Role of dissipative effects in the loop quantum gravitational onset of warm Starobinsky inflation in a closed universe

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One can consider a closed oscillating universe

$$H^2 = \frac{8\pi G}{3}\rho - \frac{1}{a^2}, \tag{1}$$

where the matter density is homogeneous scalar field with energy density and pressure as follows

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi), \qquad P = \frac{1}{2}\dot{\phi}^2 - V(\phi) \tag{2}$$

and its corresponding equation of motion is given by

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = 0, \tag{3}$$

Therefore, scalar field experiences two asymptotic regimes [V. Sahni and A.Toporensky, PRD 2012]

$$P = -\rho \qquad \text{during expansion } (H > 0) \tag{4}$$
$$P = \rho \qquad \text{during contraction } (H < 0) \tag{5}$$

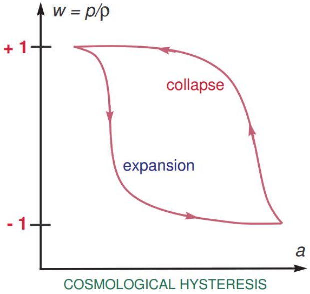


Figure: An idealized illustration of cosmological hysteresis [V. Sahni and A.Toporensky, PRD 2012].

Using conservation of energy, i.e. $\delta W = -\delta M$, one can find that

$$\delta a_{max} = -\frac{4G}{3\pi}\oint P dV \tag{6}$$

This hysteresis phase will enhance the phase space of initial conditions for inflation to happen. How?

To build an oscillating model, one need to induce a mechanism to avoid big bang/crunch singularities.

The effective dynamics for the holonomy based quantization of the $k = 1$ LQC results in the following modified Friedmann equation [A. Ashtekar et al., PRD 2007]

$$H^2 = \frac{8\pi G}{3}(\rho - \rho_{\rm min})\left(1 - \frac{\rho - \rho_{\rm min}}{\rho_{\rm max}^{\rm flat}}\right) \,. \tag{7}$$

Here $\rho_{\rm max}^{\rm flat}$ denotes the energy density at the bounce for the spatially-flat model in LQC and $\rho_{\rm min}$ and $\rho_{\rm max} = \rho_{\rm min} + \rho_{\rm max}^{\rm flat}$ are minimum and maximum value of energy density during the evolution of universe.

If the recollapses occur at the macroscopic scales, the difference in the volumes of two consecutive recollapses is found to be

$$\delta v_{\rm rec}^{1/3} = \frac{-\oint P dv}{(2\pi^2)^{2/3}\rho_{\rm max}^{\rm flat}\gamma^2\lambda^2}. \tag{8}$$

where γ is Barbero-Immirzi parameter and λ is constant.

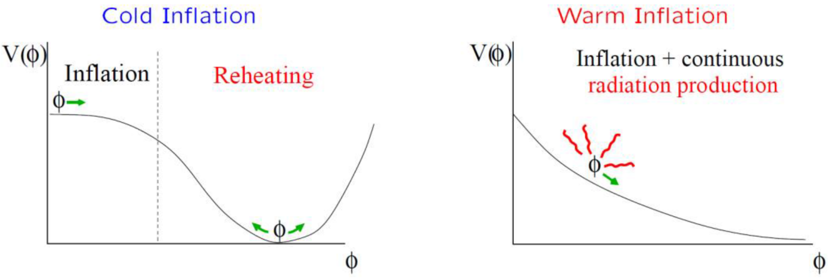


Figure: Warm Vs Cold inflation dynamics. [A. Berera, Contemp.Phys. 2006]

Due to energy conservation, the evolution equations for inflaton and radiation energy density are given by

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V_\phi = 0 \tag{9}$$

$$\dot{\rho}_r + 4H\rho_r = \Upsilon\dot{\phi}^2 \tag{10}$$

while radiation production results in entropy production

$$T(\dot{s} + 3Hs) = \Upsilon\dot{\phi}^2 \tag{11}$$

where s density entropy. We will consider following dissipation coefficients derived from quantum field theory

$\Upsilon \propto T$ Warm Little Inflaton [M. Bastero-Gil et al., PRL 2016]

$\Upsilon \propto T^{-1}$ Variant of Warm Little Inflaton [M. Bastero-Gil et al., PLB 2021]

$\Upsilon \propto T^3$ Minimal Warm Inflation [K. Berghaus, P. Graham and D. Kaplan, JCAP 2020]

During our numerical simulation, we consider Starobinsky potential

$$U(\phi) = \frac{3m^2}{32\pi}\left(1 - e^{-\sqrt{\frac{16\pi}{3}}\phi(t)}\right)^2 \tag{12}$$

Why Starobinsky potential?

- Small energy scale inflation can not occur in closed universe [A. Linde, Found.Phys. 2018].
- It was shown that inflation will happen due to hysteresis phenomena in LQC except for highly unfavorable initial conditions [L. Gordon, B. F. Li and P. Singh, PRD 2020].

Why warm inflation?

We expect that entropy production due to radiation particle production during warm inflation make the the hysteresis phenomena stronger.

Cubic Dissipation Coefficient ($\Upsilon \propto T^3$)

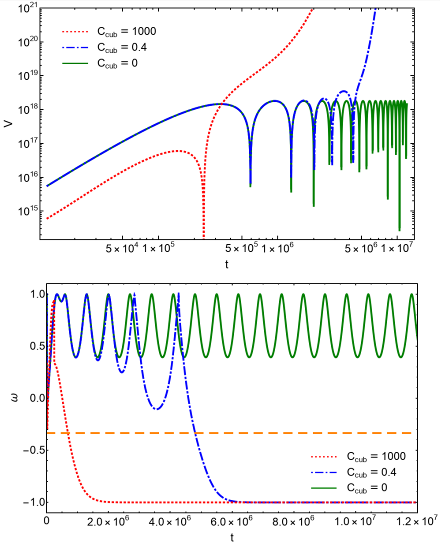


Figure: The evolution of volume and equation of state for different values of cubic dissipation coefficient. Initial conditions are chosen at the bounce with $v_0 = 5 \times 10^7$, $\phi_0 = -1$, $\rho_{r0} = 10^{-12}$, and $g = 17$ [M. Motaharfar and P. Singh, PRD 2021].

Cubic Dissipation Coefficient ($\Upsilon \propto T^3$)

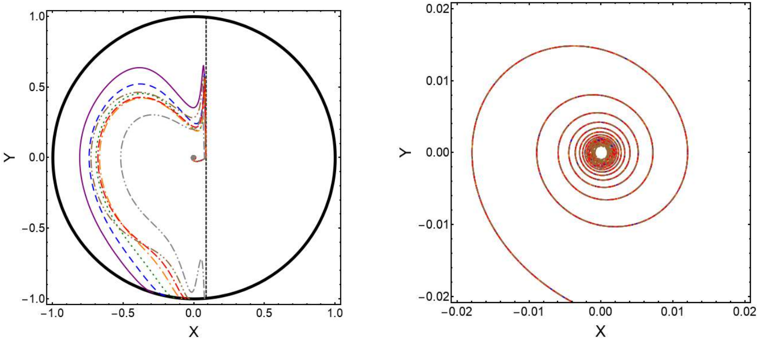


Figure: Projection of 3 dimensional phase space portrait on $Z = 0$ plane for cubic dissipation coefficient with $m = 0.62$, $C_{\text{cub}} = 7.5$, $v_0 = 35$, $\rho_{r0} = 10^{-3}$ and seven distinct initial conditions for ϕ_0 [M. Motaharfar and P. Singh, PRD 2021].

Cubic Dissipation Coefficient ($\Upsilon \propto T^3$)

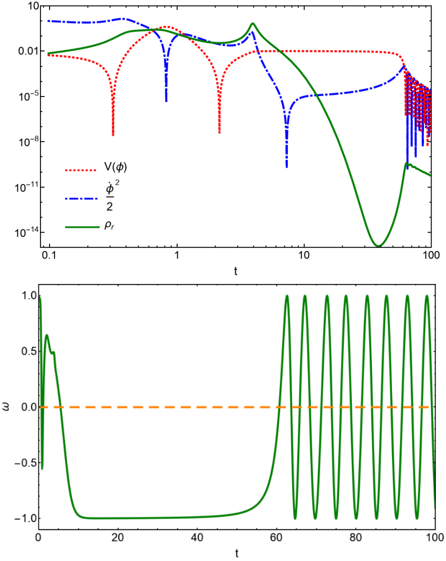


Figure: Evolution of energy components as well as equation of state for cubic dissipation coefficient with $m = 0.62$, $C_{\rm cub} = 7.5$, $v_0 = 35$, $\rho_{r0} = 10^{-3}$ and $\phi_0 = 0.5$ [M. Motaharfar and P. Singh, PRD 2021].

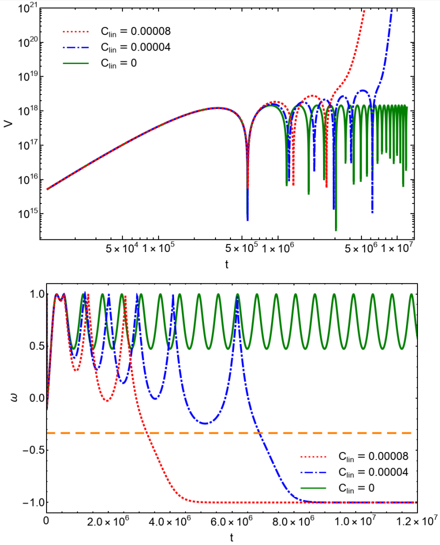


Figure: The evolution of volume and equation of state for different values of linear dissipation coefficient. Initial conditions are chosen at the bounce with $v_0 = 10^7$, $\phi_0 = -1.5$, $\rho_{r0} = 10^{-11}$, and $g = 12.5$ [M. Motaharfar and P. Singh, PRD 2021].

Linear Dissipation Coefficient $(\Upsilon \propto T)$

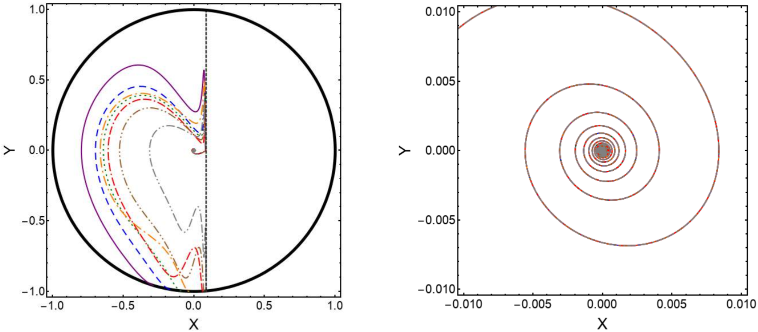
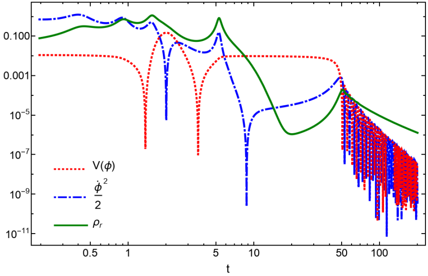


Figure: Projection of 3 dimensional phase space portrait on $Z = 0$ plane for linear dissipation coefficient with $m = 0.62$, $C_{\rm lin} = 0.8$, $v_0 = 35$, $\rho_{r0} = 10^{-3}$ and seven distinct initial conditions for ϕ_0 [M. Motaharfar and P. Singh, PRD 2021].

Linear Dissipation Coefficient $(\Upsilon \propto T)$



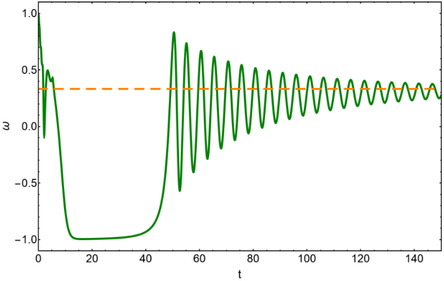


Figure: Evolution of energy components as well as equation of state for linear dissipation coefficient with $m = 0.62$, $C_{\rm lin} = 0.8$, $v_0 = 35$, $\rho_{r0} = 10^{-3}$ and $\phi_0 = 1.55$ [M. Motaharfar and P. Singh, PRD 2021].

Inverse Dissipation Coefficient $(\Upsilon \propto T^{-1})$

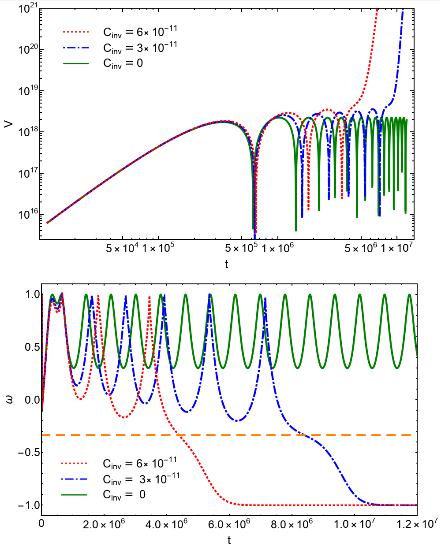


Figure: The evolution of volume and equation of state for different values of inverse dissipation coefficient. Initial conditions are chosen at the bounce with $v_0 = 2.5 \times 10^6$, $\phi_0 = -2$, $\rho_{r0} = 10^{-9}$, and $g = 12.5$ [M. Motaharfar and P. Singh, PRD 2021].

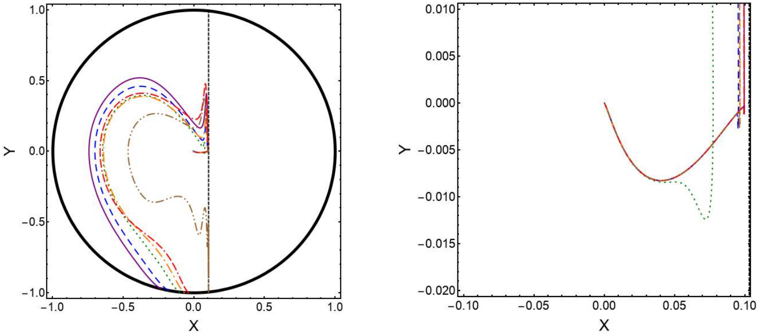


Figure: Projection of 3 dimensional phase space portrait on $Z = 0$ plane for inverse dissipation coefficient with $m = 0.79$, $C_{\rm inv} = 0.2$, $v_0 = 30$, $\rho_{r0} = 10^{-3}$ and six distinct initial conditions for ϕ_0 [M. Motaharfar and P. Singh, PRD 2021].

Inverse Dissipation Coefficient $(\Upsilon \propto T^{-1})$

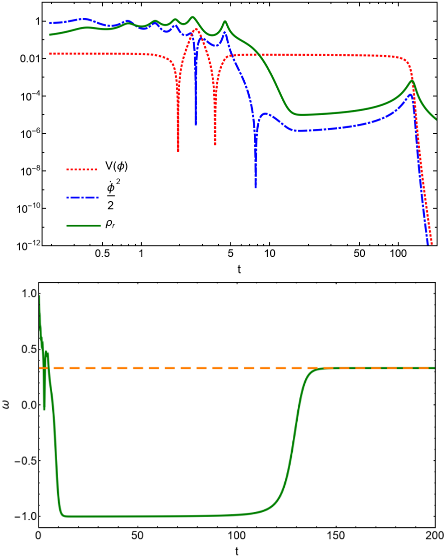


Figure: Evolution of energy components as well as equation of state for inverse dissipation coefficient with $m = 0.79$, $C_{\rm inv} = 0.2$, $v_0 = 30$, $\rho_{r0} = 10^{-3}$ and $\phi_0 = 2.2$ [M. Motaharfar and P. Singh, PRD 2021].

Summary

- Small energy scale inflationary models such as Starobinsky potential cannot be achieved in closed universe since the universe recollapse before the inflation sets in.
- Cosmological hysteresis occurs even in case of scalar field matter density and such phase may set in the stage for inflation to happen even for small energy scale inflationary models.
- To build a pre-inflationay hysteresis phase one needs to induce a mechanism to avoid big bang/big crunch singularities. This can be achieved in the context of LQC where big bang/big crunch singularities are generally replaced by bounces.
- Although Starobinsky potential results in inflationary phase in k=1 LQC model due to hysteresis phase, there here are highly unfavorable initial conditions for which the universe goes through many cycles and inflation does not occur.
- Warm inflation is different dynamical realization for inflation in which inflationary phase and radiation particle production occurs at the same time.
- This particle production results in entropy production whereby stronger hysteresis phenomena during expansion-contraction phase is achieved. Therefore, inflation will happen even for those highly unfavorable initial conditions in the presence of dissipative particle production effects.