Current constraints on cosmological scenarios with very low reheating temperatures

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based on arXiv:2501.01369 with N Barbieri, T Brinckmann, S Gariazzo, M Lattanzi & O Pisanti

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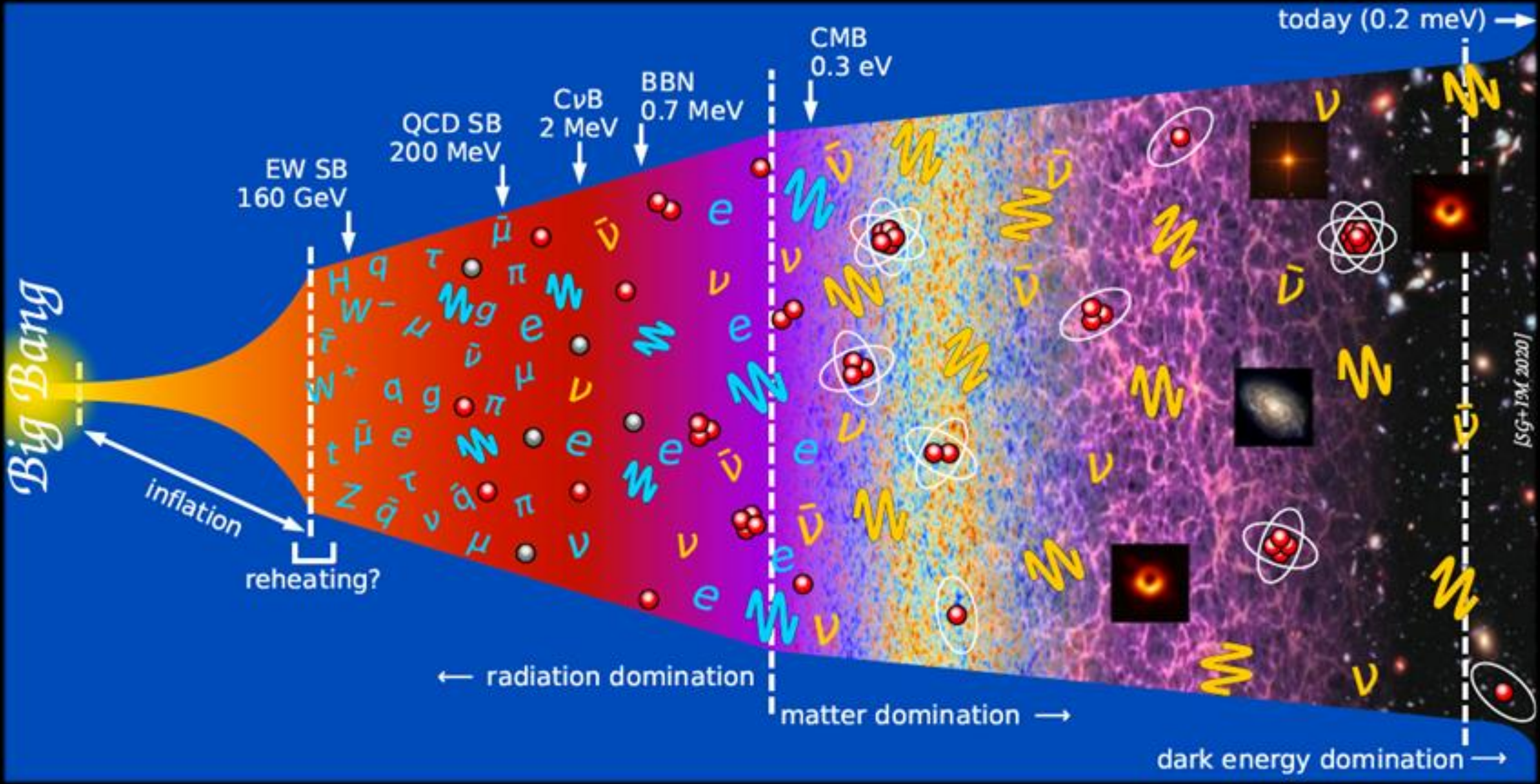
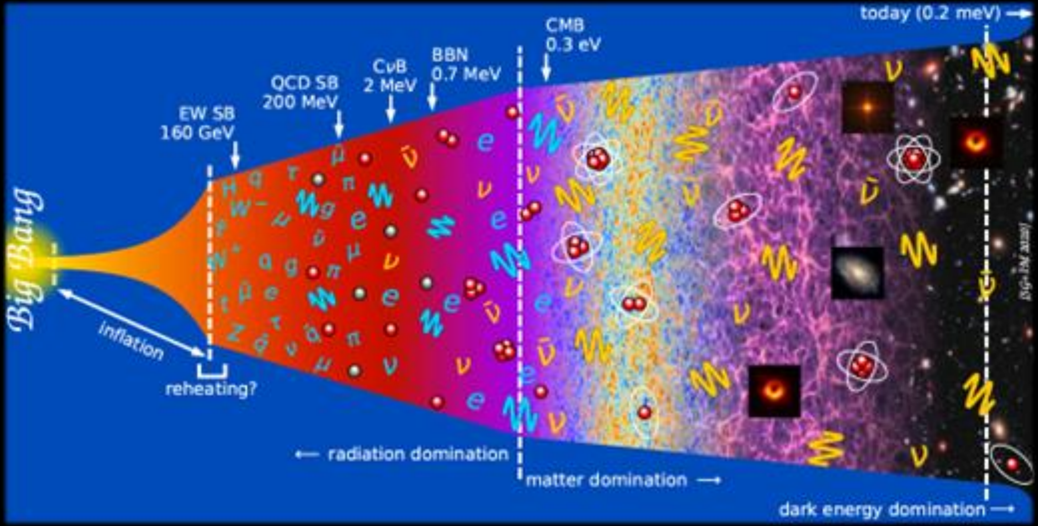
Evolution of the universe



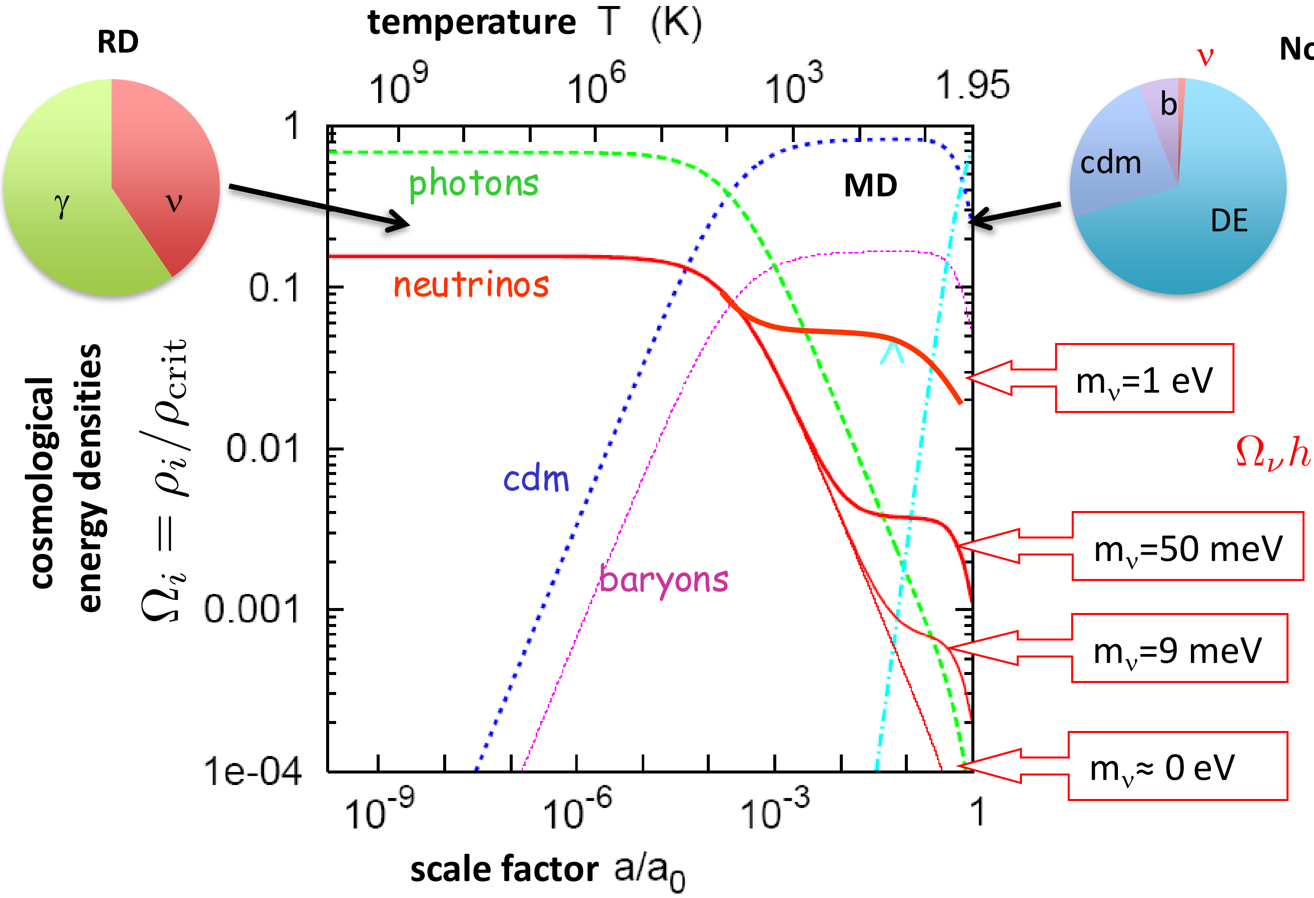
Evolution of the universe



energy density: $\rho(a) = a^{-3(1+w)}$

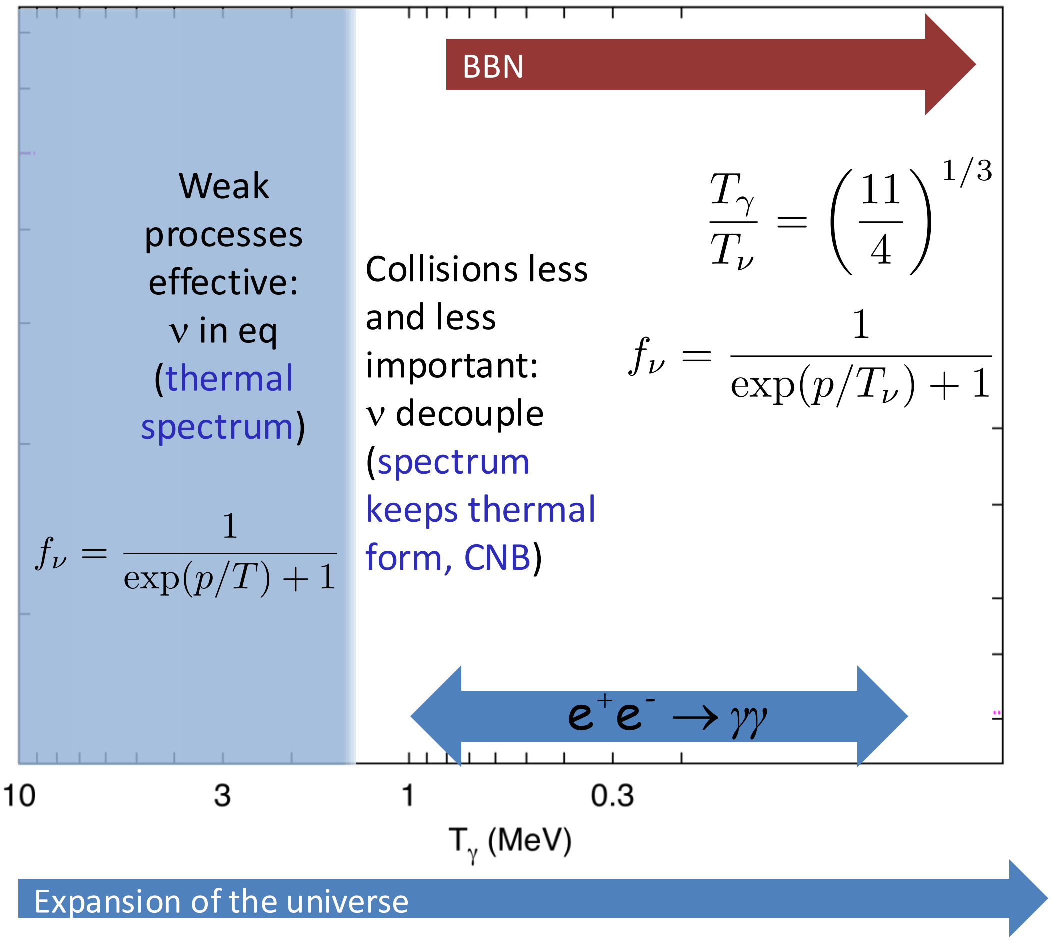
$$\rho_R \sim a^{-4} \quad , \quad w = 1/3 \quad \text{(Radiation)}$$
$$\rho_M \sim a^{-3} \quad , \quad w = 0 \quad \text{(Matter)}$$
$$\rho_\Lambda \sim \text{const.} \quad , \quad w = -1 \quad \text{(Cosmological constant)}$$

Evolution of the background densities: 1 MeV → now



$$\Omega_\nu h^2 = \frac{\sum m_{\nu_i}}{93.2\,\mathrm{eV}}$$

Neutrino decoupling and $e^{\pm}$ annihilation



Relativistic particles in the universe

At $T<m_e$, the radiation content of the Universe is

$$\rho_{\rm rad} = \rho_\gamma + \rho_\nu = \rho_\gamma \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \times 3 \right]$$

Valid for standard neutrinos in the
instantaneous decoupling approximation

Relativistic particles in the universe

At $T<m_e$, the radiation content of the Universe is

$$\rho_{\rm rad} = \rho_\gamma + \rho_\nu + \rho_x = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]$$

effective number of relativistic neutrino species

(effective number of neutrinos)

$N_{\rm eff}$ is a way to measure the ratio $\dfrac{\rho_\nu + \rho_x}{\rho_\gamma}$

K Akita & M Yamaguchi, JCAP 08 (2020) 012
J Froustey, C Pitrou & MC Volpe, JCAP 12 (2020) 015
J J Bennett et al, JCAP 04 (2021) 073

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

(3.0440 ± 0.0002)

standard value

Relativistic particles in the universe

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effective number of relativistic neutrino species

(effective number of neutrinos)

$N_{\rm eff} \neq 3$

additional relativistic particles (scalars, pseudoscalars, decay products of heavy particles,…)

non-standard neutrino physics (**primordial neutrino asymmetries**, totally or partially thermalised light sterile neutrinos, non-standard interactions with electrons,…)

next talk

$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ **(2018) Planck**

(95%, TT,TE,EE+lowE+lensing+BAO)

Very low reheating scenarios

Cosmological scenarios with low reheating temperatures (T_{RH})

REHEATING (standard picture): phase ending **inflation**

during **inflation**, a **non-relativistic scalar** (inflaton) dominates the energy density

during **reheating**, the **NR scalar** ϕ decays into standard particles

→ photons, $e^{\pm}$, etc are populated directly

Radiation Domination (RD) begins after **reheating**

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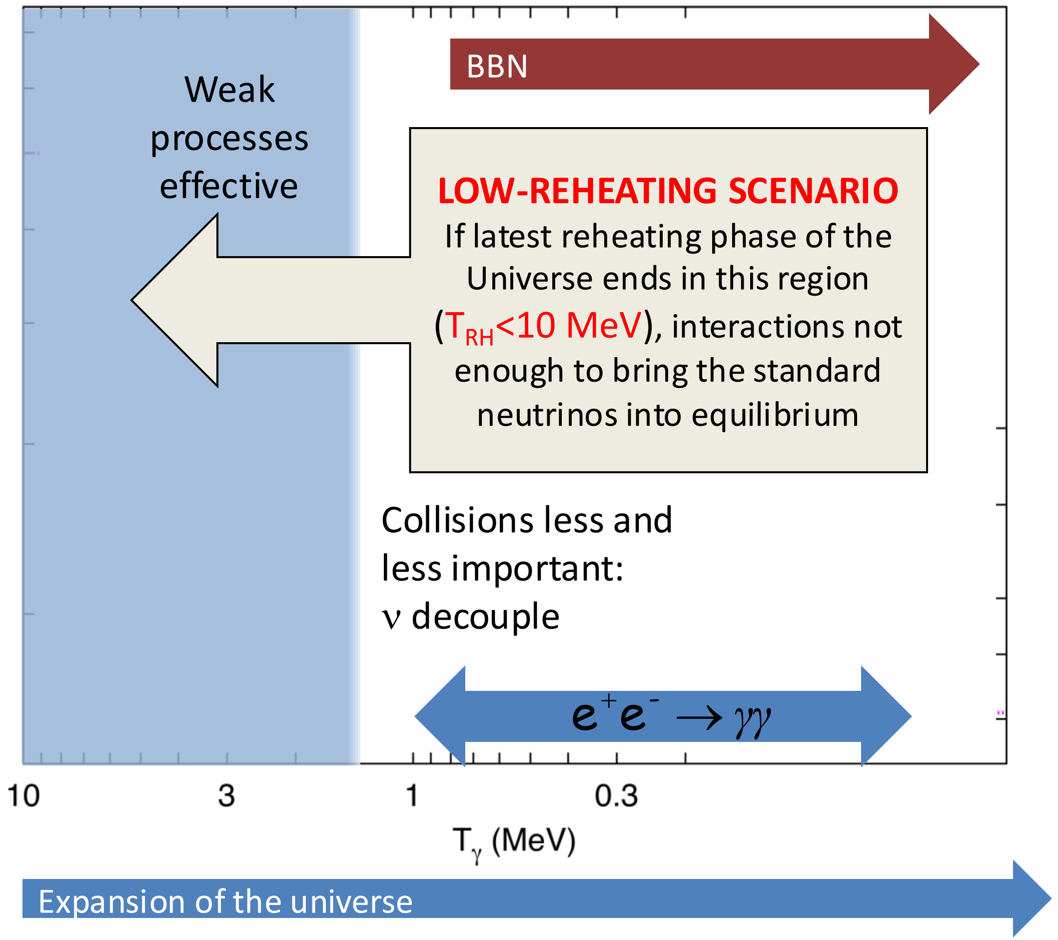
neutrinos are populated via weak interactions with **charged leptons**

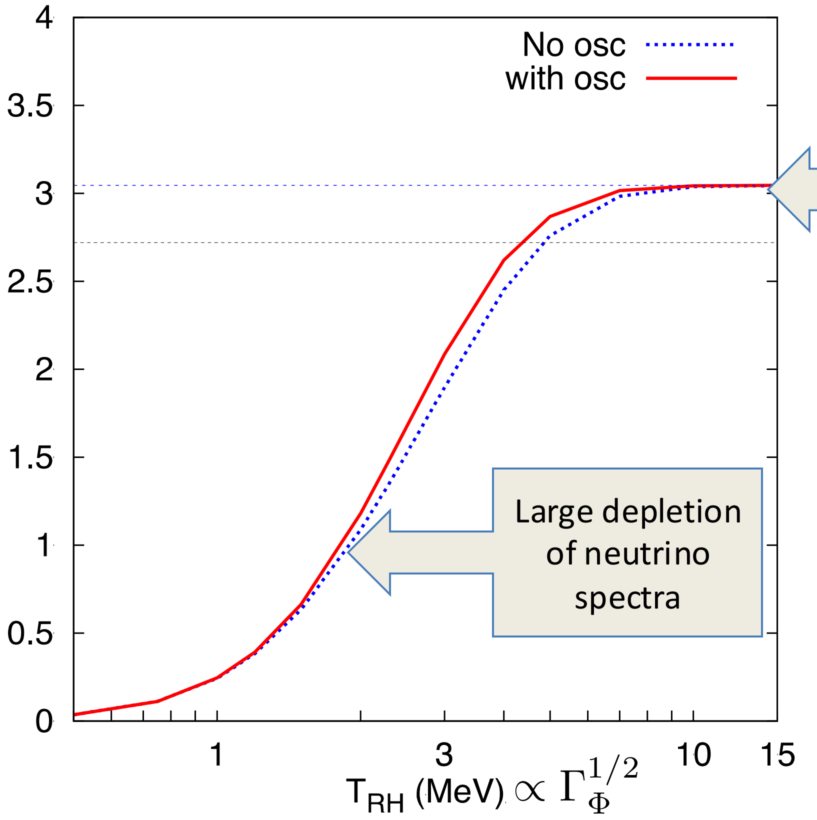
If (last period of) **reheating** occurs **too late:** $T_{\rm RH} \lesssim 10\,{\rm MeV} \to N_{\rm eff} < 3$

$N_{eff} < 3$?


BBN
Weak processes effective
LOW-REHEATING SCENARIO
If latest reheating phase of the Universe ends in this region (T_{RH}<10 MeV), interactions not enough to bring the standard neutrinos into equilibrium
Collisions less and less important:
ν decouple
$e^+e^- \to \gamma\gamma$
10
3
1
0.3
T_γ (MeV)
Expansion of the universe

3ν in very low-reheating scenarios

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



neutrinos in full equilibrum

lower bound (95%CL) on the reheating temperature

$$T_{\rm RH} > 4.7\ {\rm MeV}$$

(PlanckTT+ lowP)

M Lattanzi et al, PRD 92 (2015) 123534

+ previous works since 1998

Our work: a more precise calculation of neutrino evolution + BBN production

Boltzmann evolution equations (matrix form)

$$(\partial_t - Hp\,\partial_p)\,\varrho_p(t) = -i\left[\left(\frac{1}{2p}\mathbb{M}_\mathrm{F} - \frac{8\sqrt{2}G_\mathrm{F}p}{3m_\mathrm{W}^2}\mathbb{E}\right), \varrho_p(t)\right] + \mathcal{I}\left[\varrho_p(t)\right]$$

vacuum osc. term — matter potential term — collision integrals (α G_F^2)

take into account neutrino-electron scattering and pair annihilation

2D integrals over the momentum, take most of the computation time

\+ continuity equation

$$\dot{\rho} = -3H(\rho + P)$$

\+ evolution of scalars

$$\dot{\rho}_\phi = -(3H + \Gamma_\phi)\rho_\phi$$

Code: FORTran-Evolved PrimordIAl Neutrino Oscillations (**FortEPiaNO**)

→ $f_{\nu_\alpha}(p,t)$ **Effect on BBN (PArthENoPE code)**

↓ $^4\mathrm{He}$ abundance

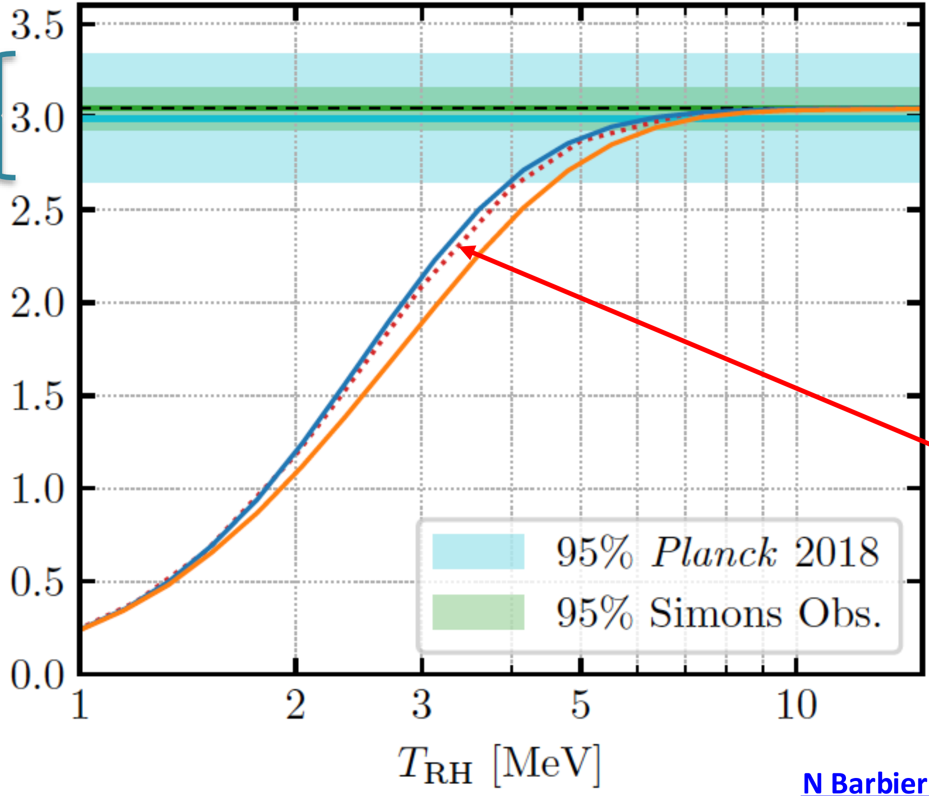
→ $\mathrm{Final}\ f_{\nu_i}(p)$ **Analysis of CMB+BAO data**

Final value of N_{eff} (T_{RH})

current 95% CL range

future 95% CL sensitivity

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

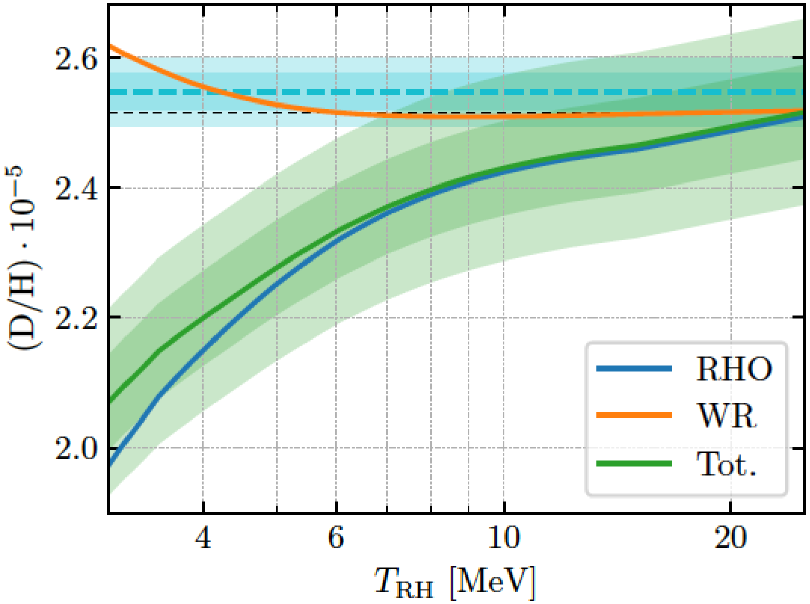


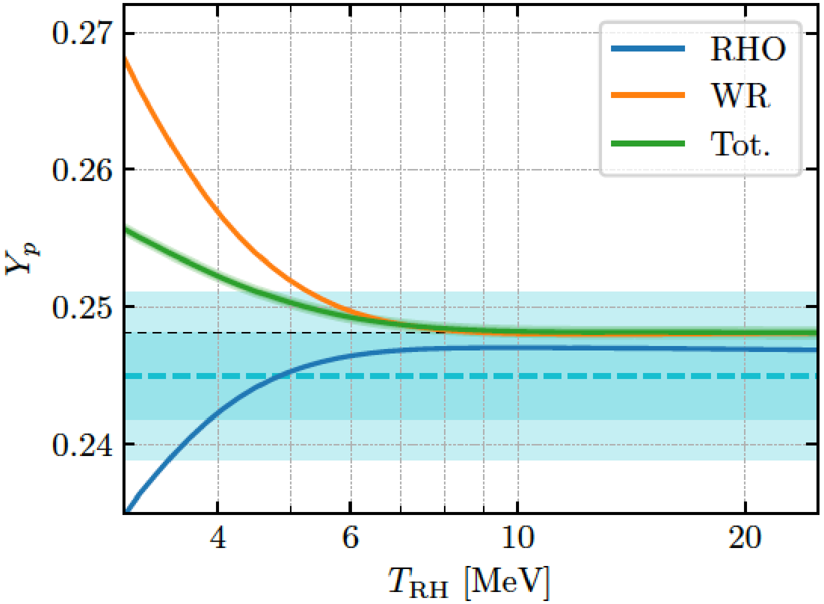
2015 result

N Barbieri et al, arXiv:2501.01369

Effect on Primordial Nucleosynthesis: PArthENoPE code

current 68/95% CL regions from measurements of primordial D and ^{4}He (PDG)





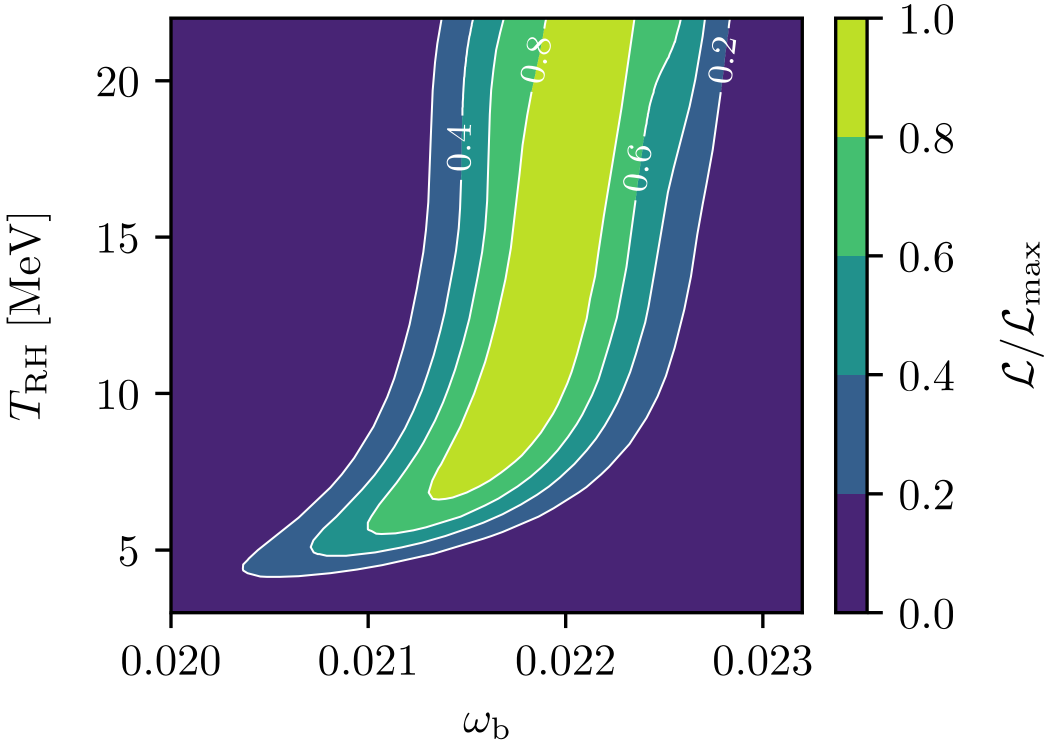
RHO : effect of N_{eff} only

WR : effect of $f(\nu_\varepsilon)$ on weak rates only

Tot. : **TOTAL effect:** D/H decreases and Y_p increases for **smaller T_{RH}**

N Barbieri et al, arXiv:2501.01369

BBN likelihood function (T_{RH})

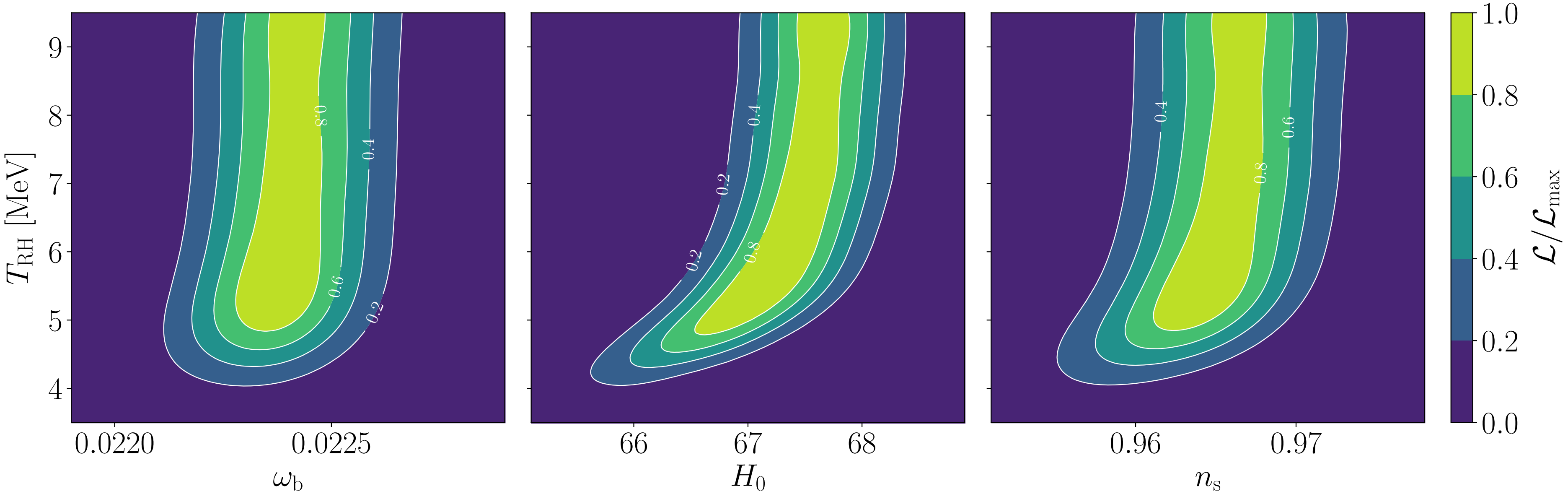


BBN only

$T_{RH} > 3.67\,\mathrm{MeV}$ (95% CL)

N Barbieri et al, arXiv:2501.01369

Planck+lensing+DESI likelihood function (T_{RH})

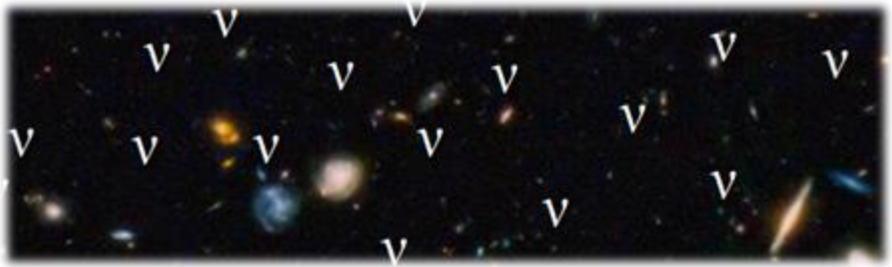


$$T_{\rm RH} > 3.79 \text{ MeV} \quad \text{(Planck+lensing+DESI)}$$

$$T_{\rm RH} > 5.96 \text{ MeV (BBN+Planck+lensing+DESI)}$$

N Barbieri et al, arXiv:2501.01369

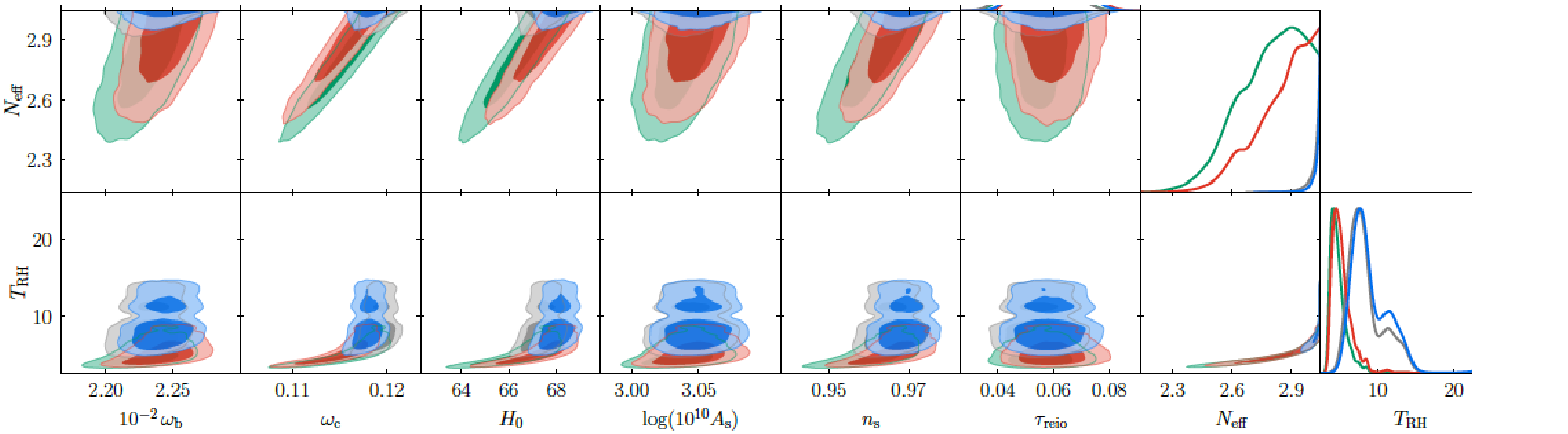
Conclusions



✓ We solved the momentum-dependent kinetic equations for neutrinos in the early universe, including flavour oscillations, in a **very low reheating scenario**: neutrino spectra are depleted ($N_{eff} < 3$)

✓ A consistent BBN+Planck+lensing+DESI analysis leads to the **most stringent bound** to date on the reheating temperature: $T_{\rm RH} > 5.96\,{\rm MeV}\ (95\%\ {\rm CL})$

Backup slides



Planck+lensing+BOSS/eBOSS: $T_{\rm RH} > 3.62$ MeV

Planck+lensing+DESI: $T_{\rm RH} > 3.79$ MeV

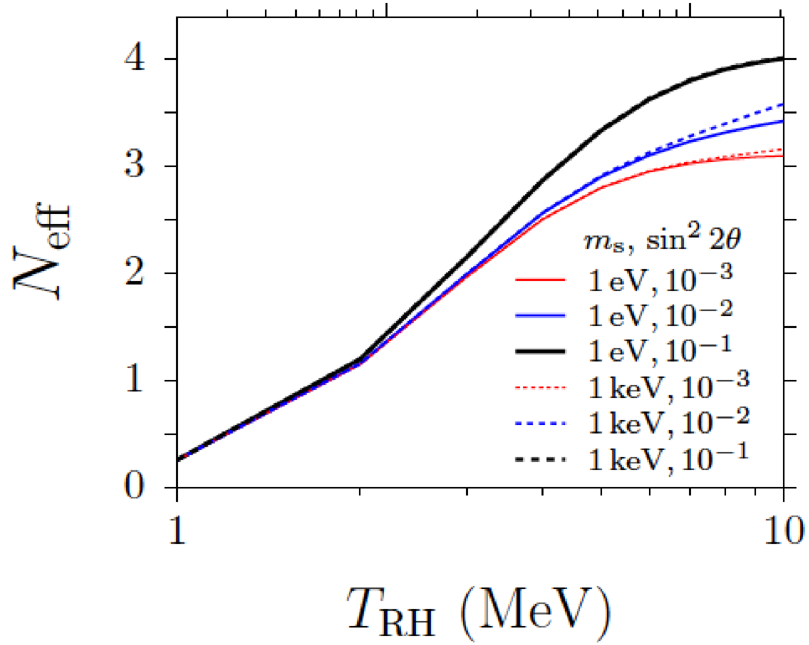
BBN+Planck+lensing+BOSS/eBOSS: $T_{\rm RH} > 5.57$ MeV

BBN+Planck+lensing+DESI: $\boldsymbol{T_{\rm RH} > 5.96}$ **MeV**

3+1 case in very low-reheating scenarios

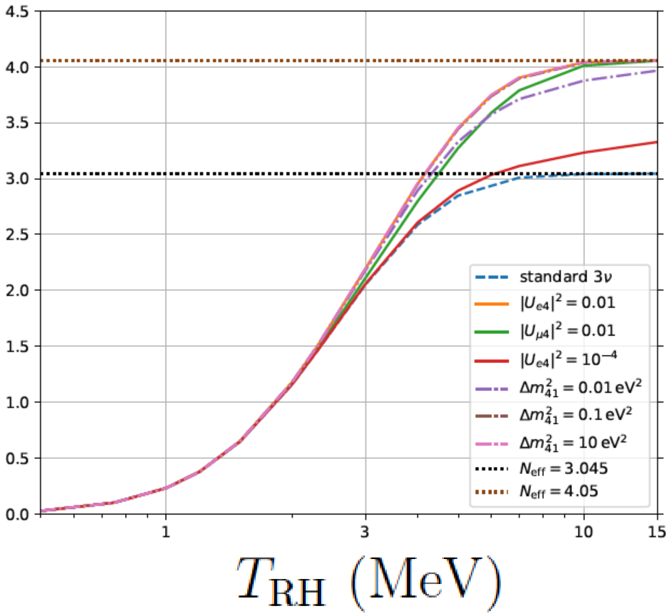
reduced N_{eff} with non-zero active-sterile neutrino mixing

1 + 1



M Hasegawa et al, JCAP 08 (2020) 015

3 + 1

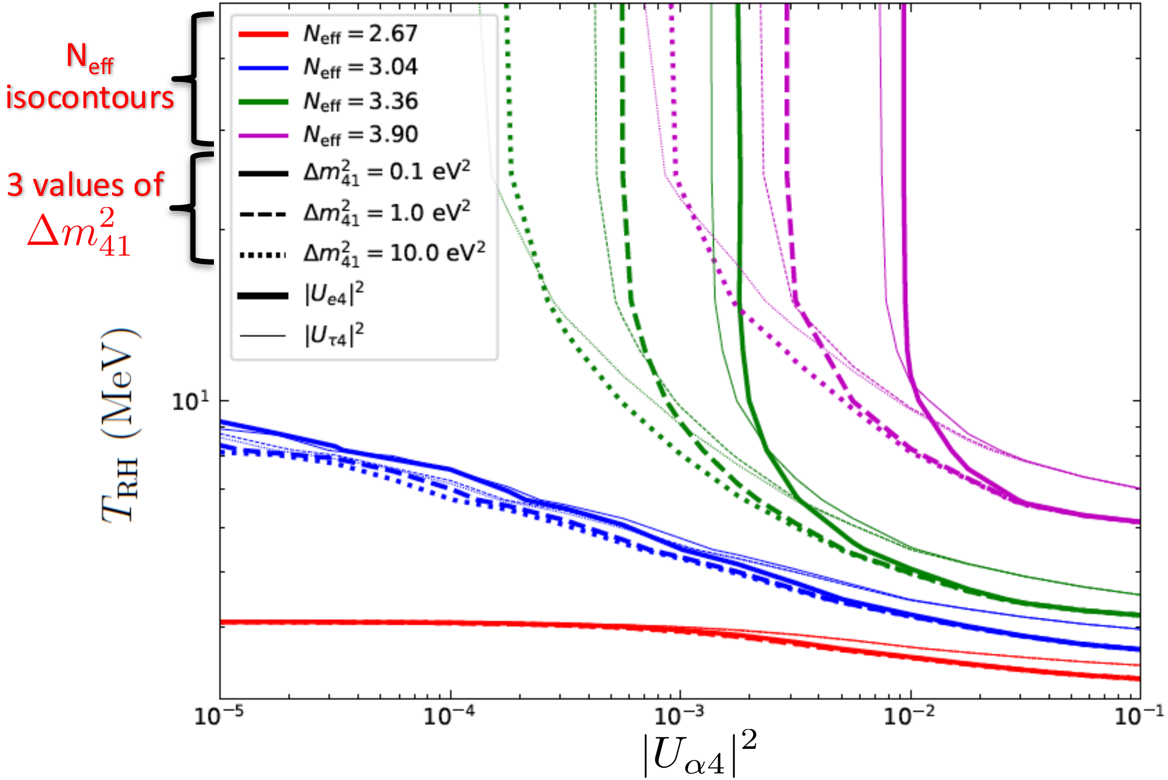


N Barbieri et al, in preparation

N_{eff} with varying mixing angle / mass splitting

for low T_{rh}, mixing parameters are irrelevant

for higher Δm^2_{41}, T_{rh} has more impact



N Barbieri et al, in preparation