Intimate Relationship between Sterile Neutrino Dark Matter and ΔN_{eff}

Kevin J. Kelly^{1,*}, Manibrata Sen^{2,3,†} and Yue Zhang^{4,‡}

¹Theory Department, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

²Department of Physics, University of California Berkeley, Berkeley, California 94720, USA

³Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA

⁴Department of Physics, Carleton University, Ottawa, Ontario K1S 5B6, Canada

(Received 10 November 2020; revised 22 March 2021; accepted 15 June 2021; published 20 July 2021)

The self-interacting neutrino hypothesis is well motivated for addressing the tension between the origin of sterile neutrino dark matter and indirect detection constraints. It can also result in a number of testable signals from the laboratories to the cosmos. We show that, in a broad class of models, where the sterile neutrino dark matter relic density is generated by a light neutrinophilic mediator, there must be a lower bound on the amount of extra radiation in early Universe, in particular, $\Delta N_{\text{eff}} > 0.12$ at the cosmic microwave background (CMB) epoch. This lower bound will be further strengthened with an improved x-ray search at the Athena observatory. Such an intimate relationship will be unambiguously tested by the upcoming CMB Stage 4 project.

DOI: [10.1103/PhysRevLett.127.041101](https://doi.org/10.1103/PhysRevLett.127.041101)

Introduction.—The origin of dark matter (DM) poses a fascinating puzzle. A sterile neutrino with a keV-scale mass and small mixing with active neutrinos is a simple, longstanding DM candidate. Along with other traditional candidates (e.g., weakly interacting massive particles and axions), sterile neutrinos are highly testable. In the minimal setup, the active-sterile neutrino mixing that can account for the observed DM relic density [1] is already in tension with searches for DM decaying into monochromatic x rays [2]. An elegant solution for alleviating this tension is to introduce a new self-interaction among active neutrinos. This keeps neutrinos in thermal equilibrium with themselves longer in the early Universe and facilitates efficient sterile neutrino DM ($S\nu$ DM) production [3,4]. This mechanism is attractive because it predicts a number of novel signatures for laboratory tests [5–7]. Interestingly, the self-interacting neutrino scenario emerges from a broad class of well-motivated beyond-standard-model frameworks [8–24].

We will soon enter a new precision era of cosmology. The Cosmic Microwave Background Stage 4 (CMB-S4) project [25] is expected to measure cosmological parameters to an unprecedented level. In particular, it could restrict the amount of extra radiation (in units of extra neutrinos, ΔN_{eff}) during the CMB epoch to a few-percent uncertainty, while it is still allowed (perhaps even favored)

to be order one by the current data [26,27]. This could shed light on existing tensions resulting from various ways of measuring the Hubble parameter [28–31], as well as fundamental theories that can accommodate deviations from the standard cosmology. Moreover, ΔN_{eff} measurement during the big bang nucleosynthesis (BBN) epoch puts further restrictions on room for new physics.

In this Letter, we point out an intriguing relationship between the two important ingredients of our Universe—the origin of $S\nu$ DM and ΔN_{eff} for both CMB and BBN. The connection is established by a light mediator with a feeble coupling to active neutrinos such that it enters the thermal bath after BBN but decays away before CMB. $S\nu$ DM then is dominantly produced from active neutrino self-scattering through the exchange of on-shell mediator. The post-BBN thermalization of the mediator inevitably modifies the standard cosmology predictions by making new contributions to $\Delta N_{\text{eff}}^{\text{CMB}}$ and $\Delta N_{\text{eff}}^{\text{BBN}}$. As a result, the viable parameter space for $S\nu$ DM relic density is highly correlated with the predictions of ΔN_{eff} . We further point out a new implication of the upcoming x-ray search by the Athena experiment for the next-generation precision measurements in cosmology—this scenario connects different frontiers of cosmological and astrophysical probes.

Models.— $S\nu$ DM is a linear combination of a gauge singlet fermion and the active neutrino states from the standard model [1], $\nu_4 = \nu_s \cos \theta + \nu_a \sin \theta$, where ν_4 denotes a mass eigenstate and θ is the active-sterile mixing angle in vacuum. The sterile neutrino is a decaying DM candidate whose longevity is attributed to its small mass and mixing. We introduce a new force among active neutrinos,

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

$$\mathcal{L}_{\text{int.}} = \frac{\lambda_{\alpha\beta}}{2} \nu_\alpha \nu_\beta \phi + \text{H.c.}, \quad (\alpha, \beta = e, \mu, \tau), \quad (1)$$

which can arise from dimension-six gauge invariant operators at energy scales well below the weak scale. The scalar field ϕ could be either real or complex. If real, ϕ could be identified as the Majoron [8,9], where $\lambda = iM_\nu/f$ and f is the spontaneous lepton-number breaking scale. If complex, ϕ also contains the radial mode and restores $B-L$ symmetry at high scales [5]. The impact of active neutrino self-interactions on the relic density of $S\nu\text{DM}$ was first explored in [3]. The new force enables more frequent active neutrino scattering than normal weak interactions; thereby, $S\nu\text{DM}$ can be produced with a smaller mixing angle than required by Dodelson and Widrow [1]. Reference [3] focuses on m_ϕ between MeV and GeV scales, where the new interaction is sufficiently strong to fully thermalize ϕ before BBN.

The present Letter broadens the focus and opens up the possibility of a sub-MeV mediator ϕ . The constraint from BBN is lifted if ϕ does not thermalize before or during the BBN epoch and has no primordial population from other high-scale physics [32–40]. This is achieved with a feeble coupling to neutrinos and a phase-space suppression for $\nu\nu \rightarrow \phi$ to occur at temperatures much higher than m_ϕ . The condition for not thermalizing ϕ before BBN sets an upper bound on λ that scales as $1/m_\phi$, whereas correct DM relic density requires λ to scale as $\sqrt{m_\phi}$ in the small coupling regime. As a result, viable parameter space opens up for m_ϕ between keV and MeV scales.

Remarkably, our result, in tandem with that from Ref. [3], nicely forms the “big picture” of Fig. 1. The thick black curve depicts the entire range of the theory space where the relic density of $S\nu\text{DM}$ is explained, aided by neutrino self-interaction. Viable mediator mass range divides into two windows, above and below MeV scale. They correspond to different histories of the neutrino and $S\nu\text{DM}$ sector in the early Universe. In the heavier mediator region, the strongest probes are from terrestrial experiments. In contrast, the sub-MeV mediator regime will be best explored by cosmological observations of ΔN_{eff} , to be detailed below.

Cosmology.— $S\nu\text{DM}$ production is governed by

$$\frac{df_4(E, z)}{dz} = \frac{\Gamma(E, z) \sin^2 2\theta}{4Hz} f_a(E, z) \Theta(E - m_4), \quad (2)$$

where f_4/f_a are phase-space distribution functions of sterile-active neutrinos, respectively. We introduce $z \equiv m_\phi/T_\nu^{\text{SC}}$ to label time, where T_ν^{SC} is defined as the neutrino temperature in the standard cosmology without ϕ ; z expands linearly with the Universe’s radius. The actual neutrino temperature T_ν is affected by the interaction in Eq. (1). After weak-interaction decoupling, T_ν deviates from T_ν^{SC} as the ϕ population builds. Γ is the thermally

FIG. 1. The big picture: full parameter space that can account for the relic density of $S\nu\text{DM}$ (thick black curve). We choose $m_4 = 4$ keV and $\sin^2 2\theta = 5 \times 10^{-9}$. The colored regions show the experimental constraints on neutrino self-interaction mediated by a real scalar ϕ , including leptonic meson decays [5,6,17,41] (purple), invisible Z width [5,7] (orange), double-beta decay [42–44] (green), and ΔN_{eff} for successful BBN [45] (blue). We will explore the $S\nu\text{DM}$ production mechanism in the sub-MeV m_ϕ region marked by “This Work,” which could be fully tested by the upcoming CMB-S4 and Athena experiments.

averaged scattering rate for an active neutrino, and H is the Hubble parameter. Since we are interested in small m_ϕ and λ , the effective active-sterile mixing angle is approximately equal to the vacuum one throughout the dominant $S\nu\text{DM}$ production window.

The distribution function f_a , after active neutrinos thermalize with ϕ , is characterized by T_ν and a chemical potential μ_ν ,

$$f_a(E, z) = \frac{1}{1 + \exp\{[E - \mu_\nu(z)]/T_\nu(z)\}}. \quad (3)$$

To derive their z dependence, we introduce three time-scales: (i) z_A : the onset of BBN—neutrinos have just decoupled from weak interaction. We assume ϕ has not yet equilibrated with neutrinos. (ii) z_B : the ν - ϕ system has just equilibrated. In general, ϕ remains ultrarelativistic. (iii) z_C : all ϕ have decayed away ($T \ll m_\phi$), mostly into neutrinos, with a small fraction decaying into $S\nu\text{DM}$.

Before z_A , neutrinos and photons obey $T_\nu = T_\nu^{\text{SC}} = T_\gamma$. The ν - ϕ interaction freezes in a subthermal population of ϕ via the Boltzmann equation

$$\frac{dY_\phi}{dz} = -\frac{\gamma_{\phi \leftrightarrow \nu\nu}}{sHz} \left(\frac{Y_\phi}{Y_\phi^{\text{EQ}}} - 1 \right), \quad (4)$$

where $Y_\phi = n_\phi/s$ is the yield, n_ϕ is the number density of ϕ , and s is the entropy density of the Universe. The thermally averaged rate is defined as $\gamma_{\phi \leftrightarrow \nu\nu} \equiv n_\nu^{\text{EQ}} \langle (m_\phi/E) \Gamma_{\phi \rightarrow \nu\nu} \rangle$, where $\Gamma_\phi = 3\lambda^2 m_\phi / (32\pi)$ is the

decay rate at rest. Here we assume ϕ couples universally to all neutrinos, $\lambda_{ee,\mu\mu,\tau\tau} = \lambda$. In the small m_ϕ limit, $\gamma_{\phi \rightarrow \nu\nu} \simeq m_\phi^3 \Gamma_\phi / (2\pi^2 z^2)$. (The $\nu\bar{\nu} \rightarrow \phi\phi^{(*)}$ process is only important for the coupling λ much larger than those of interest to this Letter [46,47].) Assuming no ϕ population at early times, integrating Eq. (4) up to z_A determines the population of ϕ and its contribution to $\Delta N_{\text{eff}}^{\text{BBN}}$.

From z_A – z_B , the ν - ϕ interaction induces chemical equilibrium. At z_B , T_ν deviates from T_ν^{SC} ; a chemical potential is also generated, $\mu_\phi = 2\mu_\nu = 2\mu_{\bar{\nu}}$ for real scalar ϕ , or $\mu_\phi = 2\mu_\nu$ and $\mu_{\phi^*} = 2\mu_{\bar{\nu}}$ for complex ϕ . Without CP violation, $\mu_\phi = \mu_{\phi^*}$. At z_B , T_ν and μ_ν are dictated by energy–lepton-number conservation [48–51]. Entropy is not preserved here; the ϕ thermalization process is irreversible. We provide details of this matching in the Supplemental Material [52].

The most important epoch for $S\nu\text{DM}$ production is from z_B – z_C , by the $\nu\nu \rightarrow \nu\nu_4$ process with on-shell, s -channel ϕ exchange. This is terminated after ϕ becomes nonrelativistic and freezes out. Entropy–lepton-number conservation allows us to derive $T_\nu(z)$ and $\mu_\nu(z)$. The total energy of the Universe increases because some ϕ decay while turning nonrelativistic. The neutrino self-interaction rate also depends on $T_\nu(z)$ and $\mu_\nu(z)$,

$$\Gamma(E, z) = \frac{3\lambda^2 m_\phi^2 T_\nu e^{\mu_\nu/T_\nu}}{4\pi E^2} [\ln(1 + e^\omega) - \omega] \sqrt{1 - \frac{m_4^2}{m_\phi^2}}, \quad (5)$$

where $\omega = m_\phi^2/(4ET_\nu)$. With the above, we integrate Eq. (2) up to z_C to obtain the relic abundance of $S\nu\text{DM}$,

$$\Omega_4 = \frac{m_4 s_0}{2\pi^2 s(z_C) \rho_0} \int_{m_4}^{\infty} E dE \sqrt{E^2 - m_4^2} f_4(E, z_C), \quad (6)$$

where $s_0 = 2891.2 \text{ cm}^{-3}$ and $\rho_0 = 1.05 \times 10^{-5} h^{-2} \text{ GeV/cm}^{-3}$ are entropy and critical energy densities today [53]. The total entropy density at time z_C (we take $z_C = 30$) is

$$s(z_C) = \frac{2\pi^2}{45} [2T_\gamma^3 + 2s_\nu(T_\nu(z_C), \mu_\nu(z_C))], \quad (7)$$

where $T_\gamma \simeq 1.39 T_\nu^{\text{SC}} = 1.39 m_\phi / z_C$, and

$$s_\nu(T_\nu, \mu_\nu) = -\frac{3}{\pi^2} \left[4\text{Li}_4(-e^{\mu_\nu/T_\nu}) - \frac{\mu_\nu}{T_\nu} \text{Li}_3(-e^{\mu_\nu/T_\nu}) \right]. \quad (8)$$

The ν - ϕ dynamics also allow one to calculate $\Delta N_{\text{eff}}^{\text{BBN}}$ and $\Delta N_{\text{eff}}^{\text{CMB}}$. A positive $\Delta N_{\text{eff}}^{\text{BBN}}$ is generated by the non-thermal production of ϕ at temperatures above the MeV scale,

$$\Delta N_{\text{eff}}^{\text{BBN}} \simeq 3.046 \left(\frac{\rho_\phi(z_A)}{\rho_\nu(z_A)} \right), \quad (9)$$

where $\rho_\nu(z_A) = 9\zeta(3)T_\nu(z_A)^4/(4\pi^2)$ and $\rho_\phi(z_A)$ can be calculated by solving Eq. (4). The thermal reaction rate $\gamma_{\phi \leftrightarrow \nu\nu}$ is proportional to $(\lambda m_\phi)^2$, implying weaker BBN constraints for light ϕ .

By CMB times, ϕ particles have decayed away. The contribution to $\Delta N_{\text{eff}}^{\text{CMB}}$ is due to the nonstandard distribution function of active neutrinos,

$$\Delta N_{\text{eff}}^{\text{CMB}} = 3.046 \left(\frac{\rho_\nu}{\rho_\nu^{\text{SC}}} - 1 \right), \quad (10)$$

where

$$\frac{\rho_\nu}{\rho_\nu^{\text{SC}}} = -\frac{720}{7\pi^4} \left(\frac{T_\nu(z_C)}{T_\nu^{\text{SC}}(z_C)} \right)^4 \text{Li}_4(-e^{\mu_\nu(z_C)/T_\nu(z_C)}). \quad (11)$$

($S\nu\text{DM}$ production via active-sterile mixing also leads to a slight reduction in the active neutrino population. However, given the lower $S\nu\text{DM}$ number density compared to that of neutrinos, this modifies $\Delta N_{\text{eff}}^{\text{CMB}}$ by less than 1%.)

In short, neutrino self-interactions in the early Universe via a light mediator ϕ imply a tight correlation between the origin of $S\nu\text{DM}$ and the amount of extra radiation. The post-BBN thermalization of ϕ provides a novel mechanism that accounts for the correct relic density of $S\nu\text{DM}$. Meanwhile, ϕ thermalization distorts the active neutrino phase-space distribution, causing $\Delta N_{\text{eff}} > 0$ for both CMB and BBN. It is then of great interest to quantify this interplay, especially the prediction for $\Delta N_{\text{eff}}^{\text{CMB}}$, which will serve as a well-motivated target for the upcoming CMB-S4.

Results and discussions.—We select three benchmark $S\nu\text{DM}$ masses, $m_4 = \{2.5, 4, 7.1\}$ keV, with the correspondingly largest active-sterile mixing parameter, $\sin^2 2\theta \simeq \{5 \times 10^{-9}, 10^{-9}, 7 \times 10^{-11}\}$, consistent with current x-ray search limits [2,54–56]. In Fig. 2, we scan over (m_ϕ, λ) , focusing on m_ϕ between keV and MeV scales, and derive the black solid curves that can account for the observed DM relic abundance, $\Omega_{\nu_4} h^2 = 0.1186$. For $m_\phi \gg m_4$, all the curves follow $\lambda \sim m_\phi^{1/2}$, matching the result for $m_\phi \gtrsim 1$ MeV [3]. As $m_\phi \rightarrow m_4$, the curves bend up, where larger coupling λ is required, compensating for the phase-space suppression of the $\phi \rightarrow \nu\nu_4$ decay. We also present contours of constant $\Delta N_{\text{eff}}^{\text{BBN}}$ and $\Delta N_{\text{eff}}^{\text{CMB}}$ generated by the ϕ - ν interaction. Their intersections with the black contours dictate the correlation between Ω_4 and ΔN_{eff} . For real (complex) scalar ϕ , we find the following predictions: $0 < \Delta N_{\text{eff}}^{\text{BBN}} < 0.57(1.14)$ and $0.12(0.19) < \Delta N_{\text{eff}}^{\text{CMB}} < 0.9(1.95)$. The maximal values correspond to strong couplings with ϕ fully thermalized by BBN, whereas the minimal values correspond to sufficiently small λ and/or m_ϕ and negligible pre-BBN population of ϕ . In the lower-left half of each $\lambda - m_\phi$ plane, both $\Delta N_{\text{eff}}^{\text{BBN}}$ and $\Delta N_{\text{eff}}^{\text{CMB}}$ follow the same parametrical dependence as the ϕ

FIG. 2. Sterile neutrino DM relic density (black contours) and ΔN_{eff} (orange and blue contours for CMB and BBN, respectively), as a function of λ and m_ϕ for real (left) and complex (right) scalar ϕ . We present three choices of the $S\nu$ DM mass with the largest experimentally allowed mixing angles (see main text).

production rate $\gamma_{\phi \leftrightarrow \nu\nu}$ in Eq. (4) and depend only on the product (λm_ϕ) .

Thanks to the late thermalization of ϕ , the predicted $\Delta N_{\text{eff}}^{\text{CMB}}$ values are always higher than $\Delta N_{\text{eff}}^{\text{BBN}}$. However, we find $\Delta N_{\text{eff}}^{\text{BBN}}$ is not always negligible and it serves as an independent test of nonstandard neutrino cosmology. The prior-to-BBN production of ϕ particles can increase the expansion rate of the Universe, leading to a higher neutron-to-proton ratio when BBN begins and thus higher helium and deuterium abundances [17]. The state-of-the-art limit $\Delta N_{\text{eff}}^{\text{BBN}} \lesssim 0.5$ [45] marginally excludes the case of fully thermalized real scalar ϕ prior to BBN and sets a stronger constraint for complex ϕ . Note that the scalar can only mediate neutrino self-interactions, ensuring that weak interactions are unaffected, and hence heat transfer from the plasma to the neutrino sea is only indirectly impacted. The changes produced in the primordial abundances of helium and deuterium are well within observational

uncertainties, and hence the state-of-the-art limit applies [57]. Precision calculations of neutrino decoupling taking into account of entropy transfer from the plasma to ν (and ϕ) could improve the accuracy of the $\Delta N_{\text{eff}}^{\text{BBN}}$ prediction to $\mathcal{O}(1\%)$ level [58,59].

From Fig. 2, for each $S\nu$ DM mass one can derive the lowest predicted values of $\Delta N_{\text{eff}}^{\text{BBN}}$ and $\Delta N_{\text{eff}}^{\text{CMB}}$. Reducing θ would require larger λ to maintain Ω_{ν_4} , resulting in larger $\Delta N_{\text{eff}}^{\text{BBN}}$ and $\Delta N_{\text{eff}}^{\text{CMB}}$ until they saturate to their maxima. Remarkably, this predicts a target ΔN_{eff} for precision BBN and CMB measurements. Moreover, because θ is more strongly constrained for higher $S\nu$ DM mass, an upper bound on ΔN_{eff} could set an upper bound on m_4 . This forms a novel interplay with DM indirect detection experiments. Inspired by this, we present Fig. 3. For each m_4 , we combine the current x-ray constraint and the Ω_{ν_4} requirement to derive minimal values of $\Delta N_{\text{eff}}^{\text{BBN}}$ and $\Delta N_{\text{eff}}^{\text{CMB}}$, as shown in the left panel. We refer to Supplemental Material

FIG. 3. Minimal value of ΔN_{eff} at the time of CMB (orange) and BBN (blue) as a function of $S\nu$ DM mass m_4 . All contours correspond to the largest allowed active-sterile mixing parameter $\sin^2(2\theta)$ by the current (left) and upcoming (right) searches of x-ray line from $\nu_4 \rightarrow \nu\gamma$ decay.

Sec. B for more details [52]. We find $\Delta N_{\text{eff}}^{\text{CMB}} > 0.12$ for all regions of interest, a favorable target for CMB-S4. For $m_4 \gtrsim 6$ keV, $\Delta N_{\text{eff}}^{\text{BBN}}$ and $\Delta N_{\text{eff}}^{\text{CMB}}$ have already reached their maxima. Figure 3 (right) shows the impact of projected $\sin^2 2\theta$ constraints by the Athena x-ray observatory [60] on ΔN_{eff} . With smaller $\sin^2 2\theta$, higher minimal values of $\Delta N_{\text{eff}}^{\text{BBN}}$ and $\Delta N_{\text{eff}}^{\text{CMB}}$, in particular, $\Delta N_{\text{eff}}^{\text{CMB}} > 0.3$, are necessary. These predictions will be robustly tested by CMB-S4, with $\Delta N_{\text{eff}}^{\text{CMB}}$ precision at the few-percent level. The two classes of probes are highly complementary and will further restrict or discover $S\nu\text{DM}$.

The range of $S\nu\text{DM}$ mass shown in Fig. 3 is $2 \text{ keV} < m_4 < 10 \text{ keV}$. Lower values of m_4 are inconsistent with the phase-space density constraint from dwarf galaxies [2,61,62]. A stronger lower bound on m_4 may be set using Lyman- α forest [63] and Milky Way satellite dwarf galaxy counts [64]. In our scenario, the DM free-streaming length can be substantially shorter than regular warm DM. In numerical calculation, we note that $S\nu\text{DM}$ is dominantly produced around $z \sim 3\text{--}4$, where ϕ already starts to turn nonrelativistic (see Fig. 2 in Supplemental Material Sec. A [52]). The initial DM velocity is thus suppressed if $m_\phi \sim m_4$. Interestingly, such a near-degeneracy exactly occurs where ΔN_{eff} is minimized (see Fig. 2). As a result, small-scale constraints are relaxed.

So far we have assumed that ϕ couples equally to all active neutrinos. Our conclusions qualitatively hold if this assumption is relaxed to generic flavor nonuniversal and/or off-diagonal couplings. By the time of ϕ thermalization, there is sufficient time for neutrino flavor conversions to occur, which necessarily equilibrates ϕ with all the active neutrinos.

Before closing, we comment on other relevant constraints. A sub-MeV ϕ that couples to the electron neutrino of the form Eq. (1) can affect the two-neutrino double-beta decay rate. The current limit, $\lambda \lesssim 10^{-4}$ [42–44], lies above Fig. 2. Another slightly weaker constraint on the ϕ - ν coupling comes from the cooling of core-collapsing supernovae [44,65–67].

In summary, we explored the impact of active neutrino self-interaction, mediated by an ultralight scalar ϕ , on the relic density of $S\nu\text{DM}$ and the amount of extra radiation (ΔN_{eff}) in the early Universe. Strong neutrino self-interactions can facilitate efficient production of DM and generate a net ΔN_{eff} at the same time. Our study reveals an intimate relationship between these two important quantities and provides a well-motivated target for the future cosmological and astrophysical experiments, including CMB-S4 and Athena. These results, together with earlier work, depict the complete parameter space for $S\nu\text{DM}$, with neutrino self-interactions mediated by a scalar whose mass spans over more than 6 orders of magnitude. They serve as a well-motivated target for future experimental tests, from laboratories to the cosmos. Observations made in this Letter could extend to other neutrino

self-interaction models mediated by vector bosons, such as gauged $U(1)_{L_\mu-L_\tau}$ [4,68,69] and other anomaly free gauge theories of baryon and lepton number.

We thank Nikita Blinov for discussions and comments on the draft. Fermilab is operated by the Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy. M. S. acknowledges support from the National Science Foundation, Grant No. PHY-1630782, and to the Heising-Simons Foundation, Grant No. 2017-228. Y. Z. is supported by the Arthur B. McDonald Canadian Astroparticle Physics Research Institute.

*kkelly12@fnal.gov

†manibrata@berkeley.edu

‡yzhang@physics.carleton.ca

- [1] S. Dodelson and L. M. Widrow, Sterile-Neutrinos as Dark Matter, *Phys. Rev. Lett.* **72**, 17 (1994).
- [2] K. N. Abazajian, Sterile neutrinos in cosmology, *Phys. Rep.* **711–712**, 1 (2017).
- [3] A. De Gouvêa, M. Sen, W. Tangarife, and Y. Zhang, The Dodelson-Widrow Mechanism in the Presence of Self-Interacting Neutrinos, *Phys. Rev. Lett.* **124**, 081802 (2020).
- [4] K. J. Kelly, M. Sen, W. Tangarife, and Y. Zhang, Origin of sterile neutrino dark matter via secret neutrino interactions with vector bosons, *Phys. Rev. D* **101**, 115031 (2020).
- [5] J. M. Berryman, A. De Gouvêa, K. J. Kelly, and Y. Zhang, Lepton-number-charged scalars and neutrino beamstrahlung, *Phys. Rev. D* **97**, 075030 (2018).
- [6] A. de Gouvêa, P. S. Bhupal Dev, B. Dutta, T. Ghosh, T. Han, and Y. Zhang, Leptonic scalars at the LHC, *J. High Energy Phys.* **07** (2020) 142.
- [7] V. Brdar, M. Lindner, S. Vogl, and X.-J. Xu, Revisiting neutrino self-interaction constraints from Z and τ decays, *Phys. Rev. D* **101**, 115001 (2020).
- [8] Y. Chikashige, R. N. Mohapatra, and R. D. Peccei, Spontaneously Broken Lepton Number and Cosmological Constraints on the Neutrino Mass Spectrum, *Phys. Rev. Lett.* **45**, 1926 (1980).
- [9] G. B. Gelmini and M. Roncadelli, Left-handed neutrino mass scale and spontaneously broken lepton number, *Phys. Lett.* **99B**, 411 (1981).
- [10] A. Das, A. Dighe, and M. Sen, New effects of non-standard self-interactions of neutrinos in a supernova, *J. Cosmol. Astropart. Phys.* **05** (2017) 051.
- [11] K. J. Kelly and Y. Zhang, Mononeutrino at DUNE: New signals from neutrinophilic thermal dark matter, *Phys. Rev. D* **99**, 055034 (2019).
- [12] K. C. Y. Ng and J. F. Beacom, Cosmic neutrino cascades from secret neutrino interactions, *Phys. Rev. D* **90**, 065035 (2014); Erratum, *Phys. Rev. D* **90**, 089904 (2014).
- [13] K. Ioka and K. Murase, IceCube PeV–EeV neutrinos and secret interactions of neutrinos, *Prog. Theor. Exp. Phys.* **(2014)**, 61E01.
- [14] F. Forastieri, M. Lattanzi, and P. Natoli, Constraints on secret neutrino interactions after Planck, *J. Cosmol. Astropart. Phys.* **07** (2015) 014.

- [15] F. Forastieri, M. Lattanzi, and P. Natoli, Cosmological constraints on neutrino self-interactions with a light mediator, *Phys. Rev. D* **100**, 103526 (2019).
- [16] C. D. Kreisch, F.-Y. Cyr-Racine, and O. Doré, The neutrino puzzle: Anomalies, interactions, and cosmological tensions, *Phys. Rev. D* **101**, 123505 (2020).
- [17] N. Blinov, K. J. Kelly, G. Z. Krnjaic, and S. D. McDermott, Constraining the Self-Interacting Neutrino Interpretation of the Hubble Tension, *Phys. Rev. Lett.* **123**, 191102 (2019).
- [18] S. Shalgar, I. Tamborra, and M. Bustamante, Core-collapse supernovae stymie secret neutrino interactions, *Phys. Rev. D* **103**, 123008 (2021).
- [19] M. Bustamante, C. A. Rosenstroem, S. Shalgar, and I. Tamborra, Bounds on secret neutrino interactions from high-energy astrophysical neutrinos, *Phys. Rev. D* **101**, 123024 (2020).
- [20] J. M. Berryman, A. de Gouvêa, D. Hernández, and R. L. N. Oliveira, Non-unitary neutrino propagation from neutrino decay, *Phys. Lett. B* **742**, 74 (2015).
- [21] P. Coloma and O. L. G. Peres, Visible neutrino decay at DUNE, [arXiv:1705.03599](https://arxiv.org/abs/1705.03599).
- [22] A. de Gouvêa, I. Martinez-Soler, and M. Sen, Impact of neutrino decays on the supernova neutronization-burst flux, *Phys. Rev. D* **101**, 043013 (2020).
- [23] Z. Chacko, A. Dev, P. Du, V. Poulin, and Y. Tsai, Cosmological limits on the neutrino mass and lifetime, *J. High Energy Phys.* **04** (2020) 020.
- [24] Z. Chacko, A. Dev, P. Du, V. Poulin, and Y. Tsai, Determining the neutrino lifetime from cosmology, *Phys. Rev. D* **103**, 043519 (2021).
- [25] K. N. Abazajian *et al.* (CMB-S4 Collaboration), CMB-S4 science book, first edition, [arXiv:1610.02743](https://arxiv.org/abs/1610.02743).
- [26] P. A. R. Ade *et al.* (Planck Collaboration), Planck 2015 results. XIII. Cosmological parameters, *Astron. Astrophys.* **594**, A13 (2016).
- [27] J. L. Bernal, L. Verde, and A. G. Riess, The trouble with H_0 , *J. Cosmol. Astropart. Phys.* **10** (2016) 019.
- [28] W. L. Freedman, Cosmology at a crossroads, *Nat. Astron.* **1**, 0121 (2017).
- [29] K. C. Wong *et al.*, H0LiCOW XIII. A 2.4% measurement of H_0 from lensed quasars: 5.3 σ tension between early and late-Universe probes, *Mon. Not. R. Astron. Soc.* **498**, 1420 (2020).
- [30] A. G. Riess, S. Casertano, W. Yuan, L. M. Macri, and D. Scolnic, Large magellanic cloud cepheid standards provide a 1% foundation for the determination of the Hubble constant and stronger evidence for physics beyond Λ CDM, *Astrophys. J.* **876**, 85 (2019).
- [31] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020).
- [32] X.-D. Shi and G. M. Fuller, A New Dark Matter Candidate: Nonthermal Sterile Neutrinos, *Phys. Rev. Lett.* **82**, 2832 (1999).
- [33] M. Shaposhnikov and I. Tkachev, The nuMSM, inflation, and dark matter, *Phys. Lett. B* **639**, 414 (2006).
- [34] T. Asaka, M. Shaposhnikov, and A. Kusenko, Opening a new window for warm dark matter, *Phys. Lett. B* **638**, 401 (2006).
- [35] S. B. Roland, B. Shakya, and J. D. Wells, Neutrino masses and sterile neutrino dark matter from the PeV scale, *Phys. Rev. D* **92**, 113009 (2015).
- [36] R. S. L. Hansen and S. Vogl, Thermalizing Sterile Neutrino Dark Matter, *Phys. Rev. Lett.* **119**, 251305 (2017).
- [37] L. Johns and G. M. Fuller, Self-interacting sterile neutrino dark matter: The heavy-mediator case, *Phys. Rev. D* **100**, 023533 (2019).
- [38] F. Bezrukov, H. Hettmansperger, and M. Lindner, keV sterile neutrino dark matter in gauge extensions of the standard model, *Phys. Rev. D* **81**, 085032 (2010).
- [39] M. Nemevsek, G. Senjanovic, and Y. Zhang, Warm dark matter in low scale left-right theory, *J. Cosmol. Astropart. Phys.* **07** (2012) 006.
- [40] J. A. Dror, D. Dunsky, L. J. Hall, and K. Harigaya, Sterile neutrino dark matter in left-right theories, *J. High Energy Phys.* **07** (2020) 168.
- [41] P. S. Pasquini and O. L. G. Peres, Bounds on neutrino-scalar Yukawa coupling, *Phys. Rev. D* **93**, 053007 (2016); Erratum, *Phys. Rev. D* **93**, 079902 (2016).
- [42] M. Agostini *et al.*, Results on $\beta\beta$ decay with emission of two neutrinos or Majorons in ^{76}Ge from GERDA Phase I, *Eur. Phys. J. C* **75**, 416 (2015).
- [43] K. Blum, Y. Nir, and M. Shavit, Neutrinoless double-beta decay with massive scalar emission, *Phys. Lett. B* **785**, 354 (2018).
- [44] T. Brune and Heinrich Päs, Massive Majorons and constraints on the Majoron-neutrino coupling, *Phys. Rev. D* **99**, 096005 (2019).
- [45] C. Pitrou, A. Coc, J.-P. Uzan, and E. Vangioni, Precision big bang nucleosynthesis with improved Helium-4 predictions, *Phys. Rep.* **754**, 1 (2018).
- [46] G.-Y. Huang, T. Ohlsson, and S. Zhou, Observational constraints on secret neutrino interactions from big bang nucleosynthesis, *Phys. Rev. D* **97**, 075009 (2018).
- [47] G. Barenboim and U. Nierste, Modified Majoron model for cosmological anomalies, *Phys. Rev. D* **104**, 023013 (2021).
- [48] Z. Chacko, L. J. Hall, T. Okui, and S. J. Oliver, CMB signals of neutrino mass generation, *Phys. Rev. D* **70**, 085008 (2004).
- [49] M. Escudero and S. J. Witte, A CMB search for the neutrino mass mechanism and its relation to the Hubble tension, *Eur. Phys. J. C* **80**, 294 (2020).
- [50] M. Escudero Abenza, Precision early universe thermodynamics made simple: N_{eff} and neutrino decoupling in the standard model and beyond, *J. Cosmol. Astropart. Phys.* **05** (2020) 048.
- [51] A. Berlin and N. Blinov, Thermal Dark Matter Below an MeV, *Phys. Rev. Lett.* **120**, 021801 (2018).
- [52] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.127.041101> for additional details regarding the matching conditions among the three time-scales used in this work, which allows us to derive the time-dependence of the neutrino temperature and chemical potential. It also provides information about how to combine the current x-ray constraints and relic constraints to derive limits on ΔN_{eff} , as shown in Fig. 3.
- [53] P. A. Zyla *et al.* (Particle Data Group), Review of particle physics, *Prog. Theor. Exp. Phys.* (2020), 083C01.

- [54] S. Horiuchi, P. J. Humphrey, J. Onorbe, K. N. Abazajian, M. Kaplinghat, and S. Garrison-Kimmel, Sterile neutrino dark matter bounds from galaxies of the local group, *Phys. Rev. D* **89**, 025017 (2014).
- [55] D. Malyshev, A. Neronov, and D. Eckert, Constraints on 3.55 keV line emission from stacked observations of dwarf spheroidal galaxies, *Phys. Rev. D* **90**, 103506 (2014).
- [56] C. Dessert, N. L. Rodd, and B. R. Safdi, The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations, *Science* **367**, 1465 (2020).
- [57] E. Grohs, G. M. Fuller, and M. Sen, Consequences of neutrino self interactions for weak decoupling and big bang nucleosynthesis, *J. Cosmol. Astropart. Phys.* **07** (2020) 001.
- [58] E. Grohs, G. M. Fuller, C. T. Kishimoto, and M. W. Paris, Probing neutrino physics with a self-consistent treatment of the weak decoupling, nucleosynthesis, and photon decoupling epochs, *J. Cosmol. Astropart. Phys.* **05** (2015) 017.
- [59] E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, and A. Vlasenko, Neutrino energy transport in weak decoupling and big bang nucleosynthesis, *Phys. Rev. D* **93**, 083522 (2016).
- [60] A. Neronov and D. Malyshev, Toward a full test of the ν MSM sterile neutrino dark matter model with Athena, *Phys. Rev. D* **93**, 063518 (2016).
- [61] S. Tremaine and J. E. Gunn, Dynamical Role of Light Neutral Leptons in Cosmology, *Phys. Rev. Lett.* **42**, 407 (1979).
- [62] A. Boyarsky, O. Ruchayskiy, and D. Iakubovskiy, A lower bound on the mass of dark matter particles, *J. Cosmol. Astropart. Phys.* **03** (2009) 005.
- [63] C. Yèche, N. Palanque-Delabrouille, J. Baur, and H. du Mas des Bourboux, Constraints on neutrino masses from Lyman-alpha forest power spectrum with BOSS and XQ-100, *J. Cosmol. Astropart. Phys.* **06** (2017) 047.
- [64] E. O. Nadler *et al.* (DES Collaboration), Milky Way Satellite Census. III. Constraints on Dark Matter Properties from Observations of Milky Way Satellite Galaxies, *Phys. Rev. Lett.* **126**, 091101 (2021).
- [65] G. G. Raffelt, *Stars as Laboratories for Fundamental Physics: The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles* (University Press, Chicago, 1996), 664 p.
- [66] L. Heurtier and Y. Zhang, Supernova constraints on massive (pseudo)scalar coupling to neutrinos, *J. Cosmol. Astropart. Phys.* **02** (2017) 042.
- [67] M. Escudero, J. Lopez-Pavon, N. Rius, and S. Sandner, Relaxing cosmological neutrino mass bounds with unstable neutrinos, *J. High Energy Phys.* **12** (2020) 119.
- [68] B. Shuve and I. Yavin, Dark matter progenitor: Light vector boson decay into sterile neutrinos, *Phys. Rev. D* **89**, 113004 (2014).
- [69] M. Escudero, D. Hooper, G. Krnjaic, and M. Pierre, Cosmology with a very light $L_\mu - L_\tau$ gauge boson, *J. High Energy Phys.* **03** (2019) 071.