A 2024 Perspective on Neutrino Cosmology

Miguel Escudero Abenza

miguel.escudero@cern.ch

CERN

DISCRETE 2024

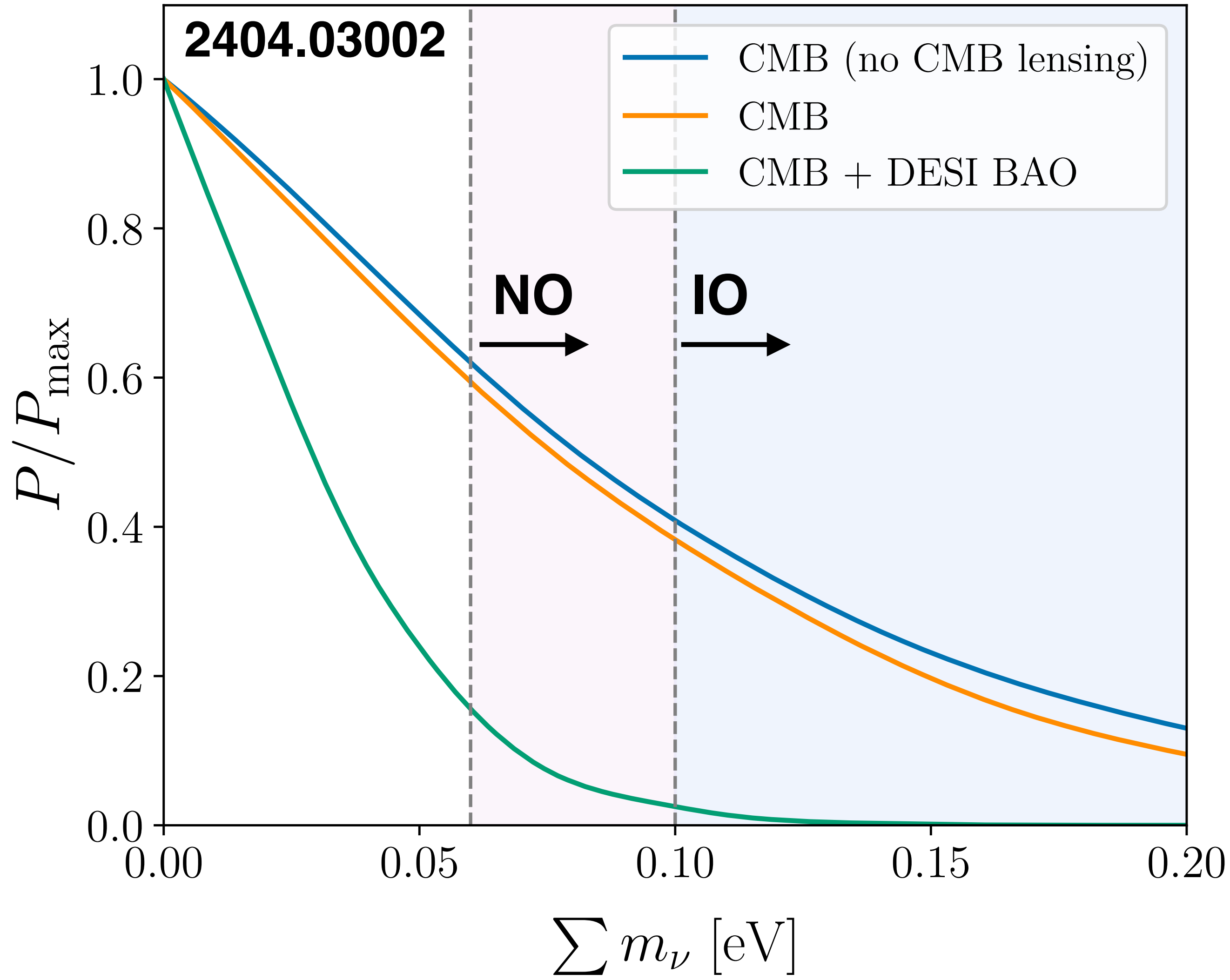
03-12-2024

The Context

On April 2024, the DESI collaboration presented the cosmological results from their 1st year of observations. The results have key implications for the neutrino mass.

$$\sum m_\nu < 0.082\,\mathrm{eV}$$ **(95 % CL, CMB+BAO-DESIY1)**

[2404.03002] DESI collaboration [2411.12022]



To be compared with the latest laboratory limit from the KATRIN experiment [2406.13516]:

$$\sum m_\nu < 1.5\,\mathrm{eV}$$ **(95 % CL)**

and the bound from Planck+SDSS [1807.06209]

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

Implications

- **Theory:** Many neutrino mass models have large regions of parameter space with $\Sigma m_\nu > 0.073$ eV.

  In fact, most of the 2-zero neutrino mass textures predict $\Sigma m_\nu > 0.17$ eV.

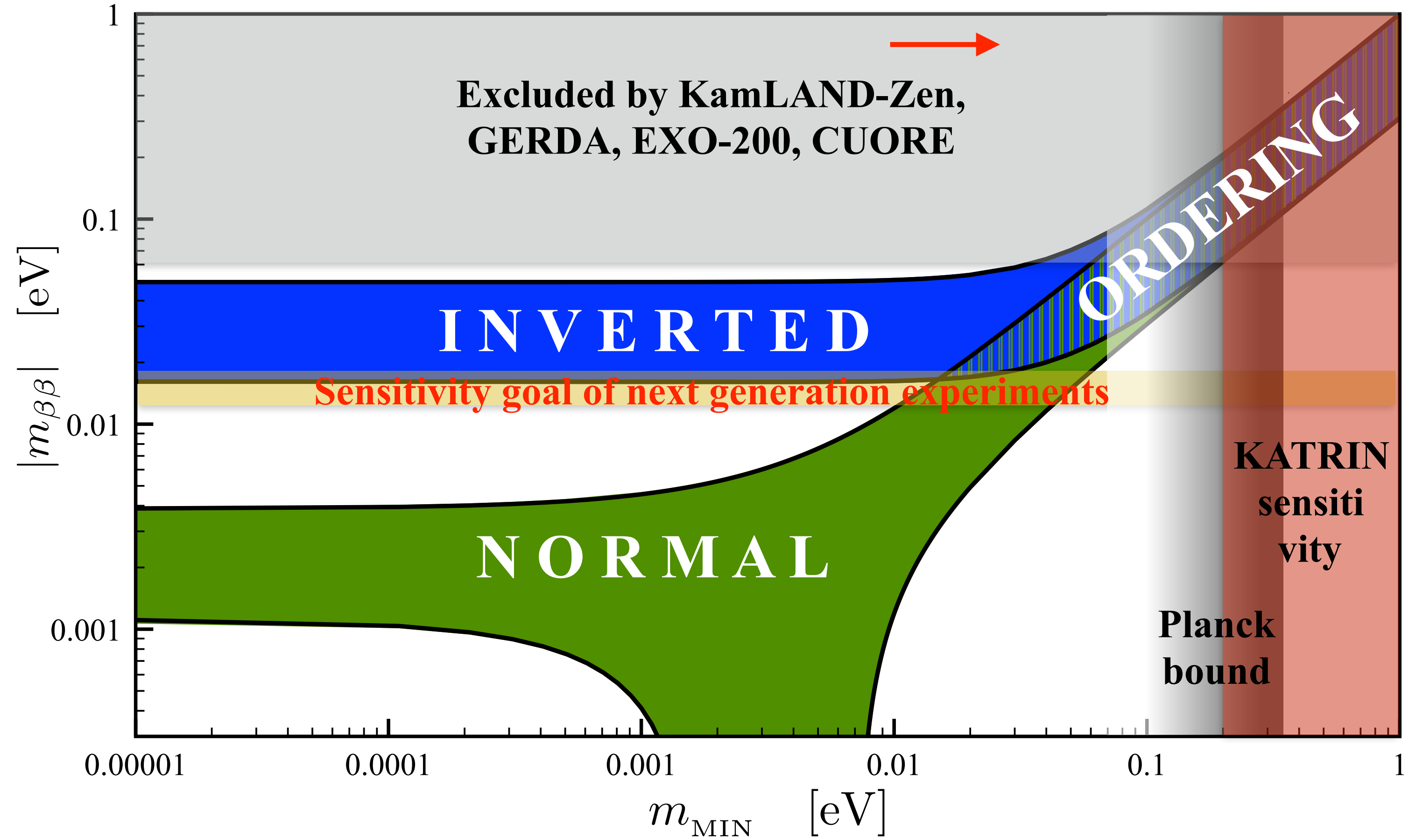
  See e.g. Alcaide, Santamaría & Salvadó, 1806.06785.

- **Experiment:** Detection prospects for $m_{\bar{\nu}_e}$ and $m_{\beta\beta}$ are strongly dependent upon $m_{\nu_{\text{lightest}}}$ or equivalently $\sum m_\nu$

$0\nu\beta\beta$ decay:

APPEC Report: Pascoli et al. 1910.04688

Ruled out in ΛCDM



The Plan/Outline

1) Understand what we actually know about neutrinos in cosmology

2) Critically asses the current cosmological bound on the neutrino mass

see: Craig et al. [2405.00836], Green & Meyers [2407.07878] Choudhury & Okumura [2409.13022]
Jiang et al. [2407.18047], Allali & Notari [2406.14554] Elbers, Frenk, Jenkins & Pascoli [2407.10965]
Wang, Mena Di Valentino & Gariazzo [2405.03368] Loverde & Weiner [2410.00090]
Bartolez, Esteban, Hajjar, Mena, Salvado [2411.14524]

(comprehensive profile likelihood analysis of the neutrino mass in cosmology)

2407.13831: Living at the Edge: A Critical Look at the Cosmological Neutrino Mass Bound

Daniel Naredo-Tuero [1,*] Miguel Escudero [2,†]
Enrique Fernandez-Martinez [1,‡] Xabier Marcano [1,§] and Vivian Poulin [3,¶]

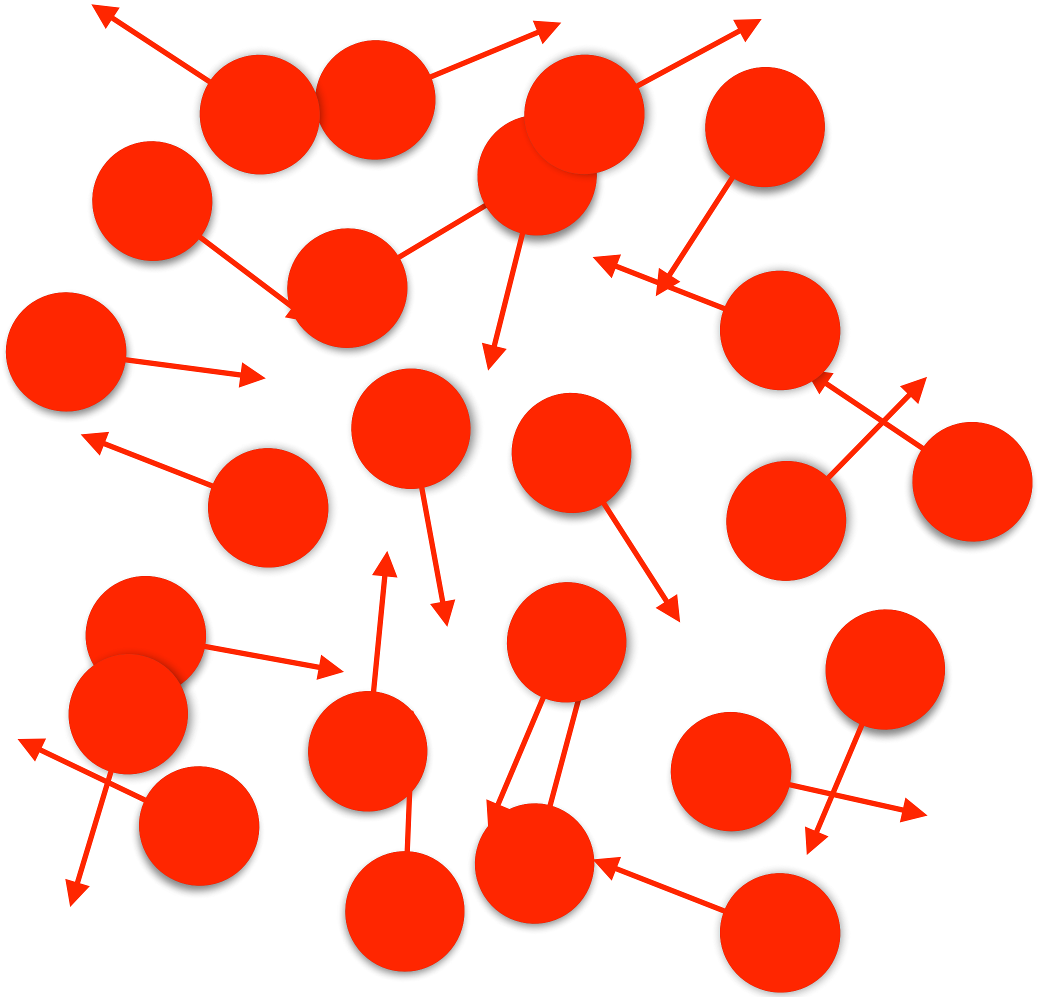
tools: CLASS & MontePython, Lesgourgues et al. Minimizer: *Procoli* Karwal et al. 2401.14225

3) Discuss the potential BSM implications of a cosmological neutrino mass bound that is in tension with the laboratory

Neutrino decays, non-standard neutrino backgrounds, annihilations, late phase transitions, time dependent masses, refractive neutrinos …

Formation of the CNB

At a time $\sim 0.1\,\mathrm{s}$ after the Big Bang when the Universe had a temperature of around $T \sim 2\,\mathrm{MeV}$ the Cosmic Neutrino Background formed



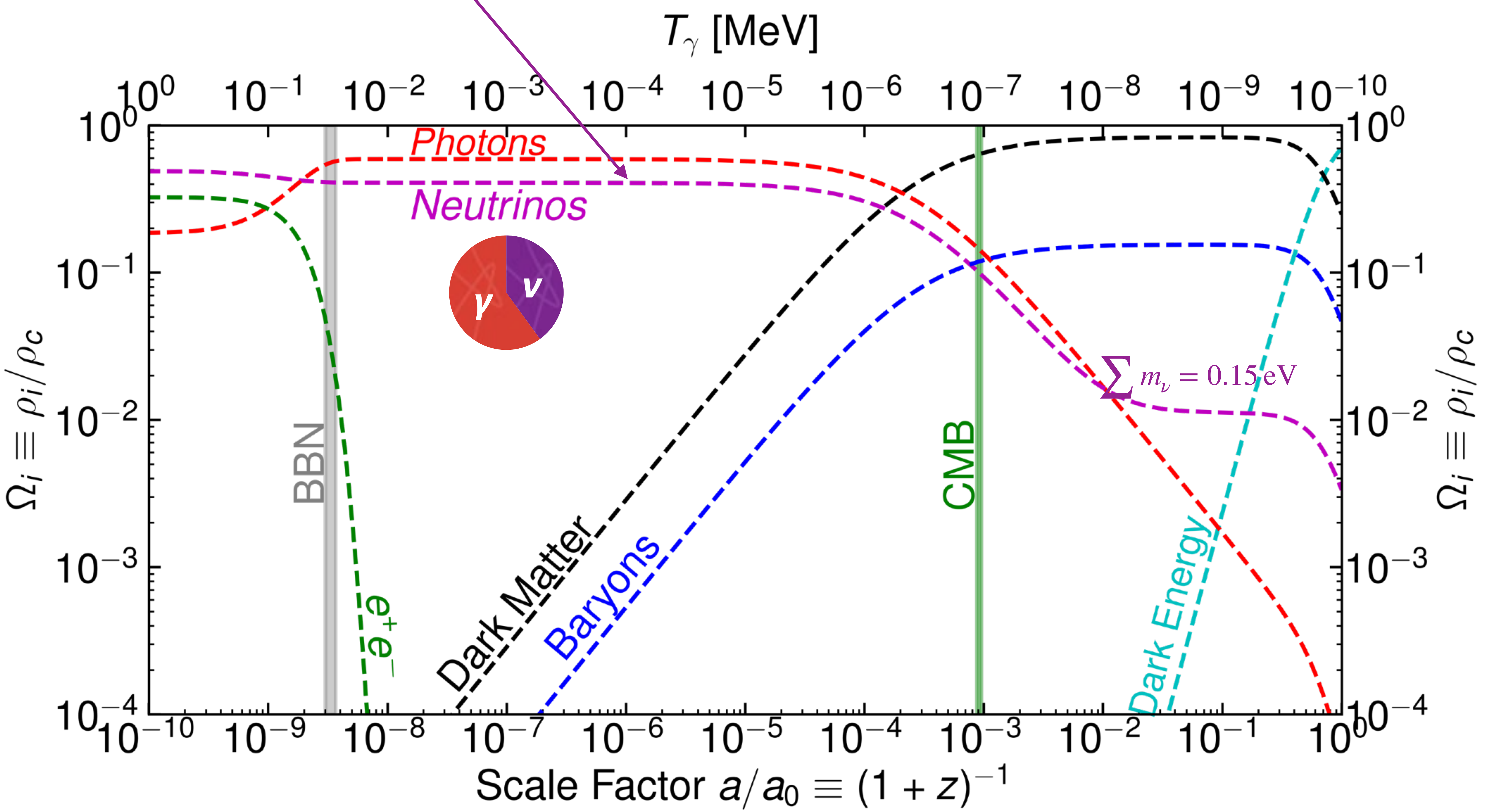
Key predictions: $T_\nu \simeq T_\gamma/1.4$ $\quad n_{\nu_i} \simeq 56\,\mathrm{cm}^{-3}$ $\quad N_{\rm eff} \simeq 3.04$

NLO corrections

Cielo, Escudero, Mangano & Pisanti [2306.05460] $\Delta N_{\rm eff} \simeq 0.0007$
Jackson & Laine [2312.07015], [2412.XXXXX] $\Delta N_{\rm eff} \simeq 0.0001$
Drewes et al. [2402.18481], [2411.14091]

Neutrino Evolution

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



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

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

Global Perspective

Current knowledge:

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

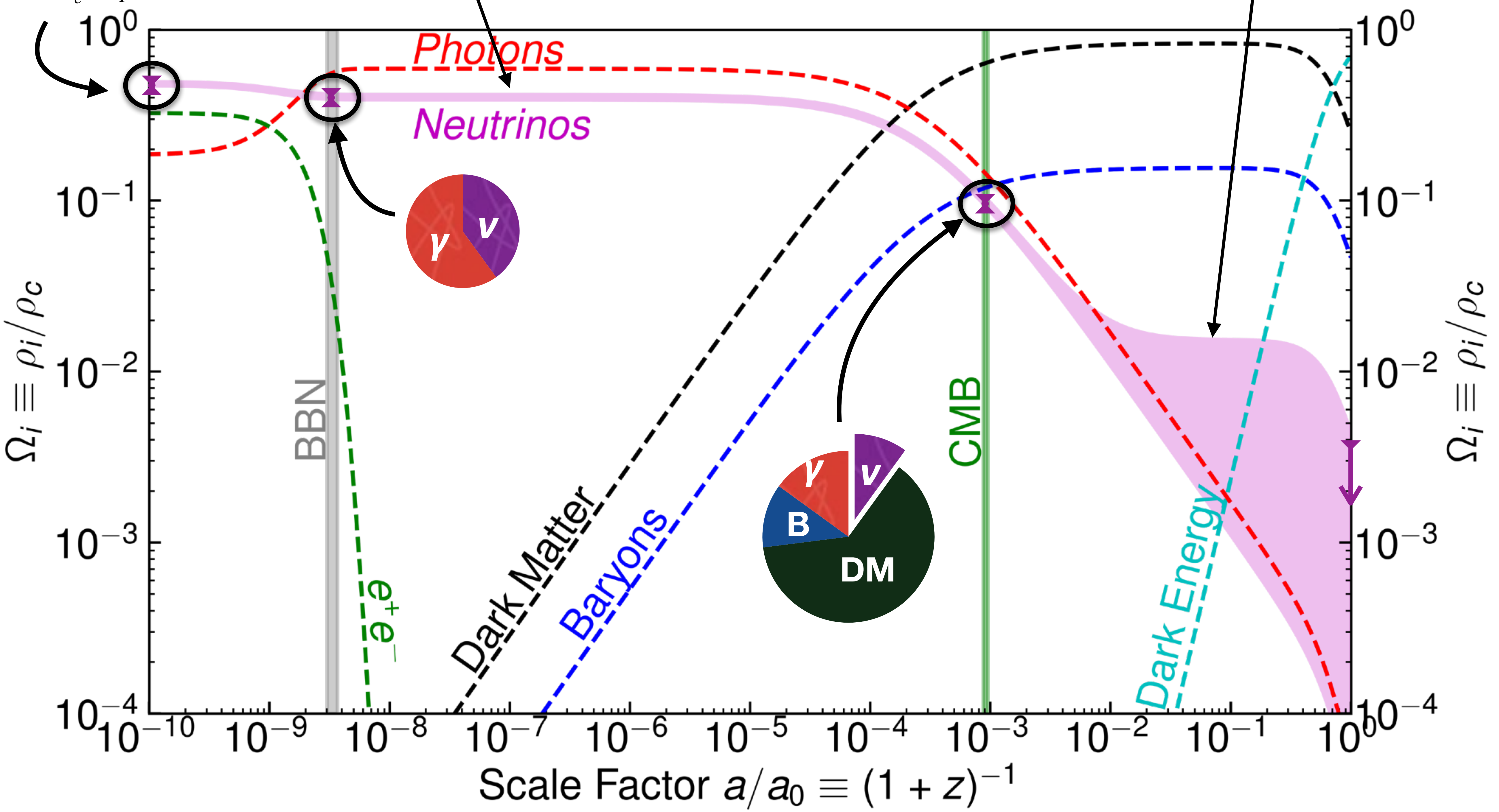
$n + e^+ \leftrightarrow p + \bar{\nu}_e$

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

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

(Planck+BAO)

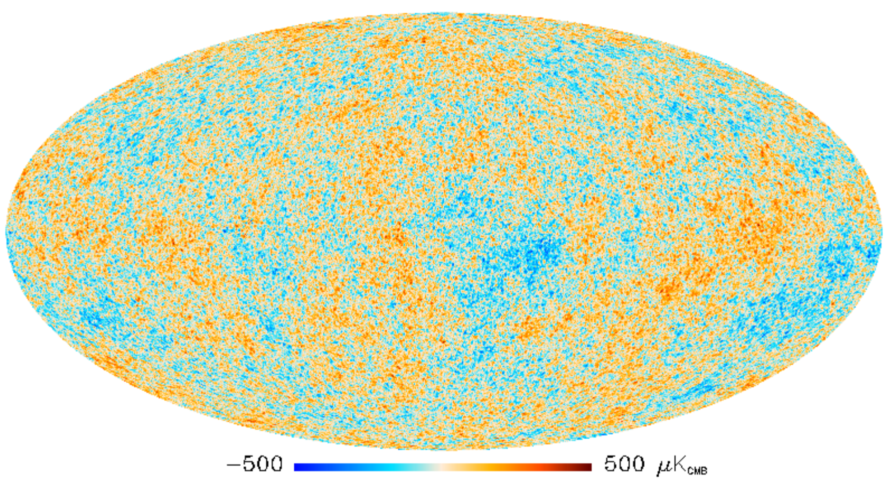
$\sum m_\nu \lesssim 0.2\,\mathrm{eV}$



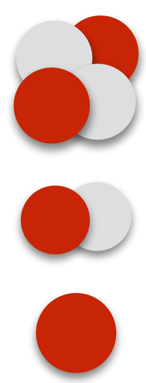
Summary

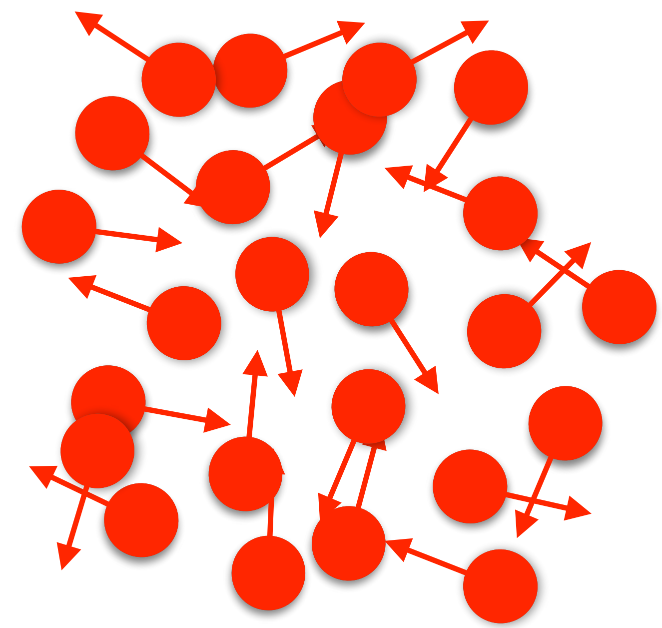
BBN & the CMB provide a powerful (albeit indirect) constraint on the Cosmic Neutrino Background as expected in the Standard Model

CMB



BBN

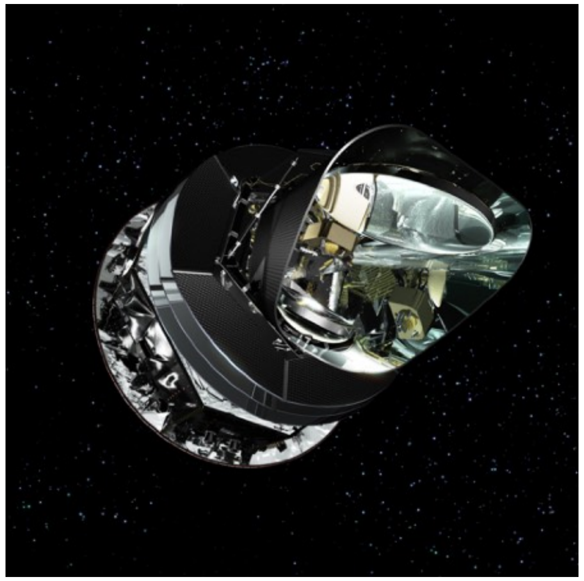




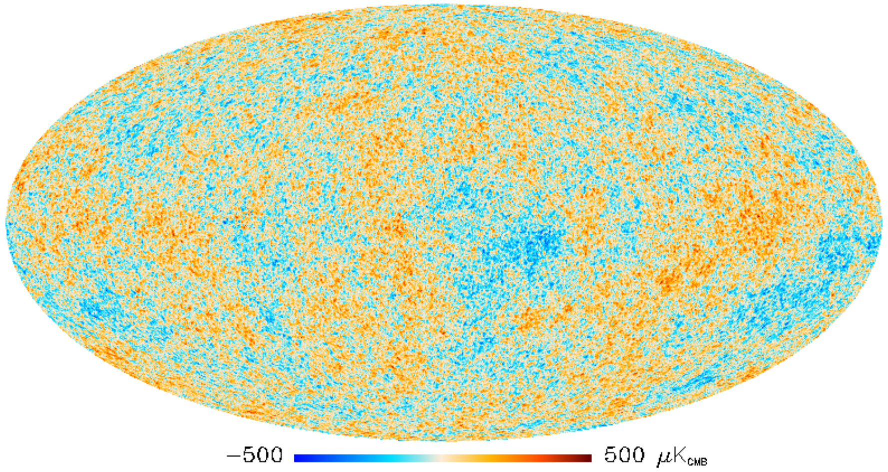
This gives us confidence to derive cosmological neutrino mass bounds

Main players of today's bound

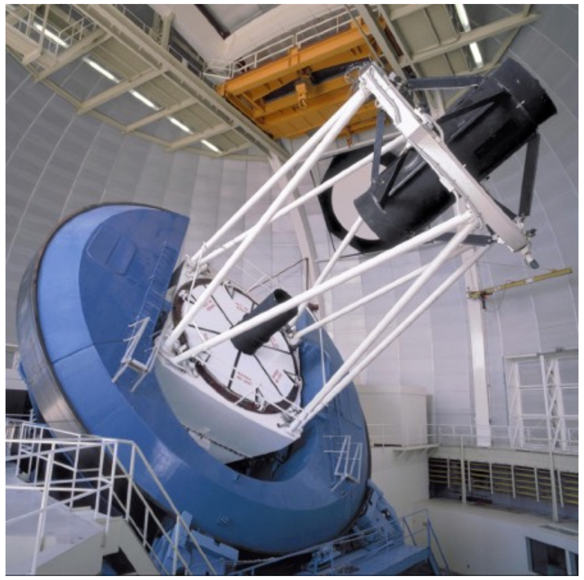
Planck



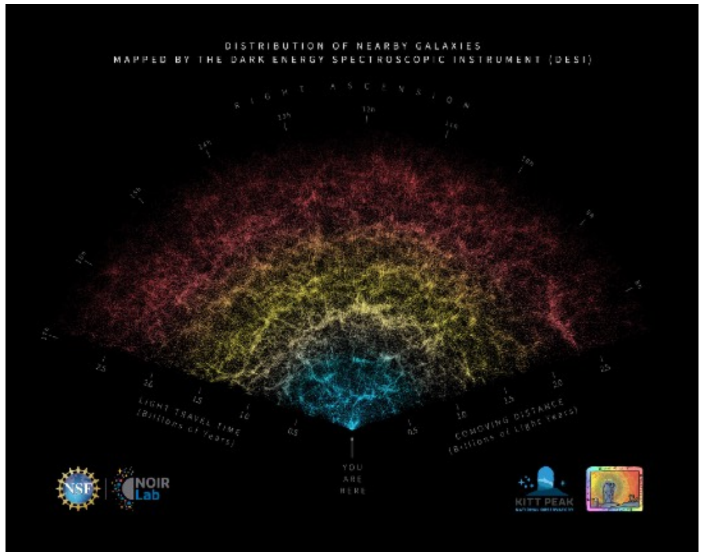
full sky, with
$\Delta T/T \simeq 2 \times 10^{-6}$ **to** $\theta \simeq 0.2^{\circ}$



DESI



5M galaxies so far



Current bound on the neutrino mass is dominated by Planck

$$\sum m_\nu < 0.34\,\mathrm{eV}$$ **at 95% CL**

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

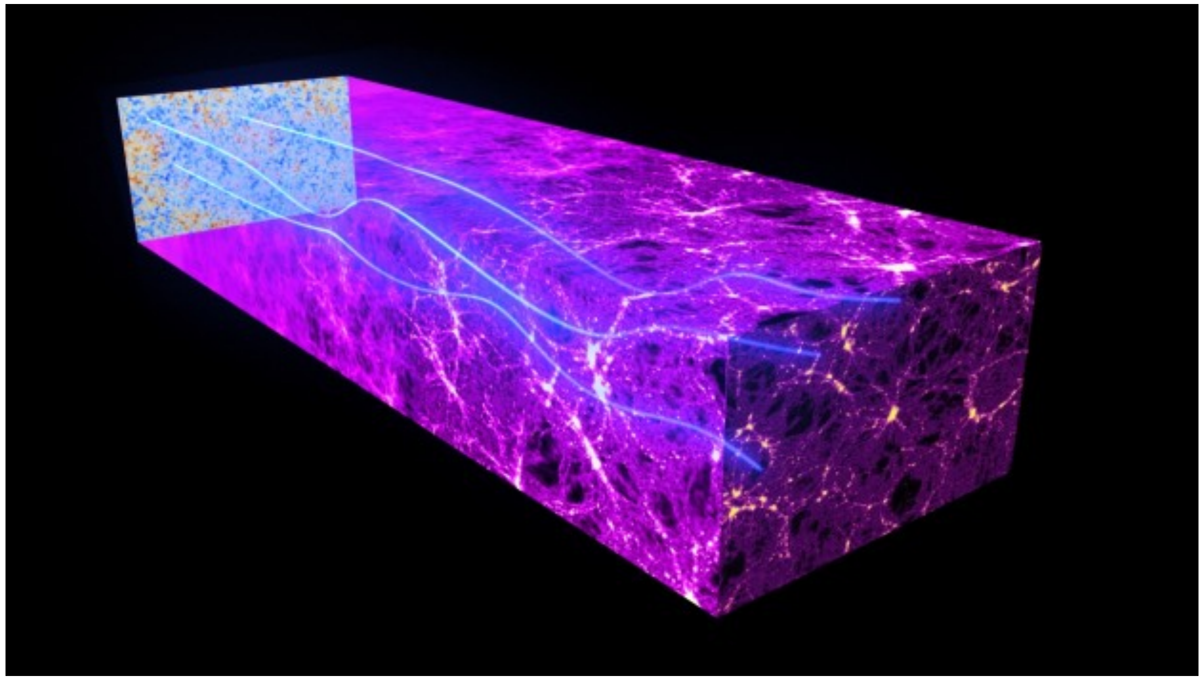
Neutrinos of $m_\nu < 0.5\,\mathrm{eV}$ become non-relativistic after recombination.
That means that their effect on the anisotropies is somewhat small!

The main implications are:

1) **They change the distance between us and the CMB (although this is strongly correlated with Ω_m and/or H_0)**

$$D_A = \int_0^{z_\star} \frac{dz}{H(z)}$$

2) **They affect the amount of CMB lensing**
The larger the neutrino mass the less the CMB light is lensed (although the effect is also correlated with $\Omega_{\rm cdm} h^2$)



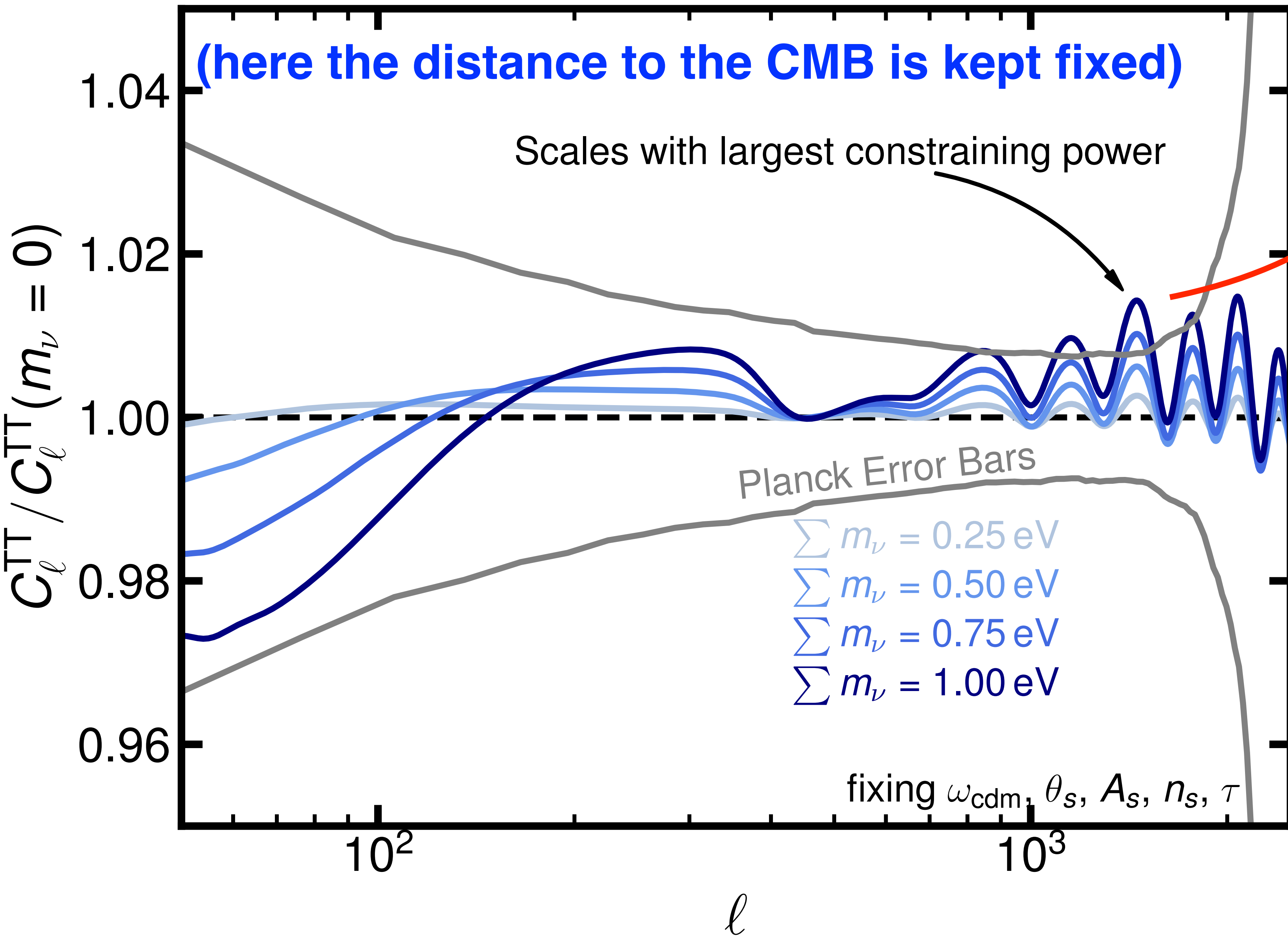
Neutrinos cannot fall in gravitational potentials for $L \lesssim 20\,\mathrm{Mpc}$

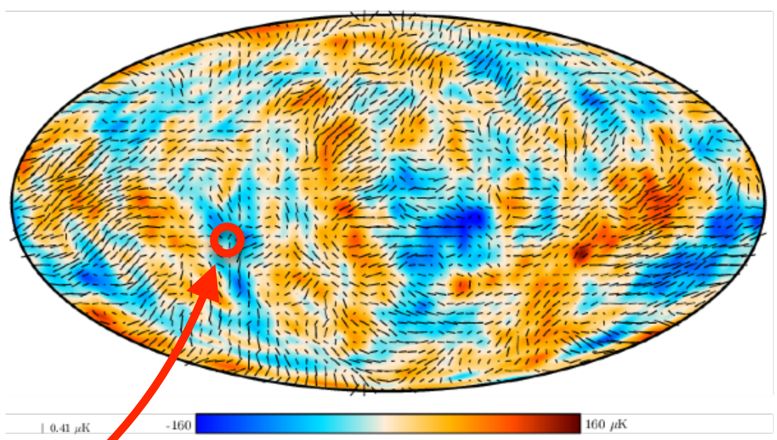
BAO data can break these parameter degeneracies

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

The effect of neutrino masses in the CMB:

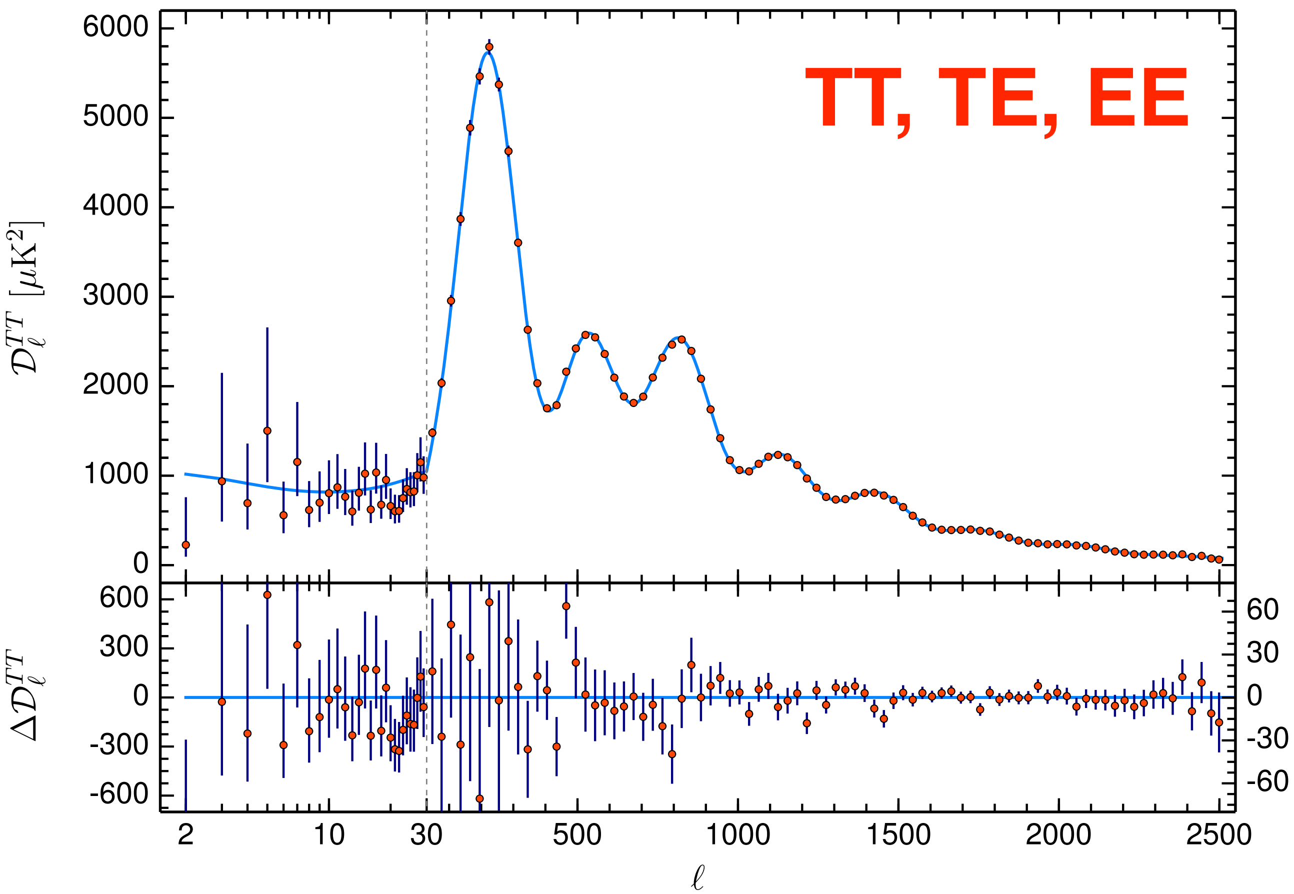


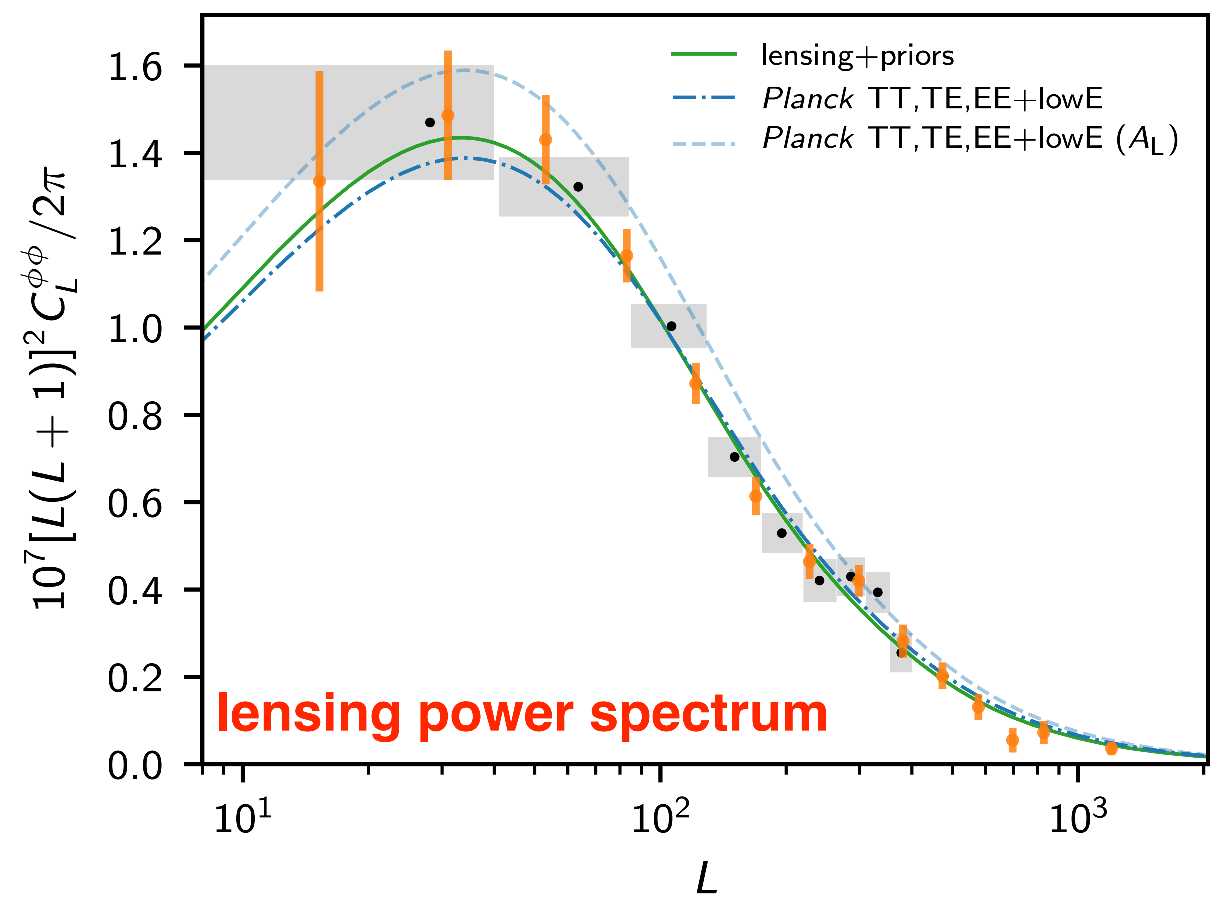


$$\sum m_\nu < 0.54\,\mathrm{eV}$$

(95 % CL, TT+lowE)

The Data: CMB anisotropies from Planck





Latest cosmological results in 2018 but in 2020 new map reanalyses were provided:

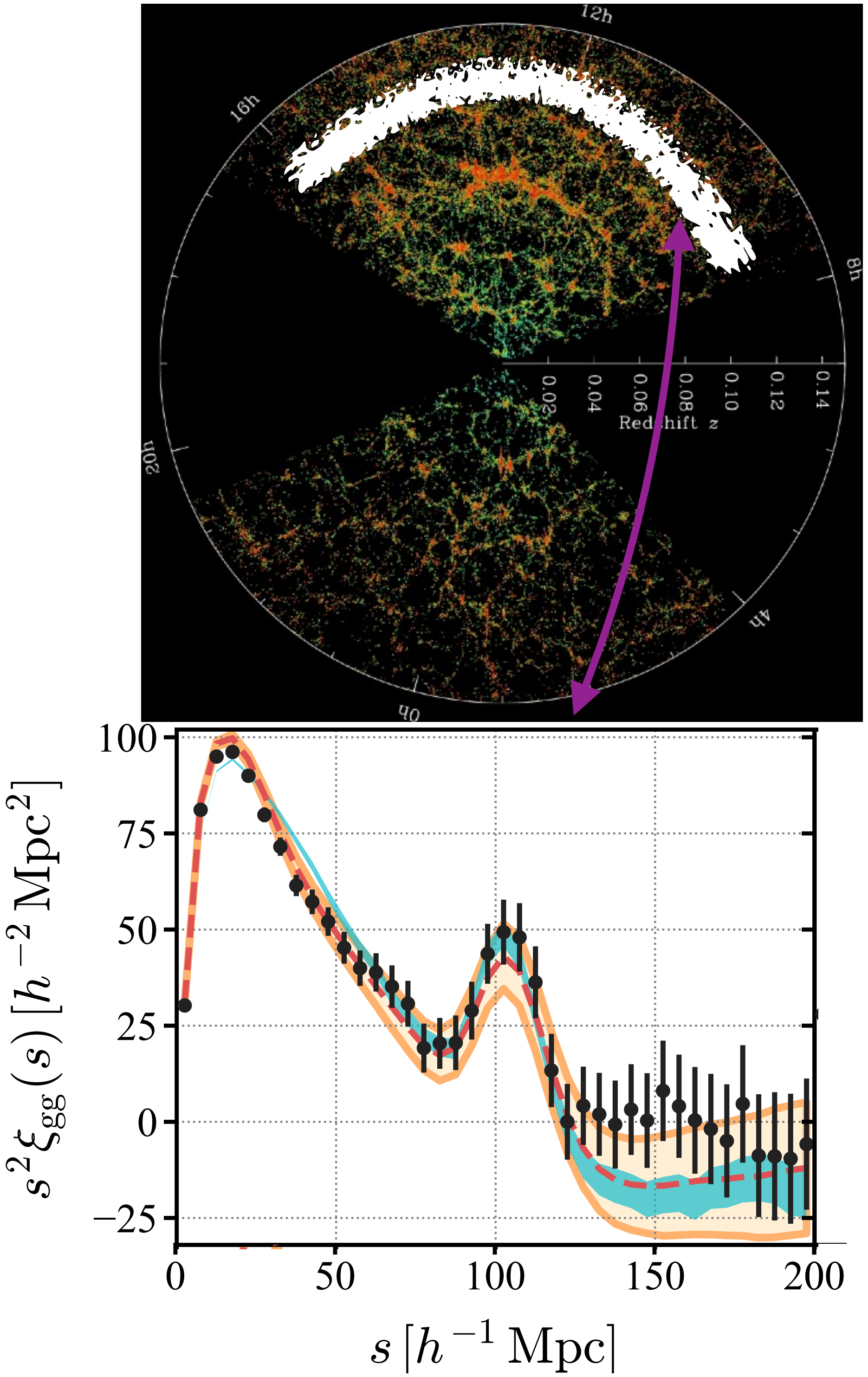
1) **with 8% more data**
2) **with less noise and systematics**

This is critical for neutrino mass inferences because Planck data featured the so called lensing anomaly (~3sigma) in the same parts of the spectrum where the neutrino mass signal appears.

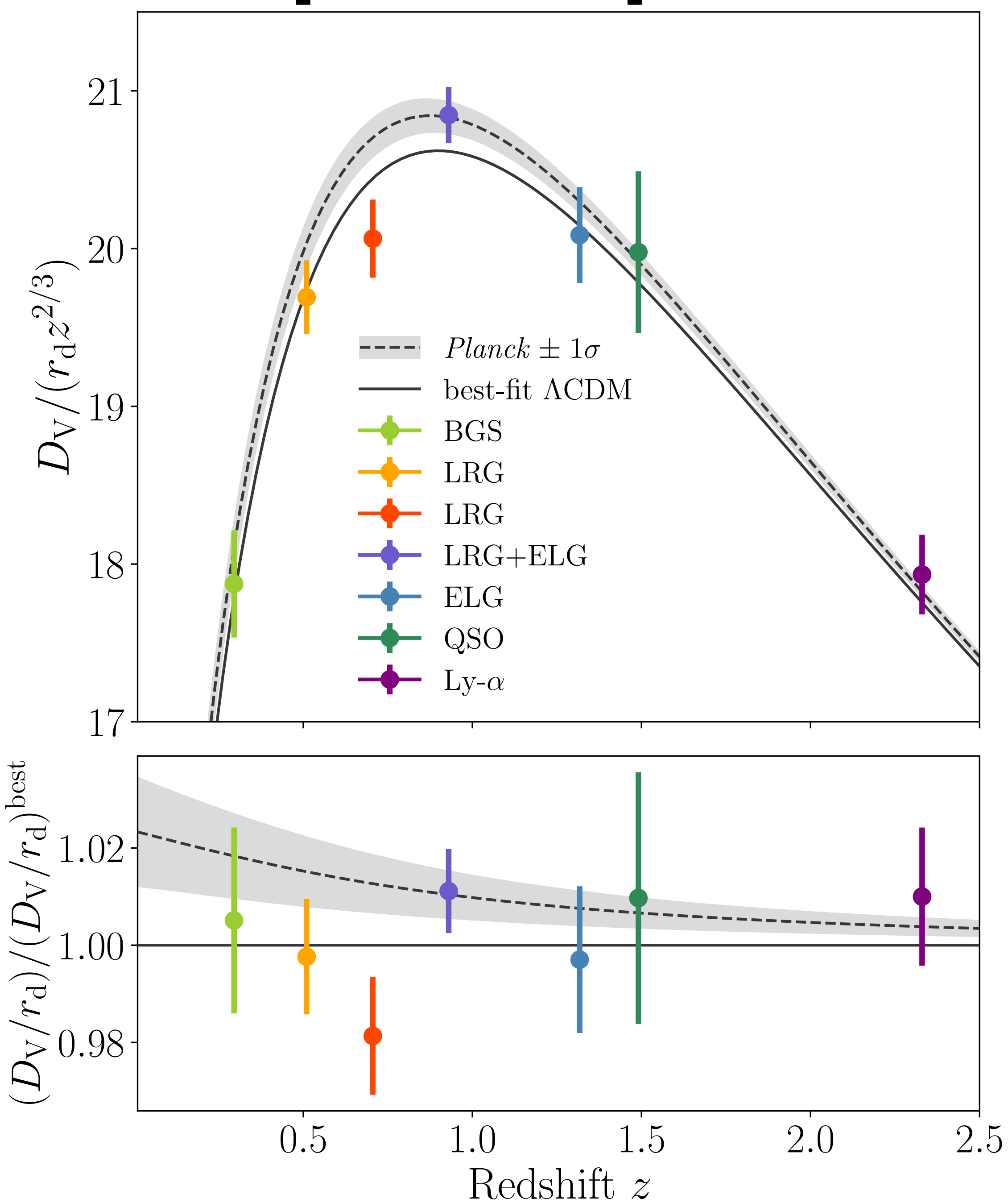
- **Planck 2018:** $\sim 2.8\sigma$ **[1807.06209]**
- **CamSpec:** $\sim 1.7\sigma$ **Rosenberg et al. [2205.10869]**
- **Hillipop:** $\sim 0.75\sigma$ **Tristram et al. [2309.10034]**

The Data: DESI-Y1 BAO

Measurement of about 5 Million redshift of galaxies and quasars up to redshift ~ 2.4



DESI [2404.03002]



DESI-Y1 BAO data is overall in 2σ tension with Planck predictions

Neutrino Masses from Cosmology

$\sum m_\nu < 0.082\,\mathrm{eV}$ **(95 % CL CMB+BAO-DESIY1)**

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

What about possible systematics or statistical fluctuations in Planck CMB and/or BAO data?

What is the dependence upon the assumed statistical procedure?

And, all cosmological bounds are cosmological model dependent

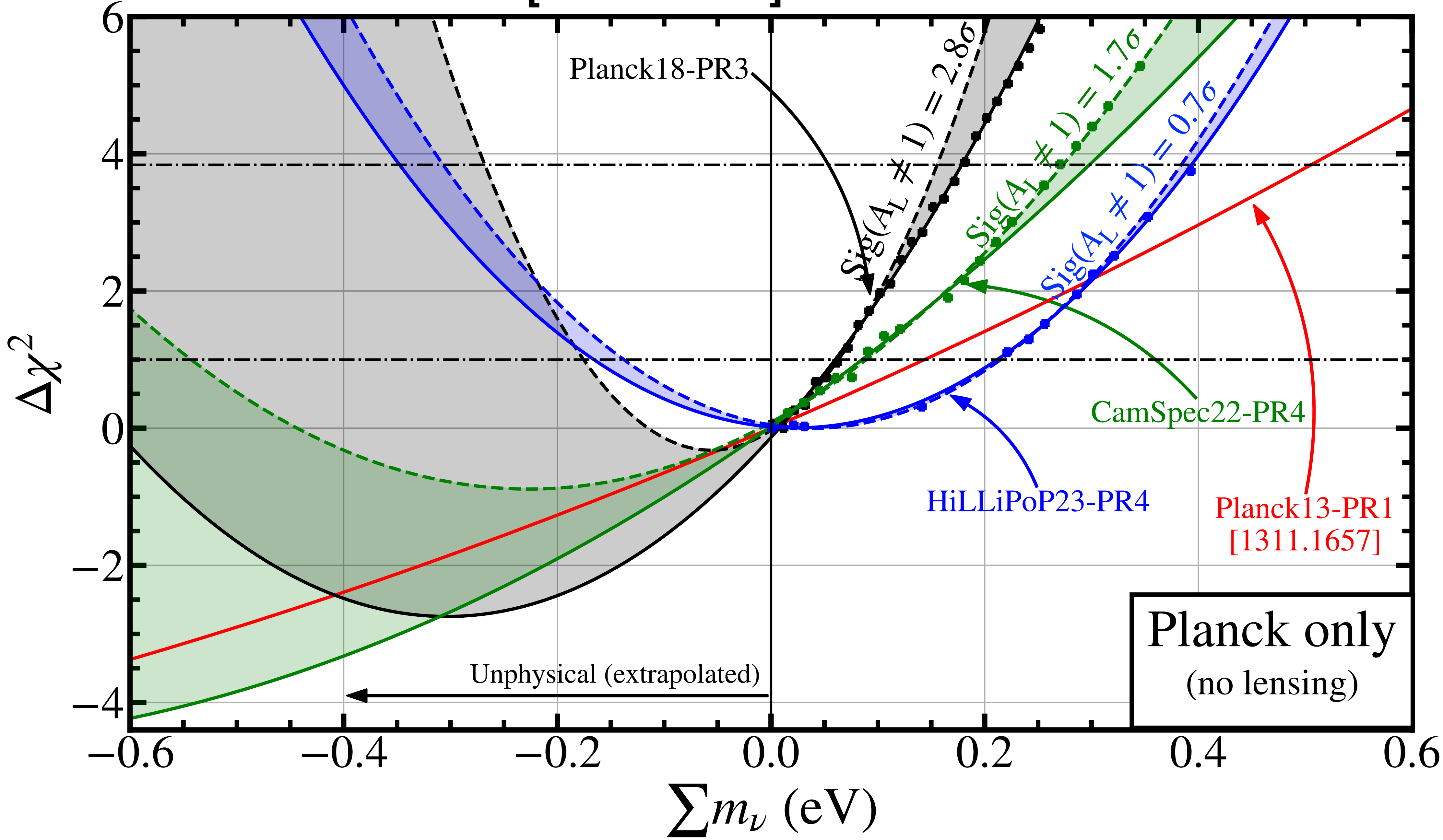
What is the dependence upon the assumed Cosmological Model?

Neutrino Masses from Cosmology

Neutrino masses and the Planck lensing anomaly

The neutrino mass bound weakens significantly in Planck implementations not featuring the lensing anomaly

Naredo-Tuero et al. [2407.13831]

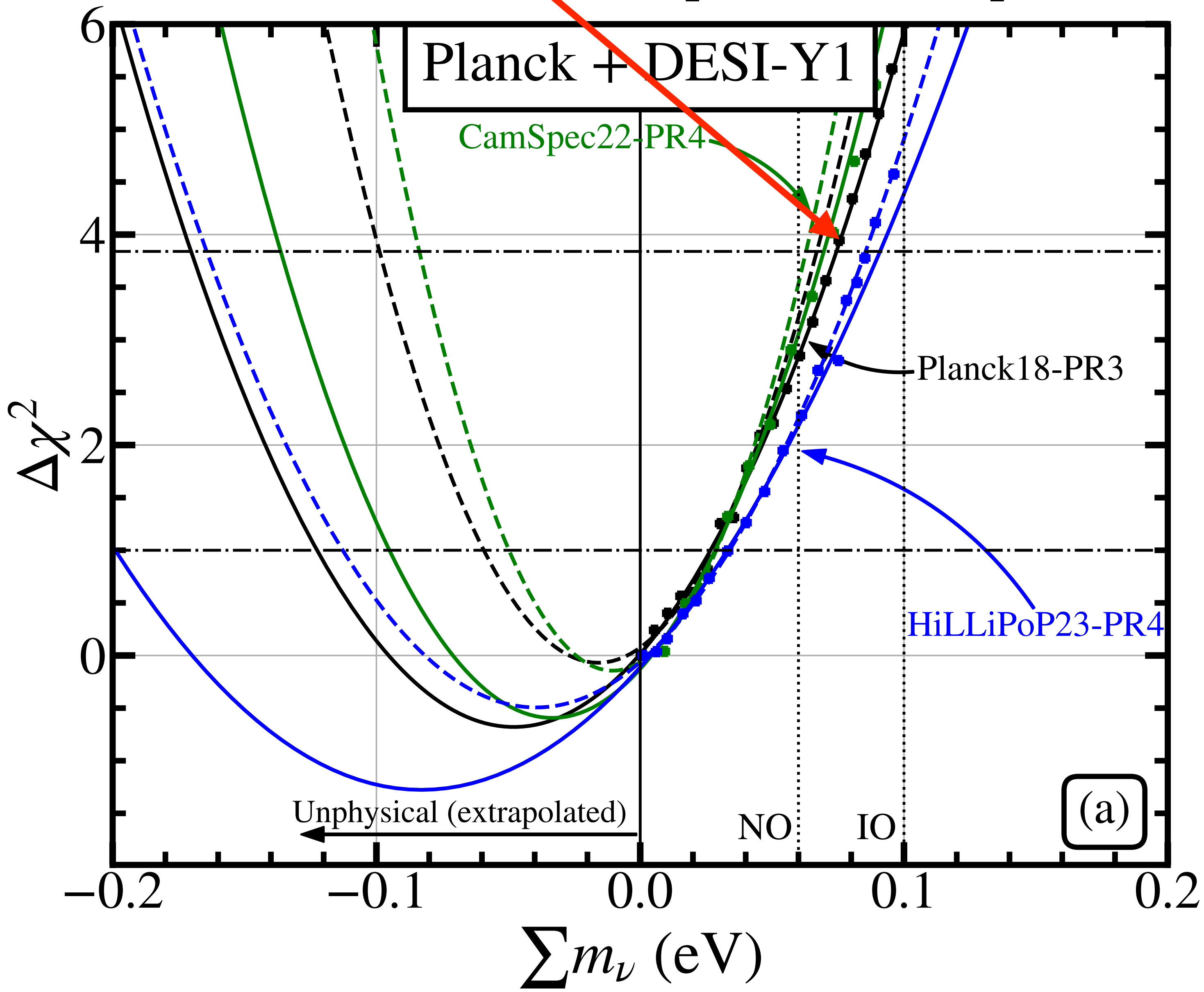


Neutrino Masses from Cosmology

Neutrino masses and the Planck lensing anomaly

The shift is not so significant when adding BAO data but the bound can still vary by 30%!

Naredo-Tuero et al. [2407.13831]

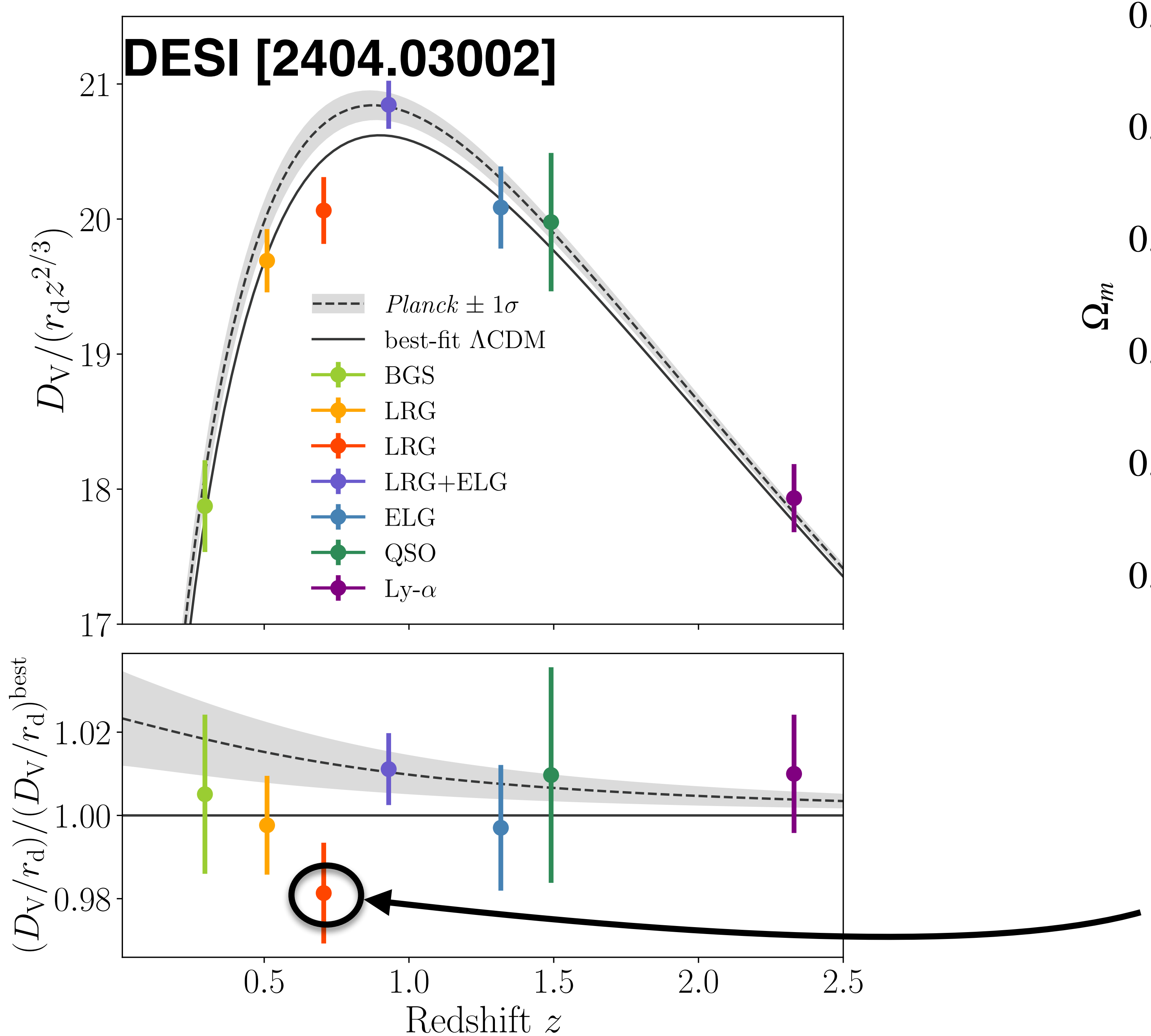


***see also Allali & Notari [2406.14554] and DESI collaboration [2411.12022]**

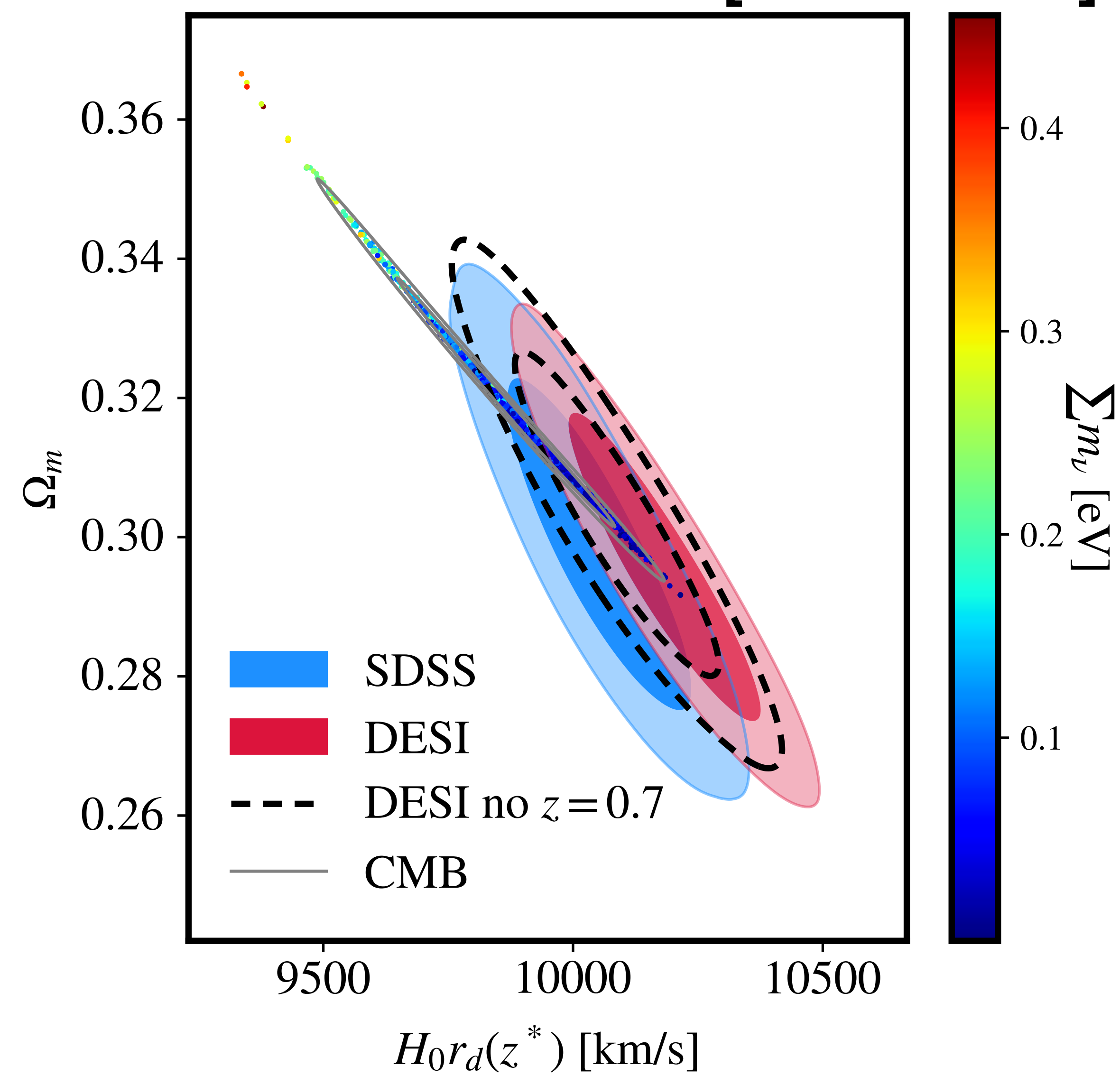
Neutrino Masses from Cosmology

Neutrino masses and DESI BAO data

DESI BAO data is overall in 2σ tension with Planck predictions and some data points are in tension with SDSS



Naredo-Tuero et al. [2407.13831]



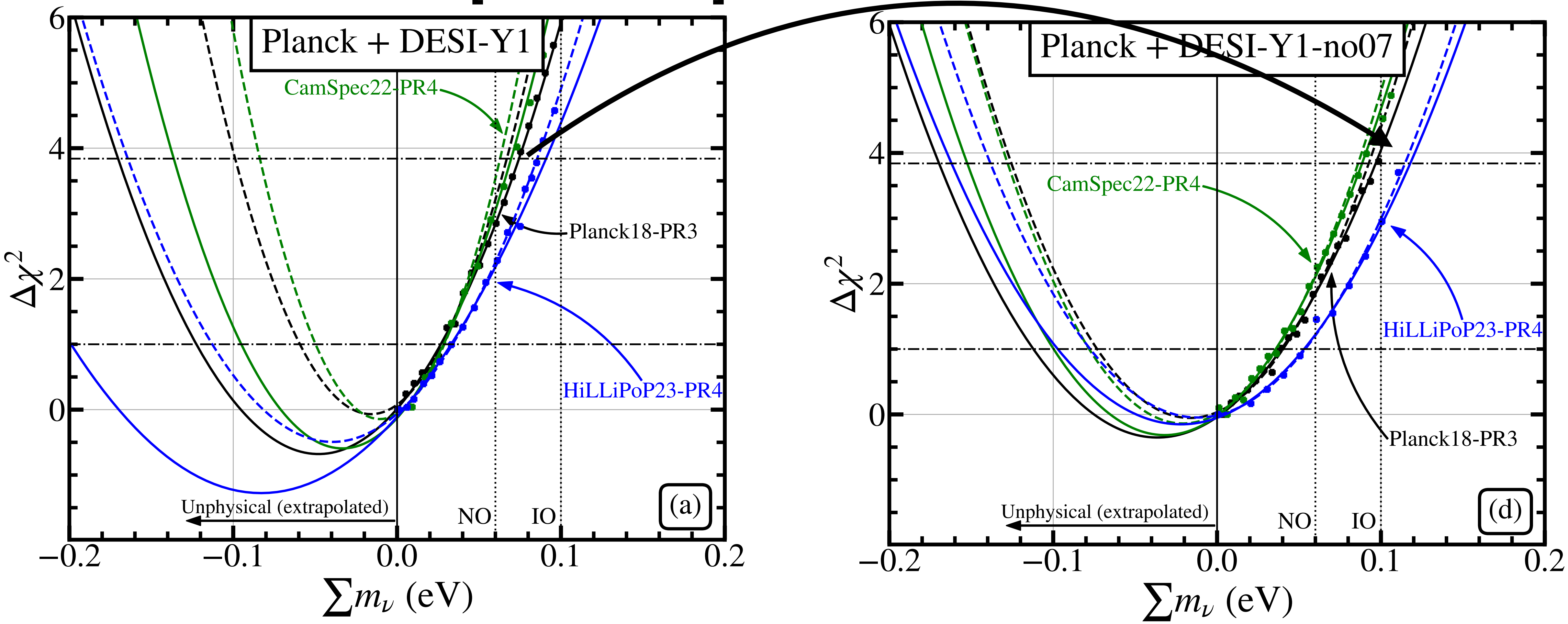
The bound is relaxed by ~30% if the z=0.7 bin is not used in the analysis (Note that this is precisely the redshift at which Dark Energy dominates)

Neutrino Masses from Cosmology

Neutrino masses and DESI BAO data

Naredo-Tuero et al. [2407.13831]

~30% relaxation



Planck2018+DESI-Y1: $\sum m_\nu < 0.084\,\mathrm{eV}$ **95% CL**

Planck2023+DESI-Y1: $\sum m_\nu < 0.102\,\mathrm{eV}$ **95% CL**

Planck2023+DESI-Y1no0.7 bin: $\sum m_\nu < 0.125\,\mathrm{eV}$ **95% CL**

Hence, still compatible with the minimal value in Inverted Ordering

Neutrino Masses from Cosmology

Neutrino masses and statistical procedure used

Bayesian credible intervals are by definition prior dependent

In addition, in frequentist statistics, when close to a physical boundary statistical statements should be taken with care

Numerical comparison between Frequentists vs Bayesian results with flat priors:

Naredo-Tuero et al. [2407.13831]

$$\sum m_\nu < 0.084\,\mathrm{eV} \quad [\mathrm{Bayesian}]\,, \tag{5a}$$
$$\sum m_\nu < 0.074\,\mathrm{eV} \quad [\mathrm{Bounded-Likelihood}]\,, \tag{5b}$$
$$\sum m_\nu < 0.071\,\mathrm{eV} \quad [\mathrm{Feldman-Cousins}]\,. \tag{5c}$$

$$\Sigma m_\nu \in [0 - 3\,\mathrm{eV}]$$

$$\sum m_\nu < 0.121\,\mathrm{eV} \quad [\mathrm{NO-Bayesian}]\,, \tag{6a}$$
$$\sum m_\nu < 0.106\,\mathrm{eV} \quad [\mathrm{NO-Bounded-Likelihood}]\,, \tag{6b}$$
$$\sum m_\nu < 0.096\,\mathrm{eV} \quad [\mathrm{NO-Feldman-Cousins}]\,, \tag{6c}$$

$$\Sigma m_\nu \in [0.06 - 3\,\mathrm{eV}]$$

$$\sum m_\nu < 0.152\,\mathrm{eV} \quad [\mathrm{IO-Bayesian}]\,, \tag{7a}$$
$$\sum m_\nu < 0.138\,\mathrm{eV} \quad [\mathrm{IO-Bounded-Likelihood}]\,, \tag{7b}$$
$$\sum m_\nu < 0.127\,\mathrm{eV} \quad [\mathrm{IO-Feldman-Cousins}]\,. \tag{7c}$$

$$\Sigma m_\nu \in [0.1 - 3\,\mathrm{eV}]$$

Overall good agreement between the two (~10-20%). Although they address different questions!

Highlights that the likelihood is fairly Gaussian

Neutrino Masses from Cosmology

What about other data sets?

Not only the bounds are stringent but there is no sign for a non-zero neutrino mass when combining with other data sets!

Jiang et al. [2407.18047]

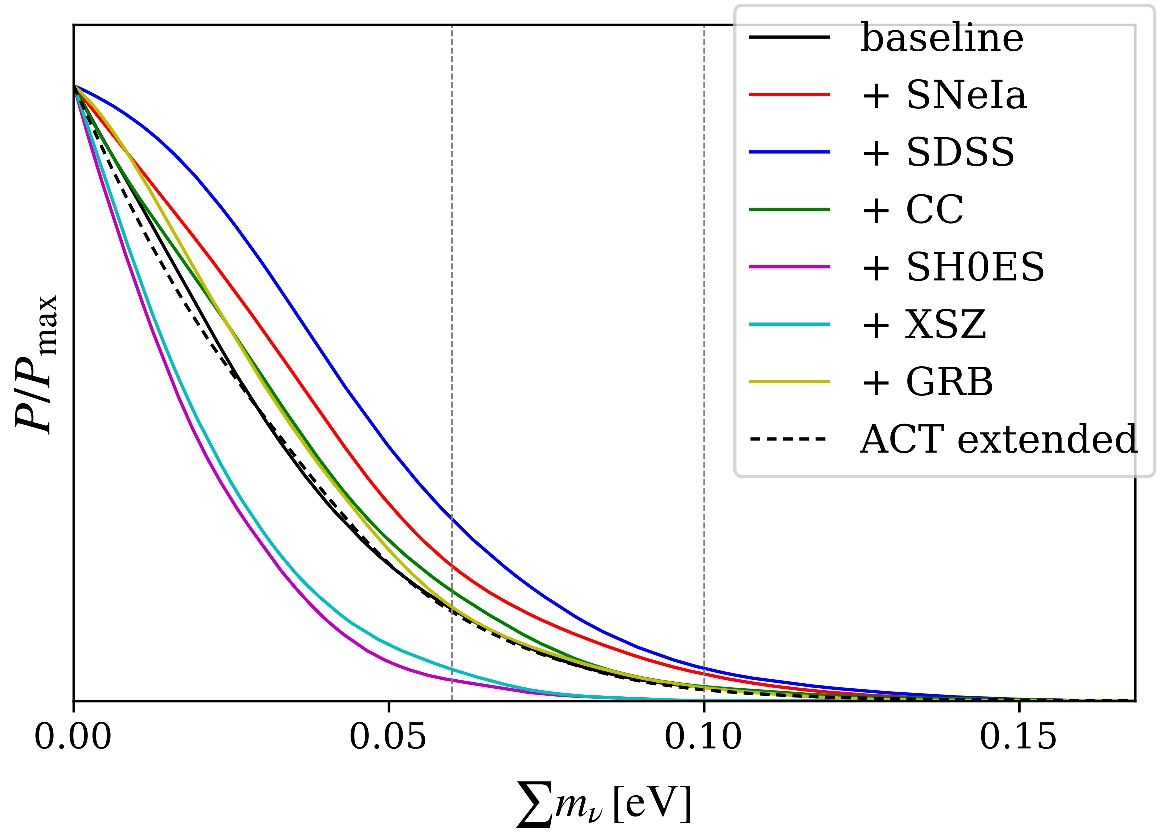
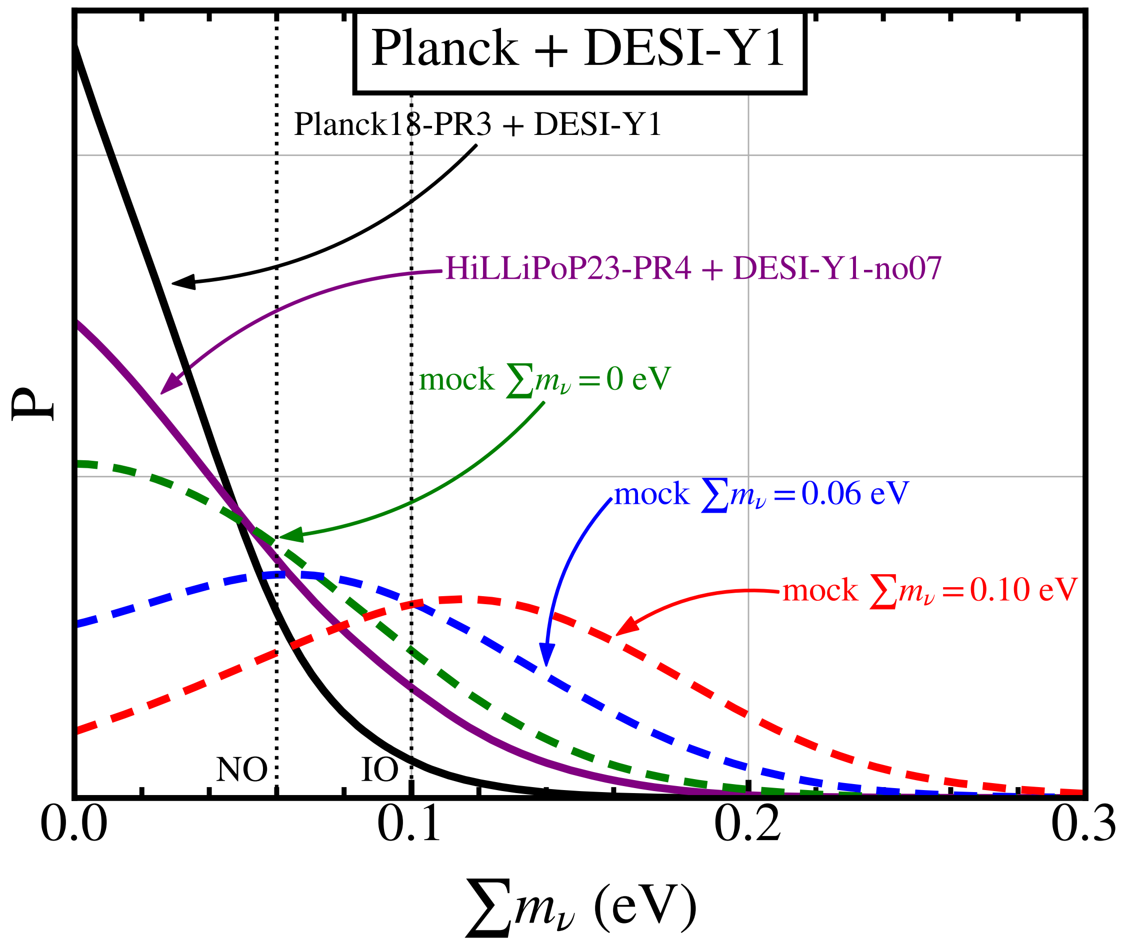


FIG. 1. Posterior distributions for the sum of the neutrino masses $\sum m_\nu$ (in eV) obtained within the 7-parameter ΛCDM+$\sum m_\nu$ model in light of different dataset combinations, as per the color coding.

see also Wang et al. [2405.03368]

Naredo-Tuero et al. [2407.13831]



current sensitivity:

$$\sigma(m_\nu) \simeq 0.06\,\mathrm{eV}$$

Neutrino Masses from Cosmology

Cosmological model dependence?

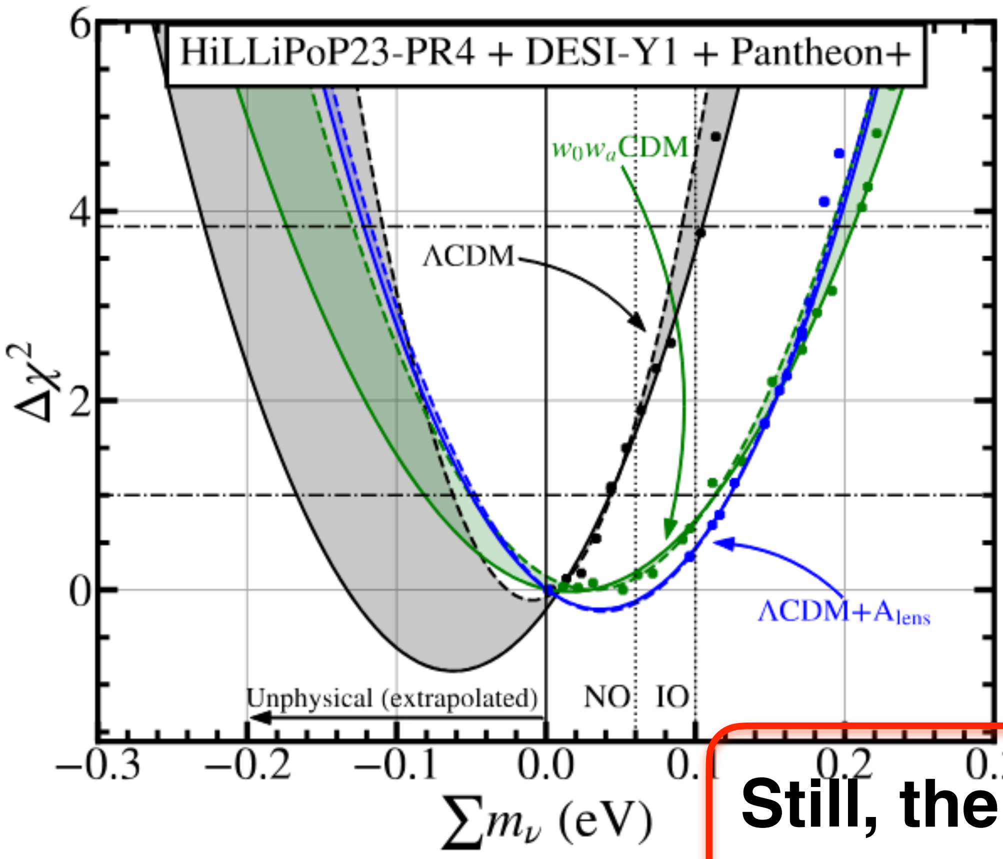
The bound is actually fairly robust upon standard modifications to the cosmological model. E.g.: the bound doesn't change if one alters $N_{\rm eff}$

The bound doesn't change if one allows to vary the equation of state of dark energy

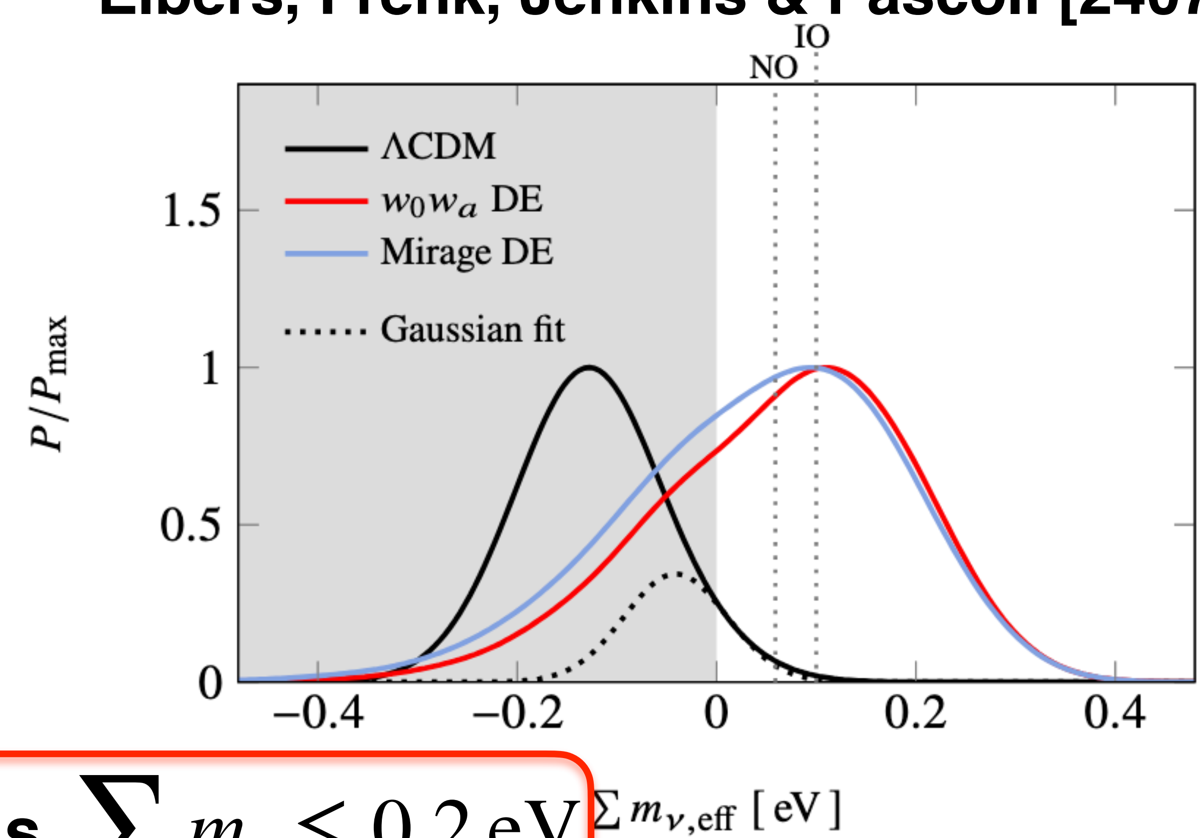
$$\underset{\text{DESI+CMB}}{\boldsymbol{\Lambda}\textbf{CDM}\boldsymbol{+\sum m_\nu}} < 0.072 \qquad \underset{\text{DESI+CMB+Panth.}}{\boldsymbol{w}\textbf{CDM}\boldsymbol{+\sum m_\nu}} < 0.079$$

The bound does change if one allows for more freedom in the Dark Energy sector with a time-dependent equation of state of dark energy:

Naredo-Tuero et al. [2407.13831]



Elbers, Frenk, Jenkins & Pascoli [2407.10965]



Still, the limit is $\sum m_\nu \lesssim 0.2\,\text{eV}$

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 et al. 2203.09075 & 2011.01502
Escudero, López-Pavón, Rius & Sandner 2007.04994

$$\nu_i \to \nu_4 \phi$$

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

Medium induced neutrino masses

Sen & Smirnov 2306.15718, 2407.02462

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
Benso, Schwetz & Vatsyayan 2410.23926

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

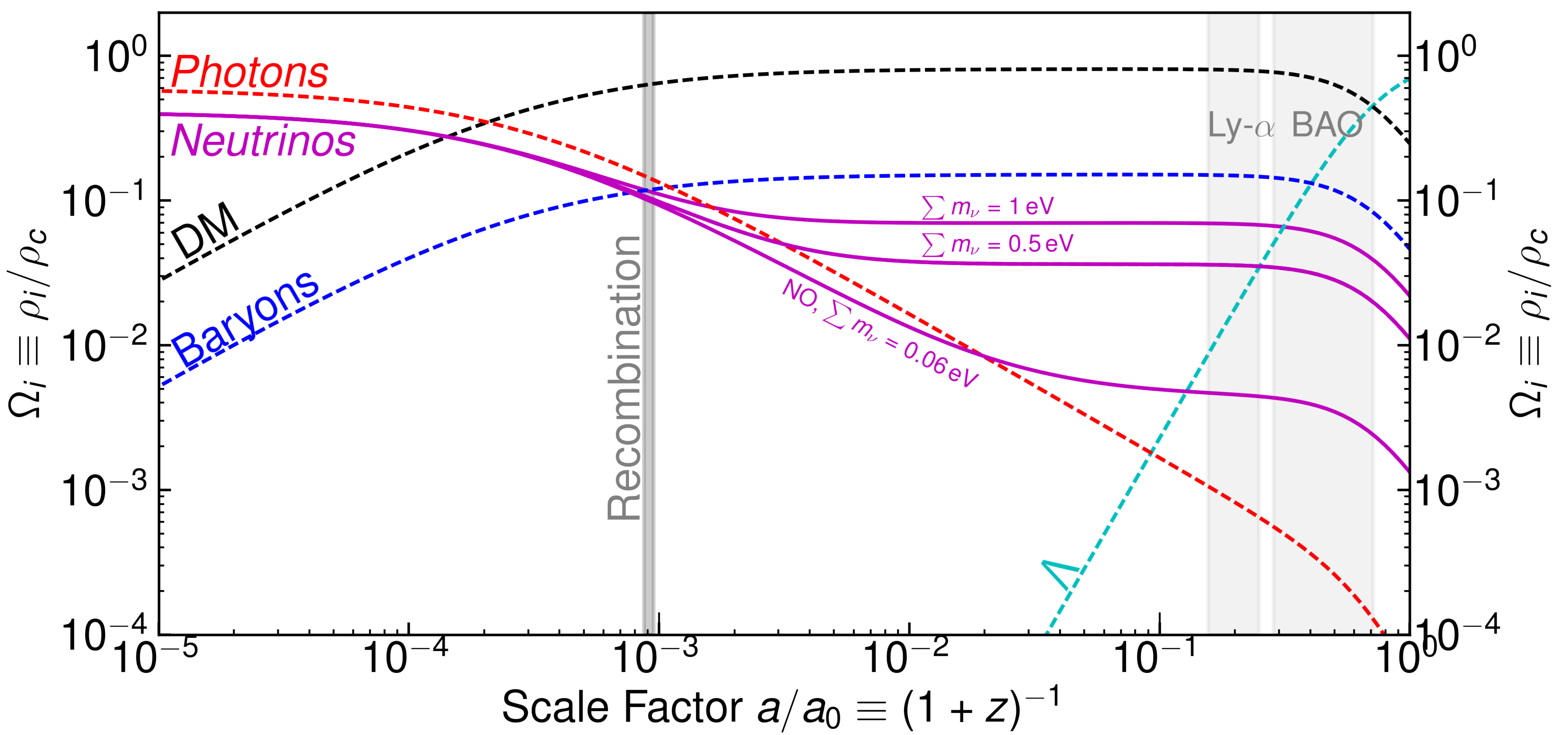
$$\sum m_\nu < 3\,\mathrm{eV}$$

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?

Neutrino Masses from Cosmology



CMB peaks fix:

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

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

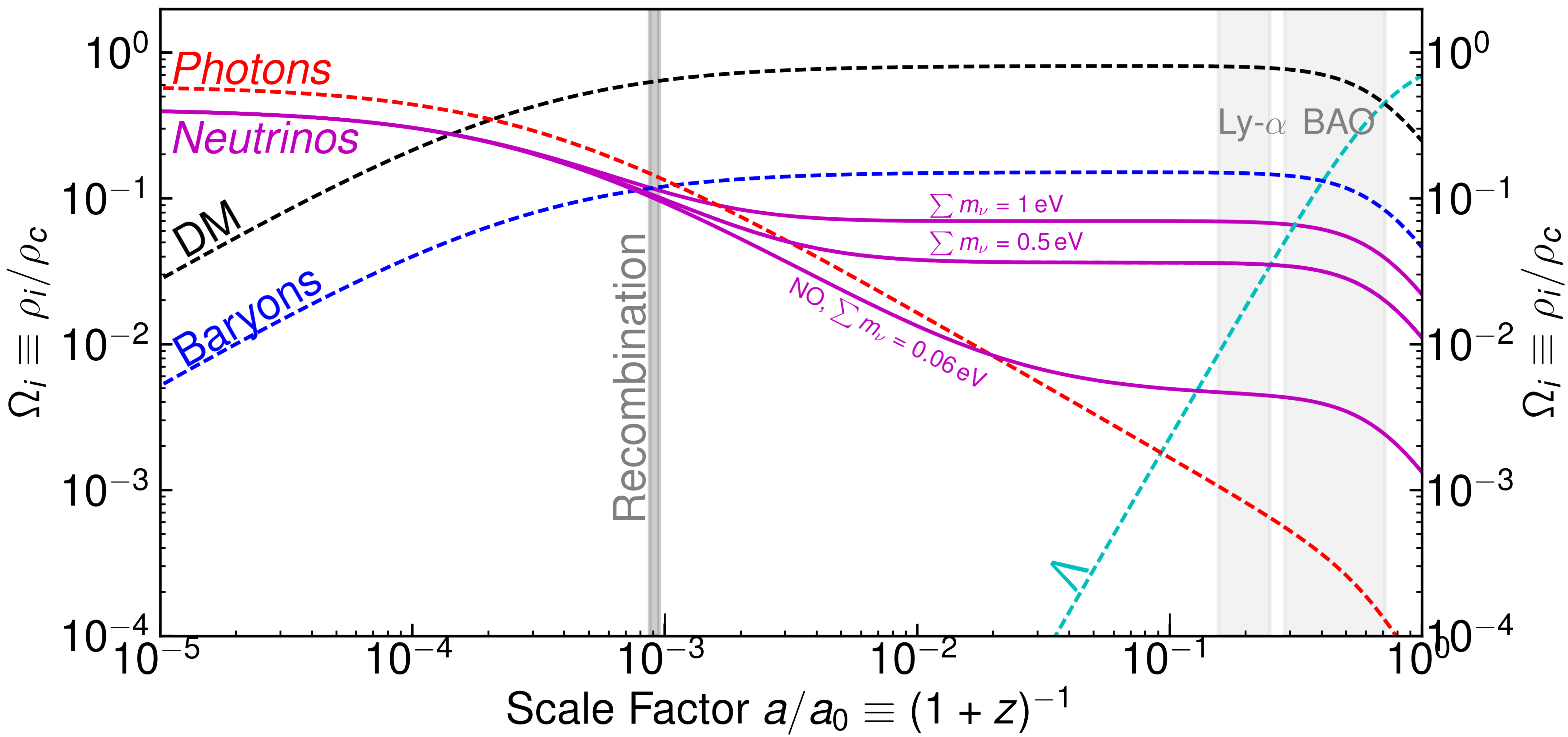
Comoving sound horizon (Early Universe)

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

Comoving angular diameter distance (Late Universe)

Massive neutrinos → $H(z')$

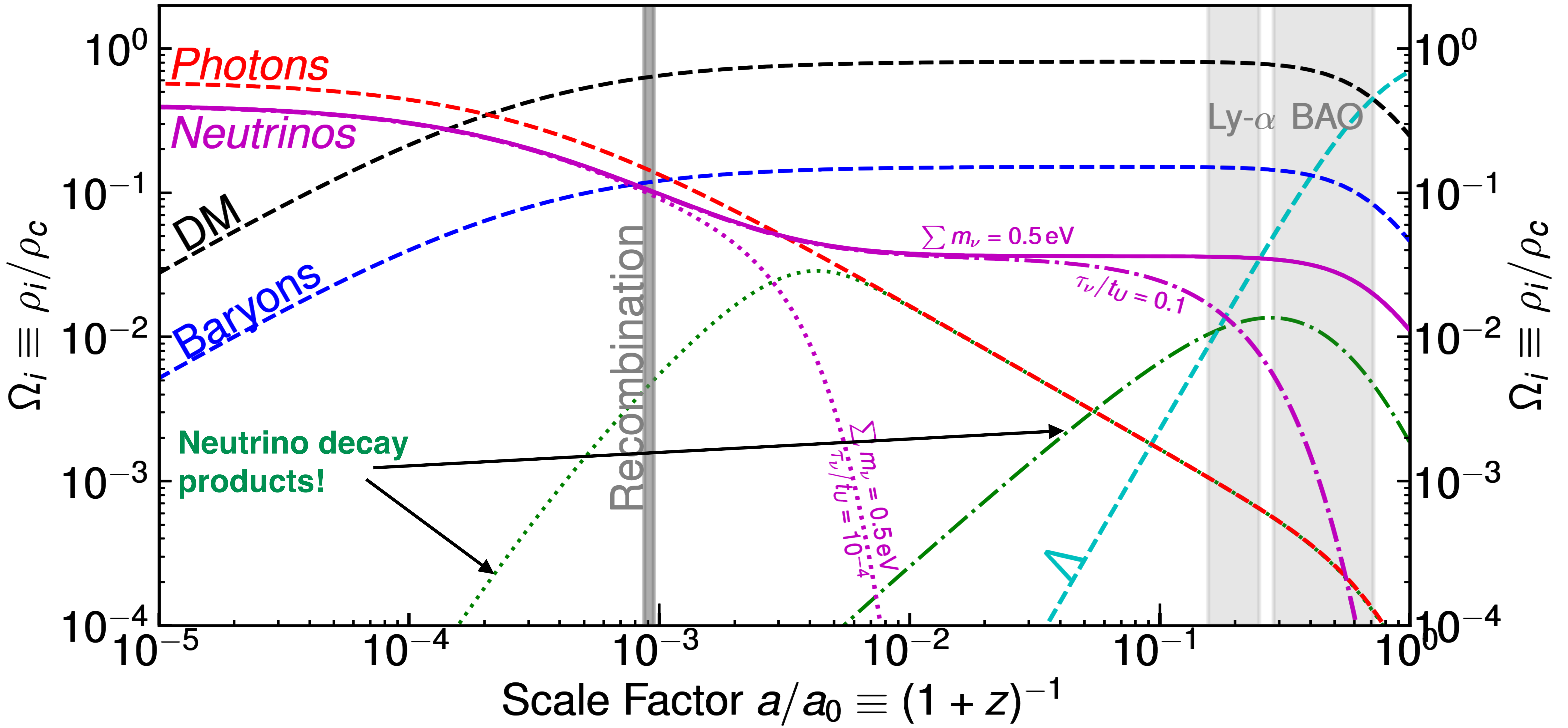
Neutrino Masses from Cosmology



Not only a background effect:

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

Neutrino Decays



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, López-Pavón, Rius & Sandner 2007.04994

$\nu_i \to \nu_4 \phi$

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

Medium induced neutrino masses

Sen & Smirnov 2306.15718, 2407.02462

Non-standard Neutrino Populations

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

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

Farzan & Hannestad 1510.02201
Escudero, Schwetz & Terol-Calvo 2211.01729
Benso, Schwetz & Vatsyayan 2410.23926

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

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

Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.14870

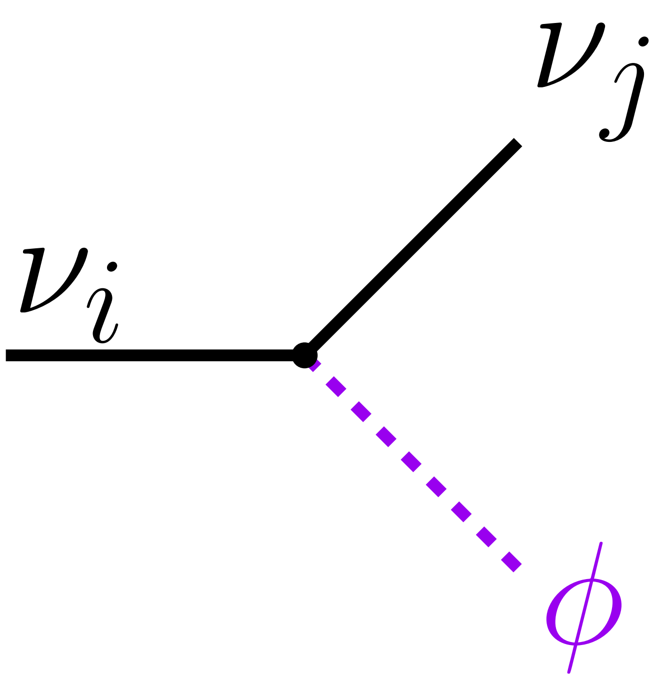
Take Away Message:

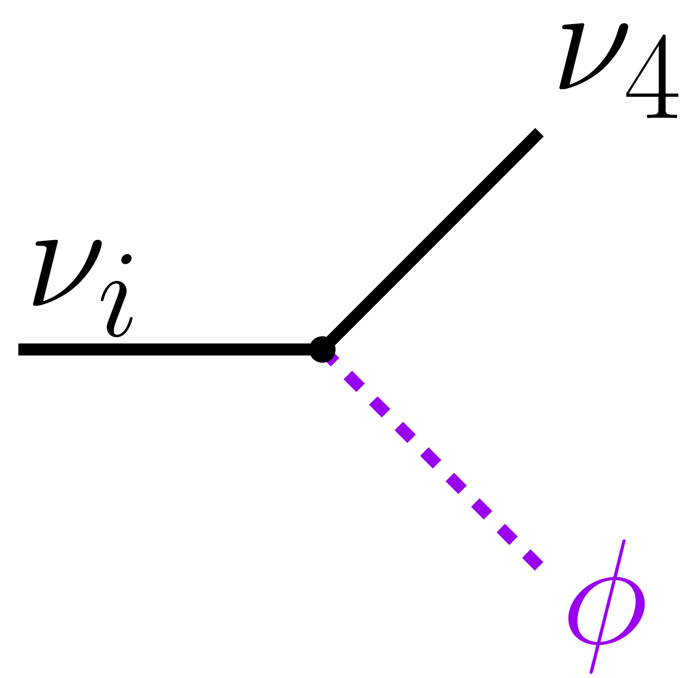
Cosmology can only constrain $\Omega_\nu(z)$ and not directly m_ν

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

Invisible Neutrino Decays

$$\Gamma_\nu \simeq \lambda^2 m_\nu \gtrsim H_0 \sim 10^{-33}\,\mathrm{eV}$$





$$\lambda \simeq \frac{m_\nu}{v} \sim 10^{-15}$$

$$v \lesssim 100\,\mathrm{TeV}$$

see e.g. Gelmini & Valle PLB 142 (1984) 181 for a model

$$\lambda \simeq y\frac{m_D}{M_N} \sim 10^{-15}$$

$$M_N \sim 10^{13}\,\mathrm{GeV}$$ **natural seesaw window**

see Escudero, López-Pavón, Rius & Sandner 2007.04994

Neutrino Decays into lighter neutrinos

$\nu_i \to \nu_j \phi$ Decays

Theory: These happen naturally in scenarios with sterile neutrinos and horizontal global and spontaneously broken flavor symmetries, e.g. $L_\mu - L_\tau$ see Gelmini & Valle PLB 142 (1984) 181

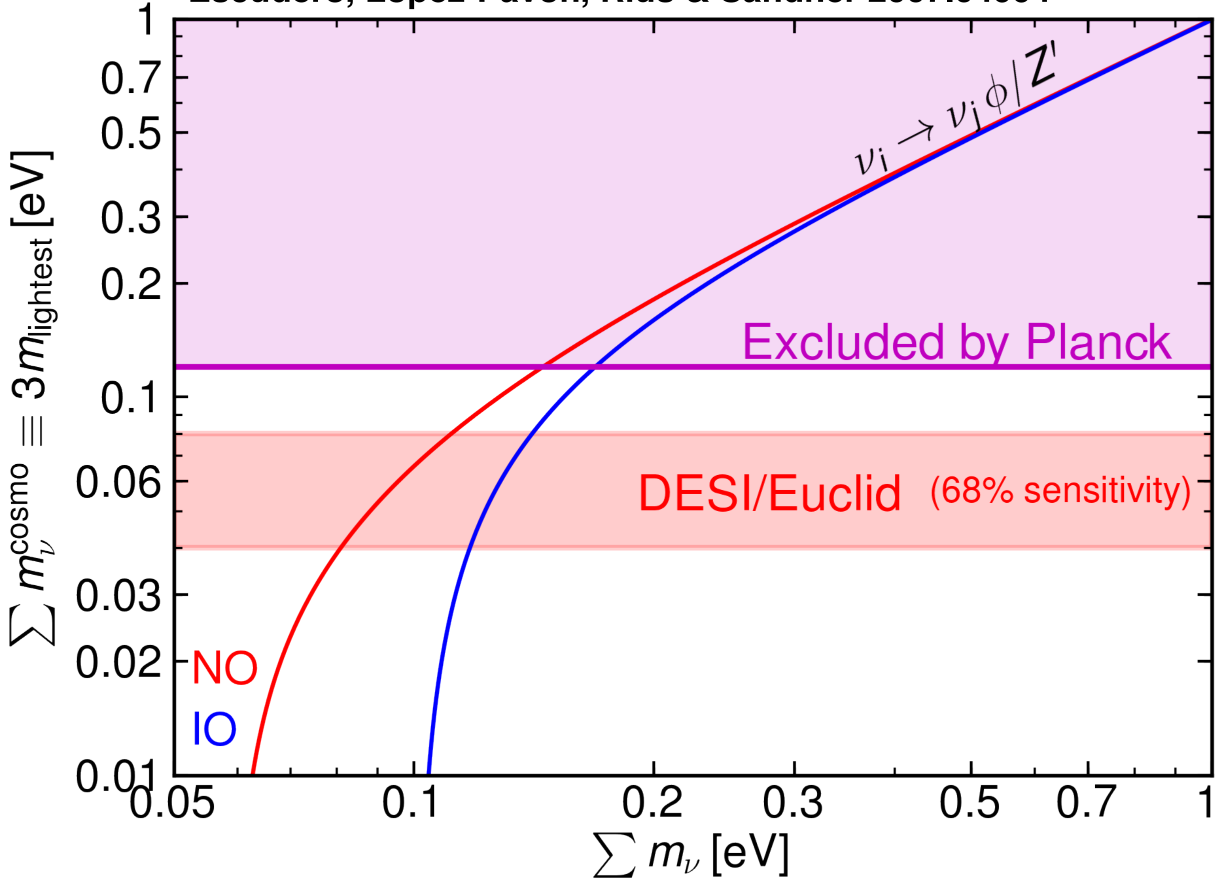
Couplings: $\tau_\nu < t_U$ taking the $L_\mu - L_\tau$ case means $v_{\mu-\tau} < 30\,\mathrm{TeV}$ for both global and gauge U(1)

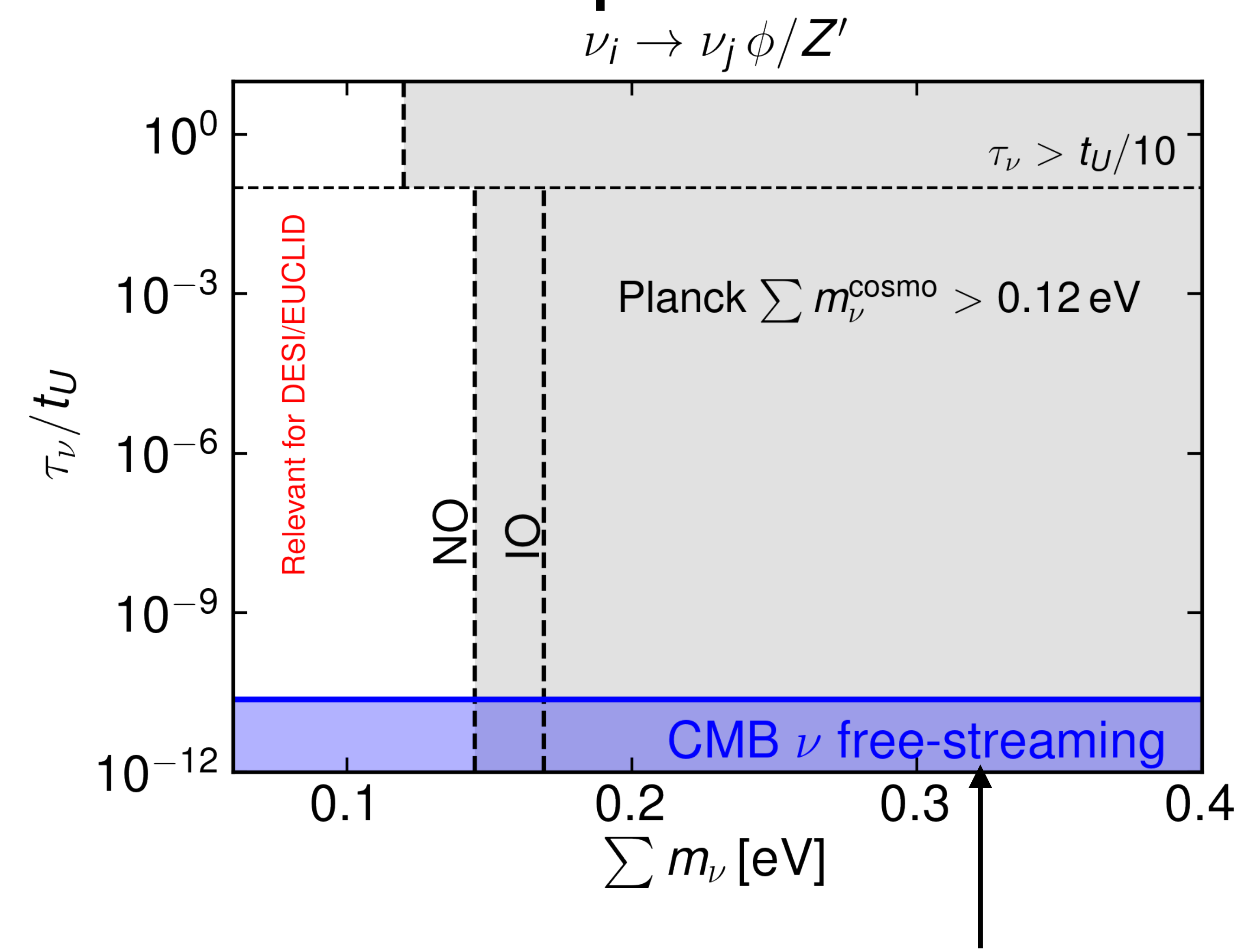
However, because there is a neutrino in the final state the mass bounds are expected to only be relaxed mildly:

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

Parameter space:

Escudero, López-Pavón, Rius & Sandner 2007.04994





Oldengott et al. 2011.01502 & 2203.09075

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

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

Summary

- We have strong, albeit indirect evidence that the Cosmic Neutrino Background should be there as predicted in the Standard Model

- Current cosmological neutrino mass bounds are very stringent. They are getting very close to the minimum expected values from the laboratory

- Given our assessment of possible systematic effects and statistical fluctuations we believe that there is currently no significant tension with laboratory

$$\sum m_\nu < 0.13\,\mathrm{eV}$$ at 95% CL seems like a conservative bound within ΛCDM

- Cosmological bounds can be significantly relaxed in extensions of ΛCDM. The only thing that cosmological observations can constrain is the energy density in neutrinos.

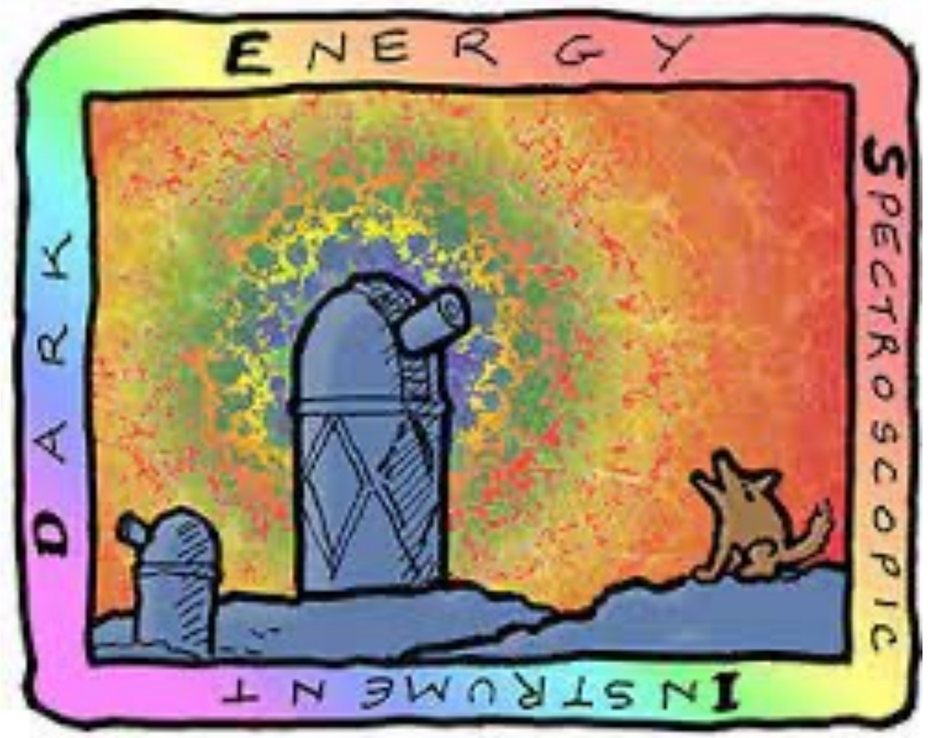
2007.04994: **Relaxing Cosmological Neutrino Mass Bounds with Unstable Neutrinos**

Miguel Escudero,[1a] Jacobo Lopez-Pavon,[2b] Nuria Rius,[3b] and Stefan Sandner,[4b]

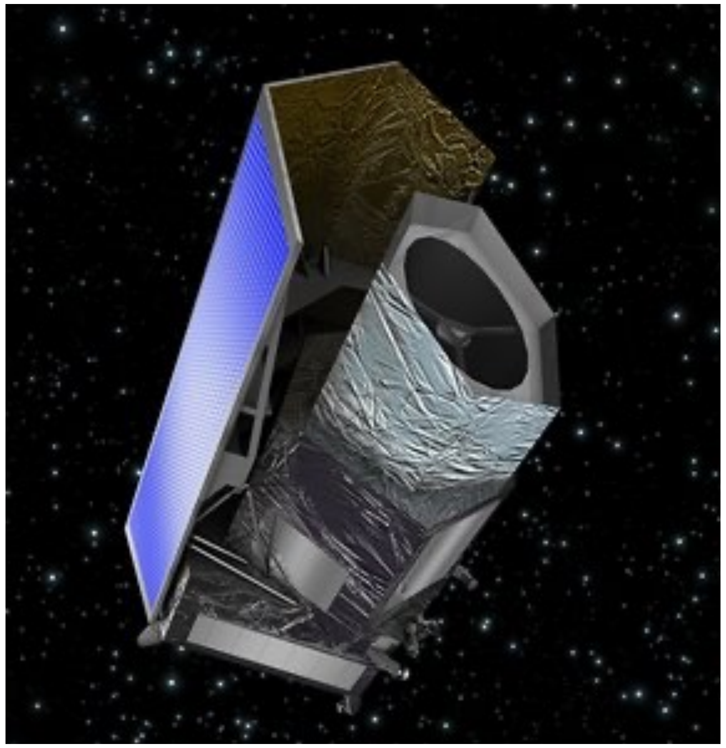
Outlook

The ongoing 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



DESI-Y3 BAO data has already been collected. Its analysis will be presented next year. This data release will clearly close the possibility of statistical fluctuations being behind the strong bound on the neutrino mass.

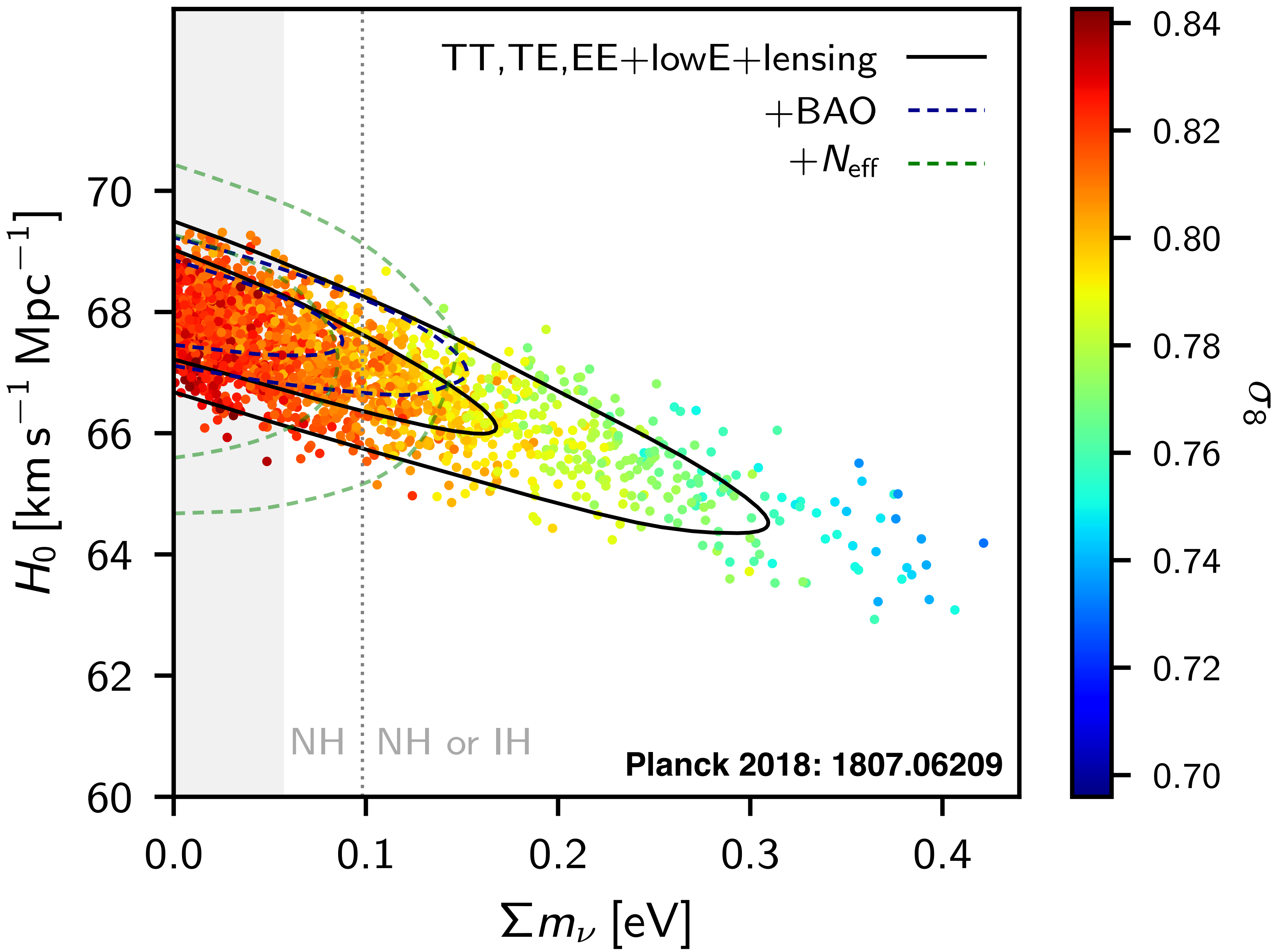
Euclid will provide also key information into the game in a couple of years.

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!**



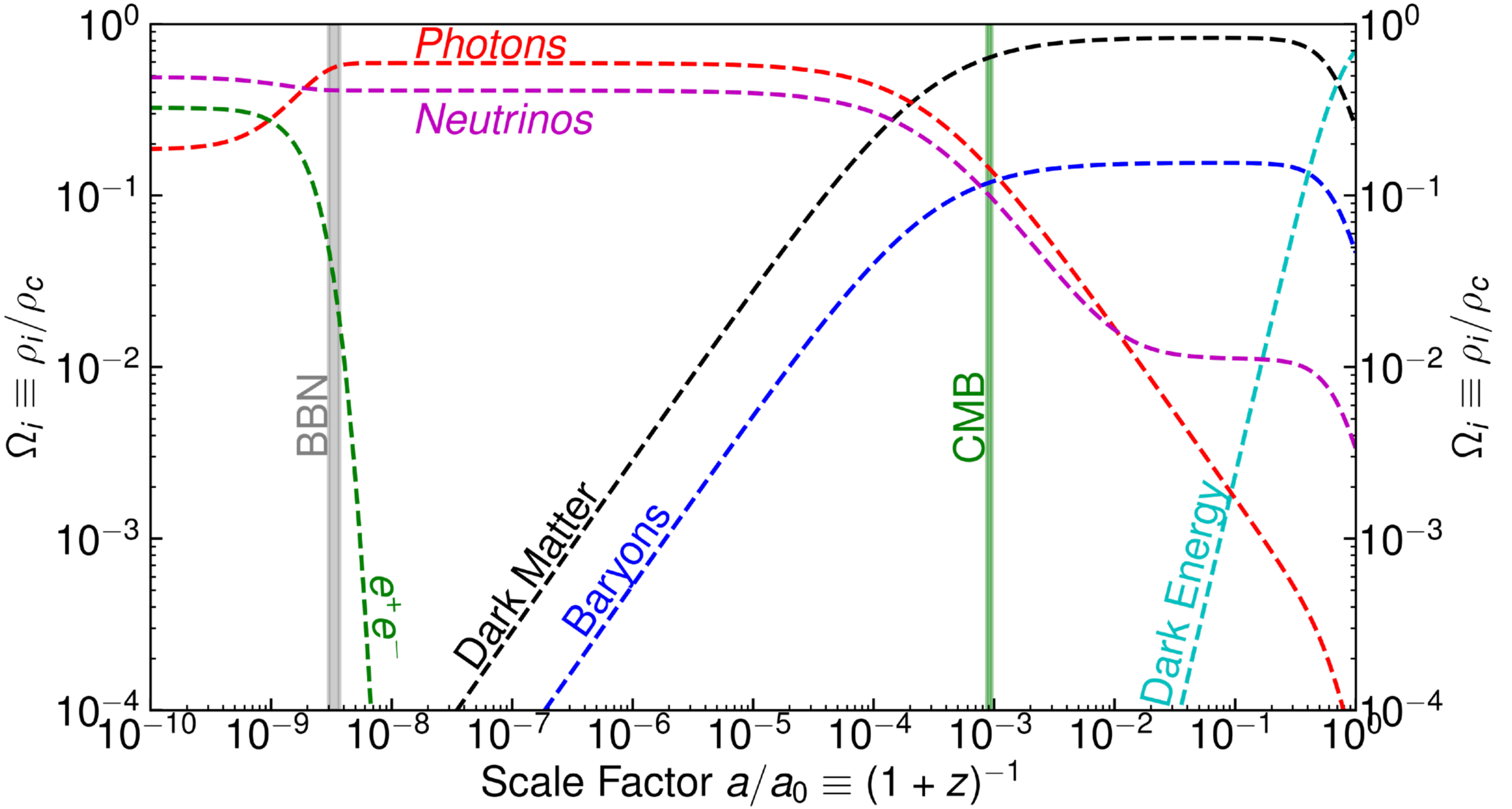
1) Will alter our inferences about neutrinos

2) Reduces our confidence on the standard cosmological model

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

Global Perspective

Standard Model Prediction



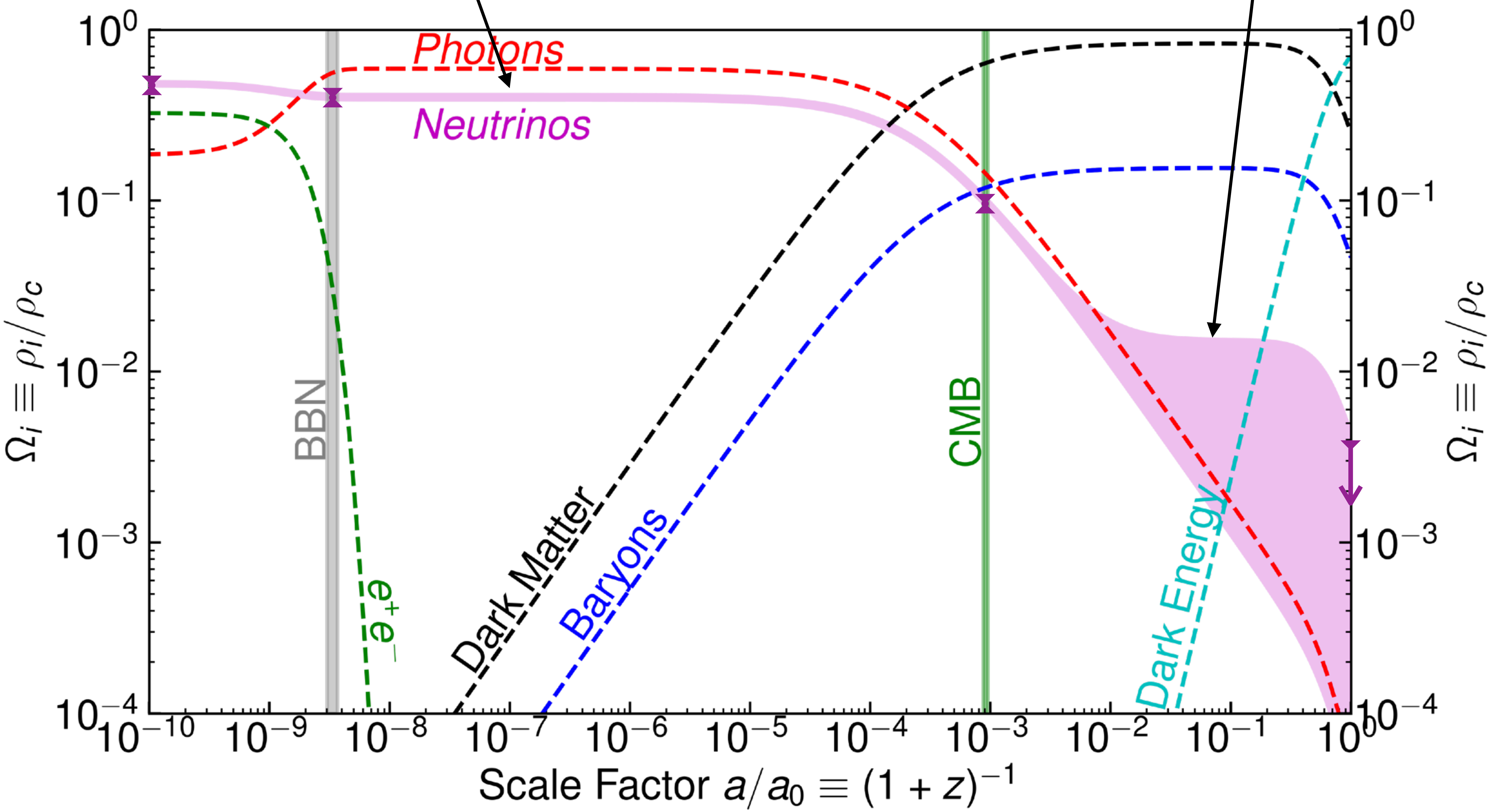
Global Perspective

Current knowledge:

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

(Planck+BAO)

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



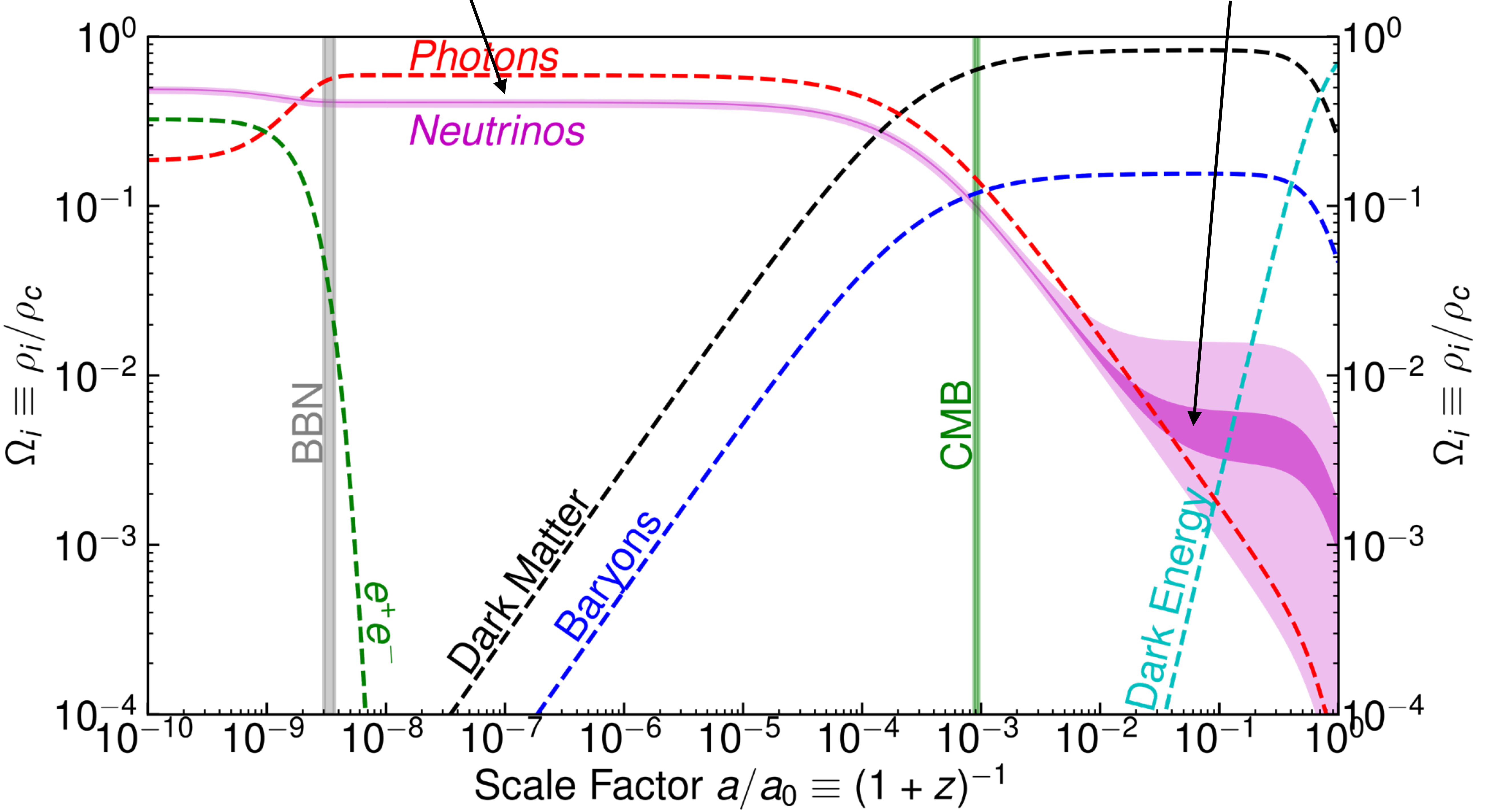
Global Perspective

In the next 5-6 years:

(DESI/Euclid + Planck)

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

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



ν

Time for Questions and Comments

Thank you for your attention!

miguel.escudero@cern.ch