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EDITORIAL
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Editorial: Loop Quantum Cosmology

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Editorial on the Research Topic

Loop Quantum Cosmology

Loop Quantum Cosmology is the application to cosmology of the nonperturbative canonical quantization program of General Relativity provided by Loop Quantum Gravity. This has been an active field of investigation for more than 20 years. Most of the work in this research direction is currently devoted to understanding how quantum gravity phenomena affected the primordial perturbations responsible for the anisotropies in the cosmic microwave background (CMB). Loop Quantum Cosmology techniques have also proven themselves useful beyond cosmology, in particular to explore effects of quantum geometry in black hole spacetimes. On the other hand, the advances in the so-called covariant formulation of Loop Quantum Gravity, handling the dynamics within a path integral formalism, have opened new ways to address questions in cosmology. This Research Topic presents different branches that have developed from Loop Quantum Cosmology. It gathers eleven publications that are an excellent sample of their progress, successes and challenges.

Ashtekar et al. have contributed with an article that is addressed both to cosmologists and to the loop quantum gravity community. They revisit the analysis of the CMB data by the Planck collaboration using the standard ΛCDM model with six cosmological parameters. In spite of the success of this model, there exist certain tensions pointing towards the statistical exceptionality of our Universe. These tensions appear in the form of power suppression at large angular scales and in an excessively high value of the lensing amplitude. A new analysis in the light of Loop Quantum Cosmology alleviates these tensions thanks to the connection between the physics of the ultraviolet and the infrared that occurs in the quantum gravitational Universe. This is what the authors call cosmic tango. Moreover, new predictions arise from this revised perspective, opening the possibility of a future confrontation of the proposed formalism with observations.

On related grounds, Agullo et al. have presented a study that shows how a modulation of the primordial power spectrum due to non-Gaussianities in Loop Quantum Cosmology can statistically alleviate some anomalous features that have been observed in the CMB. For this purpose, they provide an introduction to the statistical meaning of these anomalies in the CMB, and explain in what sense they point to the exceptionality of our Universe if it is explained with the ΛCDM model. Then, they describe how non-Gaussian correlations between perturbations with observable and super-Hubble wavelengths can lead to modulations of the angular power spectrum of the CMB. These correlations are studied within the dressed metric formalism of Loop Quantum Cosmology, taking an initial adiabatic state for the perturbations. The resulting non-Gaussian modulation is strongly scale-dependent for large wavelengths, and it is discussed that this property leads to a situation in which the aforementioned features of the CMB, regarded as anomalous within the ΛCDM model, are much more likely to appear in the Loop Quantum Cosmology scenario.

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One of the aspects of Loop Quantum Cosmology that has deserved an increasing amount of attention in recent years is the discussion of possible quantization ambiguities in the Hamiltonian constraint and how they affect the robustness of the predictions for cosmological perturbations. This is the subject of the review presented by Li et al. They consider two alternative quantizations of the standard Hamiltonian of Loop Quantum Cosmology, and compare the predictions for the CMB of these three cases (including the standard quantization). Moreover, two different approaches are analyzed for the description of the quantum geometry effects on the perturbations, namely, the dressed metric and the hybrid approaches. The review also contains a detailed investigation of the viability of different proposals for the choice of a vacuum state of the perturbations. The scalar power spectrum of all the cases under study is calculated selecting some adiabatic vacua. This spectrum shows relevant differences in the infrared, while the ultraviolet sector of the perturbations is rather insensitive to the contemplated changes in the quantization.

Elizaga Navascués and Mena Marugán provide an extensive review of the state of the so-called "hybrid quantization" scheme in Loop Quantum Cosmology. It consists in splitting the homogeneous degrees of freedom and the inhomogeneous ones, that can be thought as additional fields over a background. One can then quantize the former nonperturbatively with the loop techniques, and the latter using the conventional Fock quantization. In this way, this scheme combines tractable constraints with a mathematically robust Fock quantization. It is then possible to study the evolution of cosmological perturbations during the preinflationary and inflationary epochs. In addition, the hybrid quantization has also been applied to Gowdy spacetimes that correspond to a toroidal geometry with linearly polarized gravitational waves. Two aspects of this scheme have particular interest with respect to possible observational predictions: first, the mass of the fields that describe the cosmological perturbations results to have a specific time evolution, that distinguishes the predictions from this framework from other approaches; second, the splitting between homogeneous and inhomogeneous sectors provides a natural way to define a preferred vacuum state.

Schander and Thiemann consider the issue of backreaction in gravity, reviewing the problem of the backreaction between matter and geometric inhomogeneities in cosmology. They first provide a concise summary of concepts and procedures designed to analyze this backreaction by classical means in the late Universe. Then, they comment on semiclassical approaches to cope with the quantum backreaction of the perturbations in earlier epochs, including stochastic gravity in this discussion. Finally, they focus on the more complicated problem of studying backreaction in purely quantum formalisms, applicable to the very early stages of the Universe. Special attention is devoted to Born-Oppenheimer inspired methods in which the perturbations are regarded as fast dynamical degrees of freedom compared with a slowly evolving homogeneous cosmological spacetime. In particular, they review in some detail a formalism introduced by them, which is based on the application and extension to quantum cosmology of space adiabatic perturbation theory.

The extraction of predictions from Loop Quantum Cosmology about the early Universe crucially depends on the choice of vacuum state for the primordial perturbations. Martín-Benito et al. have studied this question when one focuses the attention on the so-called States of Low Energy, which are of Hadamard type and minimize suitably smeared versions of the energy density. Explicitly, they have shown that the shape of the primordial power spectrum resulting from such states depends strongly on the support of the smearing function in the kinetically dominated pre-inflationary regime of Loop Quantum Cosmology. In particular, if this function is only supported on the far future of the bounce, the power spectrum resembles the non-oscillatory one that was previously proposed by Martín de Blas and Olmedo. Furthermore, using the ultraviolet properties of the States of Low Energy, the authors provide a proof that this non-oscillatory vacuum state is of Hadamard type as well.

Gozzini and Vidotto explore the fundamental question of how primordial fluctuations may arise from the spinfoam dynamics of Loop Quantum Gravity. For this purpose, they consider the spinfoam transition amplitude from an empty state to the discretization of certain cosmological, closed, 3-geometries in terms of tetrahedra. This transition amplitude determines a cosmological state, given by a superposition of such closed geometries, which is argued to be the analog to the Hartle-Hawking no-boundary state in the spinfoam formalism. The authors study several properties of this state and show that, even though the average geometry of the state is that of a 3-sphere, it has a large variance and the local correlations between different regions are non-negligible even at large values of the scale factor. Furthermore, the state is highly atypical, as measured with respect to the entanglement entropy of its components. These properties hint towards a quantum gravity mechanism that might solve the horizon problem in cosmology, without the need of inflation.

Marchetti and Oriti similarly consider a quantum cosmological model based on a covariant formulation of the action, but solving its dynamics with the techniques of Group Field Theory. They address, in particular, the question of defining in this context observables in a relational manner. It is interesting then to quantify the quantum fluctuations of the resulting geometrical observables. In order to introduce an observable that plays the function of a physical clock, they include a massless scalar field and study its expectation value. They find that at later time the quantum fluctuations of all observables are suppressed, in agreement with the classical limit, but the fluctuations are important at earlier times, i.e., near the bounce. The appearance of these fluctuations may lead to different interpretations with respect to the validity of a hydrodynamical approximation for the quantum gravitational dynamics; further clarity could be shed on their nature by moving out from the approximation in which Group Field Theory interactions are neglected.

Different ideas and techniques from Loop Quantum Cosmology can be exported to study black hole physics. In this context, García-Quismondo and Mena Marugán investigate the Hamiltonian formulation of the loop quantum model for black holes proposed by Ashtekar, Olmedo and Singh (AOS). The dynamics of its classical version is quite special: it is generated by the sum of two commuting Hamiltonians, which are related to the mass of the black hole when evaluated on-shell. Loop quantum corrections are introduced in terms of regularization parameters, which the AOS model treats as constant, with values fixed by the black hole mass on each particular solution. This procedure has raised concerns about the validity of the Hamiltonian formulation of the model. García-Quismondo and Mena Marugán explore instead the possibility that these parameters may be functions of the two Hamiltonians, which should be equal to the mass only on-shell. They then show that each Hamiltonian generates dynamical equations that are equivalent to those in the AOS model, but with respect to a time that is different for each of the two Hamiltonians. In the on-shell limit of large black hole masses, both times coincide up to (known) subdominant corrections.

Gambini et al. use a similar regularization to that of the AOS model to study how the central black hole singularity is removed in spherically symmetric Loop Quantum Gravity. The resulting extension of the spacetime through the quantum region that replaces the singularity can be interpreted as a white hole. In their article, the authors investigate whether one can introduce an effective description of this quantum phenomenon by defining semi-classical states: these correspond to an approximate classical geometry with an effective anisotropic fluid coupled to the gravitational field. The resulting framework has the specific advantage of recovering diffeomorphism invariance in the semiclassical limit. This result suggests to use the requirement of small mass fluctuations in the classical limit to select the kind of modifications that the scalar constraint and the observables should inherit at the effective level from the quantization. Interestingly, what is learnt here in the context of black holes can find applications in cosmological models with a local rotational symmetry, such as the toroidal Gowdy spacetime.

It is exciting to see how ideas developed for black holes can be applied to cosmology. Another example of this is given in the paper by Amadei et al. The authors start from an interesting proposal addressing the fate of information in black hole evaporation: information can degrade by being transferred to Planckian degrees of freedom, unaccessible in the approximation for which the gravitational field is described by a smooth manifold. Analogously, cosmological states can be thought as coarse-grained ones where Planckian degrees of freedom that are not accessible to low-energy observers are suitably ignored. In this scenario, the dynamics of a bouncing universe can have a completely unitary description even if these observers experience decoherence. Furthermore, energy conservation implies that the Planckian degrees of freedom do not contribute to the energy balance, even though they are responsible for such decoherence: the energy balance allows for this to happen without the need of a contingent dissipation.

The collection of these eleven papers composes a mosaic of some active research directions in Loop Quantum Cosmology, a part of the lines of research of this exciting field which is still subject to open questions and debate. Cosmology and black hole physics are the most promising windows to observe signatures of (Loop) Quantum Gravity. Hopefully, the ideas in these papers will contribute in sharpening our sight in their search.

AUTHOR CONTRIBUTIONS

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