Freeze-in at stronger coupling

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– ***particle production during and after inflation***

– ***Planck-suppressed operators***

– ***freeze-in dark matter***

Main references :

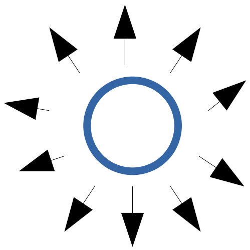
2306.13061 [hep-ph] Cosme, Costa, OL

2210.02293 [hep-ph] OL

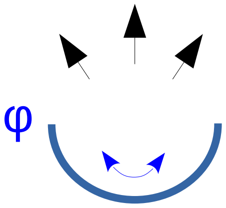
Non-thermal relics / DM have memory !

Production mechanisms (*all add up*):

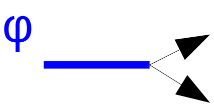
- during inflation



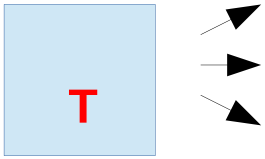
- via inflaton oscillations



- inflaton decay



- thermal emission (freeze-in)



Decoupled scalar production during inflation

Scalar “s” with

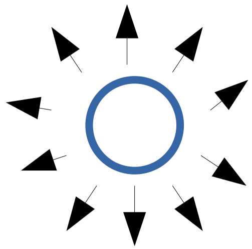
$$V(s) = \frac{1}{2}m_s^2\, s^2 + \frac{1}{4}\lambda_s\, s^4$$

$\lambda_s \ll 1 \quad , \quad m_s \ll H$

Starobinsky-Yokoyama equilibrium distribution of de Sitter fluctuations:

$$P(s) \propto \exp\left[-8\pi^2 V(s)/(3H^4)\right]$$

$$\langle s^2 \rangle \simeq 0.1 \times \frac{H_{\rm end}^2}{\sqrt{\lambda_s}}$$



scalar
fluctuation
generation

Mean field:

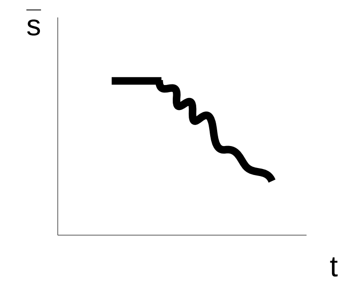
$$\bar{s} \equiv \sqrt{\langle s^2 \rangle}$$

Peebles, Vilenkin ‘99
Markkanen, Rajantie, Tenkanen ‘18

Effective mass:

$$m_{\text{eff}}^2 = m_s^2 + 3\lambda_s \bar{s}^2$$

Evolution:



$$\bar{s}_{\text{end}} \xrightarrow{a^0} \bar{s}_{\text{osc}} \xrightarrow{a^{-1}} \bar{s}_{\text{dust}}$$

frozen → oscillates in s^4 potential → oscillates in s^2 potential

$H > m_{\text{eff}}$ **$H \sim m_{\text{eff}}$** **$m_s \sim m_{\text{eff}}$**

Relic number density (*non-rel.*) = energy density / particle mass :

$$n \simeq m_s^3/\lambda_s$$

Constraints

Require

$$Y \leq 4.4 \times 10^{-10} \, \frac{\text{GeV}}{m_s}$$

instant reheating
or φ⁴

$$m_s \, \lambda_s^{-5/8} \lesssim 10^{-7} \left(\frac{M_{\rm Pl}}{H_{\rm end}} \right)^{3/2} \text{GeV}$$

Hubble rate at the end of inflation

Very strong constraint :

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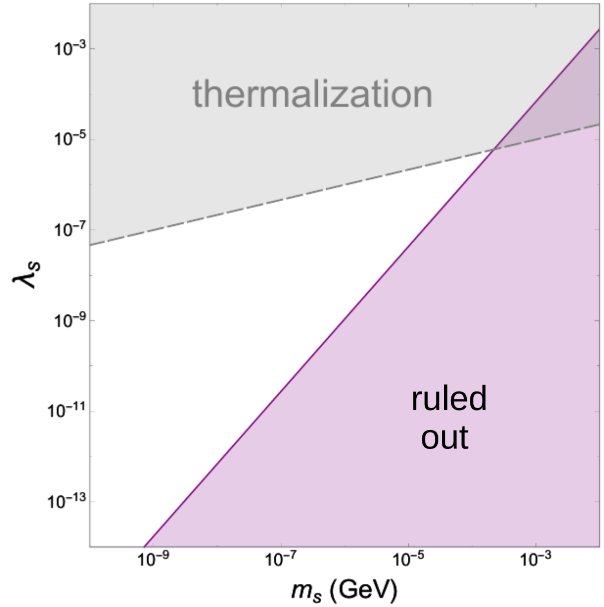


Starobinsky-Yokoyama
fluctuations

$$H_{\rm end} \sim 10^{14} \text{ GeV}$$

$$\Delta_{\rm NR} = 1$$

In general, the abundance depends on duration of the ***non-relativistic*** expansion period (φ^2 pot.):

$$H_{\rm end} \xrightarrow{a^{-3/2}} H_{\rm reh} \qquad \Delta_{\rm NR} \equiv \left(\frac{H_{\rm end}}{H_{\rm reh}}\right)^{1/2} > 1$$

Dilutes the energy in the condensate → weaker constraint

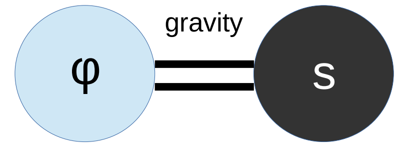
$$m_s\,\lambda_s^{-3/4} \lesssim 10^{-7}\,\Delta_{\rm NR}\left(\frac{M_{\rm Pl}}{H_{\rm end}}\right)^{3/2}\,{\rm GeV}$$

$H_{\rm end} \sim 10^{14}$ GeV ➡ $m_s \ll \Delta_{\rm NR}$ GeV

*Only particles **far below** the **GeV** scale are allowed for* $\Delta_{\rm NR} = 1$

Quantum gravity effects

Induce gauge invariant operators
(*with unknown coefficients)*



Dim-6 gravity-induced couplings:

Also induced by ***classical*** gravity!

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

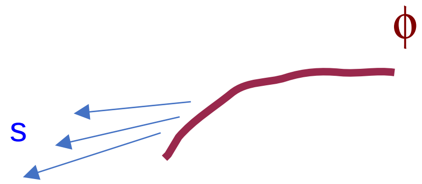
Main operators for on-shell fields contributing to s-pair production:

$$\mathcal{O}_3 = \frac{1}{M_{\rm Pl}^2}\,(\partial_\mu s)^2\phi^2 \quad , \quad \mathcal{O}_4 = \frac{1}{M_{\rm Pl}^2}\,\phi^4 s^2$$

(supplemented with dim-4 $\mathcal{O}_{\rm renorm} = \frac{m_\phi^2}{M_{\rm Pl}^2}\,\phi^2 s^2$ and 4-DM op $\frac{C_5}{M_{\rm Pl}^2}\,\phi^2 s^4$)

Particle production:

$\mathcal{O}_4$ dominates



$$\Gamma = \frac{C_4^2}{4\pi M_{\rm Pl}^4} \sum_{n=1}^{\infty} |\hat{\zeta}_n|^2 \qquad \hat{\zeta}_n = \sum_{m=-\infty}^{\infty} \zeta_{n-m}\zeta_m$$

$$\dot{n} + 3Hn = 2\Gamma$$

2210.02293

$$\Delta_{\rm NR} \equiv \left(\frac{H_{\rm end}}{H_{\rm reh}}\right)^{1/2}$$

$$|C_4| < 10^{-3}\,\Delta_{\rm NR}^{1/2}\,\frac{H_{\rm end}^{5/4}\,M_{\rm Pl}^{11/4}}{\phi_0^4}\sqrt{\frac{\rm GeV}{m_s}}$$

$$\phi_0 \sim M_{\rm Pl} \text{ and } H_{\rm end} \sim 10^{14}\ {\rm GeV} \quad \Rightarrow \quad |C_4| < \text{few} \times 10^{-9}\,\Delta_{\rm NR}^{1/2}\sqrt{\frac{\rm GeV}{m_s}}$$

$$|C_3| \lesssim 10^{-1}\,\Delta_{\rm NR}^{1/2}\sqrt{\frac{\rm GeV}{m_s}}$$

Higher dim operators:

$$\mathcal{O}^{(p)} = \frac{\phi^p s^2}{M_{\rm Pl}^{p-2}} \qquad |C^{(p)}| < 10^{-3}\,\Delta_{\rm NR}^{1/2}\,\frac{H_{\rm end}^{5/4}\,M_{\rm Pl}^{p-5/4}}{\phi_0^p}\sqrt{\frac{\rm GeV}{m_s}}$$

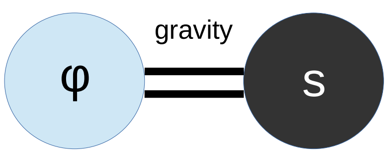
Planck-suppressed operators are very efficient in particle production!

$$\frac{\phi^4 s^2}{M_{\mathrm{Pl}}^2}\ ,\quad \frac{\phi^6 s^2}{M_{\mathrm{Pl}}^4}\ ,\quad \frac{\phi^8 s^2}{M_{\mathrm{Pl}}^6}\ ,\ \ldots$$

<u>Main observation</u> :

Planck—suppressed ("gravity--induced") operators
with <u>small</u> Wilson coefficients
can account for all of the dark matter !

Non-thermal DM model building is highly **UV sensitive** :



– abundance is additive ("memory")

– need to control quantum gravity

– **predictivity ?**

Irreducible gravity background for ***<u>Freeze-in</u>*** **:**

inflation | preheating | reheating

De Sitter fluctuations

metric oscillations
+
QG ops

$\phi^4 s^2 / M^2_{Pl}$

smaller corrections

The problem is not to produce DM, but to get rid of it !

2306.13061 [hep-ph] Cosme, Costa, OL

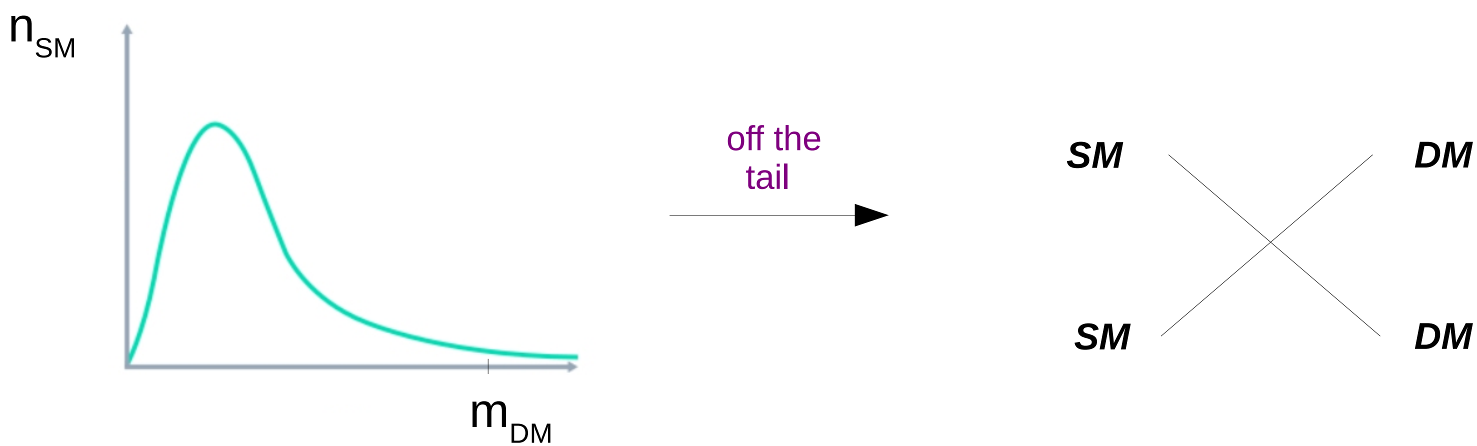
Freeze-in at stronger coupling

Need to get rid of the gravitational background → matter dominated expansion

φ^2 local inflaton potential

relics are diluted , low reheating temperature T_R

What if $T_R < m_{DM}$?



Boltzmann-suppressed DM production requires a stronger coupling → observable !

Simplest model = Higgs portal DM

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

Boltzmann equation:

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

No annihilation:

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

→

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

With annihilation:

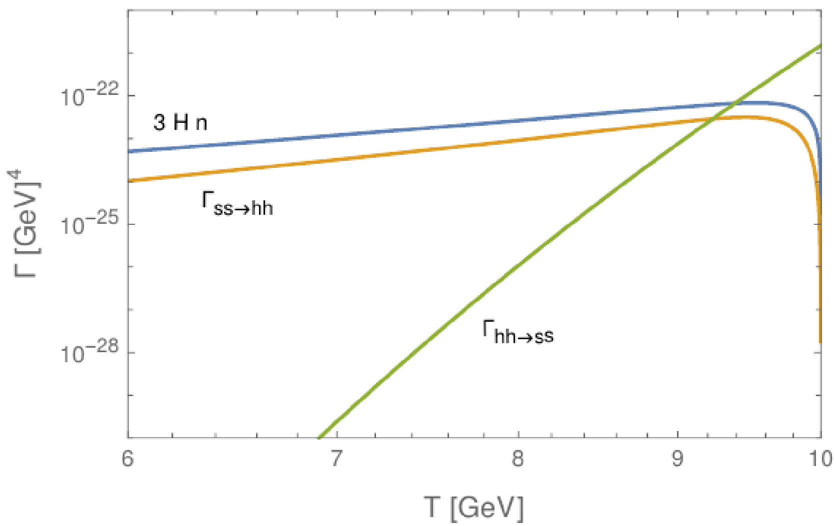
$$\Gamma(ss \to h_i h_i) = \sigma(ss \to h_i h_i) v_r\ n^2 \quad , \quad \sigma(ss \to h_i h_i) v_r = 4 \times \frac{\lambda_{hs}^2}{64\pi m_s^2}$$

No thermalization:

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

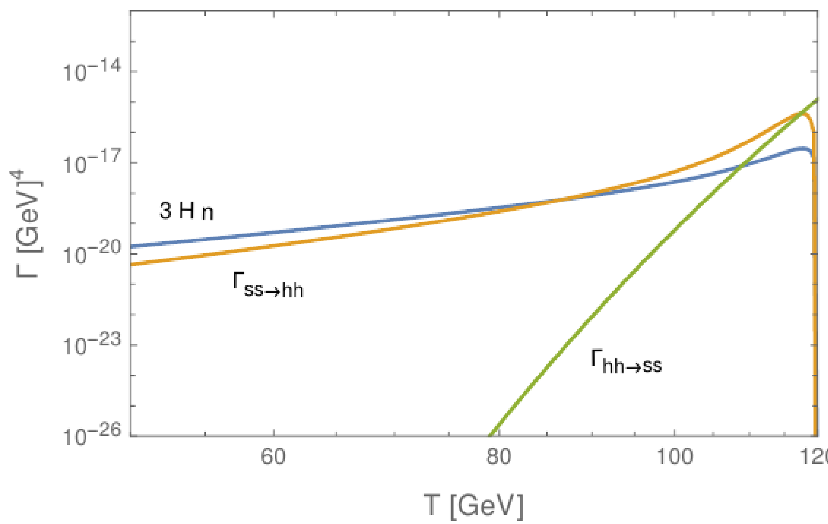
Reaction rates:

$\lambda_{hs} = 0.05$



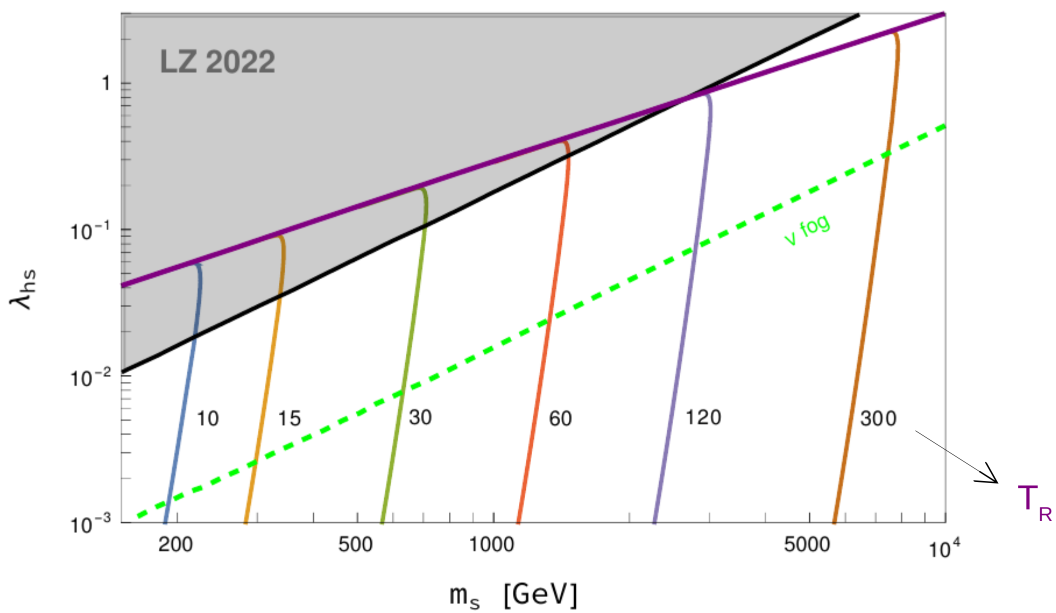
$T_R = 10\ \text{GeV},\ m_s = 223.5\ \text{GeV}$

$\lambda_{hs} = 0.82$



$T_R = 120\ \text{GeV},\ m_s = 2.81\ \text{TeV}$

Correct relic density (solid lines):



Already probed by direct detection!

As coupling ↑
FI → FO

CONCLUSION

– *gravitational DM production = strong background*

– *low T_R dilutes gravitational relics*

– *freeze-in for $m_{DM} > T_R$ requires a significant coupling*

– *freeze-in already probed by direct detection (LZ2022)*

– *further probes by XENONnT, DARWIN*