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Post-Reheating Inflaton-Mediated Dark and Visible Matter Scatterings: A Cosmological Perspective

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The initial density of both the Dark Matter(DM) and the Standard Model (SM) particles may be produced via perturbative decay of inflaton with different decay rates, creating an initial temperature ratio, $\xi = T_{DM,i}/T_{SM,i}$. This scenario implies inflaton mediated scatterings between the DM and the SM, that can modify the temperature ratio. The effect of these scatterings is studied in a gauge-invariant model of inflaton interactions upto dimension-5 with all the SM particles including Higgs. It is observed that a lower (or higher) initial dark matter (DM) temperature will rapidly rise (or fall), even with minimal couplings to the inflaton. There is a stringent lower limit on the DM mass to satisfy the relic density, as faster back-scattering processes deplete DM into SM particles. Both the BBN and CMB constraints become stronger for $\xi_i < 1$, probing values as small as 10^{-4}. In particular, CMB constraints become important to probe light dark matter scenario, with smaller ξ_i values.

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1. Introduction

The production mechanisms for dark matter (DM) have remained an open question for decades, with thermally produced DM from standard model (SM) particles facing significant constraints. In the post-inflationary epoch, both DM and SM particles can arise from the inflaton's perturbative decay, suggesting that inflaton-mediated interactions may alter DM dynamics and affect cosmological observations [1]. In this article, the complete set of inflaton interactions with Standard Model (SM) gauge, fermion, and Higgs fields is considered using dimension-5 operators consistent with gauge symmetries, with the suppression mass scale chosen such that the reheat temperature remains below it, ensuring effective field theory validity.

A scenario is considered where a scalar singlet inflaton field, ϕ, couples to the singlet scalar dark matter (DM) field, χ, as well as to the Standard Model (SM) gauge, Higgs, and fermion fields. The interaction Lagrangian is invariant under the $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ symmetries:

$$\mathcal{L} \supset \mu_\phi \phi H^\dagger H + \frac{\lambda_\phi}{2}\phi^2 H^\dagger H + \frac{\mu_\chi}{2}\phi\chi^2 + \frac{\lambda}{4}\phi^2\chi^2 + \frac{1}{\Lambda}\phi\bar{L}He_R + \frac{1}{\Lambda}\phi\bar{Q}\tilde{H}u_R + \frac{1}{\Lambda}\phi\bar{Q}Hd_R$$
$$+\frac{1}{\Lambda}(\partial_\mu\phi)(g_L\bar{f}_L\gamma^\mu f_L + g_R\bar{f}_R\gamma^\mu f_R) + \frac{1}{\Lambda}\phi B_{\mu\nu}B^{\mu\nu} + \frac{1}{\Lambda}\phi W^{a\mu\nu}W^a_{\mu\nu} + \frac{1}{\Lambda}\phi G^{a\mu\nu}G^a_{\mu\nu}, \quad (1)$$

Here, $\tilde{H} = i\sigma 2H^*$, with H representing the SM Higgs doublet, f encompassing all SM fermions. The fields L and Q are the SU(2)L doublet lepton and quark fields, while e_R, u_R, and d_R are the SU(2)L singlet fields. The field strength tensors $B_{\mu\nu}$, $W^a_{\mu\nu}$, and $G^a_{\mu\nu}$ correspond to the $\mathrm{U(1)_Y}$, $\mathrm{SU(2)_L}$, and $\mathrm{SU(3)_C}$ gauge fields, respectively.

Coupled Boltzmann equations for dark matter (DM) temperature and number density are solved, expanding on previous work focused on relativistic DM. The analysis explores a wide parameter space for DM mass and inflaton coupling consistent with observed abundance and constraints from the Cosmic Microwave Background (CMB) and Big Bang Nucleosynthesis (BBN). The findings reveal significant impacts of inflaton-mediated scatterings on cosmological observables, ruling out certain DM masses and temperatures.The DM sector can have either a lower or higher temperature than the SM sector during reheating, with the latter still consistent with radiation domination during BBN. We consider the scenario where he inflaton ϕ has renormalizable couplings primarily with the Higgs field(Sec. 2), and if this coupling is weak, DM may scatter with other SM fermions via dimension-5 operators(Sec. 3).

2. Inflaton dominantly couples with the SM Higgs

In this section, we will consider that inflaton dominantly couples with SM Higgs doublet, ignoring decay modes into other SM particles. Taking into account the trilinear DM-inflaton coupling, the partial decay widths of inflaton for the reheat temperature $\mathrm{T_R}$ greater than the electroweak symmetry breaking temperature $\mathrm{T_{EW}}$ are:

$$\Gamma_{\phi\to H^\dagger H} \simeq \frac{\mu_\phi^2}{8\pi m_\phi} \quad , \qquad \Gamma_{\phi\to\chi\chi} \simeq \frac{\mu_\chi^2}{32\pi m_\phi}. \quad (2)$$

Assuming instantaneous reheating followed by immediate thermalization, the initial temperature ratio between dark matter (T_χ) and the Standard Model ($T_{\rm SM}$) is given by

$$(T_\chi/T_{SM})_i = g_{*SM}^{1/4}(T_R)\left(\frac{\Gamma_{\phi\to\chi\chi}}{\Gamma_{\phi\to H^\dagger H}}\right)^{1/4}, \tag{3}$$

where, $g_{*SM}(T_R)$ is the number of relativistic degrees of freedom in the SM sector at temperature T_R. After reheating, the dark matter (DM) temperature evolves due to inflaton-mediated scatterings. To analyze this, it is useful to study the evolution of the temperature ratio $\xi = T_\chi/T_{\rm SM}$, which is governed by [3] :

$$\frac{d\xi}{dx} + \frac{\xi}{x} + \frac{\xi}{Y_\chi}\frac{dY_\chi}{dx} = \frac{1}{m_\chi}\left\langle\frac{p^4}{3E^3}\right\rangle + \frac{1}{Y_\chi H s m_\chi}\left\langle\frac{p^2}{3E}C[f]\right\rangle, \tag{4}$$

where, $Y_\chi = n_\chi/s$, H is the Hubble rate, s is the entropy density, and the $\langle\ldots\rangle$ is the average over the thermal distribution. Equation (4) has to be solved with the coupled equation for the evolution of DM abundance Y_χ :

$$\frac{dY_\chi}{dx} = -\frac{s}{Hx}\left[\langle\sigma v\rangle_{\chi\chi\to H^\dagger H}(T_\chi)Y_\chi^2(T_\chi) - \langle\sigma v\rangle_{\chi\chi\to H^\dagger H}(T_{SM})(Y_\chi^0(T_{SM}))^2\right]. \tag{5}$$

The thermally averaged interaction rate is expressed as:

$$\langle\sigma v\rangle_{\chi\chi\to H^\dagger H}(T) = \frac{1}{(n_\chi^0)^2(T)}\int \sigma_{\chi\chi\to H^\dagger H}\ v\ e^{-\frac{E_1+E_2}{T}}\frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3}. \tag{6}$$

Here, the relevant cross-section for DM-Higgs scattering at $T < T_{EW}$ is

$$\sigma_{\chi\chi\to hh} = \frac{1}{32\pi}\frac{\mu_\chi^2\mu_\phi^2}{\sqrt{s(s-4m_\chi^2)}}\frac{\sqrt{1-\frac{4m_h^2}{s}}}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}. \tag{7}$$

Before electroweak symmetry breaking, we consider the Higgs to be massless, requiring a modification of the cross-section. To determine DM dynamics, the coupled Boltzmann equations (4) and (5) are solved for various DM-inflaton trilinear couplings. Figure 1 displays the evolution of the temperature ratio ξ and corresponding DM yields, showing increases by factors of 3, 26, and 5×10^4 for $\mu_\chi = 10^{-2}, 10^{-4}$, and 10^{-12} GeV, respectively.

We have shown that DM-SM scatterings can alter DM dynamics, potentially impacting late-time cosmological observables. Identifying the right DM mass and coupling parameters is crucial to ensure the correct relic abundance while staying consistent with cosmological and astrophysical data. In Figure 2, the contour line illustrates the region where DM satisfies the correct relic abundance, $\Omega_{\rm DM}h^2 = 0.12$, both without (blue dashed line) and with (blue solid line) collision effects. The BBN constraint arises from the effective neutrino number $N_\nu = 2.878 \pm 0.278$ [4], limiting the contribution of relativistic DM to the Hubble parameter and light nuclei formation (yellow region in figure 2). CMB data requires DM to be non-relativistic during photon decoupling, implying a limit on the DM temperature-to-mass ratio at that epoch, linked to the scale factor $a_{\rm LS}$ as [5]:

$$\frac{T_\chi(a_{\rm LS})}{m_\chi} < 10^{-5} \qquad \text{at}\ \ \mathrm{T_{SM}(a_{LS})} \sim 0.26\ \text{eV} \tag{8}$$

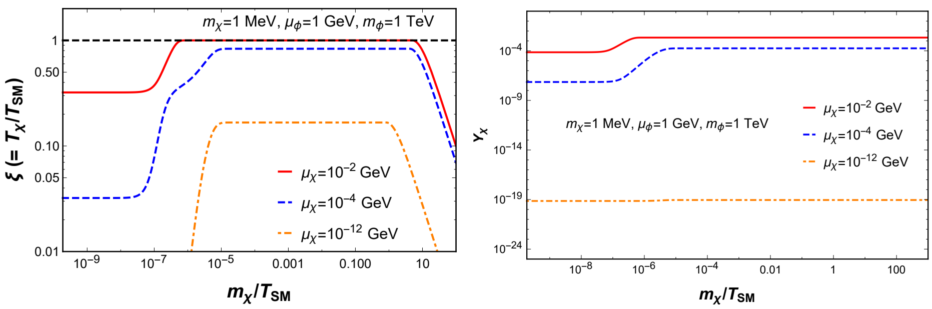

Figure 1: *Shown on the left is the evolution of the temperature ratio between DM and the SM, $\xi = T_\chi/T_{\rm SM}$, as a function of $m_\chi/T_{\rm SM}$ for DM-Higgs scattering. On the right, the corresponding evolution of the DM yield Y_χ is displayed. These results are presented for an intermediate reheat temperature of $T_{\rm R} \sim 5 \times 10^6$ GeV and an inflaton mass of $m_\phi = 10^3$ GeV.*

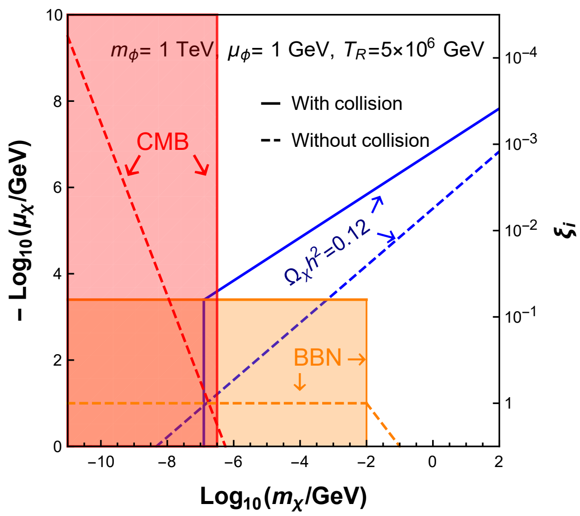

Figure 2: *Cosmological constraints on the dark matter (DM) mass m_χ and the trilinear DM-inflaton coupling μ_χ are derived from the total DM abundance, cosmic microwave background (CMB) anisotropies, and Big Bang Nucleosynthesis (BBN), both with and without considering Higgs-DM collisions. The initial values of the temperature ratio ξ_i are also displayed. Note that in the chosen convention, the coupling μ_χ decreases as you move up along the y-axis.*

A notable feature in figure 2 is that, for dark matter particles lighter than $m_\chi \sim 10^{-7}$ GeV, they cannot reach the required abundance when collisions are included, due to energy loss through scattering. This is tied to the temperature ratio ξ_i, which dictates energy flow when dark matter and Higgs are massless in the scenario.

3. Inflaton dominantly couples with the SM Fermions and Gauge Bosons

In this scenario, the inflaton primarily couples to Standard Model (SM) gauge bosons and fermions, with reheating occurring through these interactions. The relevant SM gauge-invariant couplings are of dimension-5. To ensure the validity of the effective field theory (EFT) approach, the reheating temperature T_R must remain below the energy scale Λ, where the EFT needs to be replaced by its ultraviolet (UV) completion. The inflaton decay widths to the Standard Model (SM) gauge bosons are given by:

$$\Gamma_{\phi\to i\bar{i}} = \frac{1}{g_s}\frac{1}{\pi}\frac{\sqrt{m_\phi^2 - 4m_i^2}}{\Lambda^2 m_\phi^2}\left(\frac{m_\phi^4}{2} - 2m_\phi^2 m_i^2 + 3m_i^4\right) \qquad \text{[after EWSB]} \tag{9}$$

where i denotes the weak-gauge bosons $W^\pm, Z^0$, the gluon g and the photon γ. The symmetry factors are $g_s = 2$ for identical particles (*i.e.* for γ, Z^0, g), and $g_s = 1$ for $W^\pm$. Before electroweak symmetry breaking (EWSB), the inflaton's fermionic decays are three-body processes and subdominant to two-body decays into gauge bosons, but after EWSB, two-body decays into fermion pairs become possible with decay widths :

$$\Gamma_{\phi\to f\bar{f}} = \frac{1}{16\pi}\frac{\sqrt{m_\phi^2 - 4m_f^2}}{\Lambda^2 m_\phi^2}\left(\frac{v^2}{4}(2m_\phi^2 - 5m_f^2) + 8g_A^2 m_\phi^2 m_f^2\right) \qquad \text{[after EWSB]} \tag{10}$$

where f denotes the charged leptons e, μ, τ, and the quarks q, and $g_A = \frac{g_L - g_R}{2}$ which is fixed to be 0.5 throughout this section. The relevant cross-sections for dark matter *s-channel* scatterings mediated by the inflaton with SM gauge bosons and fermions are as follows:

$$\sigma_{\chi\chi\to i\bar{i}} = \frac{1}{g_s}\frac{1}{32\pi s}\sqrt{\frac{s-4m_i^2}{s-4m_\chi^2}}\,\frac{16\mu_\chi^2}{\Lambda^2}\,\frac{\frac{s^2}{2} - 2m_i^2 s + 3m_i^2}{(s-m_\phi^2)^2 + \Gamma_\phi^2 m_\phi^2} \qquad \text{[after EWSB]} \tag{11}$$

$$\sigma_{\chi\chi\to f\bar{f}} = \frac{1}{32\pi s}\sqrt{\frac{s-4m_f^2}{s-4m_\chi^2}}\,\frac{16\mu_\chi^2}{\Lambda^2}\,\frac{\frac{v^2}{4}(2s - 5m_f^2) + 8g_A^2 m_f^2 s}{(s-m_\phi^2)^2 + \Gamma_\phi^2 m_\phi^2} \qquad \text{[after EWSB].} \tag{12}$$

here i denotes the Gauge bosons and f is to indicate the SM fermions. In addition to the limitation

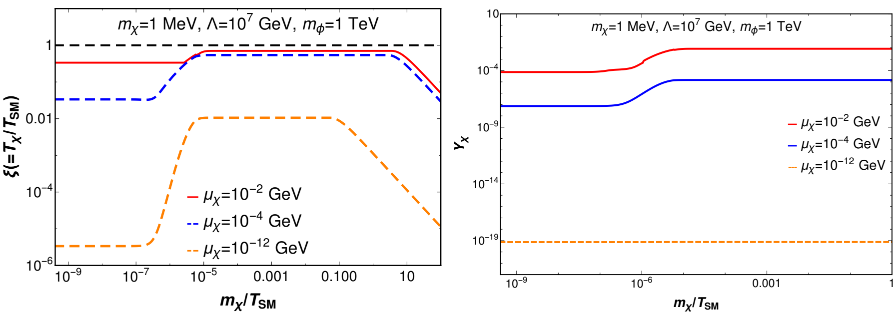

Figure 3: *Similarly to Fig. 2, for the scenario where the inflaton dominantly couples to the SM gauge bosons and fermions.*

on the suppression scale Λ mentioned earlier, which results in relatively smaller scattering rates compared to the Higgs scenario, the overall qualitative features of the results remain consistent with those in the previous section. Figure 3 illustrates the evolution of ξ and Y_χ. In this scenario, the temperature ratio ξ varies by factors of $2, 15$, and 3×10^3 for $\mu_\chi = 10^{-2}, 10^{-4}$, and 10^{-12} GeV, respectively, with other parameters fixed at $\Lambda = 10^7$ GeV, $m_\chi = 1$ MeV, and $m_\phi = 10^3$ GeV,

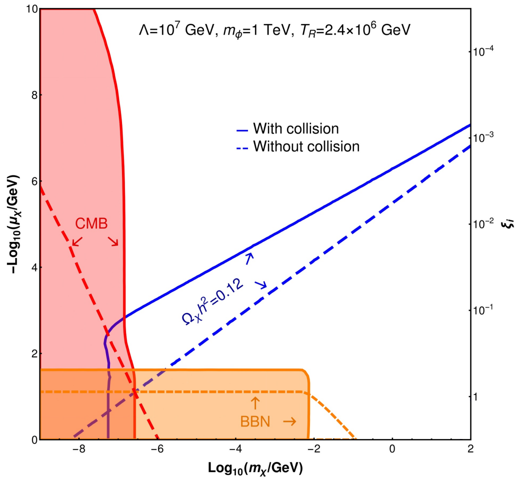

Figure 4: *Similarly to Fig. 2, for the scenario where the inflaton dominantly couples to the SM gauge bosons and fermions.*

resulting in $T_R = 2.4 \times 10^6$ GeV. In Fig. 4, we present the constraints in the m_χ and μ_χ parameter space based on total DM abundance, CMB anisotropies, and BBN. The features observed with and without collisions are similar to those in the inflaton-Higgs coupling scenario, though the numerical constraints are slightly weaker due to the higher mass scale, leading to a reduced impact on CMB constraints for smaller ξ_i values.

We thus find that, the inflaton-mediated scatterings between the Standard Model and dark matter sectors significantly influence the DM phase-space distribution and temperature, with important cosmological implications. These effects should be incorporated in different DM production studies such as DM production via preheating. Specifically, the thermalization of the dark matter sector in these scenarios is a complex process that demands a detailed, separate analysis.

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