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

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1 Introduction

1.1 Preface

More than twenty years ago, in 1998, two independent groups, the Supernova Cosmology Group [1] and the High-Z Supernova Search Team [2] made the astounding discovery that the universe is expanding in an accelerating fashion. This discovery heralded a new era in theoretical and obsvervational cosmology as the search for the true nature underlying this phenomenon commenced. This, combined with the discovery of Cold Dark Matter [3], led to the establishment of the highly succesful cosmological model, Λ-Cold Dark Matter (ΛCDM) [4, 5] where the cosmological constant Λ, interpreted as the energy density of the vacuum, sources cosmic acceleration.

While ΛCDM has been resistant to new tests up till now, it remains theoretically unsatisfying to many. The observed value of the cosmological constant, in terms of the Planck mass, is $\Lambda_{obs} \sim (10^{-30} M_{pl})^4$, about 60 orders of magnitude smaller than the theoretical prediction coming from the Standard Model. While such a small value can be reconciled with theory without any new ingredients it would imply an incredible amount of fine tuning. The *cosmological constant problem* has triggered a vast endeavour to find alternative sources of acceleration, leading to a landscape of theories which modify General Relativity (GR) in a variety of ways.

In this thesis we study the landscape of gravitational models which modify GR by introducing an additional scalar degree of freedom (d.o.f.) to source Cosmic Acceleration. In particular we answer the question "*What is the complete set of theoretical conditions a gravitational model must satisfy, in order to give a theoretically viable cosmology?*".

In Section 1.2 we present two typical extension of GR and briefly discuss the distinction. In Section 1.3 we introduce the Effective Field Theory of Dark Energy and Modified Gravity (EFToDE/MG), a unifying framework which allows us to study the landscape of gravitational models in a broad and model independent way. In Section 1.4 we discuss the notion of perturbative stability of a gravitational model. Stability will be the guiding principle in order to answer the main question of this thesis. Finally, in Section 1.5, we will present a summary of the following chapters.

1.2 Dark Energy versus Modified Gravity

Extensions of General Relativity typically fall into two categories, Dark Energy(DE) which introduces a fluid into the universe modifying the stress energy tensor, and Modified Gravity(MG) which directly modifies the gravitational sector leading to a modified Einstein tensor. We will briefly present two common candidates of cosmic acceleration: Quintessence[6–9], a typical Dark Energy model and $f(R)$[10, 11] which modifies the gravitational sector. Both introduce an additional scalar degree of freedom to General Relativity.

- **Quintessence**

  The simplest extension beyond the cosmological constant is a scalar field whose potential energy drives cosmic acceleration, in a fashion similar to cosmic inflation. Dubbed *quintessence*, this corresponds to the action of a scalar field, ϕ, minimally coupled to gravity in the presence of a potential:

$$S = \int d^4x\sqrt{-g}\Big(\frac{M_{pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\Big) + S_m\,, \tag{1.1}$$

  where R is the usual Ricci tensor and S_m is the action for any matter field present. This action leads to the usual Einstein equations with an additional stress energy tensor sourced by the scalar field:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{1}{M_{pl}^2}(T_{\mu\nu}^{\mathrm{matter}} + T_{\mu\nu}^{\phi}) \tag{1.2}$$

  where:

$$T_{\mu\nu}^{\phi} = \partial_\mu\phi\partial_\nu\phi - g_{\mu\nu}(\frac{1}{2}(\partial\phi)^2 + V(\phi)). \tag{1.3}$$

  and $T_{\mu\nu}^{\mathrm{matter}}$ is the matter stress energy tensor.

  When considering a cosmological scenario, one employs the cosmological principle which postulates that, on cosmological scales, the universe is homogeneous and isotropic. Various observations, such as the uniformity of the CMB at large scales, support the Cosmological principle to a very high degree. The metric for a homogeneous and isotropic universe is then of the Friedmann-Lemaître-Robertson-Walker (FLRW) form:

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2, \tag{1.4}$$

where $a(t)$ is dubbed the scale factor and encodes the time dependent change of the spatial volume.

On this background the scalar field has a spatially homogeneous profile, $\phi = \phi(t)$, and it behaves like a perfect fluid. The corresponding equation of state parameter, defined as the ratio of the pressure of the fluid and the density, $w = P/\rho$, has the following form:

$$w_\phi = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}\,, \tag{1.5}$$

where the dot stands for the derivative with respect to cosmic time. The cosmological constant corresponds to an equation of state parameter value $w_\Lambda = -1$ hence, in order to fit the observed expansion, $w_\phi \simeq -1$. This leads to the, so called, slow-roll condition which corresponds to $\dot{\phi}^2 \ll V(\phi)$. As in the case of inflation sourced by a slow rolling field, quintessence exhibits a vast phenomenology due to the broad range of potentials one can construct and has been deeply explored over the years.

- **f(R)**

In the case of $f(R)$, rather than explicitly introducing a field, one modifies the Einstein-Hilbert part of the action. This makes it a typical example of a modified gravity model. Its action takes on the following form:

$$S = \frac{M_{pl}^2}{2}\int d^4x\sqrt{-g}(R + f(R)) + S_m\,, \tag{1.6}$$

where $f(R)$ is a function of the Ricci Scalar. The resulting modified Einstein tensor which yields the following Einstein Equation [12]

$$(1+f_R)R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}(R+f) + (g_{\mu\nu}\Box - \nabla_\mu\nabla_\nu)f_R = \frac{1}{M_{pl}^2}T^m_{\mu\nu}. \tag{1.7}$$

with f_R being the derivative of the function $f(R)$ with respect to the Ricci scalar. The new Einstein equation is now higher order in derivatives as it contains derivatives of f_R which depends on the Ricci scalar. This will promote one constraint to a dynamical equation, hence introducing a scalar degree of freedom. We will elaborate more on this at the end of this section.

It is now possible to isolate the new contributions in (1.7) and interpret them as an effective fluid with stress energy tensor:

$$\frac{1}{M_{pl}^2}T^{\text{eff}}_{\mu\nu} \equiv f_R R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}f + (g_{\mu\nu}\Box - \nabla_\mu\nabla_\nu)f_R. \tag{1.8}$$

and an effective equation of state:

$$w_{\text{eff}} = -\frac{1}{3} - \frac{2}{3}\frac{H^2 f_R - f/6 - H\dot{f}_R - \ddot{f}_R/2}{-H^2 f_R - f/6 - H\dot{f}_R + f_R R/6}, \tag{1.9}$$

where, $H = \frac{1}{a}\frac{da}{dt}$ is the Hubble parameter.

Interpreting the modification to gravity as an effective fluid clarifies the way it can source acceleration as it provides a direct link to traditional Dark Energy models. The tradeoff is that the distinction between Dark Energy models and modified gravity models becomes obscure, yet one must keep in mind that, the effects come purely from the gravitational sector.

Let us now expose the presence of an additional scalar degree of freedom in this theory [12] by taking the trace of (1.7) which yields:

$$\Box f_R = \frac{1}{3}(R + 2f - f_R R + \frac{1}{M_{pl}^2}T) \equiv \frac{dV_{eff}}{df_R} \tag{1.10}$$

This is the equation of motion of a scalar degree of freedom f_R, called the *scalaron*, with an effective potential V_{eff}.

Concluding we would like to stress that the dark energy and modified gravity models presented here are two standard examples. There are a variety of ways to source acceleration, yet all of them introduce a scalar d.o.f. regardless of the type of modification. For a deeper discussion into the distinction between Dark Energy and Modified Gravity we refer the reader to [13], where the authors try to enhance the definition with the use of the Equivalence Principle.

1.3 The Effective Field Theory of DE/MG

The question of testing the validity of General Relativity has occupied the scientific community for over 100 years. This has lead to GR surviving a battery of tests ranging from Solar System to Galactic scales and more. Yet, at cosmological scales, GR still remains largely untested. As cosmology has entered the golden era of high accuracy data provided by ESA and NASA missions, this is bound to change in the near future. On the theoretical side, the quest to explain cosmic acceleration has led to a wealth of models modifying GR at cosmological scales. Thus it becomes crucial to develop methods which are capable of quantifying all possible deviations from GR in a structured way as well as providing an efficient framework to confront different extensions of gravity with observational data.

For gravitational models exhibiting an additional scalar degree of freedom, a framework addressing these demands was constructed in Ref [14–16] under the name of *"Effective Field Theory of Dark Energy and Modified Gravity"* (henceforth dubbed EFToDE/MG). At the core of this approach lies the notion that dynamical cosmological perturbations are the Goldstone modes of spontaneously broken time-translations, in a fashion reminiscent of inflation where the breaking of de-Sitter invariance introduces a Goldstone mode, the *inflaton*. Using techniques of Effective Field Theories in Quantum Field Theory it is then possible to construct the most general action describing linear perturbations around the symmetry-breaking background. This was initially done in the context of Inflation [17] and Quintessence [18], and subsequently applied to cosmic acceleration.

The major strength of the EFToDE/MG lies in the fact that, besides being able to parametrise all possible deviations from General Relativity in a complete set of operators, it also provides a "Unifying" framework. The latter implies that each individual model corresponds to a subset of operators and can be studied within the framework.

In order to construct the action one needs to make the following considerations.

- The Weak Equivalence Principle (WEP) is to hold. This implies that all the matter species are universally coupled to the same metric $g_{\mu\nu}$. In order to simplify the inclusion of matter we choose to work in the Jordan frame. This frame choice dictates that the matter fields are not coupled to the scalar field.

- Additionally, we choose a particular time slicing where each equal time hypersurface corresponds to a uniform field hypersurface. This sets the fluctuations of the scalar field to zero and sets the, so called, unitary gauge. This gauge is a familiar concept from the standard model where one can set it in order to absorb the Higgs d.o.f. into the gauge field. In this case the unitary gauge makes the breaking of time-translations manifest thus leaving the unbroken spatial diffeomorphisms as residual symmetries.

Having taken these considerations, one can now construct the most general action based on operators satisfying the residual gauge symmetries. In order to facilitate this procedure and identify the relevant geometrical terms, a 3+1 space and time decomposition will be employed[19]. This decomposition identifies two key quantities on the constant time hypersurfaces: the normal vector n_μ and the induced 3-dimensional metric

$h_{\mu\nu} \equiv g_{\mu\nu} + n_\mu n_\nu$. This leads to the following general form:

$$S = \int d^4x\sqrt{-g}\,\left[g^{00}, K^\mu_\mu, K^\nu_\mu K^\mu_\nu, R, \mathcal{R}, \mathcal{R}_{\mu\nu}\mathcal{R}^{\mu\nu}, .., ; t\right] + S_m[g_{\mu\nu}, \psi^i]\,, \tag{1.11}$$

where $\mathcal{R}_{\mu\nu}$ and $K^\mu_\nu = h^\rho_\nu \nabla_\rho n^\mu$ are the intrinsic and extrinsic curvatures of the constant-time hypersurfaces respectively. The matter fields ψ^i are universally coupled to the same Jordan metric as dictated by the WEP. As the EFT strictly modifies the gravitational sector we will proceed to neglect the matter fields in the rest of this introductory Chapter. Their inclusion will be significant in Chapter 3 and we refer the reader to that Chapter for their complete treatment.

Out of the set of operators, three contribute to the background. The corresponding action is then, where the Planck Mass is denoted as m_0:

$$S = \int d^4x\sqrt{-g}\left[\frac{m_0}{2}\left(1+\Omega(t)\right)R + \Lambda(t) - c(t)\delta g^{00}\right] \tag{1.12}$$

Note the presence of explicit time dependent functions, multiplying the curvature terms, dubbed *"EFT functions"* and of $\delta g^{00} \equiv g^{(00)} + 1$. Both are now allowed due to the breaking of time-translation invariance, in contrast to regular GR. The functions $\Omega(t)$ and $\Lambda(t)$ are the, time dependent, conformal coupling to the Ricci Scalar and the Cosmological constant, respectively. This action leads to the following Einstein Equations, while neglecting matter, which determine the background:

$$\begin{aligned} &3H\dot{\Omega}m_0^2 - 2c + 3H^2m_0^2(1+\Omega) + \Lambda = 0\,, \\ &3H^2m_0^2(1+\Omega) + 2\dot{H}m_0^2(1+\Omega) + 2m_0^2H\dot{\Omega} + m_0^2\ddot{\Omega} + \Lambda = 0\,. \end{aligned} \tag{1.13}$$

Finally, the complete action describing linear perturbations around the time-translation breaking background is the following

$$\begin{aligned} \mathcal{S}^{(2)} = \int d^4x\sqrt{-g}\,\Bigg[&\frac{m_0^2}{2}(1+\Omega(t))R + \Lambda(t) - c(t)\delta g^{00} + \frac{M_2^4(t)}{2}(\delta g^{00})^2 \\ &-\frac{\bar{M}_1^3(t)}{2}\delta g^{00}\delta K - \frac{\bar{M}_2^2(t)}{2}(\delta K)^2 - \frac{\bar{M}_3^2(t)}{2}\delta K^\mu_\nu \delta K^\nu_\mu + \frac{\hat{M}^2(t)}{2}\delta g^{00}\delta\mathcal{R} \\ &+m_2^2(t)h^{\mu\nu}\partial_\mu g^{00}\partial_\nu g^{00}\Bigg]\,. \end{aligned} \tag{1.14}$$

The choice of the unitary gauge in the above action guarantees that the scalar d.o.f. has been absorbed by the metric, hence it does not appear explicitly in the action. One could make it manifest by applying the so called "Stückelberg technique" [14, 15]. In this thesis we will stick to the unitary gauge, yet the results obtained will be applicable in other gauges as well.

The “effective” and “unifying” aspects of the EFToDE/MG make it ideal in order to aid the endeavour to confront the gravitational landscape with cosmological data. In order to achieve this, the EFToDE/MG framework was recently implemented into the Einstein-Boltzmann solver CAMB [20, 21] via the *EFTCAMB* patch [22–24]. This then allows users to do an agnostic exploration in the *pure EFT* mode or study individual models through the *mapping EFT* mode. In this thesis we will show how both aspects are important when approaching the vast landscape of theories which extend GR.

As a final comment it is important to stress that it is possible to include derivatives of the geometrical objects. This has not been done in this initial setup as it will introduce higher-order time derivatives. These higher order time derivatives risk the introduction of ghosts through the Ostrogradsky instability [25]. In [26] the newly developed DHOST theories[27, 28], which are free of the Ostrogradsky ghost, have been incorporated in this setup by introducing an operator with higher order time derivatives. This case will not be taken into consideration in the remainder of this thesis.

1.4 Stability in the language of Effective Field Theories

1.4.1 The Ghost Instability

A common pathology encountered in EFTs is the presence of *ghosts*, fields with negative energy quanta or negative norm. This typically corresponds to a field with the wrong sign for the kinetic term. In a vacuum this does not pose a problem for the theory as the sign is purely a matter of convention. The sign of the kinetic term does matter when one couples the ghost field with another field, which has the opposite sign as a change of convention will not alleviate the issue. A simple example is the following action of two scalar fields:

$$\mathcal{L} = \frac{1}{2}(\partial\psi)^2 - \frac{m_\psi}{2} - \frac{1}{2}(\partial\phi)^2 - \frac{m_\phi}{2} + \lambda\psi^2\phi^2. \tag{1.15}$$

Here the field ψ has the wrong sign and is directly coupled with the field ϕ with interaction strength λ . This lead to an unstable vacuum as it is sensitive to the spontaneous decay $0 \to \phi\phi + \psi\psi$ which costs zero energy and has an infinite decay rate[29, 30].

1.4.2 The Gradient Instability

In a similar way as the ghost fields appear due to a wrong sign of the kinetic term, the gradient instability manifests itself when a field has the wrong sign for its gradient term, i.e. the term containing spatial derivatives of the field. This leads to modes that grow fast leading to instabilities in the theory as we shall show. Let us consider the following scalar field, in Fourier space, with a general speed of sound:

$$\mathcal{L} = \frac{1}{2}\dot{\chi}^2 - c_s^2\frac{1}{2}(k\chi)^2. \tag{1.16}$$

Obviously the field is not Lorentz-Invariant when the speed of sound differs from 1. The solutions for the wave equation of this field are the following

$$\chi_k \sim e^{\pm i\omega t} \tag{1.17}$$

with $\omega = \sqrt{c_s^2 k^2}$. When the speed of sound is imaginary, the sign of the gradient term flips, resulting in the following unbounded solutions:

$$\chi_k \sim e^{\pm\omega t}. \tag{1.18}$$

with a typical timescale of $\tau \sim 1/(c_s k)$. Within the language of effective field theories this implies that, for modes below the energy cutoff Λ, an instability will arise if the system is allowed to evolve long enough. Additionally, the modes most sensitive are the ones with the highest-energy.

Within cosmology and in particular DE/MG the appearance of gradient instabilities are a common occurence and are thus one of the first tests a theory has to pass to be considered viable. In that case the typical timescale of the universe is taken to be the Hubble time and thus the inverse rate of instability is not allowed to exceed this timescale. As was shown in [18] it is possible, when considering a theory with higher order derivatives, to have a gradient instability for a finite range of modes which evolve over scales larger than the Hubble scale and thus do not create an unviable theory. In order to avoid unecessarily constraining such a theory we consider in the rest of this manuscript only the leading order term of the speed of sound and demand it to have the correct sign.

1.4.3 The Tachyonic Instability

Finally a, rather, underemphasized pathology in Effective Field Theories is the tachyonic instability. This instability appears at large scales and is sourced by a mass term with a wrong sign. Thus its behaviour is analogous to the gradient instability but on large scales, as will become clear below. We consider again a scalar field but now with a mass term and in the large scale limit, we ignore the gradient term:

$$\mathcal{L} = \frac{1}{2}\dot{\chi}^2 - m^2\frac{1}{2}(\chi)^2 \tag{1.19}$$

The solutions for the field are now of the same form as for the gradient instability:

$$\chi_k \sim e^{\pm i\omega t} \tag{1.20}$$

but now we have $\omega = \sqrt{m^2}$. When the mass of the field is imaginary, we have again unbounded solutions due to the appearance of the square root:

$$\chi_k \sim e^{\pm mt}. \tag{1.21}$$

As before this instability comes with a characteristic timescale $\tau \sim m^{-1}$. A clear distinction with the gradient instability is that here the timescale is not scale dependent. This implies that high-energy modes which satisfy $m \ll k \ll \Lambda$ are insensitive to the tachyonic instability and thus the theory in itself is not *a-priori* ill-defined. Rather, the tachyonic instability can be seen as a statement on the vacuum or, analogously, the cosmological background one is perturbing around. When one encounters this instability one has not chosen the true vacuum/background of the model under study. There is a well known example of this in the the Standard model, namely the the Higgs field which appears as a tachyon.

In the field of Dark Energy and Modified Gravity the study of the tachyonic instability has not been a high priority in the literature. While we argued that its appearance does not signify that the theory is ill-defined it is important to consider it for the following reasons. When one confronts a theory with cosmological data one requires initially the behaviour of the background and subsequently the perturbations to match our observed universe. Hence, when a tachyonic instability occurs on a cosmologically viable background, it is impossible to reconcile both the background and the perturbations with observations, rendering the model unviable from a cosmological rather than a stability perspective. In the remainder of this thesis the tachyonic instability will play an important role in completing the set of conditions, furthering the goal of answering the main question of this thesis .

1.5 Summary of this thesis

1.5.1 Chapter 2

In this Chapter we proceed to expand the EFToDE/MG to include Lorentz-violating theories of modified gravity. In particular we focus on the theory of high-energy Hořava gravity which has drawn much attention due to it being simultaneously a quantum gravity and a cosmic acceleration candidate. This leads to an action which encompasses a set of 6 additional operators , on top of the original construction, in order to be able to cover the additional signatures.

Having established the new, expanded, action we construct a comprehensive dictionary which provides the means to map a particular theory into the EFT. This is of importance as, besides being the most general action capturing deviations from GR, the EFT provides a unifying framework which allows models to be studied in its language. The dictionary covers models like $f(R)$, Horndeski, beyond Horndeski and the newly added Hořava gravity.

In the final part of this Chapter we start to address the main question of this thesis by doing a comprehensive stability analysis of the EFToDE/MG, while neglecting matter. In any realistic scenario matter is present during cosmic acceleration but the choice to neglect it simplifies the problem and is usually made due to the fact that the energy budget of our universe is DE dominated. Based on these assumptions, we obtain a set of conditions guaranteeing the absence of ghost, gradient and tachyonic instabilities. These conditions are not universal but were derived for all available subcases such as beyond Horndeski, Hořava gravity and so on.

This Chapter is based on [31]: *An Extended action for the effective field theory of dark energy: a stability analysis and a complete guide to the mapping at the basis of EFTCAMB* with N. Frusciante and A. Silvestri.

1.5.2 Chapter 3

In Chapter 2 the stability of the EFToDE/MG was studied in a vacuum, i.e. neglecting matter. In the present Chapter we present a generalisation of this result where we redo the calculation in the presence of radiation and Cold Dark Matter(CDM), i.e. presureless, fluids. This significantly complicates the problem at hand as the gravitational interaction couples the different degrees of freedom in a variety of ways, making the identification of the relevant quantities problematic.

Initially we focus on the Ghost and Gradient instabilities. We choose to model the fluids with the Sorkin-Schutz action, which comes with a number of advantages covered in the main text. As before, a number of subcases need to be considered and studied individually which are then compared with the previously established results. With the exception of the beyond Horndeski models, matter turns out not to significantly alter previously established results, partially vindicating the simplifying assumptions made in previous works.

Moving further, we tackle the main goal of the chapter, namely to study the tachyonic instability in the presence of matter. In order to achieve this we proceed to consider only a single matter field, as the multiple stages required in this calculation become increasingly untractable when including additional degrees of freedom. At the end we present the main novel result of this thesis, the two new conditions required to avoid the tachyonic instability when the EFToDE/MG includes the presence of the main matter component of our universe, CDM. These conditions will be the main topic of study in Chapter 5.

This Chapter is based on [32]: *On the stability conditions for theories of modified gravity in the presence of matter fields* with A. De Felice and N. Frusciante.

1.5.3 Chapter 4

The future of our universe, if cosmic acceleration keeps on acting without significant alterations, is expected to be a de-Sitter like end state. In this end state the Hubble parameter becomes a constant and matter has been diluted away. This motivation lies behind the main topic of this chapter, the EFToDE/MG in the de-Sitter limit.

Guided by the question lying at the basis of this thesis we perform a stability analysis of the EFToDE/MG in the de Sitter limit. As before, this leads to a set of conditions for different subcases such as beyond Horndeski. Additionally, we manage to solve the equations of motion analytically due to their simplicity. These results, while done in the context of DE/MG, also hold for the EFT of Inflation and can be freely applied.

Parallel to the study of the curvature perturbation described above, we construct a gauge-invariant quantity describing the DE/MG variable and derive the corresponding conditions. We do this as a test to check the validity of the original conditions, which were derived for a gauge dependent variable. This study lead us to conclude that once one set of conditions is satisfied the other one will be instantly satisfied as well, a result both expected and welcomed.

This Chapter is based on [33]: *de Sitter limit analysis for dark energy and modified gravity models* with A. De Felice and N. Frusciante.

1.5.4 Chapter 5

The final chapter of this thesis is distinct from the others as, rather than deriving viability conditions, we proceed to test them. In particular we aim to test the novel conditions forbidding tachyonic instabilities, derived in Chapter 3. The ghost and gradient conditions have been employed in previous work in the literature so, while included, we will not focus on their contribution.

In order to proceed we employ the code *EFTCAMB*, a patch adding the EFToDE/MG formalism to the Einstein Boltzmann solver CAMB, thus allowing us to study the cosmologies of different theories. Before this work, *EFTCAMB* already included the subset of ghost and gradient conditions yet lacked the tachyonic conditions. In order to deal with this deficiency and avoid diverging perturbations at large scales, it employs a set of ad-hoc mathematical conditions derived from the equation of motion of the scalar field. It is therefore these mathematical conditions to which the tachyonic conditions will be compared.

By studying a large ensemble of models we manage to achieve this comparison showing that the tachyonic conditions have an equivalent or stronger constraining impact than the ad-hoc math conditions. The parameters we took under consideration are the well known μ and Σ which encode the deviations from GR in the gravitational Poisson and lensing equation respectively. In some cases, such as the Brans-Dicke models a visible impact was seen. This led to the first work where it was possible to exclude models, at large scales, based on theoretical considerations without resorting to ad-hoc conditions which suffer from severe limitations.

This Chapter is based on [34]: *The role of the tachyonic instability in Horndeski gravity* with N. Frusciante, S. Peirone and A. Silvestri.