Letter

Minimal sterile neutrino dark matter

Torsten Bringmann,[1,2,*] Paul Frederik Depta,[3,†] Marco Hufnagel,[4,‡] Jörn Kersten,[5,6,§]
Joshua T. Ruderman,[7,‖] and Kai Schmidt-Hoberg[8,¶]

[1]*Department of Physics, University of Oslo, Box 1048, N-0316 Oslo, Norway*
[2]*Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*
[3]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[4]*Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, B-1050 Brussels, Belgium*
[5]*Korea Institute for Advanced Study, Seoul 02455, Republic of Korea*
[6]*Department of Physics and Technology, University of Bergen, 5020 Bergen, Norway*
[7]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, New York 10003, USA*
[8]*Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*

(Received 7 September 2022; revised 1 December 2022; accepted 31 March 2023; published 24 April 2023)

We propose a novel mechanism to generate sterile neutrinos ν_s in the early Universe, by converting ordinary neutrinos ν_α in scattering processes $\nu_s\nu_\alpha \to \nu_s\nu_s$. After initial production by oscillations, this leads to an exponential growth in the ν_s abundance. We show that such a production regime naturally occurs for self-interacting ν_s, and that this opens up significant new parameter space where ν_s make up all of the observed dark matter. Our results provide strong motivation to further push the sensitivity of X-ray line searches, and to improve on constraints from structure formation.

DOI: 10.1103/PhysRevD.107.L071702

I. INTRODUCTION

The existence of sterile neutrinos, putative particles that are uncharged under the standard model (SM) gauge interactions, is extremely well motivated. For example, such sterile states provide natural candidates [1–5] to explain the observed tiny nonzero neutrino masses [6]. If one of the sterile neutrinos has a mass in the keV range and is stable on cosmological time scales, furthermore, it is an excellent candidate for the dark matter (DM) in our Universe [7]. A smoking-gun signal for this scenario would be an astrophysical X-ray line, resulting from DM decaying into an active neutrino and a photon [8]. Such X-ray signatures are very actively being searched for, leading to ever more stringent limits on how much sterile and active neutrinos can mix [9] (while Refs. [10,11] report a potential detection).

Sterile neutrinos can be produced by neutrino oscillations in the early Universe, which is known as the Dodelson-Widrow (DW) mechanism [12]. However, the region of parameter space where this mechanism produces an abundance of sterile neutrinos consistent with the entirety of the observed DM is excluded [13]. Alternative scenarios that remain viable include resonant production in the presence of a large lepton asymmetry [14], production by the decay of a scalar [15–20], thermal production via an extended gauge sector [21–23], and production by oscillations modified by new self-interactions of the SM neutrinos [24–27] or by interactions between the sterile neutrinos and a significantly heavier scalar in combination with a large lepton asymmetry[1] [28].

All known viable mechanisms thus require new particles in addition to the sterile neutrino, either explicitly or implicitly (e.g., to ensure gauge invariance or to create a lepton asymmetry much larger than the observed baryon asymmetry). Our objective here is to propose a novel scenario that is minimal in the sense that it requires only a *single* real degree of freedom on top of the DM candidate.

*torsten.bringmann@fys.uio.no
†frederik.depta@mpi-hd.mpg.de
‡marco.hufnagel@ulb.be
§joern.kersten@uib.no
‖ruderman@nyu.edu
¶kai.schmidt-hoberg@desy.de

[1]With the exception of a tiny corner of parameter space where the model by Hansen and Vogl [28] is viable for a vanishing asymmetry.

Recently, some of us introduced a new generic DM production mechanism [29] that is characterized by DM particles transforming heat bath particles into more DM, thereby triggering an era of exponential growth of the DM abundance (see also Ref. [30]). As discussed there, one possibility to provide the necessary DM seed population for such a DM density evolution is through an initial freeze-in [31] period. In the scenario proposed in this article, instead, sterile neutrinos ν_s are initially generated through oscillations like in the DW mechanism and subsequently transform active neutrinos ν_α through the process $\nu_s\nu_\alpha \to \nu_s\nu_s$. We demonstrate that such a scenario generically emerges when sterile neutrinos feel the presence of a dark force, and that this opens up significant portions of parameter space for sterile neutrino DM that may be detectable with upcoming experiments.

II. MODEL SETUP

A necessary requirement to realize DM production via exponential growth is $\langle\sigma v\rangle_{\rm tr} \gg \langle\sigma v\rangle_{\rm fi}$ [29], where $\langle\sigma v\rangle_{\rm tr}$ is the thermally averaged interaction rate for the transmission process, i.e. the conversion of a heat bath particle to a DM particle, and $\langle\sigma v\rangle_{\rm fi}$ is the corresponding quantity for the more traditional freeze-in process [31], where a pair of DM particles is produced from the collision of heat bath particles. Here we point out that a simple and generic way to realize this condition is a secluded dark sector [32–35] where DM particles interact among each other via some mediator ϕ, while interacting with the visible sector only through mixing by an angle θ. In that case, both processes dominantly proceed via the s-channel exchange of ϕ, resulting in $\langle\sigma v\rangle_{\rm tr} \propto \sin^2\theta$ and $\langle\sigma v\rangle_{\rm fi} \propto \sin^4\theta$. We note that such "secret interactions" of sterile neutrinos have been studied in different cosmological contexts before [36–61].

Motivated by these general considerations, we concentrate here on a single sterile neutrino ν_s interacting with a light scalar ϕ, both singlets under the SM gauge group. Assuming Majorana masses for ν_s and the active neutrinos, ν_α, the relevant Lagrangian terms are given by

$$\mathcal{L} \supset -\frac{1}{2}\overline{\nu_s^c}m_s\nu_s - \overline{\nu_\alpha}m_{\alpha s}\nu_s - \frac{1}{2}\overline{\nu_\alpha}m_\alpha\nu_\alpha^c + \frac{y}{2}\overline{\nu_s^c}\phi\nu_s + \text{H.c.},$$

where repeated indices α are summed over and ν_α (ν_s) are left-(right-) handed spinors. We will concentrate on the case of heavy mediators, $m_\phi > 2m_s$, for most of this article, but later also briefly discuss phenomenological consequences of lighter mediators. We checked that even for large mediator self-couplings, number-changing interactions like $2\phi \leftrightarrow 4\phi$ or $3\phi \leftrightarrow 4\phi$ do not qualitatively change our results and therefore neglect the scalar potential in all practical calculations. We further assume, for simplicity and concreteness, that ν_s dominantly mixes only with the active neutrino species ν_e, and that $m_s \gg m_\alpha$. Expressed in terms of mass eigenstates, which for ease of notation we denote by the same symbols as flavor eigenstates, the interactions of the mediator then take the form

$$\mathcal{L}_\phi^{\rm I} = \frac{y}{2}\phi(\cos^2\theta\overline{\nu_s^c}\nu_s - \sin(2\theta)\overline{\nu_\alpha}\nu_s + \sin^2\theta\overline{\nu_\alpha}\nu_\alpha^c) + \text{H.c.}, \quad (1)$$

with $\theta \simeq m_{\alpha s}/m_s \ll 1$. The unsuppressed couplings among ϕ and ν_s turn out to be sufficiently strong to equilibrate the dark sector during the new exponential production phase that we consider below. On the other hand, mass-mixing-induced interactions between ν_s and electroweak gauge bosons are suppressed by the Fermi constant, G_F, and will only be relevant in setting the initial sterile neutrino abundance.

III. EVOLUTION OF ν_s NUMBER DENSITY

For an initially vanishing abundance, in particular, the interactions in Eq. (1) only allow freeze-in production of ν_s. While the corresponding rate scales as $\sin^4\theta$, active-sterile neutrino oscillations at temperatures above and around $\Lambda_{\rm QCD} \sim 150$ MeV, in combination with neutral and charged current interactions with the SM plasma, lead to a production rate scaling as $\sin^2\theta$ [12]. Adopting results from Ref. [62], we use the ν_s number density, n_s, and energy density, $\rho_s \sim \langle p\rangle n_s$, that result from this DW production. Once it is completed, and in the absence of dark sector interactions, the expansion of the Universe will decrease these quantities as $n_s \propto a^{-3}$ and $\rho_s \propto a^{-4}$, respectively, where a is the scale factor.

Some time later, various decay and scattering processes (cf. Fig. 1) become relevant due to the new interactions appearing in Eq. (1) and, for the parameter space we are interested in here, eventually thermalize the dark sector via the (inverse) decays $\nu_s\nu_s \leftrightarrow \phi$. From that point on, the phase-space densities of ν_s and ϕ follow Fermi-Dirac and Bose-Einstein distributions, respectively, that are described by a common dark sector temperature $T_{\rm d}$ as well as chemical potentials μ_s and μ_ϕ. Similar to the situation of freeze-out in a dark sector [63], the evolution of these quantities is determined by a set of Boltzmann equations

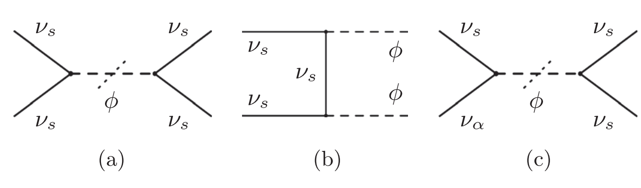

FIG. 1. Relevant diagrams for (a) dark sector thermalization, $\nu_s\nu_s \to \phi^* \to \nu_s\nu_s$, (b) additionally increasing the dark sector number density between DW production and exponential growth, $\nu_s\nu_s \to \phi\phi$, and (c) exponential growth of DM, $\nu_s\nu_\alpha \to \phi^* \to \nu_s\nu_s$. Since ϕ is (almost) on-shell for (a) and (c), it is sufficient to include only the rates for $\nu_s\nu_s \leftrightarrow \phi$ and $\nu_s\nu_\alpha \to \phi$. See text for further details.

for the number densities $n_{s,\phi}$ and total dark sector energy density $\rho = \rho_\phi + \rho_s$:

$$\dot{n}_s + 3Hn_s = C_{n_s}, \tag{2}$$

$$\dot{n}_\phi + 3Hn_\phi = C_{n_\phi}, \tag{3}$$

$$\dot{\rho} + 3H(\rho + P) = C_\rho, \tag{4}$$

where $H \equiv \dot{a}/a$ is the Hubble rate, $P = P_s + P_\phi$ is the total dark sector pressure, and C_i are the various collision operators (see [64] for details). With $\phi \leftrightarrow \nu_s\nu_s$ in equilibrium, the chemical potentials are related by $2\mu_s = \mu_\phi$, allowing us to replace the first two of the above equations with a single differential equation for $\tilde{n} \equiv n_s + 2n_\phi$. Noting that $\rho \propto a^{-4}$ and $\tilde{n} \propto a^{-3}$, both right before and after $\phi \leftrightarrow \nu_s\nu_s$ starts to dominate over the Hubble rate, the initial conditions to the coupled differential equations for $\tilde{n}$ and ρ can then be determined at the end of DW production.

In order to illustrate the subsequent evolution of the system, let us consider two concrete benchmark points, cf. Table I, for which the sterile neutrinos obtain a relic density that matches the observed DM abundance of $\Omega_{\rm DM}h^2 \simeq 0.12$ [65], with a mixing angle too small to achieve this with standard DW production. As demonstrated in Fig. 2, with solid (dashed) lines for *BP1* (*BP2*), this leads to qualitatively different behaviors:

BP1 Here the only additional process (beyond $\phi \leftrightarrow \nu_s\nu_s$) where the rate becomes comparable to H, at $m_s/T_\nu \sim 0.2$ with T_ν the active neutrino temperature, is $\nu_s\nu_\alpha \to \phi$ (left panel, light blue). This triggers exponential growth in the abundance for both ν_s and ϕ (right panel, green and orange) through $\nu_s\nu_\alpha \to \phi^* \to \nu_s\nu_s$, with ϕ being (almost) on shell, cf. Fig. 1(c). Once $T_\nu \ll m_\phi$ the transmission process becomes inefficient and the final ν_s abundance is obtained. Afterwards, since both ϕ and ν_s are nonrelativistic, the dark sector temperature decreases with $T_{\rm d} \propto a^{-2}$ both before and after kinetic decoupling (right panel, dark gray).

BP2 In this case the larger coupling y (needed to compensate for the smaller θ) leads to another process impacting the evolution of the system: at $m_s/T_\nu \sim 0.01$, the rate for $\nu_s\nu_s \to \phi\phi$ (left panel, cyan), and Fig. 1(b) starts to be comparable to H. As ϕ predominantly decays into $\nu_s\nu_s$ (left panel, orchid), this effectively transforms kinetic energy to rest mass by turning $2\nu_s$ to $4\nu_s$—very similar to the reproductive freeze-in mechanism described by Refs. [28,66,67]. As expected, this leads to a significant drop in the temperature $T_{\rm d}$ (right panel, black). This process becomes inefficient for $T_{\rm d} \ll m_\phi$, due to the Boltzmann suppression of ϕ. Subsequently, the rate for $\nu_s\nu_\alpha \to \phi$ (left panel, light blue) becomes comparable to H, leading to a phase of exponential growth in the same way as for *BP1*.

TABLE I. Parameter values for the two benchmark points considered in Fig. 2.

	m_s	m_ϕ	$\sin^2(2\theta)$	y
BP1	12 keV	36 keV	2.5×10^{-13}	1.905×10^{-4}
BP2	20 keV	60 keV	3.0×10^{-15}	1.602×10^{-3}

IV. OBSERVATIONAL CONSTRAINTS

Due to the mixing with active neutrinos, ν_s is not completely stable and subject to the same decays as in the standard scenario for keV-mass sterile neutrino DM. The strongest constraints on these decays come from a variety of X-ray line searches. We take the compilation of limits from Ref. [9] but only consider the overall envelope of constraints from Refs. [68–73]. Furthermore, we consider projections for eROSITA [74], Athena [75], and eXTP [76].

Observations of the Lyman-α forest using light from distant quasars place stringent limits on a potential cutoff in the matter-power spectrum at small scales, where the scale of this cutoff is related to the time of kinetic decoupling, $t_{\rm kd}$. In our scenario, this is determined by DM self-interactions and we estimate $t_{\rm kd}$ from $Hn_s = C_{\nu_s\nu_s\to\nu_s\nu_s}$ [77], where the collision term $C_{\nu_s\nu_s\to\nu_s\nu_s}$ is stated in [64]. A full evaluation of Lyman-α limits would require evolving cosmological perturbations into the nonlinear regime, which is beyond the scope of this work. Instead, we recast existing limits on the two main mechanisms that generate such a cutoff. At times $t < t_{\rm kd}$, DM self-scatterings prevent overdensities from growing on scales below the sound horizon $r_{\rm s} = \int_0^{t_{\rm kd}} {\rm d}t c_{\rm s}/a$, where $c_{\rm s} = \sqrt{{\rm d}P/{\rm d}\rho}$ is the speed of sound in the dark sector [78]. We use the results from Ref. [79] for cold DM in kinetic equilibrium with dark radiation (with $c_{\rm s} = 1/\sqrt{3}$) to recast the current Lyman-α constraint on the mass of a warm DM (WDM) thermal relic $m_{\rm WDM} > 1.9$ keV [80] to the bound $r_{\rm s} < 0.34$ Mpc. Overdensities are also washed out by the free streaming of DM *after* decoupling. We evaluate the free-streaming length as $\lambda_{\rm fs} = \int_{t_{\rm kd}}^{t_{\rm nl}} {\rm d}t\langle v\rangle/a$, where $\langle v\rangle = \langle p/E\rangle$ is the thermally averaged DM velocity and we integrate up to times $t_{\rm nl}$ where structure formation becomes relevant at redshifts of roughly $z \sim 50$. We translate the WDM constraint of $m_{\rm WDM} > 1.9$ keV to $\lambda_{\rm fs} < 0.24$ Mpc, which we will apply in the following to our scenario. We note that the WDM bounds from Ref. [80] are based on marginalizing over different reionization histories. Fixed reionization models tend to produce less conservative constraints, which however illustrate the future potential of Lyman-α probes once systematic errors are further reduced ($m_{\rm WDM} > 5.3$ keV [81], e.g., corresponds to $r_{\rm s} < 0.09$ Mpc and $\lambda_{\rm fs} < 0.07$ Mpc, respectively).

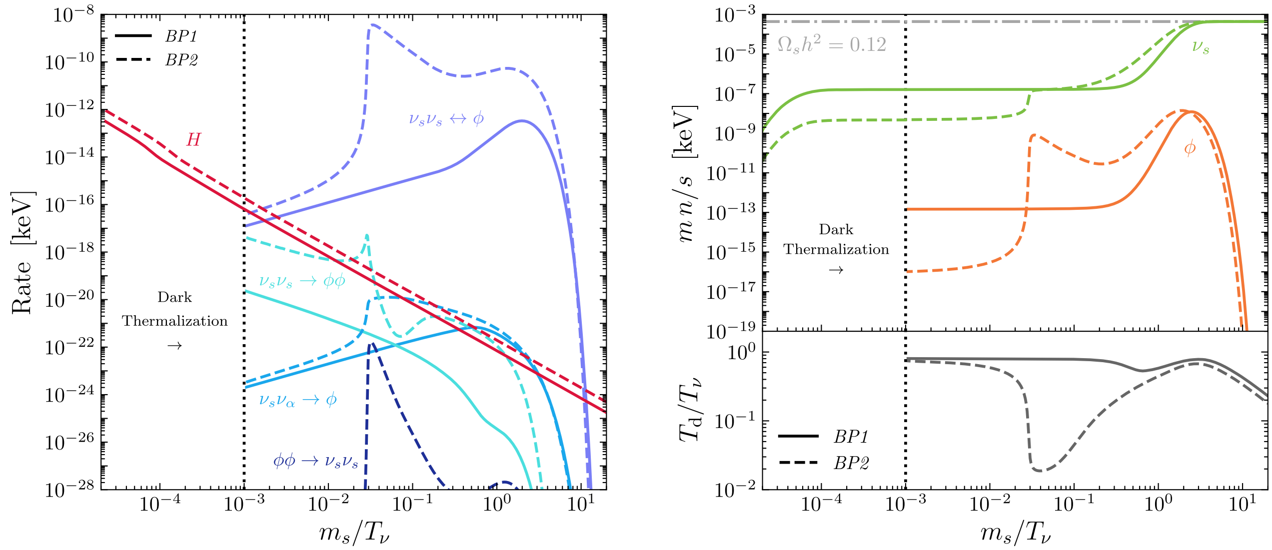

FIG. 2. Cosmological evolution for the benchmark points *BP1* (solid lines) and *BP2* (dashed lines) specified in Table I, as function of the inverse active neutrino temperature. *Left*: Comparison of Hubble rate H (red) with the contribution of the indicated processes to $|C_{n_s}|/n_s$ (blue lines), see [64] for details. *Right*: Corresponding evolution of ν_s (green) and ϕ (orange) abundances, and temperature ratio (dark gray, bottom panel). The dash-dotted gray line indicates the observed DM abundance [65].

DM self-interactions are also constrained by a variety of astrophysical observations at late times [82]. We adopt $\sigma_T/m_s < 1\ \mathrm{cm}^2/\mathrm{g}$ as a rather conservative limit, where σ_T is the momentum transfer cross section as defined in Ref. [83]. Far away from the s-channel resonance, we find $\sigma_T/m_s \simeq y^4 m_s/(4\pi m_\phi^4) + \mathcal{O}(v^2)$, largely independent of the DM velocity v. For such cross sections cluster observations [84,85], or the combination of halo surface densities over a large mass range [86], can be (at least) one order of magnitude more competitive than our reference limit of $\sigma_T/m_s < 1\ \mathrm{cm}^2/\mathrm{g}$.

V. VIABLE PARAMETER SPACE FOR STERILE NEUTRINO DM

In Fig. 3 we show a slice of the overall available parameter space for our setup in the $\sin^2(2\theta) - m_s$ plane, for a fixed mediator to DM mass ratio of $m_\phi/m_s = 3$. For every point in parameter space, the dark sector Yukawa coupling y is chosen such that the sterile neutrinos ν_s make up all of DM after the era of exponential growth. In the yellow band, DW production can give the correct relic abundance, including QCD and lepton flavor uncertainties [62]; the dashed brown line corresponds to the central prediction, which is the basis for our choice of initial conditions for number and energy densities of ν_s. In the blue region DM will be overproduced, $\Omega_s h^2 > 0.12$, while the other filled regions are excluded by bounds from X-ray searches (gray), Lyman-α observations (orange), and DM self-interactions (violet). The white region corresponds to the presently allowed parameter space.

It is worth noting that, unlike in standard freeze-out scenarios [87], later kinetic decoupling implies a shorter free-streaming length in our case because the dark sector temperature scales as $T_\mathrm{d} \propto T_\nu^2$ already before that point. At the same time, the sound horizon increases for later kinetic decoupling. The shape of the Lyman-α exclusion lines reflects this, as kinetic decoupling occurs later for larger values of y.

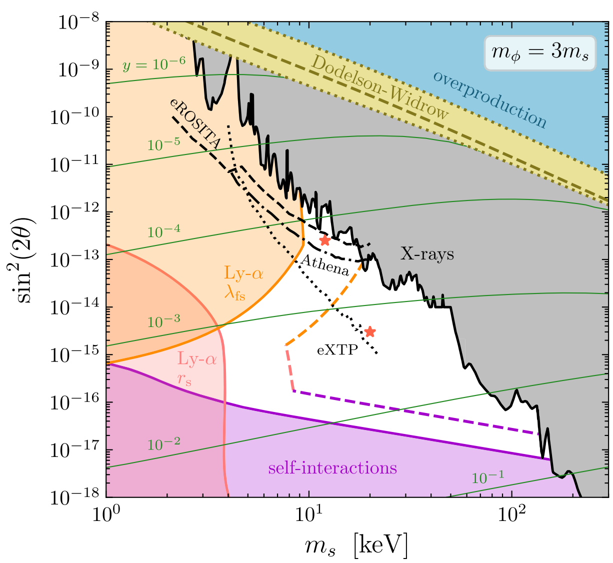

FIG. 3. Available parameter space in the $\sin^2(2\theta) - m_s$ plane, for $m_\phi = 3m_s$. The Yukawa coupling y (green lines) is chosen such that the correct DM relic abundance is achieved everywhere below the DW line. Present and projected bounds from X-rays (filled gray and black lines), Lyman-α (orange), and DM self-interactions (violet) are evaluated as described in the text. The two benchmark points *BP1* and *BP2* from Table I, see also Fig. 2, are indicated as red stars.

In Fig. 3 we also show the projected sensitivities of the future X-ray experiments eROSITA [74], Athena [75], and eXTP [76], which will probe smaller values of $\sin^2(2\theta)$. Similarly, observables related to structure formation will likely result in improved future bounds, or in fact reveal anomalies that are not easily reconcilable with a standard noninteracting cold DM scenario. While the precise reach is less clear here, we indicate with dashed orange and violet lines, respectively, the impact of choosing $\lambda_{\rm fs} < 0.12$ Mpc, $r_{\rm s} < 0.15$ Mpc, and $\sigma_T/m_s < 0.1\ \mathrm{cm}^2/\mathrm{g}$ rather than the corresponding limits described above. Overall, prospects to probe a sizable region of the presently allowed parameter space appear very promising.

VI. DISCUSSION

While an X-ray line would be the cleanest signature to claim DM discovery of the scenario suggested here, let us briefly mention other possible directions. For example, the power-spectrum of DM density perturbations at small, but only mildly nonlinear, scales may be affected in a way that could be discriminated from alternative DM production scenarios by 21 cm and high-z Lyman-α observations [88–91]. Another possibility would be to search for a suppression of intense astrophysical neutrino fluxes due to ϕ production on ν_s DM at rest. We leave an investigation of these interesting avenues for future work.

We stress that the parameter space is larger than the $m_\phi/m_s = 3$ slice shown in Fig. 3. Larger mass ratios, in particular, have the effect of tightening (weakening) bounds on $\lambda_{\rm fs}$ ($r_{\rm s}$), because kinetic decoupling happens earlier, and weakening self-interaction constraints; this extends the viable parameter space shown in Fig. 3 to smaller mixing angles and allows for a larger range of m_s (cf. Fig. 2 in [64]). Changing the interaction structure in the dark sector, e.g. by charging the sterile neutrinos under a gauge symmetry, is a further route for model building that will not qualitatively change the new production scenario suggested here.

For completeness, we finally mention that smaller mediator masses are yet another, though qualitatively different, route worthwhile to explore. For $m_s < m_\phi < 2m_s$ the mediator is no longer dominantly produced on-shell in transmission processes, so the cross section for transmission, $\nu_s\nu_\alpha \to \nu_s\nu_s$, scales as y^4 rather than y^2 and larger Yukawa couplings are needed in order to obtain the correct relic density. This, in turn, implies that it may only be possible to satisfy the correspondingly tighter self-interaction and Lyman-α constraints by adding a scalar potential for ϕ (because additional number-changing interactions would potentially allow an increase in the ν_s abundance, similar to what happens for the dashed green curve in Fig. 2, right panel, at $m_s/T_\nu \sim 0.02$). For even lighter mediators, $m_\phi < m_s$, extremely small Yukawa couplings or mixing angles would be required to prevent DM from decaying too early through $\nu_s \to \nu_\alpha\phi$ (while the decay $\nu_s \to 3\nu_\alpha$, present also in the scenario we focus on here, is automatically strongly suppressed as $\Gamma \propto y^4 \sin^6\theta$).

VII. CONCLUSIONS

Sterile neutrinos constitute an excellent DM candidate. However, X-ray observations rule out the possibility that these particles, in their simplest realization, could make up all of the observed DM. On the other hand, there has been a recent shift in focus in general DM theory, towards the possibility that DM may not just be a single, (almost) noninteracting particle. Indeed, it is perfectly conceivable that DM could belong to a more complex, secluded dark sector with its own interactions and, possibly, further particles.

By combining these ideas in the most economic way, a sterile neutrino coupled to a single additional dark sector degree of freedom allows for a qualitatively new DM production mechanism and thereby opens up ample parameter space where sterile neutrinos could still explain the entirety of DM. Excitingly, much of this parameter space is testable in the foreseeable future. In particular, our results provide a strong motivation for further pushing the sensitivity of X-ray line searches, beyond what would be expected from standard DW production.

ACKNOWLEDGMENTS

We would like to thank Hitoshi Murayama and Manibrata Sen for helpful discussions. J. T. R. also thanks Cristina Mondino, Maxim Pospelov, and Oren Slone for discussions on reproductive freeze-in applied to sterile neutrinos. This work is supported by the Deutsche Forschungsgemeinschaft under Germany's Excellence Strategy—EXC 2121 "Quantum Universe"—390833306, the National Science Foundation under Grant No. NSF PHY-1748958, and the National Research Foundation of Korea under Grant No. NRF-2019R1A2C3005009. M. H. is further supported by the F. R. S./FNRS. T. R. is also supported by NSF Grant No. PHY-1915409 and NSF CAREER Grant No. PHY-1554858.

[1] P. Minkowski, $\mu \to e\gamma$ at a rate of one out of 10^9 muon decays?, Phys. Lett. B **67**, 421 (1977).
[2] T. Yanagida, Horizontal gauge symmetry and masses of neutrinos, in *Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe*, edited by O. Sawada and A. Sugamoto (KEK, Tsukuba, Japan, 1979), p. 95.
[3] S. L. Glashow, The future of elementary particle physics, in *Proceedings of the 1979 Cargèse Summer Institute on Quarks and Leptons*, edited by M. Lévy, J.-L. Basdevant, D. Speiser, J. Weyers, R. Gastmans, and M. Jacob (Plenum Press, New York, 1980), pp. 687–713.
[4] M. Gell-Mann, P. Ramond, and R. Slansky, Complex spinors and unified theories, in *Supergravity*, edited by P. van Nieuwenhuizen and D. Z. Freedman (North Holland, Amsterdam, 1979), p. 315.
[5] R. N. Mohapatra and G. Senjanović, Neutrino Mass and Spontaneous Parity Nonconservation, Phys. Rev. Lett. **44**, 912 (1980).
[6] M. Sajjad Athar *et al.*, Status and perspectives of neutrino physics, Prog. Part. Nucl. Phys. **124**, 103947 (2022).
[7] A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, and O. Ruchayskiy, Sterile neutrino dark matter, Prog. Part. Nucl. Phys. **104**, 1 (2019).
[8] K. Abazajian, G. M. Fuller, and W. H. Tucker, Direct detection of warm dark matter in the x-ray, Astrophys. J. **562**, 593 (2001).
[9] K. N. Abazajian *et al.*, Synergy between cosmological and laboratory searches in neutrino physics: A white paper, arXiv:2203.07377.
[10] E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, and S. W. Randall, Detection of an unidentified emission line in the stacked x-ray spectrum of galaxy clusters, Astrophys. J. **789**, 13 (2014).
[11] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, and J. Franse, Unidentified Line in X-Ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster, Phys. Rev. Lett. **113**, 251301 (2014).
[12] S. Dodelson and L. M. Widrow, Sterile-Neutrinos as Dark Matter, Phys. Rev. Lett. **72**, 17 (1994).
[13] K. N. Abazajian, Sterile neutrinos in cosmology, Phys. Rep. **711–712**, 1 (2017).
[14] X. Shi and G. M. Fuller, New Dark Matter Candidate: Nonthermal Sterile Neutrinos, Phys. Rev. Lett. **82**, 2832 (1999).
[15] M. Shaposhnikov and I. Tkachev, The nuMSM, inflation, and dark matter, Phys. Lett. B **639**, 414 (2006).
[16] A. Kusenko, Sterile Neutrinos, Dark Matter, and the Pulsar Velocities in Models with a Higgs Singlet, Phys. Rev. Lett. **97**, 241301 (2006).
[17] K. Petraki and A. Kusenko, Dark-matter sterile neutrinos in models with a gauge singlet in the Higgs sector, Phys. Rev. D **77**, 065014 (2008).
[18] 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).
[19] A. Merle and M. Totzauer, keV sterile neutrino dark matter from singlet scalar decays: Basic concepts and subtle features, J. Cosmol. Astropart. Phys. 06 (2015) 011.
[20] J. König, A. Merle, and M. Totzauer, keV sterile neutrino dark matter from singlet scalar decays: The most general case, J. Cosmol. Astropart. Phys. 11 (2016) 038.
[21] 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).
[22] A. Kusenko, F. Takahashi, and T. T. Yanagida, Dark matter from split seesaw, Phys. Lett. B **693**, 144 (2010).
[23] 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.
[24] A. De Gouvêa, M. Sen, W. Tangarife, and Y. Zhang, Dodelson-Widrow Mechanism in the Presence of Self-Interacting Neutrinos, Phys. Rev. Lett. **124**, 081802 (2020).
[25] 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).
[26] C. Chichiri, G. B. Gelmini, P. Lu, and V. Takhistov, Cosmological dependence of sterile neutrino dark matter with self-interacting neutrinos, J. Cosmol. Astropart. Phys. 09 (2022) 036.
[27] C. Benso, W. Rodejohann, M. Sen, and A. U. Ramachandran, Sterile neutrino dark matter production in presence of nonstandard neutrino self-interactions: An EFT approach, Phys. Rev. D **105**, 055016 (2022).
[28] R. S. L. Hansen and S. Vogl, Thermalizing Sterile Neutrino Dark Matter, Phys. Rev. Lett. **119**, 251305 (2017).
[29] T. Bringmann, P. F. Depta, M. Hufnagel, J. T. Ruderman, and K. Schmidt-Hoberg, Dark Matter from Exponential Growth, Phys. Rev. Lett. **127**, 191802 (2021).
[30] A. Hryczuk and M. Laletin, Dark matter freeze-in from semi-production, J. High Energy Phys. 06 (2021) 026.
[31] L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, Freeze-in production of FIMP dark matter, J. High Energy Phys. 03 (2010) 080.
[32] M. Pospelov, A. Ritz, and M. B. Voloshin, Secluded WIMP dark matter, Phys. Lett. B **662**, 53 (2008).
[33] J. L. Feng, H. Tu, and H.-B. Yu, Thermal relics in hidden sectors, J. Cosmol. Astropart. Phys. 10 (2008) 043.
[34] M. Pospelov, Secluded U(1) below the weak scale, Phys. Rev. D **80**, 095002 (2009).
[35] C. Cheung, G. Elor, L. J. Hall, and P. Kumar, Origins of hidden sector dark matter I: Cosmology, J. High Energy Phys. 03 (2011) 042.
[36] S. Hannestad, R. S. Hansen, and T. Tram, How Self-Interactions can Reconcile Sterile Neutrinos with Cosmology, Phys. Rev. Lett. **112**, 031802 (2014).
[37] B. Dasgupta and J. Kopp, Cosmologically Safe eV-Scale Sterile Neutrinos and Improved Dark Matter Structure, Phys. Rev. Lett. **112**, 031803 (2014).
[38] T. Bringmann, J. Hasenkamp, and J. Kersten, Tight bonds between sterile neutrinos and dark matter, J. Cosmol. Astropart. Phys. 07 (2014) 042.
[39] P. Ko and Y. Tang, $\nu\Lambda$MDM: A model for sterile neutrino and dark matter reconciles cosmological and neutrino oscillation data after BICEP2, Phys. Lett. B **739**, 62 (2014).
[40] M. Archidiacono, S. Hannestad, R. S. Hansen, and T. Tram, Cosmology with self-interacting sterile neutrinos and dark matter—A pseudoscalar model, Phys. Rev. D **91**, 065021 (2015).

[41] A. Mirizzi, G. Mangano, O. Pisanti, and N. Saviano, Collisional production of sterile neutrinos via secret interactions and cosmological implications, Phys. Rev. D **91**, 025019 (2015).
[42] Y. Tang, More is different: Reconciling eV sterile neutrinos with cosmological mass bounds, Phys. Lett. B **750**, 201 (2015).
[43] N. Saviano, O. Pisanti, G. Mangano, and A. Mirizzi, Unveiling secret interactions among sterile neutrinos with big-bang nucleosynthesis, Phys. Rev. D **90**, 113009 (2014).
[44] C. Kouvaris, I. M. Shoemaker, and K. Tuominen, Self-interacting dark matter through the Higgs portal, Phys. Rev. D **91**, 043519 (2015).
[45] X. Chu, B. Dasgupta, and J. Kopp, Sterile neutrinos with secret interactions—lasting friendship with cosmology, J. Cosmol. Astropart. Phys. 10 (**2015**) 011.
[46] M. Archidiacono, S. Hannestad, R. S. Hansen, and T. Tram, Sterile neutrinos with pseudoscalar self-interactions and cosmology, Phys. Rev. D **93**, 045004 (2016).
[47] Z. Tabrizi and O. L. G. Peres, Hidden interactions of sterile neutrinos as a probe for new physics, Phys. Rev. D **93**, 053003 (2016).
[48] T. Binder, L. Covi, A. Kamada, H. Murayama, T. Takahashi, and N. Yoshida, Matter power spectrum in hidden neutrino interacting dark matter models: A closer look at the collision term, J. Cosmol. Astropart. Phys. 11 (2016) 043.
[49] M. Archidiacono, S. Gariazzo, C. Giunti, S. Hannestad, R. Hansen, M. Laveder, and T. Tram, Pseudoscalar—sterile neutrino interactions: Reconciling the cosmos with neutrino oscillations, J. Cosmol. Astropart. Phys. 08 (2016) 067.
[50] F. Forastieri, M. Lattanzi, G. Mangano, A. Mirizzi, P. Natoli, and N. Saviano, Cosmic microwave background constraints on secret interactions among sterile neutrinos, J. Cosmol. Astropart. Phys. 07 (2017) 038.
[51] F. Bezrukov, A. Chudaykin, and D. Gorbunov, Hiding an elephant: Heavy sterile neutrino with large mixing angle does not contradict cosmology, J. Cosmol. Astropart. Phys. 06 (2017) 051.
[52] Y. S. Jeong, S. Palomares-Ruiz, M. H. Reno, and I. Sarcevic, Probing secret interactions of eV-scale sterile neutrinos with the diffuse supernova neutrino background, J. Cosmol. Astropart. Phys. 06 (2018) 019.
[53] N. Song, M. C. Gonzalez-Garcia, and J. Salvado, Cosmological constraints with self-interacting sterile neutrinos, J. Cosmol. Astropart. Phys. 10 (**2018**) 055.
[54] X. Chu, B. Dasgupta, M. Dentler, J. Kopp, and N. Saviano, Sterile neutrinos with secret interactions—cosmological discord?, J. Cosmol. Astropart. Phys. 11 (2018) 049.
[55] M. Blennow, E. Fernandez-Martinez, A. Olivares-Del Campo, S. Pascoli, S. Rosauro-Alcaraz, and A. V. Titov, Neutrino portals to dark matter, Eur. Phys. J. C **79**, 555 (2019).
[56] P. Ballett, M. Hostert, and S. Pascoli, Dark neutrinos and a three portal connection to the Standard Model, Phys. Rev. D **101**, 115025 (2020).
[57] L. Johns and G. M. Fuller, Self-interacting sterile neutrino dark matter: The heavy-mediator case, Phys. Rev. D **100**, 023533 (2019).
[58] C. A. de S. Pires, A cosmologically viable eV sterile neutrino model, Phys. Lett. B **800**, 135135 (2020).
[59] M. Archidiacono, S. Gariazzo, C. Giunti, S. Hannestad, and T. Tram, Sterile neutrino self-interactions: H_0 tension and short-baseline anomalies, J. Cosmol. Astropart. Phys. 12 (2020) 029.
[60] M. Berbig, S. Jana, and A. Trautner, The Hubble tension and a renormalizable model of gauged neutrino self-interactions, Phys. Rev. D **102**, 115008 (2020).
[61] M. A. Corona, R. Murgia, M. Cadeddu, M. Archidiacono, S. Gariazzo, C. Giunti, and S. Hannestad, Pseudoscalar sterile neutrino self-interactions in light of Planck, SPT and ACT data, J. Cosmol. Astropart. Phys. 06 (2022) 010.
[62] T. Asaka, M. Laine, and M. Shaposhnikov, Lightest sterile neutrino abundance within the nuMSM, J. High Energy Phys. 01 (2007) 091; 02 (2015) 028.
[63] T. Bringmann, P. F. Depta, M. Hufnagel, and K. Schmidt-Hoberg, Precise dark matter relic abundance in decoupled sectors, Phys. Lett. B **817**, 136341 (2021).
[64] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevD.107.L071702 for more technical details and additional plots relevant to our setup.
[65] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, Astron. Astrophys. **641**, A6 (2020); **652**, C4(E) (2021).
[66] C. Mondino, M. Pospelov, J. T. Ruderman, and O. Slone, Dark Higgs dark matter, Phys. Rev. D **103**, 035027 (2021).
[67] J. March-Russell, H. Tillim, and S. M. West, Reproductive freeze-in of self-interacting dark matter, Phys. Rev. D **102**, 083018 (2020).
[68] 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).
[69] 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).
[70] J. W. Foster, M. Kongsore, C. Dessert, Y. Park, N. L. Rodd, K. Cranmer, and B. R. Safdi, Deep Search for Decaying Dark Matter with XMM-Newton Blank-Sky Observations, Phys. Rev. Lett. **127**, 051101 (2021).
[71] D. Sicilian, N. Cappelluti, E. Bulbul, F. Civano, M. Moscetti, and C. S. Reynolds, Probing the Milky Way's dark matter halo for the 3.5 keV line, Astrophys. J. **905**, 146 (2020).
[72] B. M. Roach, K. C. Y. Ng, K. Perez, J. F. Beacom, S. Horiuchi, R. Krivonos, and D. R. Wik, NuSTAR tests of sterile-neutrino dark matter: New galactic bulge observations and combined impact, Phys. Rev. D **101**, 103011 (2020).
[73] A. Boyarsky, D. Malyshev, A. Neronov, and O. Ruchayskiy, Constraining DM properties with SPI, Mon. Not. R. Astron. Soc. **387**, 1345 (2008).
[74] A. Dekker, E. Peerbooms, F. Zimmer, K. C. Y. Ng, and S. Ando, Searches for sterile neutrinos and axionlike particles from the Galactic halo with eROSITA, Phys. Rev. D **104**, 023021 (2021).
[75] S. Ando *et al.*, Decaying dark matter in dwarf spheroidal galaxies: Prospects for x-ray and gamma-ray telescopes, Phys. Rev. D **104**, 023022 (2021).
[76] D. Malyshev, C. Thorpe-Morgan, A. Santangelo, J. Jochum, and S.-N. Zhang, *eXTP* perspectives for the νMSM sterile

neutrino dark matter model, Phys. Rev. D **101**, 123009 (2020).
[77] A. Hryczuk and M. Laletin, Impact of dark matter self-scattering on its relic abundance, Phys. Rev. D **106**, 023007 (2022).
[78] D. Egana-Ugrinovic, R. Essig, D. Gift, and M. LoVerde, The cosmological evolution of self-interacting dark matter, J. Cosmol. Astropart. Phys. 05 (2021) 013.
[79] M. Vogelsberger, J. Zavala, F.-Y. Cyr-Racine, C. Pfrommer, T. Bringmann, and K. Sigurdson, ETHOS—an effective theory of structure formation: Dark matter physics as a possible explanation of the small-scale CDM problems, Mon. Not. R. Astron. Soc. **460**, 1399 (2016).
[80] A. Garzilli, A. Magalich, O. Ruchayskiy, and A. Boyarsky, How to constrain warm dark matter with the Lyman-α forest, Mon. Not. R. Astron. Soc. **502**, 2356 (2021).
[81] N. Palanque-Delabrouille, C. Yèche, N. Schöneberg, J. Lesgourgues, M. Walther, S. Chabanier, and E. Armengaud, Hints, neutrino bounds and WDM constraints from SDSS DR14 Lyman-α and Planck full-survey data, J. Cosmol. Astropart. Phys. 04 (2020) 038.
[82] S. Tulin and H.-B. Yu, Dark matter self-interactions and small scale structure, Phys. Rep. **730**, 1 (2018).
[83] F. Kahlhoefer, K. Schmidt-Hoberg, M. T. Frandsen, and S. Sarkar, Colliding clusters and dark matter self-interactions, Mon. Not. R. Astron. Soc. **437**, 2865 (2014).
[84] M. Kaplinghat, S. Tulin, and H.-B. Yu, Dark Matter Halos as Particle Colliders: Unified Solution to Small-Scale Structure Puzzles from Dwarfs to Clusters, Phys. Rev. Lett. **116**, 041302 (2016).
[85] K. E. Andrade, J. Fuson, S. Gad-Nasr, D. Kong, Q. Minor, M. G. Roberts, and M. Kaplinghat, A stringent upper limit on dark matter self-interaction cross section from cluster strong lensing, Mon. Not. R. Astron. Soc. **510**, 54 (2021).
[86] K. Bondarenko, A. Boyarsky, T. Bringmann, and A. Sokolenko, Constraining self-interacting dark matter with scaling laws of observed halo surface densities, J. Cosmol. Astropart. Phys. 04 (2018) 049.
[87] T. Bringmann, Particle models and the small-scale structure of dark matter, New J. Phys. **11**, 105027 (2009).
[88] S. Bose, M. Vogelsberger, J. Zavala, C. Pfrommer, F.-Y. Cyr-Racine, S. Bohr, and T. Bringmann, ETHOS—an effective theory of structure formation: Detecting dark matter interactions through the Lyman-α forest, Mon. Not. R. Astron. Soc. **487**, 522 (2019).
[89] J. B. Muñoz, C. Dvorkin, and F.-Y. Cyr-Racine, Probing the small-scale matter power spectrum with large-scale 21-cm data, Phys. Rev. D **101**, 063526 (2020).
[90] J. B. Muñoz, S. Bohr, F.-Y. Cyr-Racine, J. Zavala, and M. Vogelsberger, ETHOS—an effective theory of structure formation: Impact of dark acoustic oscillations on cosmic dawn, Phys. Rev. D **103**, 043512 (2021).
[91] T. Schaeffer and A. Schneider, Dark acoustic oscillations: Imprints on the matter power spectrum and the halo mass function, Mon. Not. R. Astron. Soc. **504**, 3773 (2021).