Asymmetric Dark Matter

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Abstract. We review the theoretical framework underlying models of asymmetric dark matter, describe astrophysical constraints which arise from observations of neutron stars, and discuss the prospects for detecting asymmetric dark matter.

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INTRODUCTION

Dark matter accounts for roughly 80% of the matter in the universe. Dark matter models which attempt to naturally explain this dark matter density generally rely on one of two “coincidences.” WIMP models (or WIMPless variants [1]) rely on the fact that, for certain motivated choices of dark matter particle mass and coupling, the relic density [2] which one would calculate from thermal freeze-out is approximately that required by observation. This coincidence is sometimes referred to as the “WIMP Miracle.” Asymmetric dark matter relies on the second coincidence, namely, that the dark matter and baryonic matter densities are similar (they differ by a factor of ∼ 4).

The basic idea of asymmetric dark matter is that the dark matter particle is distinct from the anti-particle, and the current abundance arises almost entirely from one species (conventionally taken as the particle). In this way, dark matter is similar to baryonic matter. A variety of mechanisms have been suggested for generating the asymmetry between baryonic matter and anti-matter. If the same mechanism also generates the asymmetry between dark matter and dark anti-matter, then the number density of dark matter should be simply related to the baryonic number density. If the mass of the dark matter particle is also similar to mass of the nucleon (∼ 1 GeV), then the dark matter and baryon energy densities will be similar. For recent reviews of asymmetric dark matter, see [3, 4].

The two generic features of asymmetric dark matter models are

- dark matter annihilation is suppressed because only the particle is abundant in nature, while the anti-particle is not,
- the dark matter particle is light, with a mass similar to that of the nucleon (though there are exceptions [5] to this result).

In particular, many asymmetric dark matter models may thus be able address recent hints for low-mass dark matter arising from the DAMA [6], CoGeNT [7, 8], CRESST [9] and CDMS [10] experiments.

In these proceedings, we will discuss the theoretical motivations for these features, the classes of models which satisfy the needed criteria, and the impact of these features on asymmetric dark matter constraints and detection possibilities.

THEORETICAL FRAMEWORK

Symmetries. An asymmetric dark matter candidate must be a particle excitation of a complex field, for example, a complex scalar or a Dirac fermion. Only in this case is the particle distinct from the anti-particle. Generically, one expects that this should only be the case if the field is charged under an unbroken U(1) symmetry (or a subgroup of U(1) which rotates the field by a nontrivial complex phase). The charge of the field under this “complexifying” symmetry is what distinguishes the particle from the anti-particle. Another way of seeing this is to note that a complex field will have two degenerate mass eigenstates which correspond the particle and the anti-particle. The complexifying symmetry forbids any terms in the Lagrangian (such as a Majorana mass term) which could split these eigenstates. In the absence of this symmetry, one would generically expect the presence of terms in the Lagrangian which break the degeneracy, resulting in two non-degenerate mass eigenstates, each of which is its own anti-particle.
If dark matter is truly stable, then generically it should be the lightest particle charged under some unbroken symmetry. Although this “stabilizing” symmetry may be the same as the complexifying symmetry described above, it does not have to be. Importantly, the complexifying symmetry cannot be a $\mathbb{Z}_2$ parity, and dark matter need not be the lightest particle charged under it. Dark matter must be the lightest particle charged under the stabilizing symmetry, and that symmetry may be a parity.

**Self-annihilation.** The expectation for asymmetric dark matter is that there is no self-annihilation. Particles can thus only annihilate against anti-particles, which are not abundant in nature. It is easy to see the origin of this expectation; a particle/anti-particle system has no conserved charge which could obstruct the annihilation process, while a particle/particle system has a conserved charge provided the particle is charged under a symmetry which is not a parity. Since asymmetric dark matter is charged under the complexifying symmetry, which is necessarily not a parity, two asymmetric dark matter particles cannot annihilate except to a lighter state with the same charge.

But there is a caveat to this argument. Since dark matter need not be the lightest particle charged under the complexifying symmetry, there is no a priori reason why there should not be a lighter charged state to which two asymmetric dark matter particles could annihilate. Asymmetric dark matter self-annihilation is not forbidden unless the stabilizing symmetry is the same as the complexifying symmetry. If the stabilizing symmetry is instead a parity, then charge under the stabilizing symmetry is only conserved modulo 2; although dark matter decay is forbidden, annihilation would be allowed.

A simple example of this issue, familiar from the Standard Model, is the proton. If we ignore the internal structure of the proton and treat it as a fundamental particle, then the proton is distinct from the anti-proton because of its charge ($+1$) under $U(1)_{EM}$. But this complexifying symmetry is not the stabilizing symmetry, since the proton is not the lightest particle charged under $U(1)_{EM}$ (this is $e^\pm$). The proton is the lightest particle with baryon number, and its annihilation is forbidden if this stabilizing symmetry is also a continuous complexifying symmetry, $U(1)_B$. But if baryon and lepton number were just parity symmetries, then the proton would still be stable, but the process $pp \rightarrow e^+e^+$ would be allowed.

If asymmetric dark matter can self-annihilate with a large enough cross section, then the asymmetry can be washed out. In order for asymmetric dark matter to remain asymmetric, its self-annihilation cross section must be small enough to have frozen out in the early universe, resulting in an asymmetry which persists to the current epoch. Such a small self-annihilation cross section could arise if the stabilizing symmetry were a continuous symmetry which was very weakly broken to a parity. An alternative approach would be for the complexifying symmetry to be very weakly broken, thus implying that the dark matter was “almost” complex [11].

**Particle Mass.** Although asymmetric dark matter does not in principle require a connection between the dark matter and baryon asymmetries, much of the motivation is lost in the absence of this connection. We will thus focus on models for which these asymmetries are related. For such models, it is worth noting that asymmetric dark matter really requires two coincidences. In addition to a mechanism connecting the net dark matter number density to the net baryon number density, one requires a mechanism for relating the dark matter particle mass to the mass of the lightest baryon ($\sim 1$ GeV).

**CLASSES OF MODELS**

For a model of asymmetric dark matter, it is not enough for the particle and anti-particle to be distinguishable; one must also have mechanism for generating the dark matter asymmetry. As with the baryon asymmetry, this amounts to satisfying the Sakharov conditions. There are a vast array of asymmetric dark matter models [5, 12, 13, 14] which satisfy these conditions in a variety of ways.

One loose way of classifying asymmetric dark matter models is by the method for relating the dark matter asymmetry to the baryon asymmetry. Either the dark matter asymmetry could be generated first and then transferred to baryons in some way, or vice versa, or both asymmetries could be generated at the same time by the same mechanism. These classifications are of course somewhat ambiguous, since the definition of dark sector vs. visible sector is sometimes just a matter of taste. One can write a general template for creating a model of asymmetric dark matter as follows:

- **Pick a class:** decide if an asymmetry is first generated in the dark sector, in the Standard Model sector, or in both simultaneously;
• **Pick a generation mechanism:** choose a mechanism for satisfying the Sakharov conditions and generating the initial asymmetry in the chosen sector;

• **Pick a transfer mechanism:** choose a mechanism for transferring the asymmetry, if needed, from the sector where it was generated to the other sector;

• **Pick a mass:** find a mechanism for setting the dark matter particle mass so as to generate the correct dark matter density.

For each of these steps, a variety of possibilities have been studied. Regardless of which sector contains the initial asymmetry, the generation of this asymmetry requires that the Sakharov conditions be satisfied. Mechanisms for generating the initial asymmetry are thus typically generalizations of standard mechanisms for baryogenesis/leptogenesis, and include strongly first-order phase transitions, out-of-equilibrium annihilation or decay, the Affleck-Dine mechanism [15], etc.

The asymmetry can then be transferred from one sector to another by sphalerons, annihilations, co-annihilations, decays, etc. If the asymmetry is being transferred to the Standard Model sector, then this mechanism must violate $B$ or $L$. If it is transferred to the dark sector, then it must violate $D$, where $D$ is a dark sector quantum number which counts the asymmetry between dark particles and dark anti-particles. But this transfer mechanism need not violate $CP$ or include an intrinsic departure from thermal equilibrium, since these conditions have already been achieved with the generation of the initial asymmetry.

Finally, there are some models for which the dark matter mass can naturally be tied to the GeV scale, thus explaining the relic density. For example, for models of mirror matter [13], the dark sector is a mirror copy of the Standard Model sector. In this case, the dark matter candidate is a mirror baryon, and its mass is automatically of the same scale as the Standard Model baryons. In models where asymmetric dark matter is generated from Hidden Sector Baryogenesis [16, 14], the dark matter candidate is chirally charged under a symmetry $U(1)_{T3R}$, under which the right-handed $b$- and $c$-quarks and $\tau$-lepton are also charged. Since all of these fields are chiral under $U(1)_{T3R}$, all of their masses are proportional to the symmetry-breaking scale of $U(1)_{T3R}$. The mass of $b$, $c$ and $\tau$ are all $\mathcal{O}(1-10)$ GeV, implying that the symmetry-breaking scale of $U(1)_{T3R}$, and thus the mass of the dark matter, are similar.

**CONSTRAINTS AND DETECTION POSSIBILITIES**

From the point of view of detection, the main constraints on asymmetric dark matter arise from its relatively low mass and small self-annihilation cross section. We can summarize the difference between asymmetric dark matter and WIMPs, in this context, as follows:

• **Direct Detection:** similar to low-mass WIMP searches. Current sensitivity is greatly degraded for the lighter asymmetric dark matter candidates;

• **Indirect Detection:** no signals expected. A self-annihilation cross section large enough to be detected would erase the dark matter asymmetry;

• **Collider Searches:** similar to low-mass WIMP searches. Sensitivity improves as the dark matter mass decreases;

• **Astrophysical constraints:** asymmetric dark matter which is captured in large astrophysical objects can collapse to form a black hole. Constraints can be placed on the dark matter capture rate by the observation of old neutron stars which have not collapsed.

**Constraints from Old Neutron Stars**

An interesting new feature arising for asymmetric dark matter is the possibility of constraining dark matter-nucleon interactions based on the absence of black hole formation within large astrophysical bodies. The basic idea is a variant of the dark matter search strategy used by neutrino detectors. When a dark matter particle scatters off a nucleus in any dense astrophysical body (such as the sun), it will lose kinetic energy to the nucleus elastic recoil. If the dark matter particle velocity falls below the escape velocity of the astrophysical body, it will be gravitationally captured. After many orbits the dark matter particle will have scattered enough to thermalize, and the dark matter will collect in a dense region near the core of the astrophysical body.

Neutrino detectors search for the neutrinos which are emitted from the sun or earth when dark matter in this dense region annihilates. But what if dark matter annihilation were highly suppressed, as in the case of asymmetric dark
matter? In this case, dark matter would keep collecting within the astrophysical body, with no mechanism for depleting the dark matter. If enough dark matter is captured, the dark matter would become gravitationally unstable to collapse into a black hole. If this black hole grows, it could then destroy the astrophysical body. Observations of astrophysical bodies which have not been destroyed thus place a bound on the dark matter capture rate, and in turn on the dark matter-nucleon scattering cross section.

Several authors have considered this class of constraints [17, 18, 19] for neutron stars in globular clusters. The tightest constraints arise for bosonic asymmetric dark matter, for which there is no Fermi degeneracy pressure to obstruct dark matter collapse. We can briefly summarize the path of this type of analysis:

1. **Dark matter accumulates:** the accumulation rate depends on $\sigma_{nX}$ and $\langle \sigma_A V \rangle$, the dark matter-neutron scattering cross section and the thermally-averaged dark matter self-annihilation cross section, respectively.
2. **Dark matter thermalizes:** if the lifetime of the neutron star is not sufficient for thermalization, then there is no constraint.
3. **Dark matter forms a Bose-Einstein Condensate:** for the relevant parameter space, when sufficient dark matter collects at the neutron star core, it will form a Bose-Einstein condensate (BEC).
4. **Dark matter in the BEC phase crosses the bosonic Chandrasekhar bound:** this bound depends on the dark matter mass, $m_X$, and the strength of self-interactions. Once dark matter crosses this bound, a black hole will form.
5. **The black hole evolves:** a large black hole will grow by accreting baryonic and dark matter. A small black hole will quickly evaporate away. If the black hole will grow large enough to consume the astrophysical body within its lifetime, the point in parameter-space would be ruled out by observation.

We consider an asymmetric dark matter field $\phi$ with self-annihilation cross section $\sigma_A$ and a repulsive $\lambda |\phi|^2/4!$ self-interaction. This interaction is not generically forbidden by any symmetry of the theory, so one does not expect $\lambda$ to be particularly small [18, 19]. We will take the dark matter density within a globular cluster, $\rho_X$, to be $10^7$ GeV/cm$^3$, as a benchmark. The actual density may be much smaller, but this would just result in a rescaling of the constraint on $\sigma_{nX}$.

We can express the Chandrasekhar bound for self-interacting bosonic matter as [20]

$$N_{\text{Chand}} \approx \frac{2m_{pl}^2}{\pi m_X^2} \left( 1 + \frac{\lambda}{32\pi} \frac{m_{pl}^2}{m_X^2} \right)^{1/2}. \tag{1}$$

A black hole will form when the number of particles in the BEC phase exceeds $N_{\text{Chand}}$. If $\lambda$ is extremely small, then $N_{\text{Chand}} \propto (m_{pl}/m_X)^2$, but for natural values of $\lambda$ we instead find $N_{\text{Chand}} \propto \langle \sigma_A V \rangle$, similar to the fermionic Chandrasekhar bound.

$N_{\text{acc}}$, the number of dark matter particles accumulated within the core of the neutron star, is given by

$$N_{\text{acc}} \sim \sqrt{\frac{C_X V_{th}}{\langle \sigma_A V \rangle}} \tanh \left[ \sqrt{\frac{C_X \langle \sigma_A V \rangle}{V_{th} t_{\text{inst}}}} \right]. \tag{2}$$

where $V_{th}$ is the volume of the thermalization region, $t_{\text{inst}} \sim 10$ Gyr is the neutron star lifetime and $C_X$ is the capture rate. The capture rate is proportional to $\rho_X \sigma_{nX}$ [21] provided $\sigma_{nX} \lesssim \sigma_{\text{sat}} \sim 2.1 \times 10^{-9}$ pb. A bound on $N_{\text{acc}}$ can thus be rephrased as a bound on $\sigma_{nX}$, which can be compared to results from direct detection experiments. But it is important to note that, for $\sigma_{nX} \gtrsim \sigma_{\text{sat}}$, all dark matter particles which reach the neutron star scatter against it; as a result, increasing $\sigma_{nX}$ cannot increase the capture rate any further. Thus, if dark matter is not excluded for $\sigma_{nX} \leq \sigma_{\text{sat}}$, then there exists no value of $\sigma_{nX}$ for which it is excluded.

In figure 1 [18], we plot bounds on $\sigma_{nX}$ arising from observations of old neutron stars in globular clusters for a variety of choices for $\langle \sigma_A V \rangle$ and $\lambda$. One can see that as $m_X$ increases, constraints on $\sigma_{nX}$ initially become tighter because fewer dark matter particles are needed for black hole formation. But for large enough $m_X$, constraints on $\sigma_{nX}$ become very weak because the black hole which is formed is so small that it evaporates away unless the black hole can capture dark matter rapidly enough to “feed” the black hole and keep it growing. For this reason, an extremely small

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1. Note, such a quartic interaction can be forbidden in some supersymmetric theories, but will in general be generated by terms which break supersymmetry [19].
self-interaction coupling \( \lambda \) can cause these constraints to be slightly tighter; self-interaction causes a the formation of a larger black hole, which can then grow to consume the neutron star. But for even a moderate value of \( \lambda \), a black hole will never form. Similarly, for \( \langle \sigma v \rangle \gtrsim 10^{-12} \) pb, dark matter depletion will be rapid enough that a black hole will never form. Thus, even a self-annihilation cross section which is so small as to be unobservable at any current or anticipated experiments would completely eliminate any constraints from neutron star observations.

We see that these bounds can be tightly constraining for the case of bosonic dark matter, especially in the low-mass region which would be relevant for the data of DAMA, CoGeNT, CRESST and CDMS. But for this to be the case, the stabilizing symmetry must also be a complexifying symmetry (thus forbidding self-annihilation); if it is broken to a parity, it must be broken extremely weakly. Likewise, these constraints are only relevant if self-interactions are either non-existent or attractive.

If we had instead chosen \( \rho_X \sim 0.3 \) GeV/cm\(^3\), the constraint on \( \sigma_{nX} \) would be weakened by a factor \( \sim 3000 \). Interestingly, asymmetric dark matter can also be constrained by its effect on stellar evolution [22]. In particular, a large density of asymmetric dark matter in the core of the sun can lead to a change in the expected solar neutrino flux which differs from observation. Since the ambient dark matter density near the solar system is much less uncertain than in globular clusters, this type of analysis of solar evolution provides a nice complement to bounds based on old neutron stars in globular clusters.

**FIGURE 1.** Constraints on bosonic asymmetric dark matter, in the \((m_X, \sigma_{nX})\) plane, arising from observations of old neutron stars in globular clusters. We assume a globular cluster density \( \rho_X \sim 10^3 \) GeV/cm\(^3\). The red, green, blue, and purple contours (from left to right) denote \( \lambda = \{0, 10^{-30}, 10^{-25}, 10^{-15}\} \), respectively. Solid, dotted, dashed, and dot-dashed contours denote self-annihilation cross sections \( \langle \sigma v \rangle = \{0, 10^{-50}, 10^{-45}, 10^{-42}\} \) cm\(^3\)/s, respectively. In the gray region, dark matter does not thermalize within the lifetime of the neutron star.
Detection Strategies and Sensitivities

For $m_X \lesssim \mathcal{O}(10)$ GeV, current direct detection experiments tend to rapidly lose sensitivity. For such models collider-based searches may provide the best possibility for detection. Colliders can search for direct dark matter pair production, through the same contact operator which mediates dark matter-nucleon scattering interactions [23, 24]. These “mono-anything” searches will produce missing transverse momentum from the dark matter pair, along with some radiated Standard Model particles which recoil against the dark matter pair. Alternatively, colliders can produce heavy exotic particles which are charged both under $SU(3)_{QCD}$ and under the dark matter stabilizing symmetry. The cascade decay of these heavy exotic particles will produce Standard Model jets, plus missing transverse momentum.

An advantage of direct collider searches is that they probe the same effective contact operators which mediate direct detection, thus potentially allowing one to correlate data from the two detection strategies. An advantage of cascade searches, however, is that they are based on the production of QCD-coupled particles, a task at which hadron colliders excel. But in the context of asymmetric dark matter, an advantage of both search strategies is that they increase in sensitivity for low-mass dark matter, since it is easier to produce low-mass dark matter at a collider.

For asymmetric dark matter at the lower end of the expected mass range, colliders may thus provide the best sensitivity. Future direct detection experiments may also begin to become sensitive to this region of parameter space, but only for detectors using lighter target materials (to maximize the recoil energy arising from the scattering of a low-mass dark matter particle) and for detectors with lower recoil energy thresholds.

Asymmetric dark matter in the $5 - 20$ GeV range could potentially explain the data from DAMA, CoGeNT, CRESST and CDMS. These low-mass signals are in some tension with bounds from XENON100 [26], and there has much recent work on potential resolutions of this tension arising from deviations from typical assumptions about dark matter interactions and astrophysical distributions [27, 28]. Most of these results also hold for asymmetric dark matter models.

Asymmetric dark matter models which are relevant for the low-mass direct detection signals are tightly constrained by LHC monojet searches [25]. However, the sensitivity of such searches depends in detail on the spin of the dark matter particle, the choice of effective operator, as well as the flavor structure of the quark couplings. Different choices can lead to a dramatic weakening of these constraints, allowing consistency between the low-mass direct detection signals and LHC bounds [24, 29]. Moreover, if the particle mediating the interaction has a relatively small mass ($\sim 1$ GeV), then the scattering interaction may still be short-ranged, while the effective operator approximation will not be valid for dark matter production at the LHC. For such models, monojet signals may be significantly suppressed, though it may be possible to directly produce the mediating particle at colliders [30].

Although asymmetric dark matter may potentially explain the low-mass direct detection signals, it cannot explain the potential gamma-ray excess from the galactic center [31]. Although this excess could be consistent with low-mass dark matter, an annihilation cross section large enough to produce these signals would erase any dark matter asymmetry.

OUTLOOK

It is interesting to consider how one may distinguish asymmetric dark matter from a more standard WIMP candidate. As we have seen, the main features one would expect from asymmetric dark matter are a low-mass particle with no indirect detection signatures. However, such a signature could also be reproduced by a particle with $p$-wave suppressed annihilation. In this case, a distinguishing signature may arise from dark matter searches at neutrino detectors.

Neutrino detectors search for the neutrinos which arise when dark matter annihilates in the core of the sun. If the sun is in equilibrium, then the rate at which dark matter is captured is the same as the rate at which it is annihilated. The key point here is that, if the sun is in equilibrium, then the annihilation rate is independent of the annihilation cross section because the annihilation rate is equal to the capture rate, which is determined by the scattering cross section. In particular, a very small annihilation cross section would imply a very large equilibrium density. As a result, even dark matter with a very small annihilation cross section can still yield a detectable neutrino rate, provided the dark matter is in equilibrium.

If dark matter has a small mass, the ambient number density will be very large. As a result, dark matter with a scattering cross section large enough to explain the low mass direct detection data could be in equilibrium even if $\langle \sigma v \rangle \lesssim 0.01$ pb [32, 33]. As a result, low-mass dark matter with a largely $p$-wave annihilation cross section and very small $s$-wave contribution (perhaps arising from chirality-suppressed annihilation to $b$-quarks or $\tau$-leptons) can still yield a large event rate at neutrino detectors.
On the other hand, if low-mass dark matter is found using direct and collider search strategies, but low-energy events are not seen at neutrino detectors, this implies that the annihilation cross section is indeed very small. While by no means determinative, this may perhaps provide evidence suggesting that dark matter is asymmetric, with an annihilation cross section which is more heavily suppressed than \( p \)-wave/chirality suppression.

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