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Late time cosmic acceleration from natural infrared cutoff

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ABSTRACT

In this paper, inspired by the ultraviolet deformation of the Friedmann–Lemaître–Robertson–Walker geometry in loop quantum cosmology, we formulate an infrared-modified cosmological model. We obtain the associated deformed Friedmann and Raychaudhuri equations and we show that the late time cosmic acceleration can be addressed by the infrared corrections. As a particular example, we applied the setup to the case of matter dominated universe. This model has the same number of parameters as ΛCDM, but a dynamical dark energy generates in the matter dominated era at the late time. According to our model, as the universe expands, the energy density of the cold dark matter dilutes and when the Hubble parameter approaches to its minimum, the infrared effects dominate such that the effective equation of state parameter smoothly changes from $w_{\rm eff} = 0$ to $w_{\rm eff} = -2$. Interestingly and nontrivially, the unstable de Sitter phase with $w_{\rm eff} = -1$ is corresponding to $\Omega_m = \Omega_d = 0.5$ and the universe crosses the phantom divide from the quintessence phase with $w_{\rm eff} > -1$ and $\Omega_m > \Omega_d$ to the phantom phase with $w_{\rm eff} < -1$ and $\Omega_m < \Omega_d$ which shows that the model is observationally viable. The results show that the universe finally ends up in a big rip singularity for a finite time proportional to the inverse of the minimum of the Hubble parameter. Moreover, we consider the dynamical stability of the model and we show that the universe starts from the matter dominated era at the past attractor with $w_{\rm eff} = 0$ and ends up in a future attractor at the big rip with $w_{\rm eff} = -2$.

1. Introduction

Cosmological observations indicate that the Universe accelerates positively at the small redshifts [1] which leads to the so-called dark energy problem [2,3]. In the standard ΛCDM model, cosmological constant dominates at the late time and derives cosmic speed-up. But, the models in favor of cosmological constant clue to the cosmological constant problem due to the possible identification of the cosmological constant with the vacuum energy of the quantum fields [2,4]. Furthermore, increasing evidences from the cosmological data reveal that the energy density corresponds to the dark energy evolves very slowly in time and the associated equation of state parameter lies in a narrow strip around $w = -1$ [1]. Thus, cosmological constant with sharp value $w = -1$ for the equation of state parameter is an appropriate candidate in the first order of approximation [5]. In order to explain the dynamical nature of the dark energy, the quintessence scenarios with $w > -1$ and phantom models with $w < -1$ are proposed. In this respect, one usually interested in models which support the transition from the quintessence era to the phantom phase. These scenarios are usually based on two postulates: i) assuming general relativity is applicable even on cosmological scales and then considering some sort of unusual matter component(s) costing violation of some energy conditions, ii) deformation of general relativity at the cosmological scales. For the first case the matter source is usually given by a scalar field [6–8] and for the latter case, there are many candidates such as the extra dimensions models, $f(R)$ theories [9,10] and recently proposed massive gravity models [11].

From the theoretical point of view, de Sitter spacetime is a maximally symmetric space and its constant curvature is completely determined by the cosmological constant. Apart from the very small variation of cosmological constant with time, it can be interpreted as a fundamental constant of nature much similar to the speed of light and Planck constant. It therefore provides a universal infrared (IR) cutoff (corresponding to the large length scale $\sim 10^{-56}$ cm^{-2}) for the universe. For instance, existence of cosmological constant as an IR cutoff is essential for the quantization of scalar field in de Sitter spacetime. More precisely, it provides a minimum scale for the momenta of modes through the uncertainty principle and removes the IR divergences in this setup [12]. In this respect the uncertainty principle will be modified in curved spacetimes in order to respect the existence of cosmological constant as

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a universal IR cutoff [13]. On the other hand, existence of a minimal length scale is suggested by any quantum theory of gravity such as loop quantum gravity [14] and string theory [15]. It is also shown that the uncertainty principle is modified in the presence of a minimal length scale [16]. Thus, the uncertainty principle gets modifications in IR and ultraviolet (UV) regimes in order to respect the existence of cosmological constant and minimal length scale respectively [17]. Taking these universal IR and UV cutoffs into account, the quantum field theories turn out to be renormalizable [18]. Therefore, natural IR and UV cutoffs would be emerged in the context of ultimate quantum gravity theory. While the existence of a universal IR cutoff is supported by the standard general relativity framework through the de Sitter spacetime,[1] there is not any explanation for the UV cutoff (minimal length scale) in this setup. On the other hand, a minimal length scale as a UV cutoff emerges in loop quantum gravity framework [19] but there is not a well-defined explanation for taking a cosmological constant into account in this setup (see however Refs. [20] where some attempts have done in this direction). In this paper, we follow the UV deformation of the Friedmann–Lemaître–Robertson–Walker (FLRW) universe in loop quantum cosmology and we construct the corresponding IR-deformed case. We show that the late time cosmic acceleration arises in this setup which is significantly different from the ΛCDM model such that the universe crosses the phantom divide from $w_{\rm eff} > -1$ to $w_{\rm eff} < -1$.

2. FLRW universe

The spatial part of the spatially flat FLRW universe is 3-manifold M with the Euclidean isometry group and $\mathbf{R}^3$ topology. One then can fix a constant orthonormal triad e^a_i and a co-triad ω^i_a compatible with a flat fiducial metric ${}^o q_{ab}$ on M. The corresponding gravitational phase space consists of pairs (A^i_a, E^a_i) on M, where A^i_a is a $SU(2)$ connection and E^a_i is its canonically conjugate field [21]. Because of the symmetries of the 3-manifold M, all the information of the phase space variables (A^i_a, E^a_i) are summarized in two variables (β, V) which satisfy canonical Poisson algebra

$$\{\beta, V\} = \frac{\kappa\gamma}{2}\,, \tag{1}$$

on two-dimensional phase space Γ, where $\kappa = 8\pi G$ (we work in unit $c = 1$, where c is the speed of light in vacuum) and $\gamma \approx 0.2375$ is the Barbero–Immirizi parameter which is fixed by the black hole entropy calculations in loop quantum gravity [22]. These variables are related to the old geometrodynamics variables as

$$\beta = \gamma\,\frac{\dot a}{a}, \qquad V = a^3\,. \tag{2}$$

So, V is the comoving volume and its canonically conjugate variable β is (up to a constant) the Hubble parameter.

Considering a perfect fluid as a source for the matter content, the associated energy density consisting of non-relativistic and relativistic matters will be a function of volume as $\rho = \rho(V)$ and the corresponding Hamiltonian function is given by

$$\mathcal{H} = -\frac{3}{\kappa\gamma^2}\beta^2 V + \rho V\,. \tag{3}$$

The Hamiltonian system of the FLRW universe in terms of Ashtekar variables (β, V) is therefore defined by the relations (1) and (3) on two-dimensional phase space Γ: The kinematics is defined by the Poisson bracket (1) and the dynamical evolution is governed by the Hamiltonian (3). It is easy to show that the associated Hamilton's equations together with the Hamiltonian constraint $\mathcal{H} \approx 0$ lead to the standard Friedmann and Raychaudhuri equations.

2.1. UV-deformed phase space

In loop quantum cosmology scenario however this Hamiltonian system gets holonomy corrections at the UV regime. At the semiclassical regime, these UV effects can be taken into account in two equivalent ways on the corresponding UV-deformed phase space Γ_λ. One can work in noncanonical chart on Γ_λ in which the Poisson bracket (1) gets UV modification while the Hamiltonian function (3) retains its standard functional form [26]. Equivalently, one can also work in canonical chart on Γ_λ such that the form of Poisson bracket (1) remains unchanged and the Hamiltonian function (3) gets modified functional form [23]. These two different representations are related to each other through the Darboux transformation and lead to the same Friedmann and Raychaudhuri equations [24,25]. In this paper we work in the first picture in which the Poisson bracket gets UV modification as [26]

$$\{\beta, V\} = \frac{\kappa\gamma}{2}\sqrt{1-\lambda^2\beta^2}, \tag{4}$$

where λ is the UV deformation parameter which is preferably of the order of the Planck length $\lambda \sim l_{\rm Pl}$. Clearly, β gets maximum value as $\beta < \lambda^{-1}$ in this setup. More precisely, the space of β is compactified to a circle S^1 with radius λ^{-1} [23]. The UV-deformed Poisson algebra (4) implies the following modified Hamilton's equations

$$\dot V = \{V, \mathcal{H}\} = \frac{\kappa\gamma}{2}\sqrt{1-\lambda^2\beta^2}\,\frac{\partial\mathcal{H}}{\partial\beta}\,, \tag{5}$$

$$\dot\beta = \{\beta, \mathcal{H}\} = -\frac{\kappa\gamma}{2}\sqrt{1-\lambda^2\beta^2}\,\frac{\partial\mathcal{H}}{\partial V}\,. \tag{6}$$

The above equations correctly reduce to the standard Hamilton's equations in the limit of $\lambda \to 0$. Substituting (3) into (5) gives

$$\dot V = \frac{3V\beta}{\gamma}\sqrt{1-\lambda^2\beta^2}.$$

Using Hamiltonian constraint $\mathcal{H} \approx 0$ and after some manipulations, it is straightforward to obtain the following UV-deformed Friedmann equation

$$H^2 = \frac{\kappa}{3}\rho\left(1-\frac{\rho}{\rho_{\rm max}}\right), \tag{7}$$

where $H = \frac{\dot a}{a}$ is the Hubble parameter and we have also defined $\rho_{\rm max} = \frac{3}{\kappa\gamma^2\lambda^2}$. The energy density and the Hubble parameter get maximum bounds $\rho \le \rho_{\rm max}$ and $H < H_{\rm max} = \left(\frac{\kappa\rho_{\rm max}}{12}\right)^{\frac{1}{2}}$ in this setup and the big bang singularity problem resolves such that the initial singularity in standard model of cosmology replaces with a bounce [27]. Existence of the minimal length scale as a UV cutoff for the system thus naturally leads to the spacetime singularity resolution in cosmological setup. In this paper, we are interested to study the effect of the existence of an IR cutoff on the late time cosmic acceleration in order to address the dark energy problem. As we will show in the next subsection, taking an IR cutoff into account leads to the self-accelerating universe at the late time.

[1] Note that the anti-de Sitter spacetime with negative cosmological constant is also an appropriate candidate from the theoretical point of view. But it rejects by cosmological observations.