Freeze-in Dark Matter Through Forbidden Channel in $U(1)_{B-L}$

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Abstract

We examine a scenario for freeze-in production of dark matter, which occurs due to the large thermal correction to the mass of a decaying mediator particle present in the thermal bath of the early Universe. We show that the decays, which are kinematically forbidden otherwise, can open up at very high temperatures and dominate the dark matter production. We explore such forbidden production of dark matter in the minimal $U(1)_{B-L}$ model, comparing dark matter phenomenology in the context of forbidden frozen-in with the standard picture.

Model

The present scenario explores the possibility of a $U(1)_{B-L}$ extension of the SM gauge symmetry. Here, the particle content is enlarged by adding three right-handed neutrinos N_i with $i = 1, 2, 3$ together with a complex scalar S, all of them charged under the $U(1)_{B-L}$ symmetry. In addition, the SM leptons and quarks are also carries $U(1)_{B-L}$ charges of -1 and $+\frac{1}{3}$, respectively. The kinetic terms $\mathcal{L}_{KE}$ for the BSM fields are given by,

$$\mathcal{L}_{KE} = |D_\mu S|^2 + \sum_{i=1,2,3} \bar{N}_i i\gamma^\mu D_\mu N_i - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu}, \tag{1}$$

with $Z^{\mu\nu} = \partial^\mu Z^\nu_{BL} - \partial^\nu Z^\mu_{BL}$, and $D_\mu = \partial_\mu + i\,[Y g' + Y_{BL}\, g_{BL}]\,(Z_{BL})_\mu$. the most general renormalizable scalar potential for this setup is given by

$$V(\phi, S) = -\mu_\phi^2 \phi^\dagger \phi - \mu_S^2 |S|^2 + \frac{\lambda_\phi}{2}(\phi^\dagger\phi)^2 + \lambda_{\phi S}(\phi^\dagger\phi)|S|^2 + \lambda_S |S|^4. \tag{2}$$

The masses of the $B-L$ scalar (ϕ_S) and gauge boson after the $B-L$ symmetry breaking

$$m_S^2 = 2\,\lambda_S\, v_{BL}^2, \tag{3}$$

$$M_{Z_{BL}} = 2\, g_{BL}\, v_{BL}. \tag{4}$$

After Electroweak symmetry breaking (EWSB), mass mixing occurs between the scalars and the mass eigenstates (h, s) have the following masses

$$m_{h,s}^2 = \frac{1}{2}\Big[\big(\lambda_\phi v^2 + 2\lambda_S v_{BL}^2\big) \pm \sqrt{\big(\lambda_\phi v^2 - 2\lambda_S v_{BL}^2\big)^2 + 4\lambda_{\phi S}^2 v^2 v_{BL}^2}\Big]. \tag{5}$$

the Yukawa interactions for the present scenario is expressed as,

$$-\mathcal{L}_y \supset y_{11} \bar{N}_1^c N_1 S + y_{\alpha\beta} \bar{N}_\alpha^c N_\beta S + h_{i\alpha} \overline{l_L} \tilde{\phi} N_\alpha + h.c., \tag{6}$$

The mass of the RHNs are

$$M_i = \sqrt{2}\, y_{ii}\, v_{BL}. \tag{7}$$

For simplicity we assume the other two RHNs to be nearly mass degenerate for rest of the analysis and take $y_{22} \simeq y_{33} = y$. Finally, for our analysis purpose, we choose the following sets of independent parameters:

$$\{m_s, M_1, y, v_{BL}, g_{BL}, s_\theta\}. \tag{8}$$

Thermal Corrections

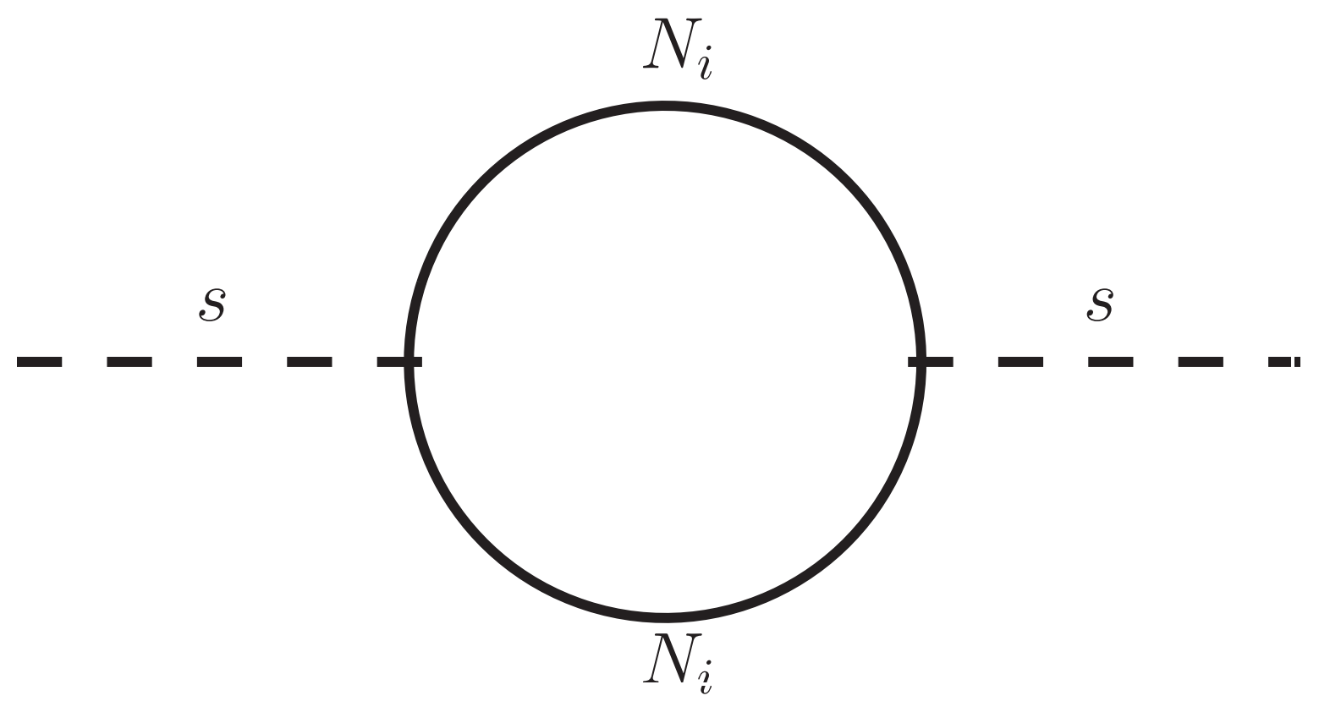


Figure 1: One-loop diagram contributing dominantly towards thermally corrected mass of scalar s.

The thermal contribution to the mass of s

$$\Pi^2_{N_i}(T) = \frac{y_{ii}^2}{6} T^2. \tag{9}$$

Finally, the effective mass of the scalar is expressed as,

$$M_s(T) = \sqrt{m_s^2 + \Pi_s^2(T) + \Pi_H^2(T) + \Pi_{Z_{BL}}^2(T) + \Pi_{N_i}^2(T)} \tag{10}$$

DM Phenomenology

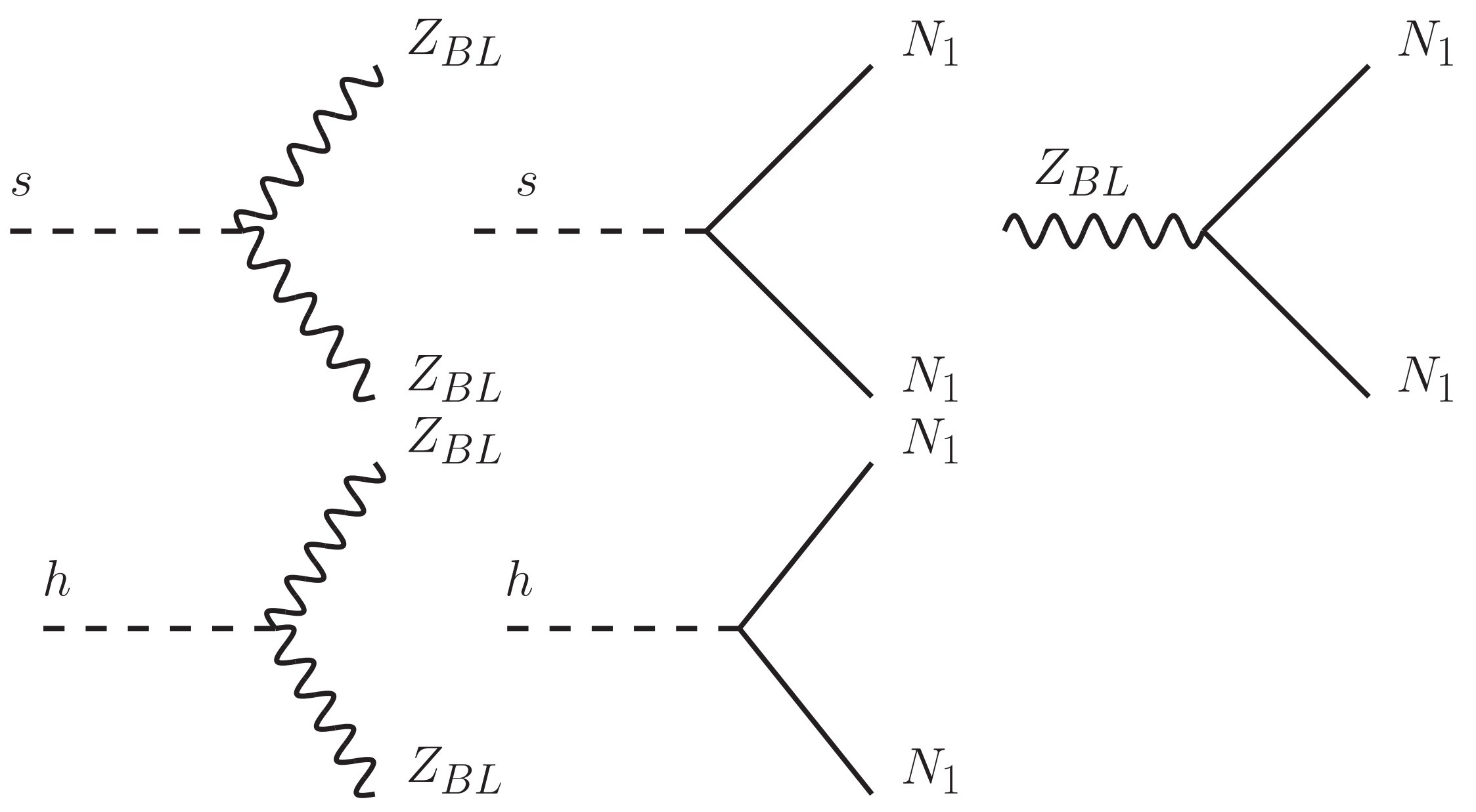


Figure 2: Possible production channels of Z_{BL} and the DM (N_1).

$$\frac{dY_{Z_{BL}}}{dx} = \frac{1}{Hx}\Big[\theta(M_s(m_s/x) - 2M_{Z_{BL}})\,\langle\Gamma_{s\to Z_{BL}Z_{BL}}\rangle Y_s^{EQ} - \langle\Gamma_{Z_{BL}\to\, all}\rangle Y_{Z_{BL}}\Big], \tag{11}$$

$$\frac{dY_{N_1}}{dx} = \frac{1}{Hx}\Big[\langle\Gamma_{Z_{BL}\to N_1N_1}\rangle Y_{Z_{BL}} + \theta(M_s(m_s/x) - 2M_1)\,\langle\Gamma_{s\to N_1N_1}\rangle Y_s^{EQ}\Big], \tag{12}$$

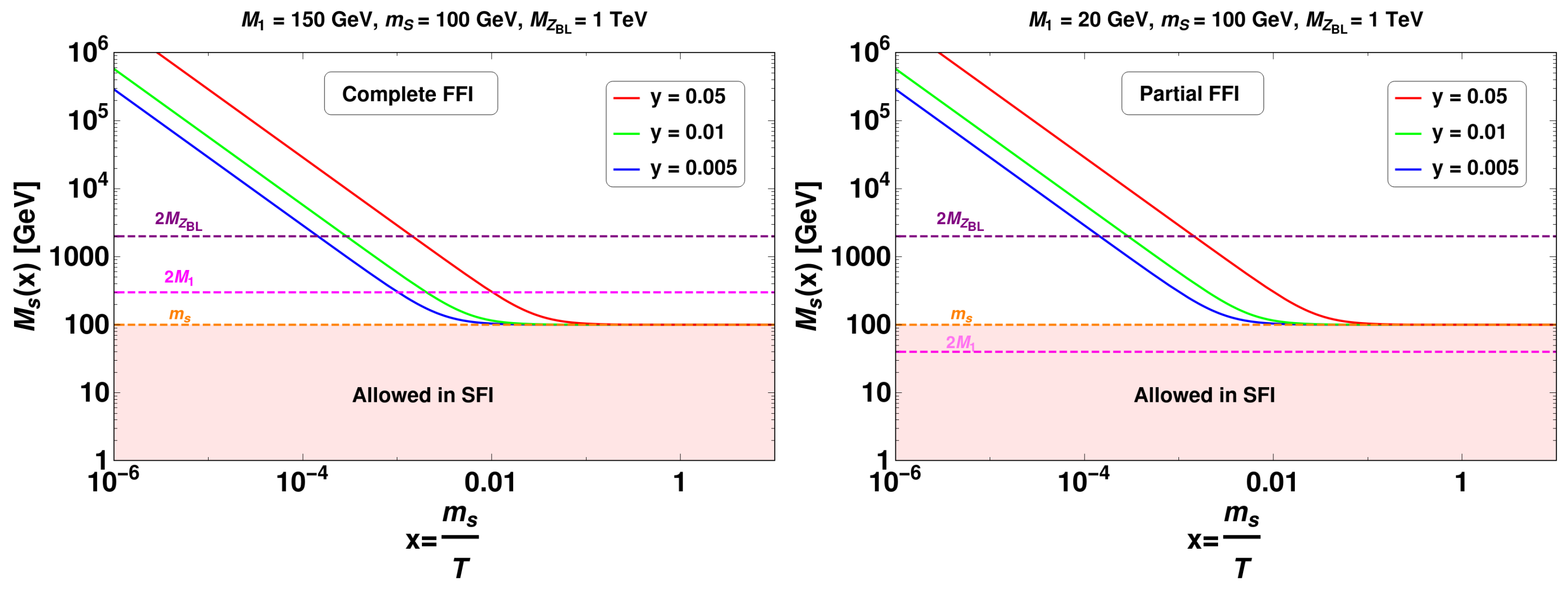
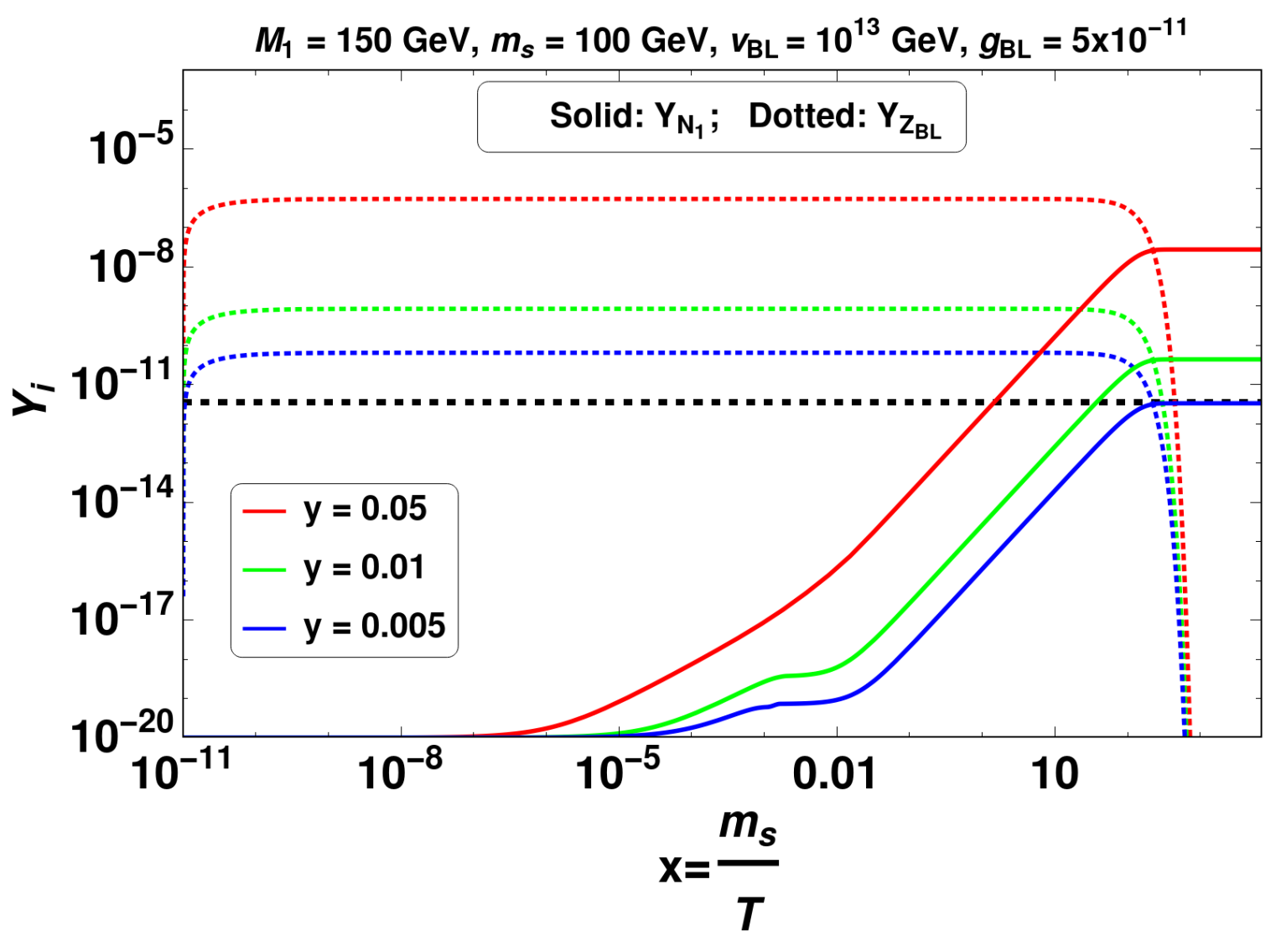
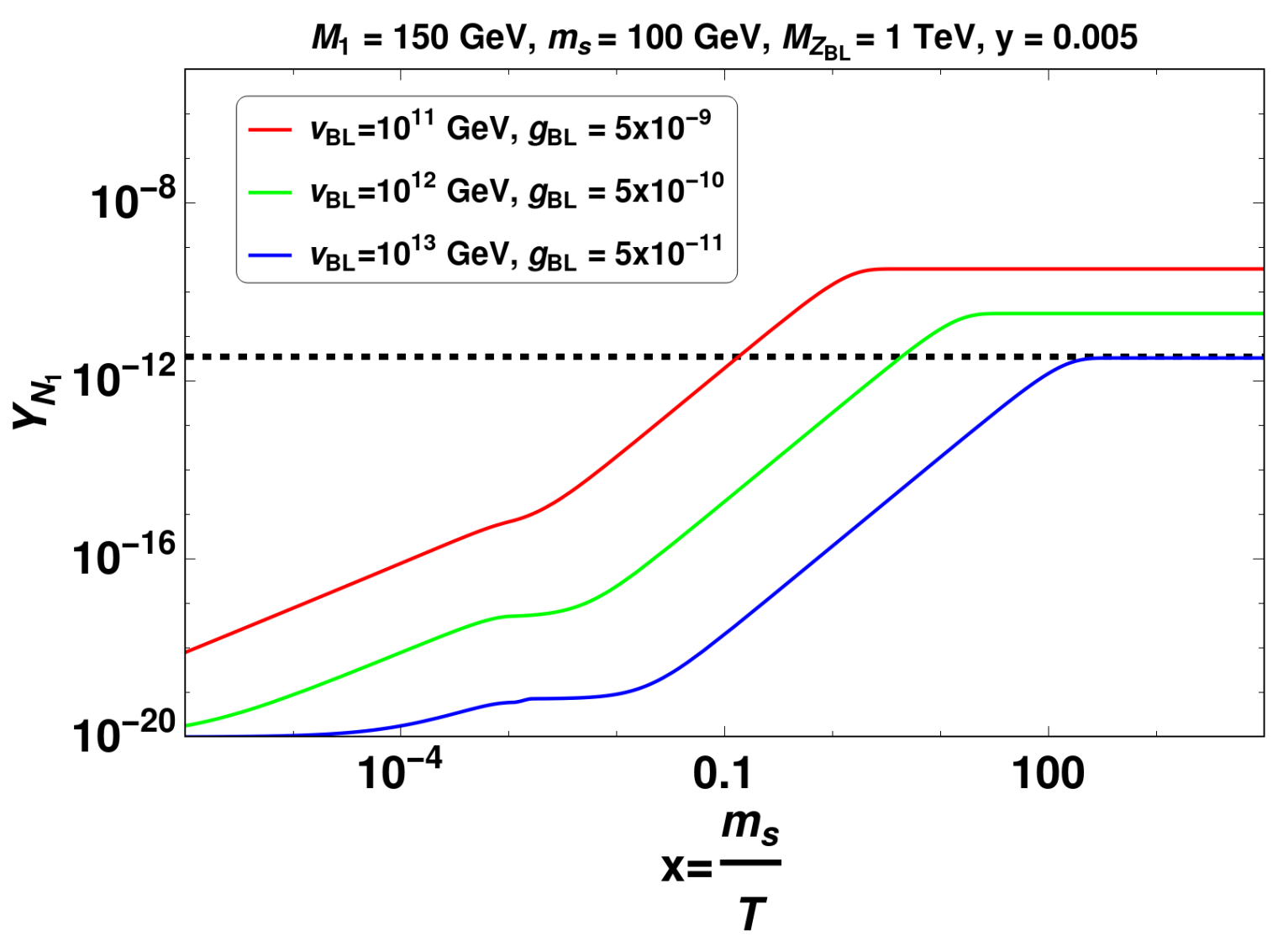


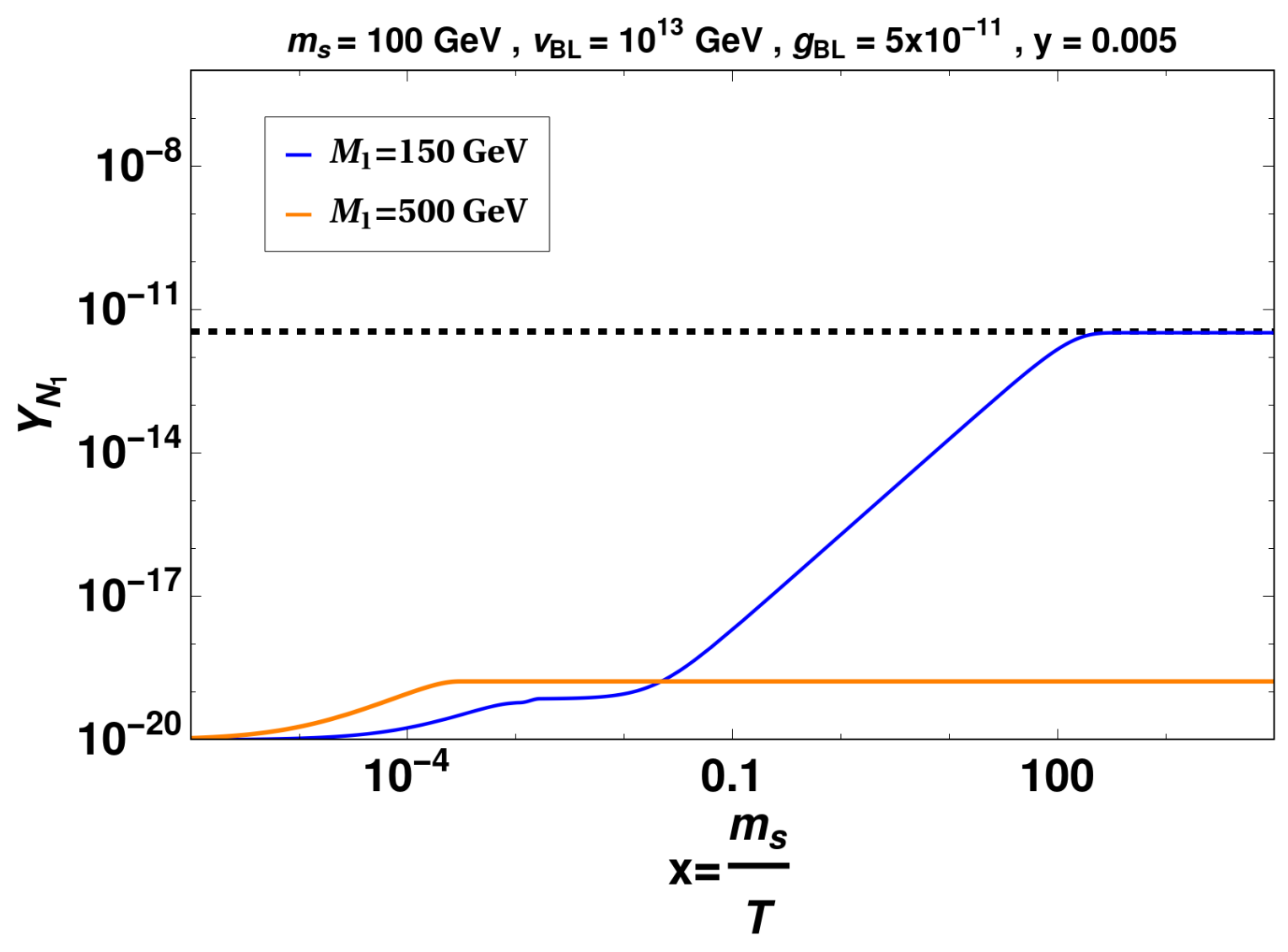
Figure 3: Variation of thermal mass with $x = m_s/T$

Case A: Complete FFI region when $M_{Z_{BL}} > M_1 > m_s$

Decay-Channels	SFI	FFI
$s \to Z_{BL}Z_{BL}$	X	✓
$s \to N_1N_1$	X	✓
$Z_{BL} \to N_1N_1$	X	✓

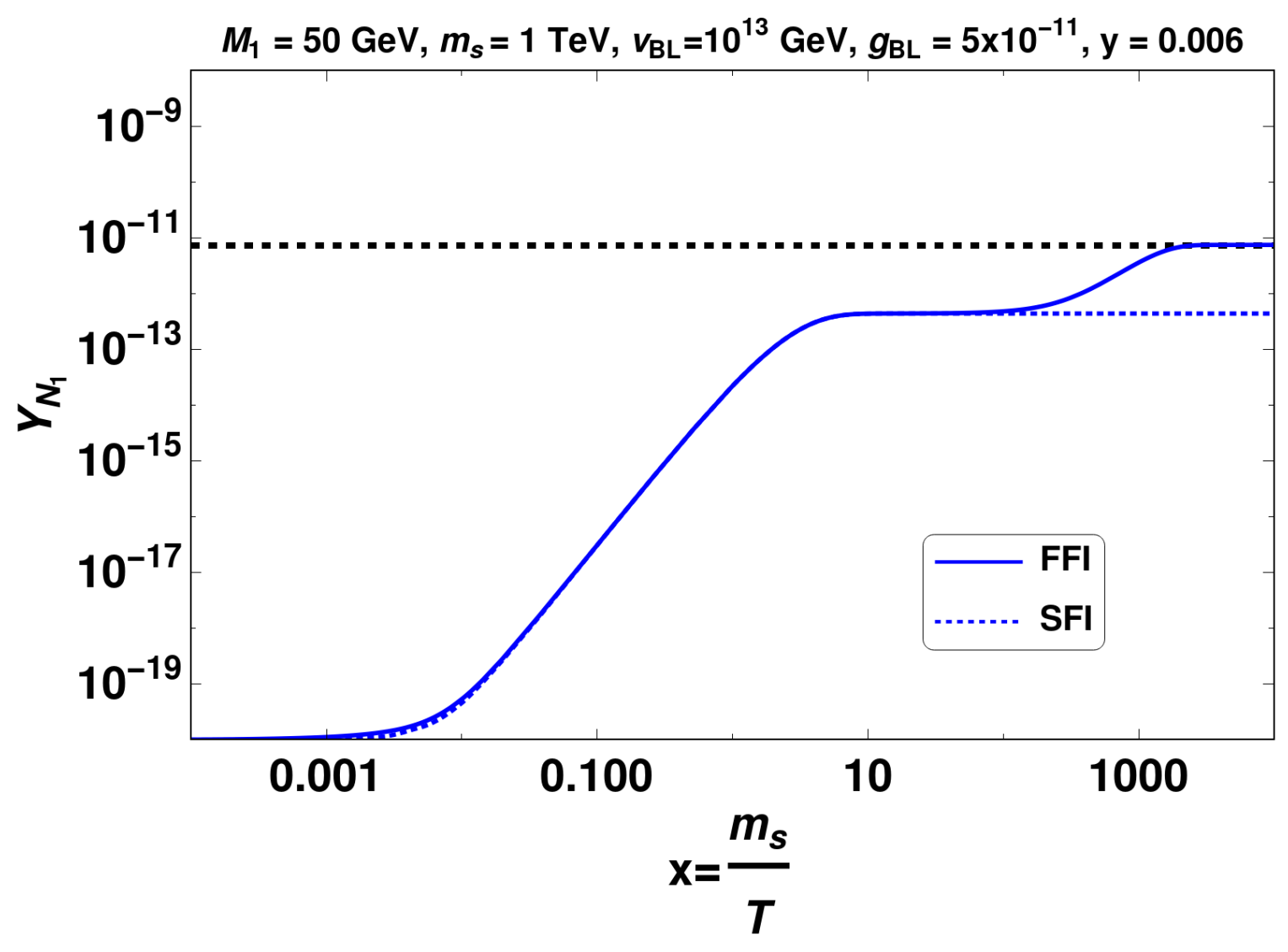






Case B: Partial FFI region when $M_{Z_{BL}} > m_s > M_1$

Decay-Channels	SFI	FFI
$s \to Z_{BL}Z_{BL}$	X	✓
$s \to N_1N_1$	✓	✓
$Z_{BL} \to N_1N_1$	X	✓



Conclusions

- We study a picture where the forbidden freeze-in production of dark matter occurs in the presence of significant thermal mass.
- We have seen that dark matter mainly produced from the Z_{BL} decay though Z_{BL} can not be produced in SFI case.
- We also discuss that production of Z_{BL} in FFI helps to distinguish it from SFI scenario.
- FFI actually enhances the parameter space of dark matter by allowing the disallowed region.