

Effective theory of light Dirac neutrino portal dark matter with observable ΔN_{eff}

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We study the possibility of light Dirac neutrino portal dark matter (DM) in an effective field theory setup. Dirac nature of light neutrino automatically includes its right chiral part ν_R which, in our setup, also acts like a portal between DM and the standard model (SM) particles. Considering a Dirac fermion singlet DM stabilized by an unbroken Z_2 symmetry, we write down all possible dimension-6 effective operators involving DM- ν_R as well as ν_R -SM which conserve Z_2 , global lepton number and SM gauge symmetries. DM thermalization also ensures the thermalization of ν_R , leading to enhanced effective relativistic degrees of freedom N_{eff} , within reach of future cosmic microwave background (CMB) experiments. We study the complementarity among DM and CMB related observations for different Lorentz structures of effective operators. We also propose a UV complete gauged B-L symmetric model with Dirac neutrino portal dark matter.

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I. INTRODUCTION

The nature of dark matter (DM) and the origin of neutrino masses remain two of the most pressing questions in particle physics and cosmology [1]. The existence of dark matter is strongly supported by cosmic microwave background (CMB) data and numerous astrophysical observations, including galaxy rotation curves, weak gravitational lensing, and the large-scale structure of the Universe. Recent data from the PLANCK satellite mission [2] indicates that DM constitutes about 26.8% of the total energy density of the Universe. However, none of the standard model (SM) particles meets all the necessary criteria to be a viable DM candidate, leading to the development of numerous beyond the Standard Model (BSM) frameworks.

Similarly, neutrino oscillation experiments [3–7] have revealed that neutrinos possess tiny masses and exhibit large leptonic mixing, which can not be accounted for in the SM where neutrinos remain massless. While these experiments have provided crucial insights regarding the mixing angles and mass squared differences, they remain insensitive to the fundamental nature of neutrinos, whether they are Dirac or Majorana fermions. Although the experiments searching for neutrinoless double-beta decay could potentially confirm the Majorana nature of neutrinos, no such observations have been made to date [1]. This has sparked growing interest in exploring the possibility that light neutrinos could be Dirac fermions, challenging the long-held focus on Majorana neutrinos in conventional neutrino mass models [8–29].

In light of these open questions, there is growing interest in models that connect dark matter and neutrino physics, potentially providing a unified solution to these fundamental puzzles [30–34]. One such approach involves the concept of neutrino portal dark matter, where either SM light neutrinos or heavy neutrinos serve as a mediator between the dark sector and the visible sector [35–48]. Due to the absence of tree level DM-nucleon scattering, this framework is particularly intriguing in light of the null results from direct DM searches. Direct search experiments such as PandaX-II [49], XENON-nT [50,51], and LUX-ZEPLIN [52] have probed spin-independent

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DM-nucleon cross sections down to 10^{-48} GeV $^{-2}$ for DM masses ranging from a few GeV to $\mathcal{O}(10^4)$ GeV with weaker constraints for lighter DM masses from experiments like DarkSide [53], CDMSlite [54], and CRESST-III [55]. Similar bounds also exist for DM-electron scattering [56]. These null detections motivate the exploration of novel scenarios like neutrino portal DM and their search strategies.

Motivated by these, here we consider right chiral neutrinos (ν_R) introduced to explain light Dirac neutrino mass act like a portal between DM and the visible sector. In earlier works [34,57,58], light Dirac neutrino portal DM was studied by considering specific models. In the present work, we adopt a more general effective field theory (EFT) approach, focusing on dimension-6 operators that respect relevant symmetries like the SM gauge symmetries, accidental global symmetries like lepton and baryon numbers and a Z_2 symmetry protecting the stability of DM, chosen to be a vectorlike singlet fermion χ . The effective interactions of such ν_R -philic DM with ν_R and interactions of ν_R with SM arise at the order of dimension-6 or above. We consider such dimension-6 operators of all possible Lorentz structures. There exist no DM-SM operators at dimension-6 in the spirit of ν_R -philic DM, keeping direct detection rates suppressed, in agreement with experimental results.

A key aspect of this scenario is the potential impact on cosmological observables, particularly the effective number of relativistic species (N_{eff}). The thermalization of right-handed neutrinos in the early Universe can lead to an enhancement in N_{eff} , potentially detectable by future CMB experiments. This connection between particle physics and cosmology offers a unique opportunity to probe the dark sector and neutrino properties simultaneously. Our study aims to explore the complementarity between dark matter phenomenology and CMB observations, considering various Lorentz structures of the effective operators. We also propose a gauge extension of the SM: the B-L model. This UV completion provide concrete realizations of the EFT framework and offer additional avenues for experimental tests.

In the following sections, we present our EFT setup, analyze the resulting phenomenology, and discuss implications for future experiments and theoretical model-building in the context of neutrino portal dark matter. Section II A discusses the temperature evolution of ν_R and its contribution to ΔN_{eff} , followed by an analysis of DM relic abundance and loop-suppressed direct detection signatures in Sec. II B. Section III examines the parameter space of UV-complete gauged $B-L$ model considering ΔN_{eff} bounds and finally we conclude in Sec. IV.

II. EFFECTIVE FIELD THEORY APPROACH TO ΔN_{eff} AND DARK MATTER

The EFT approach serves as a powerful tool to study interactions involving new particles without committing to a specific ultraviolet (UV) completion. By parametrizing

the effects of heavy mediators through higher-dimensional operators, EFT provides a model-independent framework that captures a wide range of phenomenological possibilities. This is particularly useful for scenarios where the new physics scale is significantly higher than the energies accessible in current experiments or where direct detection is not feasible. The dark matter phenomenology in such an EFT setup can be discussed with very few free parameters, namely, DM mass, cutoff scale, and the corresponding coupling or Wilson coefficients. Such DM EFT has been studied extensively in the context of direct detection, indirect detection as well as collider searches in several works [59–63], also summarized in a recent review [64].

In this study, we extend the SM particle content by introducing three copies of right-handed neutrinos (ν_R) constituting Dirac neutrinos with ν_L in SM and a massive vectorlike fermion (χ) that is a candidate for DM with mass $M_{\text{DM}}(\equiv M_\chi)$. Both ν_R and χ are singlets under the SM gauge group. The vectorlike fermion χ is stabilized by an additional unbroken Z_2 symmetry, under which all SM particles, including ν_R are even. In this framework, ν_R carries a leptonic charge similar to SM leptons, keeping light neutrinos purely Dirac in the limit of unbroken global lepton number symmetry. We consider a subclass of leptophilic DM EFT with light Dirac neutrinos [65] where DM is only ‘ ν_R -philic’ i.e., χ interacts exclusively with ν_R via EFT operators, making ν_R a portal between the visible sector and the dark sector. While this keeps direct detection cross section of DM highly suppressed at one-loop, it opens up other detection aspects as we discuss in the upcoming sections. We emphasize that our assumption of vanishing interactions among χ and SM leptons f requires additional symmetries in a UV complete setup. Such symmetries can either forbid $\chi-f$ interactions at all orders or at the leading order. In the latter scenario, such operators involving $\chi-f$ interactions are generated only at loop level and hence are suppressed in our EFT analysis. Such a possibility can indeed be achieved in UV complete scenario which we discuss in Sec. III.

In a minimal setup, we propose the following EFT Lagrangian:

$$\begin{aligned} -\mathcal{L} \supset & G_S \bar{f}_L \nu_R \bar{\nu}_R f_L + G_V \bar{f}_L \gamma^\mu f_L \bar{\nu}_R \gamma_\mu \nu_R \\ & + G_T (\bar{L} \sigma^{\mu\nu} \nu_R \tilde{H} B_{\mu\nu} + \bar{L} \sigma^{\mu\nu} \nu_R \tilde{H} \sigma_i W_{\mu\nu}^i) \\ & + G'_V \bar{\chi} \gamma^\mu \chi \bar{\nu}_R \gamma_\mu \nu_R + G'_S \bar{\chi} \nu_R \bar{\nu}_R \chi_L. \end{aligned} \quad (1)$$

Using Fierz transformation, this can be written as

$$\begin{aligned} -\mathcal{L} \supset & (G_V - k G_S) \bar{f}_L \gamma^\mu f_L \bar{\nu}_R \gamma_\mu \nu_R \\ & + G_T (\bar{L} \sigma^{\mu\nu} \nu_R \tilde{H} B_{\mu\nu} + \bar{L} \sigma^{\mu\nu} \nu_R \tilde{H} \sigma_i W_{\mu\nu}^i) \\ & + (G'_V - k' G'_S) \bar{\chi} \gamma^\mu \chi \bar{\nu}_R \gamma_\mu \nu_R \\ & + G'_V \bar{\chi} \gamma^\mu \chi \bar{\nu}_R \gamma_\mu \nu_R, \end{aligned} \quad (2)$$

where $x \in L, R$ and $G_S, G_V, G_T, G'_S, G'_V$ are the dimensionful effective coefficients of the dimension-6 operators. The dimensionless parameters, k and k' carry a value of $1/2$ [66]. The first three terms describe ν_R -SM interactions that can give rise to number changing and elastic scattering processes of ν_R with SM fermions $f_{L,R}$ and lepton doublet, L , whereas the last two terms represent the interaction between DM and ν_R . Since DM interacts only with ν_R at leading order while ν_R interacts with both SM and DM at the same order, it justifies the ν_R -philic nature of DM. Furthermore, the tensor type ν_R -SM effective interaction, with coefficient G_T , can give rise to neutrino magnetic moment (NMM). The measured upper bound on the NMM (μ_ν) from electron scattering experiment is approximately $\mu_\nu \sim 2.9 \times 10^{-11} \mu_B$ [67], where $\mu_B = \frac{e}{2m_e}$ is the Bohr magneton. More recent data from laboratory experiments such as XENONnT [68] and Borexino [69] have provided a significantly stricter limit on the NMM, yielding $\mu_\nu \sim 6.4 \times 10^{-12} \mu_B$ and $\mu_\nu \sim 28 \times 10^{-12} \mu_B$, respectively. In contrast, the astrophysical bound derived from the red giant branch [70], place a much stronger constraint, $\mu_\nu \sim 1.5 \times 10^{-12} \mu_B$.

A. EFT approach to ΔN_{eff}

The thermalization of ν_R contributes to the effective relativistic degrees of freedom defined as

$$N_{\text{eff}} \equiv \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \left(\frac{\rho_{\text{Tot}} - \rho_\gamma}{\rho_\gamma} \right), \quad (3)$$

where ρ_{Tot} is the total radiation content of the Universe with ρ_γ being the photon energy density. CMB measurements constrain such additional relativistic degrees of freedom as $N_{\text{eff}} = 2.99^{+0.34}_{-0.33}$ at 2σ or 95% CL including baryon acoustic oscillation (BAO) data [2]. The translated bound on $\Delta N_{\text{eff}} (= N_{\text{eff}} - N_{\text{eff}}^{\text{SM}})$ at 2σ can be written as $\Delta N_{\text{eff}} \lesssim 0.285$, where $N_{\text{eff}}^{\text{SM}} = 3.045$ [71–73]. The latest DESI 2024 data give a slightly weaker bound $\Delta N_{\text{eff}} \lesssim 0.4$ at 2σ CL [74]. The recent result from ACT [75] combined with PLANCK and the measurements of primordial deuterium and helium is also consistent with a positive contribution to $\Delta N_{\text{eff}} < 0.075$ at 2σ CL. Similar bound also exists from big bang nucleosynthesis (BBN) $2.5 < N_{\text{eff}} < 3.2$ at 95% CL [76]. These cosmological bounds are consistent with the SM predictions. Future CMB experiment CMB-S4 is expected to reach a much better sensitivity of $\Delta N_{\text{eff}} = 0.06$ [77], taking it closer to the SM prediction. Another future experiment CMB-HD [78] can probe ΔN_{eff} up to 0.027 at 2σ .

There have been several recent works on enhanced N_{eff} with Dirac neutrinos [32,34,57,79–97]. EFT of light Dirac neutrino interactions has also been studied in the context of N_{eff} [82,85]. In another recent work [65], EFT of leptophilic DM with light Dirac neutrinos was studied in the context of collider and N_{eff} phenomenology. In another

recent work [98], EFT of Dirac neutrino phenomenology was studied up to dimension-6. Here, we consider a similar EFT setup where DM is ν_R -philic uniting thermalization of DM and ν_R with the visible sector.

To study the evolution of ν_R energy density, we consider the continuity equation for a homogeneous and isotropic universe,

$$\dot{\rho}_{\text{Tot}} + 3\mathcal{H}(\rho_{\text{Tot}} + P_{\text{Tot}}) = 0, \quad (4)$$

where $\mathcal{H} = \sqrt{\frac{8\pi}{3M_{\text{Pl}}^2}} \rho_{\text{Tot}}$ is the Hubble parameter, and ρ_{Tot} and P_{Tot} are the total energy density and pressure, respectively. These can be decomposed into contributions from the SM bath and $\nu_R - \chi$ bath as

$$\rho_{\text{Tot}} = \rho_{\text{SM}} + (\rho_{\nu_R} + \rho_\chi), \quad (5)$$

$$P_{\text{Tot}} = P_{\text{SM}} + (P_{\nu_R} + P_\chi). \quad (6)$$

The evolution of two separate sectors namely, ν_R -DM and the SM bath is described by a coupled system as ν_R couples to the SM via similar dimension-6 operators. The effective coupling for $\chi - \nu_R$ interaction is chosen to be larger than $0.1 \times G_F$, ensuring that the DM remains in thermal equilibrium with the ν_R bath in the early Universe. While these baths can maintain thermal equilibrium with each other, observational constraints from PLANCK 2018 indicate that for three ν_R species, they must have decoupled from the SM plasma at temperatures above 600 MeV [79]—much earlier than the decoupling of left-handed neutrinos (ν_L). When the ν_R -SM interaction rate drops below the Hubble rate, the two baths decouple and evolve independently according to

$$\dot{\rho}_{\nu_R} + \dot{\rho}_\chi + 3\mathcal{H}(\rho_{\nu_R} + P_{\nu_R}) + 3\mathcal{H}(\rho_\chi + P_\chi) = C_{\nu_R}^{(\rho)}, \quad (7)$$

$$\dot{\rho}_{\text{SM}} + 3\mathcal{H}(\rho_{\text{SM}} + P_{\text{SM}}) = -C_{\nu_R}^{(\rho)}. \quad (8)$$

Here, $C_{\nu_R}^{(\rho)}$ represents the collision term that quantifies energy transfer between the baths through annihilation and scattering processes. For a generic process $1 + 2 \leftrightarrow 3 + 4$, this term is given by

$$\begin{aligned} C_{\nu_R}^{(\rho)} = & -N_{\nu_R} \int E_1 d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 (2\pi)^4 \\ & \times \delta^4(p_1 + p_2 - p_3 - p_4) S \\ & \times [|\mathcal{M}|_{1+2 \rightarrow 3+4}^2 f_1 f_2 (1-f_3)(1-f_4) \\ & - |\mathcal{M}|_{3+4 \rightarrow 1+2}^2 f_3 f_4 (1-f_1)(1-f_2)], \end{aligned} \quad (9)$$

where

$$d\Pi_i = \frac{g_i}{(2\pi)^3} \frac{d^3 p_i}{2E_i}, \quad f_i = \frac{1}{e^{E_i/T_i} + 1}, \quad (i=1,2,3,4). \quad (10)$$

In these equations, N_{ν_R} represents the degrees of freedom for ν_R species, and S is the symmetry factor for the relevant processes. Each particle i is characterized by its internal degrees of freedom (g_i), energy (E_i), and temperature (T_i). Here, it is worth mentioning that, for temperatures around and above the ν_R -SM decoupling temperature ($\gtrsim 500$ MeV), the collision term is dominated by interactions with light SM fermions (electrons and neutrinos), whose masses can be safely neglected at these energy scales.

The evolution equations namely, Eqs. (7) and (8), can be reformulated to show the temperature evolution of ν_R relative to the SM bath temperature as

$$\begin{aligned} \frac{d(\rho_{\nu_R} + \rho_\chi)}{d\rho_{\text{SM}}} &= \frac{3\mathcal{H}(\rho_{\nu_R} + P_{\nu_R}) + 3\mathcal{H}(\rho_\chi + P_\chi) - C_{\nu_R}^{(\rho)}}{3\mathcal{H}(\rho_{\text{SM}} + P_{\text{SM}}) - C_{\nu_R}^{(\rho)}}, \\ \frac{dT_{\nu_R}}{dT_\gamma} &= \frac{3\mathcal{H}(\rho_{\nu_R} + P_{\nu_R}) + 3\mathcal{H}(\rho_\chi + P_\chi) - C_{\nu_R}^{(\rho)}}{3\mathcal{H}(\rho_{\text{SM}} + P_{\text{SM}}) - C_{\nu_R}^{(\rho)}} \\ &\quad \times \frac{\partial \rho_{\text{SM}}}{\partial T_\gamma} \left(\frac{\partial \rho_{\nu_R}}{\partial T_{\nu_R}} + \frac{\partial \rho_\chi}{\partial T_{\nu_R}} \right)^{-1}. \end{aligned} \quad (11)$$

We have calculated the evolution of right-handed neutrino temperature (T_{ν_R}) in the early Universe, focusing on the period when the SM bath temperature (T_γ) cooled from 10^6 MeV down to 10 MeV. The expressions for $C_{\nu_R}^{(\rho)}$ corresponding to the ν_R -SM interactions are provided in Appendix A. We assume the right-handed neutrinos to be thermally equilibrated with the SM bath particles initially. Figure 1 shows the temperature ratio $(T_{\nu_R}/T_\gamma)^4$ versus T_γ for different choices of the effective four-fermion interaction strength as mentioned in the inset of the same figure.

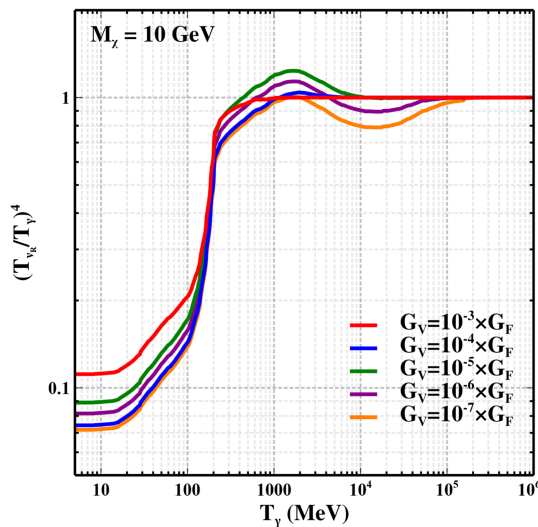


FIG. 1. The evolution of $(T_{\nu_R}/T_\gamma)^4$ for several benchmark values of G_V with $M_\chi = 10$ GeV.

We show the temperature evolution only for vector-like ν_R -SM coupling G_V and denote its strength relative to the Fermi coupling G_F , where we considered the DM mass to be 10 GeV. As previously mentioned, here the $\chi - \nu_R$ coupling G'_V is chosen such that χ remains in thermal equilibrium with the ν_R bath. Deviations from the $(T_{\nu_R}/T_\gamma)^4 = 1$ at lower temperatures indicate the decoupling of ν_R bath from the SM bath. The plot shows that a smaller value of G_V leads to an early decoupling of ν_R bath, as expected. In addition to the effective coefficients, the T_{ν_R} evolution also depends on DM mass. As noted previously, the DM interacts solely with the ν_R bath. Therefore, when T_{ν_R} falls below the DM mass, the DM transfers its entropy to the ν_R thermal bath. At this epoch, if the ν_R bath remains in equilibrium with the SM thermal bath, the ratio T_{ν_R}/T_γ will remain constant due to quick dissipation of ν_R energy into the SM bath. However, if the ν_R thermal bath has decoupled from the SM thermal bath, the entropy discharge from the DM leads to an increase in ν_R bath temperature. This behavior is clearly shown in Fig. 1. The DM of mass 10 GeV transfers its entropy during the epoch of $1 \text{ GeV} \lesssim T_\gamma \lesssim 10 \text{ GeV}$. The purple and orange colored contours correspond to the decoupling of ν_R from the SM bath before $T_\gamma \simeq 10^4$ MeV, and receive the maximum entropy contribution from the DM, leading to an increase in T_{ν_R} once $T_{\nu_R} \simeq M_\chi$. In contrast, the red colored contour shows ν_R -SM decoupling at $T_{\nu_R} \simeq 1 \text{ GeV}$ and does not receive any further contribution from DM entropy transfer. The green and blue contours show ν_R -SM decoupling in the same epoch when DM transfers entropy to ν_R bath. Between these two contours, the green contour corresponds to earlier ν_R -SM decoupling, leading to a larger T_{ν_R}/T_γ ratio, as it receives a greater contribution from the DM entropy transfer compared to the blue contour. We also find similar behavior of T_{ν_R} evolution for both scalar and tensor type interactions.

The contribution of ν_R to the effective number of neutrino species N_{eff} can be expressed as

$$\Delta N_{\text{eff}} = N_\nu \left(\frac{11}{4} \right)^{4/3} \frac{\rho_{\nu_R,0}}{\rho_{\text{SM},0}} = N_\nu \left(\frac{11}{4} \right)^{4/3} \frac{T_{\nu_R,0}^4}{T_{\gamma,0}^4} \quad (12)$$

$$= N_\nu \left(\frac{T_{\nu_R,10}}{T_{\gamma,10}} \right)^4, \quad (13)$$

where subscript “0” refers to the CMB formation temperature and “10” indicates a photon bath temperature of 10 MeV. N_ν represents the number of ν_R species present in the model.

In Fig. 2, we showcase the ΔN_{eff} due to ν_R as a function of the effective couplings G_S and G_V , for $M_\chi = 10$ GeV. In the horizontal axis, the strength of G_S and G_V are shown relative to the Fermi constant G_F . For $G_\chi < 10^{-5} \times G_F$, ν_R

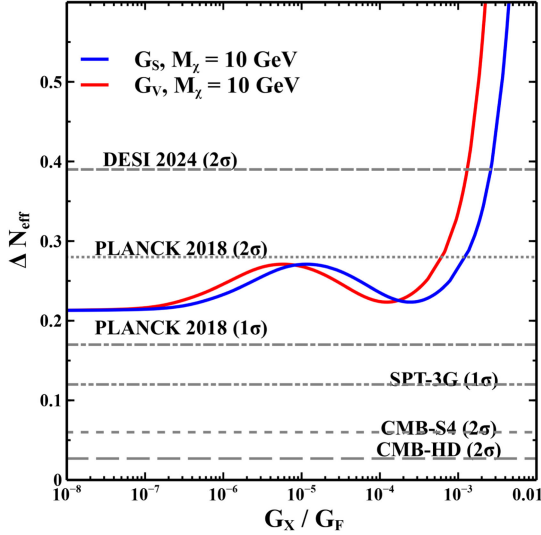


FIG. 2. ΔN_{eff} as a function of G_X ($X \equiv S, V$) with $M_\chi = 10$ GeV. We have shown the current upper bounds from PLANCK 2018 [2] and the analysis by [100] using the recent DESI 2024 data. The sensitivity of upcoming experiments SPT-3G [101], CMB-S4 [77] and CMB-HD [78] are also shown.

decouples before $T_\gamma \simeq 10$ GeV, resulting in an equal contribution to ΔN_{eff} with a minimum value $\Delta N_{\text{eff}} \approx 0.21$. It should be noted that the minimum value of ΔN_{eff} may vary depending on the DM mass, in general. A dip is observed around $G_X \simeq 10^{-4} \times G_F$, which results from the interplay between the epochs of the ν_R decoupling and entropy transfer from DM. We have shown the existing constraints from PLANCK 2018 and recent results of DESI 2024. We also project the future sensitivities of SPT-3G, CMB-S4 and CMB-HD. While PLANCK 2018 results rule out G_S/G_F and G_V/G_F larger than 5.7×10^{-6} , DESI 2024 results allows G_S and G_V as large as 5.6×10^{-4} . Notably, the projected sensitivities of future experiments like SPT-3G, CMB-S4, and CMB-HD can completely probe these scenarios in which ν_R is thermalized with SM bath in the early Universe. Similarly, Fig. 3 illustrates the contribution to ΔN_{eff} arising from the ν_R -SM tensorial interaction term as a function of the respective coupling G_T . The variation in ΔN_{eff} for $M_\chi = (1, 10, 100)$ GeV is shown as colored contours. The horizontal gray lines represent the current bounds and future sensitivities from CMB experiments, while the shaded regions indicate the exclusion limit due to upper bound on Dirac NMM from experiments such as XENONnT [68], Borexino [69] and astrophysical observations related to red-giants [70]. We have used these limits to constrain the effective tensorial operator, G_T , and it excludes $G_T \geq 3.82 \times 10^{-8} G_F$. Due to the presence of DM interacting via ν_R -portal, we get enhanced contribution to N_{eff} compared to a scenario without DM [99].

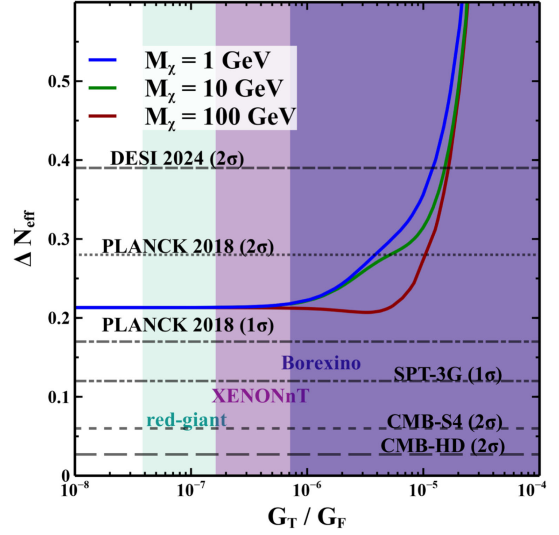


FIG. 3. ΔN_{eff} as a function of G_T is shown for $M_\chi = (1, 10, 100)$ GeV. The shaded regions represent the values of G_T that are excluded by the NMM constraints. The current upper bounds and future sensitivities from CMB experiments are indicated by the horizontal gray lines.

B. Phenomenology of ν_R -philic dark matter

1. DM relic density

In this section, we explore the relic density of vector-like fermionic dark matter (χ), which interacts exclusively with right-handed neutrinos (ν_R) through dimension-6 effective operators. These interactions are crucial in determining the annihilation of DM into ν_R as shown in Fig. 4 and the resulting relic density. The relevant terms in the EFT Lagrangian include a scalar-type interaction, governed by the effective coupling G'_S (i.e., $G'_S \bar{\chi}_L \nu_R \bar{\nu}_R \chi_L$) and a vector-type interaction proportional to effective coupling G'_V (i.e., $G'_V \bar{\chi}_x \gamma^\mu \chi_x \bar{\nu}_R \gamma_\mu \nu_R$ where $x \equiv L, R$). In a UV complete framework, the scalar interaction can contribute to a t -channel annihilation process of the DM, whereas the vector interaction can contribute to a s -channel annihilation of DM into ν_R .

In Sec. II A, we discussed the evolution of the ν_R thermal bath temperature relative to the SM temperature, as illustrated in Fig. 1. As DM χ exclusively interacts with ν_R , the thermal evolution of ν_R bath directly impacts the dynamics of DM freeze-out. Notably, it can give rise to two distinct scenarios as follows:

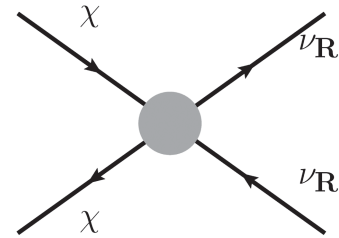


FIG. 4. DM annihilation to ν_R .

- (1) Early freeze-out: If dark matter freezes out before ν_R decouples from the SM bath, the conventional freeze-out mechanism applies. In this case, the SM bath temperature governs the whole process;
- (2) Late freeze-out: When dark matter freeze-out occurs after ν_R decoupling, a more complex scenario emerges. Here, ν_R and dark matter form a separate thermal bath, necessitating appropriate consideration of both SM and ν_R bath temperatures in the Boltzmann equations.

The temperature of right-handed neutrinos T_{ν_R} is expressed as a function of the SM bath temperature (T_γ), with their decoupling governed by the effective coefficient G_X . Initially, when temperatures are high, T_{ν_R} closely tracks T_γ . As the Universe cools, ν_R eventually decouples from the SM bath, with the epoch of decoupling determined by G_X . A larger G_X value delays the decoupling, resulting in a higher T_{ν_R} at later epochs relative to scenarios with smaller G_X . The Boltzmann equation governing the evolution of comoving DM density can then be expressed as [102]

$$\frac{dY_\chi}{dx} = -\beta(T_\gamma) \frac{s(T_\gamma)}{\mathcal{H}(T_\gamma, T_{\nu_R}, M_\chi)} \frac{1}{x} \langle \sigma v \rangle (Y_\chi^2 - (Y_\chi^{\text{eq}})^2), \quad (14)$$

where $x = M_\chi/T_\gamma$, M_χ is the mass of χ and $\langle \sigma v \rangle$ is the thermally averaged cross section of $\bar{\chi}\chi \rightarrow \bar{\nu}_R \nu_R$. The other relevant quantities appearing in the above Boltzmann equation can be defined as

$$Y_\chi = \frac{n_\chi}{s}, \quad n_\chi(T_{\nu_R}, M_\chi) = \frac{g_\chi}{2\pi} T_{\nu_R} M_\chi^2 K_2\left(\frac{M_\chi}{T_{\nu_R}}\right), \quad (15)$$

$$s(T_\gamma) = \frac{2\pi^2}{45} g_{*s}(T_\gamma) T_\gamma^3, \quad (16)$$

$$\mathcal{H}(T_\gamma, T_{\nu_R}, M_\chi) = \sqrt{\frac{8\pi}{3M_{\text{pl}}^2} \rho_{\text{Tot}}(T_\gamma, T_{\nu_R}, M_\chi)}, \quad (17)$$

$$\beta(T_\gamma) = 1 + \frac{T_\gamma}{3g_{*s}(T_\gamma)} \frac{dg_{*s}(T_\gamma)}{dT_\gamma}, \quad (18)$$

$$\sigma(\bar{\chi}\chi \rightarrow \bar{\nu}_R \nu_R) = \frac{G_V'^2}{4\pi} \frac{1}{s} \left(1 - \frac{4M_\chi^2}{s}\right)^{-1/2} \times \left(\frac{s^2}{3} + \frac{2M_\chi^2 s}{3} - 2M_\chi^4\right). \quad (19)$$

Here g_χ is the internal degrees of freedom of χ , $g_{*s}(T_\gamma)$ is the effective degrees of freedom, $\rho_{\text{Tot}} (= \rho_\gamma(T_\gamma) + \rho_{\nu_R}(T_{\nu_R}) + \rho_\chi(T_{\nu_R}, M_\chi))$ is the total energy density, and M_{pl} is the Planck mass ($= 1.22 \times 10^{19}$ GeV). Figure 5 illustrates the evolution of DM number density, obtained by solving the Boltzmann equation [cf. Eq. (14)]. We present

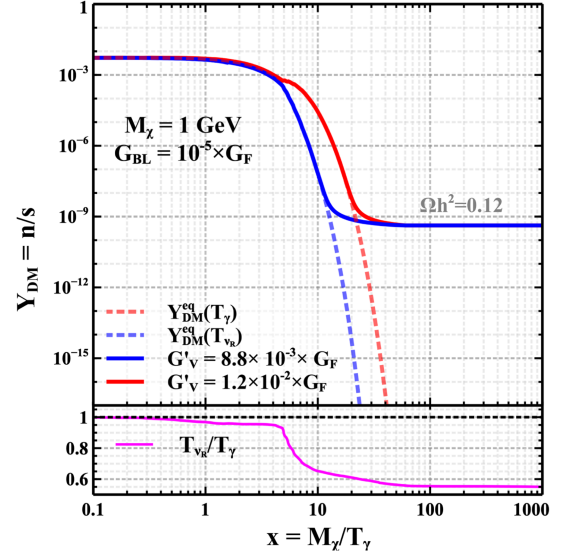


FIG. 5. Here we have shown the evolution of DM abundance (top) and (T_{ν_R}/T_γ) (magenta line in the bottom panels) with respect to $x = M_\chi/T_\gamma$. The bottom panels depict the ν_R decoupling from SM thermal bath.

results for a benchmark DM mass of 1 GeV. As discussed previously, the DM dynamics are primarily governed by the temperature of the right-handed neutrino (ν_R) bath, which in turn depends on its interaction rate with the SM bath, controlled by the effective operator coefficient G_X . The bottom insets of Fig. 5 depict the corresponding evolution of T_{ν_R} relative to the photon temperature T_γ . The magenta line (T_{ν_R}/T_γ) deviates from the thick black dotted line ($T_{\nu_R}/T_\gamma = 1$), indicating the decoupling of ν_R from the SM bath. The blue dashed line represents the equilibrium abundance of DM as a function of T_{ν_R} , while the red dashed line shows the equilibrium DM density as a function of the photon temperature T_γ . Once ν_R decouples from the SM bath, these two lines diverge. We investigated two scenarios for the decoupling of DM. In one scenario, we assumed the ν_R bath shares the same temperature with SM bath and the red solid line shows the evolution of DM. In contrast, the blue line corresponds to DM decoupling from ν_R thermal bath where the evolution of T_{ν_R} is decided by solving Eq. (11). The G'_V is fine-tuned in both cases such that the red and blue lines yield the correct relic density. As shown in the plot, earlier decoupling of the ν_R bath necessitates earlier decoupling of dark matter from the ν_R sector, due to Boltzmann suppression of the equilibrium dark matter abundance. Consequently, achieving the correct relic density in this case requires a smaller annihilation cross section. In Fig. 6, we summarize the correct relic density parameter space in the plane of ΔN_{eff} and DM mass (lower x-axis) ranging from 1 GeV to 1000 GeV, while different colors of solid contours represent the effective coefficient G_S in the left panel and G_V in the right panel. For a fixed value of G_S (or G_V), the DM mass and G'_V show

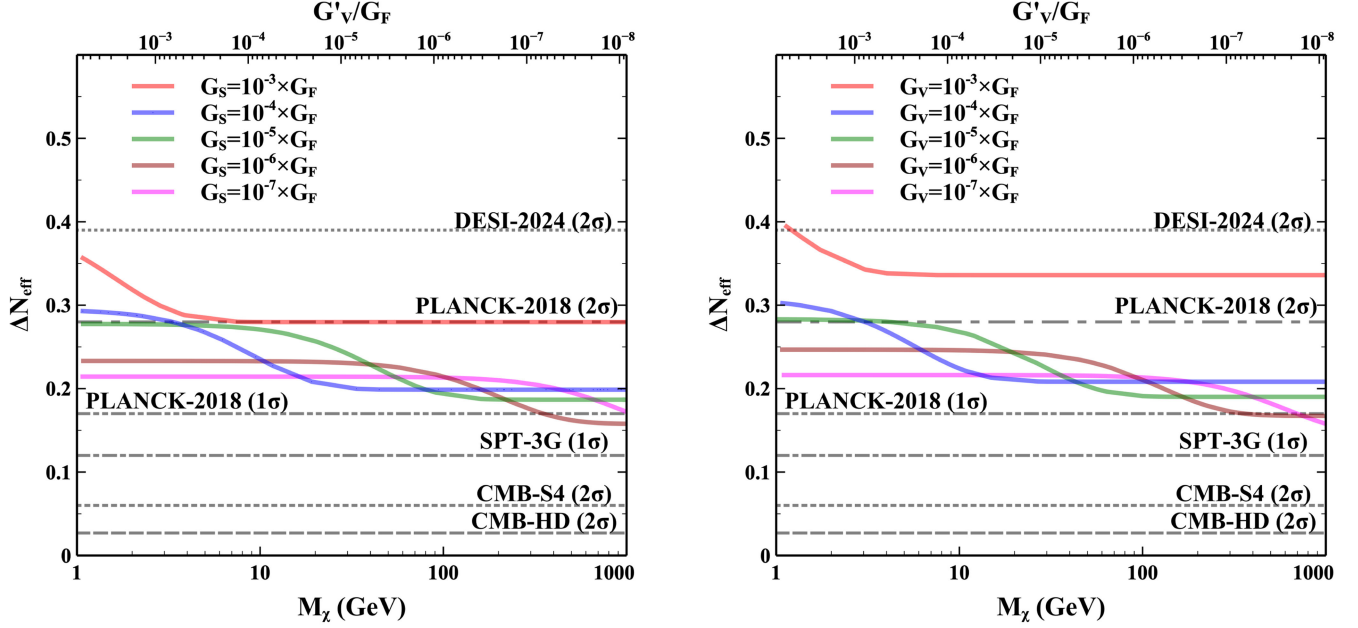


FIG. 6. Relic satisfying points are plotted in the plane of DM mass and ΔN_{eff} . In the left panel, the colored contours represent the corresponding effective coefficient G_S , while in the right panel, they represent the corresponding G_V value.

one-to-one correspondence to provide correct relic density, which is shown in the upper x -axis. For simplicity, we consider only vector-type effective interactions for the DM. We constrain the DM mass to be below the EFT scale. The DM annihilation cross section increases with the center-of-mass energy and, consequently, with DM mass [103]. As the cross section grows with increasing mass, a smaller effective coefficient is required to achieve the correct relic density. This inverse relationship is clearly demonstrated in the figure, where lower G'_V values correspond to larger DM masses. Similarly, in Fig. 7, we present the DM relic

density that satisfies the parameter space for three benchmark values of G_T . As shown in Fig. 3, a substantial range of G_T values is ruled out by the NMM bounds. However, there exists a narrow range of $G_T (< 3.82 \times 10^{-8} G_F)$ where the thermal relic density of ν_R can contribute minimally to ΔN_{eff} .

2. Direct detection

In the ν_R -philic DM model, DM lacks direct interactions with the SM and hence DM-nucleon scattering is not possible at the tree-level. However, DM direct detection remains feasible through a loop-mediated process involving right-handed neutrinos (ν_R), as illustrated in Fig. 8. The direct detection cross section for loop-level DM-nucleon scattering is given by

$$\sigma_{\chi N} = \int_0^{4v^2\mu_{\chi N}^2} dp^2 \frac{1}{64\pi} \frac{1}{M_\chi^2 M_N^2} \frac{1}{v^2} |\overline{\mathcal{M}}_{\chi N}|^2, \quad (20)$$

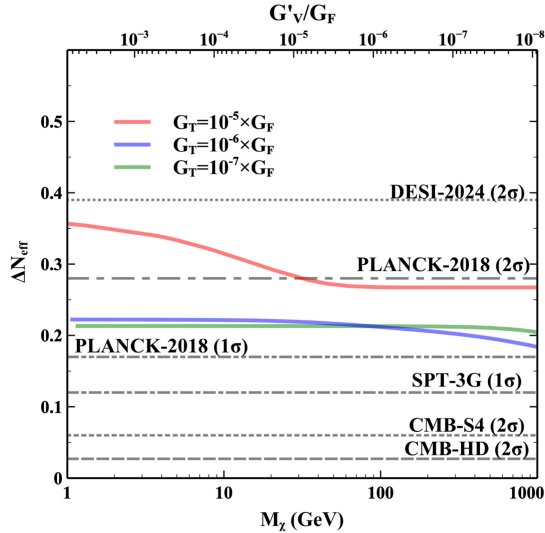


FIG. 7. Relic satisfying points are plotted in the plane of DM mass and ΔN_{eff} . The colored contours represent the corresponding G_T value.

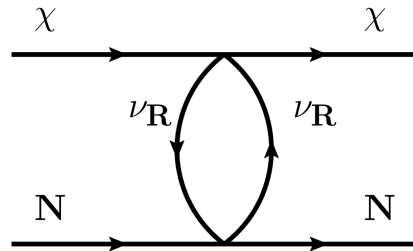


FIG. 8. DM-nucleon scattering processes for DM direct detection.

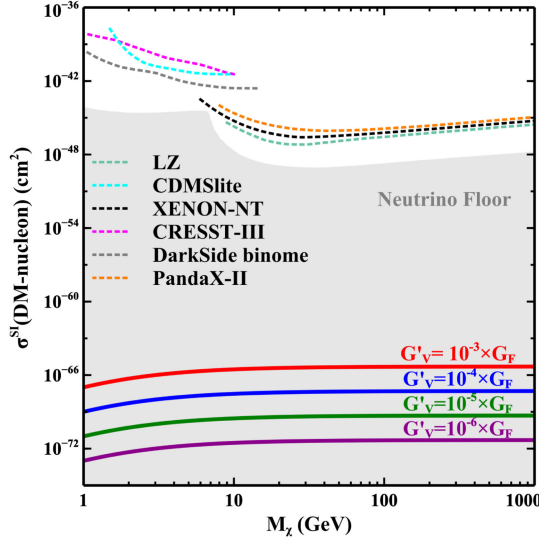


FIG. 9. Spin-independent DM-nucleon scattering cross section as a function of DM mass.

where the reduced mass of the DM-nucleon system is given as, $\mu_{\chi N} = \frac{M_\chi M_N}{M_\chi + M_N}$. We assume a DM velocity of $v \sim 10^{-3}$ for DM in the galactic halo. The amplitude of the loop diagram $|\mathcal{M}_{\chi N}|^2$ is detailed in Appendix B. In Fig. 9, we present the spin-independent DM-nucleus scattering cross section as a function of DM mass (thick colored lines) along with the existing experimental constraints (dotted lines). The solid lines represent the DM-nucleus scattering cross section for benchmark values of G'_V scaled with G_F , with G_V fixed at $10^{-3} \times G_F$. The dashed lines show the experimental bounds from XENON [50,51], LUX-ZEPLIN(LZ) [52], CDMSlite [54], CRESST-III [55], DarkSide-50 Binomial Fluctuation [53], and PandaX-II [49]. The gray shaded region shows the neutrino floor [104]. For each G'_V value, we impose a perturbative-unitarity cutoff on the DM mass to ensure the validity of the EFT treatment. This can be seen from some of the solid contours appearing only below a certain value of DM mass. The loop contribution significantly suppresses the direct detection cross section, placing it far below the present and future sensitivity of DM direct search experiments. Consequently, this ν_R -philic DM scenario could potentially explain the null detection of DM in terrestrial direct detection facilities.

3. Indirect detection

In addition to direct detection, our ν_R -philic DM model allows for indirect detection through loop-induced processes involving ν_R . These processes enable DM annihilation to charged fermions, which can be constrained by various gamma-ray and cosmic-ray experiments as well as from CMB anisotropy.

Figure 10 illustrates the thermal averaged annihilation cross section of DM to e^+e^- via the s -wave channel as a

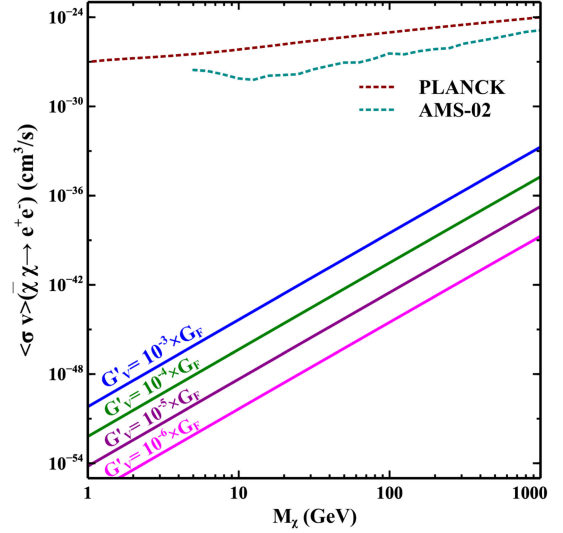


FIG. 10. DM annihilation cross section $\langle\sigma v\rangle_{\chi\chi\rightarrow e^+e^-}$ as a function of DM mass.

function of DM mass. We present results for several benchmark values of G'_V scaled with G_F . The solid lines represent the annihilation cross section, while the dashed lines show the current observational bounds from CMB measurement [105] and AMS02 [106]. Similar to the case of direct detection, here also we apply the upper bound on DM mass from validity of EFT, as seen for the chosen values of effective couplings in green and blue colored contours.

III. $U(1)_{B-L}$: AN EXAMPLE OF UV COMPLETION

In this section, we extend our effective theory framework of $\nu_R - SM$ and $\nu_R - \chi$ interactions with a UV complete scenario. Gauged $B - L$ extension of the SM [107–112] has been a popular BSM framework studied extensively in the literature. Here, we augment SM gauge symmetry with a gauged $U(1)_{B-L}$ symmetry, under which the quarks and leptons carry a charge of $\frac{1}{3}$ and -1 , respectively. The inclusion of three right-handed neutrinos becomes a natural requirement for anomaly cancellation. In order to prevent Majorana mass of right-handed neutrinos, one can have an unbroken $U(1)_{B-L}$ with a massive neutral gauge boson, Z' , using the Stueckelberg mechanism [80]. Alternatively, one can choose the scalar content in a way which breaks $B - L$ symmetry by more than 2 units to forbid the Majorana mass term [113]. The Dirac mass term can be generated from the usual Yukawa Lagrangian, given by

$$\mathcal{L} \supset y_{\alpha\beta} \bar{l}_{L\alpha} \tilde{H} \nu_{R\beta} + \text{H.c.}, \quad (21)$$

where α and β are flavor indices, l_L is the lepton doublet, $\tilde{H} = i\sigma_2 H^*$. The Yukawa couplings ($y_{\alpha\beta}$) are required to be sufficiently small to generate the observed small neutrino masses, consistent with the neutrino mass scale inferred

from experimental data. In addition to the Yukawa interactions, the RHNs couple to SM fermions through gauge interactions, with the exchange of a Z' boson. These interactions govern the decoupling of the ν_R from the SM bath. Furthermore, we extend the particle content of the SM by introducing a singlet fermion, χ and a scalar singlet, ϕ . We propose an additional Z_2 -symmetry to ensure the stability of the dark sector particles, wherein both χ and ϕ are odd under the Z_2 symmetry and all other particles are even. We consider χ as the lightest Z_2 odd particles and thus serves as a fermionic DM candidate. To exhibit the ν_R -philic DM nature, we keep χ as neutral under SM and $U(1)_{B-L}$ gauge group, whereas ϕ is assigned with a -1 charge under $U(1)_{B-L}$ symmetry and transforms trivially under SM symmetries. ν_R acts as a portal between the SM thermal bath and dark sector particles which is dictated by the interaction term in the Lagrangian,

$$\mathcal{L} \supseteq y_\chi \bar{\nu}_R \chi \phi + \text{H.c.} \quad (22)$$

Here it is worth mentioning that, ϕ being a Z_2 odd particle, does not get vacuum expectation value and ensures the stability of χ . The scalar Lagrangian is given by

$$\mathcal{L} \supseteq (D_\mu \phi)^\dagger D^\mu \phi - \mu_\phi^2 (\phi^\dagger \phi) - \lambda_\phi (\phi^\dagger \phi)^2 - \lambda_{\phi H} (\phi^\dagger \phi) (H^\dagger H), \quad (23)$$

where $D_\mu = \partial_\mu - i g_{BL} Z'_\mu$, g_{BL} is gauge coupling and Z' is the gauge boson for the $U(1)_{B-L}$ gauge symmetry. The inclusion of ϕ in the model is merely to have $\chi - \nu_R$ interaction. Therefore, for simplicity, we consider a heavy ϕ ($M_\phi = 10^4$ GeV), such that the abundance of ϕ does not affect the DM phenomenology.

In this model, ν_R interacts with SM fermions via exchange of Z' boson and maintains thermal equilibrium with SM bath in the early Universe. As the Universe cools down, the interaction rate drops below the expansion rate resulting a new thermal bath with temperature $T_{\nu_R} (\neq T_\gamma)$. The evolution of T_{ν_R} can be tracked by solving Eqs. (8) and (7), and the corresponding collision term is given as

$$C_{\nu_R}^0 = \frac{N_{\nu_R}}{64\pi^4} \int_0^\infty ds s^2 \sigma(s) \left[T_\gamma K_2 \left(\frac{\sqrt{s}}{T_\gamma} \right) - T_{\nu_R} K_2 \left(\frac{\sqrt{s}}{T_{\nu_R}} \right) \right], \quad (24)$$

where

$$\sigma(s) = \frac{1}{24\pi} \frac{g_{BL}^4 s}{(M_{Z'}^2 - s)^2}. \quad (25)$$

In Fig. 11, we present the variation of ΔN_{eff} as a function of the gauge coupling g_{BL} , with the colored contours corresponding to different values of the Z' boson mass, $M_{Z'}$. For each contour, there exists a minimum thermal

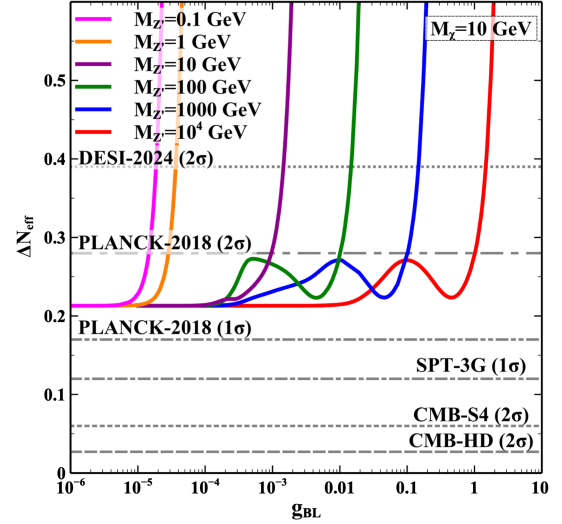


FIG. 11. ΔN_{eff} as a function of g_{BL} for DM mass of 10 GeV. The colored contours correspond to a fixed value of $M_{Z'}$. The current upper bounds and future sensitivities are shown as gray lines.

contribution to ΔN_{eff} up to a certain value of g_{BL} . Beyond this point, increasing g_{BL} results in a delayed decoupling of the right-handed neutrino thermal bath, leading to a higher value of ΔN_{eff} . Similarly, a lower $M_{Z'}$ enhances the interaction rate, thus postponing the decoupling of the ν_R bath. This trend is evident in the plot, where the contours corresponding to smaller $M_{Z'}$ exhibit an earlier rise in ΔN_{eff} along the g_{BL} axis.

In Fig. 12, we present the allowed parameter space in $M_{Z'} - g_{BL}$ plane based on the constraints coming from

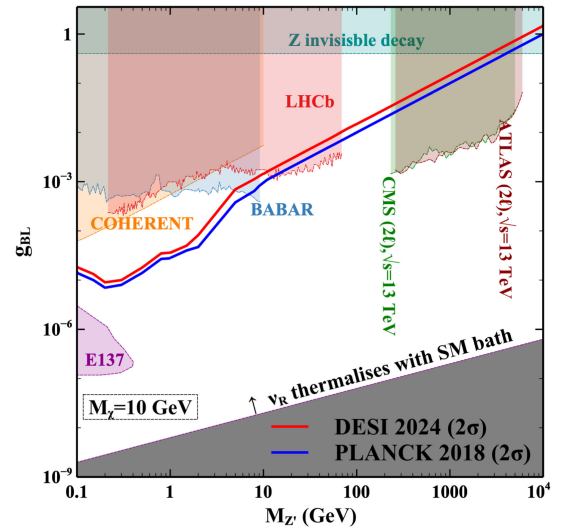


FIG. 12. The allowed parameter space in the g_{BL} vs $M_{Z'}$ plane. The red (blue) solid line represents the constraint on ΔN_{eff} from the DESI 2024 (PLANCK 2018) results at the 2σ CL. The gray shaded region represents the out of equilibrium condition for ν_R/Z' .

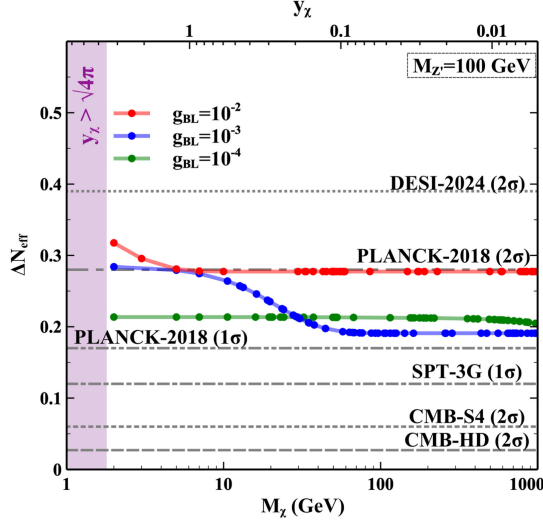


FIG. 13. ΔN_{eff} as a function of DM mass M_χ consistent with correct relic abundance and fixed Z' mass. The upper x -axis indicates the corresponding Yukawa coupling, y_χ . The colored contours represent different values of the gauge coupling, g_{BL} . The purple shaded region indicates the perturbative bound on the Yukawa coupling y_χ .

DESI 2024 [74,100] and PLANCK 2018 [2], indicated by the red and blue colored solid lines, respectively. The shaded regions correspond to the updated constraints coming from various other experiments, such as CMS [114], ATLAS [115], LHCb [116], BABAR [117], COHERENT [118], E137 [119], and Z invisible decay [1],¹ on the gauge coupling (g_{BL}) for the Z' boson mass, within the range of 0.1 GeV to 10^4 GeV. The region above gray shaded region represents the $g_{BL} - M_{Z'}$ value for which the ν_R can come to equilibrium with SM bath.

In this model, the DM relic is established by DM annihilation to ν_R mediated by ϕ particle via the t -channel diagram. The corresponding cross section is provided in Appendix C. Figure 13 illustrates the parameter space yielding the correct DM relic abundance, where the colored contours correspond to different values of the gauge coupling g_{BL} , as indicated in the legend. In this analysis, we fix the Z' boson mass at 100 GeV. The vertical axis displays the resulting values of ΔN_{eff} , while the lower horizontal axis represents the DM mass. The corresponding Yukawa coupling y_χ , required to achieve the observed relic density, is shown on the upper horizontal axis. It is worth noting that the behavior observed here closely mimics the trend exhibited in the left panel of Fig. 6, derived within the

¹In this model, Z can mix with Z' boson naturally via SM fermions in the loop. By adding all the one-loop contributions, we have estimated the natural mixing parameter, $\epsilon = 0.08g_{BL}$. Consequently, Z can decay to ν_R . Using the constraint from invisible decay of Z boson, we have shown the upper bound on g_{BL} in cyan colored shade in Fig. 12.

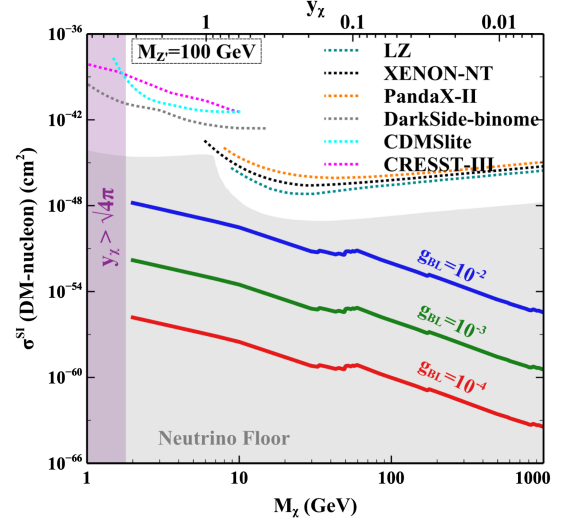


FIG. 14. Direct detection cross section corresponding to the parameter space that yields the correct relic density, as a function of the DM mass. The associated Yukawa couplings, y_χ , are indicated on the upper x -axis. The colored contours denote different values of the gauge coupling g_{BL} . Existing experimental bounds from direct detection searches are presented as dotted colored lines, while the gray shaded region indicates the neutrino floor.

EFT framework. In this model, DM does not interact with Standard Model particles at tree level. However, it can contribute to direct detection signals via two distinct loop-mediated processes. One of which is mediated by Higgs and the other diagram is mediated by Z' boson. Here, the Higgs-mediated diagram remains suppressed because of small coupling, so we have considered only the Z' -mediated diagram in this analysis. In Fig. 14, we display the direct detection cross section for parameter points consistent with the observed relic abundance, considering DM masses in the range of 1 GeV to 1000 GeV. The dotted lines represent current experimental limits from direct detection searches.

Since our DM sector couples only to ν_R , direct detection via nuclear or electron recoils lies entirely below the neutrino floor and is not expected to yield observable signals in current or near-future weakly interacting massive particle searches. However, this feature could provide a plausible explanation for the absence of DM signals in terrestrial detectors. Notably, cosmological probes such as measurements of the effective number of relativistic degrees of freedom N_{eff} , and effects on small-scale structure caused by DM- ν scattering offer complementary tests of ν_R -portal DM models. Precision CMB/BAO data and Lyman- α constraints can thus play a critical role in probing this framework which is otherwise invisible to direct detection experiments. Since our model predicts $\Delta N_{\text{eff}} \geq 0.21$, any future nonobservation of such dark radiation can falsify our setup.

IV. CONCLUSIONS

In this work, we have studied an effective field theory of light Dirac neutrinos and dark matter, assuming the latter to interact with the standard model only via right chiral parts of Dirac neutrinos. Assuming DM to be a vectorlike singlet fermion stabilized by an unbroken Z_2 symmetry, we systematically write down effective operators of the lowest possible dimension involving DM- ν_R and ν_R -SM interactions. This naturally connects the thermalization of DM with that of ν_R leading to enhancement of the effective relativistic degrees of freedom N_{eff} , within reach of future CMB experiments. We found that the relic abundance of dark matter is intricately tied to the temperature evolution of the ν_R bath, which is further influenced by its interactions with the SM bath. This allows one to distinguish two distinct freeze-out scenarios, each with unique implications for the dark matter parameter space. We also find enhancement of N_{eff} in the presence of both DM- ν_R and ν_R -SM interactions compared to the scenarios without DM discussed in earlier works. While typical direct and indirect detection prospects of such DM remain suppressed in agreement with null results, future CMB experiments bring complementary detection avenues.

Finally, we studied UV complete $U(1)_{B-L}$ gauge extension with light Dirac neutrinos. This model naturally incorporate right-handed neutrinos thereby accommodating light Dirac neutrinos and offer interesting complementarity between detection prospects at CMB and collider experiments. Inclusion of DM in such setups can further enhance ΔN_{eff} improving the detection prospects.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: POSSIBLE ν_R INTERACTIONS WITH SM BATH AND THEIR COLLISION TERMS

Following the four-fermion effective terms in Eq. (1), the energy transfer between the ν_R and SM baths happen through the interactions,

$$\nu_R + \bar{\nu}_R \leftrightarrow f_L + \bar{f}_L, \quad (\text{A1})$$

$$\nu_R + f_L \leftrightarrow \nu_R + f_L, \quad (\text{A2})$$

$$\nu_R + \bar{f}_L \leftrightarrow \nu_R + \bar{f}_L, \quad (\text{A3})$$

$$\nu_R + \bar{\nu}_L \leftrightarrow \bar{f} + f. \quad (\text{A4})$$

The collision terms for the scalar and vector type interactions are given in Table I, and for tensorial interactions, we have followed the prescription given in [98].

APPENDIX B: LOOP CONTRIBUTION IN DIRECT DETECTION

The loop factor, for the diagram given in Fig. 8, is given by

$$I = \frac{G_V G'_V}{(2\pi)^4} \int d^4 k \frac{\not{k}}{k^2 + i\epsilon} \frac{\not{p} + \not{k}}{(p+k)^2 + i\epsilon}. \quad (\text{B1})$$

The integration above diverges for large loop momentum, so we employ dimensional regularization to regularize the integration. In n -dimensions, the integration takes the form

$$I = \frac{G_V G'_V \mu^{4-n}}{(2\pi)^n} \int d^n k \frac{\not{k}}{k^2 + i\epsilon} \frac{\not{p} + \not{k}}{(p+k)^2 + i\epsilon} \quad (\text{B2})$$

$$= \frac{n G_V G'_V \mu^{4-n}}{(2\pi)^n} \int d^n k \frac{p \cdot k + k^2}{(k^2 + i\epsilon)((p+k)^2 + i\epsilon)}, \quad (\text{B3})$$

TABLE I. Collision terms $C_{\nu_R}^{(\rho)}$.

Process	$C_{\nu_R}^{(\rho)}$ from MB statistics	$1 - \delta_{\text{FD}}$
$\nu_R(p_1) + \bar{\nu}_R(p_2) \leftrightarrow \nu_L(p_3) + \bar{\nu}_L(p_4)$	$\frac{2}{\pi} G_S - 2G_V ^2 N_{\nu_R} (T_{\text{SM}}^9 - T_{\nu_R}^9)$	0.8841
$\nu_R(p_1) + \nu_L(p_2) \leftrightarrow \nu_R(p_3) + \nu_L(p_4)$	$\frac{1}{2\pi^2} G_S - 2G_V ^2 N_{\nu_R} T_{\text{SM}}^4 T_{\nu_R}^4 (T_{\text{SM}} - T_{\nu_R})$	0.8518
$\nu_R(p_1) + \bar{\nu}_L(p_2) \leftrightarrow \nu_R(p_3) + \bar{\nu}_L(p_4)$	$\frac{3}{\pi^2} G_S - 2G_V ^2 N_{\nu_R} T_{\text{SM}}^4 T_{\nu_R}^4 (T_{\text{SM}} - T_{\nu_R})$	0.8249

where k is the loop momentum, p is the momentum transfer from χ to nucleus and μ is chosen to have mass dimension 1. Using the Feynman parameter, x , and replacing $k \rightarrow k - px$, one can write the Eq. (B3) as

$$I = \frac{nG_V G'_V \mu^{4-n}}{(2\pi)^n} \int_0^1 dx \int d^n k \frac{k^2 - \overline{Q^2}}{(k^2 + \overline{Q^2})^2}, \quad (\text{B4})$$

where $\overline{Q^2} = x(1-x)p^2$. After applying Wick's rotation ($d^n k \rightarrow id^n l_E = idl_E l_E^{n-1} d\Omega_{n-1} = id\Omega_{n-1} \frac{1}{2} dl_E^2 l_E^{n-2}, k^2 \rightarrow -l_E^2$ and $p^2 \rightarrow -p_E^2$) and simplifying

$$I = \frac{-inG_V G'_V \mu^{4-n}}{(2\pi)^n} \frac{2\pi^{n/2}}{\Gamma(n/2)} \frac{1}{2} \int_0^1 dx \int_0^\infty dl_E^2 \frac{l_E^{n-2} (l_E^2 - Q^2)}{(l_E^2 + Q^2)^2}, \quad (\text{B5})$$

where $Q^2 = x(1-x)p_E^2$ and we used $\int d\Omega_{n-1} = \frac{2\pi^{n/2}}{\Gamma(n/2)}$. For further simplification, we used variable replacement $\frac{l_E^2}{Q^2} \rightarrow \xi$ and the Eq. (B5) can be read as

$$I = \frac{-inG_V G'_V \mu^{4-n}}{(2\pi)^n} \frac{\pi^{n/2}}{\Gamma(n/2)} \int_0^1 dx Q^{n-2} \int_0^\infty d\xi \frac{\xi^{\frac{n}{2}-1} (\xi - 1)}{(\xi + 1)^2} \quad (\text{B6})$$

$$= iG_V G'_V \left[\frac{p_E^2}{8\pi^2 \epsilon} + \frac{p_E^2}{8\pi^2} \left(\gamma_E - \frac{3}{2} + \ln \frac{p_E^2}{4\pi\mu^2} \right) + \mathcal{O}(\epsilon) \right], \quad (\text{B7})$$

where γ_E is defined as Euler's constant and carries a value of 0.577216 and $n = 4 - 2\epsilon$. While solving from Eq. (B6) to Eq. (B7), we used the definition of β -function, $\beta(m+1, n+1) = \int_0^\infty \frac{du u^m}{(1+u)^{m+n+2}}$. We note that the loop factor can be regularized for any finite value of ϵ . Now, applying Wick's rotation on Eq. (B7),

$$I = -iG_V G'_V \left[\frac{p^2}{8\pi^2} \left(\gamma_E - \frac{3}{2} + \ln \left| \frac{p^2}{4\pi\mu^2} \right| - i\pi \right) + \mathcal{O}(\epsilon) \right]. \quad (\text{B8})$$

Equation (B8) represents the effective coefficient of the DM-nucleus scattering through a loop mediated process. For practical purposes, one may choose the μ value such that the logarithmic term can be neglected.

$$|\overline{\mathcal{M}_{\chi N}}|^2 = 16(Z\alpha_p + (A-Z)\alpha_n)^2 M_{\text{DM}}^2 M_N^2 |I|^2, \quad (\text{B9})$$

where A, Z are mass number and atomic number, respectively, $\alpha_{p,n} \simeq 3$ and M_n is the nucleon mass.

APPENDIX C: DM ANNIHILATION CROSS SECTION

$$\sigma(\bar{\chi}\chi \rightarrow \bar{\nu}_R \nu_R) = -\frac{y_\chi^4}{32\pi s(s-4M_\chi^2)} \left(4(M_\chi - M_\phi)(M_\chi + M_\phi) \log \left(\frac{s \left(\sqrt{\frac{s-4M_\chi^2}{s}} - 1 \right) + 2M_\chi^2 - 2M_\phi^2}{-s \left(\sqrt{\frac{s-4M_\chi^2}{s}} + 1 \right) + 2M_\chi^2 - 2M_\phi^2} \right) \right. \\ \left. - \frac{2s \sqrt{\frac{s-4M_\chi^2}{s}} (sM_\phi^2 + 2(M_\chi - M_\phi)(M_\chi + M_\phi)(M_\chi^2 - M_\phi^2))}{sM_\phi^2 + M_\chi^4 - 2M_\chi^2 M_\phi^2 + M_\phi^4} \right). \quad (\text{C1})$$

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