PROCEEDINGS OF SCIENCE

Curing Sterile Neutrino Dark Matter with a Dark Force

Jörn Kersten[*]

Department of Physics and Technology, University of Bergen
5020 Bergen, Norway

E-mail: `joern.kersten@uib.no`

We propose a novel mechanism to generate sterile neutrinos ν_s in the early Universe, by converting ordinary neutrinos ν_a in scattering processes $\nu_s \nu_a \to \nu_s \nu_s$. 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.

Neutrino Oscillation Workshop – NOW2022
4–11 September, 2022
Rosa Marina (Ostuni, Italy)

---

[*] Speaker

PoS(NOW2022)090

1. Introduction

A sterile neutrino with a mass $m_s \sim 10\,\mathrm{keV}$ and a mixing angle θ with Standard Model (SM) neutrinos is an excellent dark matter (DM) candidate [1]. In the early Universe, it is produced by the interplay between oscillations and scatterings. This *Dodelson-Widrow mechanism* yields an abundance [2]

$$\Omega_s h^2 \simeq 0.1 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{1\,\mathrm{keV}}\right)^2 , \tag{1}$$

where h is the Hubble parameter in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Sterile neutrino DM can decay to a SM neutrino and a photon at the one-loop level, resulting in an X-ray line [3]. Unfortunately, searches for such a line restrict the mixing angle to such small values that the Dodelson-Widrow mechanism cannot produce the entirety of the observed DM [4].

As a consequence, a lot of alternative production mechanisms have been considered, involving resonant production in the presence of a large lepton asymmetry [5], scalar decay [6–11], new interactions of the SM neutrinos [12–15], an extended gauge sector [16–18], or interactions between the sterile neutrino and a new scalar [19–21].

2. Model Setup

Here we present a model [21] that realizes the idea of *DM production via exponential growth* [22] (or *Pandemic Dark Matter* [23]) and can generate the correct amount of DM with only a single new ingredient in addition to the DM candidate itself. This second ingredient is a gauge singlet scalar with mass $m_\phi \gtrsim 2\,m_s$. It couples to the sterile neutrino gauge eigenstate ν_s',

$$\mathcal{L}_\phi^{\mathrm{int}} = \frac{y}{2}\, \overline{\nu_s'^c}\, \phi\, \nu_s' + \mathrm{h.c.} \tag{2}$$

In the mass eigenstate basis, the scalar couples to all neutrinos, but with a suppression by the tiny mixing angle in terms containing the light eigenstate ν_a (considering the 2-flavor case for simplicity),

$$\mathcal{L}_\phi^{\mathrm{int}} = \frac{y}{2}\, \phi \left(\cos^2\theta\, \overline{\nu_s^c}\nu_s - \sin 2\theta\, \overline{\nu_a}\nu_s + \sin^2\theta\, \overline{\nu_a}\nu_a^c\right) + \mathrm{h.c.} \tag{3}$$

Scalar self-couplings and Higgs portal couplings are taken to be sufficiently small to be negligible.

3. Production of Sterile Neutrino Dark Matter

After a small initial sterile neutrino abundance is produced by the Dodelson-Widrow mechanism in the early Universe, the phase of exponential growth starts when the rate of the *conversion process* $\nu_s\nu_a \to 2\nu_s$ mediated by scalar exchange exceeds the expansion rate of the Universe. Exponential growth ends when the temperature drops below the scalar mass, which leads to a decrease of the conversion rate.

The evolution of the densities of the sterile neutrino and the scalar is governed by the Boltzmann equations

$$\begin{aligned} \dot{n}_s + 3Hn_s &= C_{n_s} , \\ \dot{n}_\phi + 3Hn_\phi &= C_{n_\phi} , \\ \dot{\rho} + 3H\left(\rho + P\right) &= C_\rho , \end{aligned} \tag{4}$$

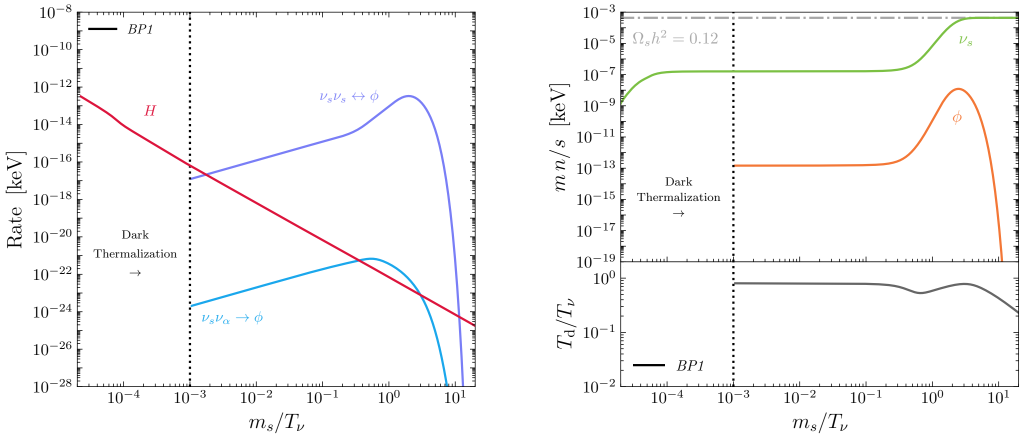

Figure 1: Evolution of reaction rates (left), abundances (top right), and neutrino temperature ratio (bottom right) in the early Universe for $m_s = 12\,\text{keV}$, $m_\phi = 36\,\text{keV}$, $\sin^2 2\theta = 2.5 \cdot 10^{-13}$, and $y = 1.905 \cdot 10^{-4}$. For comparison, the expansion rate H (left) and the observed DM abundance $\Omega_s h^2 = 0.12$ [25] (right) are shown as well. The exponential growth of the sterile neutrino abundance happens around $m_s/T_\nu \sim 10^0$.

where H is the expansion rate, n_s and n_ϕ are number densities, and ρ and P are the energy density and pressure of the dark sector particles ν_s and ϕ, respectively. The right-hand-sides of the equations contain the collision operators involving all relevant reactions. To determine the initial sterile neutrino density from Dodelson-Widrow production we used the results of [24]. The calculations are simplified by the fact that decays and inverse decays of the scalar, $\phi \leftrightarrow 2\nu_s$, quickly thermalize the dark sector. The results are shown in figure 1 for a benchmark point with $m_s = 12\,\text{keV}$, $m_\phi = 36\,\text{keV}$, $\sin^2 2\theta = 2.5 \cdot 10^{-13}$, and $y = 1.905 \cdot 10^{-4}$. This demonstrates that the observed DM abundance can be reached even though the mixing angle is so small that Dodelson-Widrow production accounts only for a small fraction of the sterile neutrino density.

4. Viable Parameter Space

The model is constrained by X-ray line searches [26] in exactly the same way as the standard sterile neutrino DM scenario without the new scalar. In addition, observations of the Lyman-α forest probe the distribution of matter on relatively small cosmological scales, which is affected by sterile neutrino scatterings before their kinetic decoupling and by free streaming after kinetic decoupling; this leads to a lower limit on the DM mass [27]. Finally, DM self-interactions at late times have an impact on the matter distribution in galaxies and galaxy clusters [28], which results in an upper limit on the Yukawa coupling to the scalar, limiting the exponential growth of the DM abundance; consequently, the sterile neutrino density from Dodelson-Widrow production cannot be arbitrarily small if the correct DM density is to be reached, which implies a lower limit on the mixing angle.

Parameter space regions consistent with these constraints are shown in white in figure 2. For every point, the Yukawa coupling is chosen such that the sterile neutrino density matches the observed DM density [25]. The figure also shows estimates of sensitivities (dashed and dotted lines) that can be expected from future X-ray searches and improved observations of cosmic structures.

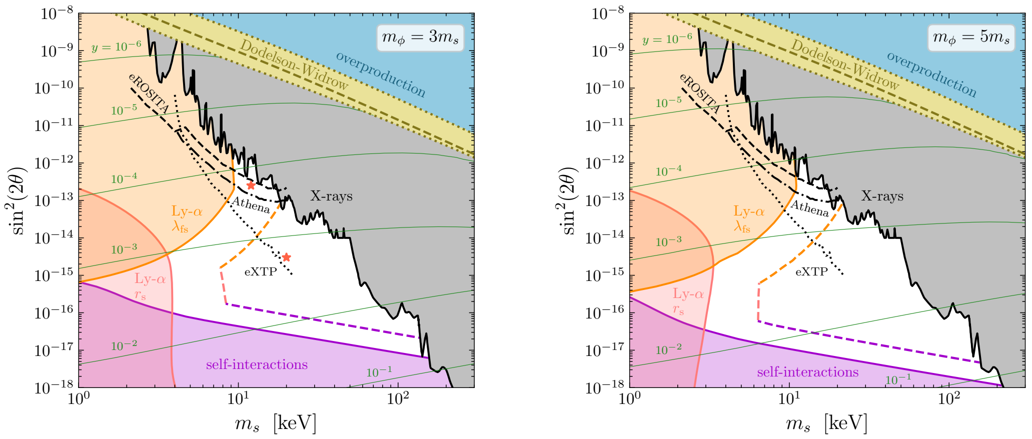

Figure 2: Viable parameter space regions (white) for two different mass ratios of scalar and sterile neutrino. Colored regions are ruled out by X-ray searches, Lyman-α observations, and constraints on DM self-interactions, respectively. Dashed and dotted lines indicate projected future bounds. The benchmark point considered in figure 1 corresponds to the upper red star in the left plot. Taken from [21].

5. Conclusions

We have arguably presented the most minimal viable model for sterile neutrino DM. The correct DM abundance is obtained in a phase of exponential growth that drastically increases a small initial abundance from Dodelson-Widrow production. Much of the viable parameter space will be probed in the foreseeable future. Apart from the constraints from X-ray searches, the Lyman-α forest, and DM self-interactions discussed here, potential probes include supernovae [20], the astrophysical neutrino flux (which could be suppressed by the reaction $\nu_a \nu_s \to \phi$), and 21 cm observations.

Acknowledgments

I would like to thank Torsten Bringmann, Frederik Depta, Marco Hufnagel, Joshua Ruderman, and Kai Schmidt-Hoberg for the collaboration on [21], upon which this talk was based. Special thanks go to the NOW organizers, in particular Eligio Lisi, for the absolutely outstanding organization and hospitality.

References

[1] A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens and O. Ruchayskiy, *Sterile neutrino Dark Matter*, *Prog. Part. Nucl. Phys.* **104** (2019) 1 [`1807.07938`].

[2] S. Dodelson and L.M. Widrow, *Sterile-neutrinos as dark matter*, *Phys. Rev. Lett.* **72** (1994) 17 [`hep-ph/9303287`].

[3] K. Abazajian, G.M. Fuller and W.H. Tucker, *Direct detection of warm dark matter in the X-ray*, *Astrophys. J.* **562** (2001) 593 [`astro-ph/0106002`].

[4] K.N. Abazajian, *Sterile neutrinos in cosmology*, *Phys. Rept.* **711-712** (2017) 1 [`1705.01837`].

[5] X. Shi and G.M. Fuller, *New Dark Matter Candidate: Nonthermal Sterile Neutrinos*, *Phys. Rev. Lett.* **82** (1999) 2832 [`astro-ph/9810076`].

[6] M. Shaposhnikov and I. Tkachev, *The nuMSM, inflation, and dark matter*, *Phys. Lett. B* **639** (2006) 414 [`hep-ph/0604236`].

[7] A. Kusenko, *Sterile neutrinos, dark matter, and the pulsar velocities in models with a Higgs singlet*, *Phys. Rev. Lett.* **97** (2006) 241301 [`hep-ph/0609081`].

[8] K. Petraki and A. Kusenko, *Dark-matter sterile neutrinos in models with a gauge singlet in the Higgs sector*, *Phys. Rev. D* **77** (2008) 065014 [`0711.4646`].

[9] S.B. Roland, B. Shakya and J.D. Wells, *Neutrino Masses and Sterile Neutrino Dark Matter from the PeV Scale*, *Phys. Rev. D* **92** (2015) 113009 [`1412.4791`].

[10] A. Merle and M. Totzauer, *keV Sterile Neutrino Dark Matter from Singlet Scalar Decays: Basic Concepts and Subtle Features*, *JCAP* **06** (2015) 011 [`1502.01011`].

[11] J. König, A. Merle and M. Totzauer, *keV Sterile Neutrino Dark Matter from Singlet Scalar Decays: The Most General Case*, *JCAP* **11** (2016) 038 [`1609.01289`].

[12] A. De Gouvêa, M. Sen, W. Tangarife and Y. Zhang, *Dodelson-Widrow Mechanism in the Presence of Self-Interacting Neutrinos*, *Phys. Rev. Lett.* **124** (2020) 081802 [`1910.04901`].

[13] 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** (2020) 115031 [`2005.03681`].

[14] C. Chichiri, G.B. Gelmini, P. Lu and V. Takhistov, *Cosmological Dependence of Sterile Neutrino Dark Matter With Self-Interacting Neutrinos*, `2111.04087`.

[15] 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** (2022) 055016 [`2112.00758`].

[16] F. Bezrukov, H. Hettmansperger and M. Lindner, *keV sterile neutrino Dark Matter in gauge extensions of the Standard Model*, *Phys. Rev. D* **81** (2010) 085032 [`0912.4415`].

[17] A. Kusenko, F. Takahashi and T.T. Yanagida, *Dark Matter from Split Seesaw*, *Phys. Lett. B* **693** (2010) 144 [`1006.1731`].

[18] J.A. Dror, D. Dunsky, L.J. Hall and K. Harigaya, *Sterile Neutrino Dark Matter in Left-Right Theories*, *JHEP* **07** (2020) 168 [`2004.09511`].

[19] R.S.L. Hansen and S. Vogl, *Thermalizing sterile neutrino dark matter*, *Phys. Rev. Lett.* **119** (2017) 251305 [`1706.02707`].

[20] L. Johns and G.M. Fuller, *Self-interacting sterile neutrino dark matter: the heavy-mediator case*, *Phys. Rev. D* **100** (2019) 023533 [`1903.08296`].

[21] T. Bringmann, P.F. Depta, M. Hufnagel, J. Kersten, J.T. Ruderman and K. Schmidt-Hoberg, *A new life for sterile neutrino dark matter after the pandemic*, `2206.10630`.

[22] T. Bringmann, P.F. Depta, M. Hufnagel, J.T. Ruderman and K. Schmidt-Hoberg, *Dark Matter from Exponential Growth*, *Phys. Rev. Lett.* **127** (2021) 191802 [`2103.16572`].

[23] T. Bringmann, P.F. Depta, M. Hufnagel, J.T. Ruderman and K. Schmidt-Hoberg, *Pandemic Dark Matter*, `2103.16572v1`.

[24] T. Asaka, M. Laine and M. Shaposhnikov, *Lightest sterile neutrino abundance within the nuMSM*, *JHEP* **01** (2007) 091 [`hep-ph/0612182`].

[25] PLANCK collaboration, *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* **641** (2020) A6 [`1807.06209`].

[26] K.N. Abazajian et al., *Synergy between cosmological and laboratory searches in neutrino physics: a white paper*, `2203.07377`.

[27] A. Garzilli, A. Magalich, O. Ruchayskiy and A. Boyarsky, *How to constrain warm dark matter with the Lyman-α forest*, *Mon. Not. Roy. Astron. Soc.* **502** (2021) 2356 [`1912.09397`].

[28] S. Tulin and H.-B. Yu, *Dark Matter Self-interactions and Small Scale Structure*, *Phys. Rept.* **730** (2018) 1 [`1705.02358`].