Large Neutrino Masses in Cosmology:
DARK SECTOR TO THE RESCUE

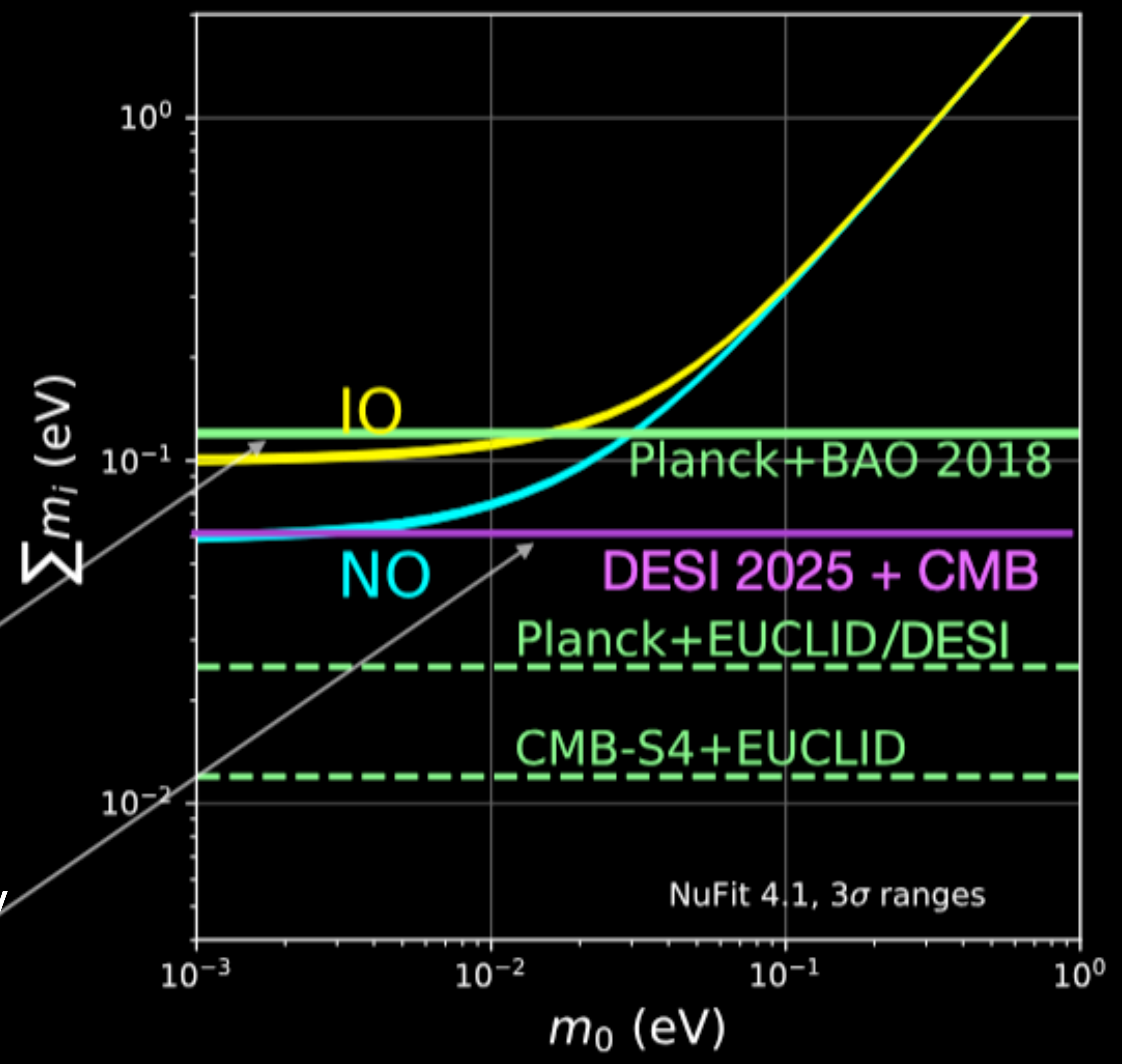
Drona Vatsyayan

11th June 2025, SIDM Workshop 2025, Valencia

Based on:
JCAP 04 (2025) 054 [Cristina Benso, Thomas Schwetz, **DV**]
arXiv: 2410.23926

Neutrino Mass Bounds

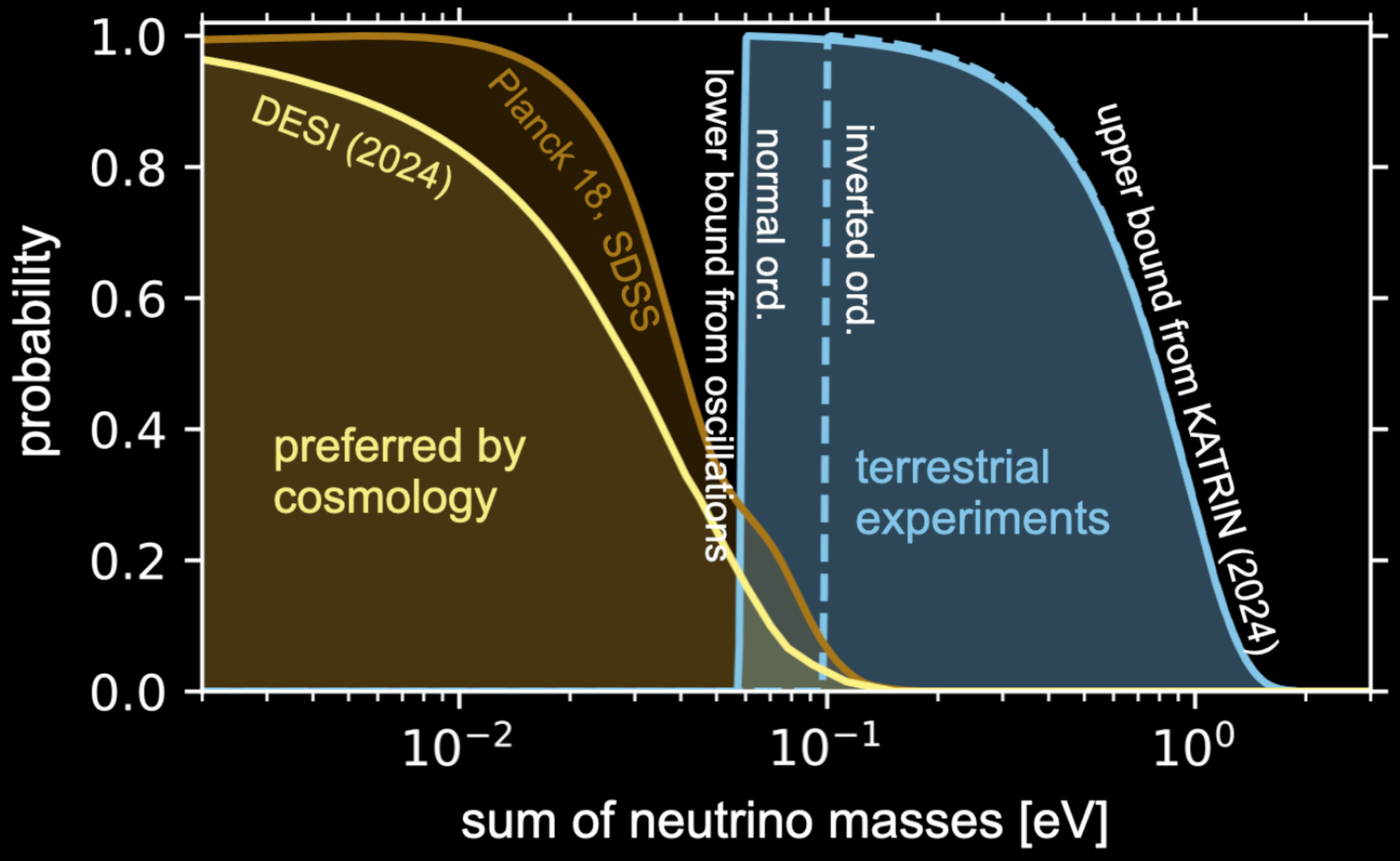
Laboratory vs. Cosmology



0.12 eV

0.064 eV

Courtesy: Thomas Schwetz (Durham 2025); updated from 2302.14159

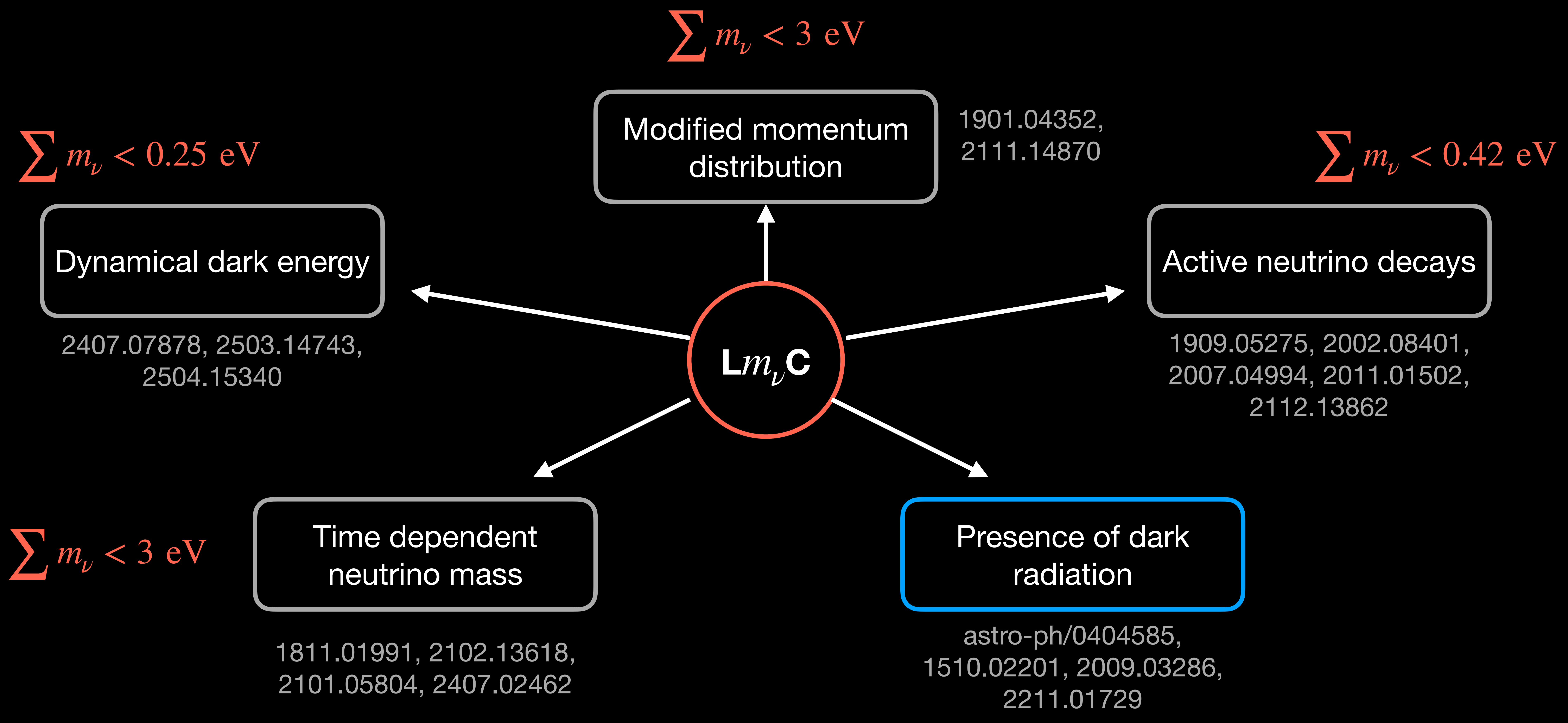


Standard cosmological scenario → We may not observe finite absolute neutrino mass in the laboratory

Can the two be reconciled? Can cosmological bounds be relaxed?

Relaxing the Cosmological ν mass bound

Large ν mass cosmology



$\sum m_\nu < 3\ \mathrm{eV}$

Modified momentum distribution

1901.04352, 2111.14870

$\sum m_\nu < 0.25\ \mathrm{eV}$

Dynamical dark energy

2407.07878, 2503.14743, 2504.15340

Lm_νC

$\sum m_\nu < 0.42\ \mathrm{eV}$

Active neutrino decays

1909.05275, 2002.08401, 2007.04994, 2011.01502, 2112.13862

$\sum m_\nu < 3\ \mathrm{eV}$

Time dependent neutrino mass

1811.01991, 2102.13618, 2101.05804, 2407.02462

Presence of dark radiation

astro-ph/0404585, 1510.02201, 2009.03286, 2211.01729

Large m_ν Cosmology

Presence of dark radiation

Cosmological bounds are sensitive to neutrino energy density

$$\Omega_\nu h^2 \equiv \frac{\sum m_\nu n_\nu^0 h^2}{\rho_{\text{critical}}} < 1.3 \times 10^{-3}\ (95\,\%\ \text{CL}) \longrightarrow \sum m_\nu \times \left(\frac{n_\nu^0}{56\ \text{cm}^{-3}}\right) < 0.12\ \text{eV}\ (95\,\%\ \text{CL})$$

PLANCK 2018

Reduce number density of neutrinos → Mass bound can be relaxed

At earlier times for ultra-relativistic νs: Energy density characterised by $N_{\text{eff}} \propto \langle p_\nu \rangle n_\nu$

- 2.99 ± 0.17 PLANCK 2018
- $3.044(1)$ SM prediction

$$N_{\text{eff}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\text{rad}} - \rho_\gamma}{\rho_\gamma}\right)$$

Compensate decrease in n_ν : Add new light/massless d.o.f → Dark radiation

Large m_ν Cosmology

Presence of dark radiation + dark matter

BBN ⟷ CMB

Introduce a mechanism to reduce n_ν

Add BSM states: X, χs, ψ that thermalise with νs

$100\ \mathrm{keV} \gtrsim T_\gamma \gtrsim 10\ \mathrm{eV}$

Post $\nu-$decoupling ($T_\gamma \sim 2\ \mathrm{MeV}$):
Neutrinos cannot be produced anymore:
Production of new states at their expense
→ n_ν reduced

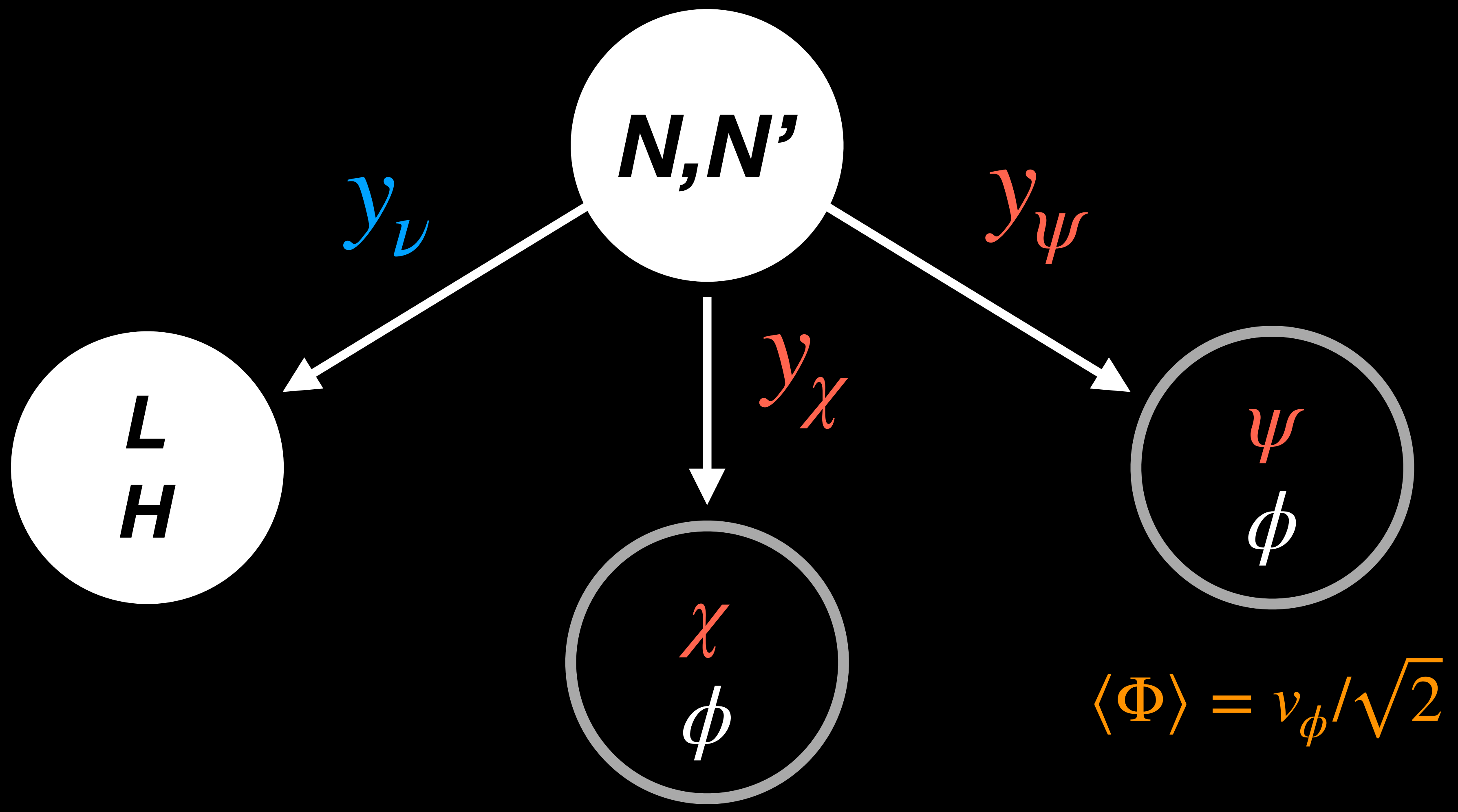
$$\left[\sum m_\nu\right]_{\mathrm{eff}} = \sum m_\nu \frac{n_\nu}{n_\nu^{\mathrm{SM}}}$$

Thermal DM below MeV possible if DM comes into thermal equilibrium post ν-decoupling

Berlin, Blinov: 1706.07046

The Model

Minimally Extended Type-I Seesaw with U(1)X

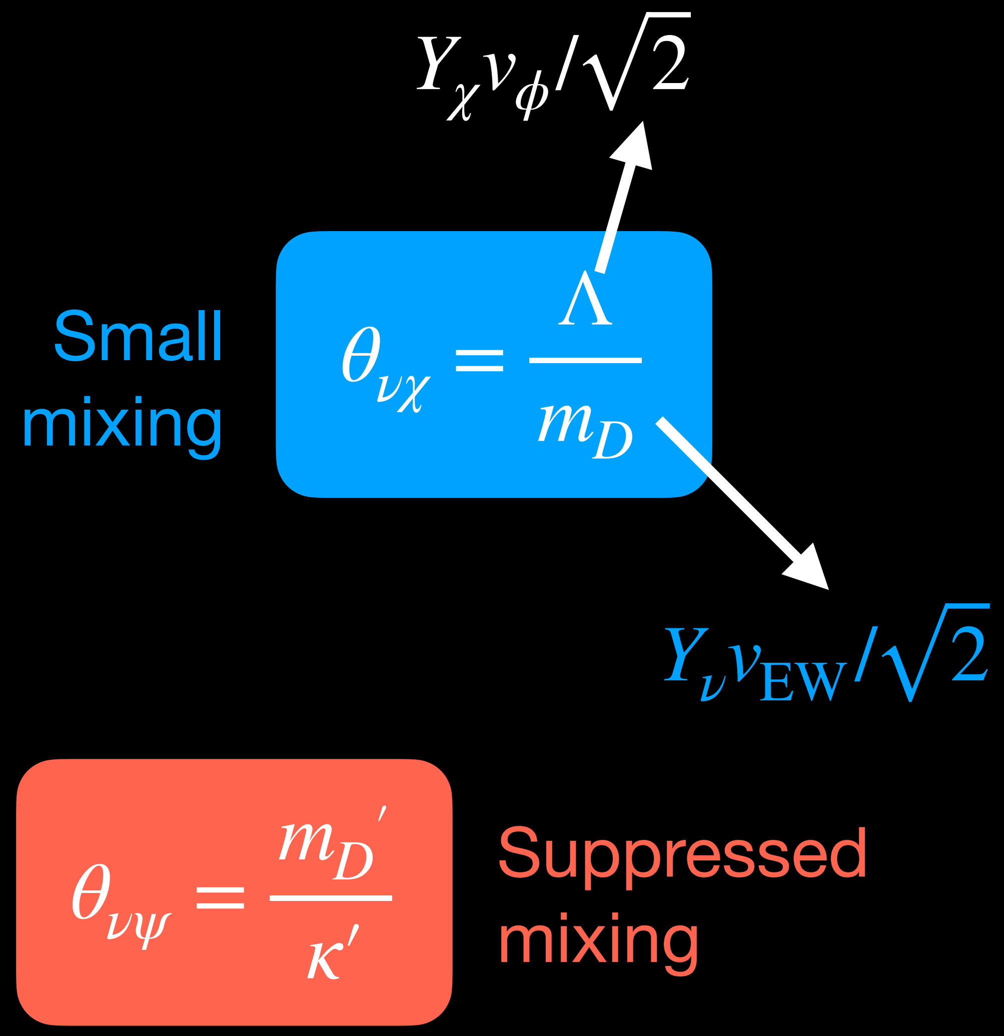


Massless: $(3 + N_{\text{light}} - N_{\text{heavy}})$

N_χ massless fermions

Massive: $2N_{\text{heavy}}$

$$\boxed{\begin{aligned} m_\nu &\approx m_D M^{-1} m_D^T \\ m_\psi &\approx \kappa' M'^{-1} \kappa'^T \end{aligned}}$$



Similar to $\nu\Lambda$MDM: Ko and Tang: 1404.0236

DM freeze-out in DS

Production & Depletion

$$\nu\nu \leftrightarrow Z' \leftrightarrow \chi\chi$$

DM can be produced by $Z' \leftrightarrow \psi\psi\ (m_{Z'} > 2m_\psi)$ or $Z'Z' \leftrightarrow \psi\psi$ and $\chi\chi \leftrightarrow \psi\psi\ (m_\psi > m_{Z'})$

Freeze-out: $\psi\psi \leftrightarrow \chi\chi$ and $\psi\psi \leftrightarrow Z'Z'$ freeze-out at $T_{\text{dark}} < m_\psi$

$$\psi\psi \rightarrow \psi\psi$$

$$\psi\chi \rightarrow \psi\chi$$

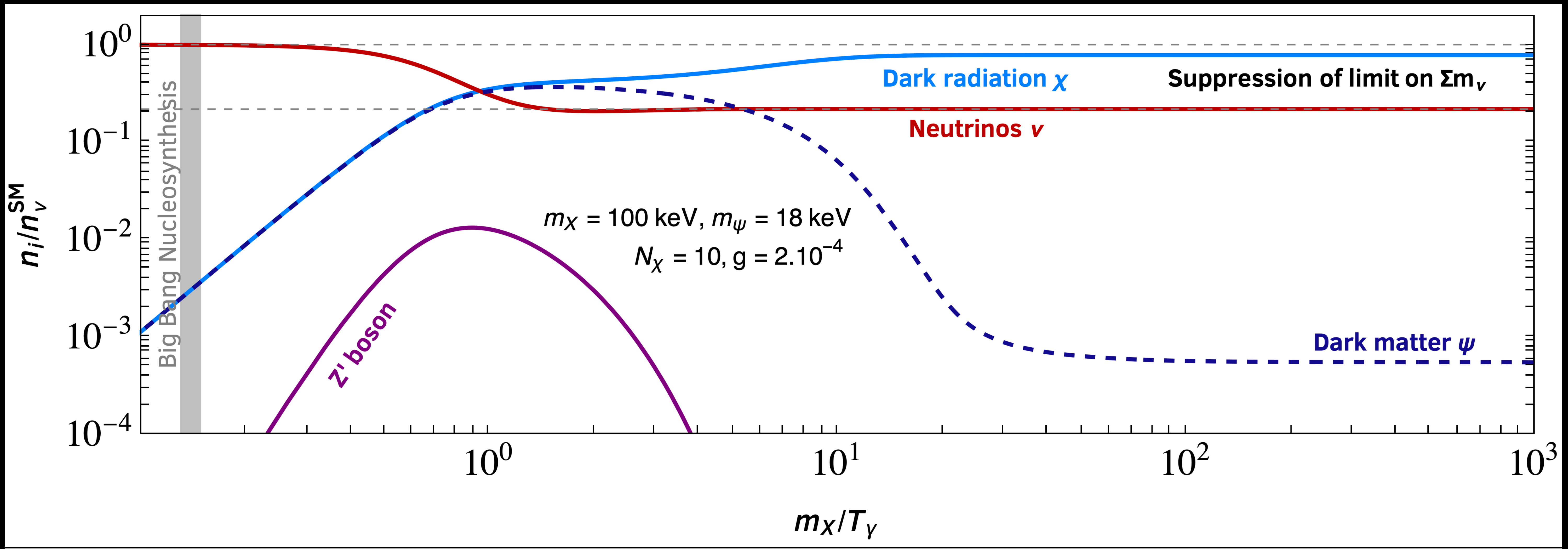
$$\mathscr{L}_{\text{int}} = \sum_f Q_f g Z'_\mu \bar{f}\gamma^\mu f$$

$$\lambda_{Z'}^{\nu\nu} \simeq \frac{m_{Z'}}{v_\phi}\theta_{\nu\chi}^2$$

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

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

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



DM freeze-out in DS

Relic abundance

ψ comes into thermal equilibrium with the DS and finally freezes out

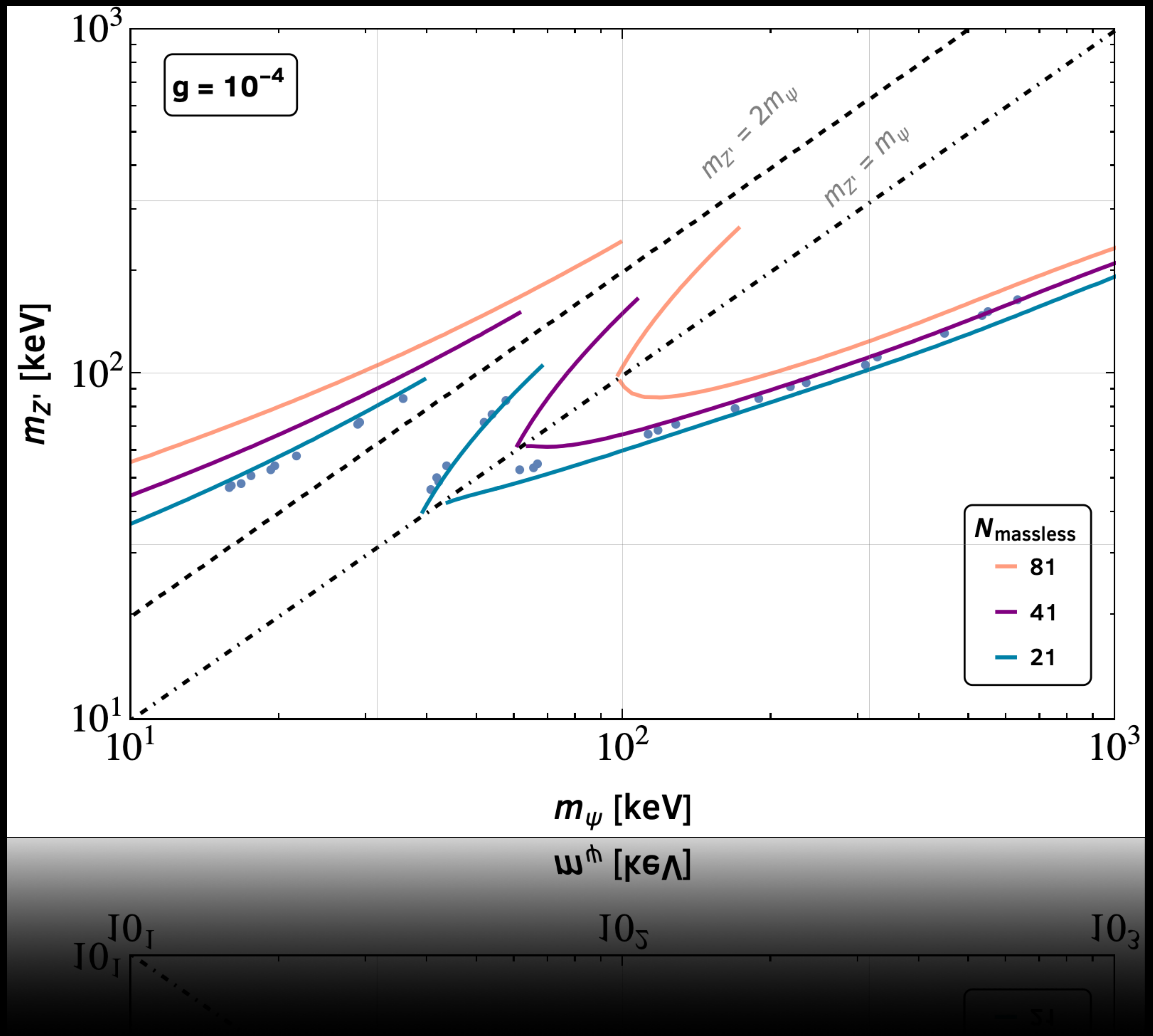
$$\Omega_\psi h^2 \simeq x_f \frac{10^{-10}\,\mathrm{GeV}^{-2}}{\langle \sigma v\rangle_{\mathrm{tot}}}$$

$$(\sigma v)_{\psi\psi\to\chi\chi} \approx \tilde{N}\frac{g^4}{48\pi}\frac{m_\psi^2}{(m_{Z'}^2-4m_\psi^2)^2}v^2$$

p-wave suppressed

$$(\sigma v)_{\psi\psi\to Z'Z'} \approx \frac{g^4}{16\pi\, m_\psi^2}\left(1-\frac{m_{Z'}^2}{m_\psi^2}\right)^{1/2}\left(1+\frac{m_\psi^4}{m_{Z'}^4}v^2\right)$$

Extreme limits: $m_{Z'} \gg m_\psi$ or vice versa $\rightarrow (\sigma v) \propto v_\phi^{-4}$



Constraints

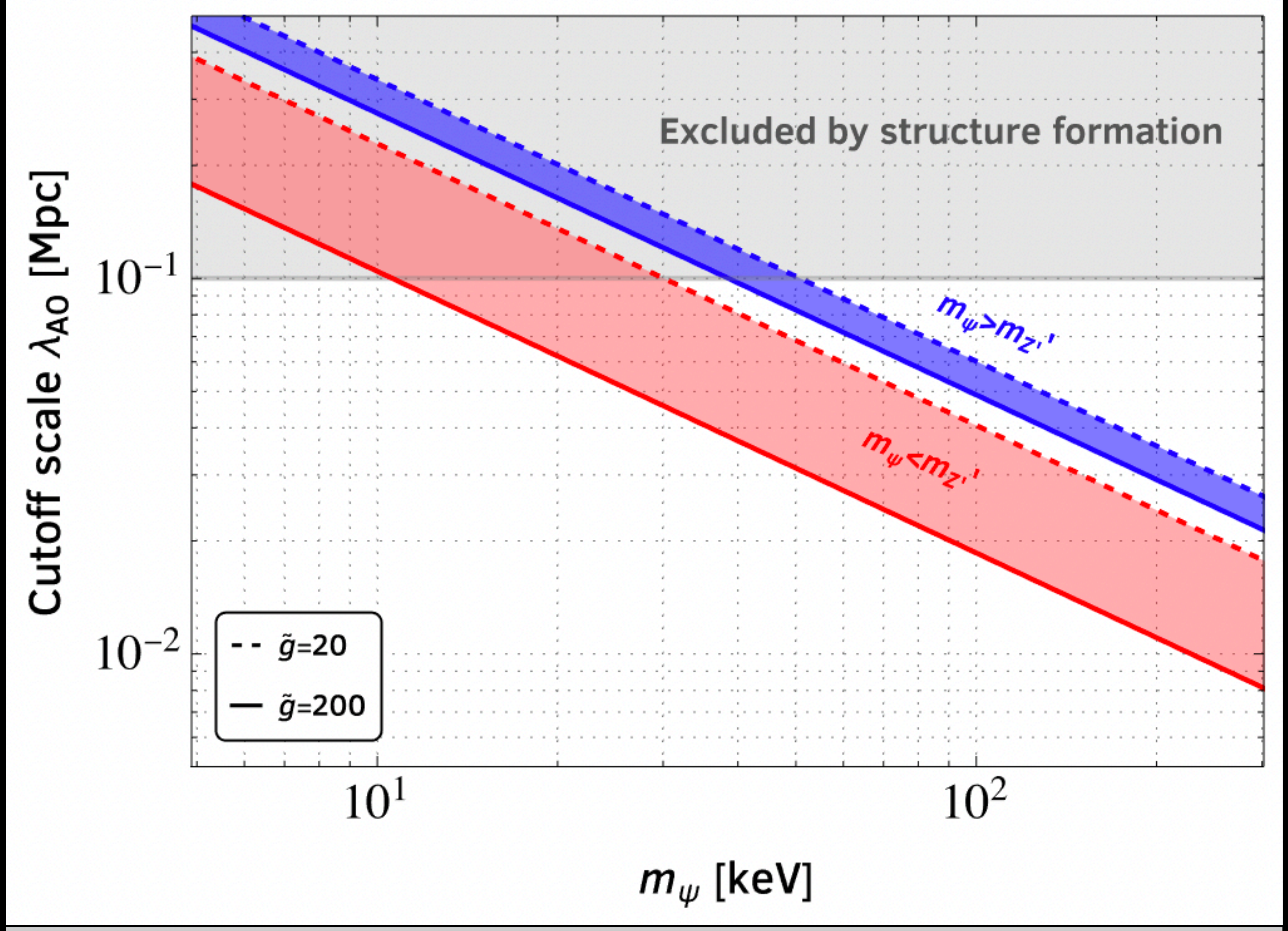
Structure formation

Potentially large free-streaming scale →
Prevent formation of small scale structures

Post freeze-out DM ψ remains in thermal contact with dark radiation χ via elastic processes $\psi\chi \leftrightarrow \psi\chi$

$$M_{\rm hm} = \frac{4\pi}{3}\rho_{\rm DM}\left(\frac{\lambda_{\rm hm}}{2}\right)^3 \approx 1.9\times 10^7\, M_\odot \left(\frac{\lambda_{\rm hm}}{0.1\,\rm Mpc}\right)^3$$

Depends on
temperature of
kinetic decoupling
$T_{\rm kd}$



Viable Parameter Space

Putting everything together

Thermalisation

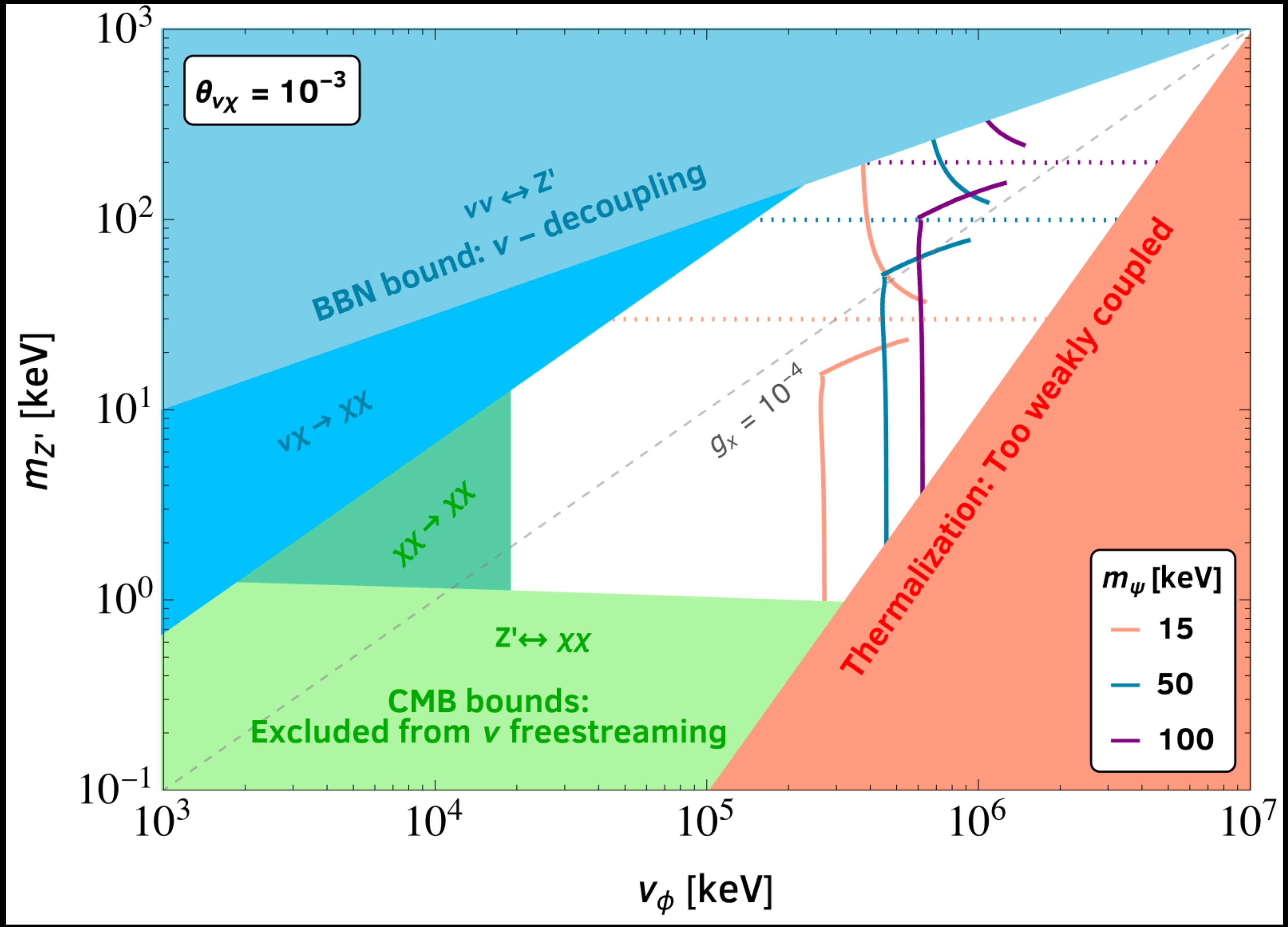
νs should thermalise with Z' in $0.7\ \text{MeV} > T_\gamma > 10\ \text{eV}$

BBN constraints

νs should not thermalise with Z'; avoid χ's exponential growth $\nu\chi \leftrightarrow \chi\chi$ at $T_\gamma > 0.7\ \text{MeV}$

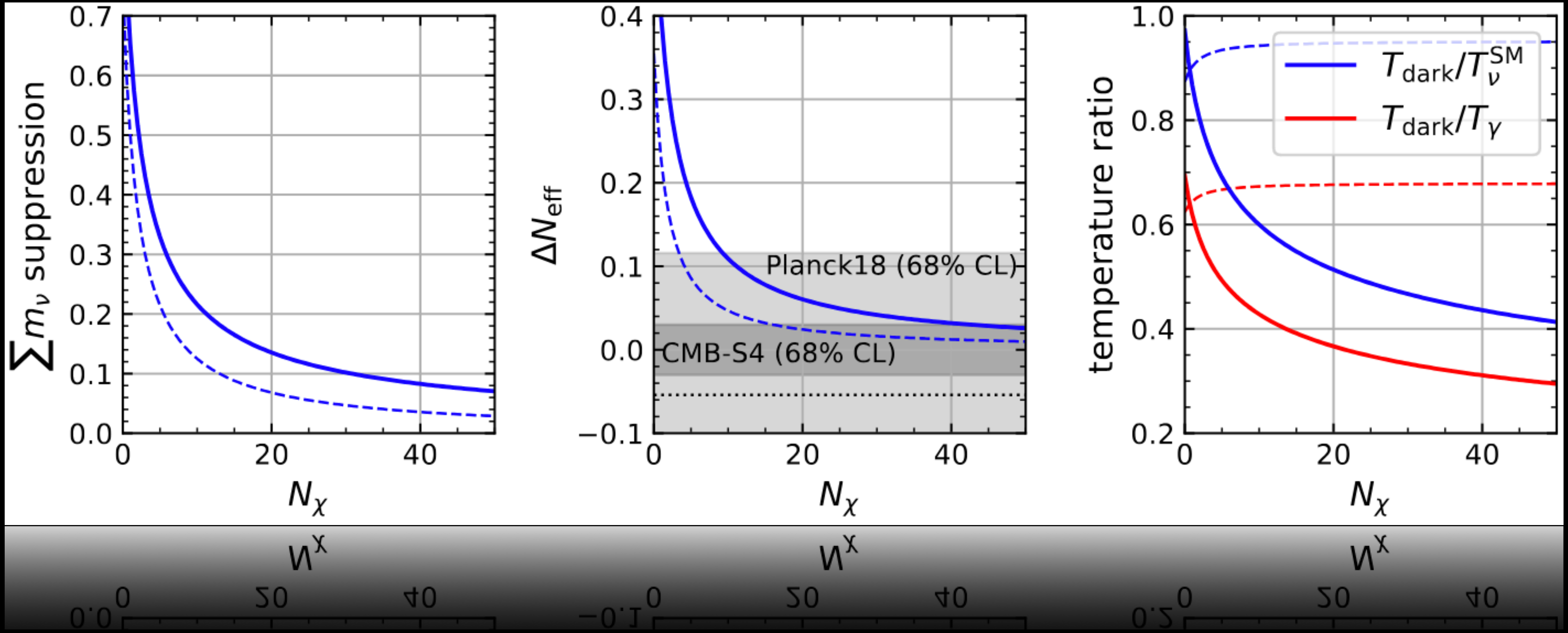
CMB constraints

$\nu\nu \rightarrow Z'$ and $Z' \rightarrow \chi\chi$ must be inefficient at $z \sim 10^5$; CMB not perturbed by lack of χ free streaming



Neutrino Mass Suppression

N_{eff} and DS Temperature



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_ν/n_ν^{SM}	ΔN_{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

Summary

Comparing cosmology and laboratory bounds on $\sum m_\nu$ → Hints of new physics

The cosmological neutrino mass bound can be relaxed with a light dark sector: many new interactions!

DM thermalises with the DS and then freezes out → Abundance set by DS gauge interactions, not by mixing with SM neutrinos

Signatures of the model → Slightly increased N_{eff} at late times, Suppressed matter power spectrum at small scales

Backup

Neutrino Mass Suppression

N_{eff} and DS Temperature

New degrees of freedom come into equilibrium with neutrinos at T_ν^{eq} to form a system with T_{eq}

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

System evolves adiabatically from T_{eq} to T_{fin} when ψ, Z' become non-relativistic, use $a_{\text{eq}}^3 s_{\text{eq}}(T_{\text{eq}}) = a_{\text{fin}}^3 s_{\text{fin}}(T_{\text{fin}})$

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

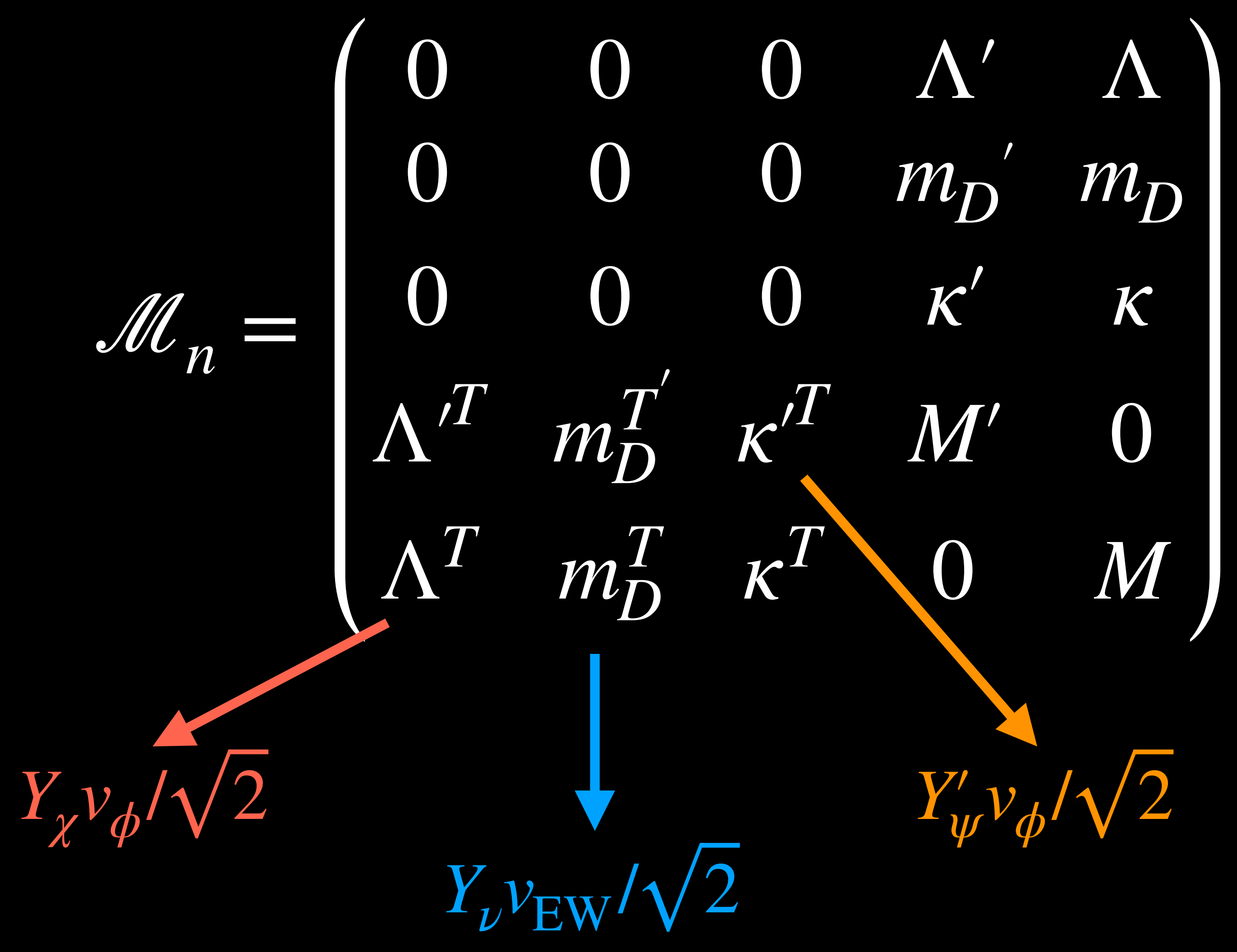
$$N_{\text{eff}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_{\text{dark}}}{\rho_\gamma} = \frac{g_\nu + \tilde{g}}{2}\left(\frac{T_{\text{dark}}}{T_\nu^{\text{SM}}}\right)^4$$

$$\left[\sum m_\nu\right]_{\text{eff}} = \sum m_\nu \frac{n_\nu}{n_\nu^{\text{SM}}}$$

The Model

Masses & Mixings

Neutral fermion mixing matrix:
$(\chi_L^c, \nu_L^c, \psi_L^c, N', N)$ basis



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

$Y_\chi v_\phi/\sqrt{2}$

$Y_\nu v_{\mathrm{EW}}/\sqrt{2}$

$Y'_\psi v_\phi/\sqrt{2}$

$$\xrightarrow{M \gg M' \gg m_D \gg \kappa', \Lambda \gg m'_D, \Lambda', \kappa}$$

Massive: $2N_{\mathrm{heavy}}$
Massless: $(3 + N_{\mathrm{light}} - N_{\mathrm{heavy}})$

$m_N \approx M\,, m_{N'} \approx M'$

$\boxed{m_\chi = 0}$ N_χ massless fermions

$$\boxed{\begin{aligned} m_\nu &\approx m_D M^{-1} m_D^T \\ m_\psi &\approx \kappa' M'^{-1} \kappa'^T \end{aligned}}$$

Seesaw induced
Majorana masses

$$m_\psi \sim 10\ \mathrm{keV} \left(\frac{\kappa'}{10^4\ \mathrm{keV}}\right)^2 \left(\frac{10\ \mathrm{GeV}}{M'}\right)$$

Small mixing $\boxed{\theta_{\nu\chi} = \frac{\Lambda}{m_D}}$

$\boxed{\theta_{\nu\psi} = \frac{m_D{}'}{\kappa'}}$ Suppressed mixing

ψ becomes the DM candidate in the model

Constraints

Structure formation

Free-streaming $$\lambda_{\mathrm{FS}} \approx \frac{1}{2}\int_{t_{\mathrm{kd}}}^{t_{\mathrm{MRE}}} dt\,\frac{v_\psi}{a(t)} \approx \frac{1}{2}\left(\frac{4\pi^3 g_{\mathrm{eff}}}{135}\right)^{-1/2}\sqrt{\frac{\xi}{T_{\mathrm{kd}} m_\psi}}\,\frac{M_{\mathrm{pl}}}{T_0}\log\frac{T_{\mathrm{kd}}}{T_{\mathrm{MRE}}}$$

Acoustic oscillations $$\lambda_{\mathrm{AO}} = \int_0^{t_{\mathrm{kd}}} \frac{dt}{a(t)} = \frac{1}{aH}\bigg|_{\mathrm{kd}} \approx \left(\frac{4\pi^3 g_{\mathrm{eff}}}{45}\right)^{-1/2}\frac{M_{\mathrm{pl}}}{T_{\mathrm{kd}} T_0}$$

$$\lambda_{\mathrm{cutoff}} = \max(\lambda_{\mathrm{FS}}, \lambda_{\mathrm{AO}}) < 0.1\,\mathrm{Mpc}$$

Constraints

Stability & X-ray bounds

DM decay → ψ lifetime should be larger than the age of the universe

$m_\psi < m_{Z'}$

$\boxed{\psi \to \nu\chi\chi}$

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

$m_\psi > m_{Z'}$

$\boxed{\psi \to Z'\nu}$

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

Sterile νDM mixing with active νs → Observable monochromatic X-ray line

$\boxed{\psi \to \nu\gamma}$

$$\Gamma_{\psi\to\nu\gamma} = \frac{9\,\alpha\,G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta_{\nu\psi})\, m_\psi^5$$

$$\theta^2_{\nu\psi} \lesssim 7.65 \times 10^{-13} \left(\frac{15\ \text{keV}}{m_\psi}\right)^5$$

$\theta_{\nu\psi}$ should be really suppressed