Dark matter production during preheating

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Contents

- Dark matter production via inflaton interactions
- Preheating
- If renormalizable couplings are negligible

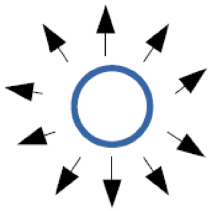
- Dim-6 (gravity-induced) operators
- Relative size of the operators
- Perturbative estimate and resonant effect

- Conclusion

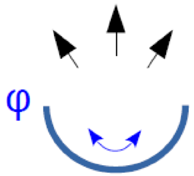
O. Lebedev, **JH Yoon**, "On gravitational preheating", 2203.15808

Dark matter production via inflaton interactions

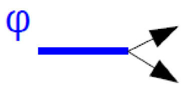
- During inflation



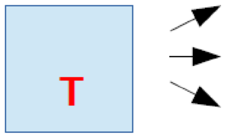
- Preheating



- Inflaton decay



- Thermal production



O. Lebedev, 2210.02293

Preheating

- Pre + reheating

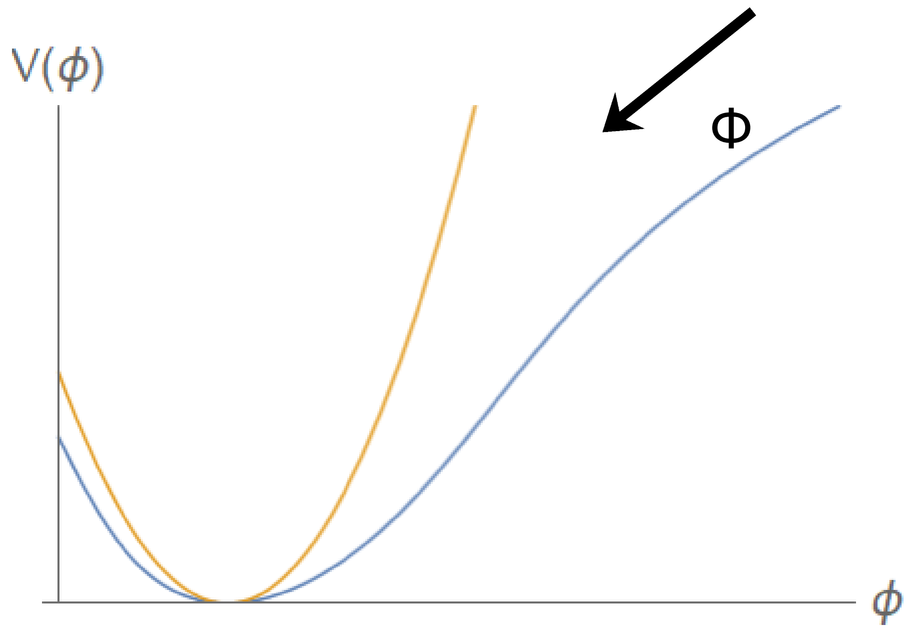
- Intense particle creation right after inflation
due to the oscillation of inflaton background with a large amplitude

- Collective effects

- Resonances, Backreaction, and Rescattering
- Lattice simulations

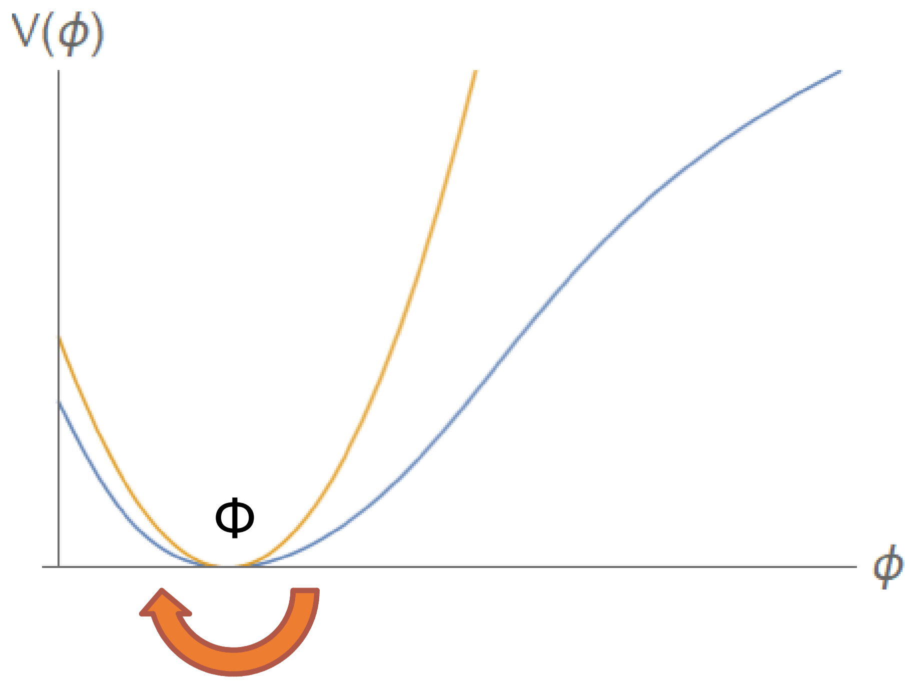
Preheating

- Φ rolling down to the minimum



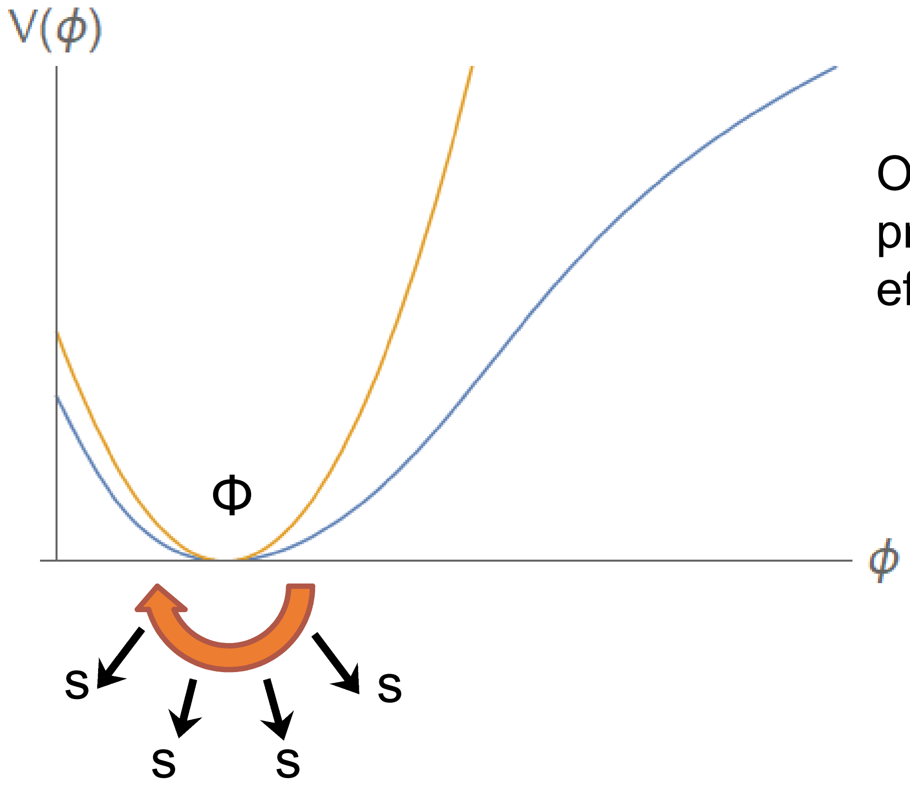
Preheating

- Oscillation described locally by a monomial function



DM production in preheating

- Renormalizable interactions between inflaton and DM



O. Lebedev, F. Smirnov, T. Solomko, **JH Yoon**, "Dark matter production and reheating via direct inflaton couplings: collective effects", 2107.06292

Gravity–induced dim–6 couplings

- Suppose the renormalizable interactions are negligible

- Inflaton-(gravity)-DM → higher dimensional operators

 - graviton exchange (tree/loop level)

 - frame change (conf. transf. with non-minimal coupling to gravity)

 - ...

Gravity–induced dim–6 couplings

- Planck-suppressed operators

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

- Unknown coefficients (in the absence of UV complete theory)

- Relative size of the different operators?

Gravity–induced dim–6 couplings

- Integration by parts eliminates two derivative operators

$$(\partial_\mu \phi)^2 s^2 \to (\partial_\mu s)^2 \phi^2 + m_\phi^2 \phi^2 s^2$$
$$(\phi \partial_\mu \phi)(s \partial^\mu s) \to -\frac{1}{2} (\partial_\mu s)^2 \phi^2 \ ,$$

$\longrightarrow$ $$\mathcal{O}_{\rm renorm} = \frac{m_\phi^2}{M_{\rm Pl}^2}\, \phi^2 s^2 \quad \mathcal{O}_3 = \frac{1}{M_{\rm Pl}^2}\, (\partial_\mu s)^2 \phi^2 \ , \ \mathcal{O}_4 = \frac{1}{M_{\rm Pl}^2}\, \phi^4 s^2 \quad \mathcal{O}_5 = \frac{1}{M_{\rm Pl}^2}\, \phi^2 s^4$$

Gravity–induced dim–6 couplings

- ① Perturbative dark matter production + relative efficiency

$$\mathcal{O}_{\rm renorm} = \frac{m_\phi^2}{M_{\rm Pl}^2}\,\phi^2 s^2 \quad \mathcal{O}_3 = \frac{1}{M_{\rm Pl}^2}\,(\partial_\mu s)^2\phi^2 \;\;,\;\; \mathcal{O}_4 = \frac{1}{M_{\rm Pl}^2}\,\phi^4 s^2 \quad \mathcal{O}_5 = \frac{1}{M_{\rm Pl}^2}\,\phi^2 s^4$$

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- ② Resonant dark matter production (due to B.E.)

- solve EOMs

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- solve EOMs

- ③ Lattice simulations: reproducing the correct DM abundance

① Perturbative dark matter production

- O_{renorm} $$-\Delta\mathcal{L}_{\text{renorm}} = \frac{1}{4}\lambda_{\phi s}\,\phi^2 s^2$$

- Φ considered an external source $$\phi^2(t) = \sum_{n=-\infty}^{\infty} \zeta_n e^{-in\omega t}$$

① Perturbative dark matter production

- S-matrix and amplitude $\mathcal{M}_n = -\lambda_{\phi s}\zeta_n/2$

$$-i\int_{-\infty}^{\infty} dt\langle f|V(t)|i\rangle = -i\,\frac{\lambda_{\phi s}}{2}\,(2\pi)^4\delta(\mathbf{p}+\mathbf{q})\sum_{n=1}^{\infty}\zeta_n\delta(E_p+E_q-n\omega)$$

- Reaction rate per unit volume

$$\Gamma = \sum_{n=1}^{\infty}\Gamma_n = \sum_{n=1}^{\infty}\frac{1}{2}\int|\mathcal{M}_n|^2 d\Pi_n = \frac{\lambda_{\phi s}^2}{64\pi}\sum_{n=1}^{\infty}|\zeta_n|^2\sqrt{1-\left(\frac{2m_s}{n\omega}\right)^2}\,\theta(n\omega-2m_s)$$

① Perturbative dark matter production

- O_3 $\phi^2(\partial_\mu s)^2$ **interaction**

$$p \cdot q = \frac{1}{2}(p+q)^2 = \frac{1}{2}(E_p + E_q)^2 = \frac{1}{2}n^2\omega^2$$

$$\lambda_{\phi s} \to 4C_3/M_{\rm Pl}^2\, p \cdot q$$

$$\Gamma = \frac{C_3^2\,\omega^4}{16\pi M_{\rm Pl}^4}\sum_{n=1}^{\infty} n^4|\zeta_n|^2$$

① Perturbative dark matter production

- O$_4$ $\phi^4 s^2$ **interaction**

$$\phi^4(t) = \sum_{n=-\infty}^{\infty} \hat{\zeta}_n e^{-in\omega t} \qquad \hat{\zeta}_n = \sum_{m=-\infty}^{\infty} \zeta_{n-m}\zeta_m$$

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

- Relative efficiency

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

① Perturbative dark matter production

- O_5 $\phi^2 s^4$

Suppressed by E_ϕ^4/ϕ_0^4 as compared with $\mathcal{O}_4 = \frac{1}{M_{\rm Pl}^2}\phi^4 s^2$

- Interestingly, for higher dimensional operators

$\frac{\tilde{C}_6}{M_{\rm Pl}^4}\phi^6 s^2 + \frac{\tilde{C}_8}{M_{\rm Pl}^6}\phi^8 s^2 + ...$, suppression factor $\phi_0^4/M_{\rm Pl}^4$ (as compared with O_4) is not significant

② Resonant dark matter production

- Generalized action and equations of motion

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

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

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

② Resonant dark matter production

- a) V=0 and K!=0 (O3) $\mathcal{K} = 1 + \frac{2C_3}{M_{\rm Pl}^2}\,\phi^2$

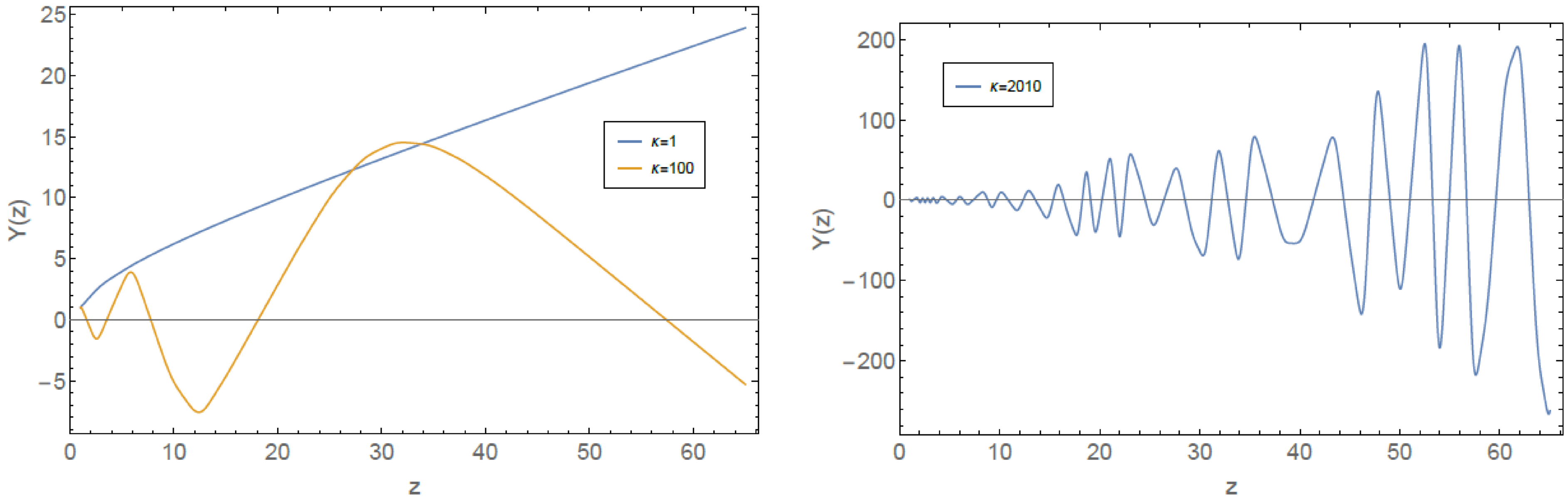
- b) K=1 and V!=0 (O4) $\mathcal{V} = \frac{C_4}{M_{\rm Pl}^2}\,\phi^4 s^2$

Resulting Eqs. belong to Hill's equation, but production depends on resonance parameters (O4 wins)

② Resonant dark matter production

- $\mathcal{O}_5 = \phi^2 s^4$ does not belong to Hill's equation

- compute numerically → no resonance unless C5>>1



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$$\mathcal{O}_{\rm renorm} = \frac{m_\phi^2}{M_{\rm Pl}^2}\,\phi^2 s^2 \qquad \mathcal{O}_3 = \frac{1}{M_{\rm Pl}^2}\,(\partial_\mu s)^2\phi^2 \;\;,\quad \boxed{\mathcal{O}_4 = \frac{1}{M_{\rm Pl}^2}\,\phi^4 s^2} \quad \mathcal{O}_5 = \frac{1}{M_{\rm Pl}^2}\,\phi^2 s^4$$

- ② Resonant dark matter production (due to B.E.)

- solve EOMs
- O_4 wins

- ③ Lattice simulations: reproducing the correct DM abundance

- O_4 ?

③ Lattice simulations: reproducing the correct DM abundance

- Reheating via Φ→hh

$$V_{\phi h} = \sigma_{\phi h} \phi H^\dagger H$$

$$H_R \simeq \Gamma_{\phi \to hh} \,, \quad \Gamma_{\phi \to hh} = \frac{\sigma_{\phi h}^2}{8\pi m_\phi}$$

- DM relic abundance

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

③ Lattice simulations: reproducing the correct DM abundance

- Non-rel. expansion by inflaton $a_e \xrightarrow{\text{rel}} a_* \xrightarrow{\text{nrel}} a_R$

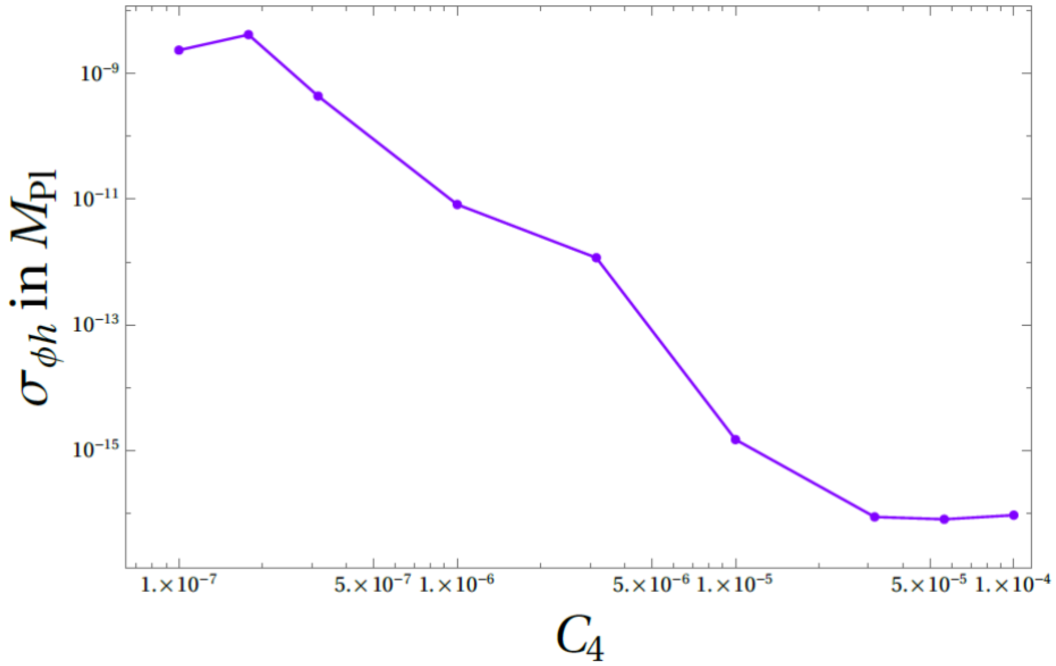
$$H_R = \frac{H_e}{\sqrt{1+\delta}} \frac{a_e^2}{a_*^2} \frac{a_*^{3/2}}{a_R^{3/2}} \qquad \rho_e(s) = \delta\, \rho_e(\phi)$$

$$\sigma_{\phi h} \simeq 1.6 \times 10^{-8} \sqrt{m_\phi M_{\rm Pl}^3} \frac{H_e^2}{(1+\delta)\, n_e} \frac{a_e}{a_*} \left(\frac{\rm GeV}{m_s}\right)$$

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

③ Lattice simulations:
reproducing the correct DM abundance

- O_4 can explain DM with small C_4



- $\phi^n s^2 \; (n \geq 4)$

also dominates particle production

$m_\phi = 10^{13}$ GeV, $m_s = 1$ GeV, $\varphi_0 \simeq M_{\rm Pl}$

We have studied

- Non-thermal DM production during preheating in case renormalizable couplings are negligible
- Relative importance of Gravity-induced dim-6 operators (pert./resont. regimes)

Conclusion

- Planck-suppressed operators may produce enough DM
- Operators of the form $\phi^n s^2 \ (n \geq 4)$ can also dominate particle production
- Their presence is important in non-thermal DM models