Non-thermal production of Dark Matter after Inflation

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ABSTRACT: The existence of Dark Matter (DM) has been well established from various cosmological and astrophysical evidences. However, the particle properties of DM are largely undetermined and attempts to probe its interactions with the Standard Model (SM) particles have, so far, not met with any success. The stringent constraints on the DM-SM interactions, while does not exclude the standard lore of producing weakly massive interacting particle DM candidates through thermal freeze-out mechanism in its entirety, have certainly cast shadow on the same. In this work, we consider non-thermal production of DM within a simple extension of the SM including an inflaton field and a scalar DM candidate. Assuming negligible interactions between the SM particles and the DM, we study the production of the latter at the end of inflation, during the (p)reheating epoch. In this context, we explore the role of DM self-interactions and its interaction with the inflaton field, and find that DM can be over produced in a significant region of the parameter space. We further demonstrate that large self-interaction of the DM can suppress its abundance during preheating and to a certain extent helps to achieve the observed relic abundance via cannibalization.

Contents

1 Introduction

The existence of non-luminous Dark Matter (DM) has been well established thanks to several evidences in cosmology and astrophysics at different scales [1]. While these signatures only require DM to posses gravitational interactions and to be non-relativistic sufficiently early, the possibility that it can interact weakly with the Standard Model (SM) particles have been widely considered in various well motivated extensions of the SM [1–3].

However, very little is known about the particle properties of DM and its interactions with the SM particles. It is generally assumed that DM consists of Weakly Interacting Massive Particles (WIMPs), which, as the name suggests, weakly interact with SM particles [4]. This assumption opens up the the possibility that DM particles were in thermal equilibrium with the SM in the early Universe; and thus, were produced via the standard freeze-out mechanism. Further, such an assumption provided several avenues to search for DM. However, the various direct [5–7] and indirect [8, 9] DM detectors, as well as the collider experiments [10, 11], have not measured any of such interactions so far. The most constraining limits for WIMP DM come from the direct detection experiments, especially for DM masses in the GeV ballpark.

Moreover, while the large scale structure and Lyman-α data [12, 13] constraint the mass of the DM particle to be greater than $\mathcal{O}(10)$ keV, the success of Big Bang Nucleosynthesis (BBN) prevents any non-SM relativistic degree of freedom to be in thermal equilibrium with the SM particles at the onset of BBN ($\simeq 1$ MeV) [14]. This clearly disfavors a DM candidate with mass $\lesssim 1$ MeV which thermalizes with the SM particles.[1]

While, in no way the current searches exclude the WIMP scenarios in its entirety, it may be worth exploring different kind of DM candidates which feebly interact with the SM

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[1]However, in certain scenarios it is possible to accommodate such a light thermal DM invoking additional interactions [15–17].

particles. Generically such DM candidates do not thermalize with the SM particles in the early Universe, due to the feeble interaction strength. Several such scenarios have been proposed [18–22], both with a simple DM candidate, or even with a more complex Dark Sector (DS). Since in all these scenarios, DM is initially not in thermal equilibrium with the SM particles, the production mechanisms usually involve assumptions on the initial abundance of the DM or DS particles in the very early Universe. For example, in the simplest Feebly Interacting Massive Particle (FIMP) scenario, the initial abundance of the FIMP DM is usually assumed to be zero (see Ref. [23] for a recent review). Therefore, an estimation of the initial abundance of DM or DS particles can be important in establishing the viability of a particular DM scenario.

In the very early Universe, the paradigm of cosmological inflation [24–26] has been well-established, single field slow-roll inflation scenario have been very successful in the light of present data [27]. In this framework, post-inflationary particle production takes place during the (p)reheating epoch [28–31]. While during reheating particles are produced due to perturbative decay of the inflaton, preheating is a fast and efficient process, when particles are produced due to parametric resonance. This takes place even before the reheating epoch. Thanks to the Bose enhancement, this process is especially efficient in producing bosons which couple to the inflation.

In the present article a simple extension of the SM, accommodating an inflaton and a scalar DM (stabilized using an effective $\mathbb{Z}_2$ symmetry), has been considered. Further, DM is assumed to posses negligible interaction with SM particles. Within this framework, we have studied the production of DM after inflation, during the epoch of preheating and reheating. The role of various interaction terms between the inflaton and the DM, as well as the DM self-interactions, have been analyzed in details.

This article is organized as follows. In section 2 the model is presented, making especial emphasis on requirements for driving the inflation. In the following section 3 existing constraints on the relevant model parameters various cosmological and astrophysical considerations have been sketched. Subsequently, in section 4 we discuss the production of the scalar DM during (p)reheating and estimate the relic abundance of the DM. Finally, in section 5 we summarize our findings.

2   The Model

The production of a scalar DM and SM particles during (p)reheating epoch generally depends on the inflaton potential at the end of inflation, and also on the interaction terms between the inflaton and the respective sectors. In this section, we sketch the model of our interest, elaborating on the inflationary scenario and the relevant interaction terms.

On top of the SM field content, our model contains two real scalar fields, the inflaton ϕ and the DM χ.[2] In order to ensure the stability of the DM, a $\mathbb{Z}_2$ symmetry is imposed

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[2]Note that a stable inflaton could also play the role of DM [32–52].

under which only the DM is odd. The scalar potential is, then, given by

$$V = \frac{m_\phi^2}{2}\phi^2 + \frac{m_\chi^2}{2}\chi^2 - \frac{\mu_H^2}{2}|H|^2 + \frac{\sigma_3}{3}\phi^3 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_\chi}{4}\chi^4 + \frac{\lambda_H}{4}|H|^4$$
$$+ \frac{\sigma_{\phi\chi}}{2}\phi\chi^2 + \frac{\sigma_{\phi H}}{2}\phi|H|^2 + \frac{\lambda_{\phi\chi}}{2}\phi^2\chi^2 + \frac{\lambda_{\phi H}}{2}\phi^2|H|^2 + \frac{\lambda_{\chi H}}{2}\chi^2|H|^2 + V_{\text{gravity}}\,, \quad (2.1)$$

where H is the SM Higgs field. Note that μ_H and λ_H, at the electroweak scale, are constrained in order to reproduce the observed Higgs mass and vacuum expectation value (*vev*).

In the present context, we will consider large field inflationary models. Two such scenarios have been widely studied, one with the quartic potential [53] and another with quadratic potential [54] for the inflaton field ϕ, see also Refs. [55, 56] for reviews. In their simplest incarnations, both of these scenarios have been in tension with the present constraints from the CMB data [27], the quartic one being worse. However, it has been pointed out that introduction of a non-minimal coupling with gravity can render both these scenarios viable [57–59]. While we will consider quadratic inflation in the presence of a non-minimal gravitational coupling, we will also comment on the consequences of considering a quartic potential, especially in the context of DM production during (p)reheating. The non-minimal couplings to gravity are expressed as

$$V_{\text{gravity}} = \frac{1}{2}\left(\xi_\phi\phi^2 + \xi_\chi\chi^2 + 2\xi_H|H|^2\right)\mathcal{R}, \quad (2.2)$$

where $\mathcal{R}$ is the Ricci scalar [60]. For simplicity, we will set $\xi_\chi = 0 = \xi_H$.

Before discussing more on the inflationary aspects, which include terms depending only on the inflaton ϕ, a discussion on various other relevant parameters are in order. As we will see in section 4, they play an important role during the (p)reheating. The trilinear terms $\frac{\sigma_{\phi\chi}}{2}\phi\chi^2$, $\frac{\sigma_{\phi H}}{2}\phi|H|^2$ and $\frac{\sigma_3}{3}\phi^3$ can potentially give rise to a non-zero *vev* for the inflaton field at the end of inflation.[3] This will generate an effective mass term, presumably large, for both the scalars coupled to the inflaton. In order to keep the (p)reheating dynamics simple, and the DM mass as a free parameter of the theory (independent of $\lambda_{\phi\chi}$), we discard this possibility. Further, we also ensure that the minima of the scalar potential is at zero, and is achieved when all the scalar fields assume zero *vev*.[4] These lead to the conditions $\lambda_\chi > \frac{\sigma_{\phi\chi}^2}{2\alpha^2 m_\phi^2}$, $\lambda_H > \frac{\sigma_{\phi H}^2}{2\beta^2 m_\phi^2}$ and $\lambda_\phi > \frac{2\sigma_3^2}{9\gamma^2 m_\phi^2}$ given arbitrary real constants α, β and γ, such that $\alpha^2 + \beta^2 + \gamma^2 = 1$. Also the quartic couplings $\lambda_{\phi\chi}$, $\lambda_{\phi H}$ and $\lambda_{\chi H}$ need to be positive. Note that at high scales ($\sim 10^{-5}M_{\text{Pl}}$) the quartic coupling λ_H becomes negative, due to the large quantum corrections mostly from the top quark Yukawa coupling.[5] This has been well studied in the literature, see e.g. Refs. [61–64]. Its consequence during

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[3] These terms are allowed by symmetries and required for the draining of the excess energy stored in inflaton after preheating, as 2-to-2 scatterings of inflatons into DM or SM through terms $\frac{\lambda_{\phi\chi}}{2}\phi^2\chi^2$ and $\frac{\lambda_{\phi H}}{2}\phi^2|H|^2$ can not transfer the energy stored in inflaton completely.

[4] Since we are interested in the the epoch after inflation, where all relevant scales are much larger compared to the electroweak scale, we ignore the zero-temperature electroweak *vev* of the Higgs field.

[5] Since in our context both $\lambda_{\phi\chi}$ and $\lambda_{\phi H}$ remain small, as we will discuss latter, the quantum contribution from the scalar fields ϕ and χ do not improve the situation.

inflation and possible remedies are also known, see e.g. Refs. [65–69] (also Ref. [65, 70–72] for $\xi_H \neq 0$). Since our main focus is on the post inflationary production of DM particle during (p)reheating, we will assume that the quartic coupling λ_H remains positive during (p)reheating epoch. This can be simply achieved by introducing another scalar field, which couples to the Higgs boson [73, 74]. We will assume that such a scalar, if exists, thermalizes with the SM particles, and if coupled to the inflaton, its production and dynamics during (p)reheating would be similar as that of the Higgs boson itself; but we will not explicitly include it in our discussion. For the rest of this article, we will simply assume that during (p)reheating λ_H remains positive.

For the inflationary paradigm we consider the quadratic potential for the inflaton ϕ. In this case, in Eq. (2.1) the quadratic term for the inflaton field ϕ dominates over the quartic term, which is assumed to be small. Introducing a non-minimal coupling $\xi_\phi \simeq \mathcal{O}(10^{-3})$ with $m_\phi \simeq \mathcal{O}(10^{-6})\, M_{\mathrm{Pl}}$ [58] the quadratic potential can produce the scalar spectral index n_s, the tensor-to-scalar ratio r and the amplitude of the scalar perturbation A_s, consistently with the current Planck data [27]. In particular, a benchmark with $\xi_\phi = 2 \times 10^{-3}$, $m_\phi = 5.3 \times 10^{-6}\, M_{\mathrm{Pl}}$ (with $\phi_{\mathrm{pivot}} \simeq 14\, M_{\mathrm{Pl}}$ and $\phi_{\mathrm{end}} \simeq M_{\mathrm{Pl}}$), leads to the following values of the observable parameters: the scalar spectral index $n_s \simeq 0.963$, the amplitude of the scalar perturbation $A_s \simeq 2.22 \times 10^{-9}$ and the tensor-to-scalar ratio $r \simeq 0.043$, while the inflation lasts for ~ 62 e-foldings. It has also been shown in literatures [75, 76] that a non-minimal coupling of χ to gravity can produce DM gravitationally, even if the DM has no other coupling with any other sector.

Note that, the success of inflation critically depends on the flatness of the inflaton potential, such that the slow-roll parameters remains small during the entire inflation. In case of the quadratic inflation, the contribution from the quartic term, therefore, must remain insignificant. Note that, simply forbidding λ_ϕ at the tree-level, would not suffice, since it can be generated due to quantum corrections. The relevant renormalization group equations (RGE) are given by [77–79],

$$16\pi^2 \frac{d\lambda_\phi}{d\ln\mu} = 8\lambda_{\phi H}^2 + 2\lambda_{\phi\chi}^2 + 18c_\phi^2\lambda_\phi^2, \tag{2.3}$$

$$16\pi^2 \frac{d\lambda_{\phi H}}{d\ln\mu} = \lambda_{\phi H}\left[8c_\phi\lambda_{\phi H} + 12\lambda_H + 6c_\phi^2\lambda_\phi - \frac{3}{2}(3g_L^2 + g_Y^2) + 6y_t^2\right], \tag{2.4}$$

$$16\pi^2 \frac{d\xi_\phi}{d\ln\mu} = 6\left(\xi_\phi - \frac{1}{6}\right)c_\phi\lambda_\phi, \tag{2.5}$$

where

$$c_\phi = \frac{1 + \xi_\phi\phi_i^2/M_{\mathrm{Pl}}^2}{1 + (6\xi_\phi - 1)\,\xi_\phi\phi_i^2/M_{\mathrm{Pl}}^2}, \tag{2.6}$$

with g_L and g_Y corresponding to the $SU(2)$ and $U(1)$ gauge couplings and y_t being the Yukawa coupling of the top quark. As shown in the equations above, the radiative contribution to λ_ϕ involves both $\lambda_{\phi\chi}$ and $\lambda_{\phi H}$. Thus, for requiring $\lambda_\phi \lesssim 10^{-14}$ (to ensure the smallness of this term during inflation) without invoking any tuning, we assume that $\lambda_{\phi\chi}$, $\lambda_{\phi H} \lesssim \mathcal{O}(10^{-7})$ during inflation and right after the inflation at the onset of (p)reheating epoch. Similar argument prevents σ_3 from being large. Further, $\sigma_{\phi\chi}$ and $\sigma_{\phi H}$ can also

contribute to the RGE of m_ϕ and σ_3, and we ensure that these parameters remain small during (p)reheating after inflation in our discussion in section 4.

Finally, we comment on the possibility of considering the quartic inflation where the quadratic term $\frac{m_\phi^2}{2}\phi^2$ is negligible in Eq. (2.1) compared to $\frac{\lambda_\phi}{4}\phi^4$ during inflation [57, 80–83]. However, to ensure that ϕ remains massive after inflation (without the necessity of a phase transition), and to ensure that the minima of the scalar potential remains at zero, when all the scalar fields are set to zero, a mass term for $m_\phi \ll 10^{-6}M_{\rm Pl}$ would be desired. It has been shown that, in this case, the current CMB data can be matched with $N \sim 60$ e-folds and $\xi_\phi \sim 790N\sqrt{\lambda_\phi}$. Note that the nature of the inflaton potential, whether quartic or quadratic, affects the post inflation dynamics of the inflaton, and hence the preheating process. Furthermore, a heavy inflaton can possibly behave as matter after the rapid preheating process, before it decays injecting significant entropy, and diluting the abundance of any light particle produced during preheating. In section 4, a quadratic potential will be assumed for ϕ. However, we will also comment on the impact of the choice of quartic inflation in the same context.

3 Constraints

In this section, we briefly discuss the relevant constraints, especially focusing on a light DM candidate.

- While only active neutrinos lead to $N_{\rm eff} = 3.046$ [84], the presence of any additional relativistic species enhances $N_{\rm eff}$. Primordial nucleosynthesis yields, independently of measurement of the baryon density from CMB observations, $\Delta N_{\rm eff} < 1$ at 95% CL [85]. Using CMB measurements along with the BBN yields data can improve the constraint to $\Delta N_{\rm eff} < 0.38$ at 95% CL [14] (see also Refs. [86, 87]). This is a constraint we keep in mind when having a DM of the mass range keV-MeV (i.e. relativistic during BBN). To satisfy it, the ratio of dark sector energy density to energy density of relativistic SM particles is required to be $\lesssim 0.051$ at the onset of BBN [14].

- We consider DM particles with mass range of minimum $m_\chi \gtrsim \mathcal{O}(10)$ keV as constrained by Lyman-α observations [12, 13].

- The presence of a light scalar field, the DM, during inflation can leave imprints in the primordial power spectrum. In the context of curvaton scenarios [88–92] these possibilities have been considered. The generic signatures include significant non-Gaussianity and isocurvature modes in the primordial power spectrum.[6] Recent results from Planck [27] find no evidence for isocurvature perturbation, imposing stringent constraints. The success of single field slow-roll inflation paradigm in the light of present CMB data implies that such an additional light field, if present during inflation, can only contribute subdominantly to the energy density of the Universe during inflation. For a light field during inflation, $m_\chi^{\rm eff} \ll H_{\rm inf}$, where $m_\chi^{\rm eff}$ and $H_{\rm inf}$ denote the effective mass of the light scalar and Hubble parameter during inflation, respectively. The light field will acquire quantum fluctuations

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[6]Note that, in the context of multi-field inflation scenarios, where more than one fields contribute to the exponential expansion with comparable energy densities, isocurvature perturbation can also arise [93–96].
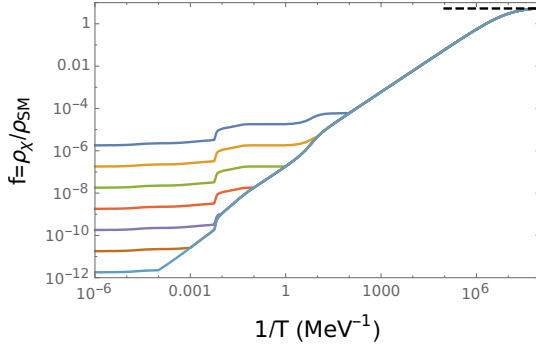
Figure 1. Energy fraction $f(T) \equiv \frac{\rho_\chi(T')}{\rho_{SM}(T)}$ required to get the observed DM abundance as a function of $1/T$ (in MeV^{-1}), for $m_\chi = 0.01,\ 0.05,\ 0.3,\ 2,\ 10,\ 50$ and 300 MeV (from top to bottom). The dashed line at the top-right corner corresponds to the observed $f(T_0) \sim 5.3$, as measured by Planck.

proportional to H_{inf} [97–100] with its root mean squared value given by $\frac{\mathcal{O}(0.1)}{\lambda_\chi^{1/4}} H_{inf}$ [100]. The condensate, thus formed, remains frozen until the end of inflation while the Hubble parameter becomes small compared to the (possibly thermal) mass of the light field. At this point the field starts to oscillate and behaves like matter before finally decaying into the χ particles (in the quartic region [101]). Note that, since we assume very small coupling with the SM fields (i.e. negligible portal coupling with the Higgs boson), χ particles never thermalize with the SM sector. Similar ideas have been studied in Refs. [101–103]. In Ref. [101] it has been shown that, such a scenario would be quite constrained from non-observation of isocurvature perturbation, in particular, for large field inflation models (with large $H_{inf} \simeq 10^{13} - 10^{14}$ GeV). In order to evade this issue, as we will elaborate in the subsequent section, we consider sizable coupling of the χ field with the inflaton ϕ. This enhances the effective mass (i.e. the second derivative of the relevant potential) of the χ field during inflation and ensures that the field does not receive large fluctuations during the same period.

• We demand a successful inflation, able to reproduce the observed scalar spectral index n_s, the tensor-to-scalar ratio r and the amplitude of the scalar perturbation A_s.

• We finally demand to reproduce the observed DM relic abundance.

4 Dark Matter Production

The ratio of the energy density of the DM to that of the SM at a temperature T, $f(T) \equiv \frac{\rho_\chi(T')}{\rho_{SM}(T)}$, measured at the present day CMB temperature T_0 is $f(T_0) \sim 5.3$ [104] (and a corresponding DM temperature T'). In the early Universe, however, this ratio is expected to be much smaller since SM radiation cools down faster than the DM component. Assuming the two sectors were always completely disconnected, with corresponding entropies separately conserved, the evolution of f is shows in Fig. 1, for different DM masses: $m_\chi = 0.01,\ 0.05,\ 0.3,\ 2,\ 10,\ 50$ and 300 MeV (from top to bottom). The initial values (at high temperatures) for all curves are tuned so that at low temperatures they reproduce the observed DM abundance, as measured by Planck, and showed with a dashed line.
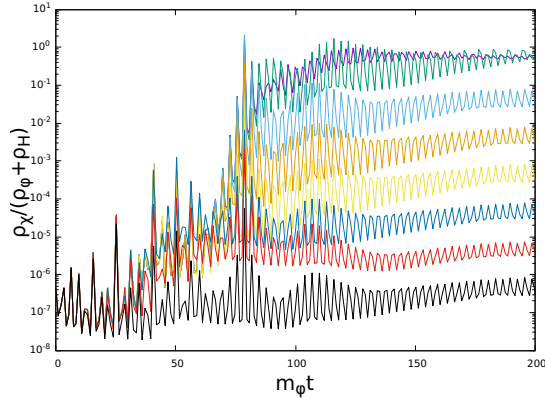
Figure 2. Evolution of the energy fraction $\rho_\chi/(\rho_\phi + \rho_H)$ as a function of time for $m_\phi = 10^{-6}M_{\rm Pl}$, $\lambda_\phi = 10^{-14}$, $\lambda_{\phi\chi} = 10^{-7}$, $\lambda_{\phi H} = 10^{-7}$, $\lambda_H = 10^{-7}$ and $\sigma_{\phi H} = 10^{-10}M_{\rm Pl}$. $\lambda_\chi = 10^i$, for $i = -7$ (uppermost line) to $i = 0$ (lowermost line), increasing i in one unit each time. Higher values of λ_χ give rise to more suppression of DM energy density.

When $T' \gtrsim m_\chi$, f tends to be constant showing that both components scale in the same way, as radiation. An analog behavior appears for $T < 0.7$ eV, near the matter-radiation equality, when both the SM and the DM behave like matter. The kinks at $T \sim 0.1$ MeV and $T \sim 100$ MeV correspond to the electron-positron annihilation and the QCD phase transition, respectively.

In the following we will focus on how (p)reheating could generate the DM to SM energy density ratio in order to reproduce the observed DM abundance, firstly assuming that there are no sizable self-interactions for the DM, and secondly taking them into account.

4.1 Dark Matter Production during (P)reheating

In this subsection we consider the DM production after inflation during the (p)reheating epoch. The process of reheating involves perturbative decay of the inflaton and the production of a particular species during this epoch can be estimated by the branching fractions of the inflaton into it. However, during preheating, which precedes the reheating epoch, bosonic particles coupled to the inflaton field are produced via parametric or tachyonic resonance, and it is a rapid non-perturbative process. The initial stage of preheating can be described in terms of a set of Mathieu equations in the Fourier space and can be studied analytically [29]. The Fourier modes, which are present in the well-known instability bands, grow exponentially at the onset of preheating and are interpreted as exponential particle production [29]. However, after the initial stage of preheating, non-linear effects including back-reaction and re-scatterings become relevant [31]. Thus, during this phase, accurate analytical estimations are hard to obtain. Therefore, numerical codes have been developed and used to estimate the particle production during this epoch. We have used the publicly available code LATTICEEASY [105] in order to the study the DM production during preheating. The inflationary production of scalar DM with intermediate masses has been studied by various authors [101, 103, 106–111].

In Fig. 2, we plot the evolution during preheating of the ratio of energy density of χ (ρ_χ) to the combined energy density of ϕ (ρ_ϕ) and Higgs (ρ_H) together, i.e. $\frac{\rho_\chi}{\rho_\phi + \rho_H}$. We vary λ_χ while keeping the other parameters fixed as follows: In order to ensure a successful inflationary phase, $m_\phi = 10^{-6} \, M_{Pl}$ and $\lambda_\phi = 10^{-14}$. Further, $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}$ such that the flatness of the inflationary potential is not ruined, as discussed in section 2. A small $\lambda_H = 10^{-7}$, as we will elaborate in the subsequent discussion, avoids the suppression of the energy flow into Higgs during preheating. Finally, we have assumed $\sigma_{\phi H} = 10^{-10} M_{Pl}$ respecting the relation $\lambda_H > \frac{\sigma_{\phi H}^2}{2\beta^2 m_\phi^2}$, again as discussed in section 2, while $\sigma_{\chi H} = 0$ in order to avoid thermalization of χ and Higgs. In the figure, $m_\phi t = 0$ denotes the onset of preheating at the end of inflation where we set $\phi_{ini} \simeq 0.2 \, M_{Pl}$ at which LATTICEEASY starts to evolve the preheating dynamics. While for different values of λ_χ while the ratio changes significantly, as shown in Fig. 2, the generic features of the curves resemble each other, since these are dependent on the dynamics of preheating in general. As emphasized already, production of χ and H quanta during the initial stage of preheating is governed by the relevant Mathieu equation and the energy transfer from the oscillating inflaton condensate to the χ and H sector is significant. The energy transfer is most efficient when the inflaton is near the minimum of the potential, i.e. $\phi(t) \simeq 0$, since during this phase the adiabatic conditions are strongly violated (due to large $\dot\phi$) and also the contribution of $\phi(t)(\simeq 0)$ to the effective mass of χ and H becomes small. While the production of χ is dominated by the parametric resonance due to the absence of the trilinear term $\sigma_{\phi\chi}$, the production of H can receive contributions due to both parametric and tachyonic resonances (for small k modes in particular, in our context) [112]. The oscillatory features in the energy densities (and in their ratio, as shown in Fig. 2) during the initial stage of preheating can be attributed to the characteristic solution of Mathieu equation. However, as the χ and H fields are populated, as discussed in the previous paragraph, the back-reaction and re-scattering become significant, gradually suppressing the energy transfer to the χ and H fields, and the ratio $\frac{\rho_\chi}{\rho_\phi + \rho_H}$ eventually stabilizes.[7] For example, as shown in the figure, with $\lambda_\chi = 10^{-7}$ (the highest line) the increment continues until $m_\phi t \sim 80$, at which point ρ_χ becomes comparable to that of the inflaton and does not grow any further. Note that, with $\lambda_{\phi H} \simeq \lambda_{\phi\chi}$ (both set to $\mathcal{O}(10^{-7})$), as the self-coupling of χ (λ_χ) is enhanced compared to that of H, the energy flow in the χ sector decreases substantially. In particular, as shown in the figure, for higher quartic couplings: $\lambda_\chi = 10^0$ (lowermost line), 10^{-1}, ... 10^{-6} and 10^{-7} (uppermost line) the ratio $\frac{\rho_\chi}{\rho_\phi + \rho_H}$ varies from $\mathcal{O}(10^{-6})$ to $\mathcal{O}(10^{-1})$, respectively. A similar suppression due to quartic self-interaction has also been observed in Refs. [114, 115]. This feature can be attributed to the fact that the quartic coupling, after initial exponential production of DM, contributes to the

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[7]In particular, once in the initial stage the resonant modes k_* of χ (H) get excited, annihilation of those quanta generate inflaton quanta, re-scattering of χ (H) quanta against inflaton zero mode produces χ (H) and inflaton quanta with the momentum $k_*/2$. In the next stage, violent phase of non-linear dynamics, the $k_*/2$ modes grow in amplitude and shift towards k_*. In the third stage, the distribution smooths out and spreads towards higher momentas. For an elaborate discussion, see Ref. [113].

effective mass of χ as $\sqrt{\frac{\lambda_\chi}{2}\langle\chi^2\rangle}$. This large contribution makes subsequent production of χ energetically expensive, effectively blocking the same [112]. It is worth mentioning here that the production of a boson during preheating can be suppressed by reducing its interaction strength with the inflaton $\lambda_{\phi\chi} \lesssim 4 \times 10^{-8}$, which leads to an inefficient and short period of preheating, due to the smallness of the relevant parameter $\lambda_{\phi\chi}\phi_{ini}^2/m_\phi^2 \lesssim 1$ [116].[8] Finally, although not explicitly shown in Fig. 2 at the end of preheating, the remaining energy density in the inflaton condensate continues to oscillate before it eventually decays, in our context, mostly producing the SM Higgs, thanks to the trilinear $\sigma_{\phi H}$ term.[9]

While we are interested in the initial value of $f = \rho_\chi/\rho_{\rm SM}$ at the end of (p)reheating, the decay mentioned above ensures that $\dfrac{\rho_\chi}{\rho_\phi + \rho_H}$, as plotted in the figure above, gives a good estimate of f at the end of (p)reheating assuming that the inflaton does not go through a non-relativistic phase before it decays. However, as shown in Fig. 1, only a small initial DM energy density (compared to that of the SM) at high temperature suffices to produce the right DM relic abundance. Even with a rather large λ_χ, and assuming that the perturbative decay of the inflaton ϕ only contributes to $\rho_{\rm SM}$, we find it difficult to achieve such a small ratio, and produce substantially large initial abundance of χ at the end of preheating, especially for $m_\chi \gtrsim 0.02$ MeV. However, as will be discussed subsequently in this section, the mass range $m_\chi \lesssim 0.02$ MeV, giving rise to the right initial abundance with large λ_χ, as discussed above, have been disfavored due to rather large self-interaction from the Bullet cluster bounds. This makes it apparent that the scenario, as described so far, requires mechanisms to suppress the initial abundance of χ in order to be viable.

It is well-known that the energy density associated to the oscillations of the inflaton, in the context of quadratic potential, behaves as matter. However, it has been shown that, although substantial energy density remains in the inflaton (condensate and the excitation combined) at the end of preheating, in presence of the trilinear σ terms the equation of state right after preheating is rather close to that of the radiation $w \simeq \frac{1}{4}$ [112]. This is in contrast to the case of quartic inflation, where the equation of state, under similar circumstances, resembles that of radiation.[10]

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[8]However, this does not seem to lead to adequate suppression for different DM masses we have considered. Also, if the interaction is significantly reduced, the effective mass of the boson may fall below $H_{\rm inf}$. We will not consider this possibility.

[9]Note that during the oscillation of the inflaton, an effective trilinear coupling proportional to $\lambda_{\phi\chi}\phi(t)$ can be generated. Thus, setting $\sigma_{\phi\chi} = 0$ does not completely prohibit the perturbative decay of the inflaton into χ. However with time, as the amplitude of inflaton oscillation $\phi(t)$ decreases below $\mathcal{O}(10^{-3}M_{\rm Pl})$, $\sigma_{\phi H} \simeq \mathcal{O}(10^{-10}M_{\rm Pl})$ becomes dominant. For simplicity we have ignored this contribution in our estimation.

[10]In Ref. [112], the equation of state during the preheating period has been studied in detail. It has been shown that for a preheating scenario (with quadratic inflaton potential) where there is no trilinear coupling of inflaton to other species, the equation of state at first increases to 1/4, then it decreases slowly towards 0. On the other hand, in a scenario with trilinear term, the equation of state increases to a value above 1/4 and does not decrease thereafter. This phenomenon has been explained by studying the fraction of number density stored in the relativistic modes of the fields. It has been observed that, for the first scenario, it decreases after initial increment for the inflaton field. Whereas for the second scenario, this fraction remains stable for the entire simulation time scale. Therefore, for simplicity, we can assume the inflaton to be a relativistic species after preheating for our case with trilinear coupling.
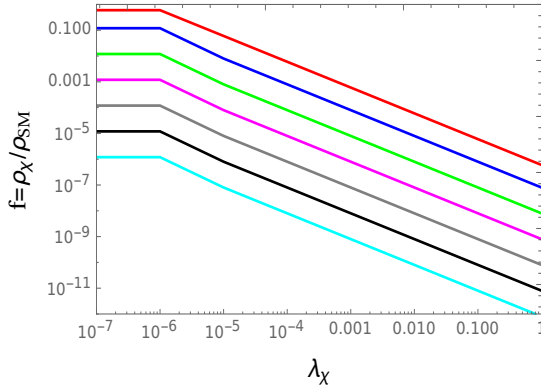
Figure 3. Energy fraction $f \equiv \rho_\chi/\rho_{\text{SM}}$ at the end of reheating as a function of λ_χ, for the same benchmark point of Fig. 2. The lines correspond to $a_d/a_t = 10^0$ (uppermost) to 10^6 (lowermost), increasing by an order of magnitude each time.

However, if inflaton becomes non-relativistic before it decays, its energy density after the relativistic to non-relativistic transition, scales as a^{-3}, while for the relativistic species (SM and DM particles) the energy density scales as a^{-4}, where a is the scale factor. This can lead to an enhancement in the relative energy fraction stored in the inflaton field at the end of preheating, and the subsequent decay process into SM can suppress the DM energy density relative to SM. The dynamics of the Universe during the phase between the end of preheating (defined as the initial exponential particle production) and the decay of inflaton (governed by the decay width Γ_ϕ of inflaton, which is generally much larger than the preheating time scale) is complicated and contains processes like turbulence and thermalization [117–125]. The enhancement of the relative energy density of inflaton from the end of preheating to its decay depends on details of this stage. Although the parameter a_d/a_t, written as a ratio of scale factors during the decay of inflaton a_d and during the transition of inflaton energy density from relativistic to non-relativistic a_t (where we assume that both the inflaton decay and its transition from relativistic to non-relativistic phase are instantaneous), enhances the inflaton energy density relative to the other (relativistic) energy densities, the full details of the phase between end of preheating and decay of inflaton may add additional information to get the correct enhancement factor. We use a_d/a_t as an effective enhancement factor of inflaton energy density with respect to other energy densities. The factor a_d/a_t is by construction ≥ 1, as even if the inflaton decays when it is relativistic, i.e. $a_d < a_t$, the inflaton energy density does not get enhanced. In Fig. 3, we plot $f \equiv \frac{\rho_\chi}{\rho_{\text{SM}}} = \frac{\rho_\chi^{ini}}{\rho_\phi^{ini} \times \frac{a_d}{a_t} + \rho_H^{ini}}$ (where ρ_i^{ini} is the initial energy density of species i just after preheating) as a function of λ_χ at the end of preheating for different values of a_d/a_t. For the top-most line of this plot, it is clear from Fig. 2 why the ratio does not change with λ_χ, when λ_χ is not significantly larger than $\lambda_{\phi\chi}$, and after that the ratio falls off with increasing λ_χ. The other lines in this plot correspond to the cases where the inflaton energy density gets a boost by a factor $a_d/a_t > 1$.

Fig. 4 combines the information of Figs. 1 and 3. It depicts the values of the quartic coupling λ_χ required in order to reproduce the observed DM relic abundance as a function

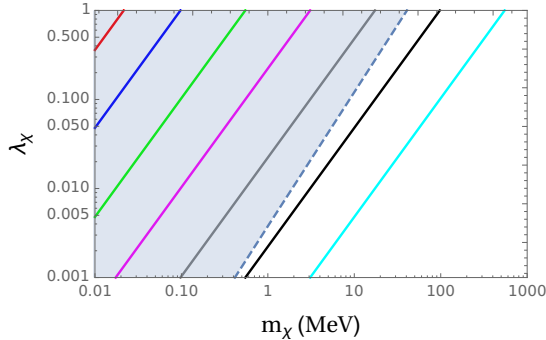**Figure 4**. λ_χ vs m_χ (in MeV) plot for allowed relic abundance (without any depletion mechanism in DM sector). The lines from top-left corresponds to $a_d/a_t = 10^0$ to 10^6. The shaded region is excluded from Bullet cluster bounds.

of the DM mass, for different ratios a_d/a_t: from 10^0 (uppermost) until 10^6 (lowermost), increasing by an order of magnitude each time. The shaded gray region is in tension with the Bullet cluster constraint on DM self-interactions. The figure shows that the case where $a_d/a_t = 1$ is excluded by observations. However, having $a_d/a_t \gg 1$ gives additional suppression of the DM to SM ratio if the inflaton fully decays into SM only. An additional suppression in the ratio f by this factor can reproduce the right DM abundance of a specific m_χ with a smaller value of λ_χ. Thus, as shown in Fig. 4, an appropriate a_d/a_t may lead to the right DM abundance, evading Bullet cluster bounds.[11] Let us emphasize that in this figure we are assuming that there are no interactions within the dark sector able to modify the DM number density. However, when λ_χ becomes sizable, that may not be a suitable assumption. In fact, in this case DM cannibalization will inevitably deplete the DM sector. This is especially efficient in the presence of large self-interaction parameter λ_χ which, incidentally, also helps to suppress the DM production during preheating. We will discuss this possibility in detail in the next subsection.

4.2 Dark Matter Cannibalization

In this scenario DM particles never reach thermal equilibrium with the SM, due to the very small coupling between the two sectors, and hence they can not be produced via the standard WIMP scenario. First DM particles could be produced by reheating and preheating mechanisms, but also by the FIMP mechanism. However here we focus on a scenario where the bulk of the original DM particles were produced by the (p)reheating dynamics. In fact, FIMP mechanism typically requires a portal coupling $\lambda_{\chi H} \sim 10^{-10}$ in order to reproduce the observed DM abundance. In our case however, we have $\lambda_{\chi H} \ll 10^{-10}$, so that the FIMP production via SM particle annihilation and Higgs decays is subdominant with respect to the (p)reheating production.

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[11]Quartic inflation does not give a better result in terms of getting right DM relic abundance. This is because, the energy density of a quartic potential evolves as radiation while oscillating around its minima. For the same trilinear coupling strength, the inflaton may decay while still relativistic (because inflation may be rather light in this case), thereby possibly decreasing the duration of a non-relativistic phase.

Moreover, due to the dynamics within the dark sector, characterized by sizable couplings between DM particles, DM self-interactions could play a crucial role in the generation of the DM relic abundance. In fact, one can consider a framework where the freeze-out proceeds via N-to-n number-changing processes, where N DM particles annihilate into n of them (with $N > n \geq 2$). This possibility was first studied in Ref. [126] and recently named the 'SIMP paradigm' [127]. This has been entertained recently in strongly self-interacting DM models that annihilate in number-depleting 3-to-2 [126–150] or 4-to-2 interactions [151–155].

In the case where the Higgs portal is very suppressed, the Boltzmann equation which describes the evolution of the DM number density $n(T')$ is:

$$\frac{dn}{dt} + 3\,H(T)\,n = -\langle\sigma v^2\rangle_{3\to2}\left[n^3 - n\,n_{\mathrm{eq}}^2\right] - \langle\sigma v^3\rangle_{4\to2}\left[n^4 - n^2\,n_{\mathrm{eq}}^2\right], \qquad (4.1)$$

where $H(T)$ is the Hubble expansion rate as a function of the temperature T of the visible sector and $n_{\mathrm{eq}}(T')$ represents the equilibrium DM number density at a dark temperature T'. The factors $\langle\sigma v^2\rangle_{3\to2}$ and $\langle\sigma v^3\rangle_{4\to2}$ correspond to the generalized annihilation cross sections of the 3-to-2 and 4-to-2 DM annihilations, respectively. In the case where the DM stability is guaranteed by a $\mathbb{Z}_2$ symmetry, 3-to-2 processes are forbidden and the DM annihilations are driven by the 4-to-2 processes, with a cross section that in the non-relativistic limit is given by [151]

$$\langle\sigma v^3\rangle_{4\to2} \sim \frac{27\sqrt{3}}{8\pi}\frac{\lambda_\chi^4}{m_\chi^8}. \qquad (4.2)$$

Let us recall that the entropies of the dark and the visible sectors are separately conserved, because they were always kinetically decoupled from each other. It is then useful to compute the entropy ratio ξ between them, which is also a conserved quantity. In particular, if the freeze-out happens non-relativistically, one has

$$\xi \equiv \frac{s}{s'} \sim \frac{T'_{\mathrm{FO}}}{3.6\ \mathrm{eV}\,(1 + 2.5\,T'_{\mathrm{FO}}/m_\chi)\times\Omega_\chi h^2}\,, \qquad (4.3)$$

where s and s' are the entropy densities of the SM sector and the dark sector, respectively, and T'_{FO} is the temperature of the dark sector when the DM freeze-out takes place [126, 151]. Substituting $\Omega_\chi h^2 \sim 0.12$ [104] and the solution of T'_{FO} [151], the proper DM abundance requires

$$\xi \sim 7\times10^9\left(\frac{m_\chi}{\mathrm{GeV}}\right)\frac{1}{1 + 0.03\left(\lambda_\chi\frac{\mathrm{GeV}}{m_\chi}\right)^{4/7}}\,. \qquad (4.4)$$

The entropy ratio is nearly proportional to the DM mass, up to a weak dependence on the self-coupling λ_χ. Moreover, to match the observed DM relic abundance there is always a $\xi \gg 10^2$ for each DM mass. The model therefore never leads to observable extra radiation [126], consistent with BBN/CMB bounds.

Fig. 5 shows the entropy ratio ξ (left panel) and the energy density ratio f (right panel) between the two sectors needed in order to reproduce the observed DM abundance, in the (m_χ, λ_χ) plane. Let us emphasize that even if the entropy ratio is a constant, the energy
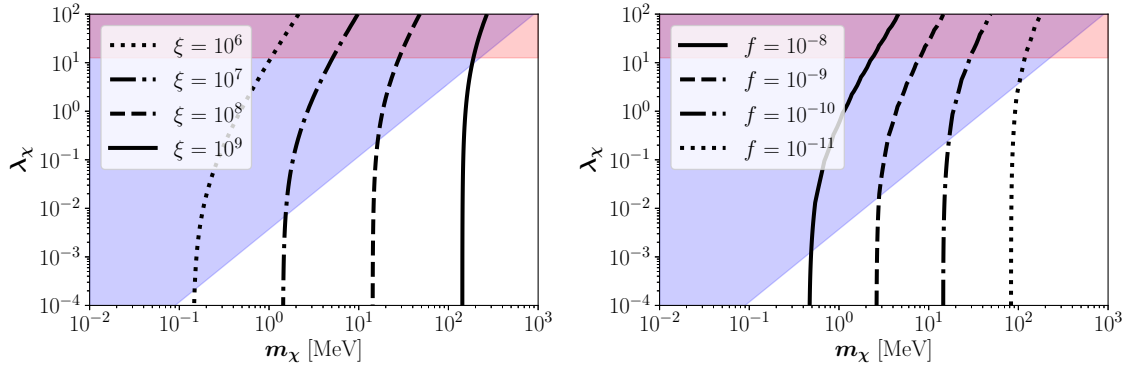
Figure 5. Values of ξ and f that yield the observed DM relic density, in the (m_χ, λ_χ) plane. The light blue region corresponds to $\sigma/m_\chi > 1.25$ cm^2/g and it is excluded by cluster observations. The area where $\lambda_\chi > 4\pi$ is shown in light red.

density ratio in general is not. For a fixed number of relativistic degrees of freedom, f does not vary while the DM stays relativistic. During that period, the two quantities are related by

$$f = \frac{g_{\star S}^{4/3}}{g_\star}\,\xi^{-4/3}. \tag{4.5}$$

In Fig. 5 the upper left corner (light blue) shows the region where DM elastic scatterings are too strong, and in tension with the Bullet Cluster constraints: $\sigma/m_\chi < 1.25$ cm^2/g at 68% CL [156–158]. Additionally, the upper band corresponding to non-perturbative quartic couplings ($\lambda_\chi > 4\pi$) is also discarded.

5 Conclusion

In this work we have explored the possibility of reproducing the measured relic DM abundance from (p)reheating. This scenario is interesting because it does not rely on interaction of DM particles with the SM particles, as required for standard freeze-out mechanism, of which no hint has been observed in direct and indirect searches. While the production of DM during reheating (perturbative decay) is rather simple to estimate and the abundances can directly be obtained from the branching ratios of SM and DM from inflaton, the dynamics of preheating dynamics can not be solved analytically as the equation of evolution becomes non-linear after the initial stage of preheating. We have used publicly available code `LATTICEEASY` to simulate the dynamics of preheating for quadratic inflation and find that DM self-interactions can suppress the production of DM from preheating. However, this suppression remains inadequate to reproduce the observed DM relic abundance, respecting the Bullet cluster bound. We show that, in order to achieve further depletion in the DM number density, a non-relativistic phase of the inflaton before it decays completely to SM and a cannibalization mechanism needs to be invoked. Note that the same DM quartic parameter which suppresses the preheating production, naturally generates cannibalization processes through 4-to-2 annihilations which can deplete the DM

relic abundance. In more general models, DM annihilation into other dark sector particles could help depleting the DM abundance, relaxing the length of the non-relativistic phase of the inflaton.

Acknowledgments

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