Gravitational Particle Production in Gravity Theories with Non-minimal Derivative Couplings

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The Lagrangian density of a scalar field in curved spacetime

$$\mathcal{L} = \sqrt{-g}\{\frac{1}{2}\left[g^{\kappa\lambda}\partial_\kappa\phi\partial_\lambda\phi\right] - V(\phi)\}$$

leads to the equation of motion Euler-Lagrange

$$\Box\phi + V_\phi = 0 \qquad \text{where} \qquad \Box\phi = (-g)^{-1/2}\partial_\mu\left[(-g)^{1/2}g^{\mu\nu}\partial_\nu\phi\right] \tag{1}$$

We define the inner product of the solutions of (1) as

$$(\phi_1, \phi_2) \equiv i\int(-g)^{1/2}g^{0\nu}\left(\phi_1^*(x)\partial_\nu\phi_2(x) - \phi_2(x)\partial_\nu\phi_1^*(x)\right)d^3x$$

We expand the field ϕ in terms a complete set of modes $\chi_\mathbf{k}$

$$\phi(x) = \sum_\mathbf{k}\left(\hat{a}_\mathbf{k}\chi_\mathbf{k}(x) + \hat{a}_\mathbf{k}^\dagger\chi_\mathbf{k}^*(x)\right)$$

with $\chi_\mathbf{k}$ satisfying

$$(\chi_\mathbf{k}, \chi_{\mathbf{k}'}) = \delta_{\mathbf{k}\mathbf{k}'} \qquad (\chi_\mathbf{k}^*, \chi_{\mathbf{k}'}^*) = -\delta_{\mathbf{k}\mathbf{k}'} \qquad (\chi_\mathbf{k}, \chi_{\mathbf{k}'}^*) = 0$$

The $n_\mathbf{k}$ excitations are given by

$$|n_\mathbf{k}\rangle = \frac{1}{\sqrt{n_\mathbf{k}!}}(\hat{a}_\mathbf{k}^\dagger)^{n_\mathbf{k}}|0_\chi\rangle$$

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The scalar field ϕ can be expanded in terms of any of the two sets

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An observer in $|0_\psi\rangle$ vacuum using the $\chi_{\mathbf{k}}$ modes can count the average number of χ particles

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Knowledge of the Bogolyubov coefficients $\beta_{\mathbf{k}\mathbf{k}'}$ is essential in order to calculate the χ particles produced

- Inflation is an exponential expansion of the universe taking place after the Big Bang
- It seems necessary in order to understand observables that cannot be explained by the Big Bang model.
- The scalar field ϕ which drives the inflation is called inflaton. It is homogeneous and only time-dependent

We consider a FRW Universe with a metric $ds^2 = dt^2 - a^2(t)d\mathbf{x}^2$ and a scalar field with the action

$$S_\phi = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] \quad \text{with} \quad V(\phi) = \frac{1}{2}M_\phi^2\phi^2$$

Einstein equations

$$G_{\mu\nu} = -8\pi G T_{\mu\nu}$$

Friedmann equation

$$H^2(t) \equiv \frac{\dot{a}^2(t)}{a^2(t)} = \frac{8\pi}{3M_{pl}^2}\left[\frac{\dot{\phi}^2}{2} + V(\phi)\right]$$

acceleration equation

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi}{3M_{pl}^2}(\rho_\phi + 3p_\phi)$$

equation of motion $\longrightarrow$ $\ddot{\phi}(t) + 3H(t)\dot{\phi}(t) + V_\phi = 0$

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We define the dimensionless time $\tau = M_\phi t$ and the dimensionless field $\psi(\tau) = \phi(\tau)/M_\phi$

- We use the slow - roll approximation $\ddot{\phi} \ll 3H\dot{\phi}$ and $\dot{\phi}^2 \ll V(\phi)$

$$\text{Friedmann equation} \rightarrow H^2(\tau) \simeq \frac{4\pi}{3}\psi^2(\tau)$$

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Inflation ends at

$$\tau_f = 2\sqrt{3\pi}\psi_0 - 1$$

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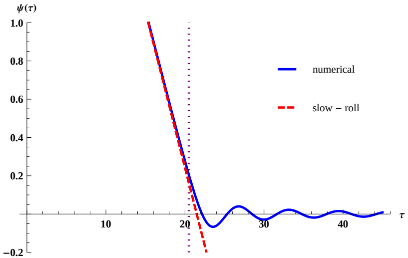
Dimensionless inflaton ψ in terms of the dimensionless time τ



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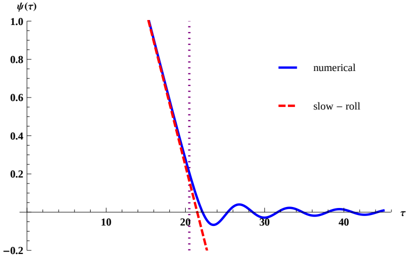
Dimensionless inflaton ψ in terms of the dimensionless time τ



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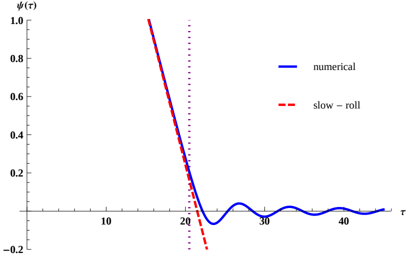

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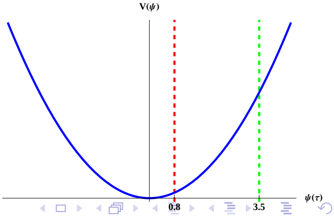

We consider the action

$$S_\phi = \int d^4x\sqrt{-g}\left\{\frac{R}{16\pi G} + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{1}{2}\lambda_1 G^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right\}$$

Friedmann equation

$$H^2(\tau) = \frac{4\pi}{3}\left[\dot{\psi}^2(\tau)\left(1-9\overline{\lambda_1}H^2(\tau)\right) + \psi^2(\tau)\right] \qquad (\overline{\lambda_1} = \lambda_1 M_\phi^2)$$

equation of motion

$$\left(1-3\overline{\lambda_1}H(\tau)^2\right)\ddot{\psi}(t) + \left(3H(\tau) - 3\overline{\lambda_1}H(\tau)\left(2\dot{H}(\tau)+3H^2(\tau)\right)\right)\dot{\psi}(\tau) + \psi(\tau) = 0$$

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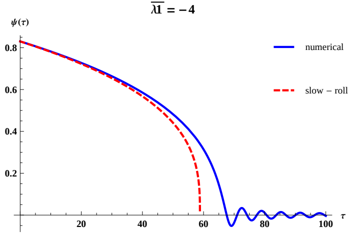
inflaton ψ in terms of τ for $\overline{\lambda_1} = -4$



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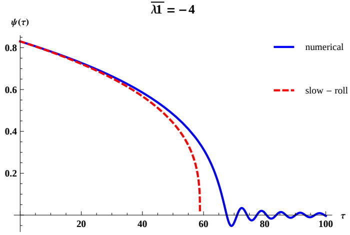
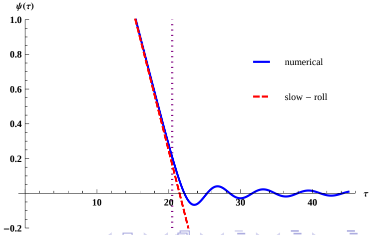


inflaton ψ in terms of τ for $\overline{\lambda_1} = 0$



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$$S_\phi = \int d^4x\sqrt{-g}\left\{\frac{R}{16\pi G} + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{1}{2}\lambda_1 G^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right\}$$

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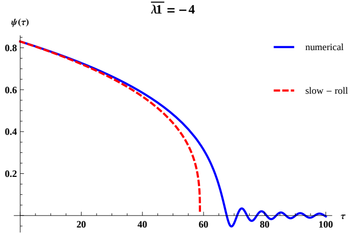
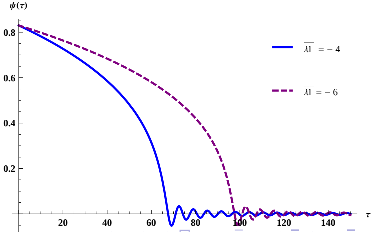


inflaton ψ in terms of τ for $\overline{\lambda_1} \neq 0$



The complete action of the theory is

$$S=\int d^4x\sqrt{-g}\frac{M_{pl}^2R}{16\pi}+\int d^4x\sqrt{-g}\Big\{\frac{1}{2}\Big[\big(g^{\mu\nu}+\lambda_1 G^{\mu\nu}\big)\partial_\mu\phi\partial_\nu\phi-M_\phi^2\phi^2\Big]$$
$$+\frac{1}{2}\Big[\big(g^{\mu\nu}+\lambda_2 G^{\mu\nu}\big)\partial_\mu X\partial_\nu X-(M_X^2+\zeta R(t)+g^2\phi^2(t))X^2\Big]\Big\}$$

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Equation of motion for the quantum field X

$$\Big[1-3\lambda_2M_\phi^2\frac{\dot a^2(\tau)}{a^2(\tau)}\Big]\ddot\chi_{\mathbf{k}}(\tau)+3\Big[\frac{\dot a(\tau)}{a(\tau)}-\lambda_2M_\phi^2\Big(\frac{\dot a^3(\tau)}{a^3(\tau)}+\frac{2\dot a(\tau)\ddot a(\tau)}{a^2(\tau)}\Big)\Big]\dot\chi_{\mathbf{k}}(\tau)+$$
$$\Big[\frac{k^2}{M_\phi^2a^2(\tau)}-\lambda_2k^2\frac{2\ddot a(\tau)a(\tau)+\dot a^2(\tau)}{a^4(\tau)}+\frac{m_X^2}{M_\phi^2}+\frac{\zeta R(\tau)}{M_\phi^2}+\frac{g^2\psi^2(\tau)M_{pl}^2}{M_\phi^2}\Big]\chi_{\mathbf{k}}(\tau)=0$$

The complete action of the theory is

$$S = \int d^4x\sqrt{-g}\frac{M_{pl}^2 R}{16\pi} + \int d^4x\sqrt{-g}\Big\{\frac{1}{2}\Big[\left(g^{\mu\nu} + \lambda_1 G^{\mu\nu}\right)\partial_\mu\phi\partial_\nu\phi - M_\phi^2\phi^2\Big] + \frac{1}{2}\Big[\left(g^{\mu\nu} + \lambda_2 G^{\mu\nu}\right)\partial_\mu X\partial_\nu X - (M_X^2 + \zeta R(t) + g^2\phi^2(t))X^2\Big]\Big\}$$

Writing $\chi_{\mathbf{k}}(\tau) = f(\tau)h_{\mathbf{k}}(\tau)$ we get a more "convenient" form

$$\ddot{h}_{\mathbf{k}}(\tau) + \left[B(\tau) - \frac{\dot{A}(\tau)}{2} - \frac{A^2(\tau)}{4}\right]h_{\mathbf{k}}(\tau) = 0$$

where

$$A(\tau) = 3\frac{\frac{\dot{a}(\tau)}{a(\tau)} - \overline{\lambda_2}\left(\frac{\dot{a}^3(\tau)}{a^3(\tau)} + 2\frac{\dot{a}(\tau)\ddot{a}(\tau)}{a^2(\tau)}\right)}{1 - 3\overline{\lambda_2}\frac{\dot{a}^2(\tau)}{a^2(\tau)}} \qquad (\overline{\lambda_2} = \lambda_2 M_\phi^2)$$

$$B(\tau) = \frac{\frac{k^2}{M_\phi^2 a^2(\tau)} - \lambda_2 k^2\frac{2a(\tau)\ddot{a}(\tau)+\dot{a}^2(\tau)}{a^4(\tau)} + \frac{M_x^2}{M_\phi^2} + \frac{\zeta R(\tau)}{M_\phi^2} + \frac{g^2\psi^2(\tau)M_{pl}^2}{M_\phi^2}}{1 - 3\overline{\lambda_2}\frac{\dot{a}^2(\tau)}{a^2(\tau)}}$$

The complete action of the theory is

$$S=\int d^4x\sqrt{-g}\frac{M_{pl}^2R}{16\pi}+\int d^4x\sqrt{-g}\Big\{\frac{1}{2}\Big[\big(g^{\mu\nu}+\lambda_1G^{\mu\nu}\big)\partial_\mu\phi\partial_\nu\phi-M_\phi^2\phi^2\Big]$$
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For the differential equation

$$\ddot{h}_{\mathbf{k}}(\tau)+\Omega^2(\tau)h_{\mathbf{k}}(\tau)=0$$

there is a solution

$$h_{\mathbf{k}}(\tau)=\frac{\alpha_k(\tau)}{\sqrt{2\Omega(\tau)}}e^{-i\int\Omega(\tau')d\tau}+\frac{\beta_k(\tau)}{\sqrt{2\Omega(\tau)}}e^{i\int\Omega(\tau')d\tau}$$

if we define the Bogolyubov coefficients through a system of differential equations

$$\dot{\alpha}_k(\tau)=\frac{\dot{\Omega}_k(\tau)}{2\Omega_k(\tau)}\exp\Big[2i\int\Omega_k(\tau')d\tau'\Big]\beta_k(\tau)$$
$$\dot{\beta}_k(\tau)=\frac{\dot{\Omega}_k(\tau)}{2\Omega_k(\tau)}\exp\Big[-2i\int\Omega_k(\tau')d\tau'\Big]\alpha_k(\tau)$$

- The quantity $|\beta_{\mathbf{k}}|^2$ is the mean number of particles in state k.
- The system should obey the relations $\Omega^2 > 0$ and $\frac{\dot{\Omega}}{\Omega} \ll 1$ (adiabatic approximation)
- After the end of inflation we enter the phase of matter domination, $\left(a(\tau) = \tau^{2/3}\right)$
- There are no particles before the end of inflation $\left(\beta_{\mathbf{k}}(\tau_f) = 0\ ,\ \alpha_{\mathbf{k}}(\tau_f) = 1\right)$
- We measure the X field production at the time τ_{flat} when the Bogolyubov coefficients have become time-independent
- We set the value of the inflaton mass $M_\phi = 10^{-6} M_{pl}$
- $\overline{\lambda_1}$ and $\overline{\lambda_2}$ are the couplings of the Einstein tensor with the kinetic terms of the fields ϕ and X respectively
- We study the quantity $|\beta_{\mathbf{k}}|^2$ in terms of the mass M_X for different values of the couplings

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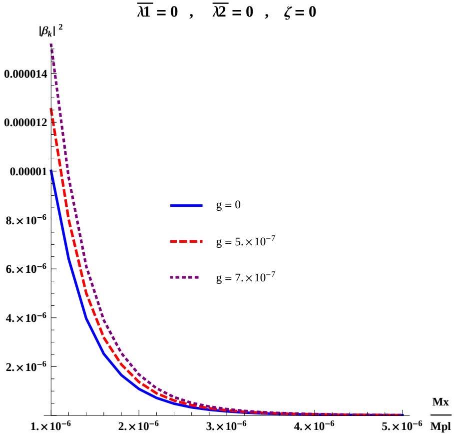
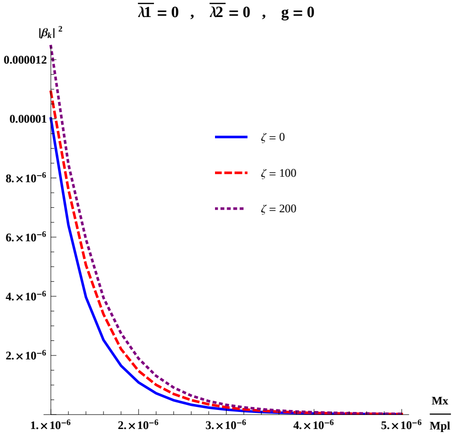
Fields ϕ and X without non-minimal kinetic terms





- Enhancement of the particle production as the couplings g , ζ are increased
- Possible correlation of the results $\left(\zeta R(t) + g^2\phi^2(t)\right)X^2$

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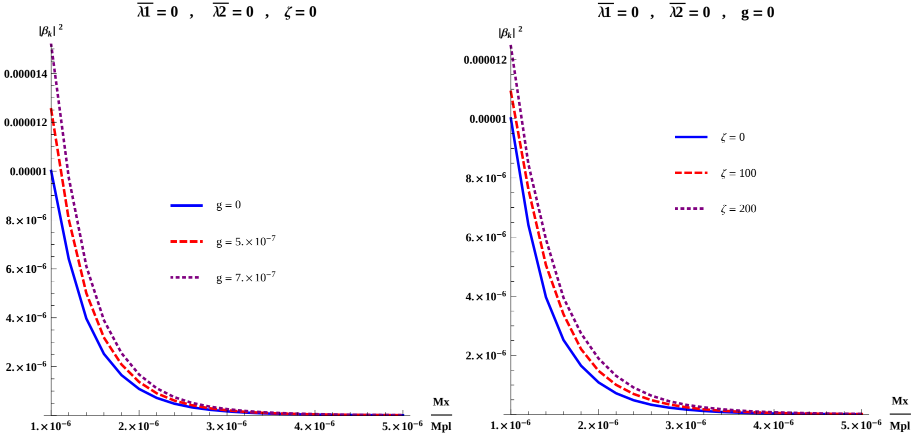

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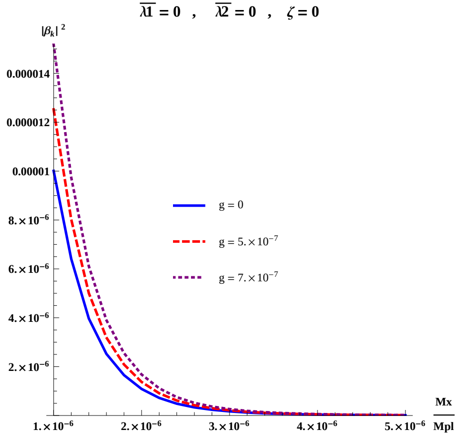

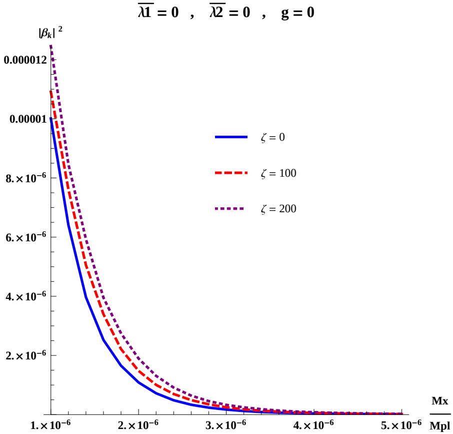

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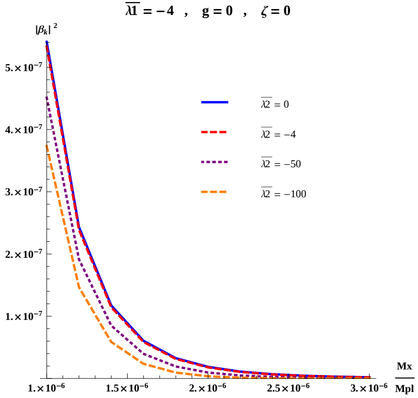
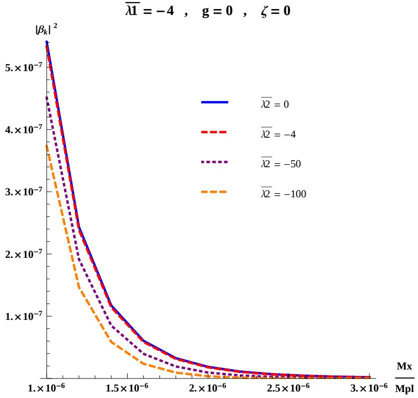
Field ϕ with coupling $\overline{\lambda_1} = -4$ and X with $\overline{\lambda_2} \neq 0$



- We need quite larger $\overline{\lambda_2}$ than $\overline{\lambda_1}$ in order to have some change in particle production
- After the end of inflation Einstein tensor has been weakened so we need stronger coupling $\overline{\lambda_2}$

Field ϕ with coupling $\overline{\lambda_1} = -4$ and X with $\overline{\lambda_2} \neq 0$



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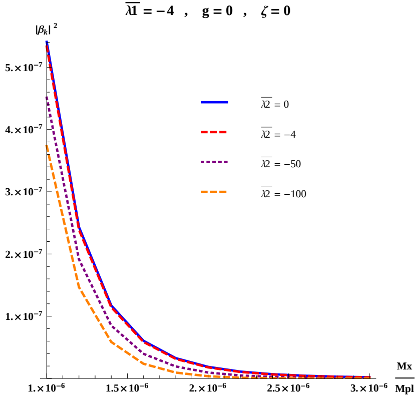

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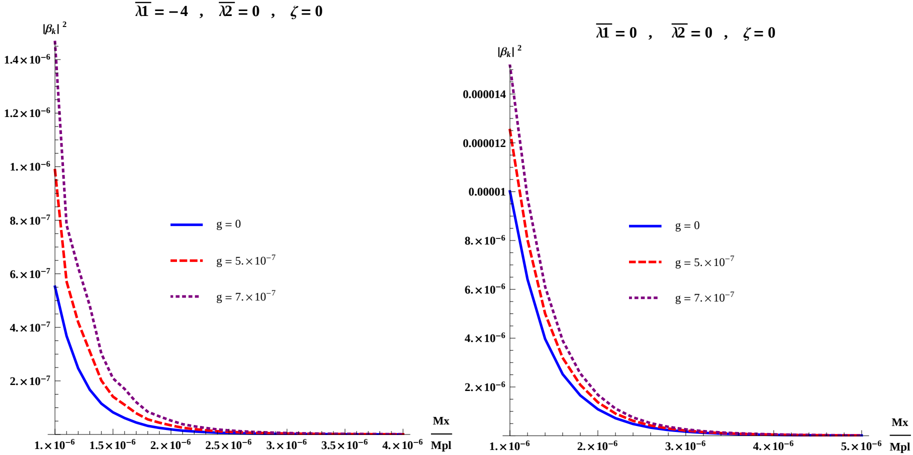
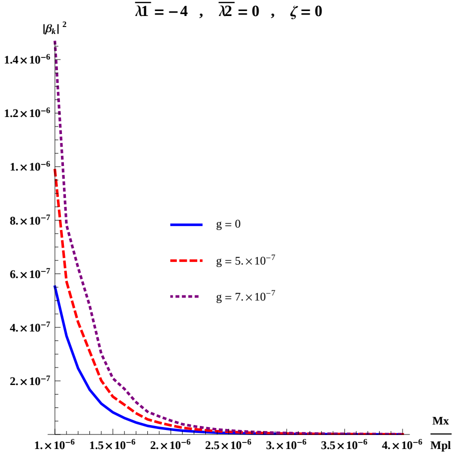
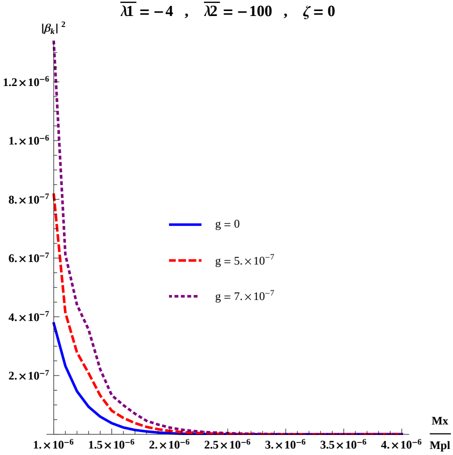
Field ϕ with coupling $\overline{\lambda_1} = -4$, $\overline{\lambda_1} = 0$ and X with $\overline{\lambda_2} = 0$



Suppression of particle production with the introduction of non-minimal kinetic terms to the inflaton

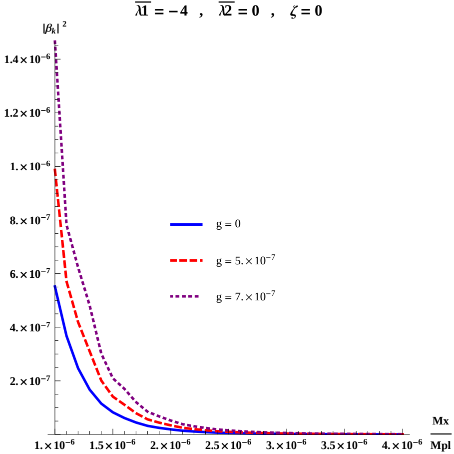
Field ϕ with coupling $\overline{\lambda_1} = -4$, $\overline{\lambda_1} = 0$ and X with $\overline{\lambda_2} = 0$

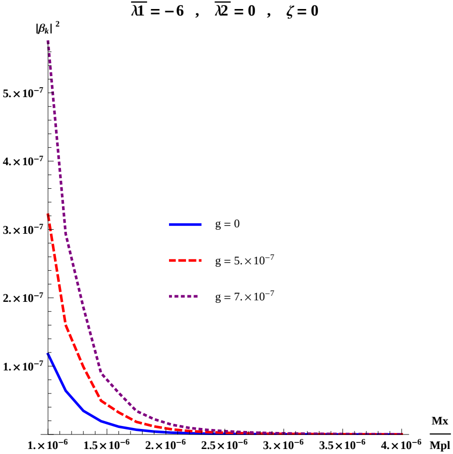




Further suppression of particle production with the introduction of non-minimal kinetic terms to the X field

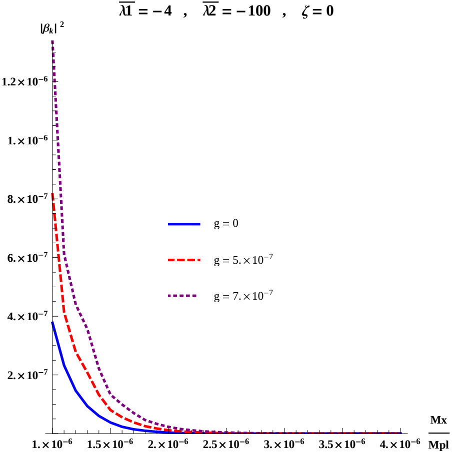
Field ϕ with coupling $\overline{\lambda_1} = -4$, $\overline{\lambda_1} = -6$ and X with $\overline{\lambda_2} = 0$

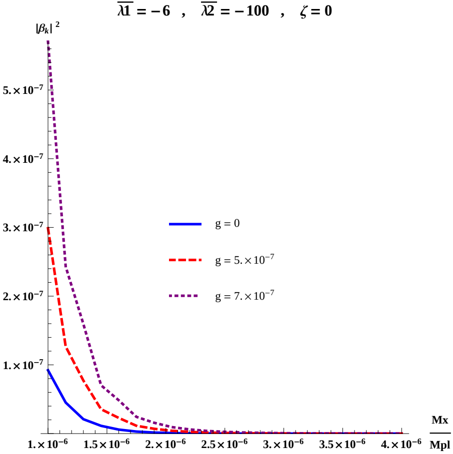




Suppression of particle production with the increase of the coupling $\overline{\lambda_1}$

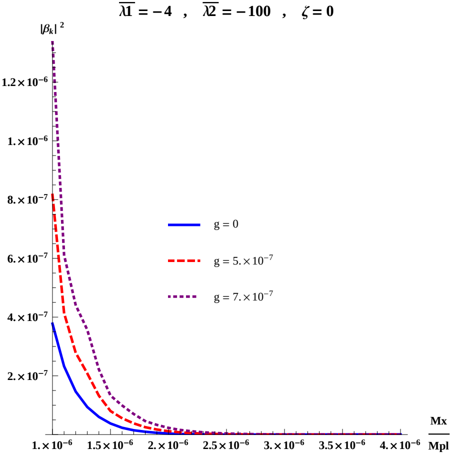
Field ϕ with coupling $\overline{\lambda_1} = -4$, $\overline{\lambda_1} = -6$ and X with $\overline{\lambda_2} = -100$

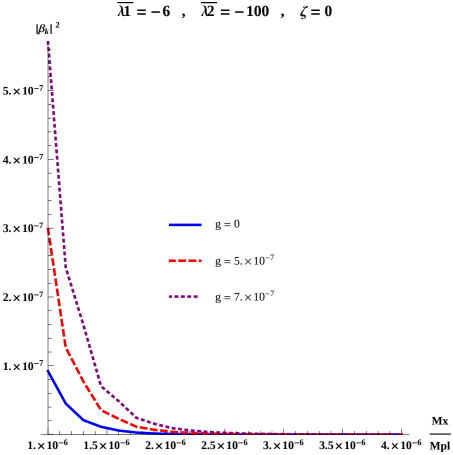




Suppression of particle production with the increase of the couplings $\overline{\lambda_1}$ and $\overline{\lambda_2}$

Field ϕ with coupling $\overline{\lambda_1} = -4$, $\overline{\lambda_1} = -6$ and X with $\overline{\lambda_2} = -100$





Suppression of particle production with the increase of the couplings $\overline{\lambda_1}$ and $\overline{\lambda_2}$

which can be reversed with the increase of the coupling g

Conclusions

- Enhancement of particle production with the increase of the couplings g , ζ
- After the end of inflation Einstein tensor has been weakened so we need stronger coupling $\overline{\lambda_2}$
- Suppression of particle production with the introduction of non-minimal kinetic terms to the inflaton
- Further suppression of particle production with the introduction of non-minimal kinetic terms to the X field
- Suppression of particle production with the increase of the couplings $\overline{\lambda_1}$ and $\overline{\lambda_2}$
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