Loop quantum gravity with matter fields: continuum limit and emergent phenomenology

Abstract for the general public

One of the main challenges of modern theoretical physics is the reconciliation of general relativity, the classical theory of the gravitational interaction, and the principles of quantum mechanics. This long-standing problem consists of seeking a quantum theory of gravity, which allows a consistent coupling of gravity to the Standard Model matter fields and provides a complete description of systems where gravity reaches critical scales and quantum effects cannot be ignored, for instance within black holes and at the early evolution phase of the Universe. If such theory is obtained, it would undoubtedly revolutionize our understanding of fundamental physics. This line of research is known as the field of quantum gravity.

There are several approaches which attempt to resolve the problem of quantum gravity, one of which is the loop quantum gravity program and that is the subject of the present project. Loop quantum gravity follows the conceptual ideas of a quantization of general relativity. It provides a common framework where gravity and the Standard Model matter fields are quantized in a background independent setting. There has been many developments in this program and the resulting theory has very solid mathematical foundations. However several issues remain unresolved, in particular the ambiguities in the implementation of the dynamics, the construction of the physical states and observables, and the recovery of the continuum limit of the theory. The issue of the continuum limit is the most significant problem faced in the theory. It can roughly be phrased in the question of how quantum field theory on a fixed spacetime arises from the quantum theory of gravity coupled to matter fields. Fundamentally, this question is not much different from asking how to recover the theory of fluid dynamics from quantum mechanics.

The research in the direction of answering this question is growing rapidly, and the current prevalent consensus supports the idea of developing a renormalization scheme for the quantum theory. Renormalization in this context is to be understood as a procedure to construct effective theories from the fundamental quantum theory, which takes into account the quantum dynamics as well as possible symmetries associated to the particular systems under consideration. This is similar to the renormalization procedures used in lattice field theory and statistical physics.

The main objective of the present project is to contribute to the understanding of the emergence of the continuum limit in loop quantum gravity, through the study of semi-classical and dynamical properties of certain classes of quantum states, the construction of a sensible renormalization scheme, the investigation of the implementation of symmetries in the theory as well as the construction of effective models in order to evaluate the emergent phenomenology of quantum gravity coupled to the Standard Model matter fields. I will begin with investigating the semi-classical and dynamical properties of the graph coherent states in the context the loop quantum theory of gravity coupled to matter fields. Then I will evaluate possible connections between the graph coherent states construction and the coarse grained loopy spin network states, and study the emergence and implementation of effective dynamics for the coarse grained states. Using these results, I will attempt to construct a renormalization procedure for the loop quantum theory of gravity coupled to matter fields. Furthermore, I will study the emergence of symmetries in covariant gauge theories confined to bounded regions, then investigate their role in the formulation of a quantum theory. Additionally, I will study the implementation of spacetime and matter symmetries in the quantum theory as well as within a potential renormalization scheme. Finally, I will investigate the construction of effective models from the loop quantum gravity theory and evaluate their phenomenological consequences.