Snowmass2021 - Letter of Interest

Key Topics in Quantum Gravity

Thematic Areas: (check all that apply ☐/■)

■ (TF01) String theory, quantum gravity, black holes
☐ (TF02) Effective field theory techniques
■ (TF03) CFT and formal QFT
☐ (TF04) Scattering amplitudes
■ (TF05) Lattice gauge theory
☐ (TF06) Theory techniques for precision physics
☐ (TF07) Collider phenomenology
■ (TF08) BSM model building
■ (TF09) Astro-particle physics & cosmology
☐ (TF10) Quantum Information Science
☐ (TF11) Theory of neutrino physics

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Abstract: Understanding the quantum nature of spacetime and gravity remains one of the most ambitious goals of theoretical physics. It promises to provide key new insights into fundamental particle theory, astrophysics, cosmology and the foundations of physics. Despite there being a common goal, the community of quantum gravity researchers is sometimes seen as divided into sub-communities working on different, mutually exclusive approaches. In practice however, recent years have shown the emergence of common techniques, results and physical ideas arising from different quantum gravity sub-communities, suggesting exciting new prospects for collaboration and interaction between traditionally distinct approaches. In this Letter of Interest we discuss some of these common themes which have seen a growing interest from various directions, and argue that they can be used to steer the quantum gravity community towards common goals.

Introduction and overview. — Quantum gravity (QG) promises to shake the very foundations of our understanding of nature by redefining its pillars, namely our current notions of space, time and matter. This is potentially of immense physical relevance and can lead to new phenomenology in gravitational physics, astrophysics, particle physics and cosmology, in addition to resolving the mysteries of black hole physics and the very early Universe. Several approaches to QG have developed over the last few decades, starting from diverse, and sometimes even contradictory assumptions and key ingredients. Nevertheless, while retaining their distinct character, they sometimes converge, both in broad technique as well as results. Some pertinent examples are: string theory, with its many diversifications like the AdS/CFT correspondence and holography, geometric compactifications and geometric landscape, topological field theory (also prominent in spin foam models) and (swampland) conjectures about the form of low energy effective field theories, resonating with similar developments in asymptotically safe gravity; complementary approaches like simplicial path integral methods, tensor models, group field theory and canonical loop quantum gravity, all dealing with dynamical graphs/lattices and spin network states, suggested as fundamental degrees of freedom of quantum spacetime; causal sets with their similar emphasis on discreteness and causality. Tensor networks appear in AdS/CFT, group field theory and loop quantum gravity. Dynamical topology occurs in string theory, tensor models as well as group field theory. Noncommutative geometry is relevant to string theory, loop quantum gravity, spin foam models as well as perturbative gravity. Moreover, the relationship between entanglement and geometry as well as that of an "emergent spacetime" are common to many of the approaches. These approaches complement each other by illuminating different aspects of the fundamental questions while tackling them from different perspectives. Thus, an increased dialogue and cross-fertilization between different QG approaches benefits the whole endeavor, and should be actively encouraged.

Below we give an overview of current research in QG (mostly complementary to string theory), which exemplifies this and shows an increasing convergence of methods and results. This will only intensify further in the coming years, leading to paradigm shifts and new insights of wide relevance to physics as a whole.

Renormalization group. — The Renormalization Group, with its corresponding concepts of universality, (quantum) scale symmetry and coarse-graining, is currently emerging as a focal point for different QG approaches, most notably asymptotically safe gravity[1], spin foams[2], dynamical triangulations[3], tensor models[4] and group field theories[5]. It provides a common language that helps to establish links between distinct approaches: questions of universality, the continuum limit, and the fate of symmetries take center stage here. Moreover, the Renormalization Group flow acts as a bridge between the microscopic QG regime and macrophysics, where observations are possible. The interplay of QG with matter fields is being investigated within such a framework, and connects QG with high-energy physics in (beyond) Standard Model settings[6–8] which also links to ongoing efforts in particle physics such as the search for dark matter[9].

Causality and analyticity. — Causality is an essential ingredient of relativistic physics, and a guiding principle in quantum field theory; together with analyticity, it often provides powerful constraints. The causal structure encodes all but one degree of freedom[10,11], which suggests that causality is one of the most rudimentary principles in nature. Causality is also important in constructing the covariant observables of QG since these must be space-time in character[12]. QG approaches which incorporate causality in a fundamental way thus give us a vantage point not easily afforded by other approaches. These include causal dynamical triangulations[13] as well as causal set theory[14], both of which are discrete approaches. In the former, discreteness is used as a tool whereas in the latter it is fundamental, but without violating local Lorentz invariance[15]. The Lorentzian path integral is well defined in both approaches and can gives us concrete insights into the broad path integral framework. Causality and analyticity also play key roles in modern studies of gravitational scattering amplitudes, and their relation to gauge theories[16].

Symmetries and boundary charges. — A fundamental aspect of QG research is symmetry. This includes possible modifications of the relativity principle within our quantum Universe, which can arise due to the graininess of space-time at the Planck scale[17]. The investigation of bulk symmetries and boundary charges, at both classical and quantum levels, and their holographic interplay, has led to convergence between a number of approaches[18–21] and quasi-local implementations of the holographic principle[22]. These developments have also offered an enlightening interface between QG and extended topological quantum field theories[23] as well as related condensed matter models, and have provided new perspectives on coarse-graining and renormalization in QG[24,25].

Quantum first approach. — A newer approach to QG is the "quantum-first" approach, advocated in[26,27]. Here, the postulates of quantum mechanics are assumed, and the appropriate mathematical structure on a Hilbert space is obtained guided by the weak gravity "correspondence" limit and the properties of black holes. This is partly motivated by the mathematical structure of quantum field theory (QFT), in terms of a net of subalgebras within the algebra of quantum observables on the Hilbert space. The subsystem structure for gravity is apparently different from that for QFT[28–30], but can be described perturbatively, while making contact with ideas of holography[31]. Other important constraints come from imposing unitary evolution in the high-energy sector when black holes are produced, and parameterizing that evolution in an effective approach[32,33]. The latter has the potential to make contact with strong-gravity observations[34].

Observables. — A longstanding question across approaches, intimately connected to tests of QG, is to define observables in QG. Gauge invariant observables in gravity cannot be local[35]. An approach going back to DeWitt[36] is to define observables relationally, and localizing with respect to the quantum state. There have been recent developments in this direction and understanding its consistency[37], which however reveal fundamental limitations on spacetime localization[38]. Another approach is to construct gauge-invariant observables by gravitationally dressing field theory observables[39]. These observables begin to reveal noncommutativity[39,40], and potentially important aspects of the mathematical structure of QG[30]. A better understanding of these issues is important in understanding the mathematical structure of QG.

Phenomenology. — A formidable challenge faced by QG is the longstanding lack of experimental/observational guidance. QG phenomenology[41] is a field of research that aims at filling this gap by extracting theoretical predictions for new physics in accessible energy regimes, from within different QG approaches, and testing them via observations and experiments in windows of opportunity where even tiny, Planck suppressed, effects could be probed. This search for tests of QG predictions has over time developed in several directions: tests of breaking/quantum deformation of local spacetime symmetries such as local Lorentz invariance (e.g. via high energy astrophysics observations[42,43]); tests of departures from locality[44] (e.g. via tabletop experiments[45]); tests of QG induced modifications of gravitational dynamics (e.g. observing black holes via gravitational waves[46] and/or[34] very long baseline interferometery (VLBI)[47], or studying the consequences of dimensional flow for the luminosity distance scaling of gravitational waves[48,49]); and searches for extra dimensions (e.g. in microgravity experiments and at LHC[50,51]). All these avenues have required cross-field collaborations and an interplay between theoretical and experimental/observational teams.

Foundations of cosmology. — A deeper understanding of QG will help in bridging the gap between the Standard Model of particle physics and the Λ Cold Dark Matter (ΛCDM) model of cosmology, and its observables. In ΛCDM, dark energy, dark matter and inflation need to be added to general relativity in order to describe the observed Universe[52,53]. QG likewise suggests that general relativity receives corrections which can become relevant in cosmology[54]. The origin of dark energy is tied to the quantum structure of spacetime, and dynamical dark energy scenarios can be confronted with observation[55]. In the early Universe, QG should resolve the Big Bang singularity[56,57] and give insights into cosmological initial conditions beyond those of ΛCDM. One possible scenario is that our expanding Universe originated in a prior contracting phase[58,59]. QG can also constrain early-universe dynamics within inflation or propose an early era of accelerated expansion in the absence of a scalar field[56,57]. For instance, the swampland conjectures in string theory constrain inflationary models and are in tension with a cosmological constant as dark energy[60].

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