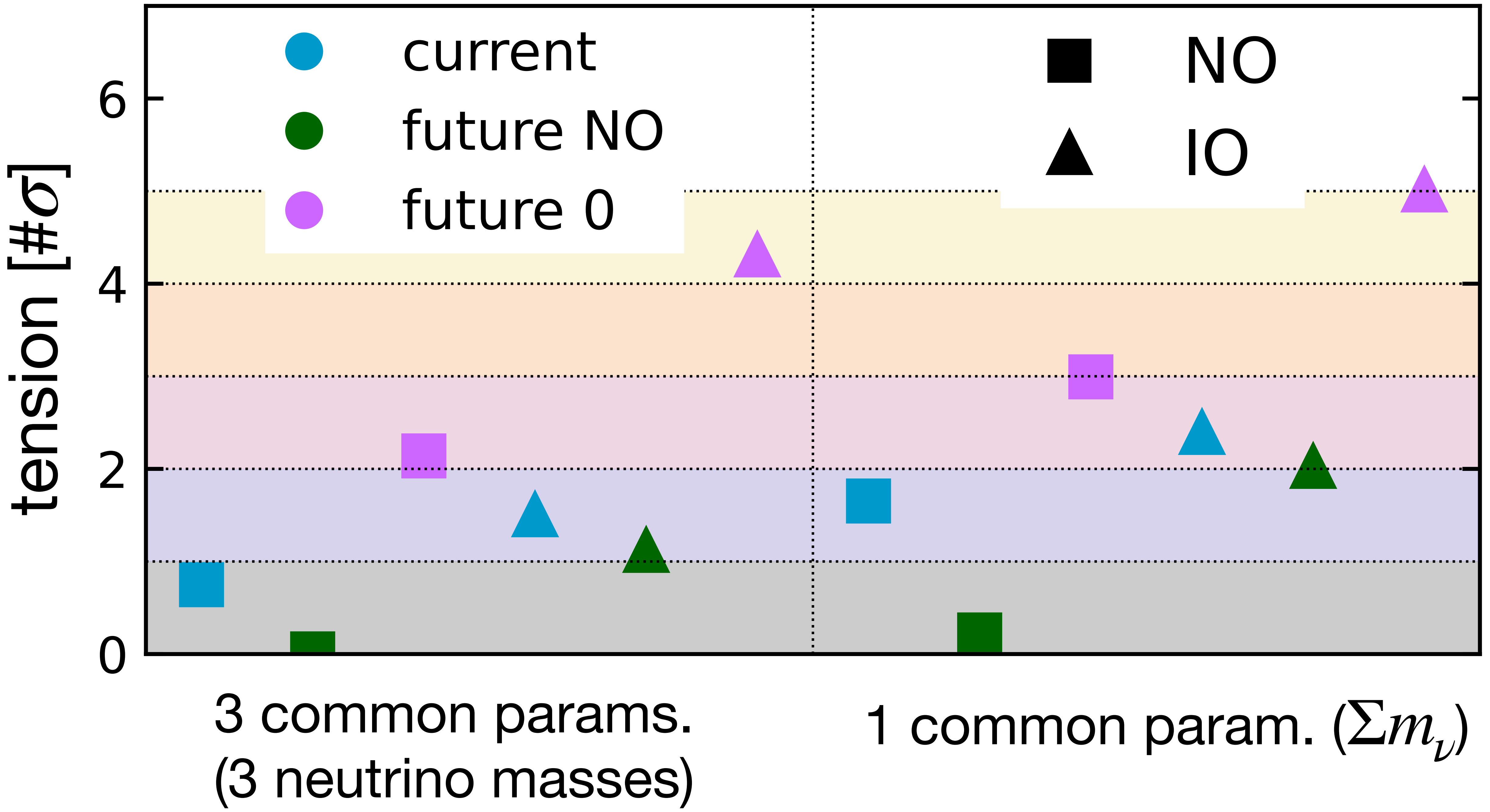
Gariazzo, Mena, Schwetz, 2302.14159




future NO: $\Sigma m_\nu = (0.06 \pm 0.02)\,\mathrm{eV}(1\sigma)$

- What if cosmology does not see finite neutrino mass and upper bounds become tighter than the minimal value predicted by neutrino oscillation?
- Can we relax cosmological bounds such that neutrino mass can be in reach for terrestrial experiments?

# Cosmology bounds can be relaxed in non-standard scenarios

- neutrino decay into dark radiation
  Chacko et al. 1909.05275; 2002.08401; Escudero et al., 2007.04994;
  Barenboim et al.,2011.01502; Chacko et al. 2112.13862: $\sum m_\nu < 0.42\,\mathrm{eV}$

- time dependent neutrino mass
  Lorenz et al. 1811.01991; 2102.13618; Esteban, Salvado, 2101.05804

- modified momentum distribution
  Cuoco et al., astro-ph/0502465; Barenboim et al., 1901.04352;
  Alvey, Sabti, Escudero, 2111.14870

- reduced neutrino density + dark radiation
  Beacom, Bell, Dodelson, 04; Farzan, Hannestad, 1510.02201;
  Renk, Stöcker et al., 2009.03286; Escudero, TS, Terol-Calvo, 2211.01729

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# Relaxing the neutrino mass bound from cosmology

**Cosmology is sensitive to:**

- energy density in non-relativistic neutrinos (late times)

$$\rho_\nu^{\text{non.rel.}} \approx n_\nu \sum m_\nu < 14\,\text{eV}\,\text{cm}^{-3}$$

- energy density in relativistic neutrinos (early times, BBN, CMB)

$$N_{\text{eff}}^{\text{relat.}} = 2.99 \pm 0.17$$

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$$N_{\text{eff}}^{\text{relat.}} = 2.99 \pm 0.17$$

relax bound on $m_\nu$ by reducing neutrino number density

$$\sum m_\nu < 0.12\,\text{eV} \left(\frac{n_\nu^{\text{SM}}}{n_\nu}\right)$$

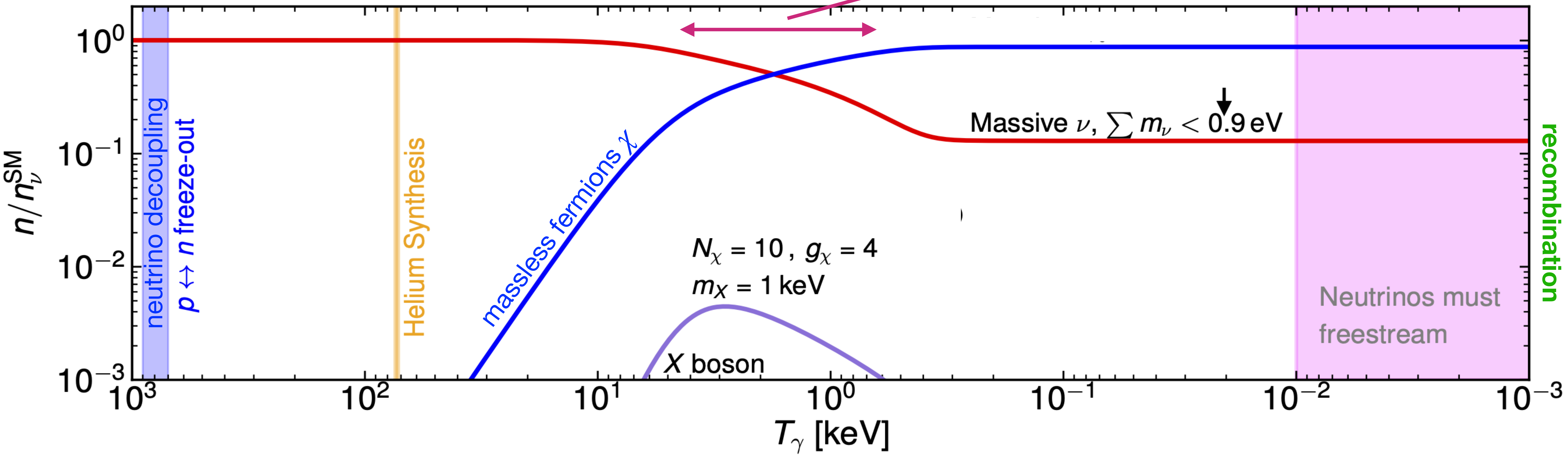
introduce „dark radiation“ to keep $N_{\text{eff}}^{\text{relat.}} \approx 3$

$$N_{\text{eff}}^{\text{relat.}} = N_{\text{eff}}^{\nu} + N_{\text{eff}}^{\text{DR}} \approx 3$$

- introduce a set of $N_\chi$ massless fermions
- a mediator $X$ coupled to neutrinos (scalar or vector)
- convert active neutrinos into massless fermions after BBN but before CMB decoupling

Farzan, Hannestad, 1510.02201;
Escudero, TS, Terol-Calvo, 2211.01729

$$\Gamma(\nu\nu \leftrightarrow X) \gtrsim H$$
$$\Gamma(X \leftrightarrow \chi\chi) \gtrsim H$$

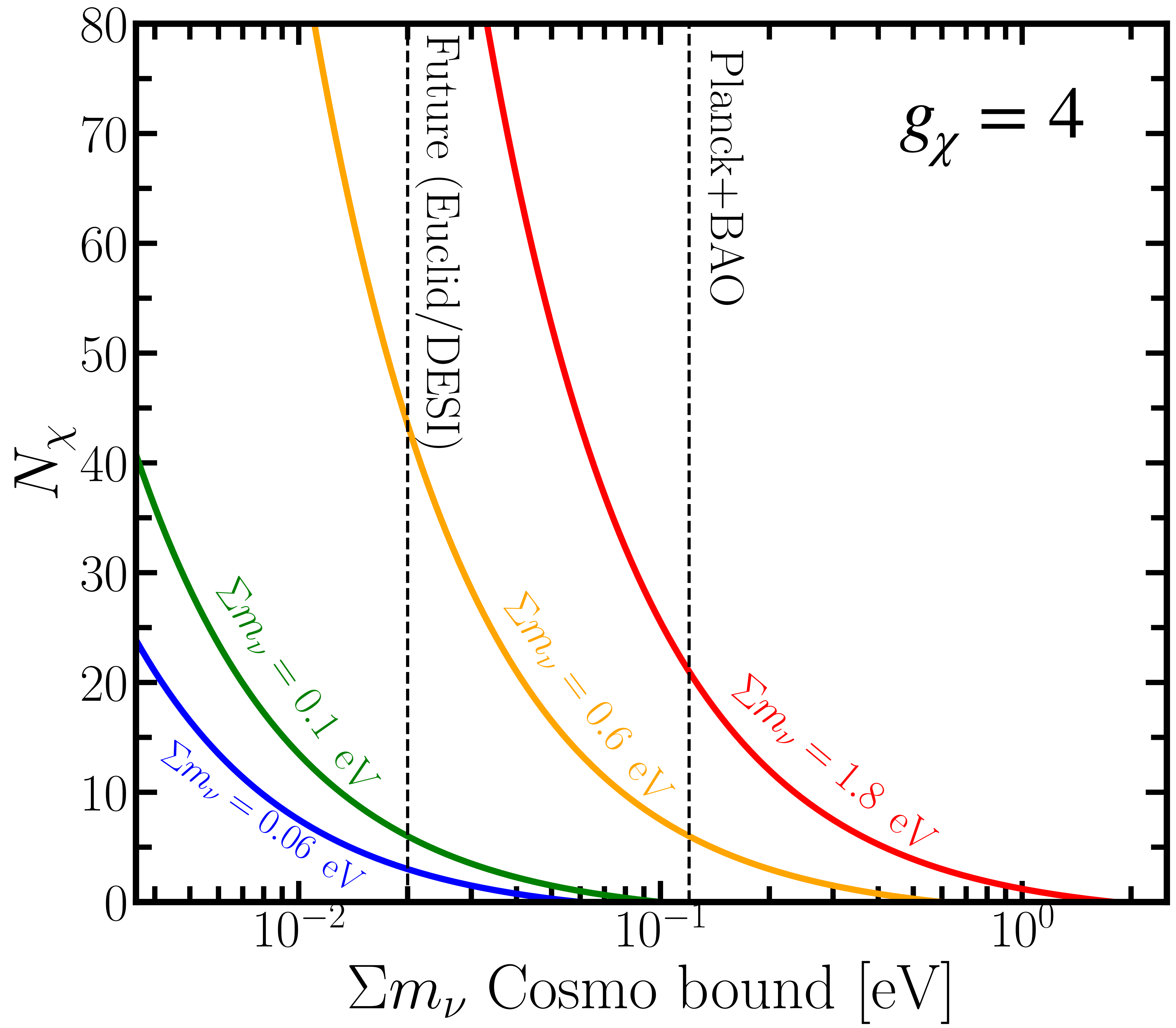


# Relaxed bound from cosmology

Farzan, Hannestad, 1510.02201
Escudero, TS, Terol-Calvo, 2211.01729

relaxing the present bound by converting neutrinos into $N_\chi$ generations of massless fermions with $g_\chi$ internal degrees of freedom:

$$\sum m_\nu < 0.12\,\mathrm{eV}\,(1 + g_\chi N_\chi/6)$$




need $\gtrsim 10$ massless species for $m_\nu \sim 1$ eV

# A seesaw model for large neutrino mass and dark radiation

Escudero, TS, Terol-Calvo, 2211.01729

- 3 heavy right-handed neutrinos (seesaw)
- new abelian symmetry $U(1)_X$ local or global
- a scalar $\Phi$ charged under $U(1)_X$
- a set of $N_\chi$ massless fermions charged under $U(1)_X$

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$$m_D = \frac{v_{\rm EW}}{\sqrt{2}} Y_\nu \,, \quad \Lambda = \frac{v_\Phi}{\sqrt{2}} Y_\Phi$$

$$-\mathcal{L} = \overline{N_R}\, Y_\nu\, \ell_L\, \widetilde{H}^\dagger + \frac{1}{2}\overline{N_R}\, M_R\, N_R^c + \overline{N_R} Y_\Phi\, \chi_L\, \Phi + \text{h.c.}$$

$$m_{\rm heavy} \approx M_R$$

$$m_{\rm active} \approx m_D^2 / M_R$$

$$\mathcal{M}_n = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & \Lambda \\ 0 & \Lambda^T & 0 \end{pmatrix} \qquad \Lambda \ll m_D \ll M_R$$

$$m_\chi = 0 \,, \quad \theta_{\nu\chi} \approx \Lambda / m_D$$

# A seesaw model for large neutrino mass and dark radiation

Escudero, TS, Terol-Calvo, 2211.01729

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$$\mathscr{L}_{\text{int}} = g_X\, Z'_\mu\, \bar{\chi}\gamma^\mu \chi \qquad g_X = \frac{m_{Z'}}{v_\Phi}$$

$$\lambda_{Z'}^{\chi\chi} = g_X$$

$$\lambda_{Z'}^{\chi\nu} = g_X \theta_{\nu\chi}$$

$$\lambda_{Z'}^{\nu\nu} = g_X \theta_{\nu\chi}^2$$

couplings to neutrinos induced by mixing: $Z' \leftrightarrow \nu\nu/\nu\chi/\chi\chi$

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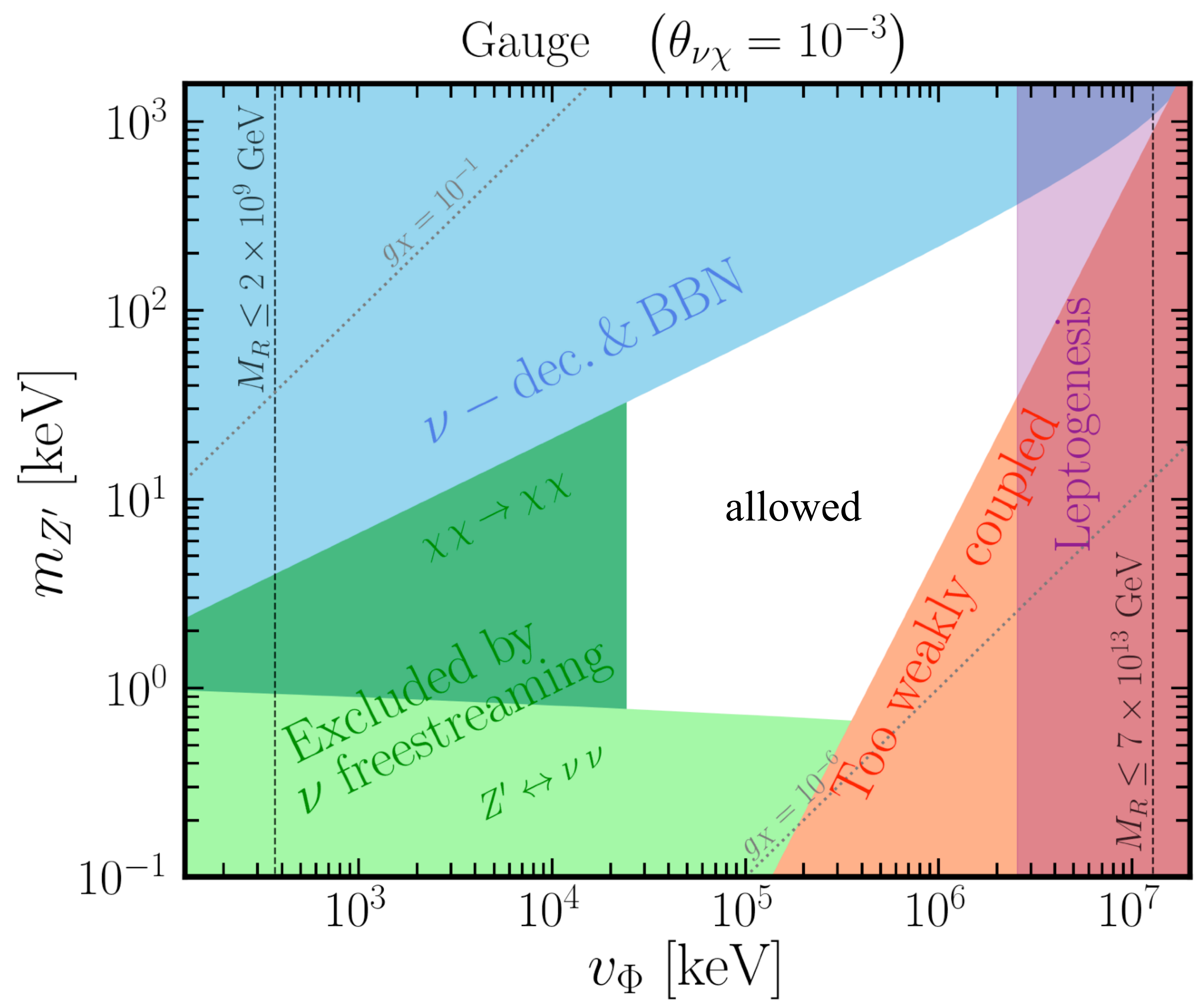
$$\mathscr{L}_{\text{int}} = g_X\, Z'_\mu\, \bar{\chi}\gamma^\mu \chi \qquad\qquad g_X = \frac{m_{Z'}}{v_\Phi}$$

**indep. params for pheno:**

$$m_\nu, M_R, \theta_{\nu\chi}$$

$$v_\Phi, m_{Z'}$$

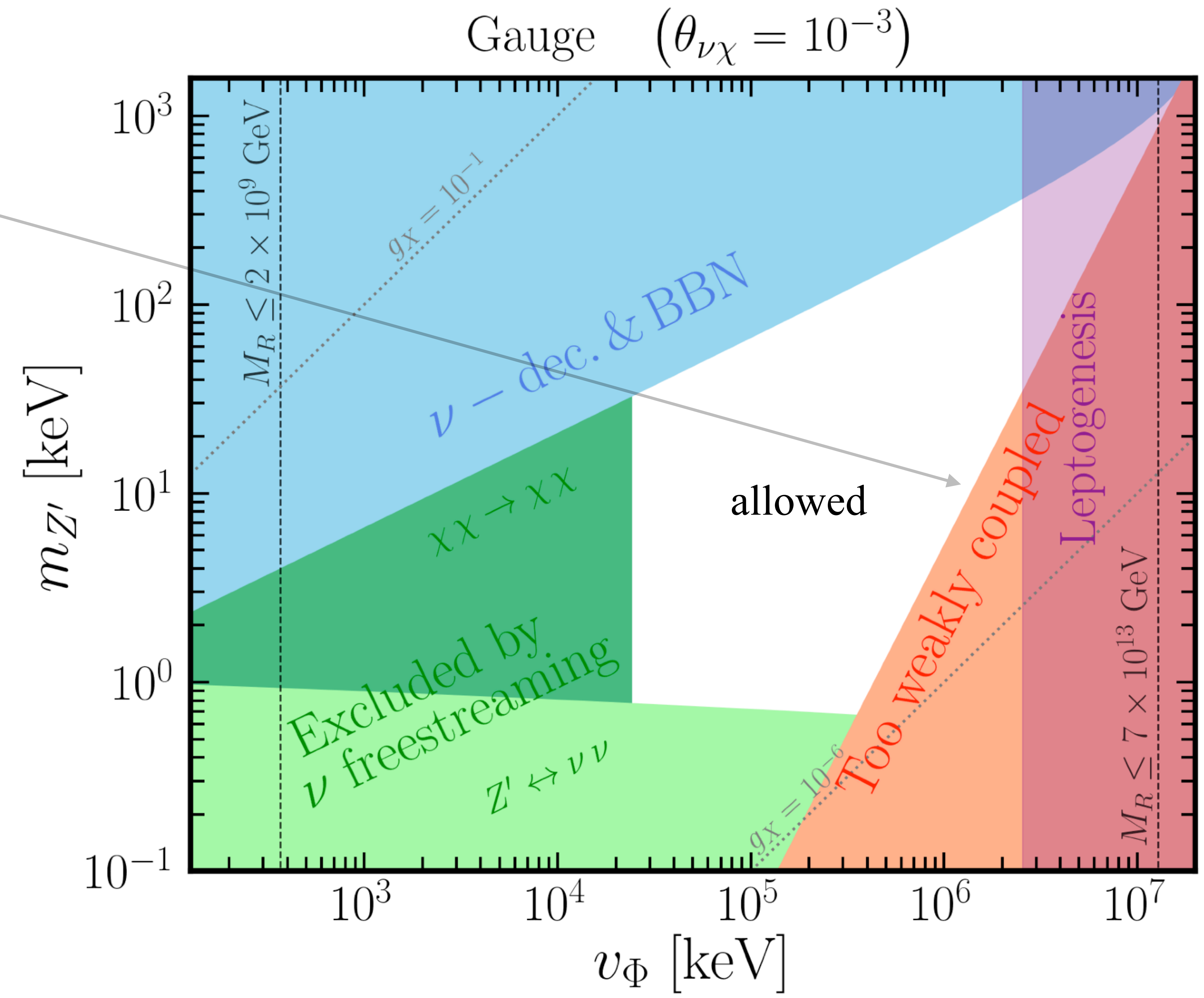
# Available parameter space



# Available parameter space

- thermalization of the dark sector:

$$\Rightarrow \quad \langle \Gamma(\nu\nu \to Z') \rangle \gtrsim H(T = m_{Z'}/3)$$



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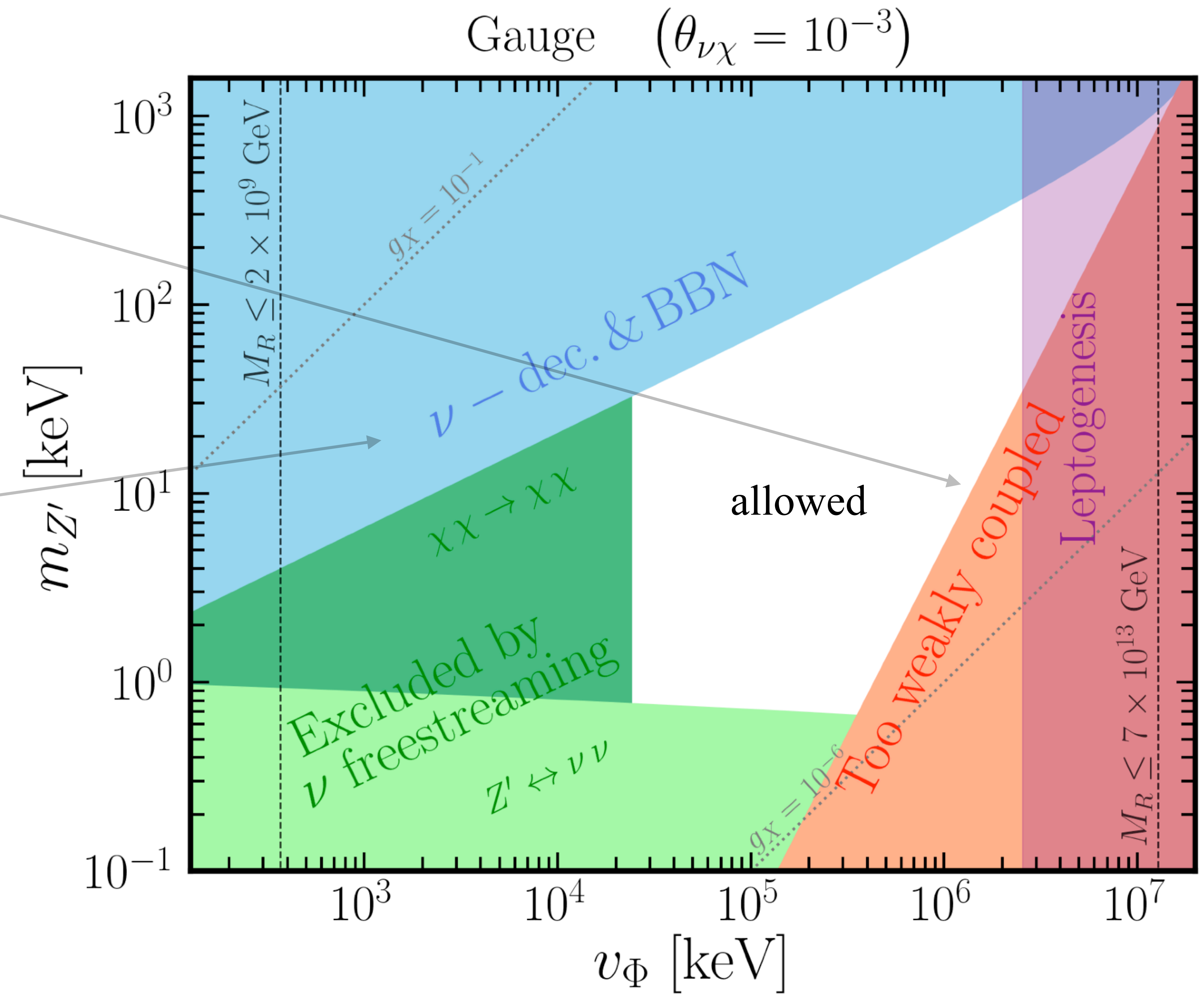
- avoid thermalization of the dark sector before BBN:

  $$\langle \Gamma(\nu\nu \to Z') \rangle < H(T = 0.7\,\mathrm{MeV})$$



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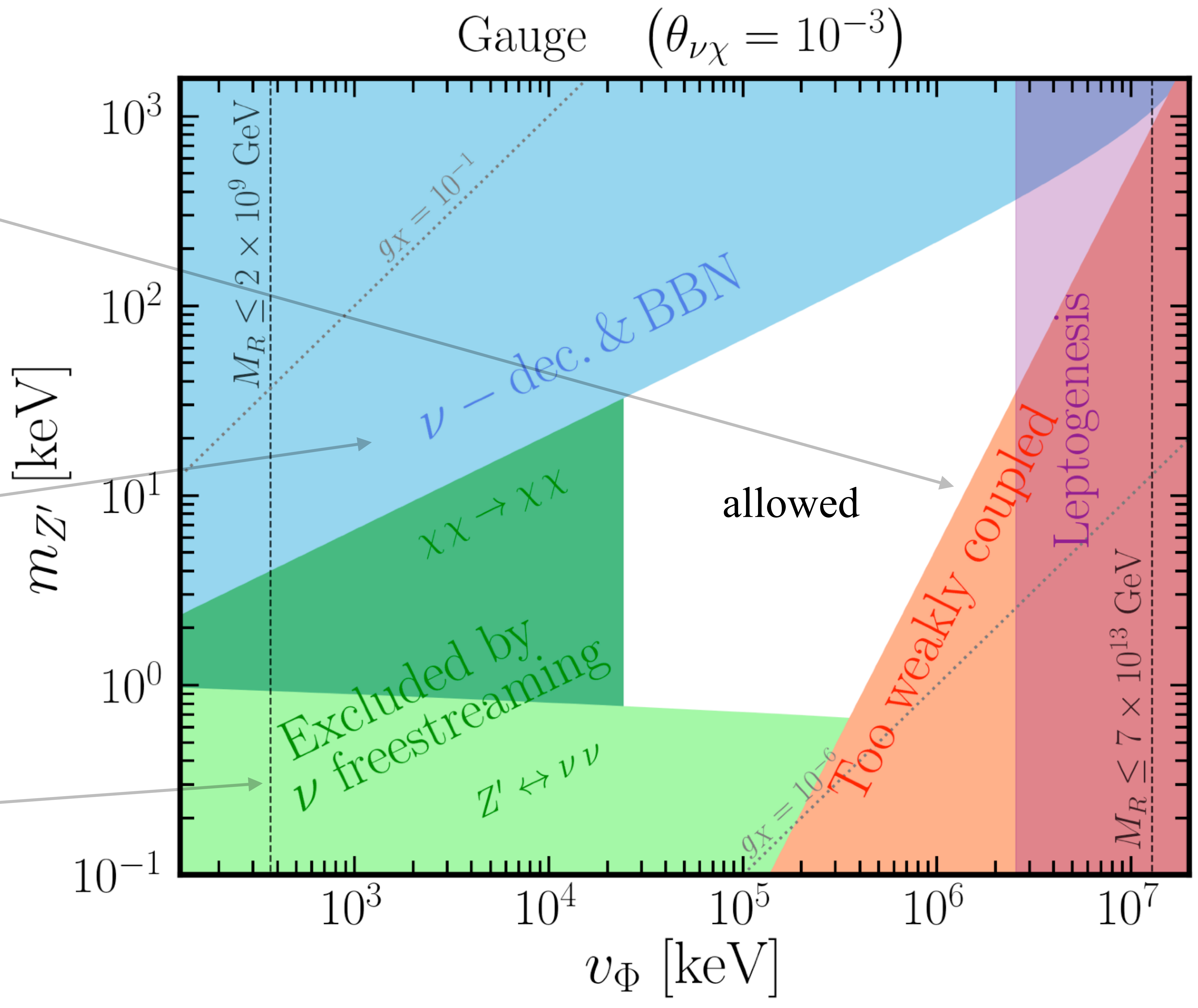
- free-streaming of neutrinos & dark radiation before/around recombination

  $\langle \Gamma \rangle < H$ for $z < 10^5$

  Taule, Escudero, Garny, 2207.04062

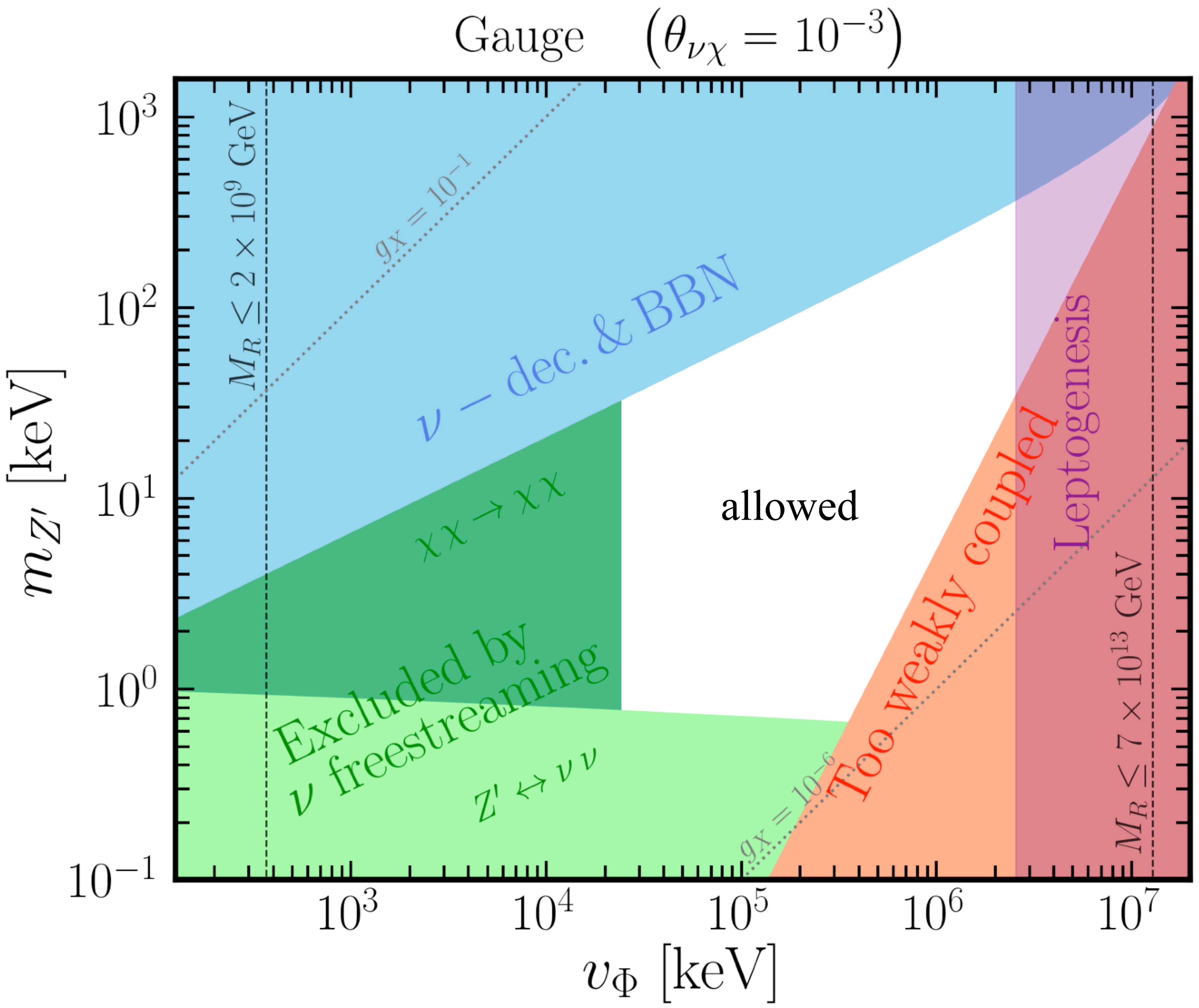


# Available parameter space

- avoid thermalization of $\chi$ prior neutrino decoupling due to oscillations

$$|\theta_{\nu\chi}| \lesssim 10^{-3}\sqrt{\frac{10}{N_\chi}}\sqrt{\frac{0.2\,\mathrm{eV}}{m_\nu}}$$

too small to be tested in SBL oscillation experiments



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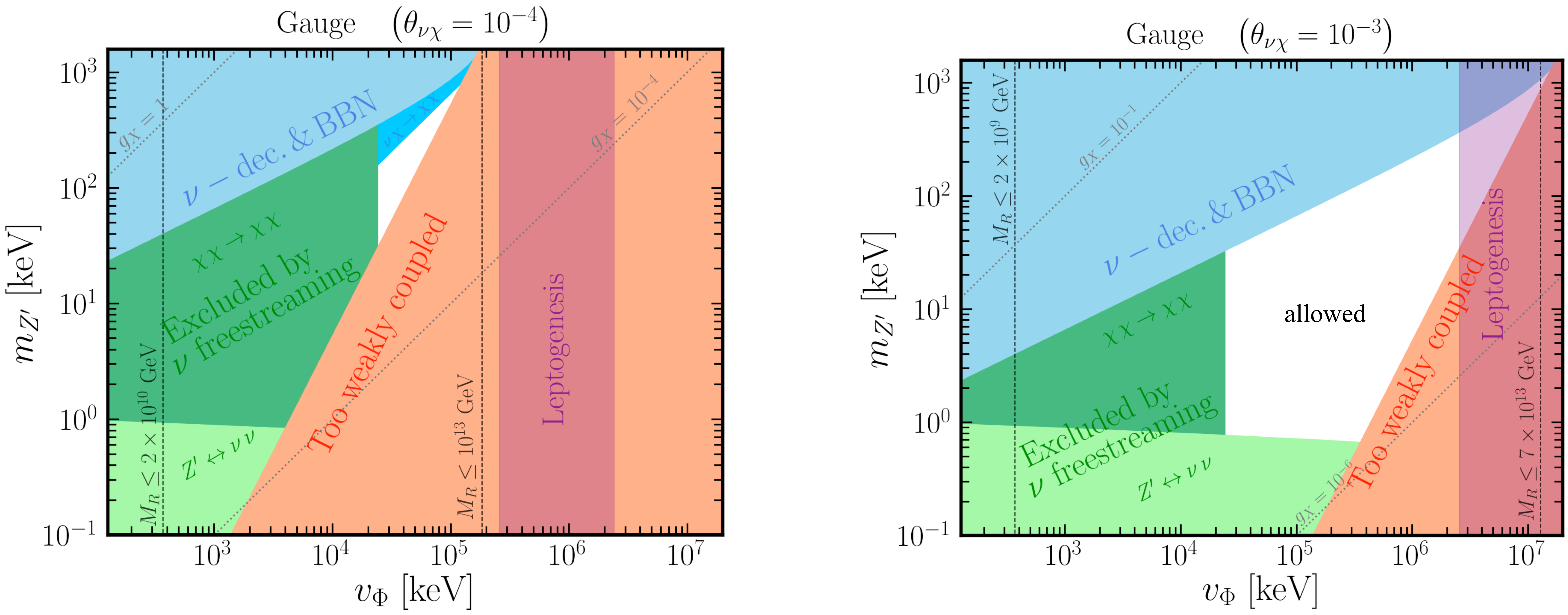
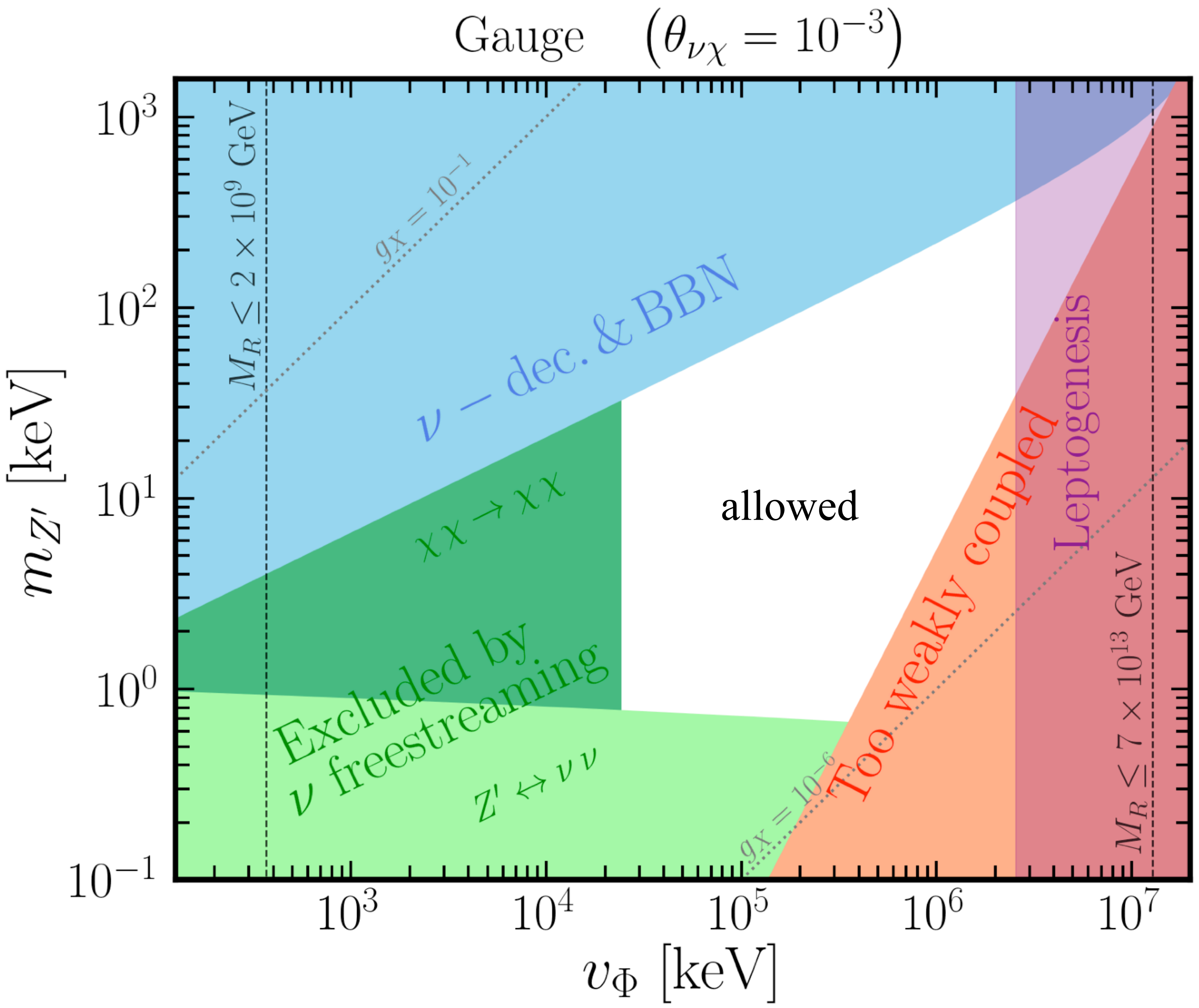


# Available parameter space

- constraints on heavy RH neutrinos:

$$M_R \lesssim 10^{10} - 10^{14}\,\mathrm{GeV}$$

  - perturbativity of Yukawa $Y_\Phi \overline{N}_R \chi_L \Phi$
  - loop-induced Higgs portal $\lambda_{\Phi H} |\Phi|^2 H^\dagger H$ remains small enough to avoid thermalization of $\Phi$ prior BBN



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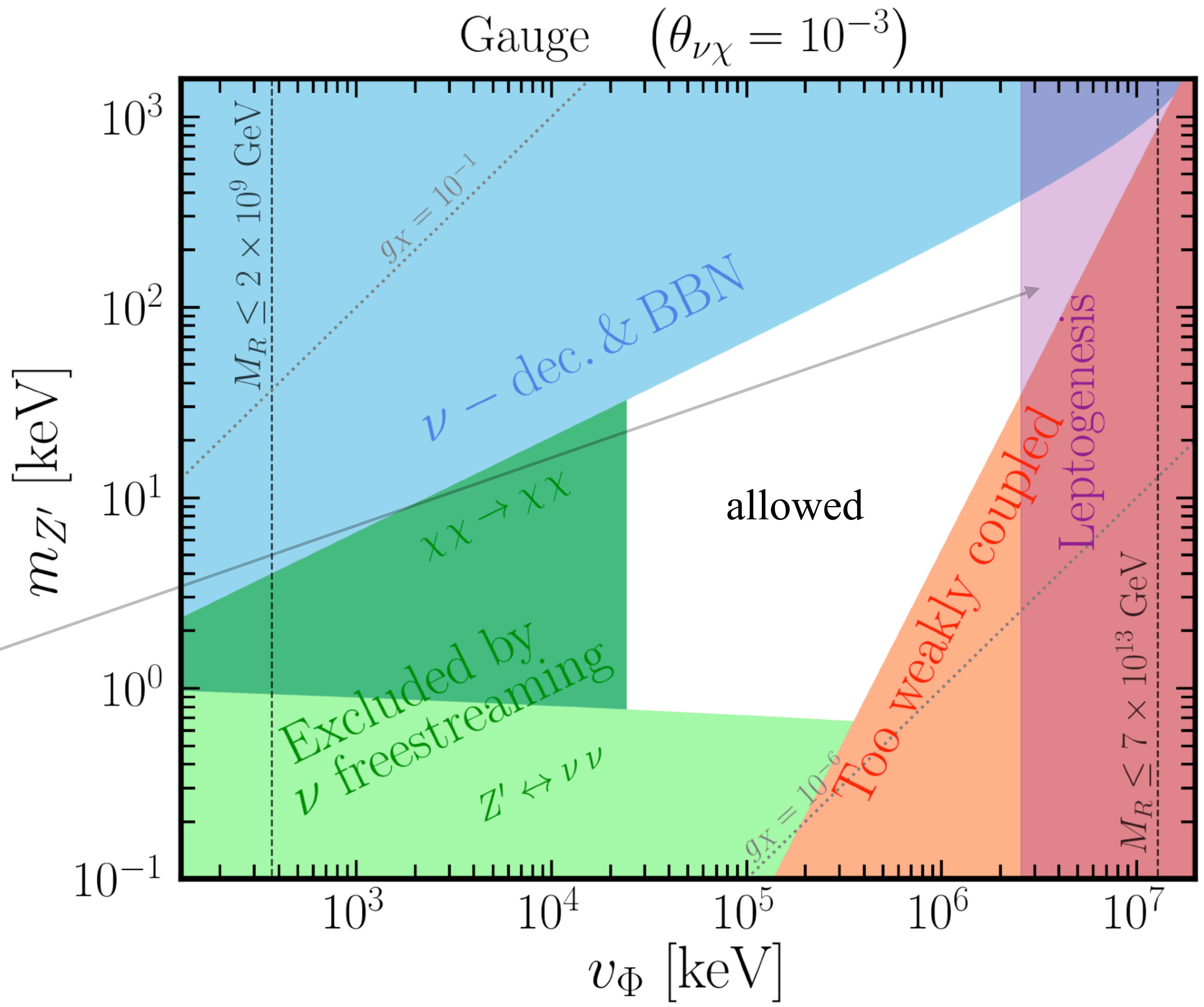
  - standard thermal leptogensis works if $N \to HL$ dominates over $N \to \chi\Phi$
  - otherwise $\chi$ would thermalize and conflict with $N_{\rm eff}$ during BBN $\Rightarrow$ require $T_{RH} < M_R$ (allows still for $T_{RH} \gg T_{EW}$)



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# Further signatures of the model

- SN cooling arguments for SN1987A exclude

$$3 \times 10^{-7} \frac{\text{keV}}{m_{Z'}} \lesssim \lambda_{Z'}^{\nu\nu} \lesssim 10^{-4} \frac{\text{keV}}{m_{Z'}}$$

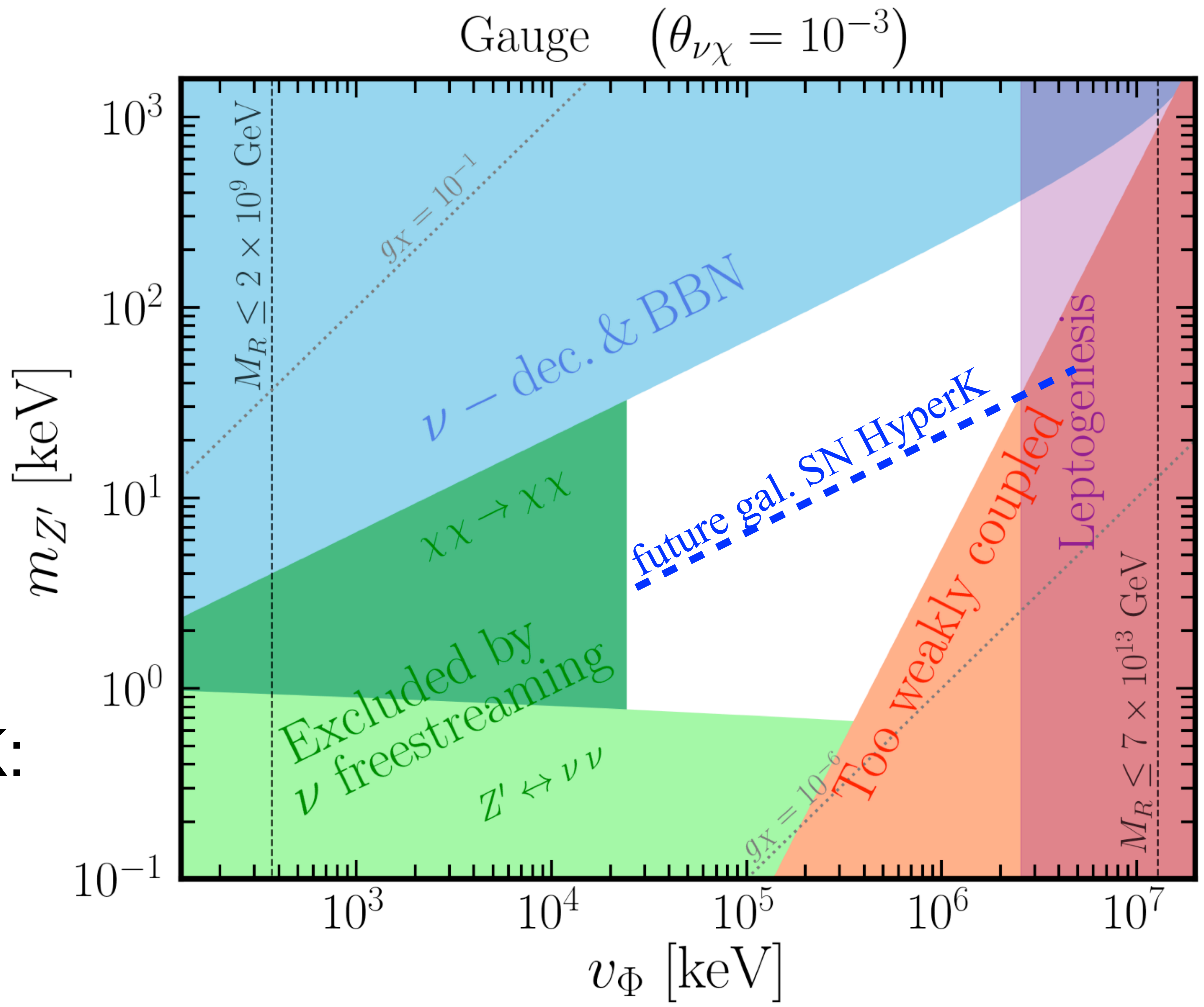
Fiorillo, Raffelt, Vitagliano, 2209.11773

weaker than BBN constraint
$\lambda_{Z'}^{\nu\nu} \lesssim 10^{-7}(\text{keV}/m_{Z'})$

- Future galactic SN at 10 kpc detected by HyperK: sensitivity down to

$$\lambda_{Z'}^{\nu\nu} \sim 10^{-9}(\text{keV}/m_{Z'})$$

Akita, Im, Masud, 2206.06852



# Summary

- Exciting interplay of cosmology and terrestrial neutrino mass determinations
- Cosmological bounds reaching minimal values required by oscillations
- Relaxing cosmo bound requires new physics
- Presented simple seesaw model:
  - large number of massless sterile neutrinos ($N_\chi \gtrsim 10 - 30$)
  - dark U(1) symmetry with breaking scale between 10 MeV and 10 GeV
  - weakly coupled $Z'$ with mass 1 — 100 keV with $\lambda_{Z'}^{\nu\nu} \sim 10^{-9}$

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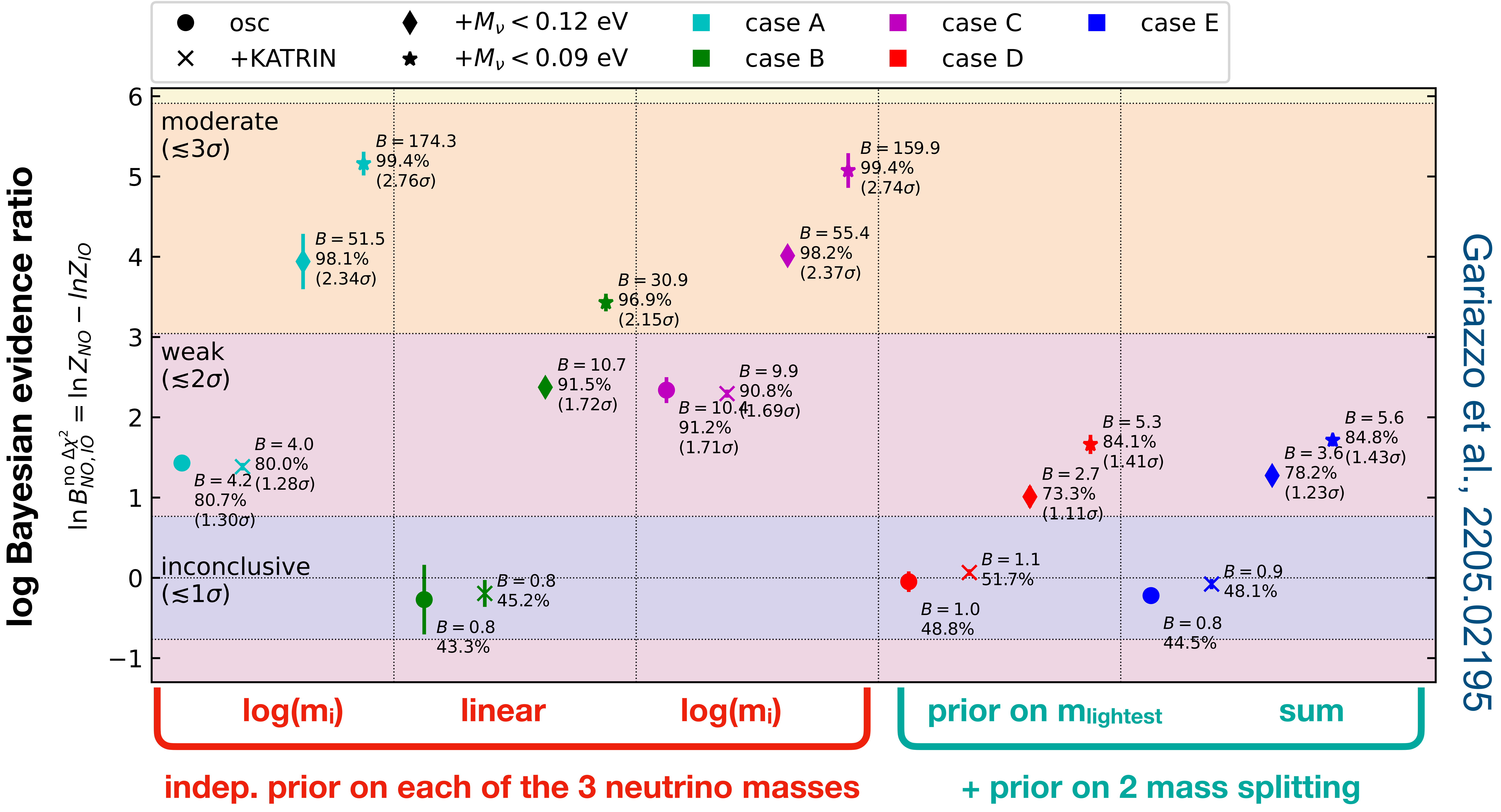
Thank You!

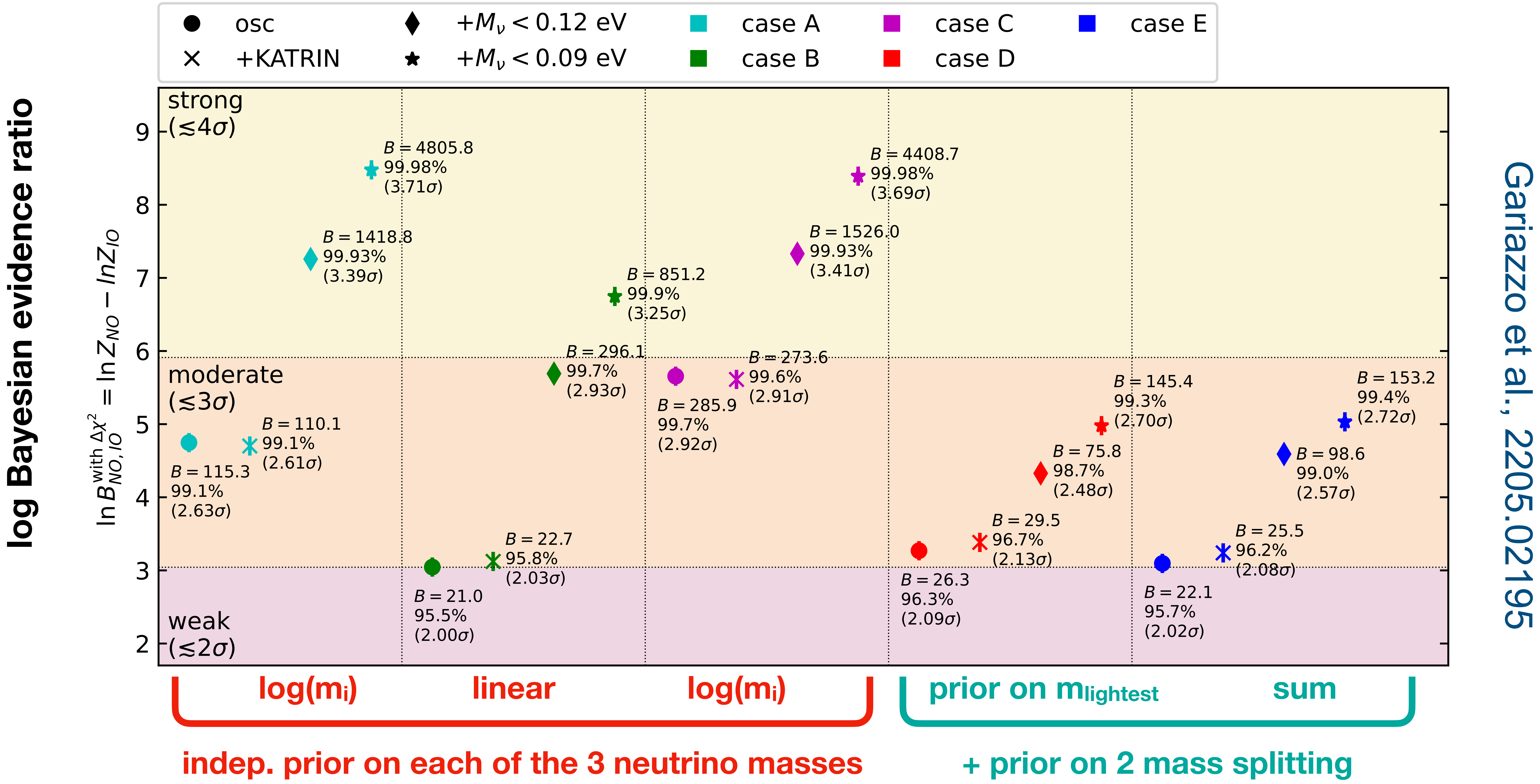
# Supplementary slides

# Preference for normal ordering (w/o $\Delta\chi^2_{\mathrm{IO/NO}}$ from osc.)

including $\Delta\chi^2$ from oscillation increases preference by $\simeq 1\sigma$



# Preference for normal ordering (including $\Delta\chi^2_{\mathrm{IO/NO}}$ from oscillation)



# Complementarity between mass determinations from heaven and earth

link between neutrino mass observables *in the standard scenario*:

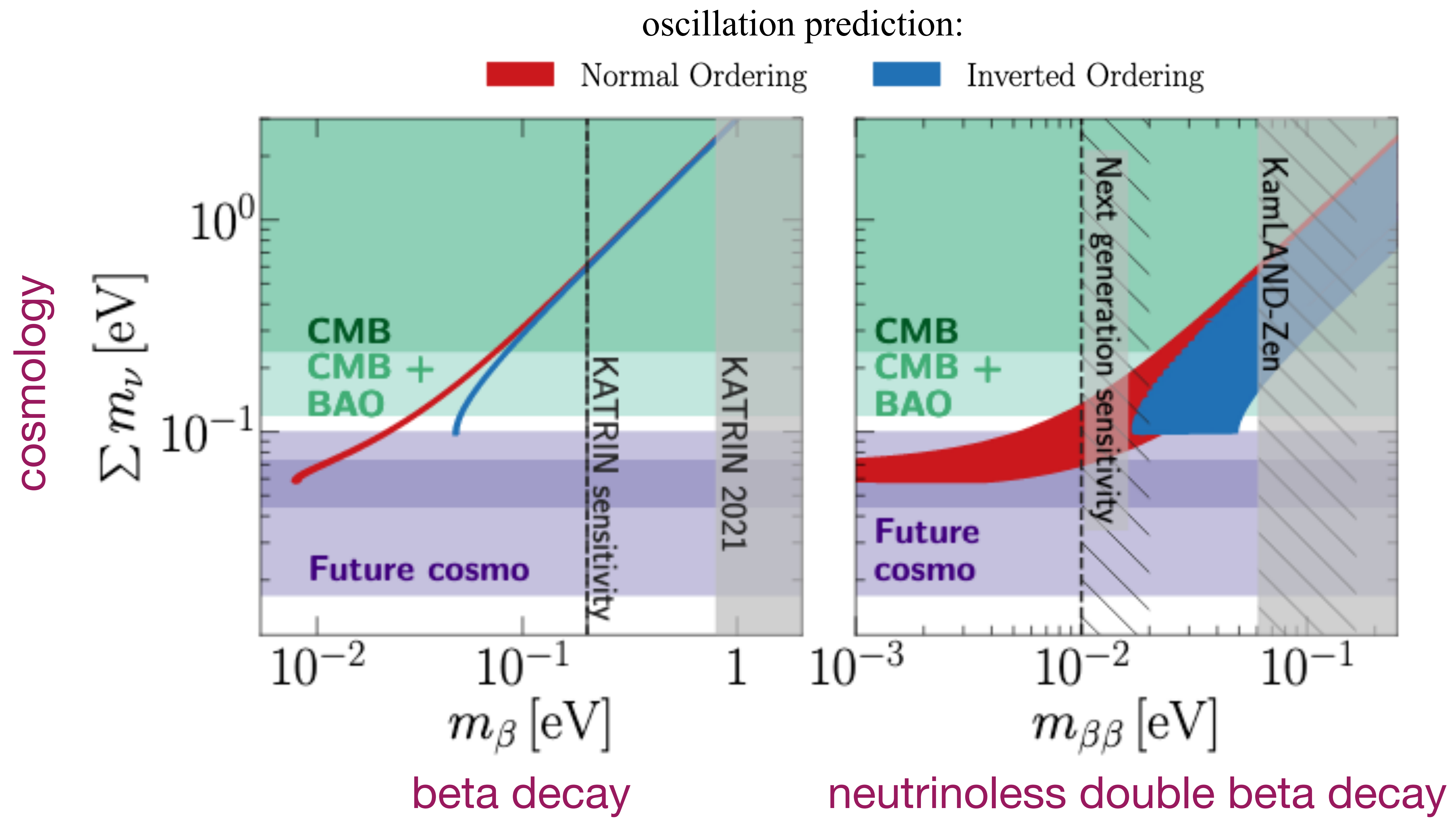



fig. by I. Esteban
based on NuFit 5.0

# Neutrino mass from cosmology

$$\sum m_\nu < 0.24\,\text{eV (CMB)}$$

$$\sum m_\nu < 0.12\,\text{eV (CMB+BAO)}$$

limits at 95% CL

Planck 1807.06209