Boosting Assisted Annihilation for a Cosmologically Safe MeV Scale Dark Matter

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ABSTRACT: Assisted annihilation generates thermal sub-GeV dark matter through a novel annihilation between a pair of dark matter and one or more SM-like states, called the \textit{assisters}. We show that depending on the mass hierarchy between the assister and dark matter there can be either a suppression or a boost from the Boltzmann factor in the effective cross section. This augmentation enables the possibility of MeV scale thermal dark matter with perturbative coupling that saturate the relic density estimates while being relatively insulated from cosmological constraints like BBN and CMB.

KEYWORDS: dark matter theory, dark matter simulations
1 Introduction

The landscape of particulate interpretation of dark matter (DM) is dominated by the weakly interacting massive particles (WIMP) that can explain the astrophysically measured dark matter abundance with masses in the GeV scale. The WIMPs, which fits well within the ΛCDM framework, have been increasingly constrained from a synergy of non-observation in direct and indirect detection experiments. Additionally the small-scale crisis [1, 2] in the ΛCDM arising from the mismatch between observations and simulations, calls for DM properties different than WIMPs. While the direct detection experiments leave comfortable breathing space for sub-GeV light dark matter (LDM), they are also well-suited for the explanation of the galactic scale structure formation issues possibly with the introduction of self-interaction [3]. Unlike the conventional two-body annihilations a \( N(\geq 3) \rightarrow 2 \) process driving thermal freeze-out in the early universe, can naturally lead to LDM [4–9]. This type of annihilation process can be relevant if (i) the 2-body cross section is forbidden or strongly suppressed, (ii) densities of the annihilating species are appreciable and (iii) lower relative velocity of the interacting particles [10]. One novel example of this class of models is the assisted annihilation where along with DM particles there are standard model(SM)-like assisters in the initial state facilitating the annihilation of LDM [11]. Scenarios where freeze-out is dominated by assisted annihilation with \( 4 \rightarrow 2 \) and \( 3 \rightarrow 2 \) topologies are shown to accommodate DM masses in the keV and MeV range respectively, that satisfy the observed relic abundance.

In this paper we focus on the generic features of the assisted annihilation mechanism in light of stringent constraints on LDM from big bang nucleosynthesis (BBN) and cosmic microwave background (CMB). The \( 4 \rightarrow 2 \) annihilation scenario implies a keV range DM
which may entail non-perturbative couplings and are strongly constrained from CMB observations. Thus, we focus on $3 \to 2$ assisted annihilation scenario that can lead to MeV scale DM. The mass hierarchy between the DM and the assisters regulates the Boltzmann factor resulting in a boost or a suppression of the effective thermally averaged annihilation cross section. We show that depending on the mass hierarchy between the assister and the DM, the allowed mass range for DM can be enhanced. The Boltzmann boost, generated when the assisters are lighter that the DM, can raise the allowed mass of the DM up to hundreds of MeV while maintaining constraints from relic density, perturbativity etc. This may be contrasted with usual co-annihilation where the DM being necessarily the lighter particle the effective cross section is suppressed by the Boltzmann factor. However due to the existence of additional sub-GeV degrees of freedom in terms of the DM and the assister there may be strong constraints from BBN and CMB. Crucially the presence of not only a relatively light DM particles but also the light assisters which can decay to SM particles is capable of altering the primordial light elements' abundances i.e., BBN observations. The consonance in the baryon to photon ratio ($\eta$) measurement from BBN and CMB and the $N_{\text{eff}}$ measurements from CMB put additional constraints. We make a systematic study of these constraints to present allowed parameter space of a real scalar assisted annihilation framework that simultaneously satisfy the bounds from relic density and perturbativity while being insulated from the cosmological constraints. We present our results in a model-independent framework for a $3 \to 2$ assisted annihilation scenario before briefly sketching out an explicit model for this framework.

2 Effective Parametrization for Assisted Annihilation

Once it is pared down, this framework includes a stable particle $\phi$ which is the DM candidate and an assister $A$. While the $\phi$ particles are stable due to some underlying stabilizing (e.g., $Z_2$) symmetry, the assisters $A$ can decay to SM particles. Therefore after chemical decoupling the number density of assisters starts depleting and essentially becomes zero at the present time. We will confine ourselves to real scalar DM and assister only. In this framework the dominant DM annihilation takes place through the processes where two (or more) DM and one (or more) number of assisters are in the initial state and two (or more) SM or SM-like states are in the final state. Thus the relic density is controlled by $N \to 2$ annihilation processes. This can arise in scenarios where all other lower order processes are suppressed. With increasing number of initial state particles, for annihilation to occur in an appreciable rate one must have a large flux of incoming particles which tantamounts to having large couplings or very light DM. Evidently, the large couplings bring in the perturbativity issues [12] and ultralight DM has severe constraints from BBN and CMB observations [13]. To enjoy optimum freedom form these bounds we focus on the $3 \to 2$ assisted annihilation scenarios. A schematic representation of assisted annihilation mechanism is shown in figure 1a. Remaining agnostic with the details of the model we can
parametrize the relevant thermally averaged cross sections as,

$$
\langle \sigma v \rangle_{\phi A \rightarrow SM} = \frac{\alpha_1^2}{m_\phi},
$$

$$
\langle \sigma v \rangle_{AA \leftrightarrow \phi \phi} = \frac{\alpha_2^2}{m_\phi^2}, \quad \langle \sigma v \rangle_{AA \rightarrow SM SM} = \frac{\alpha_3^2}{m_A^2},
$$

where $\alpha_{1,2,3}$ are corresponding couplings while $m_\phi$ and $m_A$ are the masses of DM and assister respectively. In the rest of the paper we will focus on the region of parameter space where the $3 \rightarrow 2$ assisted annihilation processes has the dominant contribution to relic density calculations. For this we will assume $\alpha_1 \gg \alpha_2 \sim 10^{-6}$. A specific realization that naturally leads to these choices will be presented later in this paper. Note that the DM relic density is relatively independent of $\alpha_3$ and the assister decay rate $\Gamma_{A \rightarrow SM SM}$. With these parametrization we now go on to discuss the coupled Boltzmann equations for $\phi$ and $A$ relevant for the calculation of DM relic density.

### 3 Relic Density

The rate of the assisted annihilation at any instant depends on the number density of DM particles as well as assisters. Therefore, to determine the present day relic abundance of the DM particles we need to keep track of the evolution of number densities of both the DM particles and assisters. This mandates a numerical solution of the coupled Boltzmann equations involving number densities of both the species. The coupled Boltzmann equations in terms of co-moving number densities of DM ($Y_\phi = n_\phi/s$) and assister ($Y_A = n_A/s$) in

![Figure 1](a) Block diagram of a typical $3 \rightarrow 2$ assisted annihilation channel. (b) Boltzmann factor $N_{Bolt}$ as a function of mass ratio between assister and DM mass for various $x$ with $3 \rightarrow 2$ assisted annihilation.
terms of the parametrization given Eq. (2.1), can be written as,

\[
\frac{dY_\phi}{dx} = -\frac{xs^2}{H}s\frac{g_A^{1/2}}{45}N_{\text{Bolt}}(\sigma v^2)_{\phi A}\rightarrow SM \left( Y_\phi^2 - \left( \frac{Y_\phi^{eq}}{Y_\phi^{eq}} \right)^2 \right) + \frac{xsg_A^{1/2}}{H}(\sigma v)_{AA}\rightarrow \phi \phi
\]

\[
\times \left\{ \Theta(m_A - m_\phi) \left( \left( \frac{Y_A Y_\phi^{eq}}{Y_\phi^{eq}} \right)^2 - \Theta(m_\phi - m_A) \left( \frac{Y_\phi^{eq}}{Y_\phi^{eq}} \right)^2 \right) \right\},
\]

(3.1a)

\[
\frac{dY_A}{dx} = -\frac{xs^2}{H}(\sigma v)_{AA}\rightarrow SM \left\{ Y_A^2 - \left( \frac{Y_A^{eq}}{Y_A^{eq}} \right)^2 \right\} - \frac{g_A^{1/2}}{xH}(\sigma v)_{AA}\rightarrow SM \left( Y_A - \frac{Y_A^{eq}}{Y_A^{eq}} \right)
\]

(3.1b)

with \( N_{\text{Bolt}} = e^{2(1-\epsilon)/3} \), \( g_A^{1/2} = 1 + \frac{1}{3} \frac{d(\ln g_s)}{d(\ln T)} \).

(3.1c)

In these expressions \( x = m_\phi/T \), \( \epsilon = m_A/m_\phi \), entropy density \( s = 2\pi^2 g_s T^3/45 \), Hubble constant \( H = \sqrt{\pi^2 g_s/90} \left( T^2/M_{Pl} \right) \), \( g_s \) and \( g_\rho \) are the effective number of relativistic degrees of freedom corresponding to entropy and energy density respectively. In these equations we have taken into account of the temperature dependence of \( g_s \) and \( g_\rho \), and consequently of \( g_\star^{1/2} \). The relevant temperature dependencies are adopted from Ref. [14]. The parameter \( N_{\text{Bolt}} \) modulates the annihilation cross section of the process and physically it reflects the fact that assisted annihilation can continue as long as the number density of both the DM and the assister are appreciable in the early universe. The variation of \( N_{\text{Bolt}} \) against the mass ratio of assister and DM, \( \epsilon \), has been depicted in figure 1b. From this figure it is evident that either there will be a boost or a suppression depending on mass hierarchy between DM and assister. A systematic discussion of both scenarios is now in order.

### 3.1 Case I \((m_\phi < m_A)\)

This is the typical case where the DM is the lightest particle in the initial state and can be viewed as a generalization of the co-annihilation topology. With the evolution of the Universe, the equilibrium co-moving number density of a species falls as \( \sim \exp(-m/T) \) (where \( m \) is the mass of the species). This implies that lower the value of \( m \) larger the number density of the species for a given temperature. Therefore for \( m_\phi < m_A \) smaller number of assisters are available in the thermal soup to interact with the DM. This leads to a suppression in the effective cross section through \( N_{\text{Bolt}} \). The figure 1b illustrates this where we see that the value of \( N_{\text{Bolt}} \) gradually decreases with increasing \( \epsilon \). Note that, the final relic density of the DM does not depend on lifetime of the assister.

With this mass hierarchy, a freeze-out driven by assisted annihilation would require DM and assister masses to be relatively degenerate. A relatively large mass hierarchy would
lead to a Boltzmann suppression pushing the viable thermal DM mass to keV range, which faces strong constraint from BBN, CMB etc. In figure 2 we show the relic density allowed region for \( m_\phi < m_\Lambda \) in \( m_\phi \) vs. \( \alpha_1 \) plane by the light brown band. As is demonstrated in figure 2, BBN constraints and perturbativity considerations place the DM mass to be between 1 – 30 MeV.

### 3.2 Case II \((m_\phi > m_\Lambda)\)

One of the distinguishing feature of the assisted annihilation set-up is that the DM and the assister are not charged under the same stabilizing symmetry. Thus in contrast to the usual co-annihilation scenario it is not mandatory that the lightest species of the spectrum be the DM. We may have a scenario where the mass of the DM particle is greater than the assister, i.e., \( m_\phi > m_\Lambda \). Such a scenario shows an interesting evolution of the co-moving number densities of allied species of DM and assisters. Since assister(s) are lighter than the DM, in the thermal soup a large number assisters are available to interact with the DM during the phase of freeze-out. This results in a boost in the interaction rate, which is also evident from figure 1b. We call this a Boltzmann boost. We find that this helps to keep the DM mass in the range of hundreds of MeV while satisfying the required relic abundance. This has been depicted in figure 2. The orange band in figure 2 represents Planck \([15]\) relic density allowed region for \( m_\phi > m_\Lambda \). This boost is crucial for viable DM masses beyond 30 MeV with perturbative couplings. As is evident from figure 3 as \( \epsilon \) decreases the boost increases allowing assisted annihilation to saturate the relic density bound with smaller couplings. This facilitates a natural \( \mathcal{O}(100) \) MeV thermal DM within the \( 3 \rightarrow 2 \) annihilation framework with perturbative couplings. This is an unique element of the assisted annihilation set-up which we will now show to be crucial to evade all cosmological
4 Cosmological Constraints

Presence MeV scale light species can effect the BBN and CMB observations in two ways. (i) Existence of a particle species with mass less than a few MeV will increase the Hubble expansion rate which in turn modifies the freeze-out time of neutron-proton interaction which increases the $^4$He abundance. The BBN constraint [13] from this is shown as the light red region in figure 2 and pushes the masses of both DM and the assisters to be greater than $\sim 1$ MeV. (ii) Subject to the lifetime, various decay modes of the assister will also alter BBN and CMB observations. Note that BBN or CMB constraints on such decaying species put upper bound in the pre-decay yields for a given lifetime. We will make the conservative assumption that the DM freeze-out via assisted annihilation is the dominant operative process that keep the assisters in thermal equilibrium. To constrain such scenario we take the assister yields at the time of DM freeze-out which is calculated at $n_{eq}^\phi n_{eq}^A \langle \sigma v^2 \rangle_{\phi \phi A \rightarrow SM SM} = H$. If the predominant decay mode of the assister is to photons or light leptons or hadrons then that leads to change light elements abundance. Note that a direct coupling to light leptons inhibited by the corresponding $g - 2$ measurement [11], therefore we will not consider light leptonic decay modes here. Since the assister’s mass is only a few hundreds of MeV and hadronic decay channels are phase space suppressed we concentrate on photophilic assisters in the rest of the discussion.

Cosmological constraint on electromagnetically decaying particle has been studied extensively in the literature [16–22]. We follow the prescription of [20] to calculate the non-thermal photon spectra arising from the decay of the assisters and incorporate the photo-dissociation processes of D, $^3$He and $^4$He [18] in AlterBBN v2.0 [23, 24] along with the additional contribution to the Hubble parameter to compute the light element abundances in the presence of the light DM-assister states. The most stringent constraint for an assister of mass 60 MeV comes from the D photo-dissociation and not from $^3$He or $^4$He photo-dissociation [13]. Note that the assister abundance, $n_A/n_\gamma$ at the time of DM freeze-out for dotted and dashed blue lines of figure 3 refer to $\sim 2 \times 10^{-3}$, $\sim 10^{-4}$ and the maximum allowed lifetime from D photo-dissociation are $\tau_{\text{max}} \sim 4 \times 10^3, 5 \times 10^3$ s respectively. Further the decay of the assister into photon shall reheat the photon bath in comparison to neutrino. This may lead to the reduction of effective number of relativistic degrees of freedom $N_{\text{eff}}$. We have calculated this effect following [25] and compared with the combined bound of $N_{\text{eff}} = 3.13 \pm 0.32$ [26] to constrain the allowed assister yields at the assisted DM freeze-out. For blue dotted contour of figure 3 the constraint is $10^2$ s while for the blue dashed contour it is sub-dominant compared to other constraints. The decay of the assister after BBN leads to entropy injection which shall change the baryon to photon ratio ($\eta$). This effect has been calculated through the fractional change in the entropy [20, 27]

$$ \frac{\Delta S}{S} \simeq 2.14 \times 10^{-4} \frac{m_A}{10^{-9} \text{ GeV}} \left( \frac{n_A}{n_\gamma} \right) \left( \frac{\tau}{10^6 \text{s}} \right)^{1/2} , $$

(4.1)
Figure 3: BBN constraint on the lifetime for assister of mass \( m_A = 60 \) MeV. The black solid line represents the relic density allowed value. The blue dotted and dashed contours show the maximum allowed lifetime 5s and \( 10^3 \) s with \( n_A/n_\gamma = 2 \times 10^{-5}, 10^{-4} \) respectively, at the DM freeze-out. The grey dashed line shows the perturbative bound on the effective coupling.

where \( n_A/n_\gamma \) is calculated at the DM freeze-out. A tolerance of 5% change in the entropy to be compatible with BBN and CMB observation, the maximum allowed lifetime of the assister are 5 s and \( 10^3 \) s for the dotted and dashed contours in figure 3. The most stringent limit on the lifetime of a assister of mass 60 MeV arise from entropy injection which has been depicted in figure 3.

5 Model Sketch

We present a toy model for the effective framework that we have explored in this paper. Consider scalar DM state \( \phi \) with mass \( m_\phi \), an assister \( A \) of mass \( m_A \) and a relatively heavy mediator \( S \) having mass \( m_S \). The relevant part of the Lagrangian reads as follows,

\[
\mathcal{L} \supset \lambda_1 \phi^2 S A + \lambda_2 S^2 A^2 + \lambda_3 S A^2 + \frac{\lambda_4}{f} A F^{\mu\nu} F_{\mu\nu},
\]

where \( F_{\mu\nu} \) is the usual electromagnetic field strength tensor. The photophilic decay of the assister may proceed to SM fermion loops as sketched out in [11]. The DM state is stabilized by the discrete \( Z_2 \) symmetry \( \phi \rightarrow -\phi \) while both the assister and the mediator can decay to SM states.

In the region of parameter space of interest the other interactions between the assister and the mediator with SM and with each other is assumed to be absent or negligible. The \( 3 \rightarrow 2 \) assisted annihilation processes \( (\phi\phi A \rightarrow AA) \) can occur through \( S \) mediation as shown in figure 4. As pointed out in [10], we can also have a \( 2 \rightarrow 2 \) process \( \phi\phi \leftrightarrow AS \).
that would usually dominate over the $3 \to 2$ assisted annihilation to control the freeze out. However, in the limit $m_S \gg m_A, m_\phi$ the forward rate of $\phi\phi \leftrightarrow AS$ has phase space suppression and backward rate has Boltzmann suppression from the comparatively large mass difference between the mediator $S$ and the assister $A$. For example for a DM and assister mass of 200 MeV and 100 MeV respectively, $m_S > 500$ MeV the channel $\phi\phi \leftrightarrow AS$ becomes ineffective. This will leave the $\phi\phi A \to AA$ assisted annihilation dominant in driving freeze-out and setting the relic density. For the aforementioned values of masses one can achieve the required relic density with $\lambda_1 \sim 1$ and $\lambda_3 \sim 1$ whereas upper bound on the coupling $\lambda_4/f$ can be obtained by the maximum allowed lifetime of the assiter.

6 Summary and Conclusion

The mechanism of assisted annihilation accommodates appropriate freeze-out for light dark matter with the help of the assisters in the initial state. The DM mass can be in keV to MeV for $4 \to 2$ and $3 \to 2$ processes respectively. In this paper, we show that when assister(s) are lighter than the DM a Boltzmann boost can significantly enhance the contribution of the assisted annihilation and push the the viable DM mass to be as high as $\sim O(100)$ MeV with perturbative couplings for $3 \to 2$ annihilations topology. Although a DM particle with this type of mass range do not affect BBN but the decay of lighter assister species plays a crucial role in the BBN and CMB. We perform an extensive numerical simulations of BBN and $N_{\text{eff}}$ to demonstrate that boosted assisted annihilation parameter space can easily evade these cosmological bounds while satisfying the observed relic density within the LDM framework. Inclusion of self interactions within this scenario can provide a handle on galactic scale structure formation issues.

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