COSMOLOGY OF "VISIBLE" STERILE NEUTRINOS∗

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Abstract

We point out that in scenarios with a low reheating temperature \(T_R \ll 100\) MeV at the end of (the last episode of) inflation or entropy production, the abundance of sterile neutrinos becomes largely independent of their coupling to active neutrinos. Thus, cosmological bounds become less stringent than usually assumed, allowing sterile neutrinos to be “visible” in future experiments. For example, the sterile neutrino required by the LSND result does not have any cosmological problem within these scenarios.

Keywords: Sterile neutrinos; cosmology.

1 Why Sterile Neutrinos?

In the Standard Model of Elementary Particles (SM) there are three massless active neutrinos, \(\nu_\alpha\), coupled to the W and Z weak gauge bosons through gauge couplings. In trivial extensions of the SM there are one or more “sterile” neutrinos, \(\nu_s\), not coupled directly to the Z and W bosons, coupled to the Higgs boson and the active neutrinos through terms in the Lagrangian which yield non-zero neutrino masses. All extensions of the SM need to be explored in any event, but in the case of sterile neutrinos we have the extra motivation of knowing that neutrinos have non-zero masses. In fact the solar mass-square difference \(\Delta m^2_{12} \simeq 8.1 \times 10^{-5} \text{ eV}^2\) and the atmospheric mass difference \(\Delta m^2_{23} \simeq 2.2 \times 10^{-3} \text{ eV}^2\) [2] imply that there are at least three neutrino mass eigenstates. If confirmed, the LSND result [3] (soon to be tested by MiniBooNE [4]) can be explained with a third square mass difference requiring a fourth neutrino mass eigenstate, and, consequently, the existence of at least one sterile neutrino. However, the usual belief is that the existence of this sterile neutrino is rejected by cosmology (see for example Ref. [5]). In fact, all sterile neutrinos which could be found in laboratory experiments in the near future, would have problems with usual cosmological bounds.

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2 Why “Visible” Sterile Neutrinos?

Here we call “visible” the sterile neutrinos which could be found in laboratory experiments. In fact, in order to be found, these sterile neutrinos would necessarily have relatively large active-sterile mixings $\sin \theta$. In the approximation of two-neutrino mixing the interaction neutrino eigenstates $|\nu_{\alpha,s}\rangle$ ($\alpha$ stands for $e, \mu$ or $\tau$) are $|\nu_{\alpha}\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle$ and $|\nu_s\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle$, where $|\nu_{1,2}\rangle$ are the neutrino mass eigenstates. We assume masses $m_1 < m_2 \equiv m_s$ (we call $m_s$ the mass of the heavier, mostly sterile, neutrino mass eigenstate).

The LSND result, would require the third mass-square difference to be $\Delta m^2 \simeq 1 \text{eV}^2$, and $\sin^2 2\theta_{\text{LSND}} \sim 0.001$, where, for small mixing angles, $\theta_{\text{LSND}} = \theta_{se}\theta_{su}$ (and $\sin \theta_{se}$, $\sin \theta_{su}$ are the two-neutrino mixings of $\nu_s$ with $\nu_e$ and with $\nu_\mu$ respectively). But sterile neutrinos could be found in other experiments too: in reactor-$\bar{\nu}_e$ experiments if $\Delta m^2 \simeq \text{eV}^2$, and $\sin^2 2\theta \sim 0.1$; in accelerator-$\bar{\nu}_e$ and $\nu_\mu$ $\bar{\nu}_\mu$ disappearance experiments if $\Delta m^2 \simeq 10 \text{eV}^2$ and $\sin^2 2\theta \sim 0.01 - 0.001$; in $\beta$–decay experiments if $\Delta m^2 \simeq \text{keV}^2$ and $\sin^2 2\theta \sim 0.1 - 0.001$ and in $(\beta\beta)_{0\nu}$ –decays if $(m_s \sin^2 2\theta) < 4 \text{ eV}$ (see Ref.[1] and references therein). All these required active-sterile neutrino mixings much larger that standard bounds on dark matter abundance allow for. The reason is that the sterile neutrinos without extra-SM interactions considered here, are produced in the early universe through their mixing with active neutrinos [6] and (see, for example in Fig. 2 of Ref. [7]) have an acceptable abundance only if their mixing is small, for example $\sin^2 2\theta < 10^{-5}$ for masses $m_s \leq 10 \text{ eV}$. This conclusion follows from standard assumptions made about the history of the Universe before nucleosynthesis, which could be different.

3 Why a Non-Standard Cosmology?

Dodelson and Widrow [8] (see also Ref.[9]) provided the first analytical calculation of the production of sterile neutrinos (without extra-SM interactions) in the early Universe, under the assumption (which we maintain here, for simplicity) of a negligible primordial lepton number, say as small as the baryon number in the Universe $L_{\nu} \simeq 10^{-10}$.

Because the mass eigenstates $\nu_{1,2}$ evolve with different phases, $\simeq e^{-im^2/2E}$ for $E >> m_i$ (we are considering here neutrinos that are relativistic at production), an interaction eigenstate $\nu_s$ produced at $t = 0$, evolves into a mixed state at a later time $t$, $\nu(t) = a(t)\nu_\alpha + b(t)\nu_s$. The probability of $\nu_\alpha$ to become $\nu_s$ at a time $t$ is

$$P(\nu_\alpha \rightarrow \nu_s) = |b(t)|^2 = \sin^2 2\theta \sin^2 \left(\frac{\ell}{L}\right) ,$$

(1)

where $\ell = \Delta m^2 / 2E$ is the vacuum oscillation length. Matter effects change $\ell$ into the oscillations length in matter, $\ell_m$, and $\sin^2 2\theta$ into $\sin^2 2\theta_m = (\ell_m^2 / \ell^2) \sin^2 2\theta$. Collisions force the wave function to collapse after a charateristic time $t_{coll}$. In the early Universe
\( t_{\text{coll}} \gg \ell_m \), so the \( \sin^2 \left( \frac{t_{\text{coll}}}{\ell_m} \right) \) factor appearing in the probability \( P \) averages to \( 1/2 \) (this is called the “averaging regime”).

The rate of production of sterile neutrinos \( \Gamma_s \) is given by the rate of interaction of active neutrinos \( \Gamma_\nu \) multiplied by the probability that in each collision the neutrino state would collapse into a sterile neutrino, i.e. \( \Gamma_s \simeq P(\nu_\alpha \to \nu_s)\Gamma_\nu \), which in the averaging regime is \( \Gamma_s \simeq \left( \frac{\ell_m^2}{\ell^2} \right) \sin^2 2\theta \Gamma_\nu \). With a negligible lepton number,

\[
\ell_m \simeq \frac{\ell}{\left\{ \sin^2 2\theta + \left[ \cos 2\theta - \frac{2E V^T}{\Delta m^2} \right]^2 \right\}^{1/2}}
\]

(2)

where \( V^T \sim T^5 \) is a thermal potential due to finite temperature effects [10] and \( T \) is the temperature of the Universe. From this equation we see that at low temperatures the term containing \( V^T \) is negligible, thus matter effects are negligible, so \( \ell_m \simeq \ell \) as in vacuum and the rate of production of sterile neutrinos decreases very fast with decreasing \( T \), i.e. \( \Gamma_s \simeq n\sigma \sim nT^3 \) (\( n \sim T^3 \) is the number density of particles and \( \sigma \sim T^2/M^4_Z \) is the weak cross section). At high enough temperatures instead, the \( V^T \) term dominates, so \( (\ell_m/\ell) \simeq \Delta m^2/(V^T 2E) \), and the rate of production of sterile neutrinos increases very fast as the temperature decreases, i.e. \( \Gamma_s \simeq \left( \frac{\Delta m^2}{V^T 2E} \right)^2 \Gamma_\nu \sim T^{-7} \). Thus the rate of production of sterile neutrinos has a sharp maximum. The temperature of maximum production is [8]

\[
T_{\text{max}} \approx 130 \text{ MeV} \left( \frac{m_s}{1 \text{ keV}} \right)^{1/3}.
\]

(3)

It is now clear that if the temperature of the Universe is always smaller than \( T_{\text{max}} \) the production of sterile neutrinos is suppressed.

### 4 Low Reheating Temperature Scenarios

In inflationary models, or after a late period of entropy production, the beginning of the radiation dominated era of the Universe results from the decay of coherent oscillations of a scalar field, and the subsequent thermalization of the decay products into a thermal bath, at the so called “reheating temperature” \( T_R \). This temperature may have been as low as 0.7 MeV [11] (a recent analysis strengthens this bound to \( \sim 4 \) MeV [12]). It is well known that a low reheating temperature inhibits the production of particles which are non-relativistic or would decouple at \( T > T_R \) [13]. The final number density of active neutrinos starts departing from the standard number for \( T_R \leq 8 \) MeV but stays within 10% of it for \( T_R \geq 5 \) MeV [14]. For \( T_R = 1 \) MeV the number of \( \nu_{\mu,\tau} \) would be about 2.7% of the standard number. This would have allowed one of the active neutrinos to be a warm dark matter (WDM) candidate (with mass in the keV range), as proposed in Ref. [14], if this were not forbidden by experimental bounds.
Following Ref. [8], but considering that the production of sterile neutrinos starts when the temperature of the universe is \( T_R < T_{max} \), the \( \nu_s \) distribution function turns out to be [1]

\[
f_s(E, T) \simeq 3.2 \, d_\alpha \left( \frac{T_R}{5 \text{ MeV}} \right)^3 \sin^2 2\theta \left( \frac{E}{T} \right) f_\alpha(E, T)
\]

(4)

where \( d_\alpha = 1.13 \) for \( \nu_\alpha = \nu_e \) and \( d_\alpha = 0.79 \) for \( \nu_\alpha = \nu_{\mu,\tau} \) [15].

In the calculation the active neutrinos are assumed to have the usual thermal equilibrium distribution \( f_A = (\exp E/T + 1)^{-1} \), thus, following Ref. [14], we restrict ourselves to \( T_R \geq 5 \text{ MeV} \). For simplicity, we also restrict ourselves to the case of mass \( m_s < 1 \text{ MeV} \). Moreover, for values of \( m_s \) such that the finite temperature potential [10] \( V_T \ll m_s^2/2E \), all matter effects disappear, so the oscillations are as in the vacuum and no dependence on \( m_s \) remains (notice that these oscillations are in the averaging regime). For \( T_R = 5 \text{ MeV} \), the specific value used for the figures, this happens for \( m_s \geq 0.2 \text{ eV} \) (0.1 eV) for \( \nu_e \leftrightarrow \nu_s \) (\( \nu_{\mu,\tau} \leftrightarrow \nu_s \)).

The resulting number fraction of sterile over active neutrinos plus antineutrinos depends only on the active-sterile mixing angle and the reheating temperature,

\[
\frac{n_{\nu_s}}{n_{\nu_\alpha}} \simeq 10 \, d_\alpha \, \sin^2 2\theta \left( \frac{T_R}{5 \text{ MeV}} \right)^3.
\]

Thus, a low reheating temperature insures a small sterile number density, even for very large active-sterile mixing angles. This makes sterile neutrinos in our scenario potentially detectable in future experiments. Notice that the \( \nu_s \)-number density is independent of the mass of the sterile neutrinos (contrary to the result of Ref. [8]). Thus, the mass density of non-relativistic sterile neutrinos, \( \Omega_s h^2 = (m_s \, n_{\nu_s}/\rho_c)h^2 \) depends linearly on the mass and on \( \sin^2 2\theta \),

\[
\Omega_s h^2 \simeq 0.1 \, d_\alpha \, \left( \frac{\sin^2 2\theta}{10^{-3}} \right) \left( \frac{m_s}{1 \text{ keV}} \right) \left( \frac{T_R}{5 \text{ MeV}} \right)^3.
\]

(6)

The condition \( \Omega_s h^2 \leq \Omega_{DM} h^2 = 0.135 \) [16] rejects the triangular dark gray region of masses and mixings shown in Figs. 1 and 2. The values of masses and mixings for which sterile neutrinos constitute 10% of the dark matter are also shown with a dotted line.

Figs. 1 and 2 show bounds for \( \nu_\alpha = \nu_e \) and \( \nu_\alpha = \nu_{\mu,\tau} \), respectively, and for \( T_R = 5 \text{ MeV} \). They show that \( \nu_s \) in our scenario could only be part of the hot dark matter (HDM) in the Universe (i.e. \( m_s << \text{ keV} \)), while neutrinos with \( m_s > 1 \text{ keV} \) are disfavored, if not rejected, as WDM (\( m_s \simeq \text{ keV} \)) or CDM (cold dark matter, \( m_s >> \text{ keV} \)), by bounds coming from supernovae cooling (which exclude the region diagonally hatched with thin lines) and astrophysical bounds due to radiative decays (which exclude the region above the line labeled “DEBRA” for “diffused extragalactic background radiation”), explained in detail in Ref. 1. The region denoted with “X-ray Observatories” could be rejected by observations of galaxy clusters by the Chandra
Figure 1: Bounds and sensitivity regions for $\nu_e \leftrightarrow \nu_s$ oscillations for $T_R \sim 5$ MeV.

Figure 2: Same as Fig. 1 for $\nu_{\mu,\tau} \leftrightarrow \nu_s$. For $\nu_\tau \leftrightarrow \nu_s$ the darkest gray-blue excluded region does not apply.
observatory[17], and the region labeled “Pulsar kicks” shows where sterile neutrinos could possibly explain the large velocity of pulsars [18]. The SN1987A bound on neutrino radiative decays, excludes the region above the line labeled “SMM” (for the “Solar Maximum Mission” satellite) in both figures. The 3σ upper bound imposed by big bang nucleosynthesis on any extra contribution to the energy density \( \Delta N\nu \leq 0.73 \) (see Fig. 7 of Ref. [19]), translates into the vertical excluded band labeled “BBN” in Figs. 1 and 2.

Experimental bounds are also shown (see Ref. [1] for more details). Negative results from reactor-\( \bar{\nu}_e \) and accelerator-\( \nu_\mu \) disappearance experiments reject the darkest/blue regions so labeled in Fig.1 and in Fig. 2 respectively. The absence of kinks in the e\(^-\) spectra in \( \beta\)-decays constrain the \( \nu_e - \nu_s \) mixing (darkest/blue region in Fig. 1). If neutrinos are Majorana particles, present bounds on neutrinoless double beta decay constrain the contribution of the mostly sterile neutrino to the effective \( \nu_e \) Majorana mass, which conservatively translates into the upper bound \( (m_s \sin^2 2\theta) < 4 \text{ eV} \) (allowed region below the dashed line in Fig. 1).

In conclusion, in cosmological scenarios with a low reheating temperature at the end of the last episode of inflation or entropy production, such as \( T_R \sim 5 \text{ MeV} \), the coupling of sterile to active neutrinos can be much larger than standard cosmological scenarios permit. For example, the sterile neutrino required by the LSND result does not have any cosmological problem. In these scenarios, the baryon asymmetry and the bulk of the dark matter in the Universe should also originate in novel ways. The experimental discovery of a sterile neutrino in the region of \( m_s - \sin^2 2\theta \) opened up in this paper, would require an unusual cosmology, such as one with a low reheating temperature as presented here.

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