Neutrino Masses, Interactions, and Asymmetries from Cosmology

Miguel Escudero Abenza
miguel.escudero@cern.ch

CERN

Max Planck Institute for Kernphysik
Heidelberg
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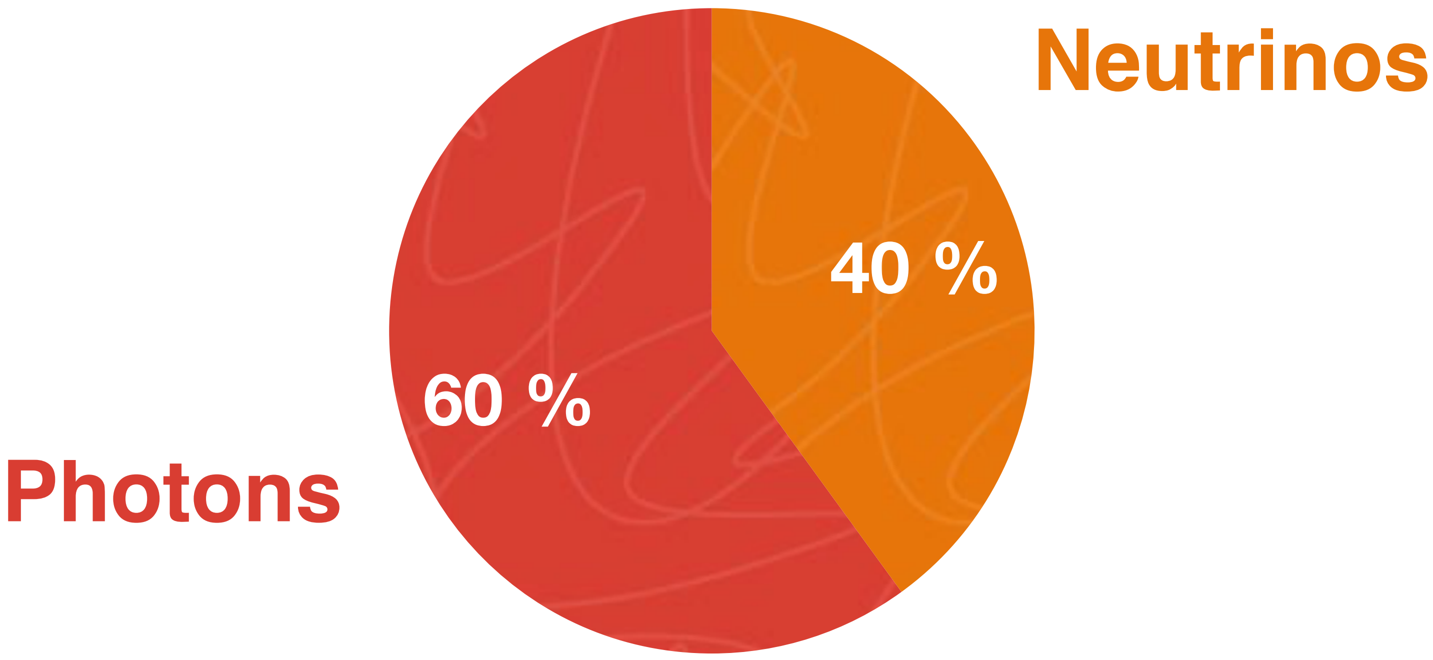
Motivation

- **Neutrino masses are the only laboratory evidence of physics beyond the Standard Model**

Use neutrinos to understand open problems in cosmology

- **Neutrinos are ubiquitous in Cosmology**



Use cosmological data to understand their properties

Topics Covered

Topics covered:

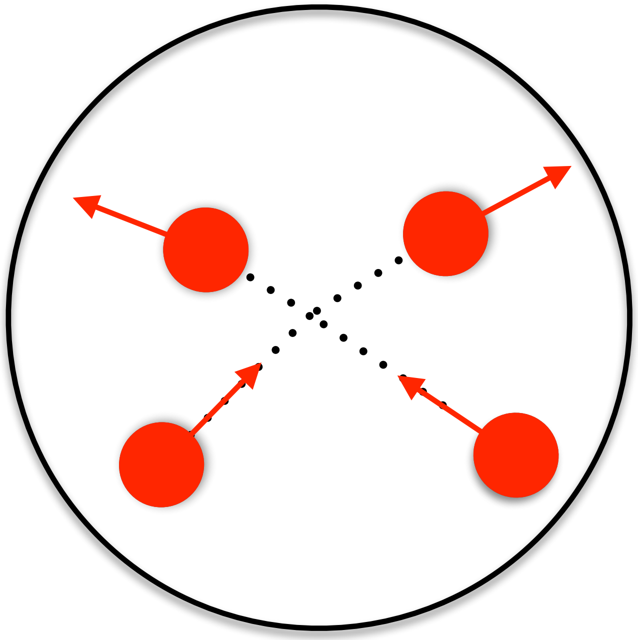
CNB

$$N_{\text{eff}}$$

Neutrino Masses

$$\sum m_\nu$$

Neutrino Interactions



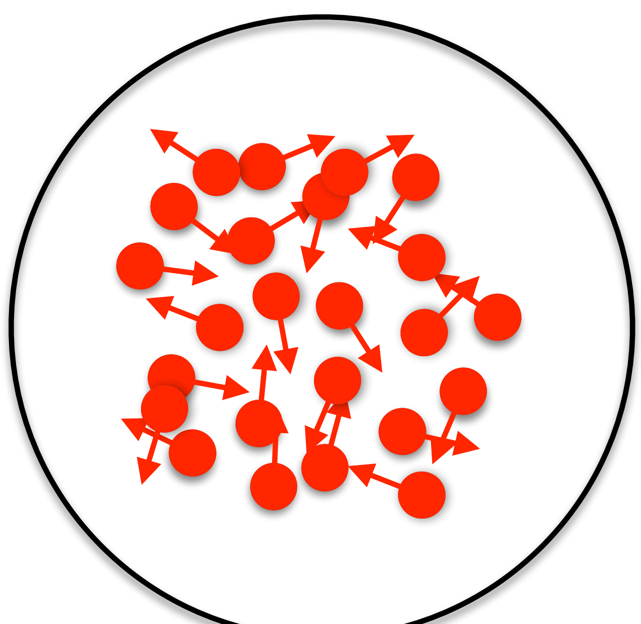
Neutrino Asymmetries

$$\eta_\nu = (n_\nu - n_{\bar{\nu}})/n_\gamma$$

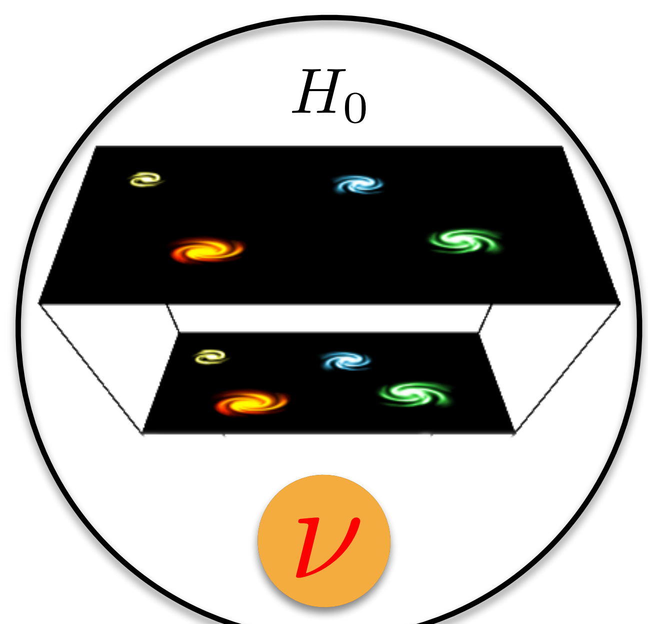
Topics not covered:

(but happy to discuss offline)

CNB Detection



Neutrinos and H0



Outline

1) **Neutrinos in ΛCDM**

2) **Neutrino Masses in and beyond ΛCDM**

3) **Neutrinos interactions and CMB observations**

4) **A Hint for a Large Primordial Lepton Asymmetry?**

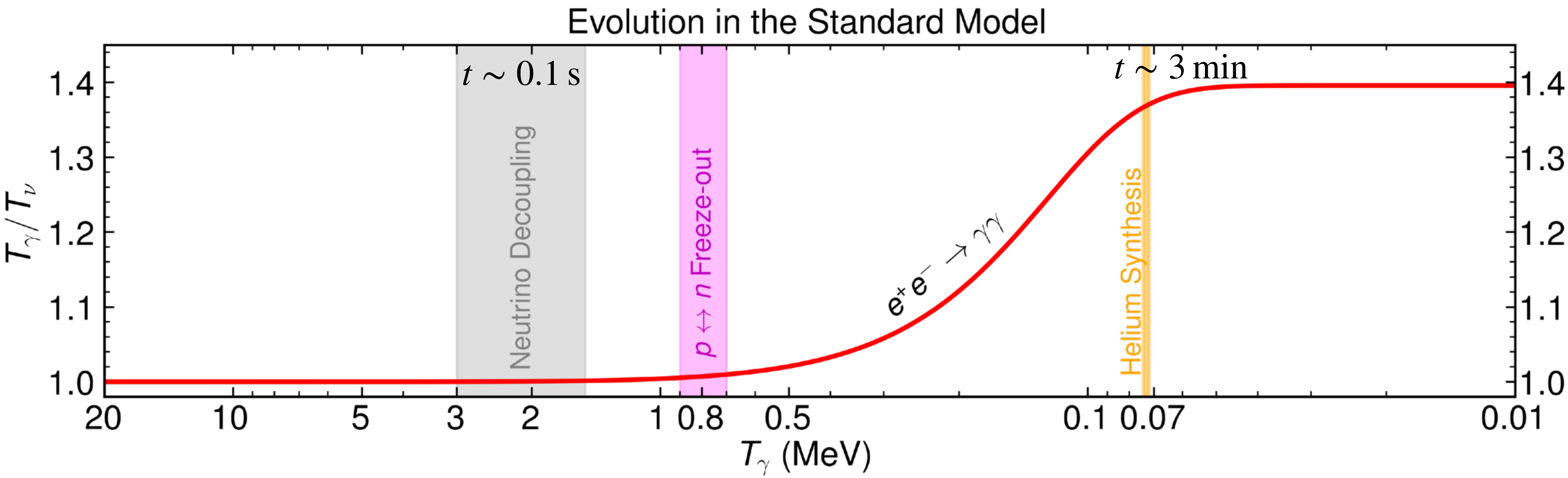
5) **Conclusions and Outlook**

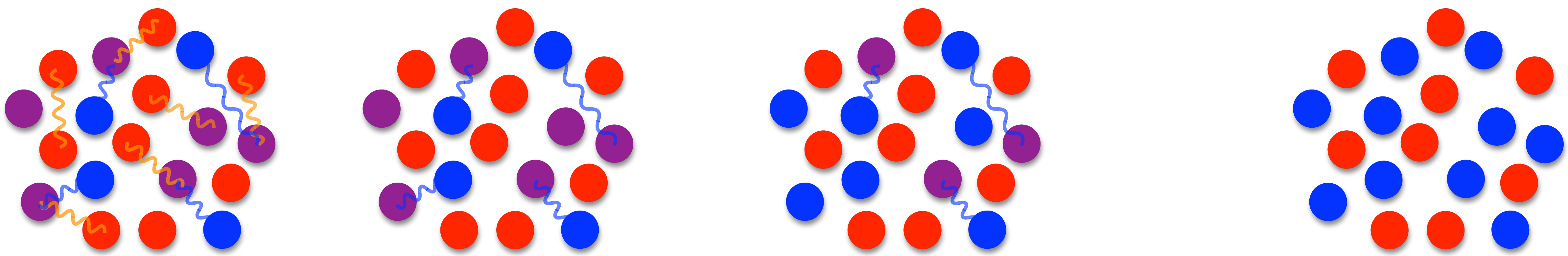
Set Up

Unlike neutrinos, I like to interact 😃

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

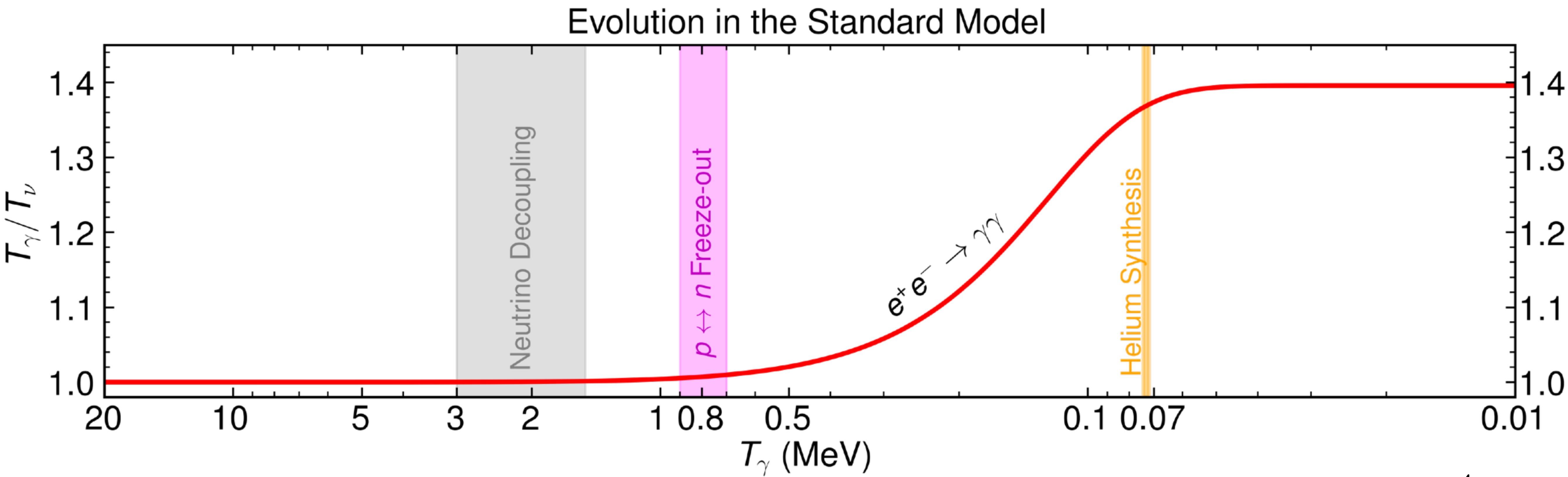
Neutrino Decoupling





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

Cosmic Neutrino Background



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

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

de Salas & Pastor 1606.06986
Bennett, Buldgen, Drewes & Wong 1911.04504
Escudero 2001.04466

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

Relic Neutrino Decoupling

$$t \sim 0.1\,{\rm s}$$
$$T_\nu \sim 2\,{\rm MeV}$$

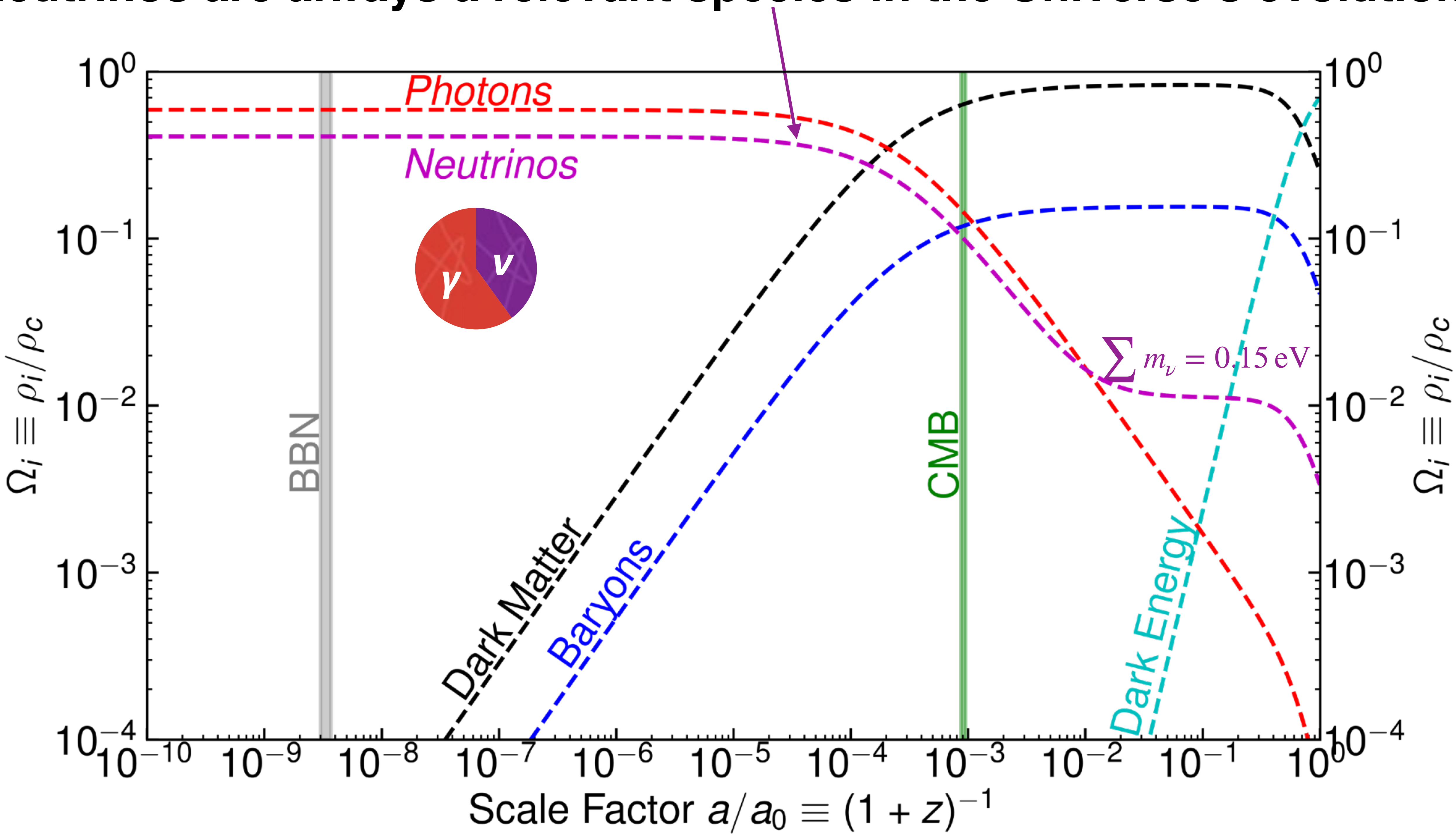
Why is it not 3?

Some e^+e^- heating
Non-instantaneous decoupling
QED thermal corrections
Neutrino Oscillations

Excellent review
by Dolgov hep-ph/0202122

Neutrino Evolution

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



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

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

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:

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

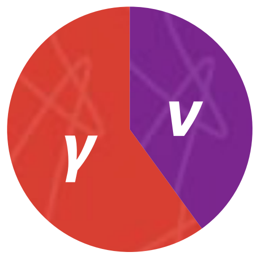
see e.g. Pisanti et al. 2011.11537

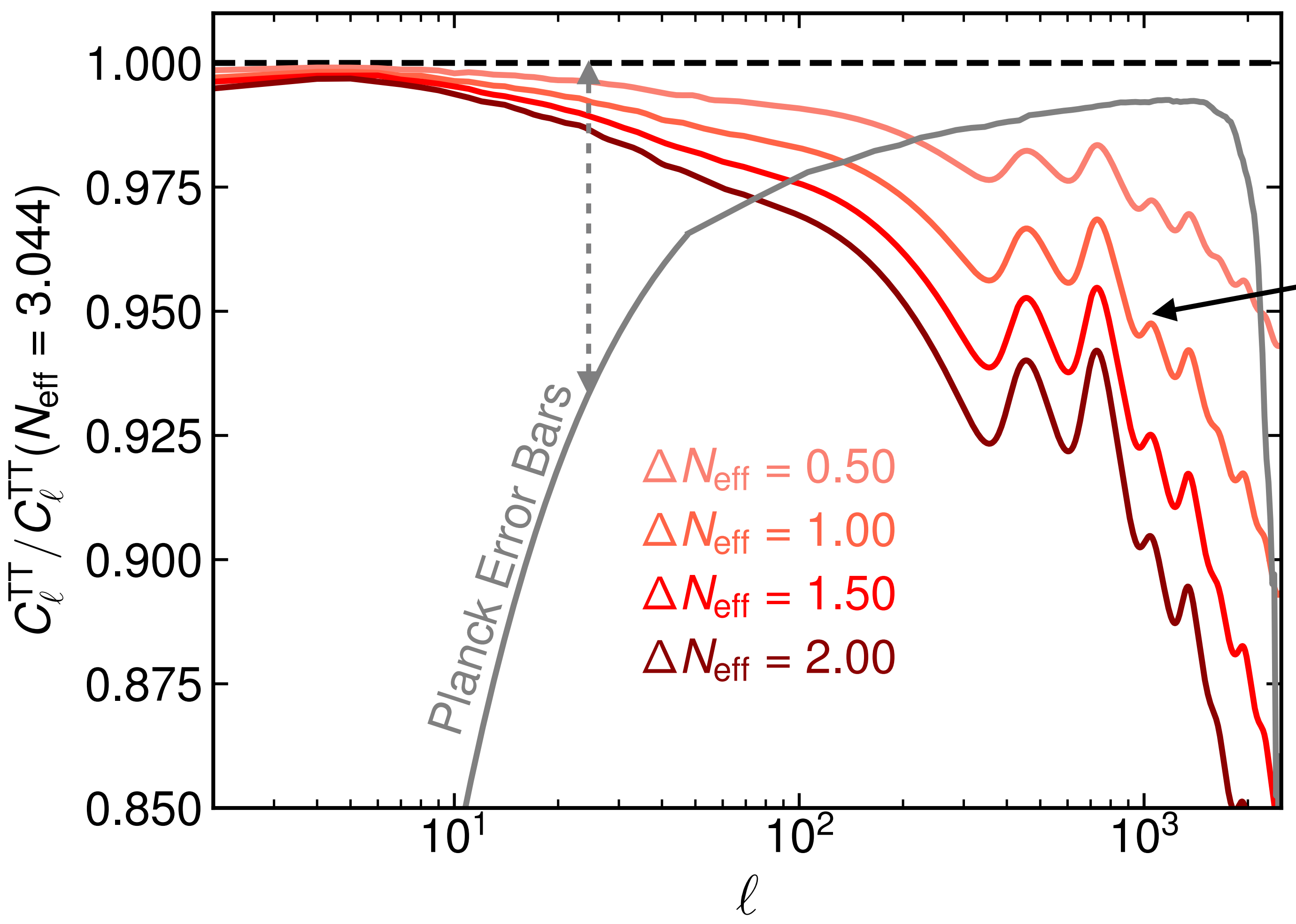
***A very recent measurement of the primordial Helium abundance 3σ smaller than the SM expectation could indicate the presence of a large lepton asymmetry: $L_{\nu_e} \sim 10^{-3}$ (but which would not alter the $N_{\rm eff}^{\rm BBN}$ bound significantly)**

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

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

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

- **Standard Model prediction:** $N_{\rm eff}^{\rm SM} = 3.044(1)$
- **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

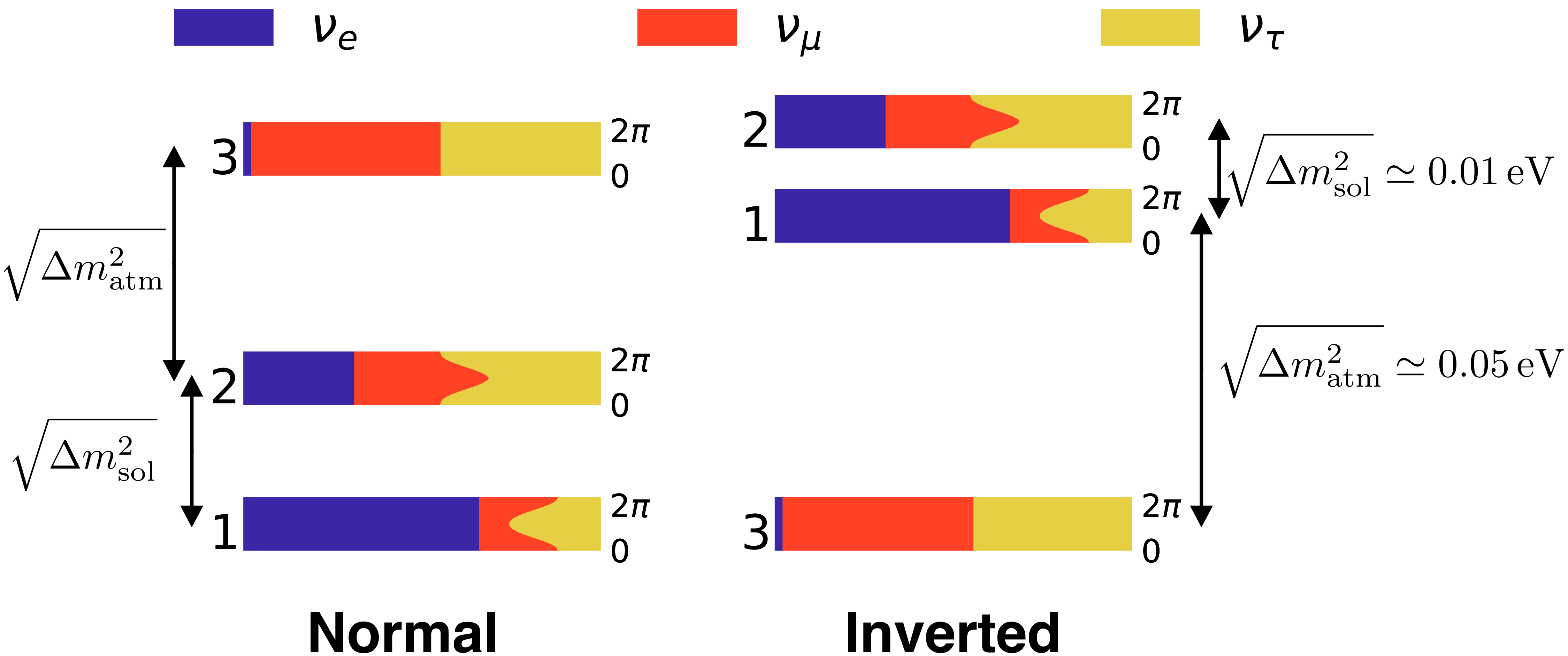
Sterile neutrinos, Goldstone bosons, hidden sector particles, GW …

see 2006.16182 Vaskonen & Tenkanen et al. (Escudero & Poulin)

2) We can use cosmological data to test neutrino properties

Neutrino Properties

Figure from de Salas et al. 1806.11051

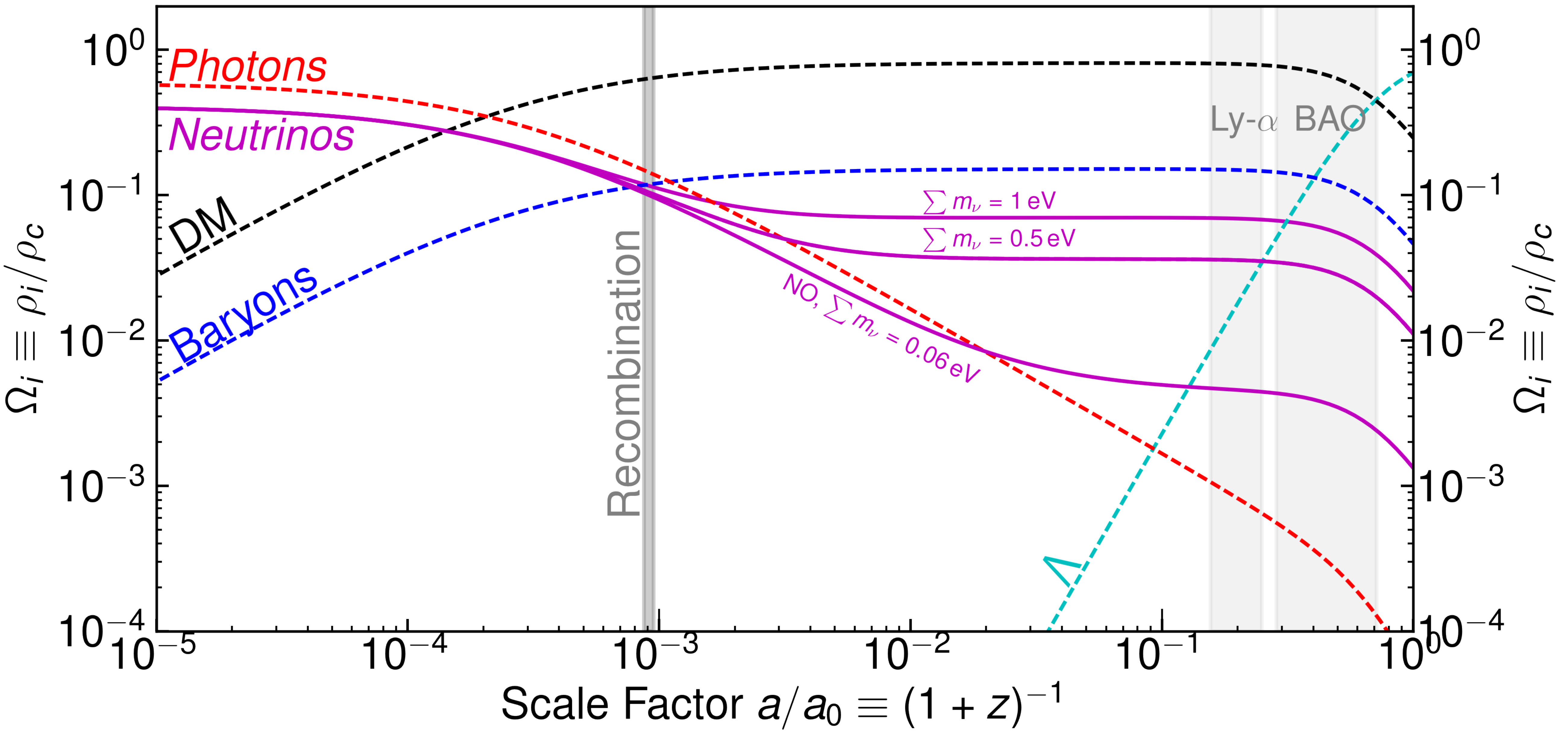


$\sum m_\nu \gtrsim 0.06\,{\rm eV}$ $\quad$ $\sum m_\nu \gtrsim 0.10\,{\rm eV}$

- **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**



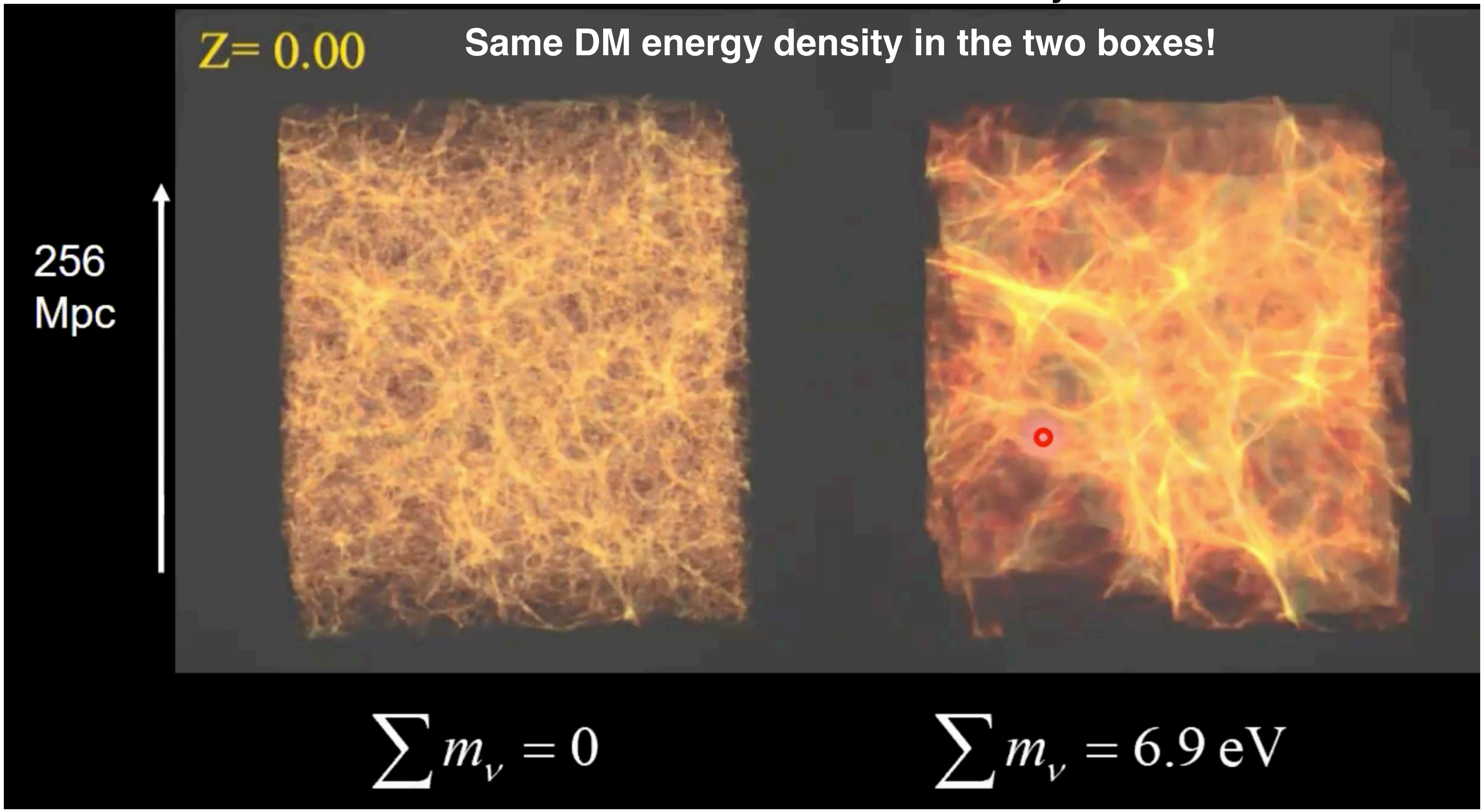
Non-Rel: $z_\nu^{\mathrm{non-rel}} \simeq 200 \frac{m_\nu}{0.1\,\mathrm{eV}}$

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.



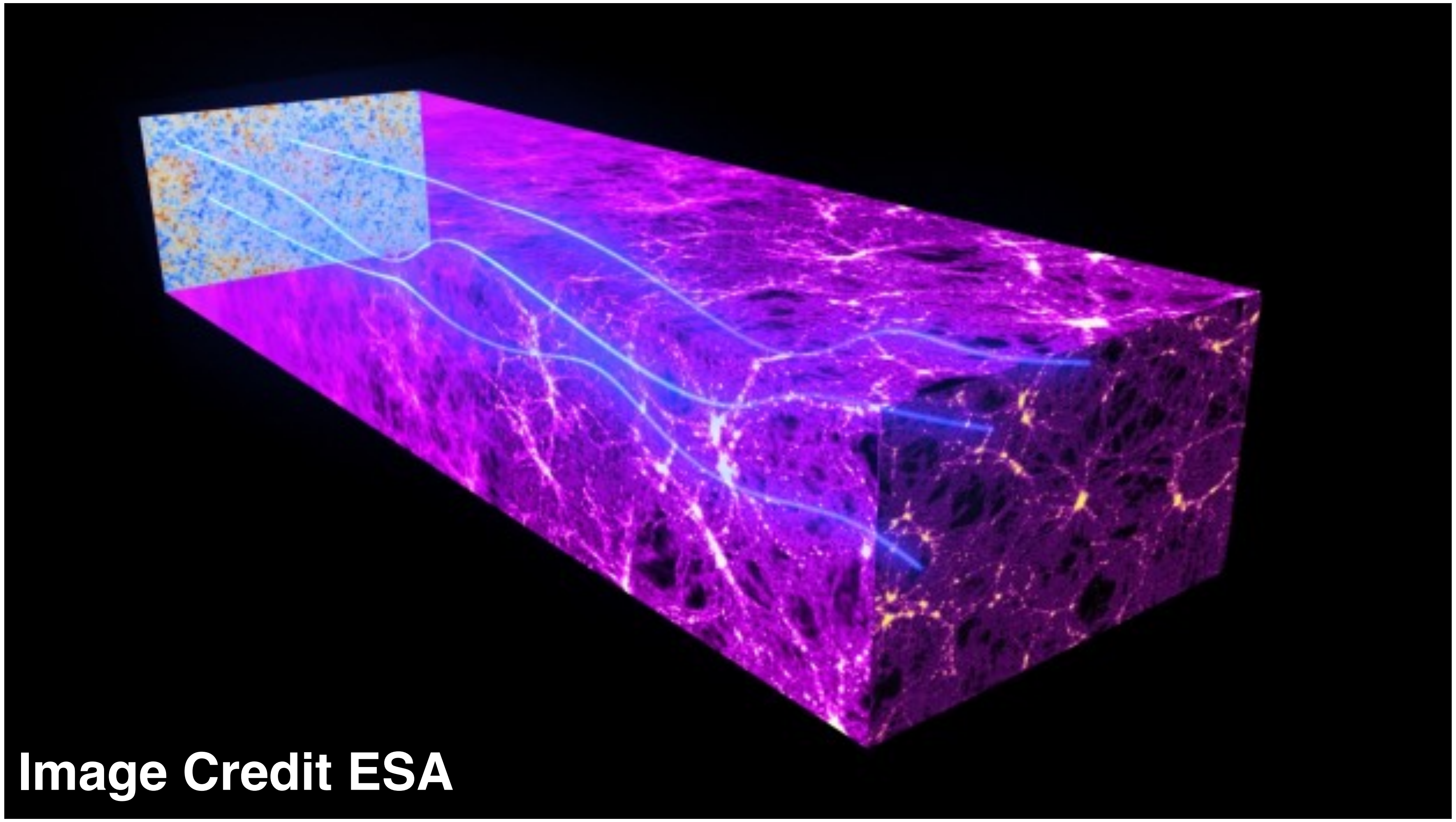
This happens because neutrinos travel very fast and therefore cannot fall in gravitational potentials. The effect of this smoothing is proportional to Ω_ν

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:

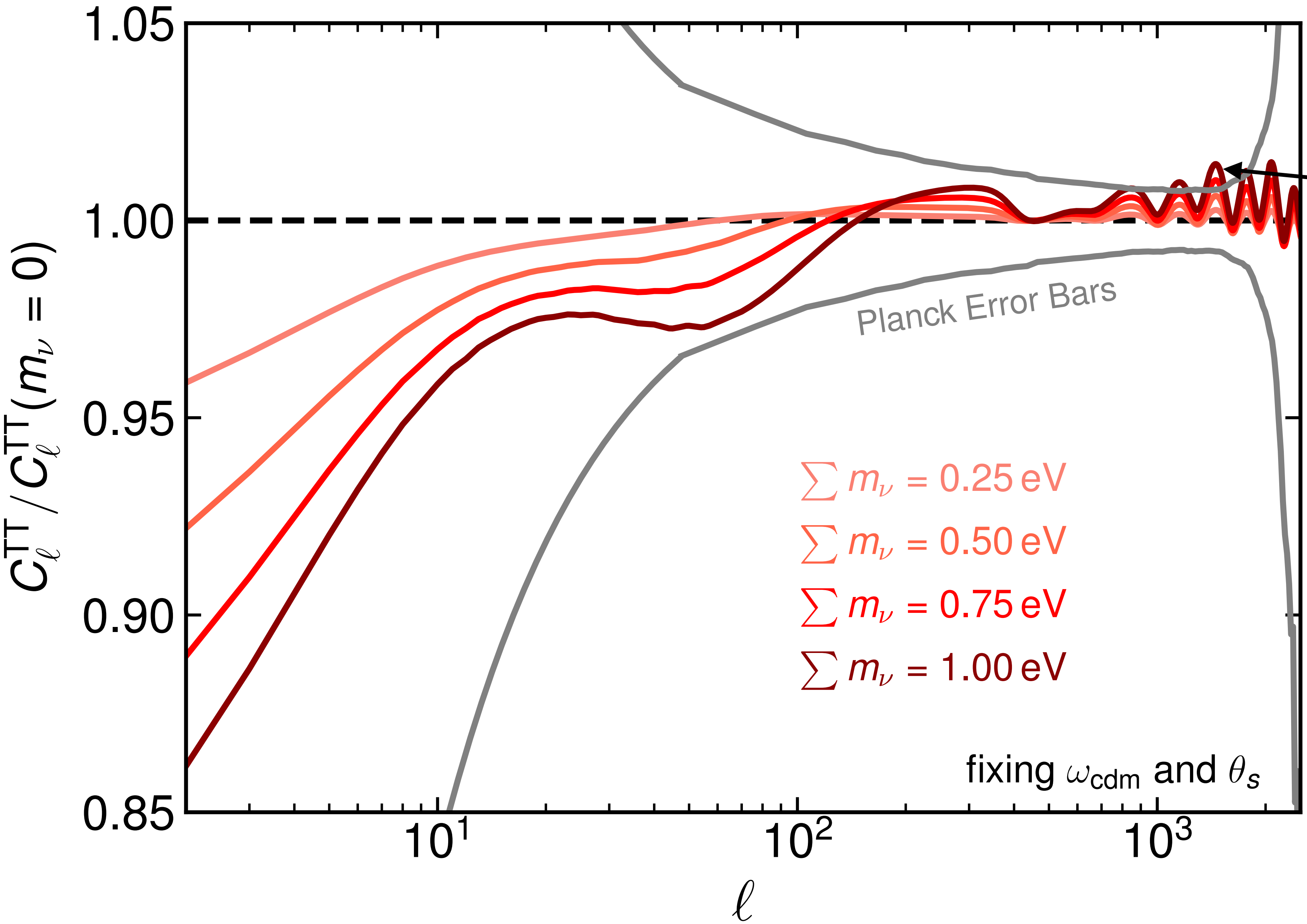


The larger the neutrino mass the less is the CMB light lensed!

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

The effect of neutrino masses in the CMB:



Main constraining power

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

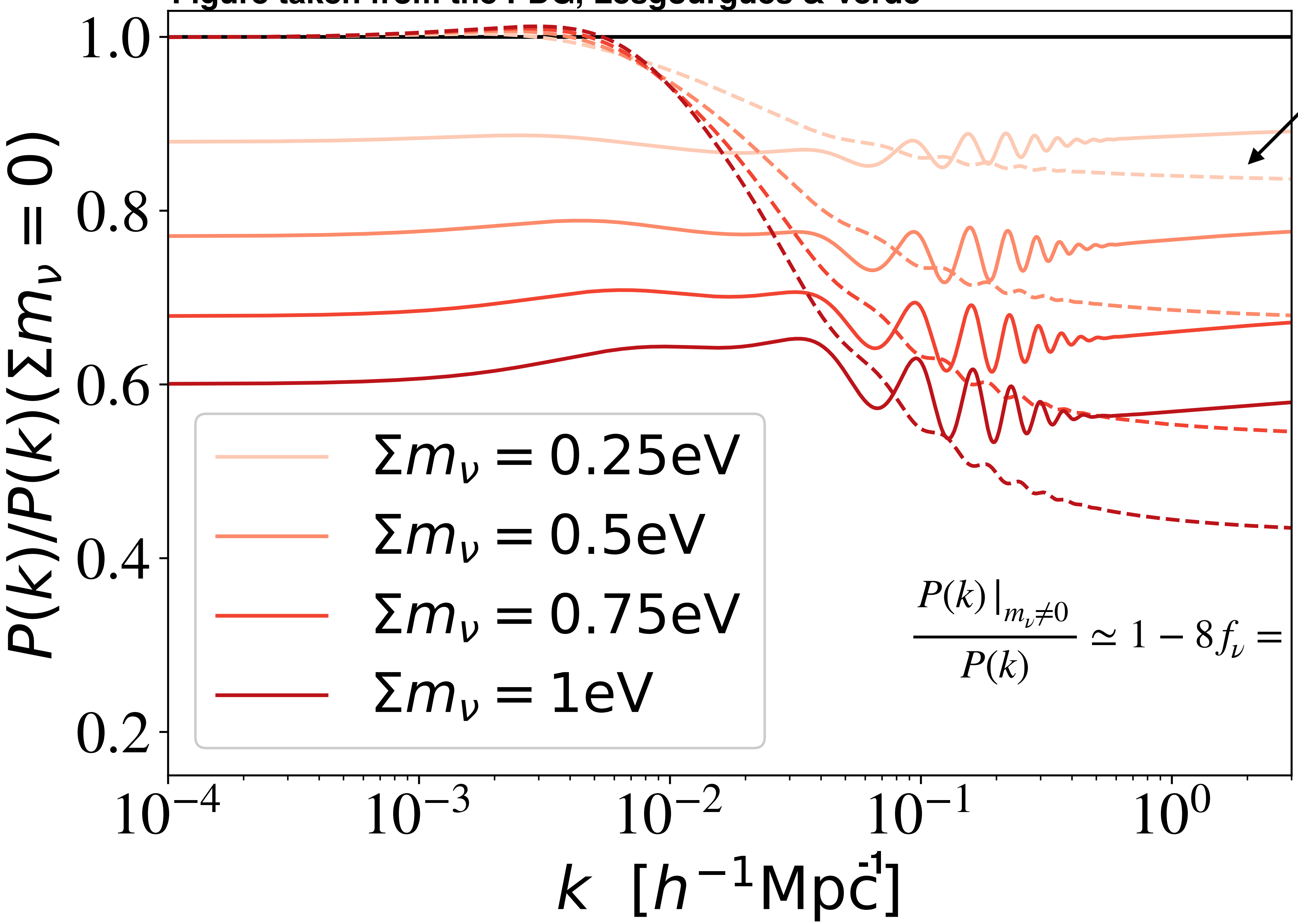
(95 % CL, TT+lowE)

Neutrino Masses in Cosmology

Galaxy Surveys

Suppression from $\Omega_\nu h^2$

Figure taken from the PDG, 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 $N_{\rm eff}$** Planck 1807.06209	ΛCDM+m_ν+$N_{\rm eff}$
$\sum m_\nu < 0.17\,\mathrm{eV}$	**Varying $N_{\rm eff}$+ω+α_s+m_ν** di Valentino et al. 1908.01391	CDM+m_ν+$N_{\rm eff}$+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

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

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

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

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

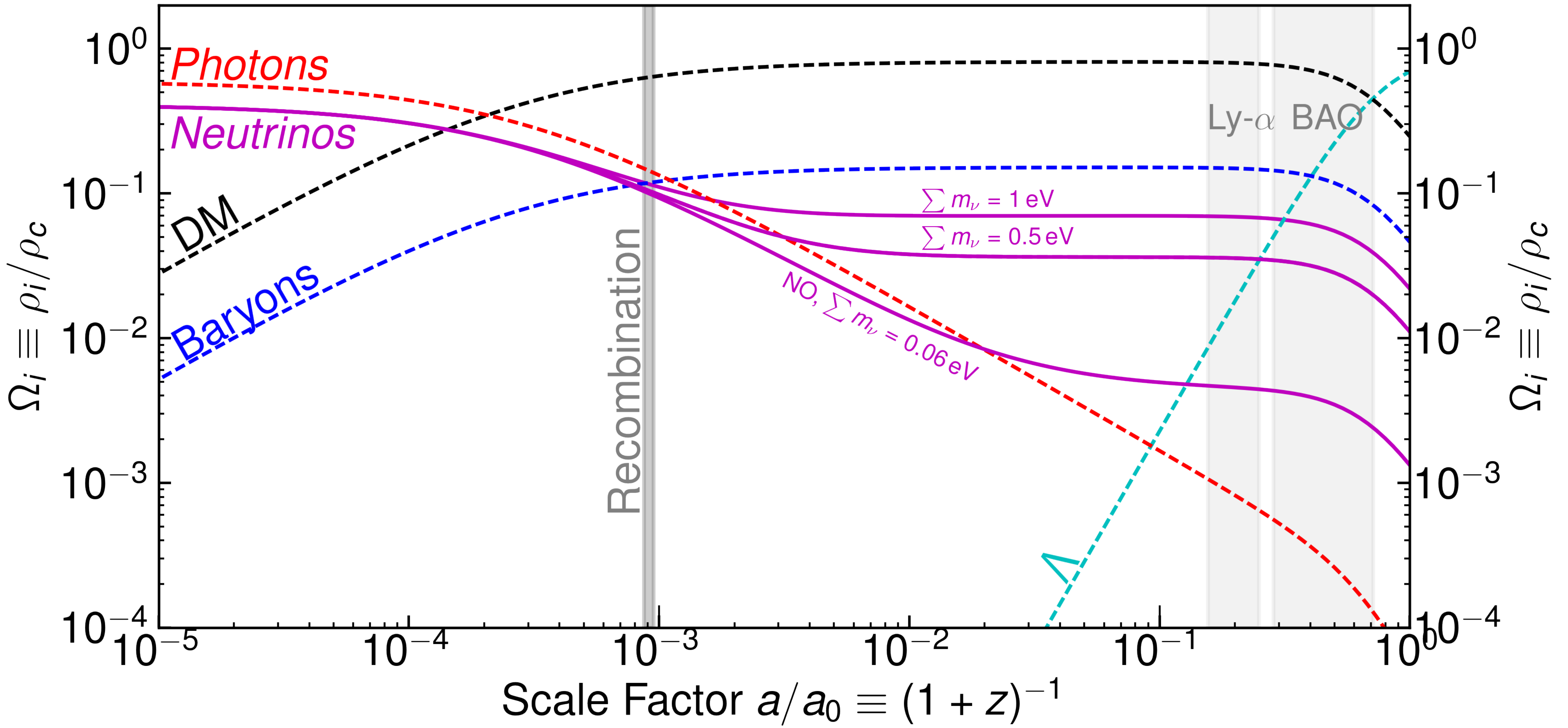
$$\sum m_\nu < 3\,\mathrm{eV}$$

Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.14870

- **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:

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

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

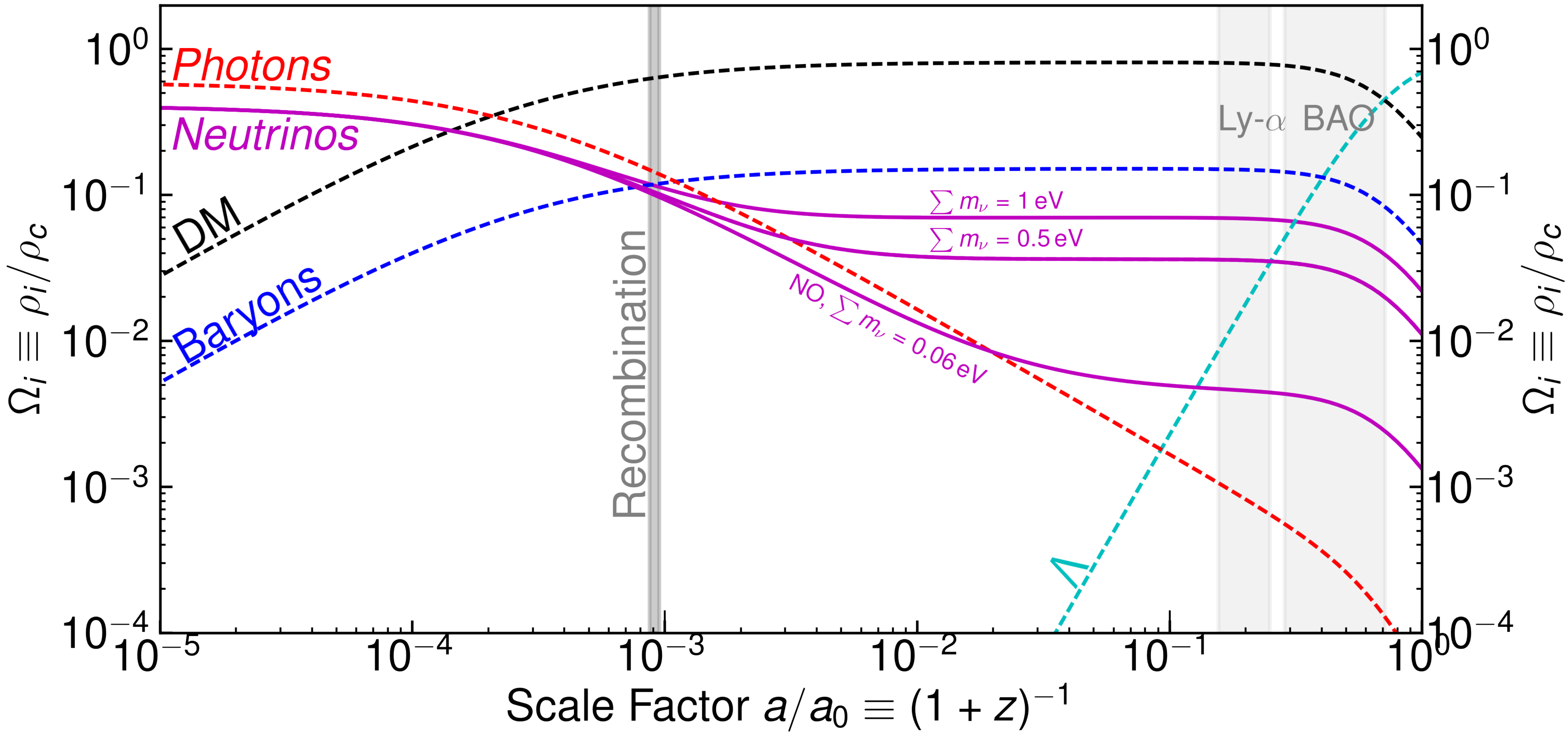
Comoving sound horizon (Early Universe)

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

Comoving angular diameter distance (Late Universe)

Massive neutrinos → $H(z')$

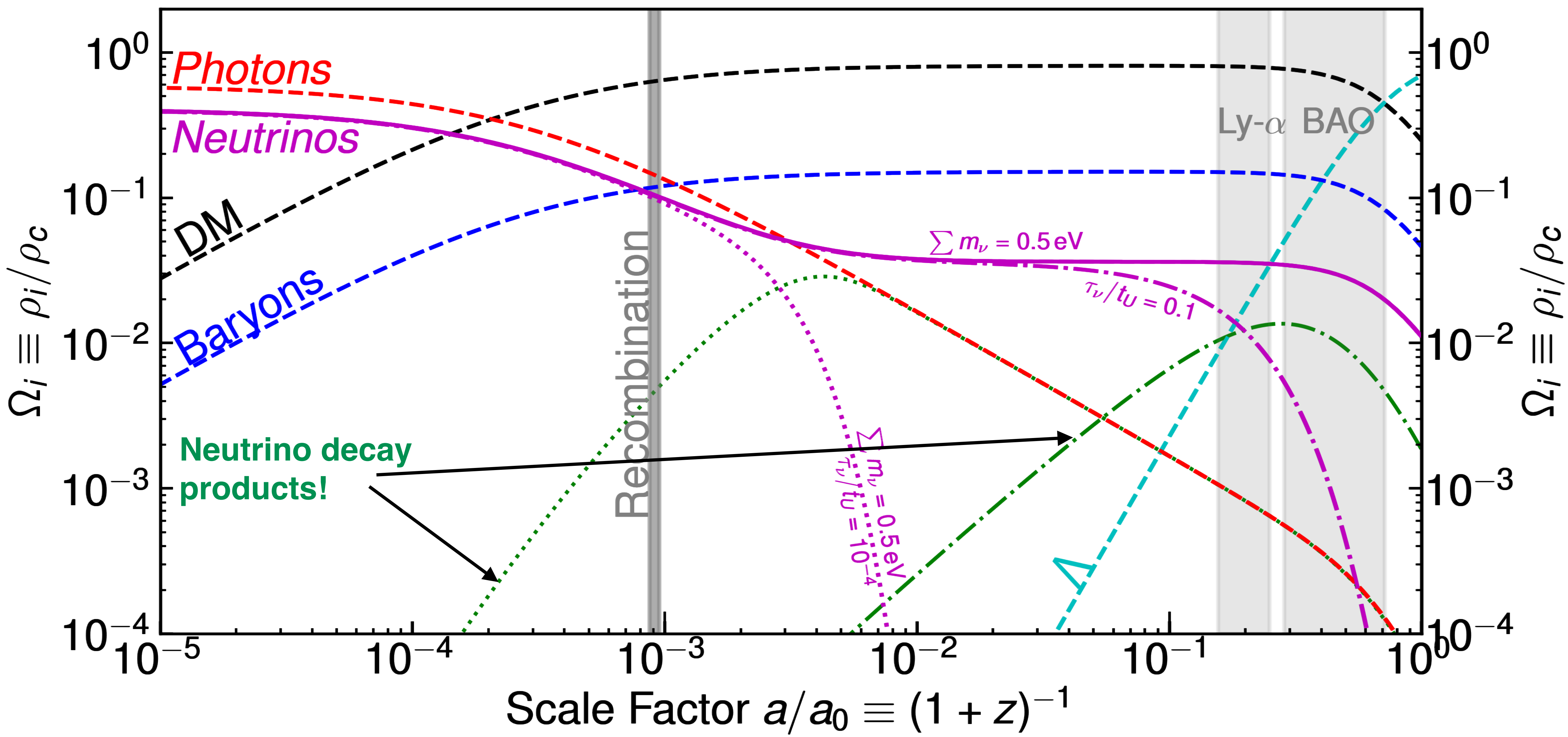
Neutrino Masses from Cosmology



Not only a background effect:

Massive neutrinos also affect CMB lensing $\propto$ Ω_ν

Neutrino Decays



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

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Oldengott, Wong et al. 2203.09075 & 2011.01502
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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
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$$\sum m_\nu < 3\,\mathrm{eV}$$

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Alvey, Escudero & Sabti 2111.14870

Take Away Messages:

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

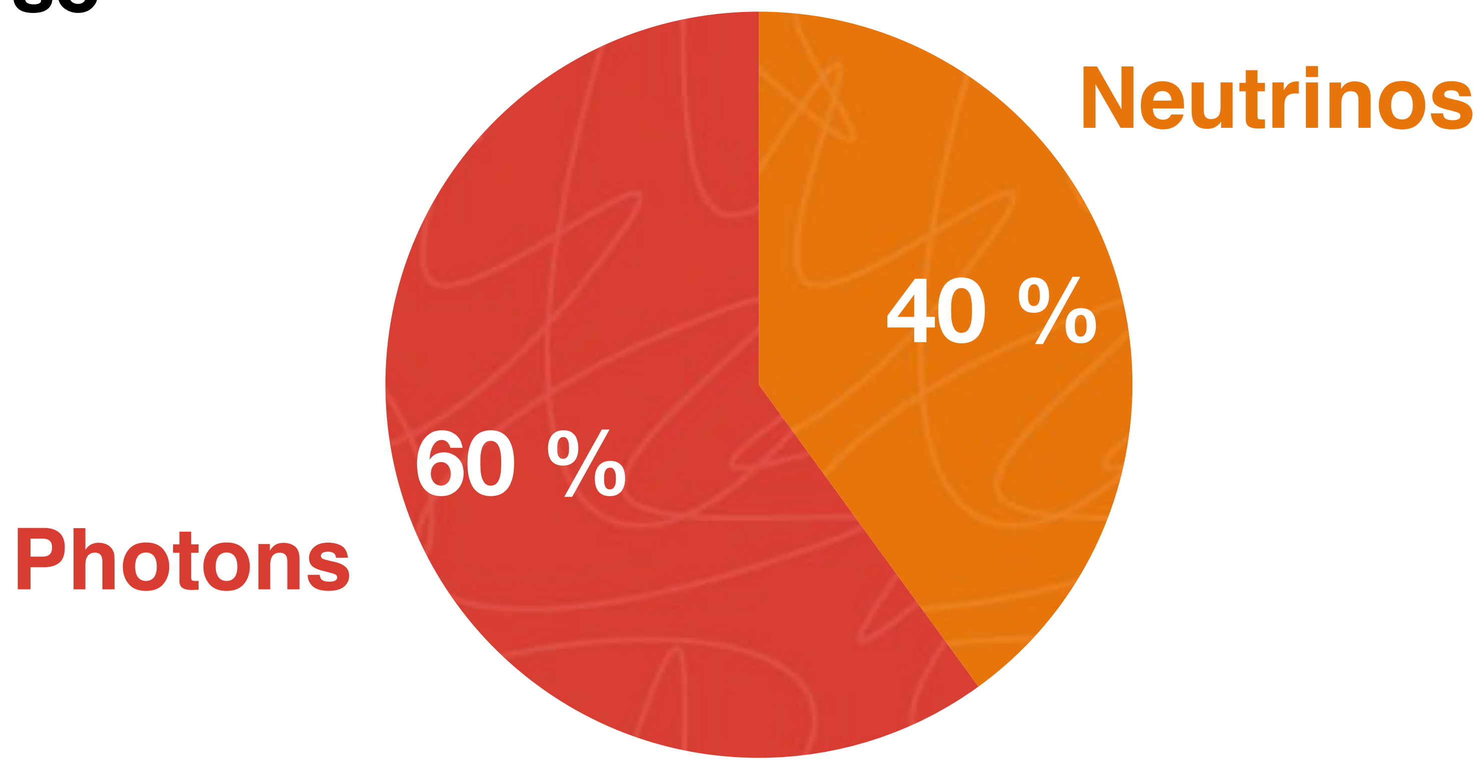
— Of course, in ΛCDM there is a direct link between $\Omega_\nu(z)$ and m_ν

— 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**

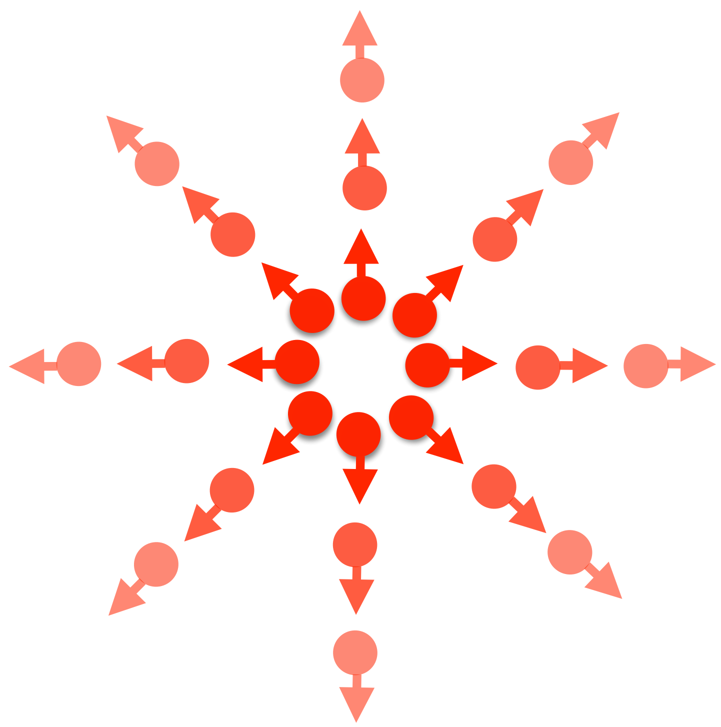
$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$ **Background expansion: Neff**

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

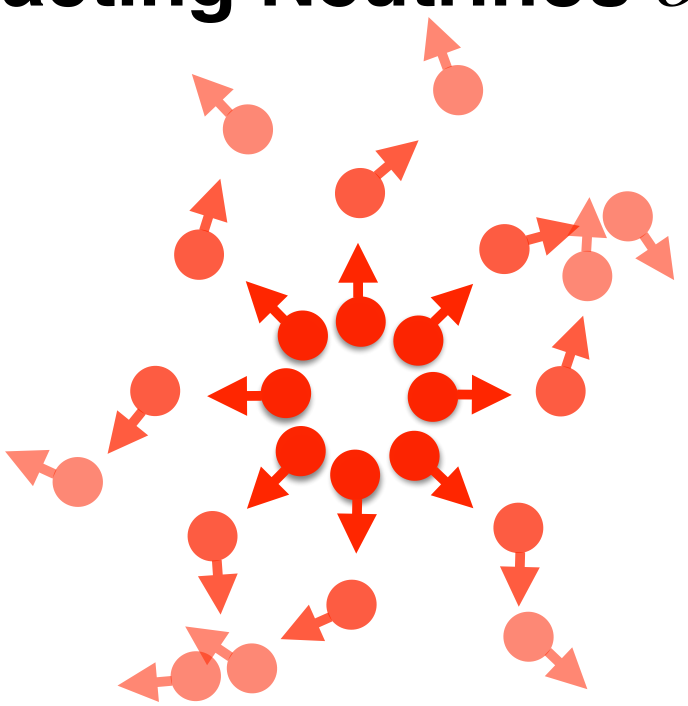
Neutrino anisotropic stress — **Metric** — **CMB spectra**

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

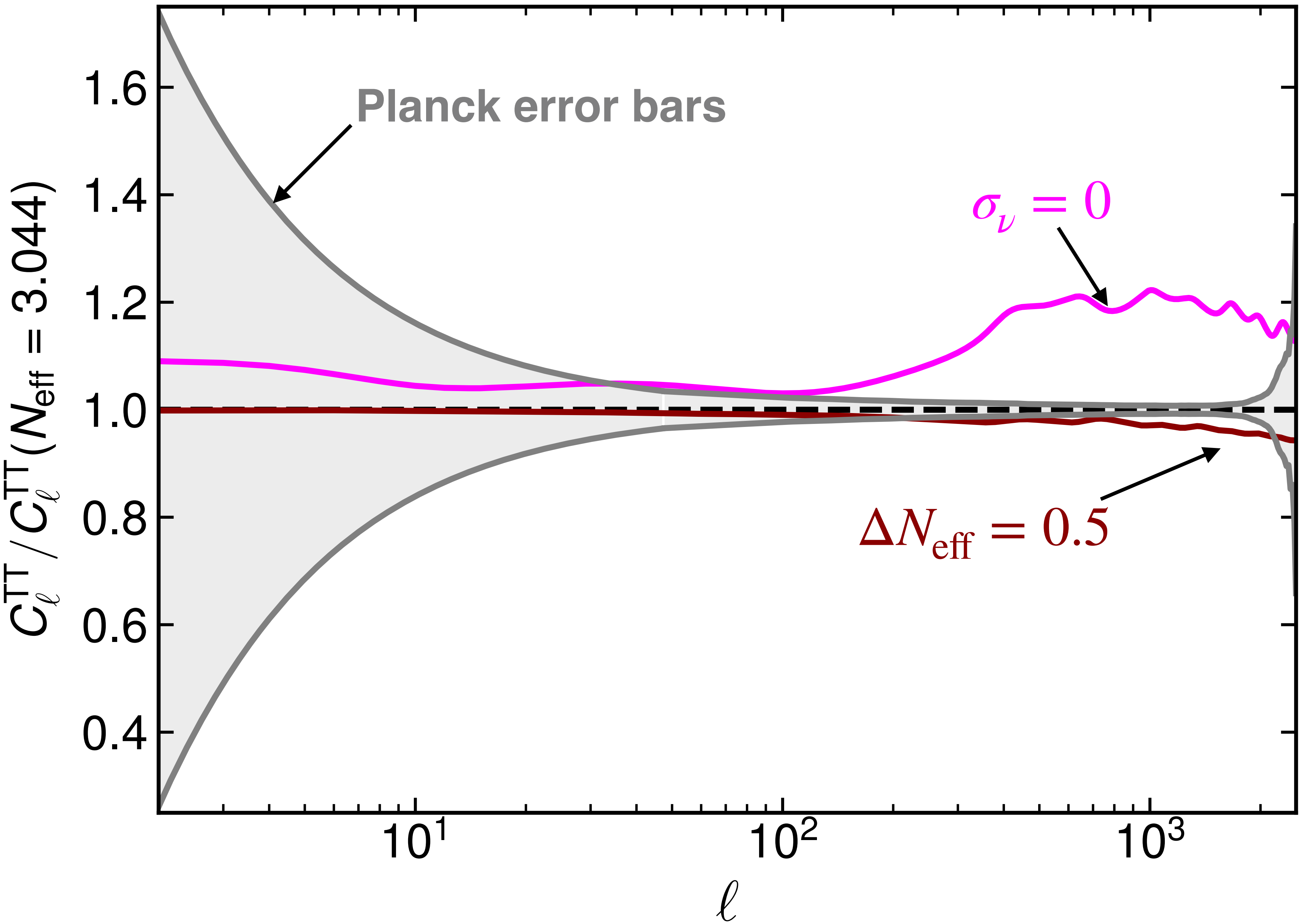
Free Streaming Neutrinos $\sigma_\nu \neq 0$



Interacting Neutrinos $\sigma_\nu \to 0$

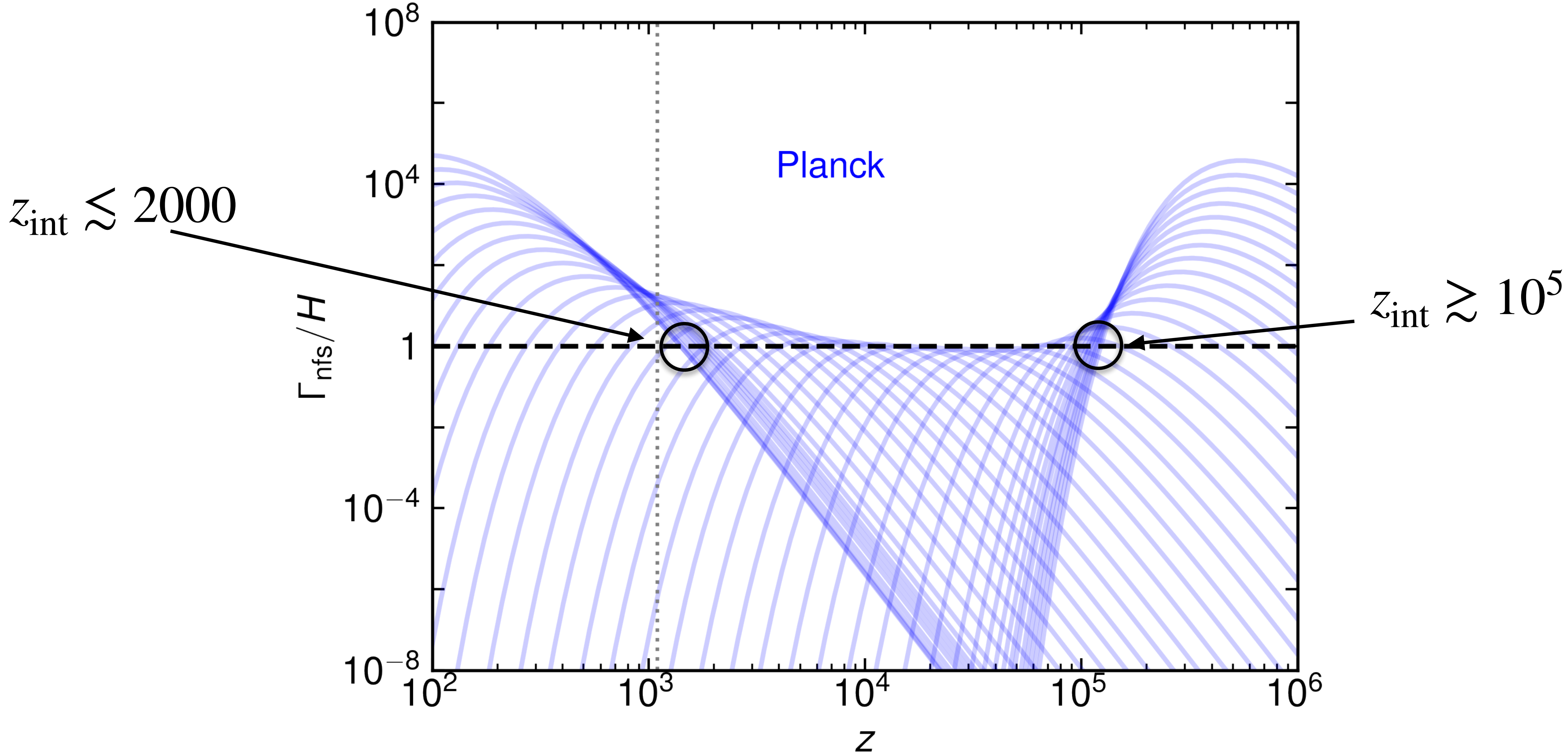


Effect of Neutrino Free-streaming in the CMB



The Neutrino Freestreaming window

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



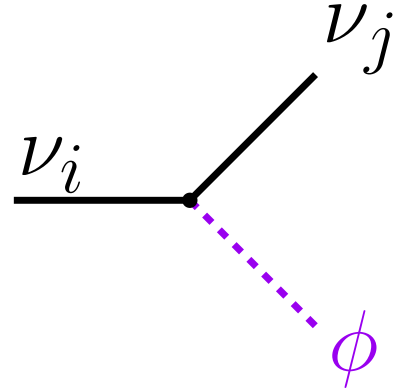
This analysis reinforces the fact that neutrino free streaming cannot be suppressed in

$$2000 \lesssim z_{\rm int} \lesssim 10^5$$

$$0.3\,\text{eV} \lesssim T_\nu \lesssim 15\,\text{eV}$$

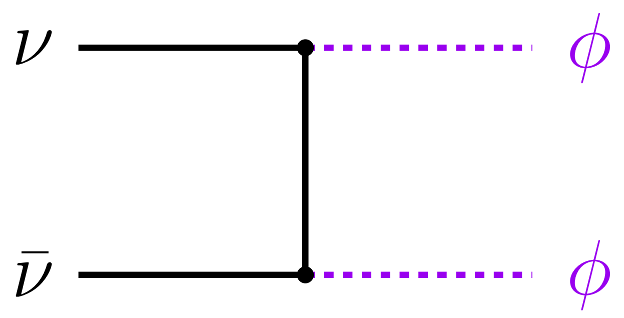
Models

Neutrino Decays



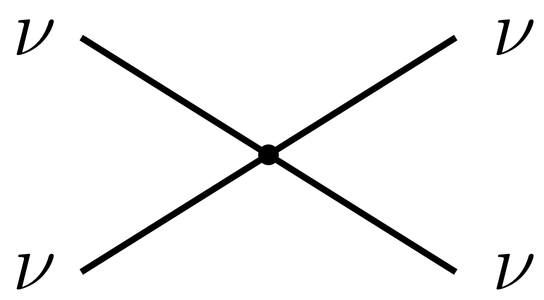
Hannestad & Raffelt [hep-ph/0509278]
Basboll, Bjaelde, Hannestad & Raffelt [0806.1735]
Escudero & Fairbairn [1907.05425]
Chacko, Dev, Du, V. Poulin and Y. Tsai [1909.05275]
Barenboim, Chen, Hannestad, Oldengott, Tram & Wong [2011.01502]
Abellán, Chacko, Dev, Du, Poulin & Tsai [2112.13862]
Chen, Oldengott,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

Neutrino Annihilations



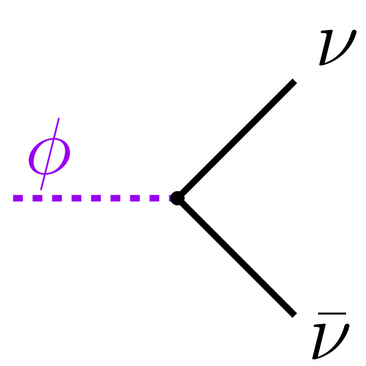
Beacom, Bell & Dodelson [astro-ph/0404585]
Hannestad [astro-ph/0411475]
Archidiacono & Hannestad [1311.3873]
Forastieri, Lattanzi & Natoli [1904.07810]

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]

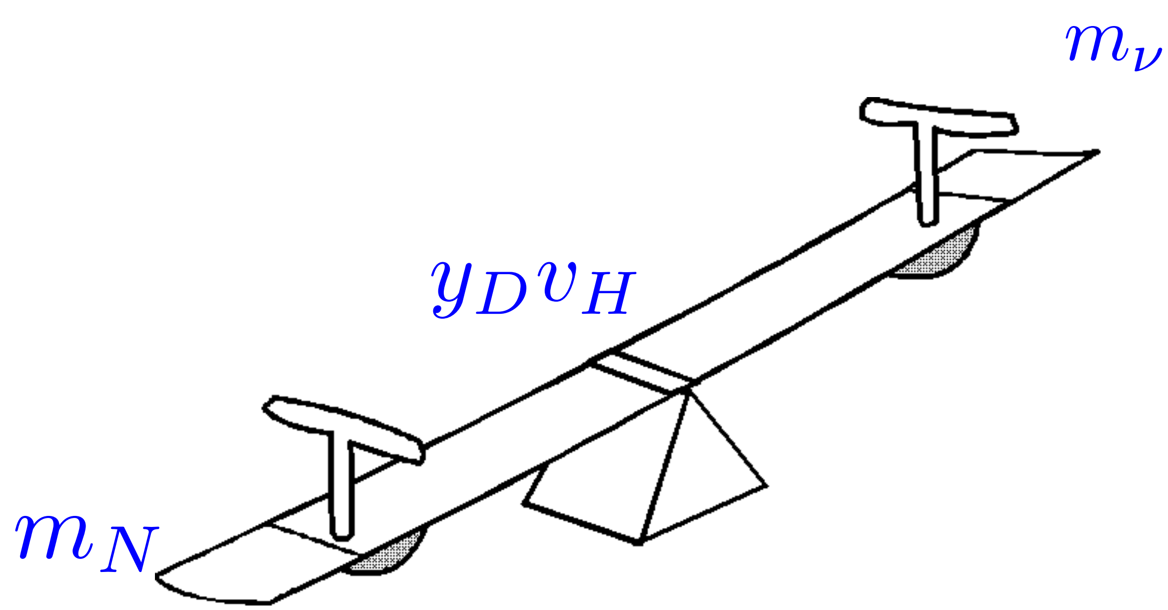
eV-scale neutrinophilic bosons



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

The case of the Majoron

Type-I seesaw



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

Are There Real Goldstone Bosons Associated with Broken Lepton Number? #3

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)

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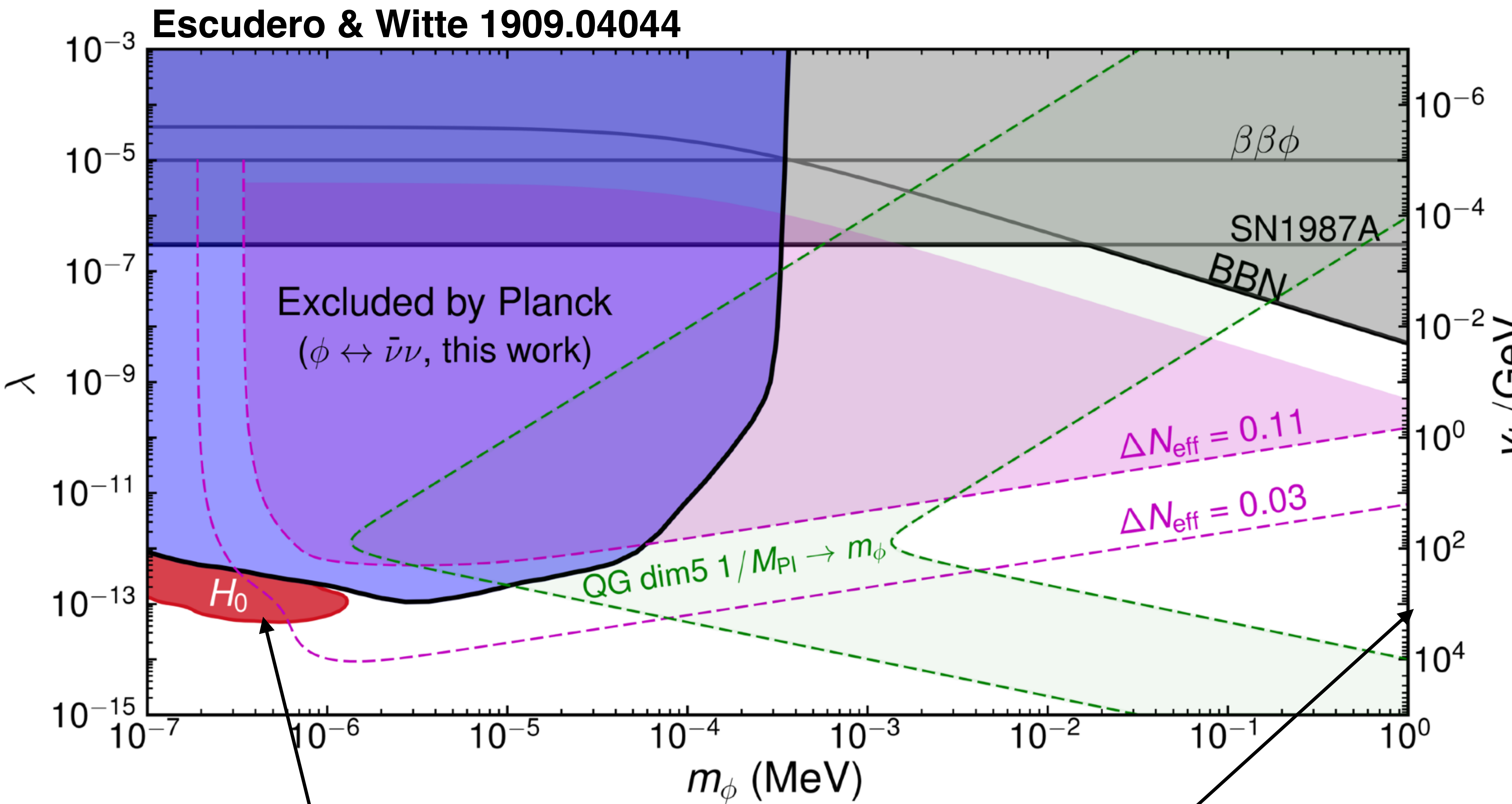
The Majoron is the pseudo-Goldstone boson associated with the spontaneous breaking of $U(1)_L$

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

The case of the Majoron



- **CMB observations can test a well motivated neutrino mass model up to TeV scales!**
- **The model features an enhanced expansion history and together with the majoron-neutrino interactions can ameliorate the Hubble tension**

Recent Anomalous Helium Measurement

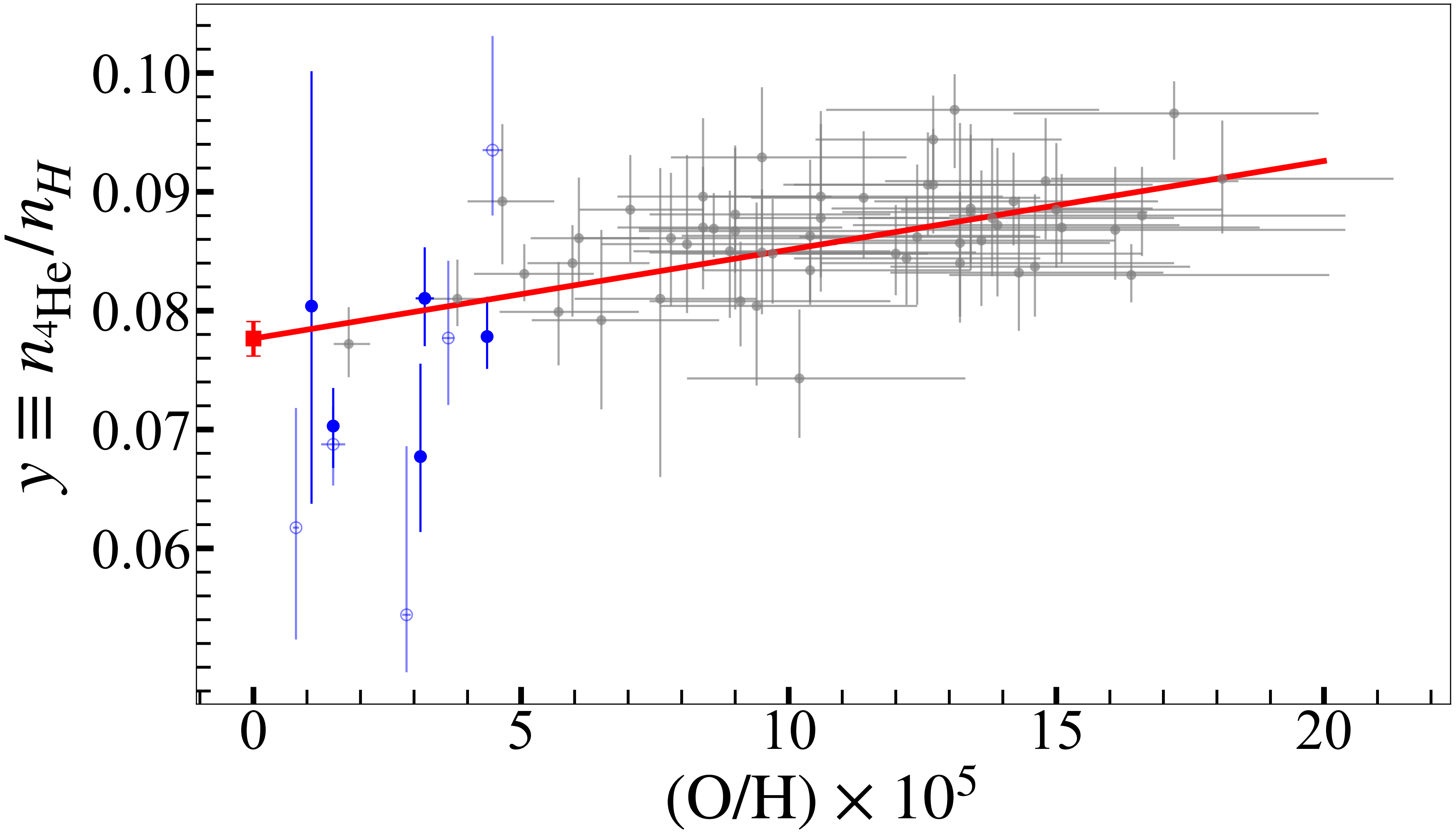
The EMPRESS collaboration reported a Primordial Helium abundance smaller than the SM value by 3 sigma

$$Y_P \equiv \frac{\rho_{^4\mathrm{He}}}{\rho_b}$$

$Y_P = 0.2370(34)$ **Matsumoto et al. [2203.09617]**

$Y_P^{\mathrm{SBBN}} = 0.2471(02)$ **Pitrou et al. [1801.08023]**

There are several other recent Yp determinations that are in agreement with the SM but their new measurement is interesting because they have 5 new extremely metal poor systems:



Primordial Lepton Asymmetries

The simplest BSM interpretation of a lower value of the primordial helium abundance is the presence of a non-zero lepton asymmetry in electron neutrinos at the time of BBN

Matsumoto et al. [2203.09617] Burns, Tait & Valli [2206.00693] Escudero, Ibarra & Maura [2208.03201]

Some basics about lepton asymmetries:

The lepton asymmetries are parametrized with a comoving neutrino chemical potential:

$$\xi_\nu \equiv \mu_\nu / T_\nu \qquad \frac{n_{\nu_e} - n_{\nu_{\bar{e}}}}{n_\gamma} \simeq 0.25 \times \xi_{\nu_e}$$

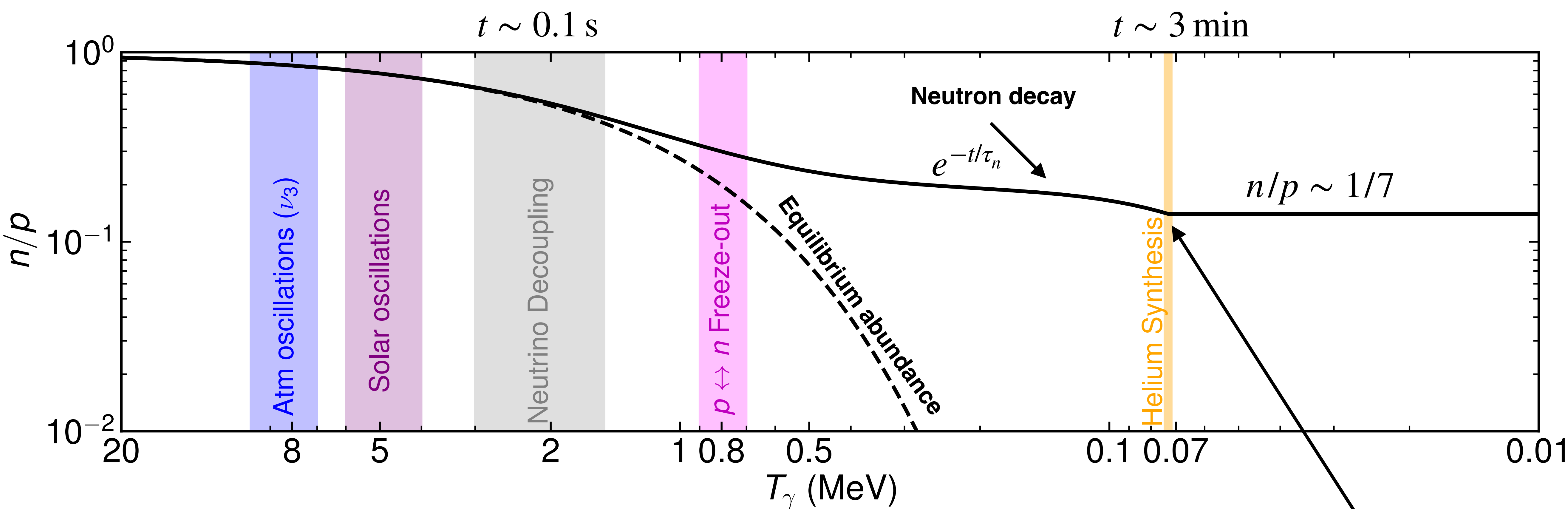
Neutrinos start to oscillate at $T \sim 8\,\mathrm{MeV}$

This means that $|\xi_{\nu_e}| \simeq |\xi_{\nu_\mu}| \simeq |\xi_{\nu_\tau}|$ **by the time of BBN**

see e.g.: 0809.0631 Iocco, Mangano, Miele, Pisanti & Serpico

This implies that a constraint on ξ_{ν_e} **generically applies to** $\xi_{\nu_{\mu/\tau}}$

Primordial Helium and ν_e-Asymmetry



The key processes

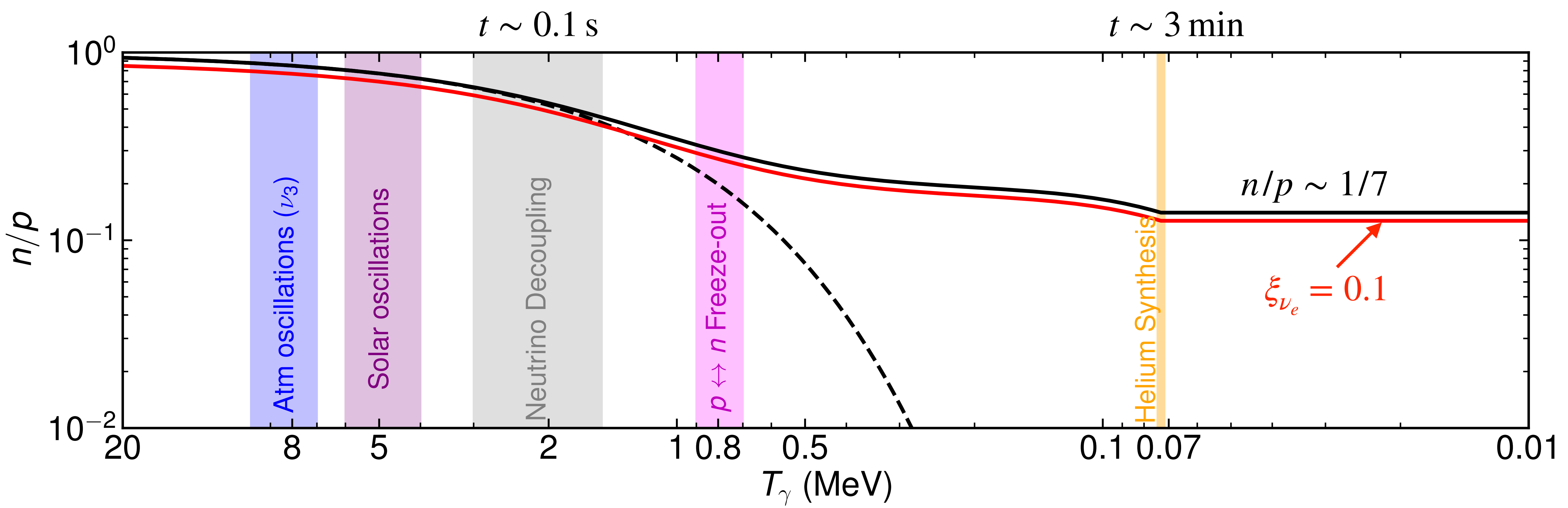
$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

$$n + \nu_e \leftrightarrow p + e^-$$

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

$$Y_{\rm P} \simeq \left. \frac{2n/p}{1+2n/p} \right|_{T=T_{\rm BBN}}$$

Primordial Helium and ν_e-Asymmetry



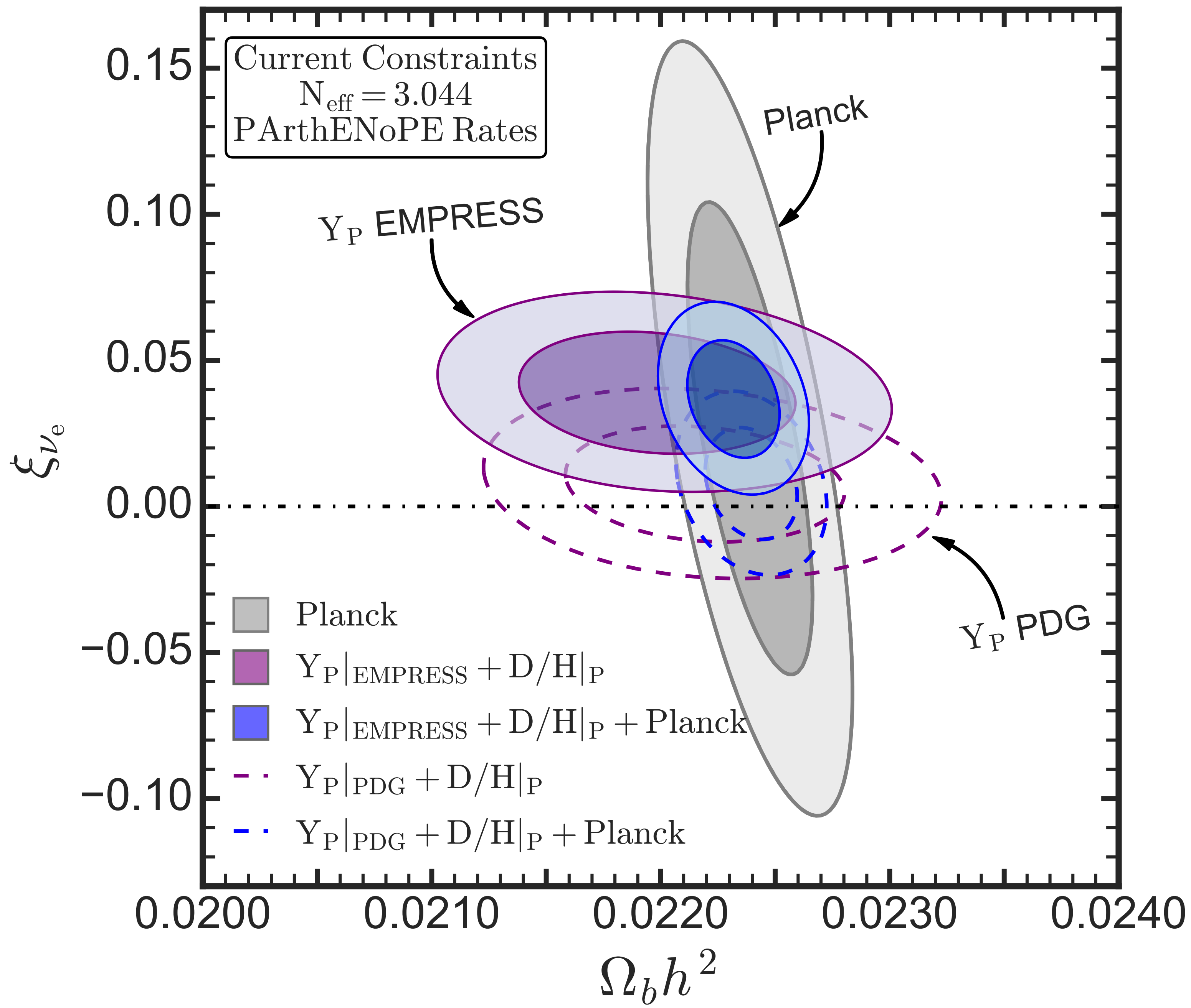
The key processes

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

$$Y_\mathrm{P} \simeq \left.\frac{2n/p}{1+2n/p}\right|_{T=T_\mathrm{BBN}}$$

ν_e-Asymmetry: Current Status

Escudero, Ibarra & Maura [2208.03201] (to appear in PRD)

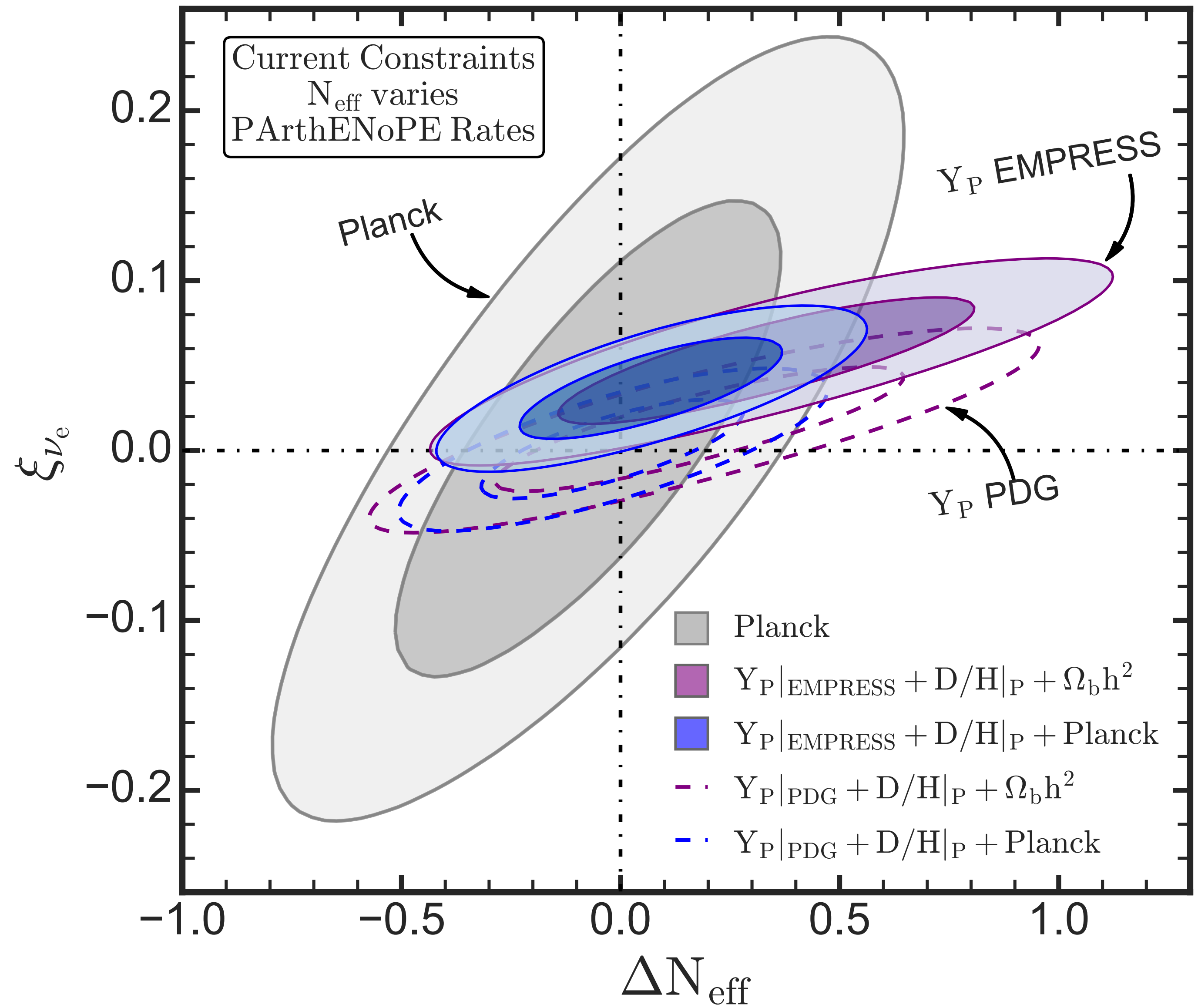


Planck is compatible with a zero lepton asymmetry

The preference for a non-zero asymmetry is driven only by EMPRESS. Taking the PDG-21 recommended value points to $\xi_{\nu_e} = 0$

ν_e-Asymmetry: Current Status

Escudero, Ibarra & Maura [2208.03201] (to appear in PRD)



The presence of a non-zero $\Delta N_{\rm eff}$ changes the inference on ξ_{ν_e}

Taking EMPRESS: Preference for $\xi_{\nu_e} > 0$:

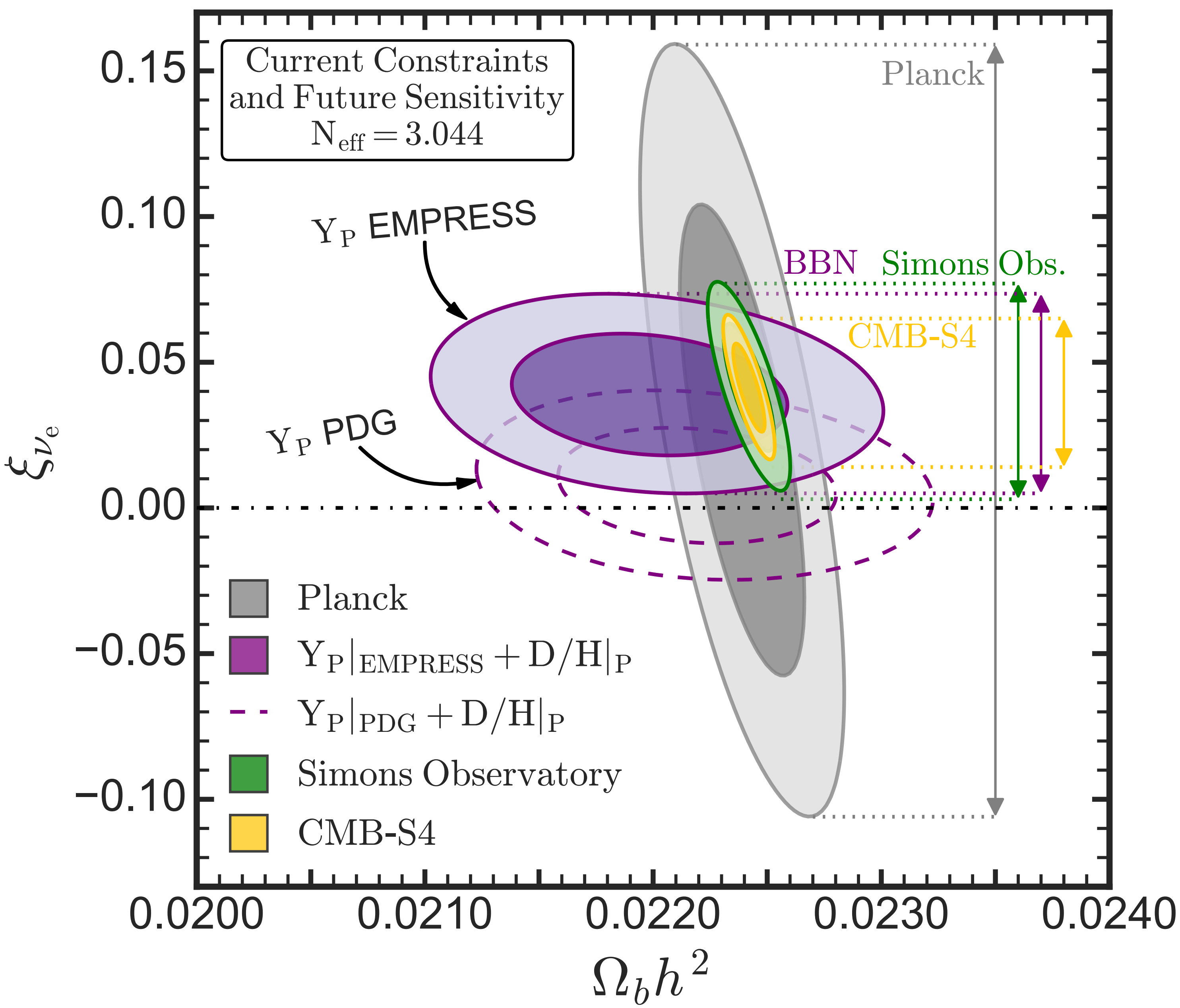
2.9σ **Fixed Neff = 3.044**

1.9σ **Varying Neff**

2.9σ **Varying Neff but with $\Delta N_{\rm eff} > 0$**

ν_e-Asymmetry: Future Sensitivity

Escudero, Ibarra & Maura [2208.03201] (to appear in PRD)

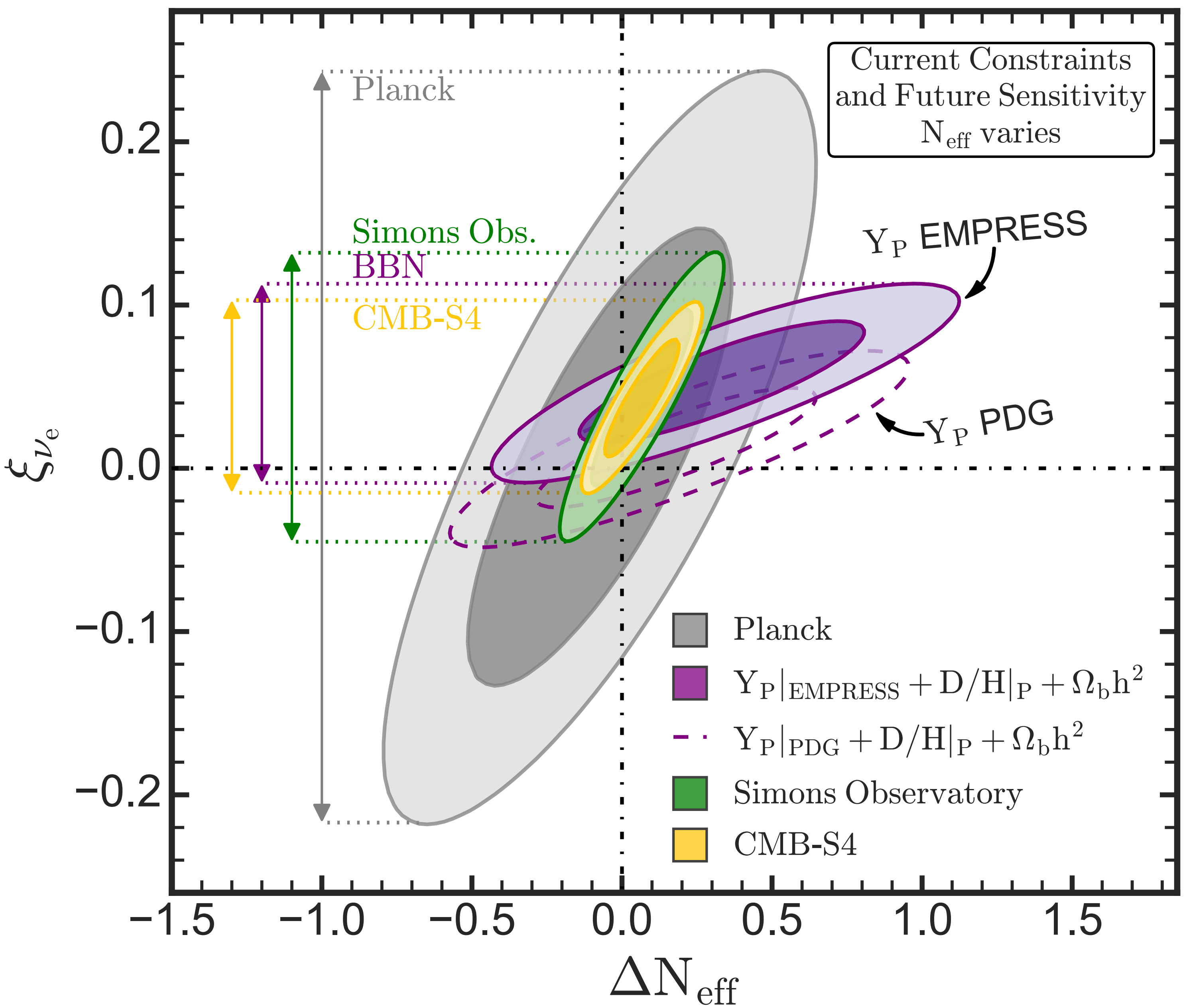


Simons will reach a similar sensitivity than current BBN analyses. CMB-S4 will do even better:

EMPRESS: 2.9σ **EMPRESS+Simons:** 4.3σ **EMPRESS+CMB-S4:** 5.2σ

ν_e-Asymmetry: Future Sensitivity

Escudero, Ibarra & Maura [2208.03201] (to appear in PRD)



With $\Delta N_{\rm eff}$ it will be harder to break the degeneracies, even with Simons or CMB-S4. The tension will have low significance

EMPRESS: 1.9σ **EMPRESS+Simons:** 2.8σ **EMPRESS+CMB-S4:** 3.1σ

Conclusions

Neutrino Masses:

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

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

Unstable neutrinos are a plausible particle physics possibility

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

Neutrino Asymmetries:

The EMPRESS survey has recently reported an anomalously low Helium abundance

We have performed a global BBN and CMB analysis showing:

$$\frac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} \sim 1\,\%$$

Outlook

Neutrino Masses:

KATRIN reach: $\sum m_\nu < 0.6\,\mathrm{eV}$ **(90% CL)**

Next generation of 0ν2β experiments, e.g. LEGEND: $m_{\beta\beta} \sim 0.02 - 0.04\,\mathrm{eV}$

JUNO/DUNE expected to determine the neutrino ordering

Next Galaxy Surveys+CMB should detect neutrino masses

e.g.: 1308.4164 Font-Ribera et al., 1408.7052 Kitching et al.

DESI/EUCLID+Planck: $\sigma\left(\sum m_\nu\right) \simeq 0.02\,\mathrm{eV}\ \ (1\,\sigma)$

Lepton Asymmetries:

Simons Observatory in ~ 6 years: $\sigma(\xi_{\nu_e}) = 0.014$, $\sigma(N_{\rm eff}) = 0.06$

CMB-S4 in >10 years $\sigma(\xi_{\nu_e}) = 0.010$, $\sigma(N_{\rm eff}) = 0.03$

Should be able to clarify the situation independently on local measurements.

Of course, further scrutiny is needed in the local measurements that are currently dominated by systematic effects

What about BSM models?

Time for Questions and Comments

Upcoming years are going to be exciting!

Thank you for your attention!

miguel.escudero@cern.ch