

Neutrino Cosmology

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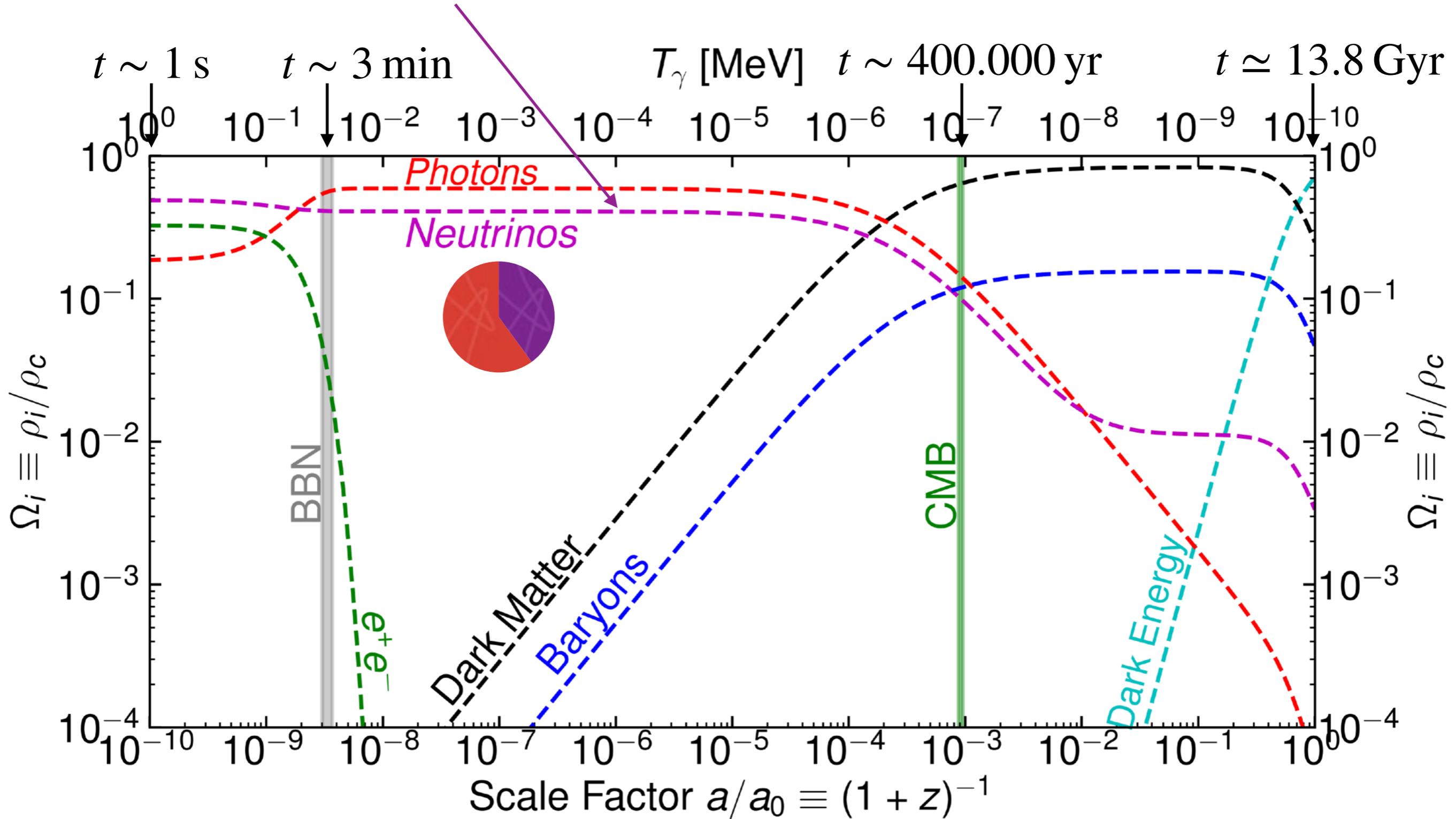
**21st Rencontres du Vietnam
Neutrino School
24-07-2025**

Neutrino Evolution

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

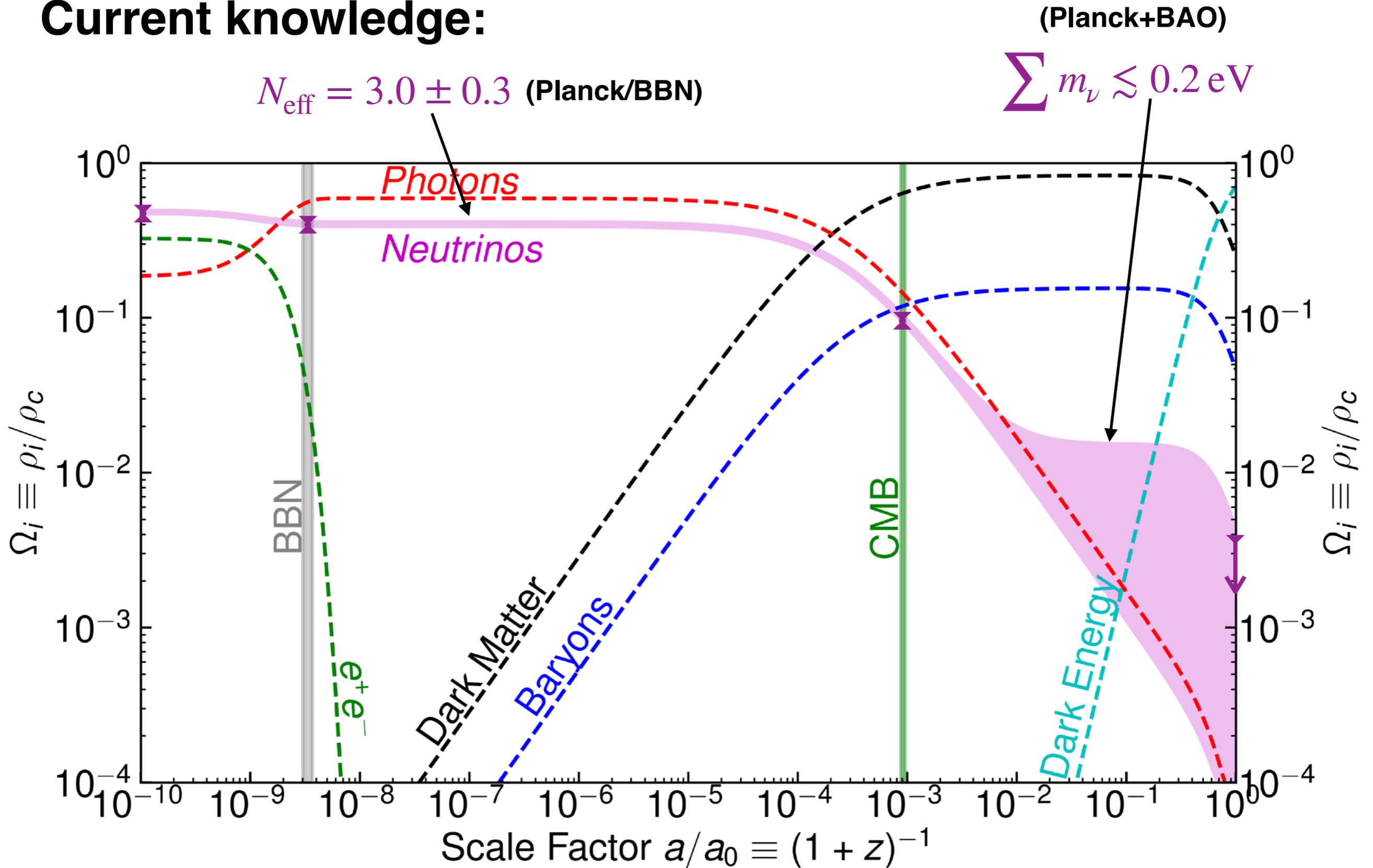
Neutrino Evolution

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Global Perspective

Current knowledge:



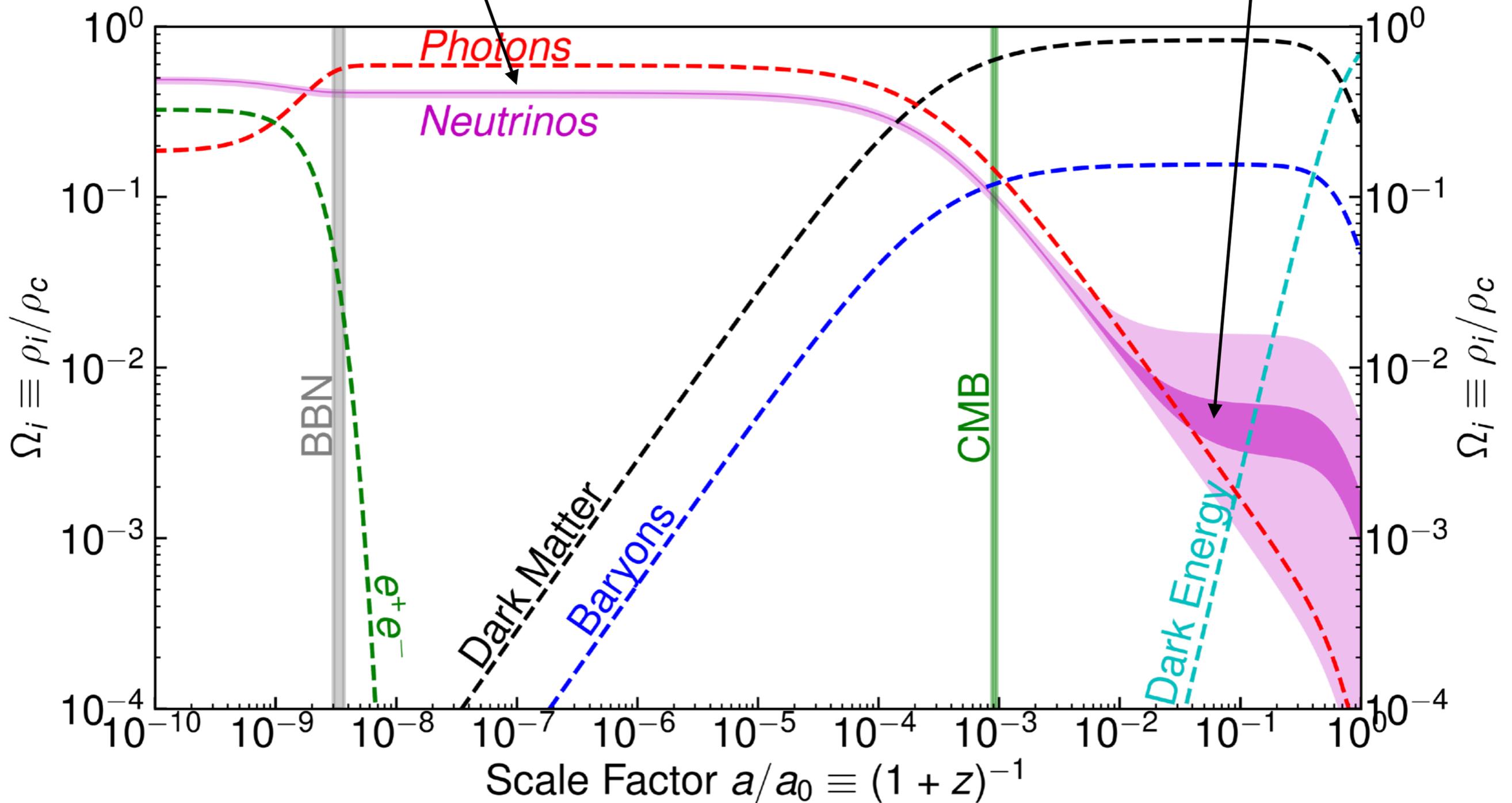
Global Perspective

In the next 5-6 years:

(DESI/Euclid + Planck)

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

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



Goals

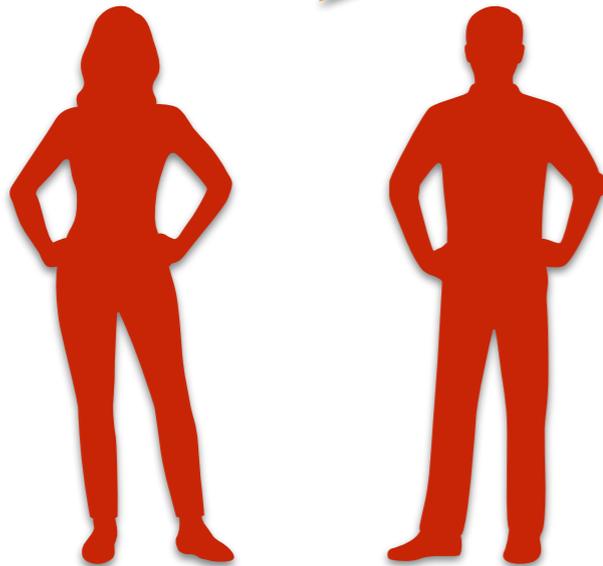
- 1) Understand what is the role played by neutrinos in Cosmology**
- 2) Understand the evidence that we have for the Cosmic Neutrino Background and have a flavor of the types of BSM physics that can be tested with neutrinos in cosmology**
- 3) Understand why can one derive neutrino mass bounds using cosmological data and what are the assumptions behind these constraints**
- 4) What are we going to learn in the upcoming years?**

Set Up

Unlike neutrinos, I do like to interact 😊

The plan is to learn and therefore:

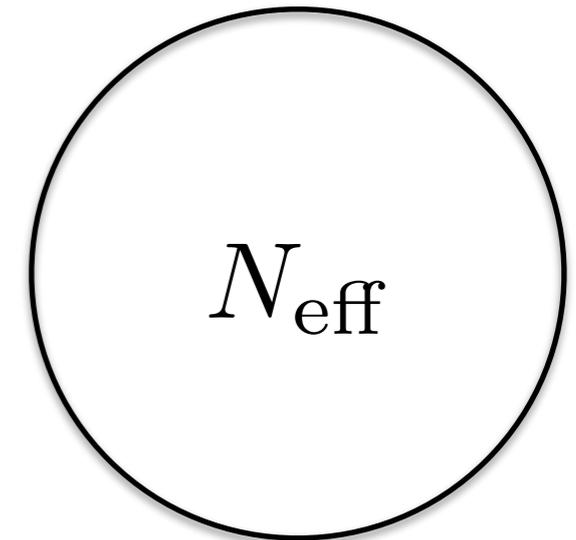
**Questions and Comments
are most welcome, at any
time!!!!**

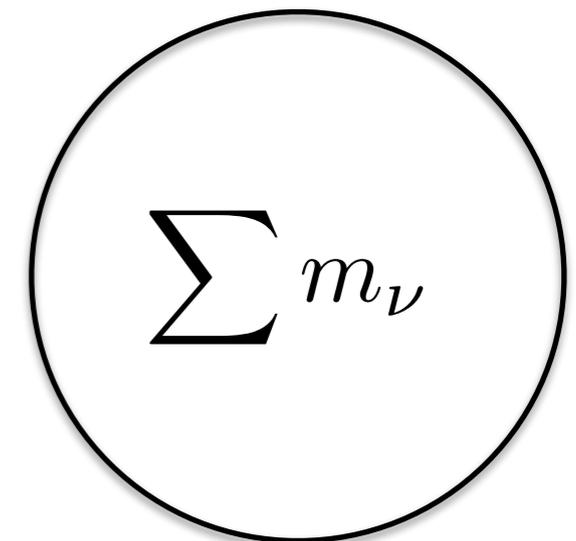


The Cosmic Neutrino Background

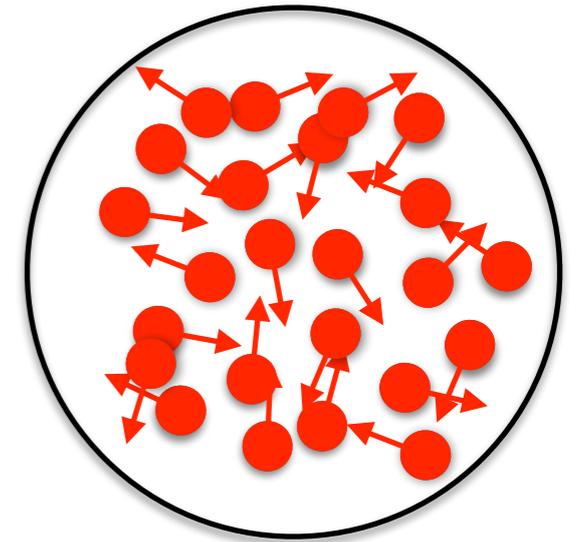
Neff and its implications

Neutrino masses in Cosmology

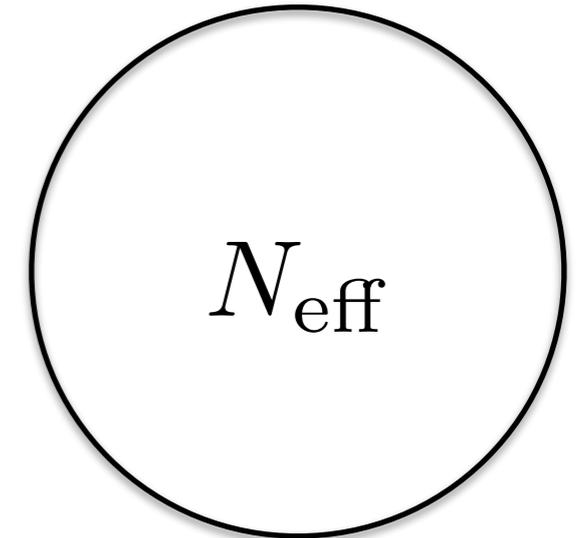

$$N_{\text{eff}}$$


$$\sum m_\nu$$

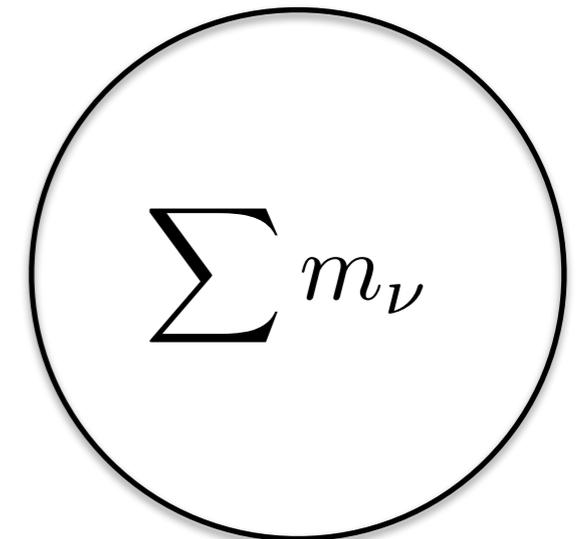
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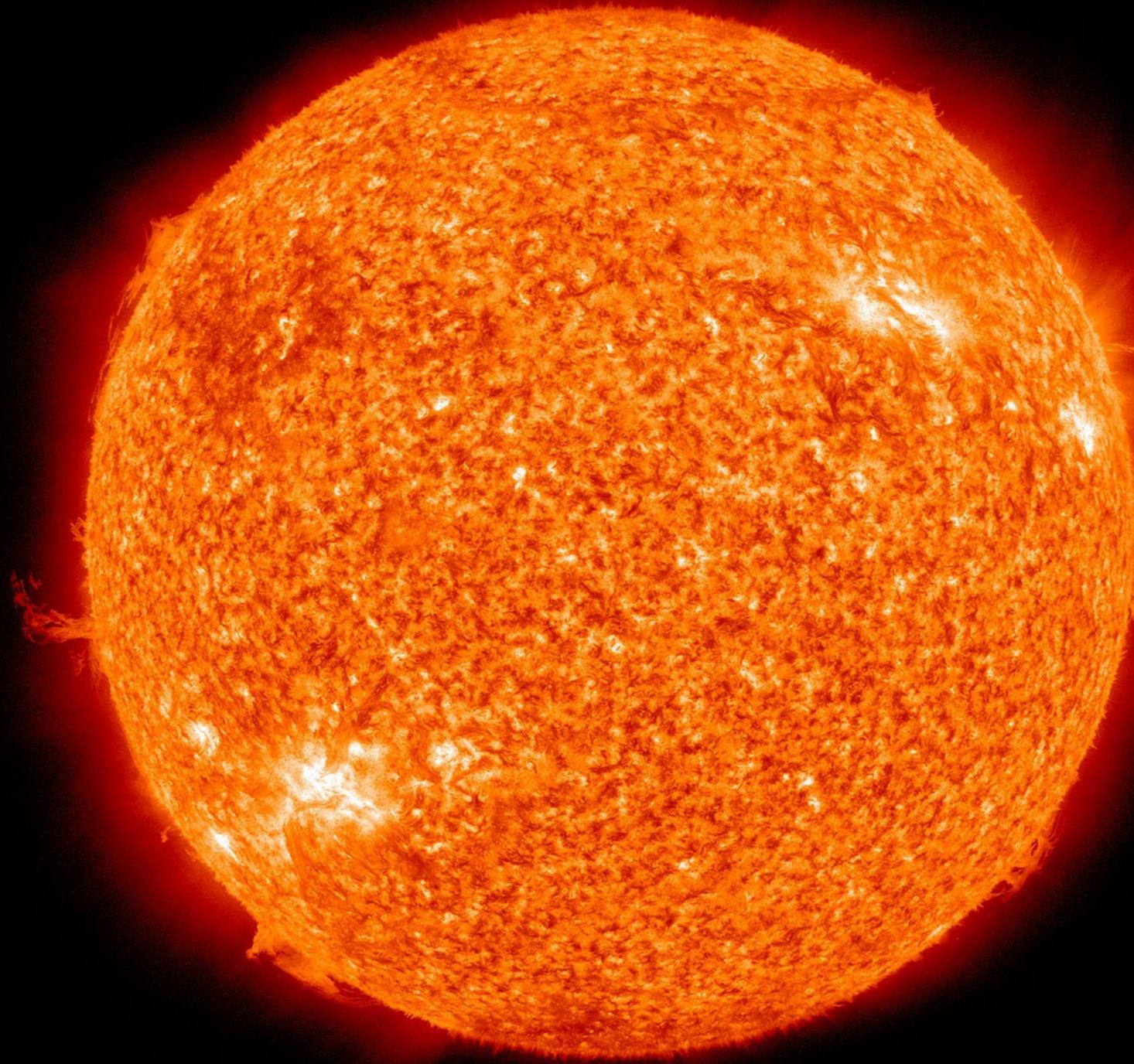
N_{eff} and its implications



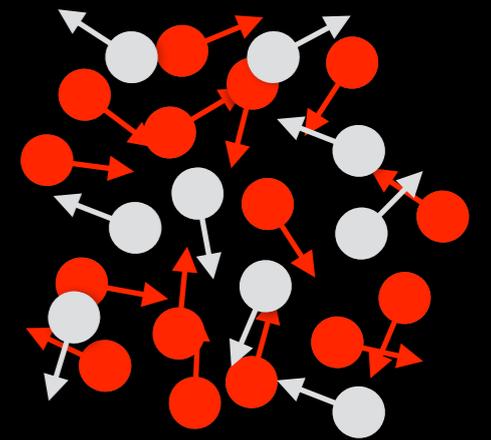
Neutrino masses in Cosmology



The Early Universe



T = MeV

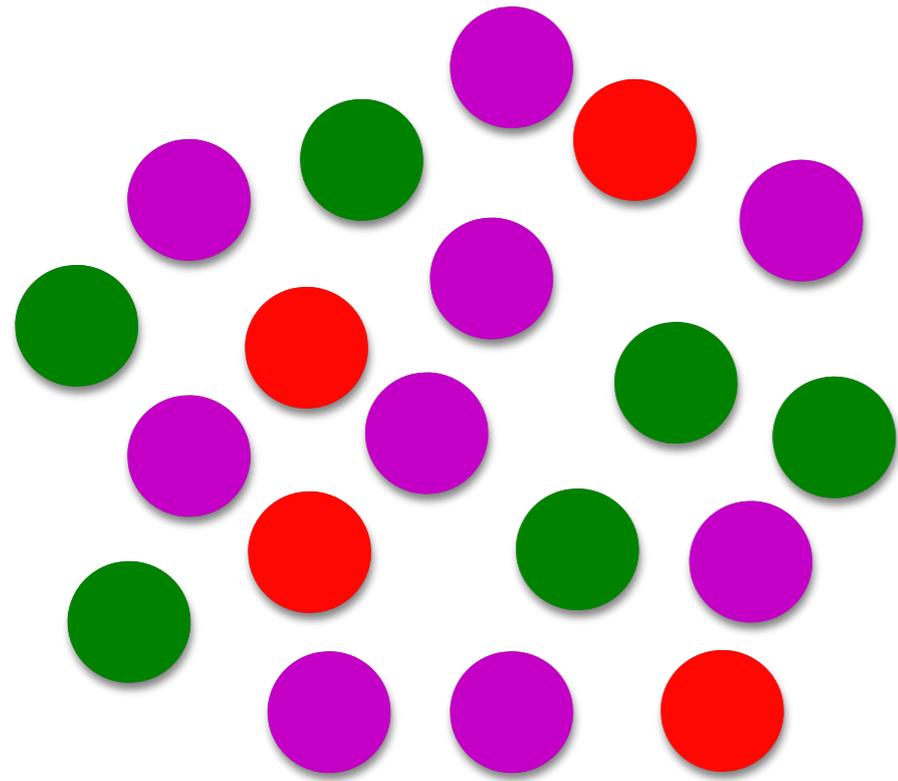


t = 1s

**[1000 times hotter than
the core of the sun!]**

T = 10¹⁰ K

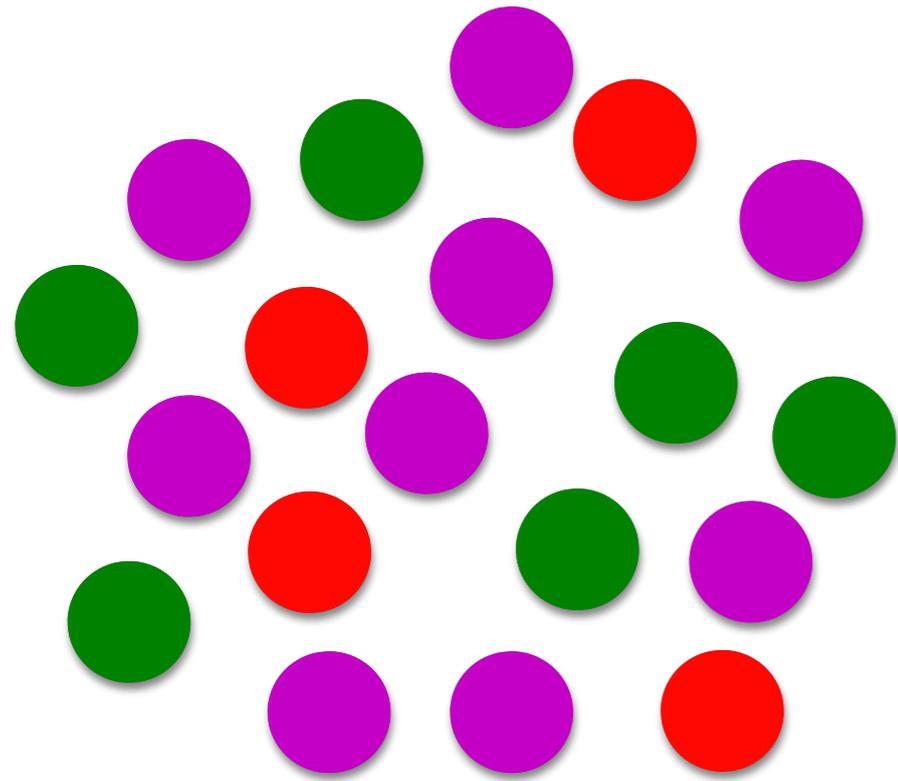
The Cosmic Neutrino Background



$$\Gamma = n_e \langle \sigma v \rangle$$

-  **Neutrinos**
-  **Electrons & Positrons**
-  **Photons**

The Cosmic Neutrino Background



$$\Gamma = n_e \langle \sigma v \rangle$$

$$\sigma \simeq G_F^2 s$$

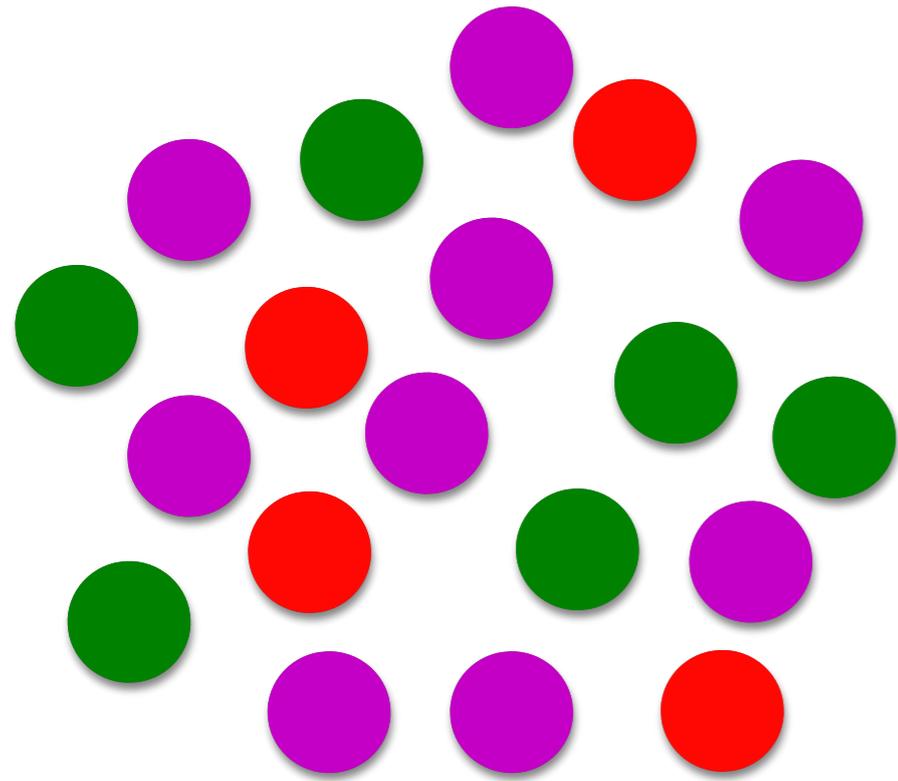
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The Cosmic Neutrino Background



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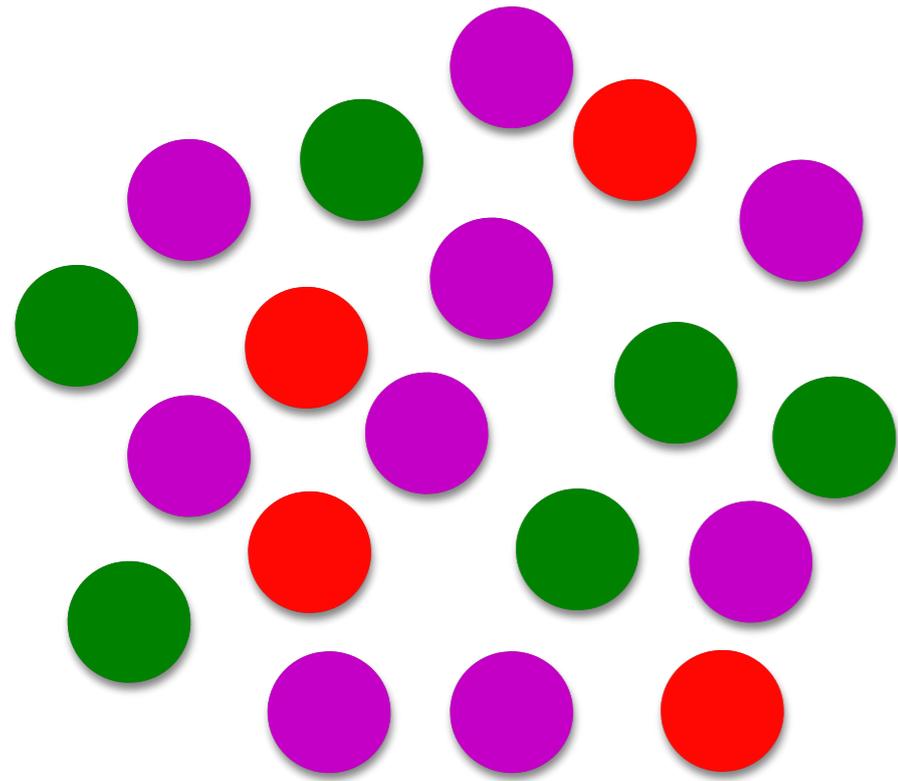
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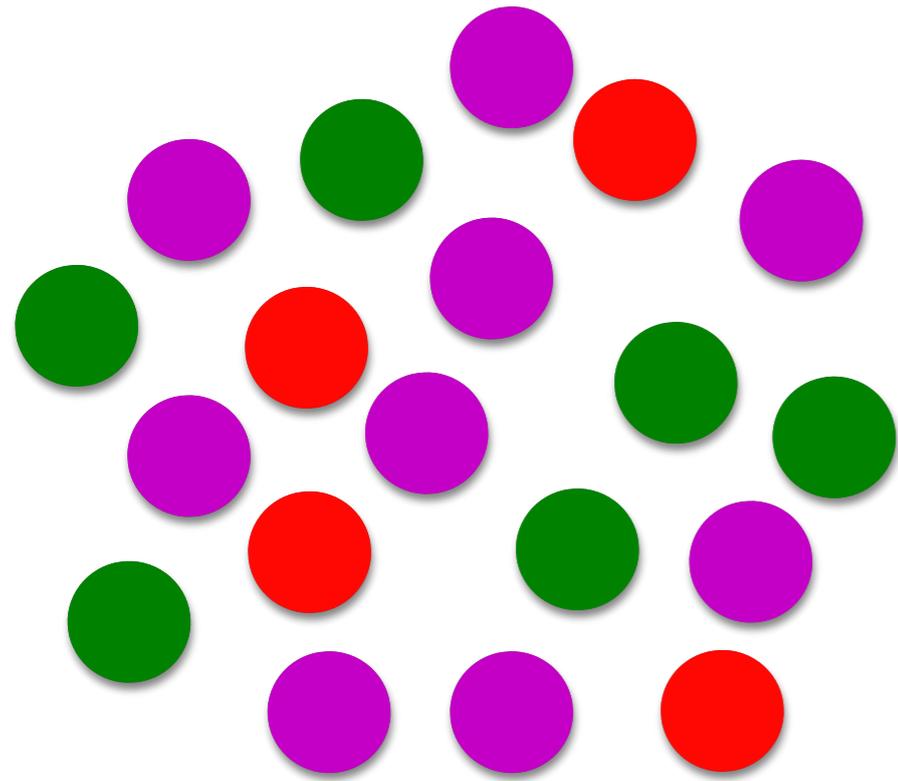
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$$\Gamma \simeq G_F^2 T^5 \quad \langle \sigma v \rangle \simeq G_F^2 T^2$$

$$H = 1.66 \sqrt{g_\star} T^2 / M_{\text{Pl}}$$

The Cosmic Neutrino Background



Neutrinos



Electrons & Positrons



Photons

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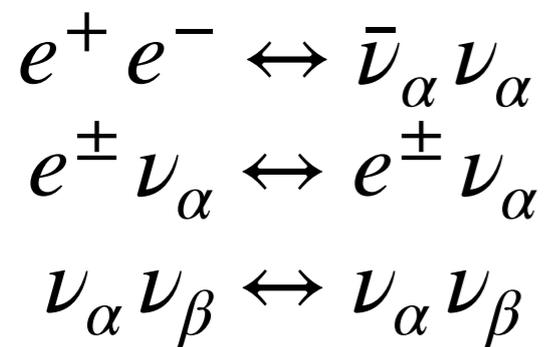
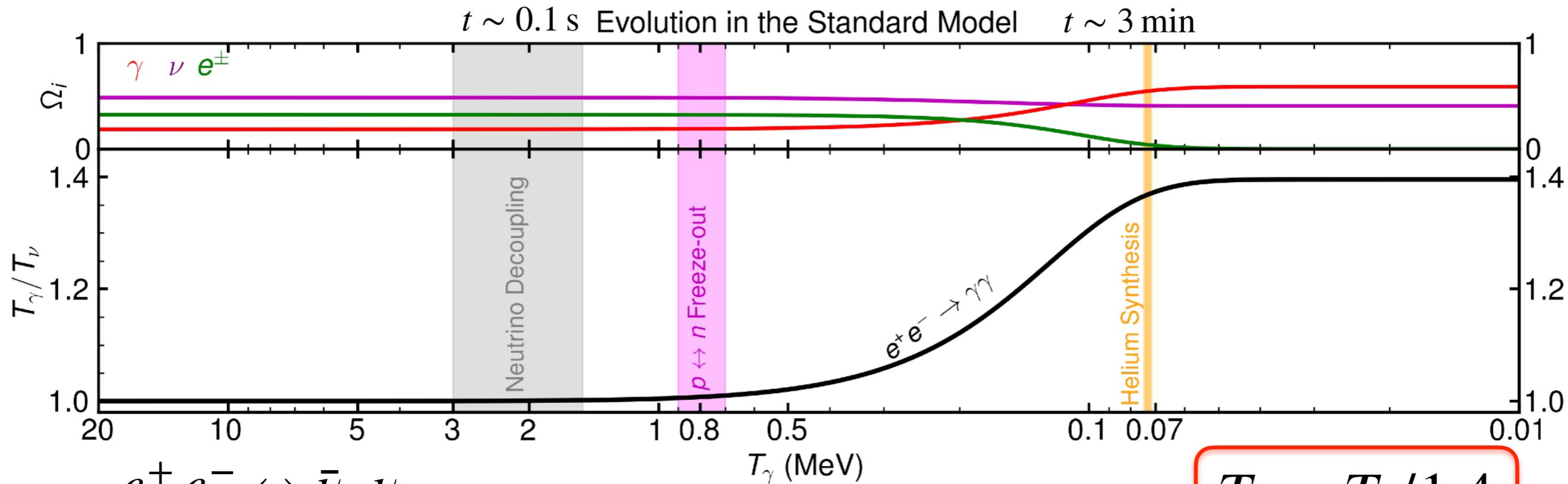
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$$\Gamma \simeq H \quad T \simeq 2 \text{ MeV}$$

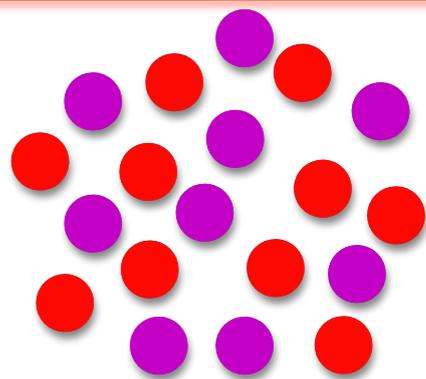
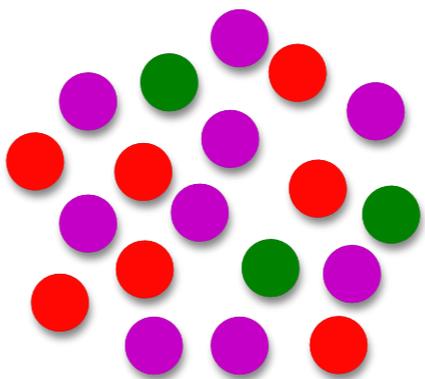
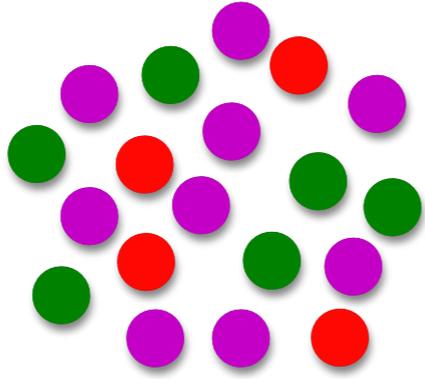
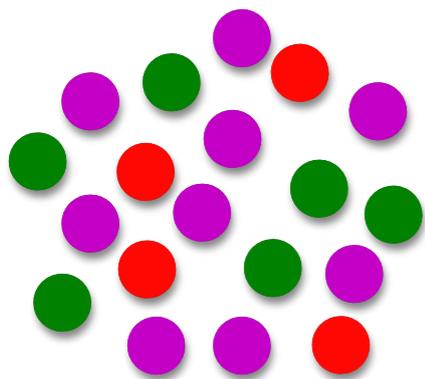
The formation of the Cosmic Neutrino Background

Neutrino Decoupling



$$T_\nu = T_\gamma / 1.4$$

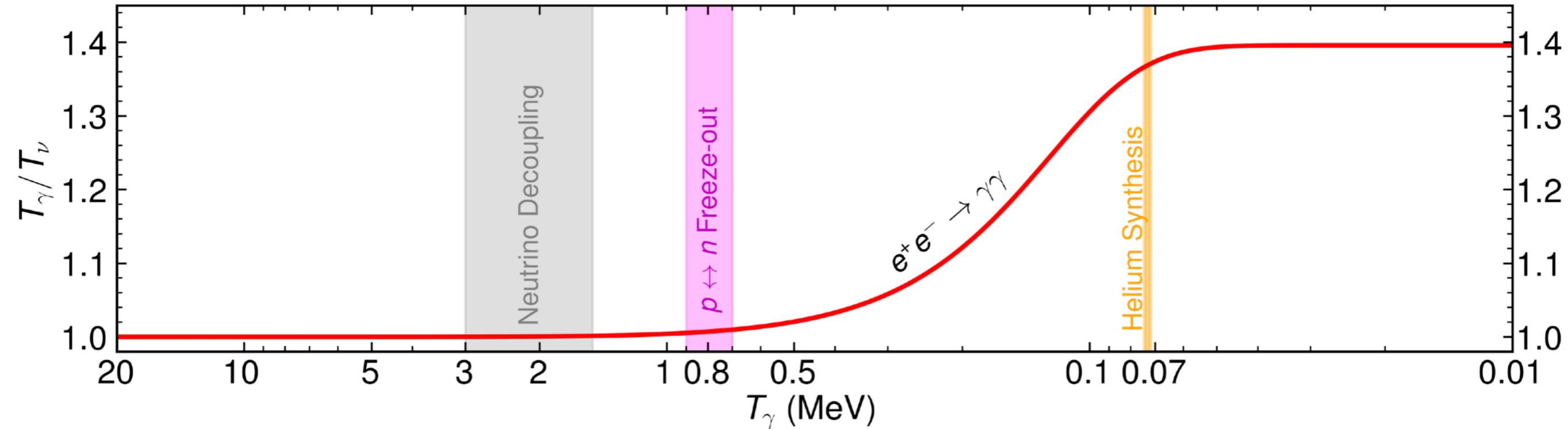
$$n_\nu \simeq 300 \text{ cm}^{-3}$$



Neutrinos
 Electrons
 Photons

Neutrino Decoupling

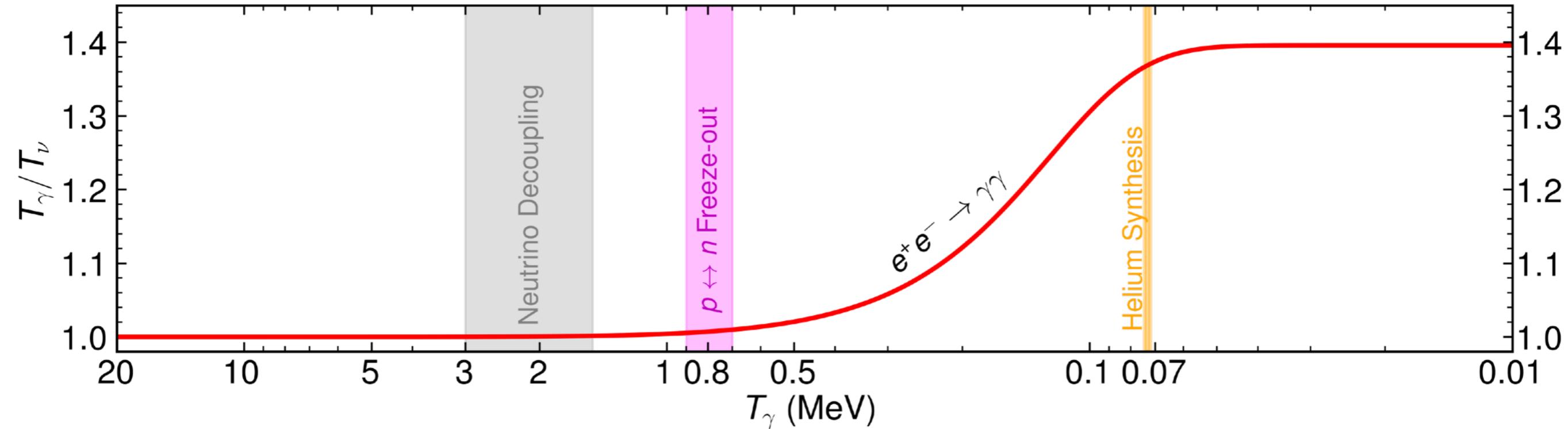
Evolution in the Standard Model



- How do we measure the energy density in relativistic neutrino species?

Neutrino Decoupling

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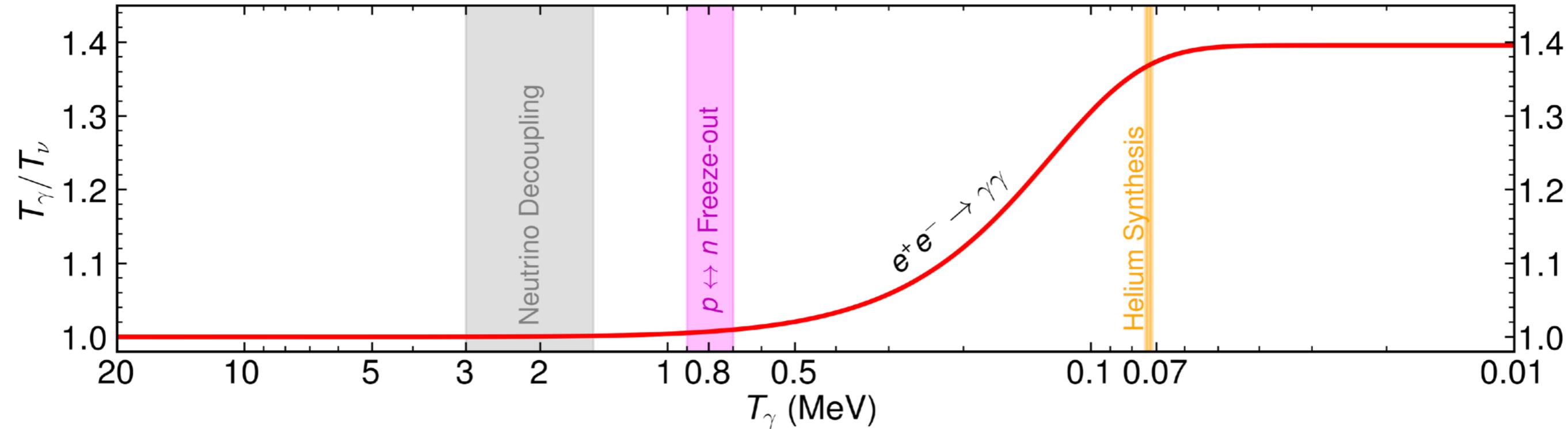


- How do we measure the energy density in relativistic neutrino species?

- The key parameter is:
$$N_{\text{eff}} \equiv \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \left(\frac{\rho_{\text{rad}} - \rho_\gamma}{\rho_\gamma} \right)$$

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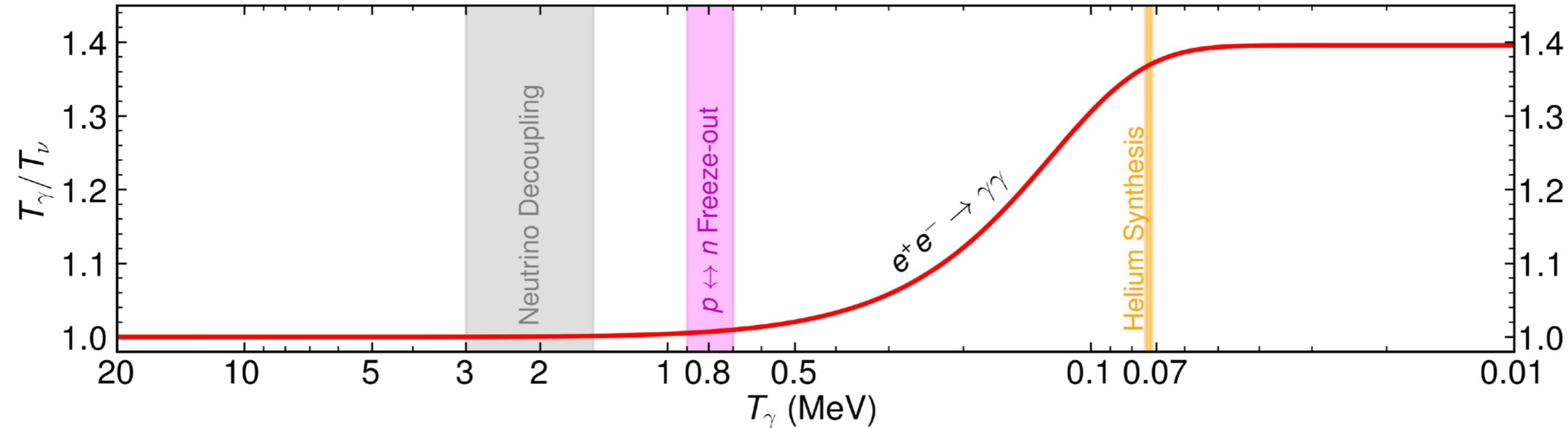


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- when only neutrinos and photons are present:
$$N_{\text{eff}} = 3 \left(\frac{1.4 T_\nu}{T_\gamma} \right)^4$$

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- The Standard Model value is:
$$N_{\text{eff}}^{\text{SM}} = 3.044$$

Bennett, Buldgen, Drewes & Wong 1911.04504
 Escudero Abenza 2001.04466
 Akita & Yamaguchi 2005.07047
 Froustey, Pitrou & Volpe 2008.01074
 Gariazzo, de Salas, Pastor et al. 2012.02726
 Hansen, Shalgar & Tamborra 2012.03948

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hence, some heating from e^+e^- annihilation

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$$\delta m_e^2(T), \delta m_\gamma^2(T)$$

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$$t_\nu^{\text{os}} \sim \frac{12T}{\Delta m^2} \quad t_{\text{exp}} = \frac{1}{2H} \sim \frac{m_{Pl}}{3.44\sqrt{10.75}T^2} \quad t_\nu^{\text{scat}} \sim \frac{1}{G_F^2 T^5}$$

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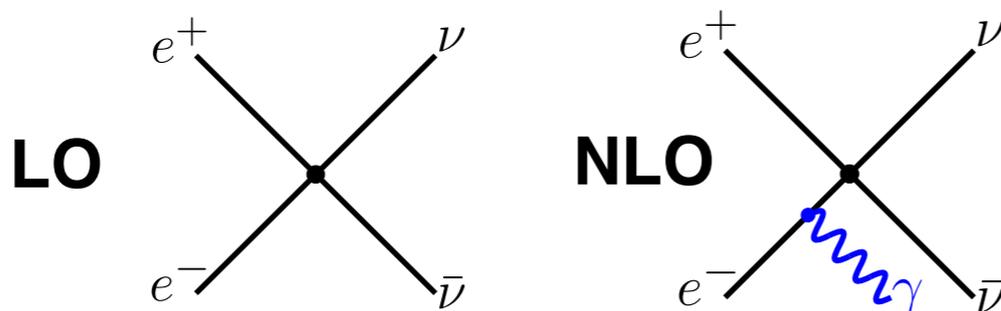
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$$\Delta N_{\text{eff}} \simeq + 0.03$$

Kolb et al. '82
Dolgov et al. '97

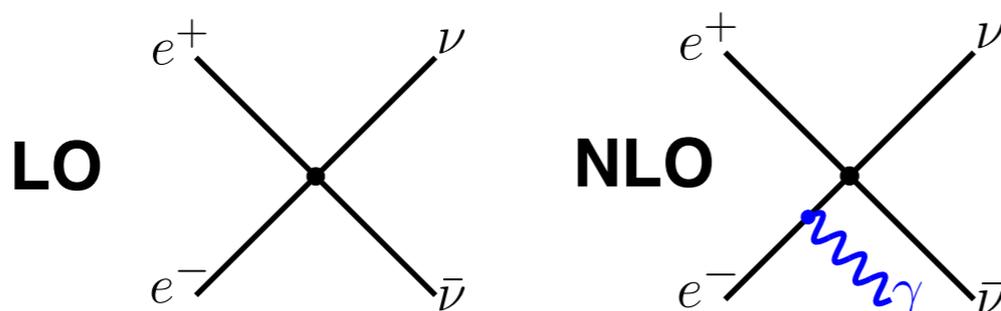
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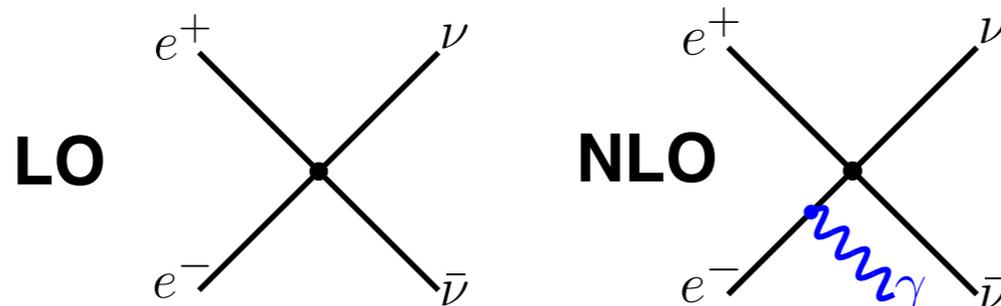
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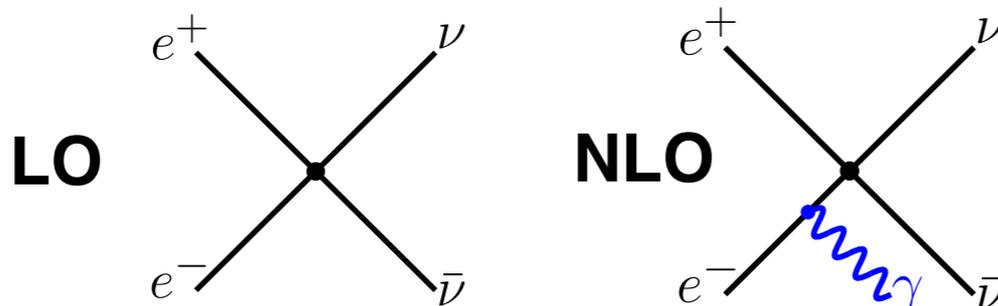
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$$\Delta N_{\text{eff}} \simeq + 0.0007 \quad \text{Mangano et al. '05} \\ \text{de Salas & Pastor '16}$$

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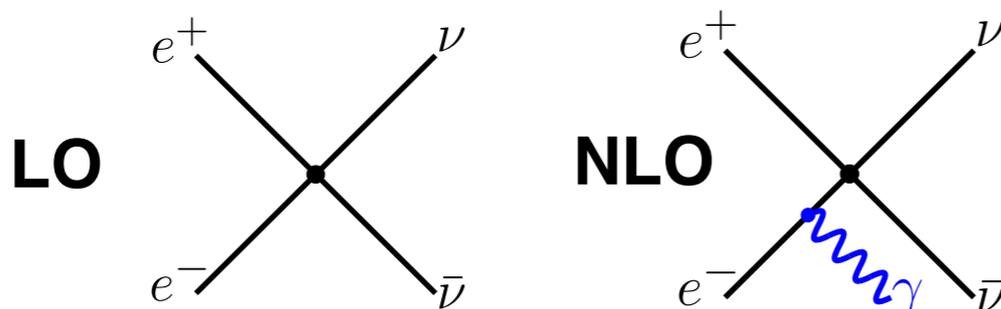
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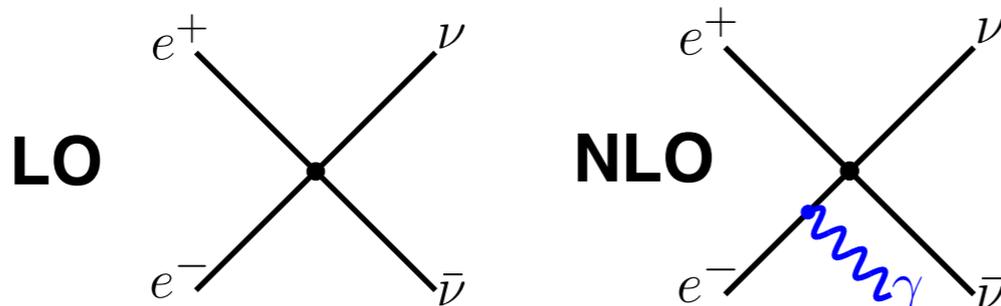
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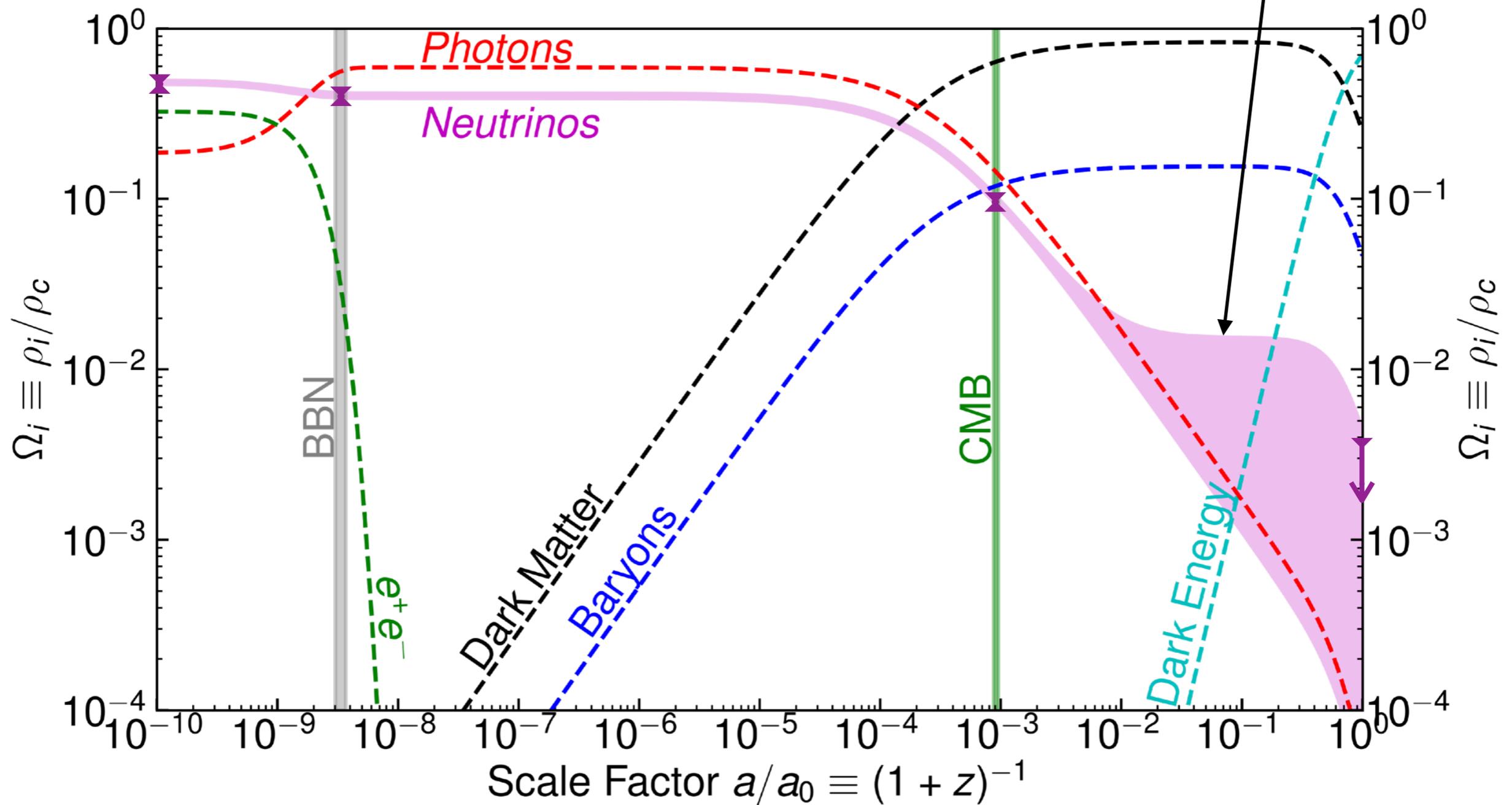
$$\text{CMB-S4} \\ \delta N_{\text{eff}} \simeq 0.03$$

Global Perspective

Current knowledge:

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

$$(\text{Planck+BAO}) \quad \sum m_\nu \lesssim 0.2 \text{ eV}$$

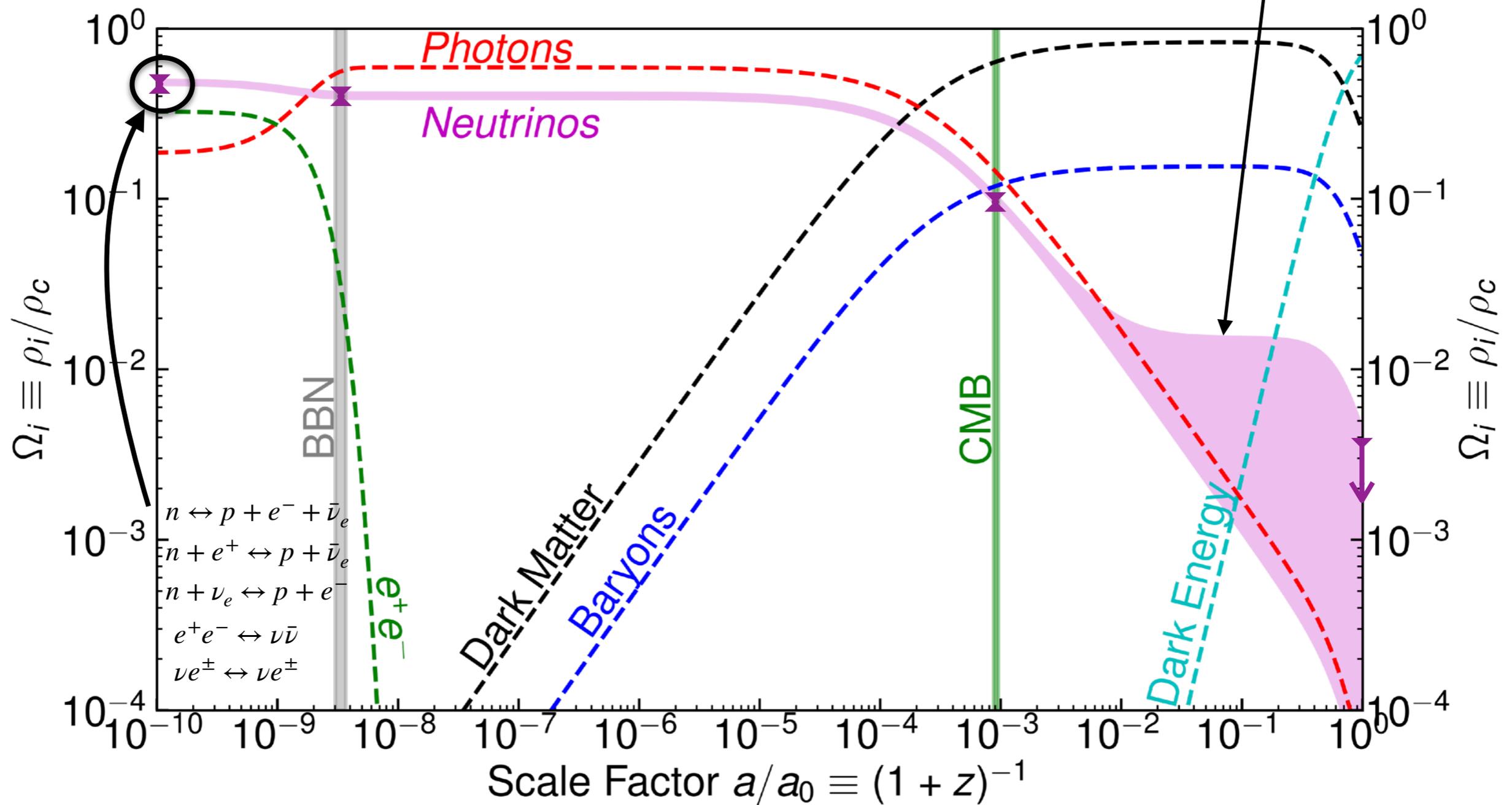


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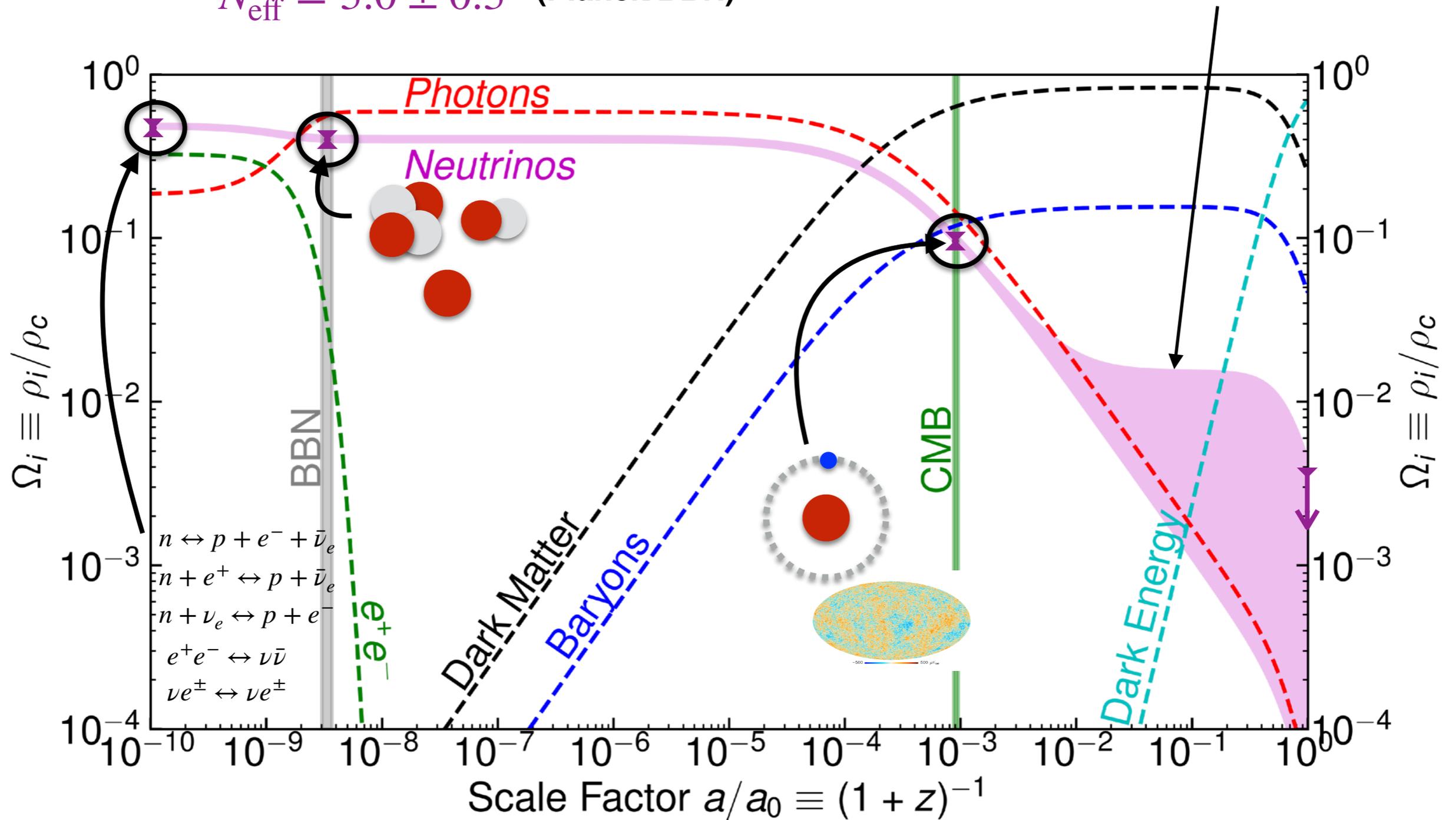


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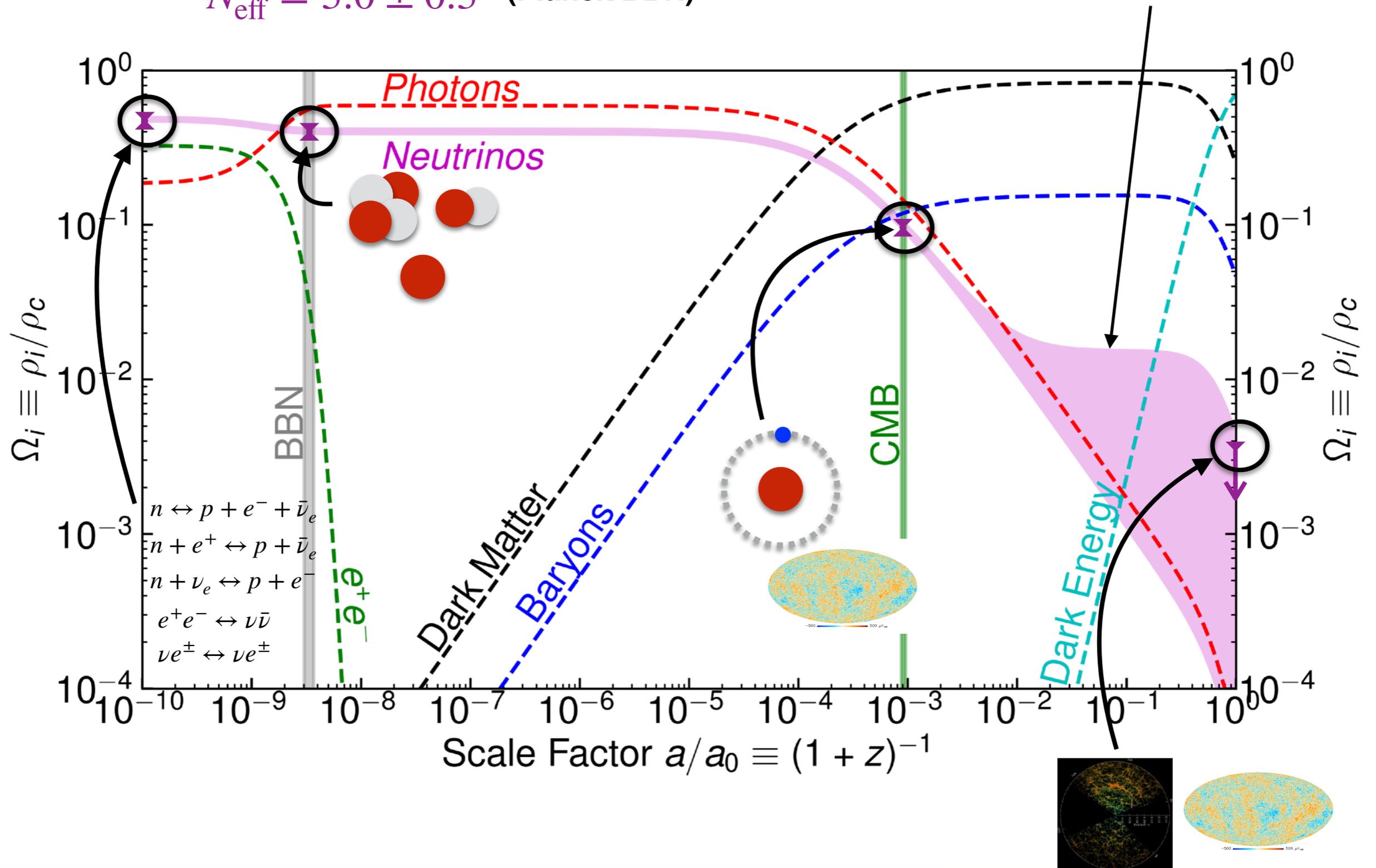


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Big Bang Nucleosynthesis

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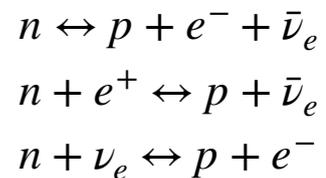
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- 1) It is impossible to have successful BBN without neutrinos. They participate in $p \leftrightarrow n$ conversions up to $T \gtrsim 0.7 \text{ MeV}$



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Big Bang Nucleosynthesis

Current measurements are broadly consistent with the SM picture

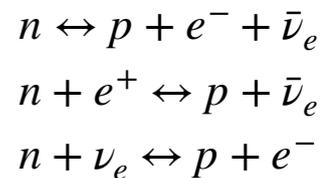
● H ~ 75%

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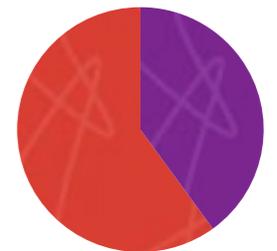
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This implies that neutrinos should have been present:

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



2) Neutrinos contribute to the expansion rate $H \propto \sqrt{\rho}$



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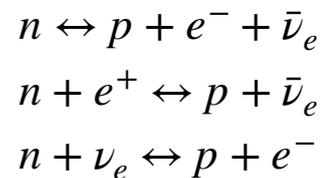
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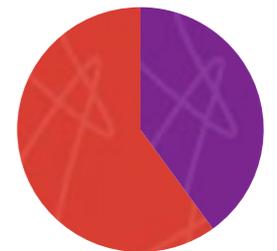
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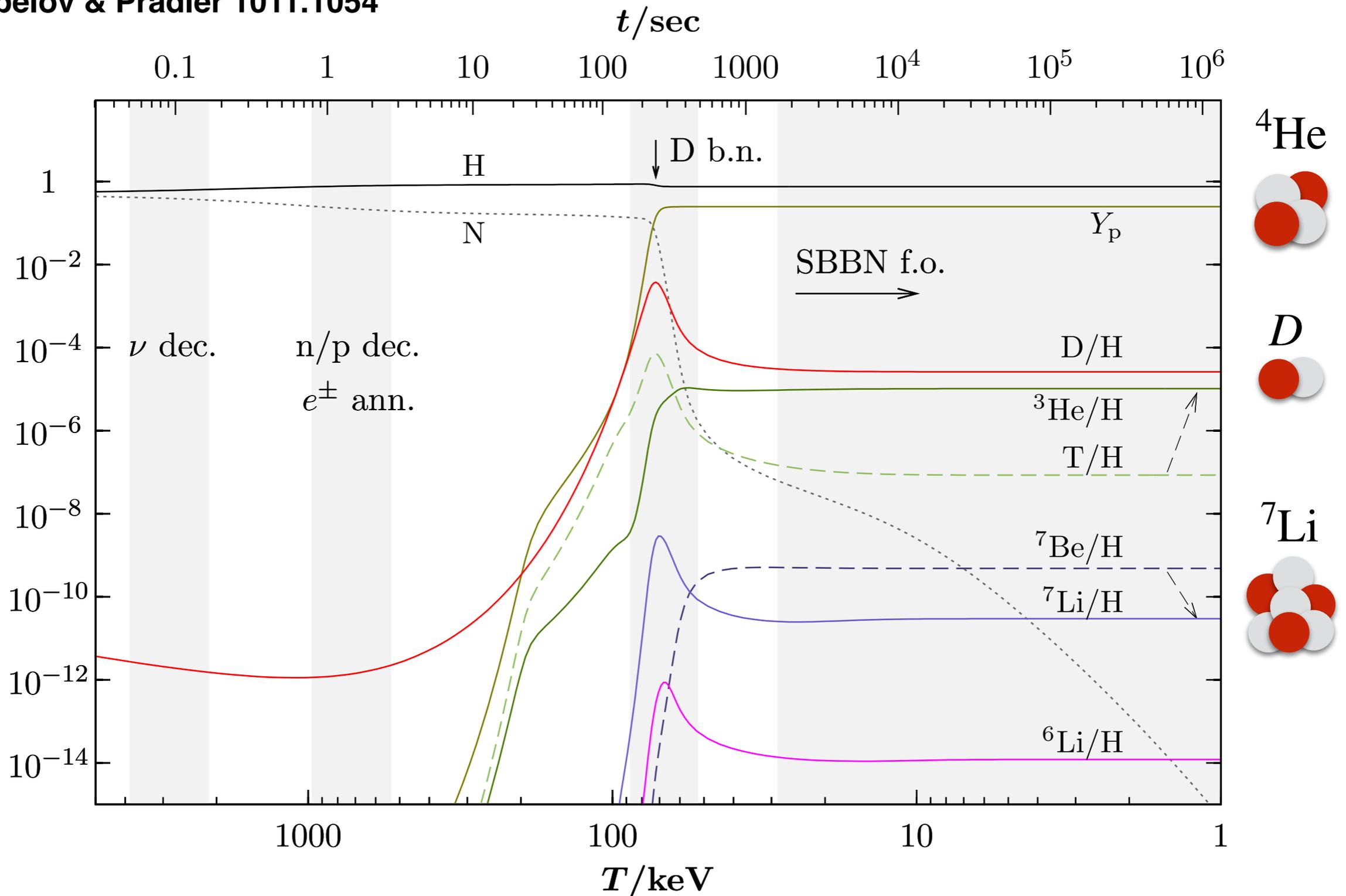
By comparing predictions against observations, we know:

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

see e.g. Pisanti et al. 2011.11537

Big Bang Nucleosynthesis and Neff

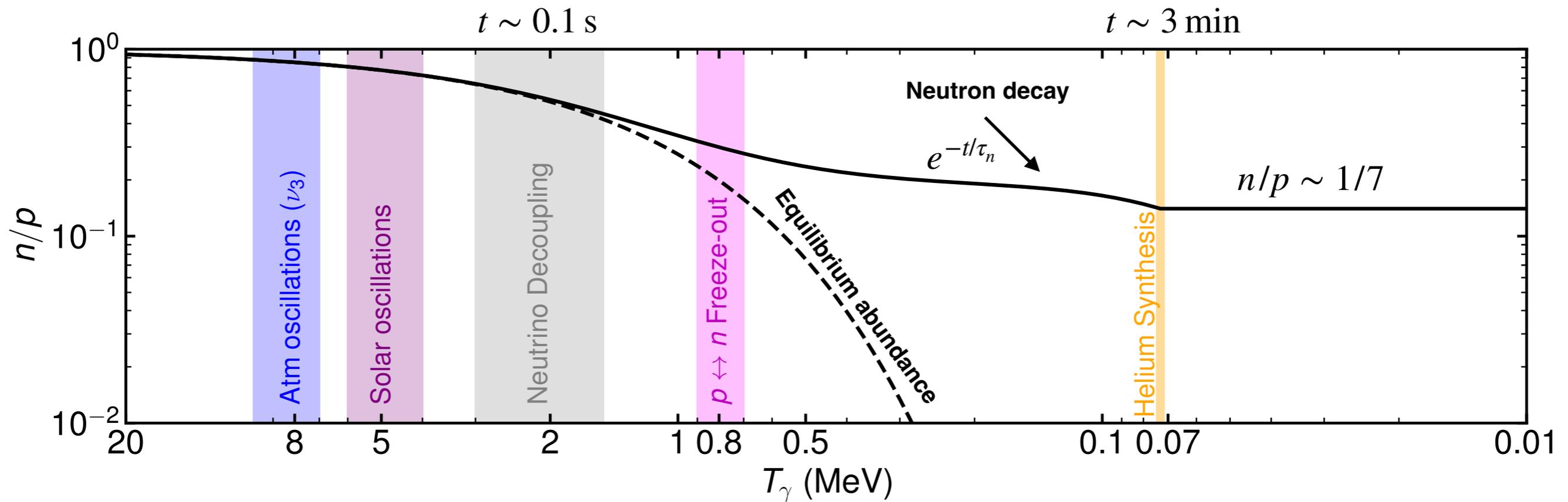
Pospelov & Pradler 1011.1054



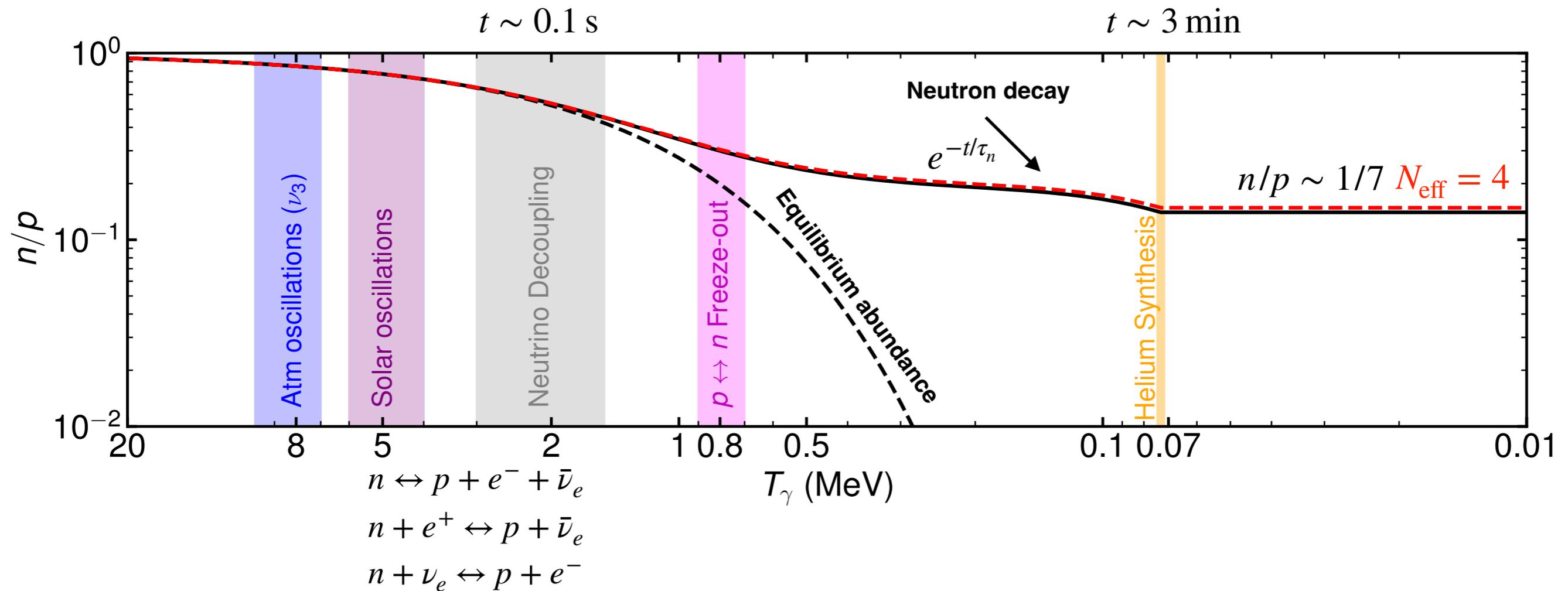
Predictions that expand 10 orders of magnitude!!!

Big Bang Nucleosynthesis and Neff

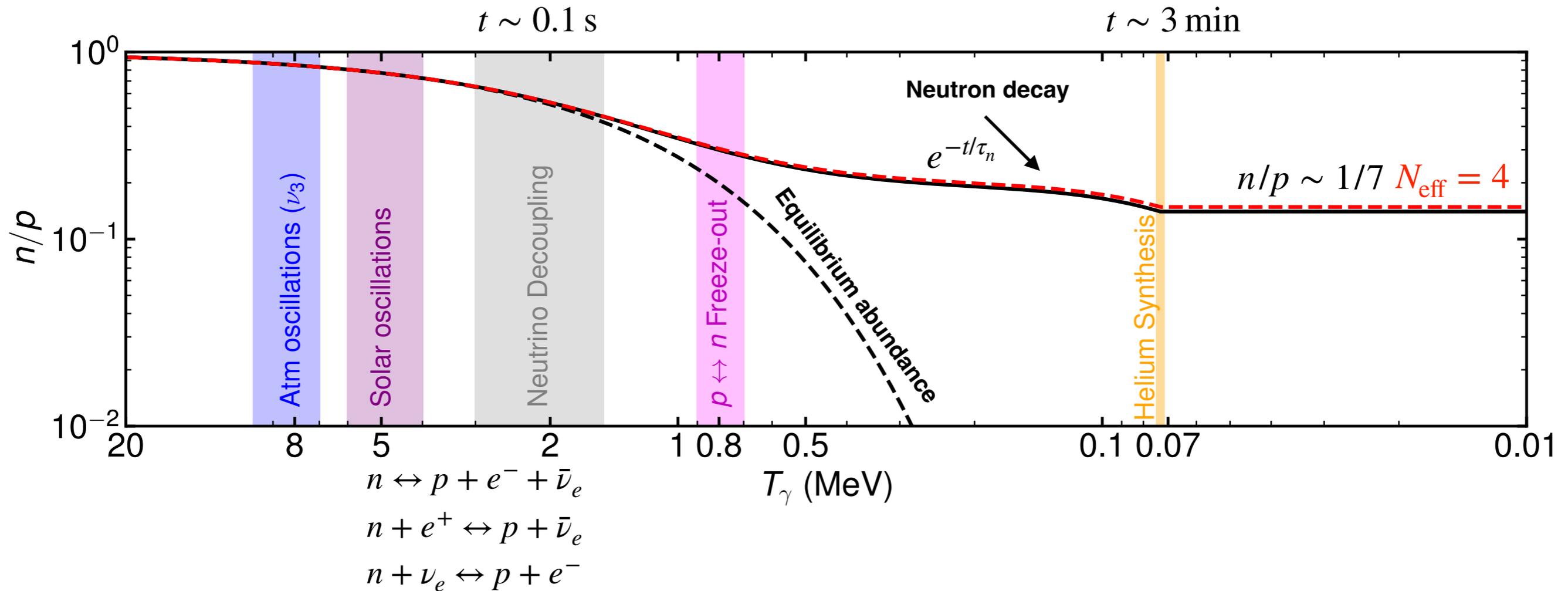
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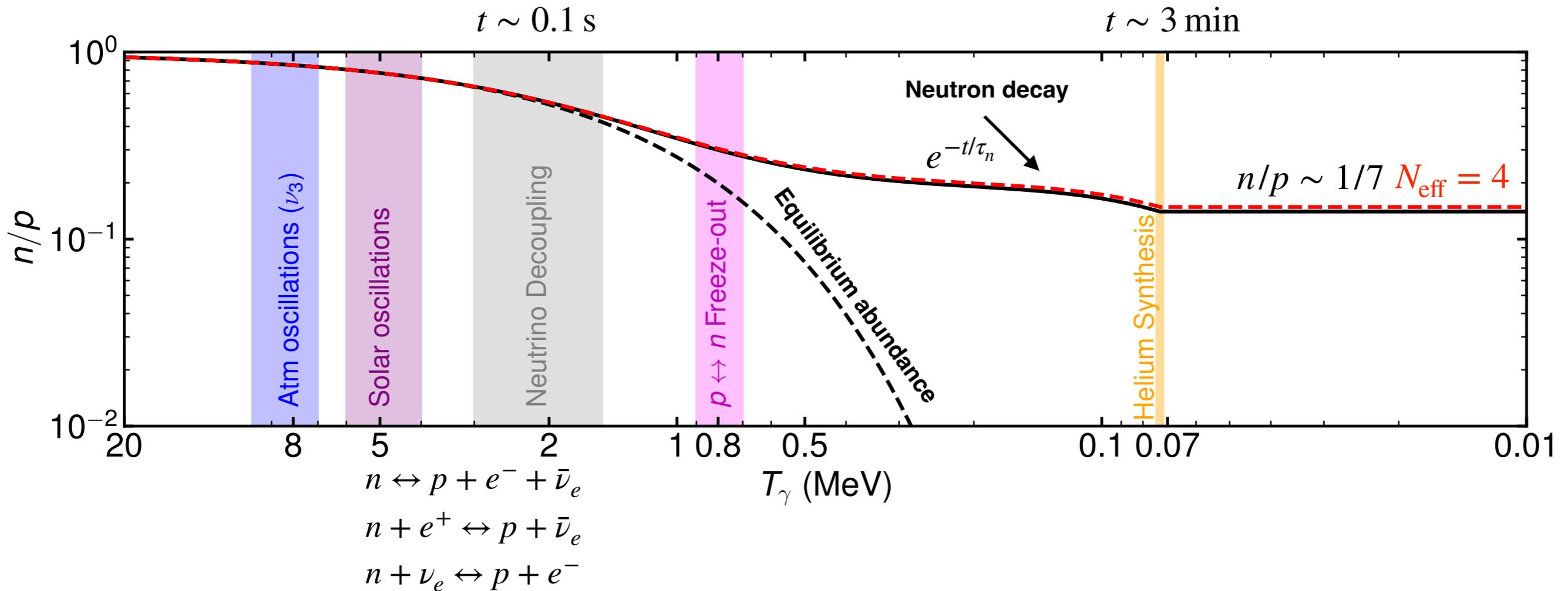


Theory: Fields, Olive, Yeh & Young [1912.01132]

$$Y_p = 0.24696 \times \left[\frac{\eta_{10}}{6.129} \right]^{0.039} \times \left[\frac{N_{\text{eff}}}{3.044} \right]^{0.163}$$

$$D/H = (2.60 \pm 0.13) \times 10^{-5} \times \left[\frac{\eta_{10}}{6.129} \right]^{-1.597} \times \left[\frac{N_{\text{eff}}}{3.044} \right]^{0.396}$$

Big Bang Nucleosynthesis and Neff



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Observations: PDG 2024 1% errors

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$$Y_p = 0.245 \pm 0.003 \quad \text{sys dom}$$

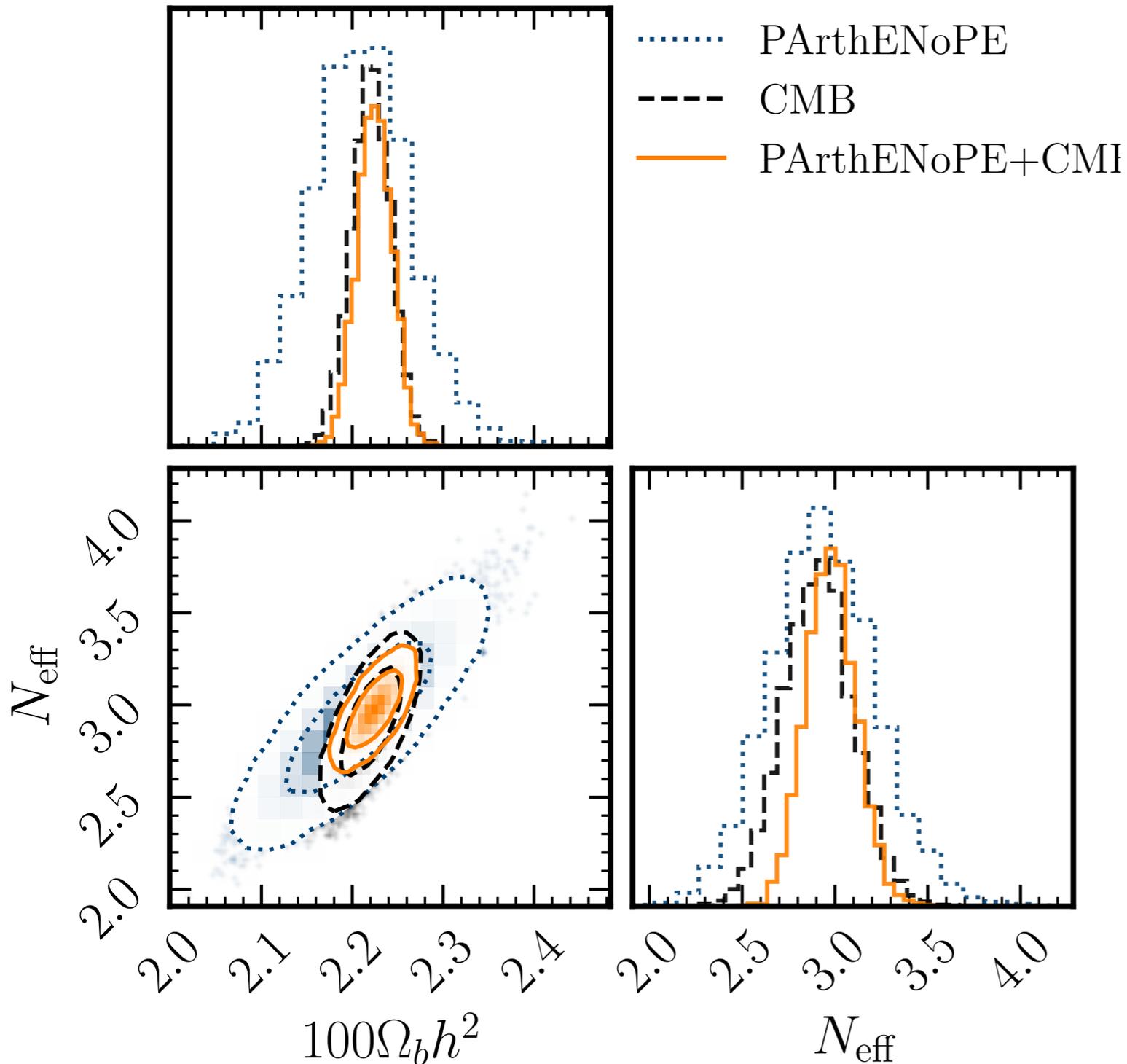
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stat dom

Big Bang Nucleosynthesis and N_{eff}

2408.14531 Giovanetti et al.



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Evidence for Cosmic Neutrinos

Cosmic Microwave Background

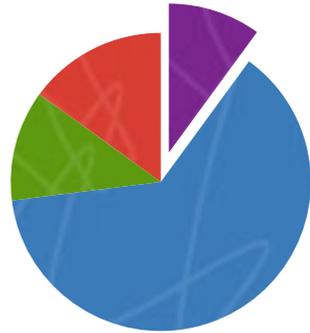
Why?

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

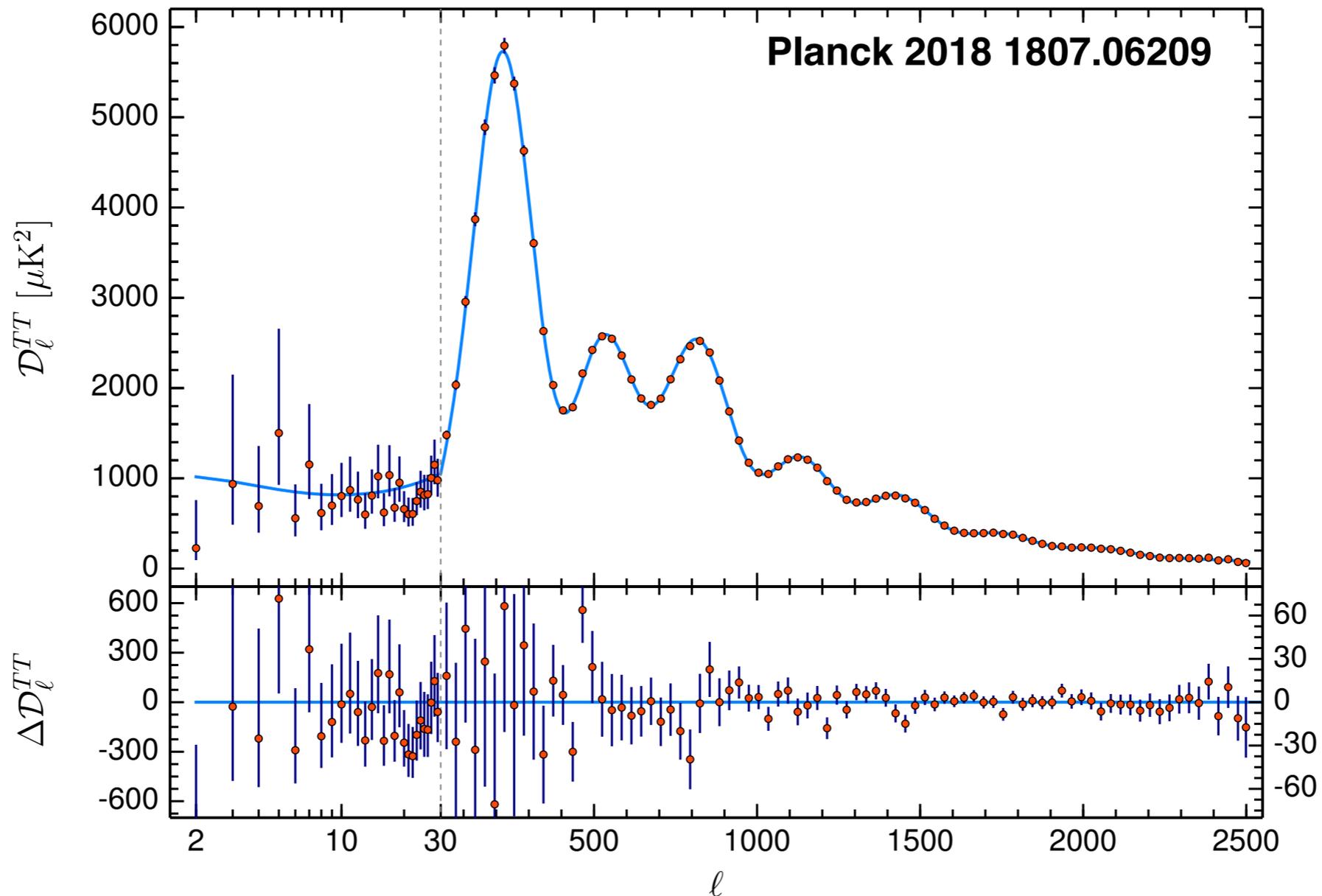
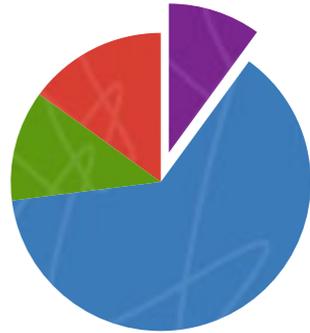


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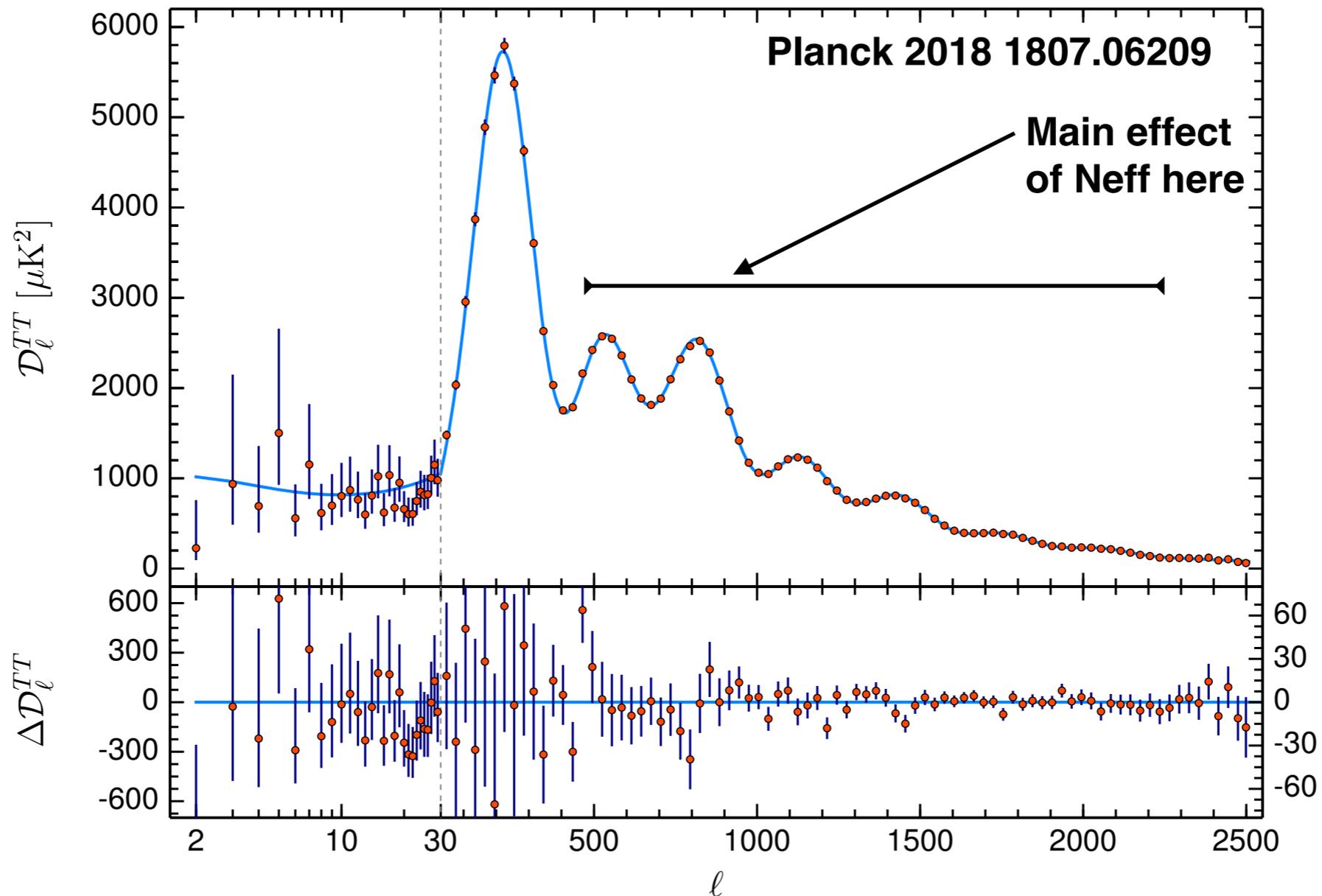
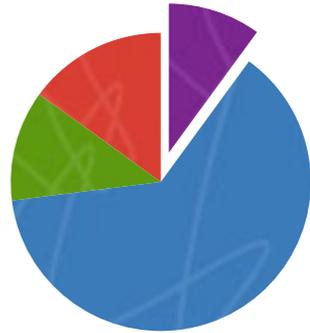


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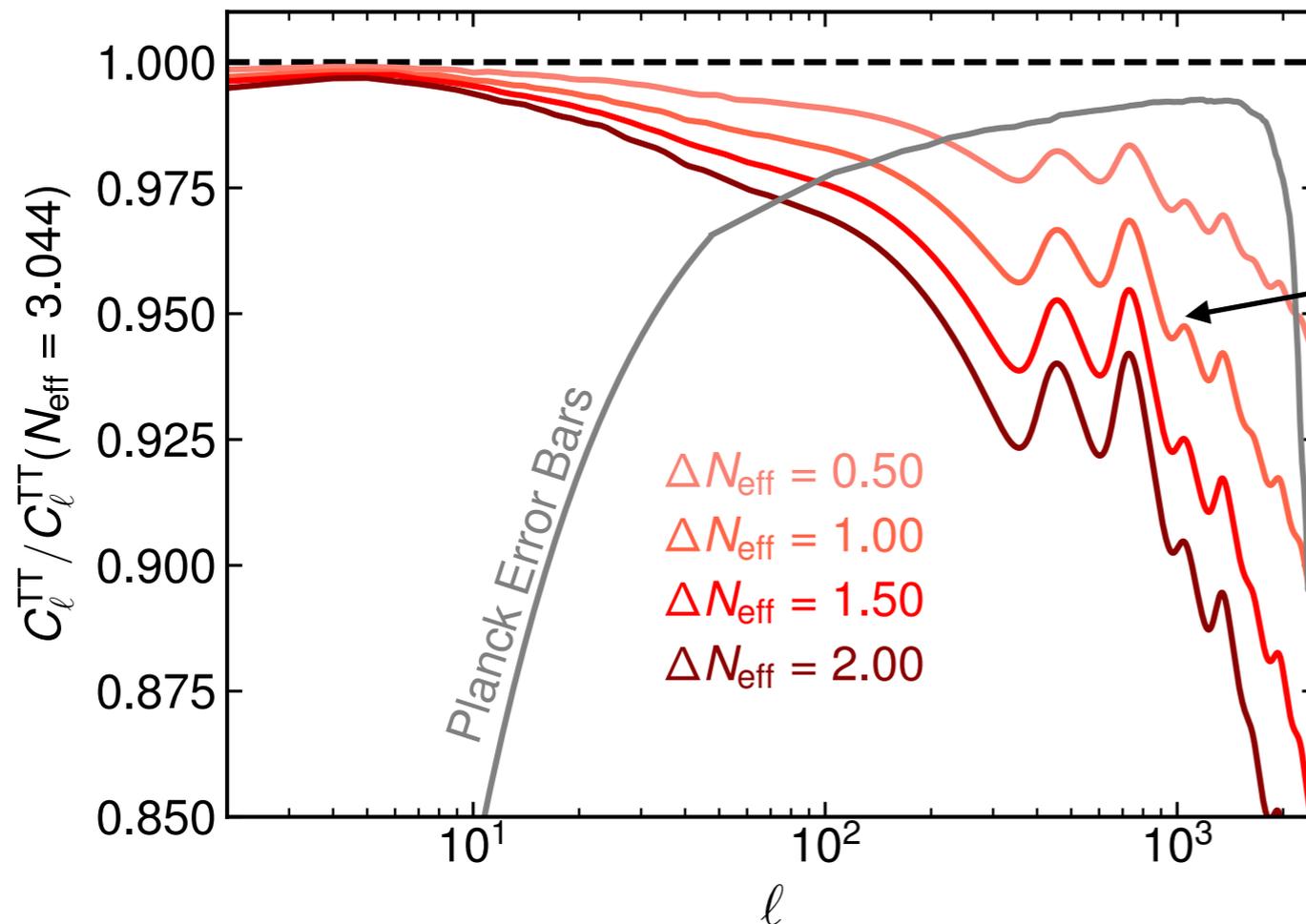
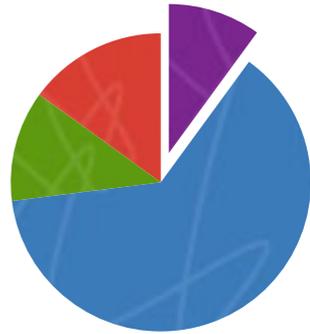


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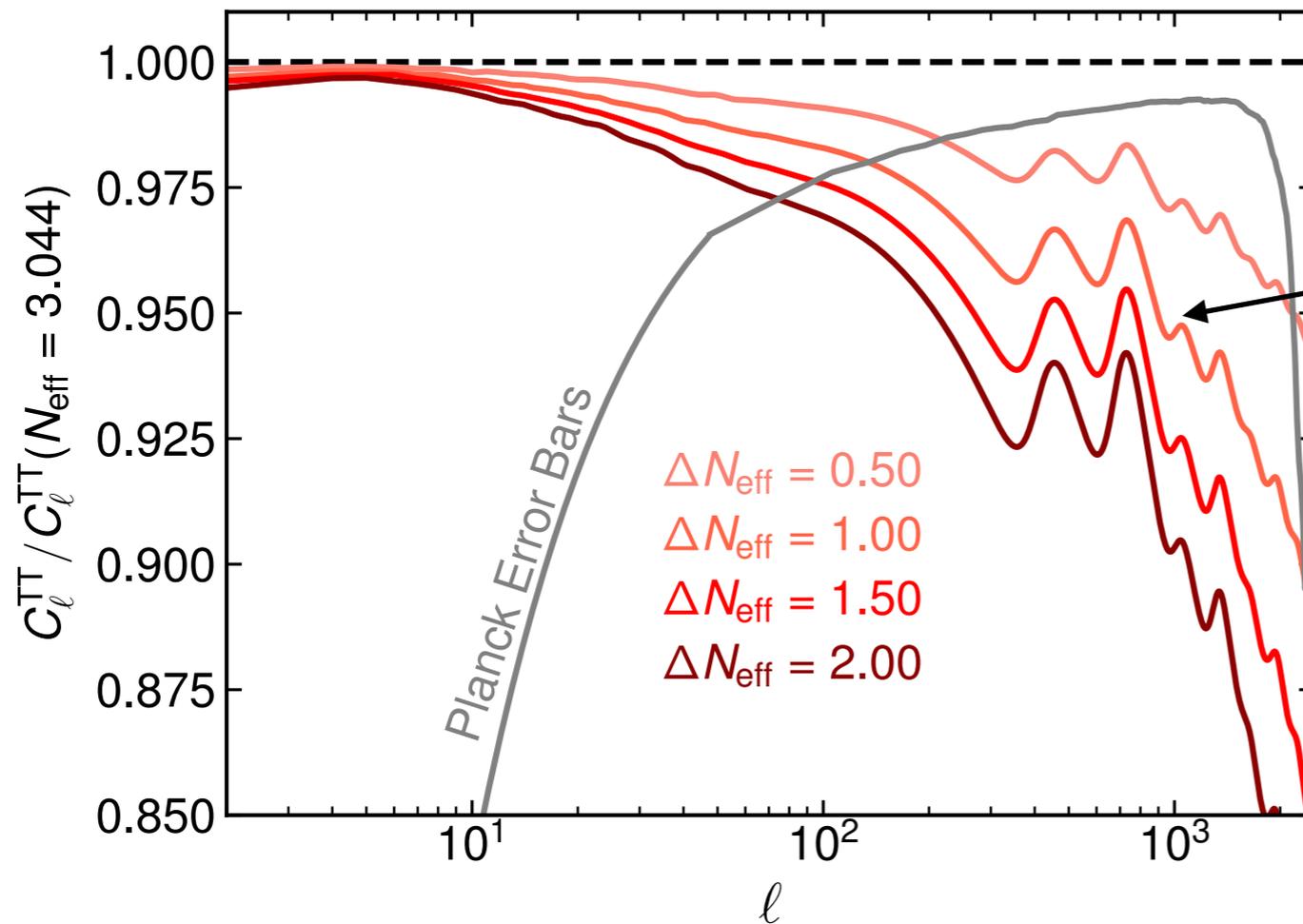
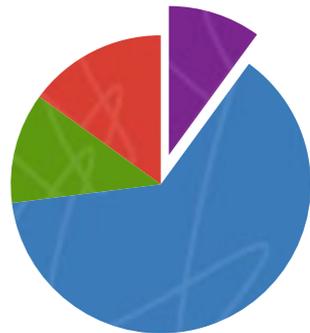
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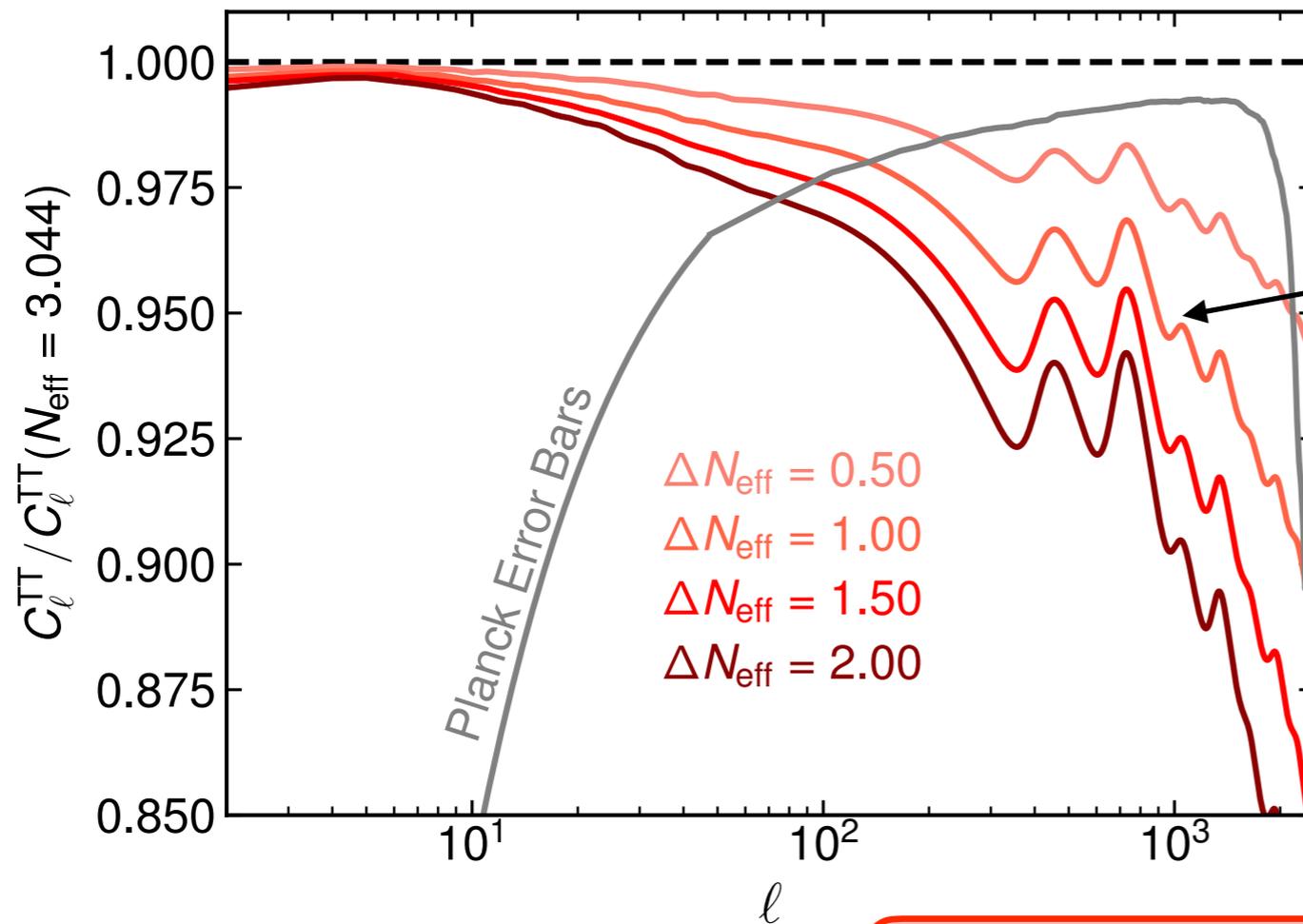
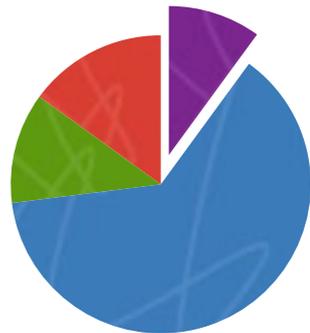
Planck 2018 1807.06209

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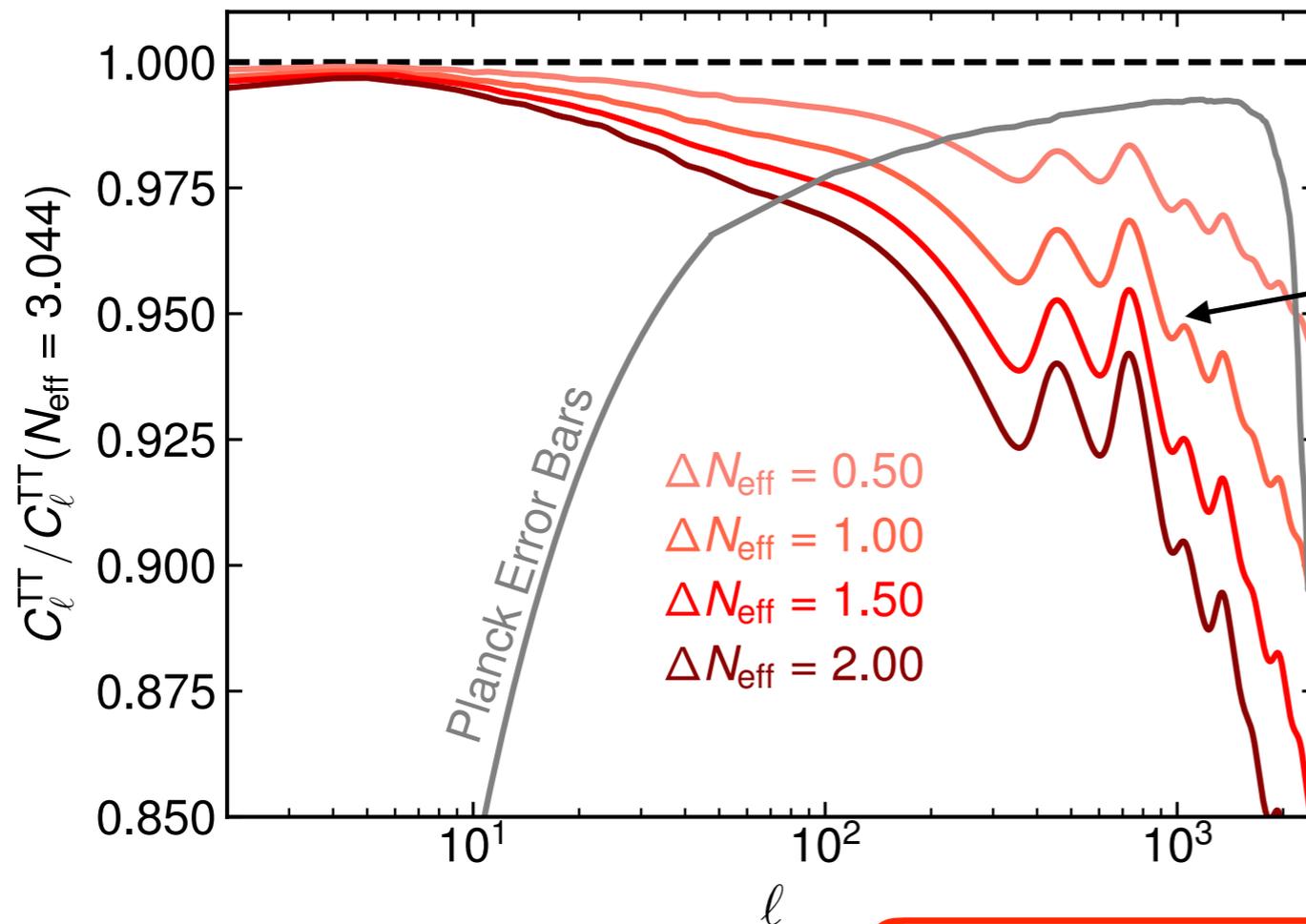
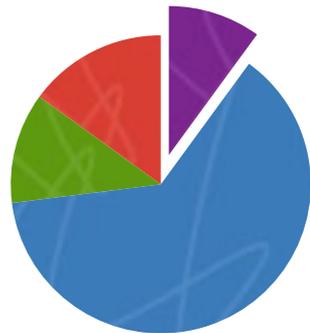
ACT+Planck+DESIR1
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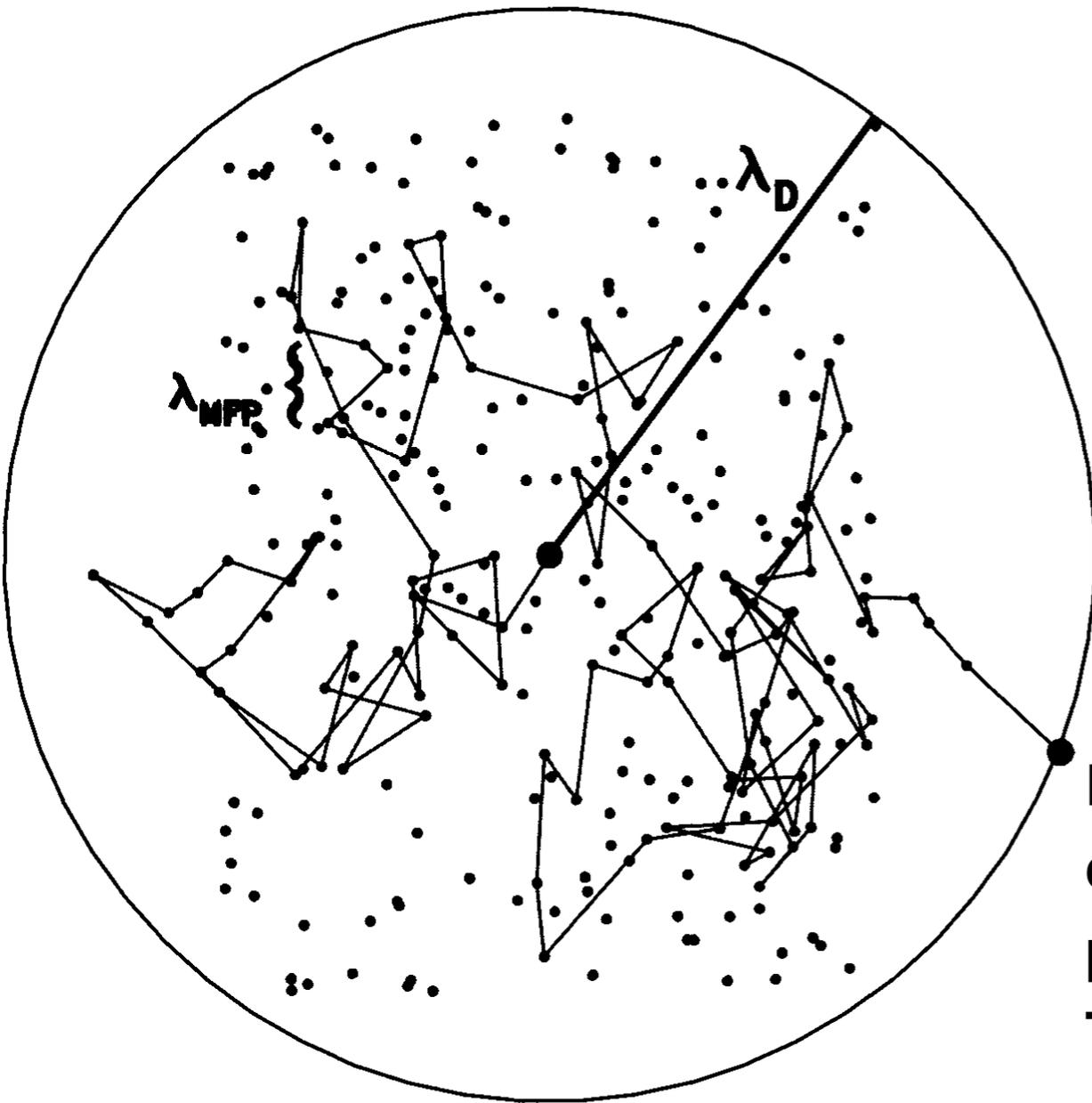
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ACT+SPT+Planck
2506.20707

The physics of diffusion damping

Photon Diffusion



Perturbations on scales are $\lambda < \lambda_D$ are erased:

$$\lambda < \lambda_D = \lambda_{\text{Mean-Free-Path}} \sqrt{N_{\text{steps}}} = (n_e \sigma_T)^{-1} \sqrt{n_e \sigma_T H^{-1}}$$

$$\lambda < \lambda_D = \frac{1}{\sqrt{n_e \sigma_T H}}$$

Effectively, the energy density of neutrinos controls the physical length scale over which photons diffuse.

The larger N_{eff} the smaller this distance is.

Evidence for Cosmic Neutrinos

- **Current constraints**

BBN

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Pisanti et al. 2011.11537

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Constraints from N_{eff}

N_{eff} measurements constrain very light particles that decoupled while relativistic after the Big Bang (very much like neutrinos). Their energy density is parametrized by

$$\Delta N_{\text{eff}} = N_{\text{eff}} - 3.044$$

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Editors' Suggestion

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Steven Weinberg
Phys. Rev. Lett. **110**, 241301 – Published 10 June 2013

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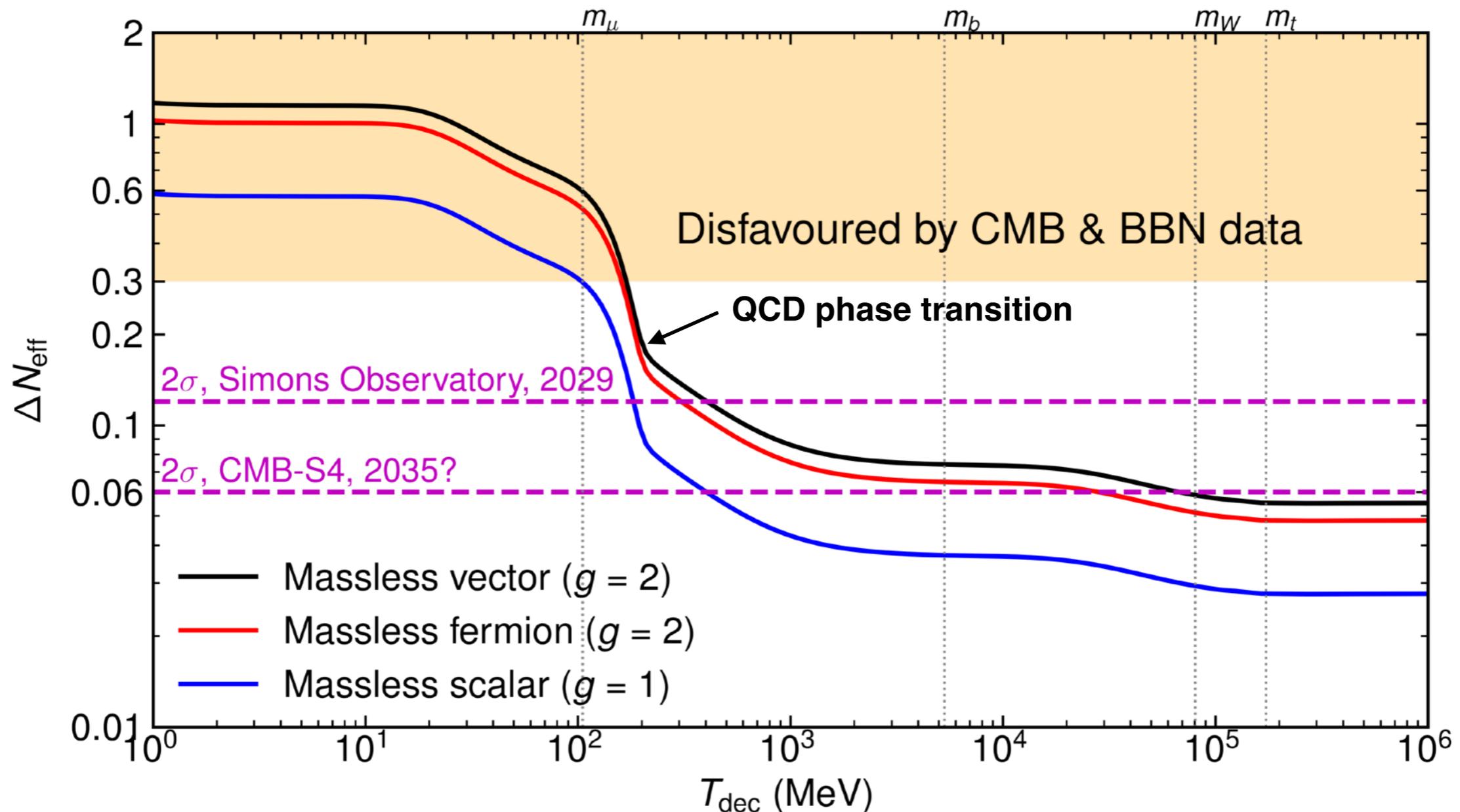
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- **Other sterile long-lived particles** Gravitino, hidden sector particles ...

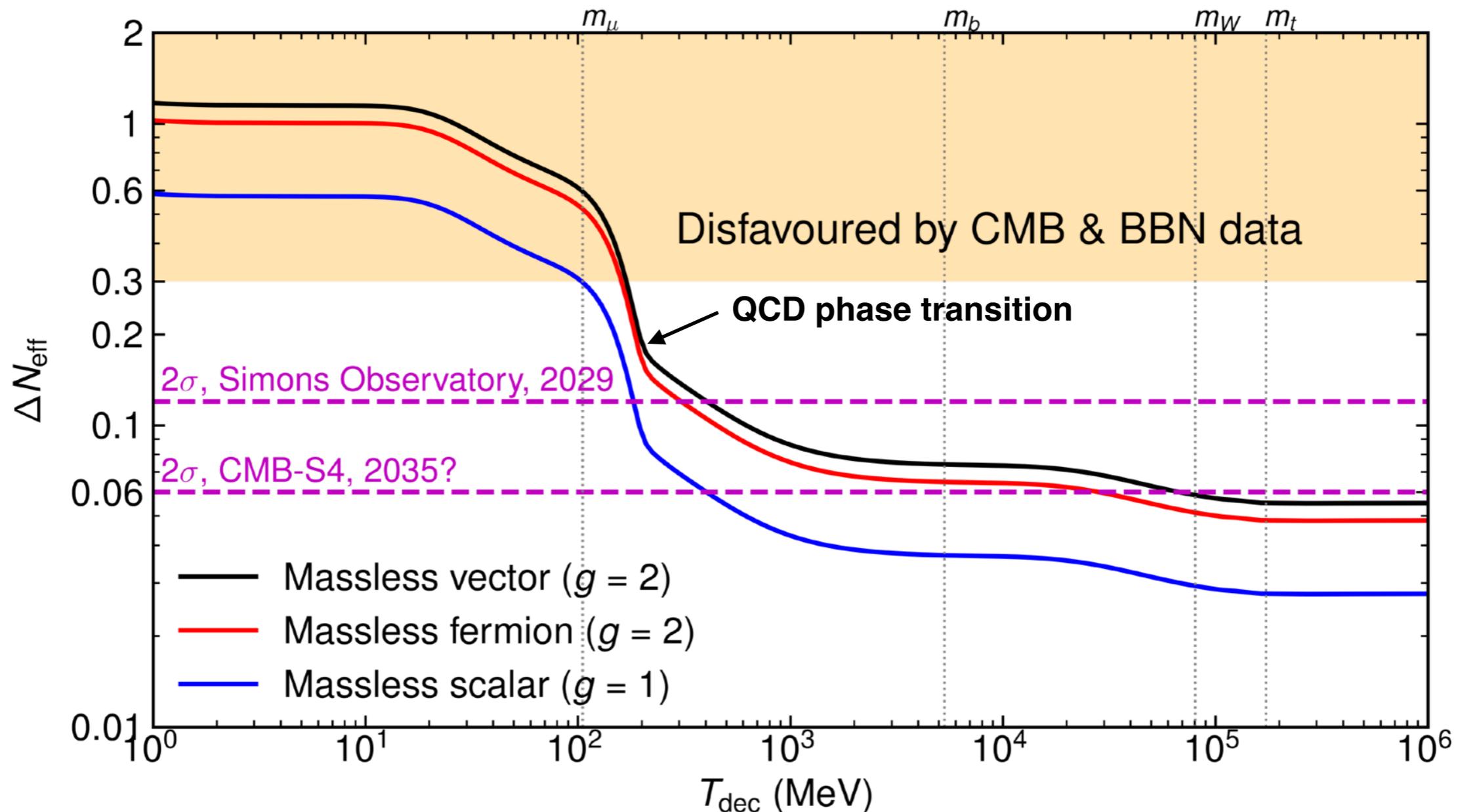
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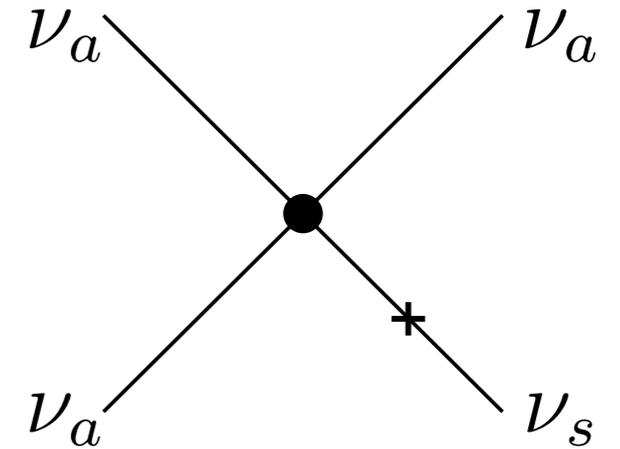


Take Away:

Any new massless state in thermal equilibrium with the SM plasma should have decoupled at $T_{\text{dec}} \gtrsim 100 \text{ MeV}$

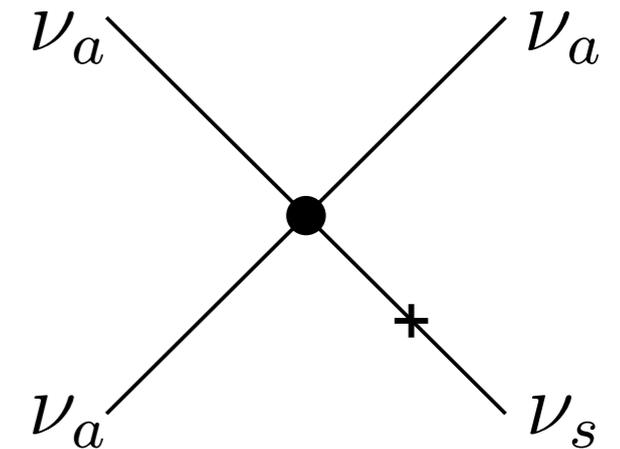
Sterile Neutrinos and Neff

Production of sterile neutrinos in the early Universe proceeds via collisions/neutrino oscillations



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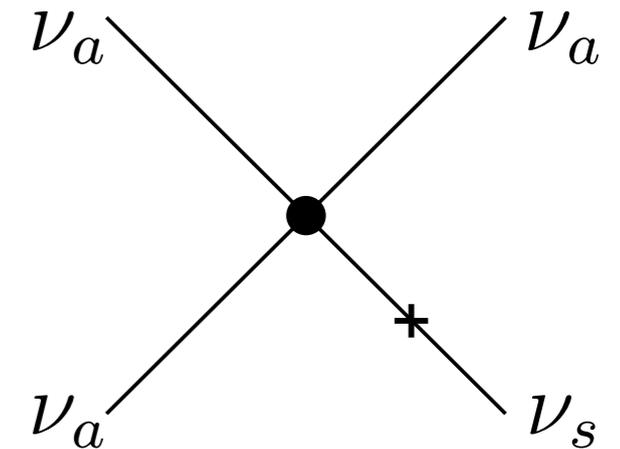
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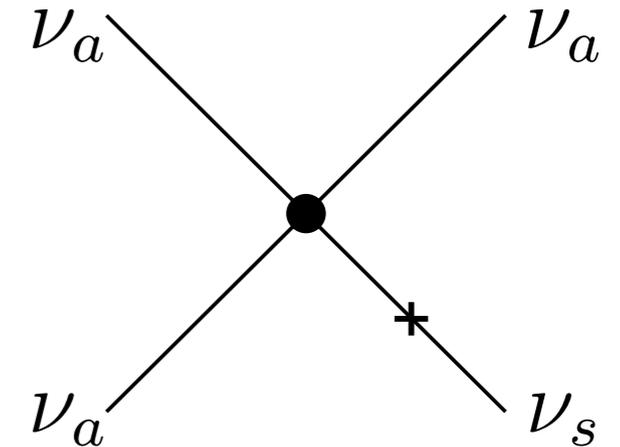
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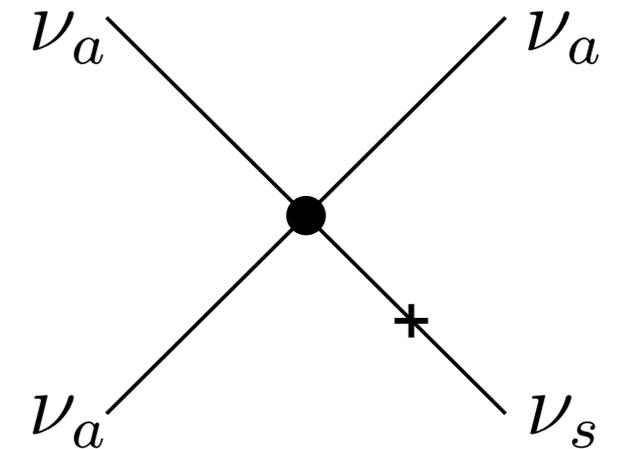
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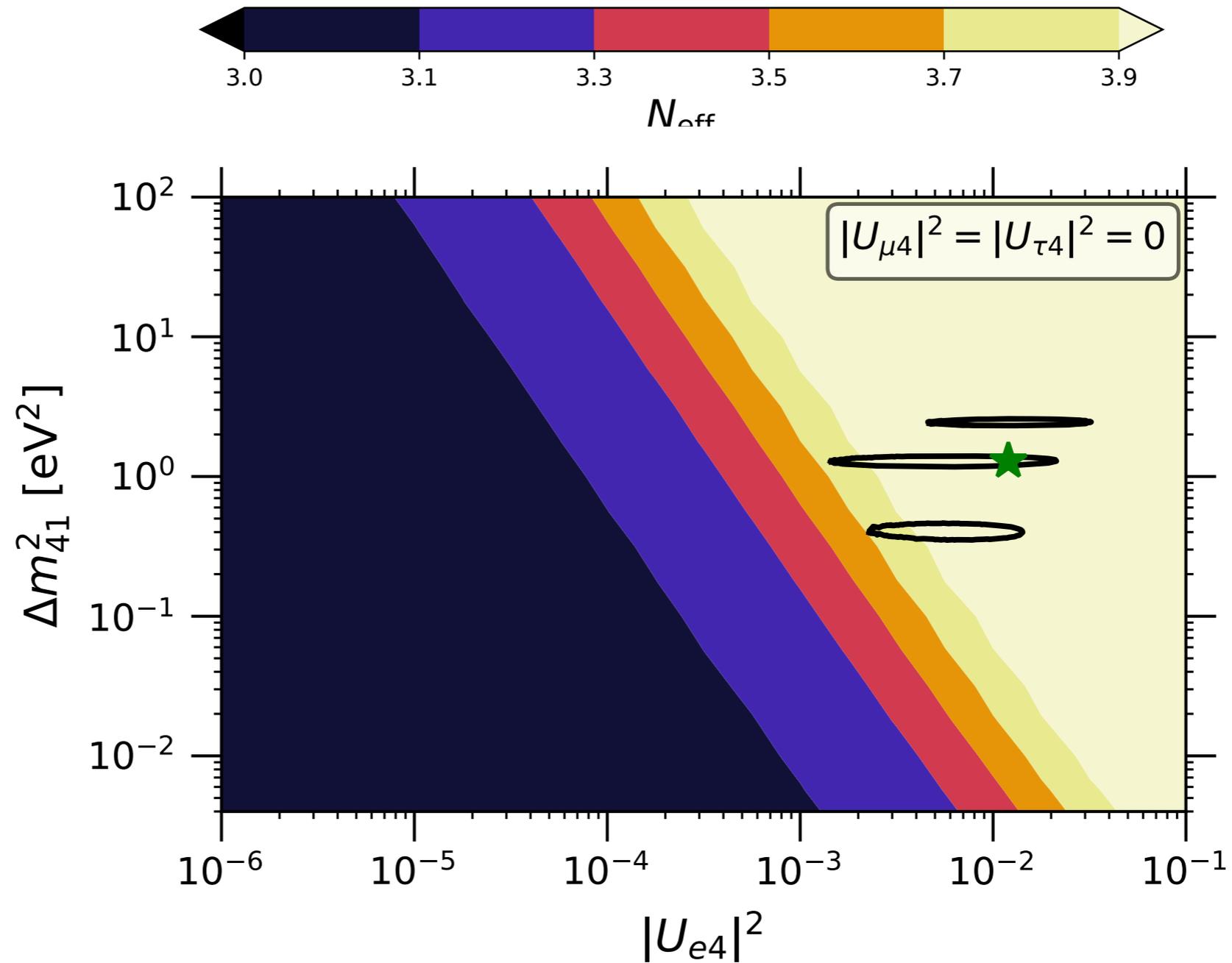
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Production can be suppressed in the presence of a low-reheating temperature *see e.g. Hasegawa et al. [2003.13302]*

Sterile Neutrino Constraints

Standard case for sterile neutrinos



From Gariazzo, de Salas & Pastor
1905.11290

Figure 9. Final N_{eff} in the 3+1 case for different values of Δm_{41}^2 and $|U_{e4}|^2$ when considering normal ordering for the active neutrinos. The other two active-sterile components of the mixing matrix take the values as labelled. The black closed contours represent the 3σ preferred regions and the green star the best-fit point from [44].

Summary

Number of effective neutrino species

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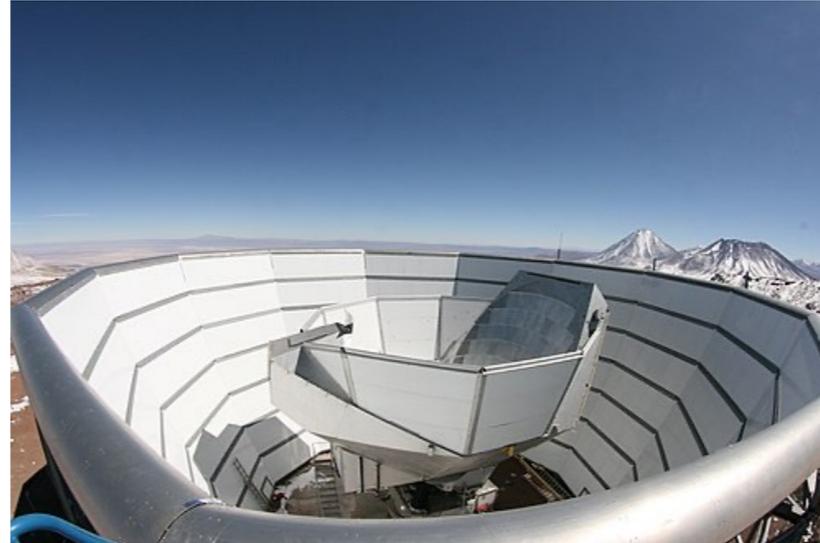
This represents an important constraint on many BSM settings

e.g.: $\theta_s^2 \lesssim 10^{-3} \text{ eV} / \sqrt{(m_s^2 - m_\nu^2)}$

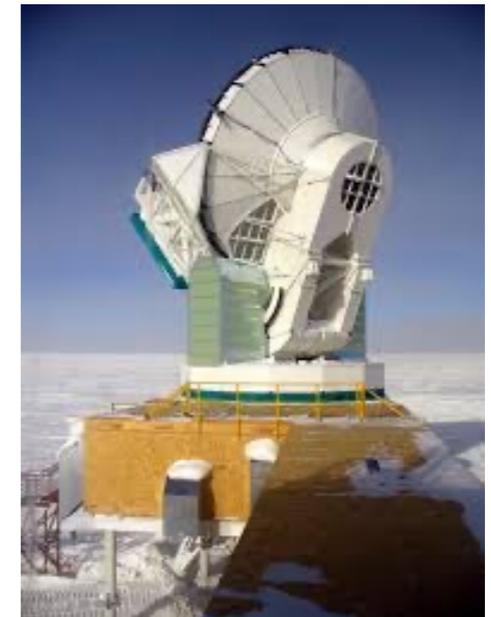
Outlook: Number of Neutrinos

The current generation of CMB experiments have already improved Planck's sensitivity by a factor of ~ 2 .

Atacama Cosmology Telescope



South Pole Telescope



The next generation is expected to improve it another factor of two!

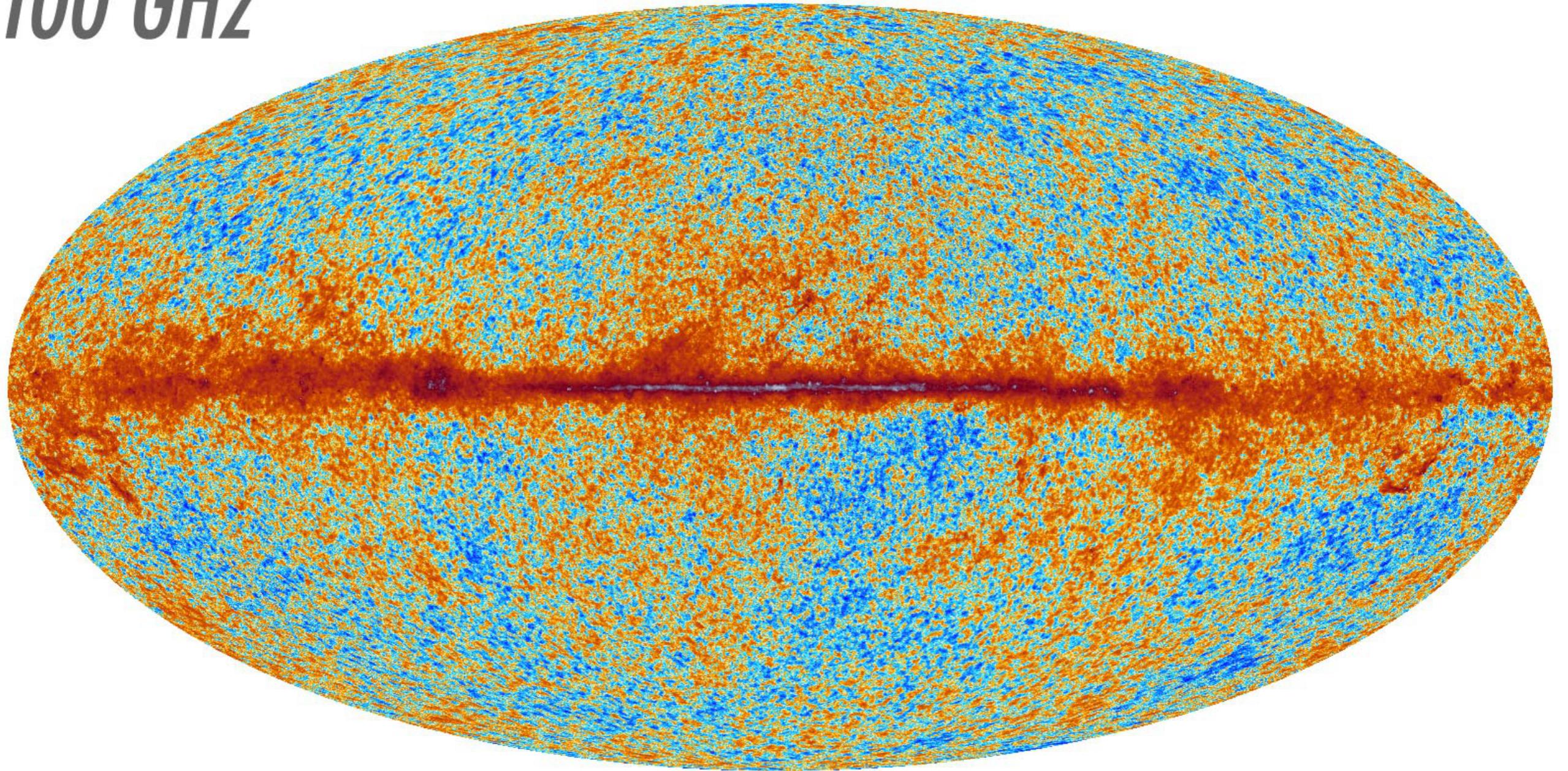
Simons Observatory



$$\sigma(N_{\text{eff}}) = 0.06 \sim 2029$$

Planck's Temperature Map

100 GHz





Planck E
frequency coadd

New cosmological data to the rescue!



ACT+Planck E
frequency coadd

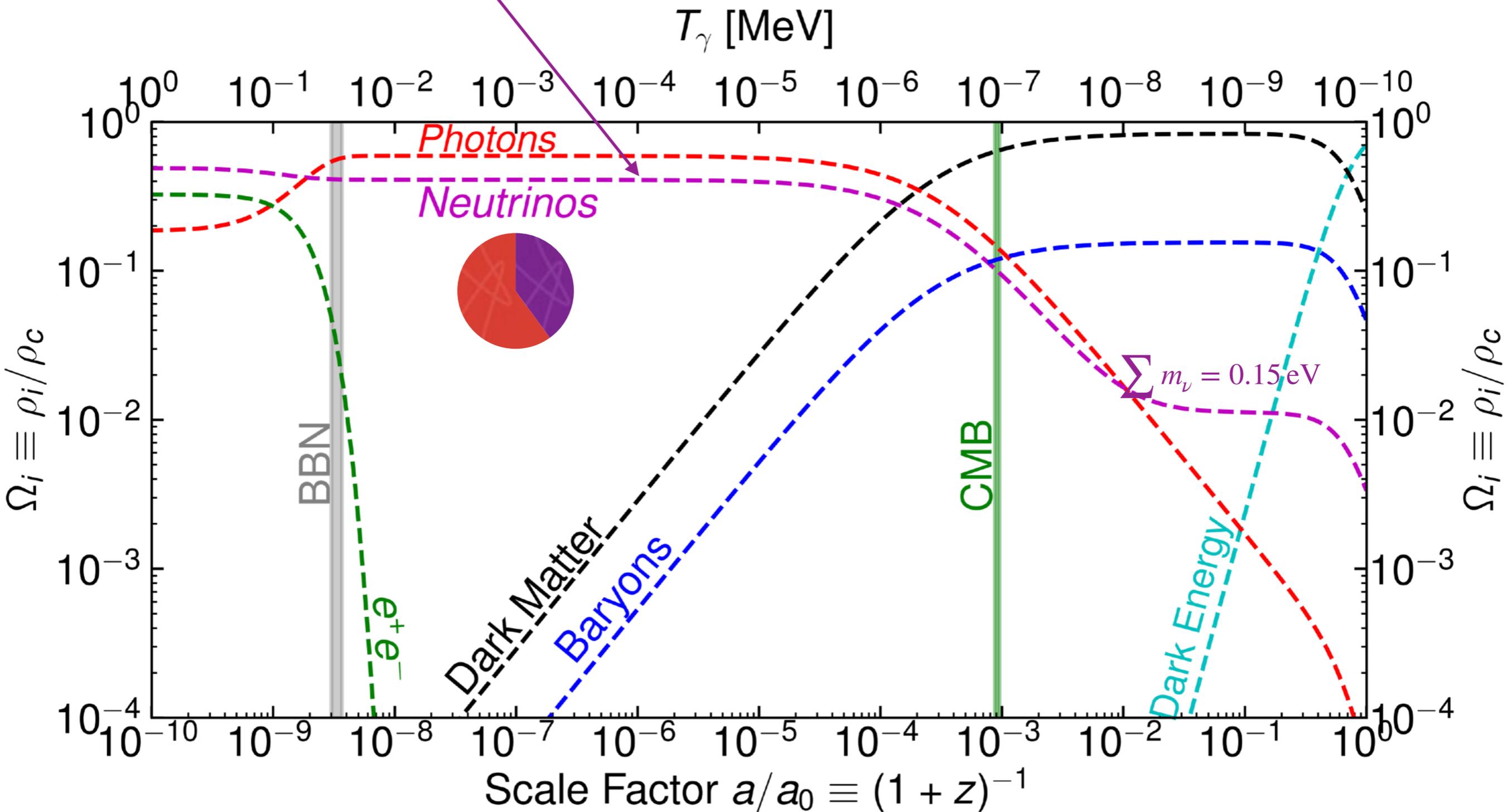
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[released three months ago!]

Neutrino Evolution

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Neutrino Evolution

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

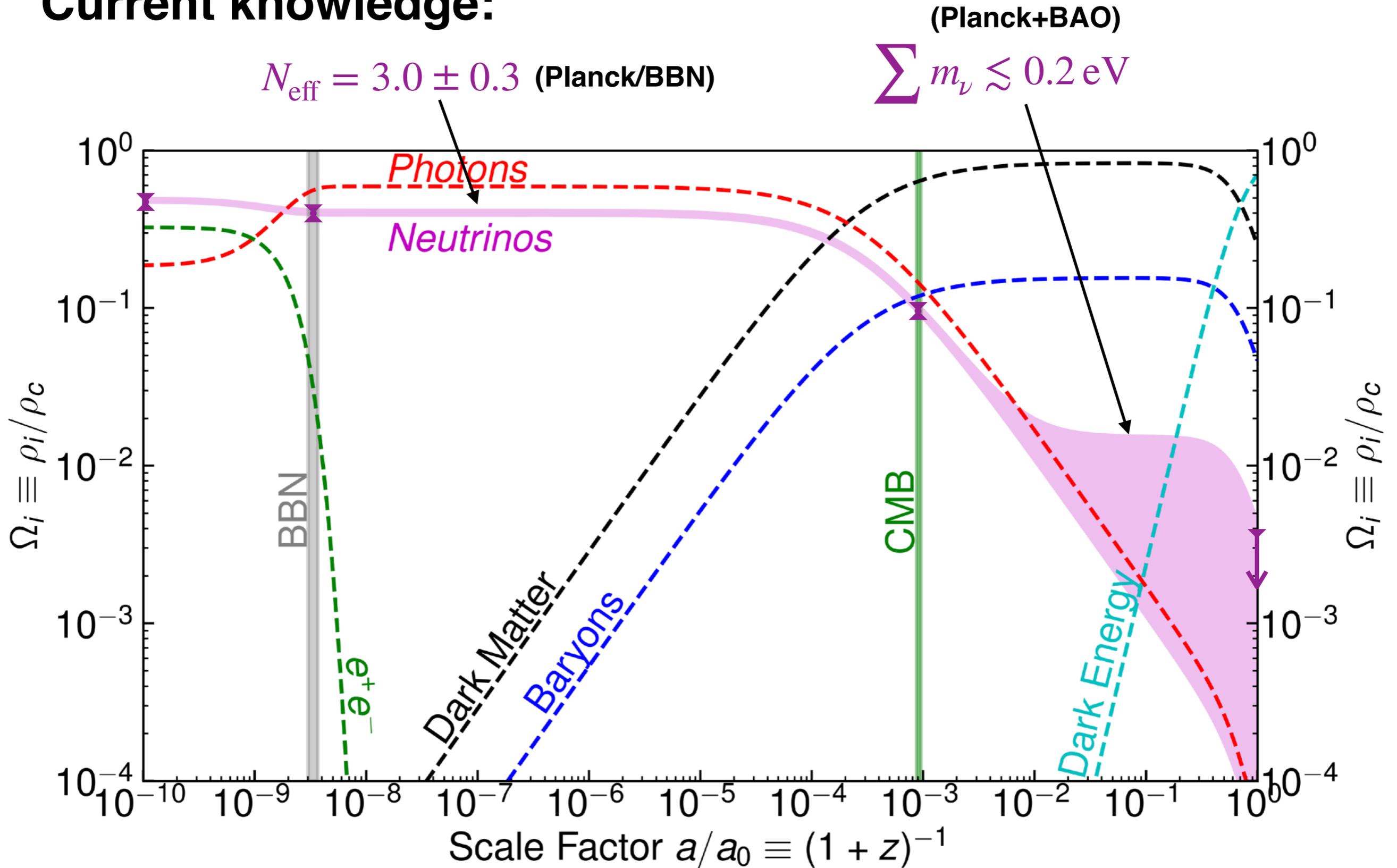


Non-Rel: $z_\nu^{\text{non-rel}} \simeq 200 \frac{m_\nu}{0.1 \text{ eV}}$

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

Global Perspective

Current knowledge:

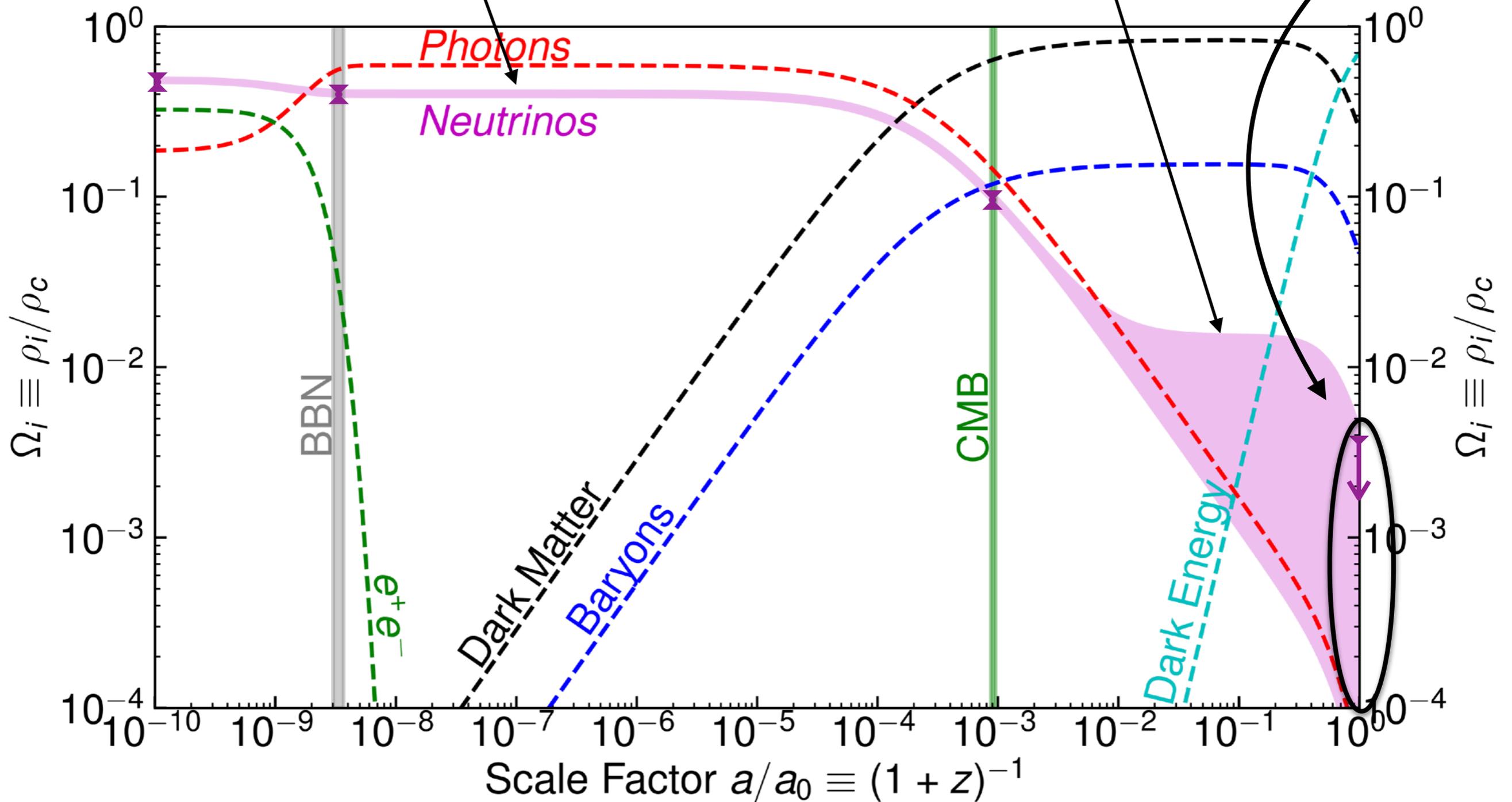
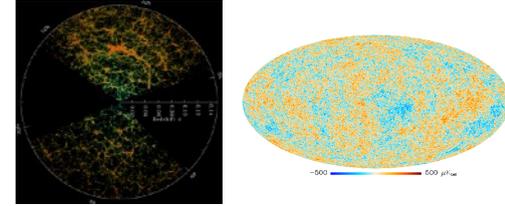


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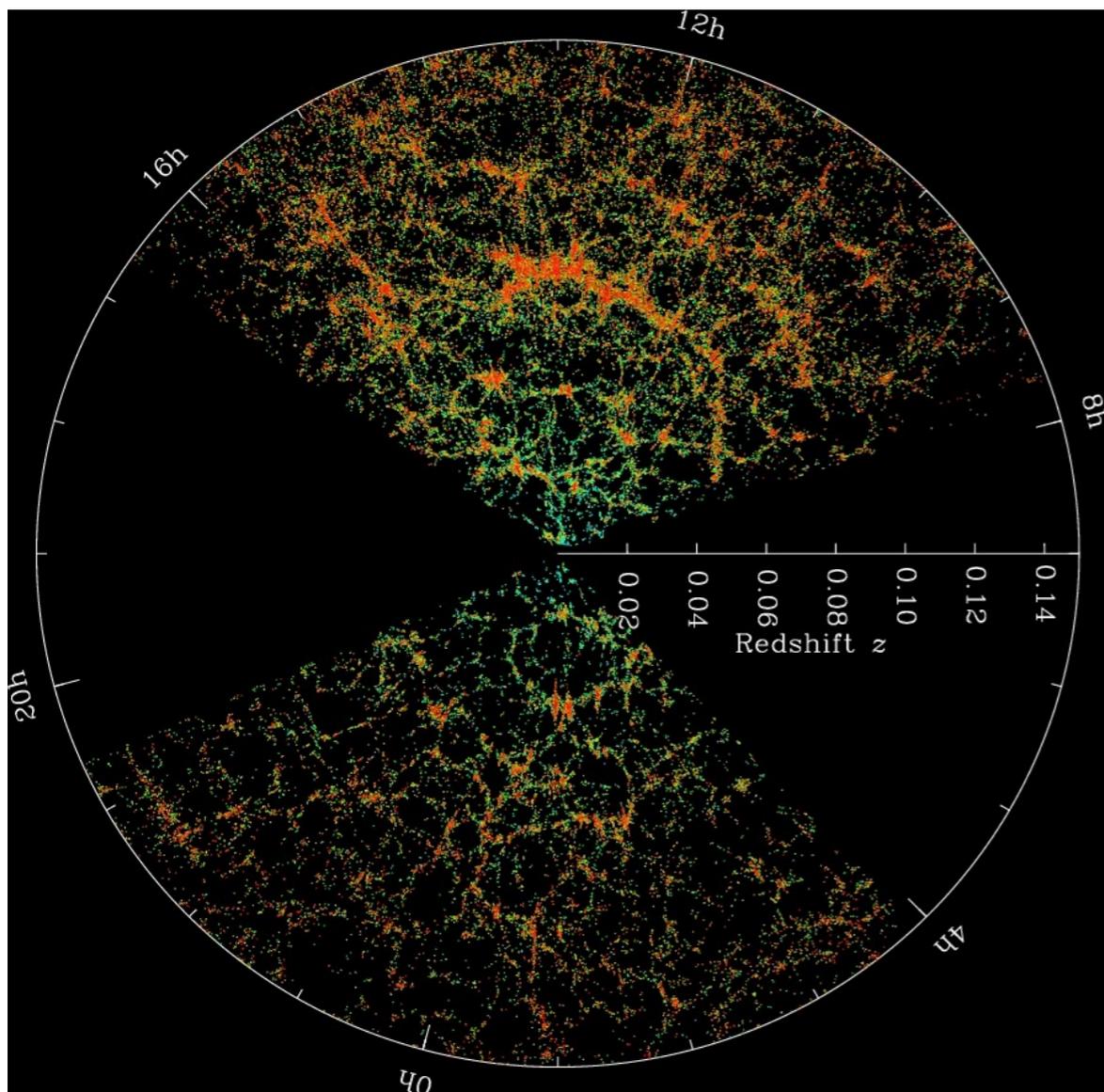
Current knowledge:

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

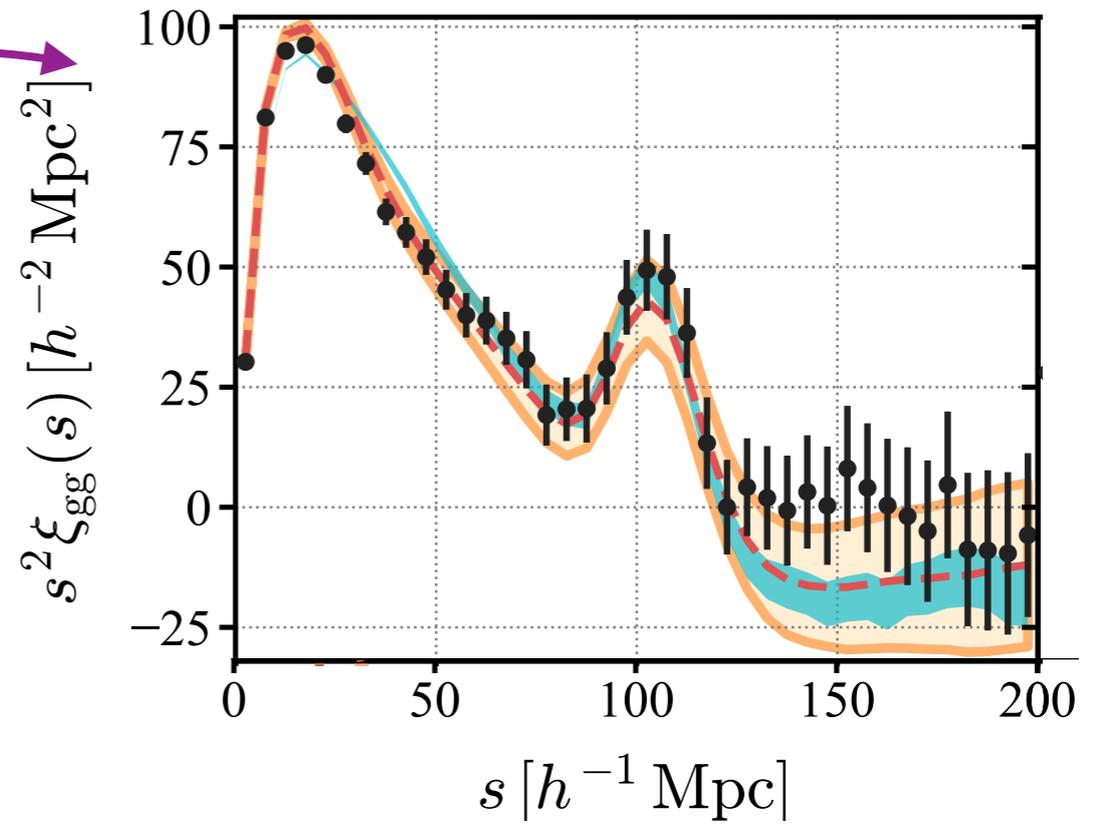
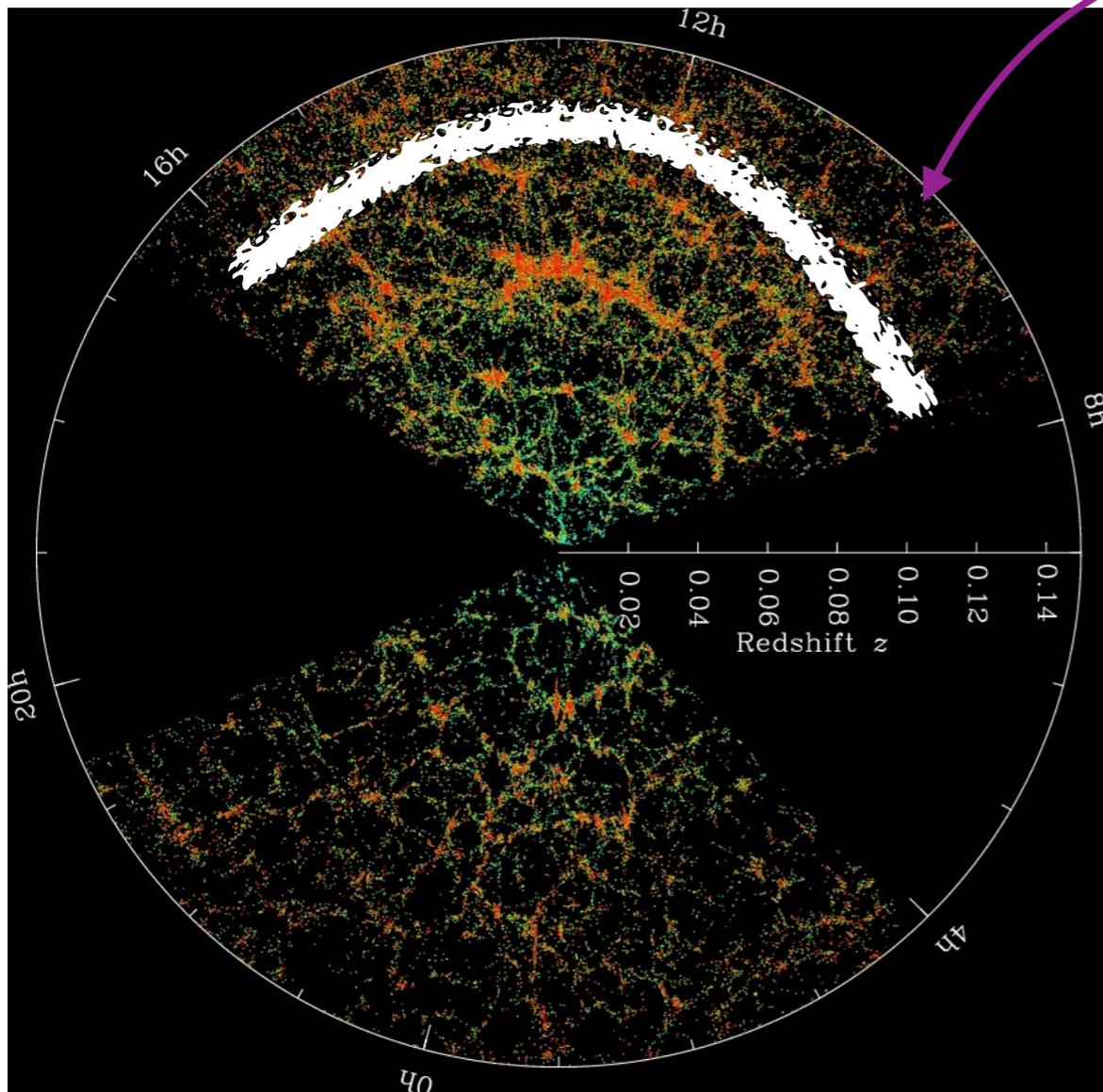
$$\sum m_\nu \lesssim 0.2 \text{ eV (Planck+BAO)}$$



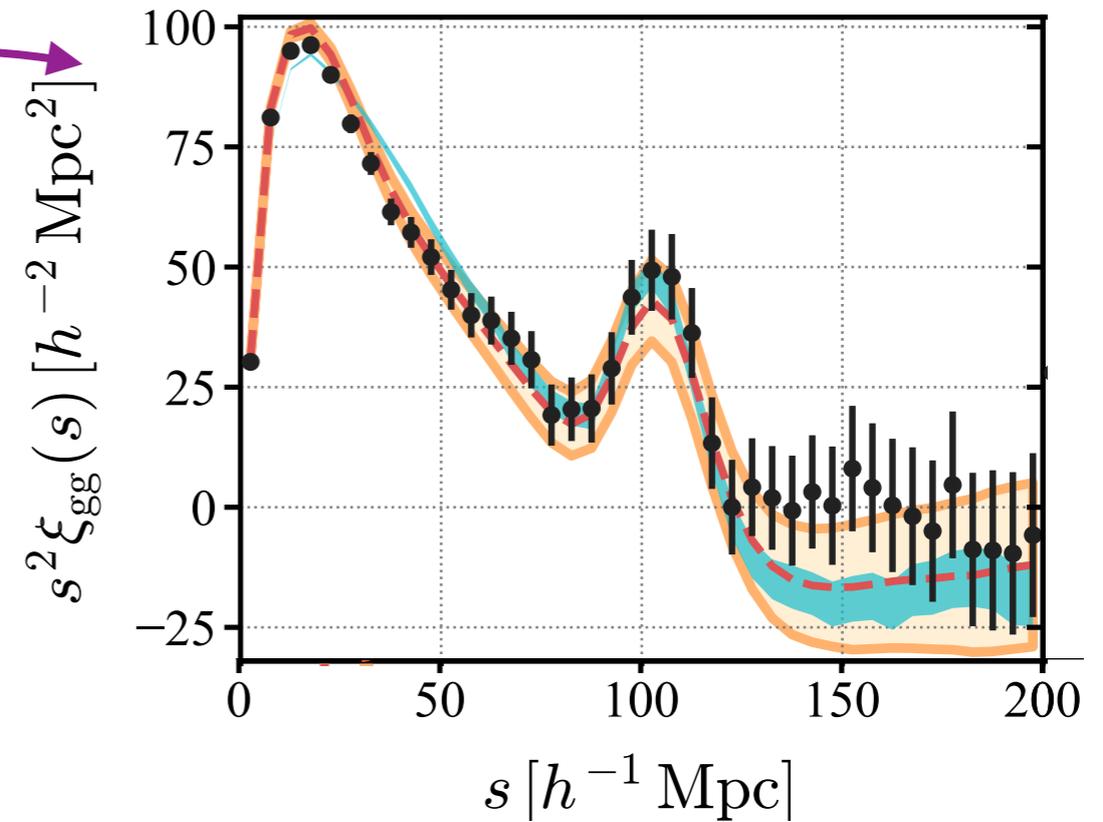
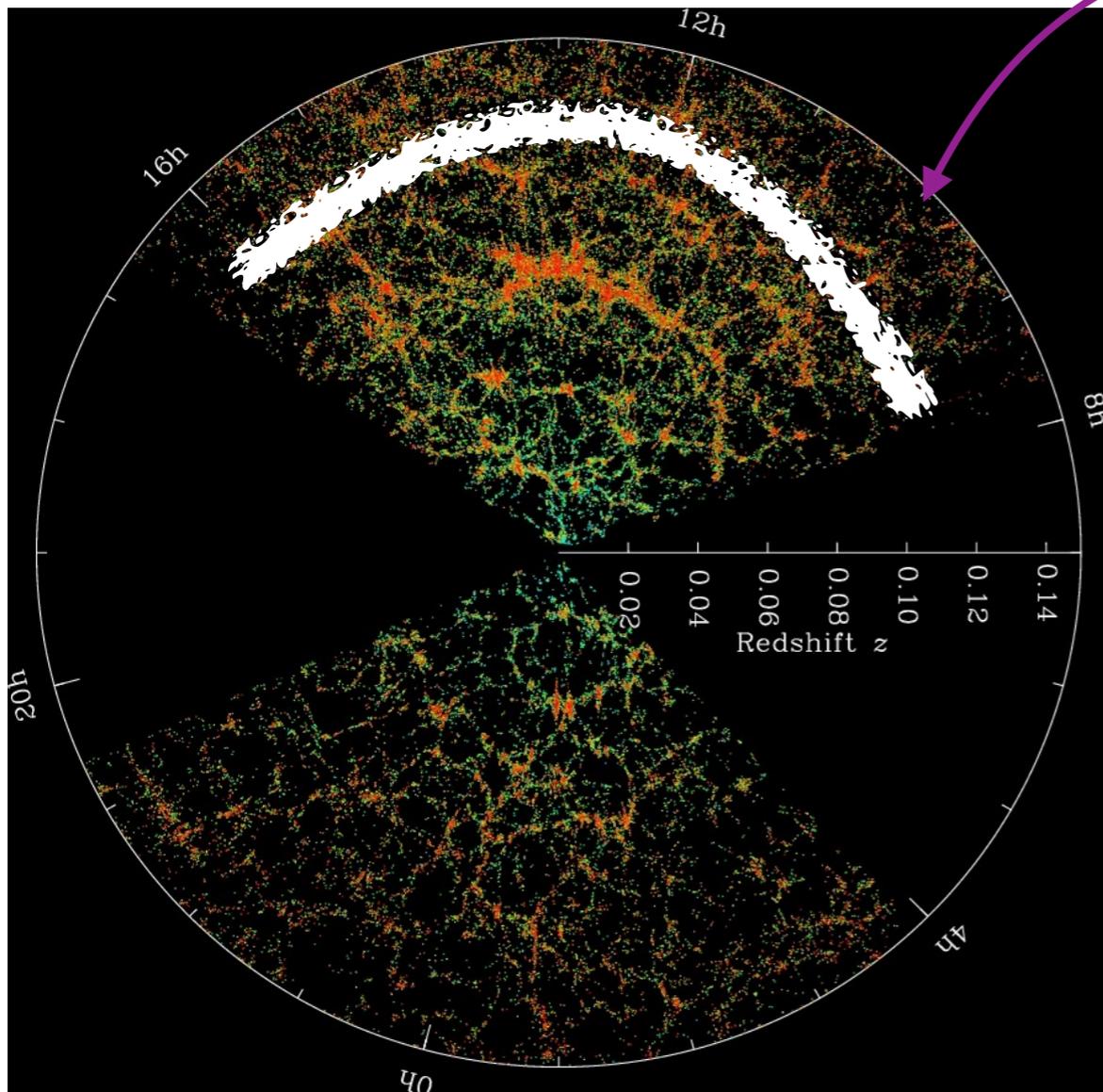
The Data: Galaxy Clustering



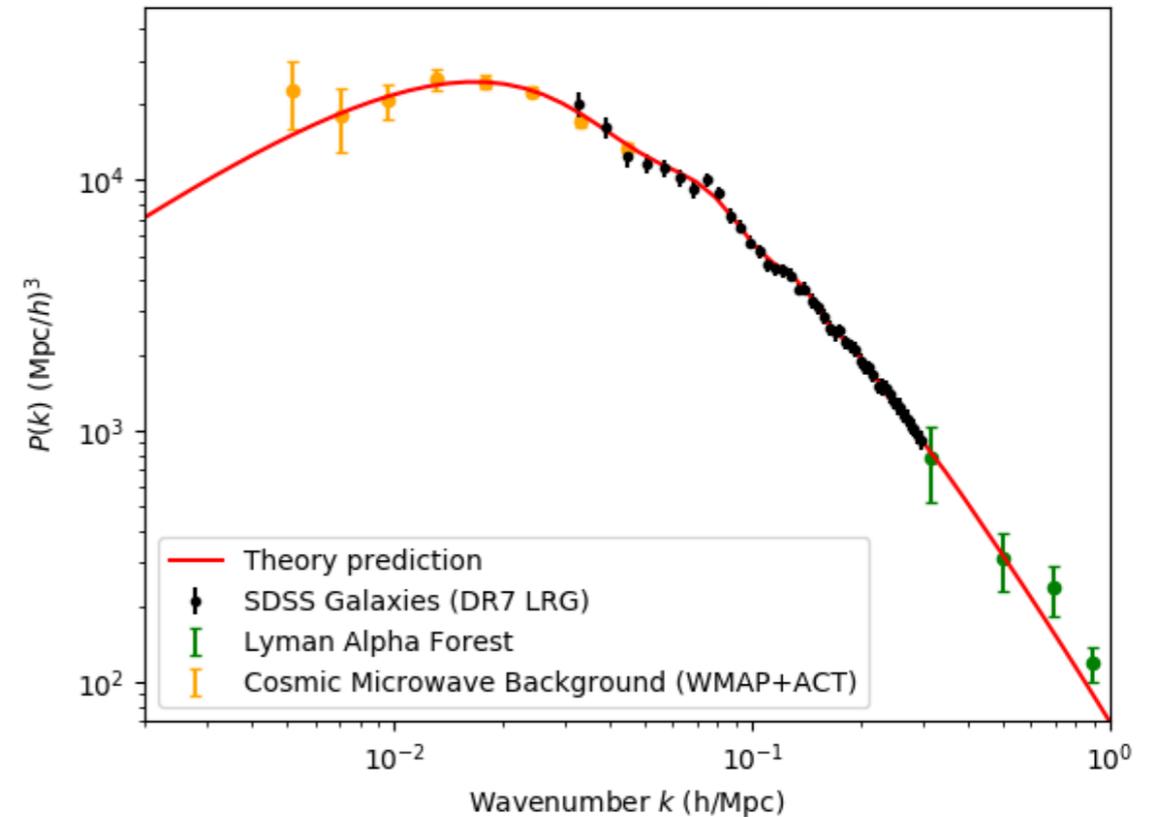
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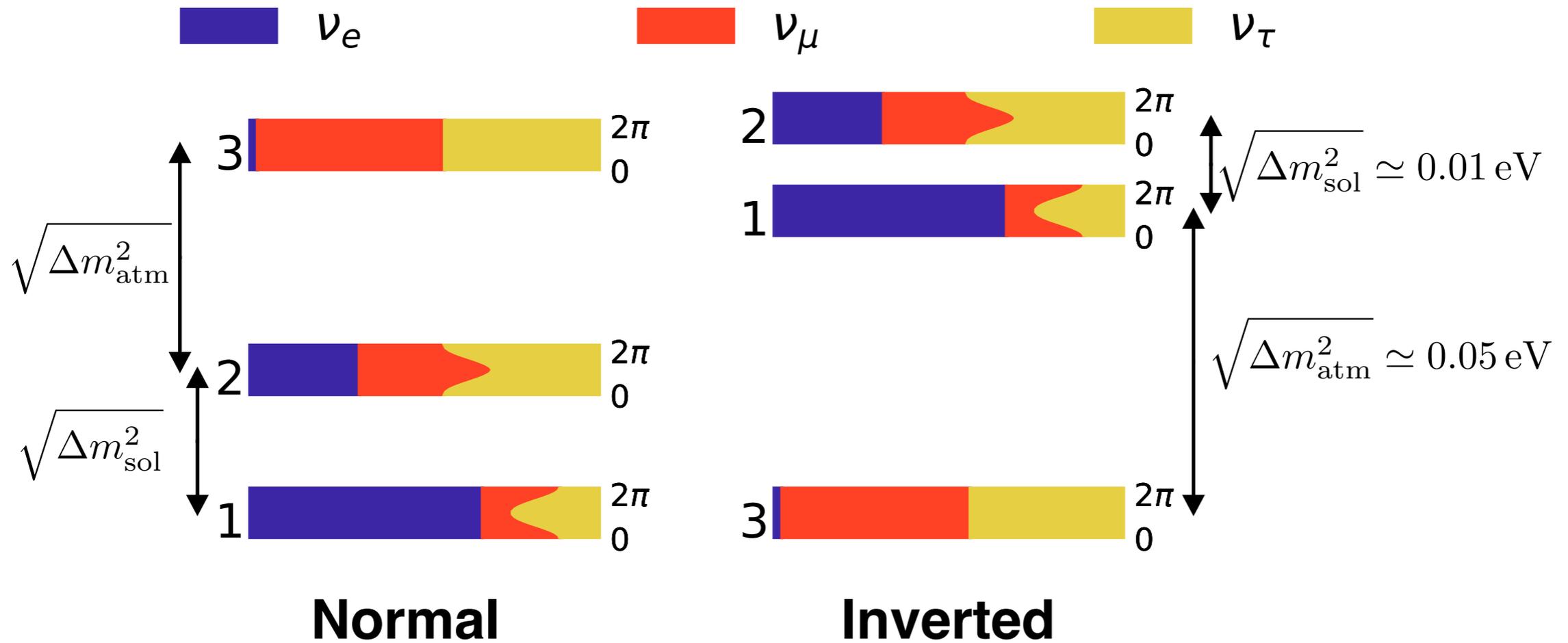


The total matter power-spectrum



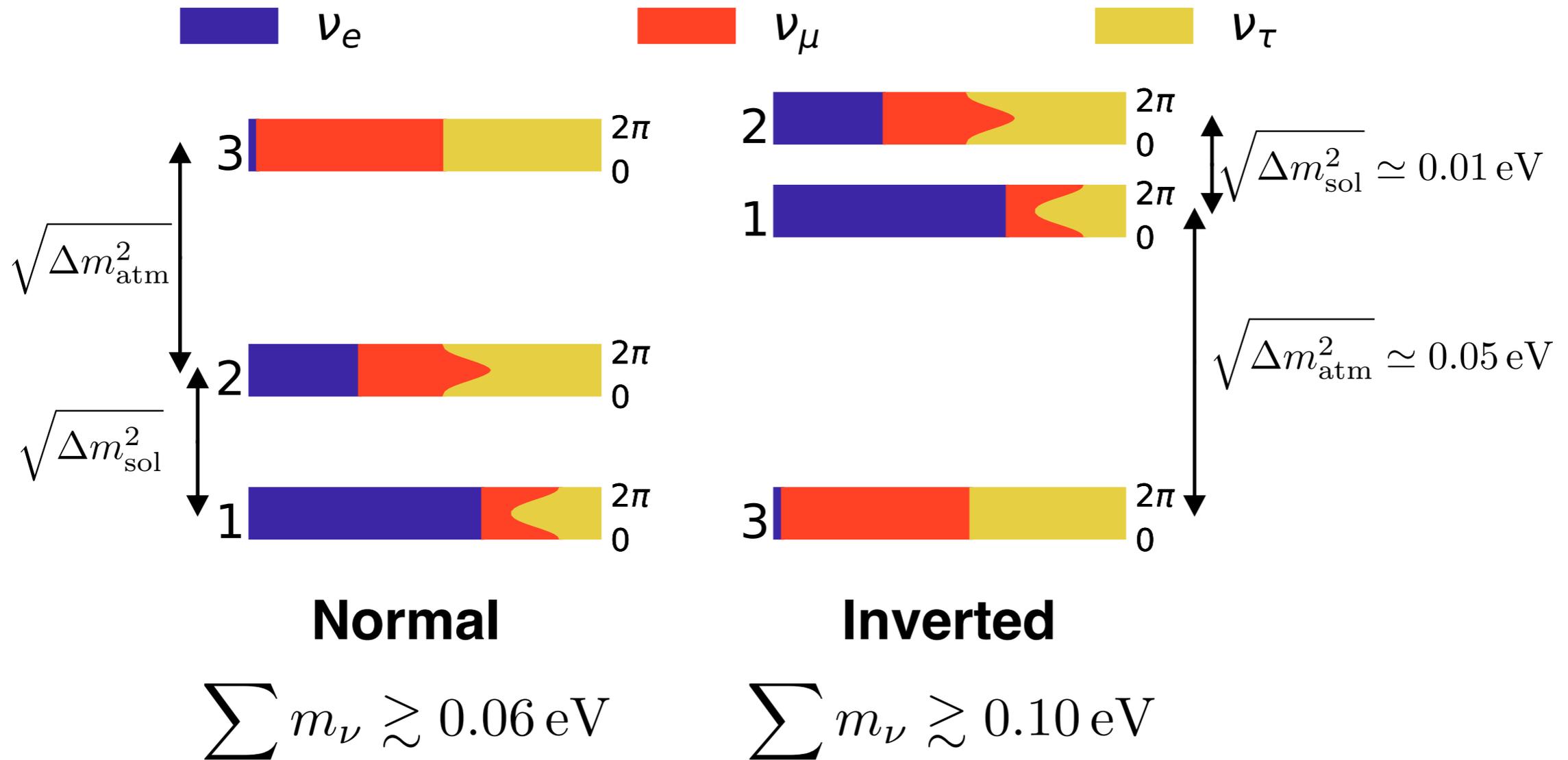
Neutrino Properties

Figure from de Salas et al. 1806.11051



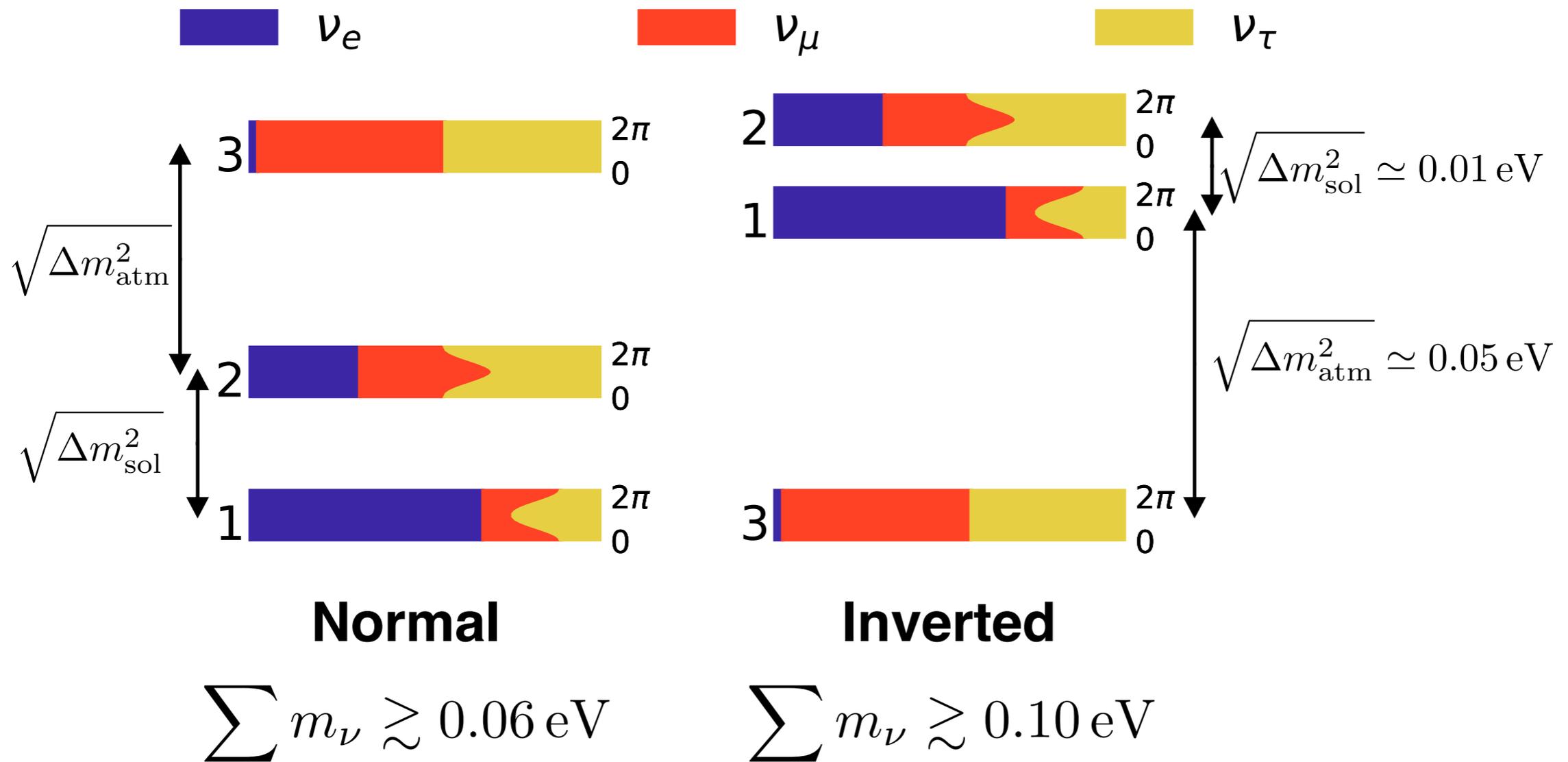
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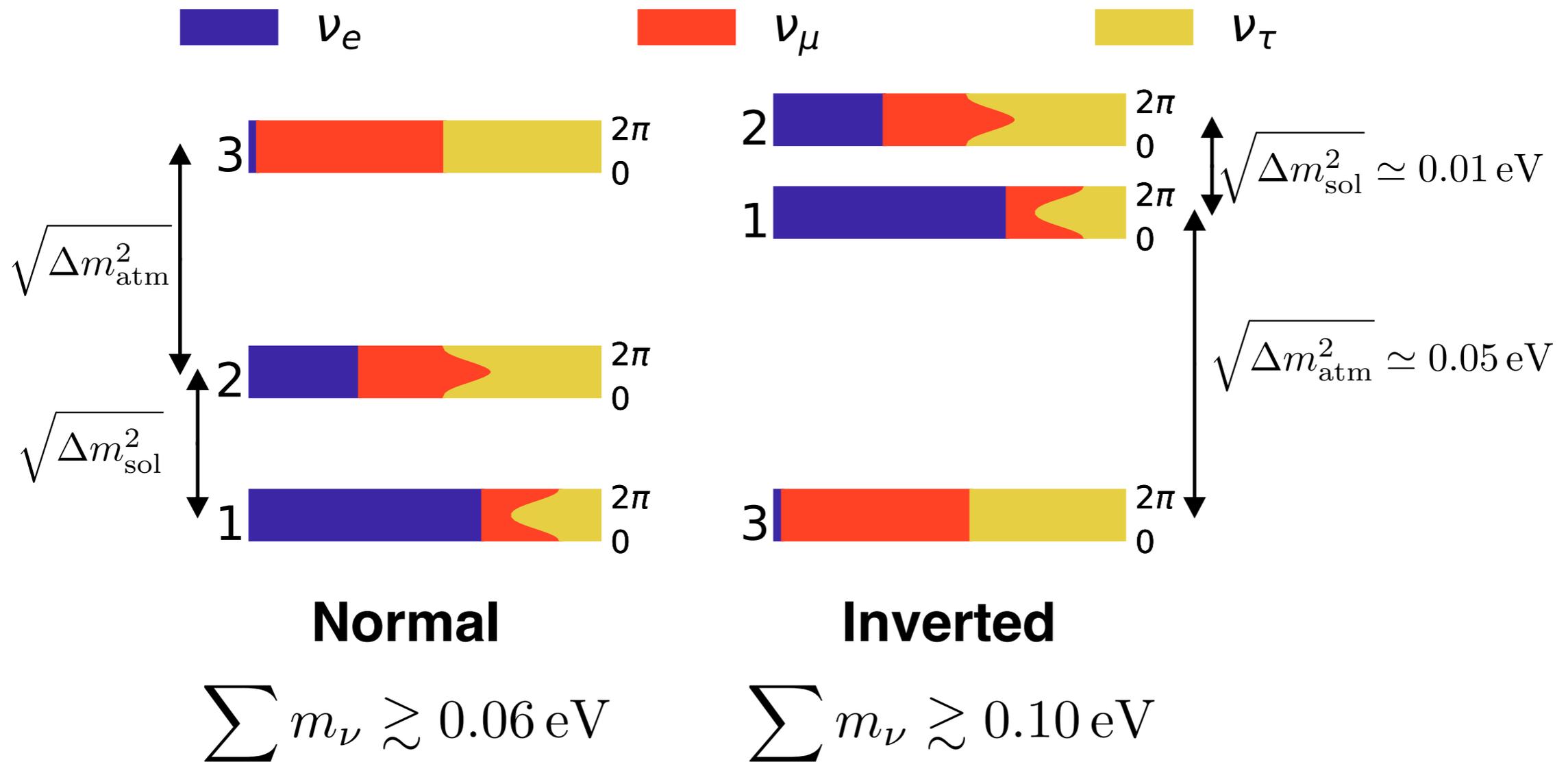
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- Mass differences and mixings measured with high precision

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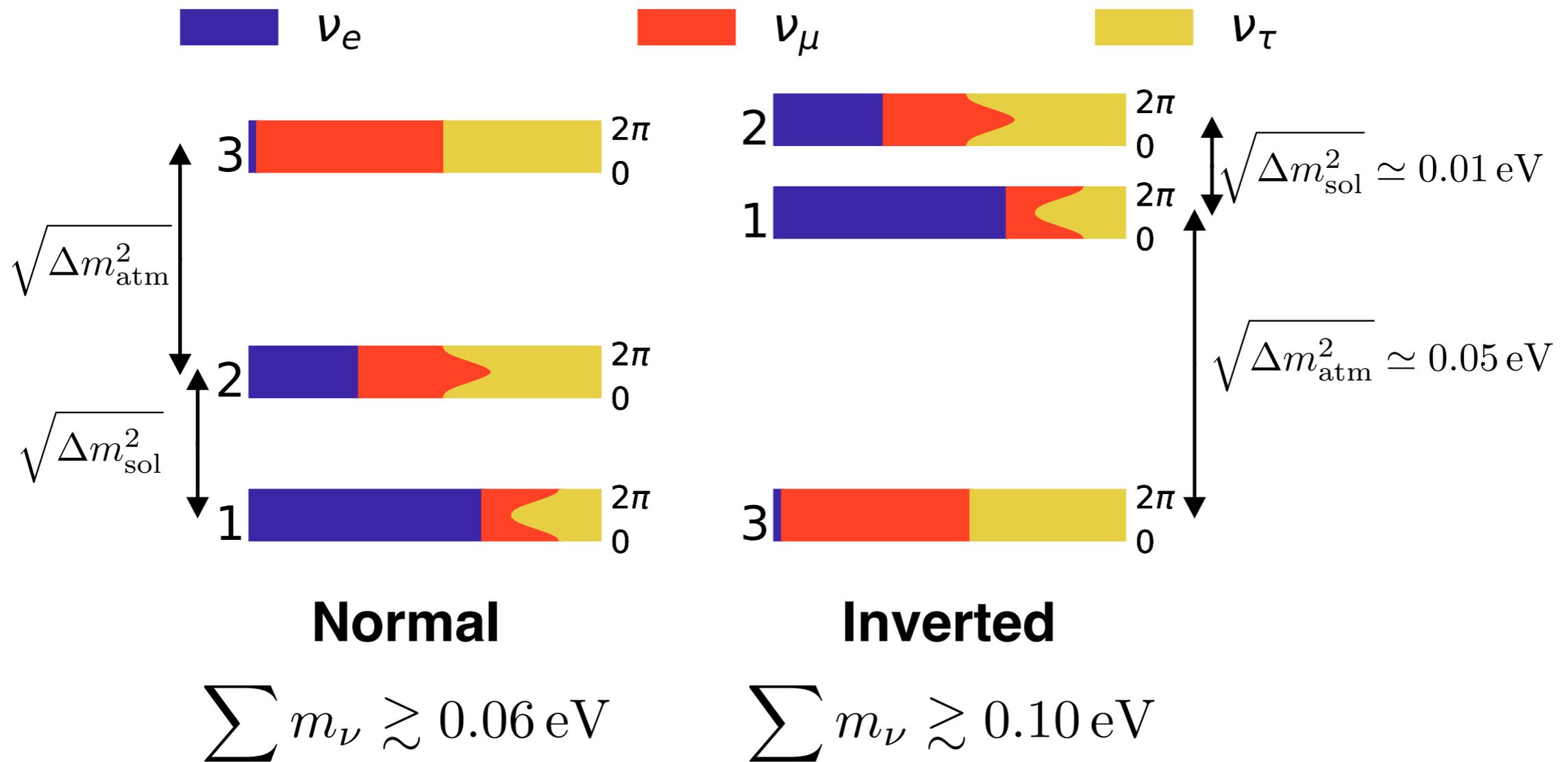
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- What is δ_{CP} and what is the mass ordering? [Neutrino Oscillations](#)

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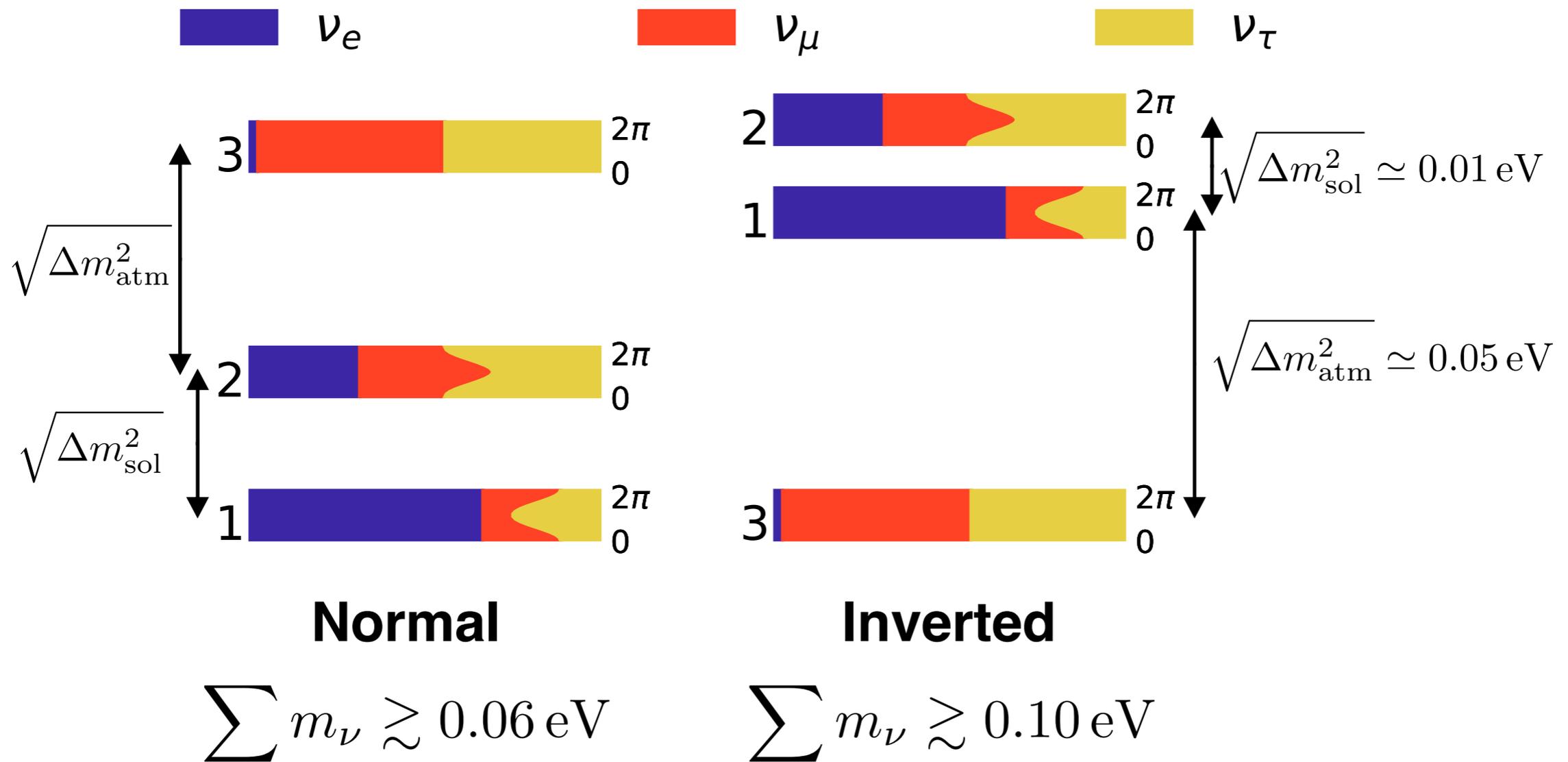
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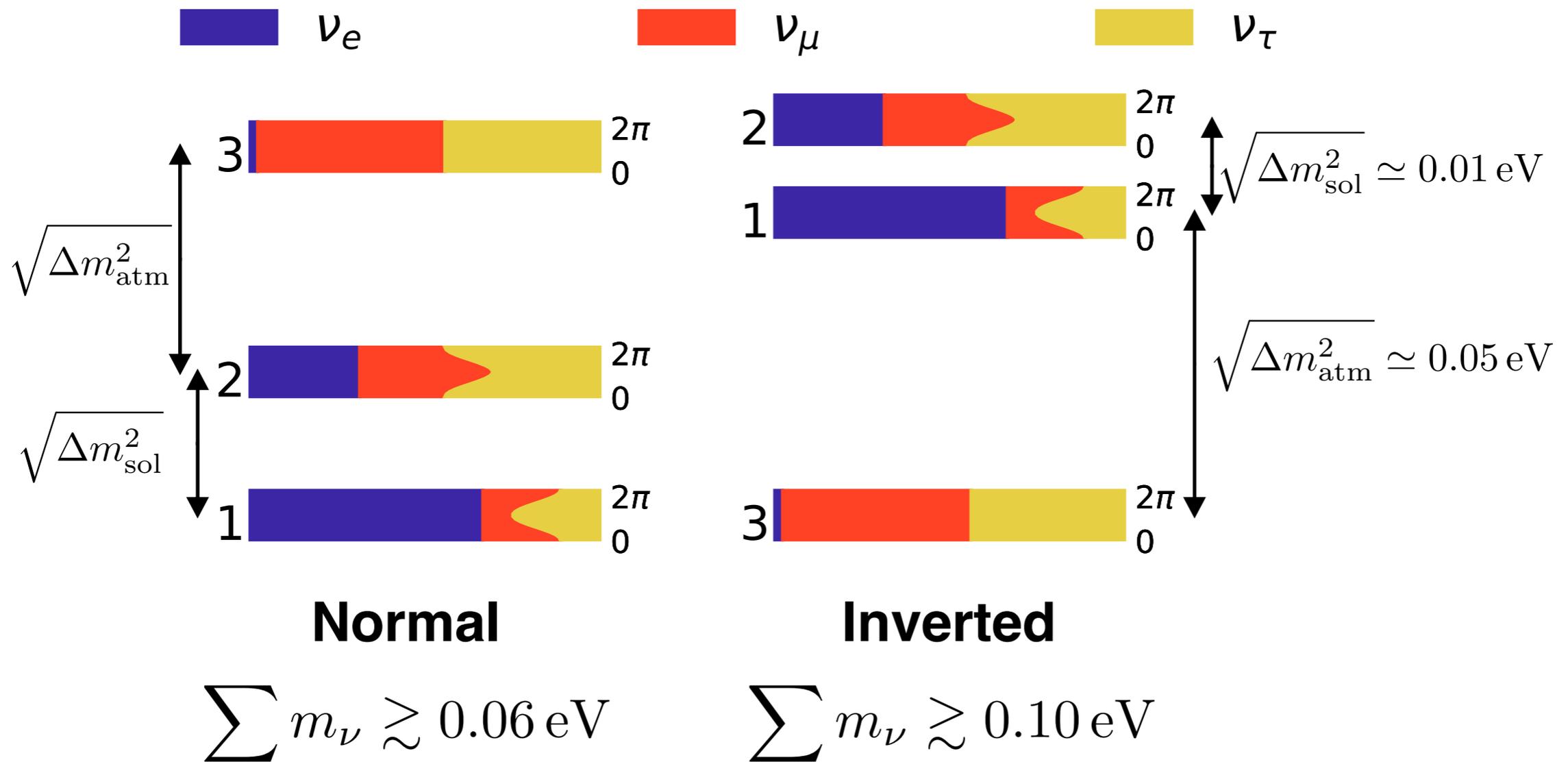
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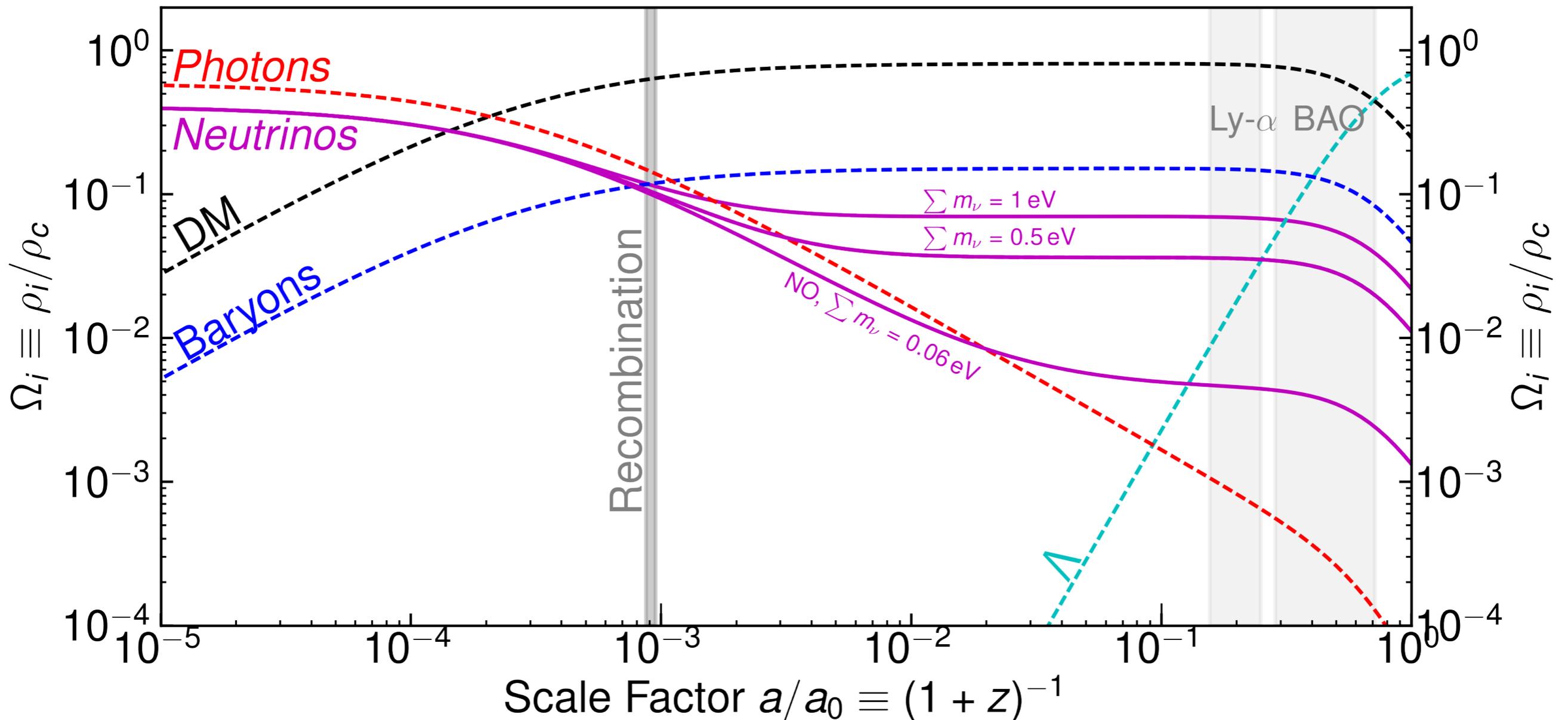
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- Are Neutrinos Dirac or Majorana particles? **$0\nu 2\beta$ Experiments**
- What is the neutrino mass scale? i.e. $\sum m_\nu$? i.e. m_{lightest} ? **KATRIN & Cosmology**

Neutrino Masses in Cosmology

- 1) Massive neutrinos enhance the expansion history $H \propto \sqrt{\rho}$



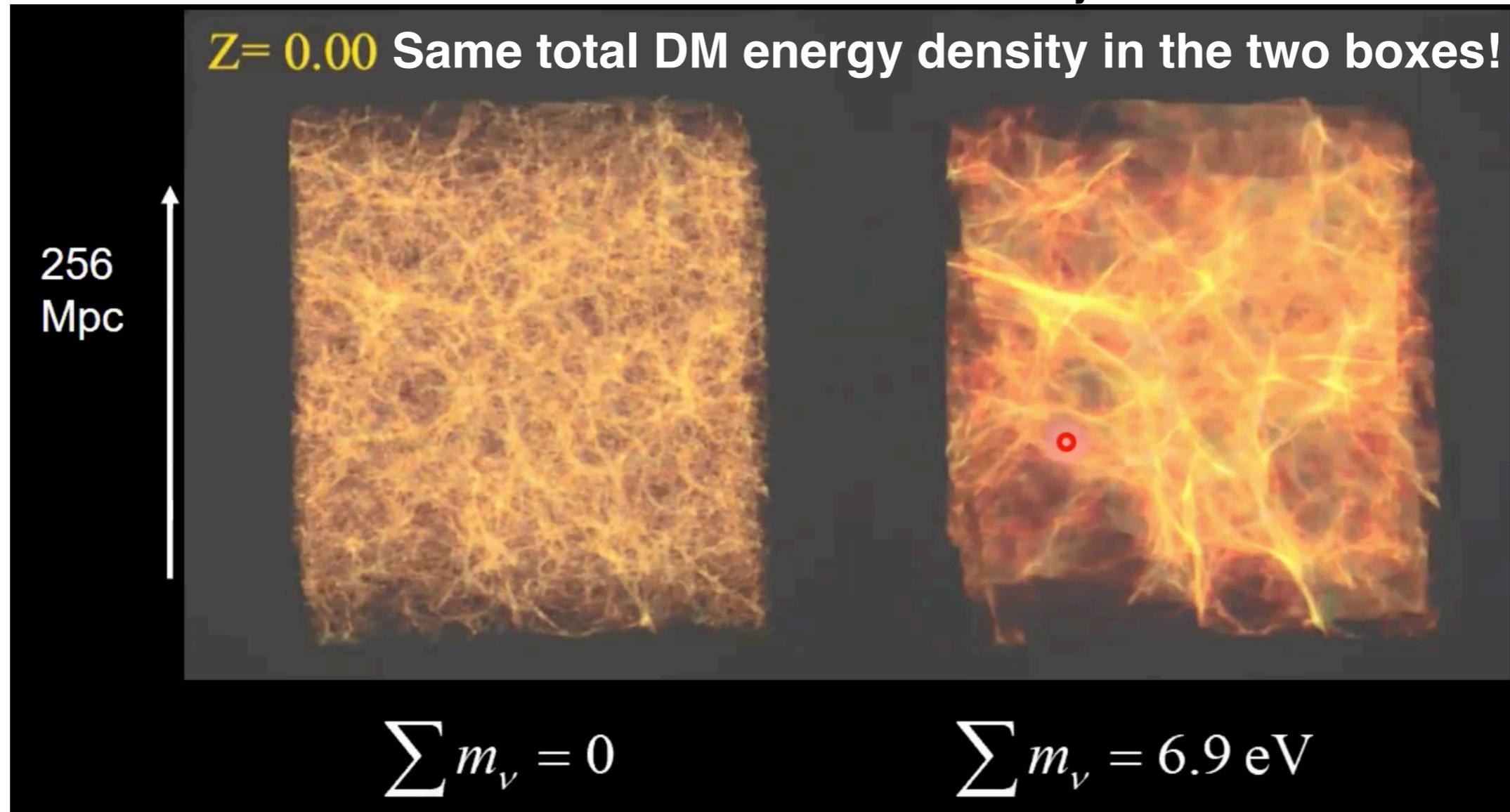
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Neutrino Masses in Cosmology

- 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

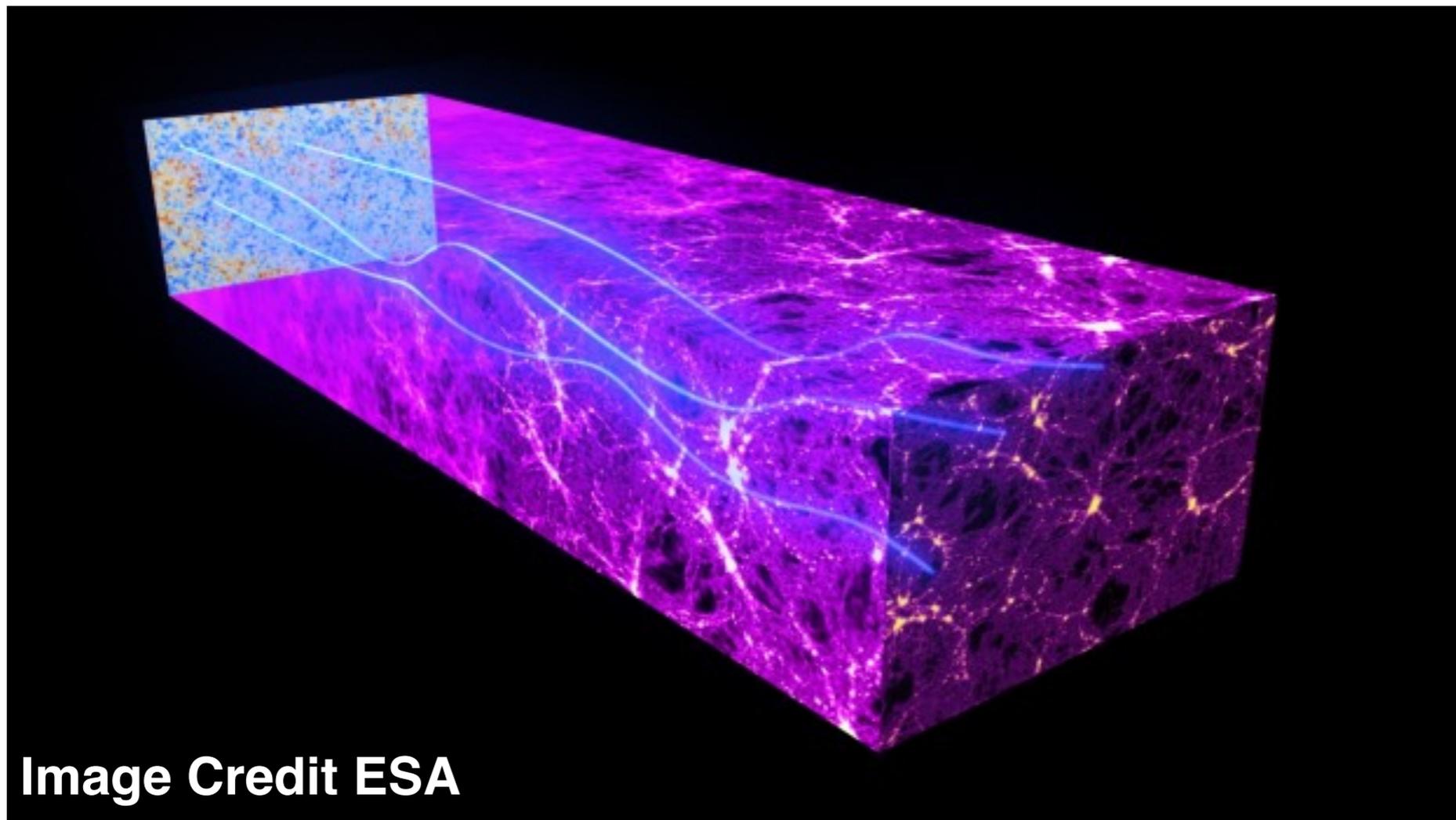
**Neutrinos of $m_\nu < 0.5 \text{ eV}$ become non-relativistic after recombination.
That means that their effect on the anisotropies is somewhat small!**

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

Neutrinos of $m_\nu < 0.5 \text{ eV}$ 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:

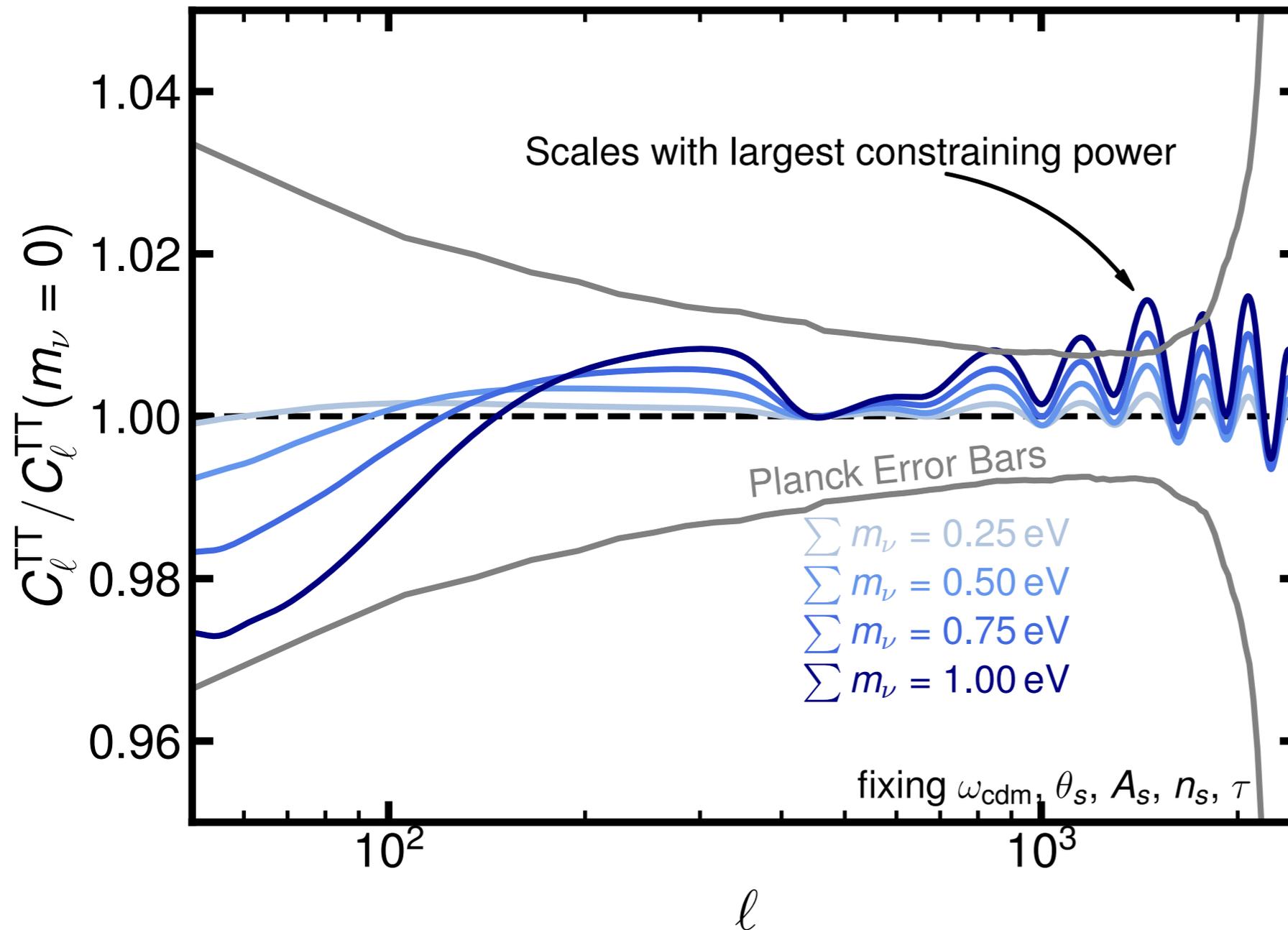


The larger the neutrino mass the less is the CMB light lensed!

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

The effect of neutrino masses in the CMB:



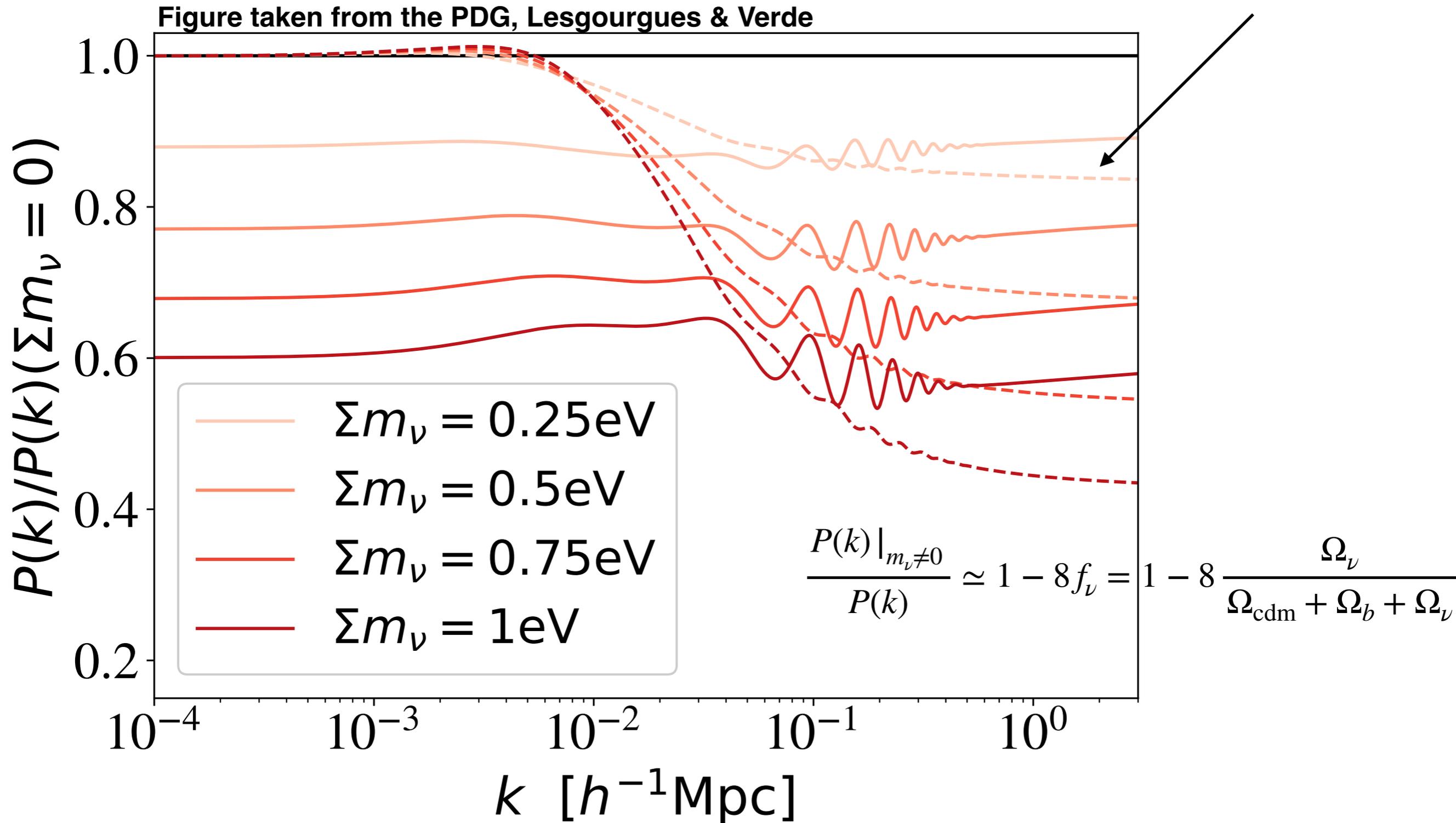
$$\sum m_\nu < 0.54 \text{ eV}$$

(95 % CL, TT+lowE)

Neutrino Masses in Cosmology

Galaxy Surveys

Suppression from $\Omega_\nu h^2$



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On the Standard Model of Cosmology:

Λ CDM \equiv Universe currently dominated by a Cosmological Constant and with Cold Dark Matter

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Model parametrized by 6 parameters: $\Omega_b h^2$ $\Omega_{\text{cdm}} h^2$ A_s n_s τ_{reio} θ_s

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see e.g. Archidiacono et al. [1610.09852]

$\sum m_\nu$ is strongly correlated with H_0 and Ω_m

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because:

- 1) The amount of lensing is strongly correlated with the dark matter abundance too
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BAO data can break precisely these degeneracies!

Neutrino Masses from Cosmology

Planck 2018 for Λ CDM (1807.06209)

$$\sum m_\nu < 0.54 \text{ eV} \quad (95 \% \text{ CL, TT+lowE})$$

$$\sum m_\nu < 0.26 \text{ eV} \quad (95 \% \text{ CL, TTTEEE+lowE})$$

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$$\sum m_\nu < 0.073 \text{ eV} \quad (95 \% \text{ CL, CMB+BAO-DESIY1})$$

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To be compared to the KATRIN bound: But also with the minimal possible value!

$$\sum m_\nu < 1.5 \text{ eV}$$

$$\sum m_\nu \gtrsim 0.06 \text{ eV}$$

$$\sum m_\nu \gtrsim 0.10 \text{ eV}$$

Neutrino Masses from Cosmology

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

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Next slide!

Neutrino Masses from Cosmology

Cosmological Model Dependence

Planck+SDSS and 3 degenerate neutrinos

Neutrino Masses from Cosmology

Cosmological Model Dependence

Planck+SDSS and 3 degenerate neutrinos

$$\sum m_\nu < 0.12 \text{ eV}$$

Standard Case

Planck 1807.06209

Λ CDM+m _{ν}

$$\sum m_\nu < 0.25 \text{ eV}$$

Dark Energy dynamics

Choudhury & Hannestad 19'

CDM+m _{ν} + ω_a + ω

$$\sum m_\nu < 0.15 \text{ eV}$$

Varying Curvature

Choudhury & Hannestad 19'

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Dynamical Dark Energy: $\sum m_\nu < 0.163 \text{ eV}$ W_a+W₀+m_ν DESI 2503.14744

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- **Constraints are robust upon standard modifications of Λ CDM and weaken only substantially for dynamical dark energy**

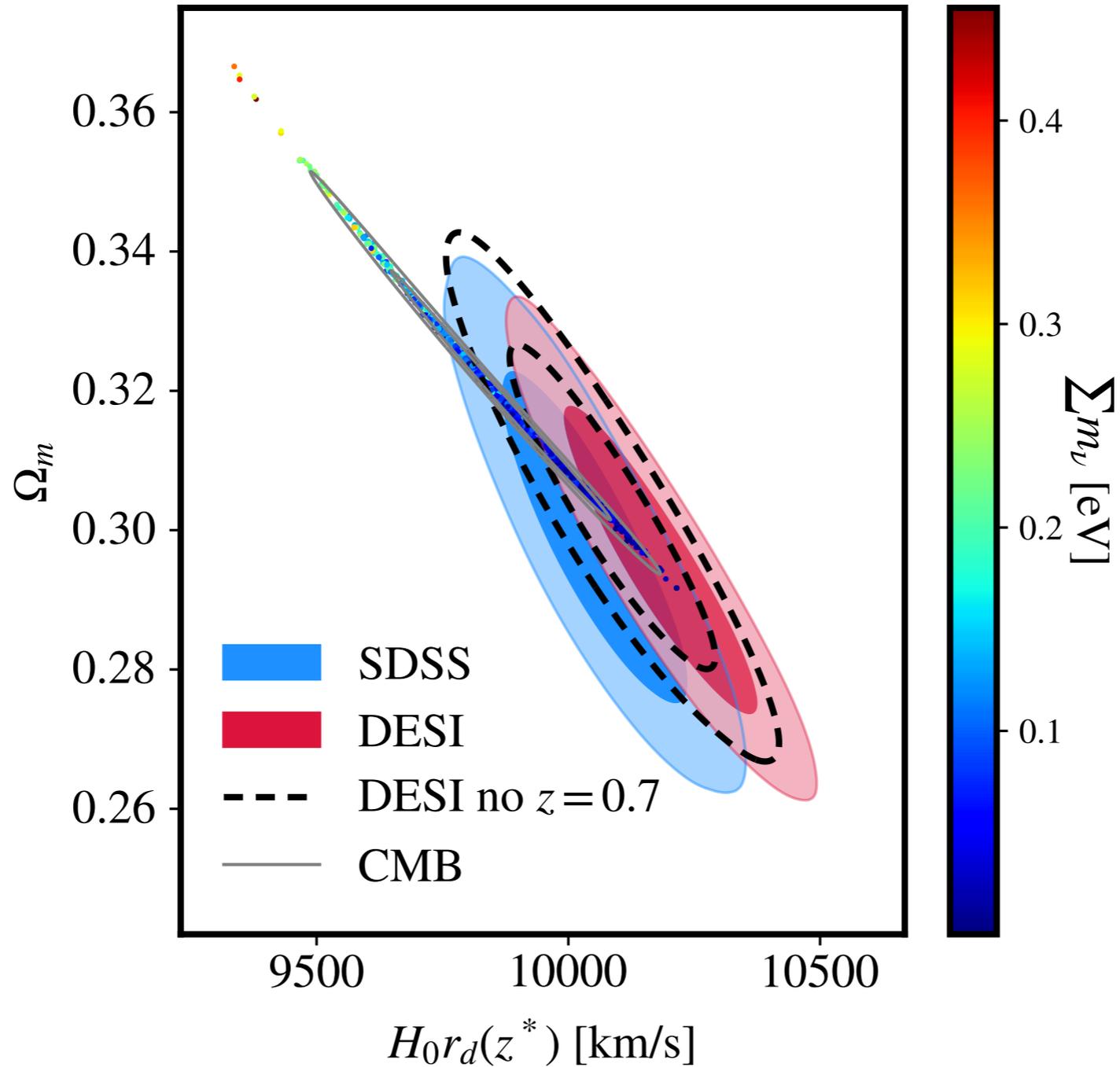
Neutrino Masses from Cosmology

The main source of the tension:

Neutrino Masses from Cosmology

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Naredo-Tuero et al. [2407.13831]



Neutrino Masses from Cosmology

Cosmological Model Dependence

Non-standard Neutrino Cosmologies:

Neutrino Masses from Cosmology

Cosmological Model Dependence

Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

$$\nu_i \rightarrow \nu_j \phi$$
$$\sum m_\nu \lesssim 0.2 \text{ eV}$$

Oldengott et al. 2203.09075 & 2011.01502
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$$\nu_i \rightarrow \nu_4 \phi$$

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Time Dependent Neutrino Masses

Late phase transition

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Dvali & Funcke 1602.03191
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$$T_\nu < T_\nu^{\text{SM}} + \text{DR}$$

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

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- **Bounds can be significantly relaxed in some extensions of Λ CDM. They require modifications to the neutrino sector.**

Neutrino Masses from Cosmology

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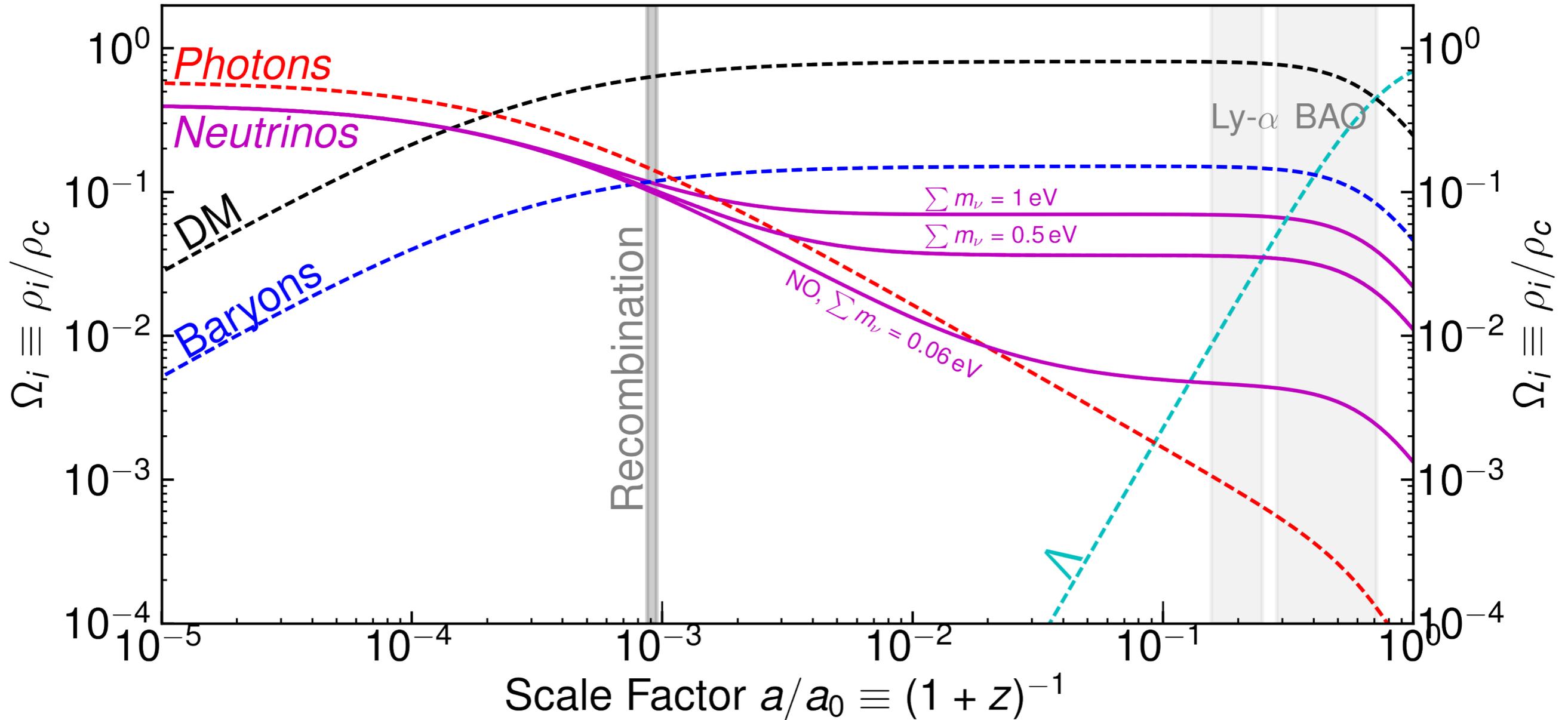
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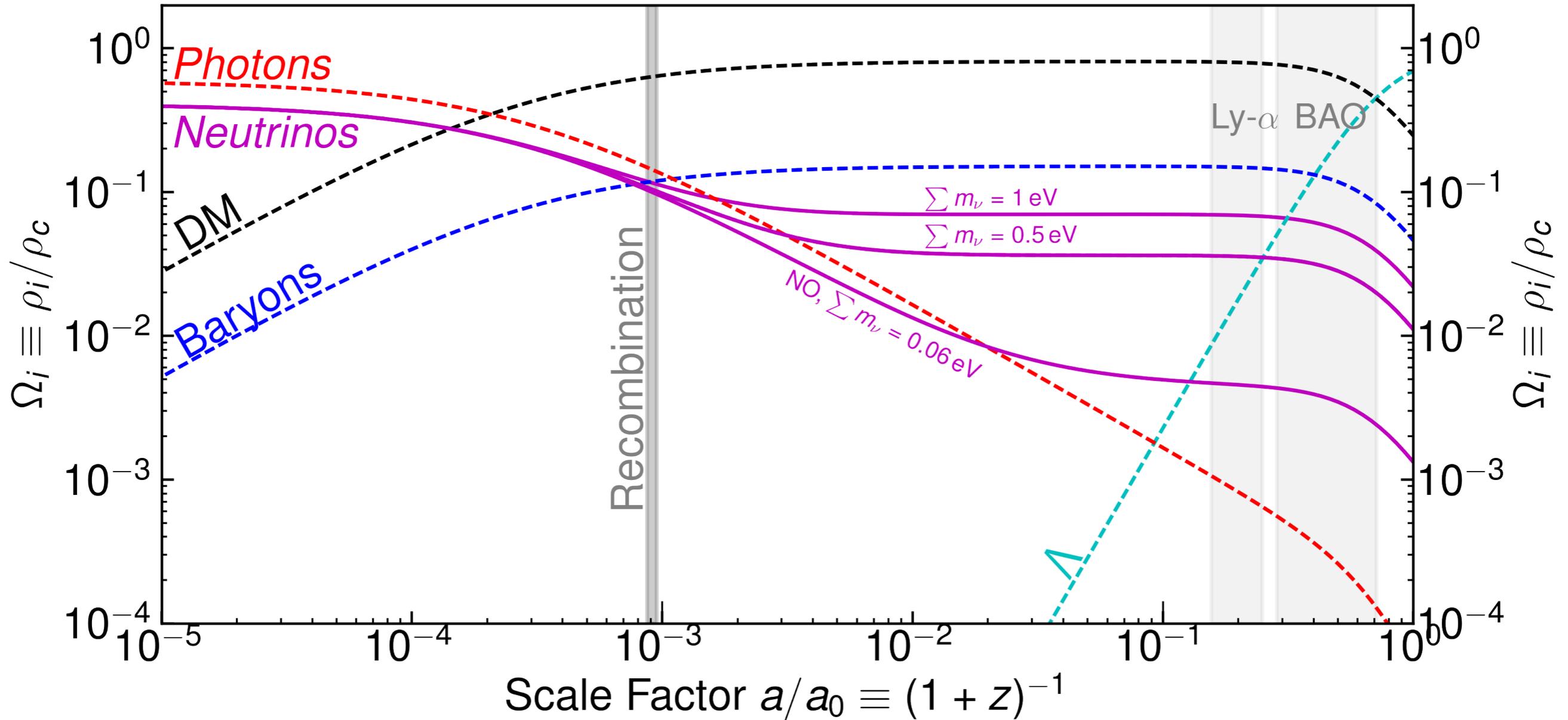
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Neutrino Masses from Cosmology



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

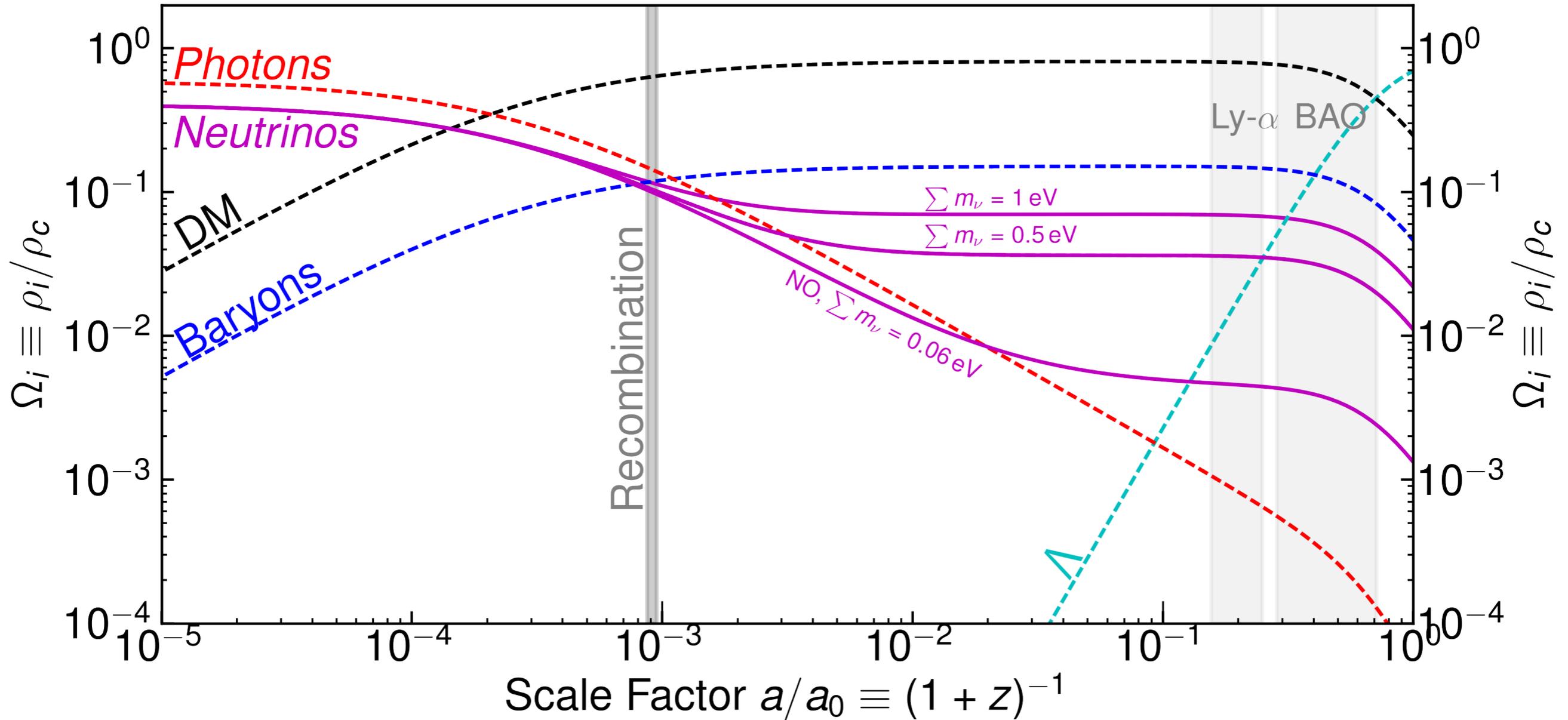
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**Comoving sound horizon
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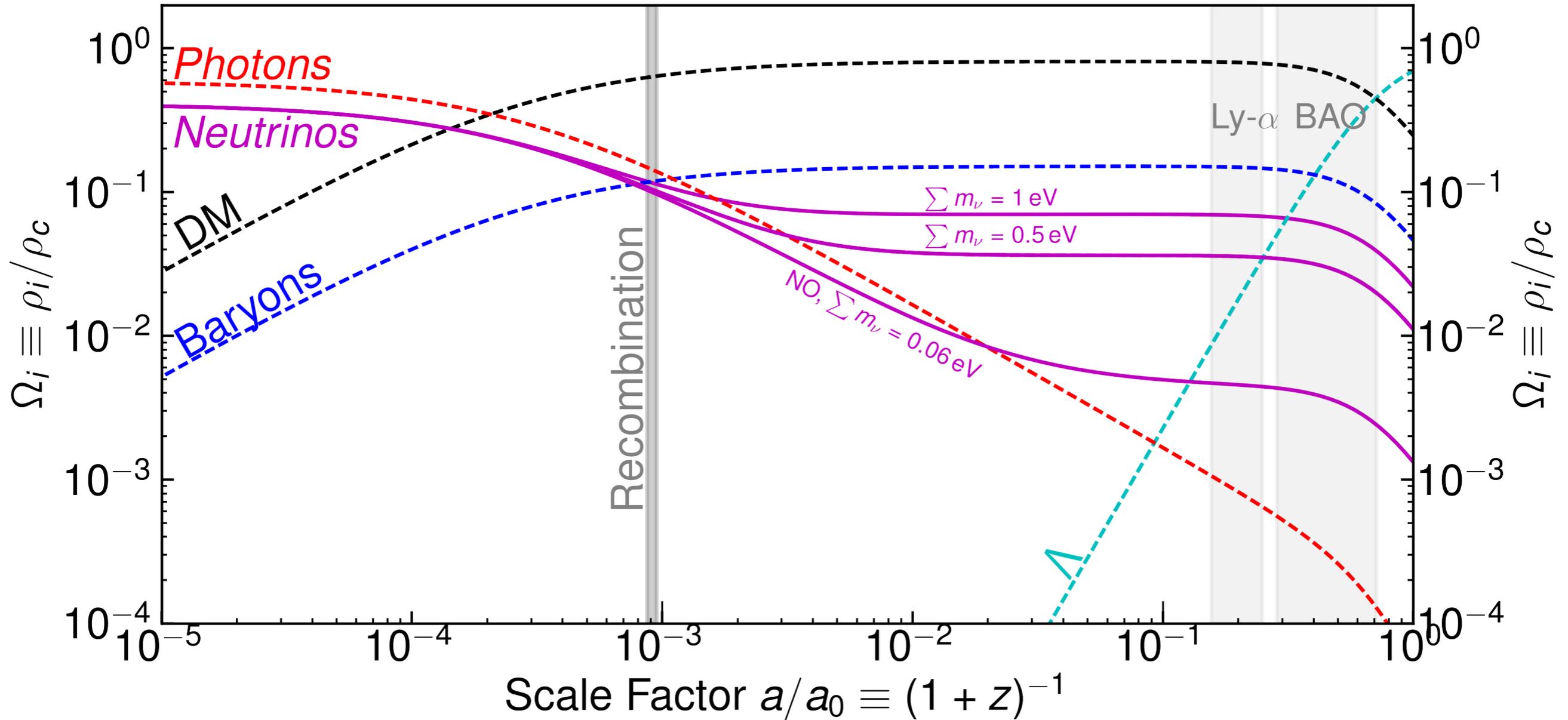
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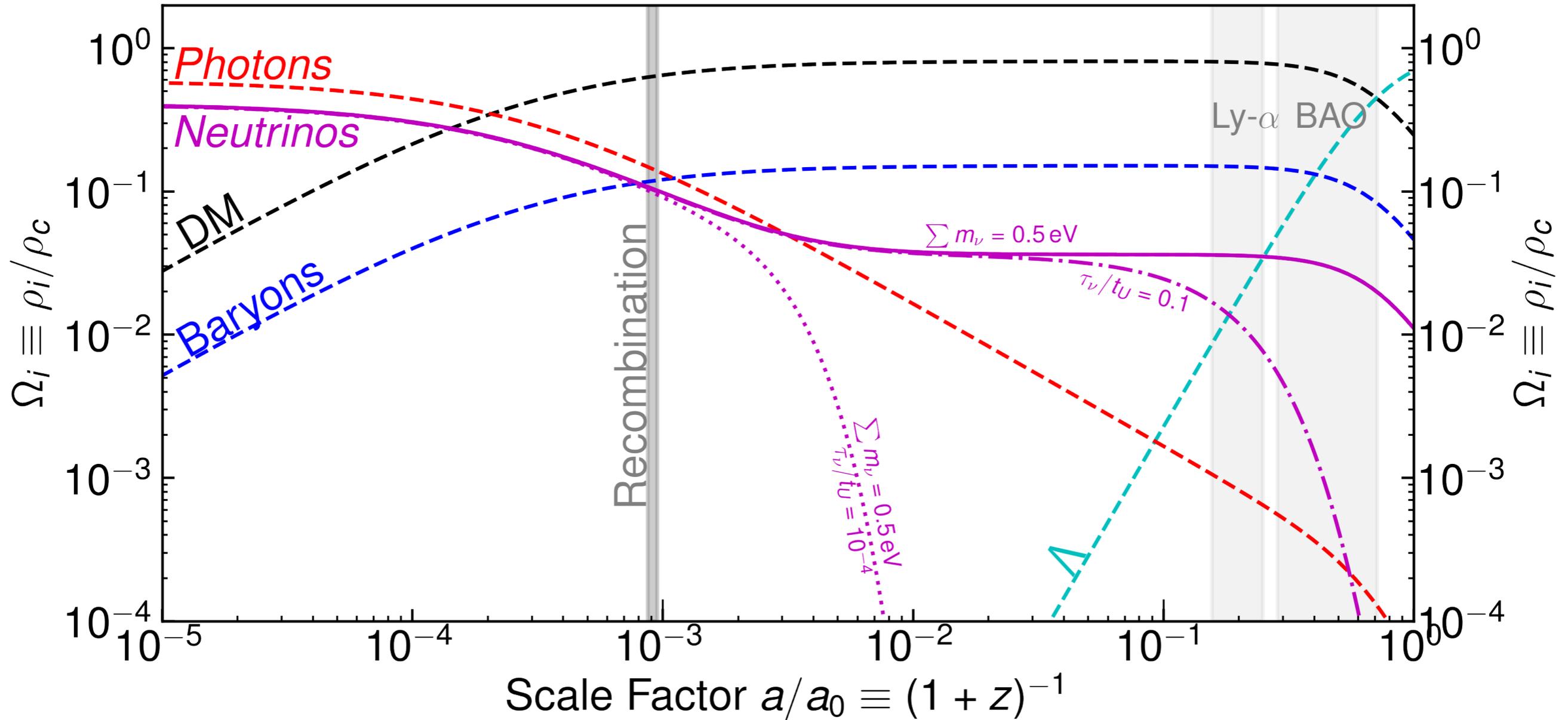
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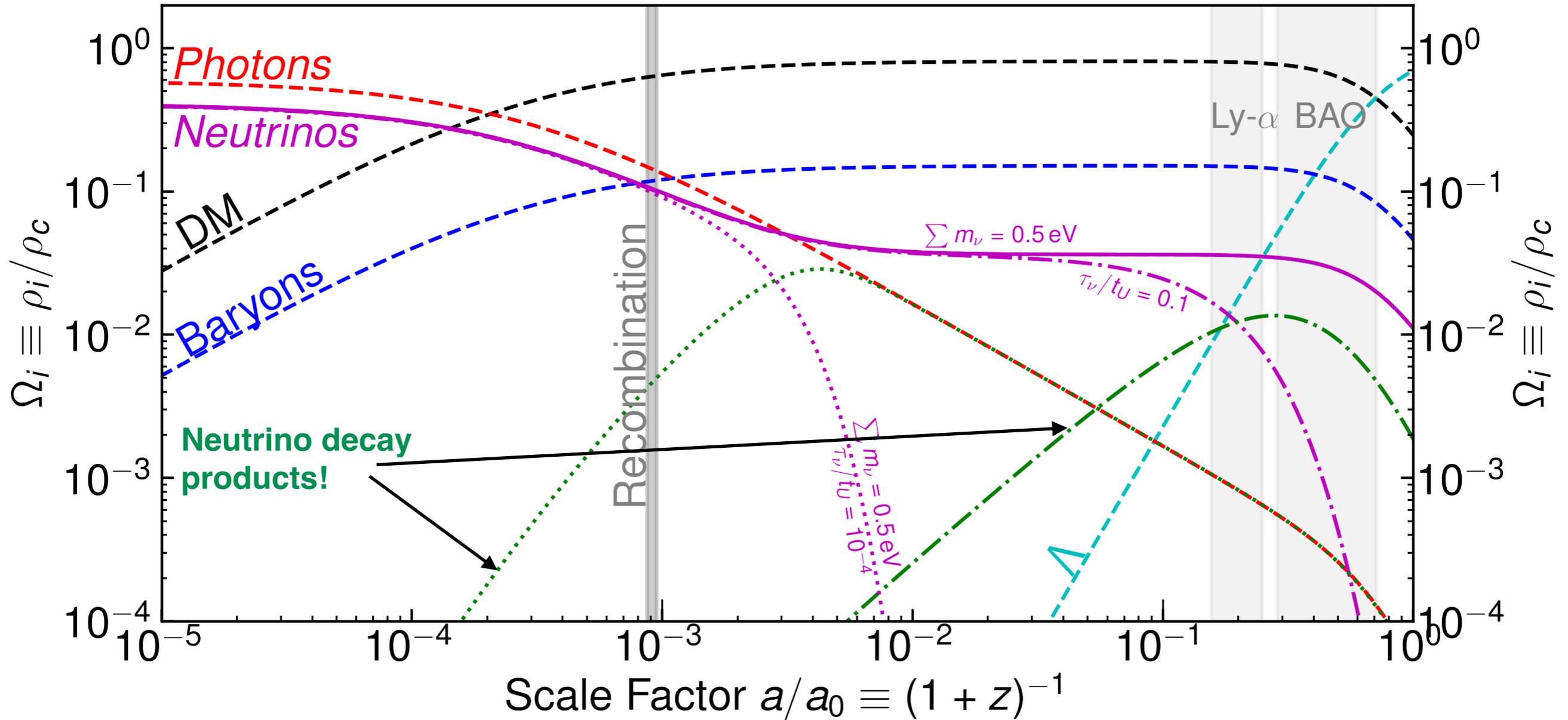
Not only a background effect:

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

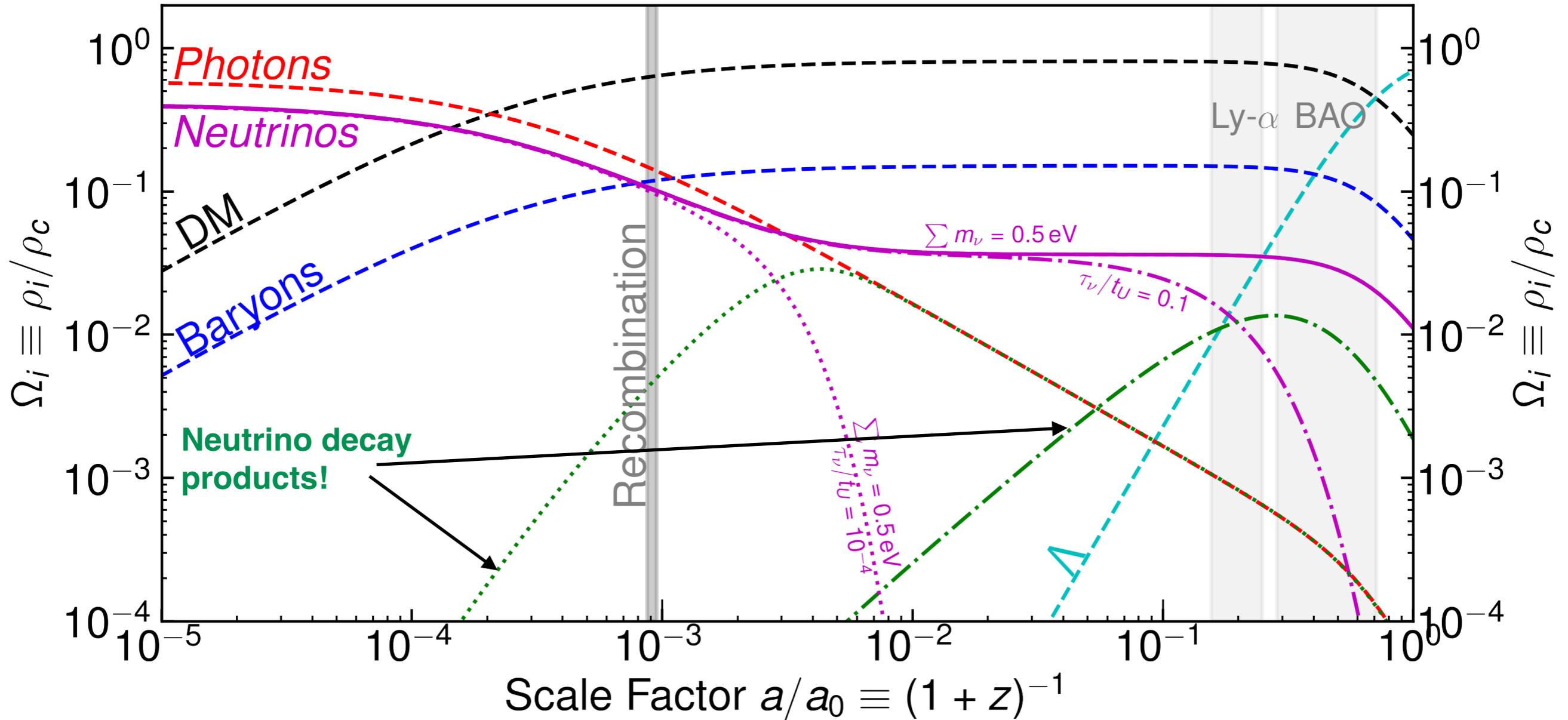
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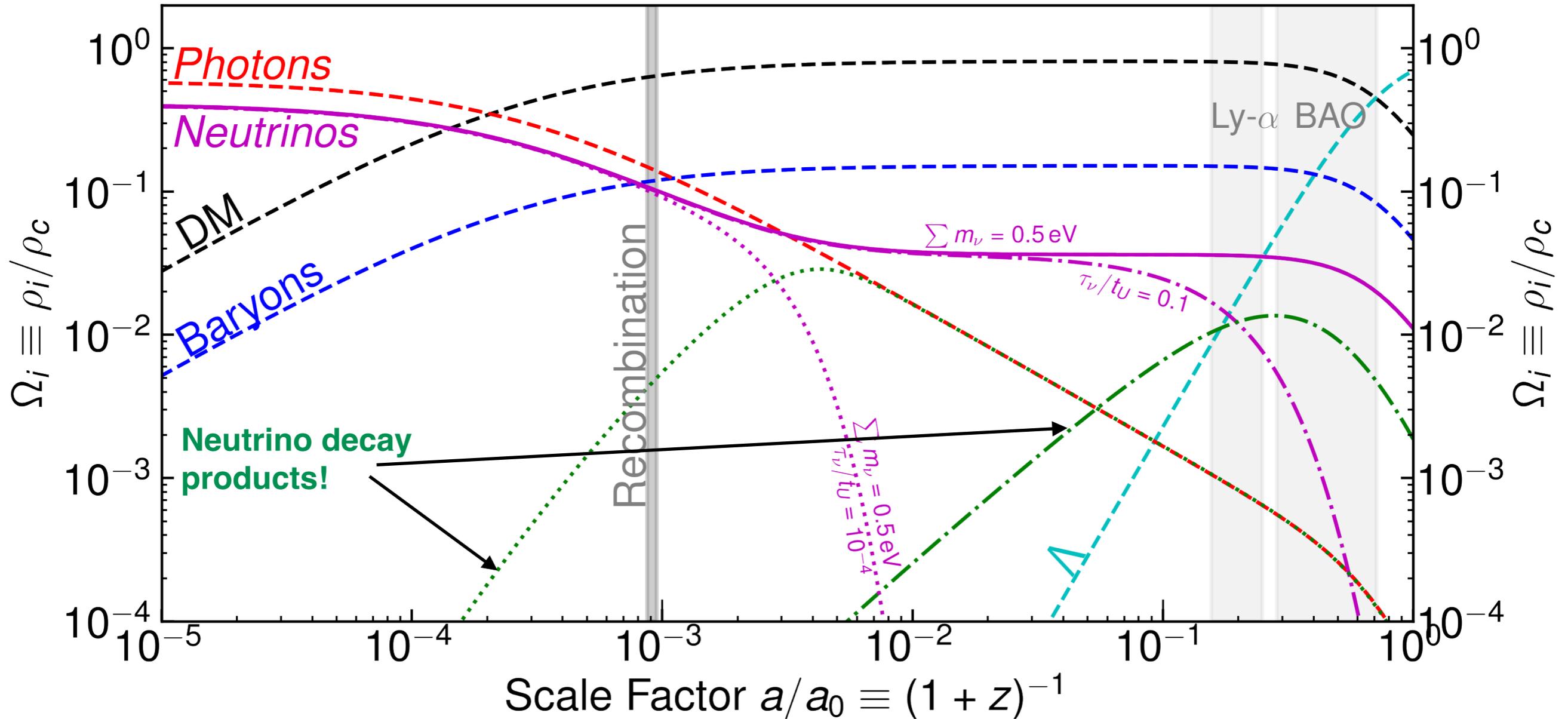


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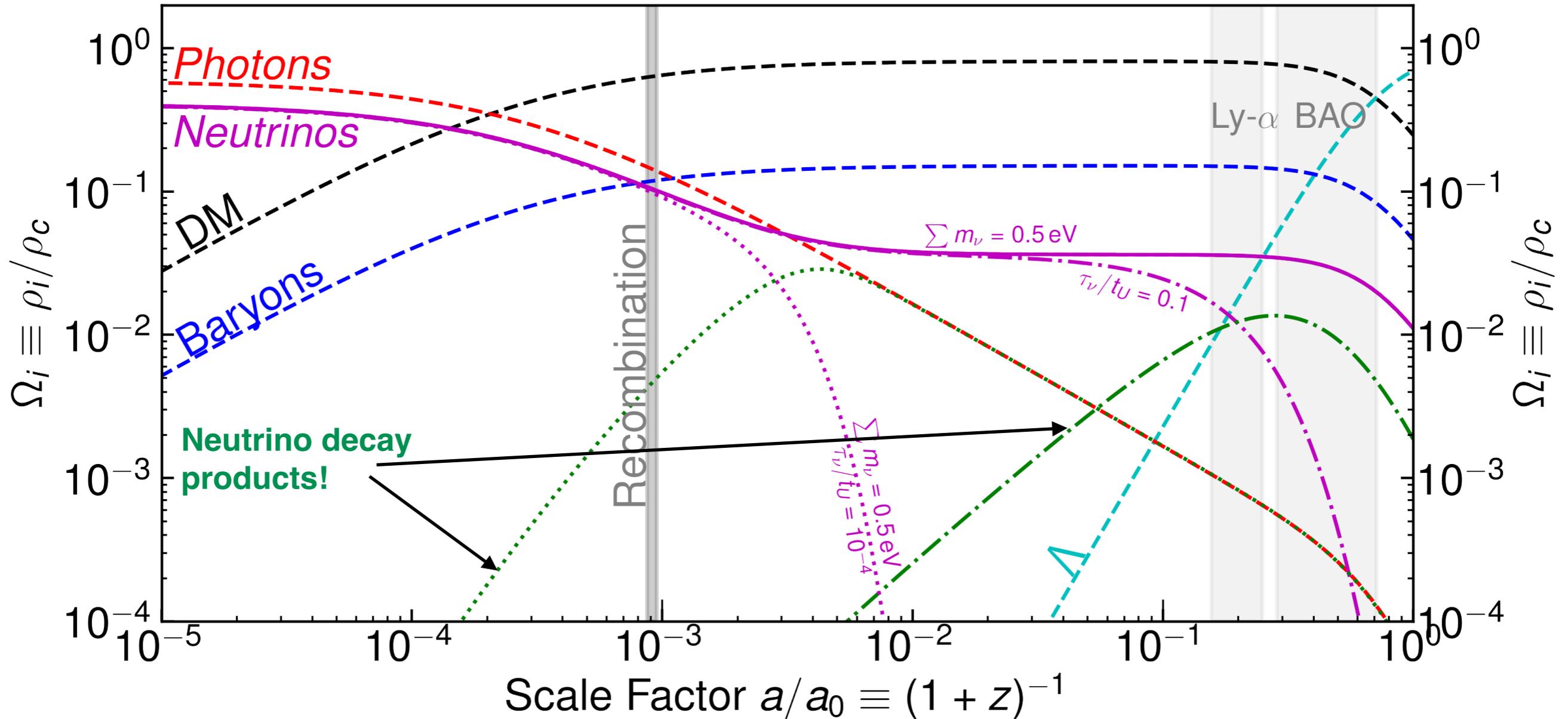
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Unstable Neutrinos can relax the bounds on Σm_ν !

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

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- 4) Cosmological bounds are cosmological model dependent, but given a cosmological model in some scenarios very strong constraints can be drawn**

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4) Cosmological neutrino masses are getting extremely strong. This is in part due to a small tension between CMB and BAO predictions on Ω_m and H_0

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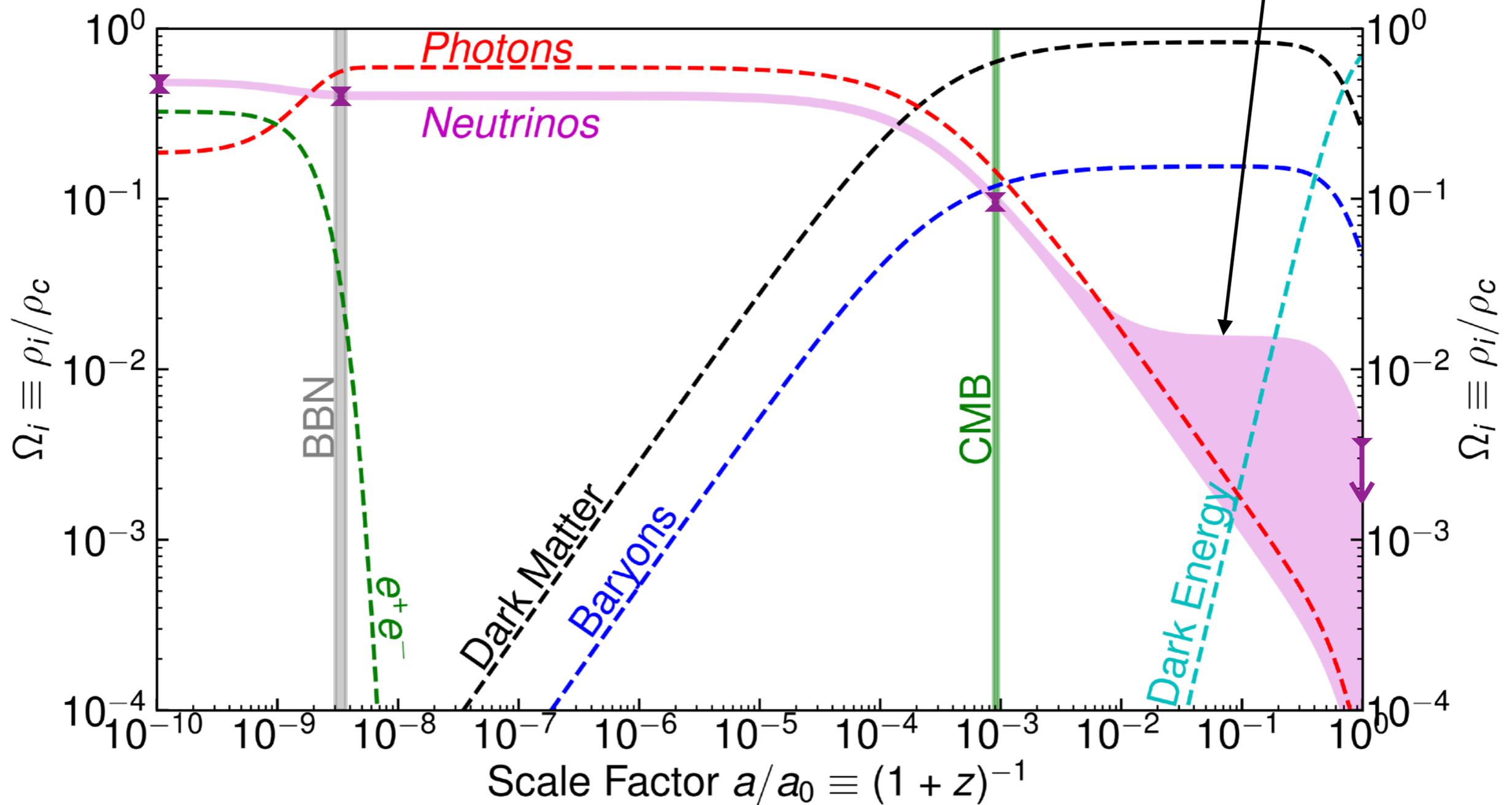
5) All cosmological neutrino mass bounds are cosmological model dependent. There are models which can be compatible with laboratory data even if the cosmological bound looks very stringent

Global Perspective

Current knowledge:

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

(Planck+BAO) $\sum m_\nu \lesssim 0.2 \text{ eV}$

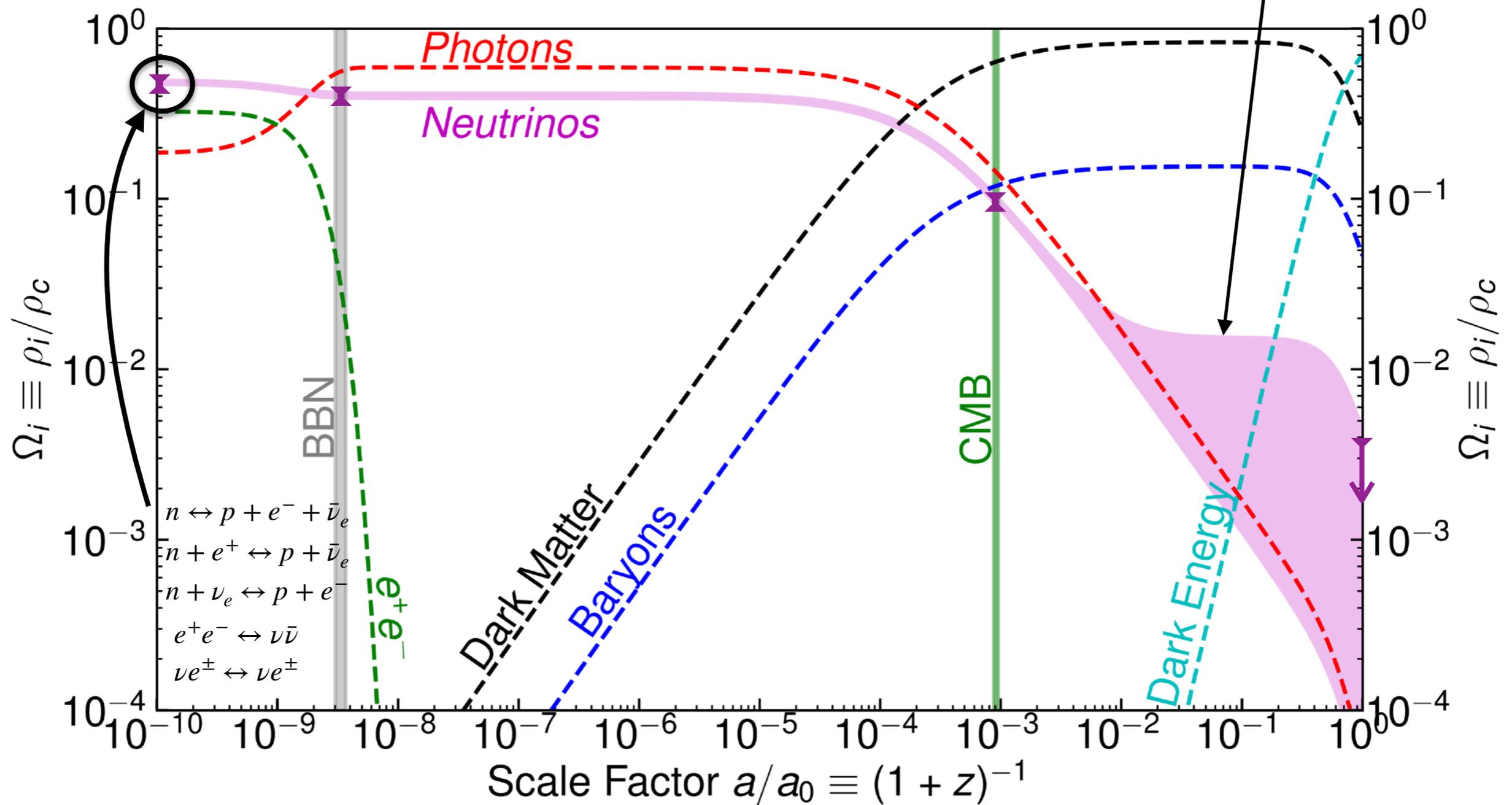


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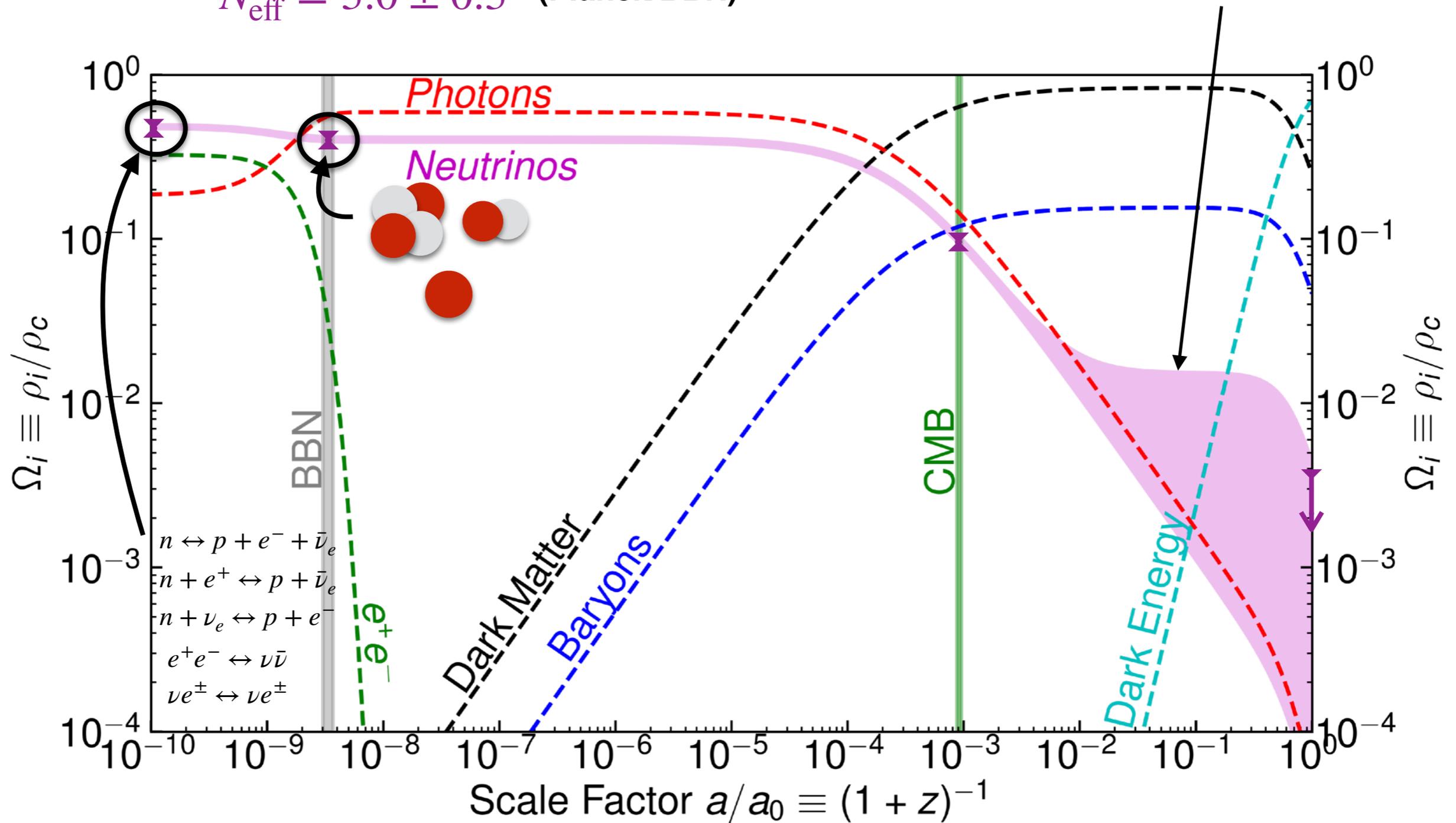


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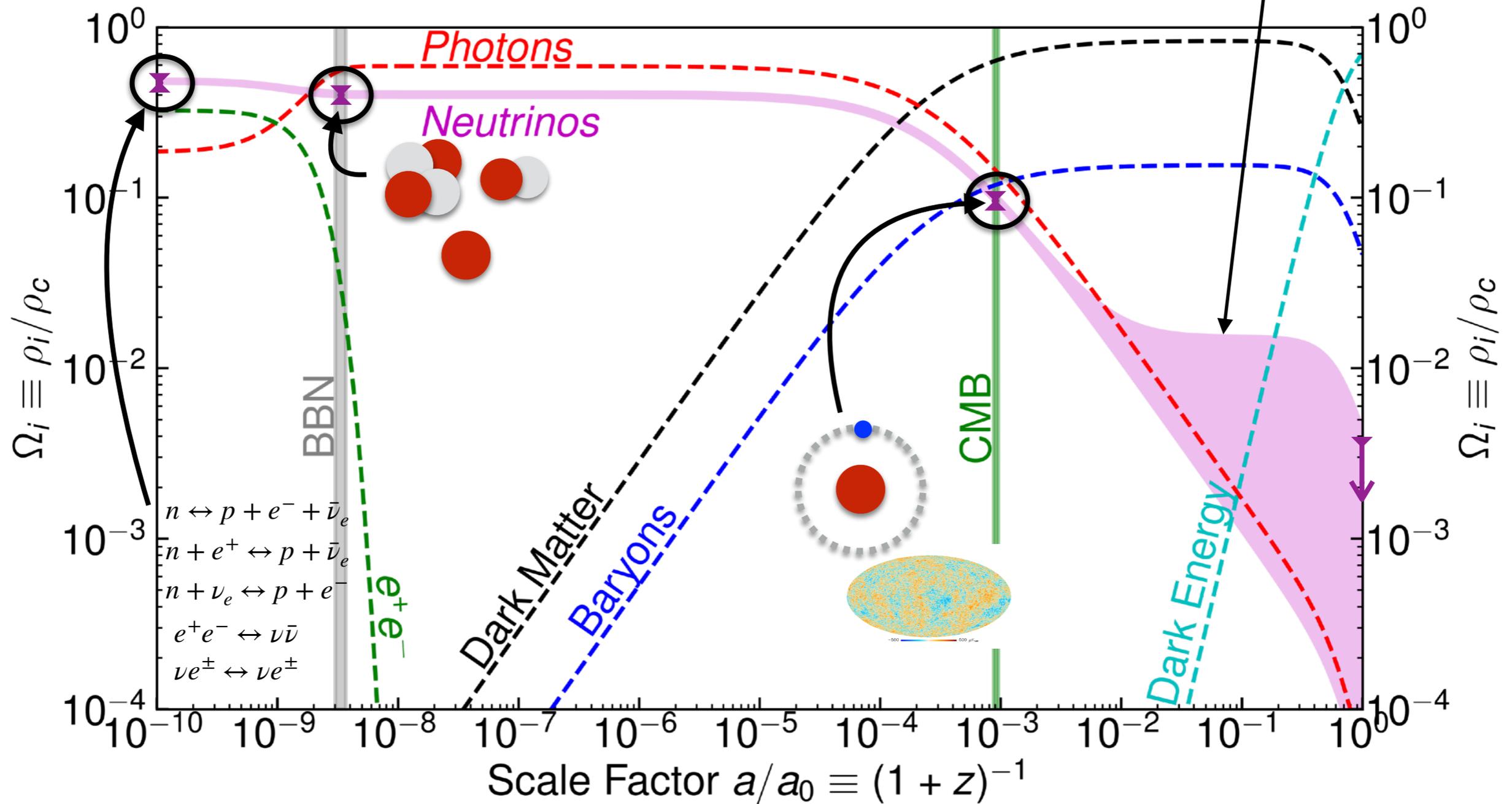


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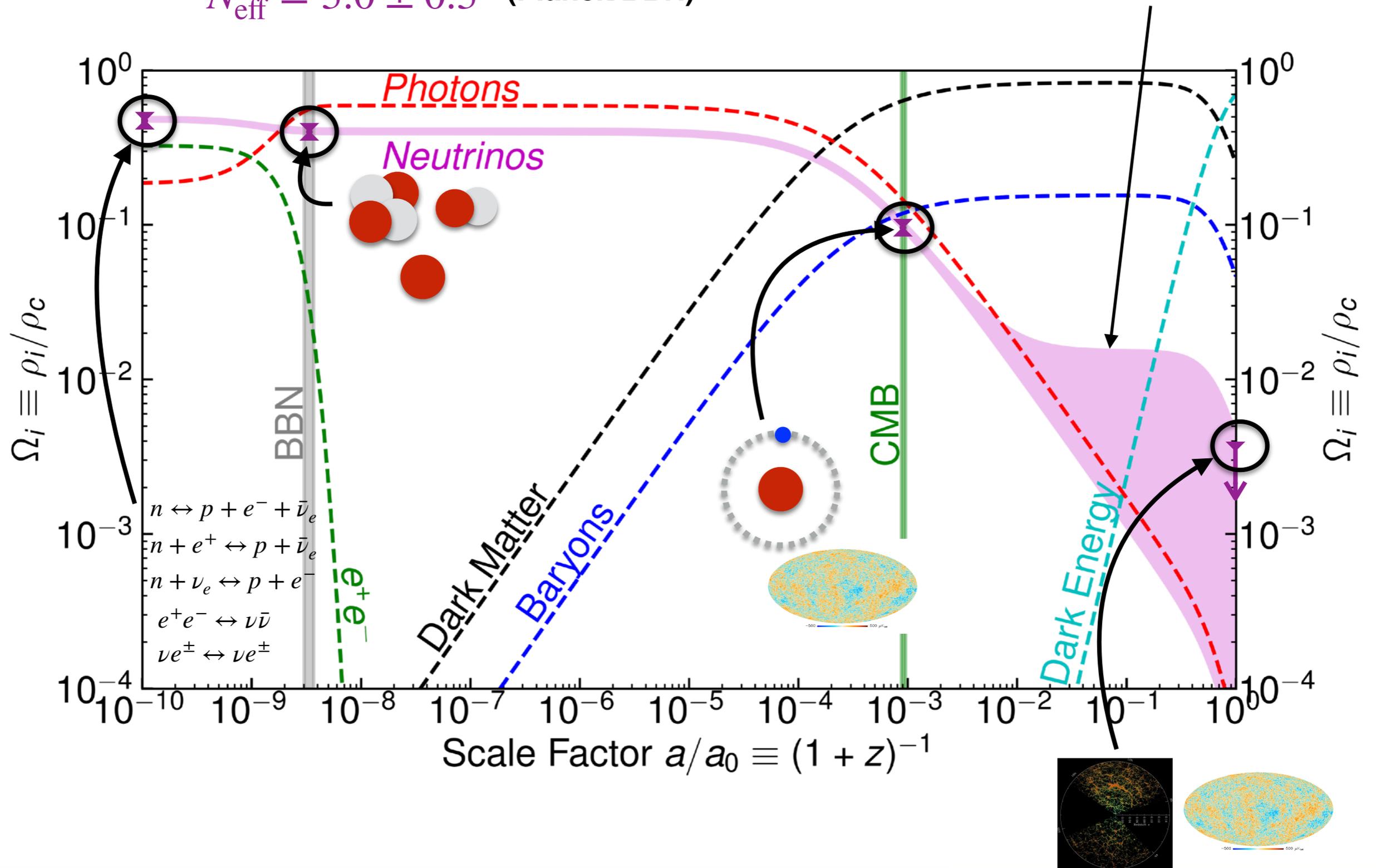


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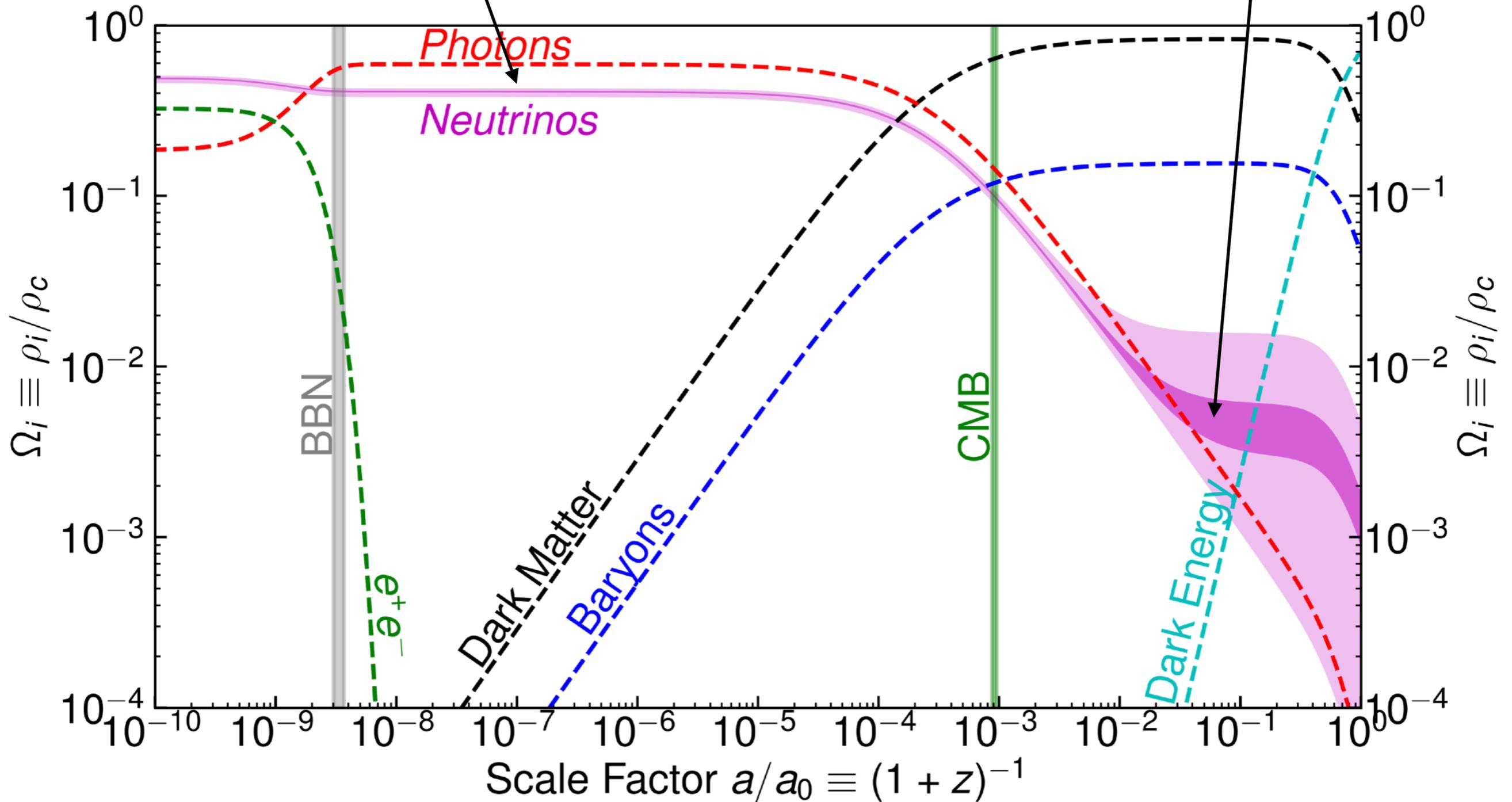
Global Perspective

In the next 5-6 years:

(DESI/Euclid + Planck)

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

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



Time for Questions and Comments



Thank you for your attention!

miguel.escudero@cern.ch

Back Up

Neutrino Masses from Cosmology

Data beyond Planck within Λ CDM

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Planck 1807.06209

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- **Planck+BAO drive current cosmological constraints [compare DESI and SDSS]**
- **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!)

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Not only the bounds are stringent but there is no sign for a non-zero neutrino mass!

Jiang et al. [2407.18047]

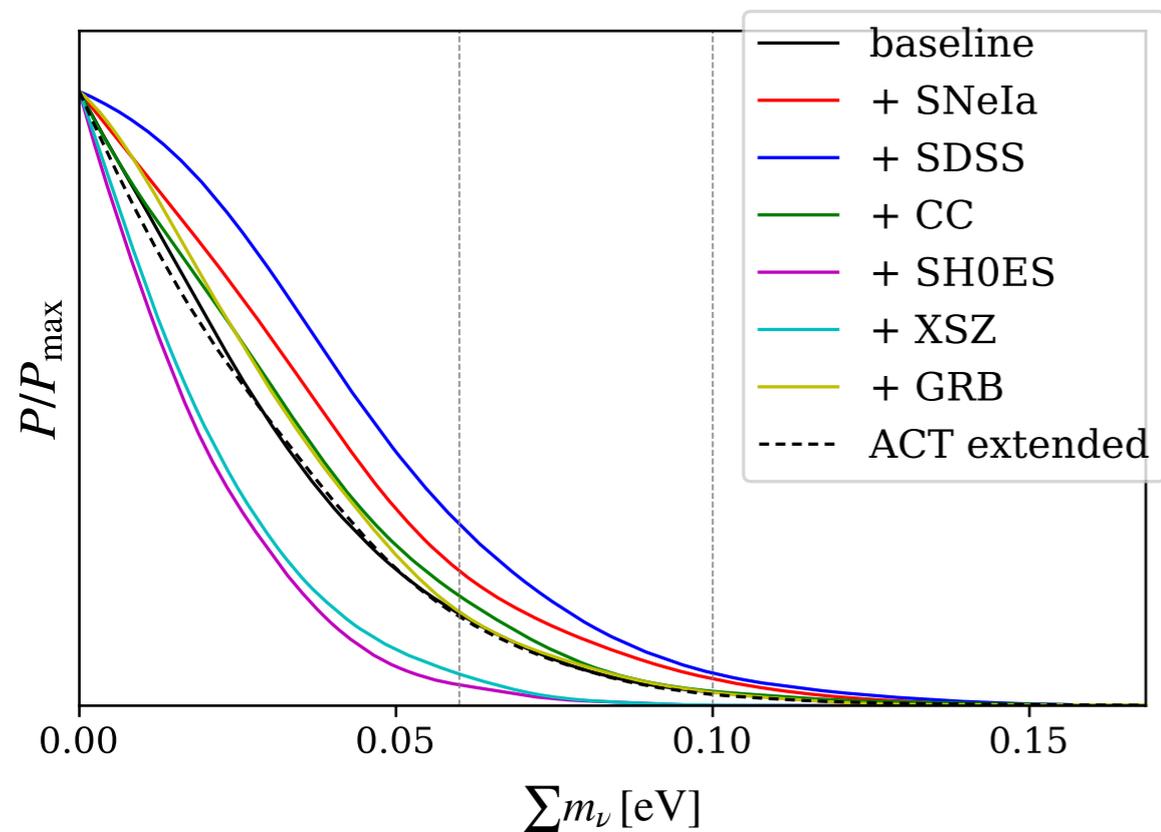
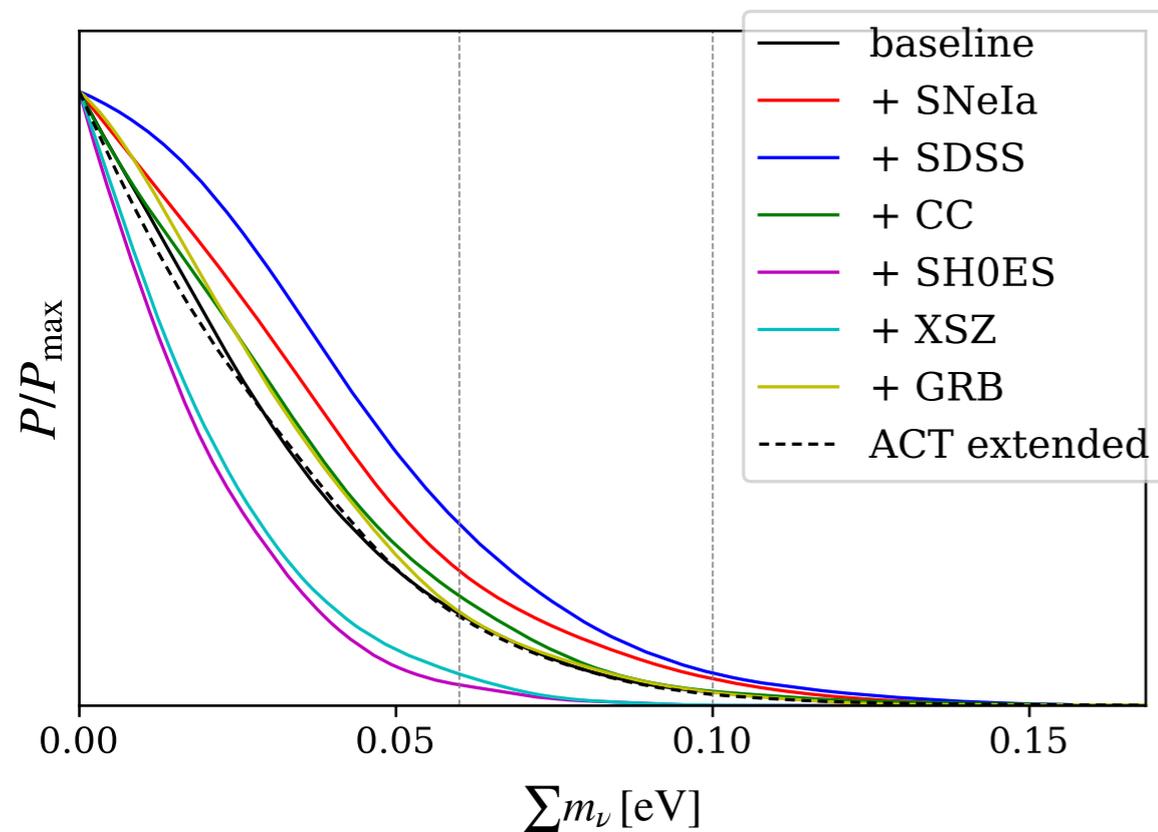


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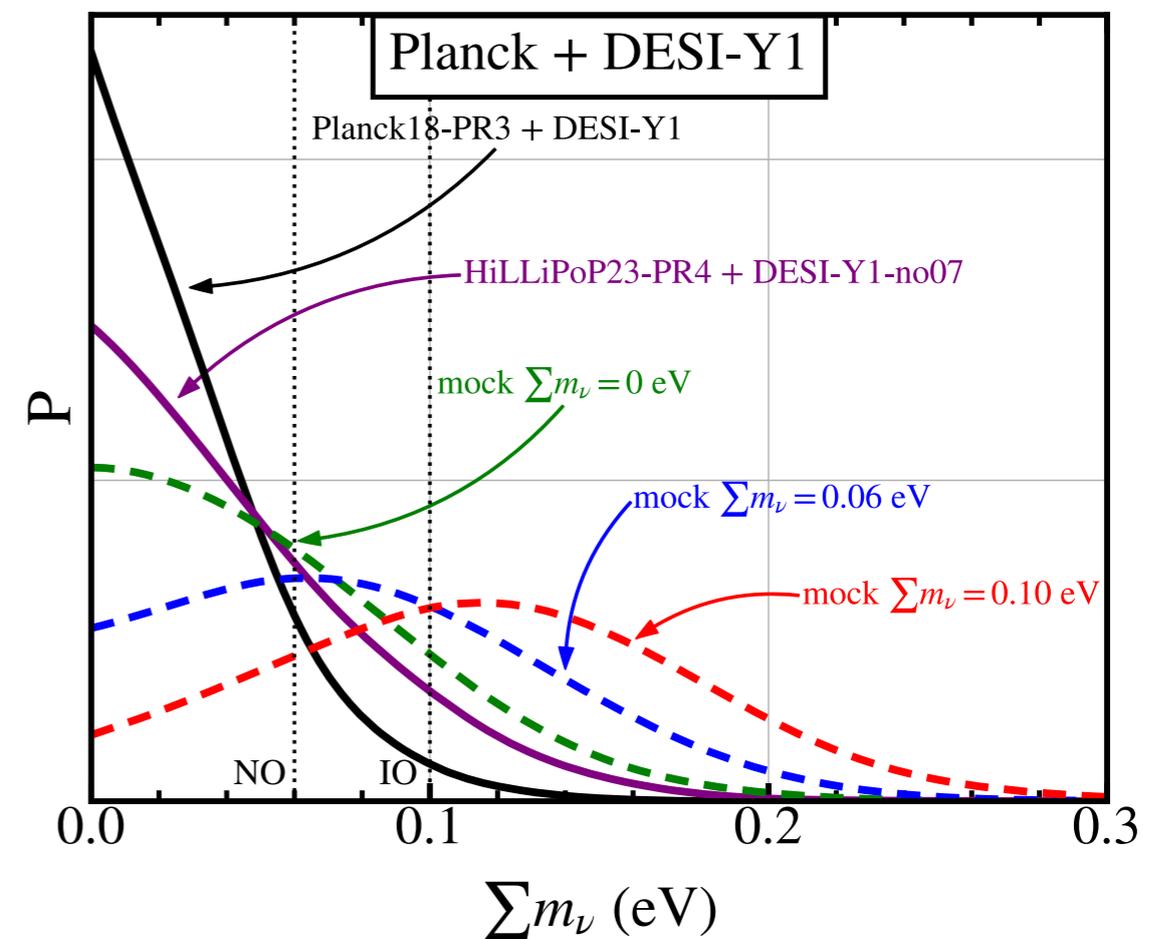


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1807.06209

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 $\sim 10\%$ improvement in most Λ CDM parameters in TTTEEE due primarily to improvements in polarization. For Λ CDM 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 Λ CDM 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 2018 data at high multipoles which could potentially have relevant implications for the neutrino mass constraints

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

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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see Tristan et al 2309.10034

With *Planck* PR4, we find results even more compatible with unity compared to previous releases. Indeed for TTTEEE, we now obtain

$$A_L = 1.039 \pm 0.052, \quad (35)$$

which is compatible with the Λ CDM expectation (at the 0.7σ level). As shown in Table 6, while the results for EE and TE

Neutrino Masses from Cosmology

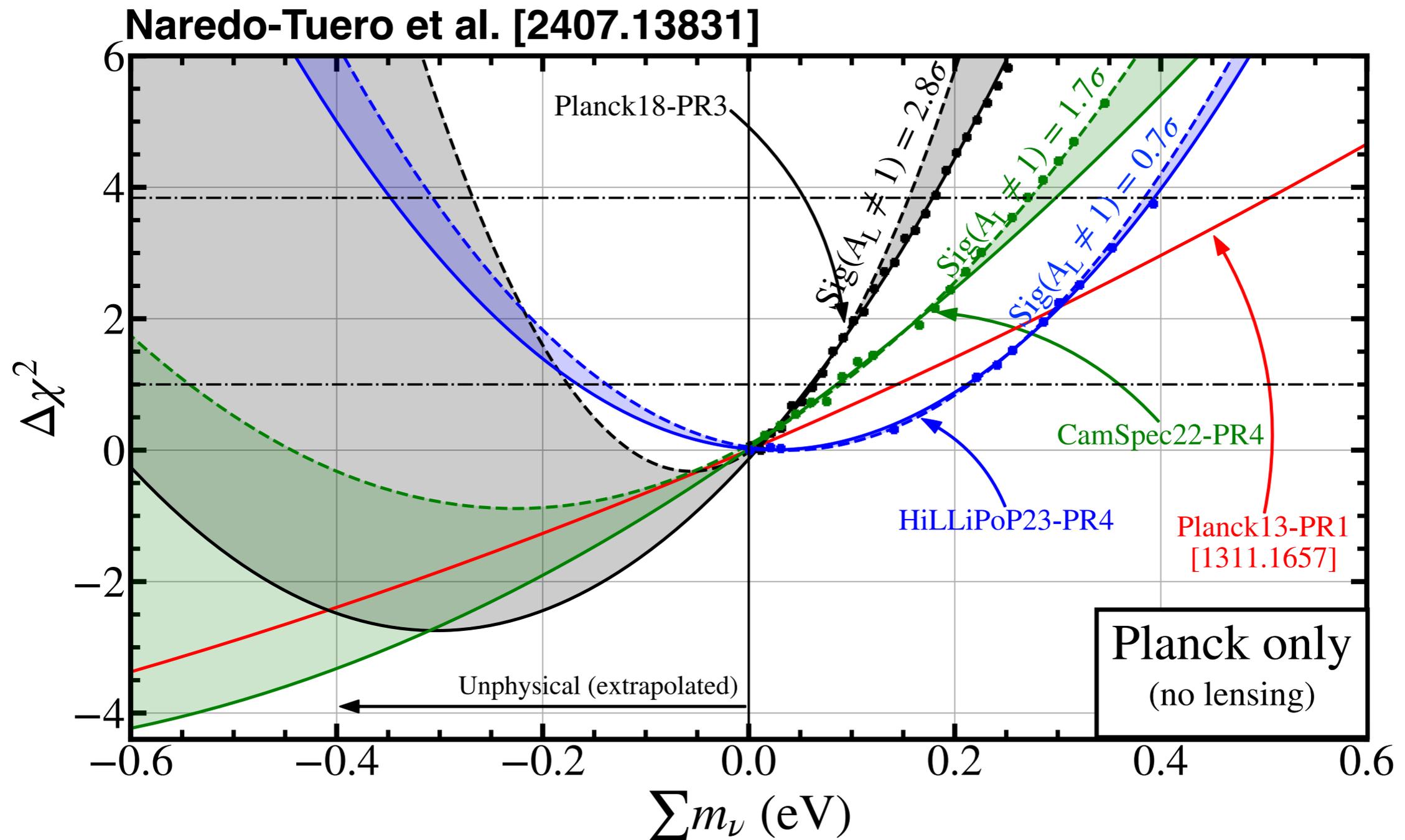
Neutrino masses and the Planck lensing anomaly

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

Neutrino Masses from Cosmology

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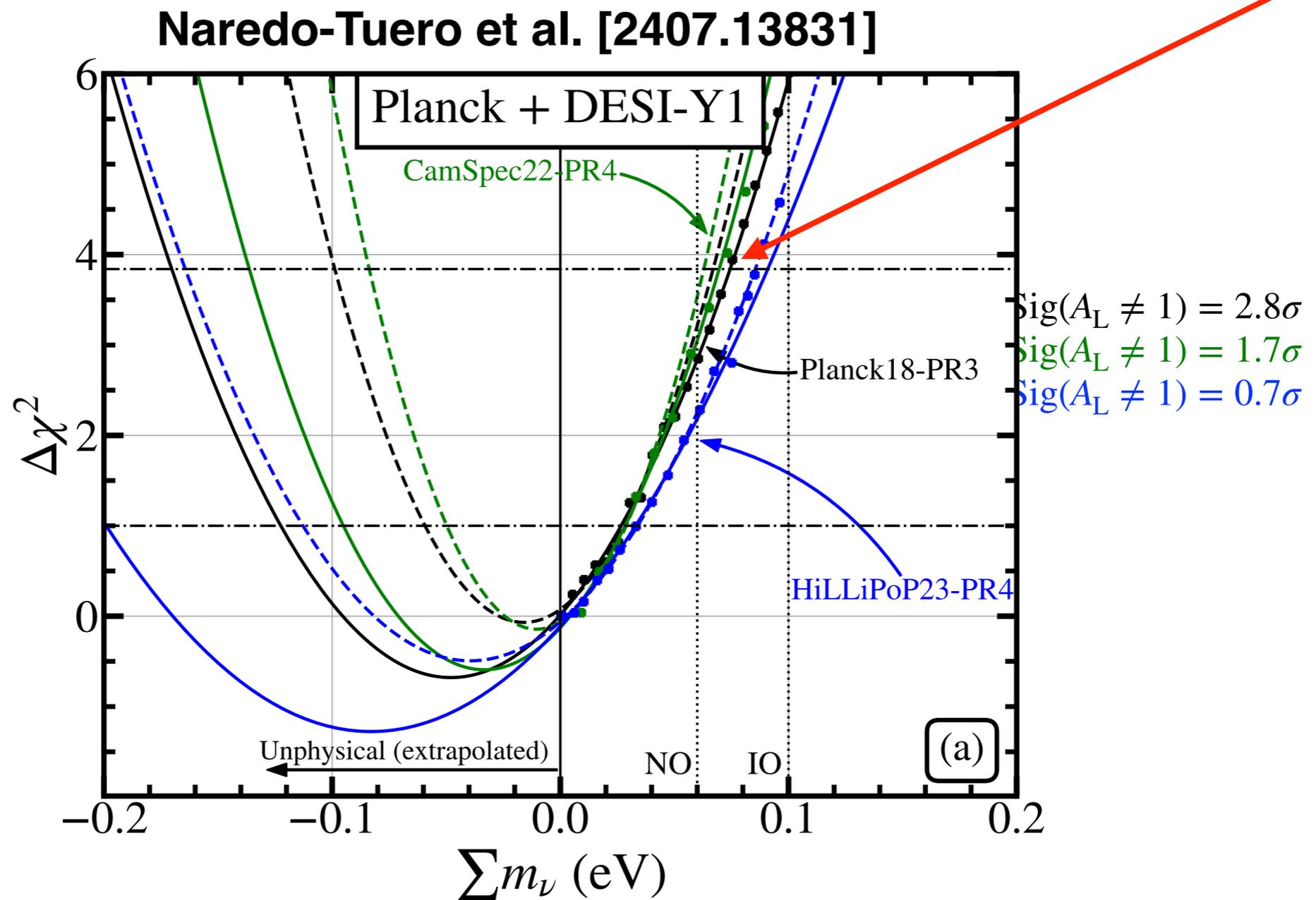
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Neutrino Masses from Cosmology

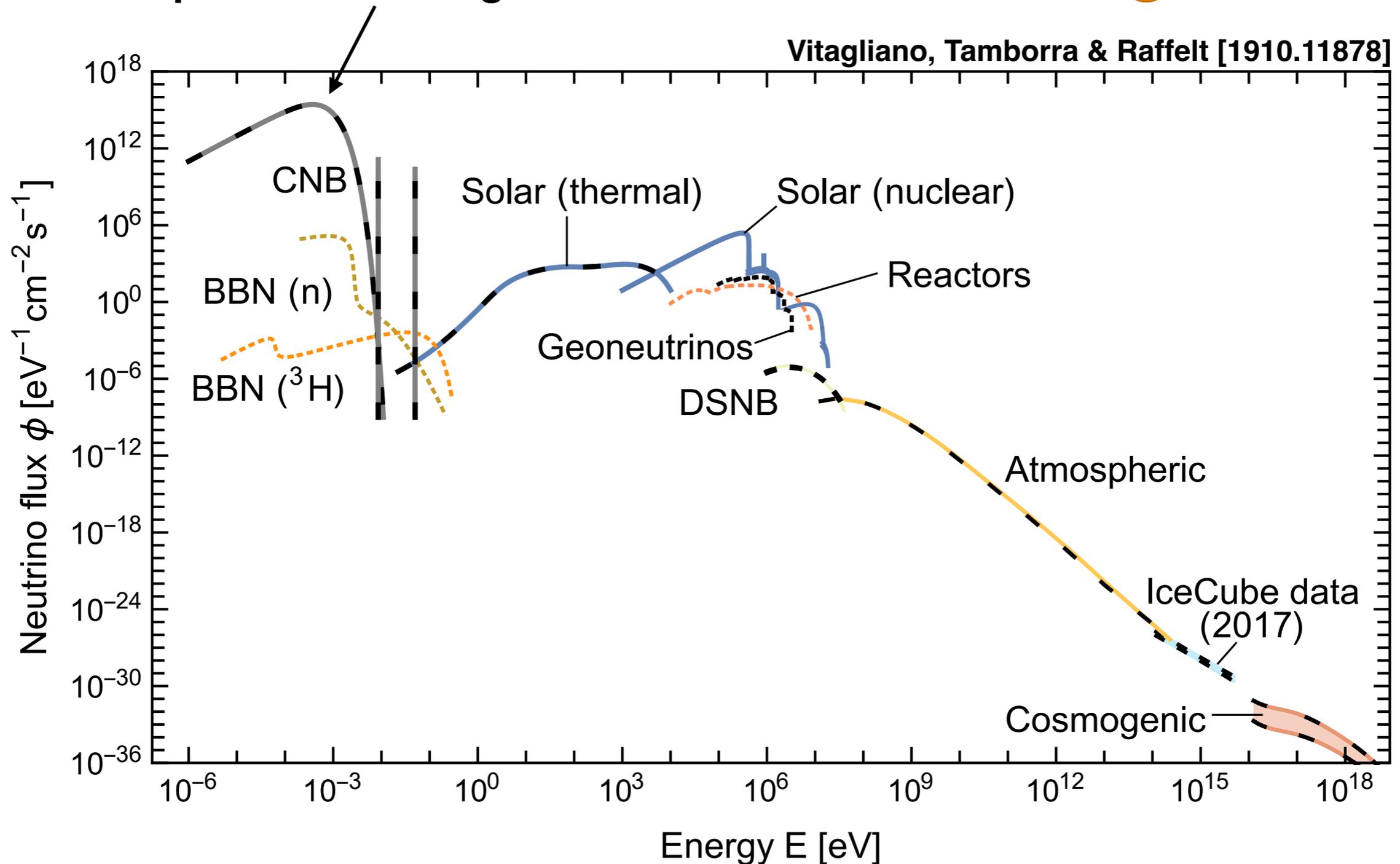
Neutrino masses and the Planck lensing anomaly

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



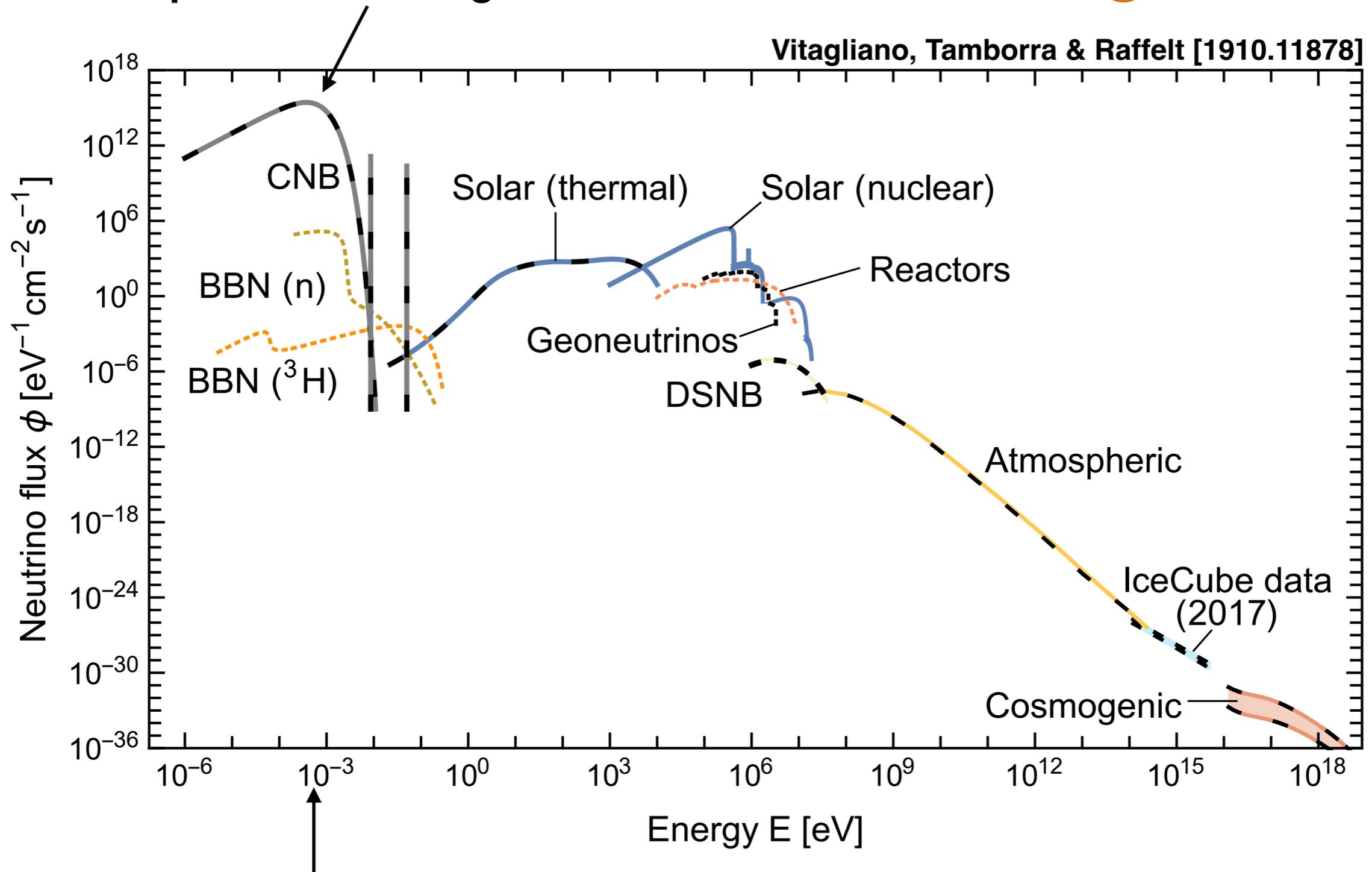
CNB Detection?

The CNB represents the largest flux of neutrinos on Earth! 😊



CNB Detection?

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However, they are very low energetic 😞