Freezing-in Cannibal Dark Matter during early matter domination

Based on: arXiv:2506.09155

Esau Cervantes

Collaboration with Andrzej Hryczuk (supervisor) Nicolás Bernal and Kuldeep Deka

June 19th, 2025

NATIONAL CENTRE FOR NUCLEAR RESEARCH
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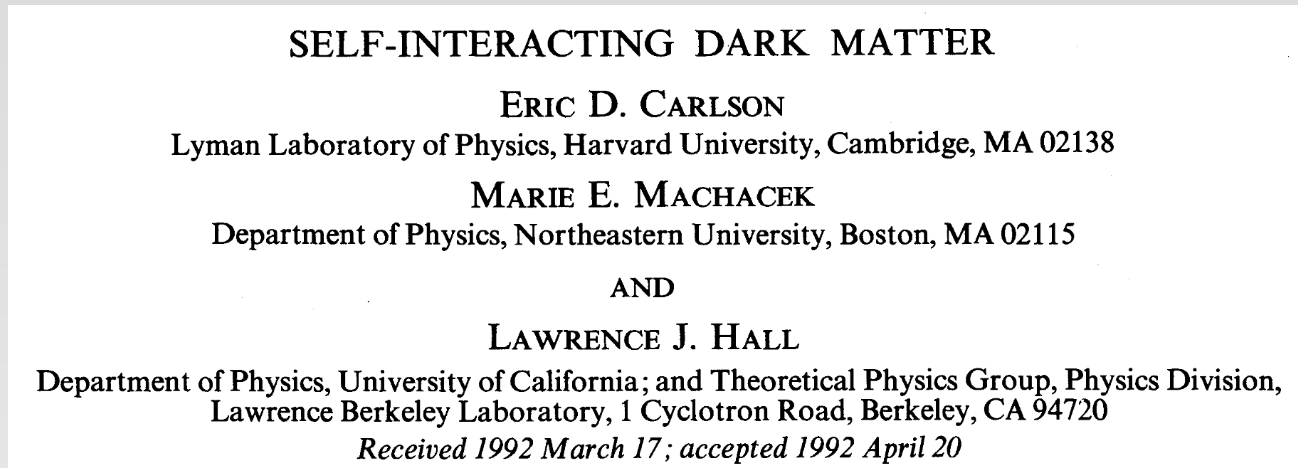
Valencia workshop on Self Interacting DM

Cannibal Dark Matter


SELF-INTERACTING DARK MATTER

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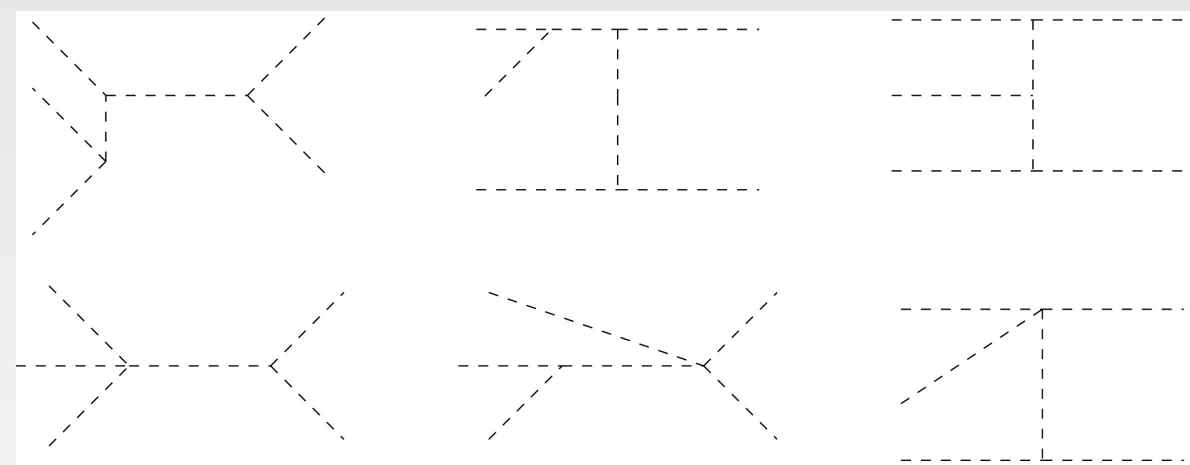
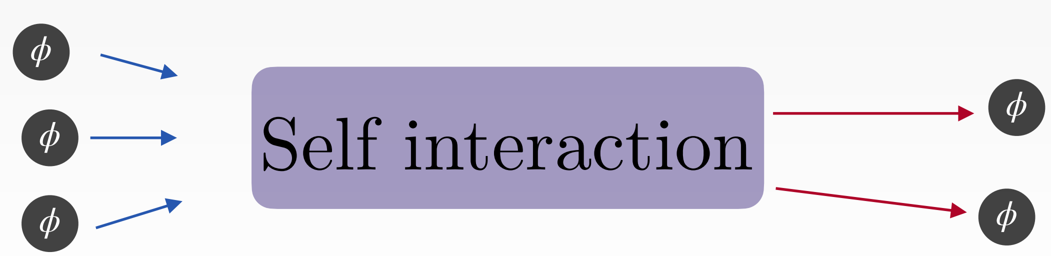
Simple realisation with a scalar field: $\frac{g}{3!}\phi^3 + \frac{\lambda}{4!}\phi^4$



If DM is non-relativstic, $\Gamma_{3\to 2} > \Gamma_{2\to 3}$. The DM fluid **exchanges** particle number for kinetic energy!



Evolution of Cannibal DM

Absence of portals leads to $T_{DM} \neq T_{SM}$. Temperature evolution becomes relevant:

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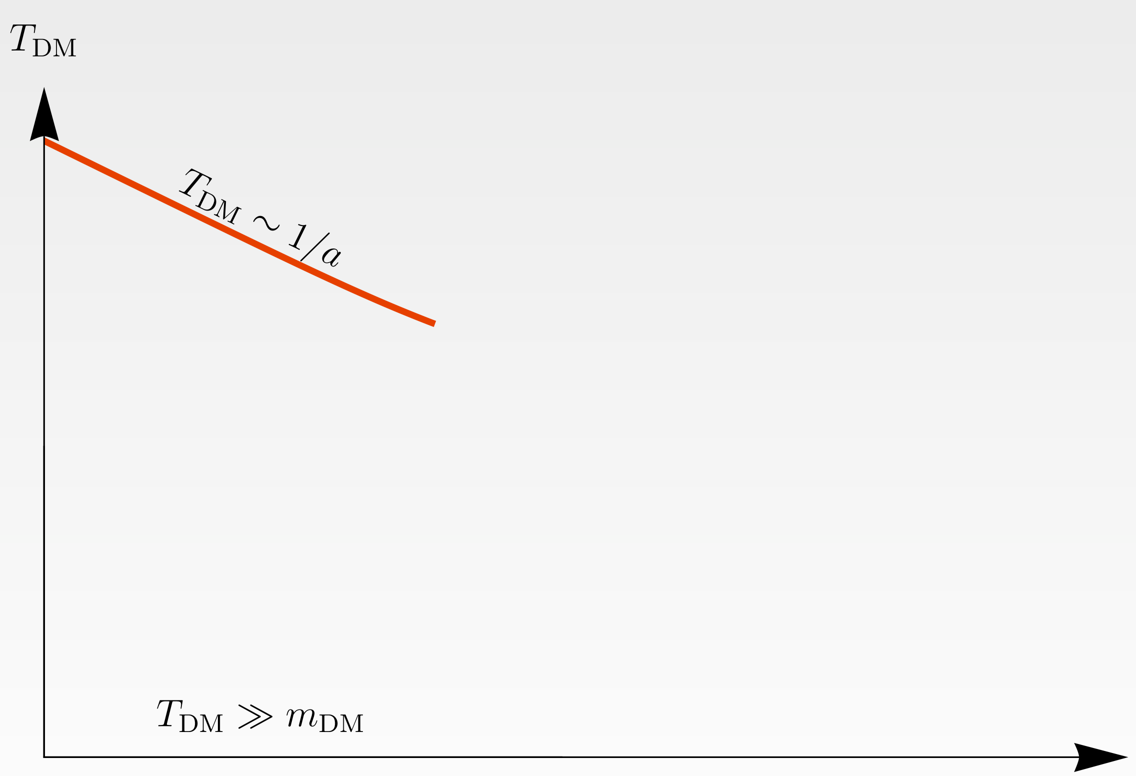

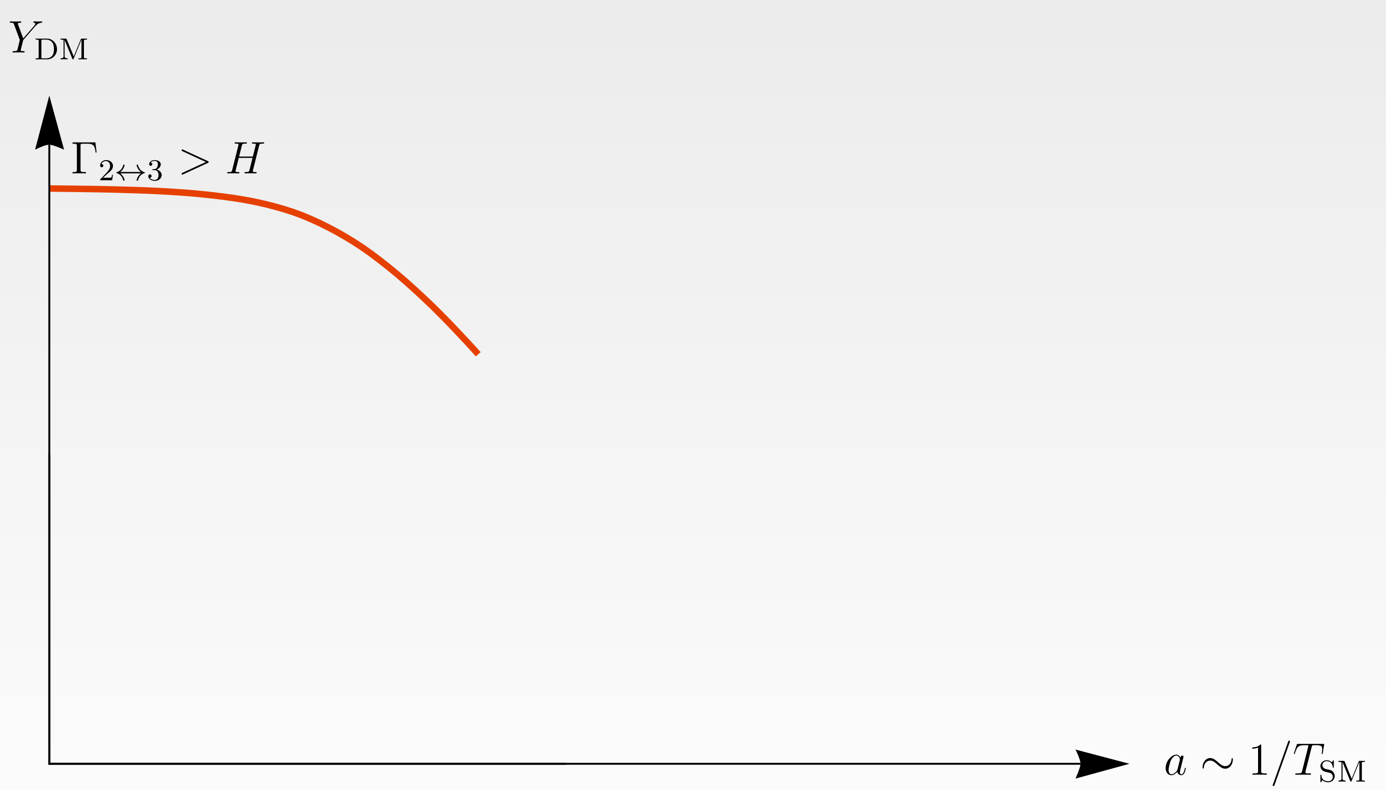

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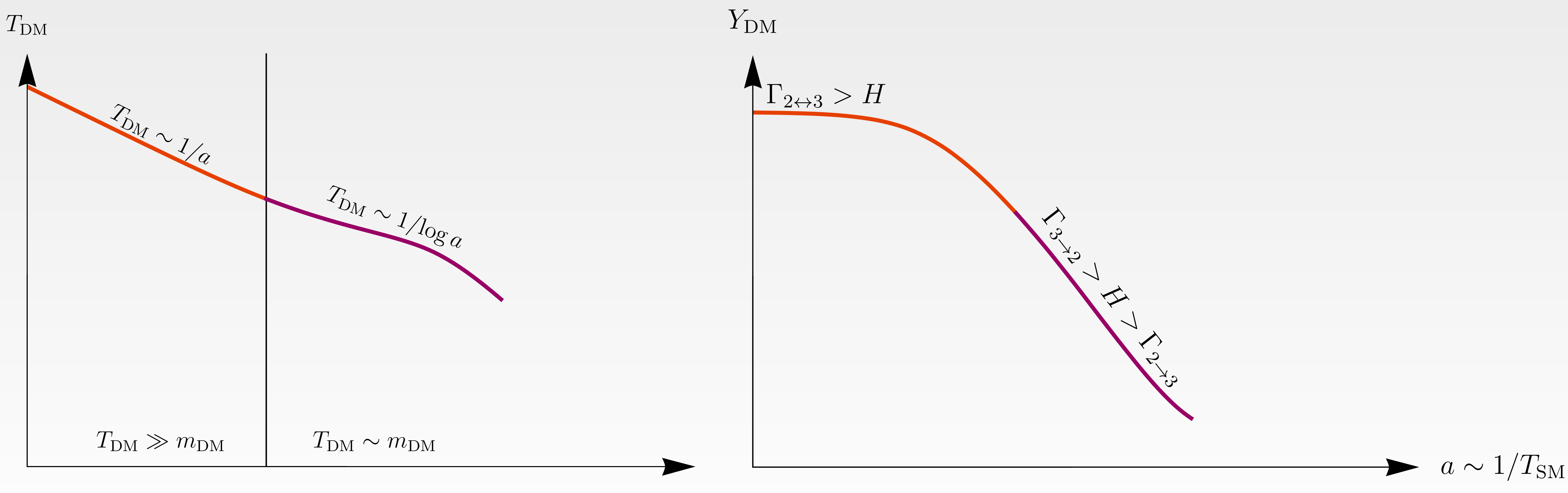
Absence of portals leads to $T_{DM} \neq T_{SM}$. Temperature evolution becomes relevant:

- DM is initially *relativistic*;
- as the DM fluid cools down, the dark sector *exchanges* number of particles for kinetic energy;



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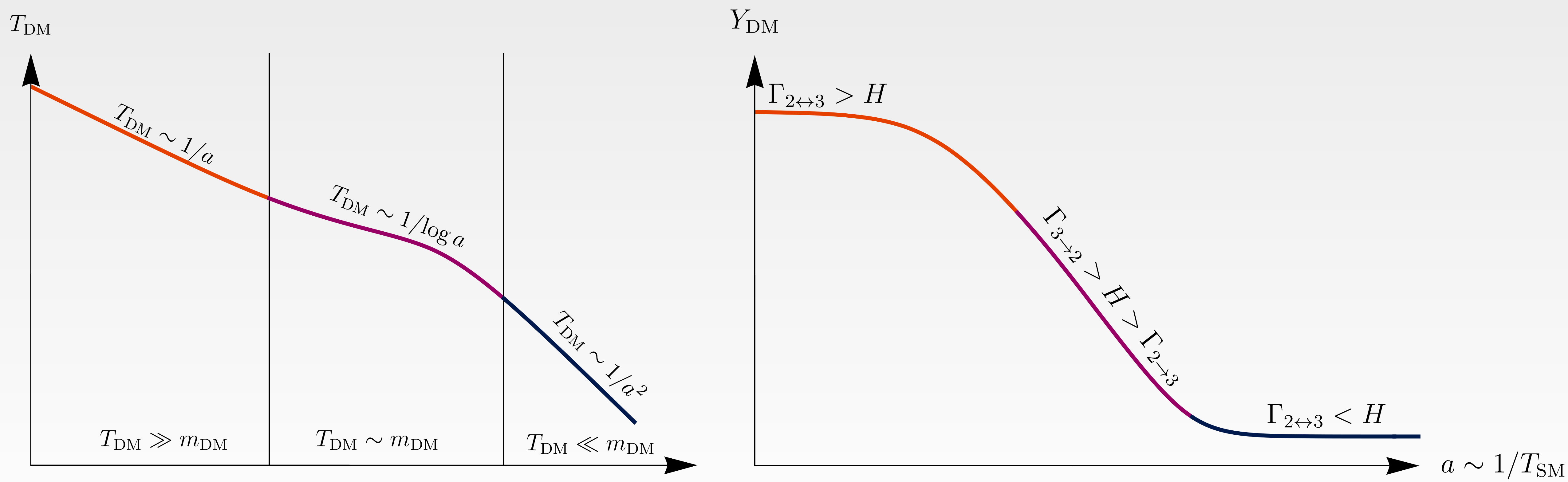

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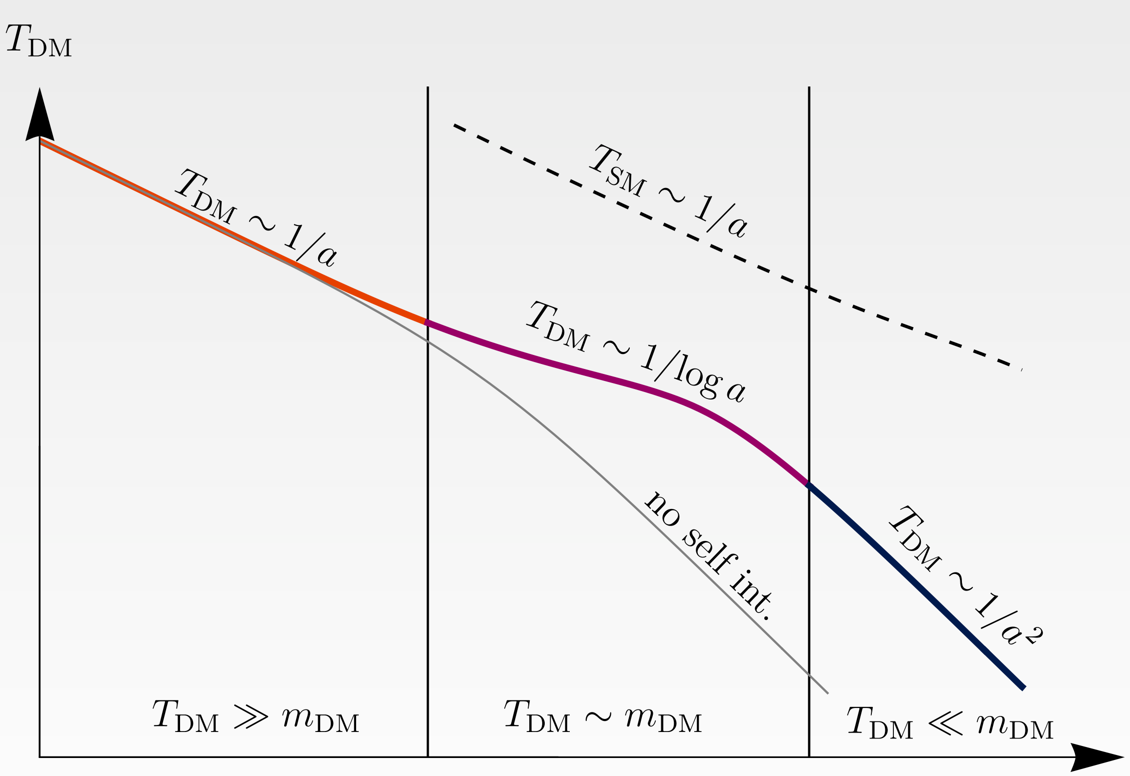
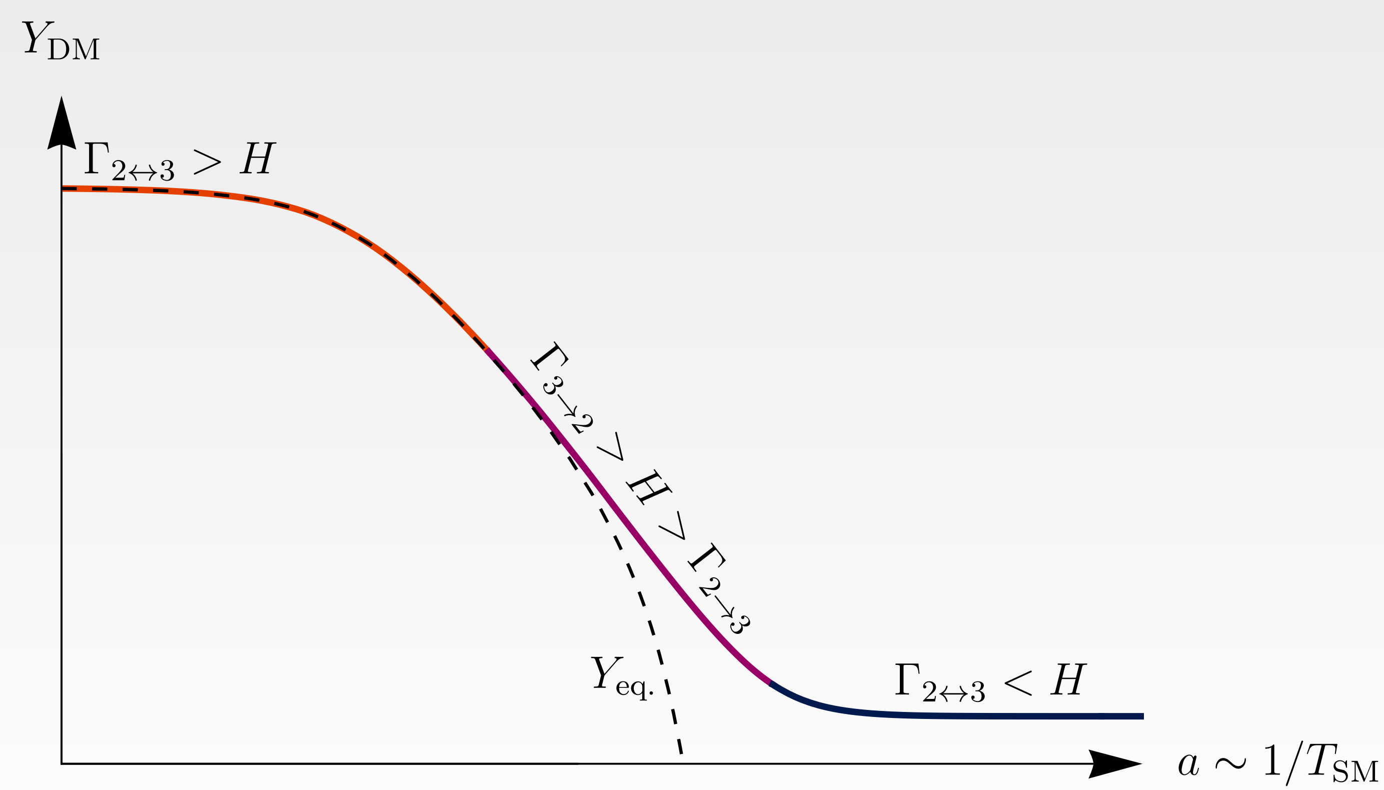
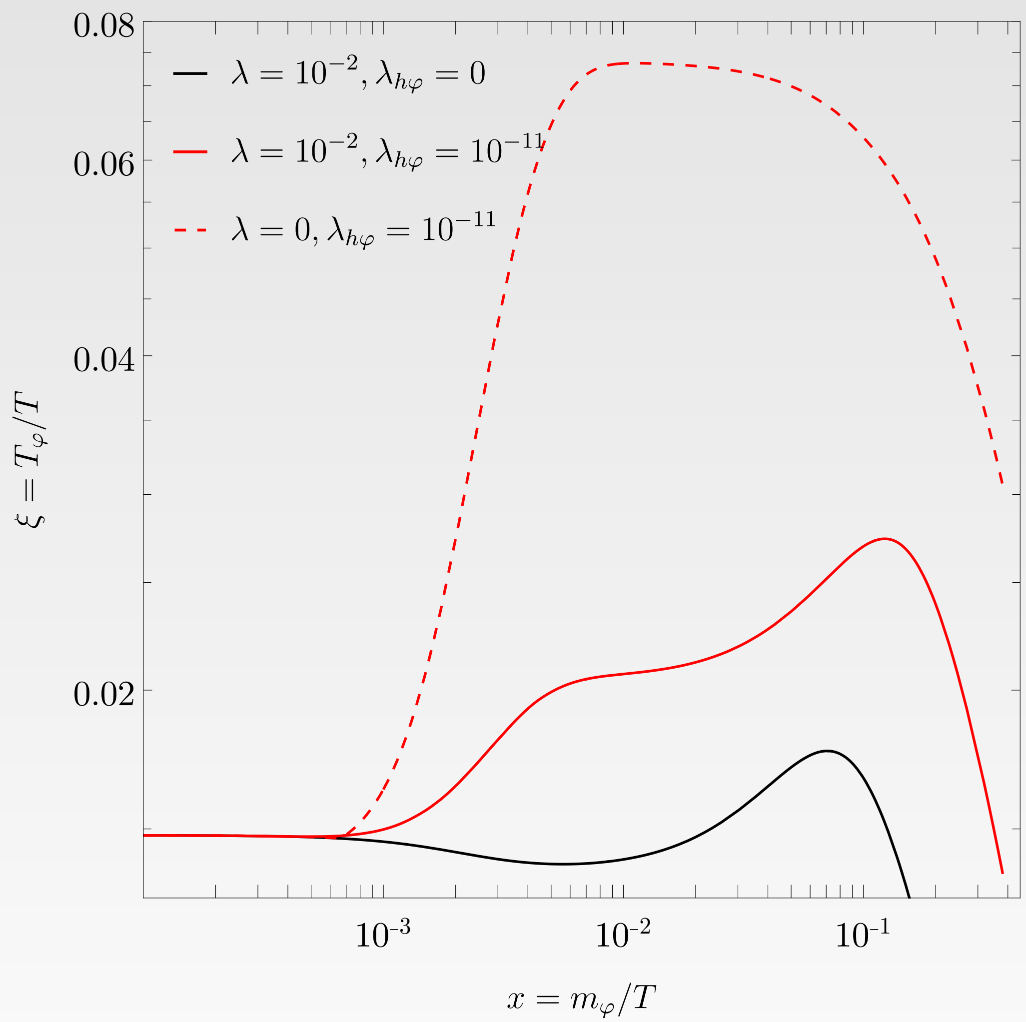


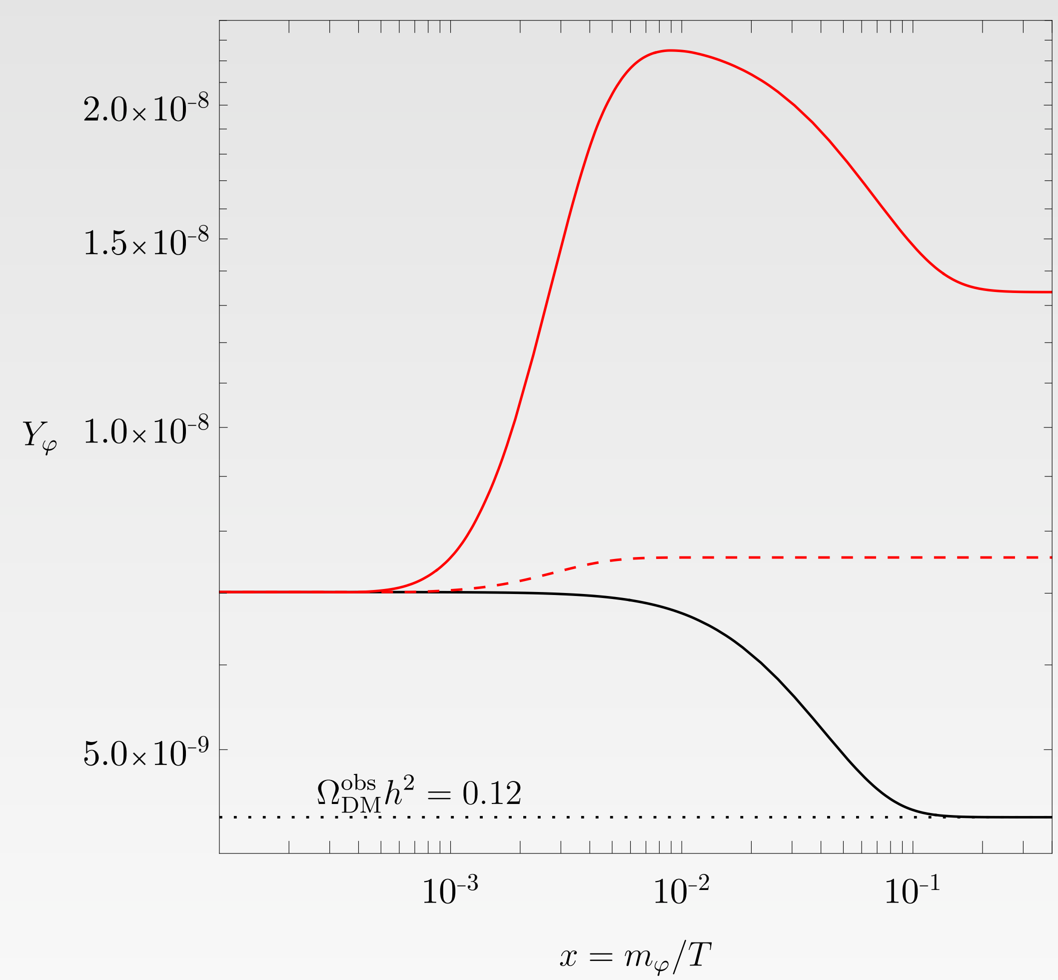


See also Hufnagel, Tygat 22 and Arcadi, Lebedev 19

Cannibals produced via freeze-in

Consider $\mathscr{L} \supset -\lambda_{h\varphi}\varphi^2 H^\dagger H$, $\lambda_{h\varphi} \ll 1$, $\lambda_\varphi \geq 10^{-4}$ and initially cold DM; $T_{DM}/T_{SM} = 10^{-2}$:





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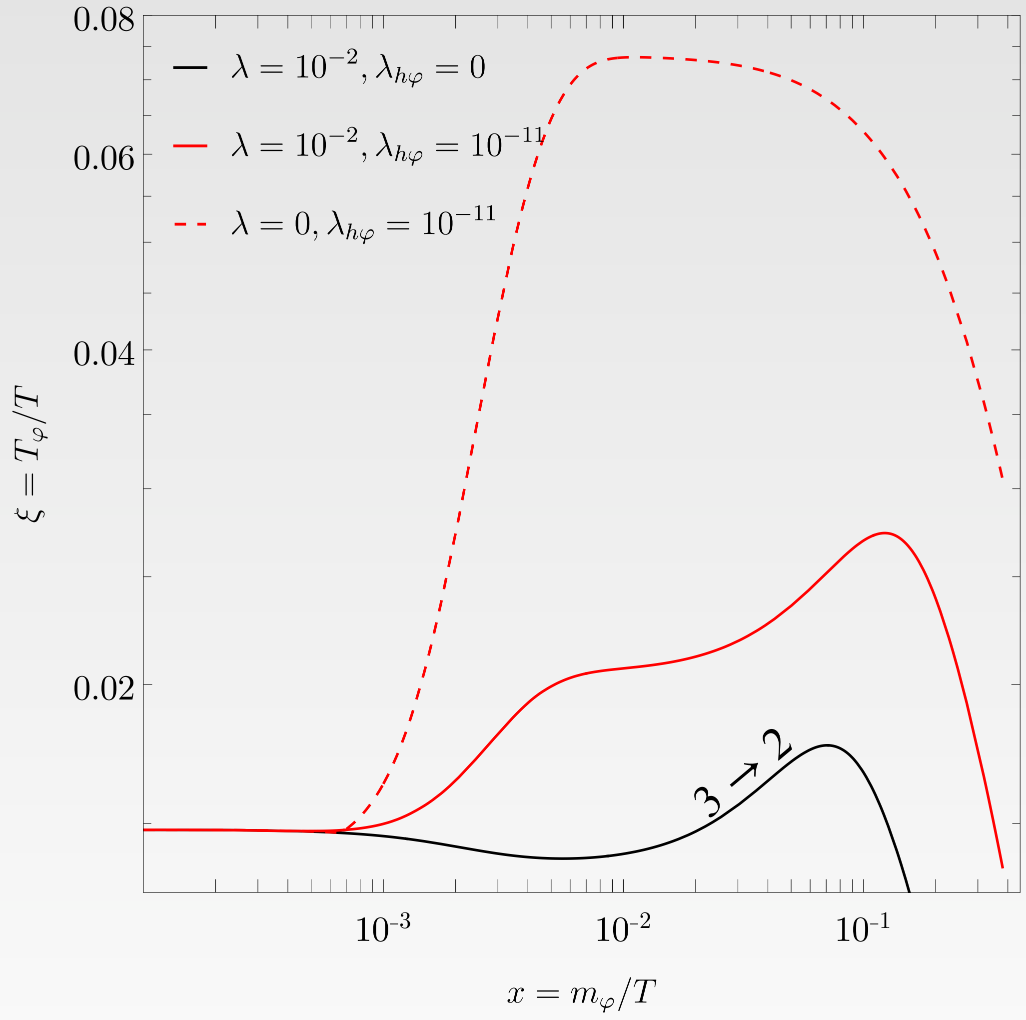

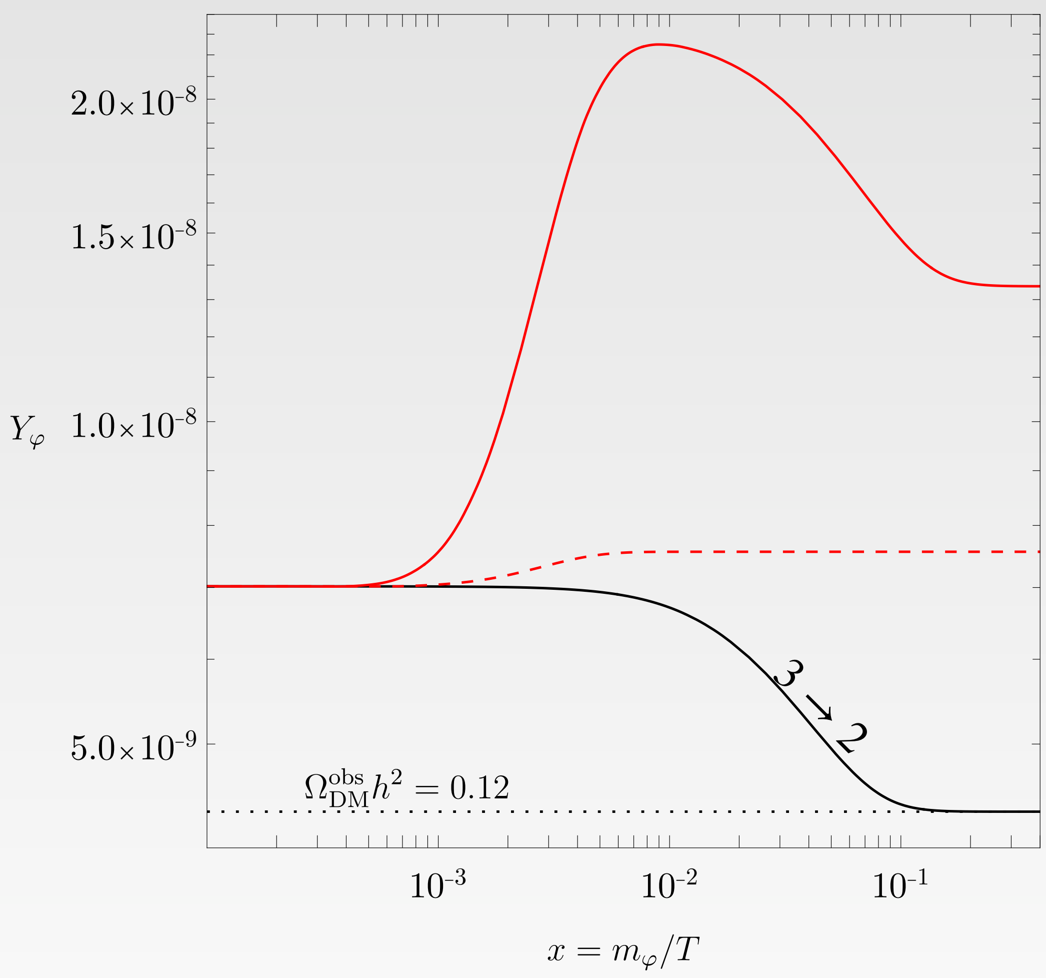

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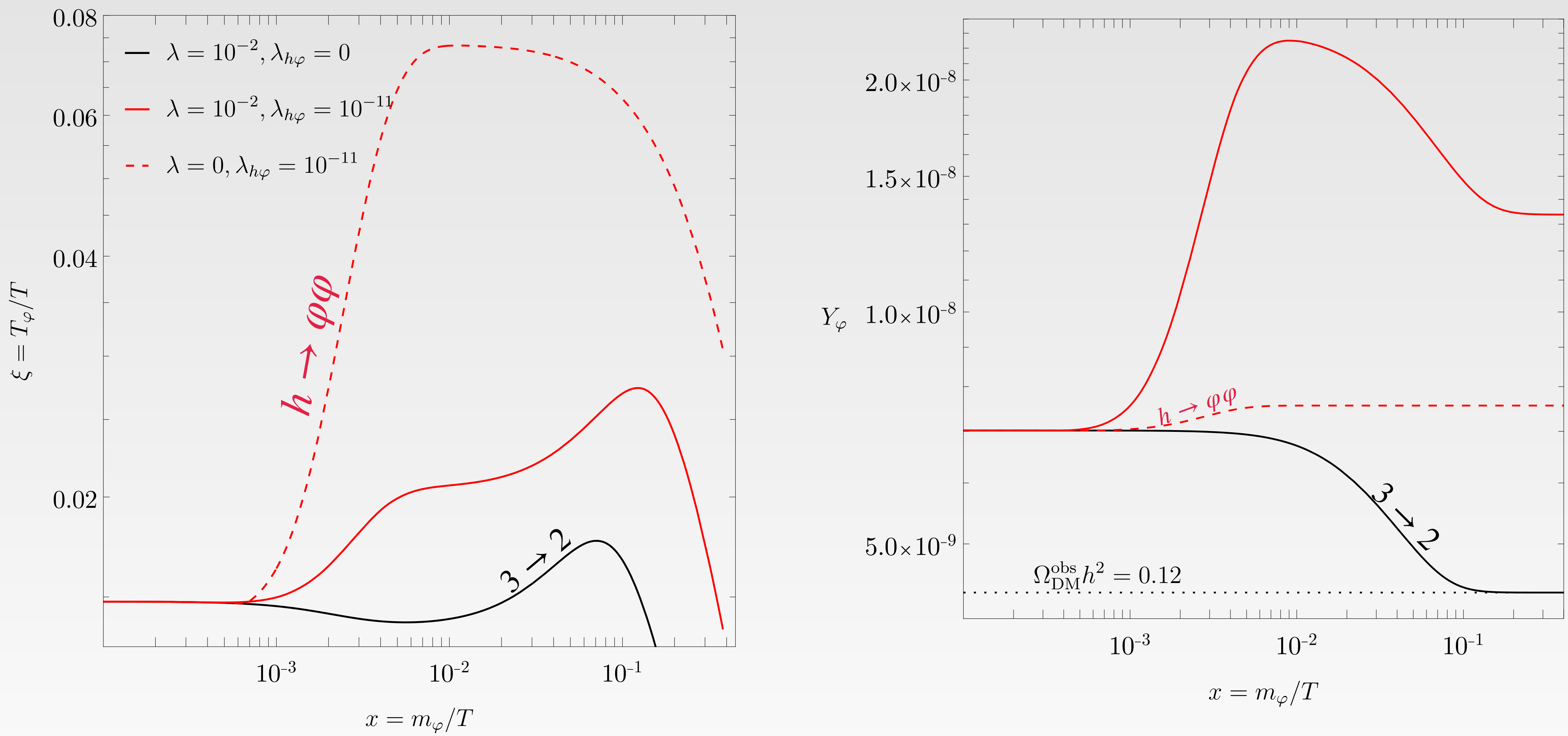

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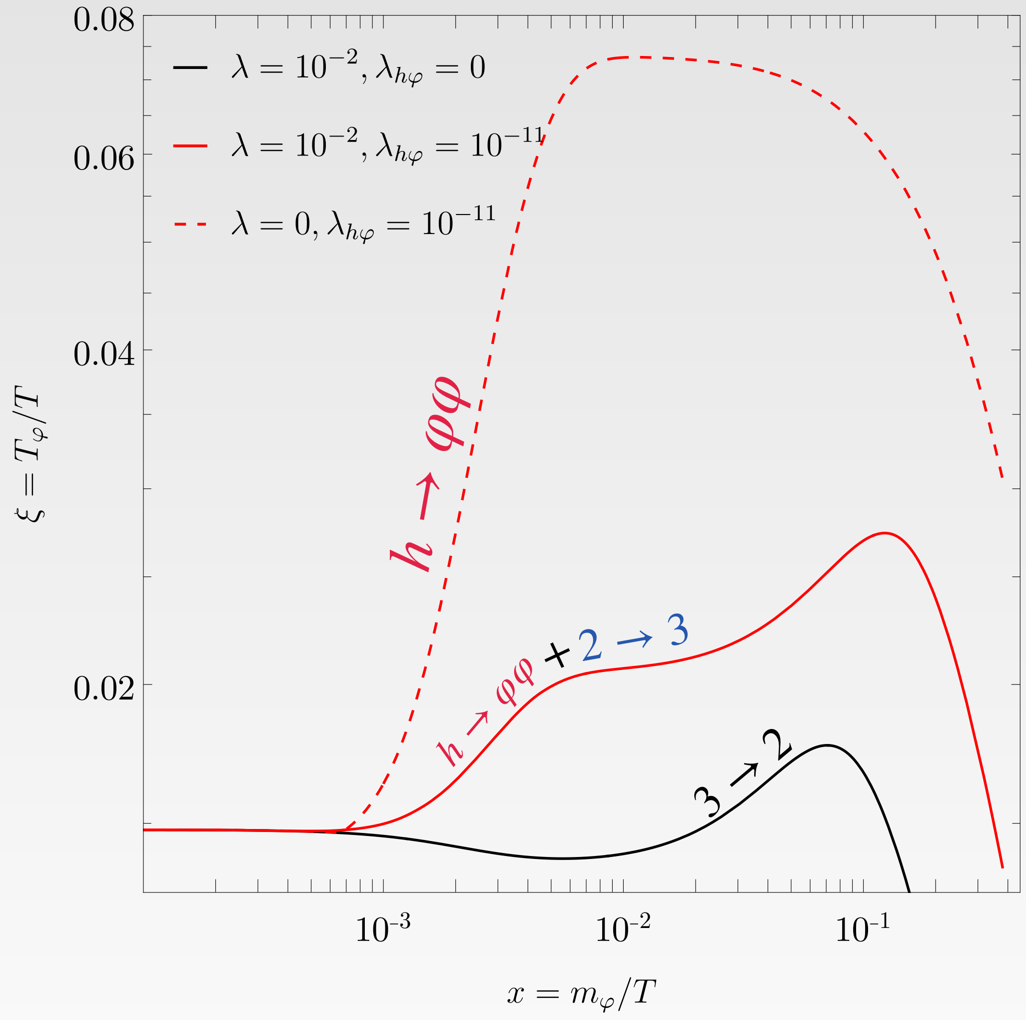

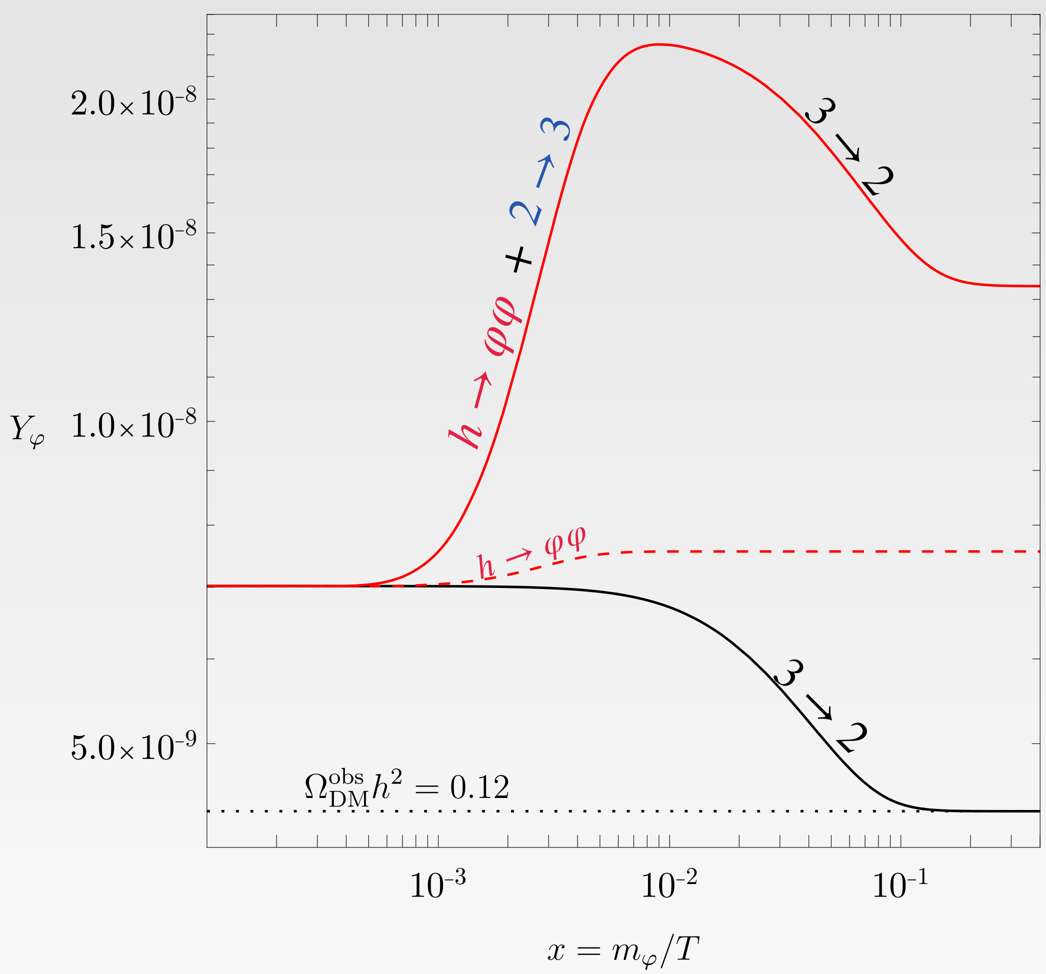

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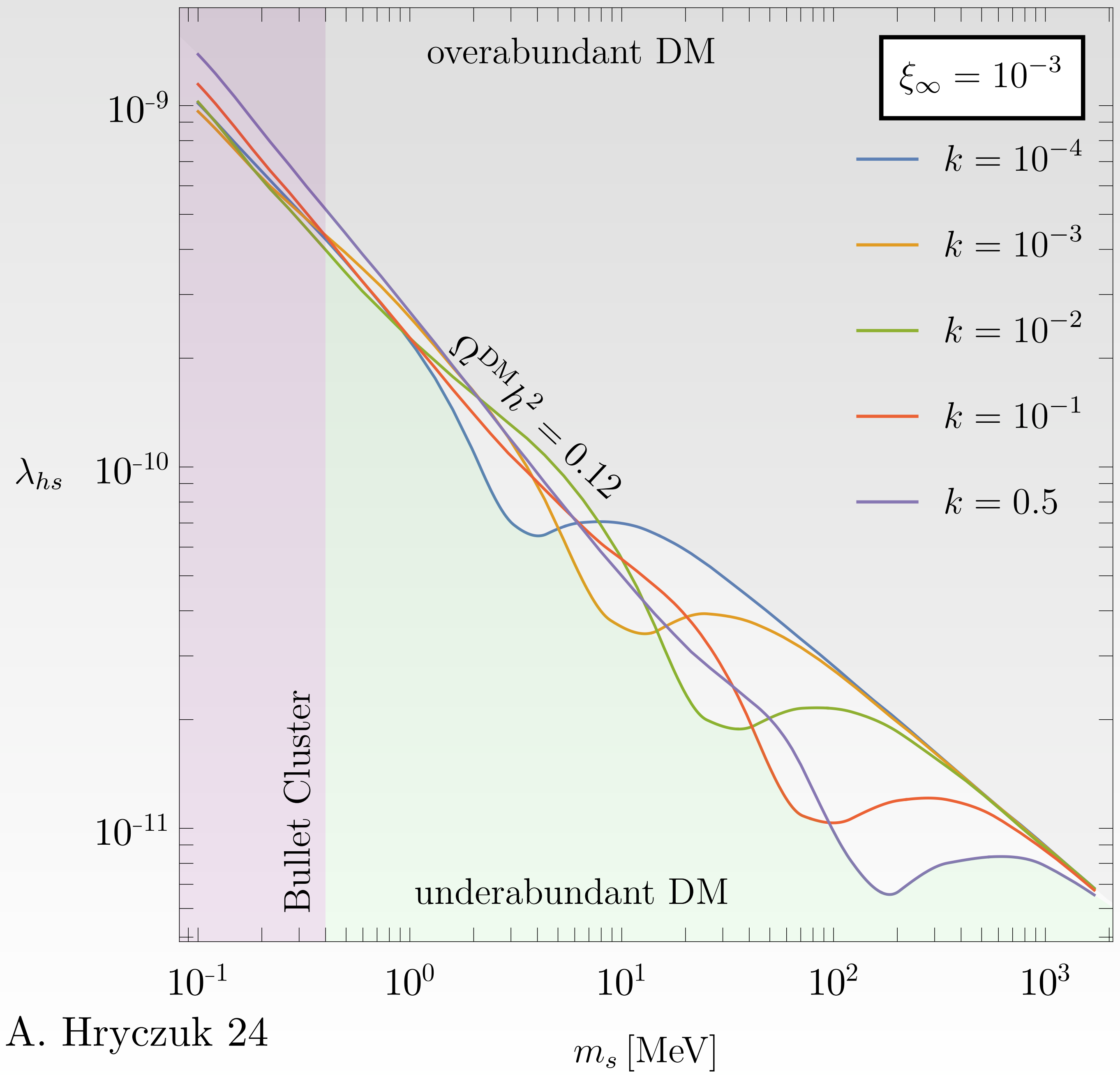
Cannibals produced via freeze-in

Toy model: $$\mathscr{L} \supset -\frac{1}{3!} g_s (S^3 + (S^*)^3) - \frac{\lambda_s}{4} |S|^4 - \lambda_{hs} |S|^2 |H|^2$$

DM self interactions (cannibal) — Portal



$$k := g^2/(3\lambda_s m_s^2)$$

See EC, A. Hryczuk 24

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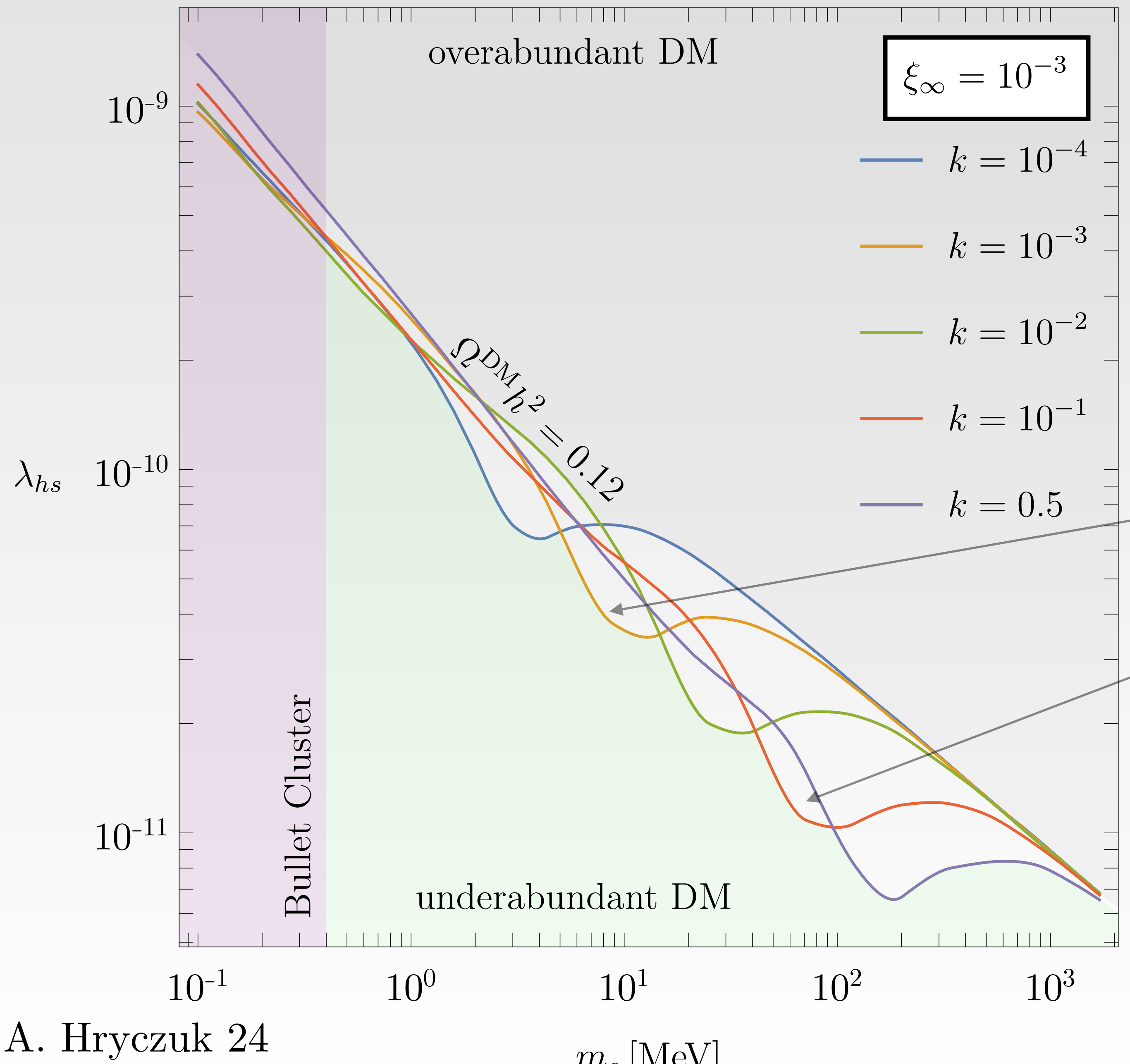

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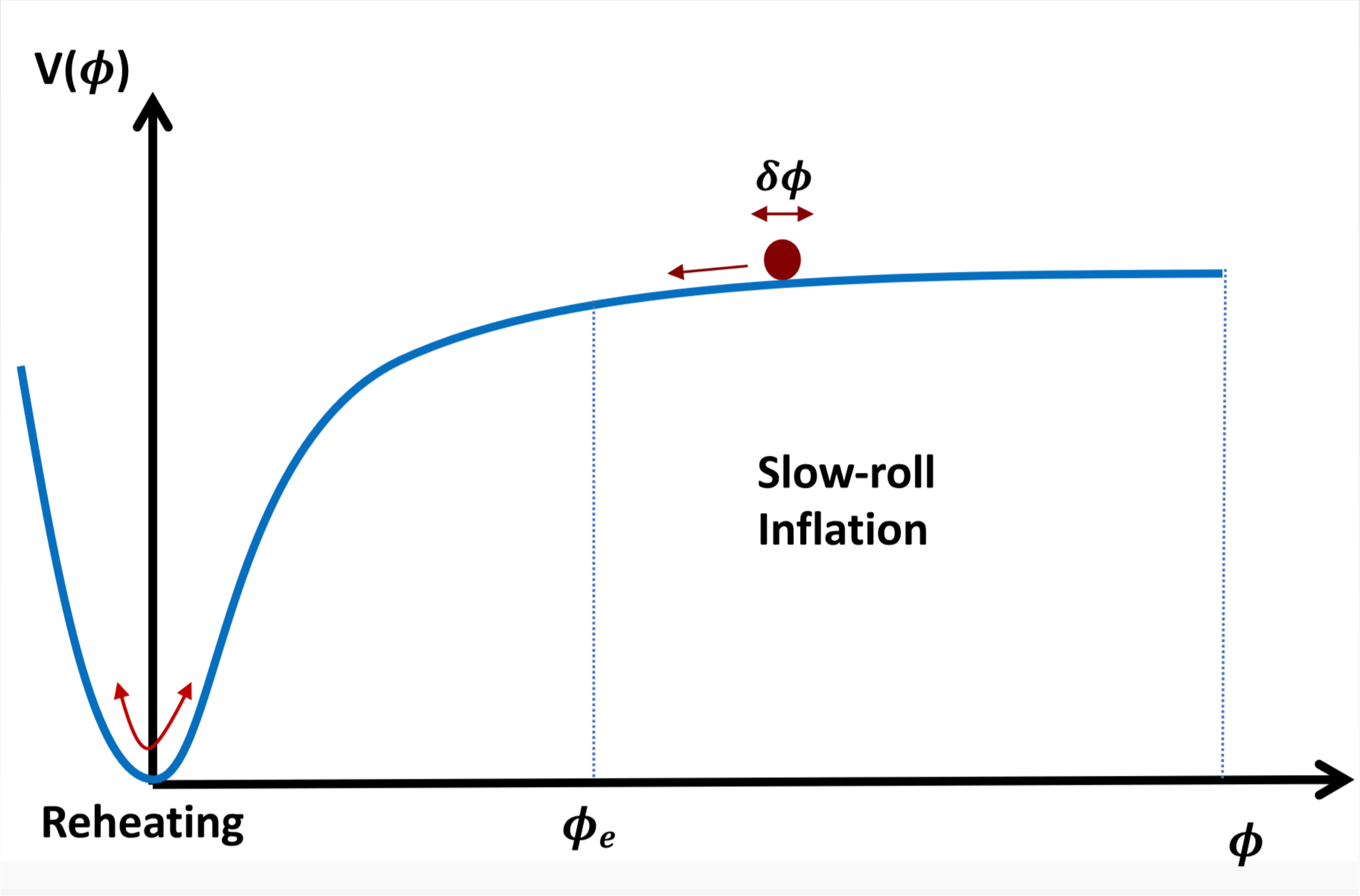
Impact of self interactions

See EC, A. Hryczuk 24

Inflaton decay and reheating

Transition between ***matter*** domination and ***radiation*** can be due to a scalar (**inflaton**) field ϕ that rolls ($a \propto e^{Ht}$) in the potential and subsequently oscillates in the minimum decaying into SM states.



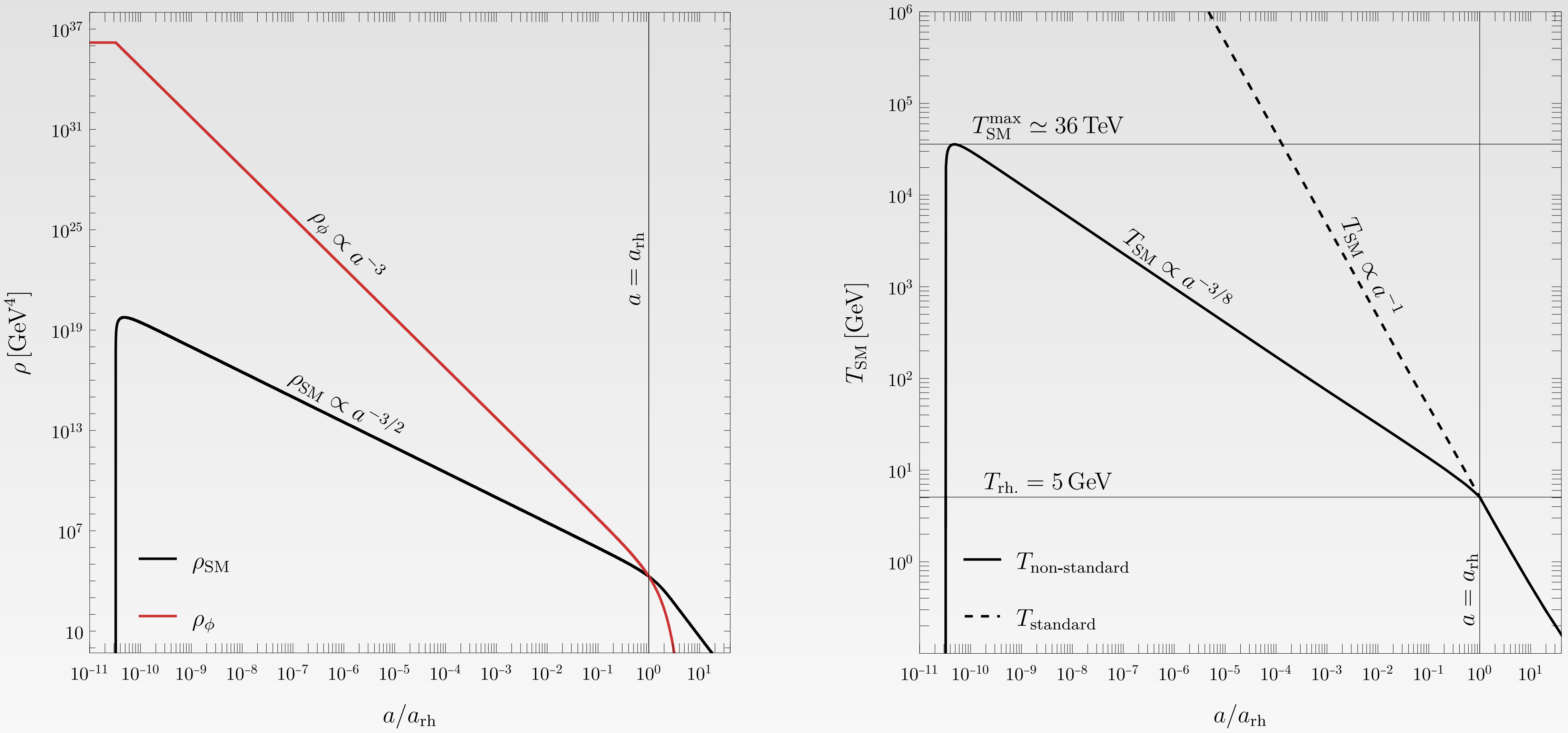
$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma\rho_\phi\,,$$

$$\frac{d\rho_R}{dt} + 4H\rho_R = +\Gamma\rho_\phi\,,$$

Cicoli, String Cosmology 2303.04819

Inflaton decay and reheating

During reheating $T \propto a^{-3/8}$ (matter domination), and $H \propto T^4$, i.e., rapid expansion of the universe



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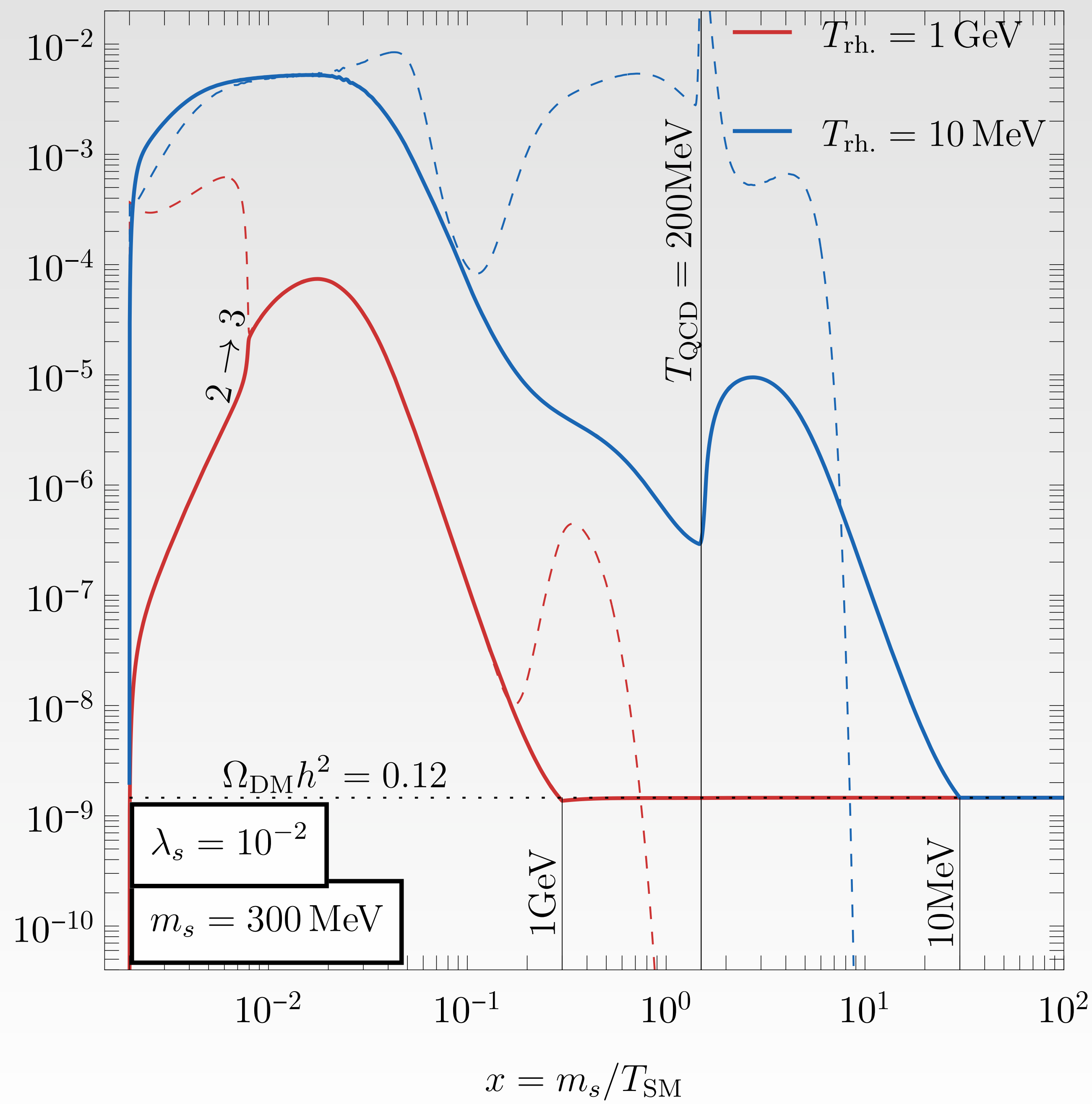

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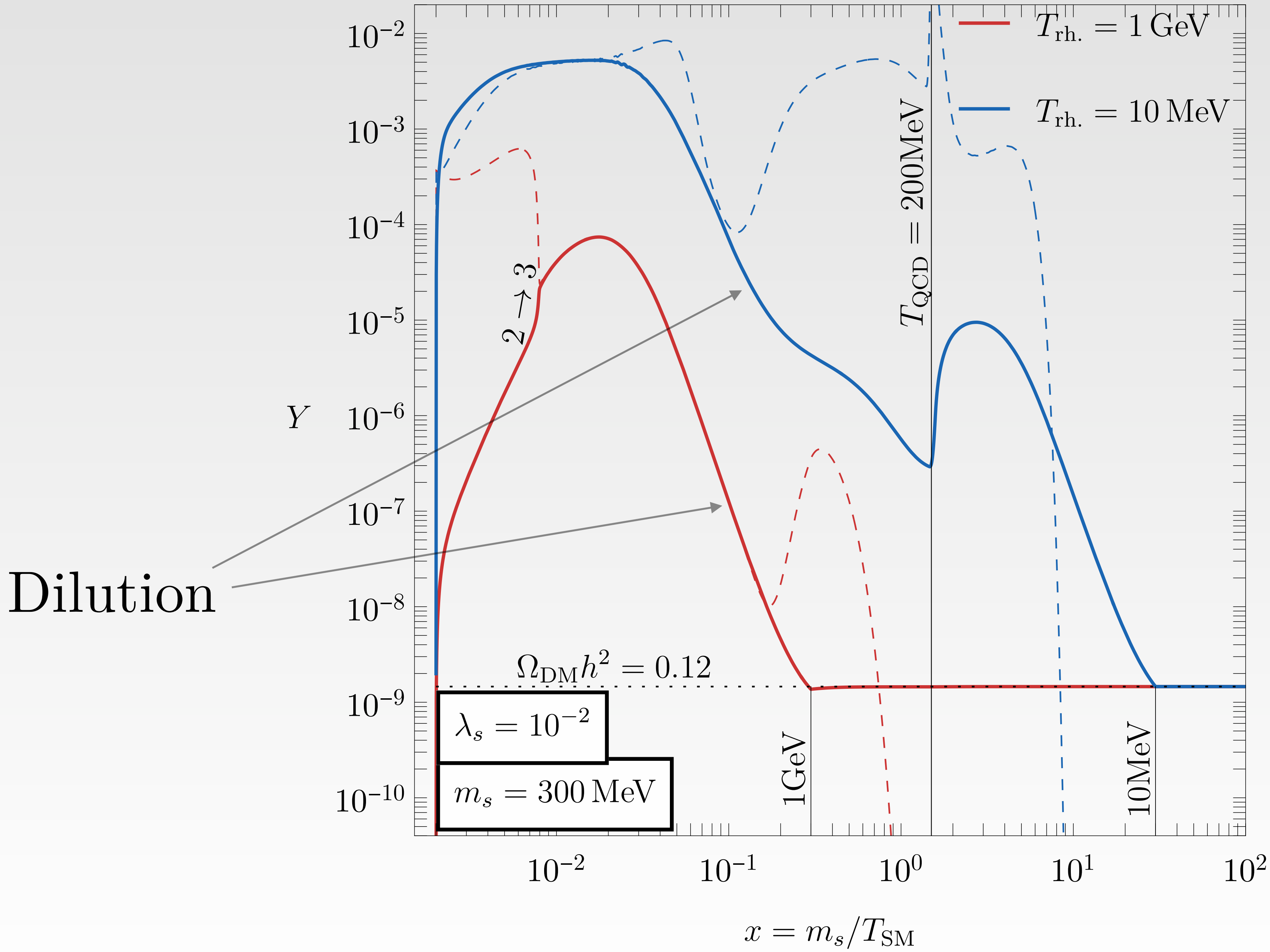
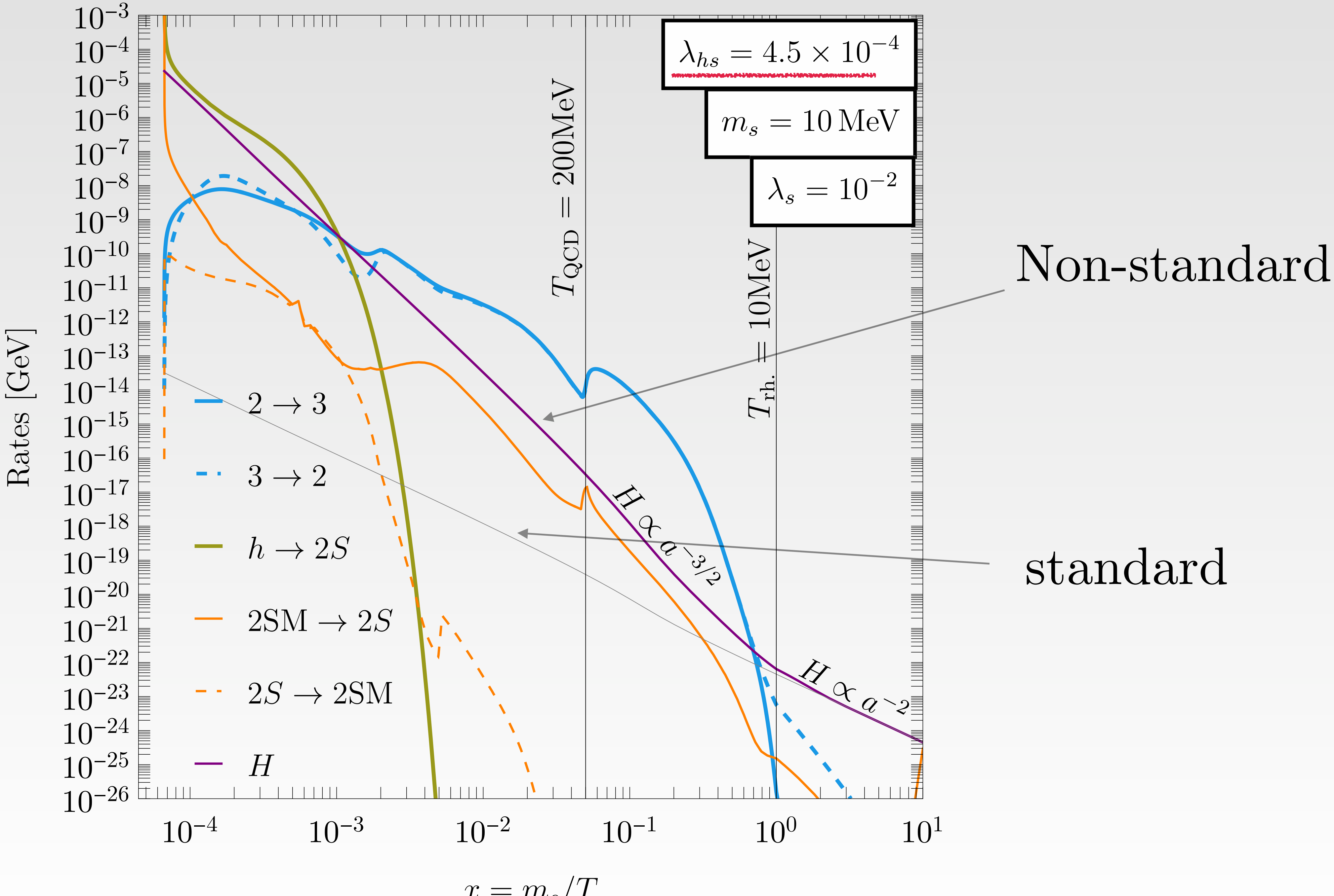
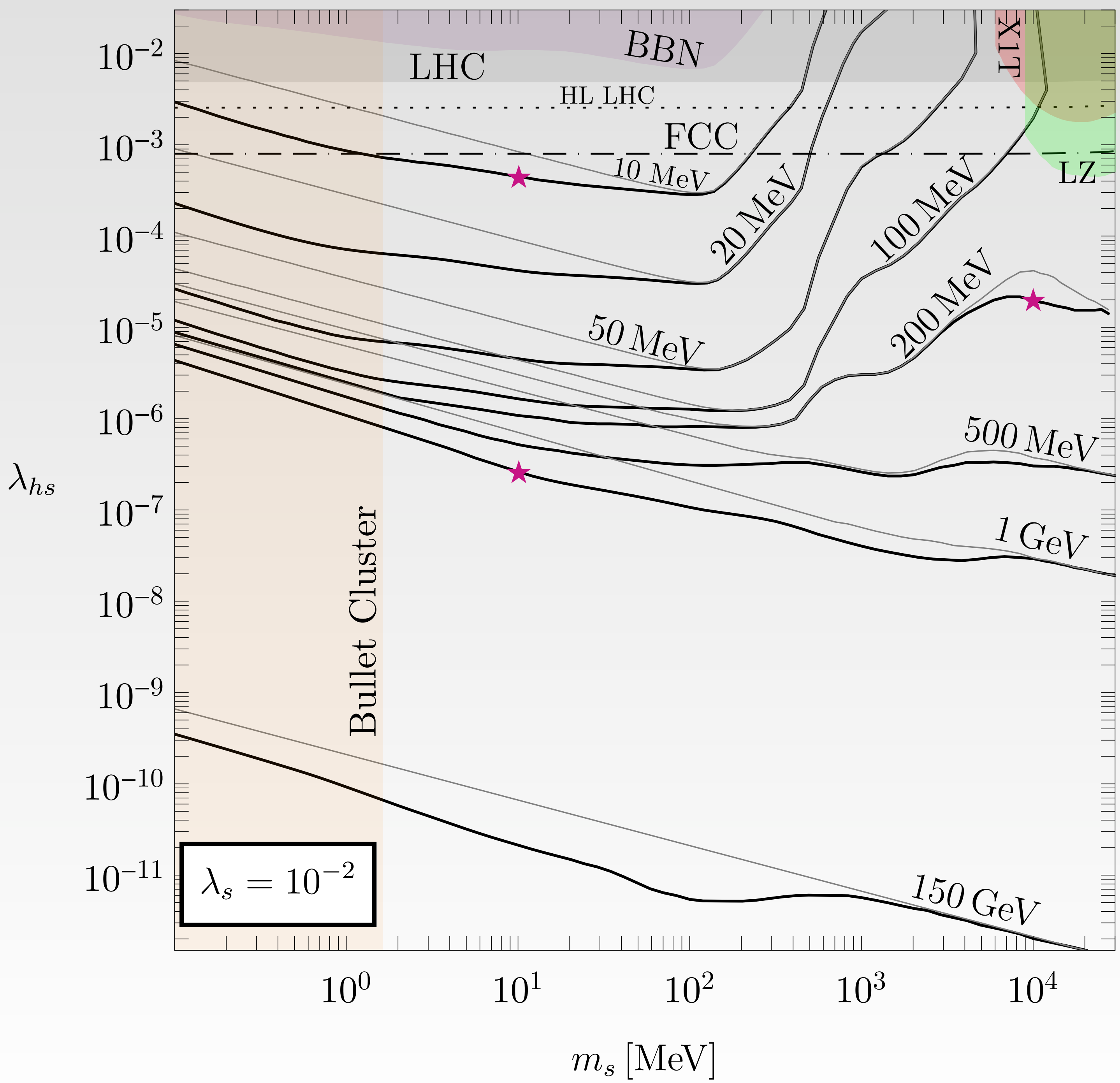


Production during reheating

Production rate from SM has to catch up with $H \propto T^4$, and ρ_{DM} dilutes during reheating.

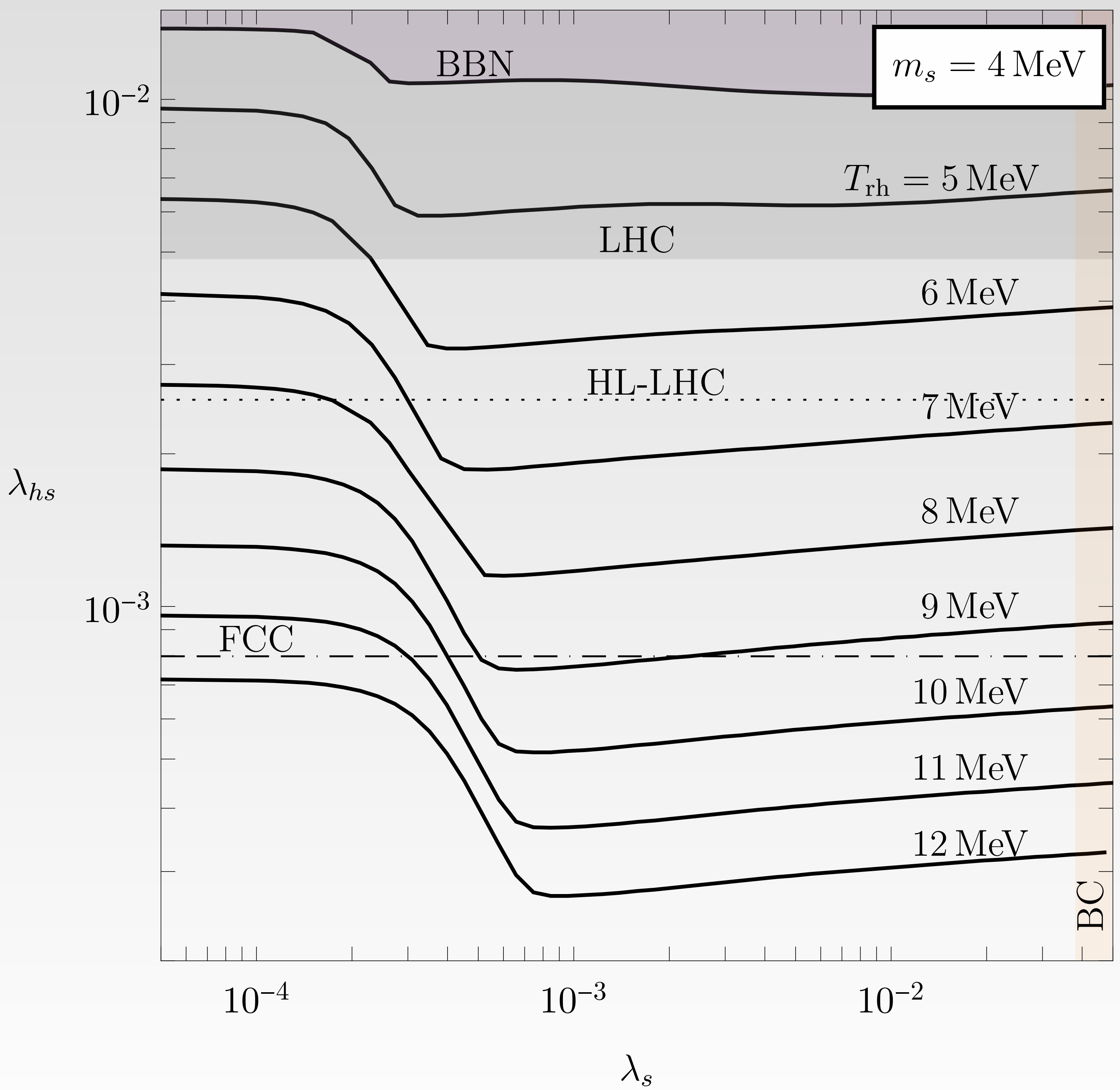


Impact on collider phenomenology



- Low T_{rh} leads to detectability;
- The case of instantaneous reheating is studied in Lebedev, Morais, Oliveira, Pasechnik 24.

Self interactions with low T_{rh}



- $T_{\rm rh} = 6\,\mathrm{MeV}$ is either **excluded** or **detectable** depending on λ_s;
- $T_{\rm rh} = 11\,\mathrm{MeV}$ is either **out of reach** or **detectable** depending on λ_s;
- The peculiar behaviour of the curves is due to the $2 \to 3$ reaction overproducing DM.

Summary

- SIDM produced via the freeze-in mechanism has a unique evolution in the Early Universe;
- Temperature can have a **non-trivial** impact in such scenarios and **need to be studied** carefully;
- Non-standard cosmologies might be able to test SIDM.

Coupled Boltzmann equations

From the fBE we can obtain a ‘temperature’ Boltzmann equation:

We define $T' := \frac{g_{dm}}{3n}\int \frac{d^3p}{(2\pi)^3}\frac{p^2}{E}f(p);$

we integrate $g(2\pi)^{-3}\int d^3p\,\frac{p^2}{E}(\partial_t - H\vec{p}\cdot\vec{\nabla}_p)f = g(2\pi)^{-3}\int d^3p\,\frac{p^2}{E}C[f] =: C_2;$

to obtain $\frac{dT'}{da} = -\frac{2\,T'}{a} + \frac{1}{3\,a}\left\langle\frac{p^4}{E^3}\right\rangle + \frac{a^2}{3\,H\,N}C_2 - \frac{a^2\,T'}{H\,N}C_0;$

along with the usual nBE: $\frac{dN}{da} = \frac{a^2}{H}\,g\int\frac{d^3p}{(2\pi)^3}C[f] =: \frac{a^2}{H}C_0\,,\; N = na^3;$

we close the system by assuming $f(E,T') = \frac{n}{n_{\rm eq}}\,\exp\left[-\frac{E}{T'}\right].$