Exotic Sterile Neutrinos and Pseudo-Goldstone Phenomenology

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We study the phenomenology of a light (GeV scale) sterile neutrino sector and the pseudo-Goldstone boson (not the majoron) associated with a global symmetry in this sector that is broken at a high scale. Such scenarios can be motivated from considerations of singlet fermions from a hidden sector coupling to active neutrinos via heavy right-handed seesaw neutrinos, effectively giving rise to a secondary, low-energy seesaw framework. Such scenarios allow for rich phenomenology with observable implications for cosmology, dark matter, and direct searches, involving novel sterile neutrino dark matter production mechanisms from the pseudo-Goldstone-mediated scattering or decay, modifications of BBN bounds on sterile neutrinos, suppression of canonical sterile neutrino decay channels at direct search experiments, late injection of an additional population of neutrinos in the Universe after neutrino decoupling, and measurable dark radiation at BBN or CMB decoupling.

**MOTIVATION**

The most straightforward explanation of tiny neutrino masses is the seesaw mechanism, involving Standard Model (SM) singlet (sterile) right-handed neutrinos at a heavier scale. GUT (grand unified theory) scale seesaw models\textsuperscript{11-15} accomplish this with $\mathcal{O}(1)$ couplings with heavy sterile neutrinos at $M \sim 10^{10} - 10^{15}$ GeV. However, the seesaw mechanism is also consistent with light sterile neutrinos below the electroweak scale, which finds additional motivation from dark matter (DM) and leptogenesis considerations as in the Neutrino Minimal Standard Model ($\nu$MSM)\textsuperscript{6-8}, and is also attractive due to rich phenomenology, offering signals in cosmology, indirect detection, as well as direct searches\textsuperscript{9, 10}.

Drastic departures from this phenomenology, which is dictated by the mixing between the active and sterile neutrino sectors as necessitated by the seesaw mechanism, is possible if additional structure (such as additional symmetries or particles) exists in the sterile neutrino sector beyond the basic elements of the seesaw framework (see e.g. discussions in\textsuperscript{11-13}). Charges under an additional symmetry are plausibly necessary for sterile neutrinos to be light, since the Majorana mass of a pure singlet fermion is expected to lie at the ultraviolet (UV) cutoff scale of the theory (such as the GUT or Planck scale). A well-motivated choice is to draw a connection to lepton number, tying the sterile neutrino masses with a low scale of lepton number breaking\textsuperscript{14, 20}; rich phenomenology ensues from the existence of additional scalars\textsuperscript{21, 22} and massive gauge bosons\textsuperscript{2, 24, 25} or a (pseudo-) Goldstone boson, the majoron\textsuperscript{14, 20}.

It is, however, also possible that the protecting symmetry is confined entirely to the sterile neutrino sector. This can occur, for instance, if the sterile neutrinos originate from a separate hidden sector. In the next section, we will see that even with a GUT-scale realization of the seesaw mechanism, exotic fermions from hidden sectors that couple to the GUT scale right-handed neutrinos develop couplings to the SM neutrinos, mimicking a low energy seesaw setup, thus effectively acting as light sterile neutrinos akin to those studied in, e.g. the $\nu$MSM.

In this letter, we study the phenomenology associated with a pseudo-Goldstone boson $\eta$ of a global symmetry confined to, and spontaneously broken in, a light (GeV scale) exotic sterile neutrino sector. Since GeV scale seesaw sterile neutrinos play an important role in the early Universe — they equilibrate with the thermal bath and dominate the energy density before big bang nucleosynthesis (BBN)\textsuperscript{26} — their interplay with $\eta$ can lead to novel cosmological scenarios. The $\eta$ phenomenology can be very different from the more familiar majoron phenomenology, as the scale of symmetry breaking, lepton number breaking, and sterile neutrino masses are all different. This could enable the $\eta$ and the sterile neutrinos to have similar masses. This freedom of scale separation and coincidence of masses gives rise to many rich possibilities for cosmology, dark matter, and direct searches that are not possible in the majoron framework.

**CHARGED-SINGLET SEESEWAS**

The canonical seesaw mechanism involves three SM-singlet, right-handed neutrinos $N_i$ with the following Dirac and Majorana masses:

$$\mathcal{L} \supset y_{ij} L_i h N_j + M_i \bar{N}_i \bar{N}_i.$$  \hspace{1cm} (1)

$L_i$ and $h$ are the SM lepton doublet and Higgs fields, and $y_{ij}$ are dimensionless Yukawa couplings. The hierarchy $M \gg y v$ (where $v$ is the Higgs vacuum expectation value (vev)) leads to the familiar seesaw mechanism, resulting in active and sterile neutrino masses $m_\alpha \sim y^2 v^2 / M$, $m_s \sim M$, with an active-sterile mixing angle $\sin \theta \sim y \nu / M$. $M \sim 10^{14}$ GeV produces the...
desired neutrino masses for $y \sim \mathcal{O}(1)$, whereas $M \sim \text{GeV}$ requires $y \sim 10^{-7}$.

A global or gauged $U(1)_{\text{lepton}}$ or $U(1)_{B-L}$ symmetry for $N_i$ [14–20] allows for the Dirac mass term but precludes the Majorana mass term until the symmetry is broken. In this case, the lagrangian is instead

$$\mathcal{L} \supset y_{ij} L_i h N_j + x_i \phi N_i^c N_i + \lambda (H^H H) \phi^2 + V(\phi),$$

with the singlet Higgs field $\phi$ appropriately charged under the lepton or $B-L$ symmetry. A $\phi$ vev breaks the symmetry and gives rise to sterile neutrino masses $M_i \sim x(\phi)$. If the symmetry is global, a physical light degree of freedom, the Goldstone boson, the majoron, emerges [13-15].

In this paper, we consider instead a global symmetry, for instance a $U(1)'$, that is confined to the sterile neutrinos and does not extend to any of the SM fields. Such a symmetry forbids both the Dirac and Majorana mass terms in Eq. 1. Nevertheless, a scalar field $\phi$ carrying the opposite $U(1)'$ charge to $N_i$ enables the higher dimensional operator $\frac{1}{\Lambda} L h N \phi$, where $\Lambda$ is a UV-cutoff scale. 1 Once $\phi$ gets a vev, the $U(1)'$ is broken and the Dirac mass term is recovered with the effective Yukawa coupling $y \sim \lambda_1 \langle \phi \rangle / \Lambda$; thus such an operator also provides a natural explanation for the tiny Yukawas in terms of the hierarchy between the two scales $\langle \phi \rangle$ and $\Lambda$. We now discuss a UV completion of this setup in terms of singlet fermions from a hidden sector that couple to heavy right-handed seesaw neutrinos.

“Sterile neutrinos” from a hidden sector with a heavy right-handed neutrino portal

We start with the original seesaw motivation of pure singlet, heavy (scale $M$, possibly close to the GUT scale) right-handed neutrinos that couple through Yukawa terms $y_{ij} L_i h N_j$. If the $N_j$ also act as portals to a hidden sector 2, then we also have the generic prospect of an analogous Yukawa term $y'_{ij} L'_i h' N_j$, where $L'_i h'$ is a singlet combination of hidden sector fields analogous to $L_i h$. Integrating out the $N_i$ produces the following dimension-5 operators connecting the visible and hidden sectors (we ignore flavor structure and drop indices for simplicity):

$$\mathcal{L} \supset \frac{1}{M} y^2 (L h)^2 + \frac{1}{M} y y' (L h) (L' h')^2 + \frac{1}{M} y'^2 (L' h')^2.$$  

If the hidden sector scalar acquires a vev $v'$, this can be rewritten as

$$\mathcal{L} \supset \frac{1}{M_{\text{eff}}} (L h)^2 + y_{\text{eff}} L h L' + M_{\text{eff}} L'L'$$

where we have defined $\Lambda_{\text{eff}}^{-1} \equiv y^2 / M$, $y_{\text{eff}} \equiv y y' / M$ and $M_{\text{eff}} \equiv y'^2 v'^2 / M$. Here, the first term accounts for the active neutrino masses $y^2 v^2 / M$ from the primary seesaw involving integrating out the pure singlet neutrinos $N_i$. The latter two terms give a similar contribution to the active neutrino masses from the secondary seesaw resulting from integrating out the $L'_i$ fermions (note the analogy between Eq. 2 and Eq. 1).

The mixing angle between the active neutrinos and these hidden sector singlets $L'$ is approximately

$$\sin \theta' \sim \frac{y_{\text{eff}} v}{M_{\text{eff}}} = \frac{y v}{y' v'} = \sqrt{m_\alpha M_{\text{eff}}},$$

which is precisely the relation expected from a seesaw framework. Therefore, light sterile neutrinos that appear to satisfy the seesaw relation could have exotic origins in a hidden sector connected via a high scale neutrino portal, be charged under symmetries unrelated to the SM, and themselves obtain light masses via the seesaw mechanism, which is active at a much higher scale $M$. 3 We will henceforth ignore the “true” right-handed seesaw neutrinos at scale $M$ that have been integrated out, and reserve the notation $N_i$ to refer to these light sterile states $L'$, whose phenomenology we will pursue in this paper.

Pseudo-Goldstone Boson

The spontaneous breaking of the global $U(1)'$ by $\langle \phi \rangle \equiv f$ gives rise to a massless Goldstone boson, which we will call the $\eta$-boson. It is conjectured that non-perturbative gravitational effects explicitly break global symmetries, leading to a pseudo-Goldstone boson mass of order $m_\eta^2 \sim f^3 / M_{P1}$ via an operator of the form $\phi \, 3f / M_{P1}$ [48, 49]. 4 For generality, we treat $m_\eta$ as a free parameter, but this approximate mass scale should be kept in mind.

Next, we draw the distinction between the $\eta$-boson and the more familiar majoron [14–20]. For both the majoron and $\eta$, couplings to (both active and sterile) neutrinos are proportional to the neutrino mass suppressed by the scale of symmetry breaking, as expected for Goldstone bosons, hence several phenomenological bounds on the majoron symmetry breaking scale [10, 18, 51–54] are also applicable to $\eta$. However, the majoron is associated with the breaking of lepton number — a symmetry shared by the SM leptons as well as the sterile neutrinos — and the sterile neutrino mass scale approximately coincides with the scale of lepton number breaking. This results in

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1 Such operators have been studied in the context of supersymmetry [27, 31], including the freeze-in production of sterile neutrino DM [33-34].

2 For recent studies of right-handed neutrinos acting as portals to a hidden/dark sector, see [25-22].

3 This setup holds similarities with extended seesaw models [43–47], which also employ a seesaw suppression for sterile neutrino masses to naturally accommodate an eV scale sterile neutrino.

4 An explicit $U(1)'$ breaking Goldstone mass term is also possible. A small $\eta$ mass is also generated from the Yukawa coupling [50], but is negligible for the parameters we are interested in.
FIG. 1: Contours of lifetime \( \log_{10}(\tau_\eta/s) \) with \( M_{N_{2,3}} = 1 \text{ GeV}, M_{N_1} = 7 \text{ keV} \) for \( f = 10^9 \text{ GeV} \) (blue solid) and \( f = 10^3 \text{ GeV} \) (red dotted). The horizontal lines represent the age of the Universe (top) and the time of BBN (bottom).

the majoron being much lighter that the sterile neutrinos. In addition, this scaling results in specific relations between majoron couplings and sterile neutrino masses, which drives many of the constraints on majoron parameter space [11 12 51 54].

In contrast, these energy scales are distinct in the \( \eta \) framework: the symmetry breaking scale \( f \) (i.e., the scale of \( U(1)' \) breaking) is independent of the breaking of lepton number, which occurs at a much higher scale \( M \), and is also distinct from the sterile neutrino mass scale \( (M_{\text{eff}} \sim f^2/M) \), which, as discussed above, can itself be suppressed by a seesaw mechanism. The ability to vary them independently opens up phenomenologically interesting regions of parameter space. Furthermore, the sterile neutrino masses \( M_{\text{eff}} \sim f^2/M \) can be comparable to the \( \eta \)-boson mass \( m_\eta^2 \sim f^4/M^2 \eta^2 \) (if \( f \sim M^2/M_{\text{Pl}} \)); this coincidence of mass scales can have important implications for cosmology and DM, as we will see later.

FRAMEWORK AND PHENOMENOLOGY

We focus on a low-energy effective theory containing three sterile neutrinos (which we have reset to the label \( N_i \) rather than \( L' \)), and the pseudo-Goldstone boson \( \eta \).

\[
\mathcal{L} \supset y_{ij}L_i h N_j + m_{N_i} \bar{N}_i^c N_i + \frac{m_\eta^2}{2} \eta^2 + \frac{y_{ij} v}{f} \eta L_i N_j + \frac{m_{N_i}}{f} \eta \bar{N}_i^c N_i + \cdots \tag{6}
\]

We treat \( m_{N_i}, f \), and \( m_\eta \) as independent parameters. We assume \( m_{N_i} \sim \text{GeV} \) scale, and \( y_{ij} \) are correspondingly small in a natural way that matches the measured \( \Delta m^2_{\nu} \) and mixings among the light active neutrinos. We will consider the possibility that the lightest sterile neutrino \( N_1 \) is DM, since this is an interesting and widely studied case, and especially appealing given recent claims of a 3.5 keV X-ray line [55 56] compatible with decays of a 7 keV sterile neutrino DM particle. We also assume that \( f \gg v \) so that the \( U(1)' \) breaking singlet scalar is decoupled and irrelevant for phenomenology.

**Lifetime:** The \( \eta \) lifetime is controlled by decay rates into (both active and sterile) neutrinos. For instance,

\[
\Gamma(\eta \rightarrow \nu \nu) \simeq \frac{1}{8\pi} \left( \frac{m_\nu}{f} \right)^2 m_\eta, \tag{7}
\]

where \( m_\nu \sim 0.1 \text{ eV} \) is the active neutrino mass scale. For decay channels \( \eta \rightarrow N_i \nu \) and \( \eta \rightarrow N_i N_j \) involving the sterile neutrinos, the \( m_\nu \) in the above formula is replaced by \( \sqrt{m_{N_i} m_\nu} \) and \( m_{N_i} \) respectively.

Fig. 1 shows the \( \eta \) lifetime as a function of \( m_\eta \), with \( M_{N_{2,3}} = 1 \text{ GeV} \) and \( M_{N_1} = 7 \text{ keV} \), for two different values of \( f \). Depending on the scale \( f \) and the available decay channels, a range of interesting lifetimes are possible: \( \eta \) can decay before or after BBN (and before/after Cosmic Microwave Background (CMB) decoupling), or live longer than the age of the Universe, providing a potential DM candidate (for studies of majoron DM, see [17 48 50 57 62]).

A pseudo-Goldstone coupling to neutrinos faces several constraints [63 67]. However, many of these constraints weaken/become inapplicable if the pseudo-Goldstone is heavy or can decay into sterile neutrinos. We remark that these constraints are generally not very stringent in the parameter space of interest in our framework.

**Cosmology:** In the early Universe, GeV scale sterile neutrinos \( N_{2,3} \) (but not the DM candidate \( N_1 \), which has suppressed couplings to neutrinos) are in equilibrium with the thermal bath due to their mixing with active neutrinos, decouple while still relativistic at \( T \sim 20 \text{ GeV} \) [26], can grow to dominate the energy density of the Universe, and decay before BBN [26 48 59].

On the other hand, \( \eta \) couples appreciably only to the sterile neutrinos, and is produced via sterile neutrino annihilation processes \( N_i N_j \rightarrow \eta \eta \) (see Fig. 2(a)) or decay (if kinematically open). The annihilation process, although \( p \)-wave suppressed, is nevertheless efficient at high temperatures \( T \gtrsim m_{N_{2,3}} \). One can estimate the magnitude of \( f \) for such annihilations to be rapid compared to Hubble expansion by comparing the annihilation cross section [70 71] with the Hubble rate at \( T \sim m_{N_{2,3}} \).

\[
n_{N_i} \sigma v \sim H \Rightarrow \frac{m_{N_i}^4}{f^4} m_{N_i} \sim \frac{m_\eta^2}{M_{\text{Pl}}} \Rightarrow \ f \sim m_{N_{2,3}}^{3/4} M_{\text{Pl}}^{-1/4}. \tag{8}
\]

For \( m_{N_{2,3}} \sim \text{GeV} \), this process is efficient for \( f \lesssim 10^5 \text{ GeV} \), and produces an \( \eta \) abundance comparable to the \( N_{2,3} \) abundance. For larger values of \( f \), the annihilation process is feeble, and a small \( \eta \) abundance will accumulate via the freeze-in process instead [72 73].

**Dark Matter Production:** \( \eta \) can also mediate \( N_i N_j \rightarrow N_j N_j \) interactions between the sterile neutrinos (Fig. 2(b)), which enables a novel DM production mechanism \( N_i N_j \rightarrow N_1 N_1 \). One can analogously estimate the
scale $f$ below which this production cross section \cite{74} is efficient: $f \sim \sqrt{m_{N_1}} (M_P m_{N_{2,3}})^{1/4}$. This would generate an $N_1$ abundance comparable to relativistic freezeout, which generally overcrosses the Universe, hence this scenario is best avoided. Likewise, $\eta$ decays can also produce DM if $m_\eta > 2m_{N_1}$. By comparing rates, we find that production from such decays dominates over the annihilation process provided $m_\eta > m_{N_{2,3}}^3/f^2$, which generally holds over most of our parameter space. Additional DM production processes, such as $\eta$ annihilation and $N_{2,3}$ decays via an off-shell $\eta$, are always subdominant and therefore neglected. The novel production processes discussed here do not rely on $N_1$ mixing with active neutrinos, which is particularly appealing since this canonical (Dodelson-Widrow) production mechanism \cite{73} is now ruled out by various constraints \cite{8} [76].

Next, we discuss various interesting cosmological histories that are possible with this framework. Our purpose is not to provide a comprehensive survey of all possibilities, which is beyond the scope of this note, but simply to point out some interesting features. Since available decay channels and lifetimes are crucial to the subsequent evolution of these particles, we find it useful to organize our discussion into three different regimes.

**Heavy regime**: $m_\eta > m_{N_1}$

When $m_\eta > m_{N_1}$, all $\eta$ decay channels to sterile neutrinos are open, and $\eta$ decays rapidly, long before BBN. If $N_1 N_1 \rightarrow \eta \eta$ is rapid, $\eta$ maintains an equilibrium distribution at $T \gtrsim m_\eta$, and the decay $\eta \rightarrow N_1 N_1$ generates a freeze-in abundance of $N_1$, which can be estimated to be \cite{82} [41] [73] [54] [89]

$$Y_{eq} \sim 0.1 \frac{M_P l}{m_\eta} \left( \frac{m_{N_i}}{f} \right)^2. \quad (9)$$

The observed DM abundance is produced, for instance, with $f \sim 10^5$ GeV, $m_\eta \sim 10$ GeV, and $m_{N_1} \sim 10$ keV.

If the $N_1 N_1 \rightarrow \eta \eta$ annihilation process is feeble, a freeze-in abundance of $\eta$ is generated instead, and its decays produce a small abundance of $N_1$. The $N_1$ yield is suppressed by the branching fraction $\text{BR}(\eta \rightarrow N_1 N_1) = \frac{\Gamma(\eta \rightarrow N_1 N_1)}{\Gamma(\eta \rightarrow N_{2,3} N_{2,3})} = \frac{m_{N_{2,3}}^2}{m_{N_{2,3}}^3}$. The resulting abundance is much smaller than $Y_{eq}$ from Eq.9 and cannot account for all of DM unless $m_{N_1} \sim m_{N_{2,3}}$.

**Intermediate regime**: $m_{N_{2,3}} > m_\eta > m_{N_1}$

In addition to annihilation processes, $\eta$ can now also be produced directly from heavy sterile neutrino decay when $m_{N_{2,3}} > m_\eta$. Ignoring phase space suppression, the decay rate is

$$\Gamma(N_i \rightarrow \eta \nu) \approx \frac{1}{16\pi} \frac{m_{N_i} m_\nu}{f^2} m_{N_i}. \quad (10)$$

If this width is sufficiently large, this exotic decay channel can compete with the traditional sterile neutrino decay channels induced by active-sterile mixing \cite{90}. In Fig.3 we plot (blue curve) the scale $f$ below which this decay channel dominates (assuming the standard seesaw relations). This region carries important implications for collider and direct searches for sterile neutrinos (such as at DUNE \cite{91} and SHIP \cite{92}), as the new dominant channel suppresses the traditionally searched-for decay modes, rendering the sterile neutrinos invisible at such detectors (unless $N_1$ also decays in the detector, as can occur if it is not DM and participates in the seesaw instead).

It is well known that $N_2, N_3$ are constrained by several recombination era observables \cite{93} [95] and generally are required to decay before BBN, necessitating $\tau_{N_2, N_3} \lesssim 1$ s and consequently $m_{N_{2,3}} \gtrsim \mathcal{O}(100)$ MeV in the standard seesaw formalism. The above decay channel $N_1 \rightarrow \eta \nu$, if sufficiently large, can reduce the sterile neutrino lifetime, thus allowing lighter masses to be compatible with BBN.

In Fig.3 the red dashed line shows the scale $f$ below which the sterile neutrino decays before BBN. For $f \lesssim 10^6$ GeV, even lighter (MeV scale) sterile neutrinos are compatible with the seesaw as well as BBN constraints, in stark contrast to the standard seesaw implications.

Depending on parameters, $\eta$ can decay before or after BBN (see Fig.4), but its dominant decay channel is $\eta \rightarrow N_1 N_1$, which can be DM. If $N_{2,3}$ decay dominantly into $\eta$, or if $N_1$ thermalizes with $N_{2,3}$, the $N_1$ abundance

![FIG. 2: Sterile neutrino annihilation processes involving the pseudo-Goldstone boson $\eta$.](image-url)

![FIG. 3: Solid blue: Symmetry breaking scale $f$ below which the exotic decay $N \rightarrow \eta \nu$ dominates over the traditional sterile neutrino decay channels from the seesaw. Below the dashed red line, this decay channel causes the sterile neutrinos to decay before BBN. Below the dotted green line, sterile neutrino pseudo-Goldstone interactions are sufficiently rapid to thermalize the two populations in the early Universe.](image-url)
is comparable to that from relativistic freezeout, which would likely overclose the Universe. Viable regions of parameter space instead involve a small fraction of $N_{2,3}$ decaying into $\eta$, which subsequently decays to $N_1$. In this case, the heavy sterile neutrinos $N_{2,3}$ undergo relativistic freezeout, and their branching ratio into $\eta$ gets converted completely to $N_1$; one can thus derive the following approximate relation for $N_1$ to account for the observed DM abundance for $m_{N_{2,3}} = 1$ GeV:

$$f \approx 10^9 \text{GeV} \sqrt{\frac{m_{N_1}}{\text{GeV}}}.$$  \hfill (11)

For instance, $m_{N_1} = 7$ keV requires $f \sim 10^6$ GeV.

Here, DM ($N_1$) is produced from late decays of heavier particles ($\eta$ and $N_{2,3}$) and can be warm. Such late production of warm DM can carry interesting cosmological signatures and structure formation implications, but a detailed study lies beyond the scope of this paper.

**Light regime: $m_{N_1} > m_\eta > m_\nu$**

The most interesting aspect of the $m_{N_1} > m_\eta > m_\nu$ hierarchy is that all sterile neutrinos (including the DM candidate $N_1$) can decay into $\eta$. In particular, a new very long-lived DM decay channel $N_1 \rightarrow \eta \nu$ exists. Since $\eta$ subsequently decays into two neutrinos, this can provide distinct signatures at neutrino detectors such as IceCube, Borexino, KamLAND, and Super-Kamiokande. Note that, unlike the standard $N_1 \rightarrow \gamma \nu$ decay channel, this has no gamma ray counterpart.

Another intriguing possibility with this hierarchy is that $\eta$ is extremely long-lived, and if sufficiently light, can contribute measurably to dark radiation at BBN or CMB. Ref. [98] pointed out that a Goldstone that freezes out above 100 MeV contributes to CMB [70, 96, 97]. Ref. [98] pointed out that a Goldstone can contribute measurably to dark radiation at BBN or sterile neutrino annihilation to $\eta$ at CMB; this can be matched in the current setup if the $\eta$ that is extremely long-lived, and if sufficiently light, can contribute measurably to dark radiation at BBN or CMB; this can be matched in the current setup if the sterile neutrino annihilation to $\eta$ is efficient or if sterile neutrinos decay dominantly to $\eta$. A particularly interesting variation occurs if $\eta$ decays after neutrino decoupling, resulting in a late injection of energetic neutrinos, particularly around the eV era, imparting an additional radiation energy density in the CMB [74].

Finally, if $\eta$ is sufficiently long-lived and heavy, it can also account for part or all of DM. The phenomenology in this case is similar to that of the majoron [47, 48, 50, 57-62], with neutrino lines as an interesting signal [54].

**DISCUSSION**

We studied phenomenological implications of a pseudo-Goldstone boson $\eta$ associated with a spontaneously broken global symmetry in a light (GeV scale) sterile neutrino sector. The presence of sterile neutrinos and $\eta$ at similar mass scales gives rise to many rich possibilities for cosmology, DM, and direct searches. Primary among these are novel sterile neutrino DM production mechanisms from $\eta$-mediated scattering or decay. $\eta$ can also provide new decay channels for heavy sterile neutrinos, which can alleviate BBN bounds and suppress traditional search channels at direct search experiments, or for DM, which can provide distinct signals at neutrino detectors. Likewise, $\eta$ can contribute measurably to dark radiation at BBN or CMB, inject a late population of SM neutrinos from its late decays, or account for DM.

We have only touched upon various interesting phenomenological possibilities in this framework, and several directions could be worthy of further detailed study. A late decay of $\eta$ into energetic neutrinos could lead to interesting CMB observables. It would also be interesting to study how the presence of $\eta$ affects a proper realization of leptogenesis [6, 8, 71, 99]. Likewise, a more careful study of the flavor structure and mixing angles from the hidden sector interpretation could reveal interesting differences from the canonical seesaw mechanism. We leave these and other intriguing aspects for future work.

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