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Secretly Asymmetric Dark Matter

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We study a mechanism where the dark matter number density today arises from asymmetries generated in the dark sector in the early universe, even though total dark matter number remains zero throughout the history of the universe. The dark matter population today can be completely symmetric, with annihilation rates above those expected from thermal WIMPs. We give a simple example of this mechanism using a benchmark model of flavored dark matter. We discuss the experimental signatures of this setup, which arise mainly from the sector that annihilates the symmetric component of dark matter.

Asymmetric dark matter (ADM) [1–8] is motivated by the observation that the dark matter and baryon energy densities today are comparable, so that for dark matter masses of a few GeV, the number densities of the dark and visible sectors are also roughly comparable. The baryon number density today is set by an asymmetry, which suggests that dark matter could also be asymmetric, with the origin of the two asymmetries being related. In order to realize the conventional ADM scenario, a mechanism has to be put in place in order to break $U(1)_\chi$, a symmetry which guarantees conservation of dark matter (DM) number, in much the same way that baryon number has to be broken in order to generate an asymmetry in the visible sector.

In this paper we study the possibility that for a dark sector with multiple states, the ADM paradigm can be realized without having to break $U(1)_\chi$. Asymmetries can be generated in the different dark sector states, while keeping the total charge under the $U(1)_\chi$ at zero. If heavier states in the dark sector decay to lighter ones after DM annihilations have frozen out [9, 10], then the final DM population is in fact symmetric, even though its abundance was set by an asymmetry. For this reason we will refer to this mechanism as Secretly Asymmetric Dark Matter (SADM). The idea of repopulating the symmetric component of DM at late times through oscillations has also been explored [11–15].

The relic abundance of DM in this mechanism is in some ways similar to the abundance of charged stable particles in the Standard Model (SM). Even though the abundances of baryons and leptons are set by an initial asymmetry, the universe is always charge neutral and $U(1)_{\rm EM}$ is never broken. If protons were to decay at late times, the universe could end up with a symmetric population of electrons and positrons which is secretly asymmetric.

The Generation of the Asymmetry: Flavored dark matter (FDM) models [16–32] have multiple dark matter states by construction, as well as a simple way to connect the DM states with baryons or leptons that allows the transfer of asymmetries between the two sectors. Therefore, the SADM mechanism can be naturally realized in FDM models. In this work we will use a model of lepton flavored dark matter to demonstrate how the proposed mechanism works. We will assume that high-scale leptogenesis [33] (see refs. [34, 35] for a review and comprehensive list of references) generates an asymmetry in the lepton sector, which will then be transferred to baryons and to the dark sector.

Specifically, consider a model of FDM in which three flavors of SM singlet Dirac fermions $(\chi, \chi^c)_i$ $(i = 1, 2, 3)$ interact with the right-handed leptons of the SM via a scalar mediator ϕ, with the interaction given by

$$\mathcal{L}_{\rm FDM} = \lambda_{ij}\, \phi\, \chi_i\, e^c_j + \text{h.c.} \tag{1}$$

We will denote the mass of the lightest χ by m_χ and the typical mass splitting between the χ flavors by δm.

It is worth commenting on the conserved quantum numbers in the presence of the interaction in equation 1. Individual lepton numbers L_i in the SM can be extended by assigning charges to χ_i. We will refer to the extended lepton numbers by $\tilde{L}_i$. Then $U(1)_{B-\tilde{L}}$ remains unbroken and anomaly-free, except for the explicit breaking from heavy right-handed neutrinos. If the coupling matrix λ_{ij} is flavor-diagonal in the charged lepton and χ mass basis, the $U(1)^3_{\tilde{L}}$ flavor symmetry is preserved to a good approximation at low energies, broken only by the light neutrino mass matrix. The neutrino masses are small enough to have no effect on the physics to be discussed here, and will therefore be neglected from here on. The presence of off-diagonal entries in the couplings λ_{ij} do have interesting phenomenological consequences; however for the sake

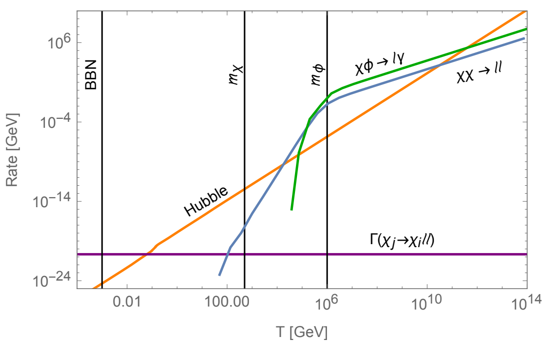

FIG. 1. Rates of the most important FDM processes and the Hubble scale as a function of temperature for the parameter point defined in the main text.

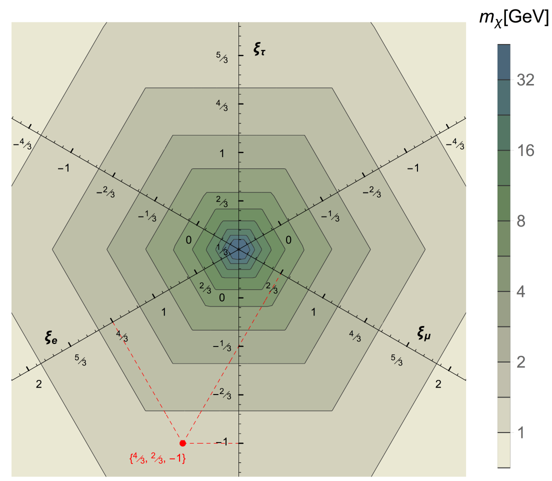

FIG. 2. The values of m_χ needed to obtain the correct ρ_B and ρ_{DM} as the initial lepton asymmetries Δ_i^0 are varied subject to the constraint of equation 4, assuming there is no symmetric component to the relic. The values of $\xi_i \equiv \Delta_i^0/\Delta Y_{B-L}$ for any point can be read off by drawing perpendiculars to the three axes shown.

of simplicity we will defer the discussion of these effects to a more detailed study and we will restrict ourselves to the flavor-universal case with $\lambda_{ij} \equiv \delta_{ij}\lambda$. Note that there is also a separate $U(1)_\chi$ symmetry under which all three χ_i have the same charge and the mediator ϕ has the opposite charge.

As mentioned above, we assume that out-of-equilibrium decays of the lightest right handed neutrino N_1 generate a net $B - \tilde{L}$ asymmetry in the SM sector. The comoving quantum numbers

$$\tilde{\Delta}_i = \left(B/3 - \tilde{L}_i\right)/s \equiv \Delta_i - \Delta Y_{\chi_i} \tag{2}$$

are conserved from the end of leptogenesis down to scales where neutrino oscillations become important. Here s is the entropy density, $Y_{\chi_i} = n_{\chi_i}/s$ are the comoving number densities of dark matter, and $\Delta_i = (B/3 - L_i)/s$ are the conserved comoving quantum numbers in the absence of the dark sector. Depending on which linear superposition of the e, μ and τ flavors N_1 couples to, leptogenesis generates nonzero values for these conserved quantities, which we will take as the initial conditions for the SADM mechanism.

Let us now follow the thermal history of the universe from the end of leptogenesis to lower temperatures. For concreteness we will use a specific parameter point ($\lambda = 0.05, m_\chi = 500$ GeV, $m_\phi = 10^6$ GeV, $\delta m = 0.4 m_\chi$, $T_{\text{leptogenesis}} > 10^{12}$ GeV), and in figure 1 we show for this parameter point how the rates of the most important processes in the model compare to the Hubble scale as a function of temperature. With these values, the FDM interaction of equation 1 goes into chemical equilibrium after all N have decayed. This is not a necessary condition for the SADM mechanism to work and merely simplifies the discussion, as it lets us take initial conditions from leptogenesis (values of Δ_i, denoted henceforth as Δ_i^0) in a modular fashion. If the FDM interaction is already in equilibrium during leptogenesis one can solve the Boltzmann equation to track the asymmetries in the two sectors as a function of time.

As the universe continues to cool down, the asymmetry originally generated in the left-handed leptons is transferred to the right-handed leptons (through the SM Yukawas), the baryons (through sphalerons) and to the χ_i (through the FDM interactions). With all these interactions in equilibrium, the comoving asymmetries of all species can be related to the conserved quantities during this epoch (the $\tilde{\Delta}_i$) through equilibrium thermodynamics, with the constraints that the total hypercharge and the total $U(1)_\chi$ number of the universe stay zero. Since individual χ numbers are all zero until the FDM interaction goes into equilibrium, the value of $\left(\tilde{\Delta}_i\right)$ just after equilibrium is equal to the value of $(\Delta_i) - (\Delta Y_{\chi_i})$ just before, namely Δ_i^0.

At our parameter point, the next step in the thermal evolution is the FDM interaction falling out of equilibrium as the temperature drops below m_ϕ. This decouples the SM and FDM sector asymmetries. Now the comoving asymmetries ΔY_{χ_i} are all separately conserved, and their values are given in terms of the initial conditions as

$$\begin{pmatrix} \Delta Y_{\chi_e} \\ \Delta Y_{\chi_\mu} \\ \Delta Y_{\chi_\tau} \end{pmatrix} = \frac{2}{15} \begin{pmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{pmatrix} \begin{pmatrix} \Delta_e^0 \\ \Delta_\mu^0 \\ \Delta_\tau^0 \end{pmatrix}. \tag{3}$$

At the same time, the total $B - \tilde{L}$ comoving asymmetry in the SM sector at early times can be related to the baryon number density B_0 and entropy density s_0 today,

$$\Delta Y_{B-\tilde{L}} = \sum_i \Delta_i^0 \approx \frac{79}{28}\frac{B_0}{s_0}, \tag{4}$$

which imposes a constraint on the possible initial conditions. From this point on, the thermal evolution of the

SM sector proceeds as usual.

After the symmetric component of DM annihilates away (through mechanisms discussed below), the DM relic abundance today is given by

$$\rho_{DM} = m_\chi \; s_0 \left(|\Delta Y_{\chi_e}| + |\Delta Y_{\chi_\mu}| + |\Delta Y_{\chi_\tau}|\right). \quad (5)$$

Therefore, the ratio

$$\frac{\rho_B}{\rho_{DM}} = \frac{m_p}{m_\chi} \, \frac{28/79 \left(\Delta_e^0 + \Delta_\mu^0 + \Delta_\tau^0\right)}{|\Delta Y_{\chi_e}| + |\Delta Y_{\chi_\mu}| + |\Delta Y_{\chi_\tau}|} \quad (6)$$

relates the value of m_χ to observed values of ρ_B and ρ_{DM} (with $\rho_B/\rho_{DM} = 0.185$ [36]), given any initial condition Δ_i^0. This is illustrated in figure 2. Note that ρ_B and ρ_{DM} depend on different combinations of the initial conditions.

While for generic initial conditions we expect m_χ to be a few GeV, both larger and smaller values are possible in the following two limits: If the leptogenesis mechanism generates almost equal Δ_i^0 then equation 3 sets the ΔY_{χ_i} to be small, and therefore the DM mass needs to be large to obtain the right ρ_{DM}. On the other hand, if the leptogenesis mechanism generates large individual asymmetries for the SM lepton flavors that almost cancel [37] (e.g. $\Delta_\tau^0 = -\Delta_\mu^0 \gg \Delta_e^0 \sim \Delta Y_{B-L}$) then the denominator in equation 6 is large, and the DM mass needs to be small.

Decays in the dark sector: If the mass splitting $\delta m_{ij} \equiv m_{\chi_i} - m_{\chi_j}$ is less than $m_{\ell_i} + m_{\ell_j}$, the decays $\chi_i \to \chi_j$+X can only proceed through χ-flavor mixing or through strongly suppressed loop processes [38], and the lifetime can be so long that all three χ can be treated as stable for practical purposes. For larger splittings however, the decay $\chi_i \to \chi_j \ell_i \bar{\ell}_j$ proceeds at tree level, with

$$\Gamma \simeq \frac{\lambda^4 (\delta m_{ij})^5}{480 \pi^3 m_\phi^4}. \quad (7)$$

If decays become important before χ-$\bar{\chi}$ annihilations freeze out, then they depopulate the heavier flavors and the dark matter abundance is set by the usual symmetric thermal freeze-out. Therefore, if the relic abundance based on the initial asymmetry is to survive at late times, then decays need to happen after annihilations freeze-out, but before Big-Bang Nucleosynthesis (BBN) in order to avoid early universe constraints. This is a core requirement of our set up. It is straightforward to check that this condition is satisfied at our parameter point. The width of the heavier flavors for these parameters is illustrated by the horizontal line in figure 1.

Annihilation of the symmetric DM component: If FDM annihilations $\chi_i \bar{\chi}_j \to l_i^- l_j^+$ are still active below $T \sim m_\chi$, then they deplete the asymmetry in the dark sector. Therefore, another core requirement for SADM is to ensure that the FDM interaction decouples while χ is relativistic. This also implies that we need additional interactions which can annihilate the symmetric component of DM, without depleting the asymmetry. We consider the setup, referred from here on as the Z'-model, where the $U(1)_\chi$ symmetry is gauged with a coupling g_D, and where the gauge boson Z'_μ acquires a small mass $m_{Z'} < m_\chi$. The Z' couples to the χ_i in a flavor-diagonal fashion and leads to efficient χ_i-$\bar{\chi}_i$ annihilations, such that the symmetric component of DM annihilates away for $g_D \gtrsim g_{\rm WIMP}$, where $g_{\rm WIMP}$ is the coupling that leads to the correct relic abundance for a thermal relic with the same mass.

Since ϕ carries a unit charge under $U(1)_\chi$ as well as hypercharge, it leads to kinetic mixing [39, 40] between these groups

$$\mathcal{L}_{\rm mix.} = -\frac{\epsilon}{2} B^{\mu\nu} Z'_{\mu\nu}, \quad (8)$$

where the loop of ϕ generates $\epsilon \sim 10^{-3} - 10^{-4}$ for couplings needed to annihilate the symmetric part. However, other UV contributions to the kinetic mixing can lead to a larger or smaller value of ϵ. The Z' can decay to the light SM fermions through the kinetic mixing.

Experimental Signatures of the Z'-model: If all flavors of χ are long-lived on cosmological timescales then there are no annihilations happening today and therefore indirect detection experiments are not sensitive to this case. If on the other hand only the lightest flavor survives today, then the DM distribution is symmetric. Since there is only a lower limit on g_D, one can obtain a stronger signal in indirect detection for a given m_χ compared to a WIMP. In particular, the annihilations will take the form $\bar{\chi}\chi \to Z'Z' \to 4f$, where f denotes SM fermions with $m_f < m_{Z'}/2$. Depending on $m_{Z'}$, the leading constraint from indirect detection may arise from positrons [41, 42], photons [43] or CMB measurements of ionization [36]. These constraints were considered in ref. [44–46], and they are shown in the right-hand plot of figure 3.

The Z'-hypercharge mixing also gives rise to a signal in direct detection experiments such as LUX [47, 48], SuperCDMS [49] and CRESST-II [50]. Since tree-level Z-exchange is excluded by orders of magnitude, this translates to a strong constraint on the model parameters. In the left-hand plot of figure 3 we show the bounds in the m_χ-σ_0 plane for a specific choice of $m_{Z'} = m_\chi/2$.

Finally, there are also bounds on the model from dark photon searches, which can be quite stringent for a very light Z' [52, 53]. However for $m_{Z'} \gtrsim 1$ GeV, the bound for ϵ is typically at the 10^{-3} level, and generic values in our model are compatible with this constraint.

We see that direct detection, indirect detection and dark photon searches provide a complementary set of constraints for the parameter space of the Z' model. Light DM with $m_\chi \simeq 5$ GeV, which can be obtained from generic initial conditions (see figure 2), is unconstrained by direct detection even for generic values of ϵ,

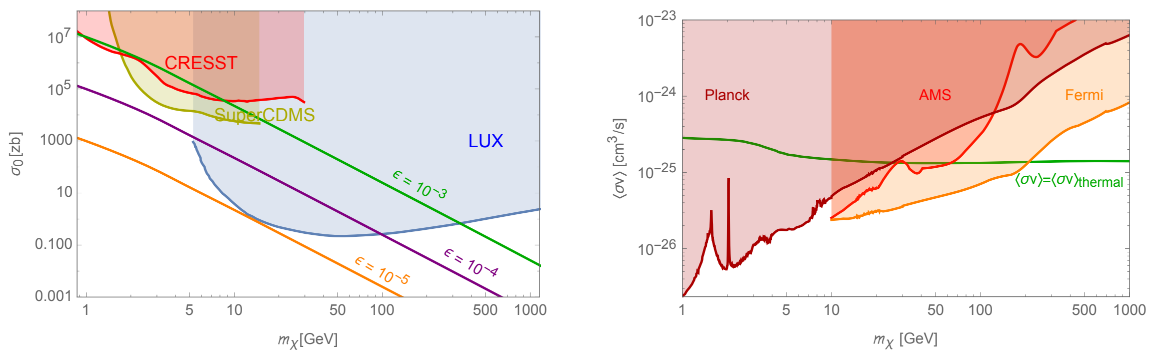

FIG. 3. Constraints on the Z'-model. *Left:* Direct detection constraints from LUX [47, 48], SuperCDMS [49] and CRESST-II [50] for representative values of ϵ and $g_D = g_{\rm WIMP}$. *Right:* Indirect detection constraints from Planck [36], Fermi [43] and AMS [41, 42]. For reference we also show the annihilation cross section [51] which gives the correct relic abundance in our model with no asymmetry. $m_{Z'}$ is taken to be $m_\chi/2$ for both plots.

and can be within reach of future experiments probing light dark matter. The low m_χ region is in tension with indirect detection bounds, but the constraints may be evaded in a modified version of the model, for example if the main annihilation channel is into neutrinos. Heavier $m_\chi \gtrsim O(100 \text{ GeV})$ are unconstrained by either set of bounds.

Alternative model for annihilating the symmetric part: In order to stress the model dependence of some of the bounds considered above, we describe a variation of the model where DM annihilates via a scalar instead of a Z'. In particular, consider a light real scalar S with the interactions

$$\mathcal{L}_S = \kappa_{ij} S \chi_i \chi_j^c - V(S)\,. \tag{9}$$

Consistent with the $U(1)^3_{\bar{L}}$ global symmetry we will take $\kappa_{ij} \equiv \delta_{ij}\kappa$. S develops a coupling to the right-handed SM leptons at one loop through the FDM interaction, and can therefore efficiently annihilate the symmetric part of the DM distribution. S does not mix with the Higgs boson until at least the two-loop order, and even this mixing is suppressed by lepton Yukawa couplings. Therefore, unlike the Z', tree-level S exchange only gives a negligible signal in direct detection experiments. Furthermore, the annihilation channel $\bar{\chi}\chi \to SS$ is p-wave suppressed, which means that even for a fully symmetric χ distribution today, indirect detection signals are expected to be very weak. Thus, this alternative model is basically unconstrained by the experiments discussed above.

Conclusions: We have studied the SADM mechanism where for a dark sector with multiple states, the relic abundance is set by an asymmetry even though the DM number remains zero. If heavier DM states can decay to the lightest state, then DM is symmetric at late times, whereas otherwise multiple DM components can be present today. This mechanism is realized naturally in models of FDM. Experimental signals, if present, arise mainly due to the sector of the model that is responsible for annihilating the symmetric component of the DM. We have presented two alternatives for this sector: a Z'-model where Z'-hypercharge mixing generically takes place at the one-loop level, and a scalar model where mixing with the Higgs can naturally be very small. For the former model there are a number of experimental constraints from DM searches as well as dark photon searches, and future experiments should be able to probe a sizable fraction of the parameter space currently consistent with constraints. The latter model on the other hand is very difficult to probe experimentally, and its parameter space is largely unconstrained.

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