Neutrino frontiers 2024 - focus week

Neutrinos in very low reheating scenarios

NICOLA BARBIERI (UNIFE) - 02/07/2024

Work done in collaboration with
T. Brinckmann (UniFE), S. Gariazzo (UniTO),
M. Lattanzi (INFN-FE), S. Pastor (IFIC), O. Pisanti (UniNA)

Updated constraints on very low reheating scenarios

Models of reheating

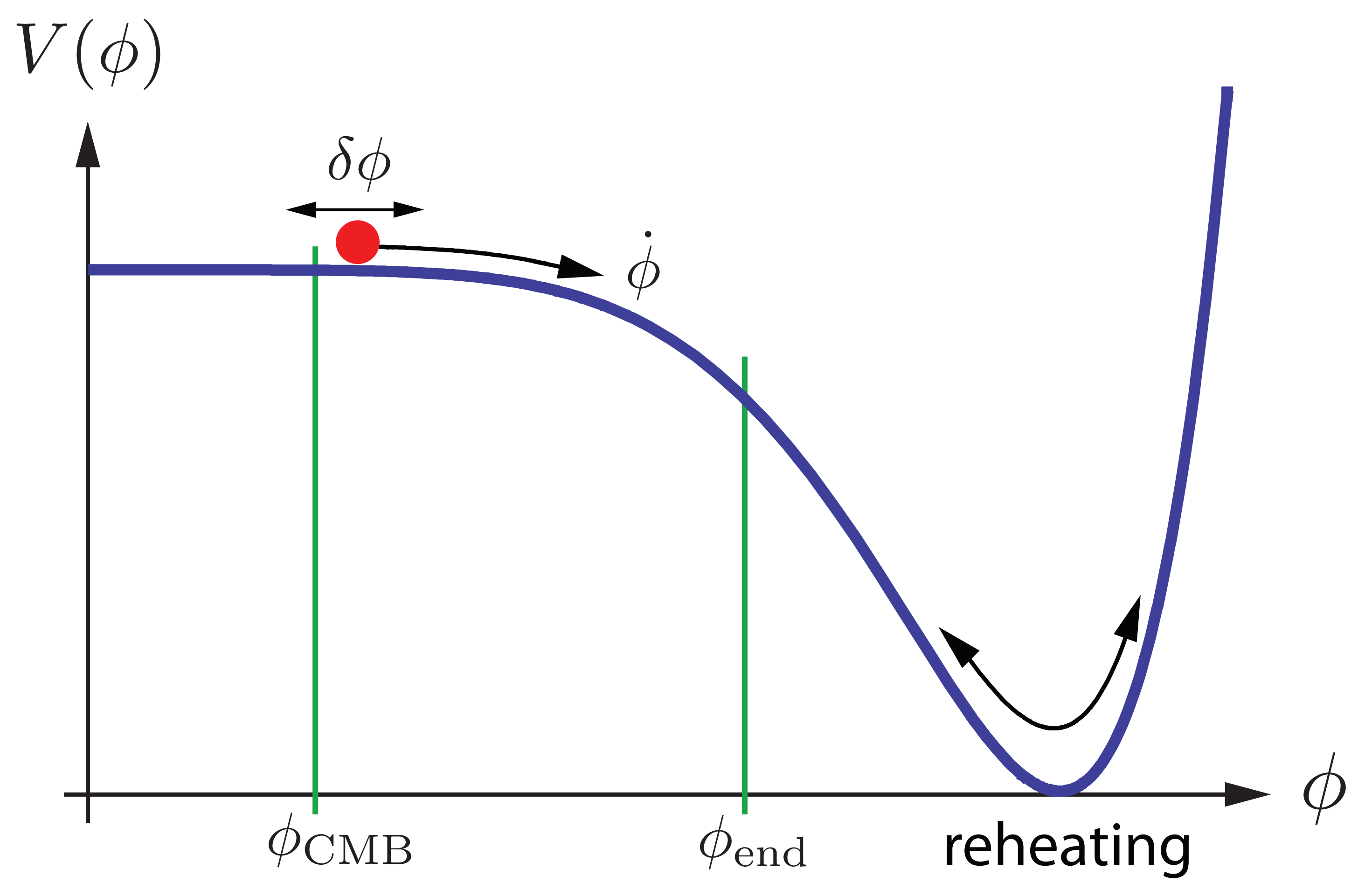
- In inflation paradigm, a final reheating phase is needed to reconcile with the standard FLRW radiation dominated Universe

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

- What is the reheating temperature?

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

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



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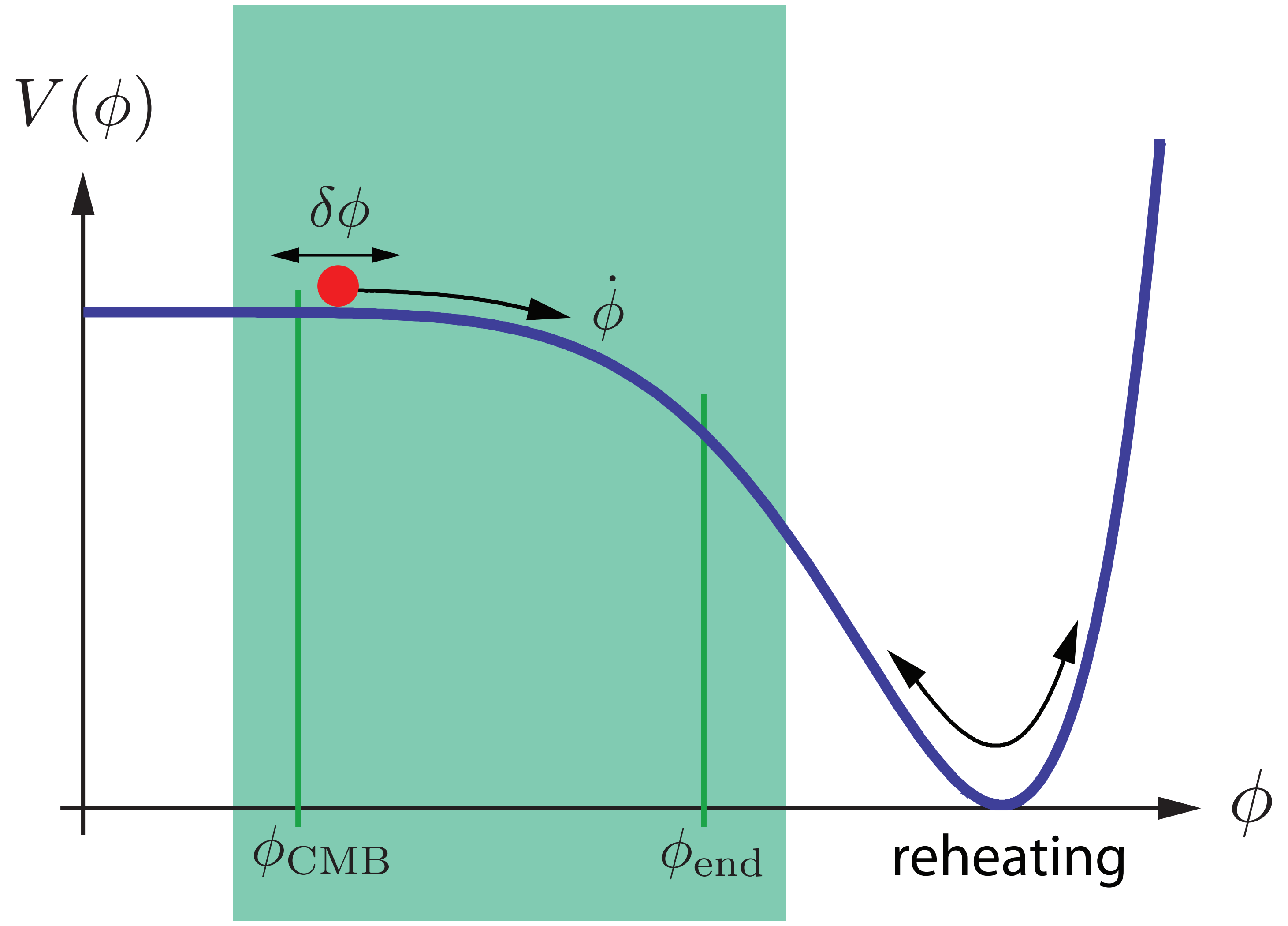
During **inflation** the inflaton dominates the energy density (as pressure-less matter)



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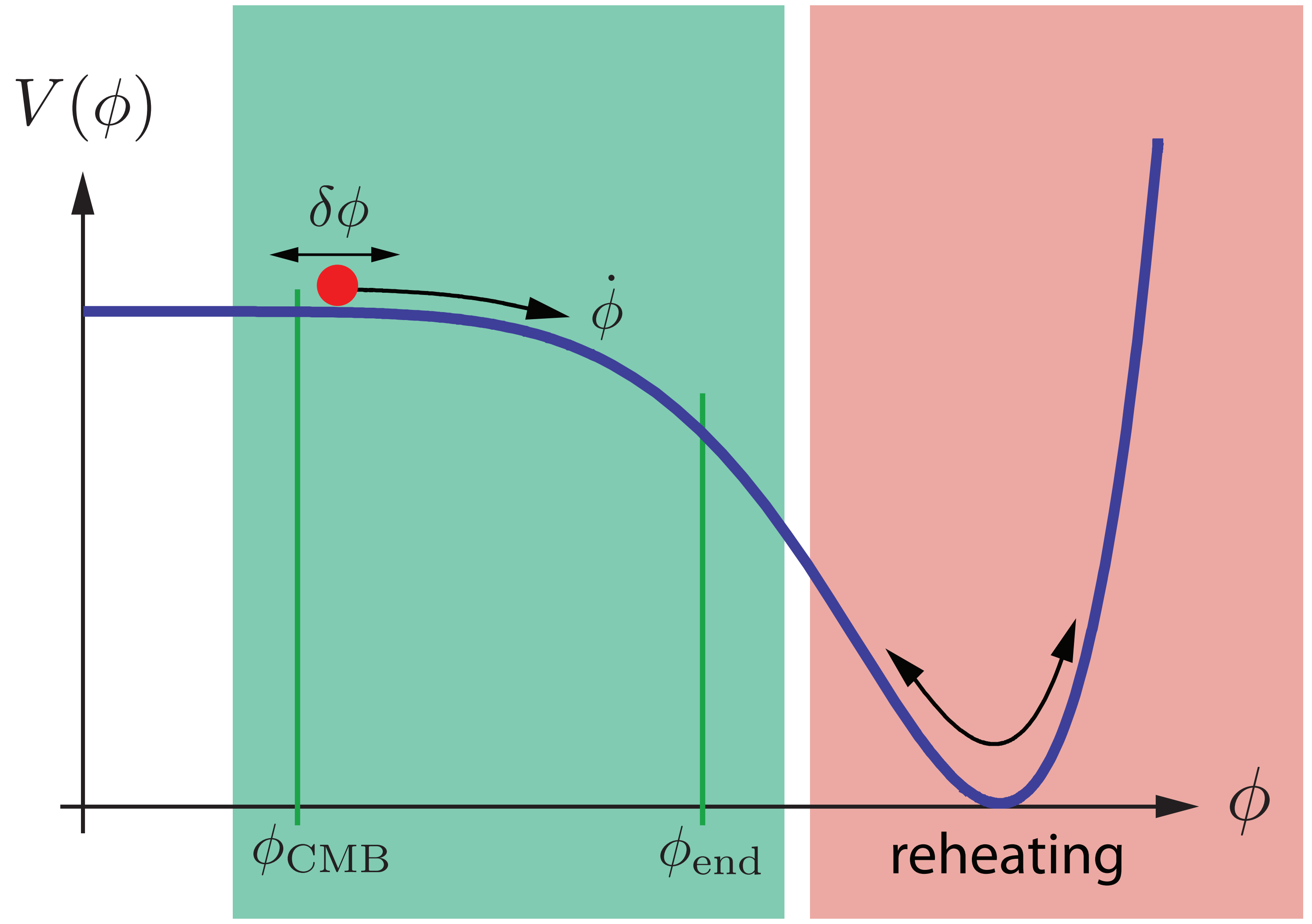

During **reheating** the inflaton decays into Standard Model degrees of freedom

Interest in low reheating

MeV scale reheating temperature and thermalization of neutrino background #1

M. Kawasaki (Tokyo U., RESCEU), Kazunori Kohri (Tokyo U., RESCEU), Naoshi Sugiyama (Kyoto U.) (Feb, 2000)

Published in: *Phys.Rev.D* 62 (2000) 023506 • e-Print: astro-ph/0002127 [astro-ph]

pdf DOI cite claim reference search 510 citations

What is the lowest possible reheating temperature? #3

Steen Hannestad (Odense U. and Nordita) (Mar, 2004)

Published in: *Phys.Rev.D* 70 (2004) 043506 • e-Print: astro-ph/0403291 [astro-ph]

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The Oscillation effects on thermalization of the neutrinos in the Universe with low reheating temperature #1

Kazuhide Ichikawa (Tokyo U., ICRR), Masahiro Kawasaki (Tokyo U., ICRR), Fuminobu Takahashi (Tokyo U., ICRR) (May, 2005)

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Bounds on very low reheating scenarios after Planck #2

P.F. de Salas (Valencia U., IFIC), M. Lattanzi (Ferrara U. and INFN, Ferrara), G. Mangano (INFN, Naples), G. Miele (INFN, Naples and Naples U.), S. Pastor (Valencia U., IFIC) et al. (Nov 2, 2015)

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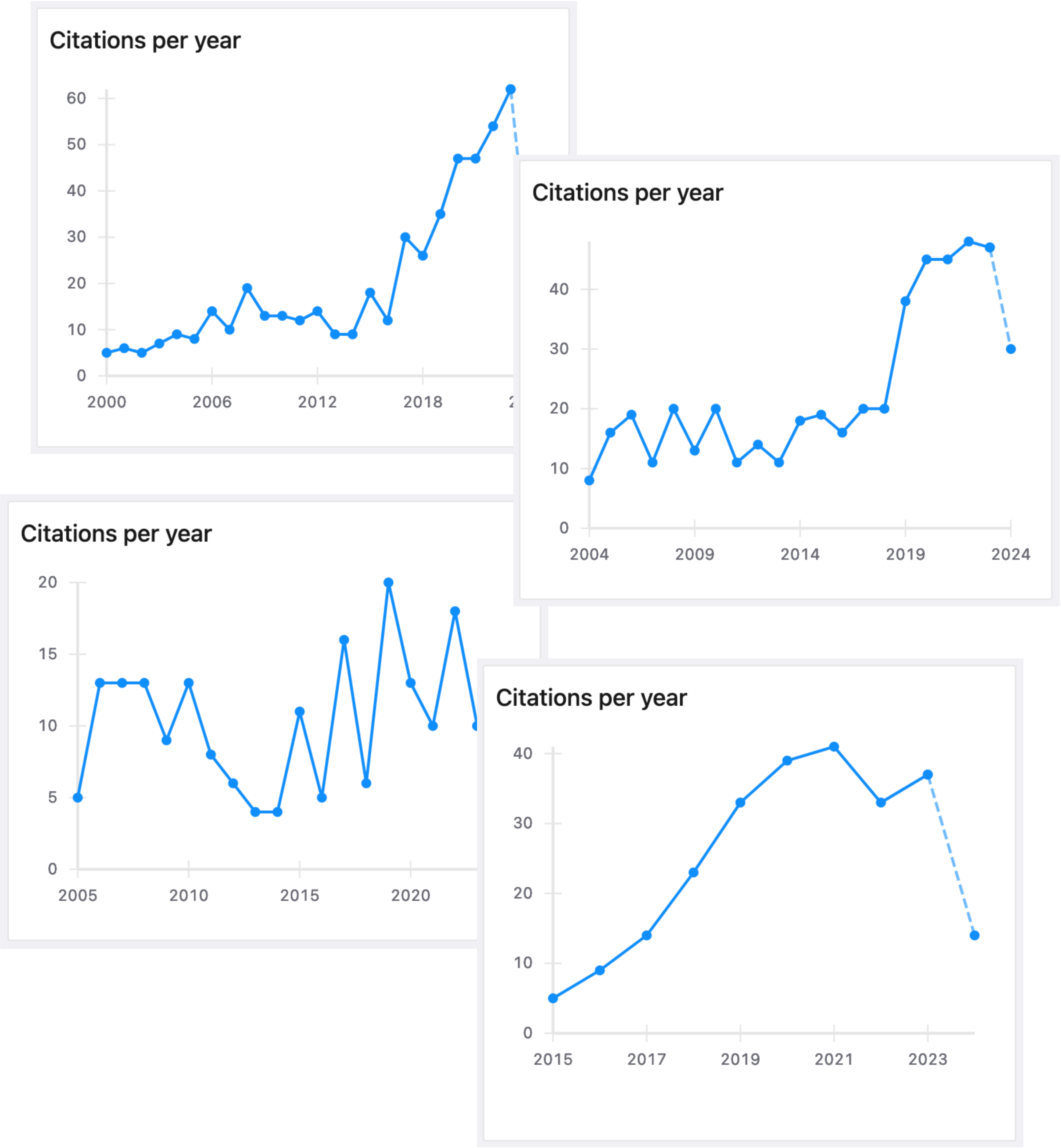

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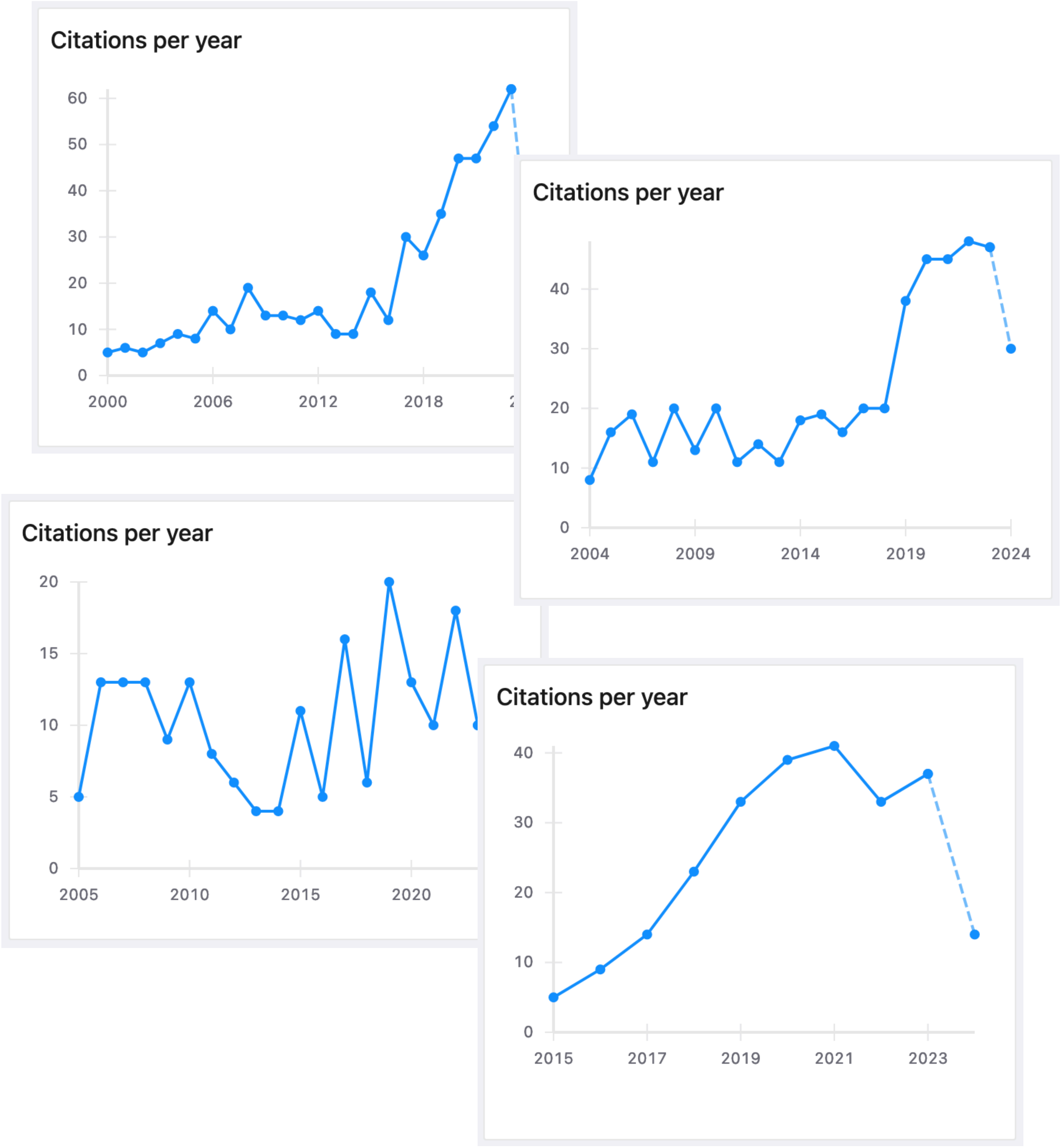

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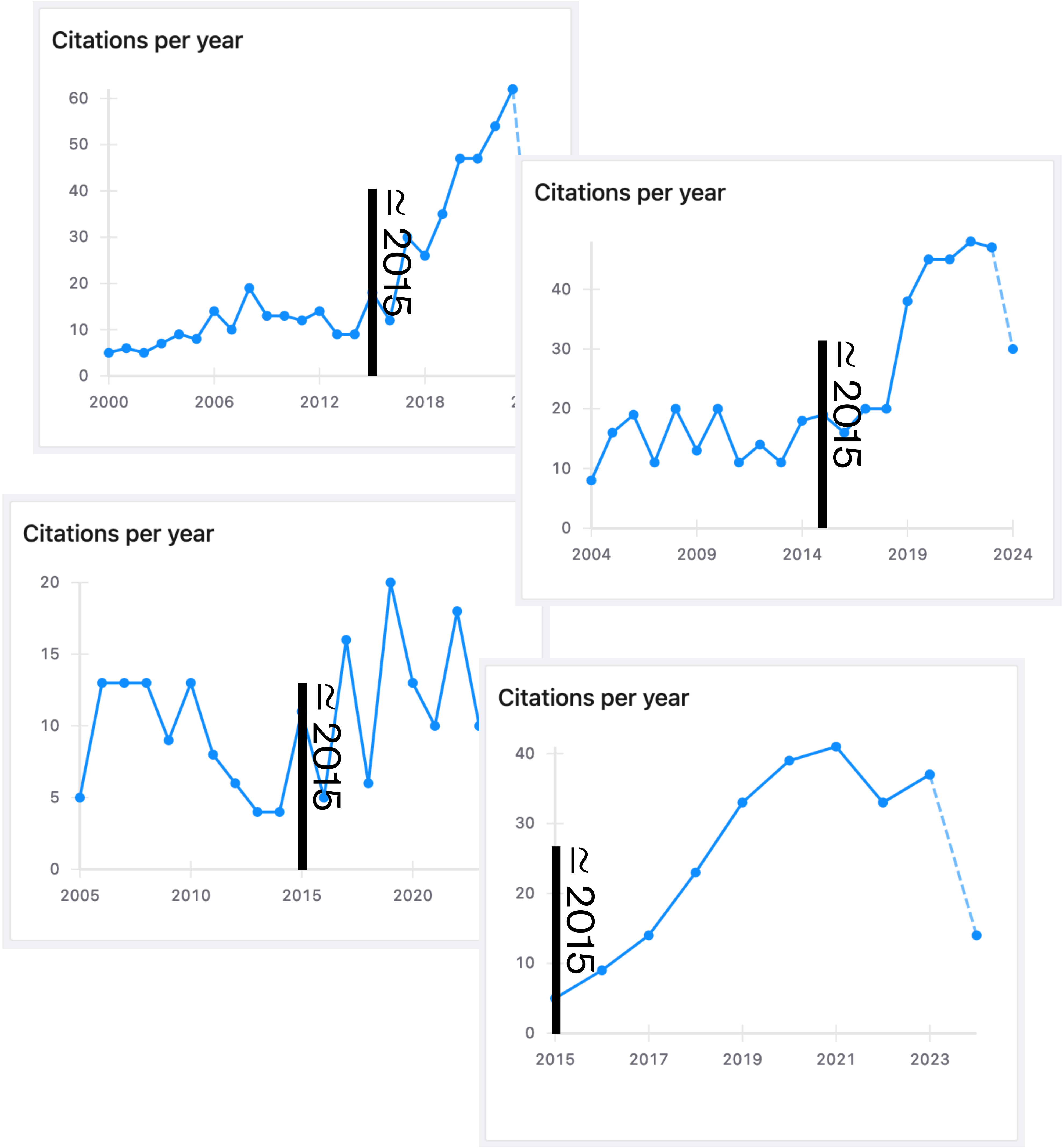

Assumptions and remarks

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

[See S. Gariazzo's and S. Pastor's talks]

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

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

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

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

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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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Neutrino production - I

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Neutrino production - I

[See S. Gariazzo's and S. Pastor's talks]

- 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

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

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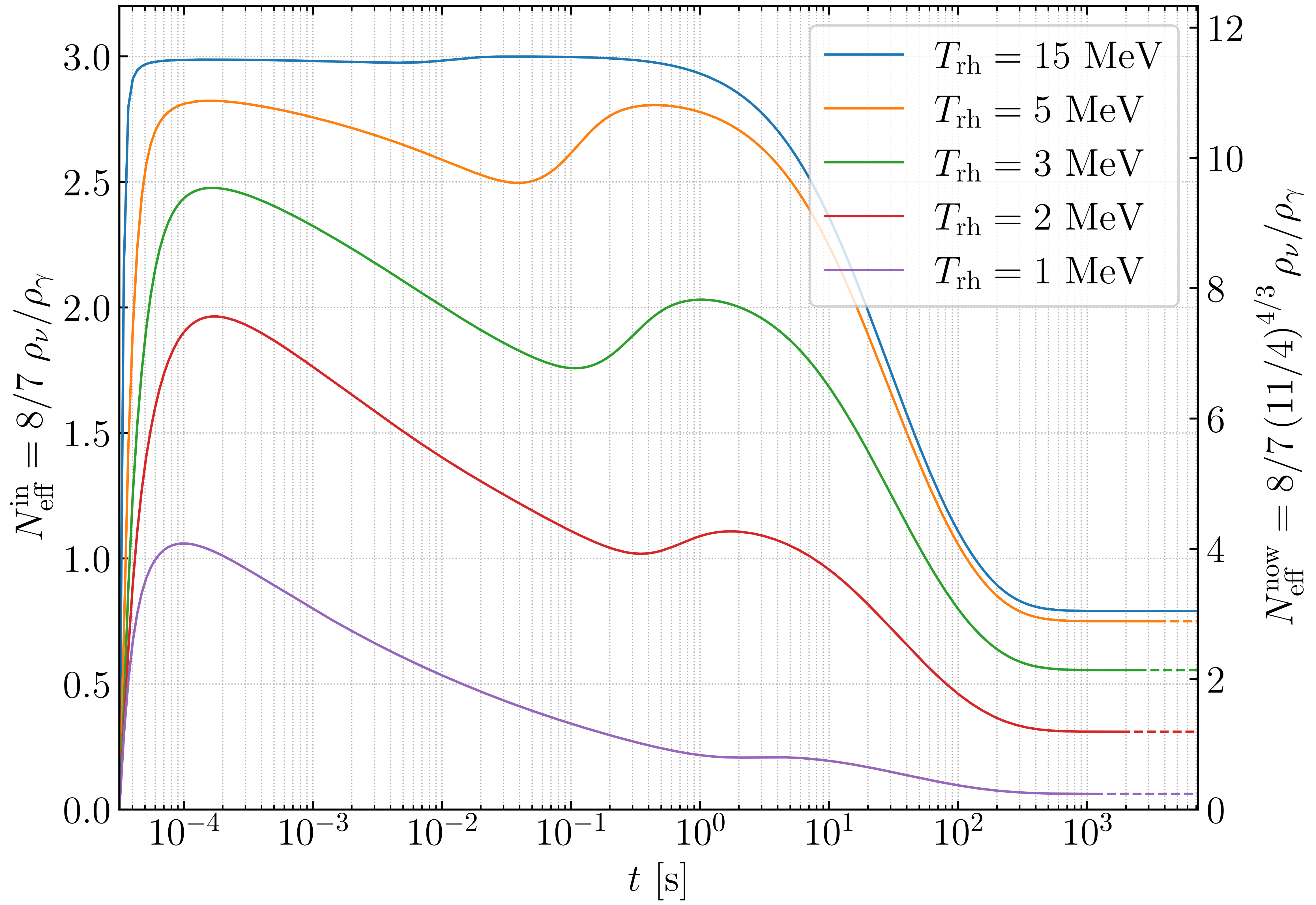
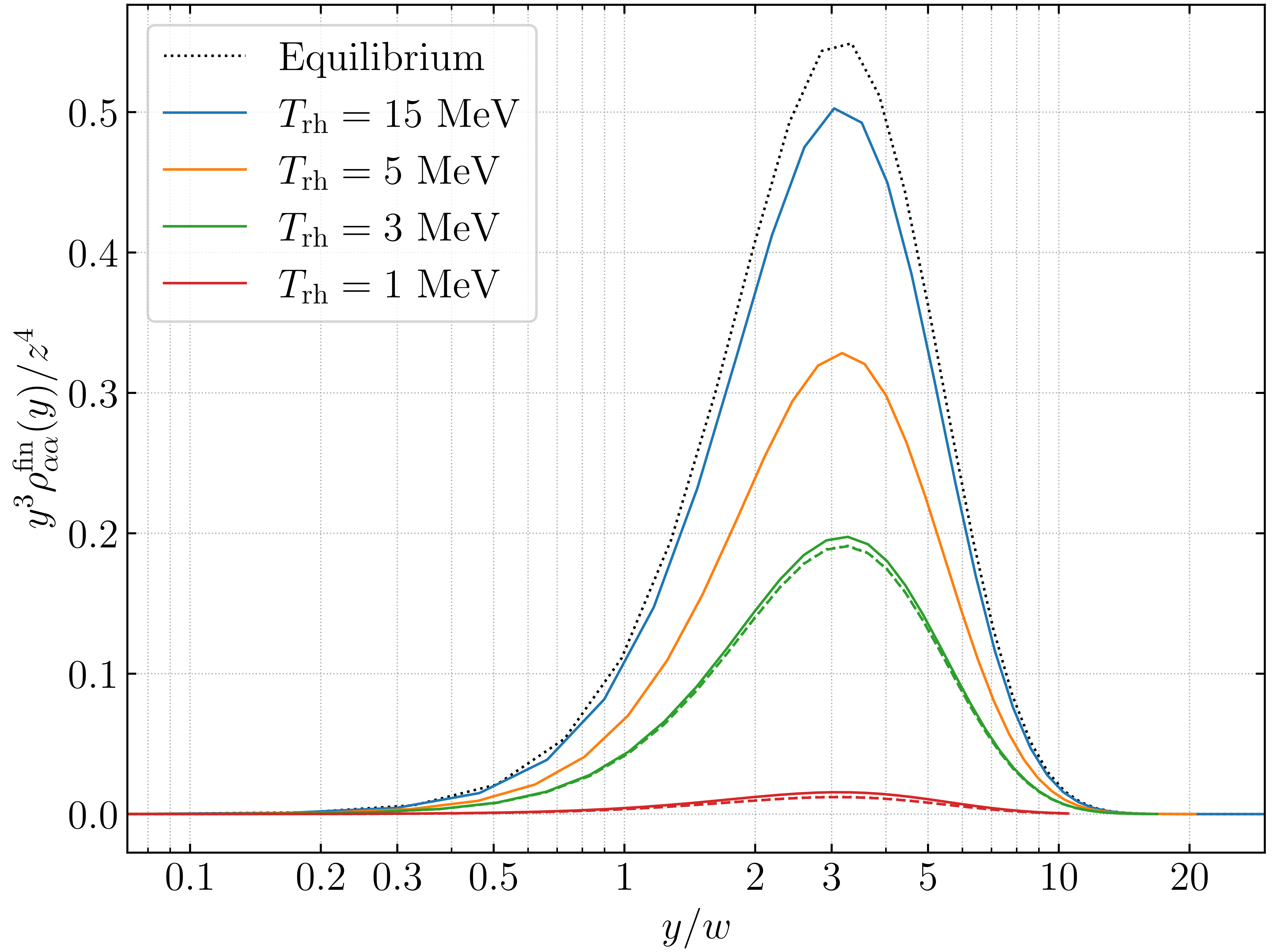
Neutrino production - II



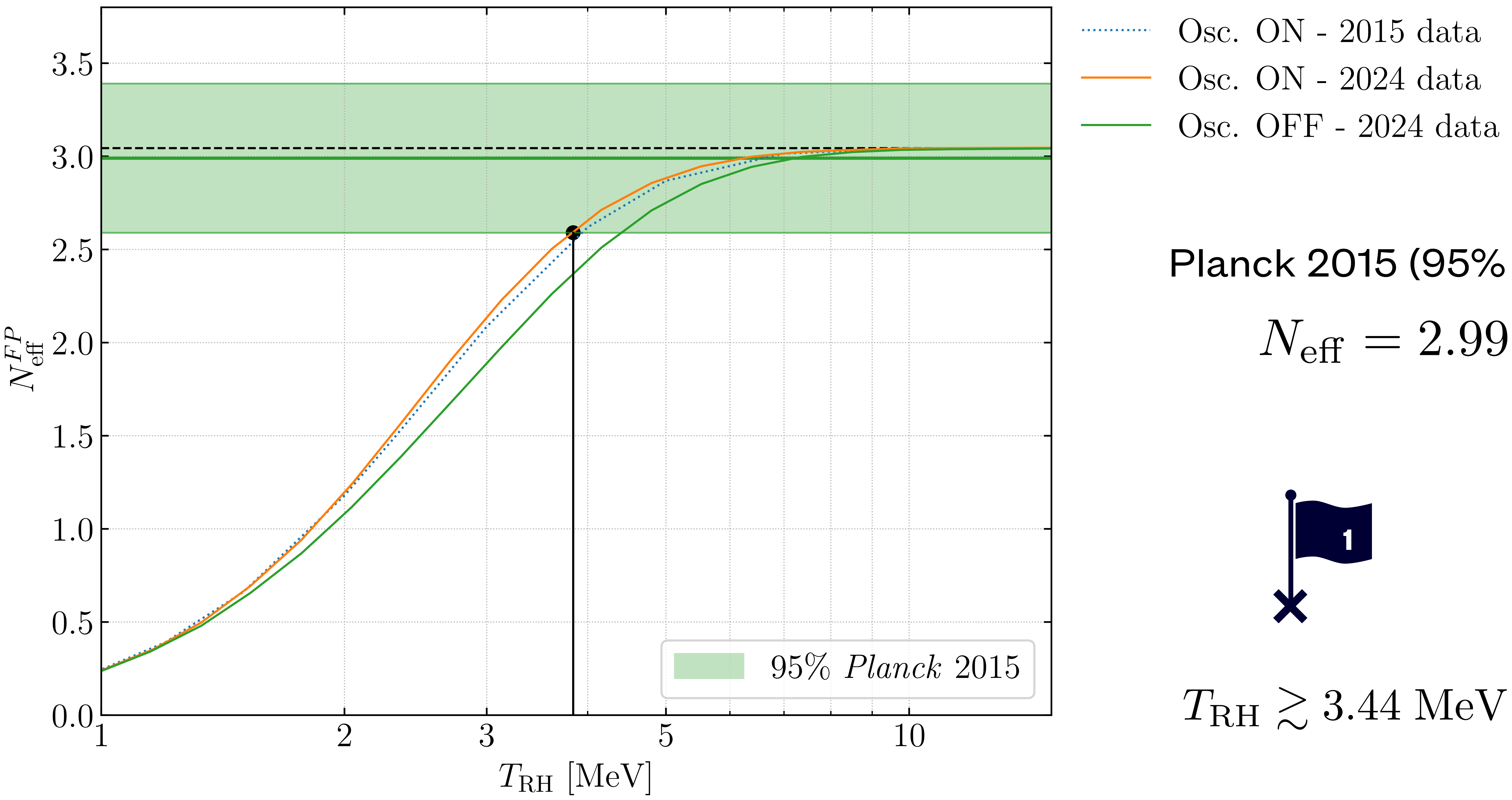
Time evolution of the ratio of energy densities of neutrinos and photons.



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):

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

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

Neutrino production - III

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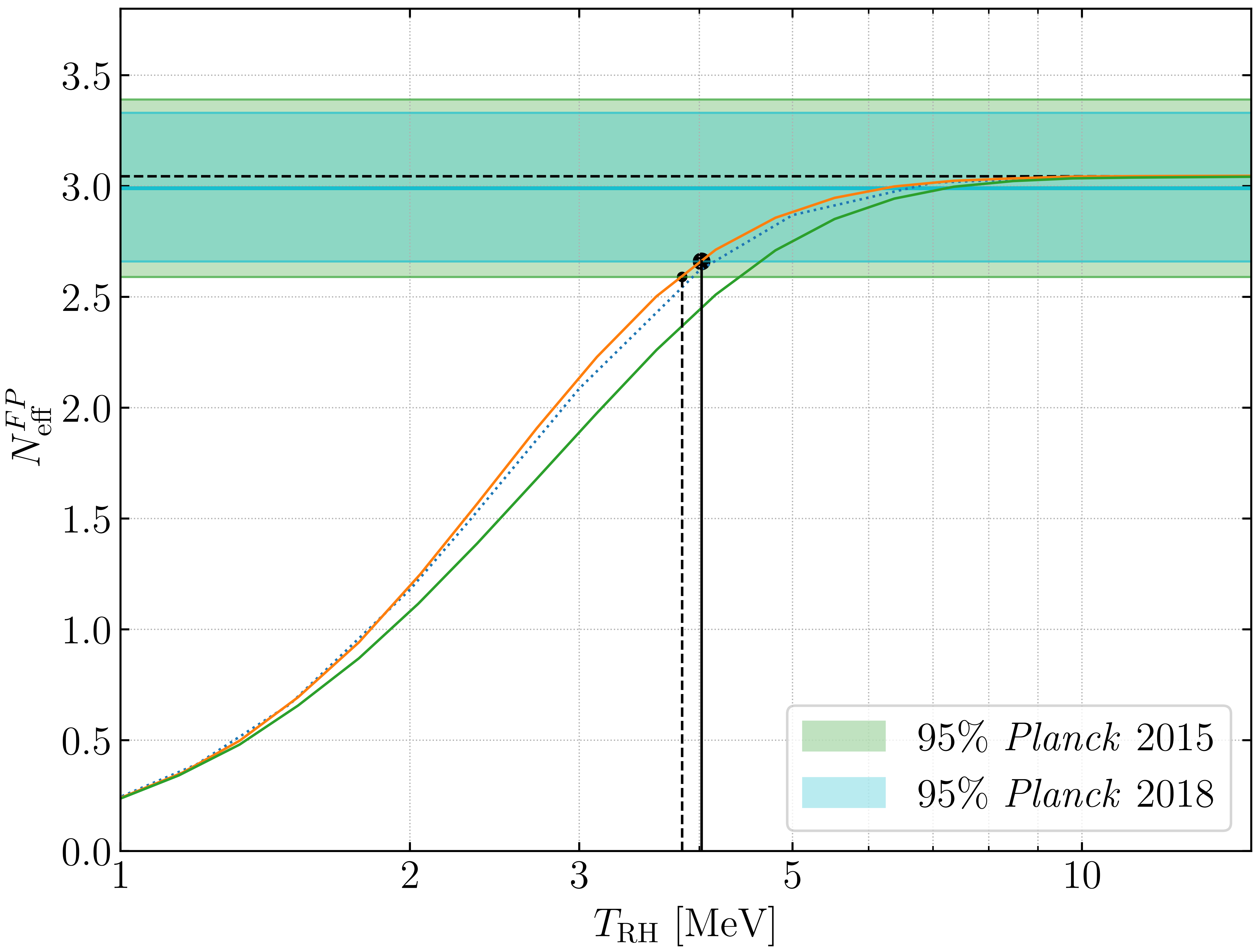


Planck 2018 (95% TT,TE,EE+lowE+lensing+BAO):

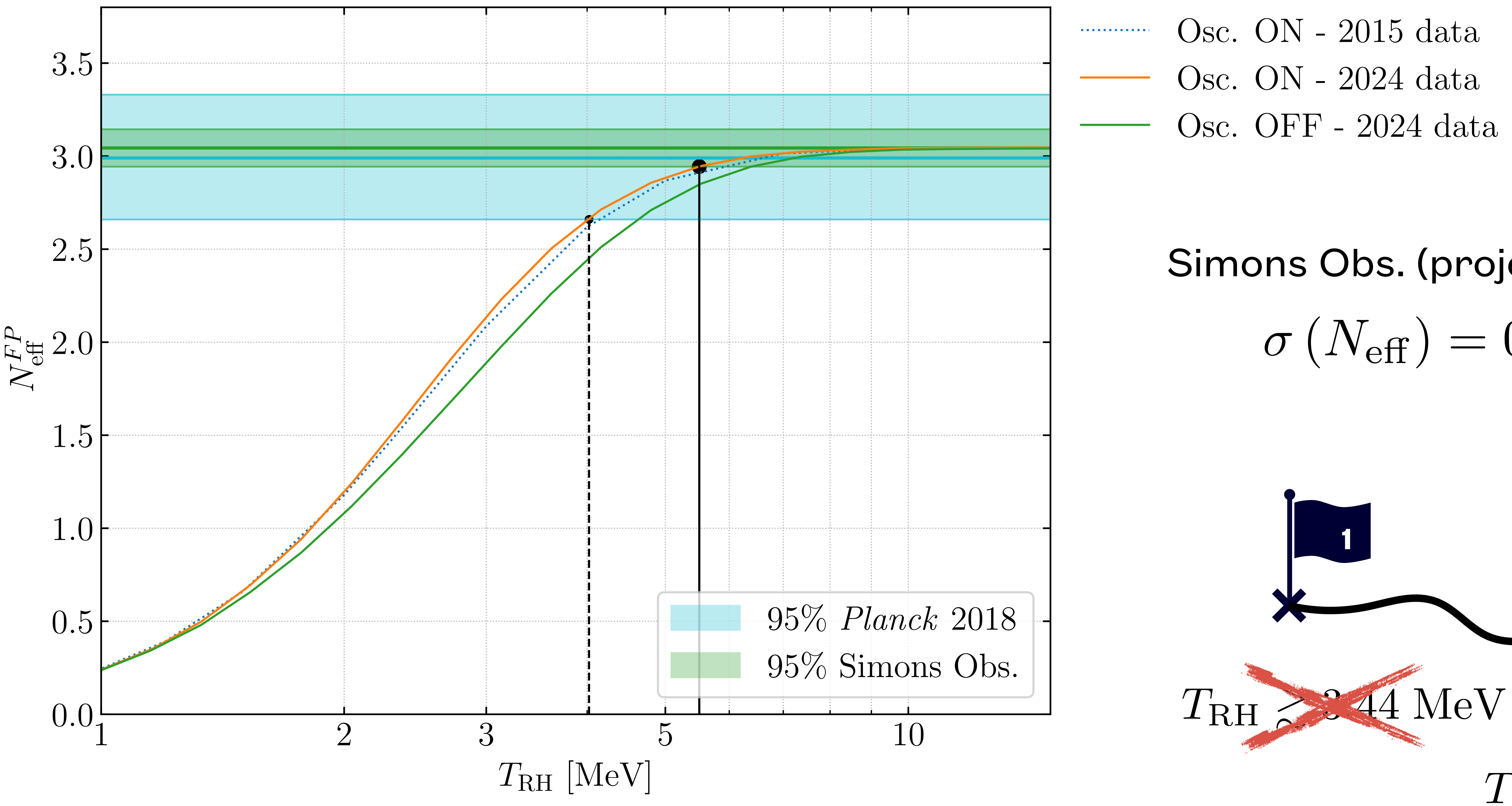
$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$$

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

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

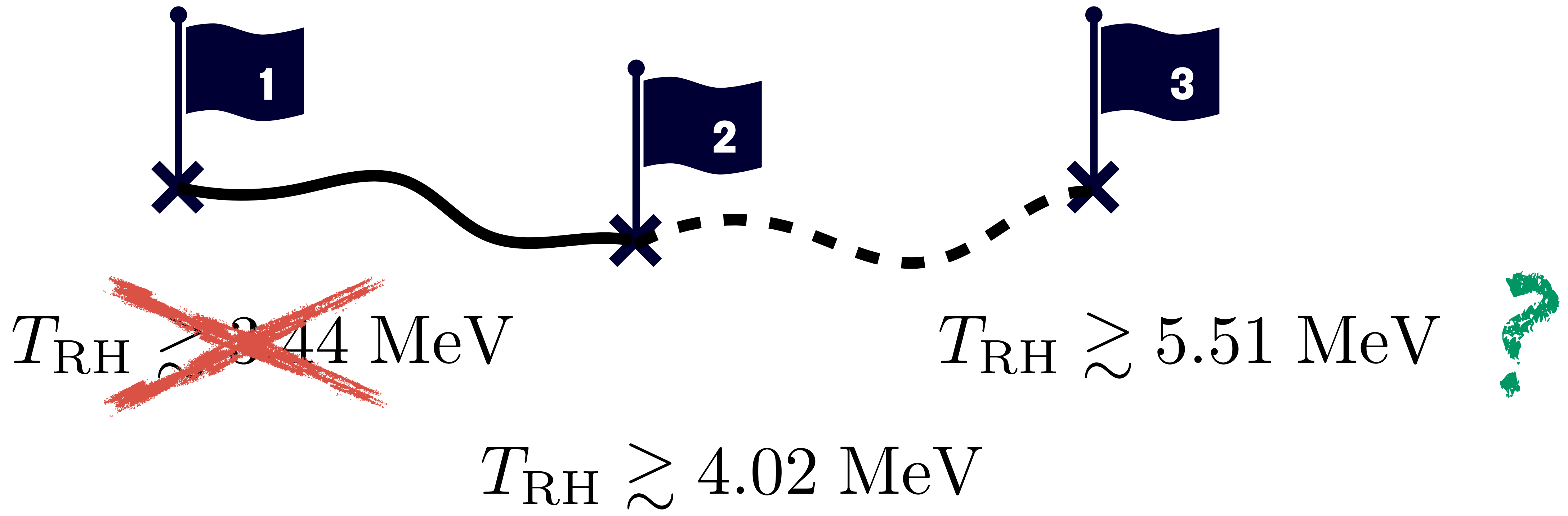
Neutrino production - III

MODIFIED VERSION OF FORTEPIANO CODE



Simons Obs. (projected sensitivity):

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



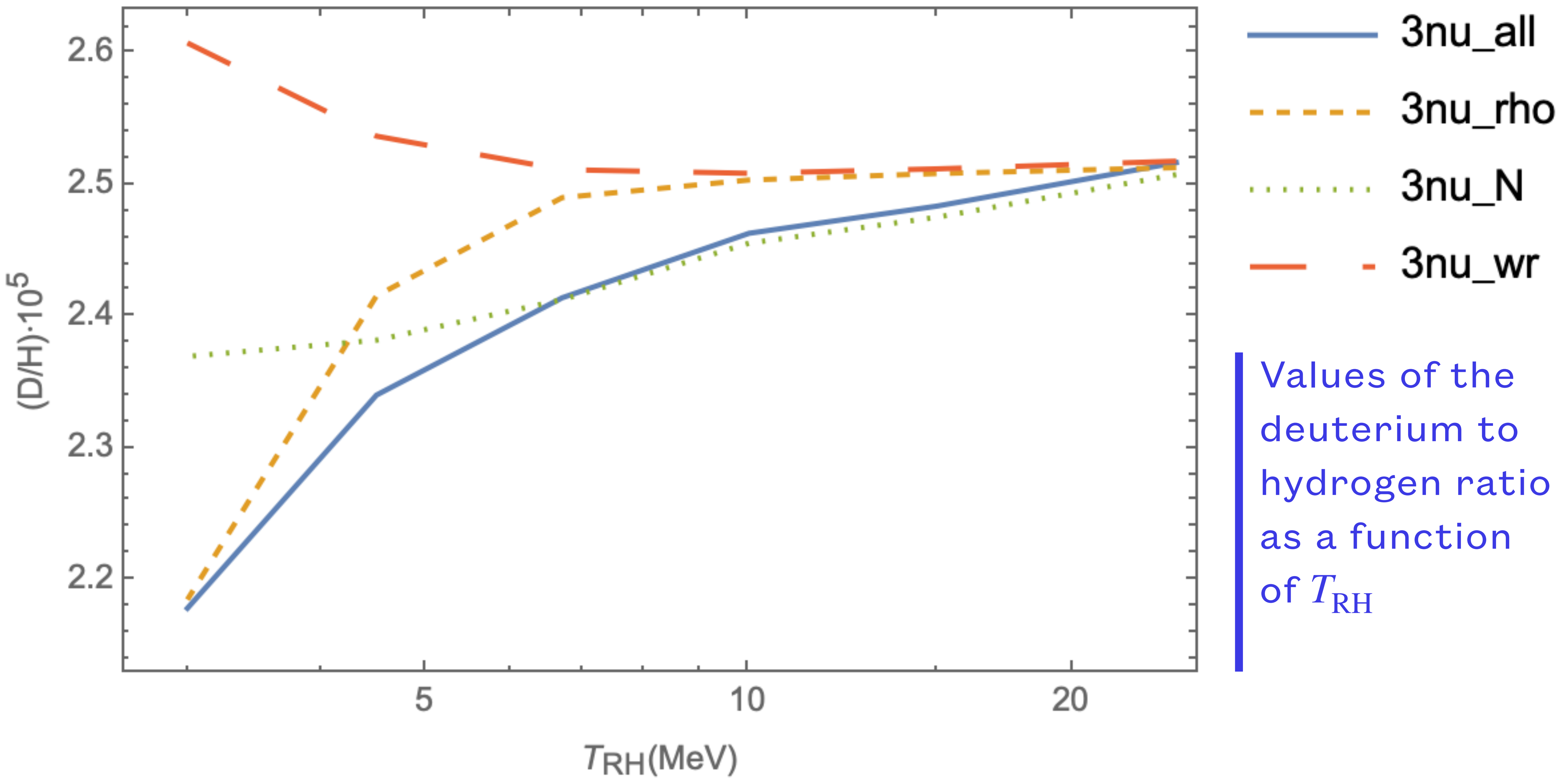
Probes of low reheating: BBN

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**, whose is conventionally handled by defining

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

[Credits: O. Pisanti]



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

$$\left(\chi^2_{^4\rm He}\chi^2_{^2\rm H}\right)(T_{\rm RH}) \leq 4 \quad \Rightarrow \quad T_{\rm RH} \geq 4.1 \text{ MeV}$$

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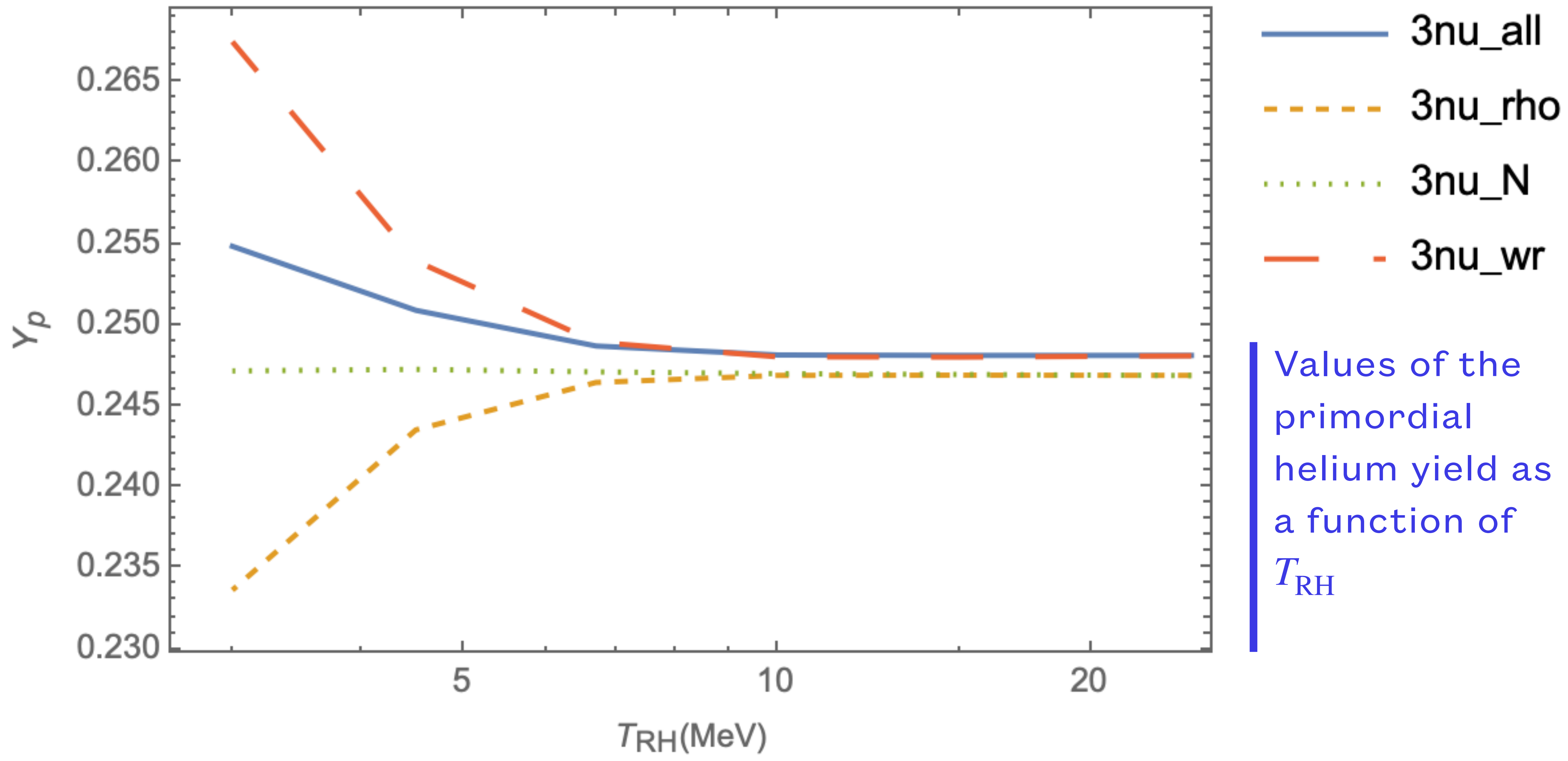


Values of the primordial helium yield as a function of $T_{\rm RH}$

$$\left(\chi^2_{^4{\rm He}}\chi^2_{^2{\rm H}}\right)(T_{\rm RH}) \leq 4 \quad \Rightarrow \quad T_{\rm RH} \geq 4.1 \text{ MeV}$$

Probes of low reheating: CMB

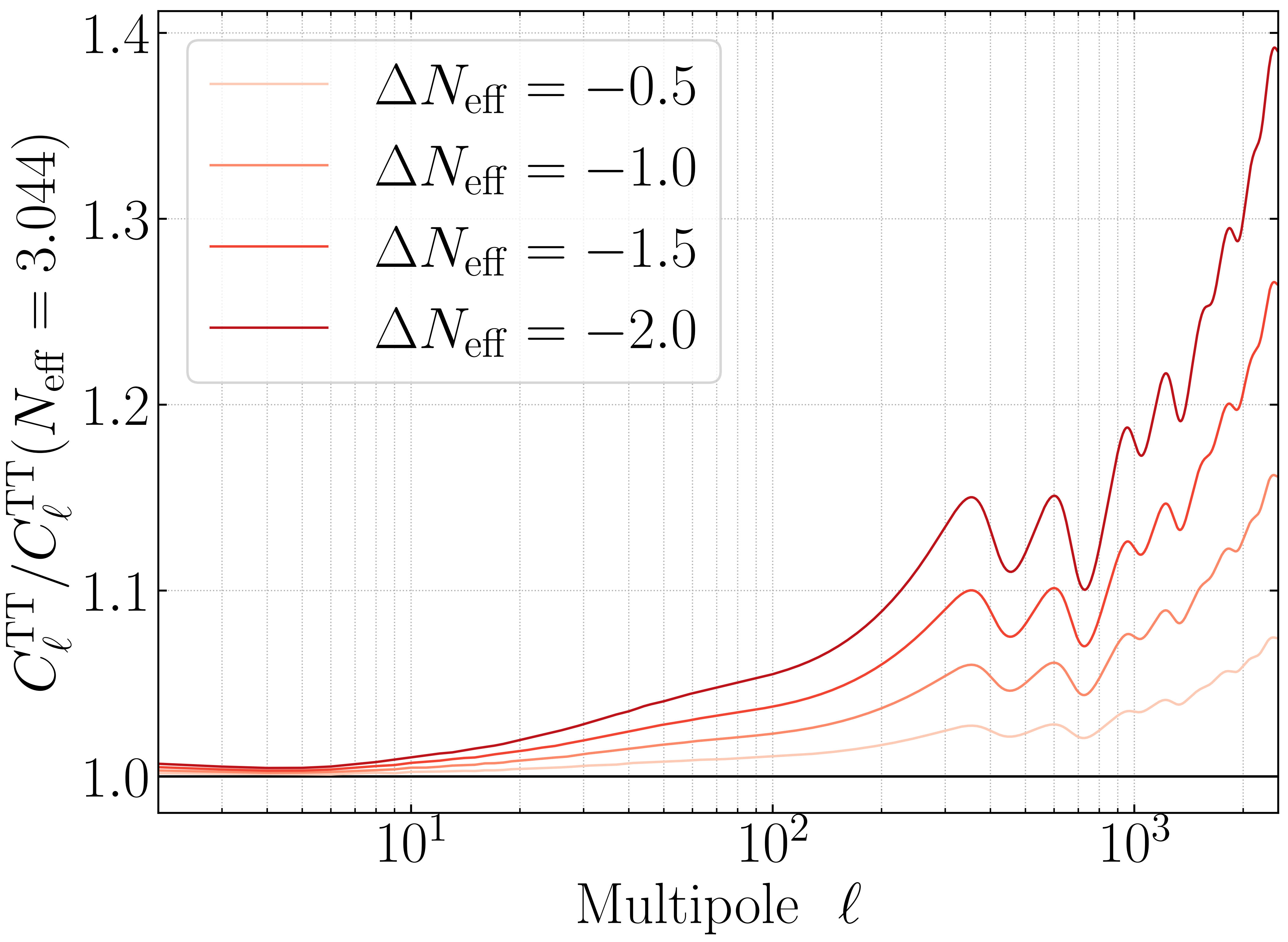
MODIFIED VERSION OF MONTEPYTHON SAMPLER

- 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 stases PDSs

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

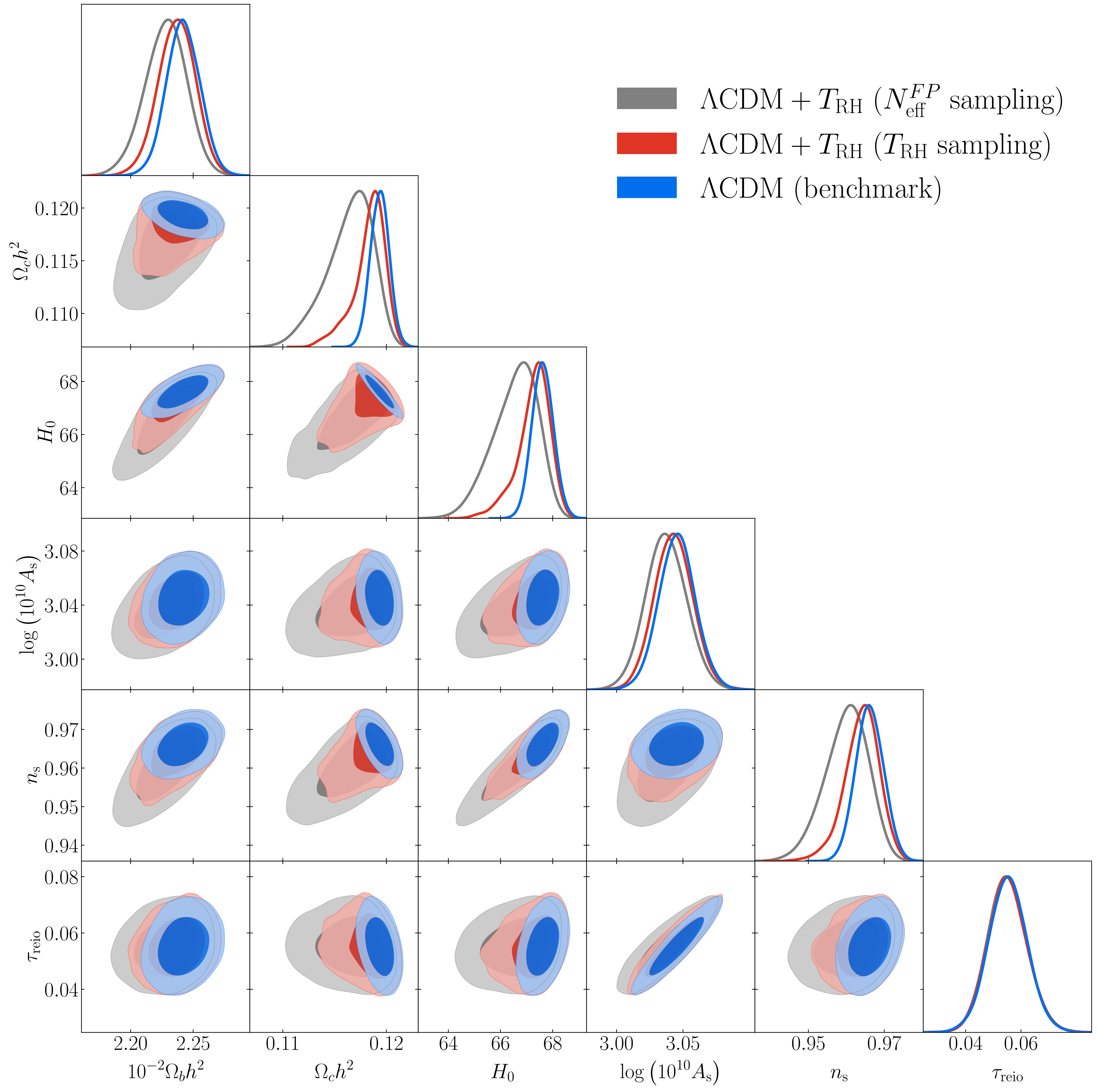
- CMB anisotropies spectrum is sensitive to the primordial helium abundance through its influence on the recombination history.



How to sample $T_{\rm RH}$?

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

	ΛCDM + $T_{\rm RH}$ ($N_{\rm eff}^{FP}$ sampling)	ΛCDM + $T_{\rm RH}$ ($T_{\rm RH}$ sampling)	ΛCDM ($T_{\rm RH}$ = 25 MeV)	ΛCDM (Planck 2018)
Parameter	68% limits	68% limits	68% limits	68% limits
$\Omega_b h^2$	$0.02228^{+0.00018}_{-0.00015}$	0.02237 ± 0.00015	0.02242 ± 0.00013	0.02242 ± 0.00014
$\Omega_c h^2$	$0.1164^{+0.0027}_{-0.0017}$	$0.1183^{+0.0018}_{-0.00090}$	0.11936 ± 0.00092	0.11933 ± 0.00091
$\log(10^{10} A_s)$	3.037 ± 0.016	3.043 ± 0.015	3.046 ± 0.014	3.047 ± 0.014
n_s	$0.9600^{+0.0064}_{-0.0050}$	$0.9640^{+0.0049}_{-0.0039}$	0.9662 ± 0.0037	0.9665 ± 0.0038
$\tau_{\rm reio}$	$0.0550^{+0.0067}_{-0.0074}$	0.0552 ± 0.0072	0.0553 ± 0.0070	0.0561 ± 0.0071
H_0	$66.6^{+1.0}_{-0.68}$	$67.26^{+0.73}_{-0.42}$	67.62 ± 0.41	67.66 ± 0.42



Bounds on $T_{\rm RH}$ [MeV]

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

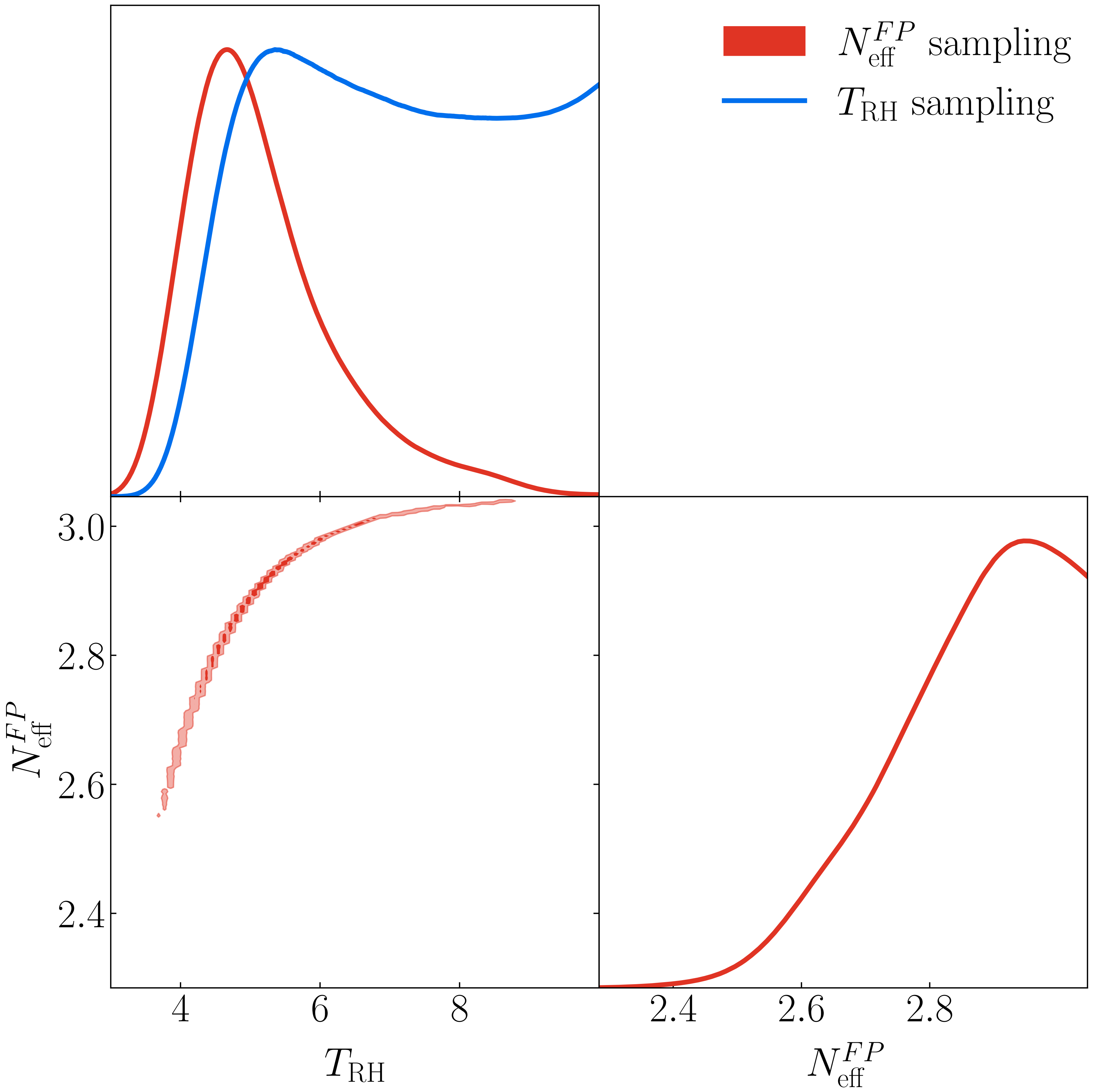
- $N_{\rm eff}^{FP}$ **sampling:** most direct relationship with the data, uniform sampling of all parameter space, difficult interpretation of the results.

- Summary table:

	$N_{\rm eff}^{FP}$ sampling	$T_{\rm RH}$ sampling
Parameter	95% limits	95% limits
$N_{\rm eff}^{FP}$	> 2.61	–
$T_{\rm RH}$	$5.2^{+2.5}_{-1.9}$ (> 3.86)	> 4.41

Slightly **relaxed** by new sampling strategy

Compatible with previous works



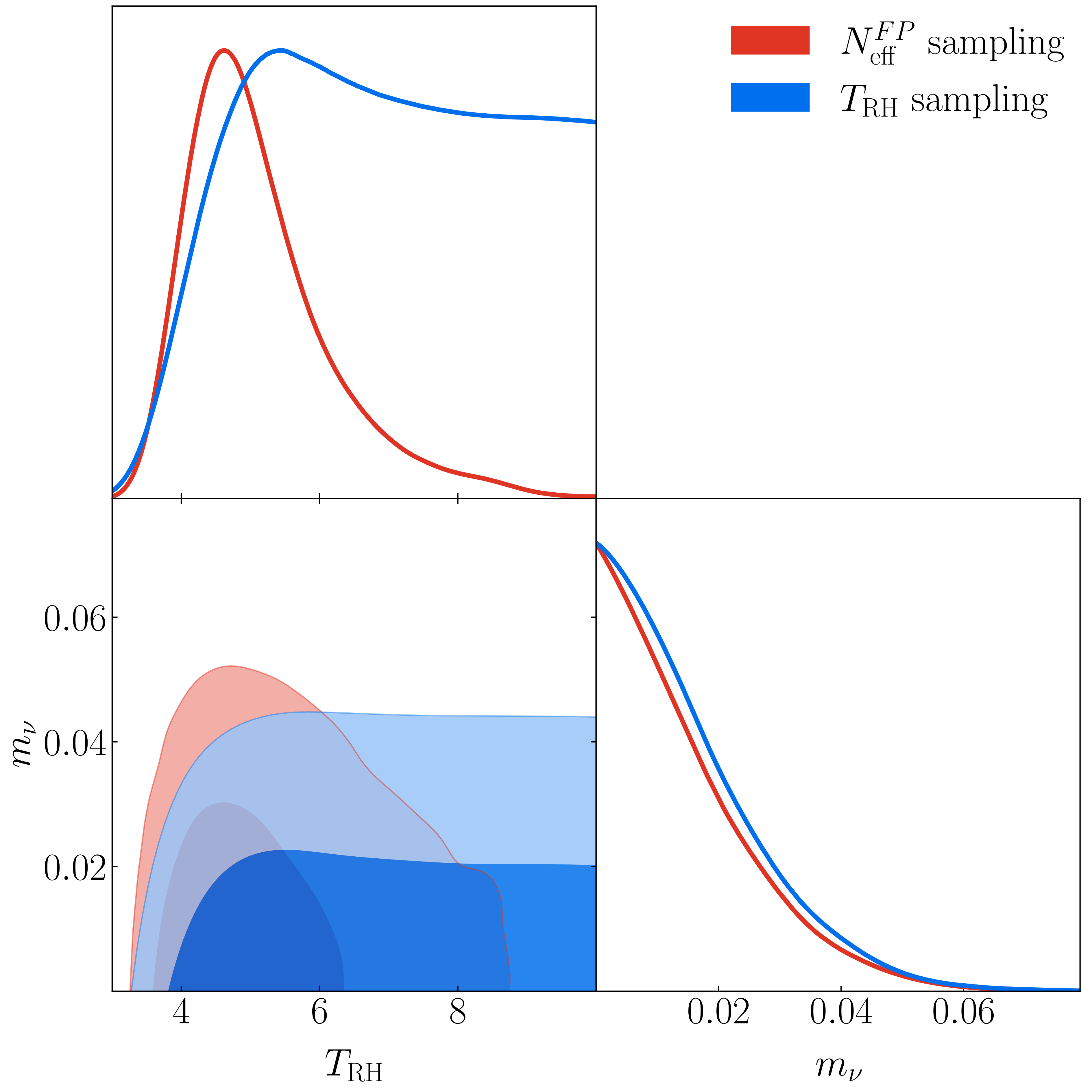
Bounds on $\Sigma\, m_\nu$ [eV]

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

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

- Summary table:

	$N_{\rm eff}^{FP}$ **sampling**	$T_{\rm RH}$ **sampling**
Parameter	95% limits	95% limits
$N_{\rm eff}^{FP}$	> 2.60	–
$T_{\rm RH}$	$5.2^{+2.5}_{-1.6}$ (> 3.83)	> 4.09
m_ν	< 0.0389	< 0.0399



The Kullback-Leibler divergence

- Measure of the “distance” between two distributions

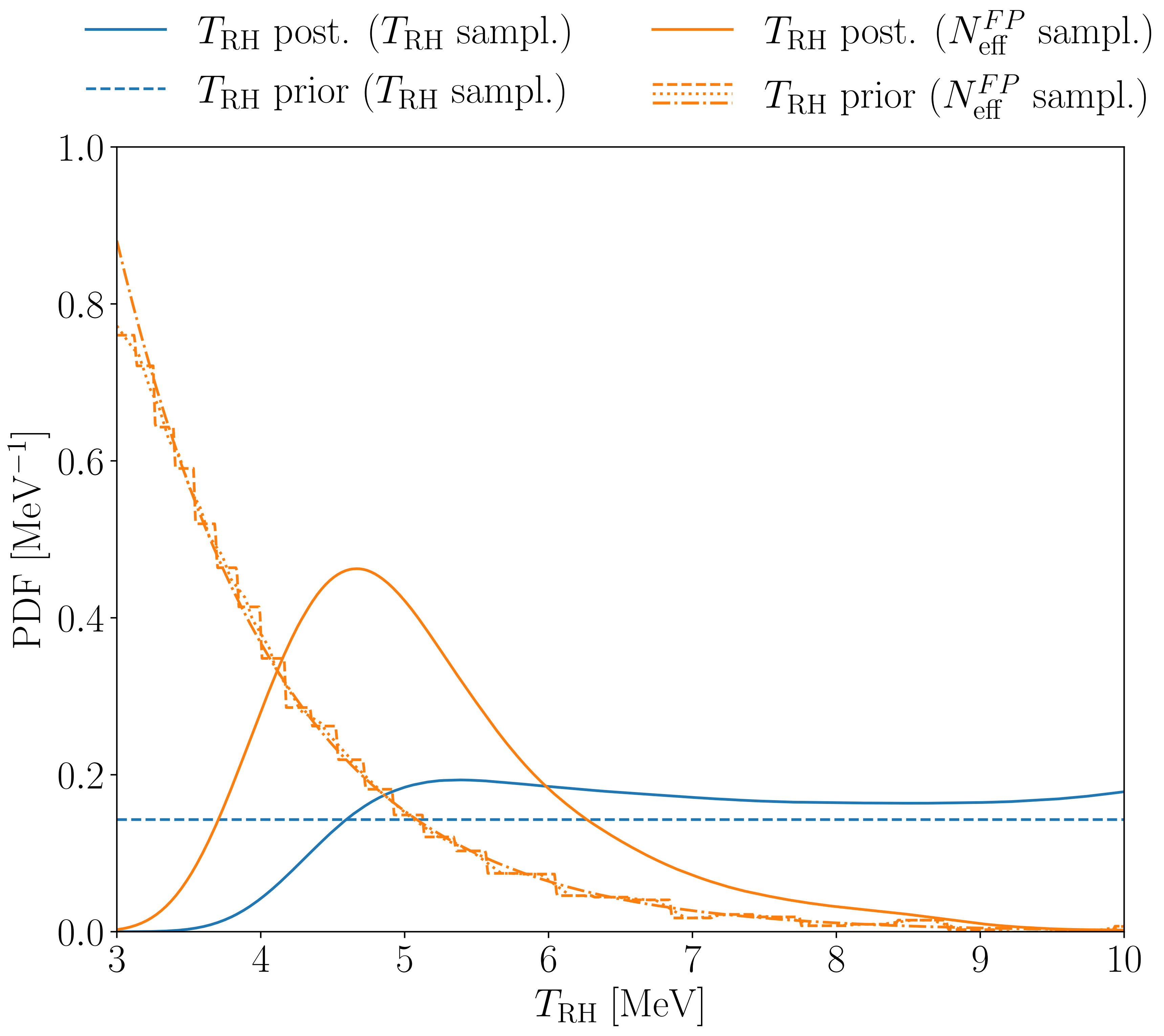
$$\mathcal{D}_{\rm KL}\left(P \parallel Q\right) \equiv \int d\boldsymbol{\theta}\; p\left(\boldsymbol{\theta}\right) \log\left[\frac{p\left(\boldsymbol{\theta}\right)}{q\left(\boldsymbol{\theta}\right)}\right]$$

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 $N_{\rm eff}^{FP}$ sampling



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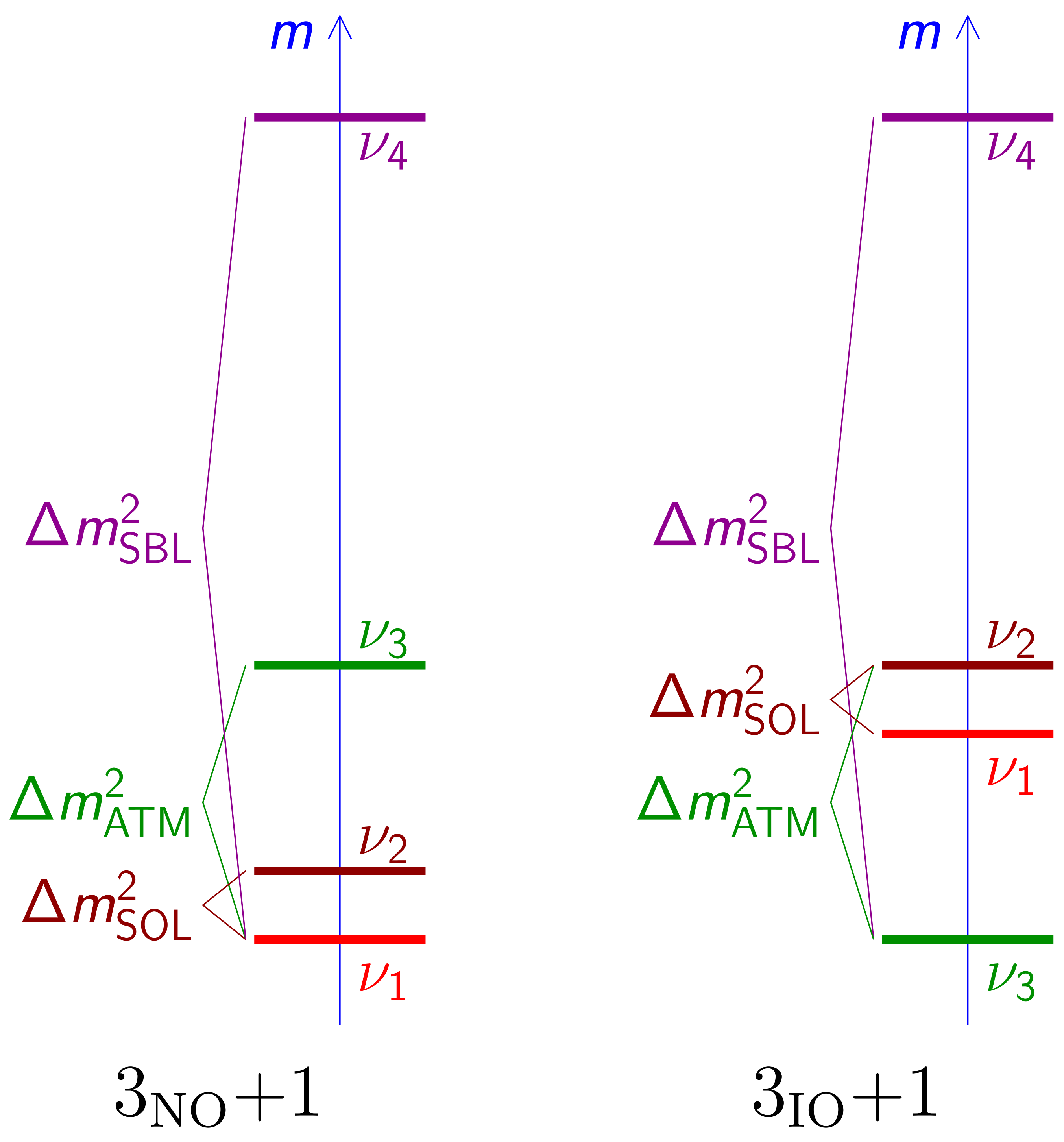
T. Brinckmann (UniFE), P. F. de Salas (Stockholm U.), M. F. Navarro (Glasgow U.),
S. Gariazzo (UniTO), M. Lattanzi (INFN-FE), S. Pastor (IFIC), O. Pisanti (UniNA)

Bounds on sterile neutrinos oscillations in very low reheating scenarios

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.

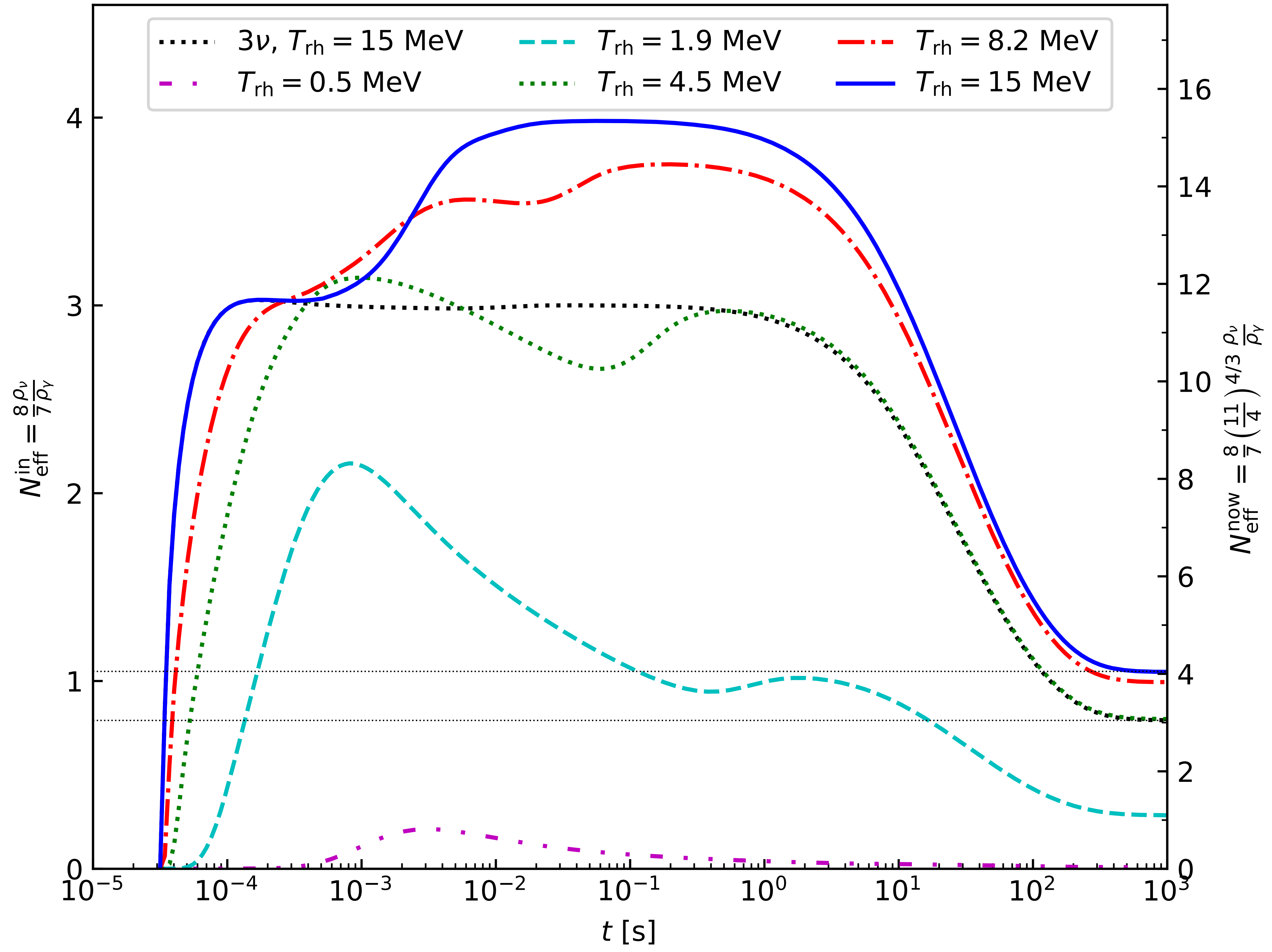
[See S. Pastor's talk]



[Credits: Giunti and Lasserre (2019)]

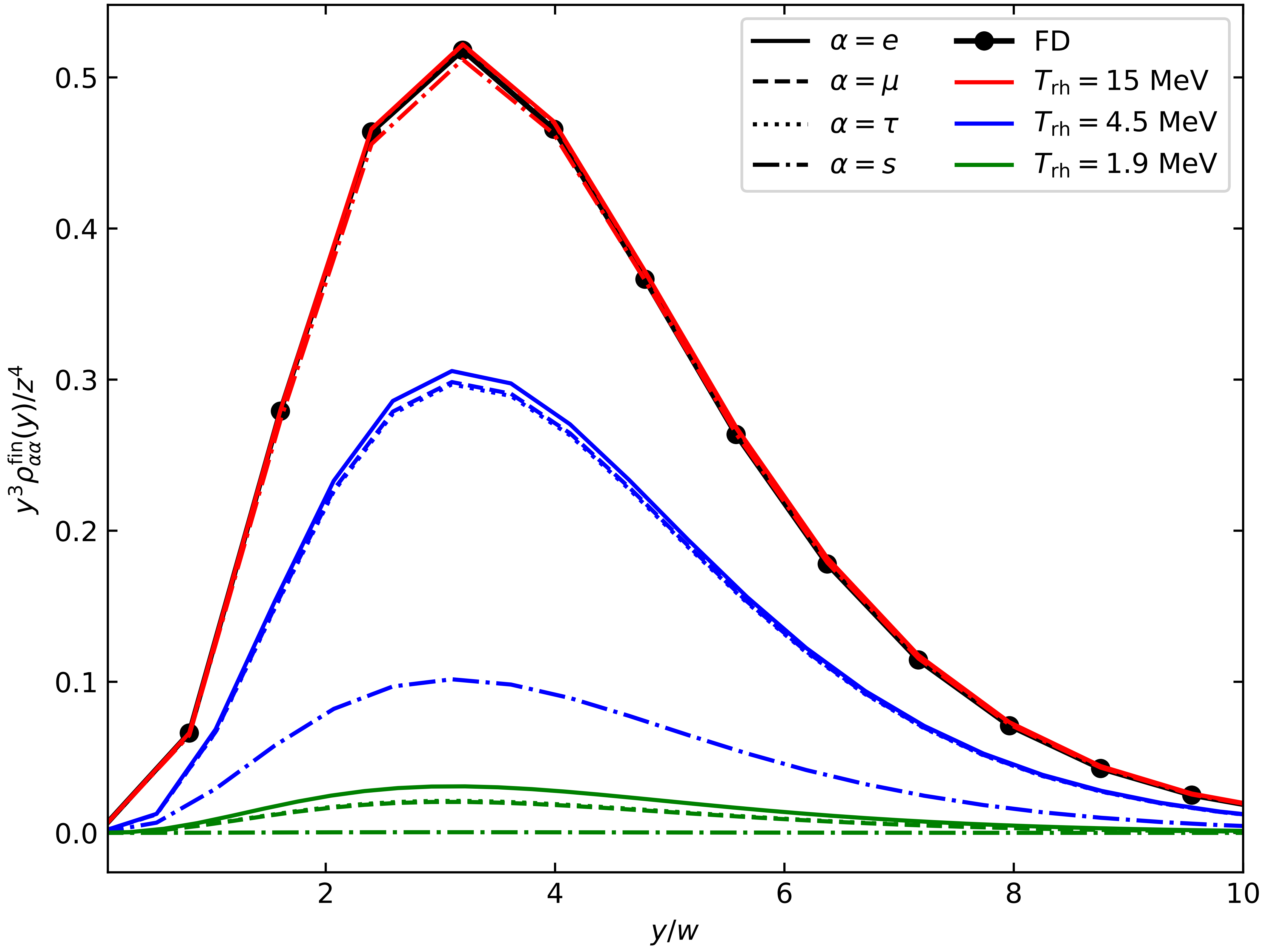
Neutrino production in (3+1) models

[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.

Conclusions

- New improved bounds on T_{RH} from new cosmological data with a new sampling strategy;
- Test of the robustness of bounds on the sum of neutrinos masses;
- Low reheating is a quite complicated scenario but it provides an interesting way to reduce N_{eff}, leaving room for relativistic particles, such as sterile neutrinos.

Thank you!