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Accelerated expansion of the Universe without an inflaton and resolution of the initial singularity from Group Field Theory condensates

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ABSTRACT

We study the expansion of the Universe using an effective Friedmann equation obtained from the dynamics of GFT (Group Field Theory) isotropic condensates. The evolution equations are classical, with quantum correction terms to the Friedmann equation given in the form of effective fluids coupled to the emergent classical background. The occurrence of a bounce, which resolves the initial spacetime singularity, is shown to be a general property of the model. A promising feature of this model is the occurrence of an era of accelerated expansion, without the need to introduce an inflaton field with an appropriately chosen potential. We discuss possible viability issues of this scenario as an alternative to inflation.

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1. Introduction

Inflation, despite its undoubtful success in explaining cosmological data and the numerous models studied in the literature, still remains a paradigm in search of a theory. The inflationary era should have occurred at the very early stages of our Universe, however the inflationary dynamics are commonly studied in the context of Einstein's classical gravity and assuming the existence of a classical scalar field with a particularly tuned potential. Clearly, the onset of inflation [1,2] and the inflationary dynamics must be addressed within a quantum gravity proposal. In this letter, employing results from Group Field Theory [3,4] (GFT), we attempt to bridge the gap between the quantum gravity era and the standard classical cosmological model. In particular, in the context of GFT we propose a model that can account for an early accelerated expansion of our Universe in the absence of an inflaton field. We hence show that modifications in the gravitational sector of the theory can account for its early stage dynamics. Indeed, it is reasonable to expect that quantum gravity corrections at very early times – when geometry, space and time lose the meaning we are familiar with – may effectively lead to the same dynamics as the introduction of a hypothetical inflaton field with a suitable potential to satisfy cosmological data.

Group Field Theory is a non-perturbative and background independent approach to quantum gravity. In GFT, the fundamental degrees of freedom of quantum space are associated to graphs labelled by algebraic data of group theoretic nature. The quantum spacetime is seen as a superposition of discrete quantum spaces, each one generated through an interaction of fundamental building blocks (called "quanta of geometry"), typically considered as tetrahedra. In the continuum classical limit, one then expects to recover the standard dynamics of General Relativity. In this sense, the notion of spacetime geometry, gravity and time can be seen as emergent phenomena. Group Field Theory cosmology is built upon the existence of a condensate state of GFT quanta, interpreted macroscopically as a homogeneous universe.

2. GFT cosmology

In this work we study the properties of solutions of the modified Friedmann equation [5], obtained within the context of GFT condensates. The condensate wave function can be written as $\sigma_j = \rho_j e^{i\theta_j}$, where j is a representation index. Evolution is purely relational, thus all dynamical quantities are regarded as functions of a massless scalar field ϕ. Derivatives with respect to ϕ will be denoted by a prime. There is a conserved charge associated to θ_j:

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$$\rho_j^2\theta_j' = Q_j. \quad (1)$$

The modulus satisfies the equation of motion

$$\rho_j'' - \frac{Q^2}{\rho_j^3} - m_j^2\rho_j = 0, \quad (2)$$

leading to another conserved current, the *GFT energy*:

$$E_j = (\rho_j')^2 + \frac{Q_j^2}{\rho_j^2} - m_j^2\rho_j^2\ , \quad (3)$$

where m_j^2 can be expressed in terms of coefficients in the corresponding GFT theory, see Ref. [5] for details. Equation (2) admits the following solution

$$\rho_j(\phi) = \frac{e^{(-b-\phi)\sqrt{m_j^2}}\Delta(\phi)}{2\sqrt{m_j^2}}, \quad (4)$$

where

$$\Delta(\phi) = \sqrt{a^2 - 2ae^{2(b+\phi)\sqrt{m_j^2}} + e^{4(b+\phi)\sqrt{m_j^2}} + 4m_j^2Q_j^2} \quad (5)$$

and a, b are integration constants. From Eq. (3) follows

$$E_j = a, \quad (6)$$

whereas the charge Q_j contributes to the canonical momentum of the scalar field (see Ref. [5])

$$\sum_j Q_j = \pi_\phi. \quad (7)$$

The dynamics of macroscopic observables is defined through that of the expectation values of the corresponding quantum operators. In GFT, as in Loop Quantum Gravity, the fundamental observables are geometric operators, such as areas and volumes. The volume of space at a given value of relational time ϕ, is thus obtained from the condensate wave function as

$$V = \sum_j V_j\rho_j^2, \quad (8)$$

where $V_j \propto j^{3/2}\ell_{Pl}$ is the eigenvalue of the volume operator corresponding to a given representation j. Using this as a definition and differentiating w.r.t. relational time ϕ one obtains, as in Ref. [5] the following equations, which play the rôle of effective Friedmann (and acceleration) equations describing the dynamics of the cosmos as it arises from that of a condensate of spacetime quanta

$$\frac{V'}{V} = \frac{2\sum_j V_j\rho_j\rho_j'}{\sum_j V_j\rho_j^2}, \quad (9)$$

$$\frac{V''}{V} = \frac{2\sum_j V_j\left(E_j + 2m_j^2\rho_j^2\right)}{\sum_j V_j\rho_j^2}. \quad (10)$$

In the context of GFT, spacetime is thus seen to emerge in the hydrodynamic limit of the theory; the evolution of a homogeneous and isotropic Universe is completely determined by that of its volume. Notice that the above equations are written in terms of functions of ϕ. In fact, as implied by the background independence of GFT, and more in general of any theory of quantum geometry, *a priori* there is no spacetime at the level of the microscopic theory and therefore no way of selecting a coordinate time. Nevertheless, we will show how it is possible to introduce a preferred choice of time, namely proper time, in order to study the dynamics of the model in a way similar to the one followed for standard homogeneous and isotropic models. This will be particularly useful for the study of the accelerated expansion of the Universe. In the following we will restrict our attention to the case in which the condensate belongs to one particular representation of the symmetry group. This special case can be obtained from the equations written above by considering a condensate wave function σ_j with support only on $j = j_0$. Representation indices will hereafter be omitted. Hence, we have

$$\frac{V'}{V} = 2\frac{\rho'}{\rho} \equiv 2g(\phi), \quad (11)$$

$$\frac{V''}{V} = 2\left(\frac{E}{\rho^2} + 2m^2\right). \quad (12)$$

As $\phi \to \pm\infty$, $g(\phi) \to \sqrt{m^2}$ and the standard Friedmann and acceleration equations with a constant gravitational coupling and a fluid with a stiff equation of state are recovered. We will introduce proper time by means of the relation between velocity and momentum of the scalar field

$$\pi_\phi = \dot{\phi}V. \quad (13)$$

Furthermore, we can *define* the scale factor as the cubic root of the volume

$$a \propto V^{1/3}. \quad (14)$$

We can therefore write the evolution equation of the Universe obtained from GFT in the form of an *effective Friedmann equation* ($H = \frac{\dot{V}}{3V}$ is the Hubble expansion rate and $\varepsilon = \frac{\dot{\phi}^2}{2}$ the energy density)

$$H^2 = \left(\frac{V'}{3V}\right)^2\dot{\phi}^2 = \frac{8}{9}g^2\varepsilon. \quad (15)$$

Using Eqs. (3), (7), (13) we can recast Eq. (15) in the following form

$$H^2 = \frac{8}{9}Q^2\left(\frac{\gamma_m}{V^2} + \frac{\gamma_E}{V^3} + \frac{\gamma_Q}{V^4}\right), \quad (16)$$

where we introduced the quantities

$$\gamma_m = \frac{m^2}{2}, \quad \gamma_E = \frac{V_jE}{2}, \quad \gamma_Q = -\frac{V_j^2Q^2}{2}. \quad (17)$$

The first term in Eq. (16) is, up to a constant factor, the energy density of a massless scalar field on a conventional FLRW background, whereas the others represent the contribution of effective fluids with distinct equations of state and express departures from the ordinary Friedmann dynamics. Respectively, the equations of state of the terms in Eq. (17) are given by $w = 1, 2, 3$, consistently with the (quantum corrected) Raychaudhuri equation Eq. (27). Effective fluids have been already considered in the context of LQC as a a way to encode quantum corrections, see *e.g.* [6].

This equation reduces to the conventional Friedmann equation in the large ϕ limit, where the contributions of the extra fluid components are negligible

$$H^2 = \frac{8\pi G}{3}\varepsilon. \quad (18)$$

Thus, consistency in the limit demands $m^2 = 3\pi G$, which puts some constraints on the parameters of the microscopic model based on its macroscopic limit (see Ref. [5]).

The interpretation of our model is made clear by Eq. (16). In fact the dynamics has the usual Friedmann form with a classical background represented by the scale factor a and quantum geometrical corrections given by two effective fluids, corresponding to

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