Sterile Neutrino in Non-standard Cosmology

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Introduction

Neutrinos are subatomic particles that are at the forefront of modern high energy physics research. Unlike their more well-understood cousins of leptons in the Standard Model, they have a small and yet-to-be-identified mass. The three active flavors of neutrinos also have a curious, but not necessarily unique, characteristic of "mixing", that is they can turn into one another. What is unique about them is that they are fermions without a right-handed counterpart, commonly referred to as sterile neutrino. This is one among many flaws of the elegant Standard Model of particle physics. Another flaw of the Standard Model is that it fails to account for the existence of dark matter, an invisible form of matter that decelerates the expansion of our universe and allows for the formation of galaxies. Our research aims two connect these missing links by exploring physics beyond the Standard Model. We have created a mathematically coherent, experimentally falsifiable, and symmetry-abiding model for the right-handed neutrinos to act as dark matter (DM) in a non-standard thermal history of our universe.

Non-standard Cosmologies

There are many contentions in mainstream literature regarding the early history of our universe, particularly during the reheating epoch right after inflation, a period of super-cooled expansion immediately after the big bang. Early during this reheating period, the universe's energy budget, which was dominated by radiation in standard cosmology, decayed into and filled the universe with Standard Model particles. Standard post-inflationary reheating expands with a Hubble rate of $H^2 \propto a^{-4}$. However, if our ancient universe's energy budget is sufficient, it can expands even faster. Generically, we introduce an extra species θ whose contribution to the Hubble rate is $H^2 \propto a^{-(4+n)}$. Under this assumption, we can use Friedmann equation to write our total Hubble rate explicitly as a function of the temperature of our universe accordingly,

$$H(T) \approx \underbrace{\frac{\pi g_*(T)^{-1/2}}{3\sqrt{10}}\frac{T^2}{M_{\rm Pl}}}_{\text{Standard rate}}\left(\frac{T}{T_r}\right)^{n/2} \tag{4}$$

Dark Matter Production

The Dodelson-Widrow (DW) mechanism is a type of seesaw mechanism that was proposed to explain the mass discrepancy of the active neutrinos (ν_a) when compared to the rest of the other fermions. For a certain distribution of active neutrinos in the early universe, f_{ν_a}, it posits that they have a small probability to irreversibly oscillate into right-handed sterile neutrinos (ν_s, with distribution f_{ν_s}) as described in the following Boltzmann equation:

$$(\partial_t - HE\partial_E)\, f_{\nu_s} = \frac{1}{2}\sin^2(2\theta_{\rm eff})\Gamma f_{\nu_a} \tag{1}$$

Of particular note to us is the sin of the effective mixing angle $\theta_{\rm eff}$ and the interaction rate Γ as they contain terms that correspond to the strength of coupling of neutrinos to their environment,

$$\sin^2 2\theta_{\rm eff} \simeq \frac{\Delta^2 \sin^2 2\theta}{\Delta^2\sin^2 2\theta + \Gamma^2/4 + (\Delta\cos 2\theta - V_T)^2} \tag{2}$$

$$\Gamma \sim G_F^2 E T^4 \tag{3}$$

For this simple case, V_T only contains the potential from the weak force's bosons.

THE CASE FOR A SCALAR MEDIATOR

To facilitate DM production by enabling the efficient production of sterile neutrinos in the early universe via the DW mechanism, we introduce a complex scalar field ϕ with mass m_ϕ and coupling strength λ_ϕ with the neutrinos. In the presence of the mediator, the neutrino flavors self-interact by exchanging ϕ, which introduces new production channels for sterile neutrinos in presence of a nonzero θ as depicted below. This is reflected in our Boltzmann equation through new contributions to the interaction rate Γ_ϕ and the thermal potential V_T^ϕ embedded in the calculation of our mixing angle.

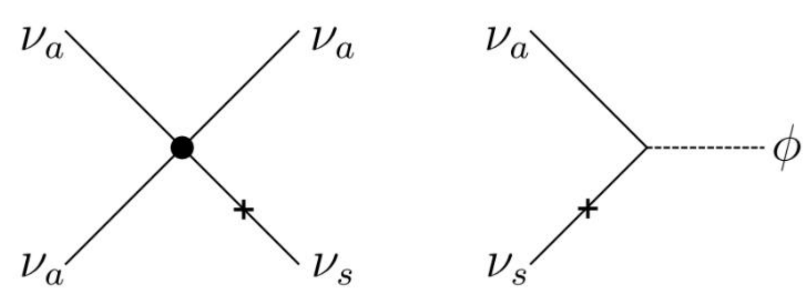

FIG. 1. Heavy (left) vs. light (right) scalar mediator ϕ.

Result

We used separation of variable to rewrite the original Boltzmann equation after re-paramatrizing T and E into dimensionless variables such as $z \equiv \frac{0.001\text{GeV}}{T}$

$$\frac{df_{\nu_s}}{dz} = \frac{\Gamma\sin^2 2\theta_{\rm eff}}{4Hz} f_{\nu_a}, \tag{5}$$

we then used Mathematica to numerically integrate the left-hand side to find the abundance of sterile neutrino. We assume that sterile neutrinos can account for all the dark matter in the universe and find the set parameters for our scalar mediators to produce the solution plot below for different expansion rates in the reheating epoch.

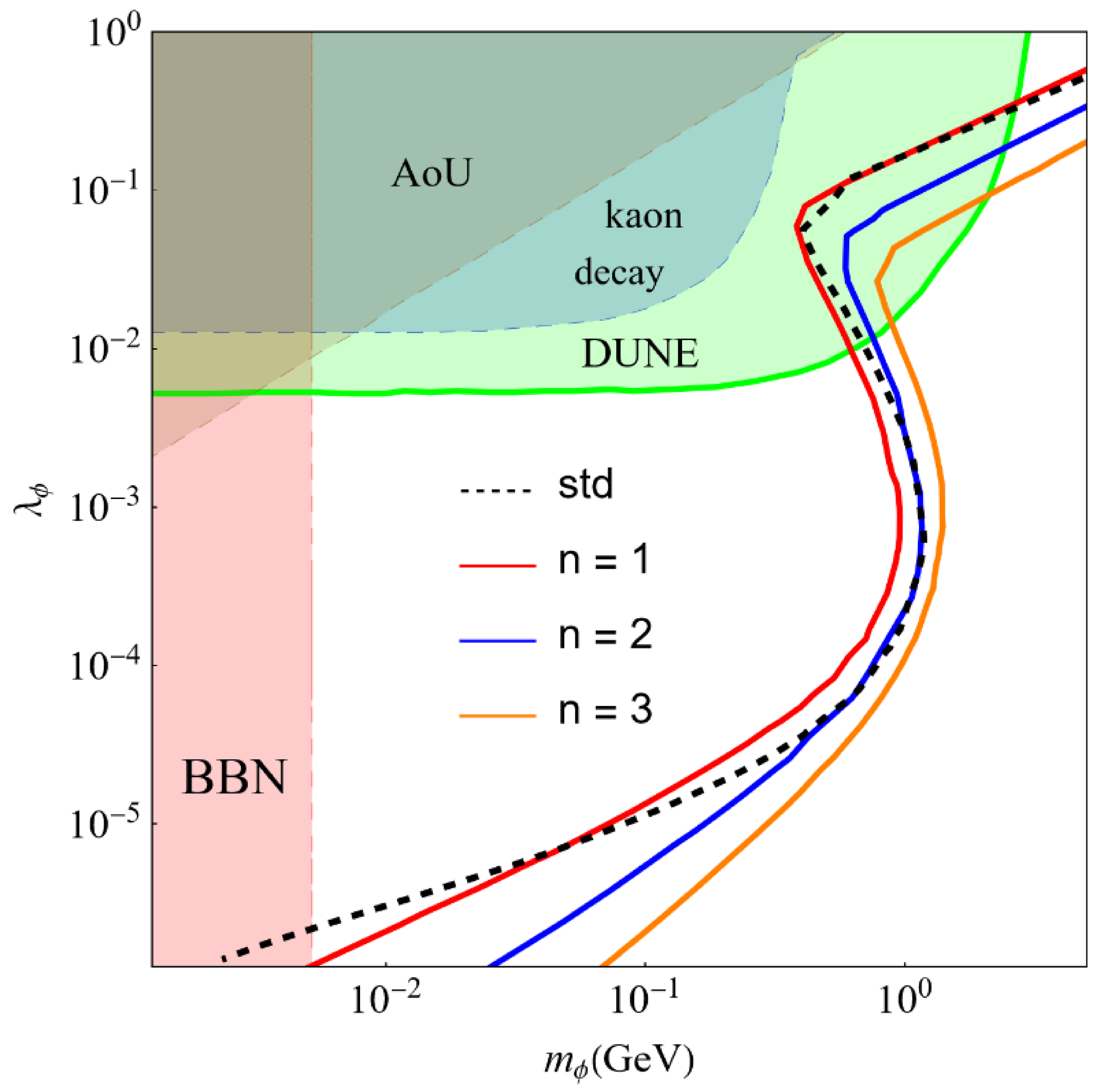

FIG. 2. The red (n = 1), blue (n = 2), and orange (n = 3) curves show the parameters for ϕ that yield the right amount of dark matter relic abundance for different Hubble rates in Eq. 4. All other parameters, such as the mass of keV-range sterile neutrino, are fixed. DUNE (Deep Underground Neutrino Experiment) is sensitive in the light green region

Conclusion

Non-standard cosmologies have a stronger effect on this production mechanism in the lower-mass region as they allow for the right relic abundance at smaller couplings when compared to standard cosmology. Furthermore, in addition to solving the dark matter problem, experimental data supporting this mechanism will also shed light on the ambiguous thermal history of our universe.

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