Into the darkness : forging a stable path through the gravitational landscape

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Summary

The discovery of the accelerating expansion of our universe, dubbed cosmic acceleration, has been one of the biggest in recent history and as such sent ripples through the cosmological community. Combined with that of Dark Matter, it led to the formulation of a concordance model, dubbed ΛCDM. In order to explain cosmic acceleration, that model postulates the existence of a, so-called, Cosmological Constant in the action of General Relativity. First introduced by Albert Einstein, this constant can be interpreted as the energy of the vacuum. The Dark Matter sector is represented by a presureless fluid composed of slowly moving particles, also called Cold Dark Matter. Up to this day, ΛCDM has been very succesfull in explaining the vast quantity of observations, a remarkable feat in view of the simplicity of the model.

Despite its success, ΛCDM is problematic from a theoretical point of view. In particular, the interpretation of the Cosmological Constant as the energy of the vacuum carries a fundamental issue. The observed value, in terms of the Planck Mass, is of the order of $\Lambda_{obs} \sim (10^{-30} M_{pl})^4$. On the other hand, when calculating the expected value of the Cosmological Constant within the Standard Model, the value turns out to be larger by 60 orders of magnitude. This discrepancy motivated the search for alternatives to the Cosmological Constant, creating a vast landscape of gravitational models which explain the observed acceleration in a multitude of ways.

Most models explaining cosmic acceleration introduce new degrees of freedom in addition to those of General Relativity, ranging from scalar fields all the way to including additional tensor fields. The resulting wealth of models make the challenge of ΛCDM very inefficient, as one needs to compare each model individually to the available observational data. This process can be streamlined by constraining the parameter space of models through a set of theoretical conditions, which eliminate models containing theoretical instabilities.

In this thesis we present the derivation, and the subsequent test, of a complete set of conditions which any model extending General Relativity must satisfy, in order to be considered a viable cosmological candidate. Our work focused on the subcase of models which introduces an additional scalar field in addition to General Relativity, as it is the most diverse and broadly populated set of models. An example of such a scalar-tensor

theory is the Horndeski theory which, for a long time, was considered the most general scalar-tensor theory with second order equations of motion. In order to achieve our goal we employ the unifying and effective framework provided by the Effective Field Theory of Dark Energy and Modified Gravity. This allows us to construct the desired conditions in a model-independent and efficient way.

The set of conditions under consideration guarantees the absence of ghost, gradient and tachyonic instabilities. In the literature the tachyonic instability has been severely neglected and therefore deserves particular attention. In the first three Chapters we proceed to derive this set of conditions in, subsequently, vacuum, in the presence of two dominant matter fields, radiation and Cold Dark Matter, and in the de-Sitter limit.

While the set of conditions derived in the presence of matter fields is the physically interesting one, it is a substantially more involved problem and one usually chooses the vacuum case for determining the conditions. Our work covers this deficiency and allows us to compare the two cases and to quantify the errors when neglecting matter. It is found that the ghost and gradient conditions remain largely unchanged with respect to the vacuum case, partially validating the assumption. In the case of beyond Horndeski, an extension of the standard Horndeski models, the previous statement does not hold as the speed of propagation of the new scalar degree of freedom is modified by the presence of the radiation field. In contrast, the condition guaranteeing the absence of the tachyonic instability changes drastically as every additional field introduces a new, non-trivial, condition, modifying the vacuum results beyond recognition. This is a direct effect of the gravitational interactions between the new scalar degree of freedom and the matter fields. The new tachyonic conditions constitute the main results of this thesis with a high potential impact on future work.

Having derived the new conditions guaranteeing the absence of tachyonic instabilities it is paramount to test and exhibit their constraining power. In Chapter five we proceed to do this with the help of EFTCAMB, a patch of the Boltzmann solver CAMB, which incorporates the EFToDE/MG. Up till this work, in order to guarantee the stability of models at all length scales, a set of ad-hoc mathematical conditions were employed which, while seemingly effective, were based on some limiting assumptions. Thus we wished to substitute them with the tachyonic conditions and compare the results. The comparison yields a similar constraining power between the two types of conditions with the tachyonic ones being slightly more constraining. Subsequently, we proceed to study the impact on the (μ, Σ) parameter space which encodes the deviations from General Relativity in the Poisson and lensing equation respectively. This leads to the observation of some noticeable effects, in particular for non-minimally coupled theories with a canonical kinetic term, known as Generalised Brans Dicke (GBD). As the tachyonic conditions are theoretically well motivated, in contrast to the mathematical ones, it is evident that they deserve to be chosen as the conditions guaranteeing a stable theory at large length scales.

In parallel to the work on the viability conditions we enhance the EFToDE/MG framework in a number of ways. In the first Chapter we present an expansion of the EFToDE/MG formalism to include the Hořava gravity model, a potential candidate for both quantum gravity as well as cosmic acceleration. Subsequently, we provide a complete dictionary mapping individual models into the unifying framework. This includes all known scalar field models, with the exception of the newly developed DHOST models which require an additional operator, not taken into consideration. Finally, we present a new basis for the operators, inspired by the ReParametrized Horndeski or "alpha" basis which aims to make the physical effects of the operators clearer.

The work presented in this thesis represents a research line which has reached its natural end. It is now important to turn to applications of the presented theoretical results. An initial step in this direction is presented in Chapter five where a number of parameter space studies are presented. These studies will be extended as more data become available and it becomes increasingly possible to constrain models for cosmic acceleration. Furthermore, the vast amount of data allows one to directly reconstruct cosmological functions in a model-independent way. These reconstructions can then use the derived theoretical conditions as a guiding principle, avoiding parameter space sections which cannot belong to a viable extension of gravity. It is thus our hope that this body of work will play an important role in the ongoing golden era of cosmology.