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Testing quantum gravity with cosmology / Tester les théories de la gravitation quantique à l'aide de la cosmologie

The universe as a quantum gravity condensate

L'univers comme un condensat de gravitation quantique

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ABSTRACT

This is an introduction to the approach to the extraction of cosmological dynamics from full quantum gravity based on group field theory condensates. We outline its general perspective, which sees cosmology as the hydrodynamics of the fundamental quantum gravity degrees of freedom, as well as its concrete implementation within the group field theory formalism. We summarize recent work showing the emergence of a bouncing cosmological dynamics from a fundamental group field theory model, and provide a brief but complete survey of other results in the literature. Finally, we discuss open issues and directions for further research.

RÉSUMÉ

Ce texte constitue une introduction à l'approche de l'extraction de la dynamique cosmologique à partir de la gravitation quantique complète sur la base de condensats de la théorie des champs de groupe. Nous soulignons sa perspective générale, qui voit la cosmologie comme l'hydrodynamique des degrés de liberté de la gravitation quantique fondamentale, aussi bien que comme son implémentation concrète dans le cadre du formalisme de la théorie des champs de groupe. Nous résumons les travaux récents montrant l'émergence d'une dynamique du rebond cosmologique à partir d'un modèle fondamental de théorie des champs de groupe, et proposons une revue, brève mais exhaustive, des autres résultats de la littérature. Finalement, nous discutons les problèmes ouverts et les axes de recherché futurs.

1. Introduction

We work on quantum gravity because we want to answer, among others, two fundamental questions: what is the universe made of? what happens to it in extreme physical situations like the big bang, where General Relativity breaks down?

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The first has to do with the very definition of a theory of quantum gravity, the identification of the candidate microscopic degrees of freedom of spacetime and geometry and matter (the 'universe', after the relativistic revolution) and their fundamental dynamics. The second requires modeling the large-scale features of the same degrees of freedom *from within* the complete theory, under some approximation, and showing that they reproduce observational aspects of the universe as described by semi-classical relativistic cosmological models, while at the same time completing them with a deeper understanding of the regimes beyond their range of applicability. In fact, this last issue is also necessarily part of the first. Only after having a convincing story of how the usual description of spacetime and geometry at large scales arises from the more fundamental quantum gravity one, we can claim to have identified solid candidates for the microscopic building blocks of the universe. This is "the problem of emergent spacetime in quantum gravity" [1].

This is still the outstanding problem of most quantum gravity approaches, despite decades of successes on various fronts. This is not to say, of course, that there has not been considerable progress also in this respect. On the one hand, a number of simplified models have been developed, which, while not yet derived from or embedded into a fundamental theory, are however directly inspired by it. One example is loop quantum cosmology [2], which imports insights from loop quantum gravity [3] into minisuperspace quantization of cosmological spacetimes, and, beside a large number of interesting formal developments (including mechanisms for the replacement of the cosmological singularity with a quantum bounce), even suggests phenomenologically testable effects [4].

On the other hand, fundamental quantum gravity formalisms have made their first moves towards a derivation of cosmology from first principles, using a variety of strategies [5–7].

In this contribution, we motivate and review one recent line of research that addresses this issue, in the context of the group field theory formalism for quantum gravity [8], in turn strictly related to loop quantum gravity, tensor models [9] and lattice quantum gravity [10]: *group field theory condensate cosmology*. Its promise lies in the results already obtained, of course, but even more in the guiding ideas and in the potential for further developments, which we will try to elucidate.

2. The group field theory formalism

Group field theories (GFTs) [8] are quantum field theories on a group manifold, characterized by a peculiar type of (combinatorially) non-local interactions.

The basic variable is a (complex) field $\varphi : G^{\times d} \to \mathbb{C}$, with G a Lie group and d an integer. The key point is that the domain of the fields should not be interpreted as a spacetime manifold. Rather, GFT models of quantum gravity should be understood as *quantum field theories of spacetime*, and spacetime should emerge from them only in some regime. The classical phase space of each 'quantum' of the GFT field, an 'atom of space', is then $(\mathcal{T}^*G)^d$, while its corresponding Hilbert space of states is $\mathcal{H} = L^2\left(G^d\right)$. The fields $\varphi(g_i) = \varphi(g_1, ..., g_d)$ and the quantum states can also be written in terms of dual Lie algebra variables (the 'momenta' of the GFT quanta) via non-commutative Fourier transform [11] or in terms of irreducible representations of G, which label a complete basis of the Hilbert space. For 4d Lorentzian quantum gravity models, and in the absence of additional, matter-like degrees of freedom, the relevant group is usually the Lorentz group $SO(3,1)$ ($Spin(4)$ in the Riemannian case) or its rotation subgroup $SU(2)$. Each GFT quantum can be depicted as a topological three-dimensional polyhedron with d faces [12] (or as a vertex with d outgoing links) labeled by the d arguments of the field. In fact, 3-simplices, i.e. tetrahedra, are the most common choice, corresponding to $d = 4$. A guiding principle for model building is the requirement that the same polyhedra are *geometric* ones (in the sense of piecewise-flat geometry), at least in a classical limit. This translates in precise 'geometricity' conditions on the fields and their dynamics (the 'simplicity' conditions used in spin foam models [17]). The group, Lie algebra or representation variables labeling GFT states acquire then the interpretation as discrete connection or metric variables, encoding the geometry of the associated polyhedral structures.

The GFT (kinematical) Hilbert space is a Fock space

$$\mathcal{F}(\mathcal{H}) = \bigoplus_{N=0}^{\infty} sym\left\{\mathcal{H}^{(1)} \otimes \cdots \otimes \mathcal{H}^{(N)}\right\} \qquad \mathcal{H} = L^2\left(G^{\times d}\right)$$

where we have *assumed* bosonic statistics, and we use ladder field operators $\hat{\varphi}(g_1, g_2, g_3, g_4)$, $\hat{\varphi}^\dagger(g_1, g_2, g_3, g_4)$ [13]. Generic states of this Fock space, build out of a Fock vacuum that corresponds to a total absence of either topological or discrete geometric structures, are arbitrary collections of tetrahedra, including those corresponding (via appropriate restrictions) to connected simplicial complexes. Each combinatorial pattern corresponding to a choice of connectivity among the quanta encodes a specific simplicial topology of space, and the GFT formalism naturally allows for quantum superpositions of the same. Equivalently, GFT states can be associated with (superpositions of) open spin network states, analogous to those of loop quantum gravity [13]. Interesting operators, whose meaning is suggested by the simplicial geometric interpretation of the quantities associated with the GFT quanta, can be constructed in the same 2nd-quantized language. In fact, one can construct, as GFT observables, all the 2nd-quantized counterparts of the kinematical operators of loop quantum gravity, including operators encoding the quantum dynamics of the theory, like the Hamiltonian constraint, suitably re-expressed as acting on the GFT Fock space of spin networks [13]. Simple one-body operators are of the form $\widehat{O} = \int d\tilde{g}_i dg_i\, \hat{\varphi}^\dagger(\tilde{g}_i)\, O(\tilde{g}_i, g_i)\, \hat{\varphi}(g_i)$, where $O(\tilde{g}_i, g_i)$ are the matrix elements, in the group representation, of 1st-quantized operators in the Hilbert space asso-