Moduli Portal Dark Matter

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in collaboration w/

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[arXiv:1809.xxxxx]

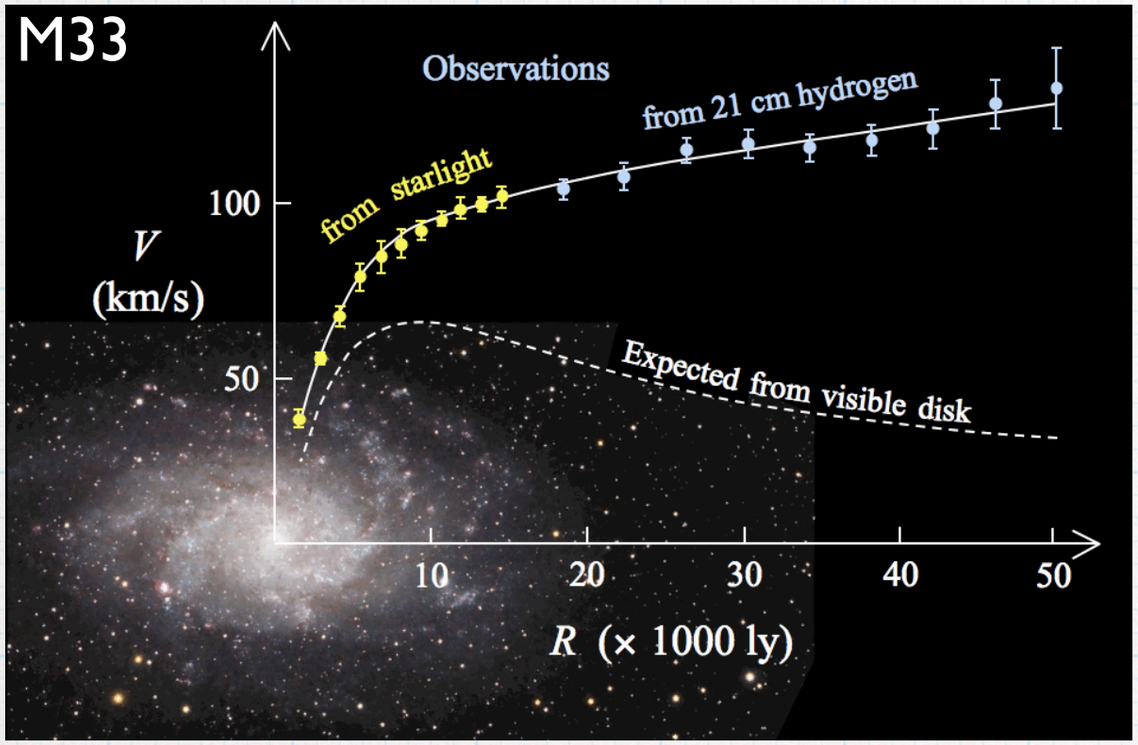
IRN Terascale, Durham

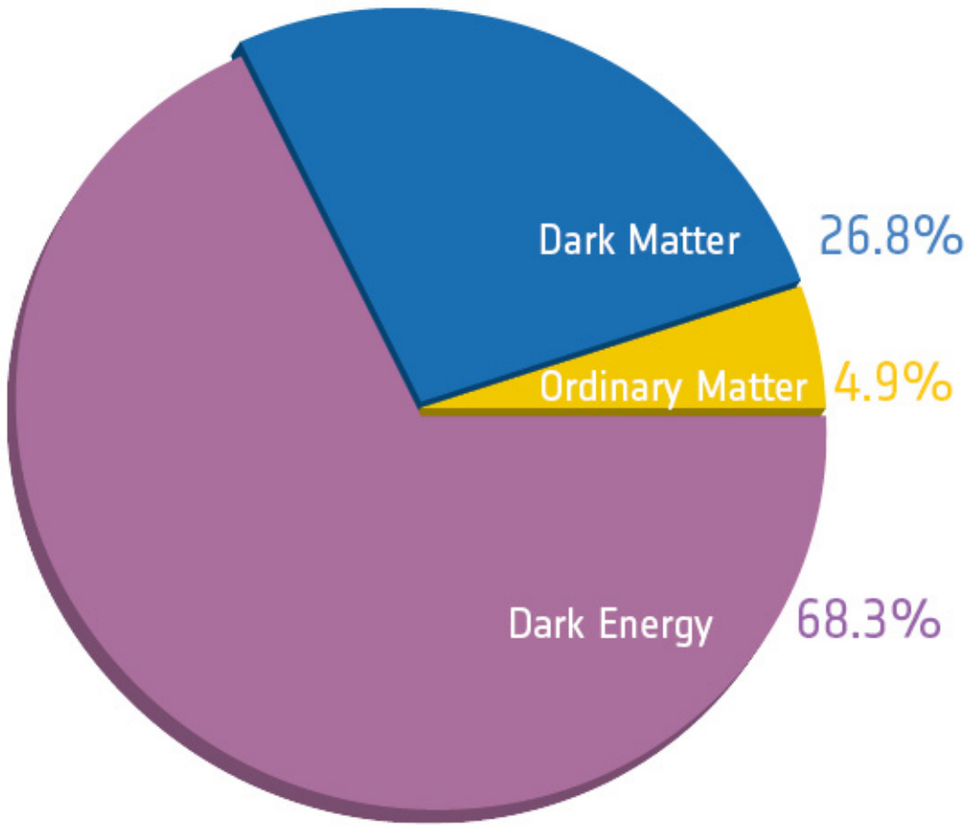
Sep 4, 2018

Talk at a glance

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

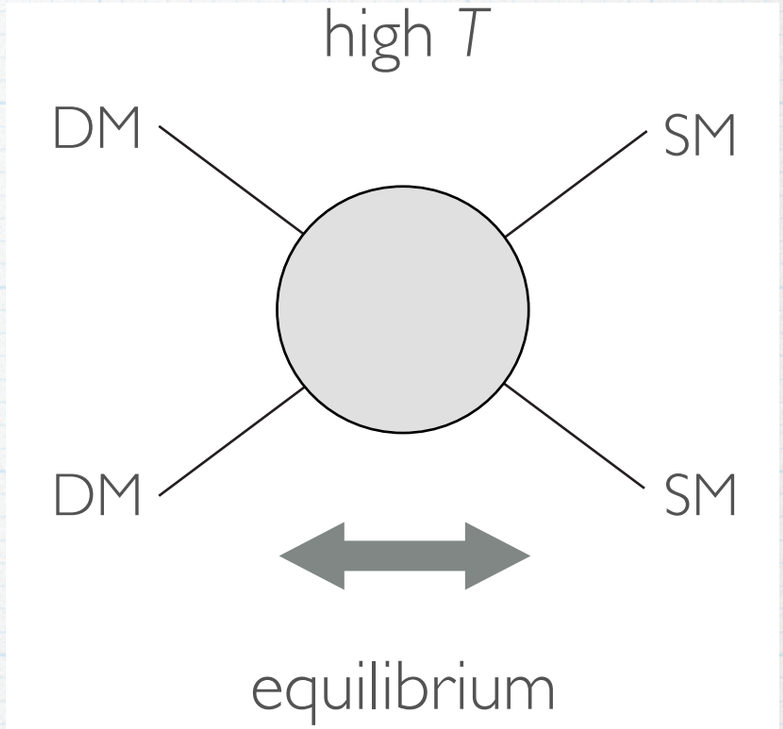
Evidence of Dark Matter

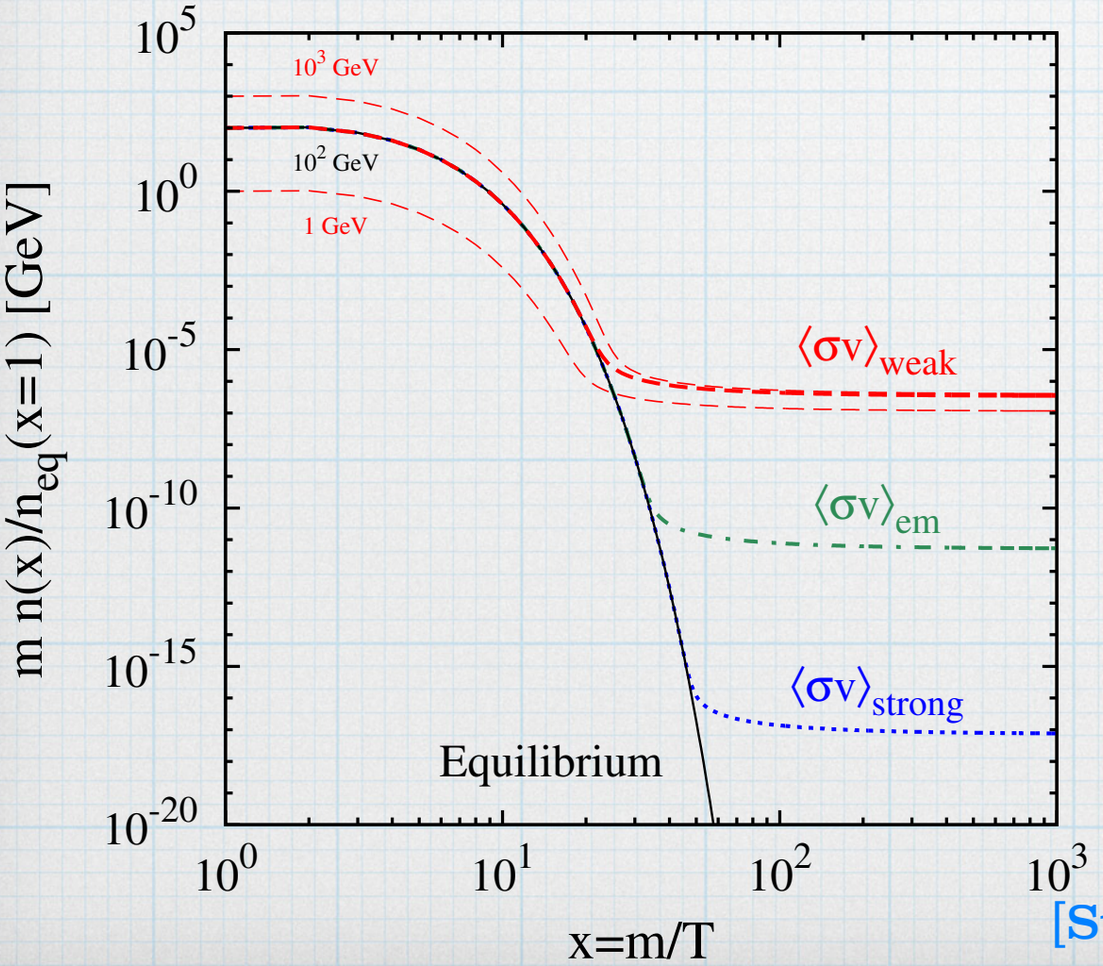




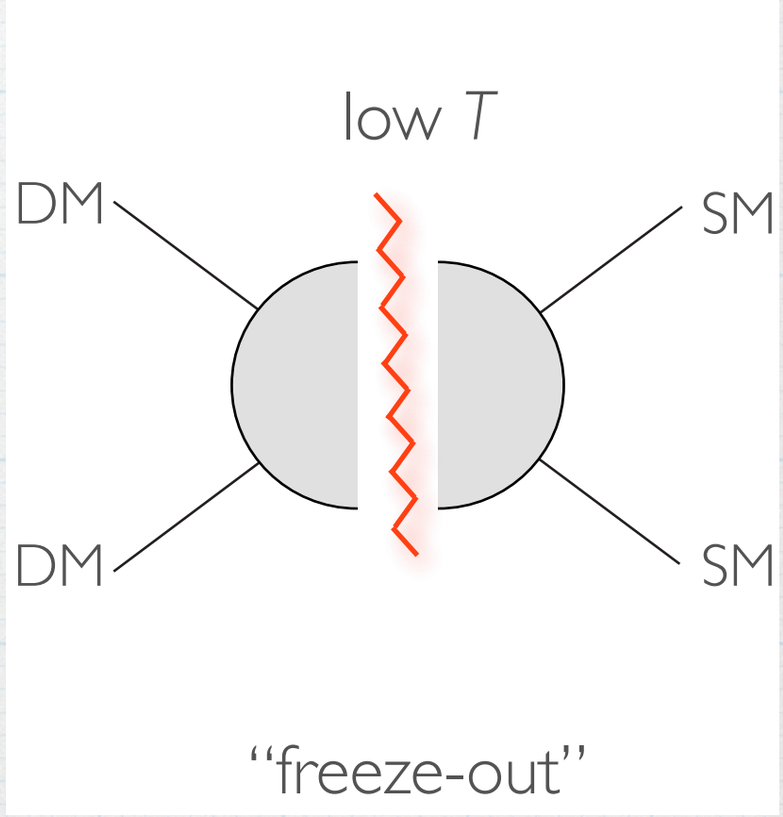
Thermal Relic

* In early Universe DM DM $\Leftrightarrow$ SM SM.
* Universe cools down DM DM $\Rightarrow$ SM SM.
* After further cooling, the interactions stop. DM **"freezes out"**.



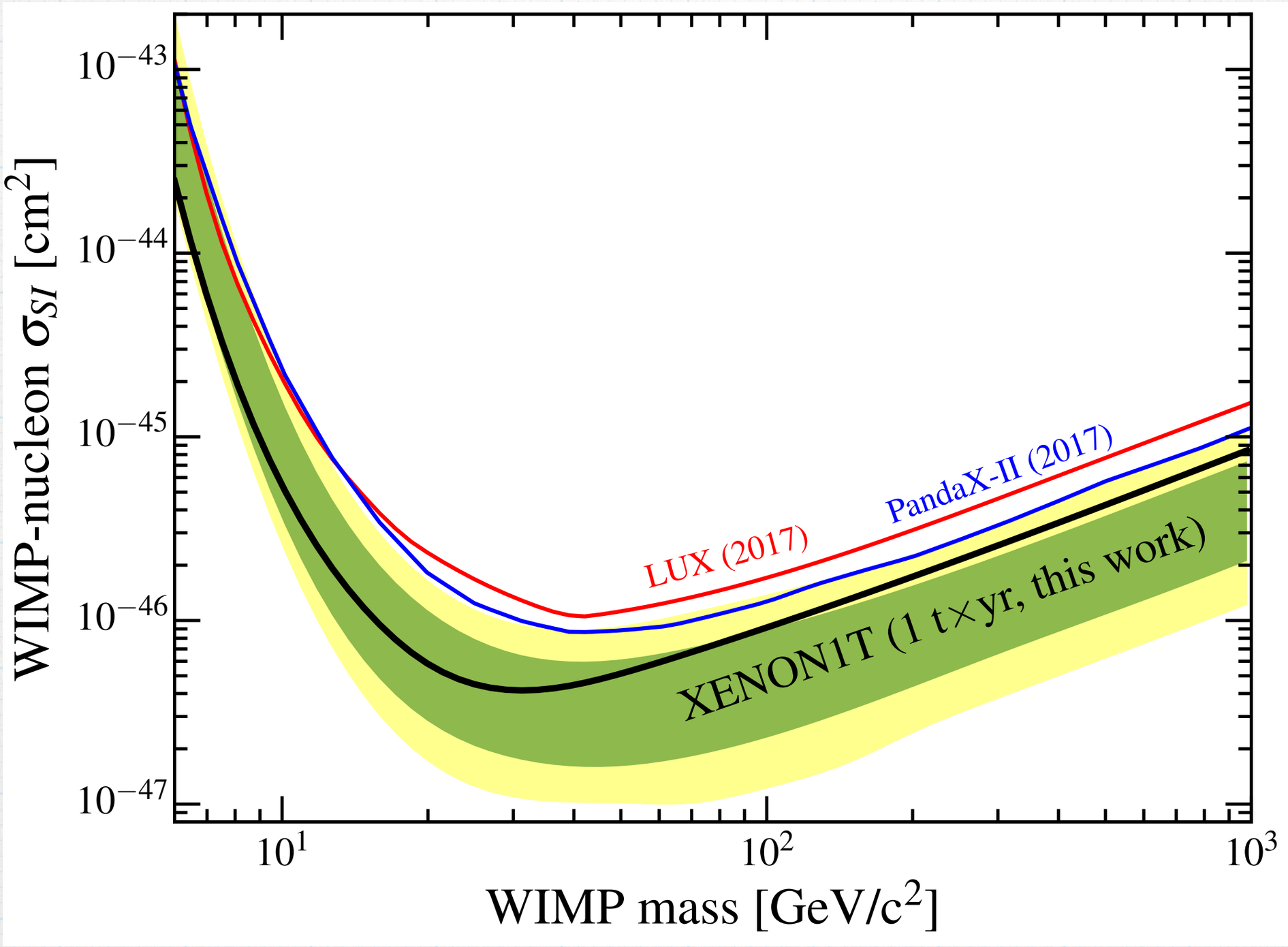


$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}$$



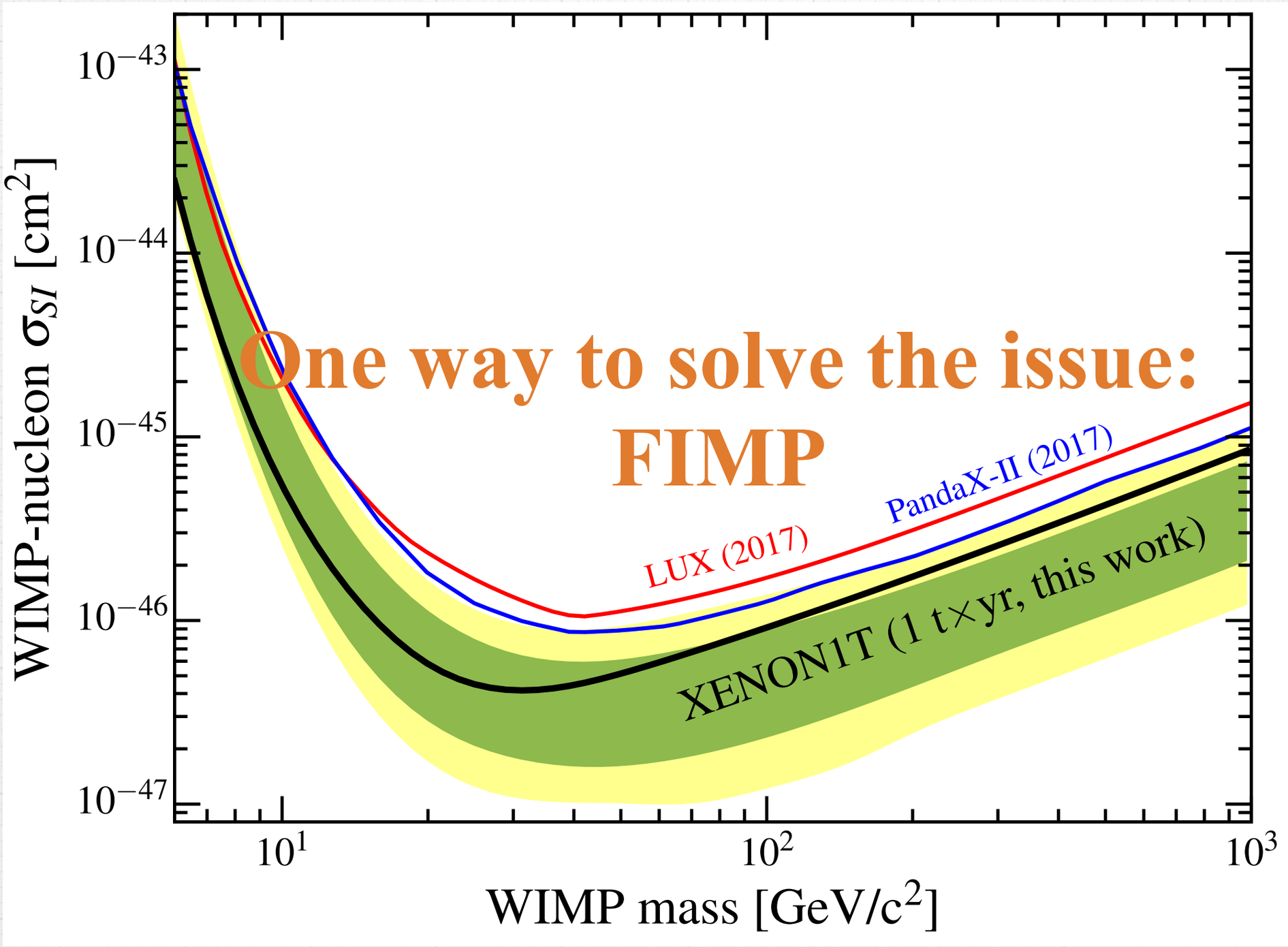
[Steigman, Dasgupta, Beacom '12]

WIMP Direct Detection



XENON1T; 1805.12562

WIMP Direct Detection



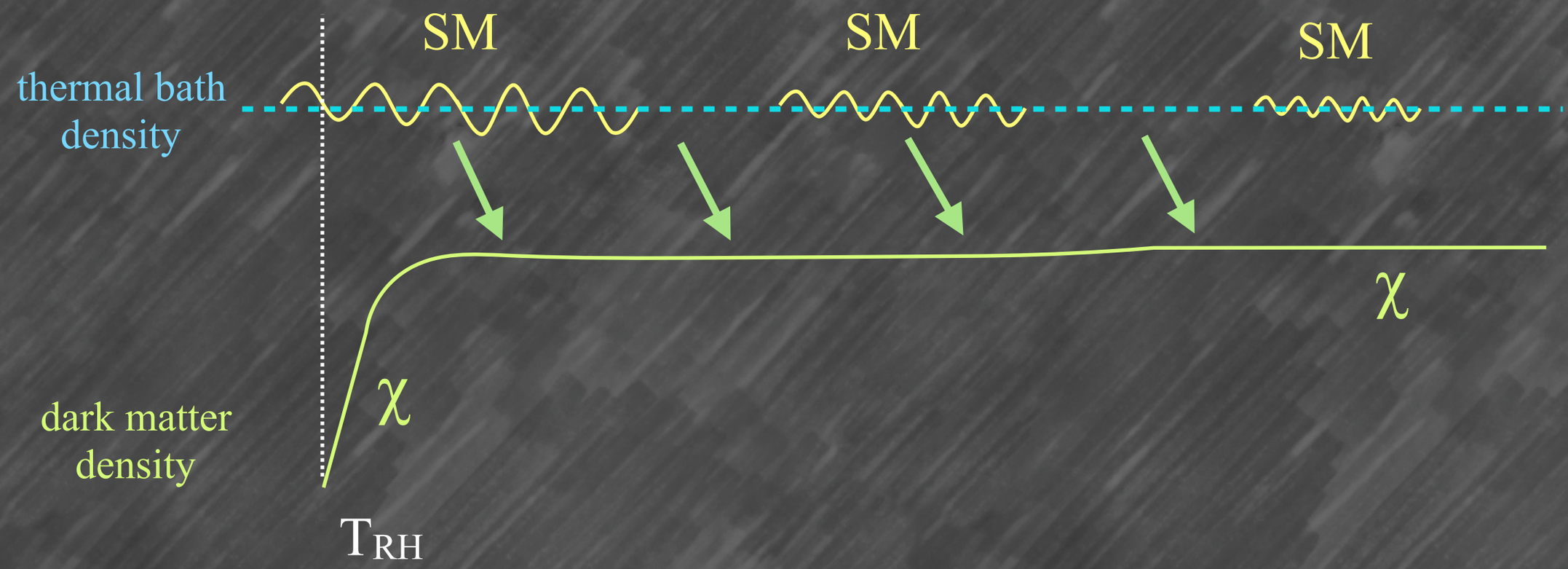
XENON1T; 1805.12562

Production of Dark Matter in early Universe

$$1 + 2 \rightarrow 3 + 4$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = R(T)$$

$$R(T) = n_{Eq}^2 \langle \sigma v \rangle = \int f_1 f_2 \frac{E_1 E_2 dE_1 dE_2 \; d\cos\theta_{12}}{1024\pi^6} \int |\mathcal{M}_{fi}|^2 d\Omega_{13} \propto \frac{T^{n+6}}{\Lambda^{n+2}}$$



Introduction to Moduli

* 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 ⇒ long lived!

* Moduli would decay at present time if

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

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

* for 20 MeV $< m_{\mathcal{T}} < 10$ 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
de Carlos et al., ‘93

Model Set-up

* **We decompose the moduli as** $\mathcal{T} = s + ia$

$$\begin{aligned}\mathcal{L} = \mathcal{L}_0^{SM} + \mathcal{L}_{eff}^{SM} =& \mathcal{Z}_H |D_\mu H|^2 + \mu^2(\mathcal{T},\bar{\mathcal{T}})|H|^2 + \lambda(\mathcal{T},\bar{\mathcal{T}})|H|^4 \\ & - \mathcal{Z}_Y \bar{f}_L H f_R - \mathcal{Z}_Y^* \bar{f}_R H^\dagger f_L \\ & + \mathcal{Z}_L \overline{f}_L i\gamma^\mu D_\mu f_L - \mathcal{Z}_L^* D_\mu \overline{f}_L i\gamma^\mu f_L \\ & + \mathcal{Z}_R \overline{f}_R i\gamma^\mu D_\mu f_R - \mathcal{Z}_R^* D_\mu \overline{f}_R i\gamma^\mu f_R \\ & - \frac{1}{4}\Re(\mathcal{Z}_G)\, G_{\mu\nu}G^{\mu\nu} - \Im(\mathcal{Z}_{\tilde{G}})\, G_{\mu\nu}\tilde{G}^{\mu\nu}\end{aligned}$$

Where $$\begin{aligned}\mathcal{Z}_i(\mathcal{T},\bar{\mathcal{T}}) &= 1 + \frac{c_i}{\Lambda}\mathcal{T} + \frac{d_i}{\Lambda}\bar{\mathcal{T}} + \cdots \\ &\approx 1 + \frac{c_i + d_i}{\Lambda}s + i\frac{c_i - d_i}{\Lambda}a\end{aligned}$$

* **c_i and d_i's are real ⇒ effective Lagrangian is CP-symmetric.**

* **consider terms until dim=6.**

Lagrangian

Scalar sector

$$\mathcal{L}_{eff}^{SM} \supset \frac{\alpha_H}{\Lambda} s(D^\mu H)^2 + s|H|^2 \times \begin{cases} \frac{2c_H \mu_0^2}{\Lambda} & \text{(case A)} \\ \frac{2M_{susy}^2}{M_P} & \text{(case B)} \end{cases}$$

$$\mu^2(\mathcal{T}, \bar{\mathcal{T}}) = \begin{cases} \mu_0^2\left(1 + \frac{c_H}{\Lambda}(\mathcal{T} + \bar{\mathcal{T}})\right) & \text{(case A)} \\ \mu_0^2 + \frac{M_{susy}^2}{M_P}(\mathcal{T} + \bar{\mathcal{T}}) & \text{(case B)} \end{cases}$$

Fermion sector

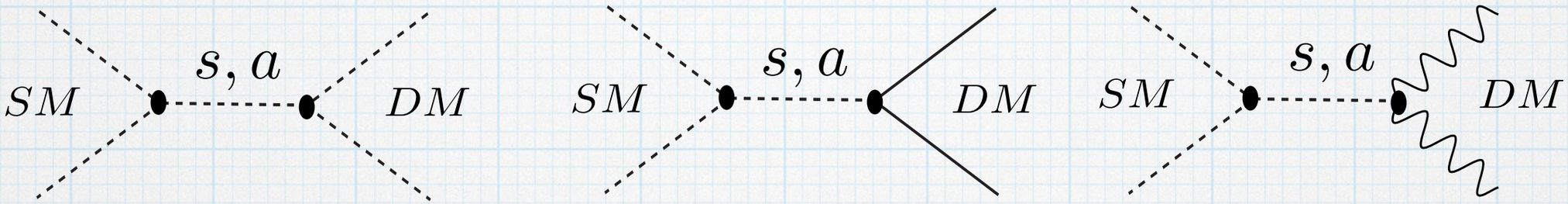
$$\mathcal{L}_{eff}^{SM} \supset \frac{1}{\Lambda}[\partial_\mu a \bar{f}\gamma^\mu(\beta_V^f - \beta_A^f\gamma^5)f + 2s\bar{f}i\gamma^\mu(\alpha_V^f - \alpha_A^f\gamma^5)D_\mu f + \text{h.c.}]$$

Gauge sector

$$\mathcal{L}_{eff}^{SM} \supset -\frac{1}{\Lambda}(\alpha_G\ s\ G_{\mu\nu}G^{\mu\nu} + \beta_G\ a\ G_{\mu\nu}\tilde{G}^{\mu\nu})$$

Rates

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



DM production rates

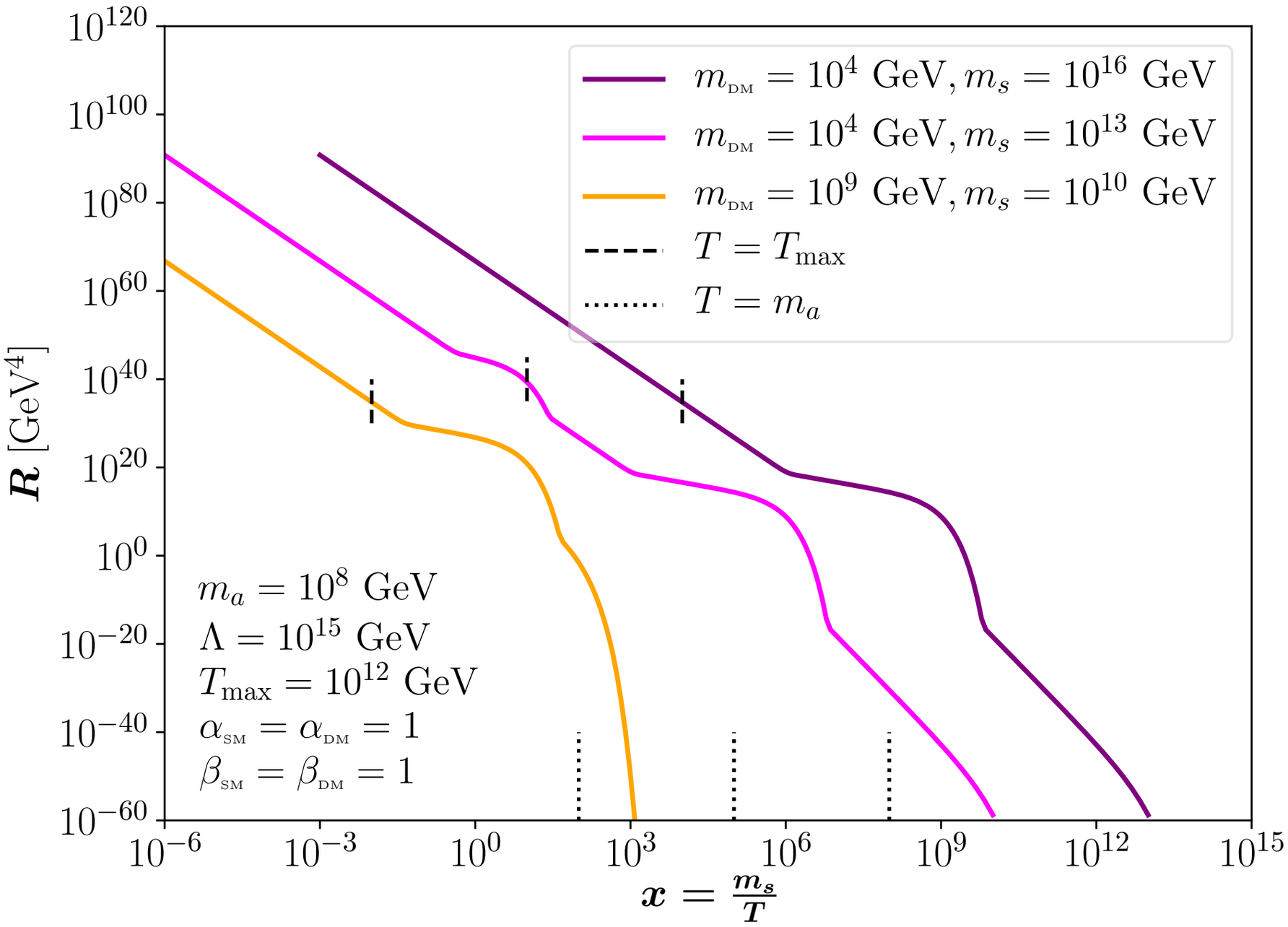
$$R^j_{0,1}(T) \propto \begin{cases} \frac{T^8}{\Lambda^4} & \text{Light regime } (m_j^2 \ll T) \\ \frac{m_j^8}{\Lambda^4} \frac{T}{\Gamma_j} K_1\left(\frac{m_j}{T}\right) & \text{NWA regime } (m_j^2 \sim T) \\ \frac{T^{12}}{m_j^4 \Lambda^4} & \text{Heavy regime } (m_j^2 \gg T) \end{cases}$$

Scalar & Vector

$$R^j_{1/2}(T) \propto \begin{cases} \frac{m_{DM}^2 T^6}{\Lambda^4} & \text{Light regime } (m_j^2 \ll T) \\ \frac{m_{DM}^2 m_j^6}{\Lambda^4} \frac{T}{\Gamma_j} K_1\left(\frac{m_j}{T}\right) & \text{NWA regime } (m_j^2 \sim T) \\ \frac{m_{DM}^2 T^{10}}{m_j^4 \Lambda^4} & \text{Heavy regime } (m_j^2 \gg T) \end{cases}$$

Fermion

Rates for vector DM



Dark Matter Production

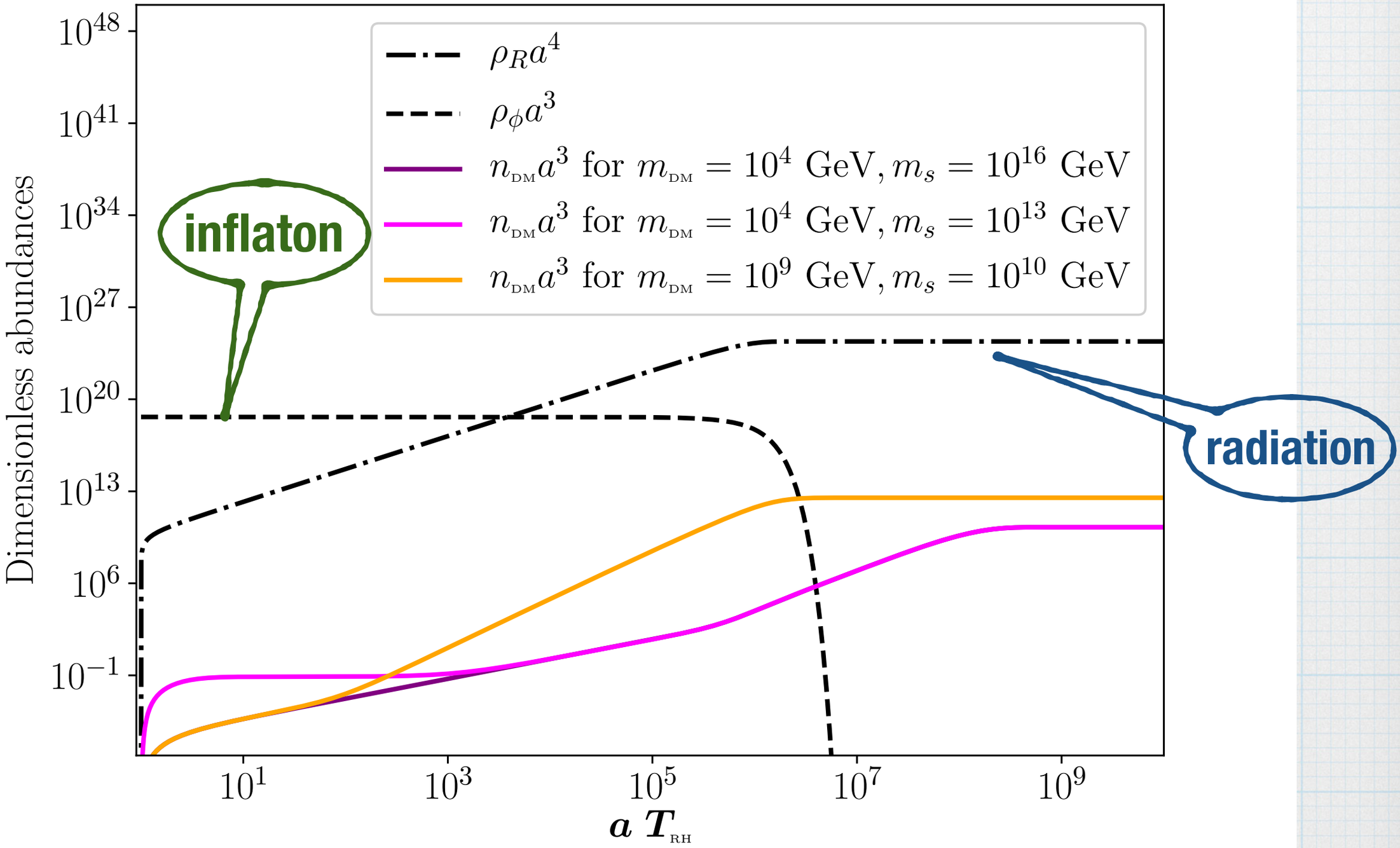
$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi \rho_\phi$$

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

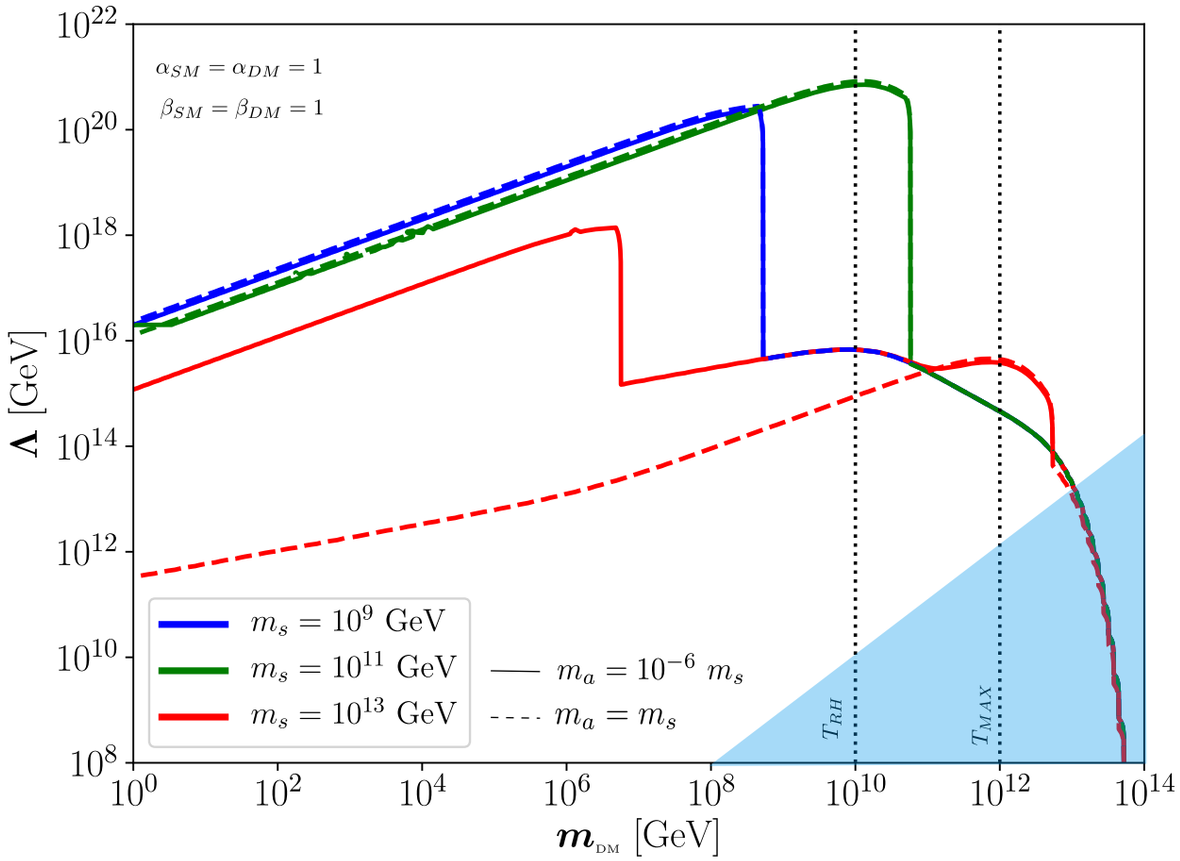
$$\frac{dn_{\rm DM}}{dt} = -3H n_{\rm DM} - \langle\sigma v\rangle\langle E_{\rm DM}\rangle\left[n_{\rm DM}^2 - \left(n_{\rm DM}^{\rm eq}\right)^2\right]$$

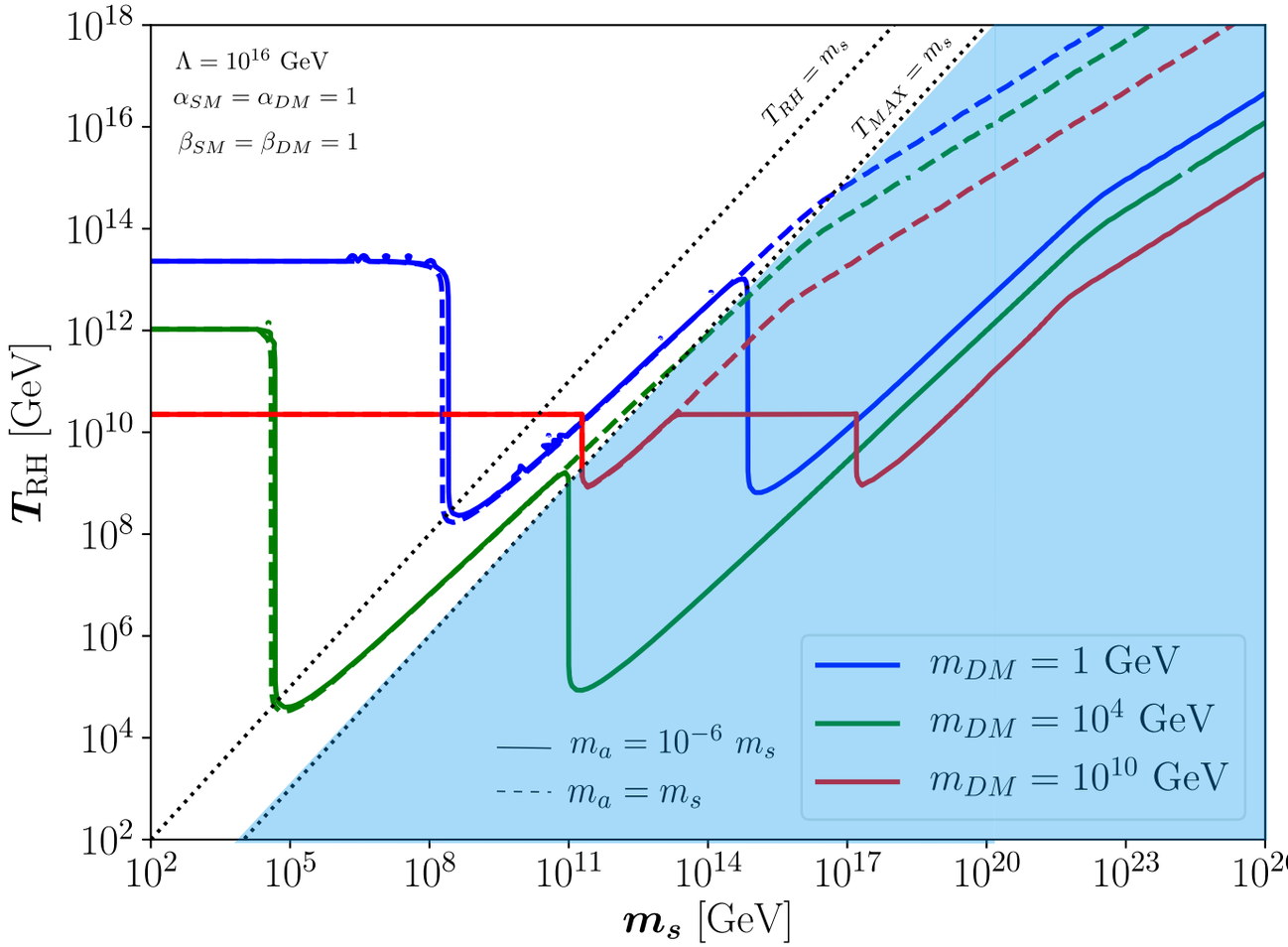
Chung et al. ’99,
Giudice et al. ’01

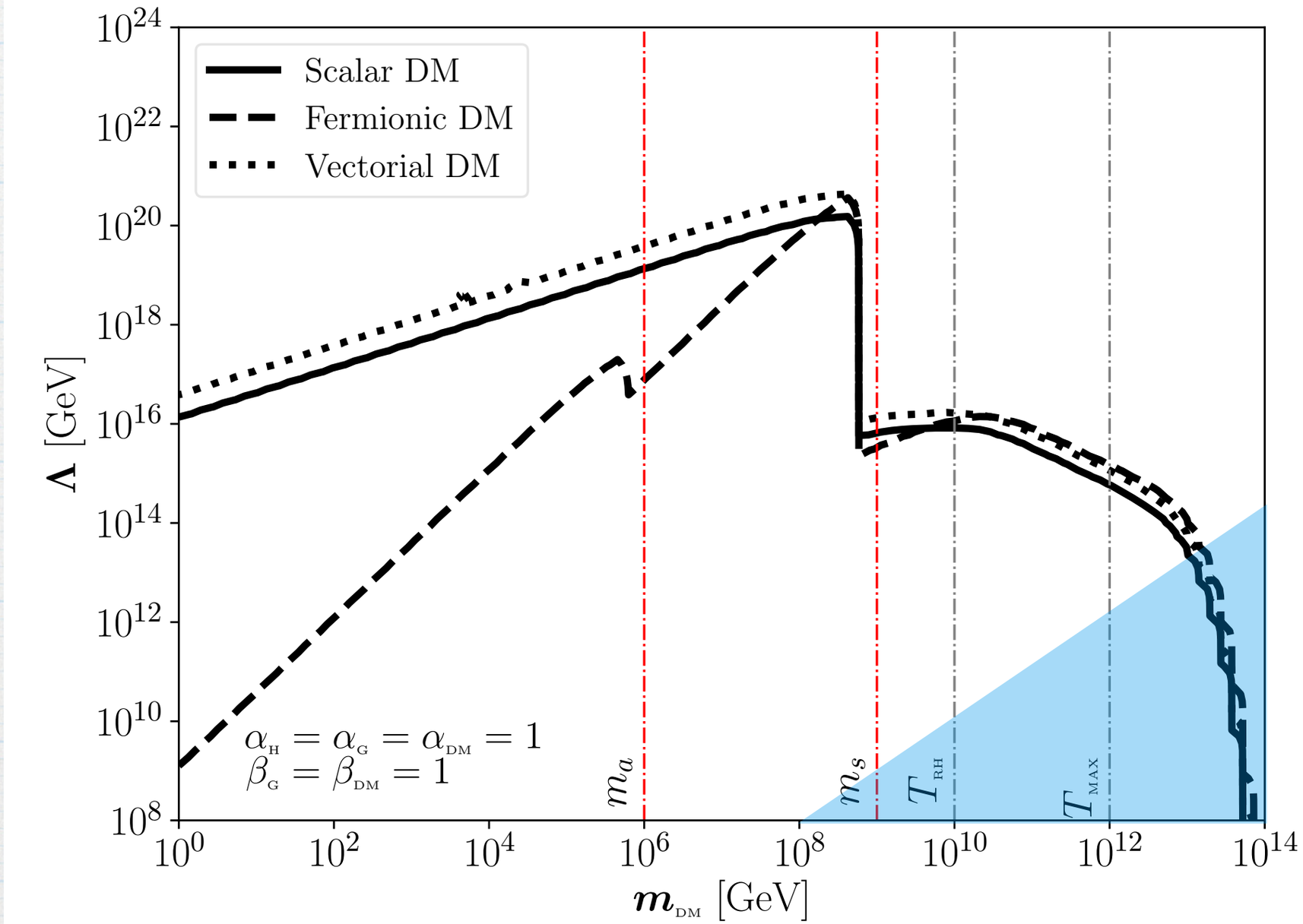
$$H^2 = \frac{1}{3M_P^2}\left(\rho_\phi + \rho_R + \rho_{\rm DM}\right)$$


$\rho_R a^4$
$\rho_\phi a^3$
$n_{\rm DM} a^3$ 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
inflaton
radiation
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


$\alpha_{SM} = \alpha_{DM} = 1$
$\beta_{SM} = \beta_{DM} = 1$
$m_s = 10^9$ GeV
$m_s = 10^{11}$ GeV
$m_s = 10^{13}$ GeV
$m_a = 10^{-6}\ m_s$
$m_a = m_s$
T_{RH}
T_{MAX}
Λ [GeV]
m_{DM} [GeV]


$\Lambda = 10^{16}$ GeV
$\alpha_{SM} = \alpha_{DM} = 1$
$\beta_{SM} = \beta_{DM} = 1$
$T_{RH} = m_s$
$T_{MAX} = m_s$
$m_{DM} = 1$ GeV
$m_{DM} = 10^4$ GeV
$m_{DM} = 10^{10}$ GeV
$m_a = 10^{-6}\ m_s$
$m_a = m_s$
T_{RH} [GeV]
m_s [GeV]


Scalar DM
Fermionic DM
Vectorial DM
Λ [GeV]
10^{24}
10^{22}
10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
$\alpha_{\rm H} = \alpha_{\rm G} = \alpha_{\rm DM} = 1$
$\beta_{\rm G} = \beta_{\rm DM} = 1$
m_a
m_s
$T_{\rm RH}$
$T_{\rm MAX}$
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
$m_{\rm DM}$ [GeV]

Conclusion

* Moduli fields 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 $T \simeq m_{\mathcal{T}} \approx 2m_{\text{DM}}$.

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

Thank You!!

Extras

Lagrangian

Scalar DM

$$\mathcal{L}^{\phi}_{eff} = \frac{\alpha_\phi}{\Lambda} s(\partial^\mu \phi)^2$$

Fermionic DM

$$\mathcal{L}^{\chi}_{eff} \supset \frac{1}{\Lambda}[\partial_\mu a \bar{\chi}\gamma^\mu(\beta^\chi_V - \beta^\chi_A\gamma^5)\chi + 2s\bar{\chi}i\gamma^\mu(\alpha^\chi_V - \alpha^\chi_A\gamma^5)D_\mu\chi + \text{h.c.}]$$

Vector DM

$$\mathcal{L}^{\mathcal{V}}_{eff} = -\frac{1}{\Lambda}\left(\alpha_{\mathcal{V}}\, s\, \mathcal{V}_{\mu\nu}\mathcal{V}^{\mu\nu} + \beta_{\mathcal{V}}\, a\, \mathcal{V}_{\mu\nu}\tilde{\mathcal{V}}^{\mu\nu}\right)$$

regimes of s \ DM	spin-0	spin-1/2	spin-1
Light	$\frac{\pi^3}{5400}\alpha_\phi^2\alpha_{SM}^2$	$\frac{2\zeta(3)^2}{\pi^5}\left(\alpha_V^\chi\right)^2\alpha_{SM}^2$	$\frac{\pi^3}{675}\alpha_\mathcal{V}^2\alpha_{SM}^2$
NWA	$\frac{1}{512\pi^4}\alpha_\phi^2\alpha_{SM}^2$	$\frac{1}{16\pi^4}\left(\alpha_V^\chi\right)^2\alpha_{SM}^2$	$\frac{1}{64\pi^4}\alpha_\mathcal{V}^2\alpha_{SM}^2$
Heavy	$\frac{128\pi^7}{19845}\alpha_\phi^2\alpha_{SM}^2$	$\frac{2304\zeta(5)^2}{\pi^5}\left(\alpha_V^\chi\right)^2\alpha_{SM}^2$	$\frac{1024\pi^7}{19845}\alpha_\mathcal{V}^2\alpha_{SM}^2$

regimes of a \ DM	spin-0	spin-1/2	spin-1
Light	0	$\frac{12\zeta(3)^2}{\pi^5}\left(\beta_A^\chi\right)^2\beta_G^2$	$\frac{8\pi^3}{225}\beta_\mathcal{V}^2\beta_G^2$
NWA	0	$\frac{3}{8\pi^4}\left(\beta_A^\chi\right)^2\beta_G^2$	$\frac{3}{8\pi^4}\beta_\mathcal{V}^2\beta_G^2$
Heavy	0	$\frac{13824\zeta(5)^2}{\pi^5}\left(\beta_A^\chi\right)^2\beta_G^2$	$\frac{8192\pi^7}{6615}\beta_\mathcal{V}^2\beta_G^2$

In a radiation dominated Universe, instantaneous reheating

$$H^2 = \frac{8\pi}{3} G\rho_R = \frac{\rho_R}{3M_P^2} = \frac{\alpha T^4}{3M_P^2} \quad \Rightarrow \quad H = \sqrt{\frac{\alpha}{3}} \frac{T^2}{M_P}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = R(T) \quad \Rightarrow \quad \frac{dY_\chi}{dT} = -M_P \sqrt{\frac{3}{\alpha}} \frac{R(T)}{T^6} \quad \text{with} \quad Y_\chi = \frac{n_\chi}{T^3}$$

$$\boxed{R(T) = \frac{T^{6+n}}{\Lambda^{n+2}}}$$

Radiation dominated

$$\Omega = \frac{n(T_0) \times m}{\rho_c^0} \Rightarrow \Omega h^2 = 1.6 \times 10^8 \sqrt{\frac{3}{\alpha}} \frac{M_P}{(n+1)} \frac{T_{RH}^{n+1}}{\Lambda^{n+2}} \left(\frac{m}{1 \text{ GeV}}\right)$$

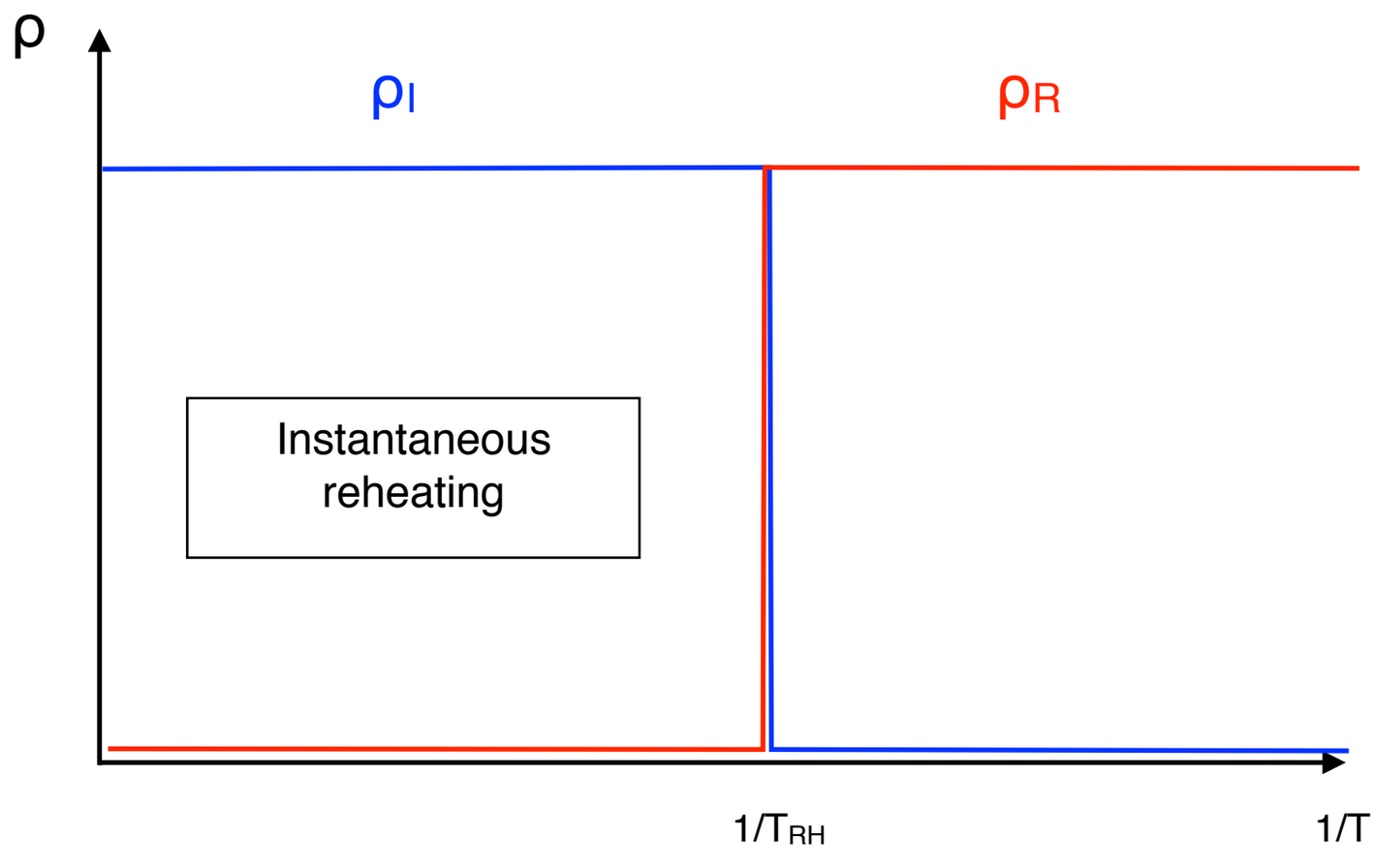
$$\boxed{\Omega h^2 = 0.12 \left(\frac{m}{(n+1) \text{ GeV}}\right) \left(\frac{T_{RH}}{10^{10} \text{ GeV}}\right)^{n+1} \left(\frac{10^{13} \text{ GeV}}{\Lambda}\right)^{n+2} \times 10^{11-3n}}$$

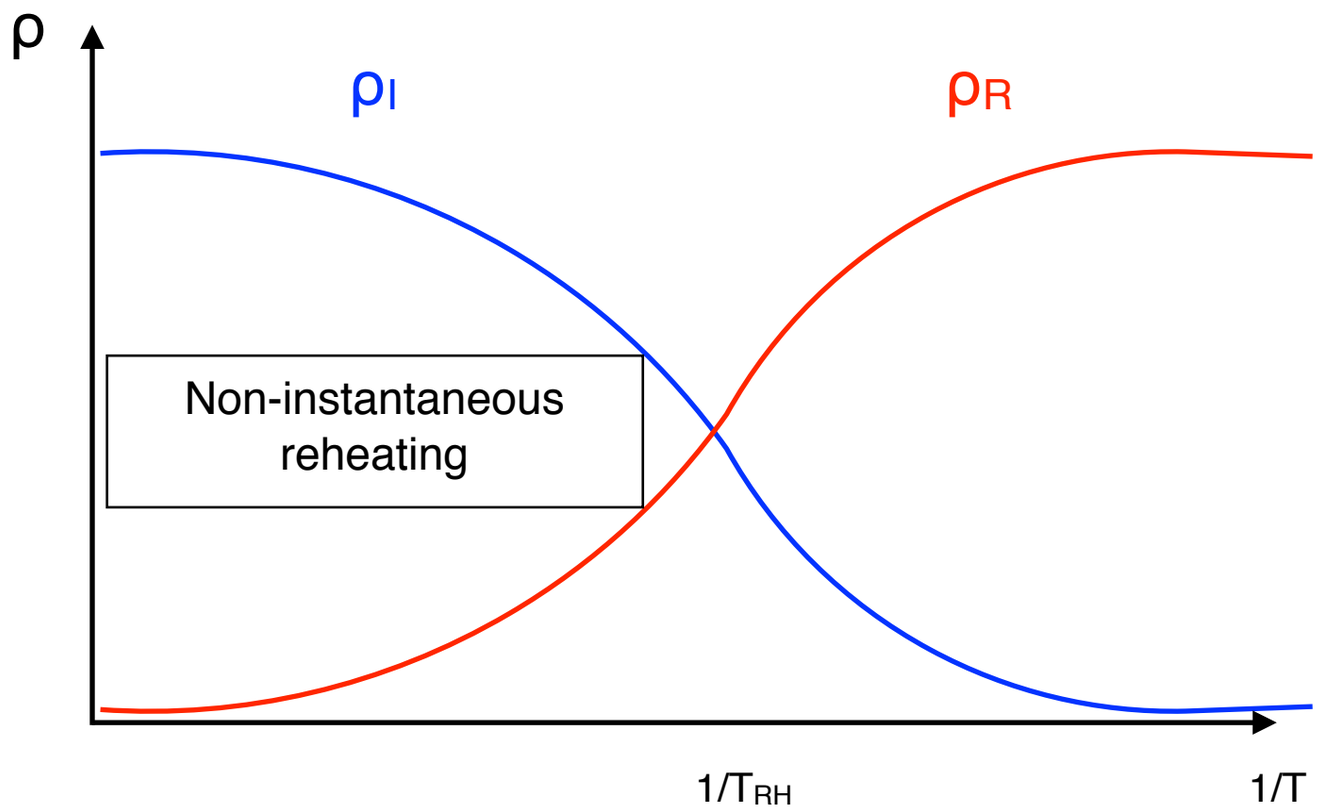
Non-instantaneous reheating: introducing the inflaton

Before the end of the reheating process, while the Universe was still dominated by the matter (inflaton), but temperature was higher than T_{RH}

In other words, one should compare the total DM production releasing the hypothesis of instantaneous reheating

M.A.G. Garcia et al. arXiv:1709.01549


ρ
ρI
ρR
Instantaneous reheating
1/TRH
1/T


ρ
ρI
ρR
Non-instantaneous reheating
1/TRH
1/T

$$\frac{d\rho_I}{dt} + 3H\rho_I = -\Gamma_I \rho_I$$

$$\frac{d\rho_R}{dt} + 4H\rho_R = \Gamma_I \rho_I$$

$$\frac{dn_\chi}{dt} + 3H\, n_\chi = R(T)$$

$$H^2 = \frac{\rho_I}{3M_P^2} + \frac{\rho_R}{3M_P^2}$$

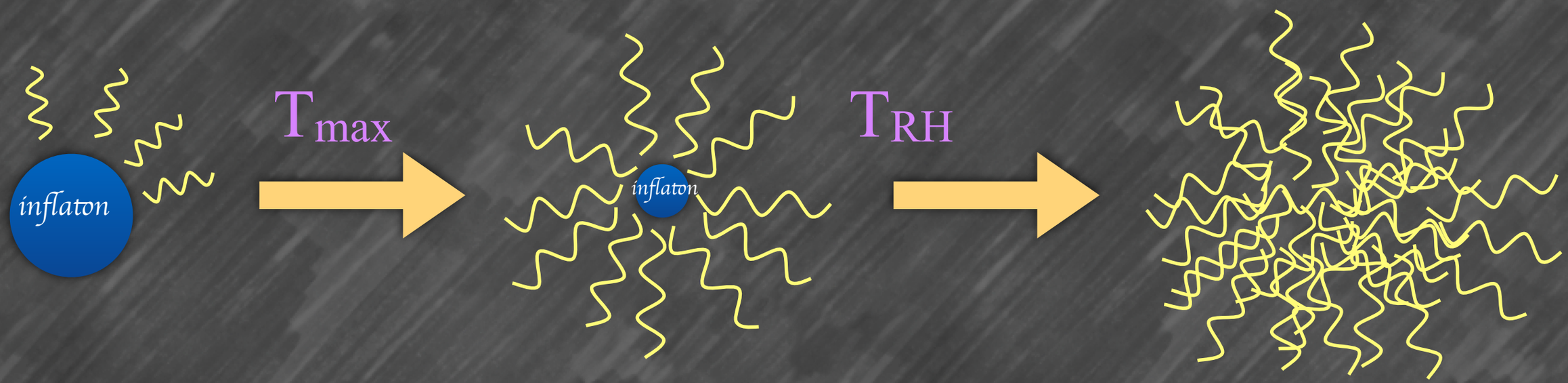
$$\Rightarrow \quad T = \beta a^{-3/8} \quad (H = \frac{\dot{a}}{a})$$

[$T = \beta a^{-1}$ in radiation dominated universe]

$$\Rightarrow \quad H(T) = \frac{5}{6}\frac{\alpha}{\Gamma_I M_P^2} T^4$$

[$H(T) = \frac{\alpha}{3M_P} T^2$ in radiation dominated universe]

$$\boxed{\frac{dY_\chi}{dT} = -\frac{8}{3}\frac{R(T)}{H\ T^9} \quad \text{with } Y_\chi = \frac{n_\chi}{T^8}}$$



Temperature

$\mathcal{T}_{max}$

mixed universe
H α T^4
$T=\beta a^{-3/8}$

$\rho_I = \rho_R$

$\mathcal{T}_{\mathcal{RH}}$

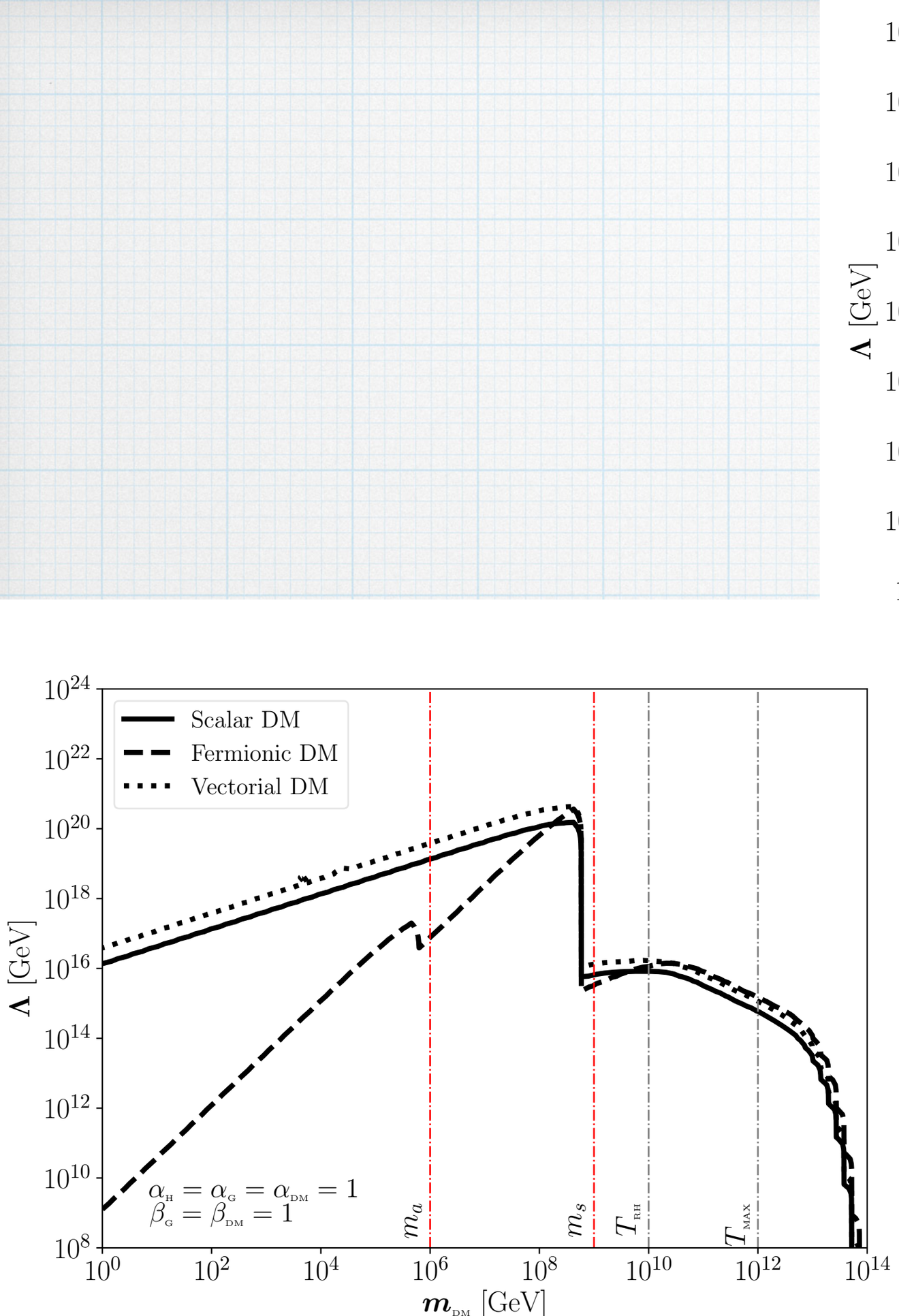
Radiative universe
H α T^2
$T=\beta a^{-1}$

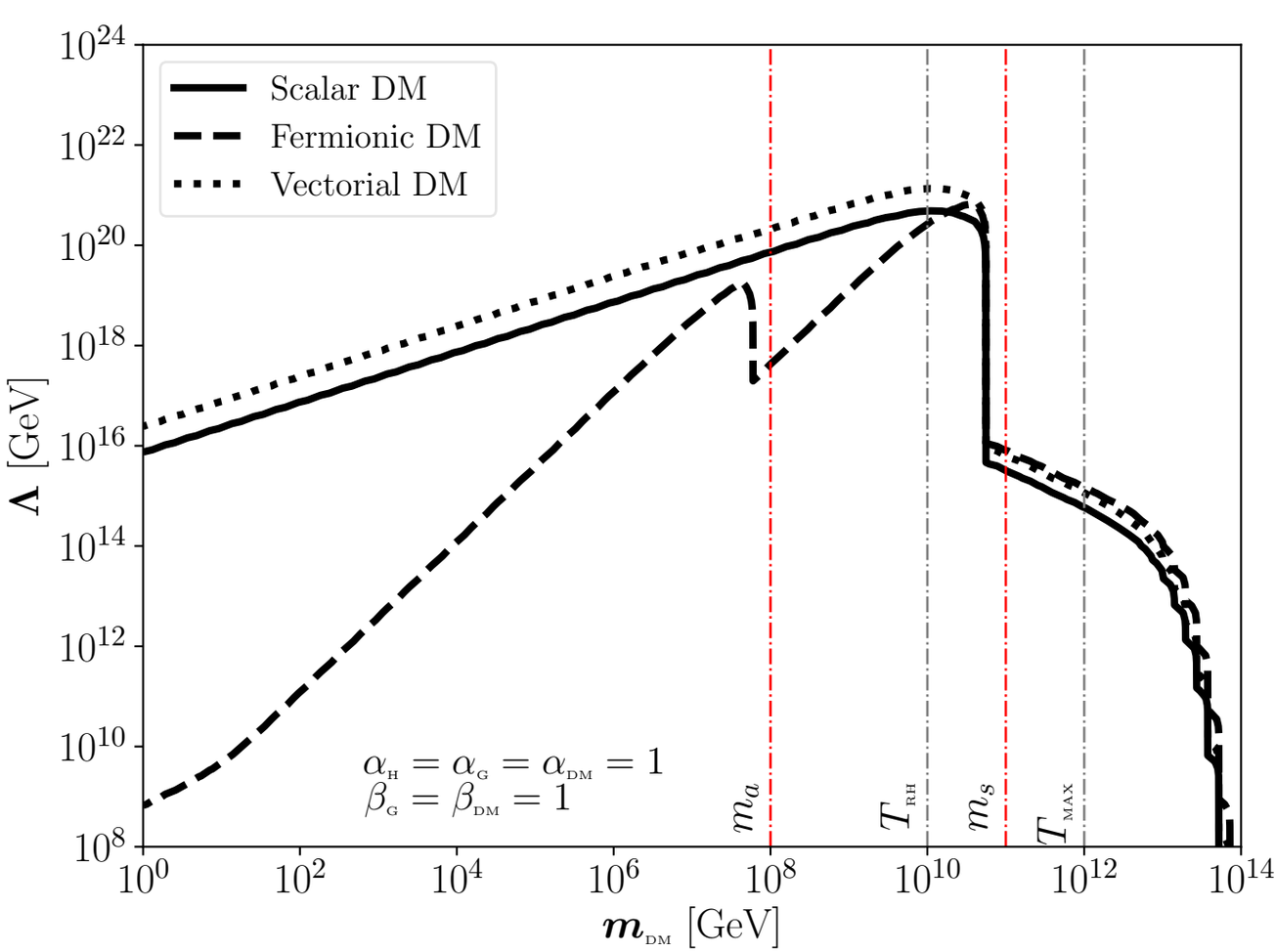
inflaton

inflaton

time

Courtesy to Y. Mambrini


Scalar DM
Fermionic DM
Vectorial DM
$\alpha_{\rm H} = \alpha_{\rm G} = \alpha_{\rm DM} = 1$
$\beta_{\rm G} = \beta_{\rm DM} = 1$
m_a
m_s
$T_{\rm RH}$
$T_{\rm MAX}$
Λ [GeV]
$m_{\rm DM}$ [GeV]


Scalar DM
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m_a
$T_{\rm RH}$
m_s
$T_{\rm MAX}$
Λ [GeV]
$m_{\rm DM}$ [GeV]