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Massive sterile neutrinos in the Early Universe: from thermal decoupling to cosmological constraints

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Based on L. Mastrototaro, P. D. Serpico, A. Mirizzi, N. Saviano ArXiv:2104.11752 - DOI:10.1103/PhysRevD.104.016026

OUTLINE

- Introduction
- Sterile and active neutrino evolution in the Early Universe
- Temperature evolution
- Bounds on ν_s parameter space
- Conclusions

WORK'S AIMS

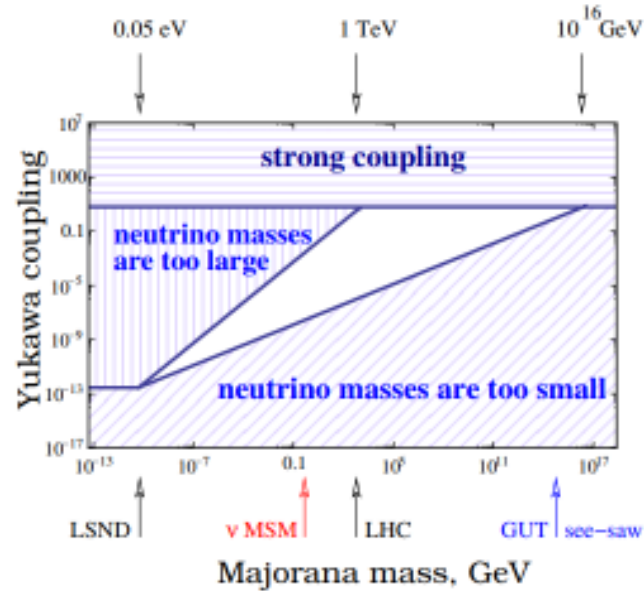
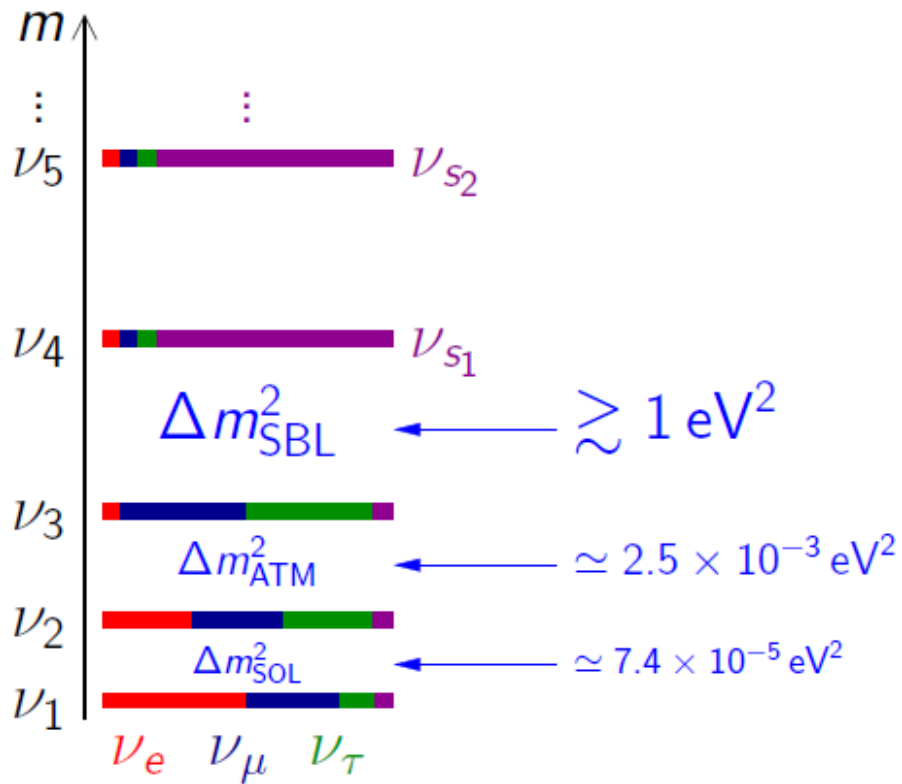
- In this work we focused on obtaining:
 - a precise calculation of the sterile neutrino evolution in the Early Universe;
 - bounds on the sterile neutrino parameters from the BBN and CMB measurement.
- The existence of sterile neutrino emerges naturally in extensions of the Standard Model, like ν MSM. [*Shaposhnikov et al, arXiv: hep-ph/0505031*]



Interest in investigating their parameter space (m_s, τ_s)

- From BBN and CMB one can obtain precise measurement to constraint ν_s parameters.
- Expected improvement in the measurement from the future Stage 4 ground-based CMB experiments (CMB-S4)

HEAVY STERILE NEUTRINOS



	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see-saw	10^{16} GeV	YES	NO	YES	NO	NO	NO	-
EWSB	$10^2 - 10^3$ GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV - GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Extra sterile neutrinos with masses $m_s \gg m_a$ and mixed with the active ones through a mixing angle θ_s are predicted in different extensions of the Standard Model

HEAVY STERILE ν EVOLUTION

- We investigate the possibility of the existence of heavy sterile neutrinos ($m < m_\pi$) might be thermally produced in the Early Universe.
- We numerically solved the exact Boltzmann equation for sterile and active neutrino population

$$x = m_0 a(t) \quad y = m_0 p$$
$$\partial_x f = \frac{I}{xH}$$

- Already studied in:
 - [Dolgov et al, ArXiv:hep-ph/0002223](#) → analytical treatment
 - [Ruchayskiy and Ivashko, ArXiv:1202.2841](#)
 - [Nashwan et al, ArXiv:2006.07387](#)
- } Numerical treatment focused on Y_p

COLLISIONAL INTEGRAL

$$I = \frac{(2\pi)^4}{2E_1} \int d^3\widehat{p}_2 d^3\widehat{p}_3 d^3\widehat{p}_4 F(f_1, f_2, f_3, f_4) S |M|^2 \delta^4(p_1 + p_2 - p_3 - p_4)$$

$|M|^2$ sum of scattering and decay processes for ν_s and

$$F(f_1, f_2, f_3, f_4) = - \prod_i f_i \prod_f (1 \pm f_f) + \prod_i (1 \pm f_i) \prod_f f_f$$

I is a 9-dimensional integral that we reduce to a 3-dimensional integral to solve numerically using the technique developed by [\[Hannestad et al, arXiv:astro-ph/9506015\]](#)

For active neutrinos, we include the neutrino oscillation:

$$I_\alpha \rightarrow \sum_\beta P_{\beta\alpha} I_\beta$$

$P_{\beta\alpha}$ is the time-average transition probability from flavour β to α

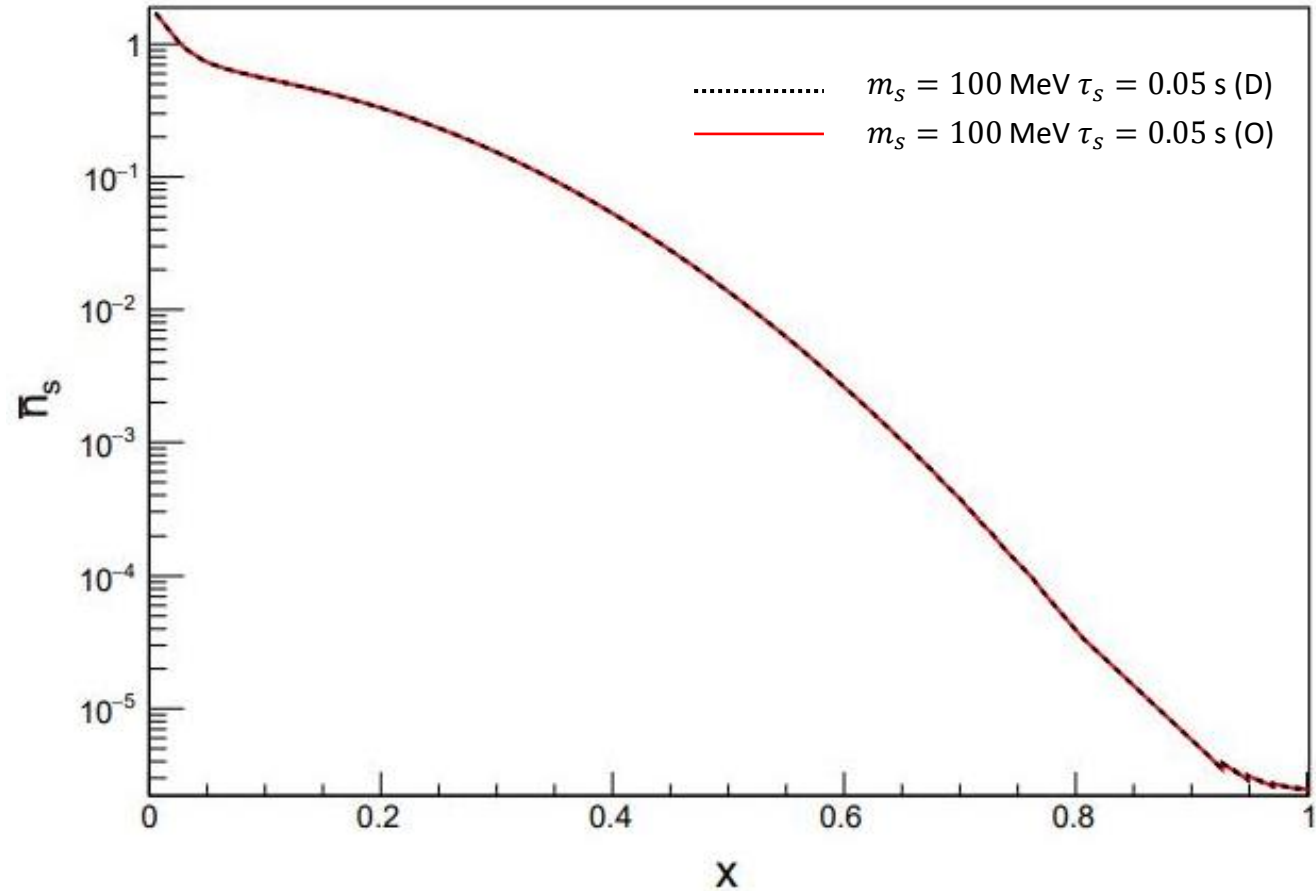
STERILE NEUTRINO PROCESSES

Process	$G_F^{-2} U_{\tau s} ^{-2} M ^2$
$\nu_s + \bar{\nu}_\alpha \rightarrow \nu_\alpha + \bar{\nu}_\alpha$	$64(p_1 \cdot p_4)(p_2 \cdot p_3)$
$\nu_s + \nu_\alpha \rightarrow \nu_\alpha + \nu_\alpha$	$32(p_1 \cdot p_2)(p_3 \cdot p_4)$
$\nu_s + \bar{\nu}_\alpha \rightarrow \nu_\beta + \bar{\nu}_\beta$	$16(p_1 \cdot p_4)(p_2 \cdot p_3)$
$\nu_s + \bar{\nu}_\beta \rightarrow \nu_\alpha + \bar{\nu}_\beta$	$16(p_1 \cdot p_4)(p_2 \cdot p_3)$
$\nu_s + \bar{\nu}_\alpha \rightarrow e^+ + e^-$	$64[\tilde{g}_L^2(p_1 \cdot p_4)(p_2 \cdot p_3) + g_R^2(p_1 \cdot p_3)(p_2 \cdot p_4) - \tilde{g}_L g_R m_e^2(p_1 \cdot p_3)]$
$\nu_s + e^- \rightarrow \nu_\alpha + e^-$	$64[\tilde{g}_L^2(p_1 \cdot p_2)(p_3 \cdot p_4) + g_R^2(p_1 \cdot p_4)(p_2 \cdot p_3) - \tilde{g}_L g_R m_e^2(p_1 \cdot p_3)]$
$\nu_s + e^+ \rightarrow \nu_\alpha + e^+$	$64[g_R^2(p_1 \cdot p_2)(p_3 \cdot p_4) + \tilde{g}_L^2(p_1 \cdot p_4)(p_2 \cdot p_3) - \tilde{g}_L g_R m_e^2(p_1 \cdot p_3)]$

Process	$G_F^{-2} U_{\alpha s} ^{-2} M ^2$
$\nu_s \rightarrow \nu_\alpha + \bar{\nu}_\alpha + \nu_\alpha$	$32(p_1 \cdot p_4)(p_2 \cdot p_3)$
$\nu_s \rightarrow \nu_\alpha + \nu_\beta + \bar{\nu}_\beta$	$16(p_1 \cdot p_4)(p_2 \cdot p_3)$
$\nu_s \rightarrow \nu_\alpha + e^+ + e^-$	$64[\tilde{g}_L^2(p_1 \cdot p_4)(p_2 \cdot p_3) + g_R^2(p_1 \cdot p_3)(p_2 \cdot p_4) - \tilde{g}_L g_R m_e^2(p_1 \cdot p_3)]$

TEST ON NEUTRINO EVOLUTION

- We have compared our evolution with the analytical treatment in [[Dolgov et al, arXiv: hep-ph/0002223](#)]
- Approximations in [[Dolgov et al, arXiv: hep-ph/0002223](#)] :
 - the Boltzmann limit for the equilibrium distribution;
 - $m_e = 0$.



STERILE NEUTRINO DECOUPLING

The temperature evolution is taken into account using

$$\frac{d}{dx} \bar{\rho}(x) = \frac{1}{x} (\bar{\rho}(x) - 3P),$$

$$\bar{\rho}_a = \frac{1}{\pi^2} \int dy y^2 \sqrt{\frac{m_a^2 x^2}{m^2} + y^2} f_a(x, y) \quad P_a = \frac{1}{3\pi^2} \int \frac{dy y^4}{\sqrt{\frac{m_a^2 x^2}{m^2} + y^2}} f_a(x, y)$$

We define $z = Ta(t)$ and consider two main situations:

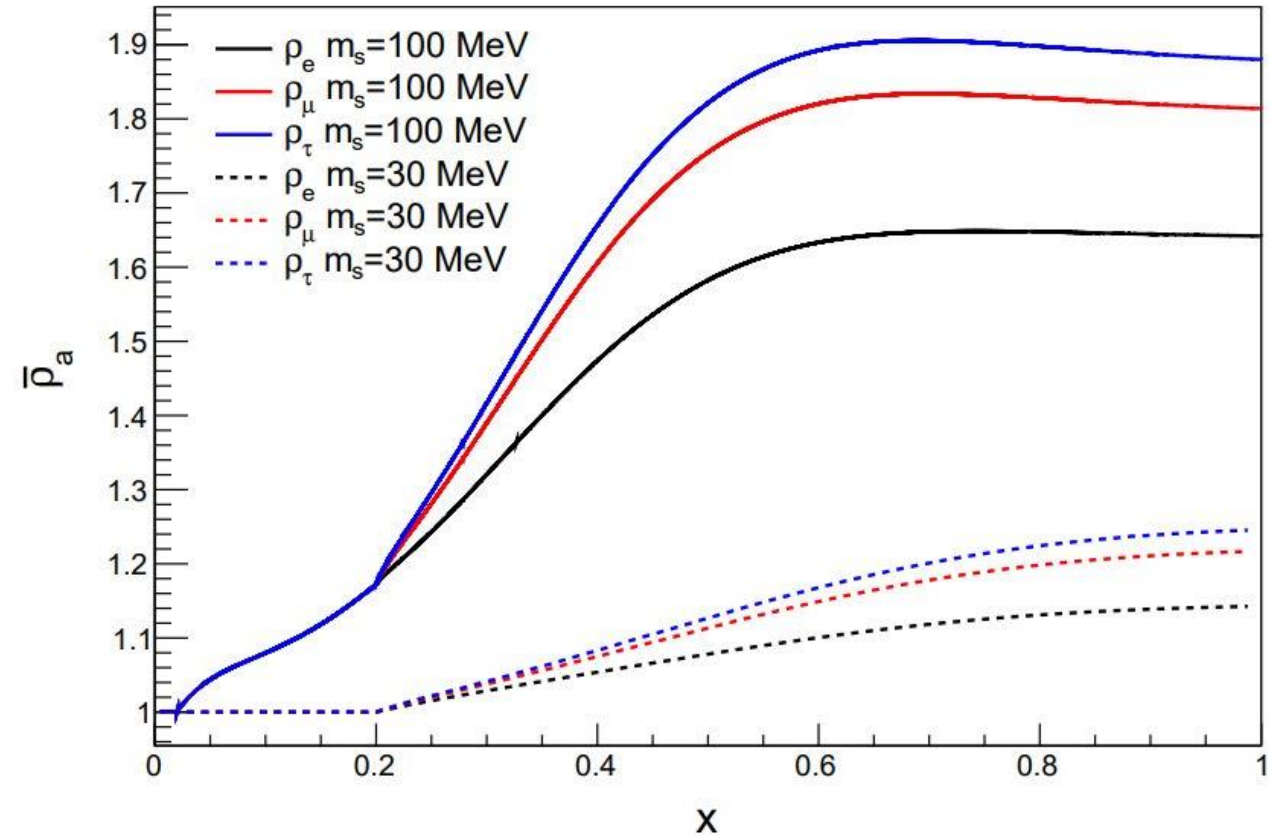
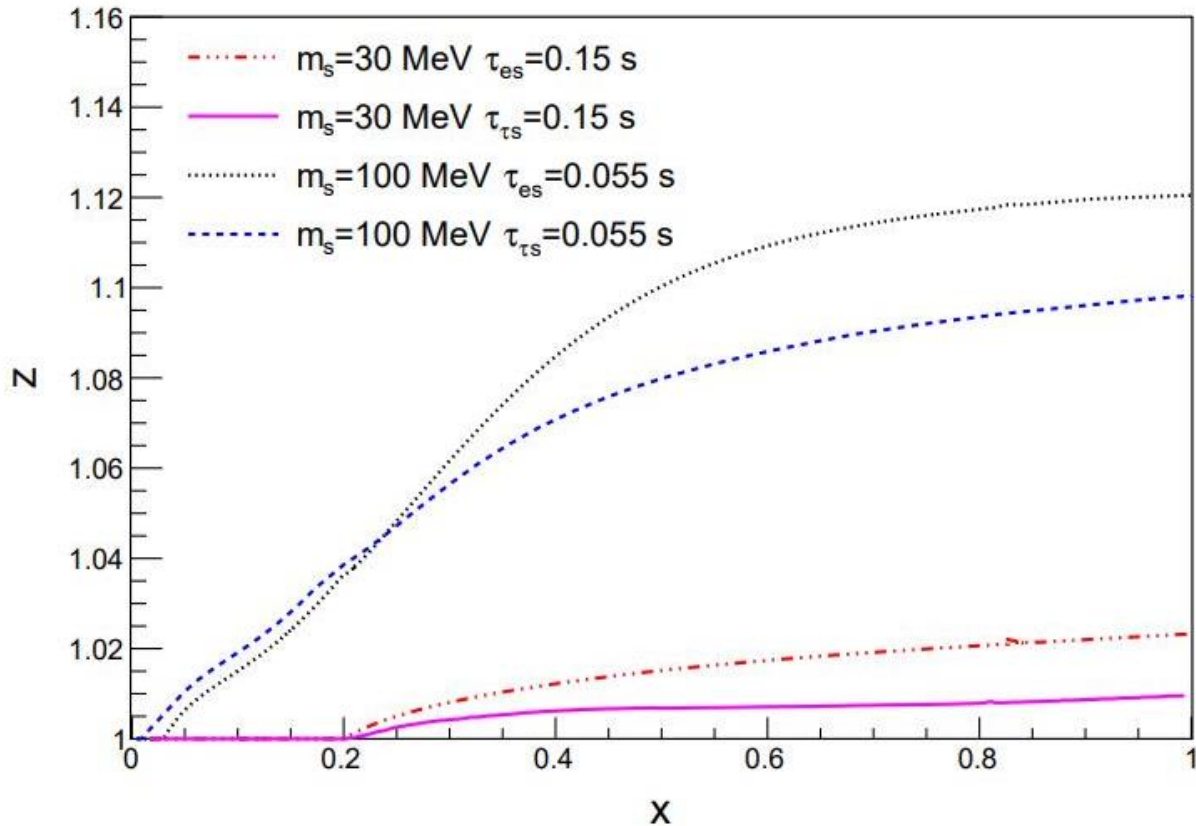
- Sterile neutrino decoupled (active-EM in equilibrium);
- Sterile neutrino and active neutrino decoupled (at x_d).

Decoupling condition: $\Gamma = \int d^3\widehat{p}_1 I = H$

m_s [MeV]	$\sin^2 \theta_{\tau 4}$	τ [s]	T_D^n [MeV]
20.0	2.6×10^{-2}	3.0×10^{-1}	4.35
40.0	2.8×10^{-3}	8.8×10^{-2}	9.24
60.0	5.5×10^{-4}	6.0×10^{-2}	16.83
80.0	1.5×10^{-4}	5.0×10^{-2}	26.53
100.0	5.8×10^{-5}	4.4×10^{-2}	37.10
130.0	1.6×10^{-5}	4.2×10^{-2}	59.13

COMPUTATIONAL SCHEME

- Sterile neutrino distribution evolves from $\min(150 \text{ MeV}, 2m_s)$;
- Temperature starts to evolve from the sterile neutrino decoupling;
- At $x_d = 0.2$ active neutrino decouples and we track the distortion in the active neutrino spectrum.



IMPACT ON N_{eff}

- Heavy ν_s affect N_{eff} due to active spectral distortion

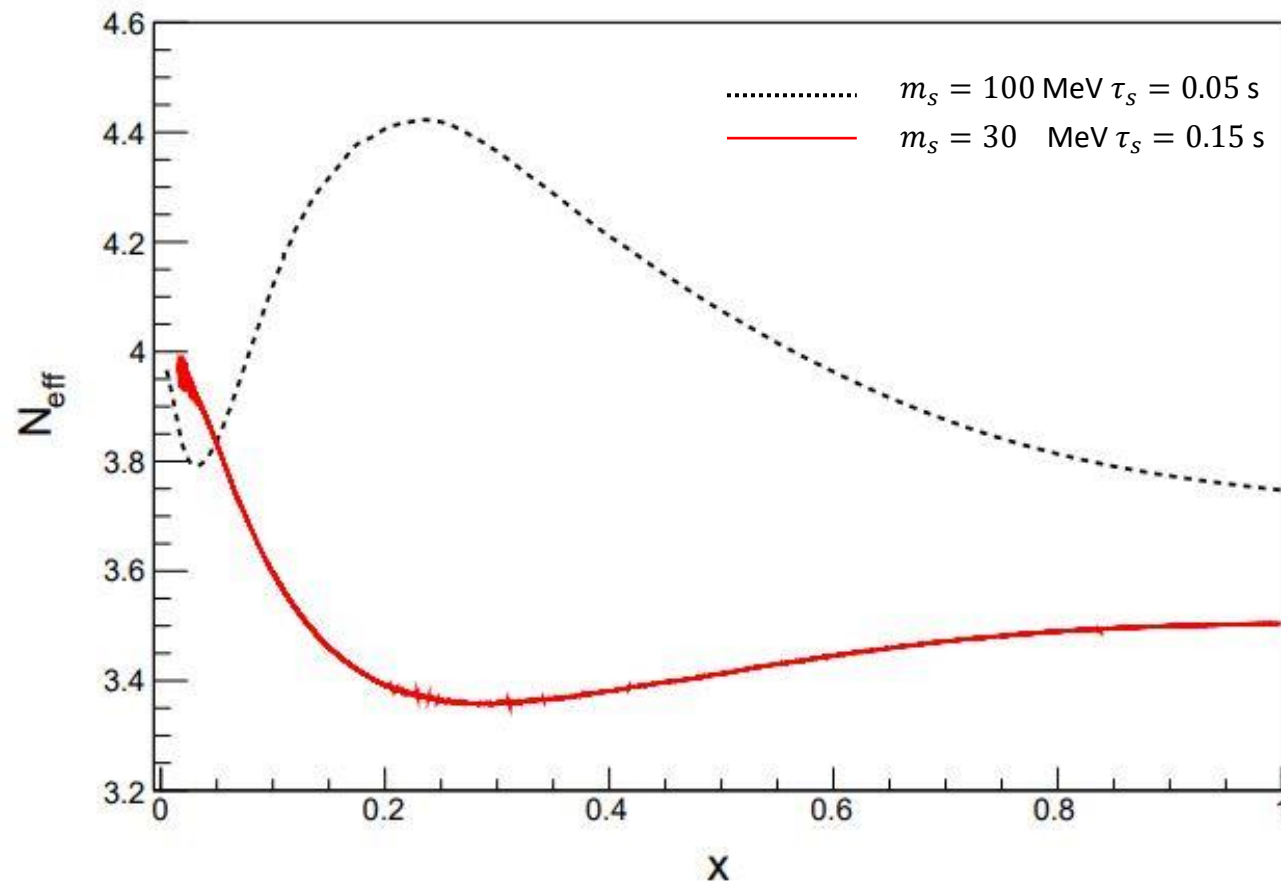
$$N_{eff} = \left(\frac{z_0}{z}\right)^4 \left(3 + \sum_{\alpha=e}^{\tau} \frac{\Delta\rho_{\nu\alpha}}{\rho_{\nu_0}} + \frac{\rho_{\nu_s}}{\rho_{\nu_0}} \right)$$

$$z_0 = 1.40$$

- $N_{eff} = 4$ at the beginning. At the end it tends to a constant value.
- The difference for the two masses is due to the early decouple for the heavier ν_s



Boltzmann suppression only at the beginning



IMPACT ON Y_p

Massive sterile neutrinos affect the Y_p value linked to the primordial ^4He mass fraction.

Born estimate calculation, rescaling it to correct the systematic errors :

$$Y_p = Y_{p,SM}^{prec} \frac{Y_{p,\nu_s}^{Born}}{Y_{p,SM}^{Born}}$$

$$Y_p = 2X_n e^{-\frac{180}{\tau_n}} \quad X_n = \frac{n_n}{n_n + n_p}$$

$$\frac{dX_n}{dx} = \frac{\omega_B(p \rightarrow n)(1 - X_n) - \omega_b(n \rightarrow p)X_n}{xH}$$

The value of Y_p is affected by ν_s in two ways:

- I. Spectral neutrino distortions;
- II. Hubble parameter changes.

COMPARISON WITH COSMOLOGICAL OBSERVATION

Planck results: $N_{eff} = 2.99 \pm 0.17$ and $Y_p = 0.245 \pm 0.003$ [*Aghanimet al, arXiv:1807.06209*]

Sterile neutrinos affect N_{eff} and Y_p that are both relevant for CMB. We used a likelihood analysis

$$\chi_{CMB}^2 = (\Theta - \Theta_{obs}) \Sigma_{CMB}^{-1} (\Theta - \Theta_{obs})^T$$

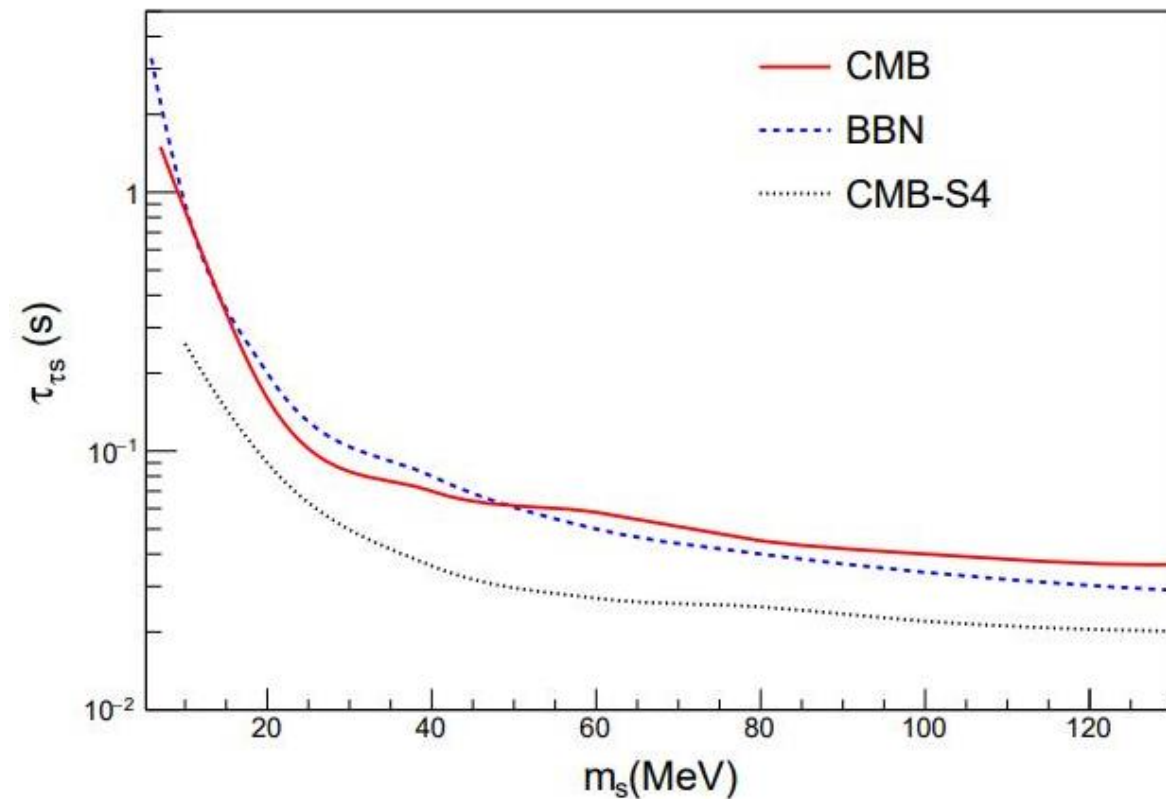
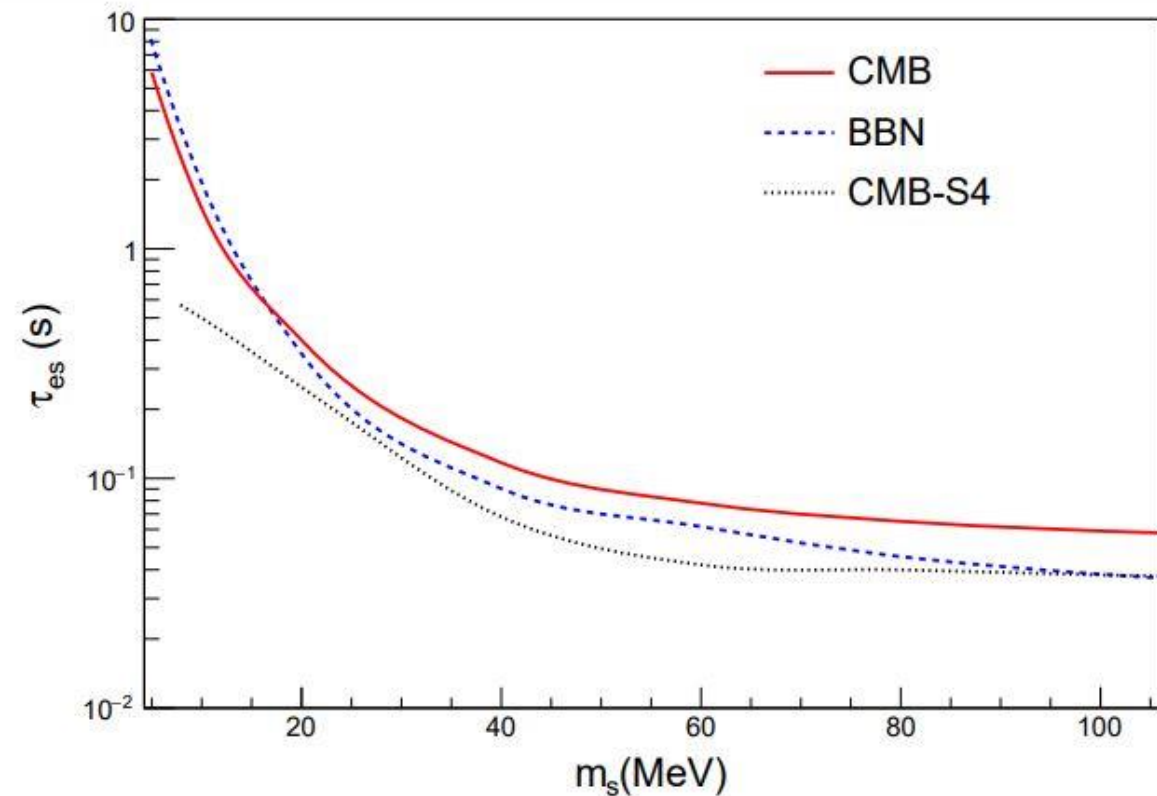
$$\Theta = (N_{eff}, Y_p) \quad \Theta_{obs} (2.97, 0.246)$$

$$\Sigma_{CMB} = \begin{pmatrix} \sigma_1^2 & \sigma_1 \sigma_2 \rho \\ \sigma_1 \sigma_2 \rho & \sigma_2^2 \end{pmatrix}$$

$$\sigma_1 = 0.2650 \quad \sigma_2 = 0.0177 \quad \rho = -0.845$$

Considered a value of $\chi^2 = 6.18$ corresponding to 95.45% CL.

CMB and Y_p CONSTRAINTS



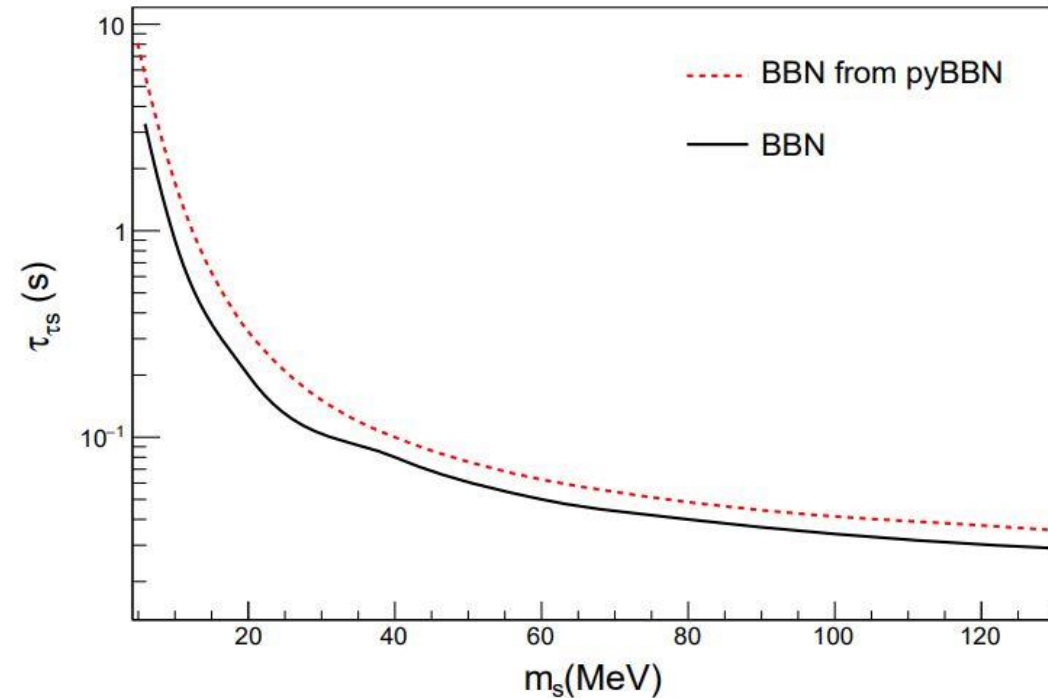
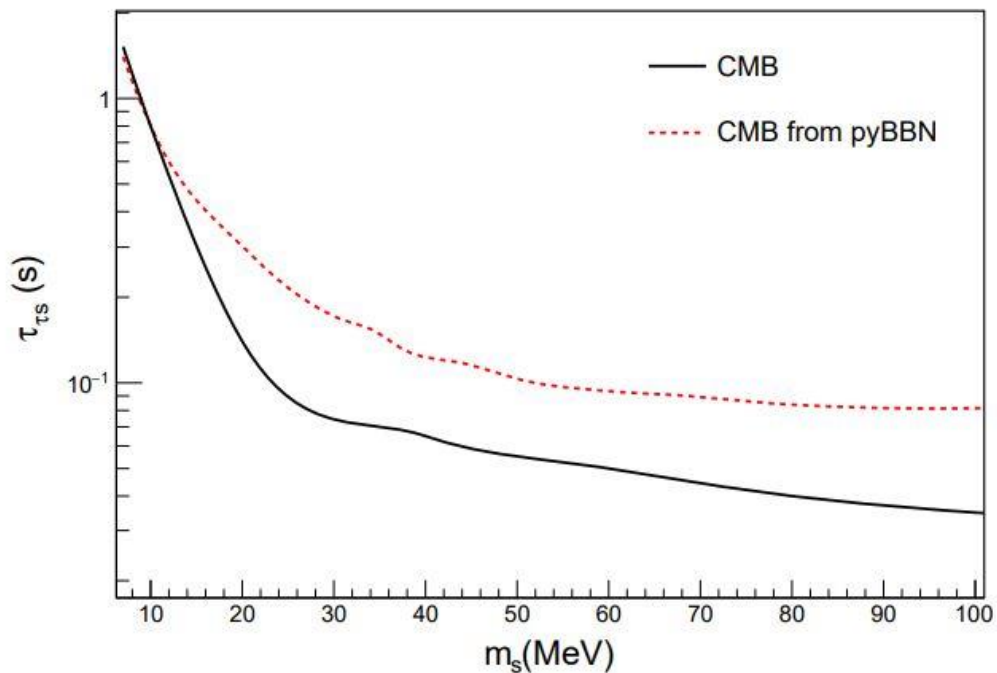
Bounds in the plane (m_s, τ_s) obtained from CMB (red curve) and BBN- Y_p (blue curve), as well as forecast sensitivity of CMB-S4 (black curve), for a sterile neutrino mixed with ν_τ (or ν_μ) and ν_e . The 2σ excluded region is the one above the curves.

For the CMB-S4, the expected sensitivity is $\sigma_1 = 0.062$ and $\sigma_2 = 0.0053$

[Baumann et al, arXiv:1508.06342]

COMPARISON WITH PREVIOUS BOUND

- The main improvement is obtained for the CMB. Smaller differences in the case of BBN.



Comparison of results from the CMB and BBN constraints for the decay time of ν_s mixed only with active tauonic (or muonic) neutrino in [\[Nashwan et al, arXiv:2006.07387\]](#) and the one from our code.

CONCLUSIONS

- We analyzed the phenomenology of sterile neutrino with $m_s < 135$ MeV present in the Early Universe at the time of BBN
- We study sterile neutrino and temperature evolution.
- Using the constrain on Y_p and N_{eff} we have improved the bounds on the sterile parameters $(m_s, \sin^2 \theta)$
- Finally, we have shown that the CMB-S4 will lead to constraints stronger or equal to that of the BBN.

Thanks for the attention

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