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Ghost Free Extension of Gravitational Theory

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Abstract

Many gravitational theories have been proposed based on various motivations, e.g. primordial inflation, late time acceleration of the universe, or quantum gravity and so on. Thus, it is important to clarify what extension is allowed theoretically. The strongest constraint comes from the requirement of absence of ghost instability, namely, absence of a field with negative (wrong) signed kinetic term. The presence of ghost fields makes the theory pathological, and hence gravitational theory must be free from ghost degrees of freedom. In this thesis, we focus on the ghost problem in the following gravitational theories: scalar-tensor theory, vector-tensor theory, higher derivative gravity, massive gravity, and bi-gravity.

The simplest extension of gravitational theory can be done by introducing an additional fields which are non-minimally coupled with the metric tensor. In the first part of this thesis, we consider new coupling between a vector field and the metric tensor, called extended vector-tensor theory. We clarify the condition that the number of degrees of freedom coincide with that of massless graviton and massive vector field.

Another direction to extend general relativity is higher derivative gravity. It is well known that higher derivative interactions tend to lead to ghost instability. It is also well known that $f(R)$ gravity, which is one of the theories of higher derivative gravity, is free from ghost instabilities. The key observations for the ghost freeness of $f(R)$ gravity is the equivalence between $f(R)$ gravity and ghost free canonical scalar theory. In this thesis we generalized such observations to more general higher derivative gravity. We found the equivalence between some class of the higher derivative gravity and ghost free scalar tensor theories. Thus we proposed new higher derivative gravity without ghost problem.

Yet another direction to modify general relativity is to add the mass potential of graviton, which breaks general covariance of the theory. Recently, such a theory have been actively investigated by motivating to explain current accelerated universe. The linear theory of ghost free massive gravity is constructed by Fierz and Pauli in 1939. Nevertheless, non-linear extension of ghost free massive gravity had not been succeed until 2010 due to ghost problem. The key techniques to construct the ghost free massive gravity is Stückelberg trick and decoupling limit. Through these procedures, the theory of massive gravity reduces to scalar-tensor theory. It is easy to see the presence/absence of ghost in the context of scalar-tensor theory, one can find the ghost free condition of mass potential of the graviton. The massive gravity includes non-dynamical tensor field called fiducial metric. The original ghost free nonlinear massive gravity is based on flat fiducial metric but it is shown that massive gravity is ghost free even if flat fiducial metric is replaced by a curved one. In addition, it is also shown that if fiducial metric has Einstein-Hilbert kinetic term, and hence become dynamical, ghost free nature is held. This theory is called bi-gravity. The proof of the ghost freeness of such theories is based on formal Hamiltonian analysis and understanding of ghost free nature by decoupling limit analysis have not been established so far. Then, we develop the new formalism of Stückelberg trick around curved or dynamical fiducial metric and investigate the decoupling limit, namely scalar-tensor form, of massive gravity with curved fiducial metric and confirmed the equations of motion consists of terms up to second order derivatives. We apply above analysis to bi-gravity, and find higher derivative interactions appear at higher order in perturbations. However we confirm that such higher derivative interactions appearing at higher

order in perturbation do not need to lead Ostrogradski's ghost instability. Thus we confirm that higher derivative appearing here is not contradict with the ghost free nature of bi-gravity. It should be emphasized that the ghost freeness of massive or bi-gravity is confirmed with the assumption that all other fields are minimally coupled with gravity. Thus it is non-trivial whether ghost is present or not if non-minimal coupling exists. We investigate ghost instability of Horndeski scalar field coupled with massive gravity through so called composite metrics, and find that ghost mode reappears if higher order Horndeski terms exist.

Although the massive gravity can avoid the ghost instability coming from higher derivative in the context of decoupling limit, it is non-trivial that remaining degrees of freedom include ghost or not. The simplest way to check the stability is to investigate the perturbations around the exact solution of the theory. Then we construct the exact solutions of massive gravity including self accelerated universe. After that we generalize this analysis of massive gravity to bi-gravity and investigate the perturbations around this solution in both massive and bi-gravity. We confirm that perturbations around our solution do not suffer from instability, but the number of degrees of freedom is less that that expected by non-perturbative analysis. Therefor our solution is stable against perturbations but it is not clear the stability about non-perturbative deformation of the solutions.