# Quantum Tunneling During Inflation: Non-linear Analysis of the Quantum Fluctuations

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While inflation is now part of the standard cosmology, our knowledge of the physics behind inflation is very limited. The energy scale of inflation is far beyond that of the standard model of particle physics and there is no hope to realize accelerator experiments at such high energy. However, string theory, the most studied candidate of the ultimate theory, recently offered a new framework on inflation: the string theory landscape.

The motivation of this work is in testing this theory-motivated framework by observation, which possibly has an extremely large impact on both cosmology and string theory. The string theory landscape is a huge landscape of potential for scalar fields, which are originated from the degrees of freedom of the extra dimension geometry in string theory. Although details of landscape are not clear yet, string theory generally suggests the existence of local potential minima, where scalar fields jump around by quantum tunneling. Such quantum tunneling can generate distinctive observational signatures, which differentiate inflation models in the string theory landscape from conventional inflation models.

In this work, we focus on the non-Gaussianity of the primordial fluctuations generated from quantum tunneling during inflation, which can become a key to observationally test the string theory landscape in future. The non-Gaussianity of the primordial fluctuations is generated through non-linear interactions among them. Although its amplitude is expected to be small, the non-Gaussianity is going to be precisely measured from observation of the higher order correlations of the primordial fluctuations in the coming era of high precision cosmology. Thus, the non-Gaussianity is expected to be a powerful tool to probe inflation at that time.

Since there was no previous work on the non-Gaussianity from quantum tunneling, we start with developing formulation to calculate it. The commonly used formulation to calculate the non-Gaussianity, the so-called in-in formalism, is not directly applicable to systems with quantum tunneling, because the evolution of the quantum fluctuations during quantum tunneling cannot be described as real (Lorentzian) time evolution.

Based on the WKB analysis of tunneling wave functions, we derive extended in-in formalism on a quantum tunneling background in a system of multi-dimensional quantum mechanics, a simplified analogue of cosmological systems with quantum tunneling. With the resulting formalism, the non-Gaussianity of the quantum fluctuation can be computed with non-linear evolution both during and after quantum tunneling. In this formulation, the system is assumed to be in the ground state before quantum tunneling. The evolution of the quantum fluctuations during quantum tunneling is described as imaginary (Euclidean) time evolution.

We discuss a further extension of this formalism to cosmological systems where Coleman-De Luccia instantons describe quantum tunneling of scalar fields with gravity, and succeed in developing extended in-in formalism that can be used to calculate the non-Gaussianity of the primordial fluctuations generated from quantum tunneling during inflation. In the resulting formulation, the evolution of the quantum fluctuations during quantum tunneling is described as the evolution on a Coleman-De Luccia instanton, a classical solution to the Euclidean equations of motion for both spacetime and scalar fields. The initial quantum state before quantum tunneling corresponds to the Bunch-Davies vacuum state, the ground state for the universe before quantum tunneling.

We apply this newly developed formulation to a couple of models motivated by the string theory landscape, namely, models where slow-roll inflation is triggered by quantum tunneling and ones where bubbles are nucleated via quantum tunneling during slow-roll inflation, to predict the non-Gaussianity of the primordial fluctuations from these models for the first time.

In the case of slow-roll inflation triggered by quantum tunneling, we calculate the bispectrum of the primordial fluctuations. In such a model, the quantum state at the beginning of slow-roll inflation is modified away from the Bunch-Davies vacuum state due to quantum tunneling. Therefore, this study can be regarded as the study of the non-Gaussianity from excited states, where the excitation mechanism can be described within the theory. In the literature, the non-Gaussianity from excited states was studied with arbitrarily chosen initial excited states. As a result of calculation, we find that the bispectrum can be generated in long-wavelength modes due to quantum tunneling. The bispectrum is important in testing inflation models, since it contains more observational information than the power spectrum.

In the case bubbles are nucleated during slow-roll inflation, we calculate the skewness of the CMB temperature anisotropies. We find that large skewness regions with azimuthal symmetric spatial dependence can be generated due to non-linear interactions between the primordial fluctuations and background bubbles. Thanks to their distinctive azimuthal symmetric spatial dependence, we may find the first observational evidence of bubble nucleation, or moreover string theory, by making specialized analysis targeting this newly proposed observational signature.