



TeV Particle Astrophysics
TeVPA
Valencia 2025



European Research Council
Established by the European Commission



INFN
FERRARA

Based on **Barbieri+** (2025)
Phys. Rev. Lett. **135**, 181003

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 & IFIC, CSIC-UV) – 04/11/2025

Models of reheating

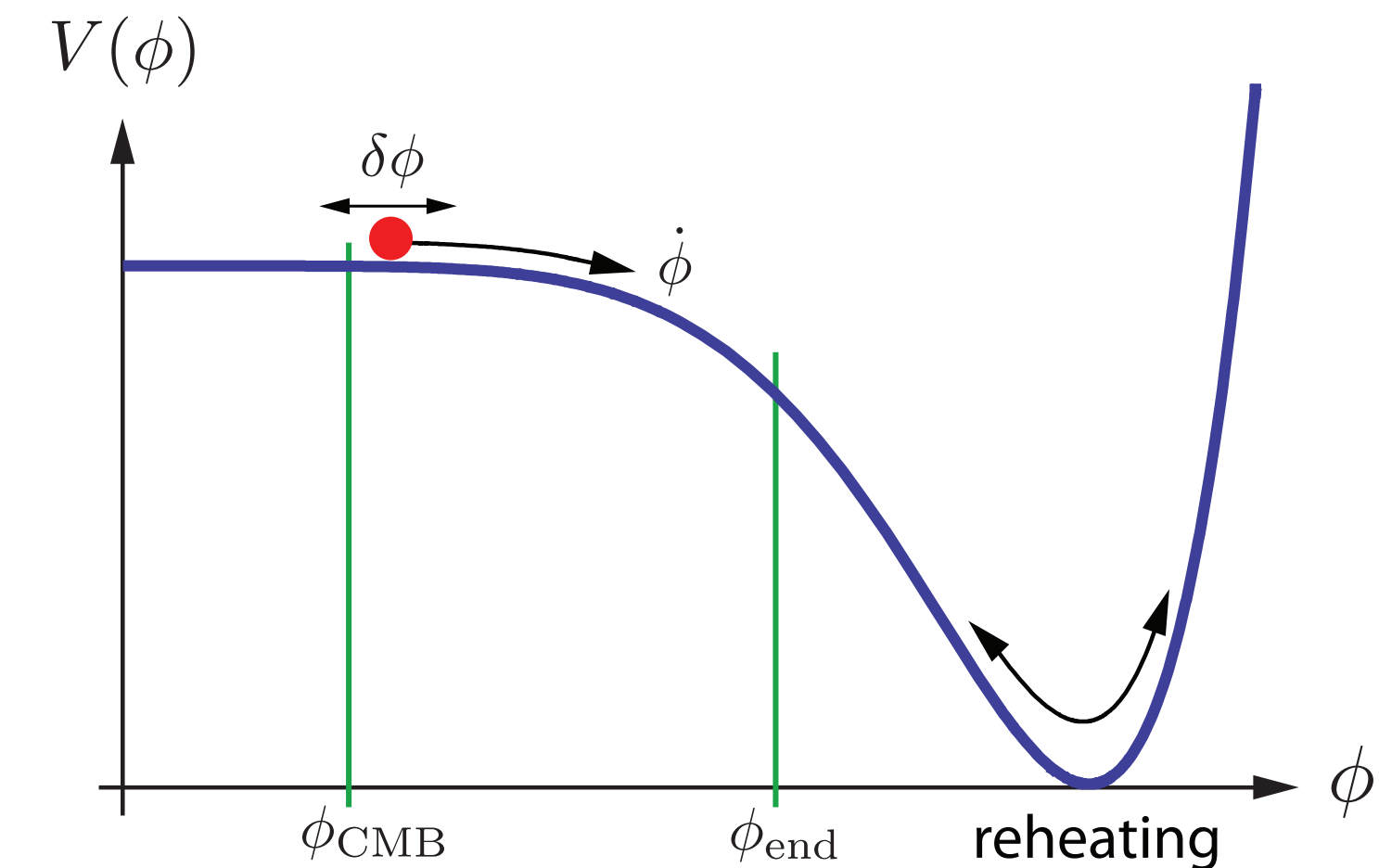
- In inflation paradigm, a final reheating phase is needed to reconcile with the standard FLRW radiation dominated Universe

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

- What is the reheating temperature?

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

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



Models of reheating

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

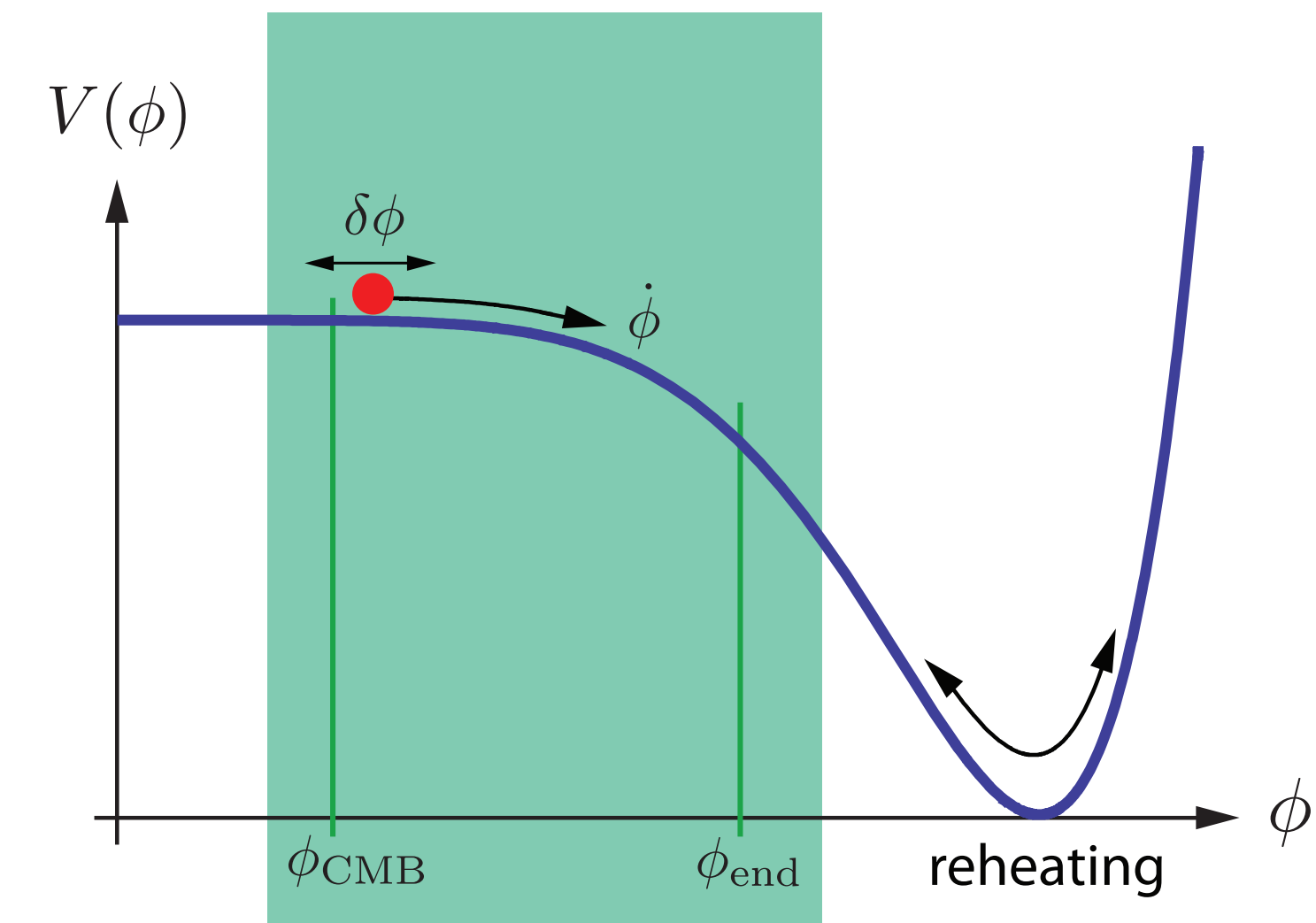
$$\frac{d\rho_\phi}{dt} + (3H + \Gamma_\phi) \rho_\phi = 0$$

- What is the reheating temperature?

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

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

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



Models of reheating

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

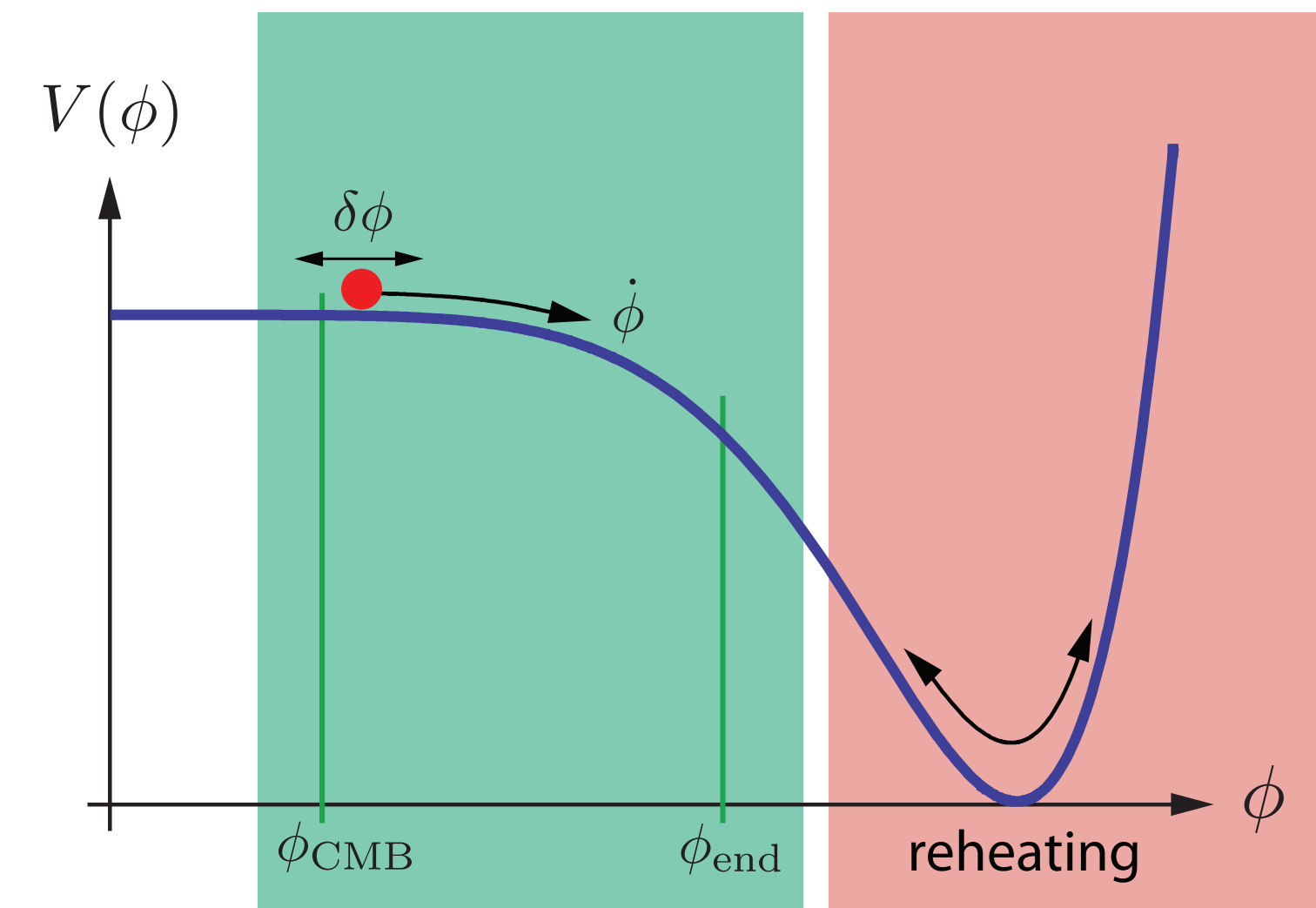
$$\frac{d\rho_\phi}{dt} + (3H + \Gamma_\phi) \rho_\phi = 0$$

- What is the reheating temperature?

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

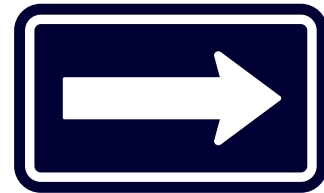
$$H(T_{\text{RH}}) = \sqrt{\frac{8\pi}{3m_{\text{pl}}^2} \rho_{\text{rad}}(T_{\text{RH}})} = \sqrt{\frac{8\pi}{90} g_*(T_{\text{RH}})} \frac{T_{\text{RH}}^2}{m_{\text{pl}}}$$

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



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

Assumptions and remarks



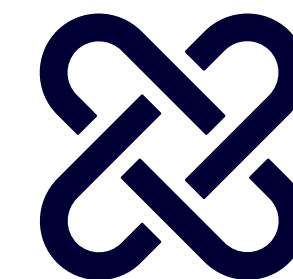
Photons, electrons, and other SM particles are populated directly by the **decay of the scalar**

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



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

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



Neutrino production - I

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

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

NB: everything expressed in terms of comoving variables

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

Neutrino production - I

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

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

Density matrix:

transition probability between
different flavour states

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

NB: everything expressed
in terms of comoving variables

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

Neutrino production - I

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

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

Density matrix:
transition probability between
different flavour states

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

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

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

NB: everything expressed
in terms of comoving variables

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

Neutrino production - I

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

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

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

Density matrix: transition probability between different flavour states

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

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

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

NB: everything expressed in terms of comoving variables

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

Neutrino production - I

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

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

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

Density matrix: transition probability between different flavour states

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

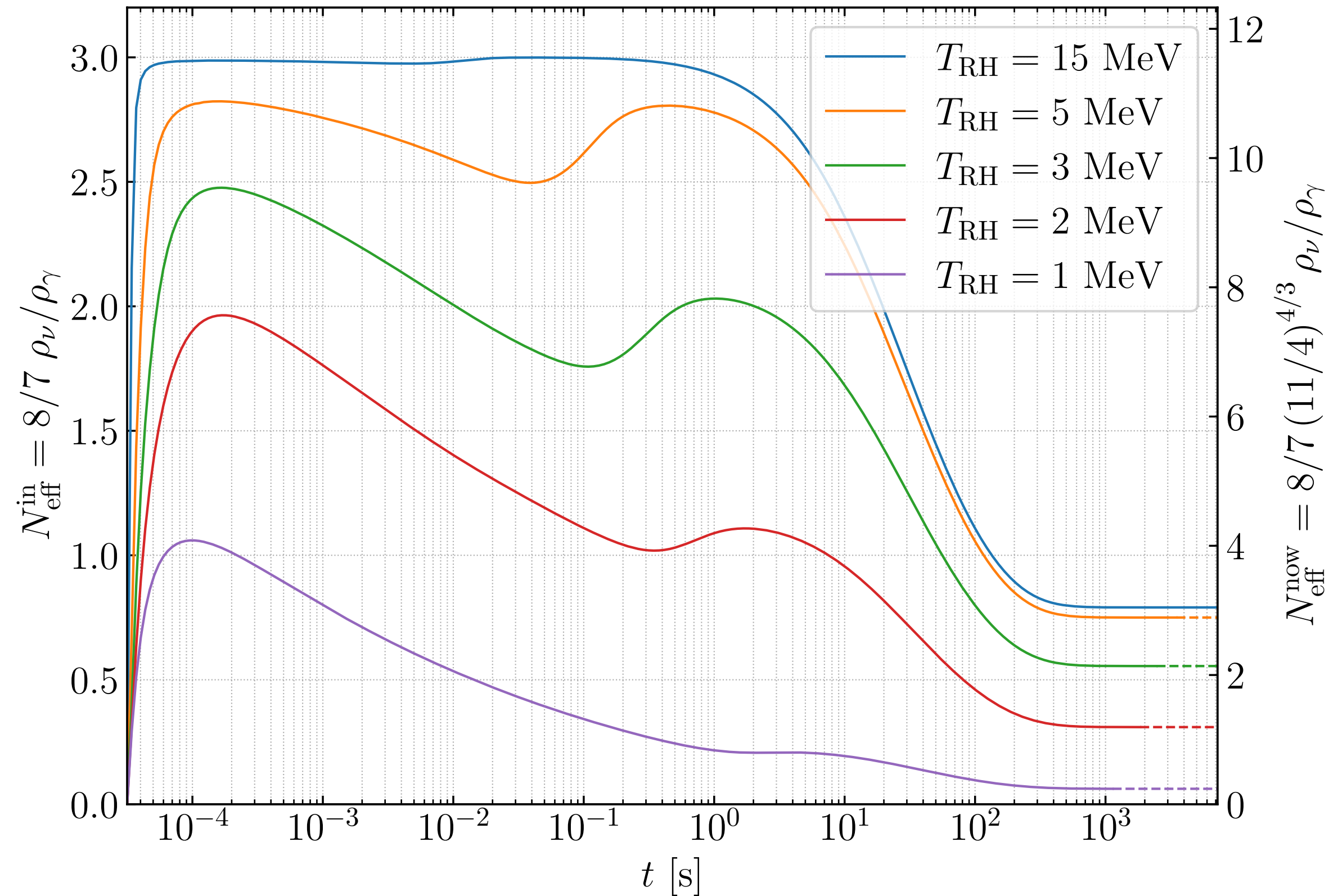
Vacuum oscillations: quantum effect only due to non-zero mass splittings between neutrino states

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

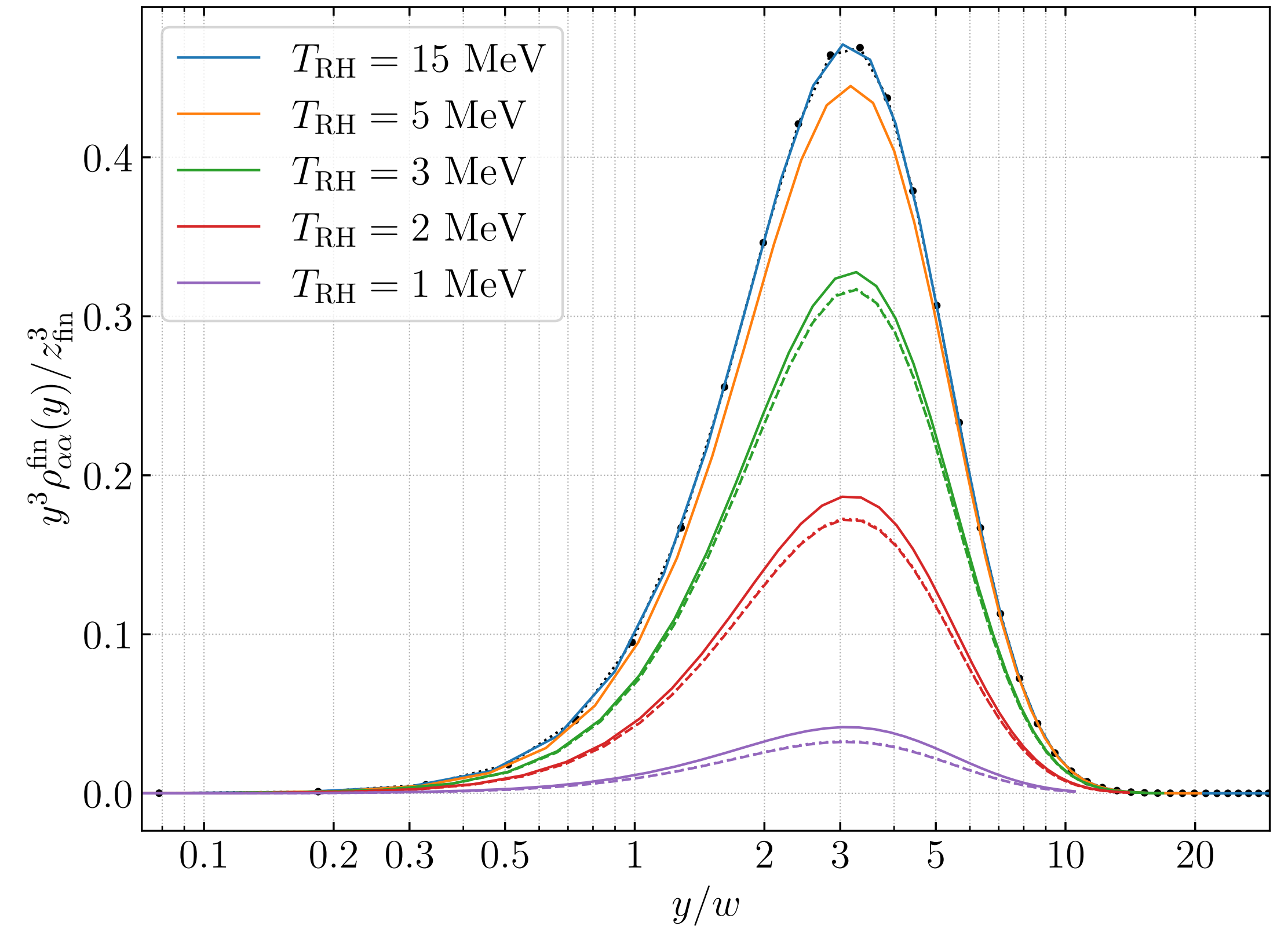
NB: everything expressed in terms of comoving variables

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

Neutrino production - II



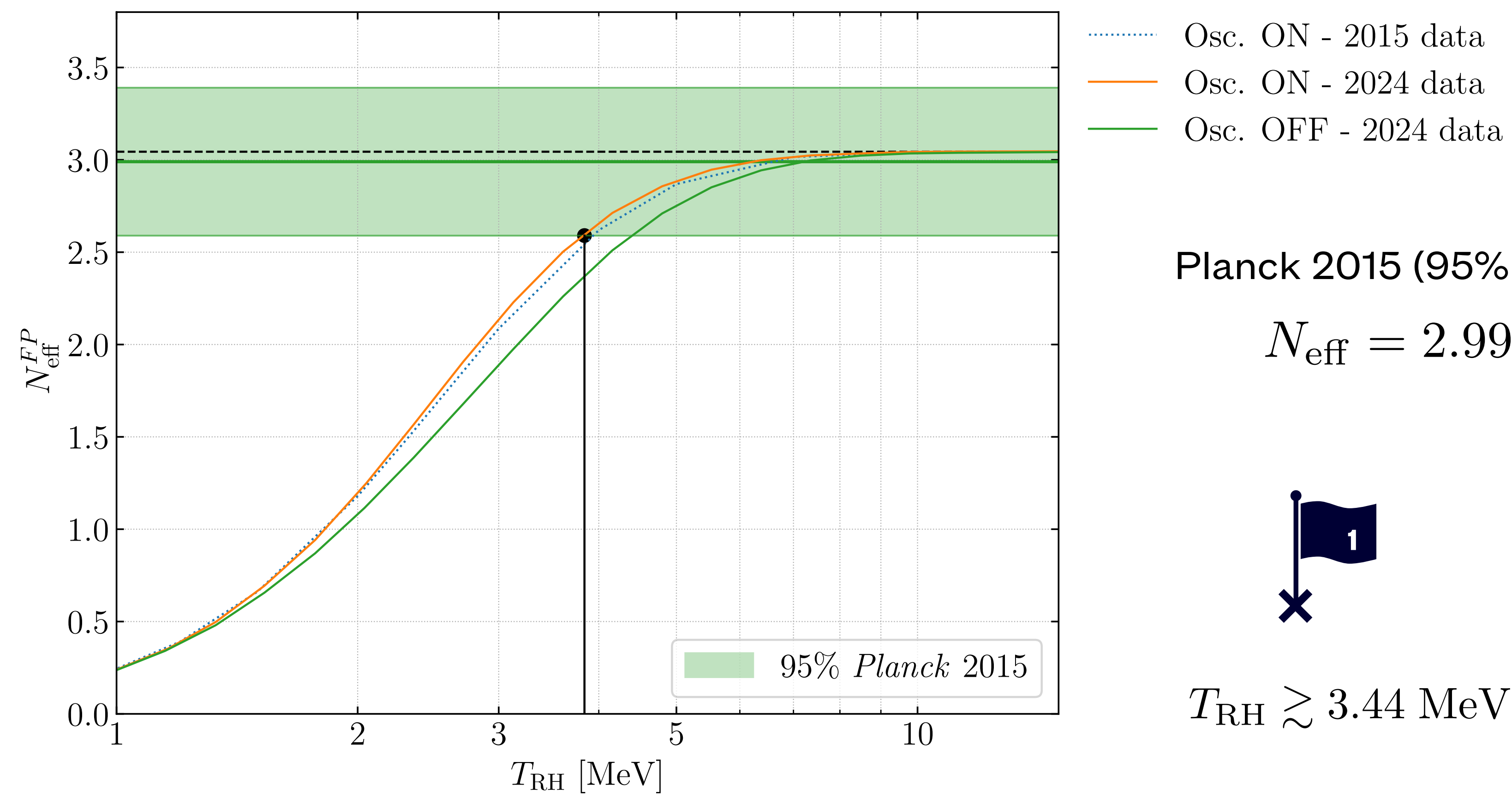
Time evolution of the ratio of energy densities of neutrinos and photons.



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

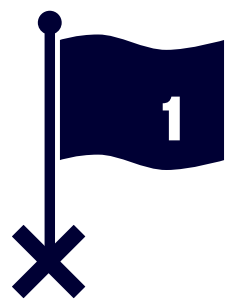
Neutrino production - III

MODIFIED VERSION OF
FORTEPIANO CODE



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

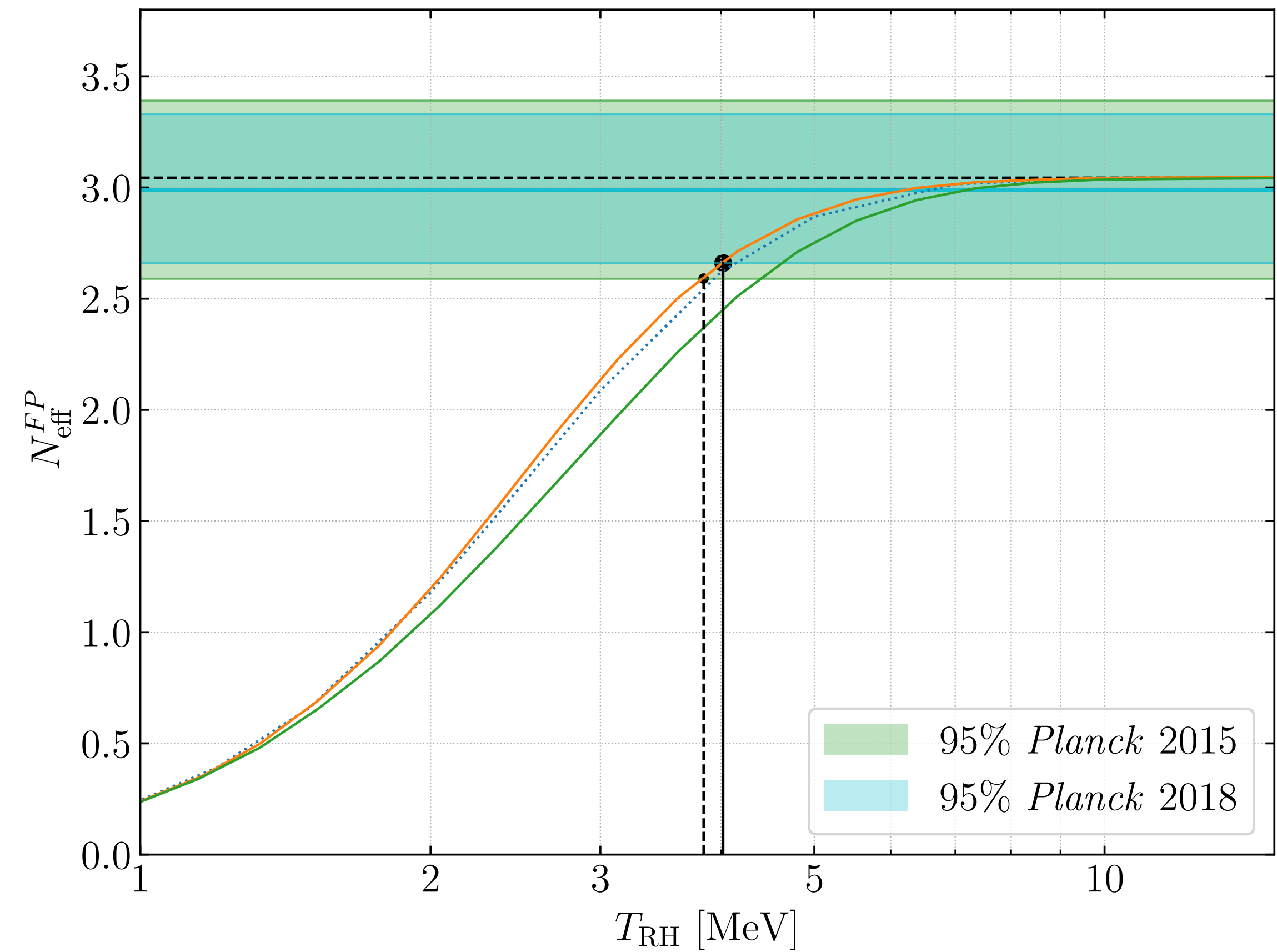
$$N_{\text{eff}} = 2.99 \pm 0.4$$



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

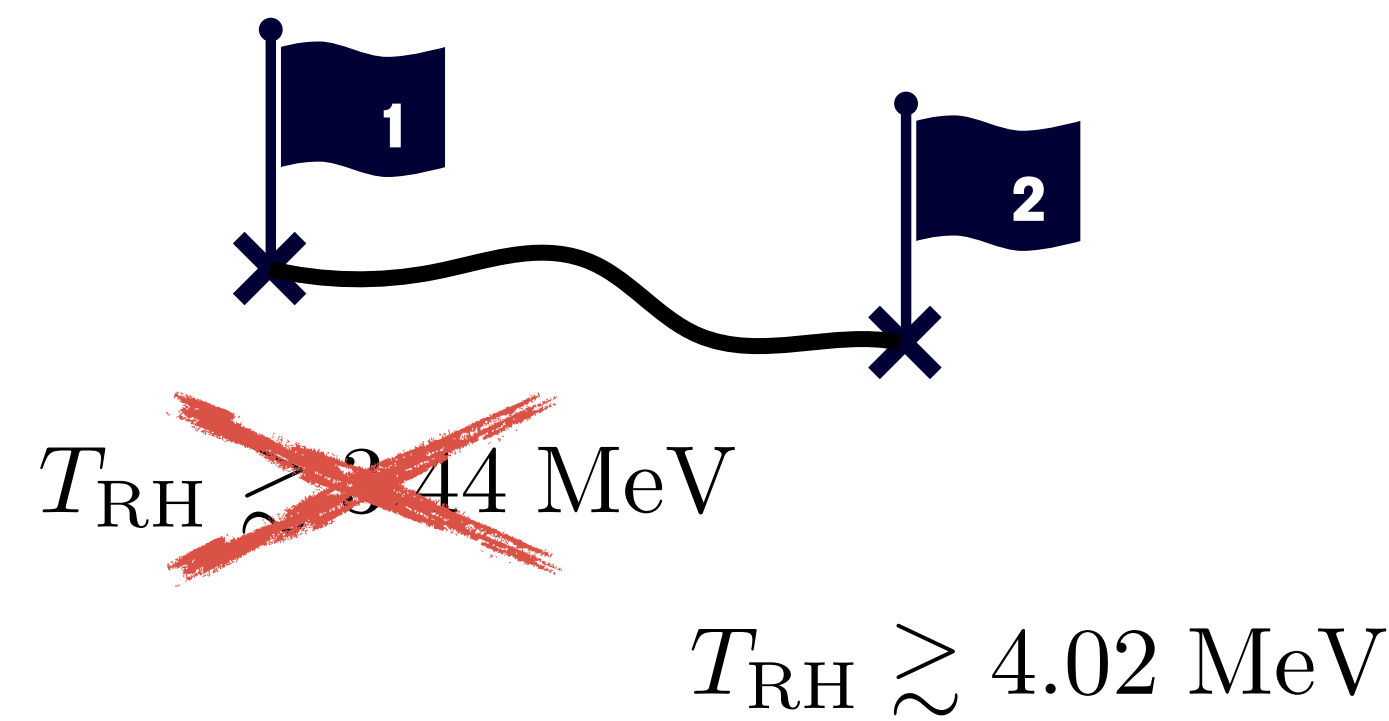
Neutrino production - III

**MODIFIED VERSION OF
FORTEPIANO CODE**



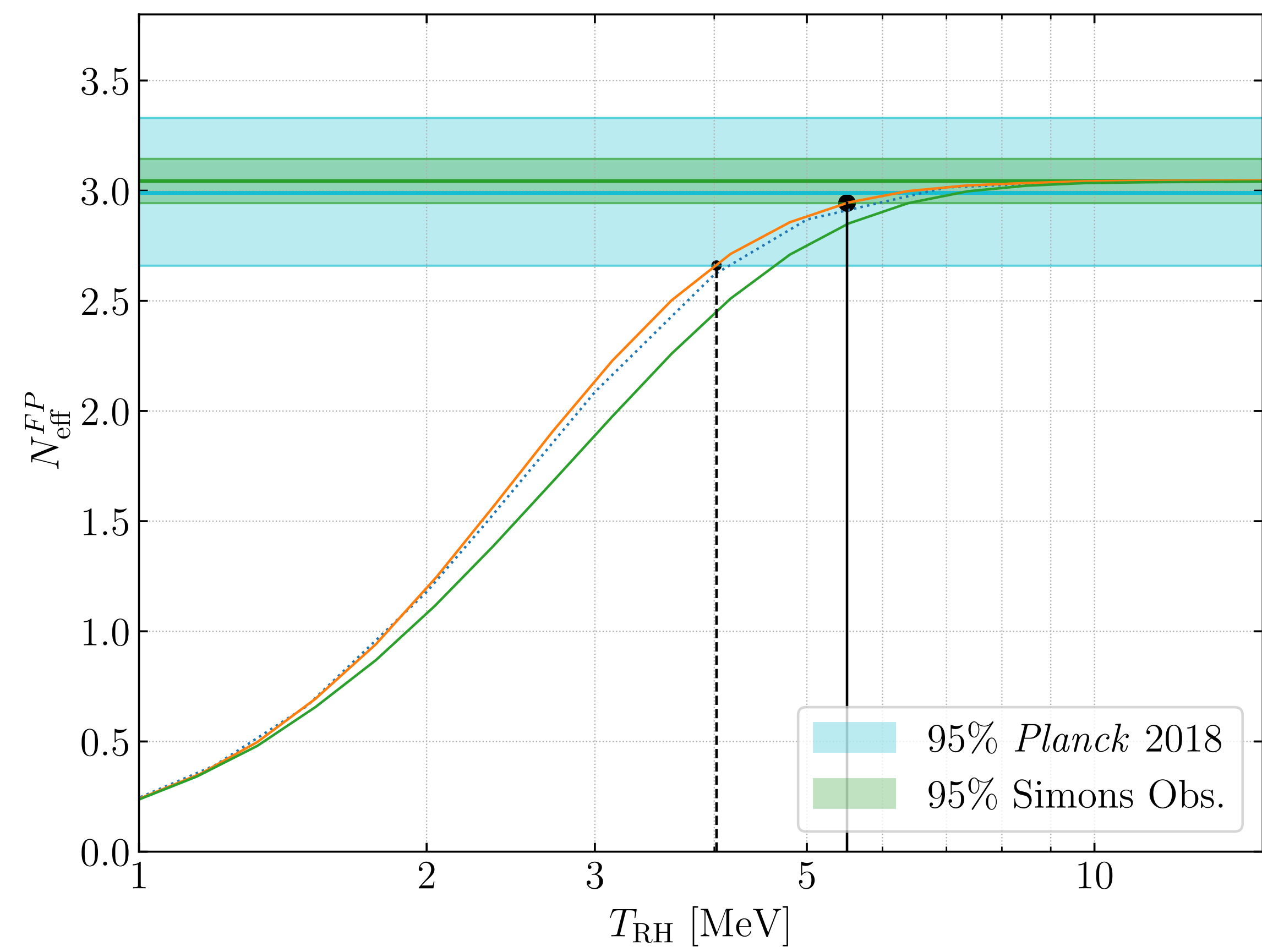
Planck 2018 (95% TT,TE,EE+lowE+lensing+BAO):

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



Neutrino production - III

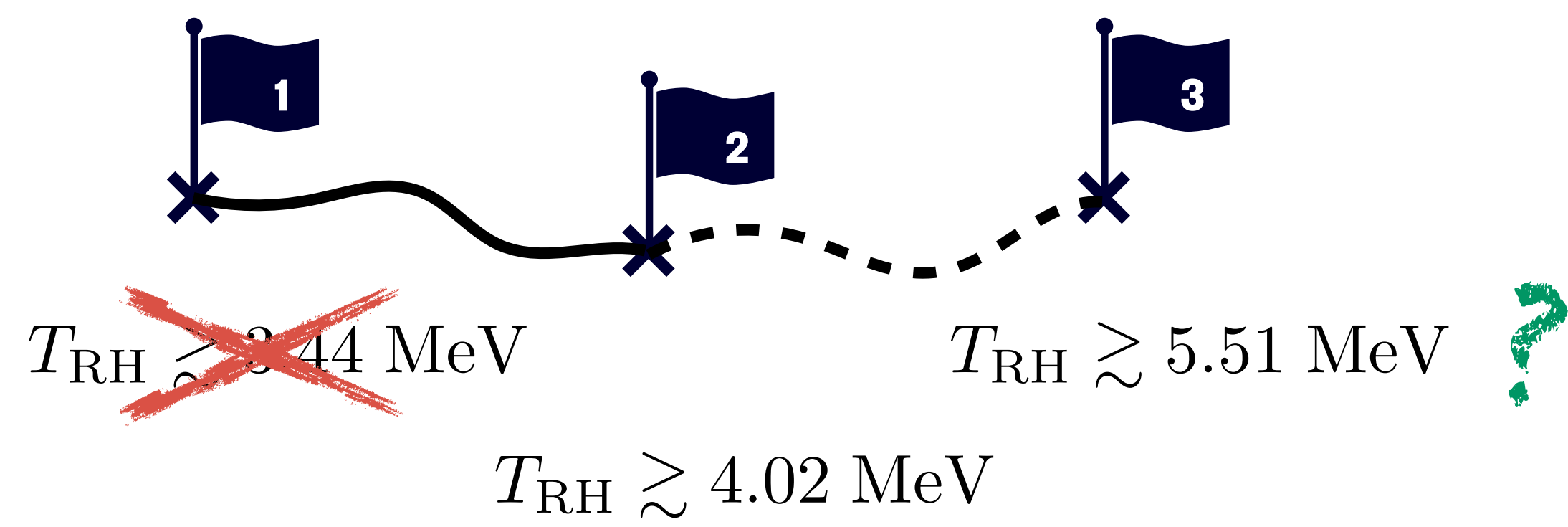
MODIFIED VERSION OF
FORTEPIANO CODE



- Osc. ON - 2015 data
- Osc. ON - 2024 data
- Osc. OFF - 2024 data

Simons Obs. (projected sensitivity):

$$\sigma(N_{\text{eff}}) = 0.050$$

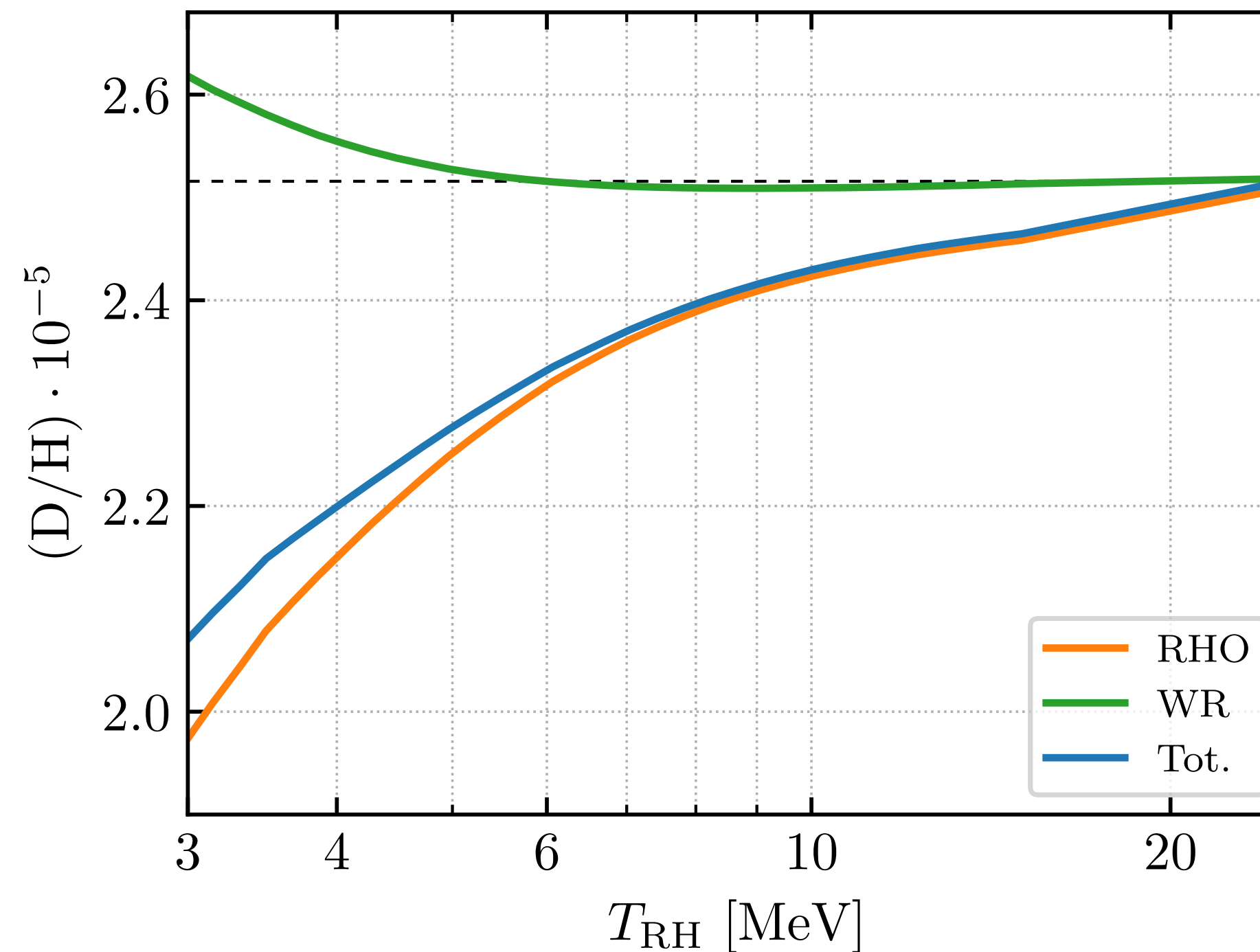


Probes of low reheating: BBN

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_{RH}

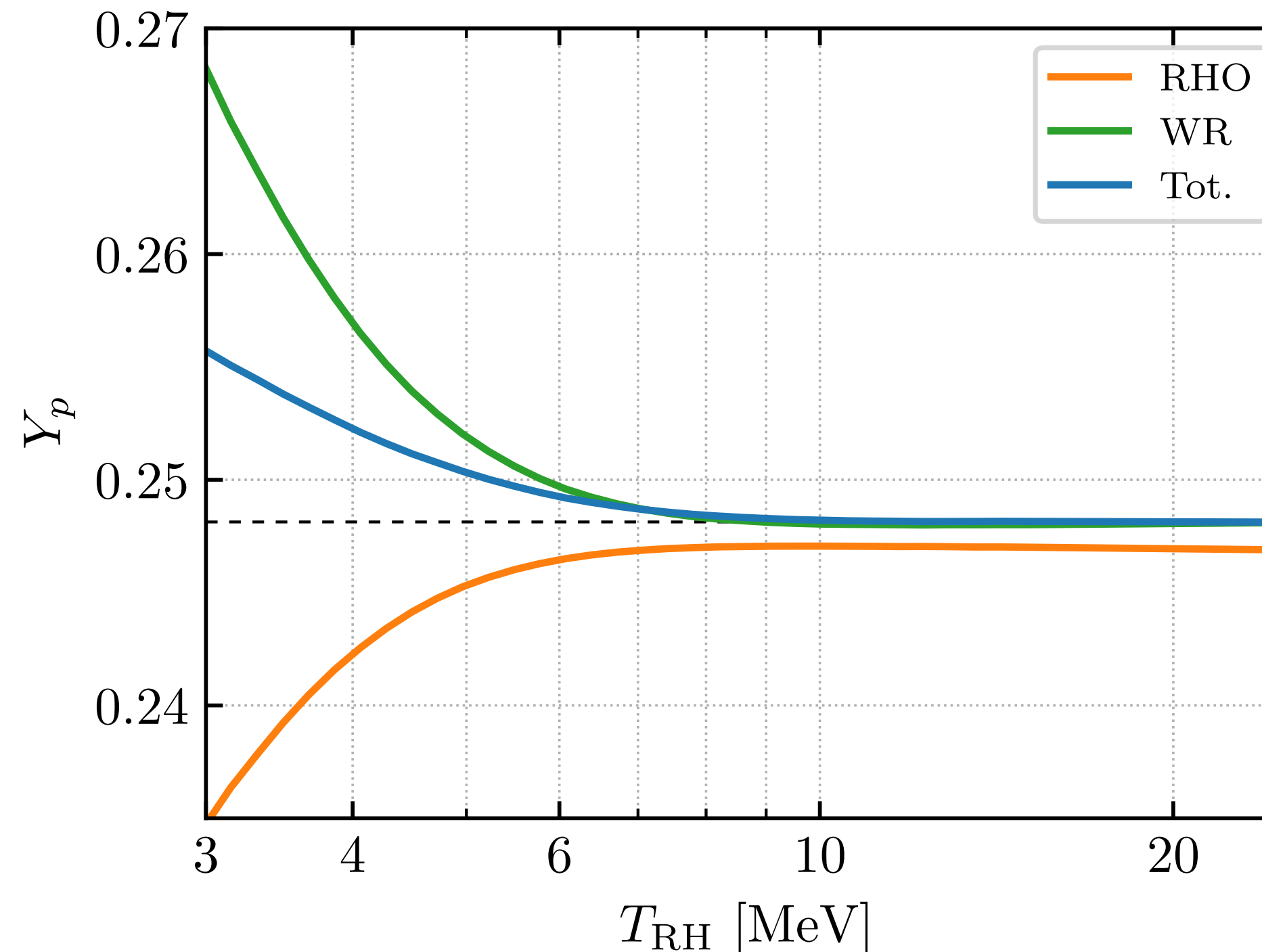
$$(\chi^2_{4He} \chi^2_{2H})(T_{RH}) \leq 4 \quad \Rightarrow \quad T_{RH} \geq 3.67 \text{ MeV}$$

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
primordial
helium yield as
a function of
 T_{RH}

$$(\chi^2_{He} \chi^2_H)(T_{RH}) \leq 4 \quad \Rightarrow \quad T_{RH} \geq 3.67 \text{ MeV}$$

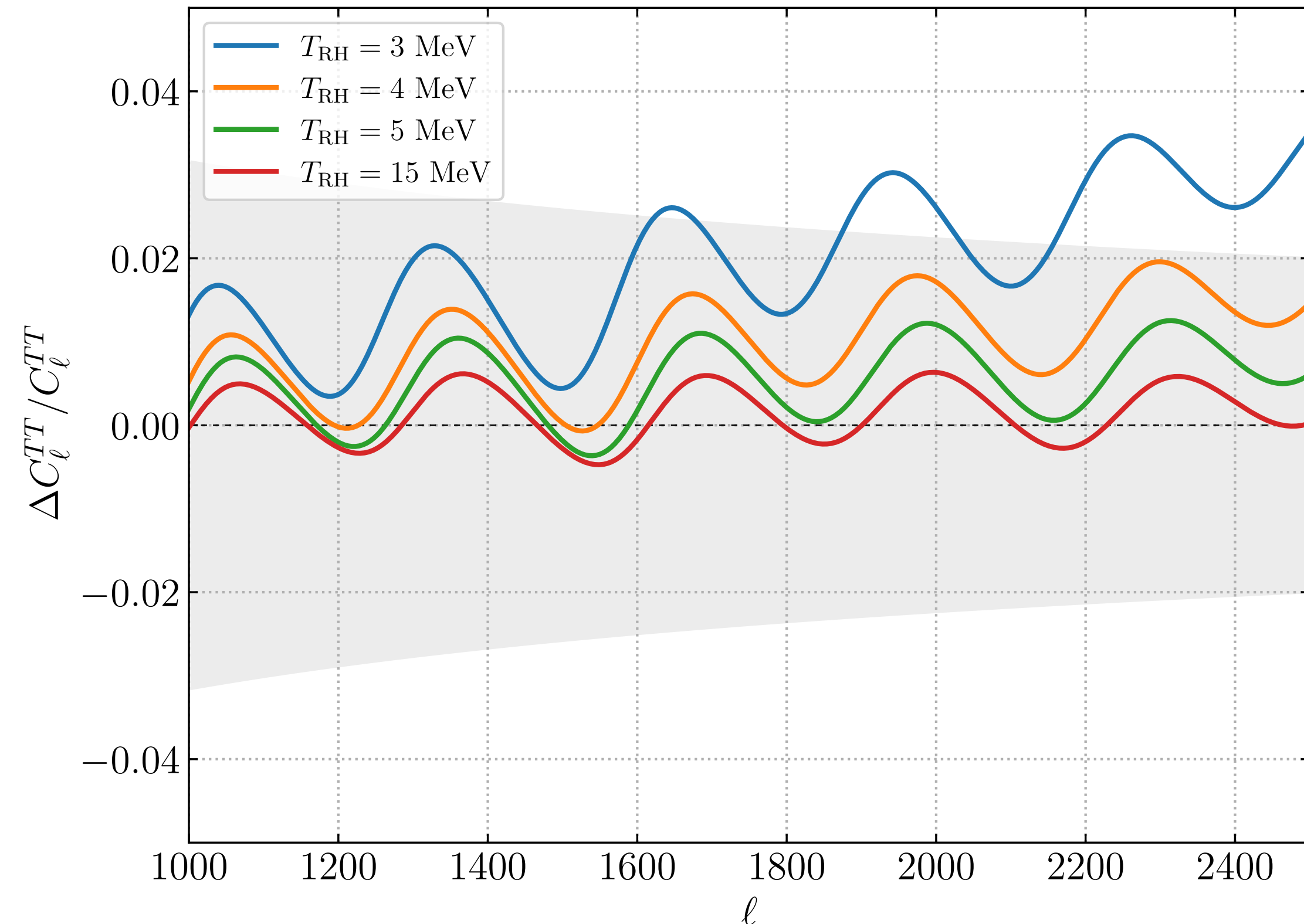
Probes of low reheating: CMB

MODIFIED VERSION OF
MONTEPYTHON SAMPLER

- 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 states 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.



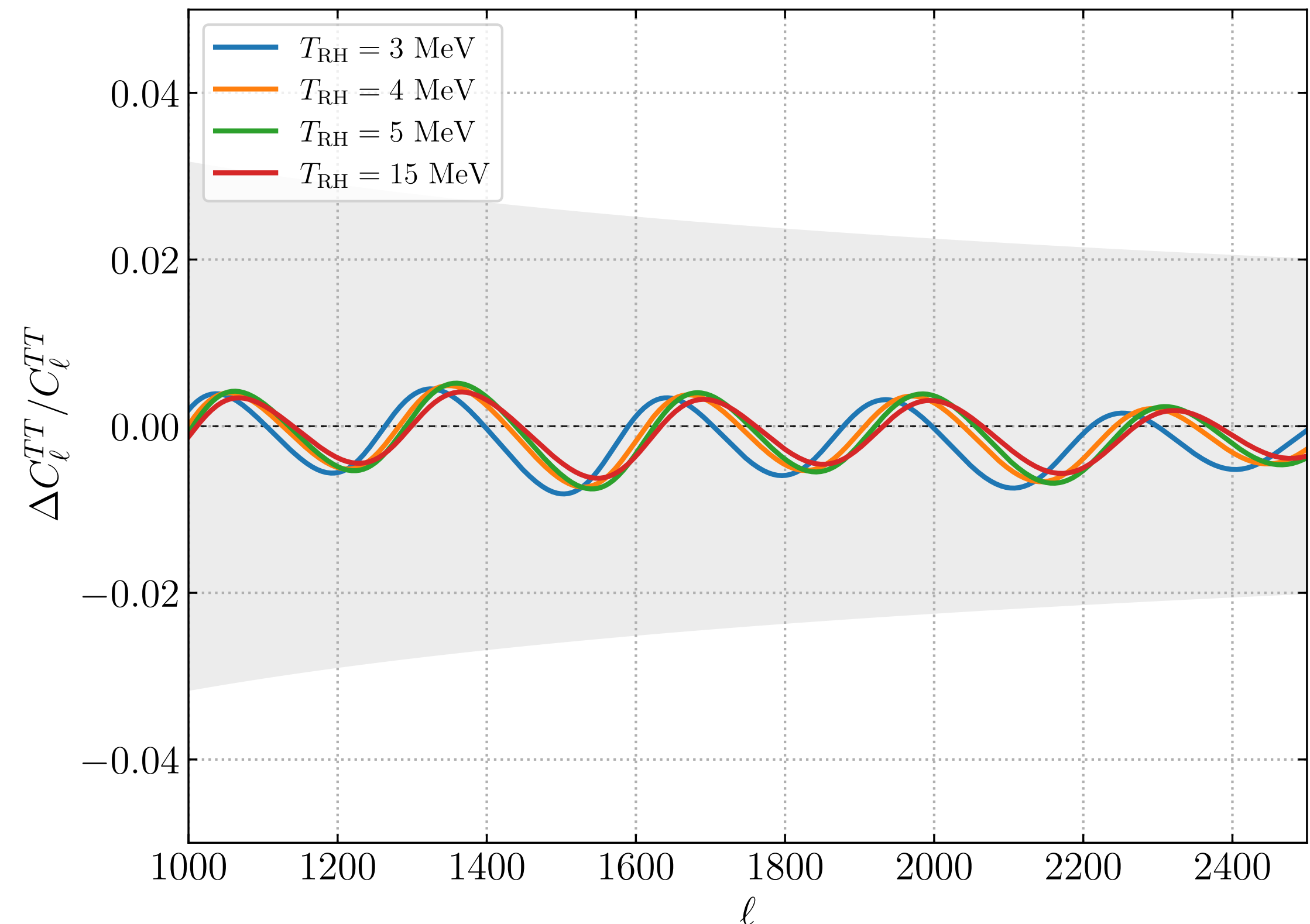
Probes of low reheating: CMB

MODIFIED VERSION OF
MONTEPYTHON SAMPLER

- 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 states 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.



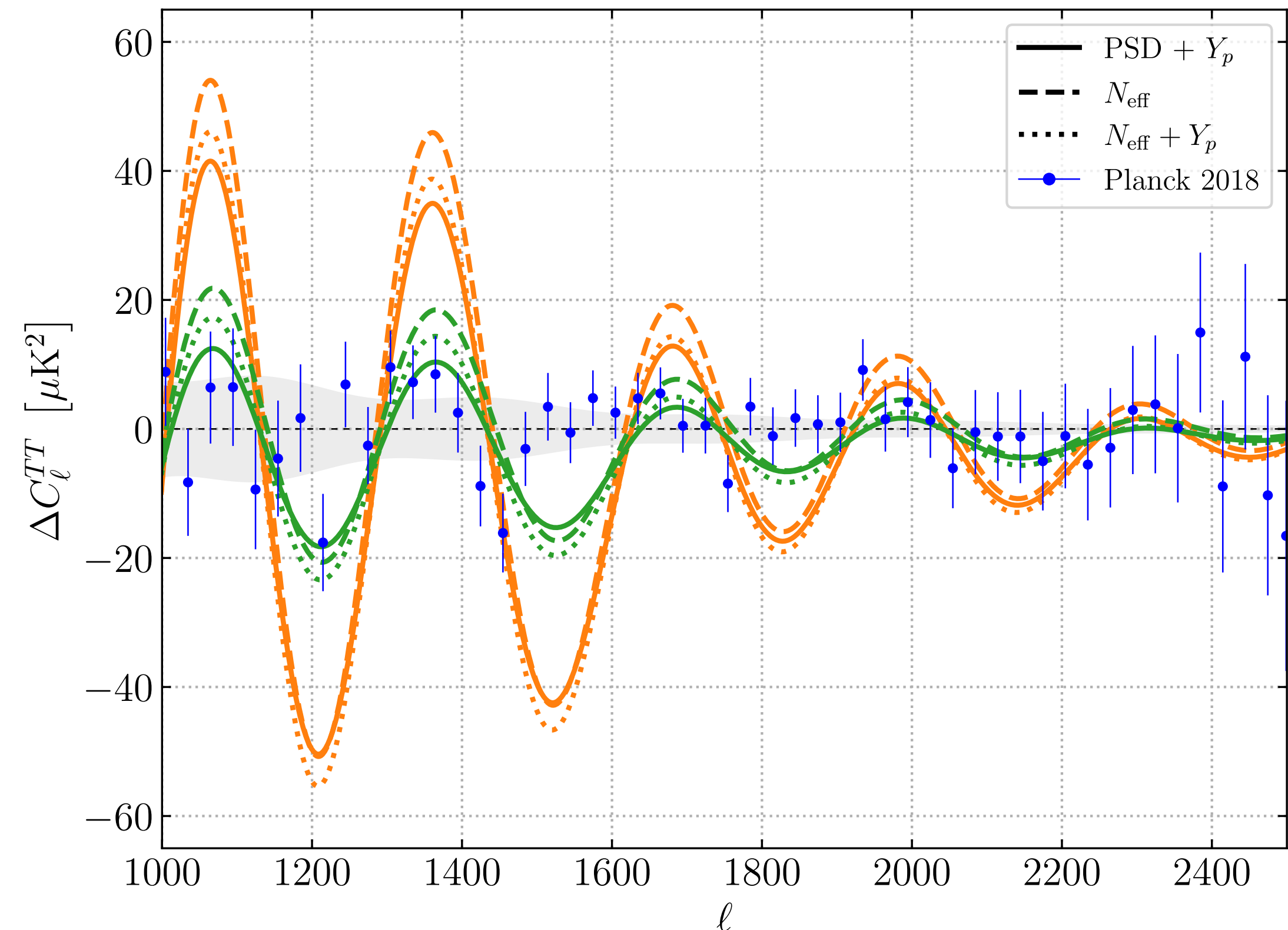
Probes of low reheating: CMB

**MODIFIED VERSION OF
MONTEPYTHON SAMPLER**

- 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 states PSDs

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

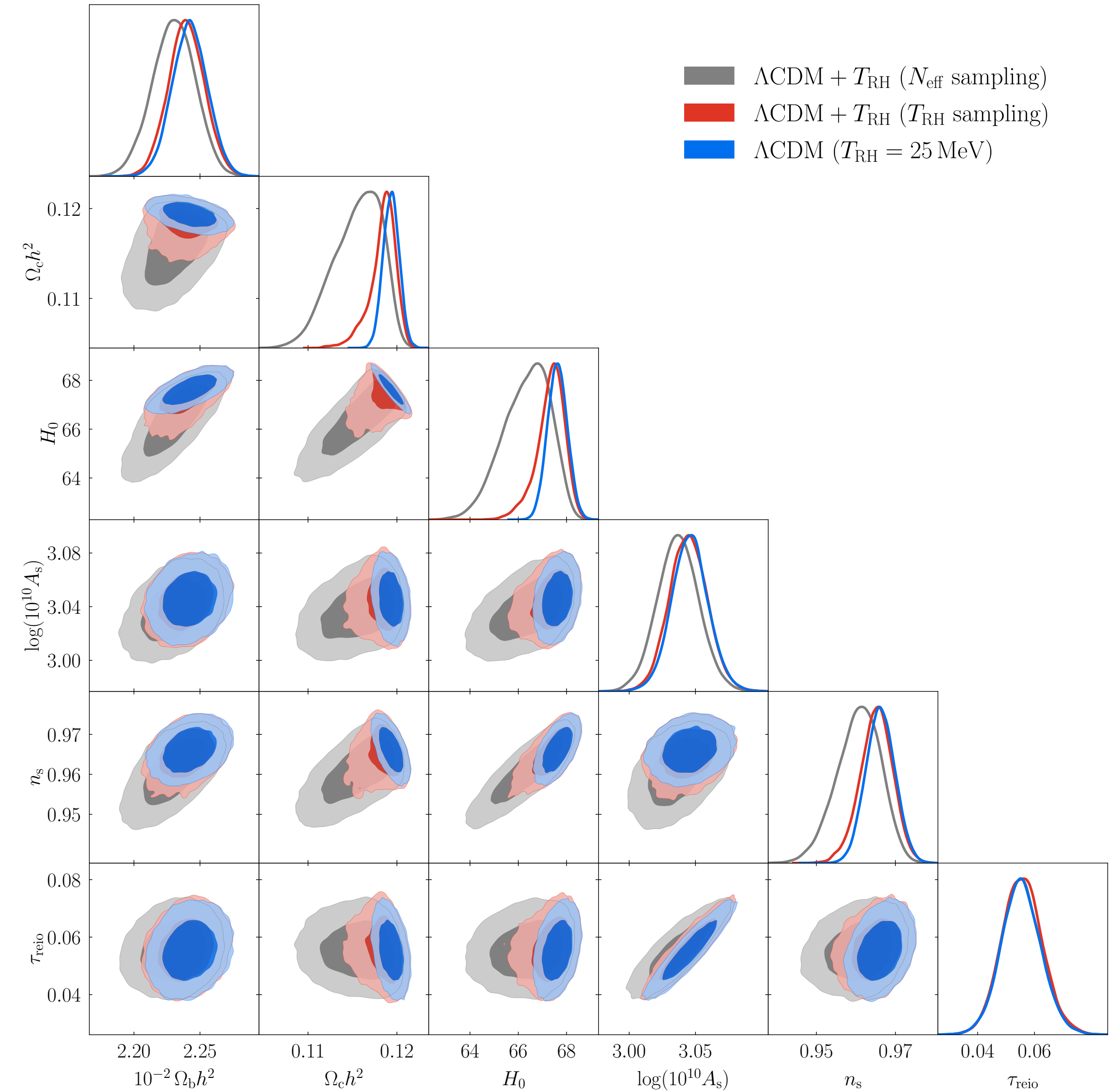
- CMB anisotropies spectrum is sensitive to the primordial helium abundance through its influence on the recombination history.



How to sample T_{RH} ?

- **T_{RH} sampling:** employed in previous works, poor sampling of low reheating temperatures region, direct interpretation of the physical results;
- **N_{eff} sampling:** most direct relationship with the data, uniform sampling of all parameter space, difficult interpretation of the results.

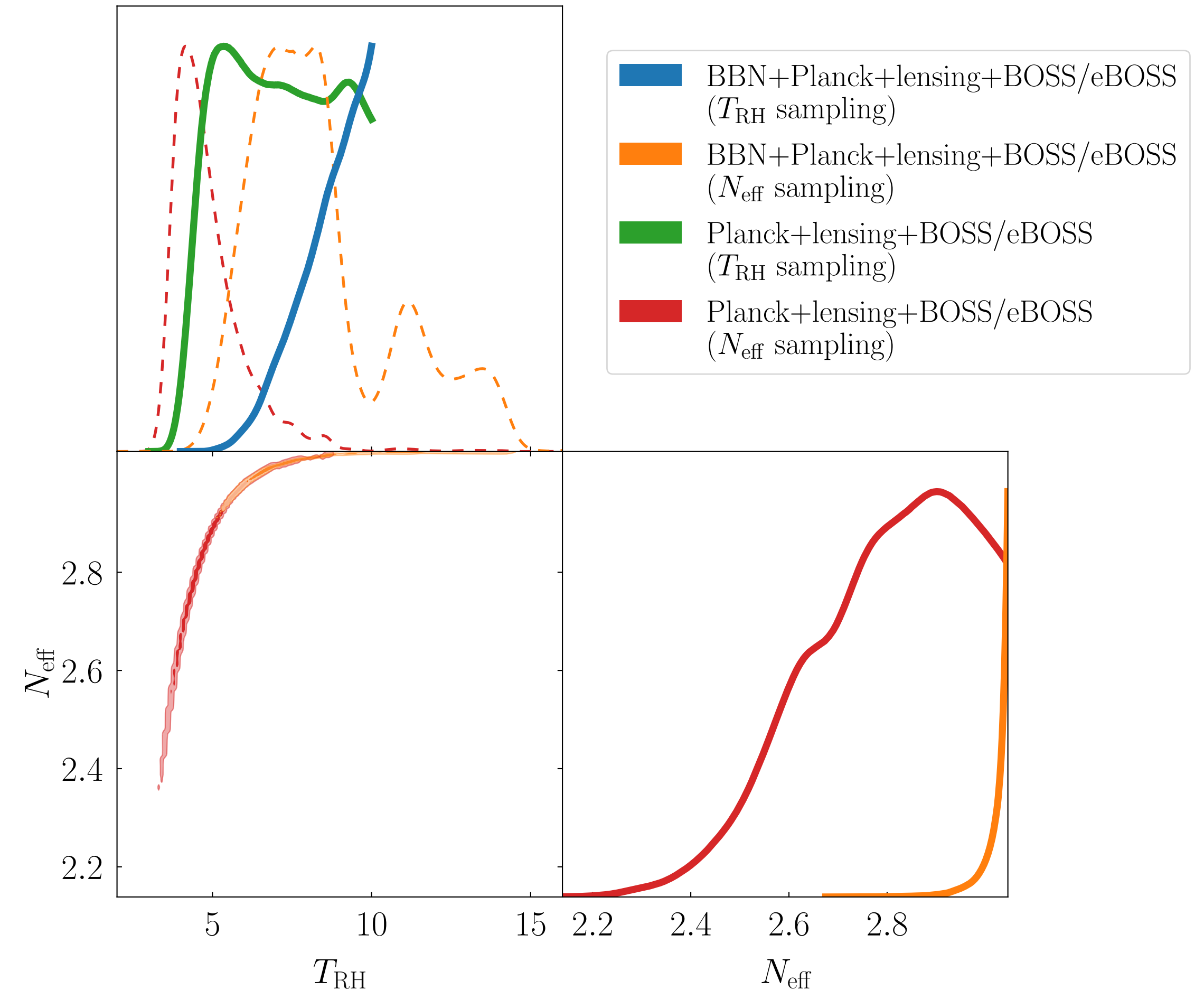
	$\Lambda\text{CDM} + T_{\text{RH}}$ (N_{eff} sampling)	$\Lambda\text{CDM} + T_{\text{RH}}$ (T_{RH} sampling)	ΛCDM ($T_{\text{RH}} = 25 \text{ MeV}$)	ΛCDM (Planck 2018)
Parameter	68% limits	68% limits	68% limits	68% limits
$\Omega_b h^2$	0.02230 ± 0.00016	0.02240 ± 0.00014	0.02242 ± 0.00013	0.02242 ± 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
τ_{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}

- **T_{RH} sampling:** employed in previous works, poor sampling of low reheating temperatures region, direct interpretation of the physical results;
- **N_{eff} sampling:** most direct relationship with the data, uniform sampling of all parameter space, difficult interpretation of the results.
- Summary table:

Dataset	N_{eff} sampling	T_{RH} sampling
	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

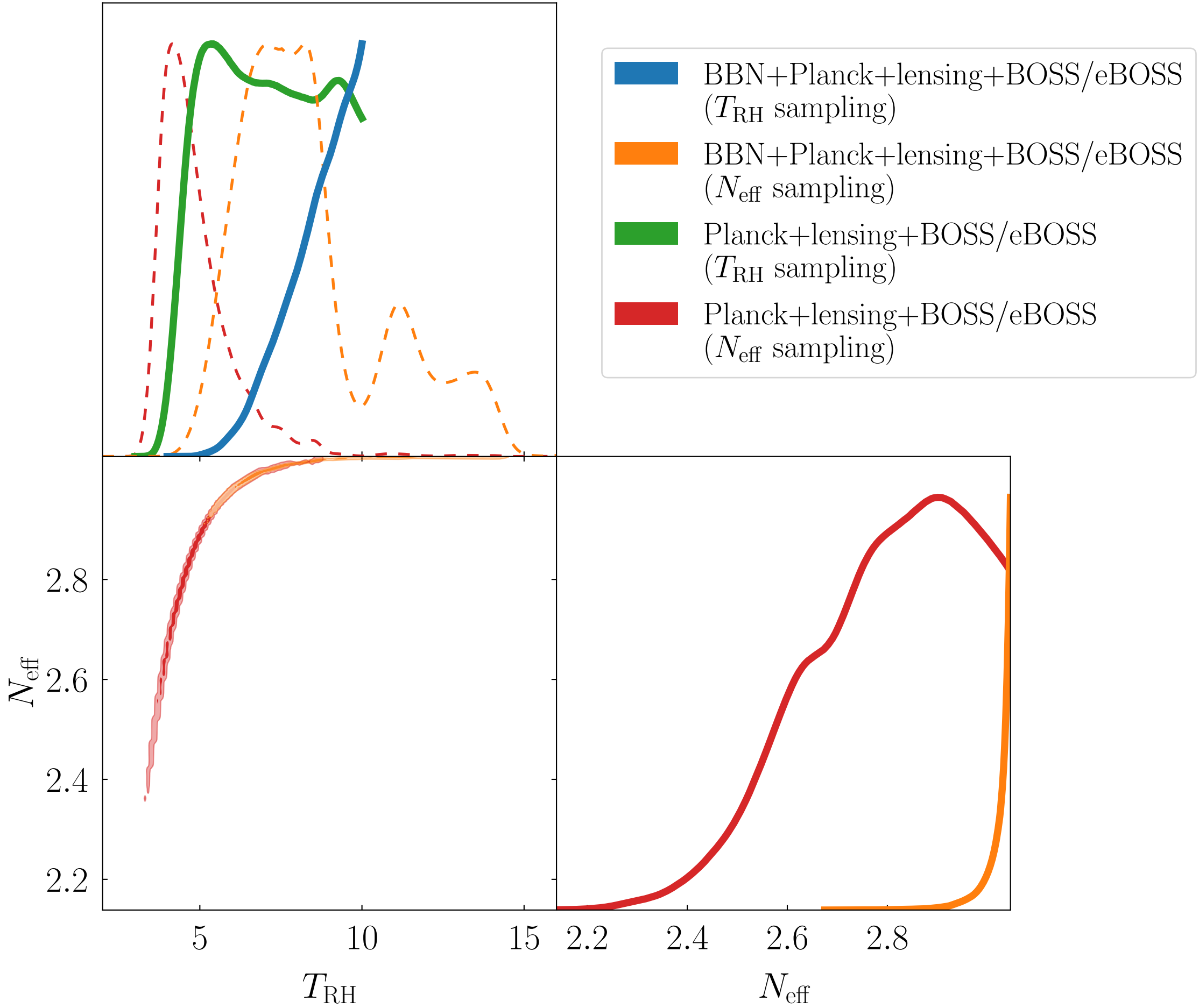


Bounds on T_{RH}

- **T_{RH} sampling:** employed in previous works, poor sampling of low reheating temperatures region, direct interpretation of the physical results;
- **N_{eff} sampling:** most direct relationship with the data, uniform sampling of all parameter space, difficult interpretation of the results.
- Summary table:

Compatible with previous works

Dataset	N_{eff} sampling	T_{RH} sampling
	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



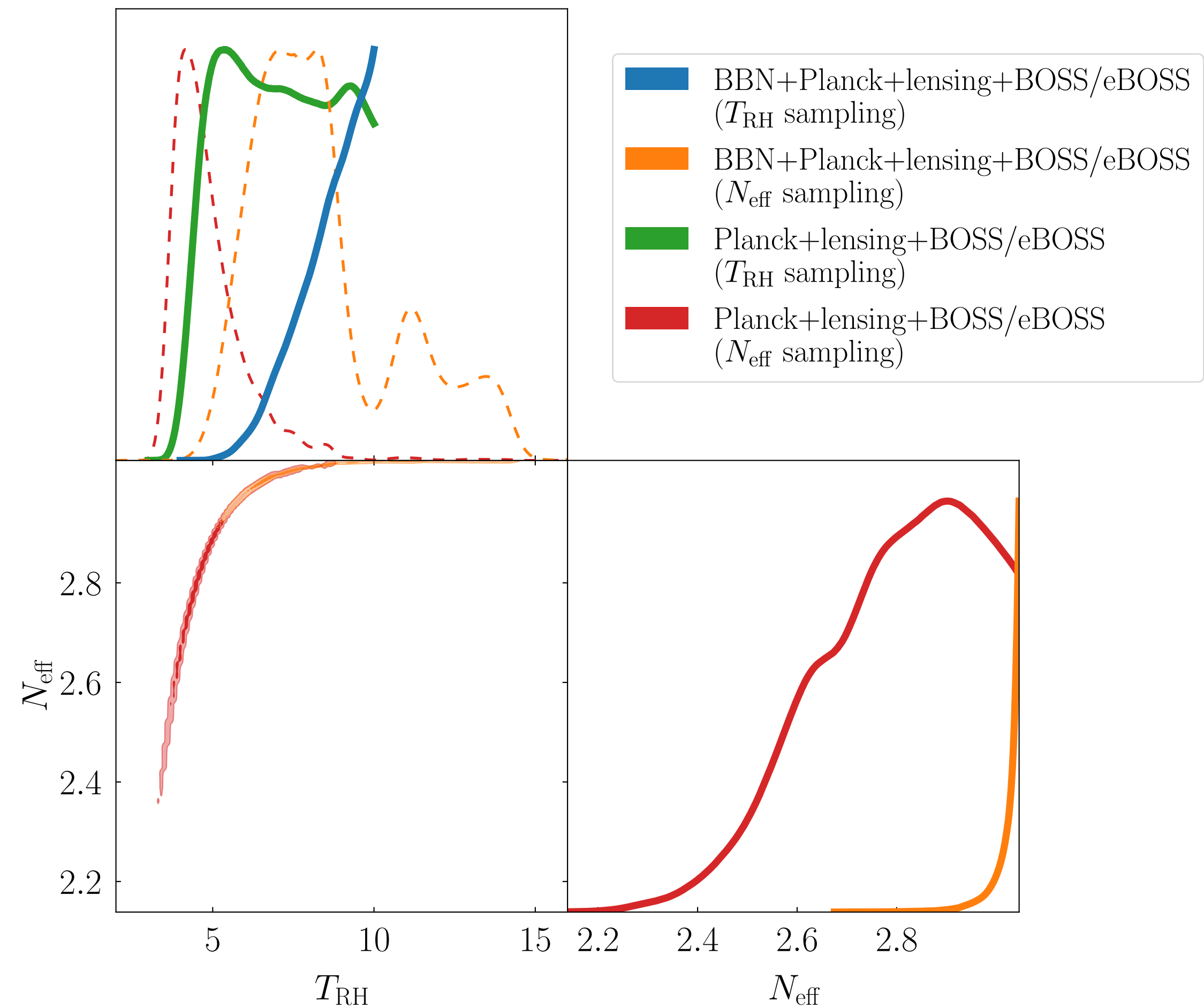
Bounds on T_{RH}

- T_{RH} **sampling**: employed in previous works, poor sampling of low reheating temperatures region, direct interpretation of the physical results;
- N_{eff} **sampling**: most direct relationship with the data, uniform sampling of all parameter space, difficult interpretation of the results.
- Summary table:

Compatible with previous works

Dataset	N_{eff} sampling	T_{RH} sampling
	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

Slightly **relaxed** by new sampling strategy



The Kullback-Leibler divergence

- Measure of the “distance” between two distributions

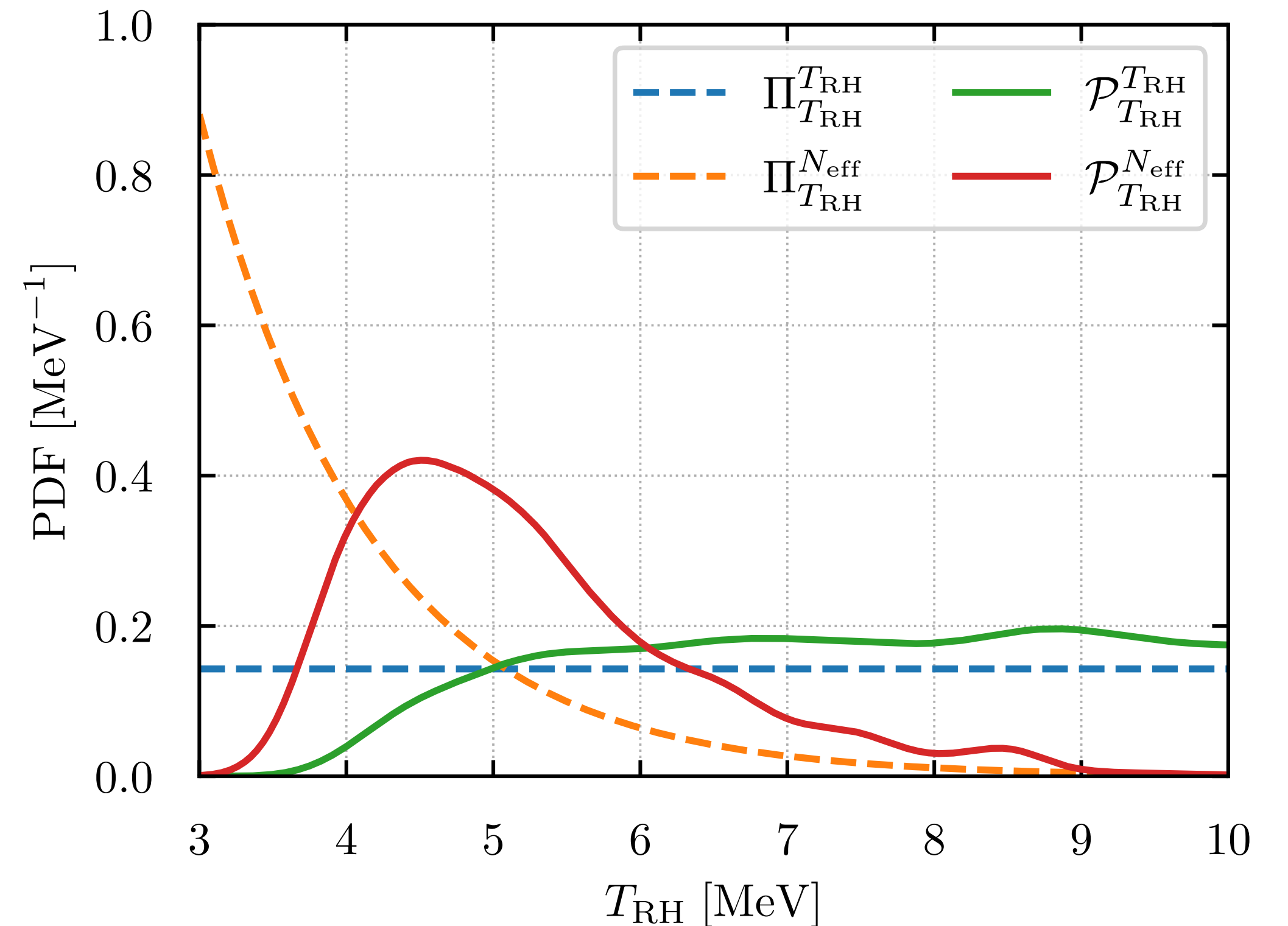
$$\mathcal{D}_{\text{KL}}(P \parallel Q) \equiv \int d\boldsymbol{\theta} p(\boldsymbol{\theta}) \log \left[\frac{p(\boldsymbol{\theta})}{q(\boldsymbol{\theta})} \right]$$

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.

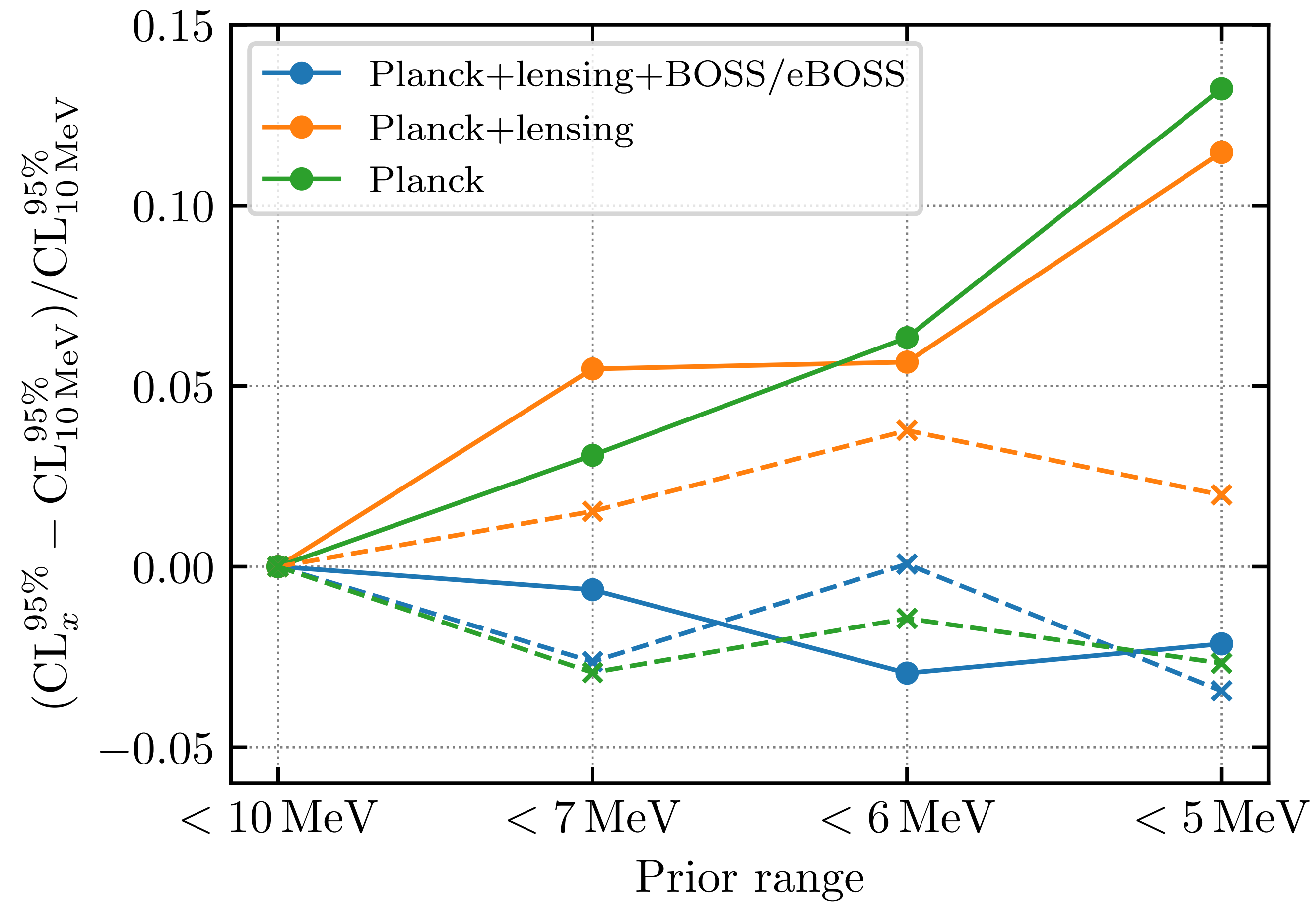
$$\mathcal{D}_{\text{KL}}(\mathcal{P}_{T_{\text{RH}}} \parallel \Pi_{T_{\text{RH}}}) = 0.14$$

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

Slight “preference”
for N_{eff} sampling

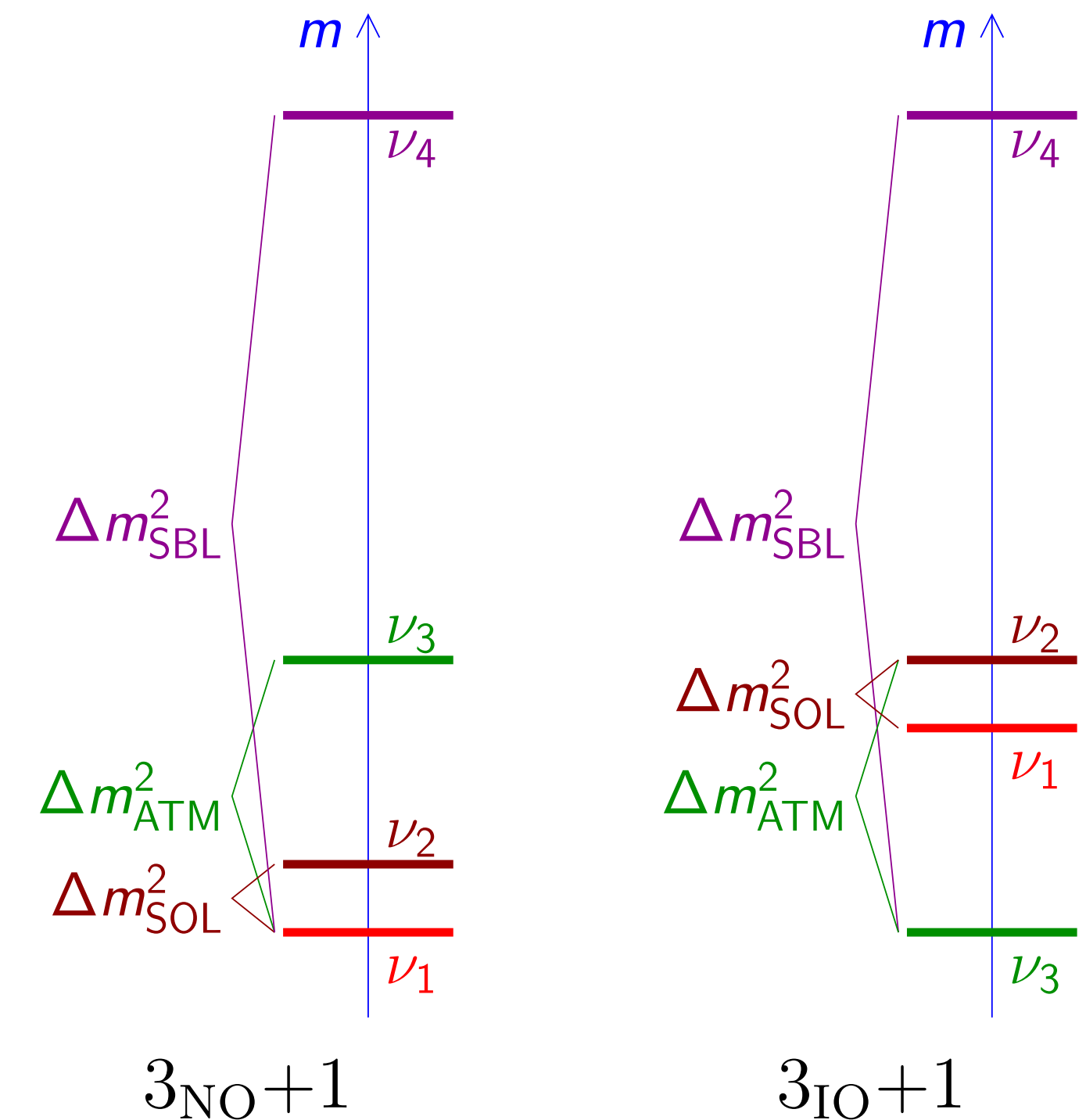


Bounds on Σm_ν



The (3+1) neutrino framework

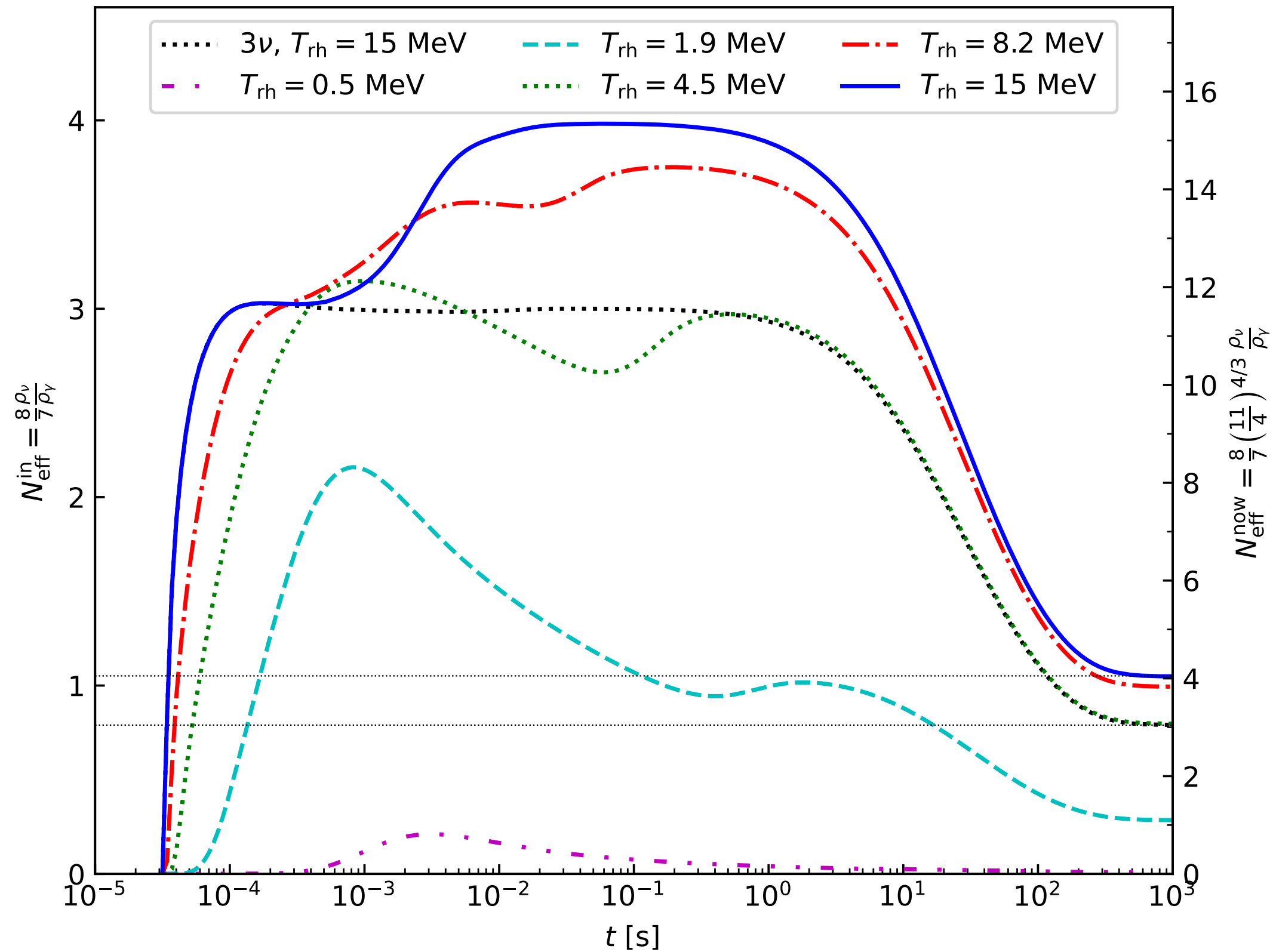
- Several anomalies in neutrino oscillation experiments seem to suggest the existence of one **additional sterile state**, mixed with the active neutrinos;
- The parameter space is enlarged by the addition of an **additional mass splitting**, Δm_{14}^2 , and **three new mixing angles** θ_{14} , θ_{24} 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)]

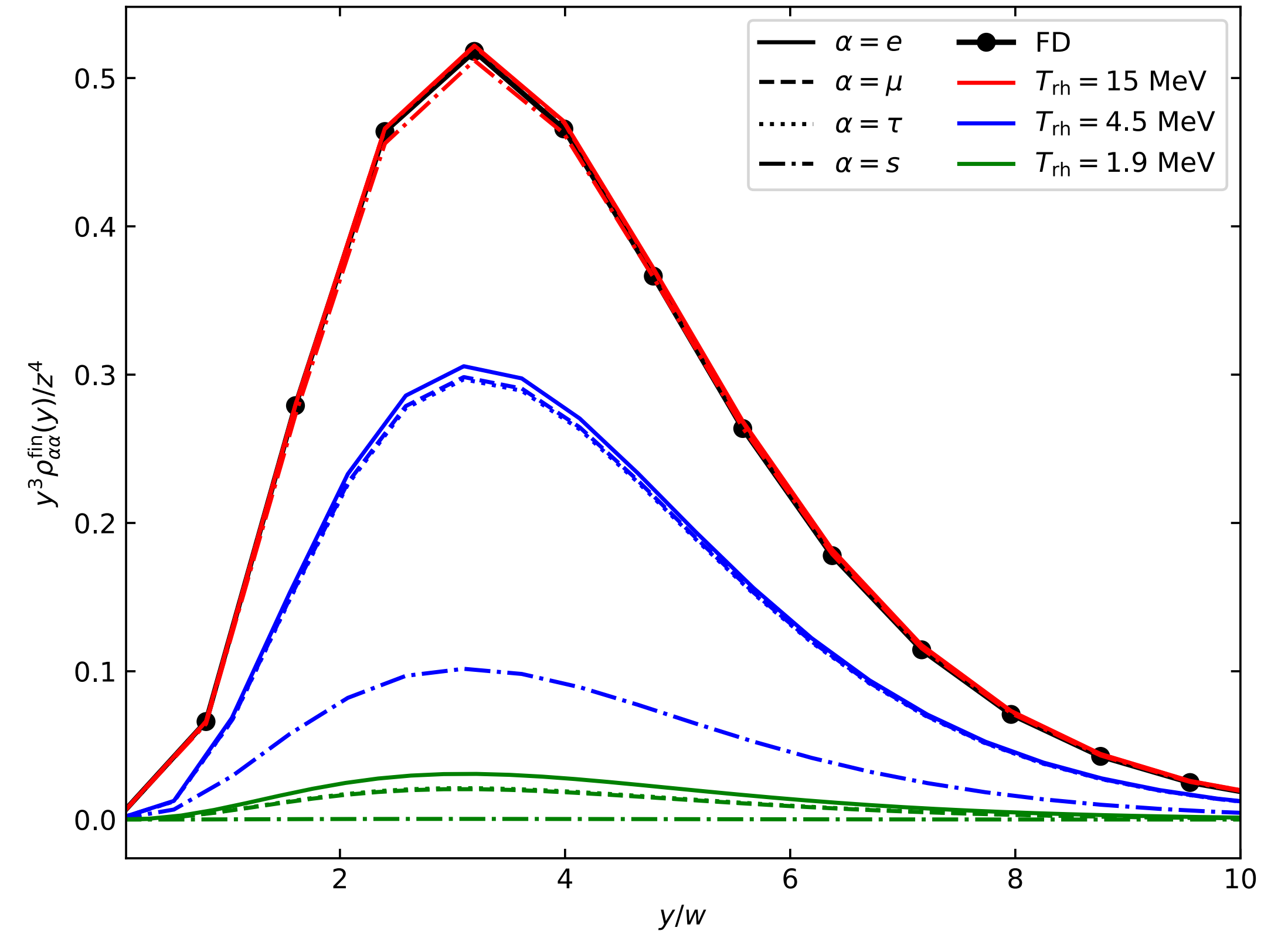
Neutrino production in (3+1) models

[Credits: S. Gariazzo]



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

[Credits: S. Gariazzo]



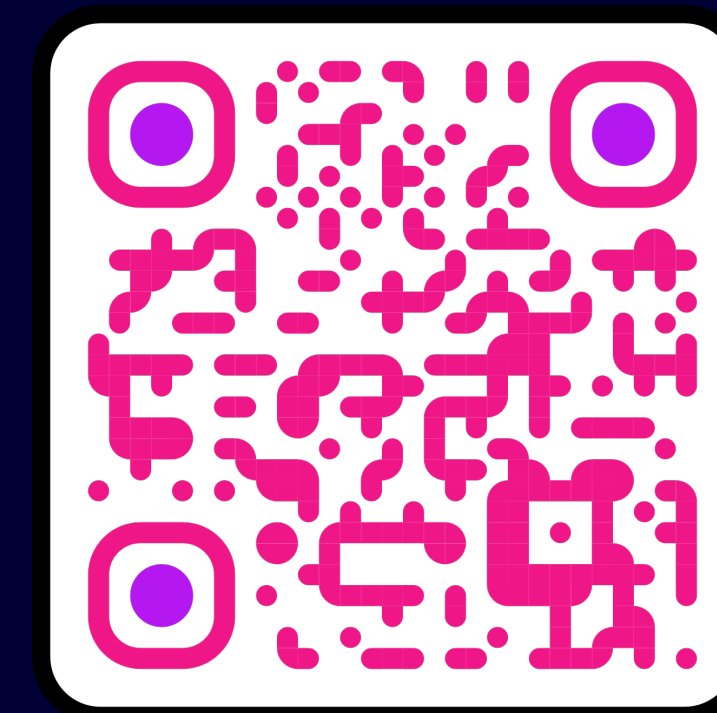
Final differential spectra of neutrino energies as a function of the comoving momentum.



TeV Particle Astrophysics
T_eVPA
Valencia 2025



European Research Council
Established by the European Commission



INFN

FERRARA

Thank you!

Based on **Barbieri+** (2025)
Phys. Rev. Lett. **135**, 181003

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 & IFIC, CSIC-UV) – 04/11/2025