Active-sterile neutrino oscillations in very low reheating scenarios

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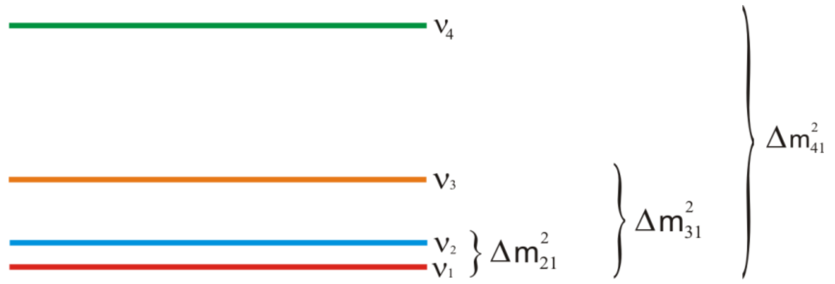
Introduction

- Most neutrino oscillation experiments are well explained through the mixing of the three standard neutrino flavours of the Standard Model **[de Salas et al., JHEP 2020]**, including two mass splittings $\Delta m^2_{31} = 2.55^{+0.02}_{-0.03} \cdot 10^{-3}\,\mathrm{eV}^2$ and $\Delta m^2_{21} = 7.50^{+0.22}_{-0.20} \cdot 10^{-5}\,\mathrm{eV}^2$.

- However, some anomalies in short baseline oscillation experiments remain unexplained, for example the anomalies of DANSS (2018) and NEOS (2017).

- These anomalies may be explained by the existence of a new neutrino with $\Delta m^2_{41} \sim \mathcal{O}(\mathrm{eV}^2)$.

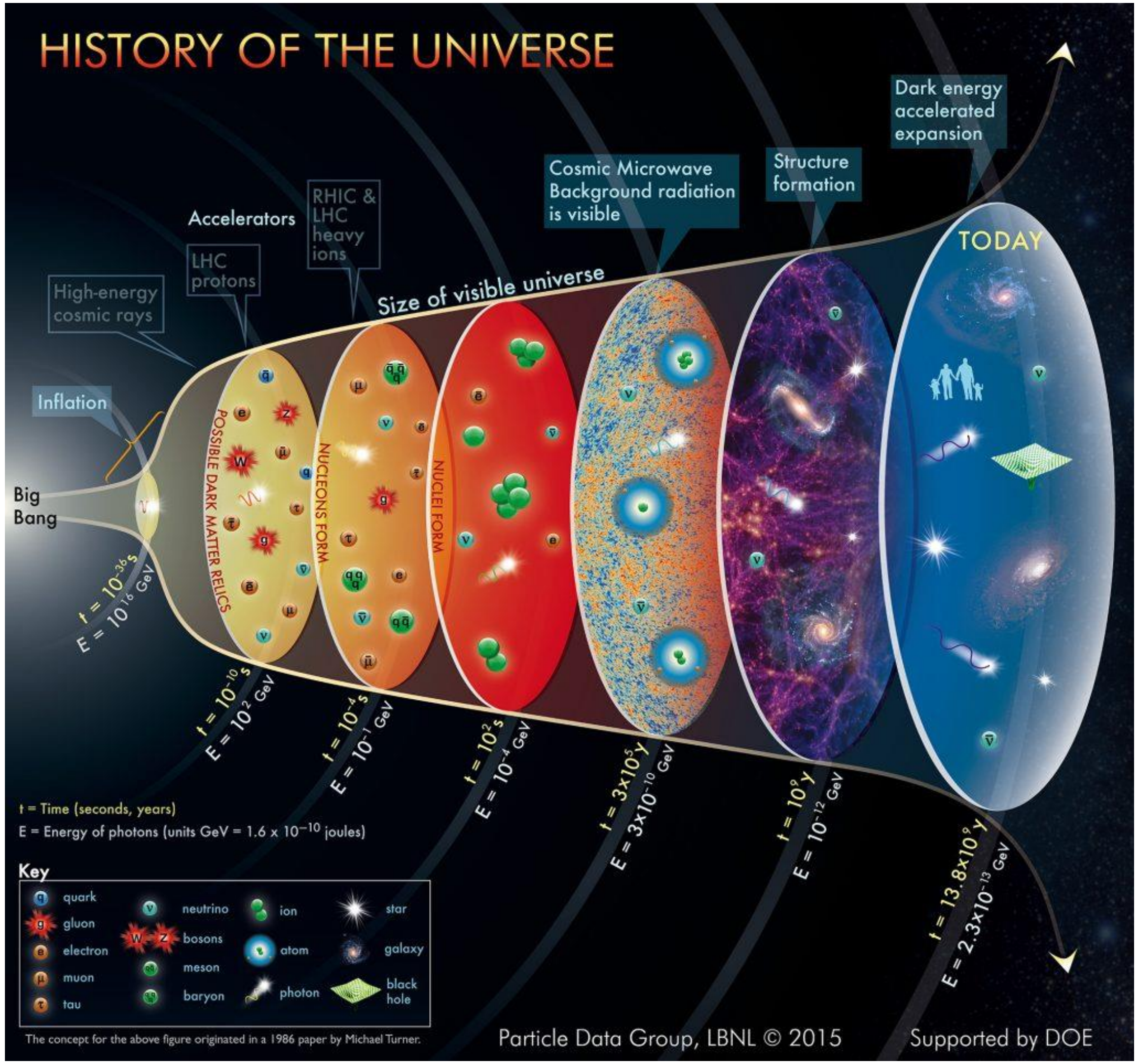


Introduction

- The number of active neutrinos is three (LEP results) → The extra neutrino must be sterile
- The sterile neutrino mixes with the active flavours → *3+1 framework*

→ Three new mixing angles $\theta_{14},\ \theta_{24},\ \theta_{34}$, along with the three mixing angles $\theta_{12},\ \theta_{13},\ \theta_{23}$ that mix the three active flavours.

• Neutrinos are also relevant for cosmology



- First stages: inflation and reheating
- Radiation domination: plasma of relativistic species in thermal equilibrium T
  - Neutrino decoupling: $\Gamma_\nu \sim H$ when $T \sim 1$ MeV → $\mathrm{C}\nu\mathrm{B}$
  - $e^{\pm}$ Annihilation → photon reheating
  - Primordial Nucleosynthesis (BBN)
  - Photon decoupling → CMB
- Matter domination
- Cosmological constant domination: accelerated expansion

- Neutrinos contribute to the radiation density of the Universe:

$$\rho_r = \left(1 + N_{\text{eff}} \frac{7}{8} \left(\frac{T_\nu}{T}\right)^{4/3}\right) \rho_\gamma$$

Measure: $N_{\text{eff}}^{\text{Planck}} = 2.91^{+0.39}_{-0.37}\ (95\%\ \text{CL})$ [Planck Collab., 2018]

Prediction: $N_{\text{eff}}^{\text{standard}} = 3.0440 \pm 0.0002$ [Bennet et al., preprint: 2012.02916]

- In the 3+1 framework, for a wide range of mixing parameters $N_{\text{eff}} \sim 4$ is obtained. [Gariazzo et al., JCAP 2019]

⟹ The sterile neutrino is strongly constrained by cosmology

- A solution ⟹ To suppress the thermalisation of the sterile neutrino in the early universe

⟹ We'll show that one way of achieving this is considering low reheating scenarios

Low reheating scenarios

We asume that a late reheating process took place before BBN:

- A massive, non-relativistic scalar component ϕ dominates the early universe, afterwards it decays to relativistic species other than neutrinos:

$$\frac{\mathrm{d}\rho_\phi}{\mathrm{d}t} = -\Gamma_\phi \rho_\phi - 3H\rho_\phi$$

- The active neutrinos are generated through weak processes, while the sterile neutrino is generated only through oscillations.

Low reheating scenarios

- The radiation epoch begins at a temperature $T_{\rm RH} \sim \mathcal{O}(\rm MeV)$:

$$T_{\rm RH} \simeq 0.7 \left(\frac{\Gamma_\phi}{\rm s^{-1}} \right)^{1/2} \rm MeV$$

- Neutrinos may decouple from the cosmic plasma before they are fully thermalised.

Low reheating scenarios

- To study neutrino thermalisation and decoupling, we solve:

$$\left.\begin{aligned} \frac{d\rho_{tot}}{dt} &= -3H\left(\rho_{tot} + P_{tot}\right) \\ \frac{d\rho_\phi}{dt} &= -\Gamma_\phi \rho_\phi - 3H\rho_\phi \\ \left(\partial_t - Hp\partial_p\right)\varrho_p &= -i\left[\Omega_p, \varrho_p\right] + C(\varrho_p) \end{aligned}\right\}$$

$$\rho_{tot} = \rho_\phi + \rho_\gamma + \rho_l + \rho_\nu$$

Collision term (inelastic scattering)

Neutrino oscillations, matter effects in neutrino oscillations (elastic scattering)

- We solve the system of equations using **FortEPiaNO [Gariazzo et al., JCAP 2019]**, modified to include the low reheating scenario.

Low reheating with three active neutrinos

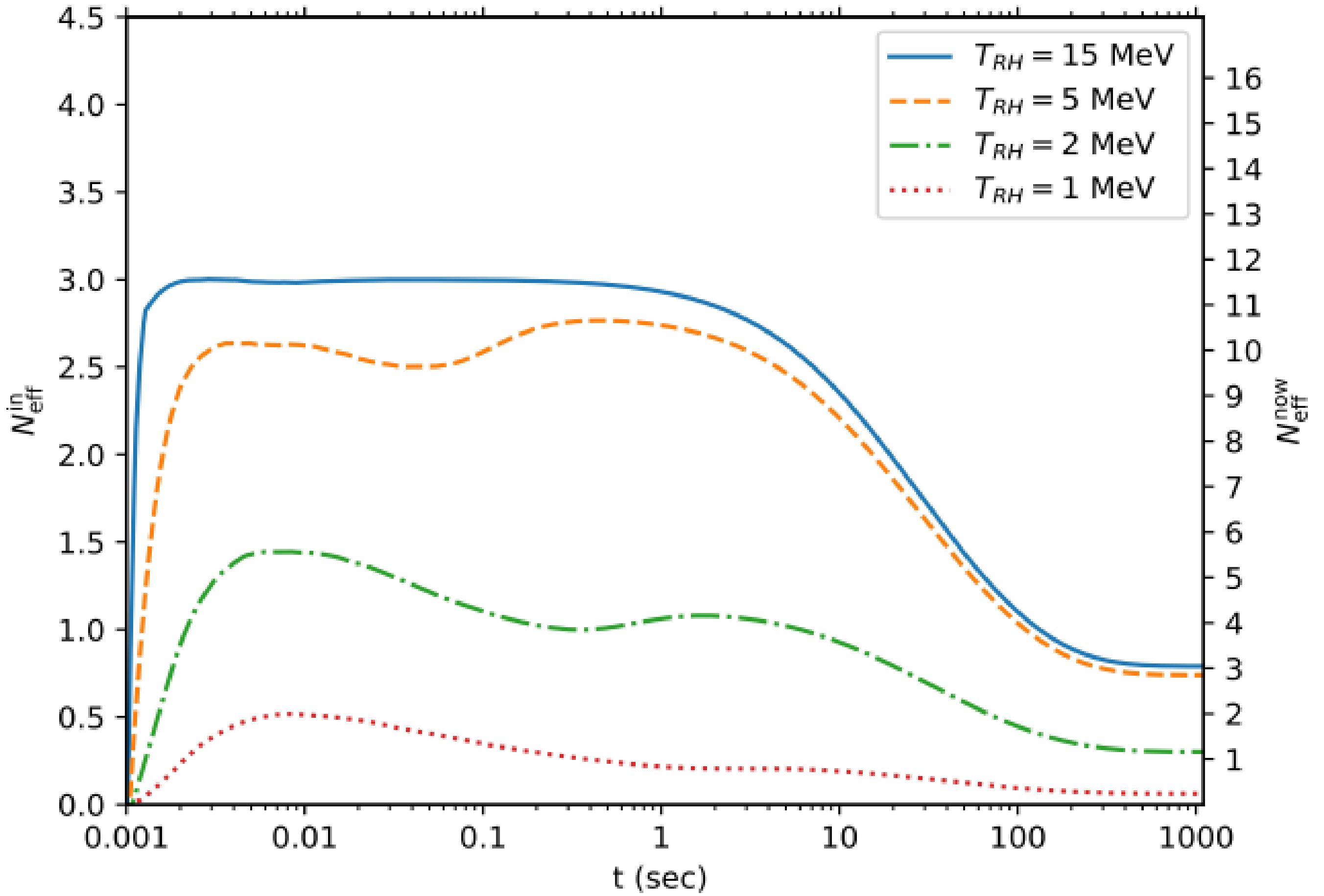
Our first step is to reproduce previous results **[de Salas et al., PRD 2015]**

$$N_{\rm eff}^{\rm in} = \frac{8}{7}\frac{\rho_\nu}{\rho_\gamma}$$

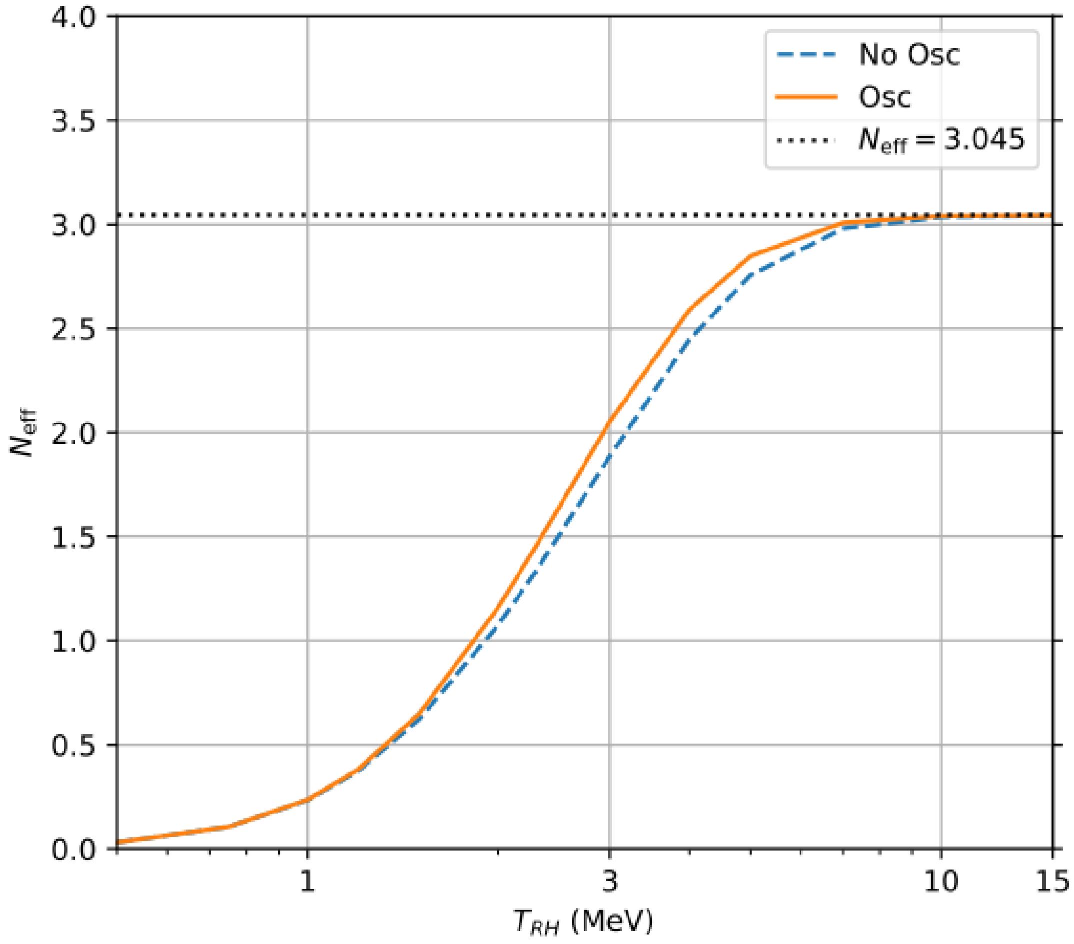
$$N_{\rm eff}^{\rm now} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

Photon heating due to $e^\pm$ annihilations

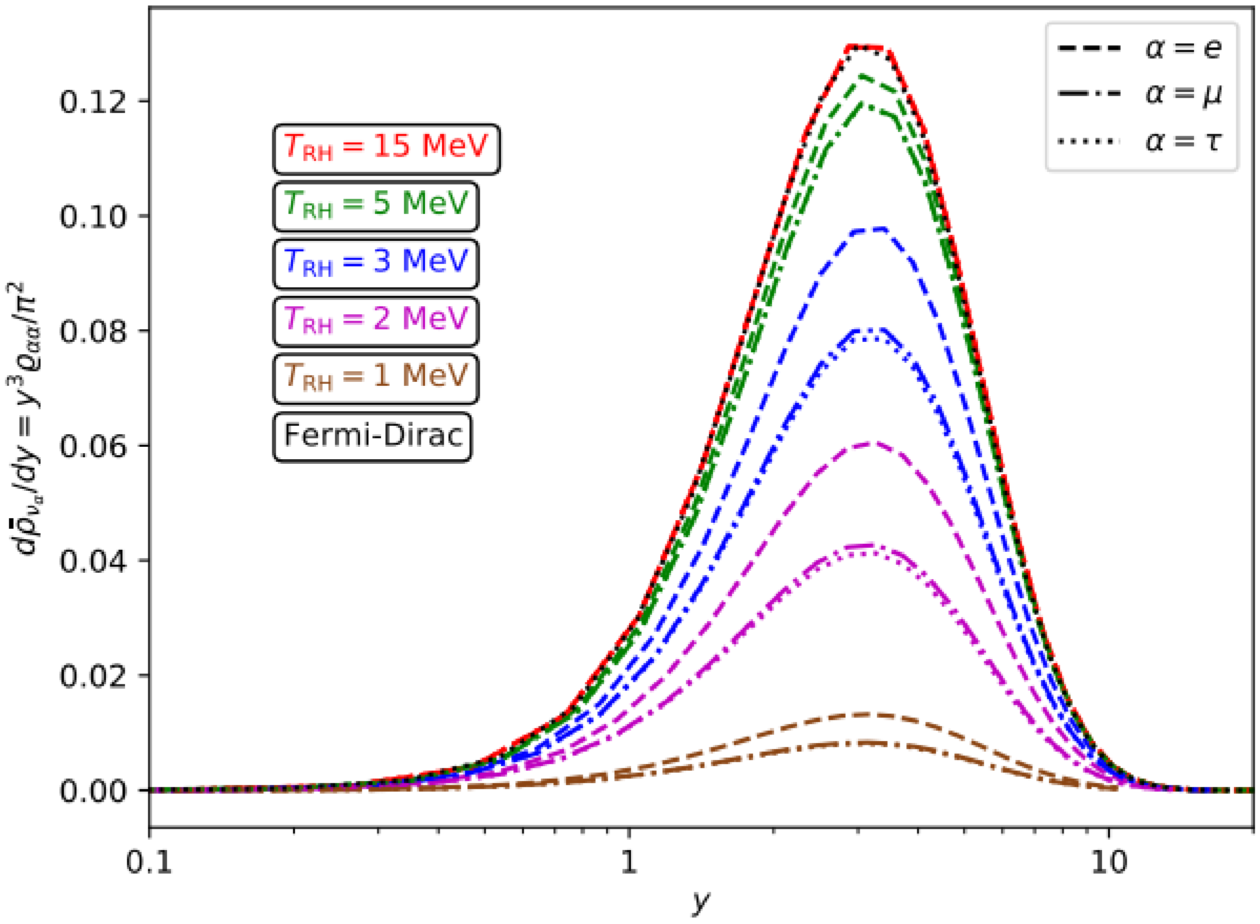
Time evolution of $N_{\rm eff}$ in the three-neutrino case



Final N_{eff} as a function of T_{RH}



Final differential spectra of neutrino comoving energies as a function of the comoving momentum $y = pa$



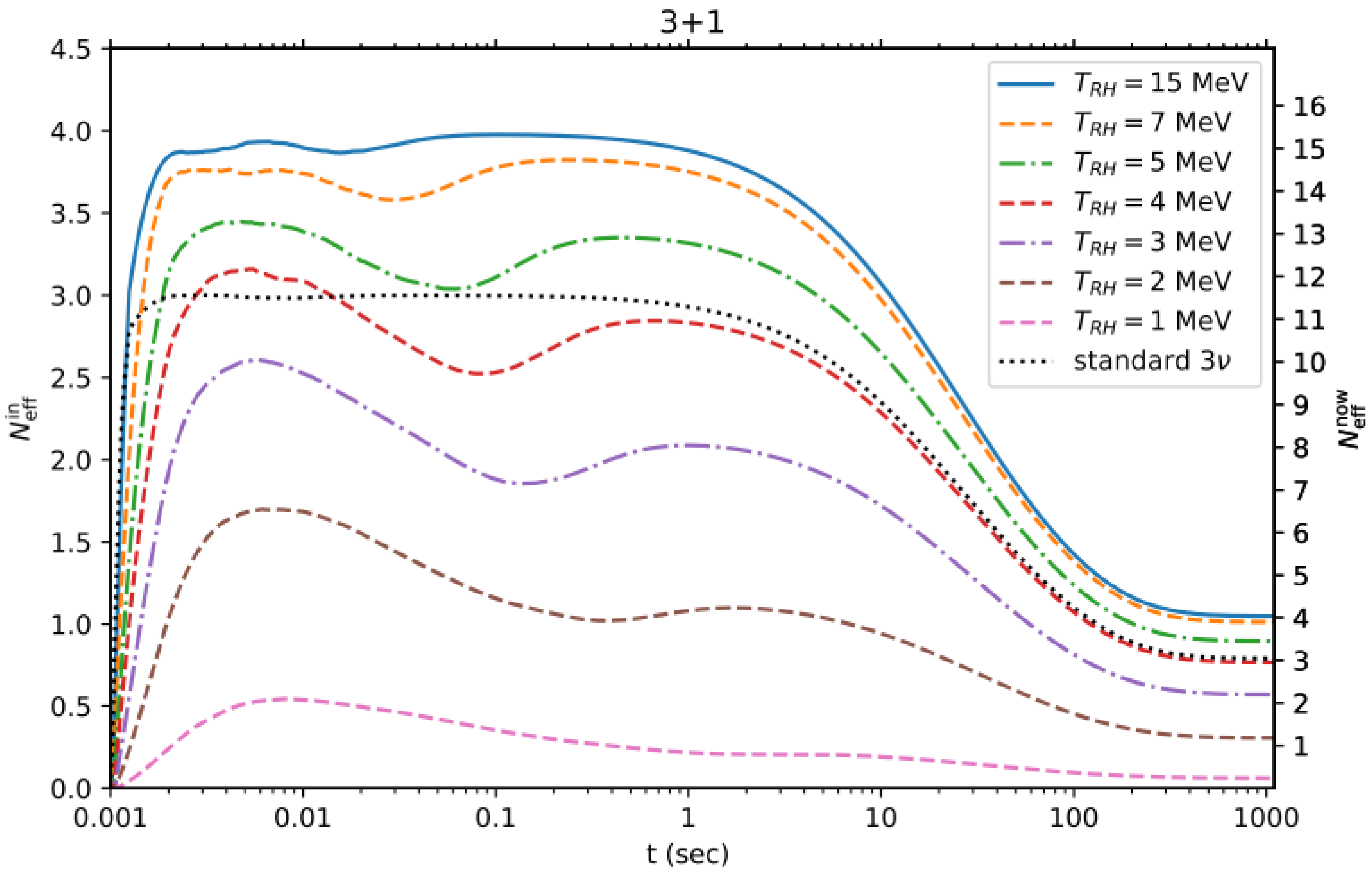
Low reheating in the 3+1 neutrino model

Benchmark [**Gariazzo et al., JHEP 2019**]

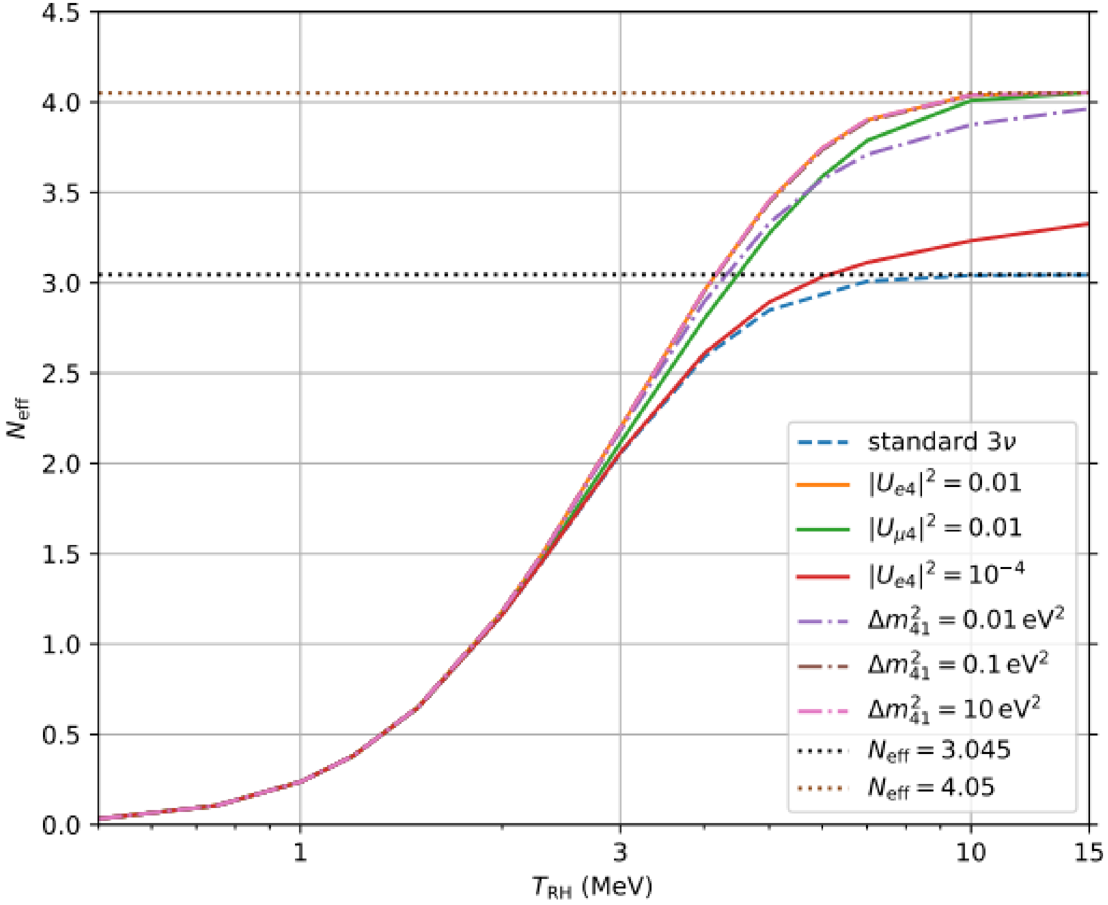
$$\left.\begin{array}{r}\Delta m^2_{41} = 1.29 \pm 0.03\,\mathrm{eV}^2 \\ \sin^2 2\theta_{14} = 0.049 \pm 0.011\,, \quad \theta_{24} = \theta_{34} = 0\end{array}\right\}$$

These are the parameters that fit the anomalies of DANSS and NEOS

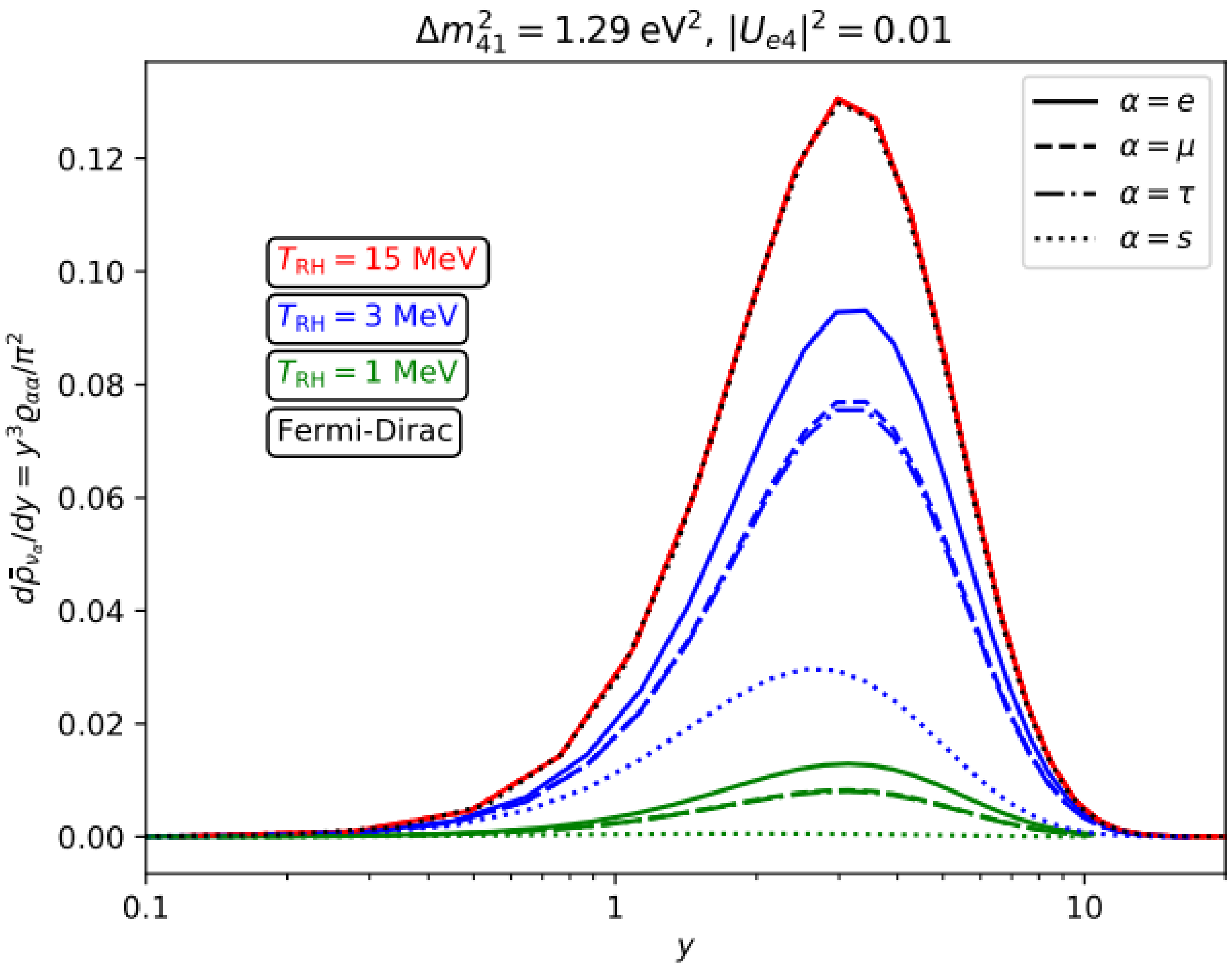
Time evolution of $N_{\rm eff}$ in the 3+1 framework



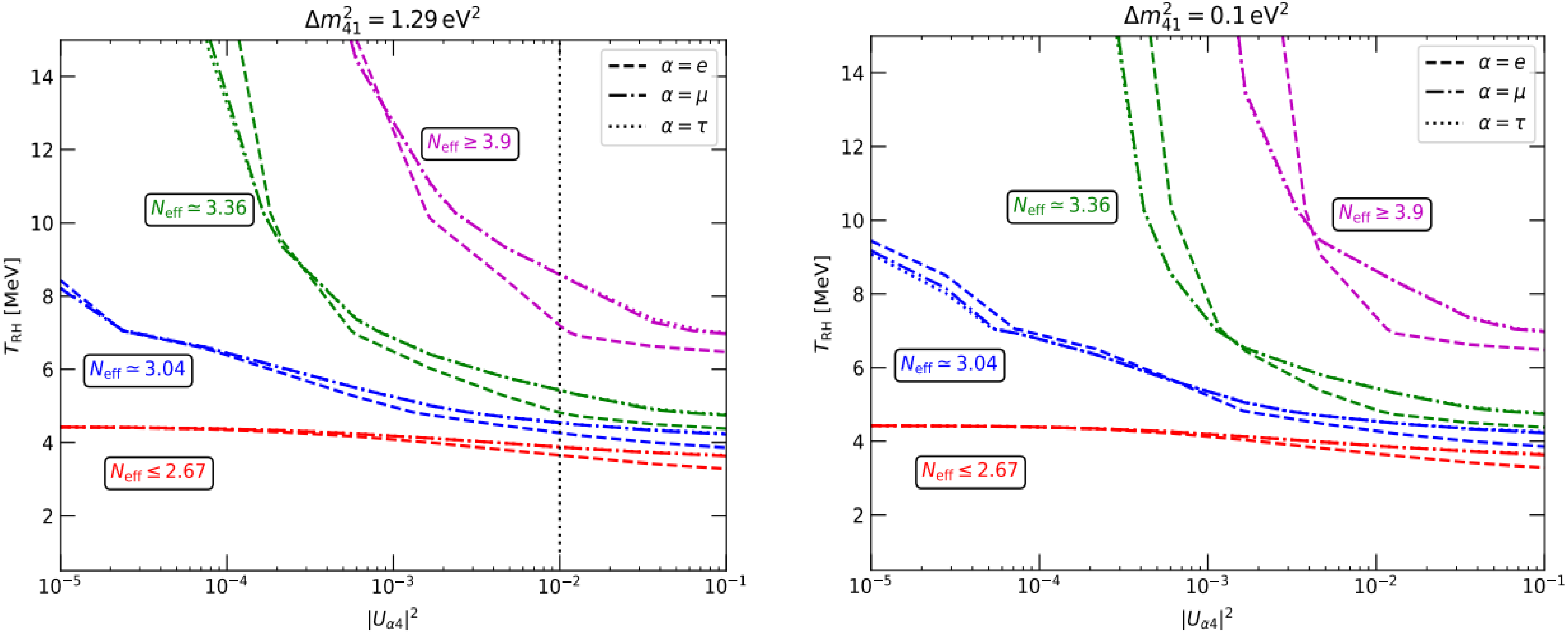
Final N_{eff} as a function of T_{RH}



Final differential spectra of neutrino comoving energies as a function of the comoving momentum $y = pa$



Final $N_{\rm eff}$ when varying only one of the active-sterile mixing angles and $T_{\rm RH}$



Benchmark → Black vertical line

$N_{\rm eff} \simeq 2.67$ (red curves) and $N_{\rm eff} \simeq 3.36$ (green curves) are the bounds of the 2σ range of Planck **[Planck Collab., 2018]**

Conclusions and next steps

- The 3+1 model is highly constrained by cosmology, since for a wide range of mixing parameters $N_{\rm eff} \sim 4$ is obtained. A possible solution is to suppress neutrino thermalization.
- In low reheating scenarios, neutrino thermalisation may be suppressed by $T_{\rm RH}$ of MeV order.
- In the standard three-neutrino case, we have seen that neutrinos are not fully thermalised for $T_{\rm RH} \lesssim 7\,\mathrm{MeV}$ and hence $N_{\rm eff} < 3$ is obtained. Here our results are in good agreement with previous studies.

Conclusions and next steps

- In the 3+1 model neutrino thermalization is suppressed for $T_{\rm RH} \lesssim 4\,\rm MeV$ by the reheating process. This is mostly independent of the mixing parameters.
- For higher values of $T_{\rm RH}$, the mixing is relevant and at least two of the mixing angles affect differently to the final $N_{\rm eff}$.
- When neutrinos are not fully thermalised, the ν_e are always closer to the equilibrium than $\nu_\mu,\ \nu_\tau$ and ν_s. This is due to the presence of electrons in the cosmic plasma.

Conclusions and next steps

- For the considered combinations of active-sterile mixing parameters, it is always possible to find a value for T_{RH} leading to a N_{eff} in the 2σ range of Planck 2018.
- Our next step is to study the impact of neutrino thermalisation in the 3+1 model over BBN and CMB observables, obtaining bounds and constrains over the active-sterile mixing parameters and T_{RH} [Ofelia Pisanti (BBN), Massimiliano Lattanzi (CMB)].

This is the end.
Thank you for your attention!

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