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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

OUTLINE

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

WORK'S AIMS

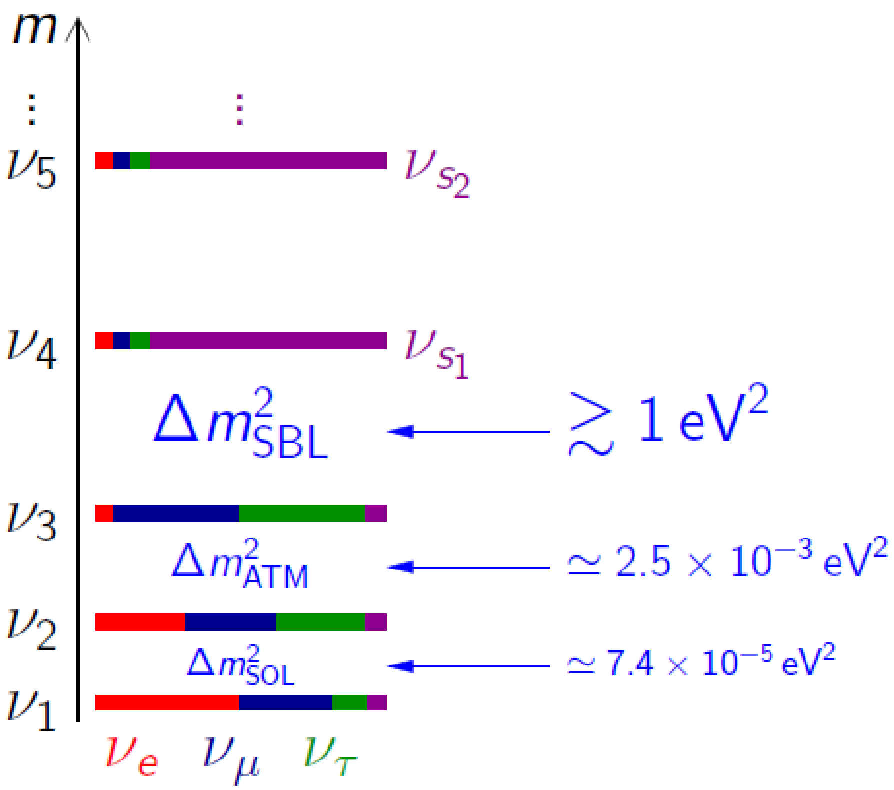
- In this work we focused on obtaining:
  - a precise calculation of the sterile neutrino evolution in the Early Universe;
  - bounds on the sterile neutrino parameters from the BBN and CMB measurement.
- The existence of sterile neutrino emerges naturally in extensions of the Standard Model, like νMSM.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

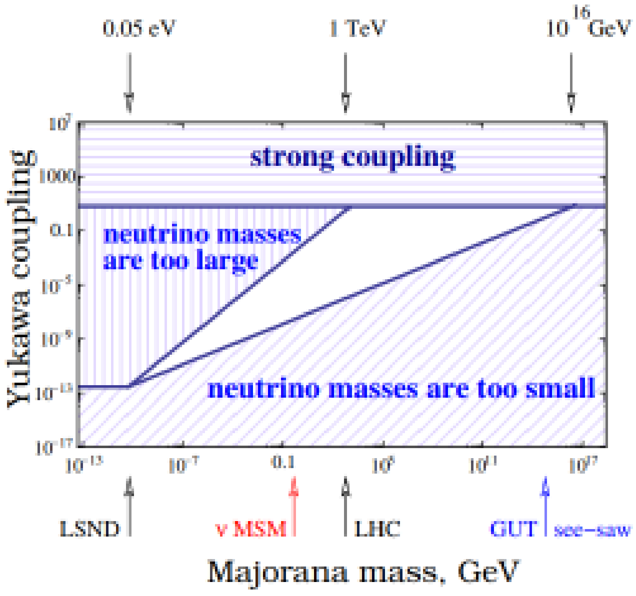
↓

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^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} 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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} .$$

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

$$x = m_0 a(t) \qquad y = m_0 p$$

$$\partial_x f = \frac{I}{xH}$$

- Already studied in:
  - Dolgov et al, ArXiv:*hep-ph/*0002223 → analytical treatment
  - Ruchayskiy and Ivashko, ArXiv:1202.2841
  - Nashwan et al, ArXiv:2006.07387

  (Ruchayskiy and Ivashko; Nashwan et al) } Numerical treatment focused on Y_p

COLLISIONAL INTEGRAL

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

$|M|^2$ 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:

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

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

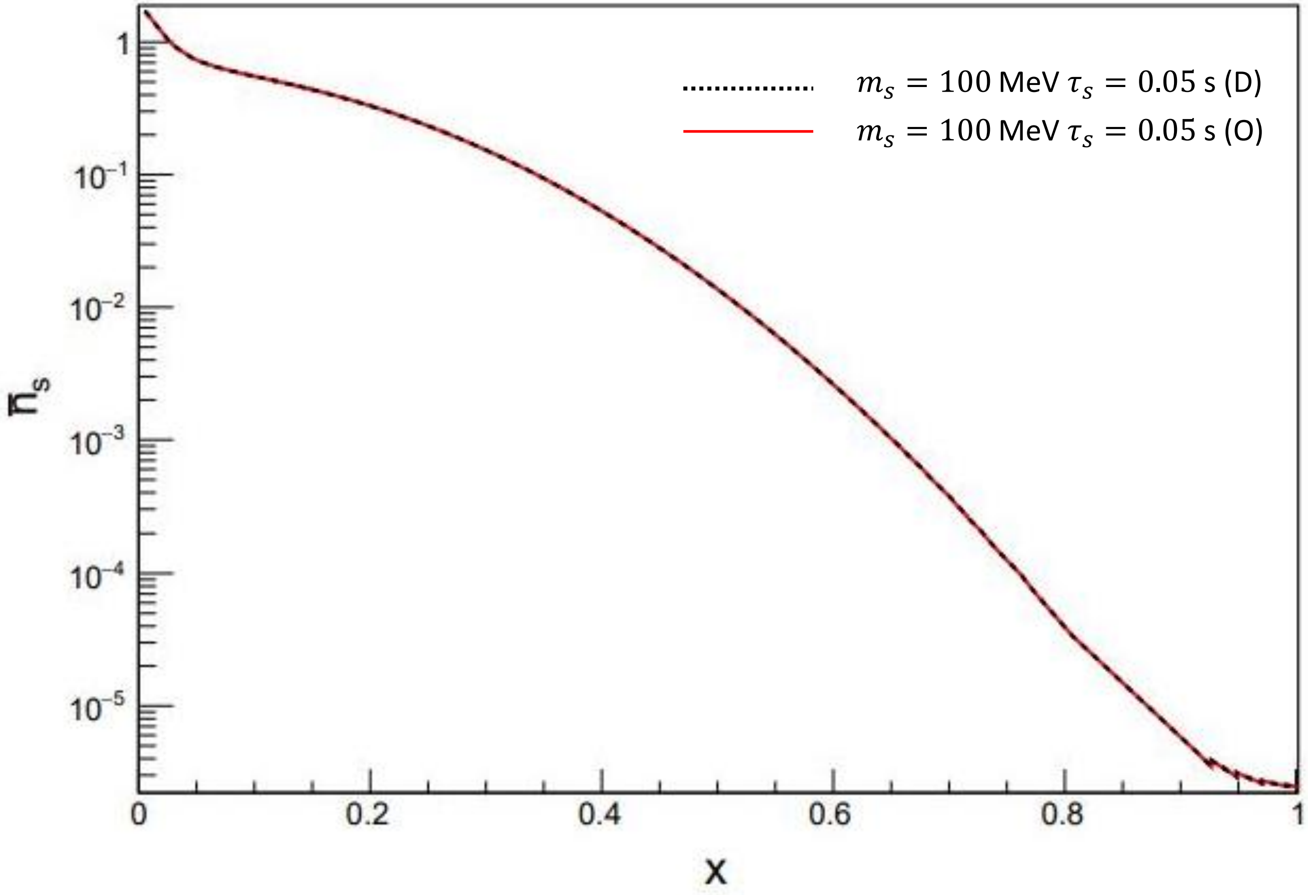
STERILE NEUTRINO PROCESSES

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

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

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

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

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

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

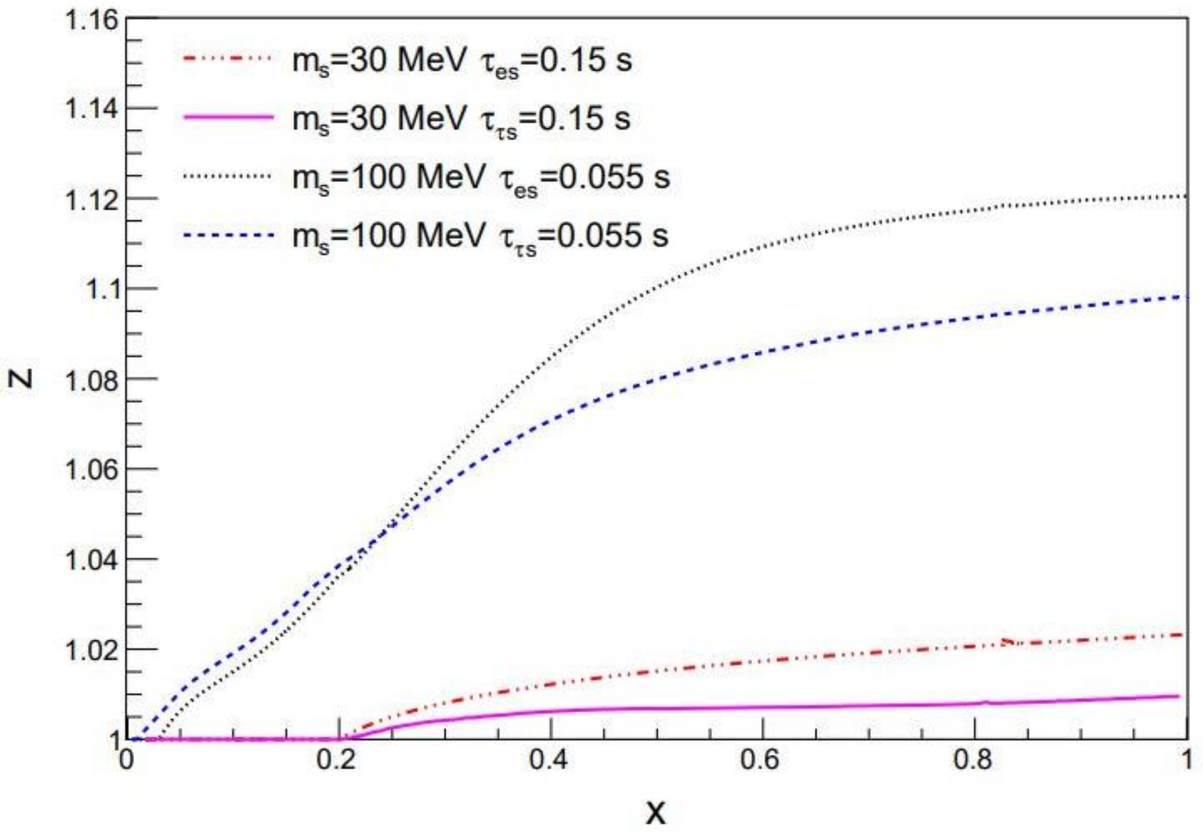
- Sterile neutrino decoupled (active-EM in equilibrium);
- Sterile neutrino and active neutrino decoupled (at x_d).

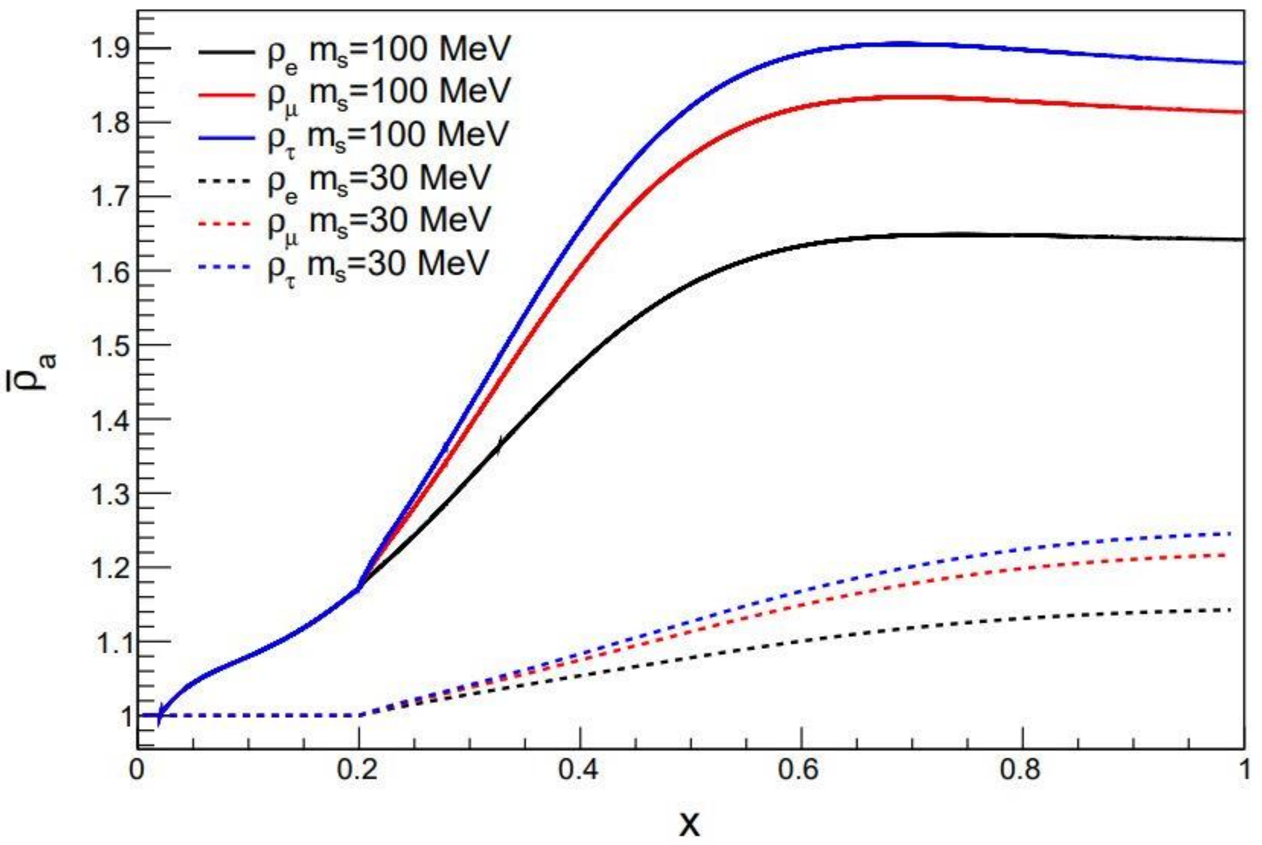
Decoupling condition: $\Gamma = \int d^3\widehat{p_1}I = H$

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

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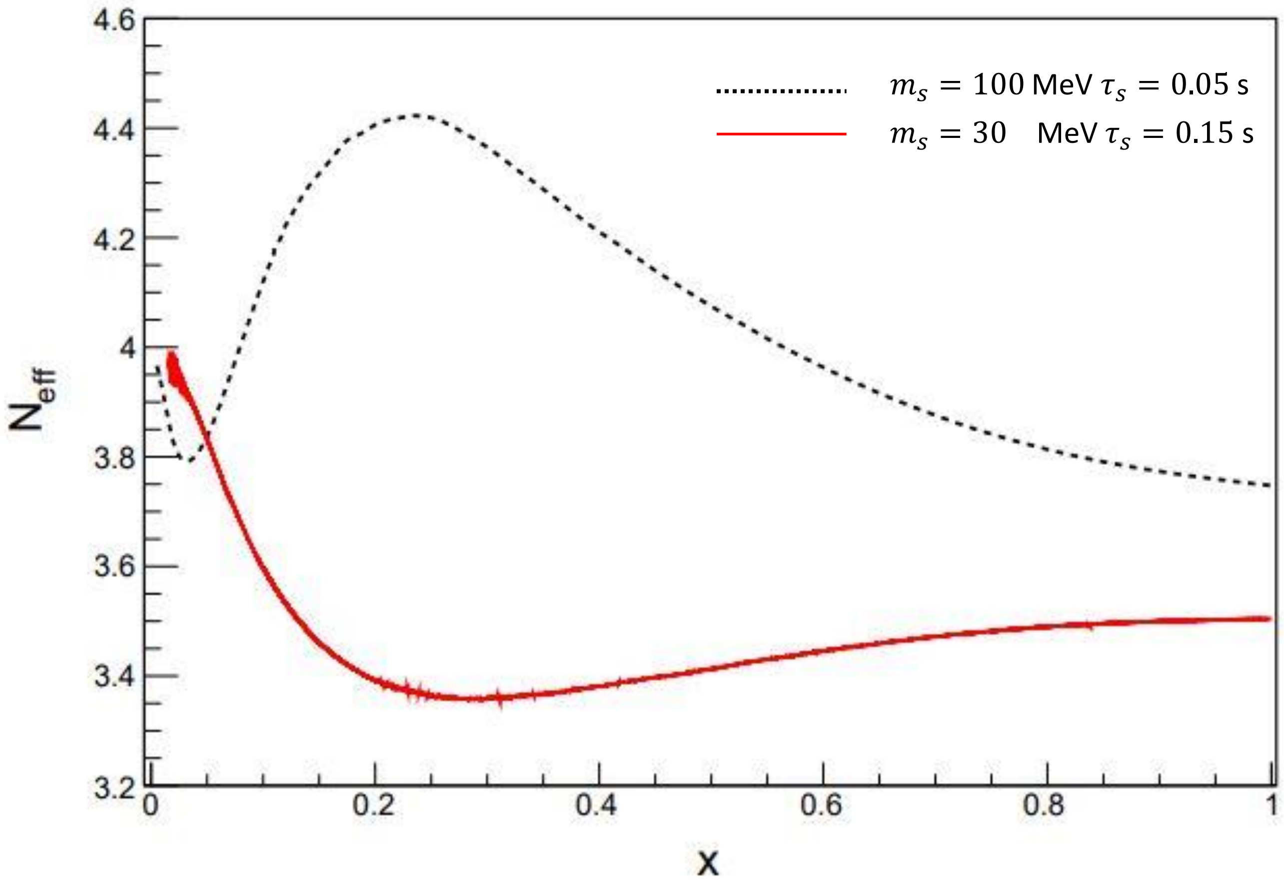
Boltzmann suppression only at the beginning



IMPACT ON Y_p

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

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

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

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

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

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 likehood analysis

$$\chi^2_{CMB} = (\Theta - \Theta_{obs})\Sigma^{-1}_{CMB}(\Theta - \Theta_{obs})^T$$

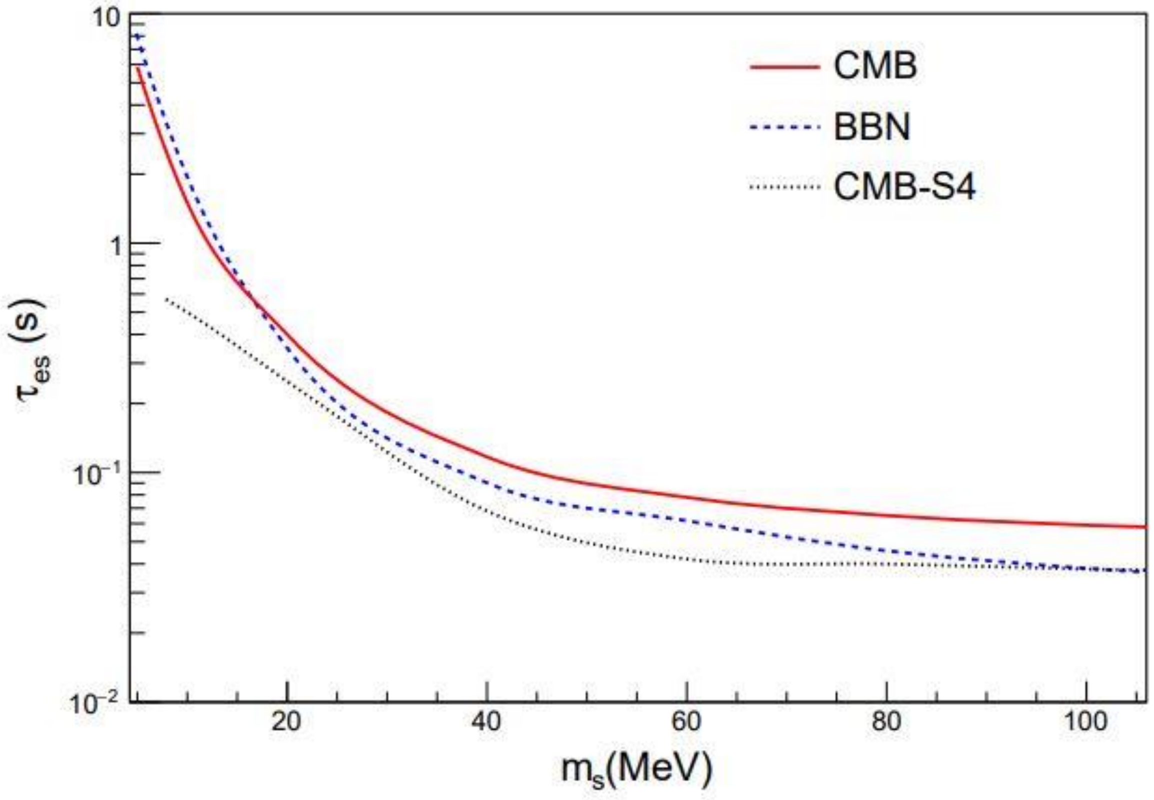
$$\Theta = \left(N_{eff}, Y_p\right) \qquad \Theta_{obs}(2.97, 0.246)$$

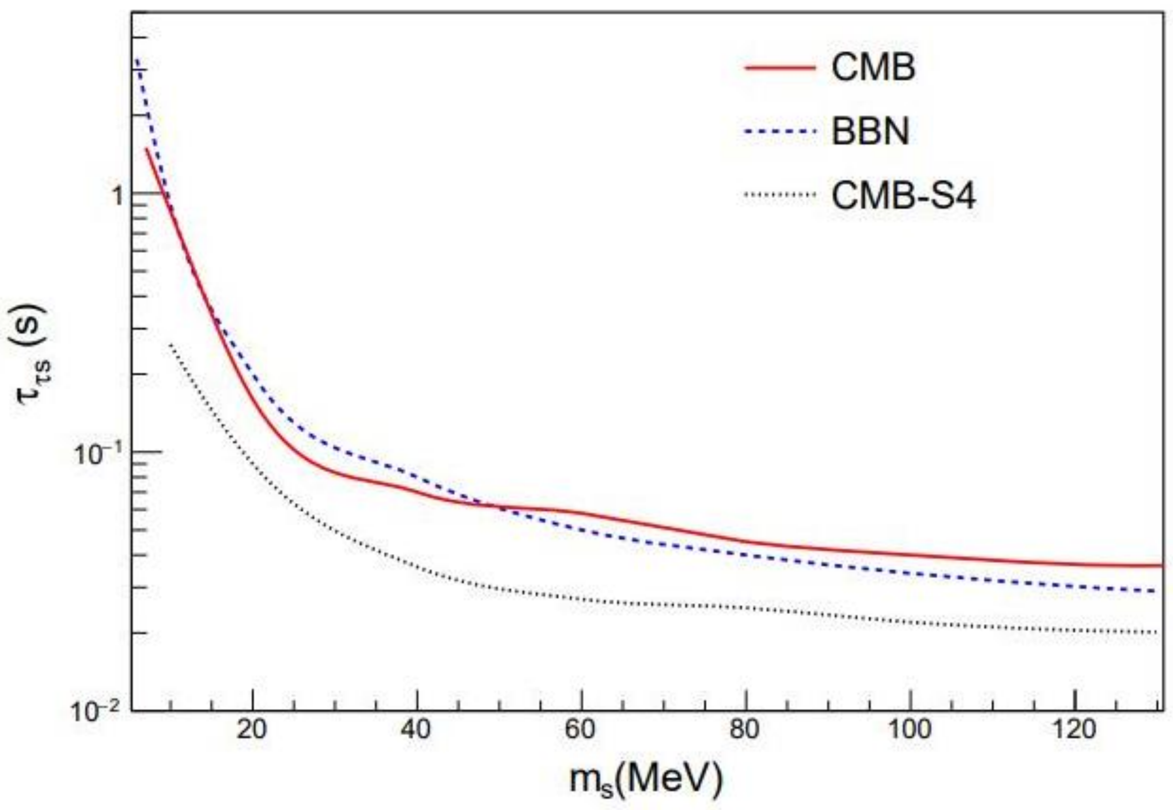
$$\Sigma_{CMB} = \begin{pmatrix} \sigma_1^2 & \sigma_1\sigma_2\rho \\ \sigma_1\sigma_2\rho & \sigma_2^2 \end{pmatrix}$$

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

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

CMB and Y_p CONSTRAINTS



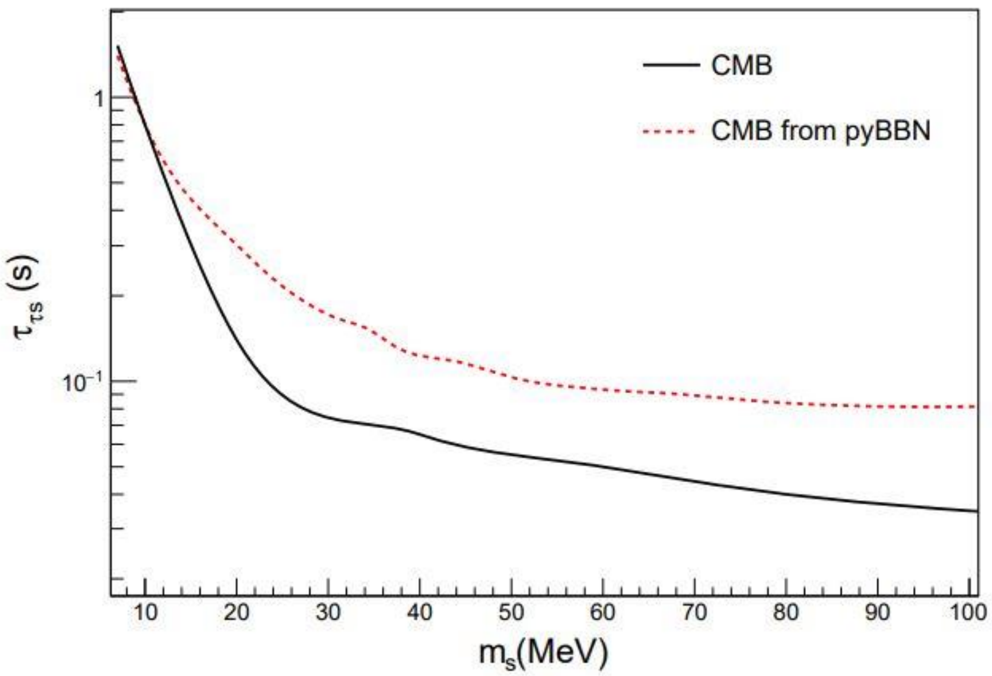


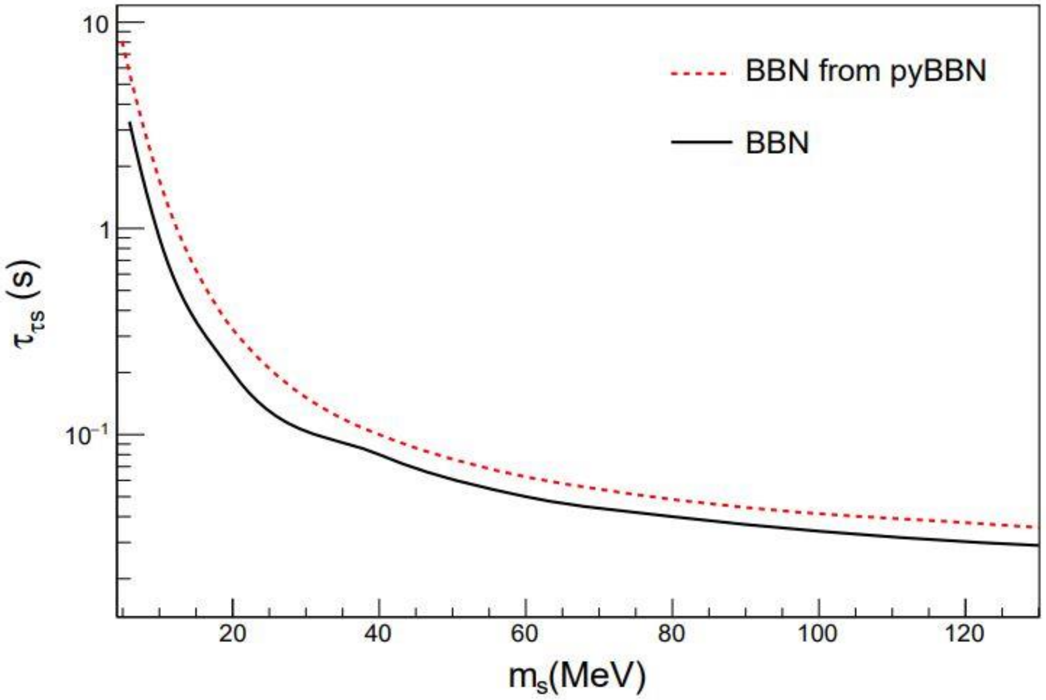
Bounds in the plane $(m_s,\ \tau_s)$ obtained from CMB (red curve) and BBN-Yp (blue curve), as well as forecast sensitivity of CMB-S4 (black curve), for a sterile neutrino mixed with ν_τ (or ν_μ) and ν_e. The 2σ excluded region is the one above the curves.

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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