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

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in collaboration with
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Phys.Rev.D 109 7 (2024), *JCAP 06* (2024) 031

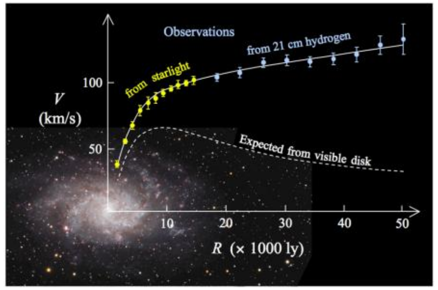
Multi Higgs Workshop, Instituto Superior Técnico, Lisboa, Portugal, 26 August 2026

Outline

- **Introduction**
  - Evidence for the existence of Dark Matter
  - Dark matter production mechanisms
- **The model – Freeze-in at stronger coupling**
- **Phenomenology**
  - Detection prospects
- **Temperature evolution and its consequences**
- **Conclusions**

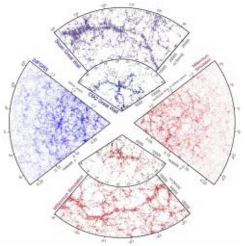
Introduction - Dark Matter (DM)

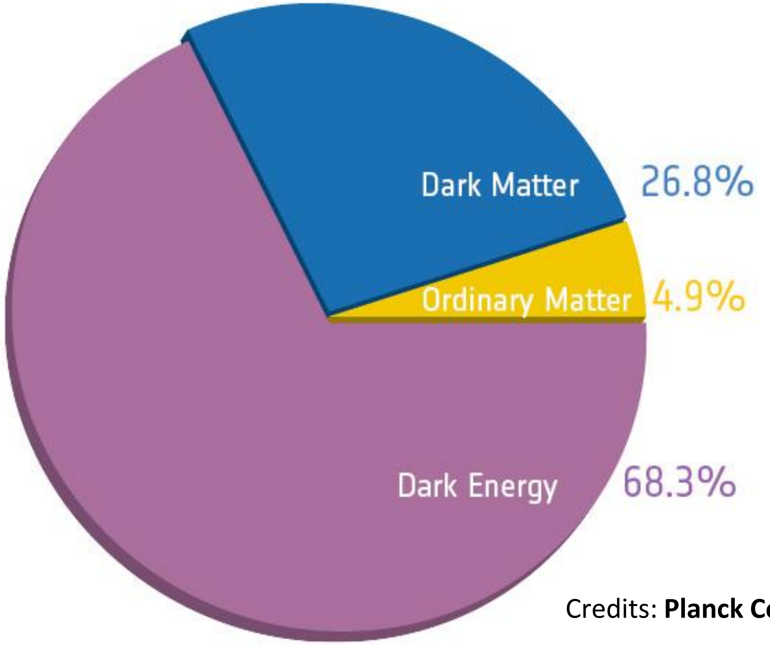
Galaxy Rotation Curves



Merging clusters (Bullet Cluster)

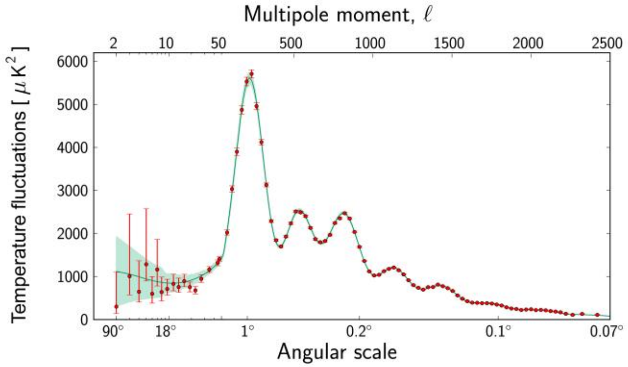
Structure formation



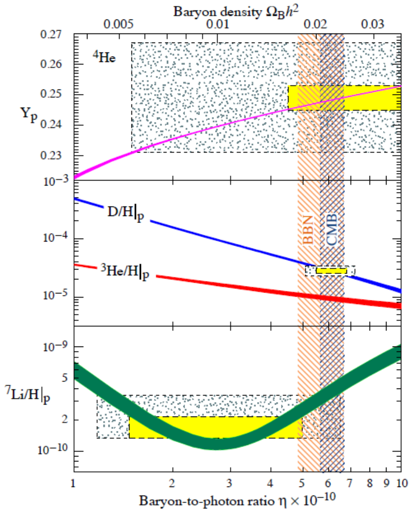


Credits: **Planck Collab.**

Cosmic Microwave Background (CMB)

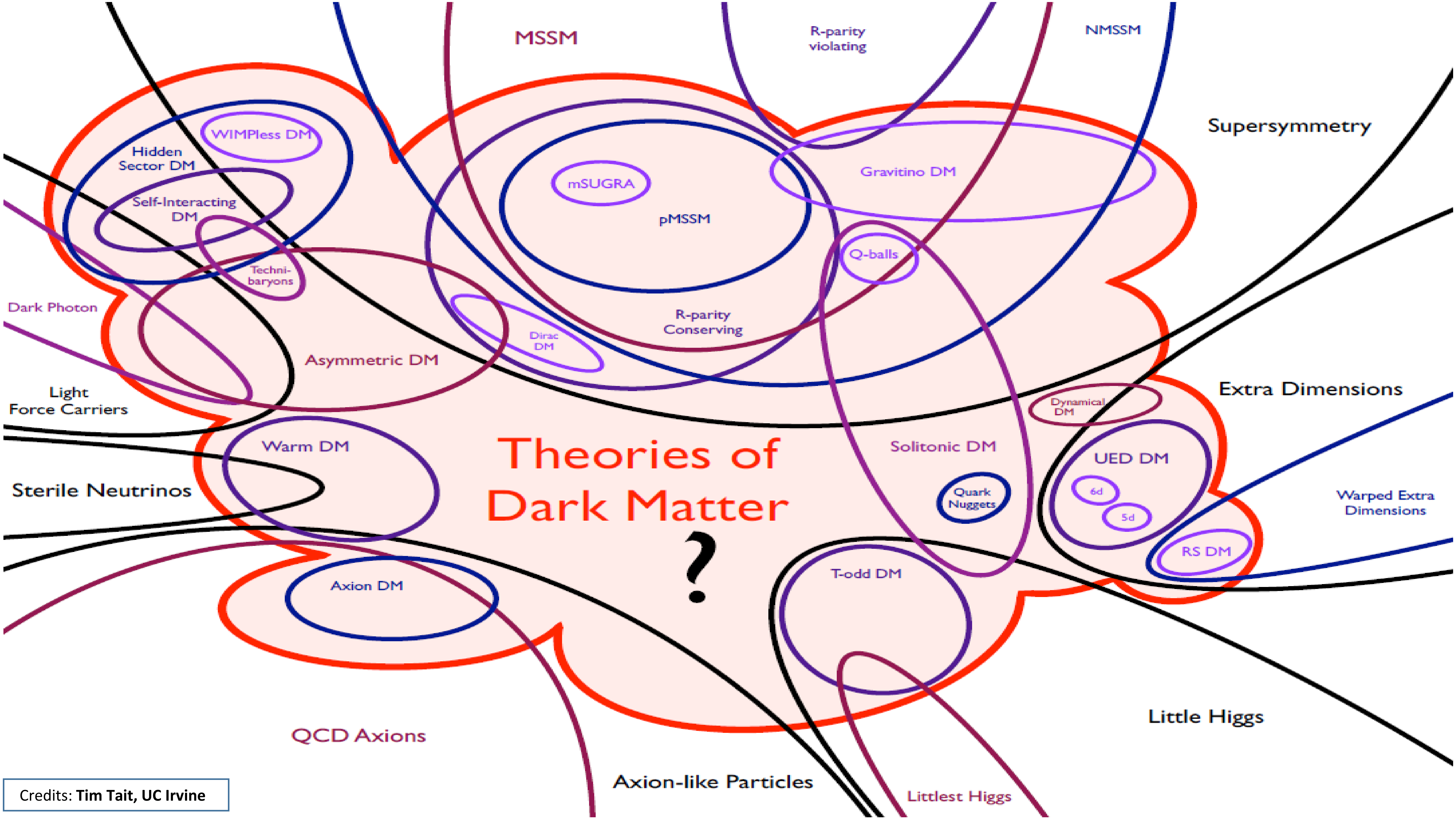


Big Bang Nucleosynthesis (BBN)



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.



Credits: **Tim Tait, UC Irvine**

Introduction - Dark Matter production mechanisms

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

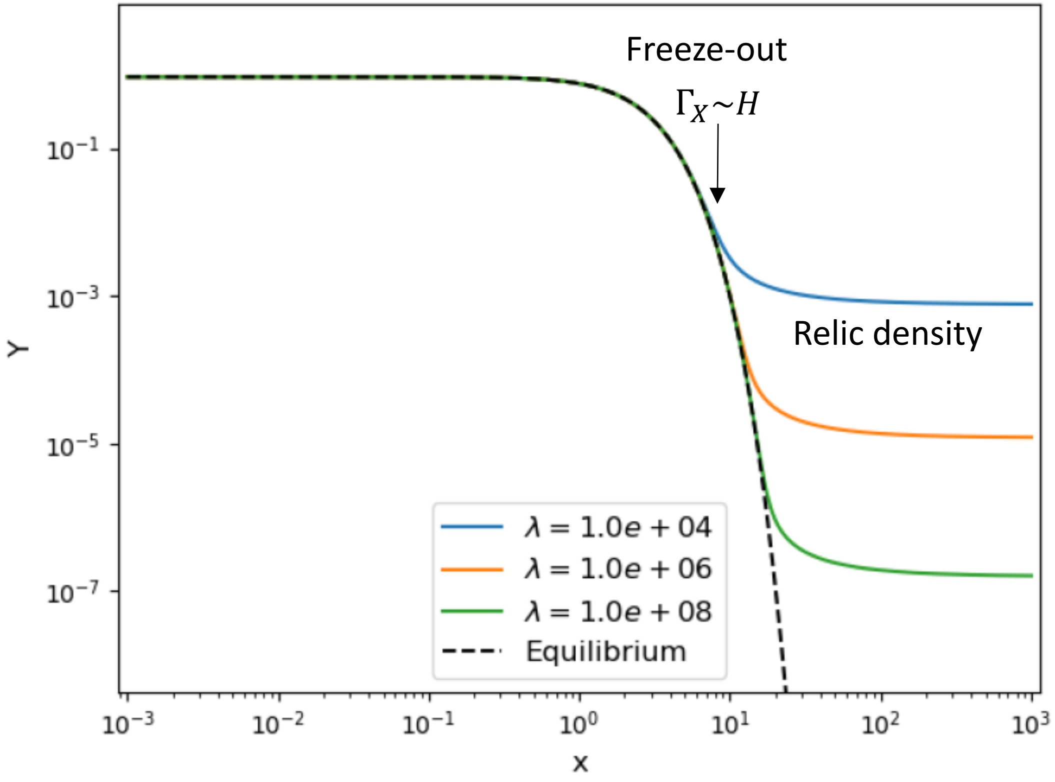
Introduction - Dark Matter production mechanisms

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

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

Introduction - Dark Matter production mechanisms

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



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

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

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:

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

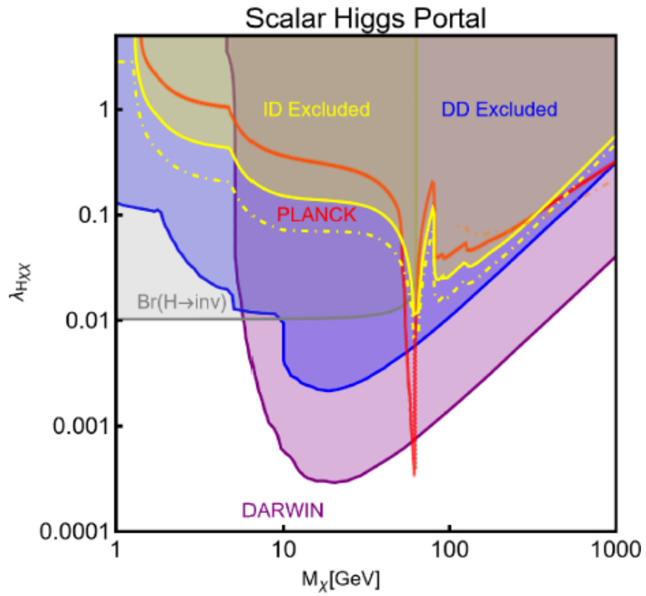
Present DM **abundance**:

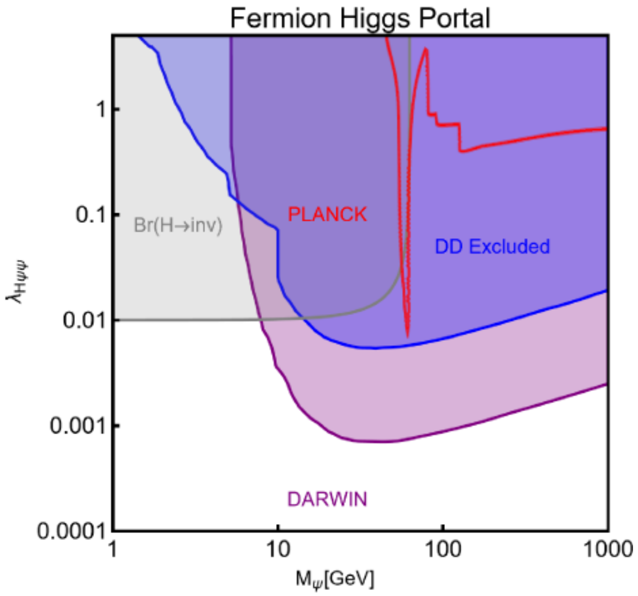
$$\Omega_{X,0}h^2 \equiv \frac{\rho_{X,0}}{\rho_{c,0}/h^2} \sim \frac{1}{\langle\sigma v\rangle} \sim \frac{1}{\lambda}$$

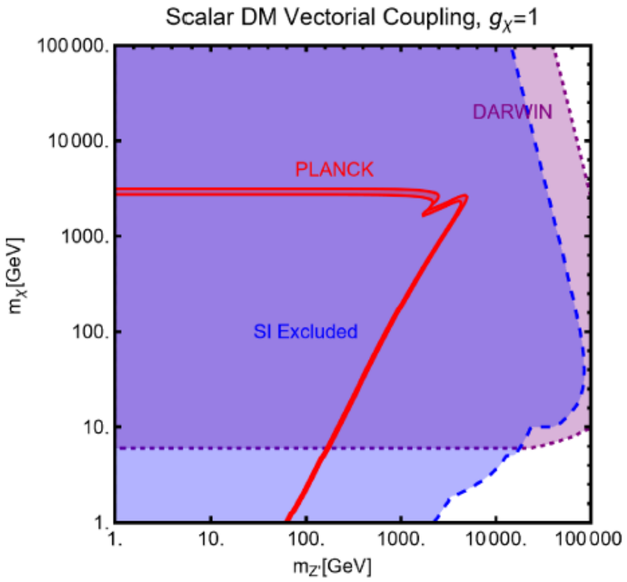
Introduction - Dark Matter production mechanisms

Freeze-out mechanism

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







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

Introduction - Dark Matter production mechanisms

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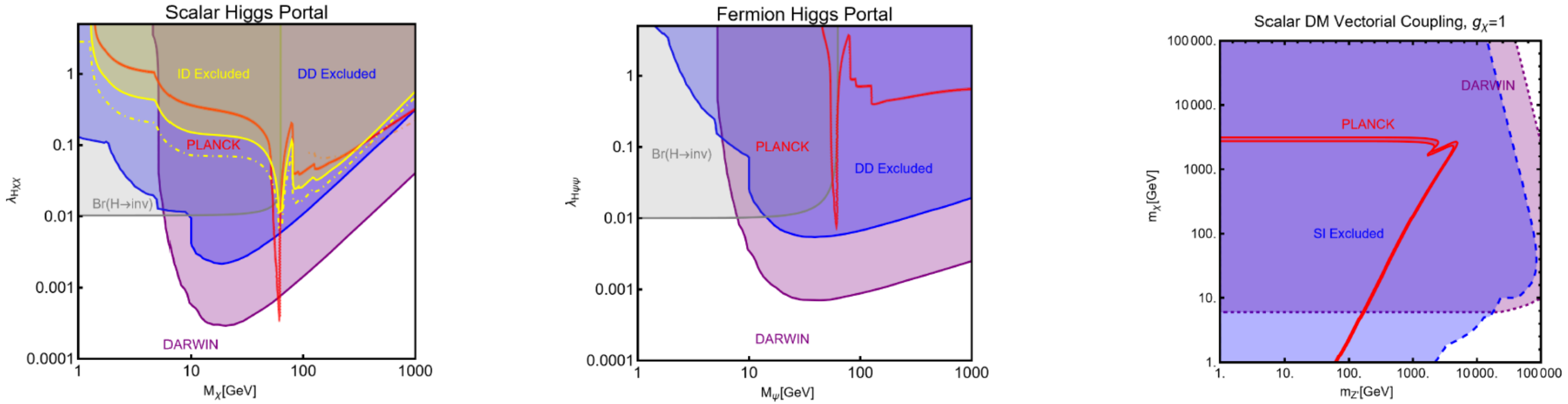

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“The waning of the WIMP?”

Introduction - Dark Matter production mechanisms

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

Introduction - Dark Matter production mechanisms

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

Introduction - Dark Matter production mechanisms

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

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

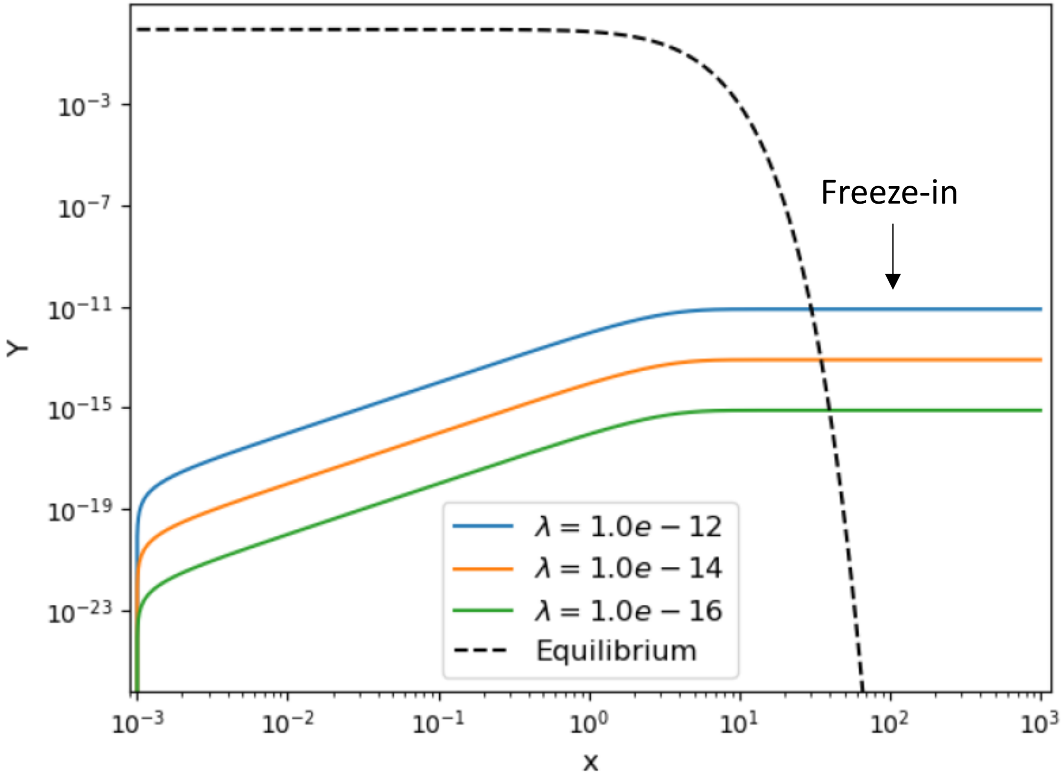
Introduction - Dark Matter production mechanisms

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

$X\bar{X} \leftrightarrow SM$

$\longleftarrow$

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



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

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

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**:

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

Introduction - Dark Matter production mechanisms

Freeze-out vs Freeze-in

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]

Freeze-in

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

- $\Gamma_X < H$ **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:

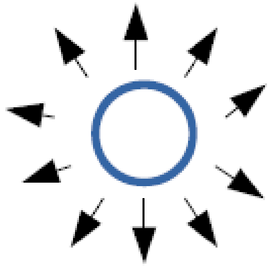
1 – **Small** couplings (hard to probe);

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

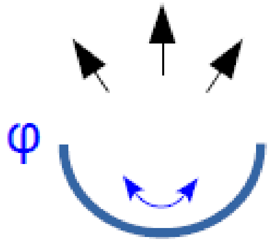
How can we probe FIMPs?

Particle Production Background

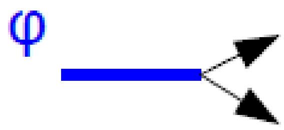
Feeble coupled particles can be copiously **produced during** and **after inflation** (all add up):



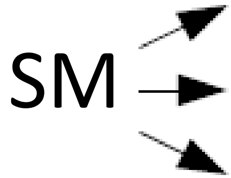
Scalar fluctuations



Inflaton oscillations



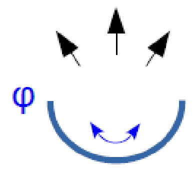
Inflaton decay



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**!

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**

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

T | $\boldsymbol{T_{end}}$ | $H_{end} \xrightarrow{a^{-3/2}} H_{reh}$ | $\boldsymbol{T_R}$ | $H_{rad} \sim a^{-2}$

$$\rho_\varphi \propto a^{-3},\ \rho_{rel\,relic} \propto a^{-4} \Rightarrow \frac{\rho_{rel\,relic}}{\rho_\varphi} \propto a^{-1}$$

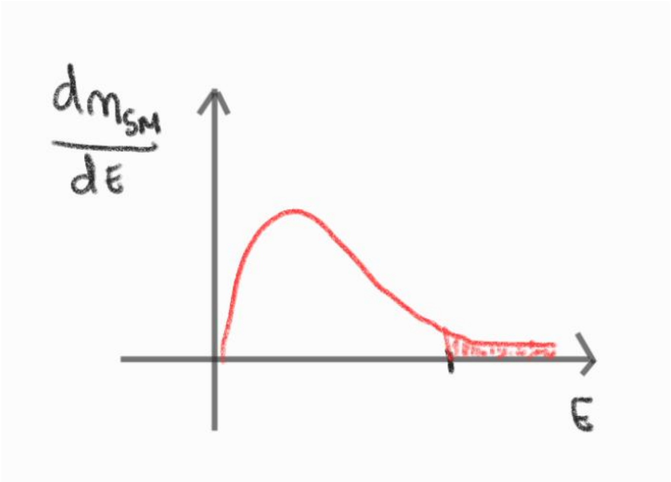
Dilution of the relics: $\Delta_{NR} \equiv \left(\frac{H_{end}}{H_{reh}}\right)^{1/2} > 1$ → **lower reheating** temperature, $\boldsymbol{T_R}$

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**

Testable!

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 – Negligible DM Annihilation

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

Solve the Boltzmann equation:

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

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

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

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

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

Freeze-in case

The model – Thermalization requirement

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Only **thermalizes** if

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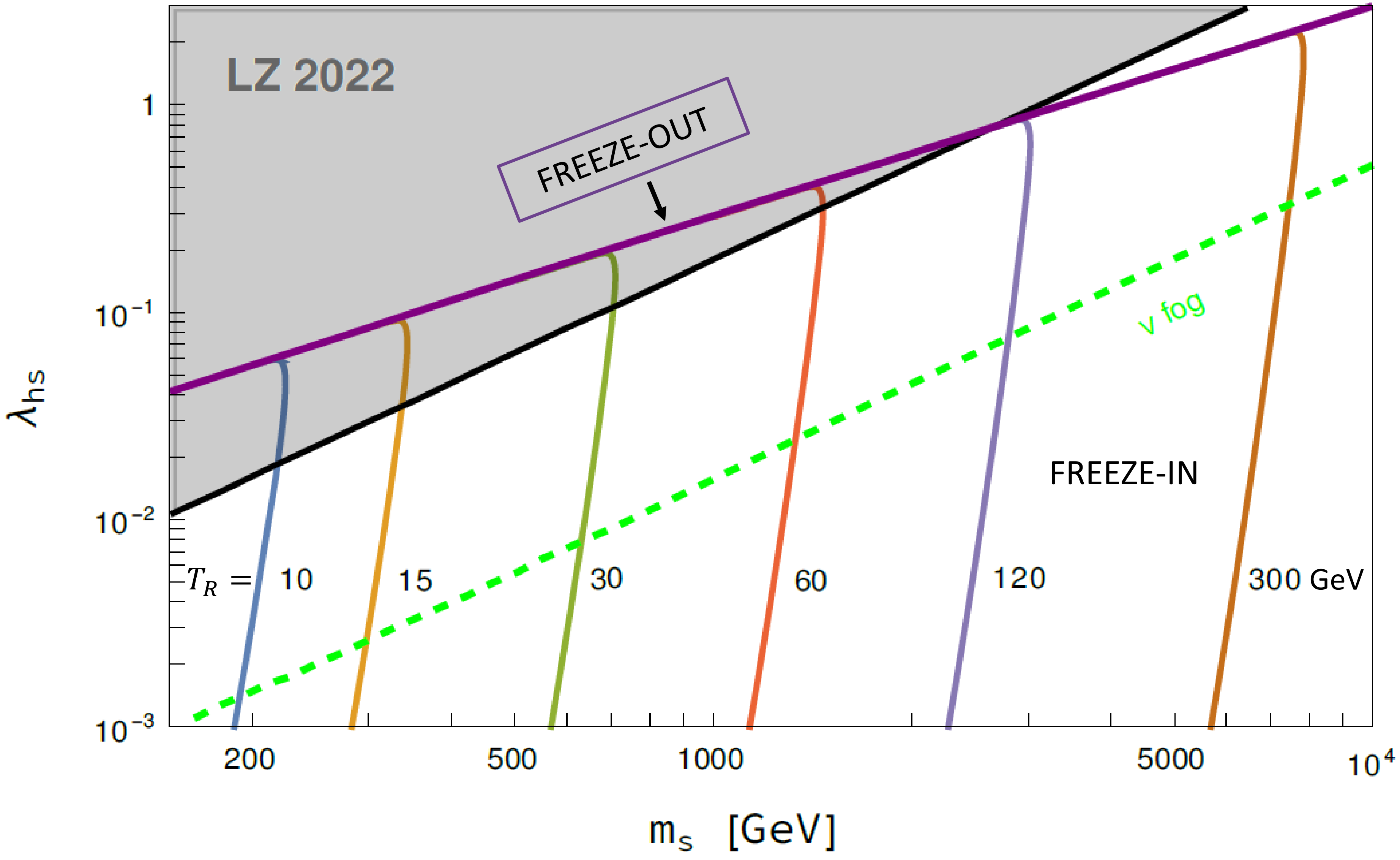
Freeze-out case

Phenomenology – Direct detection prospects



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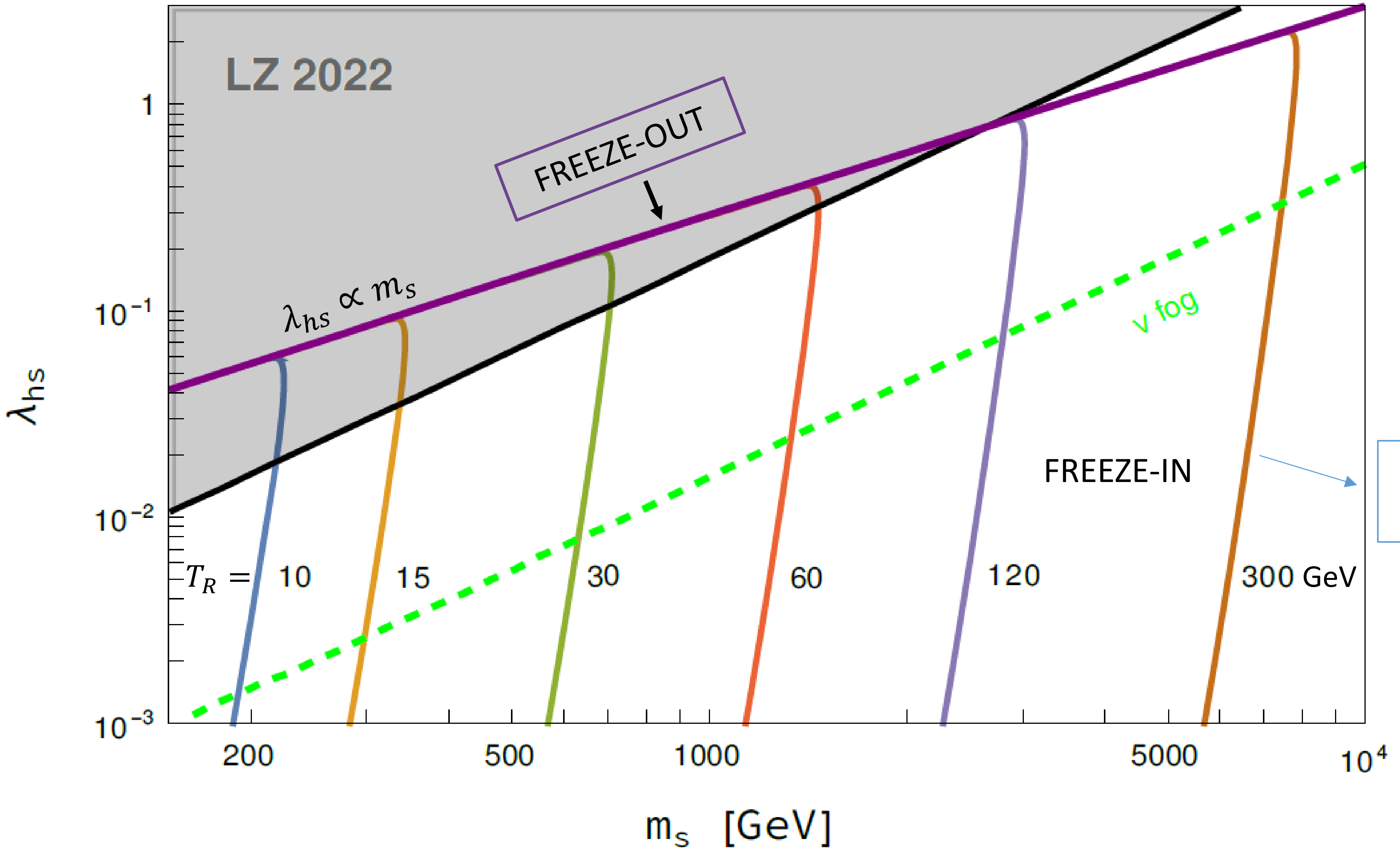
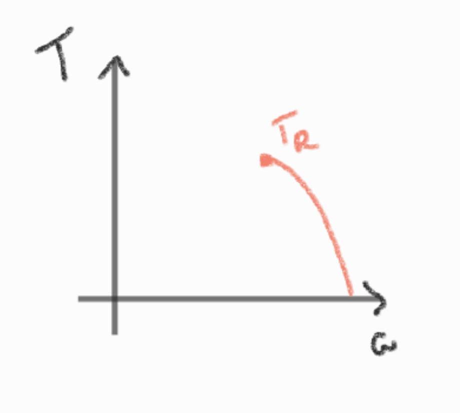


$$\lambda_{hs} \simeq 3 \times 10^{-11} e^{m_s/T_R} \sqrt{\frac{T_R}{m_s}}$$

What if reheating is not instantaneous?

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



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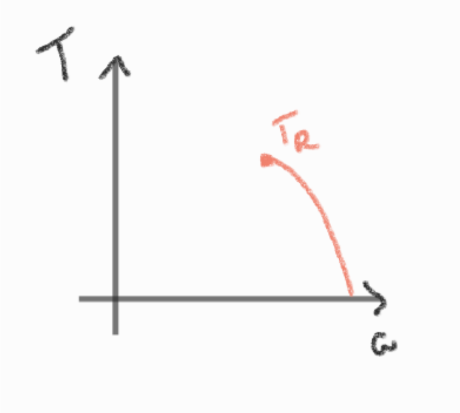

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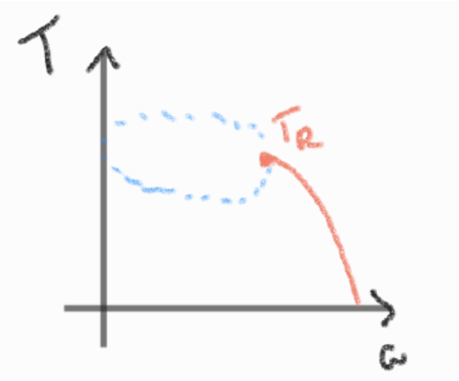

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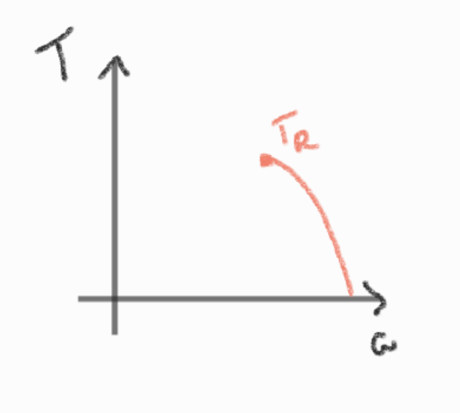

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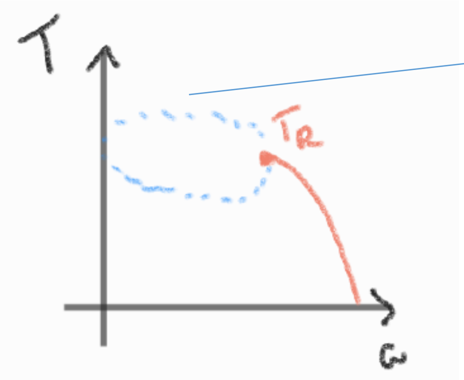

Assumption: in [CC, Costa, Lebedev, 2306.13061], **preexisting DM** abundance can be **neglected**

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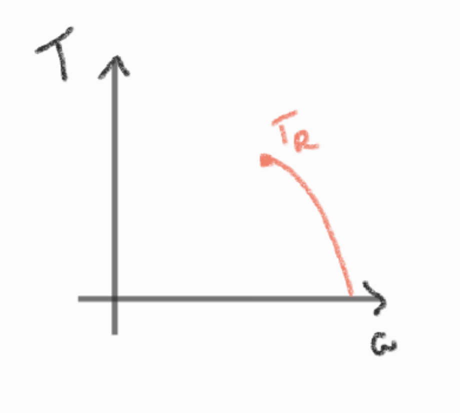

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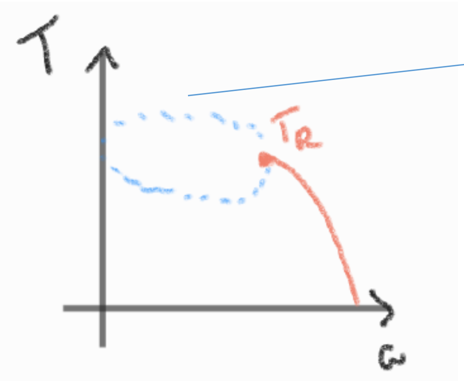

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Is this an **adequate** assumption?

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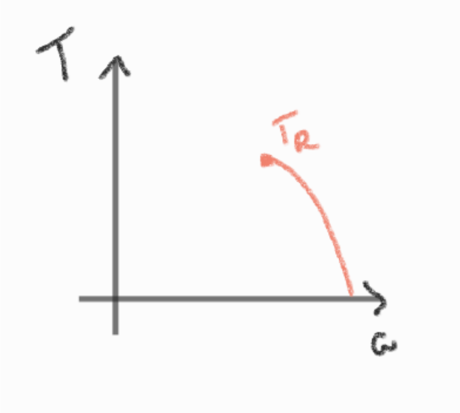

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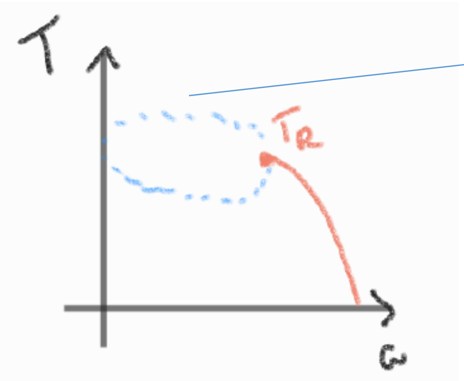


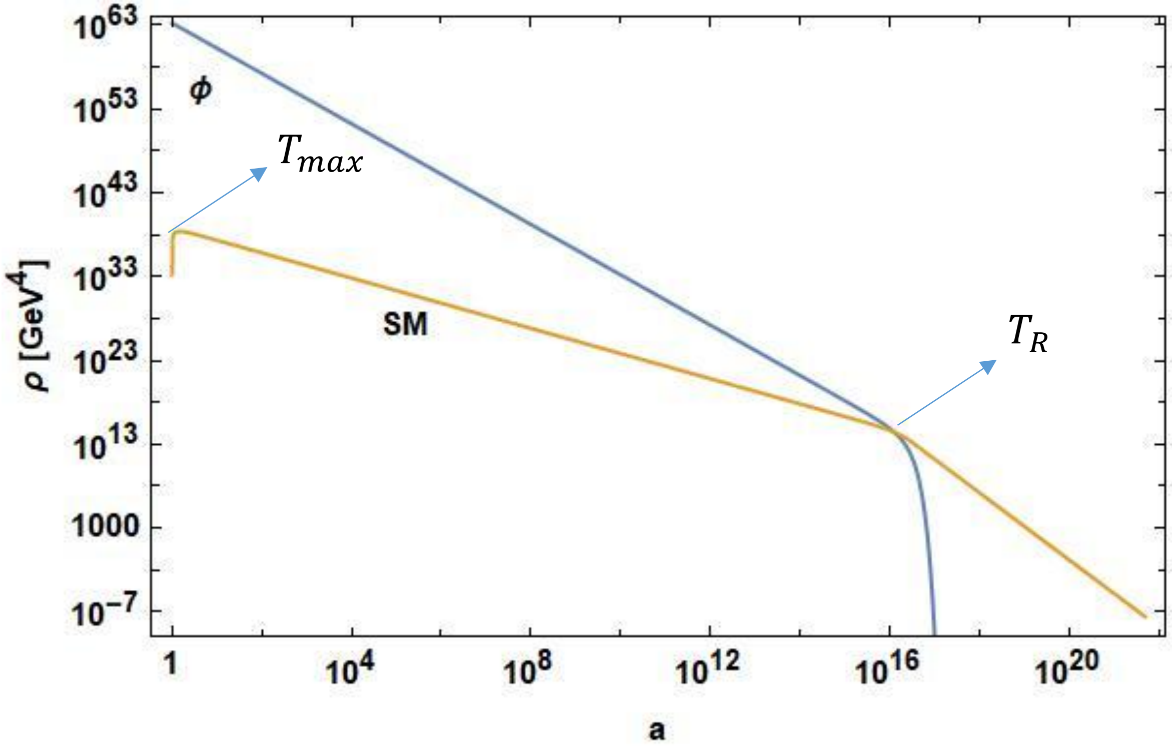
Assumption: in [CC, Costa, Lebedev, 2306.13061], **preexisting DM** abundance can be **neglected**

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

$$\varphi \to SM$$



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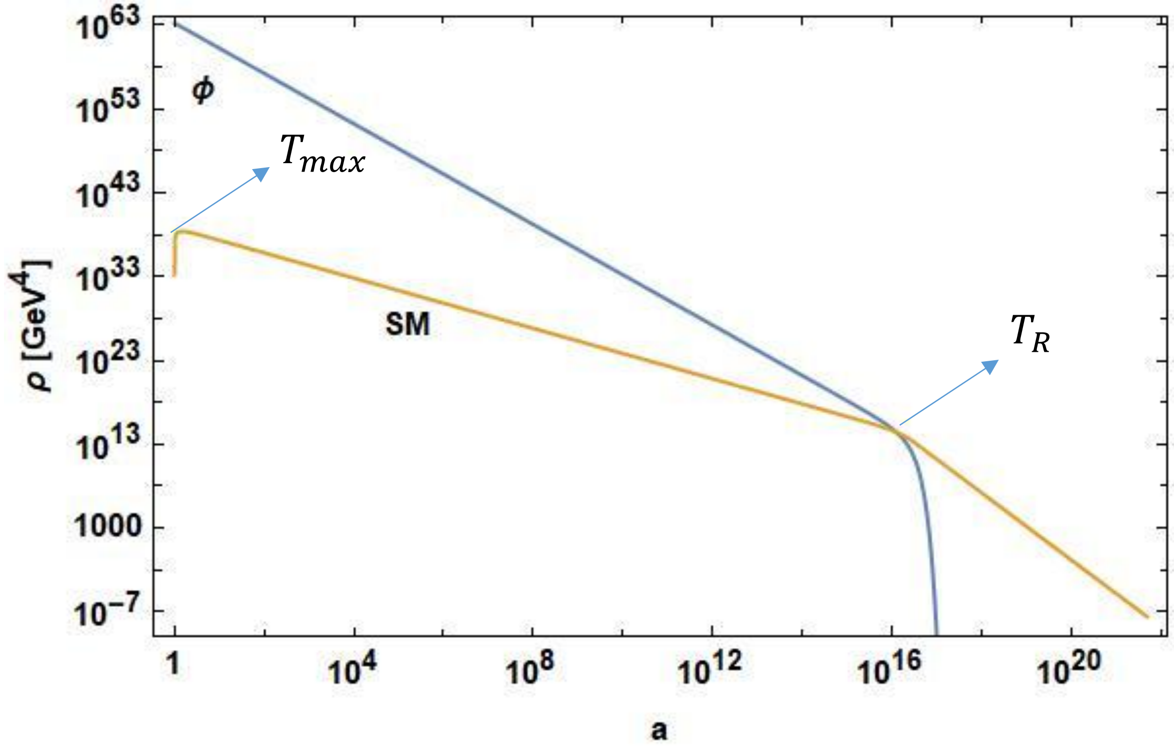

$$T_{max} \gg T_R$$

T_{max} and T_R

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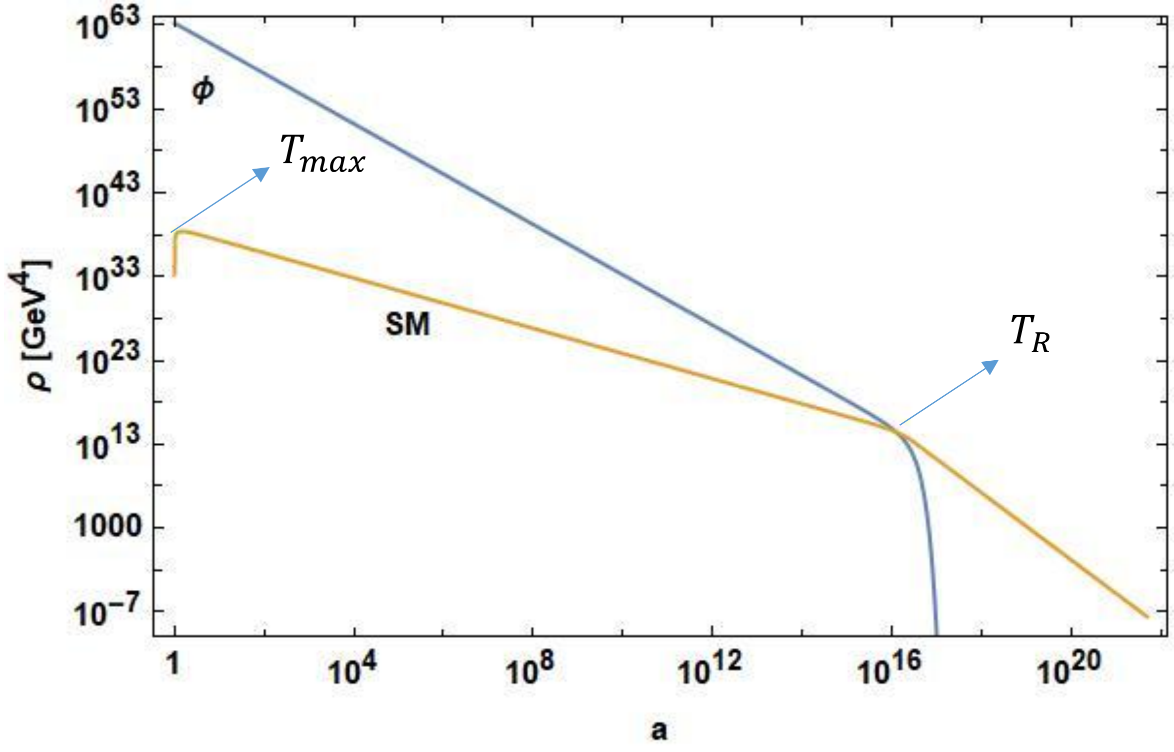
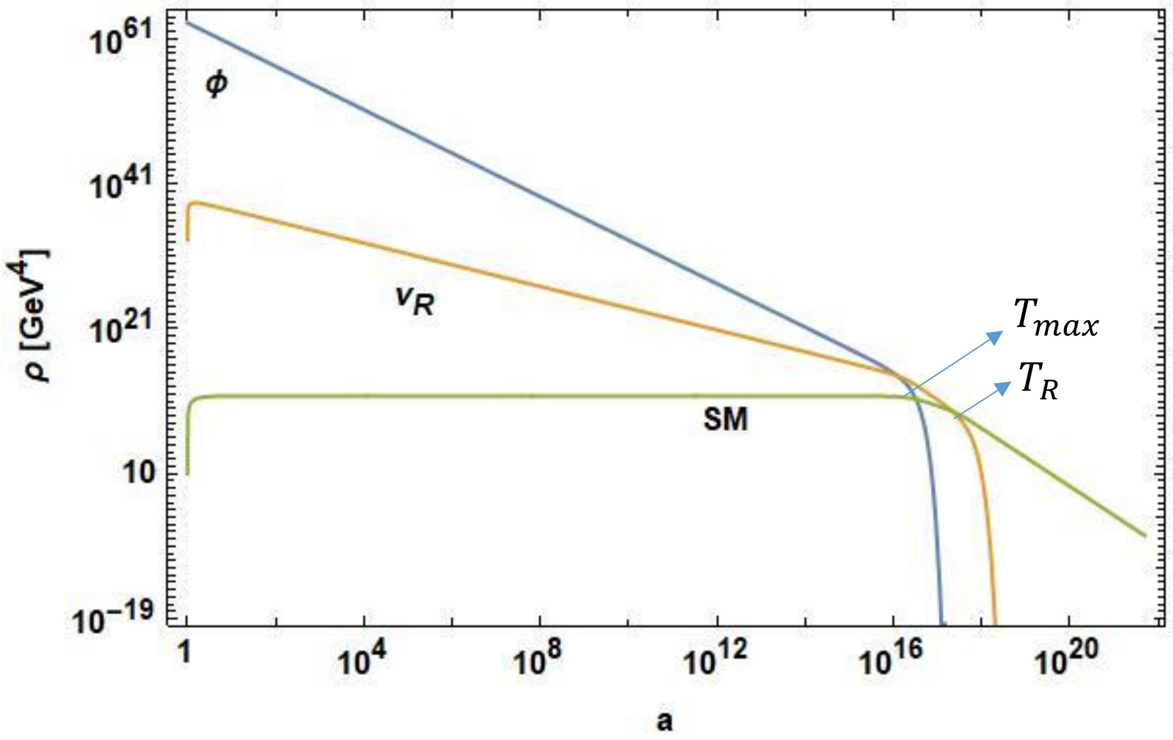


$$T_{max} \gg T_R$$

$\varphi \rightarrow \upsilon_R \rightarrow SM$



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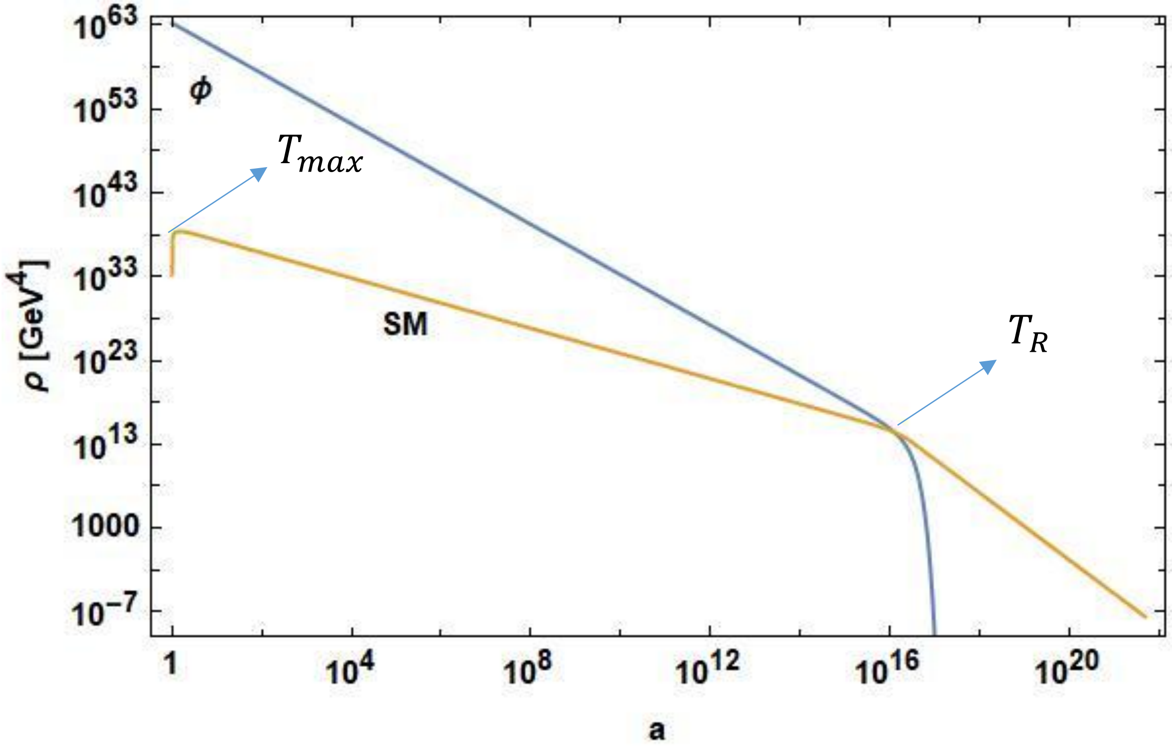
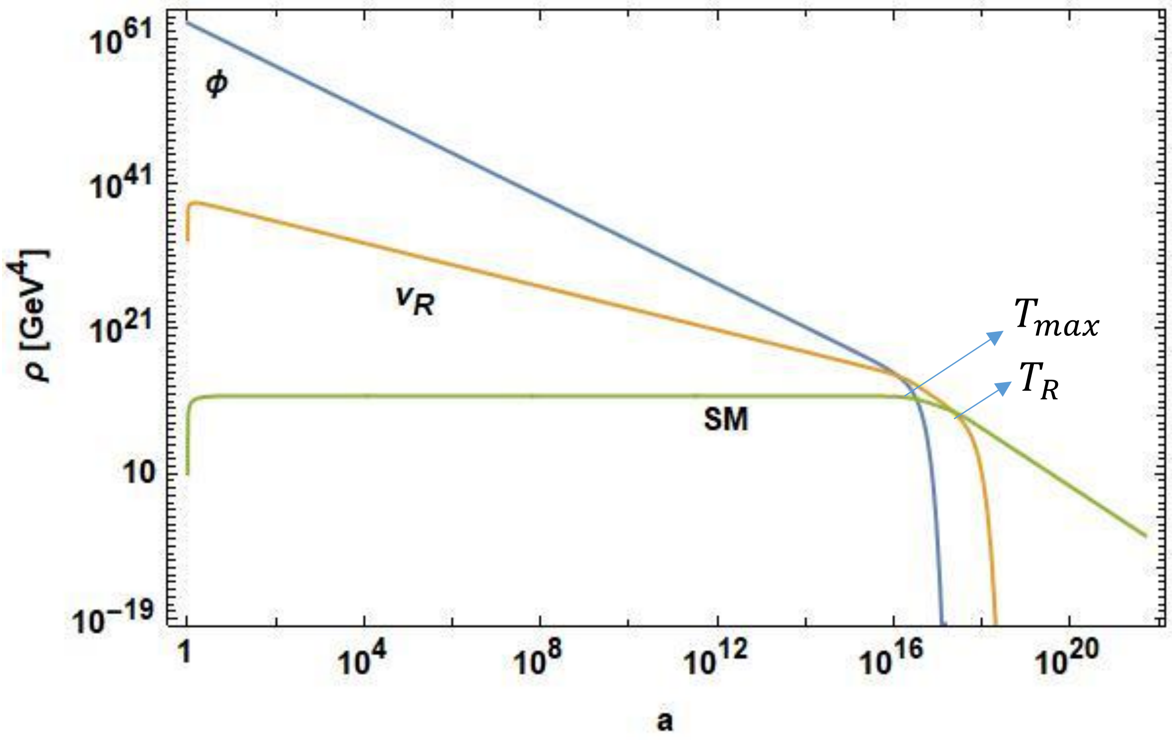


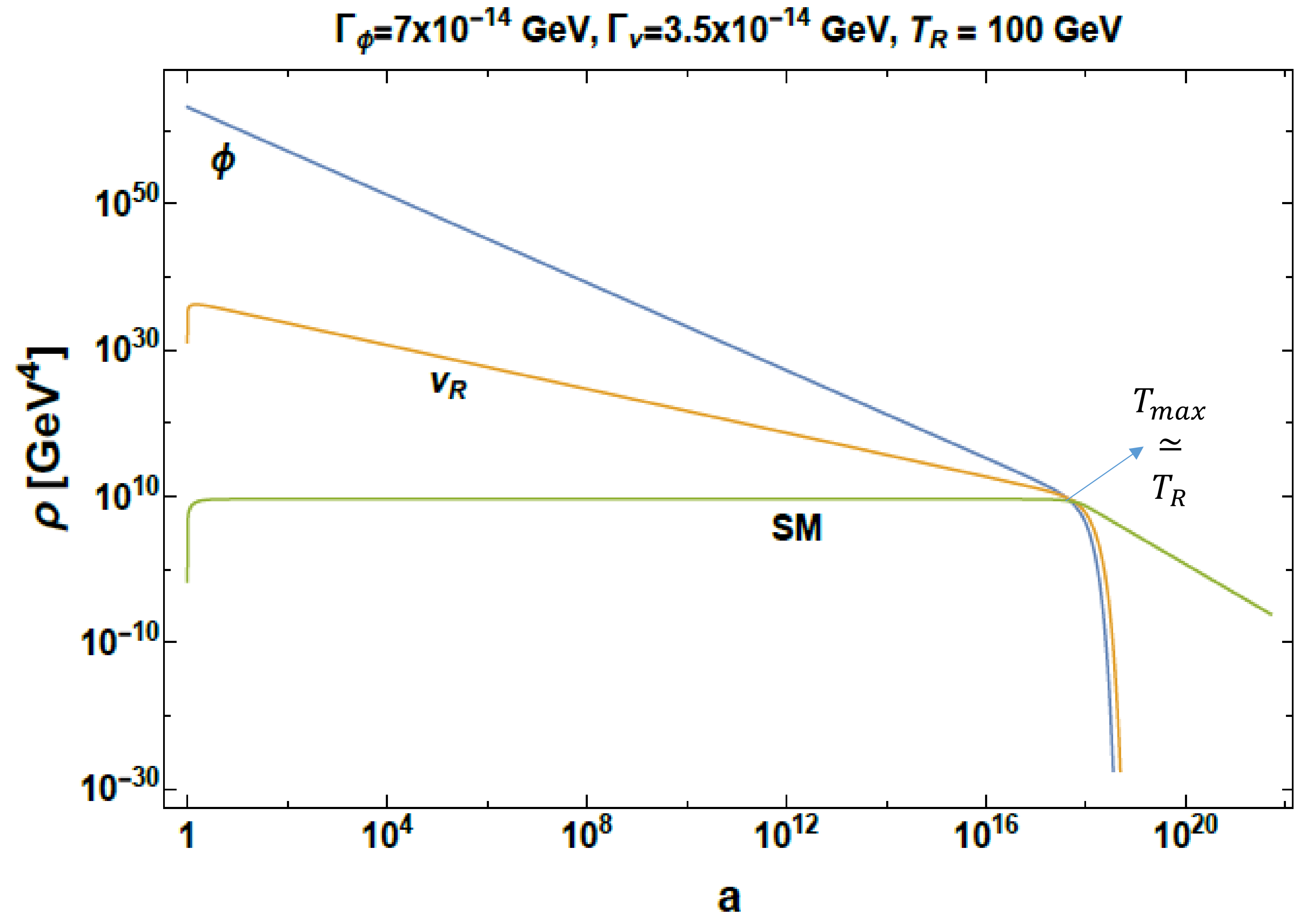
$T_{max} \gg T_R$

$\varphi \to \upsilon_R \to SM$



$T_{max} \simeq T_R$

SM sector production via υ_R decay

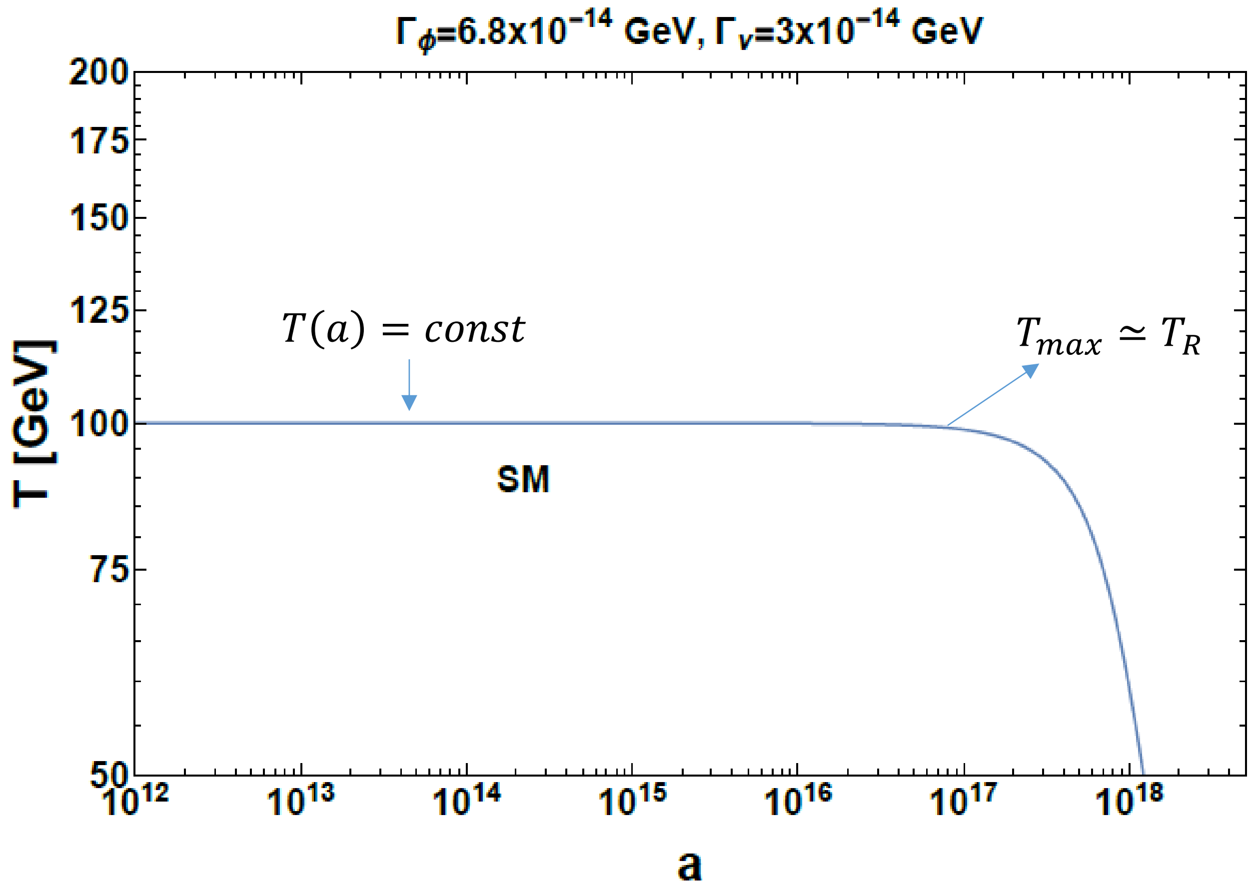


If $\Gamma_\varphi \sim \Gamma_\upsilon$

φ and υ_r decay at the same time

$T_{max} \simeq T_R$

DM abundance



Total DM particle number

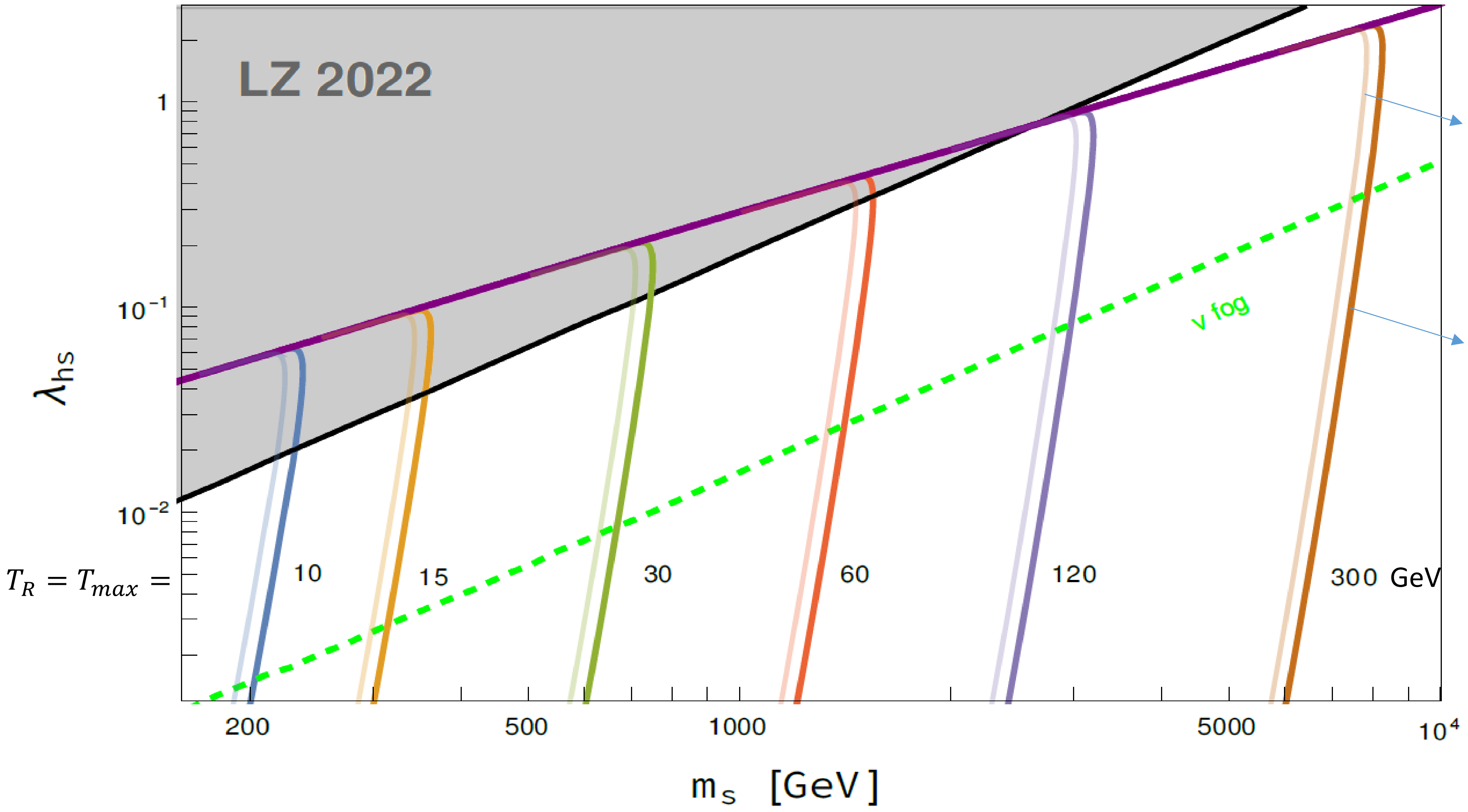
$$a^3 n\Big|_{total} = a_{max}^3 n(a_{max})\Big|_{T=const}\left(1 + (m+3)\frac{T_{max}}{2m_s}\right)$$

DM yield

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

in which $T_R \rightarrow T_{max}$

Phenomenology – Direct detection prospects



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[CC, Costa, Lebedev, 2306.13061]

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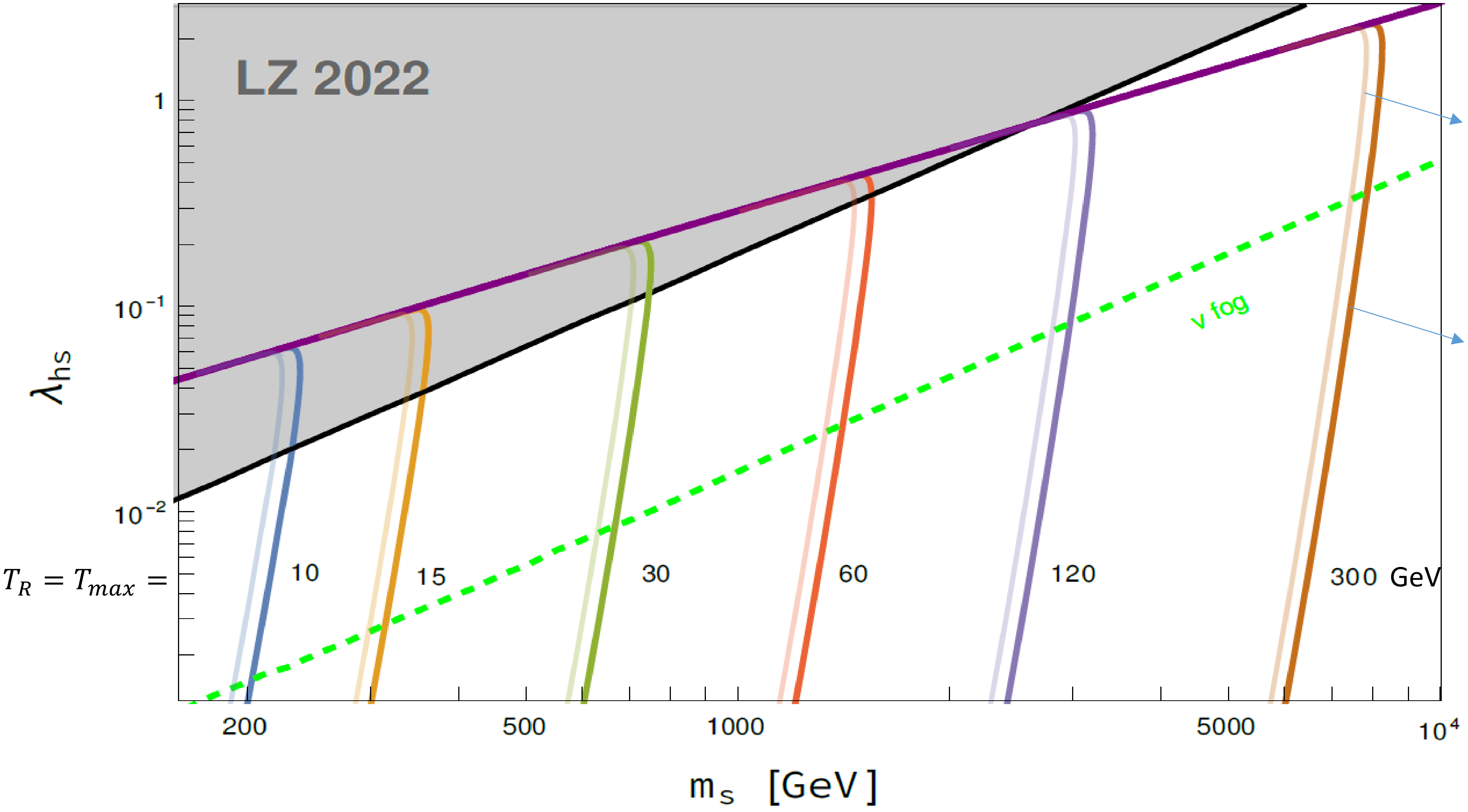

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[CC, Costa, Lebedev, 2402.04743]

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.

Thank you for your attention! / Muito obrigada pela vossa atenção!

Backup slides

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: $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \sim a^{-3}$ $\longrightarrow$ 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.

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]

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

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

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

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.

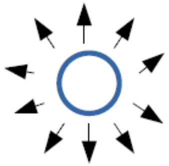
Particle Production Background - Examples

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

T ← T_{end} — T_R

Inflation

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)

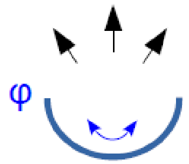
⇩

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]

(P)reheating (Matter era)

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]

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:

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

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**:

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

$$\Gamma(ss \to h_i h_i) \simeq \underbrace{\frac{\lambda_{hs}^2}{64\,\pi\,m_s^2}}_{\langle \sigma(ss \to h_i h_i) v_r \rangle} n^2$$

$$\lambda_{hs,*} \simeq 90\; e^{m_s/(2T_R)} \sqrt{\frac{m_s}{M_{Pl}}}$$

Critical coupling

SM sector production via υ_R decay

Evolution of the energy density of the Universe:

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

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

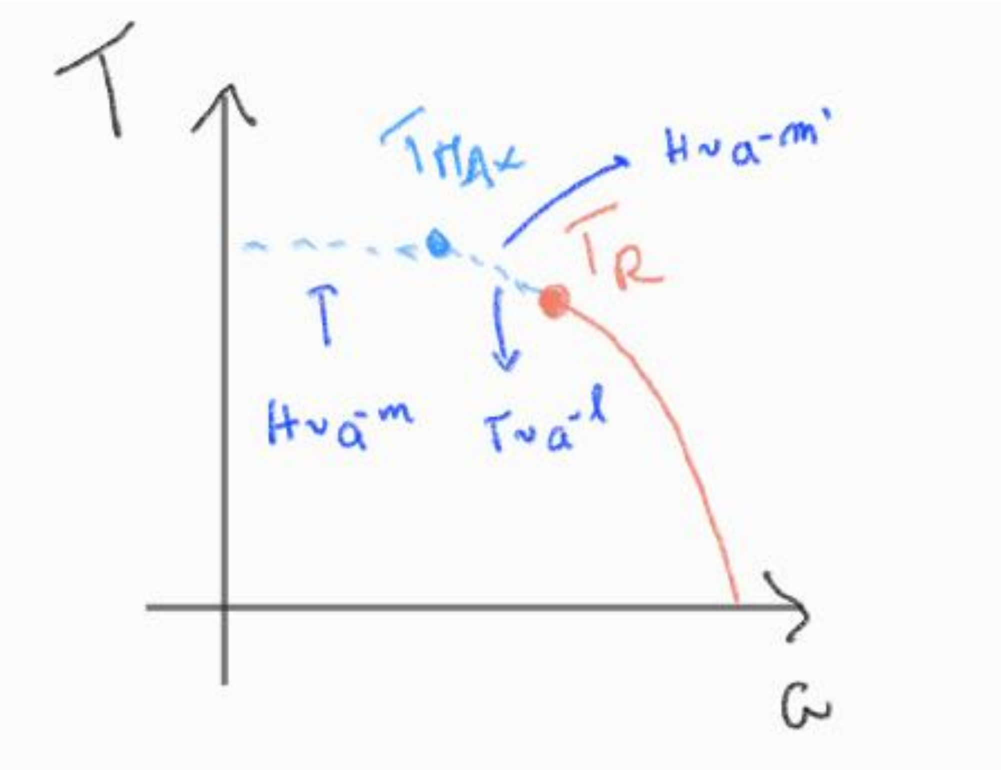
$$\dot{\rho}_{SM} + 4H\rho_{SM} = \Gamma_\upsilon \rho_\upsilon$$

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

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 $m_s \gg T_{max}$

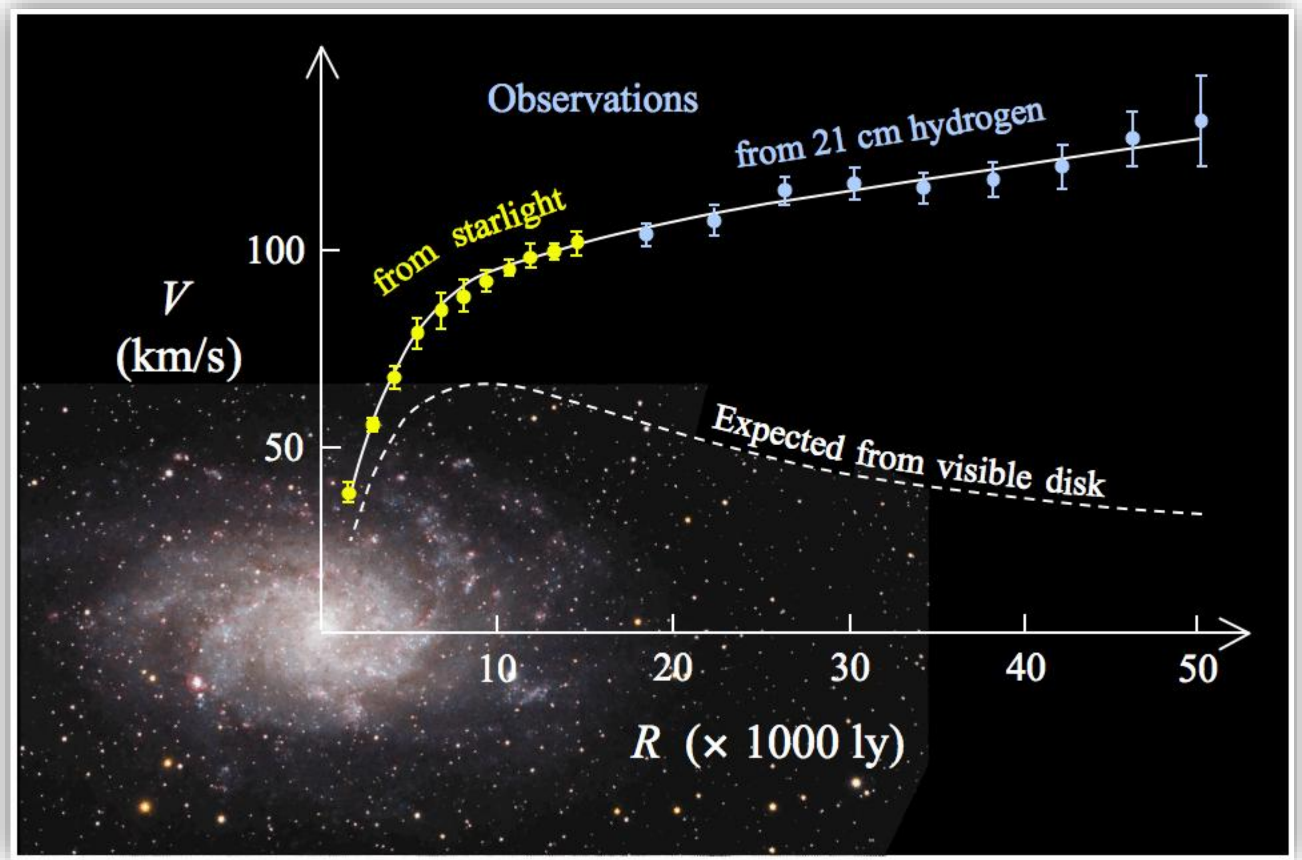


$$\lambda_{hs} \to \lambda_{hs} \times \left(\frac{T_{\max}}{T_R}\right)^{\frac{m'+3-5l}{2l}}$$

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**

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

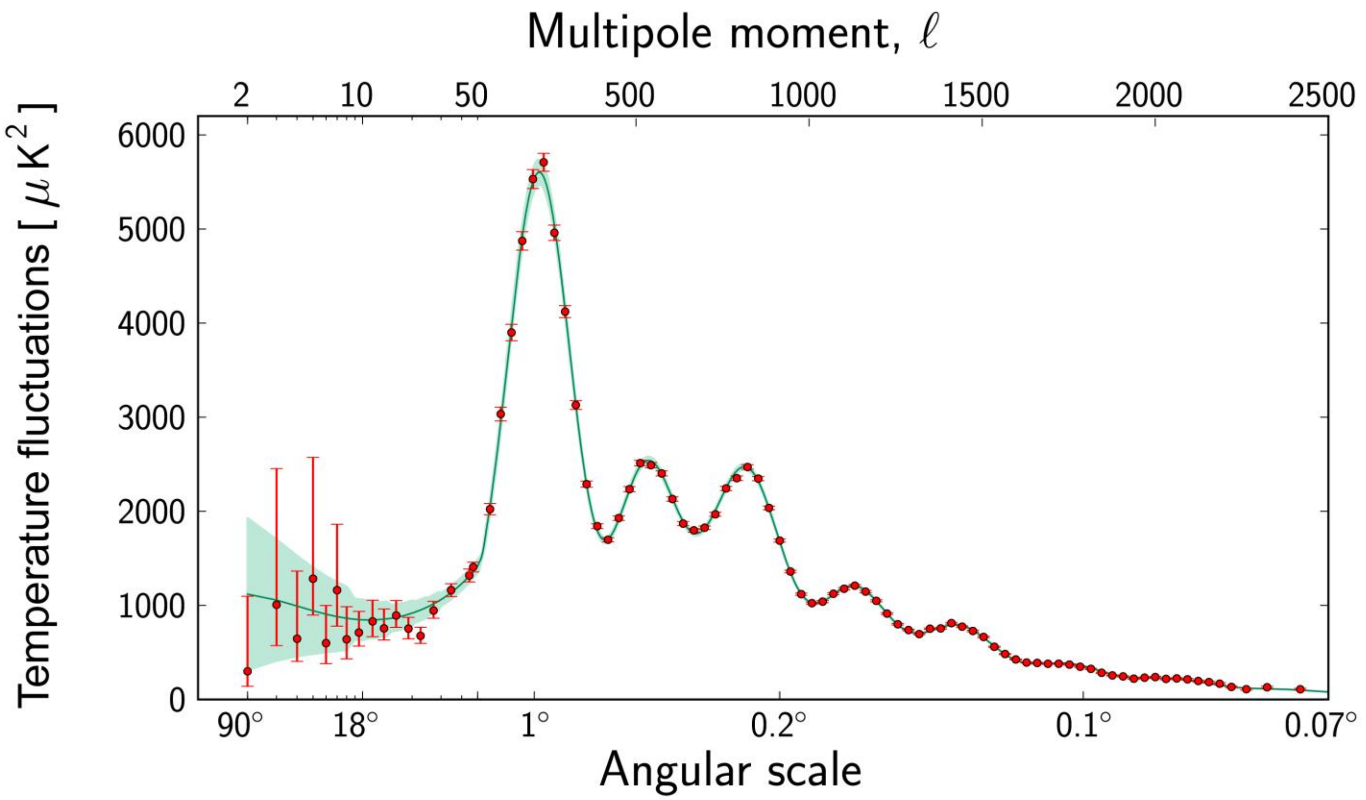
$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

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

Introduction – Why do we think that dark matter exists?

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

Baryon Acoustic Oscillations of the Cosmic Microwave Background (CMB)

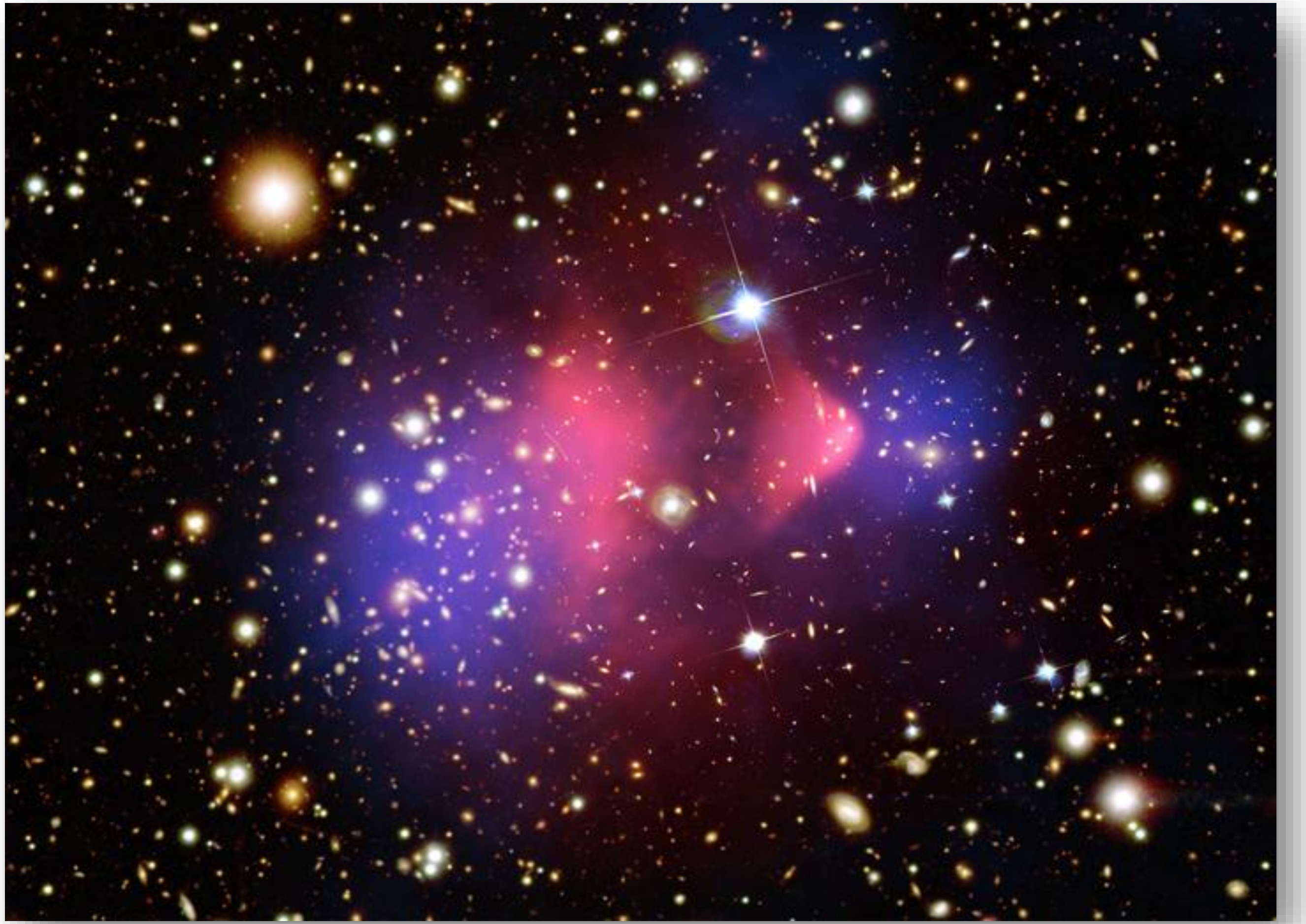


Credits: **Planck Collab.**

Introduction – Why do we think that dark matter exists?

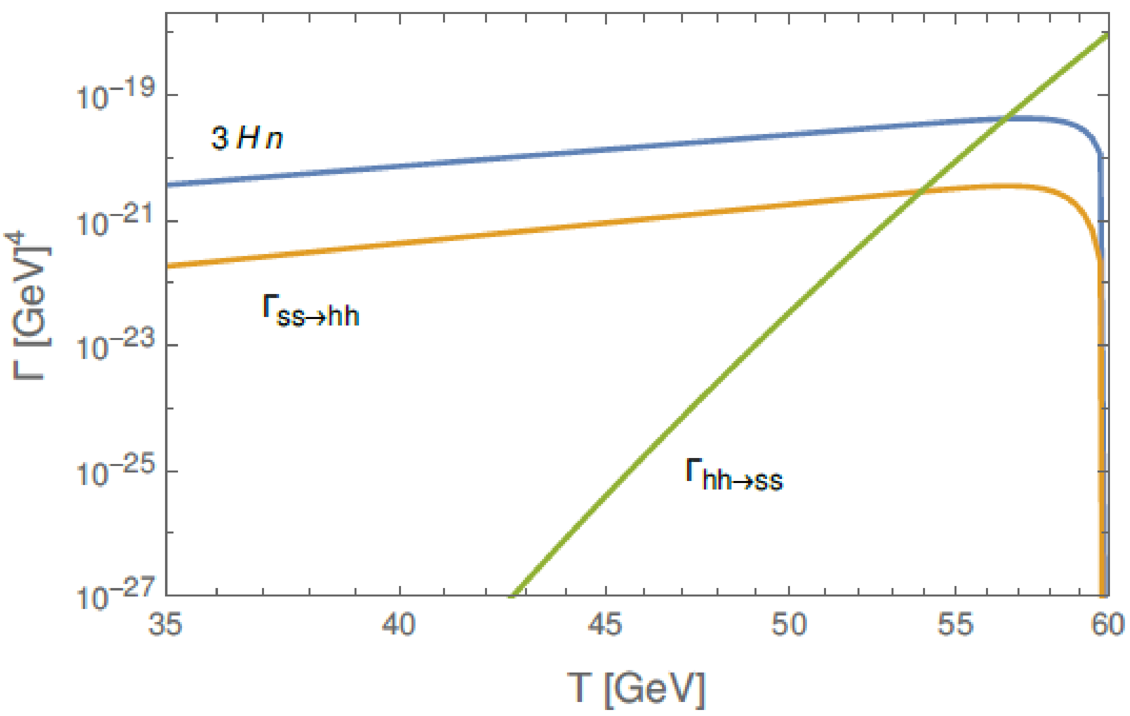
- **Evidence** for dark matter (DM) come from different sources:

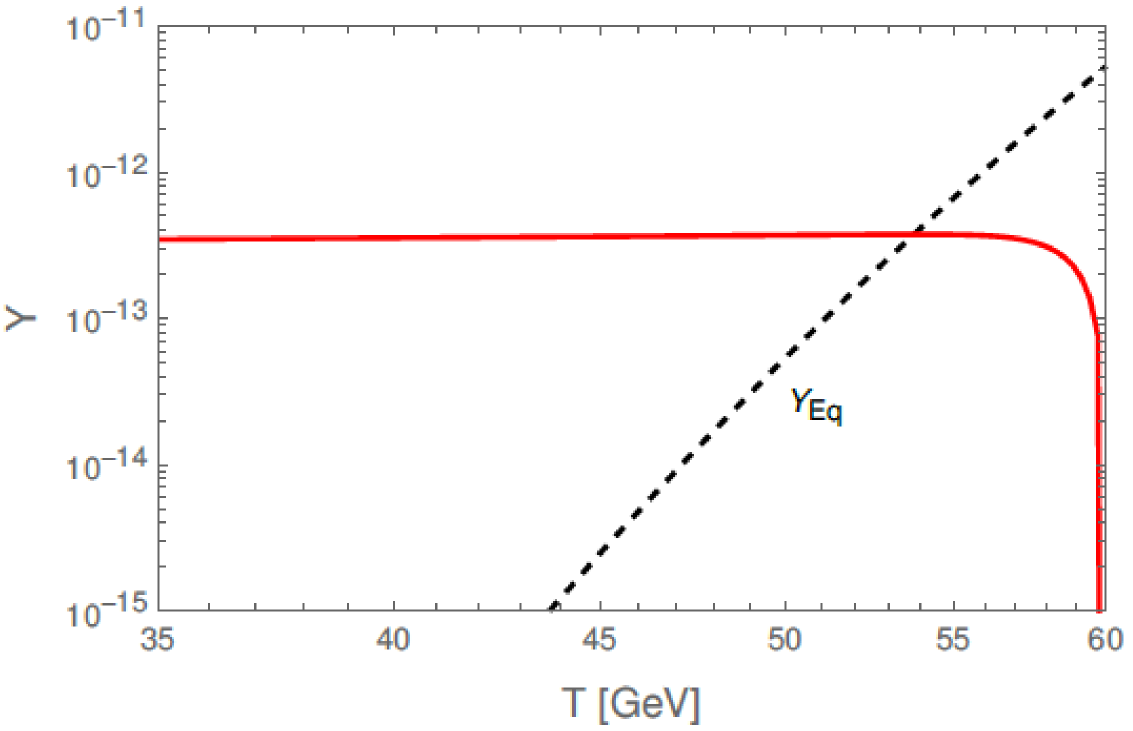
Bullet Cluster, gravitational lensing



Credits: **NASA.**

Phenomenology – Reaction rates

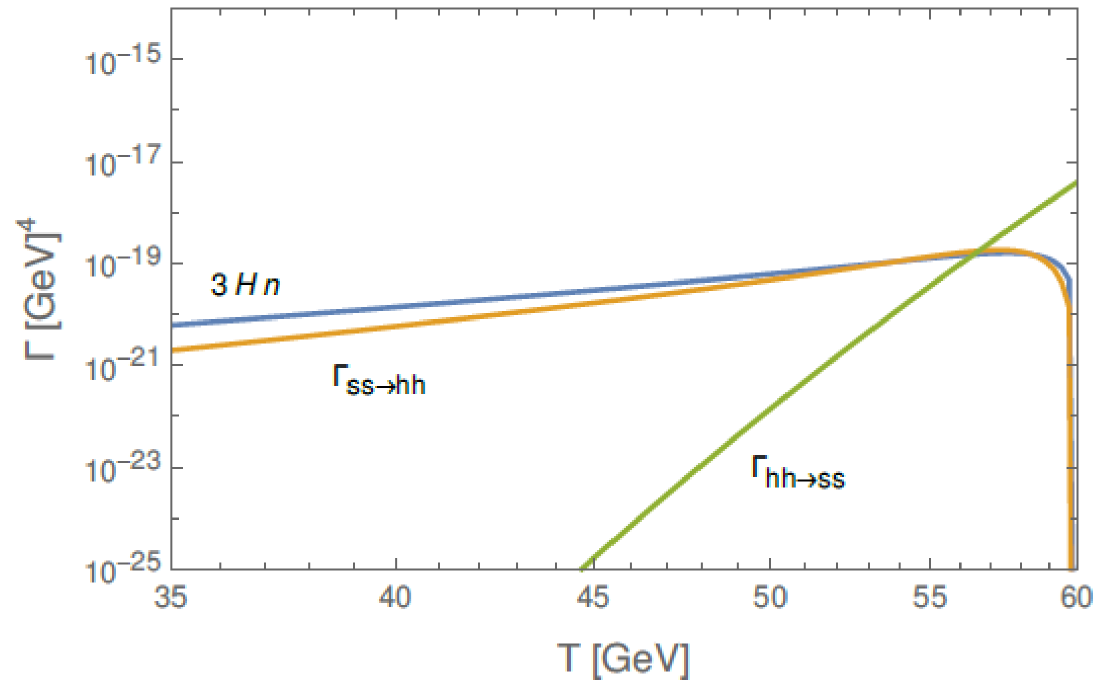


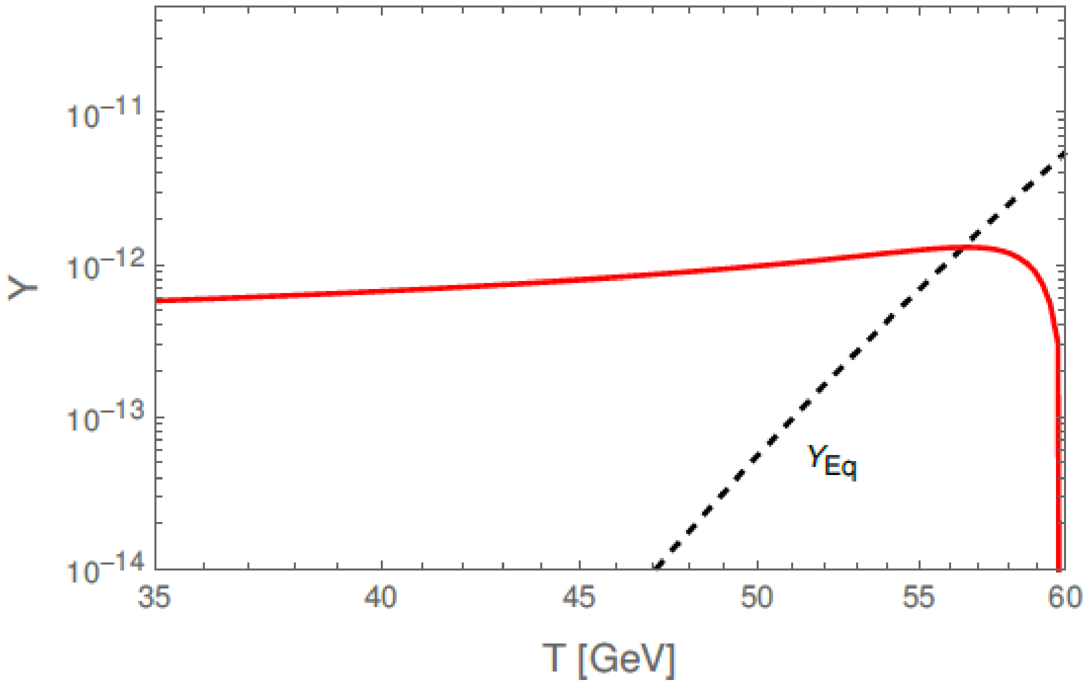


$T_R = 60$ GeV, $m_s = 1453$ GeV, $\lambda_{hs} = 0.2$

Annihilation rate is never significant → Freeze-in regime

Phenomenology – Reaction rates

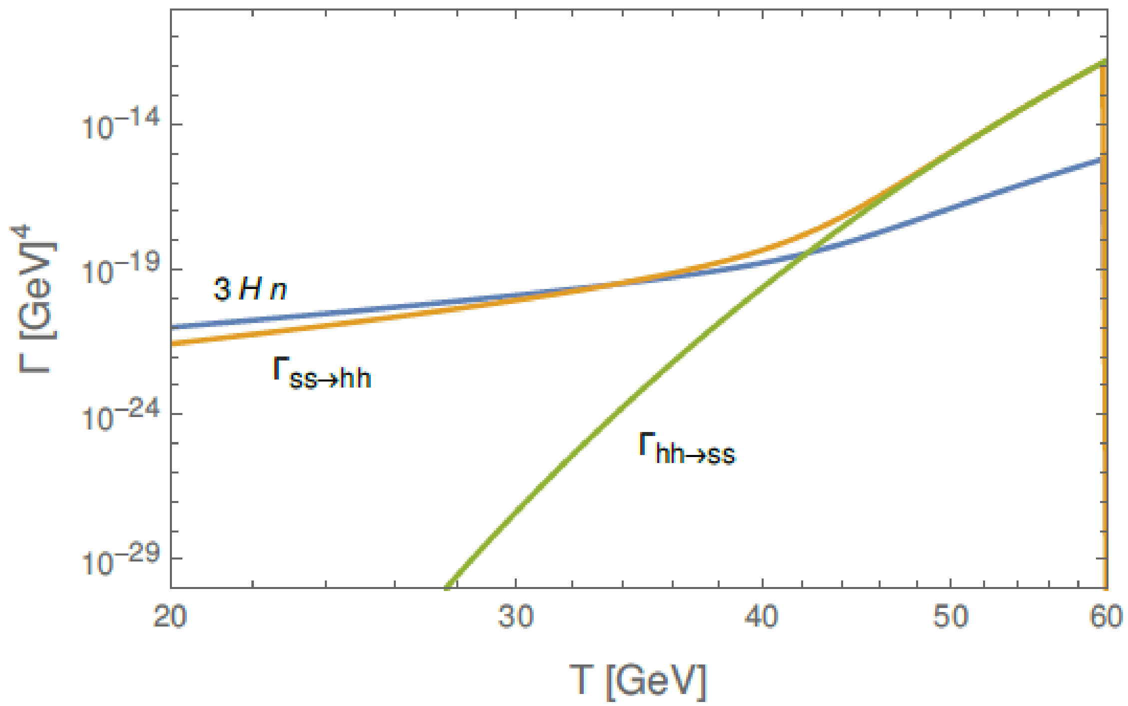


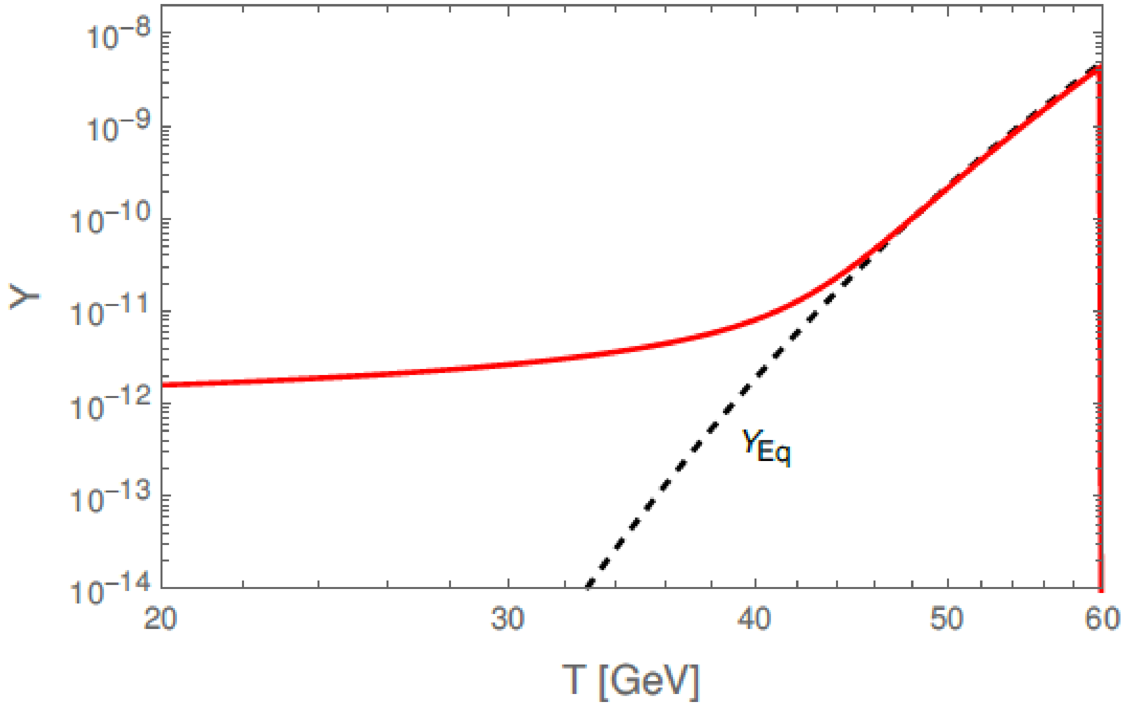


$T_R = 60$ GeV, $m_s = 1451$ GeV, $\lambda_{hs} = 0.39$

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