Realistic Sterile Neutrino Dark Matter with keV Mass does not Contradict Cosmological Bounds

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Previous fits of sterile neutrino dark matter (DM) models to cosmological data ruled out masses smaller than ~8 keV, assuming a production mechanism that is not the best motivated from a particle physics point of view. Here we focus on a realistic extension of the standard model with three sterile neutrinos, consistent with neutrino oscillation data and baryogenesis, with the lightest sterile neutrino being the DM particle. We show that for each mass ≥ 2 keV there exists at least one model accounting for 100% of DM and consistent with Lyman-α and other cosmological, astrophysical, and particle physics data.

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The sterile neutrino is a very interesting dark matter candidate [1–6]. The existence of sterile neutrinos (right-handed or gauge singlet) is one of the most simple and natural explanations of the observed flavor oscillations of active neutrinos. It was observed long ago that such particles can be produced in the early Universe through oscillations with active neutrinos [1]. For any mass [above ~0.4 keV, which is a universal lower bound on any fermionic dark matter (DM) particle, see [7] and references therein] sterile neutrinos produced in this way can end up with a correct relic density [1,2,4,8–10].

A single right-handed neutrino would be unable to explain the two observed mass splittings between standard model (SM) neutrinos. Moreover, should this neutrino play the role of DM, its mixing with active neutrinos would be too small for explaining the observed flavor oscillations [6,11]. However, in the presence of three right-handed neutrinos (one for each SM flavor), active neutrino mass splittings and DM may be explained at the same time [6]. Moreover, the mass of each sterile neutrino can be chosen below the electroweak (EW) scale and additionally explain the matter-antimatter asymmetry of the Universe (baryogenesis) [6]. These observations motivated a lot of recent efforts for developing this model, called the νMSM [8,12], and for constraining sterile neutrino DM [13–15].

Because of its mixing with flavor neutrinos, this DM particle has a small probability of decaying into an active neutrino and a photon of energy $E = m_s/2$ [16], producing a monochromatic line in the spectrum of DM dominated objects. The corresponding photons flux depends on the sterile neutrino mass m_s and mixing angle θ as $F \sim \theta^2 m_s^5$. For each value of the mass and of other parameters in the model (see below), the angle θ is fixed by the requirement of a correct DM abundance. Combining this constraint with bounds on decay lines in astrophysical spectra allows putting an *upper* limit on the mass of DM sterile neutrinos [3,5,13–15].

In the presence of a lepton asymmetry (an excess of leptons over antileptons) the production of sterile neutrino may be of the resonant type [2]. The lepton asymmetry required for this mechanism to be effective is several orders of magnitude larger than the baryon asymmetry $\eta_B \sim 10^{-10}$. In many models of baryogenesis (for a review see, e.g., [17]) both asymmetries are of the same order, as they are generated above the EW scale and sphaleron processes equalize them. In the νMSM, the lepton asymmetry is generated both above and below the EW scale in oscillations or decays of two heavy sterile neutrinos. The lepton asymmetry generated above the EW scale gets converted into a baryonic one by the sphaleron processes, while the asymmetry generated below the EW scale remains [9] (see [18] for a review). Such a large lepton asymmetry [close to the limit imposed by big bang nucleosynthesis (BBN) [19]] appears for many generic values of the parameters of the νMSM satisfying current data on neutrino oscillations, cosmological requirements (baryogenesis, BBN constraints), and particle physics constraints [20]. So, resonant production (RP) is a natural way of producing sterile neutrino DM in the νMSM. At the same time, most previous constrains on sterile neutrino DM assumed nonresonant production (NRP) [1,8].

In the NRP case, the comparison of x-ray bounds [13–15] with constraints on DM relic abundance [8] gives an *upper bound* $m_s^{\rm NRP} \leq 4$ keV on the DM sterile neutrino mass. In the more effective RP scenario, smaller mixing angles are required and the corresponding bound is much weaker: $m_s^{\rm RP} \lesssim 50$ keV [10].

The most robust *lower bound* on the DM mass comes from the analysis of the phase-space density of compact objects, e.g., dwarf spheroidals of the Milky Way halo. The universal Gunn-Tremaine bound [21] can be made stronger if one assumes a particular primordial phase-space distribution function. For NRP sterile neutrinos, this leads to $m_s^{NRP} > 1.8$ keV, while for RP particles the bound is weaker: $m_s^{RP} > 1$ keV [7].

An interesting property of sterile neutrino DM with keV mass is that it falls in the warm dark matter (WDM) category. Lyman-α (Ly-α) forest observations in quasar spectra provide strong *lower bounds* on the mass of DM sterile neutrinos produced with the NRP mechanism [22–24]. The analysis of SDSS Ly-α data led to $m_s^{NRP} >$ 13 keV in Ref. [23], or $m_s^{NRP} > 10$ keV in [22]. In [24] these bounds were revisited using the same SDSS Ly-α data (combined with WMAP5 [25]), but paying special attention to the interpretation of statistics in the parameter extraction, and to possible systematic uncertainties. It was shown that a conservative (frequentist, 3-σ) lower bound is $m_s^{NRP} > 8$ keV. The Ly-α method is still under development, and there is a possibility that some of the related physical processes are not yet fully understood. However, at this moment, it is difficult to identify a source of uncertainty that could give rise to systematic errors affecting the result by more than 30%. Even with such an uncertainty, the possibility to have all DM in the form of NRP sterile neutrinos is ruled out by the comparison of Ly-α results with x-ray upper bounds [24].

In the RP case, Ly-α bounds have not been derived yet. However, in Ref. [24], a ΛCWDM model—containing a mixture of WDM (in the form, e.g., of NRP sterile neutrinos) and cold dark matter (CDM)—was analyzed. Below we will show that although the phase-space distribution of RP sterile neutrinos does not coincide exactly with such mixed models, some results can be inferred from the ΛCWDM analysis. In particular, we will show that for each mass $\gtrsim 2$ keV, there is at least one value of the lepton asymmetry for which the RP sterile neutrino model is fully consistent with Ly-α and other cosmological data (this value of the lepton asymmetry is natural within the νMSM).

Spectra of RP sterile neutrino.—DM production in the RP scenario occurs in two stages [2,10]. In presence of a lepton asymmetry, the conditions for resonant oscillations (related to the intersection of dispersion curves for active and sterile neutrinos) are fulfilled for temperatures of a few hundred MeV. Later, at $T \sim 150(m_s^{RP}/\text{keV})^{1/3}$ MeV, nonresonant production takes place. As a result, the primordial velocity distribution of sterile neutrinos contains a narrow resonant (*cold*) component and a nonresonant (*warm*) one. Its exact form can be computed by taking into account the expansion of the Universe, the interaction of neutrinos with the content of the primeval plasma and the changes in the lepton asymmetry resulting from DM production. In this work, we used the spectra computed in Ref. [10].

Characteristic forms of the spectra are shown in Fig. 1. They are expressed as a function of the comoving momentum $q \equiv p/T_\nu$ (T_ν being the temperature of active neutrinos), and depend on the lepton asymmetry parameter [9] $L_6 \equiv 10^6(n_{\nu_e} - n_{\bar{\nu}_e})/s$ (s being the entropy density). In rest of this work, the notation M2L25 would refer to a model with $m_s^{RP} = 2$ keV and $L_6 = 25$. The shape of the nonresonant distribution tail depends on the mass, but not on L_6. For $q \gtrsim 3$, the distribution is identical to a rescaled NRP spectrum [8] with the same mass (red dashed-dotted line on Fig. 1). We call this rescaling coefficient the *warm component fraction* f_{NRP}. For the few examples shown in Fig. 1, the M3L16 models corresponds to $f_{NRP} \simeq 0.12$, M3L10 to $f_{NRP} \simeq 0.53$ and M3L25 to $f_{NRP} \simeq 0.60$. The maximum of $q^2 f(q)$ for the NRP component occurs around $q \approx 1.5$–2. We define the *cold component* to be the remaining contribution: its distribution is given by the difference between the full spectrum and the rescaled NRP one (red dashed line on Fig. 1), and peaks around $q_{res} \sim$ 0.25–1. Its width and height depend on L_6 and m_s^{RP}.

The DM clustering properties can be characterized qualitatively by the particle's *free-streaming horizon* (see, e.g., [24] for definition), proportional to its average velocity $\langle q \rangle / m$. In the RP case, the dependence of the average momentum $\langle q \rangle$ on m_s^{RP} and L_6 is not monotonic. For a given mass, the RP model departing most from an NRP model is the one with the smallest $\langle q \rangle$ (i.e., with the most significant cold component). For each mass, there is indeed a value of L_6 minimizing $\langle q \rangle$, such that $\langle q \rangle_{min} \approx 0.3 \langle q \rangle_{NRP}$ (cf. [10]). This minimum corresponds to lepton asymmetries that are likely to be generated within the νMSM. For instances, for $m_s^{RP} = 2$, 3 or 4 keV, the spectra with the smallest average momentum are M2L25, M3L16, and M4L12, all having $f_{NRP} \lesssim 0.2$.

For a quantitative analysis, we computed the power spectrum of matter density perturbations $P_{RP}(k, z)$ for these models. The standard software (i.e., CAMB [26]) is not immediately appropriate for this purpose, as it only treats massive neutrinos with a Fermi-Dirac primordial distribution. To adapt it to the problem at hand, we modified CAMB so that it could take arbitrary spectra as input data files. We analyzed the spacing in momentum space needed in order

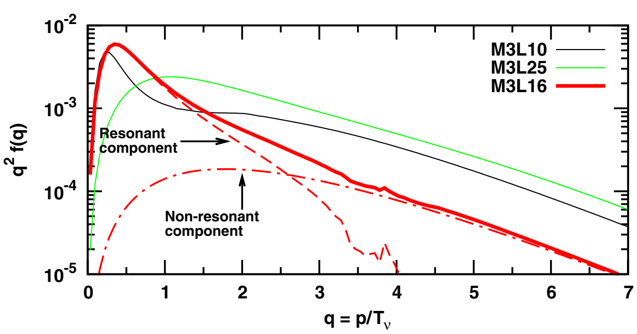

FIG. 1 (color online). Characteristic form of the RP sterile neutrino distribution function for $m_s^{RP} = 3$ keV and various values of the lepton asymmetry parameter L_6. The spectrum for $L_6 = 16$ (red solid line) is shown together with its resonant (dashed) and nonresonant (dashed-dotted) components. All these spectra have the same shape for $q \gtrsim 3$.

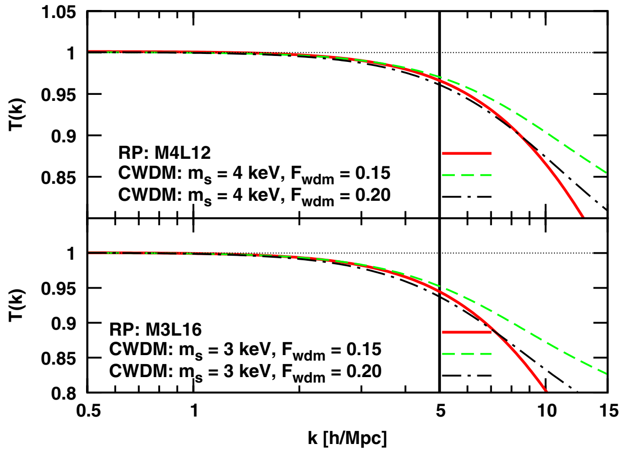

FIG. 2 (color online). TFs for the models M4L12 (top) and M3L16 (bottom), together with CWDM spectra for the same mass and $F_{\rm WDM} \simeq 0.15$ or 0.2.

to obtain precise enough results, and implemented explicit computations of distribution momenta in CAMB. We cross-checked our results by modifying another linear Boltzmann solver—CMBFAST [27], implementing a treatment of massive neutrinos with arbitrary *analytic* distribution function.

To separate the influence of primordial velocities on the evolution of density perturbations from that of cosmological parameters, it is convenient to introduce the transfer function (TF) $T(k) \equiv [P_{\rm RP}(k)/P_{\Lambda{\rm CDM}}(k)]^{1/2}$. Figure 2 shows the transfer function of the models M3L16 and M4L12. The TF becomes smaller than 1 above the wave number associated with the free-streaming horizon today, $k_{\rm FSH} \approx 0.5(m_s^{\rm RP}/1~{\rm keV})h~{\rm Mpc}^{-1}$ (cf. [24]). We see that for a large range of k values above $k_{\rm FSH}$, roughly $k \lesssim 5k_{\rm FSH}$, the transfer function $T_{\rm RP}(k)$ is very close to $T_{\Lambda{\rm CWDM}}(k)$ for the same mass and warm component fraction $F_{\rm WDM} = f_{\rm NRP}$. On smaller scales, $T_{\rm RP}(k)$ decreases faster, since the cold component of RP sterile neutrinos also has a non-negligible free-streaming scale. For all values of the mass studied in this work, $m_s^{\rm RP} \geq 2$ keV, the discrepancy appears above 5 h/Mpc (vertical line in Fig. 2); i.e., above the maximum scale in the three-dimensional power spectrum to which current Ly-α data are sensitive. Hence, for the purpose of constraining RP sterile neutrinos with Ly-α data, it is possible to use the results obtained in the ΛCWDM case. In Ref. [24], we presented the results of a WMAP5 plus SDSS Ly-α data analysis for ΛCWDM models with $m_s^{\rm RP} \geq 5$ keV. In Fig. 3, we show the Bayesian credible region for the mass and the warm component fraction, now extended till $m_s^{\rm NRP} = 2$ keV [28].

Figure 2 demonstrates that for the models M3L16 and M4L12, the function $T_{\rm RP}(k)$ lies above $T_{\Lambda{\rm CWDM}}(k)$ for the same masses and $F_{\rm WDM} = 0.2$ (at least, in the range of wave numbers probed by Ly-α data): so, it can only be in better agreement with cosmological data. We checked that the same is true for M2L25. However, ΛCWDM models with $m_s^{\rm RP} = 2, 3. 4$ keV and $F_{\rm WDM} = 0.2$ are within the 2-σ

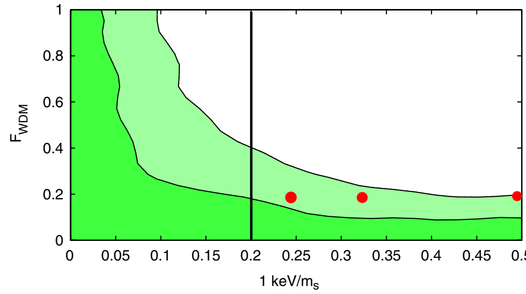

FIG. 3 (color online). 1 and 2-σ bounds from WMAP5 and SDSS Ly-α data on ΛCWDM parameters. Red points correspond to approximations for the models M4L12, M3L16, and M2L25. Results to the left of black vertical lines were already reported in [24].

contour of Fig. 3. We conclude that M2L25, M3L16, and M4L12 are clearly allowed by the data. For larger mass (and still minimal $\langle q \rangle$), the free-streaming horizon is smaller, and agreement with observations can only become easier. Therefore, we see that for each mass $m_{\rm RP} \gtrsim 2$ keV there exists *at least* one value of the lepton asymmetry for which RP sterile neutrinos are perfectly compatible with WMAP5 and SDSS Ly-α data.

Figure 4 shows the range of masses and mixing angles consistent with constraints from phase-space density [7] (left shaded region), from x rays [13,15] (upper right corner, shaded in red) and providing the correct DM abundance (curves between the lines "NRP" and $L_6^{\rm max}$: from top to bottom $L_6 = 8$, 12, 16, 25, 70, 250). The black dashed line shows approximately the RP models with minimal $\langle q \rangle$ for each mass, i.e., the family of models with the largest cold component. We have seen that all black filled circles along this line and with $m_s^{\rm RP} \geq 2$ keV are compatible with Ly-α bounds. In addition, those with $m_s^{\rm RP} \leq 4$ keV are also compatible with x-ray bounds (this conclusion does not change with the new results of Ref. [29]). Note that above 4 keV, Ly-α data allow increasingly high WDM fractions, so that agreement with both Ly-α and x-ray bounds can be maintained with larger values of L_6. This is very clear, e.g., for the models M10L25, M10L16 and M10L12, allowed by x-ray data (open circles on Fig. 4), and consistent with Ly-α data

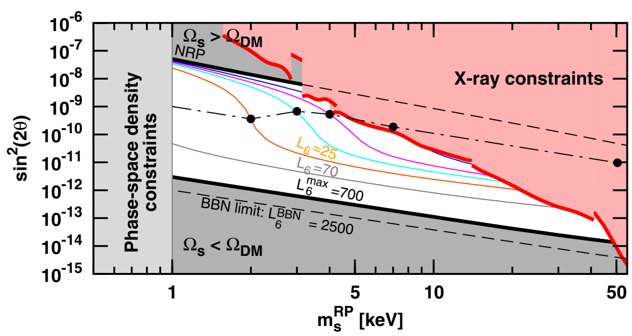

FIG. 4 (color online). Region of masses and mixing angles for RP sterile neutrinos consistent with existing constraints.

since for $m_s^{RP} = 10$ keV, up to 100% of WDM is allowed at the 2-σ level (cf. Fig. 3).

In conclusion, we show in this work that sterile neutrino DM with mass $\geq$2 keV is consistent with all existing constraints. A sterile neutrino with mass $\sim$2 keV is an interesting WDM candidate, as it may affect structure formation on galactic scales. This range of masses and corresponding mixing angles is important for laboratory and astrophysical searches.

To determine the precise shape of the allowed parameter range (which may continue below 2 keV, see Fig. 4), one should perform specific hydrodynamical simulations in order to compute the flux power spectrum on a grid of (m_s^{RP}, L_6) values, and compare with Ly-α data. We leave this for future work.

The νMSM does not require new particles apart from the three sterile neutrinos. Extensions of this model may include a scalar field providing Majorana masses to sterile neutrinos via Yukawa couplings [30,31]. Then, sterile neutrino DM can also be produced by the decay of this scalar field, and also contain a cold and a warm component. We expect a similar range of masses and mixing angles to be allowed by Ly-α data. The quantitative analysis of this model is also left for future work.

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