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# Universal features of quantum bounce in loop quantum cosmology

Tao Zhu [a,b], Anzhong Wang [a,b,*], Klaus Kirsten [c], Gerald Cleaver [d], Qin Sheng [c]

[a] Institute for Advanced Physics & Mathematics, Zhejiang University of Technology, Hangzhou, 310032, China
[b] GCAP-CASPER, Physics Department, Baylor University, Waco, TX 76798-7316, USA
[c] GCAP-CASPER, Mathematics Department, Baylor University, Waco, TX 76798-7328, USA
[d] EUCOS-CASPER, Physics Department, Baylor University, Waco, TX 76798-7316, USA

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ABSTRACT

In this Letter, we study analytically the evolutions of the flat Friedmann–Lemaitre–Robertson–Walker (FLRW) universe and its linear perturbations in the framework of *the dressed metric approach* in loop quantum cosmology (LQC). Assuming that the evolution of the background is dominated by the kinetic energy of the inflaton at the quantum bounce, we find that both evolutions of the background and its perturbations are independent of the inflationary potentials during the pre-inflationary phase. During this period the effective potentials of the perturbations can be well approximated by a Pöschl–Teller (PT) potential, from which we find analytically the mode functions and then calculate the corresponding Bogoliubov coefficients at the onset of the slow-roll inflation, valid for any inflationary model with a single scalar field. Imposing the Bunch–Davies (BD) vacuum in the contracting phase prior to the bounce when the modes are all inside the Hubble horizon, we show that particles are generically created due to the pre-inflation dynamics. Matching them to those obtained in the slow-roll inflationary phase, we investigate the effects of the pre-inflation dynamics on the scalar and tensor power spectra and find features that can be tested by current and forthcoming observations. In particular, to be consistent with the Planck 2015 data, we find that the universe must have expanded at least 141 e-folds since the bounce.



## 1. Introduction

The paradigm of cosmic inflation has achieved remarkable successes in solving several problems of the standard big bang cosmology and predicting the primordial perturbation spectra whose evolutions explain both the formation of the large scale structure of the universe and the small inhomogeneities in the cosmic microwave background (CMB) [1]. Now they are matched to observations with unprecedented precisions [2–4]. However, such successes are contingent on the understanding of physics in much earlier epochs when energies were about the Planck scale. This leads to several conceptual issues. For example, to be consistent with observations, the universe must have expanded at least 60 e-folds during its inflationary phase. However, if the universe had expanded a little bit more than 70 e-folds during inflation (as it is the case in a large class of inflationary models [5]), then one can show that the wavelengths of all fluctuation modes which are currently inside the Hubble radius were smaller than the Planck length at the beginning of the period of inflation. This was referred to as the trans-Planckian issue in [6], and leads to the question about the validity of the assumption: *the matter fields are quantum in nature but the spacetime is still classical*, which are used at the beginning of inflation in order to make predictions [1]. In addition, insisting on the use of general relativity (GR) to describe the inflationary process will inevitably lead to an initial singularity [7]. Moreover, the inflation paradigm usually sets the BD vacuum state at the time when the wavelength of fluctuations were well within the Hubble horizon during the inflationary process. However, such treatment ignores the pre-inflationary dynamics which could lead to non-BD states at the onset of inflation, even when these modes were well inside the Hubble horizon during inflation. For more detail about the sensibility of the inflationary paradigm to Planckian physics, we refer the readers to [6,8].

All the issues mentioned above are closely related to the fact that we are working in the regime where GR is known to break down. One believes that new physics in this regime – a quantum theory of gravity, will provide a complete description of inflation as

* Corresponding author.
*E-mail addresses:* Tao_Zhu@baylor.edu (T. Zhu), anzhong_wang@baylor.edu (A. Wang), klaus_kirsten@baylor.edu (K. Kirsten), gerald_cleaver@baylor.edu (G. Cleaver), qin_sheng@baylor.edu (Q. Sheng).

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well as its pre-inflationary dynamics. LQC is one of such theories that offers a framework to address these issues, in which the inflationary scenarios can be extended from the onset of the slow-roll inflation back to the Planck scale in a self-consistent way [9–11]. Remarkably, the quantum geometry effects of LQC at the Planck scale provide a natural resolution of the big bang singularity (see [12–15] and references therein). In such a picture, the singularity is replaced by a quantum bounce, and the universe that starts at the bounce can eventually evolve to the desired slow-roll inflation [16–23]. An important question now is whether the quantum bounce can leave any observational signatures to current/forthcoming observations, so LQC can be placed directly under experimental tests. The answer to this question is affirmative. In fact, with some (reasonable) assumptions and choice of the initial conditions, the *deformed algebra approach* already leads to inconsistence with current observations [21]. Note that in general there are two main approaches to implement cosmological perturbations in the framework of LQC, the *dressed metric* and *deformed algebra approaches* [12–14]. In both, the primordial perturbations have been intensively studied *numerically* [10,11,19–23].

One of our purposes of this Letter, in contrast to the previous numerical studies, is to present an *analytical* analysis of the effects of the quantum bounce and pre-inflation dynamics on the evolutions of both background and spectra of the scalar and tensor perturbations, in the framework of the dressed metric approach [9–11]. It is expected that such an analysis will provide a more complete understanding of the problem and deeper insights. In the following, we will focus on the case that the kinetic energy of the inflaton dominates the evolutions at the bounce, because a potential dominated bounce is either not able to produce the desired slow-roll inflation [22], or leads to a large amount of e-folds of expansion. This will wash out all the observational information about the pre-inflation dynamics and the resulting perturbations are the same as those given in GR [12–14]. Assuming that the influence of the potential at the bounce is negligible, our studies show that:

- During the pre-inflationary phase, the evolutions of the background and the scalar and tensor perturbations are independent of the inflationary potentials. Thus, the evolution of the background is the same for any chosen potential, and in this sense we say that it is *universal*.
- During this phase the potentials of the scalar and tensor perturbations can be well approximated by an effective PT potential, for which analytic solutions of the mode functions can be found. The Bogoliubov coefficients at the onset of the slow-roll inflation can thereby be calculated [cf. (13)], which are valid for any slow-roll inflationary model with a single scalar field. Assuming that the universe is in the BD vacuum in the contracting phase (the moments where $t \lesssim -t_s$ as shown in Fig. 2) we find that particle creations occur generically during the pre-inflation phase.
- Oscillations always happen in the power spectra, and their phases for both scalar and tensor perturbations are the same, in contrast to other theories of quantum gravity [6,24].
- Fitting the power spectra to the Planck 2015 data [4], we find the lower bound for $N_{\rm tot} \equiv \ln(a_0/a_B) > 141$ (95% C.L.), where $a_B$ and $a_0$ denote the expansion factor at the bounce and current time, respectively. Details of the calculations will be reported elsewhere [25].

## 2. Quantum bounce

In LQC, the semi-classical dynamics of a flat FLRW universe with a single scalar field $\phi$ and potential $V(\phi)$ is described by [9–11],

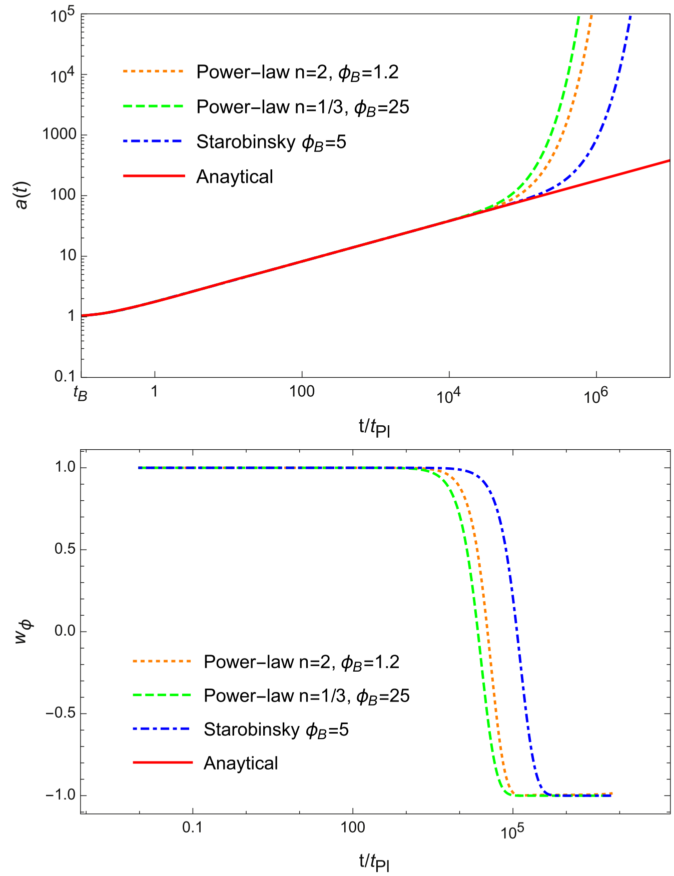


**Fig. 1.** Evolutions of $a(t)$ and $w_\phi$ for the power-law $V(\phi) = \frac{1}{2}m^{4-n}\phi^n$ and Starobinsky $V(\phi) = \frac{3}{4}M^2M_{\rm Pl}^2(1 - e^{-\sqrt{2/3}\phi/M_{\rm Pl}})^2$ potentials. Solution (3) is also shown. We choose $m = 1.3 \times 10^{-6}$ for $n = 2$, $m = 1.1 \times 10^{-3}$ for $n = 1/3$, and $M = 2.5 \times 10^{-6}$ for the Starobinsky potential. In all the cases we set $m_{\rm Pl} = 1$.

$$H^2 = \frac{8\pi}{3m_{\rm Pl}^2}\rho\left(1 - \frac{\rho}{\rho_{\rm c}}\right), \tag{1}$$

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0, \tag{2}$$

where $H \equiv \dot{a}/a$ is the Hubble parameter, a dot denotes the derivative with respect to the cosmic time $t$, and $\rho_c$ is the maximum energy density, with $\rho \equiv \dot{\phi}^2/2 + V(\phi) \le \rho_c$. Eq. (1) shows that the big bang singularity now is replaced by a non-singular quantum bounce at $\rho = \rho_c$ [cf. Fig. 1]. The background evolution has been extensively studied, and one of the main results is that, following the bounce, a desired slow-roll inflation phase is almost inevitable, provided that the evolution is dominated initially by the kinetic energy of the scalar field at the quantum bounce [12,17,18,22]. In this Letter, we will focus on this case. Then, ignoring the potential term $V(\phi)$, from Eqs. (1) and (2) we find

$$a(t) = a_{\rm B}\left(1 + \gamma_B\frac{t^2}{t_{\rm Pl}^2}\right)^{1/6}, \tag{3}$$

where $a_{\rm B} \equiv a(t_B)$, $\gamma_B \equiv 24\pi\rho_c/m_{\rm Pl}^4$, and $t_{\rm Pl}$ denotes the Planck time. In writing the above expression we also set $t_{\rm B} = 0$. In Fig. 1 we display the above analytical solution and the equation of state

$$w_\phi \equiv \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}, \tag{4}$$

together with several numerical solutions of $a(t)$ for different potentials. From this figure, specially the curves of $w_\phi$, we can see that the universe experiences three different phases: *bouncing*,