Calculation of primordial abundances of light nuclei including a heavy sterile neutrino

M.E. Mosquera\textsuperscript{a,b} and O. Civitarese\textsuperscript{b,1}

\textsuperscript{a}Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, (1900) La Plata, Argentina
\textsuperscript{b}Department of Physics, University of La Plata, c.c. 67 (1900), La Plata, Argentina

E-mail: mmosquera@fcaglp.unlp.edu.ar, osvaldo.civitarese@fisica.unlp.edu.ar

Received November 17, 2014
Revised July 17, 2015
Accepted July 21, 2015
Published August 19, 2015

Abstract. We include the coupling of a heavy sterile neutrino with active neutrinos in the calculation of primordial abundances of light-nuclei. We calculate neutrino distribution functions and primordial abundances, as functions depending on a renormalization of the sterile neutrino distribution function ($a$), the sterile neutrino mass ($m_s$) and the mixing angle ($\phi$). Using the observable data, we set constrains on these parameters, which have the values $a < 0.40$, $\sin^2 \phi \approx 0.12 - 0.39$ and $m_s < 70$ keV at 1$\sigma$ level, for a fixed value of the baryon to photon ratio. When the baryon to photon ratio is allowed to vary, its extracted value is in agreement with the values constrained by Planck observations and by the Wilkinson Microwave Anisotropy Probe (WMAP). It is found that the anomaly in the abundance of $^7$Li persists, in spite of the inclusion of a heavy sterile neutrino.

Keywords: big bang nucleosynthesis, neutrino properties, neutrino masses from cosmology

ArXiv ePrint: 1411.4030

\textsuperscript{1}Corresponding author.
1 Introduction

The observational data obtained by the WMAP Collaboration [1] and by Planck [2] signalled the existence of a deficit in the abundance of primordial lithium, which cannot be explained in the context of the standard Big Bang Nucleosynthesis (BBN). Several authors have studied the problem from different points of view: i) the turbulent transport in the radiative zones of stars [3]; ii) the existence of a stellar lithium depletion that depends on the mass of the star [4, 5]; iii) the nuclear physics aspects of the abundance of $^7$Li [6–8]; iv) variation of fundamental constants [9–13], among others, but the question is still open since none of these possible explanations, although plausible, provides a complete solution to the problem.

In previous works, we have analysed the effect of the inclusion of light sterile-neutrinos during the first three minutes of the Universe [14–17], to calculate primordial abundances as a function of the active-sterile mixing parameters in the two-state scheme, the 3 + 1 scheme, and in the 3 + 2 scheme. We have also analysed the case where the sterile-neutrino might have a variable normalization constant in its occupation factor [17]. The results of the calculations indicate that the value of the normalization constant should be of the order of (or smaller than) 0.65 and that the mixing angle must be zero, in order to be consistent with the observational data.

In this work, we extent our previous study [17], by considering a heavy sterile-neutrino coupled to the active ones. To perform the calculation we solve the evolution equation of an expanding Universe, including neutrino oscillations in the decay rates and including a matter potential. Using the available observational data we set limits on the sterile-neutrino sector.

This work is organized as follows. In section 2 we present the formalism and in section 3 we present and discuss the results of primordial abundances as functions of the baryon density, the sterile neutrino occupation factor, and the active-sterile mixing angle. Finally, in section 4, the conclusions are drawn.
2 Formalism

The matrix which relates neutrino mass-eigenstates and neutrino flavour-eigenstates is the unitary matrix \[ U = \begin{pmatrix} c_{12}c_{13}\cos\phi & c_{13}s_{12} & s_{13} & c_{12}c_{13}\sin\phi \\ \alpha\cos\phi & \delta & s_{23}c_{13} & \alpha\sin\phi \\ \epsilon\cos\phi & \lambda & c_{23}c_{13} & \epsilon\sin\phi \\ -\sin\phi & 0 & 0 & \cos\phi \end{pmatrix}, \]

where \( i, j = 1, 2, 3 \) denote mass eigenstates, \( s_{ij}(c_{ij}) \) stands for \( \sin\theta_{ij}(\cos\theta_{ij}) \), \( \alpha = -s_{12}c_{23} - s_{13}c_{12}s_{23} \), \( \delta = c_{23}c_{12} - s_{13}s_{12}s_{23} \), \( \epsilon = s_{23}s_{12} - s_{13}c_{12}c_{23} \), \( \lambda = -s_{23}c_{12} - s_{13}s_{12}c_{23} \), and \( \phi \) is the mixing-angle of the lowest mass-eigenstate with the sterile neutrino. The inclusion of a sterile-neutrino affects the statistical occupation factor of active neutrinos, quantities which are crucial for the determination of primordial abundances. In order to compute these new factors, one must solve the equation \( \frac{\partial f}{\partial t} - H_p \frac{\partial f}{\partial p} = -i[H_0, f] \), \( (2.1) \)

where \( f \) is the \( 4 \times 4 \) matrix of the occupation factors, \( t \) is the time, \( H \) is the expansion rate of the Universe \( (H = \mu\rho T^2) \), and \( H_0 \) is the unperturbed mass term of the neutrino Hamiltonian in the rest frame. We have assumed that at the temperature \( T_0 = 5 \text{ MeV} \) the occupation factors for all neutrinos in the usual flavour representation (namely electron-neutrino, muon-neutrino and tau-neutrino, respectively) are Fermi-Dirac distributions for massless particles with energy \( E_\nu = p \) (\( c = 1 \) everywhere). For the sterile-neutrino, being massive, we assume that its occupation factor is a Fermi-Dirac distribution with energies \( E_s = \sqrt{m_s^2 + p^2} \). The relationship between the sterile neutrino mass and the mass of the mass-eigenstates, \( m_i \), can be written as \( m_s = \sum_i m_i |U_{4i}|^2 \). This occupation factor is further renormalized by a constant factor \( a \) \((20) \) which varies between 0 and 1. The initial condition for the occupation factors in the mass-eigenstates representation is written

\[
\begin{pmatrix} f_{11} & f_{12} & f_{13} & f_{14} \\ f_{21} & f_{22} & f_{23} & f_{24} \\ f_{31} & f_{32} & f_{33} & f_{34} \\ f_{41} & f_{42} & f_{43} & f_{44} \end{pmatrix}_{T_0} = \frac{1}{1 + e^p/T_0} \begin{pmatrix} \cos\phi^2 & 0 & 0 & \cos\phi\sin\phi \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \cos\phi\sin\phi & 0 & 0 & \sin\phi^2 \end{pmatrix} + \frac{a}{1 + e^{E_s/T_0}} \begin{pmatrix} \sin\phi^2 & 0 & 0 & -\cos\phi\sin\phi \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\cos\phi\sin\phi & 0 & 0 & \cos\phi^2 \end{pmatrix}. \tag{2.2} \]

We have solved the differential equations analytically in order to obtain the distribution functions, using the previous initial condition. If we fix the value of the variable \( y = p/T \), the distribution functions are oscillating functions of the temperature, while their mean-values and amplitudes are depending on the initial condition \( a \), the mass of the sterile-neutrino and the mixing angles. If one fixes the value of the temperature, for the electron-type neutrino,
the distribution function is written as a Fermi-Dirac distribution function multiplied by an oscillating function of the energy.

We have also performed the numerical calculation of the distribution function with the inclusion of the matter potential [15]

$$V_{\text{flavour}} = \sqrt{2}G_F \left( n_e(T) - \frac{8}{3M_W^2} \rho_e(T) E_e \right) \text{diag}(1, 0, 0, 0),$$  \hspace{1cm} (2.3)

where the matter and energy densities of electrons, $n_e(T)$, and $\rho_e(T)$, are defined as

$$n_e(T) = \frac{1}{\pi^2} \int dq \frac{q^2}{e^{E_e/T} + 1}$$  \hspace{1cm} (2.4)

$$\rho_e(T) = \frac{1}{\pi^2} \int dq \frac{q^2 E_e}{e^{E_e/T} + 1}.$$  \hspace{1cm} (2.5)

We have solved the differential equations for the distribution functions

$$\left( \frac{\partial f}{\partial t} - H_p \frac{\partial f}{\partial p} \right) = -i \left[ \mathcal{H}_0 + V_{\text{mass}}^{\text{matt}}, f \right].$$  \hspace{1cm} (2.6)

numerically. In eq. (2.6) the superindex \textit{mass} indicates the potential acting in the basis of mass-eigenstates.

For completeness, we have also included a term due to collisions using the kinetic approximation [21], and once again, we have obtained the solutions numerically.

3 Results

In order to obtain the primordial abundances as functions of the active-sterile neutrino mixing parameters, we have modified the numerical code of Kawano [22, 23]. The active neutrino mixing parameters were extracted from the SNO, SK, GNO, CHOOZ, DAYA BAY and DOUBLE CHOOZ experiments [24–29]. The light-neutrino mass was fixed at the square root of the lowest squared mass difference. We have considered two different cases; (i) by fixing the baryon density at the value determined from WMAP [1], and (ii) by varying $\eta_B$.

To obtain the best value for the parameters of the sterile-neutrino sector we have performed a $\chi^2$-minimization in the corresponding parametric space. The observational data for deuterium have been extracted from refs. [30–34]. We use the data from refs. [35–40] for $^4\text{He}$ and, for $^7\text{Li}$ we have considered the data given by refs. [41–44]. Regarding the consistency of the data, we have followed the treatment of ref. [45] and increased the error in the abundance of $^4\text{He}$ by a fixed factor $\Theta_{^4\text{He}} = 1.30$, for the other cases the errors were not changed.

3.1 Results with $\eta_B$ fixed

In this section we present the results of the calculation of primordial abundances performed as a function of the different parameters: the sterile-neutrino mass, the active-sterile mixing angle and the renormalization factor. The value of the baryon density was fixed at the WMAP value [1].
Only oscillation effects

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Data & $a \pm \sigma$ & $m_4 \pm \sigma$ [MeV] & $\chi^2/(N-2)$ \\
\hline
D$^+\Delta^4$He$^+\Delta^7$Li & 0.36 ± 0.12 & 0.005$^{+0.010}_{-0.005}$ & 10.62 \\
D$^+\Delta^4$He & 0.20 ± 0.06 & 0.010 ± 0.010 & 2.26 \\
\hline
Considering $V_{\text{matt}}$ & & & \\
D$^+\Delta^4$He$^+\Delta^7$Li & 0.20 ± 0.09 & 0.000$^{+0.055}_{-0.055}$ & 10.63 \\
D$^+\Delta^4$He & 0.00$^{+0.08}_{-0.07}$ & 0.000$^{+0.070}_{-0.070}$ & 1.50 \\
\hline
Considering $V_{\text{matt}}$ and $I_{\text{coll}}$ & & & \\
D$^+\Delta^4$He$^+\Delta^7$Li & 0.18 ± 0.10 & 0.005$^{+0.055}_{-0.055}$ & 10.63 \\
D$^+\Delta^4$He & 0.00$^{+0.06}_{-0.05}$ & 0.005$^{+0.045}_{-0.045}$ & 1.60 \\
\hline
\end{tabular}
\caption{Results of the parameters $a$ and $m_4$. The mixing angle $\phi$ has been fixed at the value $\sin^2 2\phi = 0.15$ and the value of $\eta$ is fixed at the value determined by WMAP. The results corresponding to the inclusion of the interaction are shown in the inset denoted by $V_{\text{matt}}$. The results corresponding to the inclusion of the interaction with matter and the collision integral are presented in the inset denoted by $V_{\text{matt}}$ and $I_{\text{coll}}$.}
\end{table}

### 3.1.1 Results with $\sin^2 2\phi$ fixed

Here we present the results of the calculation of primordial abundances performed as a function of two parameters: the sterile-neutrino mass and the renormalization factor $a$. The active-sterile mixing angle was fixed at the value $\sin^2 2\phi = 0.15$. We performed a $\chi^2$-analysis in order to obtain the best-fit value of the parameters. The results for the different cases are presented in table 1. Figures 1 and 2 show the contour plots in the parametric-plane ($m_4, a$) for the distribution functions obtained by considering only the effects of neutrino-oscillations and including the matter potential in the differential equation. Since the results obtained using only the matter potential, and the ones considering the neutrino interaction in addition to the matter potential, are very similar, we only present the contours plots corresponding to the solutions obtained using the matter potential.

For each case, the first set of results has been obtained by taking all data on primordial abundances, and the second one is the set of results obtained by removing the data on the abundance of lithium. The statistical analysis shows that the data on lithium may not be consistent with the other data on primordial abundances. However, all sets yield almost the same value for the sterile-neutrino mass and comparable values for the renormalization factor of the sterile-neutrino occupation. The inclusion of the matter potential reduces the value of the normalization constant and increases the errors of the sterile neutrino mass.

### 3.1.2 Results with $m_4$ fixed

The next step was to vary the mixing angle. We performed the calculation considering the sterile neutrino mass fixed at the value $m_4 = 5$ keV. The results are presented in table 2 and in figures 3 and 4.

Once again, the inclusion of the primordial abundance of lithium in the statistical analysis gives a very poor result. However, both sets yield almost the same value for the sterile-active mixing angle. The inclusion of the matter potential affects mostly the value of the mixing angle.
Figure 1. $1\sigma$, $2\sigma$ and $3\sigma$ contour plots for the parameter $a$ (renormalization of the sterile-neutrino occupation factor) and the sterile-neutrino mass, $m_4$, when all data are considered in the $\chi^2$-test. The mixing angle $\phi$ has been fixed at the value $\sin^2 2\phi = 0.15$. Lines: only oscillation effects; lines with circles: considering only the matter potential in the calculations.

Figure 2. $1\sigma$, $2\sigma$ and $3\sigma$ contour plots, in the same notation of figure 1, when the data of $^7$Li are not considered in the $\chi^2$-test. The mixing angle $\phi$ has been fixed at the value $\sin^2 2\phi = 0.15$. Lines: only oscillation effects; lines with circles: considering only the matter potential in the calculations.
Table 2. Results of the parameters \( a \) and \( \sin^2 2\phi \). The sterile neutrino mass has been fixed at the value \( m_4 = 5 \text{ keV} \) and the value of \( \eta \) is fixed at the value of WMAP.

| Data          | \( a \pm \sigma \) | \( \sin^2 2\phi \pm \sigma \) | \( \chi^2/(N - 2) \) |
|---------------|---------------------|---------------------------------|------------------------|
| Only oscillation effects |
| \( \text{D}^+\text{He}^+\text{Li} \) | 0.30 ± 0.10 | 0.247\(_{+0.072}^{-0.159}\) | 10.61 |
| \( \text{D}^+\text{He} \) | 0.00\(_{+0.05}^{-1} \) | 0.395\(_{+0.066}^{-0.057}\) | 1.16 |
| Considering \( V_{\text{matt}} \) |
| \( \text{D}^+\text{He}^+\text{Li} \) | 0.24 ± 0.12 | 0.120\(_{+0.043}^{-0.068}\) | 10.61 |
| \( \text{D}^+\text{He} \) | 0.00\(_{+0.04}^{-0.01}\) | 0.195\(_{+0.050}^{-0.015}\) | 1.29 |
| Considering \( V_{\text{matt}} \) and \( I_{\text{coll}} \) |
| \( \text{D}^+\text{He}^+\text{Li} \) | 0.18\(_{+0.16}^{-0.099}\) | 0.152\(_{+0.061}^{-0.096}\) | 10.62 |
| \( \text{D}^+\text{He} \) | 0.00\(_{+0.02}^{-0.013}\) | 0.213\(_{+0.070}^{-0.061}\) | 1.39 |

Figure 3. 1\( \sigma \), 2\( \sigma \) and 3\( \sigma \) contour plots for the parameter \( a \) (renormalization of the sterile-neutrino occupation factor) and \( \sin^2 2\phi \), when all data are considered in the \( \chi^2 \)-test. The sterile-neutrino mass has been fixed at the value \( m_4 = 5 \text{ keV} \). Lines: only oscillation effects; lines with circles: considering only the matter potential in the calculations.
Figure 4. $1\sigma$, $2\sigma$ and $3\sigma$ contour plots, in the same notation of figure 3, when the data of $^7$Li are not considered in the $\chi^2$-test. The sterile neutrino mass has been fixed at the value $m_4 = 5$ keV. Lines: only oscillation effects; lines with circles: considering only the matter potential in the calculations.

\begin{table}[h]
\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
$a \pm \sigma$ & $\sin^2 2\phi \pm \sigma$ & $m_4 \pm \sigma$ [MeV] & $\chi^2/(N-3)$ \\
\hline
& & & \\
Only oscillation effects & & & \\
0.30$^{+0.13}_{-0.12}$ & 0.213$^{+0.144}_{-0.114}$ & 0.000$^{+0.050}$ & 11.37 \\
& & & \\
Considering $V_{\text{matt}}$ & & & \\
0.25$ \pm 0.10$ & 0.152$^{+0.090}_{-0.080}$ & 0.000$^{+0.060}$ & 11.40 \\
& & & \\
Considering $V_{\text{matt}}$ and $I_{\text{coll}}$ & & & \\
0.18$^{+0.16}_{-0.08}$ & 0.152$^{+0.070}_{-0.080}$ & 0.000$^{+0.060}$ & 11.38 \\
\hline
\end{tabular}
\end{center}
\caption{Results of the parameters $a$, $\sin^2 2\phi$ and $m_4$. The value of $\eta$ is fixed at the value given by WMAP.}
\end{table}

3.1.3 Results with $m_4$ and $\sin^2 2\phi$ as variables to adjust

Here we shall present and discuss the results obtained by varying the normalization constant of the sterile neutrino distribution function, the mixing angle, and the sterile neutrino mass. The results are presented in table 3 and figure 5.

Since we have three parameters to adjust and three set of data, we cannot exclude the data on lithium. For this case, we obtain a large value of $\chi^2$ for the minimum, indicating that the statistical test is not a good one. The best value for the parameters are the same considering only oscillation effects and considering the matter potential at $2\sigma$ level.
3.2 Results with $\eta_B$ variable

In this section we present the results obtained when the baryon density is treated as an extra parameter to adjust in the analysis.

3.2.1 Results with $\sin^2 2\phi$ fixed

The results obtained by allowing the variation of the baryon to photon ratio, $\eta_B$, and keeping the mixing angle fixed, are presented in table 4 and in figure 6.

The extracted value for $\eta_B$ is in good agreement with data, the renormalization parameter $a$ is somehow larger than the one obtained with a fixed value of $\eta_B$ [1, 2], but the fit favors a massless sterile-neutrino. The $\chi^2$-value for this case is similar to the one corresponding to the minimization with a fix $\eta_B$ when all primordial species are considered. Since we have three parameters to adjust and three set of data, we cannot, for the case of variable baryon to photon ratio, exclude the data on lithium.

3.2.2 Results with $m_4$ fixed

In table 5 and figure 7 we present the results obtained by allowing the variation of the baryon to photon ratio, $\eta_B$, and by keeping the sterile neutrino mass at a fixed value.
\[
(\eta \pm \sigma) \times 10^{-10} \quad a \pm \sigma \quad m_4 \pm \sigma \text{[MeV]} \quad \chi^2/(N-3)
\]

| Only oscillation effects | Considering \( V_{\text{matt}} \) | Considering \( V_{\text{matt}} \) and \( I_{\text{coll}} \) |
|--------------------------|-------------------------------|------------------------------------------|
| \( 6.14^{+0.08}_{-0.09} \) | \( 6.03^{+0.07}_{-0.20} \)   | \( 6.03^{+0.28}_{-0.14} \)           |
| \( 0.40^{+0.10}_{-0.12} \) | \( 0.06^{+0.10}_{-0.06} \)   | \( 0.06^{+0.21}_{-0.06} \)           |
| \( 0.000^{+0.040}_{-0.000} \) | \( 0.000^{+0.070}_{-0.000} \) | \( 0.000^{+0.060}_{-0.000} \)       |
| 11.37                    | 11.36                         | 11.38                                   |

Table 4. Results of the parameters \( \eta, a \) and \( m_4 \). The mixing angle \( \phi \) has been fixed at the value \( \sin^2 2\phi = 0.15 \).

Figure 6. 1\( \sigma \), 2\( \sigma \) and 3\( \sigma \) contour plots for \( \eta \), the parameter \( a \) and the sterile-neutrino mass. The mixing angle between the sterile and active neutrinos was fixed at \( \sin^2 2\phi = 0.15 \). Lines: only oscillation effects; lines with circles: considering only the matter potential in the calculations.
Table 5. Results of the parameters $\eta$, $a$ and $\sin^2 2\phi$. The sterile neutrino mass is fixed at the value $m_4 = 5$ keV.

| $(\eta \pm \sigma) \times 10^{-10}$ | $a \pm \sigma$ | $\sin^2 2\phi \pm \sigma$ | $\chi^2/(N-3)$ |
|-------------------------------------|----------------|----------------------------|----------------|
| Only oscillation effects
| 6.00$^{+0.21}_{-0.07}$ | 0.04$^{+0.28}_{-0.04}$ | 0.319$^{+0.096}_{-0.280}$ | 11.35 |
| Considering $V_{\text{mat}}$ |
| 6.03$^{+0.20}_{-0.17}$ | 0.06$^{+0.10}_{-0.06}$ | 0.152$^{+0.078}_{-0.152}$ | 11.36 |
| Considering $V_{\text{mat}}$ and $I_{\text{coll}}$
| 6.03$^{+0.28}_{-0.14}$ | 0.06$^{+0.28}_{-0.06}$ | 0.152$^{+0.030}_{-0.074}$ | 11.37 |

Figure 7. 1σ, 2σ and 3σ contour plots for $\eta$, the parameter $a$ and the he mixing angle between the sterile and active neutrinos. The sterile-neutrino mass was fixed at $m_4 = 5$ keV. Lines: only oscillation effects; lines with circles: considering only the matter potential in the calculations.
The best-value for $\eta$ is in good agreement with the extracted value using the Cosmological Microwave Background (CMB) data. The value for the constant $a$ and for the mixing angle are lower than the values obtained with a fix value of $\eta$, as shown by the results of the previous subsections. As one can see, from the curves shown in the figures, the calculations including the matter potential have two minima, however, the values given in the table correspond to the absolute minimum of $\chi^2$.

4 Conclusion

The presence of an extra heavy-neutrino affects the primordial abundances produced during the first three minutes of the Universe. We have calculated the occupation factors for active and sterile-neutrinos (3+1 scheme) and the neutron - proton interaction rates as a function of the new mass eigenstate, the active sterile neutrino mixing angle, and the parameter $a$, in order to obtain the primordial abundances of deuterium, helium and lithium. As in previous works, we have found a sensitivity of the abundances to the active sterile neutrino mixing [14–16, 46]. The value for the parameter $a$ remains lower than 0.4 at 1$\sigma$, in agreement with previous calculations [17]. The mixing angle between the active and sterile neutrino remains in the range $0.10 < \sin^2 2\phi < 0.32$. The sterile neutrino mass is lower than 70 keV at 1$\sigma$ level.

Acknowledgments

Support for this work was provided by the National Research Council (CONICET) of Argentina, and by the ANPCYT of Argentina. The authors are members of the Scientific Research Career of the CONICET.

References

[1] D. Larson et al., *Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: power spectra and WMAP-derived parameters*, *Astrophys. J. Suppl.* **192** (2011) 16 [arXiv:1001.4638] [inSPIRE].

[2] PLANCK collaboration, P.A.R. Ade et al., *Planck 2013 results. XVI. Cosmological parameters*, *Astron. Astrophys.* **571** (2014) A16 [arXiv:1303.5076] [inSPIRE].

[3] O. Richard, G. Michaud and J. Richer, *Implications of WMAP observations on Li abundance and stellar evolution models*, *Astrophys. J.* **619** (2005) 538 [astro-ph/0409672] [inSPIRE].

[4] J. Melendez, L. Casagrande, I. Ramirez, M. Asplund and W. Schuster, *Observational evidence for a broken Li Spite plateau and mass-dependent Li depletion*, *Astron. Astrophys.* **515** (2010) L3 [arXiv:1005.2944] [inSPIRE].

[5] K. Lind et al., *Observational signatures of lithium depletion in the metal-poor globular cluster NGC6397*, *IAU Symp.* **268** (2010) 263 [arXiv:1001.5153] [inSPIRE].

[6] O.S. Kirsebom and B. Davids, *One fewer solution to the cosmological lithium problem*, *Phys. Rev. C* **84** (2011) 058801 [arXiv:1109.4690] [inSPIRE].

[7] C. Broggini, L. Canton, G. Fiorentini and F.L. Villante, *The cosmological $^7$Li problem from a nuclear physics perspective*, *JCAP* **06** (2012) 030 [arXiv:1202.5232] [inSPIRE].

[8] O. Civitarese and M.E. Mosquera, *Nuclear structure constrains on resonant energies: a solution of the cosmological $^7$Li problem?*, *Nucl. Phys. A* **898** (2013) 1 [inSPIRE].

– 11 –
[9] S.J. Landau, M.E. Mosquera and H. Vucetich, Primordial nucleosynthesis with varying fundamental constants: a semi-analytical approach, Astrophys. J. 637 (2006) 38 [astro-ph/0411150] [inSPIRE].

[10] S.J. Landau, M.E. Mosquera, C.G. Scoccola and H. Vucetich, Early universe constraints on time variation of fundamental constants, Phys. Rev. D 78 (2008) 083527 [arXiv:0809.2033] [inSPIRE].

[11] M.E. Mosquera and O. Civitarese, Time variation of the fine structure constant and of the Higgs vacuum expectation value on cosmological time scales, Astron. Astrophys. 526 (2011) A109.

[12] M.E. Mosquera and O. Civitarese, Effect of the variation of the Higgs vacuum expectation value upon the deuterium binding energy and primordial abundances of D and 4He, Astron. Astrophys. 520 (2010) A112 [inSPIRE].

[13] M.E. Mosquera and O. Civitarese, Cosmological bounds to the variation of the Higgs vacuum expectation value: BBN constraints, Nucl. Phys. B 679 (2004) 261 [hep-ph/0308083] [inSPIRE].

[14] M.A. Moline and M.E. Mosquera, Constraints on active-sterile neutrino mixing from primordial abundances, Phys. Rev. D 84 (2011) 065803 [inSPIRE].

[15] M.A. Moline and M.E. Mosquera, Sterile neutrinos and big bang nucleosynthesis in the 3 + 1 scheme, Int. J. Mod. Phys. E 23 (2014) 1450014.

[16] K.N. Abazajian et al., Light sterile neutrinos: a white paper, arXiv:1204.5379 [inSPIRE].

[17] D.P. Kirilova and M.V. Chizhov, Cosmological nucleosynthesis and active sterile neutrinos with small mass differences: the nonresonant case, Phys. Rev. D 58 (1998) 073004 [hep-ph/9707282] [inSPIRE].

[18] A.D. Dolgov and F.L. Villante, BBN bounds on active sterile neutrino mixing, Nucl. Phys. B 679 (2004) 261 [hep-ph/0308083] [inSPIRE].

[19] L. Kawano, Let’s go: early universe. Guide to primordial nucleosynthesis programming, FERMILAB-PUB-88-034-A, Fermilab, Batavia U.S.A. (1988) [inSPIRE].

[20] L. Kawano, Let’s go: early universe II. Primordial nucleosynthesis: the computer way, FERMILAB-PUB-92-004-A, Fermilab, Batavia U.S.A. (1992) [inSPIRE].

[21] GNO collaboration, B. Aharmim et al., Combined analysis of all three phases of solar neutrino data from the Sudbury Neutrino Observatory, Phys. Rev. C 88 (2013) 025501 [arXiv:1109.0763] [inSPIRE].

[22] K2K collaboration, M.H. Ahn et al., Measurement of neutrino oscillation by the K2K experiment, Phys. Rev. D 74 (2006) 072003 [hep-ex/0606032] [inSPIRE].

[23] CHOOZ collaboration, M. Apollonio et al., Limits on neutrino oscillations from the CHOOZ experiment, Phys. Lett. B 466 (1999) 415 [hep-ex/9907037] [inSPIRE].

[24] J.CAP08(2015)038
[29] Double CHOOZ collaboration, Y. Abe et al., First measurement of $\theta_{13}$ from delayed neutron capture on hydrogen in the Double CHOOZ experiment, Phys. Lett. B 723 (2013) 66 [arXiv:1301.2948] [inSPIRE].

[30] S.A. Balashev, A.V. Ivanchik and D.A. Varshalovich, HD/H$_2$ molecular clouds in the early universe: the problem of primordial deuterium, Astron. Lett. 36 (2010) 761 [arXiv:1009.4136] [inSPIRE].

[31] M. Pettini, B.J. Zych, M.T. Murphy and C.C. Steidel, Deuterium abundance in the most metal-poor damped Lyman alpha system: converging on $\Omega_{b}0h^2$, Mon. Not. Roy. Astron. Soc. 391 (2008) 1499 [arXiv:0805.0594] [inSPIRE].

[32] R. Cooke, M. Pettini, R.A. Jorgenson, M.T. Murphy and C.C. Steidel, Precision measures of the primordial abundance of deuterium, Astrophys. J. 781 (2014) 31 [arXiv:1308.3240] [inSPIRE].

[33] P. Noterdaeme, S. Lopez, V. Dumont, C. Ledoux, P. Molaro and P. Petitjean, Deuterium at high-redshift: primordial abundance in the $z_{abs}=2.621$ damped Ly-alpha system towards CTQ 247, Astron. Astrophys. 542 (2012) L33 [arXiv:1205.3777] [inSPIRE].

[34] M. Pettini and R. Cooke, A new, precise measurement of the primordial abundance of deuterium, Mon. Not. Roy. Astron. Soc. 425 (2012) 2477 [arXiv:1205.3785] [inSPIRE].

[35] Y.I. Izotov and T.X. Thuan, The primordial abundance of $4$He: evidence for non-standard big bang nucleosynthesis, Astrophys. J. 710 (2010) L67 [arXiv:1001.4440] [inSPIRE].

[36] E. Aver, K.A. Olive and E.D. Skillman, An MCMC determination of the primordial helium abundance, JCAP 04 (2012) 004 [arXiv:1112.3713] [inSPIRE].

[37] M. Peimbert, V. Luridiana and A. Peimbert, Revised primordial helium abundance based on new atomic data, Astrophys. J. 666 (2007) 636 [astro-ph/0701580] [inSPIRE].

[38] S. Villanova, G. Piotto and R.G. Gratton, The helium content of globular clusters: light element abundance correlations and HB morphology. I. NGC 6752, Astron. Astrophys. 499 (2009) 755 [arXiv:0903.3924] [inSPIRE].

[39] E. Aver, K.A. Olive, R.L. Porter and E.D. Skillman, The primordial helium abundance from updated emissivities, JCAP 11 (2013) 017 [arXiv:1309.0047] [inSPIRE].

[40] Y.I. Izotov, G. Stasinska and N.G. Guseva, Primordial $4$He abundance: a determination based on the largest sample of HII regions with a methodology tested on model HII regions, Astron. Astrophys. 558 (2013) A57 [arXiv:1308.2100] [inSPIRE].

[41] P.E. Nissen and W.J. Schuster, Lithium abundances in high- and low-alpha halo stars, Mem. Soc. Astron. Ital. Suppl. 22 (2012) 41.

[42] C. Abate, O.R. Pols, R.G. Izzard, S.S. Mohamed and S.E. de Mink, Wind Roche-lobe overflow: application to carbon-enhanced metal-poor stars, Astron. Astrophys. 552 (2013) A26 [arXiv:1302.4441] [inSPIRE].

[43] K. Lind, F. Primas, C. Charbonnel, F. Grundahl and M. Asplund, Signatures of intrinsic Li depletion and Li-Na anti-correlation in the metal-poor globular cluster NGC6397, Astron. Astrophys. 503 (2009) 545 [arXiv:0906.2876] [inSPIRE].

[44] L. Monaco et al., Lithium and sodium in the globular cluster M4. Detection of a Li-rich dwarf star: preservation or pollution?, Astron. Astrophys. 539 (2012) A157 [arXiv:1108.0138] [inSPIRE].

[45] Particle Data Group collaboration, K.A. Olive et al., Review of particle physics, Chin. Phys. C 38 (2014) 090001 [inSPIRE].

[46] C.T. Kishimoto, G.M. Fuller and C.J. Smith, Coherent active-sterile neutrino flavor transformation in the early universe, Phys. Rev. Lett. 97 (2006) 141301 [astro-ph/0607403] [inSPIRE].