A seesaw model for large neutrino mass consistent with cosmology

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

DMLab meeting, KIT, 16 Nov. 2023

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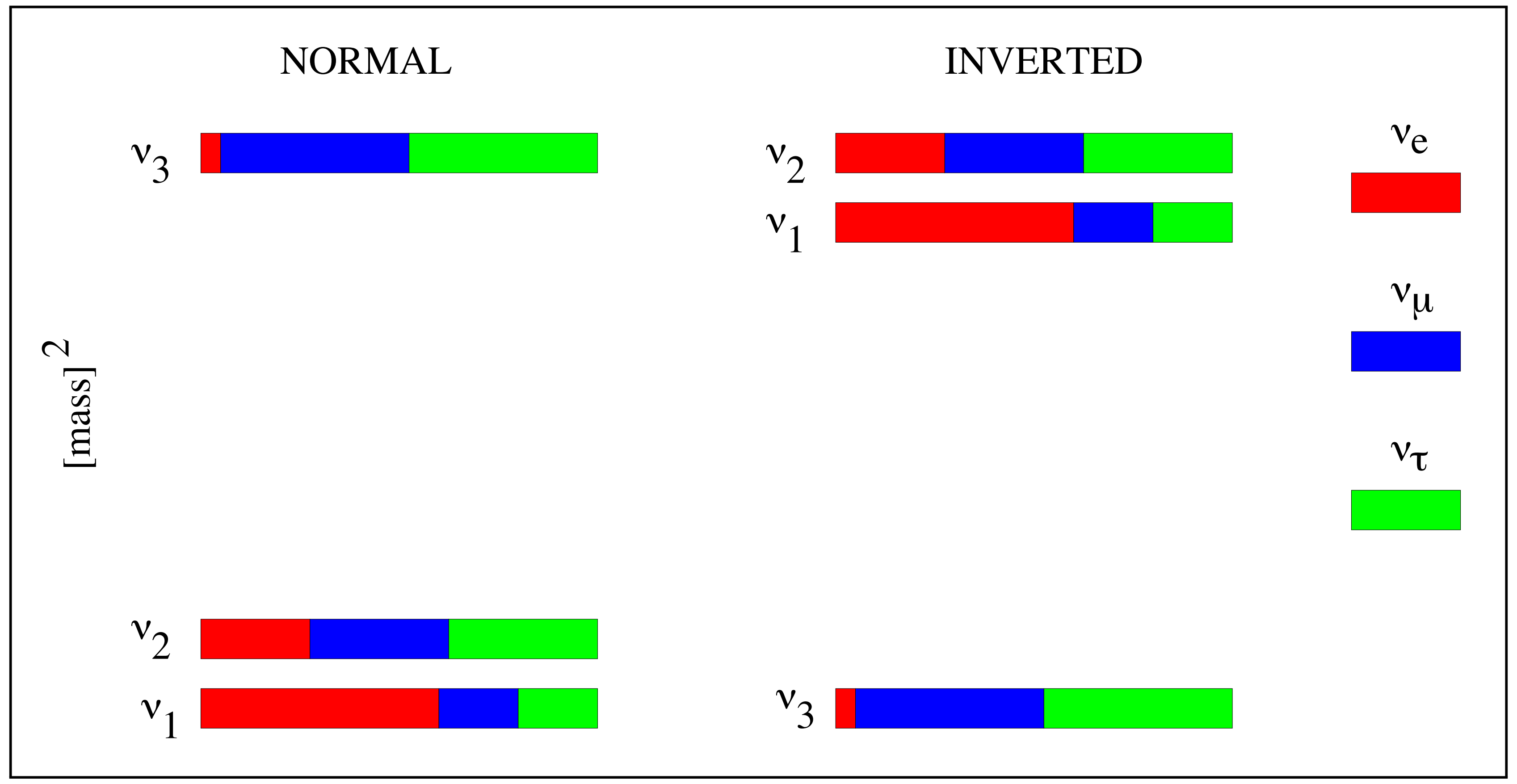
Neutrino masses



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

$$\sum_i m_i \lesssim 0.1\,\mathrm{eV}$$

Complementarity between mass determinations from heaven and earth

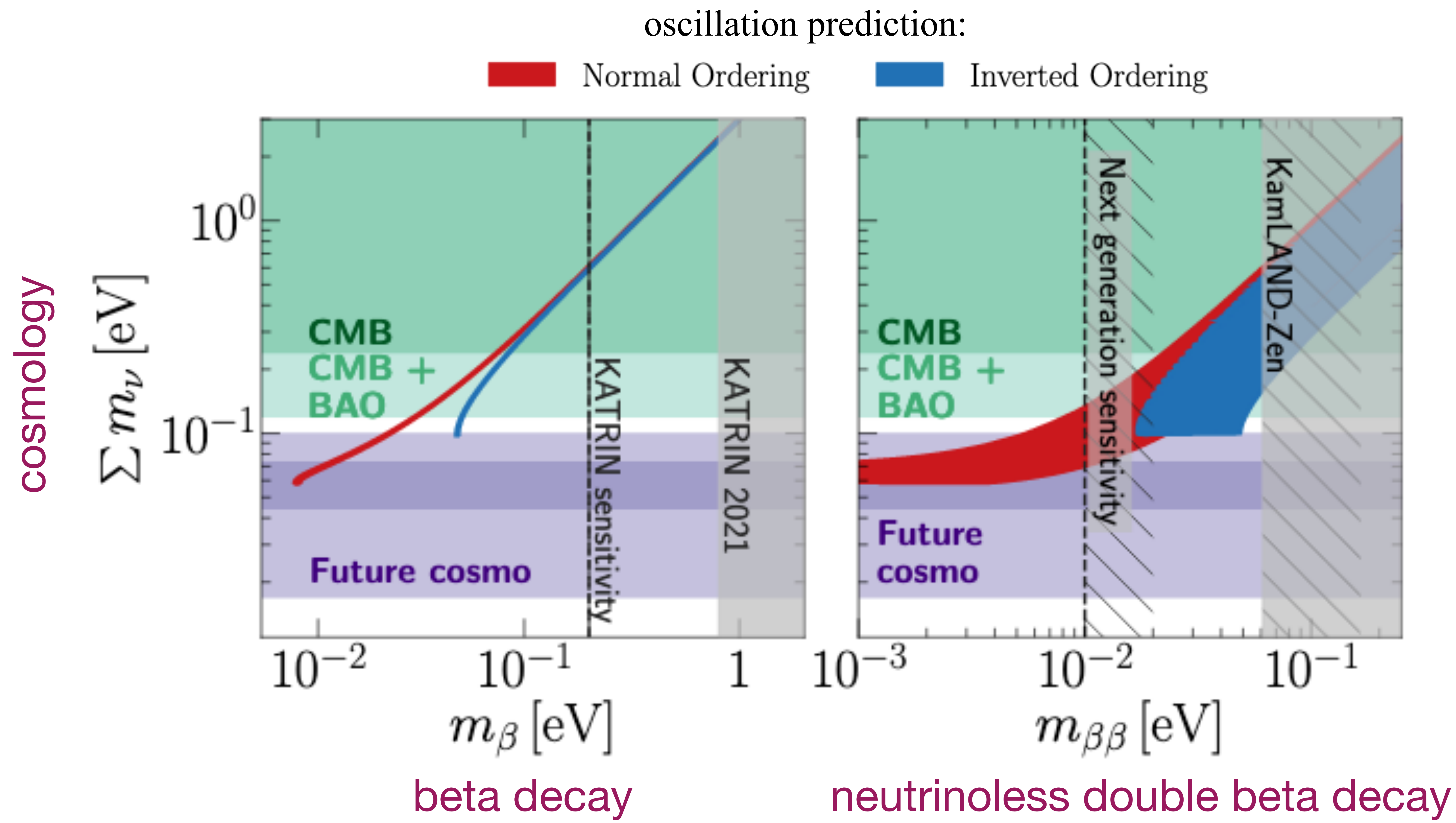
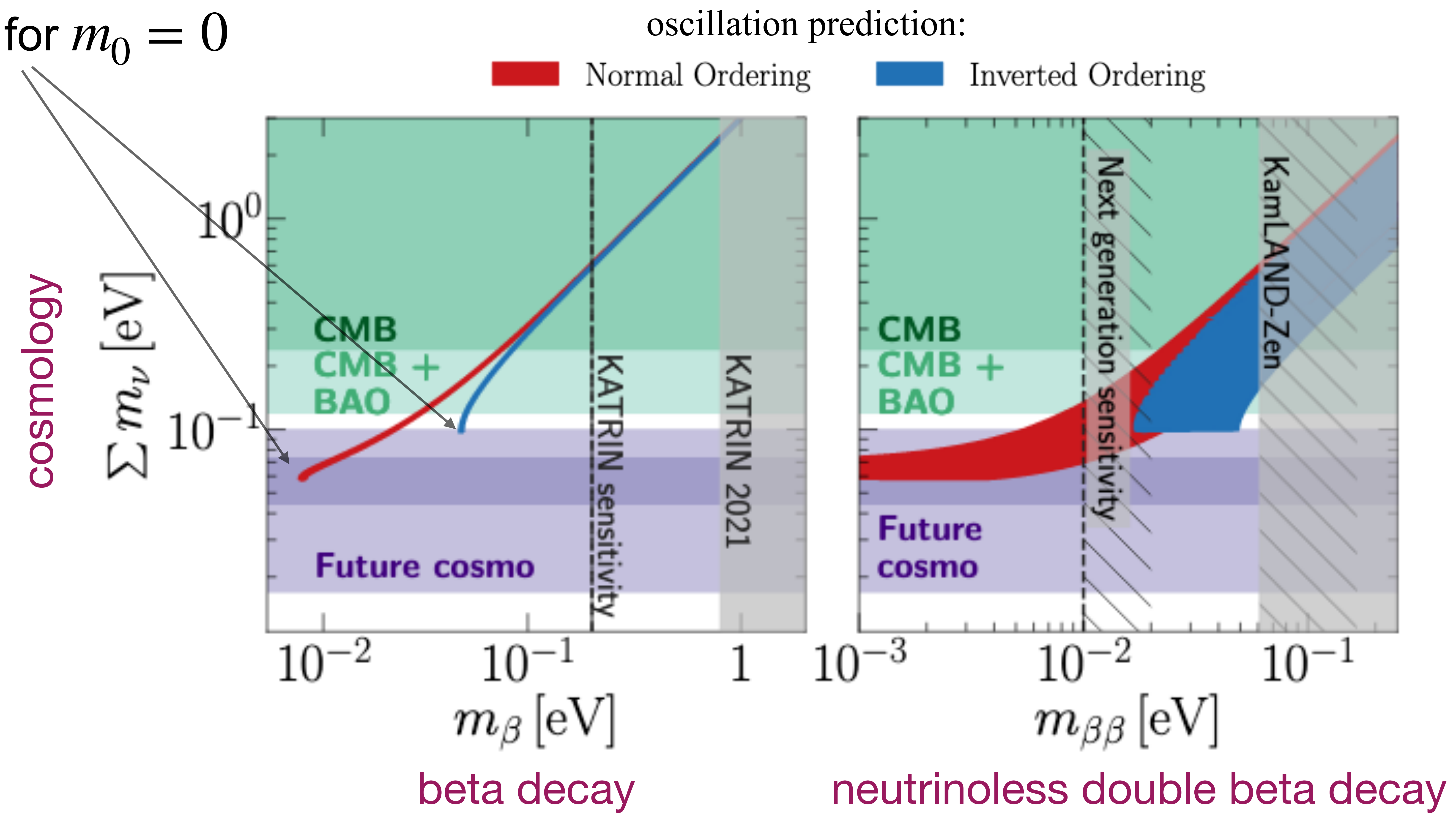


fig. by I. Esteban
based on NuFit 5.0

Complementarity between mass determinations from heaven and earth

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



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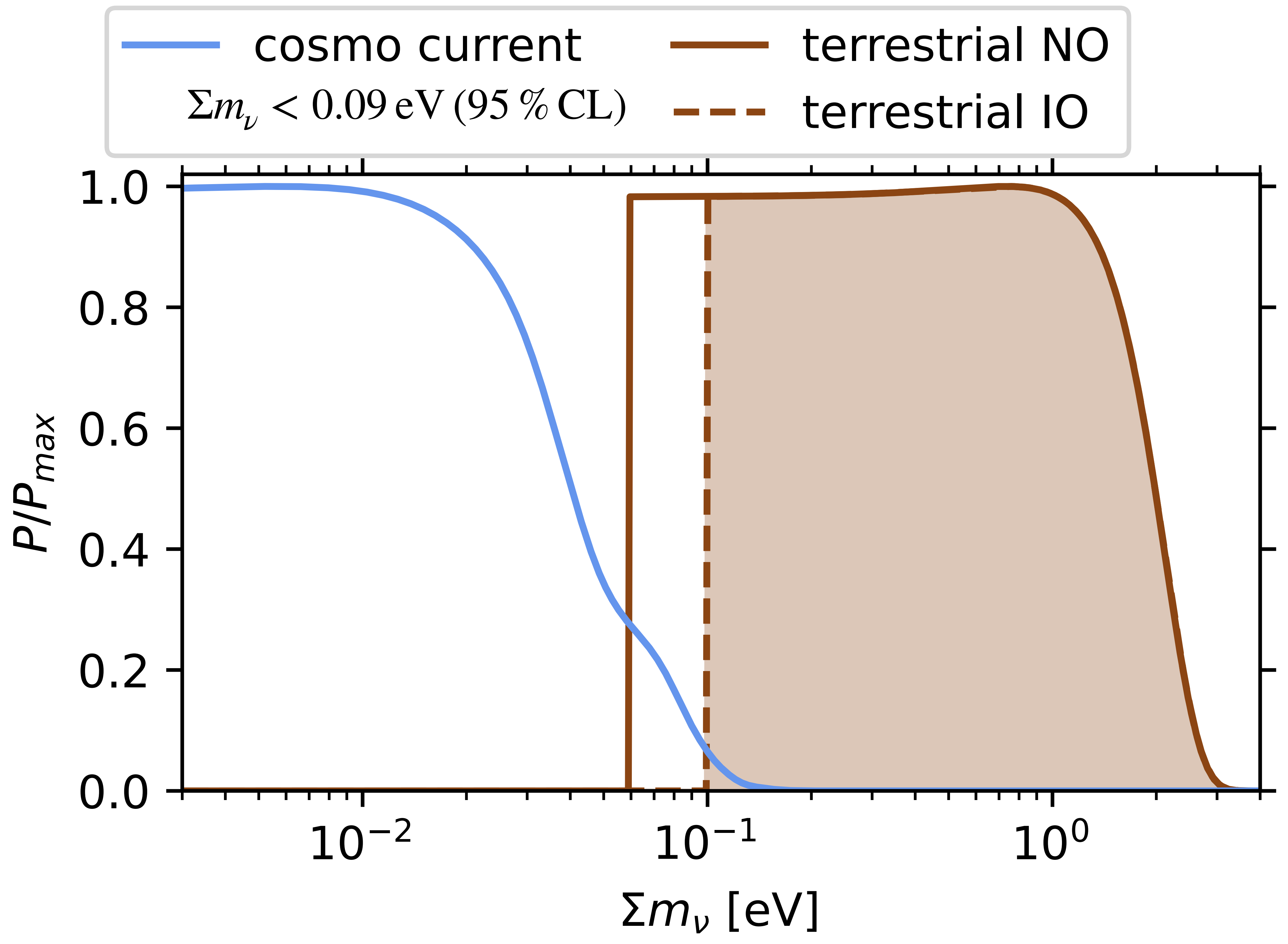
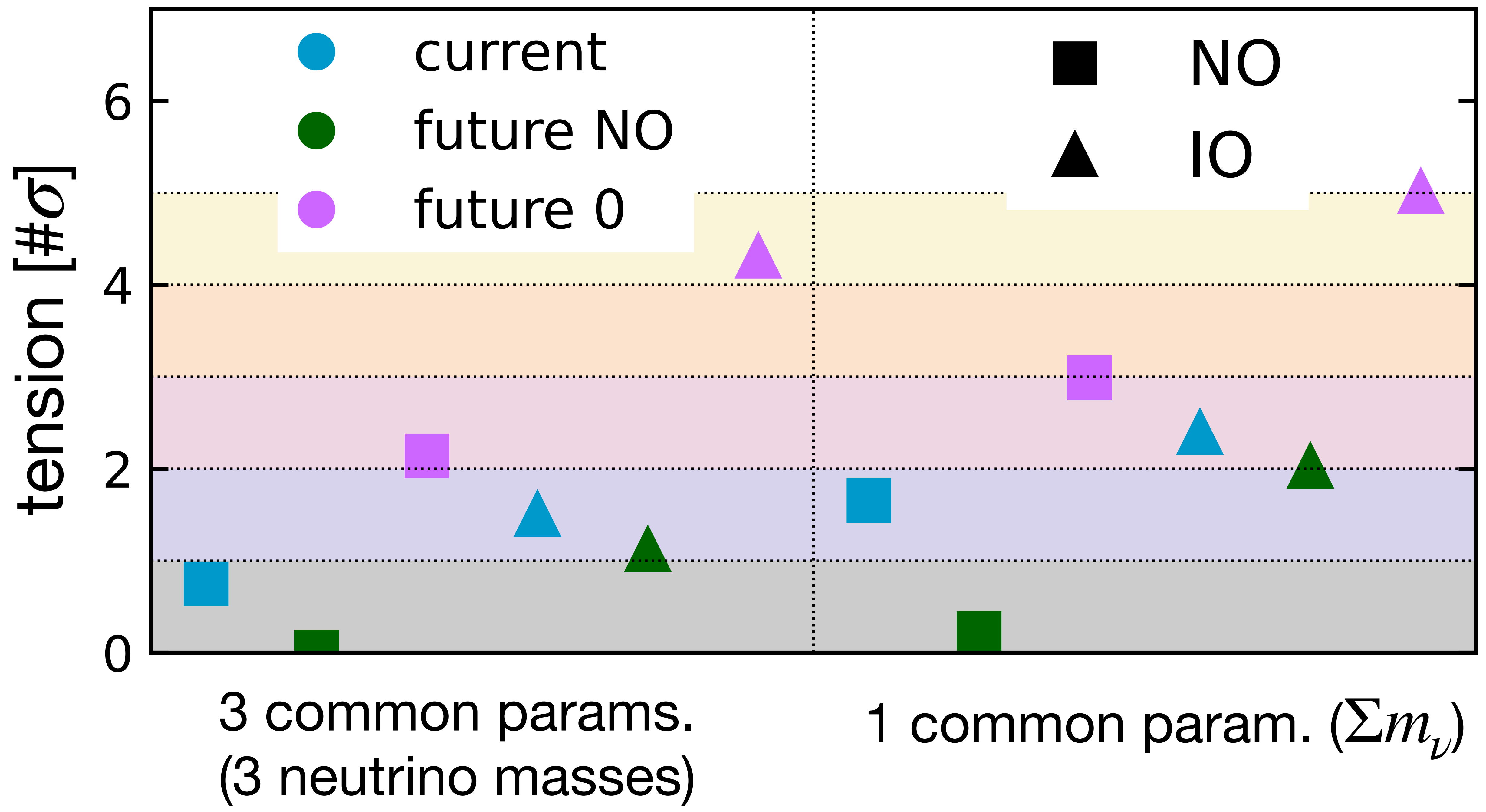
Tension between cosmology and terrestrial data



Gariazzo, Mena, Schwetz, 2302.14159



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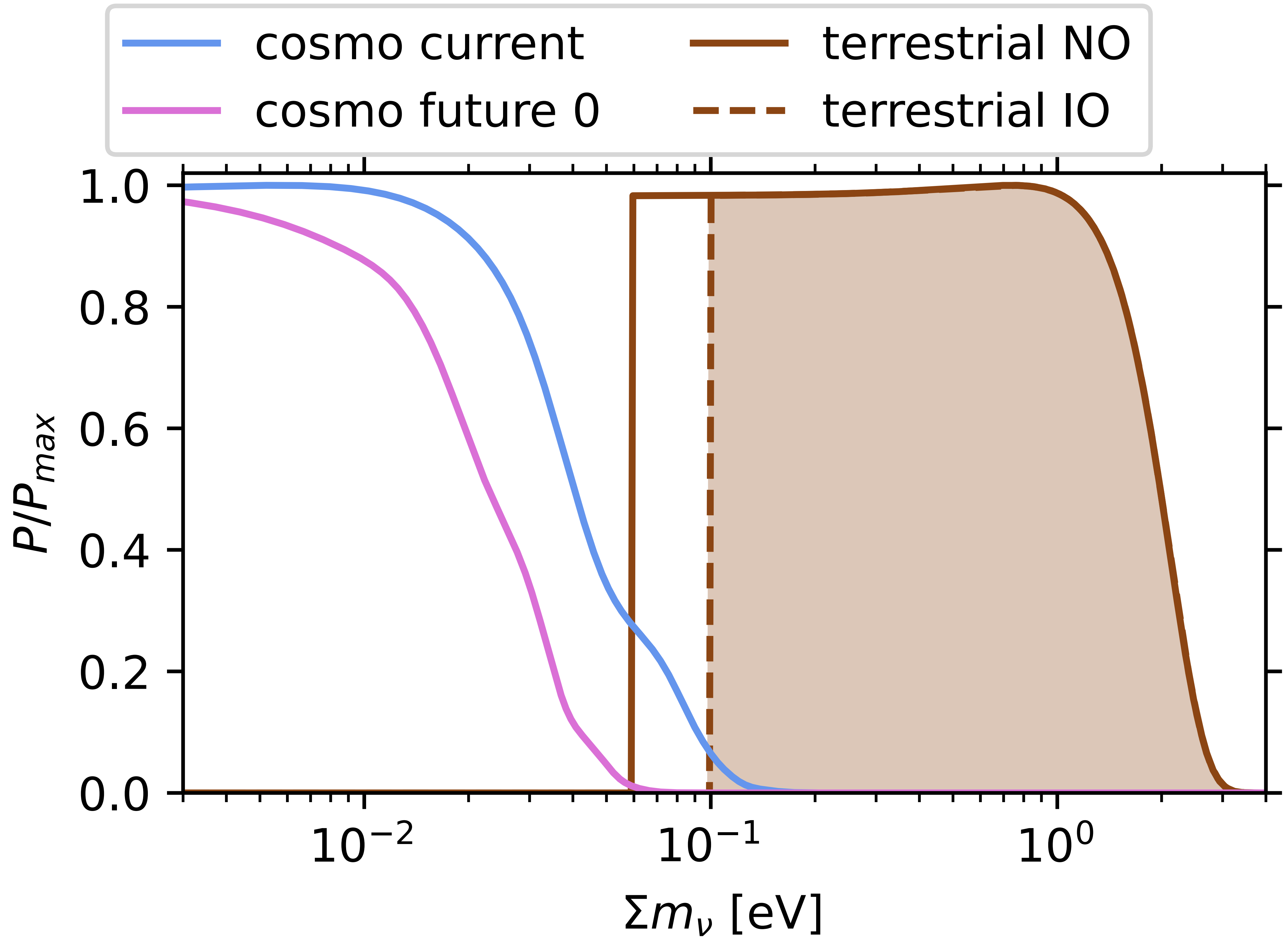
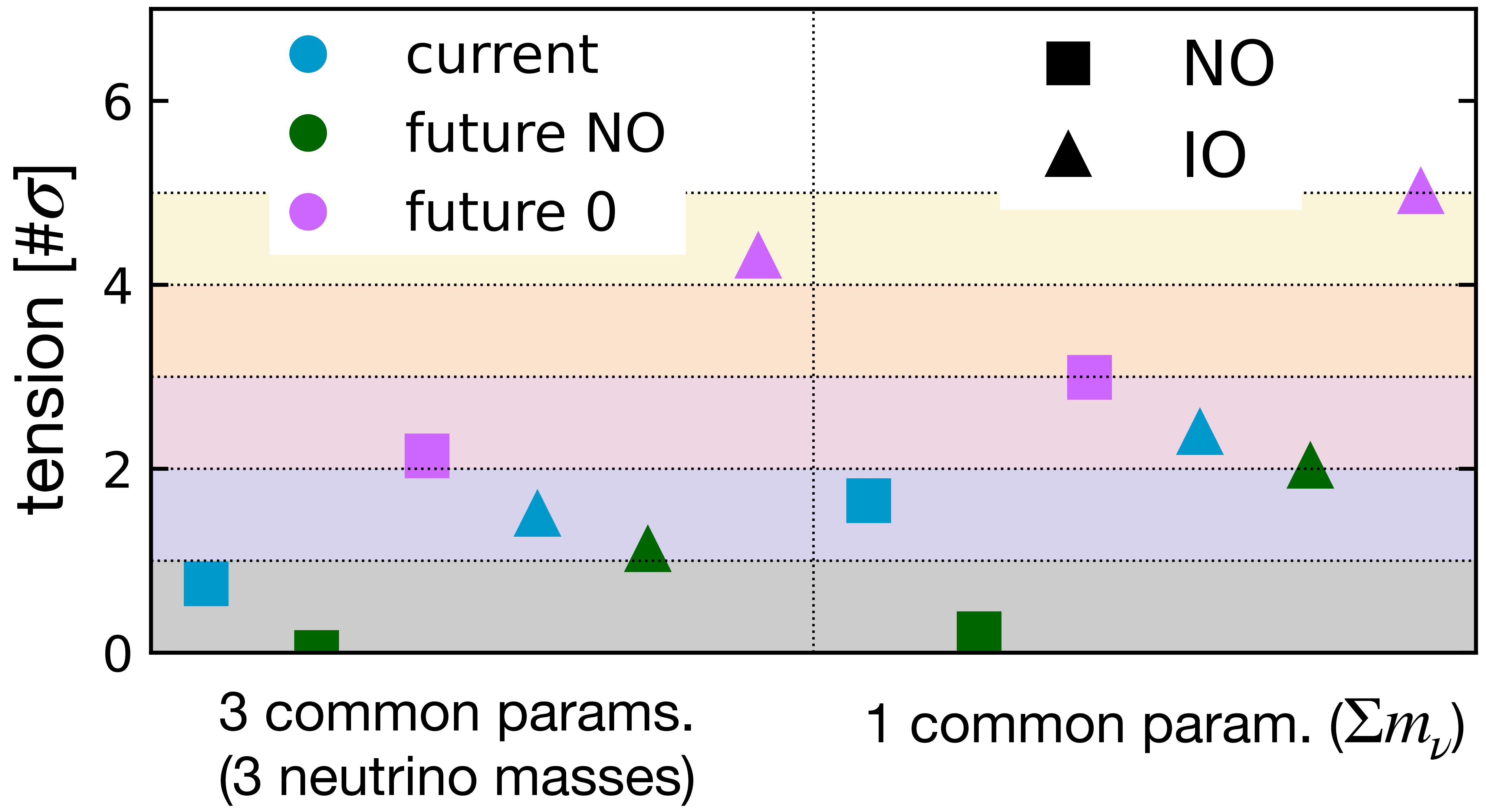


future 0: $\Sigma m_\nu < 0.02\,\mathrm{eV}(1\sigma)$

Gariazzo, Mena, Schwetz, 2302.14159



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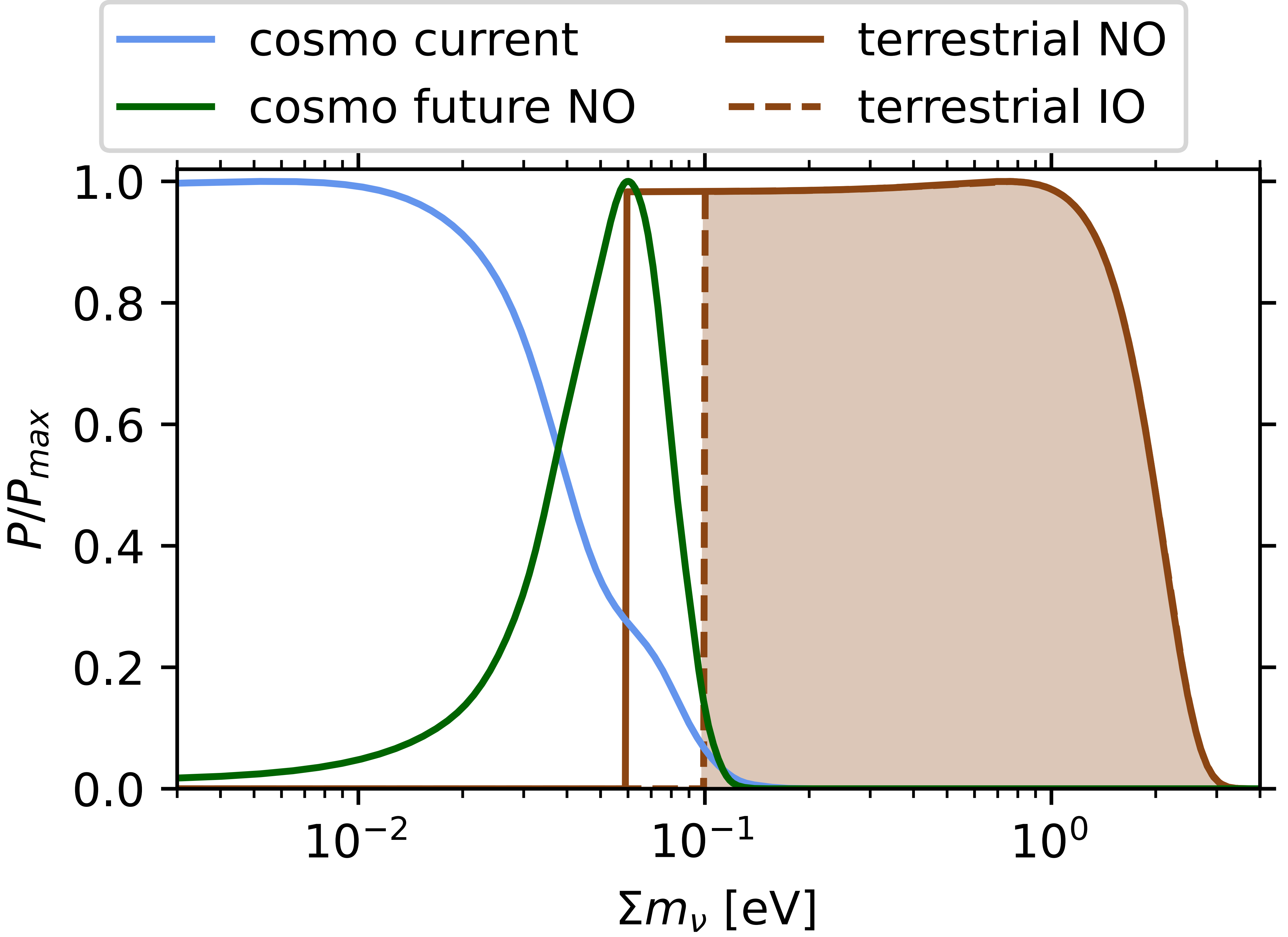

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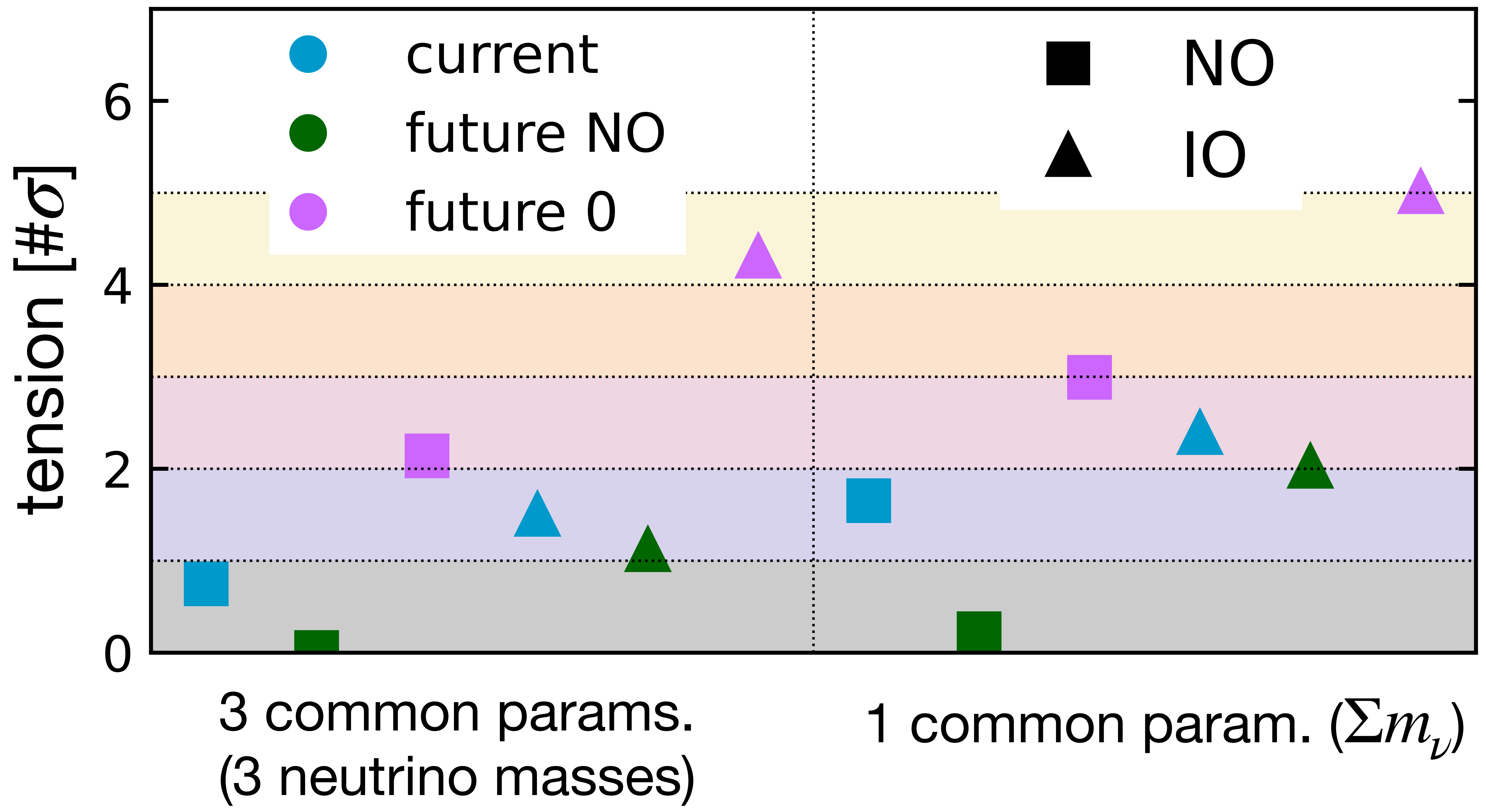

future NO: $\Sigma m_\nu = (0.06 \pm 0.02)\,\mathrm{eV}(1\sigma)$

- 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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relax bound on m_ν by reducing neutrino number density

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

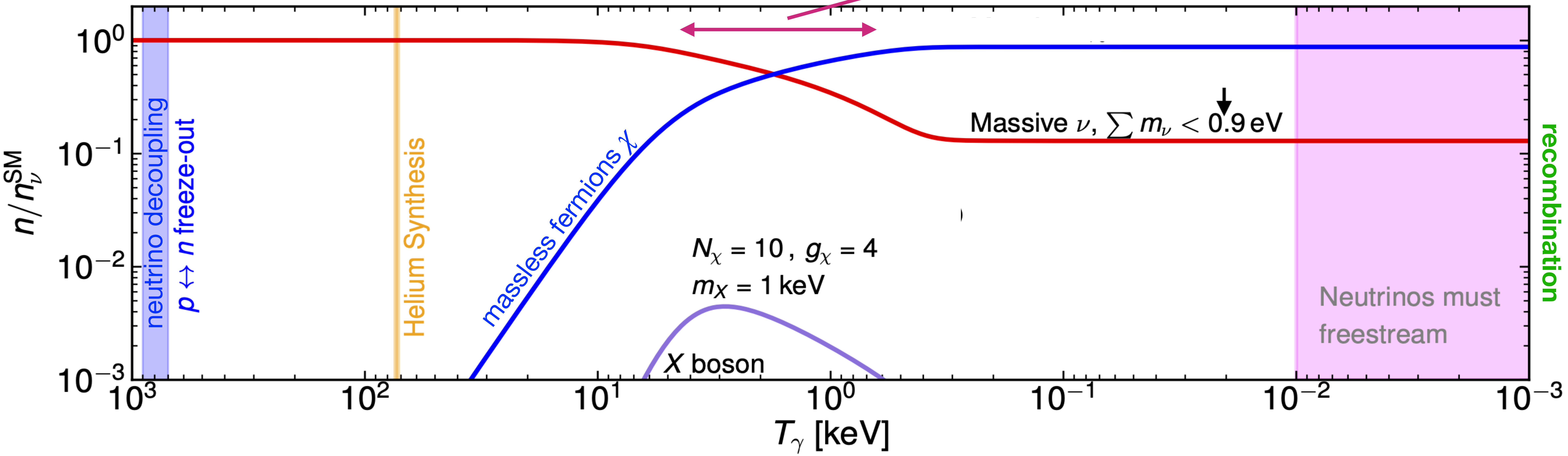
introduce „dark radiation“ to keep $N_{\text{eff}}^{\text{relat.}} \approx 3$

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

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

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

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



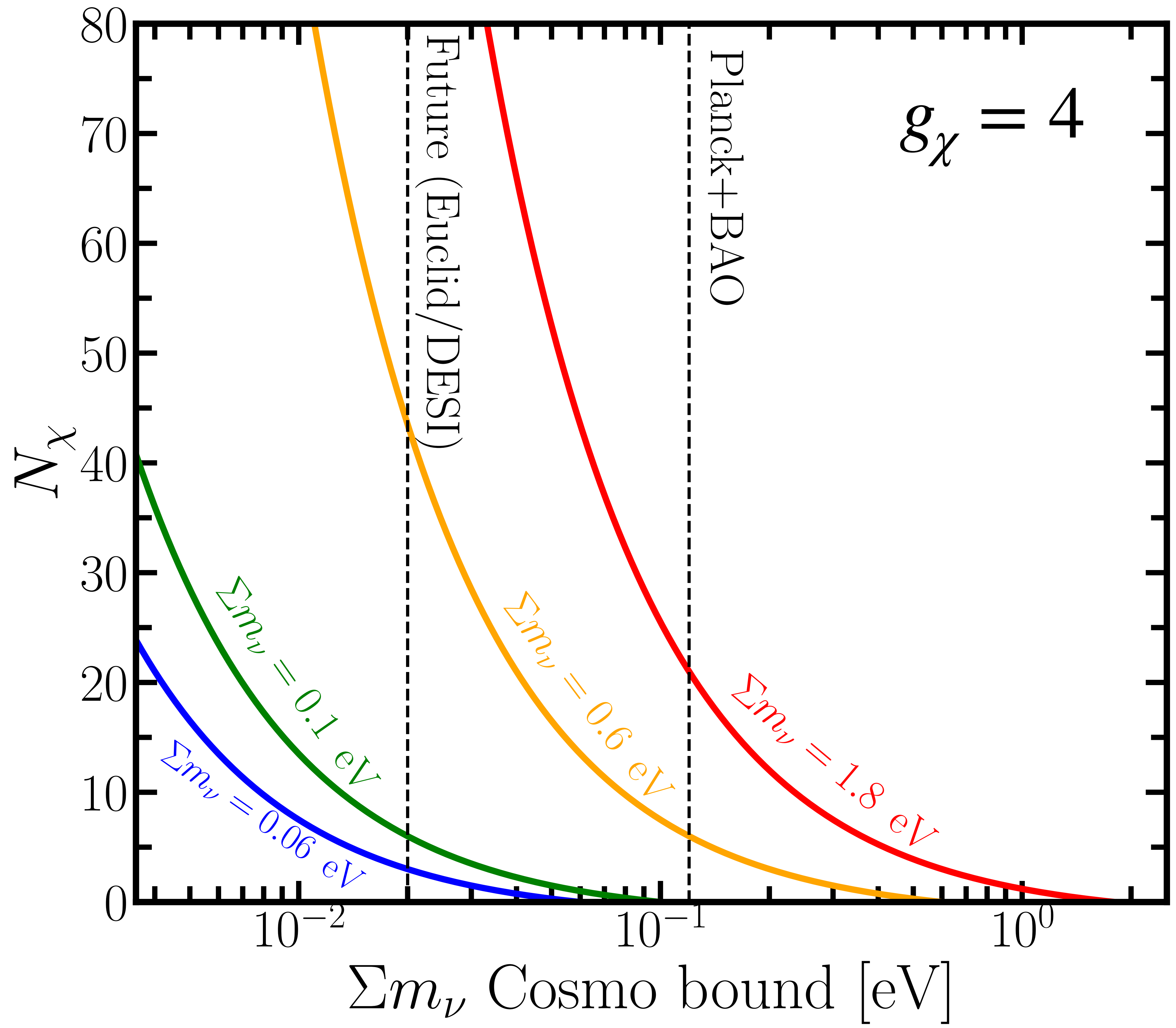
Relaxed bound from cosmology

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

relaxing the present bound by converting neutrinos into N_χ generations of massless fermions with g_χ 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 Φ charged under $U(1)_X$
- a set of N_χ massless fermions charged under $U(1)_X$

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

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

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

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

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

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

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

$$\mathscr{L}_{\text{int}} = g_X\, Z'_\mu\, \bar{\chi}\gamma^\mu \chi$$

$$g_X = \frac{m_{Z'}}{v_\Phi}$$

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

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

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

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

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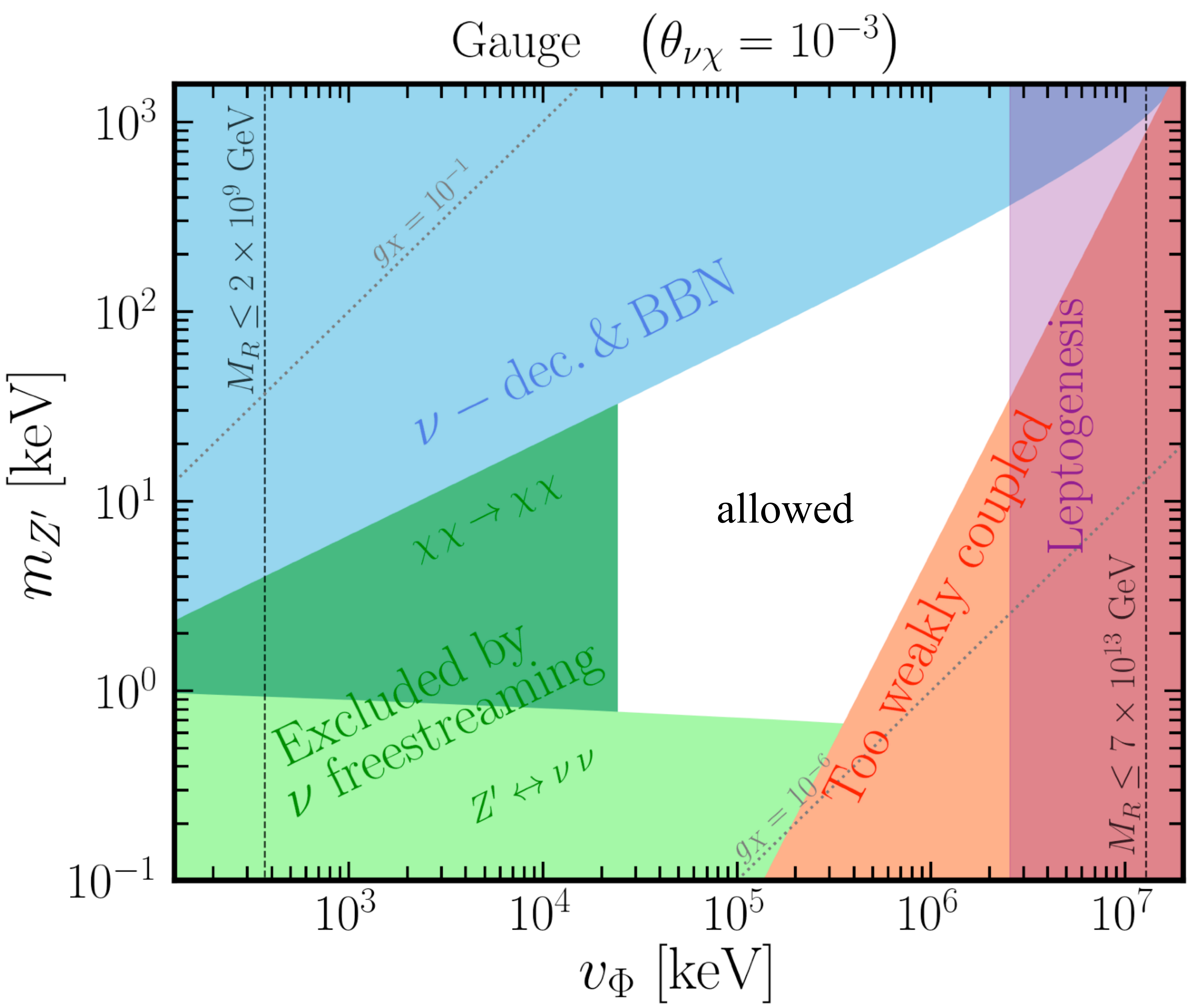
$$\mathscr{L}_{\text{int}} = g_X\, Z'_\mu\, \bar{\chi}\gamma^\mu \chi \qquad\qquad g_X = \frac{m_{Z'}}{v_\Phi}$$

indep. params for pheno:

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

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

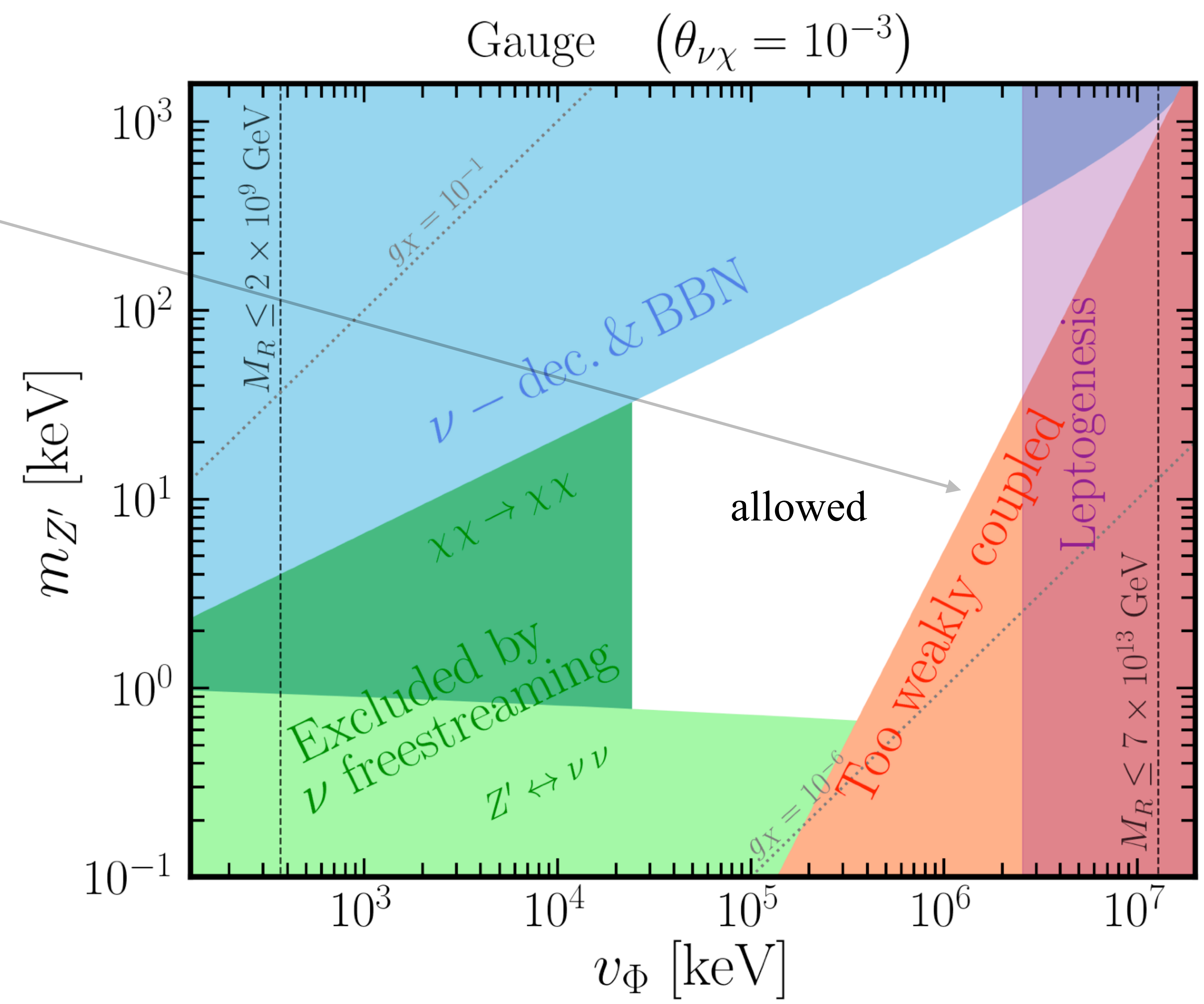
Available parameter space



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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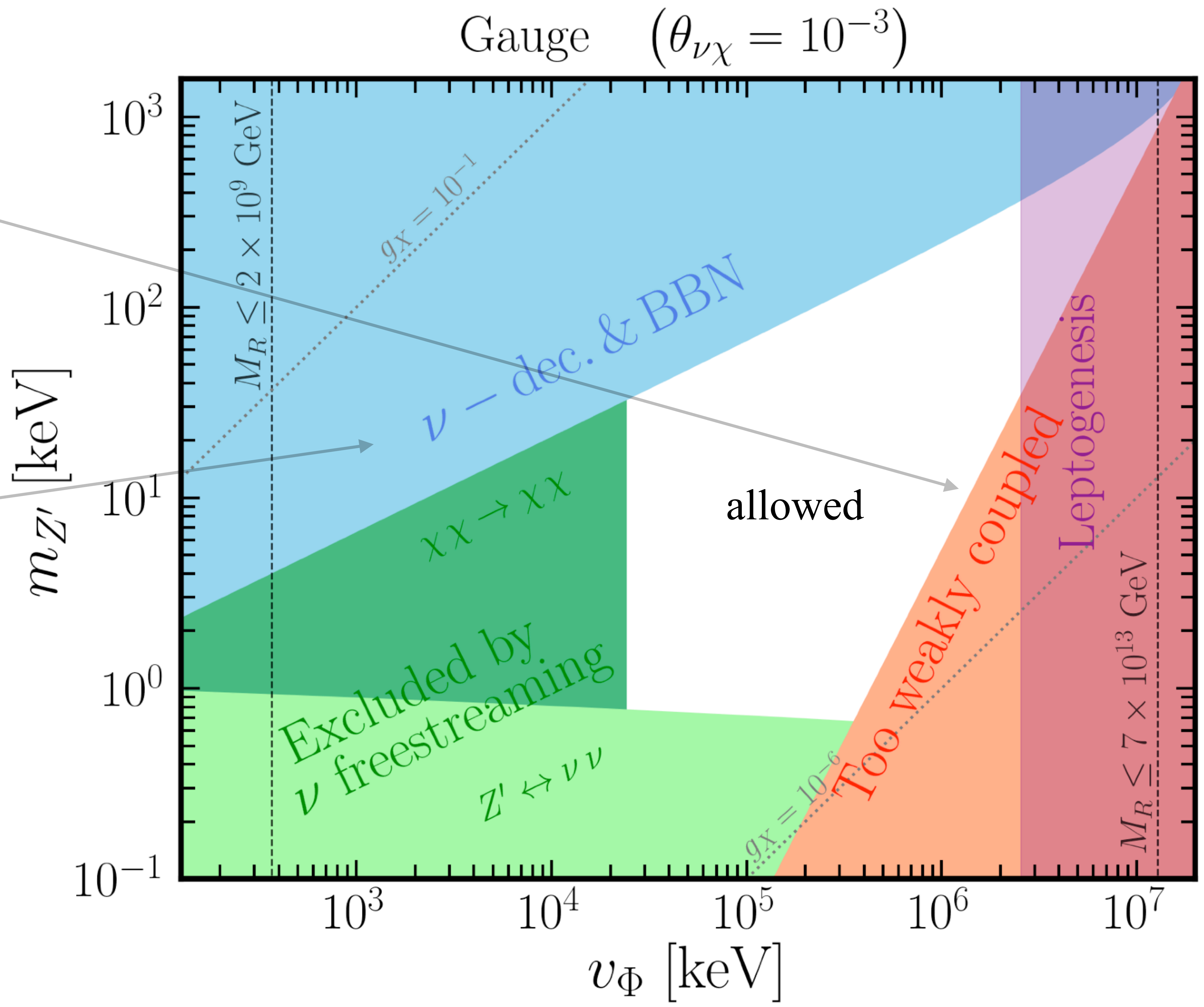
- avoid thermalization of the dark sector before BBN:

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



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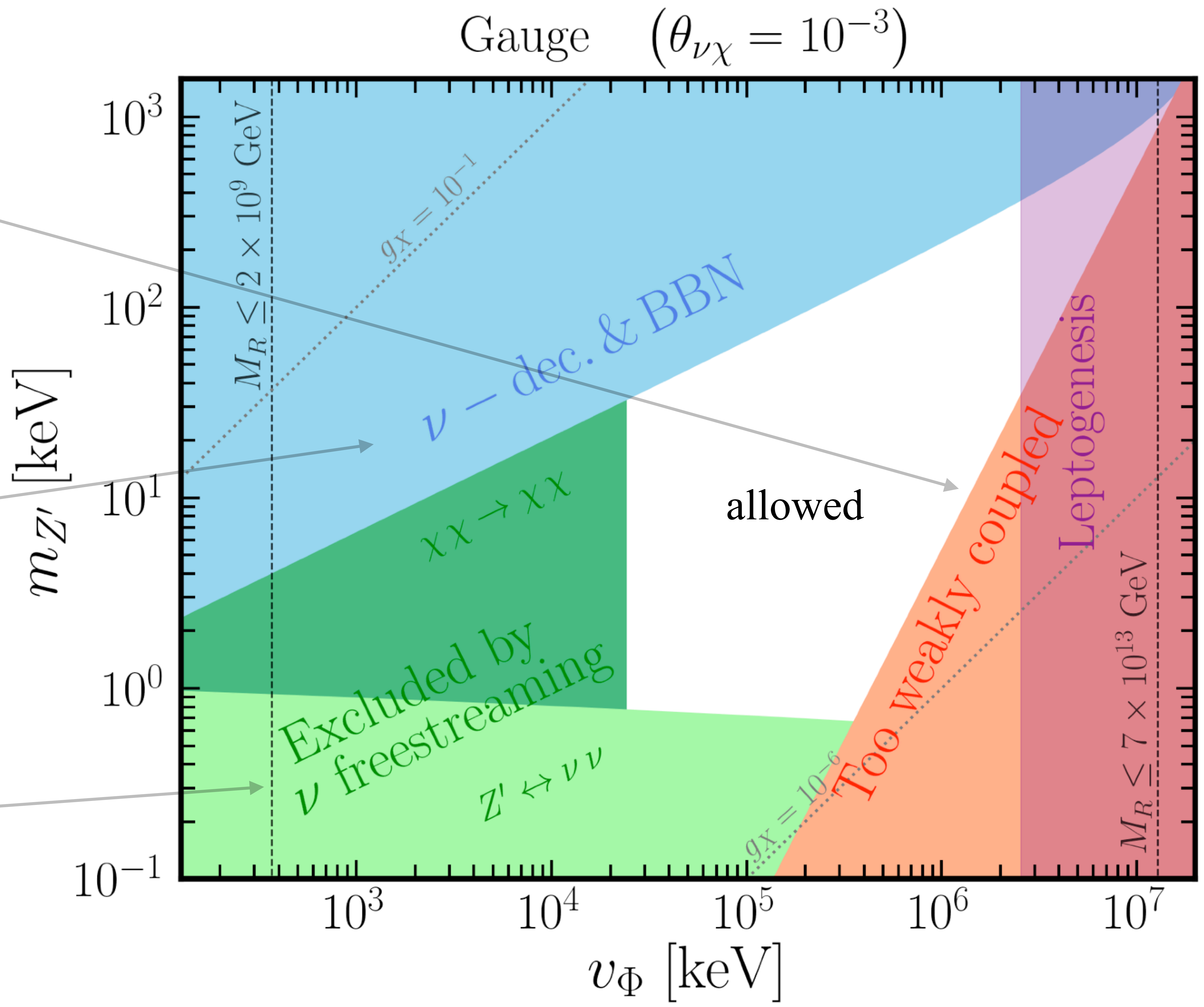
- free-streaming of neutrinos & dark radiation before/around recombination

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

  Taule, Escudero, Garny, 2207.04062

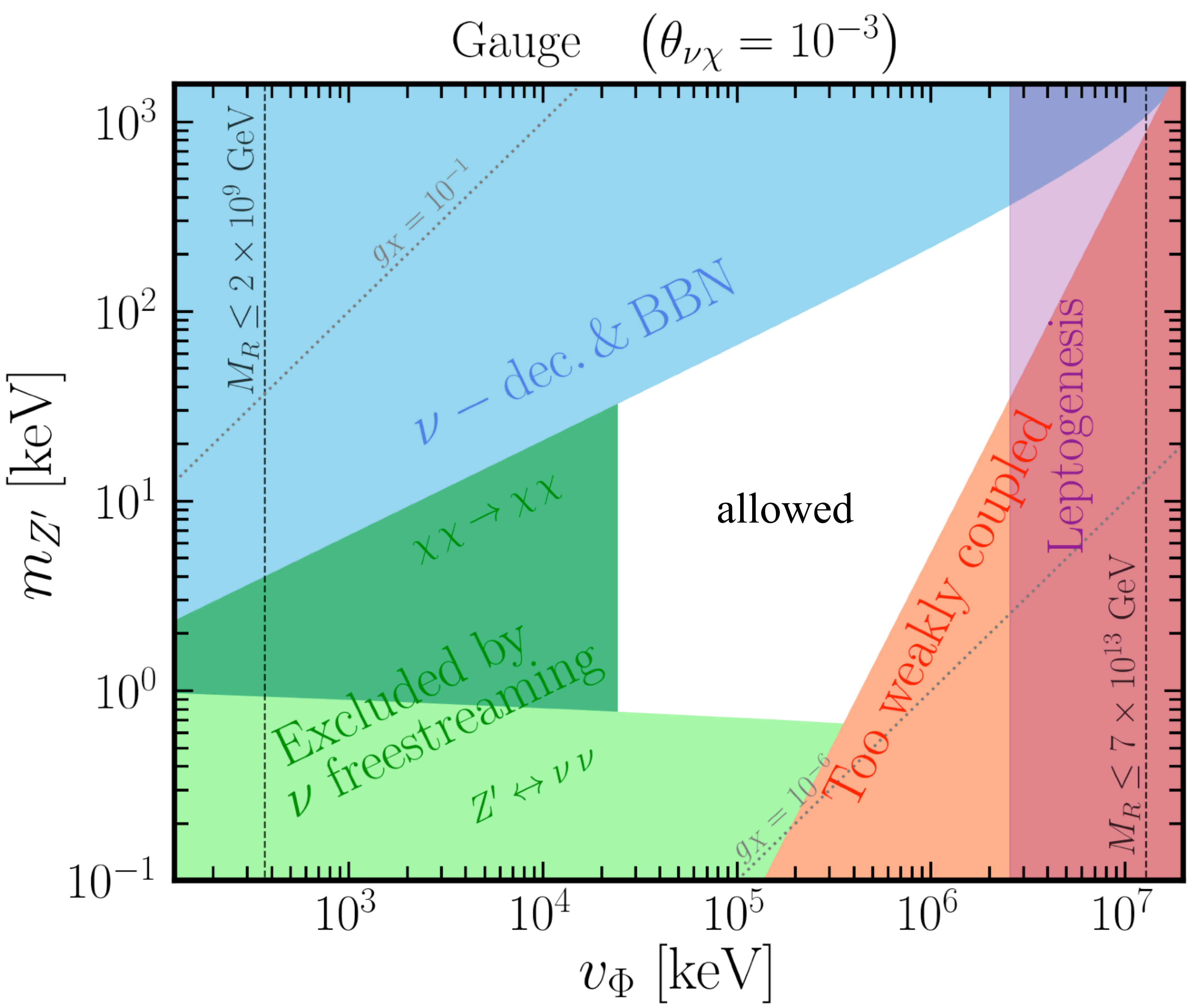


Available parameter space

- avoid thermalization of χ 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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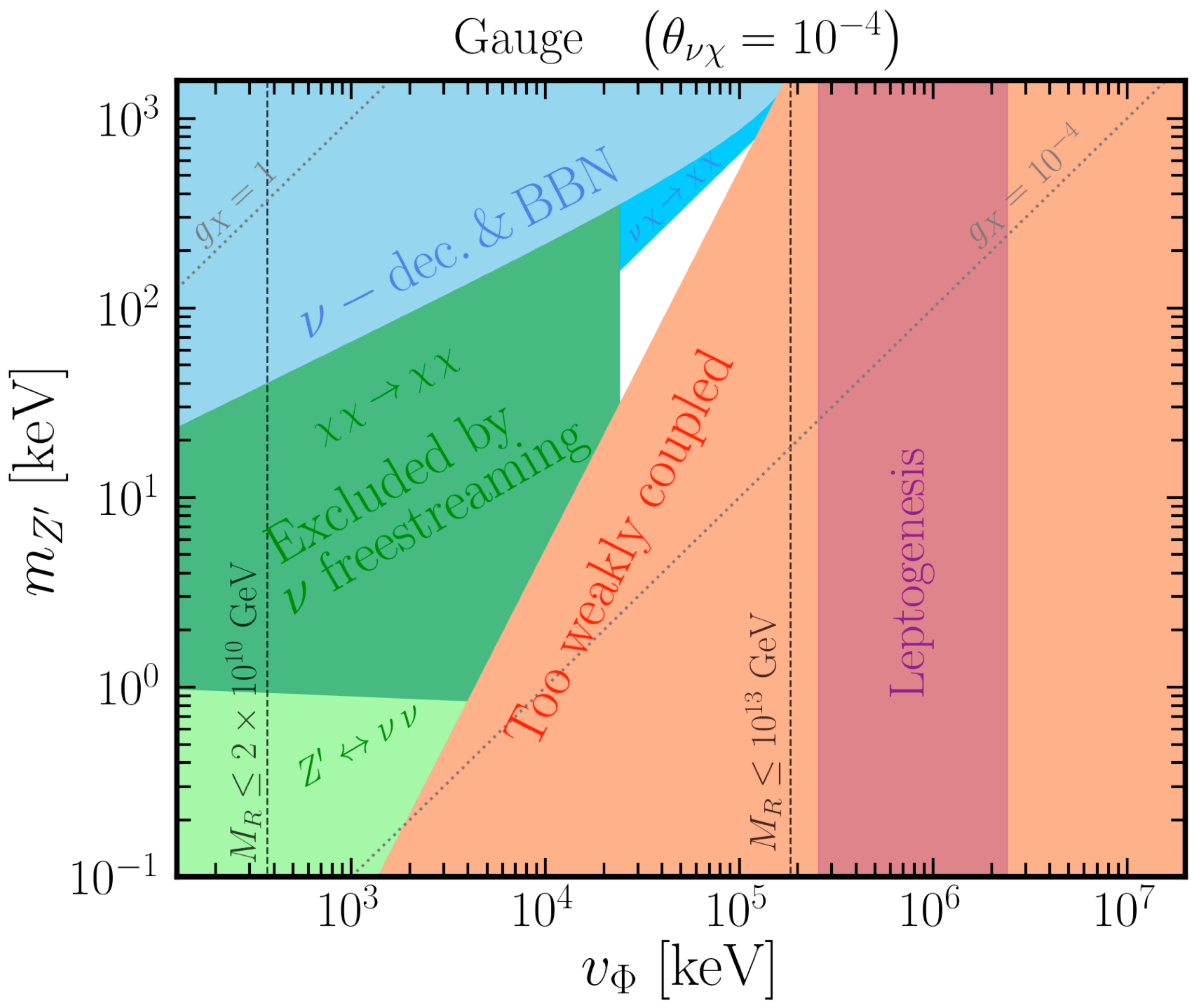
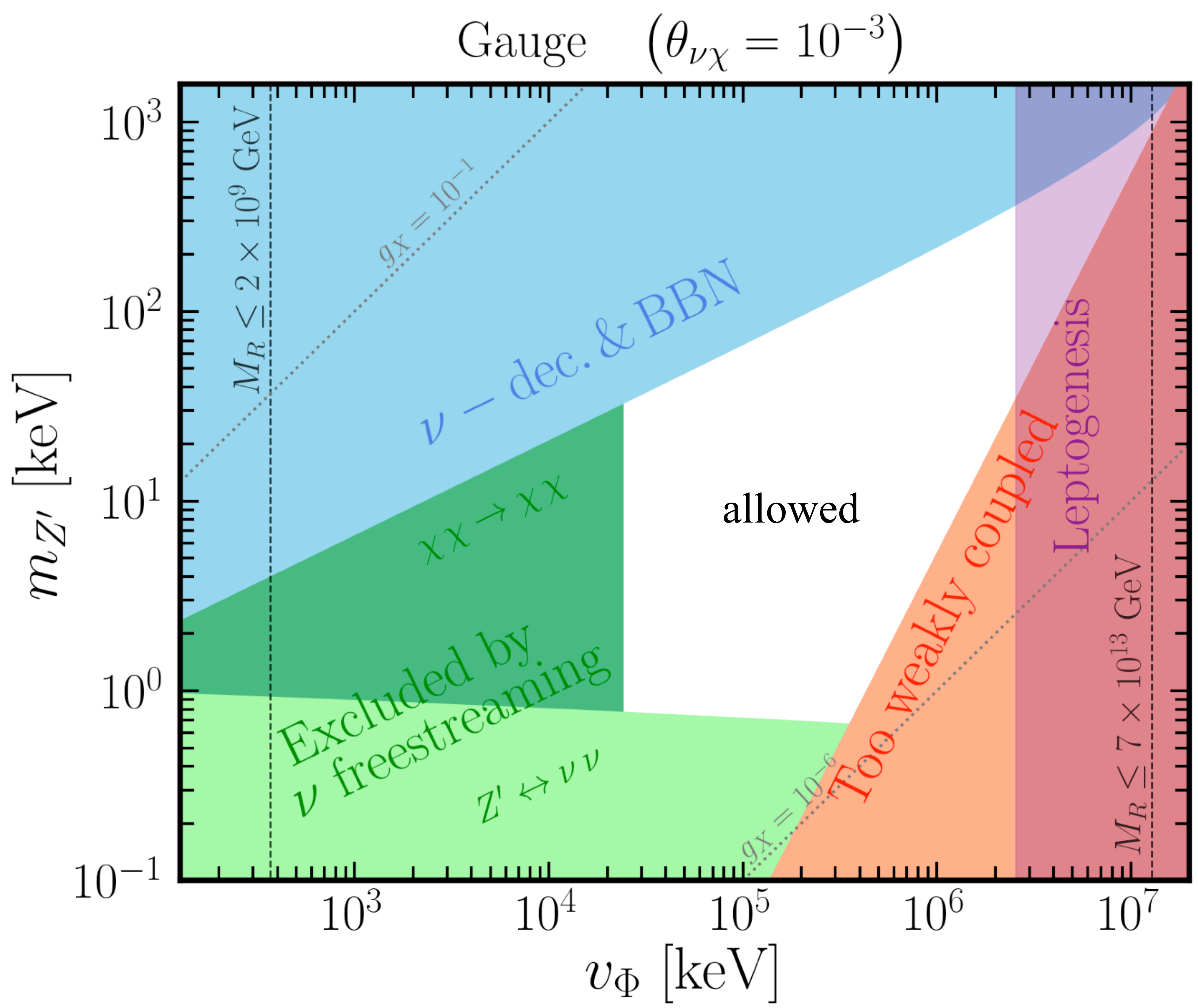


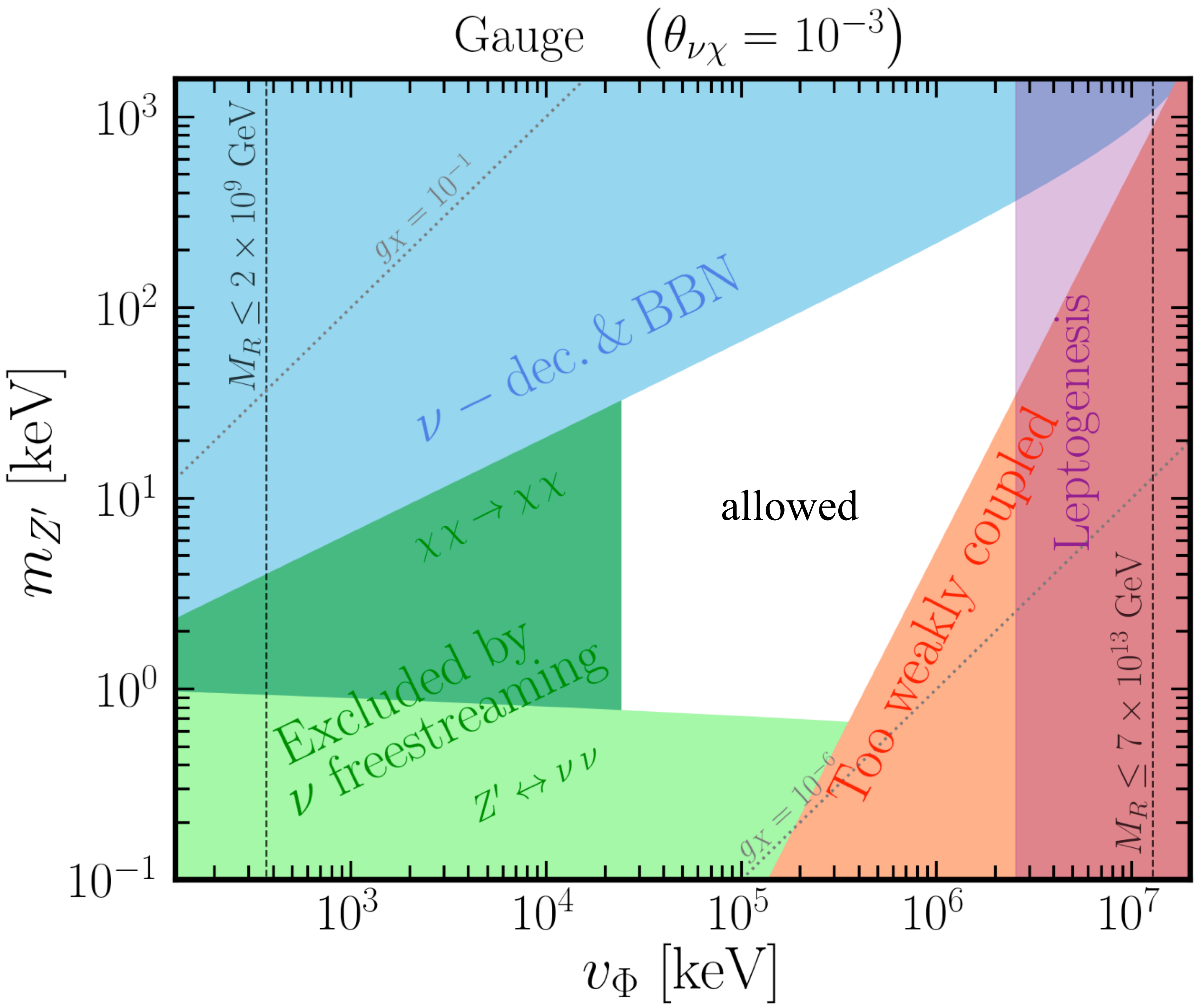


Available parameter space

- 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 Φ prior BBN



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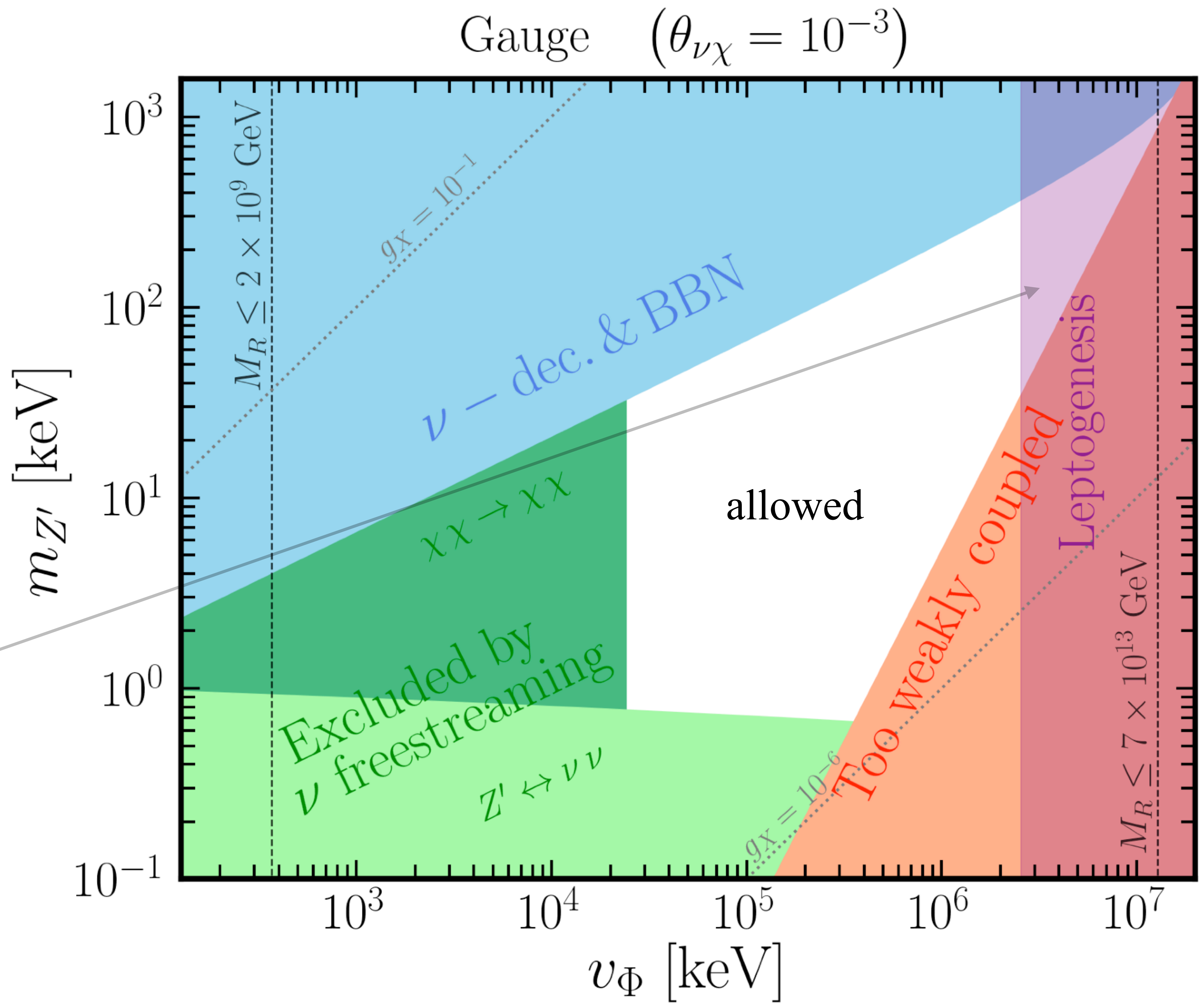
  - standard thermal leptogensis works if $N \to HL$ dominates over $N \to \chi\Phi$
  - otherwise χ would thermalize and conflict with N_{eff} during BBN $\Rightarrow$ require $T_{RH} < M_R$ (allows still for $T_{RH} \gg T_{EW}$)



Further signatures of the model

- SN cooling arguments for SN1987A exclude

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

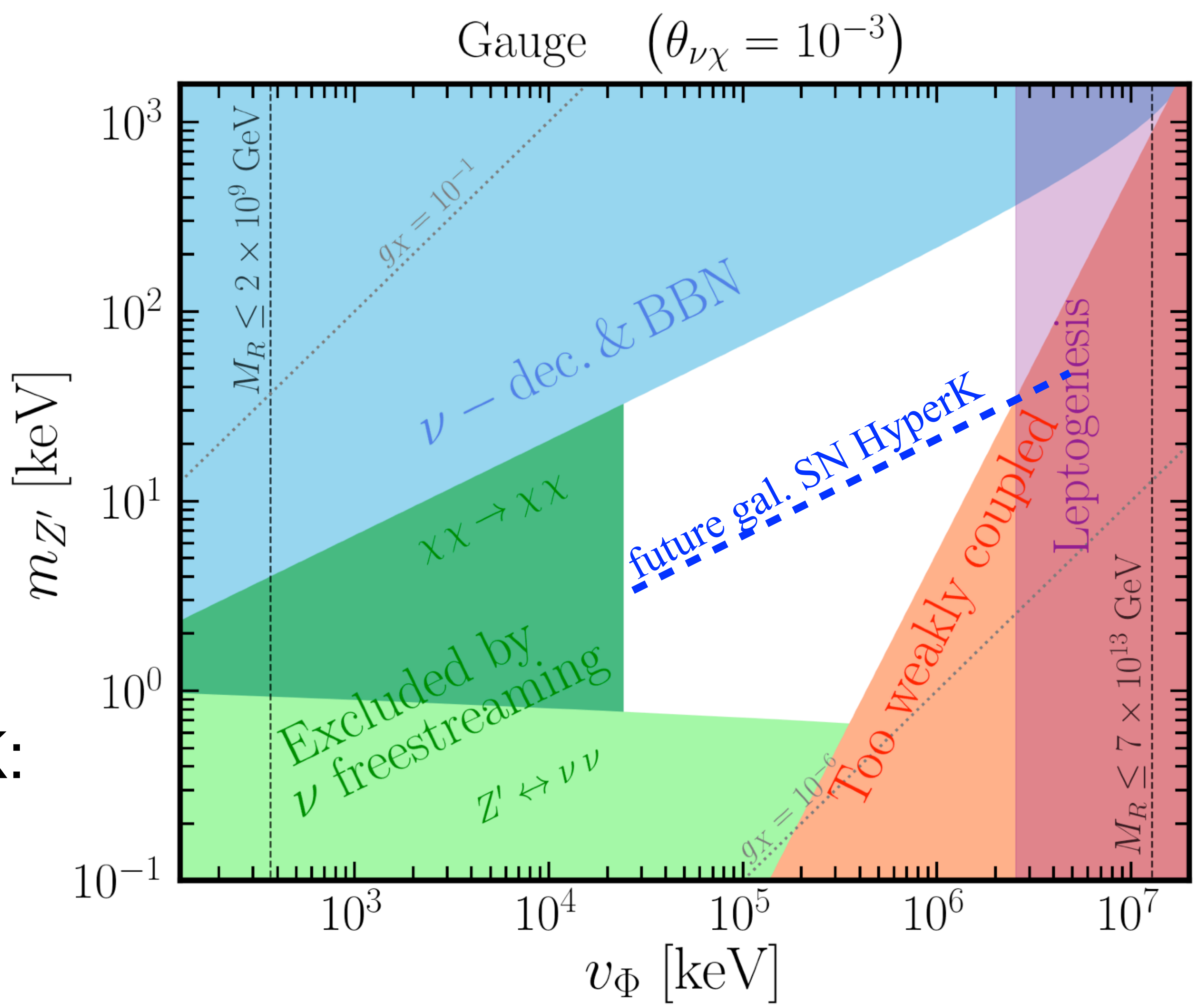
Fiorillo, Raffelt, Vitagliano, 2209.11773

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

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

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

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
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Thank You!

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