BSM Neutrino Cosmology

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Neutrino Conference
25-07-2025

Neutrino Evolution

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

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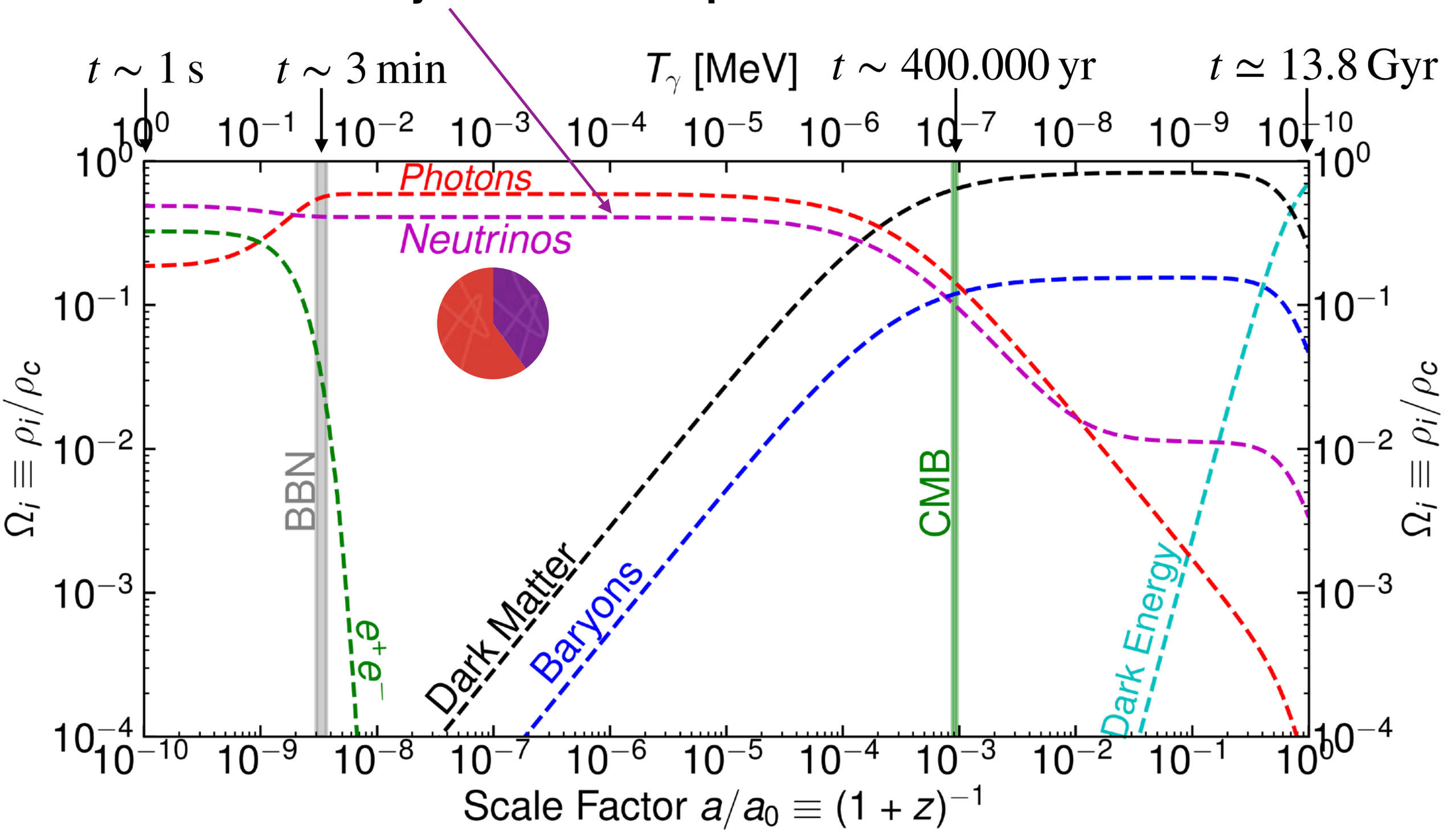


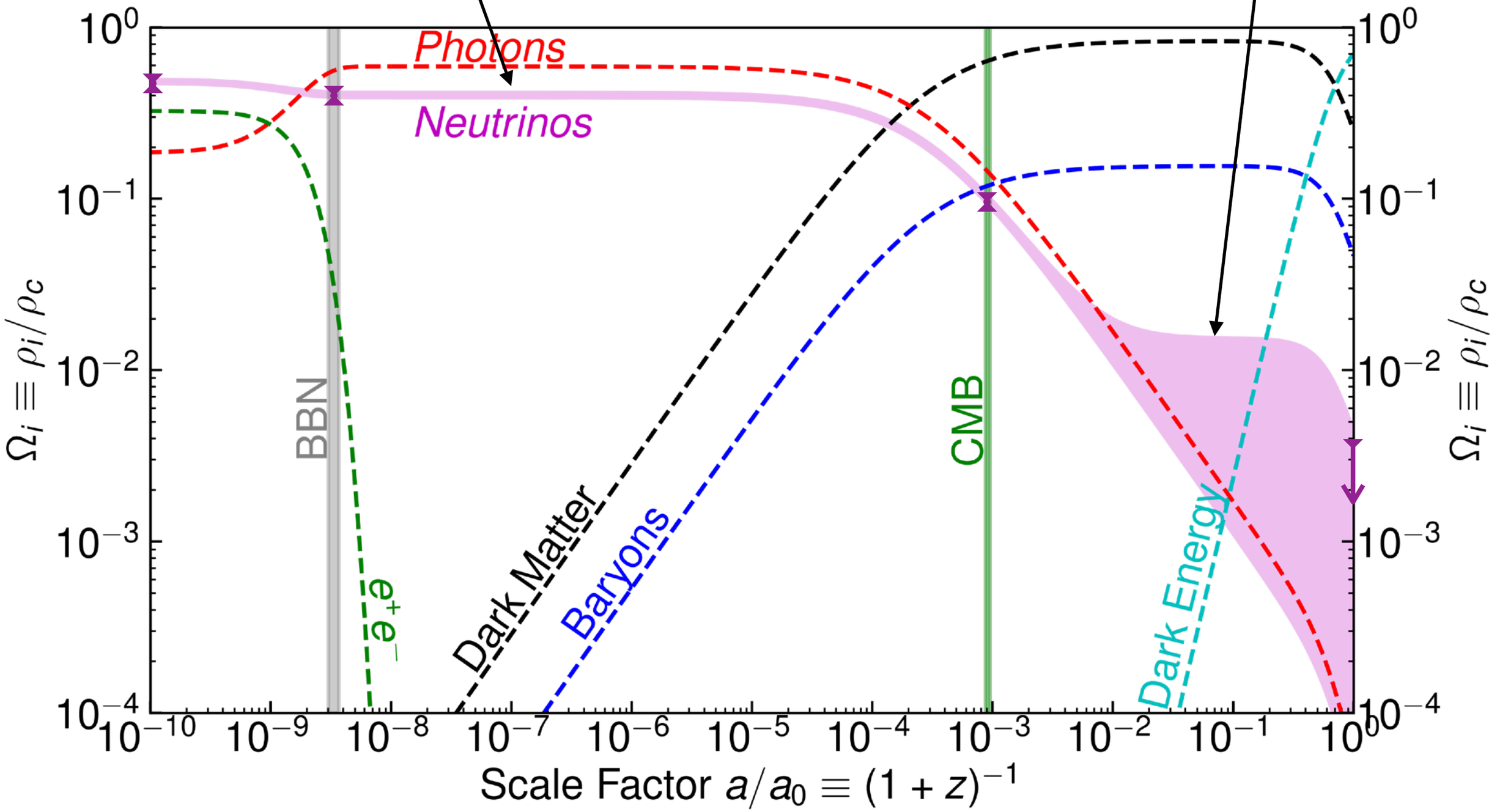
Global Perspective

The post-Planck era

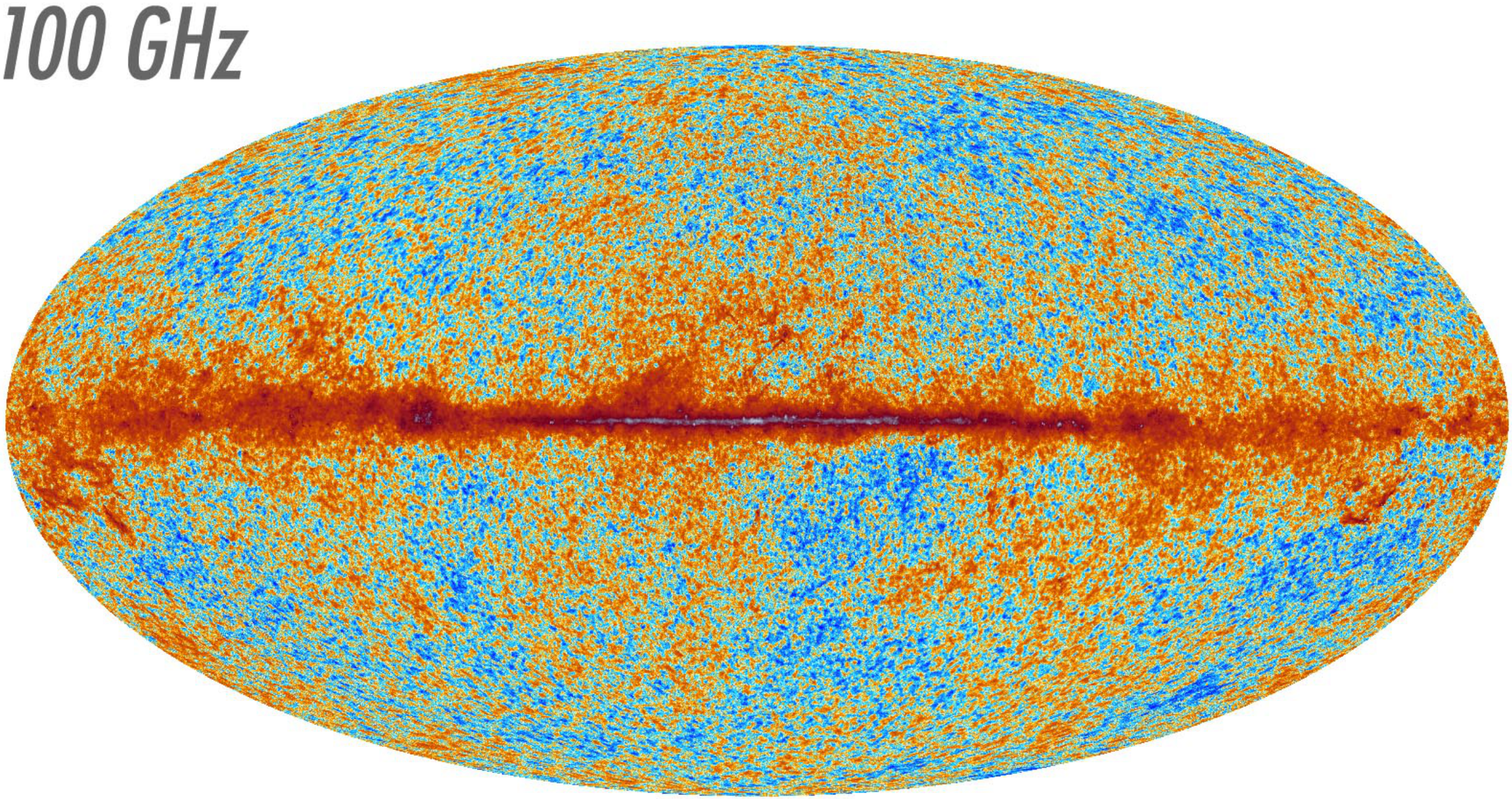
$N_{\rm eff} = 3.0 \pm 0.3$ **(Planck/BBN)**

(Planck+BAO)

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



Planck's Temperature Map



Planck E
frequency coadd

New cosmological data to the rescue!

Adrien La Posta [Atacama Cosmology Telescope]:
https://indico.in2p3.fr/event/33627/contributions/154706/

26°×14°

ACT+Planck E
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[released three months ago!]

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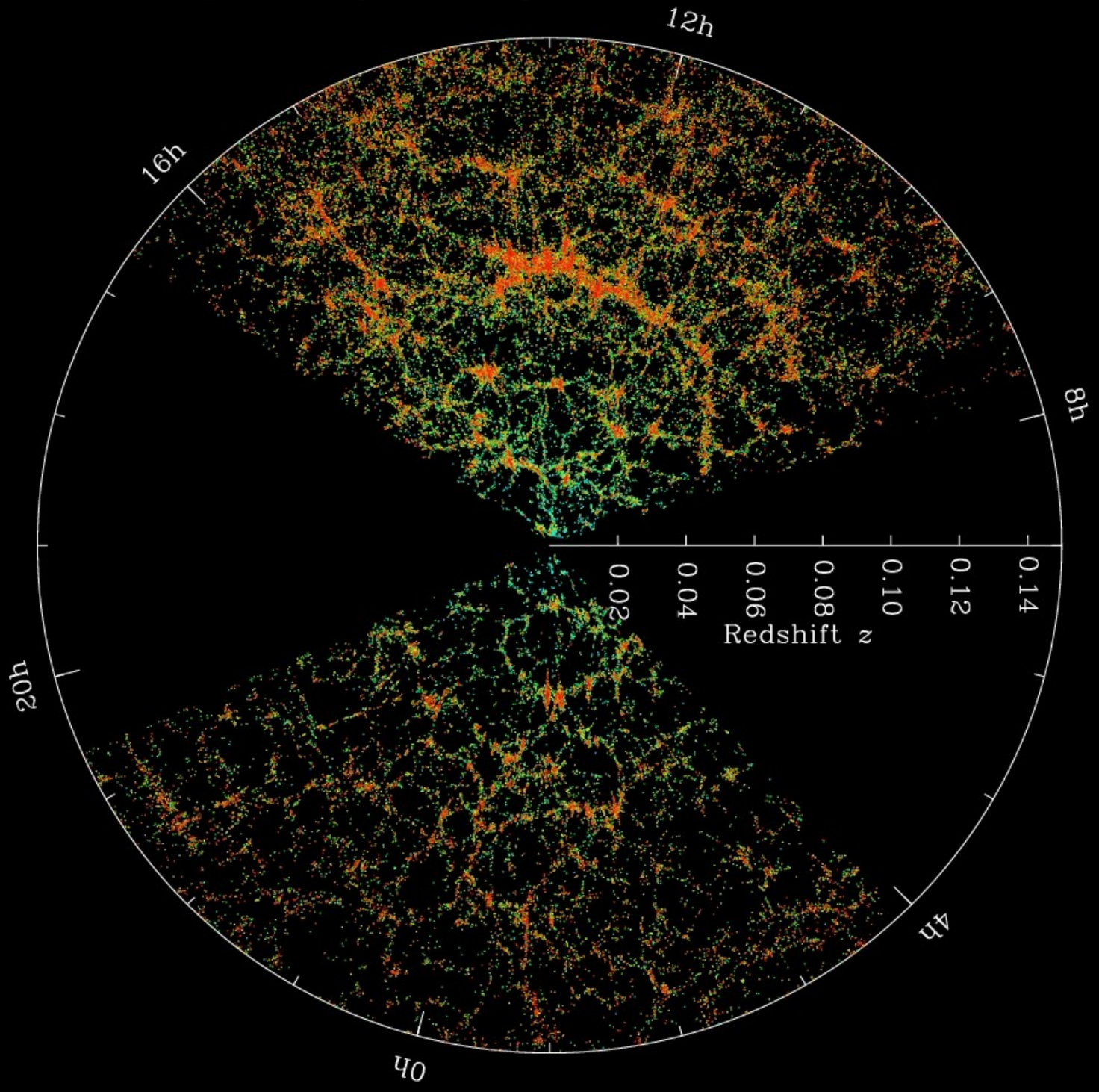
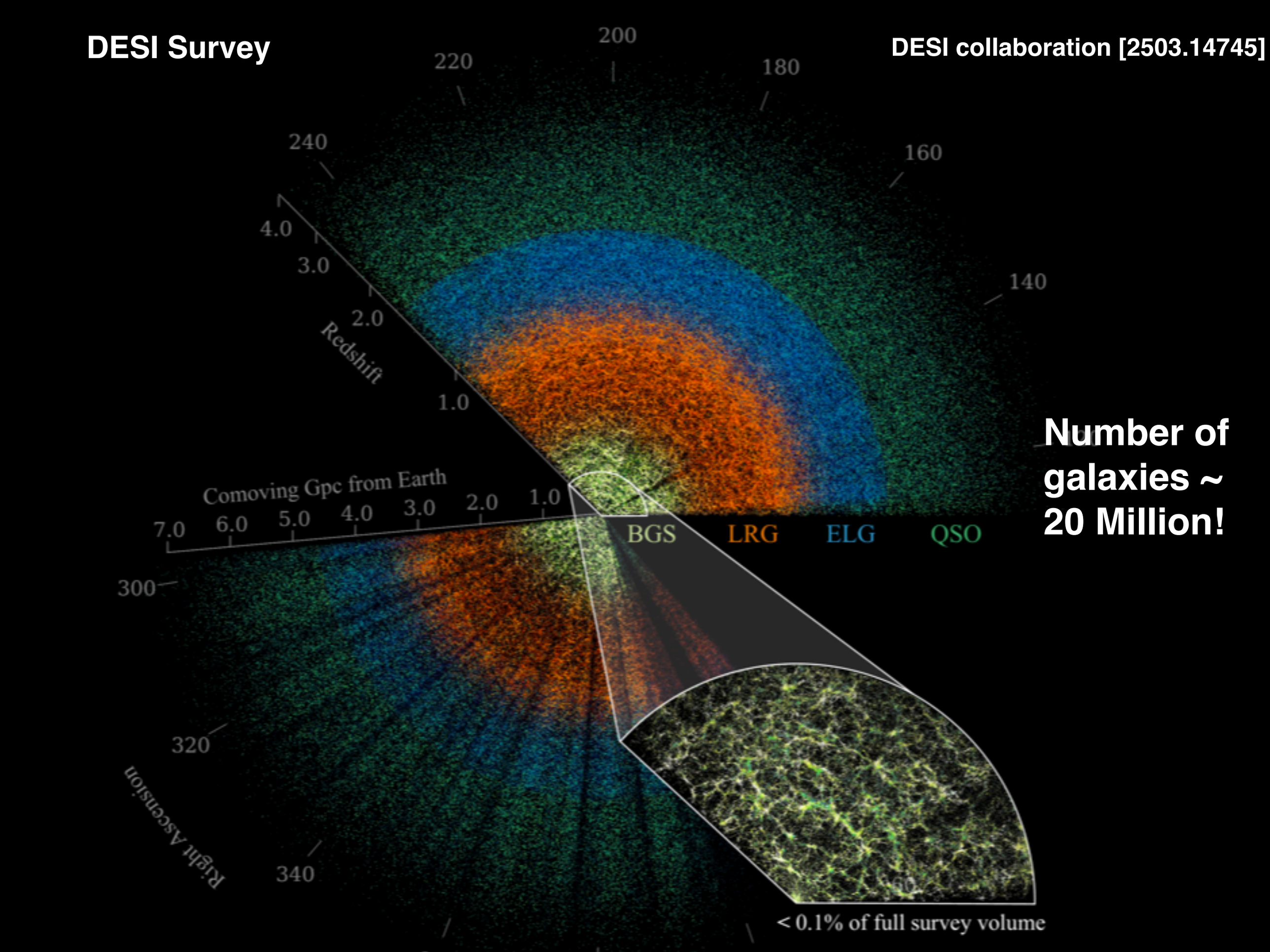
Sloan Digital Sky Survey



Number of galaxies ~ 4 Million!

DESI Survey

DESI collaboration [2503.14745]



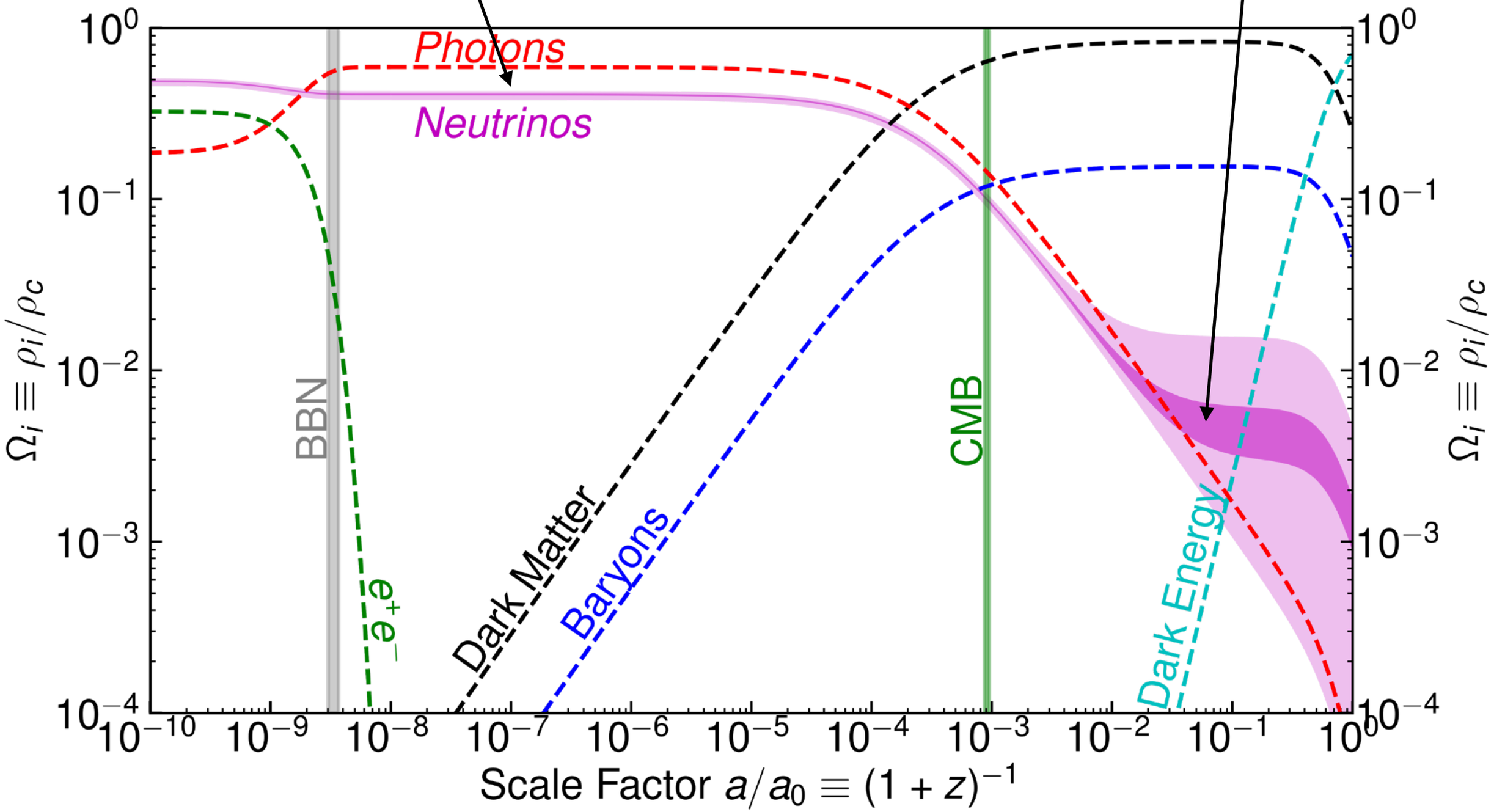
Number of galaxies ~ 20 Million!

Global Perspective

What we expected:

$N_{\rm eff} = 3.0 \pm 0.1$ **(ACT/SPT+Planck)**

$\sum m_\nu = 0.06 \pm 0.02\,\text{eV}$ **(DESI/Euclid + Planck)**



Global Perspective

Today

$$\sum m_\nu < 0.048\,\text{eV}$$

95% CL
ACT+SPT+Planck+DESI-DR2 [2506.20707]

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tension: $\sim 3\sigma$

$$\sum m_\nu > 0.06\,\text{eV} \quad [\text{NO}]$$

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Global Perspective

Today

$$N_{\rm eff} = 2.81 \pm 0.12$$

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Global Perspective

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$$N_{\rm eff} = 2.81 \pm 0.12$$

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$$N_{\rm eff}^{\rm SM} = 3.044$$

$$\sum m_\nu < 0.048\,{\rm eV}$$

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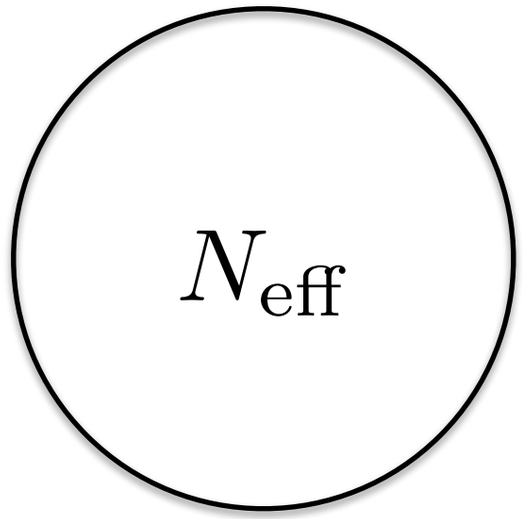
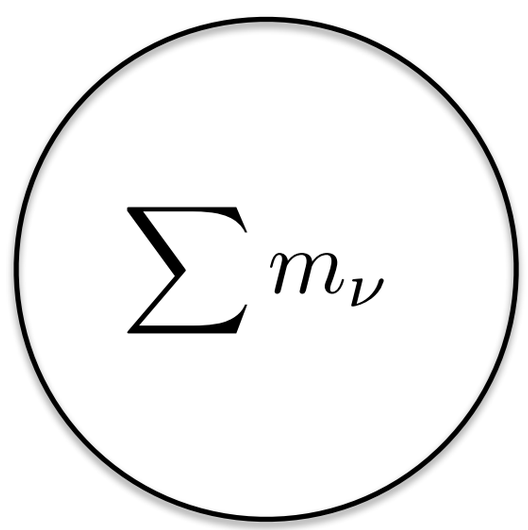
Outline

BSM scenarios for $N_{\rm eff} < 3$



BSM scenarios for $\sum m_\nu \Big|_{\rm Cosmo} = 0$



Neff definition

Neff as relevant for CMB observations is defined as:

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

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In the Standard Model this is precisely proportional to ρ_ν and one gets

$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_\nu}{\rho_\gamma}\right) \qquad \boxed{N_{\rm eff} = 3.044}$$

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Escudero Abenza 2001.04466
Akita & Yamaguchi 2005.07047
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To reduce either the neutrinos need to go down or the photons up!

Neff < 3 options: $\rho_\nu \downarrow$

Late time reheating:

Kawasaki, Kohri & Sugiyama [astro-ph/9811437, astro-ph/0002127
Giudice, Kolb & Riotto [hep-ph/0005123]
more recent papers:
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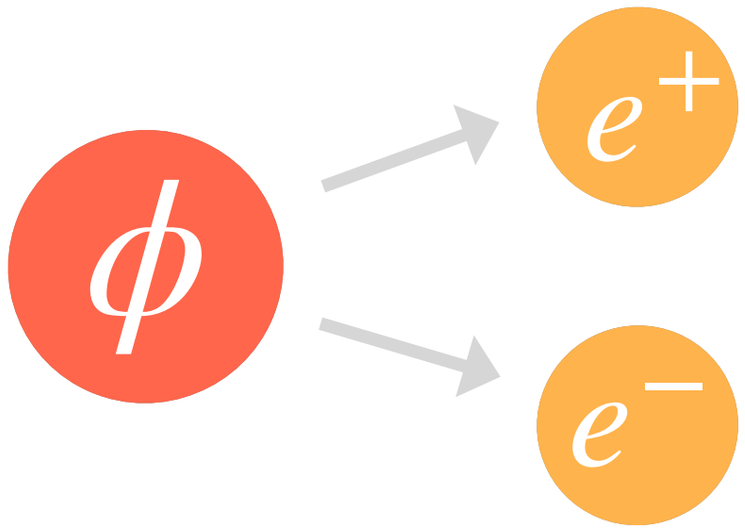
An inflation-like particle reheats the entire Universe very close to BBN before neutrinos decouple at 2 MeV



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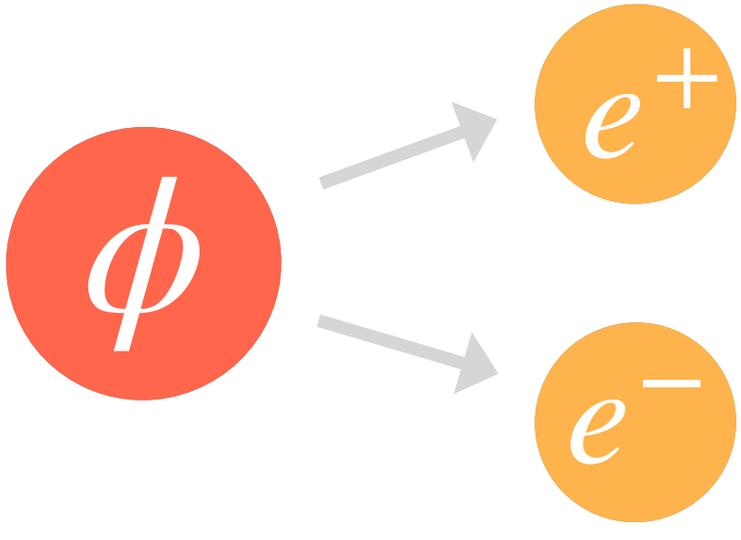

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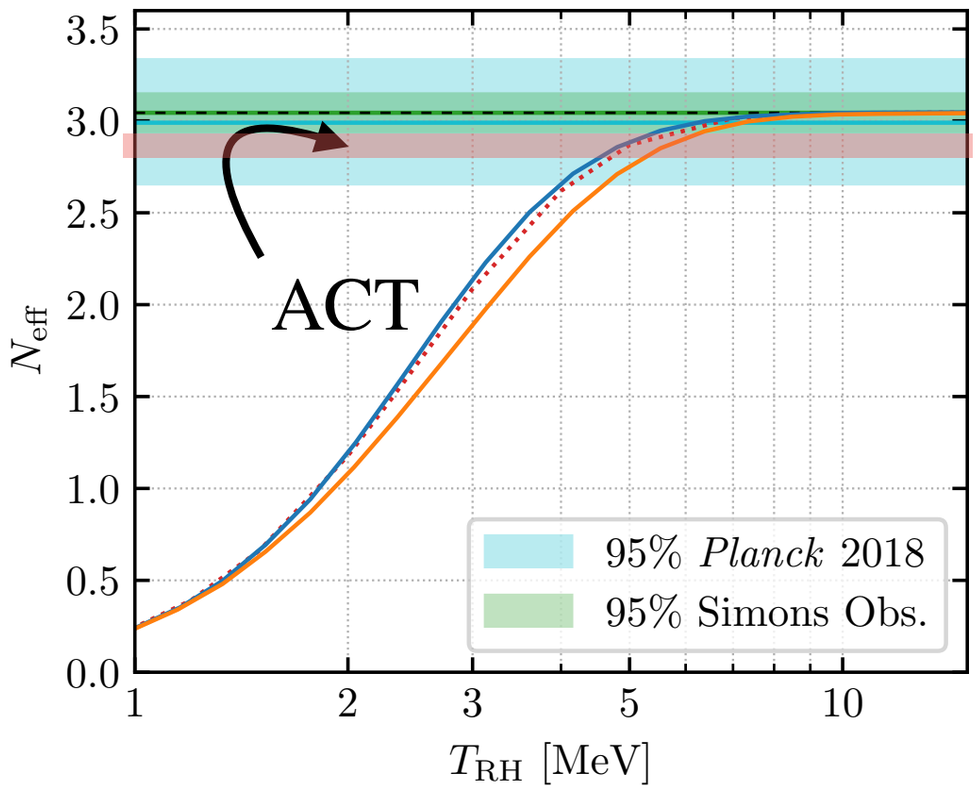

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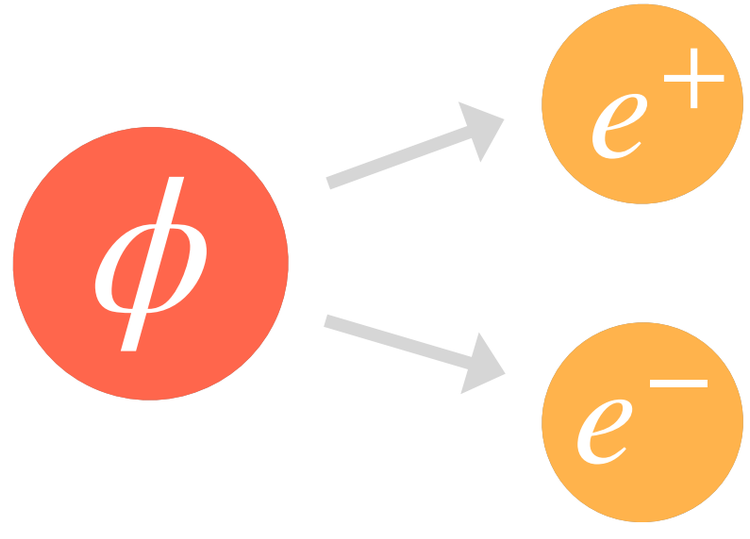
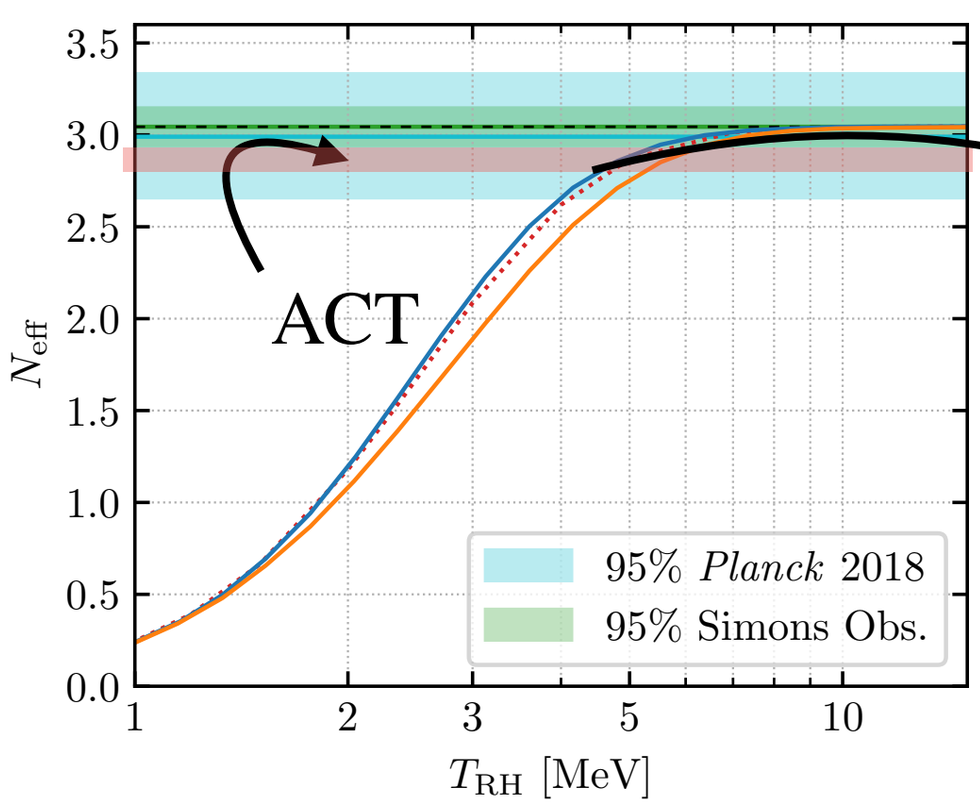
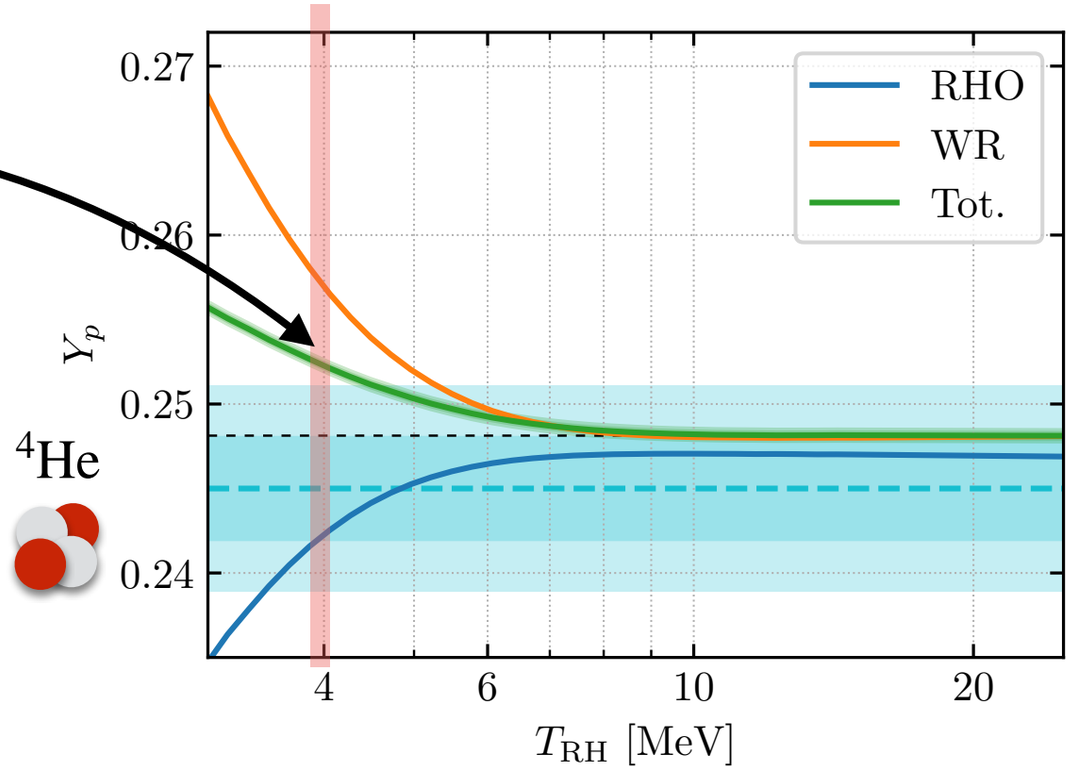


Barbieri et al. [2501.01369] **problem/probe -> BBN typically spoiled**





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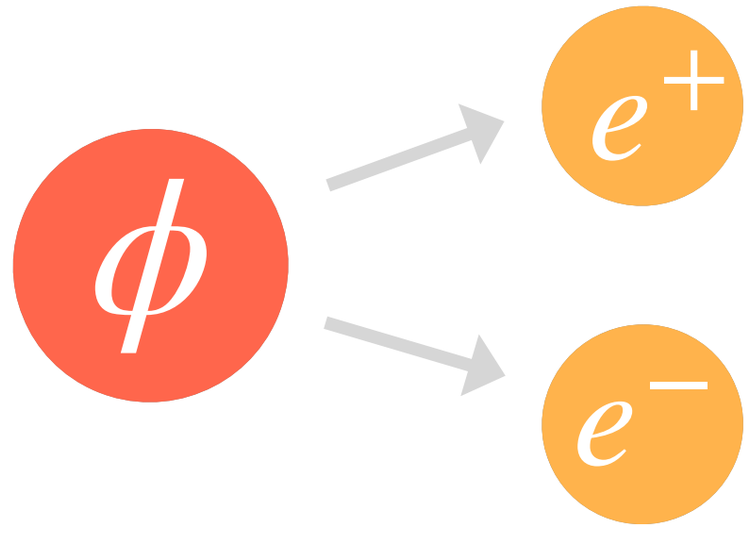

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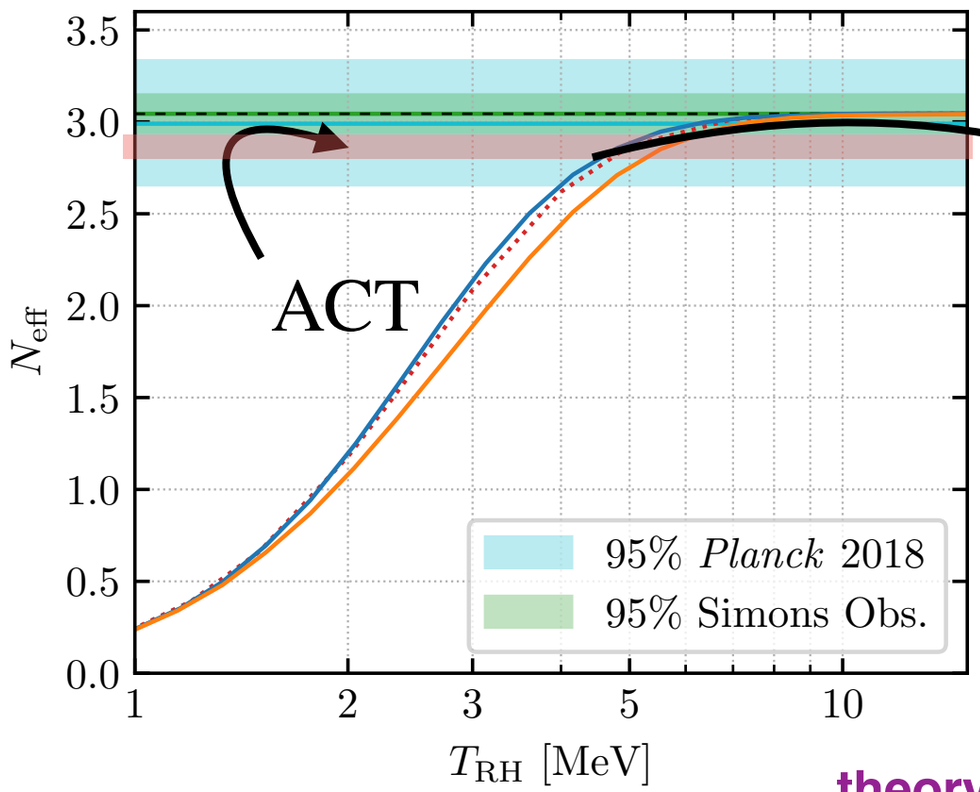
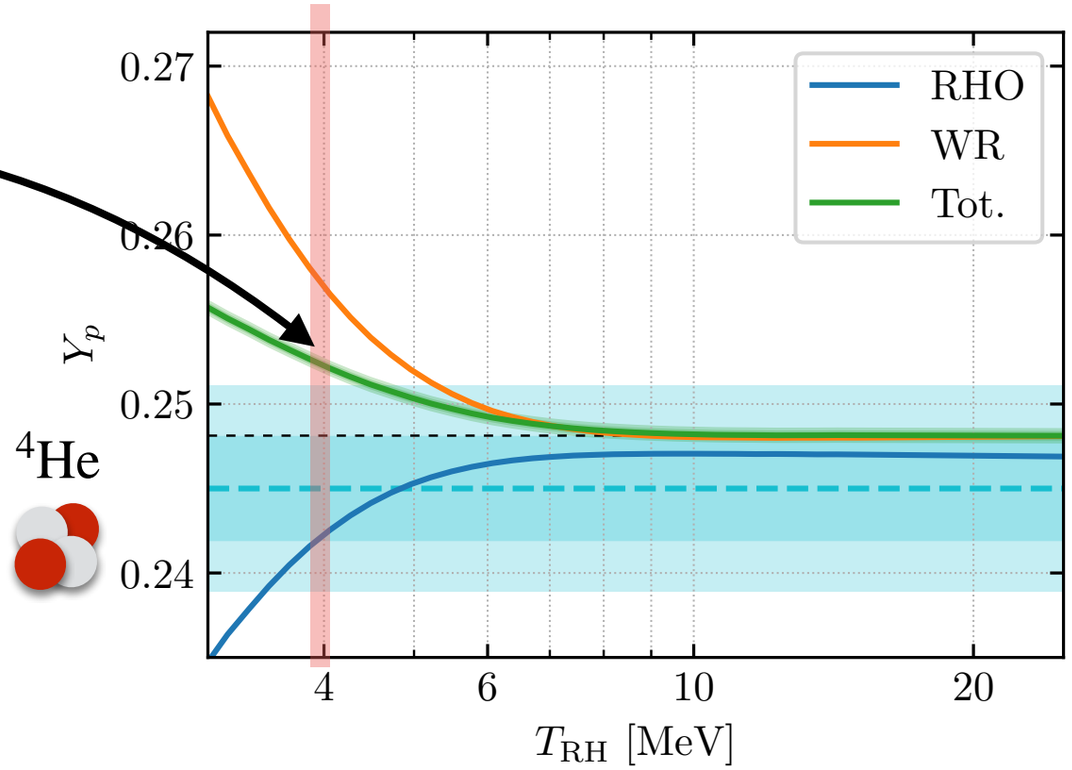




theory: hard to build, but see Elor, Escudero & Nelson [1810.00880]

Neff < 3 options: $\rho_\gamma \uparrow$

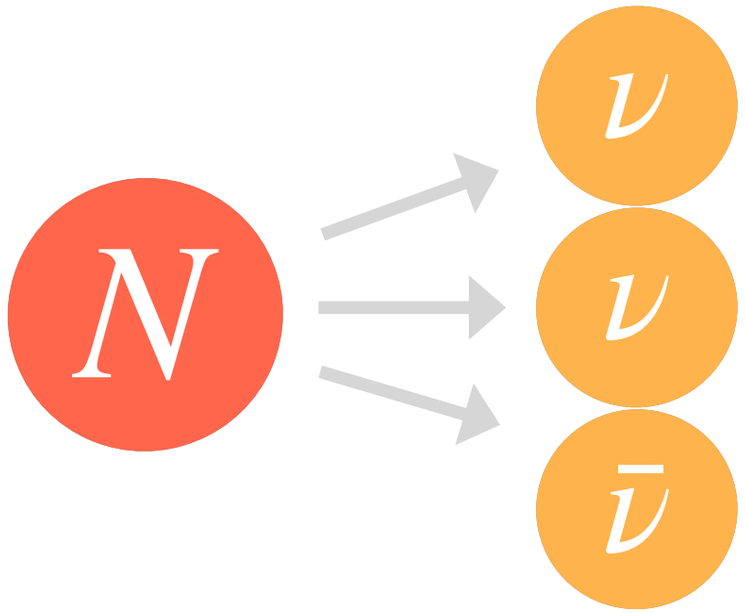
Particles decaying at BBN times

Boyarsky, Ovchynnikov, Ruchayskiy, Syvolap [2008.00749]

Boyarsky, Ovchynnikov, Sabti, Syvolap [2103.09831]

Ovchynnikov, Syvolap ++ [2409.07378, 2409.15129, 2411.00892]

Example: sterile neutrinos



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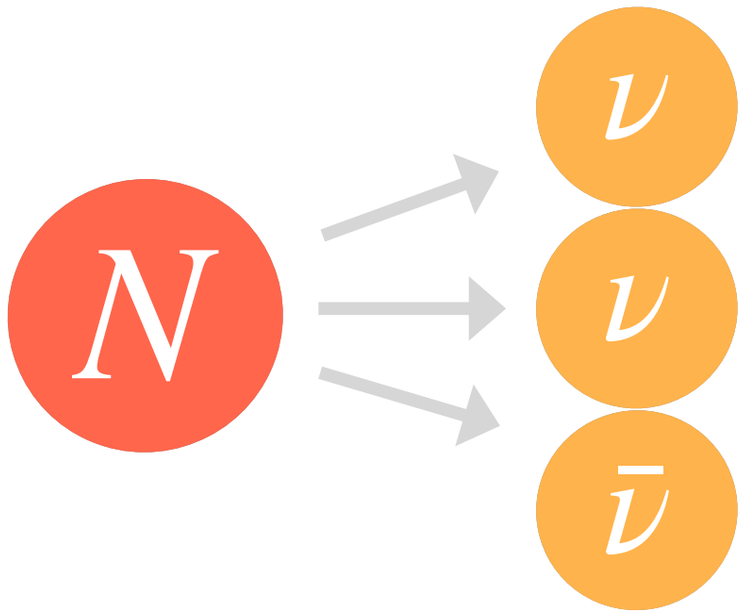
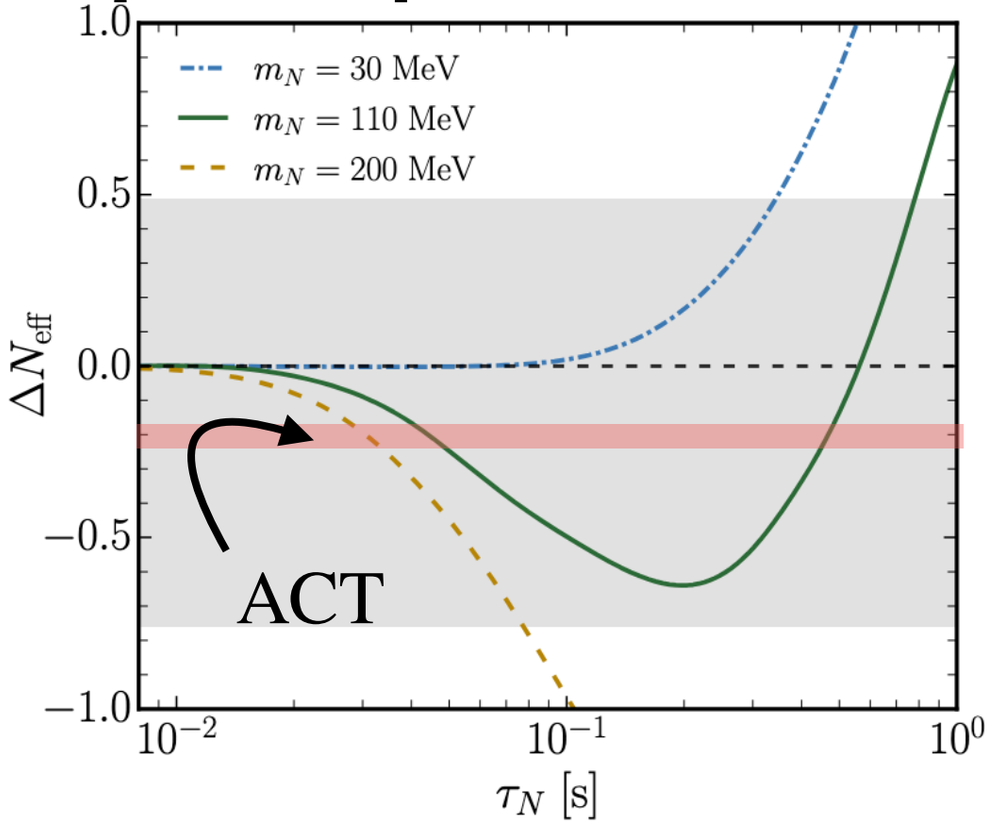


[2103.09831]



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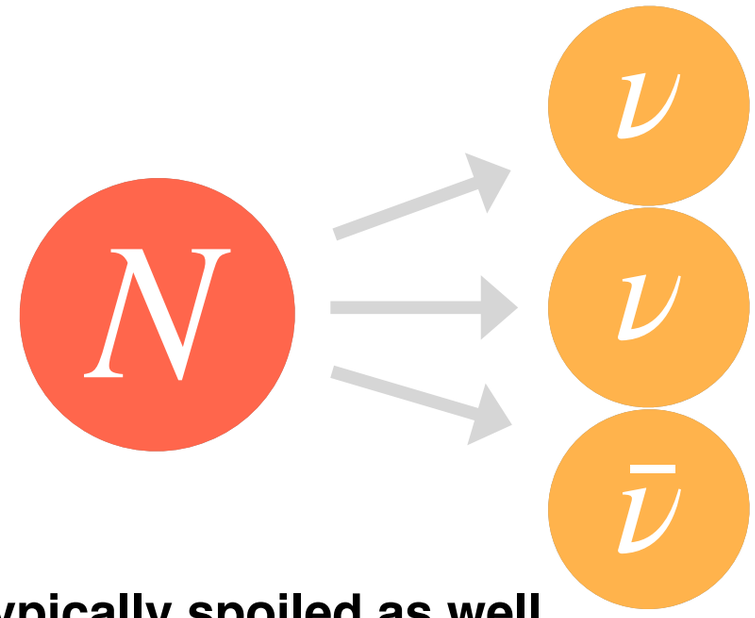

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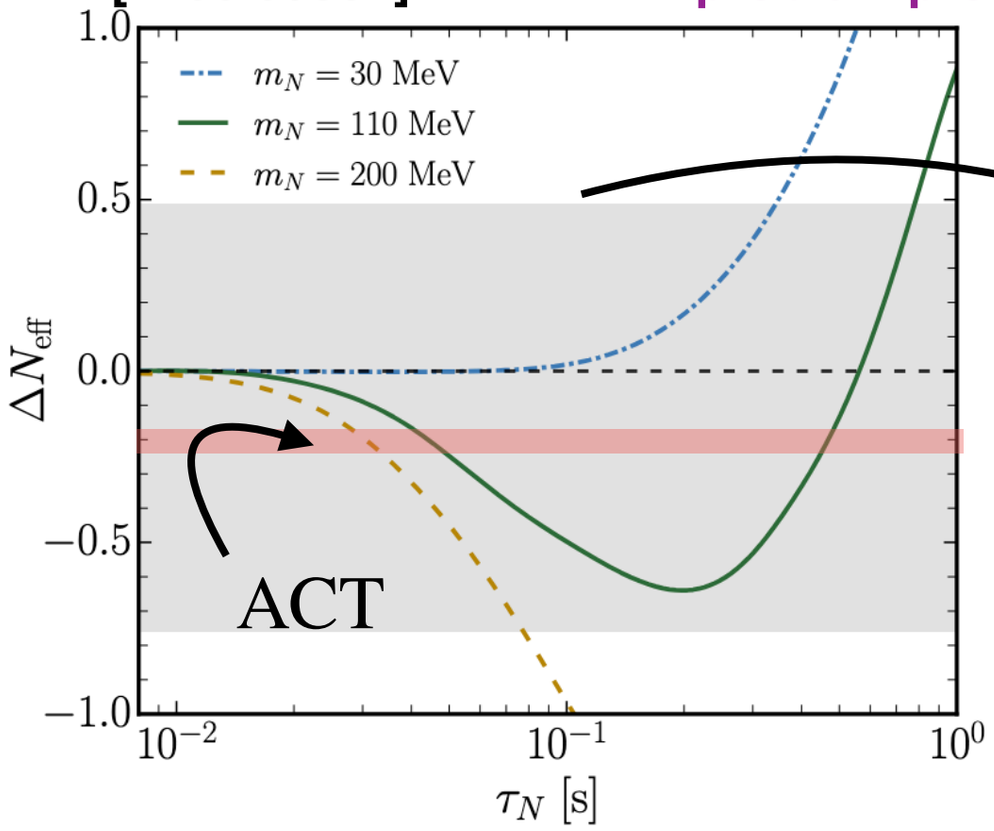

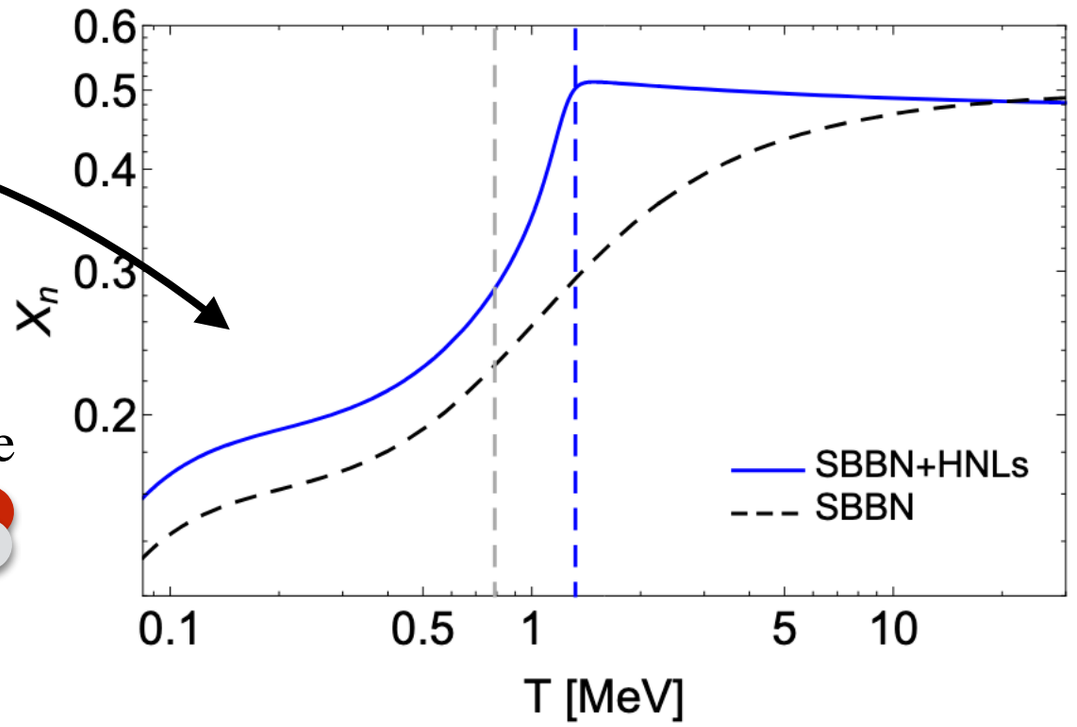

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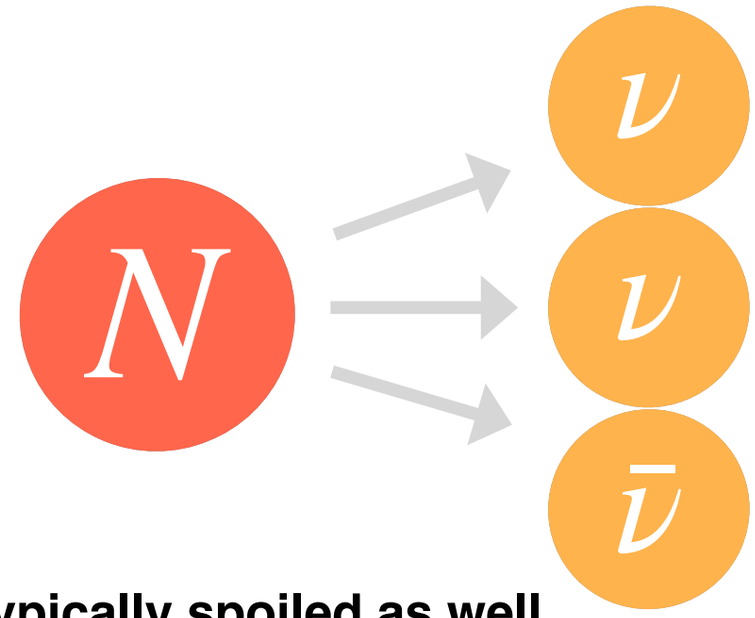

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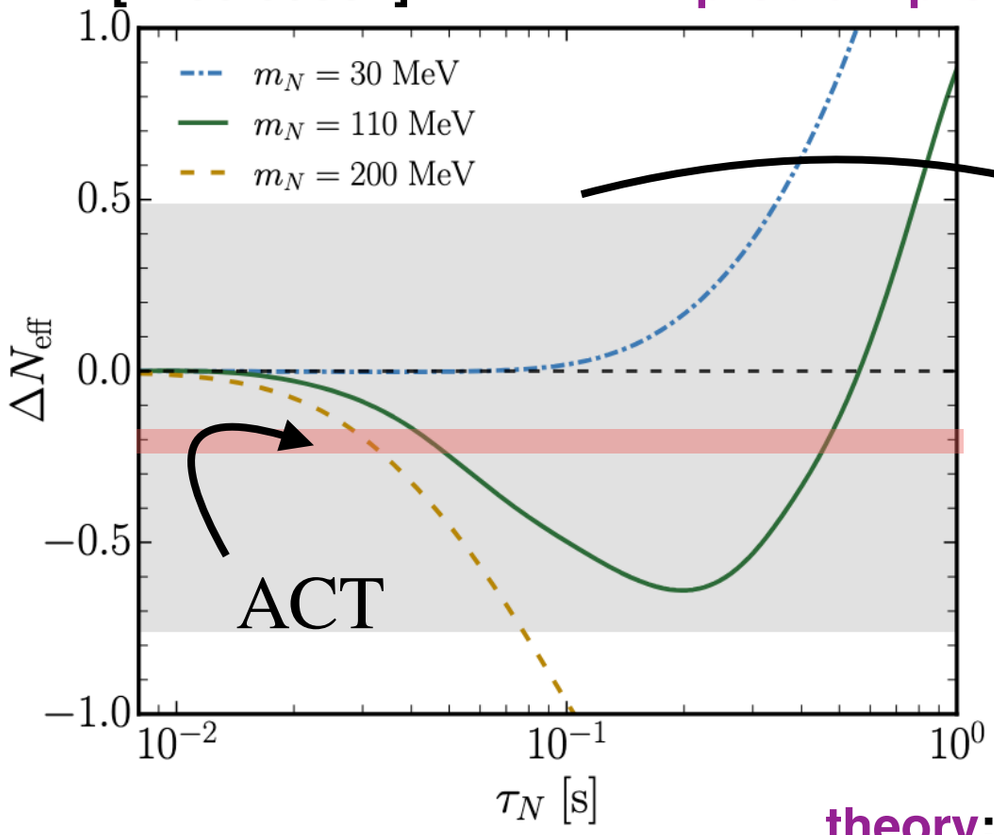

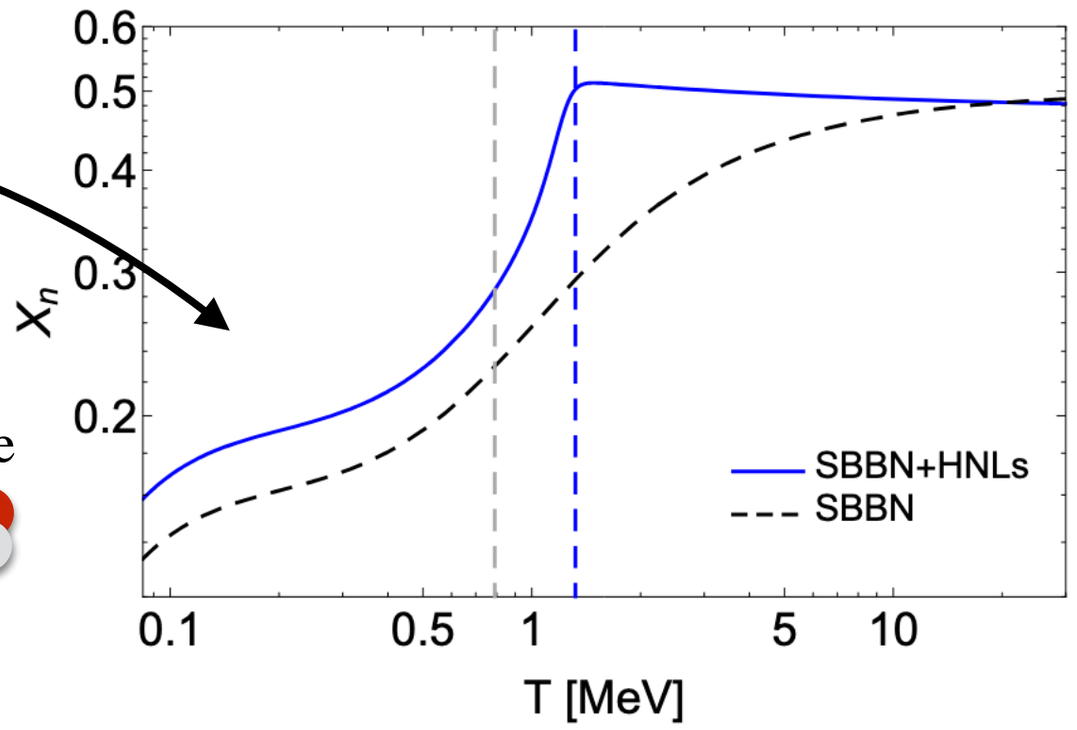

theory: well motivated!

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Electrophilic partiles in equilibrium at BBN

Boehm, Dolan and McCabe [1207.0497, 1303.6270]
Serpico and Raffelt [astro-ph/0403417]
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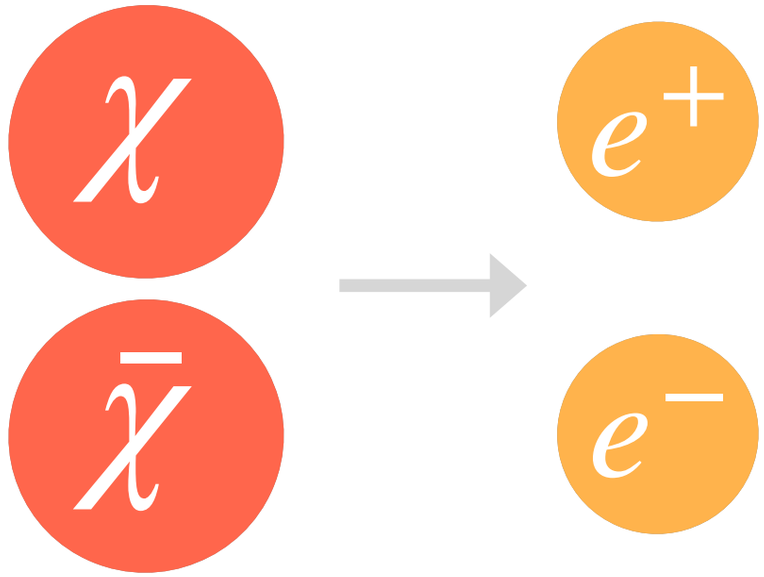

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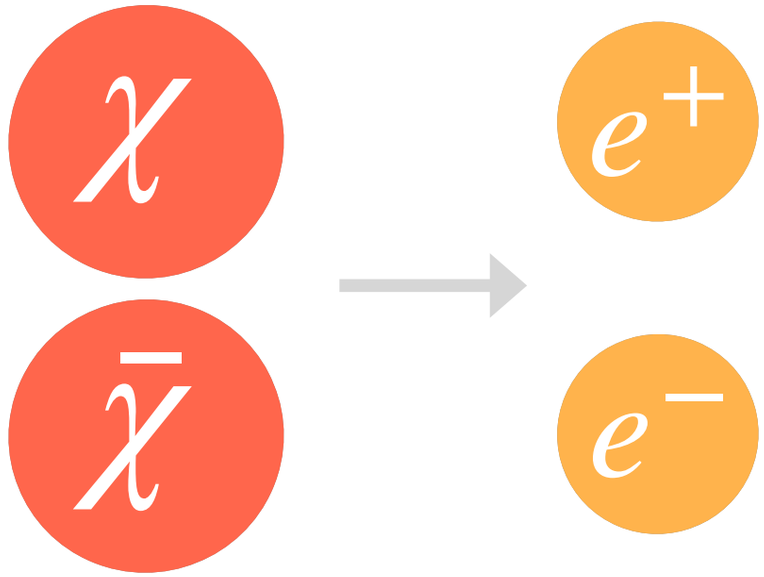

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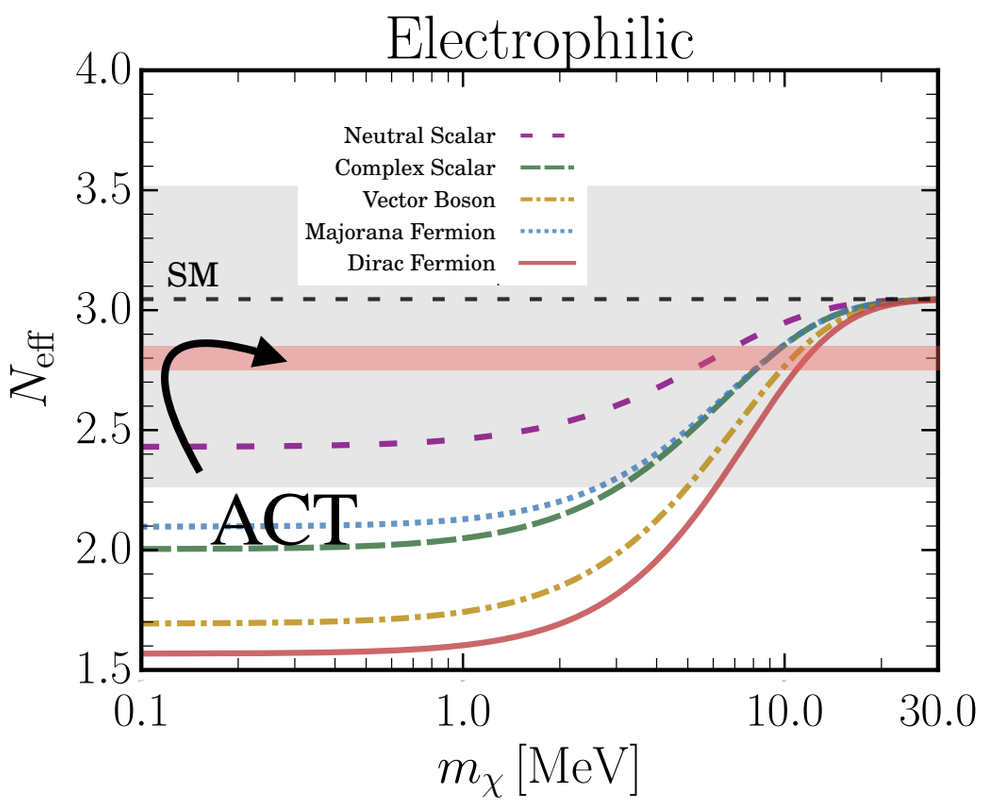

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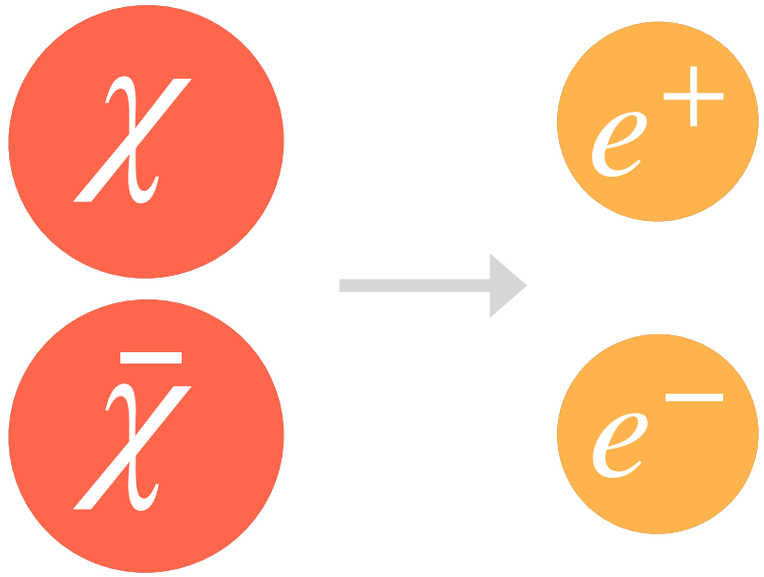

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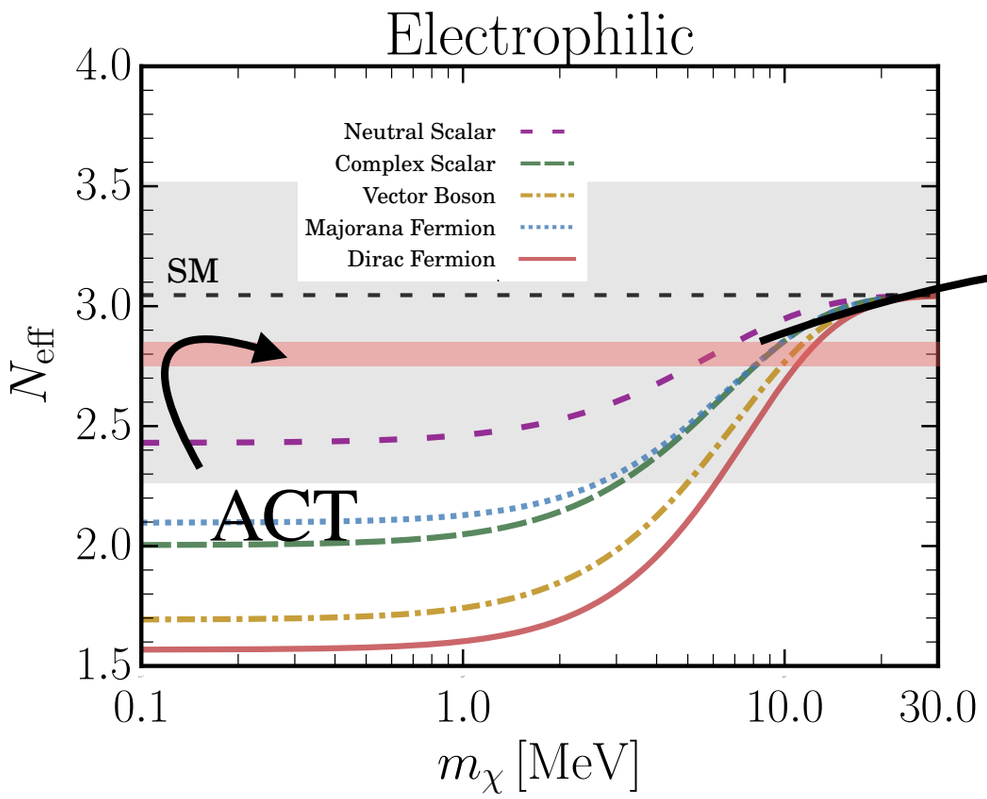
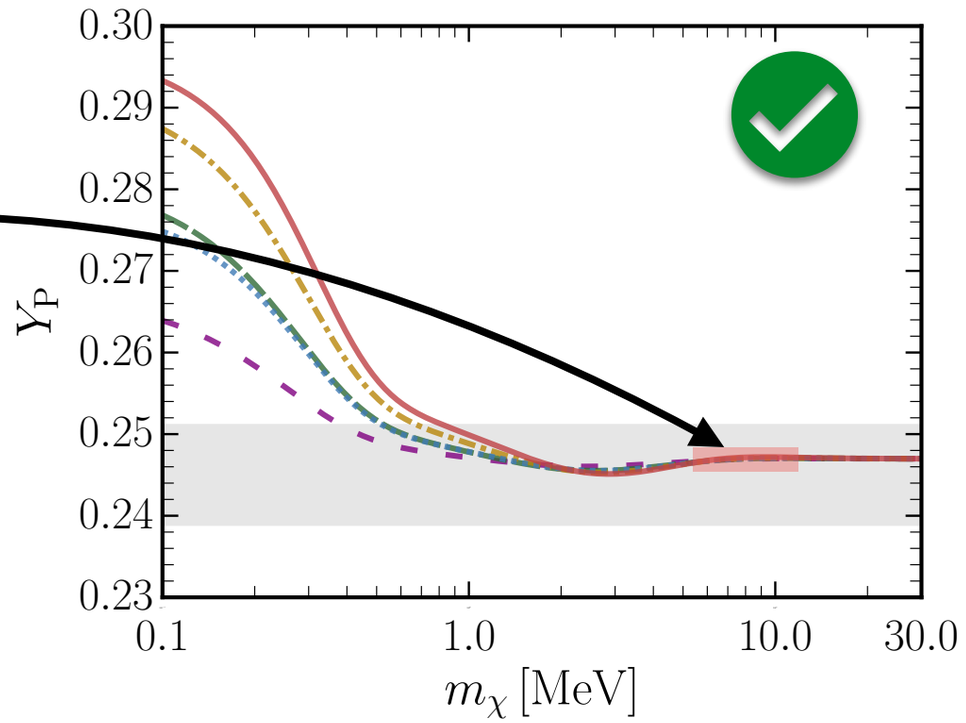
BBN is consistent due to a cancellation of effects!



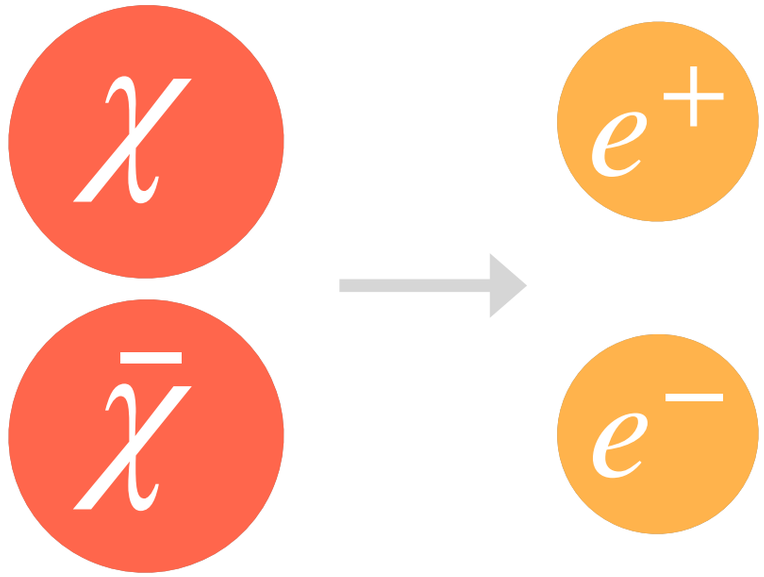
BBN?



Neff < 3 options: $\rho_\gamma \uparrow$

Electrophilic partiles in equilibrium at BBN

Boehm, Dolan and McCabe [1207.0497, 1303.6270]
Serpico and Raffelt [astro-ph/0403417]
Kolb, Turner and Walker PRD 34 (1986) 2197
Sabti, Alvey, Escudero, Fairbairn, Blas [1910.01649]



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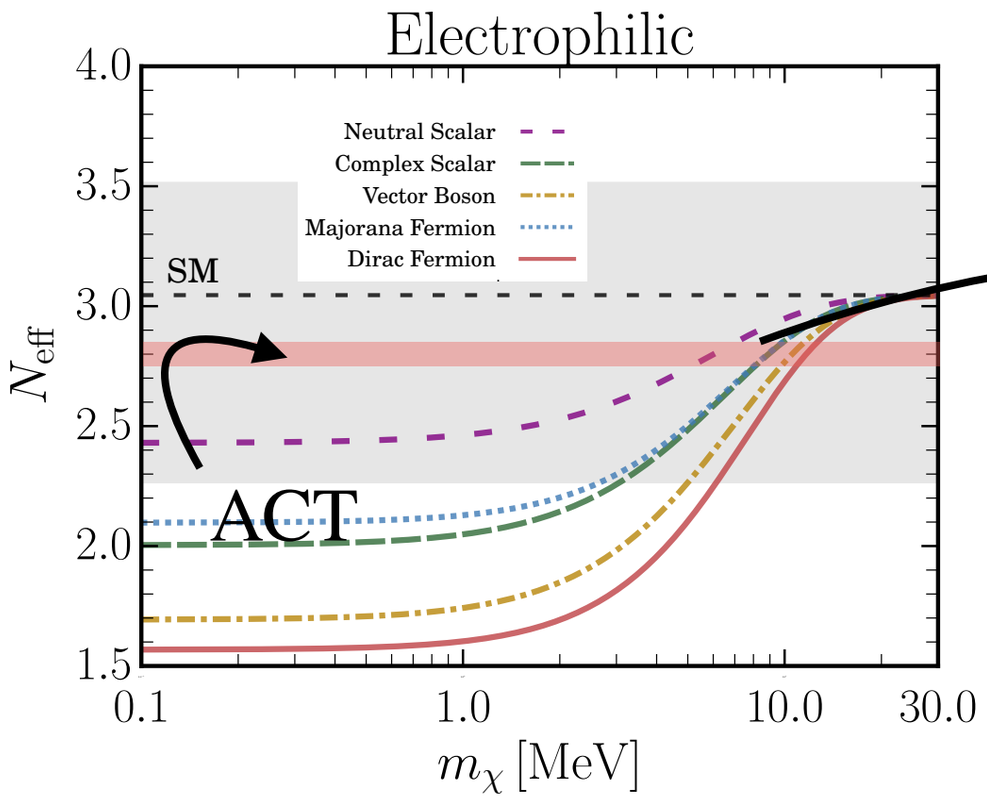
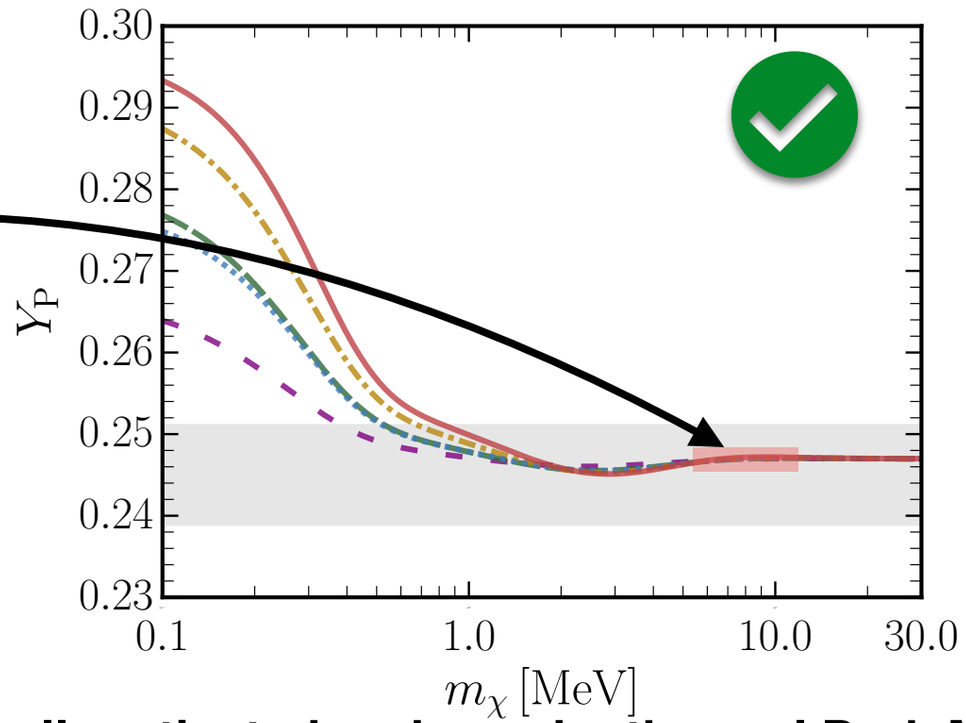


BBN?

BBN is consistent due to a cancellation of effects!

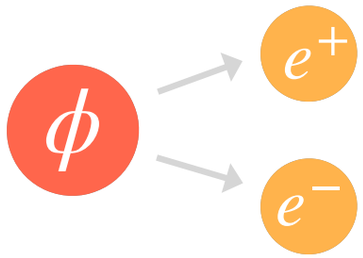


theory: well motivated and may be thermal Dark Matter

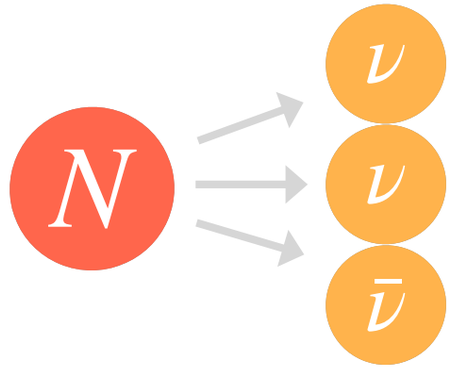
Neff < 3 options

Options:

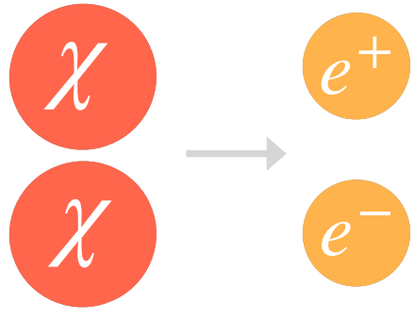
1) MeV-scale reheating, e.g. inflaton



2) Decay during neutrino decoupling, e.g. sterile neutrino



3) Thermally coupled electrophilic particle, e.g. scalar dark matter



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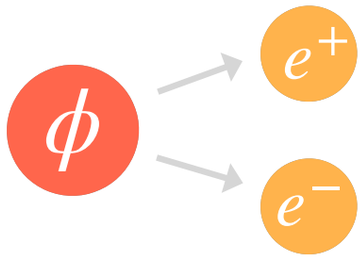

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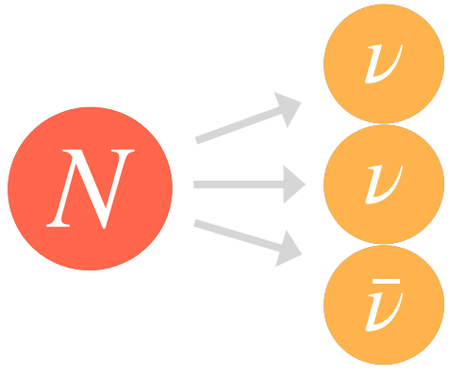

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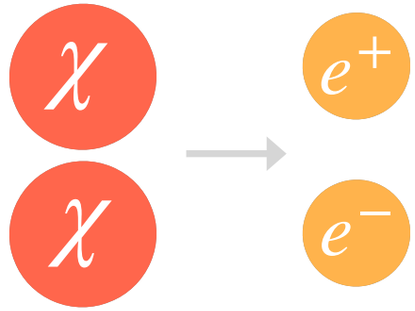
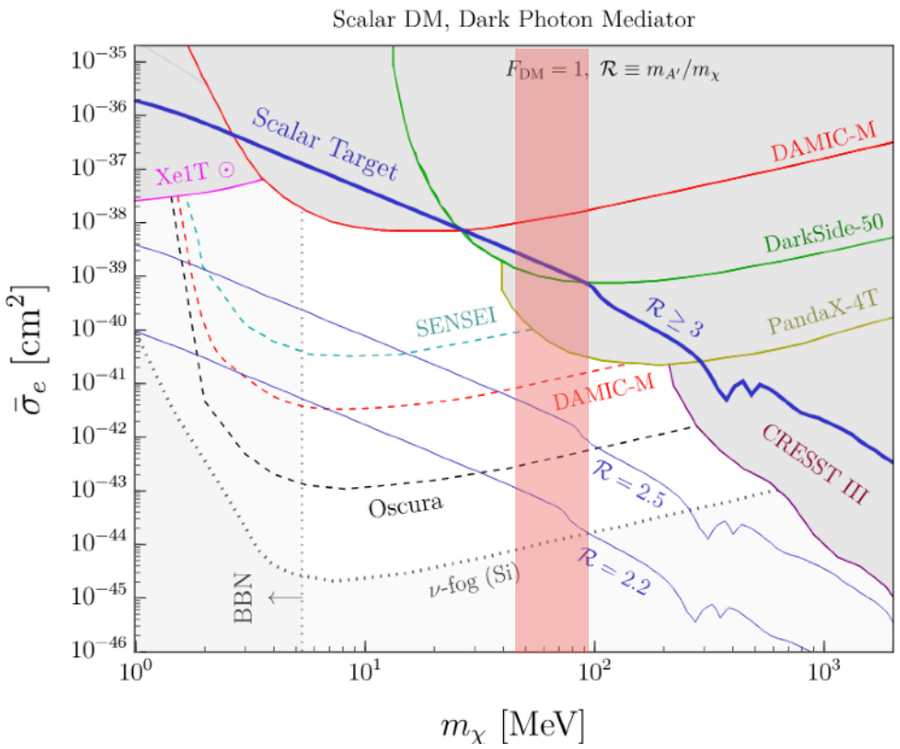


Options 1) and 2) have trouble with BBN but option 3) is viable. Prospects for dark matter detection viable!

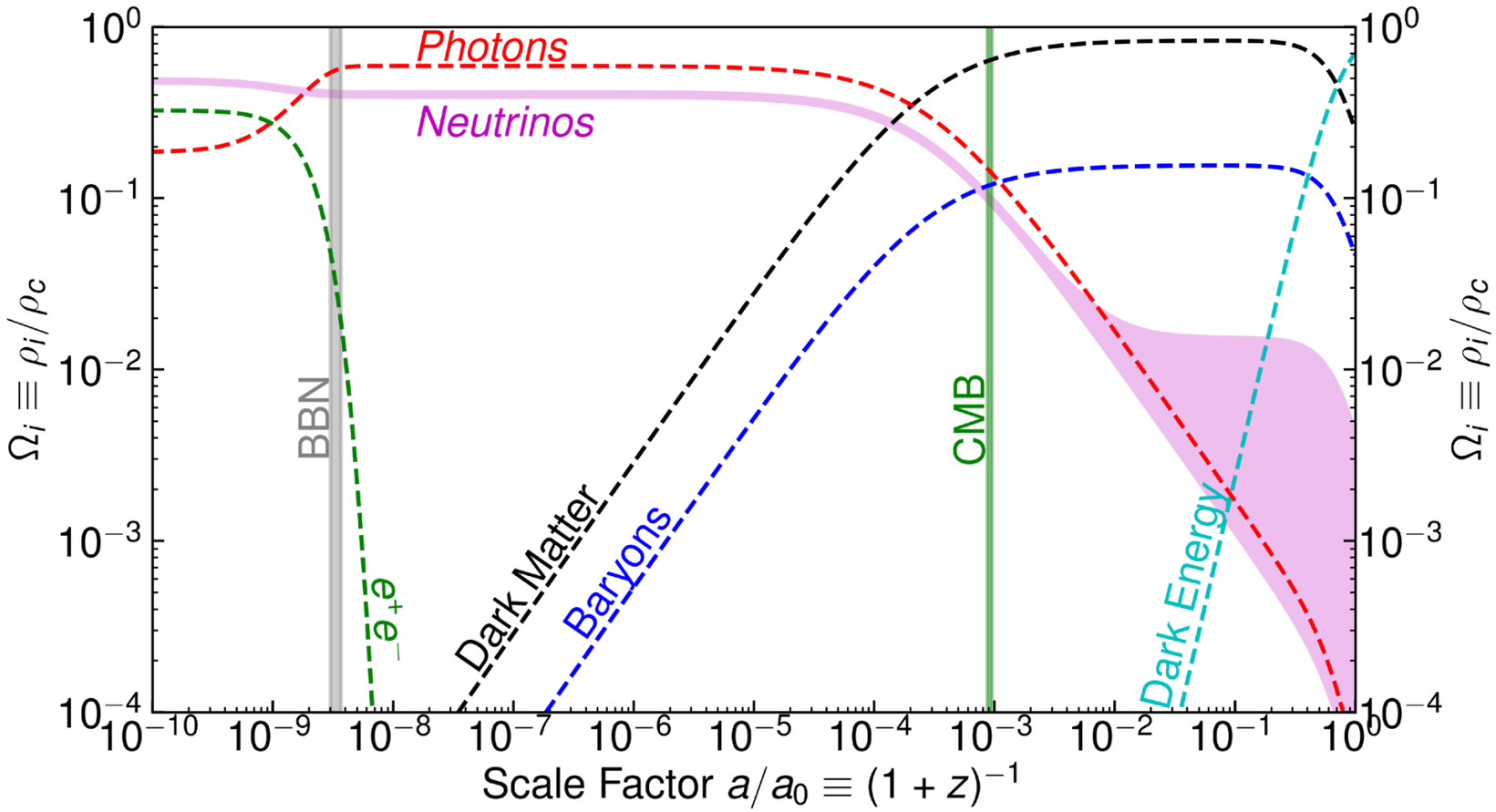
Krnjaic 2505.04626



Options for $m_\nu^{\rm Cosmo} = 0$

What cosmology can constrain is the energy density in non-relativistic neutrinos:

$$\rho_\nu = \sum m_\nu n_\nu$$

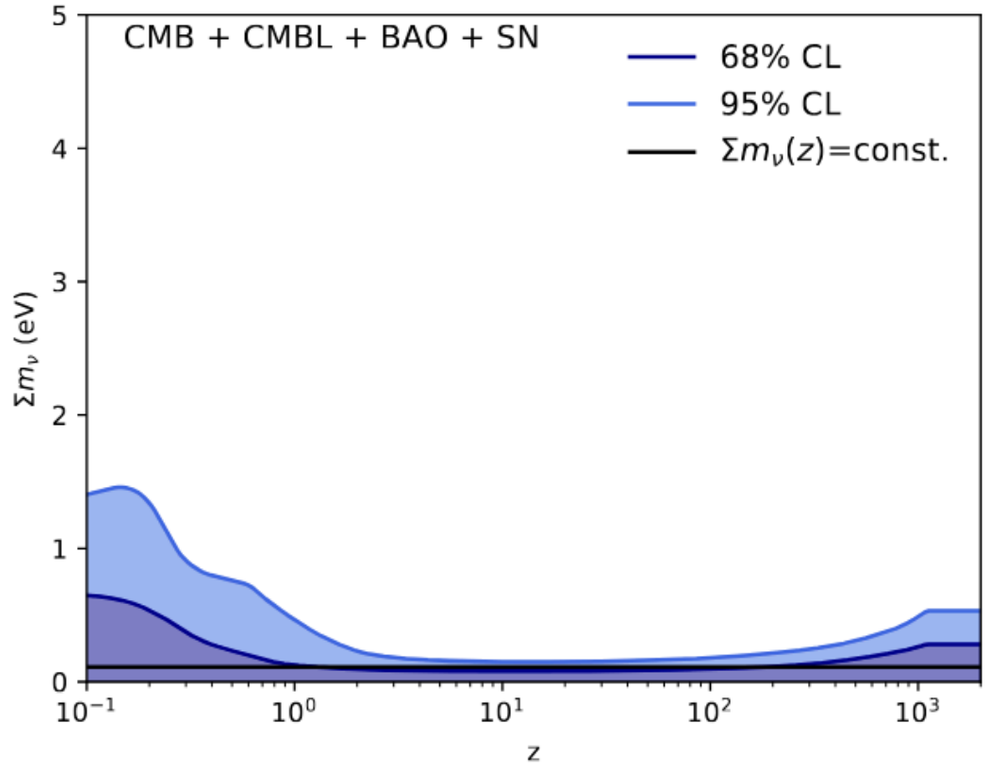


Clearly two options: either the neutrino mass is somehow different in the early Universe or the number density is somehow different

Time-dependent neutrino masses

Late time neutrino mass generation

Dvali & Funcke 1602.03191
Lorenz et al. 1811.01991 & 2102.13618



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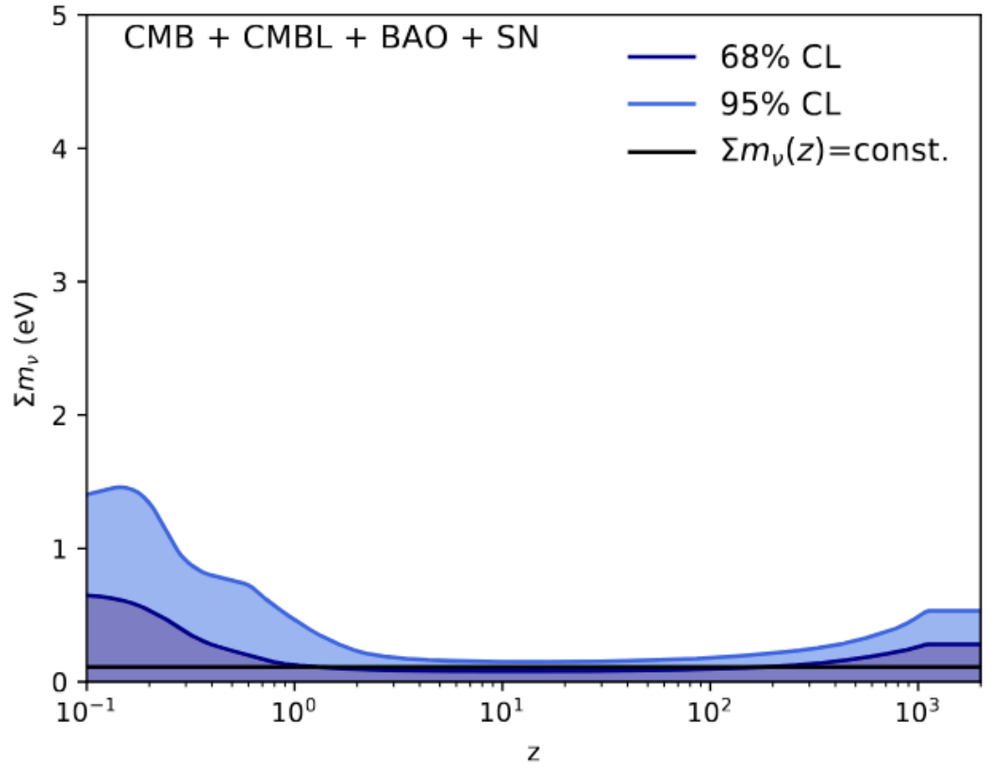

Refractive neutrino masses (interactions with Dark Matter)

Sen & Smirnov [2306.15718, 2407.02462]

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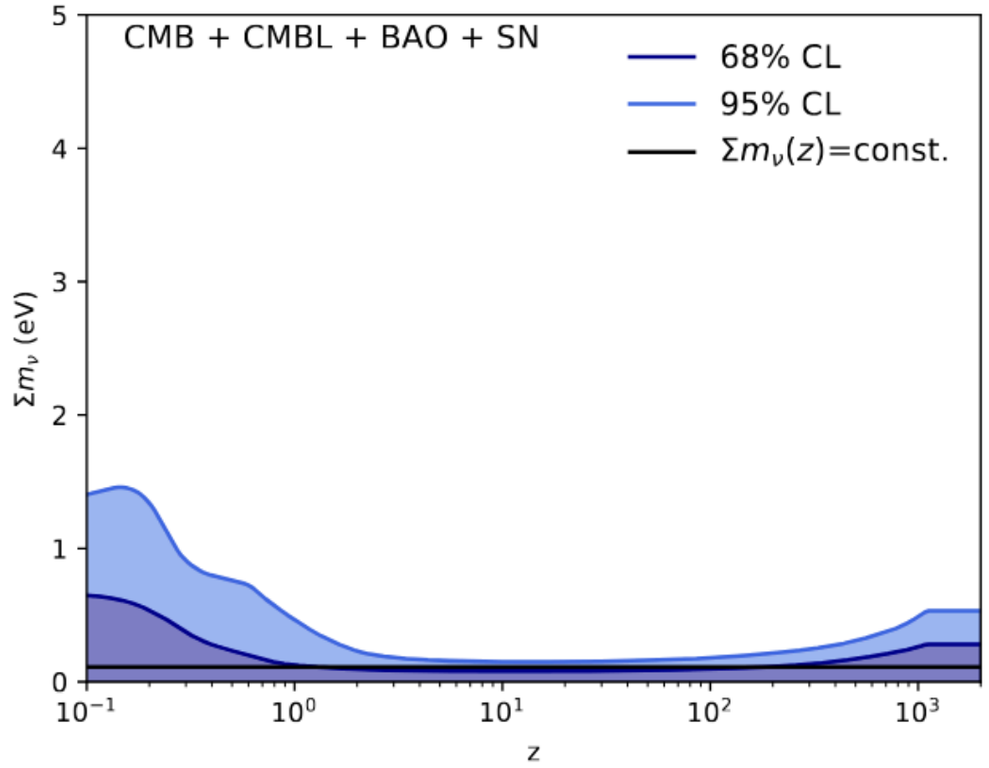

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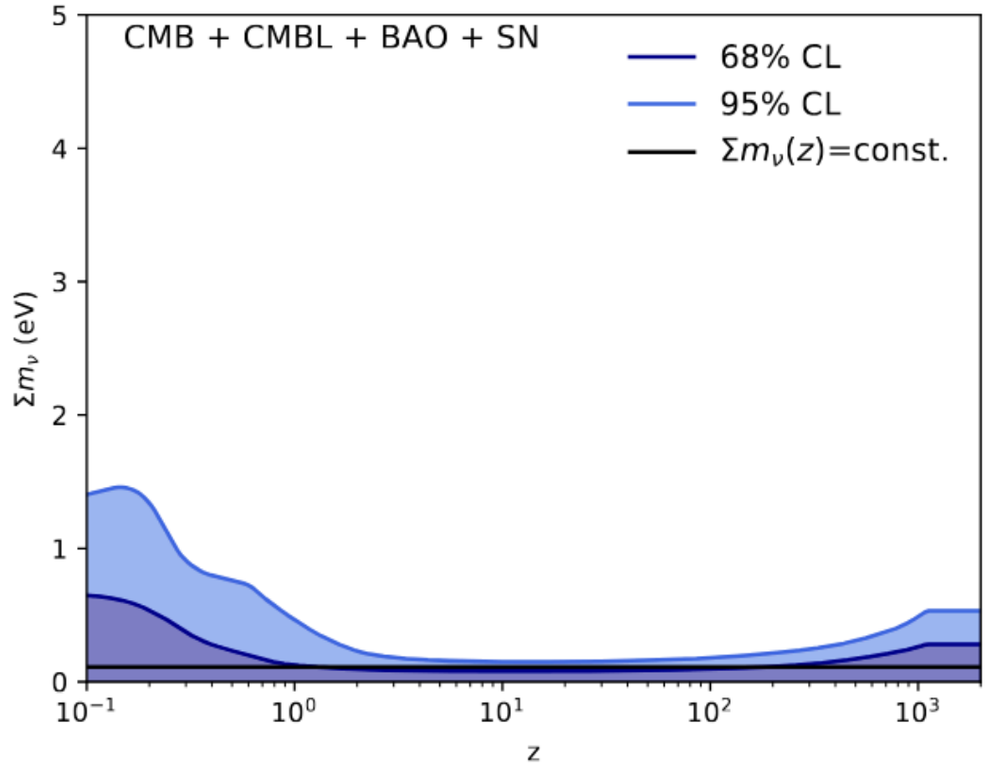

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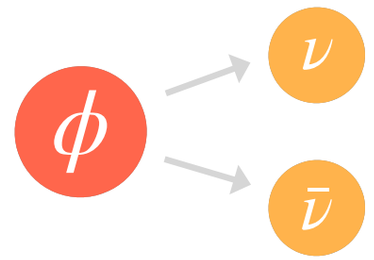
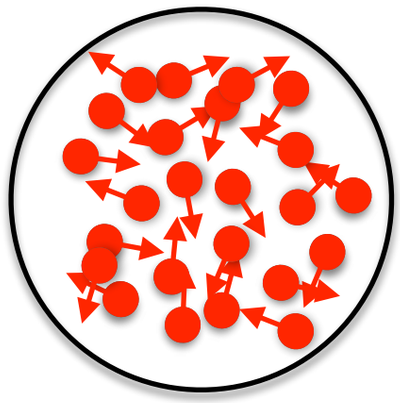
large neutrino masses allowed, in all cases interactions of the type



Non-Standard CNB

Standard CNB:



goal: somehow reduce the neutrino number density

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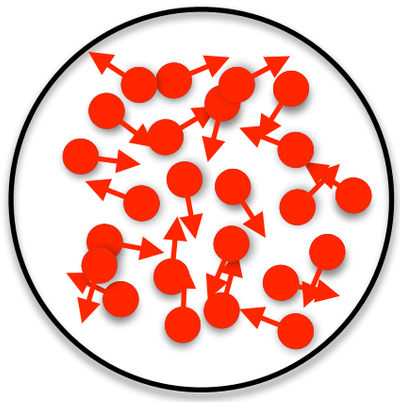

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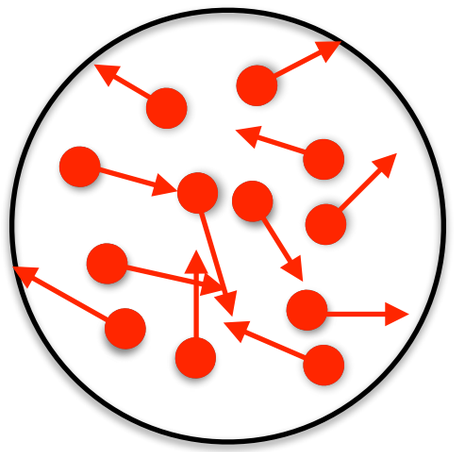
The neutrino depletion scenario

Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.14870



Not many neutrinos and they travel fast!

[no known model realizing it]

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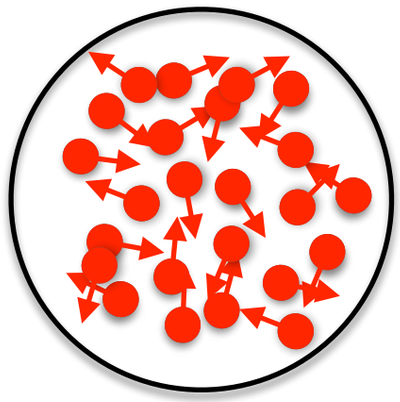

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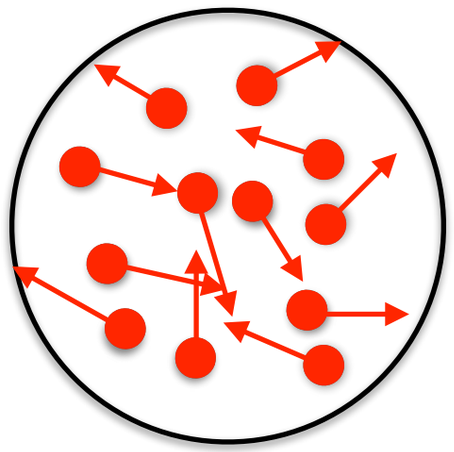

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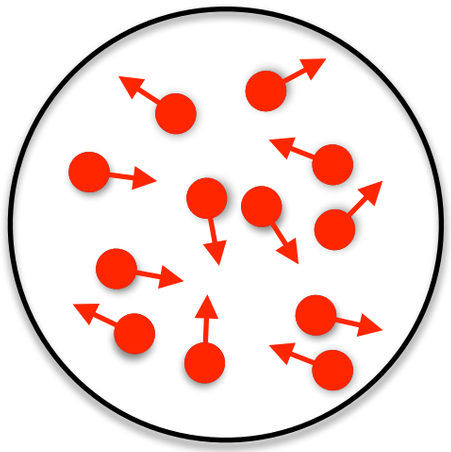

Less neutrinos accompanied by many new massless particles

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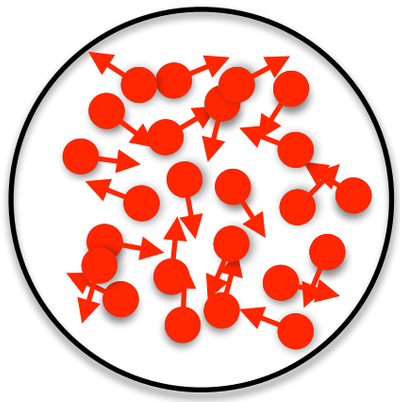

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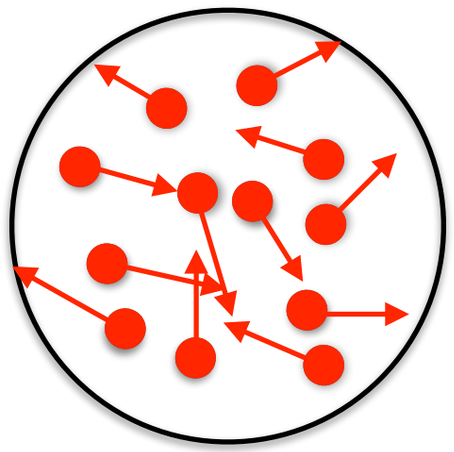

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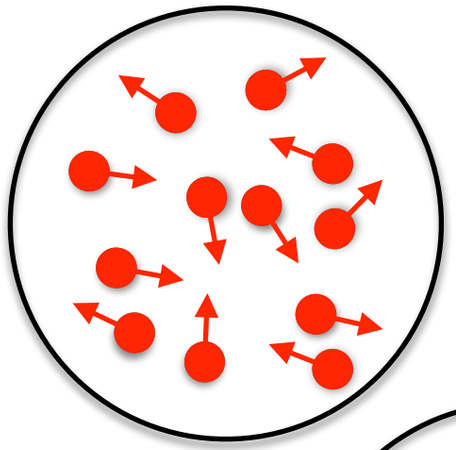

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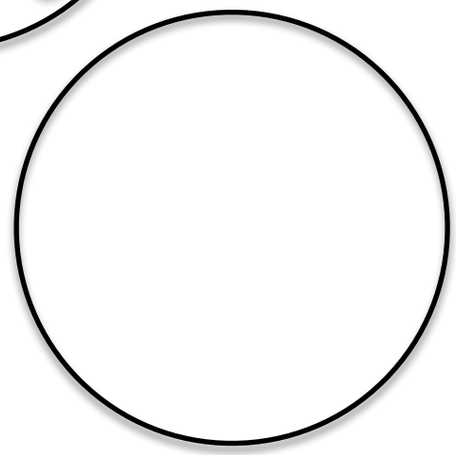
Abellán, Poulin et al. 1909.05275, 2112.13862
Escudero, López-Pavón, Rius & Sandner 2007.04994



No neutrinos today, as they have decayed away

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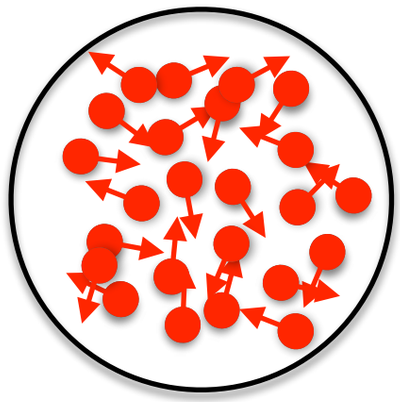

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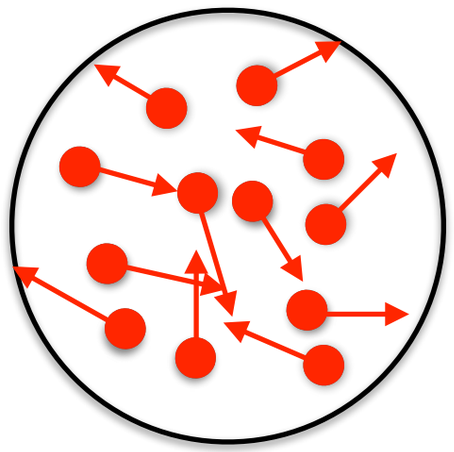

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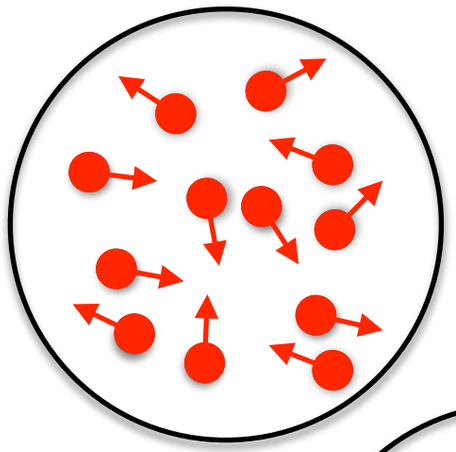

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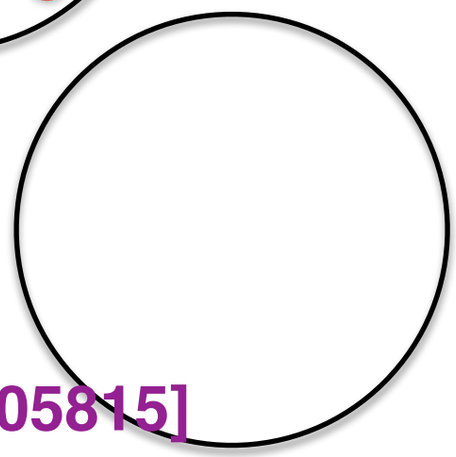

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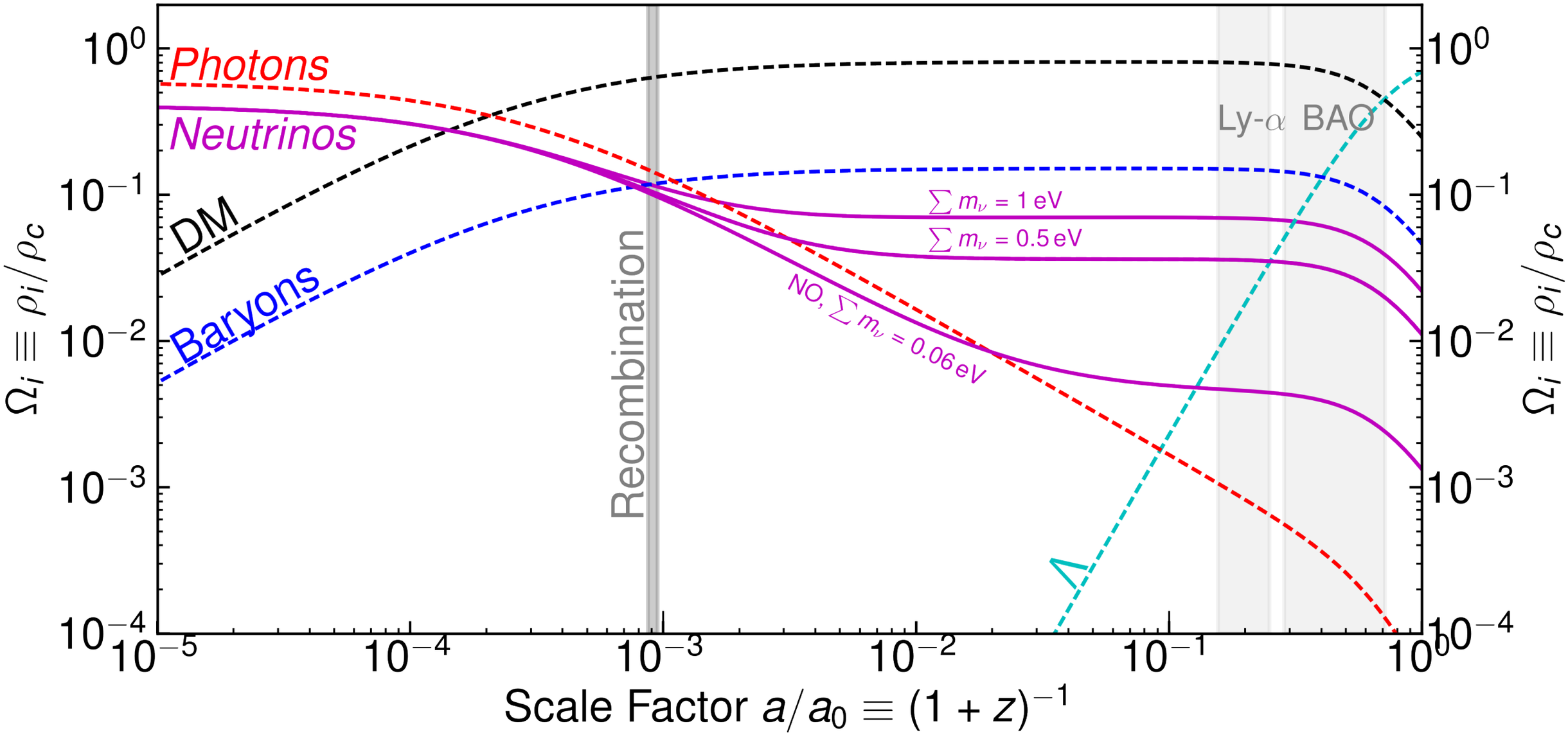
CMB lensing as a key probe! Upadhye et al. [2410.05815]

Neutrino Masses from Cosmology



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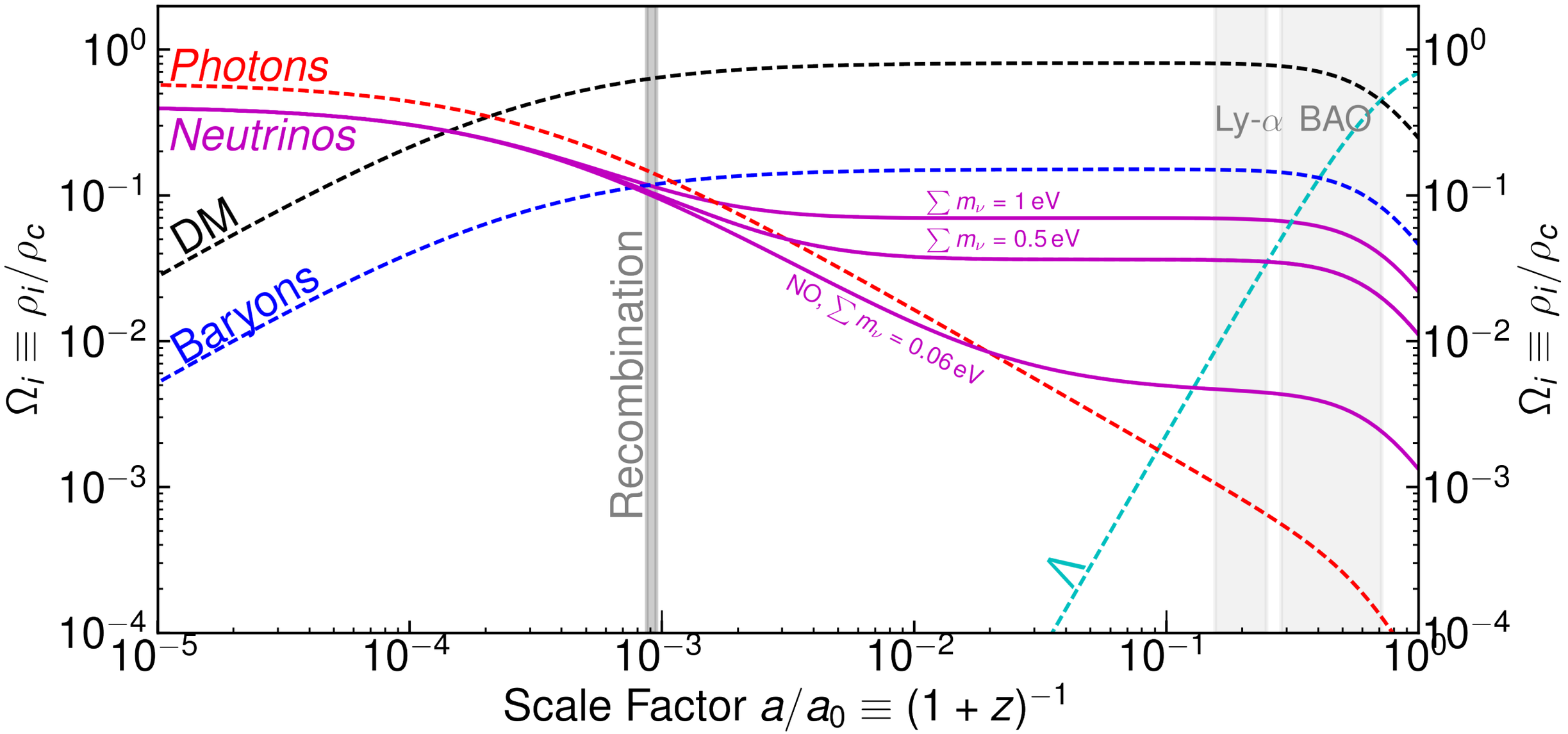

CMB peaks fix:

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

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

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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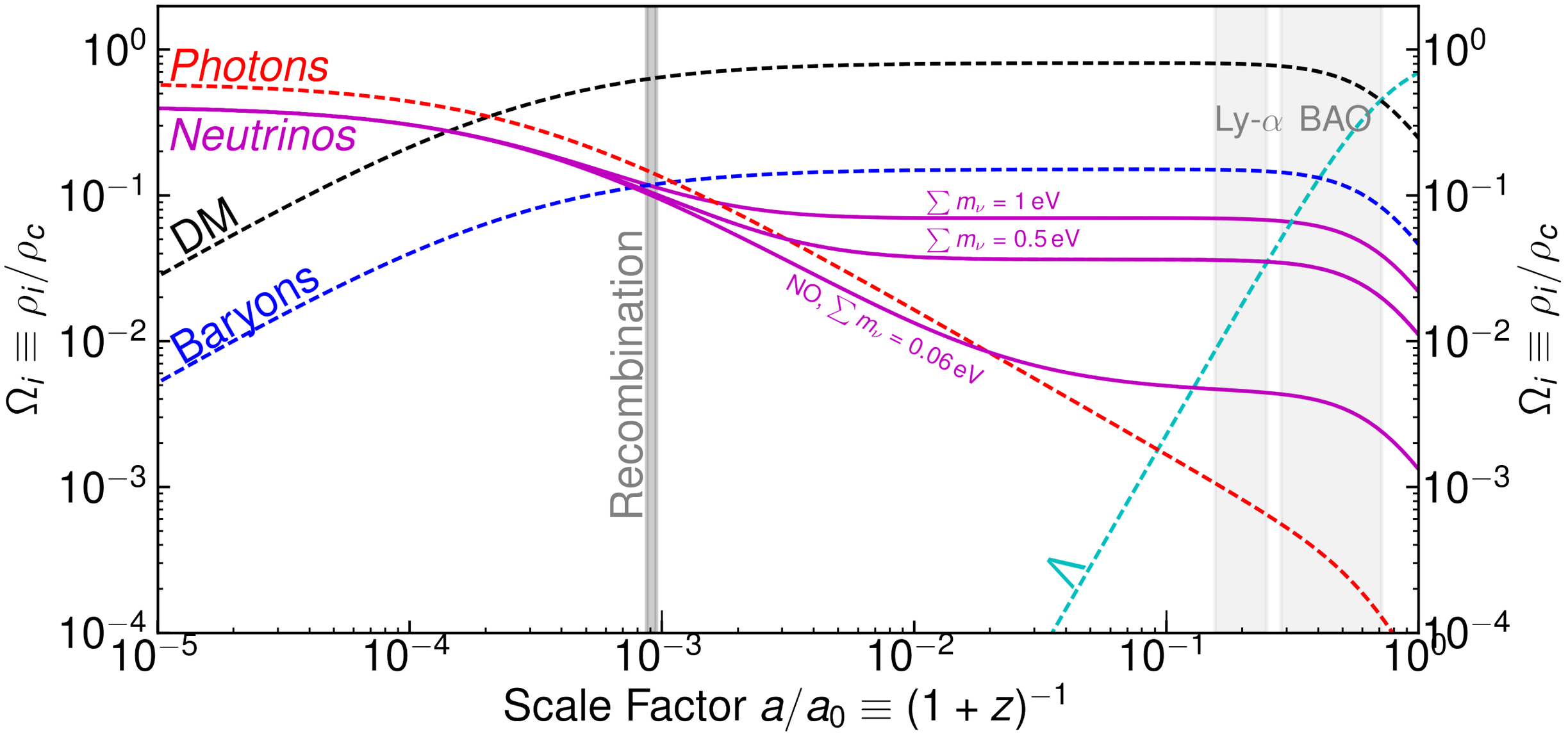

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Massive neutrinos

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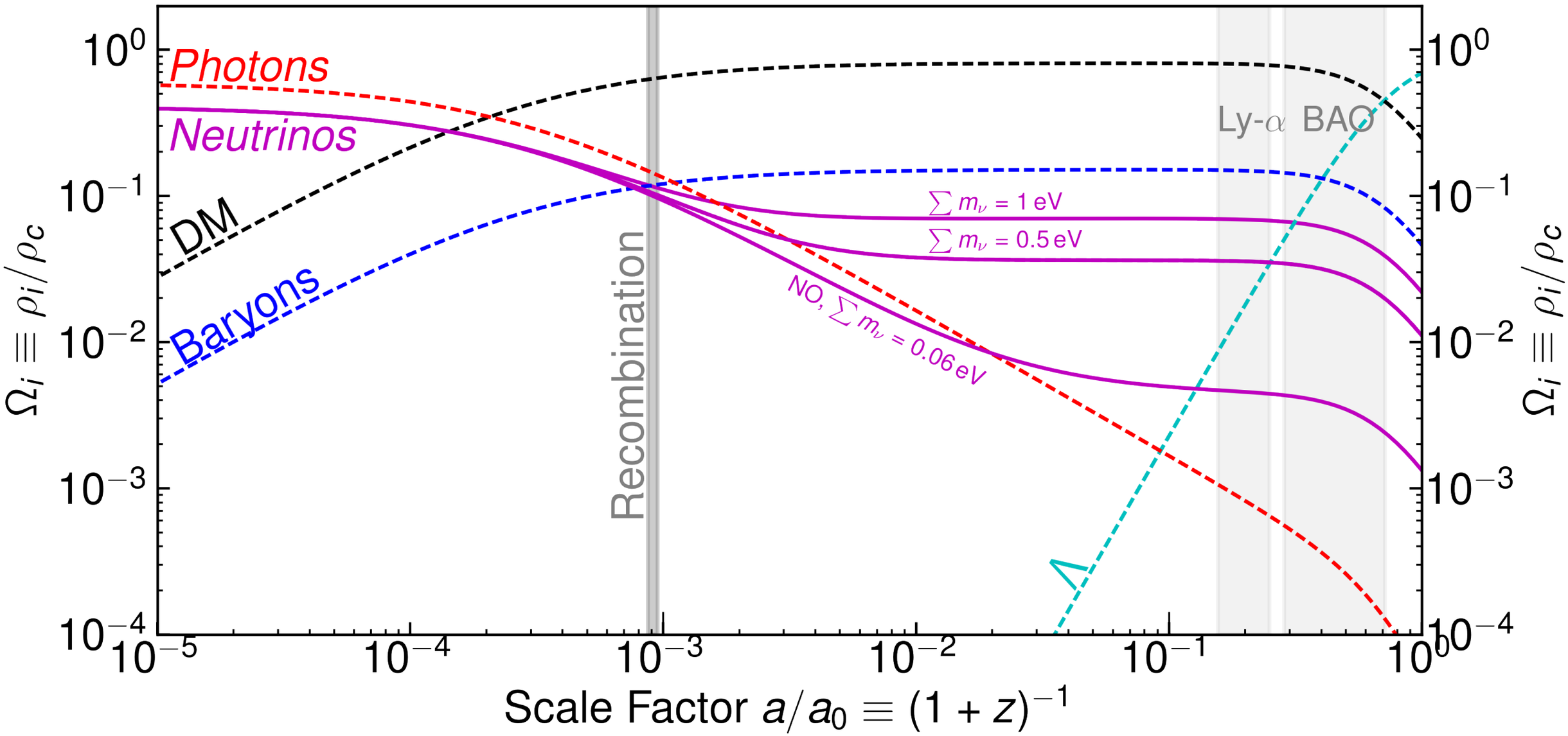
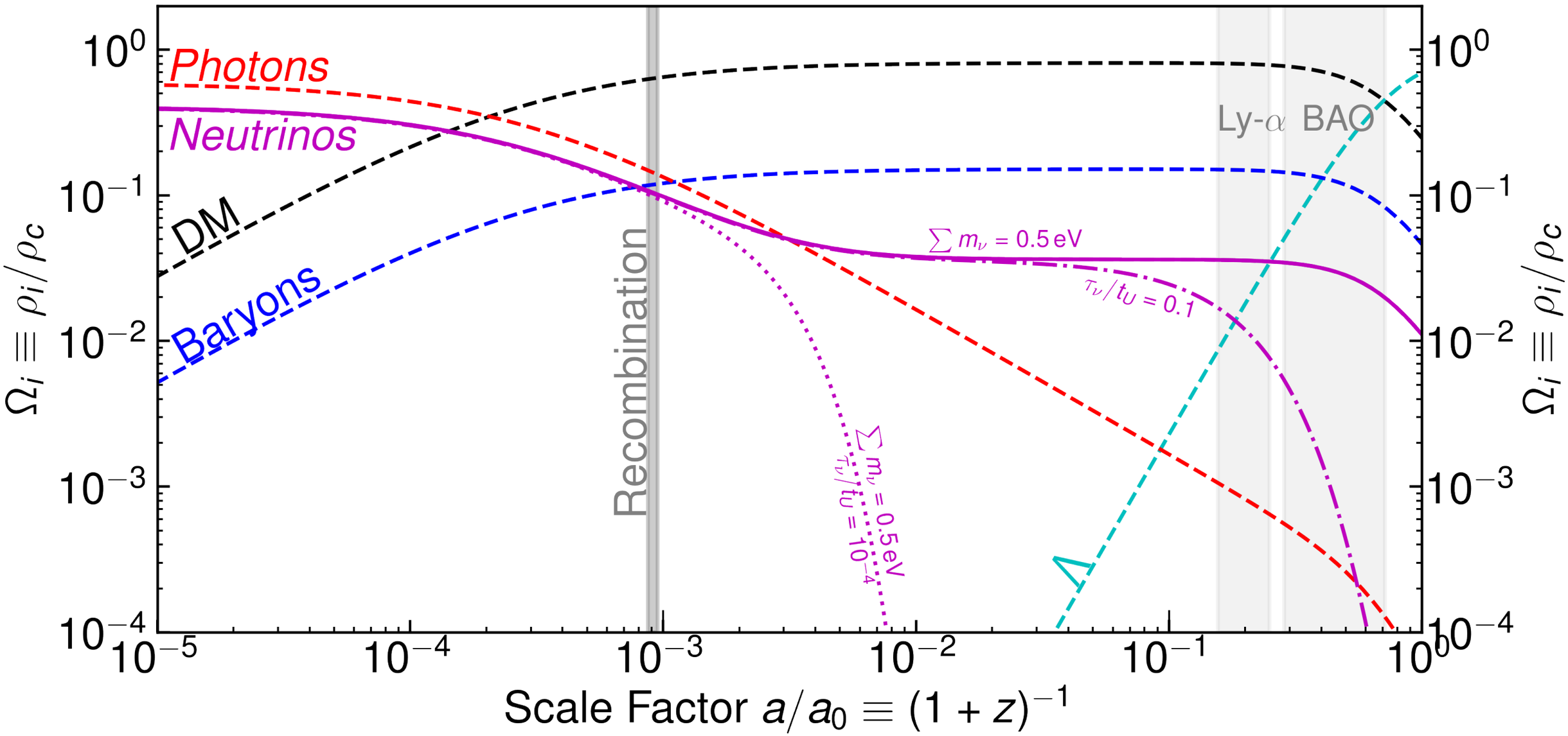


Not only a background effect:

Massive neutrinos also affect CMB lensing $\propto$ Ω_ν

Neutrino Decays



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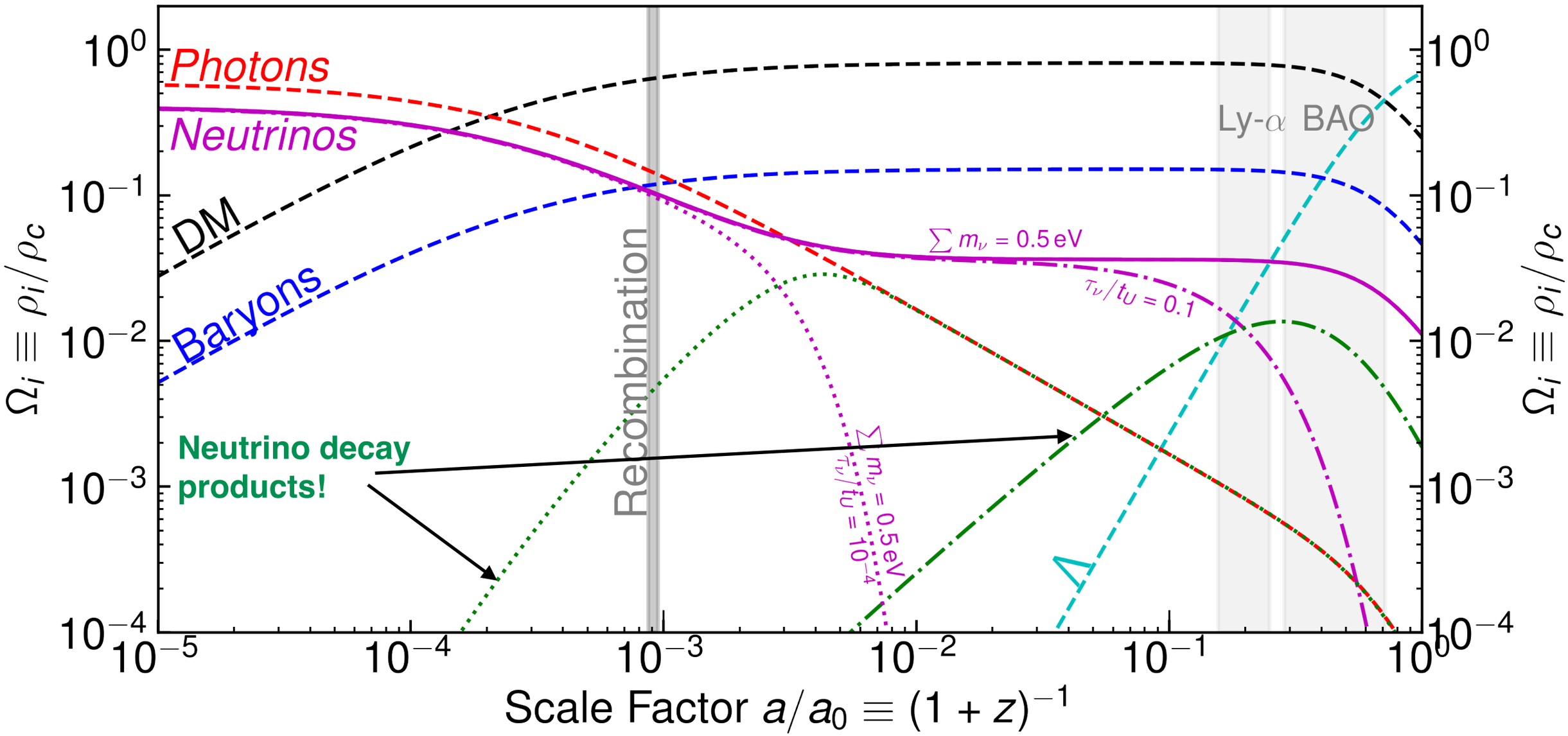

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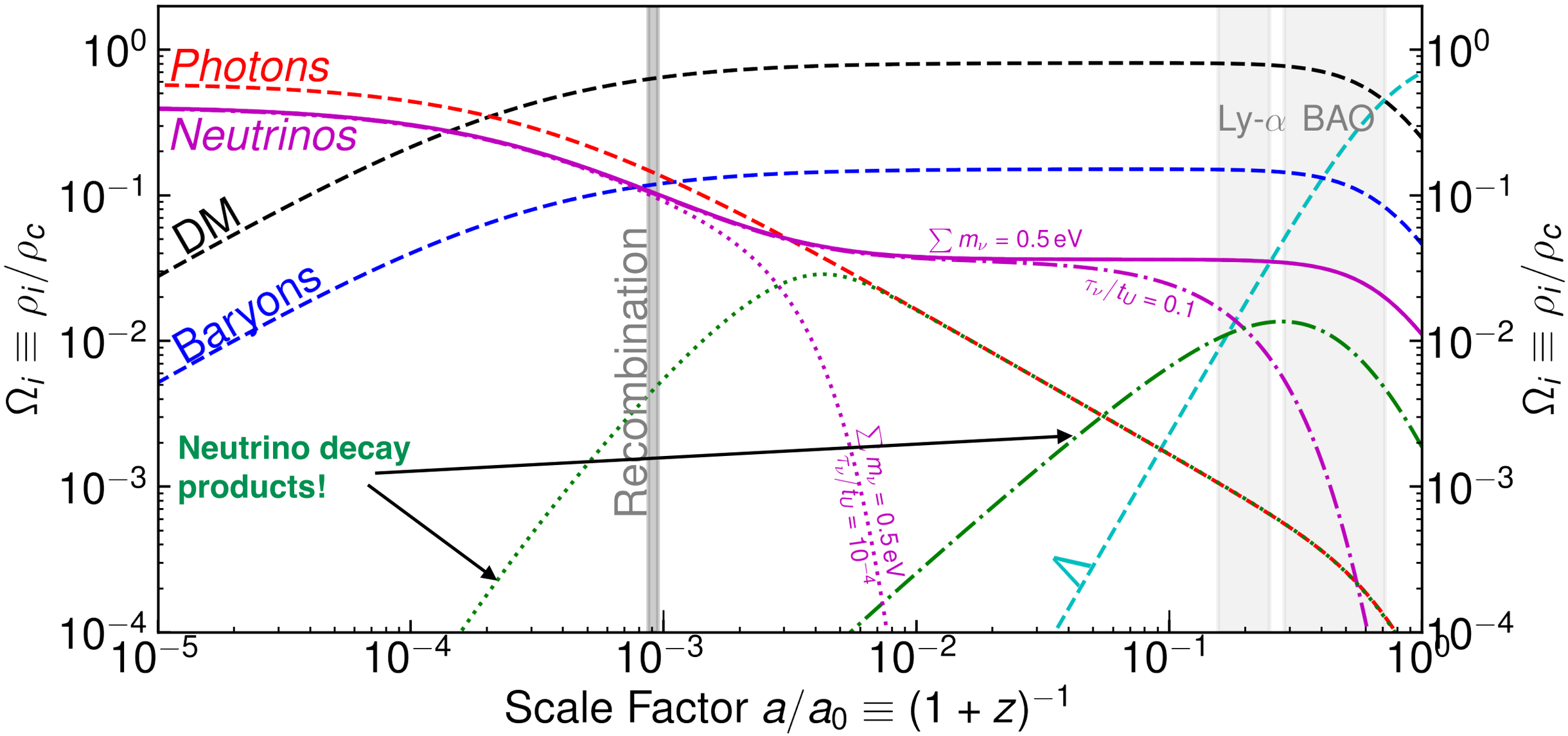

Neutrinos decaying with $\tau_\nu \lesssim t_U/10$ do not impact $D_M(z_{CMB})$

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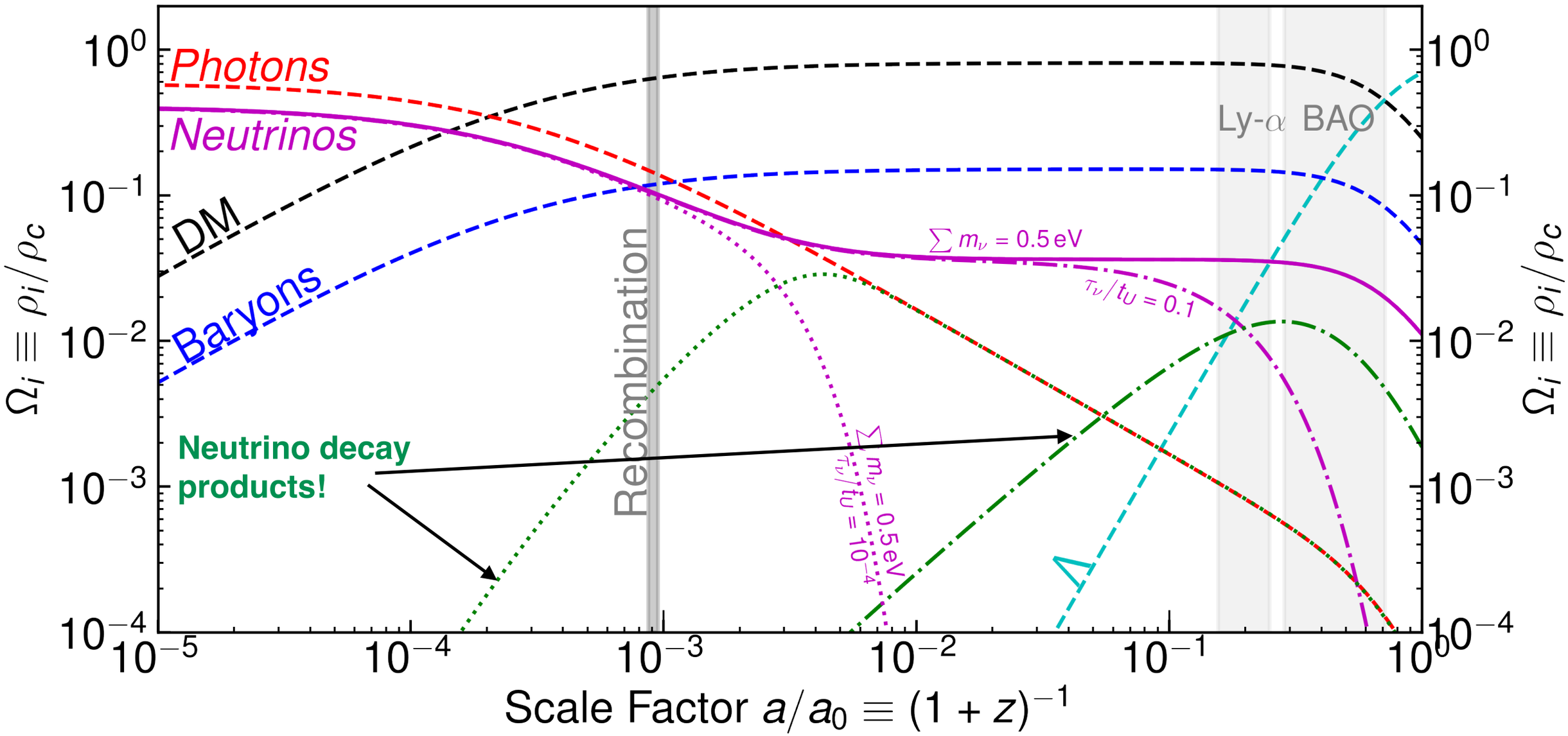

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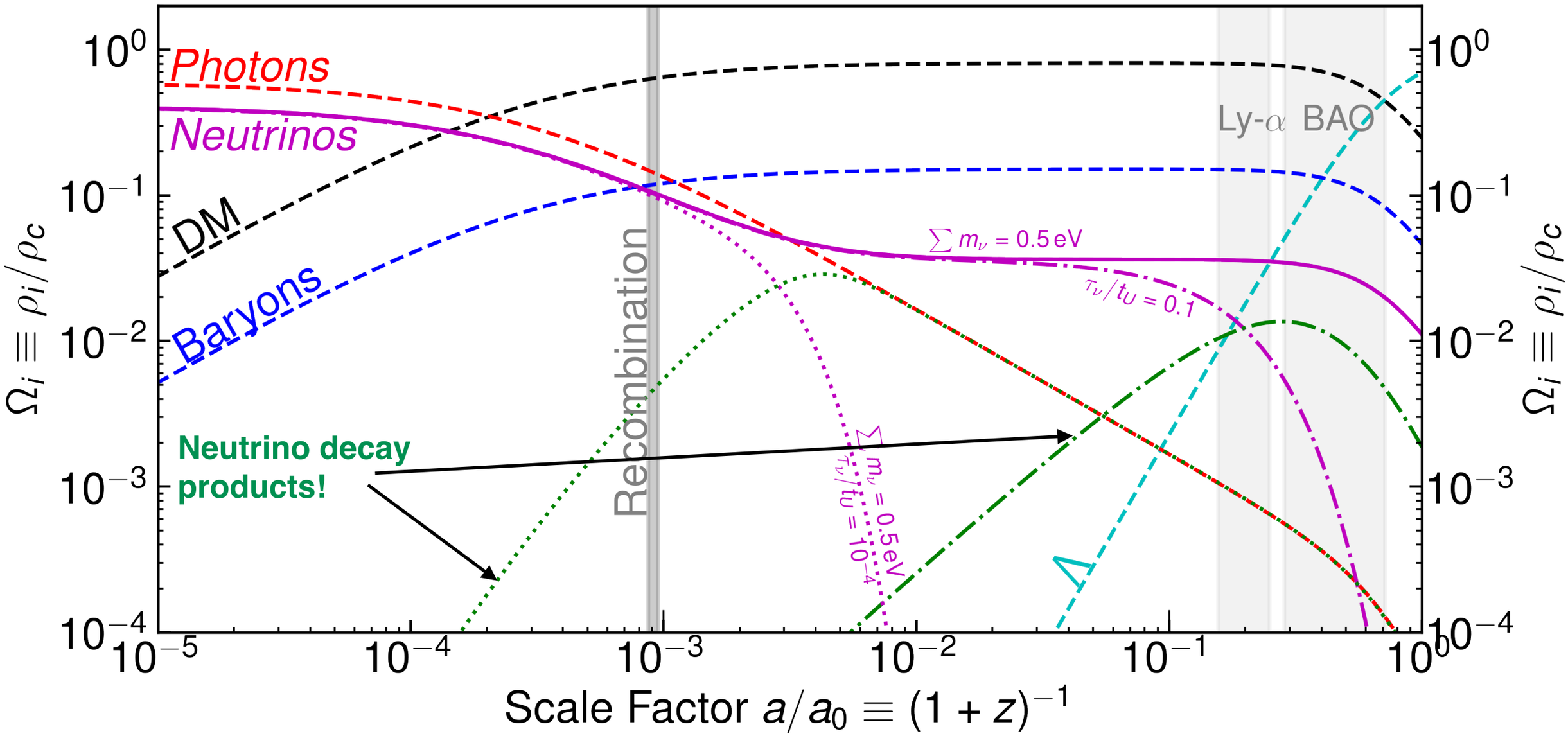
Effect of induced neutrino Lensing is substantially reduced

Neutrino Decays



Neutrinos decaying with $\tau_\nu \lesssim t_U/10$ do not impact $D_M(z_{CMB})$

Effect of induced neutrino Lensing is substantially reduced

Unstable Neutrinos can relax the bounds on Σm_ν!

Neutrino Decay Landscape

VOLUME 28, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1972

Are Neutrinos Stable Particles?*

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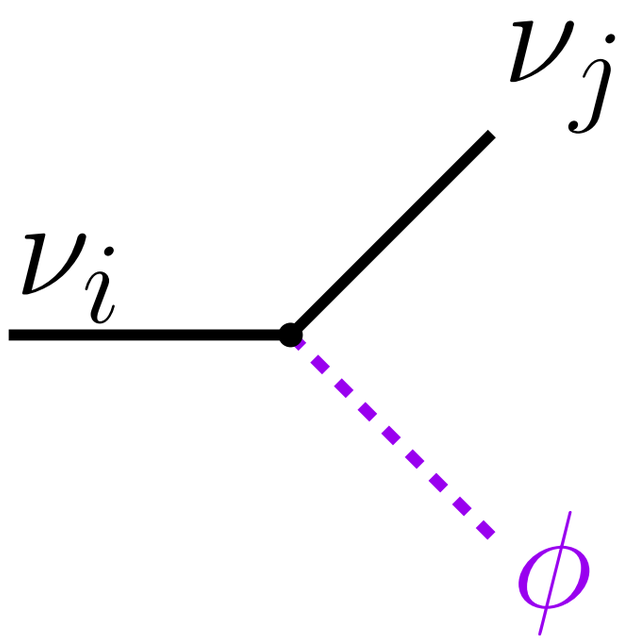

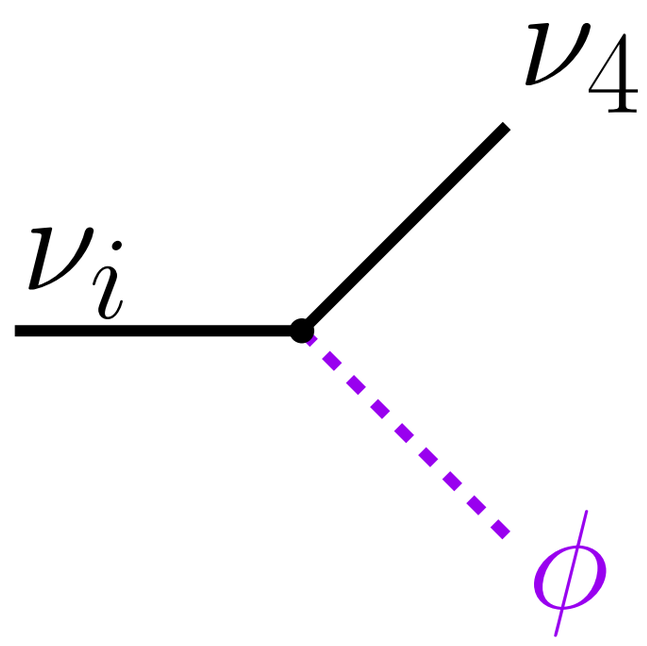

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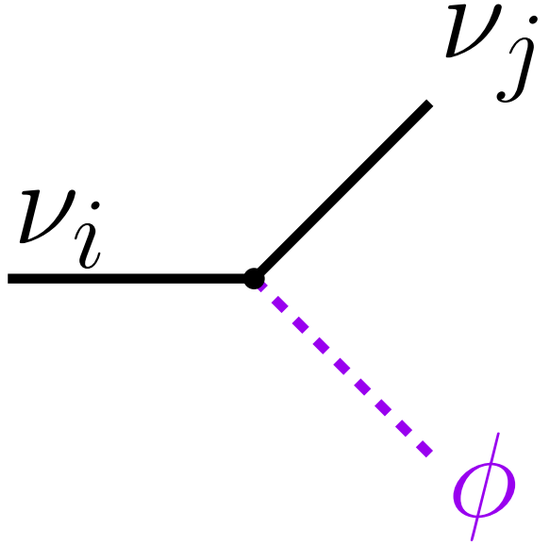

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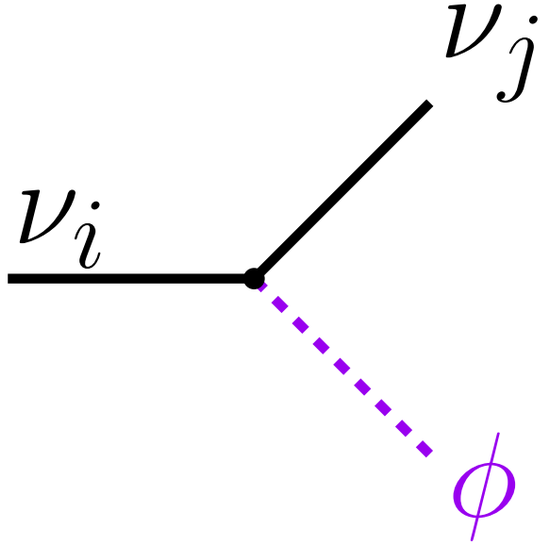

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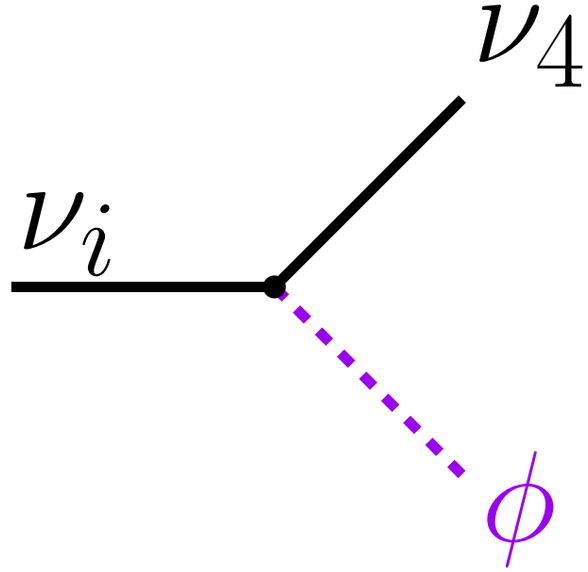

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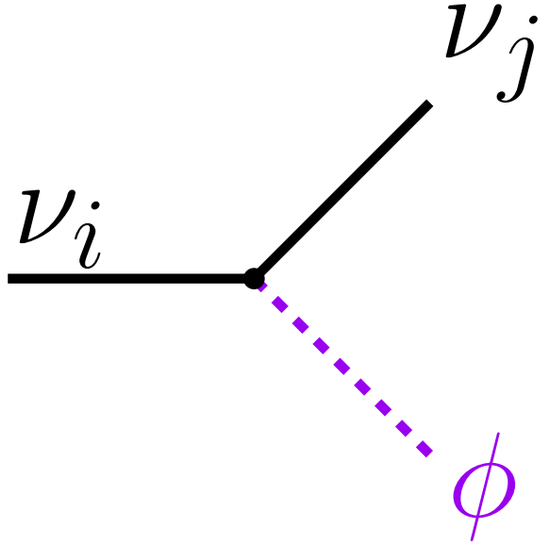

$$\lambda \simeq m_\nu / v_\phi$$
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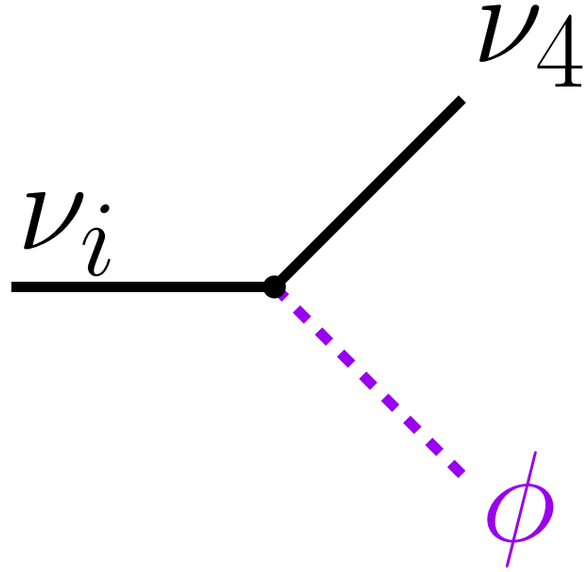

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[very reasonable particle physics scales!]

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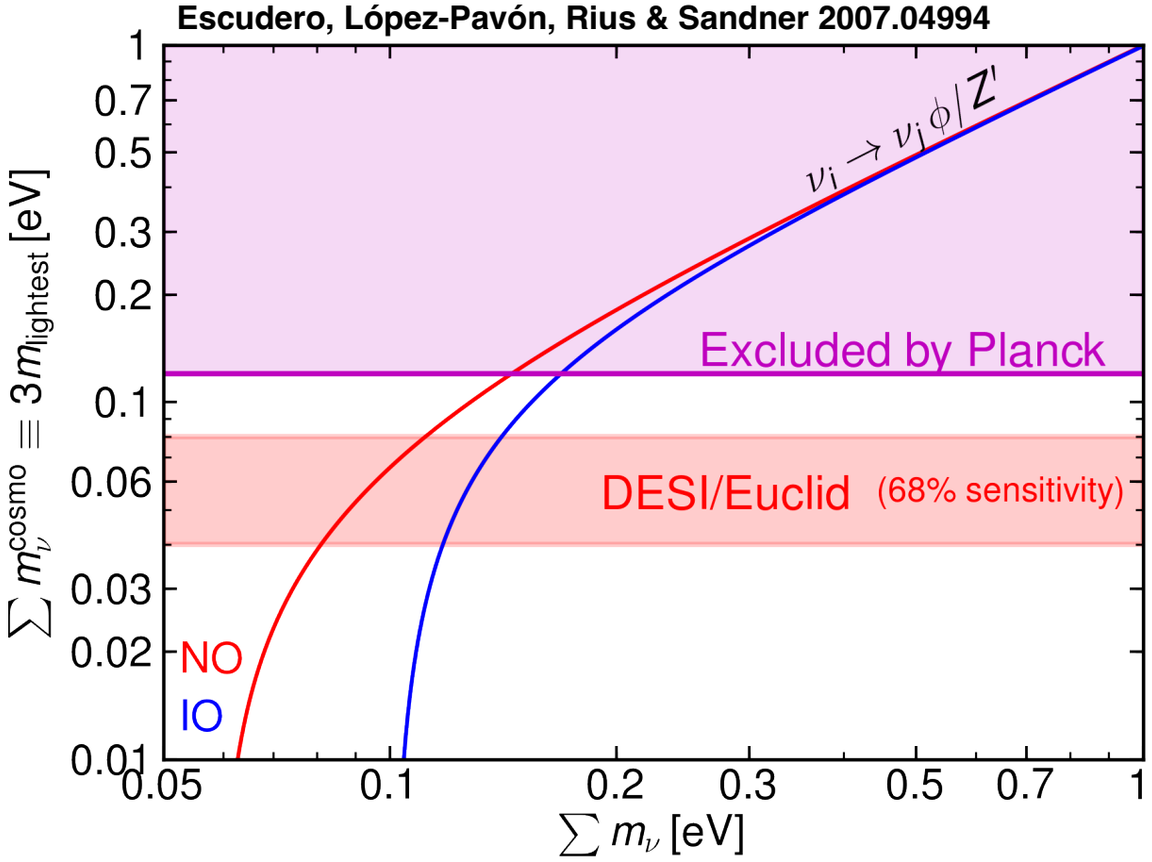

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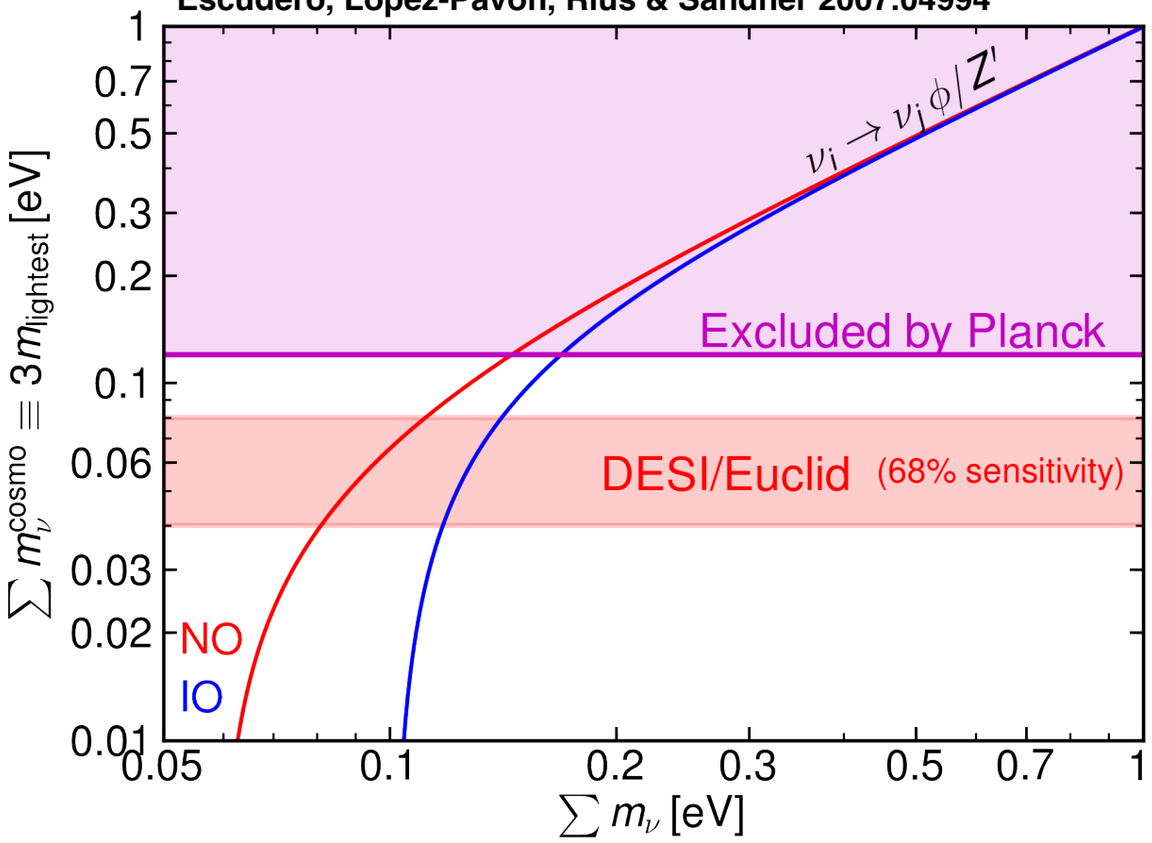
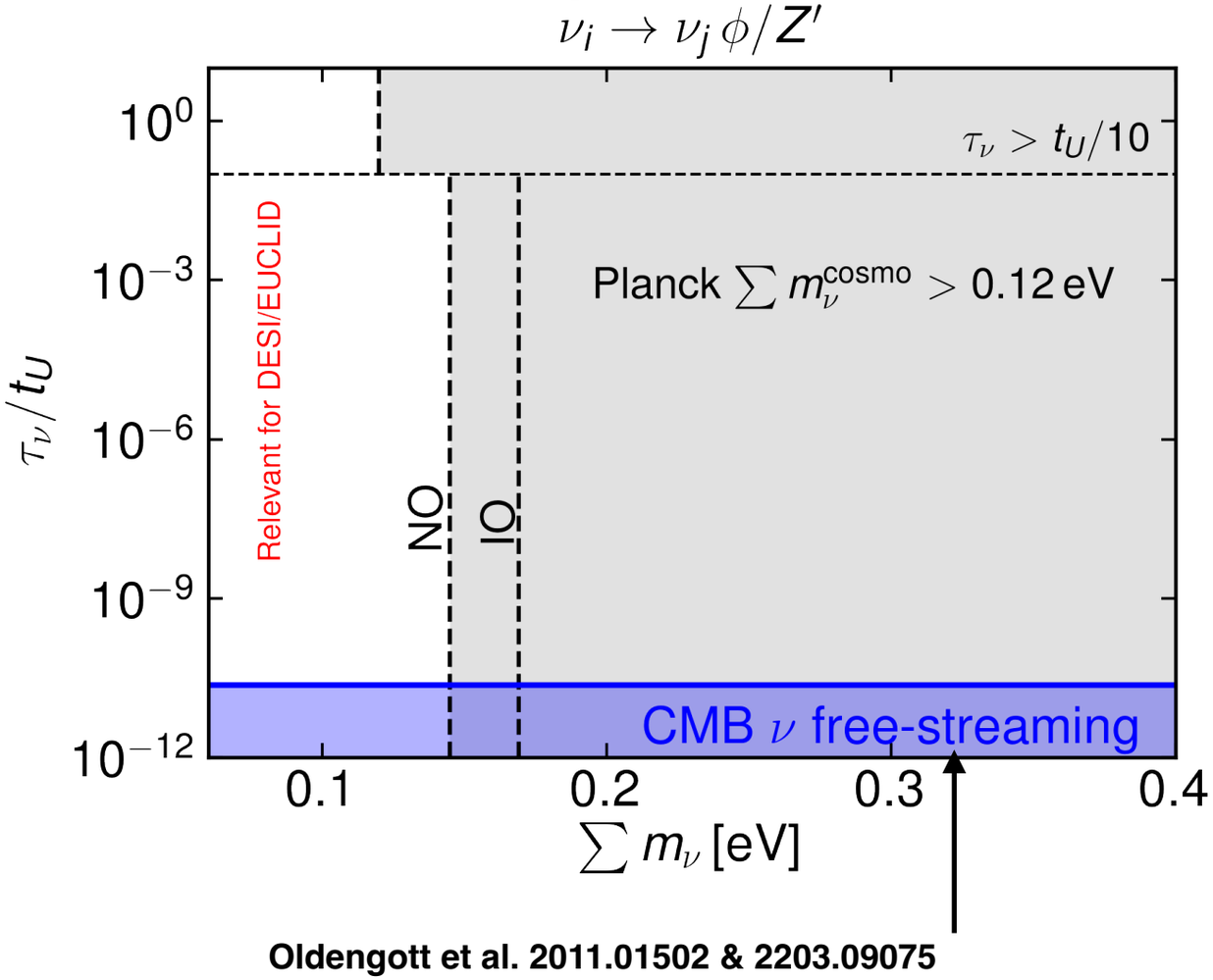


Parameter space:



Oldengott et al. 2011.01502 & 2203.09075

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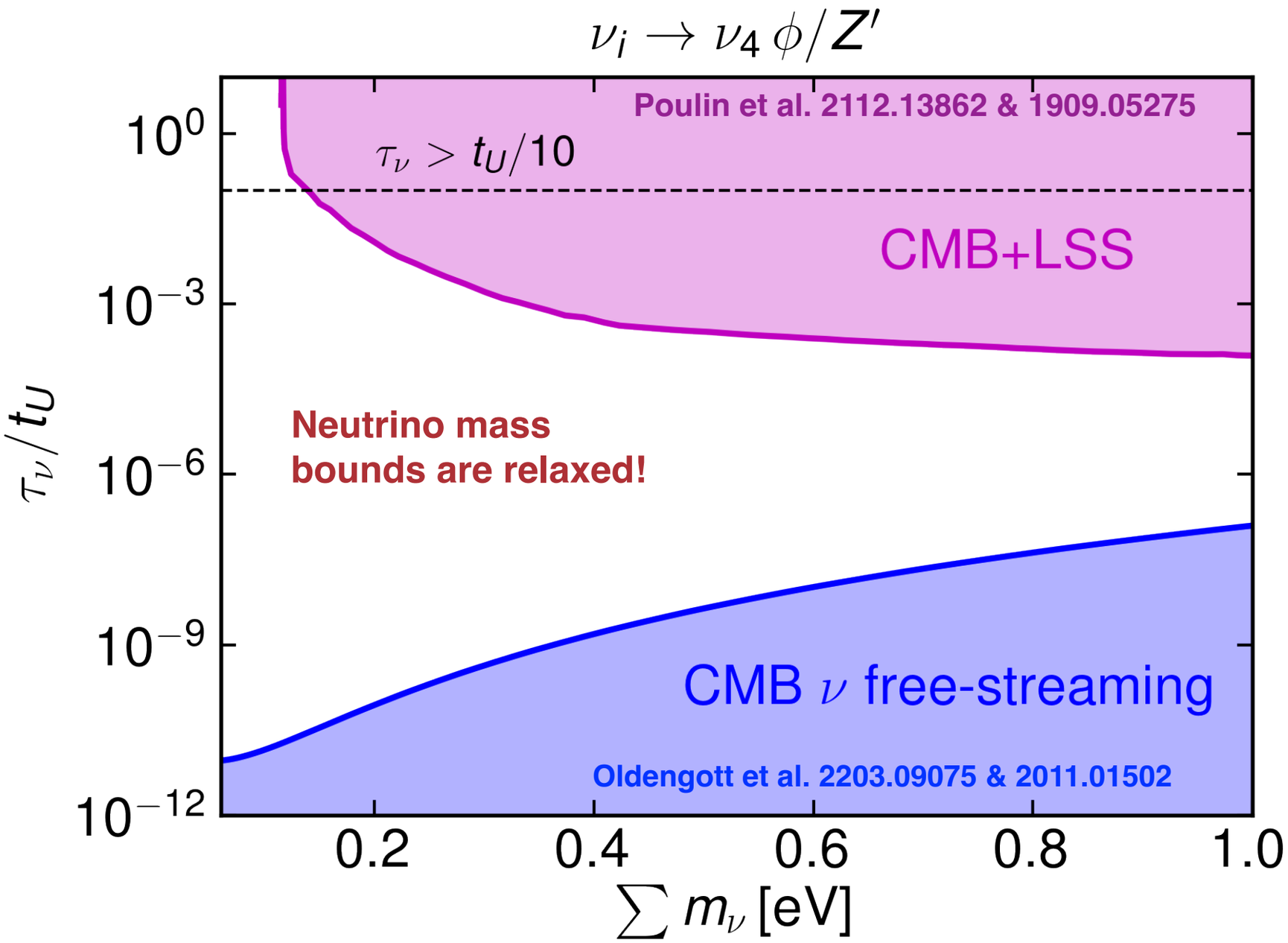

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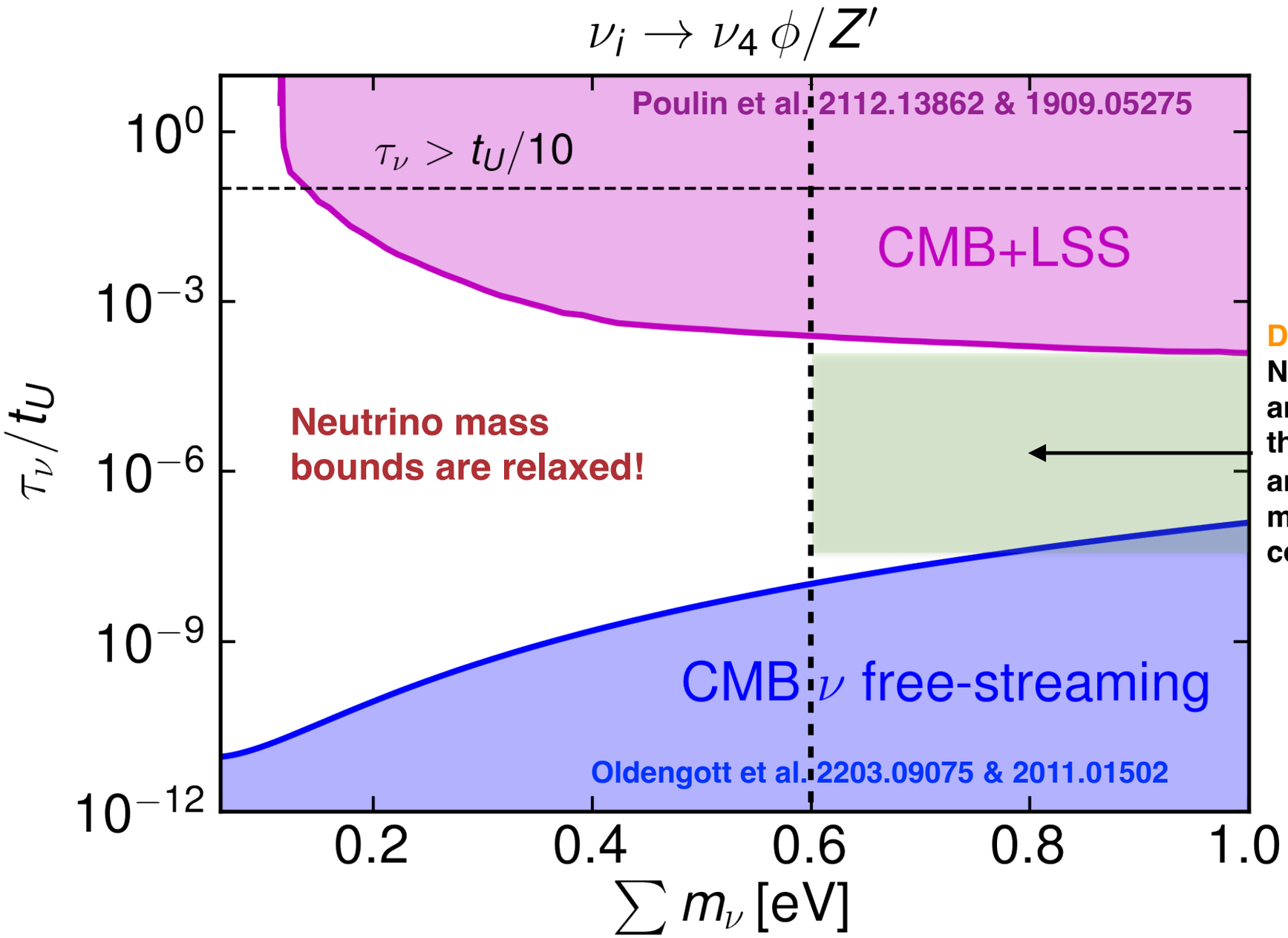

Disclaimer!
No full realistic cosmological analysis has been performed in the literature for $m_\nu > 0.2\,\mathrm{eV}$ and these lifetimes. This region may or may not be excluded by cosmological data

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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!

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- $m_\nu^{\mathrm{cosmo}} = 0?$

  Several models are in the market, some +- theoretically motivated.

  Invisible neutrino decays appear as a very motivated case

  Highlighted a neutrino mass scenario with

$$\tau_\nu \simeq 10^{-4} t_U$$
$$M_N \sim 10^{14}\,\mathrm{GeV}$$
$$\nu_\phi \simeq \nu_H$$

  CMB lensing as a cosmo probe for it!

Time for Questions and Comments

Exciting times in Cosmology!

Cosmological tensions still not significant, but if persistent may be pointing towards some new fundamental neutrino property!

Thank you for your attention!

miguel.escudero@cern.ch