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Large neutrino mass in cosmology and keV sterile neutrino dark matter from a dark sector

Seminar talk BNL
17 July 2025

Karlsruher Institut für Technologie

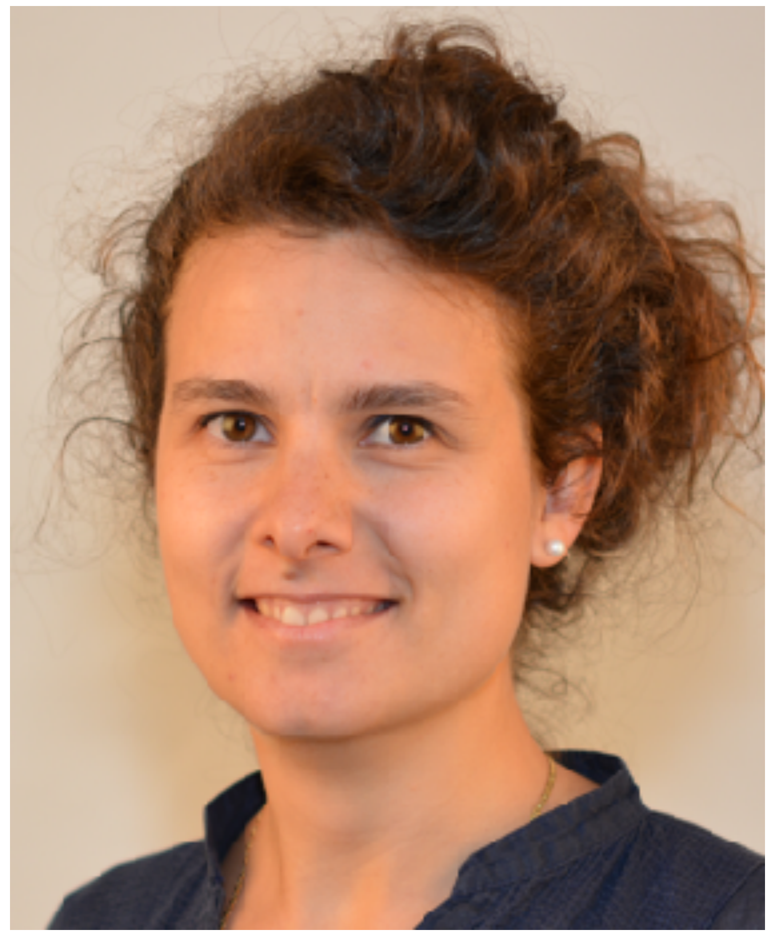
Outline

- Introduction
  - Status of neutrino mass determination
  - Neutrino mass from cosmology — the ``neutrino tension´´
- How to relax the cosmological neutrino mass bound
- Seesaw model for neutrino mass, dark radiation, keV sterile neutrino DM

Based on

M. Escudero, T. Schwetz, J. Terol-Calvo
[arXiv:2211.01729] JHEP **02** (2023) 142
A seesaw model for large neutrino masses in concordance with cosmology

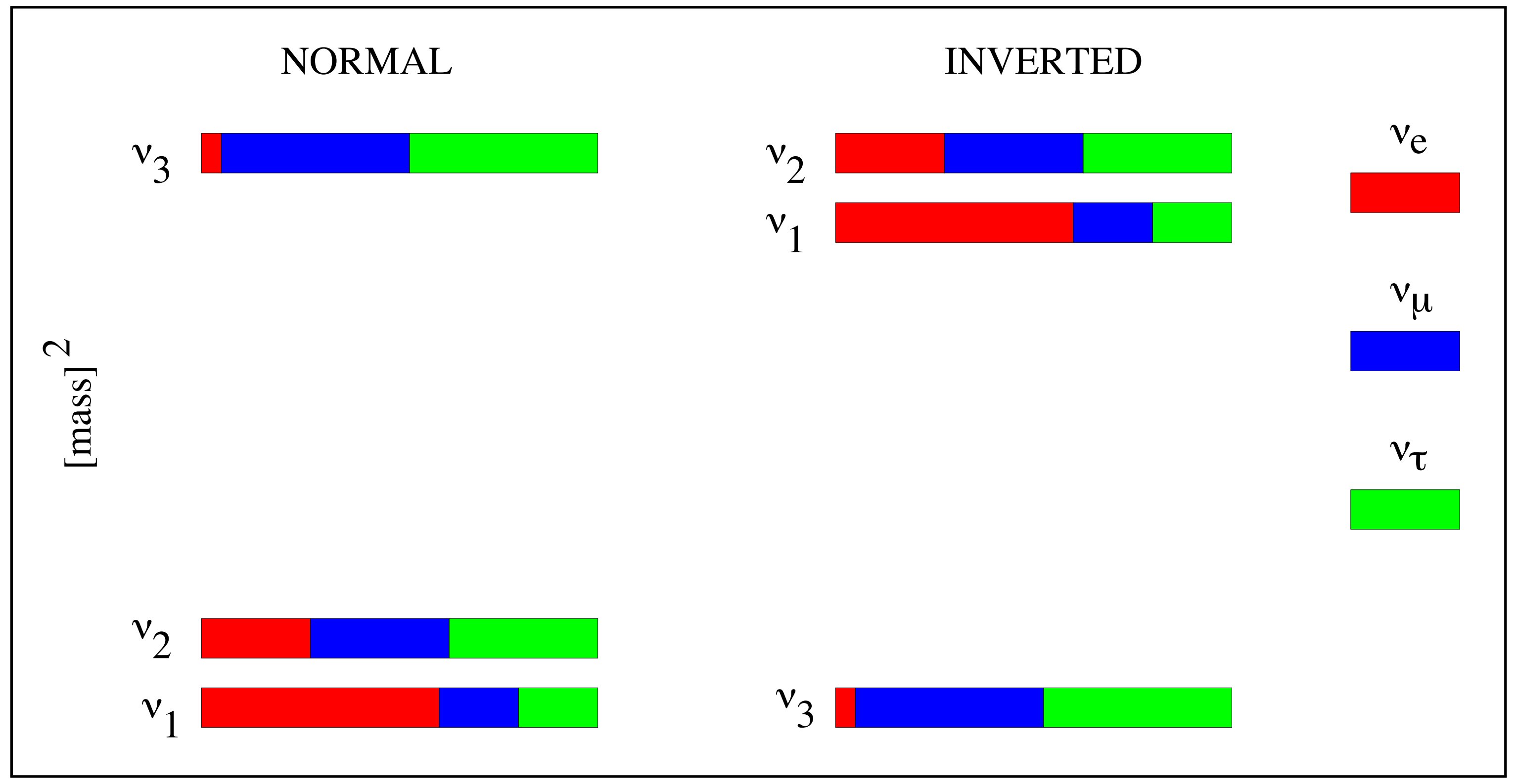
C. Benso, T. Schwetz, D. Vatsyayan
[arXiv:2410.23926] JCAP **04** (2025) 054
Large neutrino mass in cosmology and keV sterile neutrino dark matter from a dark sector

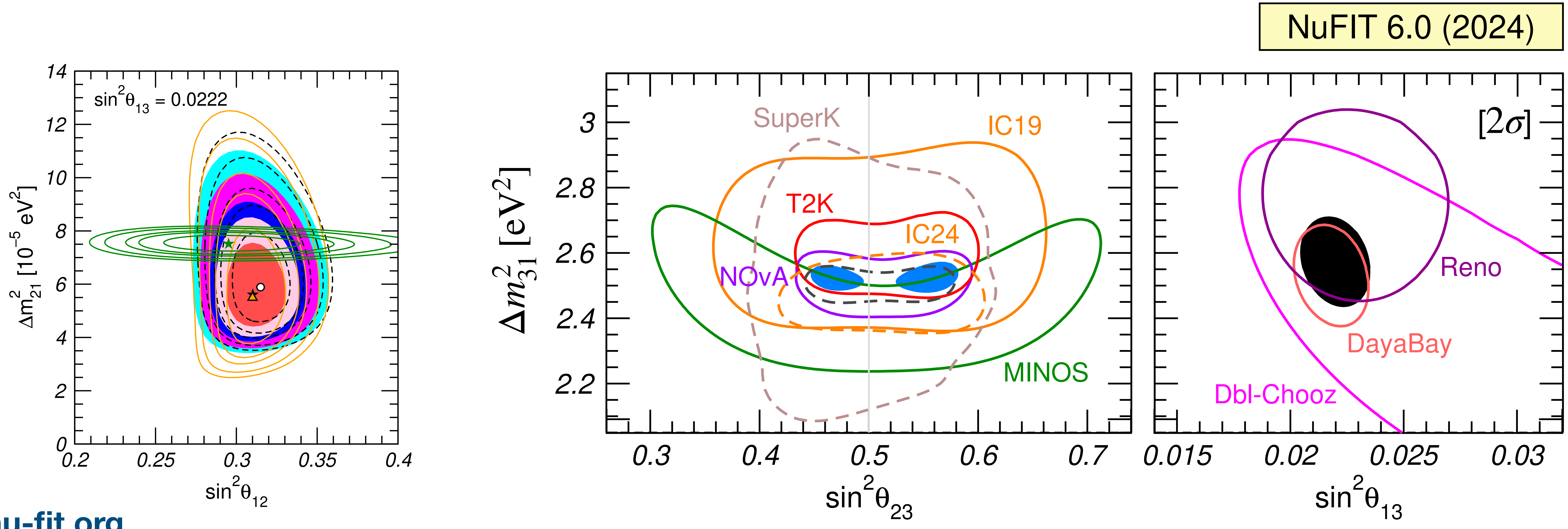


Neutrino masses

Neutrino oscillations:

- $|m_3^2 - m_1^2| \approx (2.52 \pm 0.023) \times 10^{-3}\,\text{eV}^2$
- $m_2^2 - m_1^2 = (7.49 \pm 0.19) \times 10^{-5}\,\text{eV}^2$



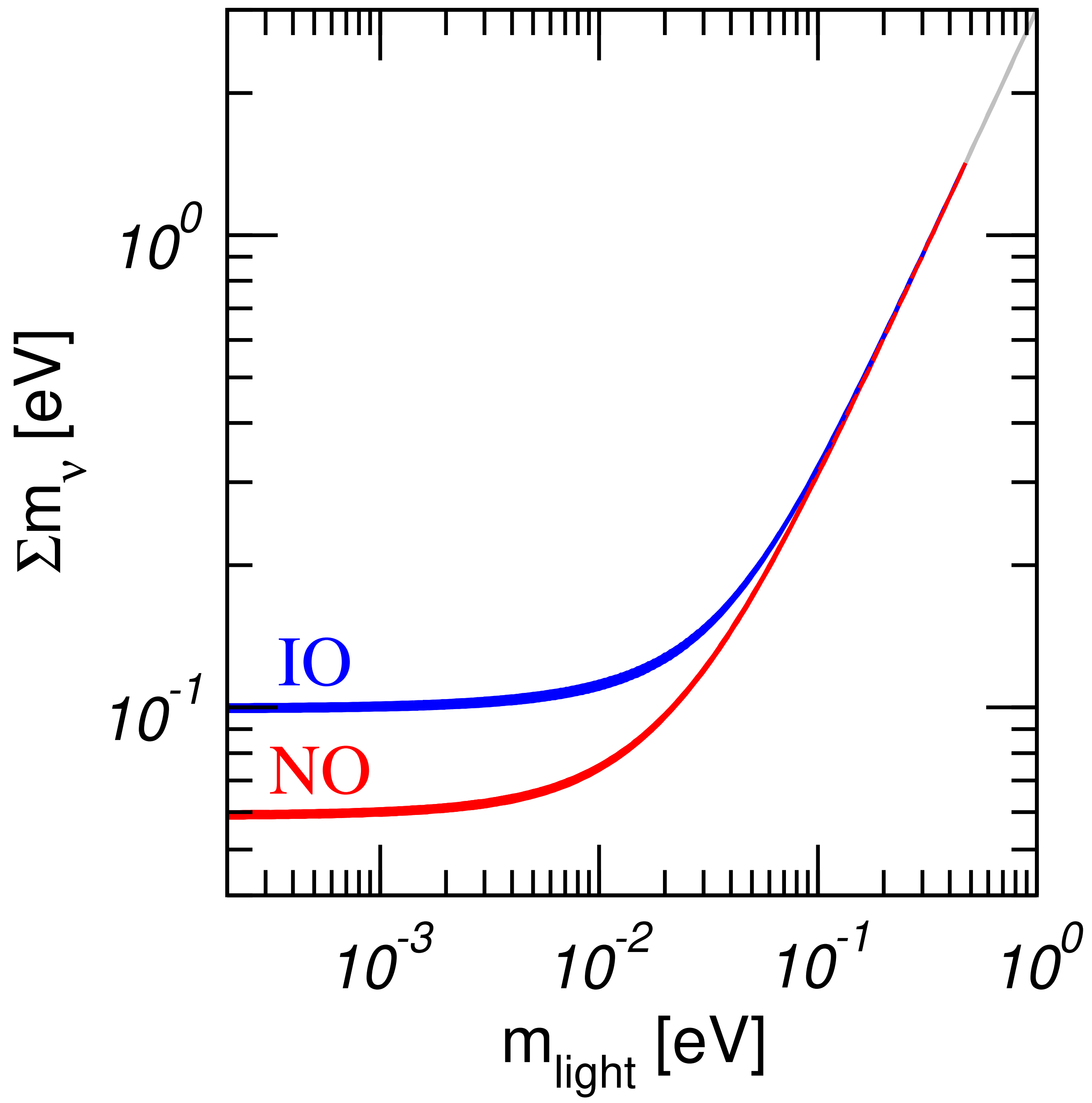


www.nu-fit.org

absolute neutrino mass

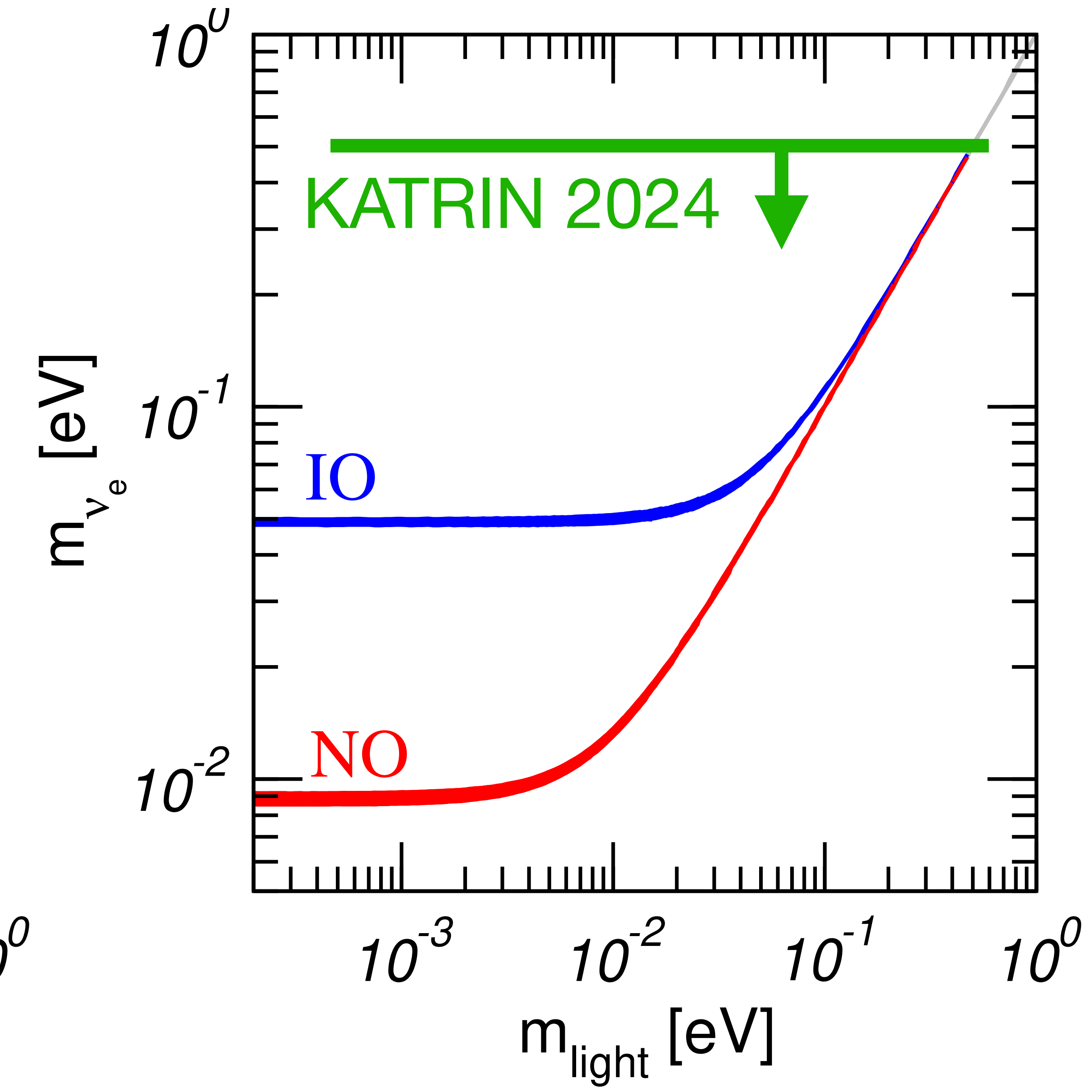
cosmology

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



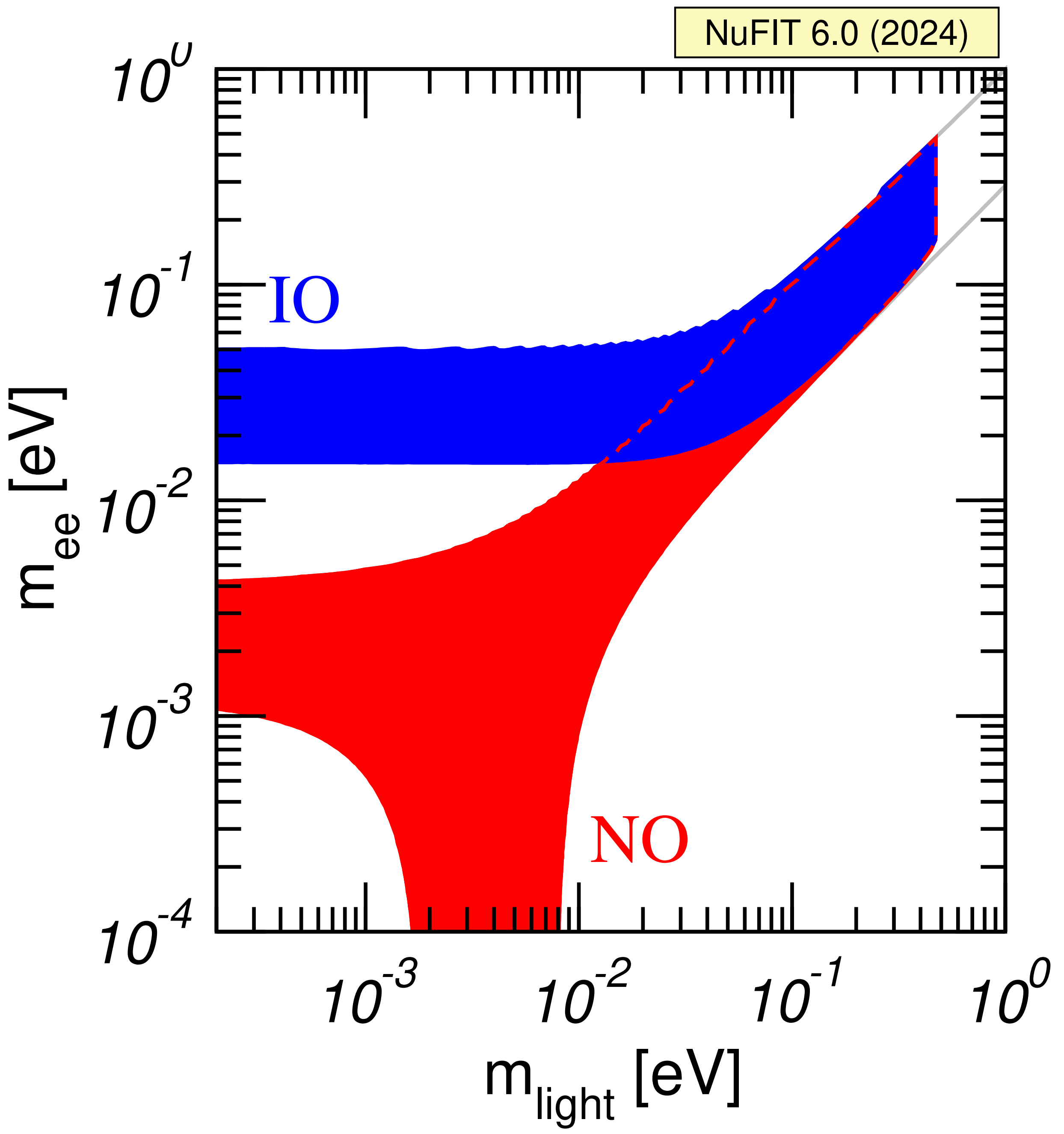
beta-decay spectrum (KATRIN)

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 0.45\,\mathrm{eV}$$



neutrinoless double-beta decay (assuming Majorana neutrinos)

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| \lesssim 0.07\,\mathrm{eV}$$



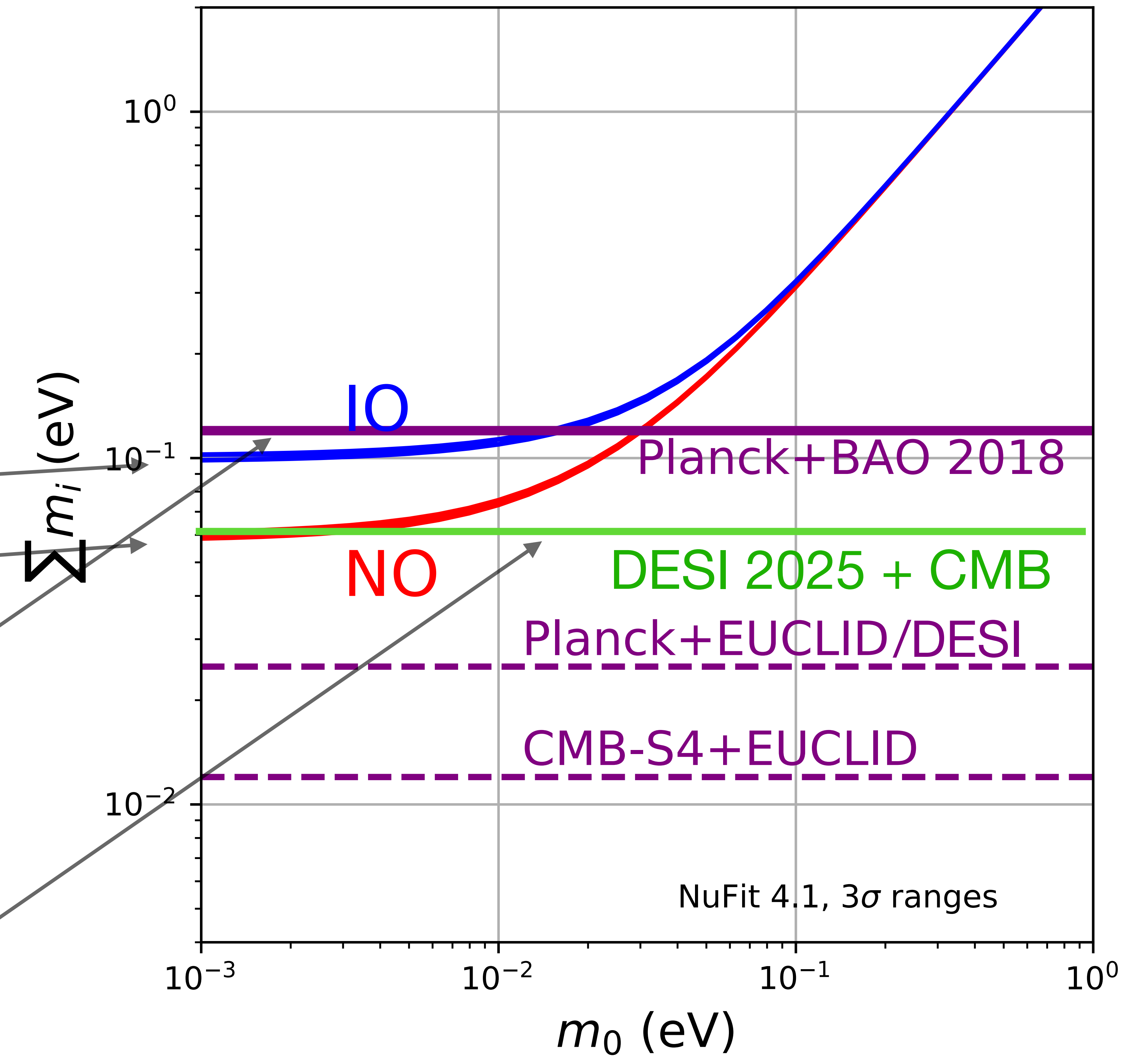
Neutrino mass from cosmology

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

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

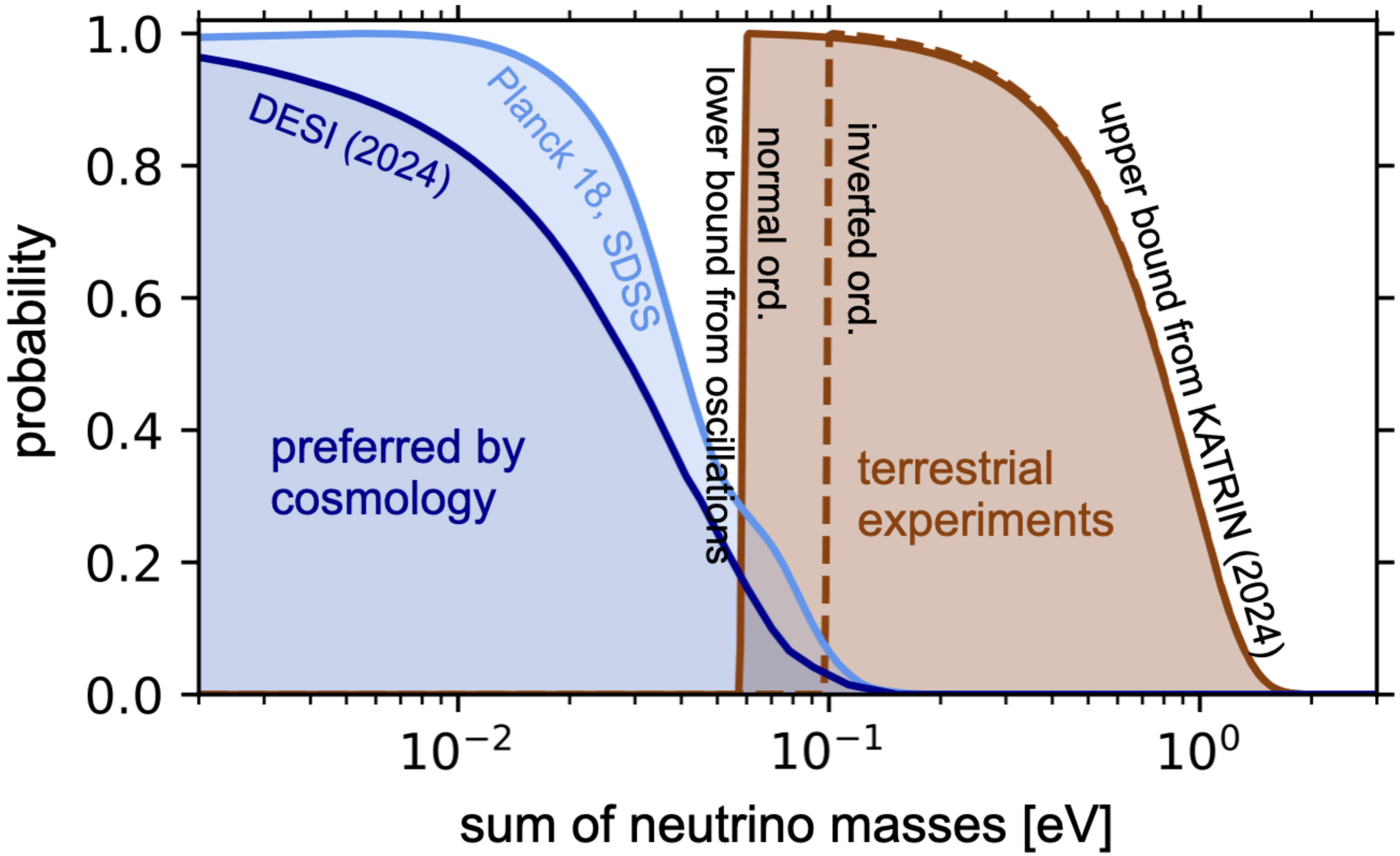
$$\Sigma_{\min} = \begin{cases} 98.6 \pm 0.85\,\text{meV} & \text{(IO)} \\ 58.5 \pm 0.48\,\text{meV} & \text{(NO)} \end{cases}$$

- **Upper bounds from current data:**
  - $\Sigma m_\nu < 0.12\,\text{eV}\ (95\,\%\ \text{CL})$ Planck CMB+BAO 2018
  - $\Sigma m_\nu < 0.064\,\text{eV}\ (95\,\%\ \text{CL})$ DESI 2025 + CMB



Tension between cosmology and laboratory?

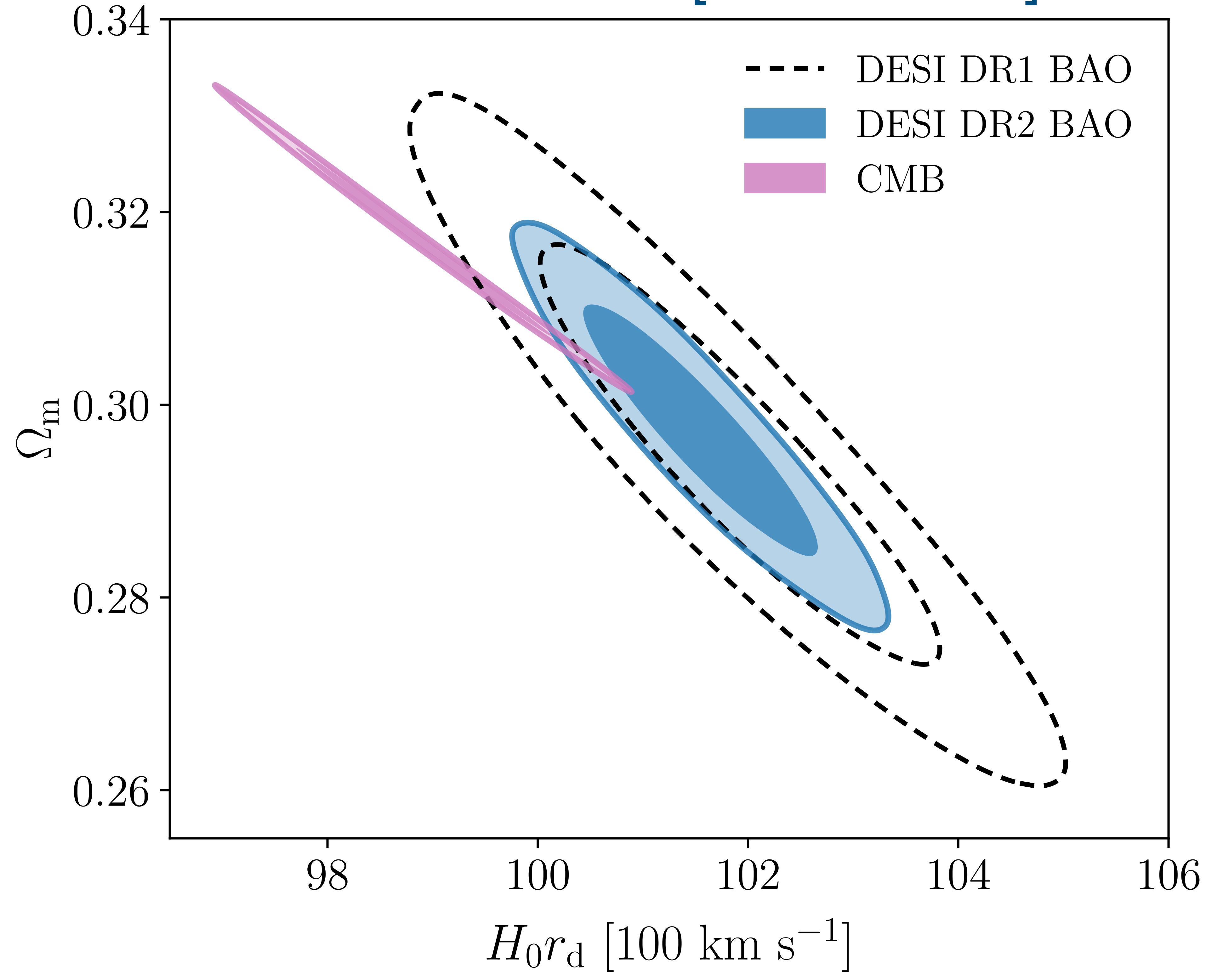
updated from Gariazzo, Mena, TS, 2302.14159



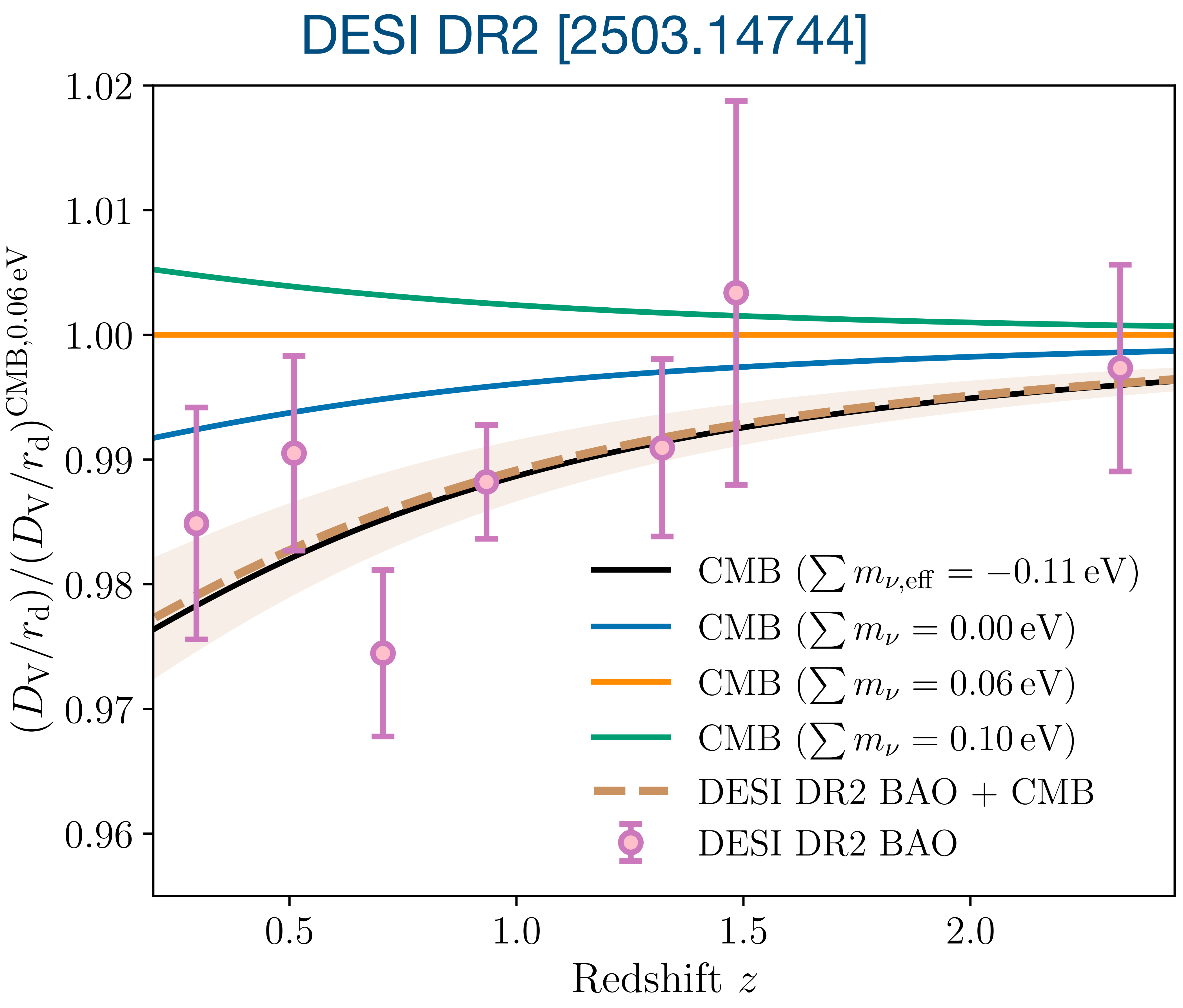
How robust are cosmological bounds?

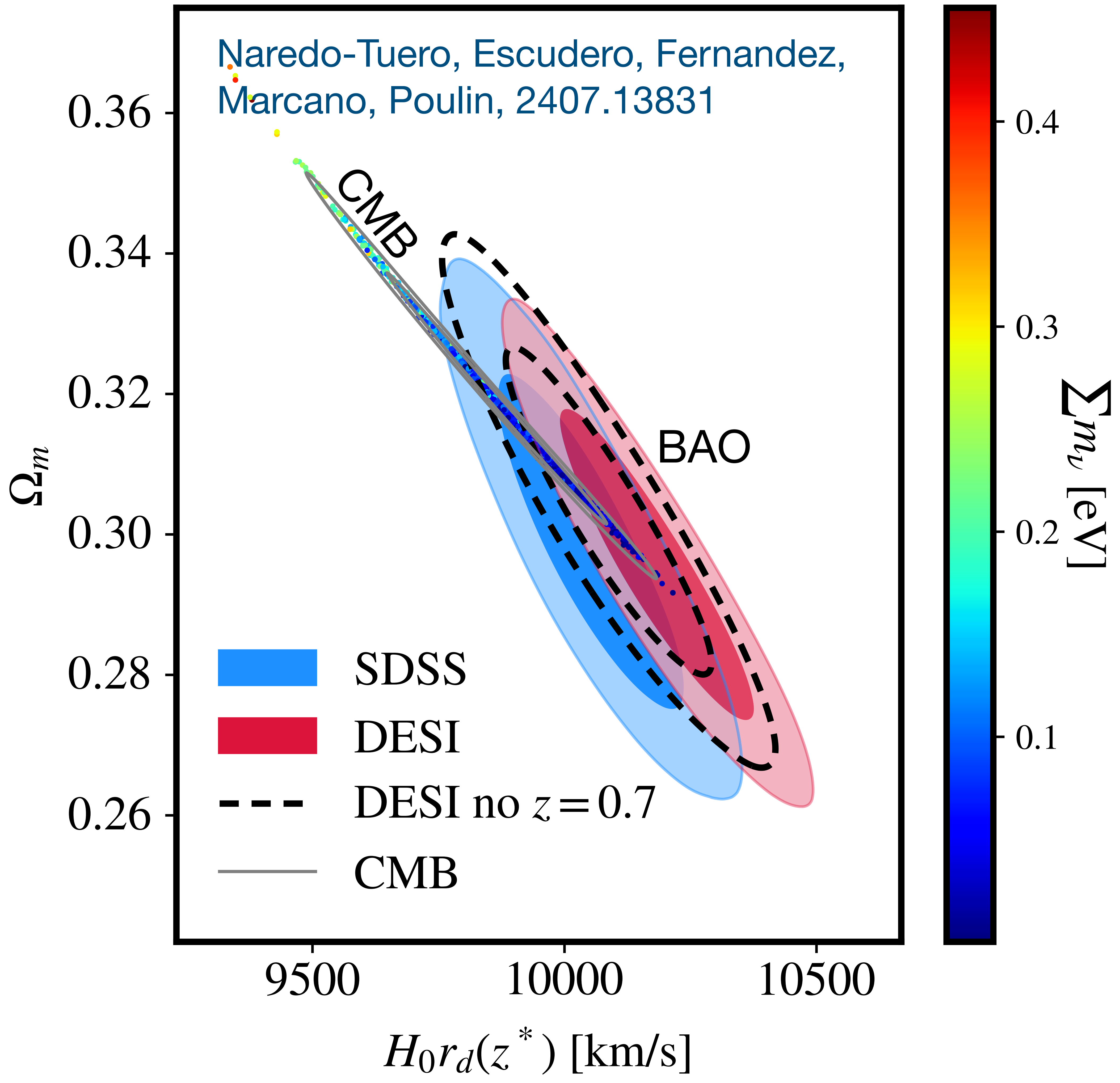
- Hubble tension
- σ_8 tension (mostly gone)
- Planck lensing anomaly
- tension between CMB and BAO?

DESI DR2 2025 [2503.14738]



Powerful complementarity between BAO and CMB





- 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?

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KIT Karlsruher Institut für Technologie

Cosmology bounds can be relaxed in non-standard scenarios

- dynamical dark energy
  Mena et al; Green, Meyers, 2407.07878; DESI 2025, 2503.14738: $\sum m_\nu < 0.14\,\mathrm{eV}$
- 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, 2306.15718, 2407.02462
- 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; Das, Dev et al., 2506.08085

incomplete!

Counting the number of neutrino flavours

N_{eff} affects

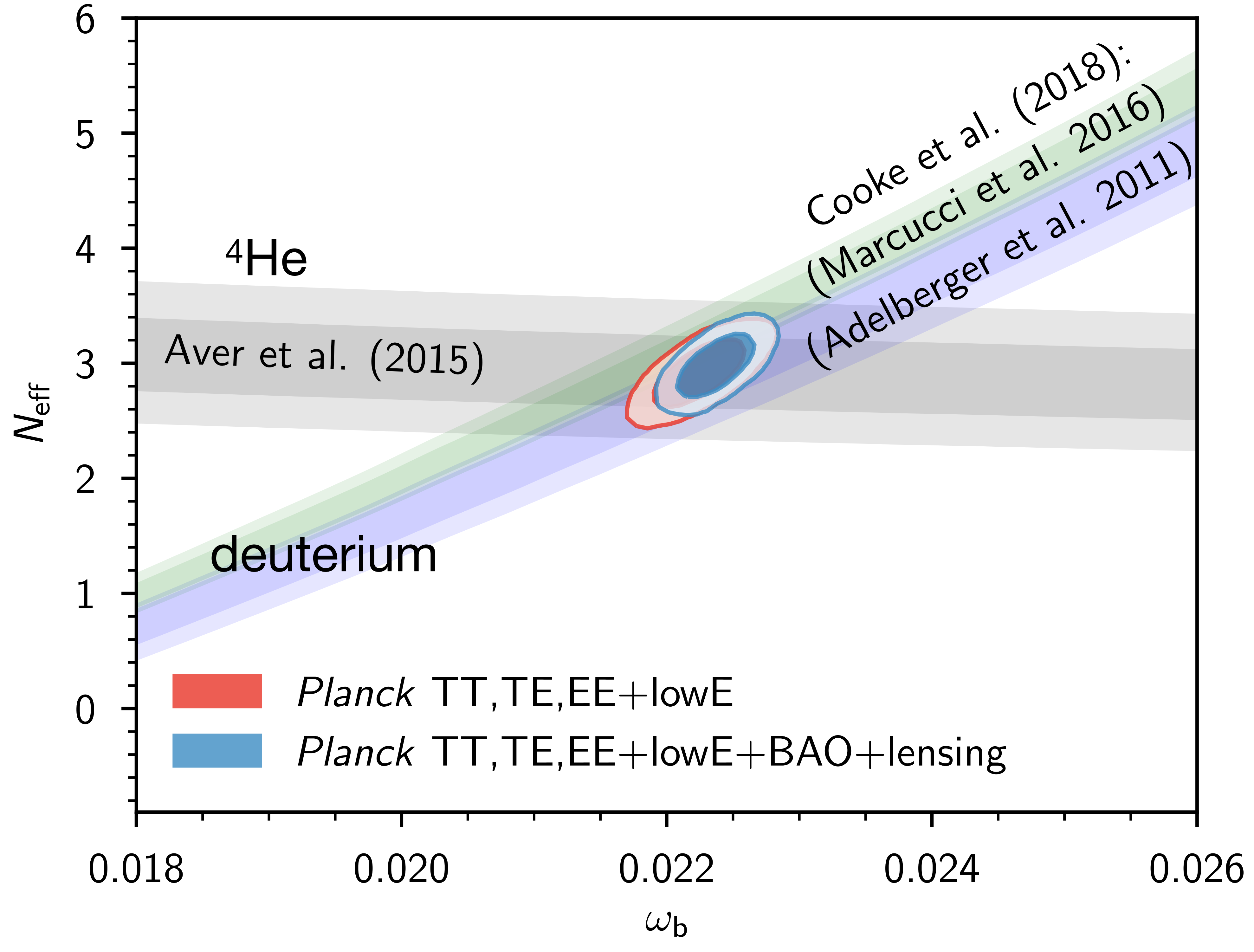
- formation of light elements (BBN), T ~ MeV, t ~ 1 min

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

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

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

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)

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

relax bound on m_ν by reducing neutrino number density

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

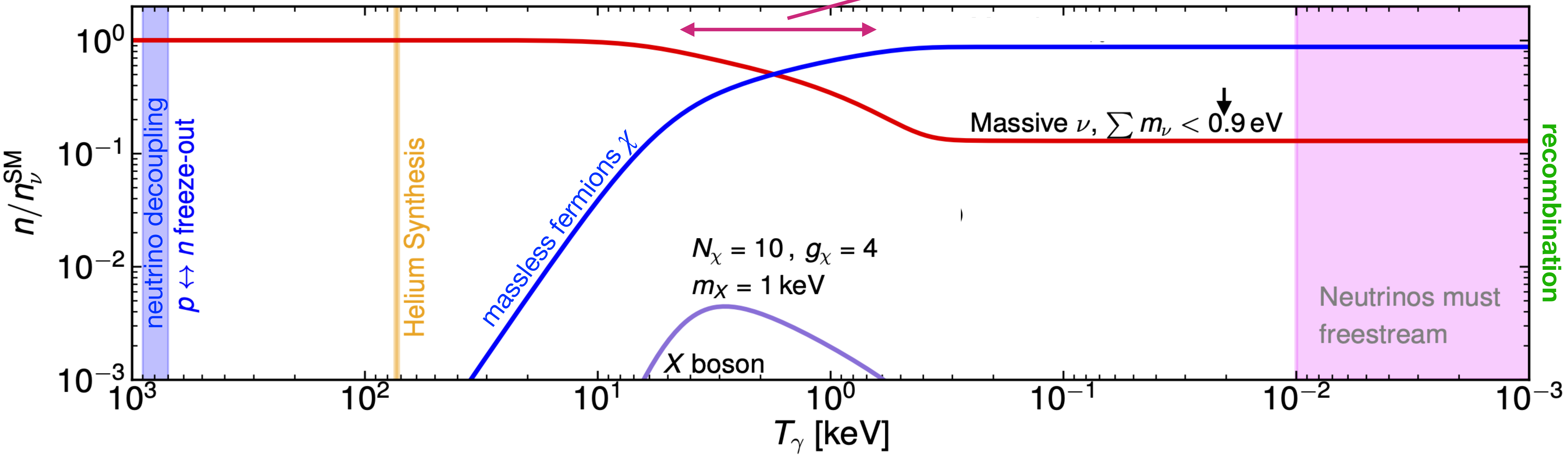
introduce „dark radiation“ to keep $N_{\text{eff}}^{\text{relat.}} \approx 3$

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

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

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

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



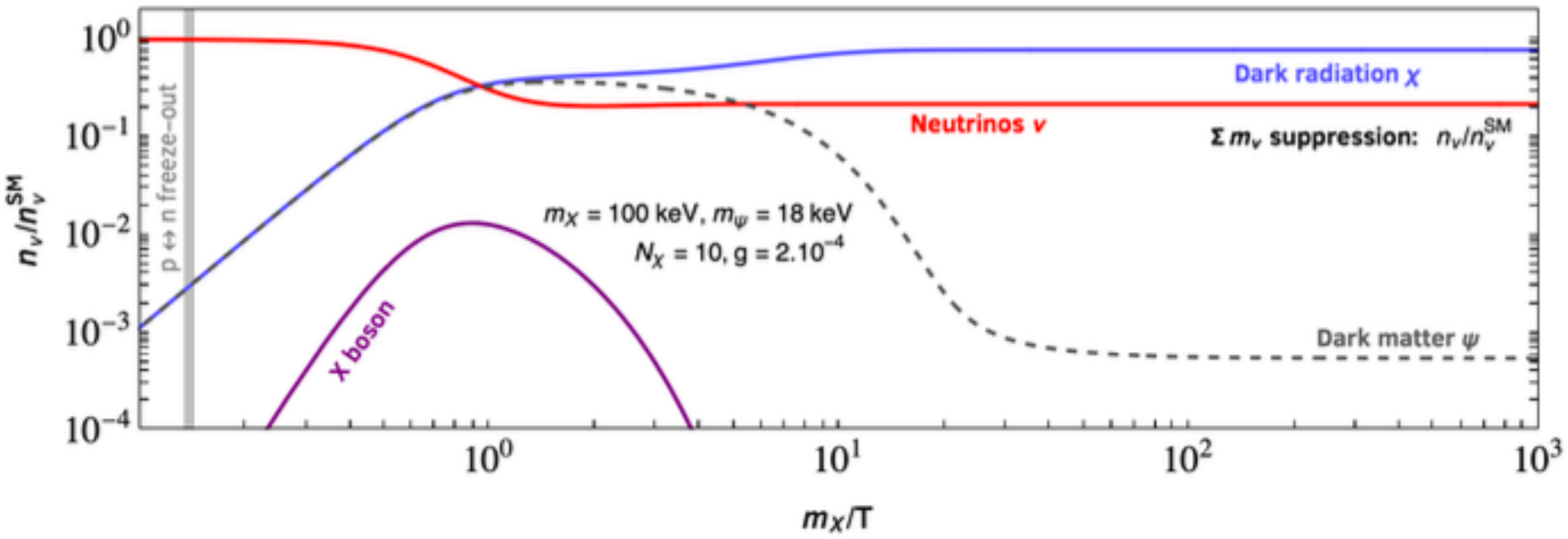
Adding keV sterile neutrino dark matter

Benso, Schwetz, Vatsyayan, 2410.23926

- freeze-out in the dark sector

$$\psi\psi \leftrightarrow \chi\chi, Z'Z'$$

similar to A. Berlin, N. Blinov, 1706.07046, 1807.04282



Equilibration of dark sector, neutrino mass suppression and $N_{\rm eff}$

- DS gets equilibrated at $T_\nu^{\rm eq}$ by

$$Z' \leftrightarrow f f\,, \quad Z' \leftrightarrow f f'\,, \quad Z' Z' \leftrightarrow f f \qquad f, f' \;=\; \nu, \chi, \psi.$$

- both, $1 \leftrightarrow 2$ and $2 \leftrightarrow 2$ prozesses are in equilibrium $\Rightarrow$ chem. potentials vanish, DS abundances fully characterized by temperature

$$\rho_\nu(T_\nu^{\rm eq}) = \sum_{f=\nu,\chi,\psi} \rho_f(T_{\rm eq}) + \rho_{Z'}(T_{\rm eq})$$

- adiabatic evolution till $T_{\rm fin} \ll m_\psi, m_{Z'}$

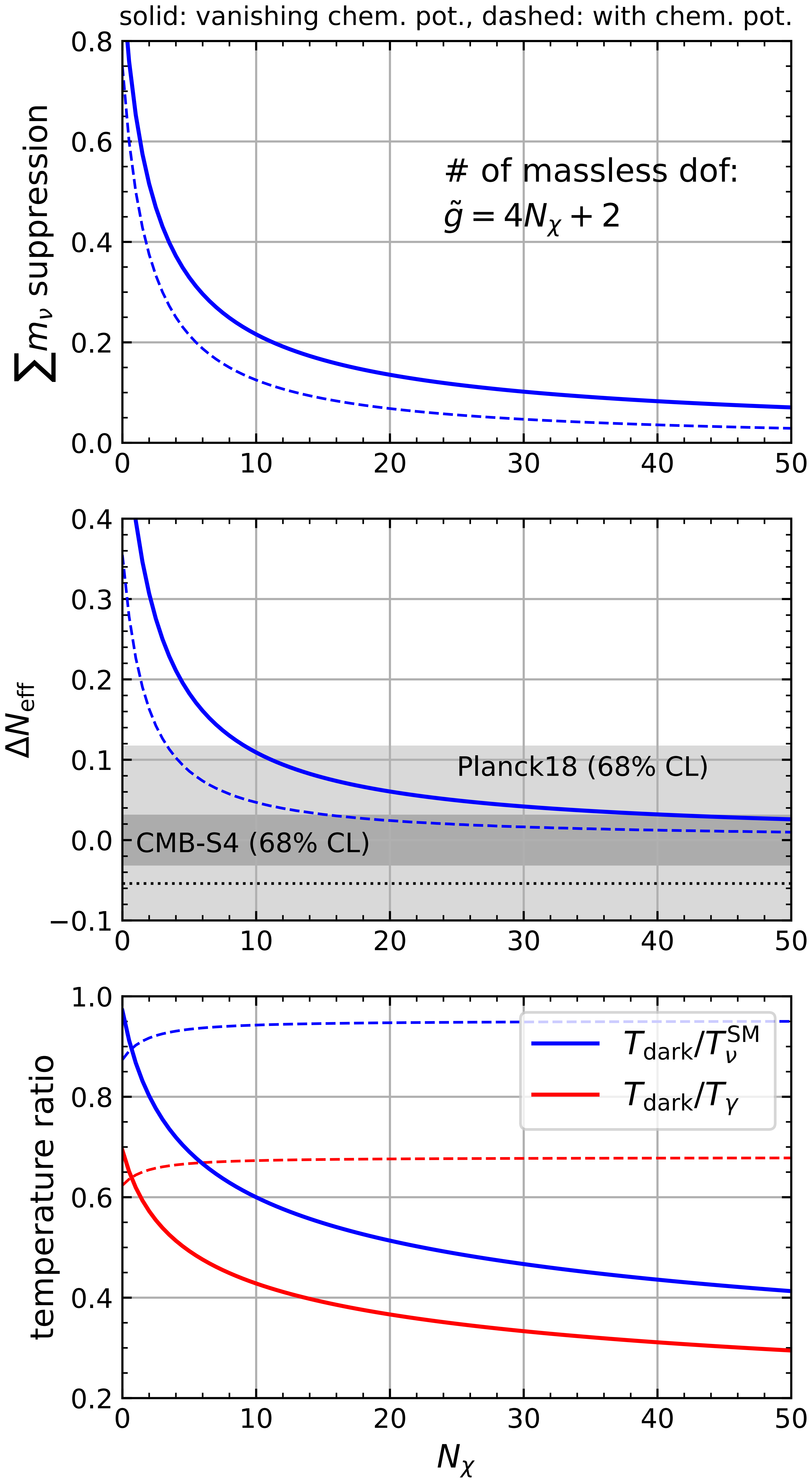
$$a_{\rm eq}^3 s_{\rm eq}(T_{\rm eq}) = a_{\rm fin}^3 s_{\rm fin}(T_{\rm fin})$$

$$\frac{n_\nu}{n_\nu^{\rm SM}} = \left(\frac{T_{\rm dark}}{T_\nu^{\rm SM}}\right)^3 = \frac{g_\nu + \tilde g + g_\psi + \frac{8}{7} g_{Z'}}{g_\nu + \tilde g} \left(\frac{g_\nu}{g_\nu + \tilde g + g_\psi + \frac{8}{7} g_{Z'}}\right)^{3/4}$$

$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_{\rm dark}}{\rho_\gamma} = \frac{g_\nu + \tilde g}{2}\left(\frac{T_{\rm dark}}{T_\nu^{\rm SM}}\right)^4$$

from energy and entropy conservation:

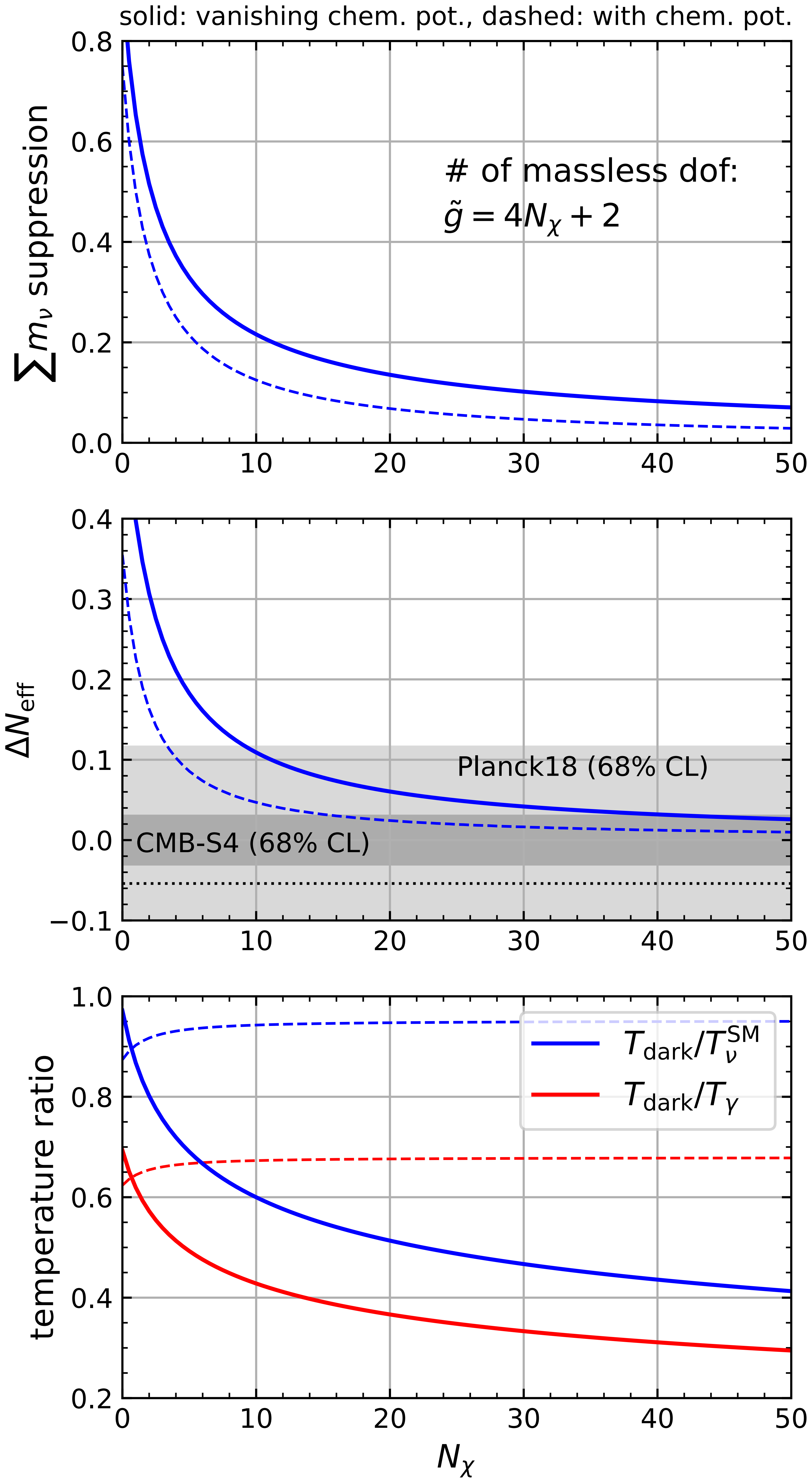
$$\frac{T_{\rm dark}}{T_\nu^{\rm SM}} = \left(\frac{g_\nu + \tilde g + g_\psi + \frac{8}{7} g_{Z'}}{g_\nu + \tilde g}\right)^{1/3} \left(\frac{g_\nu}{g_\nu + \tilde g + g_\psi + \frac{8}{7} g_{Z'}}\right)^{1/4}$$



$$\frac{n_\nu}{n_\nu^{\rm SM}} = \left(\frac{T_{\rm dark}}{T_\nu^{\rm SM}}\right)^3 = \frac{g_\nu + \tilde{g} + g_\psi + \frac{8}{7}g_{Z'}}{g_\nu + \tilde{g}}\left(\frac{g_\nu}{g_\nu + \tilde{g} + g_\psi + \frac{8}{7}g_{Z'}}\right)^{3/4}$$

- if only $1 \leftrightarrow 2$ processes $Z' \leftrightarrow ff\,, \quad Z' \leftrightarrow ff'\,,$ but not $2 \leftrightarrow 2$ processes $Z'Z' \leftrightarrow ff$ are in equilibrium, chem. potentials develop, need $T_{\rm dark}$ and μ

$$\Rightarrow \frac{n_\nu}{n_\nu^{\rm SM}} = \frac{g_\nu}{g_\nu + \tilde{g}}$$



A seesaw model for large neutrino mass and dark radiation

Escudero, TS, Terol-Calvo, 2211.01729

A seesaw model for large neutrino mass and dark radiation

- 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 $U(1)_X$

Yukawa sector

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

Scalar potential

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

Gauge interaction

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

A seesaw model for large neutrino mass and dark radiation

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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

- 3 heavy right-handed neutrinos (seesaw)
- new abelian symmetry $U(1)_X$ $\rightarrow$ gauged
- a scalar Φ charged under $U(1)_X$
- a set of N_χ massless fermions charged under $U(1)_X$

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

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

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

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

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

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

A seesaw model for large neutrino mass and dark radiation

- 3 heavy right-handed neutrinos (seesaw)
- new abelian symmetry $U(1)_X$ $\rightarrow$ gauged
- a scalar Φ charged under $U(1)_X$
- a set of N_χ massless fermions charged under $U(1)_X$

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

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

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

indep. params for pheno:

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

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

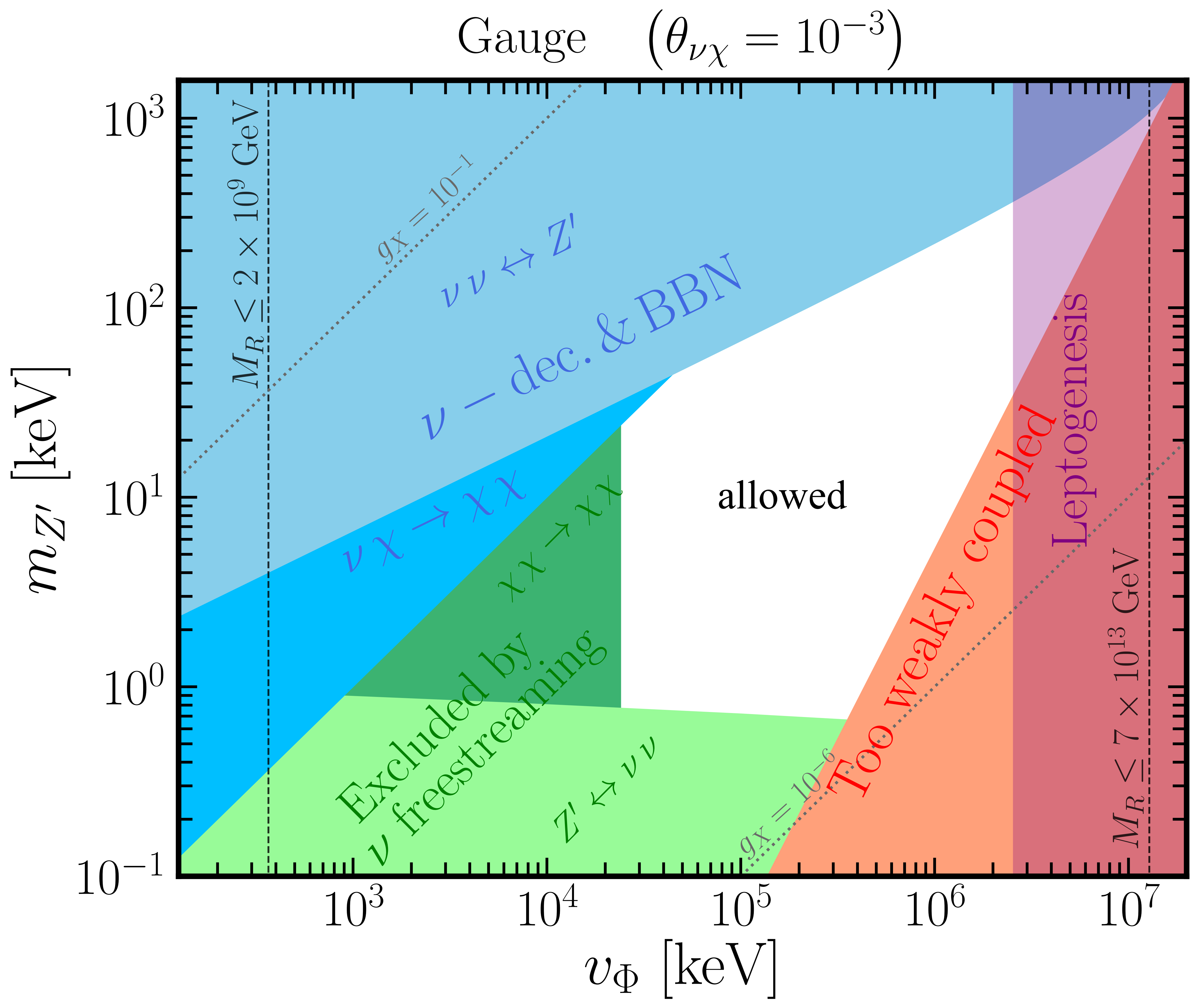
Available parameter space

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

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

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

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



Available parameter space

- thermalization of the dark sector:

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

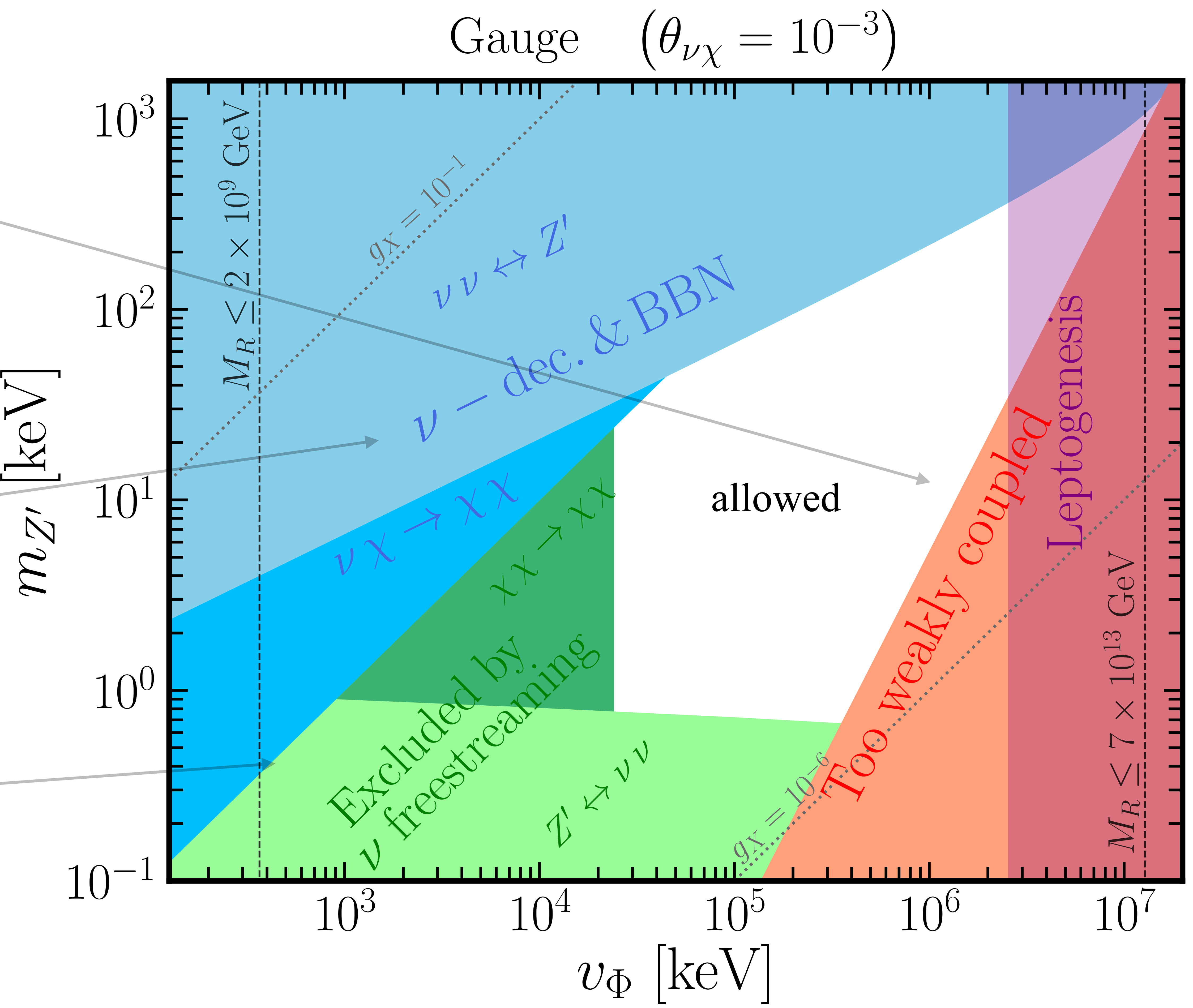
- avoid thermalization of the dark sector before BBN:

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

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

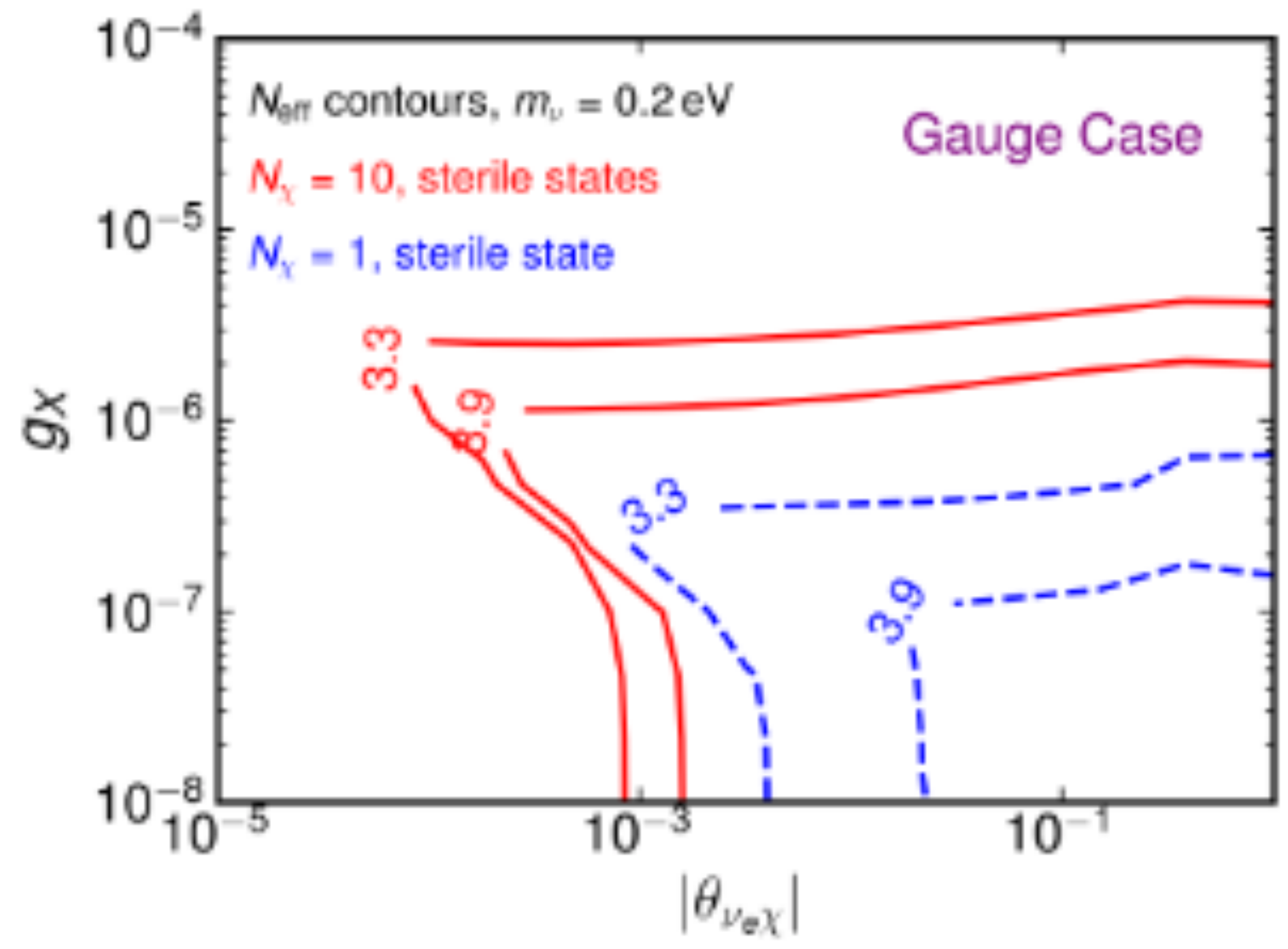
  $\langle \Gamma \rangle < H$ for $z < 10^5$

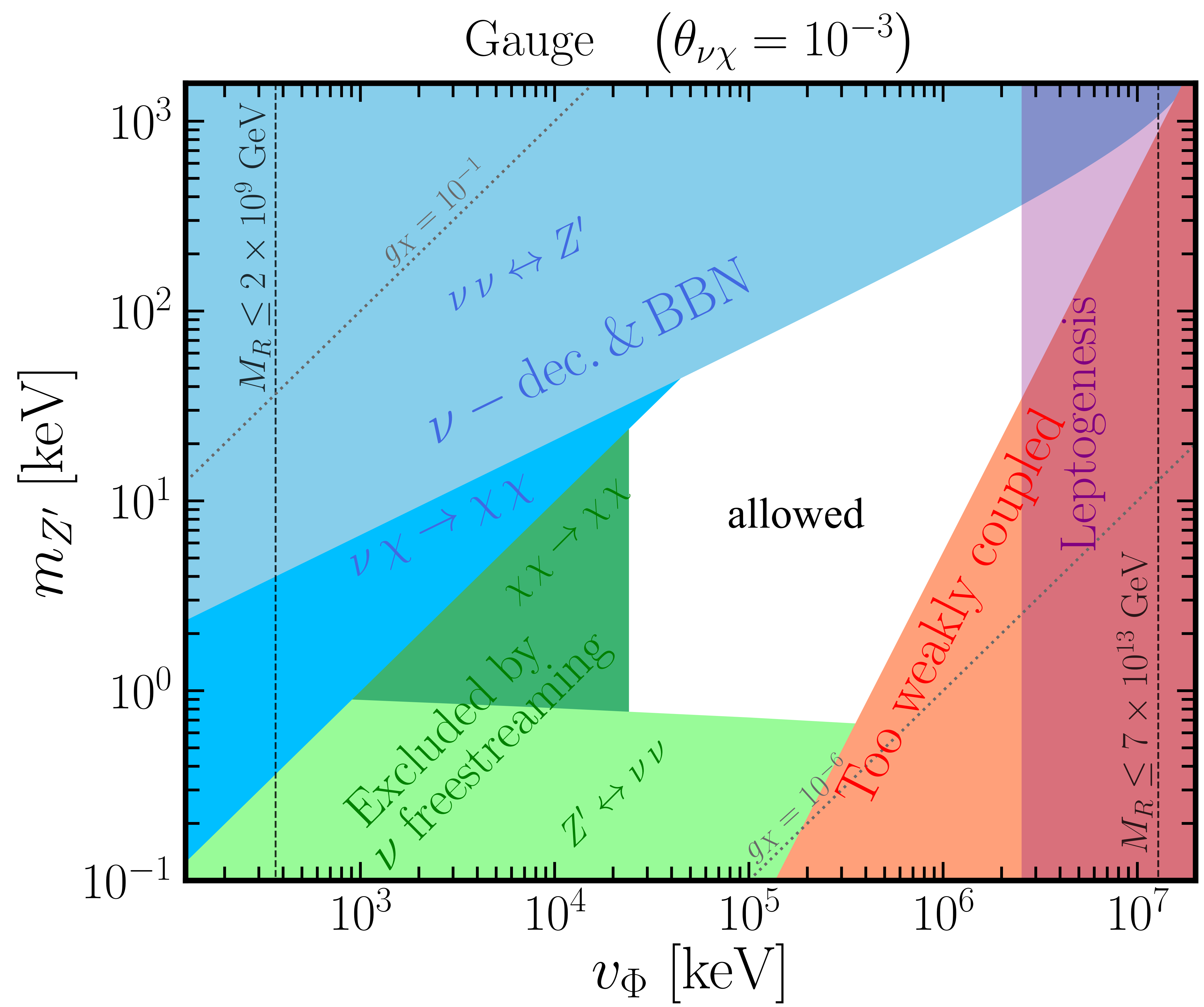
  Taule, Escudero, Garny, 2207.04062



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

T. Ota, 2411.16356

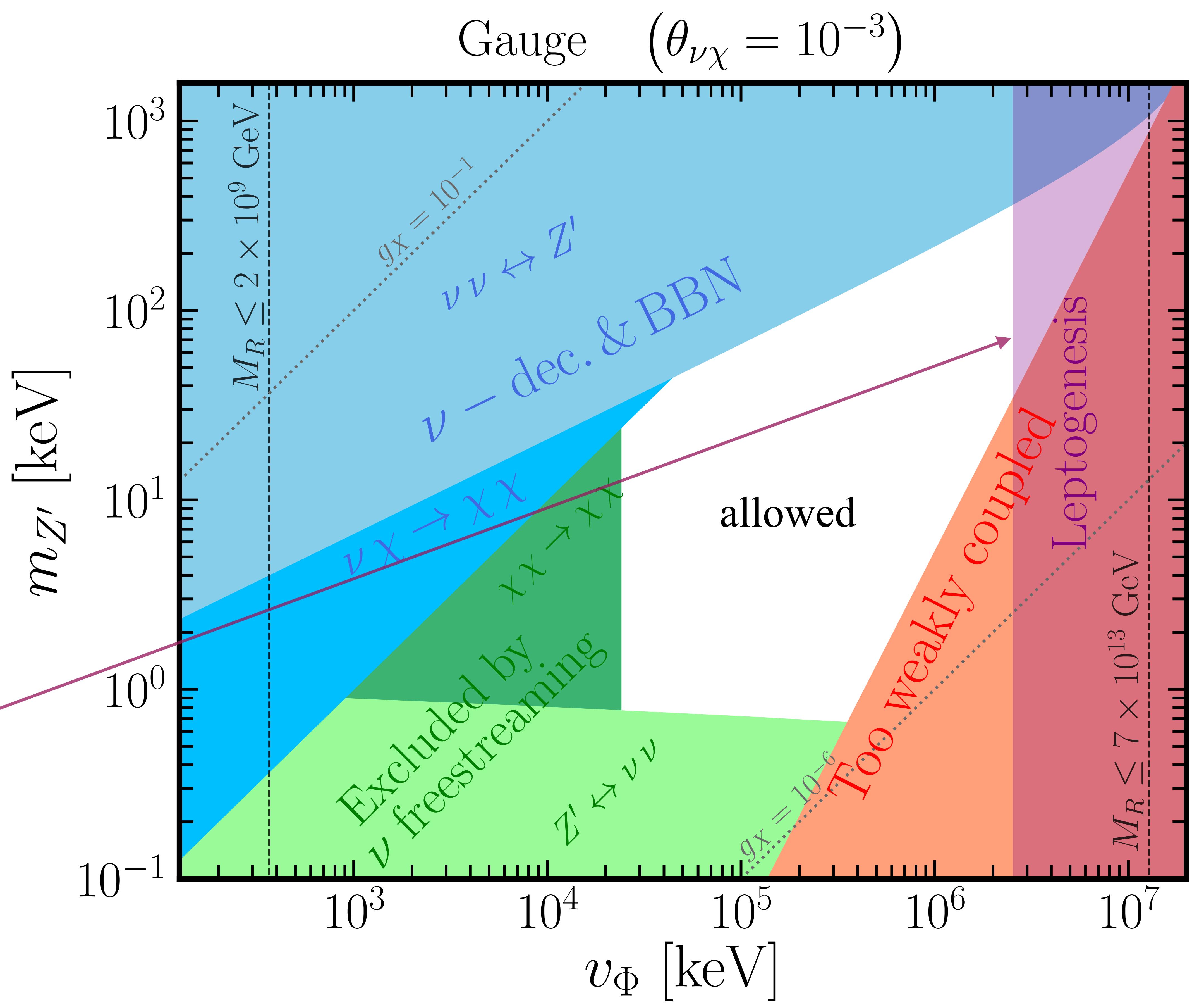
Constraints on heavy RH neutrinos

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

- 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

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_{eff} $\Rightarrow$ require $T_{RH} < M_R$ (allows still for $T_{RH} \gg T_{EW}$)



Signatures in a super nova

- SN cooling arguments for SN1987A exclude

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

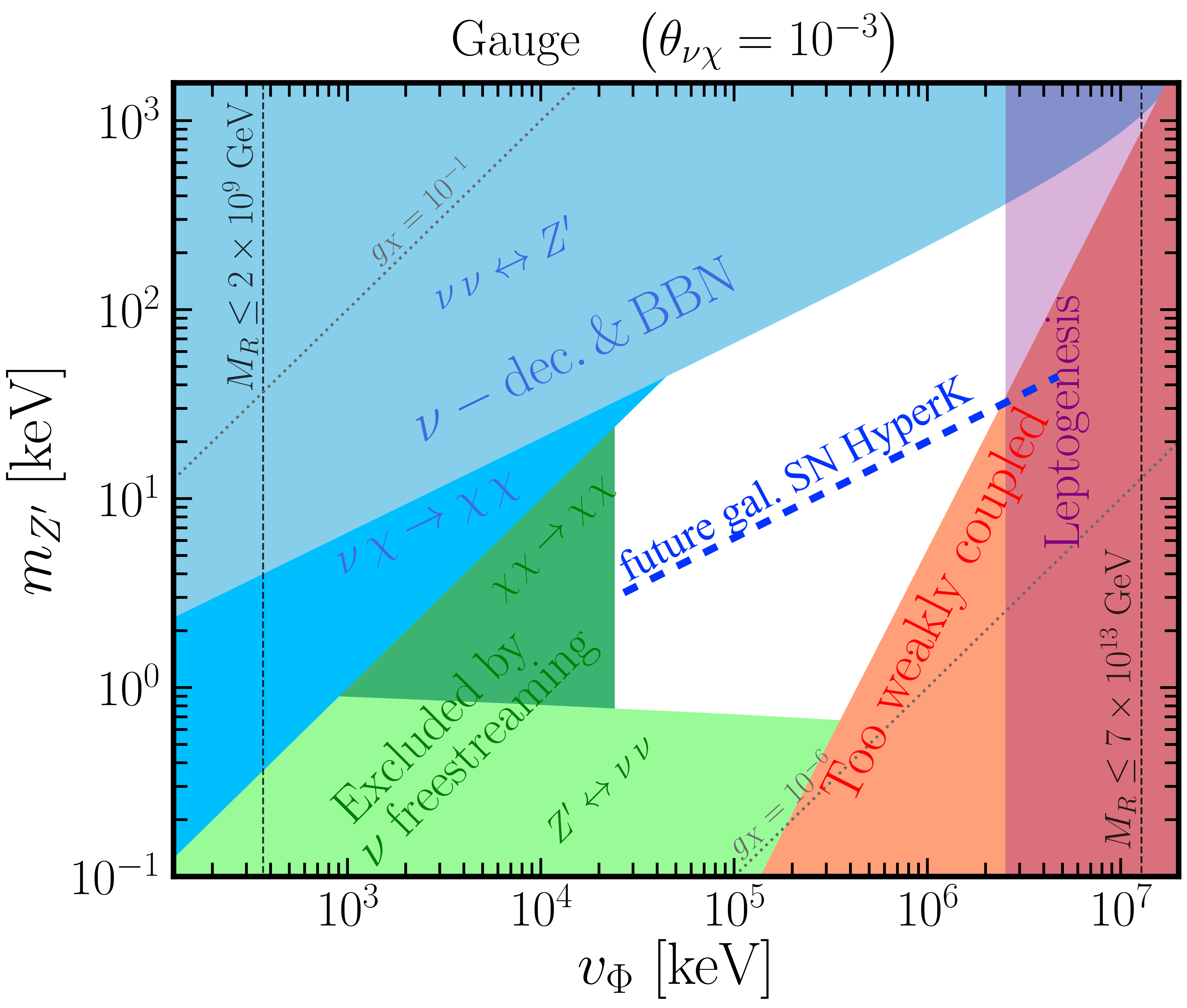
Fiorillo, Raffelt, Vitagliano, 2209.11773

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

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

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

Akita, Im, Masud, 2206.06852

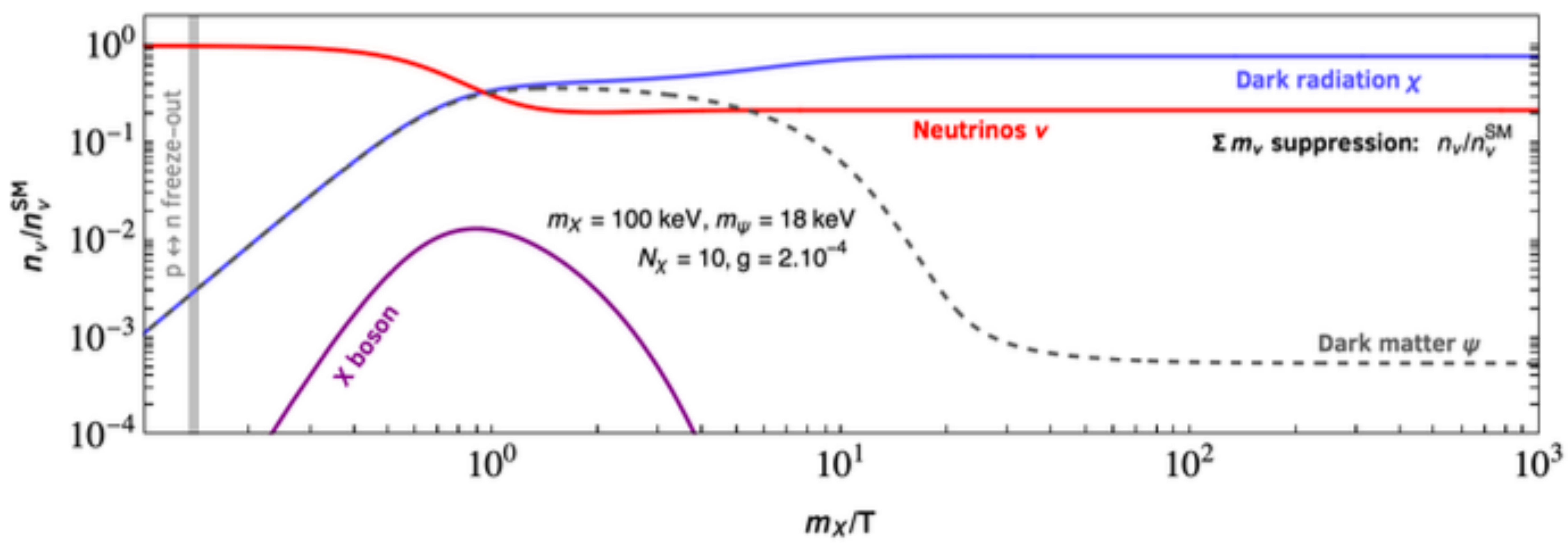


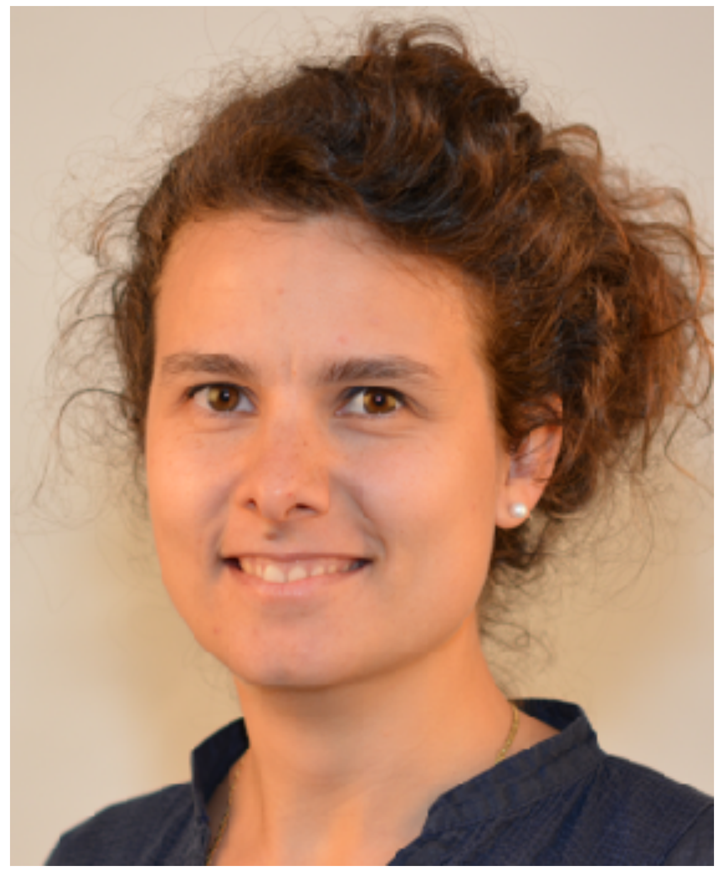
Adding keV sterile neutrino dark matter

Benso, Schwetz, Vatsyayan, 2410.23926

- freeze-out in the dark sector

$$\psi\psi \leftrightarrow \chi\chi, Z'Z'$$





Fermion sector

basis $(\chi_L^c, \nu_L^c, \psi_L^c, N', N)$:

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

assumed hierarchy:

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

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

seesaw masses

$$m_\nu \approx m_D M^{-1} m_D^T \,,$$

$$m_\psi \approx \kappa' {M'}^{-1} {\kappa'}^T \,.$$

dark freeze-out due to gauge interactions:

$$\lambda_{Z'}^{\psi\psi} = \lambda_{Z'}^{\chi\chi} = \frac{m_{Z'}}{v_\phi}$$

mixing with active neutrinos

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

Fermion sector

basis $(\chi_L^c, \nu_L^c, \psi_L^c, N', N)$:

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

assumed hierarchy:

$$M \gg M' \gg m_D \gg \kappa', \Lambda \gg m'_D, \Lambda', \kappa$$

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

seesaw masses

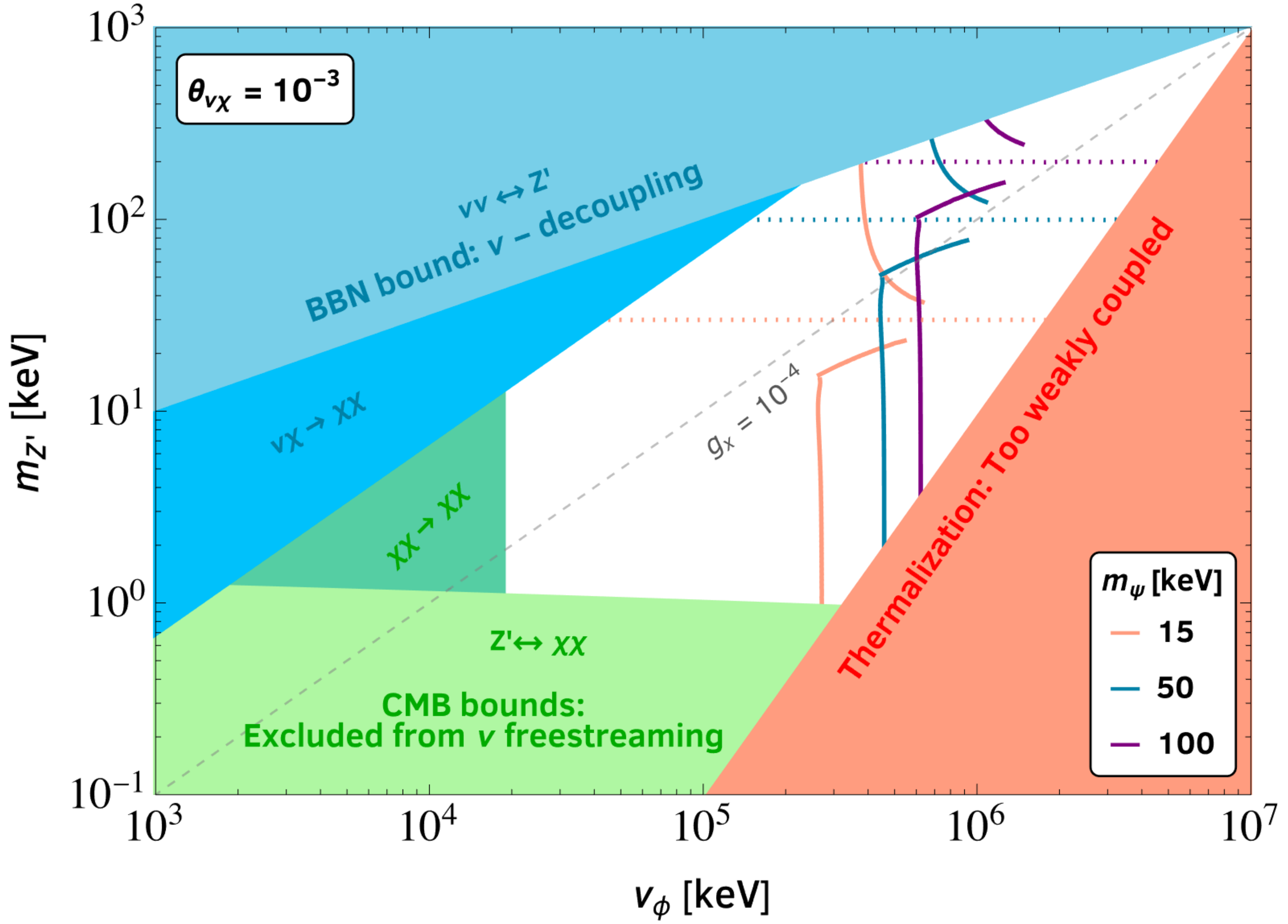
$$m_\nu \approx m_D M^{-1} m_D^T \,,$$

$$m_\psi \approx \kappa' M'^{-1} \kappa'^T \,.$$

M [GeV]	M' [GeV]	m_D [GeV]	κ' [GeV]	Λ [GeV]	v_ϕ [GeV]	m_ψ [keV]	$m_{Z'}$ [keV]	$g = m_{Z'}/v_\phi$	$\theta_{\nu\chi}$	N_χ	$n_\nu/n_\nu^{\rm SM}$	$\Delta N_{\rm eff}$
10^{11}	10^2	4.47	0.043	0.004	0.5	18.5	100	2×10^{-4}	10^{-3}	10	0.216	0.109
10^{12}	10^3	14.14	0.23	0.141	0.8	53	77	9.6×10^{-5}	10^{-2}	10	0.216	0.109
10^{13}	10^2	44.7	0.1	0.044	0.6	100	32	5.3×10^{-5}	10^{-3}	20	0.135	0.060

DM abundance: freeze-out in the dark sector

$$\langle \sigma v \rangle = \frac{m_\psi^2}{8\pi v_\phi^4 x_d} \times \begin{cases} \tilde{N} & (m_{Z'} \gg m_\psi) \\ 3 & (m_{Z'} \ll m_\psi) \end{cases} \qquad \begin{matrix} \psi\psi \leftrightarrow \chi\chi \\ \psi\psi \leftrightarrow Z'Z' \end{matrix}$$



DM-neutrino mixing strongly constrained by DM lifetime

require $\tau_\psi > 20\tau_{\rm Univ.}$ e.g., Poulin, Serpico, Lesgourgues, 1606.02073

- $m_\psi < m_{Z'}$: dominating decay $\psi \to \nu\chi\chi$ ($\psi \to 3\chi$ highly suppressed)

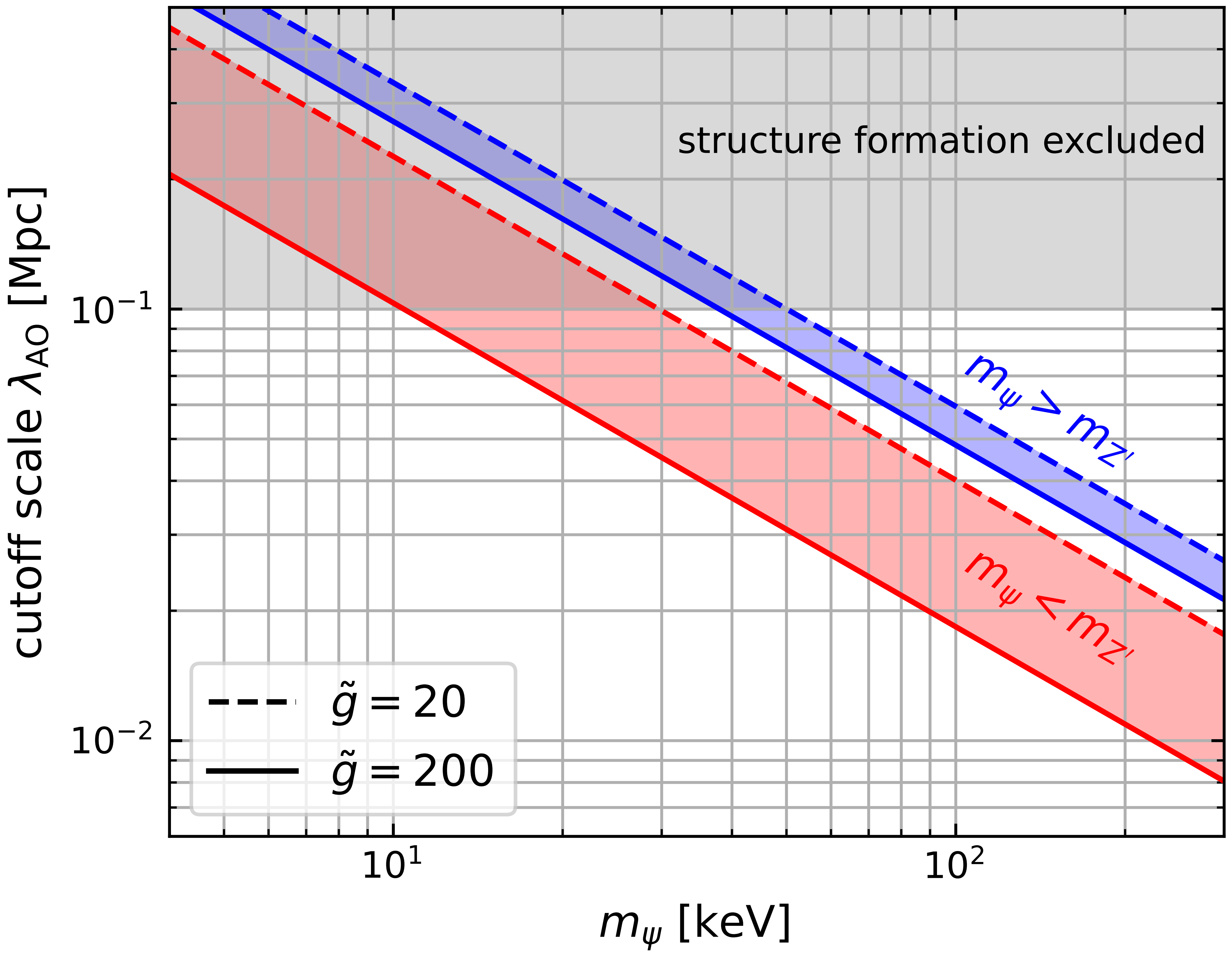
$$\theta^2_{\nu\psi} < 2 \times 10^{-16} \left(\frac{15\ \mathrm{keV}}{m_\psi}\right)^5 \left(\frac{21}{\tilde{N}}\right) \left(\frac{v_\phi}{2\ \mathrm{GeV}}\right)^4$$

- $m_\psi > m_{Z'}$: dominating decay $\psi \to \nu Z'$

$$\theta^2_{\nu\psi} < 1.2 \times 10^{-30} \left(\frac{m_{Z'}}{10\ \mathrm{keV}}\right)^2 \left(\frac{10^{-4}}{g}\right)^2 \left(\frac{40\ \mathrm{keV}}{m_\psi}\right)^3$$

Cosmic structure formation

- DM free-streaming and dark acoustic oscillations suppress growth of structure at scales $\lambda_{\text{cutoff}} = \max(\lambda_{\text{FS}}, \lambda_{\text{AO}})$ A. Berlin, N. Blinov, 1807.04282



Summary

- Relaxing cosmo bound on $\sum m_\nu$ requires exciting 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 $\lambda_{Z'}^{\nu\nu} \sim 10^{-9}$
  - including keV sterile neutrino DM
- possible signatures:
  - deviation of N_{eff} at CMB
  - galactic SN observations
  - sterile neutrino searches at oscillation experiments
  - cut-off scale in cosmic structure

Thank you for your attention!

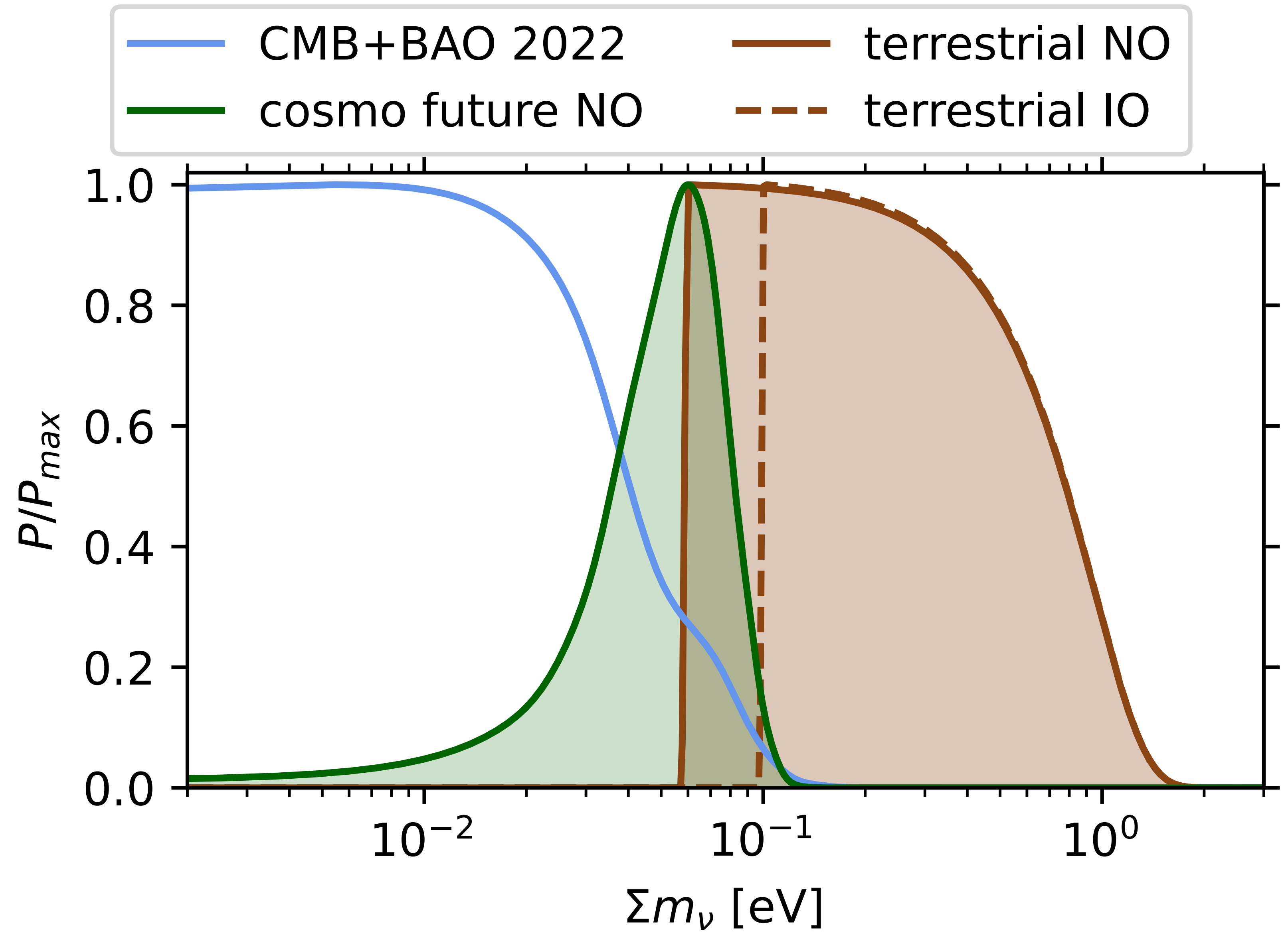
Backup

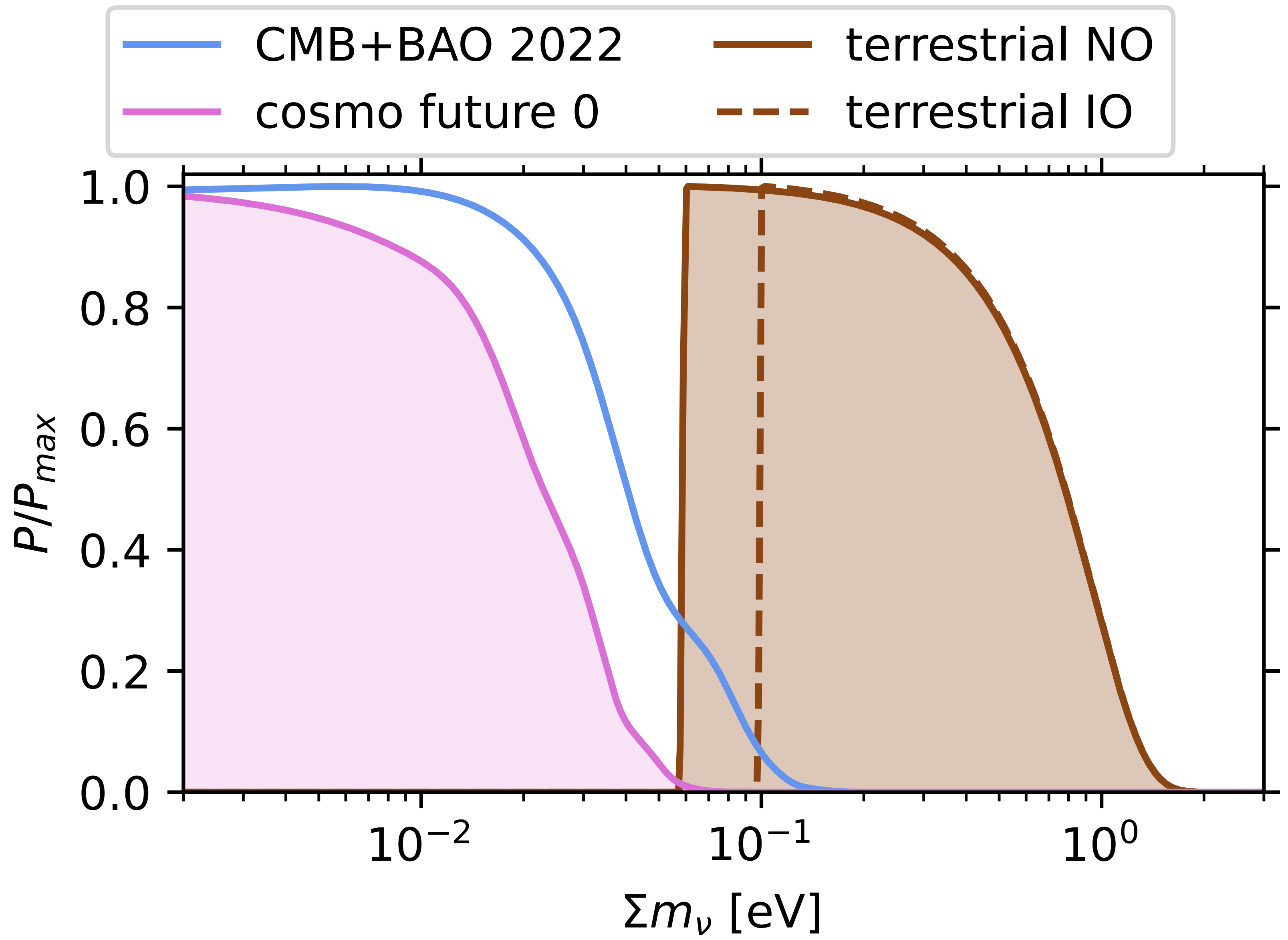
Possible near-term scenarios

$\sigma(m_\nu) = 0.02\,\mathrm{eV}$
e.g. from Planck + EUCLID or DESI 5 yr obs.
e.g., Archidiacono et al., 1808.05955

- $\sim 3\sigma$ determination of finite neutrino mass consistent with 60 meV (NO), 100 meV (IO) still consistent at $\sim 2\sigma$

- $\sim 3\sigma$ tension between cosmo and lab could indicate either non-standard cosmology or neutrino properties or both

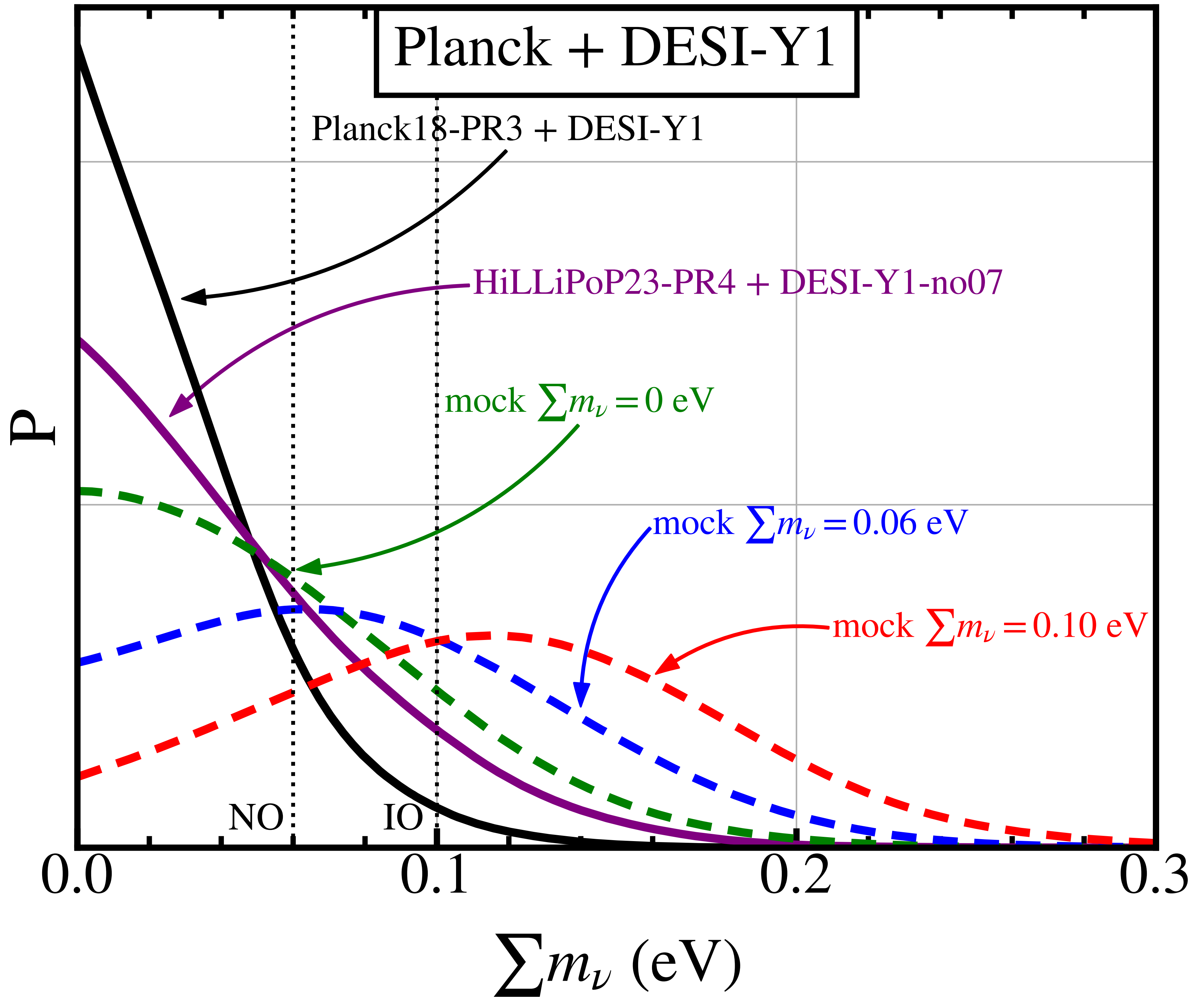




updated from Gariazzo, Mena, TS, 2302.14159

„too strong“ bound due to Planck lensing anomaly, statistical fluctuation in DESI BAO data?

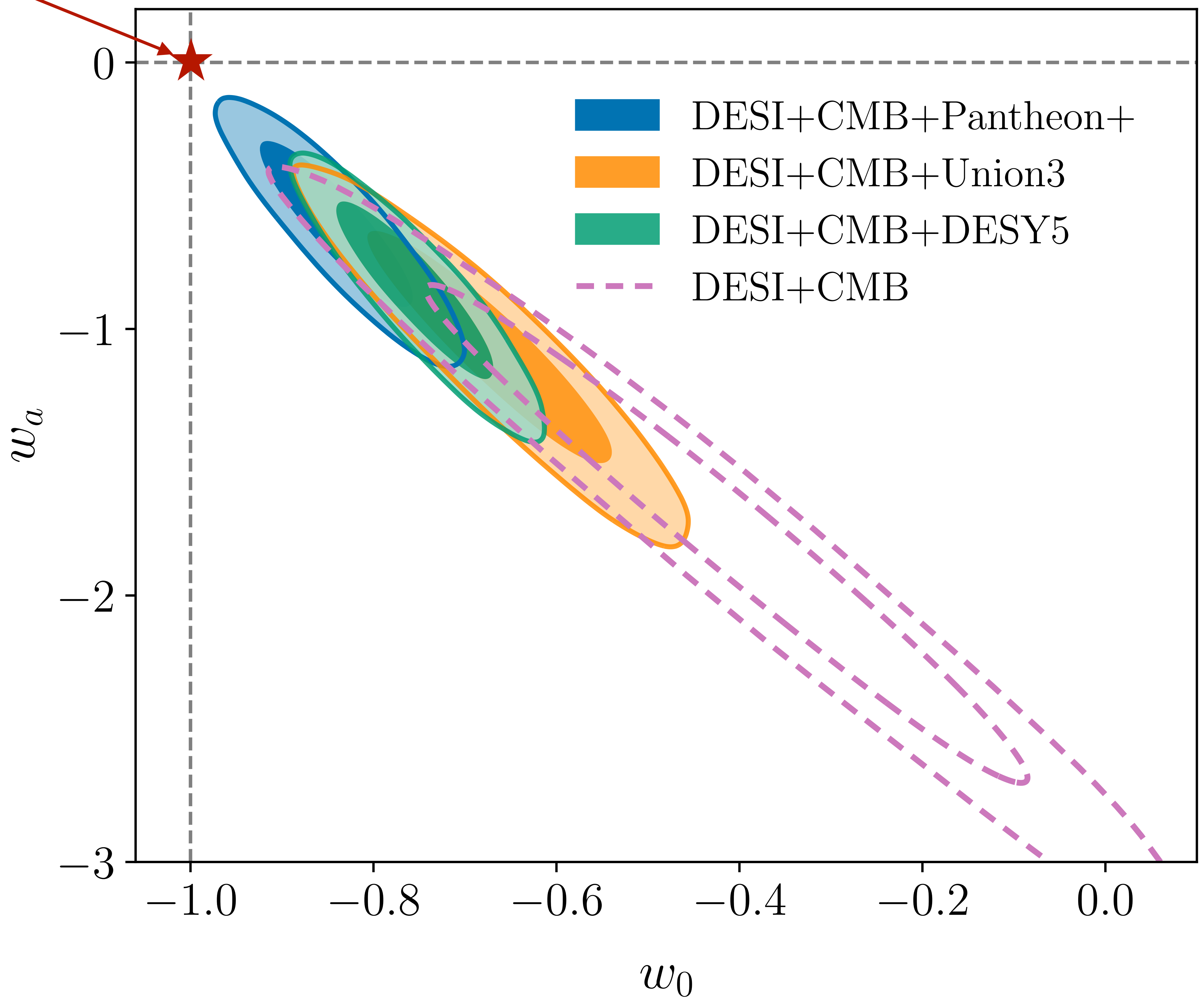
Naredo-Tuero, Escudero, Fernandez, Marcano, Poulin, 2407.13831



Example 1: hint for dynamical dark energy?

$\mathrm{cosm.const.:}\ w_0 = -1, w_a = 0$

DESI DR2 2025 [2503.14738]



DE equation of state: $p = w\rho$

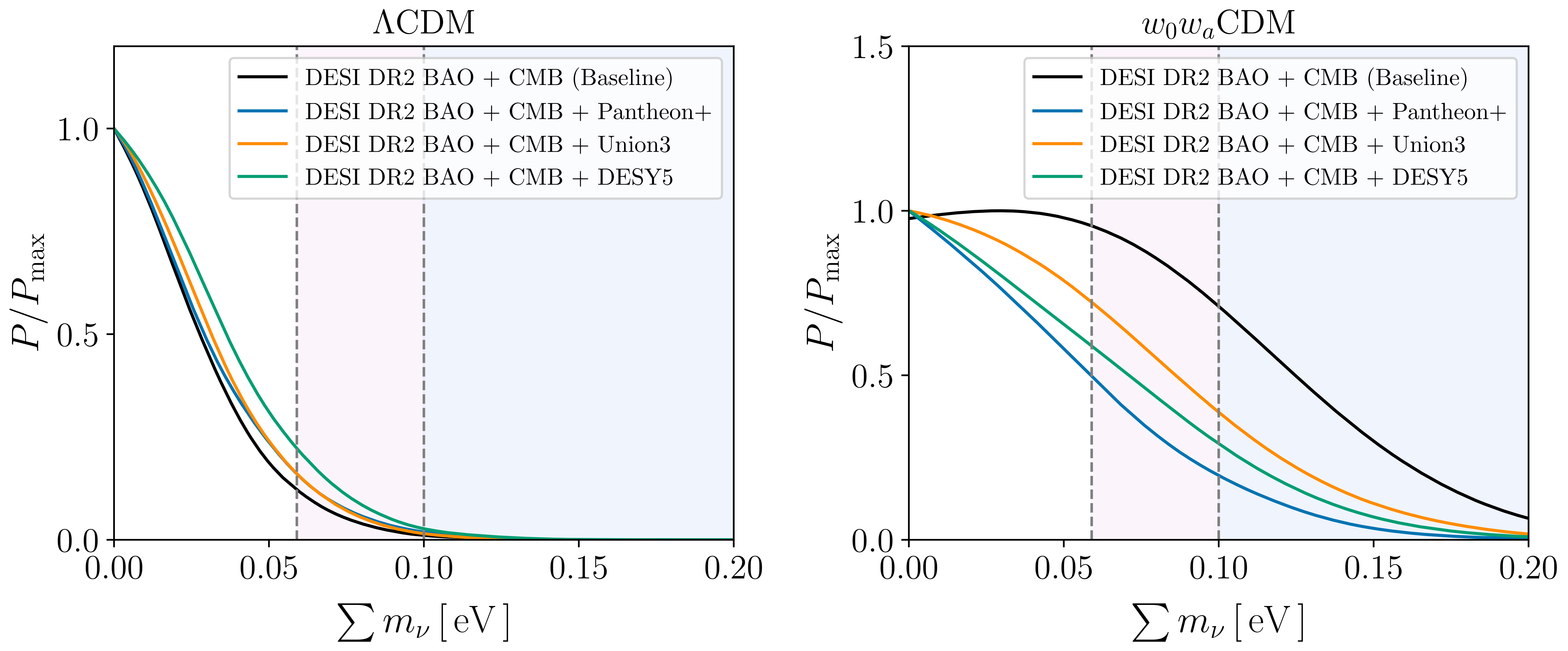
$$w(z) = w_0 + w_a \frac{z}{1+z}$$

$2.8\sigma - 4.2\sigma$ indication for deviation from cosmolog. const.

Example 1: hint for dynamical dark energy?

	$\sum m_\nu$ [eV]
$\boldsymbol{\Lambda}$**CDM**$+\sum \boldsymbol{m_\nu}$	
DESI BAO+CMB [Camspec]	< 0.0642
DESI BAO+CMB [L-H]	< 0.0774
DESI BAO+CMB [Plik]	< 0.0691

	$\sum m_\nu$ [eV]
$\boldsymbol{w_0 w_a}$**CDM**$+\sum \boldsymbol{m_\nu}$	
DESI BAO+CMB	< 0.163
DESI BAO+CMB+Pantheon+	< 0.117
DESI BAO+CMB+Union3	< 0.139
DESI BAO+CMB+DESY5	< 0.129



DESI DR2
[2503.14743]

Karlsruher Institut für Technologie

Preference for negative neutrino mass?

$$\Delta\chi^2(m_\nu = 0) \lesssim 3\,, \quad \Delta\chi^2(\text{NO}) \lesssim 6$$

DESI DR2 [arXiv:2503.14743]

Naredo-Tuero, Escudero, Fernandez, Marcano, Poulin, 2407.13831