Modern Neutrino Cosmology

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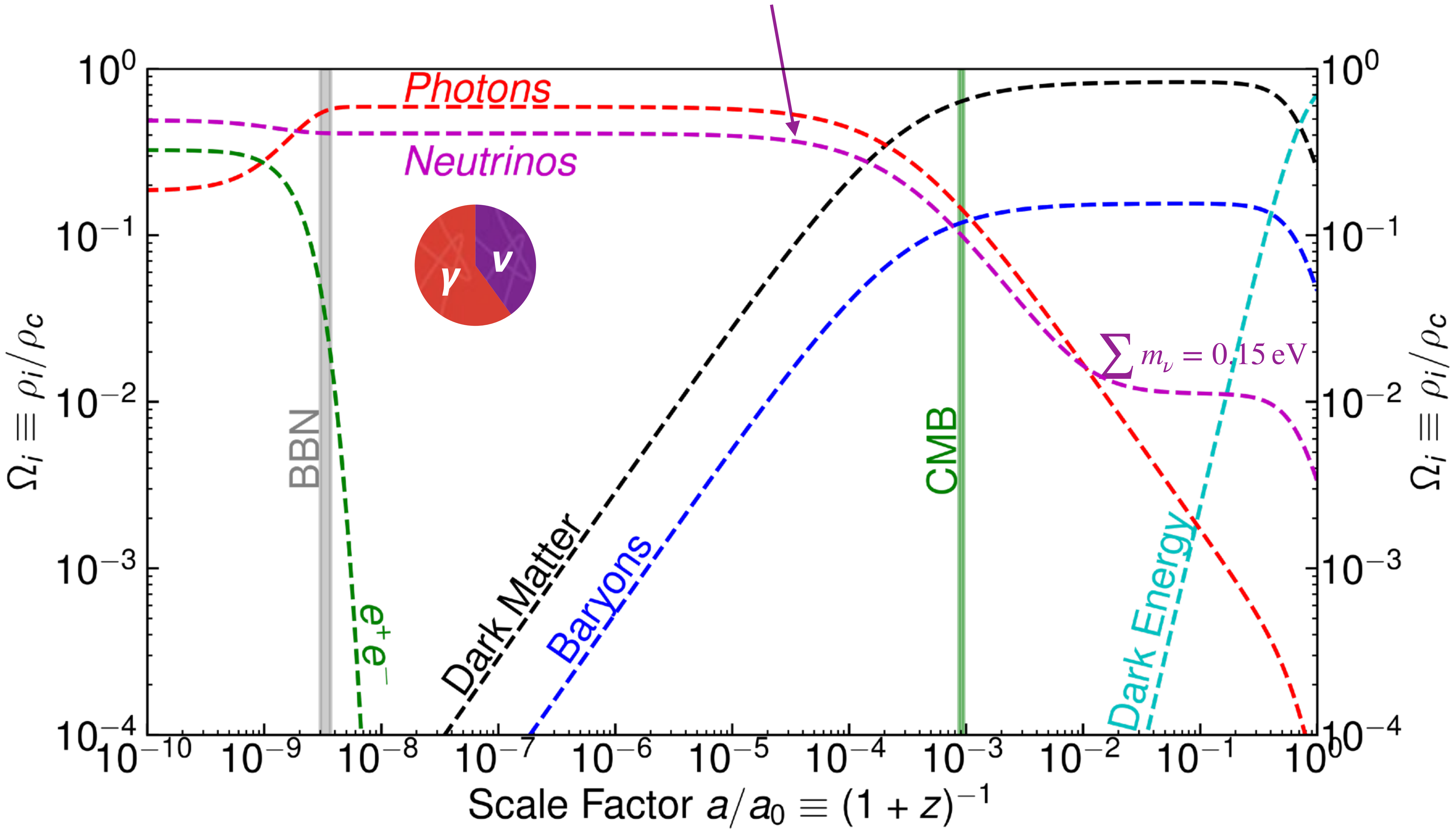
Neutrino Evolution

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

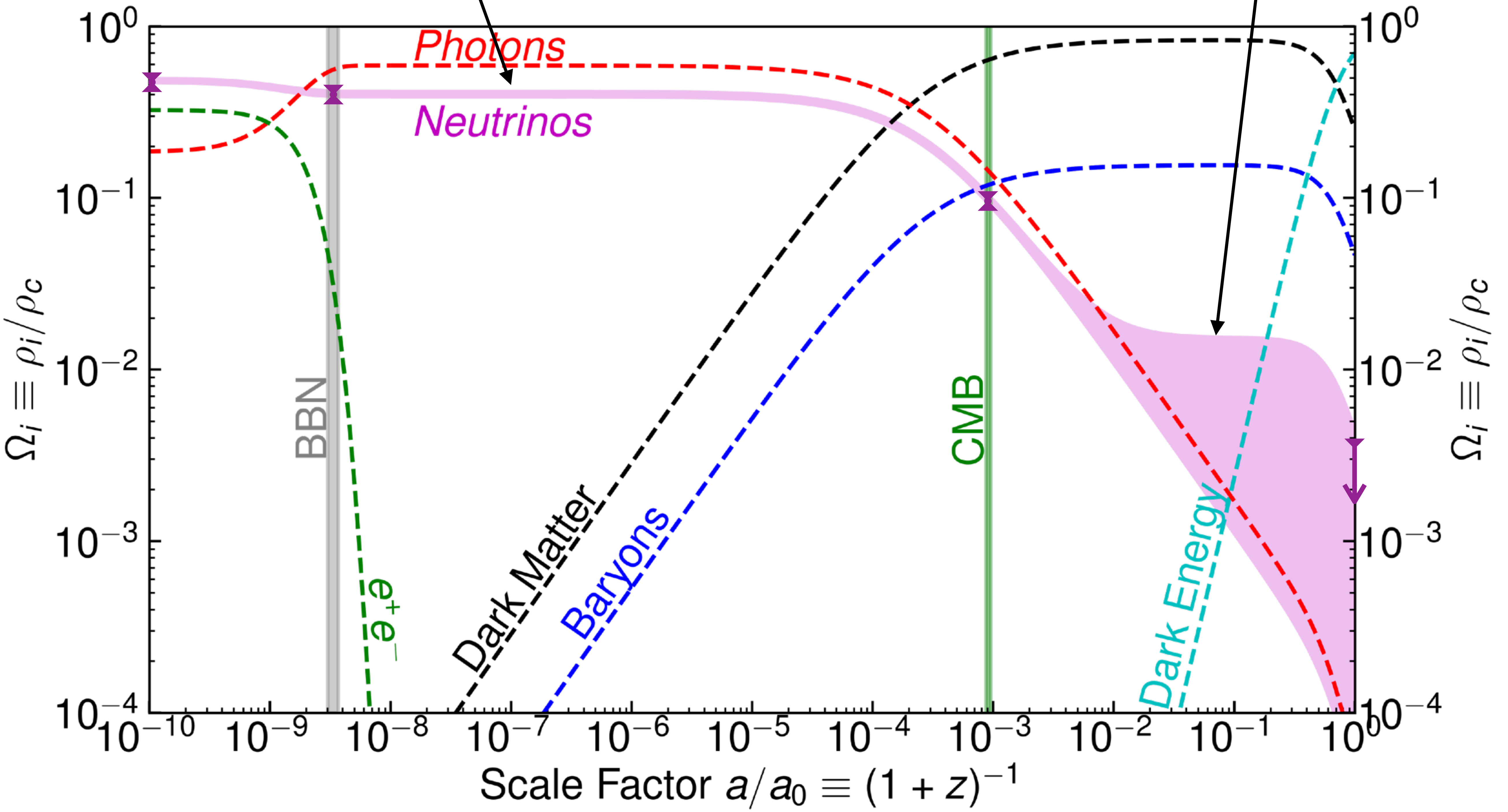
Global Perspective

Current knowledge:

(Planck+BAO)

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

$N_{\rm eff} = 3.0 \pm 0.3$ **(Planck/BBN)**



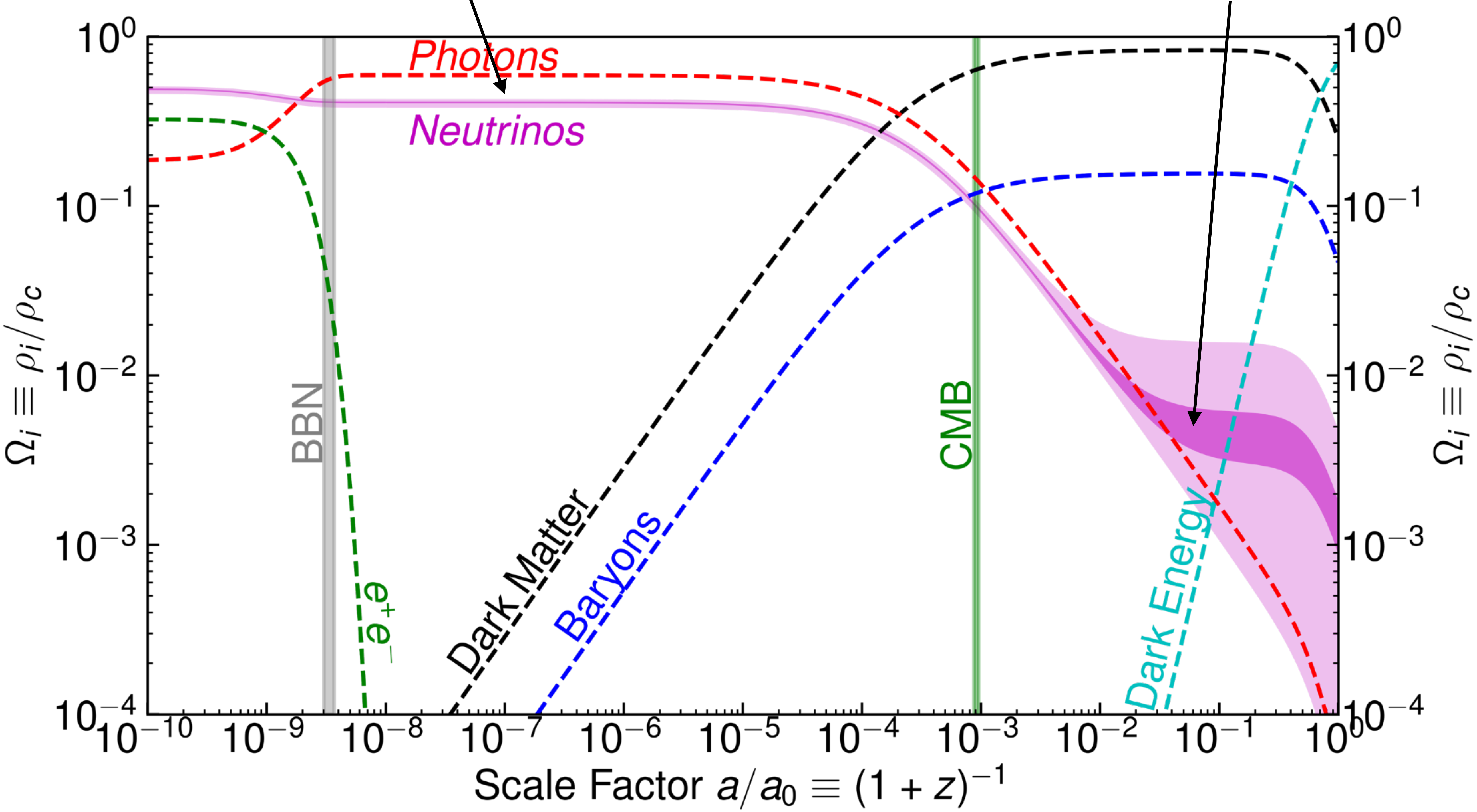
Global Perspective

In the next 5-6 years:

(DESI/Euclid + Planck)

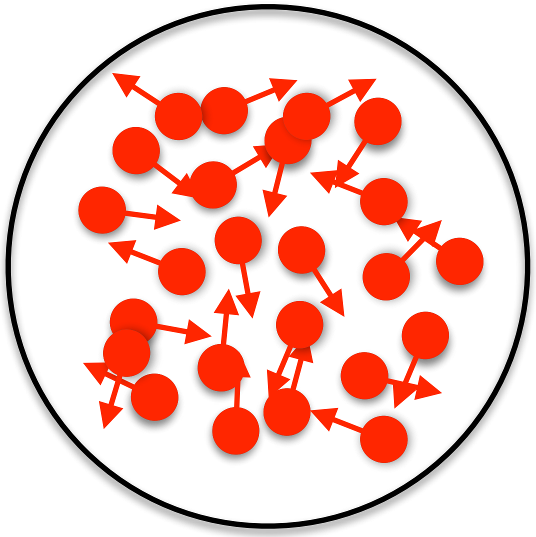
$N_{\rm eff} = 3.043 \pm 0.06$ **(Simons Observatory)**

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



Motivation/Outline

Neutrino Cosmology is about to enter the ultrahigh precision regime



1) Understand with high accuracy $N_{\rm eff}$ in the Standard Model and how to calculate it BSM

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

with Cielo, Mangano & Pisanti 2306.05460 [PRD]

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

with López-Pavón, Rius & Sandner 2007.04994 [JHEP]

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

Particularly given the strong complementarity with laboratory experiments:

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

$\sum m_\nu \Big|_{\rm NO} \geq 0.06\,\mathrm{eV}$ $\sum m_\nu \Big|_{\rm IO} \geq 0.1\,\mathrm{eV}$

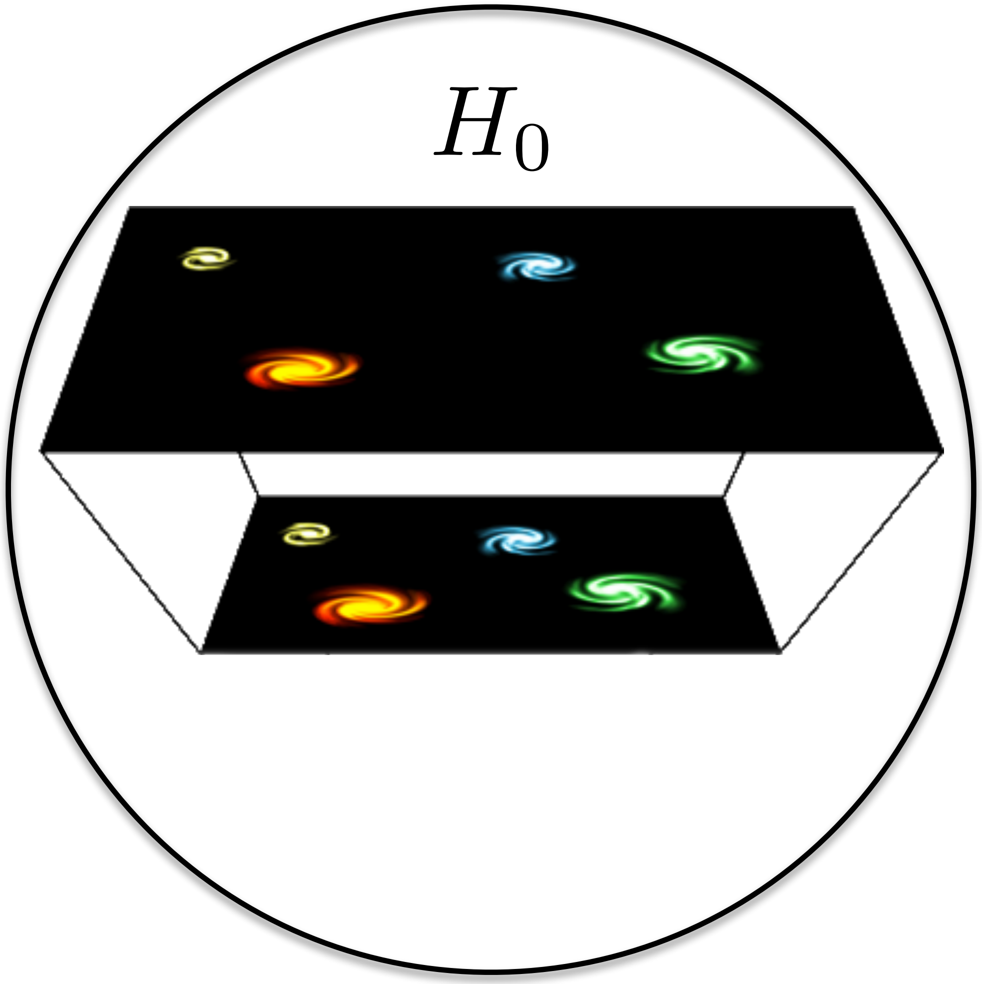
KATRIN 2023: $\sum m_\nu < 2.4\,\mathrm{eV}$ **95% CL**

KATRIN 2027: $\sum m_\nu < 0.6\,\mathrm{eV}?$ **90% CL**

Exciting $0\nu\beta\beta$ program

Motivation/Outline

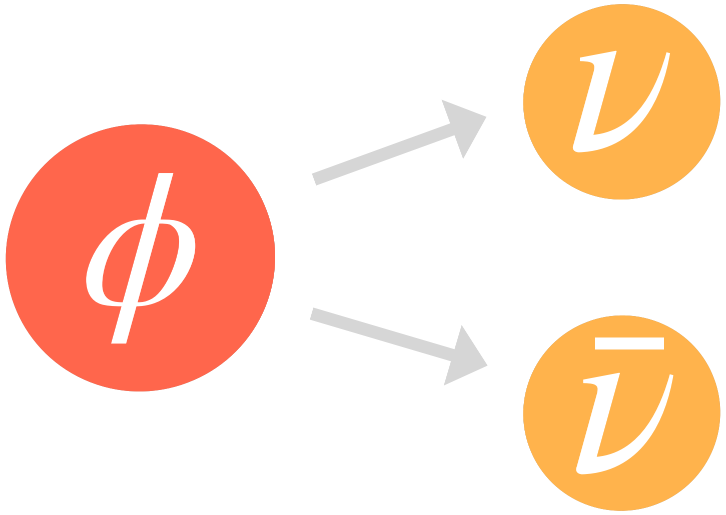
3) Understand to which degree can neutrinos be behind emerging cosmological tensions



$H_0 = 73.0 \pm 1.0\,\mathrm{km/s/Mpc}$ **Riess et al. [2112.04510]**

$H_0 = 67.7 \pm 0.4\,\mathrm{km/s/Mpc}$ **Planck [1807.06209]**

$> 5\sigma$ **discrepancy!**



with Witte
1909.04044 [EPJC]
2103.03249 [EPJC]

Understand to which degree can neutrinos have BSM interactions

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

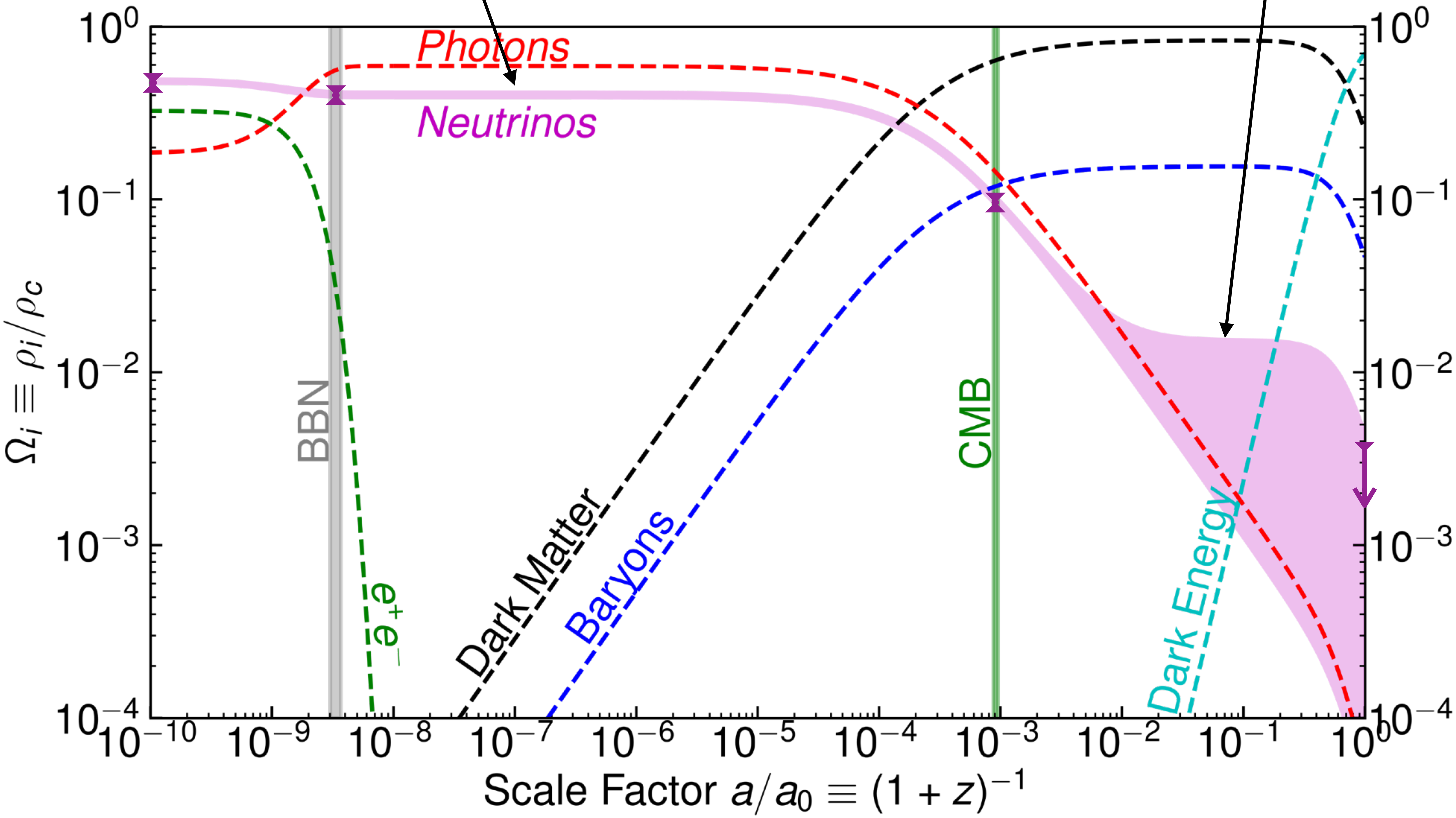
Outline

Current knowledge:

$N_{\rm eff} = 3.0 \pm 0.3$ **(Planck/BBN)**

(Planck+BAO)

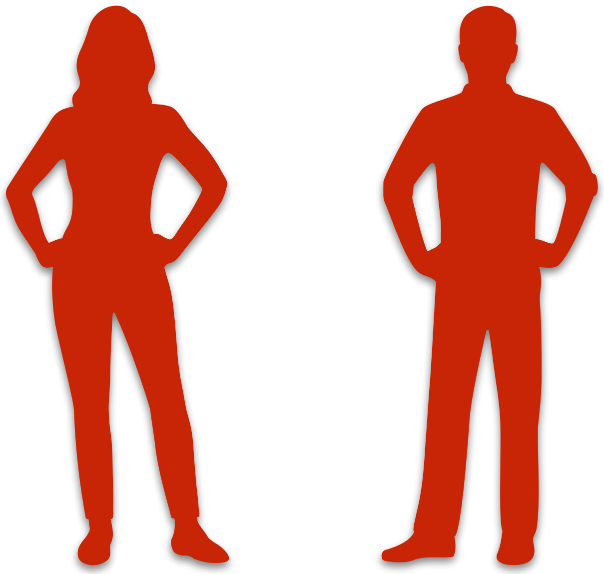
$\sum m_\nu \lesssim 0.2\,{\rm eV}$



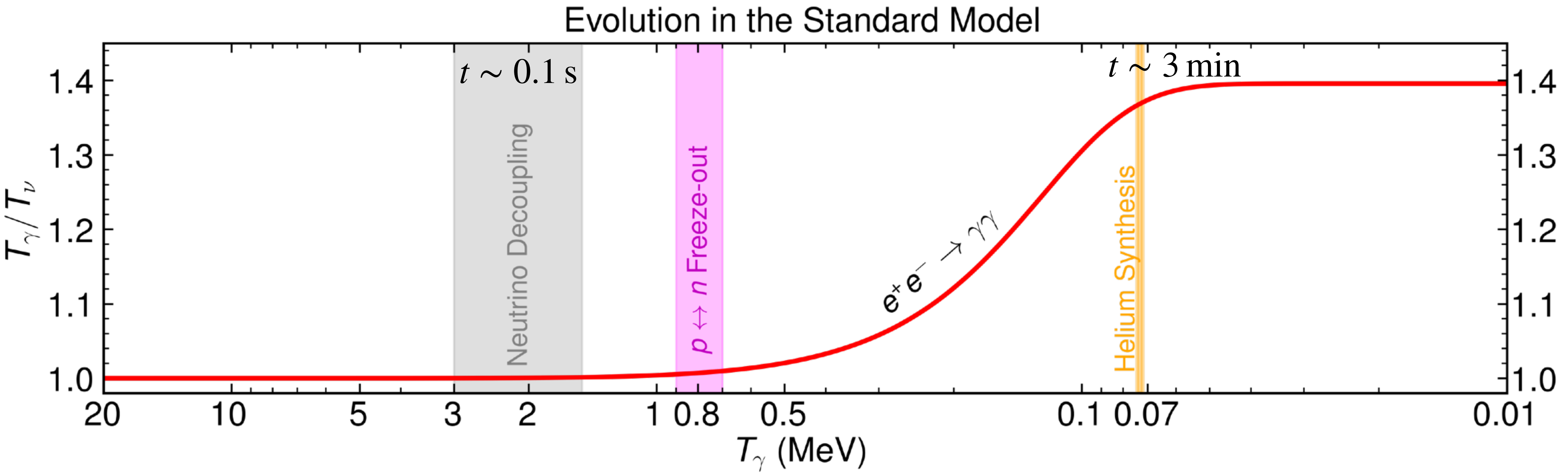
Set Up

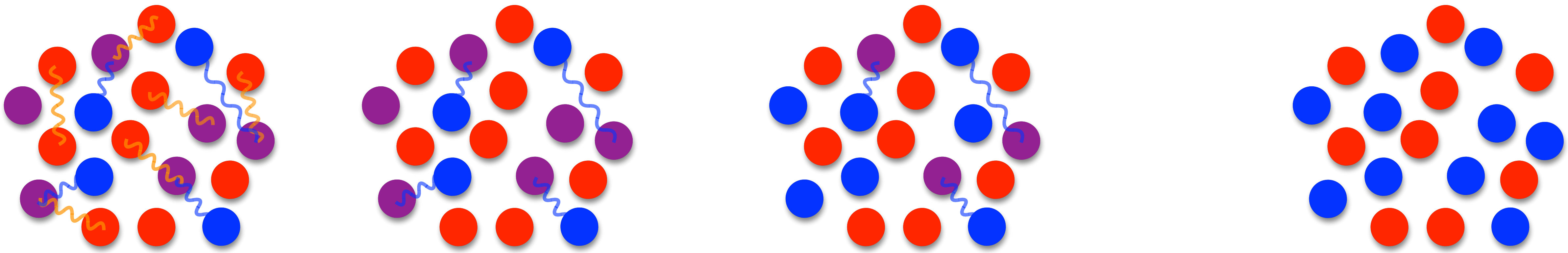
Unlike neutrinos, I do like to interact 😃

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



Starting Point: Neutrino Decoupling



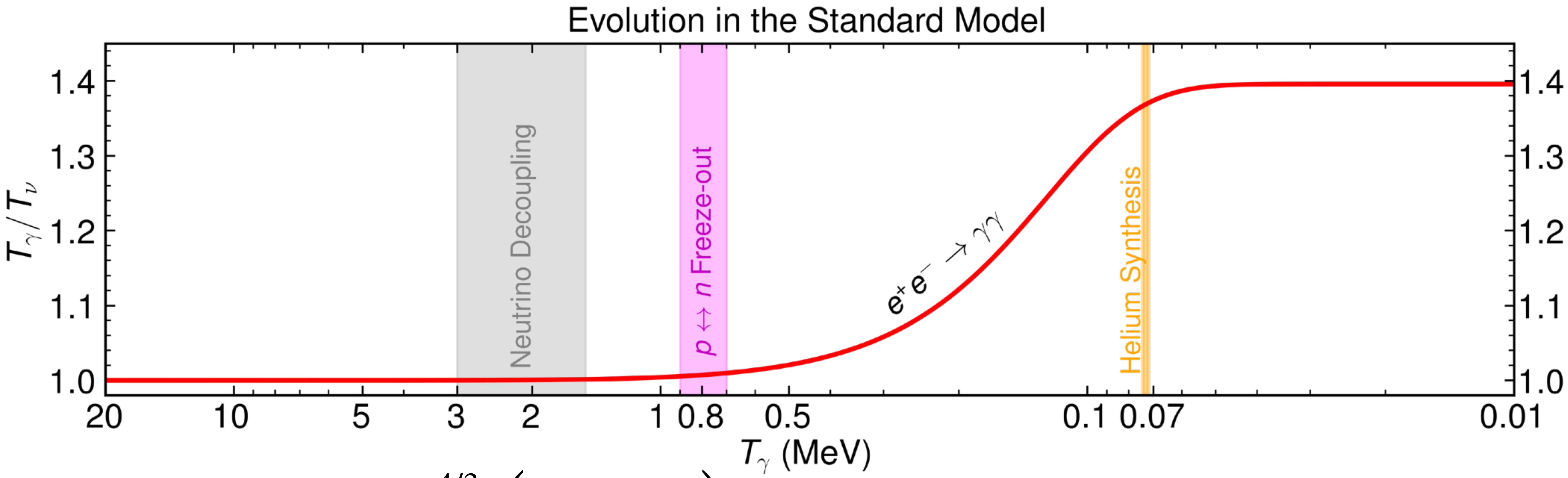


$$e^+e^- \leftrightarrow \bar{\nu}_i\nu_i$$

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

🔴 **Neutrinos** 🟣 **Electrons** 🔵 **Photons** 〰 **Z-W (off-shell)**

Cosmic Neutrino Background



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

  $$N_{\rm eff}^{\rm SM} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_\nu}{\rho_\gamma}\right) = 3\left(\frac{1.4\,T_\nu}{T_\gamma}\right)^4$$

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

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 $N_{\rm eff}$ 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 $\quad t \sim 0.1\,{\rm s} \qquad T_\nu \sim 2\,{\rm MeV}$

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

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

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

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

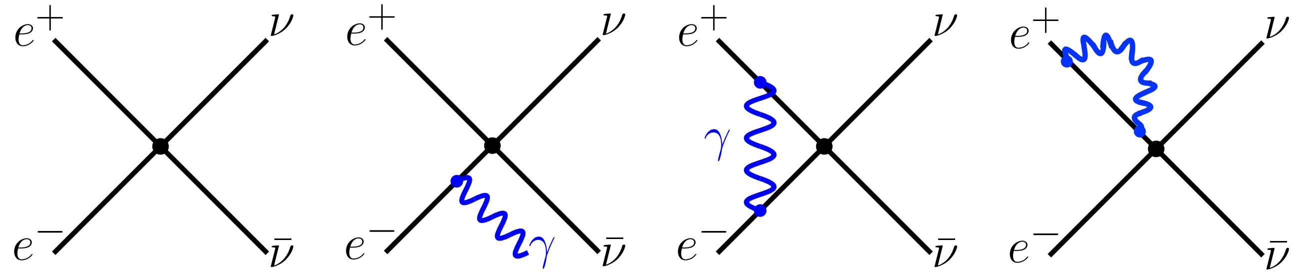
Akita & Yamaguchi 2005.07047
Froustey, Pitrou & Volpe 2008.01074
Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Wong 2012.02726

4) **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 extrapolation of the NLO rates from Esposito et al. [astro-ph/0301438]

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



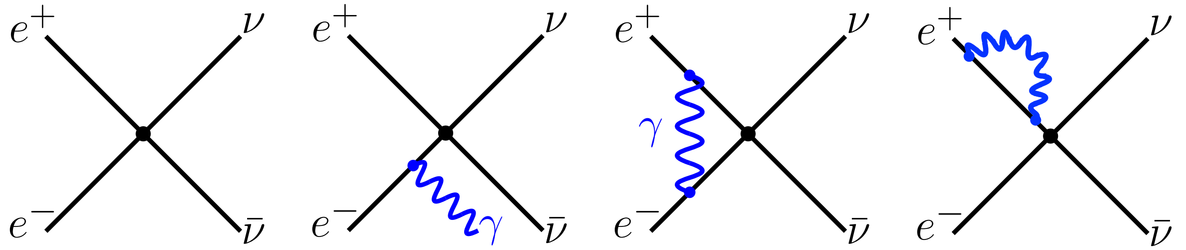
At NLO: $\Delta N_{\rm eff} \simeq -0.0007$

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

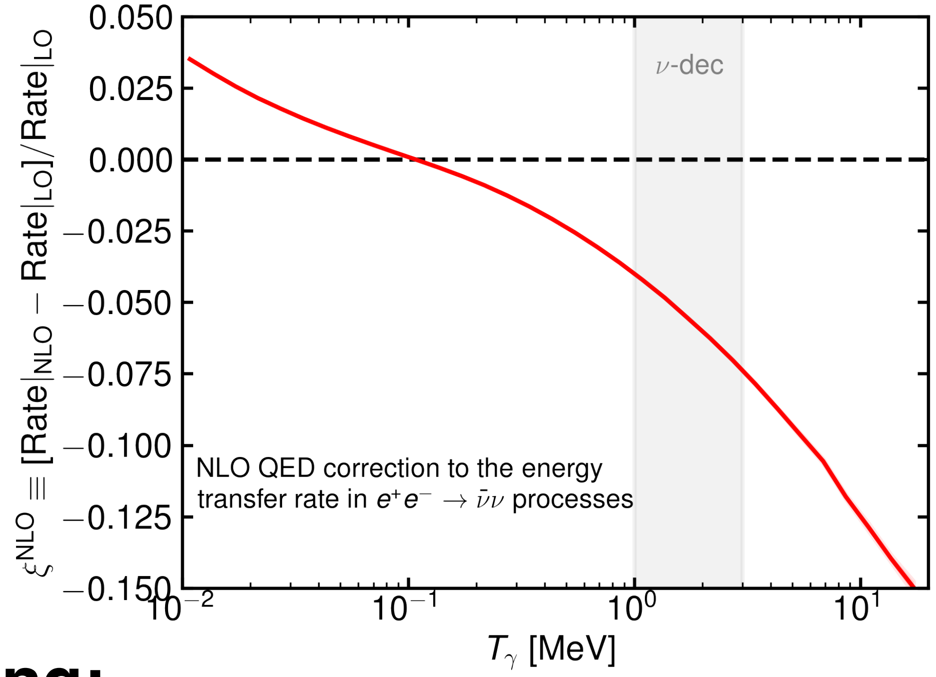
Cielo, Escudero, Mangano & Pisanti PRD [2306.05460]

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 for the thermal corrections and Passera for the radiative corrections in vacuum [hep-ph/0011190]



2) Solve for the process of neutrino decoupling:

exact:

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

stiff system of $O(100)$ integro-differential equations

approximate but very accurate and fast:

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

Escudero Abenza
1812.05605 & 2001.04466
https://github.com/MiguelEA/nudec_BSM

works because the Cosmic Neutrino Background is a very good black body $\delta\rho/\rho < 10^{-5}$

3) Result at NLO: $\Delta N_{\rm eff} \simeq -0.0007$ $\quad N_{\rm eff}^{\rm SM} = 3.0432(2) = 3.043$

Cielo, Escudero, Mangano & Pisanti 2306.05460

But, Jackson and Laine [2312.07015] have recently calculated this rate at NLO and found smaller corrections with different sign.
Also Drewes et al. [2402.18481] have performed a partial calculation.

$$\boxed{N_{\rm eff}^{\rm SM} = 3.043(1)}$$

Under investigation!

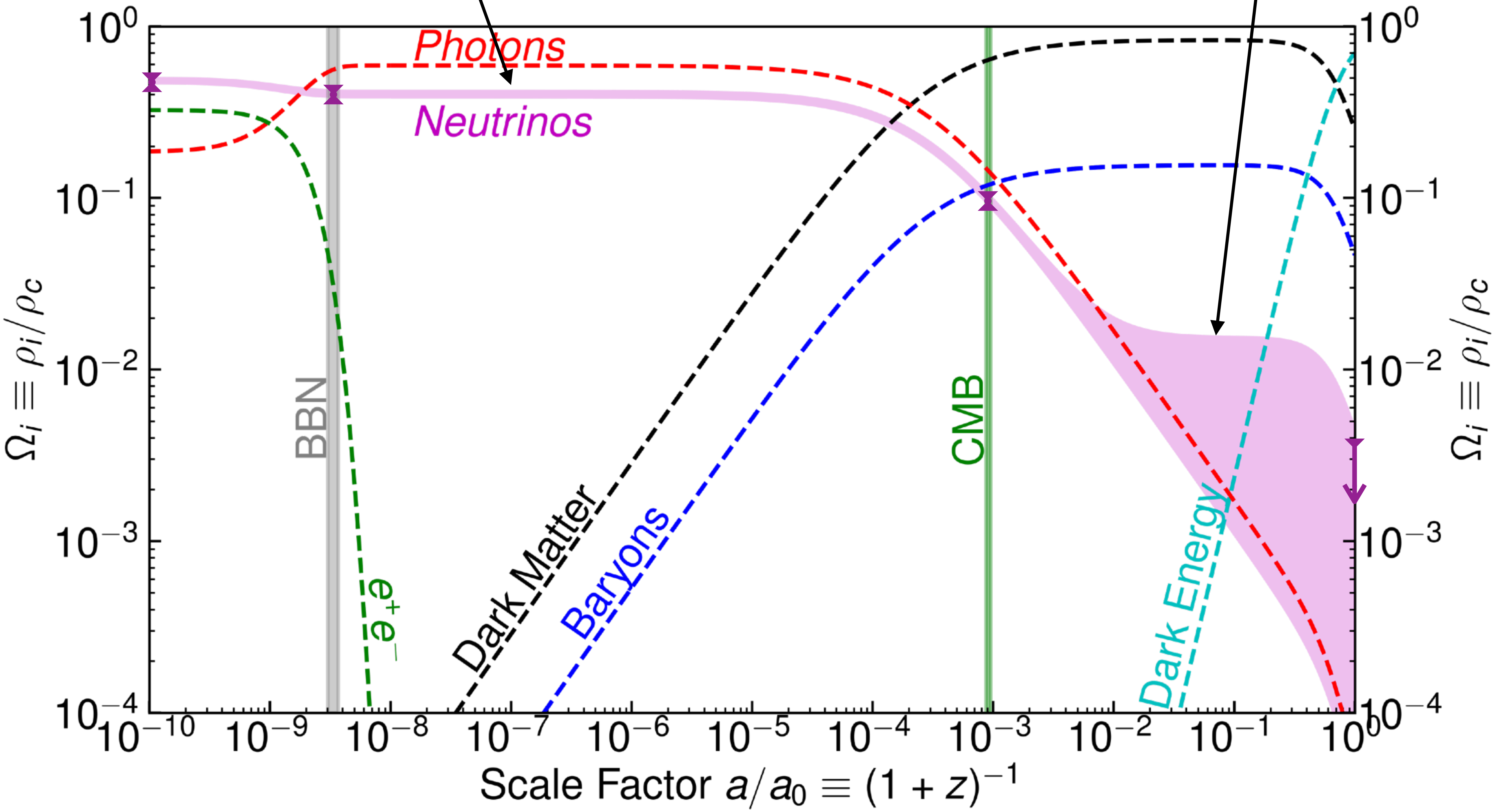
Global Perspective

Current knowledge:

(Planck+BAO)

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

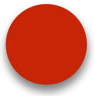
$N_{\rm eff} = 3.0 \pm 0.3$ **(Planck/BBN)**

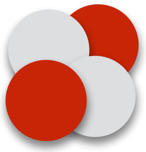


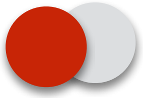
Evidence for Cosmic Neutrinos

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:

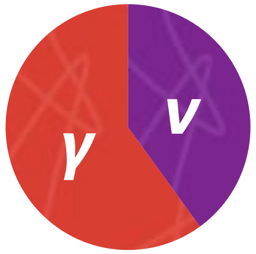
$$\boxed{N_{\mathrm{eff}}^{\mathrm{BBN}} = 2.86 \pm 0.28}$$

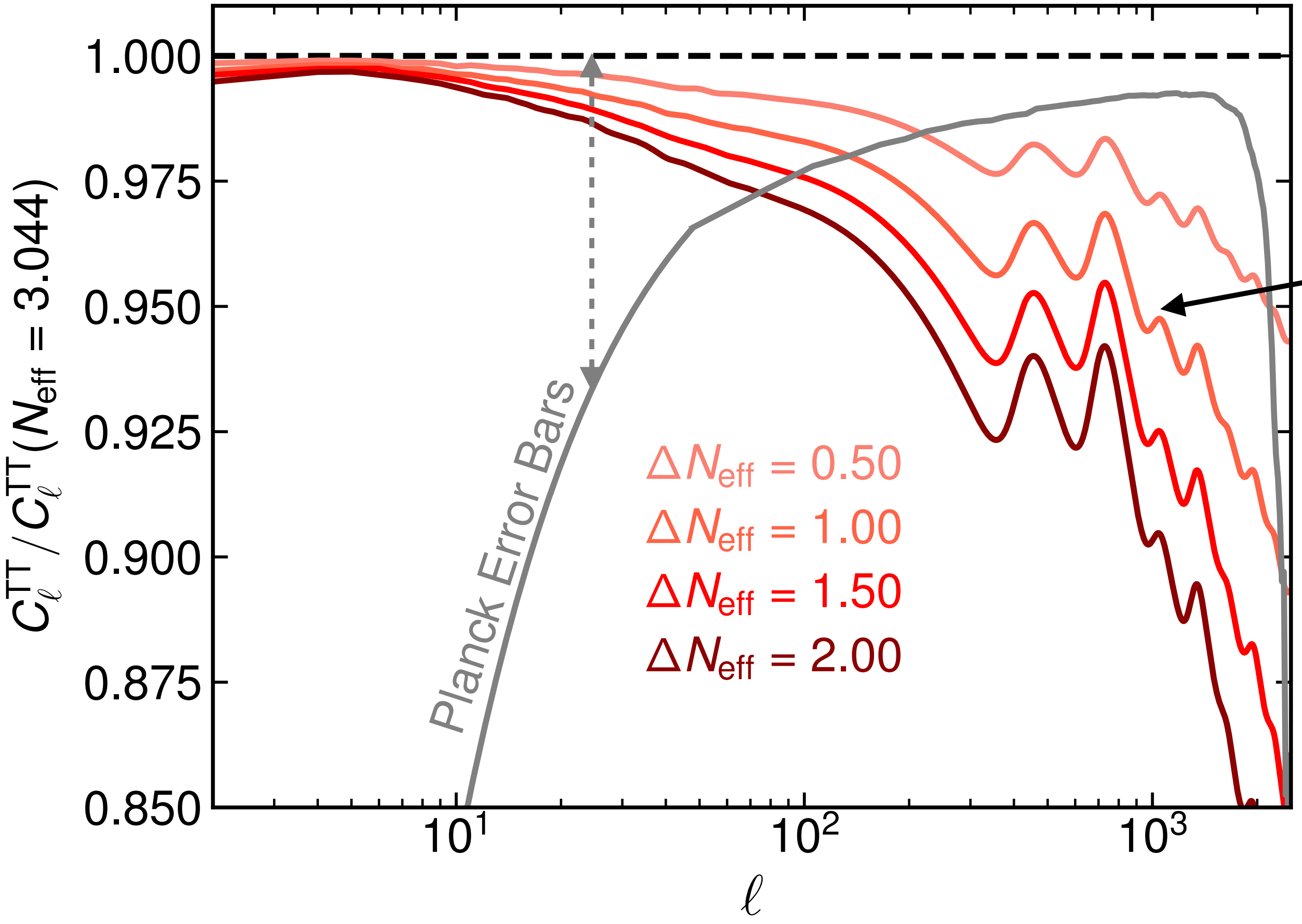
see e.g., Pisanti et al. 2011.11537 and Yeh et al. 2207.13133

Evidence for Cosmic Neutrinos

Cosmic Microwave Background **Why?**

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





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

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

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: $N_{\rm eff}^{\rm SM} = 3.043(1)$
- Data is in excellent agreement with the Standard Model prediction
- This provides strong (albeit indirect) evidence for the Cosmic Neutrino Background

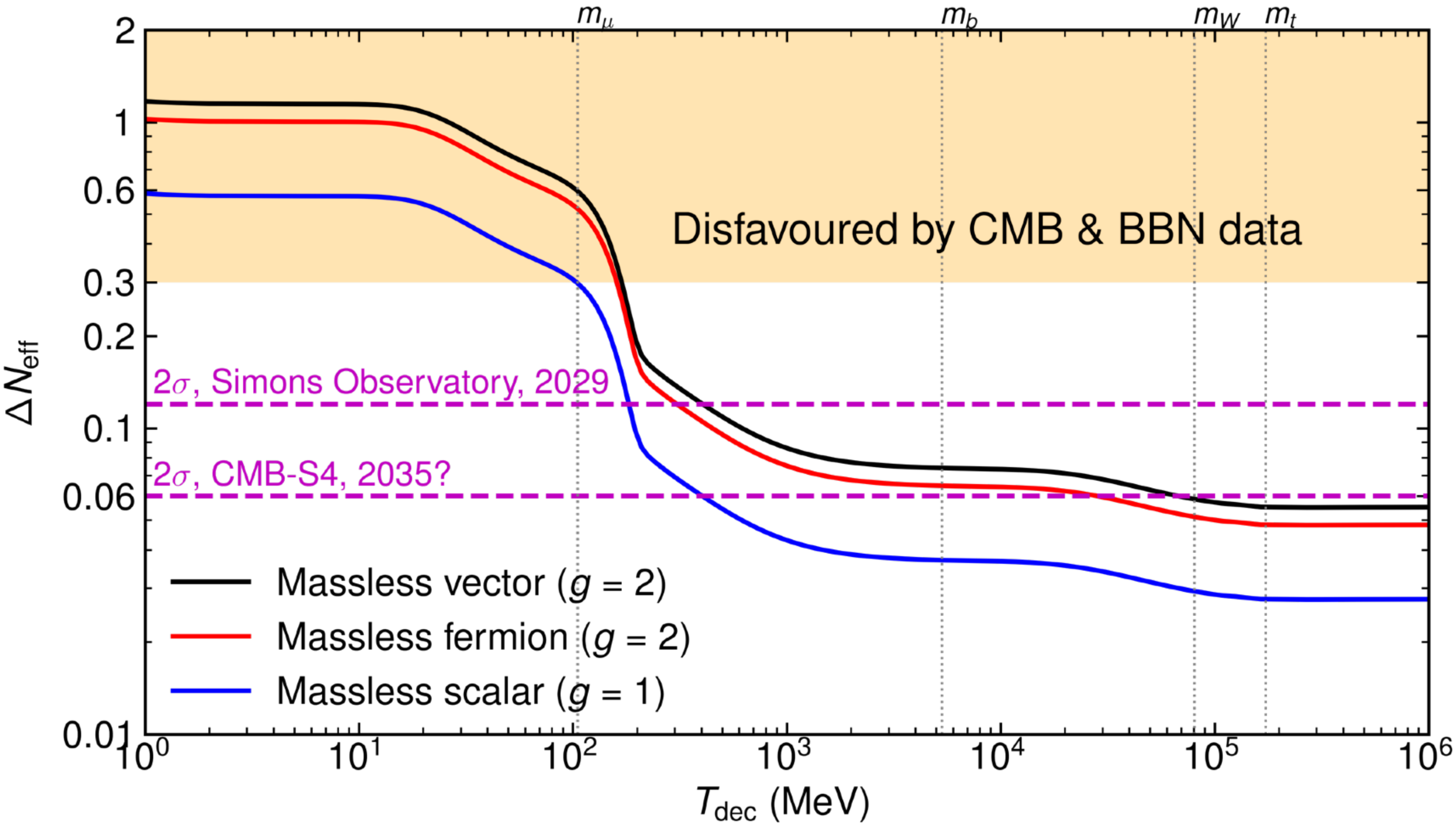
Implications:

1) Stringent constraint on many BSM scenarios

2) We can use cosmological data to test neutrino properties

Constraints on Neff

- **Sterile Neutrino** $m_{\nu_s} \sim \mathrm{eV} \quad \Delta N_{\rm eff} = 1$ **(see e.g. Gariazzo, de Salas & Pastor 1905.11290)**
- **Goldstone Bosons** **see e.g. 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	$g \lesssim 10^{-10} \quad m \lesssim 10\,{\rm MeV}$	**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:** $N_{\rm eff}^{\rm SM} = 3.043(1)$
- **Data is in excellent agreement with the Standard Model prediction**
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Implications:

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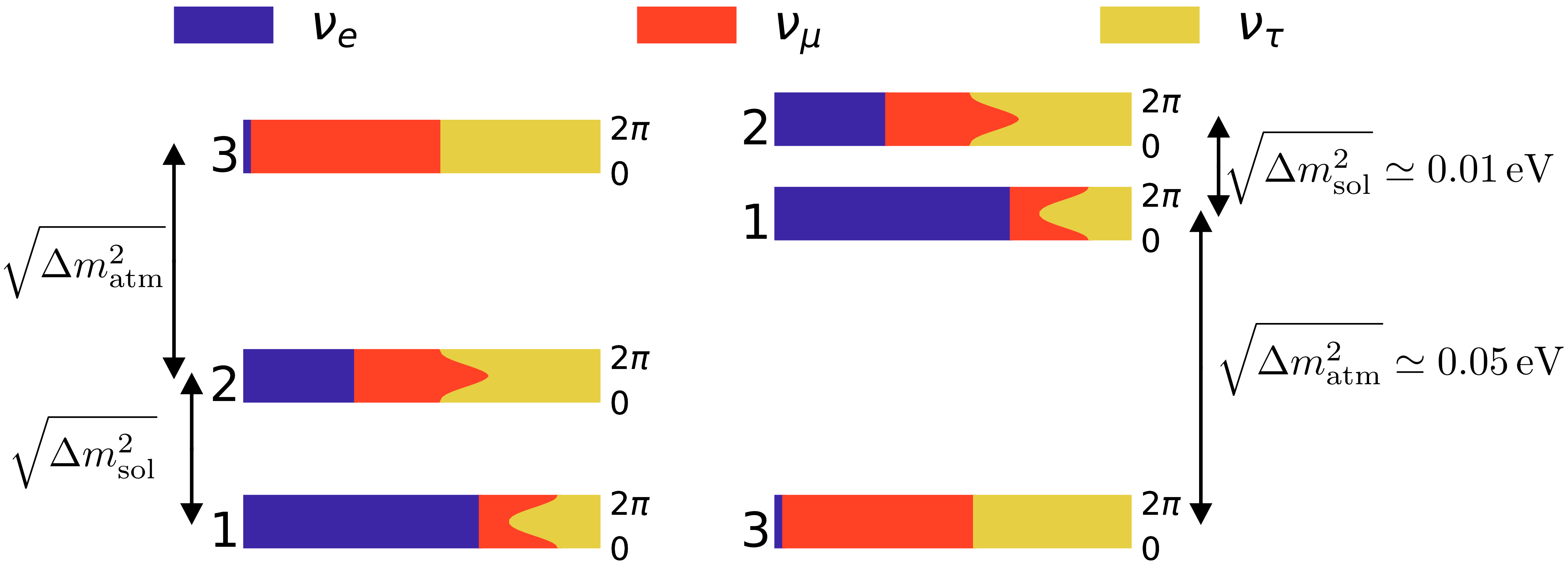
Neutrino Properties

Figure from de Salas et al. 1806.11051



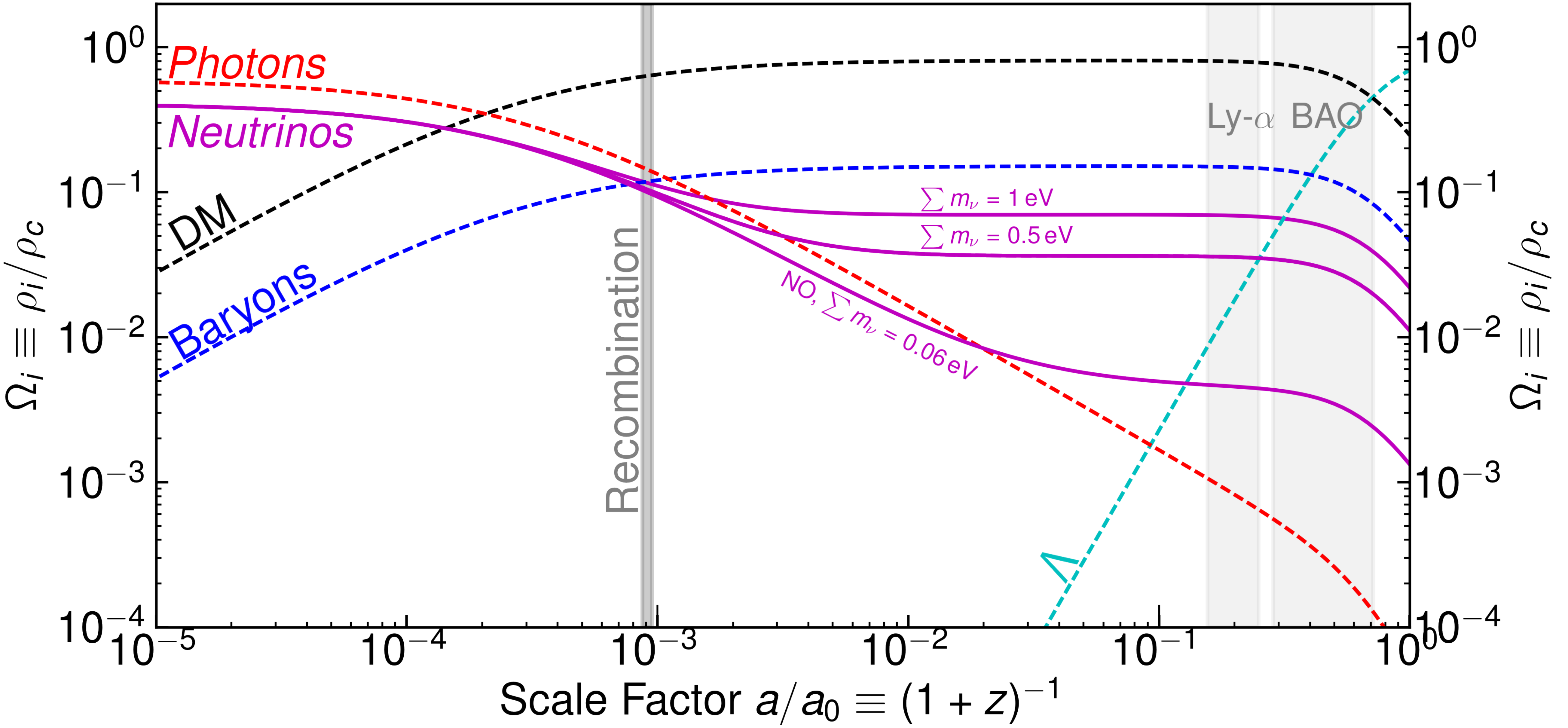
Normal **Inverted**

$$\sum m_\nu \gtrsim 0.06\,{\rm eV} \qquad \sum m_\nu \gtrsim 0.10\,{\rm eV}$$

- **Mass differences and mixing angles 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**



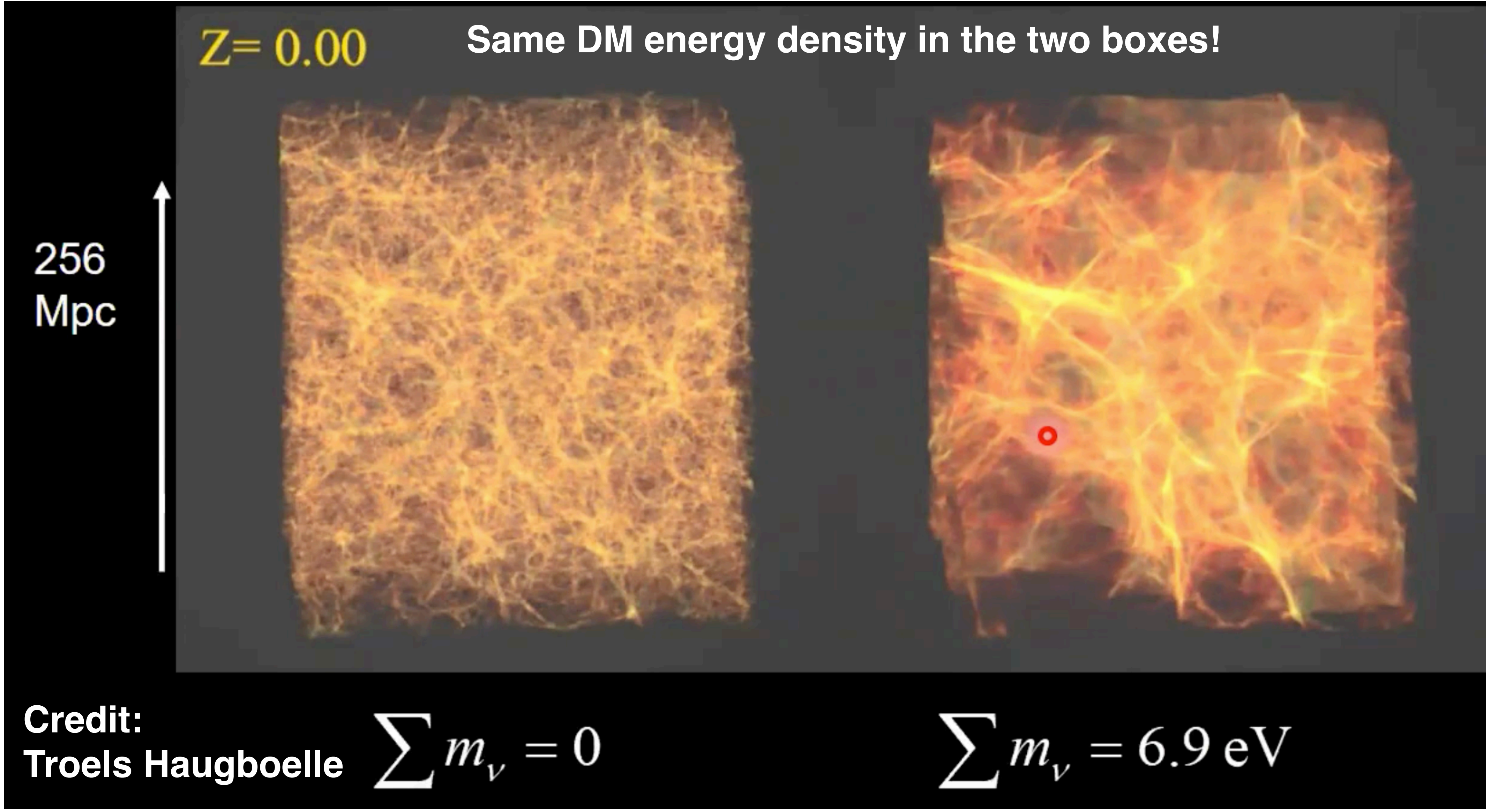
Non-Rel: $z_\nu^{\mathrm{non-rel}} \simeq 200 \frac{m_\nu}{0.1\,\mathrm{eV}}$

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

Neutrino Masses in Cosmology

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

taken from a talk by Steen Hannestad Link.



Credit: Troels Haugboelle

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:

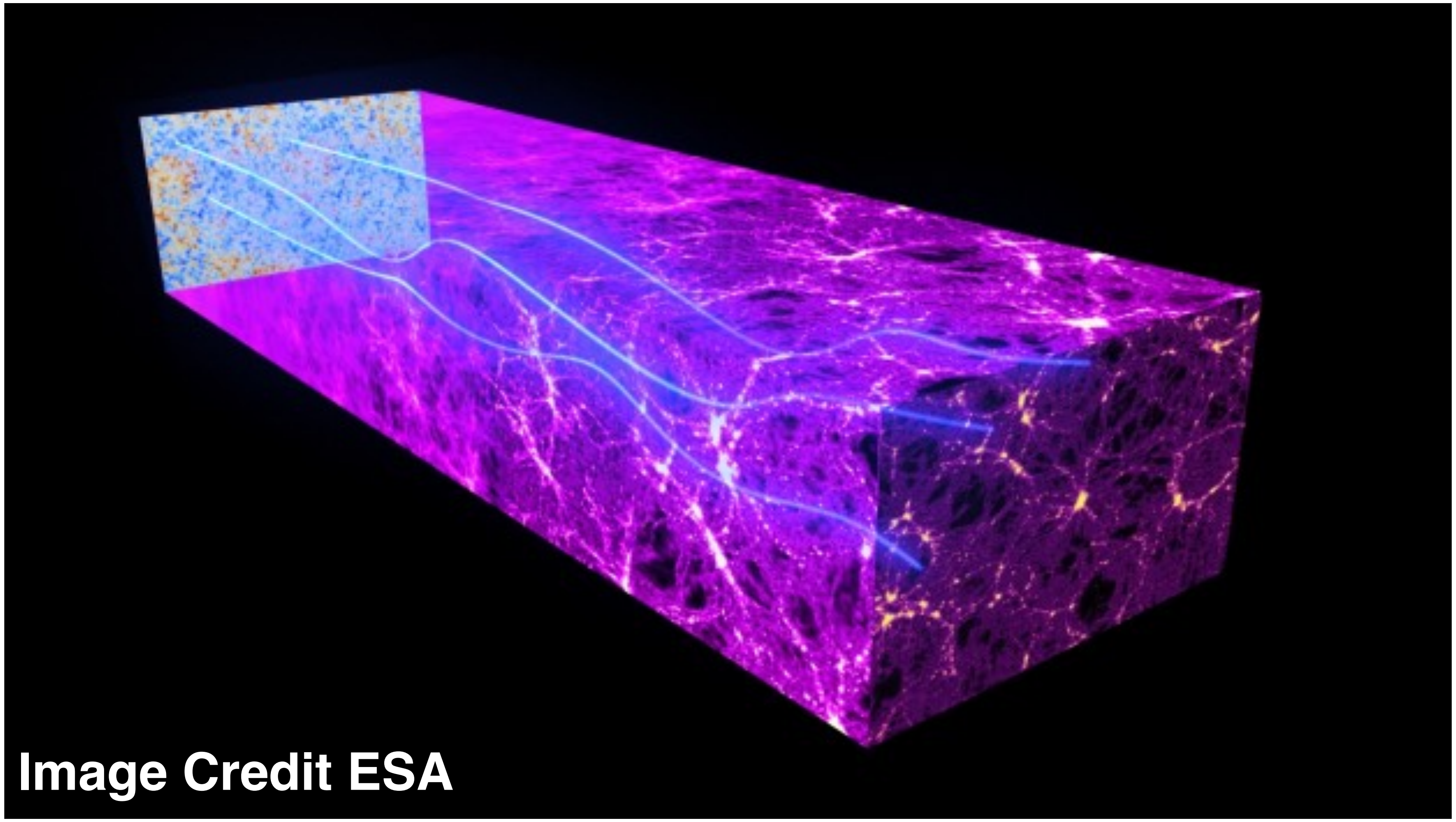


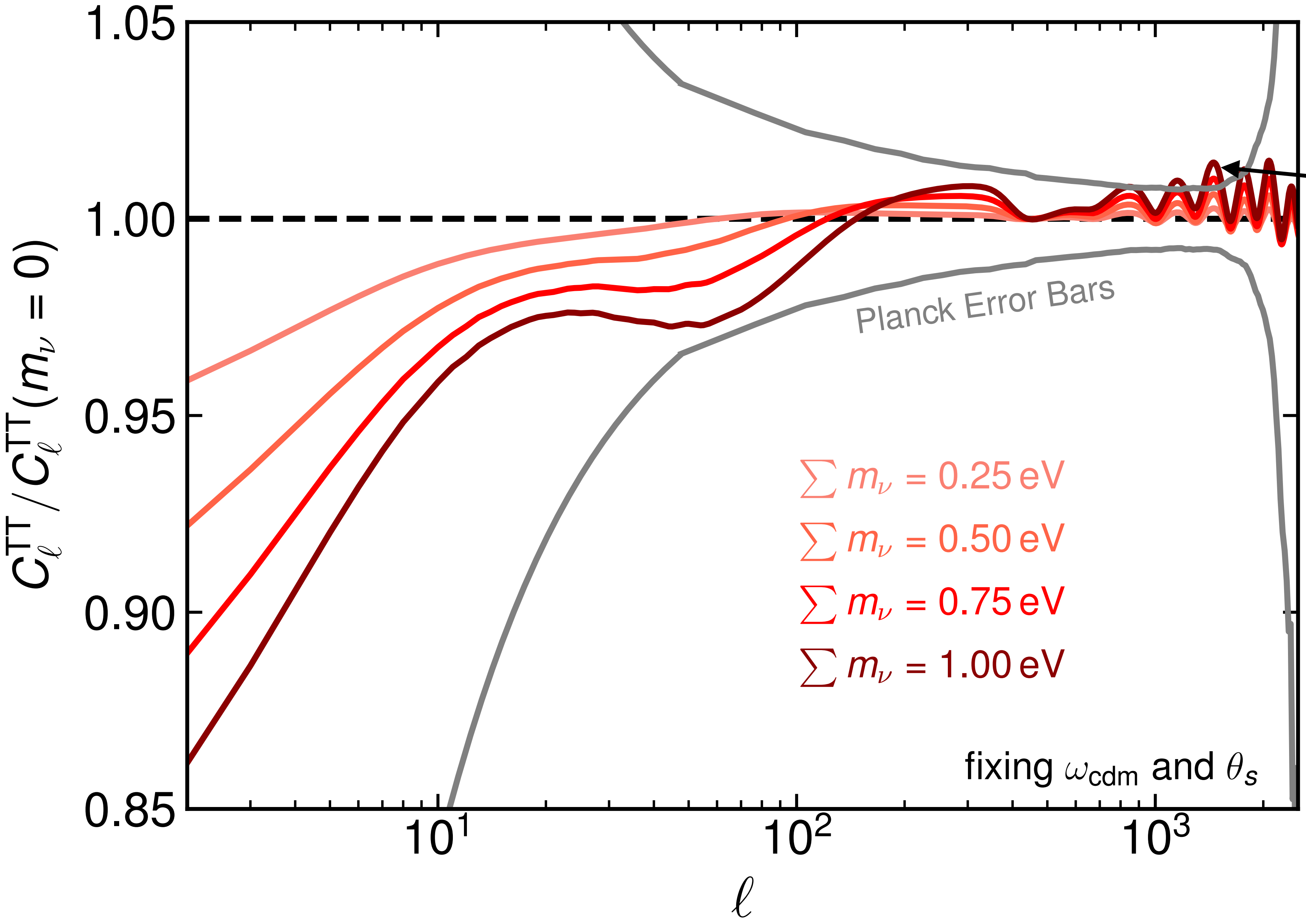
Image Credit ESA

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:



Main constraining power

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

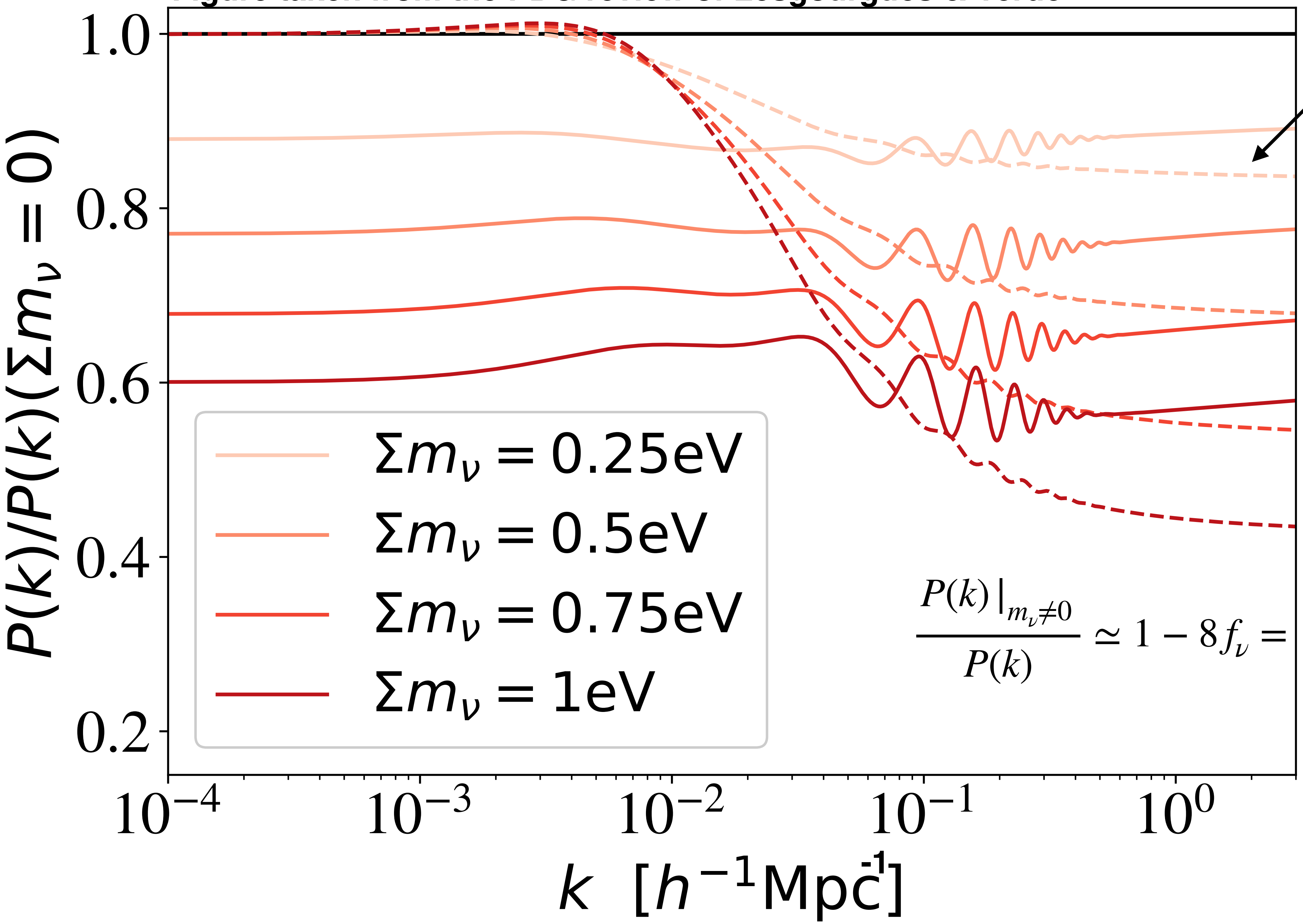
(95 % CL, TT+lowE)

Neutrino Masses in Cosmology

Galaxy Surveys

Suppression from $\Omega_\nu h^2$

Figure taken from the PDG review of 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, Simonovic & Zaldarriaga 1909.05277**
$\sum m_\nu < 0.16\,\mathrm{eV}$	**Planck+BOSS P(k)**	**Ivanov, Simonovic & Zaldarriaga 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

$\nu_i \to \nu_j \phi$

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

Oldengott et al. 2203.09075 & 2011.01502
Escudero & Fairbairn 1907.05425

$\nu_i \to \nu_4 \phi$

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

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

Time Dependent Neutrino Masses

Late phase transition

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

Dvali & Funcke 1602.03191
Lorenz et al. 1811.01991 & 2102.13618

Ultralight scalar field screening

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

Esteban & Salvadó 2101.05804
Wetterich et al. 1009.2461

Non-standard Neutrino Populations

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

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

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

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

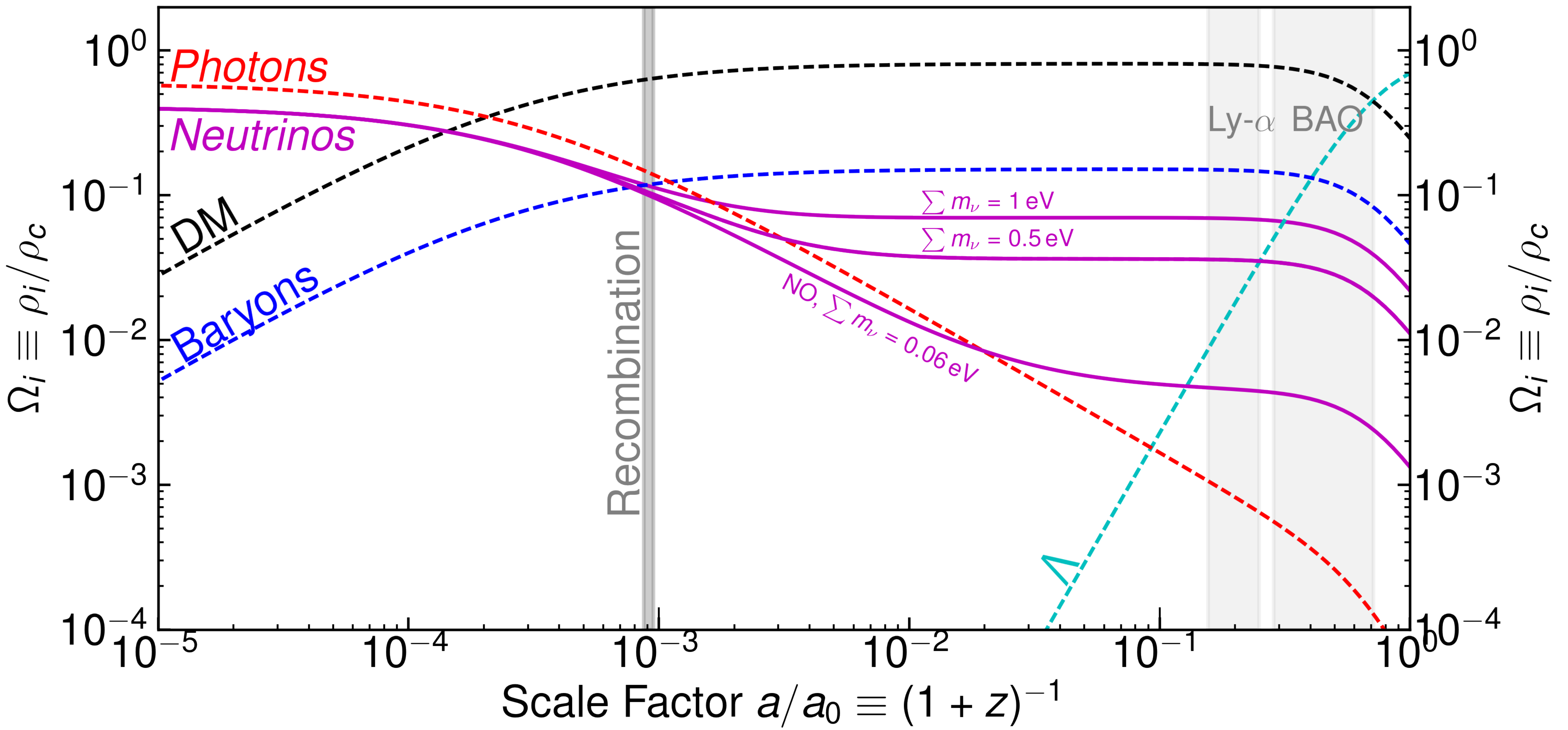
$$\sum m_\nu < 3\,\text{eV}$$

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?

Neutrino Masses from Cosmology



CMB peaks fix:

$$\theta_s \equiv r_s/D_M(z_\star)$$

$$r_s = \int_{z_\star}^{\infty} \frac{c_s}{H(z')}\,dz'$$

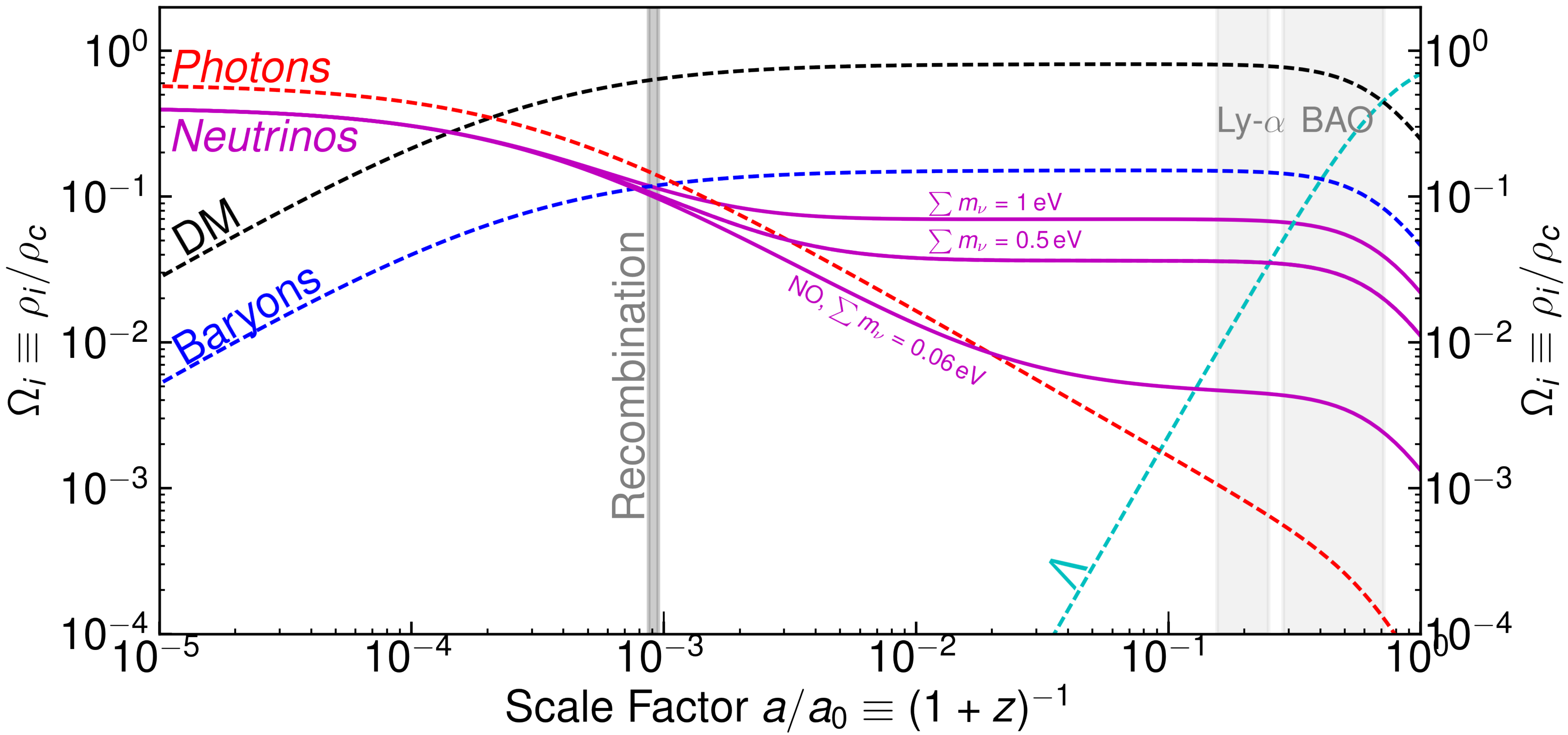
Comoving sound horizon (Early Universe)

$$D_M(z) = \int_0^{z} \frac{1}{H(z')}\,dz'$$

Comoving angular diameter distance (Late Universe)

Massive neutrinos → $H(z')$

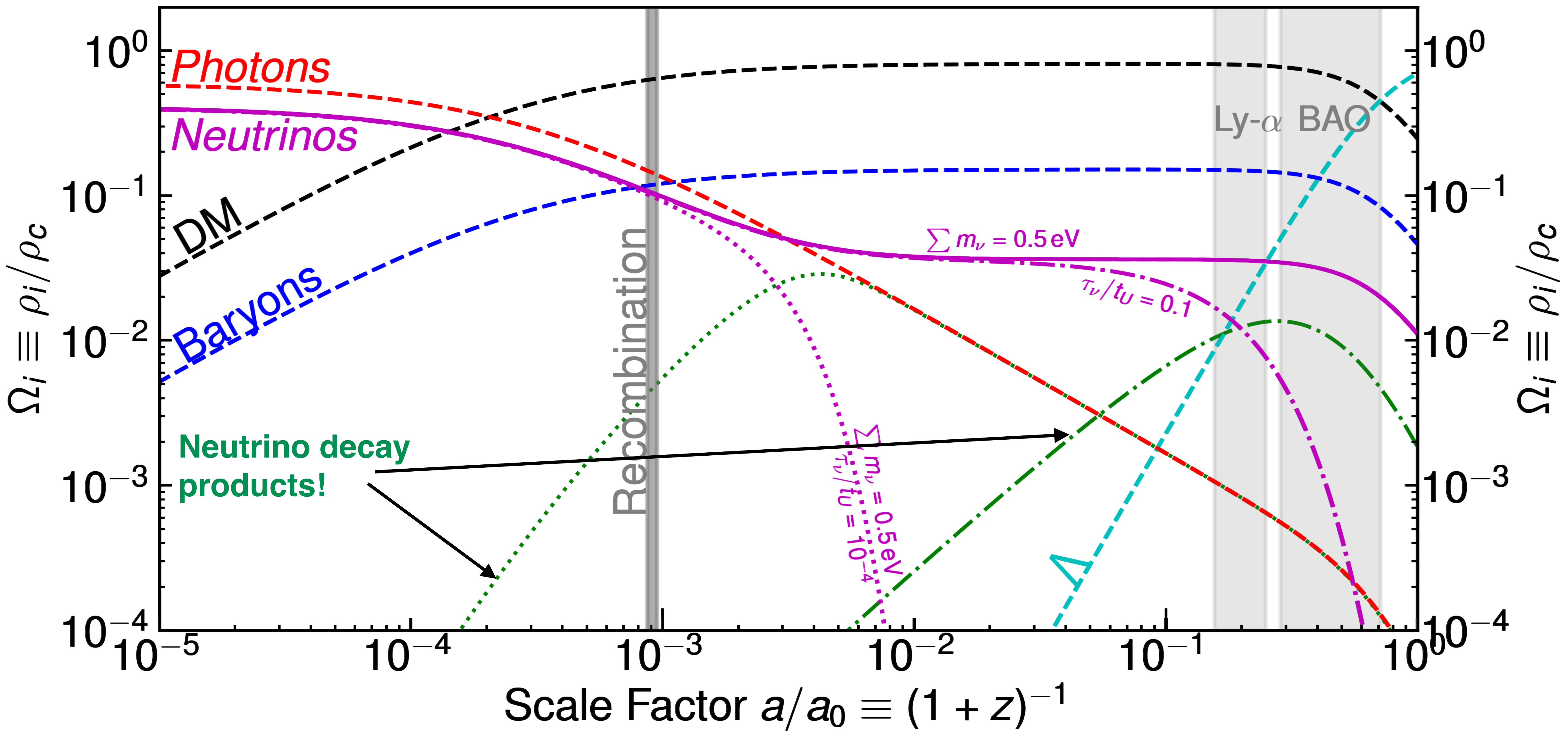
Neutrino Masses from Cosmology



Not only a background effect:

Massive neutrinos also affect CMB lensing $\propto \Omega_\nu$

Neutrino Decays



Neutrino decay products!

Neutrinos decaying with $\tau_\nu \lesssim t_U/10$ do not impact $D_M(z_{CMB})$

Effect of induced neutrino Lensing is substantially reduced

Unstable Neutrinos can relax the bounds on Σm_ν!

Neutrino Masses from Cosmology

Cosmological Model Dependence

Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

$\nu_i \to \nu_j \phi$

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

Oldengott et al. 2203.09075 & 2011.01502
Escudero & Fairbairn 1907.05425

$\nu_i \to \nu_4 \phi$

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
Esteban, Mena & Salvadó 2202.04656

Non-standard Neutrino Populations

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

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

Farzan & Hannestad 1510.02201
Renk et al. 2009.03286

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

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

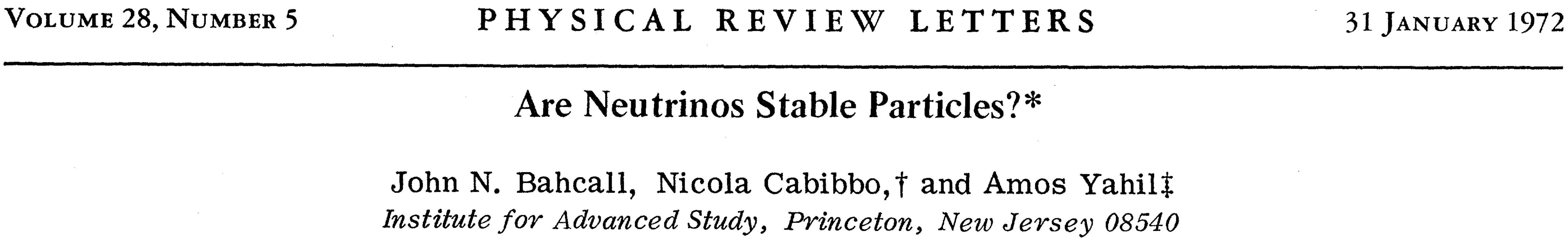
Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.14870

Take Away Message:

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

Neutrino Decay Landscape

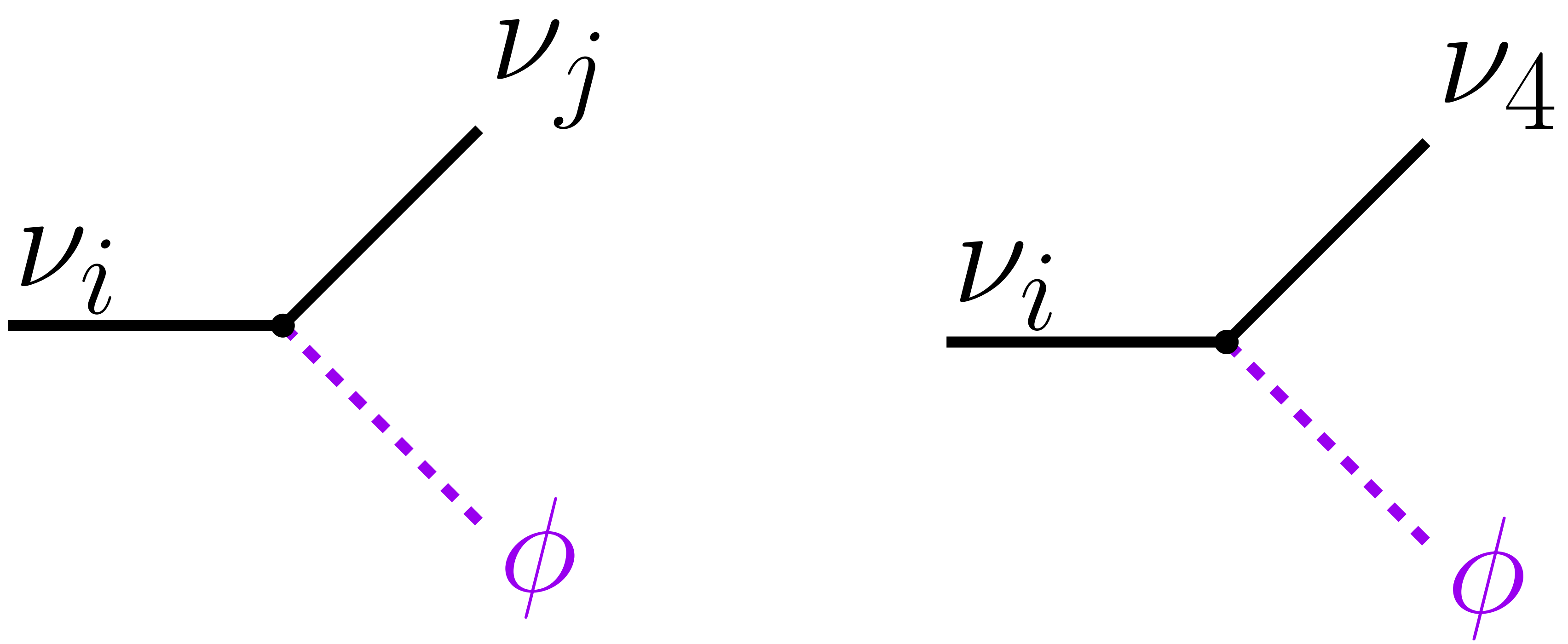


VOLUME 28, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1972

Are Neutrinos Stable Particles?*

John N. Bahcall, Nicola Cabibbo,† and Amos Yahil‡
Institute for Advanced Study, Princeton, New Jersey 08540

- **2 Neutrinos decay in the SM but with** $\tau_\nu \sim (G_F^2 m_\nu^5)^{-1} > 10^{33}\,\mathrm{yr} \gg t_U$
- **Radiative decays are strongly constrained:** $\tau_\nu > 10^2 - 10^{10}\, t_U$
- **Invisible neutrino decays are substantially less constrained:**



Neutrino Decays into lighter neutrinos

$\nu_i \to \nu_j \phi$ Decays

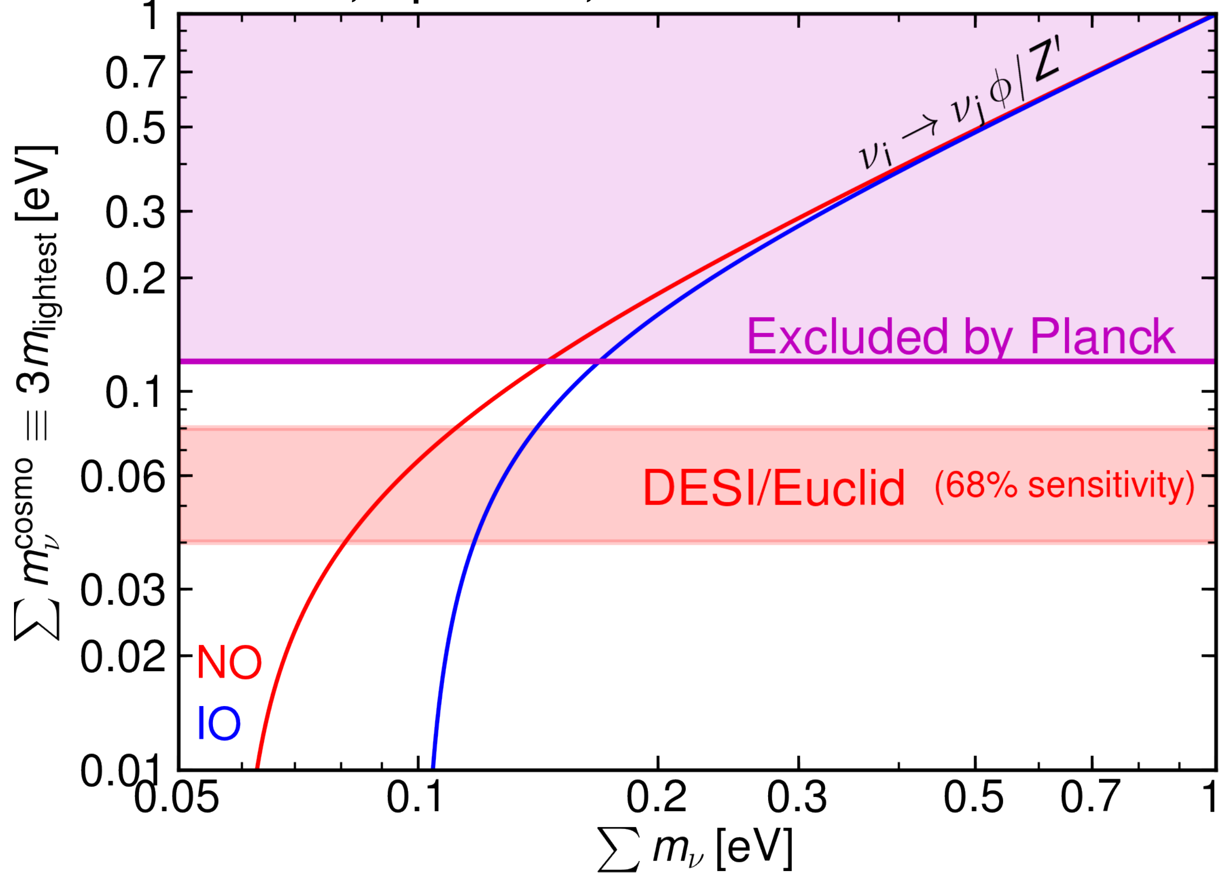
Theory: These happen naturally in scenarios with light mediators charged under horizontal flavor symmetries, e.g. $L_\mu - L_\tau$ **see e.g. Gelmini & Valle PLB 142 (1984) 181 for a model**

Couplings: $\tau_\nu < t_U$ taking the $L_\mu - L_\tau$ case means $v_{\mu-\tau} < 30\,\mathrm{TeV}$ for both global and gauge U(1)

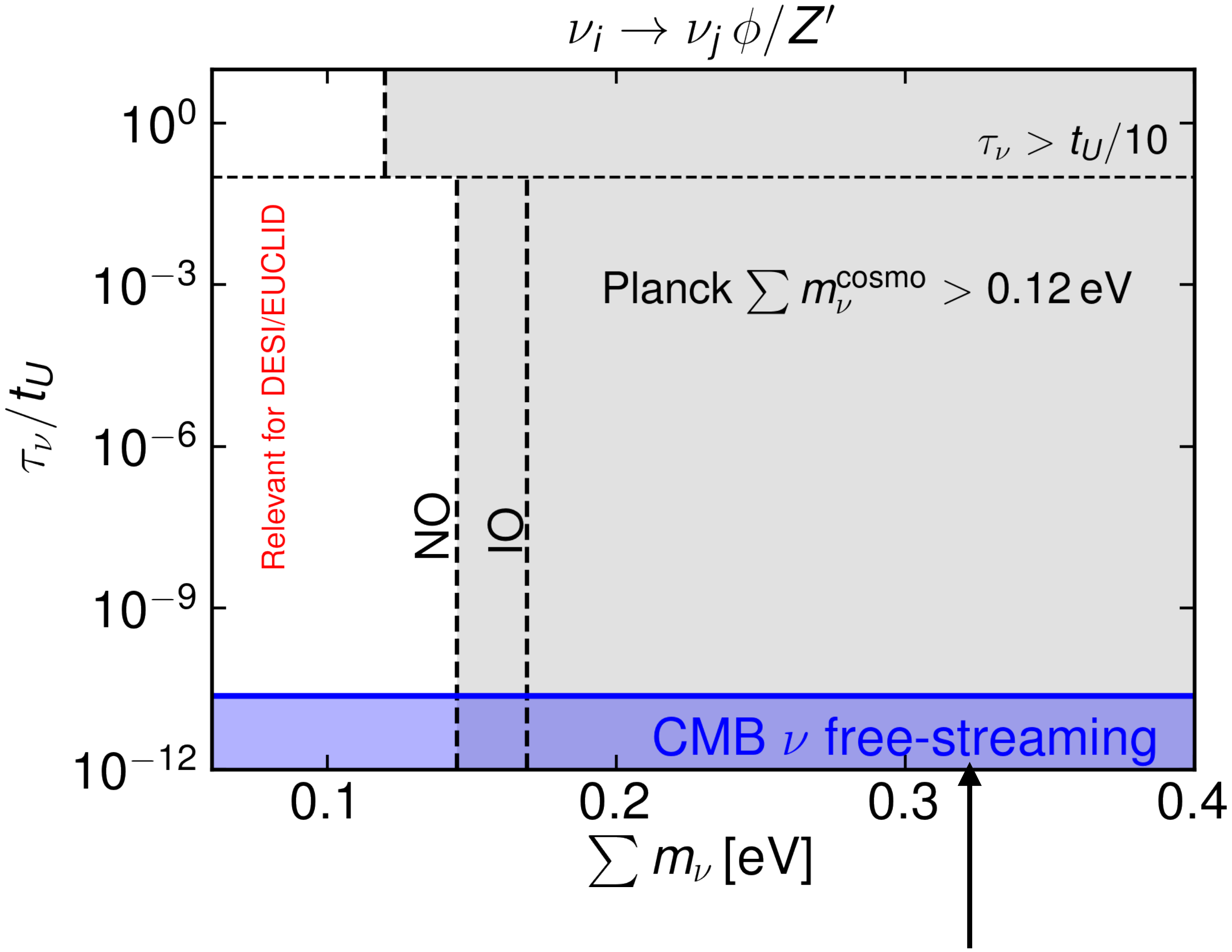
However, because there is a neutrino in the final state the mass bounds are expected to only be relaxed mildly:

$$\Omega_\nu h^2 = \frac{3 \times m_\nu^{\mathrm{lightest}}}{93.14\,\mathrm{eV}}$$

Escudero, López-Pavón, Rius & Sandner 2007.04994



Parameter space:

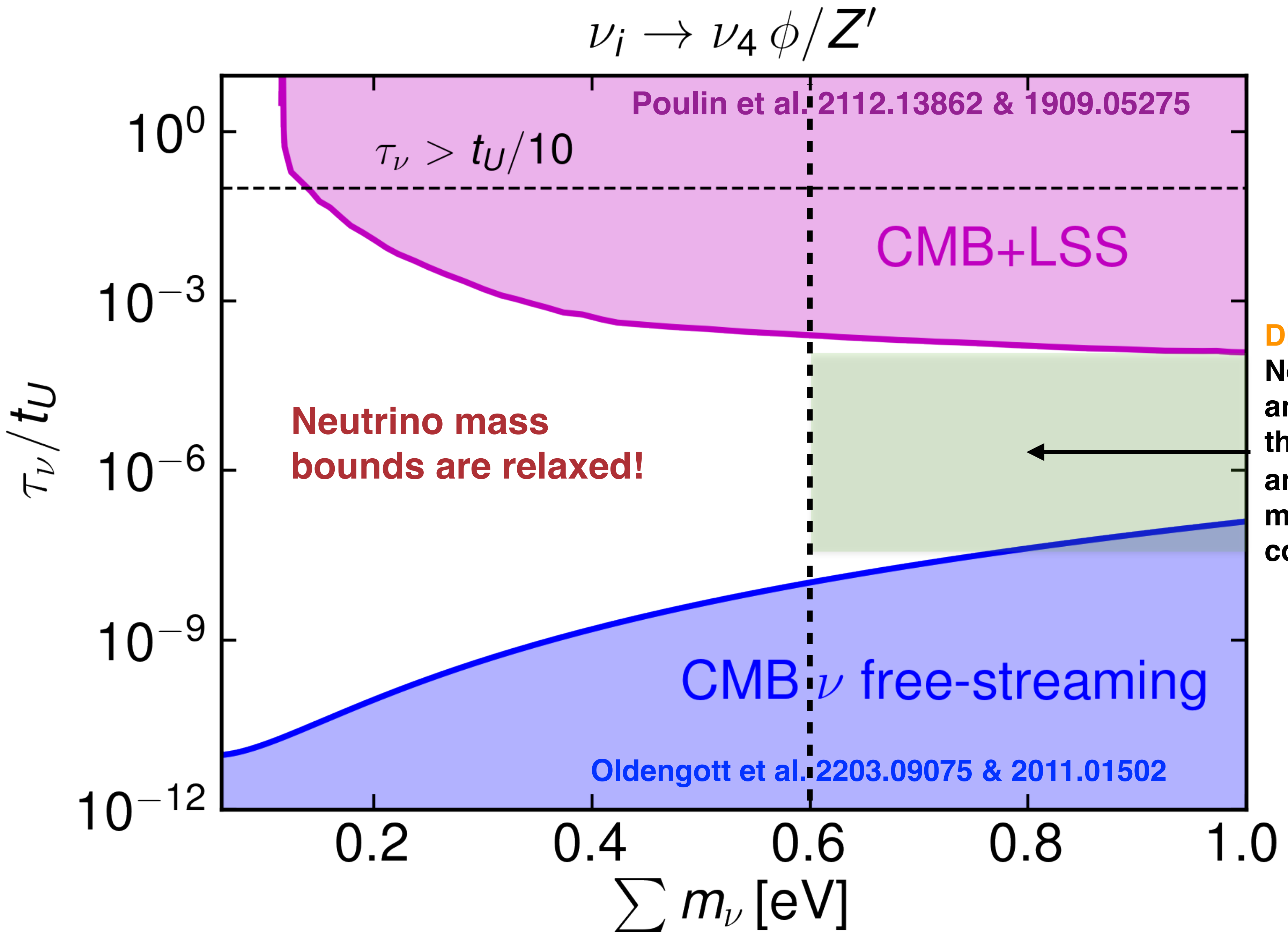


Oldengott et al. 2011.01502 & 2203.09075

Neutrino Decays into Massless States

$\nu_i \to \nu_4\,\phi$ Decays

Parameter space:



Disclaimer!

No full realistic cosmological analysis has been performed in the literature for $m_\nu > 0.2\,\mathrm{eV}$ and these lifetimes. This region may or may not be excluded by cosmological data

Neutrino Decays into Massless States

$\nu_i \to \nu_4 \phi$ **Decays** **Can relax the bounds significantly**

- **Have an almost massless sterile state but that:**
  1) Does not to spoil the neutrino mass mechanism
  2) Is weakly coupled so that evades constraints on $U_{\alpha 4}$
  3) But not so weakly coupled so that $\tau_\nu < 0.1\, t_U$

- **Simple solution:** Escudero, López-Pavón, Rius & Sandner 2007.04994
  Add global $U(1)_X$ symmetry with a scalar field and a singlet left-handed state S_L

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

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

- **Seesaw mechanism at play** $m_\nu \simeq m_D^2/M_R$
- **Right ν_4 properties:** $m_{\nu_4} \simeq 0 \quad U_{\alpha 4} \sim \dfrac{y_\alpha v_\Phi}{m_D} \ll 1$

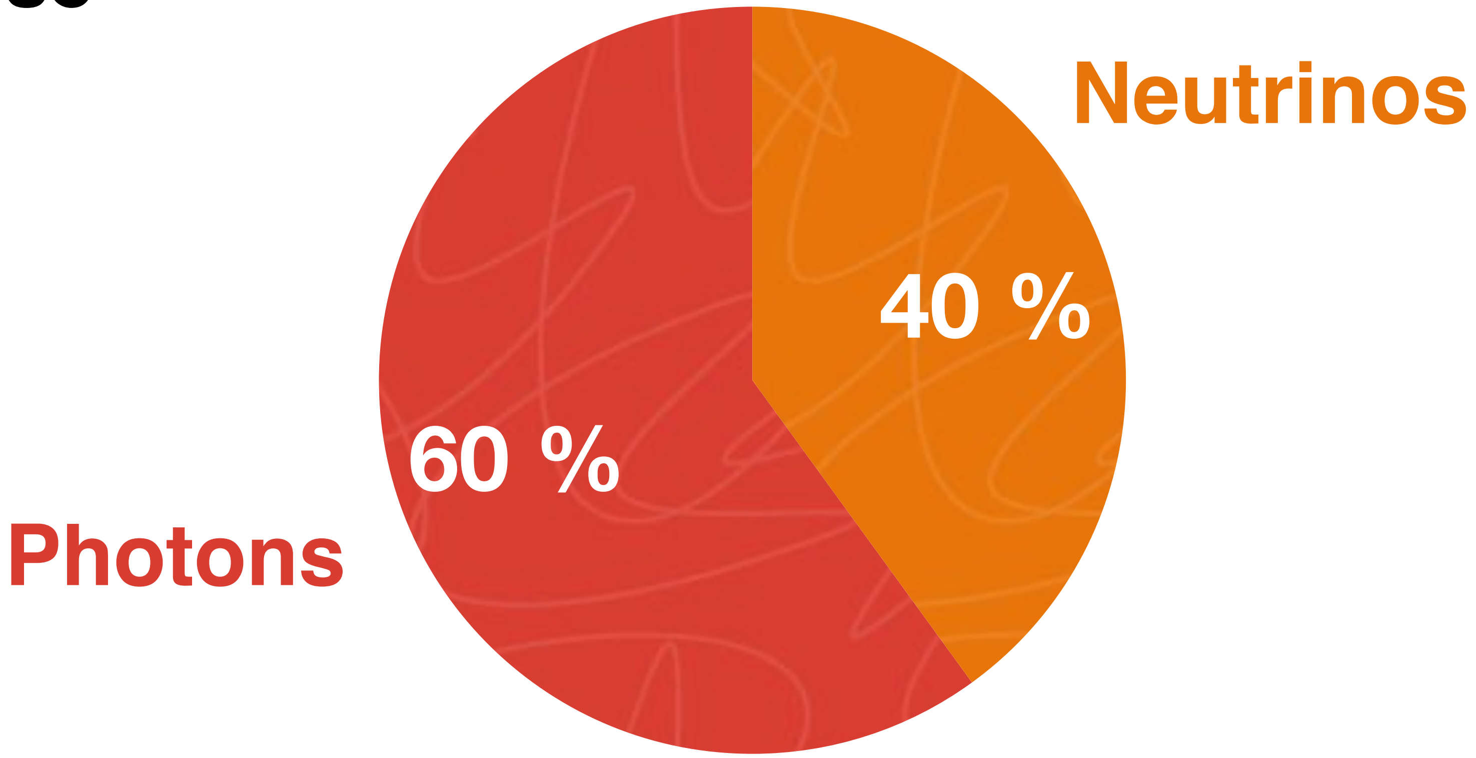
Cosmological decays:

$$\Gamma(\nu_i \to \nu_4 \phi) \sim 10^6 t_U^{-1}\, y_\alpha^2 \left(\frac{m_\nu}{0.3\text{eV}}\right)^2 \left(\frac{10^{14}\,\text{GeV}}{M_R}\right)$$

Neutrinos with a large mass can decay on cosmological timescales while being in agreement with all known laboratory and cosmological data!

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] & Hannestad [astro-ph/0411475]

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

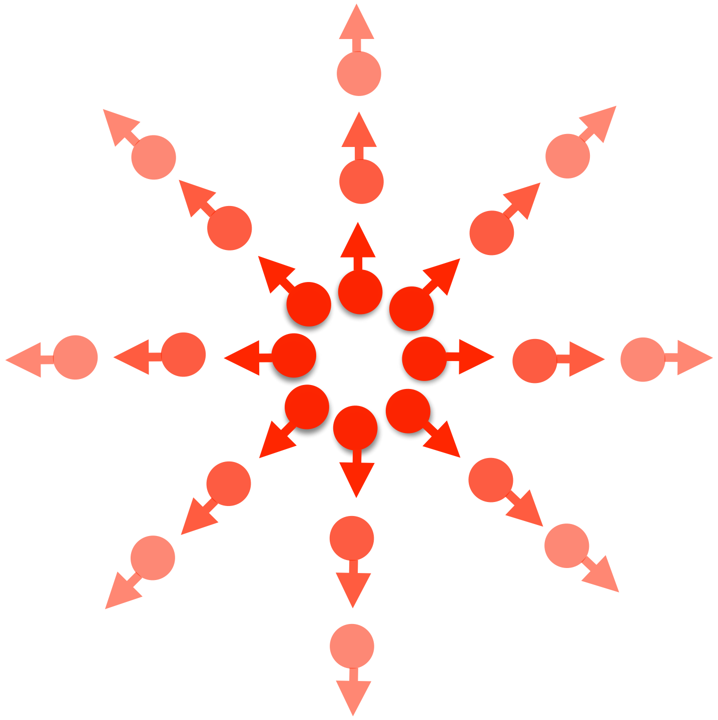
$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$ **Background expansion: Neff**

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

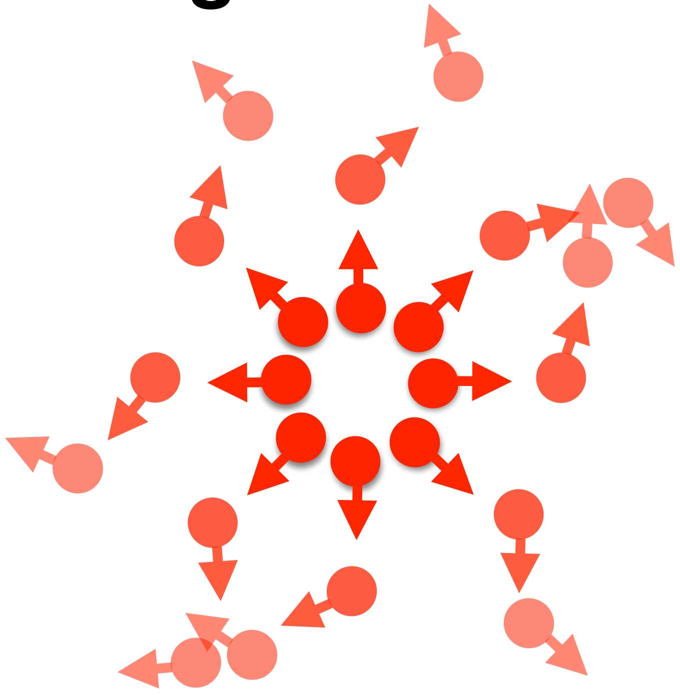
Neutrino anisotropic stress **Metric** **CMB spectra**

$$\sigma_\nu \longrightarrow \delta g_{\mu\nu} \longrightarrow \Delta T_\gamma$$

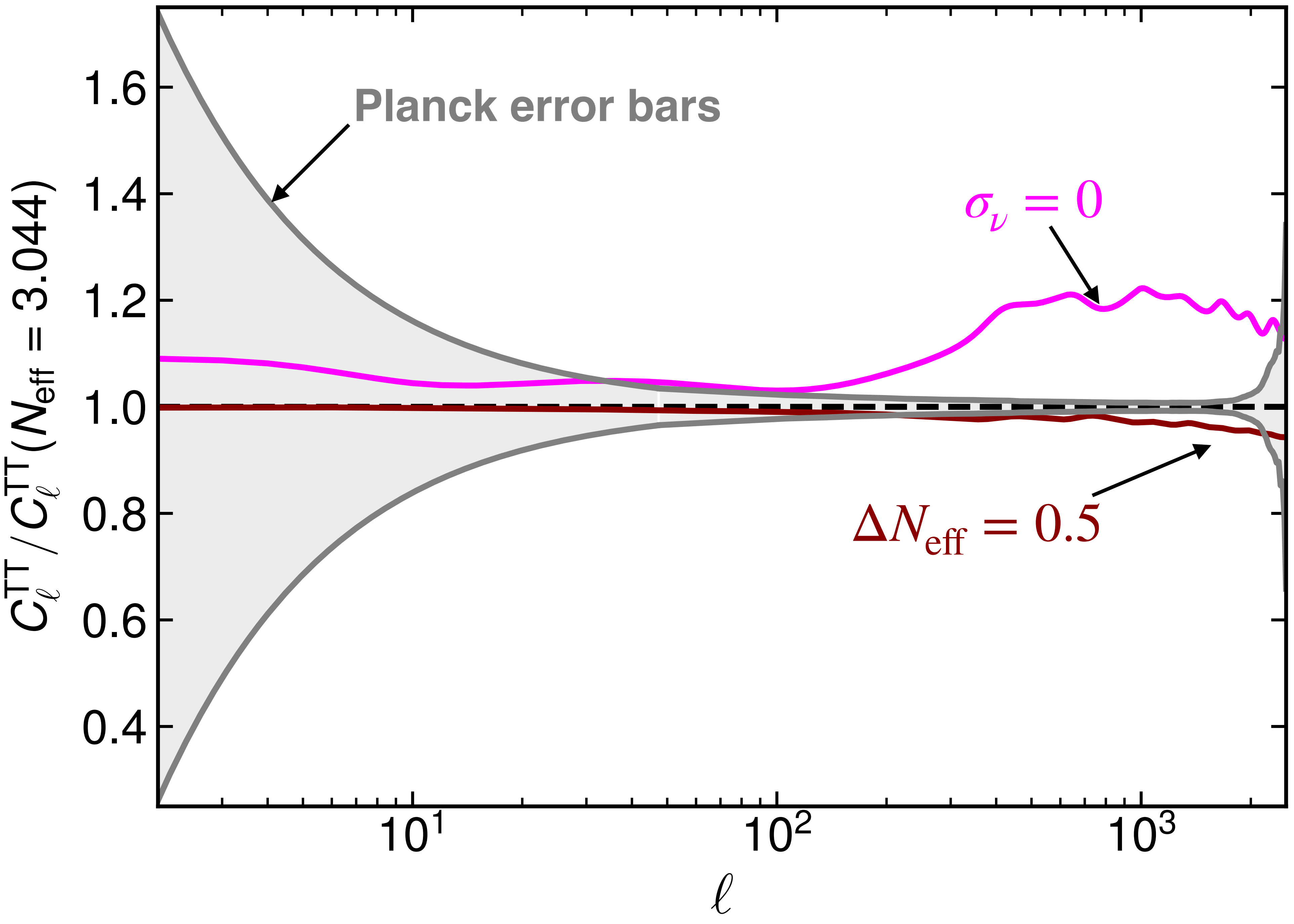
Free Streaming Neutrinos $\sigma_\nu \neq 0$



Interacting Neutrinos $\sigma_\nu \to 0$



Effect of Neutrino Free-streaming in the CMB

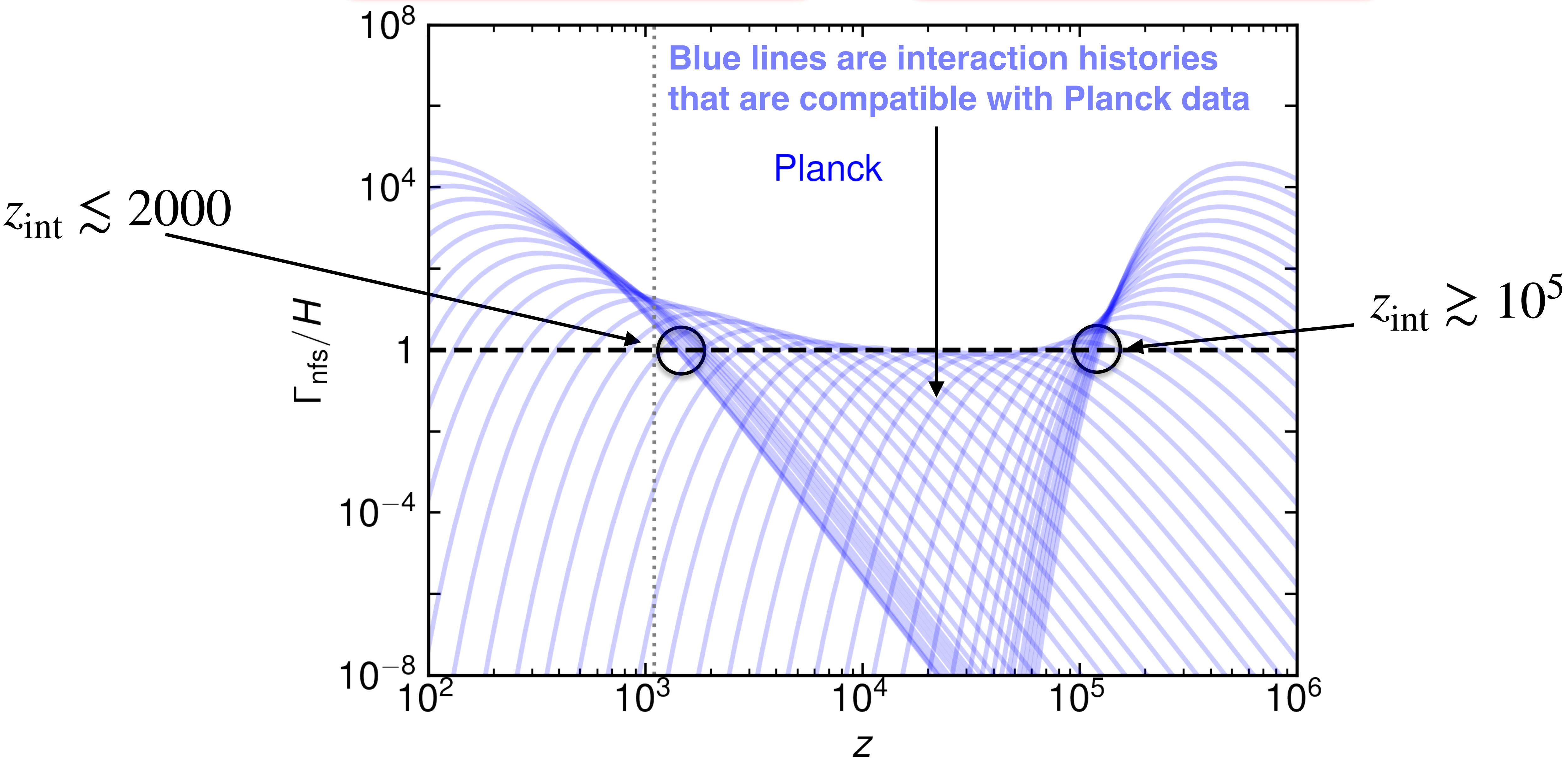


The Neutrino Freestreaming window

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

By considering a very general collision term in the neutrino perturbations, we have demonstrated in a model independent way that neutrinos cannot interact efficiently between themselves or other light particles in the range:

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



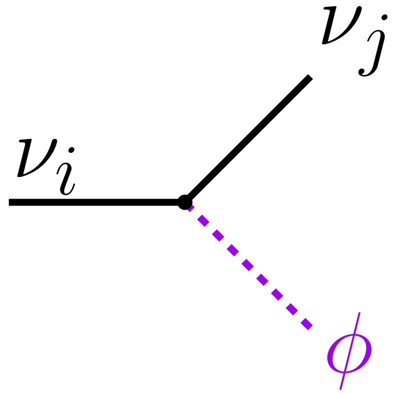
Blue lines are interaction histories that are compatible with Planck data

$z_{\rm int} \lesssim 2000$

$z_{\rm int} \gtrsim 10^5$

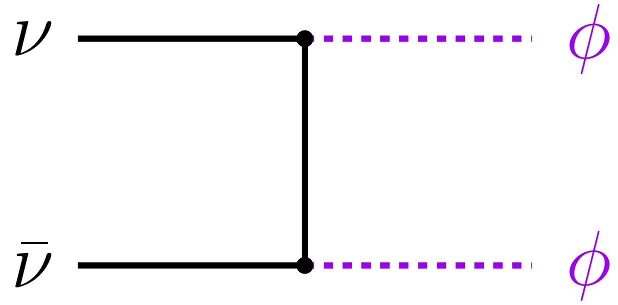
Models

Neutrino Decays



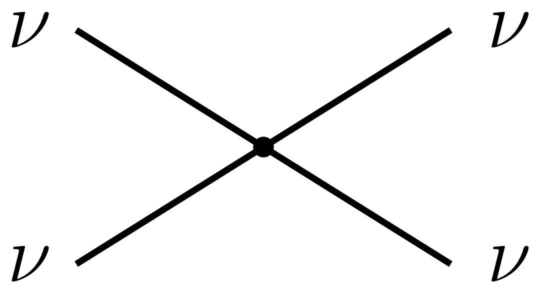
Hannestad & Raffelt [hep-ph/0509278]
Basboll, Bjaelde, Hannestad & Raffelt [0806.1735]
Escudero & Fairbairn [1907.05425]
Chacko, Dev, Du, V. Poulin and Y. Tsai [1909.05275]
Barenboim, Chen, Hannestad, Oldengott, Tram & Wong [2011.01502]
Abellán, Chacko, Dev, Du, Poulin & Tsai [2112.13862]
Chen, Oldengott,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

Neutrino Annihilations



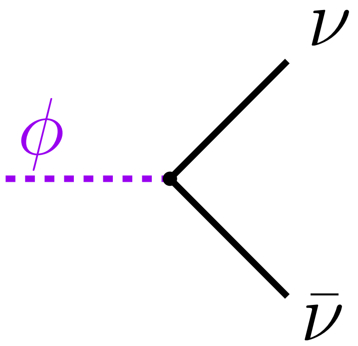
Beacom, Bell & Dodelson [astro-ph/0404585]
Hannestad [astro-ph/0411475]
Archidiacono & Hannestad [1311.3873]
Forastieri, Lattanzi & Natoli [1904.07810]

Neutrino Scatterings



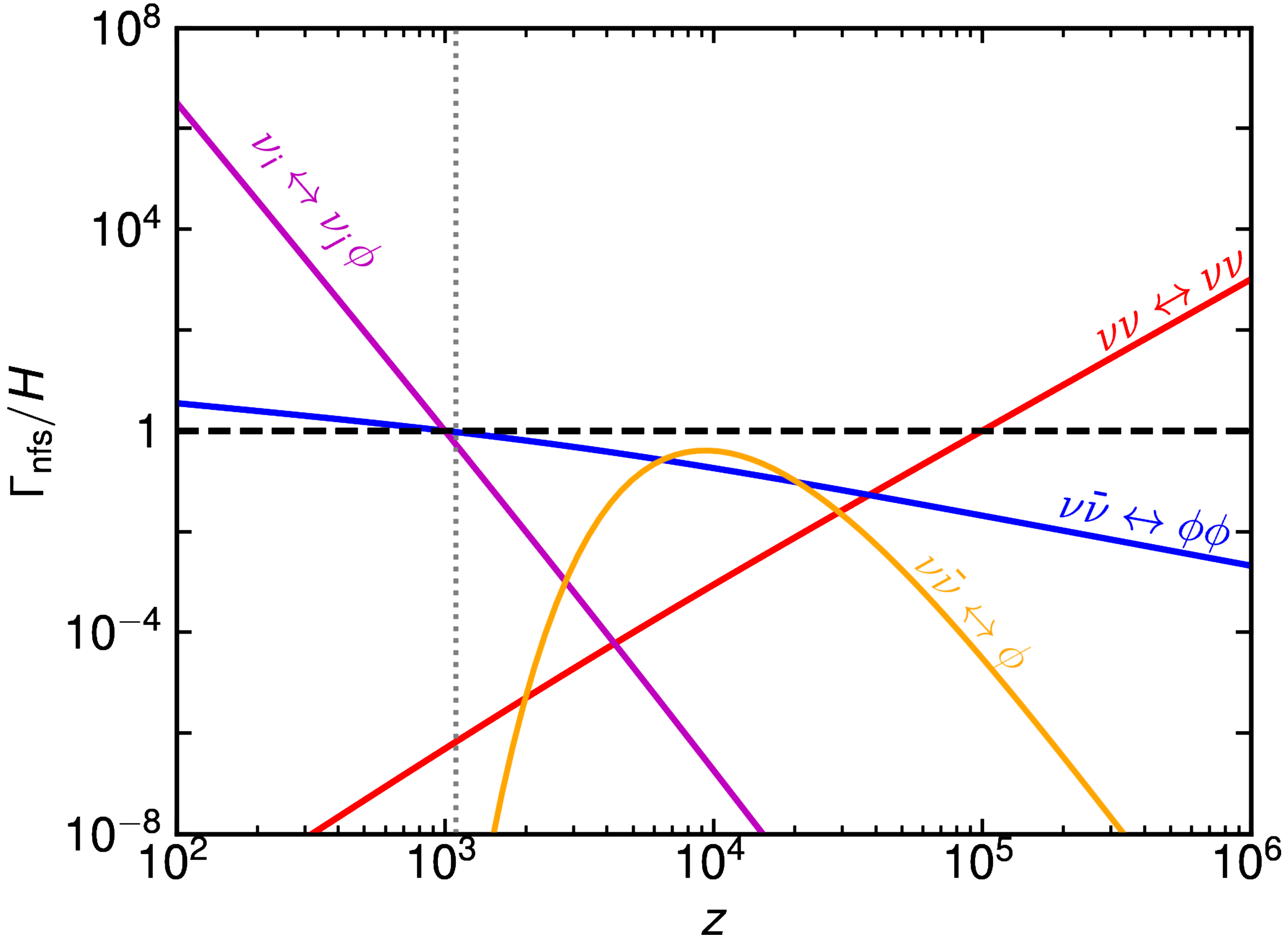
Cyr-Racine & Sigurdson [1306.1536]
Lancaster, Cyr-Racine, Knox & Pan [1704.06657]
Oldengott, Tram, Rampf & Wong [1706.02123]
Kreisch, Cyr-Racine & Doré [1902.00534]
Das & Ghosh [2011.12315]
Choudhury, Hannestad & Tram [2012.07519]
Brinckmann, Chang & LoVerde [2012.11830]
Camarena & Cyr-Racine [2403.05496]

eV-scale neutrinophilic bosons

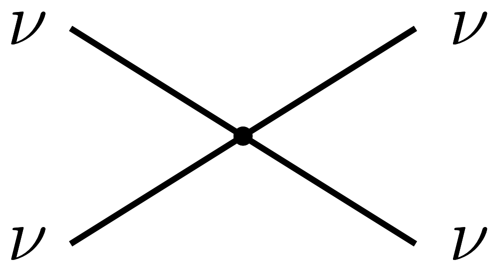


Chacko, Hall, Okui & Oliver [hep-ph/0312267]
Escudero & Witte [1909.04044]
Escudero & Witte [2103.03249]
Sandner, Escudero & Witte [2305.01692]

Rates for various models

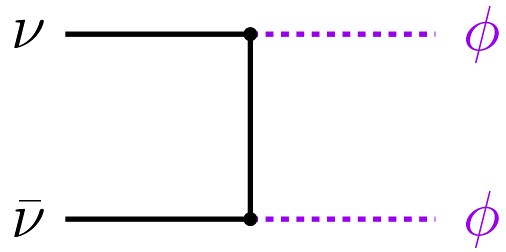


Neutrino scatterings



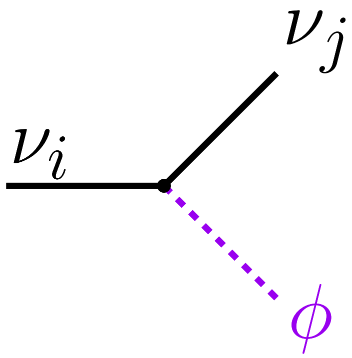
$\Gamma_{nfs} \sim T^5$

Neutrino annihilations



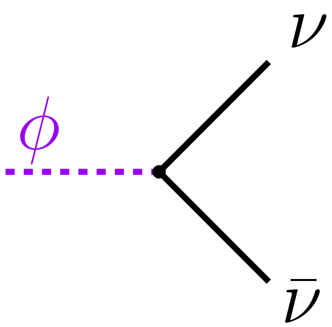
$\Gamma_{nfs} \sim T$

Neutrino decays



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

eV-scale Neutrinophilic Bosons

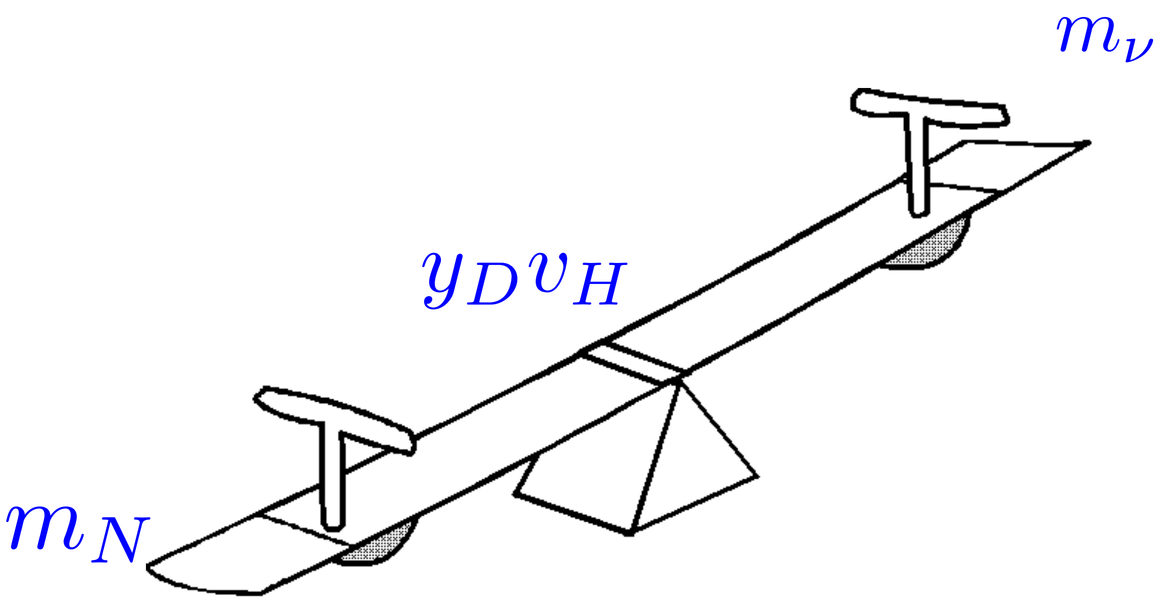


$\Gamma_{nfs} \sim T^{-5}$ $(T > m_\phi)$

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

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?

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 $U(1)_L$

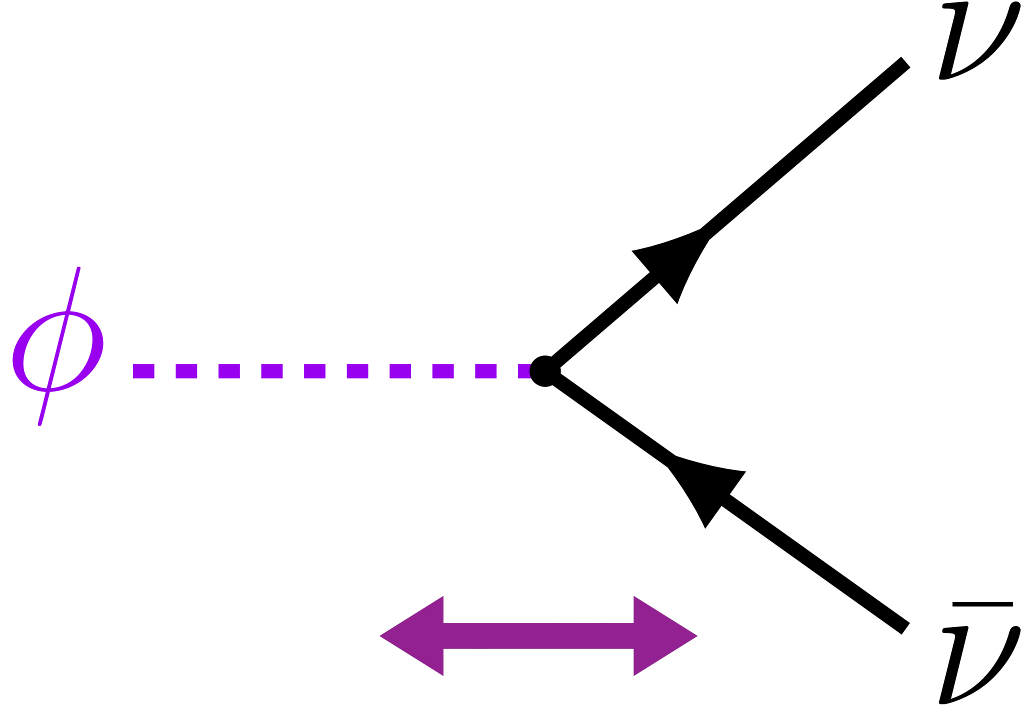
$$\boxed{\begin{gathered}\mathscr{L} = \lambda\,\phi\,\bar{\nu}\gamma_5\nu \\ \lambda = m_\nu/v_\phi\end{gathered}}$$

Mass? $\Delta V = \beta\left(\Phi^\star\Phi\right)^2\frac{\Phi^\star + \Phi}{M_{\mathrm{Pl}}}$ $\longrightarrow$ $\boxed{m_\phi \sim v_L\sqrt{\frac{v_L}{M_{\mathrm{Pl}}}} \lesssim 0.1\,\mathrm{keV}}$

Rothstein, Babu, Seckel hep-ph/9301213
Akhmedov, Berezhiani, Mohapatra, Senjanovic hep-ph/9209285

Cosmological Analysis

Only Relevant Process:



Sandner, Escudero & Witte [2305.01692]
Escudero & Witte [1909.04044]
Escudero & Witte [2103.03249]

Two main effects:

Chacko, Hall, Okui, Oliver
hep-ph/0312267

- Non-standard expansion history
- Erase the neutrino anisotropic stress

- We solve the Boltzmann equation for the background

  Escudero Abenza 1812.05605, 2001.04466

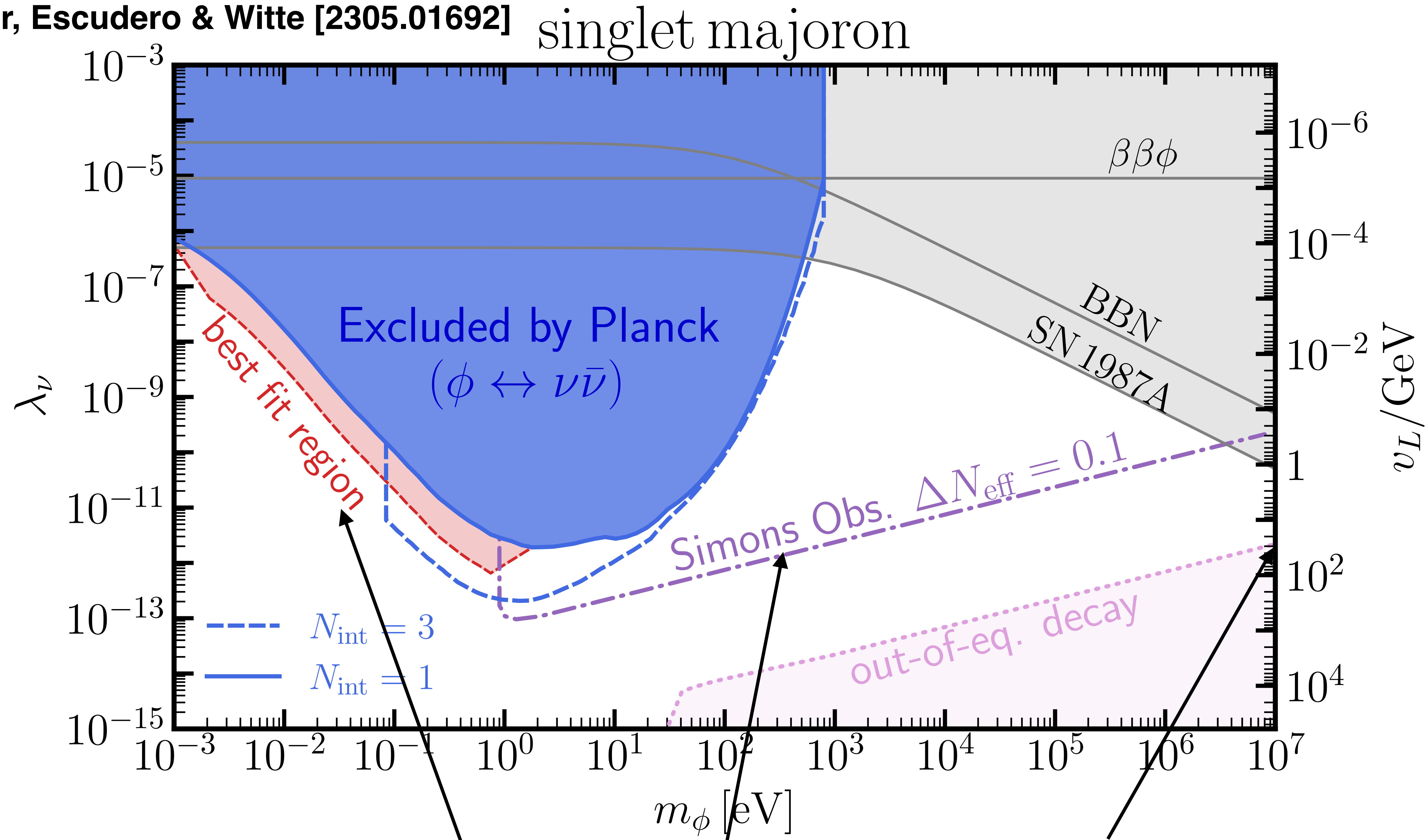
- We include the neutrino-majoron Boltzmann hierarchy in CLASS

  including the updated collision term from Oldengott et al. 2203.09075 & 2011.01502
  and considering simultaneously the ϕ and ν perturbations

Stefan Sandner: https://github.com/stefanmarinus/CLASS_neutrinophilic

The case of the Majoron

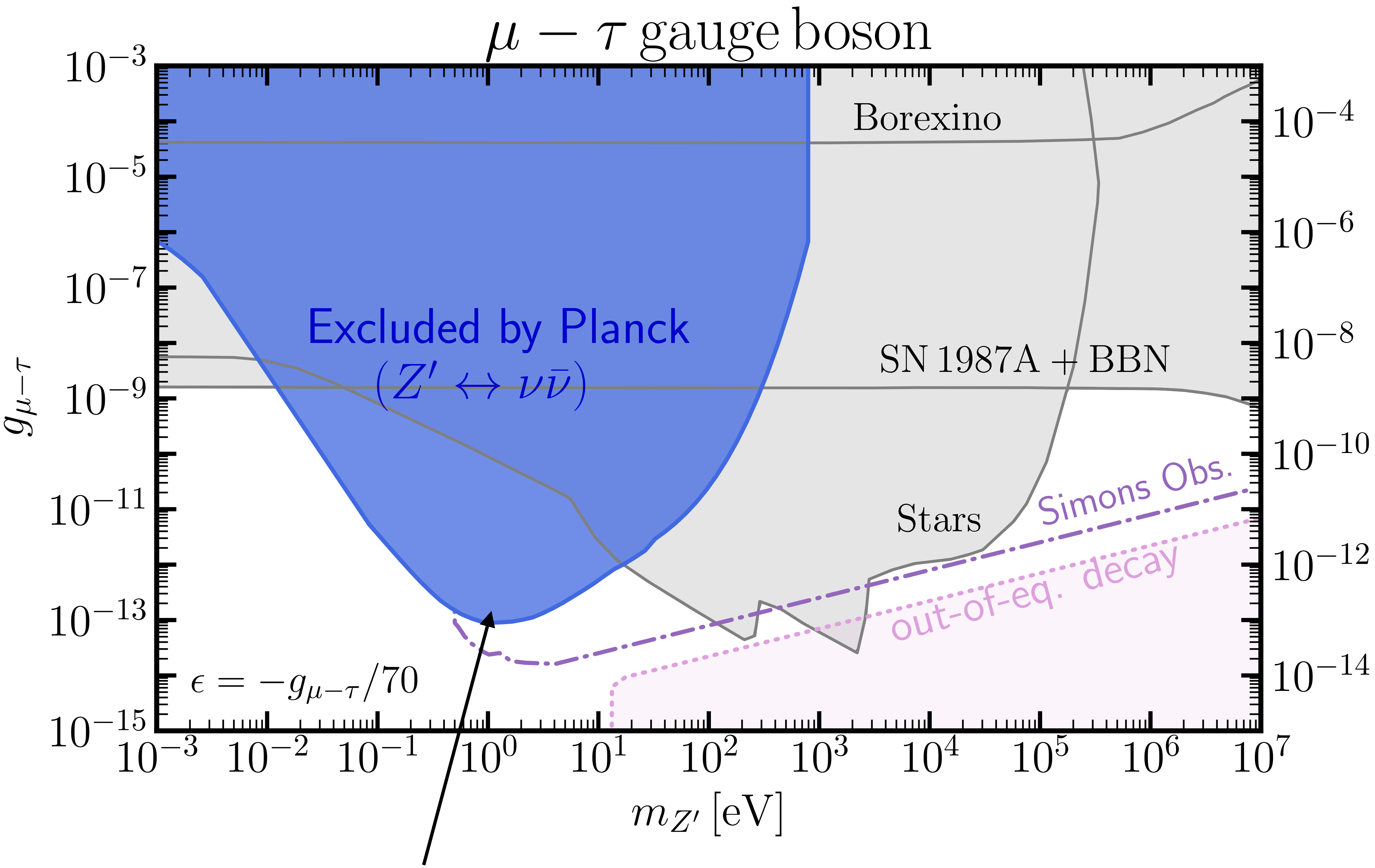
Sandner, Escudero & Witte [2305.01692]



- **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 ΔN_{eff} the model can lower the H₀ tension to the ~3.5σ 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 ~5 years wide regions of parameter space!**

A light $\mu - \tau$ gauge boson

Sandner, Escudero & Witte [2305.01692] **see also Escudero, Hooper, Krnjaic & Pierre [1901.02010]**



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

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 $N_{\rm eff} = 3.043(1)$

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

Current efforts are focused on getting <0.1% precision on this number. The game now are NLO QED corrections

$$\boxed{N_{\rm eff}^{\rm SM} = 3.043(1)}$$

Conclusions

Neutrino Masses:

Cosmological bounds are very stringent within ΛCDM:

$$\boxed{\sum m_\nu < 0.12\,\mathrm{eV}}$$ **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

Invisible neutrino decays are a plausible particle physics avenue to relax them

Developed a simple model compatible with type-I seesaw mechanism

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:

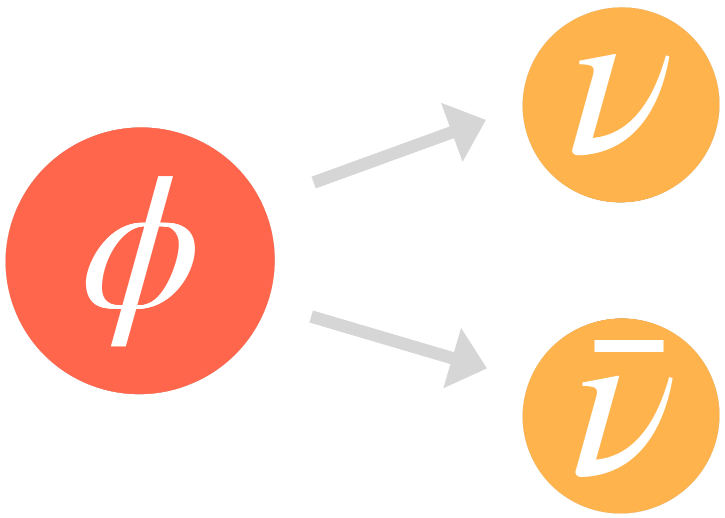
The CMB is a powerful probe of neutrino interactions

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

$$\boxed{2 \times 10^3 \lesssim z \lesssim 10^5}$$

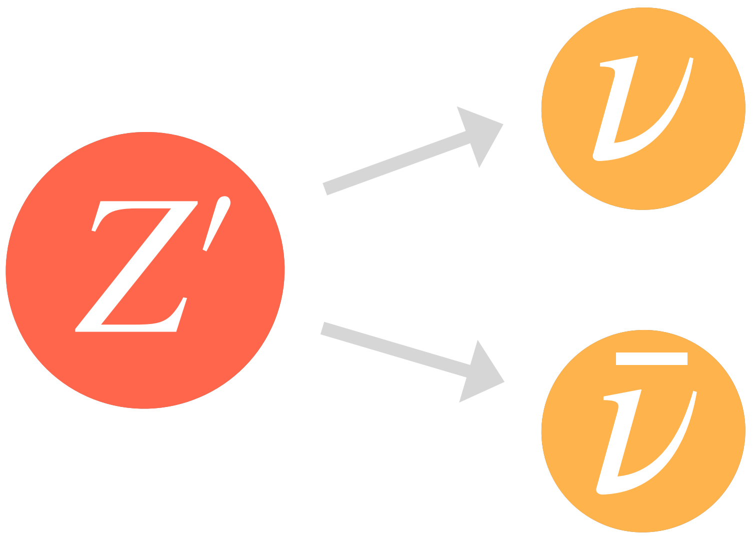
These bounds are relevant for many particle physics scenarios

Singlet majoron model

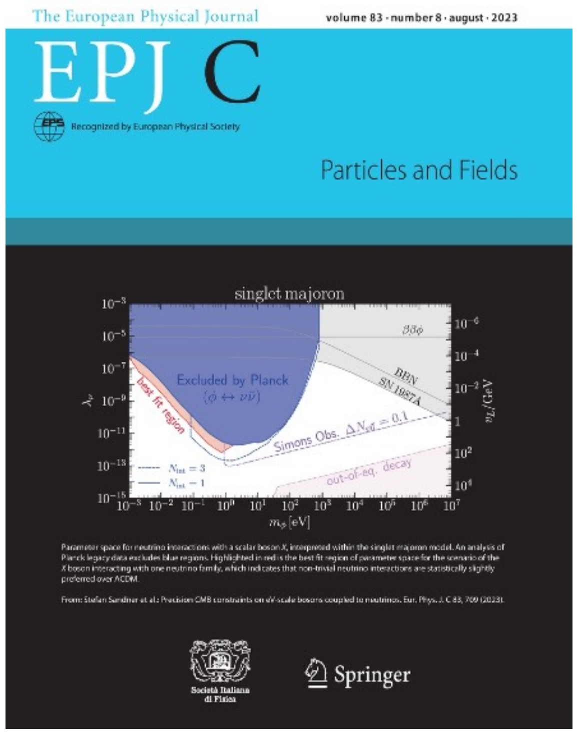


$$v_\phi \sim 100\,\text{GeV}$$

Light mu-tau Z'



$$g_{\mu-\tau} \sim 10^{-13}$$


The European Physical Journal

volume 83 · number 8 · august · 2023

EPJ C

Recognized by European Physical Society

Particles and Fields

Parameter space for neutrino interactions with a scalar boson X, interpreted within the singlet majoron model. An analysis of Planck legacy data excludes blue regions. Highlighted in red is the best fit region of parameter space for the scenario of the X boson interacting with one neutrino family, which indicates that non-trivial neutrino interactions are statistically slightly preferred over ΛCDM.

From: Stefan Sandner et al.: Precision CMB constraints on eV-scale bosons coupled to neutrinos. Eur. Phys. J. C 83, 709 (2023).

Società Italiana di Fisica

Springer

Outlook: Number of Neutrinos

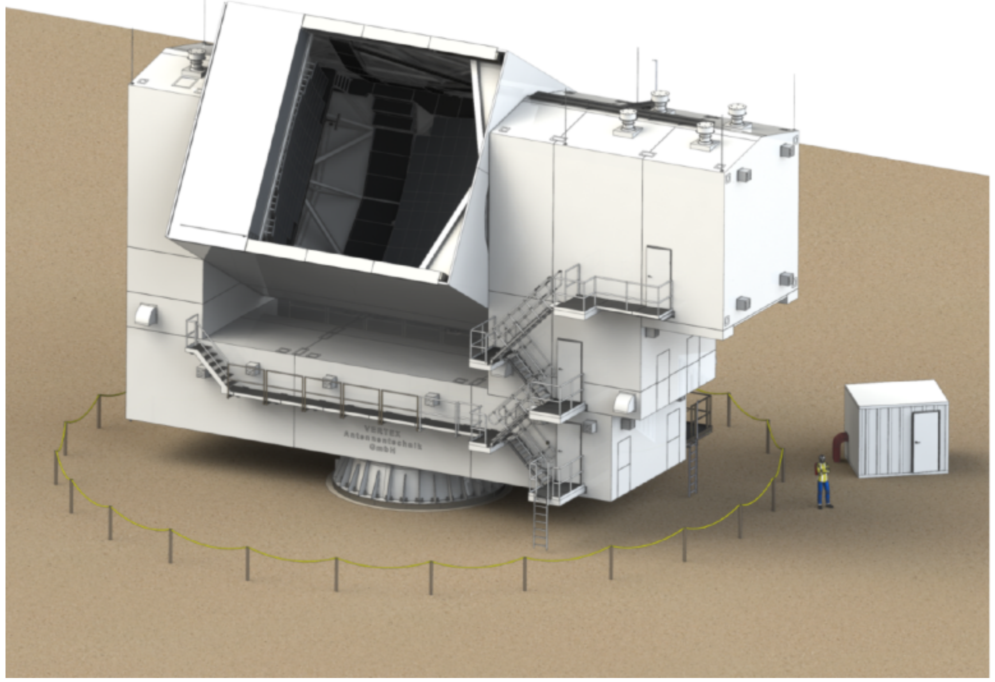
The next generation of CMB experiments are expected to significantly improve the sensitivity to Neff

Simons Observatory

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

under construction and fully funded

CMB-S4



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

one of the main recommendations of the US P5 report

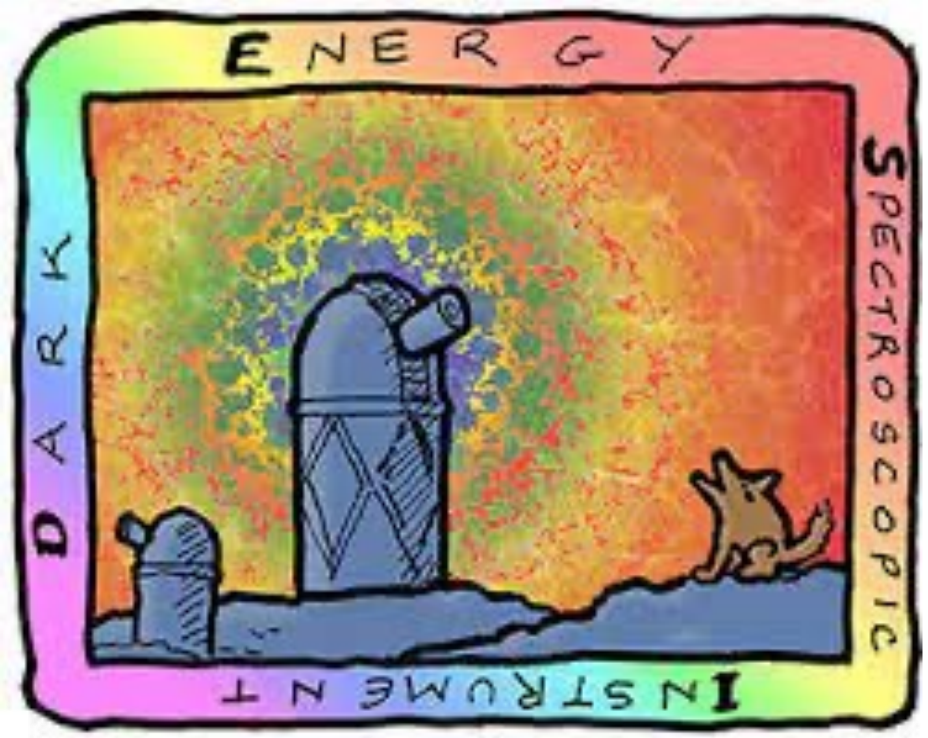
These measurements will represent an important test of the CNB and the thermal history of the SM and may perhaps yield a BSM signal!

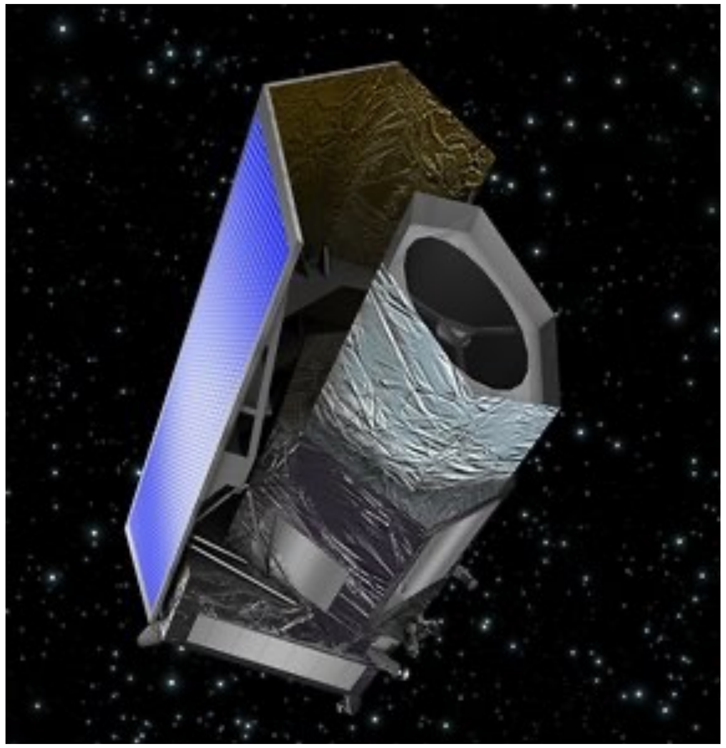
Outlook: Neutrino Masses

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 1611.00036

EUCLID 1110.3193





Why? DESI: 30M galaxies and EUCLID: 50M galaxies, but BOSS 1.5M galaxies

This is expected to happen in the next 4-5 years: $\sigma(\sum m_\nu) = 0.02\,\mathrm{eV}$

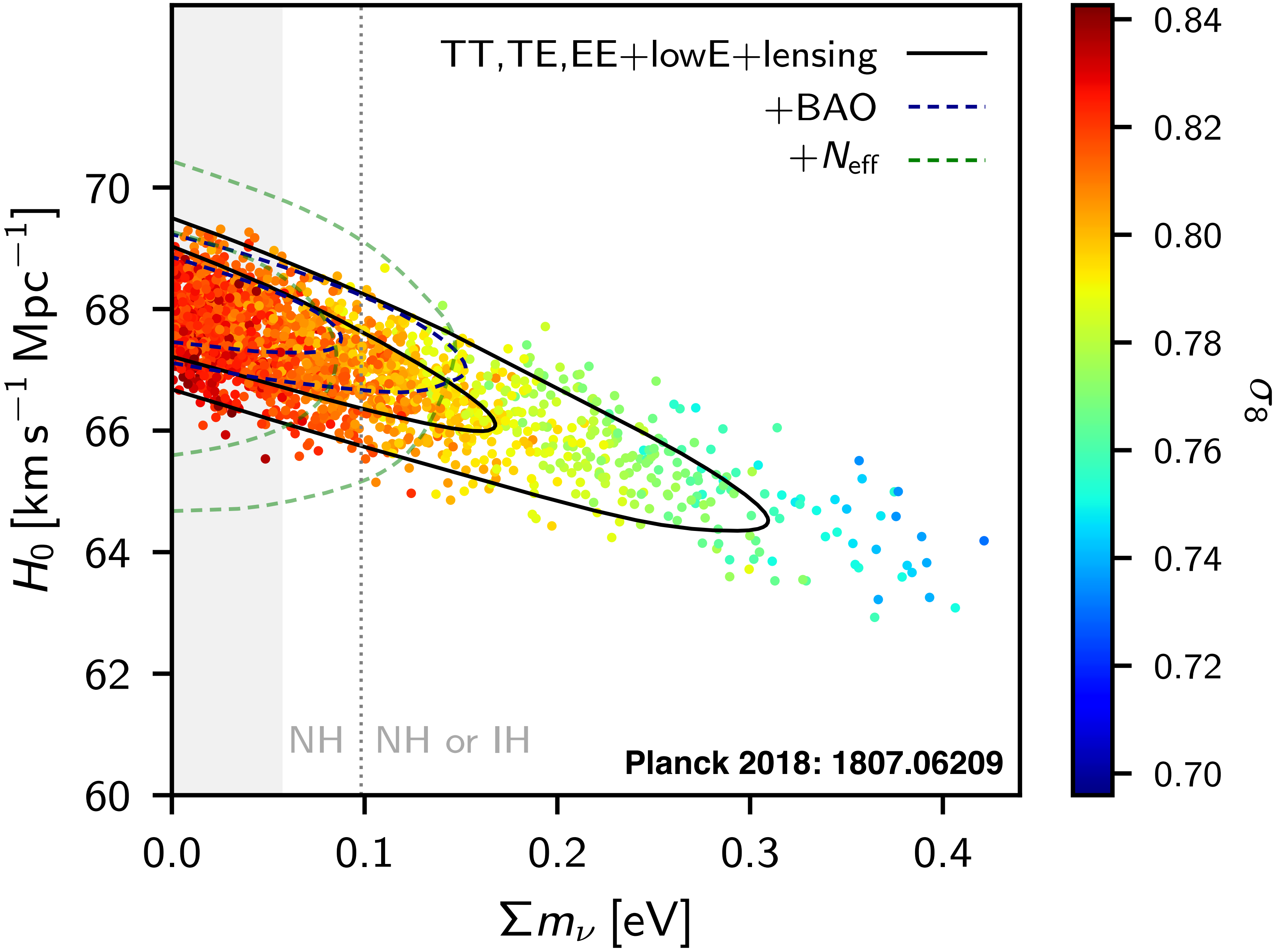
In parallel, the KATRIN experiment is taking data and should reach a sensitivity of $m_{\bar{\nu}_e} \lesssim 0.2\,\mathrm{eV}$ **at 90% CL in ~ 3-4 years.**

Outlook: Hubble tension?

Cepheids+SN typeIa: $H_0 = 73.0 \pm 1.0\,\mathrm{km/s/Mpc}$ **Riess et al. [2112.04510]**

Planck+BAO: $H_0 = 67.7 \pm 0.4\,\mathrm{km/s/Mpc}$ **Planck [1807.06209]**

$> 5\sigma$ **discrepancy!**



Planck 2018: 1807.06209

1) Will alter our inferences about neutrinos

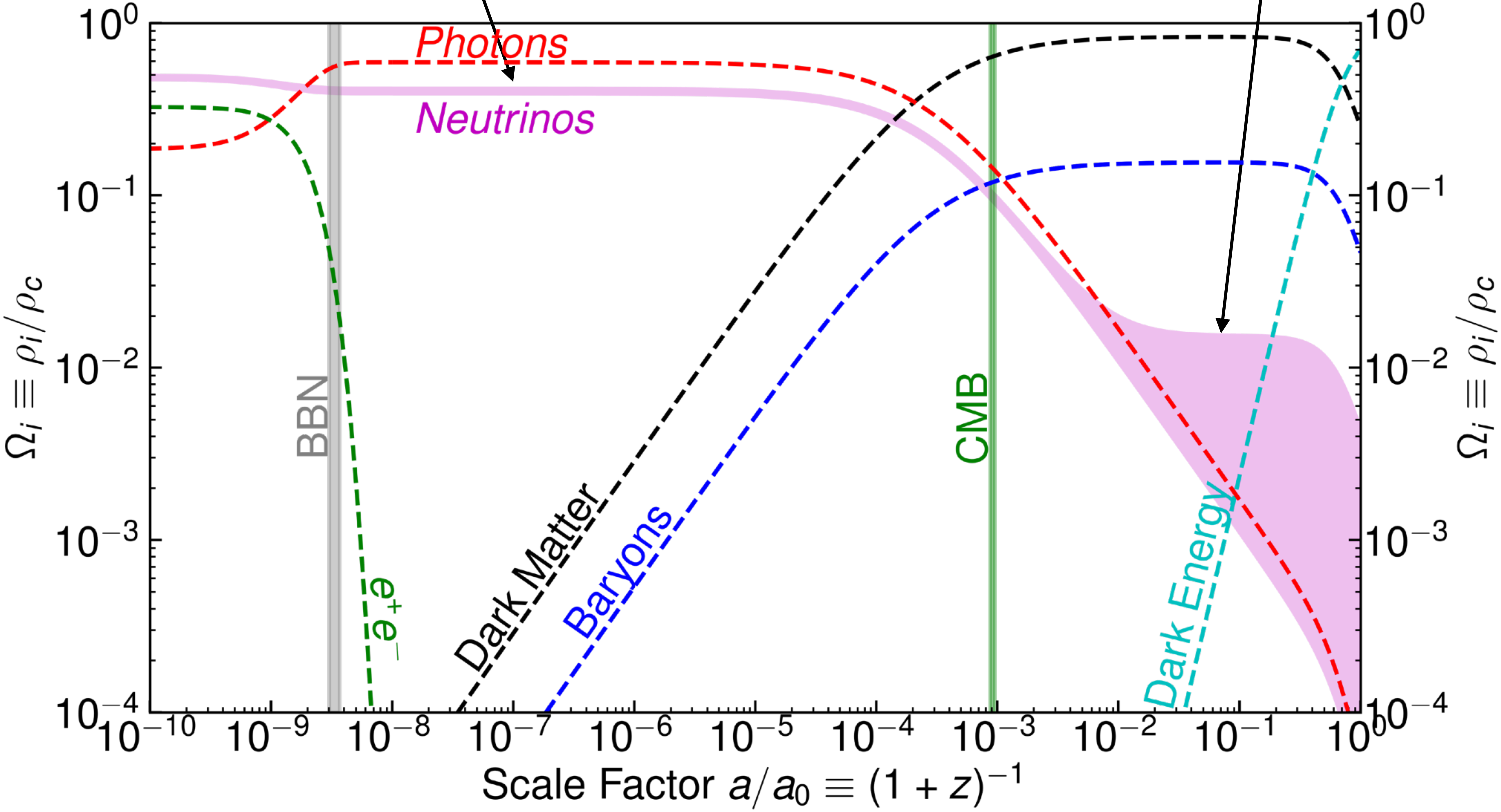
2) If true, can neutrinos or particles related to them be at its origin?

Global Perspective

Current knowledge:

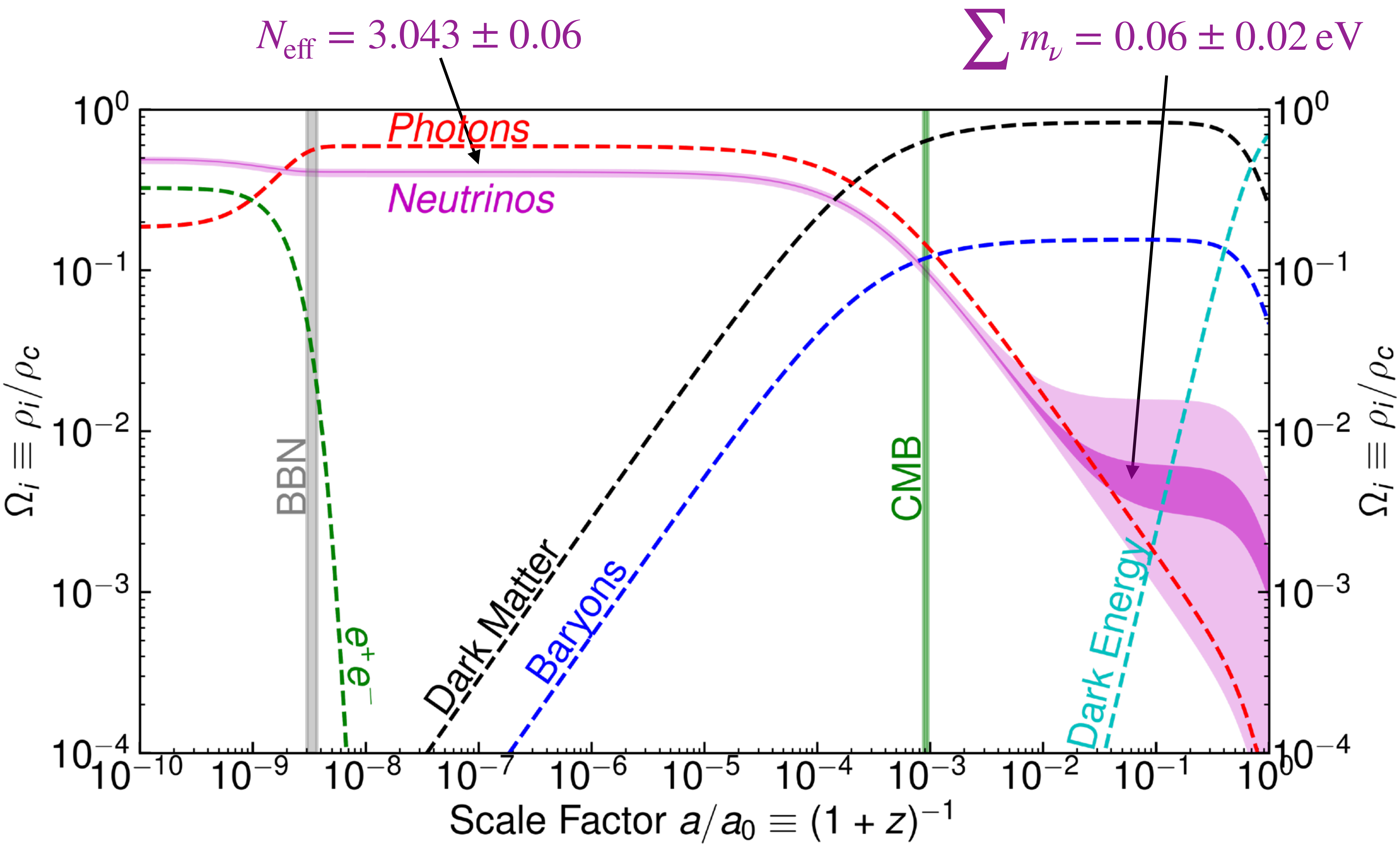
$N_{\rm eff} = 3.0 \pm 0.3$

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



Global Perspective

In the next 5-6 years:



$N_{\rm eff} = 3.043 \pm 0.06$

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

Upcoming years are going to be exciting!

Great thanks to my neutrinophilic collaborators 😃:

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Thank you for your attention!

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