Scalar (over)production in the Early Universe

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

– ***Planck-suppressed operators***

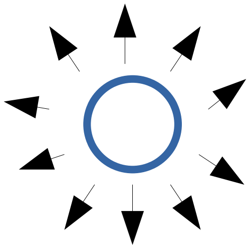
– ***non-thermal dark matter***

2210.02293 [hep-ph] **“Scalar overproduction ...”**

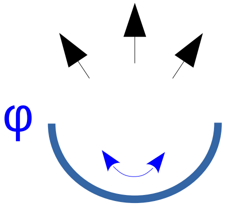
Non-thermal relics / DM have memory !

Production mechanisms (all add up):

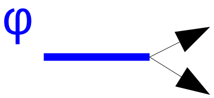
- during inflation



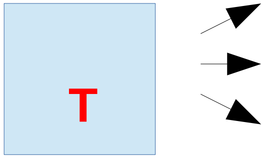
- via inflaton oscillations



- inflaton decay



- thermal emission (freeze-in)

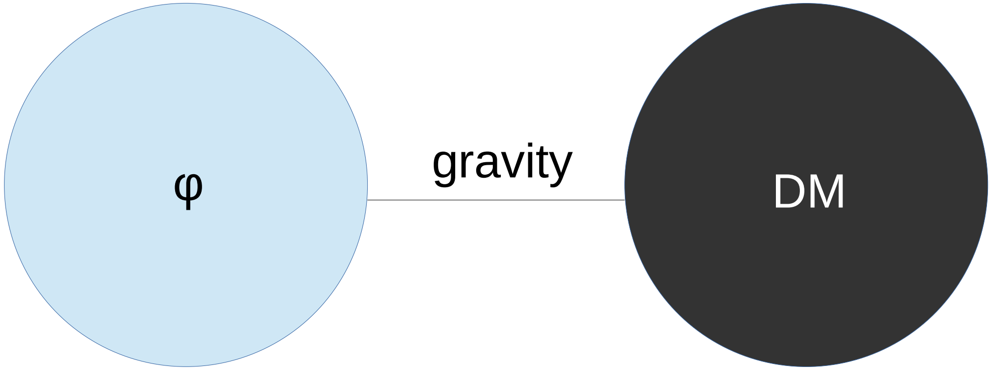


Focus:

inflation + inflaton oscillation epoch (preheating)

Assume:

no renormalizable inflaton-dark matter coupling



Decoupled scalar production during inflation

Scalar “s” with

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

Starobinsky-Yokoyama equilibrium distribution of de Sitter fluctuations:

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

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

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

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

Relic number density (non-rel.)

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

Constraints

Require

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

instant reheating or φ⁴ →

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

Hubble rate at the end of inflation

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

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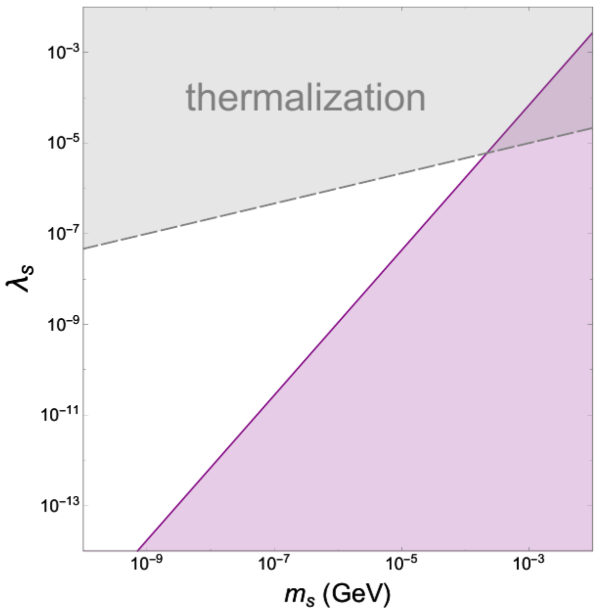
$$H_{\text{end}} \xrightarrow{a^{-3/2}} H_{\text{reh}} \qquad \Delta_{\text{NR}} \equiv \left(\frac{H_{\text{end}}}{H_{\text{reh}}} \right)^{1/2} > 1$$

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

$H_{\text{end}} \sim 10^{14}$ GeV → $m_s \ll \Delta_{\text{NR}}$ GeV



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

Decoupled scalar production after inflation

From EOM:

$$\dot{\rho}_\phi + 3H\dot{\phi}^2 = 0$$

H oscillates if φ does

The oscillating component:

Ema, Jinno, Mukaida, Nakayama '15

$$\delta H \simeq -\frac{1}{(n+2)M_{\rm Pl}^2}\,\phi\dot{\phi}$$

$$a(t) \simeq \langle a(t)\rangle \left[1 - \frac{1}{2(n+2)}\,\frac{\phi^2 - \langle\phi^2\rangle}{M_{\rm Pl}^2}\right]$$

An oscillating metric induces effective interaction terms:

$$S = \int d^4x\sqrt{|g|}\left[-\frac{1}{2}g^{\mu\nu}\partial_\mu s\,\partial_\nu s - \frac{1}{2}m_s^2 s^2\right] \quad \Rightarrow \quad \frac{C}{M_{\rm Pl}^2}\,\phi^2(\partial_\mu s)^2 \;\; , \;\; \frac{\tilde{C}}{M_{\rm Pl}^2}\,\phi^2(\partial_0 s)^2$$

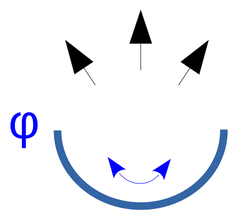
particle production!

Abundance of dark relics :

φ background → s s

Wilson coefficient of dim-6 operator

$$\phi^2(t) = \sum_{n=-\infty}^{\infty} \zeta_n e^{-in\omega t} \qquad \Gamma = \frac{C^2\,\omega^4}{16\pi M_{\rm Pl}^4} \sum_{n=1}^{\infty} n^4 |\zeta_n|^2$$



$\phi(t) = \phi_0(t) \cos m_\phi t$

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

$$n(t) \simeq \frac{c(\phi_0, n)}{a^3 H_0}$$

dominated by moments immediately after inflation!

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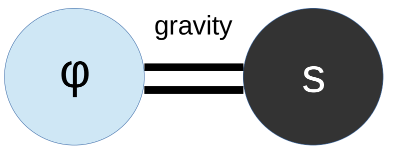
$$m_s \lesssim 10^{-6}\,\Delta_{\rm NR} \left(\frac{M_{\rm Pl}}{H_{\rm end}}\right)^{3/2} \;{\rm GeV}$$

E.g. $H_{\rm end} \sim 10^{14}\;{\rm GeV}$ → $m_s \lesssim {\rm few} \times \Delta_{\rm NR}\;{\rm GeV}$

Quantum gravity effects

Induce gauge invariant operators
(*with unknown coefficients)*



Dim-6 gravity-induced couplings:

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

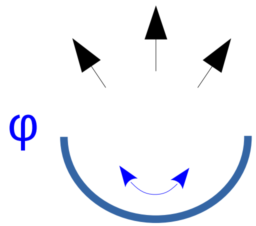
Main operators for on-shell fields contributing to s-pair production:

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

(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



$$\phi(t) = \phi_0(t)\cos m_\phi t$$

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

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

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

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

$\phi_0 \sim M_{\rm Pl}$ and $H_{\rm end} \sim 10^{14}$ GeV ⇒

$$|C_4| < \text{few} \times 10^{-9}\,\Delta_{\rm NR}^{1/2}\sqrt{\frac{\rm GeV}{m_s}}$$

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

Higher dim operators: $\mathcal{O}^{(p)} = \frac{\phi^p s^2}{M_{\rm Pl}^{p-2}}$

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

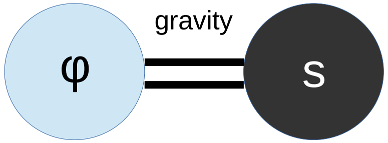
Planck-suppressed operators are very efficient in particle production!

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

Main observation :

Planck—suppressed ("gravity--induced") operators with small 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 ?**

Example: *Higgs-like inflation*

$$\mathcal{L}_J = \sqrt{-\hat{g}}\left(-\frac{1}{2}\Omega\hat{R} + \frac{1}{2}\,\partial_\mu\phi\partial^\mu\phi - V(\phi)\right) \quad , \quad \Omega = 1 + \xi_\phi\phi^2$$

Canonically normalized inflaton:

$$\frac{d\chi}{d\phi} = \sqrt{\frac{1+\xi_\phi(1+6\xi_\phi)\phi^2}{(1+\xi_\phi\phi^2)^2}} \quad \Rightarrow \quad V_E(\chi) = \frac{\lambda_\phi}{4\xi_\phi^2}\left(1 - e^{\sqrt{\frac{2}{3}}|\chi|}\right)^2$$

End of inflation:

$$H_{\rm end} \sim 10^{13}\ {\rm GeV} \quad , \quad \chi \simeq M_{\rm Pl}$$

$$\Delta_{\rm NR} \sim \xi_\phi^{1/2} \lesssim 10$$

Constraints on stable scalars / non-thermal DM:

$$m_s \lesssim 1\ {\rm TeV}$$ - preheating

$$m_s \lesssim 10^{-1}\ {\rm GeV}$$ - inflation

$$m_s \lesssim 10^{-16}\ {\rm GeV}$$ - quantum gravity (C~1)

CONCLUSION

– dark relics are (over)produced during/after inflation

– (small) Planck-suppressed operators are important

– non-thermal DM is sensitive to quantum gravity