Temperature Evolution in the Early Universe and Freeze-in at stronger coupling

Catarina M. Cosme

in collaboration with
Francesco Costa and Oleg Lebedev

arXiv:2306.13061, arXiv:2402.04743

FLASY 2025, Dipartimento di Architettura Roma Tre, Roma, 1 July 2025

1290 UNIVERSIDADE D COIMBRA

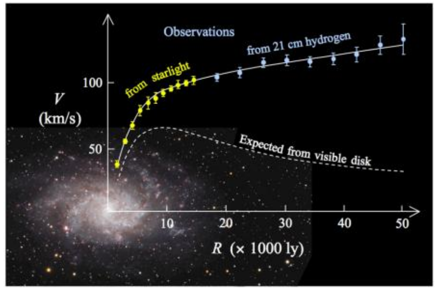
CFisUC

fct Fundação para a Ciência e a Tecnologia

REPÚBLICA PORTUGUESA

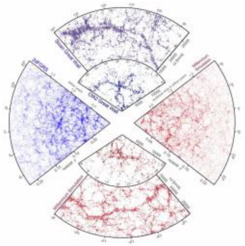
Introduction - Dark Matter (DM)

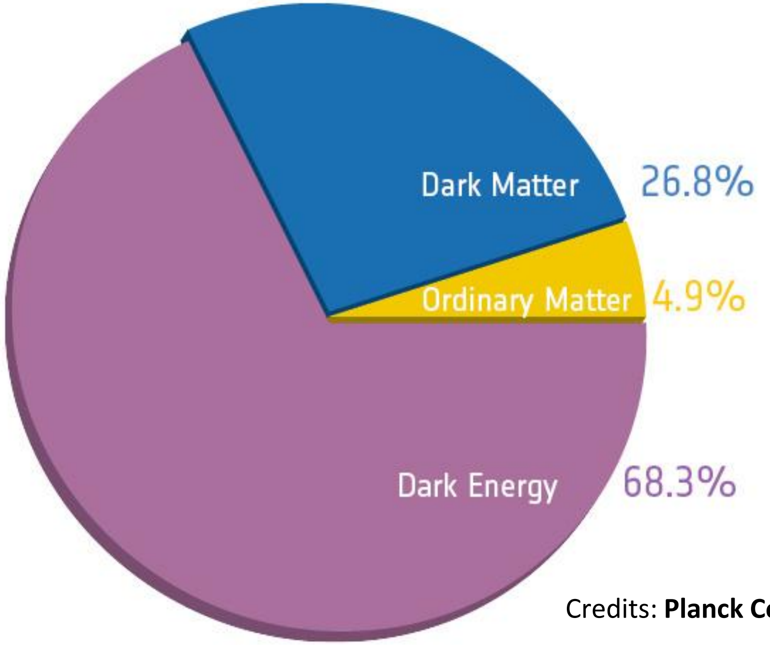
Galaxy Rotation Curves



Merging clusters (Bullet Cluster)

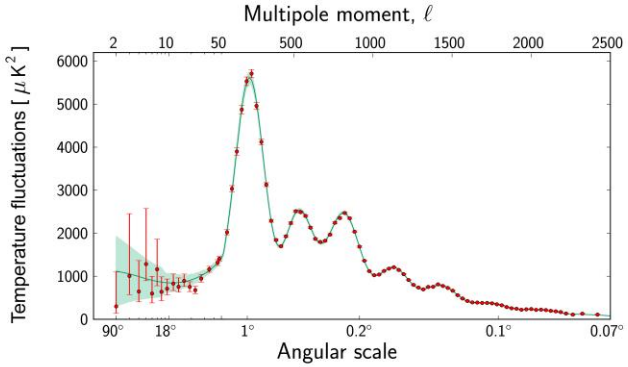
Structure formation



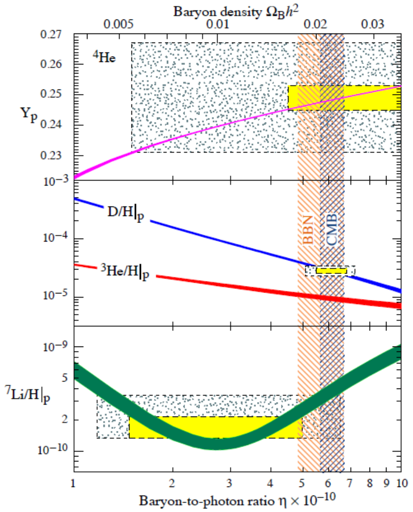


Credits: **Planck Collab.**

Cosmic Microwave Background (CMB)



Big Bang Nucleosynthesis (BBN)



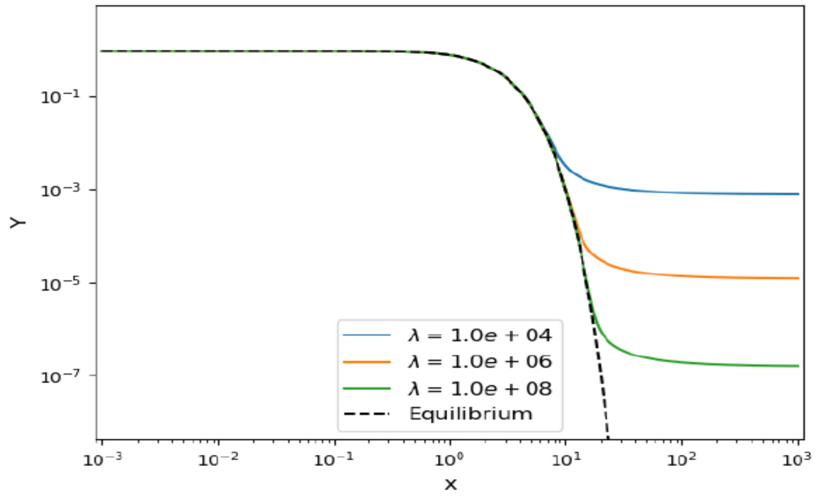
Properties of a DM candidate

- Stable or very long-lived (lifetime ≥ age of the Universe);
- Cold (non-relativistic);
- Very small interaction with the electromagnetic field;
- It must have the observed abundance.

Introduction - Dark Matter production mechanisms

Freeze-out

$$X\overline{X} \leftrightarrow SM$$



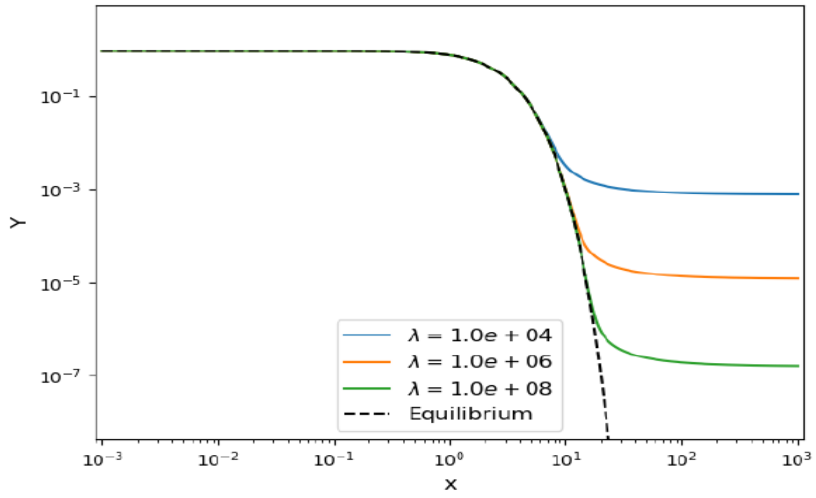
- Interactions **freeze-out** when: $\Gamma_X = n_X \langle \sigma v \rangle \lesssim H$;
- **WIMPs** – Weakly Interacting Massive Particles;
- $\Omega_{X,0} h^2 \sim \frac{1}{\lambda}$;
- But: **no detection** so far; large parameter space **very constrained by experiments.** [Arcadi et al. arXiv:2403.15860]

Introduction - Dark Matter production mechanisms

Freeze-out

vs

$$X\overline{X} \leftrightarrow SM$$



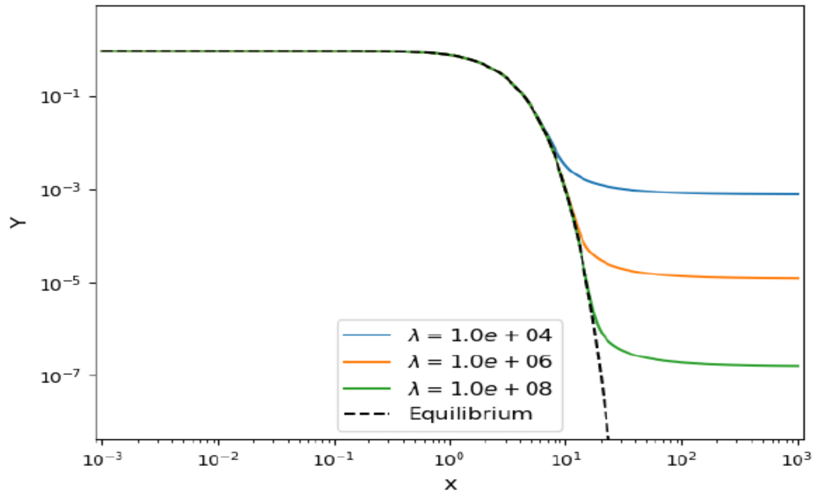
- Interactions **freeze-out** when: $\Gamma_X = n_X \langle \sigma v \rangle \lesssim H$;
- **WIMPs** – Weakly Interacting Massive Particles;
- $\Omega_{X,0} h^2 \sim \frac{1}{\lambda}$;
- But: **no detection** so far; large parameter space **very constrained by experiments.** [Arcadi et al. arXiv:2403.15860]

$$X\overline{X} \leftrightarrow SM$$

Introduction - Dark Matter production mechanisms

Freeze-out

$$X\overline{X} \leftrightarrow SM$$



- Interactions **freeze-out** when: $\Gamma_X = n_X \langle \sigma v \rangle \lesssim H$;
- **WIMPs** – Weakly Interacting Massive Particles;
- $\Omega_{X,0} h^2 \sim \frac{1}{\lambda}$;
- But: **no detection** so far; large parameter space **very constrained by experiments.** [Arcadi et al. arXiv:2403.15860]

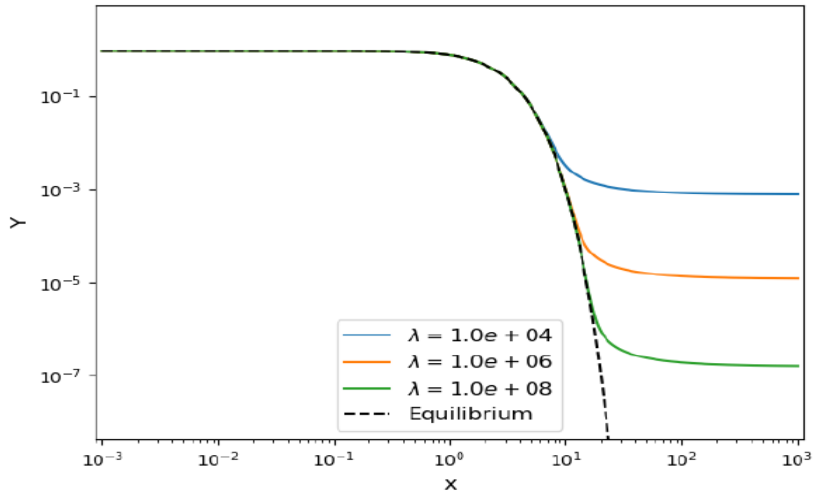
vs

$$\cancel{X\overline{X} \leftrightarrow SM}$$

Introduction - Dark Matter production mechanisms

Freeze-out

$$X\bar{X} \leftrightarrow SM$$



- Interactions **freeze-out** when: $\Gamma_X = n_X \langle \sigma v \rangle \lesssim H$;
- **WIMPs** – Weakly Interacting Massive Particles;
- $\Omega_{X,0} h^2 \sim \frac{1}{\lambda}$;
- But: **no detection** so far; large parameter space **very constrained by experiments.** [Arcadi et al. arXiv:2403.15860]

vs

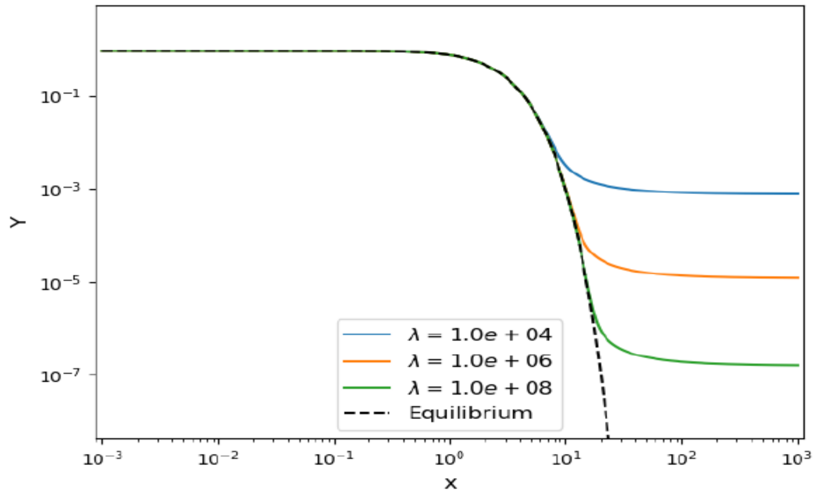
Freeze-in

$$\cancel{X\bar{X} \leftrightarrow SM}$$

Introduction - Dark Matter production mechanisms

Freeze-out

$X\overline{X} \leftrightarrow SM$

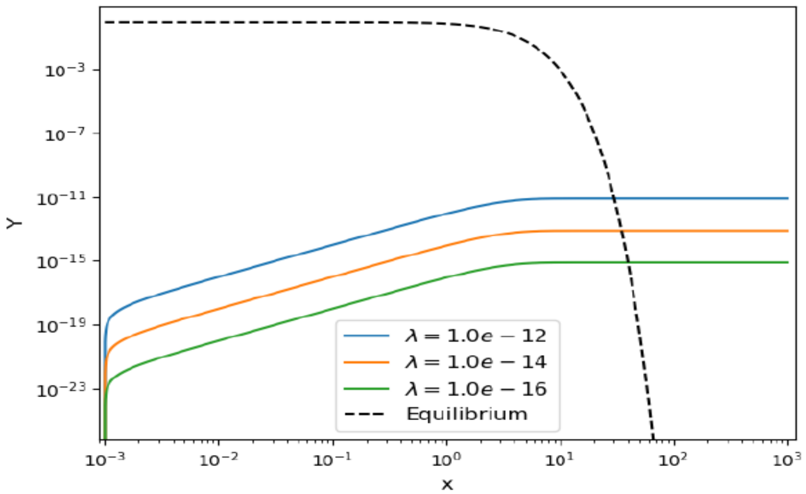


- Interactions **freeze-out** when: $\Gamma_X = n_X\langle\sigma v\rangle \lesssim H$;
- **WIMPs** – Weakly Interacting Massive Particles;
- $\Omega_{X,0}h^2 \sim \frac{1}{\lambda}$;
- But: **no detection** so far; large parameter space **very constrained by experiments.** [Arcadi et al. arXiv:2403.15860]

vs

Freeze-in

$X\overline{X} \leftrightarrow SM$



- $\Gamma_X < H$ **always**;
- **FIMPs** – Feebly Interacting Massive Particles;
- $\Omega_{X,0}h^2 \sim \lambda$; **Small couplings** to attain the **observed relic abundance**;
- Can evade stringent observational constraints; But: **hard to probe.**

Introduction - Dark Matter production mechanisms

Freeze-in mechanism challenges:

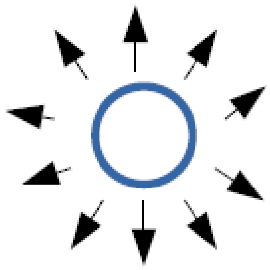
1 – **Small** couplings (hard to probe);

2 – Assumes **zero** (or negligible) **initial dark matter** abundance;

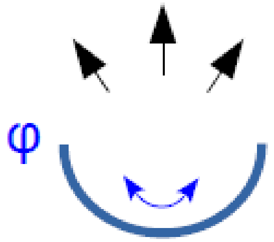
How can we probe FIMPs?

Particle Production Background

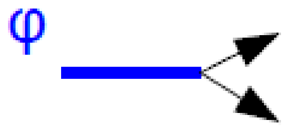
Feeble coupled particles can be copiously **produced during** and **after inflation** (all add up):



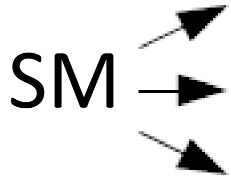
Scalar fluctuations



Inflaton oscillations



Inflaton decay

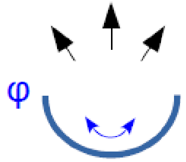


Freeze-in

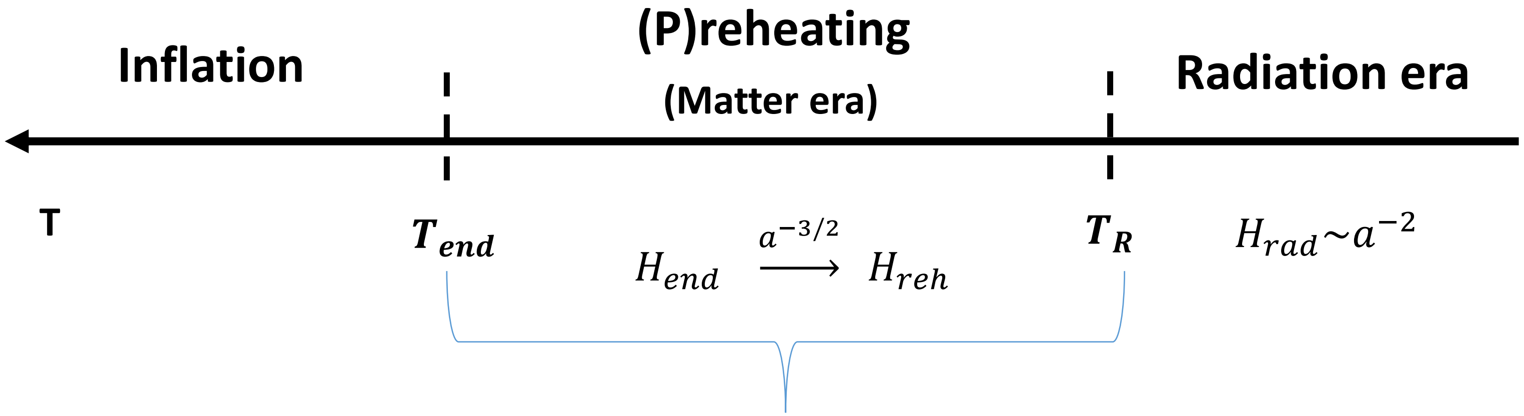
- Very small (**feeble**) couplings to other particles $\Rightarrow$ **No thermal equilibrium**;
- Even if there are **no couplings** to other fields, **gravitational** particle **production** is still **on**!

The model – Freeze-in at stronger coupling

How do we get rid of the excess of dark relics?



inflaton, φ, oscillating in a quadratic potential, $\frac{1}{2}m_\varphi^2\varphi^2$, **behaves** like **matter**



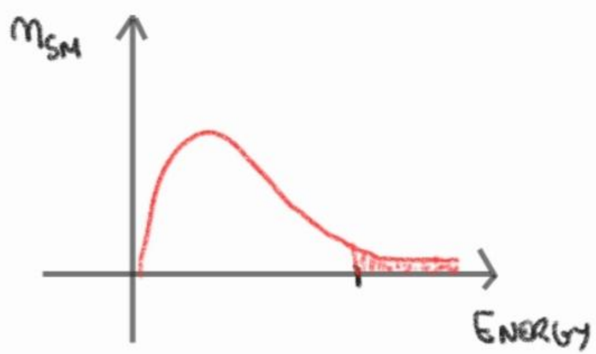
Dilution of the relics: $\Delta_{NR} \equiv \left(\frac{H_{end}}{H_{reh}}\right)^{1/2} > 1$ ⇒ **lower reheating** temperature, T_R

The model – Freeze-in at stronger coupling

- Our model: **DM freeze-in** production, in the range $\boldsymbol{T_R < m_{DM}}$

If $\boldsymbol{T_R < m_{DM}}$:

Only particles at the **Boltzmann tail**, $E/T \gg 1$, have **energy to produce DM**



Boltzmann-suppressed DM production requires a **stronger coupling**

Observable!

The model – Scalar DM Higgs portal

Real scalar dark matter **s** through the **Higgs portal**

$$\boxed{V(s) = \frac{1}{2}\,\lambda_{hs}\,s^2\,H^\dagger H + \frac{1}{2}\,m_s^2 s^2}$$

$\boldsymbol{T_R < m_s}$

DM number density, **n**:

$$\boxed{\dot{n} + 3Hn = \Gamma(h_i h_i \to ss) - \Gamma(ss \to h_i h_i)}$$

$$\Gamma(ss \to h_i h_i) = \langle \sigma(ss \to h_i h_i) v_r \rangle n^2$$

The model – Annihilation DM effect inefficient

$$\dot{n} + 3Hn = \Gamma(h_i h_i \to ss) - \cancel{\Gamma(ss \to h_i h_i)}$$

Solve the Boltzmann equation:

$$\frac{n}{T^3} = \int_{T_R}^{0} -\frac{\Gamma(h_i h_i \to ss)}{HT^4}\, dT$$

$$\Gamma\,(h_i h_i \to ss) \simeq \frac{\lambda_{hs}^2\, T^3\, m_s}{2^7\, \pi^4}\, e^{-2m_s/T}$$

$$Y_{DM} \equiv \frac{n}{s} = \frac{\sqrt{90}\; 45}{2^9\, \pi^7 g_*^{3/2}} \frac{\lambda_{hs}^2 M_{Pl}}{T_R} e^{-2m_s/T_R}$$

$$\lambda_{hs} \simeq 3 \times 10^{-11} e^{m_s/T_R} \sqrt{\frac{T_R}{m_s}}$$

$$Y_{obs} = 4.4 \times 10^{-10} \left(\frac{GeV}{m_s}\right)$$

Freeze-in case

The model – Thermalization requirement

Real scalar dark matter **s** through the **Higgs portal**

$$V(s) = \frac{1}{2}\,\lambda_{hs}\,s^2\,H^\dagger H + \frac{1}{2}\,m_s^2 s^2$$

DM number density, **n**:

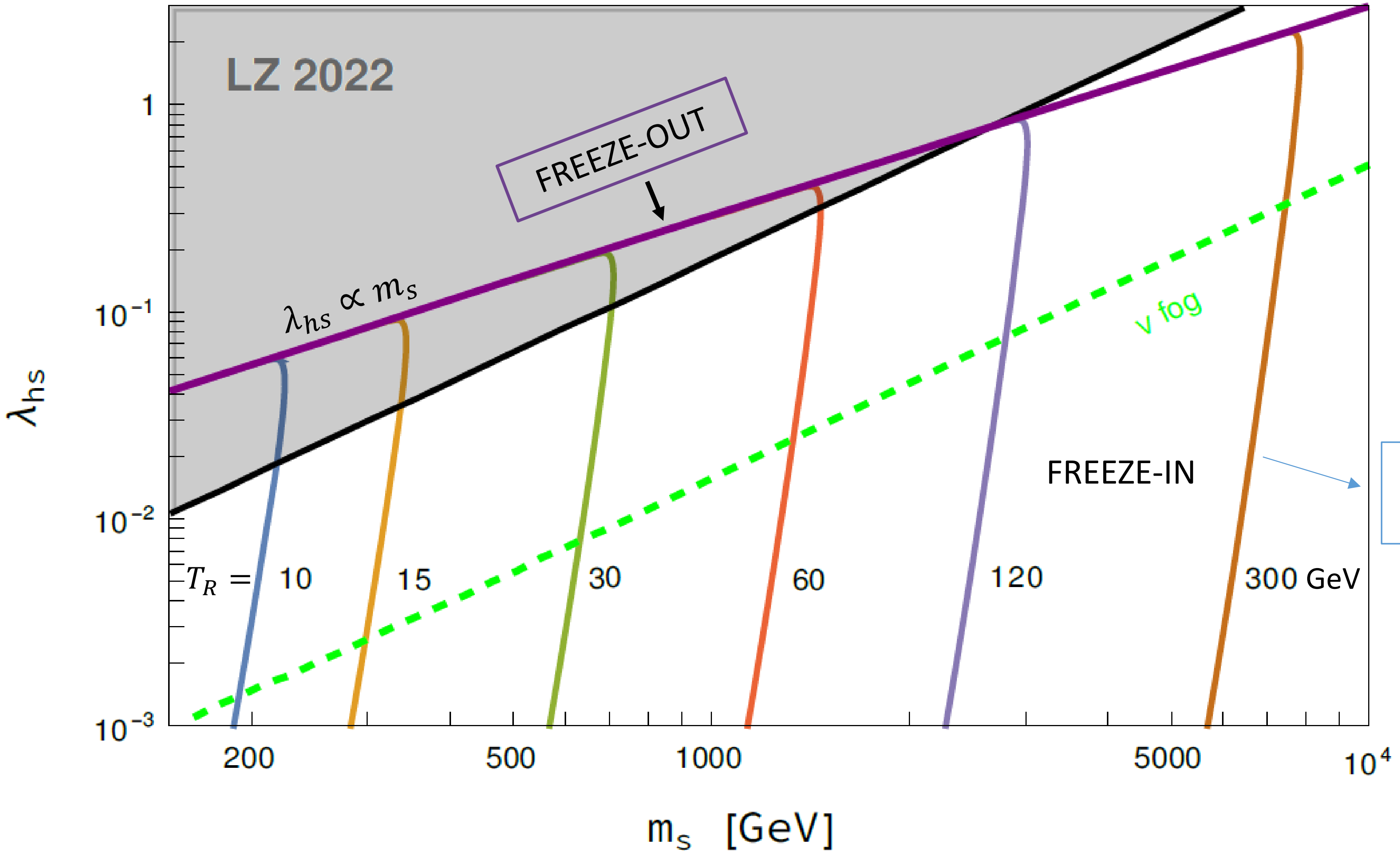
$$\dot{n} + 3Hn = \Gamma(h_i h_i \to ss) - \Gamma(ss \to h_i h_i)$$

Only **thermalizes** if

$$\Gamma(h_i h_i \to ss) = \Gamma(ss \to h_i h_i)$$

Freeze-out case

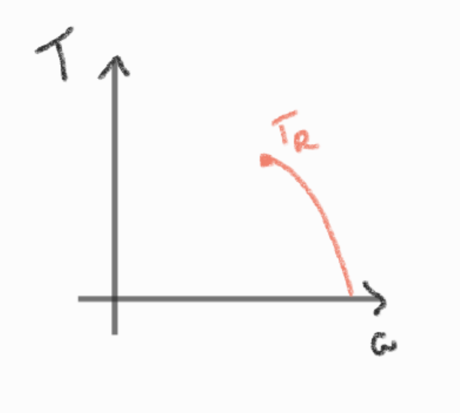
Phenomenology – Direct detection prospects



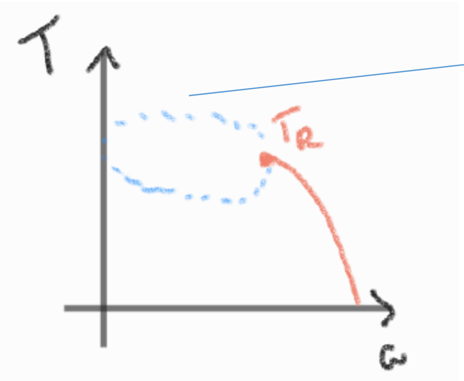
$$\lambda_{hs} \simeq 3 \times 10^{-11} e^{m_s/T_R} \sqrt{\frac{T_R}{m_s}}$$

What if reheating is not instantaneous?

So far, we are considering that most of **DM** is **produced** at T_R:



but



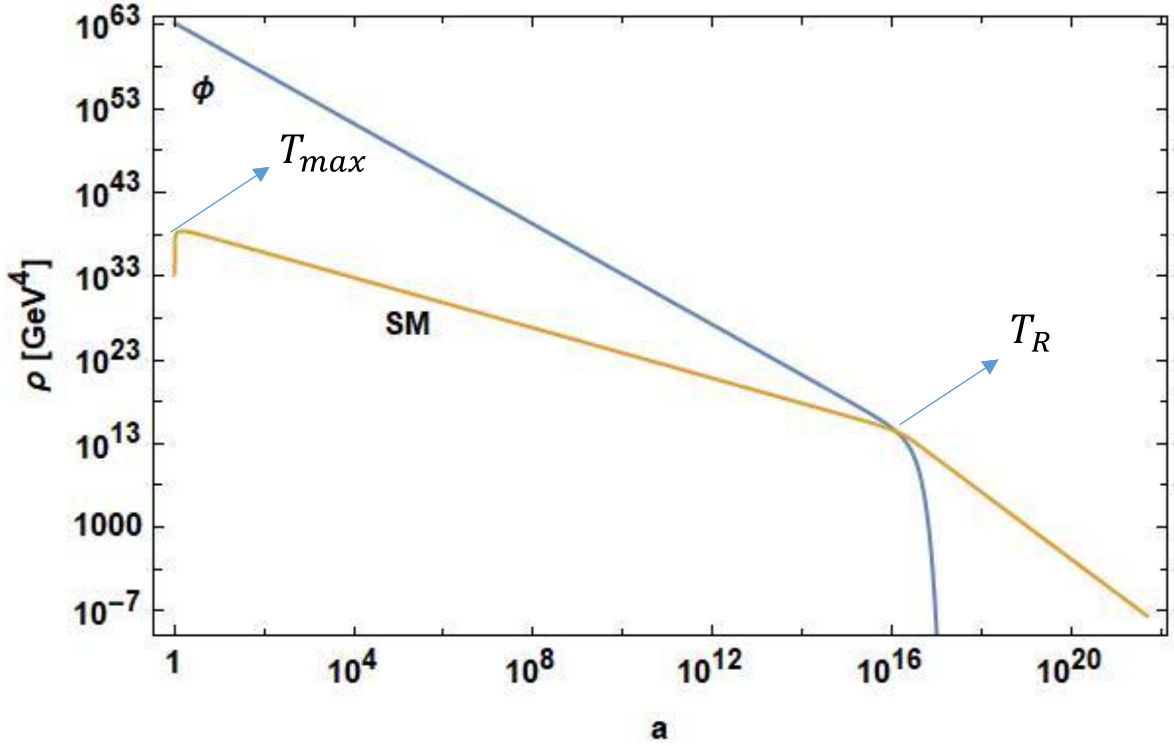
Assumption: in [CC, Costa, Lebedev, 2306.13061], **preexisting DM** abundance can be **neglected**

Is this an **adequate** assumption?

[CC, Costa, Lebedev, 2402.04743] → **Evolution** of the **SM temperature** and its consequences for **freeze-in at stronger coupling**

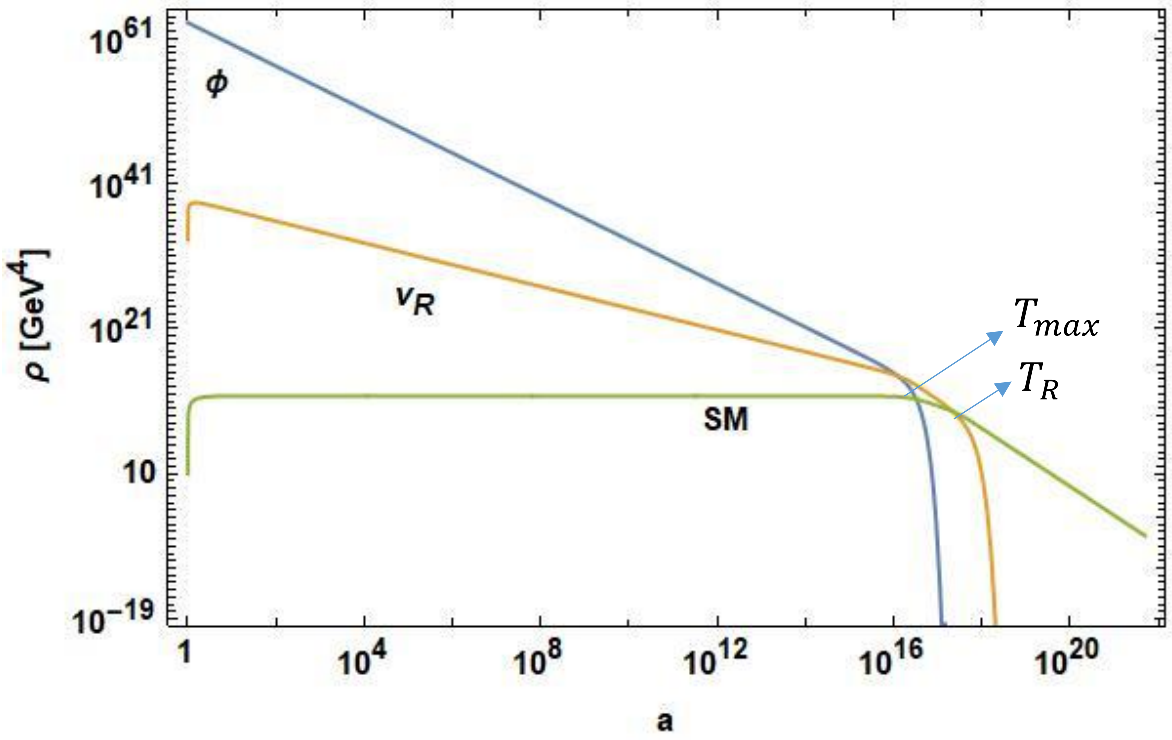
T_{max} and T_R

$\varphi \to SM$



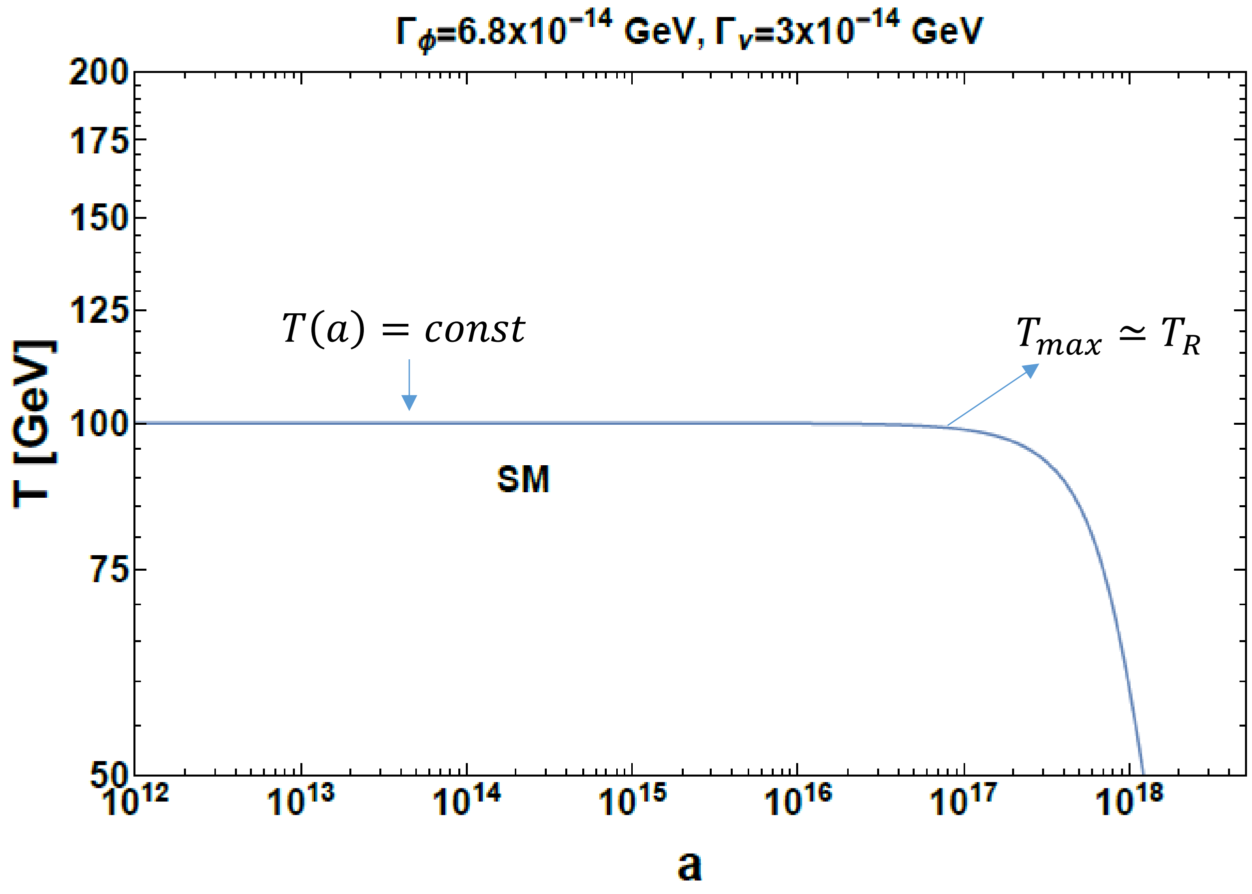
$T_{max} \gg T_R$

$\varphi \to \upsilon_R \to SM$



$T_{max} \simeq T_R$

DM abundance



Total DM particle number

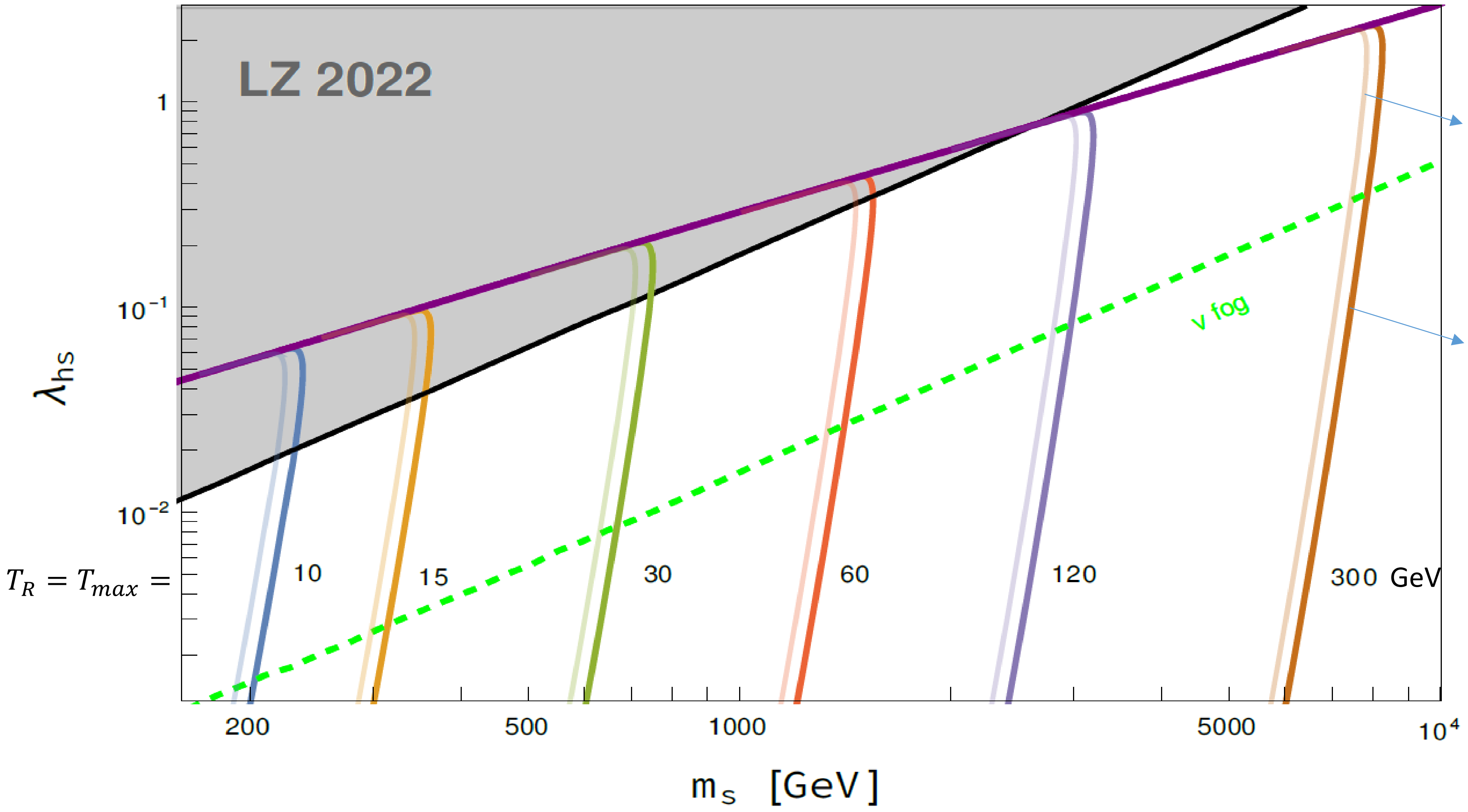
$$a^3 n\Big|_{total} = a_{max}^3 n(a_{max})\Big|_{T=const}\left(1 + (m+3)\frac{T_{max}}{2m_s}\right)$$

DM yield

$$Y_{new} \simeq Y_{old}(T_{max})\frac{m_s}{T_{max}}$$

in which $T_R \to T_{max}$

Phenomenology – Direct detection prospects



$$\lambda_{hs} \simeq 3 \times 10^{-11} e^{m_s/T_R} \sqrt{\frac{T_R}{m_s}}$$

[CC, Costa, Lebedev, 2306.13061]

$$\lambda_{hs} \simeq 10^{-11} e^{m_s/T_R} \left(\frac{T_R}{m_s}\right)$$

[CC, Costa, Lebedev, 2402.04743]

For fixed T_R, m_s increases by about 5%

Conclusions

- **DM** can be **produced abundantly** via **gravity** in the early Universe;
- An **early matter** era leads to a **lower** reheating temperature ($\boldsymbol{T_R}$) and can **dilute DM** produced gravitationally;
- We have studied the **Higgs portal DM**, with DM being produced via **freeze-in**;
- If $\boldsymbol{m_{DM} > T_R}$, freeze-in requires a **significant coupling**;
- This model **can already be tested** by **direct detection** experiments like LZ 2022; Further probes by XENONnT, DARWIN.
- Future work: **neutrino portal**.

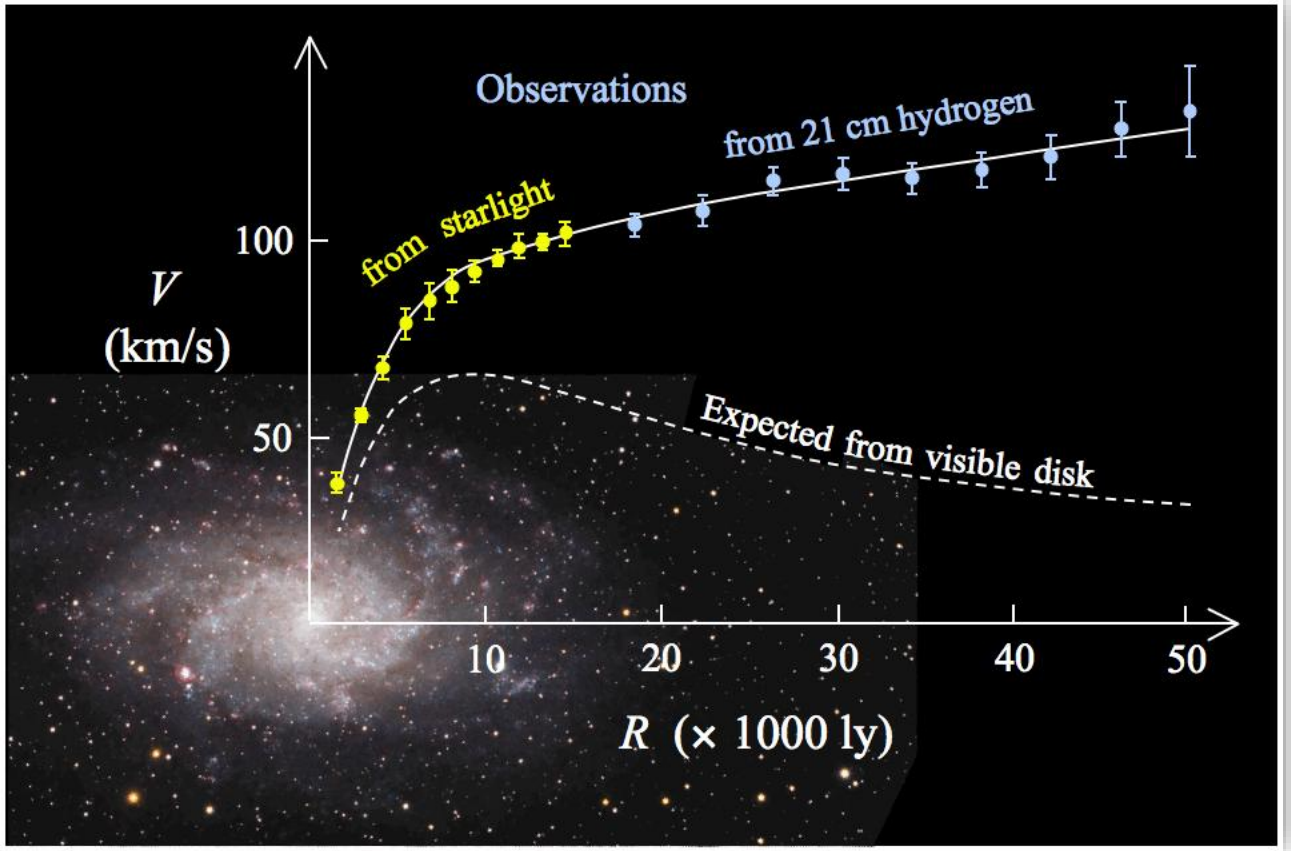
Thank you for your attention! / Grazie per l'attenzione!

Backup slides

Introduction – Why do we think that dark matter exists?

- **Evidence** for dark matter (DM) come from different sources:

Galaxy Rotation curves

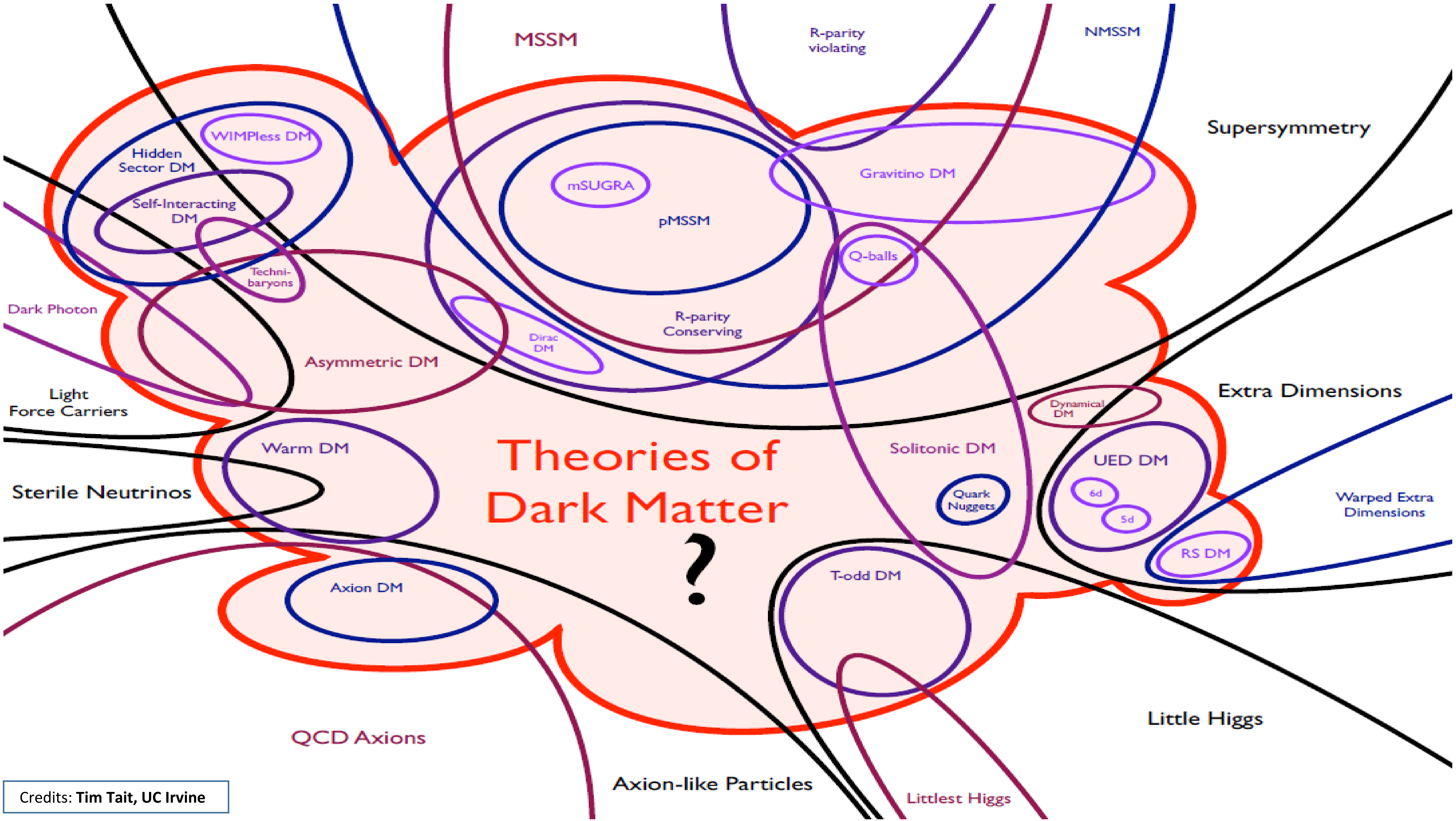


Credits: **Mark Whittle, University of Virginia**

$$m\frac{v(r)^2}{r} = \frac{GmM(r)}{r^2}$$

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

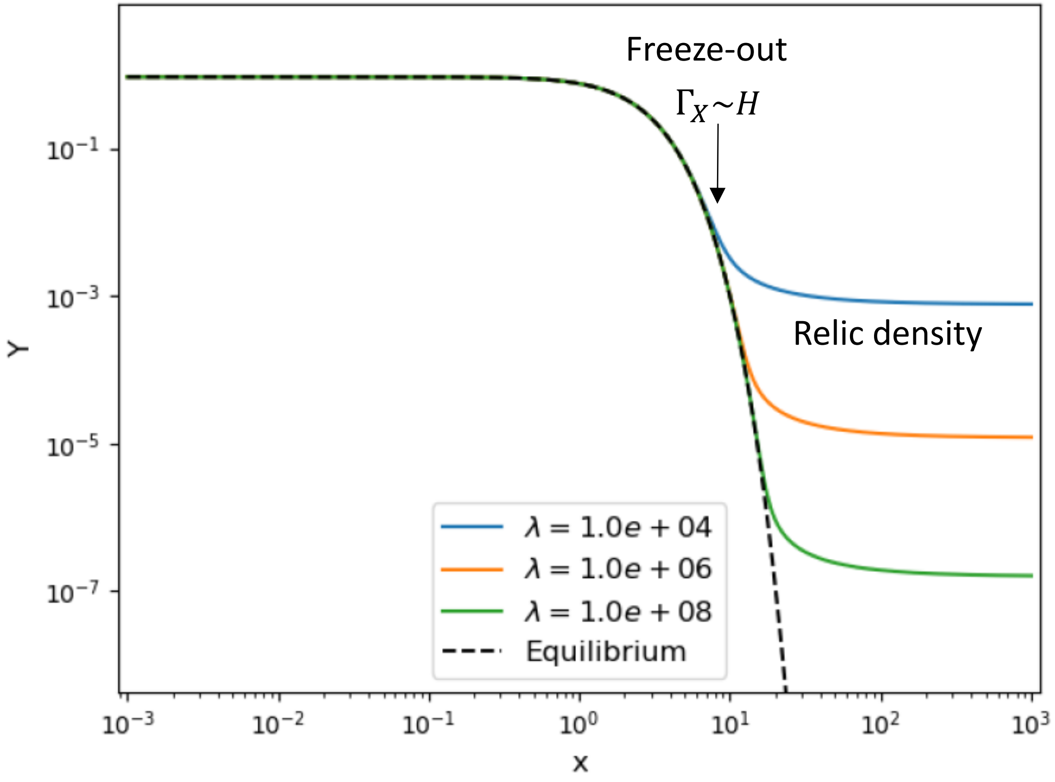
Since $v(r)$ seems to be constant in the halo, this means that $M(r) \sim r$.



Credits: **Tim Tait, UC Irvine**

Introduction - Dark Matter production mechanisms

Freeze-out mechanism (Weakly Interacting Massive Particles – WIMPs)



$$Y \equiv \frac{n_X}{s}, \quad x \equiv \frac{m}{T}$$

$$X\bar{X} \leftrightarrow SM$$

Dark Matter (DM) **evolution**:

$$\frac{dn_X}{dt} + 3Hn_X = -\langle\sigma v\rangle\left(n_X^2 - \left(n_X^{eq}\right)^2\right)$$

Interactions **freeze-out** when:

$$\Gamma_X = n_X\langle\sigma v\rangle \lesssim H$$

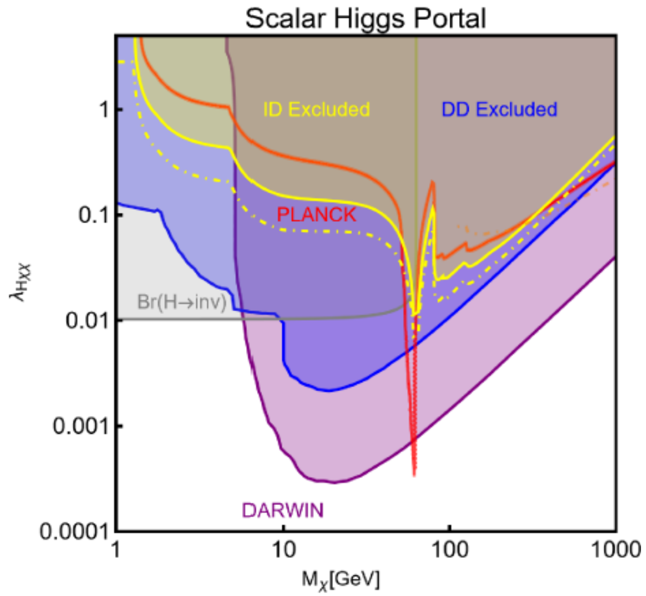
Present DM **abundance**:

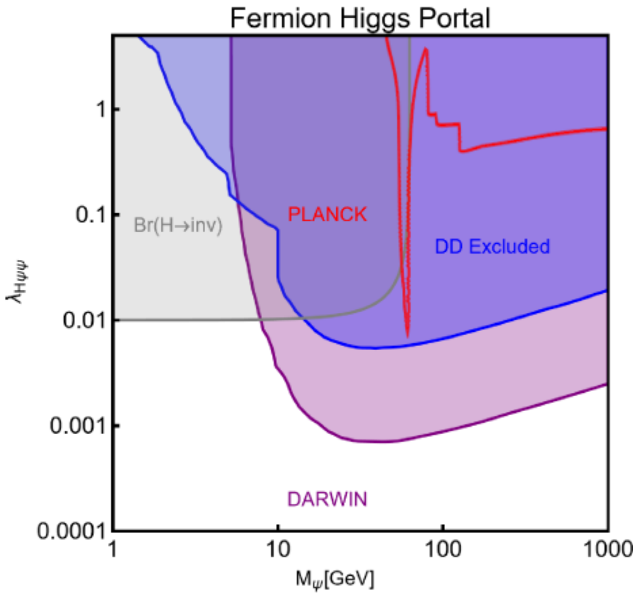
$$\Omega_{X,0}h^2 \equiv \frac{\rho_{X,0}}{\rho_{c,0}/h^2} \sim \frac{1}{\langle\sigma v\rangle} \sim \frac{1}{\lambda}$$

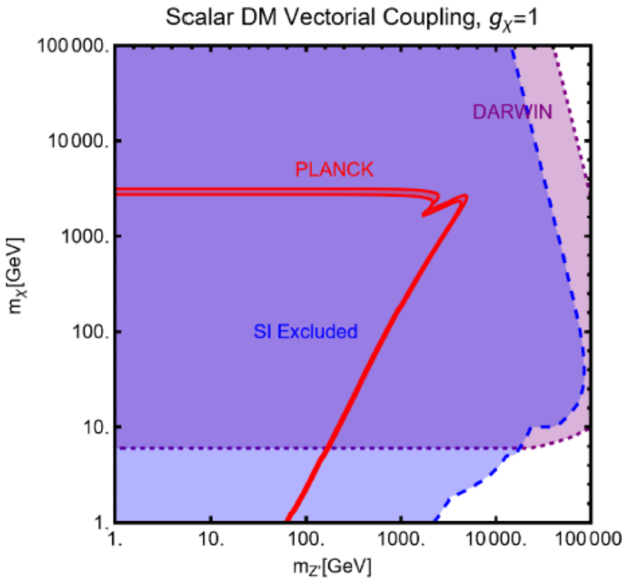
Introduction - Dark Matter production mechanisms

Freeze-out mechanism

- **WIMPs –** no detection so far; very constrained by experiments.



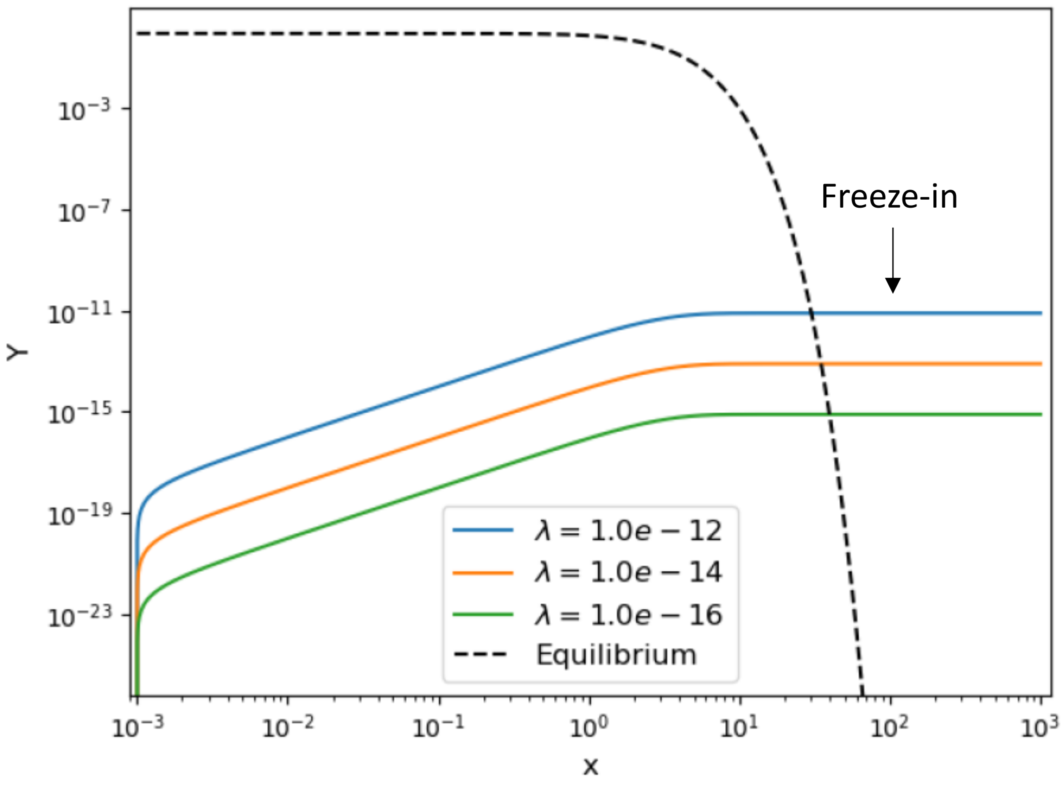




Credits: **Arcadi et. al, arXiv:2403.15860**

Introduction - Dark Matter production mechanisms

Freeze-in mechanism - Feebly Interacting Massive Particles (FIMPs)



$$Y \equiv \frac{n_X}{s}, \quad x \equiv \frac{m}{T}$$

$$\cancel{X\bar{X} \leftrightarrow SM}$$

$$\longleftarrow$$

DM **evolution**:

$$\frac{dn_X}{dt} + 3Hn_X = 2\Gamma_{\sigma\to XX}\frac{K_1(m_\sigma/T)}{K_2(m_\sigma/T)}n_\sigma^{eq}$$

Interactions rate:

$\Gamma_X < H$ **always**

Present DM **abundance**:

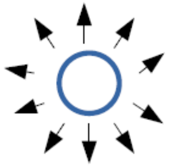
$$\Omega_{X,0}\, h^2 \sim \Gamma_{\sigma\to XX} \sim \lambda$$

Particle Production Background - Examples

Inflation | **(P)reheating (Matter era)** | **Radiation era**

T ← T_{end} ← T_R

Scalar field fluctuations



$$V(s) = \frac{1}{2}\, m_s^2 s^2 + \frac{1}{4}\, \lambda_s\, s^4$$

$\lambda_s \ll 1$

Quantum fluctuations

⇩

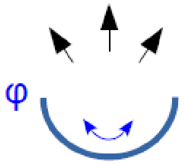
Set the **initial amplitude** of the field when it starts to oscillate (after inflation)

⇩

Long-lived **oscillating scalar condensate**

[O. Bertolami, CC, J. G. Rosa, 1603.06242]
[CC, J . G. Rosa, O. Bertolami, 1709.09674]
[CC, J . G. Rosa, O. Bertolami, 1802.09434]
[Markkanen, Rajantie, Tenkanen, 1811.02586]
[CC, T. Tenkanen, 2009.01149]

Inflaton Oscillations



⇩

Hubble and scale factor oscillate

⇩

Induce $\mathcal{L} \sim \frac{\varphi^2 (\partial s)^2}{M_{Pl}^2}$

⇩

"**Annihilation**" of **inflaton oscillations** into **s** particles (even if there are no direct couplings!)

[Y. Ema, R. Jinno, K. Mukaida, K. Nakayama, 1502.02475]
[O. Lebedev, 2210.02293]

Gravitational annihilation of the inflaton during reheating

[Y. Ema, R. Jinno, K. Mukaida, K. Nakayama, 1502.02475]

Inflaton oscillations → Scale factor (a) and Hubble parameter oscillate

The scale factor $a(t)$ is obtained by integrating $\dot{a}/a = H = \langle H \rangle + \delta H$:

$$a(t) \simeq \langle a(t) \rangle \left(1 - \frac{1}{2(n+2)} \frac{\phi^2 - \langle \phi^2 \rangle}{M_P^2}\right), \quad \langle a(t) \rangle \simeq a_i \left(\frac{t}{t_i}\right)^{\frac{n+2}{3n}}$$

Gravitational annihilation of the inflaton during reheating

[Y. Ema, R. Jinno, K. Mukaida, K. Nakayama, 1502.02475]

$$S_{\mathrm{M}} = \int d^4x \sqrt{-g} \left[-\frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - \frac{1}{2} m_\chi^2 \chi^2 \right], \tag{2.12}$$

where we assume $m_\chi \ll m_\phi$. As shown above, the scale factor and hence $\sqrt{-g}$ contains ϕ^2 dependence. Therefore, neglecting terms including m_χ, the action can be expanded as

$$S_{\mathrm{M}} = \int d\tau d^3x \, \langle a(t) \rangle^2 \left(1 - \frac{1}{n+2} \frac{\phi^2}{M_P^2} \right) \frac{1}{2} \left[\chi'^2 - (\partial_i \chi)^2 \right], \tag{2.13}$$

where we have used the conformal time $d\tau = dt/a(t)$ and the prime denotes derivative with respect to τ. This explicitly shows that the inflaton ϕ couples to $(\partial\chi)^2$ and ϕ (partially) "decays" or "annihilates" into χ particles. According to the analysis of particle production under the oscillating background ϕ [5, 6], it might be interpreted as the annihilation of the inflaton into χ particles. Thus we call this "gravitational annihilation" for convenience in the following.

Particle production background - Scalar fluctuations during inflation

- **Quantum fluctuations** for a massive field $\left(\frac{m_\phi}{H_{inf}} < \frac{3}{2}\right)$:

$$|\delta\phi_k| \simeq \frac{H_{inf}}{\sqrt{2k^3}}\left(\frac{k}{aH_{inf}}\right)^{\frac{3}{2}-\nu_\phi}$$

Integrating over all super-horizon modes

$$\langle\phi^2\rangle \simeq \frac{1}{3-2\nu_\phi}\left(\frac{H_{inf}}{2\pi}\right)^2$$

$$\boxed{\nu_\phi = \left(\frac{9}{4} - \frac{m_\phi^2}{H_{inf}{}^2}\right)^{\frac{1}{2}}}$$

- **Quantum fluctuations** for a massive field $\left(\frac{m_\phi}{H_{inf}} > \frac{3}{2}\right)$:

$$|\delta\phi_k|^2 \simeq \left(\frac{H_{inf}}{2\pi}\right)^2\left(\frac{H_{inf}}{m_\phi}\right)\frac{2\pi^2}{(aH_{inf})^3}$$

Integrating over all super-horizon modes

$$\langle\phi^2\rangle \simeq \frac{1}{3}\left(\frac{H_{inf}}{2\pi}\right)^2\left(\frac{H_{inf}}{m_\phi}\right)$$

Particle Production background - Quantum gravity effects

- Quantum gravity is believed to induce all operators consistent with gauge symmetry (including Planck-suppressed couplings between the inflaton and DM)

$$\Delta\mathcal{L}_6 = \frac{C_1}{M_{\rm Pl}^2}\,(\partial_\mu\phi)^2 s^2 + \frac{C_2}{M_{\rm Pl}^2}\,(\phi\partial_\mu\phi)(s\partial^\mu s) + \frac{C_3}{M_{\rm Pl}^2}\,(\partial_\mu s)^2\phi^2 - \frac{C_4}{M_{\rm Pl}^2}\,\phi^4 s^2 - \frac{C_5}{M_{\rm Pl}^2}\,\phi^2 s^4$$

Lead to **particle production** during the **inflaton oscillation epoch** and can produce **excessive abundance of stable scalars**

Most efficient in particle production:

$$\frac{C_4}{M_{\rm Pl}^2}\,\phi^4 s^2$$

Particle Production background – Dilution factors

During inflation:

$$\Delta_{\rm NR} \gtrsim 10^7\, \lambda_s^{-3/4} \left(\frac{H_{\rm end}}{M_{\rm Pl}}\right)^{3/2} \left(\frac{m_s}{\rm GeV}\right)$$

Inflaton oscillation:

$$m_s \lesssim 10^{-6}\, \Delta_{\rm NR} \left(\frac{M_{\rm Pl}}{H_{\rm end}}\right)^{3/2} \,{\rm GeV}$$

Quantum gravity:

$$\Delta_{\rm NR} \gtrsim 10^{17}\; C^2\; \frac{m_s}{\rm GeV}$$

Oscillating scalar field as DM candidate

Does an oscillating scalar field behave like non-relativistic matter?

Potential: $V(\phi) = \frac{1}{2} m_\phi^2 \phi^2$

Generic cosmological epoch: $a(t) = \left(\frac{t}{t_i}\right)^p, p > 0.$ Hubble parameter: $H = \frac{p}{t}$

Klein-Gordon (KG) eq. :

$$\ddot{\phi} + 3\frac{p}{t}\dot{\phi} + m_\phi^2\, \phi = 0 \xrightarrow{m_\phi t \gg 1} \phi(t) \simeq \frac{\phi_i}{a(t)^{\frac{3}{2}}} \cos(m_\phi t + \delta_\phi)$$

Energy density: $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \sim a^{-3}$ $\Rightarrow$ Non-relativistic matter.

Oscillating scalar field as DM candidate

When does it start to oscillate?

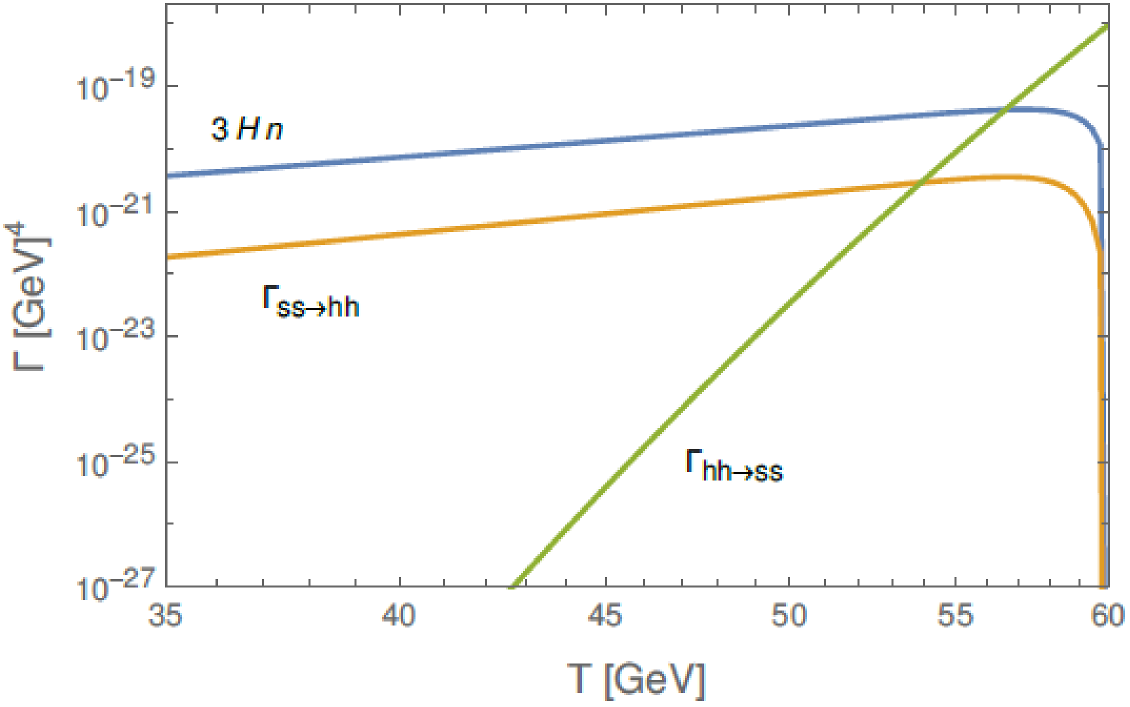
KG:

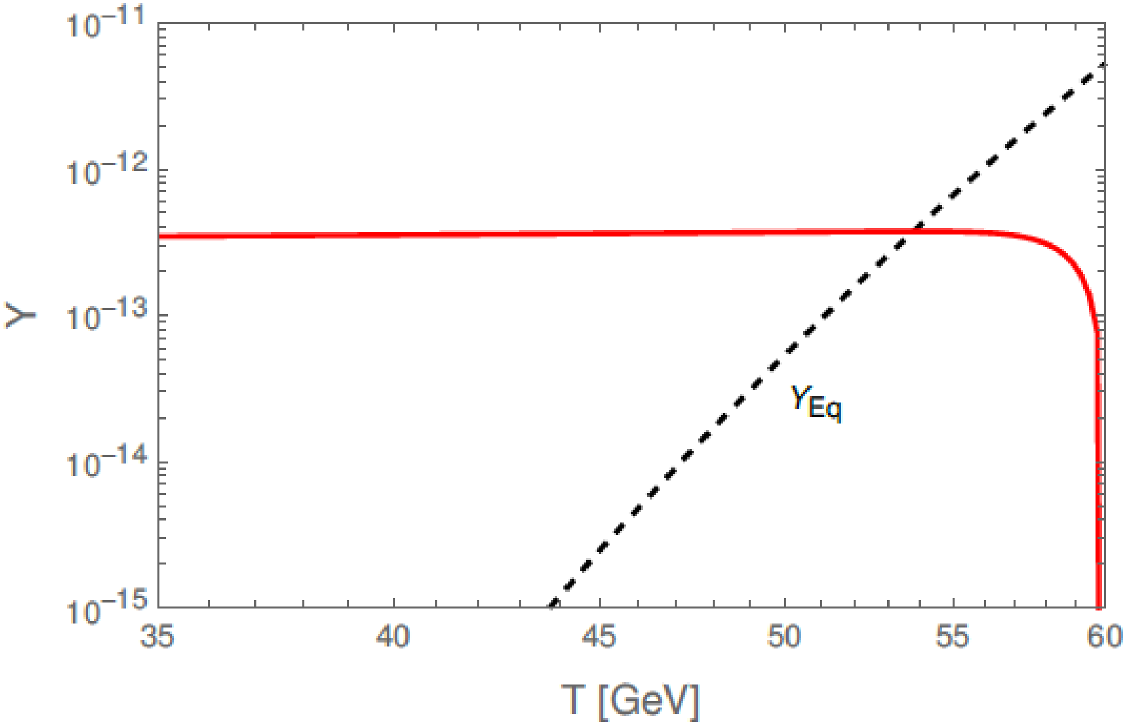
$$\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{friction term}} + m_\phi^2\, \phi = 0$$

$\boldsymbol{H > m_\phi}$ $\Rightarrow$ Overdamped regime. No oscillations.

$\boldsymbol{H < m_\phi}$ $\Rightarrow$ Underdamped regime. The field oscillates.

Phenomenology – Reaction rates

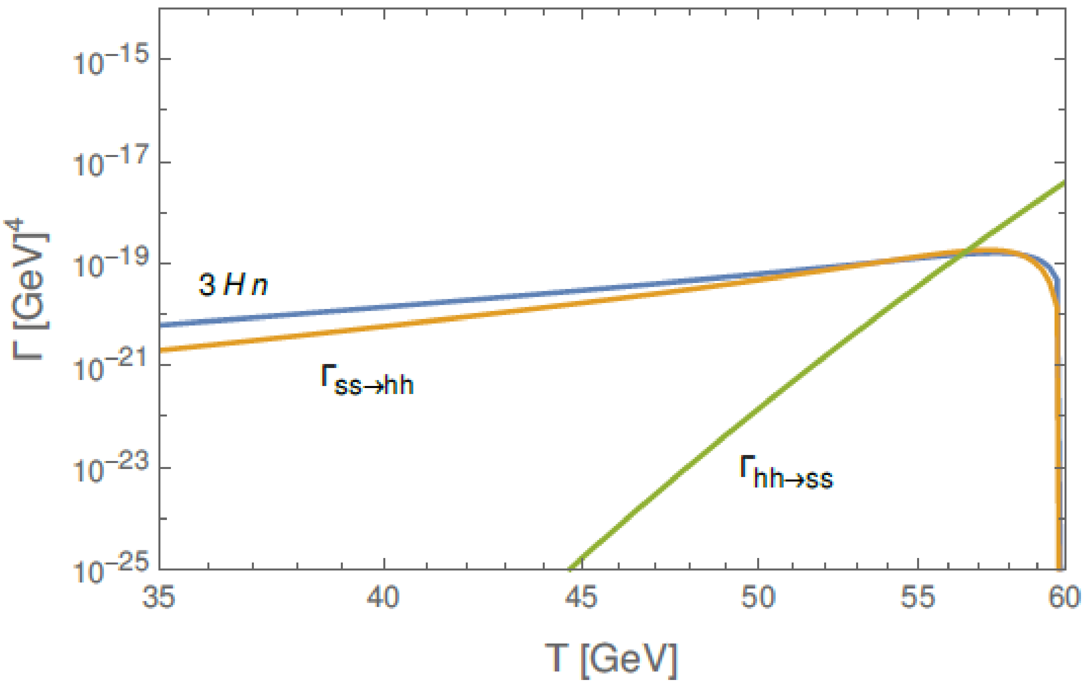


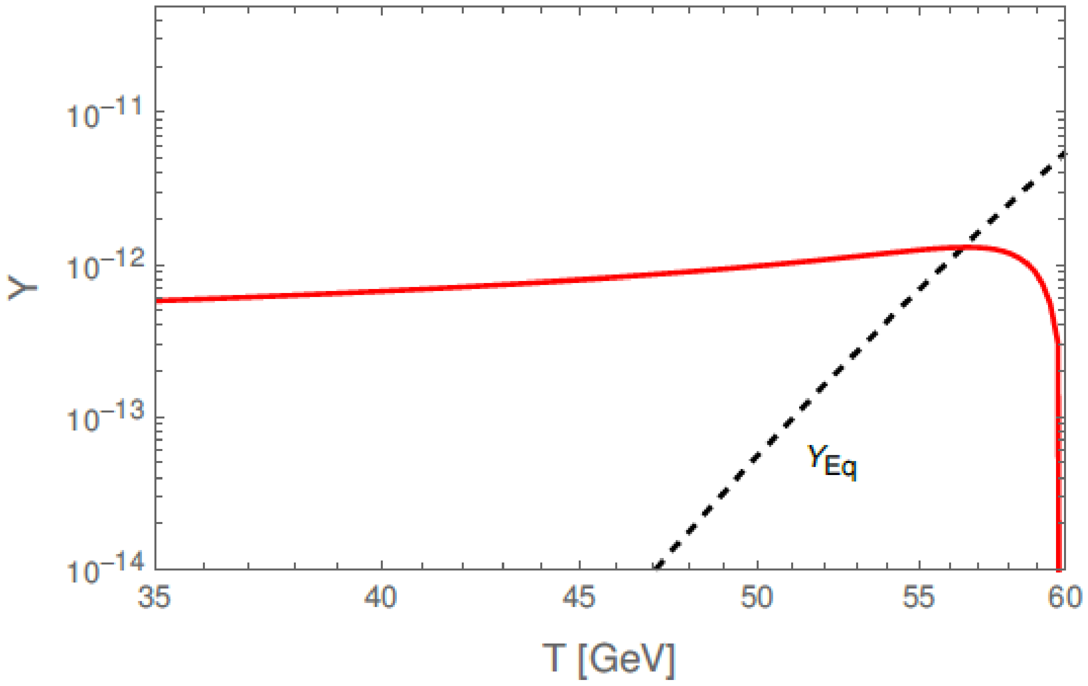


$T_R = 60$ GeV, $m_s = 1453$ GeV, $\lambda_{hs} = 0.2$

Annihilation rate is never significant → Freeze-in regime

Phenomenology – Reaction rates



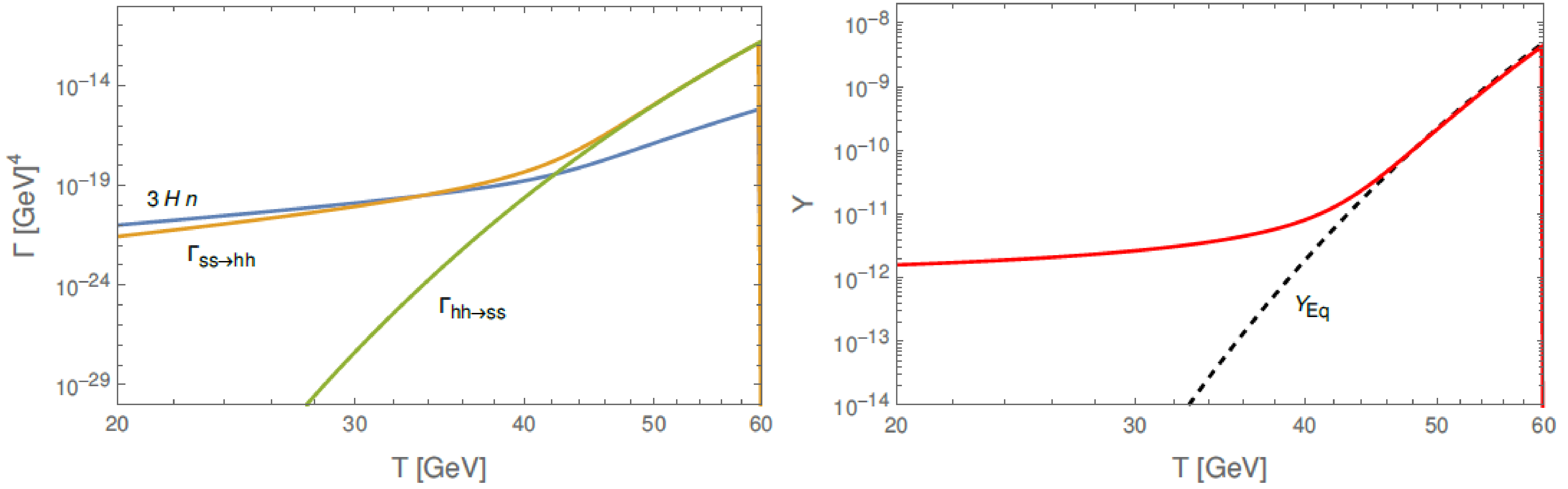


$T_R = 60$ GeV, $m_s = 1451$ GeV, $\lambda_{hs} = 0.39$

Annihilation rate is significant for some time

Freeze-in close to Freeze-out regime

Phenomenology – Reaction rates



$T_R = 60$ GeV, $m_s = 1012$ GeV, $\lambda_{hs} = 0.297$

Annihilation rate = production rate
for some time – system thermalizes

→ Freeze-out regime

The model – DM production inefficient

Real scalar dark matter **s** through the **Higgs portal**

$$V(s) = \frac{1}{2}\,\lambda_{hs}\, s^2\, H^\dagger H + \frac{1}{2}\, m_s^2 s^2$$

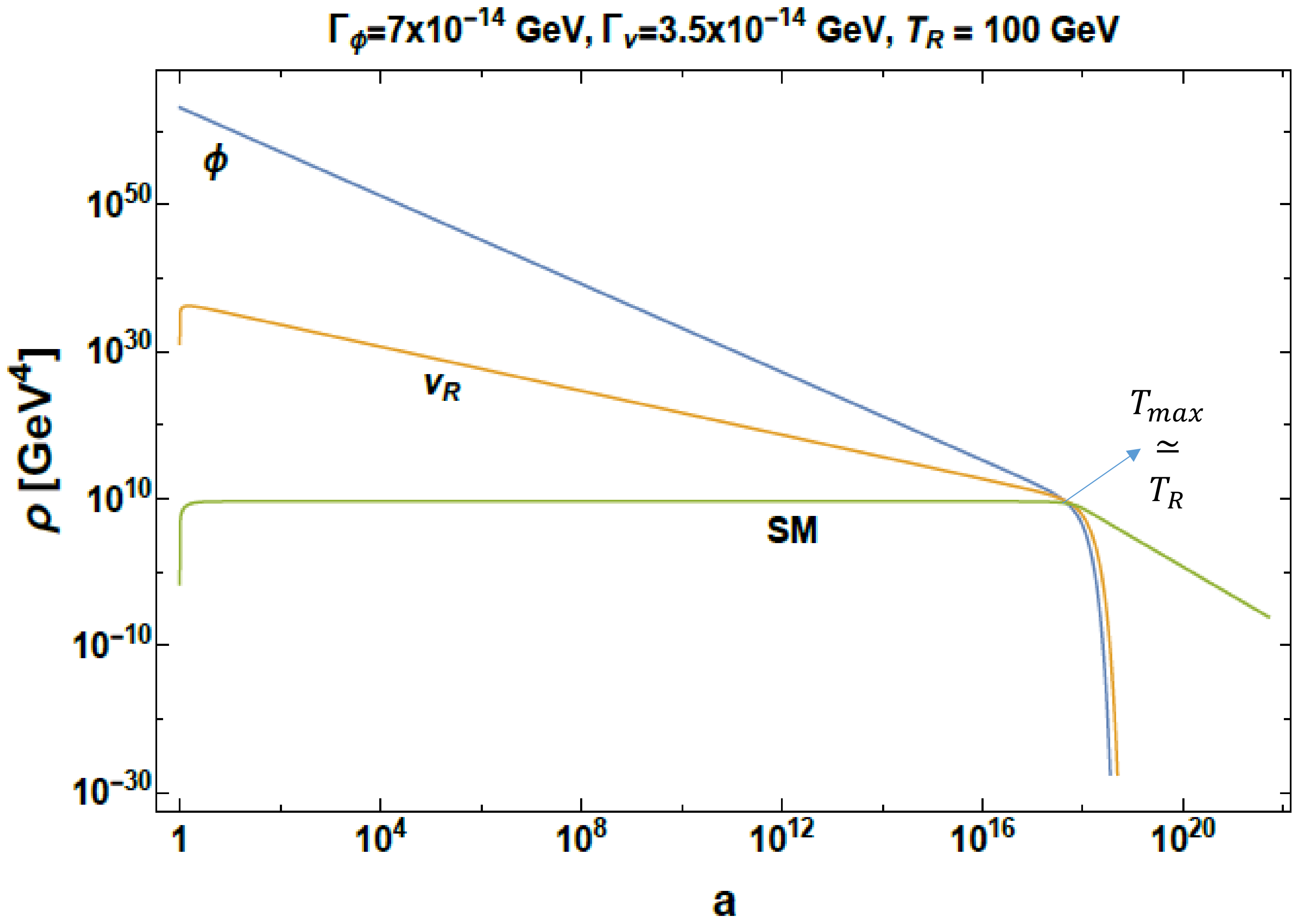
DM number density, **n**:

$$\dot{n} + 3Hn = \cancel{\Gamma(h_i h_i \to ss)} - \Gamma(ss \to h_i h_i)$$

$$\Gamma(ss \to h_i h_i) \simeq \underbrace{\frac{\lambda_{hs}^2}{64\,\pi\, m_s^2}}_{\langle \sigma(ss \to h_i h_i) v_r \rangle} n^2 \quad \Rightarrow \quad \lambda_{hs,*} \simeq 90\, e^{m_s/(2T_R)} \sqrt{\frac{m_s}{M_{Pl}}}$$

Critical coupling

SM sector production via υ_R decay



If $\Gamma_\varphi \sim \Gamma_\upsilon$

φ and υ_r decay at the same time

$T_{max} \simeq T_R$

SM energy density scaling with *a*

Decay of a field into SM particles: $\chi \to \boldsymbol{SM}$

$$\dot{\rho} + 4H\rho = \Gamma_\chi \rho_\chi \ ,$$
$$H = H_0/a^m \ ,$$
$$\rho_\chi = \rho_\chi^0/a^n \ , \tag{2.1}$$

The label 0 refers to the initial moment $a_0 = 1$ corresponding to the end of inflation and $\rho(1) = 0$. We assume here that the SM sector does not contribute significantly to the energy balance of the Universe and that n, m are constant in the regime of interest.

$$\rho(a) = \frac{\Gamma_\chi \rho_\chi^0}{(4-n+m)H_0} \left[\frac{1}{a^{n-m}} - \frac{1}{a^4}\right] \rightarrow \frac{\Gamma_\chi \rho_\chi^0}{(4-n+m)H_0} \frac{1}{a^{n-m}} \tag{2.3}$$

If $n = m$, $\rho_{SM} = const \Rightarrow T_{SM} = const$

SM sector production via υ_R decay

Evolution of the energy density of the Universe:

$$\dot{\rho}_\varphi + 3H\rho_\varphi = -\Gamma_\varphi \rho_\varphi$$

$$\dot{\rho}_\upsilon + 4H\rho_\upsilon = \Gamma_\varphi \rho_\varphi - \Gamma_\upsilon \rho_\upsilon$$

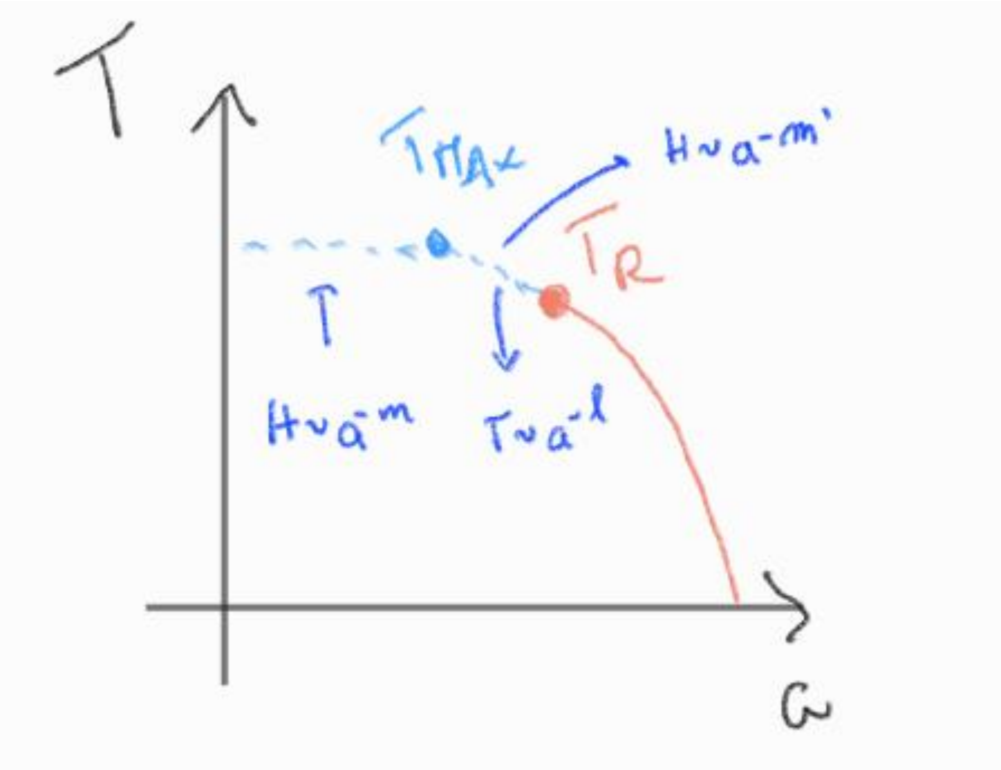
$$\dot{\rho}_{SM} + 4H\rho_{SM} = \Gamma_\upsilon \rho_\upsilon$$

$$\rho_\varphi + \rho_\upsilon + \rho_{SM} = 3H^2 M_{Pl}^2$$

If $\Gamma_\varphi \sim \Gamma_\upsilon$ ⇒ φ and υ decay at the same time ⇒ SM sector takes over the energy balance immediately thereafter ⇒ $T_{max} \simeq T_R$

$T_{max} > T_R$

In the limit $m_s \gg T_{max}$



$$\lambda_{hs} \to \lambda_{hs} \times \left(\frac{T_{\max}}{T_R}\right)^{\frac{m'+3-5l}{2l}}$$