Neutrino Cosmology

Miguel Escudero Abenza

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short review + original work 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]

Invisibles 2022 Workshop

Orsay

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Motivation

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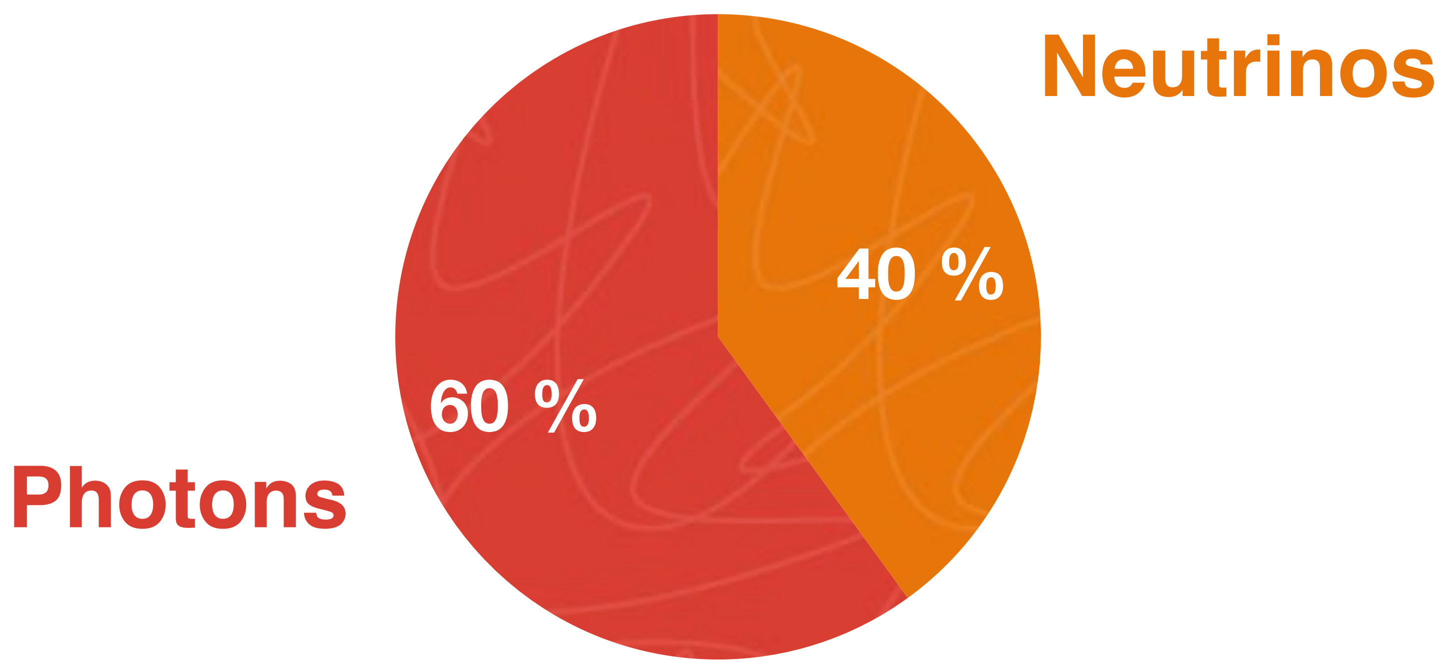

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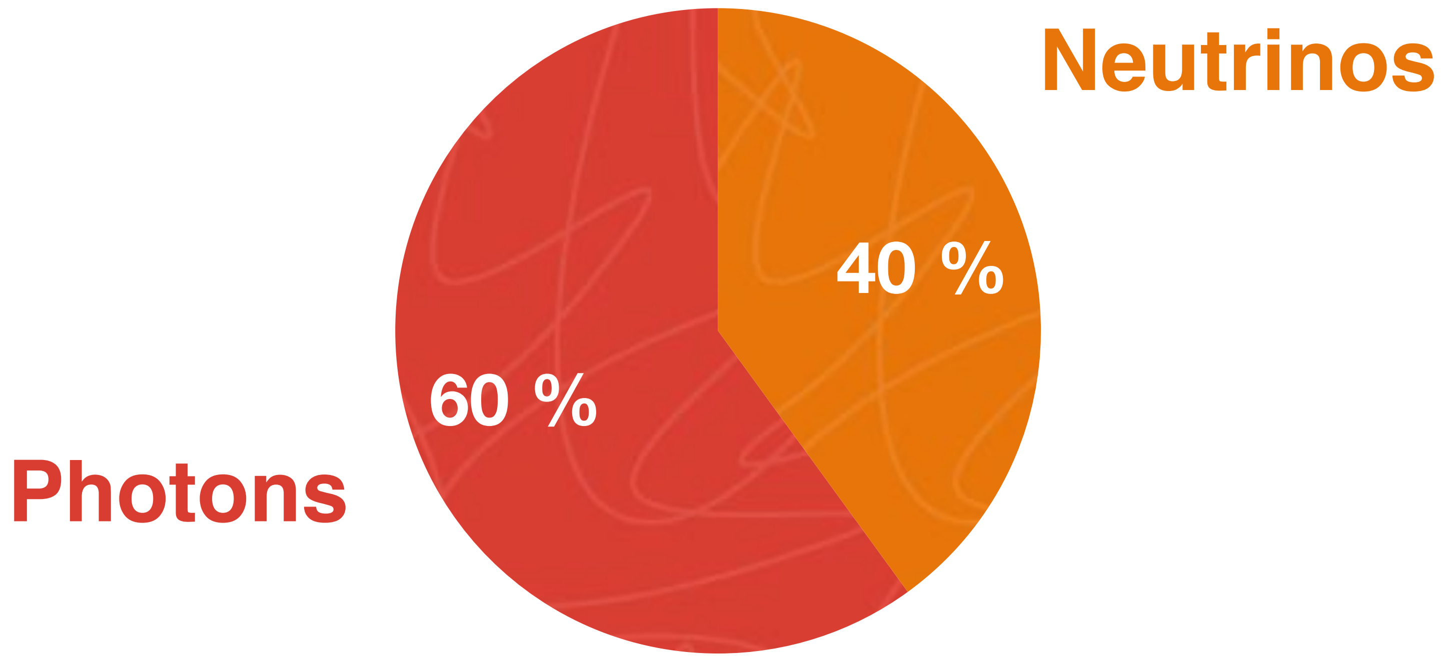

Use cosmological data to understand their properties

Outline

1) Neutrinos in ΛCDM

2) Evidence for the Cosmic Neutrino Background

Recent constraints on $N_{\rm eff}$

3) Neutrino Masses in and beyond ΛCDM

Neutrino decays as a particle physics avenue to relax the $\sum m_\nu$ bounds

4) Conclusions and Outlook

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4) Conclusions and Outlook

Not covered due to time constraints but very happy to discuss at any length offline:

Neutrinos and the Hubble tension

Neutrino interactions in cosmology

Neutrino Evolution

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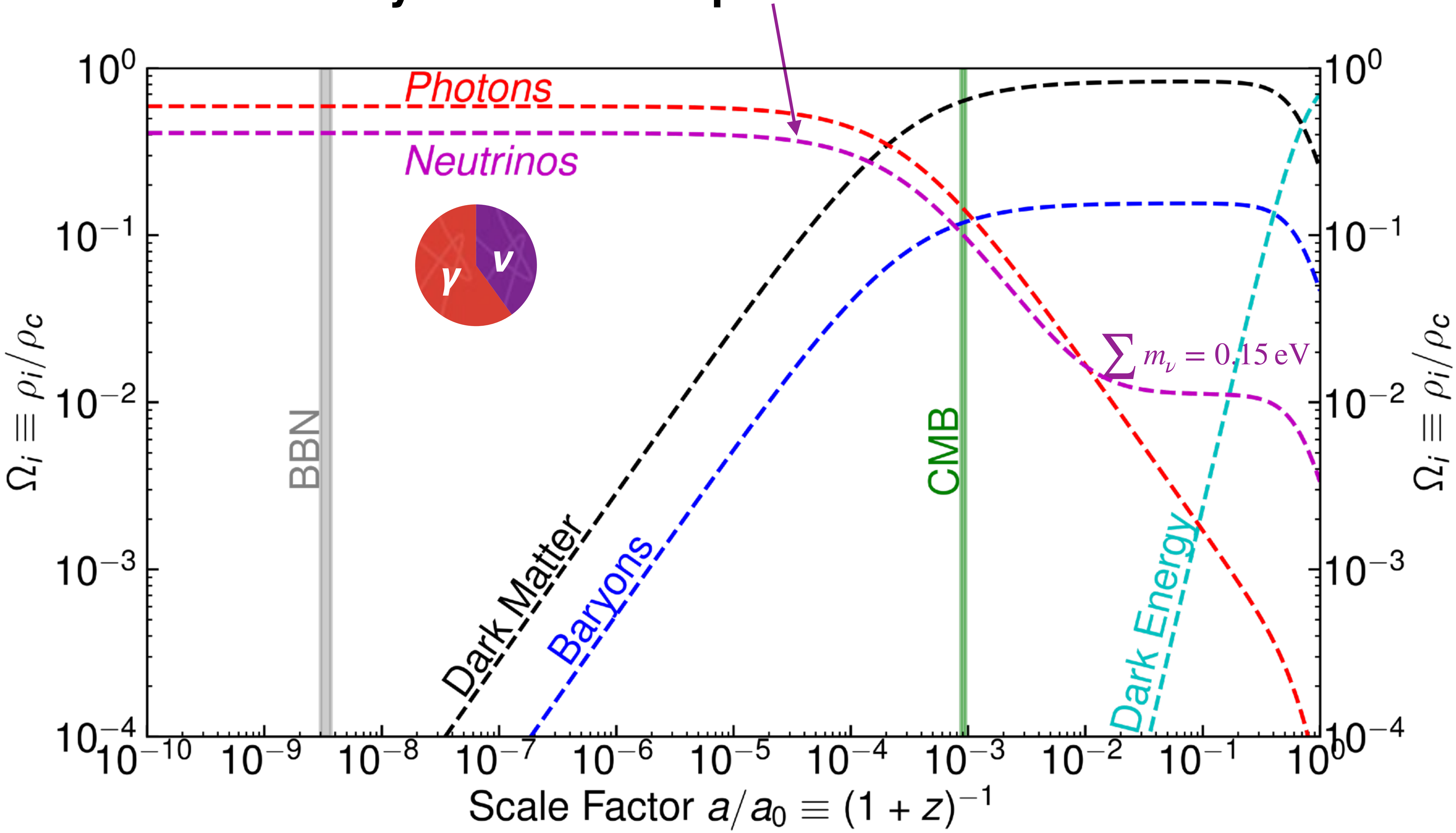

Non-Rel: $z_\nu^{\text{non-rel}} \simeq 110 \frac{m_\nu}{0.06\,\text{eV}}$ **Hot DM:** $\Omega_\nu h^2 = \sum m_\nu/(93.14\,\text{eV})$

Evidence for Cosmic Neutrinos

Big Bang Nucleosynthesis

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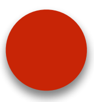
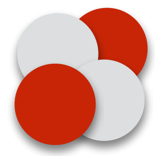
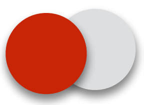
Current measurements are consistent with the SM picture*



H ~ 75%



^{4}He ~ 25%



D ~ 0.005%

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

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

see Matsumoto et al. 2203.09617
and also Burns, Tait & Valli 2206.00693

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Cosmic Microwave Background   Why?

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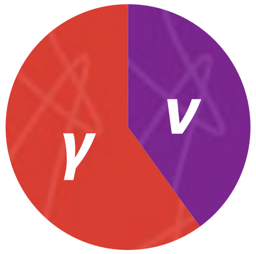

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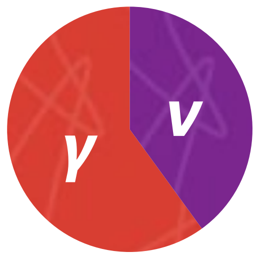

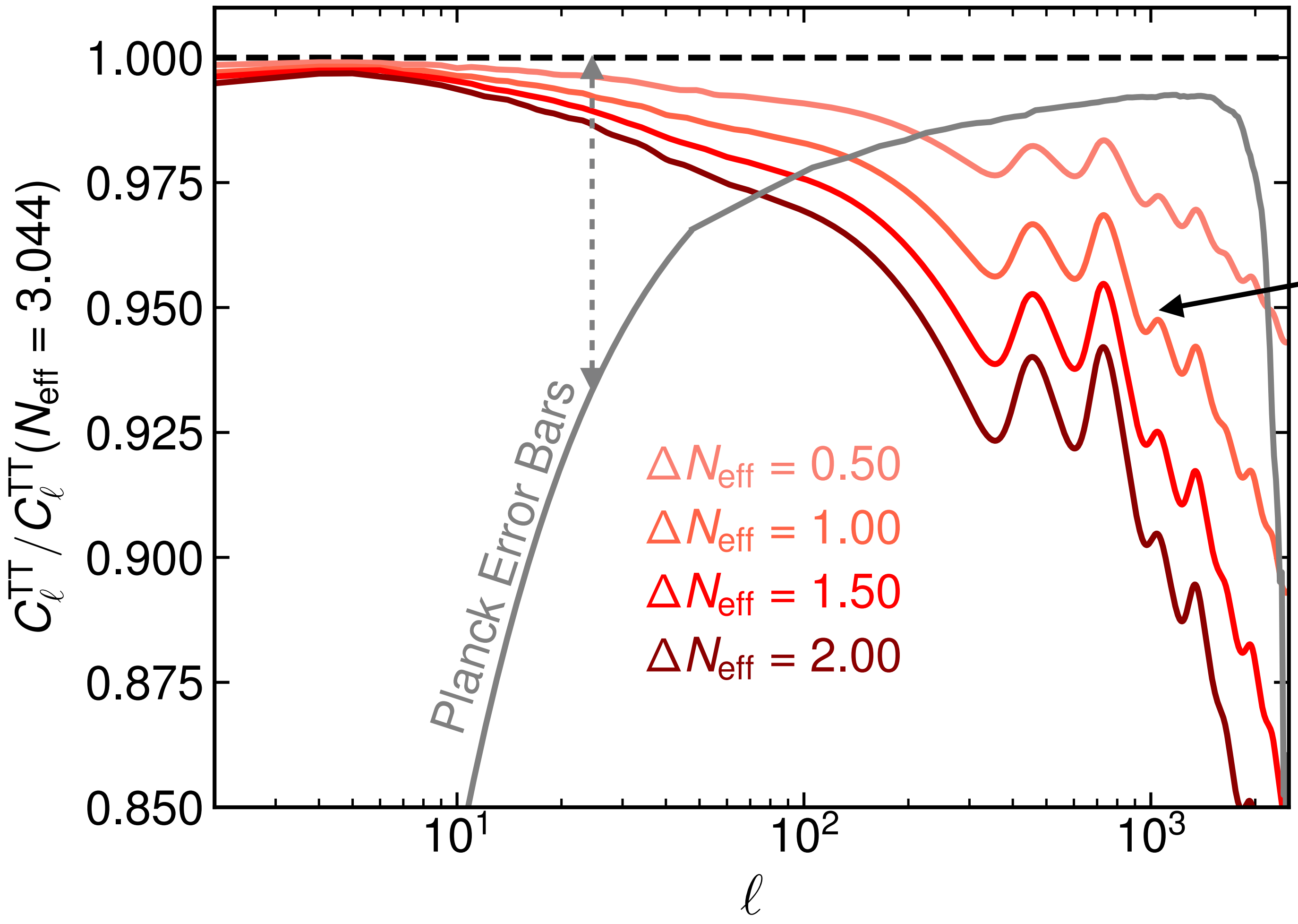

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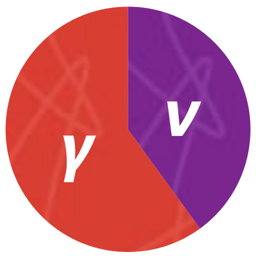

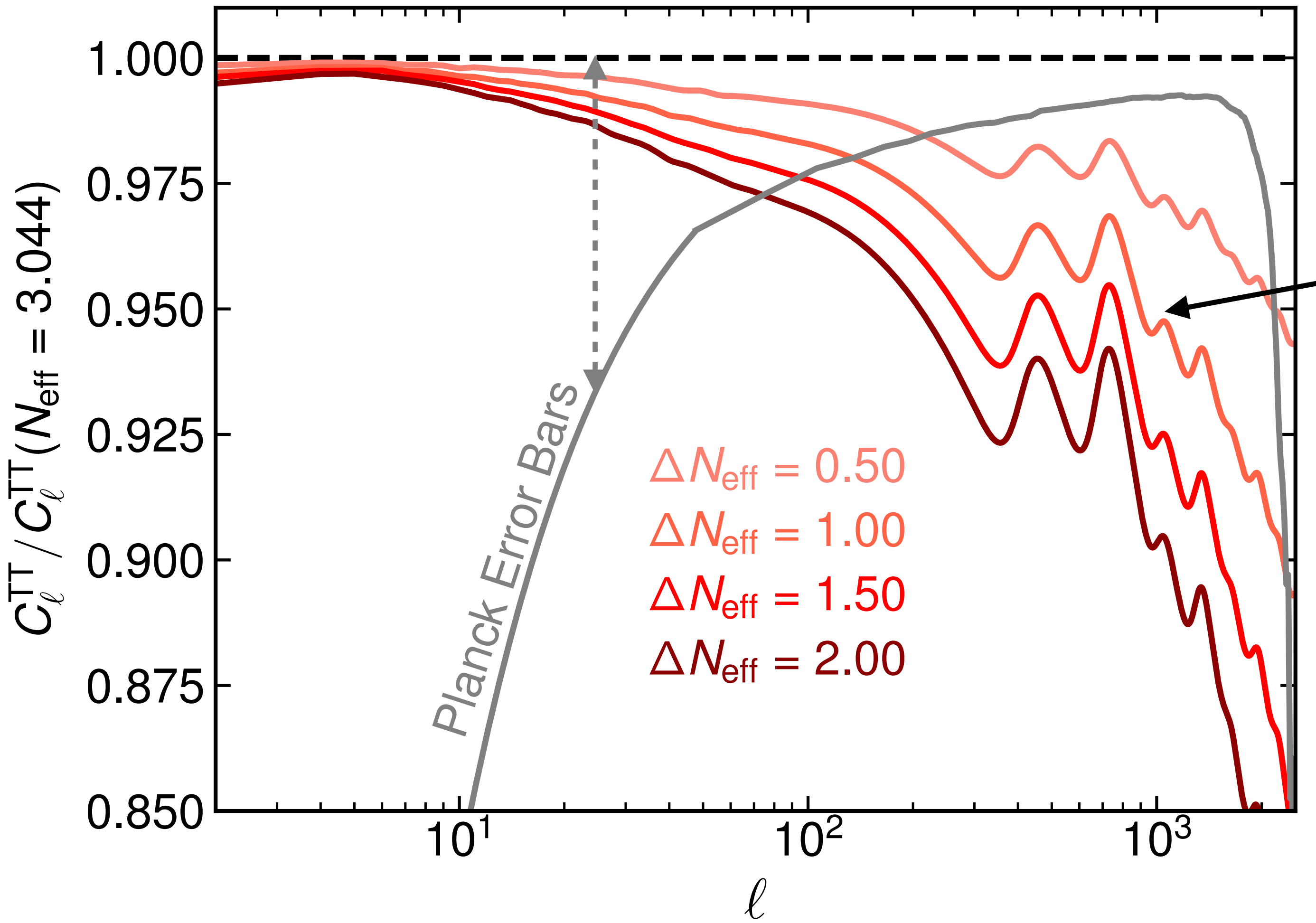

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Planck 2018 1807.06209

Evidence for Cosmic Neutrinos

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Which means we can use cosmological data to test properties of neutrinos!

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- **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

Neutrino masses and the Planck lensing anomaly

There is an anomaly in the Planck data at high multipoles which could potentially have relevant implications for the neutrino mass constraints — **see di Valentino's talk**

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Importantly, the Planck collaboration claims that the most likely origin of this tension is a statistical fluctuation:

1807.06209

***Planck* 2018 results. VI. Cosmological parameters**

If the $A_L > 1$ preference is simply a statistical excursion (perhaps the most likely explanation), this indicates that there are random features in the spectrum that are pulling some parameters unusually far from expected values.[30] There are several

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In addition, more recent analyses of the Planck data do point in that direction:

see Rosenberg, Gratton & Efstathiou 2205.10869

The lower noise of the NPIPE maps leads to tighter parameter constraints, with a ~10% improvement in most ΛCDM parameters in TTTEEE due primarily to improvements in polarization. For ΛCDM extensions we find that, relative to PR3, NPIPE polarization shrinks the error bars on Ω_K and A_L from EE by 40% and 25% respectively, and by 15% and 8% in TTTEEE. That these smaller error bars are accompanied by shifts toward the ΛCDM values continues the trend observed in EG21 of decreasing the Ω_K and A_L tensions as more data is used, as would be expected if these pulls were due to a statistical fluctuation. Overall, we conclude that NPIPE, despite

Neutrino Masses from Cosmology

Neutrino masses and the Planck lensing anomaly

There is an anomaly in the Planck data at high multipoles which could potentially have relevant implications for the neutrino mass constraints — see di Valentino's talk

This tension (3σ) is parametrized in terms of the A_L parameter, which is an *unphysical parameter* modifying the amplitude of the lensing spectrum!

Importantly, the Planck collaboration claims that the most likely origin of this tension is a statistical fluctuation:

1807.06209

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Finally, even in the presence of this anomaly the effect on the neutrino mass bound is expected to be of only 20% within ΛCDM!

Motloch and Hu 1912.06601

As is well known, the Planck lensing-like anomaly strengthens neutrino mass constraints. When combining Planck data with current BAO and SN data, we find that the lensing-like anomaly improves the neutrino mass constraints by less than 20%. Additionally allowing nonzero curvature further degrades this constraint by only about 10%. We find that when considering either PP or BAO+SN on top of Planck temperature and polarization power spectra, the data are consistent with flat Universe and this preference is not affected by the lensing anomaly.

Cosmological Model Dependence

Planck+BAO and 3 degenerate neutrinos

Neutrino Masses from Cosmology

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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**

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

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Non-standard Neutrino Cosmologies:

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Invisible Neutrino Decay

$$\nu_i \to \nu_j \phi$$

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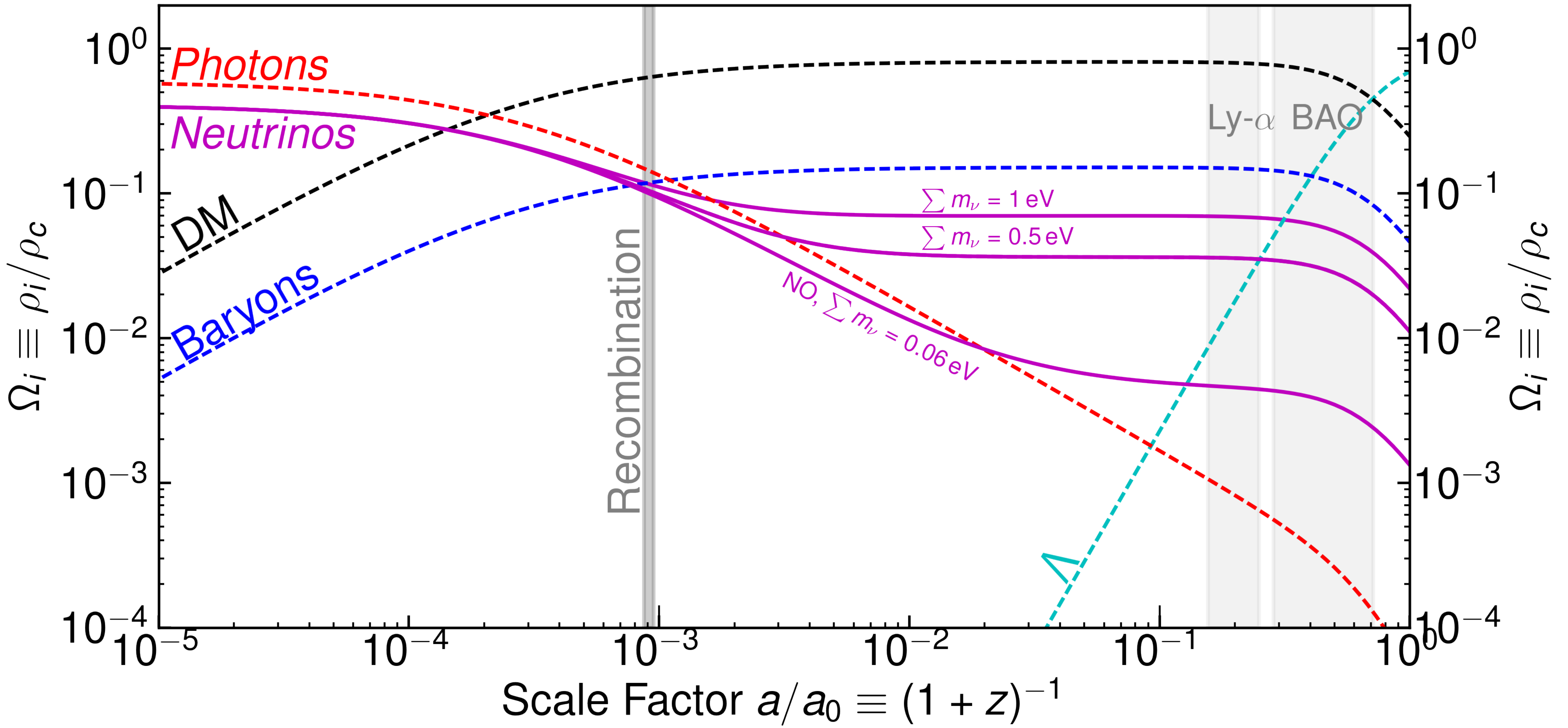

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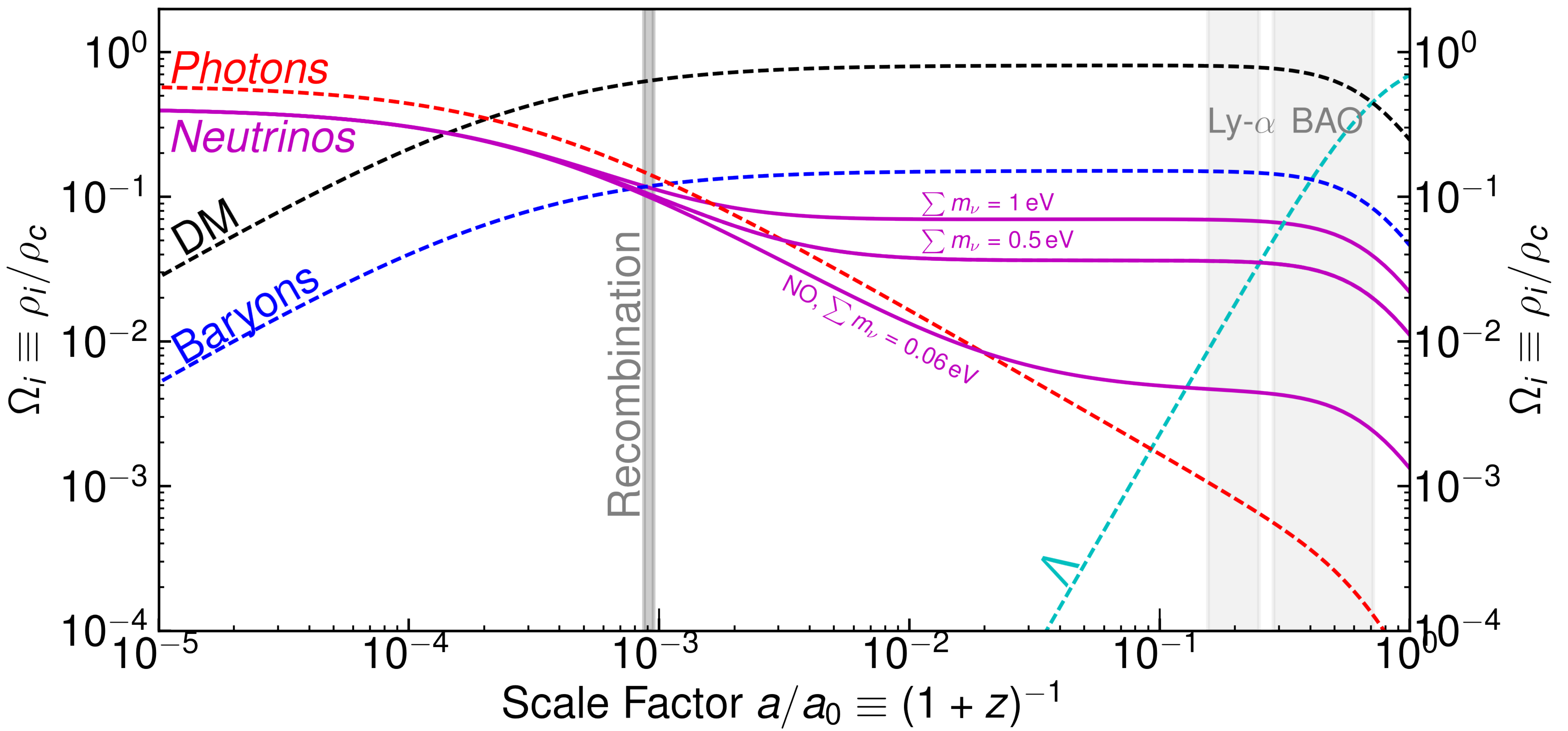

CMB peaks fix:

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

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

Comoving sound horizon (Early Universe)

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

Comoving angular diameter distance (Late Universe)

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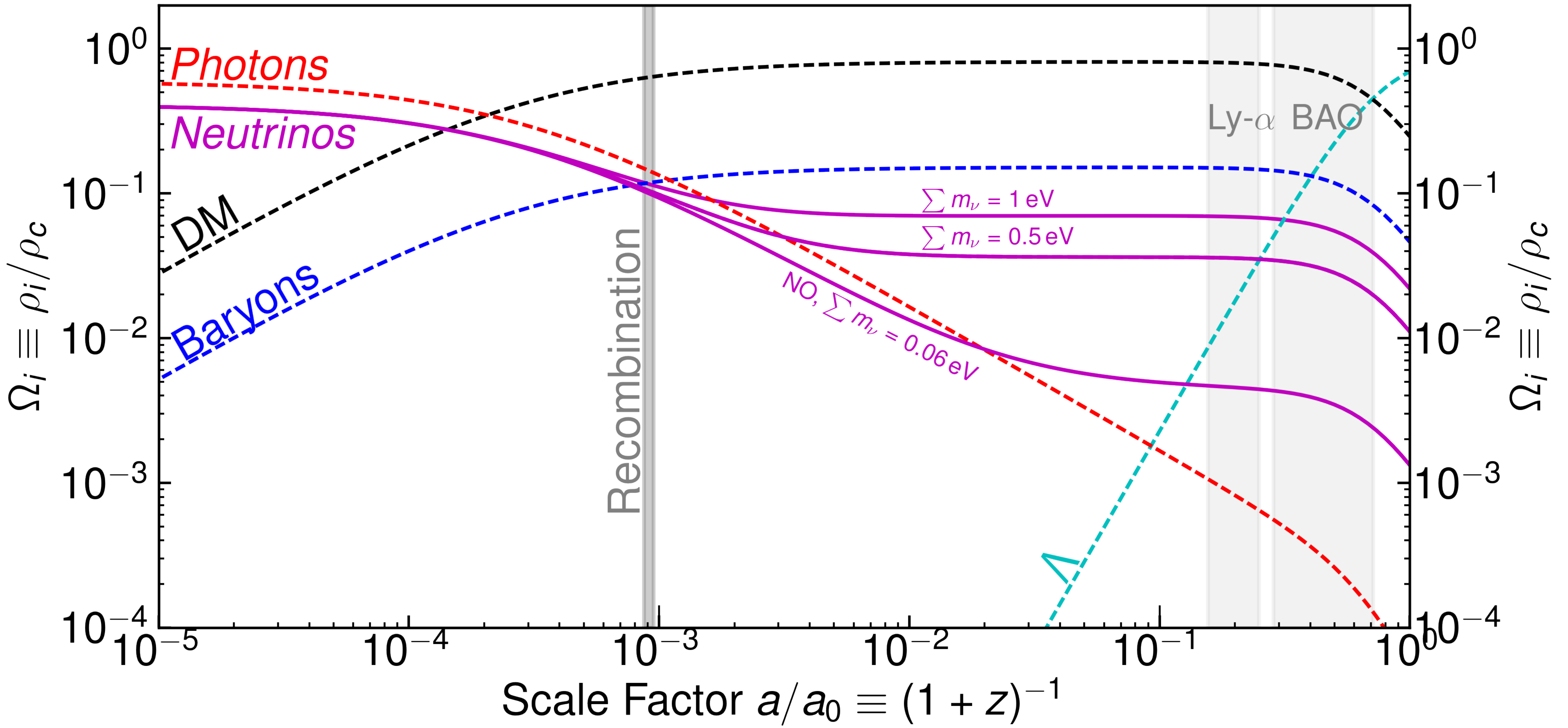

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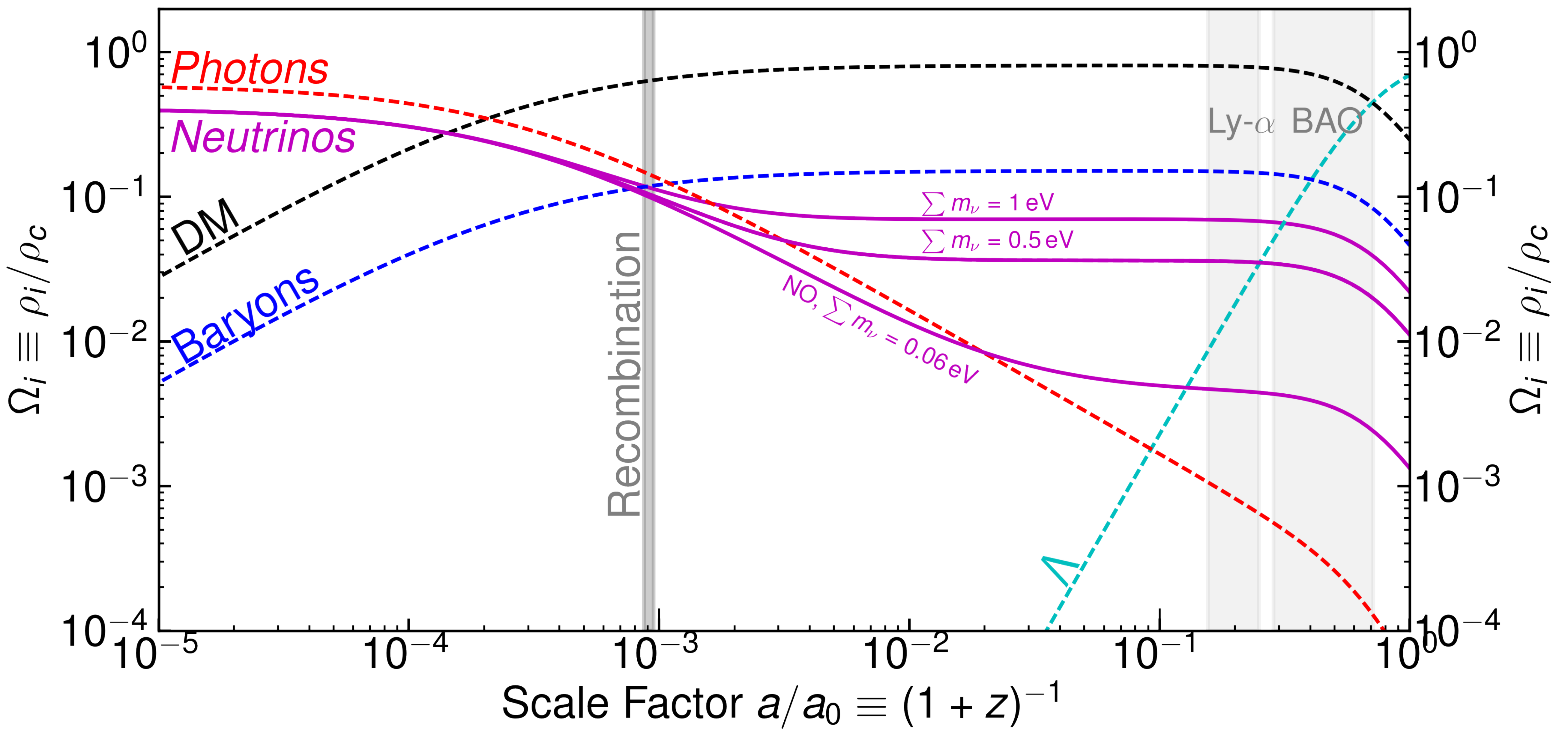
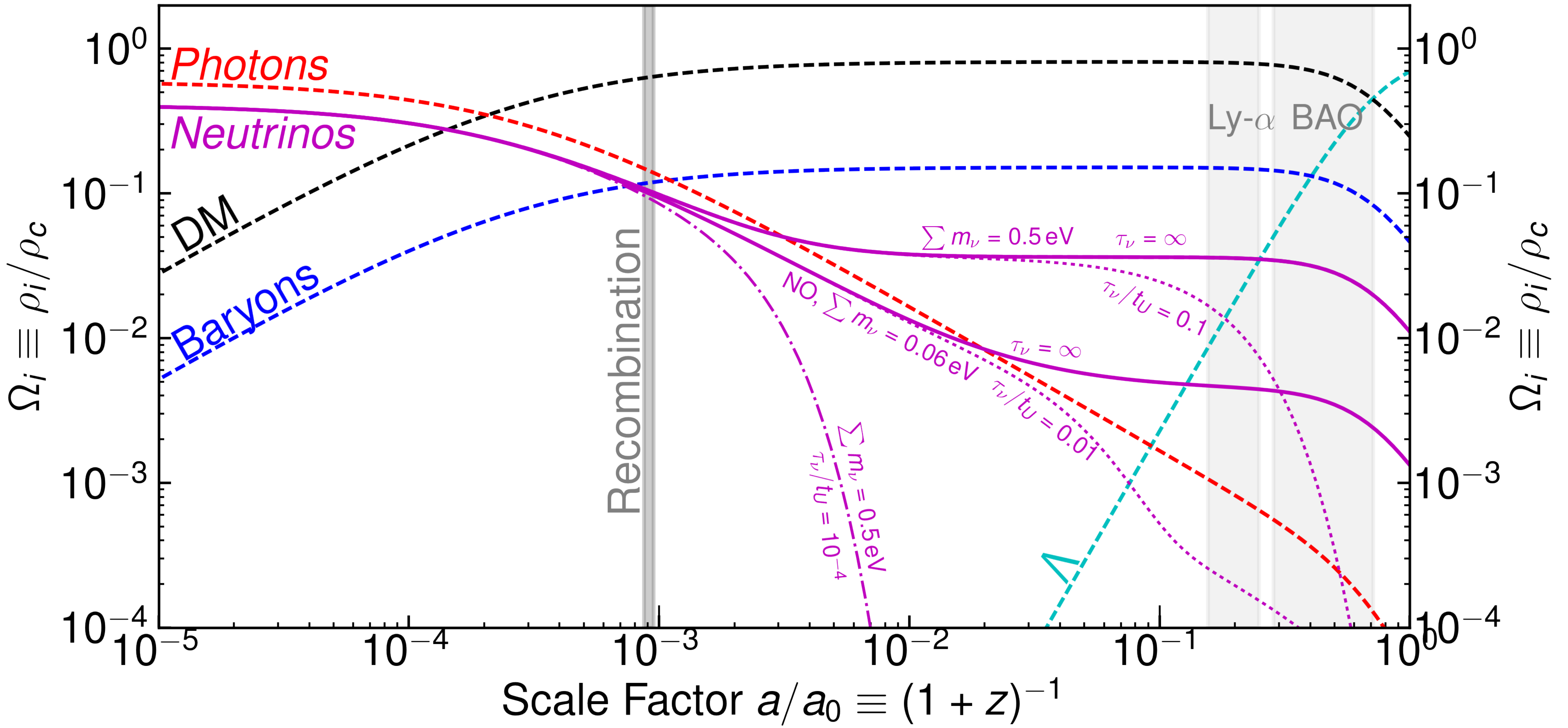


Not only a background effect:

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

Neutrino Decays



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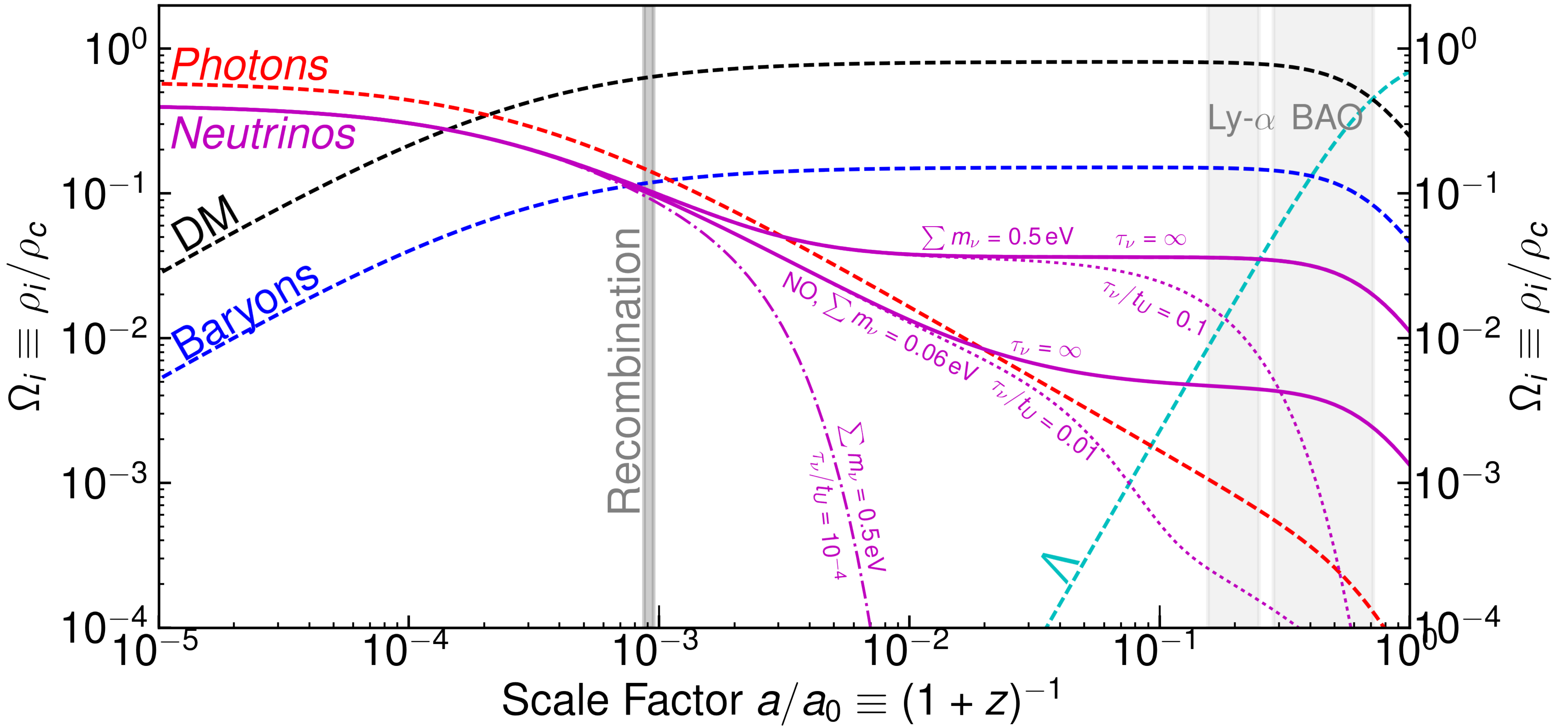

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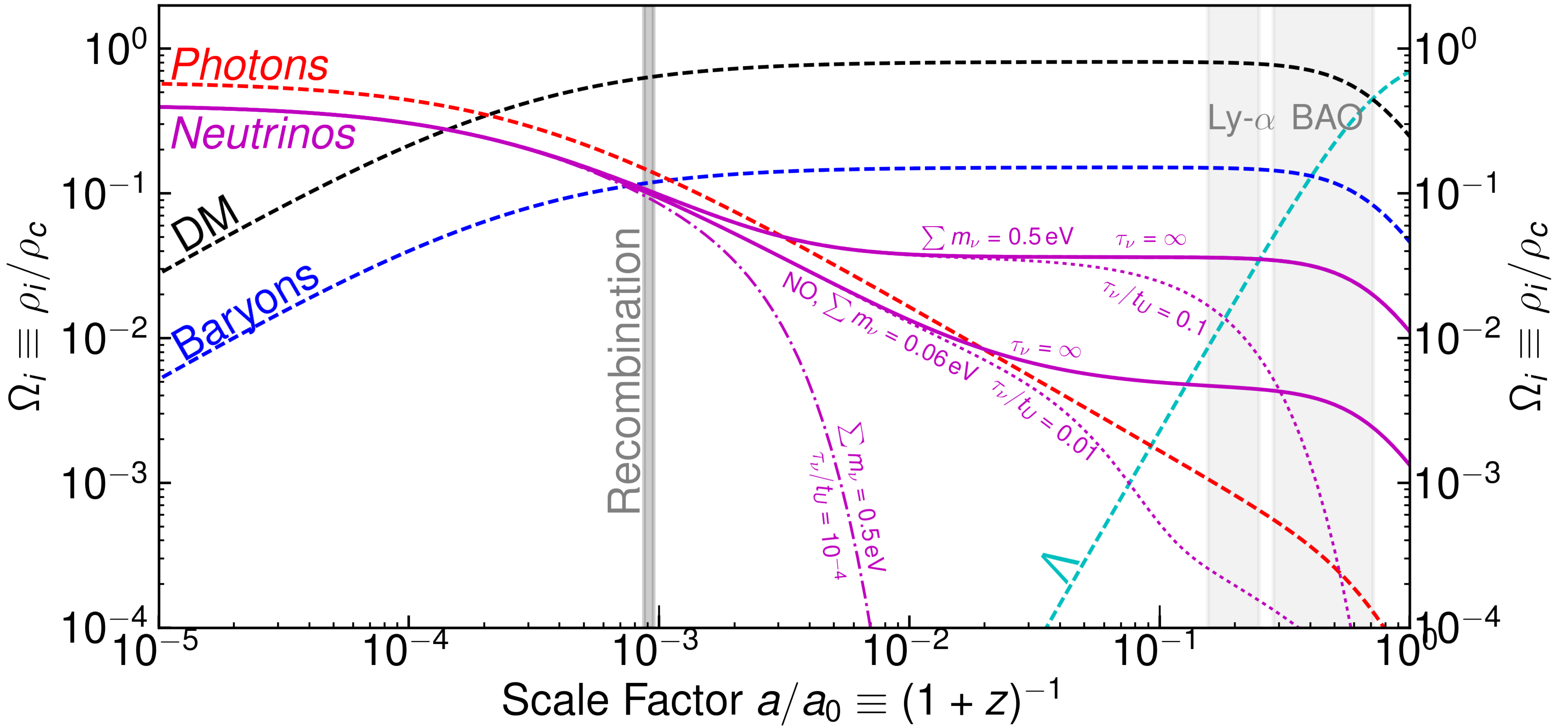

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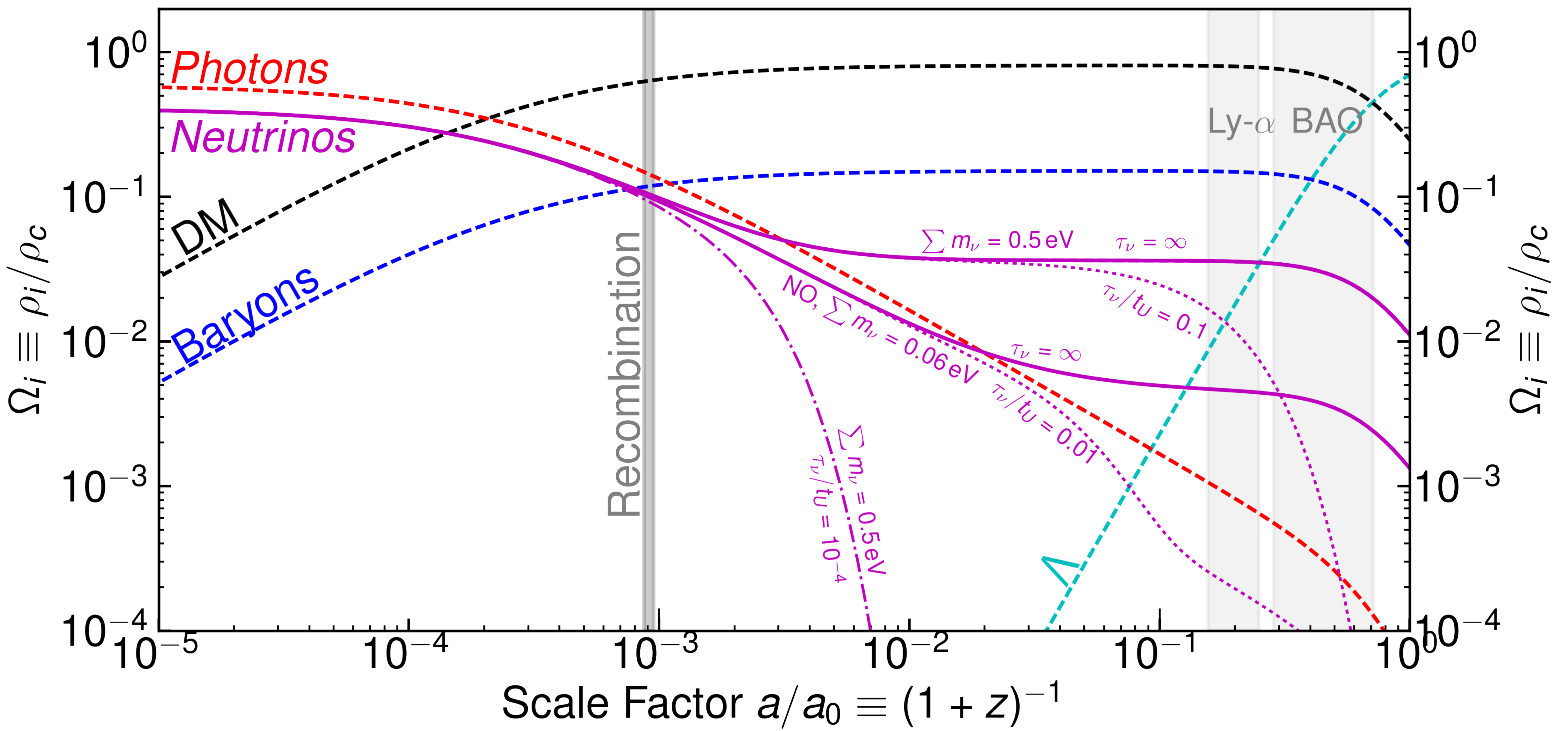

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Unstable Neutrinos can relax the bounds on Σm_ν!

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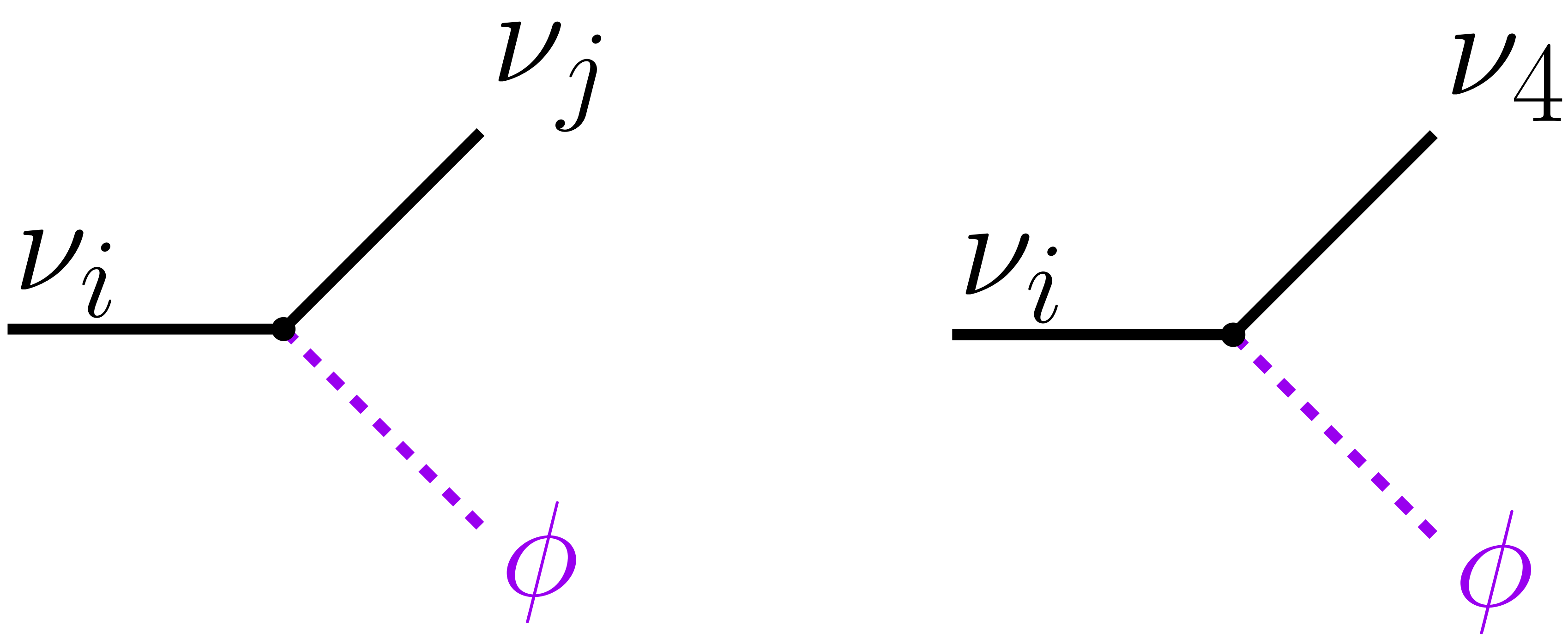

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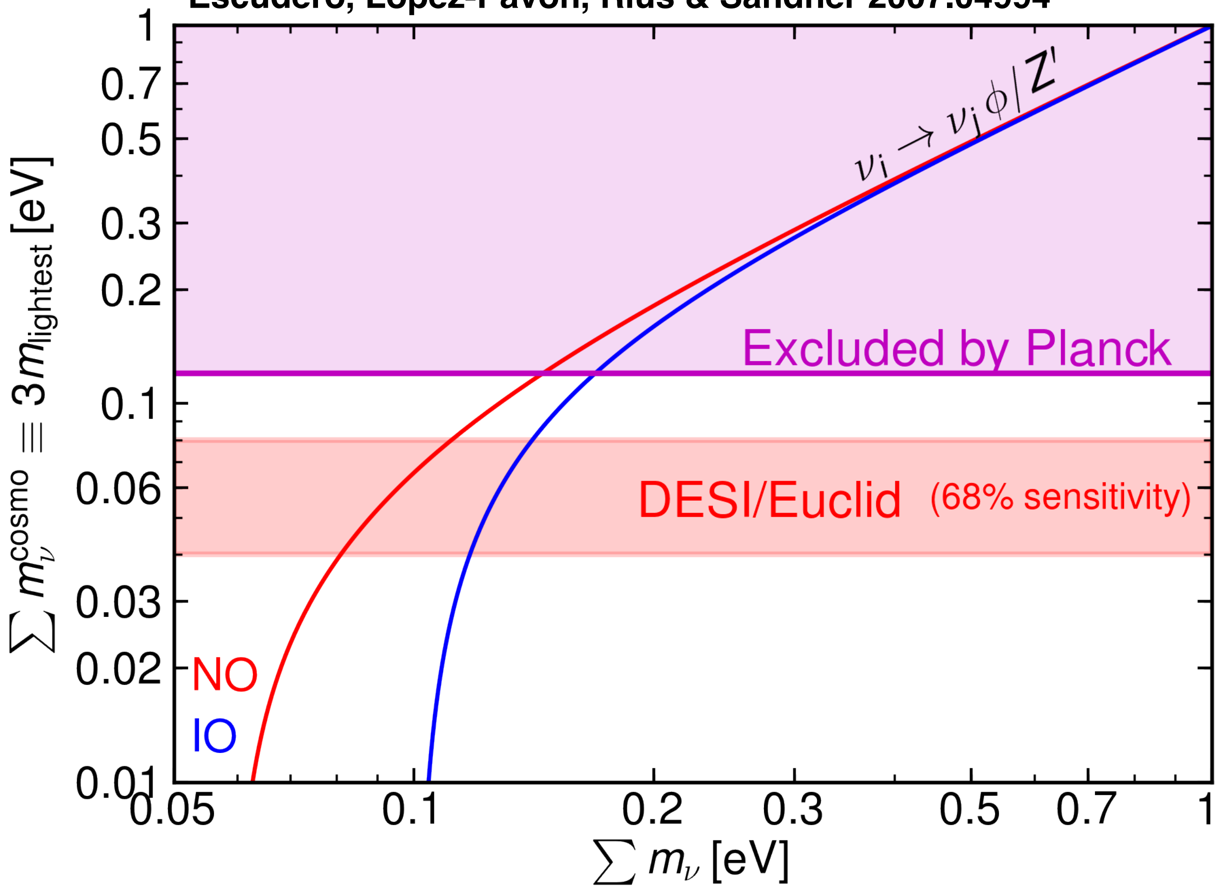

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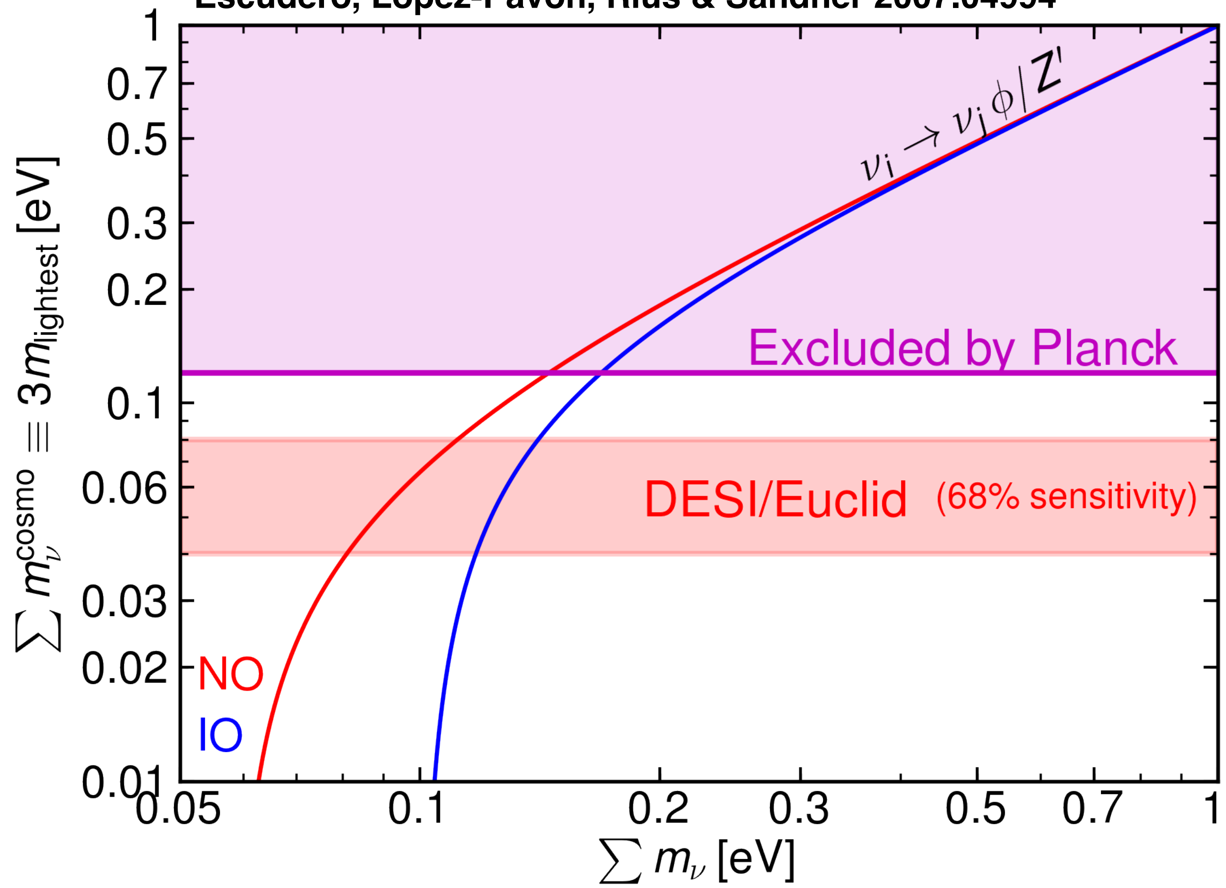
Couplings: $\tau_\nu < t_U$ taking the $L_\mu - L_\tau$ case means $v_{\mu-\tau} < 30\,\mathrm{TeV}$ for both global and gauge U(1)

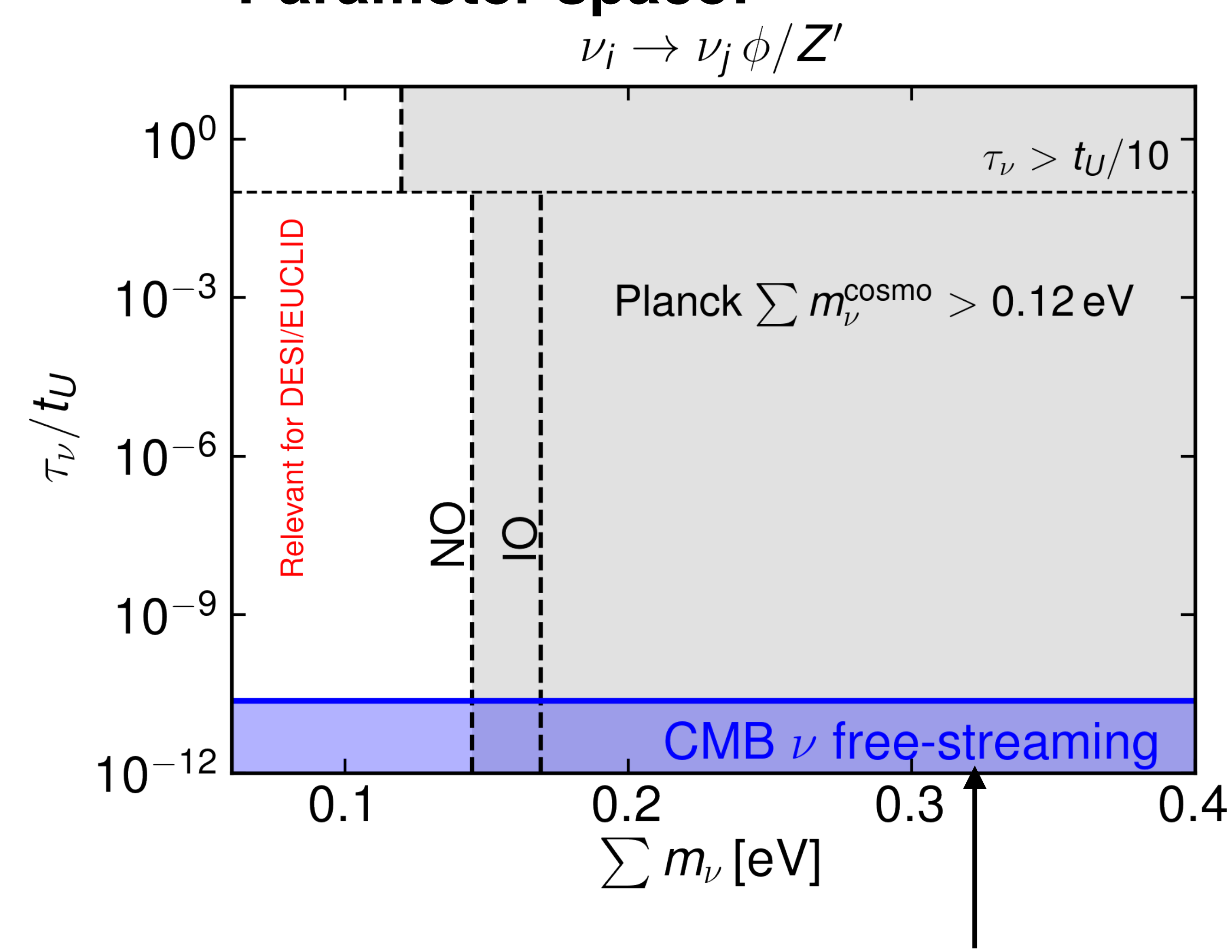
However, because there is a neutrino in the final state the mass bounds are expected to only be relaxed mildly:

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

Parameter space:

Escudero, López-Pavón, Rius & Sandner 2007.04994





Oldengott, Wong et al. 2011.01502 & 2203.09075

Neutrino Decays into Massless States

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

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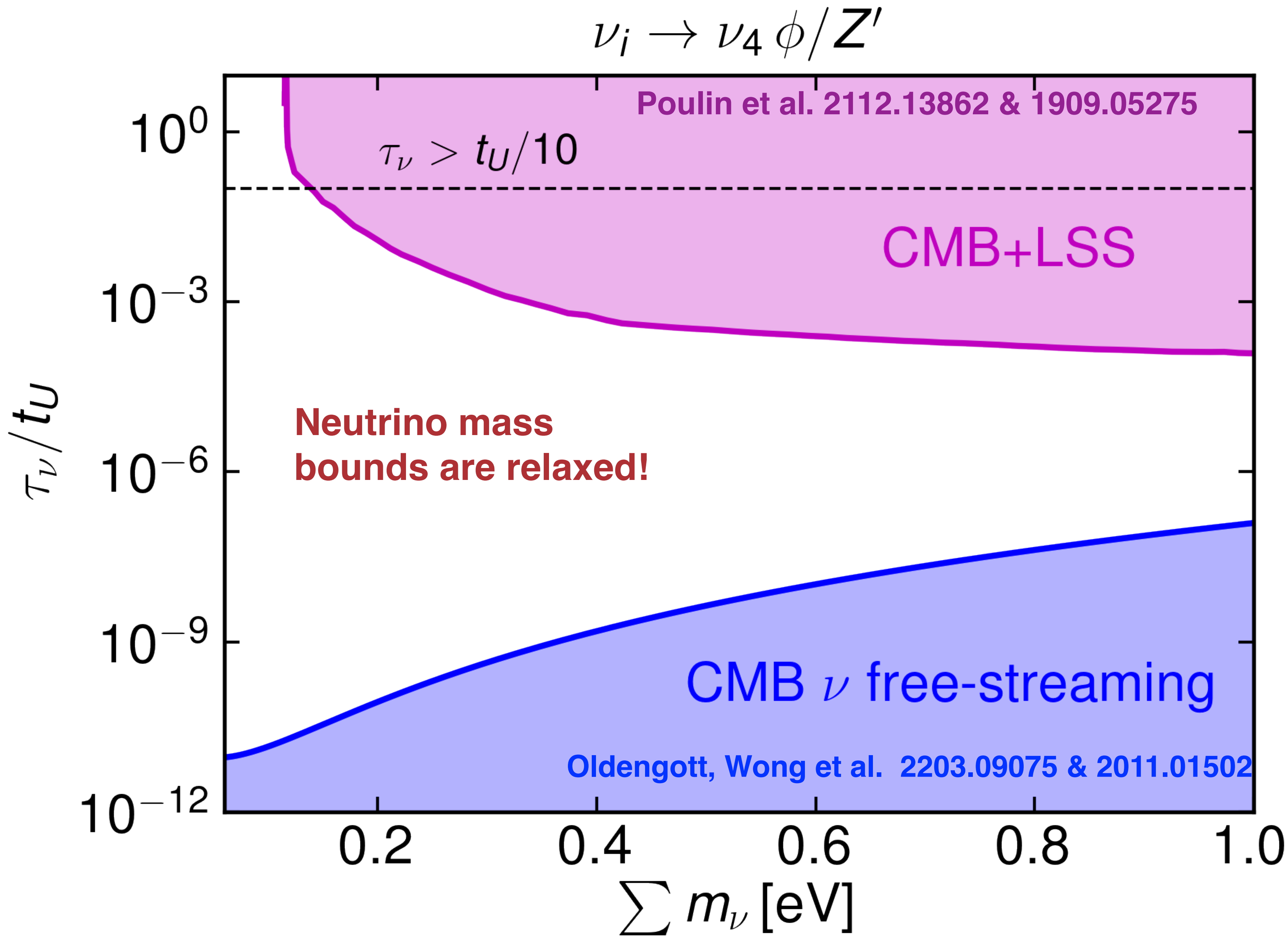

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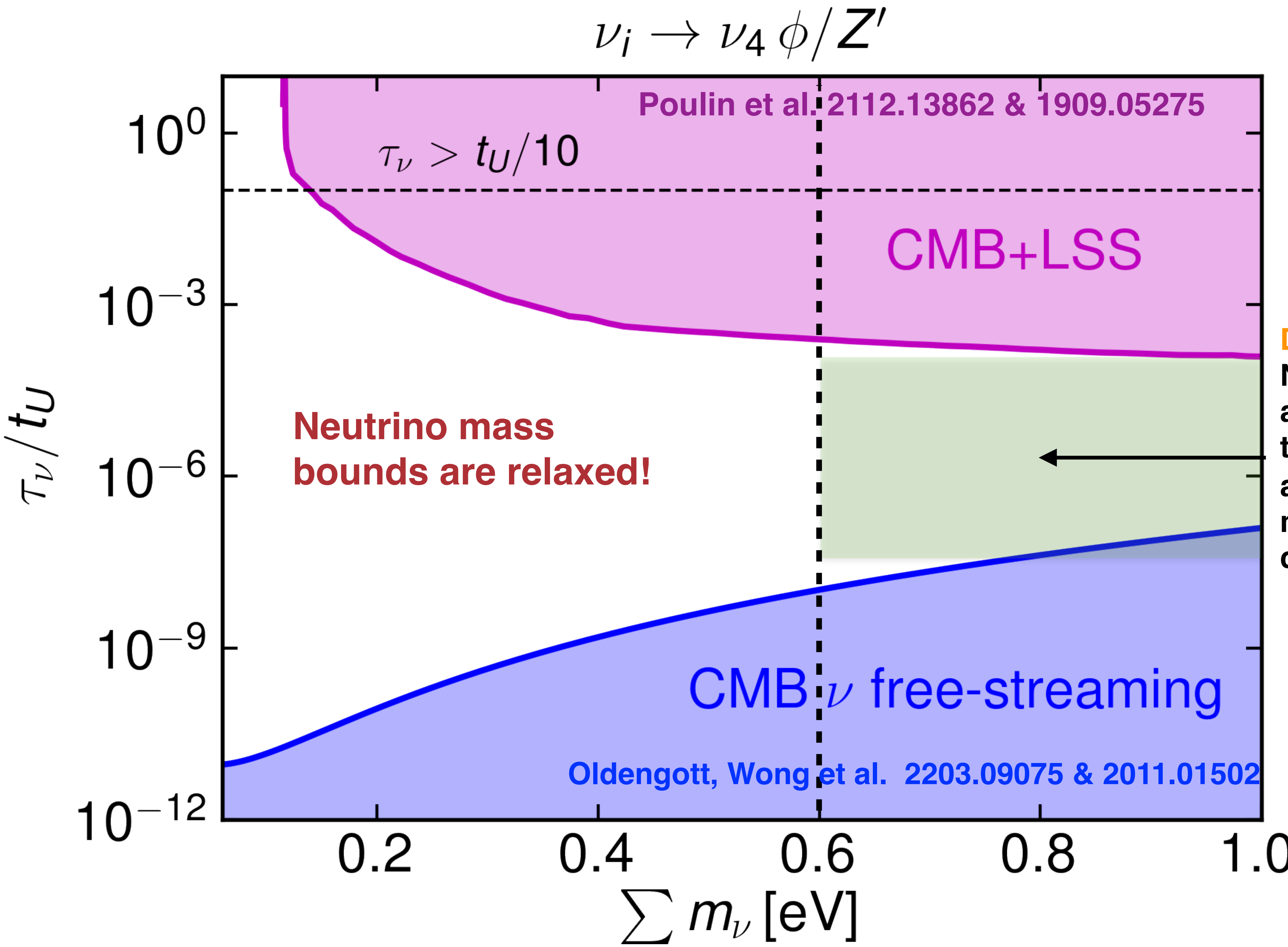

Disclaimer!
No full realistic cosmological analysis has been performed in the literature for $m_\nu > 0.2\,\mathrm{eV}$ and these lifetimes. This region may or may not be excluded by cosmological data

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

Why these models are interesting?

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See e.g. Alcaide, Santamaría & Salvadó 1806.06785 and includes $L_\mu - L_\tau$ models, see e.g. Choubey & Rodejohann, hep-ph/0411190

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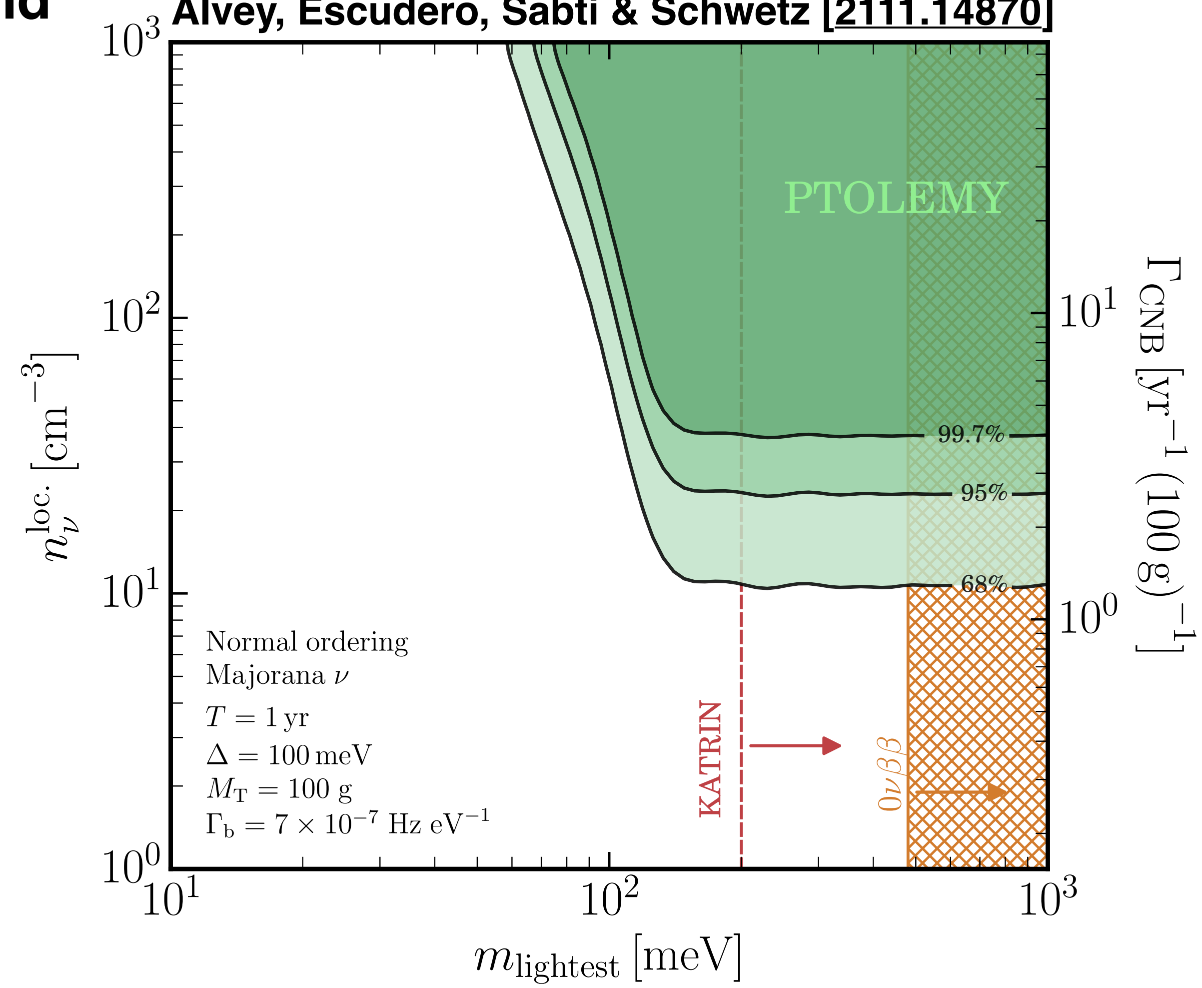

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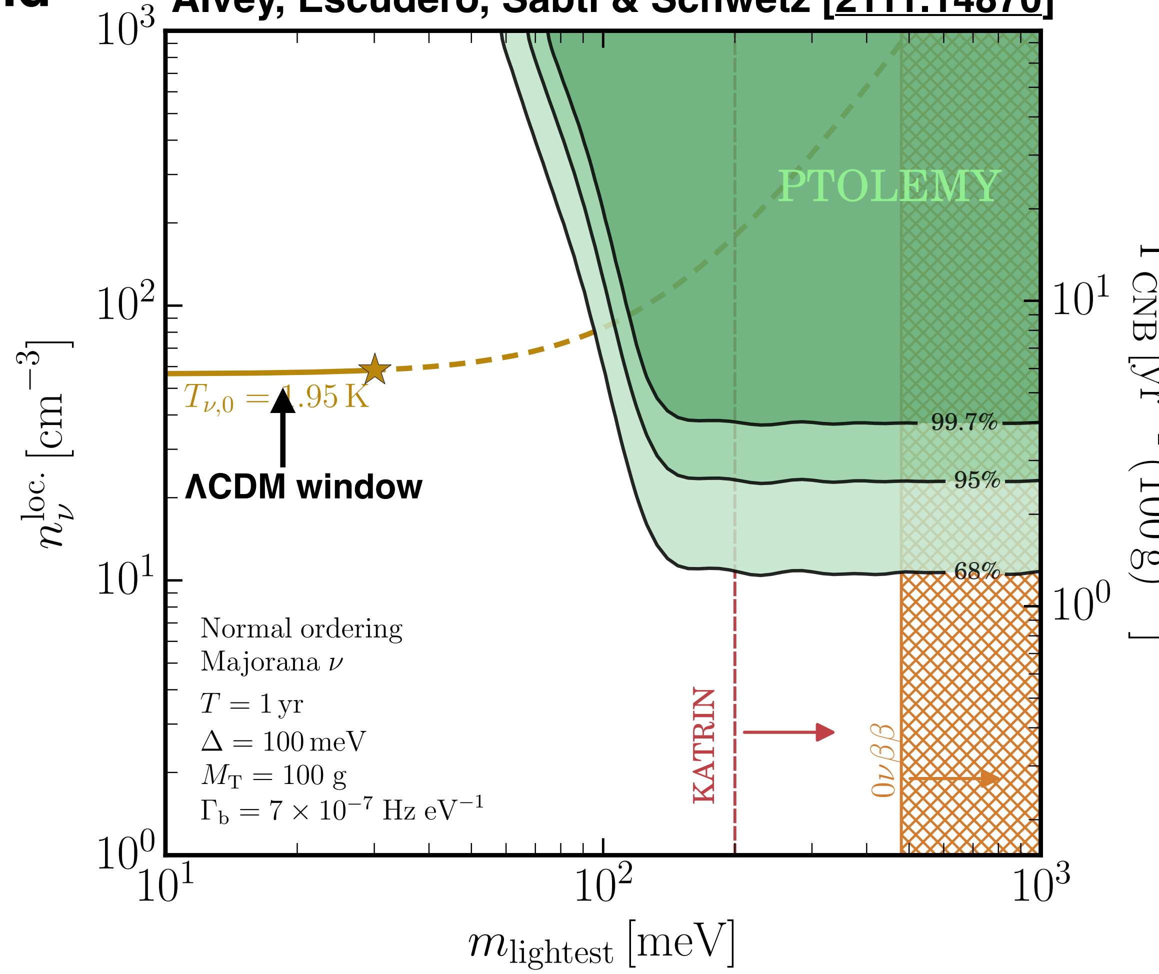

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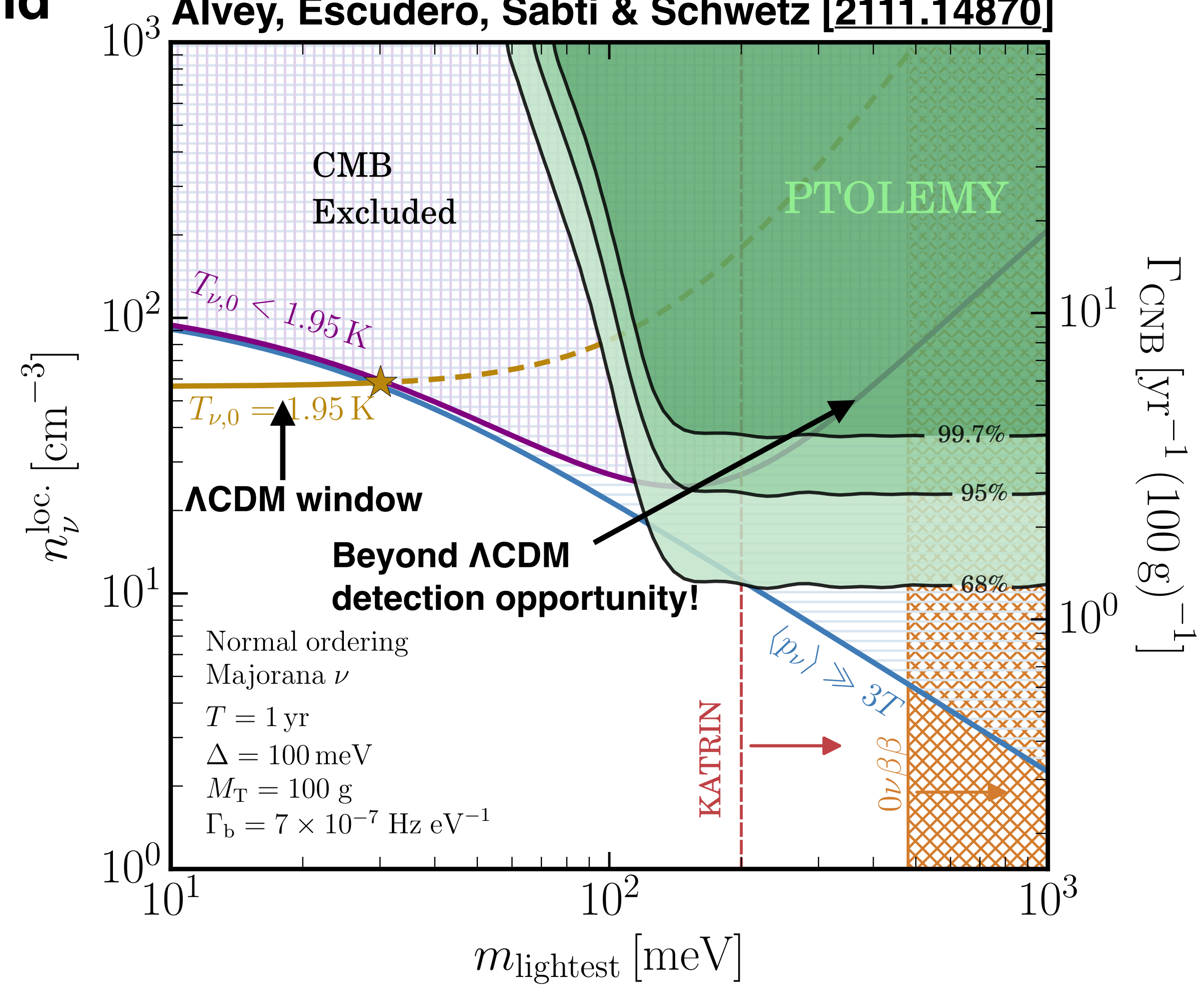

Conclusions

Number of effective neutrino species

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

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

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

Strong evidence that the CNB should be there as expected in the SM

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Neutrino Masses:

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

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

Neutrino decays as a particle physics avenue to relax them!

Outlook

Neff:

Simons Observatory expected to reach $\sigma(N_{\rm eff}) = 0.06$ by 2027

CMB-S4 could reach 1% precision on $N_{\rm eff}$ but on a longer timescale

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Neutrino Masses:

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

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

Next Galaxy Surveys+CMB should detect neutrino masses

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

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

Time for Questions and Comments

Upcoming years are going to be exciting!

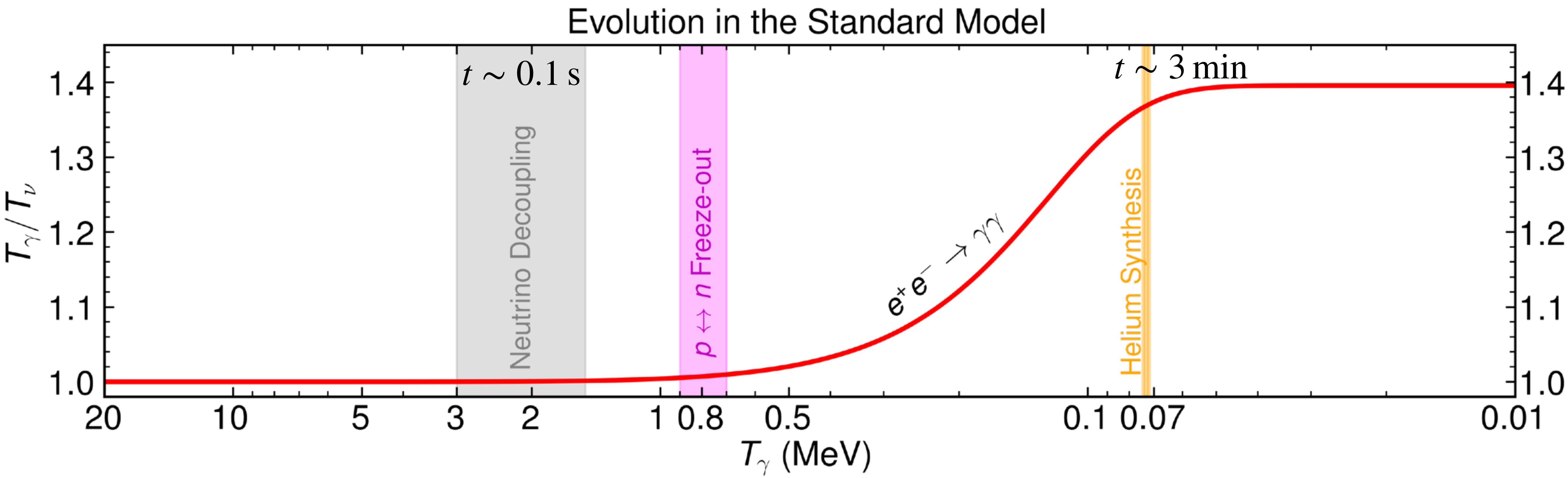
ν

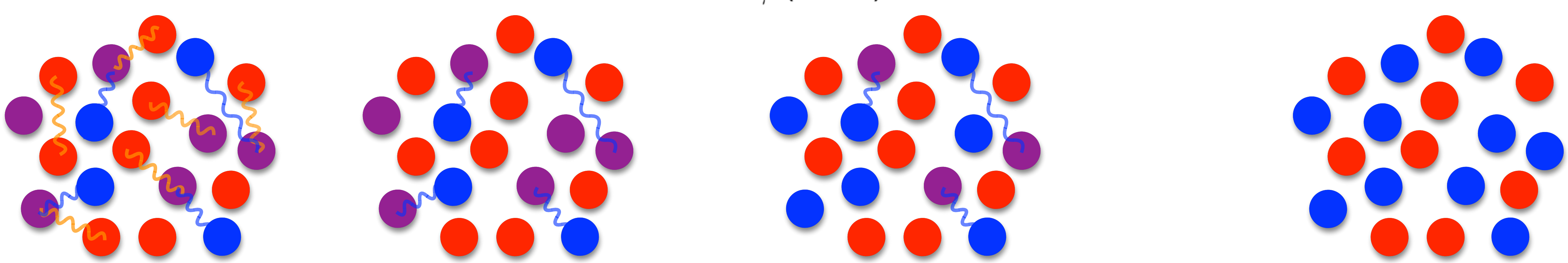
Thank you for your attention!

miguel.escudero@tum.de

Back Up

Neutrino Decoupling

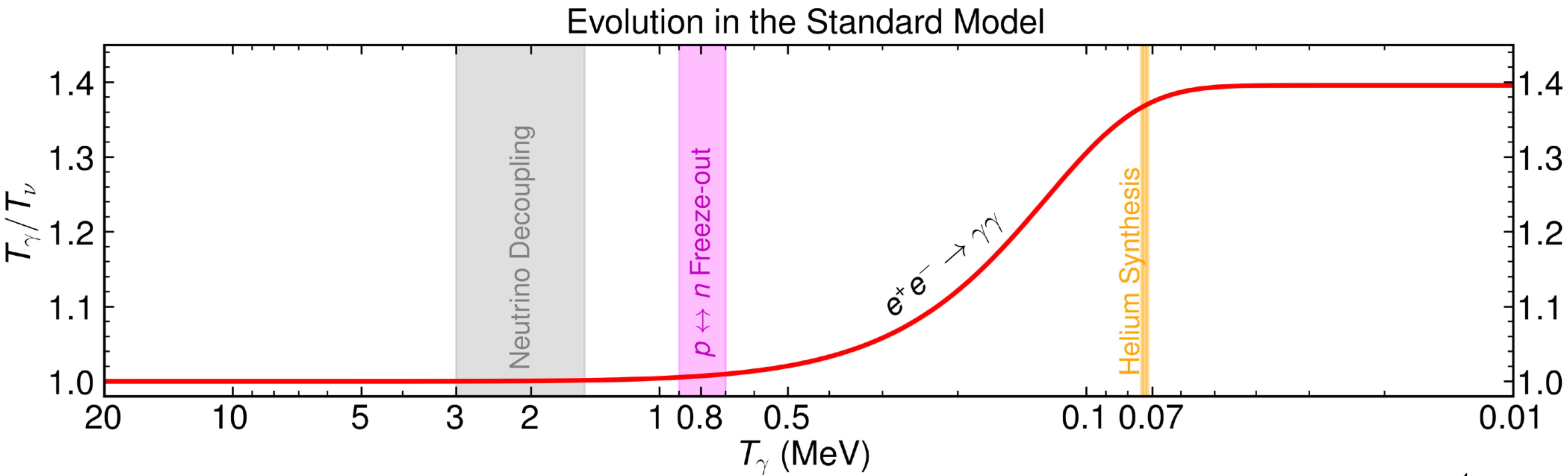




$$e^+e^- \leftrightarrow \bar{\nu}_i \nu_i$$
$$e^\pm \nu_i \leftrightarrow e^\pm \nu_i$$

Neutrinos Electrons Photons Z-W (off-shell)

Neutrino Decoupling



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

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

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

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

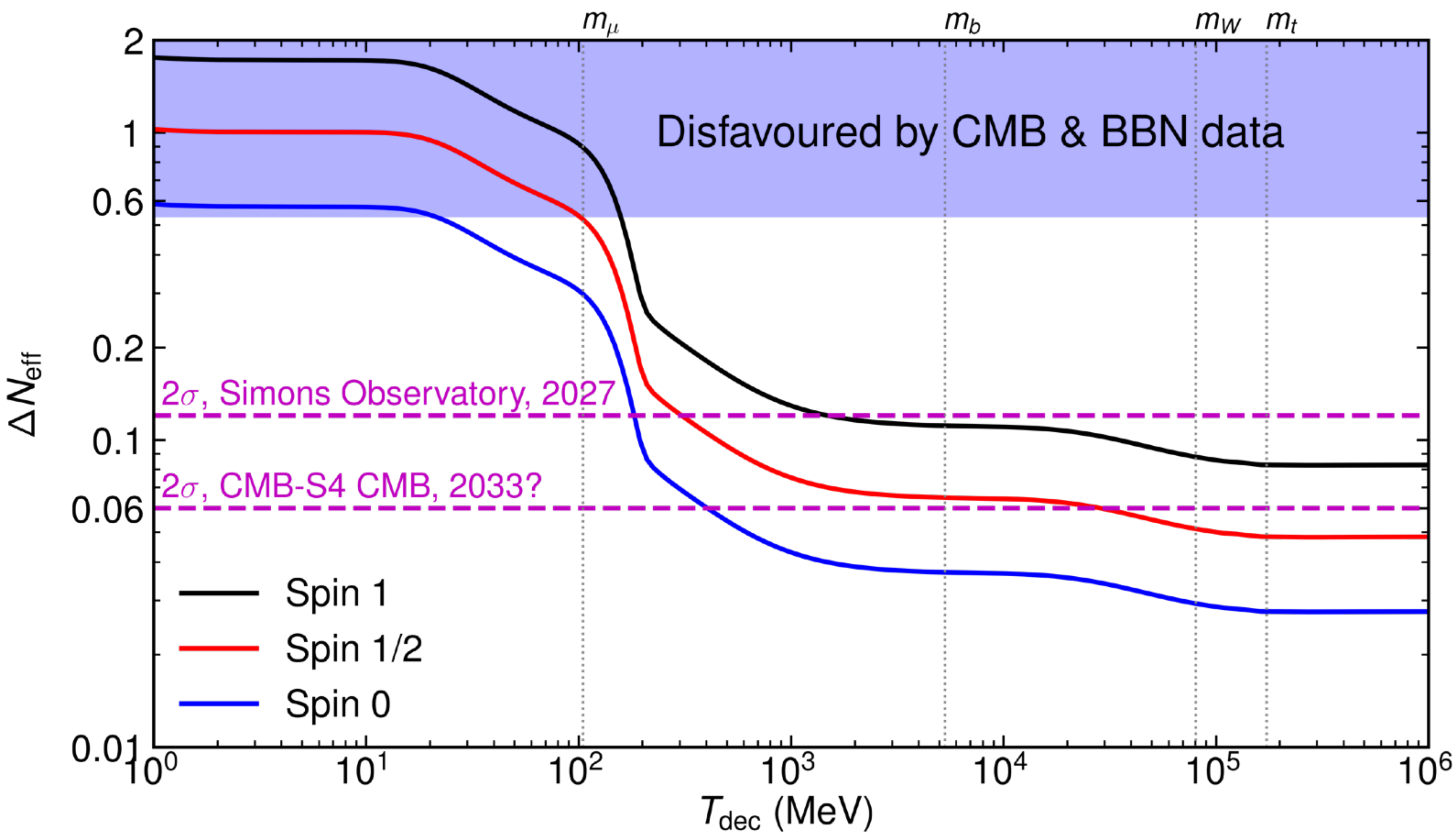
Why is it not 3?

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

Excellent review
by Dolgov hep-ph/0202122

Constraints from N_{eff}

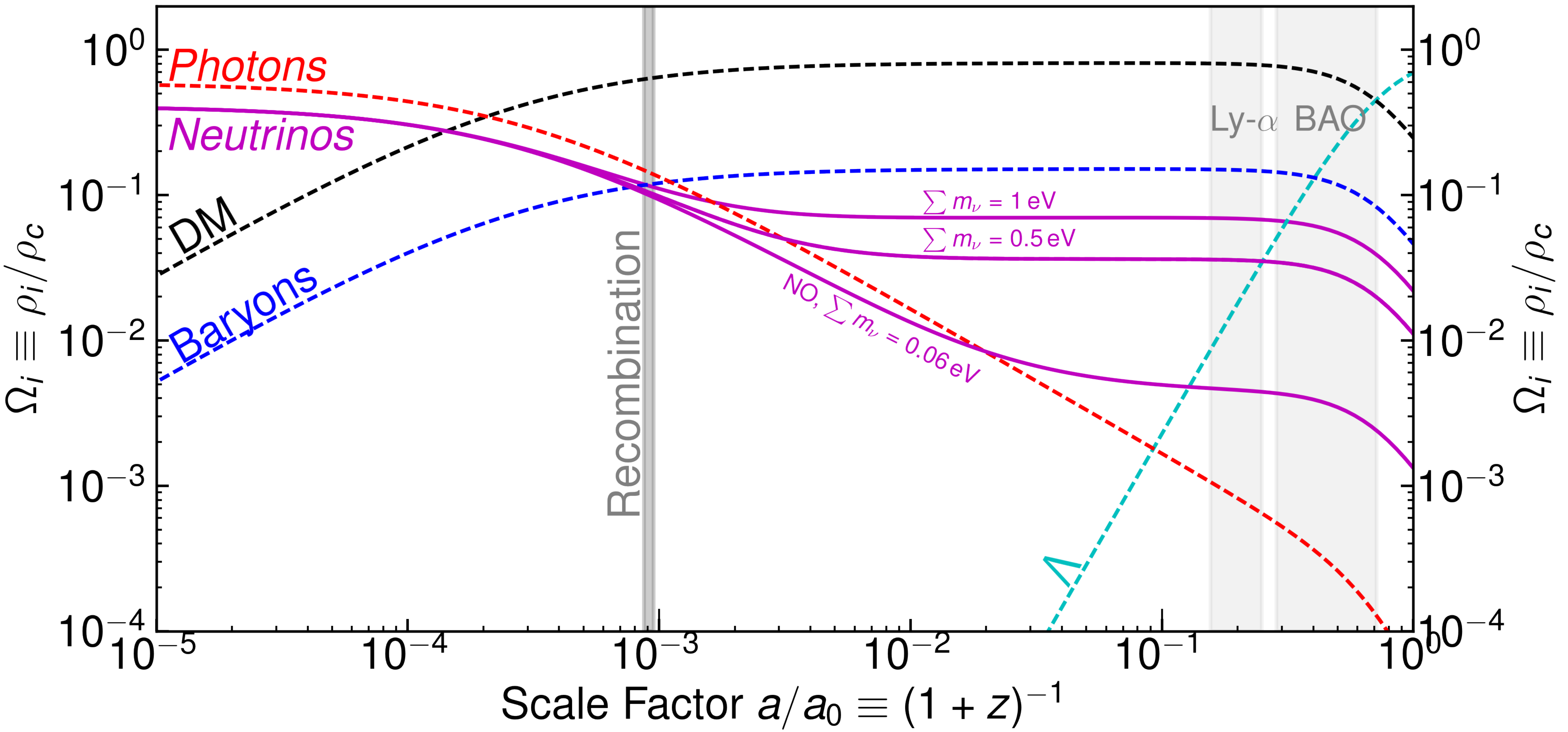
- **Sterile Neutrino** $m_N \sim \text{eV}$ $\Delta N_{\text{eff}} = 1$ **(e.g. Gariazzo, de Salas & Pastor 1905.11290)**
- **Goldstone Bosons**
  Editors' Suggestion
  Goldstone Bosons as Fractional Cosmic Neutrinos
  Steven Weinberg
  Phys. Rev. Lett. **110**, 241301 – Published 10 June 2013
- **Other sterile long-lived particles** **Gravitino, hidden sector particles, light DM ...**



- **Constraints are relevant in many other BSM settings**

Neutrino Masses in Cosmology

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

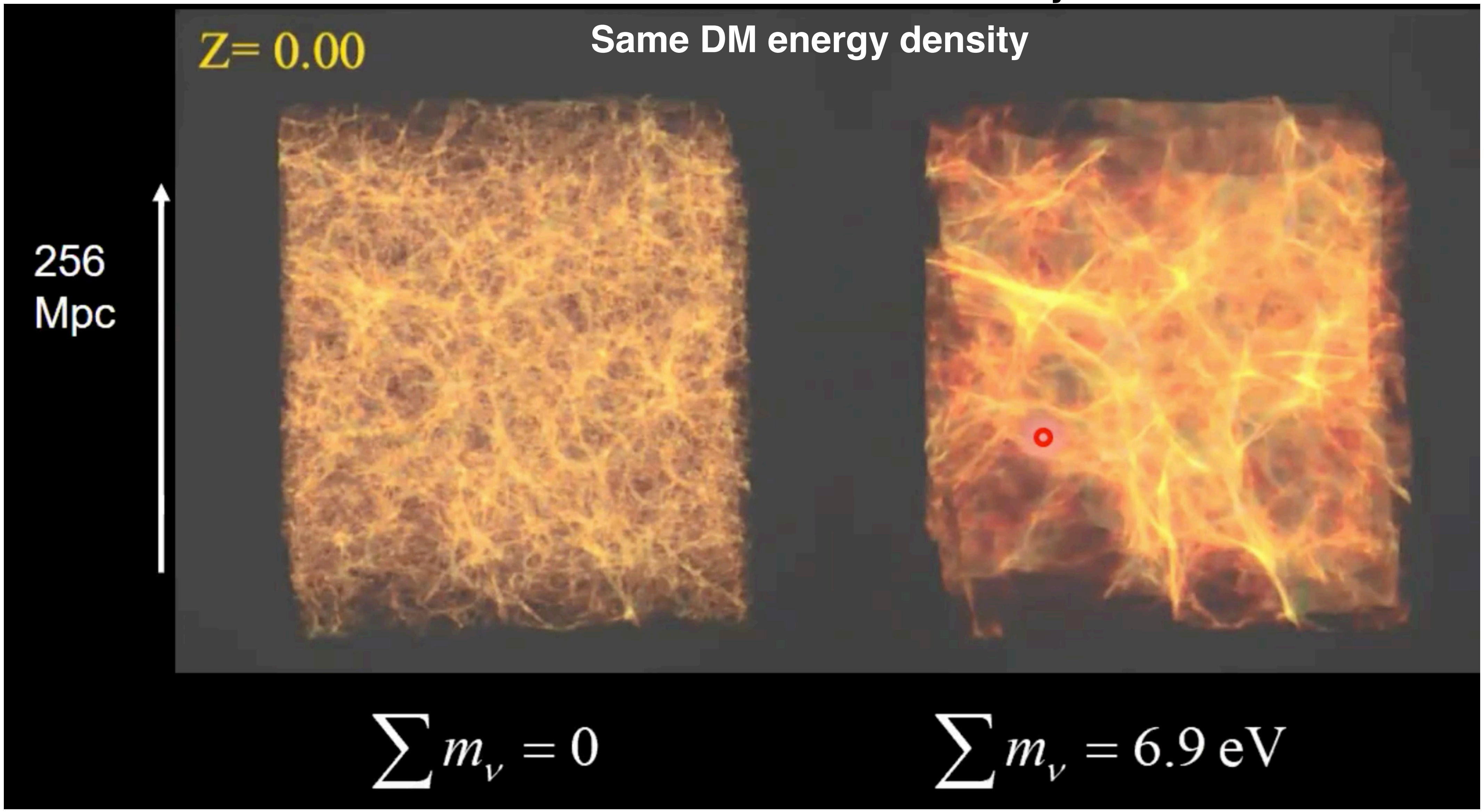


Non-Rel: $z_\nu^{\rm non-rel} \simeq 110 \frac{m_\nu}{0.06\,{\rm eV}}$ **Hot DM:** $\Omega_\nu h^2 = \sum m_\nu/(93.14\,{\rm eV})$

Neutrino Masses in Cosmology

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

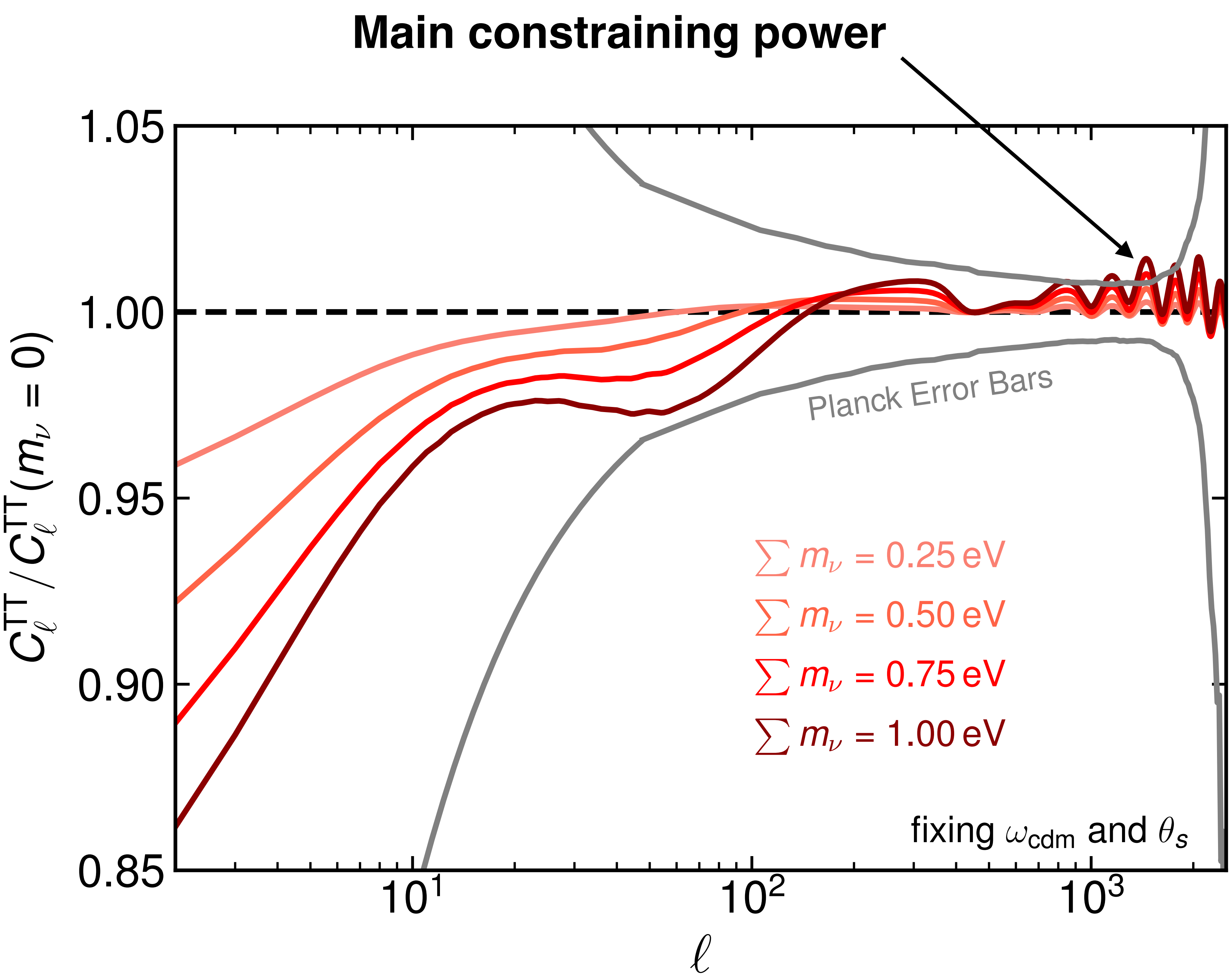
Taken from a talk by Steen Hannestad Link.



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

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies



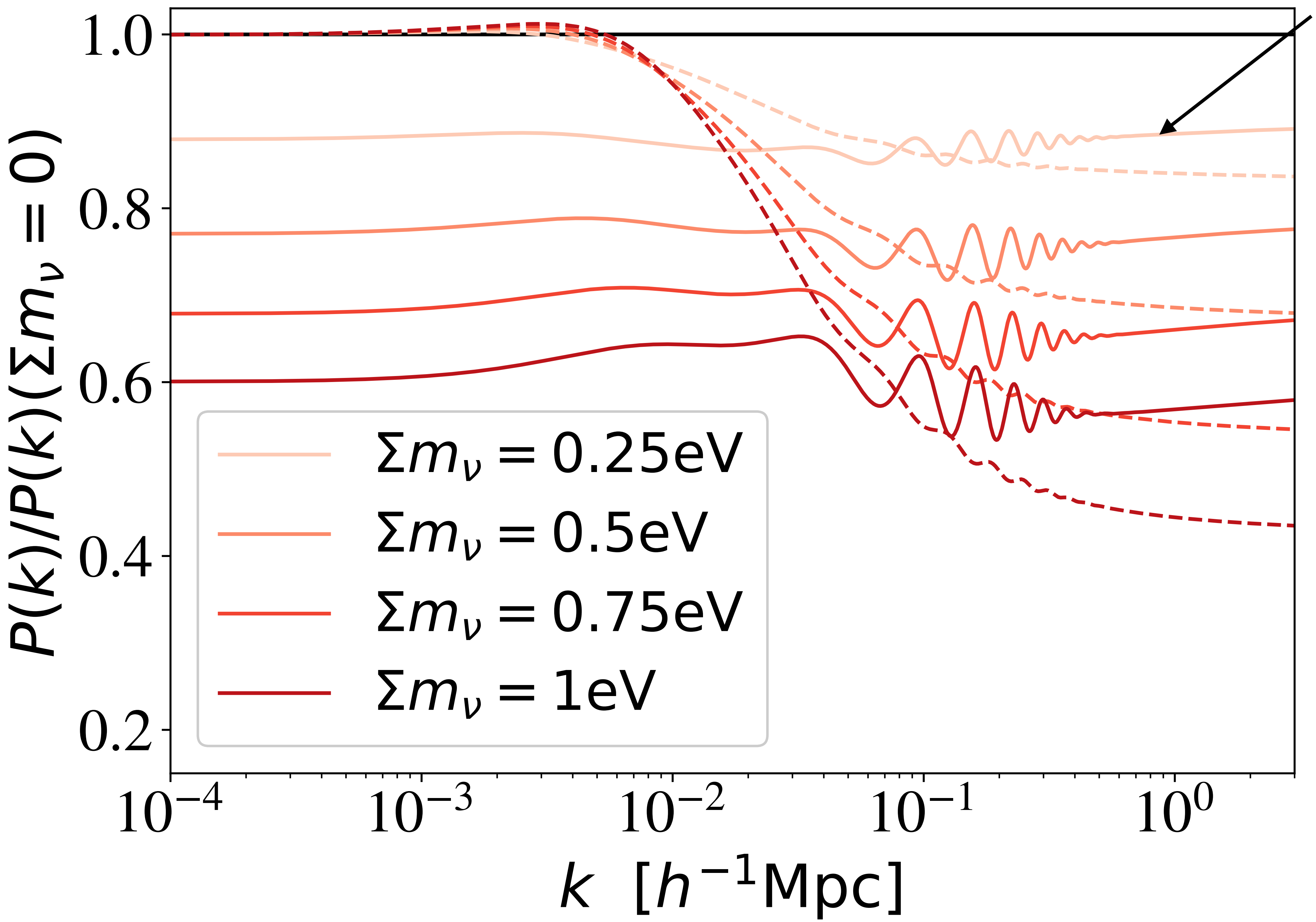
$$\sum m_\nu < 0.54\,\mathrm{eV}$$

(95 % CL, TT+lowE)

Neutrino Masses in Cosmology

Galaxy Surveys

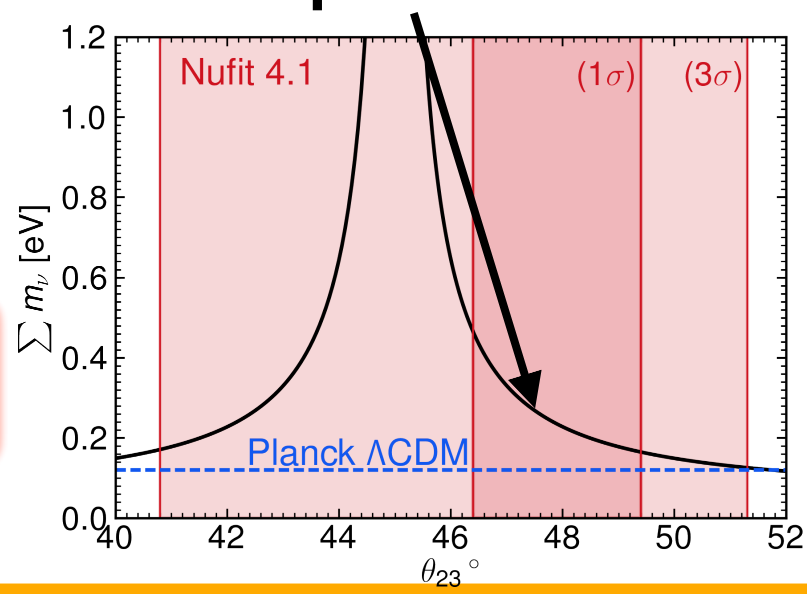
Suppression from $\Omega_\nu h^2$



Neutrino Mass Models

- Many neutrino mass models have large regions of parameter space with $\Sigma m_\nu > 0.12$ eV.
- Most of the 2-zero neutrino mass textures predict $\Sigma m_\nu > 0.12$ eV.
  See e.g. Alcaide, Santamaría & Salvadó, 1806.06785.
- Well motivated example: Neutrino models based on $U(1)_{\mu-\tau}$
  - $U(1)_{\mu-\tau}$ anomaly free
  - Very minimal: 3 Sterile Neutrinos, *N*
    1 Charged scalar field, *Δ*
    \+ *Z'* if U(1) is gauge
  - Studied extensively: Choubey & Rodejohann, hep-ph/0411190
    Araki, Heeck & Kubo, 1203.4951
    Asai et al.: 1705.00419, 1811.07571
    1907.04042, 1909.08827
  - Only one problem: $0.17\,\text{eV} < \sum m_\nu < 0.47\,\text{eV}$

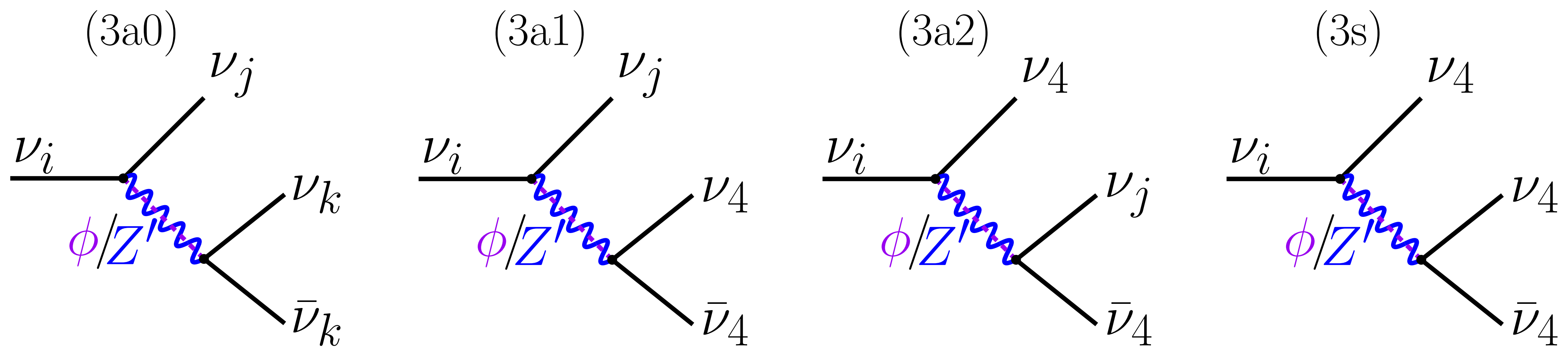
Mass prediction



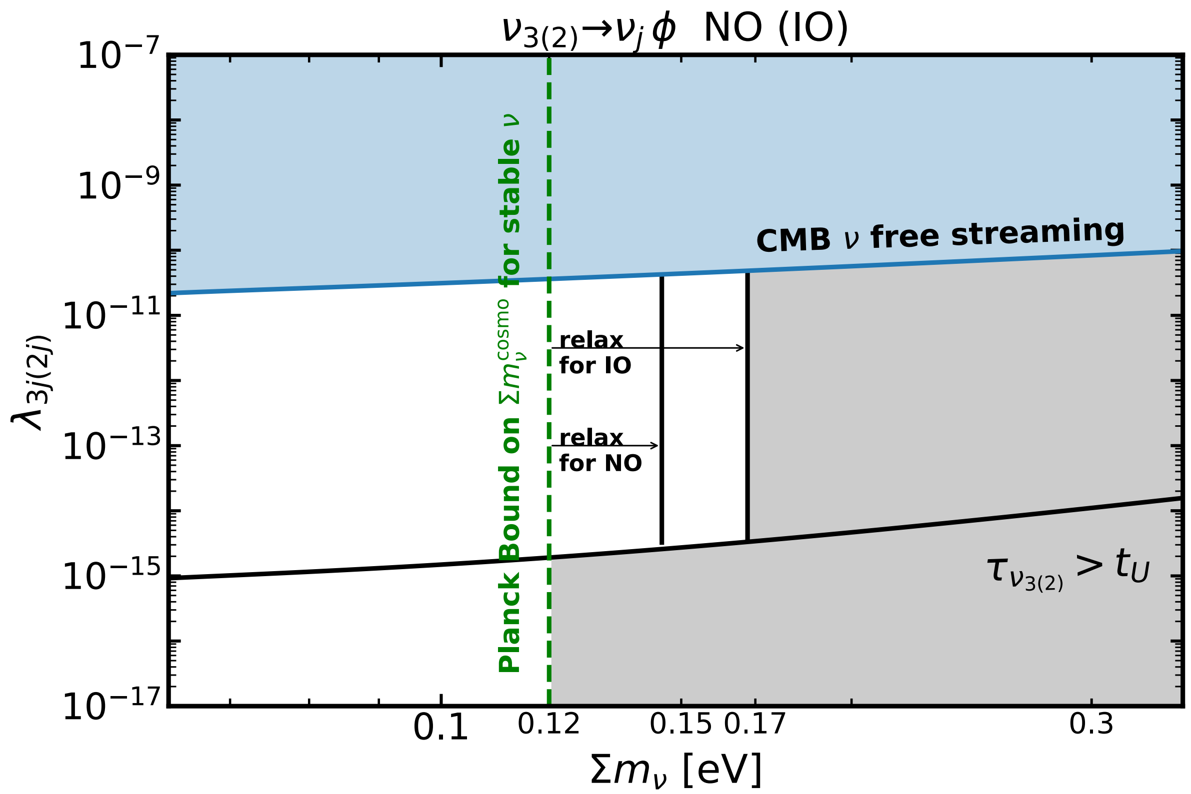
Neutrino Decay Diagrams

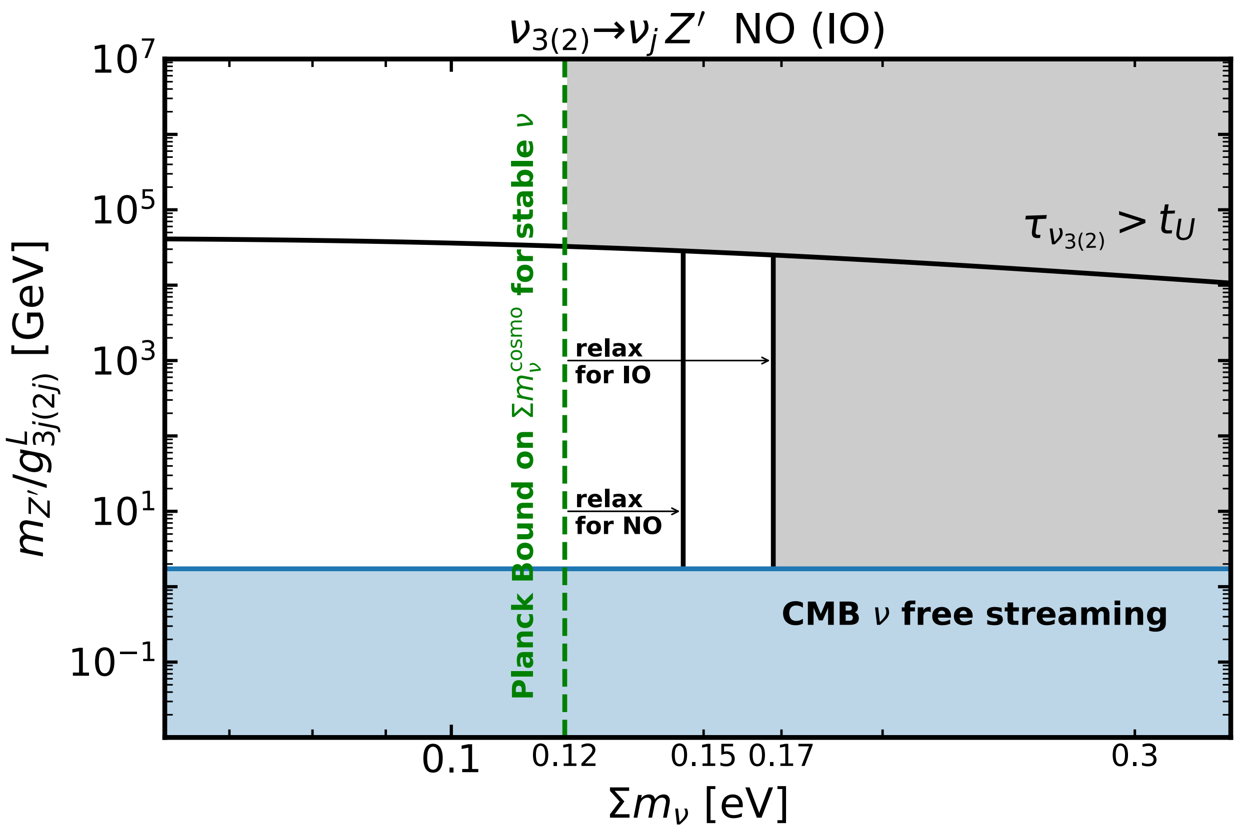
2-body Decays:

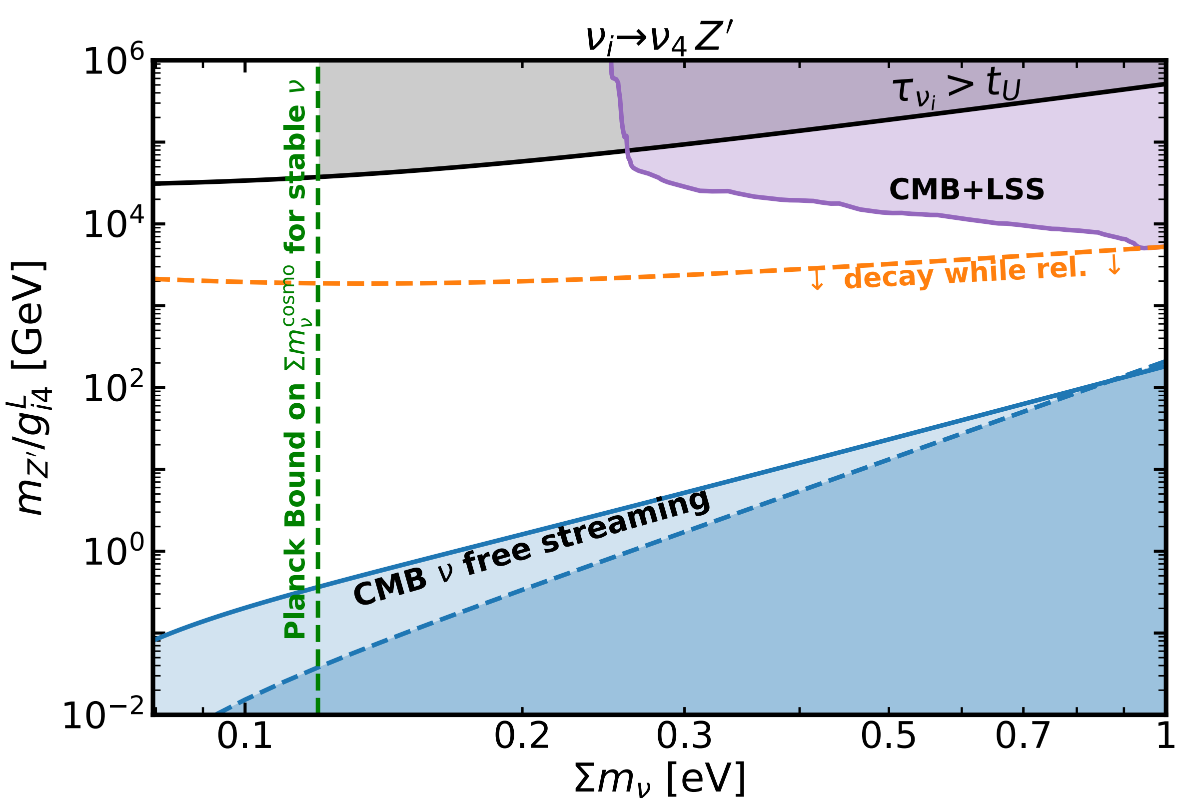
3-body Decays:

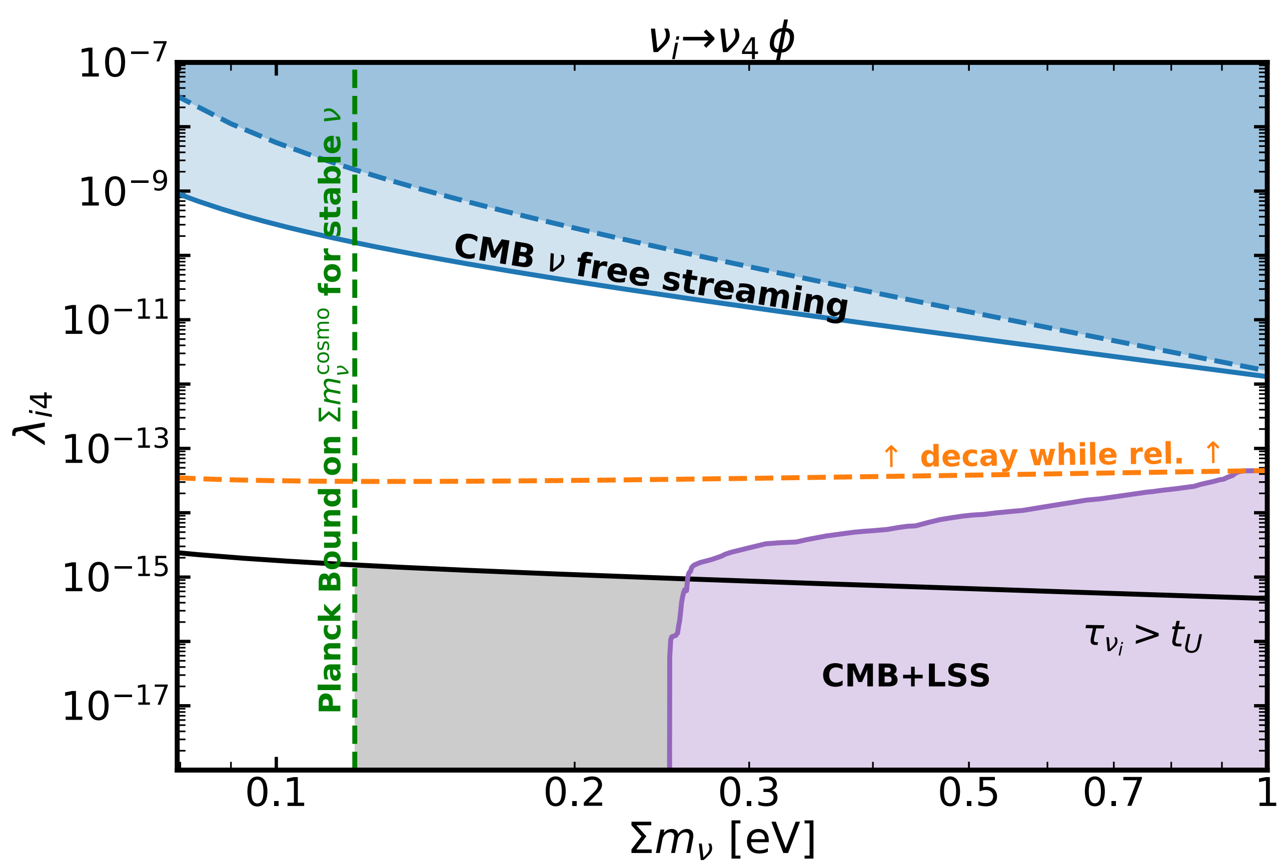


Neutrino Decay Parameter Space

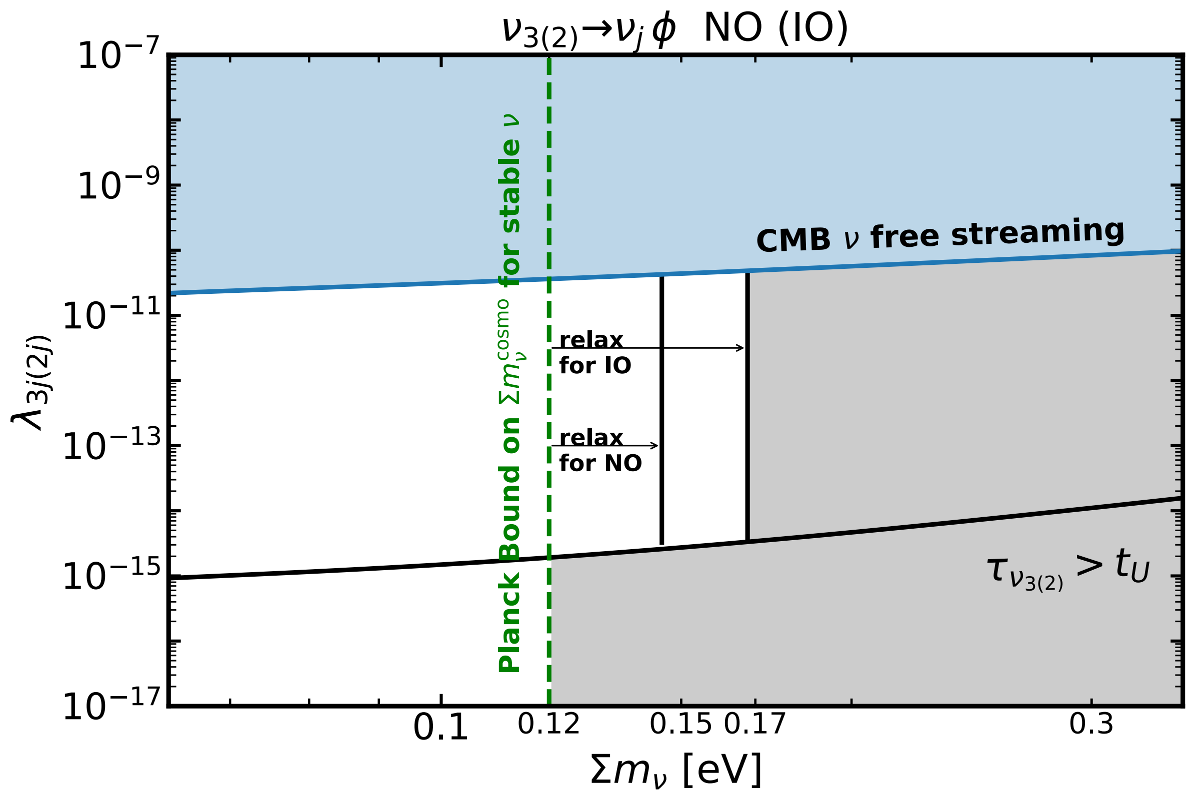


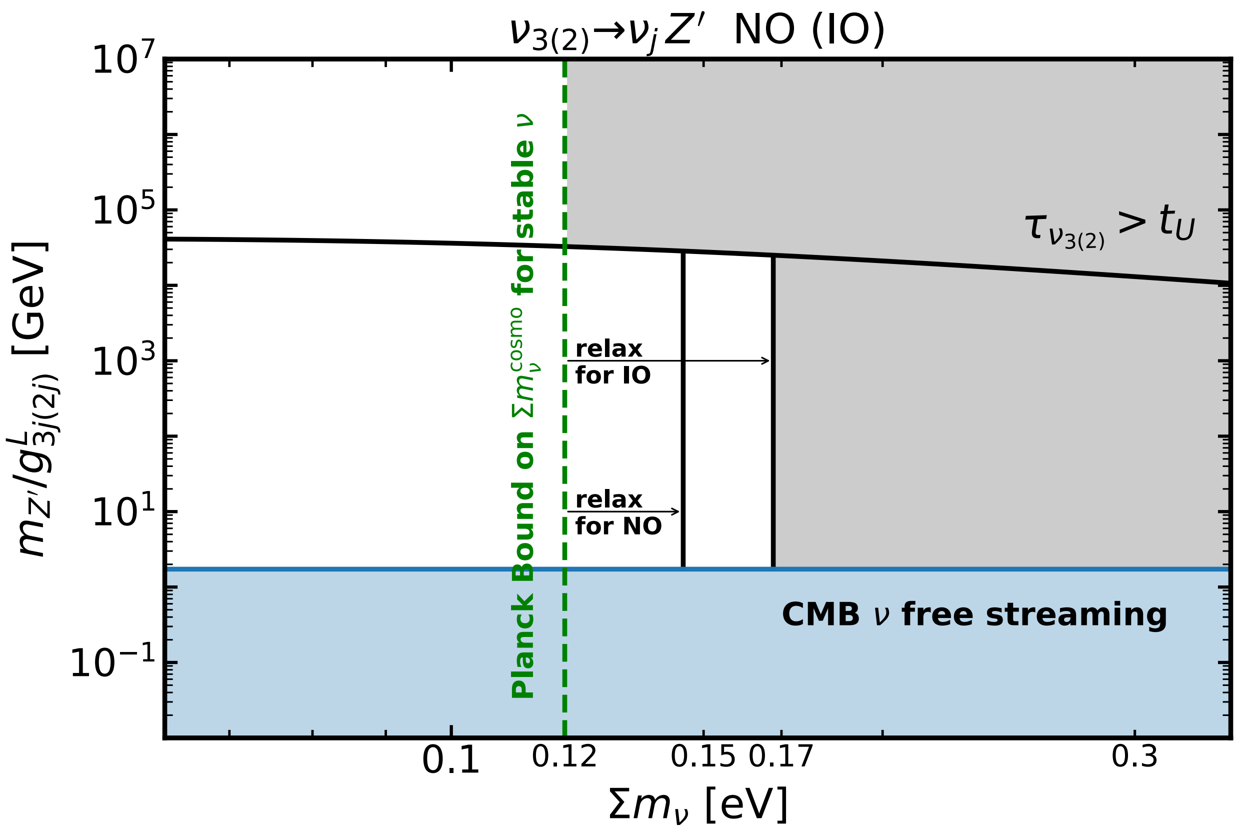


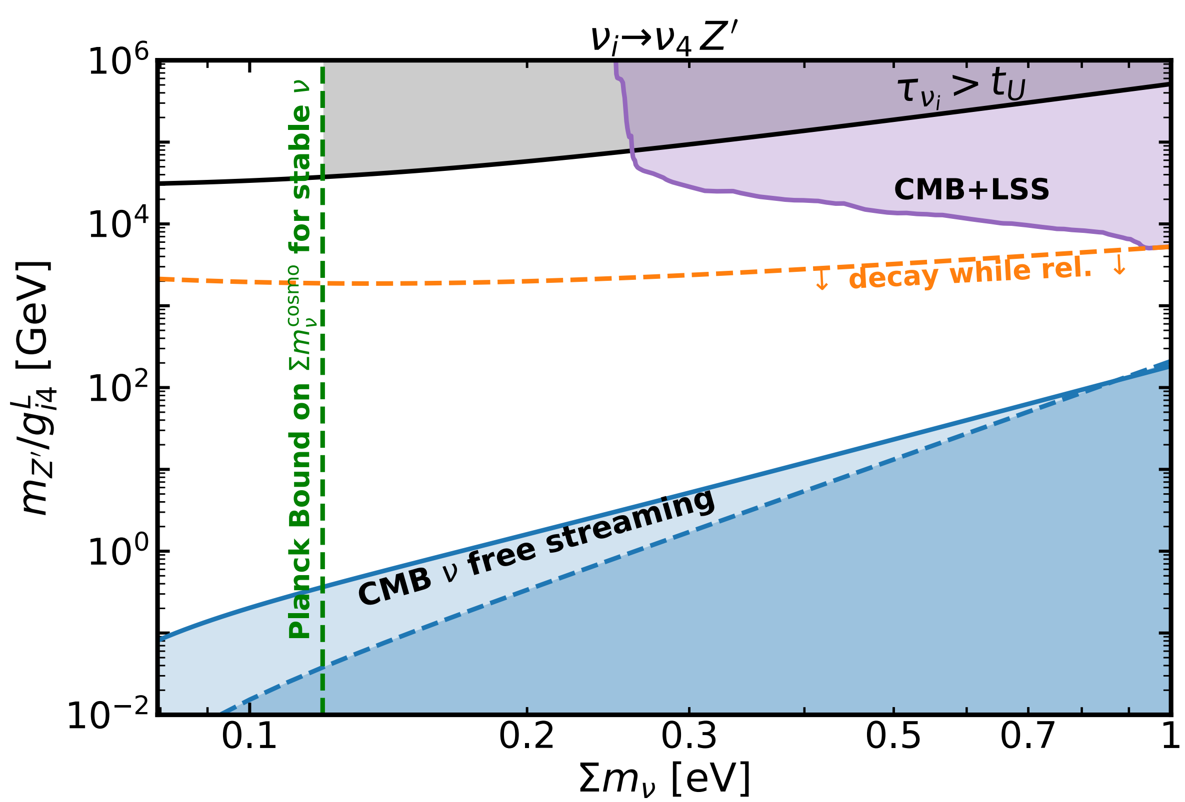


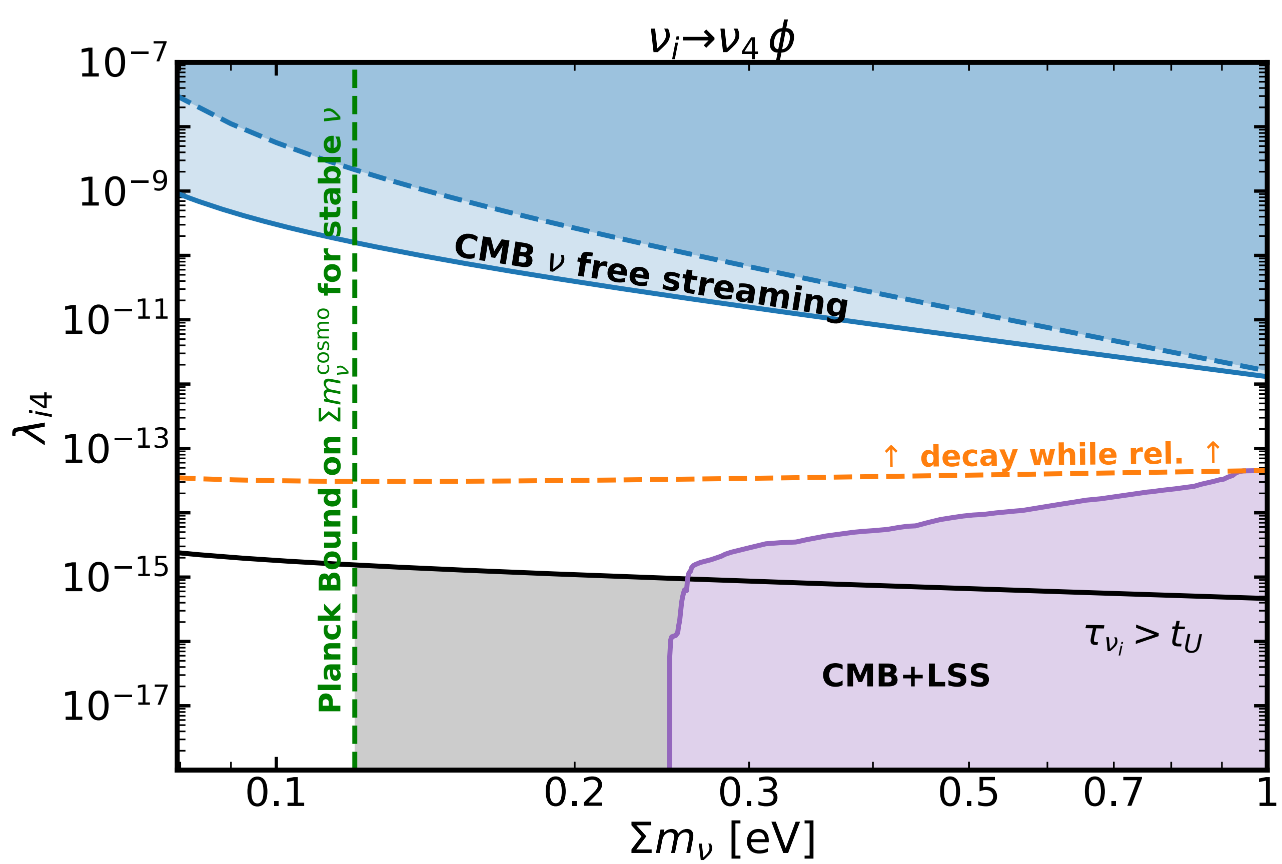


Neutrino Decay Parameter Space



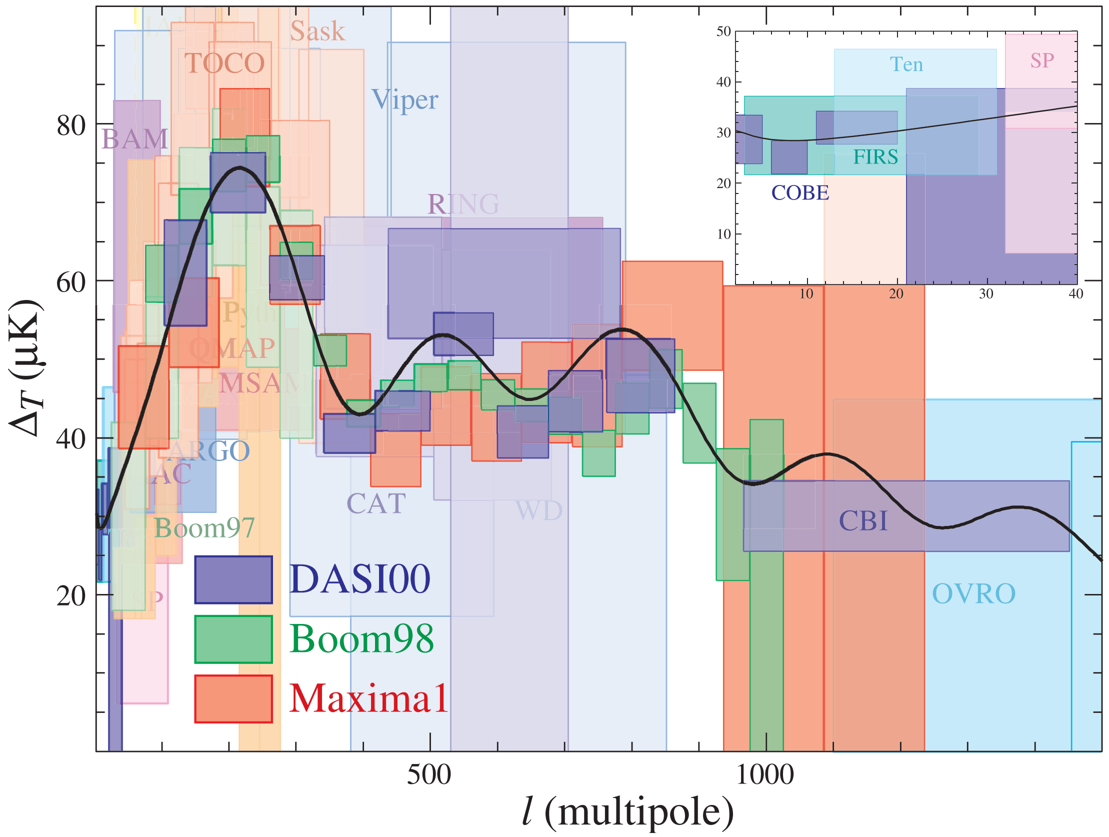




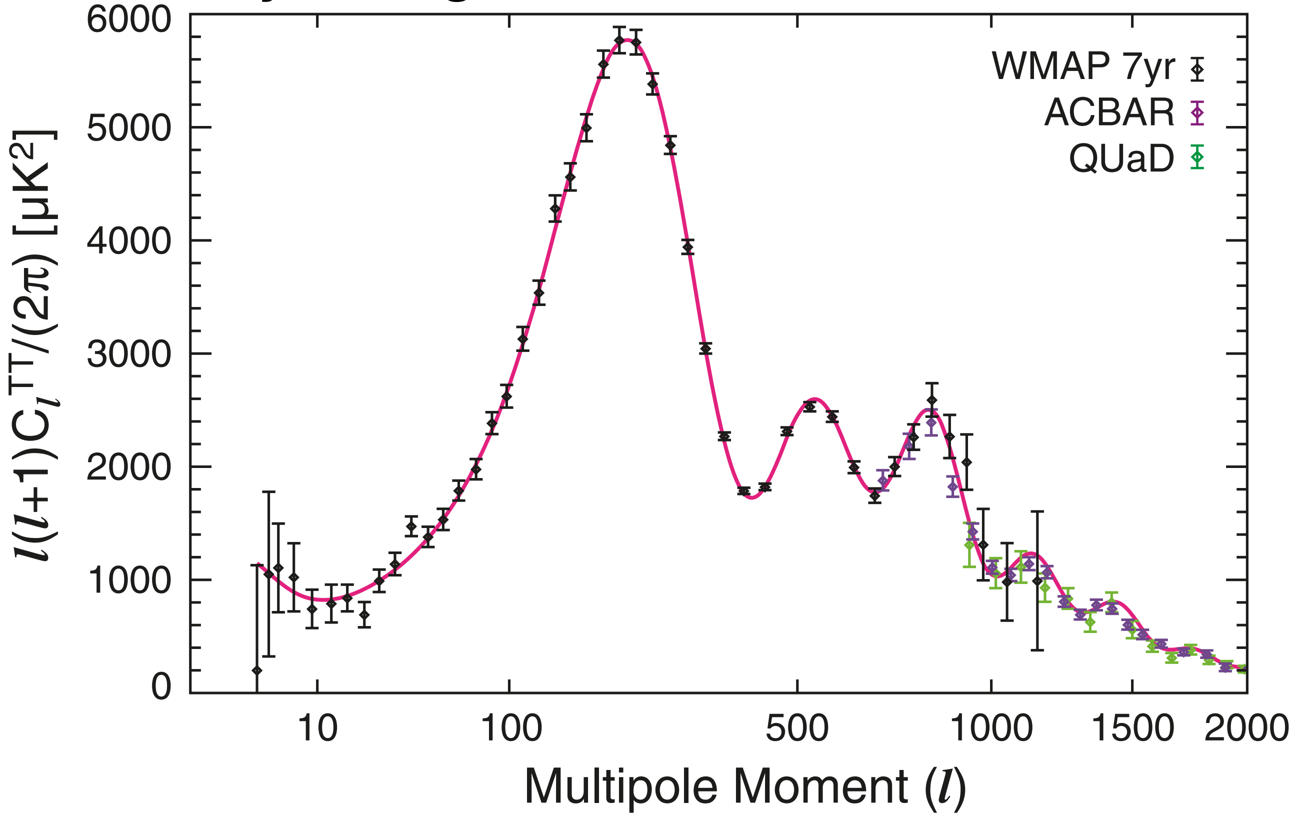


CMB History

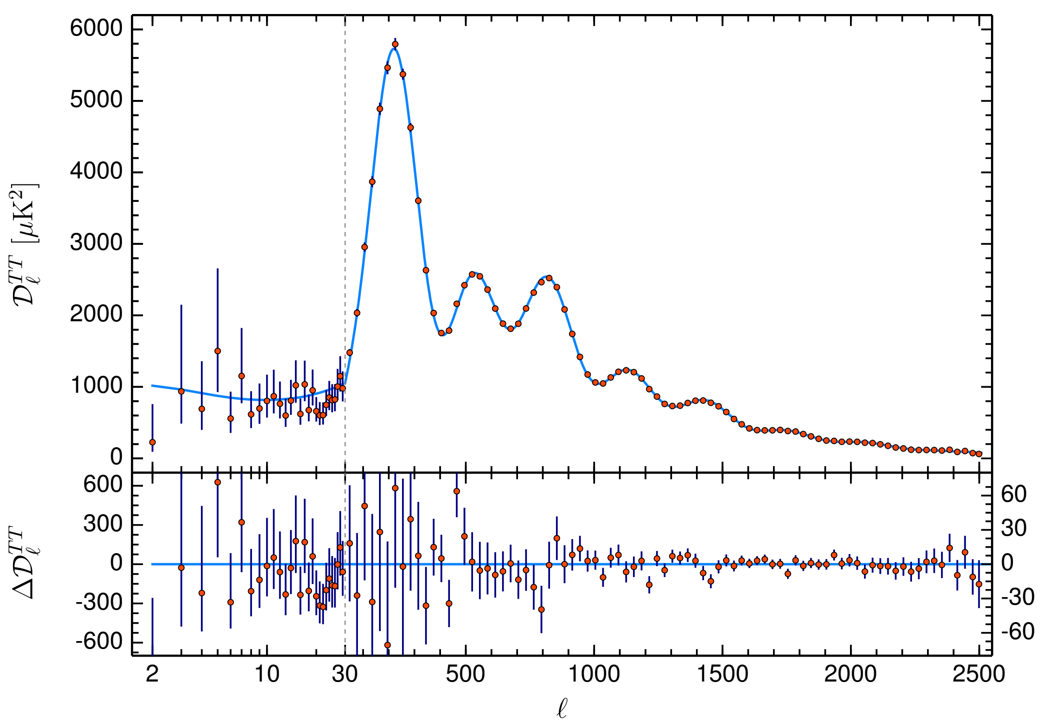
20 years ago **Dodelson & Hu astro-ph/0110414**



10 years ago **WMAP7 Komatsu et al. 1001.4538**

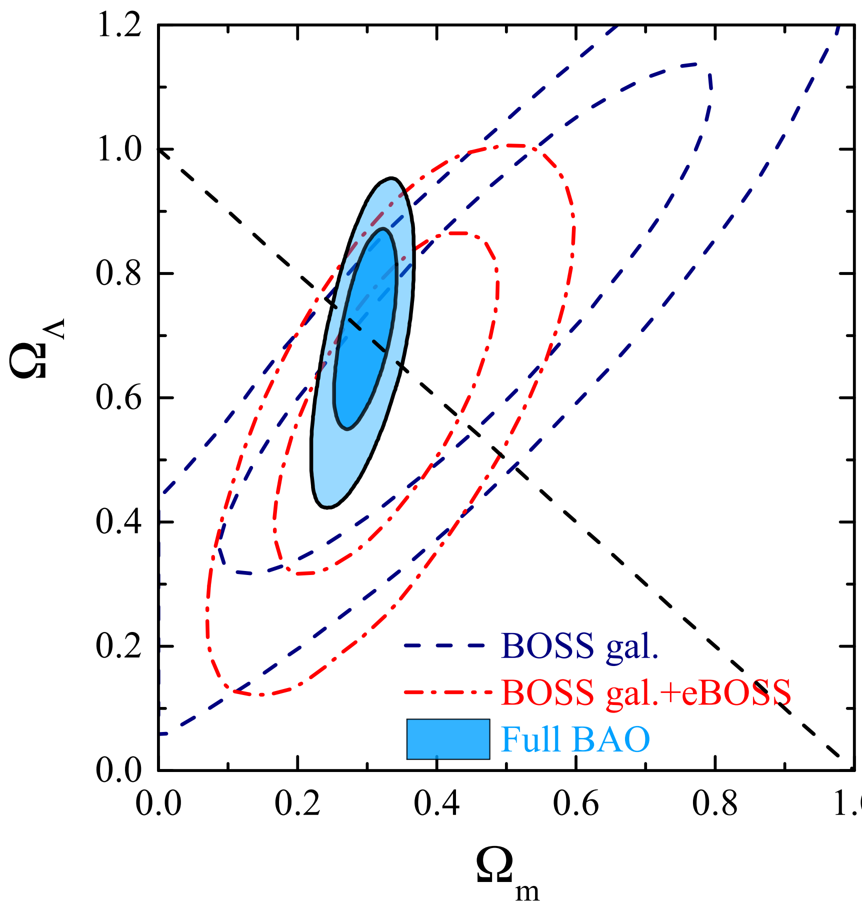


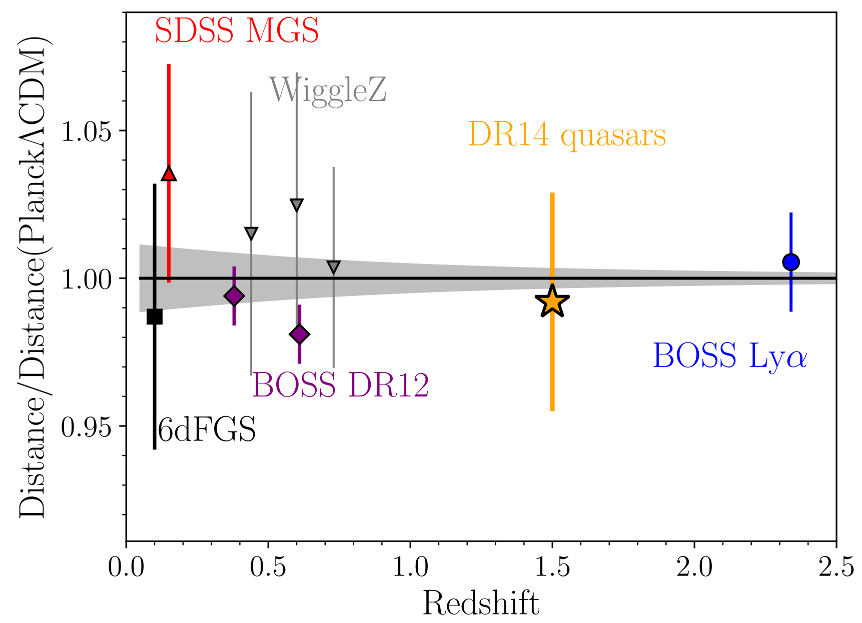
Planck:



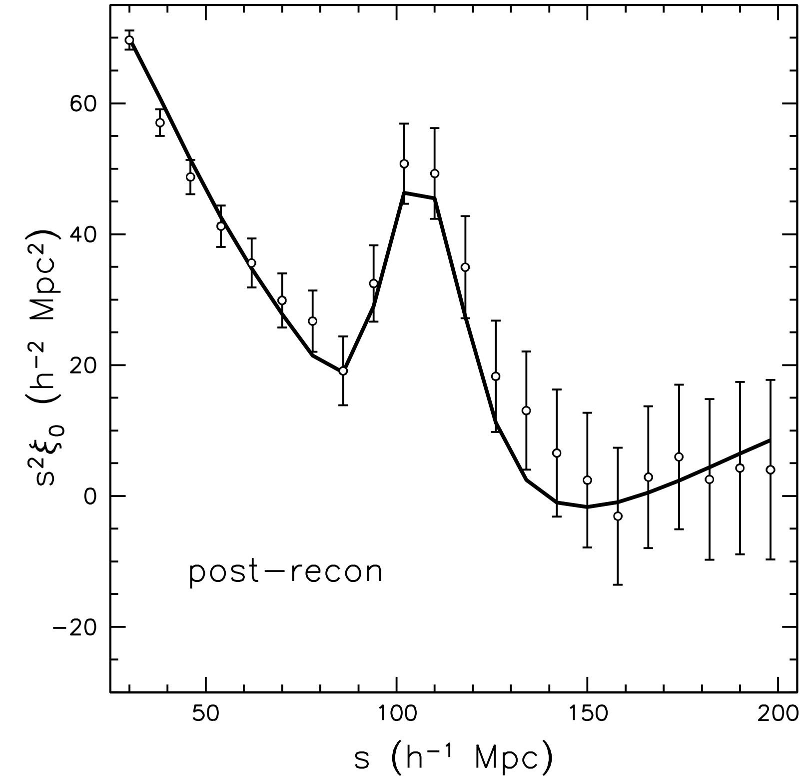
Some Cosmo Plots

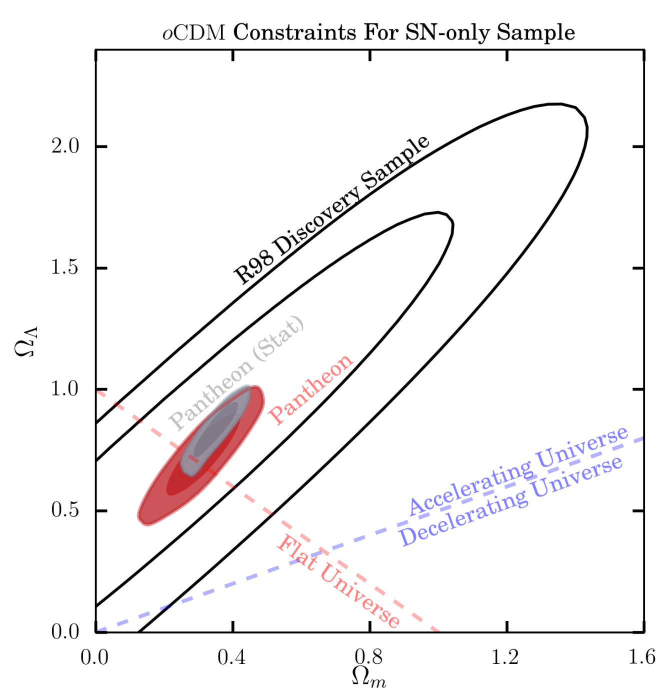
eBOSS: Ata et al. 1705.06373





BOSS: Anderson et al. 1312.4877





SNIa
Pantheon
Scolnic
1710.00845