From WIMPs to FIMPs: Impact of Early Matter Domination

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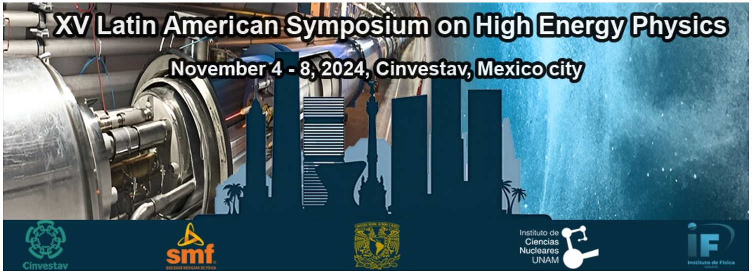
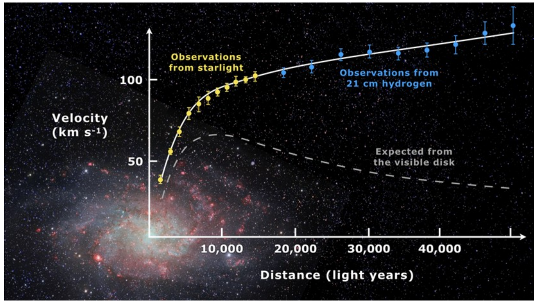
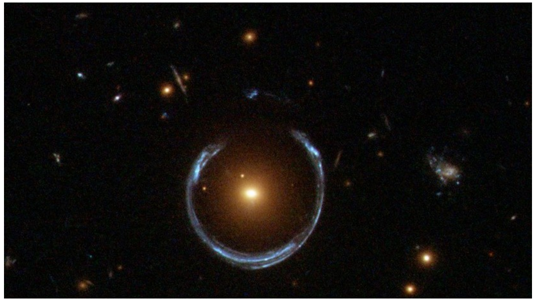
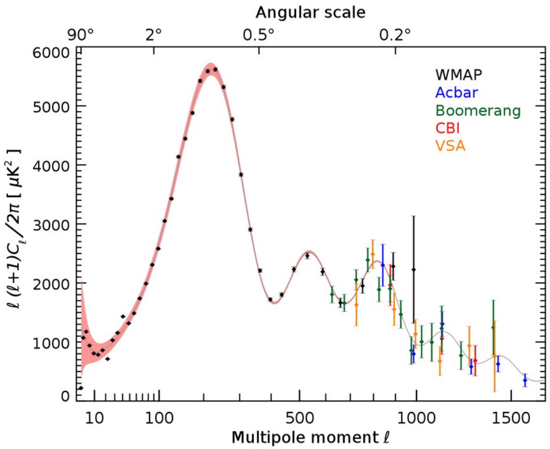
Based on the following work:
J. Jones, J. Silva, R. Lineros, N. Bernal
2408.08950 and 2306.14943



Introduction





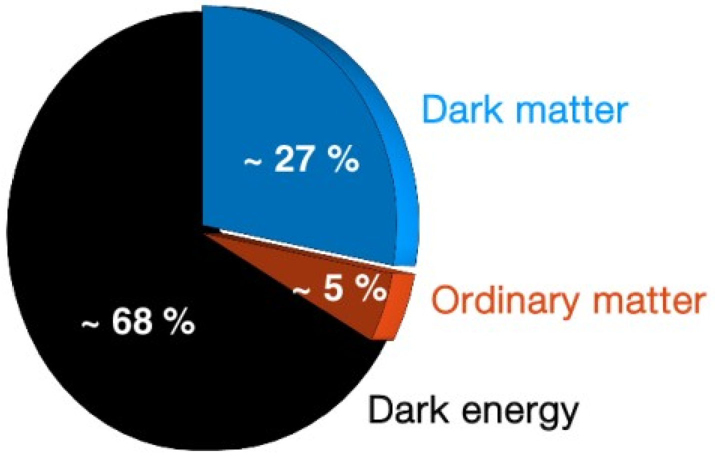


The existence of non-baryonic matter (Dark matter) in the Universe is convincing

Introduction

What is known about DM?

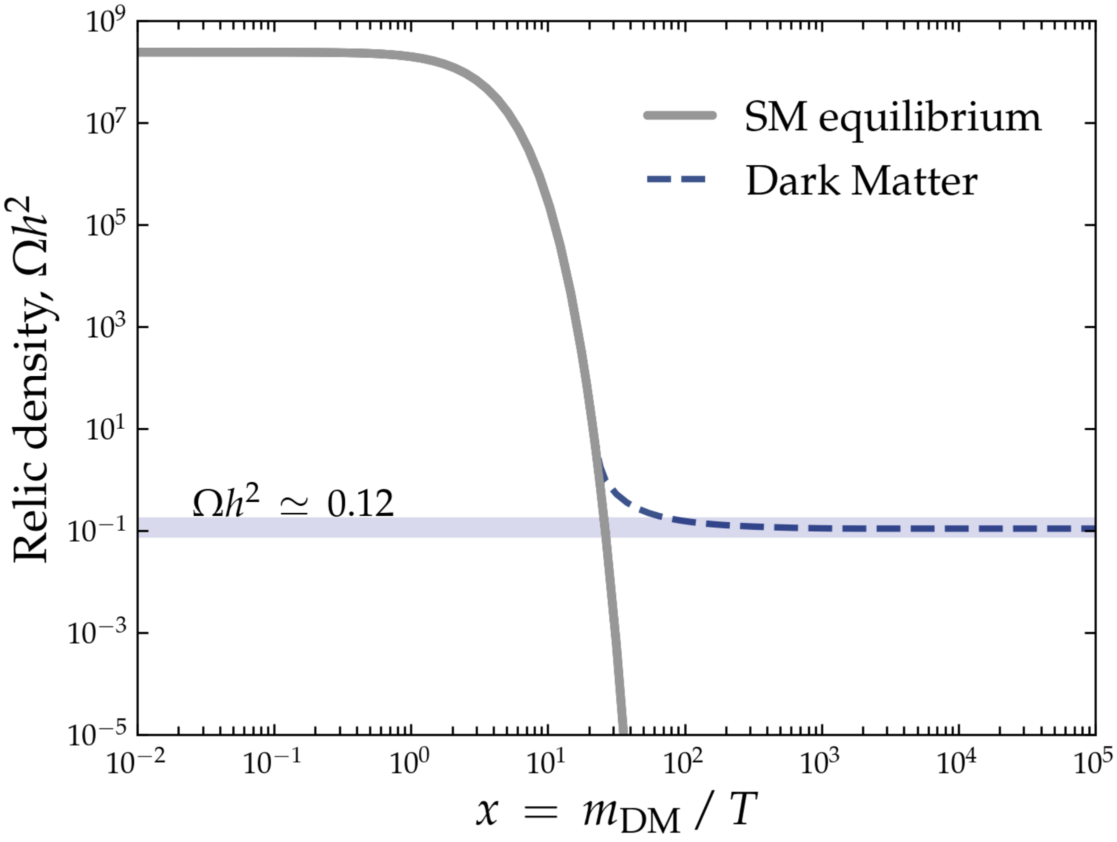
- Neutral
- Massive
- Cold
- ‘Weak’ interactions with the SM particles
- Stable or long-lived
- $\Omega_{\mathrm{Planck}}\, h^2 \sim 0.12$
- A candidate DM must be described in new physics.



Dark Matter Mechanism production

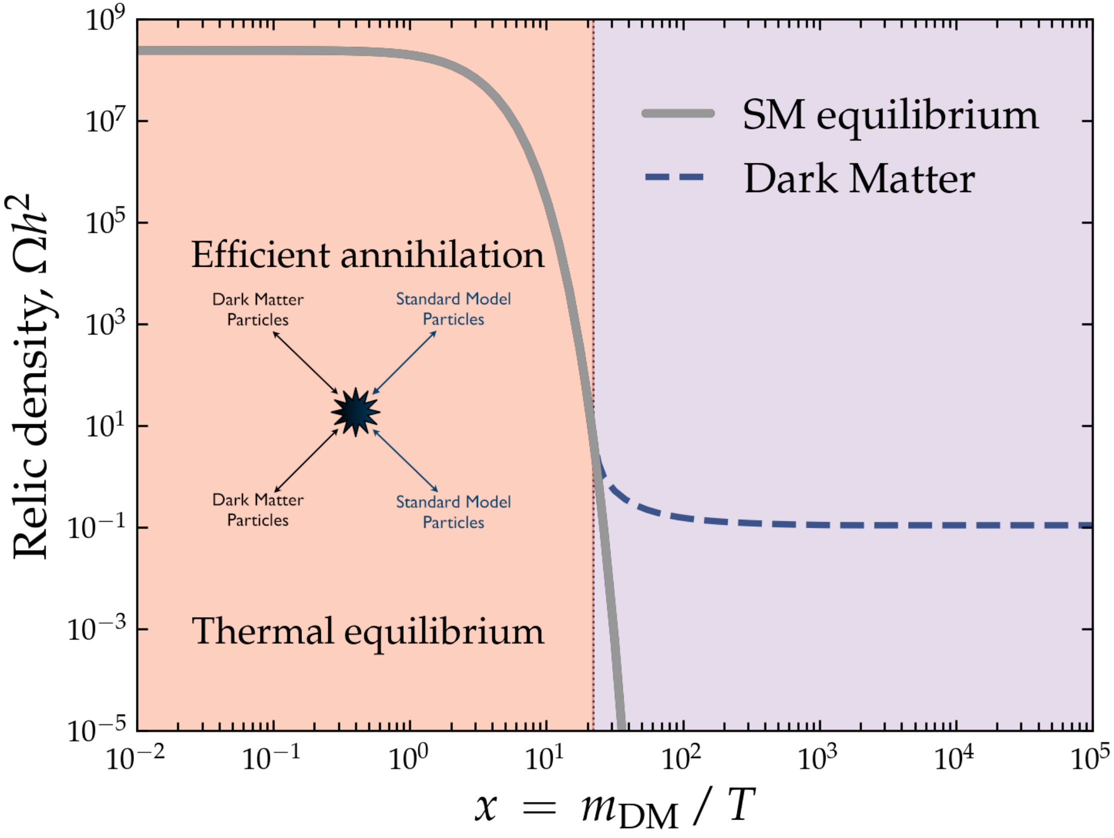
There are (mainly) two theoretical mechanisms of dark matter production, known as *Freeze-out* and *Freeze-in*, that offer fundamental insights into how DM was generated in the early stages of the universe.

Freeze-out Mechanism (Thermal DM)



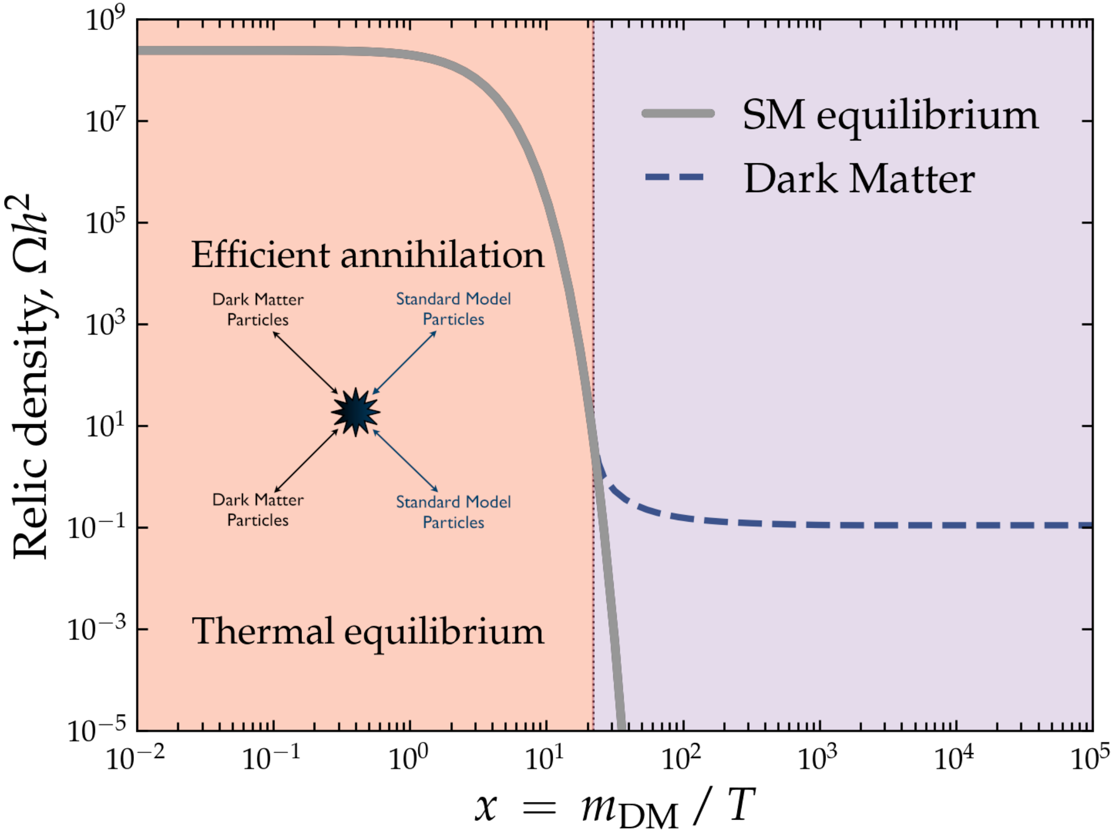
Freeze-out Mechanism (Thermal DM)

- **WIMP** (weakly interacting massive particle) is candidate.



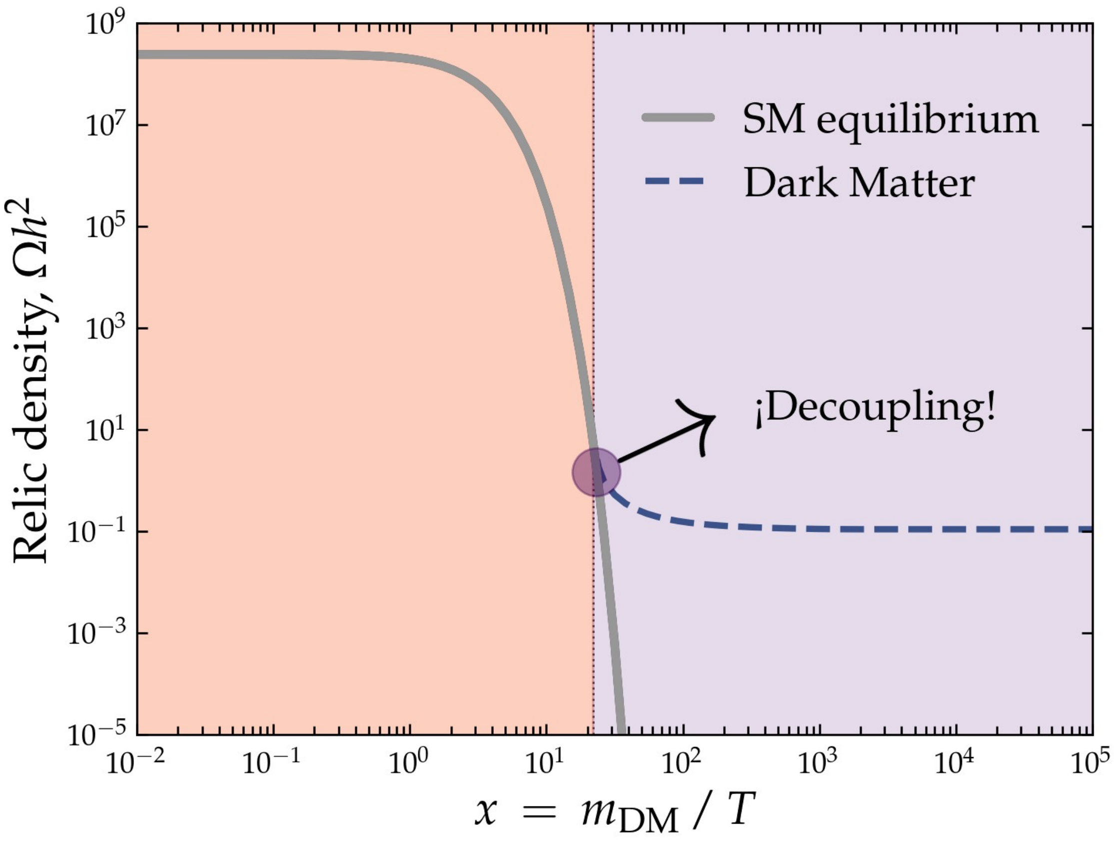
Freeze-out Mechanism (Thermal DM)

- **WIMP** (weakly interacting massive particle) is candidate.
- In the beginning, the DM and SM particles were in thermal equilibrium



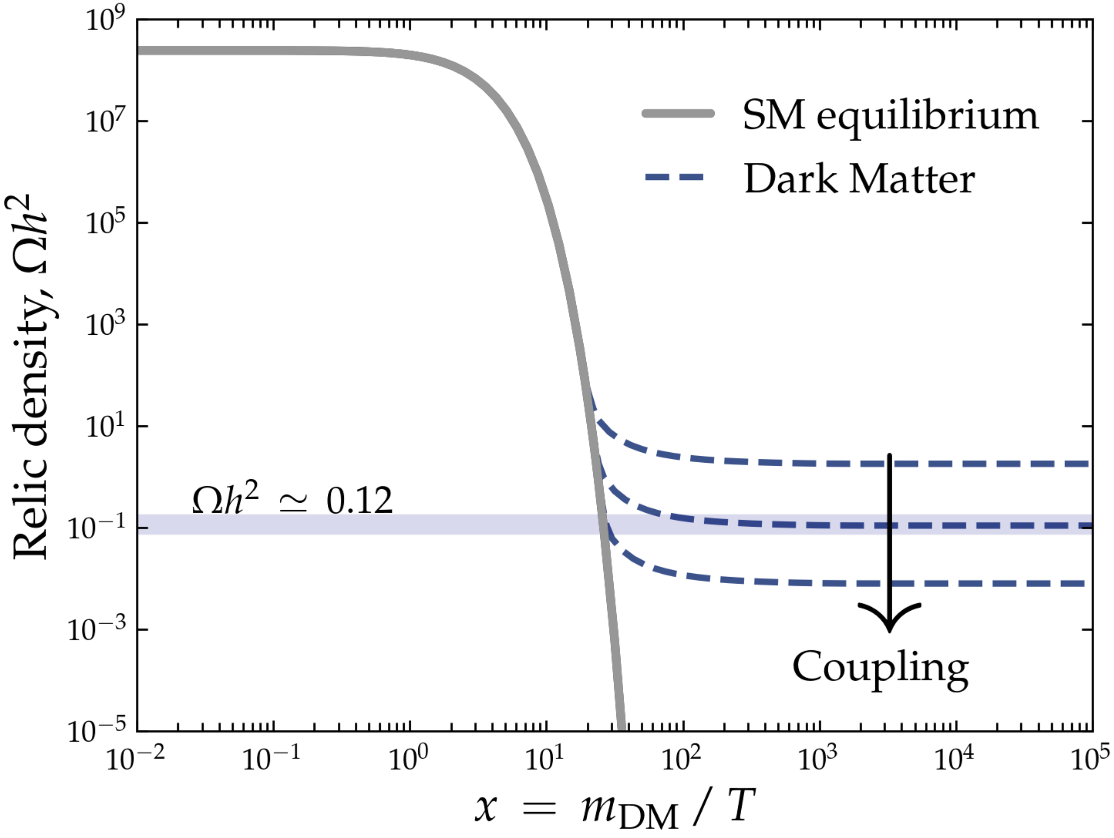
Freeze-out Mechanism (Thermal DM)

- When dark matter decouples from the rest of the SM particles is known as *Freeze-out*.



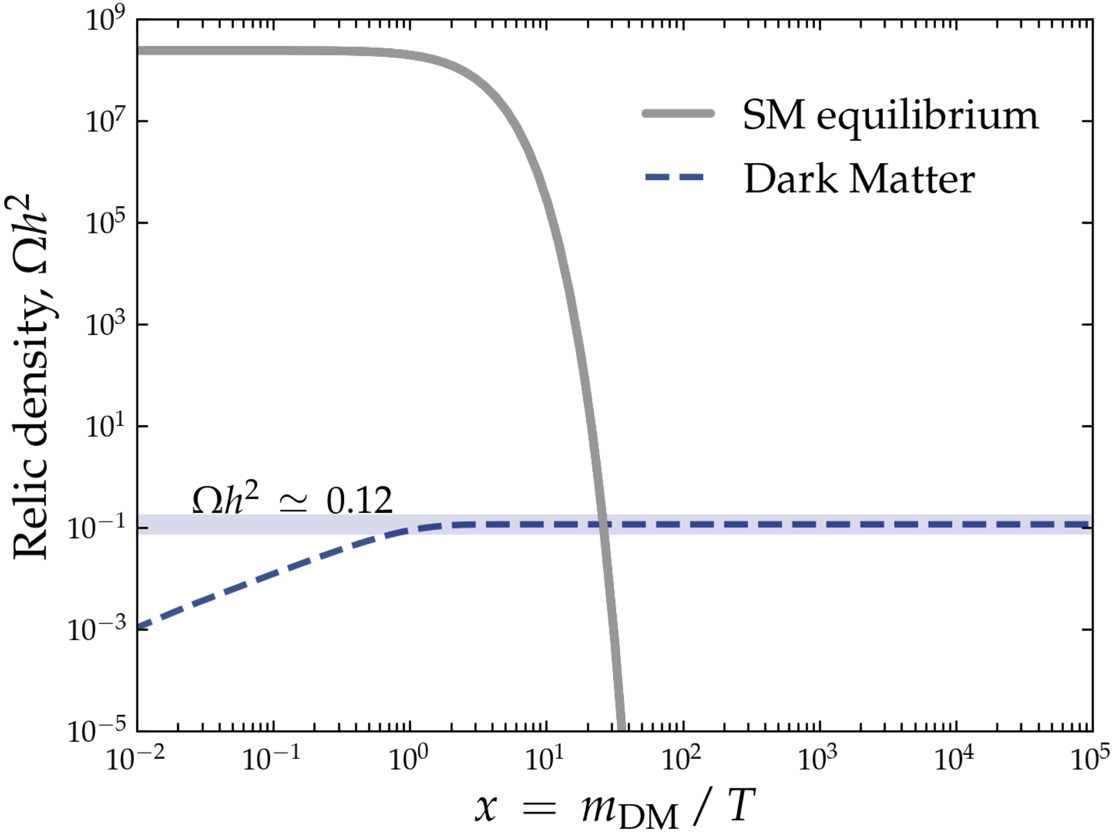
Freeze-out Mechanism (Thermal DM)

$$\Omega h^2 \propto (\text{Coupling})^{-1}$$



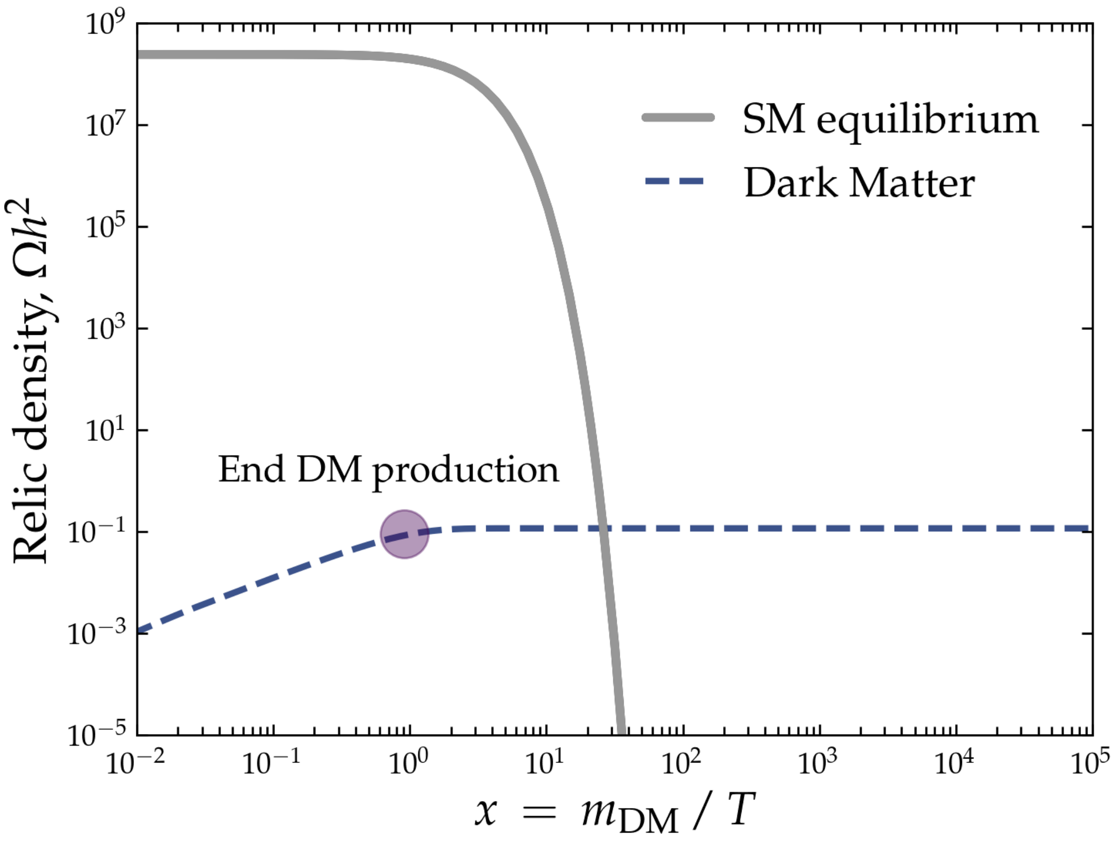
Freeze-in Mechanism (Non-thermal DM)

- **FIMP** (Feebly interacting massive particle) is candidate of DM.



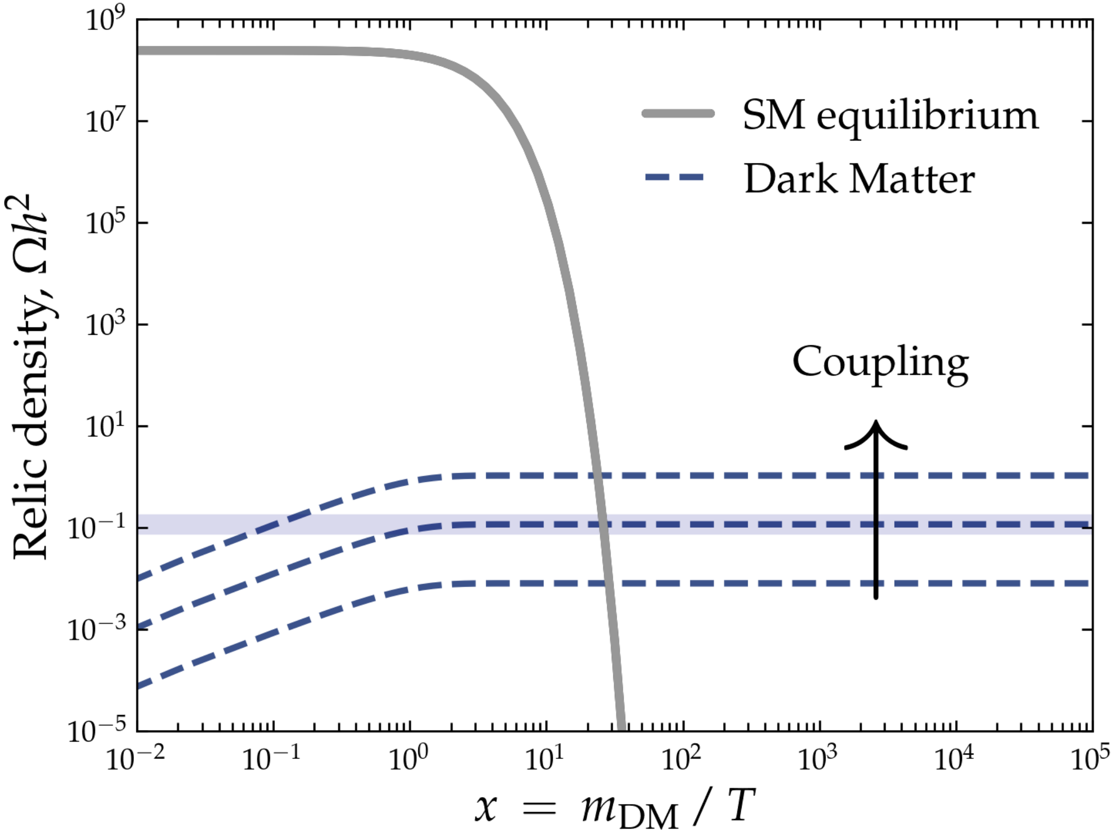
Freeze-in Mechanism (Non-thermal DM)

- **FIMP** (Feebly interacting massive particle) is candidate of DM.
- Never reaches the thermal equilibrium.



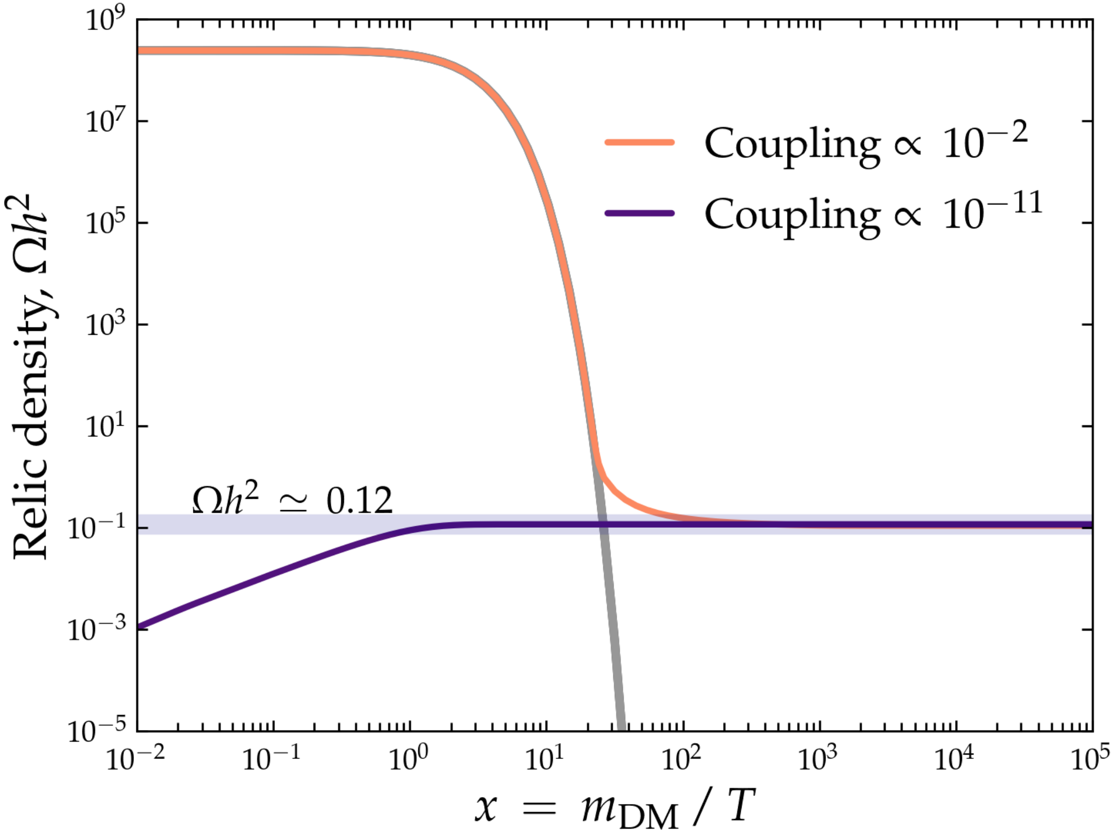
Freeze-in Mechanism (Non-thermal DM)

$$\Omega h^2 \propto \text{Coupling}$$



Freeze-out/in Mechanism

There are $\sim$ 9 orders of magnitude of difference.



Dark Matter Evolution

The evolution of DM, thermal and non-thermal, is described by the Boltzmann equation.

$$\frac{dn_s}{dt} + 3\,H\,n_s = -\langle \sigma v \rangle \left(n_s^2 - n_{\text{eq}}^2\right)$$

where $n_{s,eq}$ is the density number of DM, equilibrium particles, $H \equiv a^{-1}\,(da/dt)$ is the Hubble parameter and …

Dark Matter Evolution

… $\langle \sigma \, v \rangle$ is thermally-averaged annihilation cross-section.

$$\langle \sigma v \rangle (T) = \int_{4m_s^2}^{\infty} \mathrm{d}s \, \frac{(s - 4m_s^2)\, \sqrt{s}\, K_1 \left(\sqrt{s}/T\right) \sigma(s)}{8\, T\, m_s^4\, K_2^2\, (m_s/T)} \, ,$$

K_i is the modified Bessel function and $\sigma(s) \equiv \sigma_{s\,s \to \mathrm{SM\ SM}}(s)$. We need a particle physics model (BSM).

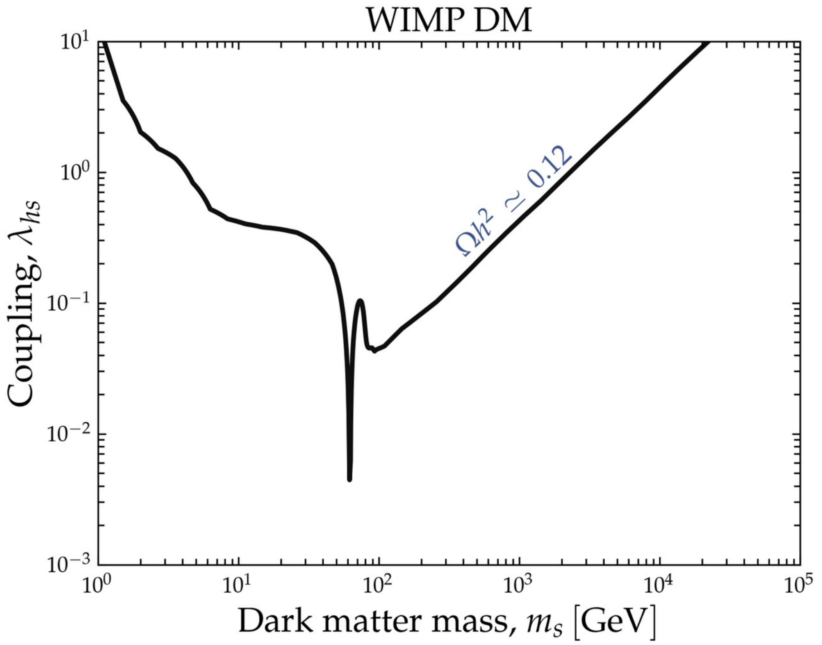
Scalar Singlet Dark Matter

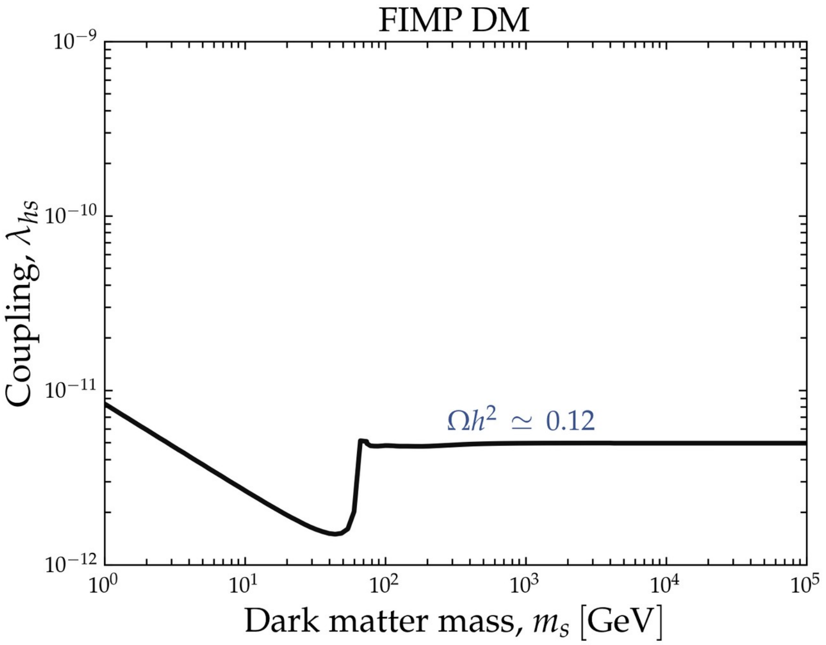
The *SSDM* extends the SM by introducing a real scalar field, ***s***, which is a singlet under the SM gauge symmetry. It includes a $\mathbb{Z}_2$ parity, under which only ***s*** is odd. The most general and renormalizable scalar potential of the model is as follows:

$$V = \lambda_H \left(|H|^2 - v_H^2\right)^2 + \mu_s^2\, s^2 + \lambda_s\, s^4 + \lambda_{hs}\, |H|^2\, s^2,$$

Here, λ_{hs} represents the coupling between the DM candidate and the Higgs boson and $m_s^2 = 2\mu_s^2 + \lambda_{hs} v_H^2$ denotes the mass of the DM candidate.

Scalar Singlet Dark Matter

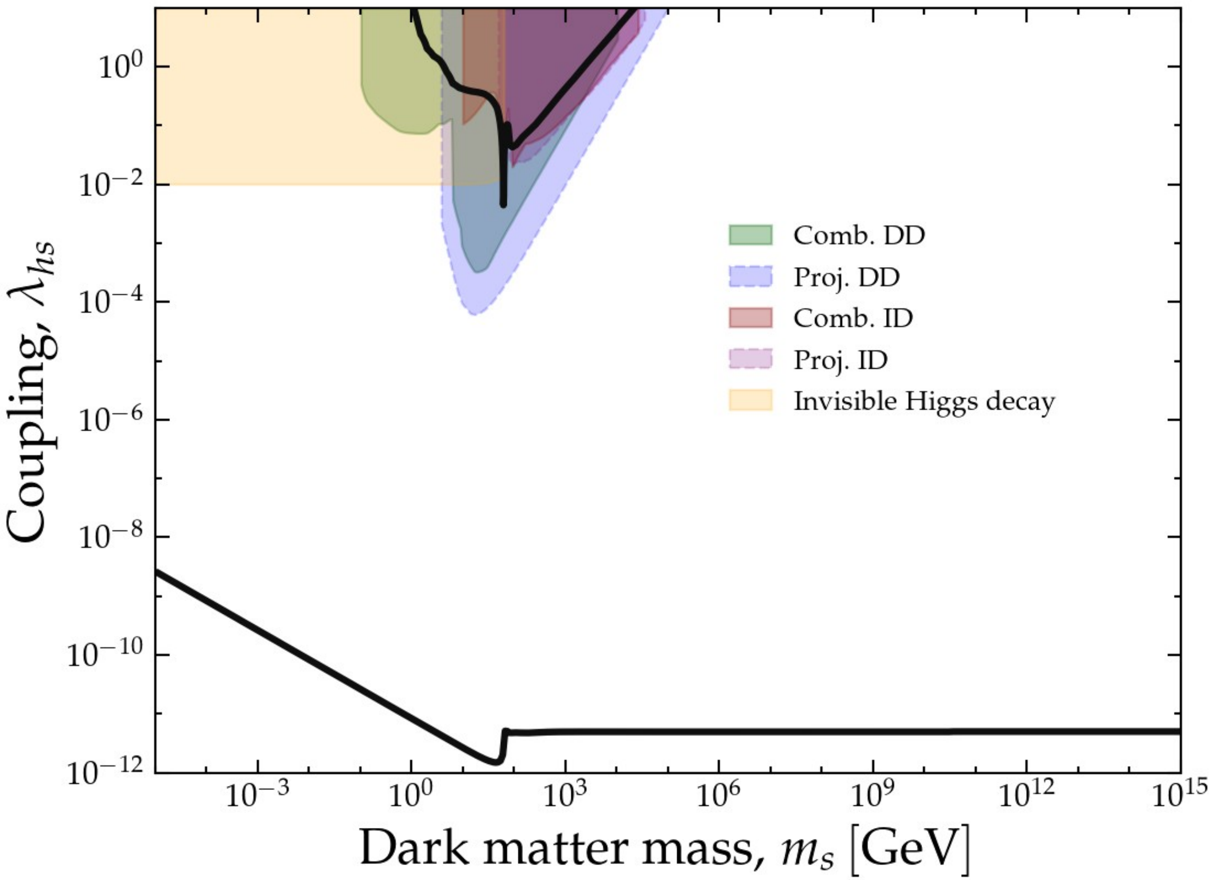




Parameters space that reproduce Planck relic density for *SSDM* candidate.

Dark Matter Detection

- *SSDM* as a WIMP candidate is disfavored by dark matter search experiments.
- We could search for another candidate for DM or …
- We could **search for DM in an alternative cosmology** arXiv:2408.08950



Early matter-dominated Universe scenario

During the period between the end of inflationary reheating and matter-radiation equality, we assumed the Universe to be dominated by Standard Model (SM) radiation and a non-relativistic field, ϕ. The Boltzmann equations describe the evolution of the energy densities ρ_ϕ and ρ_R

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

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

where Γ_ϕ is the ϕ field decay width and $\omega = 0$.

Early matter-dominated Universe scenario

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

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

Entropy injection

Early matter-dominated Universe scenario

$$\frac{d\rho_\phi}{dt} + 3\,H\,\rho_\phi = -\,\Gamma_\phi\,\rho_\phi,$$
$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\,\Gamma_\phi\,\rho_\phi$$

$\rho^i_R = 0$

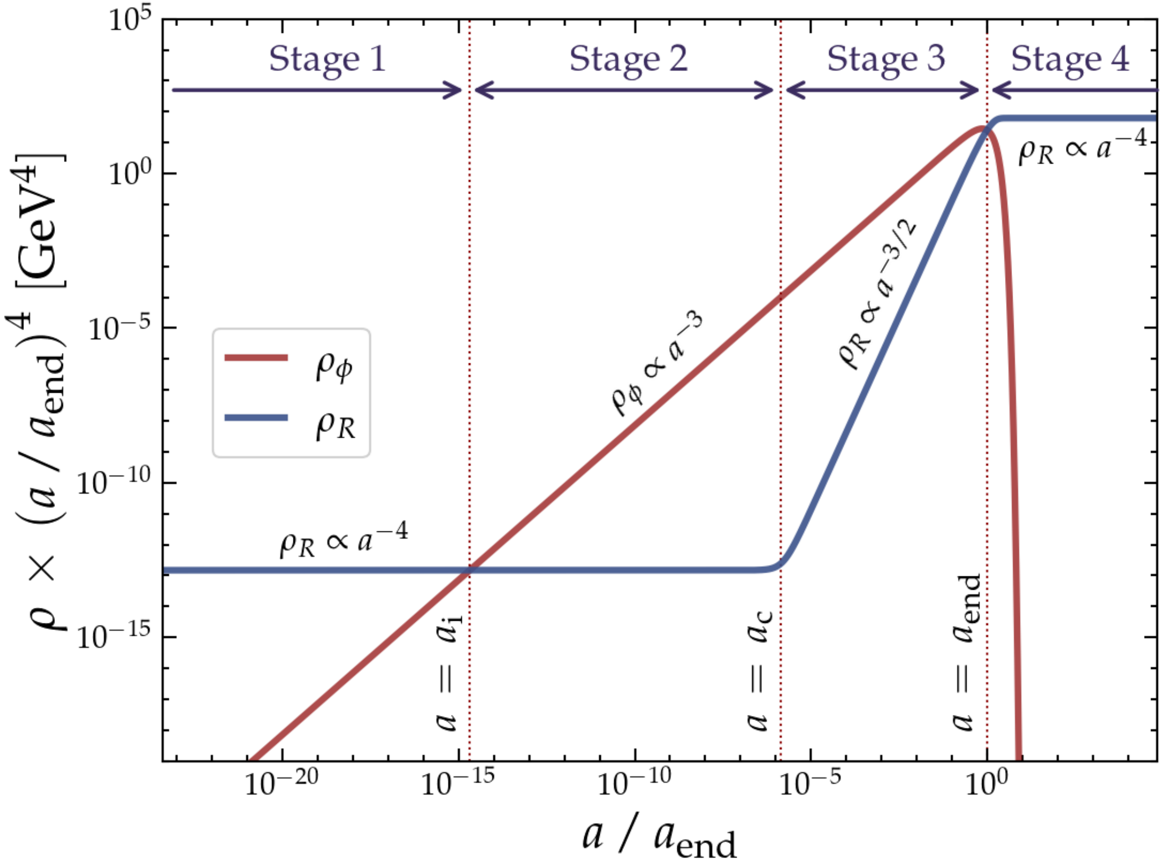
2306.14943

Early matter-dominated Universe scenario

$$\frac{d\rho_\phi}{dt} + 3\,H\,\rho_\phi = -\,\Gamma_\phi\,\rho_\phi,$$
$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\,\Gamma_\phi\,\rho_\phi$$

We have considered that ρ_R was initially the dominant component. From this assumption, four possible stages arise.

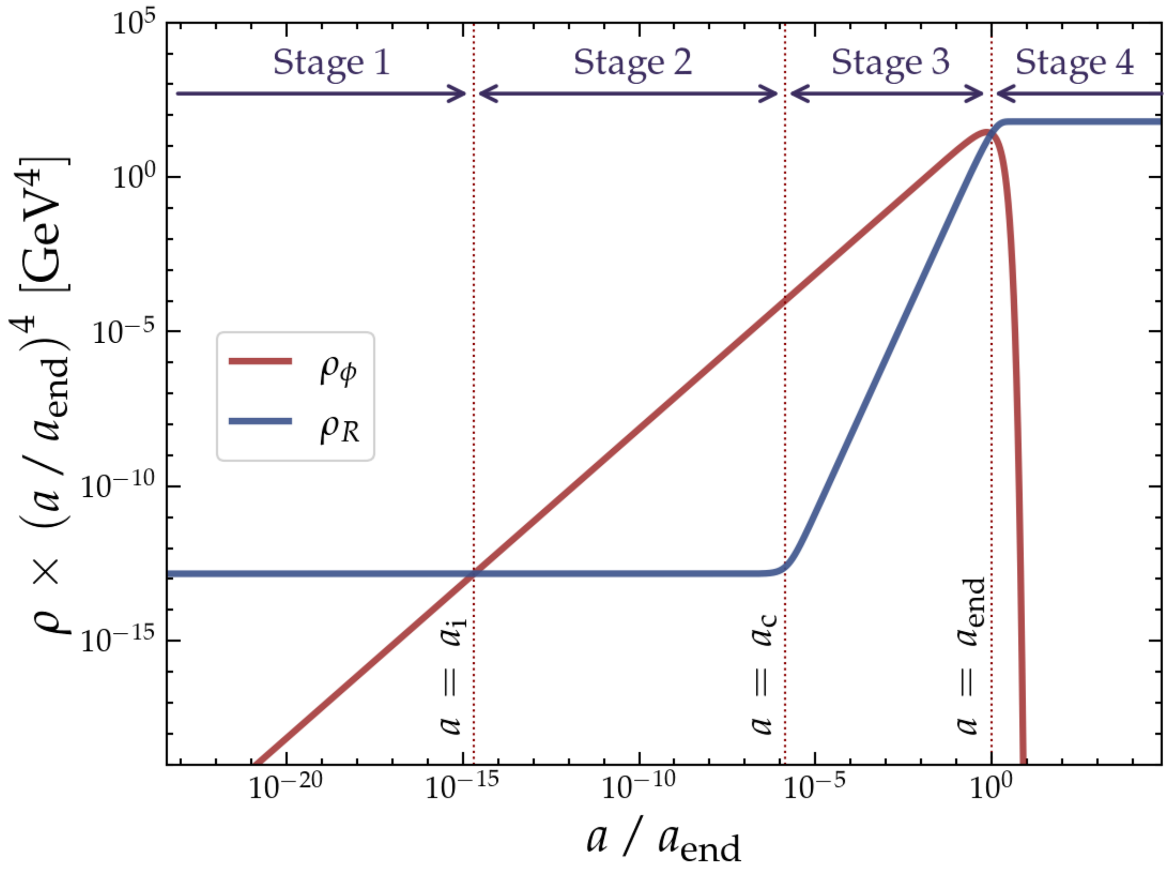
Early matter-dominated Universe scenario



Early matter-dominated Universe scenario

Stage 1

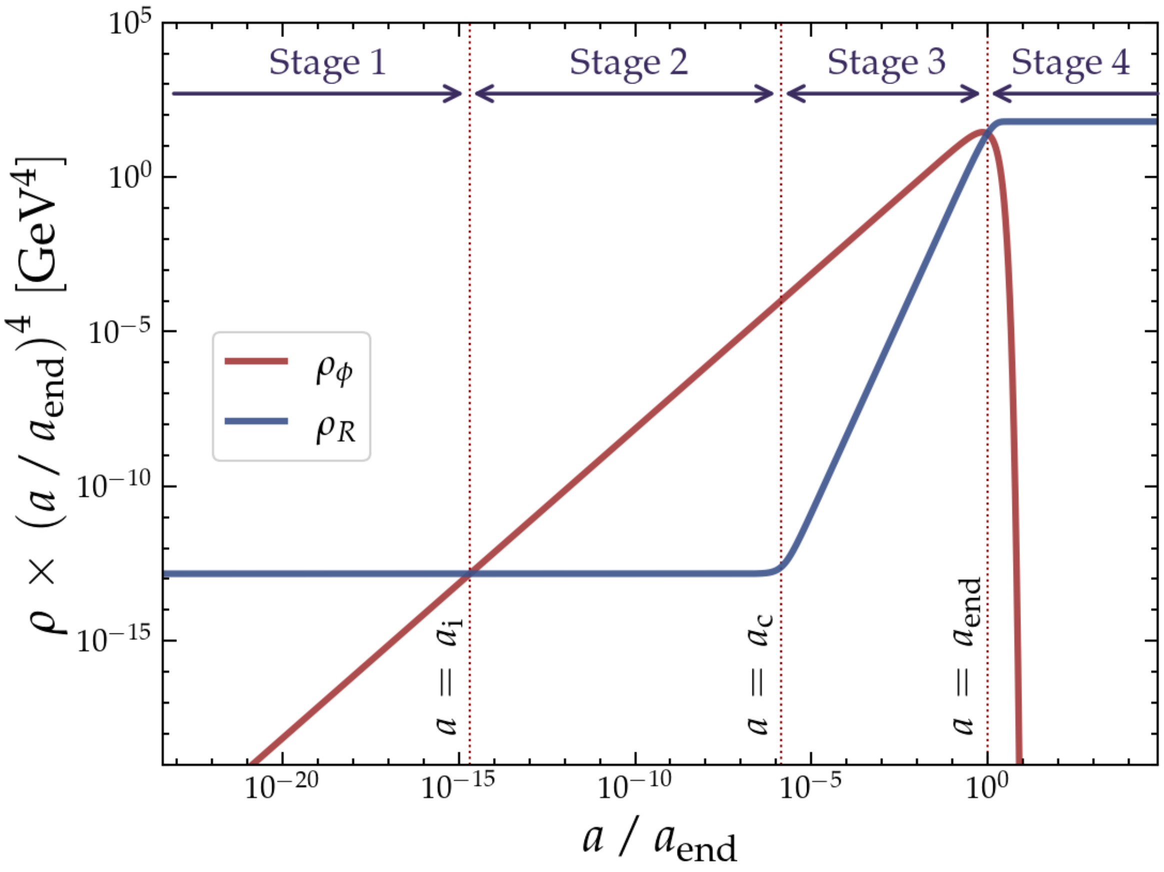
- $a < a_i \, (T > T_i)$
- The SM radiation is the dominant component $(\rho_R > \rho_\phi)$



Early matter-dominated Universe scenario

Stage 2

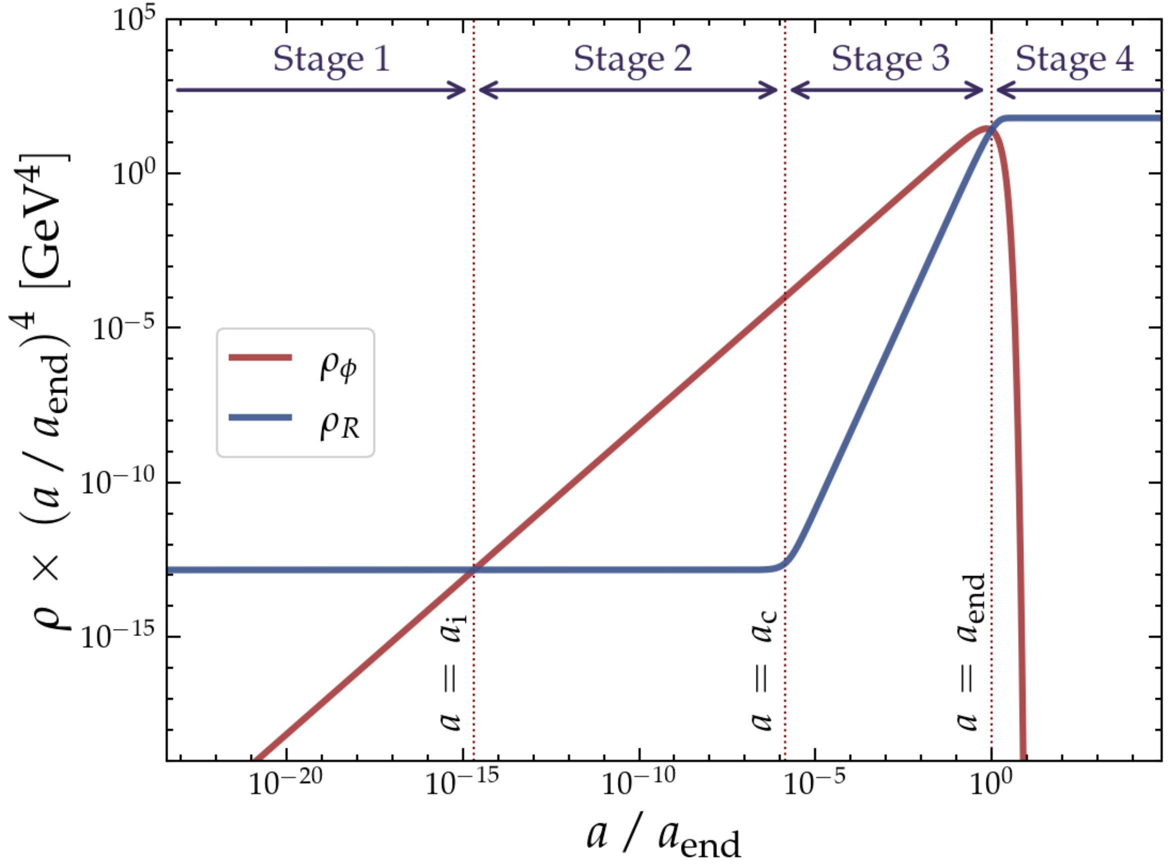
- $a_i < a < a_c \, (T_i > T > T_c)$
- The field ϕ dominates the expansion of the Universe $(\rho_R < \rho_\phi)$
- There is still no entropy injection into the SM radiation



Early matter-dominated Universe scenario

Stage 3

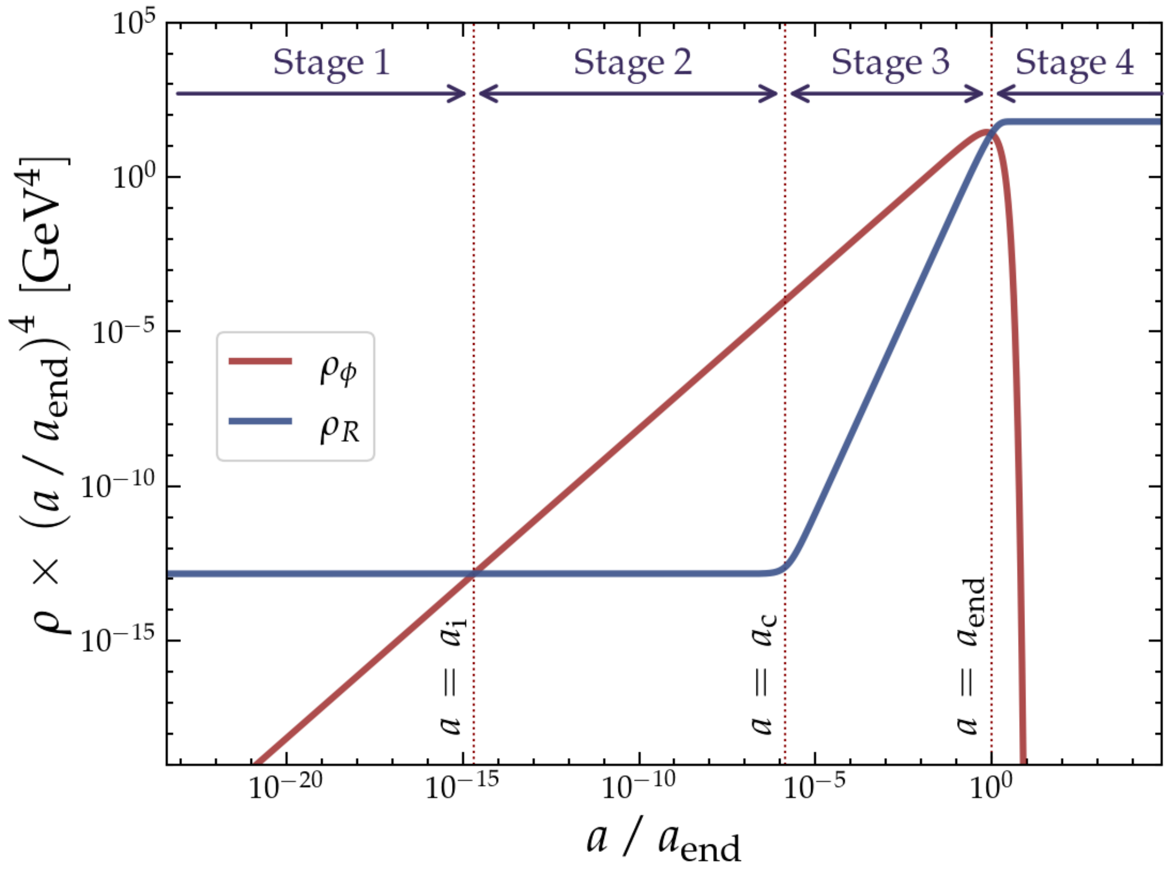
- $a_c < a < a_{\rm end}$ ($T_c > T > T_{\rm end}$)
- The field ϕ is the dominant component
- The field ϕ injects entropy into the SM radiation



Early matter-dominated Universe scenario

Stage 4

- $a > a_{\rm end}\ (T < T_{\rm end})$
- The standard cosmological evolution of the Universe is recovered



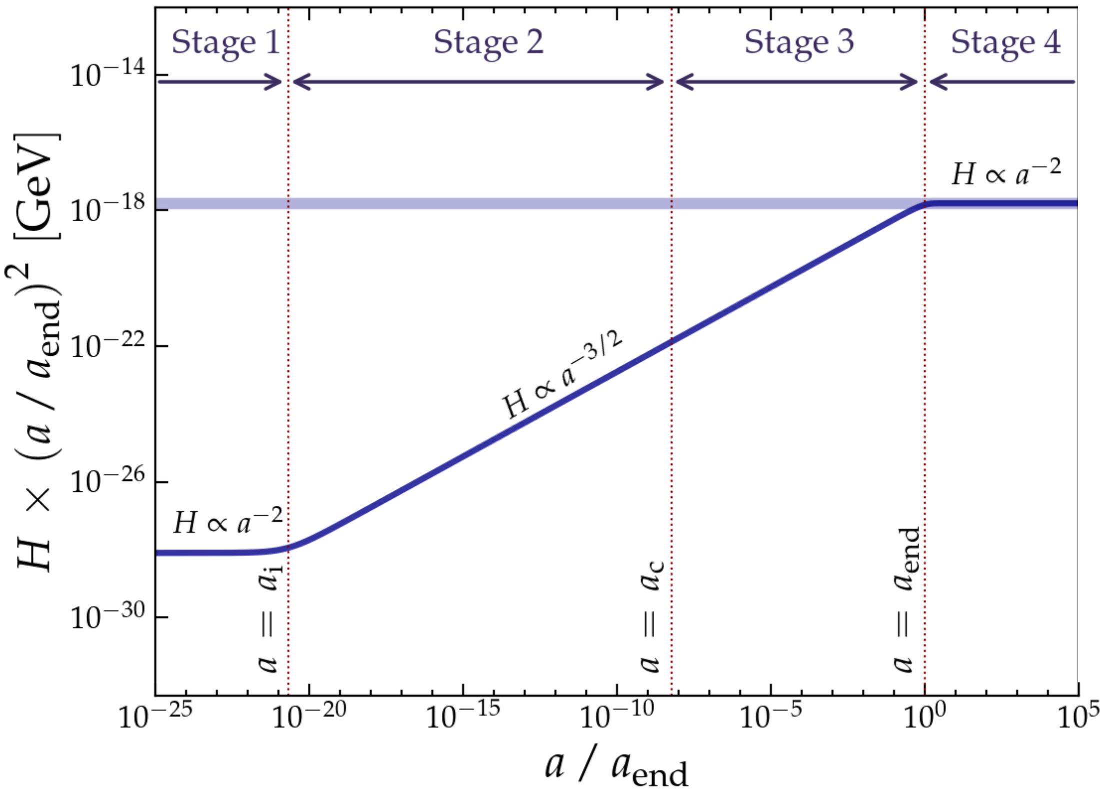
Early matter-dominated Universe scenario

$$\frac{d\rho_\phi}{dt} + 3\,H\,\rho_\phi = -\,\Gamma_\phi\,\rho_\phi,$$
$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\,\Gamma_\phi\,\rho_\phi$$

This new field modify the Friedmann equation.

$$H^2 = \frac{\rho_R + \rho_\phi}{3\,M_P^2}$$

Early matter-dominated Universe scenario



Early matter-dominated Universe scenario

$$\frac{d\rho_\phi}{dt} + 3\,H\,\rho_\phi = -\,\Gamma_\phi\,\rho_\phi,$$
$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\,\Gamma_\phi\,\rho_\phi$$

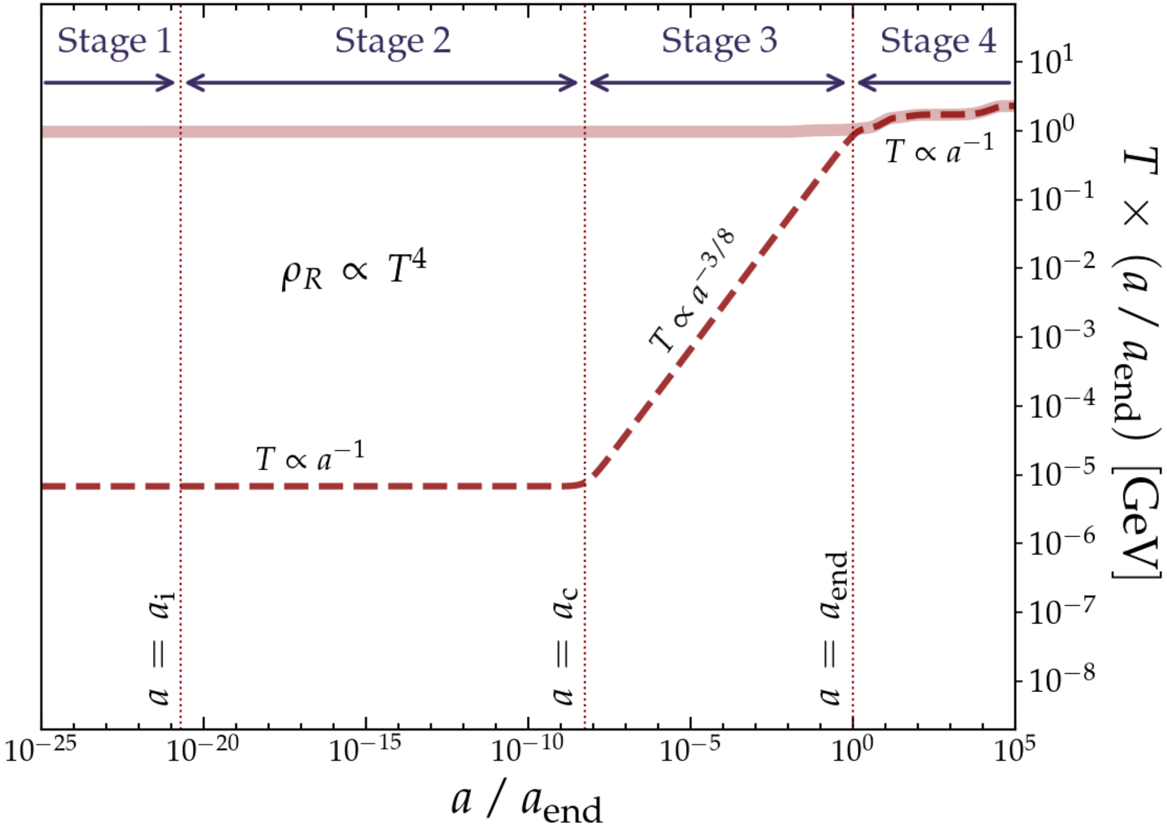
This new field modify the Friedmann equation.

$$H^2 = \frac{\rho_R + \rho_\phi}{3\,M_P^2}$$

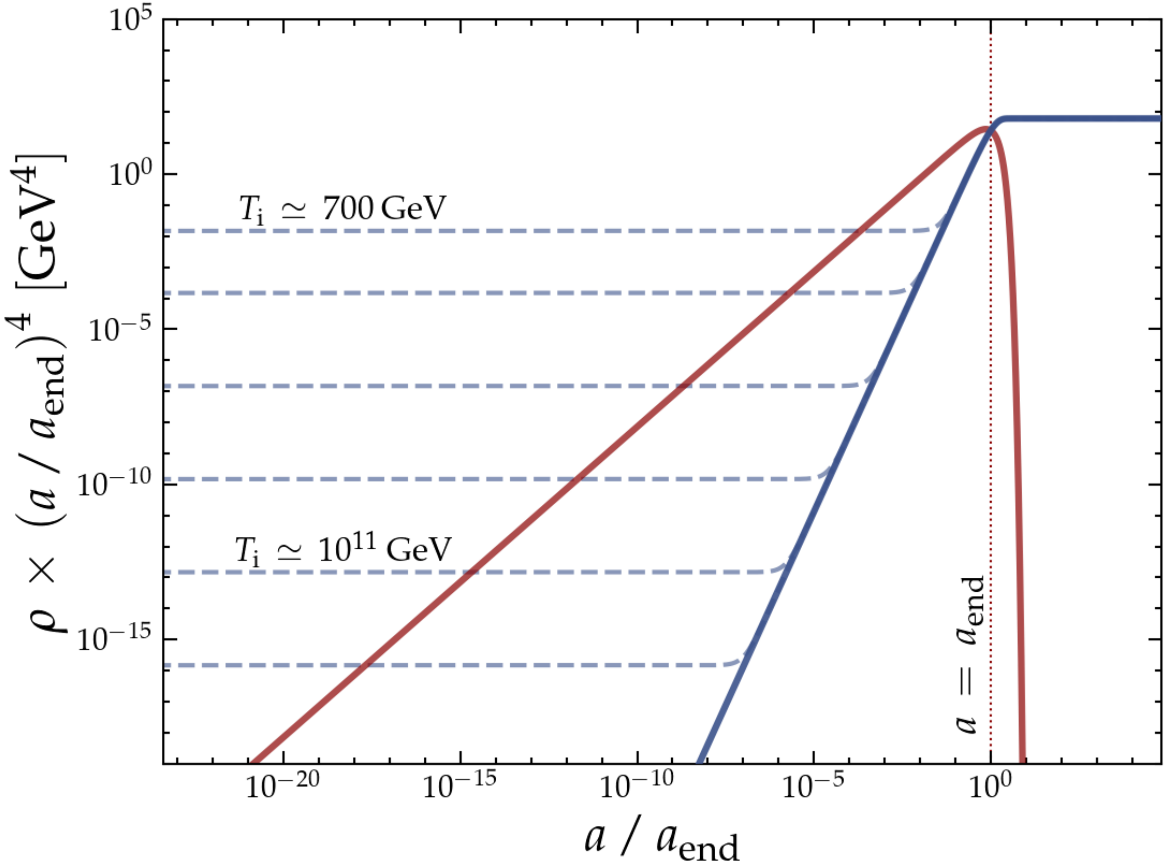
The evolution of the SM temperature is also altered.

$$\rho_R(T) = \frac{\pi^2}{30}\,g_\star(T)\,T^4$$

Early matter-dominated Universe scenario



Early matter-dominated Universe scenario



DM Genesis in EMD

For this research, we solve the Boltzmann equation for $N \equiv n_s \times a^3$,

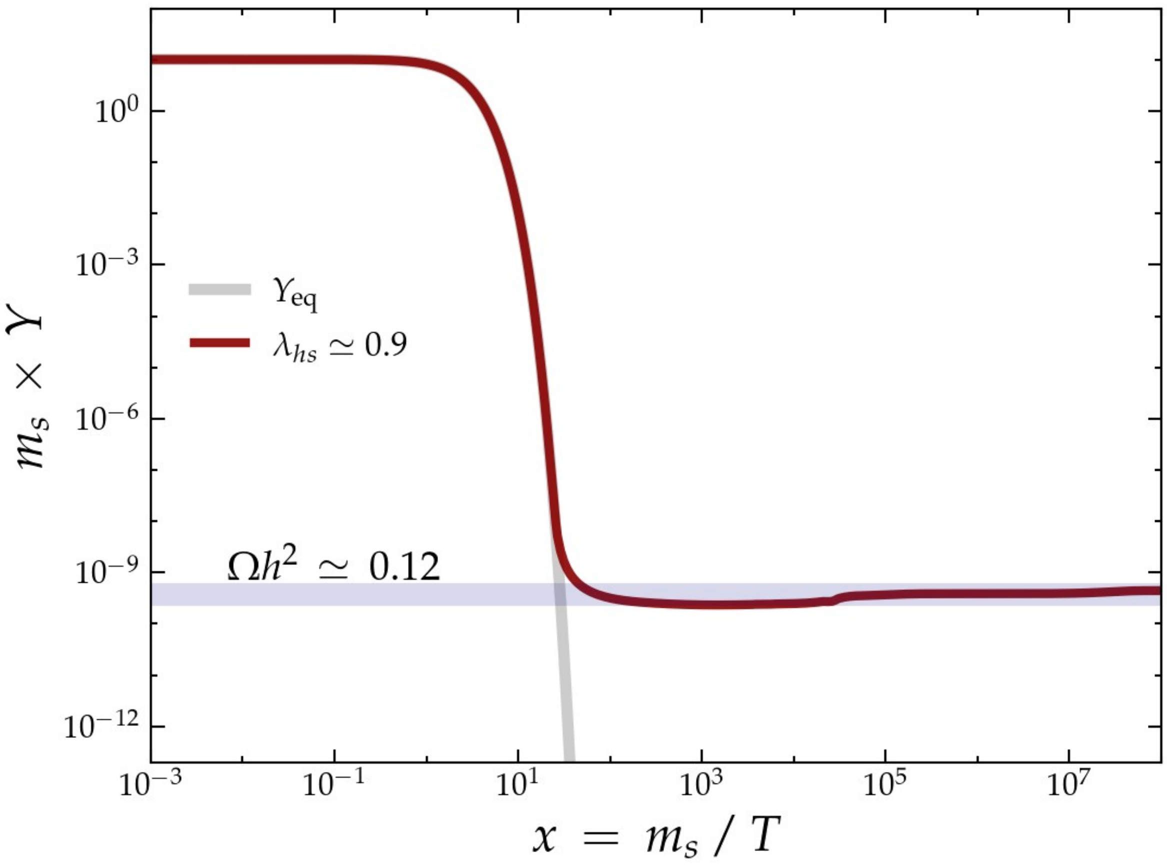
$$\frac{dN}{da} = -\frac{\langle \sigma v \rangle}{a^4 H} \left(N^2 - N_{\rm eq}^2 \right)$$

$\langle \sigma v \rangle \sim \lambda_{hs}$. It is useful to define $Y \equiv n_s / s$, where s is the entropy density.

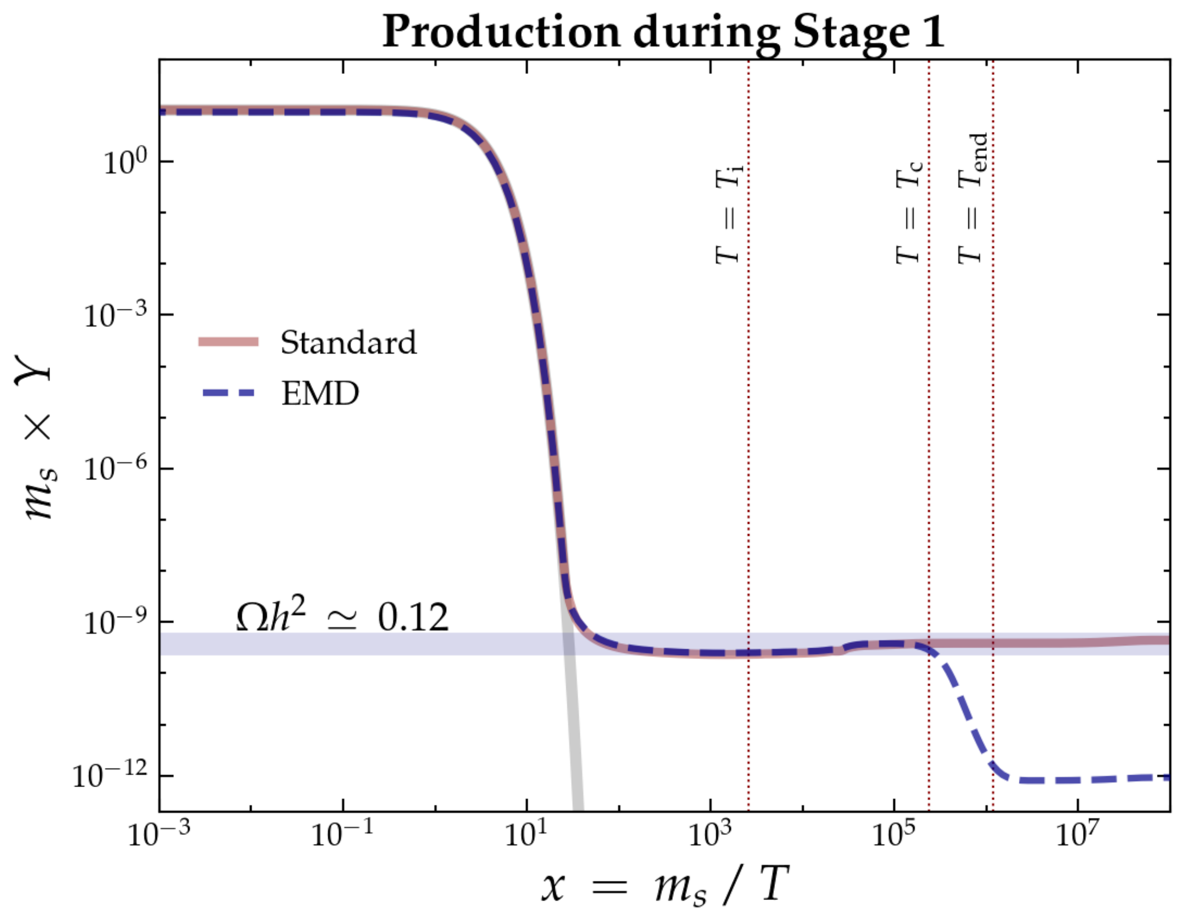
$$m_s Y_0 \simeq 4.3 \times 10^{-10} \text{ GeV}$$

where Y_0 is the asymptotic value of the DM yield at low temperatures.

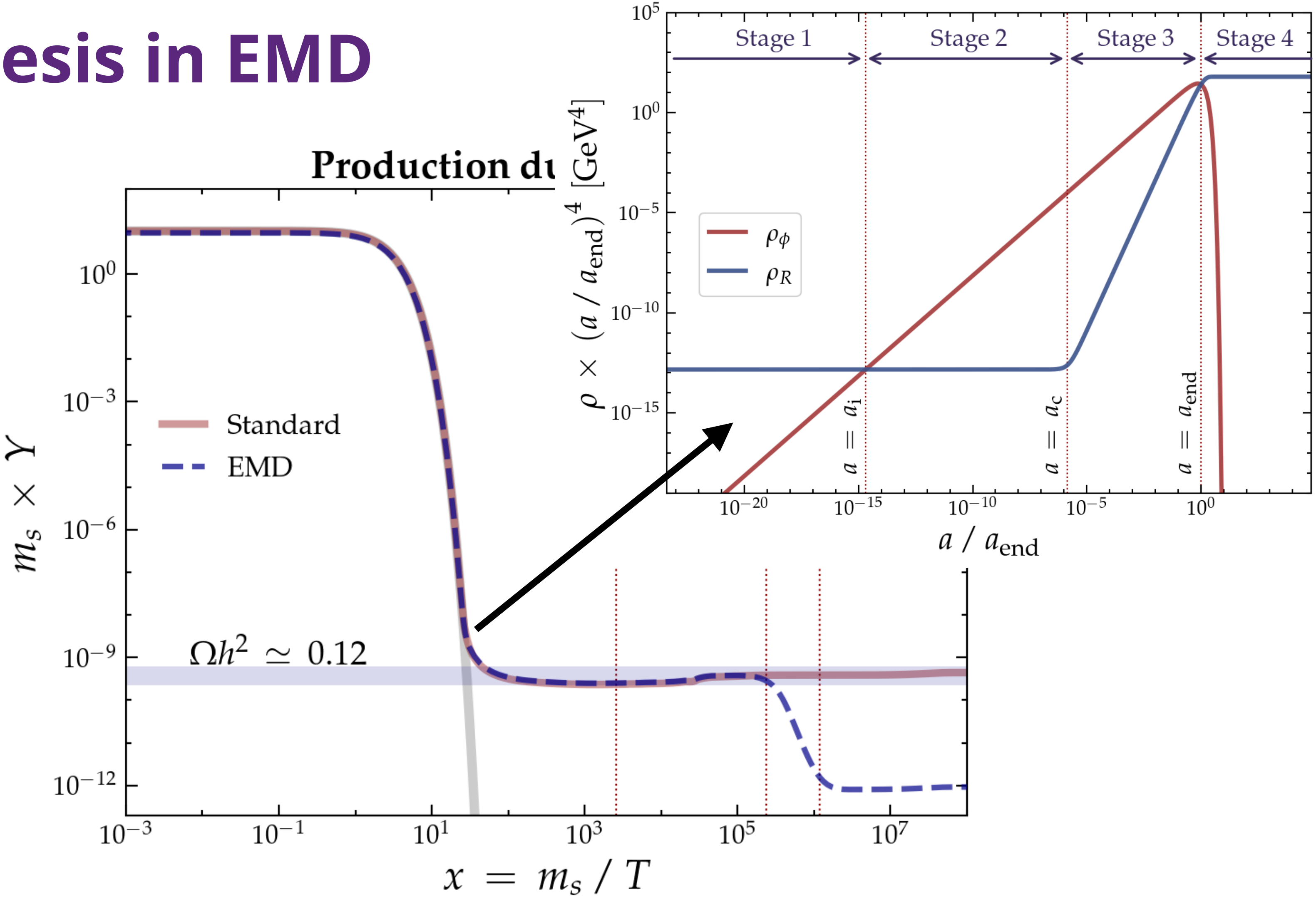
DM Genesis in EMD



DM Genesis in EMD

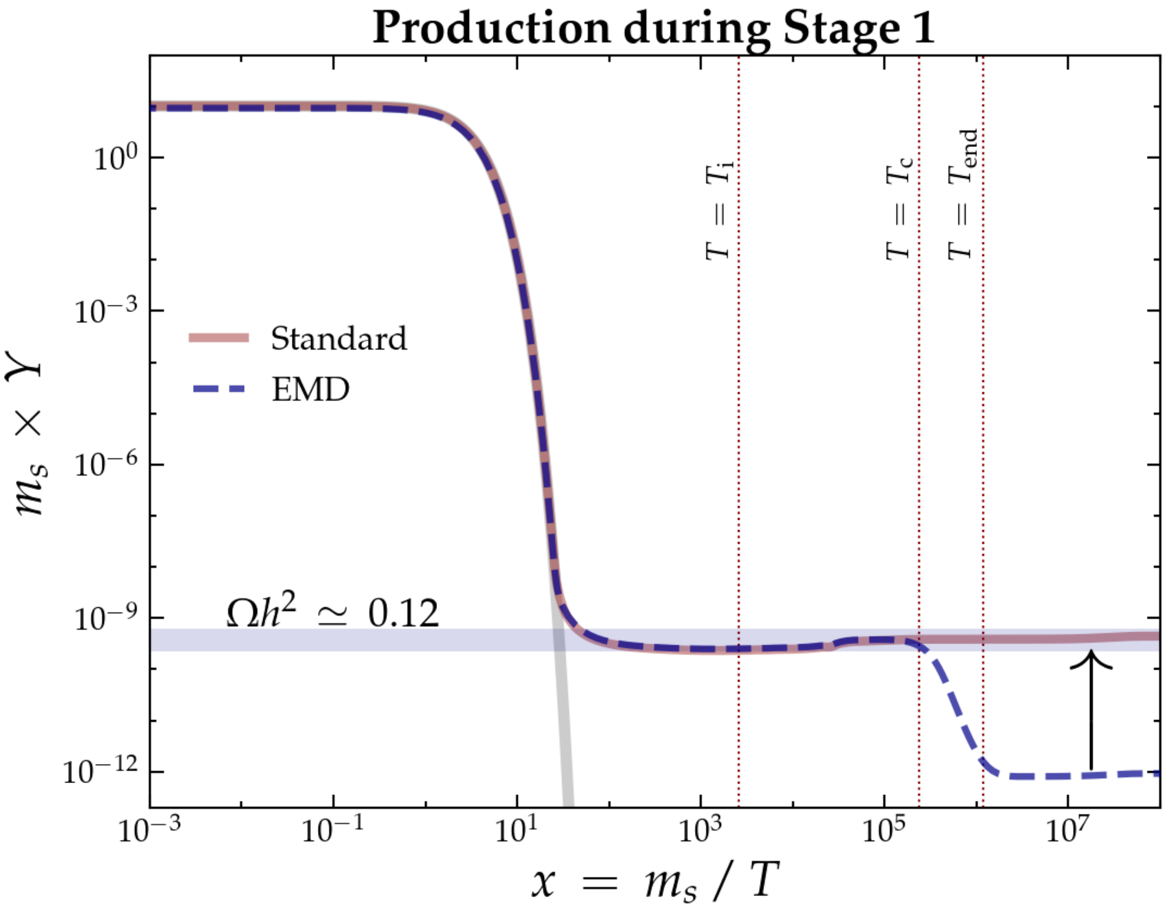


DM Genesis in EMD



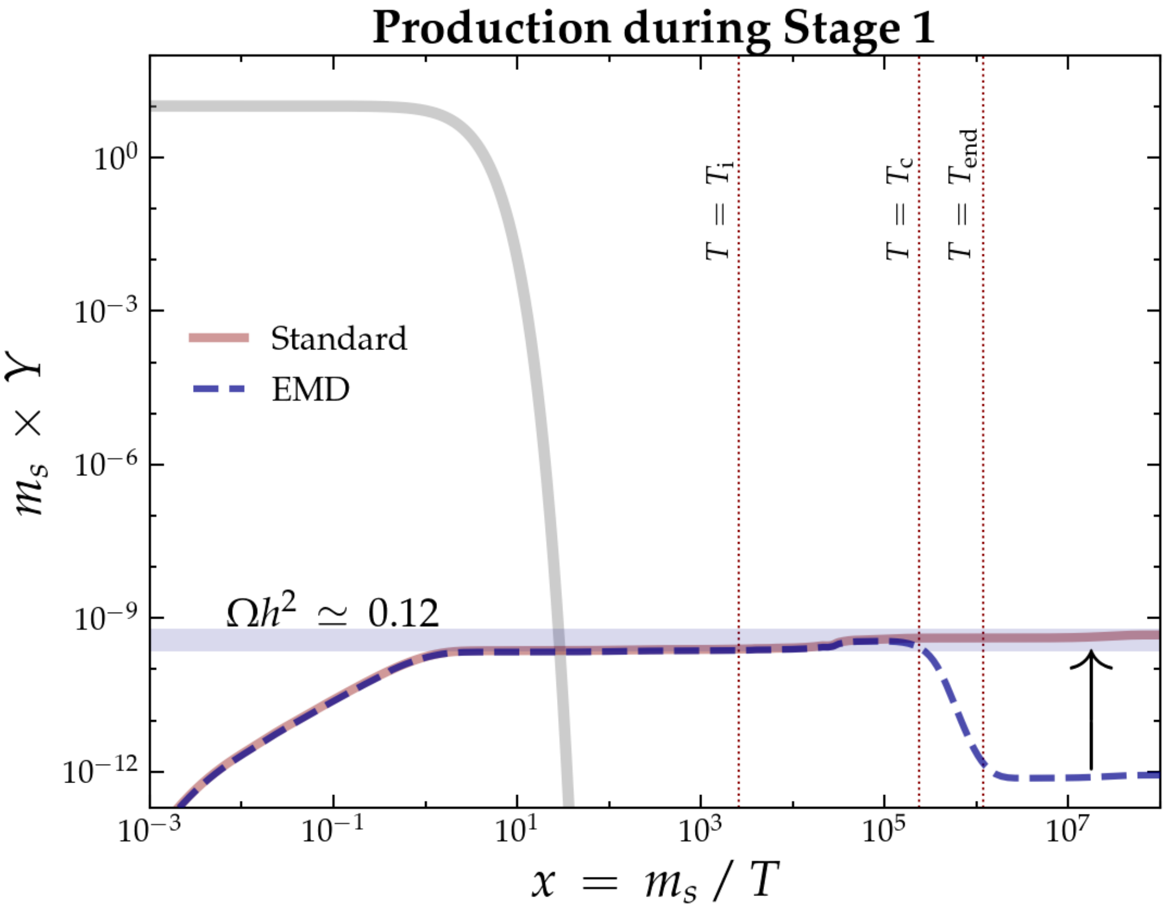
DM Genesis in EMD

- For EMD, it is necessary to increase Y
- This entails reducing the coupling ($Y \sim \lambda_{hs}^{-1}$)

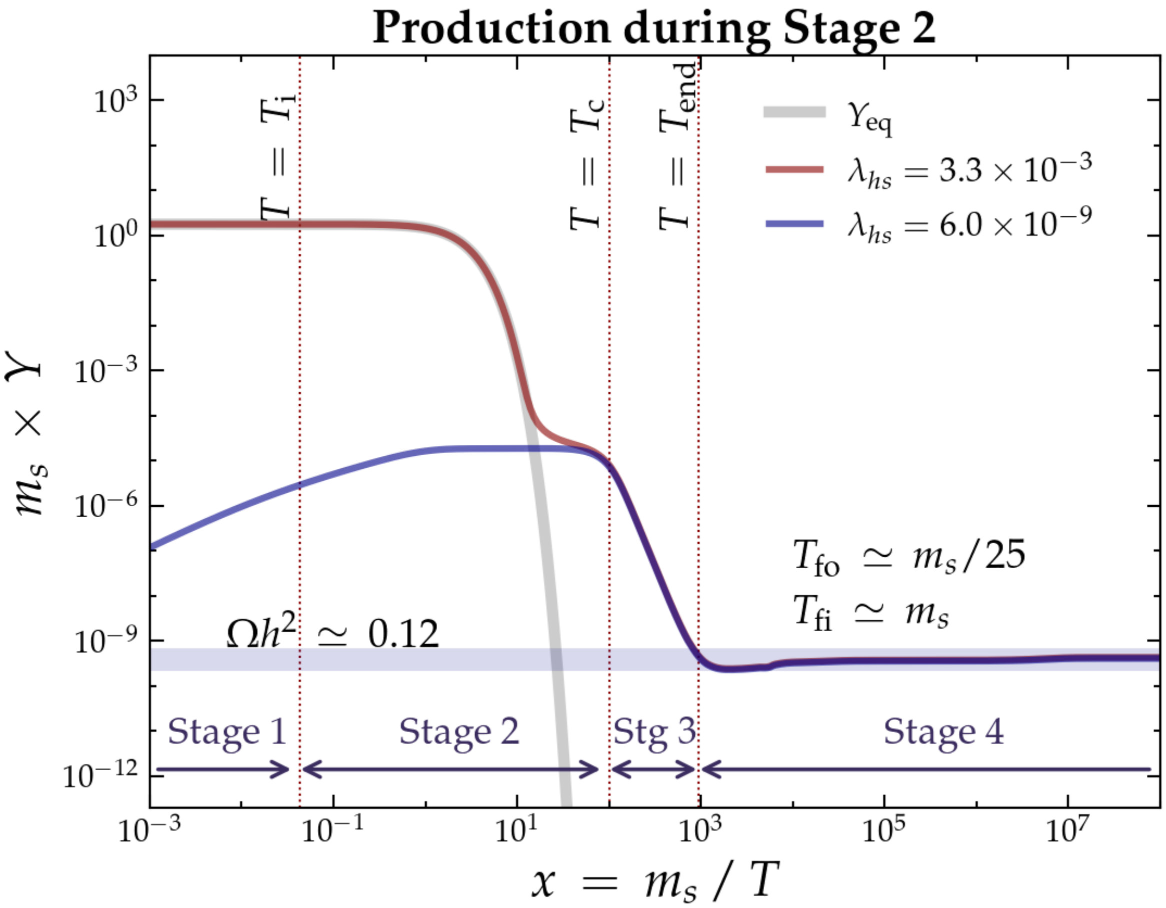


DM Genesis in EMD

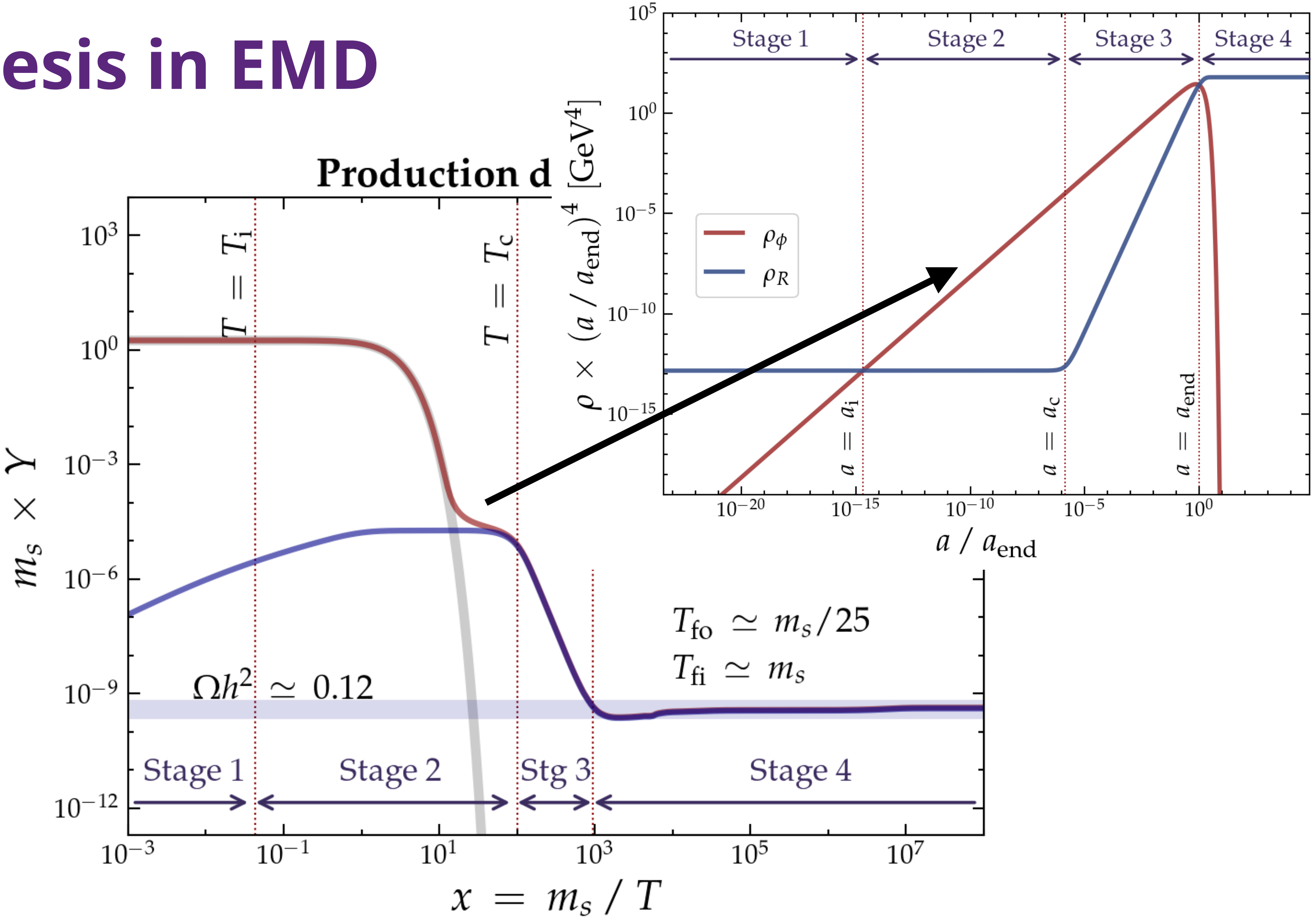
- For EMD, it is necessary to increase Y
- This entails increasing the coupling $(Y \sim \lambda_{hs})$



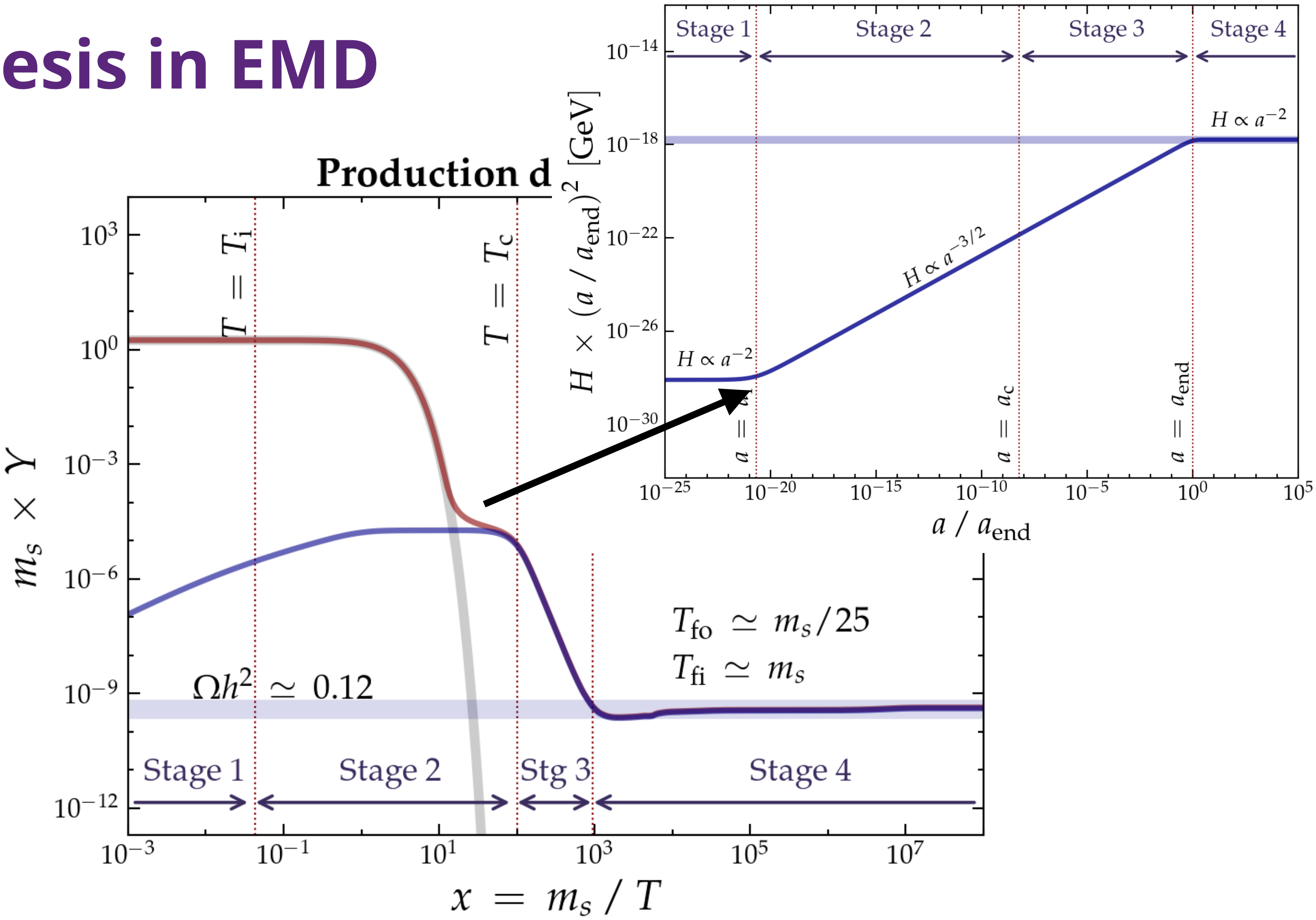
DM Genesis in EMD



DM Genesis in EMD



DM Genesis in EMD

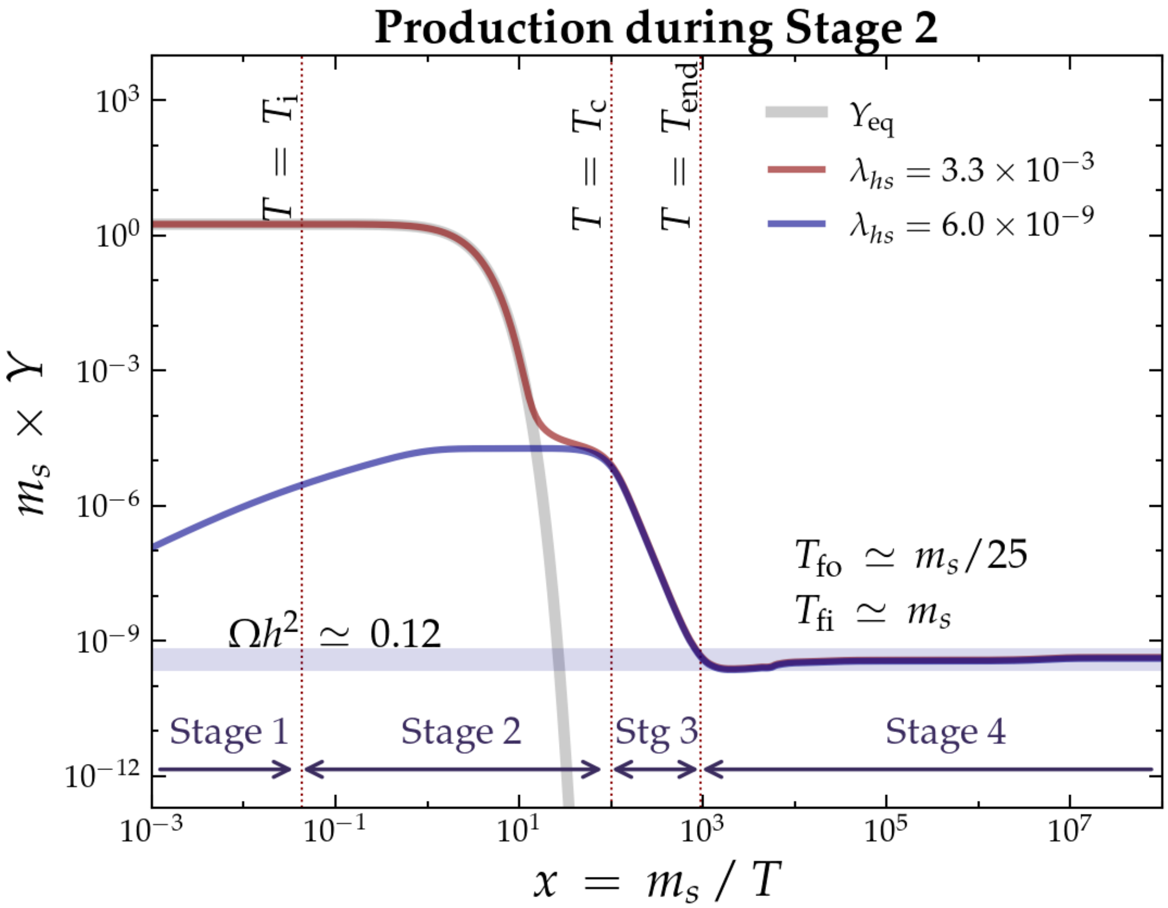


DM Genesis in EMD

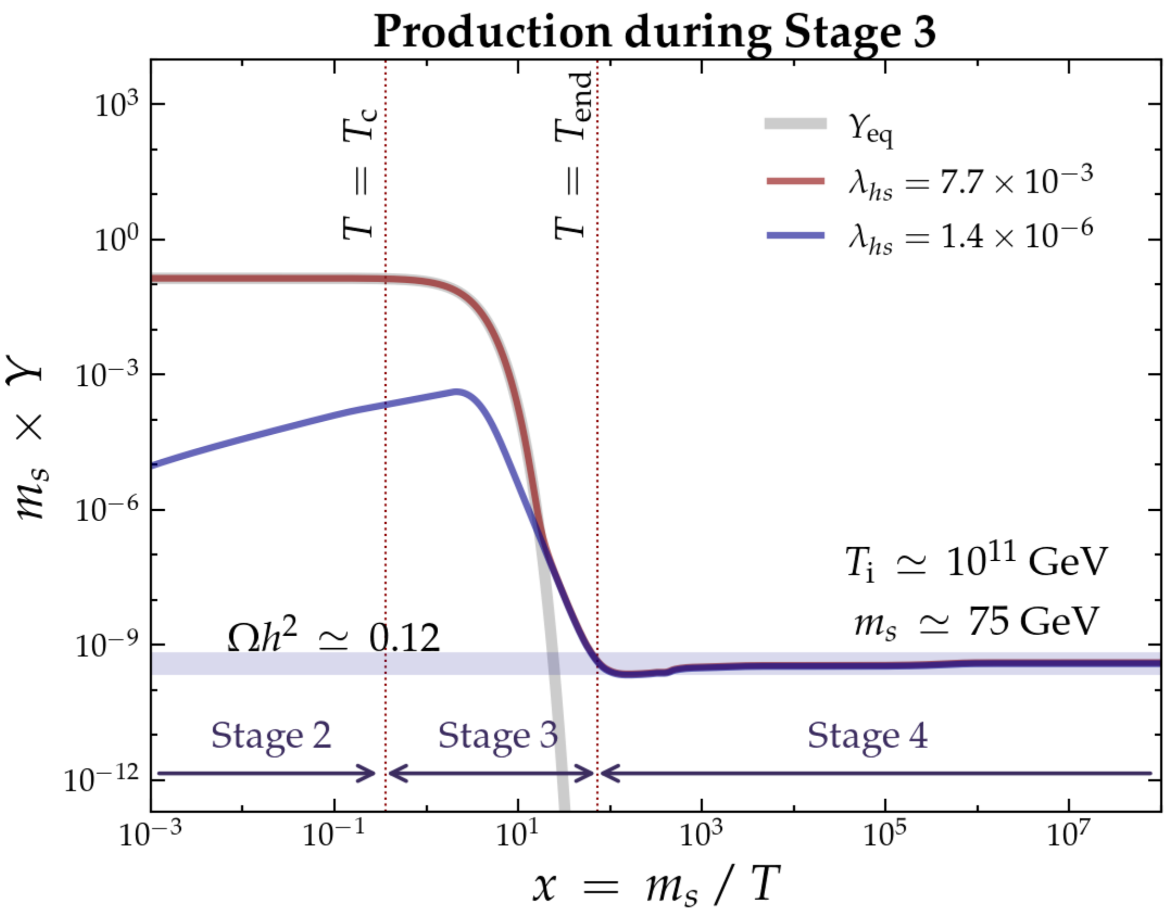
- For the FIMP case:

  $dN/da \simeq \langle \sigma v \rangle N_{\text{eq}}^2 / (a^4 H)$

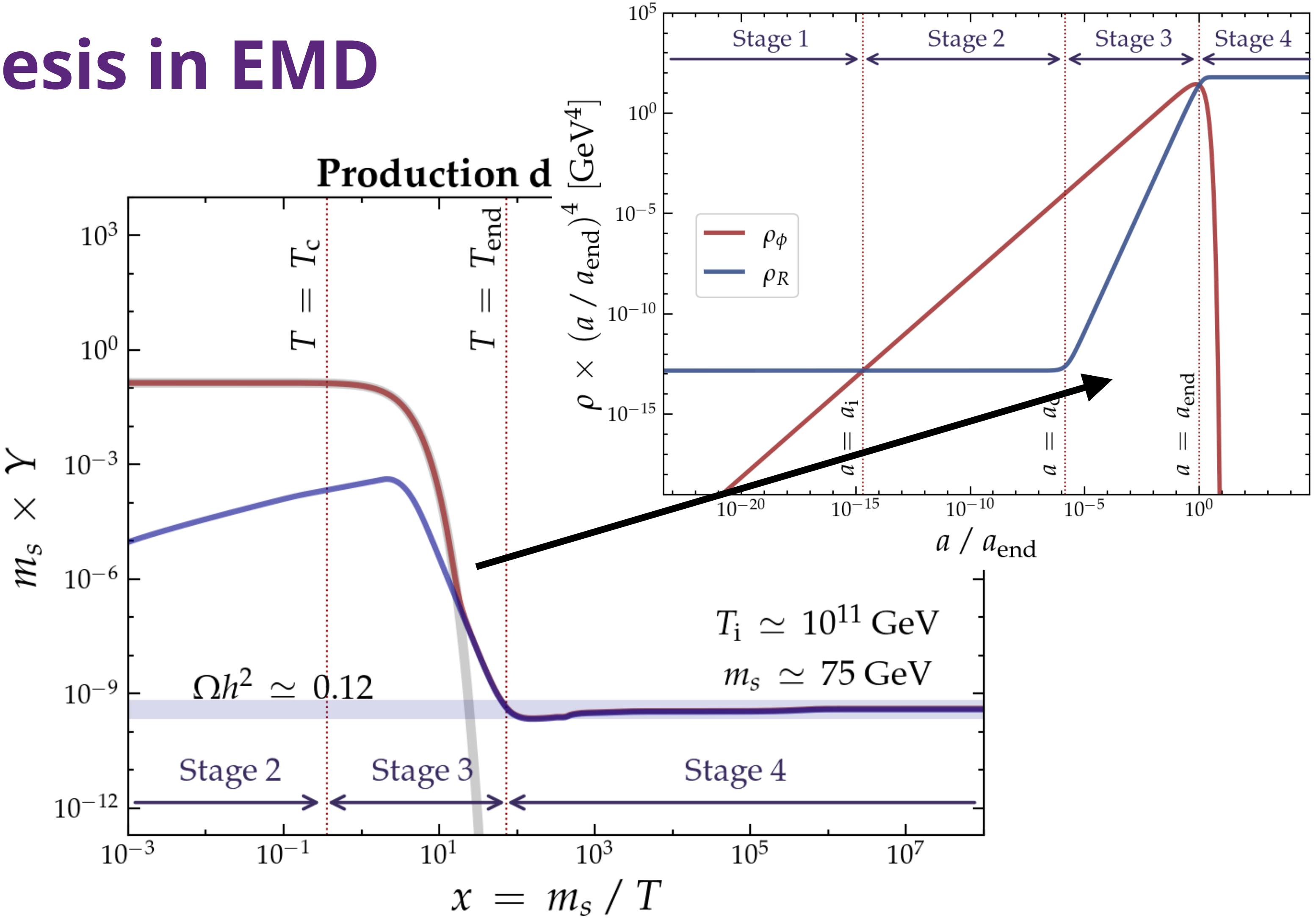
- The change in H slope must be offset by $\langle \sigma v \rangle$ $(\sim \lambda_{hs})$



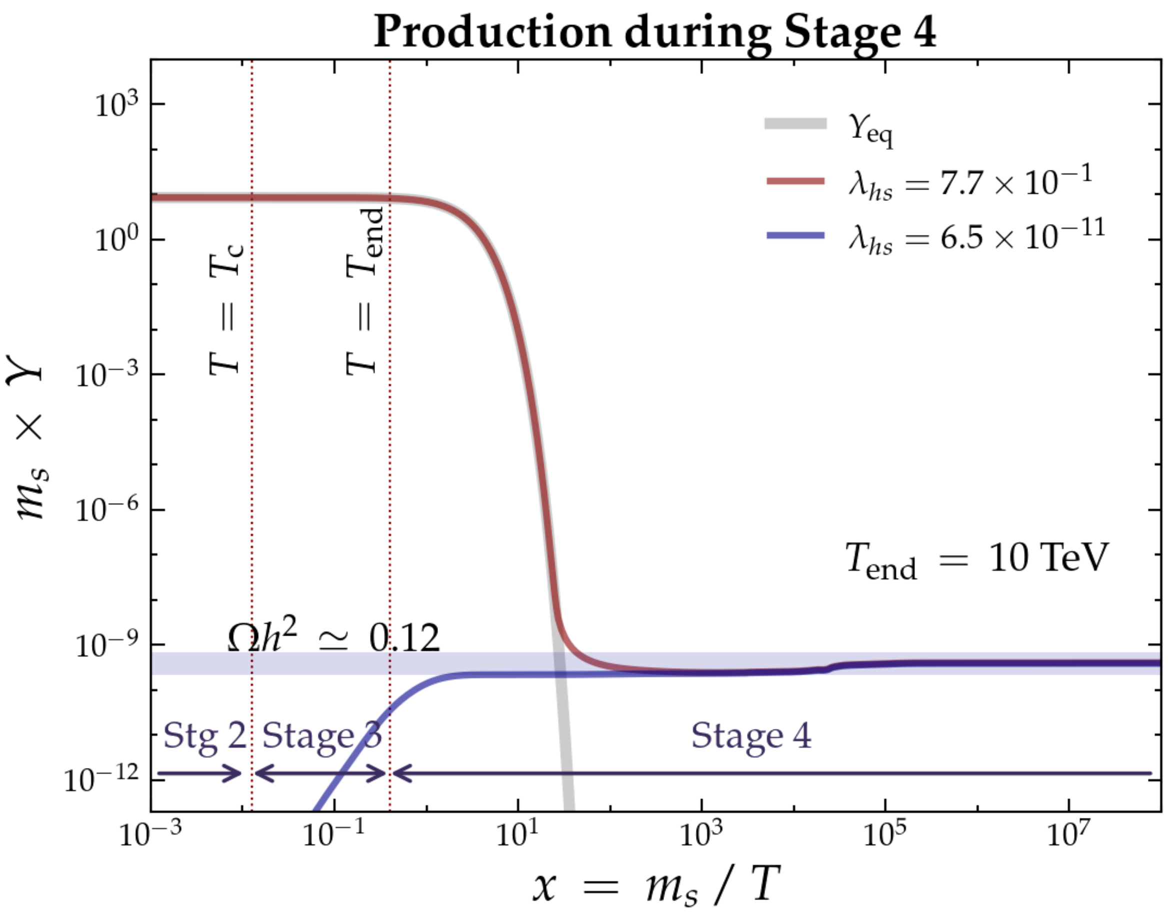
DM Genesis in EMD



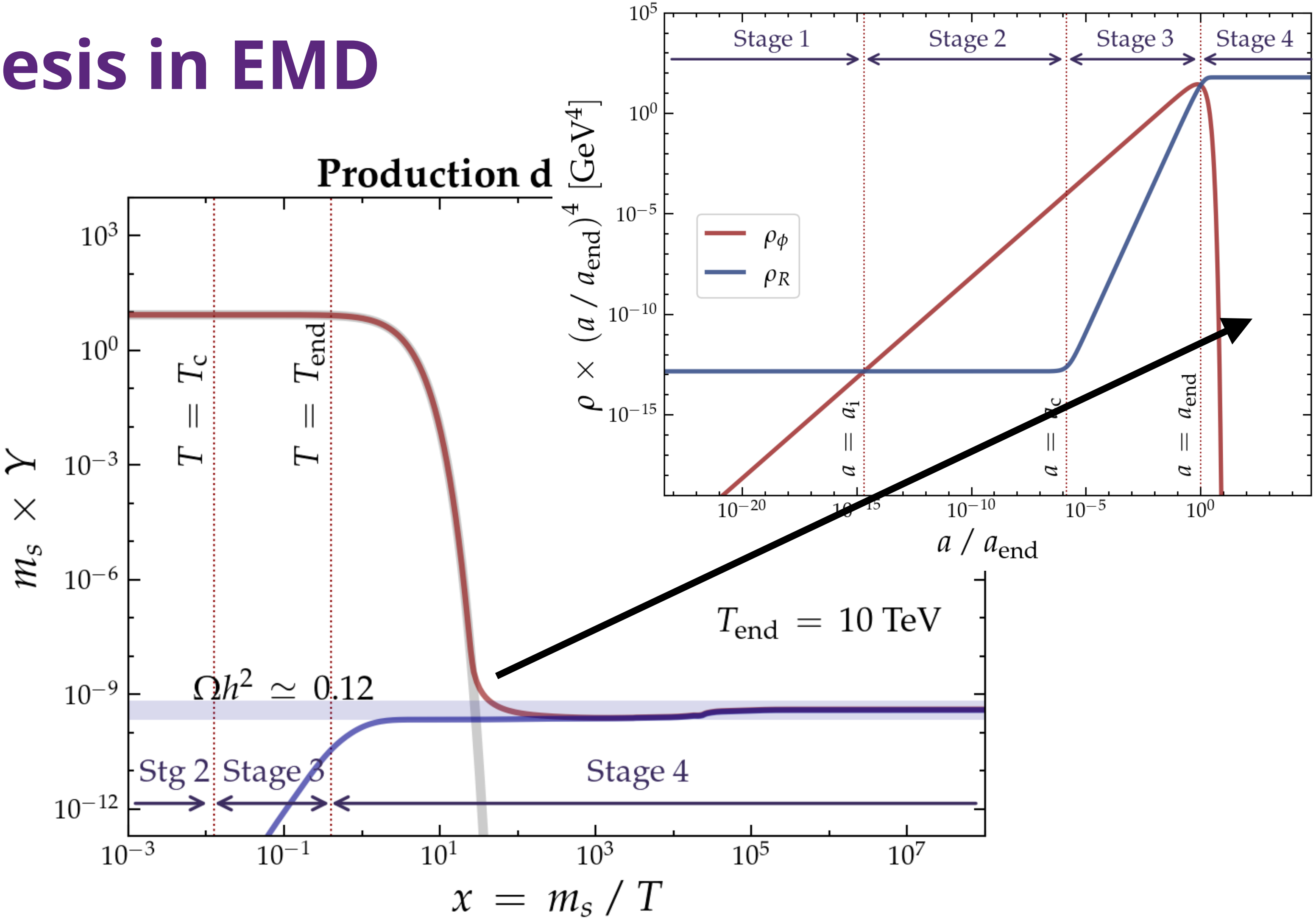
DM Genesis in EMD

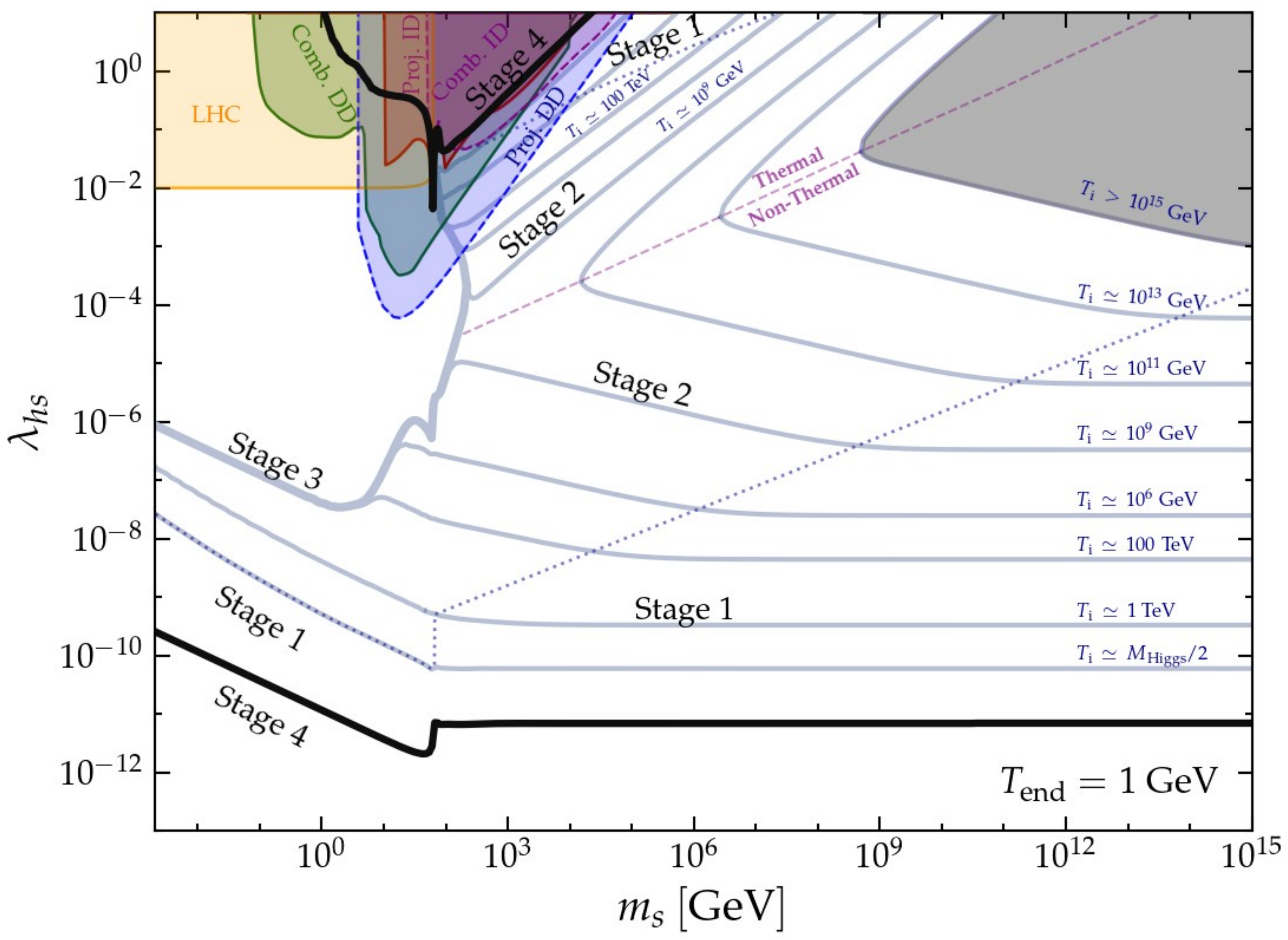


DM Genesis in EMD



DM Genesis in EMD





LHC
Comb. DD
Proj. ID
Comb. ID
Stage 4
Stage 1
Proj. DD
$T_i \simeq 100$ TeV
$T_i \simeq 10^9$ GeV
Stage 2
Thermal
Non-Thermal
$T_i > 10^{15}$ GeV
$T_i \simeq 10^{13}$ GeV
$T_i \simeq 10^{11}$ GeV
Stage 2
$T_i \simeq 10^9$ GeV
Stage 3
$T_i \simeq 10^6$ GeV
$T_i \simeq 100$ TeV
Stage 1
Stage 1
$T_i \simeq 1$ TeV
$T_i \simeq M_{\rm Higgs}/2$
Stage 4
$T_{\rm end} = 1$ GeV
λ_{hs}
m_s [GeV]

LHC

Invisible Higgs Decay (2202.07953).

Comb. DD

Xenon-nT SI (2303.14729), CDMS-Lite (1509.02448), EDELWEISS CRYOSEL (2211.04176), LZ SI (2207.03764).

Proj. DD

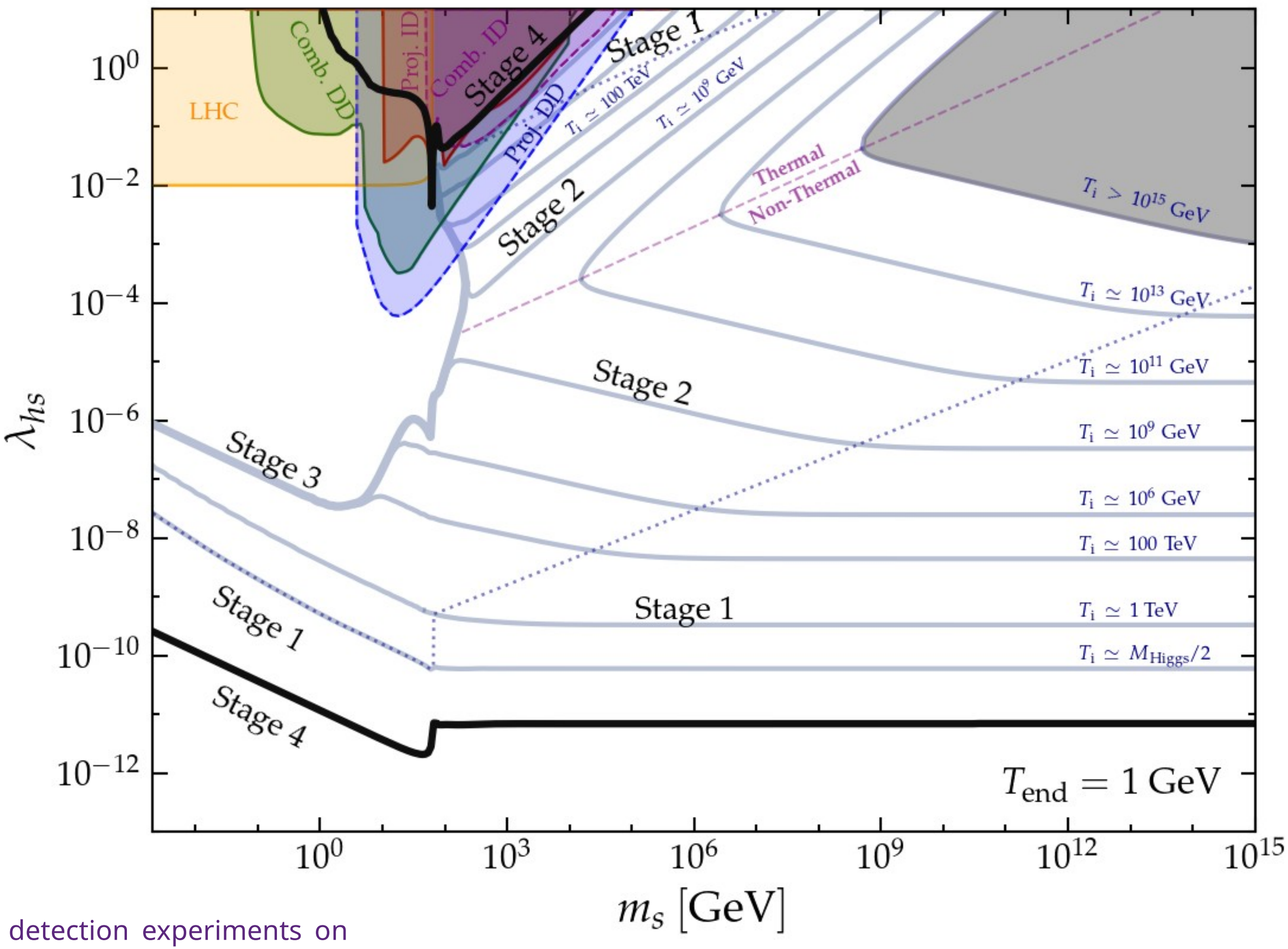
XLZD SI 18 Patras (2203.02309)

Comb. ID

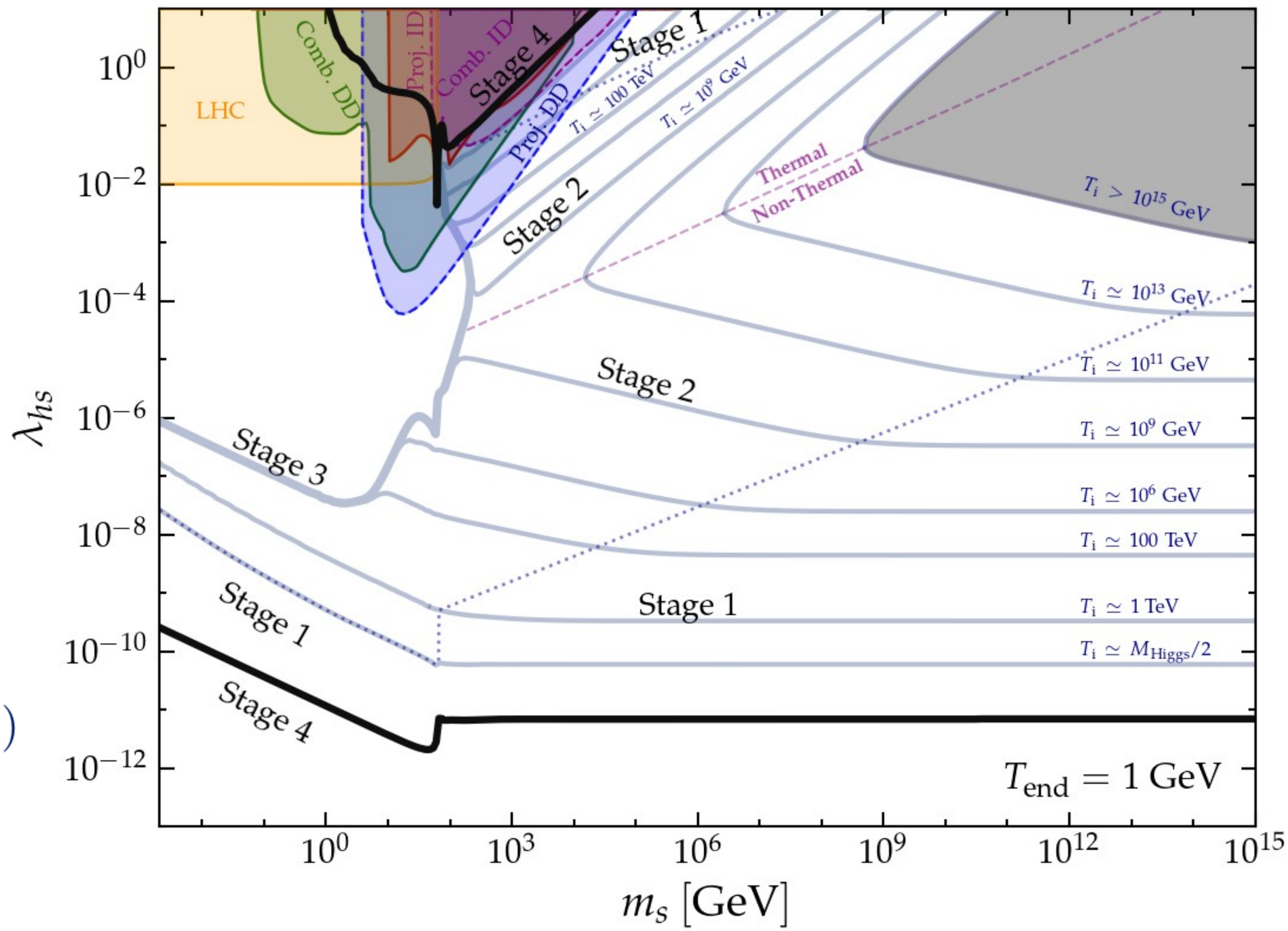
Kawasaki (2105.08334), HESS-GC (2207.10471), MAGIC+FERMI-LAT Dsph (1601.06590)

Proj. ID

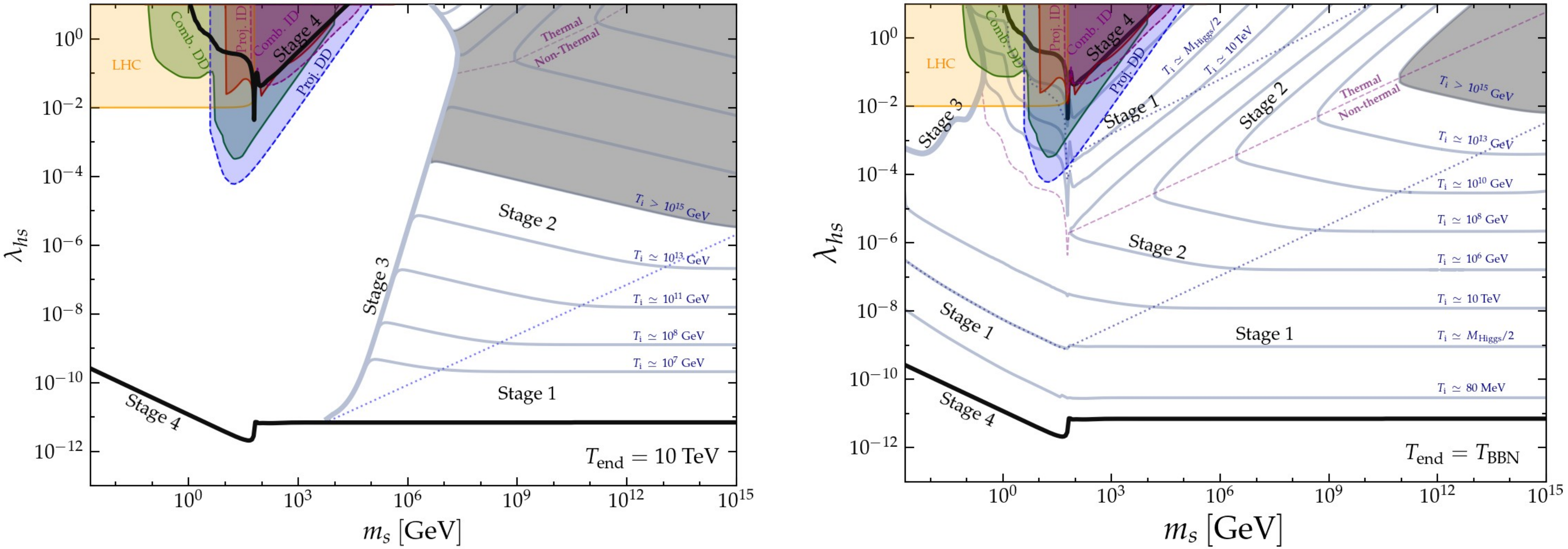
CTA-GC (1709.07997), SWGO-GC (ICRC2021)



The constraints of direct and indirect detection experiments on our parameter space is evaluated using micrOMEGAs.



- $T_{\rm fo} \sim m_s/25$.
- $T_{\rm fi} \sim M_H/2 \ (m_s \ll M_H/2)$
  $T_{\rm fi} \sim m_s \ (m_s \gg M_H/2)$


LHC
Comb. DD
Proj. ID
Comb. ID
Stage 4
Proj. DD
Thermal
Non-Thermal
Stage 2
Stage 3
Stage 1
Stage 4
$T_i > 10^{15}$ GeV
$T_i \simeq 10^{13}$ GeV
$T_i \simeq 10^{11}$ GeV
$T_i \simeq 10^{8}$ GeV
$T_i \simeq 10^{7}$ GeV
$T_{end} = 10$ TeV
λ_{hs}
m_s [GeV]
LHC
Comb. DD
Proj. ID
Comb. ID
Stage 4
Proj. DD
$T_i \simeq M_{Higgs}/2$
$T_i \simeq 10$ TeV
Stage 3
Stage 1
Stage 2
Thermal
Non-thermal
$T_i > 10^{15}$ GeV
$T_i \simeq 10^{13}$ GeV
$T_i \simeq 10^{10}$ GeV
$T_i \simeq 10^{8}$ GeV
$T_i \simeq 10^{6}$ GeV
$T_i \simeq 10$ TeV
$T_i \simeq M_{Higgs}/2$
$T_i \simeq 80$ MeV
Stage 2
Stage 1
Stage 1
Stage 4
$T_{end} = T_{BBN}$
λ_{hs}
m_s [GeV]

Conclusions

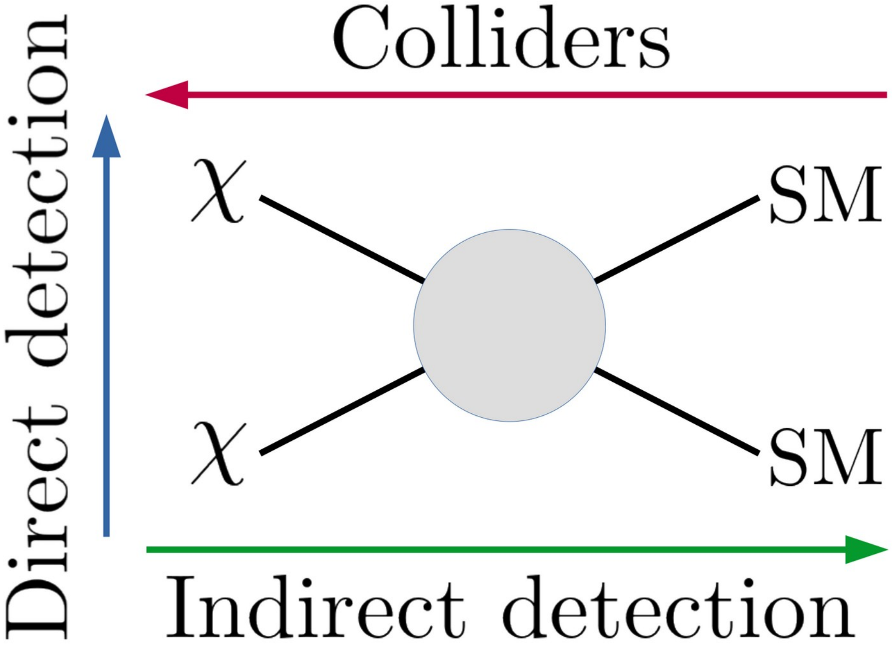
- Dark Matter exists.
- The nature of Dark Matter is still unknown.
- In this work, we focus on an alternative possibility in which DM is produced during EMD.
- The strong entropy injection caused by the ϕ field decay changes the DM genesis.
- We emphasize that although these results correspond to the *SSDM* model, the conclusions presented here are expected to be very generic.

Thanks

Back-up

Dark Matter Detection

Main methods for searching DM:



Dark Matter Detection: Colliders

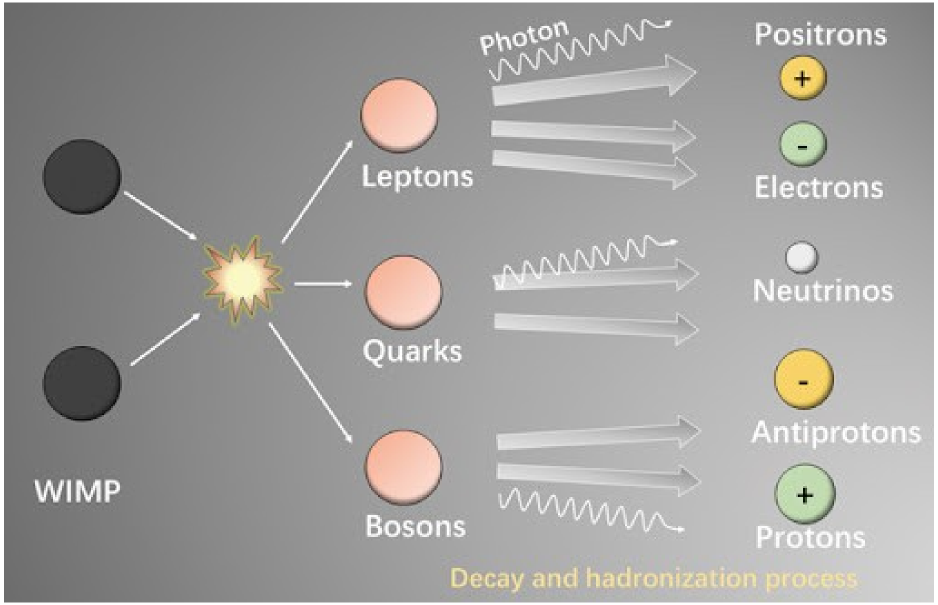
Produce DM imitating big-bang conditions.

If *SSDM* candidate $m_s < M_h / 2$, the decay $h \to s\, s$ is kinematically allowed and it contributes to its invisible decay. The partial width is given by

$$\Gamma_{h\to ss} = \frac{\lambda_{hs}^2}{8\pi} \frac{v_H^2}{m_h} \sqrt{1 - \left(\frac{2\, m_s}{m_h}\right)^2}$$

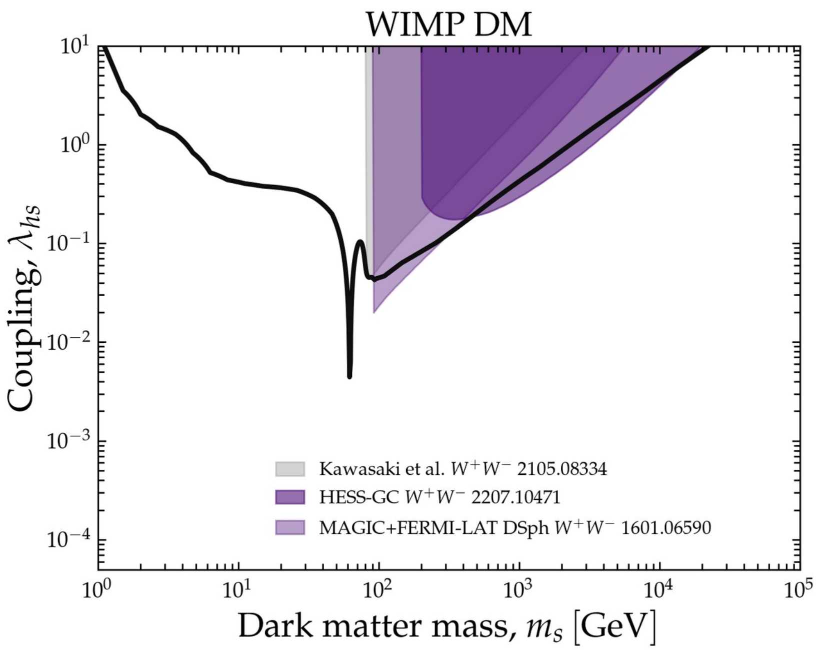
Dark Matter Detection: Indirect

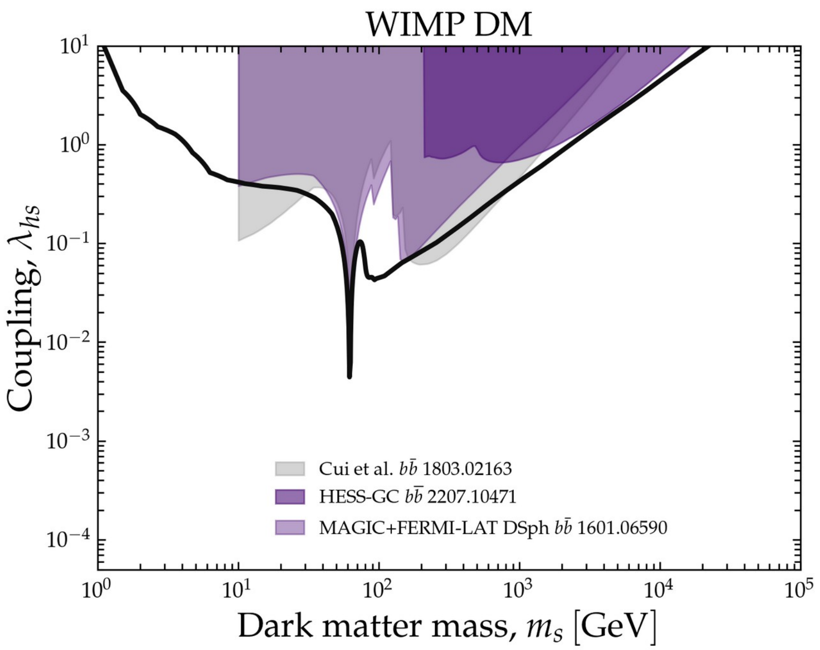
Observe products of DM annihilation (Gamma rays, SM particles/antiparticles).



GAO Linqing and LIN Sujie

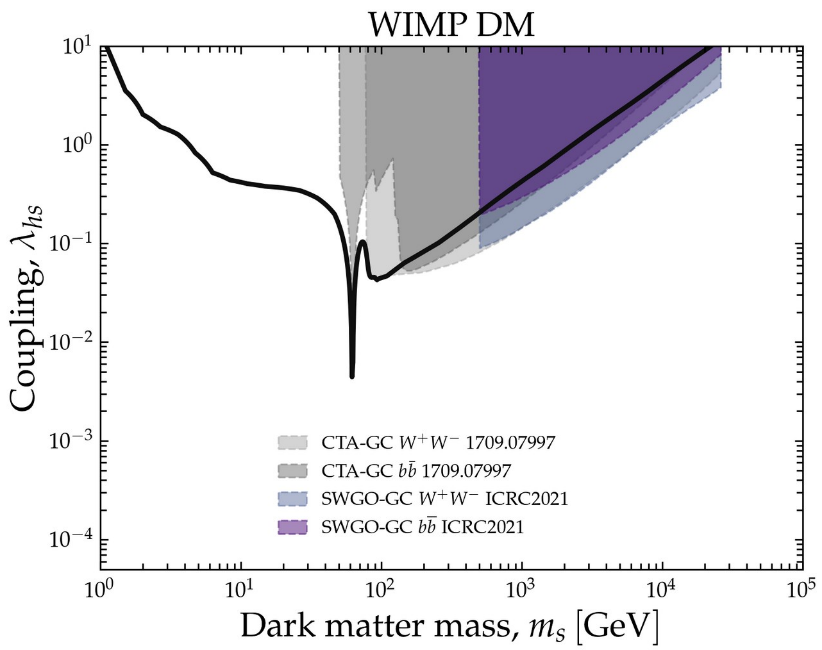
Dark Matter Detection: Indirect





ID experiments bounds for SSDM candidate

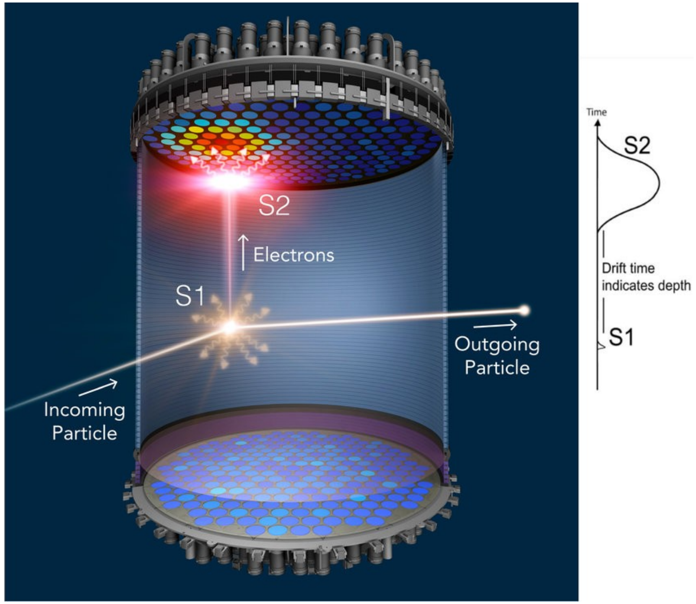
Dark Matter Detection: Indirect



ID experiments Projection

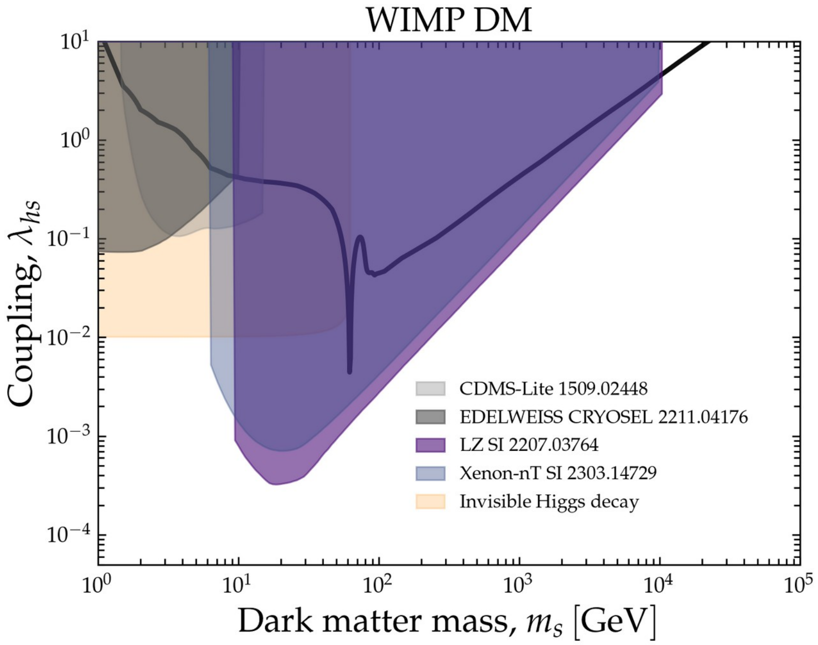
Dark Matter Detection: Direct

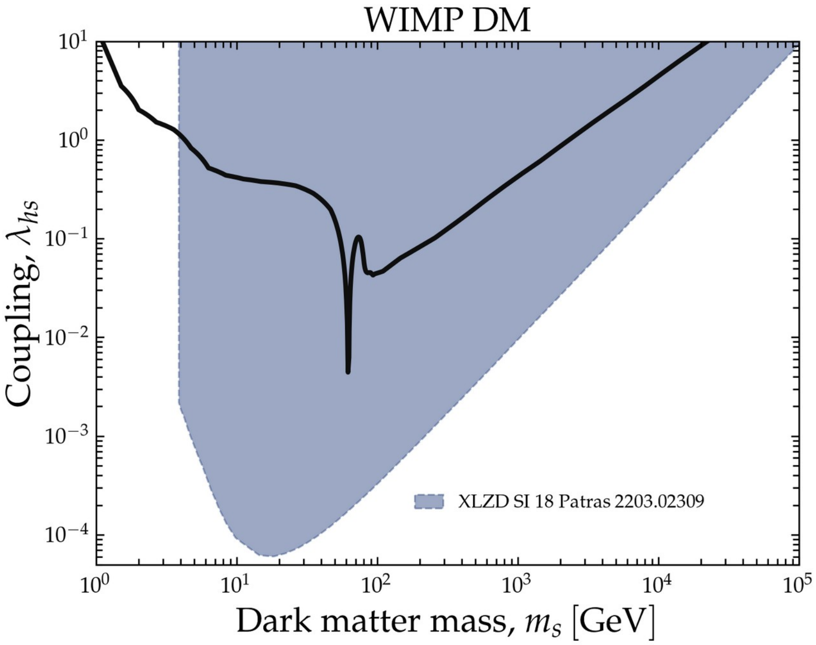
- DM should have small, but non-zero interaction with ordinary matter.
- Observe low-energy recoils of nuclei following interactions with DM.
- Operate detectors deep underground to keep cosmic backgrounds low.



Kudryavtsev, V.A., et al. Recent Results and Future Prospects for Dark Matter Searches with LZ. Universe 2019, 5, 73. https://doi.org/10.3390/universe5030073

Dark Matter Detection: Direct





DD experiments, projection (left, right) bounds for *SSDM* candidate