Self-interacting dark matter and sterile neutrinos

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Abstract. We discuss some possible astrophysical and cosmological connections between dark matter and sterile neutrinos. Both the controversies at small scales for traditional cold dark matter (CDM) and anomalies in neutrino experiments seem to suggest that there might be new self-interactions for dark matter and sterile neutrinos. Surprisingly, if the new interaction also mediates between dark matter and sterile neutrinos, “missing satellite problem” in CDM paradigm can also be solved. On the other hand, light sterile neutrinos with self-interacting can also satisfy the cosmological bounds.

1. Introduction
Recently, there have been a lot intriguing discussions on the possible connection between dark matter and sterile neutrinos with secret interactions [1, 2, 3, 4, 5, 6, 7]. The main motivations for exploring such a scenario come from the difficulties to explain some astrophysical observations for traditional collisionless cold dark matter (CCDM) paradigm and standard three active neutrinos pattern.

On the dark matter side, several possible controversies at small scales exist for CCDM, namely cusp vs. core, too-big-to-fail and missing satellites problems (see Ref. [8] for a review). The first two problems can be resolved if DM has a strong self-interaction with \( \sigma / M_{DM} \gtrsim 1 \text{cm}^2/\text{g} \). The third problem would be relaxed if the interaction between DM and some relativistic particle in cosmic background delays DM’s kinetic decoupling until the time when the temperature of cosmic photon \( T_\gamma \lesssim O(\text{keV}) \). The late-decouple would suppress structures with sizes smaller than “collisional damping scale” [9, 10].

On the neutrino side, several anomalies from neutrino experiments [11, 12, 13, 14, 15, 16, 17] indicate an eV scale sterile neutrino \( \nu_s \) that mix with active ones \( \nu_a \), although at the moment the situation is not clear enough to draw conclusive statements yet. For cosmology, introduction of new degree of freedom, especially light particles, could dramatically change the evolution of our universe, therefore interesting phenomenology or constraints could arise. The parameter space suggested by neutrino anomalies seems to be strongly disfavored by cosmological data because the mixing could equilibrate the sterile neutrinos, in conflict with Planck [18] bounds,

\[
2.53 < N_{\text{cmb}}^{\text{eff}} < 3.7, \; m_\nu^{\text{eff}} < 0.52\text{eV}. \tag{1}
\]

This is the main background that self-interacting sterile neutrinos comes in to resolve the conflict by changing the thermal history of our universe [7], see Fig. 1.
Figure 1. Thermal history of active and self-interacting sterile neutrinos. When the temperature is high, $\nu_s$s are not in thermal equilibrium with $\nu_a$s because of the suppression from a large matter potential induced by self-interaction of sterile neutrino. As the Universe cools down, equilibrium between active and sterile neutrinos could be finally reached when matter effect is small enough.

Cosmological bounds on the neutrino masses from the combination of CMB, large scale structure and distance measurements are actually constraining the following effective quantity,

$$m_\nu^{\text{eff}} \equiv \sum_i n_{\nu_i} m_{\nu_i} n_{\nu_a}^{0} \nu_a = \sum_i \left( \frac{T_{\nu_i}}{T_{\nu_a}} \right)^3 m_{\nu_i} \simeq 94.1 \text{eV} \times \Omega_\nu h^2.$$  

After the later flavor equilibrium discussed above, all neutrinos would share the same temperature, $T_{\nu_i} = T_\nu$. Assume only one of $n$ sterile neutrinos has eV mass but all others are almost massless, we can get

$$m_\nu^{\text{eff}} \simeq \left( \frac{T_\nu}{T_{\nu_a}} \right)^3 m_{\nu_4}.$$  

From the trend shown in the cases of Fig. 2, it is evident that introducing more light sterile states in the discussed scenario would relax the cosmological bounds further. When putting the lower bounds on $N_{\text{eff}}$, we should be aware of the assumption that no other relativistic particles contribute as radiations. In cases where there are quite a mount of massless particles such as Goldstone or Majaron particles, the lower bounds on $N_{\text{eff}}$ then do not apply and $n < 3$ will be allowed.

2. Self-Interacting Dark Matter and Sterile Neutrinos

Perhaps the simplest model to implement self-interacting dark matter $\chi$ and sterile neutrinos $N$ would be just introducing a scalar singlet mediator $\phi$ with Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{N}i\gamma^5 \gamma N - \left( \frac{1}{2} m_N \bar{N}cN + y \bar{L}H N + h.c. \right) + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi, H) - \frac{1}{2} \left( g \phi \bar{N}cN + h.c. \right) + \bar{\chi} \left( i\gamma^5 \phi - m_\chi \right) \chi - f \phi \bar{\chi} \chi.$$  

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Figure 2. We have chosen $m_{\nu_1} = 1$eV and assumed it is dominant on the mass. The plot shows $m_{\nu}^{\text{eff}}$ as functions of $\delta N_{\text{eff}}^{\text{cmb}}$ and number of sterile neutrinos, $n$. Parameter space inside region marked with arrows is still allowed by Planck [18].

where $V$ is the scalar potential for $\phi$ and SM Higgs doublet $H$. If parameters are chosen properly, $\phi$ can provide the needed interaction. Phenomenological study of this model is straightforward although it could be quite involved when considering the detailed cosmological evolution.

In this section, instead we focus on a gauged model [5] for self-interacting dark matter which has the standard seesaw mechanism with two right-handed neutrinos $N_i (i = 1, 2)$, a dark sector with $U(1)_X$ gauge symmetry, coupling $g_X$, and vector field $\hat{X}_\mu$, scalar field $\phi_X$ and two different Dirac fermions, $\psi$ and $\chi$, in the dark sector. The interesting gauge invariant Lagrangian is given by

$$
\mathcal{L} = \mathcal{L}_{\text{SM}} + \nu_i \bar{\psi}_i N_i - \left( \frac{1}{2} m_{\nu}^{R} \bar{N}_i^c N_j + y_{\alpha i} L_{\alpha} H N_i + h.c. \right) - \frac{1}{4} \hat{X}_{\mu\nu} \hat{X}^{\mu\nu} - \frac{1}{2} \sin \epsilon \hat{X}_{\mu\nu} \hat{B}^{\mu\nu} + \bar{\chi} \left( i \slashed{D} - m_\chi \right) \chi + \bar{\psi} \left( i \slashed{D} - m_\psi \right) \psi + D_\mu \phi_X^* D^\mu \phi_X - \left( f_{i} \phi_X^* N_i \psi + g_i \phi_X \bar{N}_i + h.c. \right) - \lambda_\phi \left[ \phi_X^* \phi_X - v_\phi^2 \right]^2 - \lambda_{\phi H} \left[ \phi_X^* \phi_X - v_\phi^2 \right] \left[ H^\dagger H - v_h^2 \right],
$$

where $L_{\alpha}$ are the SM left-handed lepton doublets, $H$ is the SM Higgs doublet, and $\hat{B}$ is the field strength for SM $U(1)_Y$. $U(1)_X$ charge for $\chi$ are chosen in such a way that the $\phi_X \bar{N}_i$ term is not allowed by $U(1)_X$ gauge symmetry. Thus $\chi$ would be stable and DM candidate.

The gauge symmetry is broken when vacuum has non-vanishing expectation value:

$$
\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_h \end{pmatrix}, \quad \langle \phi_X \rangle = \frac{v_\phi}{\sqrt{2}}
$$

where $v_h \simeq 246$GeV and $v_\phi \sim \mathcal{O}$(MeV). There will be mixings among various fields after the spontaneous symmetry breaking. For instance, the gauge kinetic mixing term results in tiny mixings among the physical gauge fields, $A_\mu, Z_\mu$ and $X_\mu$. Also there is a mixing between Higgs fields $h$ and $\phi$ with

$$
H \rightarrow (v_h + h)/\sqrt{2} \quad \text{and} \quad \phi_X \rightarrow (v_\phi + \phi)/\sqrt{2}.
$$
Two scalar excitations $h$ and $\phi$ can be expressed in terms of mass eigenstates, $H_1$ and $H_2$, as
\[ h = H_1 \cos \alpha - H_2 \sin \alpha, \quad \phi = H_1 \sin \alpha + H_2 \cos \alpha, \]
with a mixing angle $\alpha$. If the new gauge boson $X_\mu$ has mass around $O(\text{MeV})$, it can provide the correct self-interaction for TeV dark matter $\chi$.

The neutrino sector in this model would be three active neutrinos and four sterile ones. It can be seen in the Lagrangian Eq. 5 that sterile neutrinos have new gauge or Yukawa self-interactions. As we have shown in the introduction, such a setup with multiple self-interacting sterile neutrinos can evade the cosmological bounds on neutrino effective numbers and mass. This self-interaction would make sterile neutrinos not stream freely, which might also have minor effects on the cosmic microwave background.

Another important effect for this new gauge interaction is that it also mediates between dark matter $\chi$ and sterile neutrinos. Since sterile neutrinos in this model are almost massless, they constitute as dark radiation in our cosmic backgrounds. The continuing elastic scattering between dark matter and sterile neutrinos would induce DM perturbation to go through a damped oscillation, just like baryon acoustic oscillation in baryon-photon system.

3. Conclusion
Motivated by small scale problems for cold dark matter and neutrino anomalies, we have discussed some possible connections between self-interacting dark matter and sterile neutrinos, and showed that it is very simple to implement this idea in particle physics models. The interaction between dark matter might introduce new phenomena in cosmological observables, especially at the matter power spectrum at small scales, which has already been shown to be able to solve the "missing satellite problem". Other possible controversies at small scales, namely cusp vs. core and too-big-to-fail, can also be resolved in self-interacting dark matter scenario.

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