On relating the genesis of cosmic baryons and dark matter

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\textbf{Abstract.} The similar cosmological energy budgets in visible baryons and dark matter motivate one to consider a common origin for the generation of both. We outline the key features of scenarios that can accommodate a unified framework for the genesis of cosmic matter. In doing so, we provide a brief overview of some of the past and recent developments and discuss the main predictions of a number of models.

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Introduction

The nature of matter has been a question of fundamental importance in science and philosophy, for centuries. While the initial inquiries of antiquity had more of a philosophical character, it was the application of the scientific method in probing Nature that brought us to a firm understanding of matter. Over the last century, experimental examination of the structure of matter at ever-decreasing length scales culminated in the emergence of the standard model (SM) of particle physics.

The SM provides a microscopic description of the visible matter in the world around us. However, in parallel, over the last several decades, mounting evidence from various astronomical observations has led us to reach a surprising conclusion: the visible matter, most of whose mass is composed of baryons, is in fact responsible for about 5% of the cosmic energy density, while the dominant material mass in the Universe, constituting about 22% of its energy budget [1], is ‘dark’ and does not have any appreciable interactions with the visible matter. Hence, while the SM is our most precise theory of Nature, it only describes a small fraction of what makes up the cosmos! In fact, the situation is worse: even the visible content of the Universe, made up of baryons and almost devoid of anti-baryons, requires a baryogenesis mechanism to generate the requisite baryon asymmetry and it is widely believed that successful baryogenesis requires extending the SM.

Thus, it seems that our latest understanding of cosmology has left us with two unresolved puzzles: (i) the nature of dark matter (DM) and (ii) the origin of the baryon asymmetry in the Universe. The answer to the first question in some of the most popular scenarios of physics beyond SM is that DM is made up of a stable particle whose relic density is set by thermal freeze-out [2]. That is, as the Universe cooled down after the Big Bang, the interactions that annihilated DM particles became less and less efficient and at some point decoupled, leaving a relic DM population. It turns out that weak scale interactions, characterized by masses of the order of 1 TeV, roughly give the correct order of magnitude for the DM relic density. Given the importance of the weak scale in particle physics, neutral and stable weakly interacting massive particles (WIMPs) are popular candidates for DM and have been the focus of much theoretical, as well as experimental, activity. The answer to question (2) above, however, requires the introduction of a mechanism that results in a baryon asymmetry and is apparently unrelated to the physics that sets the relic density of WIMPs. Hence, it seems that the visible and dark material contents of the cosmos are set by disjoint mechanisms.

The above discussion raises an intriguing question: why would then two seemingly unrelated sectors end up having similar contributions to the energy density of the Universe? This question, which is based on firm empirical evidence, leads us to examine whether baryons and DM could have a common origin. In particular, since the relic density of baryons is set by an asymmetry, one may naturally conclude that the DM cosmic abundance was similarly obtained [3–5]. In the recent literature, this has been called the asymmetric dark matter (ADM) hypothesis, and we will use this terminology throughout this paper. Typical implementations of the ADM hypothesis generally yield similar number densities for the visible and DM populations and we give some examples below. It is clear that these theories may quite naturally be characterized by dark matter particles whose masses are not much larger than that of the proton, $m_p \sim 1$ GeV. The properties of ADM can then be quite distinct from WIMPs and motivate different search strategies, as we will discuss later.
In the next section, we will outline some of the key features of typical ADM scenarios that provide a unified framework for the generation of both baryonic and dark cosmic matter. In section 3, we will discuss some of the early and recent proposals representing different classes of ADM models. In section 4, we briefly consider the phenomenological aspects of different classes of ADM models, and the search strategies they motivate. We discuss some of the astrophysical implications of ADM scenarios in section 5. A summary and some concluding remarks are provided in section 6.

Before closing this introduction, we would like to add that this paper, given its length and scope, is not meant to be a comprehensive review of the literature. As a result, many interesting ideas, directly or indirectly relevant to the topic, could not be covered by our review; their omission is not an indication of their lesser significance. However, it is our hope that this brief survey of the subject can be a helpful reference for some of the key ideas and questions associated with unified theories of cosmic baryons and DM.

2. The main ideas

As already mentioned, the similar energy budgets in baryons and DM motivate a unified theory of their origin. While the ratio of the baryon energy density $\rho_b$ to the critical energy density $\rho_c$ is $\Omega_b \simeq 0.05$, the same ratio for the DM energy density $\rho_{dm}$ is $\Omega_{dm} \simeq 0.22$ [1]. For the purpose of the discussions that follow, let us define

$$R_{b/dm} = \frac{\Omega_b}{\Omega_{dm}},$$  \hspace{1cm} (1)

where $R_{b/dm} \simeq 0.2$. Observational data, as well as theoretical arguments, strongly indicate that the visible matter in the Universe is dominated by baryons and that the cosmic anti-baryon density is negligible in comparison [7]. Any mechanism for the generation of baryon asymmetry of the Universe (BAU) needs to have ingredients that allow for the implementation of the three Sakharov conditions [6]: (i) baryon number violation, (ii) C and CP violation and (iii) departure from equilibrium. Condition (i) is an obvious requirement, while condition (ii) ensures that the underlying physics can distinguish between matter and anti-matter. The last condition is needed to avoid washing out the asymmetry generated by the first two when various processes and their inverses are in equilibrium in the early Universe.

A unified mechanism for generation of visible and dark matter must then accommodate the above criteria. This can be arranged in a variety of ways. However, many models fall in either of the following two main categories:

(I) Models where a quantum number is assigned to DM that is also shared by the visible matter. An asymmetry in this number must then be shared between the two sectors through certain interactions. Once these interactions decouple from the thermal plasma, asymmetries of comparable size get frozen in the visible and dark sectors.

(II) Models in which the concept of baryon number $B$ is generalized, with equal and opposite asymmetries sequestered in the visible and DM particles. This can happen, for example, if the theory including the dark particles has a symmetry generated by a charge $Q_{tot} = B + Q_X$, where $Q_X$ is the charge associated with the $U(1)$ symmetry in the DM Lagrangian. In this class of models, while $B + Q_X$ is always preserved, the orthogonal combination $B - Q_X$ is broken and is responsible for the asymmetry generation. The latter guarantees that $n_B = -n_{Q_X}$. Once the asymmetries are produced out of equilibrium, processes that can wash them out should
remain decoupled and relic baryon and DM densities persist. However, the net ‘baryon number’ of the Universe remains zero in these scenarios.

In either class of ideas, one needs to ensure that processes that annihilate the symmetric population of particles and their anti-particles are efficient, so that the relic densities are set only by the asymmetries. Note that visible baryons have strong interactions that easily accomplish this, while generic DM sectors are not guaranteed to have the requisite interactions. Furthermore, ADM can be of bosonic or fermionic type.

While the experimental signatures of ADM models of types (I) and (II) could cover a wide range of possibilities, under some general assumptions, certain characteristic features may be ascribed to each type of model. For instance, in [8], assuming that the shared quantum number in type (I) models is $B-L$, a generic relation $m_{dm} \sim (5-7) \text{GeV}/q_{dm}$ between the charge $q_{dm}$ and the mass $m_{dm}$ of ADM is obtained, whereas in [9], the typical relation $m_{dm} \sim q_{dm}(2-5) \text{GeV}$ is derived for models of type (II) (with $B \rightarrow B-L$ in the above). We see that under the general assumptions in [8, 9], and also assuming $q_{dm} \lesssim 1$, one could expect models of type (I) to yield ADM masses that are typically larger than those associated with type (II) models. We note that the expected DM mass range is an important input for choosing a search strategy. For example, direct detection of DM based on measuring nuclear recoil in DM-nucleus scattering becomes less efficient for the low values of $m_{dm}$ and alternative approaches may have to be devised if one expects $m_{dm} \lesssim 1 \text{GeV}$ [10].

Finally, we note that a complete explanation of the similarity of dark and visible matter energy densities will also require an understanding of why the mass of the DM particle is similar to that of nucleons. Most models do not address this issue except for the mirror model discussed below.

3. Some early and recent proposals

3.1. Class (I) models

3.1.1. Technibaryonic ADM. The notion of a stable baryon can easily be accommodated in composite models, such as technicolor, where fermions can be bound into analogues of protons by weak scale strong dynamics. Thus both sectors, the technicolor and SM, can share a common baryon number and if techni-baryons are DM, these models will fall in class I models using our classification above. Indeed, the earliest proposals for asymmetric DM [4, 5] were based on technicolor models. For example, in [5] it was proposed that fermion-number-violating interactions in the early Universe [11], often referred to as sphalerons [12], can distribute asymmetries over the entire electroweak sector, including the techni-fermions. In this case, a similar asymmetric number density of quarks and techni-quarks can be produced, as can be seen by solving for the relevant chemical potentials and imposing neutrality conditions [13]. If the lightest techni-baryon is neutral under the SM interactions, then it could be a suitable DM candidate as long as it is stable on cosmological time scales. This scenario is of the type in category (I) above, as noted. Extensions of this idea in other theories of strong dynamics at the weak scale that address precision electroweak data [14] and may give rise to potential astrophysical signals [15] have been proposed in recent years. At first, it may seem that theories based on technicolor would lead to an unacceptable DM energy density, since techni-baryons in these models are expected to have masses $m_{TB} \sim 1 \text{TeV}$. Obviously, if baryons and DM develop similar densities in such models, one would end up with an energy density in DM
much larger than implied by the data. However, this issue can be addressed through the same fermion-number-violating sphaleron processes that lead to the asymmetries. To see this, note that the temperature at which the sphalerons decouple is typically of order of the electroweak phase transition temperature $T_c \sim 100$ GeV. If the techni-fermion changing processes stay in equilibrium below the techni-baryon mass, we generically expect a suppression in techni-baryon number of order $(m_{TB}/T_c)^{3/2} e^{-m_{TB}/T_c}$ [5, 14]. For typical values of $m_{TB}$ and $T_c$, one can then obtain an ADM number density suppression of the order of $10^{-3}$ to $10^{-2}$ and end up with an acceptable DM energy density.

3.1.2. Models based on $B$ or $B-L$ charge. A second class of proposals in category (I) is not based on the assumption of electroweak symmetry breaking (EWSB) via strong dynamics. An early example is [16] that uses extra electroweak fermions charged under an anomalous $U(1)_X$ global symmetry. In this model, it is assumed that EWSB occurs through a first order phase transition and that the new fermions have CP violating interactions with the bubble wall separating the symmetric and broken phases in the plasma. As a result, a net charge is transported into the symmetric phase that electroweak sphalerons process into baryon and DM asymmetries. The DM candidate here is the lightest particle charged under the $U(1)_X$, whose mass is near the weak scale. Here, the ratio $R_{b/dm}$ is obtained by the ratio of the scales of proton mass and the weak scale, up to a factor of the order of unity determined by the anomaly equation. A main feature of this model is the use of a quantum number that gets partitioned between the visible and the DM sectors through the effect of certain interactions. For example, a net $B-L$ is assumed to be generated in the model of [17], at a high temperature, but preserved at lower temperatures, and transferred to a DM sector that carries $B-L$ charge. If the transfer operators decouple above the mass of the DM particle, a DM asymmetry of the same order as the baryon asymmetry is generated and preserved. Such a scenario then predicts that the DM particle has a mass 5–15 GeV. Note that a net $B-L$ in the SM fermions can get processed into nonzero $B$ and $L$ asymmetries by sphalerons in thermal equilibrium [13].

3.1.3. Mirror matter models. Another example of type (I) models, but with very distinct features, is that of [18], which is based on the idea that there may be two parallel sectors in the Universe with identical matter and force content related by a discrete $Z_2$ symmetry (parity) with gravity and other SM singlet fields connecting the two sectors. These models are known in the literature as mirror models (for a review and extensive references to the literature prior to 2007, see [19]). The presence of the discrete mirror symmetry implies that all couplings in the mirror sector are the same as those of the SM, prior to symmetry breaking. This is a unique feature of this model since it helps to prevent the proliferation of coupling parameters in the theory. In fact prior to EWSB in both sectors, the parameters of the entire model are those of the SM. Once symmetry is broken, new parameters associated with symmetry-breaking vacuum expectation values (vevs) appear. This lends a certain degree of economy and predictivity to these models. The new features that help to connect visible and dark matter in these models are the following: (i) the two sectors are connected by singlet right-handed neutrinos $N_a$, $a = 1, 2, 3$, whose couplings are given by

$$L_i = h_{\nu,a} \bar{N}_a (LH + L'H') + h.c.,$$

where $L$ and $H$ denote the SM lepton and Higgs doublets, with corresponding mirror fields denoted by a prime. This makes the lepton number of the two sectors the same, which in
turn makes it a quantum number sharing model of type (I). One then adds a Majorana mass for the singlet neutrino fields $N_a$ [18] which breaks this common lepton number. Due to the presence of CP violation in the Yukawa couplings $h_{\nu,a}$, when the above Yukawa interactions go out of equilibrium, leptogenesis occurs [20] creating a lepton asymmetry in both the familiar and the mirror sector. At the tree level, due to mirror symmetry, the two lepton asymmetries are equal. The symmetry-breaking vevs which may be different in the two sectors do not affect this equality, since leptogenesis occurs much above the symmetry-breaking temperatures. Another way to see this equality is to note that the effective interaction generated after $N_a$ decouples is $L H L' H'$, which conserves the quantum number, $L-L'$. The lepton asymmetry in both sectors is subsequently converted into baryon asymmetry by the SM sphalerons and their mirror analogues. The mirror baryons are DM in these models and their abundance is equal to the observed baryon asymmetry. There may be some small differences between the asymmetries if radiative corrections are taken into account. It is important to point out that the symmetric part of the DM abundance gets annihilated by the mirror analogue of the SM quantum chromodynamics (QCD) interactions and no new postulate is needed.

An important characteristic of this class of models is that one can provide a rationale for the DM mass being slightly higher (but of the same order of magnitude) than the familiar baryons. The way to see this is as follows: when the mirror weak scale is made higher than the visible sector weak scale, running of the mirror coupling changes and if both couplings were grand unified at some high scale, the weak scale asymmetry will imply that the mirror QCD scale, $\Lambda'$, becomes non-perturbative at a much higher scale than the $\Lambda_{\text{QCD}}$ of the visible sector. This, coupled with higher quark masses of the mirror sector (due to larger $v_{\text{wk}}'$), implies that the lightest baryon of the mirror sector has a few times larger baryon mass compared with the visible sector (for details see [18]).

Prior to symmetry breaking this model has double the number of light particles in the SM. Therefore, one way to make these models compatible with the constraints of big bang nucleosynthesis (BBN) is to make the three mirror neutrinos and the mirror photon massive so that they can decay before the BBN. This can be achieved by suitably choosing the symmetry breaking in the mirror sector.

Furthermore, since a priori a kinetic mixing between the familiar photon $\gamma$ and the mirror photon $\gamma'$ is allowed by gauge invariance, this could be included in the Lagrangian, thereby connecting the familiar and the mirror sectors at lower temperatures. This mixing has the consequence that it can lead to signals in direct detection searches for mirror DM. The existence of $\gamma-\gamma'$ mixing can be tested at accelerators and we will discuss this below.

Other variations of this idea may also exist, e.g. one could assume a real scalar field with couplings

$$L_I \sim \frac{1}{\Lambda^6} S[(u^c d^c d^c)^2 + (u^{c'} d^{c'} d^{c'})^2],$$

where we have suppressed the generation index. CP violation in the $S$ couplings can then allow this operator to generate equal baryon asymmetry directly in both sectors without the intervention of sphalerons. Mirror baryons, e.g. the mirror neutrons $N'$, make up the DM. An intriguing possibility in this scenario is that over the real long-term future of the universe, DM could scatter into the visible sector via $N' + N' \rightarrow N + N$ ‘emptying the universe of all its dark matter’.
3.1.4. Other examples. There have been many other models for ADM which have the property of quantum number sharing between the visible and dark sector as their basis. For example, the work [21] assumes that DM asymmetry is generated by ‘dark sphalerons’ of a hidden non-Abelian gauge group, during a first-order phase transition. If the dark phase transition occurs below the temperature for electroweak phase transition, the asymmetry in the DM $X$ must be transferred to SM baryon directly. In a supersymmetric realization, this can be achieved via superpotentials of type $(1/\Lambda^2)X^2u^c d^c d^c$ suppressed by a scale $\Lambda$. However, if the dark phase transition takes place before electroweak phase transition, one may use electroweak sphalerons to achieve the transfer of the asymmetry to the visible sector. The typical mass of the ADM particle in this framework is in the 1–5 GeV range. For recent works that allow for much heavier ADM particles near the weak scale, see, for example, the proposals in [22] where DM number density is thermally suppressed, or [23], where a weak Dirac gaugino is the DM in the context of supersymmetric models.

In this class of ideas, there is another model [24] where the DM particle $\chi$ has a fractional lepton number so that it is stable. In this model, some $L = 0$ heavy scalar decays into $\chi$ as well as other lepton-number-carrying scalars such as the SM triplet Higgs boson $\Delta$ responsible for neutrino masses via the type II seesaw mechanism. In the presence of CP violation, these decays generate an asymmetry between $\chi$ and $\bar{\chi}$ and an asymmetry of the same order between $\Delta$ and $\bar{\Delta}$. The $\chi$ asymmetry stays as the DM, whereas the $\Delta$ asymmetry translates into a lepton number asymmetry when $\Delta$ particles decay. The lepton number asymmetry then gets converted into baryon asymmetry via the electroweak sphaleron interactions.

There are also proposals that connect the genesis of visible and dark cosmic matter through the formation of baryon-number-carrying condensates, as in the Affleck–Dine baryogenesis mechanism [25]. Such a condensate may later evolve into non-topological solitons [26] called $Q$-balls, originally introduced by Coleman [27], which can arise in supersymmetric extensions of the SM [28]. When $Q$-balls have sufficiently large baryonic (or leptonic) charges they can be cosmologically long-lived and provide a contribution to DM [26].

For other works on ADM and baryogenesis, see [29–32]. We wish to point out that there is a whole class of ADM models where there is no direct connection between baryogenesis and DM genesis [33]. Also, note that in some models [34] the generation of baryons and the abundance of DM may be controlled by the same underlying considerations, without resulting in an ADM scenario.

3.2. Class (II) models

These models are based on the possibility that the Universe has a net zero baryon number that is generalized to encompass both the visible and the dark sector. An early realization of this idea was proposed in [35], using a scalar condensate that stores anti-baryon numbers and can act as cold DM in the current epoch. Here, one can think of cosmic DM content as being effectively ‘anti-matter’, storing a baryon number that is equal and opposite to that sequestered in SM nucleons [35]. These basic features are characteristic of class (II) models and have been implemented in a variety of other proposals [36–42].

For instance, in [41], it was proposed that out-of-equilibrium decays of heavy Dirac fermions $X$ lead to the simultaneous generation of a baryon asymmetry and a DM asymmetry. This is achieved through Yukawa couplings of $X$ to a hidden fermion $Y$ and a scalar $\Phi$, and

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3 See also the second paper in [19].
mass-suppressed couplings to ‘neutron’ operators $u^c d^c d^c$, with $u$ and $d$ denoting up- and down-type quarks, respectively. In this scenario, equal and opposite baryon asymmetries are stored in nucleons and a population of $(Y, \Phi)$ particles, whose sum of masses is about 5 GeV. In order to avoid washout effects, the reheat temperature is low, around or below $\sim 1\text{ GeV}$. Here, symmetries and mass relations ensure the stability of both types of baryon, but this does not preclude induced nucleon decay (IND), that is, the destruction of SM baryons in scattering from the cosmic DM population, leading to interesting phenomenological signatures [41, 43]; see also [37] for a different model where such effects were considered. In this model, IND could be a striking signature in nucleon decay experiments, while direct detection based on nucleon recoil experiments may be suppressed, depending on the strength of the mechanism for DM symmetric annihilation into SM states.

Another example of type (II) models is that of [40], where one introduces color-charged and color singlet but baryon-number-carrying particles at the TeV scale. The color-charged particles couple to the SM particles as well as to the color singlet particles. The lightest color singlet particle plays the role of DM. The heavy color singlet particle decays to both SM color-charged states as well as to DM. In the presence of CP violation, this will generate both ADM relic density and a baryon asymmetry relating both of them in the process, via the new couplings of the exotic states.

We close this section with a couple of comments. First of all, it was noted in [44] that if a theory of ADM admits interactions that change DM to anti-DM, then DM–anti-DM oscillations [45] will remove all DM from the Universe, making the model not viable for the description of DM if the oscillation time is of the order of or less than the age of the universe. This point has been reanalyzed in [46], where it is noted that ADM in the presence of possible DM–anti-DM oscillations remains viable if the DM mass is between 100 and 1000 GeV. Also, the analysis in [47] indicates that whether or not DM–anti-DM oscillations result in the resumption of annihilations depends on the type of DM interactions with lighter fields. In many DM models however (e.g. mirror DM), such interactions are forbidden by specific symmetries (such as the mirror baryon number in mirror models).

Secondly, our classification of the models of ADM into types (I) and (II) is meant to be taken as a general guide. However, there are models that incorporate features of both classes and are not clearly of one type or the other; see, for example, [48].

4. Phenomenology

We now turn to phenomenological implications of ADM models and comment on some astrophysical implications as well. Here again we focus on some generic consequences rather than model-specific ones with the goal of distinguishing an ADM model from the conventional WIMP hypothesis. We will discuss direct detection searches, signals at colliders, novel probes and some indirect tests.

4.1. Direct detection and dark photons

Direct detection of DM requires that there must be particles in the theory that interact with both the SM particles and the DM particle. For example in the minimal supersymmetric standard model (MSSM), the lightest supersymmetric particle, which is DM, couples to the Z boson whose interactions with quarks lead to a DM signal. In the ADM models, the situation is
somewhat more complex. First of all, experiments designed for the direct detection of weak scale (~100 GeV) WIMPs generally do not have high sensitivity to signals from typical ADM particles characterized by GeV scale masses. In addition, it is possible to have ADM models where DM is completely invisible to direct searches. An example of this kind of model is the mirror ADM model where the familiar photon and the mirror photons do not mix [33]. However, one can supplement these models with the gauge invariant kinetic mixing $\epsilon B^{\mu \nu} \tilde{B}_{\mu \nu}^{\prime}$ [49], between the SM $U(1)$ and mirror $U(1)^{\prime}$ gauge fields. Such operators arise in other setups that include an additional $U(1)^{\prime}$ gauge interaction, for example as may be required for symmetric annihilation in ADM scenarios [41]. In any event, direct detection may still be quite suppressed even when $\epsilon$ is sufficiently large for this purpose [41]. The kinetic mixing parameter is, however, subject to different constraints, depending on whether the mirror (or dark) photon is massive or massless.

4.1.1. Massive dark photon. In this class of models, in addition to the kinetic mixing term, there is a mass term for the mirror photon, $m_{\gamma'}$, which may arise out of spontaneous breaking of mirror electromagnetic gauge invariance. Gauge invariance associated with familiar electromagnetic $U(1)$ of course remains unbroken [18]. In this case, there are constraints from supernova 1987A observations if $m_{\gamma'} \leq 100$ MeV, set by the core temperature (~30 MeV) of the supernova in the initial stages of the explosion. The limit [50] is $\epsilon \leq 10^{-9.5}$. There are other bounds on this from other considerations: e.g. there are constraints, from measurements of cosmic background radiation, of $\epsilon < 10^{-7}$–$10^{-5}$, for hidden photon masses between $10^{-14}$ and $10^{-7}$ eV [51].

There are also laboratory limits from a generation–regeneration experiment using the ‘light shining through a wall (LSW)’ technique in which regenerated photons are searched for [52]. The basic idea here is that if light transforms via its mixing to a dark photon, it will not interact (or very weakly interact) with matter and can therefore pass through a ‘wall’ and be visible once it reappears on the other side of the wall. Such experiments [53, 54] lead to an upper limit of $\epsilon \leq 10^{-7}$ for $m_{\gamma'}$ between 10 and $10^{-2}$ eV. Other astrophysical as well as laboratory limits are summarized in figure 1 (taken from [55]).
During the last few years, motivated by the interest from the DM-related ideas [62], searches for the photon–dark photon mixing in accelerator experiments have been conducted [56–58] and new limits have been obtained; see figure 2 (from [58]). The idea here is to conduct electron scattering and look for $e^+e^-$ in the final state with different invariant masses corresponding to the dark photon mass. Since the mixing parameter is small, the cross section for coherent electromagnetic production of the $\gamma'$ boson can be enhanced by a factor $Z^2$ by choosing a heavy nucleus as the target. The subsequent decay of the $\gamma'$ boson to a lepton pair is the signature of the reaction.

4.1.2. Massless dark photon and mini-charged matter. If the dark photon has kinetic mixing with the familiar photon and is massless, DM acquires a small amount of familiar electric charge and can therefore have interactions with familiar matter. The amount of charge in the DM (called mini-charge below) is proportional to the photon–dark photon mixing parameter $\epsilon$. The mini-charged dark particles, in a certain mass range, can manifest themselves in many astrophysical settings, e.g. supernova explosions, as well as laboratory experiments, leading to constraints on $\epsilon$ [59]. Various experimental data yield $\epsilon \lesssim 10^{-5}$ for mini-charged particles of mass at or below 1 eV, and $\epsilon \lesssim 10^{-6}$ for much smaller masses; for a recent review and more details, see [60]. Such mini-charged particles could have implications for supernova observation if they have very low masses (less than a few MeV) and can be emitted during the supernova explosion. This could affect the supernova luminosity for which there exist good estimates from the neutrino observations in SN1987A. These considerations put upper limits on the magnitude of the mini-charge, i.e. the range $10^{-9} \leq Q \leq 10^{-7}$ is excluded for masses less than 10–20 MeV[61]. If the
mini-charge value is $\geq 10^{-7}$, then minicharges get trapped in the neutrino sphere and thermalize. As a result, they do not get out of the supernova in large amounts and the luminosity constraint is avoided.

4.2. Collider searches

In many models for ADM, DM may either share some of the SM quantum numbers or interact with particles that are SM active. Depending on the embedding of the mechanism, one can expect a number of generic signals. For example, in supersymmetric contexts it is generally expected that various super-partners will emerge at the weak scale. Similarly, in models based on technicolor we may expect to find techni-hadrons at the TeV scale. However, there are also specific signals that arise in some models. For example, in [16] the possibility of a fourth family was considered that would include $(t', b')$ quarks. In [29] a new color-charged particle emerges that could lead to signals like those from long-lived or stable gluinos in supersymmetric scenarios. Other examples include exotic color-charged scalars in [40], or exotic quarks of [31] may be pair produced through QCD interactions and decay into jets and DM particles, i.e. missing energy. In models where ‘neutron operators’ of the type $u^c d^c c^c$ couple directly to the hidden sector, one may expect mono-jet plus missing energy signals at the LHC, depending on the strength of such couplings [43]. When the up-type quark is a top quark, it is possible to have interesting mono-top plus missing energy signals [43, 63, 64] that could be accessible at the LHC. Generally speaking, there may also be particles in the theory to which the SM Higgs boson can decay, such as invisible states or unstable lighter scalars.

4.3. Novel probes

An important aspect of ADM models is that they could motivate new ways of looking for DM that may not have been considered before. An interesting example of a possible new search avenue is provided by the model in [41], where there is no violation of generalized (dark plus visible) baryon number, yet exchange of baryon number between ADM and visible baryons is allowed, albeit with a small rate. In particular, DM could scatter from ordinary matter and lead to destruction of ordinary nucleons, thereby transferring baryon number into the dark sector. This process was dubbed IND in [41]. IND processes yield an effective lifetime $\tau_{\text{eff}}$ for nucleons, depending on the DM density at the position of the nucleon, and can lead to signals in nucleon decay experiments [21, 41, 43].

In [41, 43], using chiral perturbation theory methods, it was estimated that the effective lifetime of a nucleon on the Earth, with a local DM density of $\rho_{\text{DM}} = 0.3$ GeV cm$^{-3}$, is $\tau_{\text{eff}} \sim 10^{32}$ yr, if the mass scale suppressing the dim-7 baryon-number-transfer operator is $\sim 1$ TeV. Such values of $\tau_{\text{eff}}$ are indeed close to the current bounds from experiments, like super-Kamiokande [65], suggesting that current or future nucleon decay experiments may be interesting probes of certain ADM models. In these models, the IND final state includes a meson and an anti-DM particle, mimicking standard nucleon decays into a meson and a neutrino. Note, however, that bounds from nucleon decay experiments do not directly apply to IND processes, given that the kinematics of the two processes could be quite different. Standard nucleon decays are typically characterized by meson momenta of the order of 300–400 MeV, while in the models in [41, 43] the outgoing IND meson has a momentum $p_M \sim 600–1400$ MeV, depending on whether the process is an up-scattering into a heavier dark state or a down-scattering into
a lighter state. Such differences in kinematics are useful in distinguishing IND events from standard nucleon decays, but could also affect the efficiency of event identification, due to the larger boost of the meson, resulting in the collimation of its decay products or extra Čerenkov radiation [43]. Definitive bounds on these models then likely require a reanalysis of the available data. We also note that chiral perturbation methods are only expected to yield reasonable order-of-magnitude estimates for IND rates, since the momenta of the mesons are ∼1 GeV and an expansion in $p_M/\Lambda_{\text{had}}$, where $\Lambda_{\text{had}}$ is a hadronic scale of the order of 1 GeV, is not very reliable.

An indirect probe of mirror dark models based on leptogenesis as discussed above (and in fact any ADM that uses $B-L$ changing interactions) is via searches for neutron–anti-neutron ($N-\bar{N}$) oscillations [66] in reactors. If $N-\bar{N}$ oscillations are observed at currently accessible sensitivities, this would mean that these $\Delta B = 2$ transitions would have large enough strength to be in equilibrium in the early universe until below the electroweak phase transitions. This in combination with sphalerons will eraze all preexisting baryon asymmetry in the Universe and a new mechanism for generating baryons below the sphaleron decoupling must be invoked; see, for example, [67]. One would then lose the connection between the DM density and baryon density. Observation of $N-\bar{N}$ oscillation will therefore rule out this scenario. Thus a search for $N-\bar{N}$ oscillation could provide some essential information on the origin of DM. On the other hand, since leptogenesis is at the core of this idea, some way of supporting leptogenesis is essential for this mechanism to be viable.

5. Astrophysical implications of asymmetric dark matter

DM in the present Universe is most likely to collect inside massive astrophysical bodies such as stars, neutron stars, etc due to its gravitational interactions as well as scattering on the baryons inside them. In contrast with the standard supersymmetric WIMP DM for which DM pairs annihilate to leptons and neutrinos, the ADM will collect inside the stars over the lifetime of the Universe, as a result of gravitational capture. The presence of DM in significant amounts could affect the properties of stellar objects. Such effects have been considered in several papers [43, 68–71] following the classic work of Spergel and Press [72]. It has been shown that this could affect the transport properties in the interior of the Sun and possibly resolve the composition anomaly [70] which poses a conflict between the helioseismological observations and solar composition [73].

In [43], the destruction of stellar baryons, via IND processes, in models of the type proposed in [41] was studied. Such processes provide extra sources of stellar heating. However, generally speaking, effects of stellar baryon destruction were typically found to be negligible unless the density of the DM at the location of the star is extremely large, $\rho_{DM} \gtrsim 10^{10}$ GeV cm$^{-3}$. Potential bounds from white dwarf heating could be an interesting probe of such models, but are subject to uncertainties in the value of $\rho_{DM}$ at the location of the stellar object.

Another possible effect could occur in neutron stars if the ADM is a scalar particle with low mass (in the range 5–15 GeV). In this case enhanced Bose condensation of gravitationally captured DM in neutron stars could speed up the formation of black holes [69] if the DM neutron cross section is larger than $10^{-47}$ cm$^2$. This will lead to a reduction in the population of neutron stars. For other effects of ADM on the mass and size of neutron stars, see [74]. In particular, if the DM mass is lower than that of baryons, the ground state of the mixed DM neutron star

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4 Preliminary results presented at the conference on ‘Matter to the Deepest’ in Poland, 2011.
could be higher than the Chandrasekhar limit. This would then predict that neutron star masses higher than Chandrasekhar mass should exist in nature.

6. Summary and concluding remarks

In this paper, we have provided an overview of particle physics models in which DM abundance is set by an asymmetry that is related to that of baryons in the visible sector. Such proposals provide an interesting resolution of the puzzle as to why baryon and DM energy densities are of similar magnitudes. ADM models can lead to novel effects that may provide new avenues for their detection, as we have discussed here. These models can also have interesting astrophysical implications since as they accumulate in stars, they do not self-annihilate and may lead to altered stellar dynamics. Depending on the detailed nature of the ADM, it may affect the size and luminosity properties of neutron stars. In some cases, ADM can annihilate ordinary baryons, which leads to heating of stellar objects via baryon destruction. In some ADM models, a number of interesting and testable predictions emerge for collider physics, providing a complementary handle on these proposals.

ADM models will become compelling if it turns out that evidence builds in favor of light (5–10 GeV) DM and other observations put models with light symmetric (WIMP-like) candidates under stress, as has been argued in [75]. Note that in the context of MSSM, a light WIMP DM (with mass less than about 20 GeV) is already not favored [76]. In any event, the nature of DM remains unknown and, in the absence of any clear experimental signal, examination of new scenarios that motivate alternate search strategies is well worth the effort. In this regard, ADM models, a sample of which we discussed in this brief review, deserve attention and can lead to a more comprehensive theoretical, as well as experimental, approach to the mystery of DM.

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