PROCEEDINGS OF SCIENCE

Thermal effects in neutrino dark matter production

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The origin of the dark matter of the Universe and the mechanism generating light neutrino masses could be tightly linked. In this talk, based on arXiv:2308.01341, we consider the possibility to simultaneously explain oscillation data and dark matter in the form of a keV-sterile neutrino. We thoroughly study the DM production through freeze-in two-body decays, accounting for thermal effects modifying the neutrino mixing and thus the production rates. Our study shows that the freeze-in dark matter production can be efficient and thus further study is necessary to identify interesting regions of parameter space that simultaneously account for DM and neutrino masses.

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1. Introduction

The most significant experimental and observational evidence for the existence of physics beyond the Standard Model (SM) are the origin of neutrino masses and the presence of dark matter (DM) in the Universe, respectively. The introduction of right-handed (RH) neutrinos allows to accommodate both these puzzles in a straightforward way.

On the one hand, the introduction of heavy RH neutrinos allows to explain the origin of light neutrino masses via the seesaw mechanism [1–4]. We can write the following lagrangian:

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.\,, \tag{1}$$

where L_L and $\tilde{H} = i\sigma_2 H$ are the lepton and Higgs doublets, respectively, while N_R represents the RH neutrinos. The latter couple with the SM lepton doublets via the Yukawa coupling, Y_ν, and can have a Majorana mass term, M, whose origin is not related to electroweak (EW) symmetry breaking. Thus, the RH neutrino mass scale can lie from the eV-scale to the GUT-scale. Among the different seesaw mechanisms, it is particularly appealing to consider low-scale seesaw realizations, in which the smallness of light neutrino masses is related to an approximate lepton number symmetry. This in turn allows to have the heavy neutrino masses at the TeV scale, in reach of our collider searches. In order to explain oscillation data, it is necessary to introduce at least two RH neutrinos to the SM particle spectrum [5]. After spontaneous symmetry breaking (SSB), neutrinos acquire a mass, and the SM flavor neutrinos are related to the massive ones through mixing:

$$\nu_{\alpha L} = \sum_{i=1}^{3} \tilde{U}_{\alpha i} P_L \nu_i + \sum_{h=4}^{3+N} \theta_{\alpha h} P_L n_h\,. \tag{2}$$

We have separated the mass eigenstates into light neutrinos, ν_i, participating in oscillations, and the N heavy ones, n_h. The mixing matrix $\tilde{U}$ represents the would-be PMNS matrix, which does not need to be unitary as it is a sub-block of a larger $(3+N)\times(3+N)$ mixing matrix. Likewise, θ is the active-heavy mixing, and controls the strength of heavy neutrino interactions with SM particles.

On the other hand, it is straightforward to introduce a DM candidate in this type of scenarios: one of the RH neutrinos could be a viable candidate to represent the DM of the Universe. Its interactions are suppressed by its mixing with the active neutrinos, $|\theta_{\alpha \rm DM}| \ll 1$, avoiding all our direct detection DM experiments. Given that this would represent an unstable DM candidate, its lifetime needs to be longer than the age of the Universe. For this reason, we will consider that the DM mass lies in the keV range. The best probes to discover such a DM candidate would be the search for a monochromatic X-ray signal from the DM radiative decay. We have nonetheless failed to find such a signal, and thus place very strong bounds on the size of the DM mixing [6, 7], $\theta_{\alpha \rm DM}$.

Given these bounds, in the following we will explore the possibility to produce the observed DM relic abundance, $\Omega_{\rm DM}^{\rm obs} h^2 \simeq 0.12$, only relying on the introduction of RH neutrinos, both the DM as well as the heavier ones which account for oscillation data via the seesaw mechanism.

2. Neutrino dark matter production

In the following, we consider DM production mechanisms which solely rely on the presence of heavy neutrinos, one of which is the DM candidate, and their mixings with the active neutrinos.

The presence of any other new physics could contribute to DM production, but we focus here on mechanisms which are always active once if we have neutrino mixing. They are irreducible contributions to the DM relic density.

2.1 Production at $T \lesssim 1$ GeV

At temperatures, T, around the QCD phase transition the main production mechanism relying on neutrino mixing is the well known Dodelson-Widrow (DW) mechanism [8]. It relies on the freeze-in production of sterile neutrino DM through oscillations and subsequent collisions in the plasma. Given the bounds on $\theta_{\alpha\mathrm{DM}}$, it can produce at most about 30% of the observed DM [9].

2.2 Production at $T \sim 100$ GeV

One can instead consider the production at larger temperatures, at which the SM bosons and the heavy neutrinos, necessary to explain oscillation data, are in thermal equilibrium in the plasma. In this case, the freeze-in production through two-body decays after spontaneous symmetry breaking (SSB) is possible. The following two-body decays generating DM are available:

$$\left.\begin{array}{l}\Gamma\left(W \to \ell_\alpha + n_{\mathrm{DM}}\right)\\ \Gamma\left(h\left(Z\right) \to \nu_i + n_{\mathrm{DM}}\right)\\ \Gamma\left(n_h \to h\left(Z\right) + n_{\mathrm{DM}}\right)\end{array}\right\} \propto \left|\theta_{\alpha\mathrm{DM}}(T)\right|^2 . \tag{3}$$

They all depend on the size of the mixing at the temperature at which the decay happens, $\theta_{\alpha\mathrm{DM}}(T)$. Although this production mechanism had been studied previously, both for the gauge boson decay channels [10], as well as for the heavy neutrino decay one [9, 11], important thermal effects were overlooked. This was demonstrated in Ref. [12], but only for the gauge boson decay into DM.

We revisit the thermal effects affecting neutrino DM production at such temperatures, introducing, for the first time, the contribution to the relic density of the channels involving the Higgs boson and the heavy neutrinos necessary to account for oscillation data [5]. These results, and further technical details, can be found in Ref. [13]. They rely on general results from Thermal Field Theory [14, 15]. We compute the neutrino self-energies, shown in Fig. 1 , at finite temperature. This allows to obtain the correct dispersion relations for the DM in the medium consistently taking into account interactions with other particles in the plasma. The imaginary parts of the self-energies are related to the rate at which DM reaches equilibrium, while the real parts modify the dispersion relations, translating into an effective mixing angle in the medium, $\theta_{\alpha\mathrm{DM}}(T)$.

The effective mixing angle between the DM and the active neutrinos tends to be suppressed at large temperatures, such that for negative helicity DM states we find $|\theta_{\alpha\mathrm{DM}}(T)| \sim 0$ and thus, the production through Z and W boson decays is negligible at $T \sim 100$ GeV [13], as already found in Ref. [12]. This is in contrast with what was found in Ref. [10], where the mixing angle in vacuum was used, overestimating the production through gauge boson decay. Next, we can study the full production of DM taking into account the presence of the heavy neutrinos and their couplings with the Higgs [13]. To this end, one needs to include all the contributions to the neutrino self-energy, taking into account not only the gauge boson contributions, but also the Higgs one shown in the right panel of Fig. 1. In particular, the decay of a heavy neutrino into a Higgs boson and the DM could help the production, given that the couplings are proportional to the mass and equal for both

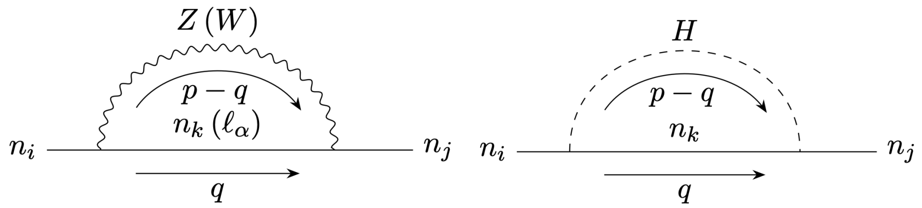

Figure 1: Self-energy diagrams contributing to the modification of the dispersion relations for neutrinos. Left panel: contribution from gauge bosons; right panel: we have the contribution from the Higgs, which is only relevant in the presence of heavy neutrinos.

helicities, and also because there can be some enhancement from Bose-Einstein statistics in the final state. This channel was studied in Refs. [9, 11], but neglecting the thermal corrections which impact the effective neutrino-DM mixing, $\theta_{\alpha \mathrm{DM}}(T)$, at large temperatures. In the context of Thermal Field Theory, given that we consistently include all the contributions to the self-energy, we automatically include all the scattering processes which can change the dispersion relations and thus we compute the effective mixing angles in the medium for all the neutrinos (including the DM) as a function of the temperature.

We show in Fig. 2 the results for the DM equilibration rates for two different points in the parameter space. When introducing the heavy neutrinos, the DM production not only depends on the DM mass and its mixing with the active neutrinos, but also on the heavy neutrino masses and their mixings with the active ones. In the left panel of Fig. 2 we compare the resulting rates in different cases, all sharing the same size for the DM mass and its mixing with the active neutrinos in vacuum, which we set to $m_{\mathrm{DM}} = 10$ keV and $\theta_{\alpha \mathrm{DM}} \sim 10^{-6}$. We show the dependence of the equilibration rate for positive helicity DM, Γ_s^{+1}, on the inverse temperature normalized by the W-boson mass, $\tau = M_W/T$. We fix the momentum to $y \equiv p/T = 0.1$. Given that neutrino mixing is only present at temperatures below spontaneous symmetry breaking (SSB), $T_{SSB} \sim 160$ GeV, we shade in gray temperatures above it for which this production mechanism is not effective. Comparing different assumptions, we can see that all the different lines lie on top of each other, except for the solid blue one. The dark purple dashed line corresponds to the DM production rate only through gauge boson decay into the DM, ignoring the channel which includes a heavy neutrino. The purple dashed-dotted line instead corresponds to these same channels, but in the presence of heavy neutrinos, whose mass is $m_N \sim 150$ GeV. Clearly, there is almost no DM production through these channels. The fraction of DM produced through gauge boson decay compared to the observed abundance is $f_{\mathrm{DM}} \lesssim 10^{-10}$. Contrary, in the blue solid line we include all the available channels, including the Higgs contribution with the heavy neutrinos, which greatly enhances the rate and thus the DM production through the decay $n_h \to h + n_{\mathrm{DM}}$. The black solid line corresponds to the Hubble expansion rate, showing that the rates satisfy the freeze-in condition, $\Gamma_s^{+1}(\tau) \ll H(\tau)$. While we cannot explain all the DM abundance for this point of parameter space, we find that in general larger heavy neutrino masses increase the final abundance given that they correspond to larger Yukawa couplings. This is the case in the right panel of Fig. 2, in which we set $m_N \sim 500$ GeV and find that in this case the Higgs channel greatly enhances the production, such as we even find a larger DM abundance than observed, $f_{\mathrm{DM}} \sim 1.2$. As a comparison, we show in purple the production rates

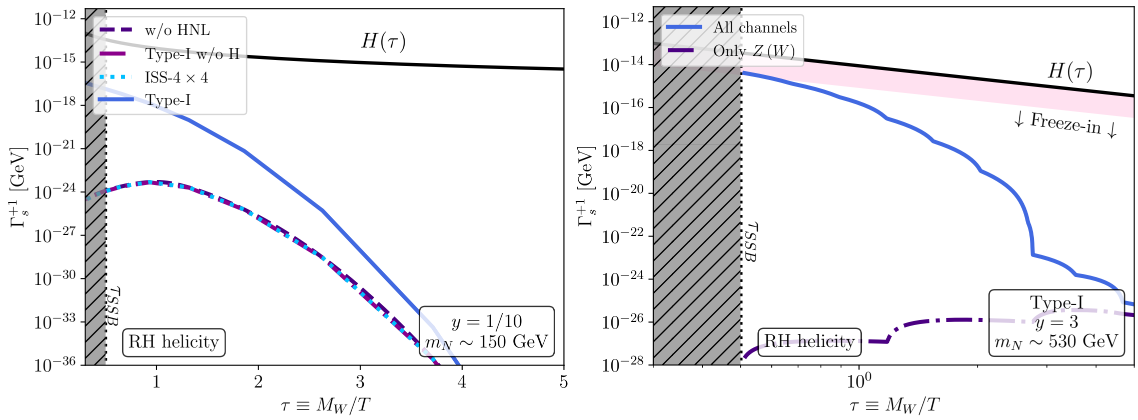

Figure 2: Dependence of the DM equilibration rates with the inverse of the temperature, for a fixed momentum, given by $y \equiv p/T$, and neutrino mixing parameters. In both cases the DM mass is $m_{\rm DM} \sim 10$ keV and $\theta_{\alpha\rm DM} \sim 10^{-6}$. In the left panel we have the heavy neutrino mass to be $m_N \sim 150$ GeV while in the right one we have $m_N \sim 530$ GeV. The different lines in both panels correspond to the production rate taking into account different channels. Purple lines correspond to the production only through gauge boson decays, while the blue ones include all possible contributions.

related to channels involving gauge bosons, and find again that we do not produce any DM.

3. Conclusions

We have studied the possibility of explaining the DM abundance arising from the same mechanism generating neutrino masses. When introducing RH singlet neutrinos to explain the phenomenon of neutrino oscillations, a DM candidate that mixes with the active neutrino naturally arises. We investigated whether the presence of mixing between the active neutrinos and the other ones is enough to explain the observed DM abundance, which would directly link the origin of neutrino masses to DM, as well as to the origin of the baryon asymmetry through leptogenesis.

We know that at temperatures around the QCD phase transition this mixing is too constrained to produce all of the observed DM through the Dodelson-Widrow mechanism. Nonetheless, this mechanism is always active and thus contributes to the total DM abundance in some amount that needs to be taken into account. At larger temperatures, when SM bosons are present in the thermal bath, there is another mechanism which only relies on neutrino mixing to produce DM. This is the freeze-in production through two-body decays, which had not been thoroughly studied in a consistent way before. We included, for the first time, the channels involving the Higgs and the heavy neutrinos necessary to explain oscillation data. It was found that for heavy neutrino masses around the TeV-scale the DM production is non-negligible, and thus should be more thoroughly studied. Additionally, one should study the production above the temperature of spontaneous symmetry breaking, dominated by $2 \to 2$ processes, and investigate the consequences for flavor probes and collider searches given that rather large active-heavy neutrino mixings are necessary to account for all the observed DM.

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