Active-Sterile neutrino oscillations and BBN+CMBR constraints

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Abstract

We show how active-sterile neutrino oscillations in the early Universe can play an interesting role in explaining the current observations of CMBR anisotropies and light element abundances. We describe different possible phenomenological scenarios in the interpretation of present data and how active-sterile neutrino oscillations can provide a viable theoretical framework.

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I. INTRODUCTION

The standard big bang model is a simple and testable theory of the evolution of the Universe. One of the quantitative tests of standard big bang cosmology lies in its predictions of the primordial abundance of light elements. Standard Big Bang Nucleosynthesis (SBBN) contains essentially just one free parameter, the baryon to photon ratio at the time of BBN η, while it predicts the primordial nuclear abundances of several light elements. Each measurement of a primordial abundance, that has to be inferred from observations at the present time, provides in principle a measurement of η. The success of the theory relies on the consistency of the values for η that can be deduced from different nuclear abundances.

In recent years two different measurements of the Helium abundance have been given. A first group [1] finds [1] 'low' values $Y_p = 0.234 \pm 0.003$, while a second group [2] finds 'high' values $Y_p = 0.244 \pm 0.002$, which are mutually compatible at about $2.5\,\sigma$ level only.

The SBBN provides numerically a relation $Y_p(\eta)$. A linear expansion gives [3] [2]:

$$Y_p^{SBBN}(\eta) = 0.2467 + 0.01 \ln\left(\frac{\eta}{5}\right). \tag{1}$$

In this way for the low value of Y_p one obtains $\eta_{SBBN}^{^4He} = 1.5 \pm 0.4$, while for the high value of Y_p one obtains $\eta_{SBBN}^{^4He} = 3.9 \pm 0.8$.

Meanwhile, the value $(D/H)_5 = 3.39 \pm 0.25$ [3] has been deduced [5] for the primordial deuterium abundance from observations toward two high redshift quasars. Deuterium is an ideal 'baryometer' [6] which gives an accurate measurement of baryon abundance in the context of SBBN. Indeed one finds $(\Omega_b\,h^2)_{SBBN}^{D/H} = 0.019 \pm 0.0024$ (95% cl) [7] and from the simple relation $\eta \simeq 273\,\Omega_b\,h^2$, this corresponds to $\eta_{SBBN}^{D/H} = 5.2 \pm 0.65$ (95% cl) [4]. This value is clearly not consistent with the η value obtained from low Helium values although it is consistent with the η value from the high Helium value.

On a new front, two balloon experiments provided the first accurate measurements of acoustic peaks in the Cosmic Microwave Background Radiation (CMBR) anisotropies [9,10] and from these observations it has been possible to infer a value for the baryon to photon ratio. The BOOMERanG experiment finds $(\Omega_b\,h^2)_{CBR} = 0.036^{+0.006}_{-0.005}$ [11] while the MAXIMA experiment finds $(\Omega_b\,h^2)_{CBR} = 0.031^{+0.007}_{-0.006}$ [12]. These two independent measurements are in quite good agreement and seem to exclude the presence of large systematic errors. A combined analysis of the two gives the result $(\Omega_b\,h^2)_{CBR} = 0.033 \pm 0.005$ [13] that corresponds

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[1]Where not otherwise indicated, all errors are meant at 68% c.l.

[2]A neutron life time $\tau_n = 887sec$ has been used. Here and everywhere η is expressed in unit of 10^{-10}. The central value for $\eta = 5$ has been updated according more recent analysis [4]. Note that this expression is accurate to within 0.001 for $3 < \eta < 10$ while is less accurate for $\eta \lesssim 3$.

[3]$(D/H)_5 = 10^5\,(D/H)$.

[4]In a very recent analysis even smaller errors are found: $(\Omega_b\,h^2)_{SBBN}^{D/H} = 0.019 \pm 0.0018$ (95% cl) and correspondingly $\eta_{SBBN}^{D/H} = 5.2 \pm 0.5$ (95% cl) [8].

to $\eta_{CBR} = 9.0 \pm 1.4$. This value is higher than the BBN predictions (given above) from the inferred values from both Deuterium and Helium. These discrepancies may be due to systematic errors but it is also interesting to consider possible explanations in terms of non standard physics. One possibility is that BBN and CMBR are probing different quantities, as they involve different physical mechanisms and at different times (see for example [14]). Instead we will consider this discrepancy as a hint for non standard BBN.

We will consider two view points:

1) The discrepancy is between CMBR and Helium while the discrepancy between CMBR and Deuterium is due to systematic uncertainties. This is plausible because it is very difficult to identify 'clean' absorption systems providing reliable measurements for deuterium and the quoted results that we used were derived from only two such measurements.

2) The discrepancy between deuterium and CMBR as well as the discrepancy between Helium and CMBR are both real and due to non standard physics [5].

The main purpose of this paper is to explore the possible explanations for these discrepancies in terms of active-sterile neutrino oscillations in the early Universe.

At the present time there is very strong evidence for neutrino oscillations coming from atmospheric, solar and the LSND experiment (for a review, see e.g. Ref. [16]). The atmospheric neutrino anomaly can be solved (most simply) via approximately maximal $\nu_\mu \to \nu_\tau$ oscillations or via $\nu_\mu \to \nu_s$ oscillations [17] (where ν_s represents a hypothetical sterile neutrino). On the other hand, the observed solar flux deficit (about 50% of the expected value) suggests approximately maximal $\nu_e \to \nu_{\mu,\tau}$ oscillations or approximately maximal $\nu_e \to \nu_s$ oscillations (see e.g. Ref. [18] and references there-in). Finally, the LSND experiment implies the existence of small angle $\nu_e \to \nu_\mu$ oscillations with $\delta m^2 \sim 1 eV^2$. The combination of these three neutrino anomalies suggests the need for at least one sterile neutrino. Perhaps the most elegant solution to these neutrino anomalies poses that each neutrino is maximally mixed with a sterile partner (with small mixing between the generations) [19]. Of course, there are many other possibilities. In any case, for illustrative purposes we will focus on the simple case of $\nu_e \to \nu_s$ oscillations in isolation and discuss some of the other possibilities qualitatively where appropriate.

Ordinary-sterile neutrino oscillations have remarkable implications for the early Universe. In particular, ordinary-sterile neutrino oscillations can generate large neutrino asymmetries in the early Universe [20–22] (see also Ref. [23]), so large in fact as to imply significant modifications to BBN [22]. In the simple scenario of $\nu_e \to \nu_s$ oscillations in isolation, large ν_e asymmetry is directly produced, while, in three (or more) meutrino mixing scenarios an α-neutrino asymmetry ($\alpha = \mu, \tau$) could be first generated by $\nu_\alpha \leftrightarrow \nu_s$ oscillations and then converted into an electron neutrino asymmetry by a $\nu_\alpha - \nu_e$ oscillations [22,24]. Focusing on the simple case of direct production, we will find the values of mixing parameters which might

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[5]Note that we will neglect from our analysis measurements of ^{7}Li abundance. This because in recent years various analysis conclude that there is still a big uncertainty on the level of depletion of the primordial abundance to the values that we currently observe (for a recent review see [15]).

explain the possible discrepancies in SBBN. Interestingly, it turns out that the suggested parameter space implies a ν_e with mass $\sim 1eV$ which is close to the current experimental bound. Furthermore it is also consistent with the measurements of the LSND experiment and thus can be potentially tested in the near future at mini-Boone.

The outline of this paper is as follows. In section II we briefly discuss the relation between Ω_m inferred from X-ray measurements in galaxy clusters and the value suggested by CMBR. Interestingly both are consistent with $\Omega_m = 1$. In section III we show how the $\nu_e \to \nu_s$ oscillation generated L_{ν_e} can reconcile the high η_{CBR} with the BBN Y_p results (case 1 above). In section IV we briefly examine ways in which the discrepancies between Deuterium, Helium and CMBR may both be reconciled (case 2 above). In section V we will present a new possible phenomenological scenario, in which large scale inhomogeneities in the nuclear abundances are admitted. Also in this case active-sterile neutrino oscillations may provide a viable theoretical model. We conclude in section VI.

II. COSMIC CONCORDANCE OR DISCORDANCE?

In this section we make some comments on the previous indications of a 'baryon catastrophe' from X-ray measurements in galaxy clusters and how it might be related to the inferred values of the baryon number from CMBR observations. Recall it is possible to estimate the baryon to total mass ratio in clusters of galaxies from X-ray measurements [25] obtaining (at 1σ) that $\Omega_b h^{\frac{3}{2}}/\Omega_m = (0.05 \pm 0.01)$ [26] (this is confirmed also by measurements based on the SZ effect that give $\Omega_b h/\Omega_m = (0.06 \pm 0.006)$ [27]). If one imposes that $\Omega_m = 1$ and using a lower limit on $h > 0.5$ finds immediately that $\Omega_b h^2 > 0.035$, much bigger than the upper bound that is deduced in a SBBN, both from Deuterium and Helium abundance (but consistent with CMBR as we will discuss in a moment). This 'baryon catastrophe' in SBBN was 'solved' by assuming that Ω_m can be much less than 1 which implies that we need to give up the inflationary paradigm ($\Omega_0 = 1$) or to admit the presence of a large cosmological constant Λ such that $\Omega_m + \Omega_\Lambda = 1$. In this way, using the SBBN value, previously given, for $\Omega_b h^2$ from Deuterium abundance, one can infer a value for $\Omega_m = 0.45 \pm 0.15$. This picture has been supported by the discovery of an acceleration expansion from SNe Ia [28], that also points to the existence of a large cosmological constant term, Ω_Λ [29]. Roughly these measurements provide the constraint, in the $\Omega_m - \Omega_\Lambda$ plane,

$$\Omega_\Lambda = 1.3\,\Omega_m + 0.4 \pm 0.2. \tag{2}$$

After the SN results, the first accurate CMBR measurements of the first acoustic peak position seem to confirm the idea of a flat Universe [30]. In this case one immediately deduces from Eq.(2) a value $\Omega_m = 0.25 \pm 0.1$ in very good agreement with galaxy cluster measurements when the SBBN value for $\Omega_b h^2$ is assumed: three independent methods match each other, with good accuracy, in a region around the point $(0.3, 0.7)$, in the plane $(\Omega_m, \Omega_\Lambda)$ ('cosmic concordance' [31]).

It is clear however that if one now uses the new CMBR estimation for $\Omega_b h^2$, then from galaxy clusters one obtains that $\Omega_m = 0.8 \pm 0.3$ suggesting 'cosmic discordance' (albeit only mildly) between galaxy cluster measurements and SNe type Ia. Moreover now the existence of a cosmological constant is not required any more from galaxy clusters [32]. This seems to

be suggested also from a recent analysis of CMBR data when a large neutrino asymmetry is allowed [33,32]. Thus, overall things are not so clear at the moment. It has also been argued in Ref. [34] that the Supernovae evidence that the expansion of the Universe is accelerating is not yet compelling. Whether or not a large cosmological constant exists needs to be confirmed independently, perhaps by future analysis from the planned satellite experiments, MAP and PLANCK will help. In the meantime, for people with the theoretical prejudice that Ω_Λ is negligible, there is now some good news since X-ray measurements from galaxy clusters and the CMBR results are both consistent with $\Omega_m = 1$.

III. CMBR ANISOTROPIES AND HELIUM OBSERVATIONS

Even assuming the high value for the Helium abundance, the resulting value of η and that one deduced from CMBR differ at about 3σ level.

Let us consider the situation from a formal point of view that will be useful for further developments. In the SBBN picture the experimental constraint $Y_p^{SBBN}(\eta) = Y_p^{exp}$ gives a measurement of $\eta = \eta_{SBBN}^{^4He}$, as we observed in the introduction. However CMBR gives an independent measurement of η and, assuming it to be a reliable one, provides a simple test for SBBN as now one has to satisfy the constraint $Y_p^{SBBN}(\eta_{CBR}) = Y_p^{exp}$. Present measurements do not pass this test and thus SBBN is somewhat discrepant with Helium and CMBR observations.

Taking this as a hint for new physics, it suggests that we need to modify SBBN introducing a new parameter X. It is clear that, if in the physical ranges of values for X, all values of Y_p are possible (with $\eta = \eta_{CBR}$), then it is always possible to find a value for X satisfying the test $Y_p(\eta_{CMBR}, X) = Y_p^{exp}$ in the non standard BBN model.

It has been known for a long time that this 'game' can be performed allowing a modification of the standard particle content before the BBN epoch [35]. This modification can be parametrized with the (extra) number of (light) neutrino species [36]:

$$\Delta N_\nu^\rho = \sum_X N_X^\rho - 3, \text{ with } \quad N_X^\rho \equiv \frac{120}{7\,\pi^2} \frac{\rho_X + \rho_{\bar{X}}}{T_\nu^4}, \tag{3}$$

($X = \nu_e, \nu_\mu, \nu_\tau + \text{new particle species}$), where $T_\nu \equiv T_d\,R_d/R$ is a fiducial temperature of ideal neutrinos that would instantaneously decouple at $T_d \gg m_e/2$ (but also $T_d \ll m_\mu/2$), without sharing any entropy release, from electron-positron annihilations, with photons [6].

With this extra parameter, the SBBN prediction for Y_p is modified and approximately the change is given by:

$$\Delta Y_p(\eta, \Delta N_\nu^\rho) \simeq \frac{1}{6} Y_p^{SBBN}(\eta) \left(1 - \frac{Y_p^{SBBN}(\eta)}{2} \right) \frac{m_n - m_p}{T_{\rm f}^{n/p}} \frac{\Delta N^\rho}{N_{\rm st}^\rho} \simeq 0.012\,\Delta N_\nu^\rho, \tag{4}$$

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[6]Note that with this definition, in the standard model of particle physics one finds that ΔN_ν^ρ is not exactly zero, due to the fact that actually neutrinos are slightly reheated during electron-positron annihilations (see [37] and references therein).

where $T_{\mathrm{f}}^{n/p} \simeq 0.75\mathrm{MeV}$ is the freezing temperature of neutron to proton ratio in the standard case, while $N_{\mathrm{st}}^{\rho} = 43/8$ is the number of particle species and again the last expression has been evaluated for $\eta_{CBR} \simeq 9$.

It has also been known for a long time [38] that the standard prediction for the neutron to proton ratio is modified if one allows the electron neutrino and anti-neutrino distributions in momentum space to deviate from the standard case in which the thermal equilibrium distributions with zero chemical potentials are assumed [7]. In this case an infinite number of new non standard parameters, the values of the extra numbers of electron neutrinos and antineutrinos in each quantum state for any momentum, can be virtually introduced. However, in realistic models, usually the deviations depend on a finite number of parameters.

A particularly simple model [39] is obtained when the distributions depend only on the neutrino degeneracy ξ_e, playing the role of a new parameter X. This has to be generated earlier than the BBN epoch and it is usually assumed that it is generated also before electron neutrino chemical decoupling so that $\xi_e + \bar{\xi}_e = 0$. This corresponds to having a neutrino asymmetry given by:

$$L_{\nu_e} \equiv \frac{n_{\nu_e} - n_{\bar{\nu}_e}}{n_\gamma} = \frac{\pi^2}{12\,\zeta(3)} \left(\xi_e + \frac{\xi_e^3}{\pi^2} \right). \tag{5}$$

In this case the modification of the SBBN prediction [see eq.(1)] for $\xi_e \ll 1$ is given by:

$$\Delta Y_p(\eta, \xi_e) \simeq -Y_p^{SBBN}(\eta) \left(1 - \frac{Y_p^{SBBN}(\eta)}{2} \right) \xi_e \simeq -0.22\,\xi_e, \tag{6}$$

where the last expression has been calculated for $\eta_{CMBR} \simeq 9$. Thus values $\xi_e \simeq 0.035$ and $\xi_e \simeq 0.08$ can easily solve the discrepancy between CMBR observations and high and low Helium values respectively.

More generally one can allow a deviation from the standard prediction for the Helium abundance due both to a modification of the expansion rate and to distortions of the electron neutrino and anti-neutrino distributions. In this case one can distinguish two different contributions to the variation of the Helium abundance compared to the standard case:

$$\Delta Y_p = \Delta Y_p^\rho + \Delta Y_p^{f_{\nu_e}}. \tag{7}$$

Note that this distinction is not ambiguous as it could appear. One can in fact always calculate at any instant the quantity ΔN_ν^ρ from the eq. (3) and from that deduce the corresponding value of ΔY_p^ρ defined as the value of ΔY_p when the standard electron neutrino and antineutrino distributions are assumed. Afterwards one can calculate $\Delta Y_p^{f_{\nu_e}} \equiv \Delta Y_p - \Delta Y_p^\rho$. It will prove to be convenient to define also a *total effective number of neutrino species* ΔN_ν that combines both the effect of a modification of the expansion rate and that one due to the distortions of electron neutrino and anti-neutrino distributions:

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[7]Electron neutrino and anti-neutrinos distributions are directly involved in determining the rates of the β-reactions ($n + \nu_e \leftrightarrow p + e^-$, $n + e^+ \leftrightarrow p + \bar{\nu}_e$) responsible for the final value of the neutron to proton ratio together with the neutron decay.

$$\Delta N_\nu \equiv \Delta N_\nu^\rho + \Delta N_\nu^{f_{\nu_e}}, \;\; \text{with} \;\; \Delta N_\nu^{f_{\nu_e}} \equiv \frac{\Delta Y_p^{f_{\nu_e}}}{0.012} \tag{8}$$

With these definitions, the procedure to calculate ΔN_ν and the specific contribution $\Delta N_\nu^{f_{\nu_e}}$ is particularly simple if one uses the linear expansion (4): $\Delta N_\nu \simeq \Delta Y_p/0.012$ and thus $\Delta N_\nu^{f_{\nu_e}} \simeq \Delta Y_p/0.012 - \Delta N_\nu^\rho$ [8].

In the case of an electron neutrino asymmetry created before the electron neutrino chemical decoupling ($\Rightarrow \xi_e + \bar{\xi}_e = 0$) it is easy to see that $\Delta N_\nu^{f_{\nu_e}} \simeq -18\,\xi_e$ [9]. In order to reconcile the discrepancy between the Helium abundance measurements and the CMBR observations, a negative ΔN_ν is required. More precisely, imposing the constraint $Y_p(\eta_{CBR}, \Delta N_\nu) = Y_p^{\exp}$, one finds:

$$\Delta N_\nu = -1.5 \pm 0.4 \;\; \text{for} \;\; Y_p^{\exp} = 0.234 \pm 0.003,$$
$$\Delta N_\nu = -0.7 \pm 0.3 \;\; \text{for} \;\; Y_p^{\exp} = 0.244 \pm 0.002. \tag{9}$$

One could simply hypothesis that a large pre-existing asymmetry exists, however a more subtle (and testable as we will show) possibility is that light sterile neutrinos exist. Naively, such neutrinos might be expected to lead to a positive ΔN_ν as they would simply generate a positive ΔN_ν^ρ, however it has been shown [22,40,24] that due to the dynamical generation of L_{ν_e} by the oscillations themselves, there will be also an important contribution to $\Delta N_\nu^{f_{\nu_e}}$ and the total effective ΔN_ν can be negative if $L_{\nu_e} > 0$ [10].

This contribution cannot be expressed in terms, for example, of the final asymmetry by a simple relation as in the case of a pre-existing asymmetry. This is because the asymmetry is generated, in the interesting cases, below the chemical decoupling temperature and even below the thermal decoupling temperature and thus is changing during the time near the freezing of the neutron to proton ratio. Moreover, as the thermal equilibrium assumption is not satisfied anymore, the electron neutrino distribution will deviate from equilibrium and this effect has also to be included. Thus the results can be only calculated numerically.

The sign of L_{ν_e} cannot be predicted because it depends on the sign and magnitude of the initial lepton number asymmetries. For the purposes of this paper, we assume that it is

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[8]Of course the choice to describe results in terms of ΔY_p or of ΔN_ν is simply a matter of taste. One can say that in the first case the astrophysical point of view is more emphasized than that one of particle physics or vice versa in the second case. In this paper we clearly prefer the second one.

[9]We remind that this is valid only for $\xi_e \ll 1$. Note also that for large neutrino asymmetries ($\xi_e, \xi_\mu, \xi_\tau \stackrel{>}{\sim} 0.5$) these would also give a non negligible contribution to ΔN_ν^ρ

[10]The problem to get a number of effective neutrinos less than three is not new. It also arises in order to alleviate the tension between Deuterium measurements and low values of Helium abundance ('BBN crisis') [41]. Also in that case the same non standard solutions can be invoked. Rounding up the usual suspects, we have a MeV τ neutrino decaying prior to the onset of BBN [42], the existence of a large electron neutrino asymmetry [43] and active-sterile neutrino oscillations [22], that we are re-considering in this new context.

positive since we need to generate $\Delta N_\nu < 0$. The simplest example of neutrino oscillation generated L_{ν_e} is the direct production of L_{ν_e} by $\nu_e \to \nu_s$ oscillations. In this case we can ignore the oscillations involving ν_μ, ν_τ provided that either their masses are very small (so that the largest $|\delta m^2|$ belongs to the $\nu_e \to \nu_s$ oscillations and the other oscillations have $|\delta m^2|$ much less than 1 eV^2) or that they do not mix with the ν_e, ν_s (i.e. the ν_e, ν_s decouple from the ν_μ, ν_τ in the neutrino mass matrix). In this way the mixing is simply described by two parameters, the difference of squared eigenstate masses δm^2 and the mixing angle in vacuum, $\sin^2 2\theta_0$.

In **Figure 1** we solve the quantum kinetic equations for $\nu_e \to \nu_s$ oscillations for $\sin^2 2\theta_0 = 10^{-8}$ and $\delta m^2/eV^2 = -0.25, -0.5, -1.0, -2.0, -4.0$. (For details of the numerical procedure see Ref. [49]). Let us now discuss the behaviour exhibited in this figure. As already discussed in detail in previous publications [20–22] the evolution of lepton number can be separated into three distinct phases. At high temperatures the oscillations are damped and evolve so that $L^{(e)} \ll \eta$ (where $L^{(e)} \equiv 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau} + \eta$, and η is related to the baryon asymmetry). In this region the resonance momentum for neutrino oscillations is approximately the same as anti-neutrino oscillations. If $\delta m^2 < 0$ (which means that the mass eigenstate which is mainly ν_s is lighter than the mass eigenstate which is mainly ν_e) then at a certain temperature, T_c, which is given roughly by [20],

$$ T_c \sim 15 \left(\frac{-\delta m^2 \cos 2\theta_0}{eV^2} \right)^{\frac{1}{6}} \ \text{MeV}, \tag{10} $$

exponential growth of neutrino asymmetry occurs (which typically generates a neutrino asymmetry of order 10^{-5}, as shown in figure 1). Taking for definiteness that the L_{ν_e} is positive, the anti-neutrino oscillation resonance moves to very low values of $p/T \sim 0.3$ while the neutrino oscillation resonance moves to high values $p/T \stackrel{>}{\sim} 10$ (see Ref. [22] for a figure illustrating this). The subsequent evolution of neutrino asymmetries, which is dominated by adiabatic MSW transitions of the antineutrinos, follows an approximate $1/T^4$ behaviour until the resonance has passed through the entire distribution. The final asymmetry generated is typically in the range $0.23 \stackrel{<}{\sim} L_{\nu_e} \stackrel{<}{\sim} 0.37$ [22]. Because the oscillations are dominated by adiabatic MSW behaviour it is possible to use a relatively simple and accurate formalism to describe the evolution of the system at 'low temperatures', $T \stackrel{<}{\sim} T_c/2$. In fact, we only need to know the values of the oscillation resonance momentum at $T \sim T_c/2$. Previous numerical work has already shown [22] that by $T \sim T_c/2$, neutrino asymmetry is generated such that $0.2 \stackrel{<}{\sim} p/T \stackrel{<}{\sim} 0.8$ (the precise value depends on $\sin^2 \theta_0, \delta m^2$). Furthermore the subsequent evolution is approximately insensitive to the initial value of p/T in this range.

For full details of the evolution of L_{ν_e} and ΔN_ν in this model see Ref. [24]. The evolution of the momentum distribution of electron neutrinos is also computed and fed into a BBN code (that is solved concurrently) which allows us to compute Y_p for each choice of δm^2 and $\sin^2 2\theta_0$ [24]. Particularly simple results are obtained when the constraint $\sin^2 2\theta_0 \sqrt{(|\delta m^2|/eV^2)} \stackrel{<}{\sim} 2.5 \times 10^{-6}$ is imposed. This corresponds to having $\Delta N_\nu^\rho \stackrel{<}{\sim} 0.1$ prior the onset of the neutrino asymmetry generation [44]. Moreover, for the interesting values $|\delta m^2| \ll 100 \, eV^2$, most of the generated neutrino asymmetry and its associated sterile neutrino production, occurs below chemical decoupling so that ΔN_ν^ρ remains negligible. In this way the only significant

contribution to ΔN_ν derives from the $\Delta N_\nu^{f_{\nu_e}}$ part which arises from the depletion of the $\bar{\nu}_e$ states as the MSW resonance passes creating L_{ν_e} in the process. For $\delta m^2 \sim -1 \ eV^2$, the large neutrino asymmetry is generated provided that $\sin^2 2\theta_0 \overset{>}{\sim} \ few \ \times 10^{-10}$ [21,22] (which is essentially the adiabatic condition for this system). With these two constraints on mixing parameters, the resulting ΔN_ν is practically independent of $\sin 2\theta_0$ and thus we have a full correspondence $\Delta N_\nu \leftrightarrow \delta m^2$. The result is given in **Figure 2**. From this figure we can translate the constraint $Y_p(\eta_{CBR}, \Delta N_\nu) = Y_p^{\exp}$ on ΔN_ν [see Eq.9], into a sort of 'measurement' of δm^2, i.e.

$$\Delta N_\nu = -1.5 \pm 0.4, \ \Rightarrow \ \delta m^2 = -2.5 \pm 1.0 \ eV^2,$$
$$\Delta N_\nu = -0.7 \pm 0.3, \ \Rightarrow \ \delta m^2 = -0.8 \pm 0.5 \ eV^2. \tag{11}$$

These values of δm^2 are interesting from several points of view. They imply that $m_{\nu_e} \sim 1 \ eV$ (assuming $m_{\nu_s} \ll m_{\nu_e}$) which is close to the present experimental limit. Furthermore, if m_{ν_e} is heavier than the ν_μ state then the LSND δm^2, δm_{lsnd}^2 is, approximately, the same as the δm^2 for $\nu_e \to \nu_s$ oscillations. Thus, if this simple scenario is the cause of the BBN discrepancy it can be potentially tested in the near future at mini-Boone.

Above we have discussed things in the model where L_{ν_e} is produced directly. It is also possible to produce L_{ν_e} indirectly. E.g. if ν_τ is the heaviest neutrino and oscillations between $\nu_\tau \to \nu_s$ generate a large L_{ν_τ} some of which is transferred to L_{ν_e} by $\nu_e \to \nu_\tau$ oscillations [22,40,24]. The indirect mechanism typically generates a smaller L_{ν_e} leading to ΔN_ν in the range $-0.7 \overset{<}{\sim} \Delta N_\nu \overset{<}{\sim} 0$ if $L_{\nu_e} > 0$. Models with three sterile neutrinos (such as models with mirror neutrinos) have also been studied [45]. These models can also accommodate negative ΔN_ν in the range $-1.5 \overset{<}{\sim} \Delta N_\nu \overset{<}{\sim} 0$ if $L_{\nu_e} > 0$. In fact it is fair to say that a deviation of ΔN_ν from zero is a generic consequence of models with light sterile neutrinos if one of the active neutrinos has mass in the eV range.

IV. 'JUST SO' BBN ?

We want now to include the Deuterium observations in our analysis. In this case the discrepancy between CMBR and nuclear abundances observations, becomes even more puzzling. In the SBBN $(D/H)(\eta) \propto \eta^{-1.7}$ [46] and this means that having $\eta_{CBR} \sim 9$ corresponds to $(D/H)_5 \simeq 1.5$, a quantity about half the measured one. One could hope that, within the model of $\nu_e \leftrightarrow \nu_s$ oscillations with $\Delta N_\nu^\rho \ll 1$ discussed in the previous section, choosing the values of δm^2 able to reconcile CMBR and Helium observations, it would also be possible to satisfy the constraint $(D/H)(\eta_{CBR}, \delta m^2) = (D/H)^{exp}$. This is however not the case as the negative values of $\Delta N_\nu^{f_{\nu_e}}$ leaves almost unchanged the standard value corresponding to η_{CBR}. Thus the only way out is to enlarge the space of parameters in the model of BBN. This can be done allowing also a non zero ΔN_ν^ρ. This possibility has also been studied for a long time [47] and recently reproposed in [32] to solve the BBN-CMBR discrepancy. In this way the problem is now to find values of ΔN_ν^ρ and $\Delta N_\nu^{f_{\nu_e}}$ that satisfy simultaneously the constraints:

$$Y_p(\eta_{CMBR}, \Delta N_\nu^\rho, \Delta N_\nu^{f_{\nu_e}}) = Y_p^{\exp}, \tag{12}$$
$$(D/H)(\eta_{CMBR}, \Delta N_\nu^\rho, \Delta N_\nu^{f_{\nu_e}}) = (D/H)^{\exp}. \tag{13}$$

In a recent analysis [48], in which a pre-existing electron neutrino asymmetry is assumed, the authors find that to reduce the discrepancy within a 2σ level, a range of values $1 \stackrel{<}{\sim} \Delta N_\nu^\rho \stackrel{<}{\sim} 11$ and correspondingly $0.07 \stackrel{<}{\sim} \xi_e \stackrel{<}{\sim} 0.43$ must be chosen.

As we said in the previous section, it is not possible to make a straightforward comparison with the active-sterile neutrino oscillations, as the effect of the generation of a neutrino asymmetry is not easily related. However we can make some qualitative comments. It is quite easy to have marginal consistency at the 2σ level by just modifying the constraints imposed on the mixing parameters to solve the discrepancy of CMBR with the Helium abundance alone. In fact simply increasing the mixing angle, with a fixed δm^2, such that $\sin^2 2\theta_0 \sqrt{(|\delta m^2|/\text{eV}^2)} \stackrel{>}{\sim} 2 \times 10^{-5}$, one gets a $\Delta N_\nu^\rho \stackrel{>}{\sim} 0.6$. It is likely that the values for δm^2 found in the previous section will be slightly increased as a higher $\Delta N_\nu^{f_{\nu_e}}$ is now required to satisfy also the constraint from the Helium abundance [11]. Therefore, within the framework of active-sterile neutrino oscillations, the search for the suitable values for $\Delta N^{f_{\nu_e}}, \Delta N^\rho$ is translated in a search for the right $\delta m^2, \sin^2 2\theta_0$ values.

It is clear however that allowing for the existence of just one sterile neutrino species, values of $\Delta N_\nu^\rho \sim 5$, required to have a best fit, are not possible. In this case one has necessarily to assume the existence of more than one light sterile neutrino species. One amusing possibility is the idea that a mirror world exists where every particle has a corresponding mirror particle [52] (see also Ref. [19] and references there-in). The main theoretical motivation for this theory is that it allows parity and time reversal to be exact unbroken symmetries of nature. In the context of this theory, it is usually assumed that the temperature of the mirror particles is less than the ordinary ones in the early Universe [45,19]. However, it is possible that interactions between the ordinary and mirror worlds may be strong enough to thermalize the mirror particles such that $T_{mirror} = T_{ordinary} \equiv T$. In this case $\Delta N_\nu^\rho \simeq 6.14$. To reconcile BBN with such a large value of ΔN_ν^ρ requires a large $\xi_e \approx 0.4$ pre-existing asymmetry. (It needs to be pre-existing because if $T_{mirror} = T$, then there are equal densities of ordinary and mirror neutrinos which means that one cannot generate significant asymmetries). Alternatively, if $0.7\,T < T_{mirror} < T$, then $1.5 \stackrel{<}{\sim} \Delta N_\nu^\rho \stackrel{<}{\sim} 6.14$. In this case neutrino oscillations can generate a significant ν_e asymmetry which may potentially lead to a model consistent with BBN for a range of parameters[12].

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[11]It must be said that increasing the mixing angle there is a region where at the onset of the asymmetry generation rapid oscillations are found [49] (see also Ref. [50]). It is still an issue whether this is a real feature if the solutions or just simply an effect due to numerical inaccuracy. However if this effect would really exist, it is possible that the sign of the asymmetry could be randomly determined in different points of the space with the creation of lepton domains [51]. This would spoil the effect that we want to get, as in this case negative values of ΔN_ν would not be allowed. In any case at the high values of mixing angles that we are requiring in order to have $\Delta N_\nu^\rho \simeq 1$ (of course ΔN_ν^ρ cannot be too close to one otherwise this will suppress the final neutrino asymmetry), there are surely no rapid oscillations [49].

[12] It may also be possible for $T_{mirror} > T$, with large L_{ν_e} generated by $\nu_\tau' \to \nu_e$ oscillations, leading to a consistent model for a range of parameters.

While such possibilities are interesting and testable, it may however seem surprising that nature should have large ΔN_ν^ρ and $\Delta N_\nu^{f\nu_e}$ which roughly cancel [13]. Maybe the discrepancy will be alleviated from more precise measurements of η from CMBR and a mild compensation with one or two extra neutrino species and a not too big neutrino asymmetry would be perhaps reasonable. From this point of view a crucial test in the future will be provided when CMBR will also be able to measure N_ν^ρ, while at the moment it only provides a rather poor upper limit $N_\nu^\rho \leq 13$ [54]. It is however possible to imagine a different kind of solution within non standard BBN models that circumvent the requirement of a fine tuned solution. We now turn our attention to one idea in this direction.

V. INHOMOGENEOUS NUCLEAR ABUNDANCES ?

CMBR measures the baryon abundance on the whole observable universe with a co-moving size of $6000 \mathrm{Mpc}\, h^{-1}$ and this would correspond to a SBBN prediction of $Y_p \simeq 0.25$ and $(D/H)_5 \simeq 1.5$. The Deuterium measurement is deduced from two Lyman absorption systems at $z_\mathrm{abs} \simeq 3$, corresponding to comoving distances of about 2000Mpc. The size of these systems is approximately equal to the comoving size of galaxies $(100\mathrm{Kpc} - 1\mathrm{Mpc})$. Primordial Helium abundance values are deduced from ionized gas surrounding hot young stars at distances within $\sim 100\mathrm{Mpc}$ around us. It is then possible to imagine that an inhomogeneous electron neutrino asymmetry could be the reason for the apparent discrepancies between Deuterium and CMBR as well as between Helium and CMBR. The quantities $Y_p^{SBBN}(\eta_{CBR}) \simeq 0.25, D/H^{SBBN}(\eta_{CBR}) \simeq 1.5$ provide us the values of the nuclear abundances as they would be in absence of neutrino asymmetry. This would mean that in the absorption systems that we observe, a large negative neutrino asymmetry is needed to change $(D/H)_5$ from ~ 1.5 to ~ 3. On the other hand to explain values of Y_p less than 0.25 in our surroundings, as we already discussed at length, a positive neutrino asymmetry is required. Note that a hint of the presence of inhomogeneities in Deuterium abundances comes from the observation of Deuterium in a $z_\mathrm{abs} = 0.701$ toward QSO 1718+4807 where it was found $(D/H)_5 = 25\pm5$ [55]. Other authors repeated the analysis and, even though they confirm an high value, they arrive at a much looser bound, $(D/H)_5 = 8-57$, concluding that the determination of D/H from QSO 1718+4807 is uncertain [56] [14]. Using a more elaborate model for the velocity distribution inside the absorber, a third group finds $(D/H)_5 = 4.1-4.7$ [57], in any case still higher than the value, 3.3 ± 0.25 deduced from the two cleanest absorption systems. Another system gives a result $(D/H)_5 < 6.7$ [58]. In a recent review the possibility of high amplitude inhomogeneities with an equal proportion of low values $(D/H)_5 \sim 3$ and high values $(D/H)_5 \sim 10$ is excluded [15]. However it cannot be excluded that rare peaks

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[13]A model employing a decaying Mev τ neutrino has also been recently proposed to get a 'just so' BBN scenario [53].

[14]They observe in fact that in this case the spectra of the Lyman series lines is missing. This is needed to determine the velocity distribution of the Hydrogen and these measurements with the high value assume a single velocity component.

with $(D/H)_5 \sim 10$ are present and in any case inhomogeneities with values changing in the range $(D/H)_5 = 1 - 4$ cannot be excluded at the moment. The possibility for Deuterium abundance inhomogeneities has already been explained with the presence of inhomogeneous electron chemical potential [59], an interpretation that could be now enforced by CMBR data.

Active-sterile neutrino oscillations can give rise to an inhomogeneous field of electron neutrino asymmetry when the presence of small inhomogeneities in the baryon number is assumed [60]. In this case, the generated neutrino asymmetry can have an *inverted sign* in points where the baryon number is lower than the average value. Large scale inhomogeneities in the electron neutrino asymmetry might be expected to generate inhomogeneities in the energy densities that would leave an imprint in the CMBR anisotropies that we do not observe. However in the case of active-sterile neutrino oscillations, inhomogeneities in the electron neutrino asymmetry would be compensated by inhomogeneities in the sterile neutrino asymmetry in a way that the energy density remains homogeneous and the mechanism is not constrained by CMBR. There is one difficulty however due to the fact that one has to require the simultaneous presence of large scale regions with positive electron neutrino asymmetry and negative neutrino asymmetry. It has been shown [60] that domains with inverted sign bigger than 10Kpc cannot be generated. In this case even though at the onset of BBN one would get values of abundances in regions with positive electron neutrino asymmetry and also in regions with negative neutrino asymmetry, later on astrophysical processes, like supernovae explosions, would mix the different elements leading to approximately homogeneous values for the abundances.

One way to circumvent this is to assume the existence of two scales. On small scales (less than the diffusion length at the time of freezing of neutron to proton ratio, ~ 100pc) baryon number inhomogenities have to be present. On large scales, as big as required by Deuterium observation, the amplitude of these inhomogeneities has to change such that only in the regions where it is large enough a structure of small scale lepton domains with both signs can form. Neutrino diffusion would afterwards make them merge such that, in these regions, electron neutrino asymmetry is diluted to negligible values prior to the freezing of the neutron to proton ratio. On the contrary in the regions where domains did not form, a non zero electron neutrino asymmetry, with the *normal sign*, would be present [60].

In this way one can easily get a field of neutrino asymmetries with values changing between zero and some maximum values. This means that it would be easily possible to accommodate CMBR with only Deuterium observations (in this case the *normal* sign should be positive) or with only Helium observations (in this case the *normal* sign should be negative).

If we want to accommodate both Deuterium, Helium and CMBR then we need domains with both positive and negative signs on scales larger than 10 Kpc. However, as we mentioned earlier, this violates the bound from Ref. [60]. Actually, the conclusion that domains with inverted sign on scales larger than 10Kpc cannot be obtained relies on a simplified assumption for which domains with inverted sign cannot merge with each other. This is what would happen in the presence of a simple spectrum of baryon inhomogeneities with just two characteristic scale lengths as we just described : one is the scale of small lepton domains ($\lesssim 100$pc) and one is a scale that modulates the amplitude of baryon inhomogeneities in a way that in some regions lepton domains can form and in some others cannot. However in

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a realistic spectrum of baryon fluctuations with a random presence of Fourier components things can be much different and one cannot exclude a priori that in some regions, small inverted sign lepton domains can occupy most of the space and they can merge with each other to form very large domains with a scale higher than about 100Kpc, both with positive and negative sign. These very large scale domains would give rise to inhomogeneities in the nuclear abundances that could not be washed out by astrophysical processes and would survive until the present. [15] A clear signature of this mechanism would be the detection of high values of Helium (~ 0.30) in the regions where Deuterium is also measured with a value $(D/H)_5 \sim 3$ while if some peaks with $(D/H)_5 \sim 10$ really exist, here the Helium abundance should be even at level of $Y_p \sim 0.50$ [59]. However these measurements at large distances seem, at the present, to be quite challenging. Anyway when more measurements from Lyman absorption systems will be available, a clear signature of inhomogeneities could be possible. On the other hand if observations will exclude Deuterium abundance inhomogeneities in the range $(D/H)_5 = 1 - 4$ or larger, then an explanation of the BBN-CMBR discrepancy in terms of a spatially variating electron neutrino asymmetry, as we are proposing, would be ruled out.

VI. CONCLUSIONS

We have discussed the discrepancy between the inferred baryon number density, η from recent CMBR measurements and the value inferred from standard big bang nucleosynthesis. This discrepancy may be due to some type of systematic error or may hint at new physics. We have explored one possible explanation in terms of active - sterile neutrino oscillations. We focussed on the simplest example to illustrate this possibility, and that is the direct production of L_{ν_e} by $\nu_e \rightarrow \nu_s$ oscillations. Within the context of this model, we have shown that $\delta m^2 \approx -1 \ eV^2$ is required to solve the discrepancy between CMBR and Helium measurements and this would suggest that the electron neutrino mass is about 1 eV. This is a particularly interesting value, since it is right near the boundary of current experimental measurements. While we focussed on the largest discrepancy between $\eta_{SBBN}^{^4He}$ and η_{CBR}, we also discussed the $\eta_{SBBN}^{D/H}$ and η_{CBR} discrepancy, and its implications for models with sterile neutrinos. In particular, we looked at two possible scenarios. The first one, would reconcile the deuterium discrepancy with a large ΔN_ν^ρ, while still needing a $\Delta N_\nu^{f_{\nu_e}}$ of the opposite sign to reconcile the Helium measurements. We also proposed a second scenario in which we argue that an inhomogeneous electron neutrino asymmetry could exist which solves these discrepancies. For both of them we showed how active-sterile neutrino oscillations can provide a viable theoretical framework.

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[15]We have to mention that in another alternative model proposed in [59] the simultaneous presence of regions with positive neutrino asymmetry together with regions with negative neutrino asymmetry is a natural consequence. Here of course we are concentrating our attention on active-sterile neutrino oscillations, but the consideration that CMBR could be pointing to the presence of large scale inhomogeneities in the nuclear abundances has a general validity.

Clearly things will soon become more interesting as more accurate measurements of CMBR and light element abundances are done, and also, as we learn more about neutrinos from current and future experiments. Thus, it seems that large neutrino asymmetries, as generated from active - sterile neutrino oscillations offer an exciting interconnection between the rapidly developing fields of neutrino physics and early Universe cosmology.

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Figure Captions

Figure 1: Evolution of $L^{(e)} = 2L_{\nu_e} + \eta$ for $\nu_e \to \nu_s$ oscillations with $\sin^2 2\theta_0 = 10^{-8}$ and, from left to right, $\delta m^2/eV^2 = -0.25, -0.5, -1.0, -2.0, -4.0$ obtained from numerically solving the quantum kinetic equations. The initial $L_{\nu_e} = 0$ is taken and $\eta = 5 \times 10^{-10}$ is assumed. Of course the low temperature evolution is approximately independent of these values.

Figure 2: Change in the effective number of neutrinos for BBN, ΔN_ν versus $-\delta m^2$ for the case $L_{\nu_e} > 0$.

Figure 1

Figure 2