Self-interacting sterile neutrino dark matter

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✧ Dodelson-Widrow (thermal) production is strongly disfavored.
✧ Shi-Fuller (resonant) production is viable in a limited window.*

* …which may encompass a detection.
Resonant production leads to **non-thermal spectra** that are typically colder than DW ones.

Shi & Fuller 1999
Abazajian, Fuller, Patel 2001
Sterile neutrinos require at least one other BSM ingredient if they are to comprise all of the DM.

A large lepton number is one possibility. What else?

1. Don’t change the dynamics of active-sterile mixing.
   - Another new particle decays to sterile neutrinos.
   - An overabundant population is diluted by new sources of entropy.
   - Reheating occurs at a low temp.
   - Number-changing interactions occur in the sterile sector.

2. Change the dynamics of active-sterile mixing.
   - A (pseudo)scalar field alters the mixing in a time-dependent way.
   - Sterile-sector interactions alter the mixing.

Also discussed in connection with eV-scale sterile neutrinos.
Production through the neutrino portal can be calculated using a Boltzmann-like equation.

\[
\frac{df_s}{dt} = \frac{\Gamma_a}{4} \frac{\sin^2 2\theta_m}{1 + \left(\frac{\Gamma_a}{2\omega_m}\right)^2} (f_a - f_s)
\]

Compare to the QKEs (with approximate collision term):

\[
\frac{dP_0}{dt} = 2D \left(f_a^{eq} - P_0 \frac{1 + P_z}{2}\right)
\]
\[
\frac{dP}{dt} = \omega_m B_m \times P - DP_T - \frac{\dot{P}_0}{P_0} P + \frac{\dot{P}_0}{P_0} z
\]

Papers by Bell, Lee, Volkas, & Wong have shown that repopulation terms in the QKEs can be ignored if the mixing angle is small:

\[
\frac{dP_0}{dt} = 0, \quad f_a = f_a^{eq}
\]

The Boltzmann equation also follows directly from a quantum relaxation-time approximation:

\[
iC = \{i\Gamma, \rho_C^{eq} - \rho\}
\]
\[
i\frac{d\rho}{dt} = \{i\Gamma_{eff}, \rho_F^{eq} - \rho\}
\]
Relaxation ansatz:

\[
\frac{d\rho}{dt} = \frac{\gamma m}{2} (\rho^\text{eq}_F - \rho)
\]

The prefactor is determined by by equating this with the QKEs.

Agreement is strong between QKE and Boltzmann solutions (as expected):

(time-independent parameters)
Repopulation is captured well by the ansatz:

\[ \frac{D}{\omega} = 10^{-2} \]

\[ P_0(t) / f_a^{eq} \]

\[ f_a(t) / f_a^{eq} \]

\[ P(t) \]

As is decoherence:

\[ \frac{P_0 P_x}{f_{eq}} \]

\[ \frac{t}{\gamma^{-1}} \]

\[ \frac{D}{\omega} = 10^{-2} \]

\[ \frac{D}{\omega} = 10 \]

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**Repopulation** is captured well by the ansatz:

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\[
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\]

\[
f_a(t) / f_a^{\text{eq}}
\]

Could this be helpful for active-active mixing?

As is **decoherence**:

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\frac{P_0 P_x}{f_{\text{eq}}}
\]

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\frac{D}{\omega} = 10
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\]

\[
\frac{D}{\omega} = 10
\]
Adding in self-interactions...

\[ \mathcal{V} = \mathcal{V}_\mu + \mathcal{V}_a + \mathcal{V}_s \]

\[ \frac{df_s}{dt} = \frac{\Gamma_a}{4} \frac{\sin^2 2\theta_m}{1 + \left( \frac{\Gamma_a}{2\omega_m} \right)^2} (f_a - f_s) + \mathcal{C}_s \]

\[ D = \frac{\Gamma_a + \Gamma_s}{2} \]

These effects have been invoked as a way to **reconcile eV sterile neutrinos with cosmology.**

Hannestad, Hansen, & Tram 2014
Dasgupta & Kopp 2014

The goal there is to **suppress** the production of sterile neutrinos rather than enhance it.
For simplicity, we’ll let the self-interactions be mediated by a heavy scalar.

Potential from sterile neutrinos coherently scattering on each other:

\[ V_s = + \frac{G_\phi}{3m_\phi^2} \rho_s p \]

\[ \mathcal{L}_s = \frac{1}{2} \bar{\psi}_s (i\partial - m_s) \psi_s + \frac{1}{2} (\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{g_\phi}{2} \bar{\psi}_s \psi_s \phi. \]

\[ m_\phi \gtrsim 1 \text{ GeV} \]

The overproduction curves shift to smaller mixing angle as the coupling is increased.
But in fact there’s more to the story…

If the coupling is large enough to appreciably enhance the scattering rate, it’s also large enough to set up a resonance.

Nonlinearity then leads to runaway production.
Fraction of DM produced vs. temp:

Why can’t the scattering rate be boosted without generating a resonance?

\[
\frac{\Gamma_s}{\Gamma_a} \gtrsim 1 \quad \Rightarrow \quad \left| \frac{\nu_s}{\nu_a} \right| \gtrsim \frac{g_w}{g_\phi}
\]

Conversely, resonance can occur with subdominant sterile scattering—but overproduction still ensues.

Logarithmic production rate vs. temp:

Johns & Fuller 2019
The resonance sweeps from high energy down to a cutoff, then doubles back...
Summary

1. Based on the BOSS Lyman-alpha measurements, constraints on the mass of resonantly produced sterile neutrinos are derived, with the production mechanism from phase space arguments that takes into account the primordial distribution of sterile neutrinos, depending on the abundances of light elements produced during Big Bang Nucleosynthesis (BBN). Lepton asymmetries required for this mechanism to work are ruled out because they would alter the baryon-to-photon ratio at temperatures of a few hundred MeV, well within the energy range that is testable in experiments, e.g., via the non-resonant mechanism due to neutrino-DM interactions.

2. The constraints on sterile neutrino DM are illustrated by the violet area, showing the abundance of sterile neutrinos that could potentially account for the observed DM density. The bounds based on the structure formation bound and the non-observation of X-rays are compared, with all X-ray bounds being smoothed and divided by a factor of 2 to account for additional interactions. All constraints depend on the sterile neutrino production via the non-resonant mechanism due to neutrino-DM interactions, and the bounds are indicated by a solid line because it applies to any sterile neutrino, i.e., a singlet fermion that mixes with the SM neutrinos. It can only be avoided if one assumes significant deviations from the Standard Model.

3. Constraints on sterile neutrino DM are also shown via the ATHENA sensitivity made in ref. [3.2], with the purple area indicating the lower bound overclosure bound. For parameter values between the solid black line and the dotted green line, the observed DM density is consistent with the constraints. For parameter values outside this line, the abundance of sterile neutrinos would exceed the observed DM density.

4. We’re beginning to extend the analysis to lighter mediators. The sub-keV range (including models motivated by issues of small-scale structure) doesn’t look promising.