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Neutrinos in cosmology after Planck data

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Summary. — The Early Universe represents an important environment to test the neutrino proprieties. Indeed Big Bang Nucleosynthesis (BBN), baryogenesis, Cosmic Microwave Background (CMB) radiation, Large Scale Structure formation (LSS) could be essentially influenced by the presence of neutrinos, in particular by their number and their mass. In recent years a renewed attention has been devoted to low-mass sterile neutrinos ($m \sim 1\,\text{eV}$), after intriguing but controversial hints coming from precision cosmological measurements and laboratory oscillation experiments. Given the doubtful situation, is necessary to study the physical conditions under which the sterile production occurs and to investigate the consequences on the cosmological observables.

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PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `98.80-k` – Cosmology.

1. – Neutrinos in the Early Universe

For much of its history, the Early Universe has been in thermal equilibrium to a good approximation. Considering a fluid composed by different particles, the equilibrium is established by interactions processes such as scatterings, which redistribute particle momenta and are crucial to reach *kinetic equilibrium*, and interactions where the number of particles of a given species is not conserved, such as pair annihilations, which keep the *chemical equilibrium* among different species.

In the Early Universe the three flavour active left-handed neutrinos ν_α, $\alpha = e, \mu, \tau$, and their antiparticles, are thermally excited in the primeval plasma of particles, being in thermal equilibrium with charged leptons, baryons and photons by weak interactions. In this regime the neutrino distribution is the Fermi-Dirac one, with a negligible contribution of their mass to the energy:

$$f_{\nu_\alpha}(p) = \frac{1}{e^{\left(\frac{p}{T}-\xi_\alpha\right)}+1}, \quad f_{\overline{\nu}_\alpha}(p) = \frac{1}{e^{\left(\frac{p}{T}+\xi_\alpha\right)}+1}, \tag{1}$$

where p is the physical momentum and $T = T_\nu = T_\gamma$.

Due the expansion of the Universe, the temperature decreases and the neutrino interaction rate decreases faster than the Hubble rate.

When $\Gamma_\nu(T) < H(T)$ occurs, the weak rates are then inefficient to keep neutrinos in equilibrium: the neutrino species decouple from the electromagnetic plasma. After the decoupling, neutrinos freely propagate becoming transparent to the Universe forming the *Cosmic Neutrino Backgorund* (CNB). They represent an hot relic, in the sense that they decouple when they are relativistic particles. In this way their FD distribution remains unchanged except for the effect of redshift of the physical momentum. In particular, the distribution in terms of physical momenta is entirely specified by a temperature parameter which scales as $T_{\nu,d}a_d/a$, with a_d the scale factor at the decoupling. Concerning the temperature of the photons T_γ, it simply scales as a^{-1} as long as electron/positron pairs are relativistic. When the temperature drops below the electron mass m_e, the electron and positrons annihilate heating the photons. Assuming the neutrinos undisturbed by pair annihilations (except for a small fraction due to the non-instantaneous decoupling but not taken into account here), the neutrino to photon temperature ratio assumes the value

$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3}. \tag{2}$$

Today, the number density of cosmic neutrinos for each flavour is $n_\nu = 56\,\mathrm{cm}^{-3}$. Even if they are not detected yet, they are well established by cosmological observables at different epochs, contributing to radiation at early times and to matter at later times. In particular the Big Bang Nucleosythesis, which starts at temperature very close to the neutrino decoupling one, is sensitive to the flavours of neutrinos and to the *effective number of neutrino species* N_{eff}. Instead the later cosmological probes, the CMB and the LSS are sensitive to the masses of the neutrinos and to N_{eff}.

After the e^+-e^- annihilation, for temperature $T < m_e$, the remaining relativistic degrees of freedom are photons, the three light neutrinos and other particles if they exist. The non-elctromagnetic energy density of the universe is then expressed in terms of the *effective number of neutrino species* N_{eff}:

$$\epsilon_R = \epsilon_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right) = \epsilon_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} (N_{\mathrm{eff}}^{\mathrm{SM}} + \Delta N)\right) \tag{3}$$

The Standard Model expectation (plus active neutrino oscillations) for this parameter is $N_{\mathrm{eff}}^{\mathrm{SM}} = 3.046$ [1], where the slightly excess with respect to 3 is to due to the non-instantaneous neutrino decoupling thanks to which neutrinos share a small part of the entropy release after the e^+-e^- annihilation.

Concerning the extra radiation, it may be accounted for by different particles, such as sterile neutrinos totally or partially thermalised, axions and axion-like particles, hidden sector photons, majorons, or even gravitons. Among them, in our study, we consider the presence of light sterile neutrinos ($\Delta m_s^2 \leq 1\,\mathrm{eV}^2$) oscillating with the active ones.

1·1. *Big bang nucleosynthesis*. – Big Bang Nucleosynthesis (BBN) is the epoch of the Early Universe when the primordial abundances of light elements were produced, in particular ^{2}H, ^{3}He, ^{4}He and ^{7}Li. Predictions of the abundances of the light elements, based on weak and nuclear processes at the MeV scale or lower, are in good overall agreement with those inferred from observational data, though the latter are still affected by systematics. Soon after neutrinos decouple, charged-current weak neutron-proton interconversions also become too slow to guarantee the *n*-*p* chemical equilibrium. For temperatures below $T_d \sim 0.7\,\mathrm{MeV}$, the n/p density ratio departs from its equilibrium value and freezes out at the asymptotic value

$$\frac{n_n}{n_p} = \frac{n}{p} = e^{-\frac{\Delta m}{T_d}} \sim \frac{1}{6} \tag{4}$$

with $\Delta m = 1.29\,\mathrm{MeV}$ the neutron-proton mass difference. The n/p ration is very important since it fixes the primordial yields, especially the helium abundance characterised by the "helium mass fraction" $Y_P = (2n/p)/(1+n/p)$.

Cosmological neutrinos influence the production of the primordial light elements in two ways:

– First, ν_e and $\overline{\nu}_e$ directly participate in the charged current weak interactions which rule the neutron/proton chemical equilibrium. Any change in the neutrino momentum distributions can shift the n/p ratio freeze out temperature and then modify the primordial abundances.

– Cosmological neutrinos of each flavor contribute to the radiation energy density that governs the expansion rate of the Universe before and during BBN epoch. Changing the expansion rate alters the n/p ratio at the onset of BBN and hence the light element abundances.

1˙2. *Extra species: impact on the cosmological observations and corresponding constraints.* – Cosmological measurements represent a powerful tool to probe the number of relativistic degrees of freedom N_{eff}. Indeed, the primordial nucleosynthesis and the spectra of both CMB anisotropies and matter fluctuations can provide strong constrains on the radiation content ϵ_R and therefore on N_{eff} and also on the mass of neutrinos.

– *Impact on BBN*

Focusing on the sterile neutrinos, if these additional states are produced before the active-neutrino decoupling, they could acquire quasi-thermal distributions (depending of their temperature) and behave as extra degrees of freedom at the time of primordial nucleosynthesis. This would anticipate weak interaction decoupling leading to a larger neutron-to-proton ratio, eventually resulting into a larger ^{4}He fraction, as is shown in fig. 1. Given the impact of extra radiation on the abundance of the primordial light nuclei, we can obtain from them robust constraints on N_{eff}. In according to several and independent works, one extra thermalised sterile neutrino specie is marginally allowed, while two extra degrees of freedom are completely excluded [2, 3].

– *Impact on CMB and LSS*

Unlike BBN, both the later time observables, CMB anisotropies and LSS distributions, are not sensitive to the flavor content of the neutrino sector, but only to N_{eff} and to the mass of the neutrino species.

If additional degrees of freedom are still relativistic at the time of CMB formation, they impact the CMB anisotropies spectrum at both large and small scales, and so it is possible to obtain important information on N_{eff} especially if the CMB data

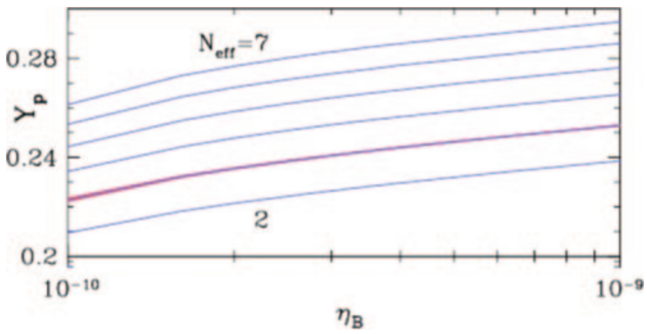

Fig. 1. – Predicted "Helium mass fraction" Y_P as a function of the baryon density η_B for different values of $N_{\rm eff}$. Modified plot from [4].

are combined with other cosmological probes. One of the main effect of increasing the radiation density, is the delay of the epoch of matter-radiation equality, with consequences on the width of the first peak and also on the peaks locations. Concerning the power spectrum of the structure formation, it is suppressed at small scale in presence of massive neutrinos, since they do not clusterize on these scales (see fig. 2).

For a long time the WMAP experiment has provided the best constraints on the CMB temperature spectrum for ($l < 1000$), complemented by smaller angular scale ($l > 1000$) observations performed by ACT and SPT experiments. In the last few years a possible cosmological hint of extra radiation was found by combing the CMB data with other experiments. This hint has stimulated a long series of investigations on the possible existence of exotic particles, in particular sterile neutrinos. A recent and important contribution in constraining the extra radiation and neutrino mass is represented by the first data release of the Planck collaboration, a satellite experiment with unprecedented sensitivity in the high multipole range. The Planck results prefer a value $N_{\rm eff} = 3.30 \pm 0.27$ at 68% CL compatible with the standard expectation [6]. Very interesting are also the joint constraints at 95% CL of $N_{\rm eff} \leq 3.80$ and the effective mass of sterile neutrinos $m_s^{\rm eff} \leq 0.42\,{\rm eV}$, namely the physical mass weighed by the sterile abundance. We will refer to these values in our analysis.

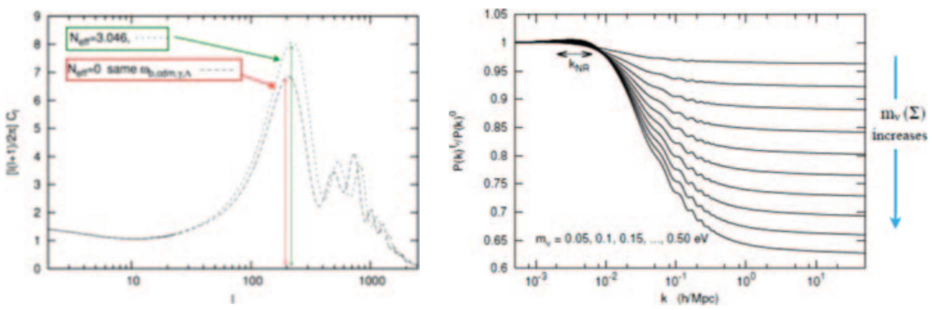

Fig. 2. – Left plot: CMB anisotropies spectrum for different values of $N_{\rm eff}$. Right plot: matter power spectrum in the presence of massive neutrinos. Plots modified by [5].

2. – Light sterile neutrinos and cosmology

Even if the 3ν standard scenario explains with success most the results coming from neutrino oscillation experiments, there are some data, called *anomaly*, that cannot be explained in this framework. If interpreted as oscillation signals, they point towards the possible existence of 1 or more sterile neutrinos with mass square difference $\Delta m^2 \sim O(1\,\mathrm{eV}^2)$. Many analyses have been performed to explain the anomalies and scenarios with one ("3 + 1") or two ("3 + 2") sterile neutrinos have been suggested in order to fit different data [7, 8]. It is commonly assumed that sterile neutrinos are produced in the primordial plasma via mixing with the active neutrinos and in presence of collisions. In order to evaluate their abundance, is necessary to solve the kinetic equations for the flavour evolution of an active-sterile system.

2˙1. *Flavour evolution for the active-sterile system.* – A proper characterization of the evolution of a neutrino ensemble, simultaneously mixing and scattering in the Early Universe, requires the use of the density matrix formalism. According to it, the neutrino (antineutrino) ensemble for the scenario $(3 + 1)$ is expressed in terms of 4×4 density matrices $\varrho(\bar{\varrho})$:

$$\rho(p) = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} & \rho_{es} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} & \rho_{\mu s} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} & \rho_{\tau s} \\ \rho_{se} & \rho_{s\mu} & \rho_{s\tau} & \rho_{ss} \end{pmatrix}. \tag{5}$$

The evolution equation for the ρ is the following:

$$\mathrm{i}\frac{\mathrm{d}\rho}{\mathrm{d}t} = [\Omega, \rho] + C[\rho], \tag{6}$$

and a similar expression holds for the antineutrino matrix $\bar{\rho}$. The first term on the right side of the eq. (6) describes the flavour conversions, where we identify different contributions:

$$\Omega = \frac{\mathsf{M}^2}{2}\frac{1}{p} + \sqrt{2}\,G_\mathrm{F}\left[-\frac{8p}{3}\left(\frac{\mathsf{E}_\ell}{m_\mathrm{W}^2} + \frac{\mathsf{E}_\nu}{m_\mathrm{Z}^2}\right)\right]. \tag{7}$$

$\mathsf{M}^2 = \mathcal{U}^\dagger \mathcal{M}^2 \mathcal{U}$ denotes the mass matrix, while the terms proportional to the Fermi constant G_F represent the matter effects. In particular, the term E_ℓ is linked to the energy density of the pairs $e^\pm$, instead E_ν to the energy density of ν e $\bar{\nu}$. The last term of the right side of eq. (6) is the collisional one which takes into account the processes proportional to G_F^2.

2˙2. *Cosmological constraints for sterile neutrinos.* – Motivated by the recent data release of the Planck experiment for the radiation content N_eff and for the neutrino mass bound, we performed an extensive scan of the sterile neutrino parameter space in a $3+1$ model, with sterile mass splitting Δm^2_st in the range $(10^{-5}$–$10^2)\,\mathrm{eV}^2$ and considering, for the first time, the possibility of two non-vanishing active-sterile mixing angles. In our study we fix the values of the three active mixing angles to the current best-fit from global analysis of the different active neutrino oscillation data [9], $\sin^2\theta_{12} = 0.307$,

$\sin^2\theta_{23} = 0.398$, and $\sin^2\theta_{13} = 0.0245$. Concerning the active-sterile mixing angles we choose as representative range $10^{-5} \leq \sin^2\theta_{i4} \leq 10^{-1}$ $(i = 1, 2, 3)$. The 4ν mass spectrum is parameterized as $\mathcal{M}^2 = \text{diag}\left(m_1^2, m_1^2 + \Delta m_{21}^2, m_1^2 + \Delta m_{31}^2, m_1^2 + \Delta m_{41}^2\right)$. We consider a hierarchical mass spectrum, obtained setting $m_1 = 0$. This is consistent with the scenario considered by Planck, to obtain the constraint on the sterile neutrino mass.

The solar and the atmospheric mass-square differences are given by $\Delta m_{21}^2 = m_2^2 - m_1^2 = 7.54 \times 10^{-5}\,\text{eV}^2$ and $|\Delta m_{31}^2| = |m_3^2 - m_1^2| = 2.43 \times 10^{-3}\,\text{eV}^2$, respectively [9]. Moreover we consider the *normal* mass hierarchy for both the active sector (NH, $\Delta m_{31}^2 > 0$) and the sterile one (SNH, $\Delta m_{41}^2 > 0$), as in fig. 3.

In our investigation we use as benchmark the Planck joint constraints for extra radiation and mass [6]. In particular, the first quantity we are exploiting to constrain the sterile neutrino parameter space is the overall non electromagnetic radiation content, parametrized via N_{eff},

$$N_{\text{eff}} = \frac{1}{2}\text{Tr}(\rho + \bar{\rho}). \tag{8}$$

Our bounds are given comparing this number with the one measured by Planck experiment, $N_{\text{eff}} < 3.80$ at 95% CL [6]. Given the current limit on the sum of the neutrino masses, we comment that the constraints on N_{eff} are valid for sterile mass $m_4 < 0.5\,\text{eV}$ considering a fully thermalised extra neutrino species. Indeed, larger values of the sterile neutrino mass would be not relativistic anymore at the CMB decoupling and therefore we cannot use radiation constraints. However, mass bounds become very important through the neutrino contribution to the energy density in the Universe. Assuming the existence of a thermalized massive sterile neutrino together with two massless active neutrinos and a massive one with mass fixed by the atmospheric mass-splitting (*i.e.* $m \sim 0.06\,\text{eV}$), the second quantity is

$$\Omega_\nu h^2 = \frac{1}{2}\frac{\sqrt{\Delta m_{41}^2}\cdot(\rho_{ss} + \overline{\rho}_{ss})}{94.1\,\text{eV}}. \tag{9}$$

The constraint on the neutrino energy density is $\Omega_\nu h^2 \leq 0,0045$ at 95% CL, coming from the Planck+ BAO bound on the effective sterile mass $m_S^{\text{eff}} \leq 0.42\,\text{eV}$.

In fig. 4 we present our exclusion plots in the planes $(\Delta m_{41}^2, \sin^2\theta_{14})$ for different values of the other mixing angle $\sin^2\theta_{24}$. In according to the analysis for the laboratory anomalies, $\sin^2\theta_{34}$ is fixed to zero. The excluded regions from N_{eff} are those on the right or at the exterior of the black contours, while the ones from $\Omega_\nu h^2$ are above the red contours. For comparison, we also show at 95% CL the slice at $\sin^2\theta_{24} = 10^{-2}$, for

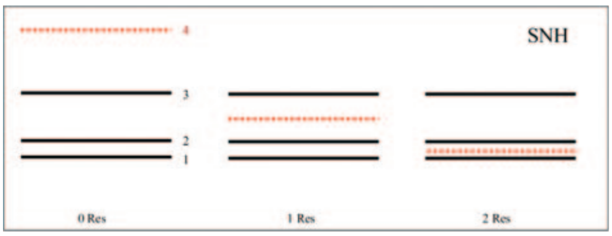

Fig. 3. – Mass hierarchy for the active and sterile sector.

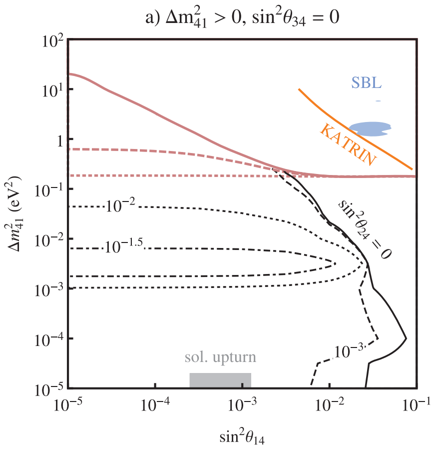

Fig. 4. – Exclusion plots for the active-sterile neutrino mixing parameter space from $N_{\rm eff}$ (black curves) and $\Omega_\nu h^2$ (red curves) at 95% CL. The contours refer to different values of $\sin^2\theta_{24}$: $\sin^2\theta_{24} = 0$ (continuous curves), $\sin^2\theta_{24} = 10^{-2}$ (dotted curves), $\sin^2\theta_{24} = 10^{-1.5}$ (dot-dashed curves).

the allowed region obtained from the global analysis of short-baseline oscillation data [7] (filled region in the up right part of the plot denoted by SBL). We observe that it is completely ruled out by the cosmological bound from $\Omega_\nu h^2$. We also plot the 90% CL expected sensitivity of the KATRIN experiment (measuring the spectrum of electrons from tritium beta decay) after 3-years of data taking [10]. Also this region would be already excluded.

Summarising, we find that the sterile neutrino parameter space is severely constrained, and the excluded area from the bound on $\Omega_\nu h^2$ covers the region accessible by current and future laboratory experiments. Moreover, from the results of our analysis we conclude that there is a tension with the sterile neutrino hints from short-baseline experiments. In particular, in the scenario we considered sterile neutrinos with $m \sim \mathcal{O}(1\,\text{eV})$ would be strongly excluded. We address the reader to our publication [11] for more details.

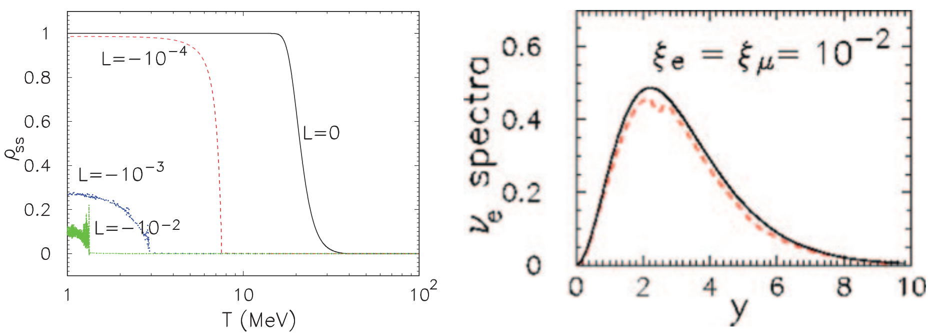

Fig. 5. – Left plot: evolution of the sterile component ρ_{ss} as a function of the temperature for different values of the primordial neutrino-antineutrino asymmetry L. Right plot: initial electrum neutrino spectrum (in black) and final one (in red) in presence of the chemical potential $\xi = 10^{-2}$.

In order to reconcile the laboratory signals in favor of extra sterile neutrino degrees of freedom with the cosmological bounds, it is necessary to suppress the sterile neutrino production. At this regards, it has been suggested by different authors to introduce a large primordial neutrino-antineutrino asymmetry term ($L \geq 10^{-2}$, or equivalently the chemical potential ξ) [12-14] in the equations for the flavor evolution. This new term, acting as a matter effect, would suppress the flavor conversions and so the sterile production, see left plot of fig. 5. However, in the presence of this large asymmetry, the flavor conversions occur at lower temperature (few MeV), around the neutrino decoupling time, leading to distortion in the active neutrino spectra and so to a non-trivial implication for the BBN [15, 16], see right plot of fig. 5.

3. – Conclusions

Light sterile neutrinos with $m \sim \mathcal{O}(1\,\text{eV})$, suggested to explain some anomalous results from neutrino oscillation experiments, are in conflict with the cosmological observations, in particular they are too heavy for the structure formation. An escape rout can be represented by the suppression of the sterile abundance, however the mechanisms proposed in the literature affect the production of the primordial abundance during the BBN epoch. The research of the sterile neutrinos is currently open from both experimental and theoretical point of view and further investigations are welcome.

* * *

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REFERENCES

[1] Mangano G., Miele G., Pastor S., Pinto T., Pisanti O. and Serpico P. D., "Relic neutrino decoupling including flavor oscillations," *Nucl. Phys. B*, **729** (2005) 221, [hep-ph/0506164].
[2] Mangano G. and Serpico P. D., "A robust upper limit on N_{eff} from BBN, circa 2011," *Phys. Lett. B*, **701** (2011) 296, [arXiv:1103.1261 [astro-ph.CO]].
[3] Cooke R., Pettini M., Jorgenson R. A., Murphy M. T. and Steidel C. C., "Precision measures of the primordial abundance of deuterium," arXiv:1308.3240 [astro-ph.CO].
[4] Cyburt R. H., Fields B. D. and Olive K. A., "Primordial nucleosynthesis with CMB inputs: Probing the early universe and light element astrophysics," *Astropart. Phys.*, **17** (2002) 87, [astro-ph/0105397].
[5] Lesgourgues J., Mangano G., Miele G. and Pastor S., *Neutrino Cosmology* (Cambridge University Press) 2013.
[6] Ade P. A. R. *et al.* [Planck Collaboration], "Planck 2013 results. XVI. Cosmological parameters," arXiv:1303.5076 [astro-ph.CO].
[7] Giunti C., Laveder M., Li Y. F., Liu Q. Y. and Long H. W., "Update of Short-Baseline Electron Neutrino and Antineutrino Disappearance," *Phys. Rev. D*, **86** (2012) 113014, [arXiv:1210.5715 [hep-ph]].
[8] Kopp J., Machado P. A. N., Maltoni M. and Schwetz T., "Sterile Neutrino Oscillations: The Global Picture," *JHEP*, **1305** (2013) 050, [arXiv:1303.3011 [hep-ph]].
[9] Fogli G. L., Lisi E., Marrone A., Montanino D., Palazzo A. and Rotunno A. M., "Global analysis of neutrino masses, mixings and phases: entering the era of leptonic CP violation searches," *Phys. Rev. D*, **86** (2012) 013012.

[10] Esmaili A. and Peres O. L. G., "KATRIN Sensitivity to Sterile Neutrino Mass in the Shadow of Lightest Neutrino Mass," *Phys. Rev. D*, **85** (2012) 117301, [arXiv:1203.2632 [hep-ph]].
[11] Mirizzi A., Mangano G., Saviano N., Borriello E., Giunti C., Miele G. and Pisanti O., *Phys. Lett. B*, **726** (2013) 8.
[12] Chu Y.-Z. and Cirelli M., *Phys. Rev. D*, **74** (2006) 085015.
[13] Hannestad S., Tamborra I. and Tram T., *JCAP*, **1207** (2012) 025.
[14] Cirelli M., Marandella G., Strumia A. and Vissani F., *Nucl. Phys. B*, **708** (2005) 215.
[15] Mirizzi A., Saviano N., Miele G. and Serpico P. D., "Light sterile neutrino production in the early universe with dynamical neutrino asymmetries," *Phys. Rev. D*, **86** (2012) 053009.
[16] Saviano N., Mirizzi A., Pisanti O., Serpico P. D., Mangano G. and Miele G., "Multi-momentum and multi-flavour active-sterile neutrino oscillations in the early universe: role of neutrino asymmetries and effects on nucleosynthesis," *Phys. Rev. D*, **87** (2013) 073006.