



Super-renormalizable or finite Lee–Wick quantum gravity

Leonardo Modesto

Center for Field Theory and Particle Physics and Department of Physics, Fudan University, 200433 Shanghai, China

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Abstract

We propose a class of multidimensional higher derivative theories of gravity without extra real degrees of freedom besides the graviton field. The propagator shows up the usual real graviton pole in $k^2 = 0$ and extra complex conjugates poles that do not contribute to the absorptive part of the physical scattering amplitudes. Indeed, they may consistently be excluded from the asymptotic observable states of the theory making use of the Lee–Wick and Cutkosky, Landshoff, Olive and Polkinghorne prescription for the construction of a unitary S-matrix. Therefore, the spectrum consists of the graviton and short lived elementary unstable particles that we named “anti-gravitons” because of their repulsive contribution to the gravitational potential at short distance. However, another interpretation of the complex conjugate pairs is proposed based on the Calmet’s suggestion, i.e. they could be understood as black hole precursors long established in the classical theory. Since the theory is CPT invariant, the conjugate complex of the micro black hole precursor can be interpreted as a white hole precursor consistently with the ’t Hooft complementarity principle. It is proved that the quantum theory is super-renormalizable in even dimension, i.e. only a finite number of divergent diagrams survive, and finite in odd dimension. Furthermore, turning on a local potential of the Riemann tensor we can make the theory finite in any dimension. The singularity-free Newtonian gravitational potential is explicitly computed for a range of higher derivative theories. Finally, we propose a new super-renormalizable or finite Lee–Wick standard model of particle physics.

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E-mail addresses: lmodesto@fudan.edu.cn, lmodesto1905@icloud.com.

1. Introduction

We propose a “local” multidimensional gravitational theory compatible with renormalizability at perturbative level in addition to Lee–Wick [1] and Cutkosky, Landshoff, Olive and Polkinghorne unitarity [2] (CLOP). This work is a generalization of the theory recently proposed in [3,4]. In the last four years a weakly nonlocal action principle for gravity has been extensively studied to make up for the shortcomings of the quantization of the Einstein–Hilbert action [5–9]. Research records show that Krasnikov in 1988 and Kuz’min in 1989 proposed a similar theory [10] following Efimov’s studies in nonlocal interacting quantum field theory [11]. Afterwards Tomboulis extended to gauge interactions the Kuz’min ideas and in 1996 proposed a class of weakly nonlocal super-renormalizable gauge and gravitational theories [12–14]. You may also refer to [15,16] about other excellent contributions in nonlocal theories. Recently in [17] it has been definitely proved that the theory is actually finite in any dimension when a local potential of the Riemann tensor is added. In [18] has been proposed and extensively studied a finite generalization of the nonlocal theory for gauge interactions proposed for the first time by Tomboulis [12]. However, the price to pay is that the classical action is weakly nonlocal, although the asymptotic polynomial behavior makes the theory very similar to any local higher derivative theory for all that concerns the divergent contributions to the quantum effective action.

In this paper we want to expand and specialize the seminal paper [20] about a general local super-renormalizable gravitational theory capitalizing what we learned in quasi-polynomial or weakly nonlocal theories. Actually, many results can be exported directly to the theory here proposed making a proper replacement of the *nonlocal form factor* in [17] with the *local form factor* that we are going to properly define later in this paper.

The theory here proposed fulfills a synthesis of minimal requirements: (i) Einstein–Hilbert action should be a good approximation of the theory at a much smaller energy scale than the Planck mass; (ii) the theory has to be super-renormalizable or finite at quantum level; (iii) the theory has to be unitary, with no other real poles in the propagator in addition to the graviton; if we require other poles neither real nor complex, then the theory will prove non-polynomial or weakly nonlocal. The outcome of previous studies is a nonlocal classical theory of gravity perturbatively super-renormalizable at quantum level. On the footprint of the nonlocal action we propose here a “local” theory that holds the same properties, but showing up extra complex conjugate poles besides the graviton.

Studies of higher derivative theories date back to quadratic gravity proposed in 1977 by Stelle [19]. This theory is renormalizable and asymptotically free, but unfortunately it violates unitarity showing up a real ghost state in the spectrum. In this paper we go behind the Stelle’s action introducing a finite number of extra higher derivative operators to make the theory even more convergent: super-renormalizable or finite. However, we do not blindly introduce all the possible operators to a fixed order in the number of derivatives of the metric tensor. We actually consider a class of local theories that avoid extra real poles in the propagator. Looking at the above list of requirements (i)–(iii), the news with respect to the previous work on non-polynomial theories sits in the third point. We indeed do not exclude the possibility of complex conjugate mass poles, which do not prevent us from constructing a unitary local theory of gravity in the Lee–Wick formalism [1]. Lee and Wick argued that, as long as all ghost degrees of freedom in the interacting theory have complex energies, one obtains a unitary theory by constraining the physical subspace to be exactly the one for the states that have real energy. In gravity we end up with a classical theory with an extended spectrum in which the graviton is free to propagate on long distances while a bunch of other virtual elementary particles can only intrinsically live for a short amount of time blandly

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