## 1. Research project objectives/Research hypothesis

The beginning of the XX century witnessed the appearance of two revolutionary new developments in theoretical physics. The first was Quantum Mechanics (QM), a new interpretation of the world at a microscopic scale. The second was General Relativity (GR), one of the most successful theories describing the Universe and its evolution at the cosmic scale. GR identified the source of gravitational interactions as resulting from the curvature of space-time. It also predicted that the Universe evolution started with a Big Bang, when it had extremely small dimensions. It was clear that in this limit a classical theory, like GR, breaks down and should be replaced by a quantum version, where the quantum field should be the quantum geometry. The standard approach of QM, to apply a theory of perturbations around a solution of GR, did not work, because the resulting theory was non-renormalizable, which meant that local quantum fluctuations of geometry drive the space-time solution away from the smooth classical background. It remains a big puzzle how to construct a theory, which at the same time describes a rapidly fluctuating geometry at a small scale and a smooth geometry in a semi-classical large-scale limit. This puzzle was partly resolved in the framework of the model studied in the past years by the project Principal Investigator.

The project is using the experience of Principal Investigator with a model of Causal Dynamical Triangulations (CDT) in four space-time dimensions. The model can be viewed as an attempt to formulate the quantum theory of geometry, using methods of Quantum Field Theory and Statistical Physics. The properties of the model were extensively studied, using Monte Carlo numerical simulations, under the assumption that the spatial Universe is a closed three-dimensional sphere. In one of the four phases of the model, the de Sitter phase, it was possible to reproduce the time evolution of the spatial volume, fully consistent with predictions of GR. At the same time, it was found that geometric properties in all phases are a result of a subtle interplay between the physical action and the number of geometric realizations of quantum geometry at particular values of the coupling constants. One of unexpected properties of the de Sitter phase was a quantum reduction of the small-scale effective dimensionality of space-time to 2.

The success of the model leaves a number of fundamental questions opened before it would be possible to fully prove the usefulness of the model as a tool to study the properties of quantum gravity. These are the main objectives of the project. The first question is: does the model reproduce in a semi-classical limit a complete GR behavior, not only in time direction, but also in spatial directions. For this one needs to define a reference frame in a system without any background geometry. The important step in this direction was made in a new version of the model, with the Universe having the spatial topology of a 3d torus. A possible definition of the reference frame for such a system was tested with very promising results. Studying the properties of the quantum theory of gravity predicted by CDT on a short scale is the next fascinating question. The quantum limit requires studying the model at the boundary between different phases in the coupling constant space and in particular near the triple points, where the three phases meet. This range became accessible only in the new version of the model. Using the toroidal topology opens a new window to study a number of new effects, including the role of matter fields and the effects they have on quantum geometry and as a consequence on a possible formulation of quantum gravity.

## 2. Research project methodology

The lack of analytic solutions is a standard problem of all known formulations of quantum gravity in dimension larger that two. In case of CDT we are forced to use large-scale computer Monte Carlo simulations, based on the code originally written by the project principal investigator and later developed by him together with collaborators. Results of Monte Carlo simulations are analyzed using finite size scaling methods, similar to these used in Quantum Chromodynamics and Statistical Physics. PI was responsible for a development of the numerical tools and for the analysis of results in the earlier approaches.

## 3. Expected impact of the research project on the development of science

Computer simulations proved to be an important tool to understand the non-perturbative aspects of Quantum Chromodynamics. The CDT model of quantum geometry may potentially play a similar role in the studies of Quantum Gravity, possibly the first step on the way to unify the four fundamental interactions of matter. This is the most ambitious problem of Theoretical Physics in recent years.

## 4. Pioneering nature of the research project

Problems presented in the project are fundamental from a point of view of theoretical physics. We plan to study the relation between the behavior of the CDT model of quantum geometry both on the large scale, where we would like to reproduce equations of GR, and on a short scale, where the quantum aspect of a theory will be visible. Both limits are highly non-trivial and require understanding the structure of composite states of geometry, very different from a smooth classical limit of GR. The quantum limit means that a typical geometry is dominated by large curvature fluctuations, possibly including local fluctuations of the space-time signature. We will use a new version of the model, which may be viewed as a completely new powerful magnifying glass, which permits to see how the structure of space-time may look at a Planck scale and what are the consequences of this behavior for the semi-classical macroscopic limit.