Dark Matter Freeze-out via Catalyzed Annihilation

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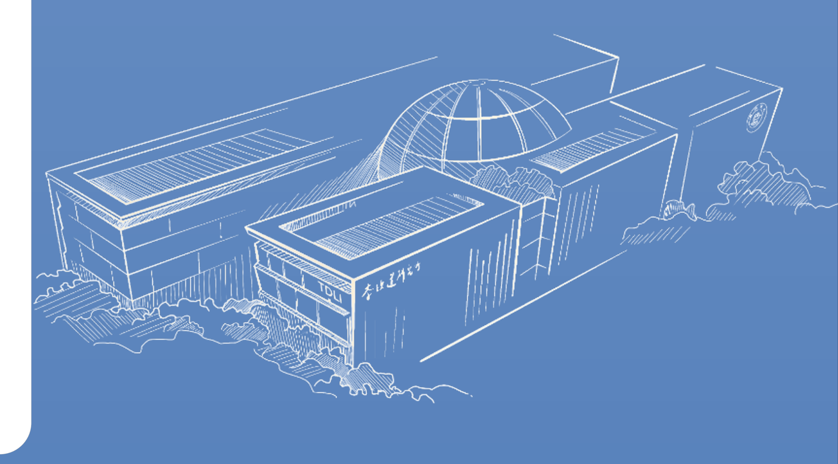


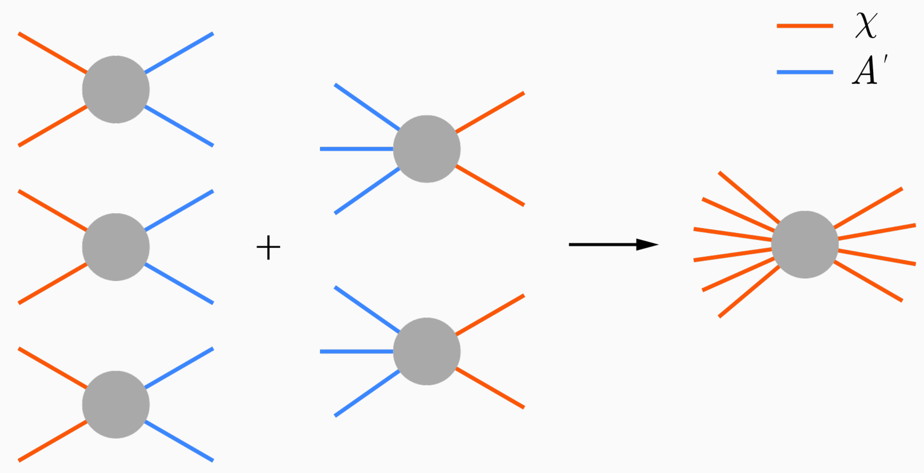
Abstract

We present a new paradigm of dark matter freeze-out, where the annihilation of dark matter particles is catalyzed. We discuss in detail the regime that the depletion of dark matter proceeds via $2\chi \to 2A'$ and $3A' \to 2\chi$ processes, in which χ and A' denote dark matter and the catalyst respectively. In this regime, the number density of dark matter decreases in power-law before freeze-out, rather than an exponential decrease due to Boltzmann suppression, as is the case with classical WIMPs and SIMPs. The paradigm applies for a secluded weakly interacting dark sector with a dark matter in the MeV − TeV mass range. It is consistent with constraints from both the Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN), and it predicts enhanced signals for indirect detection.

1. Introduction

In the freeze-out scenario of thermal dark matter (DM), DM particles remain in thermal and chemical equilibrium at high temperature. As the universe cools down, when the rate of processes that keep DM in equilibrium drops below the expansion rate of the universe, DM abundance becomes a constant. There are essentially two kinds of process that lead to the depletion of DM particles during freeze-out. The first process involves the annihilation of DM particles into other particles, primarily SM particles. The most well-known example of this process is the Weakly Interacting Massive Particles (WIMPs) paradigm. The second process involves number-changing process of DM and is exemplified by Strongly Interacting Massive Particles (SIMPs).

Here we present a new pattern of dark matter burning in the early universe, where the abundance of dark matter is determined by *catalyzed* processes [1]. We study a simple paradigm of catalyzed annihilation with two processes leading to depletion of DM particles: $2\chi \to 2A'$ and $3A' \to 2\chi$, where χ and A' denote dark matter and the catalyst respectively. We show in the figure below how these annihilation channels result in depopulation of DM particles, that is, three $2\chi \to 2A'$ processes together with two $3A' \to 2\chi$ effectively deplete two DM particles.



The thermal evolution in this paradigm is unique. Before freeze-out, DM number density will experience a power-law decreasing, as the universe cools down,

$$n_\chi \propto T^{9/2}, \quad (1)$$

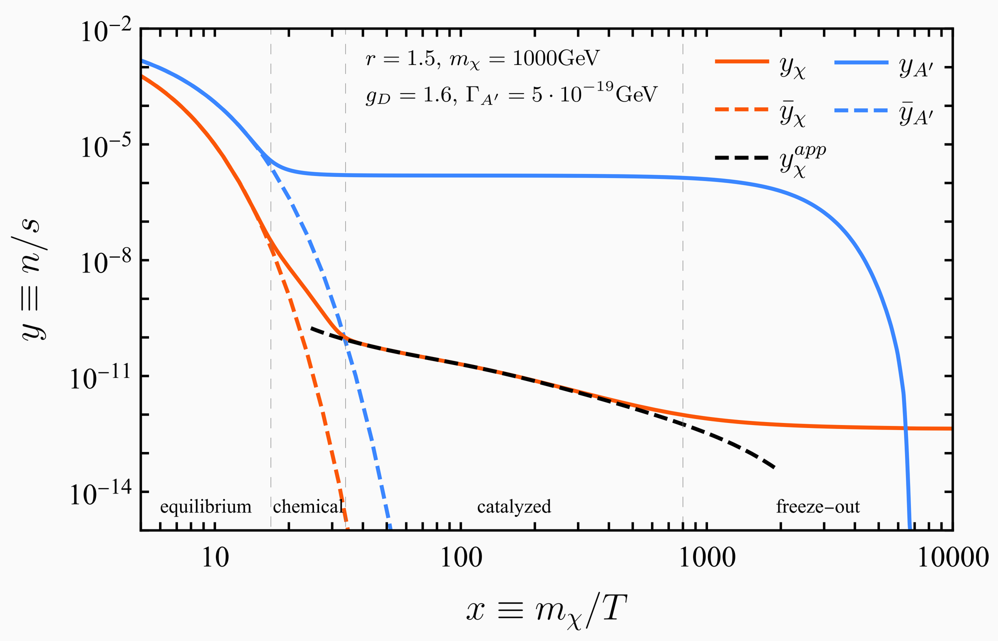
Consequently, the catalyzed annihilation lasts longer and freezes-out at late times.

2. Catalyzed Freeze-out

In catalyzed annihilation scenario, the dark sector should be secluded so that the annihilation channels to SM particles are subdominant. The catalyst should be lighter than DM and long-lived so that its number density is large and the $3A' \to 2\chi$ process is not suppressed. If A' decays fast, the paradigm recovers to the secluded DM regime [2, 3].

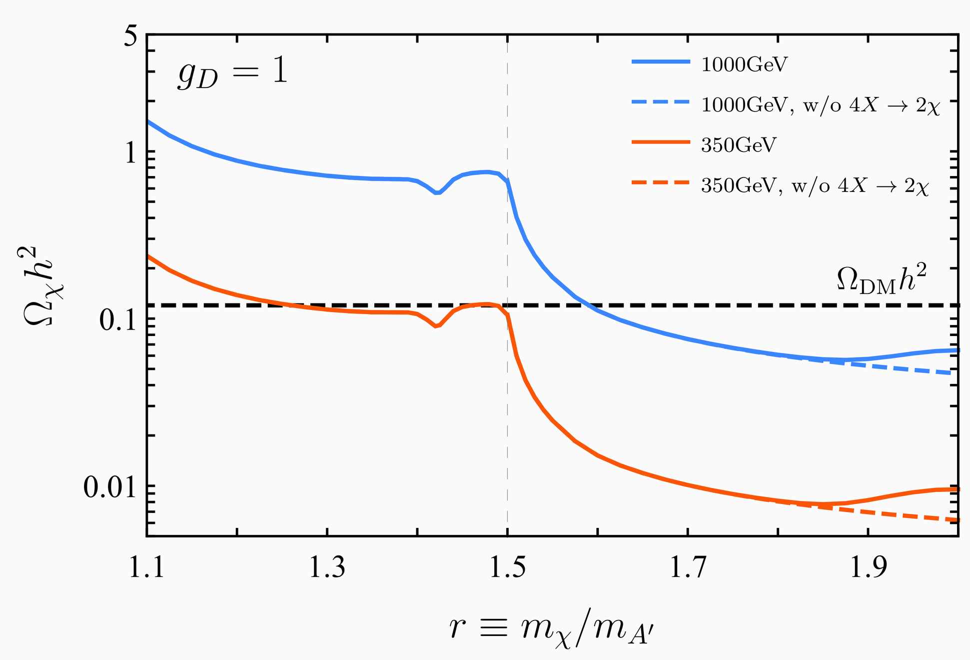
We show in the figure below a typical thermal history of dark matter that freezes-out via catalyzed annihilation. There are mainly four stages:

1. *Equilibrium stage.* Both χ and A' stay in chemical equilibrium,
2. *Chemical stage.* χ and A' are chemically decoupled from SM particles, but they can still maintain chemical equilibrium with each other via the $2\chi \leftrightarrow 2A'$ process.
3. *Catalyzed annihilation.* The $2A' \to 2\chi$ process fades away, and the $3A' \to 2\chi$ process dominates over it. The evolution of DM number density is now controlled by the catalyzed annihilation, i.e. $2\chi \to 2A'$ and $3A' \to 2\chi$. In this stage, n_χ decreases in power-law with respect to temperature.
4. *Freeze-out.* The rate of the catalyzed annihilation descends and dark matter freezes-out.



3. Mass Ratio

We concentrated on the mass ratio $r \equiv m_\chi/m_{A'} \leq 1.5$ above. When $r \lesssim 2$, it is intriguing to notice that the $4A' \to 2\chi$ process may play a part in the catalyzed annihilation. There will be an extra stage in the thermal evolution of dark matter where $4A' \to 2\chi$ takes over the role of converting A' to DM particles since the cross section of $3A' \to 2\chi$ would be exponentially suppressed at low temperature when $r > 1.5$. Neglecting this $4 \to 2$ process will result in underestimate of the dark matter relic abundance, as shown in the figure below.



For even larger mass ratio, we expect the processes with more catalysts annihilating to two DM particles, e.g. $5A' \to 2\chi$, to possibly play a role in the catalyzed annihilation, especially when the dark sector is strongly coupled.

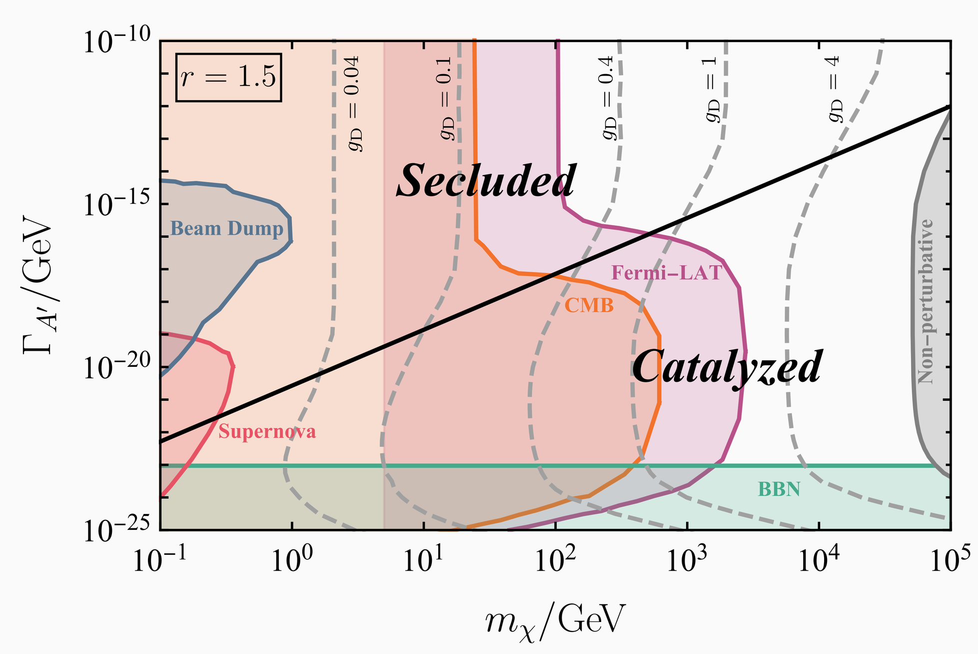
4. A Model

As an example of catalyzed annihilation, here we present a simple dark photon model [4, 5] with a Dirac fermion χ charged under a novel $U(1)'$ gauge group and A' being the gauge field. The dark photon can be kinetically mixed with SM hypercharge field,

$$\mathcal{L}_{\rm mix} = -\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu}B^{\mu\nu}. \quad (2)$$

We show in the figure below the different phases for the model in the calculation of DM relic abundance. For short-lived dark photon, it stays in equilibrium with SM particles before freeze-out. This is the secluded phase of the model. When the dark photon width $\Gamma_{A'}$ is small, the catalyzed annihilation emerges.

The model is constrained by numerous terrestrial and celestial experiments and observations, including CMB, BBN, indirect detection of dark matter, beam-dump experiments and supernova cooling. They are all shown in the figure.



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