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Cosmological implications of inflaton-mediated dark and visible matter scatterings after reheating

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Introduction

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, $\xi_i = (T_{DM}/T_{SM})_i$ considering internal thermalization. This scenario implies inflaton mediated scatterings between the DM and the SM, that can modify the temperature ratio even for high inflaton mass $\mathcal{O}(10^7 \text{ GeV})$. 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 an initially lower(higher) DM temperature will rapidly increase(decrease), even with very small couplings to the inflaton. There is a sharp lower bound on the DM mass for satisfying relic density due to faster back-scatterings depleting DM to SM. The DM-SM scatterings have also been studied considering appropriate quantum statistics for both the sectors. It is observed that the inclusion of quantum effects considering both the sectors to follow Bose-Einstein distribution, leads to enhancement in DM abundance compared to the case of the sectors obeying classical Maxwell-Boltzmann statistics. Thus inflaton-mediated collisions with predictable rates, relevant even for high-scale inflation models, can significantly impact the cosmology of light DM.

1: An Effective Theory of Reheating

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

Inflaton dominantly couples to the SM Higgs

- Inflaton, ϕ dominantly couples with the SM higgs through the renormalizable coupling : $\mu_\phi \phi H^\dagger H$.
- Relevant decay widths considering, the reheat temperature, $T_R > T_{EW}$ (electroweak phase transition temperature) : $\Gamma_{\phi\to H^\dagger H} \simeq \frac{\mu_\phi^2}{8\pi m_\phi}$, $\Gamma_{\phi\to\chi\chi} \simeq \frac{\mu_\chi^2}{32\pi m_\phi}$
- Initial DM (T_χ) and SM ($T_{\rm SM}$) temperature ratio : $(T_\chi/T_{SM})_i = g_{*SM}^{1/4}(T_R)\left(\frac{\Gamma_{\phi\to\chi\chi}}{\Gamma_{\phi\to H^\dagger H}}\right)^{1/4}$
- For $T > T_{EW}$: $\sigma_{\chi\chi\to H^\dagger H} = \frac{1}{8\pi}\frac{\mu_\chi^2\mu_\phi^2}{\sqrt{s(s-4m_\chi^2)}}\frac{1}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}$
- For $T < T_{EW}$: $\sigma_{\chi\chi\to hh} = \frac{1}{32\pi}\frac{\mu_\chi^2\mu_\phi^2}{\sqrt{s(s-4m_\chi^2)}}\frac{\sqrt{1-\frac{4m_h^2}{s}}}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}$

2: Boltzmann Equation & Collision terms

Equation for the evolution of DM phase-space density $f_\chi(\mathbf{p},t)$:

$$\frac{\partial f_\chi(\mathbf{p},t)}{\partial t} - H\mathbf{p}.\nabla_{\mathbf{p}} f_\chi(\mathbf{p},t) = C[f_\chi]$$

Integrating over $\mathbf{p}$, equation for DM number density obtained:

$$\frac{dn_\chi(t)}{dt} + 3Hn_\chi(t) = g_\chi \int \frac{d^3\mathbf{p}}{(2\pi)^3} C[f_\chi]$$

Define temperature as the average over $|\mathbf{p}|^2/3E$ over the distribution f^n :

$$T_\chi \equiv \frac{g_\chi}{n_\chi}\int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{|\mathbf{p}|^2}{3E} f_\chi(\mathbf{p},t).$$

Evolution equation for the DM temperature :

$$\frac{dT_\chi}{dt} + 2HT_\chi + \frac{T_\chi}{n_\chi}\left(\frac{dn_\chi}{dt} + 3Hn_\chi\right) - \frac{H}{3}\left\langle\frac{|\mathbf{p}|^4}{E^3}\right\rangle = \frac{1}{n_\chi}\int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{|\mathbf{p}|^2}{3E} C[f_\chi]$$

Effects of DM-SM (Higgs) scattering

For lower inflaton mass, $m_\phi = 10^3$ GeV :

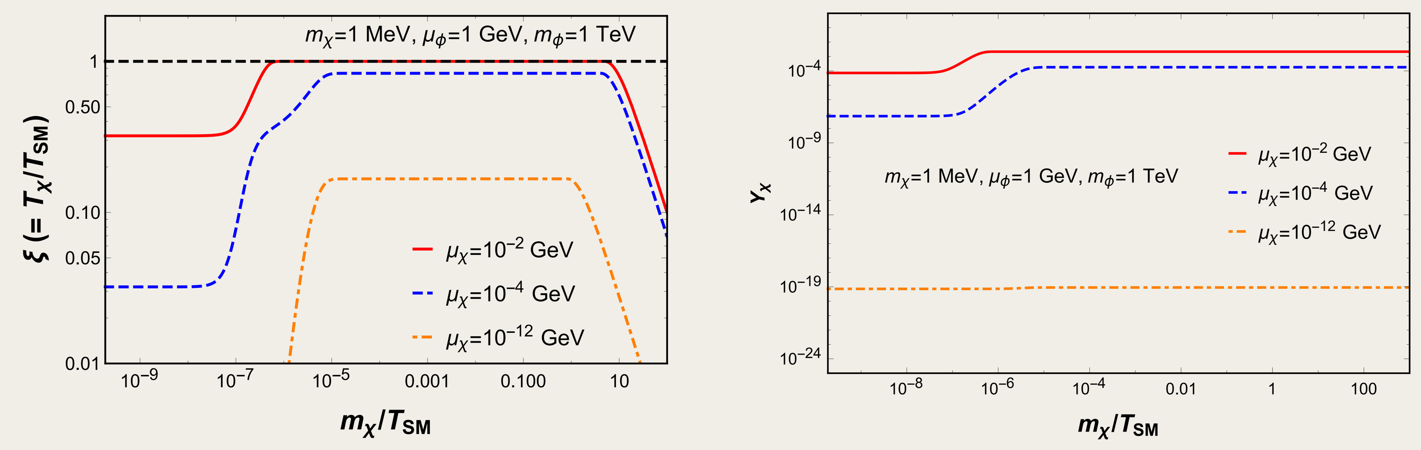


Figure 1. Evolution of $\xi = T_\chi/T_{\rm SM}$, as a function of $m_\chi/T_{\rm SM}$ (**left**), and the corresponding evolution of the DM yield Y_χ (**right**) for reheat temperature of $T_R \sim 5\times10^6$ GeV and inflaton mass of $m_\phi = 10^3$ GeV.

For higher inflaton mass, $m_\phi = 10^7$ GeV :

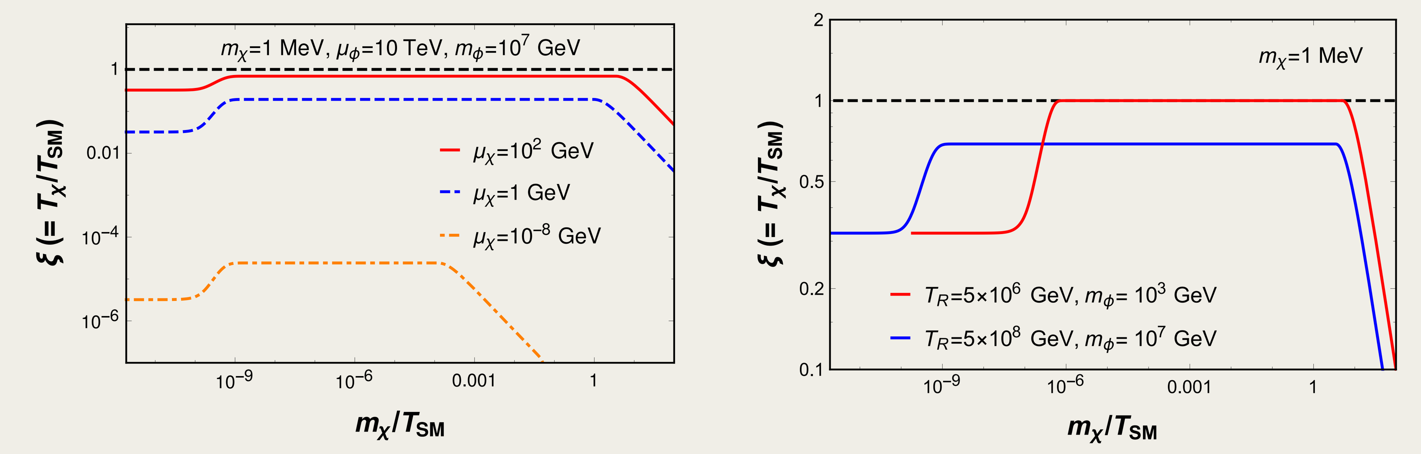


Figure 2. Same as Fig. 1 (left panel), for a reheat temperature of $T_R \sim 5\times10^8$ GeV and inflaton mass of $m_\phi = 10^7$ GeV (**left**). Comparison of the evolution of $\xi = T_\chi/T_{\rm SM}$ for two different scales of the inflaton mass and reheat temperature (**right**).

Relic density plot with cosmological constraints :

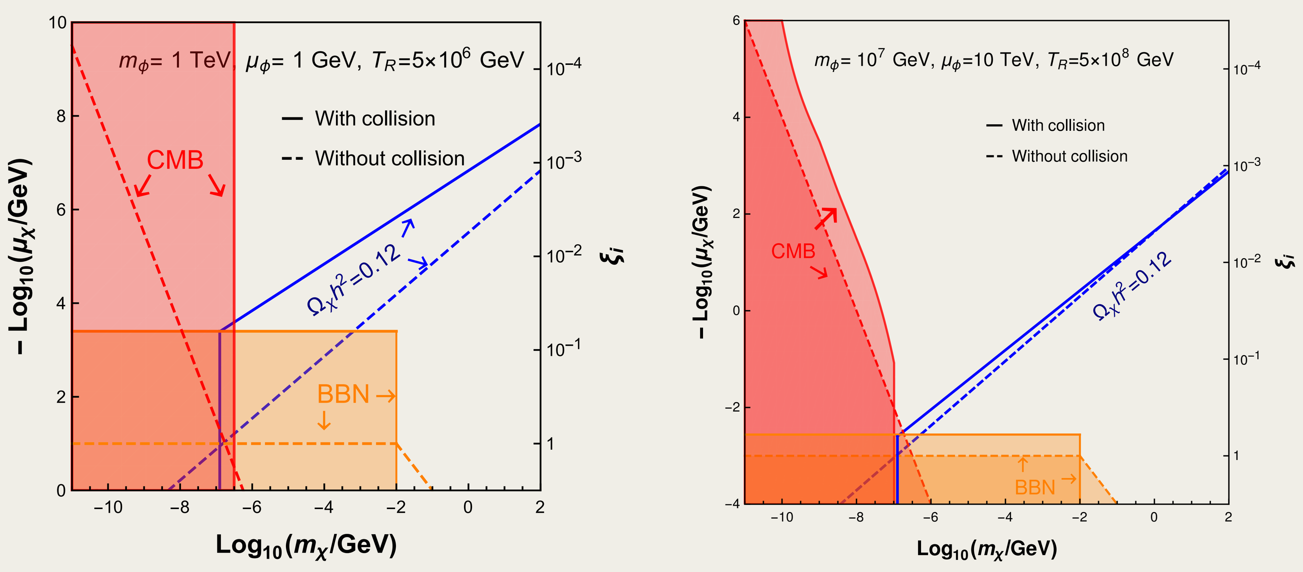


Figure 3. Cosmological constraints on the DM mass m_χ and the DM-inflaton coupling μ_χ, from considerations of the DM total abundance, the CMB anisotropies and the BBN, both without and with the effect of the collision processes. (**left**) For $m_\phi = 10^3$ GeV, $\Lambda = 10^7$ GeV ; (**right**) $m_\phi = 10^7$ GeV, $\Lambda = 10^{10}$ GeV

Inflaton dominantly couples to the SM Gauge Bosons and Fermions

- Inflaton decay widths to SM gauge bosons : $\Gamma_{\phi\to i\bar{i}} = \frac{1}{g_s}\frac{1}{2\pi}\frac{m_\phi^3}{\Lambda^2}$ [before EWSB]
  $= \frac{1}{g_s}\frac{1}{\pi}\frac{\sqrt{m_\phi^2-4m_i^2}}{\Lambda^2 m_\phi^2}\left(\frac{m_\phi^4}{2} - 2m_\phi^2 m_i^2 + 3m_i^4\right)$ [after EWSB]
- Inflaton decay widths to SM fermions after EWSB : $\Gamma_{\phi\to f\bar{f}} = \frac{1}{16\pi}\frac{\sqrt{m_\phi^2-4m_f^2}}{\Lambda^2 m_\phi^2}\left(\frac{v^2}{4}(2m_\phi^2 - 5m_f^2) + 8g_A^2 m_\phi^2 m_f^2\right)$

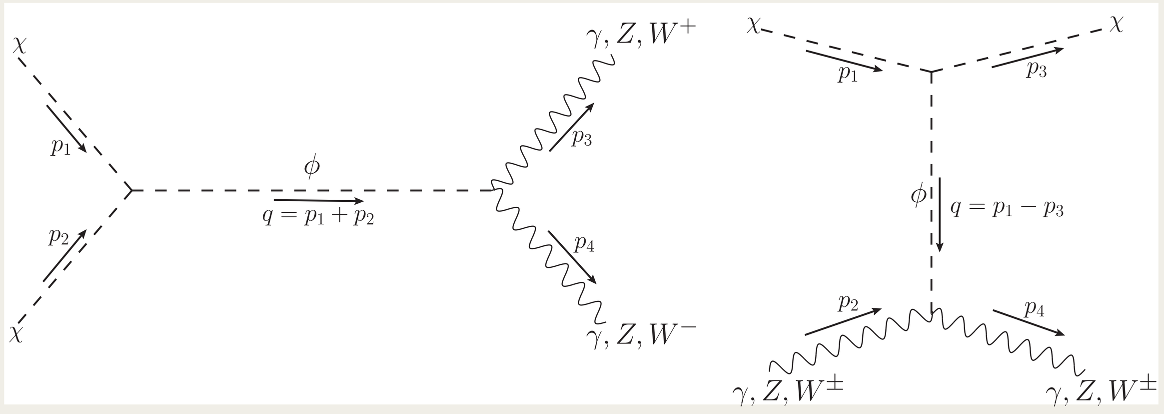


Figure 4. DM-SM(γ, Z and $W^\pm$) $2\to2$ interaction diagrams. **Left**: s-channel $\chi(\mathbf{p}_1)+\chi(\mathbf{p}_2)\to SM(\mathbf{p}_3)+SM(\mathbf{p}_4)$ annihilation. **Right**: t-channel $\chi(\mathbf{p}_1)+SM(\mathbf{p}_2)\to\chi(\mathbf{p}_3)+SM(\mathbf{p}_4)$ scattering.

- For DM-Gauge Boson scatterings : $\sigma_{\chi\chi\to i\bar{i}} = \frac{1}{g_s}\frac{1}{32\pi s}\sqrt{\frac{s-4m_i^2}{s-4m_\chi^2}}\frac{16\mu_\chi^2}{\Lambda^2}\frac{\frac{s^2}{2}-2m_i^2 s+3m_i^2}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}$ [after EWSB]
- For DM-Fermion scatterings : $\sigma_{\chi\chi\to f\bar{f}} = \frac{1}{32\pi s}\sqrt{\frac{s-4m_f^2}{s-4m_\chi^2}}\frac{16\mu_\chi^2}{\Lambda^2}\frac{\frac{v^2}{4}(2s-5m_f^2)+8g_A^2 m_f^2 s}{(s-m_\phi^2)^2+\Gamma_\phi^2 m_\phi^2}$ [after EWSB]

Effects of DM-SM (Gauge Bosons and Fermions) scattering

The evolution of temperature ratio for different inflaton masses:

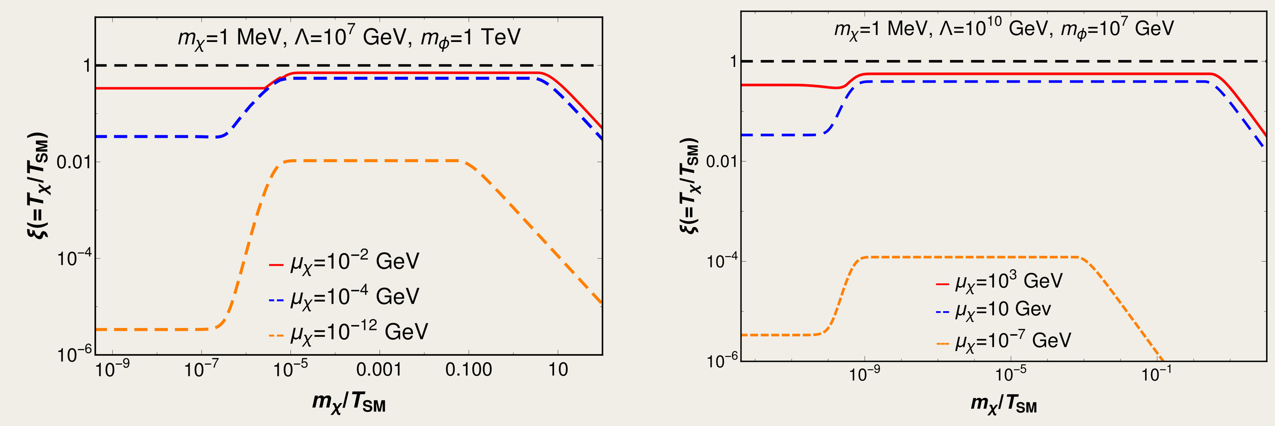
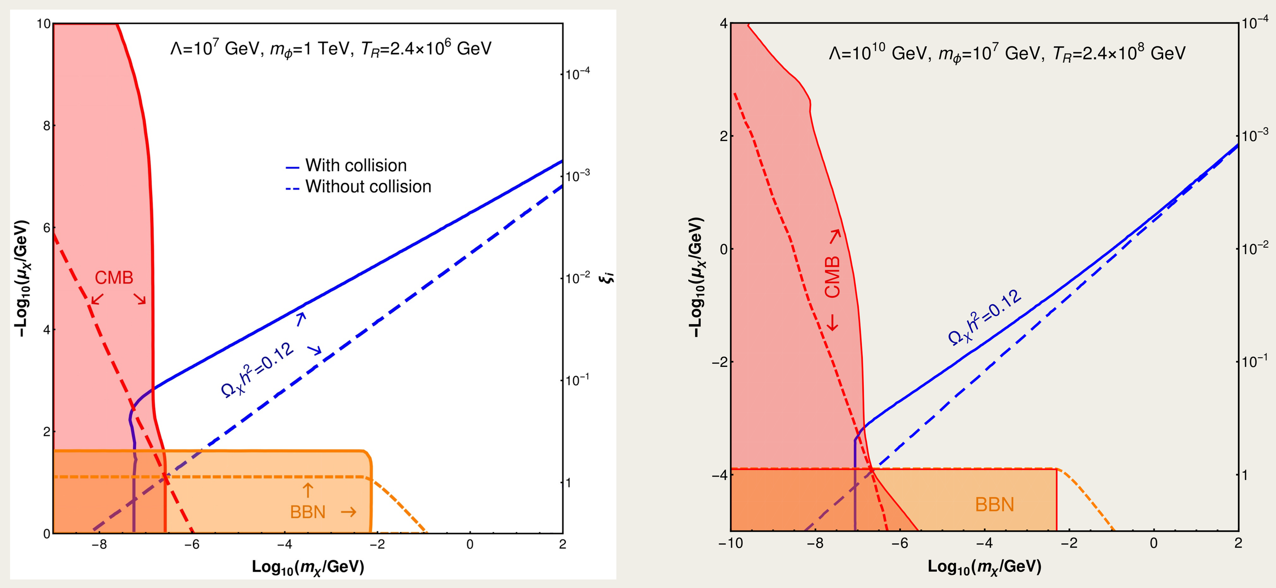


Figure 5. Evolution of $\xi = T_\chi/T_{\rm SM}$, as a function of $m_\chi/T_{\rm SM}$ for reheat temperature of $T_R \sim 5\times10^6$ GeV, inflaton mass of $m_\phi = 10^3$ GeV (**left**) and for a reheat temperature of $T_R \sim 5\times10^8$ GeV, inflaton mass of $m_\phi = 10^7$ GeV (**right**). The initial ξ_i values are same for both the plots.

Relic density plot with cosmological constraints :



Effect of Quantum Statistics in DM-SM scattering

- DM scatternigs with SM Gauge Bosons where both follow Bose-Einstein distribution :

$$\frac{dn_\chi(t)}{dt} + 3Hn_\chi(t) = \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 (2\pi)^4\delta^4(\mathbf{p}_1+\mathbf{p}_2-\mathbf{p}_3-\mathbf{p}_4)|\mathcal{M}|^2_{\chi\chi\to SMSM}$$
$$\times\left[f_{SM}^{eq}(\mathbf{p}_3)f_{SM}^{eq}(\mathbf{p}_4)(1+f_\chi(\mathbf{p}_1))(1+f_\chi(\mathbf{p}_2)) - (1+f_{SM}^{eq}(\mathbf{p}_3))(1+f_{SM}^{eq}(\mathbf{p}_4))f_\chi(\mathbf{p}_1)f_\chi(\mathbf{p}_2)\right]$$

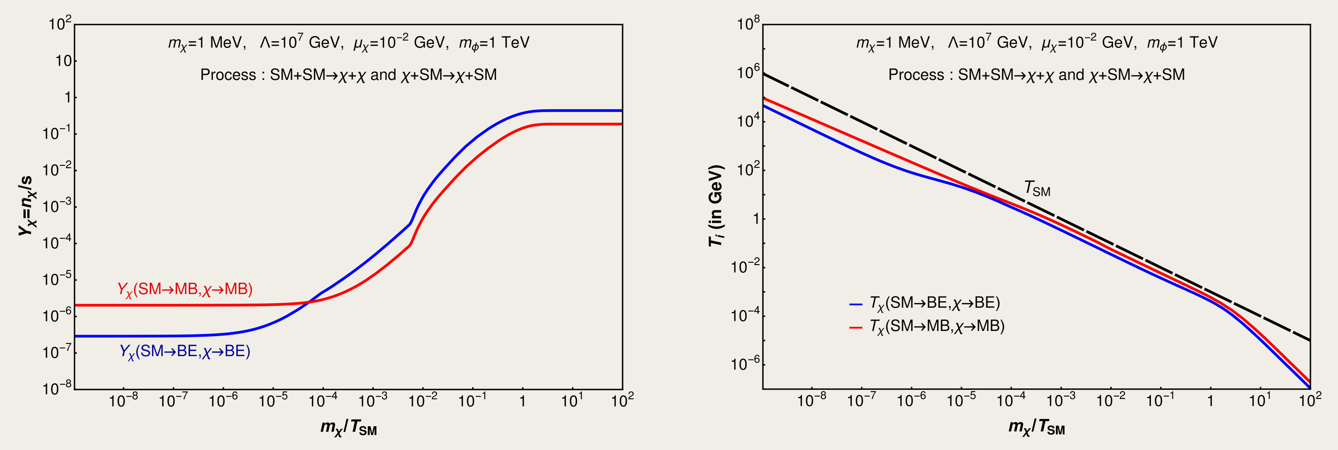


Figure 6. Evolution of DM yield Y_χ (**left**) and temperature (**right**) considering DM-SM elastic and inelastic scatterings. The red(blue) lines indicate the scenario when both the SM and DM follows Maxwell-Boltzmann(Bose-Einstein) distribution.

- Effect on DM abundance with BE distribution compared to MB distibution: **2.3-fold enhancement**

Future directions

- Scope of extension by having SM and DM produced through both perturbative and non-perturbative preheating, with detailed analysis of thermalization.

To find more about our work, please visit :

Acknowledgements

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References

★ D. Ghosh, **S. Gope** and S. Mukhopadhyay, "Cosmological implications of inflaton-mediated dark and visible matter scatterings after reheating," Phys. Rev. D **109**, no.8, 083541 (2024) [arXiv:2312.12985 [hep-ph]]