Probing the properties of dark matter particles with astrophysical observations

Magalich, A.

Author: Magalich, A.
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Chapter 2

Sterile neutrinos and Beyond the Standard Model problems

A simple and interesting extension of the SM is given by the so-called *sterile neutrinos*. All fermions in the SM can have left and right helicities – the projection of the angular momentum on the direction of motion. The only apparent exceptions are neutrinos – it was observed experimentally that only left handed participate in interactions. In the SM left handed neutrinos form a doublet with respect to $SU(2)$ gauge symmetry. A right handed neutrino, if added to the SM, would be neutral with respect to all main forces of the SM – electromagnetic, weak and strong. Naively, such a particle can not be involved in any interaction – it is "sterile" and as such could not be created and can not decay into SM particles. Therefore, right-handed neutrino are not included in the minimal version of the SM.

However, there is an interaction not prohibited by the gauge symmetries of the SM:

$$\Delta\mathcal{L} = F_{\alpha I}(\bar{L}_\alpha \cdot \tilde{H})N_I, \tag{2.0.1}$$

where L_α are SM lepton doublets, $\tilde{H} = i\sigma_2 H^*$ is the Higgs doublet in the conjugated representation and N_I are right-handed neutrinos with $I = 1, \dots, n$.

If such an interaction exists, sterile neutrino can be involved in any process where normal neutrino interacts, but suppressed by Yukawa, see Fig. 2.1. In fact, this interaction not only mixes N with ν, but also makes neutrinos massive, in the same way as all fermion masses are generated in the SM. Observations of neutrino masses (together with the fact that in the SM they should be equal to zero, see a detailed discussion below) is a very interesting argument in favor of the existence or sterile neutrinos. To explain the smallness of masses of the SM neutrino (also called "active" neutrinos as opposed to the sterile ones), the right handed neutrinos should be relatively heavy, thus another name is "heavy neutral leptons", or HNLs. With three HNLs added, the SM contains left and right handed counterparts of all species of fermions and looks more "complete". Moreover, it appears that HNLs are capable not only to explain neutrino masses, but also give a mechanism of generation of

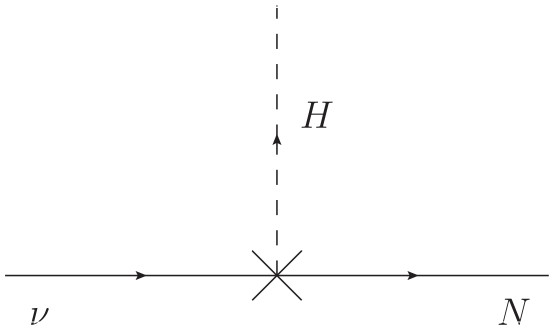

Figure 2.1: The interaction of HNLs N with SM neutrinos ν and the Higgs doublet H. After acquiring the Higgs VEV, the interaction becomes the mass mixing between N and ν.

matter-antimatter asymmetry of the Universe and a can be dark matter candidate.

In what follows we will discuss various ways to detects effects of HNLs on cosmological and astrophysical data (Chapters 4 and 3). Therefore below we present these particles and a minimal extension of the SM describing them in more details. We also discuss main particle processes where sterile neutrinos may be involved, as this will be used in the subsequent sections.

2.1 Heavy neutral leptons as a resolution of the Beyond the Standard Model problems

Lagrangian The fermion operator introduces n additional right-handed fermions – heavy neutral leptons – introducing with the SM through the gauge invariant operator $(\bar{L}_\alpha \cdot \tilde{H})$, where $L_\alpha, \alpha = 1, 2, 3$ is the lepton doublet and $\tilde{H} = i\sigma_2 H^*$ is the Higgs doublet in the conjugated representation. The general Lagrangian is

$$\mathcal{L}^c_{\text{neutrino portal}} = F_{\alpha I}(\bar{L}_\alpha \cdot \tilde{H}) N_I + i\bar{N}_I \partial\!\!\!/ N_I - \frac{M_{N,I}}{2} \bar{N}^c_I N_I + h.c., \tag{2.1.1}$$

where $I = 1, \ldots, n$.

After gaining the Higgs vacuum expectation value, the coupling $F_{\alpha I}$ provides the mass mixing between HNLs and active neutrinos. As a result of this mixing, HNL couples to the SM fields in the same way as active neutrinos,

$$\mathcal{L}_{int} = \frac{g}{2\sqrt{2}} W^+_\mu \bar{N}^c_I \sum_\alpha \theta^*_{\alpha I} \gamma^\mu (1-\gamma_5) \ell^-_\alpha + \frac{g}{4\cos\theta_W} Z_\mu \bar{N}^c_I \sum_\alpha \theta^*_{\alpha I} \gamma^\mu (1-\gamma_5) \nu_\alpha + \text{h.c.}\ , \tag{2.1.2}$$

except the coupling is strongly suppressed by the small *mixing angles*

$$\theta_{\alpha I} = M^D_{\alpha I} M^{-1}_{N,I}, \quad (M^D)_{\alpha I} = v F_{\alpha I} \tag{2.1.3}$$

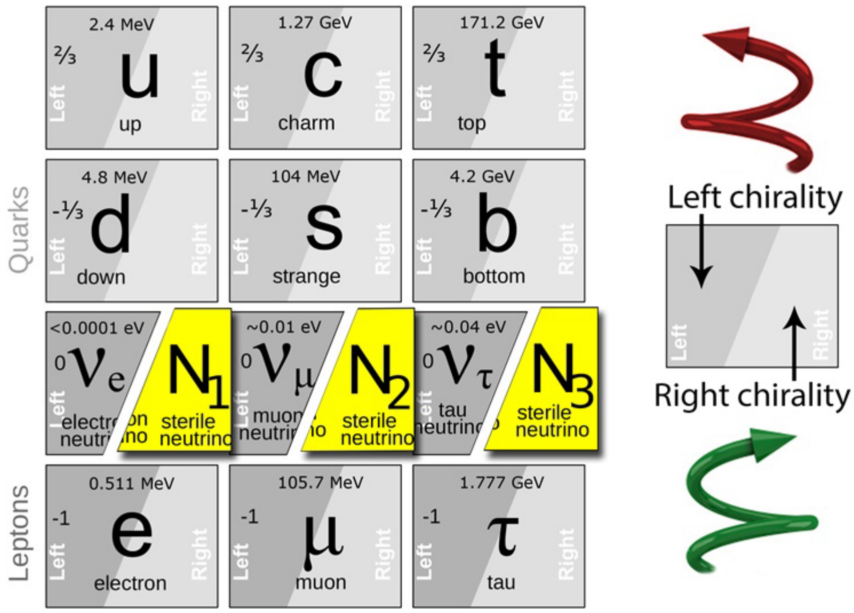

Figure 2.2: The Standard Model particles with three sterile neutrinos N_1, N_2, N_3. *Taken from [49].*

> Fermion portal allows not only connecting the BSM to the Standard Model but also explaining the BSM problems without introducing additional fields.

Neutrino masses SM neutrino masses m_{ν_α} manifest themselves experimentally through neutrino oscillations entering the oscillation length $l_{\text{osc}} = 4\pi p_\nu/\Delta m_{ij}^2$, where $\Delta m_{ij}^2 = m_i^2 - m_j^2$. In studying the oscillations of atmospheric and solar neutrinos there have been measured two mass differences [1]:

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{31}^2 = 7.55^{+0.2}_{-0.16} \cdot 10^{-5}\ \text{eV}^2, \quad \Delta m_{\text{sol}}^2 \equiv \Delta m_{31}^2 \approx 2.5^{+0.3}_{-0.3} \cdot 10^{-3}\ \text{eV}^2, \quad (2.1.4)$$

suggesting that at least two SM neutrinos are massive. A simple way to introduce masses of the SM neutrinos is by adding the Weinberg operator

$$\mathcal{L} = c_{\alpha\beta} \frac{(\bar{L}_\alpha^c \cdot \tilde{H})(\tilde{H} \cdot L_\beta)}{\Lambda}, \qquad (2.1.5)$$

where Λ is some high-energy scale, L_α is the lepton SM doublet and the superscript c denotes the charge conjugation. The operator gives Majorana masses to SM neutrinos

$$(m_\nu)_{\alpha\beta} = -\frac{c_{\alpha\beta} v^2}{\Lambda}, \qquad (2.1.6)$$

where v is the Higgs vacuum expectation value. Within the fermion portal, the Weinberg operator appears is the limit $||M_D|| \ll |M_N|$ of the Lagrangian (2.1.1), with

$$(m_\nu)_{\alpha\beta} = \sum_I M^D_{\alpha I} \frac{1}{M_{N,I}} M^D_{\beta I} \tag{2.1.7}$$

The smallness of $M^D_{\alpha I}$ comparing to the Majorana masses $M_{N,I}$ in (2.1.1) naturally leads to the smallness of SM neutrino masses comparing to masses of HNLs and the electroweak scale. Such mechanism is called the *see-saw mechanism*. It does not fix both the parameters $F_{\alpha I}$, $M_{N,I}$, but only their combination in the form of neutrino mass (2.1.7).

Adding $\mathcal{N}$ new particles N_I to the Lagrangian $\mathcal{L}_{\text{SM}}$ adds

$$N_{\text{parameters}} = 7 \times \mathcal{N} - 3 \tag{2.1.8}$$

new parameters to the Lagrangian. These parameters can be chosen as follows: $\mathcal{N}$ real Majorana masses M_I, *plus* $3 \times \mathcal{N}$ absolute values of Yukawa couplings $F_{\alpha\, I}$ *plus* $3 \times \mathcal{N}$ complex Yukawa couplings $F_{\alpha\, I}$ *minus* 3 phases absorbed in redefinitions of ν_e, ν_μ, ν_τ. The Pontecorvo-Maki-Nakagawa-Sakata matrix[1] plus three mass eigenstates m_1, m_2, m_3 of the active neutrino sector provide 9 parameters that can be determined experimentally. This shows that one needs $\mathcal{N} \geq 2$ to explain the neutrino oscillations by means of heavy neutral leptons.

If all the three SM neutrinos are massive, we need three HNLs.

Two HNLs in the broad mass range can explain the observed mass difference Δm^2_{atm} and $\Delta m^2_{\text{solar}}$.

Baryogenesis. In the Early Universe the baryogenesis requires three conditions (the so-called Sakharov conditions) [50] to be satisfied. HNLs (2.1.1) are able to satisfy all the conditions:

1. *Baryon number violation*: HNLs violate the conservation of lepton number through the Majorana mass term and gives a possibility to generate non-zero baryon number (see details below).

2. *C and CP violation (C is already violated in the standard model)*: HNLs provide additional CP-violating phases (analogously to the CKM matrix in the quark sector) and thus CP violation in processes of the production and decay of HNLs.

3. *Out of equilibrium*: HNLs allow out-of-equilibrium processes involving HNLs if their coupling to the SM is small.

[1]The Pontecorvo-Maki-Nakagawa-Sakata matrix is a matrix of active neutrinos mixing in charged current weak interactions appearing because of the mismatch between the mass eigenstates and interaction eigenstates of neutrinos, similar to the CKM matrix for quarks.

HNLs of a wide mass range – from sub-GeV to 10^{15} GeV – can be responsible for the baryon asymmetry of the Universe due to, different mechanisms (see [51–53] and references therein). In particular, two GeV scale HNLs with nearly degenerate masses can produce the baryon asymmetry through their oscillations.

The same two HNLs that provide masses to SM neutrinos can be responsible for the baryogenesis.

Dark matter HNLs are the perfect candidate for the role of the dark matter. Their mass can be significantly large to generate the observed DM energy density of the Universe. From the other side, their interaction is similar to the interaction of SM neutrinos but suppressed by the small mixing angle. If the mixing angle is so small such that HNL DM never reaches the thermal equilibrium, their number density is smaller then for usual neutrinos and they do not violate the Tremaine-Gunn bound [28]. Simultaneously, for sufficiently small mixing angles and masses, HNLs have lifetimes comparable with the age of the Universe. The current constraint on the HNL DM is shown in Fig. 2.3. The HNL DM mass is limited from

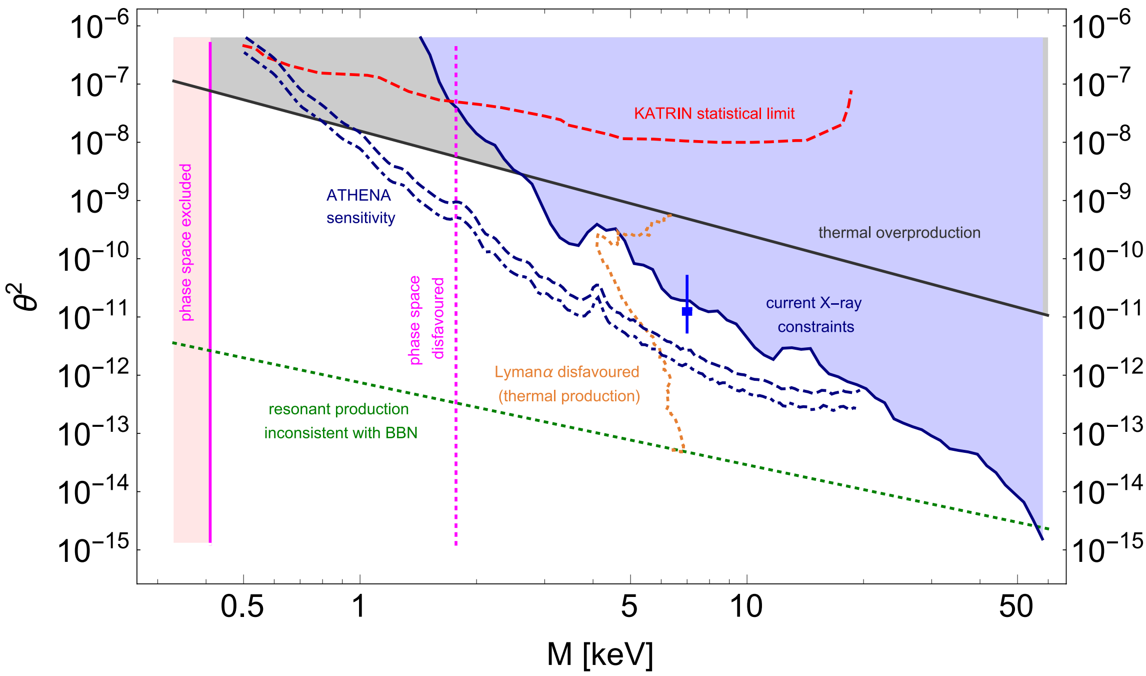

Figure 2.3: Constraints on HNL DM, see [54] for details.

below $M_N \gtrsim 1$ keV from the phase space density arguments [54]. HNL DM lifetime is strongly bounded from X-ray observations, while for small angles there is no production mechanism in this model. So HNL DM is expected to be a keV-scale particle.

Several years ago, an unidentified feature in the X-ray spectra of galaxy clusters [55, 56] as well as Andromeda [56] and the Milky Way galaxies [57] have been observed. The signal can be interpreted as coming from the decay of a DM particle with the mass ~ 7 keV (in particular of sterile neutrinos with mixing angles in the range $\sin^2 2\theta \simeq (0.2-2)\times 10^{-10}$). The signal was confirmed in the spectra of galaxy clusters [58–60] or galaxies [61–64]. Other DM-dominated objects did not reveal the presence of the line [65–72]. This non-detection, however, did not exclude dark matter interpretation of the 3.5 keV line (see discussion in the review [54]).

The DM population of such HNLs can be produced thermally or resonantly, due to the enhancement of the mixing angle in a dense medium of SM plasma (see Sec. 2.2). The HNL dark matter is warm and decaying. We will return to these statements in detail in the next sections.

Long-lived and weakly interacting HNLs can be a perfect DM candidate. The observations indicate that masses of HNL DM candidate must be in keV range. However, such HNLs cannot be responsible for masses of active neutrinos. Indeed, the latter requires large mixing angles, for which there will be produced too much dark matter particles through the Dodelson-Widrow mechanism [73].

It is possible to explain all these three BSM phenomena by introducing three HNLs – one relatively light with the mass range of $m_N \simeq \mathcal{O}(\text{keV})$ responsible for the DM and two other with close masses in the $\mathcal{O}(\text{GeV})$ mass range responsible for the active neutrino masses and the baryogenesis. This model introduces 18 new parameters – 3 neutrino masses and 15 Yukawa couplings parameters. All these quantities can be measured experimentally, so the model is fully testable. This model is called the *Neutrino Minimal Standard Model* (νMSM) [51, 52].

2.2 Phenomenology of heavy neutral leptons

Production mechanisms of HNLs in the Early Universe The main production channels of HNLs with masses $m_N \lesssim m_W$ in Early Universe are decays of W/Z bosons (if the Universe is hot, $T \gtrsim m_Z$) $W \to lN$, $Z \to \nu_l N$ and $2 \to 2$ processes $l/\nu_l f \to N f'$, where f, f' denote a fermion (either a lepton or a quark).

The production can be resonantly enhanced due to effects of medium. Namely, assuming that HNLs are ultrarelativistic, coherent forward scattering of HNLs on active neutrinos ν_l introduces a correction to the Hamiltonian describing evolution of N and $\bar{\nu}_l$,

$$H \approx \frac{m_N^2}{4E}\begin{pmatrix} -\cos(2U) & \sin(2U) \\ -\sin(2U) & \cos(2U)\end{pmatrix} + \begin{pmatrix} V_l & 0 \\ 0 & 0\end{pmatrix}, \tag{2.2.1}$$

where $V_l = -\sqrt{2}G_{\rm F}(-N_n/2 + N_{\nu_l} - N_{\bar{\nu}_l})$. This effect introduces effective mixing angle $\tan(2U_{\rm eff}) \approx 2U\Delta/(\Delta + V_l)$, where $\Delta = m_N^2/2E$. It is maximized if $V_l = -\Delta$, which leads to resonant enhancement of the HNL production.

Decays of HNLs. The main decay channels of HNLs with masses $m_N \lesssim 2m_e$ are decays into three neutrinos $N \to 3\nu$ and radiative decay into a photon and a neutrino, $N \to \gamma\nu$ (including charge conjugated channels), see Fig. 2.4. Heavier HNL decays into three leptons

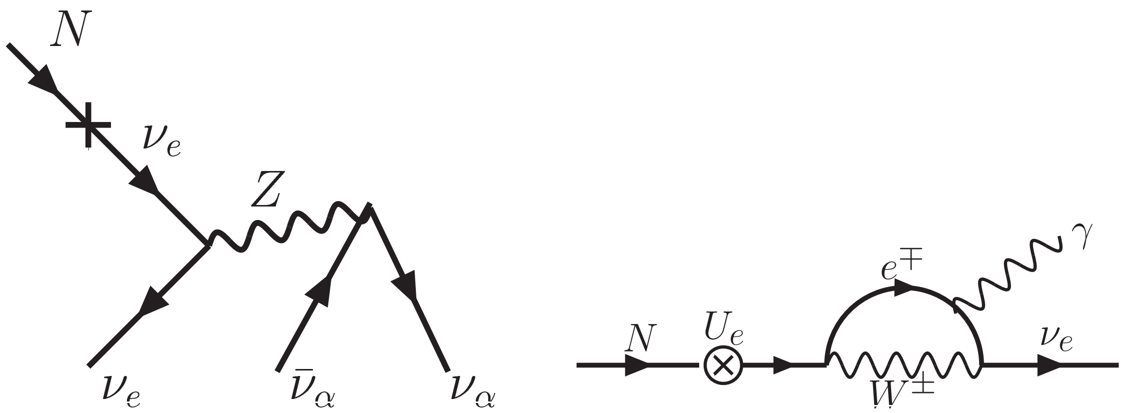

Figure 2.4: Decay channels of sterile neutrinos with masses $m_N \lesssim 2m_e$: decay into three neutrinos and into a neutrino and a photon. The figure is given from [49].

through charged and neutral weak currents, $N \to \nu_l \bar{l}' l'$ or $N \to \nu_l \bar{l} l'$. Once $m_N \gtrsim m_\pi$, semileptonic decays open. If $m_N \lesssim 1$ GeV, the decays are two-body, $N \to hl/\nu_l$, where h is a hadron. For heavy HNLs, $m_N \gtrsim 1$ GeV, decays into hadrons can be described by the three-body channels $N \to q_1\bar{q}_2 l/\nu_l$ [74]. The branching ratios of HNLs in the range $m_N < 5$ GeV are shown in Fig. 2.5.

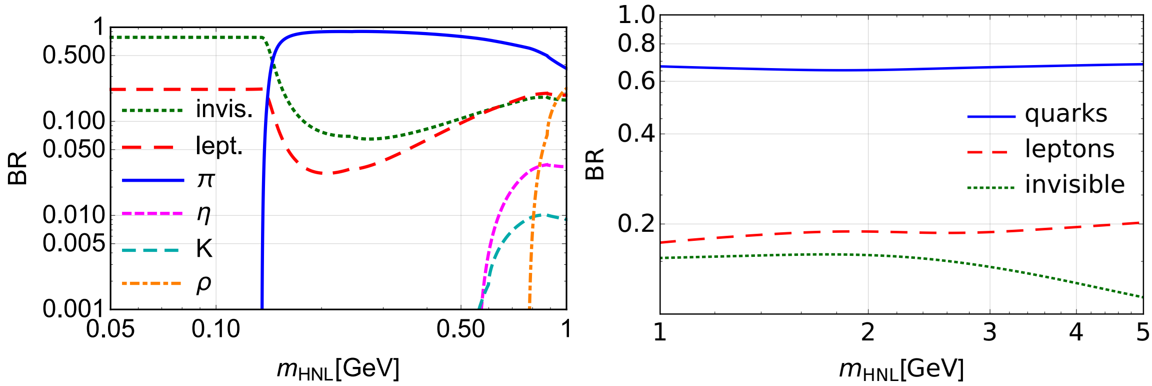

Figure 2.5: Branching ratios of HNL decays vs the HNL mass. Figures are given from [74].