Large Neutrino Mass Cosmologies and prospects for CNB detection

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Based on:

Alvey, Escudero, Sabti & Schwetz 2111.14870 [PRD]
Alvey, Escudero & Sabti 2111.12726 [JCAP]
Escudero, López-Pavón, Rius & Sandner 2007.04994 [JHEP]
Escudero & Fairbairn 1907.05425 [PRD]

Neutrino Theories Workshop
IFT, Madrid
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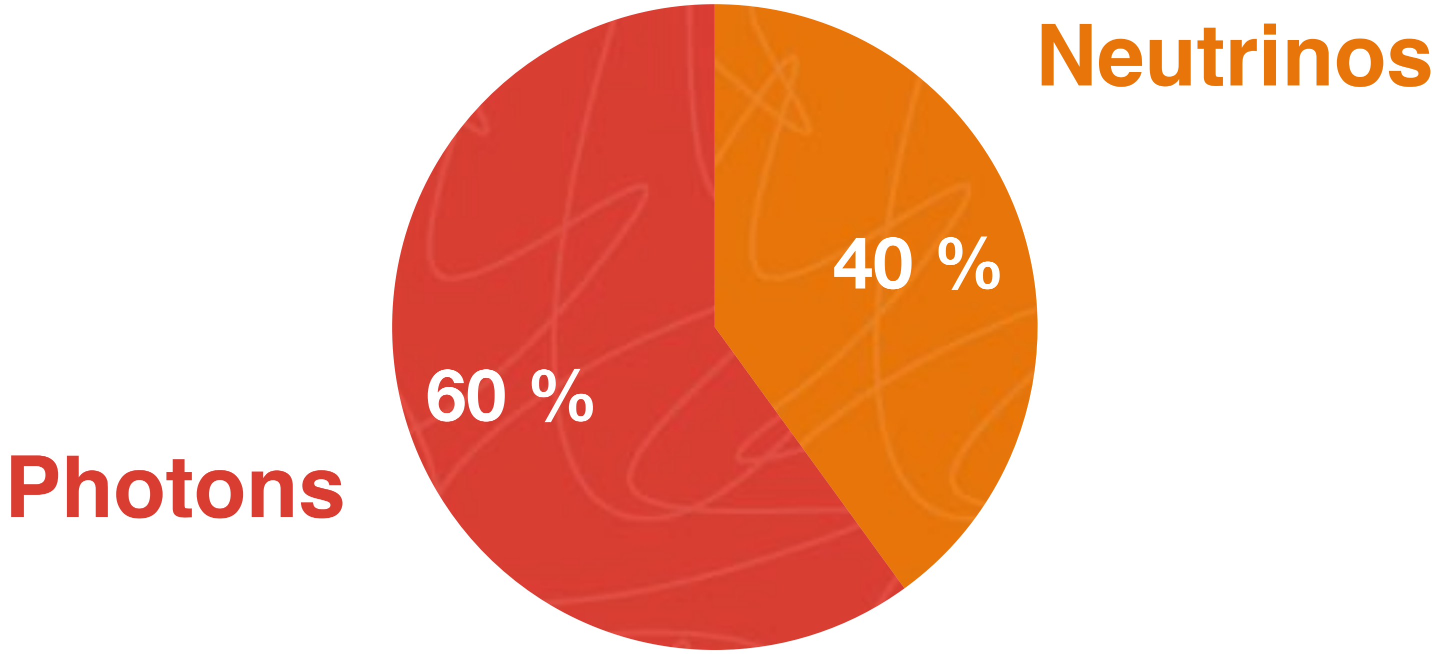
Motivation I

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

  However, as of today we do not know what the absolute neutrino mass scale is

- **Neutrinos are ubiquitous in Cosmology**



Use cosmological data to understand their properties $\boxed{\sum m_\nu}$

Motivation II

- **Within the standard cosmological model, cosmological neutrino mass bounds are more stringent than laboratory ones:**

Planck+BAO within ΛCDM: $\sum m_\nu < 0.12\,\mathrm{eV}$ **(95% CL)**

- **Many neutrino mass models have large regions of parameter space with $\Sigma m_\nu > 0.12$ eV.**

In fact, most of the 2-zero neutrino mass textures predict $\Sigma m_\nu > 0.12$ eV.

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

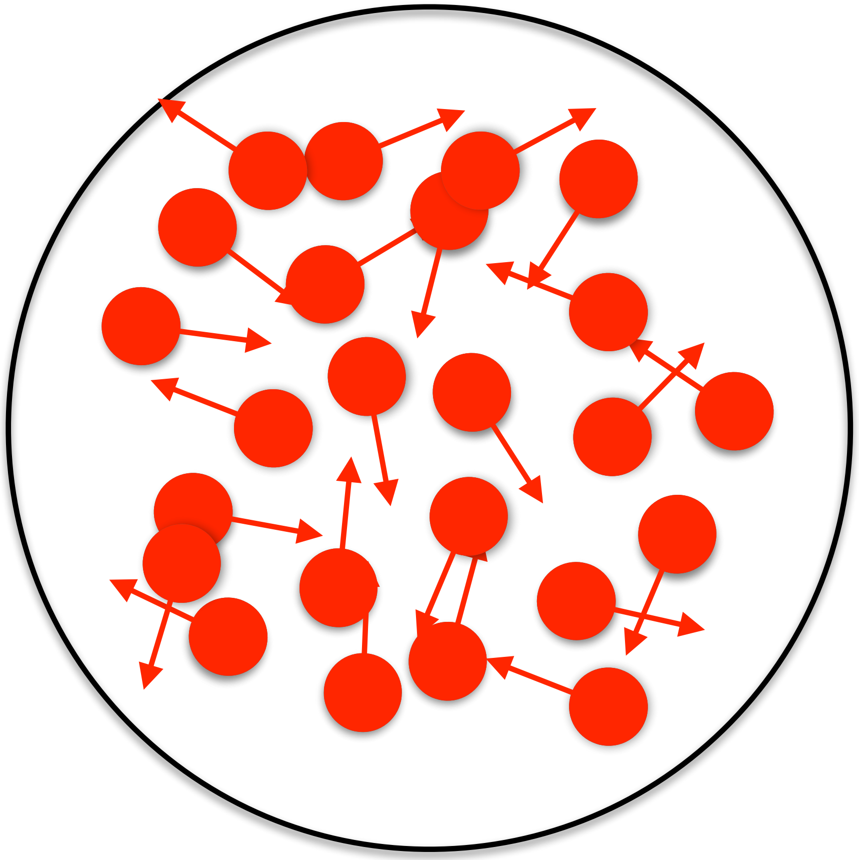
Importantly, all cosmological neutrino mass bounds are cosmological model dependent.

We therefore want to understand how sensitive are these bounds to the assumed cosmological model

Motivation III

- **The Cosmic Neutrino Background represents the last prediction from the Big Bang Theory to be directly tested!**

CNB



Detection prospects are strongly dependent upon what m_ν is.
The CNB could look very different depending upon the underlying cosmology.

A CNB search could be used to directly test different cosmological models!

The Plan

1) Cosmological neutrino mass bounds

2) Large neutrino mass cosmologies *(see also Jordi's talk)*

3) Prospects for the Cosmic Neutrino Background detection

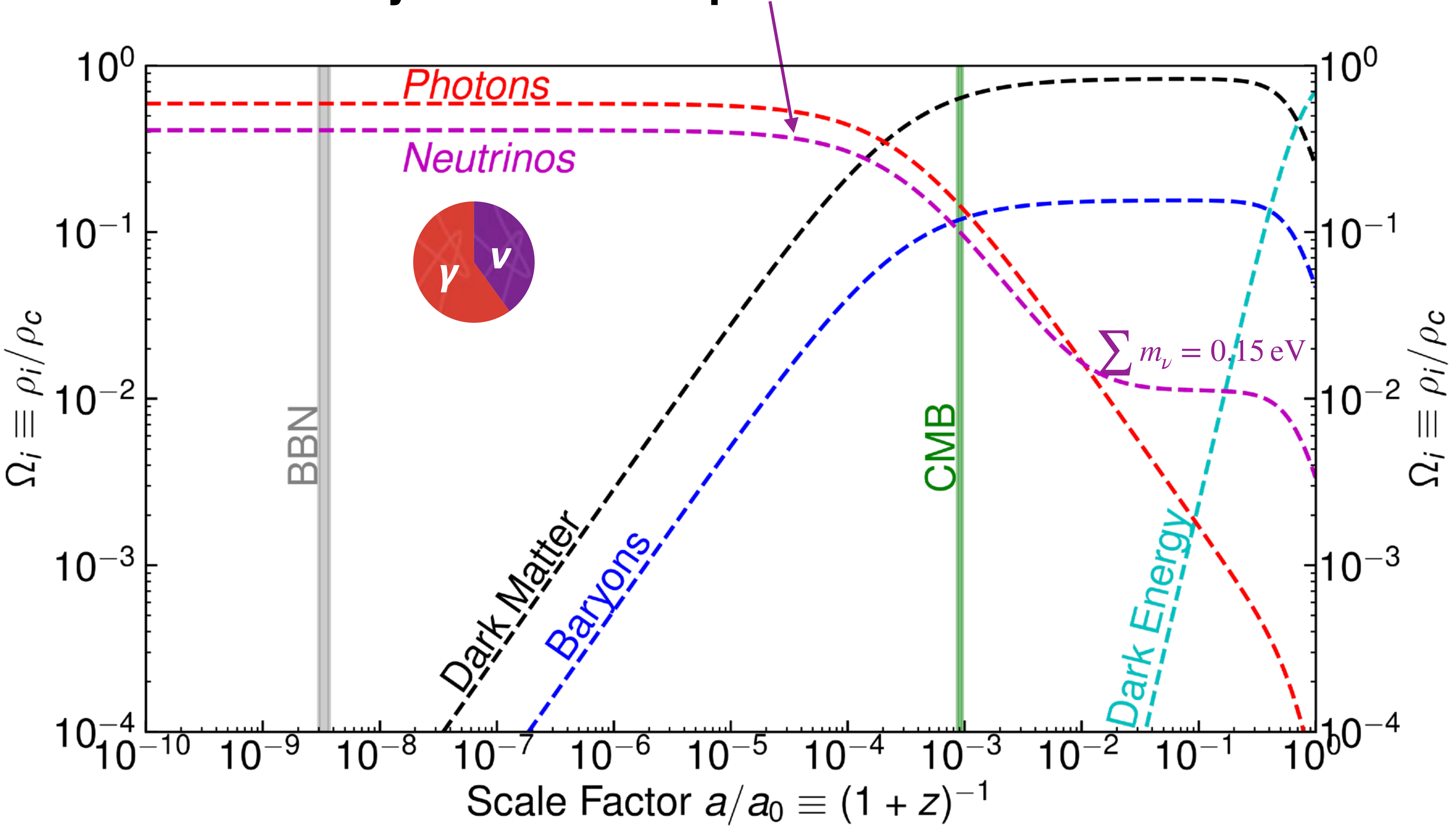
4) Conclusions and Outlook

Please, go NUTs:

I am very happy to take questions, comments, and criticism at any point in the talk!

Neutrino Evolution in ΛCDM

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

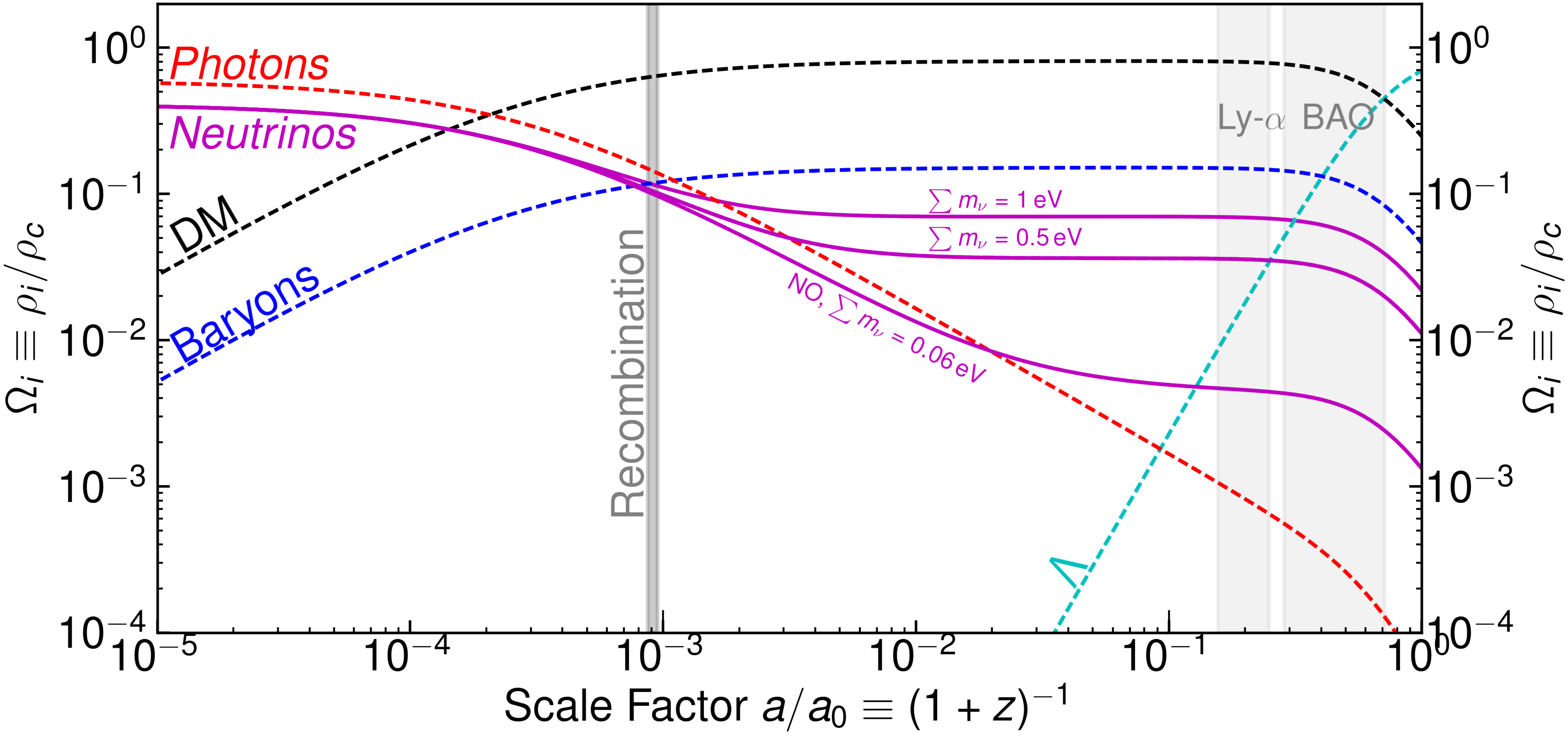


Non-Rel: $z_\nu^{\text{non-rel}} \simeq 200 \dfrac{m_\nu}{0.1\,\text{eV}}$

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

Why cosmology can constrain m_ν?

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

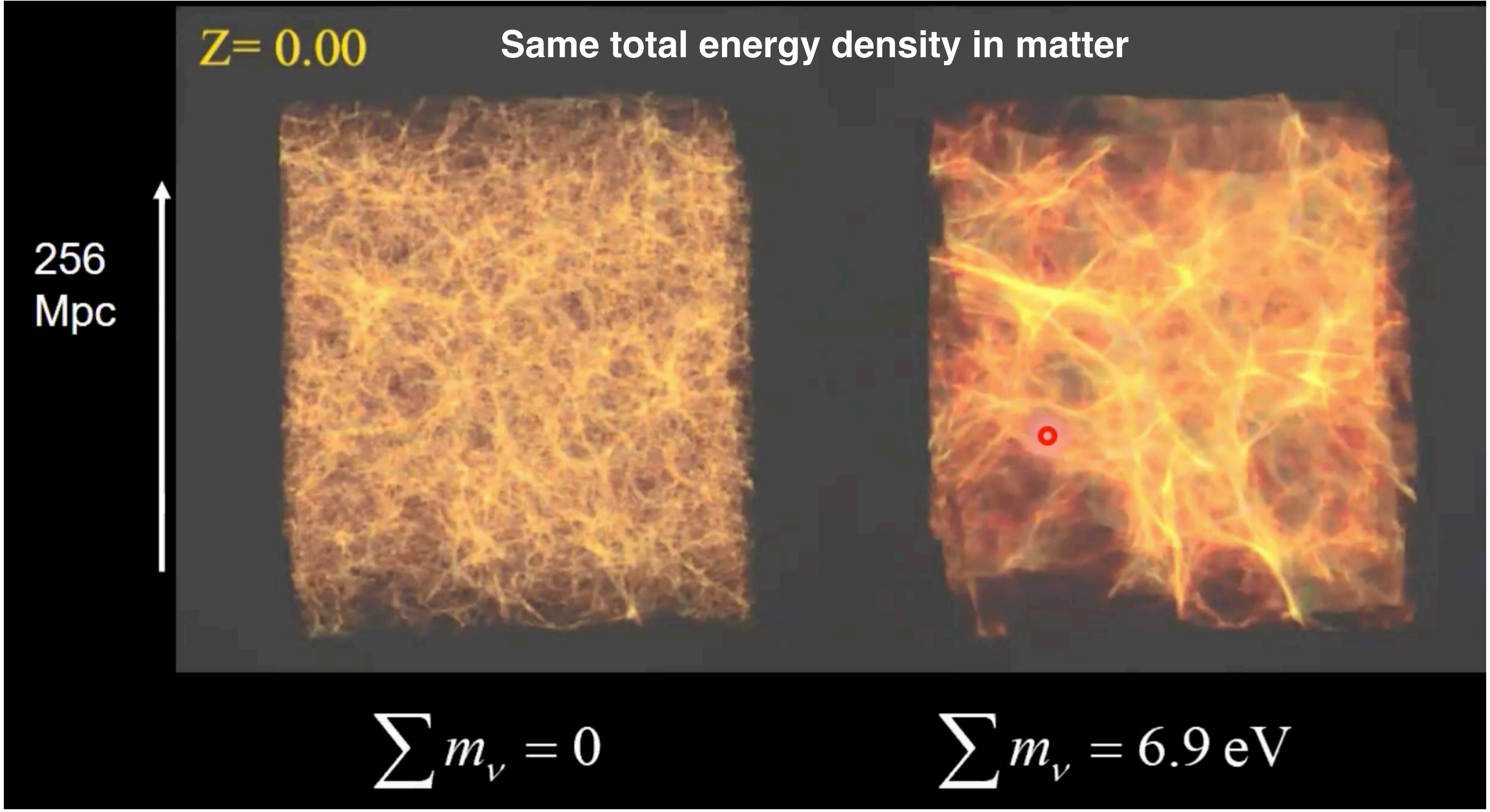


Non-Rel: $z_\nu^{\mathrm{non-rel}} \simeq 200 \frac{m_\nu}{0.1\,\mathrm{eV}}$ **Hot DM:** $\Omega_\nu h^2 = \frac{\sum m_\nu n_\nu}{\rho_c/h^2} = \sum m_\nu/(93.14\,\mathrm{eV})$

Why cosmology can constrain m_ν?

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

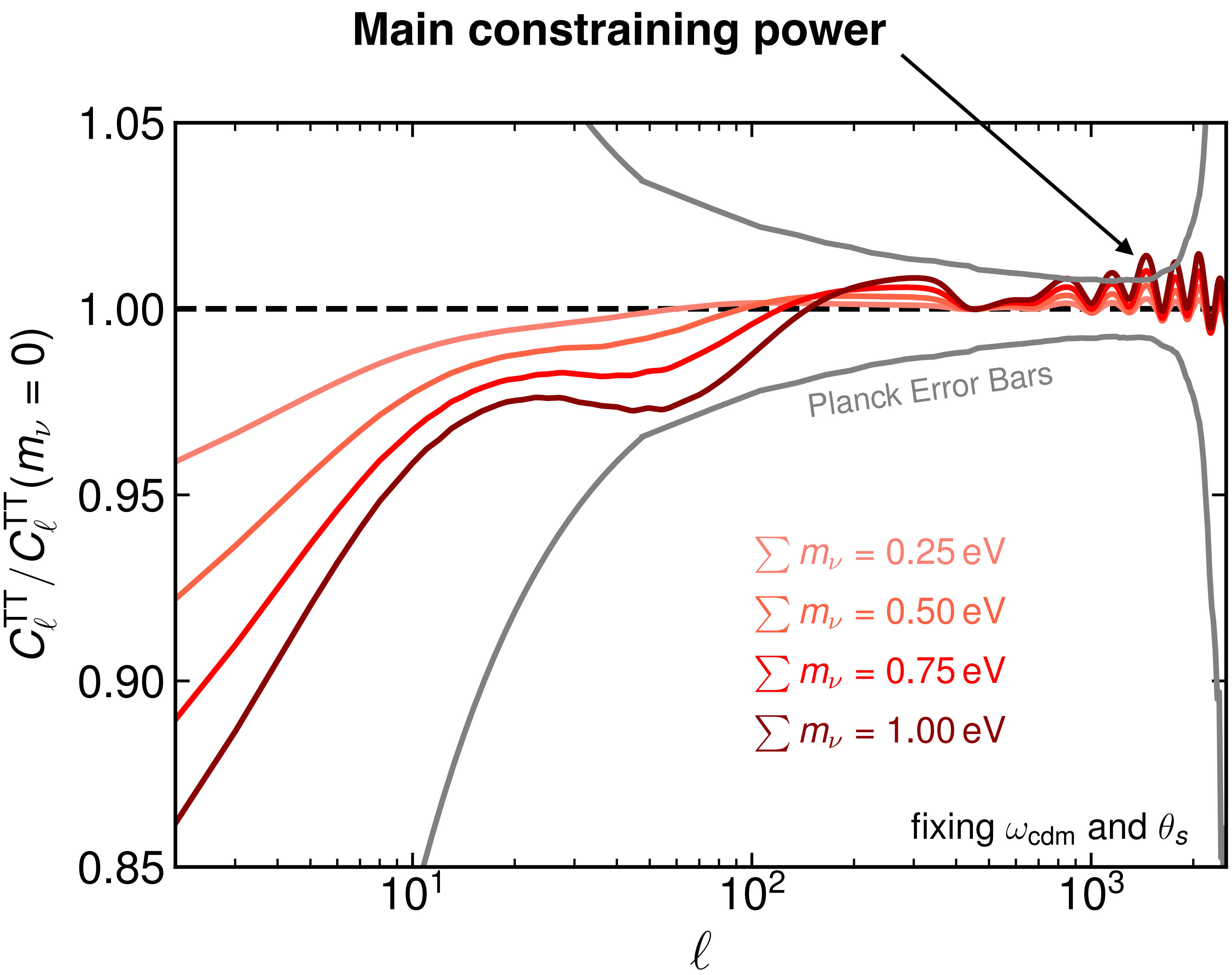
Taken from a talk by Steen Hannestad Link.



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

Effect on Cosmological Observables

Cosmic Microwave Background Anisotropies


Main constraining power

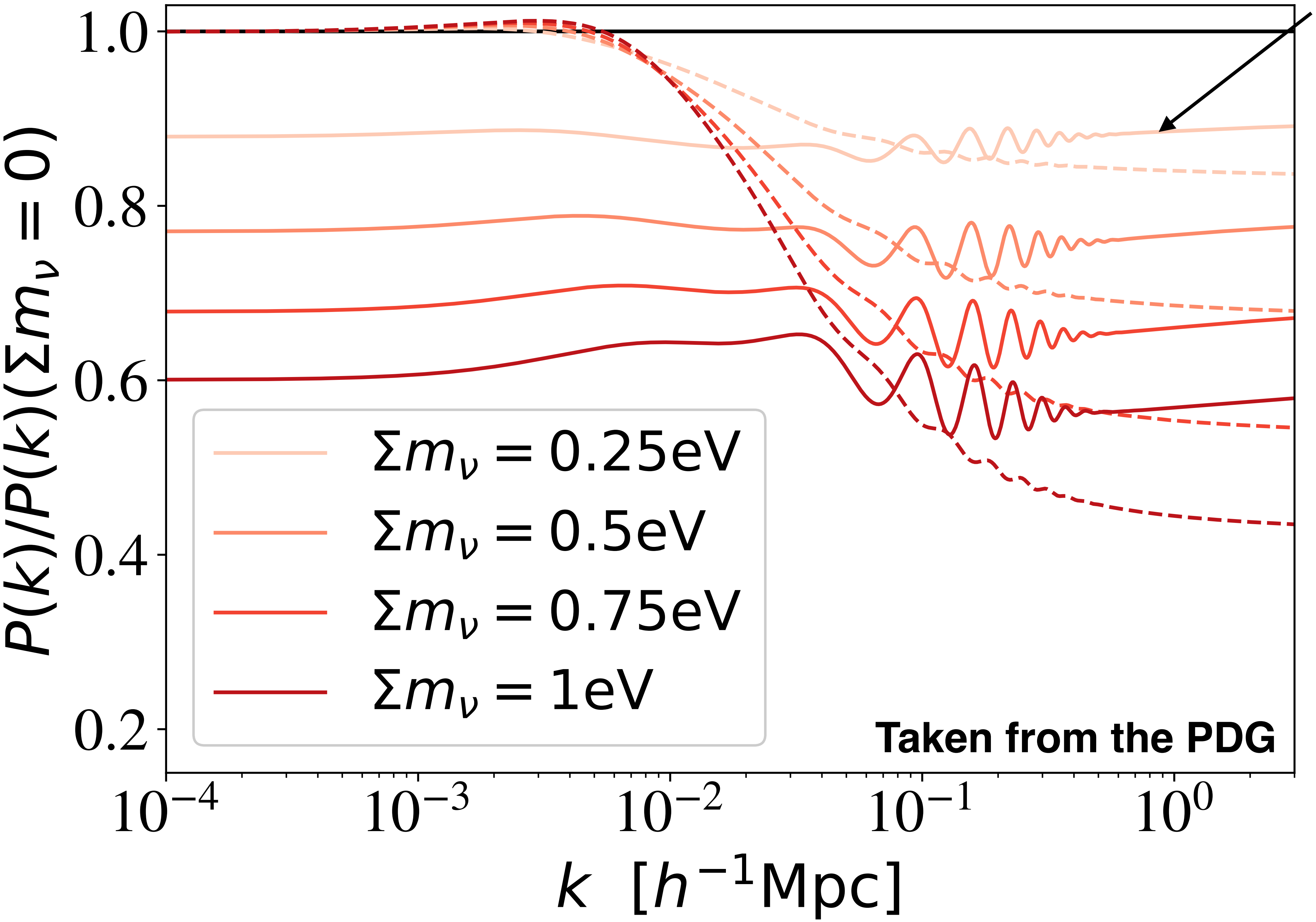
$$\sum m_\nu < 0.54\,\mathrm{eV}$$

(95 % CL, TT+lowE)

Effect on Cosmological Observables

Galaxy Surveys

Suppression from Ω_ν



Taken from the PDG

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)**

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

What about other non-linear cosmological data?

And, 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**

Neutrino Masses from Cosmology

Cosmological Model Dependence

Planck+BAO and 3 degenerate neutrinos

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

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

Neutrino Masses from Cosmology

Cosmological Model Dependence

Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

$\nu_i \to \nu_j \phi$

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

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

$\nu_i \to \nu_4 \phi$

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

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

Time Dependent Neutrino Masses

Late phase transition

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

Dvali & Funcke 1602.03191
Lorenz et al. 1811.01991 & 2102.13618

Ultralight scalar field screening

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

Esteban & Salvadó 2101.05804
Wetterich et al. 1009.2461 & 1407.8414

Non-standard Neutrino Populations

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

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

Farzan & Hannestad 1510.02201
Renk et al. 2009.03286

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

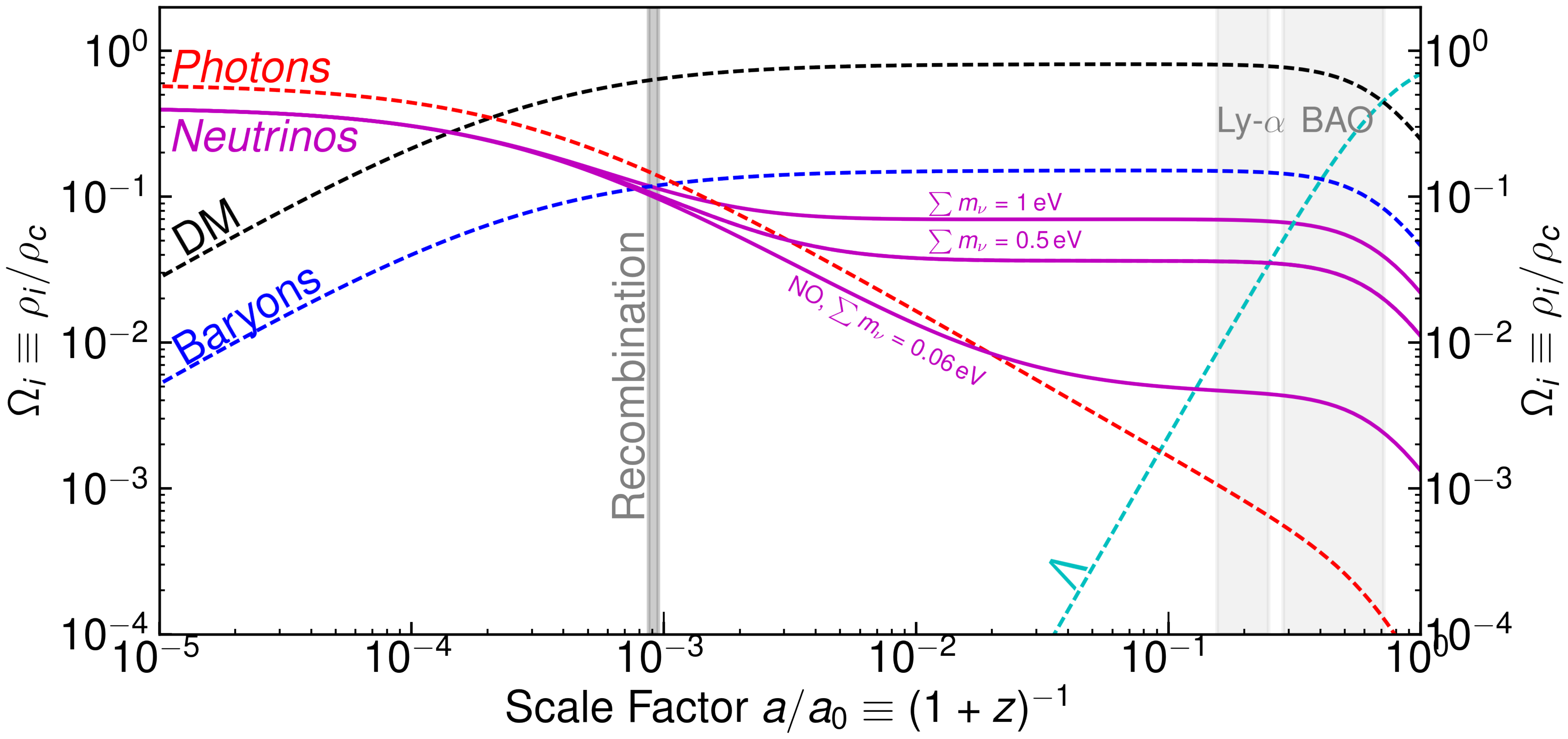
$$\sum m_\nu < 3\,\mathrm{eV}$$

Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.14870

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

But Why? and How?

Neutrino Masses from Cosmology



CMB peaks fix:

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

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

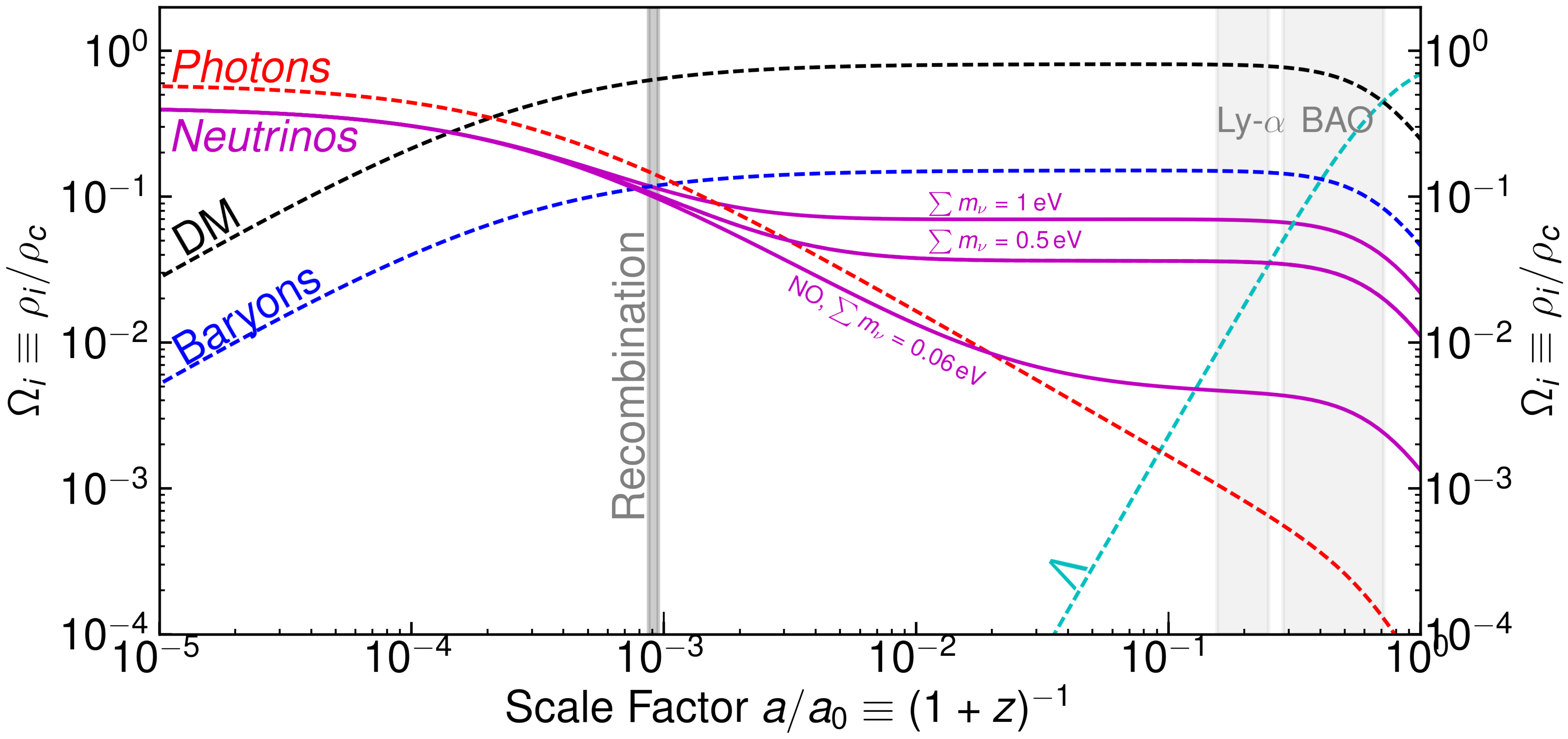
Comoving sound horizon (Early Universe)

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

Comoving angular diameter distance (Late Universe)

Massive neutrinos → $H(z')$

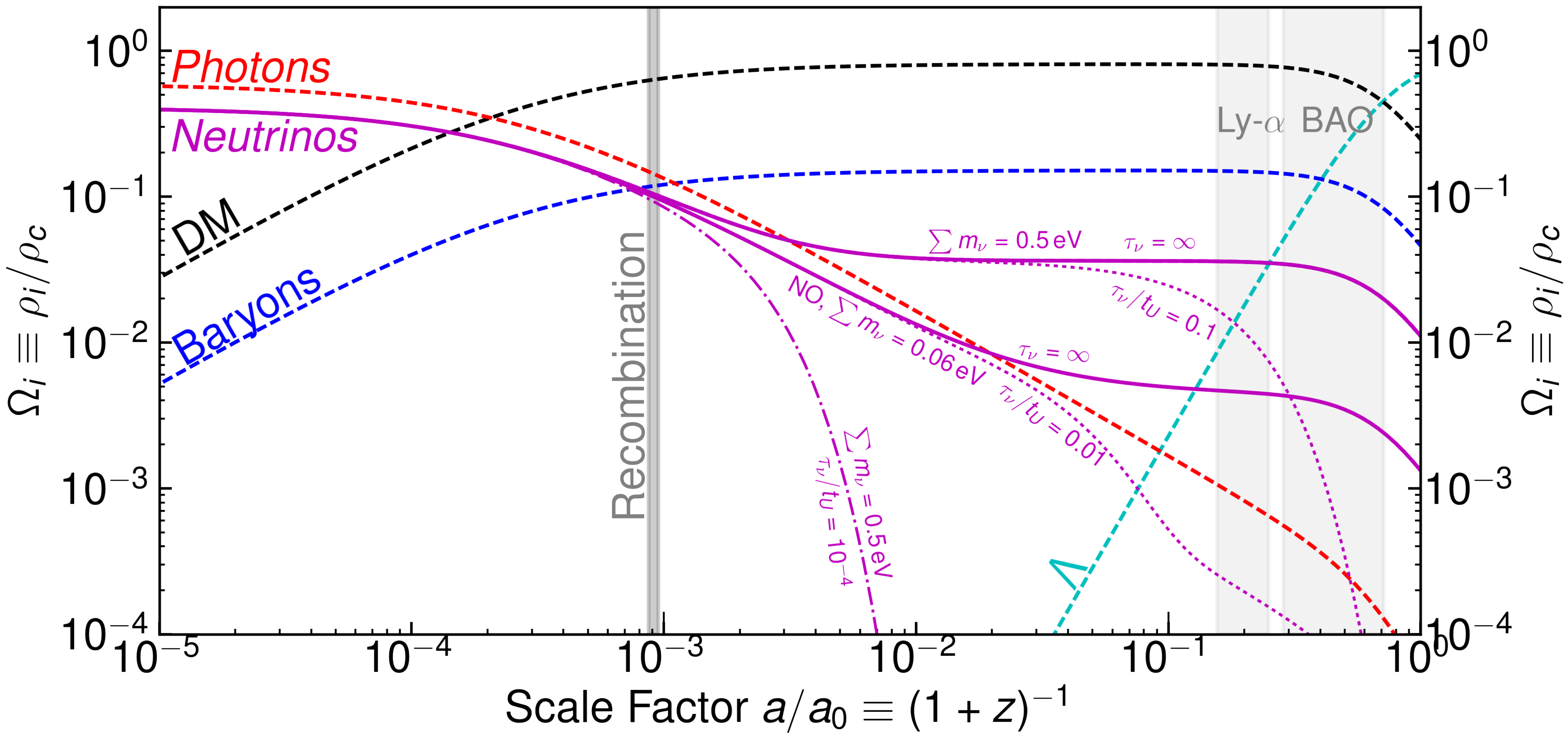
Neutrino Masses from Cosmology



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 ameliorate the bounds on Σm_ν!

Neutrino Masses from Cosmology

Cosmological Model Dependence

Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

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Oldengott, Wong et al. 2203.09075 & 2011.01502
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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 Decays into lighter neutrinos

$\nu_i \to \nu_j \phi$ Decays

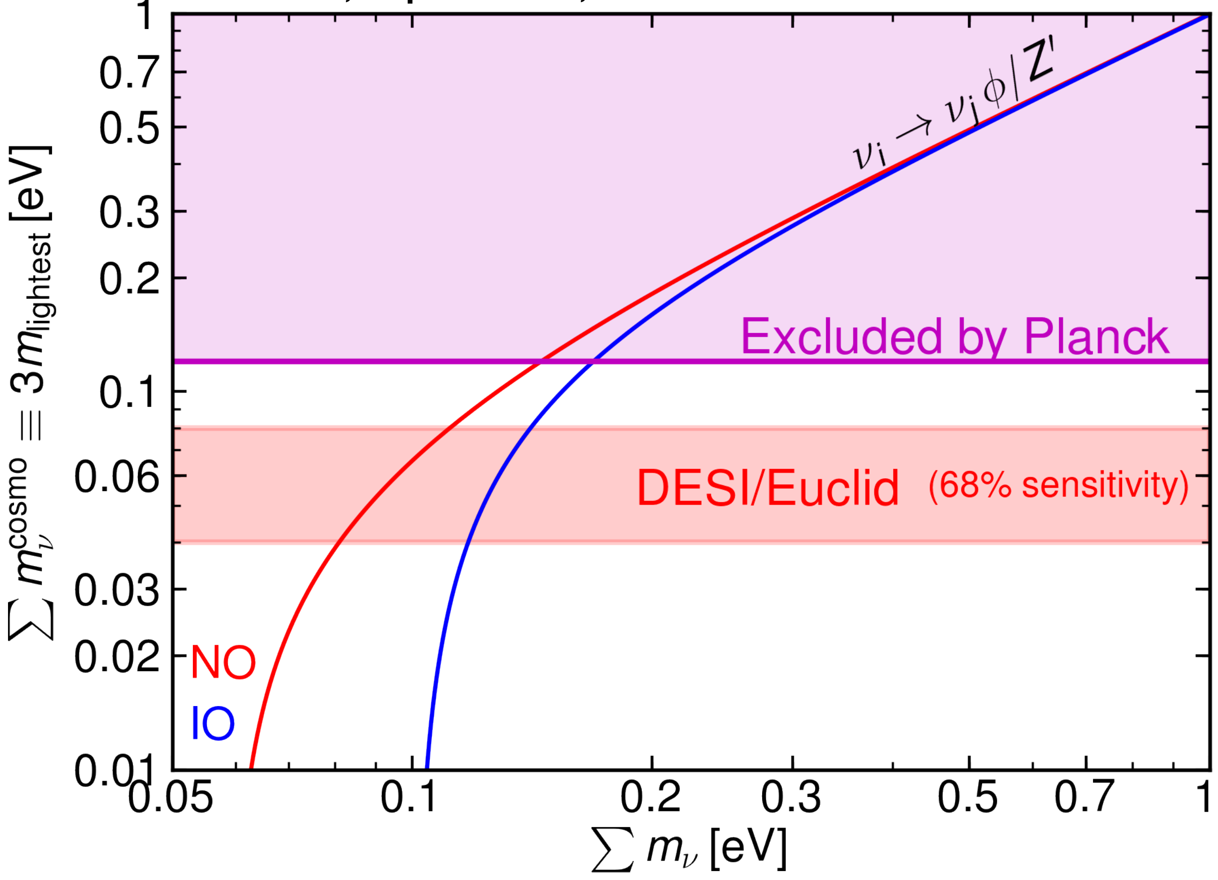
Theory: These happen naturally in scenarios with light mediators charged under horizontal flavor symmetries, e.g. $L_\mu - L_\tau$

see e.g. Gelmini & Valle PLB 142 (1984) 181 for a model and Escudero, López-Pavón, Rius & Sandner 2007.04994 for a taxonomy of possible decays

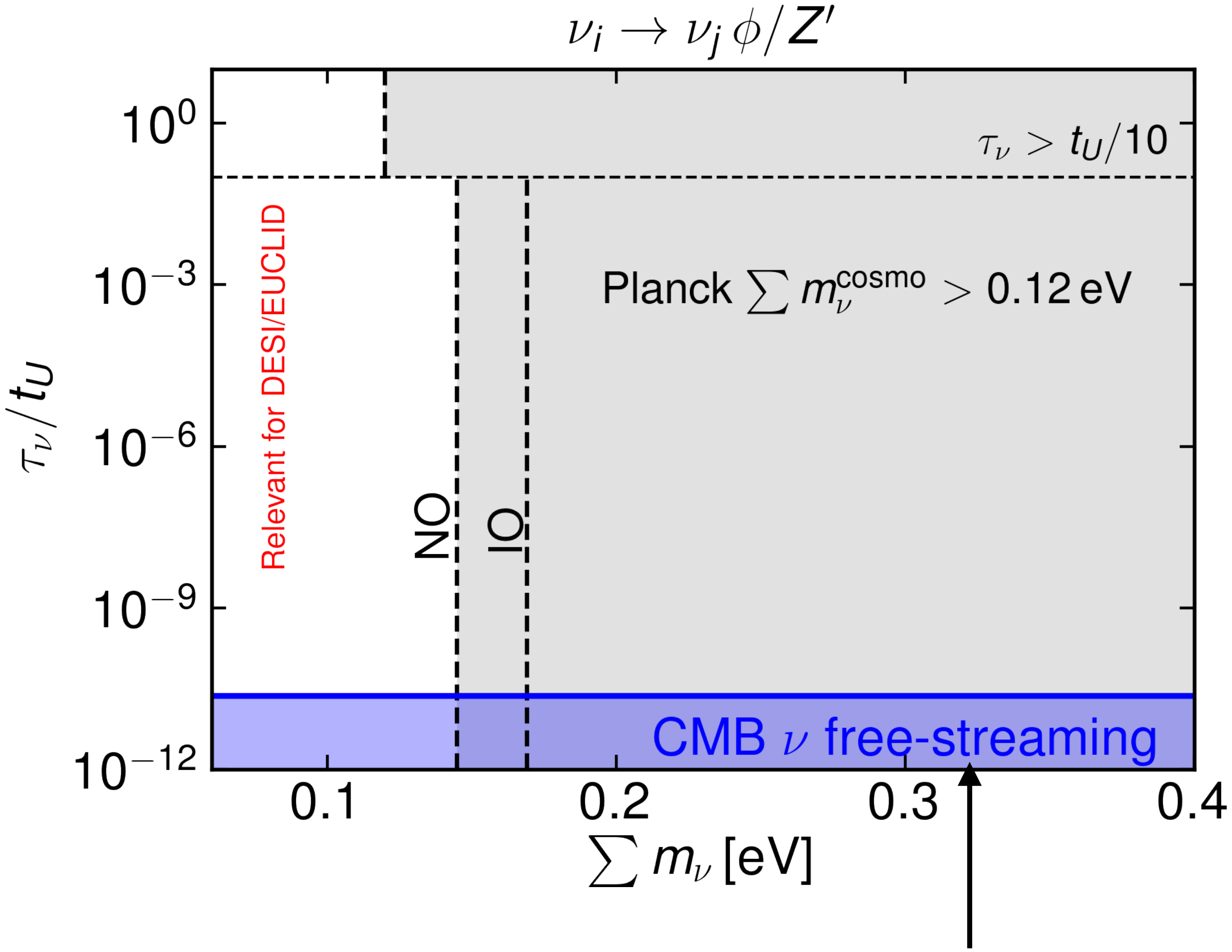
However, because there is a neutrino in the final state the mass bounds are expected to only be ameliorated mildly:

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

Escudero, López-Pavón, Rius & Sandner 2007.04994



Parameter space:



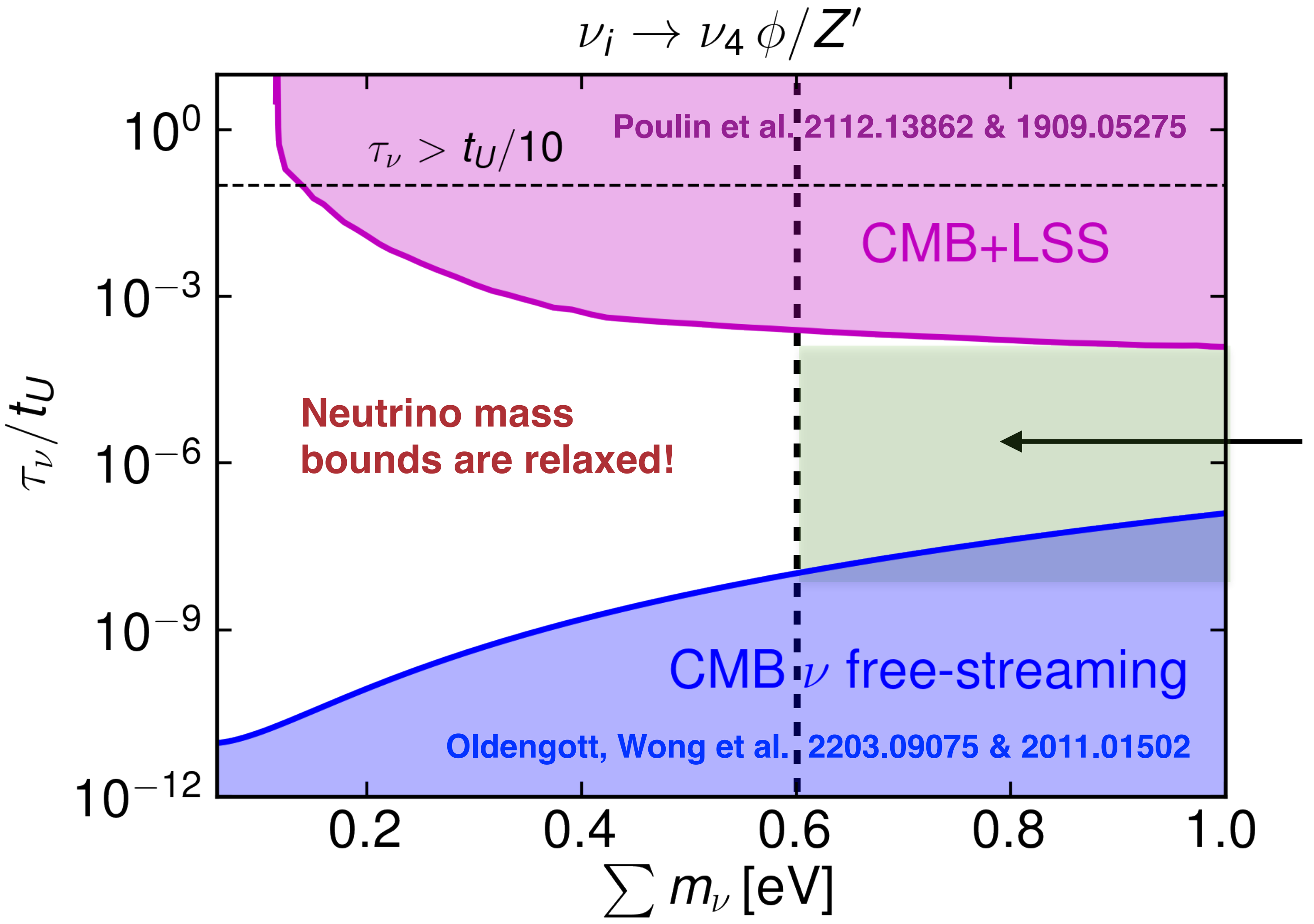
Oldengott, Wong et al. 2011.01502 & 2203.09075
see also Escudero & Fairbairn 1907.05425

Neutrino Decays into Massless States

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

Theory: One requires a very light boson and a very light sterile neutrino (which is lighter than active neutrinos). We have shown that decays of this type can be easily realized within the type-I seesaw scenario, in a model that is simple, minimal, and radiatively stable see Escudero, López-Pavón, Rius & Sandner 2007.04994

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

Time dependent m_ν

Neutrino masses from a late phase transition

Theory: There are somewhat intricate models by Dvali, Flucke & Vachaspati 1602.03191 & 2112.02107.

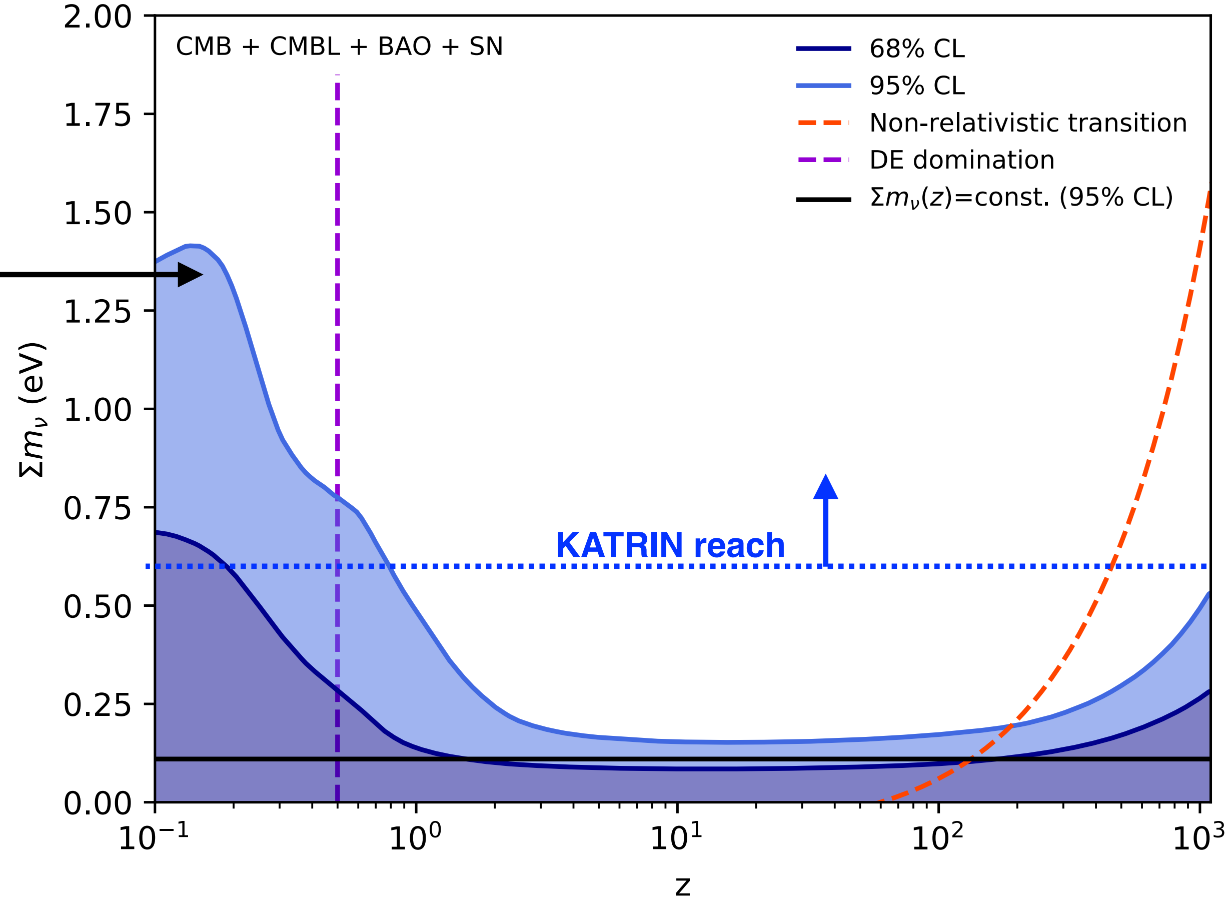
The idea is: $m_\nu = y\langle\phi\rangle \qquad \langle\phi\rangle = \begin{cases} 0 & \text{for } T > T_{\rm PT} \\ v_\phi & \text{for } T \leq T_{\rm PT} \end{cases}$

If $T_{\rm PT} \lesssim 10^{-3}\,{\rm eV}$ then the neutrino mass can bound can be relaxed

Importantly, cosmological data requires the phase transition to happen at very low redshift if the neutrino mass were to be large!

Lorenz, Funcke, Calabrese & Hannestad 1811.01991

Lorenz, Funcke, Löffler & Calabrese 2102.13618



Large Neutrino Mass Cosmologies

Neutrinos with non-standard distributions

Alvey, Escudero & Sabti 2111.12726
Oldengott et al. 1901.04352
Renk et al. 2009.03286.

Cosmology can only constrain energy densities, $H \propto \sqrt{\rho}$

When neutrinos are ultrarelativistic

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

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

Planck 2018

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

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

Planck 2018

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

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

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

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

Low Temperature Neutrinos and Dark Radiation

$n_\nu \sim T_\nu^3$ **and therefore if** $T_\nu < T_\nu^{\rm SM}$ **the cosmological bound can be ameliorated.**

However, $N_{\rm eff} \sim (T_\nu/T_\gamma)^4$**. This means that one needs to introduce some dark radiation such that** $N_{\rm eff} = N_{\rm eff}^\nu + N_{\rm eff}^{\rm DR} \simeq 3$

Farzan & Hannestad in 1510.02201 showed a way of how to do this:

One needs $\mathcal{O}(10)$ **new massless species and a boson that interacts with neutrinos and these new states in the early Universe before recombination** $10\,{\rm eV} \lesssim T \lesssim 100\,{\rm keV}$

Neutrinos with a Large Momentum

$N_{\rm eff} \sim \rho_\nu|_{T\gg m_\nu} \propto \langle p_\nu \rangle\, n_\nu$**. That means that if** $\langle p_\nu \rangle \gg \langle p_\nu \rangle|_{\rm SM}$ **then** n_ν **could be much smaller while having the right** $N_{\rm eff}$ **and a larger neutrino mass**

As far as I know there is no known mechanism capable of producing a much larger neutrino momentum and a smaller number density. Perhaps $\nu\bar{\nu}\nu\bar{\nu} \to \nu\bar{\nu}$**?**

Summary

- **Current cosmological bounds are dominated by Planck and this makes them robust**
- **However, all cosmological neutrino mass bounds are cosmological model dependent**
- **The mass bound is rather insensitive to typical modifications of the standard cosmological model**
- **There exist, however, several scenarios where the neutrino mass bound can be substantially relaxed and that are in agreement with all known cosmological data:**

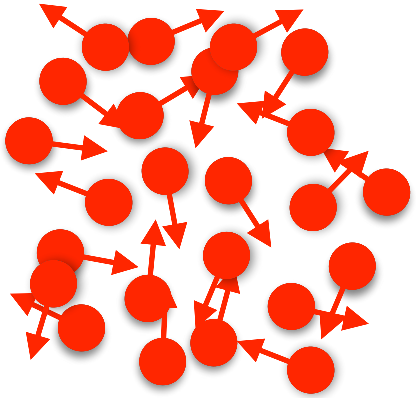
Invisible neutrino decays

Time dependent neutrino masses

Non-standard neutrino populations

The Cosmic Neutrino Background

The exact properties of the Cosmic Neutrino Background are cosmological model dependent



Importantly, the detection prospects are strongly dependent upon what the neutrino mass is!

Previous studies focused on the detection prospects in ΛCDM.
We wanted to see what happens in non-standard cosmologies:

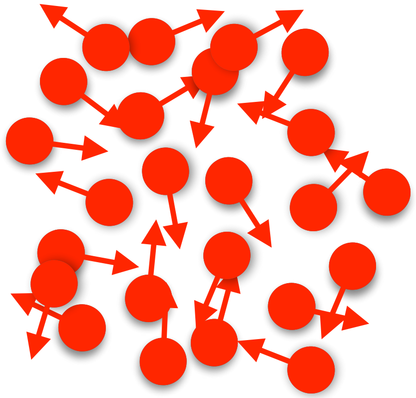
Alvey, Escudero, Sabti & Schwetz [[2111.14870]]

Direct Detection of the CNB

Can we detect the Cosmic Relic Neutrino Background in the laboratory?

Very very challenging, but potentially, Yes!

Expected ΛCDM properties



$$n_\nu^{\rm SM} \simeq 56\,{\rm cm}^{-3}$$ **Large number density**

$$T_\nu^{\rm SM} = T_\gamma/1.4 \simeq 1.95\,{\rm K}$$ **Very low energetic**

Perhaps the best search strategy is via capture in beta decaying nuclei

$$\boxed{\nu_e + {}^3{\rm H} \to e^- + {}^3{\rm He}^+}$$

Weinberg [1962]

Indeed, a recent search at KATRIN was able to bound

$$\boxed{n_\nu < 10^{10}\, n_\nu^{\rm SM}}$$

[2202.04587]

The PTOLEMY collaboration has taken seriously the possibility of actually detecting it [1808.01892, 1902.05508, 2203.11228]

Direct Detection of the CNB

Some experimental challenges:

Low number of events

$$\Gamma_{\nu_e + {}^3\mathrm{H} \to e^- + {}^3\mathrm{He}^+} \sim \frac{4(8)}{\mathrm{year}} \frac{M_T}{100\ \mathrm{g}} \frac{n_\nu}{56\,\mathrm{cm}^{-3}}$$

see e.g. Long, Lunardini & Sabancilar 1405.7654

Huge beta background

$${}^3\mathrm{H} \to e^- + {}^3\mathrm{He}^+ + \bar{\nu}_e \longrightarrow$$

High energy resolution needed

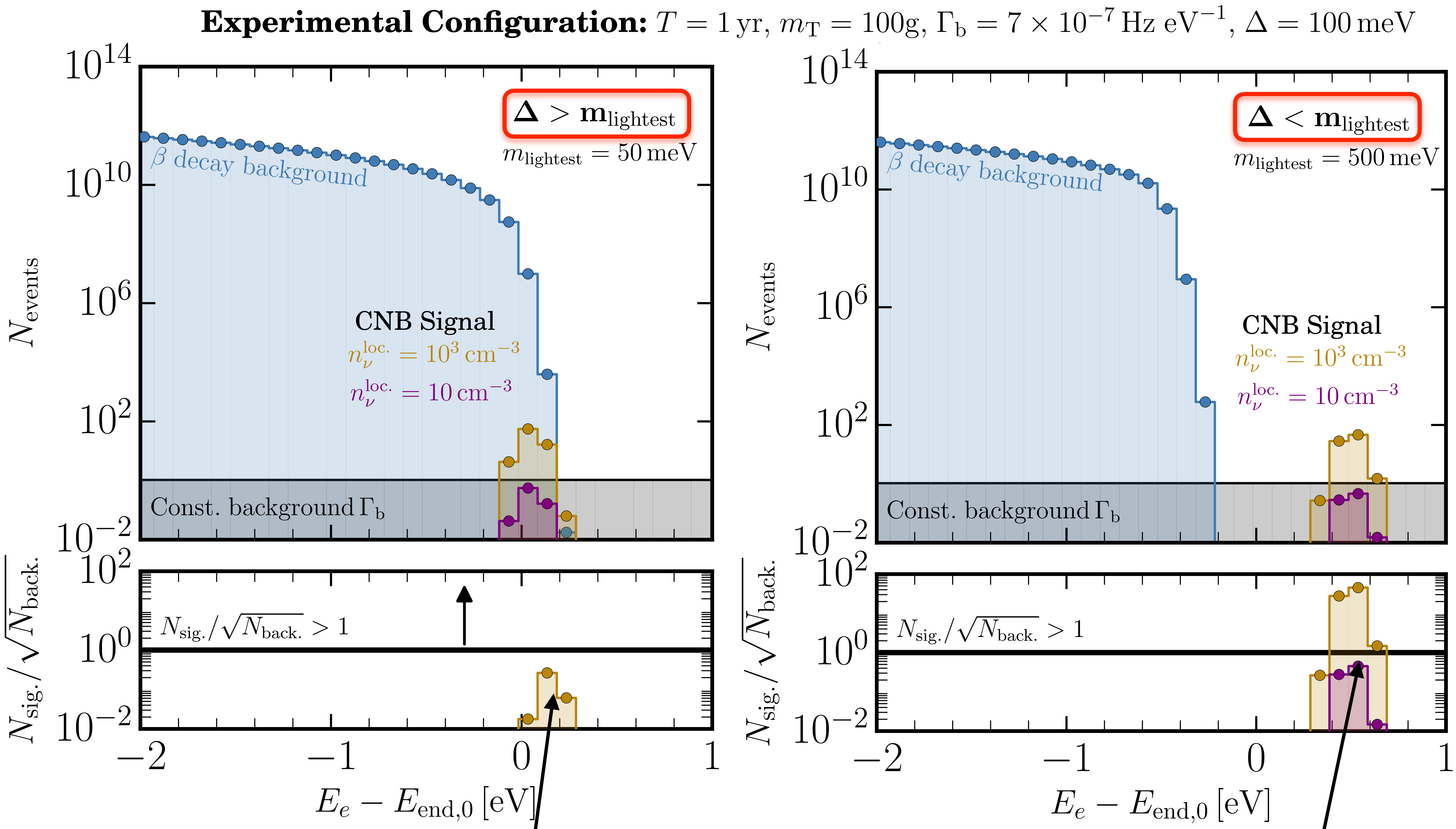
$$\Delta \lesssim m_\nu$$

Physical challenges:

The deposition of ${}^3\mathrm{H}$ on graphene will in turn lead to a smearing of the spectrum with at least $\Delta E_e \sim 0.2\,\mathrm{eV}$ **Cheipesh, Cheianov & Boyarsky [2101.10069], Nussinov & Nussinov [2108.03695]**
The PTOLEMY collaboration is looking at potential remedies for this [2203.11228].
They suggest using perhaps tubularly shaped graphene sheets.

Direct Detection of the CNB

The energy resolution required for the detector makes very complicated the detection



Experimental Configuration: $T = 1\,\mathrm{yr}$, $m_\mathrm{T} = 100\mathrm{g}$, $\Gamma_\mathrm{b} = 7\times10^{-7}\,\mathrm{Hz\,eV^{-1}}$, $\Delta = 100\,\mathrm{meV}$

No detection if $\Delta > m_\nu$

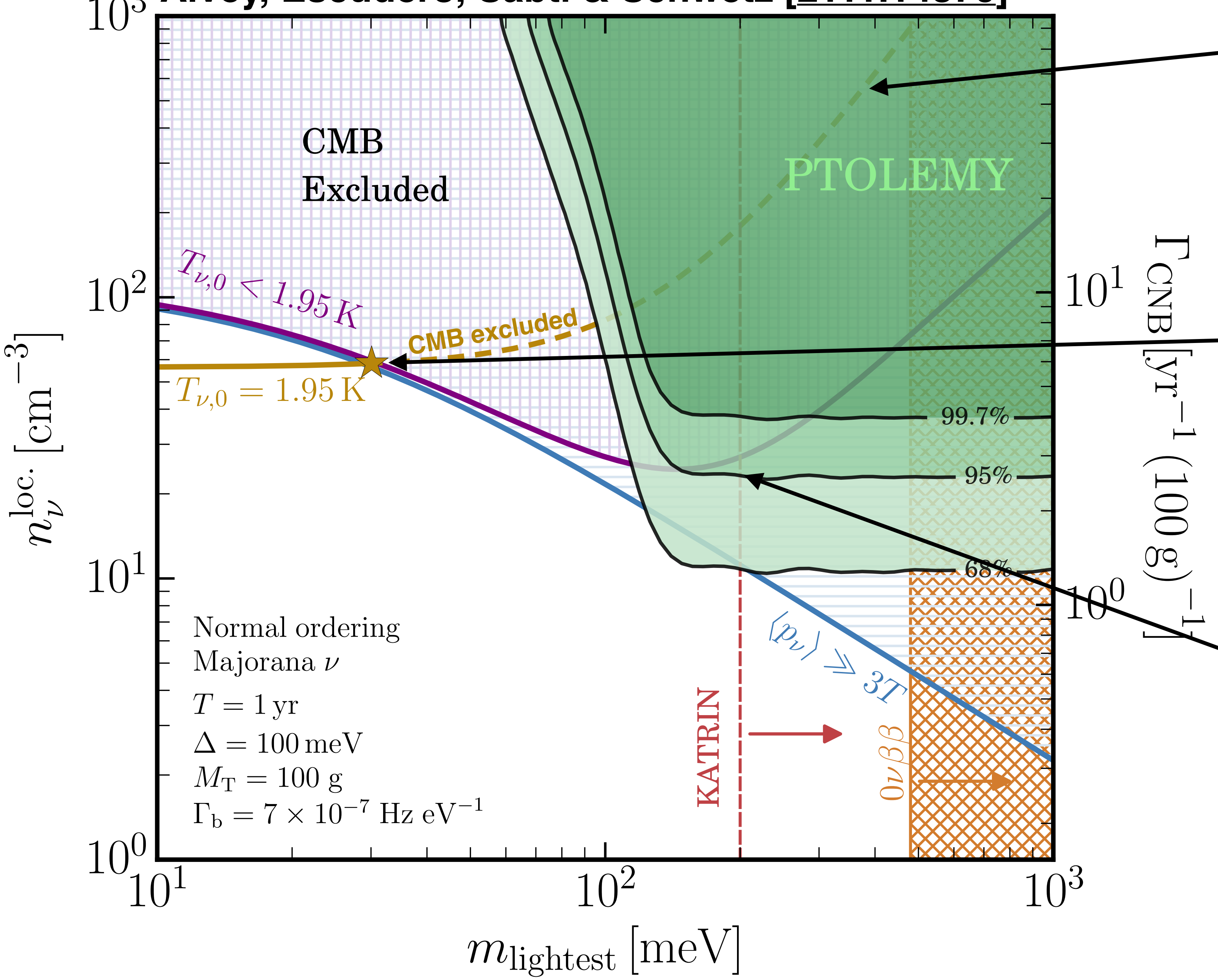
Detection possible if $\Delta < m_\nu$

But with a high exposure and low background

Direct Detection of the CNB

Despite these challenges, it appears necessary to understand in detail the required experimental sensitivities in standard and non-standard cosmologies:

Alvey, Escudero, Sabti & Schwetz [2111.14870]



0) Effect of neutrino capture by the MW halo

Ringwald & Wong hep-ph/0408241

1) Detecting the CNB within ΛCDM, is very very challenging

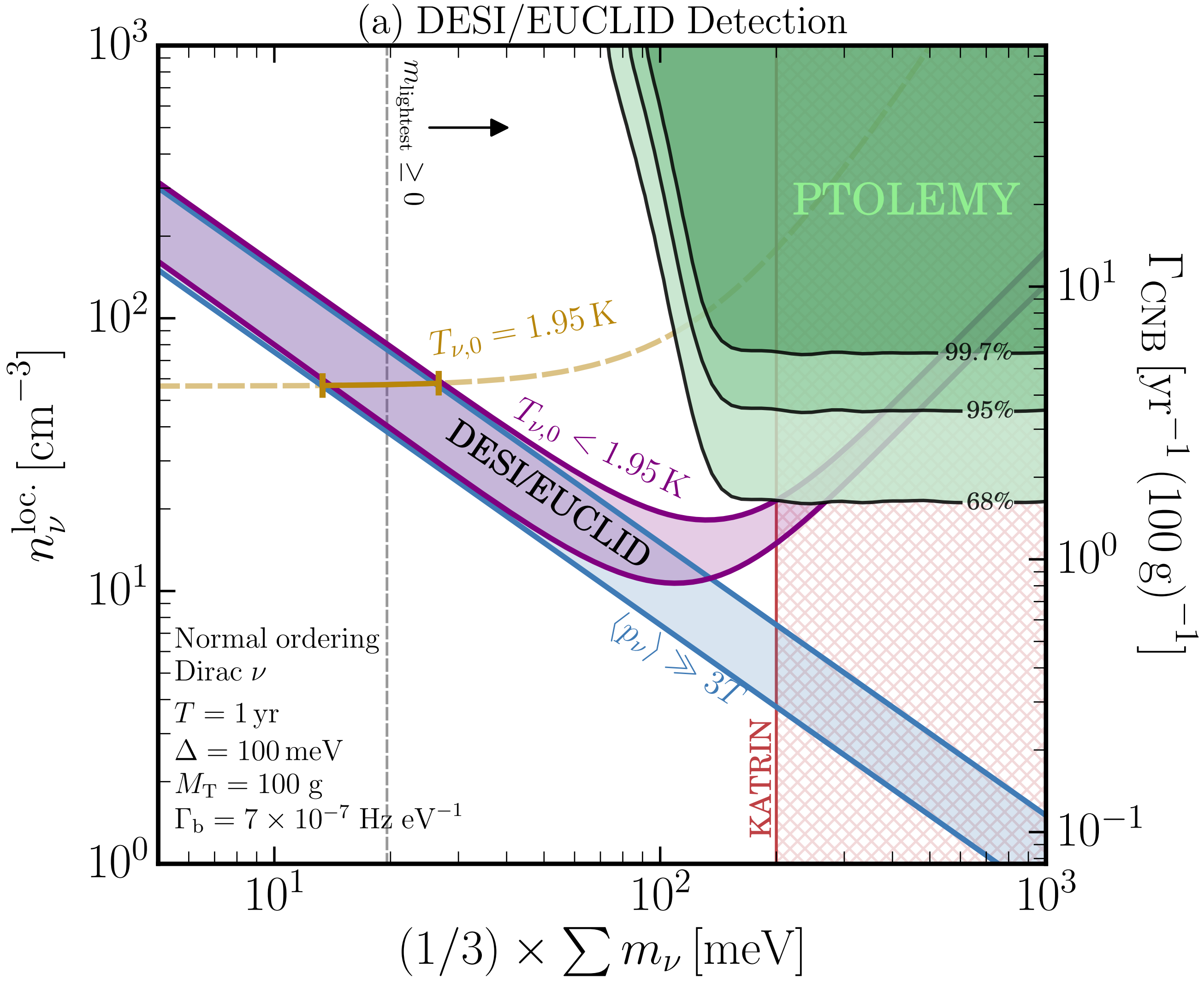
2) However, in some non-standard cosmologies the detection may be feasible. In particular, if KATRIN detects something!

Cosmic Relic Neutrino Background

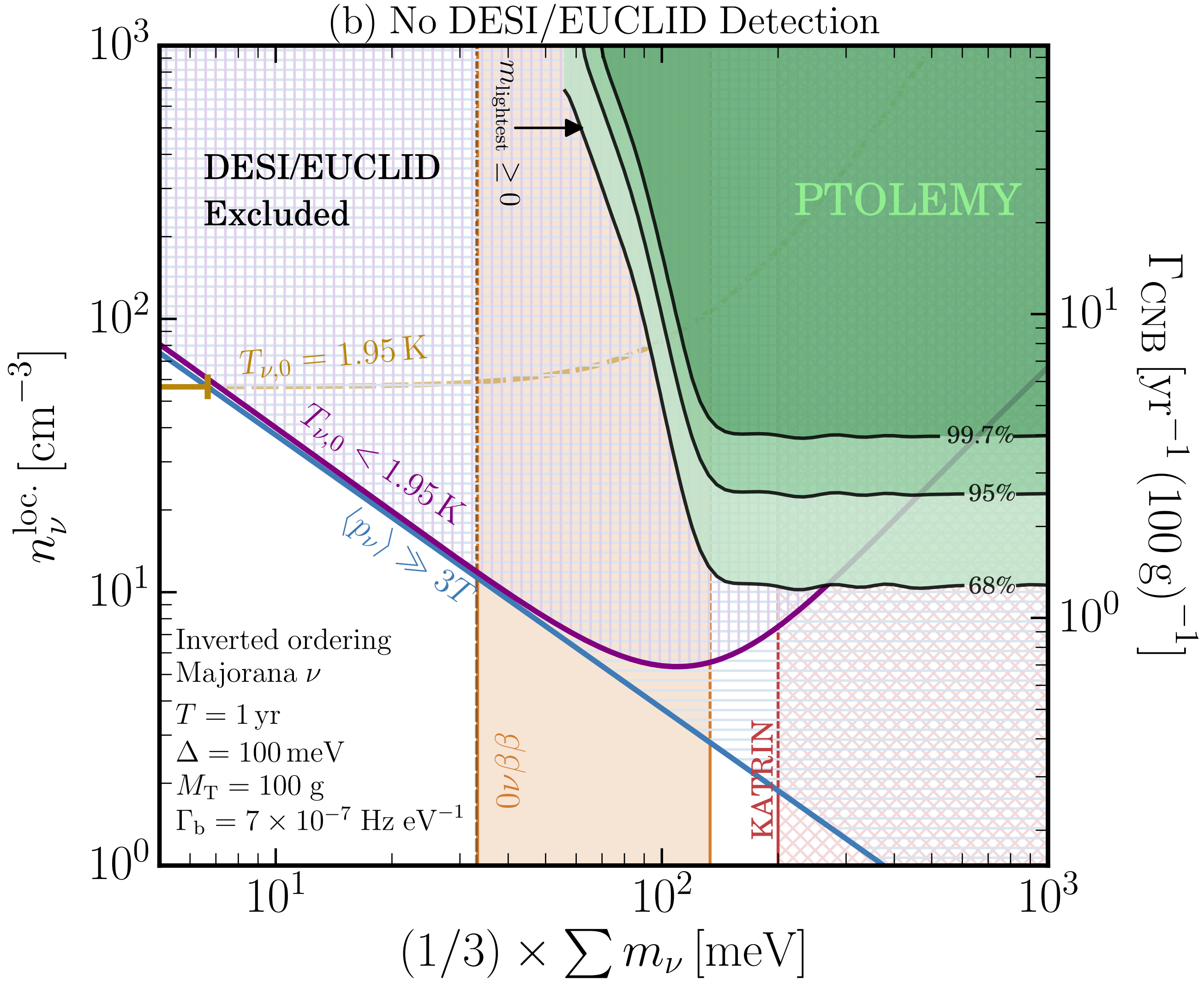
In the next ~ 5 years we expect to detect the effect of the neutrino mass in cosmology with DESI and EUCLID (see Massi's talk last week):

$$\sigma(\sum m_\nu) = 0.02\,\mathrm{eV}$$

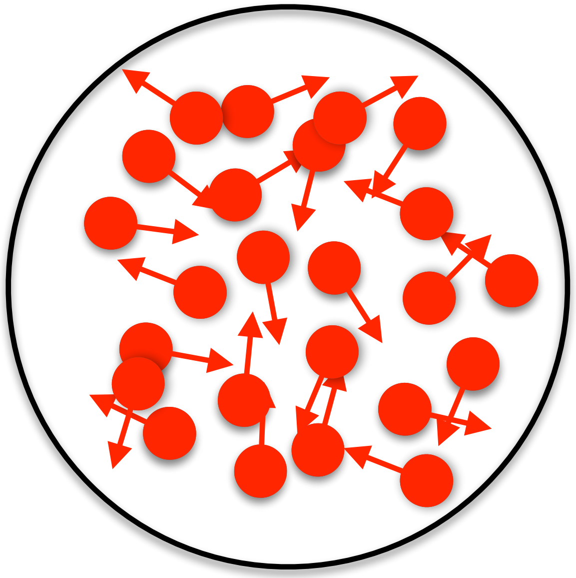
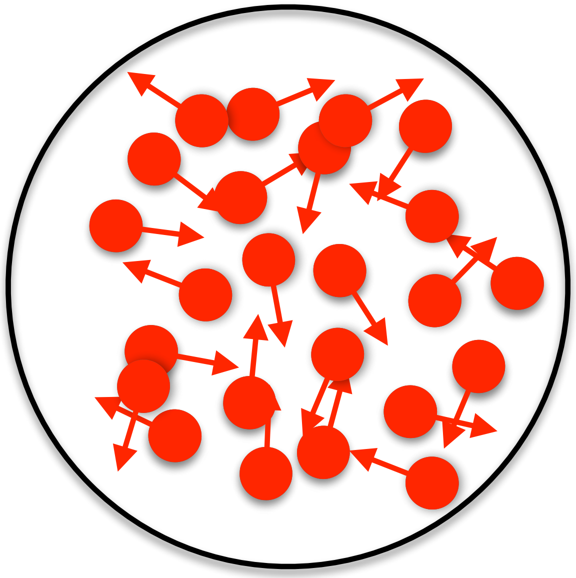
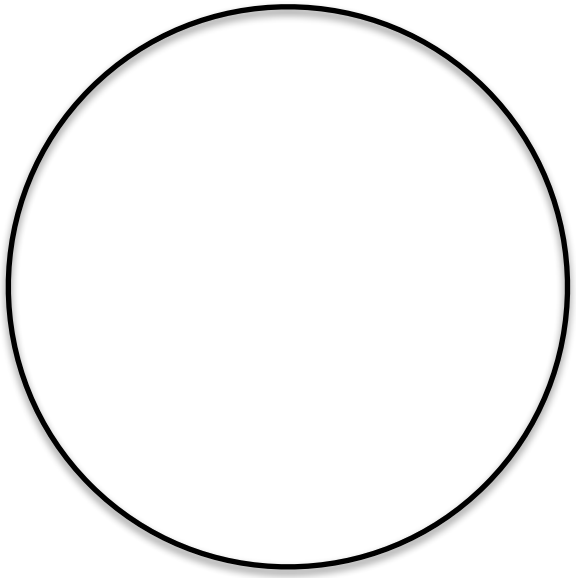
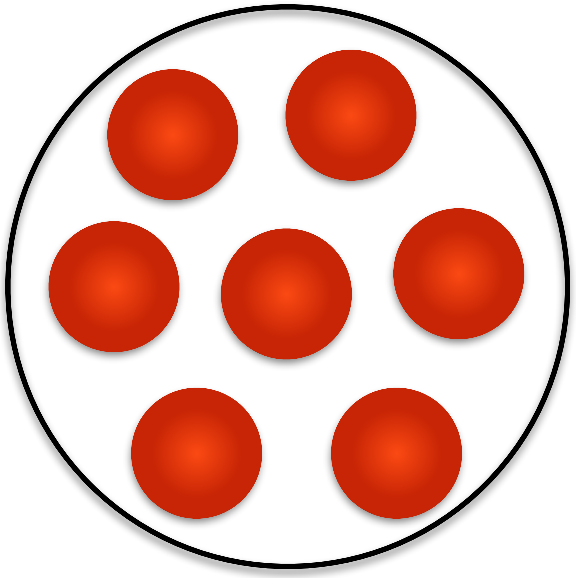
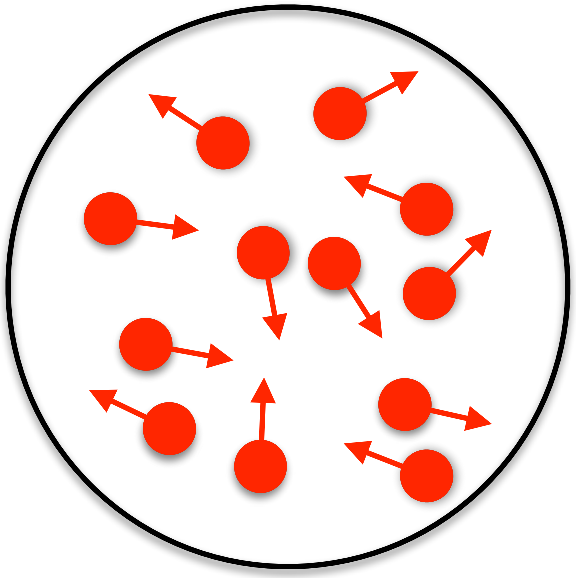
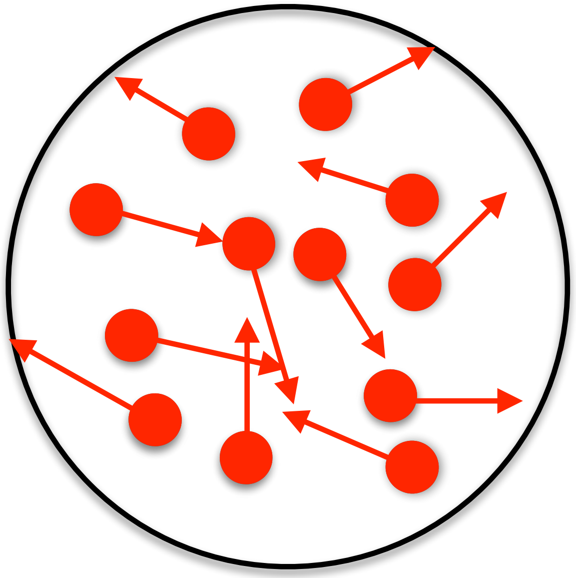
Dirac neutrinos NO


(a) DESI/EUCLID Detection

Majorana neutrinos IO


(b) No DESI/EUCLID Detection

Prospects of Direct Detection of the CNB

Cosmology:	ΛCDM	$\nu_i \to \nu_j \phi$	$\nu_i \to \nu_4 \phi$
CNB:			
Detection?	🙁 m_ν too small	🙁 m_ν too small	🙁 No CNB today
Cosmology:	Long Range	Low T_ν+DR	$p_\nu \gg 3T_\nu^{\rm SM}$
CNB:			
Detection?	😐 only if we live inside one nugget!	😃 best prospects because neutrinos are slow	🙁 Not many neutrinos and they travel fast

Conclusions

Neutrino Masses:

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

However, all cosmological mass bounds are cosmological model dependent

There are several (although not many) cosmological models that are perfectly compatible with all known cosmological data where the neutrino mass can be large

Cosmic Neutrino Background:

We have indirect evidence that the CNB should be there $N_{\mathrm{eff}} \simeq 3$

Directly detecting it is very challenging, but perhaps less so beyond ΛCDM

Outlook

Neutrino Masses:

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

Next generation of 0v2β experiments, e.g. LEGEND: $m_{\beta\beta} \sim 0.02 - 0.04\,\mathrm{eV}$

Next Galaxy Surveys+CMB should detect neutrino masses
e.g.: 1308.4164 Font-Ribera et al., 1408.7052 Kitching et al.

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

Several interesting things can happen in each case!

Detecting the Cosmic Neutrino Background

The PTOLEMY collaboration is seriously considering it

Opportunity to test cosmological models in the laboratory

Given its challenges, new bold ideas are most welcome!

Time for Questions and Comments

Upcoming years are going to be exciting!

Thank you for your attention!

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