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(Loop) quantum gravity and the inflationary scenario

Cosmologie quantique (à boucle) et paradigme inflationnaire

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ABSTRACT

Quantum gravity, as a fundamental theory of space-time, is expected to reveal how the universe may have started, perhaps during or before an inflationary epoch. It may then leave a potentially observable (but probably miniscule) trace in cosmic large-scale structures that seem to match well with predictions of inflation models. A systematic quest to derive such tiny effects using one approach, loop quantum gravity, has, however, led to unexpected obstacles. Such models remain incomplete, and it is not clear whether loop quantum gravity can be consistent as a full theory. But some surprising effects appear to be generic and would drastically alter our understanding of space-time at large density. These new high-curvature phenomena are a consequence of a widening gap between quantum gravity and ordinary quantum-field theory on a background.

RÉSUMÉ

La gravité quantique, en tant que théorie fondamentale de l'espace-temps, est supposée fournir des scénarios décrivant le début de l'univers, peut-être pendant ou avant une ère inflationnaire. Elle a alors pu laisser des signatures potentiellement observables (mais probablement minuscules) dans les grandes structures, qui semblent être en bon accord avec les prédictions des modèles d'inflation. Une recherche systématique visant à dériver ces petits effets dans le cadre d'une théorie quantique de la gravitation, la gravitation quantique à boucle, s'est heurtée à des obstacles inattendus. Ces modèles sont incomplets, et il n'est pas évident que la théorie quantique à boucle soit cohérente en tant que théorie complète. Mais des effets surprenants, qui modifieraient radicalement notre conception de l'espace-temps à grande densité, semblent être génériques. Ces nouveaux effets à grande courbure sont la conséquence d'un décalage grandissant entre la gravité quantique et la théorie quantique des champs ordinaires en espace-temps courbe.

How much of quantum gravity can be tested by cosmological observations? This question is non-trivial, not only because the understanding of "quantum gravity" depends on the approach one takes. A second, and perhaps more important, difficulty consists in the fact that several key aspects of physical properties usually associated with theories of gravity play

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interconnected roles in this context. Based on the lessons of general relativity, a quantum theory of gravity, in general terms, is expected to entail (i) a modified dynamics, given by a gravitational force with quantum corrections; (ii) new quantized modes, gravitons; and (iii) a quantum version of space-time structure.

While the first two aspects are commonly exploited for proposals of potentially observable consequences in cosmology, the last one is most crucial at a conceptual level. Only if this subtle issue is addressed can one be sure that one is testing quantum gravity, as opposed to a quantum field theory of tensor modes on some curved background: Classical gravity, described by general relativity, is characterized not only by a certain form of dynamics but also, and more fundamentally, by a large class of covariance symmetries. These symmetries characterize the structure of space-time in classical gravity as a Riemannian manifold of Lorentzian signature. Quantizing fields on such a manifold is not the same as quantizing space-time itself: The full (spatial) metric would not be subject to quantum fluctuations. A full quantization of the metric, on the other hand, requires great care because, in the absence of a background, it can be changed by a large class of transformations which must in some way be respected after quantization, or else the theory would be coordinate dependent and therefore meaningless.

Quantizing highly symmetric theories is always a delicate process, and the decades of unsuccessful attempts to find a complete and consistent theory of quantum gravity bear witness to the fact that this theory is no exception. Quantum field theory on a curved background does not quantize space-time and its symmetries, and therefore leaves out an important part of the question of quantum gravity. A common, and often implicit, assumption is that quantum field theory on curved space-time may be a good approximation to quantum gravity in relevant cosmological regimes. However, the process of gravitons seeding a background of tensor modes is a rather strong quantum-gravity effect; in fact, it is often taken as the best (or only) way to "observe" or "establish the quantization of gravity" [1]. If this is the case, is it legitimate to treat quantum gravity as some version of quantum field theory on a curved background, bypassing a quantum theory of curved space-time itself?

The present contribution does not provide a universal answer to this question. However, an example will be given in which quantum field theory on a curved background turns out to be not just a poor approximation to a specific model of quantum gravity, but to result in a different and incompatible scenario. The model has been formulated in the framework of loop quantum gravity, following systematic attempts to derive potential observational consequences of this theory. Loop quantum gravity remains incomplete, and it is not clear how generally the effects appear that are responsible for the mismatch between quantum space-time and quantum field theory on a curved background, even though at present they seem to be rather generic. The result is sobering and provides much caution against too-optimistic presentations of potentially observable quantum-gravity effects, not only in loop quantum gravity itself but perhaps also more generally. This article therefore refrains from presenting specific details of potential observations in loop quantum gravity, as they all appear to be largely ambiguous at present. For some of the known options, interested readers are referred to reviews such as [2,3].

The different aspects of quantum gravity, listed above, are all interrelated. Graviton scattering implies loop corrections in the perturbative law of the gravitational force. A fundamental version of this law remains to be found, owing to the problem that gravity is not renormalizable. But in this context it is sufficient to consider an effective theory of gravity [4,5] in which loop corrections to the gravitational force can be discussed in a well-defined way — so long as a background treatment of space-time is valid. The structure of space-time enters into the considerations because it is closely linked to the modes and dynamics of gravity. One obtains the Einstein–Hilbert action from the covariance symmetries of space-time, leaving much less freedom for interactions compared with other fields (on a given background). An effective theory of gravitons on a classical background contains the usual higher-curvature terms.

When one quantizes gravity, the structure of space-time may change, depending on the specific approach used. Well-known proposals include non-commutative geometry or discreteness. If space-time is no longer modeled by a Riemannian manifold, it is not clear how general covariance can still apply in a meaningful way, but there must be some form in any consistent approach because the breaking of covariance symmetries would amount to a gauge anomaly. Only after the form of space-time has been determined in a given approach can one proceed and compute dynamical quantum corrections. Effective theory, as the main and most powerful tool to derive reliable quantum effects, relies on knowledge of the symmetries of a theory. Symmetries determine which terms an effective action may contain, the coefficients of which one can then compute by more-detailed calculations. Non-Riemannian structures can lead to quantum-gravity effects which a treatment of quantum-field theory on a curved background of classical form would miss.

A canonical approach is often useful in order to reveal non-trivial aspects of quantum theories. It is of special importance in quantum gravity because it does not presuppose what structure space-time may have. Symmetries are represented by generators, which are quantized in a canonical approach and may have quantum corrections. If also their algebra turns out to be modified (but not broken for an anomaly-free theory), a new structure of space-time emerges. The rest of this article attempts to review these features without too many technical details, followed by an example in which quantum-field theory on a curved background differs crucially from a model of (loop) quantum gravity.

In any quantum theory, dynamics is generated by a Hamiltonian operator $\hat{H}$, in quantum mechanics following the Schrödinger equation $i\hbar\partial\psi/\partial t = \hat{H}\psi$. In a covariant theory, the time coordinate can be changed freely (and locally), so that $\hat{H}$ must also be a generator of symmetries. This dual role of Hamiltonian operators is one of the reasons why quantum gravity is complicated and incomplete, but its conceptual consequences can be explored by well-known methods.