Karlsruher Institut für Technologie

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

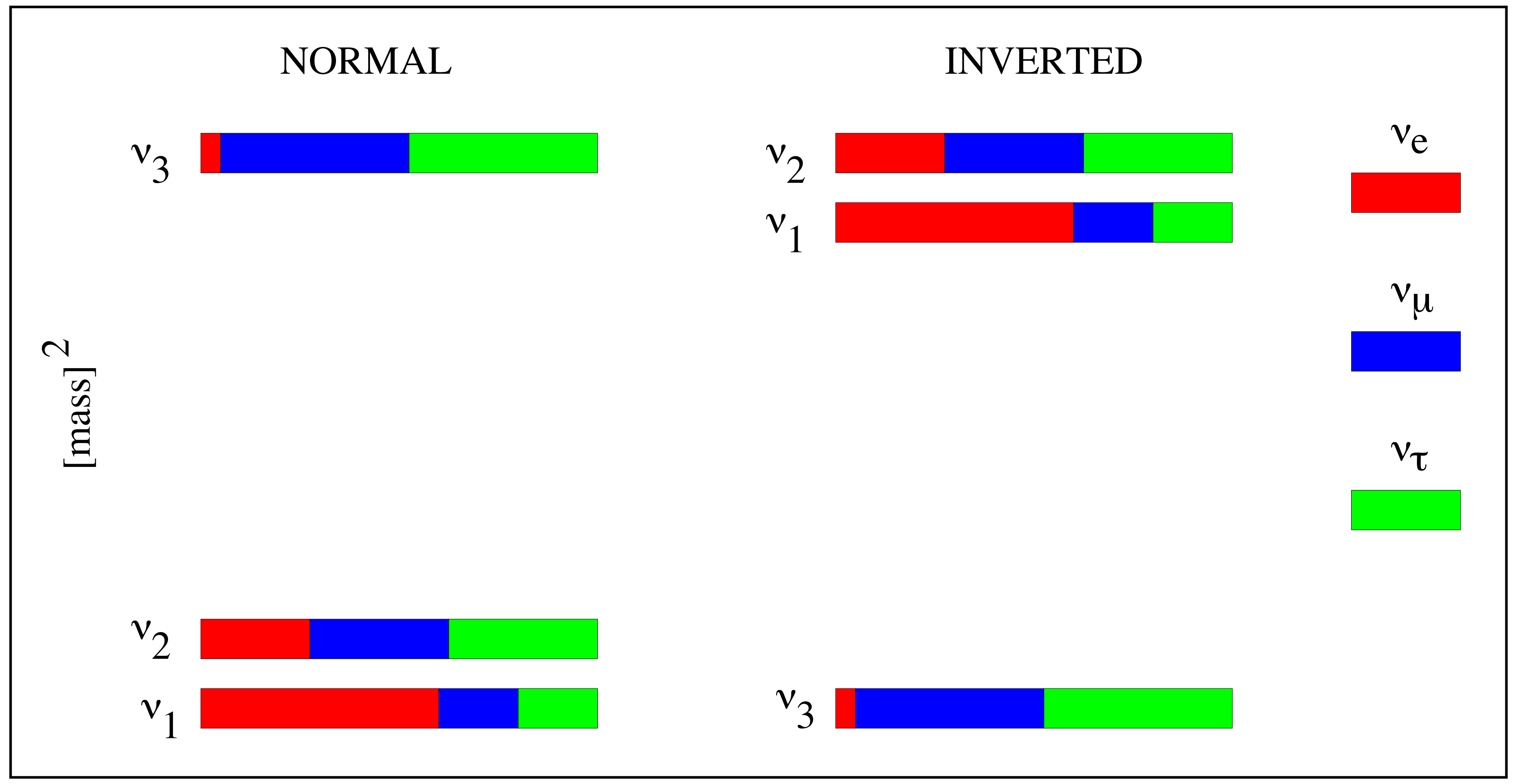
EuCAPT Astroneutrino Theory Workshop 2024

Prague, Czech Republic, Sept. 2024

Large neutrino mass in cosmology: sterile neutrinos as the rescue

Thomas Schwetz
Karlsruhe Institute of Technology, Institute for Astroparticle Physics

Neutrino masses



Neutrino oscillations:

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

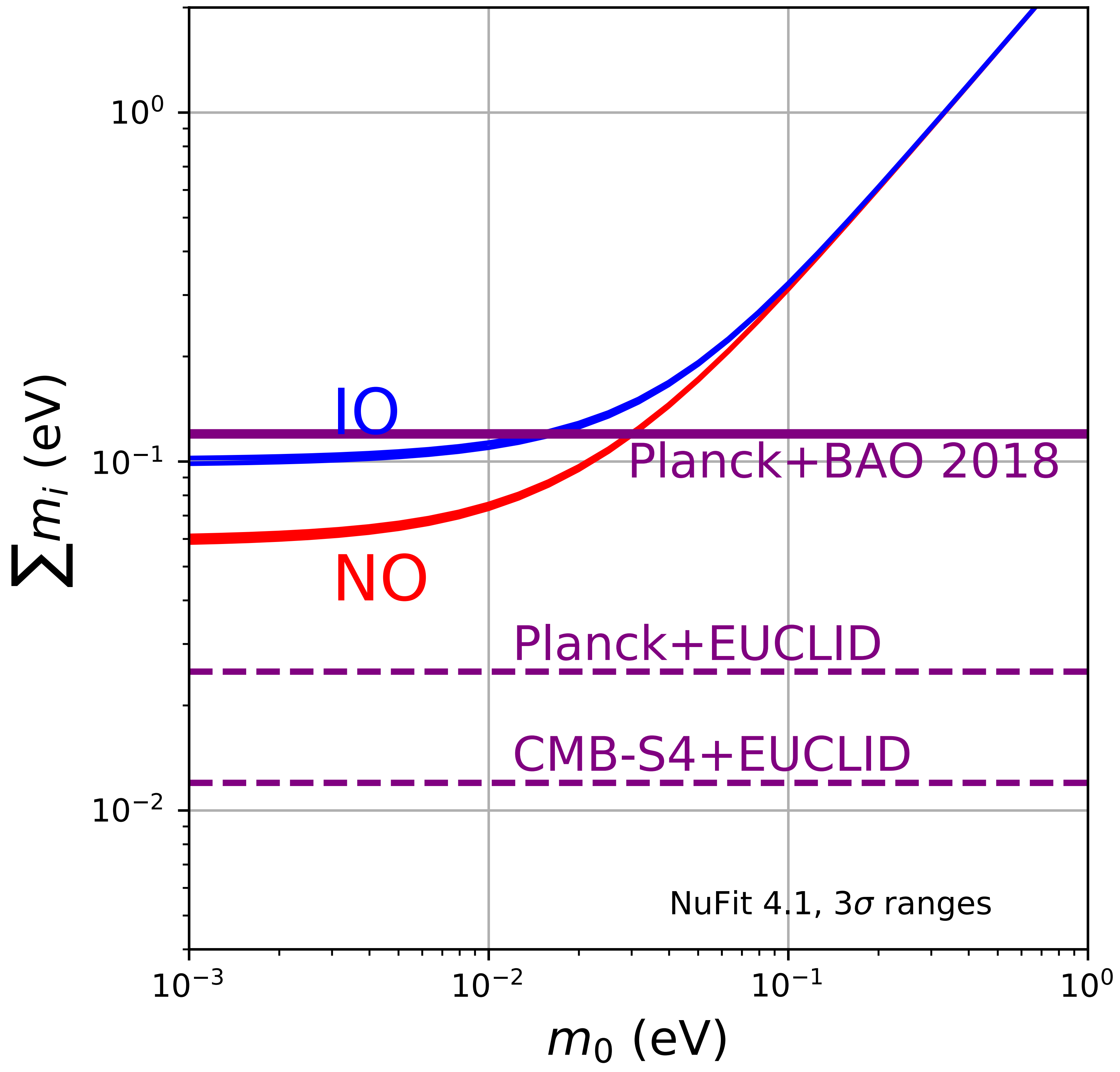
Absolute mass determinations:

- beta-decay spectrum(KATRIN) $\quad m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 0.45\,\mathrm{eV}$
- neutrinoless double-beta decay (assuming Majorana neutrinos) $\quad m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| \lesssim 0.07\,\mathrm{eV}$
- cosmology $\quad \sum_i m_i \lesssim 0.1\,\mathrm{eV}$

Neutrino mass from cosmology

s. talk by A. Bertólez-Martínez

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



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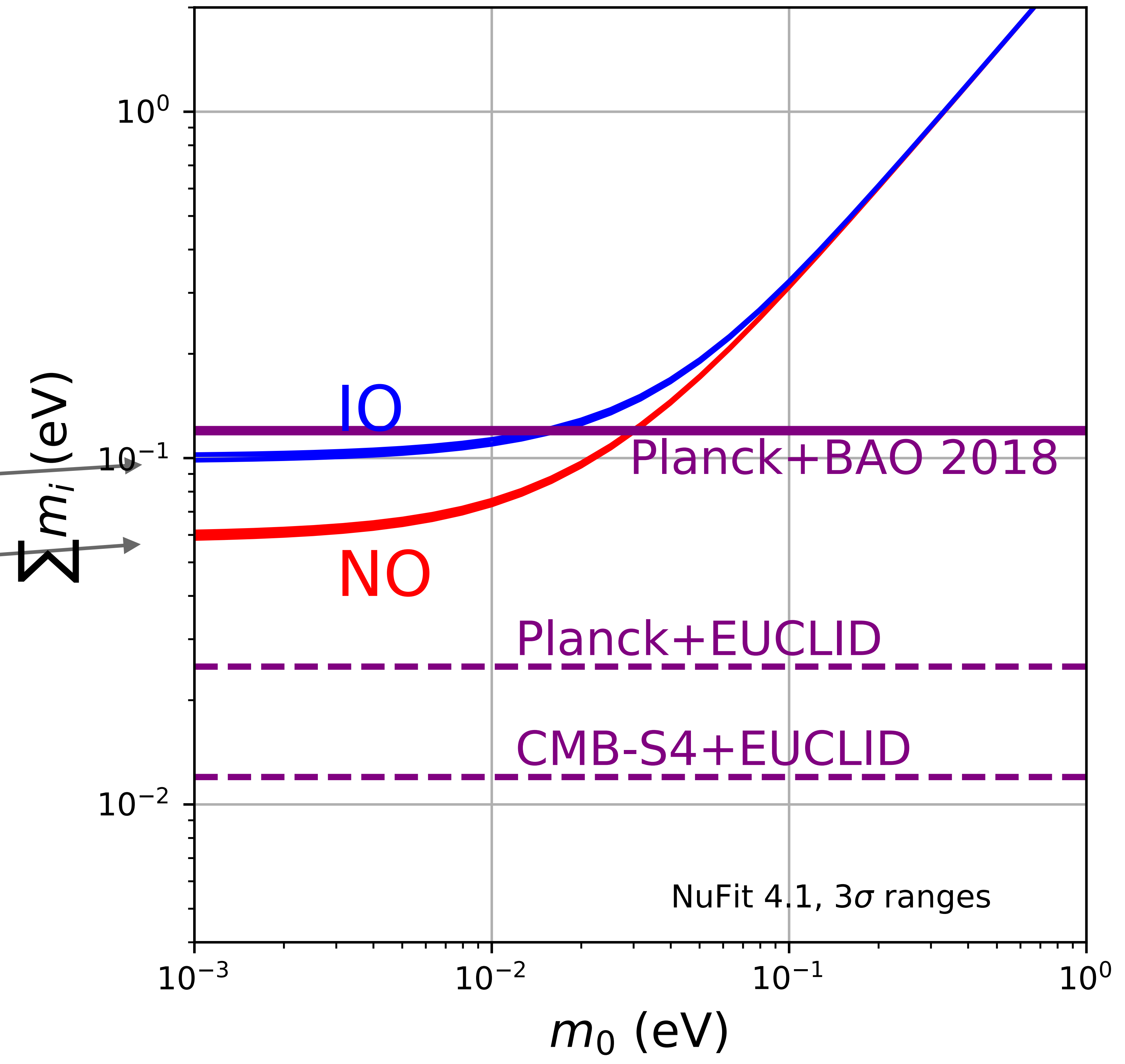
- minimal values predicted from oscillation data for $m_0 = 0$:

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



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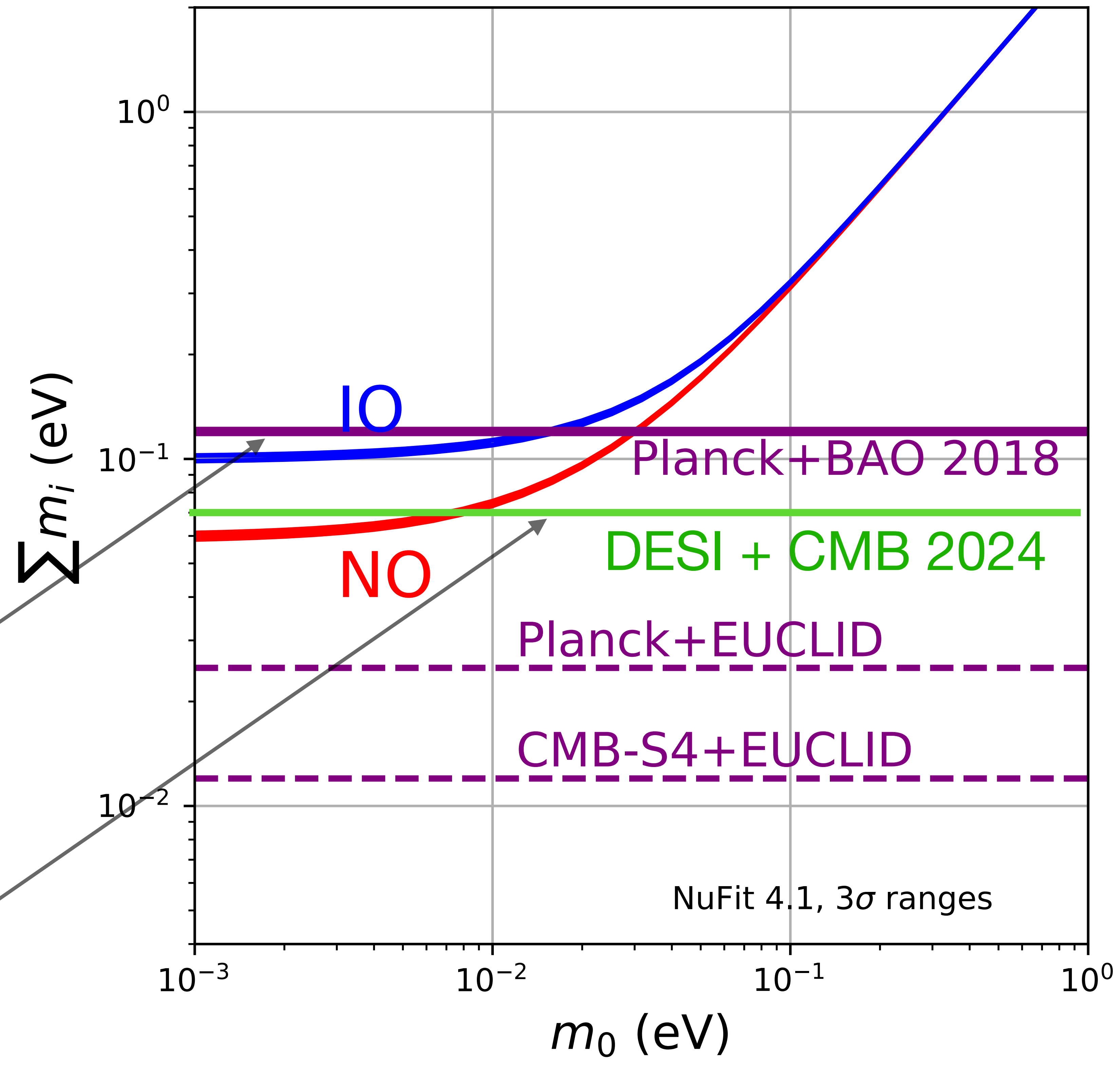
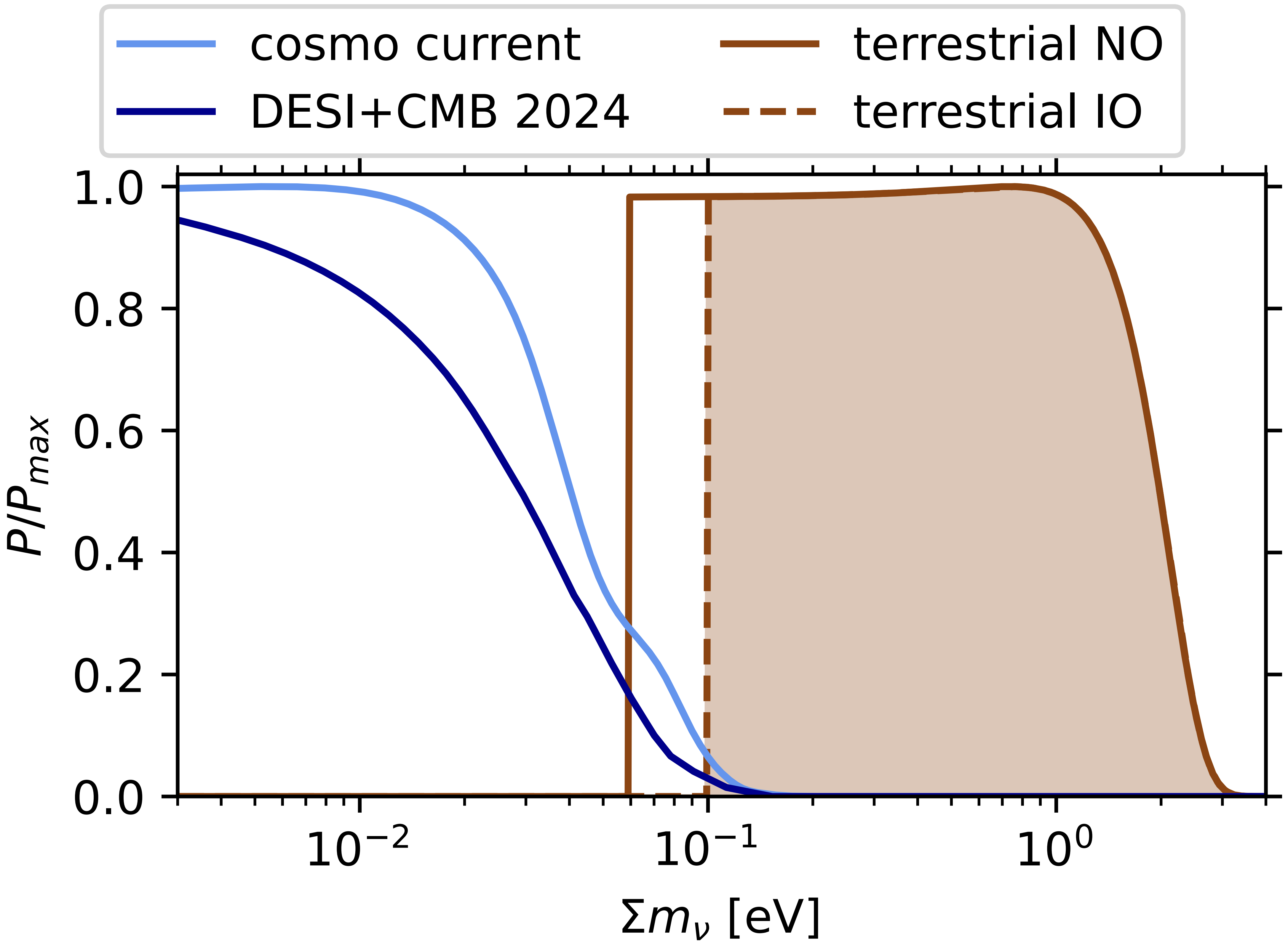


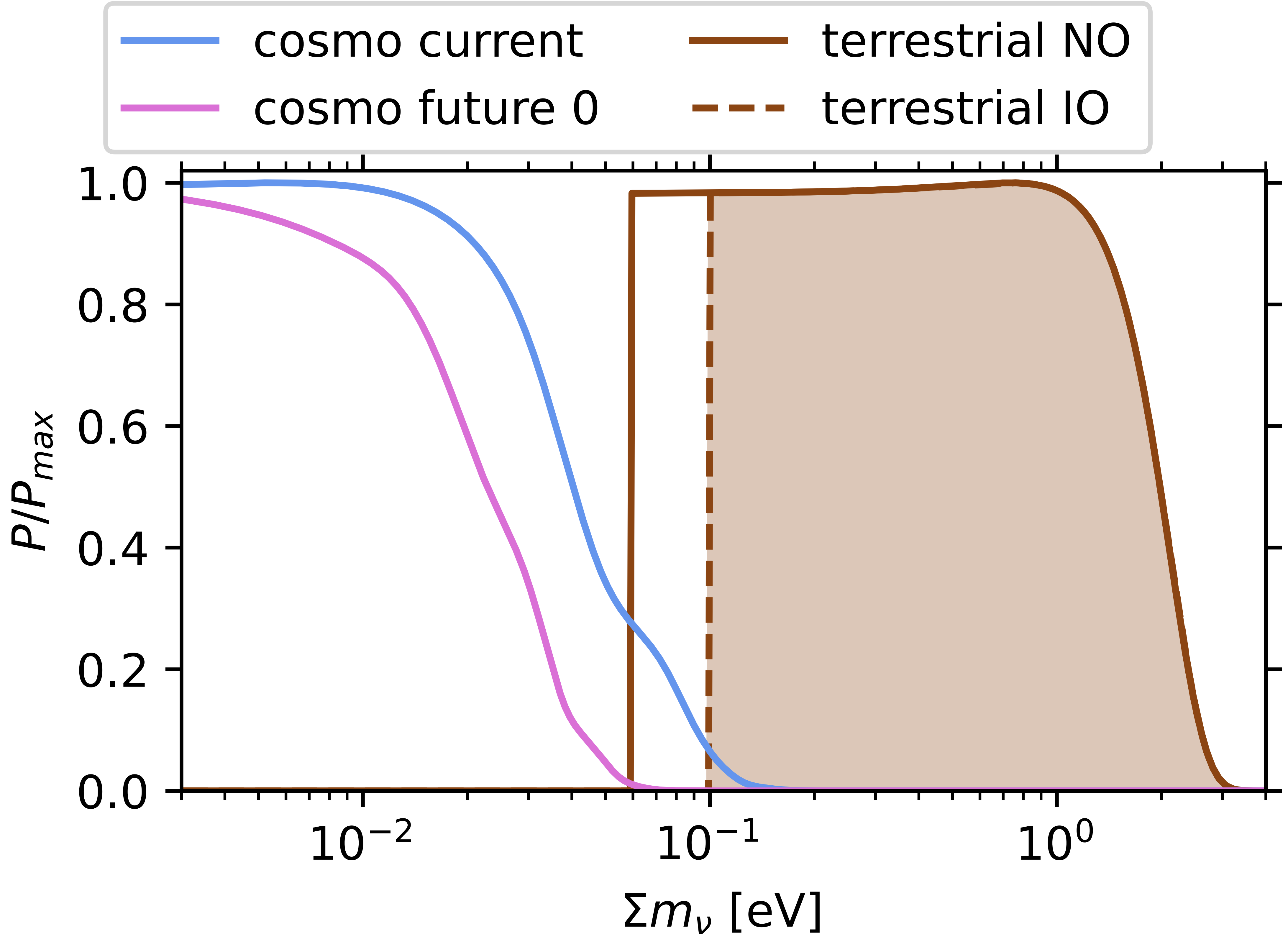
- **Upper bounds from current data:**
  - $\Sigma m_\nu < 0.12\,\text{eV}$ (95 % CL) Planck CMB+BAO 2018
  - $\Sigma m_\nu < 0.072\,\text{eV}$ (95 % CL) DESI + CMB 2024

Emerging tension between cosmology and terrestrial data

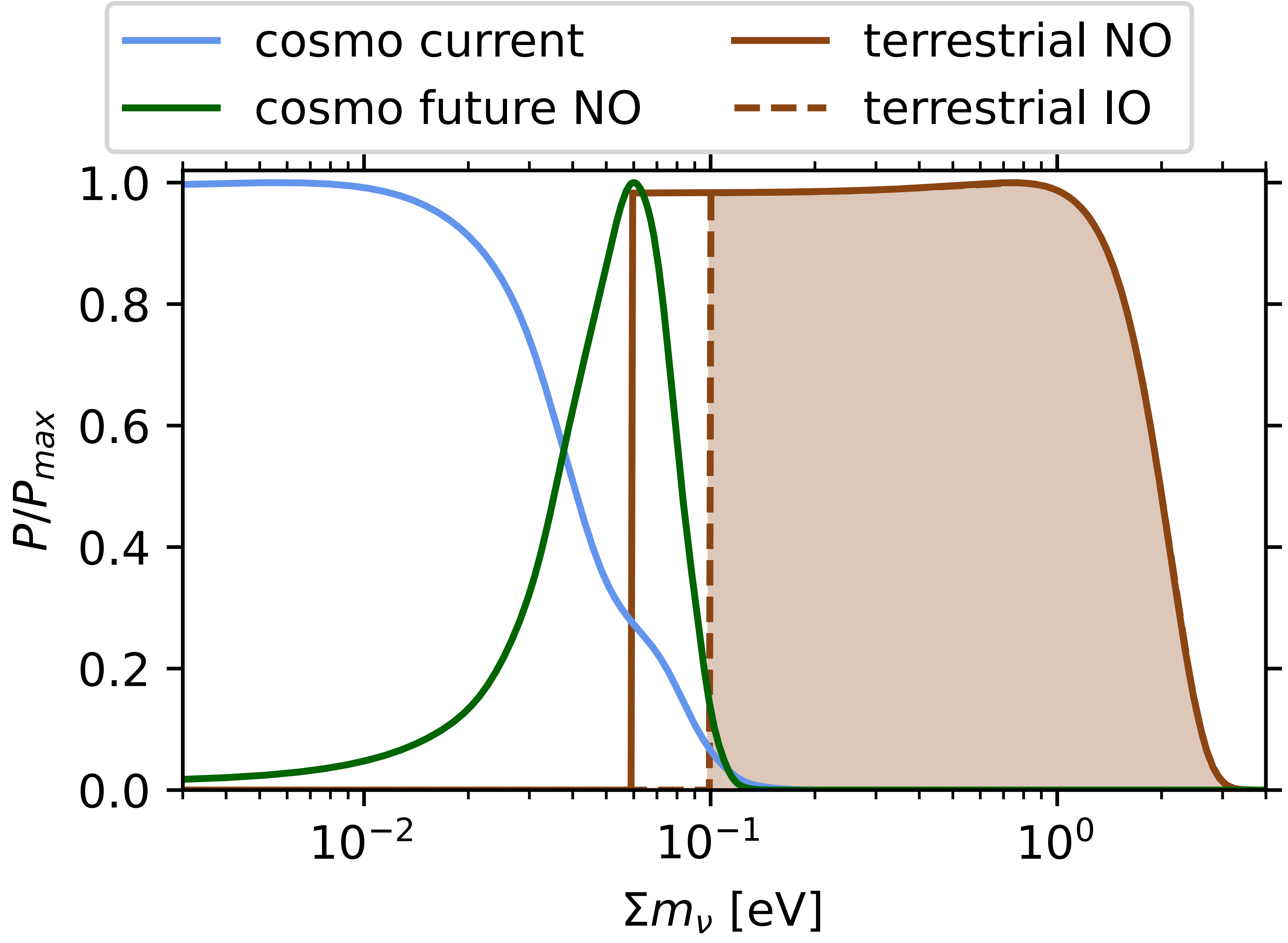


Gariazzo, Mena, Schwetz, 2302.14159

possible (near-term) future scenarios:



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



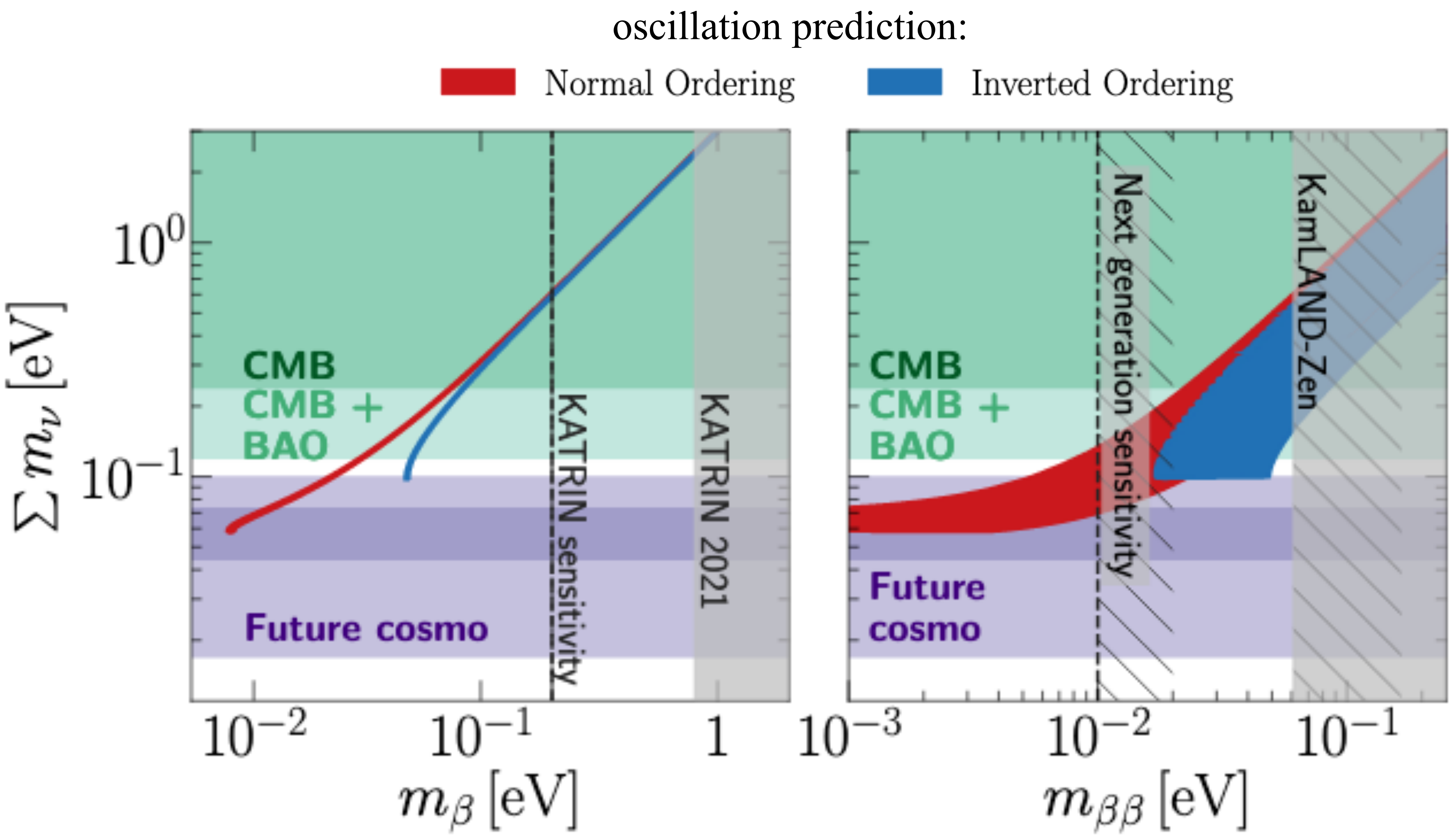
future NO: $\Sigma m_\nu = (0.06 \pm 0.02)\,\mathrm{eV}(1\sigma)$

Gariazzo, Mena, Schwetz, 2302.14159

Complementarity between mass determinations from heaven and earth

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

cosmology



beta decay

neutrinoless double beta decay

fig. by I. Esteban
based on NuFit 5.0

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- What if cosmology does not see finite neutrino mass and upper bounds become tighter than the minimal value predicted by neutrino oscillation?
- What if terrestrial experiments see a positive signal? How could this be consistent with cosmology?

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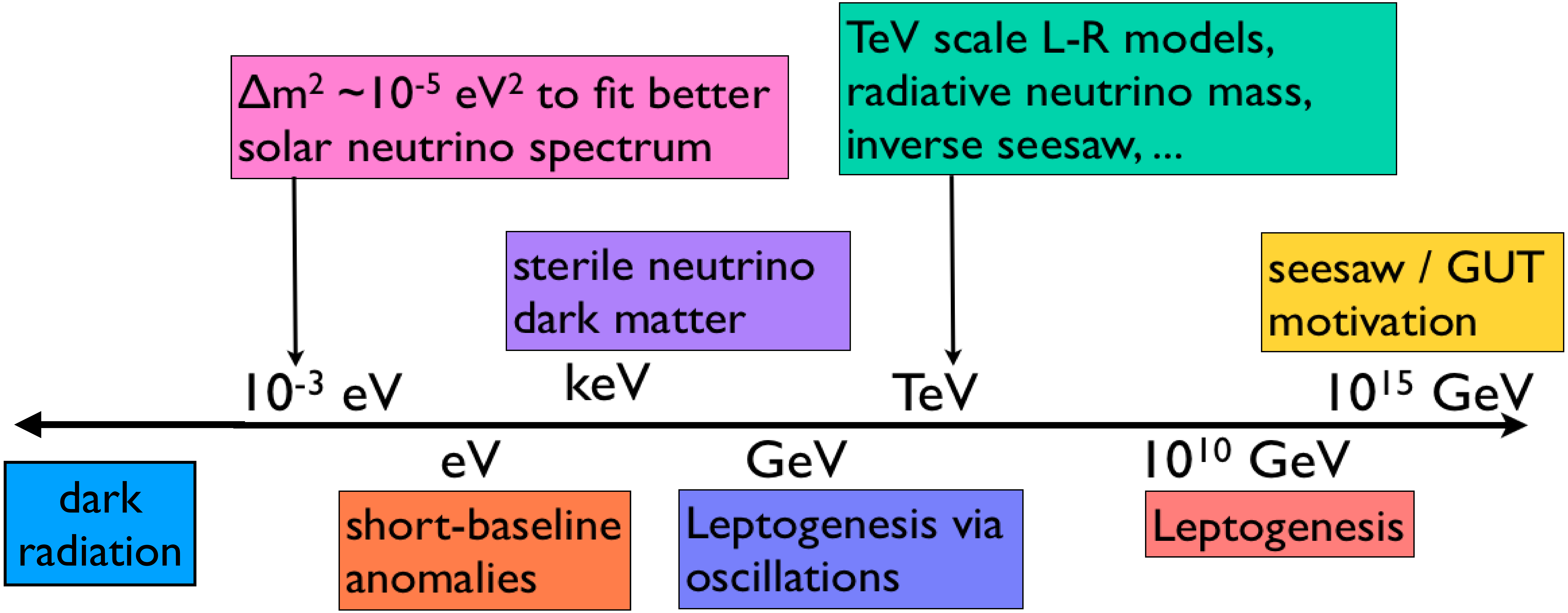
- What if terrestrial experiments see a positive signal? How could this be consistent with cosmology?

A seesaw model for „large“ neutrino mass consistent with cosmology, including sterile neutrino dark matter

work with
Miguel Escudero, Jorge Terol-Calvo, 2211.01729
Cristina Benso, Drona Vatsyayan, to appear

Sterile neutrino at which mass scale?



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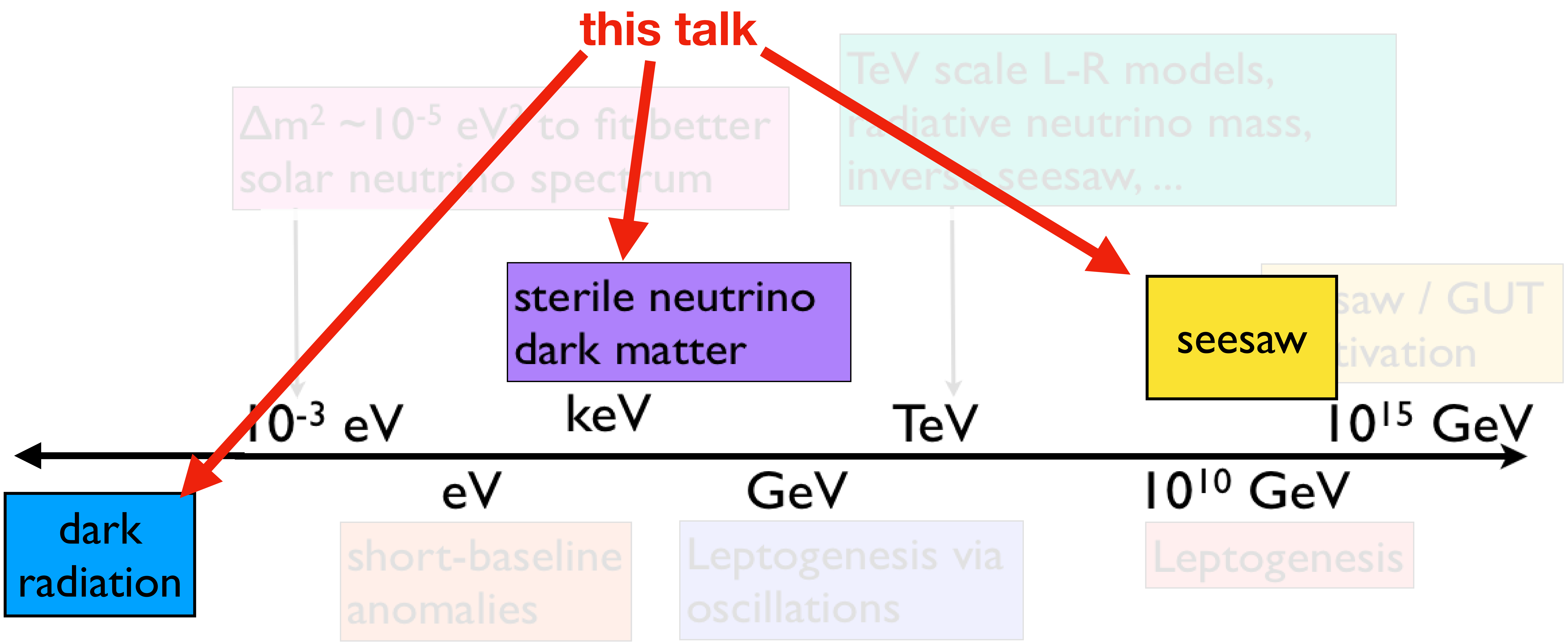

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Cosmology bounds can be relaxed in non-standard scenarios

incomplete!

- 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;
  Sen, Smirnov, 2407.02462, 2306.15718; talk by A. Smirnov

- 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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Counting the number of neutrino flavours

N_{eff} affects

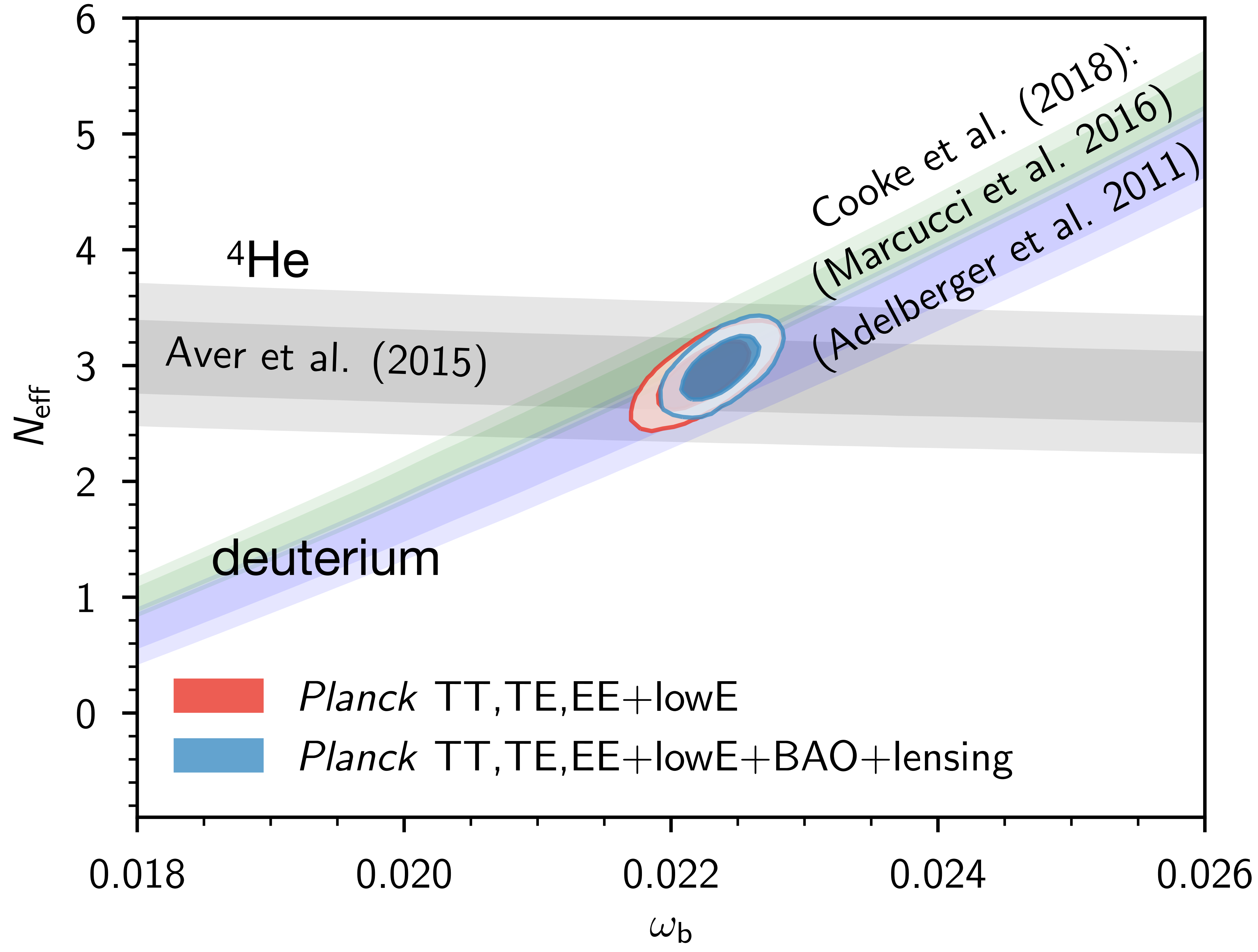
- formation of light elements (BBN), T ~ MeV, t ~ 1 min

$$N_{\text{eff}} = 2.78 \pm 0.28 \, (68\% \, \text{CL})$$

- CMB decoupling, T ~ eV, t ~ 400 000 yr

$$N_{\text{eff}} = 2.99 \pm 0.17 \, (68\% \, \text{CL})$$

Planck, 1807.06209



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)

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

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

relax bound on m_ν by reducing neutrino number density

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

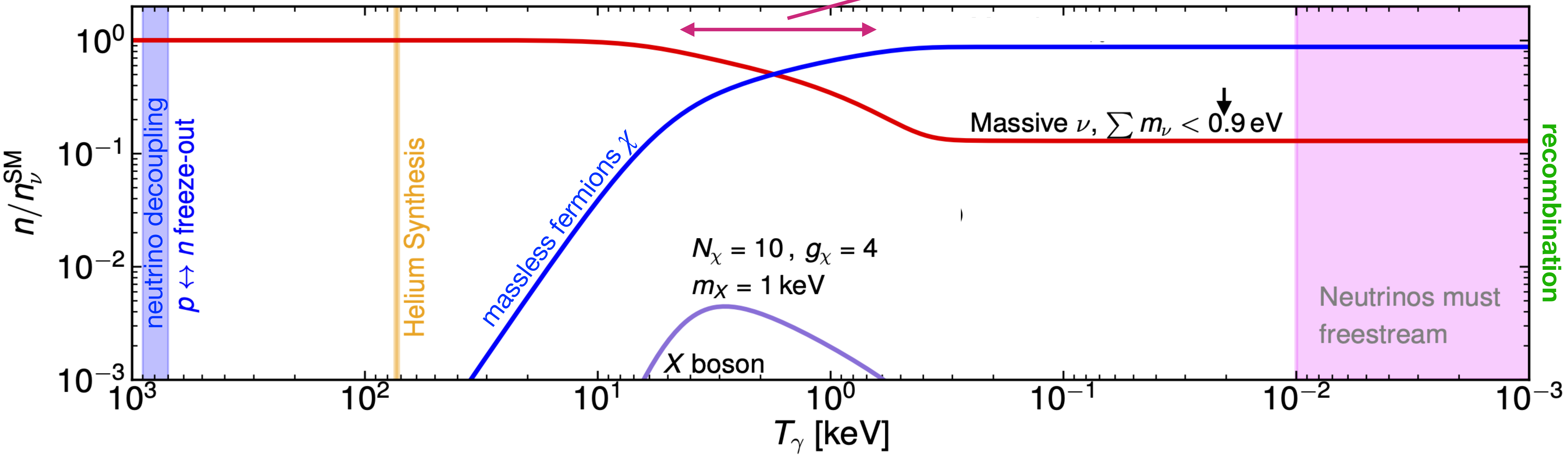
introduce „dark radiation“ to keep $N_{\text{eff}}^{\text{relat.}} \approx 3$

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

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

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

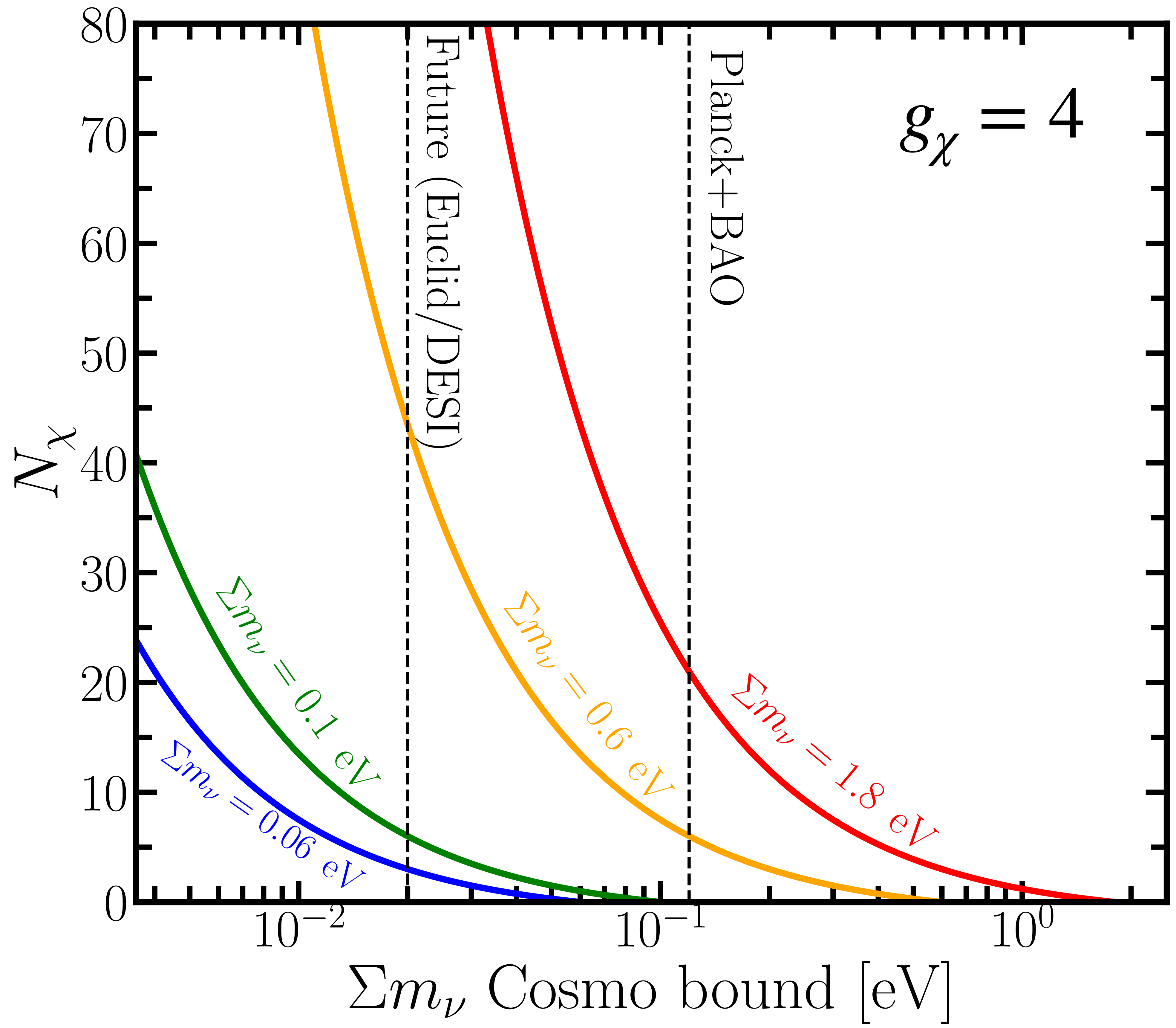


Relaxed bound from cosmology

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:

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



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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Yukawa sector

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

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Scalar potential

$$V = \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 + \mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \lambda_{H\Phi} |\Phi|^2 H^\dagger H$$

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Gauge interaction

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

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

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

$$\Lambda \ll m_D \ll M_R$$

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

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

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

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

A seesaw model for large neutrino mass and dark radiation

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

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

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

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

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

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

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

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

indep. params for pheno:

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

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

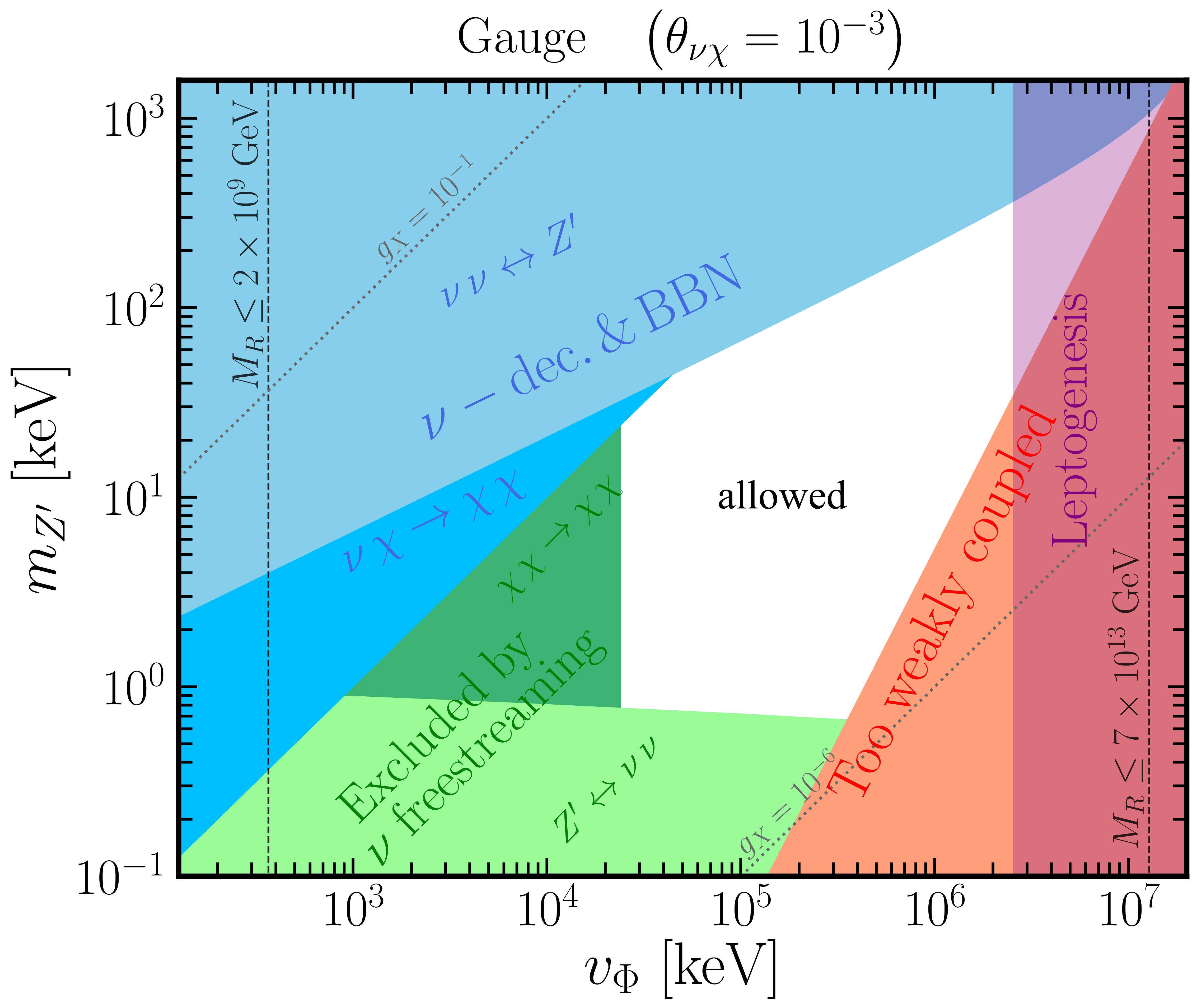
Available parameter space

$$\theta_{\nu\chi} \simeq 10^{-3}$$

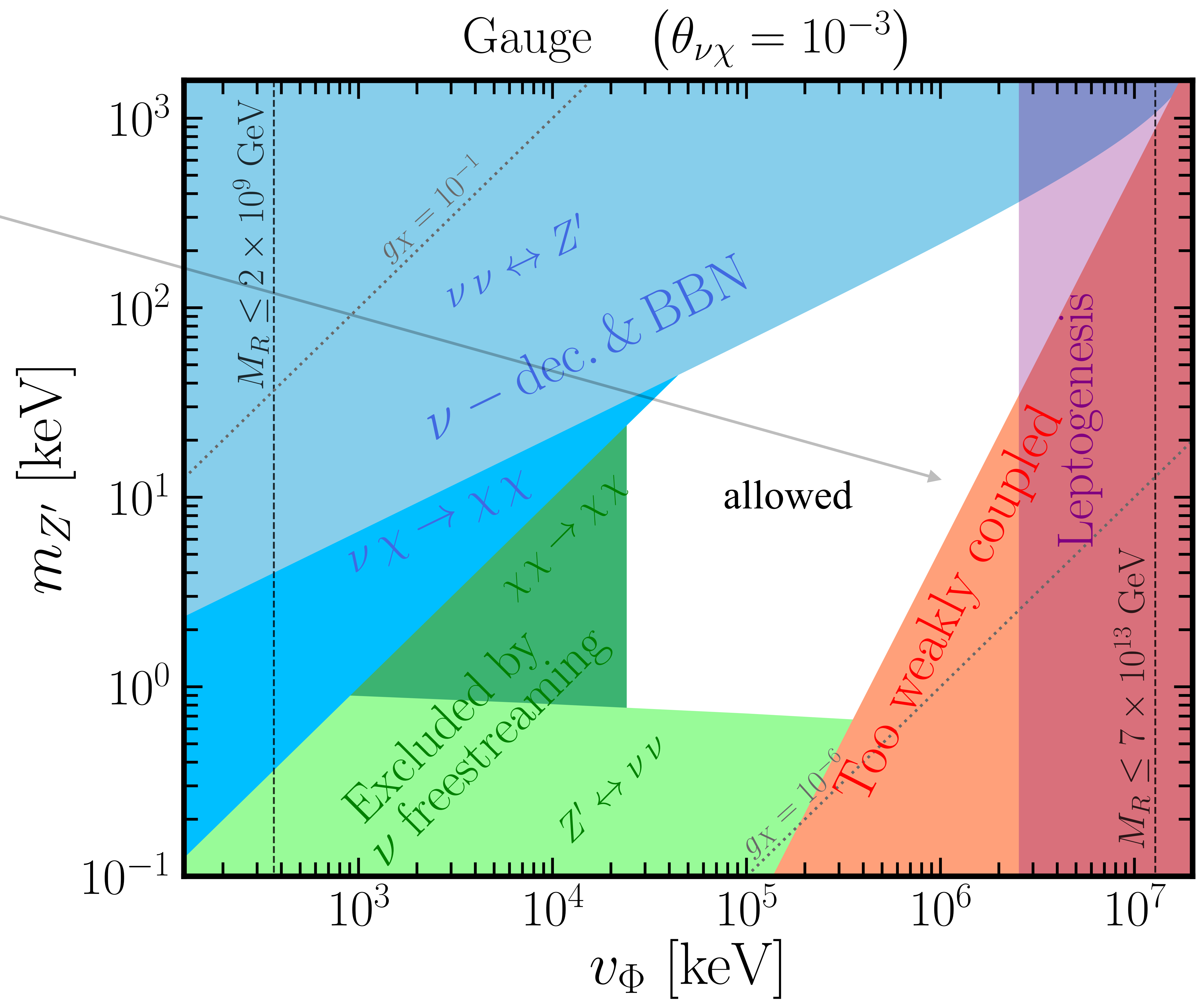
$$m_{Z'} \sim 10\,\text{keV}$$

$$v_\Phi \sim 100\,\text{MeV}$$

$$g_X = \frac{m_{Z'}}{v_\Phi} \sim 10^{-4}$$



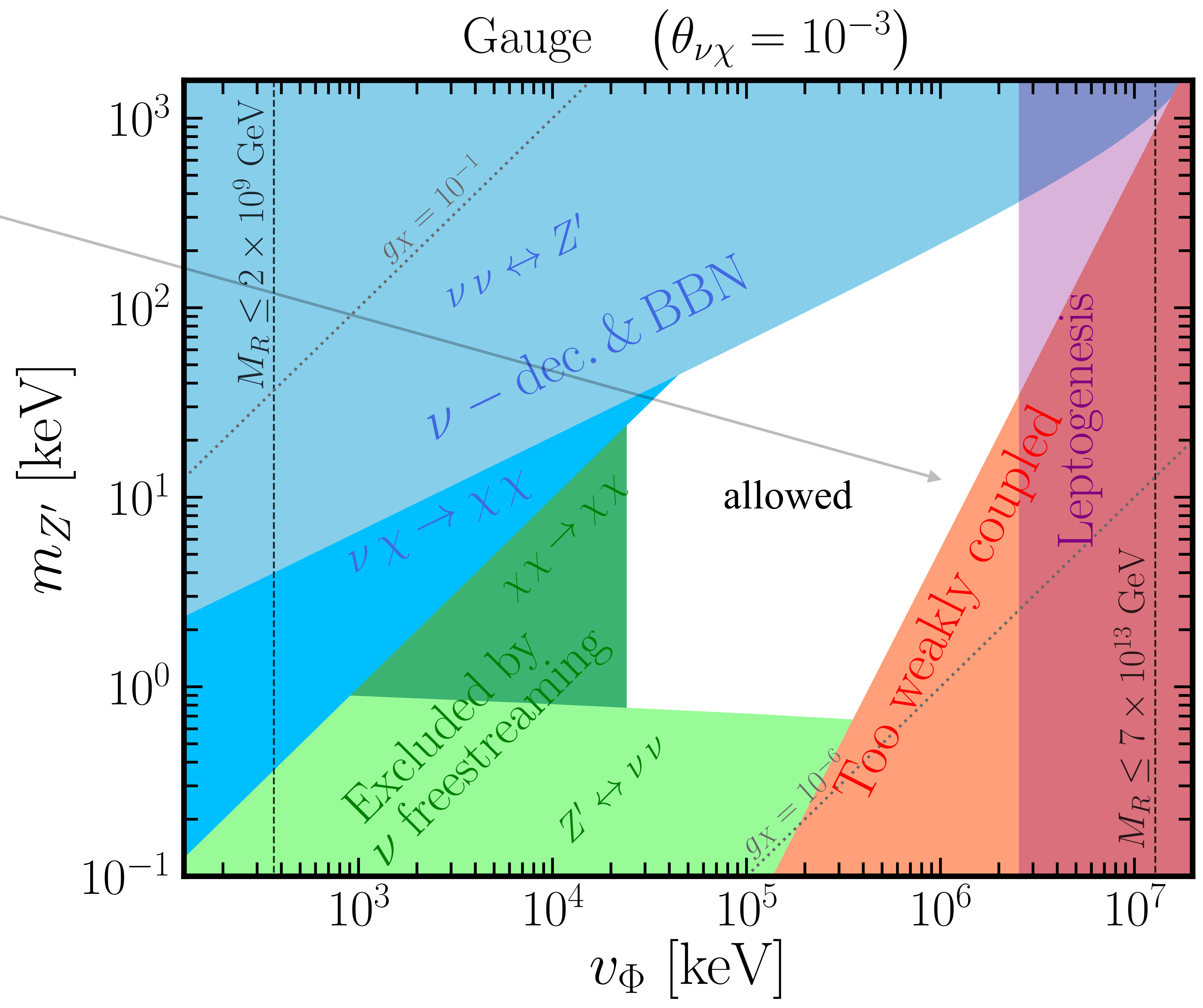
Available parameter space



Available parameter space

- thermalization of the dark sector:

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



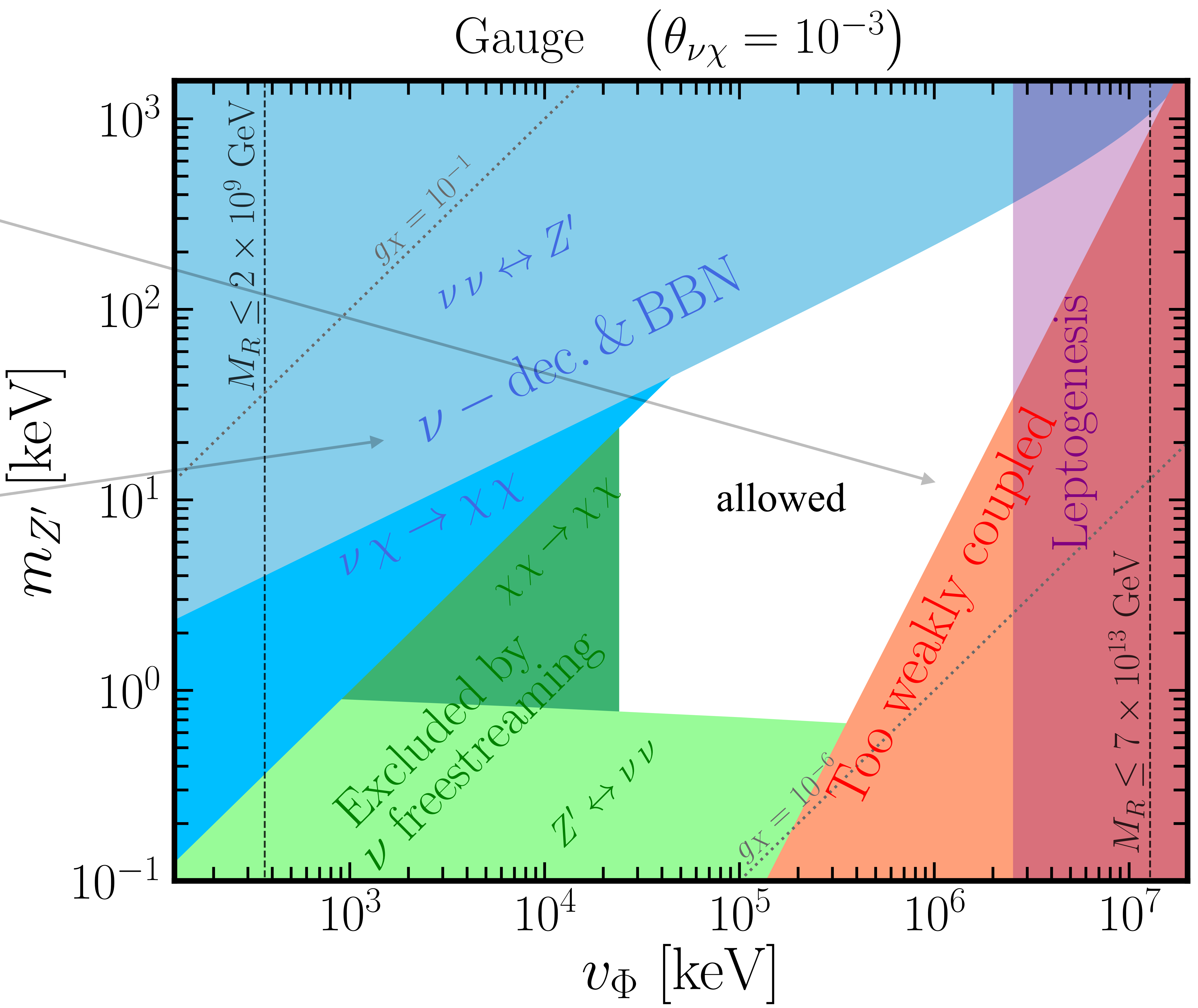
Available parameter space

- thermalization of the dark sector:

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

- avoid thermalization of the dark sector before BBN:

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



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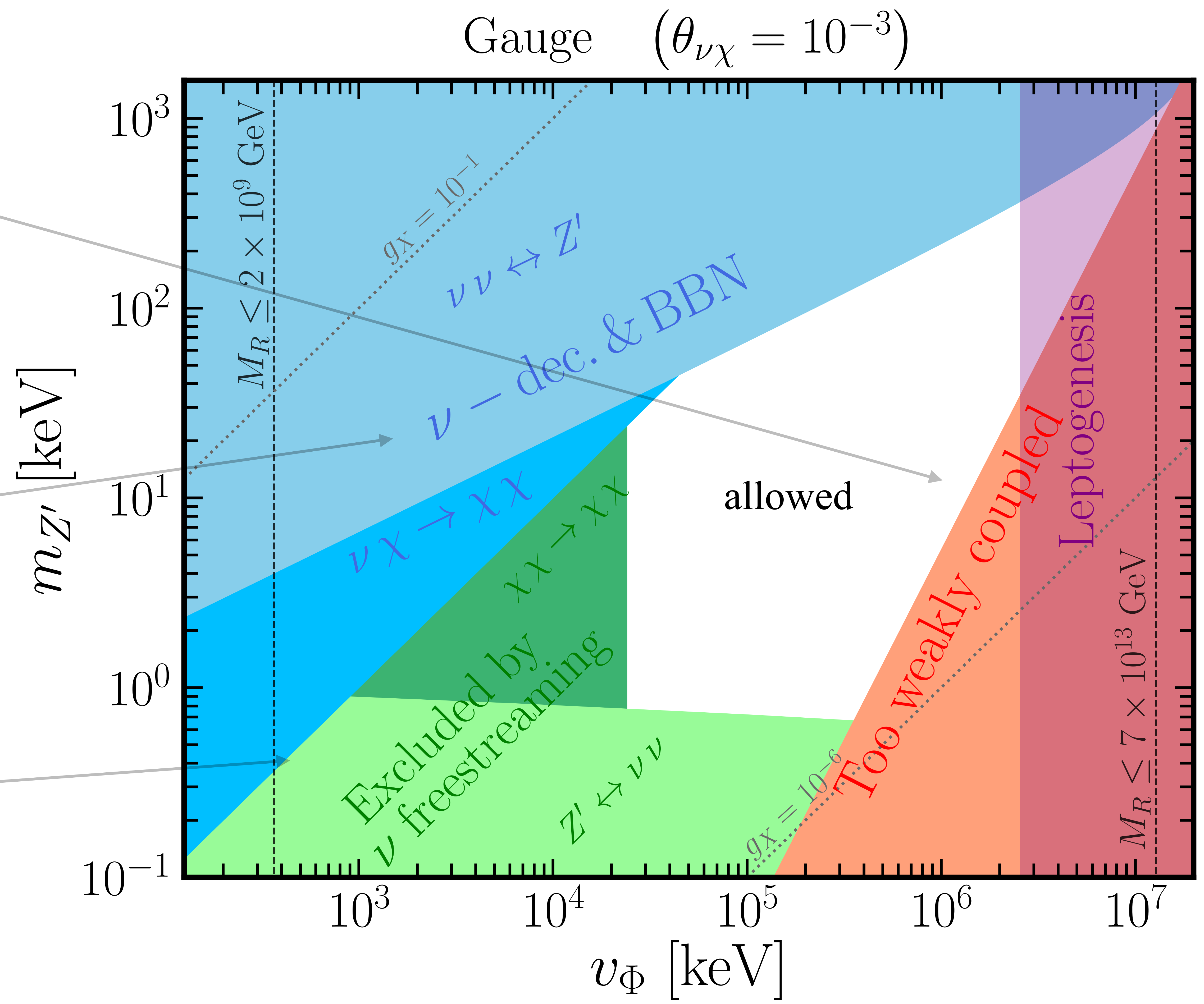
- free-streaming of neutrinos & dark radiation before/around recombination

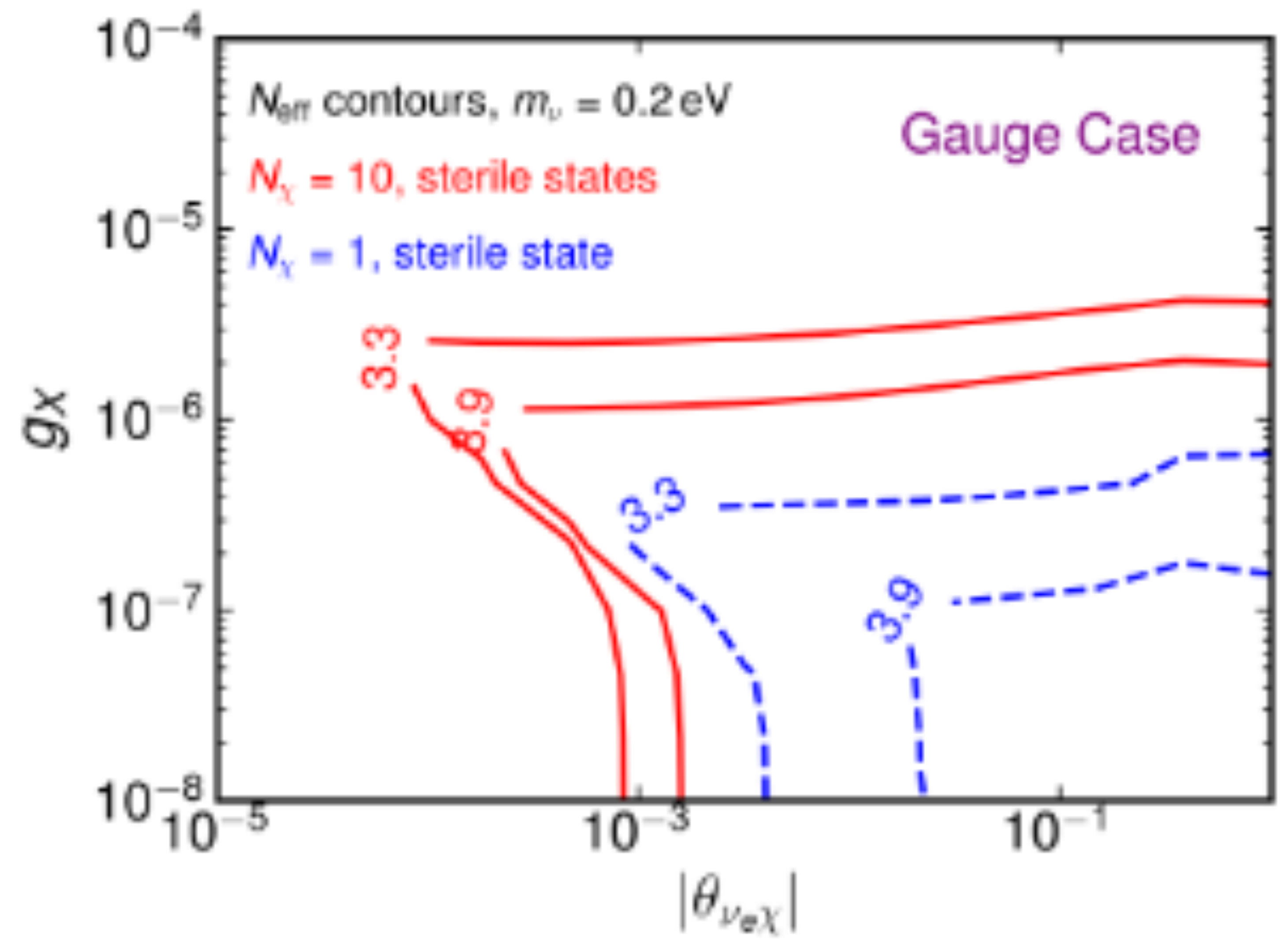
  $$\langle \Gamma \rangle < H \text{ for } z < 10^5$$

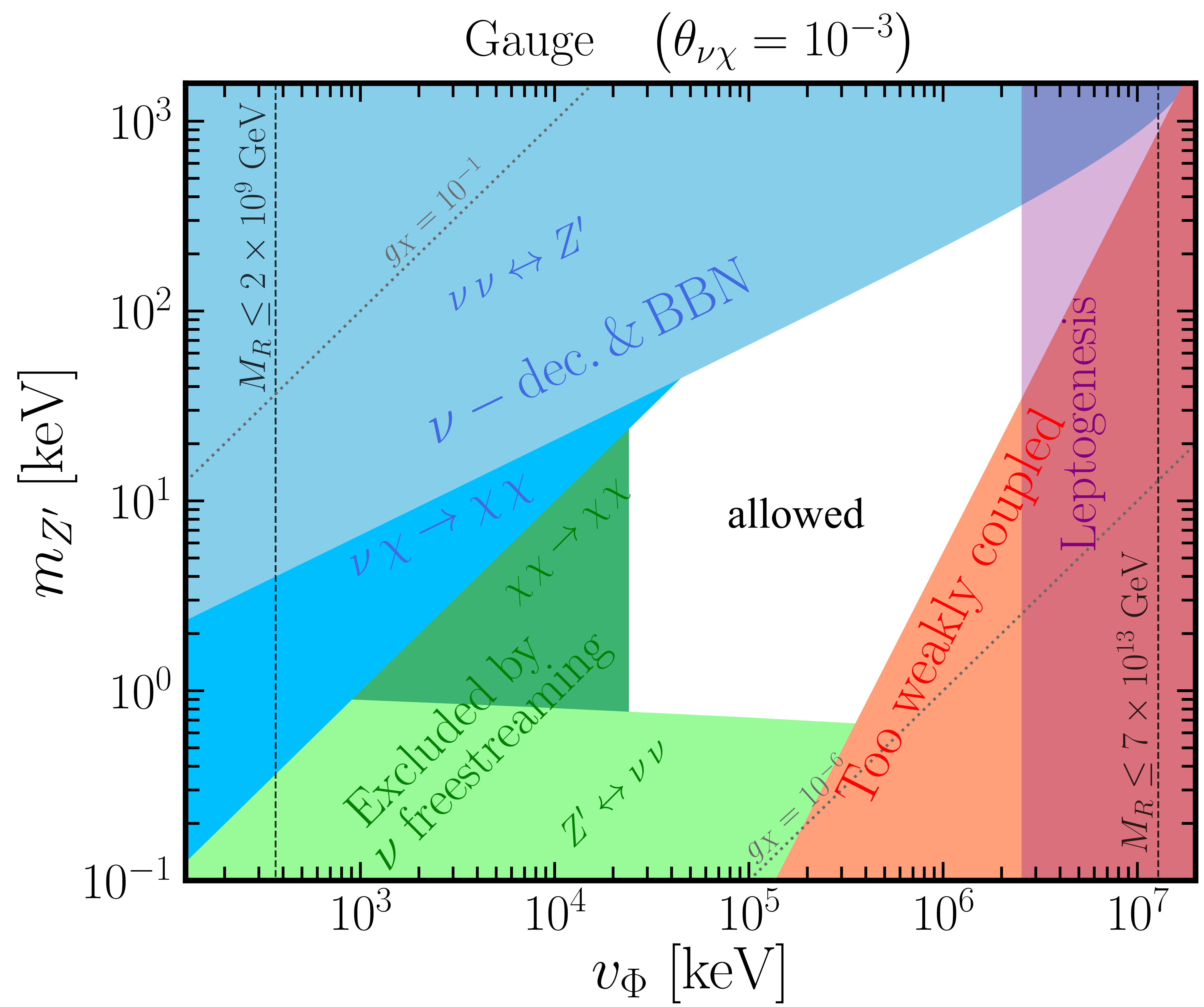
  Taule, Escudero, Garny, 2207.04062



Neutrino mixing with massless states $\theta_{\nu\chi}$

- avoid thermalization of χ prior neutrino decoupling due to oscillations
- take into account effective potential due to self-interactions





Neutrino mixing with massless states $\theta_{\nu\chi}$

$$10^{-4} \lesssim \theta_{\nu\chi} \lesssim 10^{-1}$$

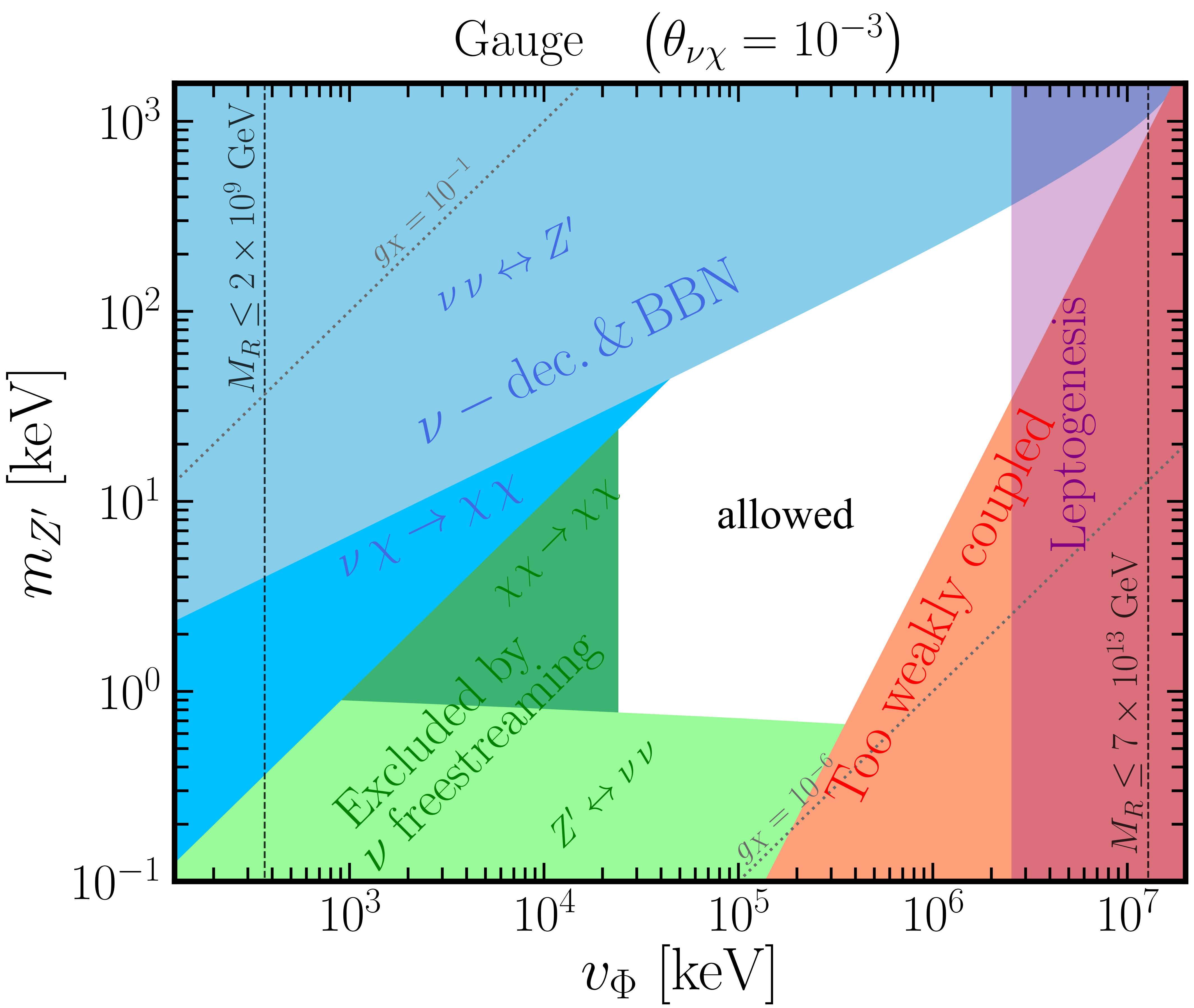
upper range potentially testable in oscillation experiments

work in progress [Escudero, Maltoni, Ota, TS]

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 to avoid thermalization of Φ prior BBN



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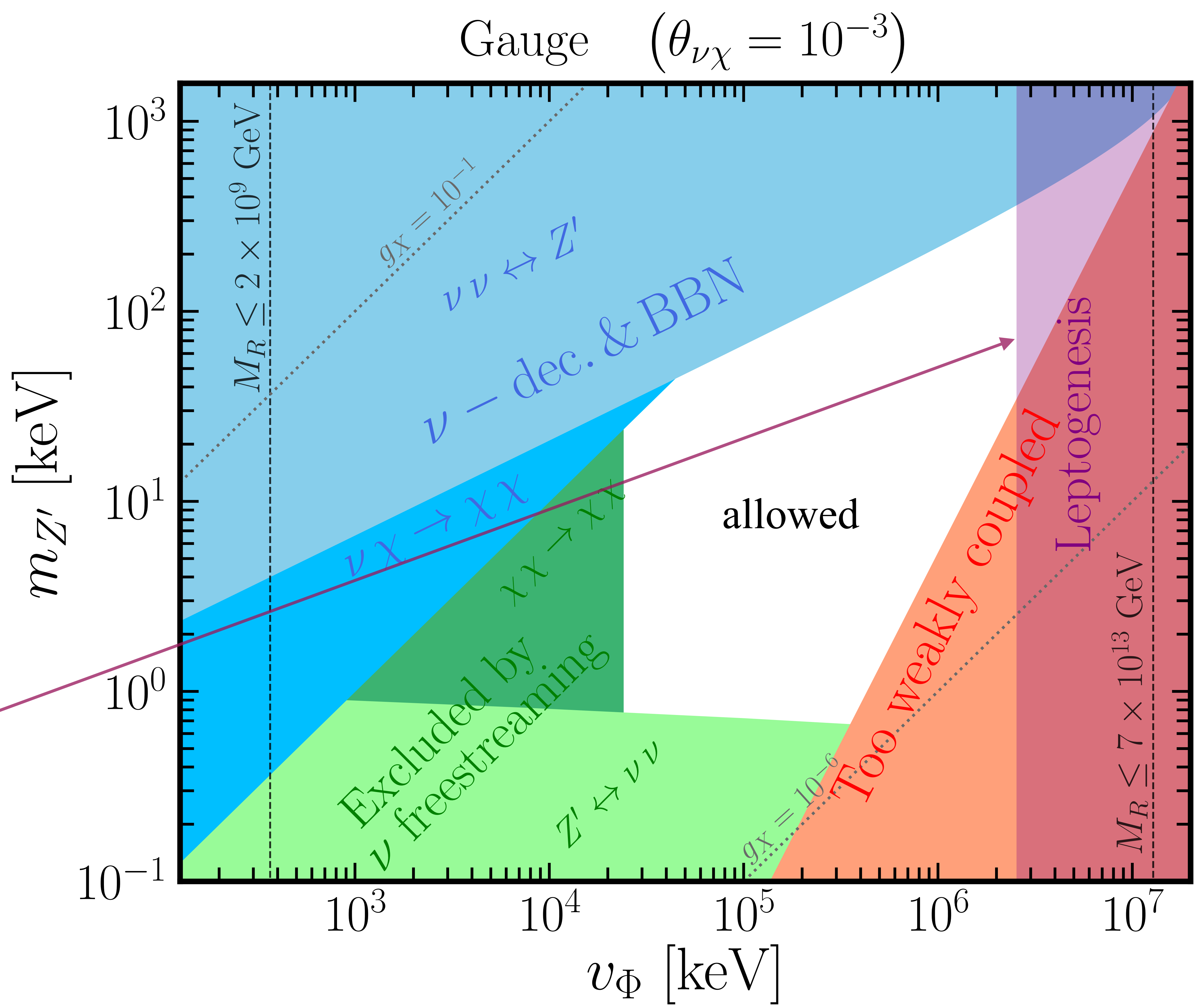
Comment on leptogenesis:

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



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Signatures in a super nova

- SN cooling arguments for SN1987A exclude

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

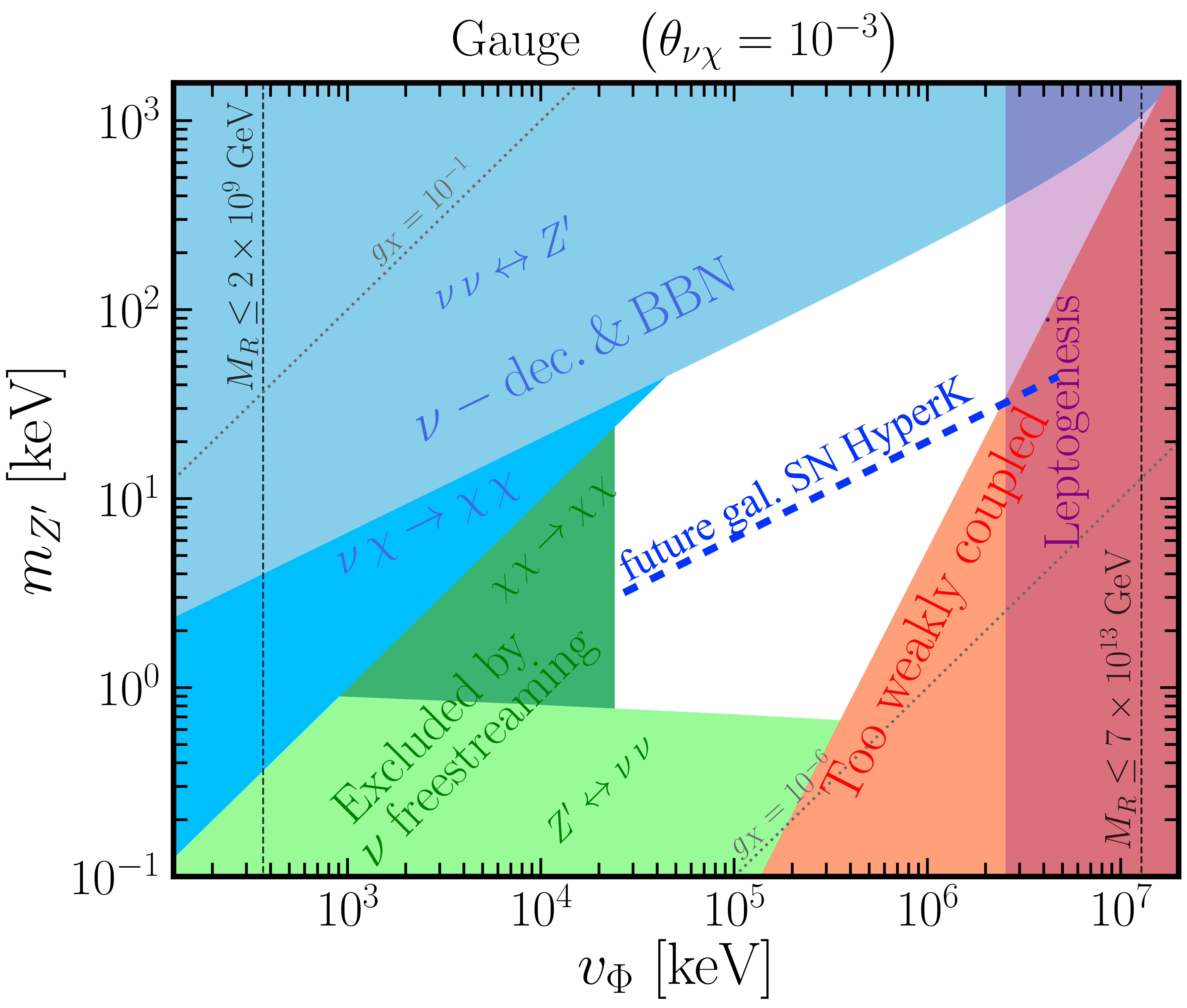
Fiorillo, Raffelt, Vitagliano, 2209.11773

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

- Future galactic SN at 10 kpc: neutrino signal in HyperK from $Z' \to \nu\nu$: sensitivity down to

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

Akita, Im, Masud, 2206.06852



Extending the model to include keV sterile neutrino dark matter

C. Benso, TS, D. Vatsyayan, to appear

Original model: [Escudero, TS, Terol-Calvo]

- 3 heavy right-handed neutrinos (seesaw) *N*
- new abelian symmetry $U(1)_X$ local or global
- a scalar Φ charged under $U(1)_X$
- a set of N_χ massless fermions χ charged under $U(1)_X$

- add one more heavy RH neutrino *N'*

  $\Rightarrow$one of the χ will also pick up a seesaw induced mass $\rightarrow \psi$

Extending the model to include keV sterile neutrino dark matter

C. Benso, TS, D. Vatsyayan, to appear

neutral fermion mass matrix
in the basis $(\chi_L^c, \nu_L^c, \psi_L^c, N', N)$

$$\mathcal{M}_n = \begin{pmatrix} 0 & 0 & 0 & \Lambda' & \Lambda \\ 0 & 0 & 0 & {m_D}' & m_D \\ 0 & 0 & 0 & \kappa' & \kappa \\ {\Lambda'}^T & {m_D^T}' & {\kappa'}^T & M' & 0 \\ \Lambda^T & m_D^T & \kappa^T & 0 & M \end{pmatrix}$$

assume hierarchies:

$$M \gg M' \gg m_D \gg \kappa' \gg \Lambda \gg m_D', \kappa, \Lambda' .$$

$$M' m_D^2 \ll M {\kappa'}^2$$

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$$m_\nu \approx m_D M^{-1} m_D^T$$
$$m_\psi \approx \kappa' M'^{-1} \kappa'^T .$$
$$m_{N'} \approx M'$$
$$m_N \approx M .$$

Extending the model to include keV sterile neutrino dark matter

C. Benso, TS, D. Vatsyayan, to appear

neutral fermion mass matrix
in the basis $(\chi_L^c, \nu_L^c, \psi_L^c, N', N)$

$$\mathcal{M}_n = \begin{pmatrix} 0 & 0 & 0 & \Lambda' & \Lambda \\ 0 & 0 & 0 & {m_D}' & m_D \\ 0 & 0 & 0 & \kappa' & \kappa \\ \Lambda'^T & m_D^{T\,\prime} & \kappa'^T & M' & 0 \\ \Lambda^T & m_D^T & \kappa^T & 0 & M \end{pmatrix}$$

assume hierarchies:

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keV DM candidate

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keV DM candidate

mixing and interactions:

$$\theta_{\nu\psi} = \frac{m_D'}{\kappa'}, \quad \theta_{\chi\psi} = 0$$

$$\mathscr{L}_{\text{int}} = g_X Z'_\mu \overline{\psi} \gamma^\mu \psi$$

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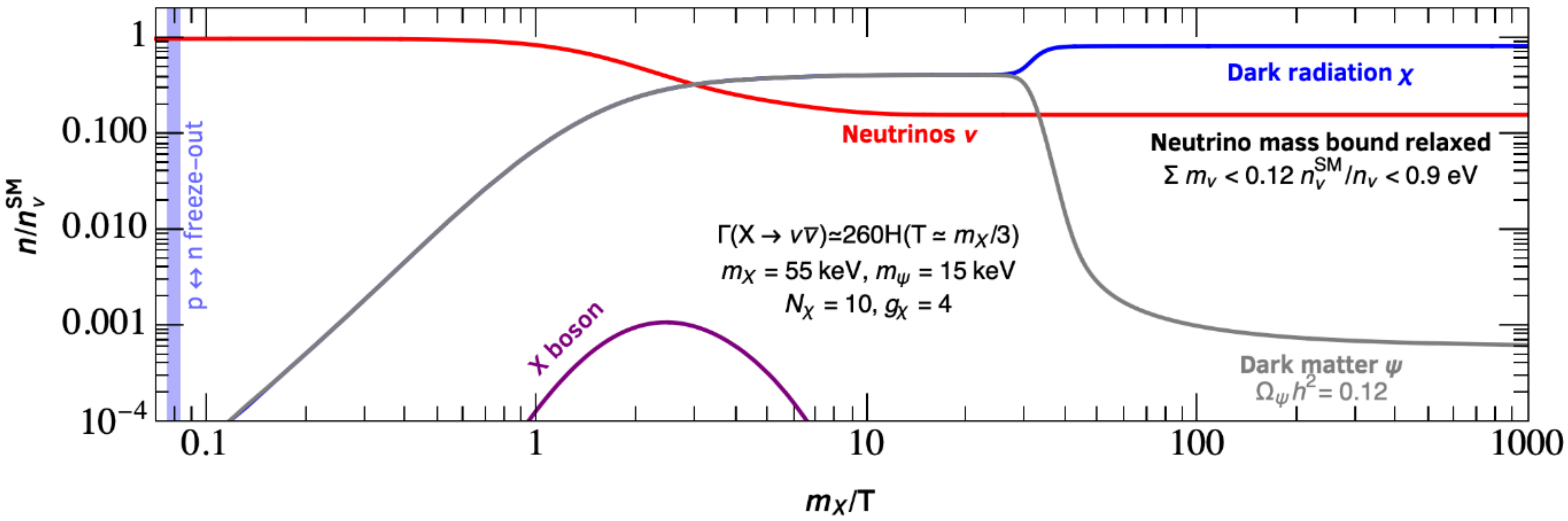
DM production via dark freeze-out



- assume $m_\psi < m_{Z'}$
- ψ thermalizes with the dark fluid via $\psi\psi \leftrightarrow Z'$
- DM freeze-out for $T_{DS} \lesssim m_\psi$

$$\Omega_\psi h^2 \simeq x_f \frac{10^{-10}\,\mathrm{GeV}^{-2}}{\langle\sigma v\rangle_{\psi\psi\to\chi\chi}}$$

$$\langle\sigma v\rangle_{\psi\psi\to\chi\chi} = N_\chi \frac{g^4}{4\pi} \frac{m_\psi^2}{(m_{Z'}^2 - 4m_\psi^2)^2}$$

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Right DM abundance in the relevant parameter region

- DM mass
  $15\,\mathrm{keV} \lesssim m_\psi \lesssim 100\,\mathrm{keV}$

- DM stability and X-ray constraints:
  $\psi \to \nu\chi\chi, \psi \to \nu\gamma$
  suppressed by $\theta^2_{\nu\psi}$
  require $\theta_{\nu\psi} \lesssim 10^{-8}$

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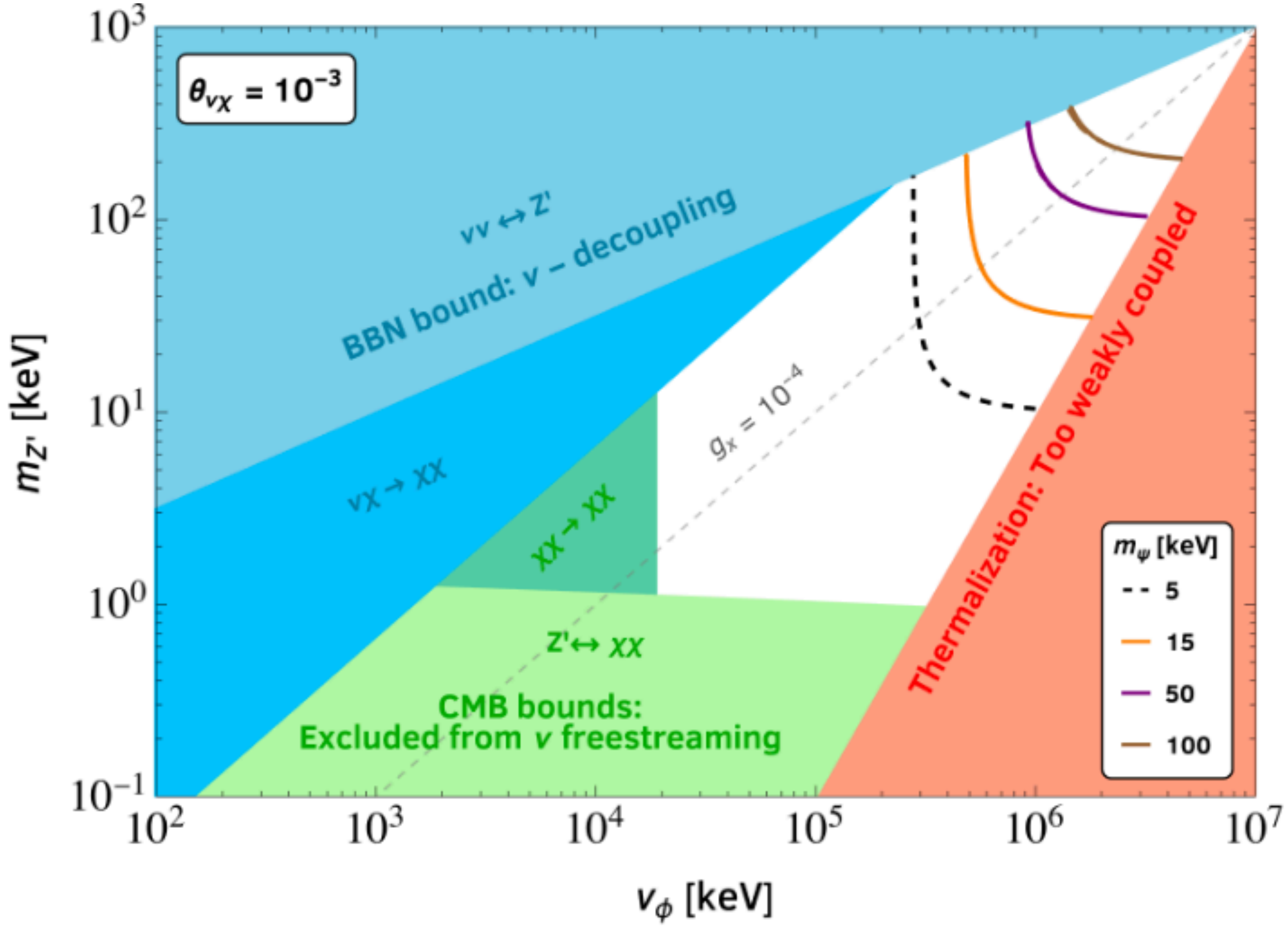

Summary & Outlook

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- 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 $\lambda_{Z'}^{\nu\nu} \sim 10^{-9}$
- keV sterile neutrino DM naturally integrated in the model [w C. Benso, D. Vatsyayan, to appear] production due to DS interactions, mixing w active neutrinos can be very small
- possible signatures:
  - galactic SN observations
  - sterile neutrino searches at oscillation experiments [work in progress w M. Escudero, T. Ota, M. Maltoni]

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Thank you for your attention!

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