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New Frontiers in Theoretical Physics 2025
CONVEGNO NAZIONALE DI FISICA TEORICA

Based on **Barbieri+** (2025)
arXiv:2501.01369 [astro-ph]

In collaboration with T. Brinckmann,
S. Gariazzo, M. Lattanzi, S. Pastor and O. Pisanti

Current constraints on cosmological scenarios with very low reheating temperatures

NICOLA BARBIERI (INFN) – 20/05/2025

Models of reheating

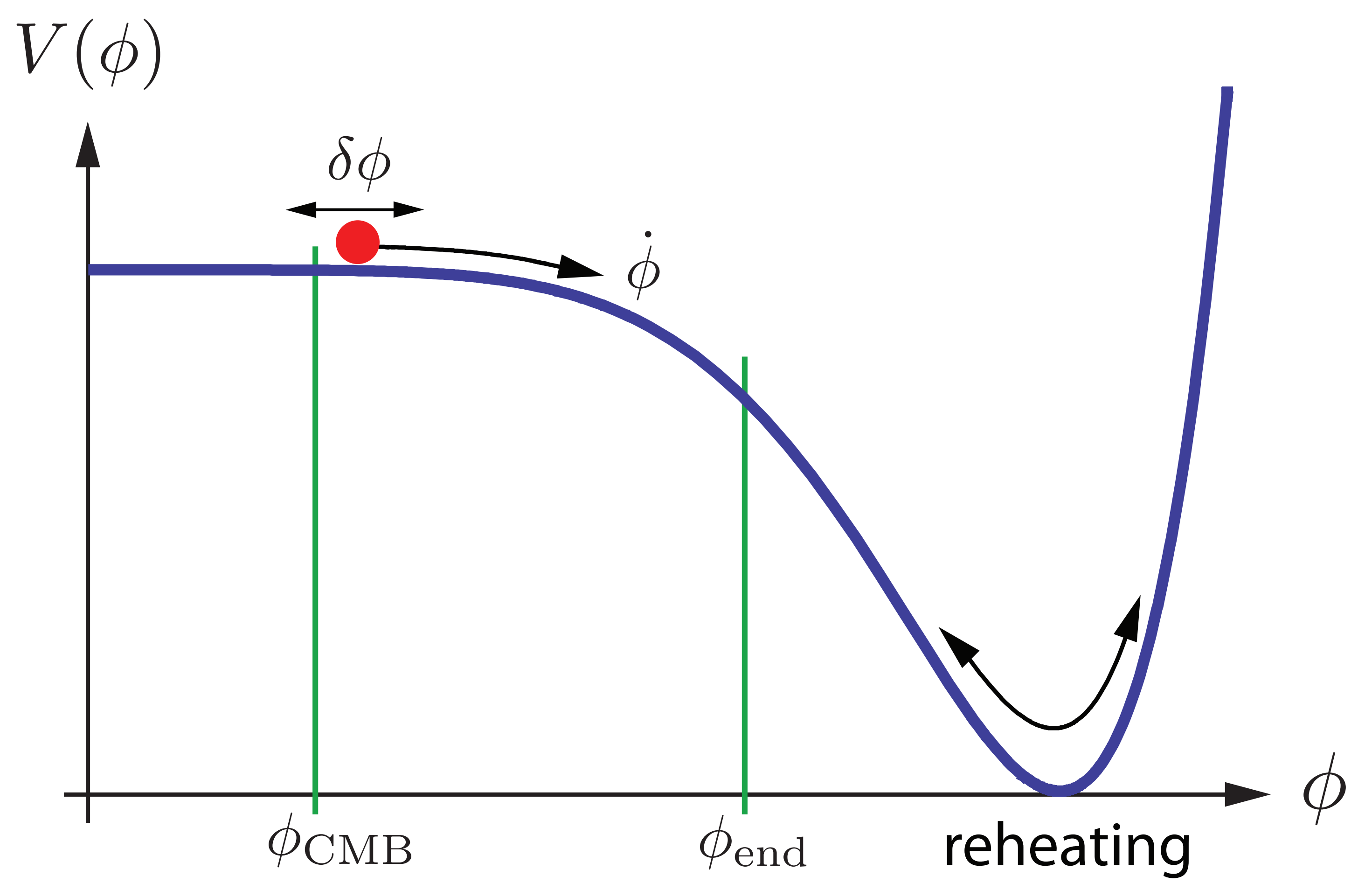
- In inflation paradigm, a final reheating phase is needed to reconcile with the standard FLRW radiation dominated Universe

$$\frac{d\rho_\phi}{dt} + (3H + \Gamma_\phi)\,\rho_\phi = 0$$

- What is the reheating temperature?

$$\Gamma_\phi \equiv 3H\left(T_{\rm RH}\right) \qquad \Rightarrow \qquad T_{\rm RH} \simeq 0.7\left(\frac{\Gamma_\phi}{\rm s^{-1}}\right)^{1/2}\ \text{MeV}$$

$$H\left(T_{\rm RH}\right) = \sqrt{\frac{8\pi}{3m_{\rm pl}^2}\rho_{\rm rad}\left(T_{\rm RH}\right)} = \sqrt{\frac{8\pi}{90}g_*\left(T_{\rm RH}\right)}\frac{T_{\rm RH}^2}{m_{\rm pl}}$$



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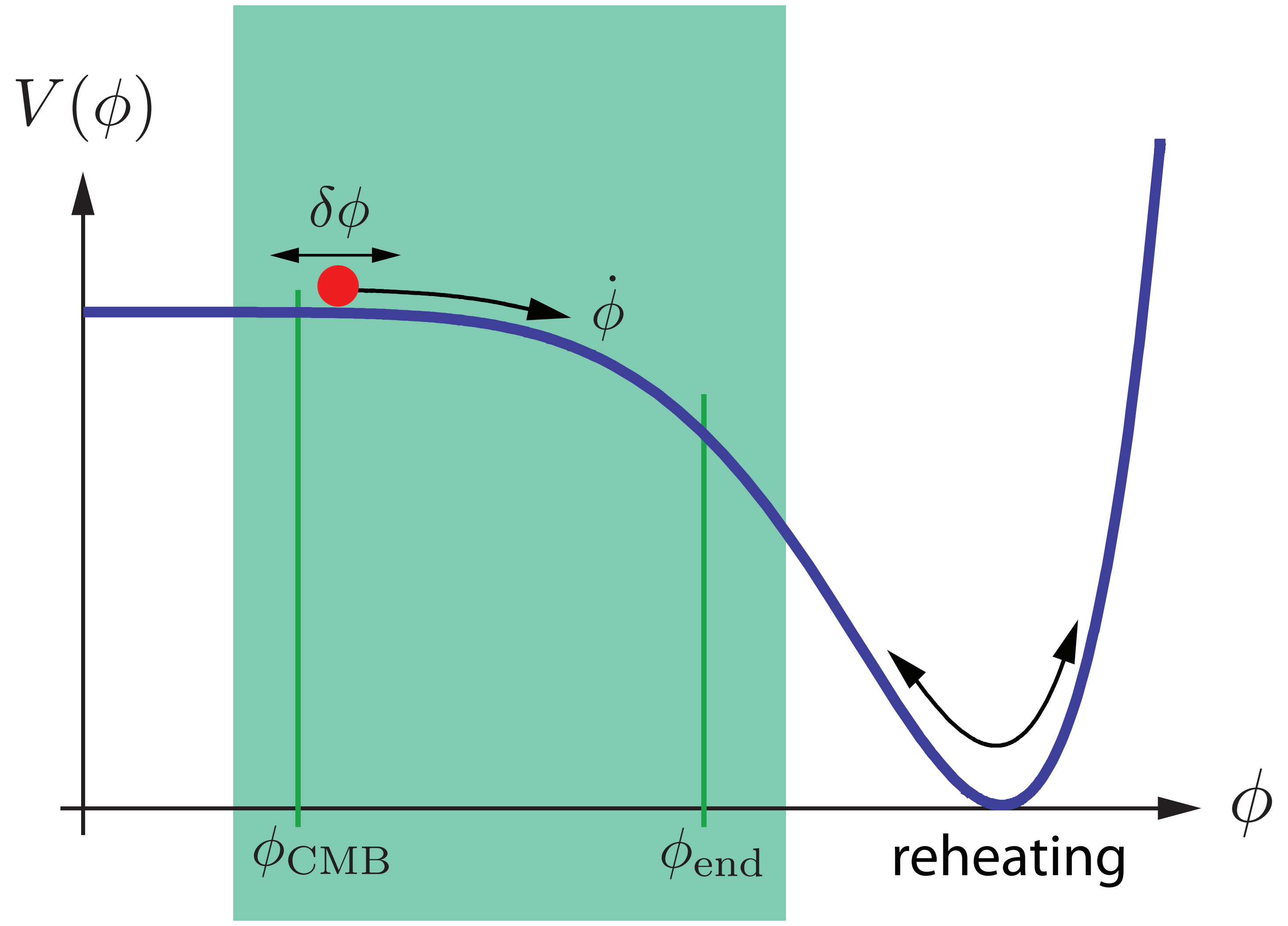
During **inflation** the inflaton dominates the energy density (as pressure-less matter)



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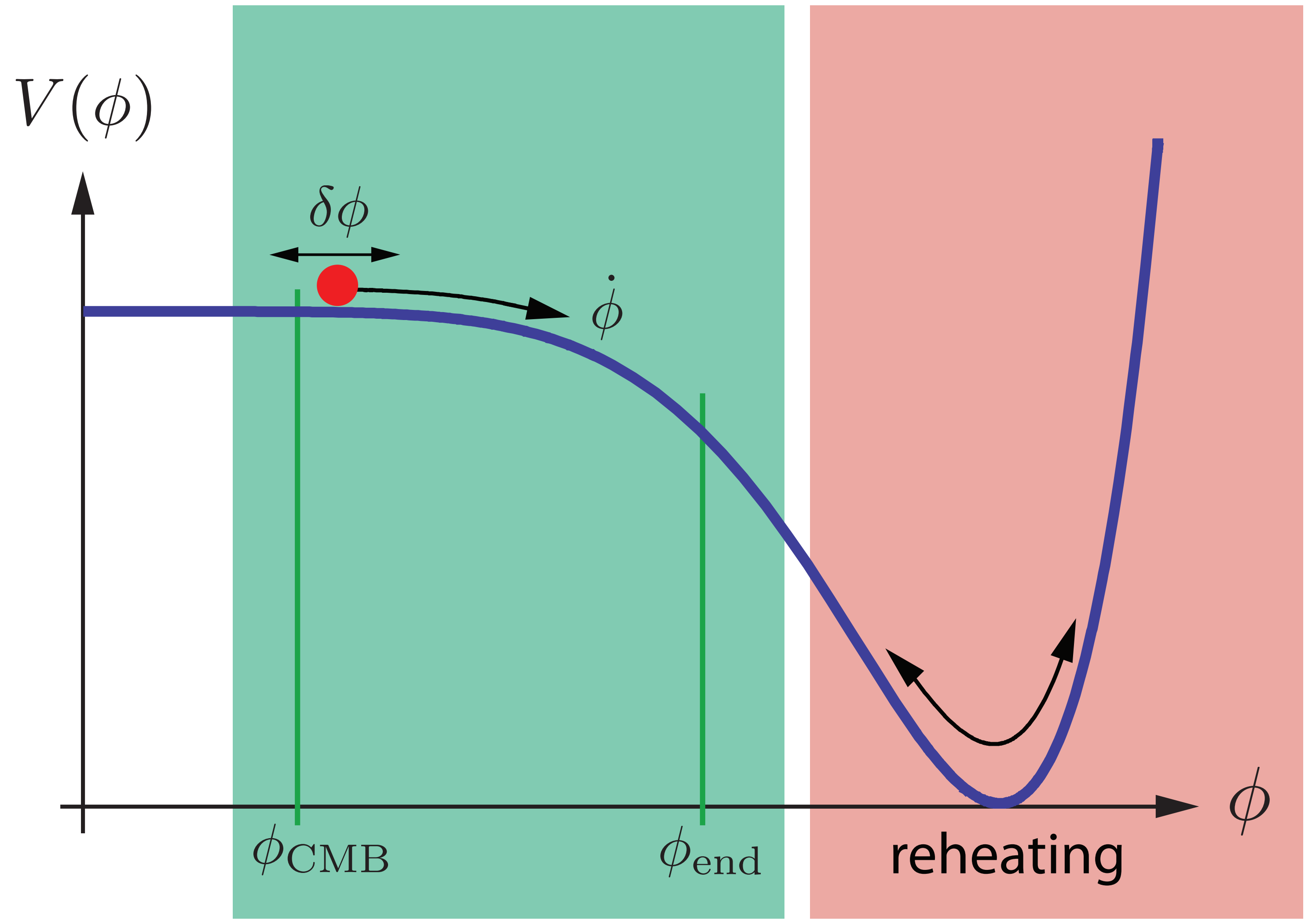

During **reheating** the inflaton decays into Standard Model degrees of freedom

Assumptions and remarks

Photons, electrons, and other SM particles are populated directly by the **decay of the scalar**

Neutrinos are populated by weak **interactions with leptons**

We define a **very low reheating** when it occurs at temperatures $T_{\rm RH} \lesssim 20$ MeV

Oscillations start to be affected at $T_{\rm RH} \lesssim 8$ MeV

Neutrino production - I

- Evolution of three flavour neutrino momentum distributions with oscillations and QED corrections

$$\frac{d\varrho\left(y,x\right)}{dx}=\sqrt{\frac{3m_{\mathrm{pl}}^{2}}{8\pi\rho}}\left\{-i\frac{x^{2}}{m_{e}^{3}}\left[\frac{\mathbb{M}_{\mathrm{F}}}{2y}-\frac{2\sqrt{2}G_{\mathrm{F}}ym_{e}^{6}}{x^{6}}\left(\frac{\mathbb{E}_{\ell}+\mathbb{P}_{\ell}}{m_{W}^{2}}+\frac{4}{3}\frac{\mathbb{E}_{\nu}}{m_{Z}^{2}}\right),\varrho\right]+\frac{m_{e}^{3}}{x^{4}}\mathcal{I}\left(\varrho\right)\right\}$$

NB: everything expressed in terms of comoving variables

$$x\equiv m_e a \quad y\equiv pa \quad z\equiv T_\gamma a$$

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Density matrix:
transition probability between different flavour states

$$\varrho(p,t) = \begin{pmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho_{\mu e} & f_{\nu_e} & \varrho_{\mu\tau} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & f_{\nu_e} \end{pmatrix}$$

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Vacuum oscillations: quantum effect only due to non-zero mass splittings between neutrino states

$$\mathbb{M}_{\rm F}=U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}U^\dagger$$

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Matter effects: forward interactions with neutrinos and leptons due to weak charged and neutral currents

Collision integrals: effect of neutrino collisions with exchange of momenta

$$\frac{d\varrho(y,x)}{dx} = \sqrt{\frac{3m_{\rm pl}^2}{8\pi\rho}} \left\{ -i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_{\rm F}}{2y} - \frac{2\sqrt{2}G_{\rm F}ym_e^6}{x^6}\left(\frac{\mathbb{E}_\ell+\mathbb{P}_\ell}{m_W^2}+\frac{4}{3}\frac{\mathbb{E}_\nu}{m_Z^2}\right),\varrho\right] + \frac{m_e^3}{x^4}\mathcal{I}(\varrho)\right\}$$

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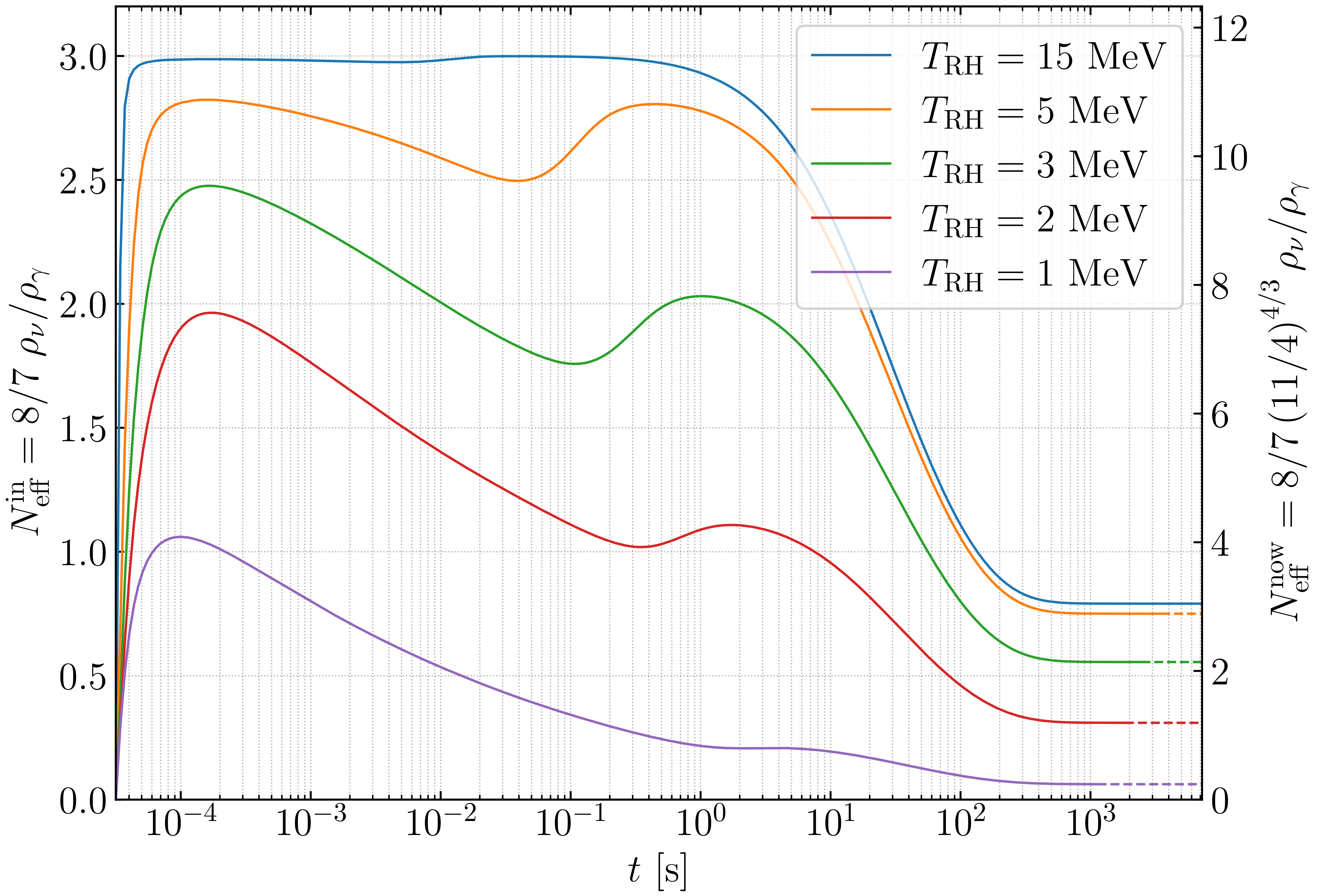
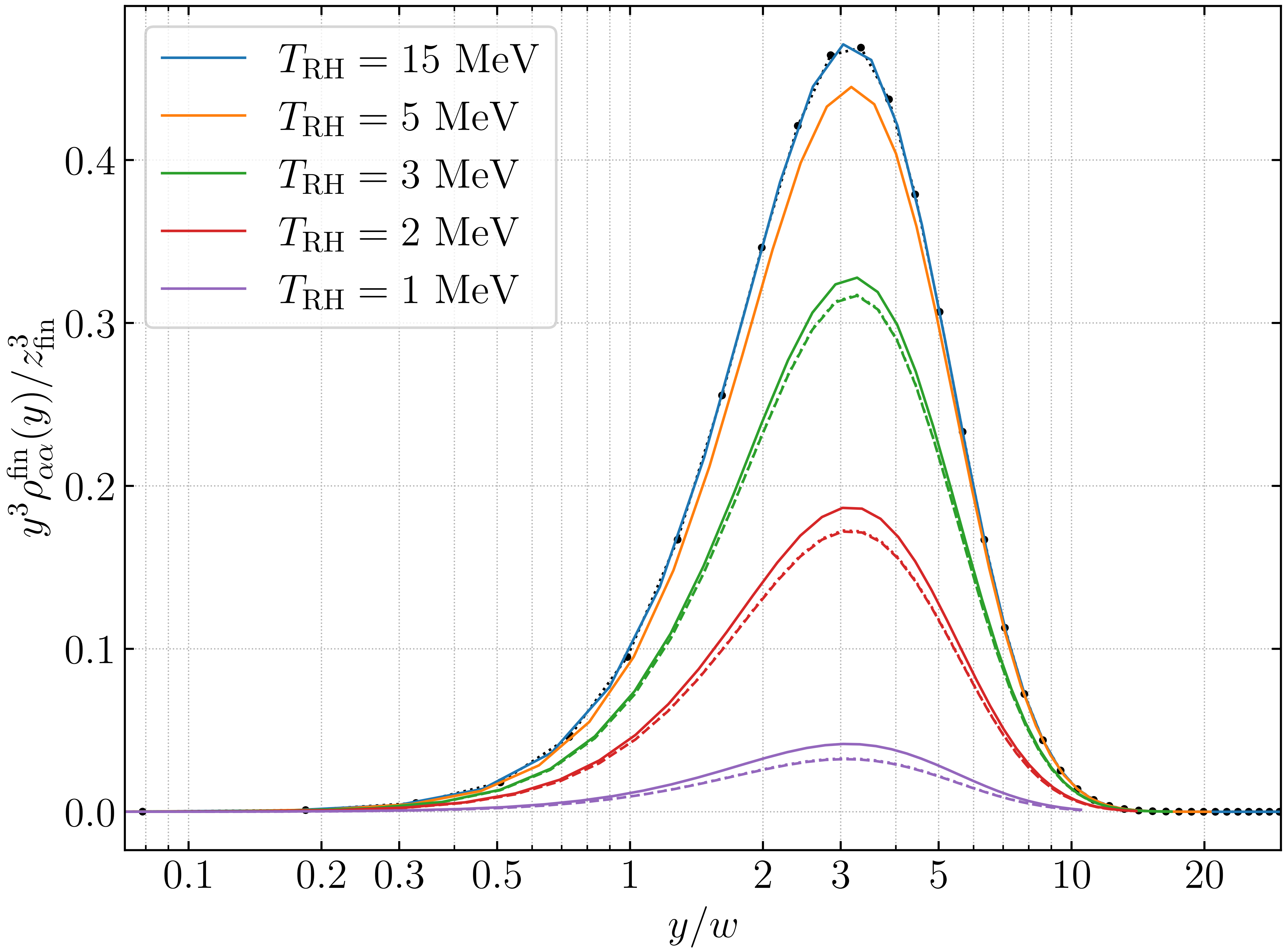


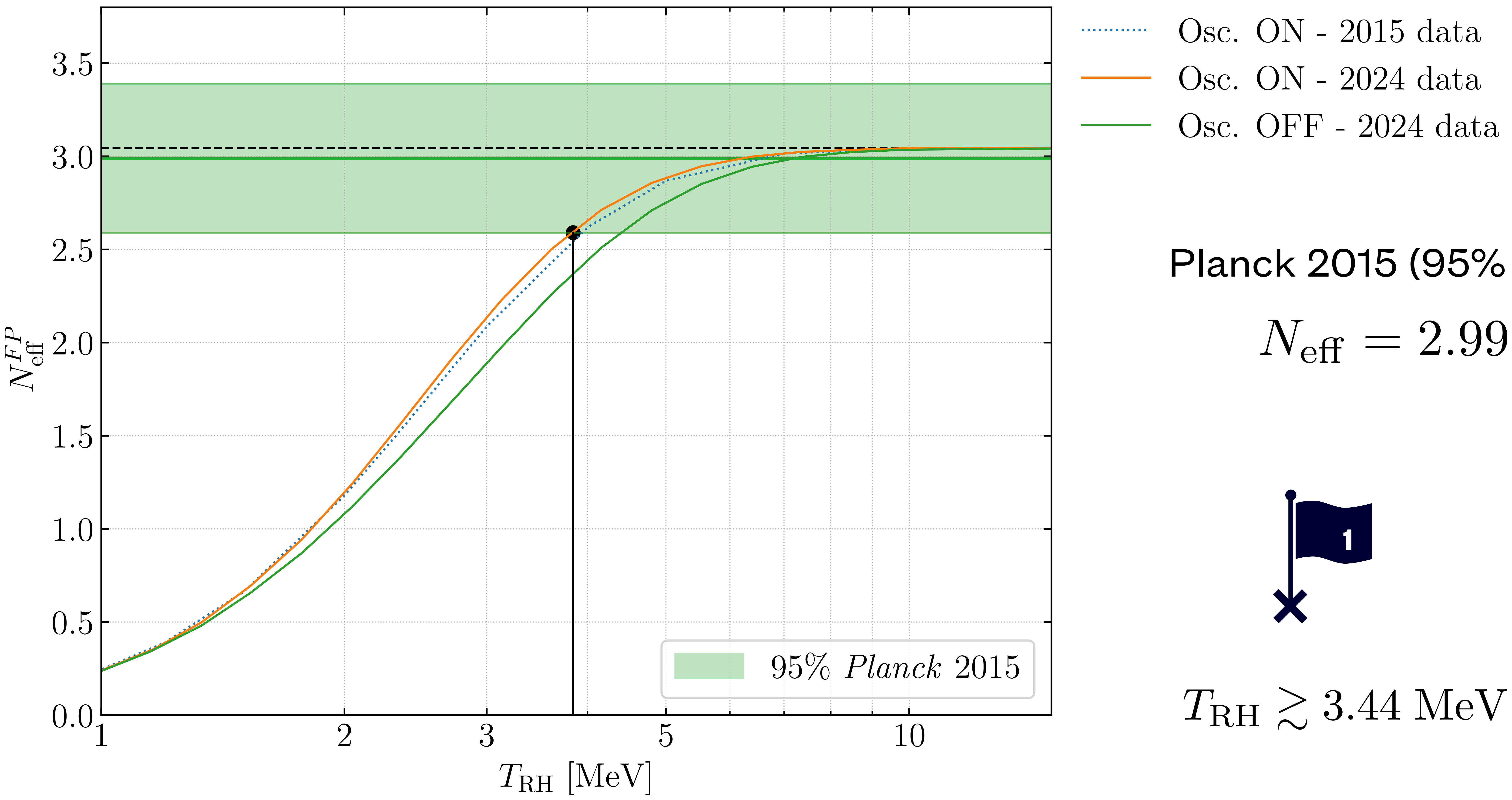
Time evolution of the ratio of energy densities of neutrinos and photons.



Final differential spectra of neutrino energies as a function of the comoving momentum.

Neutrino production - III

MODIFIED VERSION OF FORTEPIANO CODE



Planck 2015 (95% TT,TE,EE+lowP):

$$N_{\rm eff} = 2.99 \pm 0.4$$

$$T_{\rm RH} \gtrsim 3.44 \text{ MeV}$$

Neutrino production - III

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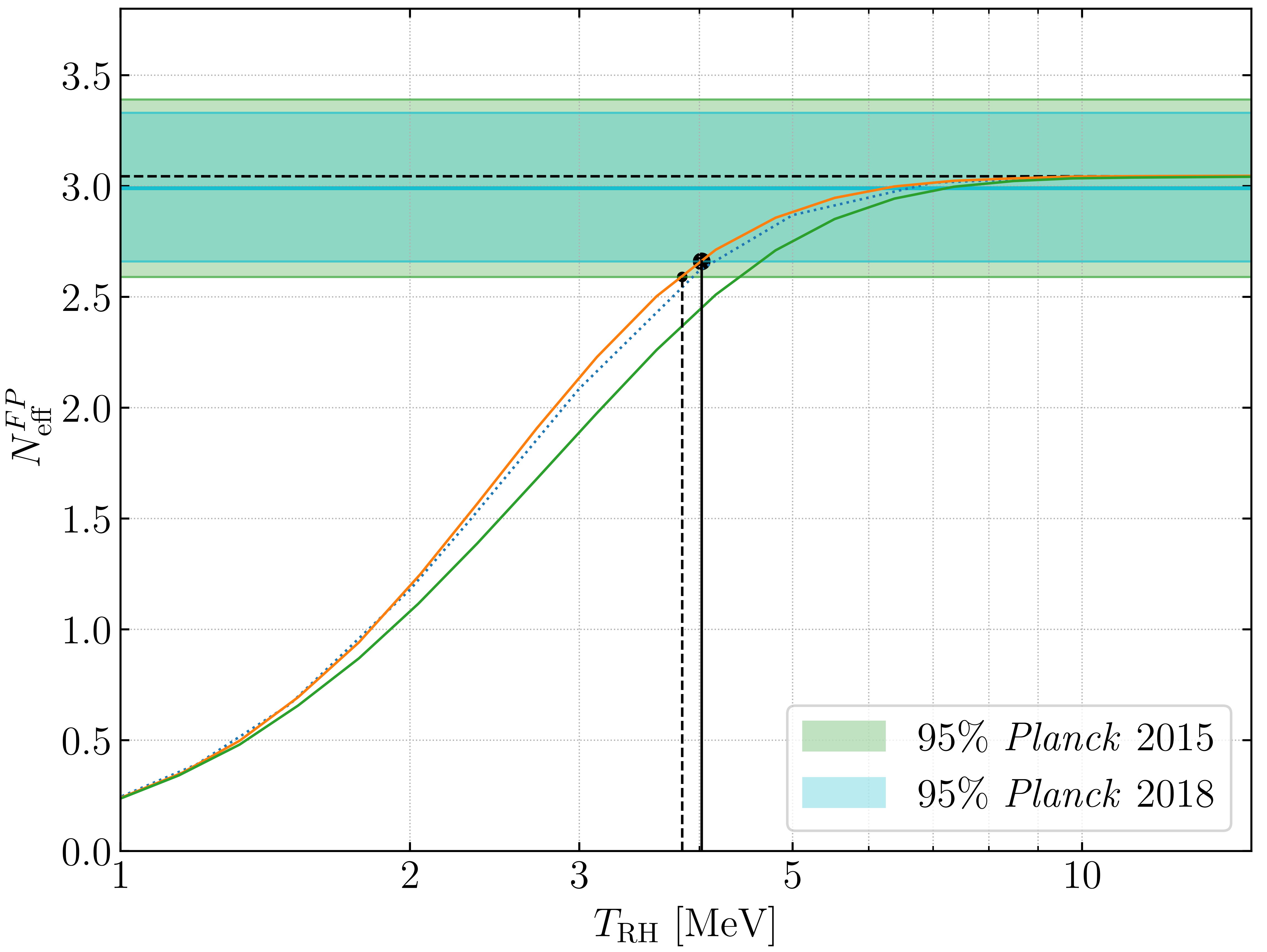
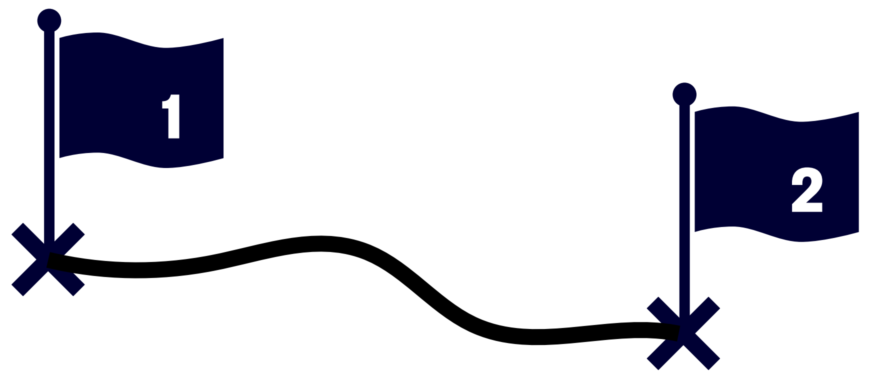


Planck 2018 (95% TT,TE,EE+lowE+lensing+BAO):

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$$



~~$T_{\rm RH} \gtrsim 3.44$ MeV~~

$T_{\rm RH} \gtrsim 4.02$ MeV

Neutrino production - III

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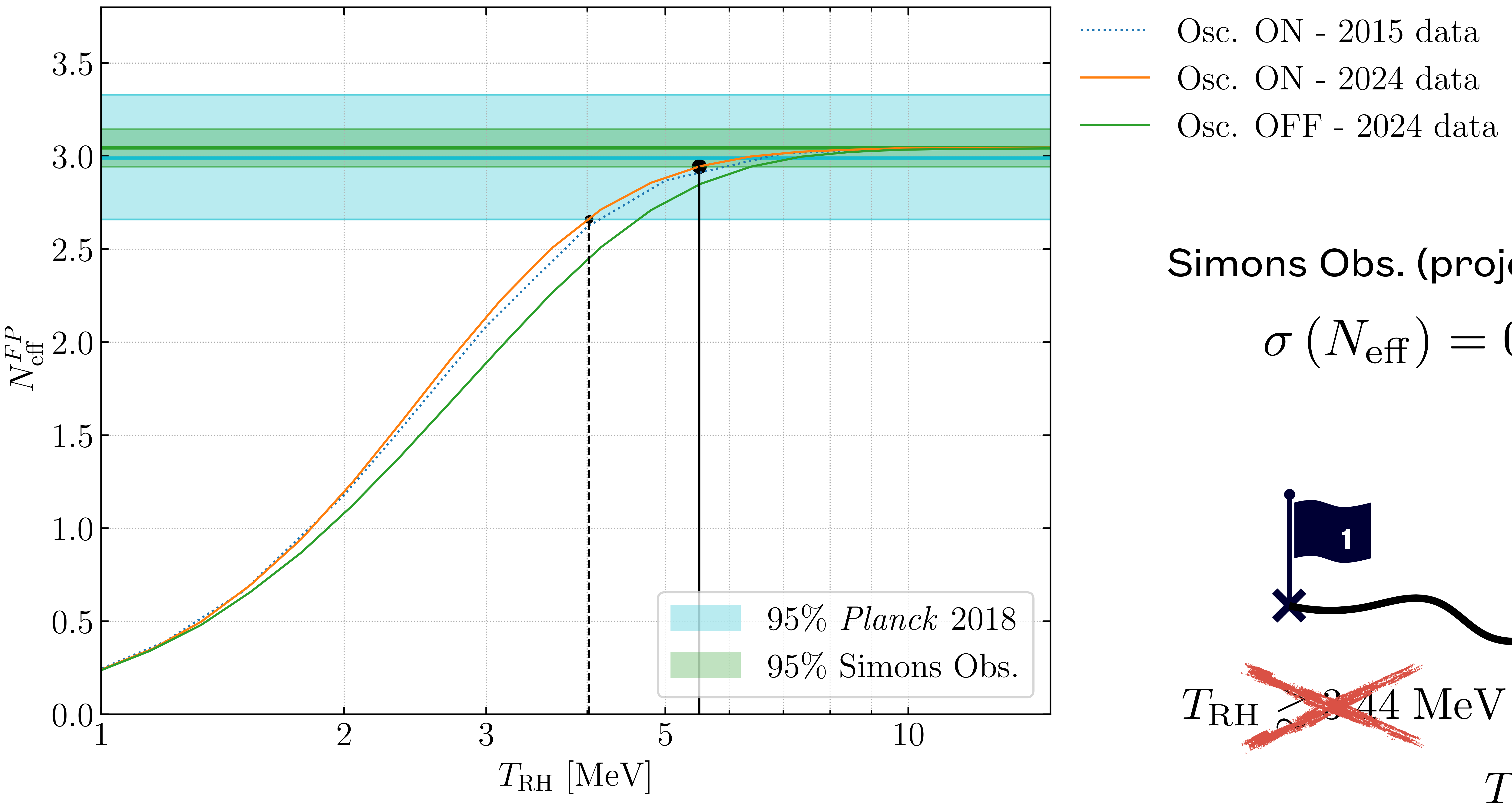
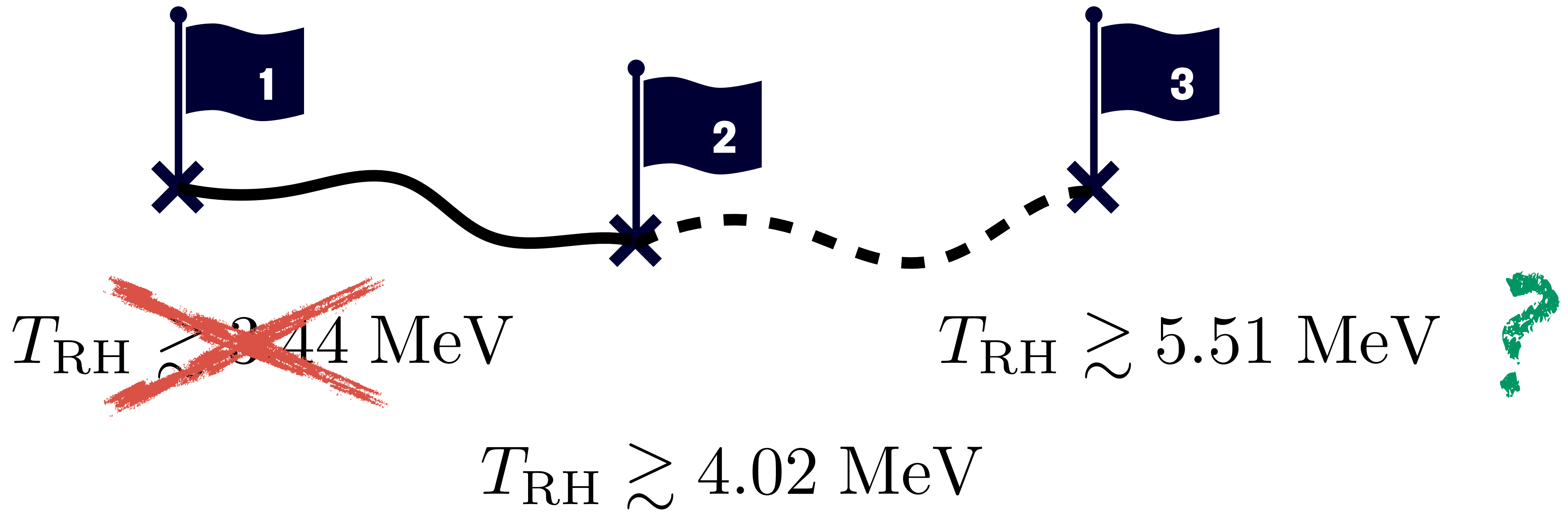


Simons Obs. (projected sensitivity):

$$\sigma\left(N_{\rm eff}\right) = 0.050$$

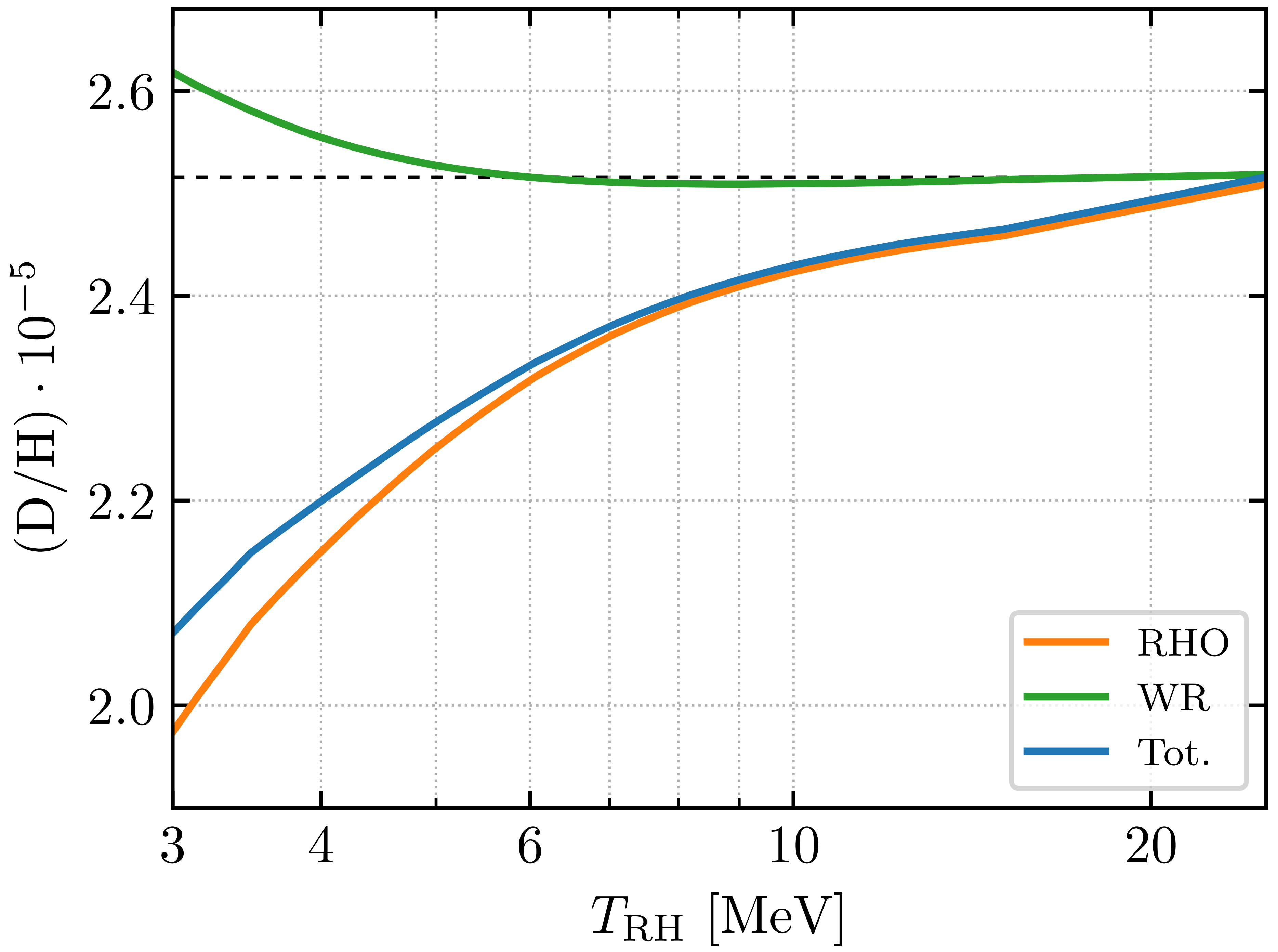


Probes of low reheating: BBN

MODIFIED VERSION OF PARTHENOPE CODE

- The total neutrino energy density contributes to the radiation energy density which leads to the **Hubble expansion rate**;
- Electron neutrinos distribution function enters the charged current weak rates, which govern the **neutron-proton chemical equilibrium**;
- The total neutrino energy density also appears in the **continuity equation**, which is conventionally handled by defining

$$\mathcal{N} = \frac{1}{z^4}\left(x\frac{d}{dx}\bar{\rho}_\nu\right)$$



Values of the deuterium to hydrogen ratio as a function of $T_{\rm RH}$

$$\left(\chi^2_{^4\rm He}\chi^2_{^2\rm H}\right)(T_{\rm RH}) \leq 4 \quad \Rightarrow \quad T_{\rm RH} \geq 3.67\,\text{MeV}$$

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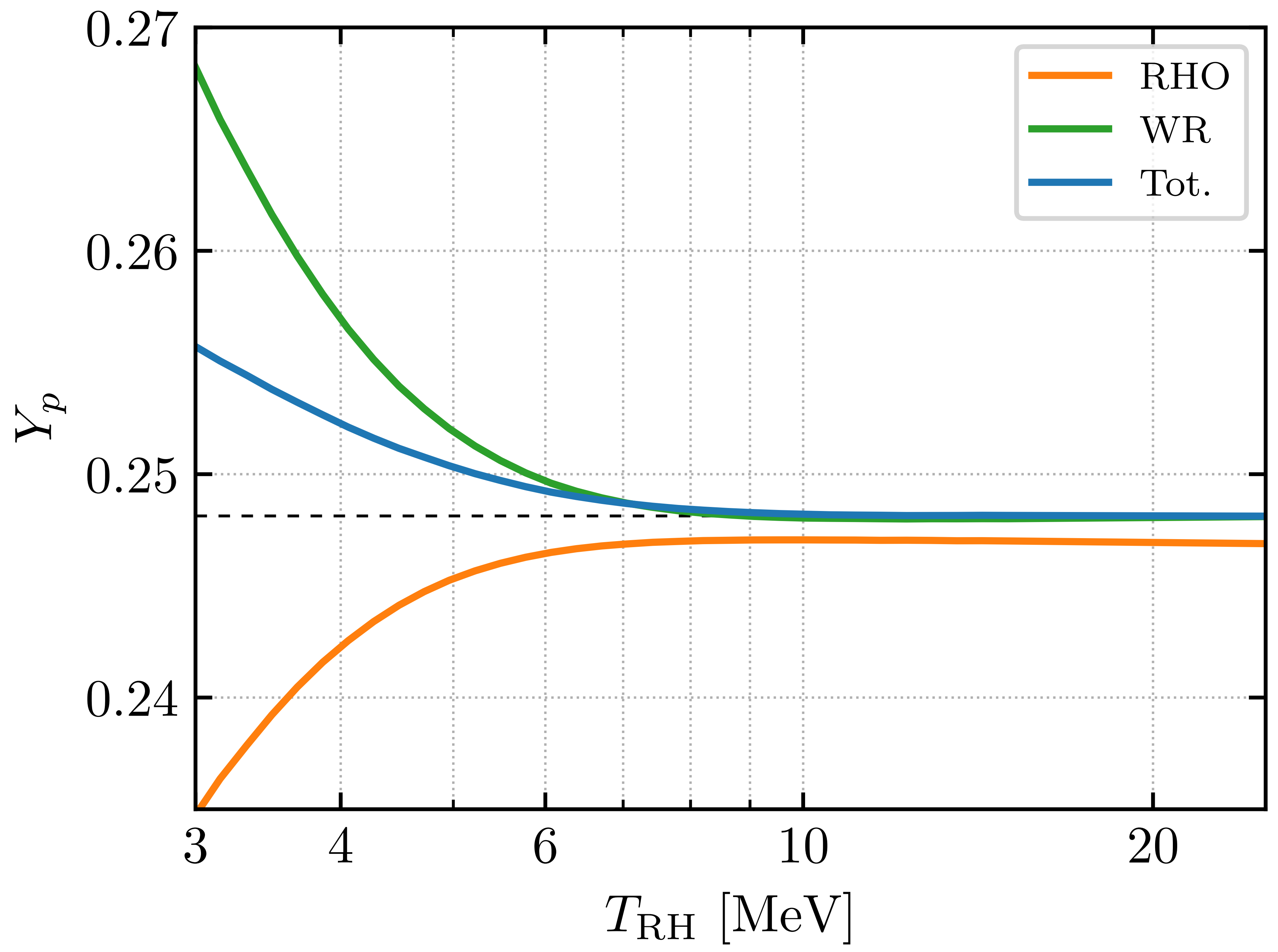


Values of the primordial helium yield as a function of $T_{\rm RH}$

$$\left(\chi^2_{^4\mathrm{He}}\chi^2_{^2\mathrm{H}}\right)(T_{\rm RH}) \leq 4 \quad \Rightarrow \quad T_{\rm RH} \geq 3.67\,\mathrm{MeV}$$

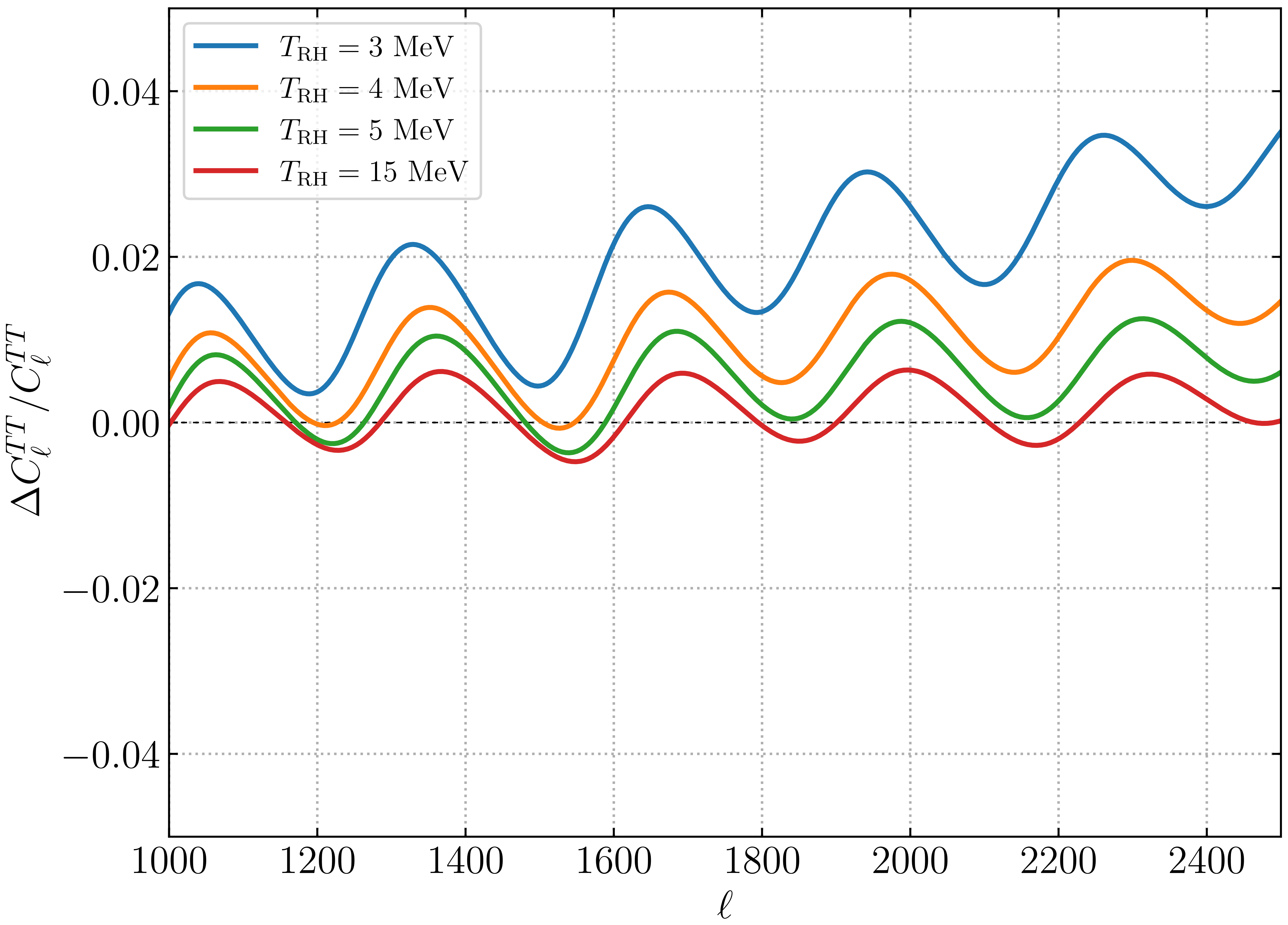
Probes of low reheating: CMB

- At the redshift of interest for the calculation of CMB anisotropies neutrino PSDs are evolving self-similarly, being only redshifted by the expansion of the Universe;

- Cosmological perturbation equations are sensitive to mass stases PSDs

$$f_{\nu_i}(y) = \sum_{\alpha} |U_{\alpha i}|^2 f_{\nu_\alpha}(y)$$

- CMB anisotropies spectrum is sensitive to the primordial helium abundance through its influence on the recombination history.



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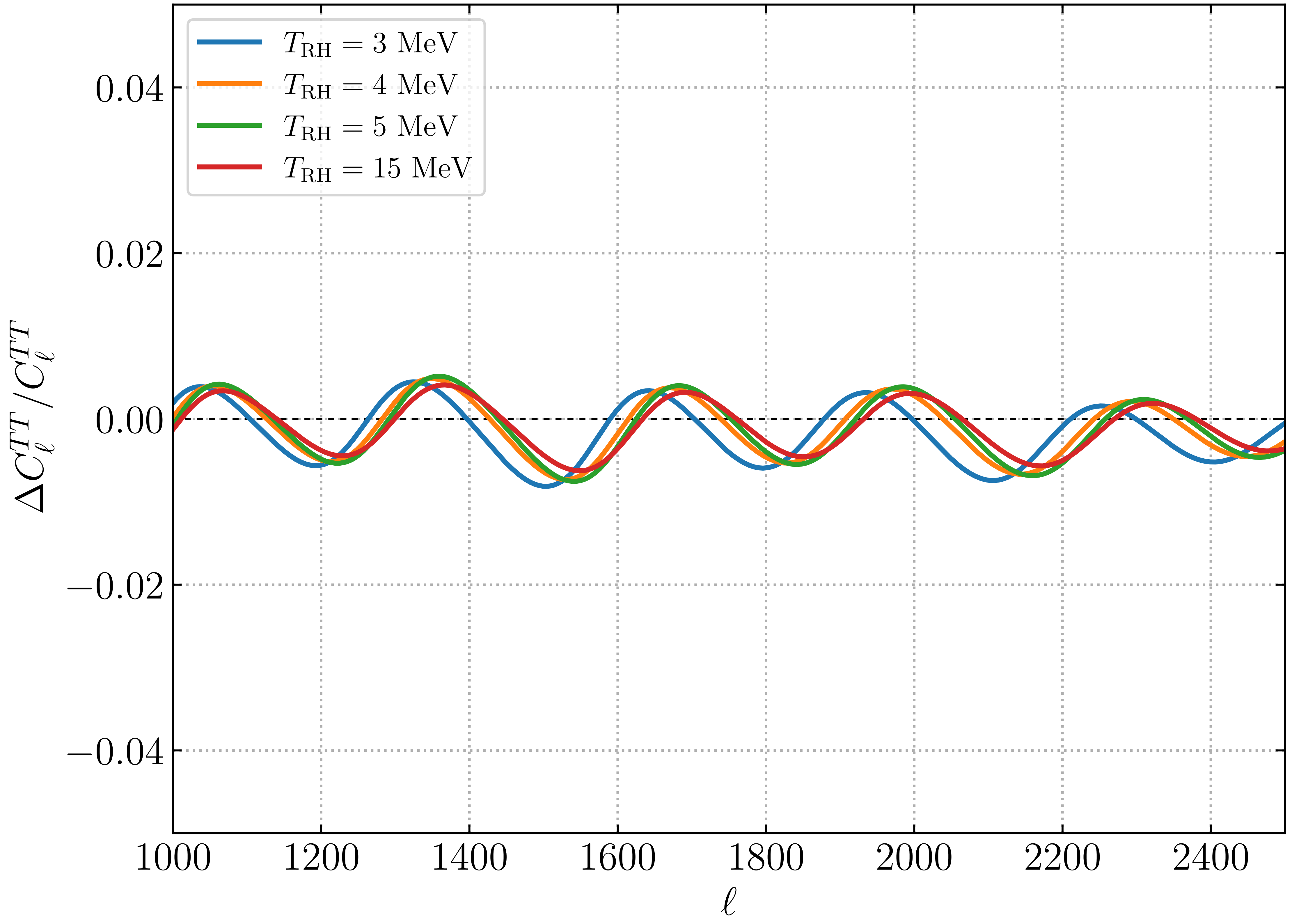

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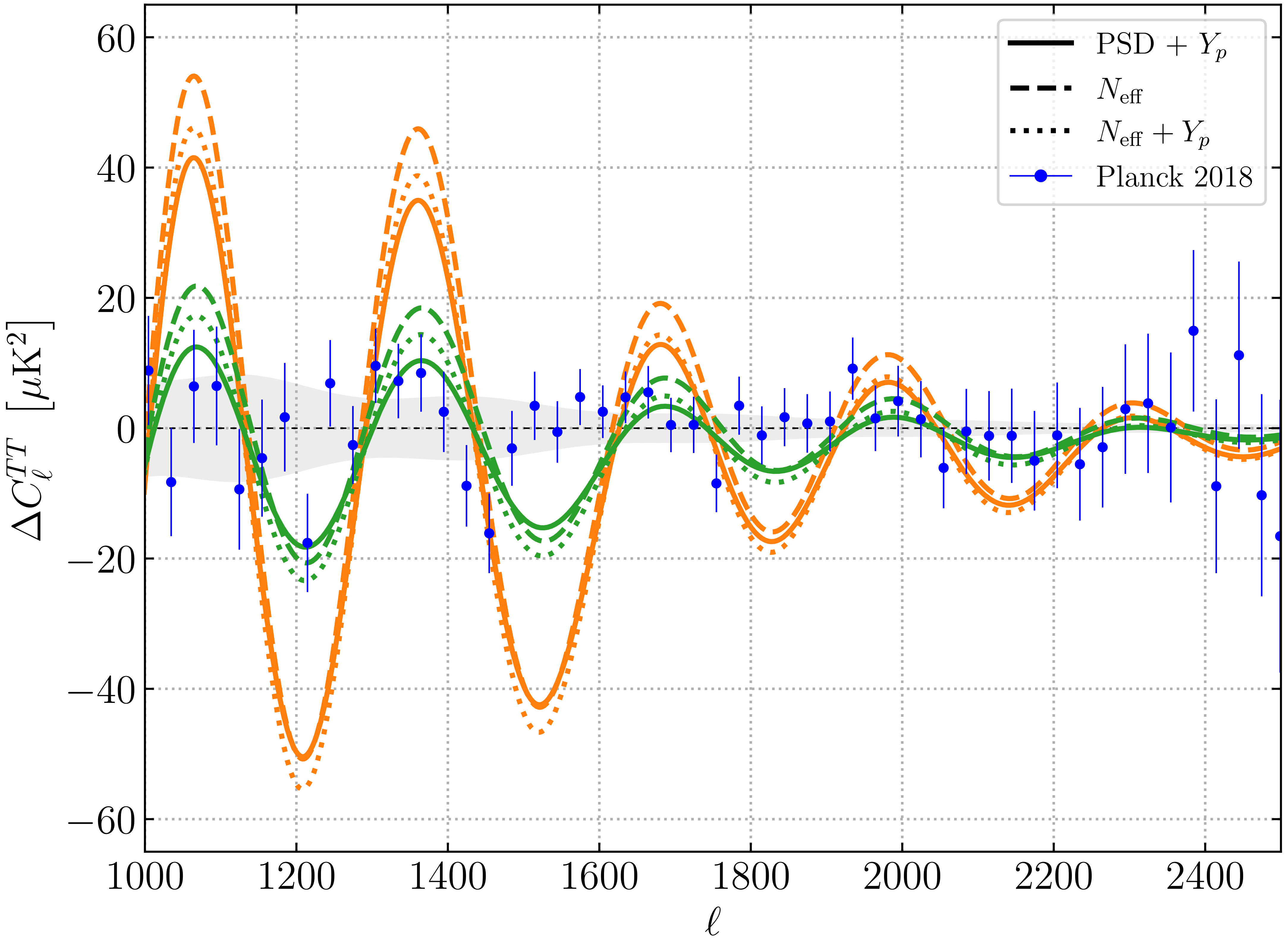

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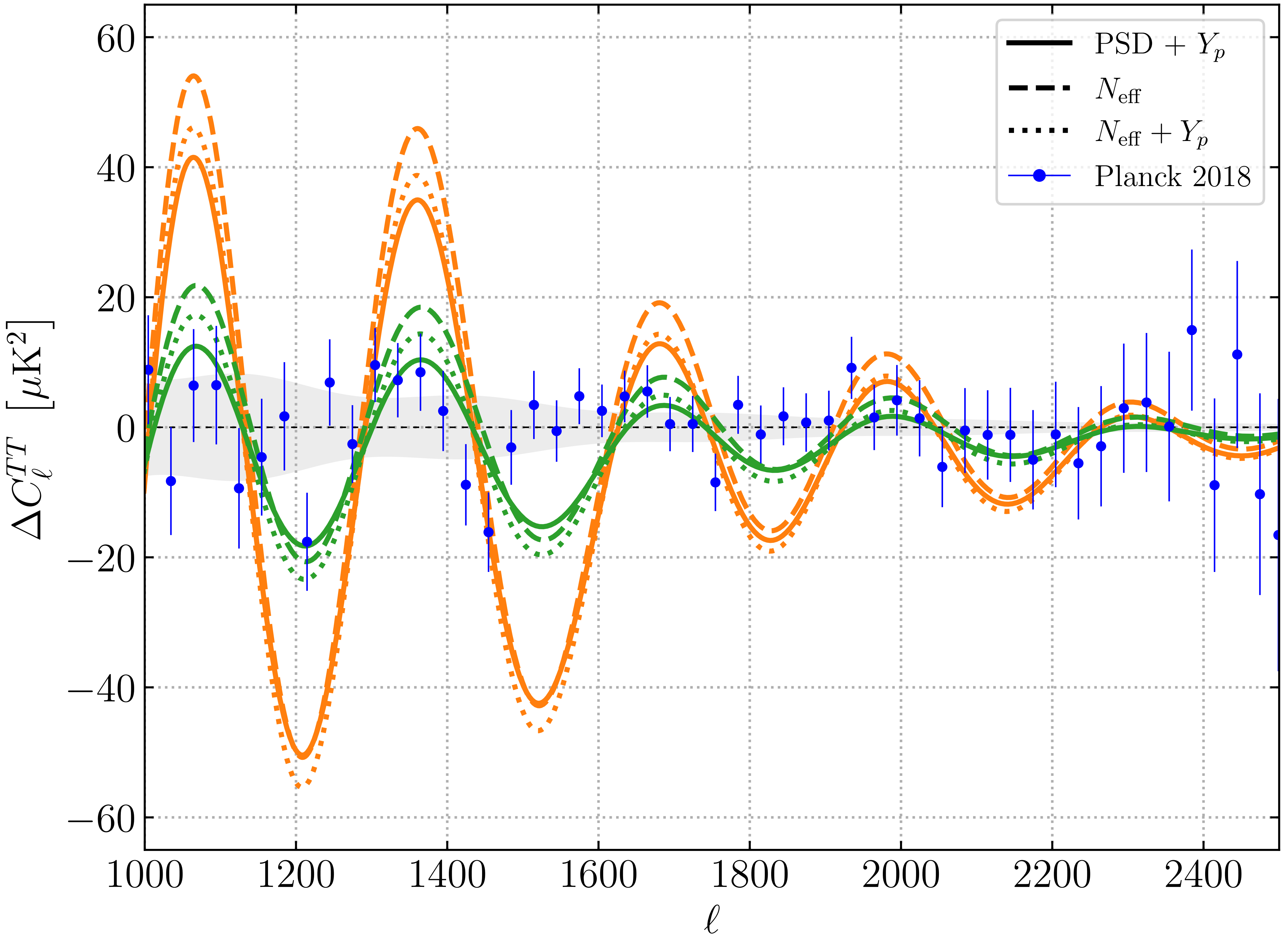
For more curiosities on the impact of non-thermal PSDs see **R. Impavido**'s talk!

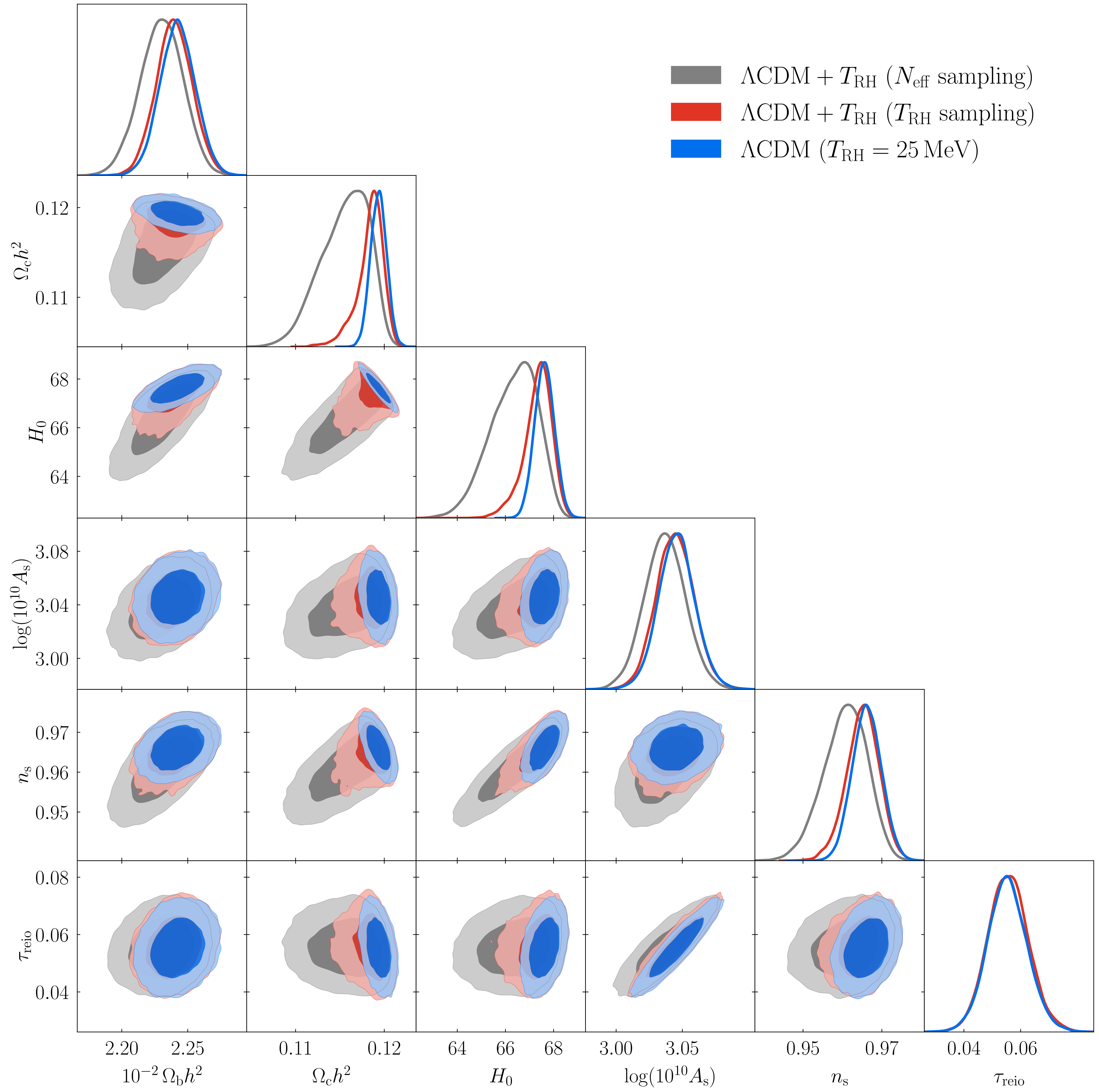


How to sample T_{RH}?

- $T_{\rm RH}$ **sampling:** employed in previous works, poor sampling of low reheating temperatures region, direct interpretation of the physical results;

- $N_{\rm eff}$ **sampling:** most direct relationship with the data, uniform sampling of all parameter space, difficult interpretation of the results.

Parameter	ΛCDM + $T_{\rm RH}$ ($N_{\rm eff}$ sampling) 68% limits	ΛCDM + $T_{\rm RH}$ ($T_{\rm RH}$ sampling) 68% limits	ΛCDM ($T_{\rm RH} = 25$ MeV) 68% limits	ΛCDM (Planck 2018) 68% limits
$\Omega_b h^2$	0.02230 ± 0.00016	0.02240 ± 0.00014	0.02242 ± 0.00013	0.02242 ± 0.00014
$\Omega_c h^2$	$0.1155^{+0.0034}_{-0.0020}$	$0.1184^{+0.0017}_{-0.00089}$	0.11935 ± 0.00092	0.11933 ± 0.00091
$\log(10^{10} A_s)$	3.037 ± 0.016	3.045 ± 0.015	3.046 ± 0.014	3.047 ± 0.014
n_s	$0.9607^{+0.0062}_{-0.0049}$	$0.9651^{+0.0043}_{-0.0039}$	0.9662 ± 0.0037	0.9665 ± 0.0038
$\tau_{\rm reio}$	$0.0554^{+0.0067}_{-0.0075}$	0.0557 ± 0.0073	0.0554 ± 0.0071	0.0561 ± 0.0071
H_0	$66.3^{+1.2}_{-0.80}$	$67.33^{+0.66}_{-0.42}$	67.62 ± 0.41	67.66 ± 0.42



Bounds on T_{RH}

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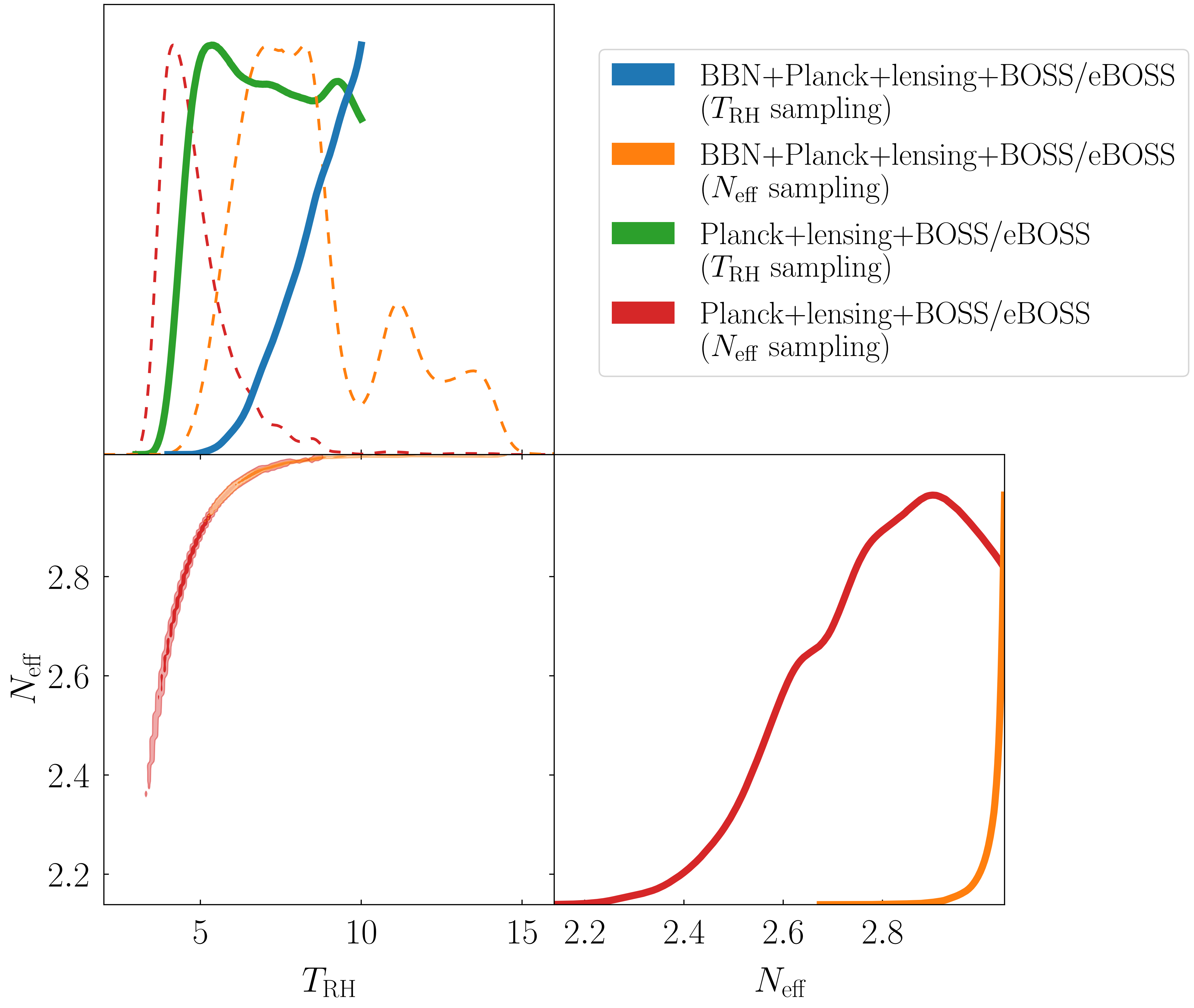
- Summary table:

	$N_{\rm eff}$ sampling	$T_{\rm RH}$ sampling
Dataset	95% limits	95% limits
Planck+lensing+BOSS/eBOSS	> 3.62 MeV	> 4.52 MeV
Planck+lensing+DESI	> 3.79 MeV	> 4.50 MeV
BBN+Planck+lensing+BOSS/eBOSS	> 5.57 MeV	> 6.71 MeV
BBN+Planck+lensing+DESI	> 5.96 MeV	> 6.76 MeV



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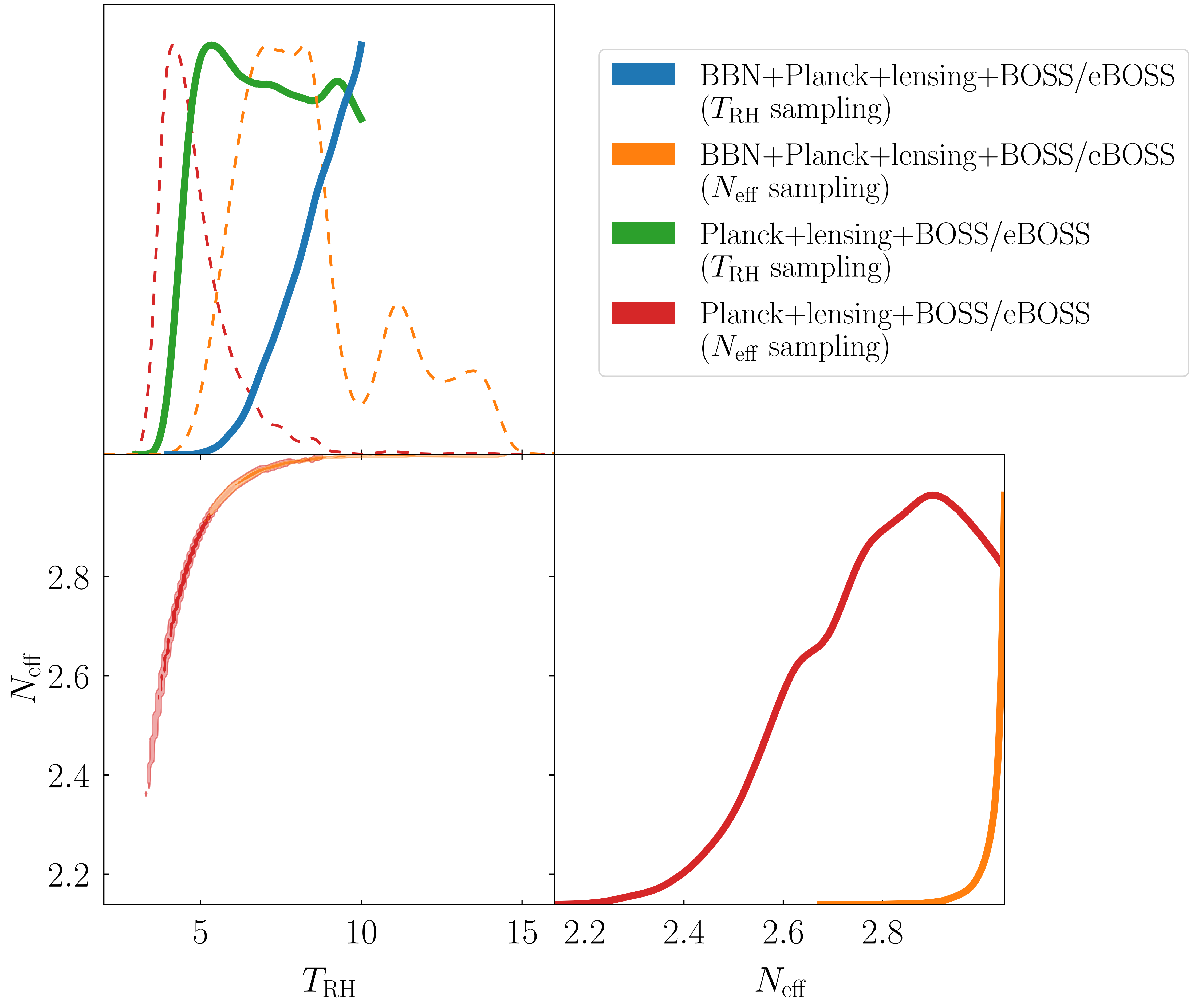

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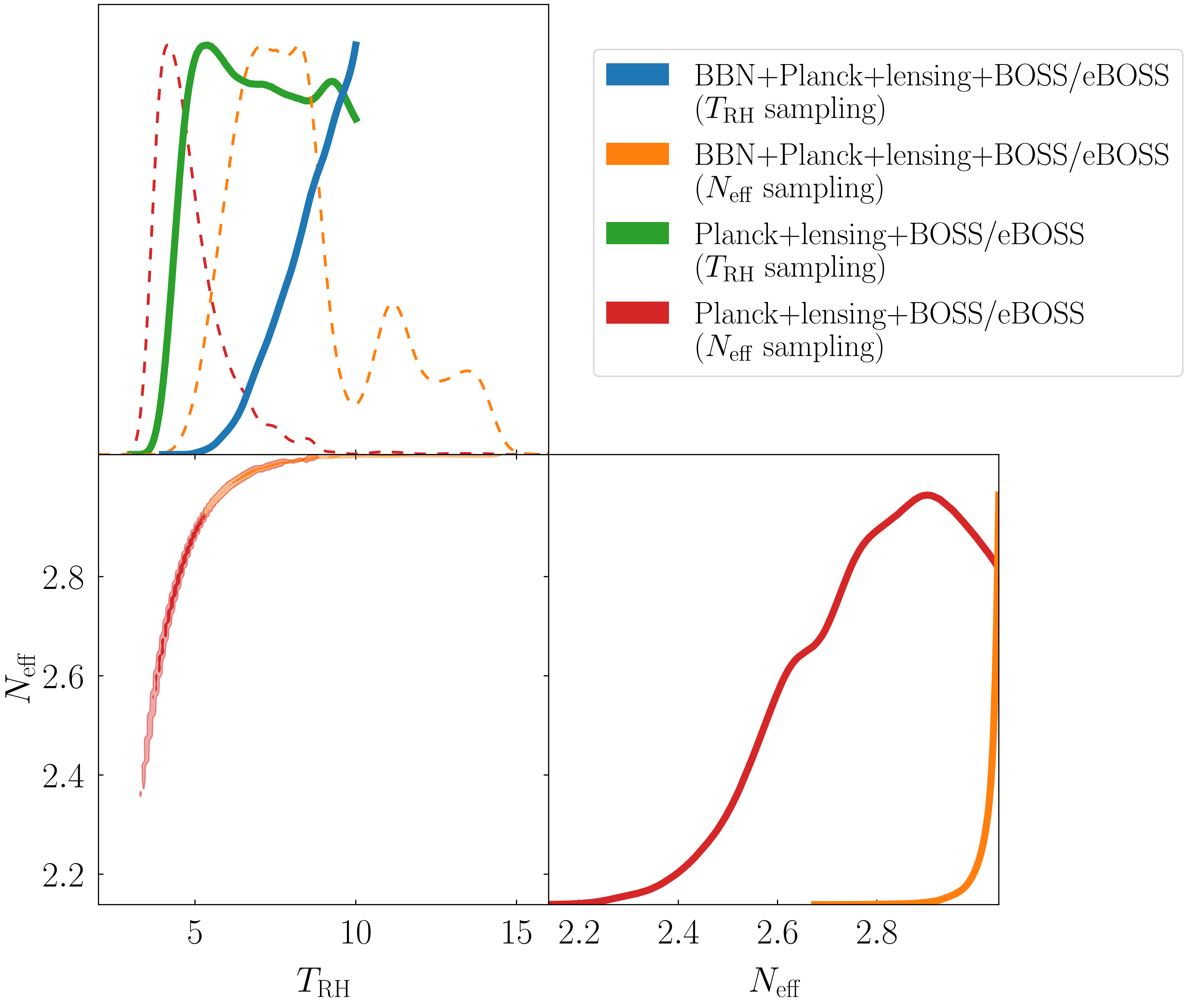
Slightly **relaxed** by new sampling strategy



The Kullback-Leibler divergence

- Measure of the "distance" between two distributions

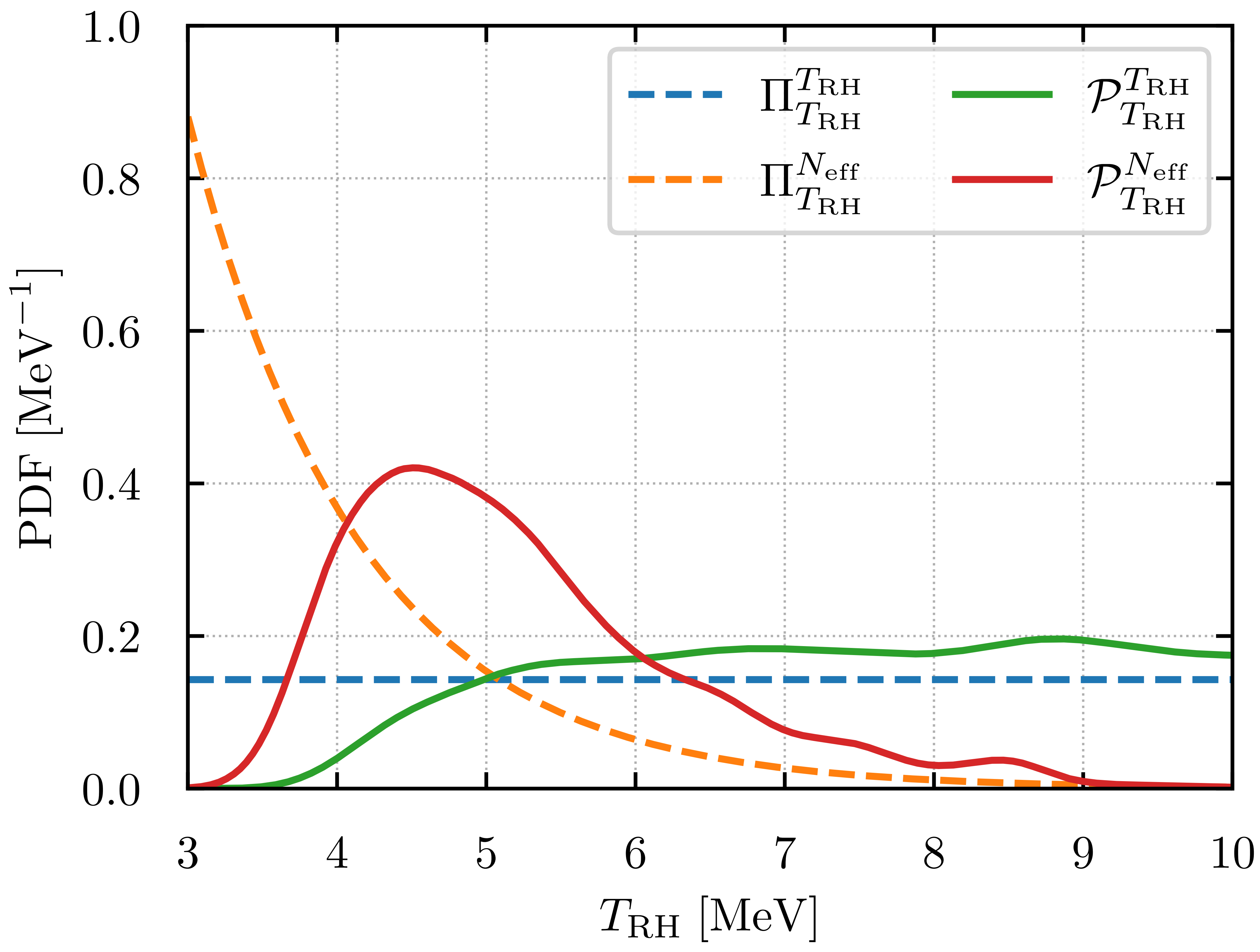
$$\mathcal{D}_{\rm KL}\left(P \parallel Q\right) \equiv \int d\boldsymbol{\theta}\; p\left(\boldsymbol{\theta}\right) \log\left[\frac{p\left(\boldsymbol{\theta}\right)}{q\left(\boldsymbol{\theta}\right)}\right]$$

In the context of bayesian analysis it is used to asses the impact of different parameterisations by computing the information gain between the prior and the posterior.

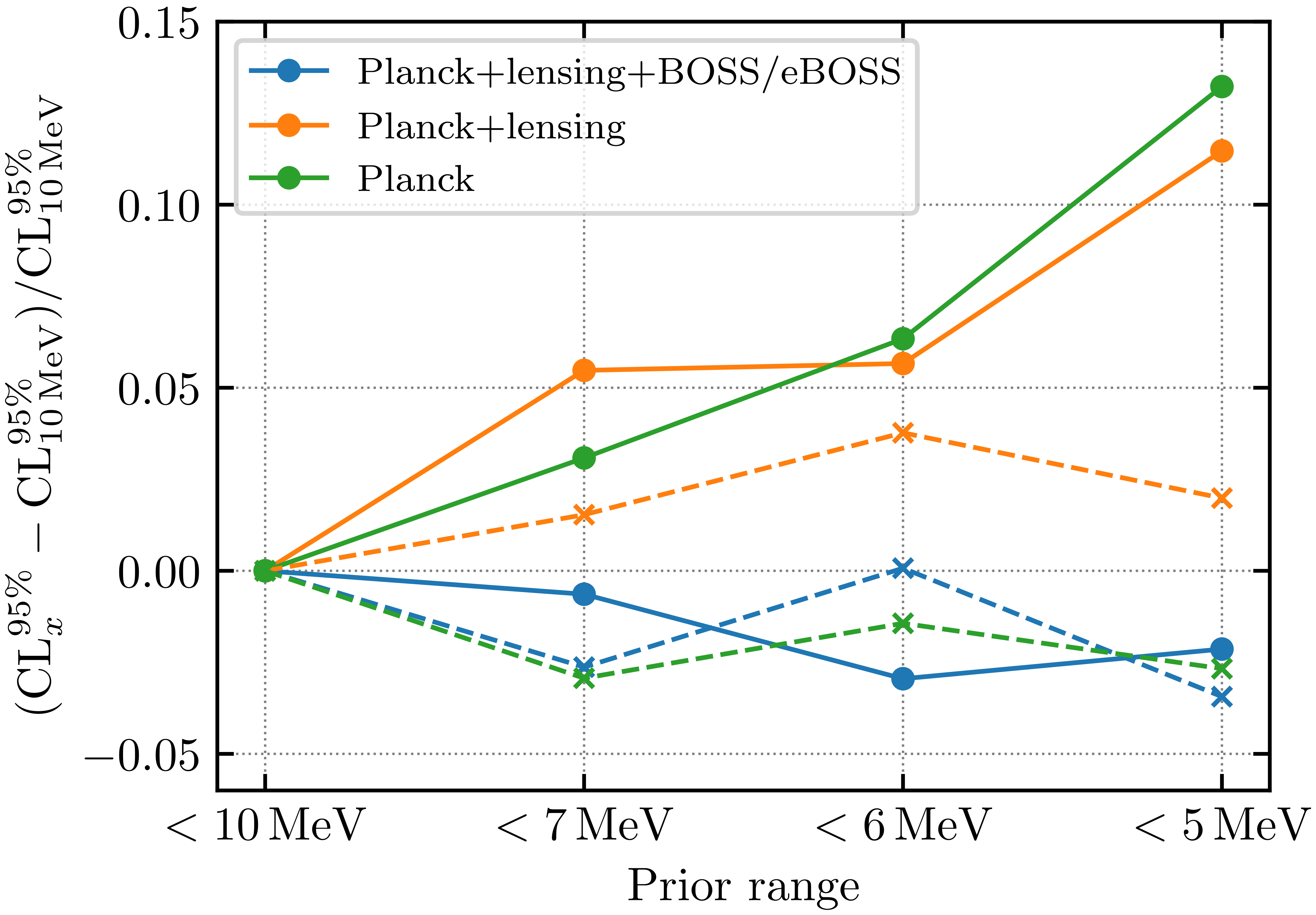
$$\mathcal{D}_{\rm KL}\left(\mathcal{P}_{T_{\rm RH}} \parallel \Pi_{T_{\rm RH}}\right) = 0.14$$

$$\mathcal{D}_{\rm KL}\left(\mathcal{P}_{N_{\rm eff}^{FP}} \parallel \Pi_{N_{\rm eff}^{FP}}\right) = 0.64$$

Slight "preference" for $N_{\rm eff}$ sampling



Bounds on Σm_ν

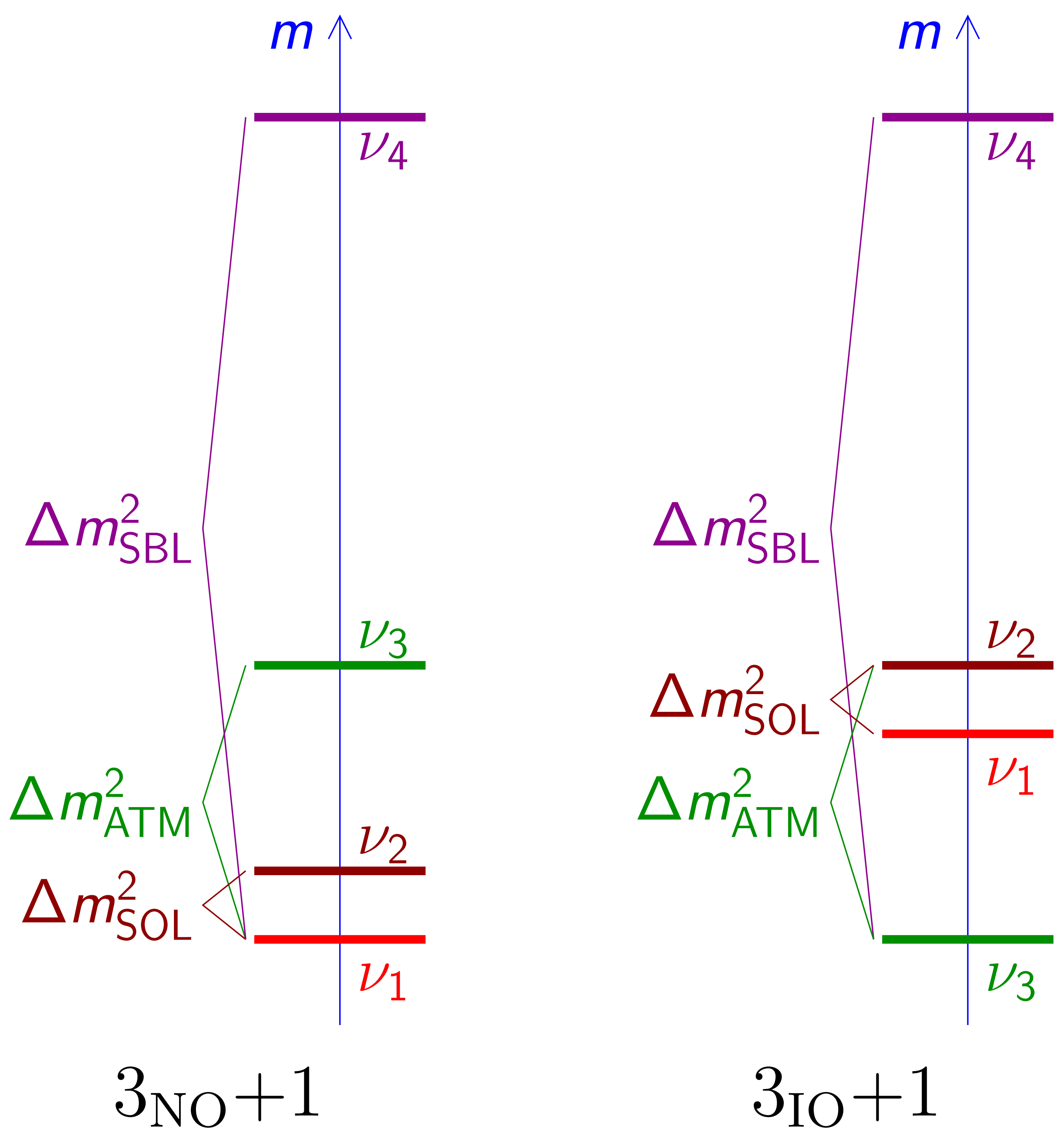


The (3+1) neutrino framework

- Several anomalies in neutrino oscillation experiments seem to suggest the existence of one **additional sterile state**, mixed with the active neutrinos;

- The parameter space is enlarged by the addition of an **additional mass splitting**, Δm^2_{14}, and **three new mixing angles** θ_{14}, θ_{24} and θ_{34};

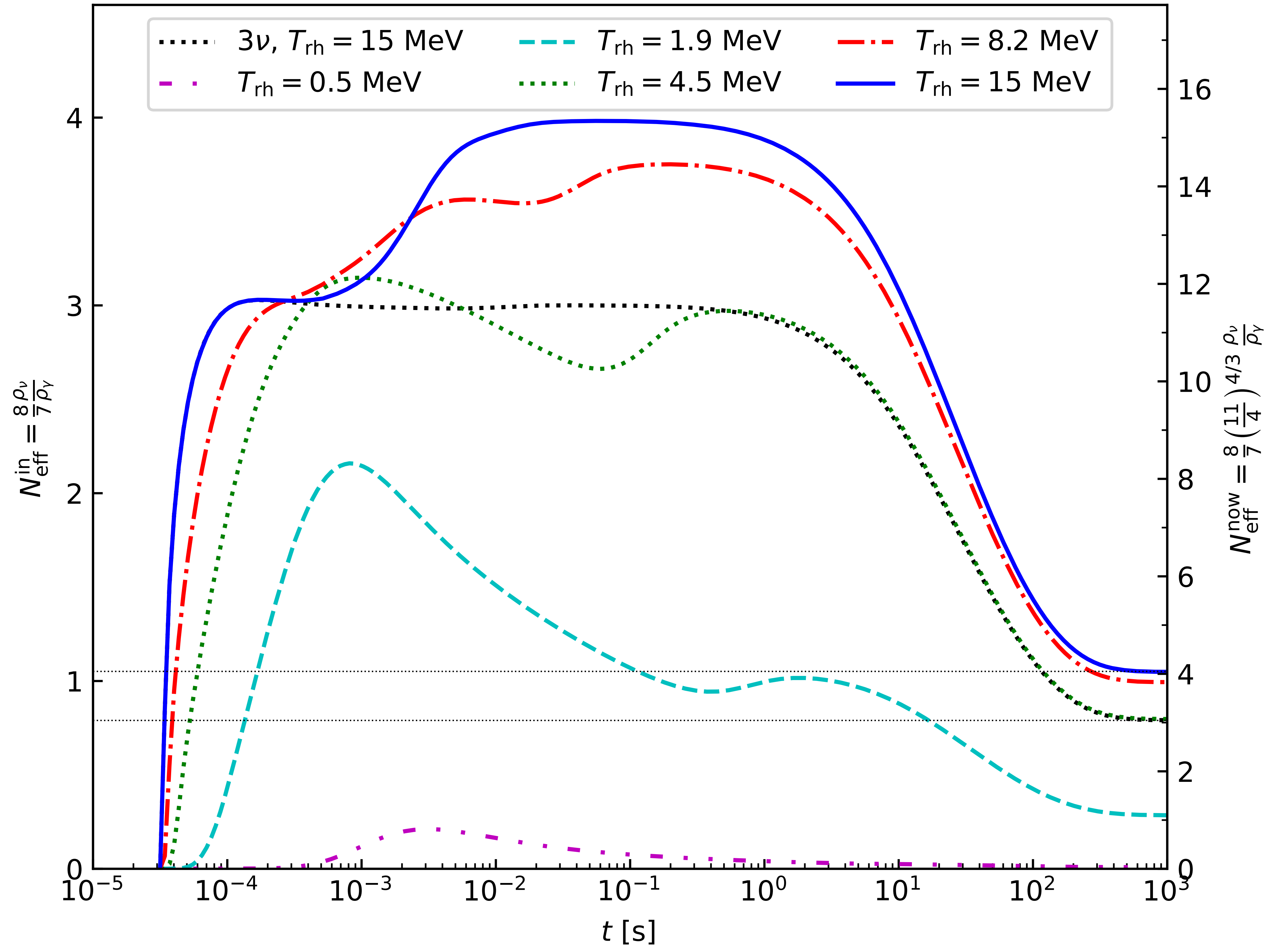
- Scenarios fitting the short baseline anomalies point to a fully thermalized sterile state which, however, is completely ruled out by cosmological observations.



[Credits: Giunti and Lasserre (2019)]

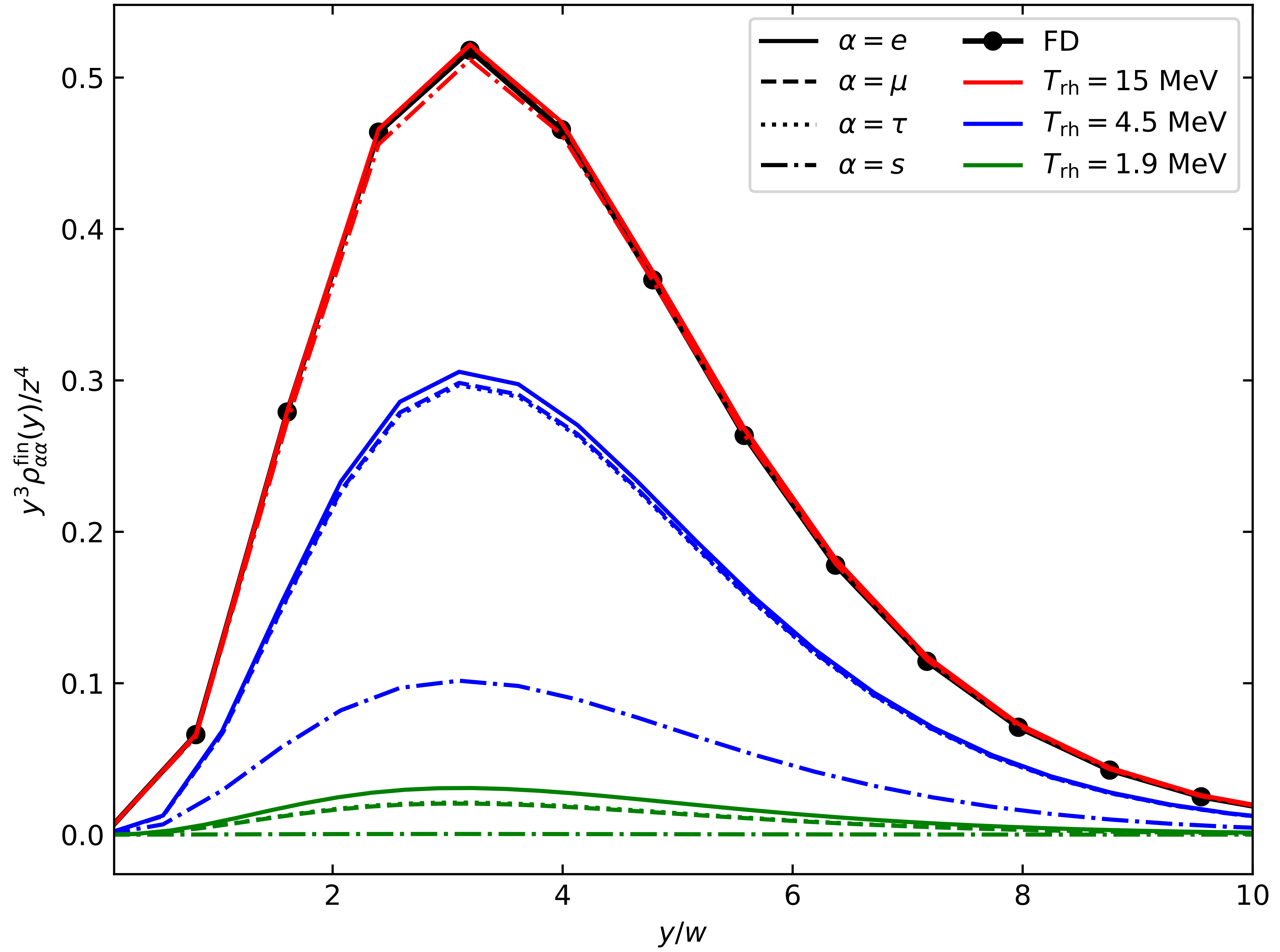
Neutrino production in (3+1) models

[Credits: S. Gariazzo]



Time evolution of the ratio of energy densities of neutrinos and photons.

[Credits: S. Gariazzo]



Final differential spectra of neutrino energies as a function of the comoving momentum.

Thank you!

Based on **Barbieri+** (2025)
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In collaboration with T. Brinckmann,
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