*universe*

MDPI

*Editorial*

# Beyond General Relativity: Models for Quantum Gravity, Loop Quantum Cosmology and Black Holes

**Nick E. Mavromatos**

Theoretical Particle Physics and Cosmology Group, Department of Physics, King's College London, Strand, London WC2R 2LS, UK; Nikolaos.Mavromatos@kcl.ac.uk

Received: 4 December 2020; Accepted: 5 December 2020; Published: 7 December 2020

check for updates

In the past two decades, we have witnessed extraordinary progress in precision measurements in cosmology. The data can be largely explained by means of Einstein's classical theory of general relativity (GR) [1], specifically its Friedmann–Lemaitre–Robertson–Walker (FLRW) global cosmological solution, in the presence of a positive cosmological constant $\Lambda > 0$, and a cold-dark-matter (CDM) component in the matter sector ($\Lambda$CDM paradigm). Local GR is tested very successfully with solar data. The $\Lambda$CDM paradigm seems to describe the Universe well at large (cosmological) scales. However, the cosmological data appear to be characterized by interesting tensions at small scales, whose potential resolution prompts research into theoretical models beyond $\Lambda$CDM, as well as beyond GR. There is also another trend, that of modified Newtonian dynamics (MOND), and its relativistic field theory variants, according to which there is no dark matter (DM) in the Universe, but only modified-gravity laws at galactic scales.

In the past five years, another extraordinary development in astrophysics took place, which experimentally confirmed one of the greatest predictions of GR: the discovery, by the LIGO/VIRGO interferometers, of gravitational waves (GWs) produced during a merger of two celestial objects, claimed to be rotating black holes (BHs). This discovery created a new branch of astronomy (GW astronomy), which can be used to test GR and modified-gravity theories, for which new BH types can exist with scalar-field secondary hair. Moreover, imaging the shadow of a supermassive BH in the center of the galaxy M87 in the Virgo constellation by the Event-Horizon Telescope is expected to contribute significantly to novel, and in some respects complementary to GW, ways of constraining BH physics, and, as a consequence, beyond-GR gravity theories.

Going beyond GR is a rather unavoidable requirement if one wishes to construct a physically and mathematically consistent theory of *quantum gravity* (QG). The Lagrangian of GR is non-renormalizable, due to the dimensionful character of its coupling, Newton's constant. String theory, for instance (which offers a consistent quantization of gravity, along with the other fundamental interactions in Nature), leads to concrete modifications of GR at low energies, amounting to an infinite-order power series of terms involving higher powers of curvature tensors and their derivatives, respecting unitarity. Higher-derivative gravity theories are known to be well-behaved in the ultra-violet (UV), in the sense of leading to renormalizable models.

Another important aspect of a QG theory is its background independence, and the dynamical emergence of space time from rather abstract fundamental building blocks ("geometry" quanta). For the purposes of this Editorial we shall deal with three such *background-independent* QG frameworks, alternative to string theory: (i) loop quantum gravity (LQG), and its application to homogeneous systems—the so-called loop quantum cosmology (LQC); (ii) the spin-foam models; and (iii) the group-field-theory approach to QG, consisting of quantum field theories of space time in which the base manifold is an appropriate Lie group, describing the dynamics of both the topology and the geometry of space time. These are "discretized" approaches to QG, in the sense that their fundamental "quanta" are networks of discrete degrees of freedom, and the emergence of a continuous space time arises after a certain degree of appropriate "coarse-graining".

In addition, we shall also deal here with continuous modified-gravity models, including conformal-gravity models, viewed as fundamental QG theories whose actions contain terms of higher order in curvature tensors and their derivatives, often in a non-local form, crucial to ensure unitarity. These models exhibit a renormalizable behavior in their UV regime.

The journal *Universe* has published several important works on the above subjects, and in this Editorial, which is part of the Special Issue entitled "*Universe*: 5th Anniversary", I highlight some of the works published during 2018–2019.

I commence the discussion with an interesting work [2], which revisits the so-called (3+1)-dimensional conformally coupled general relativity (CCGR) model, discussing the structure of the general coordinate transformation group, in which the conformal transformations may be non-linearly realized, studying canonical quantization, and arguing that CCGR might potentially serve as a viable approach to QG. This model is *not* equivalent to the standard GR action, due to its matter action, which couples only to the conformally invariant part of the metric, obtained by applying the dilaton trick to the initial metric. This is an important difference, which upon (perturbative, about a given space time background) canonical (Arnowitt–Deser–Misner (ADM)) Hamiltonian quantization leads to a different path for the quantization of gravity than the standard GR. The model, at least in its perturbative treatment, appears to be a bilinear graviton theory in the appropriate dynamical variables [2], and thus does not contain graviton–graviton scattering. The interactions of gravitons with the standard model matter, which are conformal by construction, are fixed by the conformal symmetry. The model is perturbatively renormalizable, given that due to the underlying conformal symmetry, it does not contain dimensionful couplings. However, one expects this model not to be a complete theory of QG. Quantum corrections (e.g., coming from the matter sector) are expected to generate higher-derivative and curvature counterterms, which are not considered in [2], but are important for the strong-gravity regime.

Such important issues are addressed in the context of conformal (local scale) symmetries in (3+1)-dimensional (quantum) field theory and quantum gravity in the review [3], where the structure of conformal gravity is presented in detail, and then a discussion of scattering amplitudes in such a context is given. Emphasis is placed on the fact that higher-derivative gravity theories, involving higher powers of the Riemann curvature tensors and their derivatives, are known to yield UV-renormalized perturbative theories of gravity. A detailed description of such counterterms is given. The restoration of conformal symmetry at a quantum level, through the vanishing of the renormalized stress-energy-tensor trace, despite its explicit breaking by dimensionful couplings at a classical level, is emphasized. However, detailed coupling to matter is not discussed in the review, which, in view of the conformal symmetry, will impose severe restrictions.

On the topic of non-local theories of gravity, which can be the basis for unitary, UV-finite (or at least renormalizable) theories of QG, an interesting research article was published in *Universe* [4], in which a "diffusion" method is presented as a tool to explore the non-linear dynamics of non-local gravity, by solving the non-linear dynamical equations of motion in gravitational theories characterized by fundamental nonlocalities of a certain type, corresponding to specific form factors that appear in some renormalizable QG theories.

Staying within the broad area of renormalizable QG models, I next proceed to discuss the article [5], where the author reviews some classes of *holographic* QG models, and in particular a quantization scheme for gravity based on a foliation of the background space time following the ADM formalism, and the consequent reduction of off-shell states to physical states. Renormalizability is then argued to be guaranteed by appropriately projecting the physical states onto a "three-dimensional holographic screen" in the asymptotic region. The importance of the appropriate boundary conditions for a consistent theory in such an approach is emphasized. The fact that boundary conditions on the BH event horizon allowing for reflection are highly plausible implies observable (in principle) consequences—for example, in active galactic nuclei and gravitational waves. Such physical applications are briefly discussed based on some analysis of toy holographic models of scalar fields interacting with gravity in the presence of an anti-de-Sitter cosmological constant.

Another interesting article in *Universe* deals with a *thermodynamical background-independent* approach to *quantum space time*, the "thermal quantum space time" [6]. An extension of equilibrium statistical mechanics and thermodynamics is presented, based on information-theoretic characterization of (Gibbs) thermodynamic equilibrium, which is an observer-dependent notion. The novelty lies in the use of Bayesian (evidential) probabilities to derive equilibrium statistical mechanics, in a way that allows for compatibility with the background independence of GR. The "thermal quantum space time" is then used as a candidate system for QG. Connections with the thermal-time hypothesis of Rovelli are elucidated, thereby providing arguments in favor of a thermodynamical origin of time in the Universe. The work provides a quantum statistical basis for the origin of covariant group field theories, which are shown to arise as effective statistical field theories of the underlying quanta of space in a certain class of generalized Gibbs states. The thermal quantum space time approach can also be used to study thermal condensates of QG degrees of freedom, which constitute a version of the dynamical condensates characterizing group-field-theory quantum cosmologies.

Related to group-field-theory cosmological condensates is another interesting publication in *Universe* [7], dealing with the implementation of a "material reference frame" in the cosmology stemming from the group-field-theory approach to QG. In the article [7], the author starts his presentation by using free scalar fields, whose coupling to gravity provides such a "reference frame", and then proceeds in implementing such constructions in the group-field-theory approach to QG, where a homogeneous and isotropic (at large scales) space time emerges as a "condensate" of fundamental quanta of geometry. The incorporation of inhomogeneities in such Universes via the introduction of several different scalar fields is also discussed in [7], together with a study on how such an approach could lead to locally inhomogeneous space times with black holes.

Having discussed a potential thermodynamical origin of time in [6], I move next to discuss another inspiring publication of *Universe* [8], which views time in cosmology as a quantum observable, not commuting with other quantum operators that define the cosmological states, such as the cosmological constant $\Lambda$. Such a "cosmological-constant-time non-commutativity" may be seen as providing a sort of uncertainty relation, which would imply that a Universe with a precise value of $\Lambda$ is completely delocalized in time, i.e., the Universe in that case "does not know the time". The opposite situation characterizes a Universe with a sharply defined clock time, which would have an indeterminate cosmological constant. Various scenarios in which localized-time islands emerge, giving rise to localized histories, are discussed in [8]. The time in this approach is associated with the so-called Chern–Simons time, which exhibits a "pulsation" behavior, going forwards and backwards during the Big Bang and accelerated phases of the Universe, respectively, and in this sense the Universe appears cyclic (but not necessarily periodic) in some variables.

The microscopic nature of the cosmological constant, in the context of a spin-foam QG model, has been the subject of another very interesting article published in *Universe* [9]. In this work, the author views the cosmological constant as an emergent quantity, arising from the condensation of appropriate defects. The latter are characterized by concentration of space time curvature excitations around them, which in turn induce gravity states that can describe homogeneously curved geometries at large scales. This approach is rather different from standard LQC, given that in the construction of [9], one considers the family of gravity states peaked on homogeneous curvature. Par contrast, in the standard LQC, there is no notion of homogeneous quantum states in the full theory. Moreover, the states of the construction of [9] enjoy a certain discretization independence, and thus diffeomorphism symmetry, while such features suffer some degree of ambiguity in the case of LQC.

Next, I mention a very interesting review published in *Universe* [10], which discusses one of the essential steps towards a background-independent formulation of discretized QG models, that of the *background independence* of the *initial coarse-graining*. The review focuses on tensor models, and explains why the number of relevant degrees of freedom (the size of the "tensors" in this case) can be used as a "scale" in the pertinent renormalization group (RG) flow, given that—unlike the quantum field theory lattice models defined on specific backgrounds—in tensor models, and more generally in background-independent approaches to QG, there is no local geometric notion of scale available. The review contains very practical "instructions" on how to perform such background-independent RG analysis, based on a functional (theory space) RG flow equation (including appropriate regularization) which is constructed appropriately for the tensor models under study. Such an analysis allows for a universal continuum limit in tensor models, some of which are argued to exhibit dimensional reduction to two-dimensional matrix models at their fixed points, characterized by enhanced symmetry. The authors also provide evidence for a non-trivial interacting fixed point for rank-4 tensor models, which could have important implications for the continuum limit of (3 + 1)-dimensional QG.

Having mentioned the concept of dimensional reduction in the UV (high-energy) limit of QG models, I now come to another important article in *Universe* [11], which focuses precisely on the meaning of dimension in QG, which, if answered, will also elucidate the meaning of dimensional reduction at the UV. The author's approach is motivated by the fact that quantum operators in various (and diverse in their content) approaches to QG—including asymptotically safe models—exhibit anomalous scaling at the UV fixed point in such a way that the high-energy theory behaves effectively as a two-dimensional one. After presenting a list of possible definitions of "dimension" in several contexts of relevance to QG, and discussing their subtle experimental falsification, the author concludes that the question as to whether there is true dimensional reduction in QG at the UV, which will have important implications for the small-scale structure of space time, remains wide open, since it is highly model dependent.

The last, but by far not least, articles to be discussed in this Editorial refer to research topics associated with BH properties in LQG and primordial fluctuations in LQC.

In [12], the authors discuss BH solutions in LQG deformed by quantum-gravity effects. At a linearized level, such deformations bear connections with the deformed special relativity (DSR) approach associated with $\kappa$-Poincaré symmetry, in the sense that the interior of the BH is found to be characterized by momentum-dependent metrics, resembling the so-called "gravity rainbow" type of DSR models. A characteristic prediction of the approach is an effective time-dependent Planck length.

In another quite interesting publication in *Universe* [13], the authors present a detailed analysis of the two-dimensional boundary structures that arise in cases of four-dimensional systems, whose Cauchy surfaces have non-trivial two-dimensional boundaries. Such boundary structures have been previously associated with isolated BH horizons in LQG, but what the authors realize here is that such constructions are general, and can apply to any two-dimensional conformal field theory, leading to interesting features in their quantization. The quantization procedure discussed in [13] gives rise to new localized (zero-area) degrees of freedom associated with (boundary) diffeomorphisms, which have been speculated to play a role in resolving the information paradox of an LQG-BH evolution, perhaps contributing to unitary evolution.

In the *Universe* article [14], the authors present a status report on the phenomenology of BH in LQG. The discrete area-operator spectrum of the LQG-BH leads to a modified Hawking radiation spectrum, compared to that of a standard GR BH, given that the evaporating BH will now have to undergo discontinuous "jumps". In [14], the authors explore the phenomenological consequences of the modified spectrum of Hawking radiation of an evaporating LQG-BH, and show that the final stages of the evaporation carry important modifications, which encode information on the underlying LQG structures, allowing for a discrimination, in principle, of various models—particularly holographic ones. Among several phenomenologically important features that the authors of [14] discuss in their comprehensive study, I mention explicitly the bouncing of LQG BHs into *white holes*. This latter phenomenon is purely quantum gravitational in origin, and is associated with tunneling processes that connect a decaying black hole to a white one. This phenomenon is argued to have observable consequences for both astrophysics and cosmology [14]; for instance, it may provide explanations for the fast radio bursts and $\gamma$-ray excesses (GeV energies) coming from the Galactic Centre, as observed by the Fermi-LAT telescope, or provide significant amounts of a new type of DM, in the form of white holes.

The final article I would like to discuss concerns a study of primordial fluctuations in a hybrid loop quantum cosmology (HLQC) model [15]. HLQC models are extensions of LQC where small anisotropies and inhomogeneities are included, in such a way that the dominant effects of quantum geometry are studied using the standard quantization of LQC. Such effects affect the homogeneous geometry. On the other hand, the perturbations associated with anisotropies and inhomogeneities are treated within a Fock-space quantization approach, more standard to ordinary quantum field theories. In the article, the criteria for the selection of a rather unique family of unitarily equivalent Fock representations of the perturbations are reviewed, and a careful discussion on the selection of the vacuum state is given, with the aim of describing inflationary and pre-inflationary scenarios, with appropriate initial conditions, and studying the relevant perturbations. For concreteness, the authors consider a FLRW Universe with flat topology, in the presence of a free massive scalar field (inflaton), and study perturbations at quadratic order in the action. There is a pre-inflationary era in such a Universe, when the kinetic term of the inflaton dominates its potential (mass term). The opposite situation characterizes the slow-roll inflationary phase. The work of [15] shows explicitly that the primordial power spectrum depends strongly on the choice of vacuum. In general, the adiabatic spectra are suppressed at large scales, but exhibit rapid oscillations at intermediate scales. In the specific case of the so-called "non-oscillating vacuum", the rapid oscillations are absent. The origin of such oscillations is attributed [15] to the initial conditions during the pre-inflationary era. It is conjectured that such oscillations could also characterize GR models. The dependence of the adiabatic spectrum of perturbations on changes of various parameters in the model is also discussed, with the conclusion that the spectrum appears stable against changes of the Immirzi parameter of LQG/LQC.

This concludes the Editorial. I hope the reader found the above collection of articles interesting and inspiring. They constitute a representative sample, demonstrating the progress made in the development of models of QG and their phenomenological/cosmological applications over the last two years. Enjoy!

**Funding:** This research is funded in part by STFC (UK) research grant ST/T000759/1.

**Acknowledgments:** The author acknowledges a scientific associateship ("*Doctor Vinculado*") at IFIC-CSIC-Valencia University (Spain).

**Conflicts of Interest:** The author declares no conflict of interest. The funders had no role in the writing of this manuscript, or in the decision to publish it.

## References

1. Iorio, L. Editorial for the Special Issue 100 Years of Chronogeometrodynamics: The Status of the Einstein's Theory of Gravitation in Its Centennial Year. *Universe* **2015**, *1*, 38–81. [CrossRef]
2. Arbuzov, A.; Latosh, B. Conformally Coupled General Relativity. *Universe* **2018**, *4*, 38. [CrossRef]
3. Rachwał, L. Conformal Symmetry in Field Theory and in Quantum Gravity. *Universe* **2018**, *4*, 125. [CrossRef]
4. Calcagni, G. Taming the Beast: Diffusion Method in Nonlocal Gravity.' *Universe* **2018**, *4*, 95; Erratum in **2019**, *5*, 121. [CrossRef]
5. Park, I. Foliation-Based Approach to Quantum Gravity and Applications to Astrophysics. *Universe* **2019**, *5*, 71. [CrossRef]
6. Kotecha, I. it Thermal Quantum Spacetime. *Universe* **2019**, *5*, 187. [CrossRef]
7. Gielen, S. Group field theory and its cosmology in a matter reference frame. *Universe* **2018**, *4*, 103. [CrossRef]
8. Magueijo, J.; Smolin, L. A Universe that does not know the time. *Universe* **2019**, *5*, 84. [CrossRef]
9. Dittrich, B. Cosmological constant from condensation of defect excitations. *Universe* **2018**, *4*, 81. [CrossRef]
10. Eichhorn, A.; Koslowski, T.; Pereira, A.D. Status of background-independent coarse-graining in tensor models for quantum gravity. *Universe* **2019**, *5*, 53. [CrossRef]
11. Carlip, S. Dimension and Dimensional Reduction in Quantum Gravity. *Universe* **2019**, *5*, 83. [CrossRef]
12. Lobo, I.P.; Ronco, M. Rainbow-like Black Hole metric from Loop Quantum Gravity. *Universe* **2018**, *4*, 139. [CrossRef]
13. Freidel, L.; Perez, A. Quantum gravity at the corner. *Universe* **2018**, *4*, 107. [CrossRef]

14. Barrau, A.; Martineau, K.; Moulin, F. A status report on the phenomenology of black holes in loop quantum gravity: Evaporation, tunneling to white holes, dark matter and gravitational waves. *Universe* **2018**, *4*, 102. [CrossRef]
15. Navascués, B.E.; de Blas, D.M.; Marugán, G.A.M. The Vacuum State of Primordial Fluctuations in Hybrid Loop Quantum Cosmology. *Universe* **2018**, *4*, 98. [CrossRef]