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Lavinia Heisenberg

Theoretical and Observational Consistency of Massive Gravity

Doctoral Thesis accepted by
the University of Geneva, Switzerland

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Author
Dr. Lavinia Heisenberg
Royal Institute of Technology
Stockholm
Sweden

Supervisor
Prof. Claudia de Rham
Case Western Reserve University
Cleveland, OH
USA

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This doctoral thesis covers a detailed presentation of the scientific results published in the following articles. The results are not presented in chronological order of their publication but rather in the logically most comprehensible way. The thesis also contains unpublished results, which have been pointed out at the appropriate place.

1. C. de Rham, L. Heisenberg, R.H. Ribeiro:
   Quantum Corrections in Massive Gravity:
   Phys. Rev. D 88, 084058 (2013)
2. C. de Rham, G. Gabadadze, L. Heisenberg, D. Pirtskhalava:
   Non-Renormalization and Naturalness in a Class of Scalar-Tensor Theories:
   Phys. Rev. D 87, 085017 (2013)
3. P. de Fromont, C. de Rham, L. Heisenberg, A. Matas:
   Superluminality in the Bi- and Multi- Galileon:
   JHEP 1307 (2013) 067
4. C. de Rham, L. Heisenberg:
   Cosmology of the Galileon from Massive Gravity:
   Phys. Rev. D 84, 043503 (2011)
5. C. Burrage, C. de Rham, L. Heisenberg:
   De Sitter Galileon:
   JCAP 05 (2011) 025
6. C. de Rham, G. Gabadadze, L. Heisenberg, D. Pirtskhalava:
   Cosmic Acceleration and the Helicity-0 Graviton:
   Phys. Rev. D 83, 103516 (2011)

Additional publications related to this thesis.

1. C. Burrage, C. de Rham, L. Heisenberg, A.J. Tolley:
   Chronology Protection in Galileon Models and Massive Gravity:
   JCAP 07 (2012) 004
2. J.B. Jimenez, R. Durrer, L. Heisenberg, M. Thorsrud:
   Stability of Horndeski Vector-Tensor Interactions:
   JCAP 1310 (2013) 064

The Road Not Taken

TWO roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same,

And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I –
I took the one less traveled by,
And that has made all the difference.

—Robert Frost

Dedicated to the endless memories of Rojdén and Zera.

Supervisor's Foreword

It is with great pride that I look back on the 5 years since Lavinia Heisenberg started her Ph.D. at Geneva University. Committed to work on theoretical aspects of Cosmology, Lavinia joined the field of modified gravity as a tool to explain the late-time acceleration of the Universe and tackle the Cosmological Constant problem.

The Cosmological Constant problem, or why the vacuum energy of particle physics is so small, is a longstanding puzzle existing now for more than seven decades. The recent realizations that our Universe is accelerating and that this acceleration is very well fitted by a Cosmological Constant has revived the old Cosmological Constant problem as well as the search for alternative theories.

At the time when Lavinia started her thesis research, most consistent models of modified gravity in the infrared were driven by higher-dimensional setups and the "Galileon" scalar field had just emerged as an effective description of such theories. During the first year of Lavinia's Ph.D., the field of modified gravity underwent a remarkable transition and Lavinia bonded with it in an exceptional way.

First, massive gravity (a theory of gravity where the particle responsible for the gravitational force has a mass) was derived as its own consistent theory, an effort which was previously thought to be impossible. From there, theories of bi-gravity and multi-gravity emerged as new ways to understand gravity. These new theories required the development of many new techniques that were so far lacking in the literature and Lavinia literally took the role of a forerunner in developing many of them.

Second, many properties of the Galileon scalar fields were still to be explored, and throughout her research, Lavinia has been devoted to understanding their theoretical and phenomenological properties in-depth. From extending the Galileon symmetry to other maximally symmetric spacetimes, to understanding their quantum behavior and the implications of their superluminal propagation, Lavinia's work has pushed our understanding of these fields to a new level. These studies became all the more relevant after the realization that the helicity-0 mode of the graviton in massive gravity and bi- or multi-gravity also behaves as a Galileon scalar field in a certain limit.

Motivated by this observation, Lavinia was able to establish the existence of 'degravitating' solutions in massive gravity where a large cosmological constant could effectively be 'eaten' by the graviton mass. Although these solutions cannot degravitate an arbitrarily large cosmological constant without also exciting the helicity-0 mode at an undesirably low scale, this framework still provides a proof-of-principle for circumventing Weinberg's no-go theorem when it comes to tackling the Cosmological Constant problem.

Related to the late-time acceleration of the Universe, Lavinia's thesis also shows how the helicity-0 mode of the graviton can itself 'self-accelerate' the expansion of the Universe without the need for any dark energy.

Based on these results, Lavinia was then able to describe how to derive a proxy theory for massive gravity which captures the essential ingredients of massive gravity without many of its complications. This proxy theory was shown to be a special case of Horndeski Scalar-Tensor theory, which has independently enjoyed a great deal of attention recently. Within the context of this proxy theory, Lavinia was then able to capture the essence of the self-accelerating solution in more depth, taking into account the cosmological history of the Universe and presenting the first elements toward a study of structure formation. A subsequent analysis has established that the self-accelerating solution can only be a transient regime within that proxy theory and can never be a late time attractor.

Furthermore, motivated by the derivation of the proxy theory and their relation with Horndeski scalar–tensor theories, Lavinia also generalized the Horndeski framework to vector fields and established the first most general consistent vector–tensor theory, as well as exploring the phenomenological implications for Cosmology.

Whether it is in massive gravity, in Galileon theories or in more general Horndeski theories, the presence of superluminal modes has been a source of concern and arguments for more than a decade. When Lavinia started her thesis research, it had been established that a certain class of bi-Galileon theories could avoid any superluminality issues while still exhibiting a consistent self-accelerating solution, as well as an active Vainshtein mechanism. This realization attracted much interest and theories of multi-gravity or of gravity embedded in more than one extra dimension were investigated with the hope of avoiding the superluminality issues, since they behave as multi-Galileon theories in some limit. Thanks to Lavinia's work, this issue was re-explored and it was found that the presence of superluminalities is actually unavoidable in all of these classes of theories, even though closed-time-like curves are impossible within the regime of validity of such theories.

When the new theories of modified gravity came out (massive gravity, bi- and multi-gravity, as well as their extensions), two of the most pressing questions were related to their quantum stability and their cosmological phenomenology. It is fair to say that Lavinia's work represented major advances in both directions. The quantum stability was first established in the Galileon limit at all loops, and then beyond that limit at the one-loop level. While a full analysis is yet to be performed, the arguments presented in this thesis go a long way toward understanding the technical naturalness of the graviton mass and the stability of the allowed interactions in these types of theories.

On the cosmological side, Lavinia's thesis has established many different techniques to explore the phenomenology of these theories, both at early and late-time, and combining these results with data analysis from different cosmological probes. In particular, Lavinia was able to generalize the coupling to matter in these types of theories and provide new directions to study their cosmology.

Much of Lavinia's thesis has now taken on a life of its own and the issues are being explored further. There is no doubt, however, that it gathers together many different facets of the recent developments in the field of massive gravity and will serve as a valuable reference for the field.

Cleveland, USA Prof. Claudia de Rham
December 2014

Abstract

This doctoral thesis encompasses a detailed study of phenomenological as well as theoretical consequences derived from the existence of a graviton mass within the ghost-free theory of massive gravity, the de Rham-Gabadadze-Tolley (dRGT) theory, which incorporates a two-parameter family of potentials. In this thesis we pursue to test the physical viability of the theory. To start with, we have put constraints on the parameters of the theory in the decoupling limit based on purely theoretical grounds, like classical stability in the cosmological evolution. Hereby, we were able to construct self-accelerating solutions which yield similar cosmological evolution to a cosmological constant. Furthermore, we studied the degravitating solutions, which enables us to screen an arbitrarily large cosmological constant in the decoupling limit. Nevertheless, conflicts with observations push the allowed value of the vacuum energy to a very low value rendering the found degravitating solution phenomenologically not viable for tackling the old cosmological constant problem. Next, we constructed a proxy theory to massive gravity from the decoupling limit resulting in non-minimally coupled scalar–tensor interactions as an example of a subclass of Horndeski theories. We explored the self-accelerating and degravitating solutions in this proxy theory in analogy to the decoupling limit and extended the analysis by studying the change in the linear structure formation.

Furthermore, Galileon models are a class of effective field theories that naturally arise in the decoupling limit of theories of massive gravity. We show that the existence of superluminal propagating solutions for multi-Galileon theories is an unavoidable feature.

Finally, we addressed the natural question of whether the introduced parameters in the theory are subject to strong renormalization by quantum loops. Starting with the decoupling limit we have shown how the non-renormalization theorem protects the graviton mass from quantum corrections. Beyond the decoupling limit the quantum corrections are proportional to the graviton mass, proving its technical naturalness in an explicit realization of 't Hooft's naturalness argument. Moreover, we pushed the analysis beyond the decoupling limit by studying the stability of the graviton potential when including matter and graviton loops. One-loop matter corrections contribute a cosmological constant term leaving the potential unaffected. On the contrary, the one-loop contributions from the gravitons destabilize the special structure of the potential. Nevertheless, we showed that even in the case of large background configuration, the Vainshtein mechanism redresses the one-loop effective action so that the detuning remains irrelevant below the Planck scale.

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