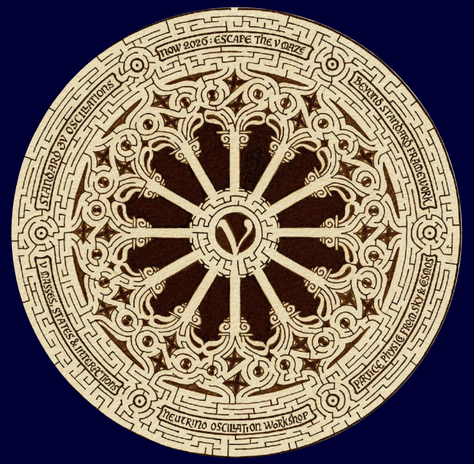


NOW 2026
Neutrino Oscillation Workshop

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

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

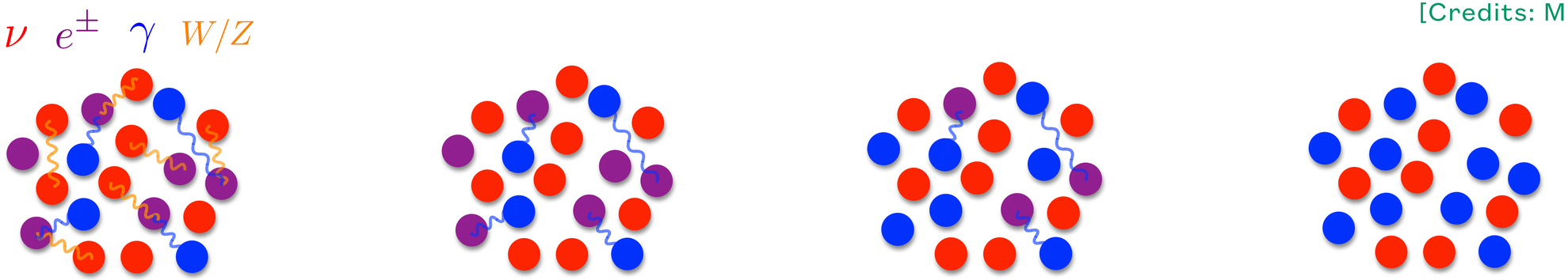
Neutrino thermalisation in very low reheating cosmologies

NICOLA BARBIERI (IFIC, CSIC-UV) – 01/09/2026

Neutrino decoupling

- Let's focus on the cosmic history at the MeV epoch:

[Credits: M. Escudero]



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$\nu \quad e^{\pm} \quad \gamma \quad W/Z$



$T_\gamma \gg \mathcal{O}(\mathrm{MeV})$

At early times, neutrinos and antineutrinos are kept in kinetic and chemical equilibrium with charged leptons, baryons and photons by electroweak interactions

$$\nu\bar{\nu} \leftrightarrow e^+e^-\,, \qquad \nu e^{\pm} \leftrightarrow \nu e^{\pm}$$

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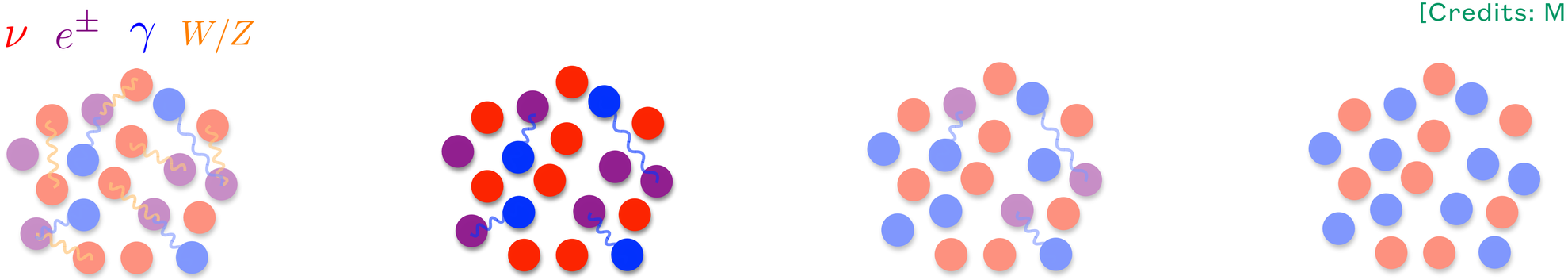
As a rule of thumb, by the comparison between the weak interaction rate, $\Gamma_{\mathrm{weak}} \sim n \langle \sigma v \rangle$, and the expansion rate, $H \sim T^2/M_{\mathrm{pl}}$, we get

$$\frac{\Gamma}{H} \sim G_{\mathrm{F}}^2 M_{\mathrm{pl}} T^3 \sim \left(\frac{T}{\mathrm{MeV}}\right)^3 \qquad \Rightarrow \qquad T_\nu = T_\gamma$$

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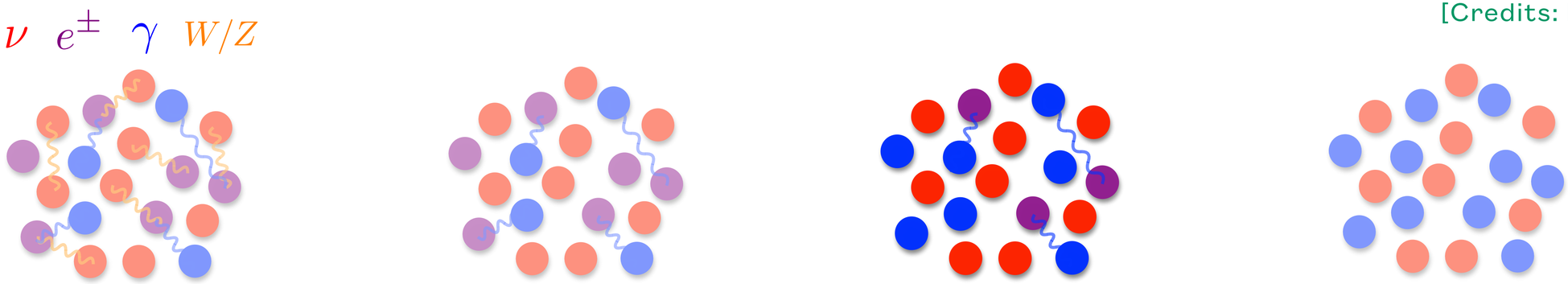
Going towards the MeV weak rates get strongly suppressed — a neutrino now expands away before it can interact again. Weak interactions effectively freeze-out and neutrinos decouple, thereafter free-streaming through the universe, $T_\nu \propto a^{-1}$.

NB: decoupling *by itself* does not change the neutrino-to-photon temperature ration. So, immediately after decoupling $T_\nu = T_\gamma$ still holds.

Neutrino decoupling

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Once the plasma temperature falls below $m_e = 0.511\,\mathrm{MeV}$, photons can no longer produce $e^{\pm}$ pairs, while the existing ones keep annihilating

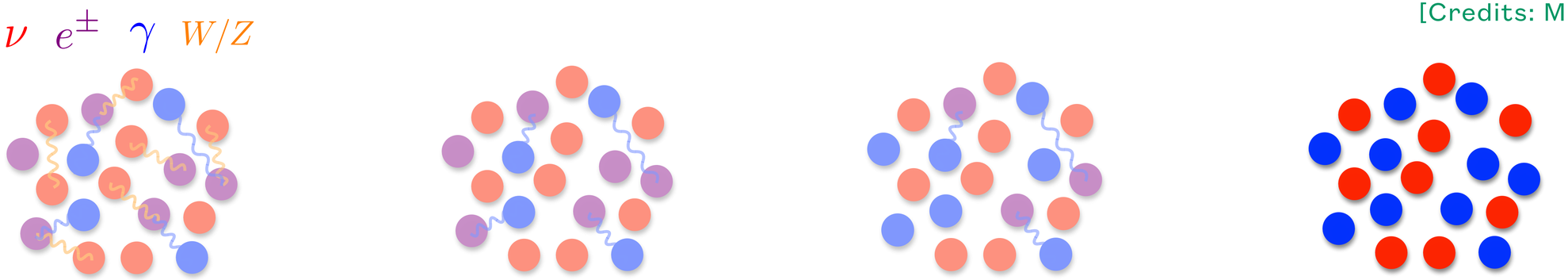
$$e^+e^- \to \gamma\gamma$$

All the rest-mass energy is dumped into the photons only and thus they get reheated with respect to the neutrino population.

Neutrino decoupling

- Let's focus on the cosmic history at the MeV epoch:

[Credits: M. Escudero]



After a while, all $e^{\pm}$ are gone and only ν and γ remain in the plasma. Their temperature ratio freezes. From the conservation of comoving entropy then follows that

$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3} \approx 0.71378$$

Observational implications

- After e^+e^- annihilation, the only relativistic species left in the plasma are neutrinos and photons. The total radiation energy density can be written as

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

CMB

Increasing the radiation density increases the expansion rate before recombination and reduces the age of the Universe at recombination. the angular scale of the photon diffusion length increases, thereby reducing power in the damping tail, at a given multipole.

BBN

Neutrino energy density sets the expansion rate at n/p freeze-out. This is the seed for the synthesis of light elements which, thus, depend on $N_{\rm eff}$.

- **Caveats:** neutrinos are still interacting with the plasma when e^+e^-annihilation begins, stronger interactions for high-temperature tail of the FD distribution, flavour oscillations, finite-temperature QED corrections, …

Quantum Kinetic Equations (QKE)

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

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

NB: everything expressed in terms of comoving variables

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

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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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Reheating modelling

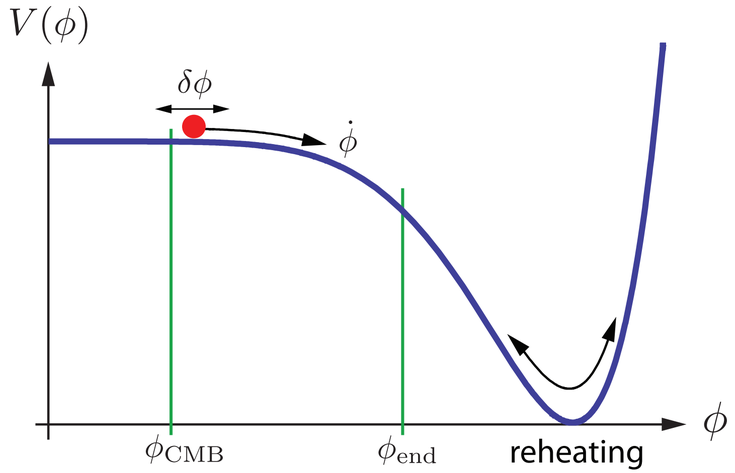
- In inflation paradigm, a final reheating phase is needed to reconcile with the standard FLRW radiation dominated Universe

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

- What is the reheating temperature?

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

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



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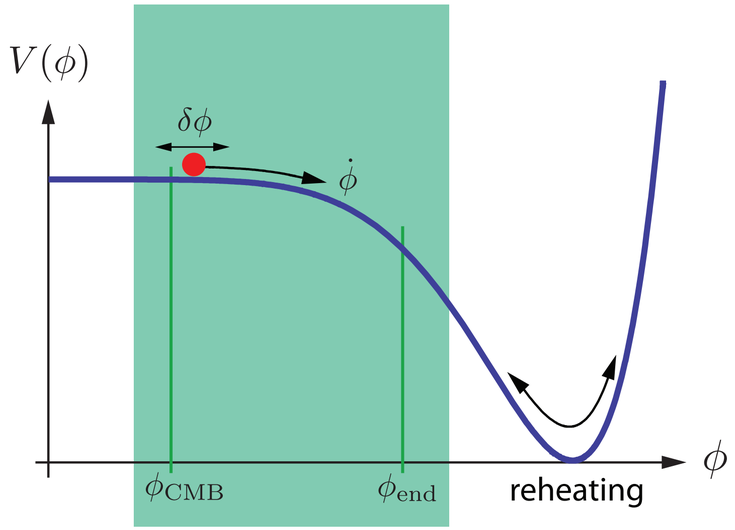
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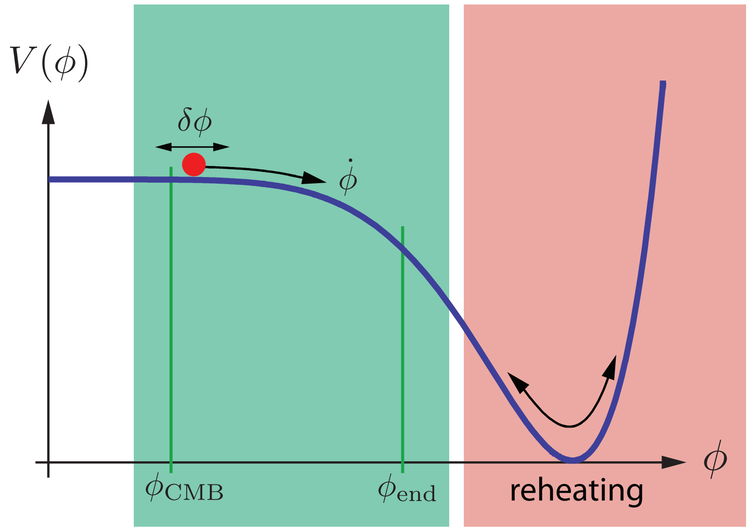
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During **reheating** the inflaton decays into Standard Model degrees of freedom

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



QKE and low reheating

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$$\frac{d\rho_\phi}{dx} + \frac{x\,\rho_\phi\Gamma_\phi}{m_e^2}\sqrt{\frac{3m_{\rm pl}^2}{8\pi\rho_{\rm tot}}} = 0\,, \qquad \text{where} \quad \rho_{\rm tot} = \sum_{i=\gamma,\nu_j,e,\mu}\rho_i + \delta\rho(x,z) + x\rho_\phi$$

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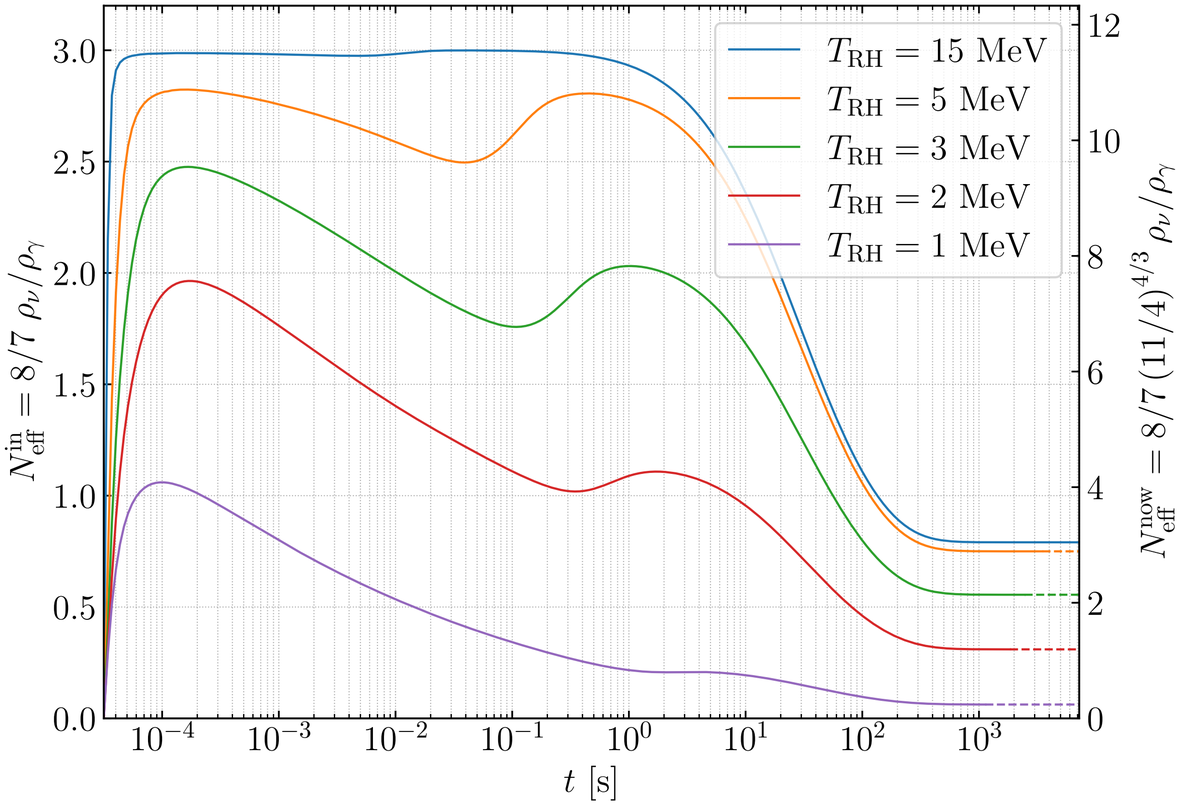
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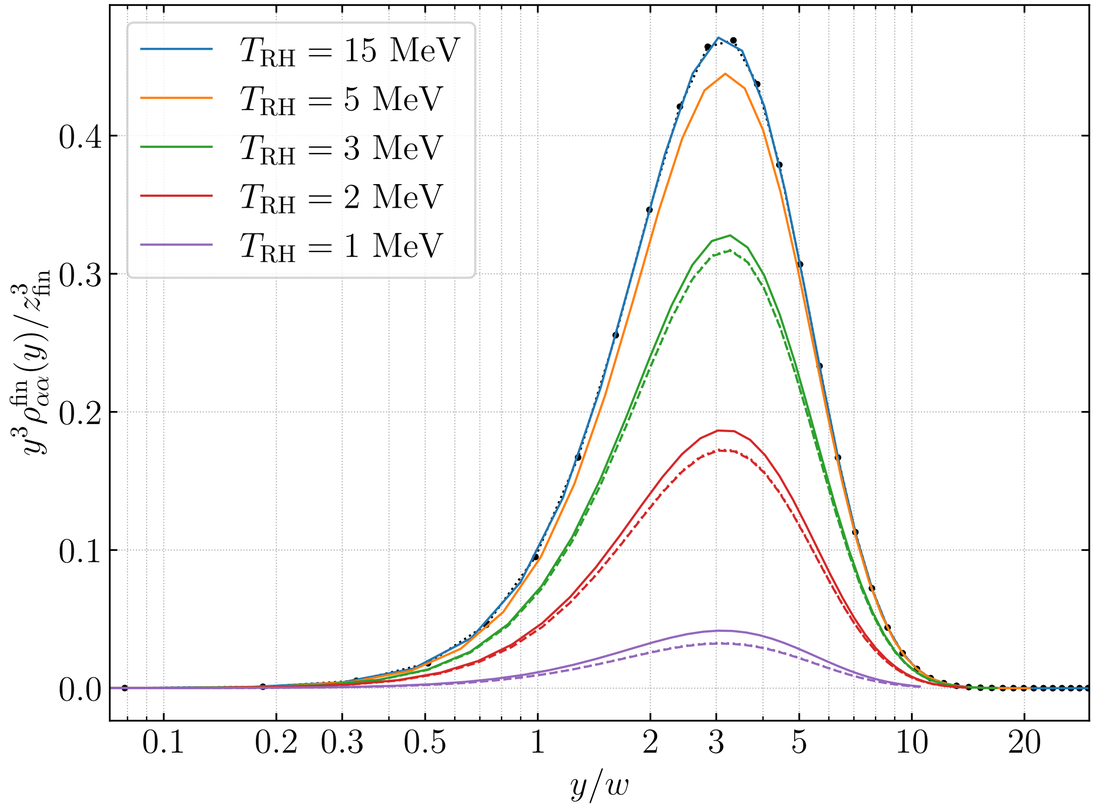
3

$$\frac{dz}{dx} = \frac{\displaystyle\sum_{\ell=e,\mu}\left[\frac{r_\ell^2}{r}J_2(r_\ell)\right] + G_1(r) - \frac{1}{2z^3}\sum_{\alpha=e}^{s}\frac{d\rho_{\nu_\alpha}}{dx} - \frac{x}{2z^3}\frac{d\rho_\phi}{dx}}{\displaystyle\sum_{\ell=e,\mu}\left[r_\ell^2 J_2(r_\ell) + J_4(r_\ell)\right] + G_2(r) + \frac{2\pi^2}{15}}$$

Neutrino production - I

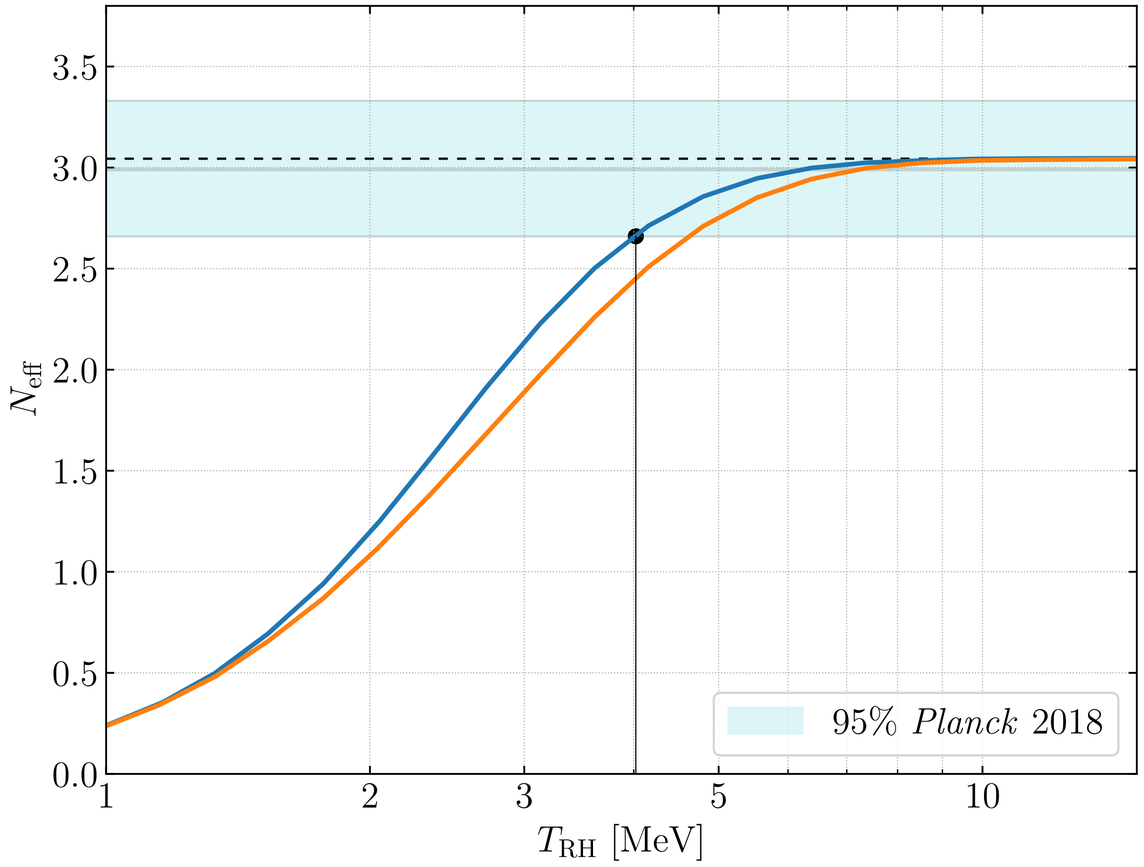


Time evolution of the ratio of energy densities of neutrinos and photons.



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

Neutrino production - II



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

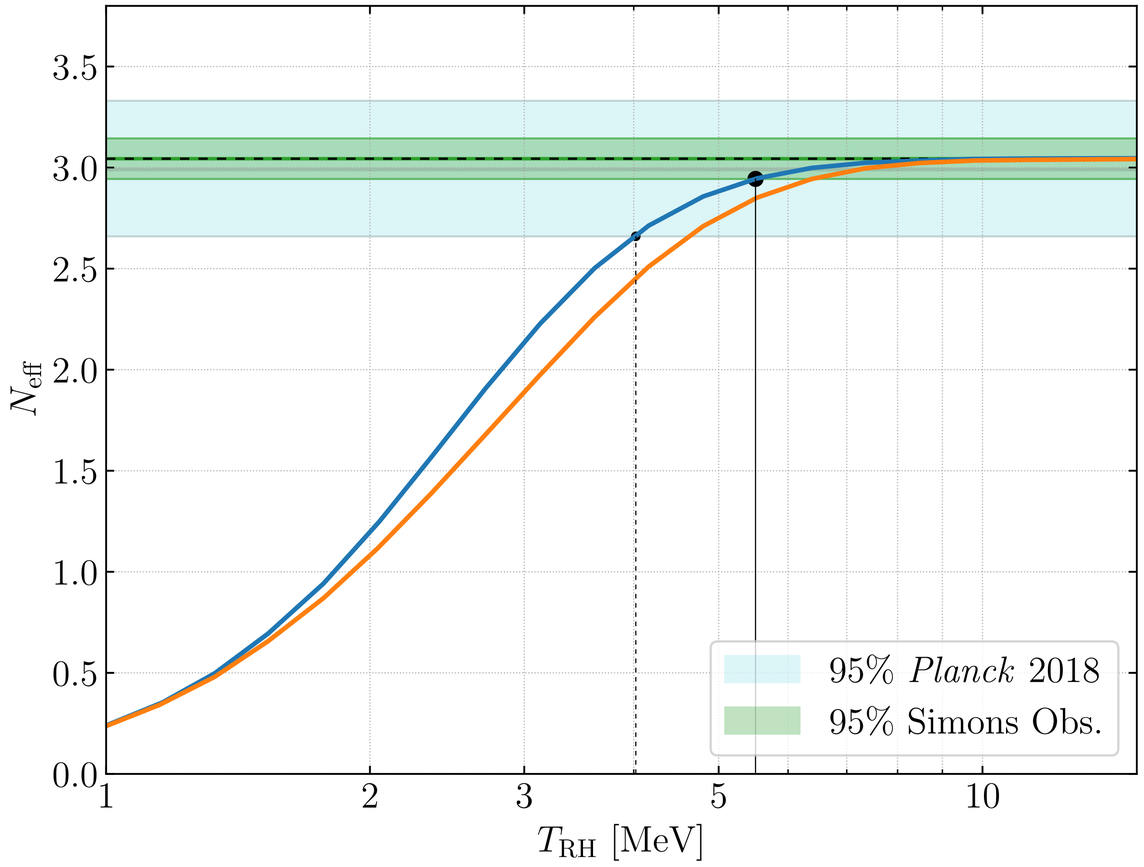
$$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$$



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

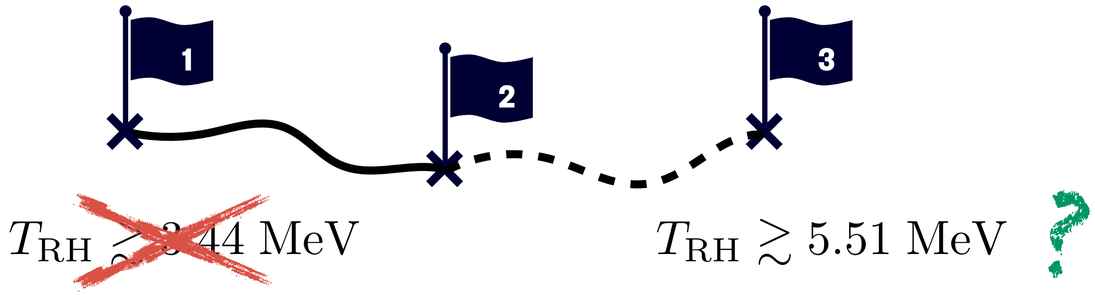
$$T_{\rm RH} \gtrsim 4.02 \text{ MeV}$$

Neutrino production - II



Simons Obs. (projected sensitivity):

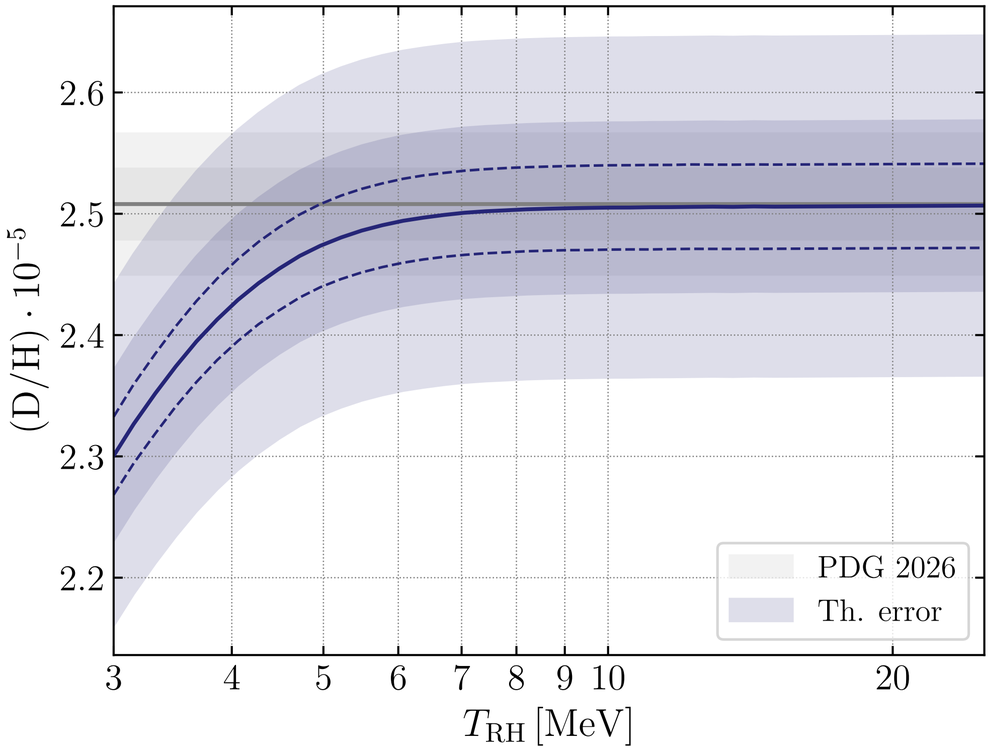
$$\sigma\left(N_{\rm eff}\right) = 0.050$$



Probes of low reheating: BBN

- 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

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

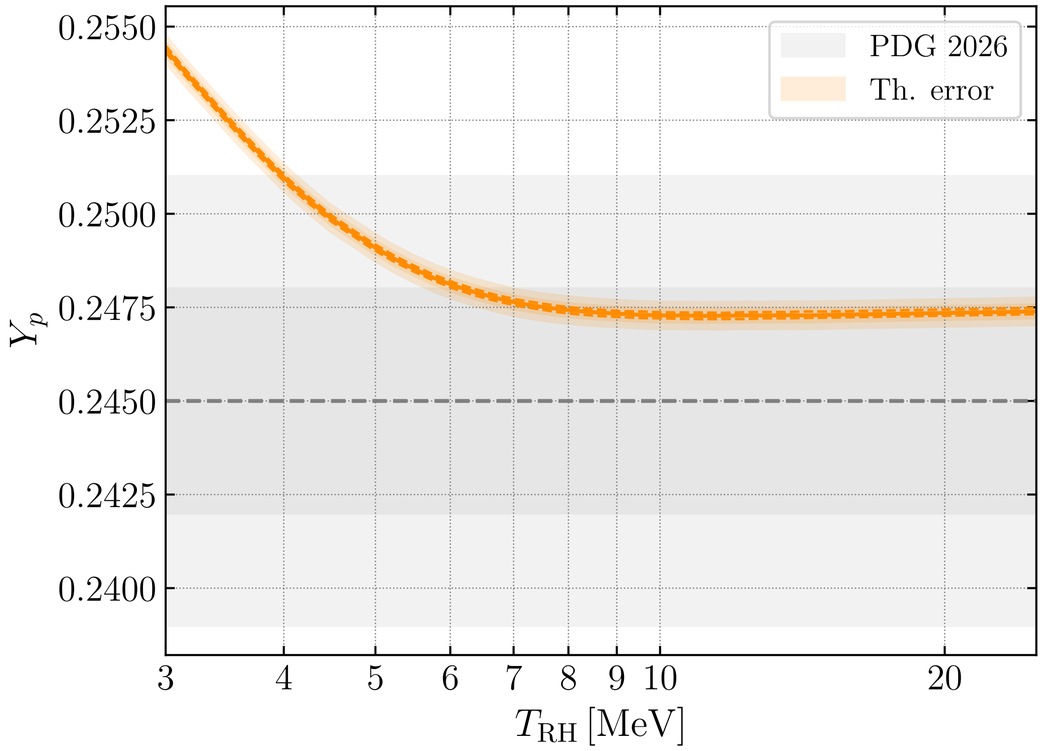


Values of the deuterium to hydrogen ratio as a function of T_{RH}

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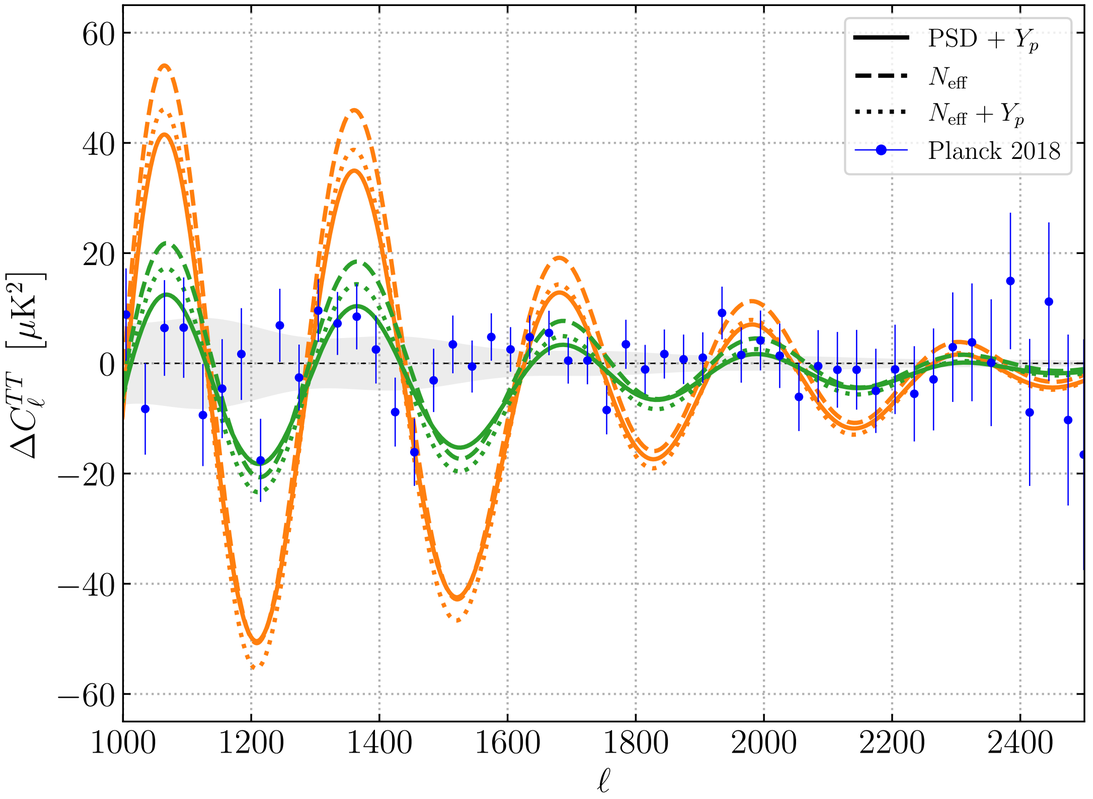
Values of the primordial helium yield as a function of $T_{\rm RH}$

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.



Pipeline and datasets

ALPs PSD from full phase spaces solution of QKEs (`FortEPiaNO` code)

$$f_{\nu_i}(y, z_{\rm fin})$$

Interface to `CLASS` and `PArthENoPE` to evolve the cosmological model

$$C_\ell,\ P(k),\ \mathrm{D/H},\ Y_{\rm He}$$

MCMC analysis through `Cobaya` sampler to get constraints

$$T_{\rm RH} < [...]$$

Datasets combinations

- Planck2018: low-ℓ TT (`Commander`) + low-ℓ EE (`SRo112`) + high-ℓ TTTEEE (`Plik_lite`)
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Extra: realistic forecasts for near future CMB (Simons Observatory and Litebird) and BAO (Euclid and DESI) experiments.

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- SPT-3G D1: TTTEEE from `cand1_like`
- Lensing: baseline combination of Planck+ACT (`act_dr6_lenslike`) and muse SPT-3G 2yr

-B

- Measurements of BAO distance from DESI DR2
- D/H ratio and He mass fraction values from weighted averages of PDG 2025.

Extra: realistic forecasts for near future CMB (Simons Observatory and Litebird) and BAO (Euclid and DESI) experiments.

Pipeline and datasets

ALPs PSD from full phase spaces solution of QKEs (`FortEPiaNO` code)

$f_{\nu_i}(y, z_{\rm fin})$

Interface to `CLASS` and `PArthENoPE` to evolve the cosmological model

C_ℓ, $P(k)$, D/H, $Y_{\rm He}$

MCMC analysis through `Cobaya` sampler to get constraints

$T_{\rm RH} < [...]$

Datasets combinations

SPA

- Planck2018: low-ℓ TT (`Commander`) + low-ℓ EE (`SRo112`) + high-ℓ TTTEEE (`Plik_lite`)
- ACT-DR6: TTTEEE from `act_dr6_cmbonly`
- SPT-3G D1: TTTEEE from `cand1_like`
- Lensing: baseline combination of Planck+ACT (`act_dr6_lenslike`) and muse SPT-3G 2yr

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- Measurements of BAO distance from DESI DR2

-D-He

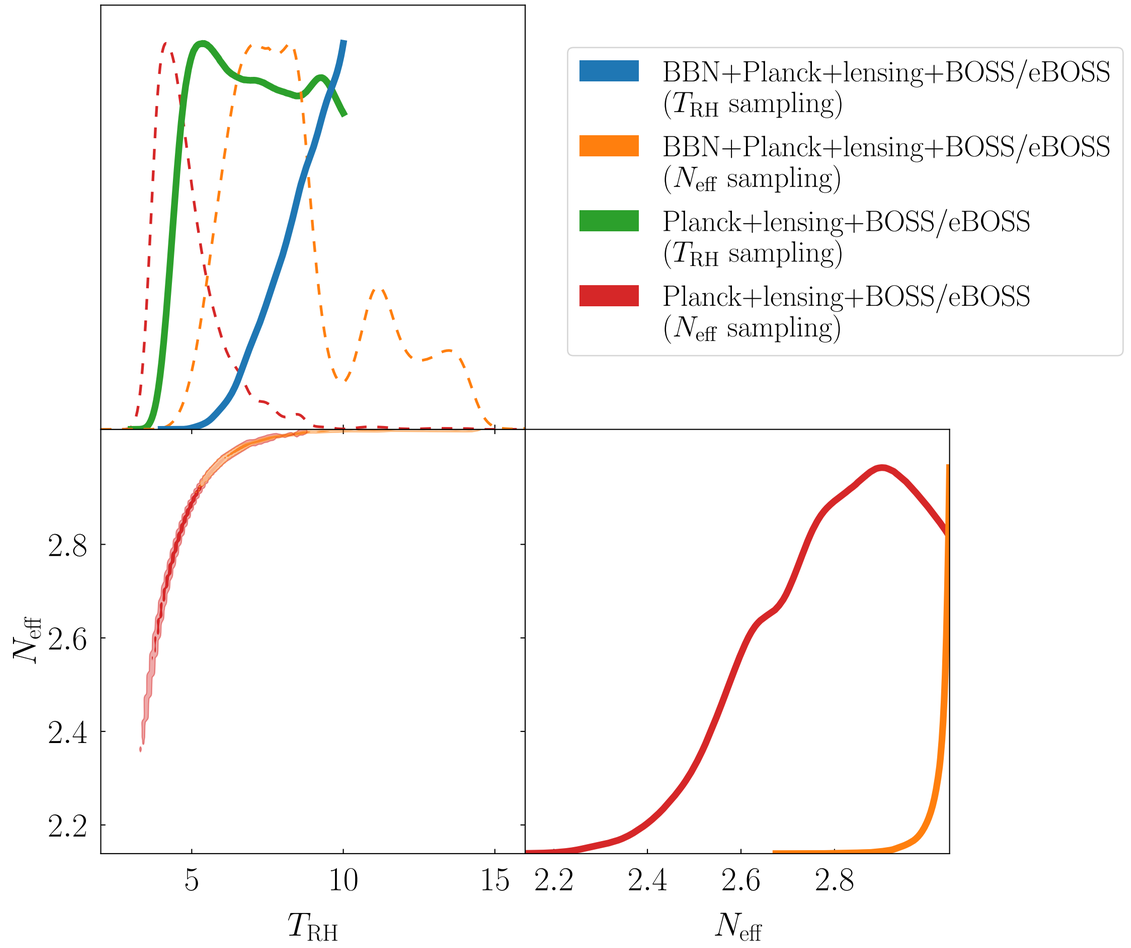
- D/H ratio and He mass fraction values from weighted averages of PDG 2025.

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Bounds on T_{RH}

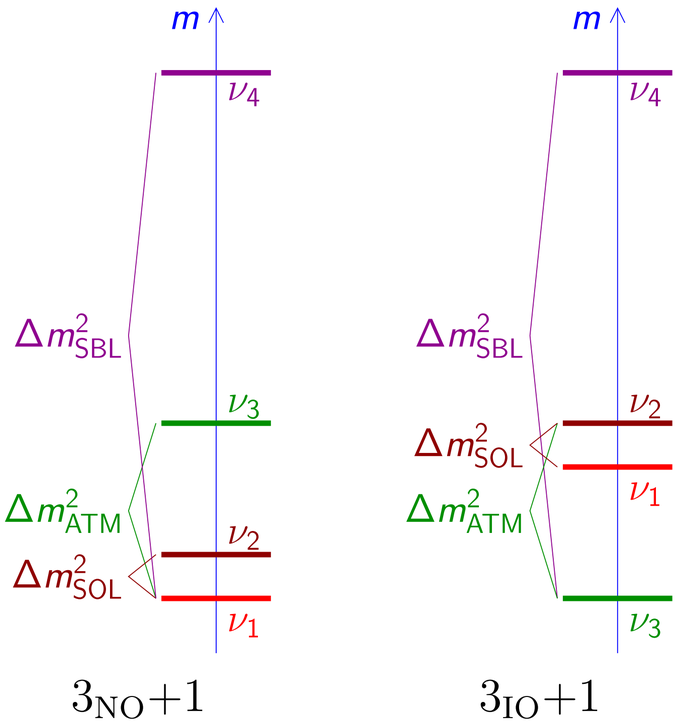
- T_{RH} **sampling:** employed in previous works, poor sampling of low reheating temperatures region, direct interpretation of the physical results;
- N_{eff} **sampling:** most direct relationship with the data, uniform sampling of all parameter space, difficult interpretation of the results.
- Summary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

	N_{eff}	T_{RH}
Dataset	95% limits	95% limits
SPA	> 2.51	$> 3.63\,\mathrm{MeV}$
SPA-B	> 2.74	$> 4.27\,\mathrm{MeV}$
SPA-D-He	> 2.62	$> 3.89\,\mathrm{MeV}$
SPA-B-D-He	> 2.81	$> 4.57\,\mathrm{MeV}$



The (3+1) neutrino framework

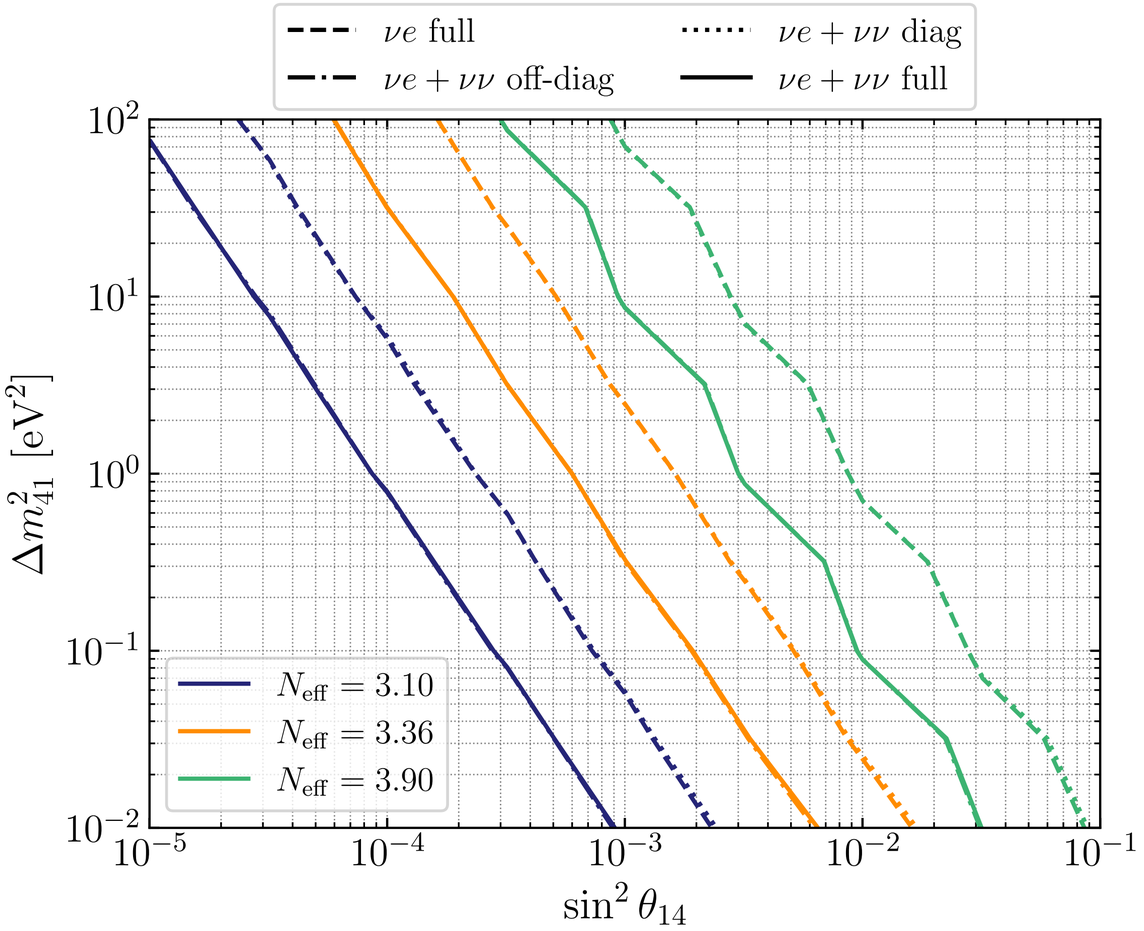
- Several anomalies in neutrino oscillation experiments seem to suggest the existence of one **additional sterile state**, mixed with the active neutrinos;
- The parameter space is enlarged by the addition of an **additional mass splitting**, Δm^2_{14}, and **three new mixing angles** θ_{14}, θ_{24}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



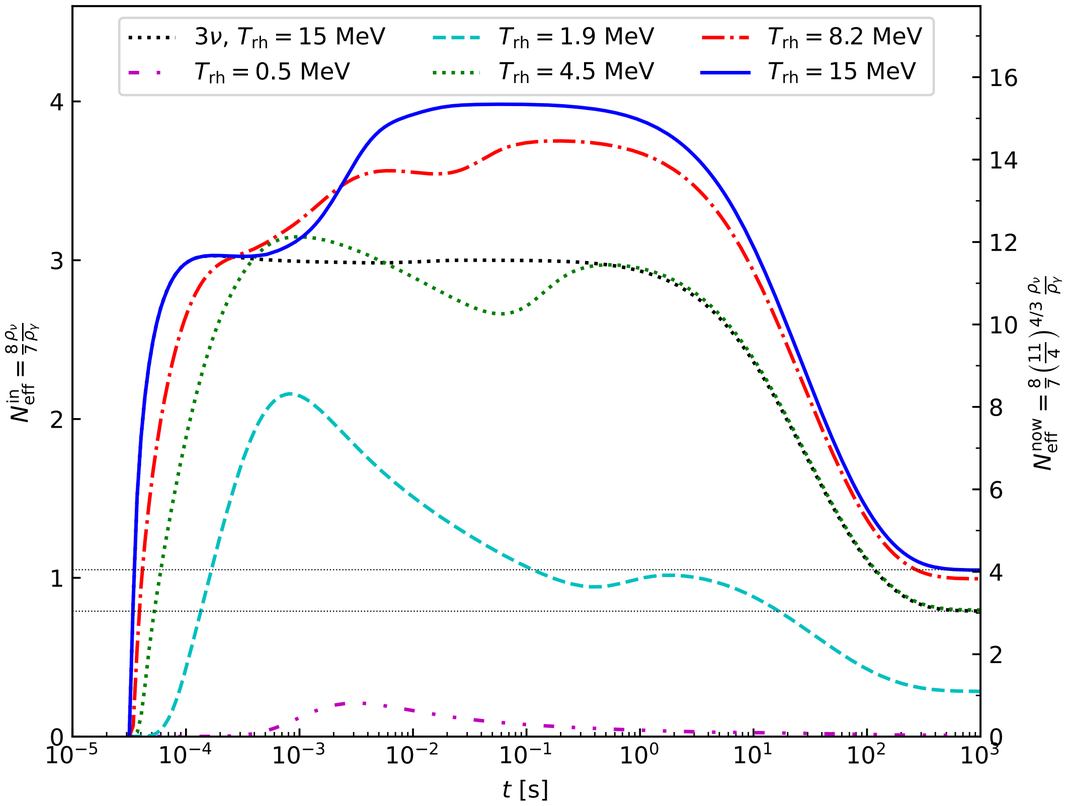
[Credits: Giunti and Lasserre (2019)]

QKE and sterile neutrinos

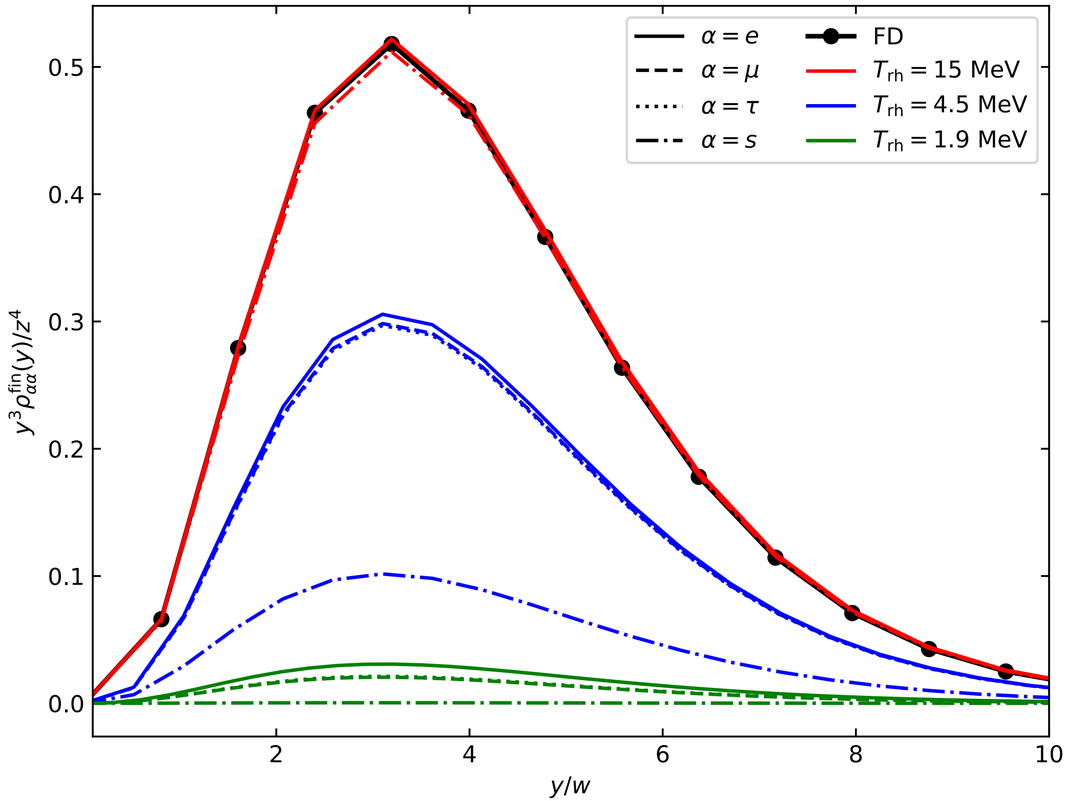
- First inclusion of the effect of $\nu\nu$ collision terms in sterile neutrino decoupling computation.
- Diagonal components of $\nu\nu$ only redistribute energy between active flavour neutrinos. Off-diagonal components feed the coherence terms related to neutrinos oscillations, making active-sterile transformations more efficient.
- Damping approximation on the off-diagonal components does not introduce sizeable differences in the results.



Neutrino production in (3+1) models



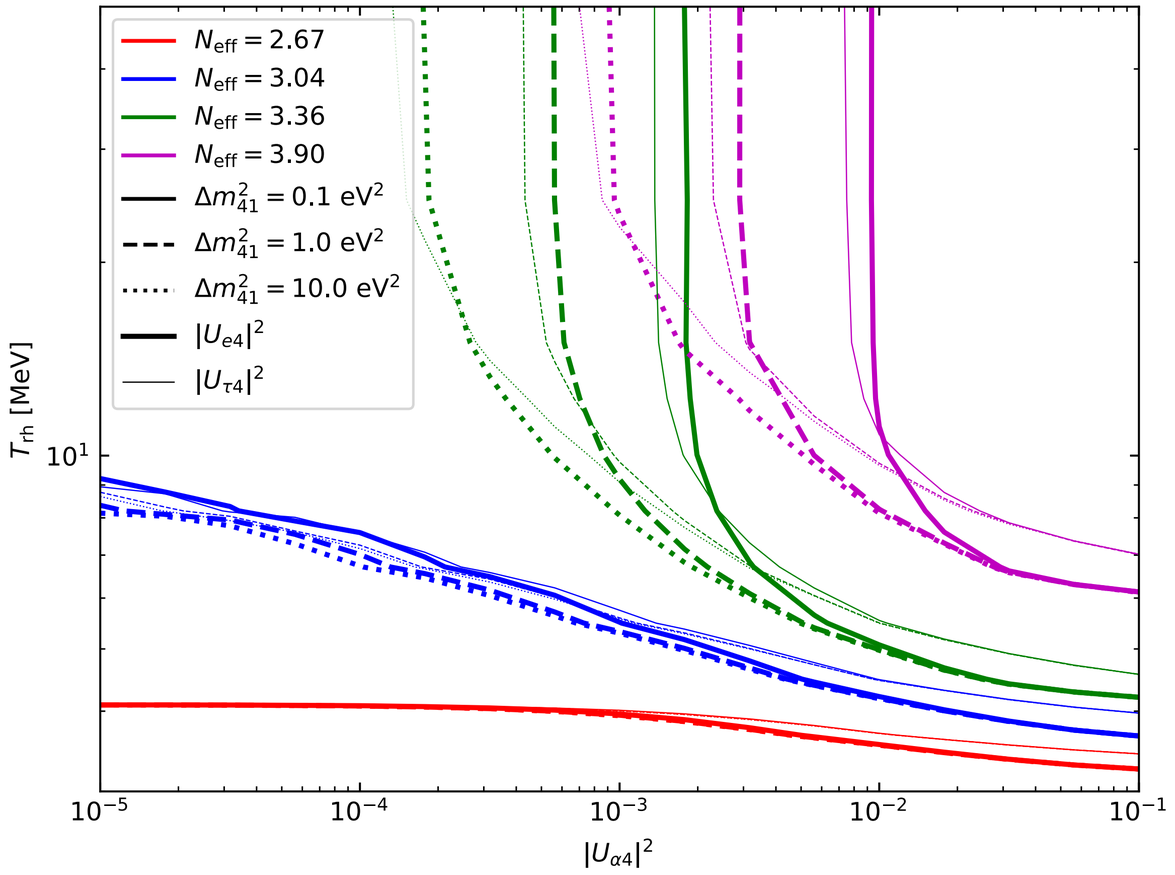
Time evolution of the ratio of energy densities of neutrinos and photons.



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

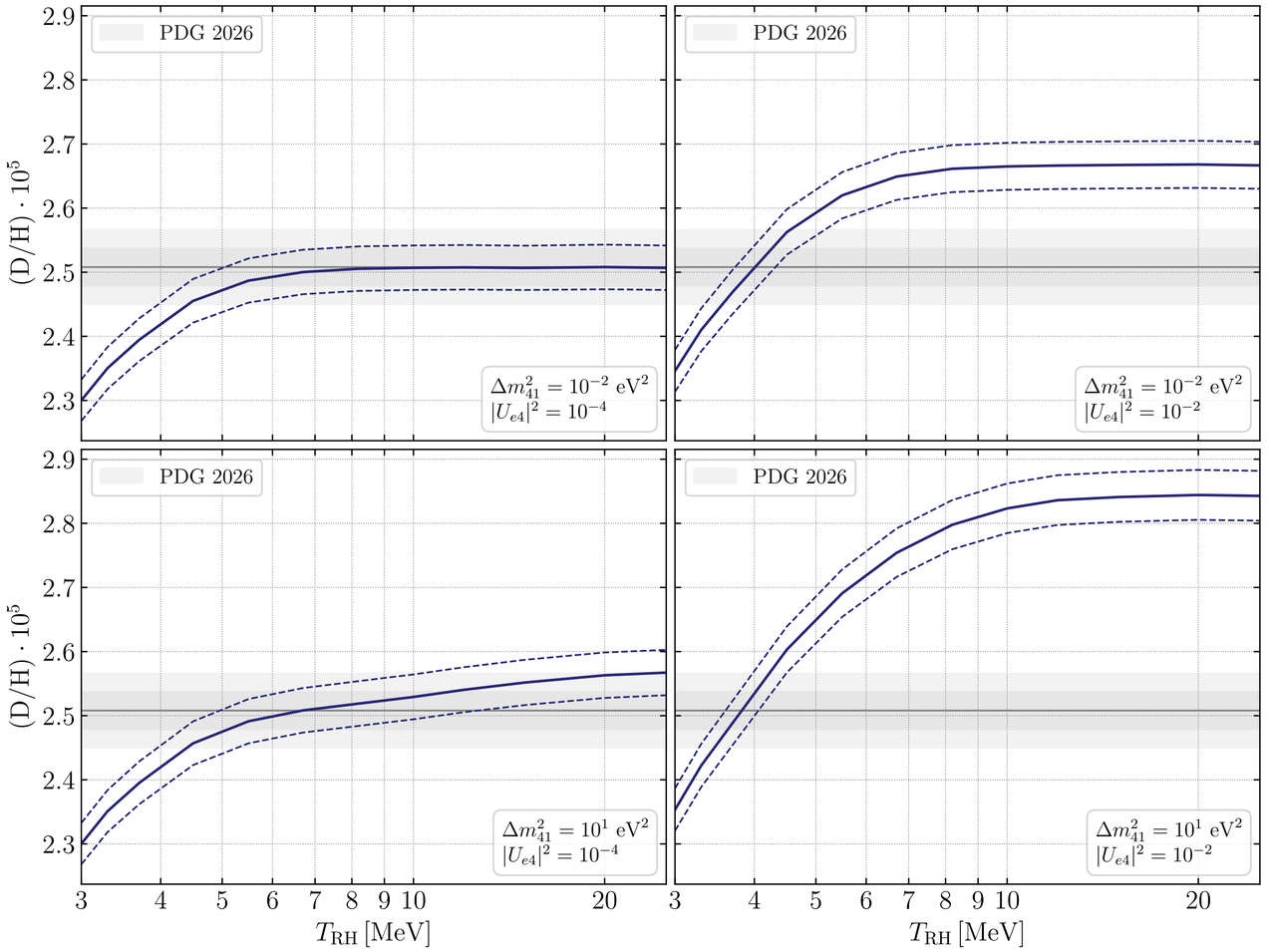
Parameter space exploration

- When $T_{\rm RH}$ is very small, the active-sterile mixing angle has almost no impact on the final value of $N_{\rm eff}$ (even the model does not really matter).
- For $T_{\rm RH} \gtrsim 10\,{\rm MeV}$ its impact is significantly reduced, but still shows some effect when large mass splitting are considered.
- Opening tau instead of electron mixing has a relatively small impact of $N_{\rm eff}$: at high $T_{\rm RH}$ it increases, while at small $T_{\rm RH}$ it decreases.



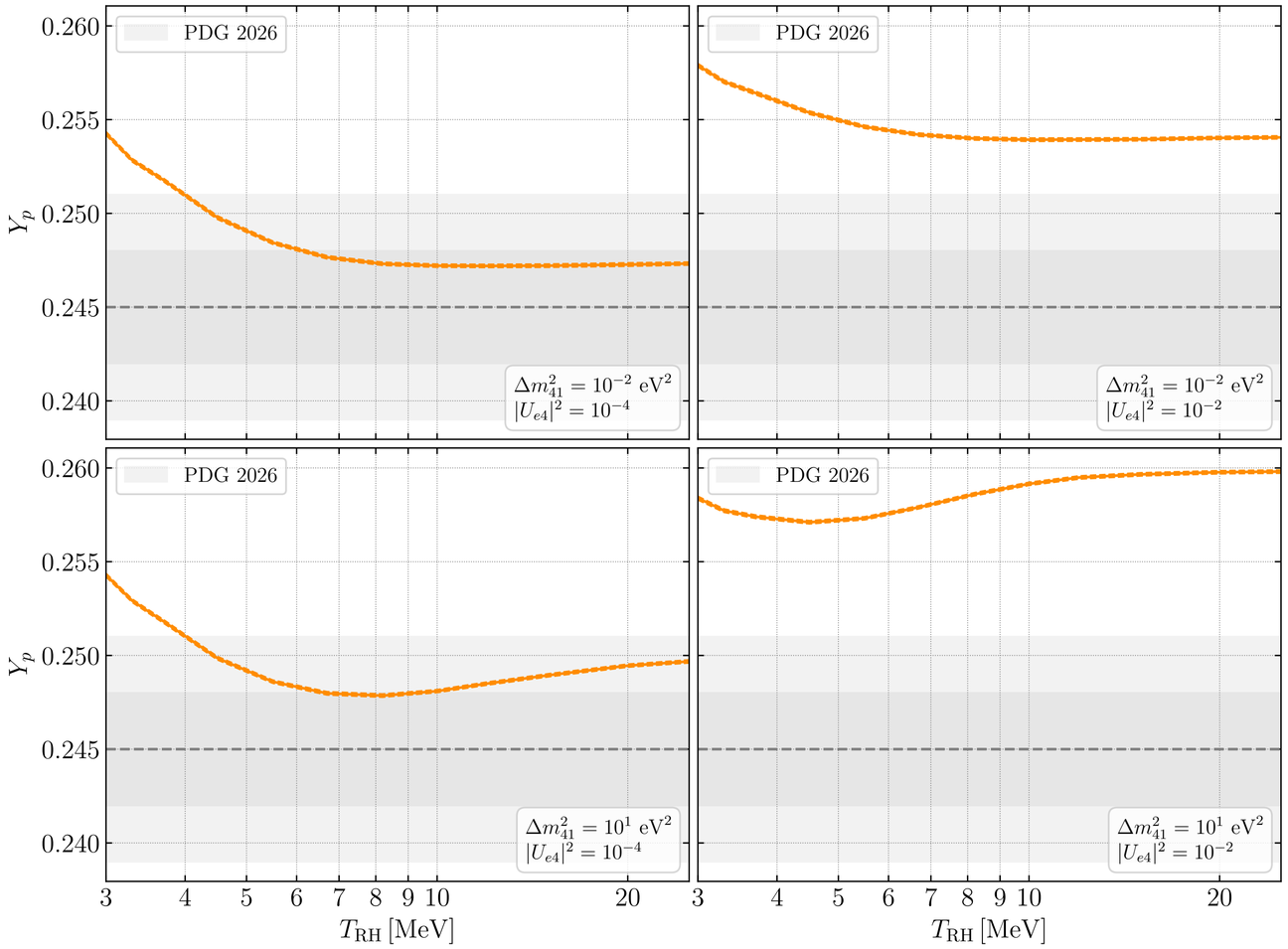
Probes of sterile neutrinos: BBN

- The behaviour with respect to T_{RH} is analogous to the 3 neutrino case, at fixed mixing parameters.
- The precise dependance on mixing parameters depends on the balance between RHO+N and WR contribution and its difficult to predict a priori.
- D/H, dominated by the RHO+N component reflect the additional ΔN_{eff} due to the sterile neutrino.
- Y_p is not anymore a strictly decreasing function of T_{RH}: some combinations of mixing parameters boost the RHO+N component enough to make it comparable to WR.



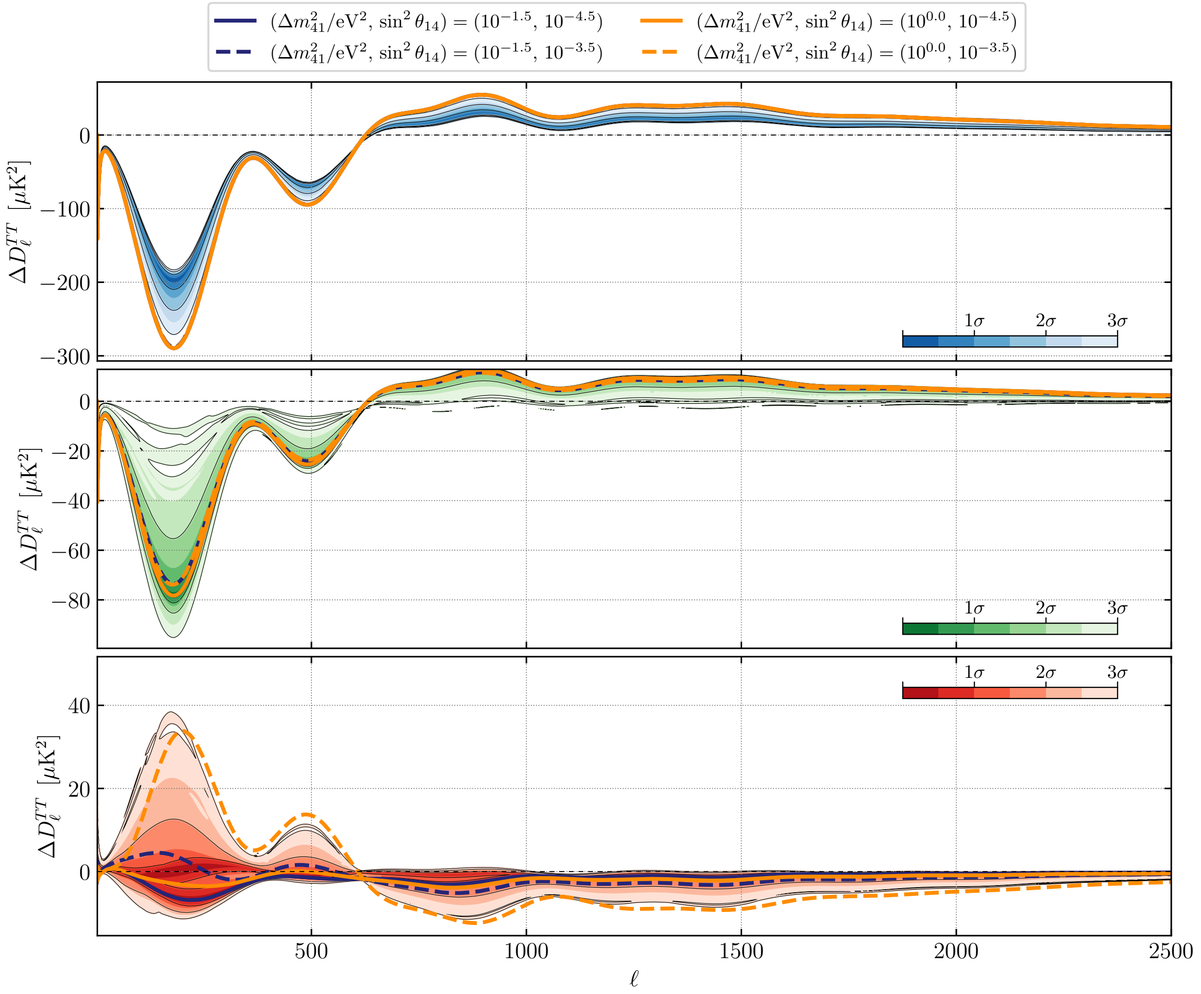
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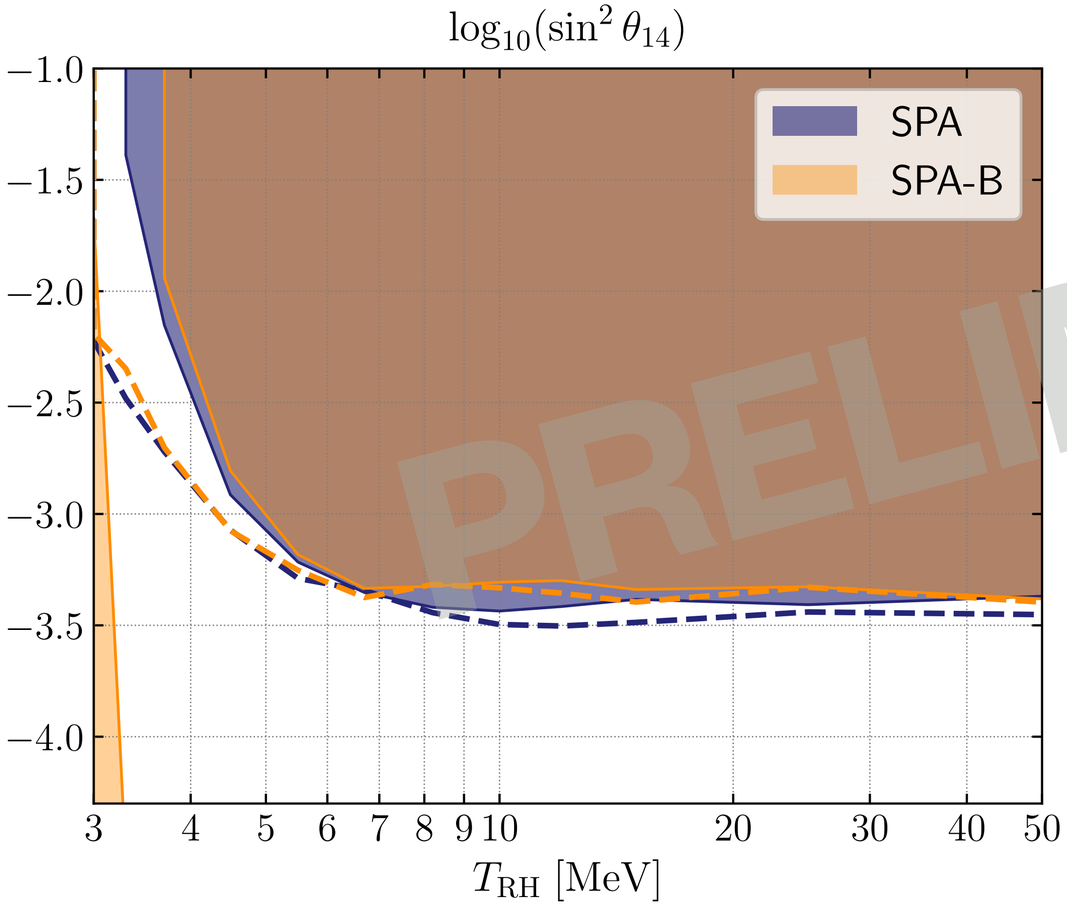


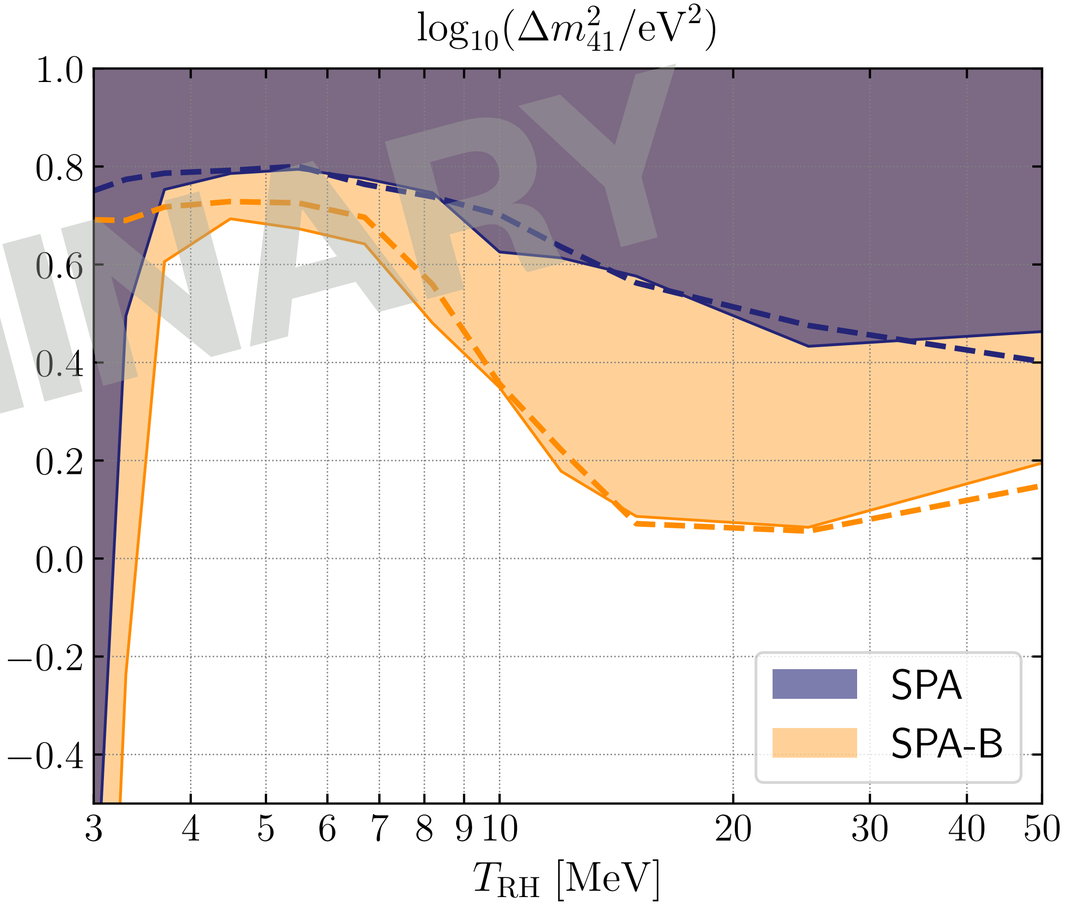
Probes of sterile neutrinos: CMB

- Two main kind of effects: via $N_{\rm eff}$ and via $m_{\rm sterile}$.
- A **phase shift** is induced on CMB peaks due to the fact that neutrinos free stream faster than the speed of sound in the baryon-photon fluid.
- Extra radiation enhance the expansion rate during radiation domination enlarging the diffusion scale and thus **suppressing power at high** ℓ.
- After non-relativistic transition, light massive relics do not cluster below the size of their free-streaming length. This generate a suppression in the clustering of matter and thus less CMB lensing.



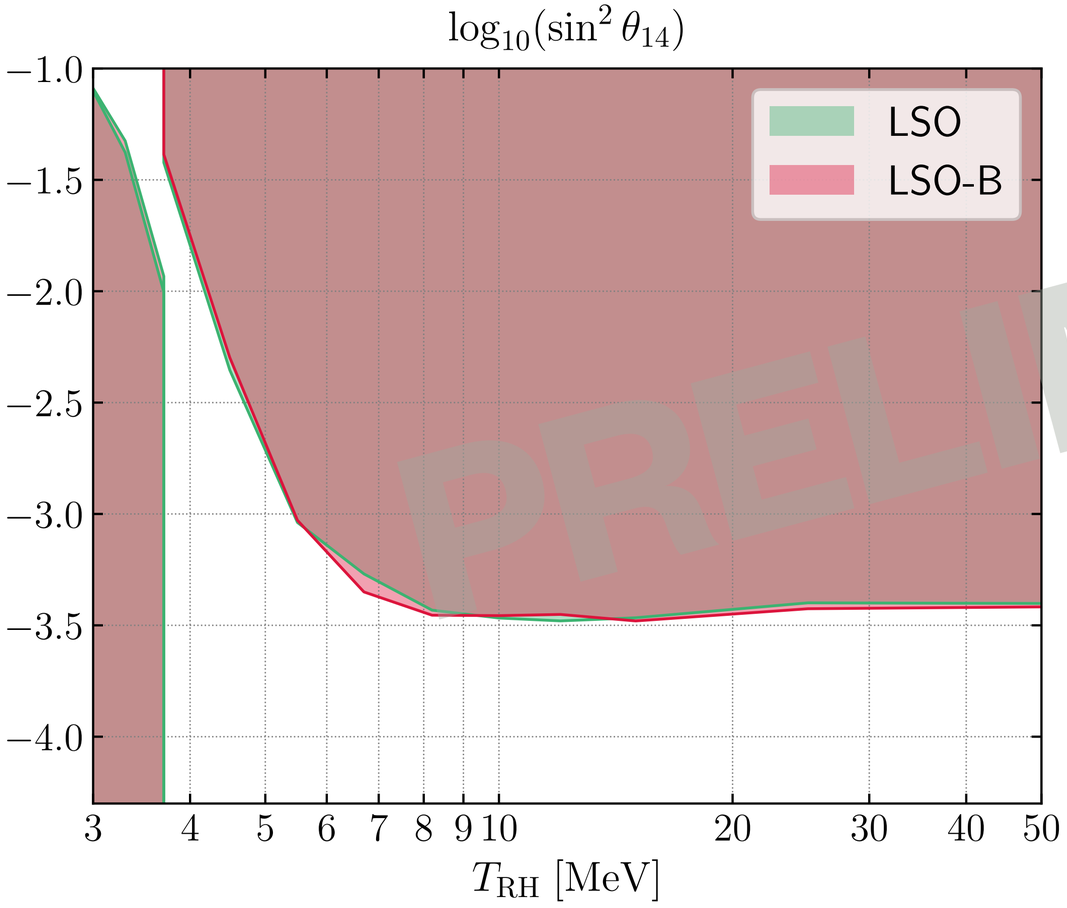
Constraints on mixing parameters

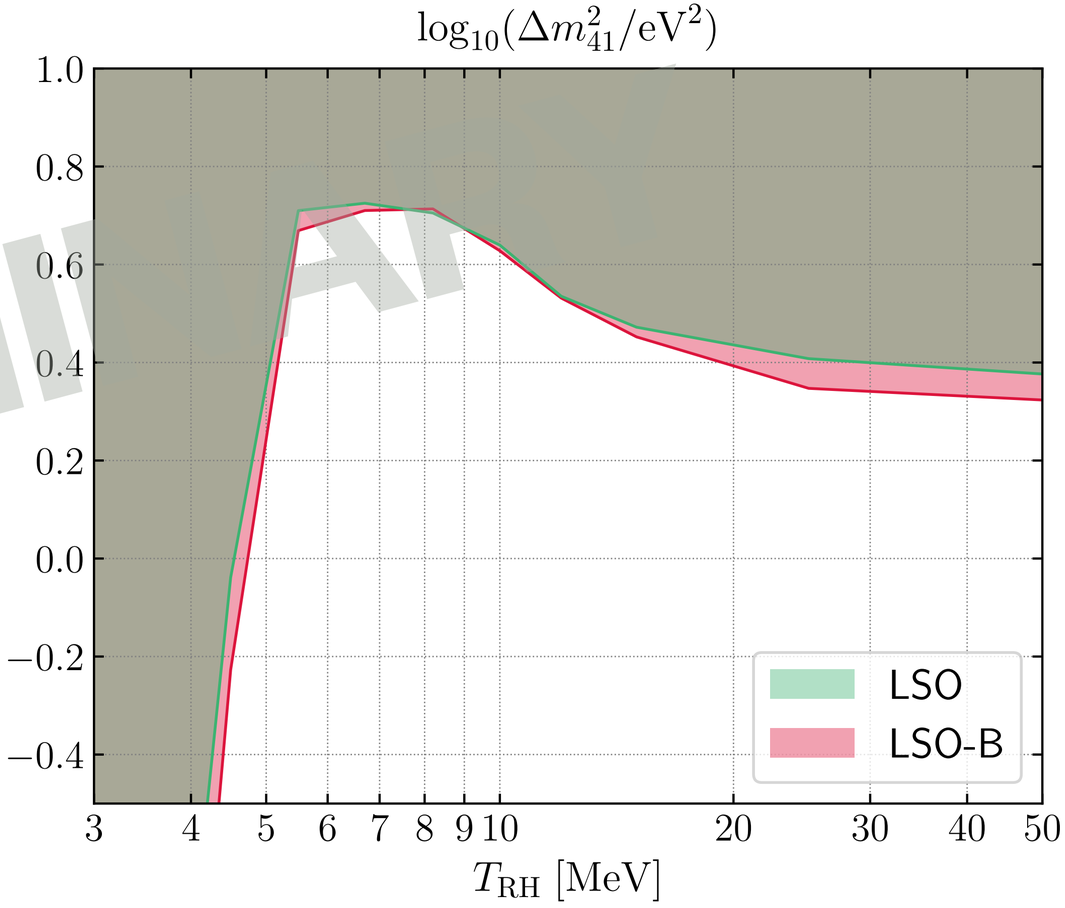




PRELIMINARY

Constraints on mixing parameters





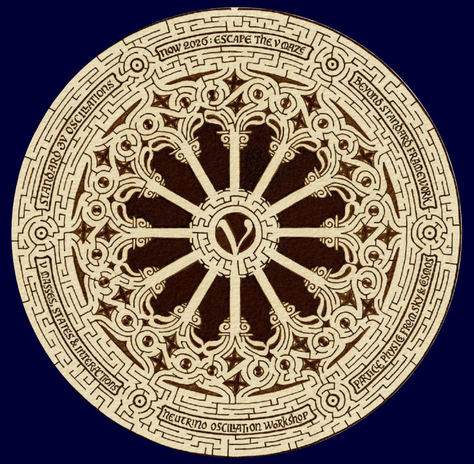
PRELIMINARY

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Excelencia Severo Ochoa



NOW 2026
Neutrino Oscillation Workshop

Thank you!

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

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

Neutrino thermalisation in very low reheating cosmologies

NICOLA BARBIERI (IFIC, CSIC-UV) – 01/09/2026