Baryon asymmetry from dark matter decay

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We propose a novel framework where baryon asymmetry can arise due to forbidden decay of dark matter (DM) enabled by finite-temperature effects in the early Universe. In order to implement it in a realistic setup, we consider the DM to be a singlet Dirac fermion that acquires a dark asymmetry from a scalar field Φ via the Affleck-Dine mechanism. Because of finite-temperature effects, DM can decay in the early Universe into leptons and a second Higgs doublet, thereby transferring a part of the dark asymmetry into lepton asymmetry, with the latter getting converted into baryon asymmetry subsequently via electroweak sphalerons. DM becomes stable below a critical temperature, leading to a stable relic. While the scalar field Φ can play the role of inflaton with specific predictions for inflationary parameters, the setup also remains verifiable via astrophysical as well as laboratory-based observations.

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I. INTRODUCTION

The matter content of the present Universe is dominated by dark matter (DM) with the visible matter comprising only around 20% of it. Additionally, the visible or baryonic matter component is highly asymmetric [1,2]. While the standard model (SM) cannot solve these long-standing puzzles of DM and baryon asymmetry of the Universe (BAU), several beyond standard model (BSM) proposals have been proposed in the last few decades. Among them, the weakly interacting massive particle (WIMP) paradigm of DM [3–8] and baryogenesis/leptogenesis [9–11] have been the most widely studied ones. While the fundamental origin of DM and BAU could be different, the striking similarity in their abundances, namely, $\Omega_{\rm DM} \approx 5\Omega_{\rm Baryon}$ might be hinting toward a common origin. Such cogenesis mechanisms broadly fall into two categories: one in which the DM sector is also asymmetric, known as asymmetric dark matter [12–18], and the other where BAU is generated from WIMP DM annihilations [19–32]. Other cogenesis scenarios motivated by the Affleck-Dine (AD) mechanism [33] also exist in the literature [34–36].

In this paper, we propose a novel scenario where BAU is generated from DM decay. While DM is cosmologically stable, it can decay in the early Universe when finite-temperature effects enable the forbidden decay modes. While the effects of forbidden decay on DM production have been discussed in the literature [37–39], its role in cogenesis has not received any attention. In this work, we show that DM can decay during a finite period into SM leptons by virtue of finite-temperature effects generating a nonzero lepton asymmetry, which later gets converted into baryon asymmetry by electroweak sphalerons. While this decay itself is not the source of asymmetry, it transfers part of the asymmetry in the DM sector into the lepton sector. The DM sector asymmetry is generated by the AD mechanism. An AD field that explicitly breaks the lepton number leads to a lepton asymmetry during cosmological evolution, followed by its transfer to the dark sector via decay. The same AD field also gives rise to nonminimal quartic inflation leading to the required inflationary parameters, as constrained by cosmic microwave background (CMB) data [40,41]. The requirement of successful cogenesis not only constrains the model parameters but also predicts a large self-interaction of DM, which can have astrophysical implications [42–44]. Therefore, the minimal setup with only four BSM fields capable of solving several cosmic puzzles remains verifiable in future cosmology and astrophysics, as well as particle-physics-based experiments.

II. THE FRAMEWORK

In order to realize the idea, we consider the four BSM fields as shown in Table I. The scalar field Φ with nonzero

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TABLE I. BSM field content of the model.

Fields	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_L$	Z_2
χ	(1, 1, 0)	1	−1
H_2	(1, 2, −1/2)	0	−1
Φ	(1, 1, 0)	2	1
S	(1, 1, 0)	0	1

lepton number plays the role of the AD field. The Dirac fermion χ, stabilized by a Z_2 symmetry, plays the role of DM. The other two scalars H_2, S assist in transferring the dark sector asymmetry partially to the lepton sector via forbidden decay of DM.

The relevant part of the Lagrangian is given by

$$-\mathcal{L} \supset M_\chi \bar{\chi}\chi + Y_\nu \bar{L}\,\tilde{H}_2 \chi_R + Y_D \overline{\chi^c}\chi \Phi^\dagger + Y_S \overline{\chi_L}\chi_R S + \text{H.c.}, \quad (1)$$

with L being the SM lepton doublet. While these interactions conserve $U(1)_L$, the scalar potential of the AD field explicitly breaks it due to the $\mu^2\Phi^2$ term. The AD field also has nonminimal coupling to gravity $\mathcal{L}_{\rm inf}(\Phi, R) = -\frac{1}{2}(M_P^2 + \xi|\Phi|^2)R$, which reproduces the successful inflationary cosmology [45]. The cosmic evolution of Φ leads to a nonzero lepton asymmetry which then gets transferred to DM sector from $\Phi \to \chi\chi$ decay. The decay products, namely, χ can reheat the Universe instantaneously due to efficient annihilations. The forbidden decay of DM $\chi \to LH_2$ is allowed at high temperatures, leading to partial transfer of dark sector asymmetry into leptons. At the same time, the symmetric part of DM annihilates away leaving only the asymmetric part. At a later epoch, the transfer of DM asymmetry to leptons via decay gets kinematically forbidden, while the transfer via scattering remains negligible throughout due to the suitable choice of parameters. This is summarized in the schematic diagram shown in Fig. 1. As shown in this schematic diagram, successful realization of the idea in this particular setup relies upon the following criteria:

(i) $\chi \to LH_2$ is forbidden below a critical temperature $T_{\rm cr}$. At $T > T_{\rm cr}$, this decay is allowed, transferring the dark asymmetry partially to the lepton sector above sphaleron decoupling temperature.

(ii) If the interaction $Y_\nu \bar{L}\,\tilde{H}_2 \chi_R$ is in equilibrium, then asymmetry can be transferred via scattering too, without relying on finite-temperature effects required for decay. This requires Yukawa coupling Y_ν to be tiny such that asymmetry gets transferred dominantly via decay while keeping the scattering out of equilibrium throughout.

(iii) For $T < T_{\rm cr}$, H_2 can start decaying into χ, L. Since H_2 is complex, it can be asymmetric due to the production from χ at $T > T_{\rm cr}$. In order to ensure that late decay of H_2 does not wash out the lepton asymmetry, $H_2 \leftrightarrow H_2^\dagger$ type of interactions should be efficient at $T \sim T_{\rm cr}$.

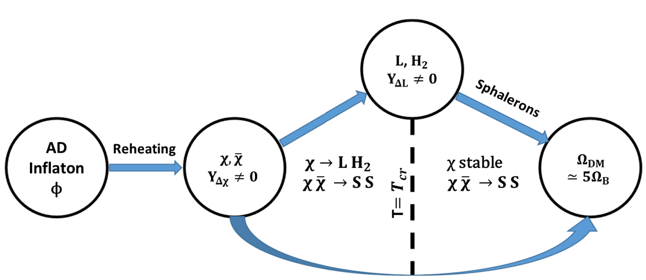

FIG. 1. Schematic timeline of the cogenesis.

III. COGENESIS OF DM AND BARYON

Before proceeding to calculate the abundances of DM and lepton asymmetry, we first find the finite-temperature masses of DM χ, second Higgs doublet H_2, and singlet scalar S, as well as lepton doublet L. The details are shown in Appendix A. The relevant parameters in Eq. (1) are chosen in such a way that the desired mass spectrum of χ, H_2, L at $T > T_{\rm cr}$ as well as $T < T_{\rm cr}$ can be obtained. While a strong coupling of S to DM helps in generating a large thermal mass of χ, a light S can also help in annihilating away the symmetric part of DM via the $\chi\bar{\chi} \to SS$ process, in the spirit of cogenesis. We consider S to be in equilibrium while writing the relevant Boltzmann equations for DM and leptons. The relevant Boltzmann equations for $\chi, \bar{\chi}, L, \bar{L}$ are written in Appendix B.

In the top panel of Fig. 2, we show the variation of the thermal mass of DM $[M_\chi(z)]$ and the sum of the thermal masses of H_2 and the SM lepton doublet, i.e., $M_{H_2}(z) + M_L(z)$ with $z = m_\chi/T$. Here we set $M_\chi(T=0) = m_\chi = 200$ GeV and $M_{H_2}(T=0) = m_{H_2} = 5$ TeV and show the variations for two different values of $Y_S = 2.5$ and 1.0. While $M_{H_2}(z) + M_L(z)$ remains independent of Y_S as expected, a clear dependence of $M_\chi(z)$ can be seen on Y_S. Note that, in order to generate the lepton asymmetry from the DM's forbidden decay, one needs to satisfy the condition $M_\chi(z) > M_{H_2}(z) + M_L(z)$ at some stage in the early Universe. From the top panel of Fig. 2, it is clear that this condition can be satisfied for an appropriate choice of Y_S. We also define a critical value ($z^{\rm cr}$) of z at which $M_\chi(z^{\rm cr}) = M_{H_2}(z^{\rm cr}) + M_L(z^{\rm cr})$ is satisfied. In other words, successful leptogenesis through the forbidden decay of DM can only be achieved in a region where $z < z^{\rm cr}$. For $z > z^{\rm cr}$, the production of lepton asymmetry stops. For $Y_S = 2.5$, $z^{\rm cr} = 0.14$. In this figure, we do not have any critical values of z with $Y_S = 1.0$ as the condition $M_\chi(z) > M_{H_2}(z) + M_L(z)$ is never achieved. Since the sphaleron decoupling occurs around a temperature $T_{\rm sph} \simeq 130$ GeV ($z_{\rm sph}$), any

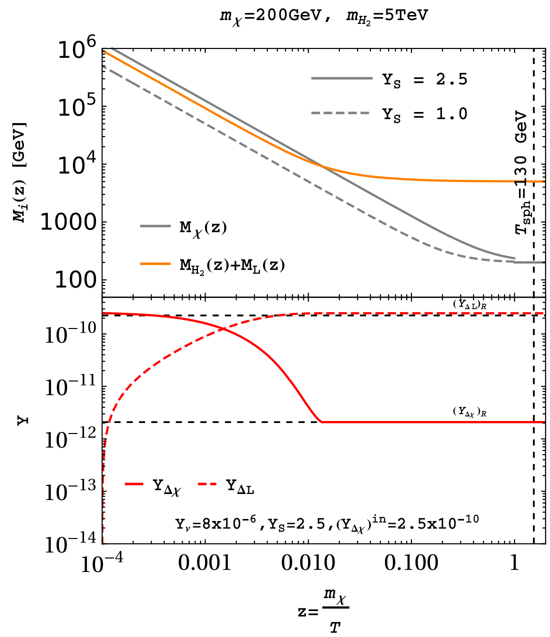

FIG. 2. Top: variation of thermal masses of different particles with $z = \frac{m_\chi}{T}$ for two different values of Y_S. Bottom: evolution of the comoving baryon and DM asymmetries with $z = \frac{m_\chi}{T}$ for a fixed value of initial dark asymmetry $(Y_{\Delta\chi})^{\rm in} = 2.5 \times 10^{-10}$. The vertical dashed line in both the panels corresponds to the sphaleron freeze-out temperature. The horizontal dashed lines in the bottom panel correspond to the required lepton asymmetry $(Y_{\Delta L})_{\rm R}$ and the required dark sector asymmetry $(Y_{\Delta\chi})_{\rm R}$, respectively. For both panels, we choose $m_{H_2} = 5$ TeV, $m_\chi = 200$ GeV.

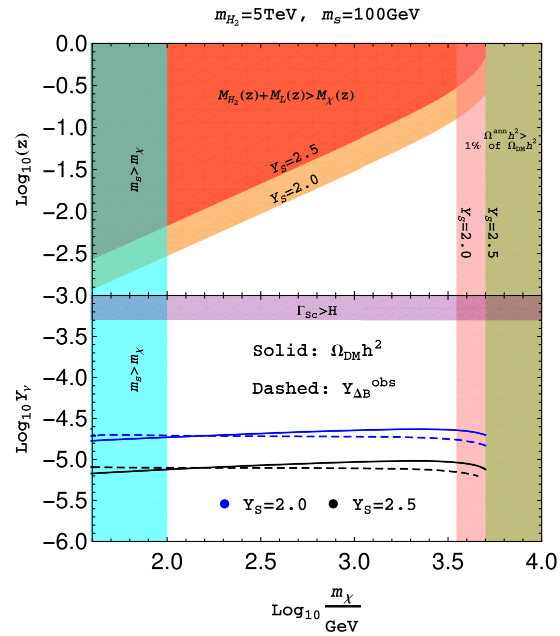

FIG. 3. Top: variation of critical temperature equivalent $z = \frac{m_\chi}{T}$ with DM mass m_χ for two different values of Y_S. Bottom: contours consistent with correct baryon asymmetry and asymmetric DM relic in $Y_\nu - m_\chi$ plane for two different values of Y_S. Rightmost shaded region corresponds to the parameter space where the symmetric component of DM contributes more than 1% of the total DM relic. Leftmost shaded region corresponds to inefficient DM annihilation due to $m_S > m_\chi$. For both panels, we have fixed $m_{H_2} = 5$ TeV, $m_S = 100$ GeV.

lepton asymmetry produced at $z > z_{\rm sph}$ is not converted into the baryon asymmetry.

In the bottom panel of Fig. 2, we show the evolution of the dark sector asymmetry (solid) together with the baryon asymmetry (dotted) with $z = m_\chi/T$ obtained after solving the set of coupled Boltzmann equations involving DM and leptons. The comoving asymmetry for a species x is defined as $Y_{\Delta x} = (n_x - n_{\bar{x}})/s$, with n_x and s being the number density of species x and entropy density of the Universe, respectively. As a result of the decay of the AD field (Φ) to the DM (χ), a lepton asymmetry is generated among the DM particle and its antiparticle. If kinematically allowed, DM can further decay to the H_2, L by virtue of finite-temperature effects, while transferring its asymmetry to the lepton sector, which can be further converted to baryon asymmetry ($Y_{\Delta B}$) via electroweak sphalerons. Here, for the first time, we show that a decay of the DM through its forbidden channel can generate the visible sector asymmetry without affecting its stability condition at the present Universe. We first set the initial asymmetry in the dark matter produced from the decay of the AD field at $Y_{\Delta\chi}^{\rm int} = 2.5 \times 10^{-10}$. As a result of the forbidden DM decay, the dark sector asymmetry is partially transferred to the lepton sector; hence a rise is observed in the yield of lepton asymmetry $Y_{\Delta L}$, whereas an equivalent fall is observed in the dark sector asymmetry. This increasing (decreasing) behavior of $Y_{\Delta L}$ ($Y_{\Delta\chi}$) stops when the threshold $M_\chi(z^{\rm cr}) = M_{H_2}(z^{\rm cr}) + M_L(z^{\rm cr})$ is hit. Thereafter, the asymmetries in both sectors saturate. We find that, for $Y_\nu = 2.5 \times 10^{-6}$, the observed baryon asymmetry of the Universe ($Y_{\Delta B}^{\rm obs} = 8.75 \times 10^{-11}$ [1]) together with observed DM relic abundance ($\Omega_{\rm DM}h^2 = 0.12$ [1]) with DM mass $m_\chi = 200$ GeV can be explained.

In the top panel of Fig. 3, we show a region of parameter space (in white) in the $z - m_\chi$ plane where baryogenesis via leptogenesis can proceed through the forbidden decay of the DM. As observed earlier, a large Y_S is required in order to have a successful leptogenesis through this forbidden channel. Such large values of Y_S also help in the rapid annihilation of DM to get rid of the symmetric part, a requirement in typical asymmetric DM scenarios. While DM has Yukawa interactions with leptons, the corresponding coupling Y_ν is required to be small for reasons discussed below. We show the region of parameter space (in pink and green) corresponding to $\Omega^{\rm ann}h^2 > 1\%$ of $\Omega_{\rm DM}h^2$ in Fig. 3, implying the symmetric part of DM contributing more than 1% of the total DM relic and hence disfavored in the spirit of asymmetric DM.

As expected, due to its rapid annihilation to a lighter scalar (here we have considered $m_s = 100$ GeV) even for satisfying $\Omega^{\rm ann}h^2 > 1\%$ of $\Omega_{\rm DM}h^2$ a heavy DM with $m_\chi \gtrsim 3.5(5)$ TeV is required for the $Y_S = 2.0(2.5)$. The cyan shaded region toward the left is disfavored as $m_S > m_\chi$ will forbid efficient DM annihilation into light scalars at low temperatures. The shaded region in the upper left part denotes the region where DM is always stable. Since DM mass receives a larger thermal correction for larger Y_S, the critical temperature turns out to be smaller (or larger $z^{\rm cr}$), as evident from this plot.

In the bottom panel of Fig. 3, we show the contours satisfying correct baryon asymmetry (dashed line) and asymmetric DM relic (solid line) in $Y_\nu - m_\chi$ plane for two different choices of Y_S. The point at which these two contours intersect corresponds to successful cogenesis. The region corresponding to large Y_ν is disfavored as it will bring scattering processes capable of transferring DM asymmetry to lepton into equilibrium leading to lesser dependence on forbidden decay of DM. It should be noted that the parameter space shown in the above figure satisfies the criteria $T_{\rm cr} > m_{H_2}$, which ensures that H_2 can be in equilibrium at $T = T_{\rm cr}$ with efficient conversions $H_2 \leftrightarrow H_2^\dagger$. Such conversions can occur independent of the parameters relevant for cogenesis and ensure that H_2 decay at $T < T_{\rm cr}$ does not wash out the lepton asymmetry generated at $T > T_{\rm cr}$ from forbidden DM decay. It should also be noted that we have remained agnostic about the origin of light neutrino masses in our setup. The AD field breaks lepton number by $\Delta L = 4$ units due to the $\mu^2\Phi^2$ term. Also, this field does not acquire any vacuum expectation value. Therefore, there is no source of generating Majorana mass of either χ or neutrinos in this minimal setup due to the absence of lepton number violation by $\Delta L = 2$ units. In other words, our setup will work even if we have purely Dirac active neutrinos. On the other hand, the AD field itself can lead to washout of asymmetries and it is preferable to have $m_\Phi > T_{\rm RH}$. We have checked that, for suitable choices of explicit lepton number violation by AD field and its coupling to DM, namely, Y_D, we can satisfy the required initial dark asymmetry while keeping the AD field out of equilibrium after reheating. Ensuring $m_\Phi > T_{\rm RH}$ also keeps the $\Delta L = 4$ washouts like $\chi\chi \to \bar{\chi}\bar{\chi}$ suppressed. The details of dark sector asymmetry and washouts are given in Appendix C.

IV. DETECTION PROSPECTS

There are several promising detection prospects of the model we have proposed here. DM can scatter nucleons due to singlet (S) mixing with the SM Higgs (h) leading to spin-independent DM-nucleon scattering tightly constrained by direct detection experiments like Lux-Zeplin (LZ) [46]. In Fig. 4, we show the current LZ limit and future sensitivity of DARWIN [47] for different choices of

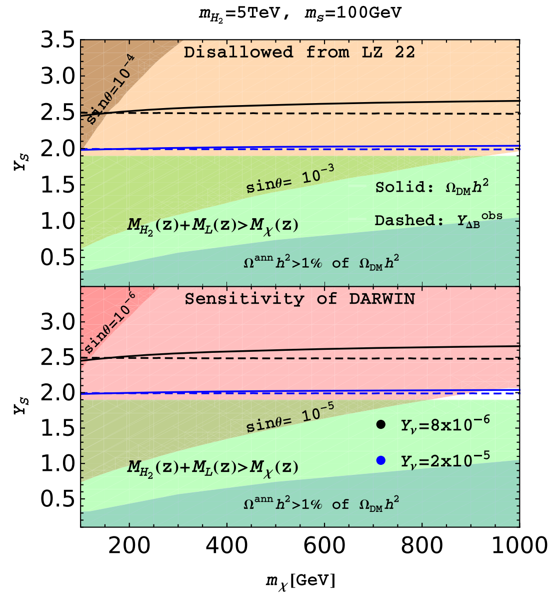

FIG. 4. Contours consistent with correct baryon asymmetry and asymmetric DM relic in $Y_S - m_\chi$ plane for two different values of Y_ν. The shaded region (dark brown and light brown) in upper panel corresponds to the current experimental constraints from DM direct detection experiments LZ 2022 while the dark pink and light pink shaded regions in bottom panel correspond to future sensitivity, for different choices of scalar mixing. The green shaded region shows the parameter space where the DM remains always stable. For both panels, we have fixed $m_{H_2} = 5$ TeV, $m_S = 100$ GeV.

singlet-SM Higgs mixing θ in $Y_S - m_\chi$ plane. The contours for chosen Y_ν indicate the cogenesis preferred parameter space. The green shaded regions corresponding to smaller values of Y_S indicate the parameter space where forbidden DM decay is never allowed. For even smaller values of Y_S, the annihilation of DM is not sufficient enough to keep the symmetric part below 1% of total the DM relic.

The model also has cosmological predictions due to the role of Φ as inflaton via nonminimal coupling (ξ) to gravity. When $\Phi > M_P/\sqrt{\xi}$, it slow rolls and causes inflation, generating the required tensor-to-scalar ratio and scalar spectral index [48–51] consistent with cosmological data from CMB experiments like Planck [40] and BICEP/Keck [41]. For example, with $\xi \gg 1$, we have predictions for inflationary observables, namely, the magnitude of spectral index (n_s) and tensor-to-scalar ratio (r) as $r = 0.003$, $n_s = 0.967$ for number of e-folds $N_e = 60$, which satisfies Planck 2018 data at 1σ level [40].

Because of the strong coupling of DM with the singlet scalar, it is possible to have large self-interactions, having the potential to solve the small scale issues of cold DM like too big to fail, missing satellite, and core-cusp problems faced by the latter [42–44]. For a light mediator, it is possible to have velocity-dependent DM self-interactions in order to solve the small scale issues, while being consistent with standard CDM properties at large scales [52–58]. For $m_S \ll m_\chi$, we can satisfy the required velocity-dependent self-interactions in our setup (similar to [59] where fermion DM with light scalar mediator was studied), which can be probed via astrophysical observations at different scales, such as dwarfs, low surface brightness galaxies, and clusters [56,60].

Collider prospects of the model can be in terms of invisible SM Higgs decay into light scalar S [61] or signatures of heavy Higgs H_2. If produced in the Large Hadron Collider, components of H_2 can lead to same-sign dilepton plus missing energy [62,63], dijet plus missing energy [64], trilepton plus missing energy [65], or even monojet signatures [66,67]. Depending upon hSS coupling, the Higgs invisible decay rate can saturate the current limit [61]. The model can also have complementary detection prospects like gravitational waves (GWs). As discussed in [68,69], the fragmentation of the Affleck-Dine condensate can either generate GWs or amplify primordial GWs bringing it within sensitivities of ongoing and near future experiments.

V. CONCLUSION

We have proposed a novel scenario where baryon asymmetry via leptogenesis occurs due to forbidden decay of dark matter. Dark matter acquires an asymmetry from an Affleck-Dine field which also plays the role of inflaton. Forbidden decay of DM into lepton and a second Higgs doublet, enabled by finite-temperature effects, leads to transfer of some dark sector asymmetry into leptons, with the latter being converted into baryon asymmetry via electroweak sphalerons. The required finite-temperature correction to DM mass can be obtained by virtue of its strong coupling to a singlet scalar. The same singlet scalar can also assist in annihilating away the symmetric component of DM in the spirit of asymmetric DM. While being consistent with correct baryon asymmetry and DM relic, the proposed setup can have a variety of detection prospects in terms of inflationary observables via CMB measurements, DM direct detection, and DM self-interactions via light scalar, as well as collider signatures of new scalars. These complementary detection prospects via cosmology, astrophysics, and laboratory-based observations will keep this framework verifiable in near future.

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APPENDIX A: THERMAL MASSES

In the proposed setup, we have four new fields beyond the standard model, namely, the Affleck-Dine inflaton field Φ, Dirac fermion dark matter χ, an inert Higgs doublet H_2, and a scalar singlet S. The finite-temperature masses of relevant particles involved in forbidden decay are given by [70]

$$M_\chi(T) = \sqrt{m_\chi^2 + \Pi_{S\chi}^2(T)}, \tag{A1}$$

$$M_{H_2}(T) = \sqrt{m_{H_2}^2 + \Pi_{\rm gauge}^2(T)}, \tag{A2}$$

$$M_L(T) = \sqrt{m_L^2 + \frac{1}{2}\Pi_{\rm gauge}^2(T)}, \tag{A3}$$

where

$$\Pi_{S\chi}^2(T) = \frac{Y_S^2}{16}T^2, \tag{A4}$$

$$\Pi_{\rm gauge}^2(T) = \left(\frac{1}{16}g'^2 + \frac{3}{16}g^2\right)T^2. \tag{A5}$$

APPENDIX B: BOLTZMANN EQUATIONS

The relevant Boltzmann equations for generating lepton asymmetry from an initial dark sector asymmetry can be written as follows:

$$\begin{aligned}\frac{dY_\chi}{dz} = &-\frac{s}{\mathbf{H}z}[\langle\sigma v_{\chi\bar\chi\to{\rm SM}}\rangle(Y_\chi Y_{\bar\chi} - Y_\chi^{\rm eq}Y_{\bar\chi}^{\rm eq})]\\ &-\frac{1}{s\mathbf{H}z}\gamma(\chi\to LH_2)\left(\frac{Y_\chi}{Y_\chi^{\rm eq}}-1\right)\\ &+\frac{1}{s\mathbf{H}z}\gamma(H_2\to\chi\bar L),\end{aligned} \tag{B1}$$

$$\begin{aligned}\frac{dY_{\bar\chi}}{dz} = &-\frac{s}{\mathbf{H}z}[\langle\sigma v_{\chi\bar\chi\to{\rm SM}}\rangle(Y_\chi Y_{\bar\chi} - Y_\chi^{\rm eq}Y_{\bar\chi}^{\rm eq})]\\ &-\frac{1}{s\mathbf{H}z}\gamma(\bar\chi\to \bar LH_2)\left(\frac{Y_{\bar\chi}}{Y_{\bar\chi}^{\rm eq}}-1\right)\\ &+\frac{1}{s\mathbf{H}z}\gamma(H_2\to\bar\chi L),\end{aligned} \tag{B2}$$

$$\frac{dY_L}{dz} = \frac{1}{s\mathbf{H}z}\gamma(\chi\to LH_2)\left(\frac{Y_\chi}{Y_\chi^{\rm eq}}-1\right)+\frac{1}{s\mathbf{H}z}\gamma(H_2\to\bar\chi L), \tag{B3}$$

$$\frac{dY_{\bar L}}{dz} = \frac{1}{s\mathbf{H}z}\gamma(\bar\chi\to \bar LH_2)\left(\frac{Y_{\bar\chi}}{Y_{\bar\chi}^{\rm eq}}-1\right)+\frac{1}{s\mathbf{H}z}\gamma(H_2\to\chi\bar L), \tag{B4}$$

where $Y_i = n_i/s$ denotes comoving number density of species "i" with s being the entropy density. Hubble expansion rate is denoted by $\mathbf{H}$, while the variable z is m_χ/T. The reaction density γ is given by

$$\gamma(a \to bc) = n^{\rm eq}\frac{K_1(z)}{K_2(z)}\Gamma(a \to bc), \tag{B5}$$

where $K_{1,2}$ are Bessel functions of the first and second kind, respectively, and the decay widths of $\chi \to L, H_2$ and $\bar{\chi} \to \bar{L}H_2$ are given by

$$\begin{aligned}\Gamma(\chi \to LH_2) &= \Gamma(\bar{\chi} \to \bar{L}H_2)\\ &= \frac{Y_\nu^2}{16\pi}M_\chi\left(1-\frac{(M_{H_2}+M_L)^2}{M_\chi^2}\right)^{1/2}\\ &\quad\times\left(1-\frac{(M_{H_2}-M_L)^2}{M_\chi^2}\right)^{1/2}\\ &\quad\times\left(1-\frac{(M_{H_2}^2-M_L^2)}{M_\chi^2}\right).\end{aligned} \tag{B6}$$

Note that we have treated H_2 and $H_2^\dagger$ on equal footing under the assumption that any asymmetry in H_2 can be washed out due to $H_2 \leftrightarrow H_2^\dagger$ conversions. Because of the possibility of scalar portal interactions with the SM Higgs doublet, such conversions can occur independent of the interactions relevant for the above equations.

Next we define $Y_{\Delta\chi} = Y_\chi - Y_{\bar{\chi}}$ and $Y_{\Delta L} = Y_L - Y_{\bar{L}}$. We choose the following initial condition for solving the above coupled Boltzmann equations:

$$Y_\chi(0) = Y_\chi^{\rm eq}, \qquad Y_{\bar{\chi}}(0) = Y_\chi^{\rm eq} - Y_{\Delta\chi}^{\rm in}, \tag{B7}$$

$$Y_L(0) = Y_L^{\rm eq}, \qquad Y_{\bar{L}}(0) = Y_L^{\rm eq}. \tag{B8}$$

The initial dark sector asymmetry $Y_{\Delta\chi}^{\rm in}$ in the required amount can be generated from the AD field as we discuss in Appendix C.

While we have considered only the decays involving χ, H_2, L in the Boltzmann equations, responsible for transferring the dark sector asymmetry into leptons, it is also possible to have scatterings like $\chi H_2 \to LX$ transferring the asymmetry with X being one of the allowed SM scalar/vector bosons present in the bath. In Fig. 5, we show the comparisons of these decay and scattering rates. While for $T > T_{\rm cr}$, decay dominates over scattering significantly, for $T < T_{\rm cr}$, where decay is forbidden, the scattering rate also remains suppressed. For the chosen values of Y_ν, the scattering remains out of equilibrium throughout, validating the production of lepton asymmetry dominantly from decay.

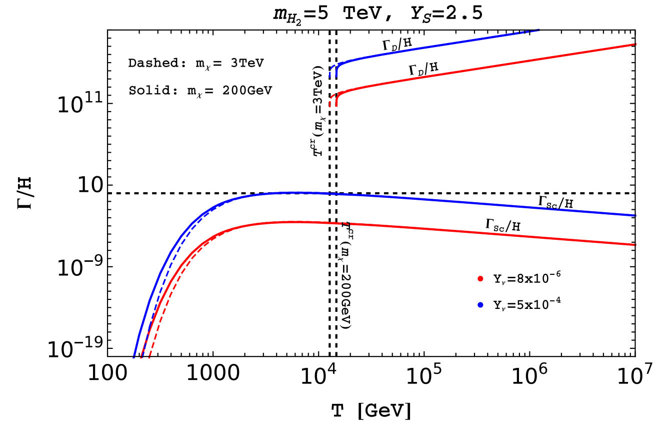

FIG. 5. Comparison of decay and scattering rates responsible for transferring dark sector asymmetry into leptons.

APPENDIX C: DARK ASYMMETRY FROM AFFLECK-DINE FIELD

Since the AD field Φ carries a nonzero lepton number, a term in the scalar potential $\epsilon m_\Phi^2\Phi^2$ breaks the lepton number symmetry explicitly, while all other terms conserve it. Because of this explicit lepton number violating term, the cosmic evolution of Φ leads to a net lepton asymmetry that gets transferred to the dark sector. The same decay of AD inflaton field to dark matter also reheats the Universe to a temperature $T_{\rm RH}$. The asymmetry initially rises from zero and then oscillates until $t \gtrsim 1/\Gamma_\Phi$, when its amplitude exponentially damps to reach the constant value given by [36,71,72]

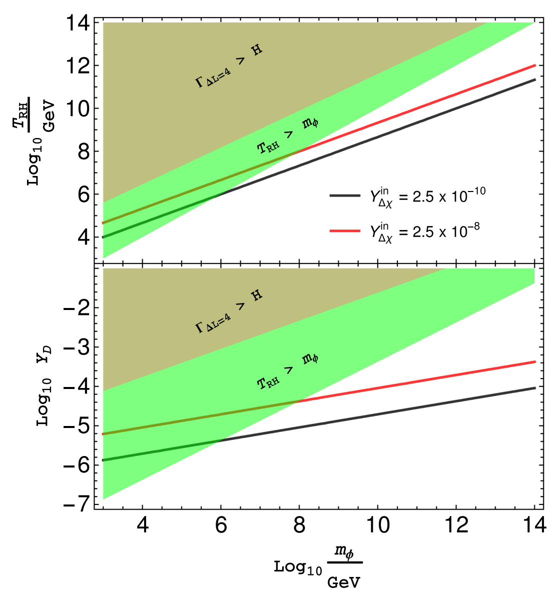

FIG. 6. Contours of $Y_{\Delta\chi}^{\rm in}$ in the $m_\Phi - T_{\rm RH}$ plane (top) and $m_\Phi - Y_D$ plane (bottom). Here, we consider $\epsilon = 1.65 \times 10^{-3}$.

$$Y^{\rm in}_{\Delta\chi} = \frac{(n_\chi - n_{\bar\chi})^{\rm in}}{s} \simeq \frac{T^3_{\rm RH}}{\epsilon m^2_\Phi M_P}. \tag{C1}$$

As the decay $\Phi \to \chi\chi$ also reheats the Universe, the reheating temperature is $T_{\rm RH} \simeq \sqrt{\Gamma_\Phi M_P}$ with Γ_Φ being the corresponding decay width. Now, the presence of the lepton number violating interaction given by ϵ can lead to the washout of the generated asymmetry. This can happen through scatterings with $\Delta L = 4$: $\chi\chi \leftrightarrow \bar\chi\bar\chi$, mediated by Φ exchange and the ϵ term. If the decoupling temperature of such process is higher than the reheat temperature $T_{\rm RH}$, the washout effect would be absent. This leads to the following condition:

$$T^3_{\rm RH} \frac{Y^4_D \epsilon^2 T^2_{\rm RH}}{4\pi m^4_\Phi} \lesssim \sqrt{\frac{\pi^2}{90} g_*} \frac{T^2_{\rm RH}}{M_P}, \tag{C2}$$

where Y_D is the coupling of the AD field to DM. In Fig. 6, we show contours of constant $Y^{\rm in}_{\Delta\chi}$ in the $m_\Phi - T_{\rm RH}$ (top panel) and $m_\Phi - Y_D$ plane (bottom panel). In the green shaded region, $T_{\rm RH} > m_\Phi$, which can lead to a washout of the asymmetry and is hence disfavored. In the brown shaded region, $\Delta L = 4$ scatterings (with interaction rate denoted by $\Gamma_{\Delta L=4}$) of the form $\chi\chi \leftrightarrow \bar\chi\bar\chi$, mediated by Φ exchange, can lead to washout of the asymmetry. This clearly justifies the choice of initial dark asymmetry considered in solving the Boltzmann equations.

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