UV sensitivity of dark matter production

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– ***non-thermal dark matter***

– ***Planck-suppressed operators***

– ***particle production after inflation***

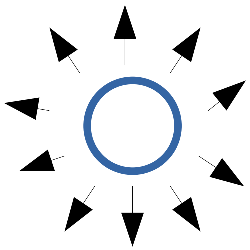
– ***relic abundance***

OL, Yoon 2203.15808 [hep-ph] **“On gravitational preheating”**

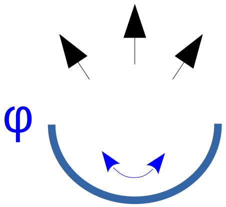
Non-thermal DM has memory !

Production mechanisms (all add up):

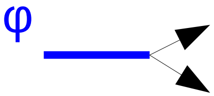
- during inflation



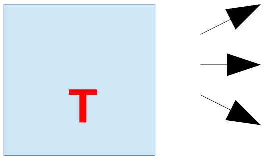
- via inflaton oscillations



- inflaton decay



- thermal emission (freeze-in)

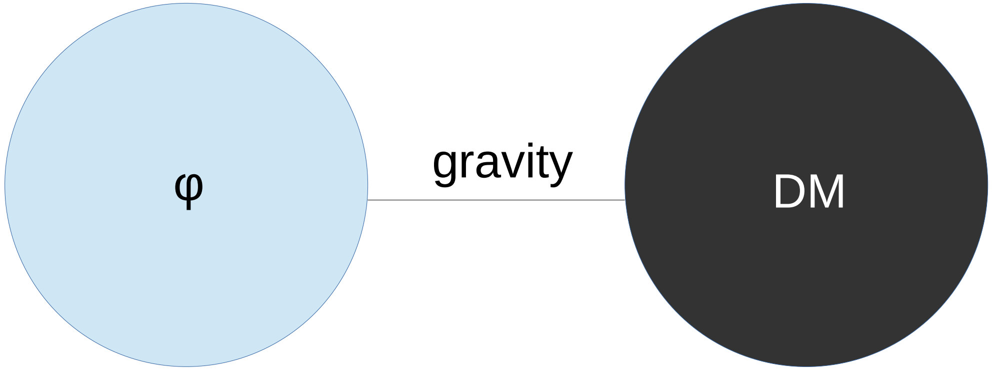


Focus:

inflaton oscillation epoch (preheating)

Assume:

no renormalizable inflaton-dark matter coupling

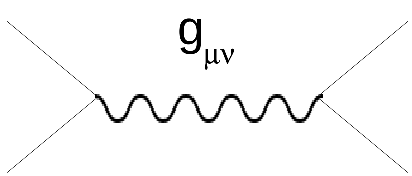


Dim-6 gravity-induced couplings:

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

Simplest examples:

graviton exchange



frame change

Jordan frame → Einstein frame

$$\xi\, s^2 R \quad \rightarrow \quad \frac{1}{M_{\rm Pl}^2}\, s^2 V(\phi)$$

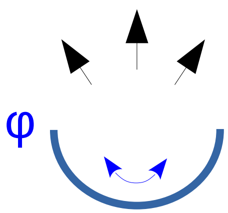
Many more sources: ***non-perturbative***, ***string states***,... → **unknown coefficients**

On shell, 2 independent dim-6 operators contribute to DM 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 $\frac{C_5}{M_{\rm Pl}^2}\,\phi^2 s^4$)

Perturbative DM production rates:



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

O_3 / O_4 ~ energy^2 / ϕ^2 ~ m_ϕ^2 / ϕ^2 << 1

$$\frac{\Gamma\left[\mathcal{O}_3\right]}{\Gamma\left[\mathcal{O}_4\right]} \sim \frac{C_3^2}{C_4^2}\,\frac{\omega^4}{\phi_0^4} \quad \sim 10^{-20}$$

➡ "*graviton exchange*" operator much **suppressed**

E.g. $\frac{\tilde{C}_6}{M_{\rm Pl}^4}\phi^6 s^2 + \frac{\tilde{C}_8}{M_{\rm Pl}^6}\phi^8 s^2$ more important

Resonant DM production:

Semiclassical analysis:

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

$$S = \int d^4x \sqrt{|g|} \left(\frac{1}{2} \mathcal{K}(\phi)\, g^{\mu\nu} \partial_\mu s\, \partial_\nu s - \mathcal{V} \right)$$

$$\ddot{s} - \frac{1}{a^2} \partial_i \partial_i s + \left(\frac{\dot{\mathcal{K}}}{\mathcal{K}} + 3H \right) \dot{s} + \frac{\mathcal{V}'_s}{\mathcal{K}} = 0$$

Change of variables
(3-momentum k-mode):

$$s_k = a^{-3/2} \mathcal{K}^{-1/2} X_k$$

$(\partial_\mu s)^2 \phi^2$

$\phi^4 s^2$

$$\ddot{X}_k + \left[\frac{2C_3 m_\phi^2 \phi_0^2}{M_{\rm Pl}^2} \cos 2m_\phi t + \frac{k^2}{a^2} \right] X_k = 0$$

$$\ddot{X}_k + \left[\frac{2C_4 \phi_0^4}{M_{\rm Pl}^2} \cos^4 m_\phi t + \frac{k^2}{a^2} \right] X_k = 0$$

no resonant production (q ~ 1)

resonant production (q >> 1)

$(\partial_\mu s)^2 \phi^2 \quad << \quad \phi^4 s^2$

On effect of $\frac{C_5}{M_{\rm Pl}^2}\,\phi^2 s^4$:

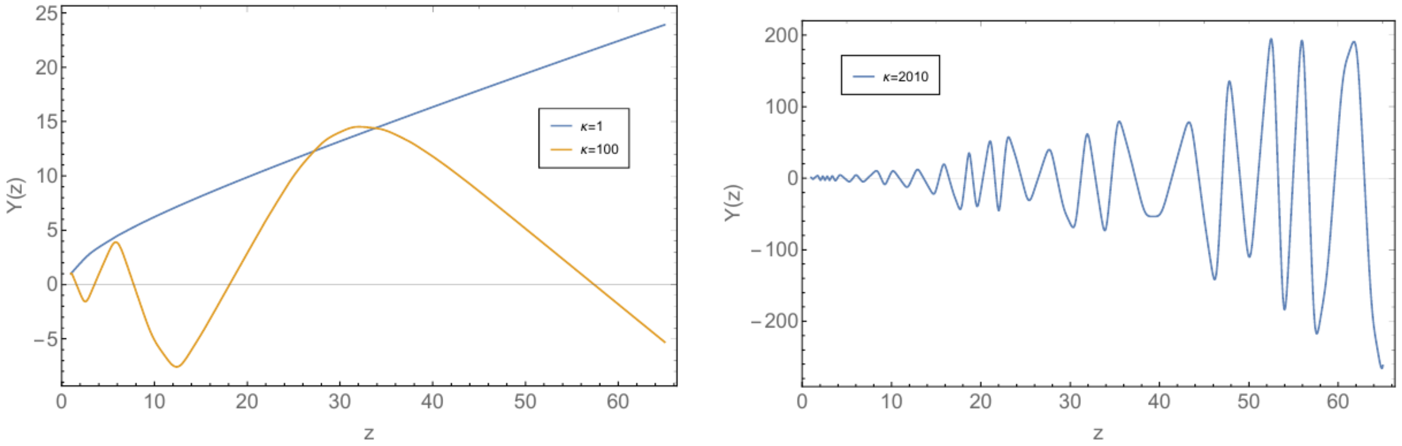
$$\ddot{s} - \frac{1}{a^2}\,\partial_i\partial_i s + 3H\,\dot{s} + \frac{4C_5\phi^2(t)}{M_{\rm Pl}^2}\,s^3 = 0$$

*Does not belong to the **Hill type** equations!*

Zero mode:

$$Y'' + \kappa\,\frac{\cos^2 z}{z^4}\,Y^3 = 0$$

$$z = m_\phi t \quad , \qquad \kappa \simeq \frac{14 C_5 \varphi_0^2}{M_{\rm Pl}^2\, a_0^3} \lesssim \mathcal{O}(1)$$



→ no resonant production for κ ~ 1

DM abundance via Planck-suppressed operators

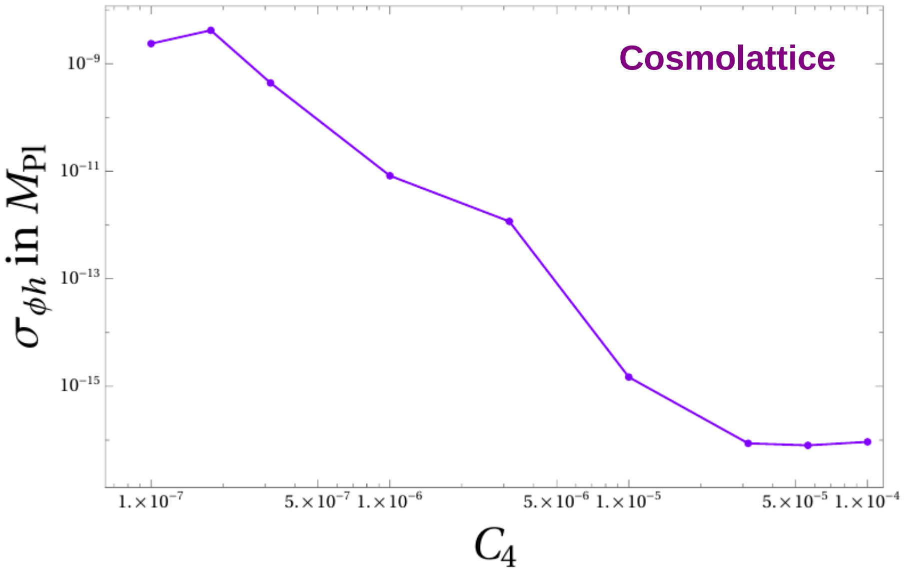
Focus on the most important op $\frac{C_4}{M_{\rm Pl}^2}\,\phi^4 s^2$

Reheating: $V_{\phi h} = \sigma_{\phi h}\phi H^\dagger H$ → $\phi \to hh$

Correct DM abundance requires:

$$\sigma_{\phi h} \simeq 5\times 10^{-9}\,\frac{m_\phi^{3/2}}{M_{\rm Pl}^{1/2}}\,\frac{n_e(\phi)}{n_e(s)}\left(\frac{\rm GeV}{m_s}\right)$$

simulation output



$m_\phi = 10^{13}$ GeV

$m_s = 1$ GeV,

$\varphi_0 \simeq M_{\rm Pl}$

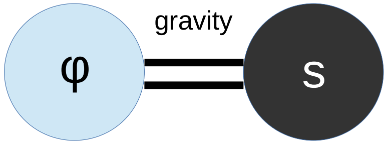
→ $C_4 \ll 1$!

<u>Main observation</u> :

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

$$\frac{C_4}{M_{\rm Pl}^2}\,\phi^4 s^2$$, etc. (dim-8, ...)

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



– abundance is additive ("memory")

– need to control quantum gravity

– predictivity ?

CONCLUSION

– *non-thermal DM production at preheating*

– *(small) Planck—suppressed operators produce enough DM*

– *strong UV sensitivity of non-thermal DM (quantum gravity)*