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Self-interacting dark matter from late decays and the H_0 tension

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We study the production mechanism of self-interacting dark matter based on decays of a messenger WIMP-like state into dark matter and dark radiation taking place after the recombination. Such transition leads to a mild relaxation of the Hubble tension while simultaneously having the potential of addressing small-scale structure problems of ΛCDM. We illustrate the mechanism within a Higgs portal dark matter model which we find to be a promising avenue.

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1. Introduction

The standard model of cosmology incorporates dark matter (DM) as a cold noninteracting matter component with a constant equation of state which leads to remarkably successful description of the Universe [2], especially at large scales. However, at smaller scales severe discrepancies between theoretical predictions based on such assumptions and observations were observed [3]. Moreover, recent advances in observational cosmology identified another source of tension within the ΛCDM, most notably the values of the Hubble rate parameter, H_0, [4] and to lesser extend the 'clumpiness' parameter, $S_8 = \sigma_8\,(\Omega_{\rm matter}/0.3)^{0.5}$.

2. The mechanism

It is well-known that self-interactions within the dark sector (DS) provide a better fit to galactic-scale data than ΛCDM [5]. Moreover, transforming a small fraction of DM into radiation has been shown [6] to significantly reduce the H_0 tension - but also note recent review of H_0-tension solutions [7] for updated analysis. It is interesting to ponder whether modification of only the DM component can provide a solution to both small and large-scale problems of ΛCDM. In light of this, we propose a mechanism of self-interacting DM (SIDM) production taking place through late decays of a messenger WIMP-like state mainly into SIDM, but also sub-dominantly into dark radiation.

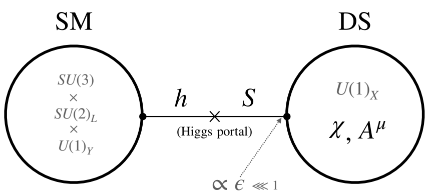

Figure 1: Setup where the proposed mechanism is realized. SM is connected through a Higgs portal connector S to the DS, built from a Dirac fermion χ charged under $U(1)_{\rm dark}$ with a massive gauge field A^μ.

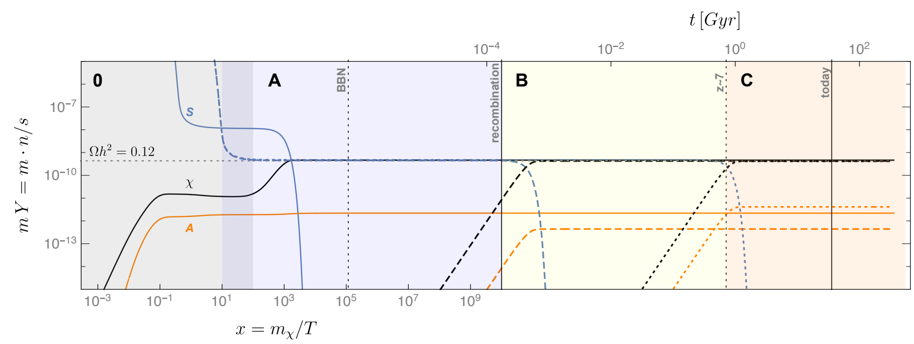

Figure 2: Thermal history: evolution of energy densities of S (blue), χ (black) and A^μ (orange) as a function of $x = m_\chi/T$ for parameters which lead to early (regime A, solid lines: very weak $\lesssim \epsilon \lesssim$ weak - SIDM viable), late (regime B, dashed: ultra weak $\lesssim \epsilon \lesssim$ very weak - SIDM with an impact on the H_0 tension) and very late (regime C, dotted: $\epsilon \lesssim$ ultra weak - two component DM (dominant pseudo-WIMP S and small component of ultrastrong self-interacting dark matter [8]) with an impact on the H_0 tension) decays of S.

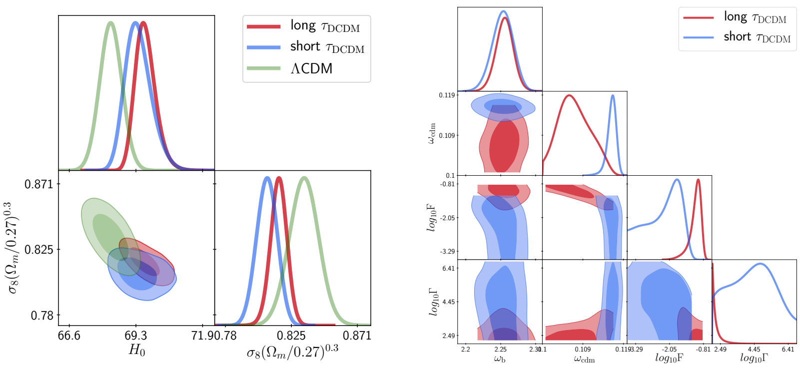

Figure 3: Constraints on the cosmological parameters for the regimes B (blue) and C (red) of the DCDM and ΛCDM. Both regimes of DCDM lead to mildly better values of H_0 and $\sigma_8\ (\Omega_{\rm matter}/0.27)^{0.3}$ over ΛCDM.

2.1 The SM-DS coupling through a portal

Going forward, we concentrate on a Higgs portal scenario, which is illustrated in Fig. 1. The DS after the $U(1)_{\rm dark}$ breaking is described by the following Lagrangian:

$$\mathcal{L}^{\rm DS} = \quad \bar{\chi}(i\gamma_\mu\partial^\mu - m_\chi)\chi + \frac{1}{2}m_A^2 A_\mu A^\mu + igA^\mu\bar{\chi}\gamma_\mu\chi + \epsilon\, S\bar{\chi}\chi, \tag{1}$$

while the connection with the DM is given by the portal interactions:

$$\mathcal{L}^{\rm portal} \supseteq \quad \epsilon\,\mu_{HS} S\, H^\dagger H + \lambda_{HS}\, S^2 H^\dagger H\,, \tag{2}$$

where H denotes the SM Higgs boson doublet. It is natural to assume that S is a pseudo-WIMP - particle freezing-out from thermal plasma that is almost stable due to a broken symmetry (in our case, Z_2: $S \to -S$). One can parameterize the symmetry breaking by a small parameter ϵ which value leads into four distinctive regimes of thermal history and impact on H_0 as illustrated in Fig. 2

3. Fit to cosmological scan

To determine the impact of decaying DM (DCDM) on cosmological evolution, we performed Monte Carlo Markov Chain scan using `CLASS` together with `MontePython` [9]. We used datasets from both early and late Universe observations. The results are presented in Fig. 3 and show 1-σ preferred regions for regime B (blue) and C (red) where the H_0 tension is mildly alleviated.

3.1 The SIDM from late decays regime and the uSIDM regime

For very small values of ϵ, S decays after the recombination which modifies the evolution of background and perturbation quantities over ΛCDM while still producing SIDM. The results for this regime are presented on the left of Fig. 4, while on the right one can see the results for even longer $\tau_S \sim 10$ Gyr, where we obtain two-component, ultrastrong self-interacting dark matter.

4. Conclusions

Summing up, we studied the cosmological implications of the SIDM production mechanism based on decays of WIMP-like state taking place at a late time. The dominant decay mode is the

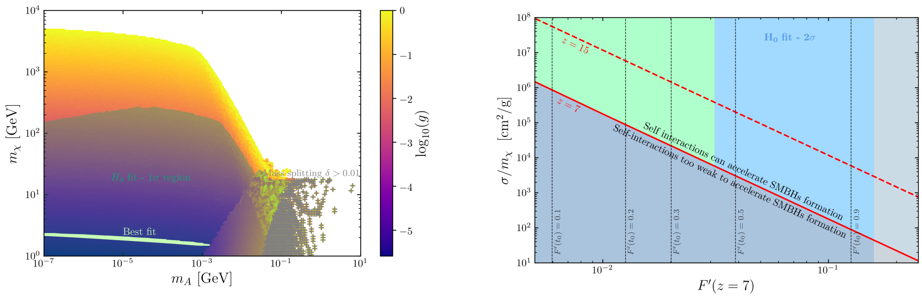

Figure 4: Cosmological scan results for the SIDM regime B (left) and uSIDM regime C (right). On the left, color coding indicates the value of the coupling g leading to $\sigma/m_\chi \sim (1 \pm 10\%)$ cm^2/g. On the right, self-interactions strong enough to accelerate SMBHs formation rates are denoted as the blue and green areas.

SIDM production taking place via a tree-level process while higher order processes transfer a small part of the WIMP-like state energy into dark radiation. Such higher order processes naturally lead to transfer of only a small part of DM energy into radiation, which is mandatory due to the stringent CMB bounds, while at the same time improving the fit to the H_0 and S_8 parameters.

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