Maximal Parameter Space of Sterile Neutrino Dark Matter with Lepton Asymmetries

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We delineate the maximal parameter space of sterile neutrino dark matter in the presence of lepton-flavor asymmetries. We focus on large flavor asymmetries with vanishing total lepton asymmetry, which are washed out by neutrino oscillations at MeV temperatures and hence are consistent with big bang nucleosynthesis and cosmic microwave background constraints. We derive a semiclassical Boltzmann equation for sterile neutrinos applicable in this regime and validate it against quantum kinetic equations. For sterile neutrino masses up to 60 keV, the viable range of mixing angles extends by up to 2 orders of magnitude, with broad prospects for tests in forthcoming x-ray, cosmic microwave background, and structure formation observations. We also release a public framework to compute the production of sterile neutrinos, and in particular their momentum distribution, enabling dedicated structure formation analyses.

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Introduction—One of the outstanding issues in both particle physics and cosmology is the nature of dark matter (DM). Among many candidates for DM, the sterile neutrino, a putative massive fermion that is a singlet under the standard model (SM) gauge group, is an attractive candidate.

Many mechanisms for producing the DM relic density of sterile neutrinos are testable by astrophysical observations. The simplest one, known as the Dodelson-Widrow mechanism [1], produces sterile neutrinos through neutrino oscillations in the Early Universe, assuming the standard ΛCDM thermal history. Unfortunately, it is excluded by observations for x-rays [2–10] and structure formation [11–17]. This promotes the search for alternative mechanisms such as resonant production in the presence of lepton asymmetry (Shi-Fuller mechanism) [18–27], production by the decays of scalars [28–38], thermal production with subsequent dilution [39–42], and production in the presence of new active or sterile neutrino self-interactions [43–53].

The Shi-Fuller mechanism efficiently produces sterile neutrinos in the presence of primordial lepton-flavor asymmetries $L_\alpha \equiv n_{L_\alpha}/s$, where n_{L_α} and s are the net lepton number density and the entropy density, respectively, while $\alpha = e, \mu, \tau$ is the lepton flavor. The asymmetries induce a resonant enhancement of the mixing between sterile and active neutrinos. The mechanism is attractive because it does not modify the sterile neutrino interaction Lagrangian beyond the minimal model. However, to produce the sterile neutrino DM while evading all observational bounds, large asymmetries $|\sum_\alpha L_\alpha| \gtrsim 10^{-3}$ may be required. If surviving down to temperatures $T \lesssim 1$ MeV, such asymmetries would heavily modify big bang nucleosynthesis (BBN) and cosmic microwave background (CMB); hence, they are disfavored [54–63].

The BBN and CMB constraints are, however, much weaker if the asymmetries were large at $T \gg 1$ MeV, but later relaxed to zero. This is possible if the L_α pattern is such that the total asymmetry is tiny, $|\sum_\alpha L_\alpha| \lesssim 10^{-3}$. The relaxation may have happened because of active neutrino oscillations, which became effective at $T \simeq 15$ MeV and mixed neutrinos of different flavors [61,62,64–68]. A recent study [62] has demonstrated that in this scenario the allowed individual asymmetries may be as large as $|L_\alpha| \simeq 0.1$.

In this Letter, we show that large lepton-flavor asymmetries with almost zero total lepton asymmetry open up a new parameter space for sterile neutrino dark matter, consistent with all current experimental bounds. To reveal this parameter space, we perform a precise calculation by solving the semiclassical kinetic equations for sterile neutrinos, improving and generalizing the approach developed by Ghiglieri and Laine [22] and Venumadhav *et al.* [23] to the large lepton asymmetries. Our results—viable parameter space of sterile neutrino DM in terms of mass m_s and coupling $\sin^2 2\theta$, marginalized over lepton-flavor asymmetries consistent with cosmological observations—are summarized in Fig. 1. We find that the sterile neutrino DM and lepton asymmetries of interest may be comprehensively tested by future CMB, x-ray, and structure formation observations.

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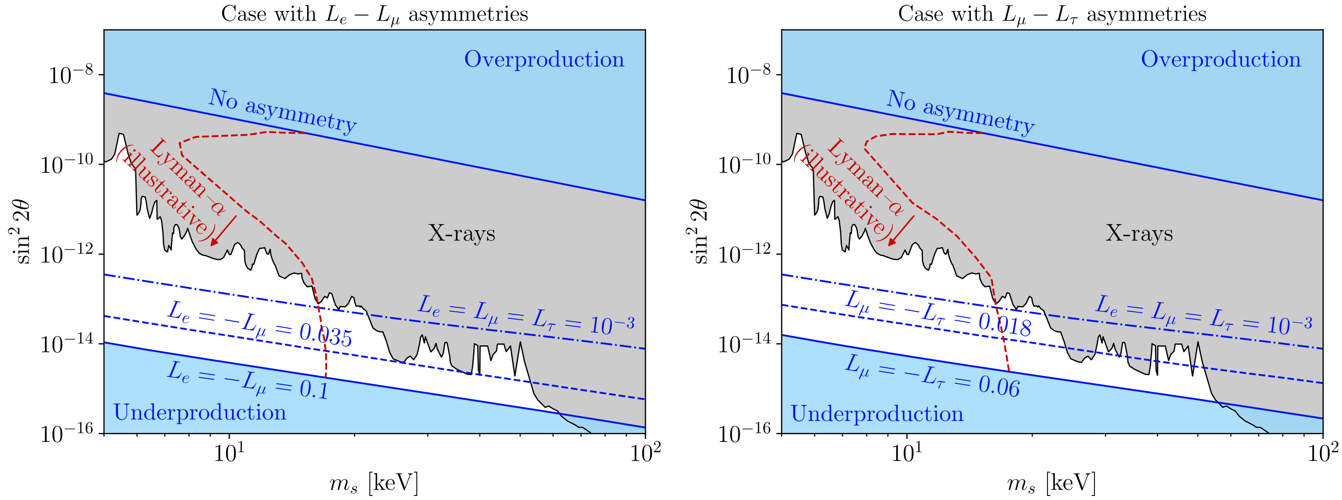

FIG. 1. Parameter space of sterile neutrino mass m_s and its mixing angle with active neutrinos $\sin^2 2\theta$. The white region is the domain where sterile neutrinos may be dark matter in the presence of lepton-flavor asymmetry, as derived in this Letter. The lower boundary corresponds to the scenarios of net-zero lepton-flavor asymmetry $\sum_\alpha L_\alpha = 0$. In the upper blue-shaded region, sterile neutrinos are overproduced, whereas in the lower blue-shaded region, no reliable treatment of the impact of lepton-flavor asymmetries on BBN and CMB exists (see text for details). Left: the case of $L_e = -L_\mu$ and ν_s mixing with ν_e. Right: the case of $L_\mu = -L_\tau$ and ν_s mixing with ν_μ. The gray shaded region is excluded by x-ray observations [2–10]. The space below the contours for $L_e = -L_\mu = 0.035$ and $L_\mu = -L_\tau = 0.018$ (dashed lines) is the target sensitivity of the ongoing Simons Observatory [62,69], assuming normal neutrino mass ordering (see text for the details). The dot-dashed line explains all dark matter with ν_s mixing with ν_e and $L_e = L_\mu = L_\tau = 10^{-3}$, which is the maximal magnitude for flavor-universal lepton asymmetry allowed by the BBN and CMB [61]. Light sterile neutrinos may be in tension with structure formation observations. While we do not derive bounds from structure formation, we mark—purely as an illustrative guide—the region where it could become relevant, using the approximate one-parameter warm dark matter, $m_{\rm WDM}$, mapping of Lyman-α forest constraints from Refs. [70,71] (see text for details); it is shown to the left of the dashed red line.

Reference [26] made a related qualitative remark for a single benchmark mass $m_s = 7.1$ keV. Here, we go substantially beyond by (i) delineating the maximally allowed region in the mass-coupling plane, and (ii) marginalizing over cosmologically allowed lepton-flavor asymmetries. In contrast to Ref. [26], we have found that increasing the lepton-flavor asymmetry tends to produce a *warmer* sterile neutrino spectrum, which is directly relevant for interpreting structure formation observations.

Large primordial lepton-flavor asymmetries may be naturally generated in a class of new physics scenarios, in particular, by the Affleck-Dine (AD) mechanism [72,73]. To motivate the scenario we consider, we propose the AD leptoflavorgenesis scenario, which can consistently generate large yet total-zero lepton-flavor asymmetries. This is discussed in detail in our upcoming paper [74].

Lastly, to reproduce our results and support further studies with any model featuring arbitrary lepton-flavor asymmetry, we publicly release the framework `sterile-dm-lfa` on GitHub [75]: the Python code that traces the evolution of the Early Universe and production of sterile neutrinos using the unintegrated Boltzmann equations in full generality, and the *Mathematica* code that solves it quickly and accurately using the narrow width approximation in the case of a negligible backreaction from sterile neutrinos on the lepton asymmetries.

Technical details and the extended discussion, such as the cross-checks and comparison with other studies (including Refs. [26,27] that appeared while our Letter was in preparation), are provided in Supplemental Material [76].

System of equations—First, we introduce the system of equations we will solve. The most reliable way to track the sterile neutrino production through the resonant oscillations would be solving the evolution equations for the density matrix of active and sterile neutrinos, called the quantum kinetic equations (QKEs) [104–108]. However, fully solving QKEs is computationally expensive.

To save time, the semiclassical Boltzmann equation on the sterile neutrino distribution function $f_{\nu_s}(p,t)$ has been considered in the previous literature [18–26]. Its central ingredient is how active-sterile oscillations are treated: they are averaged over the oscillation length. However, as discussed in Refs. [18–20,24], for very large lepton asymmetries, the resonance timescale becomes shorter than the oscillation timescale. As a result, sterile neutrinos might be produced through nonaveraged oscillations. In that case, the semiclassical Boltzmann equation with averaged oscillations may no longer be valid.

To deal with this issue, we analytically generalize the Boltzmann equation to the case of nonaveraged neutrino oscillations. The resulting equation is, in principle, applicable to arbitrary lepton asymmetries and in excellent agreement with the results of QKEs. Explicitly, for sterile neutrinos ν_s mixing with one flavor of active neutrinos ν_α with the vacuum mixing angle θ, it reads

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_{\nu_s}(p,t) = \frac{\Gamma_\alpha(p,\mu)}{2} P_{\rm eff}(\nu_\alpha \to \nu_s)[f_{\nu_\alpha}(p,\mu) - f_{\nu_s}(p,t)]. \quad (1)$$

Here, H is the Hubble parameter, p is momentum, $f_{\nu_\alpha}(p,\mu)$ is the Fermi-Dirac distribution for active neutrinos, with μ being chemical potential due to lepton asymmetries. Finally, $\Gamma_\alpha(p,\mu)$ is the interaction rate for active neutrinos, and $P_{\rm eff}(\nu_\alpha \to \nu_s)$ is the effective oscillation probability,

$$P_{\rm eff}(\nu_\alpha \to \nu_s) = \frac{1}{2}\frac{\Delta(p)^2 \sin^2 2\theta}{[\Delta(p)\cos 2\theta - V_\alpha(p,\mu)]^2 + \left(\frac{\Gamma_\alpha}{2}\right)^2}, \quad (2)$$

with $\Delta(p) \equiv (m_s^2 - m_{\nu_\alpha}^2)/(2p) \approx m_s^2/(2p)$ being the oscillation frequency in vacuum with sterile neutrino mass m_s, and $V_\alpha(p,\mu)$ the matter potential for active neutrinos. The evolution equation for sterile antineutrinos is the same as that for sterile neutrinos, with the replacement $\mu \to -\mu$.

$P_{\rm eff}(\nu_\alpha \to \nu_s)$ differs from the averaged-oscillation probability used in the literature (e.g., [19,20,23]) in that its denominator lacks the factor $\Delta^2 \sin^2 2\theta$. The reason of this absence is as follows: the oscillation probability is suppressed by the frequent collisions (quantum Zeno effects), $(\Gamma_\alpha/2)^{-1}$, which reset the active state; on the other hand, all neutrinos accumulated by free-streaming length, $(\Gamma_\alpha/2)^{-1}$, experience the resonance. Therefore, the resonance conversion is always computed over $|\Delta\cos\theta - V_\alpha| < \Gamma_\alpha/2$, and the averaged-oscillation factor $\Delta^2 \sin^2\theta$ does not appear (see Supplemental Material for the details).

The condition $\Delta(p)\cos 2\theta - V_\alpha(p,\mu) \approx 0$ defines the domain of temperatures and momenta where sterile neutrinos may be resonantly produced. Using it, we may show that sterile neutrinos with mass $m_s \gtrsim 1$ keV are produced before the flavor asymmetries were washed out by neutrino oscillations, which developed at temperatures $T < T_{\rm osc} \simeq 15$ MeV [61,62,64–68]. To this end, let us analytically estimate the resonance temperature $T_{\rm res}$. Neglecting less important $\mathcal{O}(G_F^2)$ terms, the neutrino matter potential can be sketchily written as $V_\alpha \approx \sqrt{2} G_F L s$ [109], where L is of the order of the maximal asymmetry in the system. Assuming $\theta \ll 1$, $T_{\rm res}$ is

$$T_{\rm res} \sim 27\ {\rm MeV} \times \left(\frac{10.75}{g_*}\right)^{1/4}\left(\frac{3}{y}\right)^{1/4}\left(\frac{0.1}{L}\right)^{1/4}\left(\frac{m_s}{5\ {\rm keV}}\right)^{1/2}, \quad (3)$$

where g_* is the effective number of relativistic species, $p = yT$, and $y \simeq 3$ corresponds to the average energy for neutrinos in thermal equilibrium. For $m_s \gtrsim 5$ keV and $L \lesssim 0.1$, the resonance temperature is well above $T_{\rm osc}$.

We assume that all SM particles were in equilibrium at the epoch well before neutrino decoupling. Then, the remaining equations governing the evolution of the Universe are on the plasma temperature and particle-antiparticle asymmetries. The presence of lepton asymmetries as large as $L \simeq 0.1$ heavily changes both the neutrino production rate Γ_α and the thermodynamics of the Early Universe (i.e., the quantities n, P, ρ, s). In this Letter, we account for these effects for the first time in the context of sterile neutrino production.

The evolution of the plasma temperature is given by the continuity equation (the energy conservation law of the Universe),

$$\frac{d\rho}{dt} = -3H(\rho + P), \quad (4)$$

with

$$\rho = \rho_{\rm SM}(T,\mu) + \rho_{\nu_s}(t), \qquad P = P_{\rm SM}(T,\mu) + P_{\nu_s}(t). \quad (5)$$

Here, $\rho_{\rm SM}$ and $P_{\rm SM}$ are the energy density and pressure in the SM; ρ_{ν_s} and P_{ν_s} are those for sterile neutrinos. The Hubble parameter is given by $H = \sqrt{8\pi\rho/(3m_P^2)}$, with the Planck mass $m_P = 1.22 \times 10^{19}$ GeV.

Let us now discuss particle-antiparticle asymmetries. We consider the scenario when, in the absence of sterile neutrinos, the lepton-flavor asymmetries L_α are conserved at $T \gtrsim 15$ MeV [110]. Since neutrinos and charged leptons are in thermal and chemical equilibrium with the other species, L_α s induce chemical potentials for neutrinos, μ_{ν_α}, as well as baryon and electric charge chemical potentials, μ_B and μ_Q. As the Universe cools, some of these particles become nonrelativistic and annihilate into lighter species, thereby redistributing their asymmetry under the conserved asymmetries [22,23,111–113].

This redistribution is characterized by five equations for the conservation of asymmetries,

$$\frac{\Delta n_{\nu_\alpha} + \Delta n_\alpha}{s} = L_\alpha \quad (\alpha = e, \mu, \tau), \quad (6)$$

$$\sum_i \frac{b_i \Delta n_i}{s} = B, \quad (7)$$

$$\sum_i \frac{q_i \Delta n_i}{s} = 0, \quad (8)$$

where $\Delta n_i = n_i - n_{\bar{i}}$ is the number density asymmetry, $s(T,\mu)$ is the total entropy density, L_α is the conserved lepton-flavor asymmetries, and $B = 8.75 \times 10^{-11}$ [114] is the observed baryon asymmetry. b_i and q_i are the baryon number and electric charge for species i. Solving these equations, we can trace the evolution of μ_{ν_α}, μ_B, and μ_Q. In this part, we mainly follow Ref. [112].

The presence of sterile neutrinos mixing with the lepton flavor α modifies the conservation law of the corresponding lepton asymmetry to $L_\alpha + L_{\nu_s} = \text{const}$, where $L_{\nu_s} \equiv (n_{\nu_s} - n_{\bar{\nu}_s})/s$. We have numerically incorporated this modification in the differential form

$$\frac{d}{dt}L_\alpha = -\frac{1}{s(T,\mu)}\int \frac{dp}{2\pi^2}p^2\frac{d}{dt}[f_{\nu_s}(p,t) - f_{\bar{\nu}_s}(p,t)]. \quad (9)$$

Assuming that sterile neutrinos populate all the dark matter, we may get the upper bound on the backreaction: $|\Delta L_\alpha| \lesssim 10^{-4}(5\ \text{keV}/m_s)$, which is negligible compared to the magnitude of the lepton asymmetries considered in our Letter. In addition, a nonzero total lepton asymmetry induced by L_{ν_s} is well below the upper bound on the flavor-universal asymmetry $L_\alpha \sim 10^{-3}$ imposed by BBN and CMB [61]. As a result, we may safely neglect the impact of ν_s-driven L_α nonconservation on the BBN and CMB, and use the results of [62] for the evolution of the lepton asymmetries at $T < T_{\text{osc}}$.

On the other hand, even tiny dynamical changes in L_α may influence the abundance of sterile neutrinos because of the dependence of the resonance on the asymmetry. We have confirmed that the L_α evolution only changes the sterile neutrino abundance by $< 10\%$, though.

Parameter space and limitations of our Letter—We begin by reviewing current observational bounds on primordial lepton-flavor asymmetries, which serve as input parameters in this Letter. BBN and CMB data constrain various linear combinations of L_α, although certain directions remain weakly constrained [61,62,115,116]. In particular, Refs. [62,115] identify $L_e \simeq -L_\mu$ and $L_\mu \simeq -L_\tau$ as comparatively weakly constrained directions. However, the numerical framework used in those analyses ceases to be reliable for $|L_\alpha| \gtrsim 0.1$ [118]. For this reason, in Fig. 1 we only marginalize over $|L_\alpha| \le 0.1$, which we take as the domain within which current BBN and CMB constraints are robust.

Specifically, we consider two setups to explore the allowed sterile neutrino parameter space under the condition of zero total lepton asymmetry: (i) the least constrained direction $L_e = -L_\mu \le 0.1$, with ν_s mixing with electron neutrinos, and (ii) $L_\mu = -L_\tau \le 0.06$, with ν_s mixing with muon neutrinos [119].

Now, let us summarize Fig. 1. The solid line defining the upper blue domain corresponds to the production of sterile neutrino DM in the case $L_\alpha = 0$. The parameter space below it, down to the lower blue region, is the domain of allowed masses and couplings in the presence of net-zero lepton-flavor asymmetry, as derived in this Letter. It heavily extends over the parameter space for flavor-universal lepton asymmetry. To highlight this, we show the dot-dashed contour, denoting the lowest mixing angle explaining all dark matter with ν_s mixing with ν_e and $L_e = L_\mu = L_\tau = 10^{-3}$, which is the maximal magnitude for flavor-universal lepton asymmetry allowed by the BBN and CMB [61].

From the figure, we see that the mixing pattern of ν_s affects the allowed parameter space only weakly. This is related to the fact that the lower boundary on the mixing angle of the sterile neutrino DM shows a monotonic dependence on both the modulus of L_α and m_s. In particular, for the considered asymmetry patterns, the lower bound is found to scale as $\sin^2 2\theta \propto |L_\alpha|^{-1.25} m_s^{-1.4}$.

Importantly, at the floor of allowed sterile neutrino couplings, ν_s particles are produced at temperatures well below the QCD transition, so the associated uncertainties in the dynamics of strongly interacting matter—such as possible charged-pion condensation and the limited validity of the Taylor expansion of the QCD equation of state in μ_Q/T [112,120,121]—do not affect our result. At higher couplings, production may happen during the transition, but the uncertainties are under control, within tens of percent influence on the abundances. See the detailed discussion, including the description of uncertainties, in Supplemental Material.

Let us now summarize constraints. The gray region is excluded by x-ray observations [2–10]. Additionally, light sterile neutrinos, especially in the keV-mass range, may be constrained by small-scale structure probes; the reason is that such light sterile neutrinos carry non-negligible momenta, suppressing small-scale growth. Such probes include phase-space densities in DM subhalos [14], Lyman-α forests [13], Milky Way satellite counts [15,16], and strong lensing [17] (see also Refs. [26,27]).

To flag where structure formation observations may matter in the sterile neutrino parameter space, we use the approximate "equivalent-m_{WDM}" mapping of Ref. [70] and mark its intersection with the 95% CL thermal-relic limit $m_{\text{WDM}} > 3.1$ keV from Ref. [71] (see details in Supplemental Material). The corresponding region is shown in Fig. 1. This construction is only meant as a rough guide: for nonthermal dark matter, Lyman-α constraints cannot be reduced to a single number, since they depend on the detailed shape of the small-scale cutoff and on astrophysical and systematic assumptions [13,122–124]. Consistently, several studies find that a 7.1 keV resonantly produced sterile neutrino can remain compatible with Lyman-α and Milky Way satellite data, subject to modeling choices [125–128]. Moreover, Ref. [71] reports large analysis-dependent uncertainties in the inferred thermal mass, underscoring that a dedicated study is required for robust bounds. We therefore include the m_{WDM} curve only as a guide. Nevertheless, our framework provides sterile neutrino spectra enabling future dedicated structure formation analyses.

Combining these results, we find that sterile neutrinos with masses $m_s \lesssim 60$ keV and large lepton-flavor asymmetries may explain the observed dark matter abundance without conflicting with various cosmological and astrophysical constraints.

Extending the analyses of Refs. [62,115] to larger asymmetries, $|L_\alpha| > 0.1$, could further lower the allowed floor on sterile-neutrino couplings. Given that the production of sterile neutrinos in these scenarios happens below the QCD transition, our method may be straightforwardly extended to such asymmetries; we leave this to future work.

Observational prospects—The future x-ray experiments eROSITA [129], Athena [130], and eXTP [131] will test the smaller mixing angle. In particular, eXTP may significantly improve the current x-ray constraints for $m_s \leq 100$ keV [131]. However, the systematic uncertainty of eXTP is not yet well known. Predictions for future observations of the structure formation are less clear, but these observations might test even heavier masses of sterile neutrino dark matter.

Lepton-flavor asymmetries will be further tested by future CMB and BBN observations [62]. For normal neutrino mass ordering, the Simons Observatory [69] can potentially test $L_e = -L_\mu \gtrsim 0.035$ and $L_\mu = -L_\tau \gtrsim 0.018$. For inverted neutrino mass ordering, it may not improve the current constraints. In the near future, the Dark Energy Spectroscopic Instrument and CMB observations would more precisely measure the sum of neutrino masses and thereby may explore neutrino mass ordering [132–139].

Origin of lepton-flavor asymmetries—In this scenario, large lepton-flavor asymmetries with zero total lepton asymmetry must exist in the Early Universe prior to the sterile neutrino production.

There are potentially several mechanisms for generating lepton-flavor asymmetries in the Early Universe [74,140–146]. In particular, the AD mechanism [72,73] is one of the promising scenarios that naturally explains the origins of large lepton-flavor asymmetries. In the supersymmetric theory, there are flat directions in the scalar potential that have no total lepton charge but lepton-flavor charge (e.g., $Q\bar{u}L_\alpha\bar{e}_\beta$). Scalar fields can have large expectation values along the flat direction, generating large lepton-flavor asymmetries.

Large lepton-flavor asymmetries can also offer a natural explanation of the small baryon asymmetry. The sphaleron process preserves the quantity $(B/3 - L_\alpha)$ for each lepton flavor α but violates $B + L$, where $L = \sum_\alpha L_\alpha$. If lepton-flavor asymmetries with $B - L = 0$ are generated before the sphaleron transition, the conversion from the flavor asymmetries to baryon asymmetry cancels out, but not completely [141,147,148], suggesting that large lepton-flavor asymmetries may underlie the observed small baryon asymmetry. In addition, in the AD mechanism, these scalar fields can deform into nontopological solitons called "Q balls," where the $B + L$ charge is protected from the sphaleron processes, thus allowing even larger lepton asymmetries without overproducing the baryon asymmetry.

The AD mechanism with the $Q\bar{u}L_\alpha\bar{e}_\beta$ direction can successfully produce large yet total-zero lepton asymmetries at $T \gtrsim 1$ GeV, which is much higher than the resonance temperature $T_{\rm res}$, Eq. (3), where sterile neutrinos are resonantly produced. Detailed discussions are devoted to this in the upcoming paper [74].

Conclusion—keV-mass sterile neutrinos were proposed as one of the excellent dark matter candidates. However, the minimal realizations of sterile neutrino DM are severely constrained by the observations of x-rays and structure formation.

We have demonstrated that lepton-flavor asymmetries with zero total lepton asymmetry, loosely constrained by the current BBN and CMB observations, open up a new parameter space for sterile neutrino DM. To this end, we have performed a precise calculation of the resonant production of sterile neutrinos, including, for the first time, the impact of the large lepton asymmetries on the neutrino interaction rates and thermodynamics of the Universe. The semiclassical Boltzmann equations with nonaveraged neutrino oscillations we used are confirmed by quantum kinetic equations for various regimes where oscillations may or may not be averaged over the oscillation length.

Widely marginalizing over the lepton-flavor asymmetries, we have estimated the maximal parameter space to explain all DM in the mass range $m_s \lesssim 60$ keV, and found that the allowed sterile neutrino squared couplings may cover up to 2 orders of magnitude, depending on mass. The newly opened parameter space is highly testable by future x-ray, structure formation, and CMB searches.

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Data availability—The data that support the findings of this article are openly available [75].

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