Moduli Portal Dark Matter

Debtosh Chowdhury
Ecole Polytechnique & LPT, Orsay

in collaboration w/
Emilian Dudas, Maira Dutra, and Yann Mambrini
[arXiv:1807.xxxxx]

CEFIPRA

LPT Orsay

DSU 2018, Annecy
June 25, 2018

l'X ÉCOLE POLYTECHNIQUE UNIVERSITÉ PARIS-SACLAY

Talk at a glance

* Why Dark Matter?
* Thermal vs. Non-thermal Dark Matter
* Introduction to Moduli
* Model Setup
* Results
* Conclusion

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* **Thermal vs. Non-thermal Dark Matter**
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Discussed in detail during the previous session talks

Introduction

* Scalar fields corresponding to flat directions are called moduli fields.

* They are usually massless, non-perturbative effects can give a small mass to these fields.

* Moduli fields usually have gravitational interactions, or in other words have Planck mass suppressed interactions.

* Due to Planck suppressed interaction to the matter, moduli could serve as mediator to dark matter in Freeze-in scenario.

Constraints on Moduli

* Moduli are light and have gravitational interactions $\Rightarrow$ long lived!

* Moduli would decay at present time if

$$\Gamma_{\mathscr{T}} \sim H_0 \Rightarrow m_{\mathscr{T}} = \left(H_0 m_P^2\right)^{1/3} \sim 20 \text{ MeV}$$

* if 10^{-26} eV $< m_{\mathscr{T}} < 20$ MeV, moduli has not decayed until now and there is too much energy stored in it.

* for 20 MeV $< m_{\mathscr{T}} < 10$ TeV, the entropy release following the modulus decay is too large to be consistent with present observations.

Coughlan et al., '83
Goncharov et al. '84
Ellis et al., '86

Model Set-up

* We decompose the moduli as $\mathscr{T} \equiv s + i\ a$

* We assume the imaginary part of the modulus posses a shift symmetry $\Rightarrow$ real part of the modulus has non-derivative coupling to other fields.

* Lagrangian to be CP-symmetric and we consider terms until d=6.

Lagrangian

Scalar DM

$$\mathscr{L} \supset -\frac{1}{\Lambda}\Big[\alpha_\Phi\, s\; D^\mu \Phi D_\mu \Phi + \left(\alpha_\Phi(\partial_\mu s) + \beta_\Phi(\partial_\mu a)\right)\, \Phi D^\mu \Phi\Big]$$

Fermionic DM

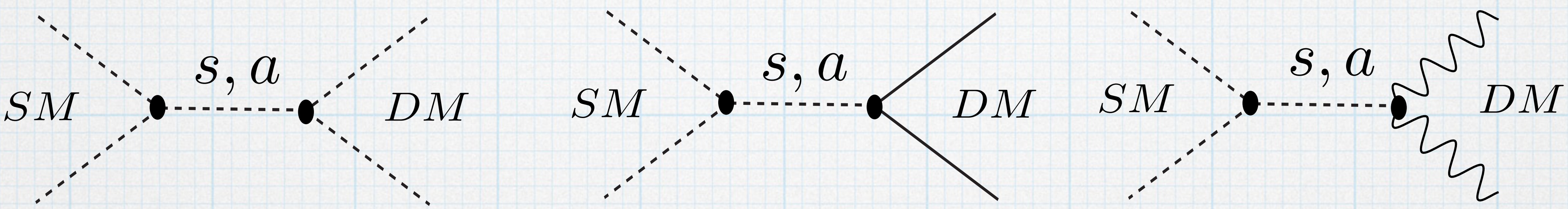
$$\begin{aligned}\mathcal{L} \supset -\frac{1}{\Lambda}\Big[&\alpha_\Psi(s\;\bar\Psi \not{D}\Psi + \partial_\mu s \bar\Psi\gamma^\mu\Psi + \partial_\mu s\bar\Psi i\gamma_5\gamma^\mu\Psi) \\ &+ \alpha'_\Psi(s\;\bar\Psi i\gamma_5 \not{D}\Psi + \partial_\mu s\bar\Psi i\gamma_5\gamma^\mu\Psi + \text{h.c.}) \\ &+ \beta_\Psi\,\partial_\mu a\bar\Psi\gamma^\mu\Psi + \beta'_\Psi\,(\partial_\mu a\bar\Psi i\gamma_5\gamma^\mu\Psi + \text{h.c.})\Big]\end{aligned}$$

Vector DM

$$\mathscr{L} \supset -\frac{1}{\Lambda}\Big[\alpha_V\, s\, V_{\mu\nu}V^{\mu\nu} + \beta_V\, a\, V_{\mu\nu}\widetilde{V}^{\mu\nu}\Big]$$

Rates

$$R(T)_{s_i\to s_f(j)} = \frac{N_i N_f S_i S_f}{32(2\pi)^6}\int_{4m_{DM}^2}^{\infty} ds \int d\Omega\,|\mathscr{M}|^2_{s_i\to s_f(j)}\sqrt{1-\frac{4m_{DM}^2}{s}}\int_0^{\infty} dp_1 f_1 \int_{\frac{s}{4p_1}}^{\infty} dp_2 f_2$$

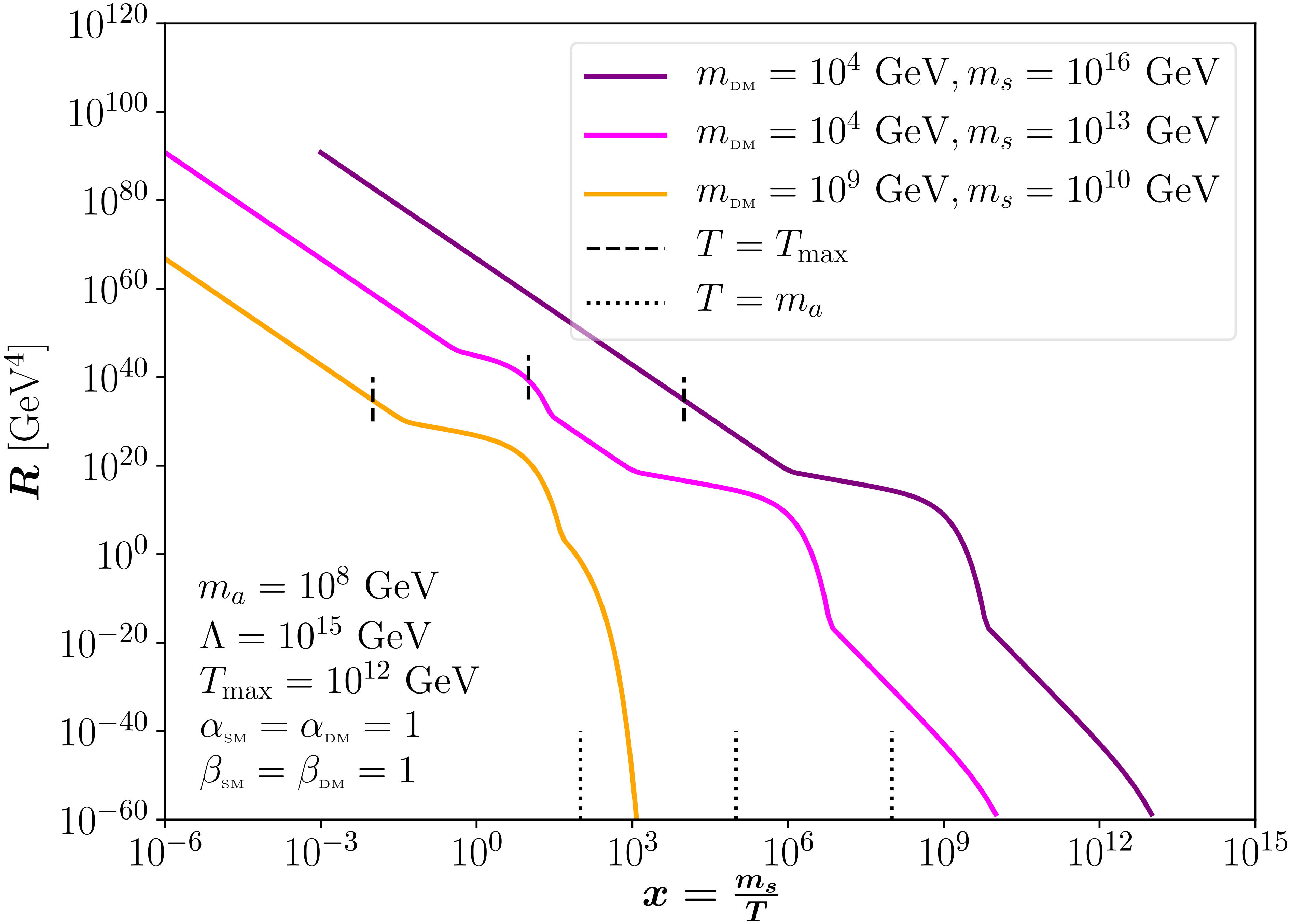


Scalar DM production rate from moduli

$\lambda^j_{i,0}$

s_i \ j	s	a
0	$16\alpha^2_{SM}\alpha^2_{DM}$	$\beta^2_{SM}\beta^2_{DM}$
1	$32\alpha^2_{SM}\alpha^2_{DM}$	$8\beta^2_{SM}\beta^2_{DM}$

$$R(T)_{s_i\to 0(M_j)} \approx \begin{cases} \dfrac{\pi^2}{43200}\lambda^j_{i,0}\dfrac{T^8}{\Lambda^4} & \text{(light regime)} \\[2ex] \dfrac{1}{4096\pi^5}\lambda^j_{i,0}\dfrac{M_j^8}{\Lambda^4\Gamma_j}TK_1\left(\dfrac{M_j}{T}\right) & \text{(NWA regime)} \\[2ex] \dfrac{16\pi^6}{19845}\lambda^j_{i,0}\dfrac{T^{12}}{\Lambda^4 M_j^4} & \text{(heavy regime)} \end{cases}$$



$m_{\rm DM} = 10^4$ GeV, $m_s = 10^{16}$ GeV
$m_{\rm DM} = 10^4$ GeV, $m_s = 10^{13}$ GeV
$m_{\rm DM} = 10^9$ GeV, $m_s = 10^{10}$ GeV
$T = T_{\rm max}$
$T = m_a$
$m_a = 10^8$ GeV
$\Lambda = 10^{15}$ GeV
$T_{\rm max} = 10^{12}$ GeV
$\alpha_{\rm SM} = \alpha_{\rm DM} = 1$
$\beta_{\rm SM} = \beta_{\rm DM} = 1$
$\boldsymbol{R}$ [GeV^4]
$\boldsymbol{x = \frac{m_s}{T}}$
10^{120}
10^{100}
10^{80}
10^{60}
10^{40}
10^{20}
10^{0}
10^{-20}
10^{-40}
10^{-60}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}

DM Evolution

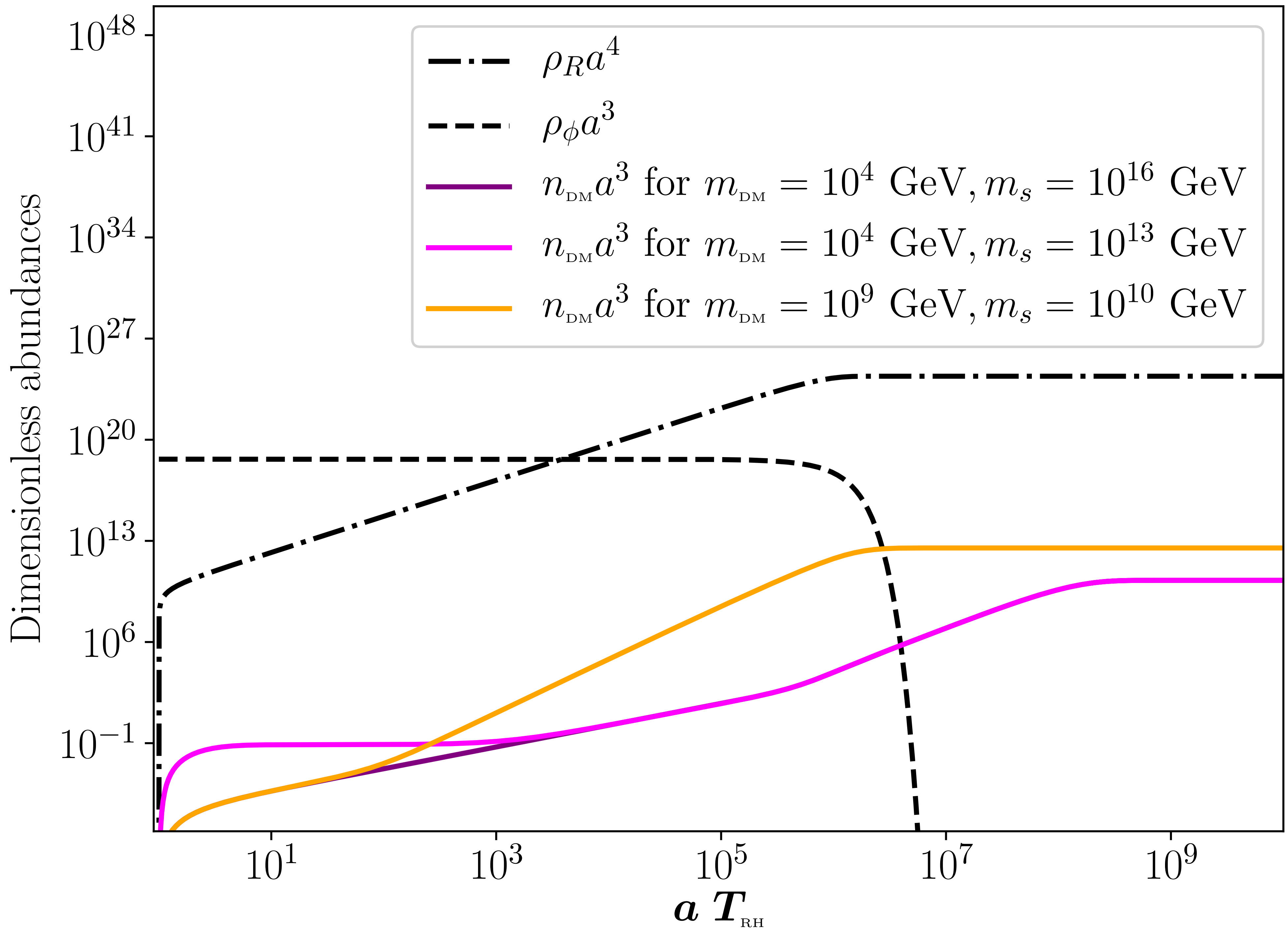
$$\frac{d\rho_\phi}{dt} = -3H\,\rho_\phi - \Gamma_\phi\,\rho_\phi$$

$$\frac{d\rho_R}{dt} = -4H\,\rho_R + \Gamma_\phi\,\rho_\phi + 2\langle\sigma v\rangle\langle E_{\rm DM}\rangle\left[n_{\rm DM}^2 - \left(n_{\rm DM}^{\rm eq}\right)^2\right]$$

$$\frac{dn_{\rm DM}}{dt} = -3H\,n_{\rm DM} - \langle\sigma v\rangle\langle E_{\rm DM}\rangle\left[n_{\rm DM}^2 - \left(n_{\rm DM}^{\rm eq}\right)^2\right]$$

Chung et al. '99,
Giudice et al. '01

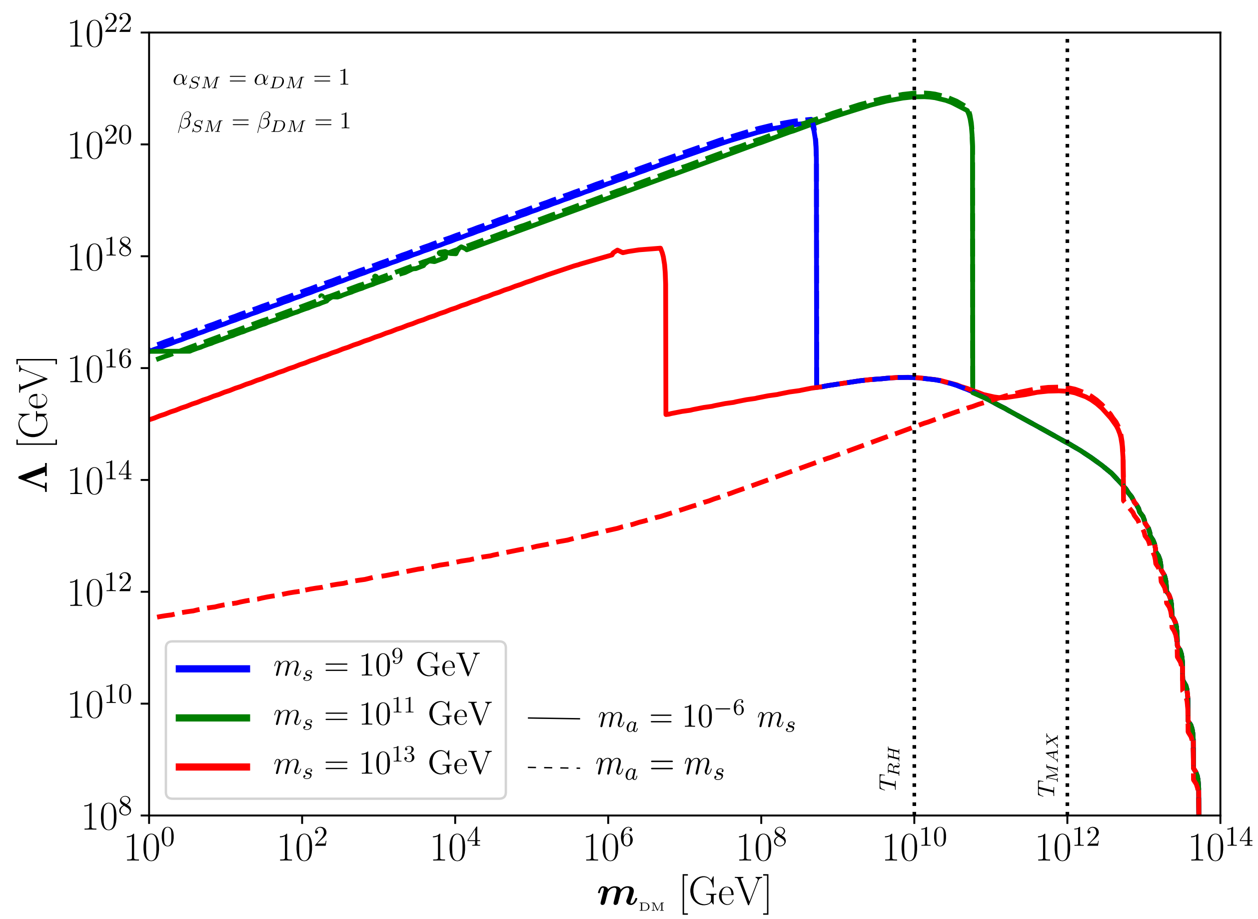
$$\boxed{H^2 = \frac{1}{3M_P^2}\left(\rho_\phi + \rho_R + \rho_{\rm DM}\right)}$$

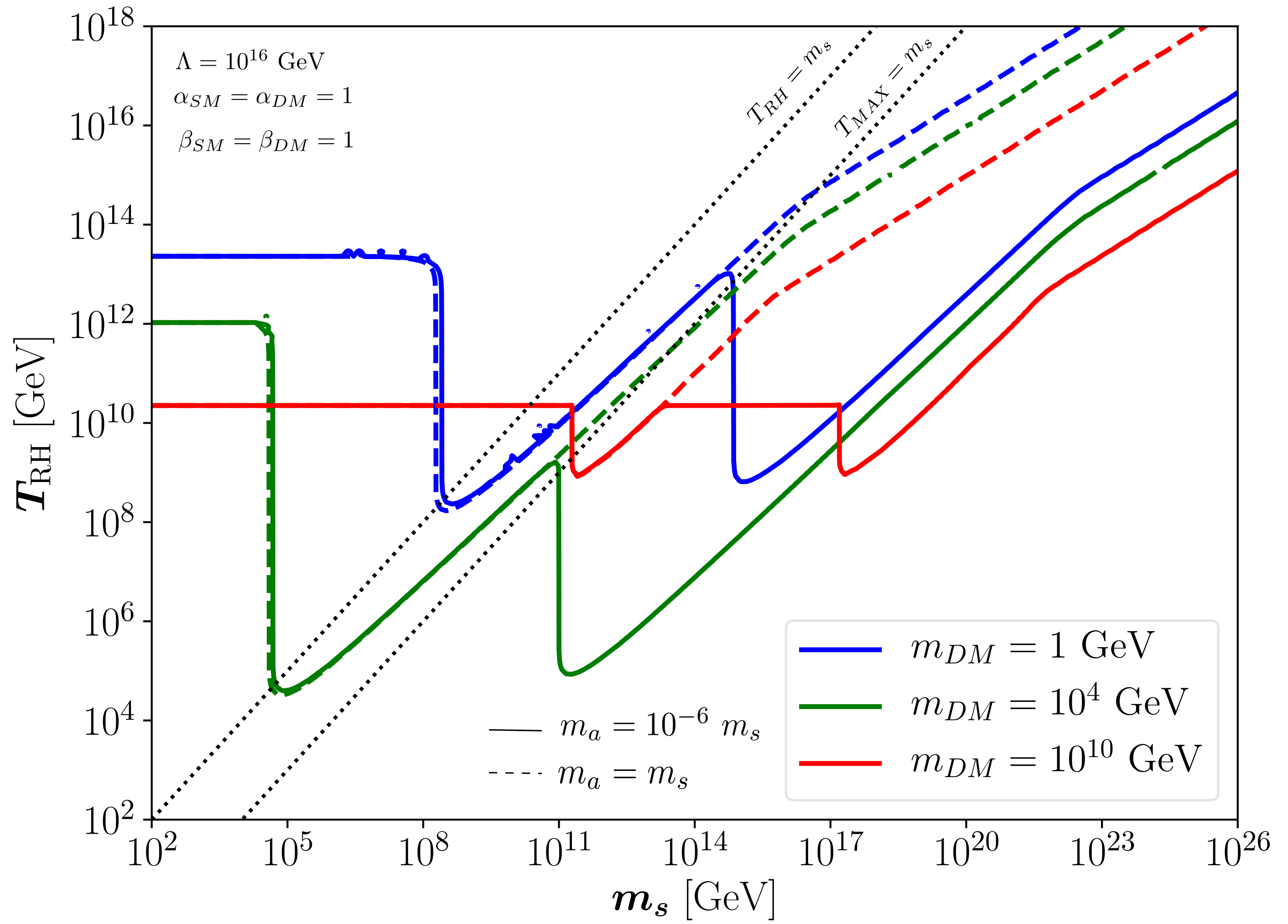


$\rho_R a^4$
$\rho_\phi a^3$
$n_{\rm DM} a^3$ for $m_{\rm DM} = 10^4$ GeV, $m_s = 10^{16}$ GeV
$n_{\rm DM} a^3$ for $m_{\rm DM} = 10^4$ GeV, $m_s = 10^{13}$ GeV
$n_{\rm DM} a^3$ for $m_{\rm DM} = 10^9$ GeV, $m_s = 10^{10}$ GeV
Dimensionless abundances
10^{48}
10^{41}
10^{34}
10^{27}
10^{20}
10^{13}
10^{6}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}
$a\,T_{\rm RH}$

Results

PRELIMINARY!





Conclusion

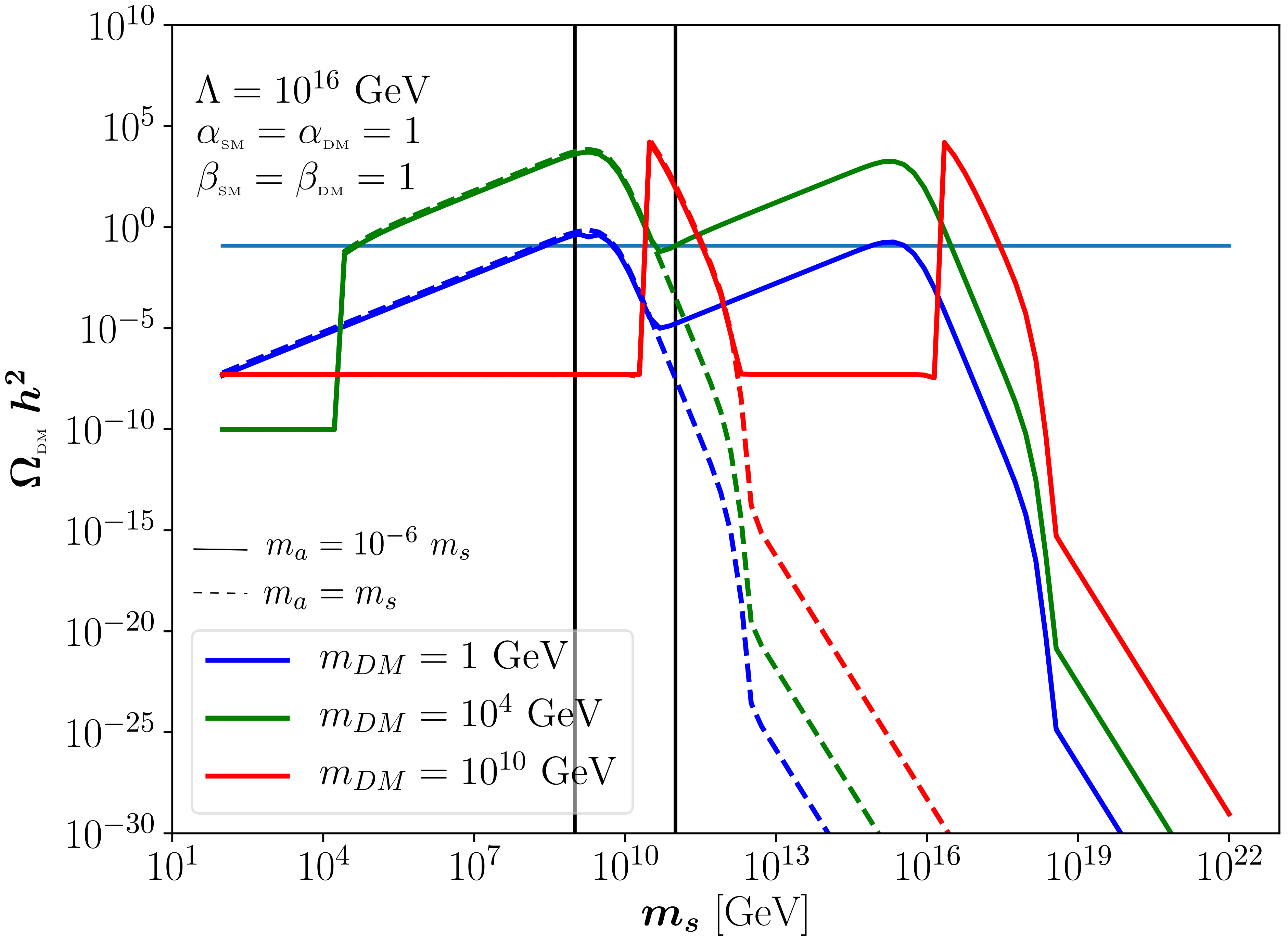
* Modulus field usually have Planck mass suppressed interactions, thus is an excellent candidate as a mediator for Freeze-in dark matter scenario.

* The DM production gets enhanced due to s-channel production at $T \simeq m_{\mathcal{T}} = 2m_{\text{DM}}$.

* In most of the parameter space considered, non-derivative terms are suppressed compared to the derivative terms.

Thank You!!

Extras



$\Lambda = 10^{16}$ GeV
$\alpha_{SM} = \alpha_{DM} = 1$
$\beta_{SM} = \beta_{DM} = 1$
$m_a = 10^{-6}\, m_s$
$m_a = m_s$
$m_{DM} = 1$ GeV
$m_{DM} = 10^4$ GeV
$m_{DM} = 10^{10}$ GeV
$\Omega_{DM}\, h^2$
m_s [GeV]
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{1}
10^{4}
10^{7}
10^{10}
10^{13}
10^{16}
10^{19}
10^{22}