Freeze-in at stronger coupling

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in collaboration with
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arXiv:2306.13061

***YOUNGST@RS – Interacting dark sectors in Astrophysics, Cosmology and the lab*, Mainz Institute for Theoretical Physics, Online Workshop, 6 November 2023**

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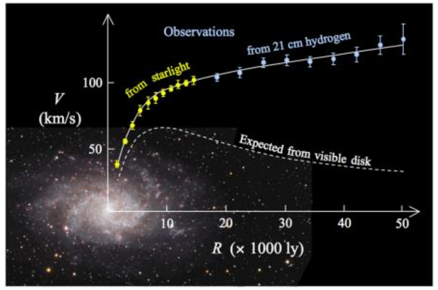
FCT Fundação para a Ciência e a Tecnologia

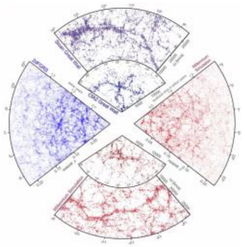
Introduction - Dark Matter (DM)

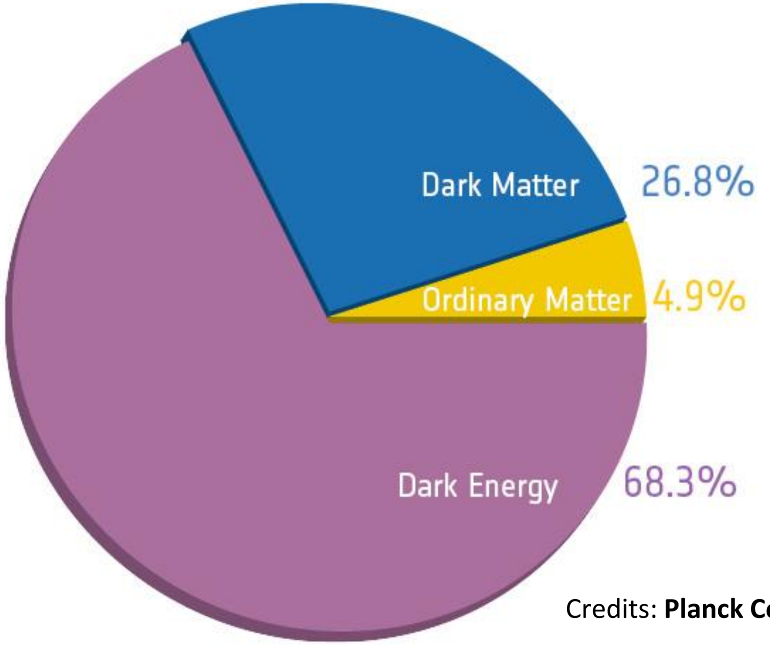
Galaxy Rotation Curves



Merging clusters (Bullet Cluster)

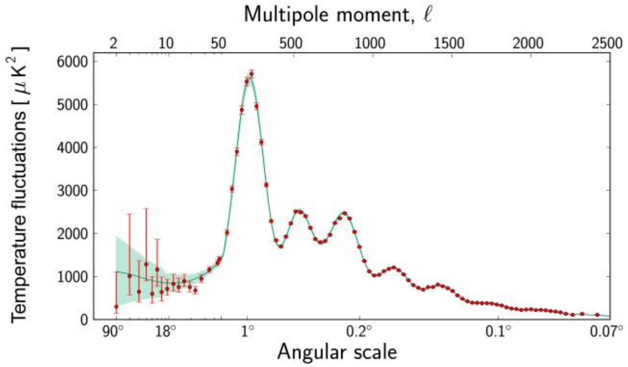
Structure formation



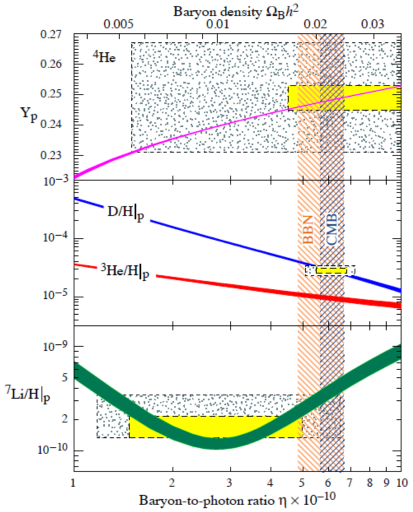


Credits: **Planck Collab.**

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:1703.07364]

Introduction - Dark Matter production mechanisms

Freeze-out vs

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Introduction - Dark Matter production mechanisms

Freeze-out vs Freeze-in

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$$\longleftarrow$$

Introduction - Dark Matter production mechanisms

Freeze-out vs Freeze-in

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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:

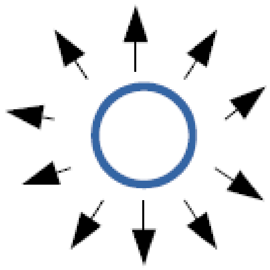
1 – **Small** couplings (hard to probe);

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

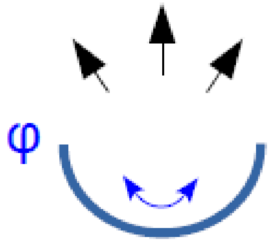
How can we probe FIMPs?

Particle Production Background

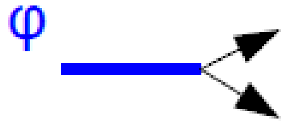
Feeble coupled particles can be copiously **produced during** and **after inflation** (all add up):



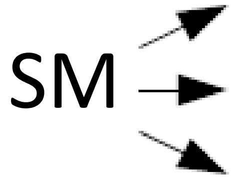
Scalar fluctuations



Inflaton oscillations



Inflaton decay



Freeze-in

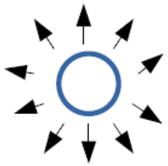
- Very small (**feeble**) couplings to other particles $\Rightarrow$ **No thermal equilibrium**;
- Even if there are **no couplings** to other fields, **gravitational** particle **production** is still **on**!

Particle Production Background - Examples

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

T ← ——— T_{end} ——— T_R ———

Scalar field fluctuations



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

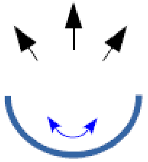
$m_s \ll H, \lambda_s \ll 1 \;\; \Rightarrow$ Quantum fluctuations

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

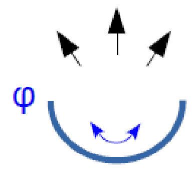
Induce $\mathcal{L} \sim \frac{\varphi^2 (\partial s)^2}{M_{Pl}^2}$

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

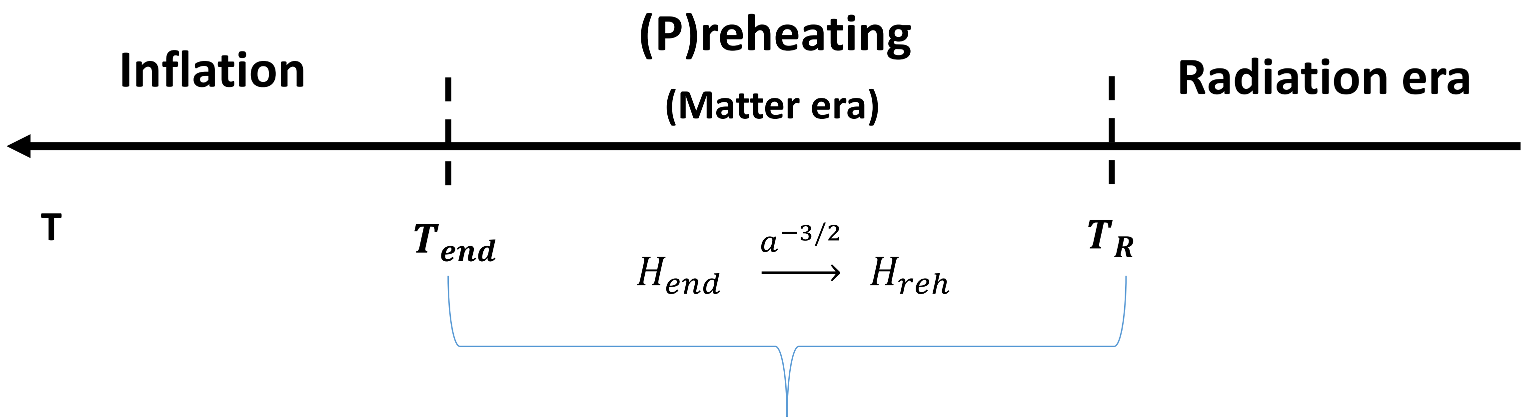
[Y. Ema, R. Jinno, K. Mukaida, K. Nakayama, 1502.02475]
[O. Lebedev, 2210.02293]

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**



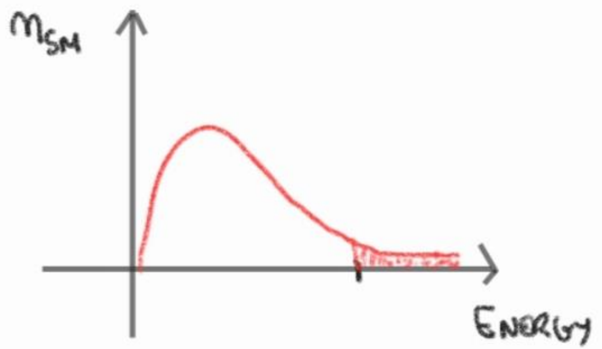
Dilution of the relics: $\Delta_{NR} \equiv \left(\frac{H_{end}}{H_{reh}}\right)^{1/2} > 1$ ⇒ **lower reheating** temperature, T_R

The model – Freeze-in at stronger coupling

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

If $T_R < m_{DM}$:

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**

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

$\boldsymbol{T_R < m_s}$

DM number density, **n**:

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

The model – Annihilation DM effect inefficient

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

→

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

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Freeze-in case

The model – Thermalization requirement

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Only **thermalizes** if

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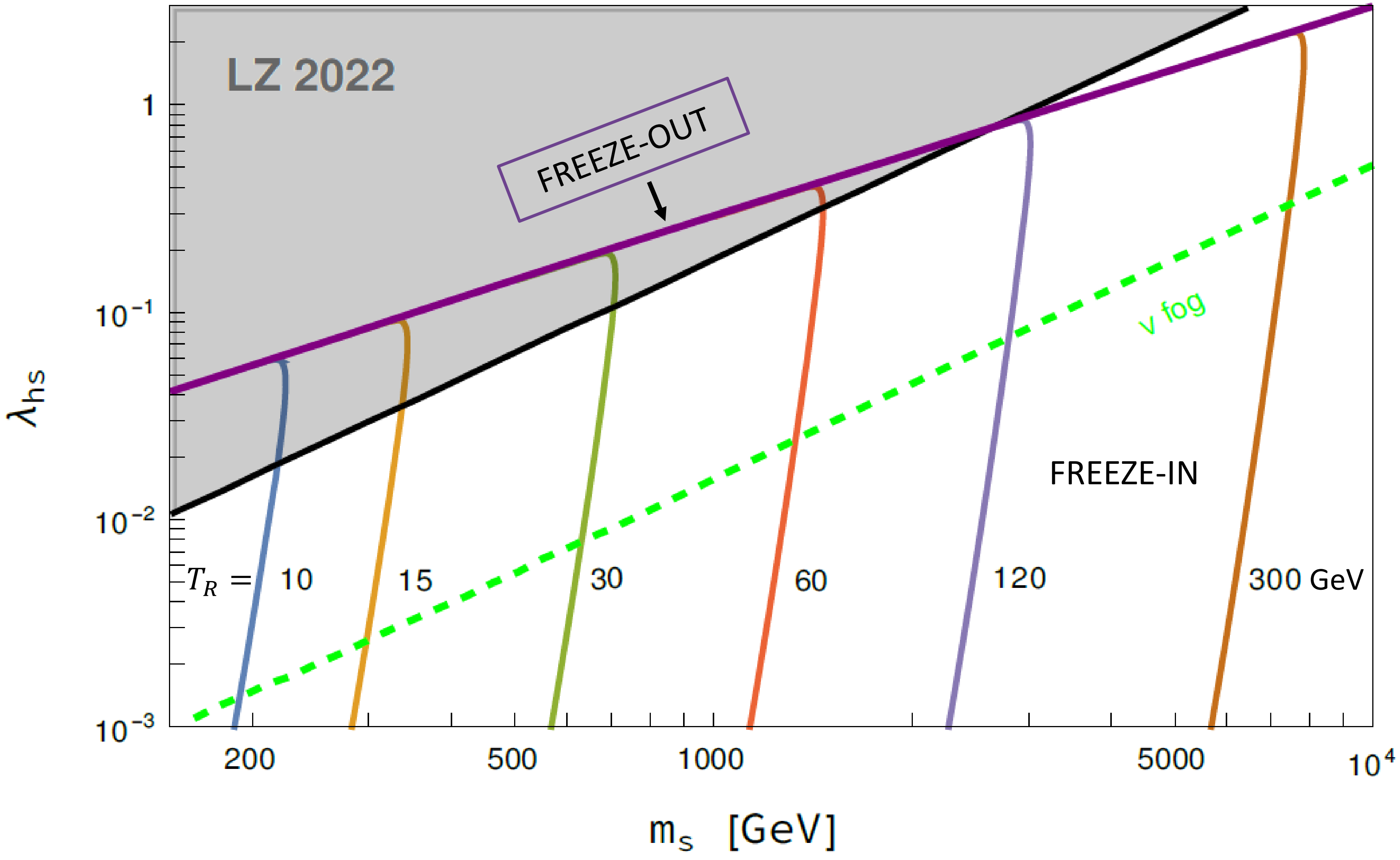
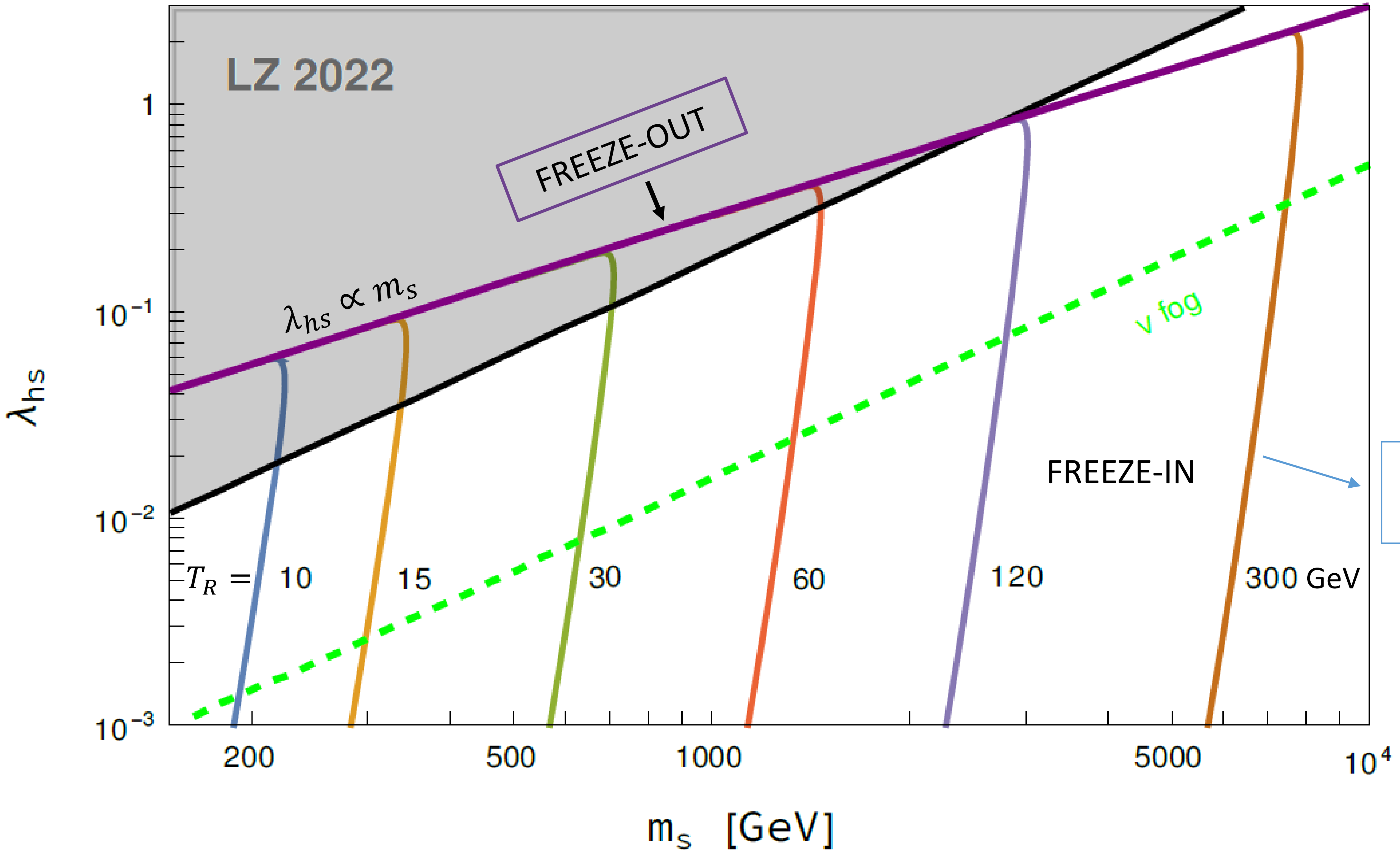
Freeze-out case

Phenomenology – Direct detection prospects



Phenomenology – Direct detection prospects



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

Conclusions

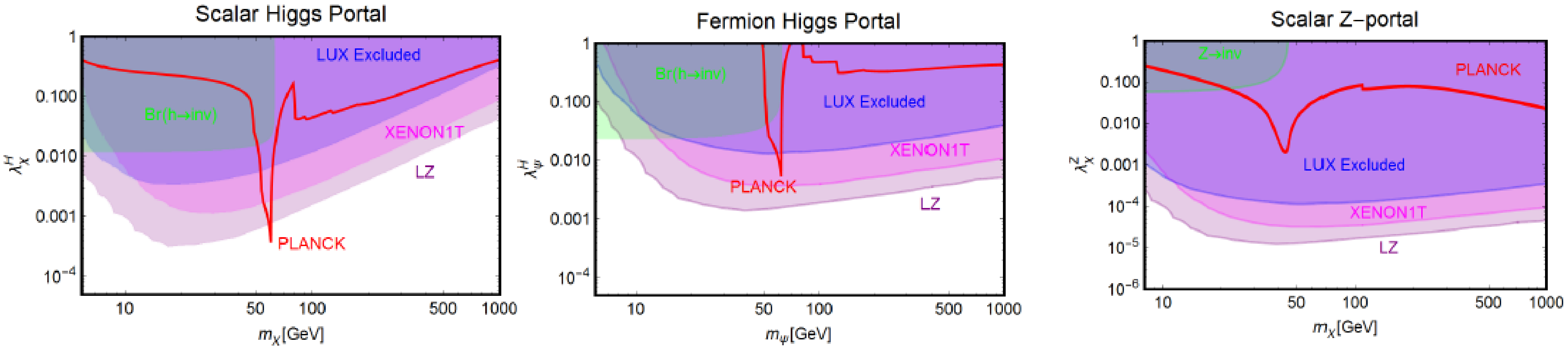
- **DM** can be **produced abundantly** via **gravity** in the early Universe;
- An **early matter** era leads to a **lower** reheating temperature (T_R) and can **dilute DM** produced gravitationally;
- We have studied the **Higgs portal DM**, with DM being produced via **freeze-in**;
- If $m_{DM} > T_R$, 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!

Backup slides

Freeze-out mechanism

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



Credits: **Arcadi et. al, arXiv:1703.07364**

Freeze-out mechanism

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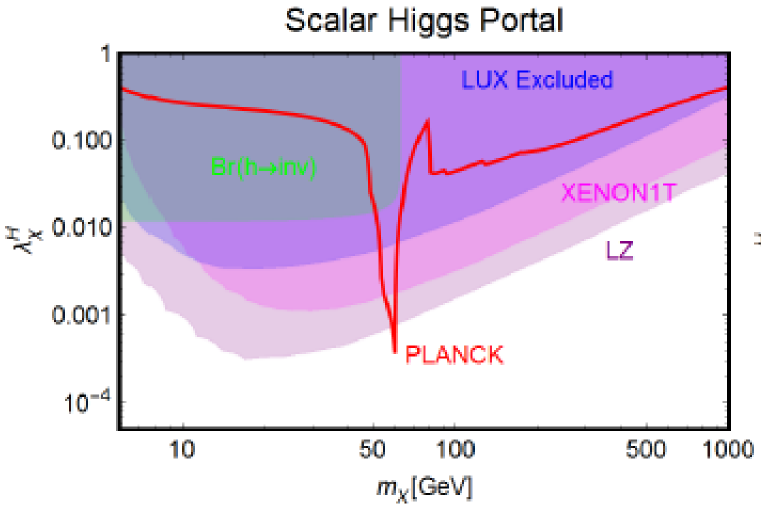

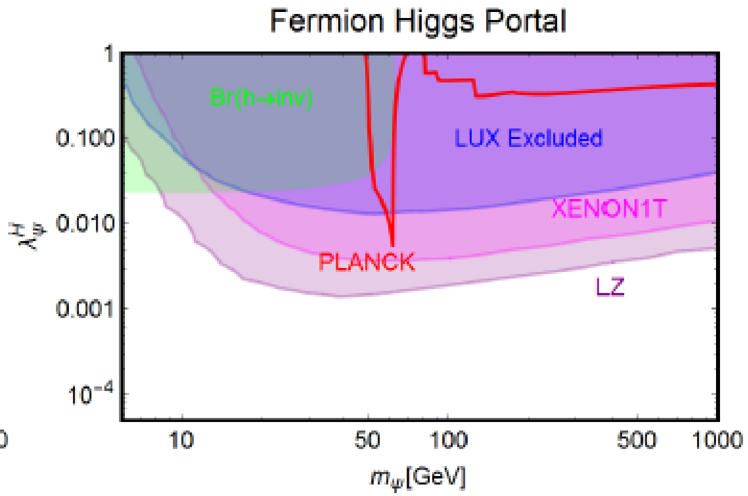

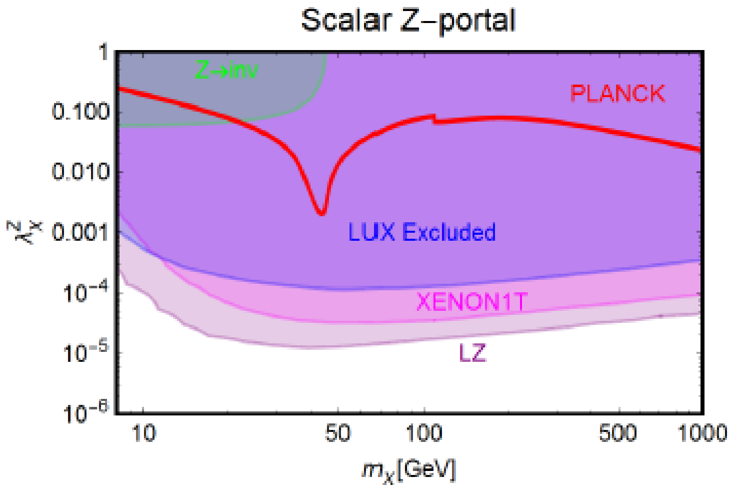

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“The waning of the WIMP?”

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.

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 →

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

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

- **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:

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

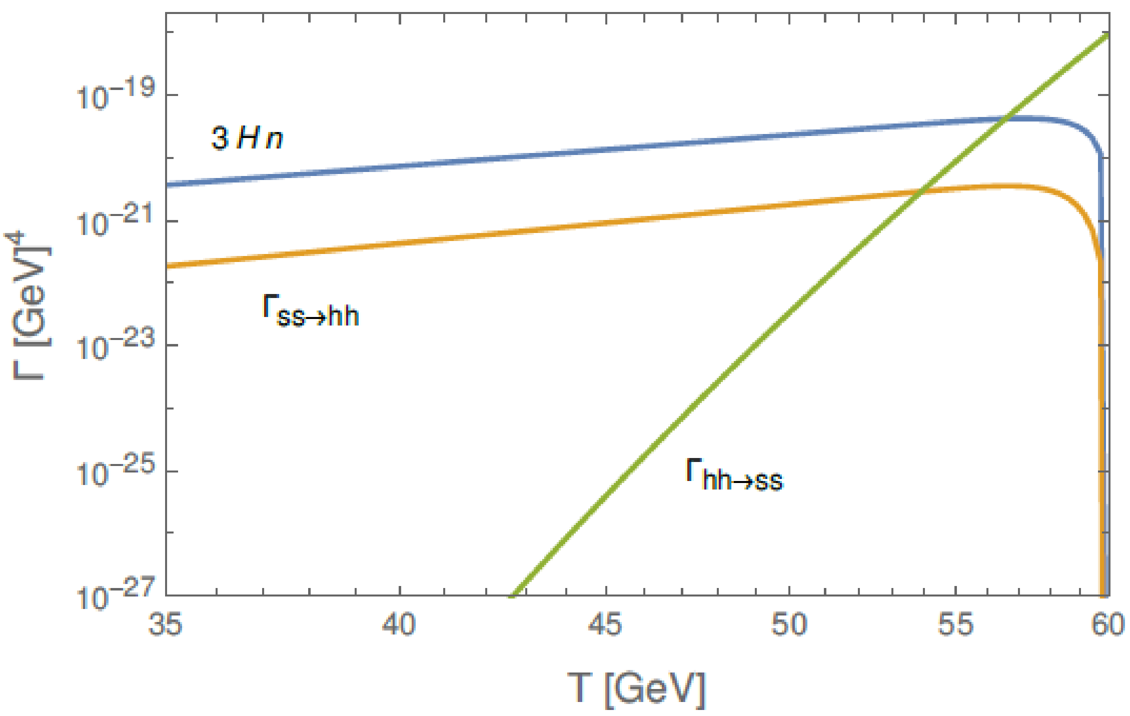
Inflaton oscillation:

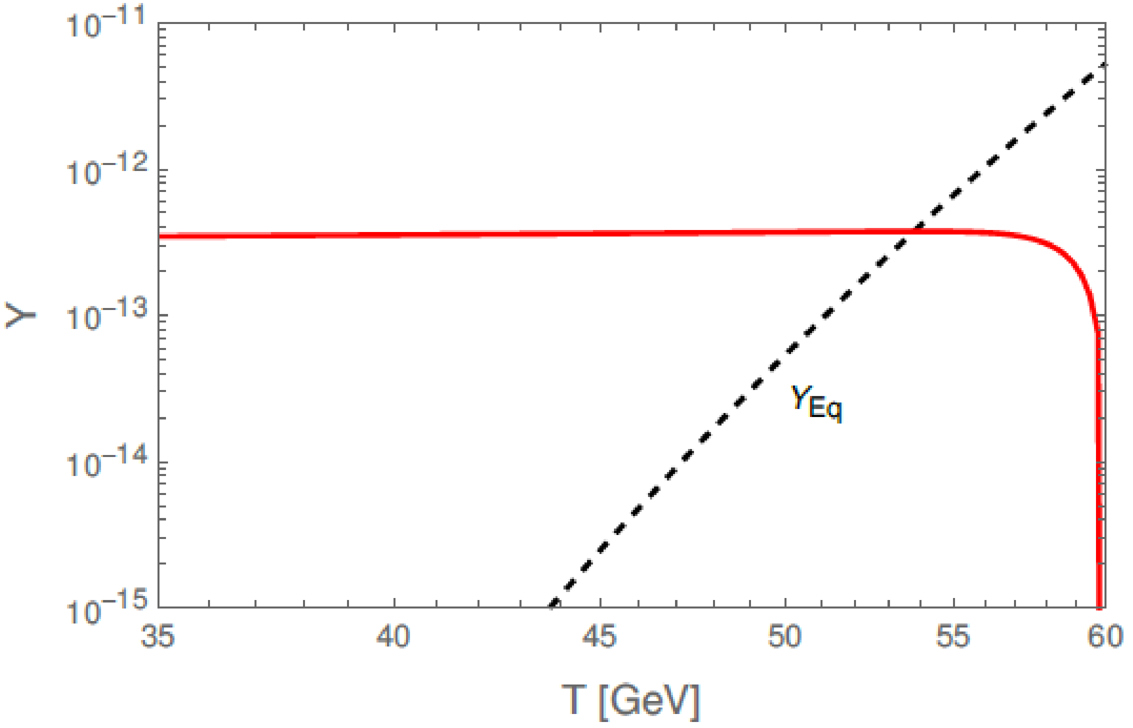
$$m_s \lesssim 10^{-6}\, \Delta_{\rm NR} \left(\frac{M_{\rm Pl}}{H_{\rm end}}\right)^{3/2} \; {\rm GeV}$$

Quantum gravity:

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

Phenomenology – Reaction rates

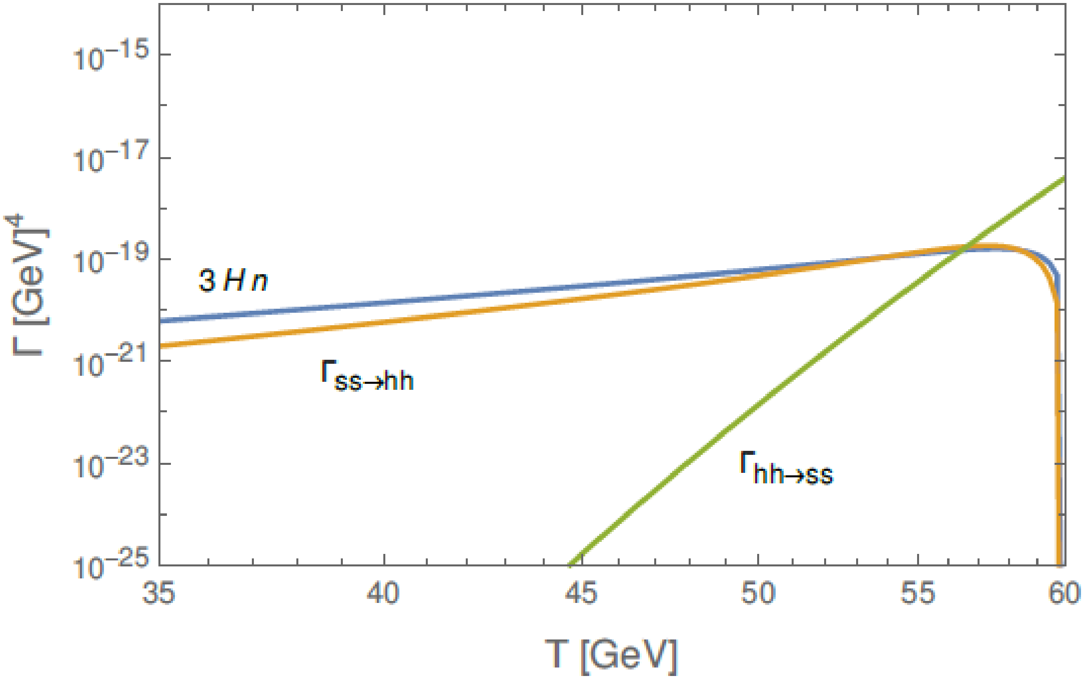


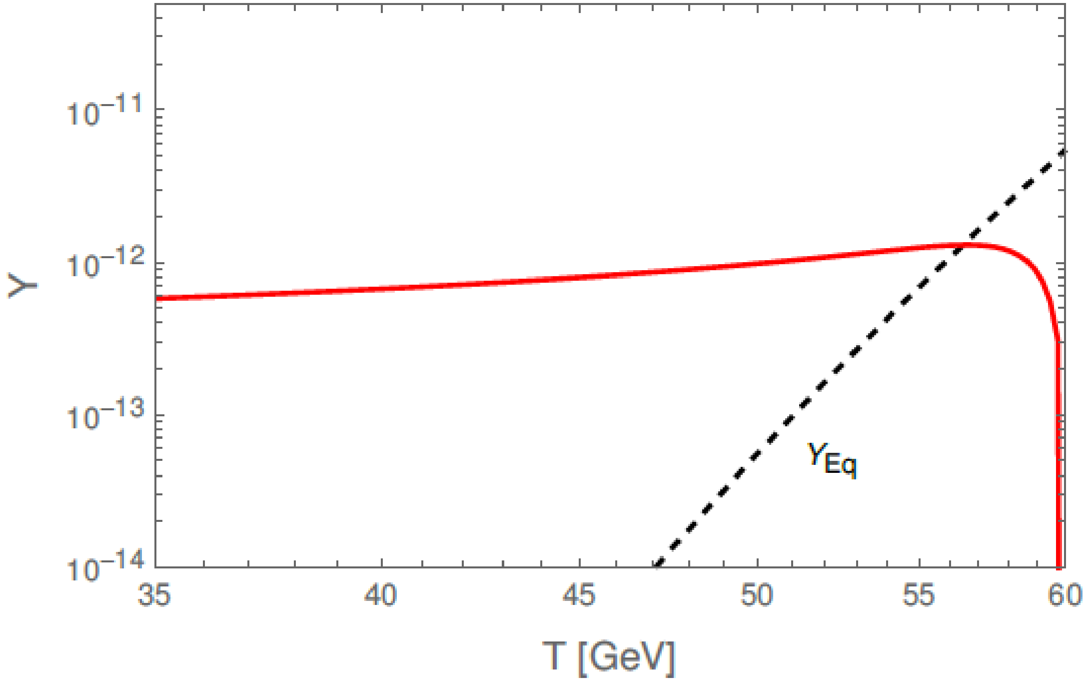


$T_R = 60$ GeV, $m_s = 1453$ GeV, $\lambda_{hs} = 0.2$

Annihilation rate is never significant → Freeze-in regime

Phenomenology – Reaction rates

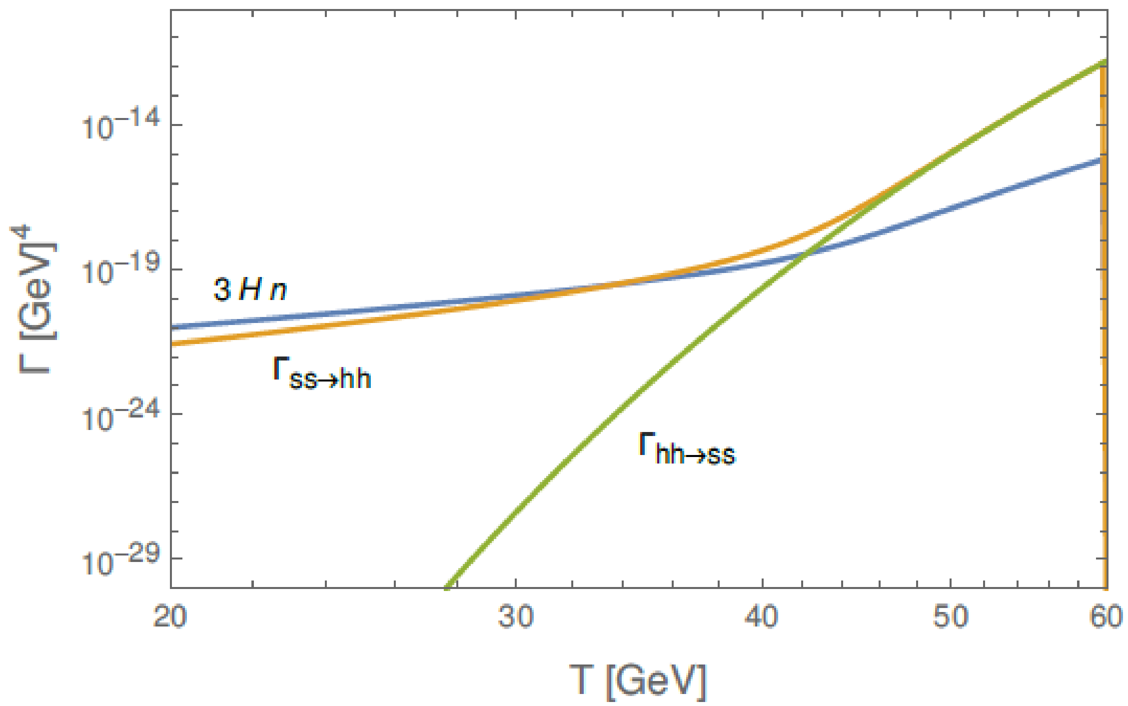


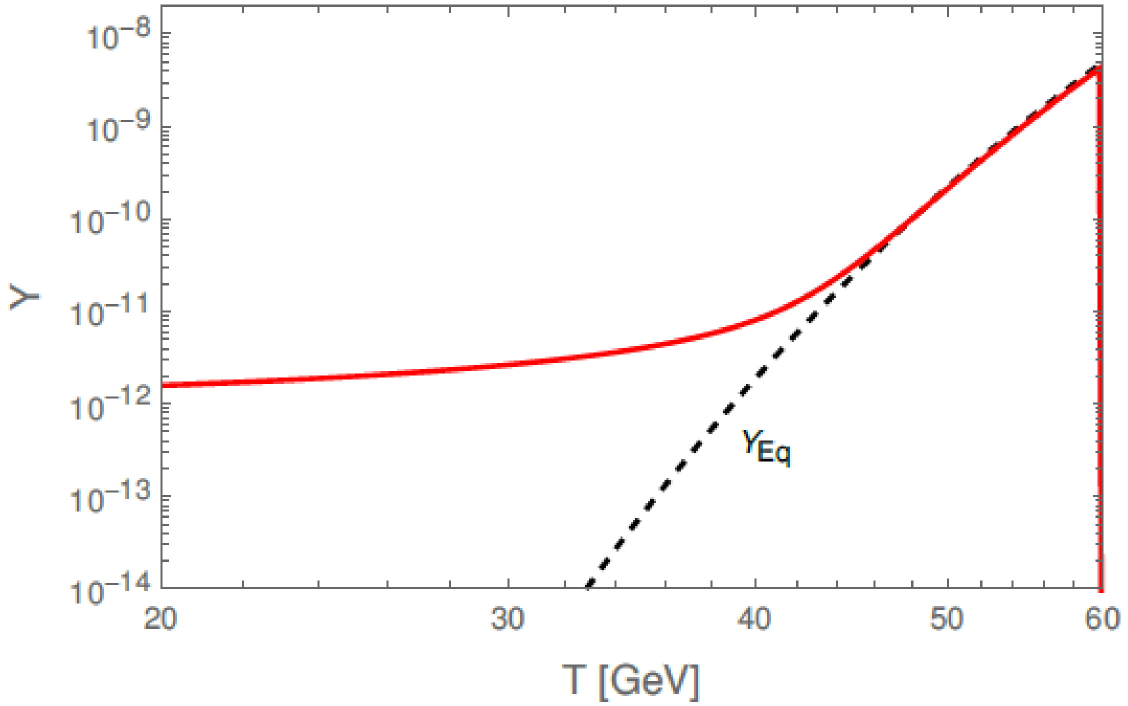


$T_R = 60$ GeV, $m_s = 1451$ GeV, $\lambda_{hs} = 0.39$

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**:

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

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

Critical coupling