Making the Universe at 20 MeV

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We present a testable mechanism of low-scale baryogenesis and dark matter production in which neither baryon nor lepton number are violated. Charged $D$ mesons are produced out-of-equilibrium at tens of MeV temperatures. The $D$ mesons quickly undergo CP-violating decays to charged pions, which then decay into dark-sector leptons without violating lepton number. To transfer this lepton asymmetry to the baryon asymmetry, the dark leptons scatter on additional dark-sector states charged under lepton and baryon number. Amusingly, this transfer proceeds without electroweak sphalerons, which are no longer active at such low scales. We present two example models which can achieve this transfer while remaining consistent with current limits. The required amount of CP violation in charged $D$ meson decays, while currently allowed, will be probed by colliders. Additionally, the relevant decays of charged pions to dark-sector leptons have been constrained by the PIENU experiment and will be further explored in upcoming experiments.

I. INTRODUCTION

The standard model of inflationary cosmology predicts a Universe born with equal parts matter and antimatter, necessitating a dynamical mechanism to generate an asymmetry which seeds the complex structures observed today. The required primordial baryon asymmetry of the Universe (BAU) is inferred to be

$$Y_B^{\text{obs}} \equiv (n_B - n_{\bar{B}})/s = (8.718 \pm 0.004) \times 10^{-11},$$

from measurements of the Cosmic Microwave Background (CMB) [1, 2] and light element abundances after Big Bang Nucleosynthesis (BBN) [3, 4]. Discovering baryogenesis, the mechanism responsible for generating this asymmetry, is therefore critical to understanding our very existence.

A mechanism of baryogenesis must satisfy the three Sakharov conditions [5]: C and CP Violation (CPV), baryon number violation, and departure from thermal equilibrium. Many mechanisms of baryogenesis have been proposed, including the perennial favorites: electroweak baryogenesis [6–16] and leptogenesis [17]. But, concrete realizations of these mechanisms encounter significant challenges. Electroweak baryogenesis models often predict electric dipole moments of electrons, neutrinos, and atoms which are ruled out by experiments [18]. On the other hand, leptogenesis models typically occur at high scales and involve very massive particles, thereby making experimental confirmation unlikely [19]. Therefore, exploring novel baryogenesis mechanisms is well motivated, especially if they address other outstanding mysteries of the Standard Model of particle physics (SM) and are discoverable in the near-future.

While the mechanism of baryogenesis is necessary to explain the origin of the complex visible structures we observe today, such structures only constitute roughly 5% of the energy budget of the Universe. The SM does not explain the nature and origin of dark matter (DM), the gravitationally inferred component of matter which makes up roughly 26% of the energy of the Universe [1, 2]. Experimental searches for DM at colliders and direct detection experiments, together with studies of the possible indirect effects of DM in astrophysical observations, have yet to shed light on its nature.

Many particle physics models have been proposed to explain the nature and origin of DM. However, with the simplest scenarios becoming ever more constrained, richer dark or hidden sectors containing multiple particles with new interactions and symmetries become more interesting. Such dark sectors open up a host of new reconstructable cosmological histories [20–22], which may be tested by colliders [23–25], direct detection and neutrino experiments [26–31], and indirect searches [32–34]. Moreover, an interesting subset of those models also explain the BAU. For instance, in many models of Asymmetric Dark Matter [35–38], DM carries a conserved charge whose asymmetry is tied to the BAU in a unified framework that explains both asymmetries (e.g., [39], and references therein).

In this work, we explore a novel scenario where a dark-sector state is charged under lepton number. Assuming late-time production at temperatures of order 20 MeV, mesons which undergo CP-violating decays may then

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See [40] for an interesting proposal.

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While a rich dark sector may seem less compelling due to its complexity, it is a well motivated scenario from a top-down perspective. Furthermore, the SM displays significant richness, present authors included, despite its meager contribution to the energy budget of the Universe. It would not be too surprising to discover a dark sector with similar complexity.
FIG. 1. Summary of the mechanism by which a lepton asymmetry is produced from late-time production of charged $D^{\pm}$ mesons. Here we consider CP-violating decays of the $D^{\pm}$ mesons into final states involving an odd number of charged pions. The charged pions decay into dark- and visible-sector leptons without violating lepton number, producing equal and opposite visible- and dark-sector asymmetries.

subsequently have their decay products quickly undergo lepton-number-conserving decays into dark leptons. In this way, an equal and opposite lepton asymmetry is generated between the visible and dark sectors. In particular, CP violation in charged $D^{\pm}$ meson decays followed by prompt decays of charged pions to light, MeV-GeV scale (dark) leptons may be used to generate such an asymmetry. Intriguingly, this asymmetry is directly linked to SM observables, making this mechanism testable at current and upcoming experiments (see Fig. 1 for a summary).

While a late-time production of a lepton asymmetry may be interesting in its own right, to explain the BAU, the lepton asymmetry must generate a baryon asymmetry. We achieve this by minimally extending the dark sector to include low-scale, dark scattering processes which produce an equal and opposite baryon asymmetry in the dark and visible sectors using the initial lepton asymmetry. The SM baryon asymmetry is Frozen-In via these dark-sector scatterings. In summary, we present here a novel, testable, mechanism of low-scale baryogenesis and DM production utilizing SM $D^{\pm}$ meson decays at late times, effectively making the Universe as we know it at 20 MeV. In contrast with previous mechanisms such as high-scale leptogenesis, this does not involve lepton- or baryon-number violation and does not require Electroweak sphalerons.

One of the most remarkable features of this model is the ability to achieve baryogenesis, as well as the production of DM, at such low temperatures. Reasonable assumptions may lead one to conclude that a baryogenesis mechanism, regardless of the source of CP violation, must set the asymmetry by $T \gtrsim 38$ MeV. Thus, constructing models of low-scale baryogenesis can be a challenge and there are only a few working examples (see e.g. [44, 45]). Furthermore, recent proposals for solutions to the gauge hierarchy problem such as $N$-naturalness and cosmological relaxation require the BAU to be generated at a low scale.

If one holds out hope that the requisite CP violation for baryogenesis exists in the SM, one is also inevitably led to consider mechanisms at such low scales. It is often claimed that there is not enough CP violation within the SM alone to provide for the baryon asymmetry, regardless of the baryogenesis mechanism. However, there are potentially abundant and untapped sources of CP violation in QCD resonances: meson oscillations and meson decays, as in this work. Thus, there’s a relatively unexplored swath of theory space in which the SM alone provides the necessary CP violation via mesons, allowing for different realizations of Mesogenesis.

This paper is organized as follows. First in Sec. II, we introduce the mechanism. Next in Sec. III, we present the details by which baryogenesis is achieved; we solve a set of Boltzmann equations for the lepton and baryon asymmetry and demonstrate that the BAU can be achieved in light of known limits on the CP violation and branching fractions of $D^{\pm}$ mesons. We also discuss the way in which the correct DM relic abundance can be achieved. Next in Sec. IV, we present two models and demonstrate that they can accommodate a sizeable dark-sector scattering to produce the BAU. We conclude with a discussion of possible extensions, additional variations of Mesogenesis, and other future directions in Sec. V. App. A contains a detailed derivation of the Boltzmann Equations. In App. B, we tabulate the relevant $D^{\pm}$ decay modes and the current limits on their branching fractions and CP asymmetries.

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3 For other models which transfer an asymmetry from the dark sector to the SM to realize baryogenesis, see e.g. [40–42].
II. THE MECHANISM

We now introduce the mechanism of baryogenesis and DM from $D^\pm$ mesons. First, we assume the late decay of an inflaton-like scalar field $\Phi$ into quarks and anti-quarks when the temperature of the Universe was roughly tens of MeV. In particular, we assume the decay occurs at temperatures in the range $T_{\text{BBN}} \lesssim T_R \lesssim T_{\text{QCD}}$, so that the produced quarks hadronize but do not spoil the predictions of BBN. $T_R$ is the “reheat temperature” corresponding to the time at which $\Phi$ decays. Such a field $\Phi$ may arise naturally out of multi-field inflation models, as well as relevant branching ratios introduced later.

The produced quarks and anti-quarks hadronize into an equal number of mesons and anti-mesons. By adjusting the mass and decay width of $\Phi$, we consider scenarios in which $D^\pm$ mesons (with mass of 1.87 GeV) are produced out of equilibrium. Thus, the temperature must be low enough so that $D^\pm$ decay before annihilating with other species. The $D$-meson lifetime is $\tau_D = 1.5 \times 10^8 \text{MeV}^{-1}$ [4], while the typical cross section for hadrons is determined by the pion mass $m_\pi = 135 \text{MeV}/c^2 \sim O(10 \text{nb})$. Following the argument in [18], we find an upper bound on the reheat temperature such that the $D^\pm$ mesons decay before annihilating:

$$3.5 \text{MeV} \lesssim T_R \lesssim 20 \text{MeV}. \quad (2)$$

The lower bound of 3.5 MeV comes from the requirement that the asymmetry generation completes before SM neutrino decoupling and we restrict our reheat temperatures to this range [50–52].

The $D^\pm$ mesons then undergo CP-violating decays into an odd number of charged pions. Since these decays occur out of equilibrium, an asymmetry in charged pions is temporarly generated. These charged pions themselves quickly decay into a lighter, dark-sector Dirac fermion $\ell_d$ which carries visible sector lepton number ($L = +1$). Since annihilations of pions are subdominant to their decays for the range of temperatures in Eq. (2), these fast pion decays are able to happen before any appreciable washout of the temporary pion asymmetry. By introducing this new, dark-sector decay channel for pions, an asymmetry can start to form between the dark and visible sectors. Without it, the generated charged pion asymmetry would wash out.

We consider decays of charged pions into dark and SM leptons that proceed through an effective operator of the form

$$\mathcal{O} = \frac{1}{16\pi^2} \left[ d\Gamma^\mu u \right] \left[ \ell_d \Gamma^\nu \ell \right] + \text{h.c.}, \quad (3)$$

where $\ell$ is a SM charged lepton and $\Gamma^\mu$ represents all possible distinct Lorentz tensors. The UV model from which the operator in Eq. (3) arises depends on the Lorentz structure. For instance, a scalar operator could arise from a charged scalar mediator similar to [53], while a vector operator could arise from a new vector of a left-right symmetric model e.g. [27]. Depending on the UV model, to be consistent with current constraints, the scale $\Lambda$ could be anywhere from hundreds of GeV to a few TeV.

The result of the fast decays,

$$\pi^+ \to \ell_d + \ell^+, \quad m_{\ell_d} < m_{\pi^+} - m_{\ell}, \quad (4)$$

along with the conjugate decays, is the generation of a lepton asymmetry in the dark sector

$$Y_{\ell_d} \equiv \left( \frac{n_{\ell_d} - n_{\bar{\ell}_d}}{s} \right), \quad (5)$$

which is equal and opposite to a lepton asymmetry created in the visible sector. Throughout this work, we use the common co-moving yield variables $Y$ defined as the ratio of the number density to the entropy density in the SM bath. In the absence of any other lepton-charged, dark-sector states, $Y_{\ell_d} = Y_{\ell_d}^{\text{dark}}$, the total lepton asymmetry in the dark sector. But, in later sections, we introduce additional dark-sector leptons in order to generate the baryon asymmetry, resulting in $Y_{\ell_d} \lesssim Y_{\ell_d}^{\text{dark}}$.

Regardless, since we never introduce lepton-violating interactions, the following is always true:

$$Y_{\ell_d}^{\text{dark}} = -Y_{\ell_d}^{\text{SM}}. \quad (6)$$

In this way, lepton asymmetries are generated in both the dark and visible sectors while conserving the total lepton number of the Universe.

The generated lepton asymmetry is directly related to SM observables,

$$Y_{\ell_d}^{\text{SM}} \propto \text{Br}_{\pi}^{\ell_d} \sum_f A_{CP}^{f} \text{Br}_{D^+}^{f}, \quad (7)$$

where $\text{Br}_{\pi}^{\ell_d} \equiv \text{Br} (\pi^+ \to \ell_d + \ell^+)$, the sum is over final states $f$ which contain an odd number of $\pi^\pm$, and $A_{CP}^{f}$ is the CP violation observable for a given decay mode, defined by

$$A_{CP}^{f} = \frac{\Gamma(D^+ \to f) - \Gamma(D^- \to \bar{f})}{\Gamma(D^+ \to f) + \Gamma(D^- \to \bar{f})}. \quad (8)$$

$\text{Br}_{D^+}^{f} \equiv \text{Br} (D^+ \to f)$ is the branching fraction of the $D^+$ decay (the relevant decay modes and the current limits on their branching fractions and CPV are summarized in Table. III). The current limits on $\text{Br}_{D^+}^{f}$ may be extracted

\[\text{In much of the parameter space that results in the measured baryon asymmetry, the dark lepton asymmetry is much greater and } Y_{\ell_d} \approx Y_{\ell_d}^{\text{dark}} \text{ even after baryogenesis completes.}\]

\[\text{This mechanism does not require lepton number violation. But the presence of lepton violation, for instance in neutrino masses, will not spoil this mechanism.}\]
from the limits on sterile neutrinos. Recasting and imposing current limits for charged pion decays into electrons [54, 55], we find that the allowed branching ratio is not large enough to generate the requisite asymmetry when \( m_{\ell_d} > 1 \text{ MeV} \). However, the branching ratio is unconstrained for sub-MeV \( \ell_d \) masses so that this decay mode can create the entire asymmetry. Recasting the most current bound from PIENU [55, 56] for final-state muons yields

\[
\begin{align*}
\text{Br}(\pi^\pm \to \mu^\pm + \text{MET}) &\lesssim 10^{-6} - 10^{-5}, \\
\text{for } 15.7 \text{ MeV} &< m_{\ell_d} < 33.8 \text{ MeV}, \\
\end{align*}
\]

(9)

which is just at the threshold of producing enough asymmetry. For lighter \( \ell_d \) masses, constraints can be recast from PSI [55, 57]

\[
\begin{align*}
\text{Br}(\pi^\pm \to \mu^\pm + \text{MET}) &\lesssim 10^{-3}, \\
\text{for } 5 \text{ MeV} &< m_{\ell_d} < 15 \text{ MeV}. \\
\end{align*}
\]

(10)

Note that for \( \sim 1-5 \text{ MeV} \), the bound on the branching fraction can be as weak as \( 10^{-2} \). Given the \( \ell_d \) mass dependence, these bounds do not constrain the entire parameter space of interest to us; as with decays to final-state electrons, sub-MeV \( \ell_d \) masses lead to completely unconstrained branching ratios.

Improved measurements of these decays will be the focus of upcoming searches at future experiments and as such will be able to further probe this mechanism [58]. In what follows, we will demonstrate that a large lepton asymmetry may be generated which is consistent with current experimental bounds and may be probed in the future.

Baryogenesis is achieved by transferring\(^6\) the dark lepton asymmetry into a SM baryon asymmetry using additional dark-sector states and dynamics which can be rich and possibly reconstructable. In particular, we consider \( \ell_d \) interactions with additional dark-sector states (\( \chi_1 \) and \( \chi_2 \)) that carry lepton- and baryon-number which can transfer the dark lepton asymmetry into a SM baryon asymmetry. Critically, this dark scattering can occur through an operator which conserves the total baryon and lepton number of the Universe: a dark-sector lepton asymmetry is partially transferred to equal and opposite dark- and visible-sector baryon asymmetries. Schematically, we consider scatterings of the form

\[
\tilde{\ell}_d + \chi_1 \to \chi_2 + B,
\]

(11)

where \( B \) is a SM baryon, and \( \chi_1 \) and \( \chi_2 \) are the gauge-singlet, dark-sector states which may be fermions or scalars depending on the exact dark-sector model. For possible baryon and lepton number charge assignments, see Table I. Note that the mass of a dark-sector state charged under baryon number must be greater than 1.2 GeV [59], but dark leptons may be considerably lighter. Additional kinematic and stability requirements will be model dependent, and we leave these details for Sec. IV.

Depending on the details of the dark-sector charge assignment and the UV model, either \( \chi_1 \) or \( \chi_2 \) (or both) may constitute (part of) DM. A \( \mathbb{Z}_2 \) discrete symmetry will generically need to be imposed to stabilize the DM and evade washing out the produced asymmetry. In Sec. IV we describe the cosmological assumptions and possible models of the dark sector that allow for a large enough cross section to transfer the asymmetry consistent with current limits as well as produce the measured DM relic abundance.

### III. THE DETAILS

Having given a broad-brush overview of the important ingredients of this mechanism in the previous section, we move on to calculate the relevant matter contents in detail. We consider the generation of the (dark-sector) lepton asymmetry, (visible-sector) baryon asymmetry, and DM in turn.

#### A. Generating a Lepton Asymmetry

In this section, we demonstrate that a dark lepton asymmetry equal to (or much greater than) the measured baryon asymmetry may be generated via the processes outlined in Fig. 1 postponing a discussion of how it may be transferred to a SM baryon asymmetry to Sec. III B.

In order to numerically solve for the generated lepton asymmetry, we consider the coupled Boltzmann equations which track the production and CP-violating decays of \( D^\pm \) mesons into \( \pi^\pm \), which then subsequently decay into dark leptons and anti-leptons. For simplicity, we compute the generated lepton asymmetry for the range of reheat temperatures in Eq. (2) so that annihilations of \( D^\pm \) and \( \pi^\pm \) mesons can be ignored. The reheat temperature is defined by \( 4H(T_R) = \Gamma_\Phi \) so that Eq. (2) corresponds to an inflaton decay width in the range \( \Gamma_\Phi \in [1 \times 10^{-22} \text{ GeV}, 3 \times 10^{-21} \text{ GeV}] \). Additionally, as the inflaton must be heavy enough to produce \( D^\pm \), its mass must be in the range \( m_\Phi \in [5 \text{ GeV}, 100 \text{ GeV}] \). \( \Phi \) late decays to radiation so that the evolution of the \( \Phi \) number density and the radiation density are governed by the interplay of the following Boltzmann equations

\[
\begin{align*}
\frac{d\rho_{\Phi}}{dt} + 3H\rho_{\Phi} &= -\Gamma_\Phi n_\Phi, \\
\frac{dn_{\Phi}}{dt} + 3Hn_{\Phi} &= -\Gamma_\Phi n_\Phi, \\
\frac{d\rho_{\text{rad}}}{dt} + 4H\rho_{\text{rad}} &= +\Gamma_\Phi m_\Phi n_\Phi, \\
\end{align*}
\]

(12)

(13)
where the Hubble parameter is given by
\[ H^2 = \frac{8\pi}{3M_{Pl}^2} (\rho_{rad} + m_\Phi n_\Phi). \] (14)

We assume that $\Phi$ was in equilibrium at some high temperature with the bath and as such has a number density $\propto T^3$. While it may be possible to achieve this mechanism in an inflationary model where $\Phi$ is identified as the inflaton, this assumption of high-temperature equilibrium simplifies this analysis at the cost of presuming other scalars responsible for inflation.

Since the focus in this section is on the lepton asymmetry, we assume a minimal dark sector with only $\ell_d$ and $\bar{\ell}_d$ and do not include any additional dark-sector states or interactions, deferring this discussion to Sec. III B. Since the formation and subsequent decay of the $D^\pm$ meson and the following decay of the $\pi^\pm$ meson occurs quickly (before any scattering effects can significantly change the abundance of these mesons), the generated dark-sector lepton asymmetry can be written simply as (for a detailed derivation, see App. [A])
\[ \frac{d}{dt}(n_{\ell_d} - n_{\bar{\ell}_d}) + 3H(n_{\ell_d} - n_{\bar{\ell}_d}) = 2\Gamma_\Phi^f n_\Phi Br_\pi^f \sum_f N_f a_{CP}^f Br_{D^+_f}, \] (15)

where $N_f^f$ is the number of $\pi^\pm$ minus the number of $\pi^-$ in each channel labeled by $f$. Note that only decay modes with an odd number of charged pions contribute, as expected. Here we define $\Gamma_\Phi^f \equiv \Gamma_\Phi (\Phi \to c) Br(c \to D)$ (where we account for the possibility that $\Phi$ can also populate dark-sector states). Also, $a_{CP}^f \equiv A_{CP}^f / (1 + A_{CP}^f) \approx A_{CP}^f$ for most decay channels since $A_{CP}^f$ is a small number. The sum is over the exclusive rates to each of the final states $f$ listed in Table III. In this way, an asymmetry in $\ell_d \bar{\ell}_d$ is generated, as defined in Eq. (15), that is equal and opposite to an asymmetry generated in the visible-sector leptons. This asymmetry is interestingly related to observable CP-asymmetries and branching fractions in SM mesons systems. Critically, note again that the total lepton number of the Universe is actually conserved, as we have not introduced any lepton-number-violating interactions.

We numerically integrate the above set of Boltzmann equations and float the values of $\sum_f N_f^f a_{CP}^f Br_{D^+_f}$, $Br_\pi^f$, $T_R$, and $m_\Phi$ to discover the parameter space in which a sizable lepton asymmetry may be generated. We find
\[ \frac{Y_L^{\text{dark}}}{Y_B^{\text{obs}}} \simeq \frac{Br_\pi^f}{6 \times 10^{-5}} \sum_f N_f^f a_{CP}^f Br_{D^+_f} \frac{T_R}{20 \text{ MeV}} \frac{10 \text{ GeV}}{m_\Phi}. \] (16)

If all the lepton asymmetry can be instantaneously converted into a baryon asymmetry, then the SM baryon asymmetry will be $Y_B^{\text{SM}} = Y_L^{\text{dark}}$. In practice, the dark-sector dynamics need not transfer the asymmetry completely. Therefore, Eq. (16) represents a lower bound on the observables such that baryogenesis can be achieved. In Fig. 2, we show contours of $Y_L^{\text{dark}}/Y_B^{\text{obs}}$ for a range of values of the experimental observables $Br_\pi^f$ and $\sum_f N_f^f a_{CP}^f Br_{D^+_f}$. Also shown for reference is the PSI constraint from Eq. (10) which holds when 5 MeV $\lesssim m_\ell \lesssim 15$ MeV.

Summing over the relevant $D^\pm$ decay modes in Table III we find
\[ \sum_f N_f^f a_{CP}^f Br_{D^+_f} = (-9.3 \times 10^{-4})^{+0.0031}_{-0.0039}, \] (17)

where the central value corresponds to taking the central values of both $A_{CP}^f$ and $Br_{D^+_f}$ for each decay channel. The lower bound corresponds to the “lowest-reasonable” value for the sum and is calculated in the following way. To make the sum as negative as possible, we take all $A_{CP}^f$ values $1\sigma$ below their mean. For channels with values of $A_{CP}^f$ which are still positive, we assume their corresponding $Br_{D^+_f}$ is $1\sigma$ below the mean. For channels which instead (now) have negative $A_{CP}^f$, we assume their corresponding $Br_{D^+_f}$ is $1\sigma$ above the mean. The upper bound in Eq. (17) is calculated in an analogous way. The measured central value is shown in dashed black in Fig. 2.
while the solid gray region corresponds to the (absolute value) of the most negative possible sum. Comparing Eq. (17) to Eq. (16), it is clear that it is possible to generate a dark-sector lepton asymmetry that is orders of magnitude larger than the measured baryon asymmetry.

Future, more precise measurements of $A_{CP}^{f}$ and $Br_{D^+}^f$ for the various pion decay channels in Table 1 will shift the gray, ruled-out region to the left. Such improvements are expected to be made by experiments such as LHCb. While $A_{CP}^{f}$ are expected to be small in the SM, quantifying them is plagued with the usual technical challenges of the charm sector. If better SM predictions result in $A_{CP}^{f}$ which are smaller than we require for this mechanism, new physics contributions could also enhance $A_{CP}^{f}$ while keeping them within current experimental bounds.

The PIENU experiment has accessed the majority of its data, and as such, an improvement in the sensitivity of $Br_{CP}^{f}$ is unlikely. However, the relevant mass range could be extended as uncertainties are improved which previously made certain areas of phase space difficult to probe. Additionally, next-generation experiments which would improve the limit on the branching fraction are being proposed [55]. Note that for a given UV model generating Eq. (3), the branching ratio $Br_{CP}^{f}$ can be computed and will depend on the scale of the higher-dimensional operator $\Lambda$. This in turn will be constrained by collider and astrophysical searches in a model-dependent way.

For a charged scalar mediator model, we find that different constraints on the scale $\Lambda$ do not exclude any of the parameter space of Fig. 2.

### B. Generating a Baryon Asymmetry

We now complete baryogenesis by elucidating the details by which equal and opposite baryon asymmetries in the dark and visible sectors are frozen-in. We remain agnostic about the dark-sector model which generates the scattering process in Eq. (11), deferring a detailed discussion to Sec. IV. Instead, we compute how large the cross section must be for the process in Eq. (11) to efficiently transfer the dark lepton asymmetry to the measured baryon asymmetry of the Universe.

For simplicity, we take $\Phi$ to also decay to $\chi_1$ and therefore require $m_{\chi_1} < m_{\Phi}$, though another scalar could instead be responsible for this late-time, out-of-equilibrium $\chi_1$ production. The number density of $\chi_1$ therefore evolves according to

$$\frac{dn_{\chi_1}}{dt} + 3Hn_{\chi_1} = \Gamma_{\phi} n_{\Phi} Br(\Phi \rightarrow \chi_1\bar{\chi}_1) - \langle \sigma v \rangle n_{\ell_d} n_{\chi_1},$$

where $\langle \sigma v \rangle$ is the thermally averaged cross section of the baryon-transfer process in Eq. (11). Detailed derivations of all of the Boltzmann equations in this section may be found in App. A.

Recall that the evolution of the asymmetry in $\ell_d$ in Eq. (15) simply tracked the production of a lepton asymmetry. We modify this equation to include the relevant scattering term and obtain the evolution equation for the asymmetry in $\ell_d$:

$$\frac{d}{dt} (n_{\ell_d} - n_{\ell_d}^f) + 3H (n_{\ell_d} - n_{\ell_d}^f) =$$

$$2\Gamma_{\phi}^D n_{\Phi} Br_{D^+}^f \sum_f N_{f} a_{CP}^f Br_{D^+}^f - \langle \sigma v \rangle n_{\chi_1} (n_{\ell_d} - n_{\ell_d}^f).$$

For simplicity, we take $n_{\chi_1} \sim n_{\bar{\chi}_1}$ here as both are initially produced in equal amounts from $\Phi$ decays. The

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While it is technically correct that this is a thermally averaged cross section, the phase space distribution functions will not be the usual thermal Maxwell-Boltzmann distributions. Rather, they are determined by the kinematics of the relevant decays and Hubble expansion.
Boltzmann equation for the evolution of the SM baryon asymmetry is then given by

\[
\frac{d}{dt}(n_B - n_{\bar{B}}) + 3H(n_B - n_{\bar{B}}) = -\langle \sigma v \rangle n_{\chi_1}(n_{\ell_d} - n_{\bar{\ell}_d}).
\]  

(20)

Next, we turn our attention to numerically solving the set of coupled Boltzmann equations for the baryon asymmetry of the Universe.

From Eq. (20), it is clear that the produced lepton asymmetry will be efficiently transferred when the scattering rate \( n_{\chi_1} \langle \sigma v \rangle \) dominates over the Hubble expansion. Since we want the transfer to happen quickly, we require the cross section satisfy

\[
\frac{n_{\chi_1} \langle \sigma v \rangle}{H(T)} \left| _{T = T_R} \right. \gtrsim \frac{Y_{\text{obs}}}{Y_L^\text{dark}}.
\]  

(21)

The number density of \( \chi_1 \) is found by integrating Eq. (18) and is roughly given by \( n_{\chi_1} \sim \text{Br}(\Phi \to \chi_1 \chi_1) T^3 \). We numerically integrate the Boltzmann equations Eqs. (12), (18), (19), (20) to solve for lepton and baryon asymmetries, floating the model parameters. We find that the dark scattering cross section is required to be greater than

\[
\langle \sigma v \rangle \gtrsim 10^{-16} \text{GeV}^{-2} \frac{Y_B^{\text{obs}}}{Y_L^\text{dark}} \times \frac{10 \text{ GeV}}{m_\Phi} \frac{20 \text{ MeV}}{T_R} \frac{10^{-1}}{\text{Br}(\Phi \to \chi_1 \chi_1)}.
\]  

(22)

In Fig. 3 we plot the solution of the Boltzmann equations for a benchmark point that achieves baryogenesis. We plot the yields corresponding to \( \Phi \) abundance, \( \ell_d \) asymmetry, and SM baryon asymmetry. There are three clearly distinct regions in the plot, particularly emphasized by the top panel which zooms in on \( Y_\ell \). First, a dark lepton asymmetry is produced as the inflaton begins to decay. Soon after, \( \ell_d \chi_1 \) scatterings begin to dominate and the \( \ell_d \) asymmetry converges to a baryon asymmetry. As inflaton decay completes, the baryon asymmetry freezes in and the \( \ell_d \) asymmetry is fixed.

In the following section, we will present possible UV models that can accommodate a cross section of the size in Eq. (22) while remaining consistent with present constraints. Note that the branching fraction of the inflaton into the dark sector \( \text{Br}(\Phi \to \chi_1 \chi_1) \) depends on the specific inflationary model, but can be sizable. Furthermore, \( \langle \sigma v \rangle n_B \) and \( \langle \sigma v \rangle n_{\chi_2} \) are easily both less than Hubble as these particles are not sourced by \( \Phi \). Therefore, any possible washout effects are negligible.

C. Generating the Dark Matter

Since baryon number is never violated, the measured SM baryon asymmetry is always balanced by an equal and opposite baryon asymmetry in the dark sector. This dark baryon asymmetry, therefore, is always an asymmetric component of DM, and a substantial fraction at that due to the lower bound on baryon-charged masses of 1.2 GeV. Further, there are equal and opposite lepton asymmetries in the dark and visible sectors. If the state(s) which comprise the dark-sector baryons due not also account for this dark-sector lepton asymmetry, then these additional dark leptons must make up a different, asymmetric subcomponent of DM. Clearly, the details depend on baryon- and lepton- number assignments to states \( \chi_1 \) and \( \chi_2 \), which we defer to the next section. Here, we just make simple qualitative remarks about how generating the correct DM abundance is relatively straightforward (as compared to generating the baryon asymmetry).

Perhaps the simplest scenario is to assume that the dark baryon-charged state comprises almost the entirety of DM, making it a well motivated case of completely asymmetric DM. In this case, the lightest dark lepton is appreciably lighter than the dark baryon so that it makes up a negligible subcomponent of DM. Thus, \( m_{\text{DM}} \sim 5 \text{ GeV} \).

As an alternative, we may also consider the case where the dark baryon state is lighter so that the other dark-sector particles must comprise the remaining relic abundance of DM. These could be new additional states, or just the dark-sector states already present to provide for the baryon-asymmetry transfer. The details here become less relevant to the baryogenesis mechanism considered since there are generic, dark-sector freeze-out possibilities with viable parameter space.

Both of the above scenarios make one important assumption which we require to be true generically. There must exist a portal between the dark and visible sectors that becomes efficient at late times (before SM neutrino decoupling) to allow the symmetric component(s) of dark-sector states to sufficiently annihilate away, preventing any overabundance of DM or non-negligible contribution to the relativistic degrees of freedom at BBN. The kinetic mixing portal involving a massive dark photon fits our needs here and is a commonly used portal to transfer entropy out of dark sectors at late times (see e.g. [39, 60, 61] for various such usages).

One additional concern is that protons and anti-protons may not be able to efficiently annihilate below 20 MeV\(^8\), so that a large, symmetric baryon component may freeze-in. One solution is to introduce other dark-sector processes which can efficiently deplete the symmetric component of \( \ell_d \) and \( \bar{\ell}_d \). As a proof of principle, one can imagine the extreme limit where such processes deplete all \( \ell_d \) and leave only the tiny necessary asymmetric amount of \( \bar{\ell}_d \). These would then only freeze-in SM baryons and not anti-baryons, avoiding the problem altogether.

\(^8\) We thank Seyda Ipek for pointing this out.
IV. THE MODELS

Thus far, we have remained agnostic about the nature of the dark-sector fields participating in the baryongenerating process in Eq. (11). The baryon asymmetry has been computed independently of the details of the dark-sector model and we have found that the dark lepton asymmetry can be efficiently transferred to a SM baryon or lepton number. In this case, DM is a single component of DM.

There are several minimal variations of the dark-sector field content which will suffice. The states $\chi_1$ and $\chi_2$ may be identified with a dark baryon and dark lepton as summarized on the left side of Table I. Alternatively, one state can be neutral and the other a dark lepton while the other uncharged under SM lepton and baryon number. In this case, the leptobaryon can be the single component of DM.

| Field | L | B | Field | L | B |
|-------|---|---|-------|---|---|
| $\chi_1$ | 1 | 0 | $\chi_1$ | 1 | 1 |
| $\chi_2$ | 0 | -1 | $\chi_2$ | 0 | 0 |
| $\chi_1$ | 0 | 1 | $\chi_1$ | 0 | 0 |
| $\chi_2$ | 1 | 0 | $\chi_2$ | -1 | -1 |

TABLE I. Possible baryon and lepton charge assignments for dark-sector states $\chi_1$ and $\chi_2$. Any baryon-charged state must be heavier than 1.2 GeV. (Left) The two states dark $\chi_2$ and $\chi_1$ involved in the scattering Eq. (11) may be charged under SM baryon or lepton number. In this case, DM is multi-component with contributions from $\chi_2$ and $\chi_1$. (Right) One of the states involved in the scattering Eq. (11) may be a leptobaryon while the other uncharged under SM lepton and baryon number. In this case, the leptobaryon can be the single component of DM.

Regardless of the charge assignment of $\chi_1$ and $\chi_2$, a coupling between a dark-sector baryon and SM fields must be generated. To do so, we simply invoke the model

\[
\psi_d \rightarrow \chi_2 + \tilde{\psi}_B, \quad \text{(25)}
\]

with charges of $\chi_1$ and $\chi_2$ chosen such that this process conserves baryon, and lepton number. $\tilde{\psi}_B$ subsequently mixes into a SM baryon through Eq. (24). Which fields make up the DM depend upon further details of the dark-sector model which we now explore.

\[\mathcal{L}_\text{eff} = \frac{y}{M_{\phi_c}} \bar{u}_i \bar{d}_j \bar{d}_k \psi_B, \quad \text{(24)}\]

where we have defined $y \equiv y_{u,i} d_j d_k$. Note that the colored mediator mass and couplings are constrained to be $M_{\phi_c} \sqrt{g} \gtrsim 1$ TeV to be consistent with collider bounds (for details, see [62] and references therein). At low scales, this generates an effective mass mixing between SM baryons and the dark-sector baryon. Note that since $\psi_B$ may couple to protons and neutrons through the operator in Eq. (24), the stability of baryonic matter must be ensured kinematically by $m_{\psi_B} > 1.2$ GeV. The field content is given in Table II.

| Field | Spin | L | B | $Z_2$ | Mass |
|-------|------|---|---|------|------|
| $\phi_c$ | 0 | 0 | -2/3 | +1 | $\gtrsim 1$ TeV |
| $\ell_d$ | 1/2 | 1 | 0 | +1 | $\mathcal{O}(10 - 140 \text{ MeV})$ |
| $\psi_B$ | 1/2 | 0 | -1 | +1 | $\gtrsim 1.2$ GeV |

TABLE II. Dark-sector states which interact directly with the SM. $\psi_B$ is a dark-sector baryon introduced in this section to generate interactions between the dark sector and SM baryons through Eq. (24).

are allowed by all the symmetries.\footnote{Such models can arise in, for instance, supersymmetric theories [49].}

\[
\mathcal{L} \supset -y_{u,i} d_j \Phi \bar{d}_j - y_{d,k} \Phi d_k + \text{h.c.} \quad \text{(23)}
\]

Here, $\psi_B$ is a dark-sector Dirac fermion carrying baryon number $B = -1$, and $\phi_c$ a colored scalar mediator with baryon number $B = -2/3$. Integrating out the heavy $\phi_c$ mediator leads to the following effective baryon-number conserving four-fermion interaction

\[\mathcal{L}_\text{eff} = \frac{y}{M_{\phi_c}} \bar{u}_i \bar{d}_j \bar{d}_k \psi_B, \quad \text{(24)}\]

where we have defined $y \equiv y_{u,i} d_j d_k$. Note that the colored mediator mass and couplings are constrained to be $M_{\phi_c} \sqrt{g} \gtrsim 1$ TeV to be consistent with collider bounds (for details, see [62] and references therein). At low scales, this generates an effective mass mixing between SM baryons and the dark-sector baryon. Note that since $\psi_B$ may couple to protons and neutrons through the operator in Eq. (24), the stability of baryonic matter must be ensured kinematically by $m_{\psi_B} > 1.2$ GeV. The field content is given in Table II.

Additional dark-sector states are necessary to transfer the asymmetry; the two states $\chi_1$ and $\chi_2$ as well as another mediator. These states are odd under a discrete $Z_2$ (while $\ell_d$ and $\psi_B$, which interact directly with the SM, must be even), thereby evading washout and ensuring the stability of the dark-sector lepton and baryon asymmetries. In this way, the dark lepton $\ell_d$ may scatter

\[\ell_d + \chi_1 \rightarrow \chi_2 + \tilde{\psi}_B, \quad \text{(25)}\]
Model 1: DM as Scalar Baryons and Leptons

In this model, we take \( \chi_1 \) to have \( (L = 1, B = 0) \) while \( \chi_2 \) has \( (L = 0, B = -1) \), corresponding to assignments in the top left two row of Table I. We take both \( \chi_{1,2} \) to be scalars and introduce a Dirac fermion mediator \( \xi \), which can be MeV scale. We make all three odd under a \( \mathbb{Z}_2 \). The DM consists of both (asymmetric components of) \( \chi_2 \) and \( \chi_1 \), stabilized under the discrete \( \mathbb{Z}_2 \) symmetry, as to maintain the equal and opposite asymmetries in the dark and visible sectors.

As discussed above, \( \chi_1 \) is produced through \( \Phi \) decays and \( \ell_d \), generated from the \( \pi^\pm \) decay through Eq. (3), then scatters off \( \chi_2 \) producing \( \chi_2 \) and the dark-sector fermion \( \psi_B \) as in Eq. (25). This scattering is mediated by the dark Dirac fermion \( \xi \) and is generated through the following baryon and lepton number conserving Yukawa interactions allowed by the \( \mathbb{Z}_2 \) symmetry:

\[
\mathcal{L} \supset y_b \bar{\psi}_B \chi_2 + y_l \bar{\ell}_d \xi \chi_1 + \text{h.c.},
\]

(26)

\( \xi \) (which can be relatively light) mediates the s-channel process in Eq. (25). An intermediate \( \bar{\psi}_B \) is produced which then quickly mixes into a SM baryon through Eq. (24). This scattering transfers the dark lepton asymmetry to the SM baryon asymmetry.

Stability of baryonic matter is ensured kinematically by \( m_{\chi_2} > 1.2 \text{ GeV} \), as with any dark-sector state charged under baryon number. Meanwhile \( \chi_1 \) can have a sub-GeV mass, unless otherwise restricted by kinematics. In general the Yukawa coupling could induce decays of \( \psi_B \) into the dark sector. Since \( \psi_B \) transforms into SM baryons via the operator in Eq. (24), we require

\[
m_{\chi_2} + m_{\xi} > m_{\psi_B} > m_B,
\]

(27)

which also ensures the stability of SM baryons.

We have computed the thermally averaged cross section corresponding to Eq. (11) for the s-channel scattering in this model and have confirmed that it can easily be sizable enough to satisfy Eq. (22). We leave a thorough exploration of the corresponding parameter space to future work (and a more detailed UV embedding) and simply present, as a proof of principle, the following result:

\[
\langle \sigma v \rangle \simeq 10^{-15} \text{ GeV}^{-2} \left( \frac{y_l y_b}{m_{\ell_d}} \right)^2 \times \left( \frac{10 \text{ MeV}}{m_{\ell_d}} \right) \left( \frac{20 \text{ GeV}}{m_{\chi_1}} \right) \left( \frac{10 \text{ GeV}}{m_{\chi_2}} \right).
\]

(28)

Here for simplicity we have taken \( m_{\psi_B} \sim 5 \text{ GeV} \). We have also fixed the dark-sector mediator mass to be \( m_\xi = 10 \text{ MeV} \)—a heavier mediator will result in a slightly smaller cross section. The color mediator mass \( M_a \sqrt{y} \) has been set to saturate the collider bound of order 1 TeV. Note that Eq. (28) holds when \( M_a \gtrsim m_{\chi_2} + m_B \) and \( M_a \gtrsim m_{\ell_d} \); as the inflaton populates both \( \ell_d \) and \( \chi_1 \) in this setup, and the energy available in the scattering will be of order \( m_a \).

The DM will consist of the asymmetric parts of both \( \chi_1 \) and \( \chi_2 \). We will need additional dark-sector interactions to annihilate away any symmetric part of the DM, as it will generically be overproduced, and to obtain the correct relic abundance. Such a set-up is simple to achieve and there exists a host of dark-sector production mechanisms that can deplete the asymmetry (for instance, see discussion in [49]).

Model 2: DM as Fermionic Leptobaryons

In this second example model, we take \( \chi_1 \) to have \( (L = 0, B = 0) \) while \( \chi_2 \) has \( (L = -1, B = -1) \), corresponding to charge assignments in the bottom right two rows of Table I. We take both \( \chi_{1,2} \) to be fermions and introduce a scalar mediator \( \Phi_L \) with \( L = 1 \) which may be light. As in the first toy model, we take all three odd under a \( \mathbb{Z}_2 \). The \( \chi_2 \) are leptobaryons in this model and could be, for instance, a neutrino multiplet in a supersymmetric model with an exact \( R \)-symmetry identified with baryon number, similar to [49] (e.g. a right handed sterile neutrino multiplet had a \( \nu_R \) with \( B = 0, L = 0 \) and \( \nu_R \) with \( B = -1, L = 1 \)). As per Model 1, we have a dark fermionic baryon field \( \bar{\psi}_B \) coupling to the SM by the same UV construction as Eq. (24). The following \( \Delta B = 0 = \Delta L \) Lagrangian is allowed by all of the symmetries

\[
\mathcal{L} \supset y_b \bar{\psi}_B \chi_2 \Phi_L + y_l \bar{\ell}_d \chi_1 \Phi_L + \text{h.c.},
\]

(29)

This generates the scattering Eq. (25) mediated by the dark scalar lepton \( \Phi_L \). As with the first model, the scattering cross section in this setup is easily large enough to accommodate baryogenesis.

In this model, DM is always (partially) comprised of asymmetric \( \chi_2 \). If \( m_{\ell_d} < m_{\chi_2} \), it will also have an asymmetric component of \( \ell_d \). As in the previous model, we do not illustrate explicitly how to obtain the remainder of the relic abundance, nor do we detail how to remove symmetric components sufficiently. The possibilities here are quite generic to dark-sector DM production and are thus decoupled from the baryogenesis mechanism at hand.

V. DISCUSSION

We have introduced a novel, low-scale mechanism for generating the BAU from the late-time production of mesons. \( D^\pm \) mesons decay in a CP-violating way to \( \pi^\pm \), which in turn decay into a dark-sector state charged under lepton number. The processes are out-of-equilibrium, occur at tens of MeV, and generate equal and opposite dark- and visible-sector lepton asymmetries. Additional dark-sector states charged under SM baryon number scatter with the dark leptons to transfer this dark lepton asymmetry into the observed SM baryon asymmetry. Since we never explicitly violate lepton or baryon number, these dark states also (partially) comprise DM.
The matter-antimatter asymmetry is related to experimental observables. The measurement of the CP violation in charged $D^\pm$ decays, $A_{CP}^+$, will be improved upon at for instance LHCb. The branching fraction of charged pions into charged leptons and missing energy, which has been constrained by the PIENU experiment, will be further probed at future experiments.

We have presented two simple, dark-sector models which can efficiently transfer the dark lepton asymmetry and achieve baryogenesis. However, we have remained agnostic about many of the details of the dark sector and have not UV completed these models. Such completions are the subject of future work and will likely open up additional model-dependent, complimentary probes. Another option is to introduce a complex, dark-sector gauge group which transfers the asymmetry through a dark Sphaleron process. We leave the details of this intriguing possibility to future work.

The study of this mechanism within the context of specific flavor and inflationary models is left to future work. We have focused here on explaining the BAU through $D^\pm$ decays to $\pi^\pm$. Depending on the flavor structure, one could also consider $D^\pm$ decays to Kaons which then decay to dark-sector leptons. Current limits allow for a sizable branching fraction of charged Kaons to muons given by $\text{Br}(K^\pm \rightarrow \mu^\pm + X) < 10^{-3} - 5 \times 10^{-6}$ \cite{63, 64}. Thus, we could repeat the calculations of this work using the currently allowed values for CP-violating decay channels of $D^\pm$ which involve an odd number of Kaons. A benefit of using Kaons is the possibility of reheating at temperatures above 20 MeV since washout-inducing Kaon annihilations stop at higher temperatures than their pion counterparts.

$\Phi$ can also decay into neutral mesons, such as $B^0$, which undergo CP-violating oscillations. Current limits allow for sizable branching fraction of charged Kaons to muons given by $\text{Br}(K^\pm \rightarrow \mu^\pm + X) < 10^{-3} - 5 \times 10^{-6}$ \cite{63, 64}. Thus, we could repeat the calculations of this work using the currently allowed values for CP-violating decay channels of $D^\pm$ which involve an odd number of Kaons. A benefit of using Kaons is the possibility of reheating at temperatures above 20 MeV since washout-inducing Kaon annihilations stop at higher temperatures than their pion counterparts.

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The matter-antimatter asymmetry is related to experimental observables. The measurement of the CP violation in charged $D^\pm$ decays, $A_{CP}^+$, will be improved upon at for instance LHCb. The branching fraction of charged pions into charged leptons and missing energy, which has been constrained by the PIENU experiment, will be further probed at future experiments.

We have presented two simple, dark-sector models which can efficiently transfer the dark lepton asymmetry and achieve baryogenesis. However, we have remained agnostic about many of the details of the dark sector and have not UV completed these models. Such completions are the subject of future work and will likely open up additional model-dependent, complimentary probes. Another option is to introduce a complex, dark-sector gauge group which transfers the asymmetry through a dark Sphaleron process. We leave the details of this intriguing possibility to future work.

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Appendix A: Boltzmann Equations for the Lepton and Baryon Asymmetries

Here we present a detailed derivation of the Boltzmann equations presented in Sec. [11]. It is useful to solve the set of Boltzmann equations in terms of temperature $T$ rather than time. In order to do so, one can write \cite{69, 71}

$$\frac{dT}{dt} = \frac{-4Hg_*T^4 + 30\pi^2\Gamma_\Phi m_\Phi n_\Phi}{T^3 (4g_* + Tdg_*/dT)} , \quad (A1)$$

which follows from energy conservation and is valid for energies above the neutrino decoupling temperature $T > 3$ MeV, as neutrinos and other light degrees of freedom are still coupled to the plasma. The number of relativistic species $g_* (g_*, S)$ contributing to the energy (entropy) density is given in \cite{72}.
The number density Boltzmann equations for charged $D$ mesons are

$$
\frac{dn_{D^+}}{dt} + 3Hn_{D^+} = \Gamma^D_\Phi n_\Phi - \Gamma_{D^+}n_{D^+},
$$
$$
\frac{dn_{D^-}}{dt} + 3Hn_{D^-} = \Gamma^D_\Phi n_\Phi - \Gamma_{D^-}n_{D^-},
$$

(A2)

where $\Gamma^D_\Phi$ is the rate of decay of $\Phi$ to a final state with 1 $D^+$ (we assume no final states with multiple) and $\Gamma_{D^\pm}$ is the total $D^\pm$ decay rate. We assume that all decays above are much faster than SM annihilations, which is true for $T_R < 20$ MeV. Note that $\Gamma^D_\Phi = \Gamma^D_\Phi$ since there is no CP violation in $\Phi$ decays.

The number density Boltzmann equations for the charged pions are:

$$
\frac{dn_{\pi^+}}{dt} + 3Hn_{\pi^+} = n_{D^+} \left( \Gamma_{D^+}Br \left( D^+ \to \pi^+ + \text{other} \right) + 2\Gamma_{D^+}Br \left( D^+ \to 2\pi^+ + \text{other} \right) \right) + \Gamma_{D^-}Br \left( D^- \to \pi^+ + \text{other} \right) n_{D^-} - \Gamma_{\pi^+}n_{\pi^+},
$$
$$
\frac{dn_{\pi^-}}{dt} + 3Hn_{\pi^-} = n_{D^-} \left( \Gamma_{D^-}Br \left( D^- \to \pi^- + \text{other} \right) + 2\Gamma_{D^-}Br \left( D^- \to 2\pi^- + \text{other} \right) \right) + \Gamma_{D^+}Br \left( D^+ \to \pi^- + \text{other} \right) n_{D^+} - \Gamma_{\pi^-}n_{\pi^-},
$$

(A3)

(A4)

where $\Gamma_{\pi^\pm}$ is the total $\pi^\pm$ decay rate. All SM annihilation terms that would appear are negligible relative to the decay terms thanks to the low reheating temperature. The number of different decay terms are due to grouping by the number of final state charged pions, where we are only interested in decays with up to two pions of the same charge (see Tab. III). We’re also neglecting $\Phi$ decays into lighter quarks which could hadronize into pions.

For intuition and simplicity, we first solve for the lepton asymmetry generated in the dark sector in the case that the additional dark-sector interactions that give rise to Eq. (11) are absent. Then, the number density Boltzmann equations for the dark leptons are

$$
\frac{dn_{\ell_\pm}}{dt} + 3Hn_{\ell_\pm} = \Gamma_{\pi^\pm}Br \left( \pi^\pm \to \ell^\pm + \ell_\pm \right) n_{\pi^\pm},
$$
$$
\frac{dn_{\bar{\ell}_\pm}}{dt} + 3Hn_{\bar{\ell}_\pm} = \Gamma_{\pi^\pm}Br \left( \pi^\pm \to \ell^- + \bar{\ell}_d \right) n_{\pi^\pm}.
$$

(A5)

We assume any possibly present dark-sector annihilations are slow, $\ell_d$ is stable, and back scatters of $\ell^+\ell_d \to \pi^+$ are slow.

To find the generated lepton asymmetry in the dark sector, we simply take the difference of the above $\ell_d/\bar{\ell}_d$ Boltzmann equations above:

$$
\frac{d}{dt} \left( n_{\ell_\pm} - n_{\bar{\ell}_\pm} \right) + 3H \left( n_{\ell_\pm} - n_{\bar{\ell}_\pm} \right) = \Gamma_{\pi^\pm}Br \left( \pi^\pm \to \ell^\pm + \ell_\pm \right) \left( n_{\pi^+} - n_{\pi^-} \right).
$$

(A6)

To simplify things analytically, we assume the $\Phi$’s, produced $D$’s, and the subsequently-produced $\pi$’s decay quickly, which is approximately true as long as $H \ll \Gamma_\Phi \ll \Gamma_D \ll \Gamma_\pi$. The right hand side of the above Boltzmann equation becomes

$$
\Gamma_{\pi^\pm}Br \left( \pi^\pm \to \ell^\pm + \ell_\pm \right) \left( n_{\pi^+} - n_{\pi^-} \right) = \Gamma^D_\Phi n_\Phi Br \left( \pi^\pm \to \ell^\pm + \ell_\pm \right)
$$
$$
\times \left[ \sum_f \left( Br \left( D^+ \to 1\pi^+ + f \right) - Br \left( D^- \to \pi^- + \bar{f} \right) \right) + 2 \sum_f \left( Br \left( D^+ \to 2\pi^+ + f \right) - Br \left( D^- \to 2\pi^- + \bar{f} \right) \right) \right. 
$$

$$
\left. - \sum_f \left( Br \left( D^+ \to \pi^- + f \right) - Br \left( D^- \to \pi^+ + \bar{f} \right) \right) \right],
$$

(A7)

In the above, the sums over final states $f$ do not include any additional charged pions. Rather, the number of charged pions we’re considering in a given sum is explicitly highlighted in the decay channel branching ratio. After some partial cancellations between channels with both signs of charged pions, we find that each channel is multiplied by its net ‘+’ charge in $\pi^+$’s vs $\pi^-$’s, which we define as $N^f_\pi$, and as expected:

$$
\frac{d}{dt} \left( n_{\ell_\pm} - n_{\bar{\ell}_\pm} \right) + 3H \left( n_{\ell_\pm} - n_{\bar{\ell}_\pm} \right) = \Gamma^D_\Phi n_\Phi Br \ell_\pm \sum_f N^f_\pi \left( Br \left( D^+ \to f \right) - Br \left( D^- \to \bar{f} \right) \right).
$$

(A8)

To simplify this further, we rewrite the branching ratio differences in terms of the observable $A^f_{CP}$ (as relevant to the $D^\pm$ decays):

$$
Br \left( D^+ \to \bar{f} \right) - Br \left( D^- \to f \right) = \frac{2A^f_{CP}}{1 + A^f_{CP}} \equiv 2Br_{D^\pm}a^f_{CP}.
$$
Thus, the generated dark-sector lepton asymmetry simplifies to
\[
\frac{d}{dt} (n_{\ell_d} - n_{\bar{\ell}_d}) + 3H (n_{\ell_d} - n_{\bar{\ell}_d}) = 2\Gamma_D^{\Phi} n_{\phi} Br_{\ell_d} \sum_f N_f a_{CP} Br_f + \langle \sigma v \rangle n_{\chi_1} (n_{\ell_d} - n_{\bar{\ell}_d}).
\] (A9)

Next, we modify the story by allowing the interactions in Eq. (11) to cause a net dark baryon asymmetry (and therefore, a net SM baryon asymmetry) to form. With this introduction, notice that \( Y_{\ell_d} \neq Y_{\ell_d}^{\text{dark}} \) since \( \chi_1 \) or \( \chi_2 \) will have lepton number. The \( \chi_1 \)'s and \( \bar{\chi}_1 \)'s are populated by \( \Phi \) decays and their Boltzmann equations are
\[
\frac{d n_{\chi_1}}{dt} + 3H n_{\chi_1} = \Gamma_{\Phi} n_{\Phi} \langle \sigma v \rangle n_{\chi_1} - \langle \sigma v \rangle n_{\ell_d} n_{\bar{\chi}_1},
\]
\[
\frac{d n_{\bar{\chi}_1}}{dt} + 3H n_{\bar{\chi}_1} = \Gamma_{\Phi} n_{\Phi} \langle \sigma v \rangle n_{\bar{\chi}_1} - \langle \sigma v \rangle n_{\bar{\ell}_d} n_{\chi_1}.
\] (A10)

\( \chi_2, B, \) and their conjugates initially have negligible abundances and we assume their abundances are always less than the abundances of \( \ell_d, \chi_1, \) and their conjugates while these scattering processes are active. We have thus neglected the reverse scattering terms that would contribute to the above.

The major modification to the previous story (prior to the inclusion of the process in Eq. (11)) is the addition of scattering terms in the Boltzmann equations for \( \ell_d \) and \( \bar{\ell}_d \). Eq. (A5) becomes
\[
\frac{d n_{\ell_d}}{dt} + 3H n_{\ell_d} = \Gamma_{\pi^+} n_{\pi^+} \langle \sigma v \rangle n_{\chi_1} - \langle \sigma v \rangle n_{\ell_d} n_{\chi_1},
\]
\[
\frac{d n_{\bar{\ell}_d}}{dt} + 3H n_{\bar{\ell}_d} = \Gamma_{\pi^-} n_{\pi^-} \langle \sigma v \rangle n_{\bar{\chi}_1} - \langle \sigma v \rangle n_{\bar{\ell}_d} n_{\chi_1}.
\] (A11)

Taking the difference, we find that the generated dark-sector lepton asymmetry may now be used to source equal and opposite dark-sector and SM baryon asymmetries:
\[
\frac{d}{dt} (n_{\ell_d} - n_{\bar{\ell}_d}) + 3H (n_{\ell_d} - n_{\bar{\ell}_d}) = 2\Gamma_D^{\Phi} n_{\phi} Br_{\ell_d} \sum_f N_f a_{CP} Br_f - \langle \sigma v \rangle n_{\chi_1} (n_{\ell_d} - n_{\bar{\ell}_d}).
\] (A12)

Note that \( n_{\bar{\chi}_1} \approx n_{\chi_1} \) for all times. Finally, the number density Boltzmann equation for the SM baryon asymmetry is simply
\[
\frac{d}{dt} (n_B - n_{\bar{B}}) + 3H (n_B - n_{\bar{B}}) = - \langle \sigma v \rangle n_{\chi_1} (n_{\ell_d} - n_{\bar{\ell}_d}),
\] (A13)

where again, we have assumed that the backreaction processes are negligible due to the minuscule number densities of \( \chi_2, B, \) and their conjugates relative to \( \ell_d, \chi_1 \) and their conjugates.


| $D^+$ decay mode | $A_{CP}^f/10^{-2}$ | Br$^f_{D^+}/10^{-2}$ |
|------------------|-------------------|---------------------|
| $K_S^0\pi^+$     | $-0.41 \pm 0.09$  | $1.562 \pm 0.031$   |
| $K^-\pi^+\pi^+$  | $-0.18 \pm 0.16$  | $9.38 \pm 0.16$     |
| $K^-\pi^+\pi^0$  | $-0.3 \pm 0.6 \pm 0.4$ | $5.98 \pm 0.08 \pm 0.16^*$ [73] |
| $K_S^0\pi^+\pi^0$ | $-0.1 \pm 0.7 \pm 0.2$ | $6.99 \pm 0.09 \pm 0.25^*$ [73] |
| $K_S^0\pi^+\pi^-\pi^-$ | $0.0 \pm 1.2 \pm 0.3$ | $3.122 \pm 0.046 \pm 0.096^*$ [73] |
| $\pi^+\pi^0$     | $2.4 \pm 1.2$     | $(1.247 \pm 0.033) \times 10^{-1}$ |
| $\pi^+\eta$      | $1.0 \pm 1.5$     | $(3.77 \pm 0.09) \times 10^{-1}$  |
| $\pi^+\eta'(958)$ | $-0.6 \pm 0.7$    | $(4.97 \pm 0.19) \times 10^{-1}$  |
| $K^+K^-\pi^+$    | $0.37 \pm 0.29$   | $(9.35 \pm 0.17 \pm 0.24^*) \times 10^{-1}$ [73] |
| $\phi\pi^+$      | $0.01 \pm 0.09$   | $(5.70 \pm 0.05 \pm 0.13) \times 10^{-1}$ |
| $a_0(1450)^0\pi^+$ | $-19 \pm 12^{+8}_{-11}$ | $4.5^{+0.9}_{-1.8} \times 10^{-2}$ [a] |
| $\phi(1680)\pi^+$ | $-9 \pm 22 \pm 14$ | $4.9^{+4.0}_{-1.9} \times 10^{-3}$ [b] |
| $\pi^+\pi^+\pi^-$ | $-1.7 \pm 4.2$    | $(3.27 \pm 0.18) \times 10^{-1}$   |

a this only includes the subsequent decay mode in which $a_0(1450) \rightarrow K^+K^-$

b this only includes the subsequent decay mode in which $\phi(1680) \rightarrow K^+K^-$

TABLE III. Summary of $D^+$ decay modes which violate $CP$ and involve an odd number of $\pi^\pm$ and therefore help to generate a dark-sector lepton asymmetry.

Appendix B: $D$ Meson Decay Modes

We summarize the relevant $D^+$ decay modes, including their values of $A_{CP}^f$ and branching ratios, in Table III. All quoted values come from the latest Particle Data Group (PDG) [74], with the following exception. There are some decay modes for which PDG does not provide their own fit to the branching ratio, denoted by an asterisk on the branching ratio value. For these, we use the top listed reference within PDG and cite it in our table accordingly.
[57] A. Aguilar-Arevalo et al. (PIENU), Phys. Lett. B 798, 134980 (2019), arXiv:1904.03269 [hep-ex].

[58] D. Bryman, private communication.

[59] D. McKeen, A. E. Nelson, S. Reddy, and D. Zhou, Phys. Rev. Lett. 121, 061802 (2018), arXiv:1802.08244 [hep-ph].

[60] K. Harigaya, R. McGehee, H. Murayama, and K. Schutz, JHEP 05, 155 (2020), arXiv:1905.08798 [hep-ph].

[61] Y.-D. Tsai, R. McGehee, and H. Murayama, (2020), arXiv:2008.08608 [hep-ph].

[62] G. Alonso-Álvarez, G. Elor, and M. Escudero, .

[63] A. V. Artamonov et al. (E949), Phys. Rev. D91, 052001 (2015), Erratum: Phys. Rev.D91,no.5,059903(2015), arXiv:1411.3963 [hep-ex].

[64] E. Cortina Gil et al. (NA62), Phys. Lett. B778, 137 (2018), arXiv:1712.00297 [hep-ex].

[65] R. Aaij et al. (LHCb), Phys. Rev. D 97, 031101 (2018), arXiv:1712.03220 [hep-ex].

[66] Y. Nir, JHEP 05, 102 (2007), arXiv:hep-ph/0703235 [hep-ph].

[67] E. Golowich, J. Hewett, S. Pakvasa, and A. A. Petrov, Phys. Rev. D76, 095009 (2007), arXiv:0705.3650 [hep-ph].

[68] G. Barenboim, W. H. Kinney, and W.-I. Park, Eur. Phys. J. C77, 590 (2017), arXiv:1609.03200 [astro-ph.CO].

[69] T. Venumadhav, F.-Y. Cyr-Racine, K. N. Abazajian, and C. M. Hirata, Phys. Rev. D 94, 043515 (2016), arXiv:1507.06655 [astro-ph.CO].

[70] R. J. Scherrer and M. S. Turner, Astrophys. J. 331, 19 (1988).

[71] S. Hannestad, Phys. Rev. D 70, 043506 (2004), arXiv:astro-ph/0403291.

[72] M. Laine and Y. Schroder, Phys. Rev. D73, 085009 (2006), arXiv:hep-ph/0603048 [hep-ph].

[73] S. Dobbs et al. (CLEO), Phys. Rev. D 76, 112001 (2007), arXiv:0709.3783 [hep-ex].

[74] P. Zyla et al. (Particle Data Group), PTEP 2020, 083C01 (2020).