Quantum mechanics and the general theory of relativity are the two cornerstones on which our current understanding of physics is based. However, in spite of their tremendous success at describing the physical world, the two theories are based on assumptions which are in clear conflict with each other. The central lesson to be learned from quantum theory is that the structure of the world is fundamentally discrete – it is made out of discrete building blocks, or quanta (such as electrons and photons). Moreover, the arena on which these quanta live, the space and time in which they are located, is assumed to be static and unchanging. Compare this with the situation in general relativity. The crucial idea of Einstein's theory is that gravitation is a geometrical phenomenon, arising from the curvature of space and time. Thus, space and time in general relativity are dynamical; a well-known example of this are gravitational waves, which are nothing but ripples of spacetime curvature traveling through the universe. On the other hand, in general relativity it is assumed that the structure of space and time is smooth and continuous, even at arbitrarily small length scales.

Therefore, we are currently lacking an understanding of general relativity and quantum theory in terms of a single framework based on a coherent and consistent set of assumptions. A framework like this would be necessary in order to give a reliable description of physical phenomena in which both gravity and quantum theory play an important role – for instance, the physics of the beginning of the universe, or the final stages in the life of a star collapsing under its own gravity. The challenge of developing such a description – a theory of quantum gravity – is among the greatest unsolved problems in theoretical physics today.

At the moment it seems that we are still quite far from having a well-established quantum theory of gravity, even though several candidates have emerged over the last several decades. One of the main proposals for such a theory is loop quantum gravity. Loop quantum gravity takes very seriously the key insight of general relativity – that gravitation is simply a manifestation of the geometry of space and time – and is able to provide a concrete realization of a quantum theory of gravity as a theory of quantized geometry. A basic prediction of loop quantum gravity is that the three-dimensional space which we inhabit has an intrinsically discrete structure, being built out of discrete units of space – quanta of volume and area.

A major difficulty, which loop quantum gravity shares with all other prospective theories of quantum gravity, is that it is very challenging to make a connection between the formalism of the theory and physical phenomena which could be observed in experiments. The mathematical structure of loop quantum gravity is quite intricate, and calculations about concrete, physically relevant questions are extremely complicated to perform. This is a challenge which must eventually be overcome before loop quantum gravity can be accepted as a physically correct theory of quantum gravity. Theories of physics should in the end be judged not by the beauty of their mathematical equations, but by using them to derive observable physical predictions and confronting them with data collected from experiments.

The goal of this project is to address the above issue by using models which are obtained from loop quantum gravity by applying a procedure known as fixing a gauge. This procedure, which could be described as making a specific choice of a coordinate system, gives rise to models whose technical structure is remarkably simple in comparison with the formalism of full loop quantum gravity. Within these models it becomes possible to perform calculations which would be essentially impractical to attempt in the setting of the full theory. The results of such calculations can hopefully tell us what loop quantum gravity has to say about concrete physical situations such as the gravitational collapse of a star, or the cosmic background radiation that was created shortly after the birth of the universe. This gives us a clearer picture of the physical content of loop quantum gravity, and brings us closer to understanding whether the theory can be eventually established as a physically correct description of the world.