Neutrino Cosmology in 2023

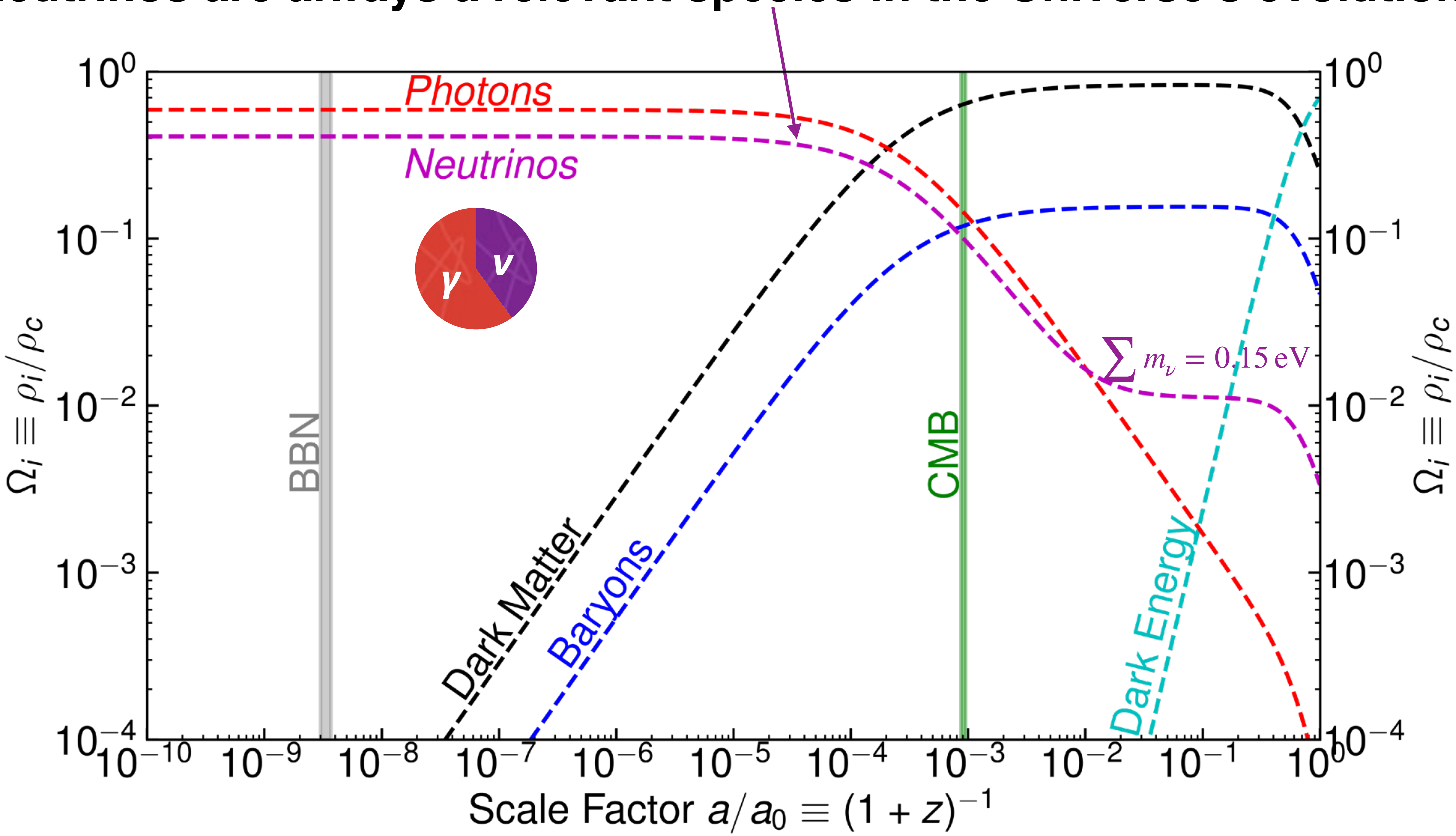
Miguel Escudero Abenza
miguel.escudero@cern.ch

CERN

IJCLab Orsay
05-12-2023

Neutrino Evolution

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



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

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

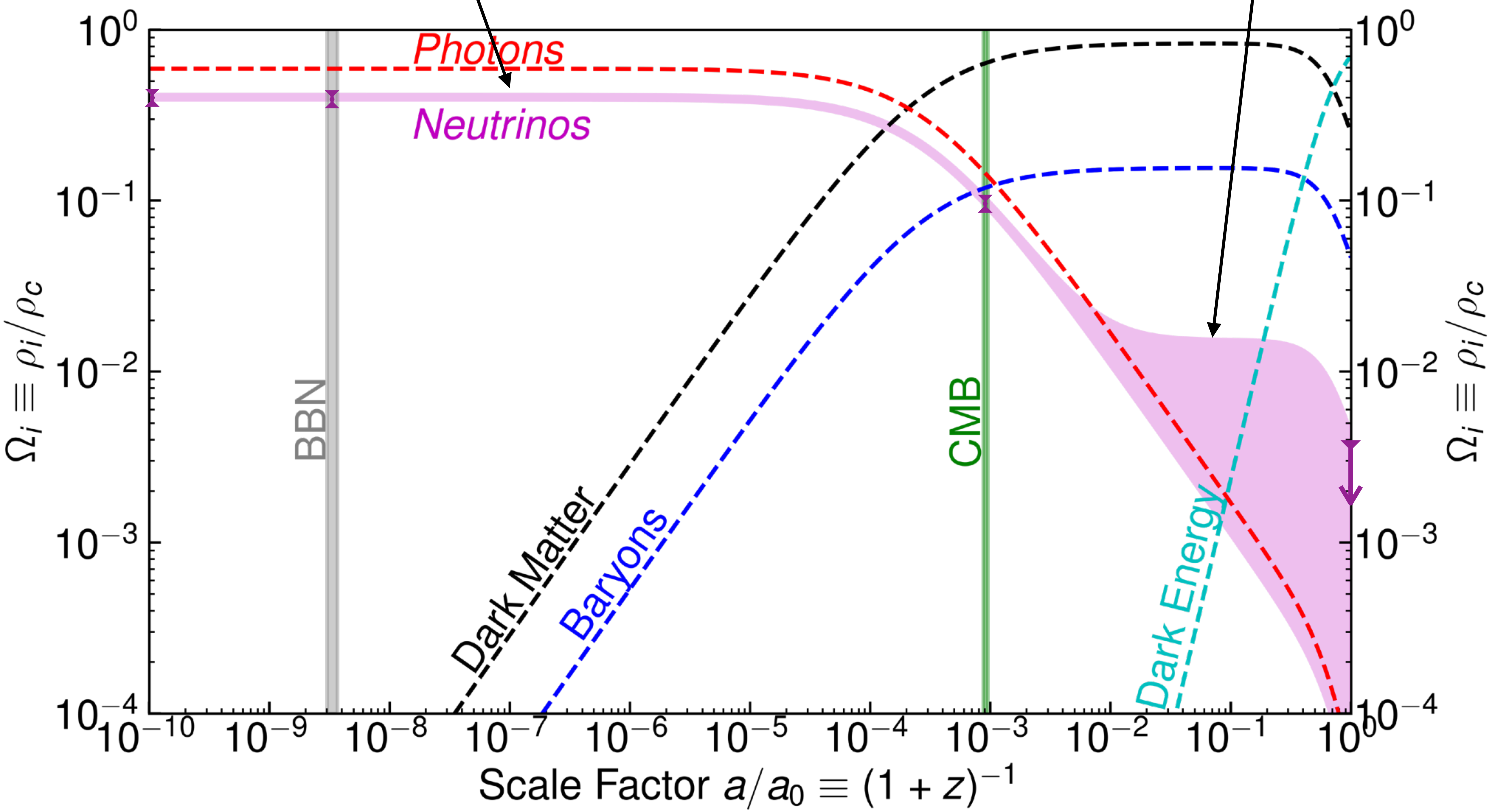
Global Perspective

Current knowledge:

$N_{\mathrm{eff}} = 3 \pm 0.3$ **(Planck/BBN)**

(Planck+BAO)

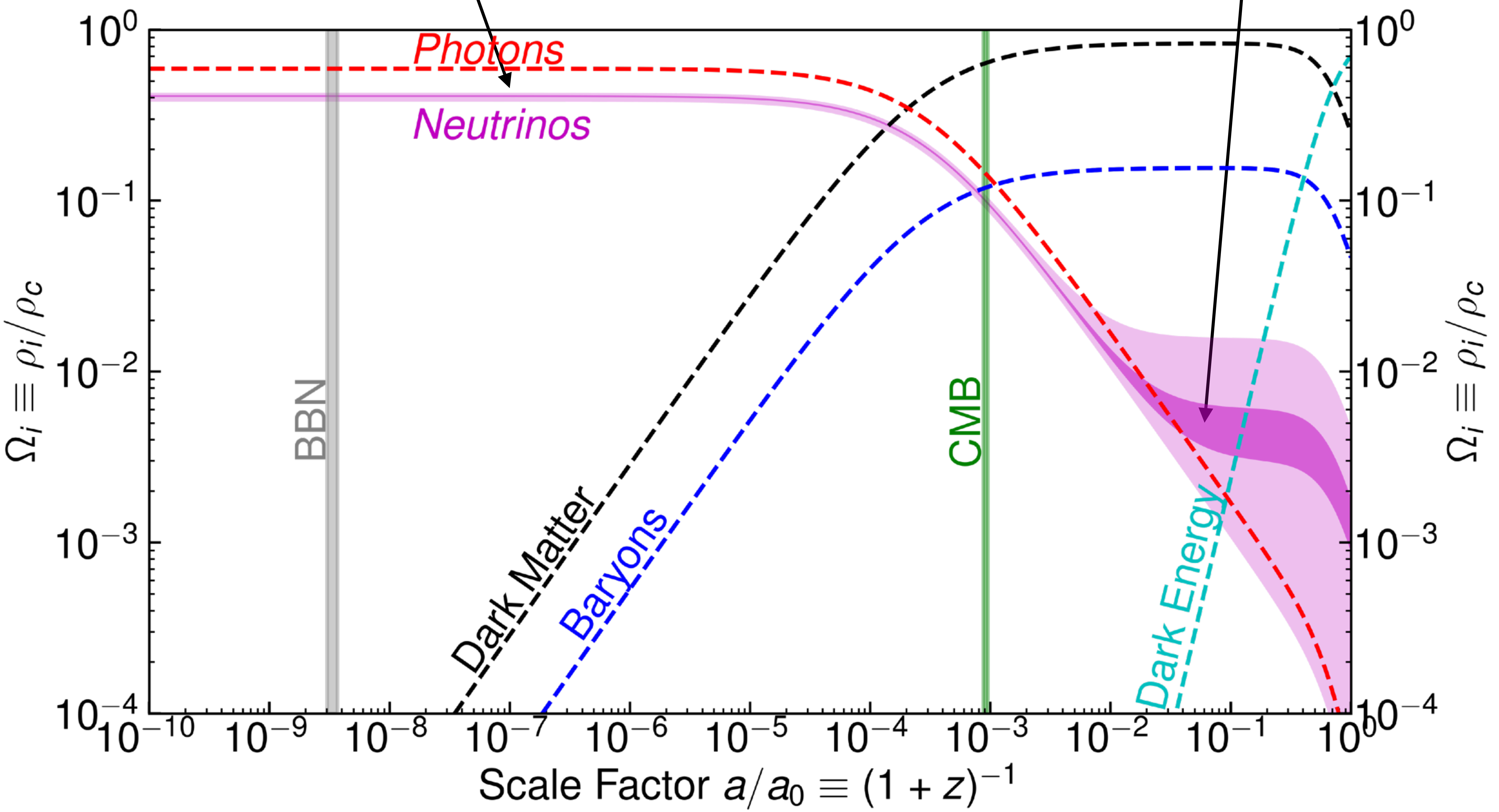
$\sum m_\nu \lesssim 0.2\,\mathrm{eV}$



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/Outline

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]

with Cielo, Mangano & Pisanti 2306.05460 [PRD]

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

with Alvey & Sabti 2111.12726 [JCAP]
with Schwetz & Terol-Calvo 2211.01729 [JHEP]

3) Understand to which degree can neutrinos have BSM interactions

with Witte 1909.04044, 2103.03249 & with Sandner 2305.01692 [EPJC]
with Taule & Garny 2207.04062 [PRD]

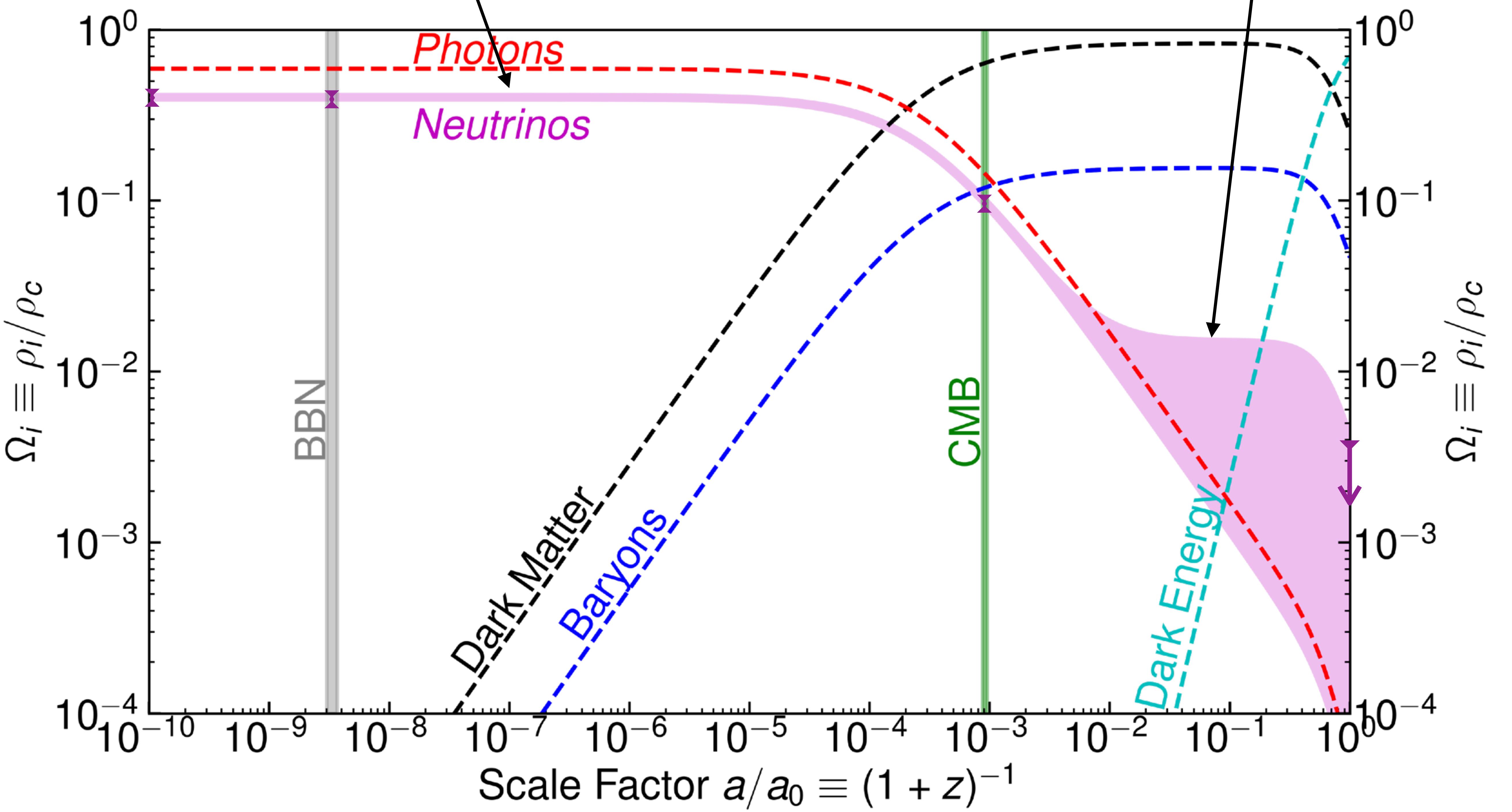
Outline

Current knowledge:

$N_{\rm eff} = 3 \pm 0.3$ **(Planck/BBN)**

(Planck+BAO)

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

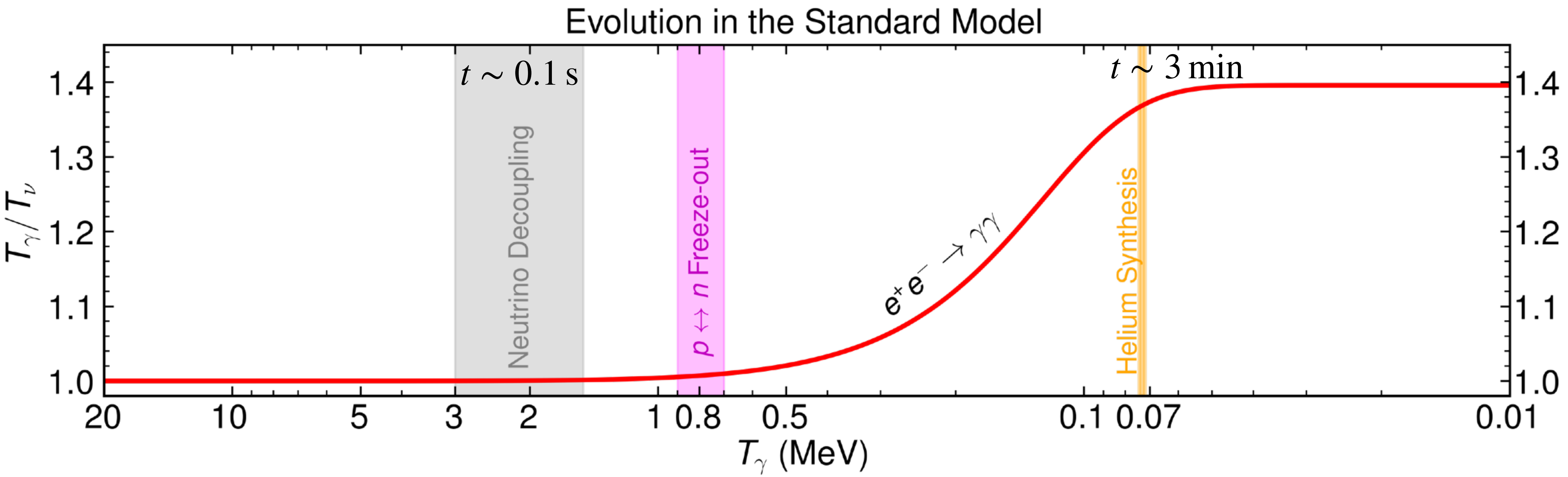


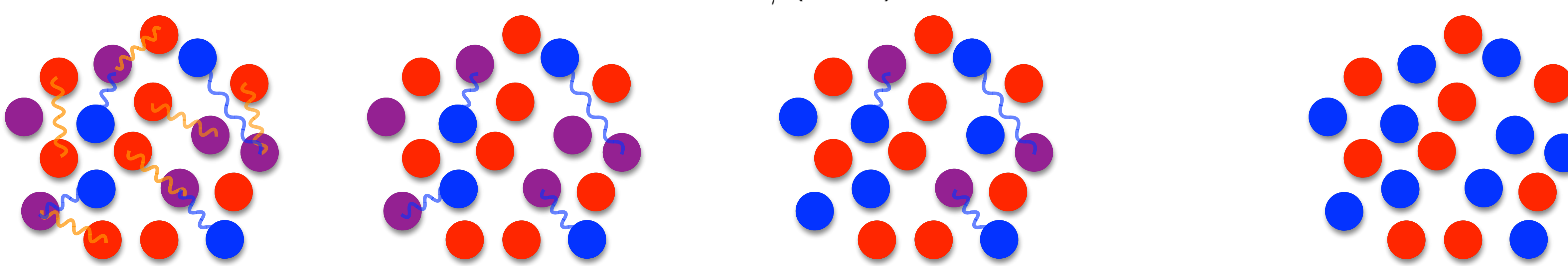
Set Up

Unlike neutrinos, I do like to interact 😃

Questions, Comments and Criticism are most welcome, at any time!!!!

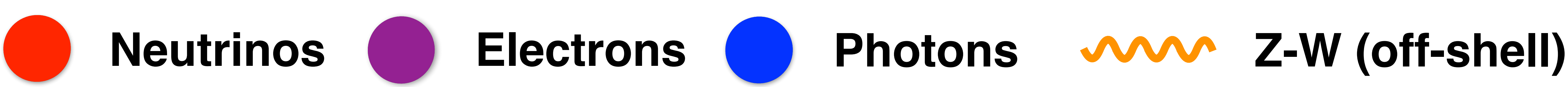
Neutrino Decoupling



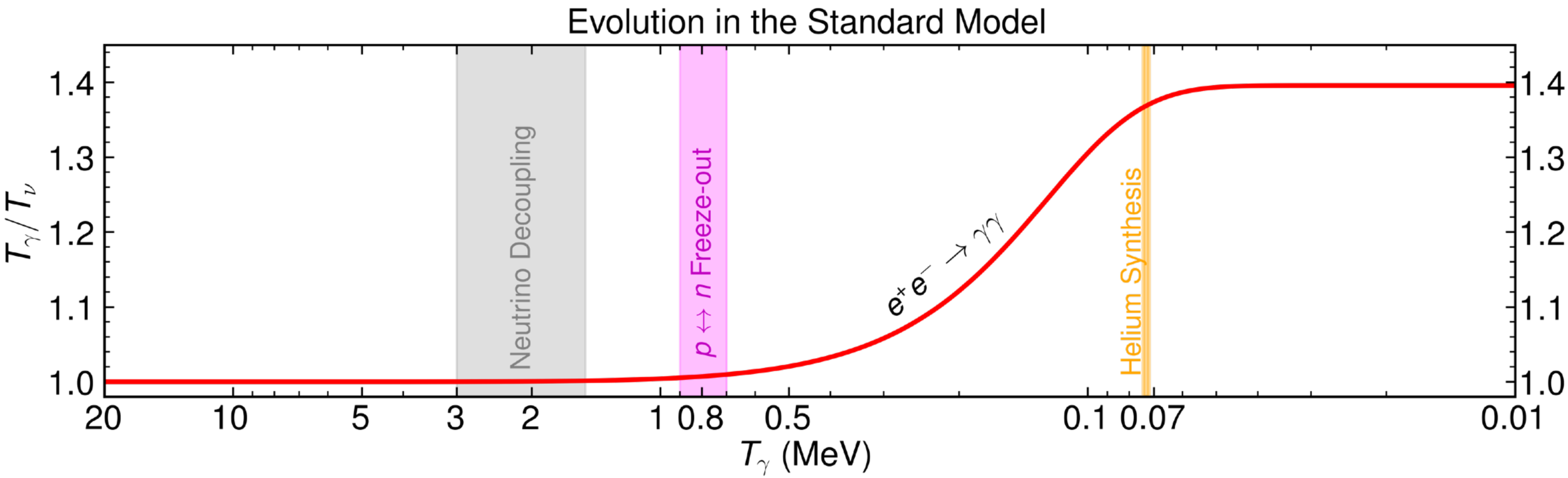


$$e^+e^- \leftrightarrow \bar{\nu}_i\nu_i$$

$$e^\pm\nu_i \leftrightarrow e^\pm\nu_i$$



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: $N_{\rm eff}^{\rm SM} = 3.0440(2)$

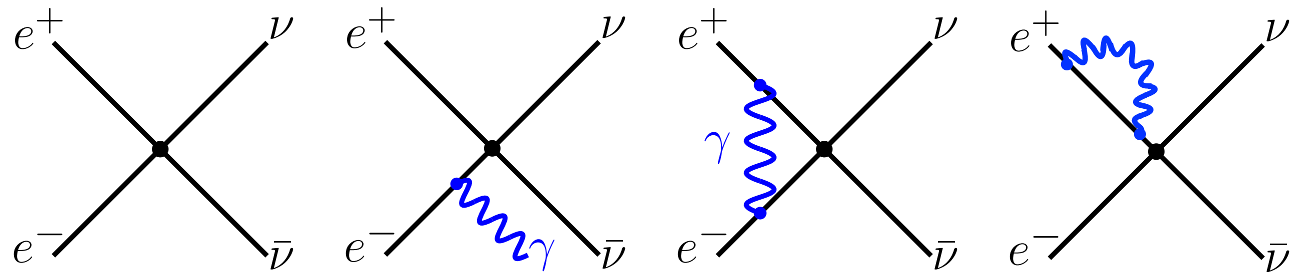
Akita & Yamaguchi 2005.07047
Froustey, Pitrou & Volpe 2008.01074
Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Wong 2012.02726

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



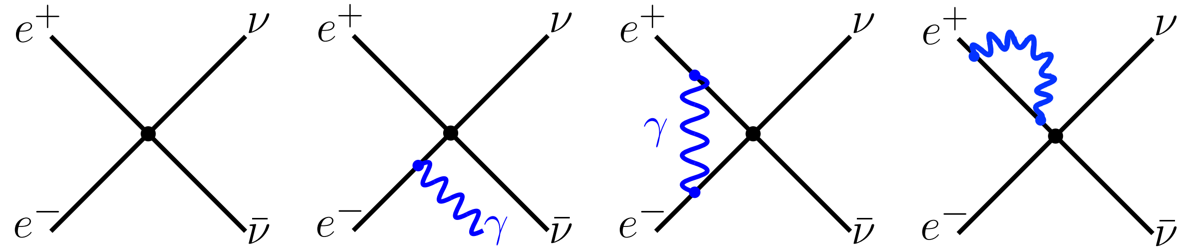
At NLO: $\Delta N_{\rm eff} \simeq -0.0007$

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

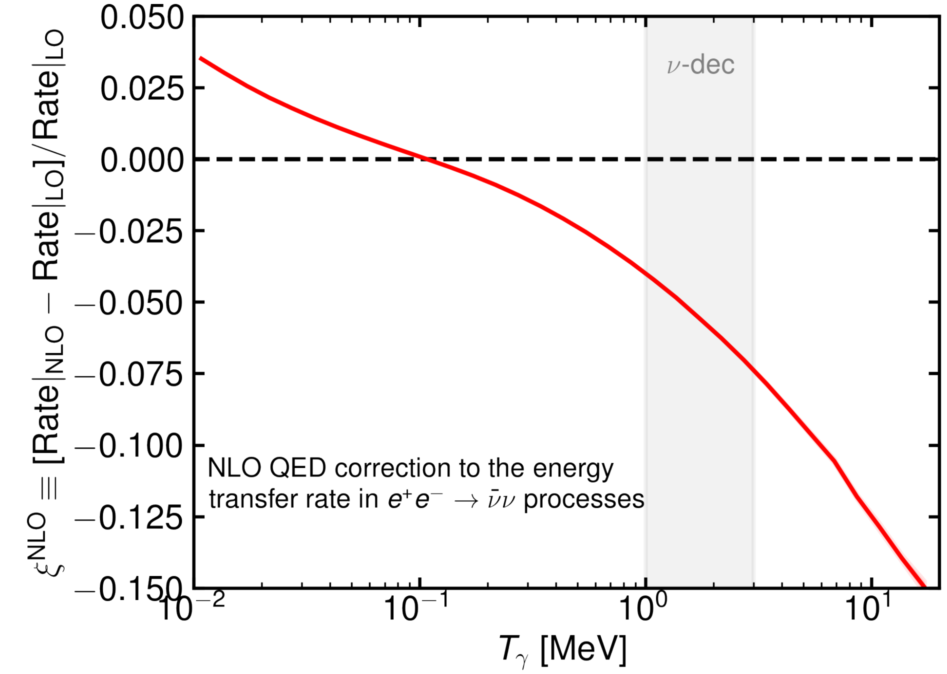
Cielo, Escudero, Mangano & Pisanti 2306.05460

The essence in 1 slide

1) Calculation performed following the real time formalism in thermal field theory



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



2) Solve for the process of neutrino decoupling:

exact:

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

approximate but very accurate:

$$\frac{dT_\nu}{dt} = -H\,T_\nu + \frac{\frac{\delta\rho_{\nu_e}}{\delta t} + 2\frac{\delta\rho_{\nu_\mu}}{\delta t}}{3\,\frac{\partial\rho_\nu}{\partial T_\nu}}$$

Escudero 1812.05605 & 2001.04466 [JCAP]

3) Result at NLO:

$$\Delta N_{\rm eff} \simeq -0.0007$$

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

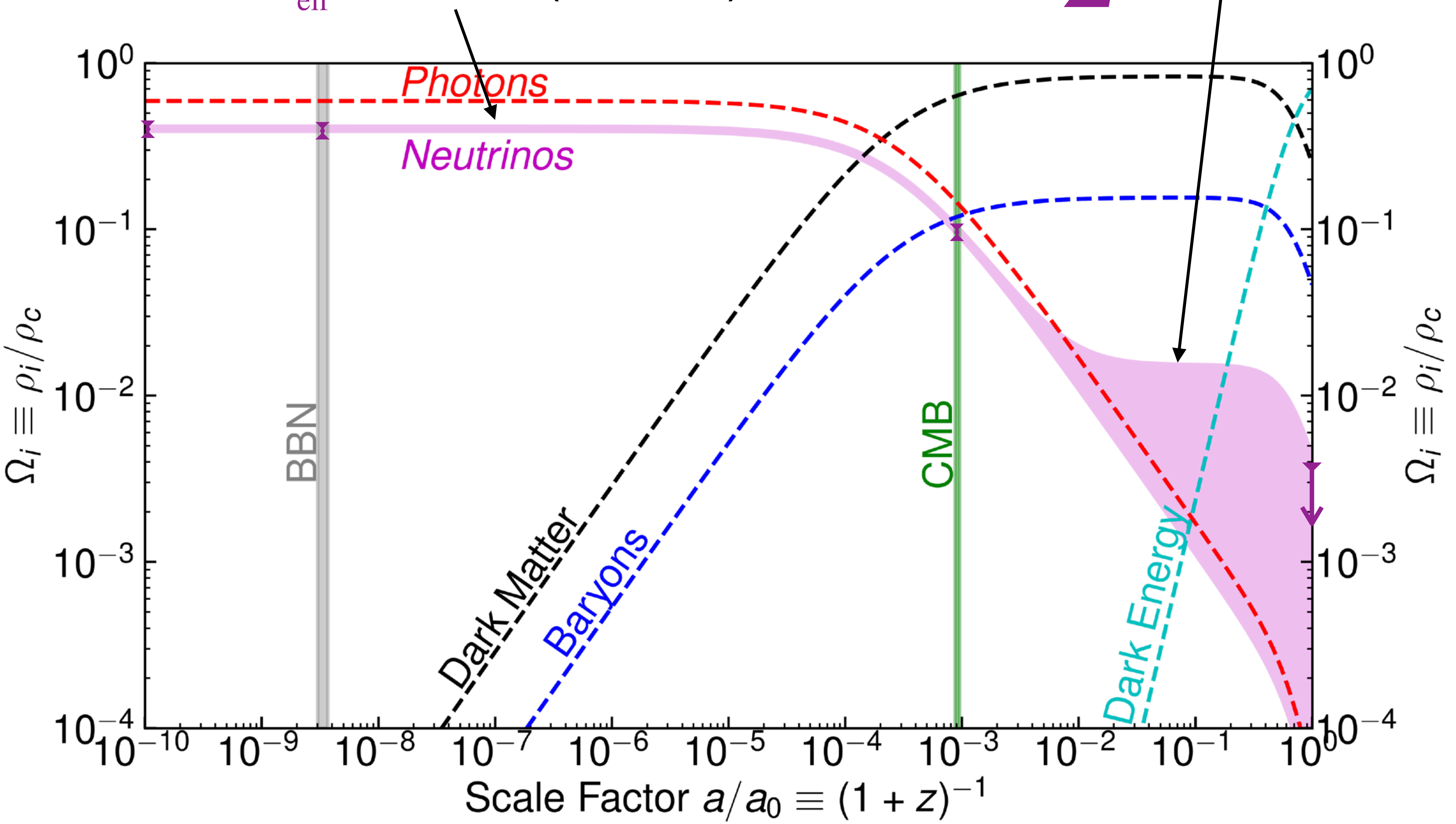
Cielo, Escudero, Mangano & Pisanti 2306.05460

Global Perspective

Current knowledge:

$N_{\rm eff} = 3 \pm 0.3$ **(Planck/BBN)**

(Planck+BAO) $\sum m_\nu \lesssim 0.2\,\mathrm{eV}$



Evidence for Cosmic Neutrinos

Big Bang Nucleosynthesis

Current measurements are consistent with the SM picture

H ~ 75% **^{4}He ~ 25%** **D ~ 0.005%**

This implies that neutrinos should have been present:

1) **It is impossible to have successful BBN without neutrinos. They participate in $p \leftrightarrow n$ conversions up to $T \gtrsim 0.7\,\mathrm{MeV}$**

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$

2) **Neutrinos contribute to the expansion rate** $H \propto \sqrt{\rho}$

By comparing predictions against observations, we know:

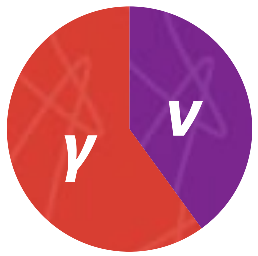
$$N_{\rm eff}^{\rm BBN} = 2.86 \pm 0.28$$

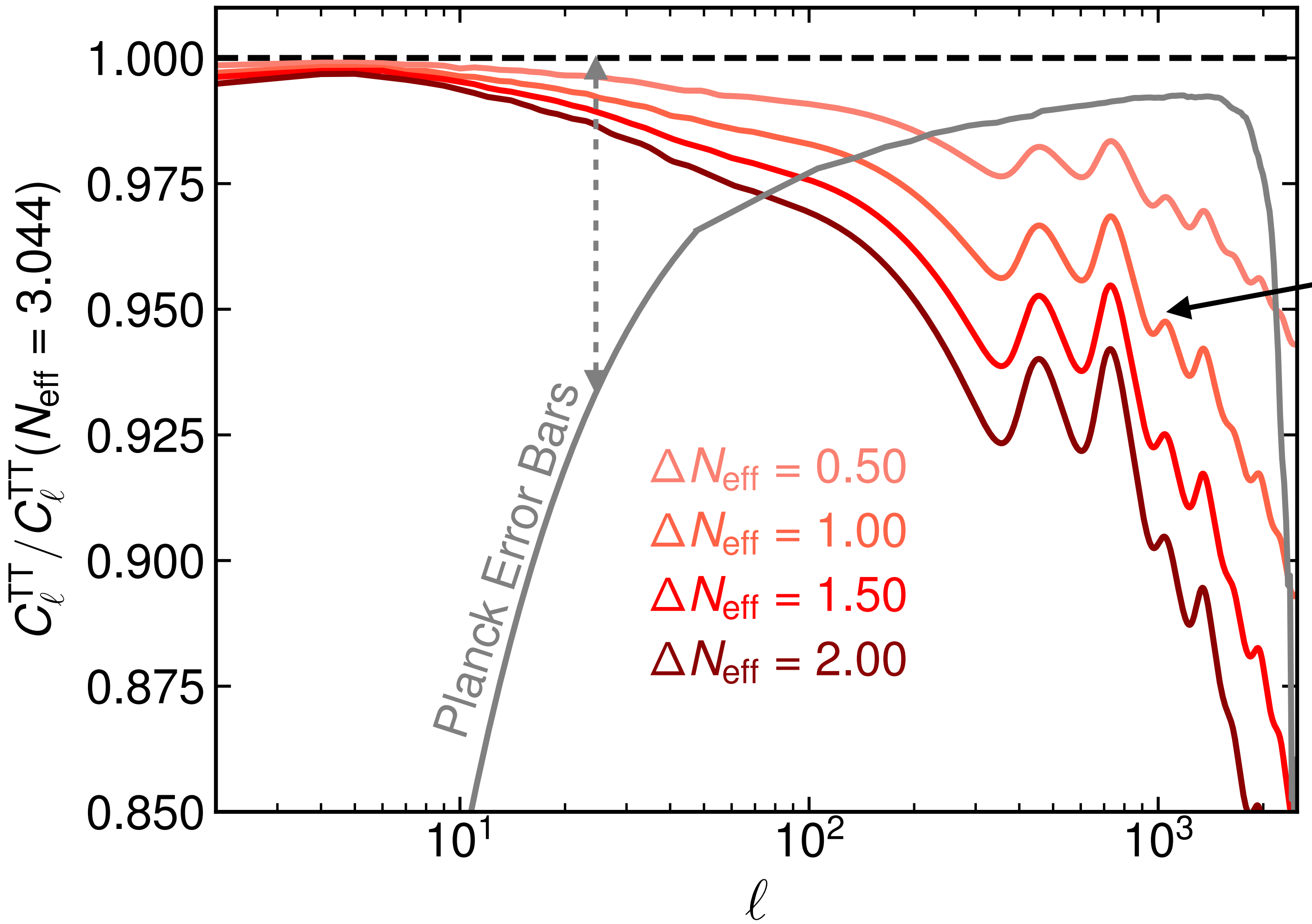
see e.g., Pisanti et al. 2011.11537 and Yeh et al. 2207.13133

Evidence for Cosmic Neutrinos

Cosmic Microwave Background **Why?**

Ultra-relativistic neutrinos represent a large fraction of the energy density of the Universe, $H \propto \sqrt{\rho}$





N_{eff} **is constrained by the high-**ℓ **multipoles, i.e. Silk damping**

$$N_{eff}^{CMB+BAO} = 2.99 \pm 0.17$$

Planck 2018 1807.06209

Evidence for Cosmic Neutrinos

- **Current constraints**

BBN $N_{\rm eff}^{\rm BBN} = 2.86 \pm 0.28$ **Pisanti et al. 2011.11537**
Yeh et al. 2207.13133

Planck+BAO $N_{\rm eff}^{\rm CMB} = 2.99 \pm 0.17$ **Planck 2018, 1807.06209**

- **Standard Model prediction:** $N_{\rm eff}^{\rm SM} = 3.043$
- **Data is in excellent agreement with the Standard Model prediction**
- **This provides strong (albeit indirect) evidence for the Cosmic Neutrino Background**

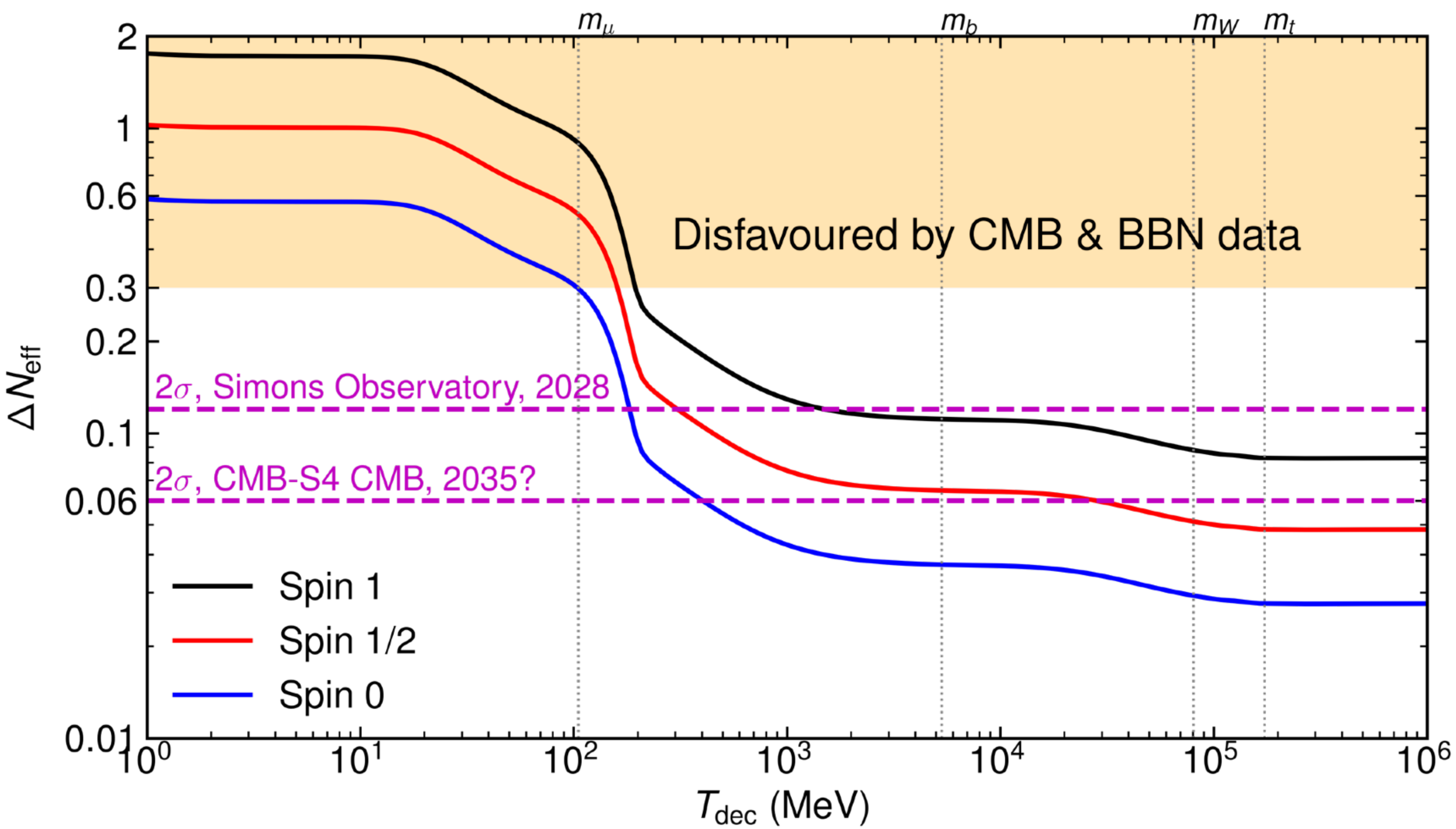
Implications:

1) Stringent constraint on many BSM scenarios

2) We can use cosmological data to test neutrino properties

Constraints on Neff

- **Sterile Neutrino** $m_N \sim \mathrm{eV}$ $\Delta N_{\rm eff} = 1$ **(e.g. Gariazzo, de Salas & Pastor 1905.11290)**
- **Goldstone Bosons** **Weinberg 1305.1971**
- **Other sterile long-lived particles** **Axion, gravitino, axino, hidden sector particles ...**



Stringent constraint on BSM physics

Constraints are relevant in many other BSM settings:

- **WIMPs** $m_{\rm WIMP} > (4-10)\,{\rm MeV}$ — Sabti et. al. 1910.01649; Boehm et. al. 1303.6270
- **GeV-Sterile Neutrinos** $\tau_N \lesssim 0.05\,{\rm s}$ — Sabti et. al. 2006.07387; Dolgov et. al. hep-ph/0008138
- **Vector Bosons** $g \lesssim 10^{-10}$ $m \lesssim 10\,{\rm MeV}$ — Escudero et. al. 1901.02010; Kamada & Yu 1504.00711
- **Axions** — Raffelt et. al. 1011.3694; Blum et.al. 1401.6460
- **Low Reheating** $T_{\rm RH} > (2-5)\,{\rm MeV}$ — de Salas et. al. 1511.00672; Hasegawa et. al. 1908.10189
- **Variations of GN** $G_{\rm BBN}/G_0 = 0.98 \pm 0.03$ — Alvey et. al. 1910.10730; Copi et.al. astro-ph/0311334
- **PBHs** $6\times 10^8\,{\rm g} < M_{\rm PBH} < 2\times 10^{13}\,{\rm g}$ — Carr et. al. 0912.5297; Keith et.al. 2006.03608

Check out a review on non-standard expansion histories:

2006.16182 Vaskonen et al. (Escudero & Poulin)

Evidence for Cosmic Neutrinos

- **Current constraints**

BBN $N_{\rm eff}^{\rm BBN} = 2.86 \pm 0.28$ Pisanti et al. 2011.11537, Yeh et al. 2207.13133

Planck+BAO $N_{\rm eff}^{\rm CMB} = 2.99 \pm 0.17$ Planck 2018, 1807.06209

- **Standard Model prediction:** $N_{\rm eff}^{\rm SM} = 3.043$
- **Data is in excellent agreement with the Standard Model prediction**
- **This provides strong (albeit indirect) evidence for the Cosmic Neutrino Background**

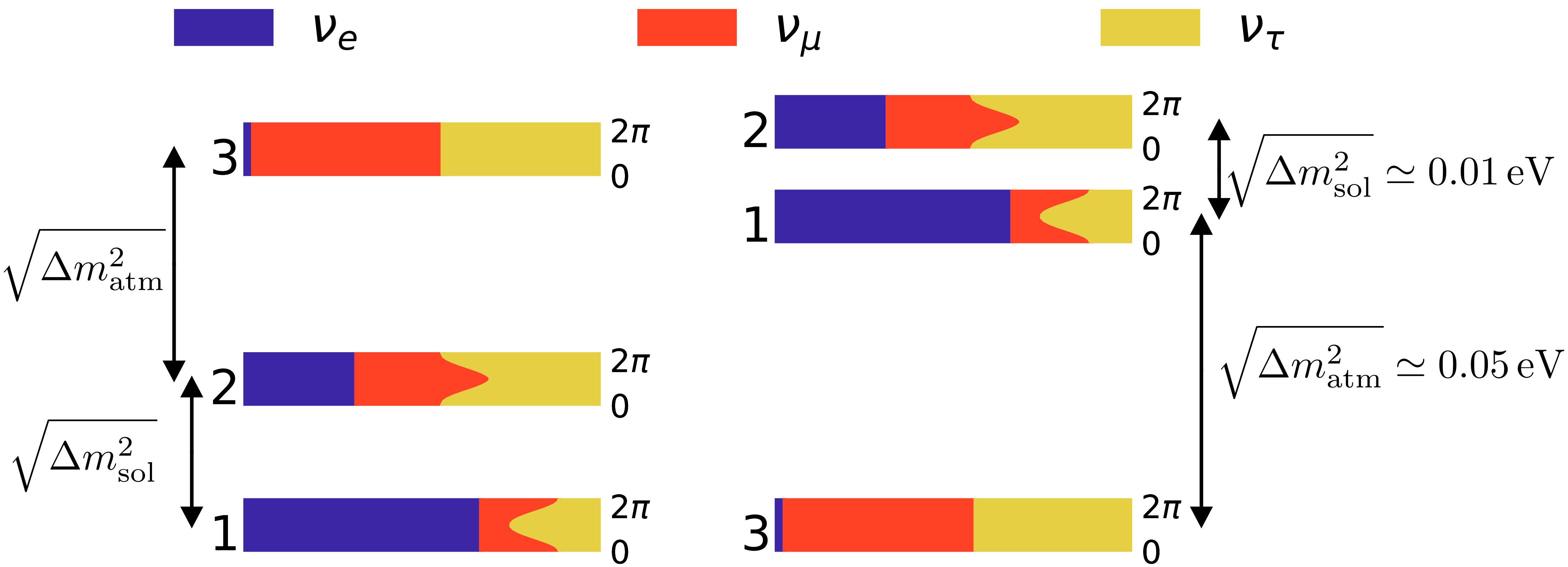
Implications:

1) Stringent constraint on many BSM scenarios

2) We can use cosmological data to test neutrino properties

Neutrino Properties

Figure from de Salas et al. 1806.11051



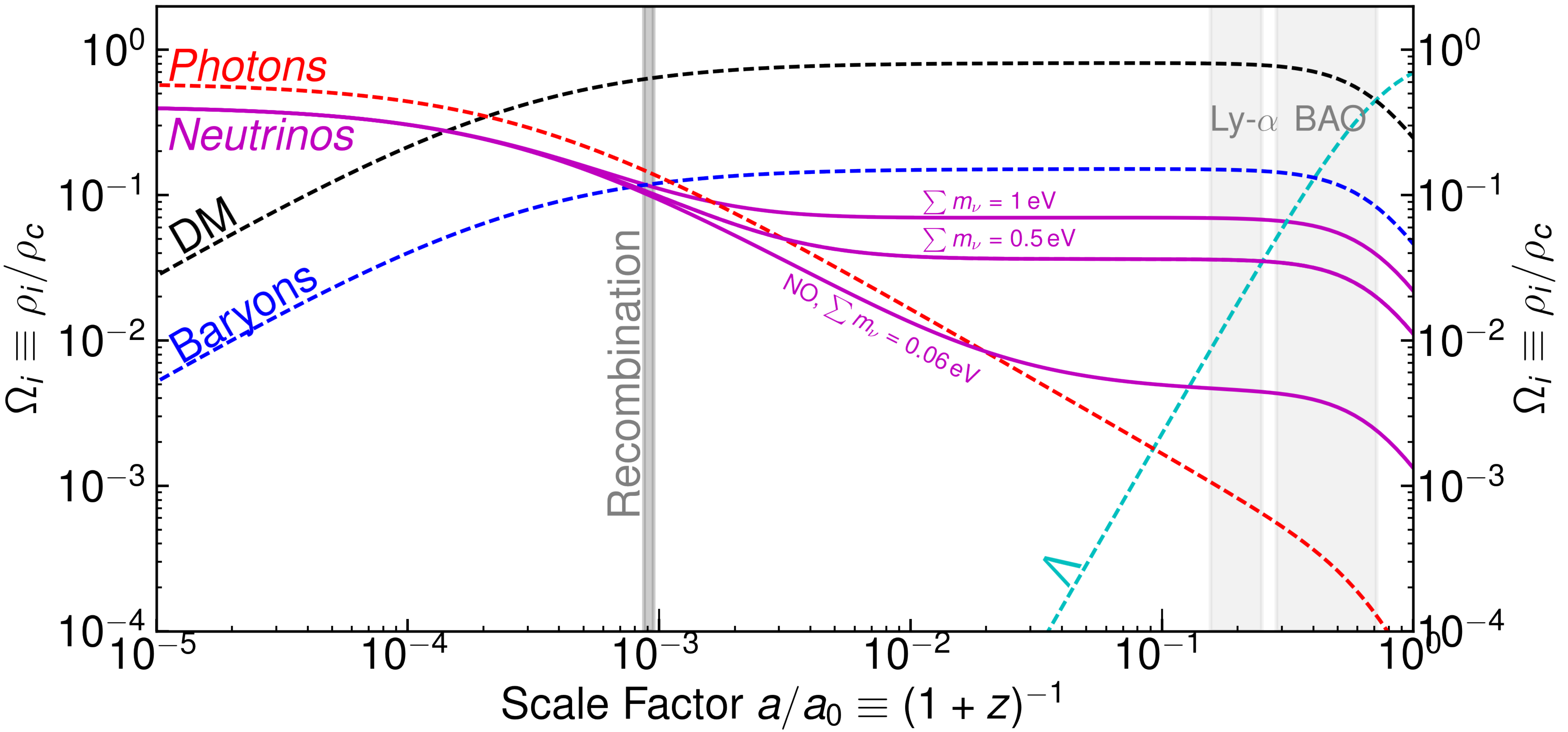
Normal $\sum m_\nu \gtrsim 0.06\,{\rm eV}$

Inverted $\sum m_\nu \gtrsim 0.10\,{\rm eV}$

- **Mass differences and mixings measured with high precision**
- **What is $\delta_{\rm CP}$ and what is the mass ordering?** **Neutrino Oscillations**
- **Are Neutrinos Dirac or Majorana Particles?** **0ν2β Experiments**
- **What is the neutrino mass scale? i.e. Σm_ν? i.e. $m_{\rm lightest}$?** **Cosmology**

Neutrino Masses in Cosmology

- **1) Massive neutrinos modify the expansion history**



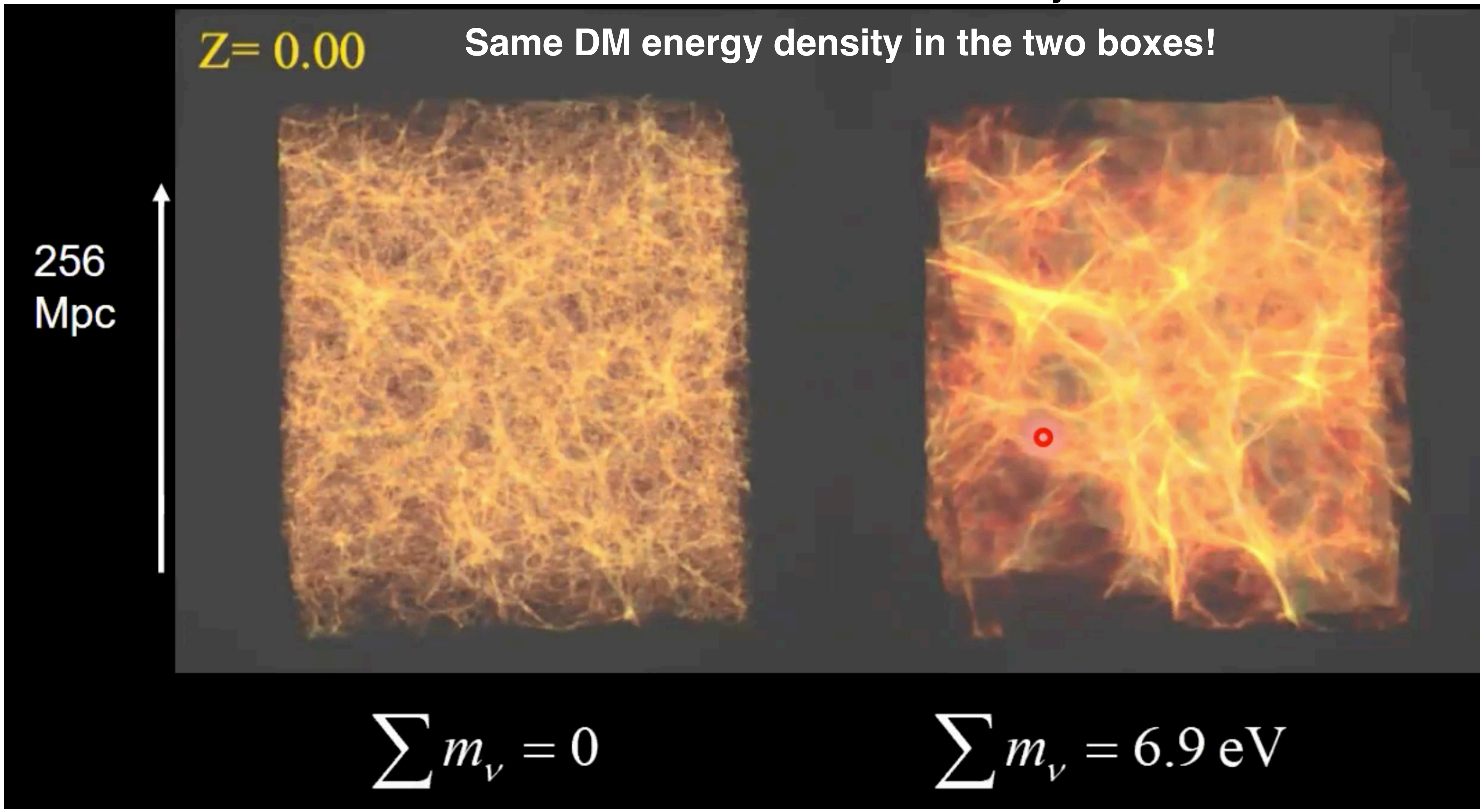
Non-Rel: $z_\nu^{\rm non-rel} \simeq 200 \frac{m_\nu}{0.1\,{\rm eV}}$

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

Neutrino Masses in Cosmology

- **2) Massive neutrinos suppress the growth of structure**

Taken from a talk by Steen Hannestad Link.



This happens because neutrinos travel very fast and therefore cannot fall in gravitational potentials. The effect of this smoothing is proportional to Ω_ν

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

Neutrinos of $m_\nu < 0.5\,\mathrm{eV}$ become non-relativistic after recombination.
That means that their effect on the anisotropies is somewhat small!

The most relevant impact is through the effect of gravitational lensing:

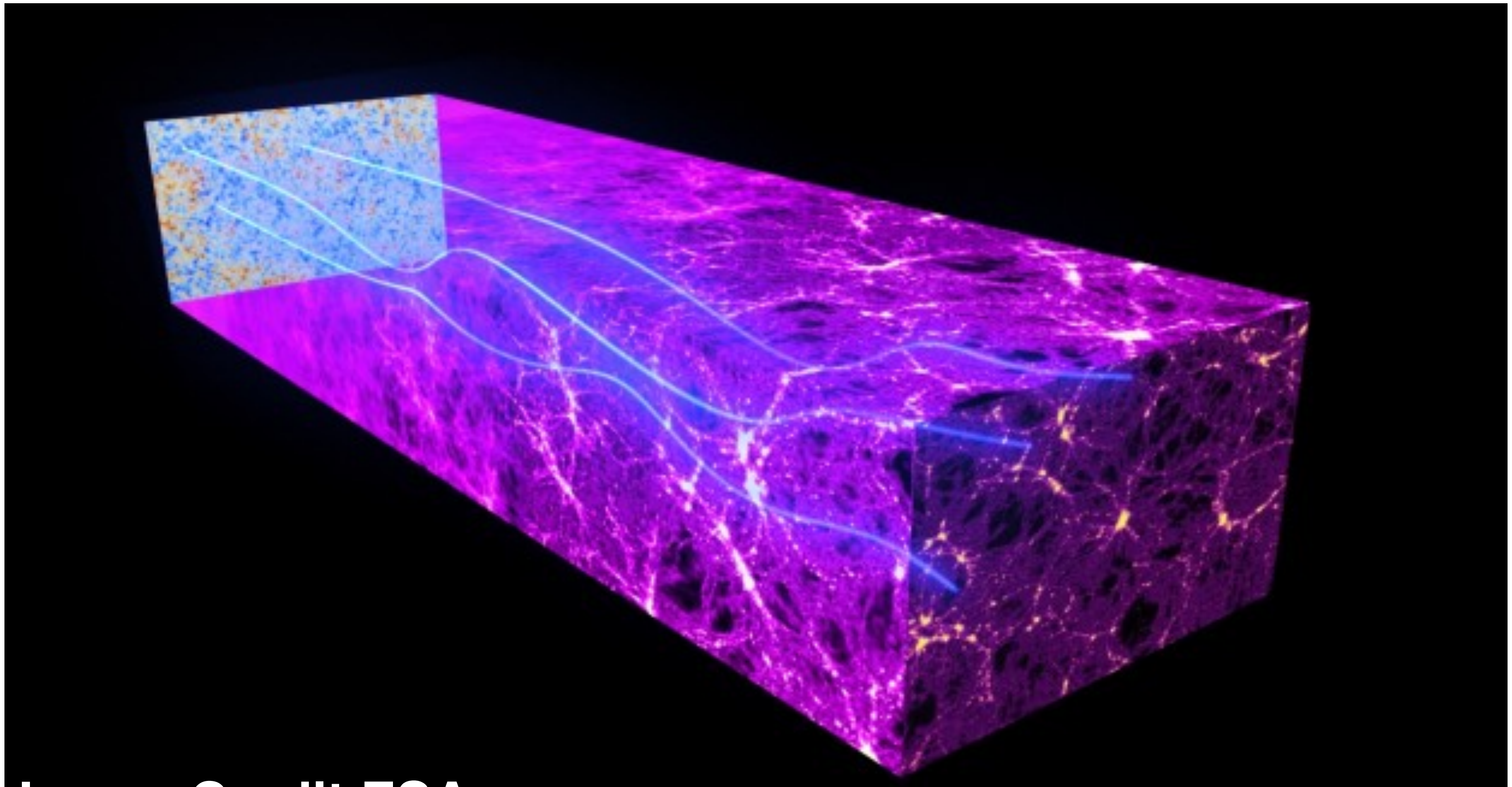


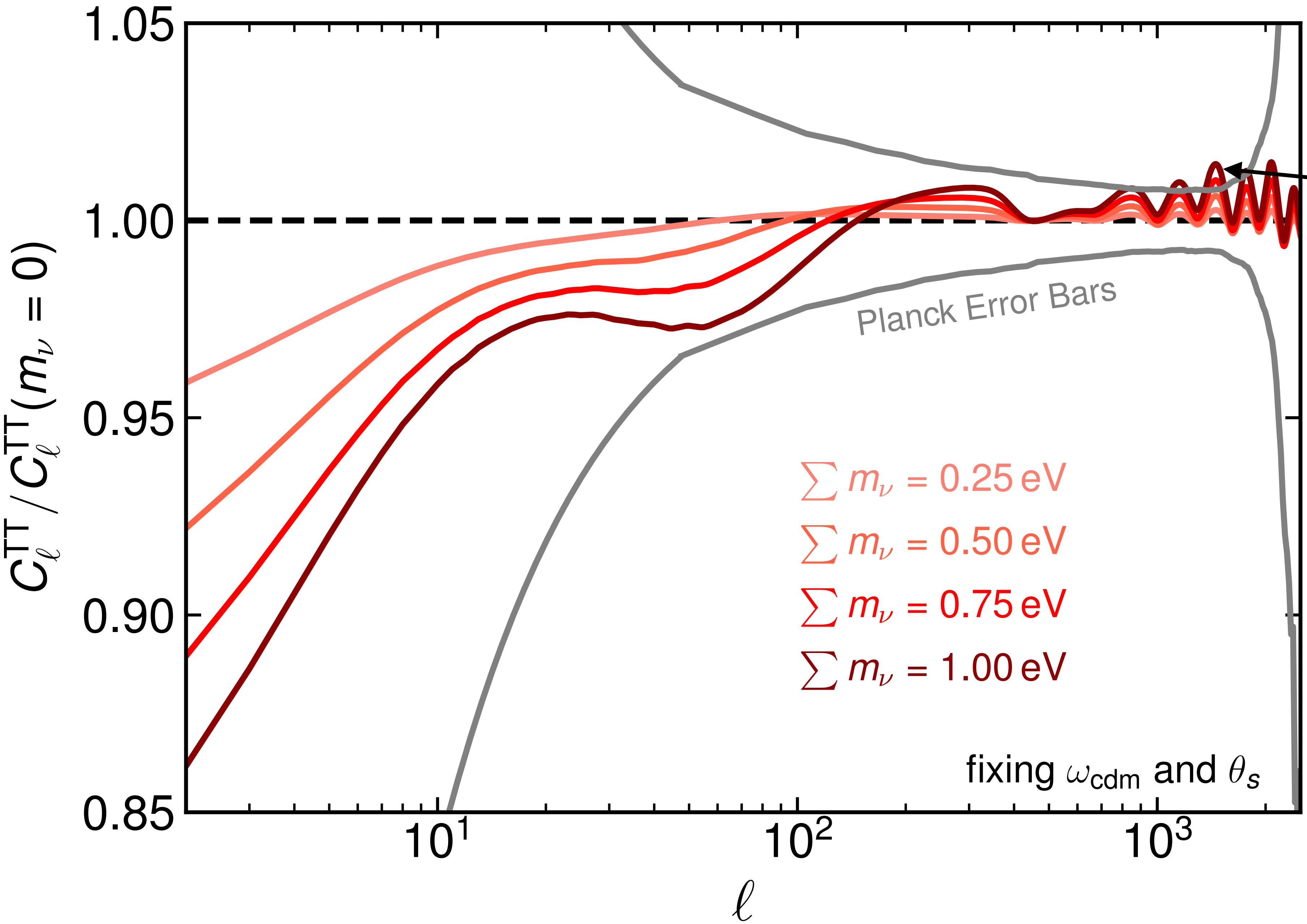
Image Credit ESA

The larger the neutrino mass the less is the CMB light lensed!

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

The effect of neutrino masses in the CMB:



$$\sum m_\nu < 0.54\,\mathrm{eV}$$

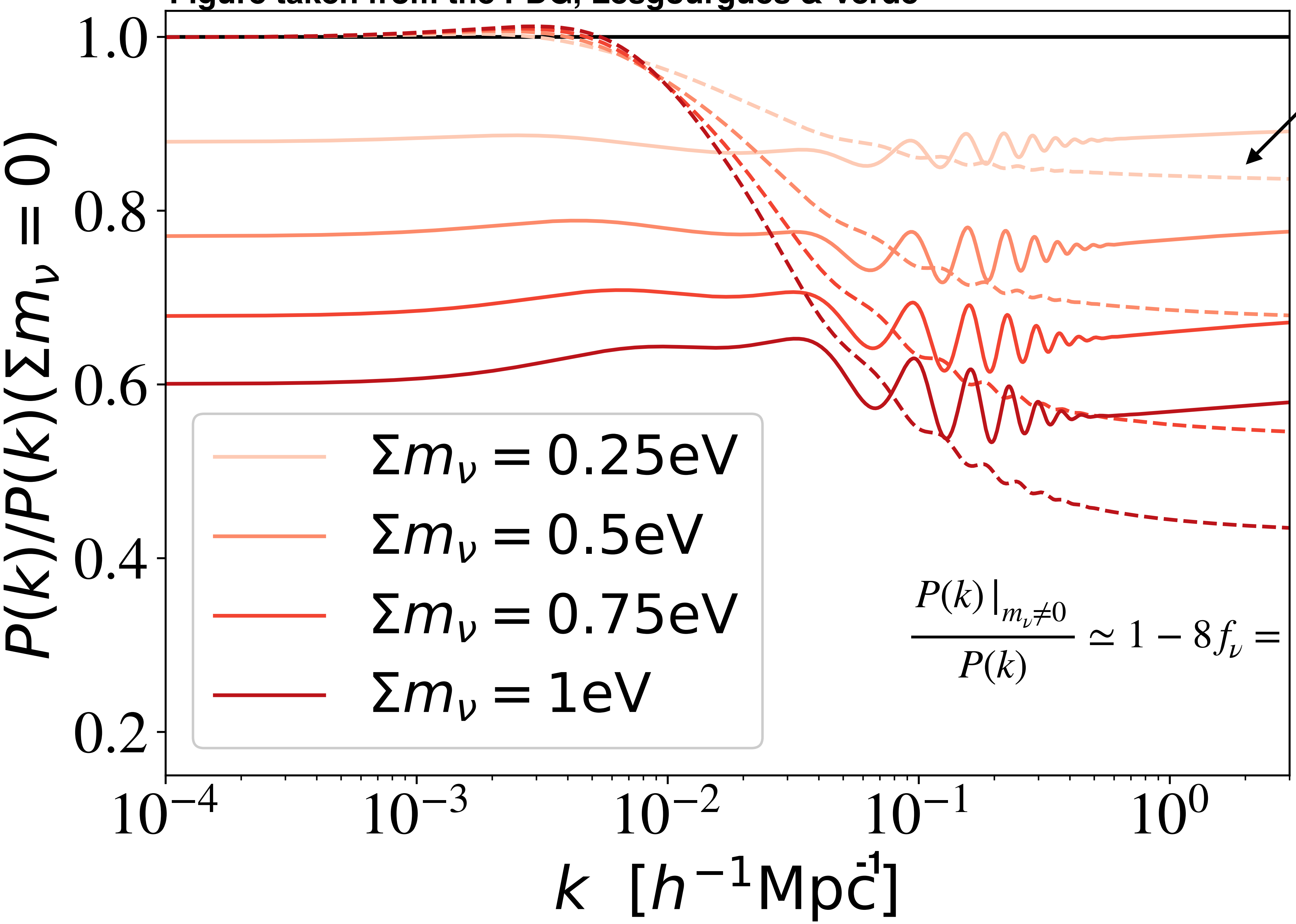
(95 % CL, TT+lowE)

Neutrino Masses in Cosmology

Galaxy Surveys

Suppression from $\Omega_\nu h^2$

Figure taken from the PDG, Lesgourgues & Verde



$$\frac{P(k)\,|_{m_\nu \neq 0}}{P(k)} \simeq 1 - 8 f_\nu = 1 - 8\,\frac{\Omega_\nu}{\Omega_{\rm cdm} + \Omega_b + \Omega_\nu}$$

Neutrino Masses from Cosmology

Planck 2018 for ΛCDM (1807.06209)

$\sum m_\nu < 0.54\,\mathrm{eV}$ **(95 % CL, TT+lowE)**

$\sum m_\nu < 0.26\,\mathrm{eV}$ **(95 % CL, TTTEEE+lowE)**

$\sum m_\nu < 0.24\,\mathrm{eV}$ **(95 % CL, TTTEEE+lowE+lensing)**

$\sum m_\nu < 0.12\,\mathrm{eV}$ **(95 % CL, TTTEEE+lowE+lensing+BAO)**

To be compared to the KATRIN bound: $\sum m_\nu < 2.4\,\mathrm{eV}$

Very robust bounds from linear Cosmology $\Delta T/T \sim 10^{-5}$

What about other non-linear cosmological data?

Importantly, all cosmological bounds are cosmological model dependent

What is the dependence upon the assumed Cosmological Model?

Neutrino Masses from Cosmology

Data beyond Planck and BAO within ΛCDM

$\sum m_\nu < 0.26\,\mathrm{eV}$	**Planck**	**Planck 1807.06209**
$\sum m_\nu < 0.12\,\mathrm{eV}$	**Planck+BAO**	**Planck 1807.06209**
$\sum m_\nu < 0.86\,\mathrm{eV}$	**BOSS P(k)**	**Ivanov et al. 1909.05277**
$\sum m_\nu < 0.16\,\mathrm{eV}$	**Planck+BOSS P(k)**	**Ivanov et al. 1912.08208**
$\sum m_\nu < 0.58\,\mathrm{eV}$	**Lyman-α+H_0prior**	**Palanque-Delabrouille et al. 1911.09073**
$\sum m_\nu < 0.10\,\mathrm{eV}$	**Planck+Lyman-α**	
$\sum m_\nu < 0.08\,\mathrm{eV}$	**Planck+BAO+H_0**	**Choudhury & Hannestad 1907.12598**
$\sum m_\nu < 0.09\,\mathrm{eV}$	**Planck+BAO+SN+RSD**	**di Valentino, Gariazzo & Mena 2106.15267**

- **Planck is driving current cosmological constraints**
- **Non-linear or mildly non-linear data sets break degeneracies in the fit**
- **The larger H_0 is, the stronger the constraint on $\sum m_\nu$ is** **(However, this comes from combining two data sets in strong tension!)**

Neutrino Masses from Cosmology

Cosmological Model Dependence

Planck+BAO and 3 degenerate neutrinos

$\sum m_\nu < 0.12\,\mathrm{eV}$	**Standard Case** Planck 1807.06209	ΛCDM+m_ν
$\sum m_\nu < 0.25\,\mathrm{eV}$	**Dark Energy dynamics** Choudhury & Hannestad 19'	CDM+m_ν+ω_a+ω
$\sum m_\nu < 0.15\,\mathrm{eV}$	**Varying Curvature** Choudhury & Hannestad 19'	ΛCDM+m_ν+Ω_k
$\sum m_\nu < 0.13\,\mathrm{eV}$	**Varying N_{eff}** Planck 1807.06209	ΛCDM+m_ν+N_{eff}
$\sum m_\nu < 0.17\,\mathrm{eV}$	**Varying N_{eff}+ω+α_s+m_ν** di Valentino et al. 1908.01391	CDM+m_ν+N_{eff}+ω+α_s+m_ν

- **Constraints are robust upon standard modifications of ΛCDM**

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

$\nu_i \to \nu_4 \phi$

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

Abellán, 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
Wetterich et al. 1009.2461

Non-standard Neutrino Populations

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

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

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

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

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

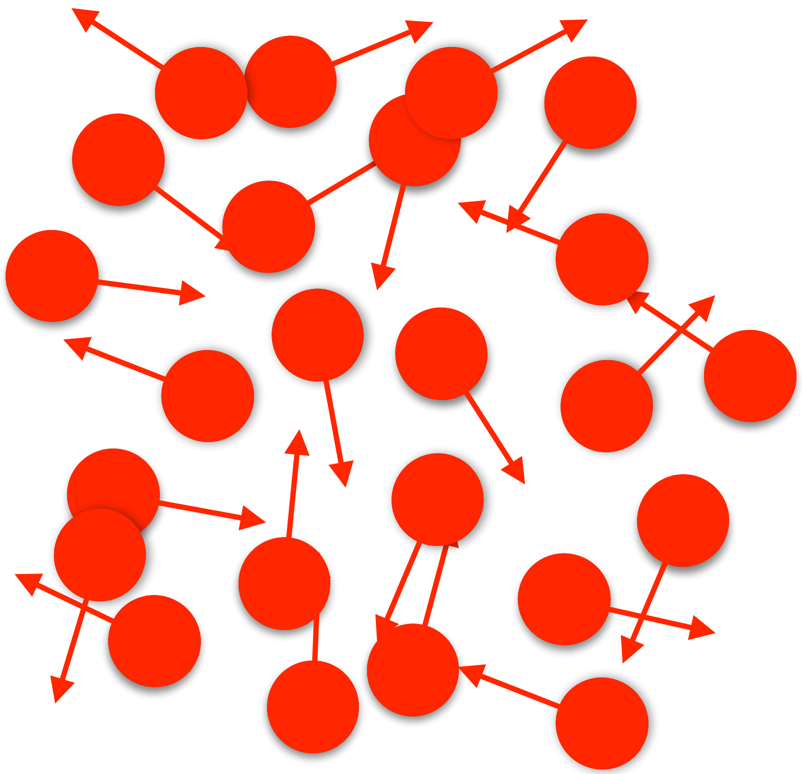
Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.12726

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

But Why? and How?

The Cosmic Neutrino Background

SM

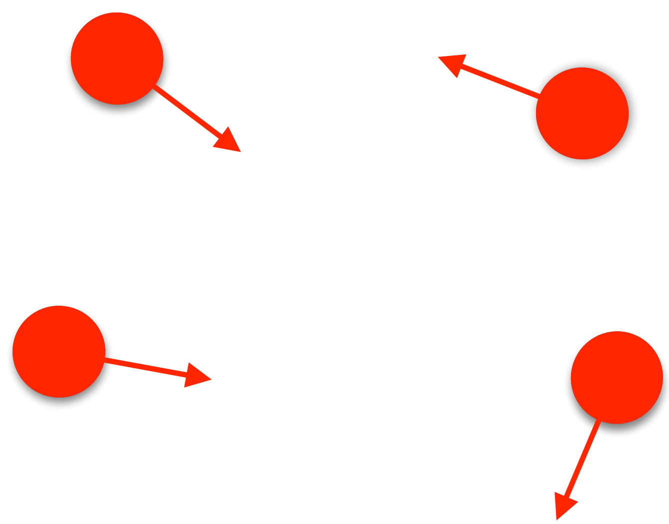


$n_\nu^{\rm SM} \sim 300\,{\rm cm}^{-3}$

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

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

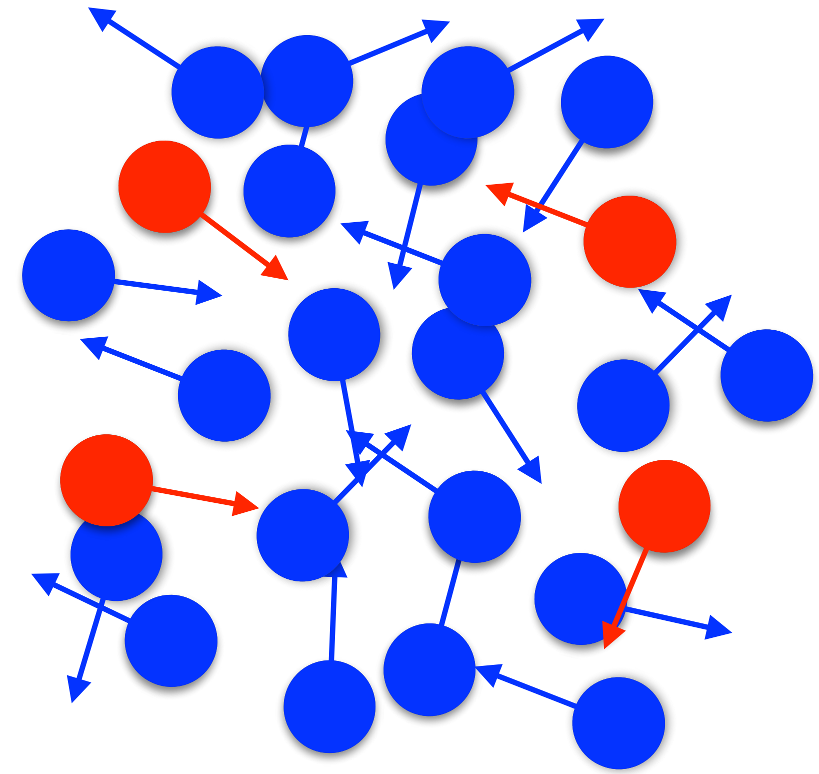
☹ $N_{\rm eff} \propto T_\nu^4 \ll 3$



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

😃 $\sum m_\nu < 1.2\,{\rm eV}$

solution:
add Dark Radiation



😃 $N_{\rm eff} \simeq 3$

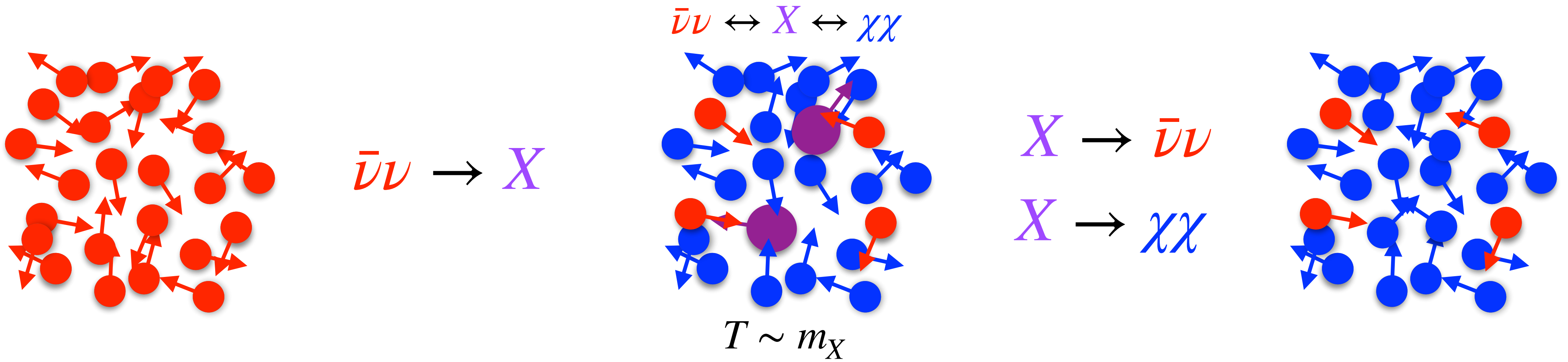
😃 $\sum m_\nu < 1.2\,{\rm eV}$

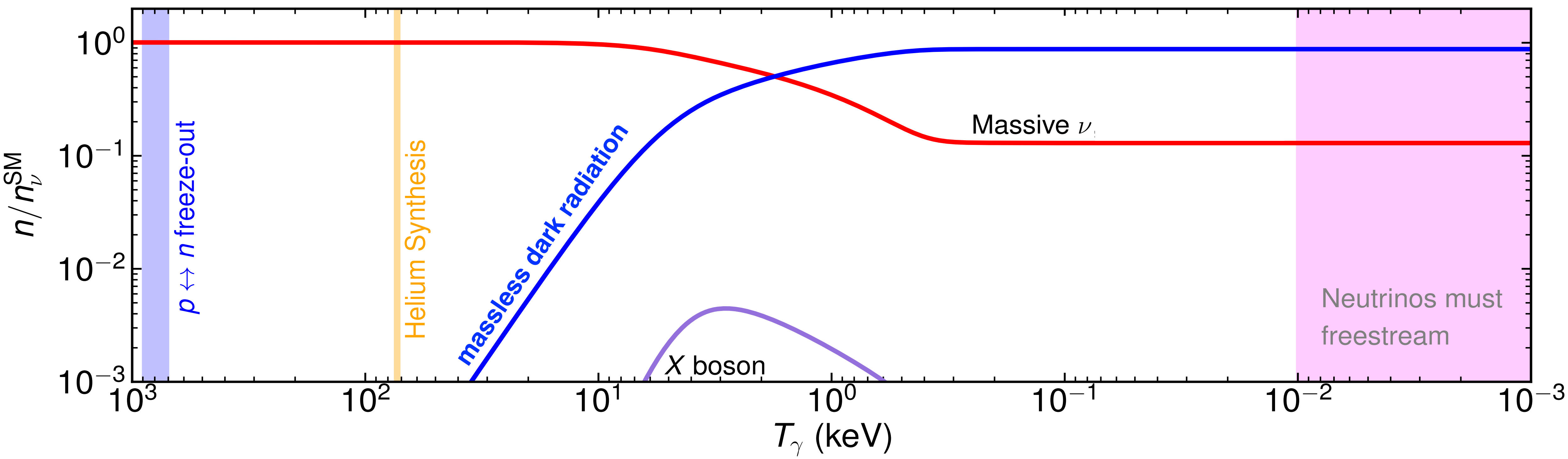
CMB observations can only constrain: $\rho_\nu^0 \equiv \sum m_\nu n_\nu$

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





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

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**

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

  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 $y_\alpha v_\Phi \ll m_D$

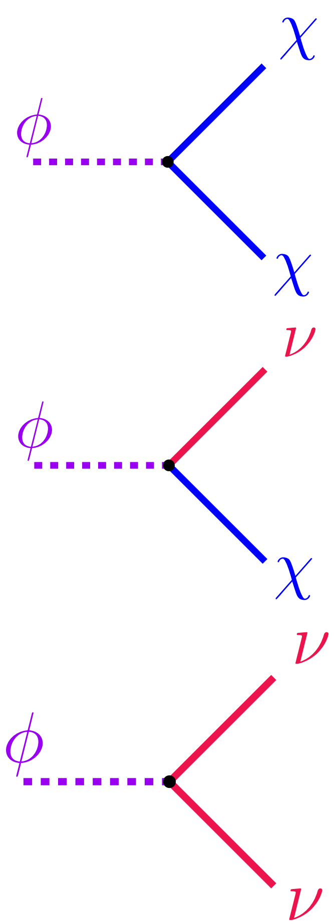
- **Seesaw mechanism at play** $m_\nu \simeq m_D^2/M_R$
- **Right ν_4 properties:** $m_\chi \simeq 0 \quad U_{\alpha 4} \sim \frac{y_\alpha v_\Phi}{m_D} \ll 1$

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 $U(1)_X$:

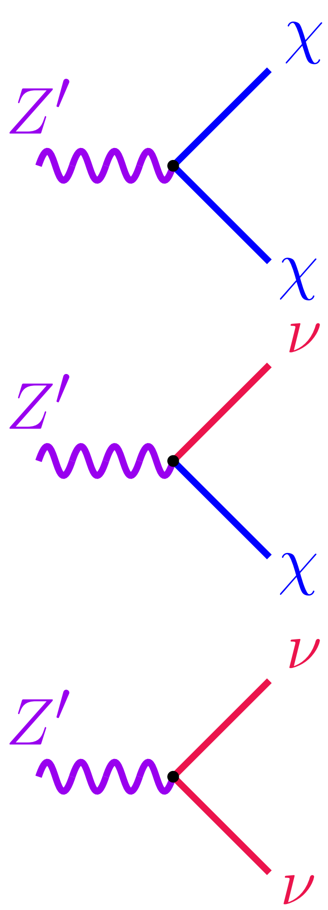


$$\lambda = 0$$

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

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

Gauge $U(1)_X$:

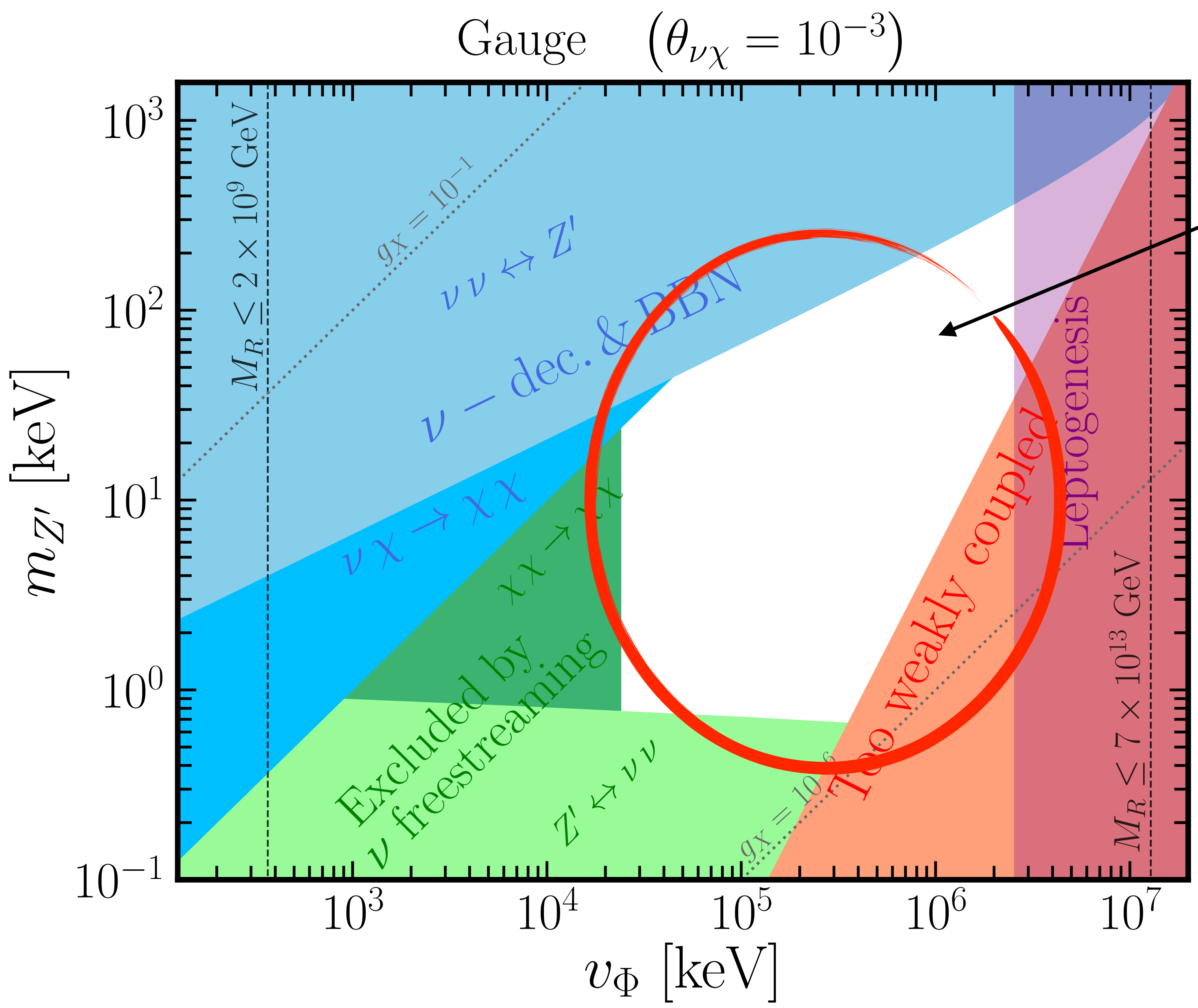


$$\lambda = g_X$$

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

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

Parameter Space



Viable Parameter space

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

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

Neutrino Masses from Cosmology

Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

$\nu_i \to \nu_j \phi$

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

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

$\nu_i \to \nu_4 \phi$

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

Abellán, 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
Wetterich et al. 1009.2461

Non-standard Neutrino Populations

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

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

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

$\langle p_\nu \rangle > 3.15\, T_\nu^{\rm SM}$

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

Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.12726

Take Away Messages:

— Cosmology can only constrain $\Omega_\nu(z)$ and not directly m_ν

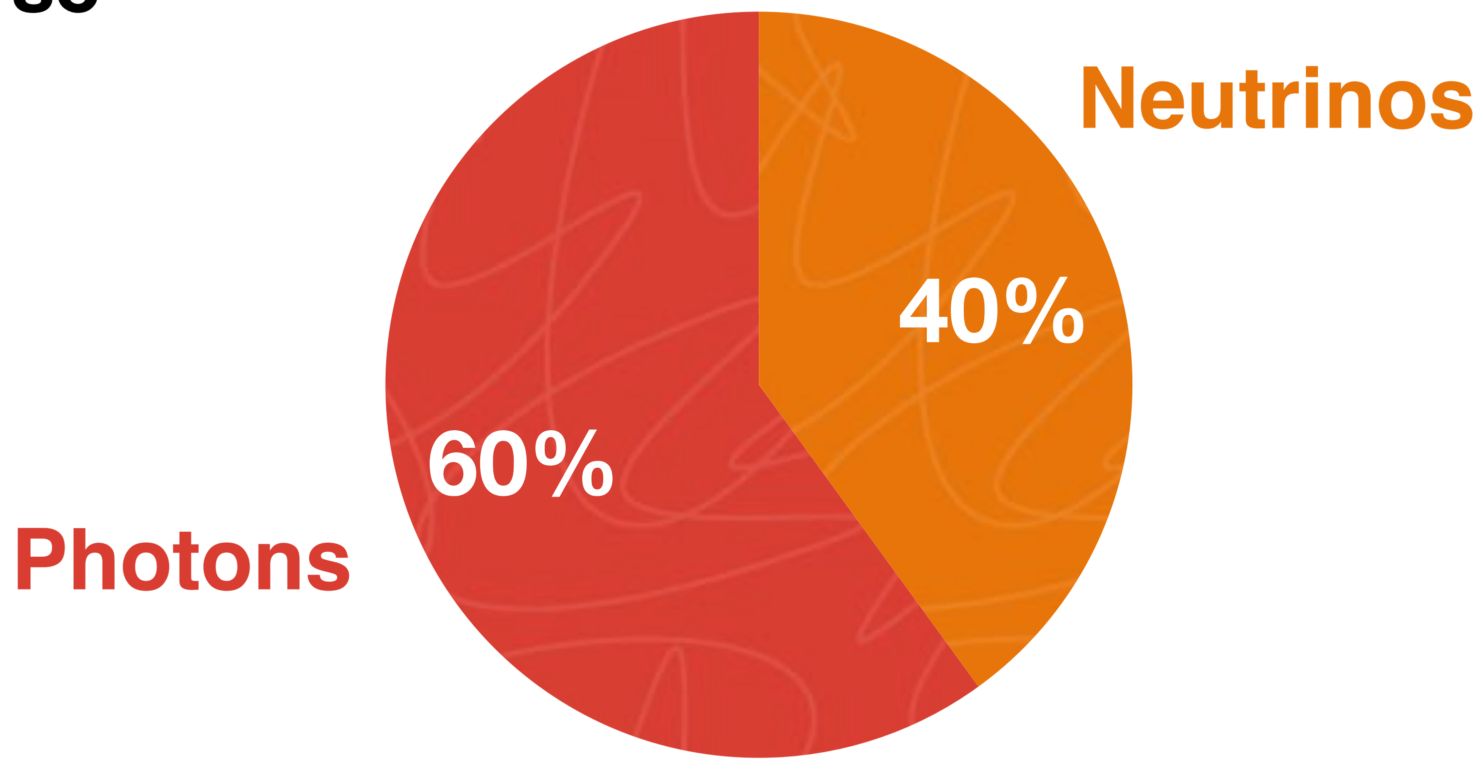
— Of course, in ΛCDM there is a direct link between $\Omega_\nu(z)$ and m_ν

— All these models reduce $\Omega_\nu(z)$ with respect to the one in ΛCDM and are in excellent agreement with all known cosmological data

— Importantly, they entail non-standard neutrino properties

Neutrino Interactions

- **Neutrinos represent a large component of the energy density of the Universe**



- **Neutrinos have very special cosmological perturbations**

1) They are ultrarelativistic until $z \sim 200\, m_\nu/0.1\,\mathrm{eV}$

2) In the SM: since $t_U \sim 0.1\,\mathrm{s}\,(T \sim 2\,\mathrm{MeV})$**, they are free streaming i.e. do not interact with anything**

These together actually mean that CMB observations can probe potential neutrino interactions!

Why?

First discussed by Bashinsky & Seljak in [astro-ph/0310198] and applied by Chacko, Hall, Okui & Oliver [hep-ph/0312267]

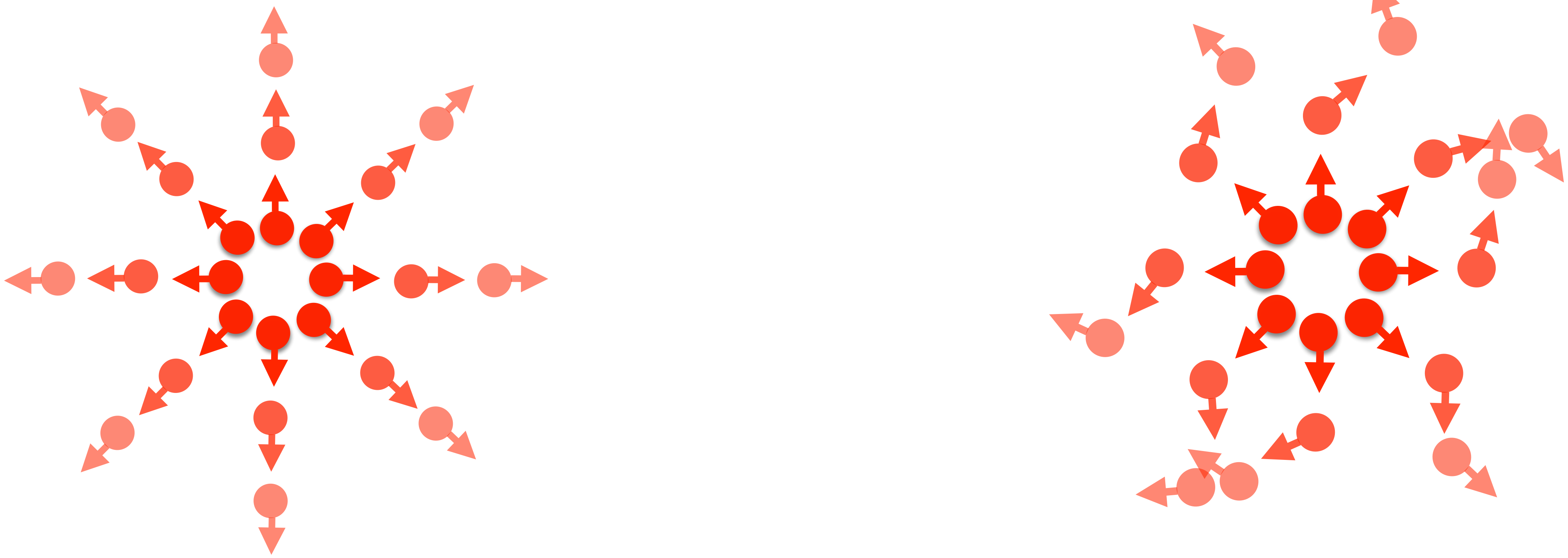
- **The key is in Einstein's equations**

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$ **Background expansion: Neff**

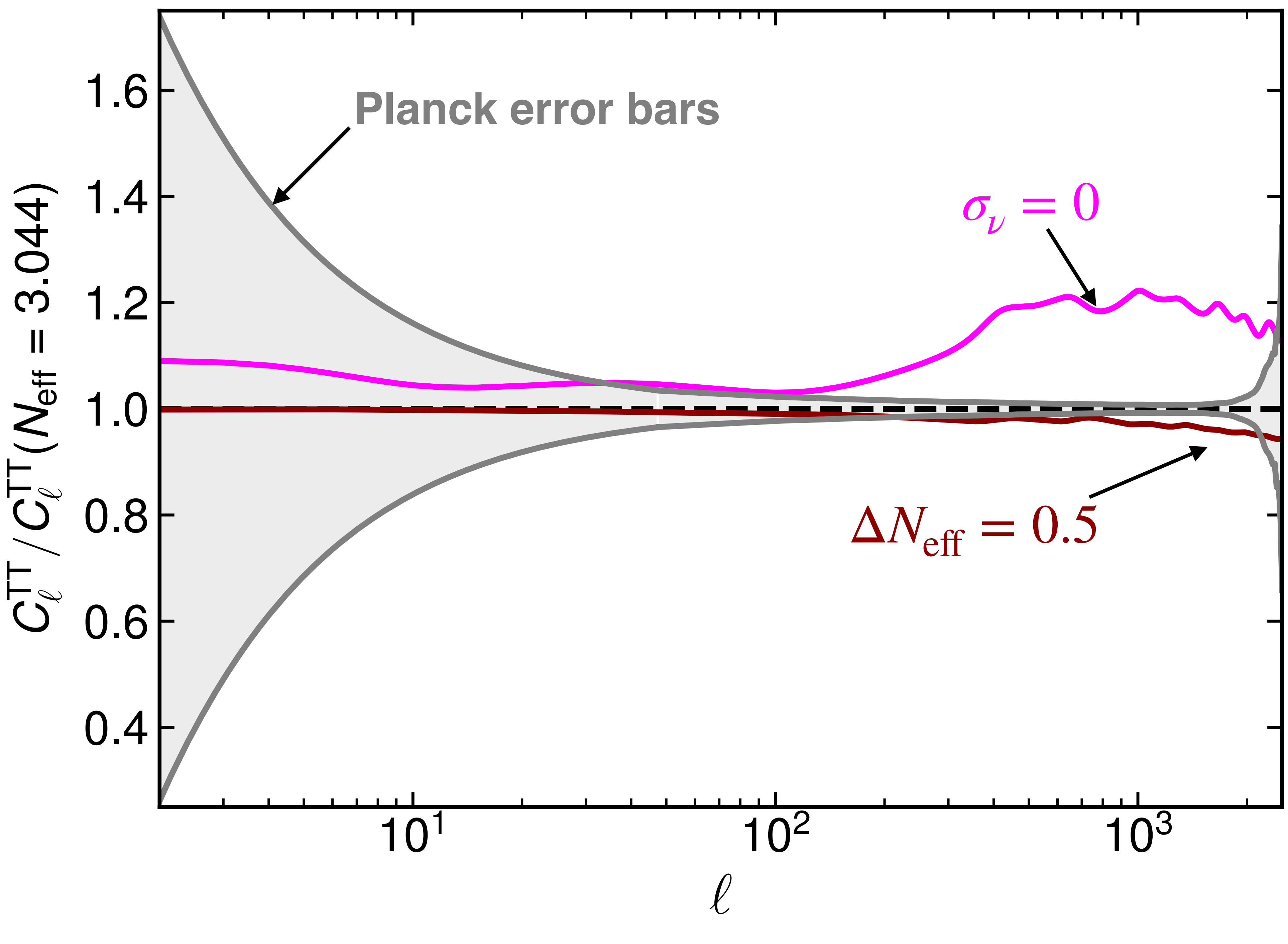
$$\delta G_{\mu\nu} = 8\pi G\, \delta T_{\mu\nu}$$ **Perturbations: can tell about interactions**

Neutrino anisotropic stress		Metric		CMB spectra
σ_ν	$\longrightarrow$	$\delta g_{\mu\nu}$	$\longrightarrow$	ΔT_γ

Free Streaming Neutrinos $\sigma_\nu \neq 0$ **Interacting Neutrinos** $\sigma_\nu \to 0$



Effect of Neutrino Free-streaming in the CMB

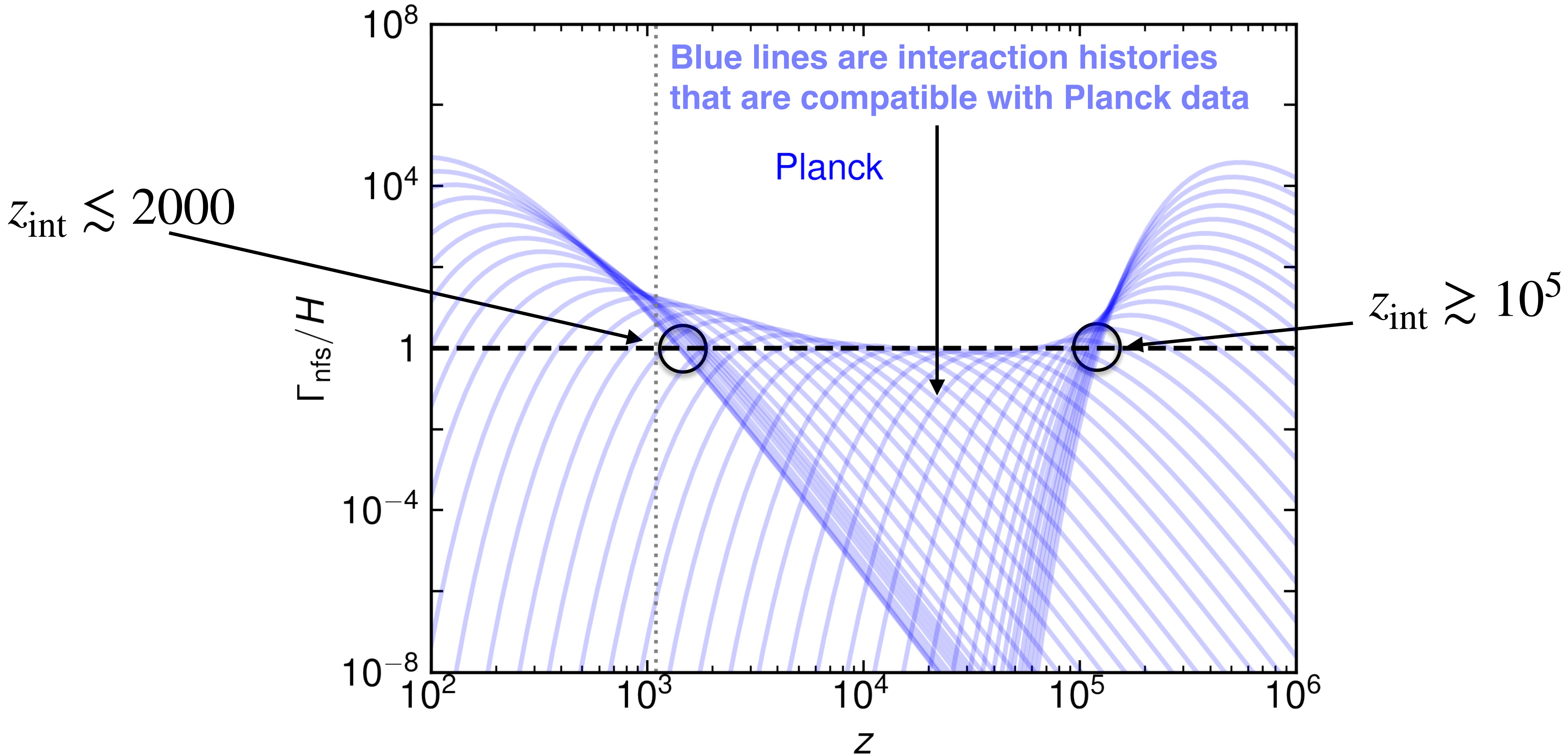


The Neutrino Freestreaming window

Together with Petter Taule and Mathias Garny in 2207.04062 we have recently stablished the presence of a neutrino free streaming window.

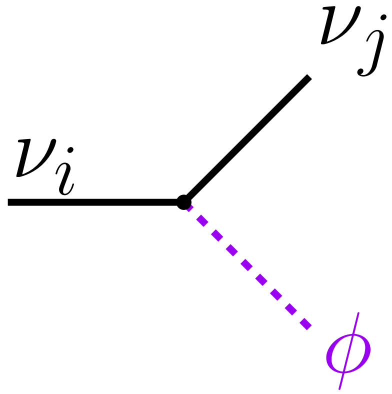
We have demonstrated in a model independent way that neutrinos cannot interact efficiently between themselves or other light particles in the range:

$2000 \lesssim z_{\rm int} \lesssim 10^5$ $\quad$ $0.3\,{\rm eV} \lesssim T_\nu \lesssim 15\,{\rm eV}$



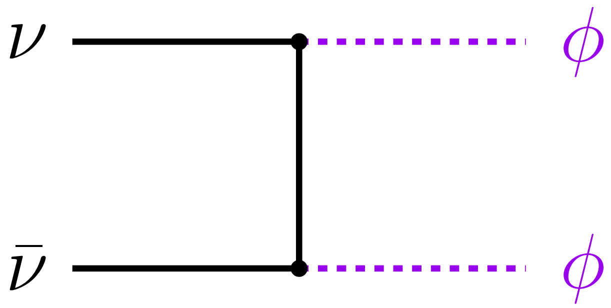
Models

Neutrino Decays



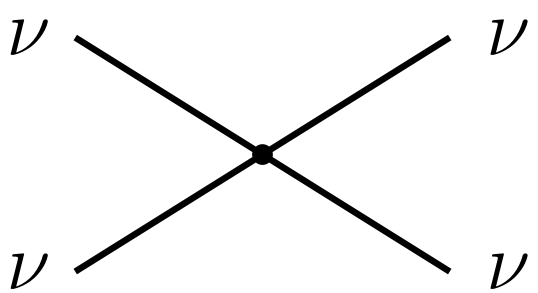
Hannestad & Raffelt [hep-ph/0509278]
Basboll, Bjaelde, Hannestad & Raffelt [0806.1735]
Escudero & Fairbairn [1907.05425]
Chacko, Dev, Du, V. Poulin and Y. Tsai [1909.05275]
Barenboim, Chen, Hannestad, Oldengott, Tram & Wong [2011.01502]
Abellán, Chacko, Dev, Du, Poulin & Tsai [2112.13862]
Chen, Oldengott, Pierobon & Wong [2203.09075]

Neutrino Annihilations



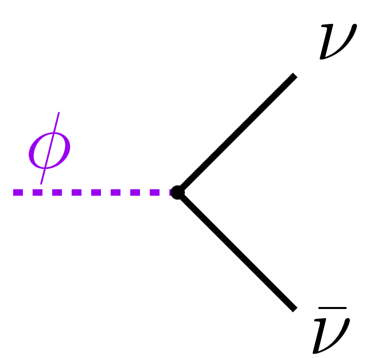
Beacom, Bell & Dodelson [astro-ph/0404585]
Hannestad [astro-ph/0411475]
Archidiacono & Hannestad [1311.3873]
Forastieri, Lattanzi & Natoli [1904.07810]

Neutrino Scatterings



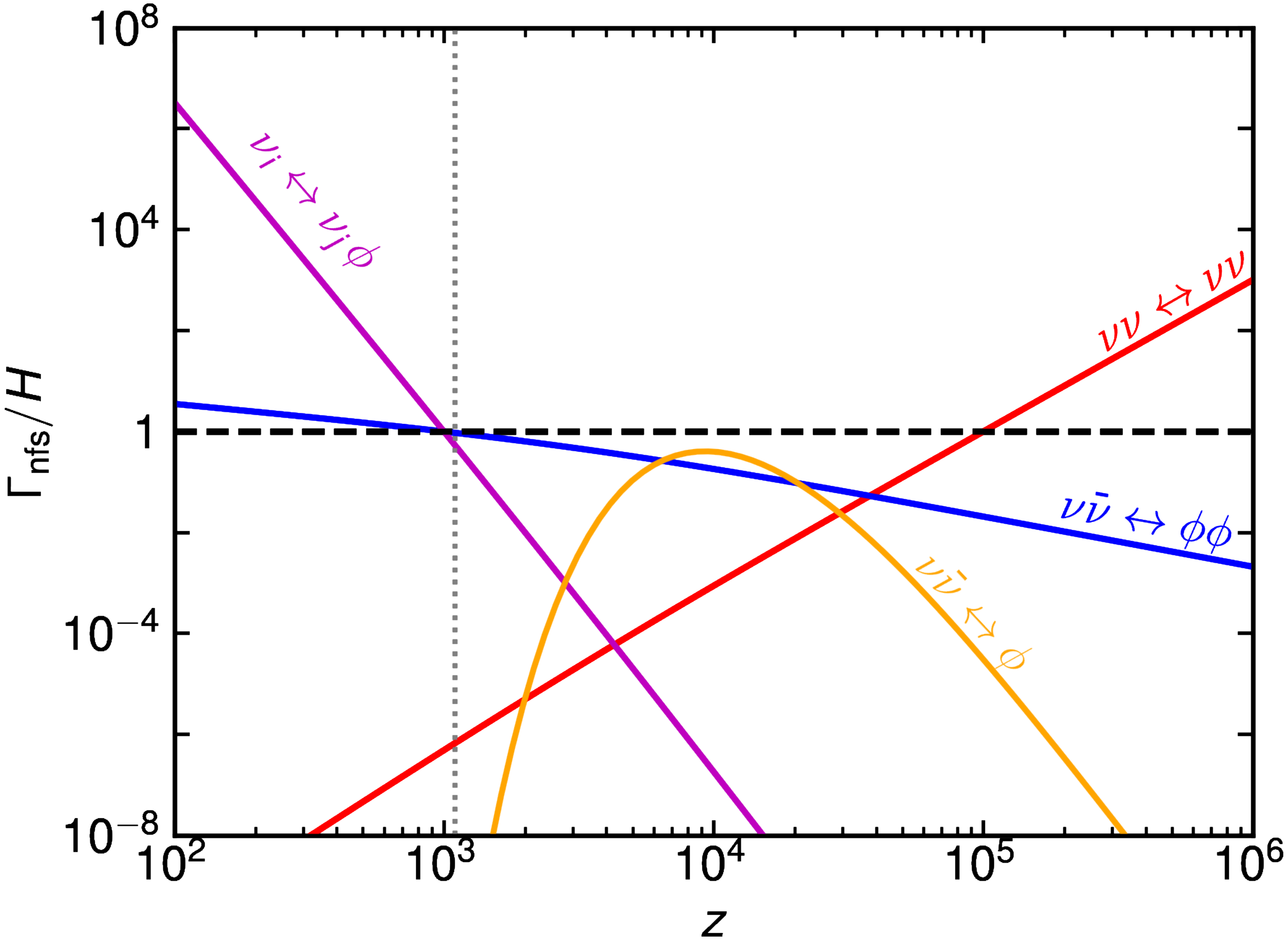
Cyr-Racine & Sigurdson [1306.1536]
Lancaster, Cyr-Racine, Knox & Pan [1704.06657]
Oldengott, Tram, Rampf & Wong [1706.02123]
Kreisch, Cyr-Racine & Doré [1902.00534]
Das & Ghosh [2011.12315]
Choudhury, Hannestad & Tram [2012.07519]
Brinckmann, Chang & LoVerde [2012.11830]

eV-scale neutrinophilic bosons

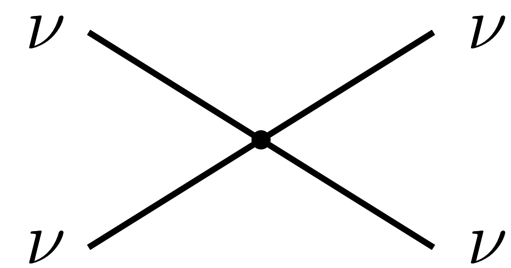


Chacko, Hall, Okui & Oliver [hep-ph/0312267]
Escudero & Witte [1909.04044]
Escudero & Witte [2103.03249]
Sandner, Escudero & Witte [2304.XXXXX]

Rates for various models

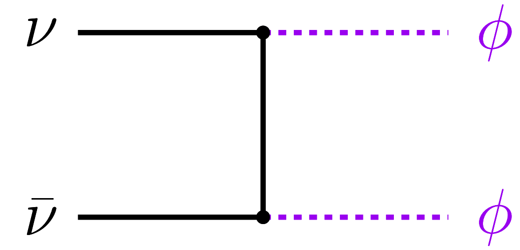


Neutrino scatterings



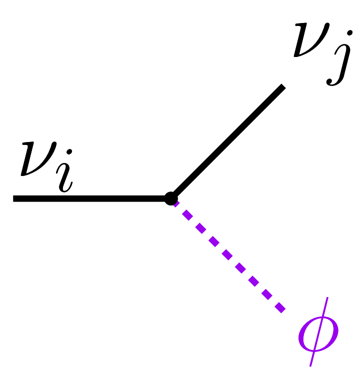
$\Gamma_{nfs} \sim T^5$

Neutrino annihilations



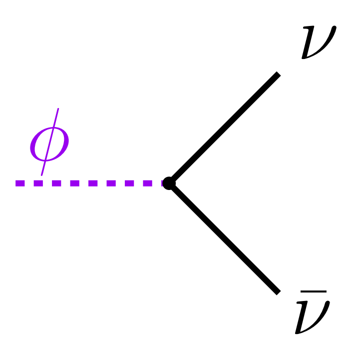
$\Gamma_{nfs} \sim T$

Neutrino decays



$\Gamma_{nfs} \sim T^{-5}$

eV-scale Neutrinophilic Bosons

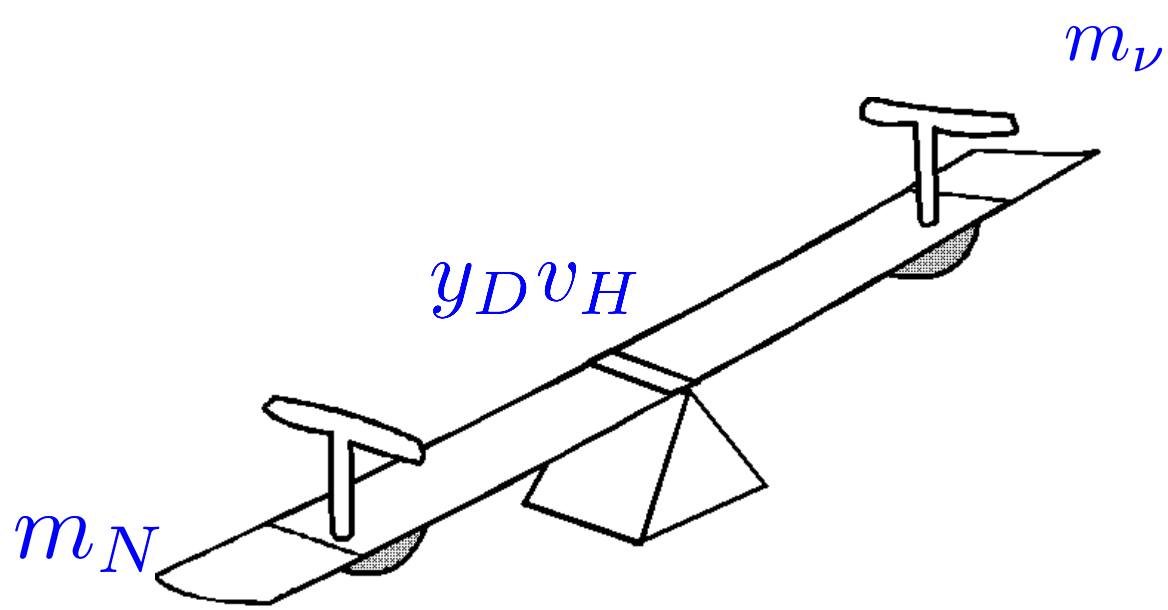


$\Gamma_{nfs} \sim T^{-5}$ $(T > m_\phi)$

$\Gamma_{nfs} \sim e^{-m_\phi/T}$ $(T < m_\phi)$

The case of the Majoron

Type-I seesaw



Neutrinos are very light Majorana particles: $m_\nu \simeq 0.03\,\mathrm{eV} \left(\frac{y_D}{10^{-6}}\right)^2 \frac{\mathrm{TeV}}{M_N}$

Are There Real Goldstone Bosons Associated with Broken Lepton Number? #1

Y. Chikashige (Munich, Max Planck Inst.), Rabindra N. Mohapatra (Munich, Max Planck Inst. and Munich U.), R.D. Peccei (Munich, Max Planck Inst.) (Sep, 1980)

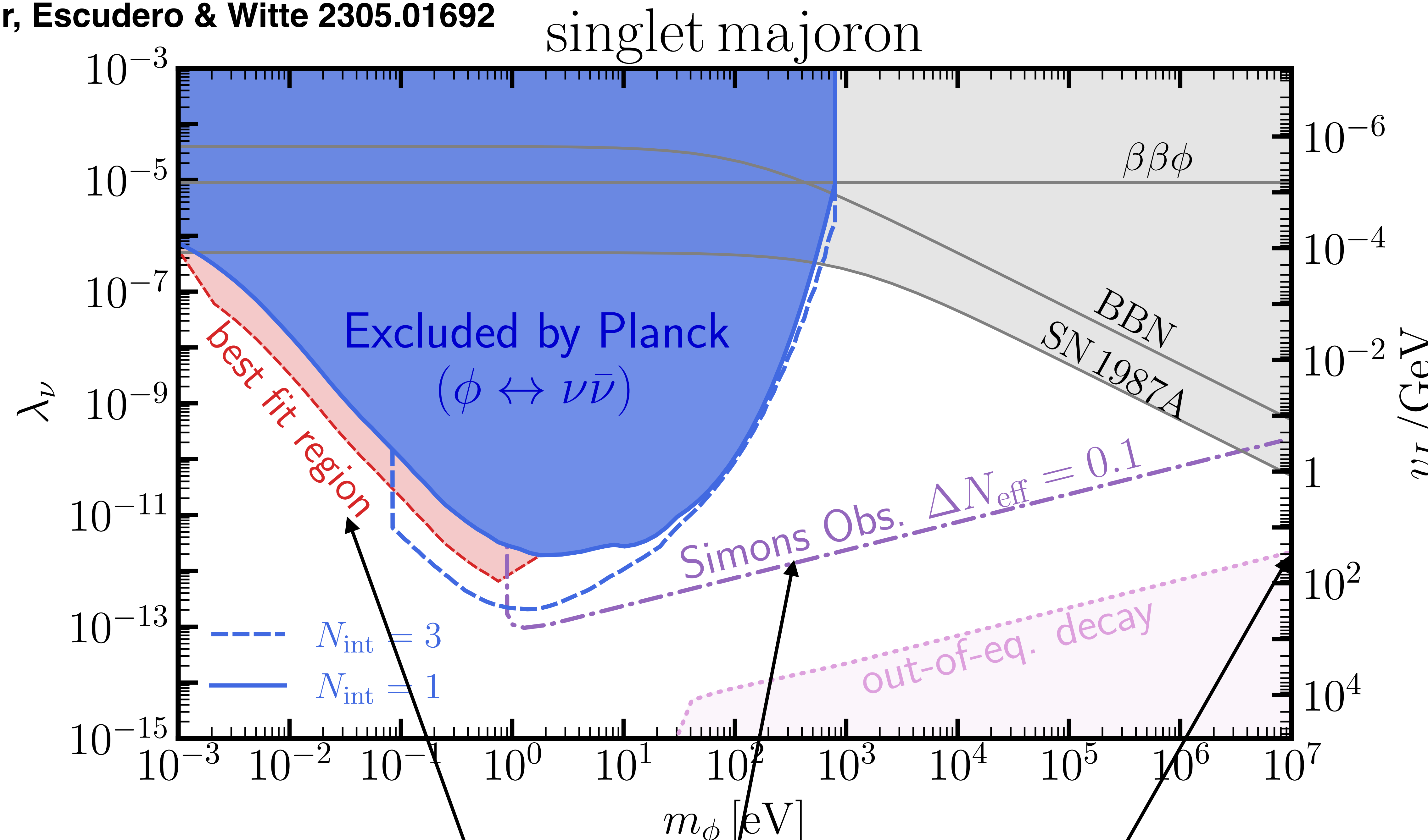
Published in: *Phys.Lett.B* 98 (1981) 265-268

The Majoron is the pseudo-Goldstone boson associated with the spontaneous breaking of global $U(1)_L$

$$\mathscr{L} = \lambda\, \phi\, \bar{\nu}\gamma_5\nu \qquad \lambda = m_\nu / v_\phi$$

The case of the Majoron

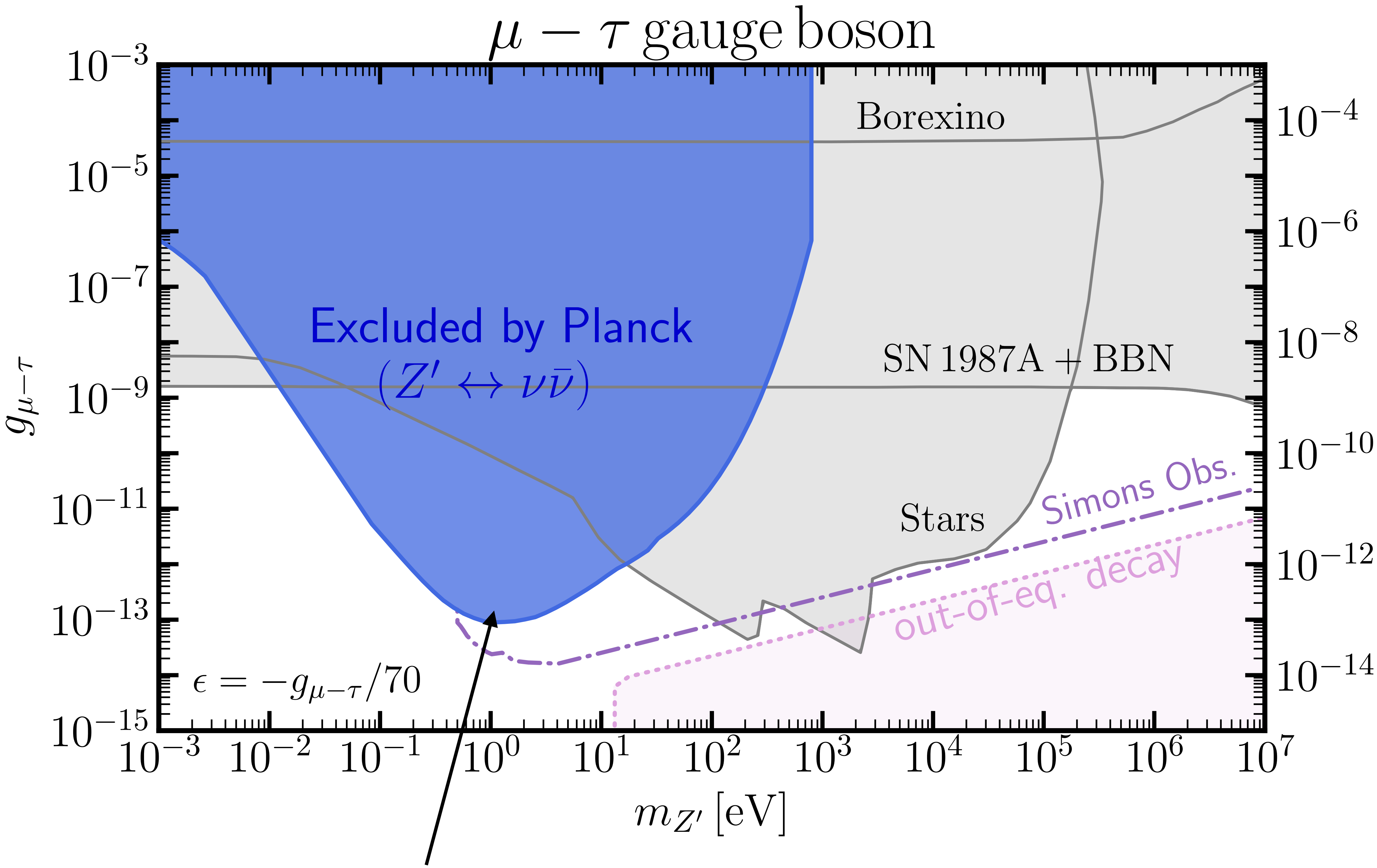
Sandner, Escudero & Witte 2305.01692



- **CMB observations can test a well motivated neutrino mass model up to $v_L \sim v_H$**
- **There is a region preferred at ~1σ. We show that together with a primordial $\Delta N_{\rm eff}$ the model can lower the H_0 tension to the 3σ level. This is 0.5-1σ worse than what we found in Escudero & Witte 1909.04044 and 2103.03249**
- **The Simons Observatory will test in the next ~6 years wide regions of parameter space!**

A light $\mu - \tau$ gauge boson

Sandner, Escudero & Witte 2305.01692



- **Planck rules out couplings as small as $g_{\mu-\tau} \sim 10^{-13}$ for $m_{Z'} \sim \text{eV}$**

Conclusions

Neff: Number of relativistic neutrino species

BBN $N_{\rm eff}^{\rm BBN} = 2.86 \pm 0.28$

Planck+BAO $N_{\rm eff}^{\rm CMB} = 2.99 \pm 0.17$

Standard Model $N_{\rm eff} = 3.043$

CMB and BBN measurements give strong evidence that the Cosmic Neutrino background should be there.

This implies:

1) **a stringent constraint on many BSM models**

2) **gives us confidence to test neutrino properties with cosmology**

We have performed the most accurate calculation of Neff to date and found

$$N_{\rm eff}|_{\rm SM} = 3.043$$

Conclusions

Neutrino Masses:

Cosmological bounds are very stringent within ΛCDM:

$$\sum m_\nu < 0.12\,\mathrm{eV}$$ **at 95% CL**

In addition, they are robust upon standard modifications of the model.

There are several non-standard neutrino cosmologies where this bound can be evaded

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 $m_{Z'} \sim 10\,\mathrm{keV}$ **and** $v_\Phi \sim 10\,\mathrm{MeV} - 1\mathrm{GeV}$

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!

Conclusions

Neutrino Interactions:

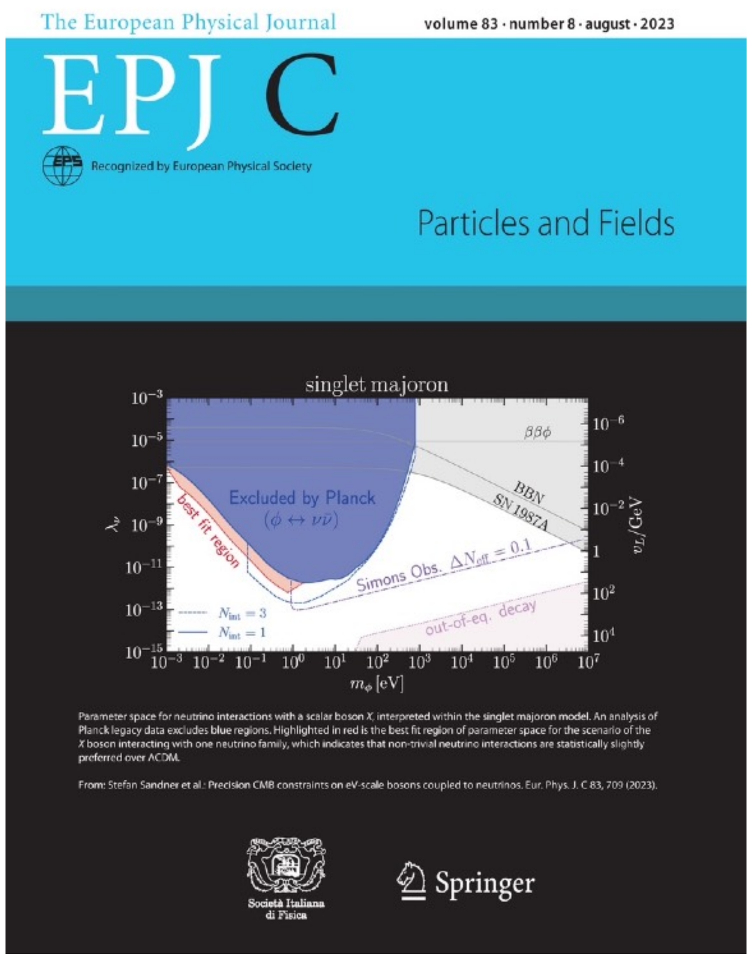
The CMB is a powerful probe of neutrino interactions

We have shown that there is a well defined redshift region where neutrinos must free stream

$$2 \times 10^3 \lesssim z \lesssim 10^5$$

These bounds are relevant for many particle physics scenarios

Including the singlet majoron model and a light mu-tau Z'



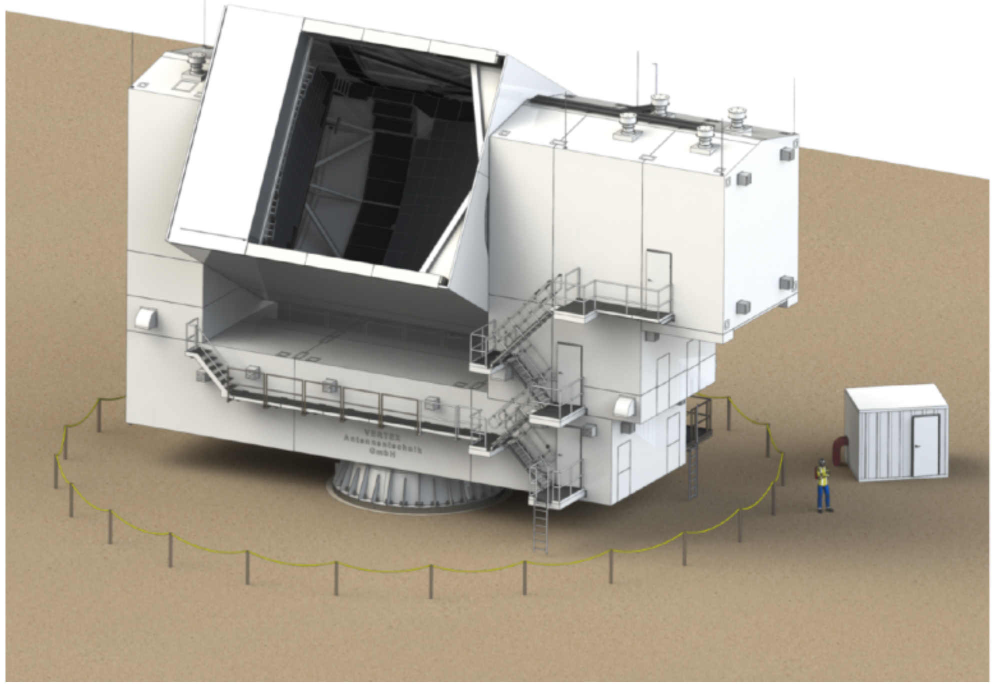
Outlook: Number of Neutrinos

The next generation of CMB experiments are expected to significantly improve the sensitivity to Neff

Simons Observatory

$\sigma(N_{\rm eff}) = 0.05$ **~2029**

CMB-S4



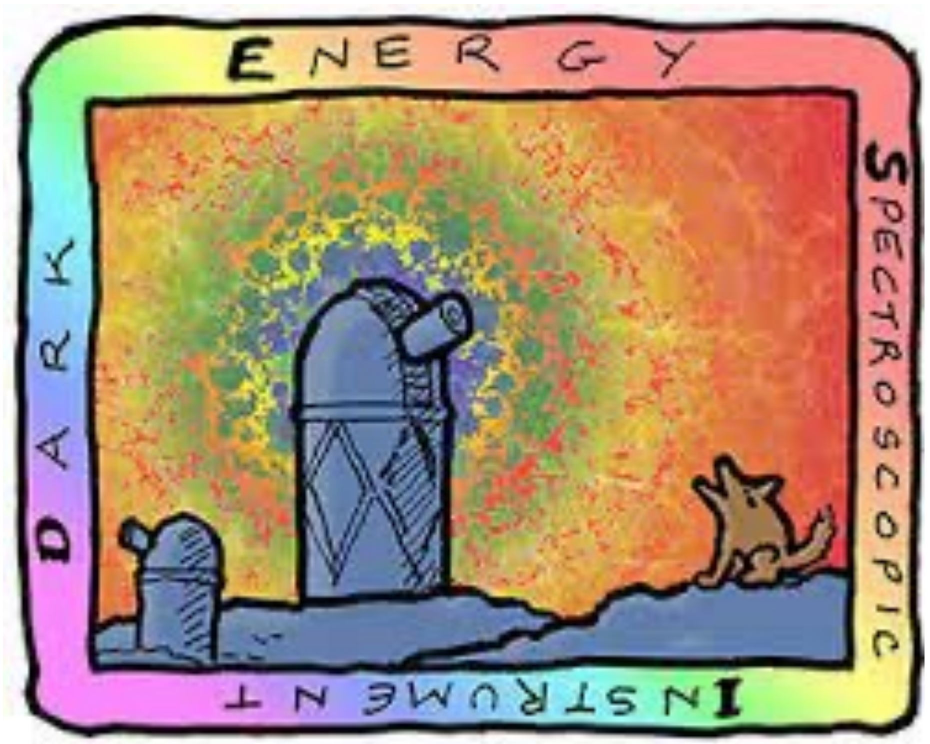
$\sigma(N_{\rm eff}) = 0.03$ **~2035?**

These measurements will represent an important test of the CNB and BBN in the SM and perhaps may yield a BSM signal!

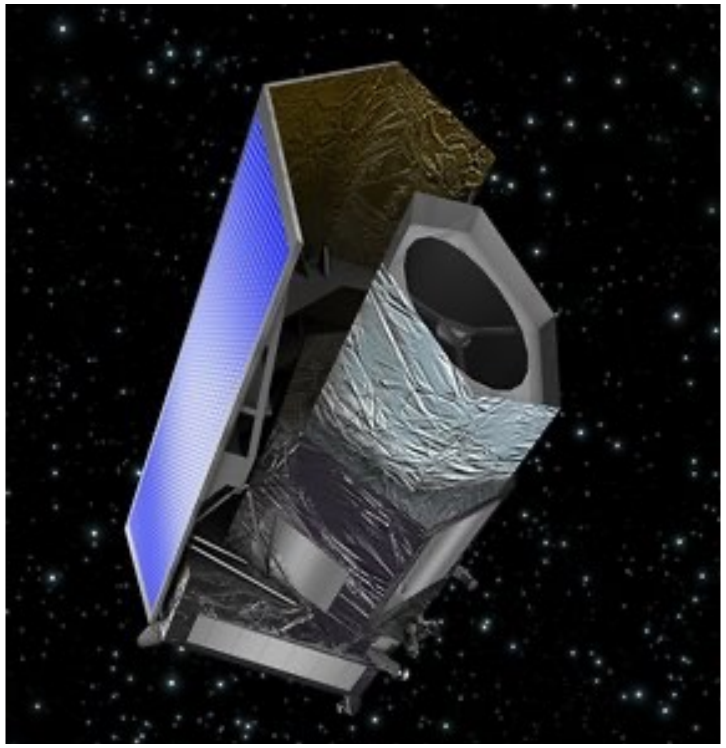
Outlook: Neutrino Masses

The next generation of galaxy surveys in combination with CMB data are expected to measure the neutrino mass if the Universe is governed by a ΛCDM cosmology

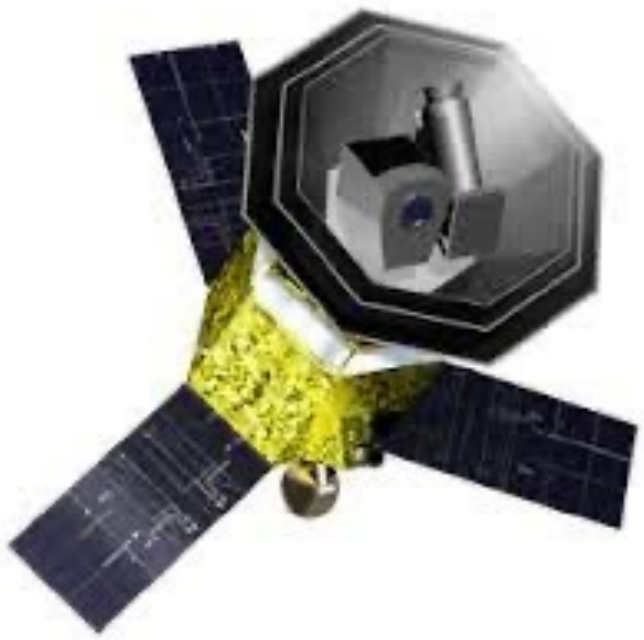
DESI



EUCLID



LiteBIRD



Why? DESI: 30M galaxies and EUCLID: 50M galaxies, but BOSS 1M galaxies

This is expected to happen in the next 3-4 years: $\sigma(\sum m_\nu) = 0.02$

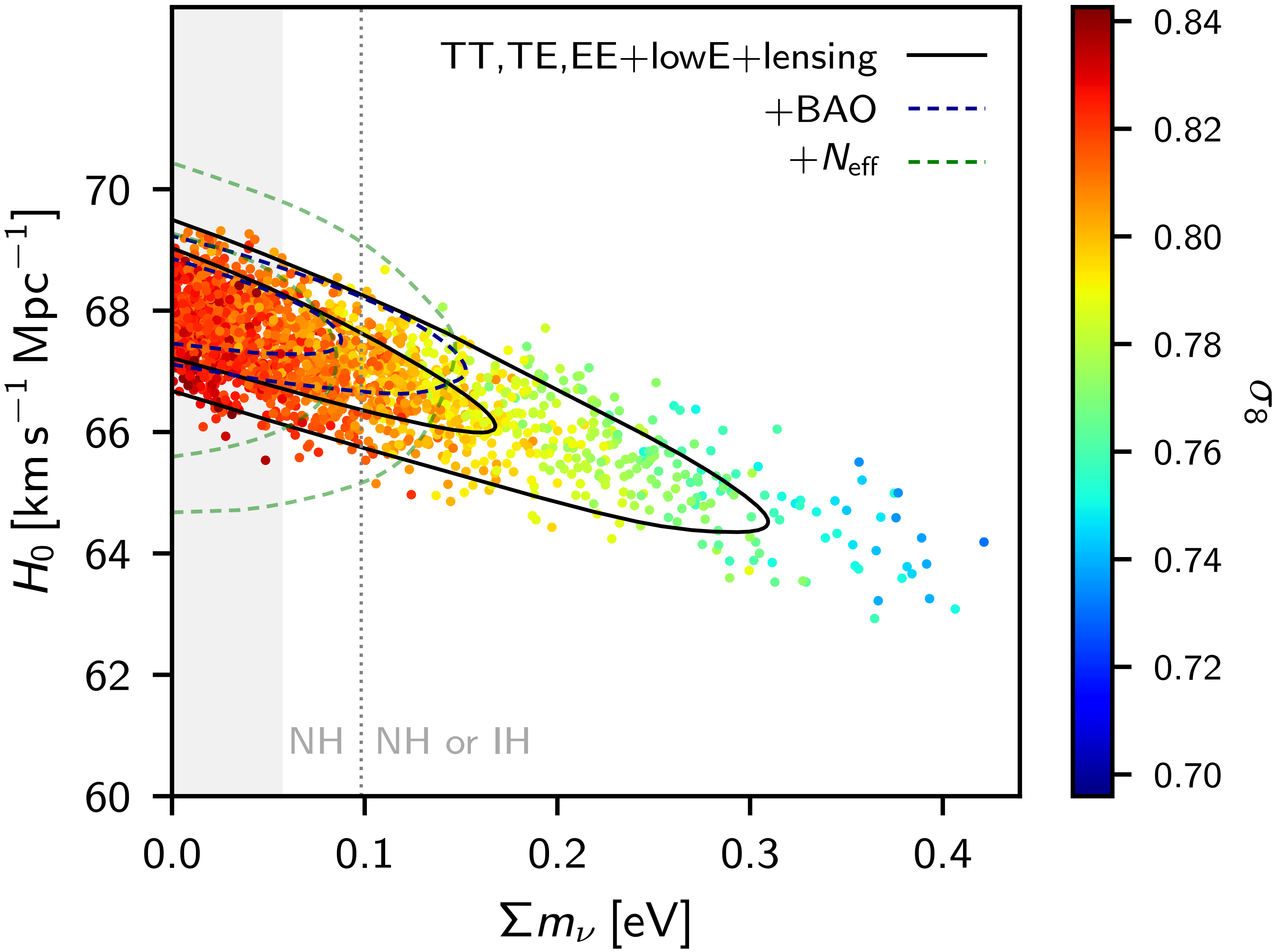
In parallel, the KATRIN experiment is taking data and should reach a sensitivity of $m_{\bar{\nu}_e} \lesssim 0.2\,\mathrm{eV}$ **at 90% CL in ~ 3-4 years.**

Hubble tension?

Local: $H_0 = 73.0 \pm 1.0\,\mathrm{km/s/Mpc}$

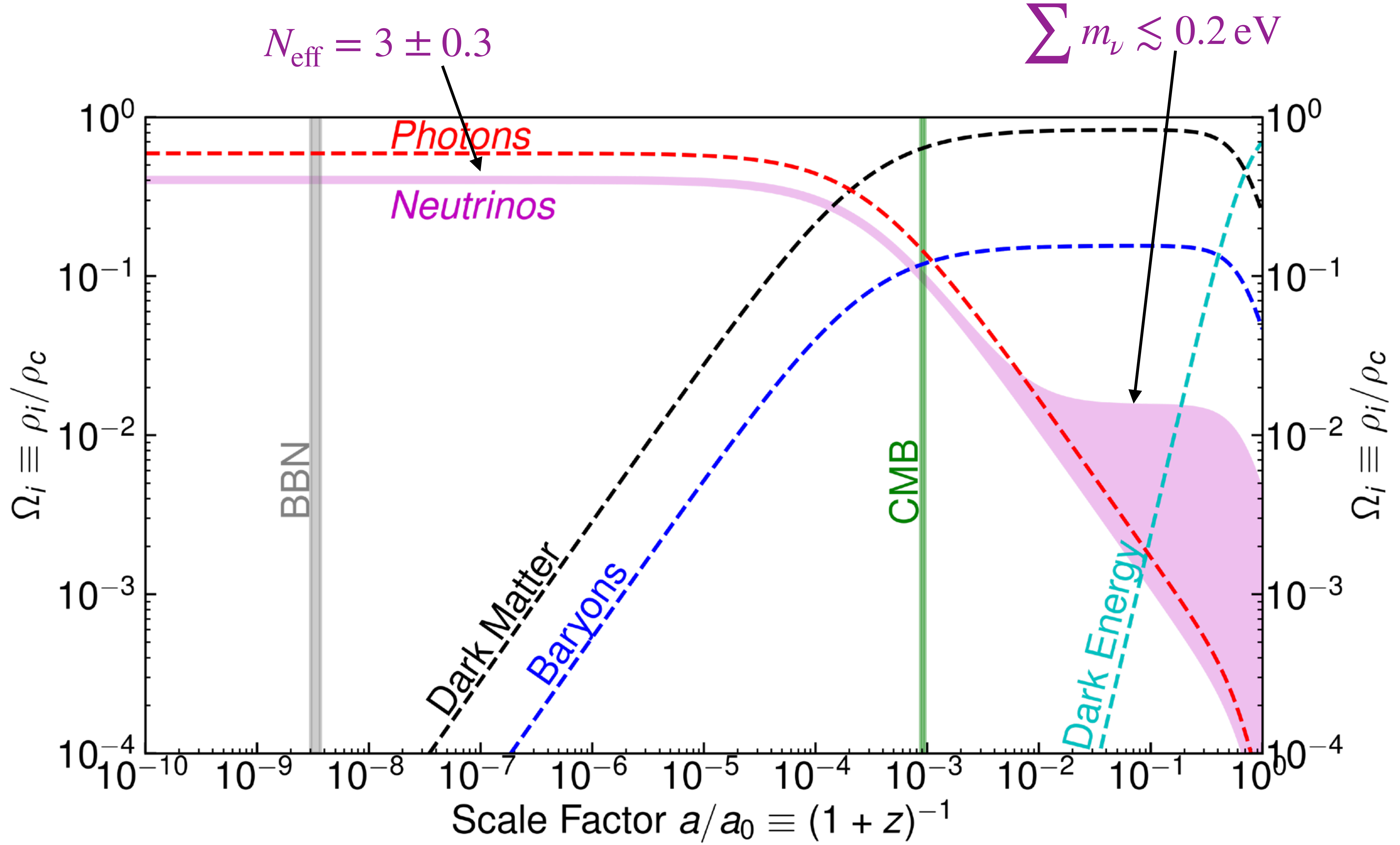
CMB+BAO: $H_0 = 67.7 \pm 0.4\,\mathrm{km/s/Mpc}$

5σ **discrepancy!**



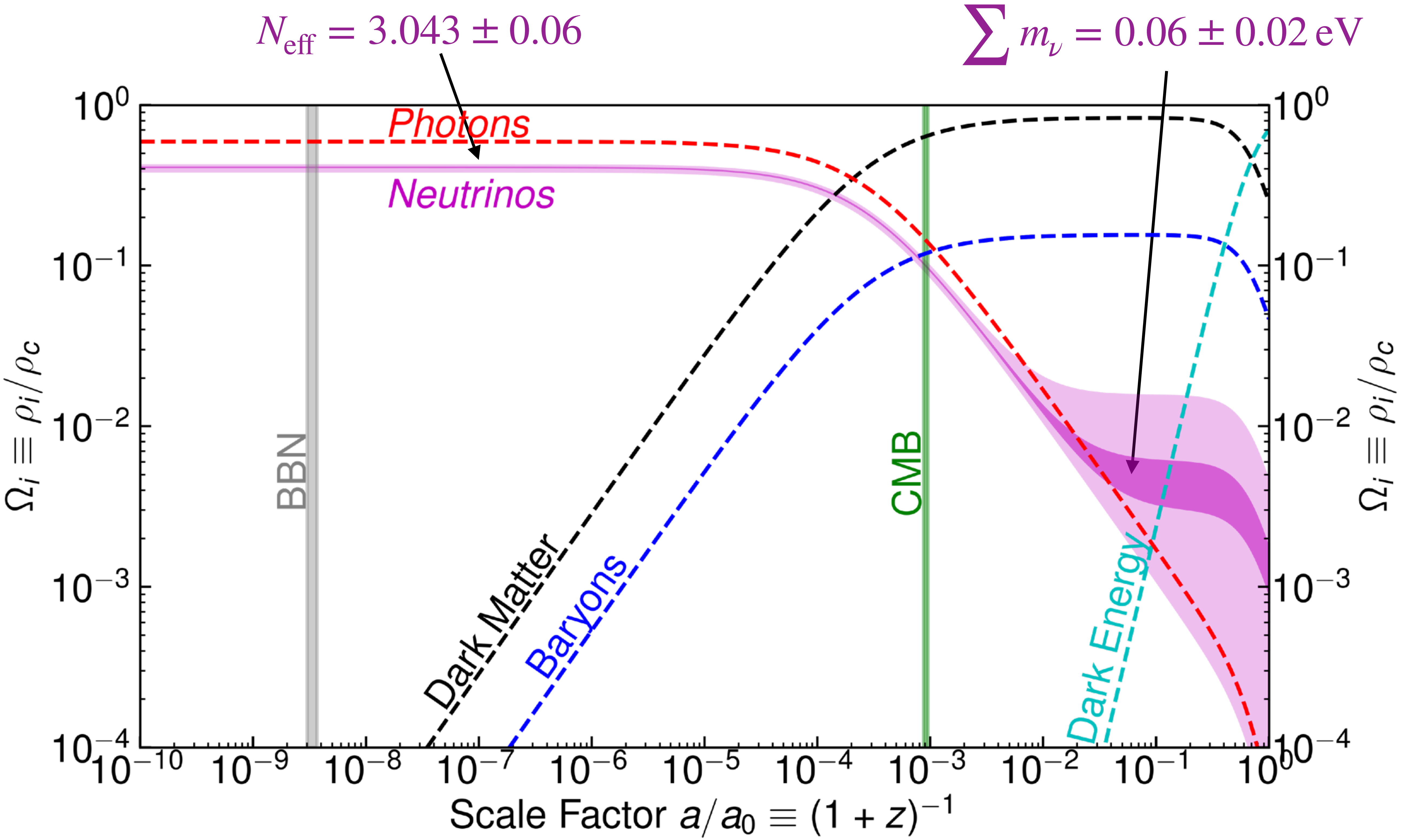
Global Perspective

Current knowledge:



Global Perspective

In the next 5-6 years:



Time for Questions and Comments

Upcoming years are going to be exciting!

Thank you for your attention!

miguel.escudero@cern.ch