Neutrinos in Cosmology

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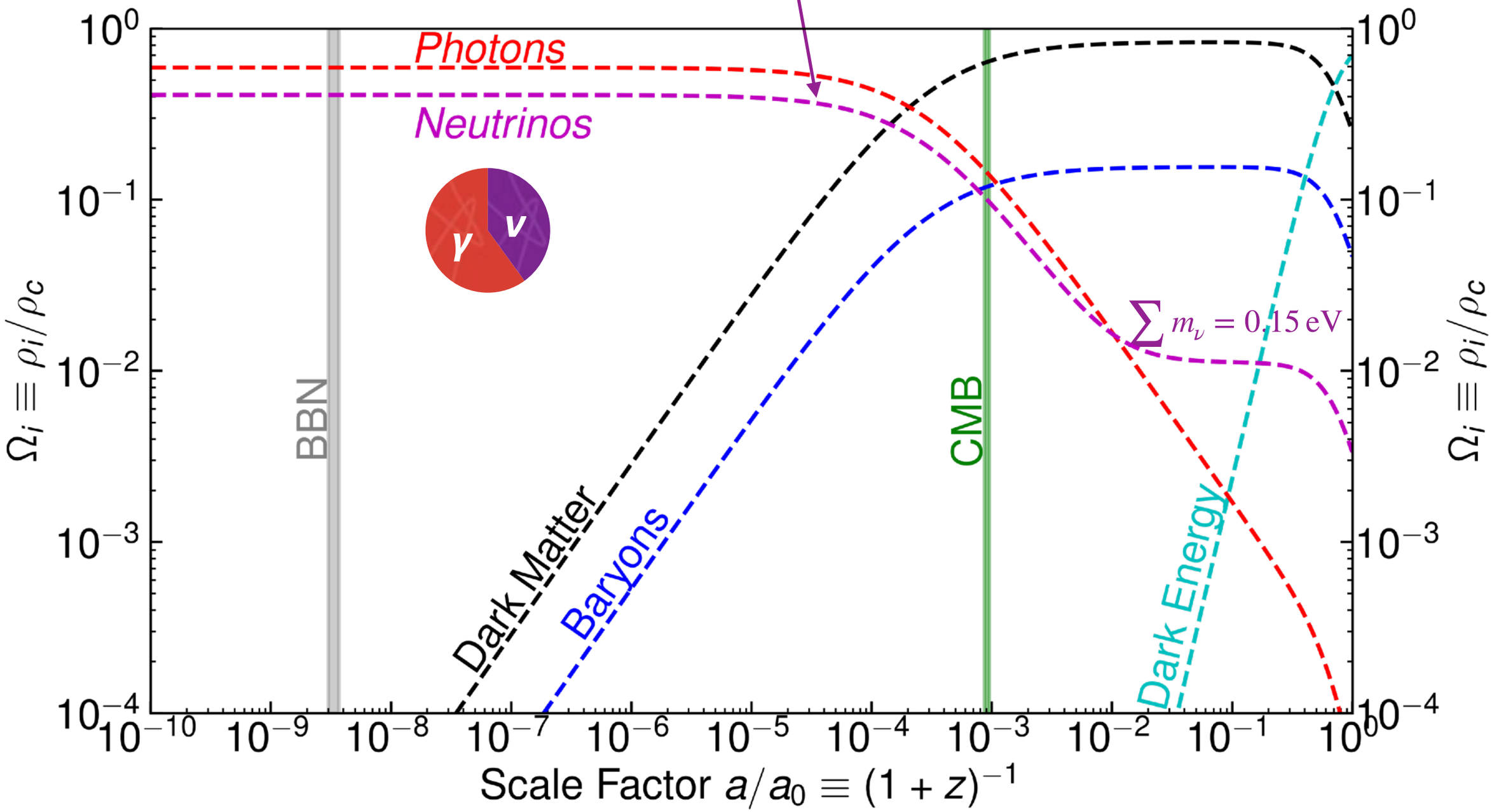
Light Dark World 2023
Karlsruhe
21-09-2023

Neutrino Evolution

Neutrinos are always a relevant species in the Universe's evolution

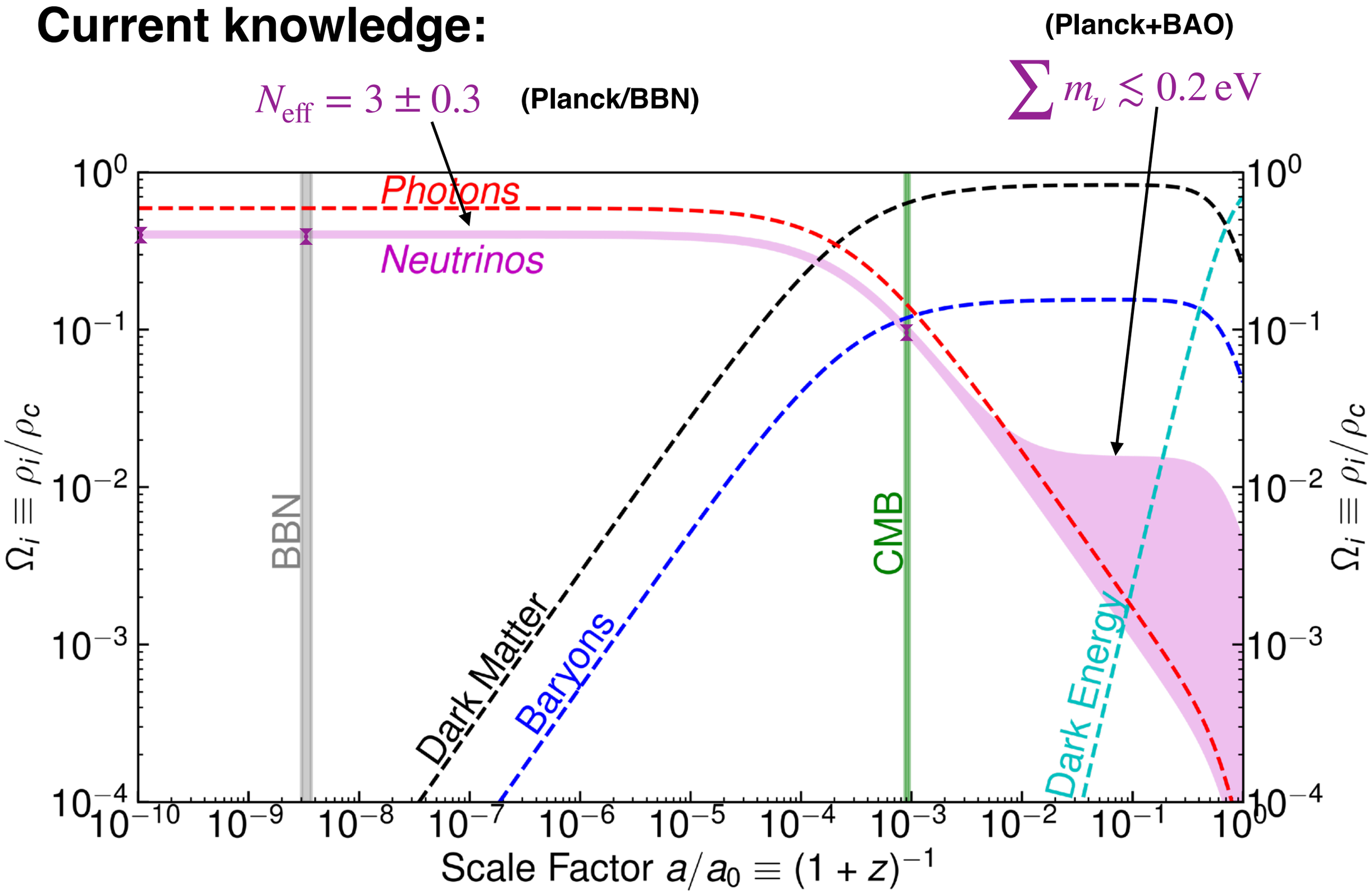


Non-Rel: $z_\nu^{\mathrm{non-rel}} \simeq 110 \dfrac{m_\nu}{0.06\,\mathrm{eV}}$

Hot DM: $\Omega_\nu h^2 = \sum m_\nu/(93.14\,\mathrm{eV})$

Global Perspective

Current knowledge:



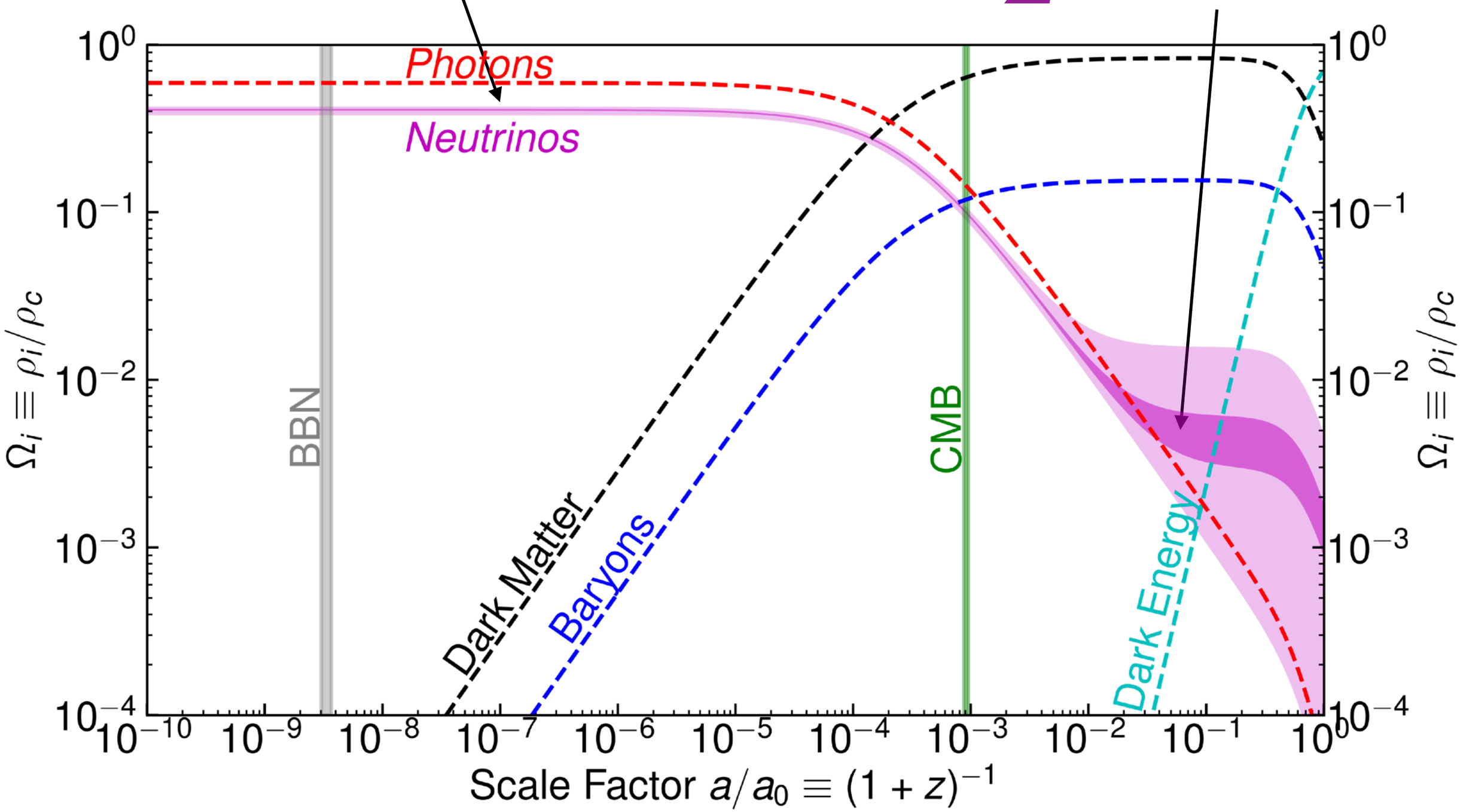
Global Perspective

In the next 5-6 years:

(DESI/Euclid + Planck)

$N_{\rm eff} = 3.043 \pm 0.06$ (Simons Observatory)

$\sum m_\nu = 0.06 \pm 0.02\,{\rm eV}$



Motivation

Neutrino Cosmology is about to enter the ultrahigh precision regime

1) Understand with high accuracy $N_{\rm eff}$ in the Standard Model

M.E.A. 1812.05605 & 2001.04466 [JCAP]

Cielo, M.E.A., Mangano & Pisanti 2306.05460

2) Understand the model dependence of the bounds on $\sum m_\nu$ from Cosmology

Particularly given the strong complementarity with laboratory experiments:

Planck: $\sum m_\nu < 0.12\,{\rm eV}$

$$\sum m_\nu \Big|_{\rm NO} \geq 0.06\,{\rm eV}$$

$$\sum m_\nu \Big|_{\rm IO} \geq 0.1\,{\rm eV}$$

KATRIN 2023: $\sum m_\nu < 2.4\,{\rm eV}$

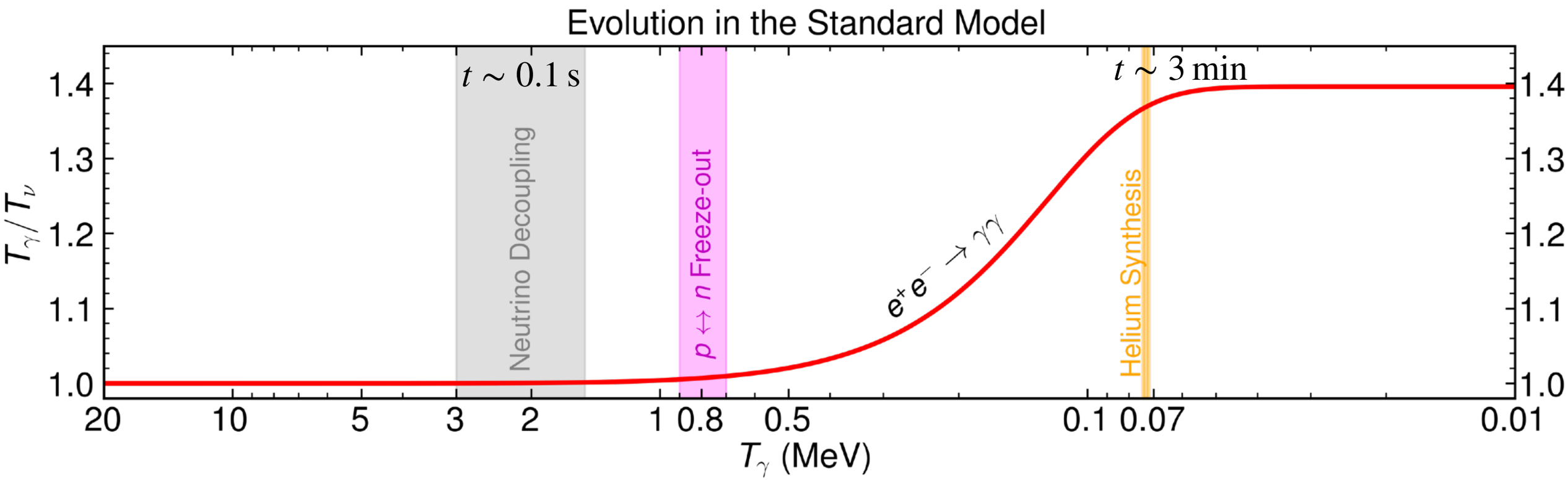
KATRIN 2027: $\sum m_\nu < 0.6\,{\rm eV}\,?$

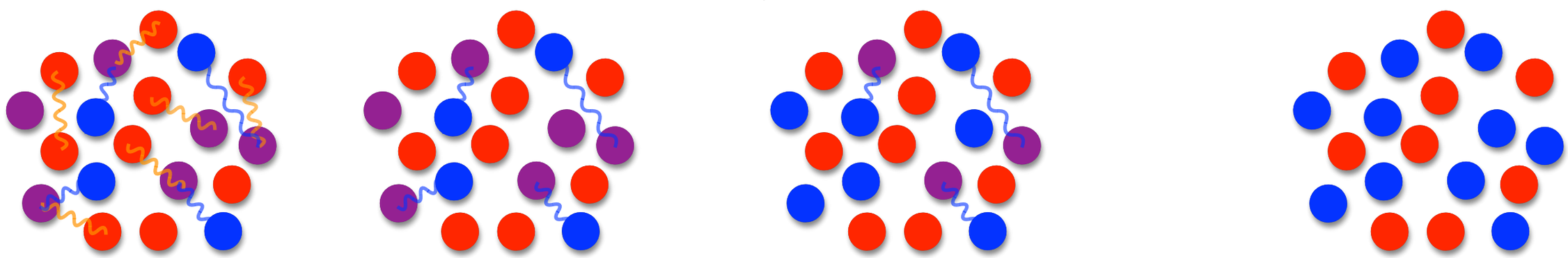
Exciting $0\nu\beta\beta$ program — see talk by Elisabetta Bossio

Alvey, M.E.A. & Sabti 2111.12726 [JCAP]

M.E.A., Schwetz & Terol-Calvo 2211.01729 [JHEP]

Neutrino Decoupling

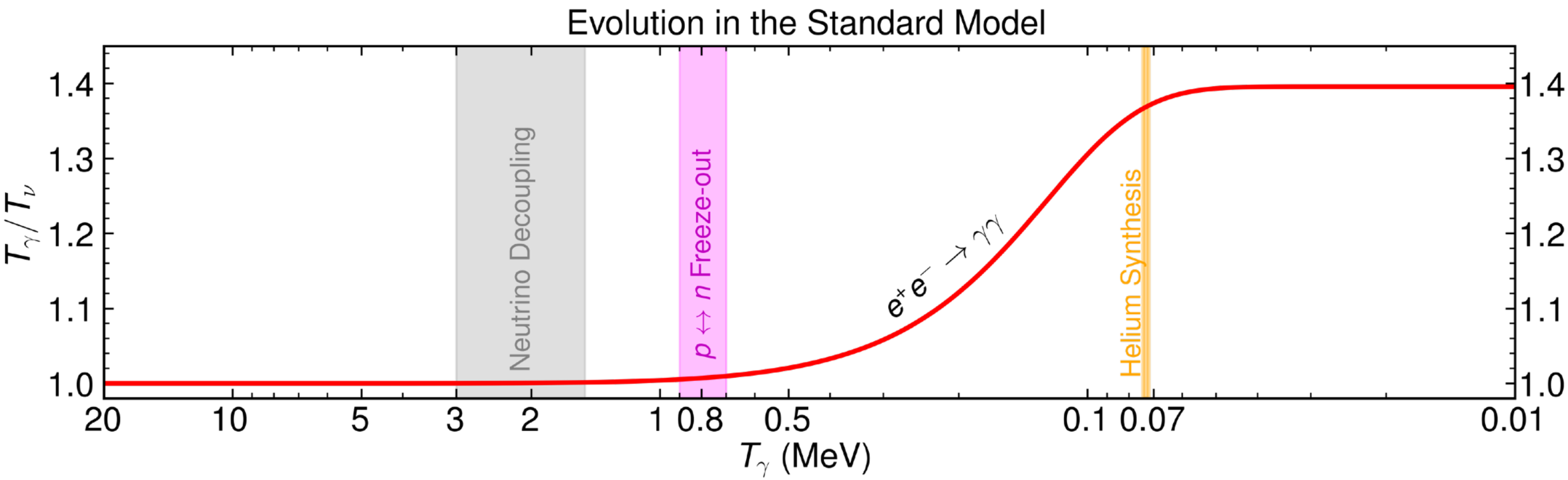




$$e^+e^- \leftrightarrow \bar{\nu}_i \nu_i$$
$$e^\pm \nu_i \leftrightarrow e^\pm \nu_i$$

Neutrinos **Electrons** **Photons** **Z-W (off-shell)**

Cosmic Neutrino Background



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

$$N_{\rm eff} = 3\left(\frac{1.4T_\nu}{T_\gamma}\right)^4$$

- $N_{\rm eff}^{\rm SM} = 3.044(1)$

Mangano et al. hep-ph/0506164
de Salas & Pastor 1606.06986
Bennett, Buldgen, Drewes & Wong 1911.04504
Escudero Abenza 2001.04466

Akita & Yamaguchi 2005.07047
Froustey, Pitrou & Volpe 2008.01074
Gariazzo, de Salas, Pastor et al. 2012.02726
Hansen, Shalgar & Tamborra 2012.03948

Why is Neff in the SM not 3?

Recently reviewed by Akita & Yamaguchi, 2210.10307, see also the nice review by Dolgov hep-ph/0202122

Relic Neutrino Decoupling $t \sim 0.1\,\mathrm{s}$ $T_\nu \sim 2\,\mathrm{MeV}$

1) **Some $e^+e^- \to \bar{\nu}\nu$ heating because $T_\nu^{\rm dec} \sim 4 \times m_e$** $\Delta N_{\rm eff} \simeq +0.03$ — Kolb et al. '82, Dolgov et al. '97

2) **Finite temperature corrections to $\delta m_\gamma^2(T)$ and $\delta m_e^2(T)$** $\Delta N_{\rm eff} \simeq +0.01$ — Heckler '94, Bennet et al. '21

3) **Neutrino oscillations** $\Delta N_{\rm eff} \simeq +0.0007$ — Mangano et al. '05, de Salas & Pastor '16

Standard Model prediction as of 2022: $N_{\rm eff}^{\rm SM} = 3.0440(2)$

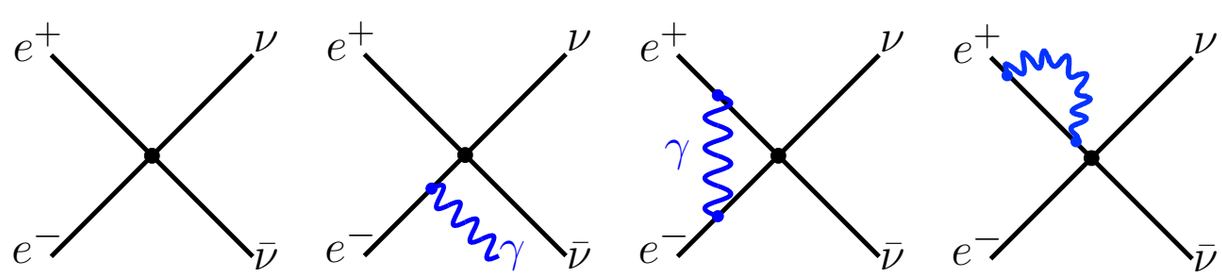
Akita & Yamaguchi 2005.07047
Froustey, Pitrou & Volpe 2008.01074
Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Wong 2012.02726

4) **Finite temperature QED corrections to $e^+e^- \to \bar{\nu}\nu$ processes**

QED corrections are well known to be sizable (~5%) for $\nu e \to \nu e$ scatterings for solar neutrinos, see e.g. Bahcall, Kamionkowski & Sirlin [astro-ph/9502003]

Estimate of this effect was made in Escudero Abenza 2001.04466 using an interpolation of the NLO rates from Esposito et al. [astro-ph/0301438]

Together with Gianpiero Mangano, Ofelia Pisanti and Mattia Cielo we have actually accurately accounted for the correction to the energy transfer rates which is ~ -4% at T = 1 MeV



At NLO: $\Delta N_{\rm eff} \simeq -0.0007$

$$N_{\rm eff}^{\rm SM} = 3.0432(2) = 3.043$$

Cielo, Escudero, Mangano & Pisanti 2306.05460

Neutrino Decoupling at LO

Traditional approach: Dodelson & Turner
Dolgov et al.
Pastor et al.

work in terms of the Liouville equation

$$\frac{df_\nu}{dt} - Hp\frac{\partial f_\nu}{\partial p} = C[f_\nu]$$

Pro 😃: Full solution

Con 😐: Very complicated system of ~200 stiff integrodifferential equations

see nice code: FortEPiaNO Gariazzo, Pastor & de Salas

Neutrino Decoupling at LO

Simplified approach: Escudero '19-'21

check code at
https://github.com/MiguelEA/nudec_BSM/

Taking advantage of the fact that neutrinos were in thermal equilibrium

And of the fact that spectral distortions are small $\Delta N_{\rm eff}^{\rm SM}/N_{\rm eff} \sim 1\,\%$

Assume that neutrinos follow Fermi-Dirac distributions parametrized by a dynamical temperature T_ν **and write down simple ODEs for them**

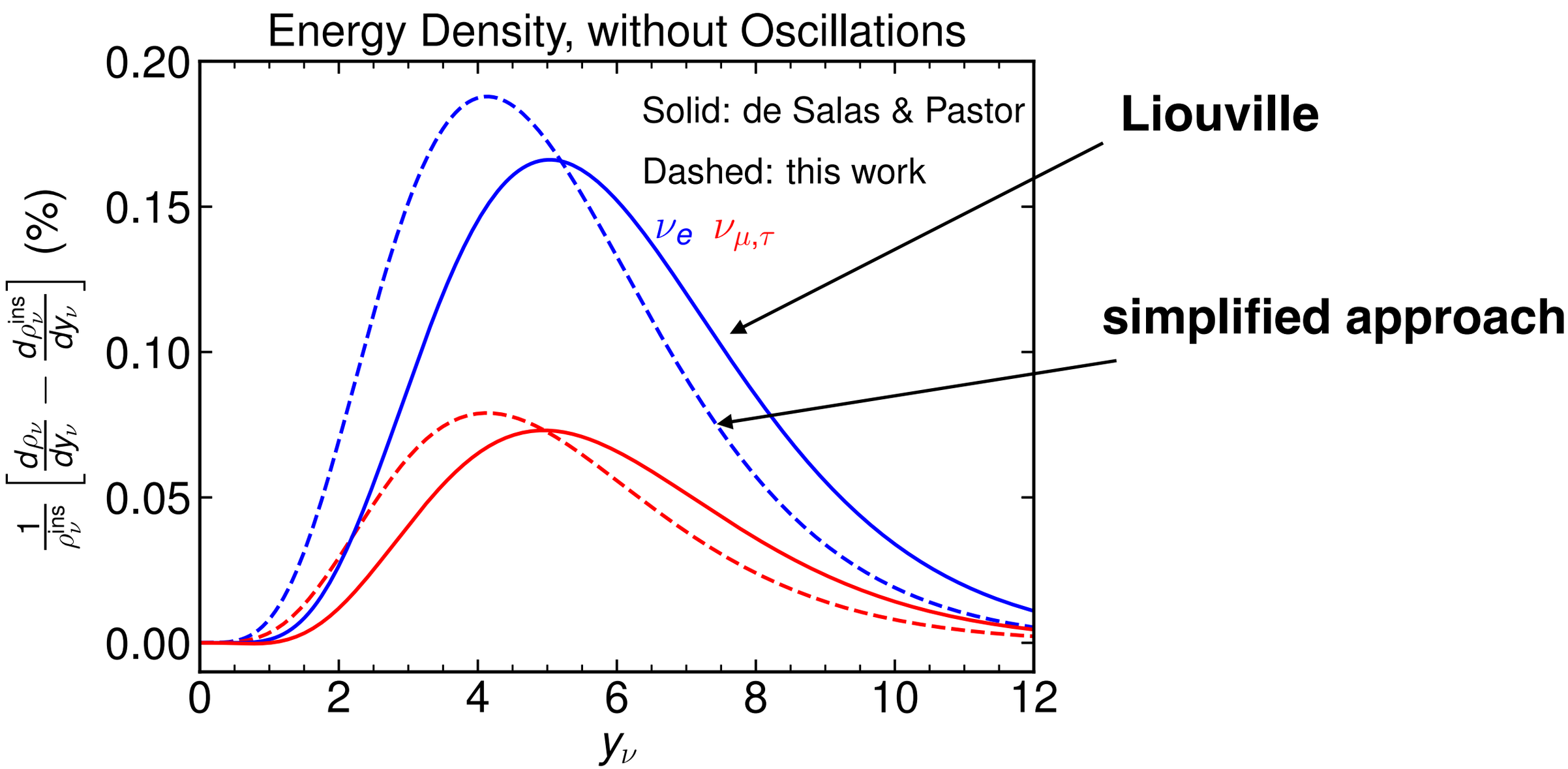
Results in: **2-3 simple coupled differential equations for** T_γ, T_ν

$$\frac{dT_\gamma}{dt} = -\frac{4H\rho_\gamma + 3H\left(\rho_e + p_e\right) + \frac{\delta\rho_{\nu_e}}{\delta t} + 2\frac{\delta\rho_{\nu_\mu}}{\delta t}}{\frac{\partial\rho_\gamma}{\partial T_\gamma} + \frac{\partial\rho_e}{\partial T_\gamma}} \qquad \frac{dT_\nu}{dt} = -H\,T_\nu + \frac{\frac{\delta\rho_{\nu_e}}{\delta t} + 2\frac{\delta\rho_{\nu_\mu}}{\delta t}}{3\,\frac{\partial\rho_\nu}{\partial T_\nu}}$$

Analytical expressions for the SM energy transfer rates: As a result of a 12 Dimensional integral!

$$\left.\frac{\delta\rho_\nu}{\delta t}\right|_{\rm SM}^{\rm MB} = \frac{G_F^2}{\pi^5}\left[4\left(g_{eL}^2 + g_{eR}^2\right)\right]\left[32\left(T_\gamma^9 - T_\nu^9\right) + 56\,T_\gamma^4 T_\nu^4 (T_\gamma - T_\nu)\right]$$

Comparison at LO

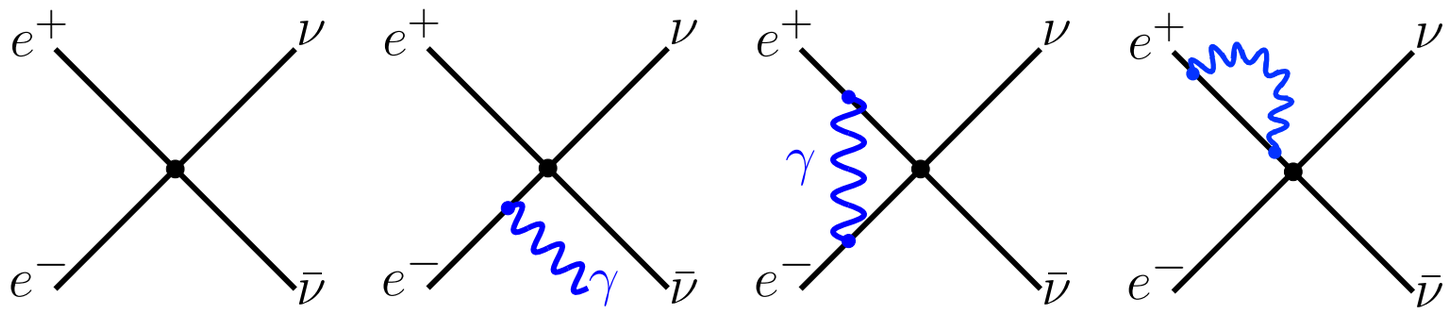


Agreement at better than the per-mille level in all relevant thermodynamic quantities!

Method can be used to calculate neutrino decoupling at NLO!

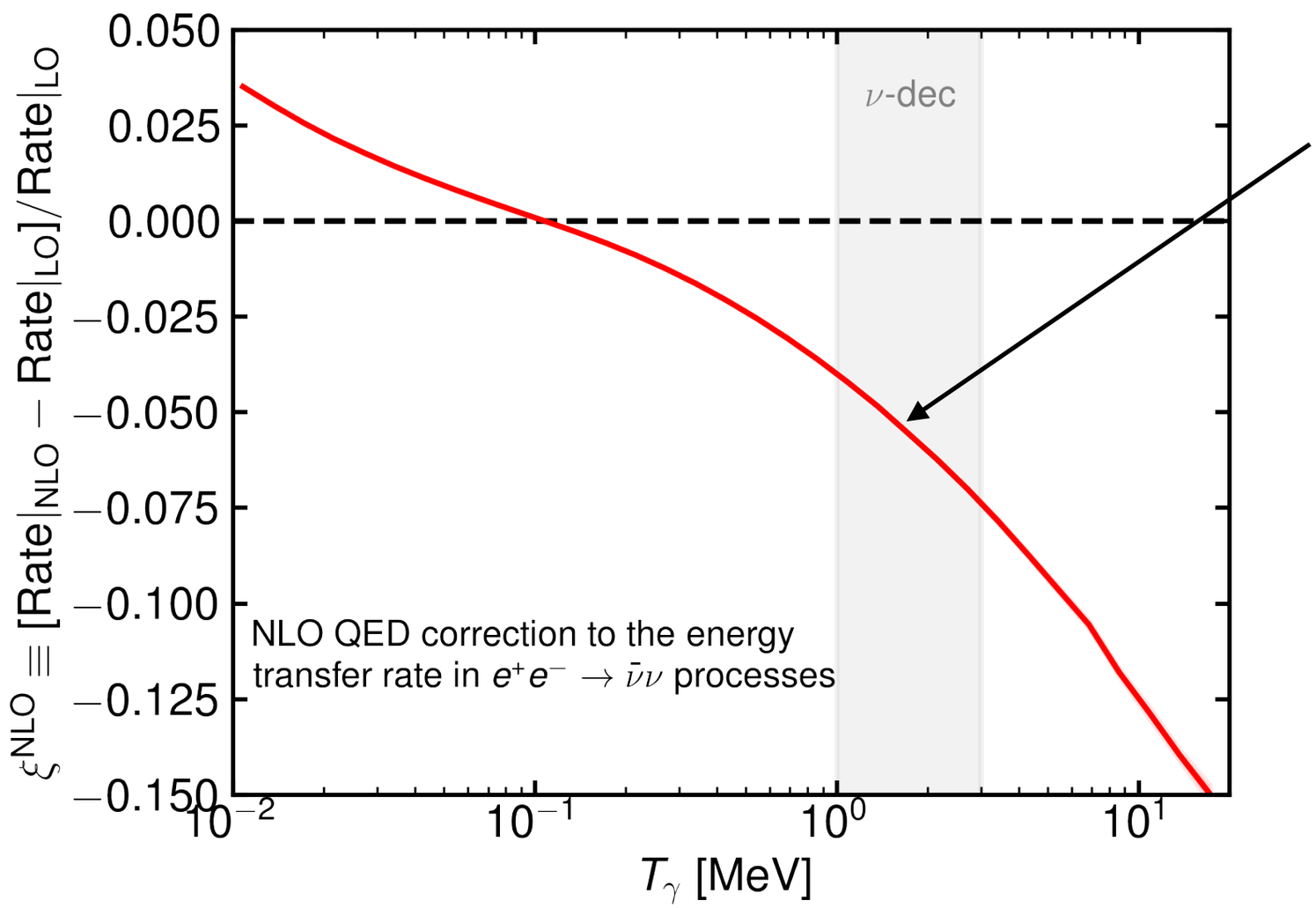
The Rate at NLO

Calculation performed following the real time formalism in thermal field theory



See Esposito, Mangano, Miele, Picard & Pisanti, astro-ph/0301438 & astro-ph/0112384

Result:



Relevant region:

Solution at NLO

Implementing the rate at NLO is trivial within the simplified approach but extremely challenging within the Liouville one due to the increase phase space integration

$$\left.\frac{\delta\rho_\nu}{\delta t}\right|_{\rm NLO} = (1+\xi^{\rm NLO}) \times \left.\frac{\delta\rho_\nu}{\delta t}\right|_{\rm LO}$$

Solving the system takes < 1 minute in my computer and the result is:

$$\boxed{N_{\rm eff}^{\rm NLO} - N_{\rm eff}^{\rm LO} = -\,0.0007}$$

Combining it with the results from the high precision calculations including the rest of the effects we find:

$$\boxed{N_{\rm eff}^{\rm SM} = 3.0432(2) = 3.043}$$

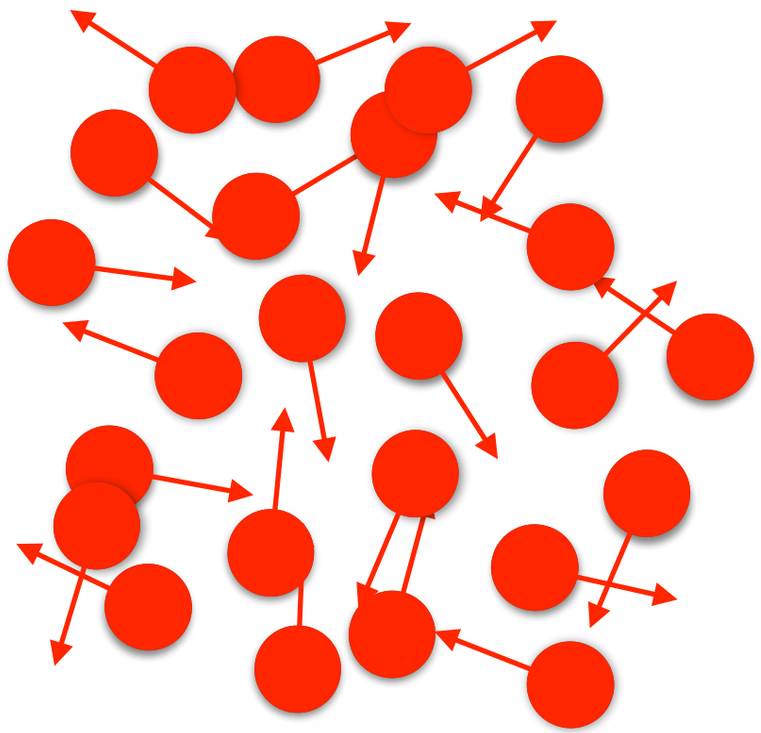
Where remaining uncertainty comes from uncertainty on θ_{12}, on NLO corrections to $\nu e \to \nu e$ and numerical precision of the solver.

Part II

One way to evade or relax the cosmological neutrino mass bound

The Cosmic Neutrino Background

SM

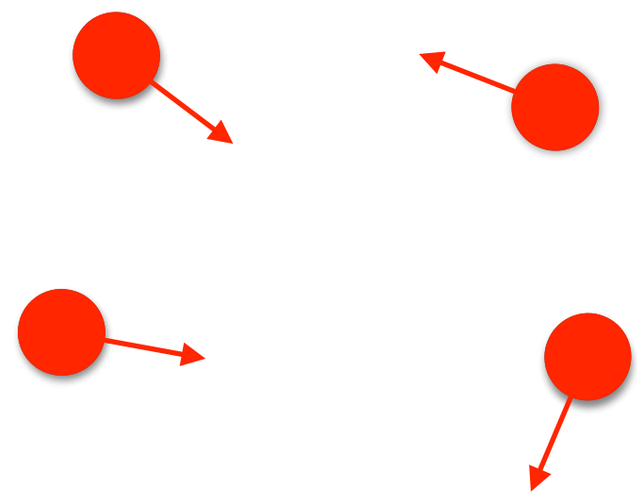


$n_\nu^{\rm SM} \sim 300\,{\rm cm}^{-3}$

$\sum m_\nu < 0.12\,{\rm eV}$

$n_\nu \propto T_\nu^3$

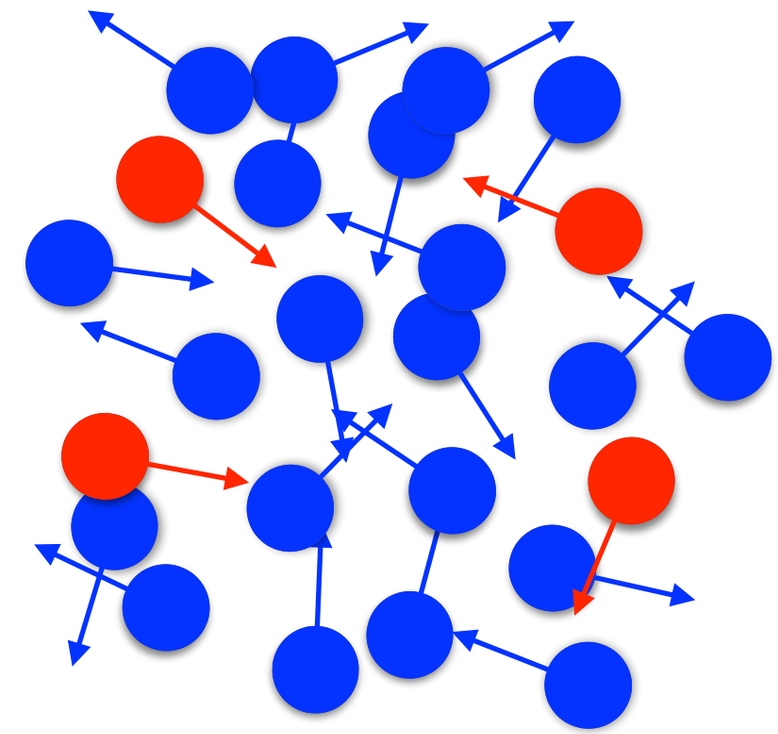
☹️ $N_{\rm eff} \propto T_\nu^4 \ll 3$



$n_\nu^{\rm SM} \sim 30\,{\rm cm}^{-3}$

😃 $\sum m_\nu < 1.2\,{\rm eV}$

solution:
add Dark Radiation



😃 $N_{\rm eff} \simeq 3$

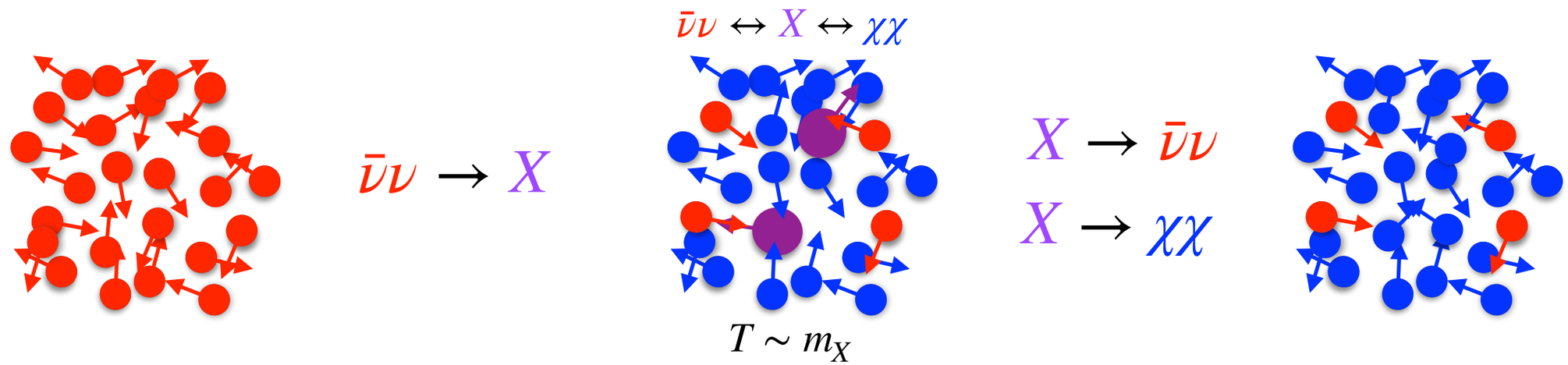
😃 $\sum m_\nu < 1.2\,{\rm eV}$

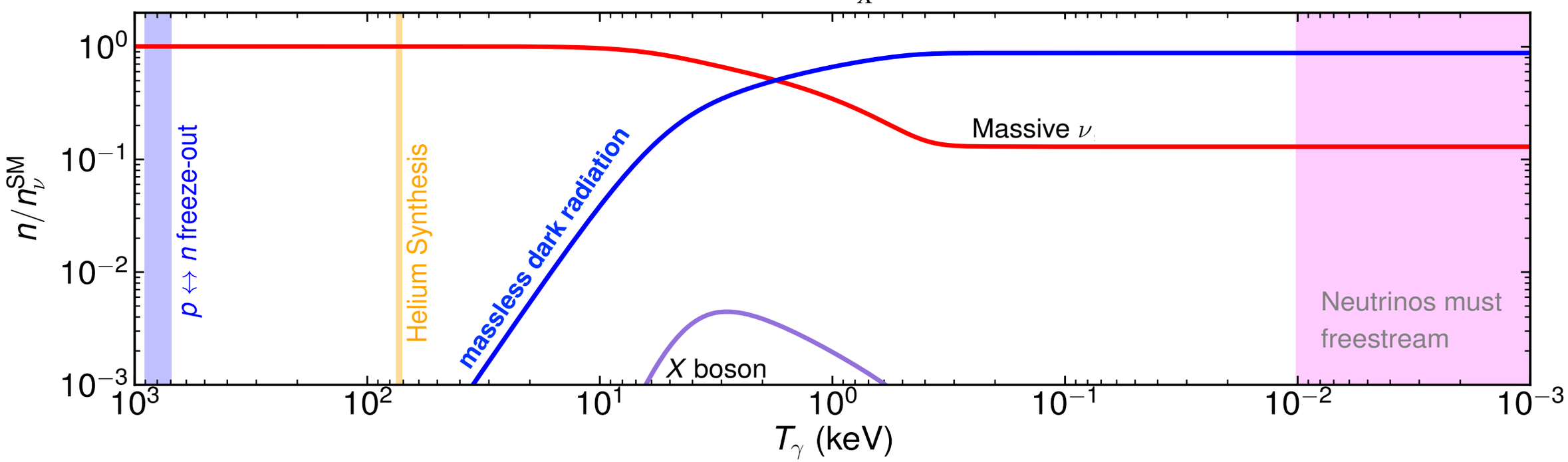
CMB observations can only constrain: $\rho_\nu^0 \equiv \sum m_\nu n_\nu$

see Alvey, M.E.A. & Sabti 2111.12726 and also Oldengott et al. 1901.04352 and Renk et al. 2009.03286

The Picture

Farzan & Hannestad 1510.02201
Escudero, Schwetz & Terol-Calvo 2211.01729





$$m_{Z'} \sim 1 - 100\,\text{keV} \qquad g_{\nu\nu} \gtrsim 10^{-10}$$

Summary of main features

Escudero, Schwetz & Terol-Calvo 2211.01729

- **Requirements:**
  1) **Features a neutrino mass mechanism (type-I seesaw)**
  2) **Have a large number of massless sterile states coupled to neutrinos**

$$\sum m_\nu < 0.12\,\text{eV}\left[1 + N_\chi/3\right] \qquad \boxed{N_\chi \sim 10 - 20}$$

  3) **These states are nevertheless coupled enough so that they can thermalize in the early Universe between BBN and recombination**
  4) **A new interacting boson at the keV scale**

- **The essence of the models:**
  - **Add a U(1)$_X$ symmetry with a scalar field and a singlet left-handed state S$_L$**

$$\mathcal{L} = y\Phi\overline{N}_R S_L \qquad M_\nu|^{7\times7} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^t & M_R & y_\alpha v_\Phi \\ 0 & (y_\alpha v_\Phi)^t & 0 \end{pmatrix}$$

Provided $y_\alpha v_\Phi \ll m_D$

- **Seesaw mechanism at play** $m_\nu \simeq m_D^2/M_R$
- **Right ν_4 properties:** $m_\chi \simeq 0 \quad U_{\alpha 4} \sim \dfrac{y_\alpha v_\Phi}{m_D} \ll 1$

Trivial to generalize to the case of $N_\chi \sim 10 - 20$**. Additional Z2 needed for Gauge case**

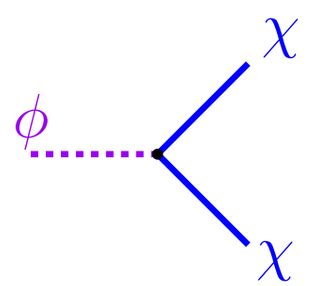
Complete UV models

- **Parameters:**

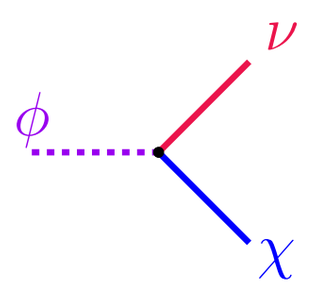
$\theta_{\nu\chi}$	**Active-sterile mixing**
v_Φ	**Scale at which $U(1)_X$ is spontaneously broken**
m_X	**Mass of mediator**

- **Two cases:**

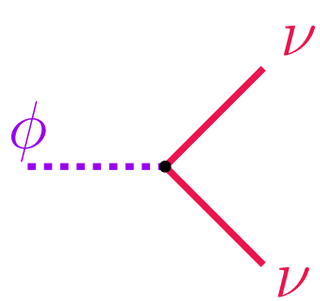
Global $U(1)_X$:



$$\lambda = 0$$

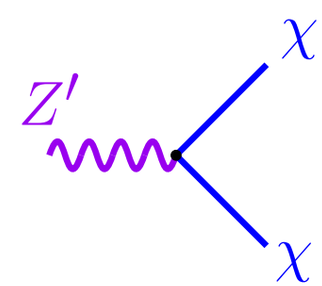


$$\lambda = \frac{m_\nu}{v_\Phi}\,\theta_{\nu\chi}$$

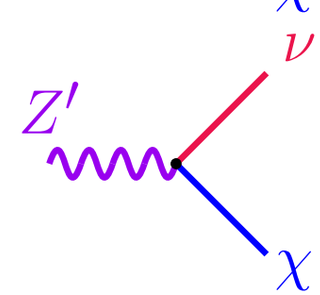


$$\lambda = \frac{m_\nu}{v_\Phi}\,\theta_{\nu\chi}^2$$

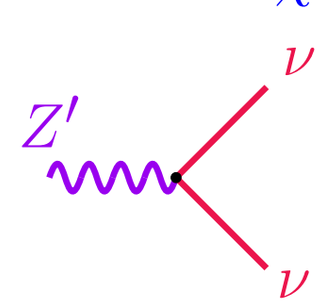
Gauge $U(1)_X$:



$$\lambda = g_X$$

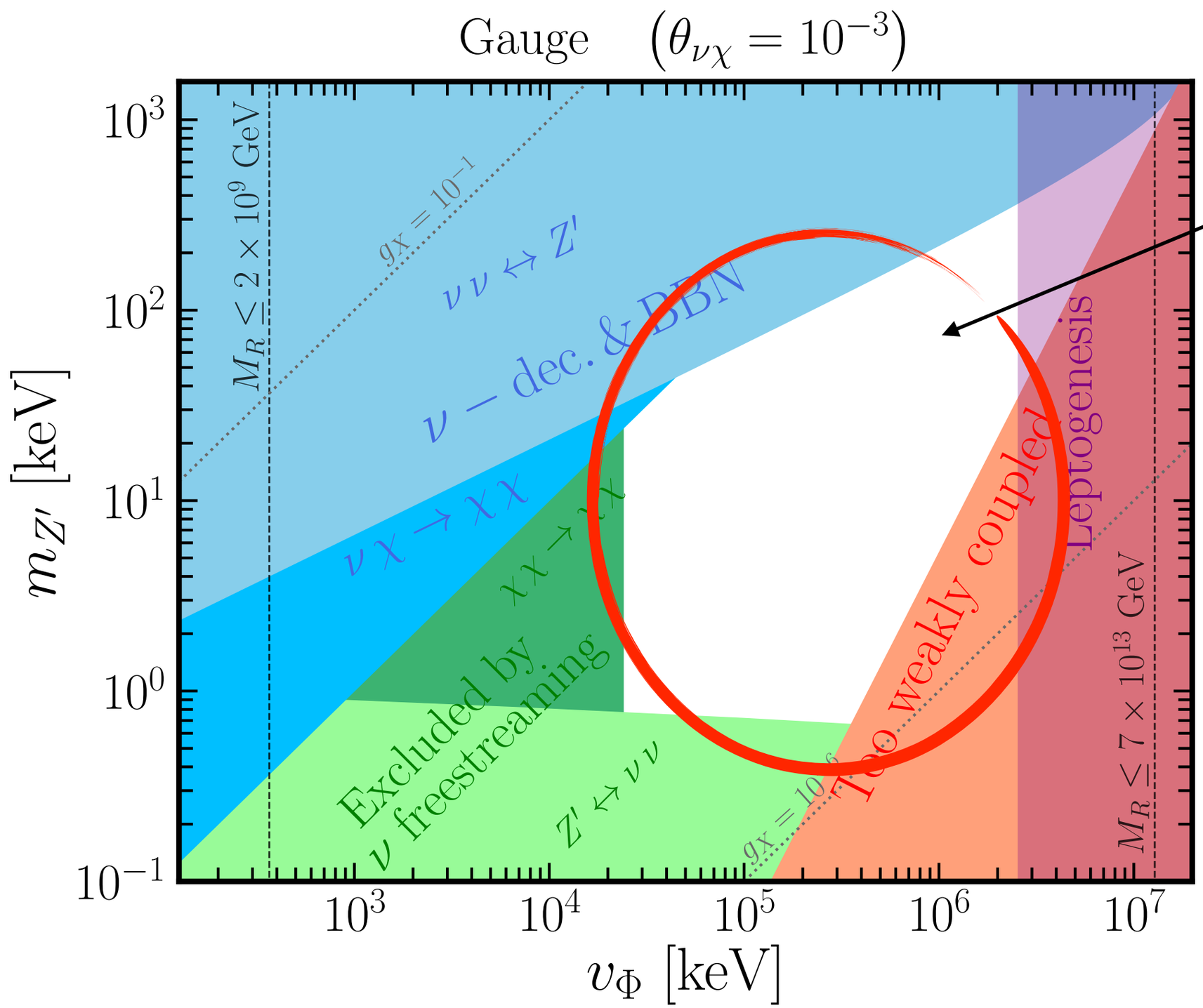


$$\lambda = g_X\,\theta_{\nu\chi}$$



$$\lambda = g_X\,\theta_{\nu\chi}^2$$

Parameter Space



Viable Parameter space

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

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

Conclusions

Number of effective neutrino species

$$N_{\rm eff}^{\rm CMB}|_{2018} = 2.99 \pm 0.17$$
$$N_{\rm eff}^{\rm CMB}|_{2028} = X.X \pm 0.06$$

Revisited the Standard Model prediction at NLO

The new number to remember is: $\boxed{N_{\rm eff}^{\rm SM} = 3.043}$

Neutrino Masses:

Cosmological bounds are very stringent in ΛCDM: $\sum m_\nu < 0.12\,{\rm eV}$

The case of a non-standard CNB to relax them

We developed a simple scenario compatible with high scale type-I seesaw

Need a large number of dark radiation species interacting with neutrinos between BBN and recombination

Parameter space of interest is $m_{Z'} \sim 10\,{\rm keV}$ **and** $v_\Phi \sim 10\,{\rm MeV} - 1{\rm GeV}$

As of now a fun model building exercise but could get more relevance if we were to detect something in the lab or nothing in cosmology!

Time for Questions and Comments

Check out my Neff code at:

https://github.com/MiguelEA/nudec_BSM/

Thank you for your attention!

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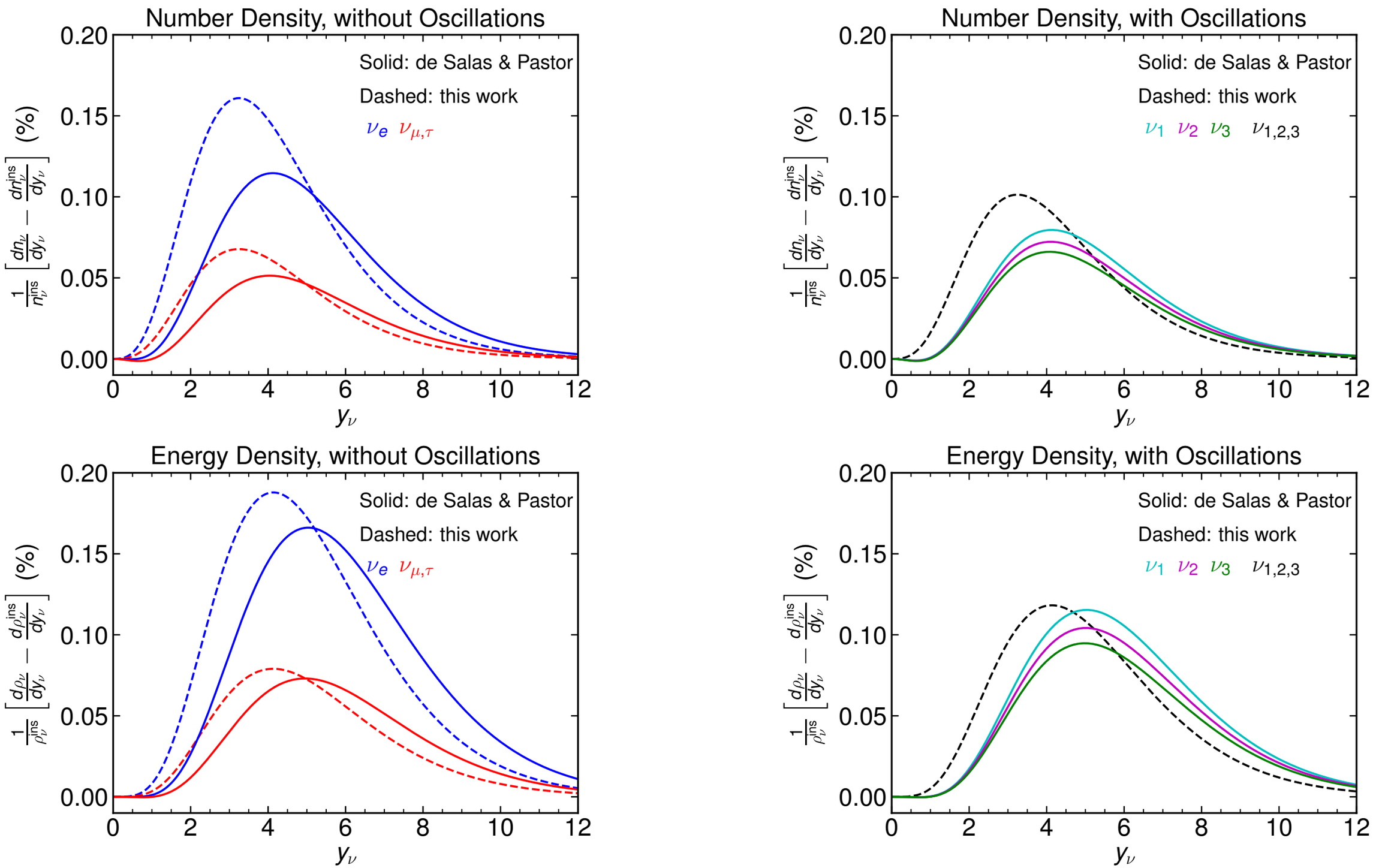
Back Up

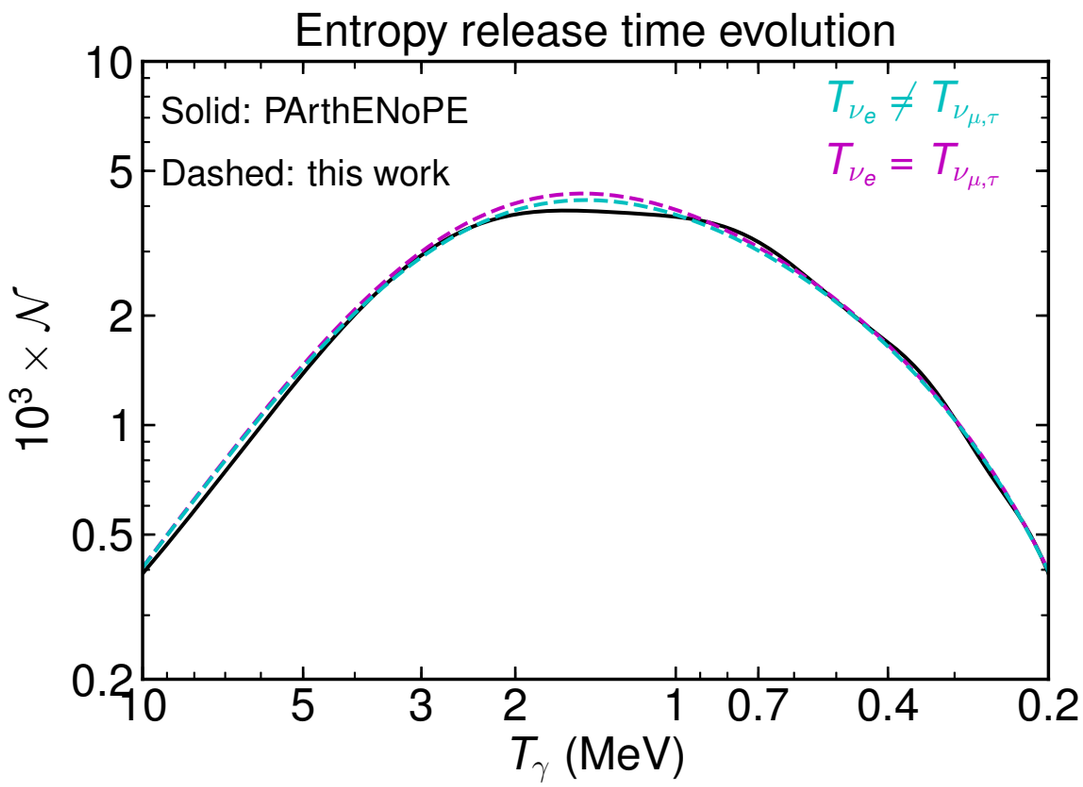
SM Neutrino Decoupling

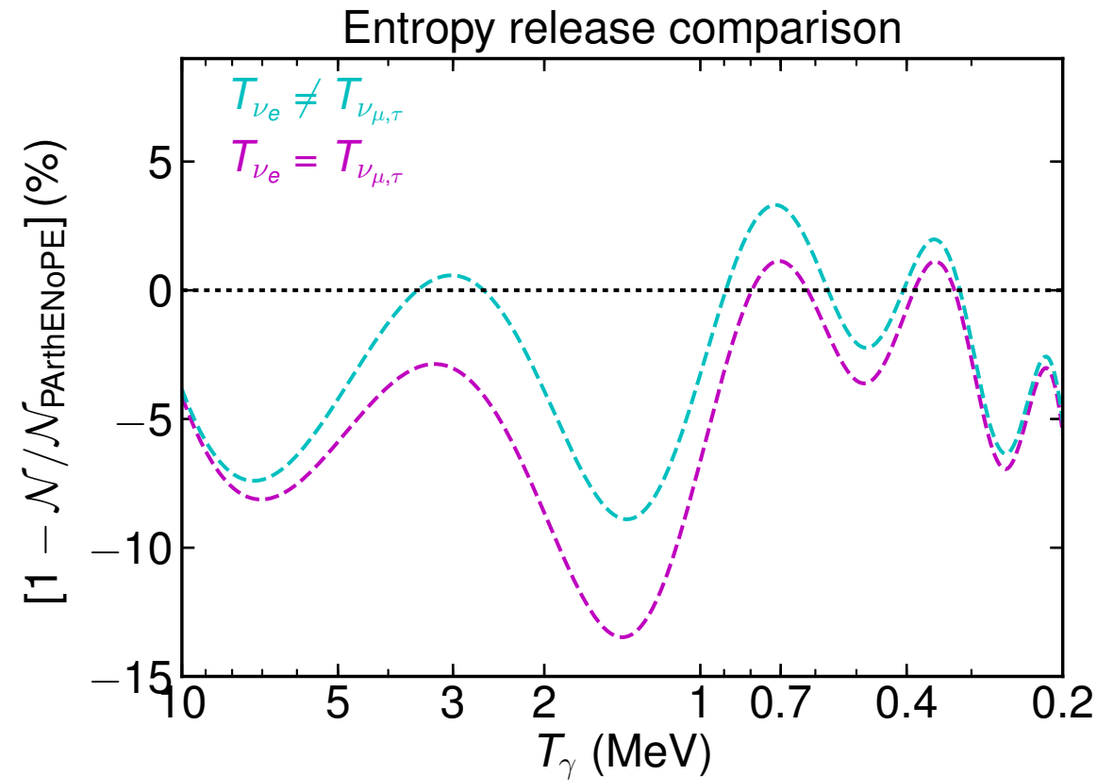
The differential number and energy density agree at the 0.05% level for any momenta y



SM Neutrino Decoupling

The entropy release matches well previous calculations





The code has been used in Parthenope and PRIMAT giving very good results:

Primordial nuclei abundances in the Standard Model				
Relative uncertainty	$\Delta_{\rm rel} Y_p$	$\Delta_{\rm rel}({\rm D/H})$	$\Delta_{\rm rel}(^3{\rm He/H})$	$\Delta_{\rm rel}(^7{\rm Li/H})$
Neutrino evolution, $T_{\nu_e} = T_{\nu_\mu}$	8×10^{-5}	8×10^{-4}	2×10^{-4}	-8×10^{-4}
Neutrino evolution, $T_{\nu_e} \neq T_{\nu_\mu}$	4×10^{-5}	1×10^{-3}	4×10^{-4}	-1×10^{-3}
Measurements, PDG [10]	1.2×10^{-2}	10^{-2}	-	1.9×10^{-1}
Nuclear rates, `PRIMAT` [88]	6.8×10^{-4}	1.49×10^{-2}	2.43×10^{-2}	4.4×10^{-2}

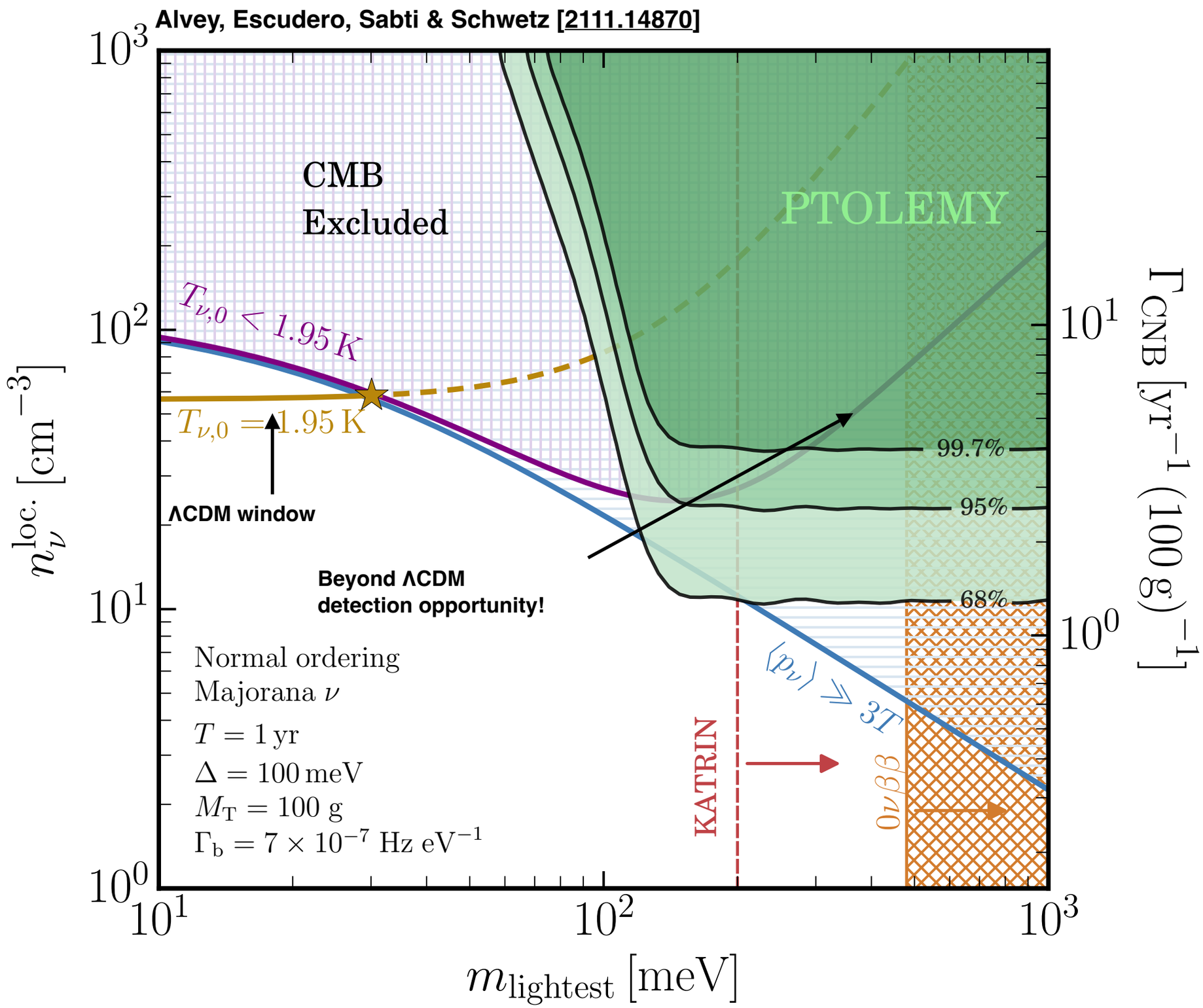
Table 4. $\Delta_{\rm rel} X \equiv \sigma_X / X$. The first two rows correspond to the relative change in the primordial nuclei abundances using the thermodynamic evolution obtained in this work to that compared to the default neutrino evolution used in `PArthENoPE` which is based on the SM calculation of [29]. We appreciate that the relative difference between the evolution used in `PArthENoPE` and that obtained here yields differences in the primordial element abundances that are at least one order of magnitude smaller than the error associated with current measurements or with nuclear uncertainties.

SM Neutrino Decoupling

Neutrino Decoupling in the Standard Model					
No oscillations, no QED	$N_{\rm eff}$	z_γ	$\delta\rho_{\nu_e}/\rho_{\nu_e}$ (%)	$\delta\rho_{\nu_\mu}/\rho_{\nu_\mu}$ (%)	$\delta\rho_{\nu_\tau}/\rho_{\nu_\tau}$ (%)
This work	3.0350	1.39903	0.971	0.407	0.407
Dolgov et. al. [65]	3.0340	1.39910	0.946	0.398	0.398
Grohs et. al. [38]	3.0340	1.39904	0.928	0.377	0.377
No oscillations, LO-QED	$N_{\rm eff}$	z_γ	$\delta\rho_{\nu_e}/\rho_{\nu_e}$ (%)	$\delta\rho_{\nu_\mu}/\rho_{\nu_\mu}$ (%)	$\delta\rho_{\nu_\tau}/\rho_{\nu_\tau}$ (%)
This work	3.0453	1.39782	0.959	0.401	0.401
de Salas & Pastor [28]	3.0446	1.39784	0.920	0.392	0.392
With oscillations, LO-QED	$N_{\rm eff}$	z_γ	$\delta\rho_{\nu_1}/\rho_{\nu_1}$ (%)	$\delta\rho_{\nu_2}/\rho_{\nu_2}$ (%)	$\delta\rho_{\nu_3}/\rho_{\nu_3}$ (%)
This work	3.0462	1.39777	0.603	0.603	0.603
NH, de Salas & Pastor [28]	3.0453	1.39779	0.636	0.574	0.519
IH, de Salas & Pastor [28]	3.0453	1.39779	0.635	0.574	0.520

Table 3. $N_{\rm eff}^{\rm SM}$ as obtained in this work and compared with the calculations of de Salas & Pastor [28] that includes neutrino oscillations and LO-finite temperature corrections, and that of Dolgov et. al. [65] and of Grohs et. al. [38] that do not. When neutrino oscillations are neglected, the difference in $N_{\rm eff}^{\rm SM}$ is 0.0007 as compared to [28] and 0.001 as compared to [38, 65]. In our case, $\delta\rho_{\nu_\alpha}/\rho_{\nu_\alpha} \equiv z_{\nu_\alpha}^4 - 1$ (see Equation (A.9)). Note also that the relative non-instantaneous contribution to the energy density of each neutrino species is accurate to the per mille level. When neutrino oscillations are considered (and here we simply assume that $T_{\nu_e} = T_{\nu_\mu} = T_{\nu_\tau}$) the difference in terms of $N_{\rm eff}^{\rm SM}$ is 0.0009.

Relic neutrino background detection



Neutrino Masses from Cosmology

Cosmological Model Dependence

Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

$\nu_i \to \nu_j \phi$

$$\sum m_\nu \lesssim 0.2\,\mathrm{eV}$$

Oldengott, Wong et al. 2203.09075 & 2011.01502
Escudero & Fairbairn 1907.05425
Archidiacono & Hannestad 1311.3873

$\nu_i \to \nu_4 \phi$

at least: $\sum m_\nu \lesssim 0.42\,\mathrm{eV}$

Poulin et al. 1909.05275, 2112.13862
Escudero, López-Pavón, Rius & Sandner 2007.04994

Time Dependent Neutrino Masses

Late phase transition

$$\sum m_\nu < 1.4\,\mathrm{eV}$$

Dvali & Funcke 1602.03191
Lorenz et al. 1811.01991 & 2102.13618

Ultralight scalar field screening

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

Esteban & Salvadó 2101.05804
Esteban, Mena & Salvadó 2202.04656

Non-standard Neutrino Populations

$T_\nu < T_\nu^{\mathrm{SM}} + \mathrm{DR}$

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

Farzan & Hannestad 1510.02201
Renk et al. 2009.03286
Escudero, Schwetz & Terol-Calvo 2211.01729

$<p_\nu> > 3.15\, T_\nu^{\mathrm{SM}}$

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

Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.14870

- **Bounds can significantly loosen in some extensions of ΛCDM. They require modifications to the neutrino sector.**

But Why? and How?

Neutrino Masses from Cosmology

Neutrinos with non-standard distributions

Cosmology can only constrain energy densities $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$

When neutrinos are ultrarelativistic

$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\gamma}\right) \propto \rho_\nu/\rho_\gamma \qquad N_{\rm eff}^{\rm CMB} = 2.99 \pm 0.17$$

Planck 2018

When neutrinos are non-relativistic: $\Omega_\nu h^2 = \sum m_\nu n_\nu/\rho_c$

$$\Omega_\nu h^2 < 0.0012\,\frac{\sum m_\nu}{0.12\,{\rm eV}}\,\frac{n_\nu}{n_\nu^{\rm SM}}$$

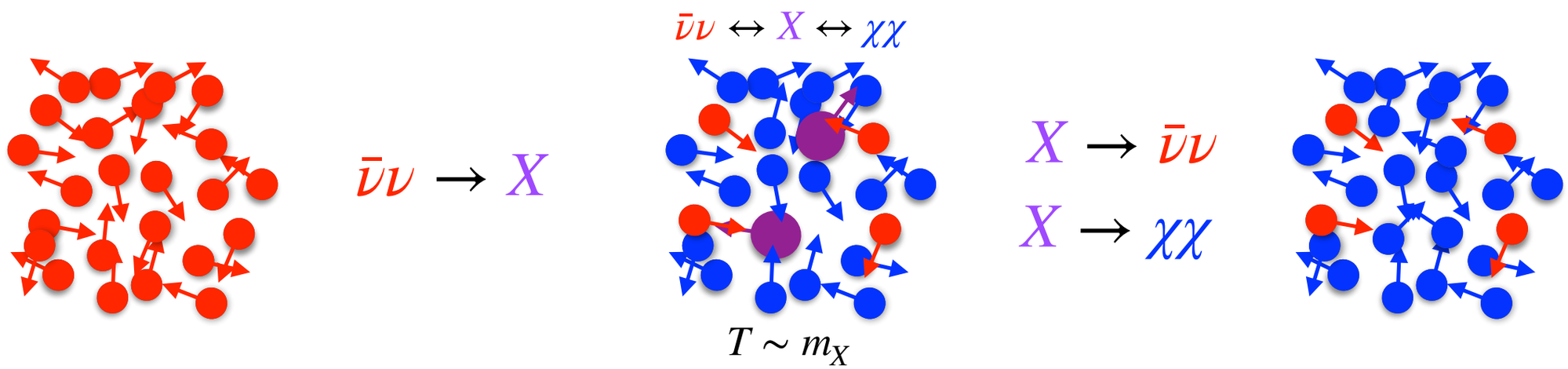
Planck 2018

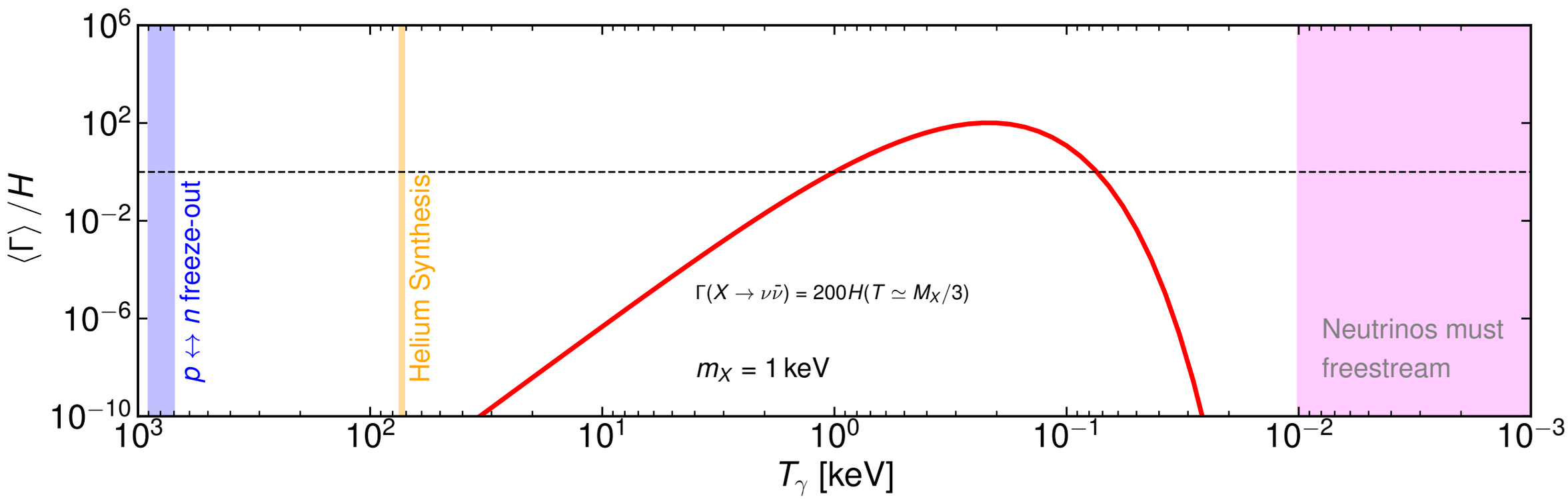
In Alvey, Escudero & Sabti 2111.12726 we have explicitly demonstrated that this bound is highly insensitive to the form of the neutrino distribution function! See also Oldengott et al. 1901.04352 and Renk et al. 2009.03286.

From this we see that a trivial way to relax the bound is by reducing the number density of neutrinos!

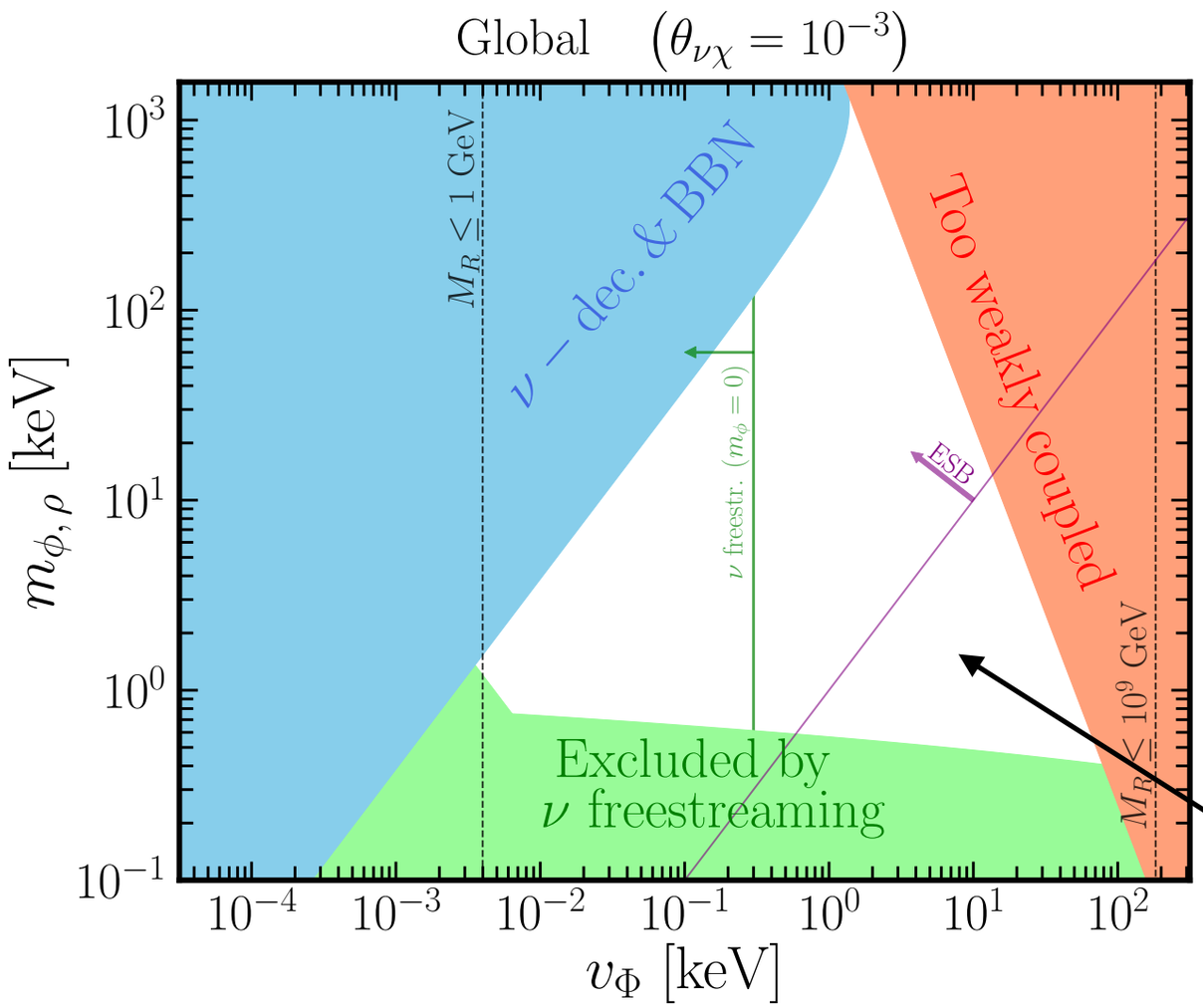
$$n_\nu < n_\nu^{\rm SM}$$

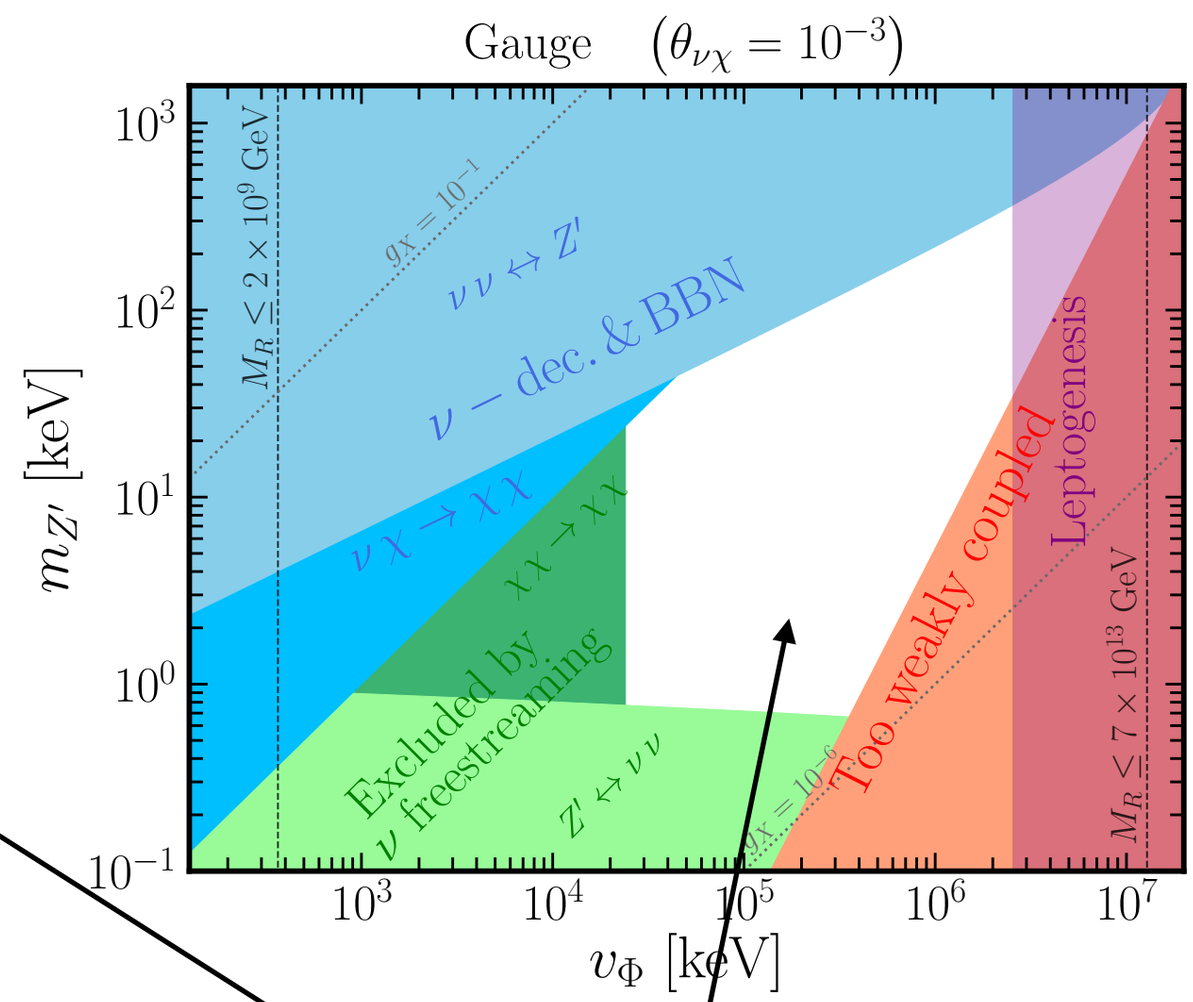
Interaction Rates





Parameter Space



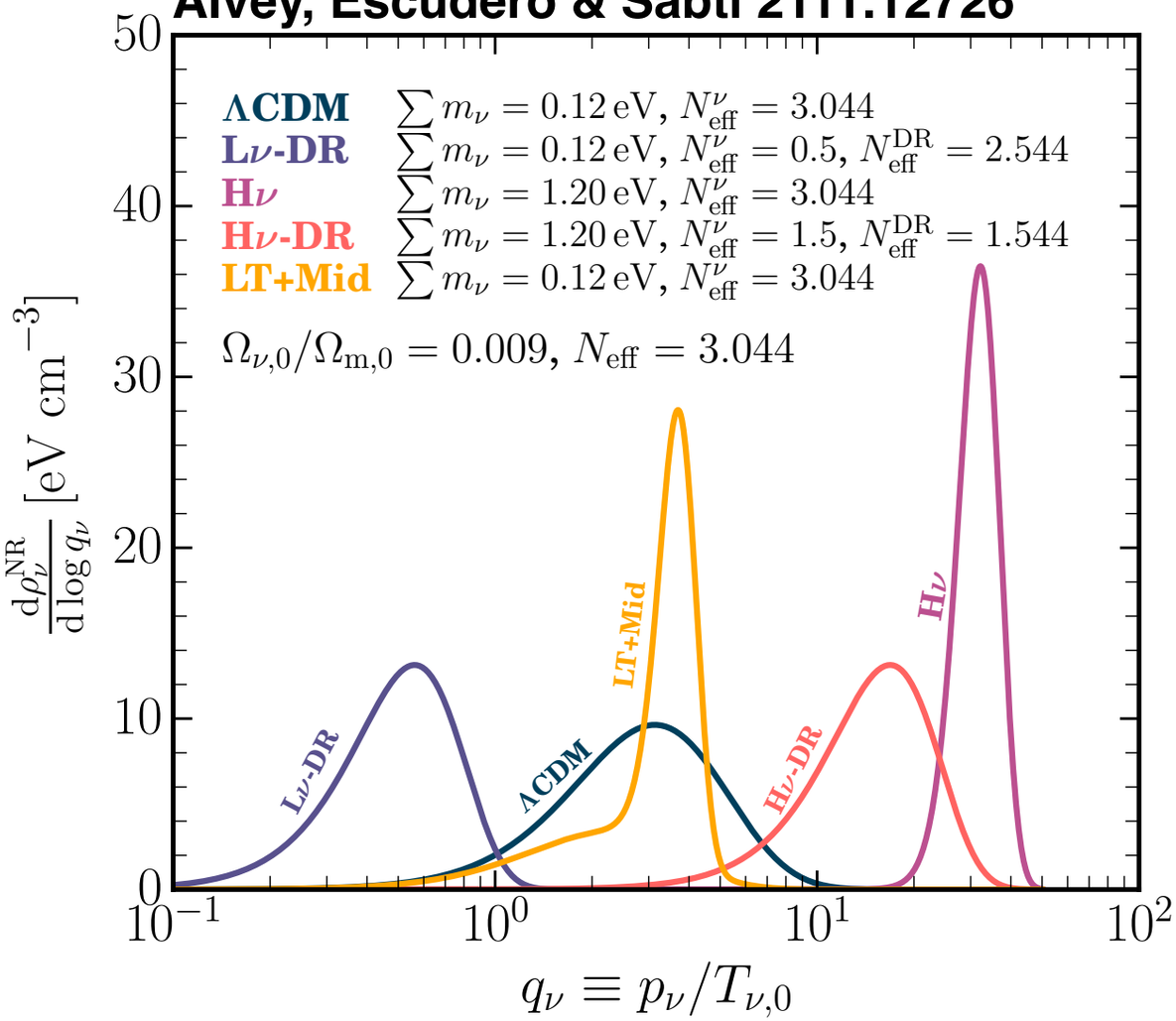


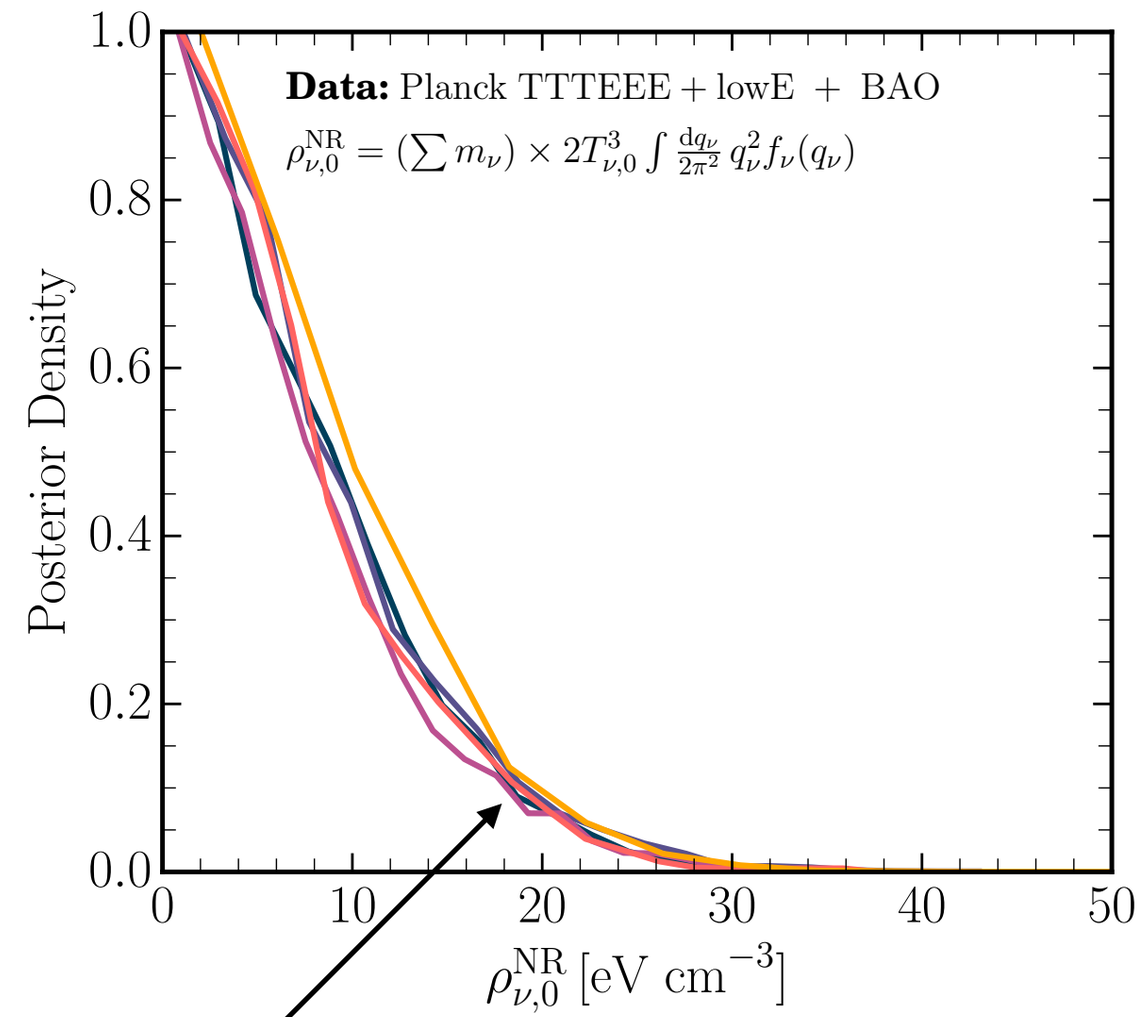
- **Mixing angles $\theta > 10^{-4}$ is needed in order for χ states to interact efficiently enougl**
- **For the global case, parameter space of interest is for $v_\Phi \simeq 10\,\mathrm{keV}$ but this is theoretically not super well motivated because the pseudo-Goldstone boson has a mass similar to v_Φ**
- **For the gauge case, parameter space of interest is for $v_\Phi \simeq 100\,\mathrm{MeV}$ and there is parameter space where this set up would also be compatible with high scale leptogenesis with $M_N \sim 10^{10}\,\mathrm{GeV}$**

The neutrino distribution function

Widely different neutrino distribution functions:

Alvey, Escudero & Sabti 2111.12726

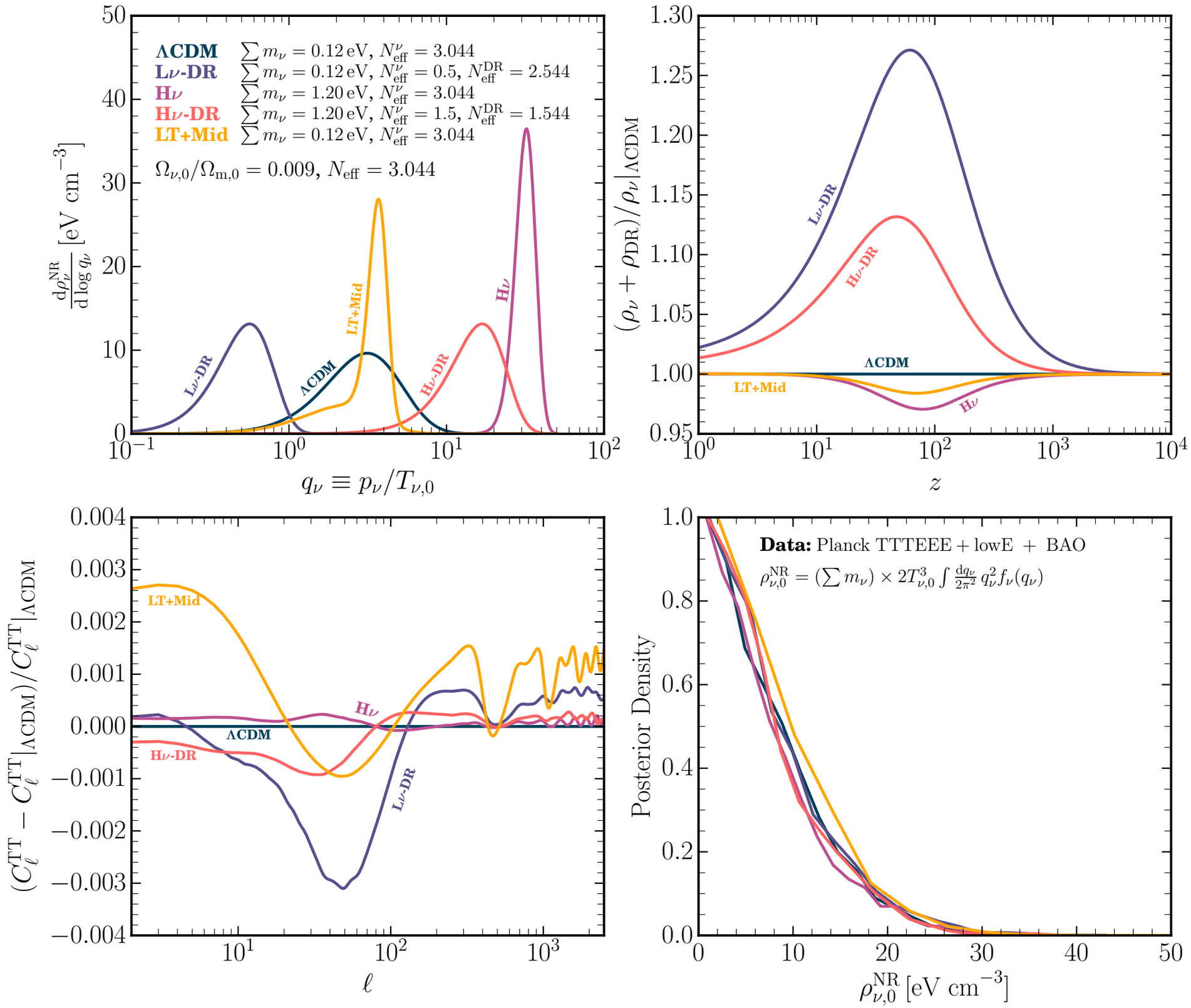




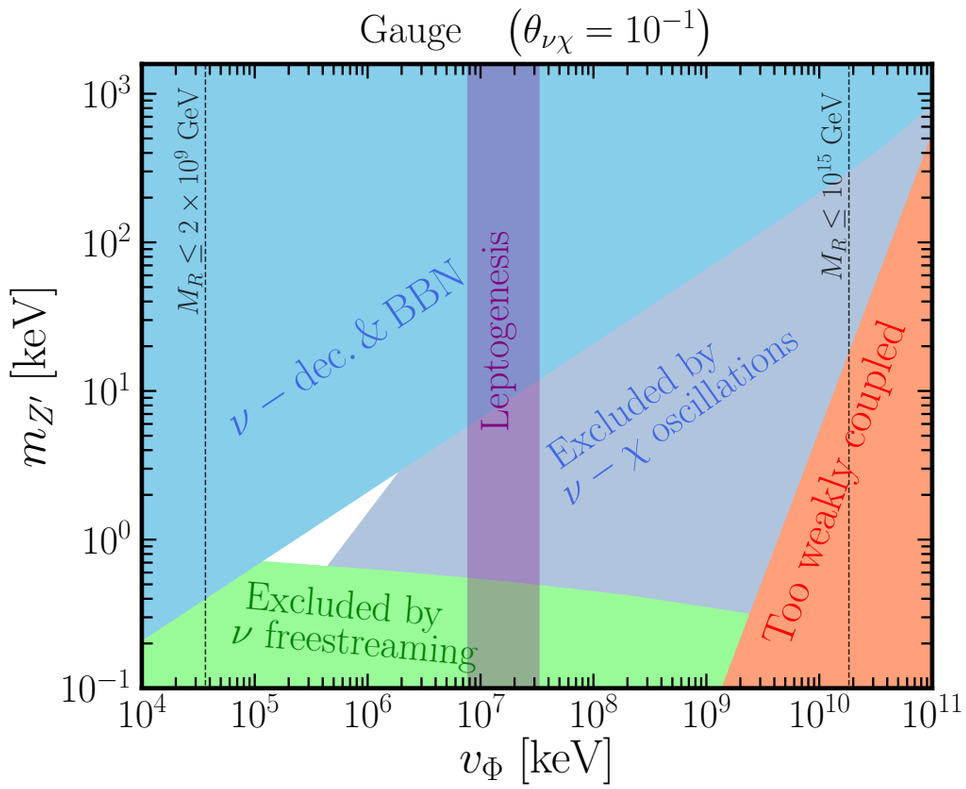
Very same bound from Planck on the energy density of non-relativistic neutrinos

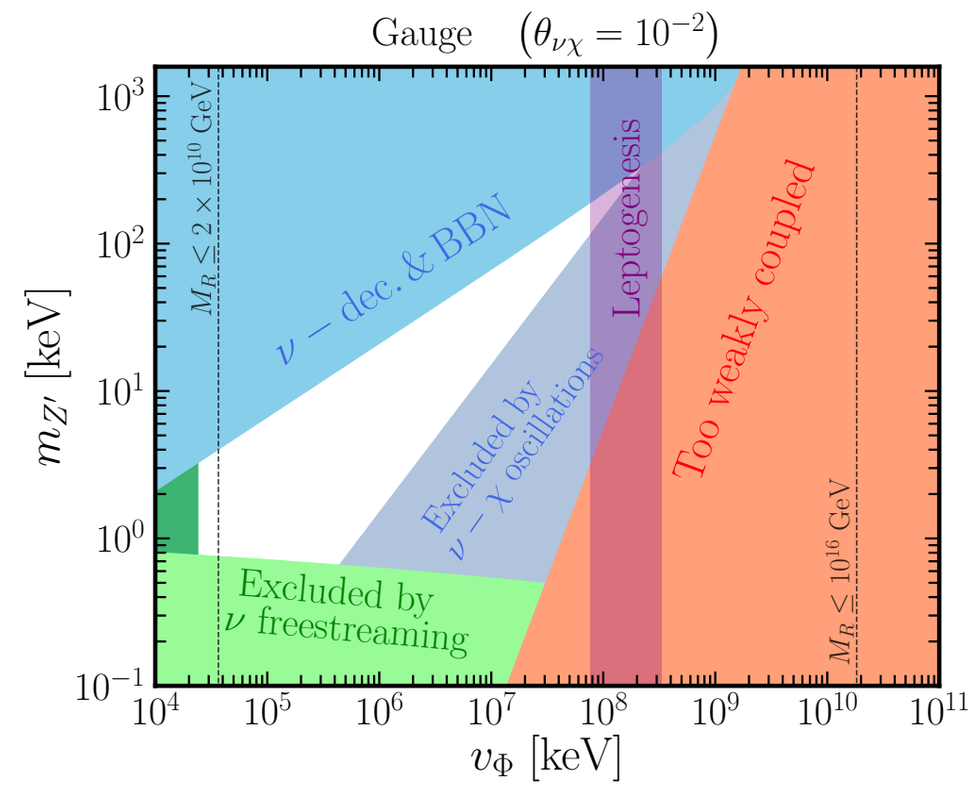
$$\rho_\nu^{\rm NR} = \sum m_\nu \times n_\nu$$

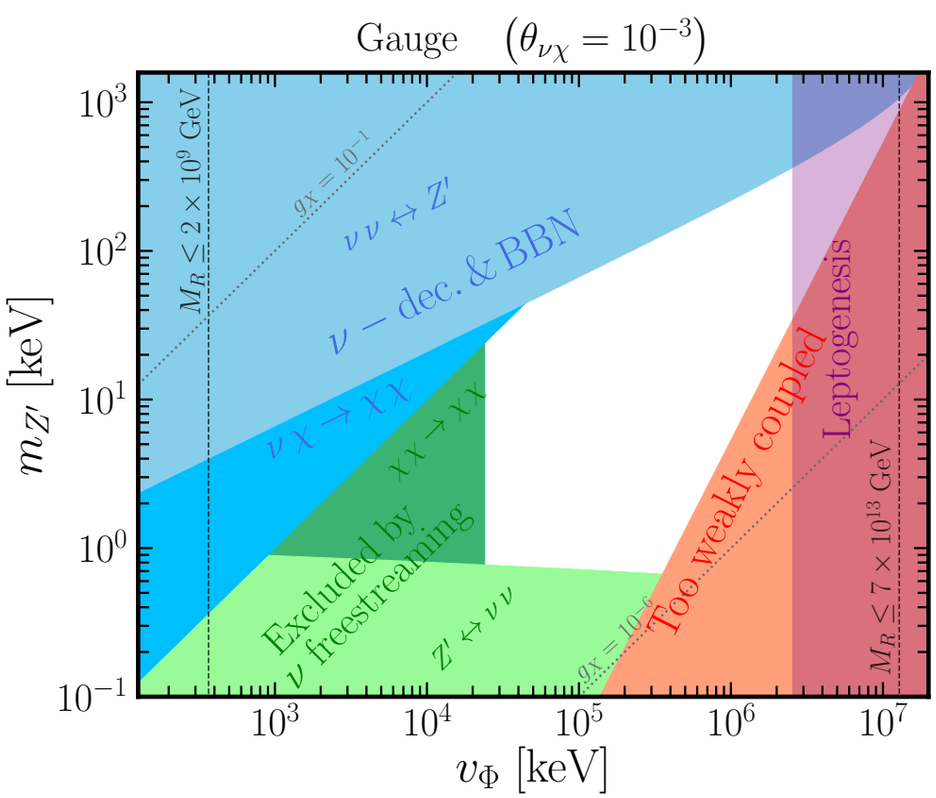
The neutrino distribution function

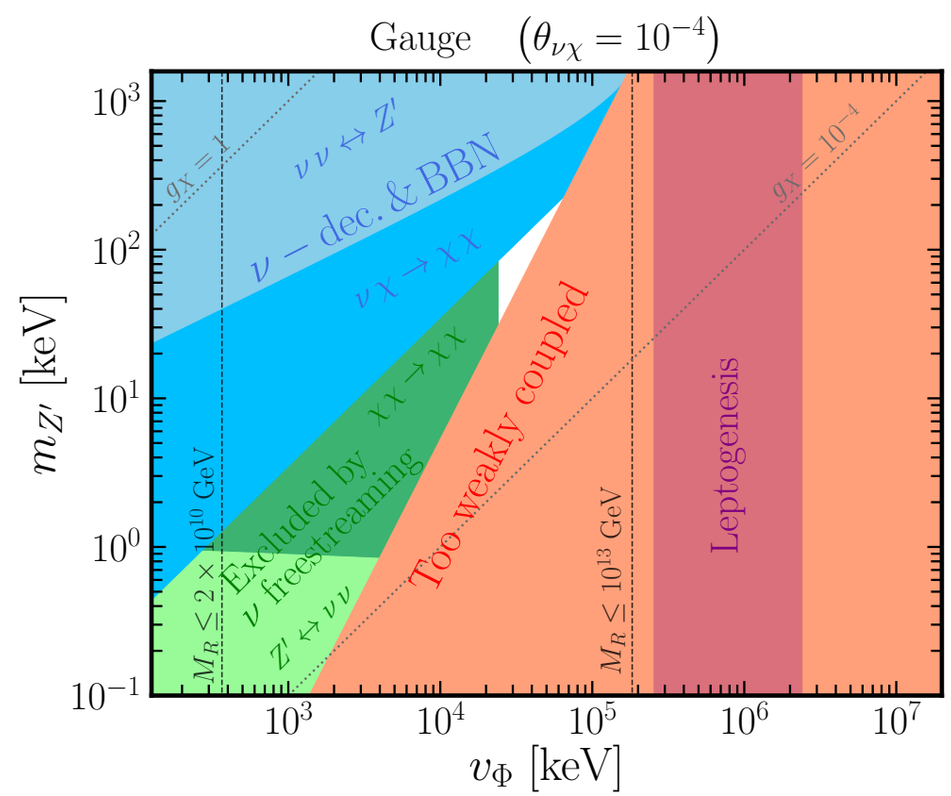
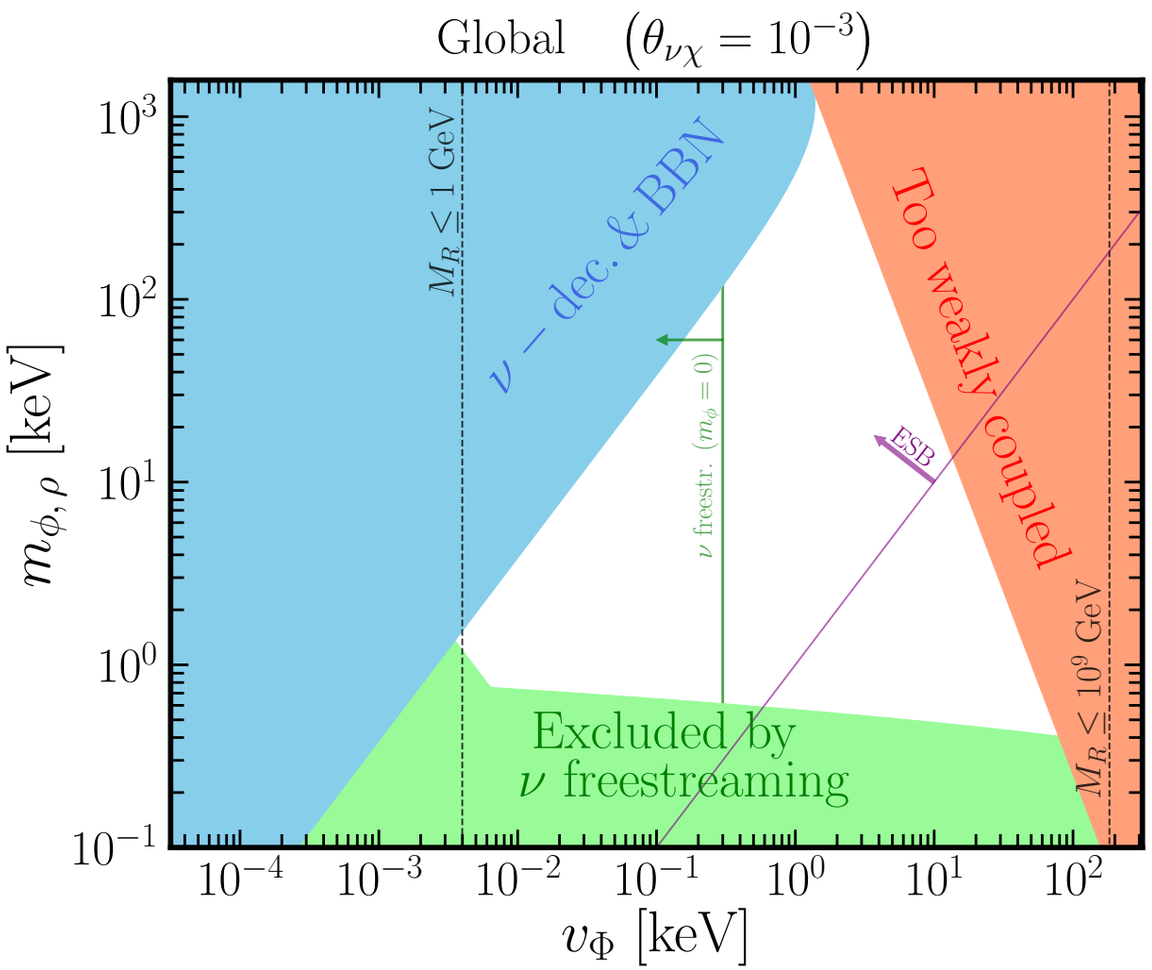
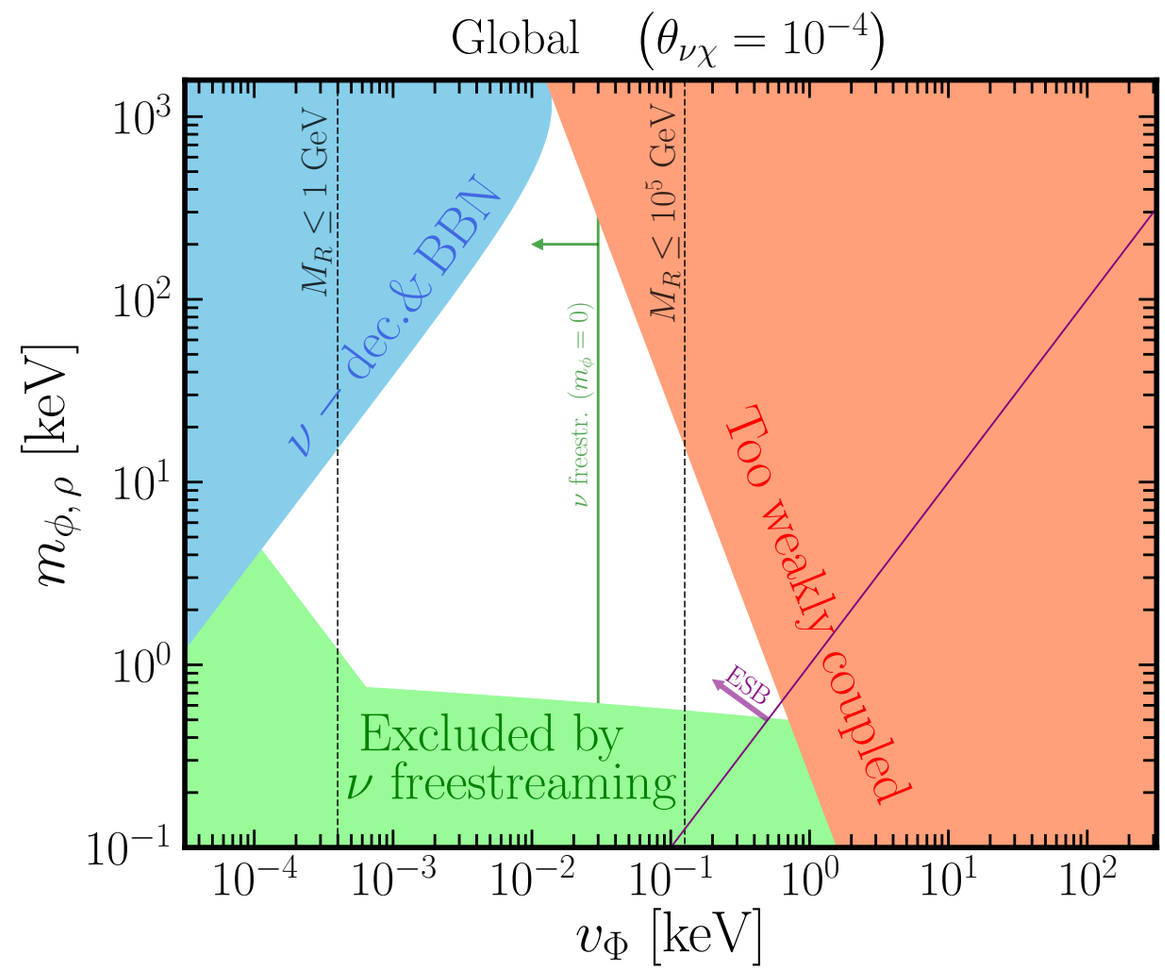


Parameter Space Gauge









Parameter Space Global