IN2P3 Prospectives 2020

GT05 - Physique de l'inflation et énergie noire

Dark energy and theories of modified gravity

Porteur: Francesco Nitti[a]

Signataires: Jacques Delabrouille,[a] **Elias Kiritsis,**[a] **David Langlois,**[a] **Karim Noui,**[a] **Julien Serreau,**[a] **Danièle Steer,**[a] **Vincent Vennin**[a]

[a]APC

Abstract

The nature of dark energy and the dynamics driving the late-time acceleration of the universe are one of the biggest open questions in cosmology. One possibility is that late-time acceleration is a signal of a deviation of gravitational dynamics from General Relativity over cosmological distances. This document summarizes different theoretical approaches to modified gravity which are at the forefront of current research (massive gravity, scalar-tensor theories, extra dimensions, holography) and discusses their observational prospects for the near future.

Contents

1 Introdution

The late-time acceleration of the universe is one of the most intriguing aspects of modern cosmology. It has led to a huge interest in the recent years in theories of gravity beyond Einstein's General Relativity (GR): could it be that the late time acceleration is due to a modification of the theory from GR on large scales, rather than to the existence of a *dark energy* component? At the same time, all modified gravity theories are subject to stringent self-consistency criteria (e.g. absence of instabilities) which puts tight restrictions on theoretical model building.

The questions raised above are some of the most actively researched in modern theoretical physics worldwide, and are intertwined with equally interesting questions concerning theories of fundamental interactions.

The minimal explanation for late time acceleration is that dark energy is in the form of a *cosmological constant*, whose energy density is independent of space and time. This however raises new puzzles: the value of the cosmological constant needed to explain late time acceleration is tiny, compared to all other known scales in fundamental physics. Quantum corrections would naturally increase this value up to unacceptable levels (the so called *Cosmological Constant (CC) problem*). Moreover, the measured amount of dark energy density is extremely close to today's amount of matter energy density. This begs for an explanation, since the former is time-independent while the latter is strongly decreasing with time *(coincidence problem)*. Finally, from a fundamental perspective, the geometry of a universe in which acceleration is driven by a cosmological constant (*de Sitter space-time*) faces important theoretical challenges on two fronts: (a) understanding and controlling QFT in de Sitter, (b) having difficulty embedding de Sitter space in a fundamental theory of gravity like string theory.

Faced with these questions, theorists are developing new frameworks to better understand gravity at a fundamental level. They almost always result in the presence of new degrees of freedom (beyond those of GR) which participate in gravitational interactions. It should be stressed that, in many of the effective modified gravity theories proposed and studied, the cosmological constant problem remains unsolved and must eventually be addressed.

In the context described above, the multiple challenges faced by theorists are met with a clear methodological strategy, which the theory group at APC plans to continue following in the future, and which consists in continuing the development of mathematically consistent theories of modified gravity, compatible with all experimental data to date, and exploring ways to connect them to current and/or future observation.

In what follows, we give a concise overview of the most studied classes of models and of some of the perspectives for future observations.

2 Modified gravity theories

2.1 Scalar-tensor theories

Among the different theories of modified gravity, *scalar-tensor theories* play a central role as they are among the "simplest" deformations of gravity: they postulate the existence of just one extra scalar field in addition to the degrees of freedom of GR. This is the smallest possible increase in the number of degrees of freedom of the theory. At the same time, scalar-tensor theories offer an incredibly rich framework to explore and parametrize a large class of modifications of gravity. The extra scalar degree of freedom can interact in a variety of ways both with gravity and with ordinary matter, from the simplest forms of Brans-Dicke theories[1] [1] to the most recently developed higher-derivative theories, in which the metric and the scalar dynamics are strictly intertwined.

Despite their simplicity, scalar-tensor theories capture several of the most interesting properties of more complex models of modified gravity like those which will be discussed in later sections (decoupling limit of massive gravity, braneworld scenarios) and which have been studied intensively at the theoretical and phenomenological level.

From the phenomenological standpoint, scalar-tensor theories are relevant for dark energy for various reasons. In simplest models, the scalar degree of freedom can play the role of *quintessence* (i.e. a dynamical form of dark energy). In more complicated models, like Horndeski theories [2] and DHOST [3, 4], the intertwined dynamics of metric and the scalar field can lead to solutions which display late-time acceleration.

Scalar-tensor theories of dark energy are tightly constraint not only from cosmology, but also from local measurements. For one, any theory containing extra degrees of freedom coupled to matter with gravitational strength must satisfy local tests of GR and of the equivalence principle. Furthermore, the recent precise measure of gravity wave speed from the detection of GW170817 has already strongly constrained scalar-tensor theories designed to account for dark energy. We expect that, when gravity wave detectors become more sensitive, we will be able to probe deeper the “very strong” gravity regime at the merger, and we could also measure deviations from Einstein gravity.

2.2 Massive gravity

A different path to large-distance modified gravity is to assume that gravitational interactions propagate at a slower speed than that of light. More precisely, this is the case where the elementary spin-2 excitations of the gravitational fields (*gravitons*) have a non-zero mass[2]. In order to satisfy existing observational constraints, this mass must be tiny (less than $10^{-23}eV$). Nevertheless, a mass of this order of magnitude would modify gravity at cosmological distances and may be relevant for explaining the late-time acceleration.

The concept of massive gravity has a long history, starting with Fierz and Pauli [5], who were the first to write down a linearized massive gravity theory. For a long time after that, it has been thought that a fully non-linear massive gravity theory would contain internal inconsistencies. Only recently, consistent fully non-linear massive gravity theories where shown to exist [6], making these models a concrete candidate to provide a substitute for dark energy. There exist other phenomenological features of massive

---

[1] We are including in this class the so-called $f(R)$ theories, which are equivalent to a subclass of Brans-Dicke models

[2] For this one does not need to quantize gravity, as a graviton mass can be introduced in a well-defined sense already at the classical level.

gravity, beside large-distance deviations from GR on cosmological scales. In fact, drastic effects may be observed on significantly shorter distances, much shorter than the characteristic distance scale associated to the graviton mass. This seemingly counterintuitive property originates from the fact that, for spin-2 fields, the $m \to 0$ limit is discontinuous, and one does not recover GR in this limit. This in turn is due to the existence of extra modes which do not decouple in the massless limit: a massive spin-2 fields contains five propagating polarizations, whereas a massless one contains only two. Therefore, even if massive gravity is introduced with the goal of modeling dark energy, the extra polarizations may have observable effects over much shorter scales (for example they may be detected in gravitational wave interferometers).

2.3 Higher dimensions, emergent gravity and holography

An important class of models which has been extensively studied is based on the idea that our universe has extra hidden dimensions which are visible only to gravity, while the other Standard Model particles and fields are confined on a four-dimensional defect (*brane*). The phenomenological consequences of these *braneworld models* [7, 8] depend on the details of the construction. In certain cases, like in the DGP model, they lead to gravity modifications at large distance and to late-time acceleration. These models have some features in common with massive gravity and scalar-tensor theories (for example, the presence of extra degrees of freedom which couple with gravitational strength) but their large-distance behavior is different.

All proposals described above address long distance modifications of gravity which may explain dark energy. However, they do not address the cosmological constant problem, nor the nature of gravitational interactions at high energies. One radical idea which has emerged time and again to address these problems is that, at a fundamental level, the gravitational interaction is *emergent* from a more fundamental, non-gravitational theory.

This idea finds a concrete realization in the context of string theories, in which semiclassical quantized theories of gravity appear naturally. Strings theories in asymptotically Anti de Sitter (AdS) backrounds are expected to be dual to holographic Quantum Field Theories (QFTs). This is a duality between QFT and string theory that in the most symmetric examples is known as the AdS/CFT Correspondence (aka holographic duality or holography).

The holographic duality has provided a concrete setup where gravity and other interactions are emergent, from the point of view of QFT. In particular the graviton and other string theory fields are bound-states of the (generalized) gluons of the QFT, [9]. This opens a vast arena of emergent gravity theories constructed from QFTs. In the dual (gravitational) formulation, the holographic QFT is replaced with a higher dimensional bulk gravitational theory. The Standard Model is represented by a four-dimensional hypersurface (a *3-brane*) embedded in this bulk gravitational theory. This setup makes contact with the braneworld framework mentioned above, that have been discussed in this context for the past 20 years, but the embedding in terms of holography allows new directions which were previously unexplored.

It is in this context where novel possibilities appear with addressing the cosmological constant problem and considering the questions of dark energy. As it was recently shown by members of the APC theory group [10], it is possible to construct a brane-bulk framework in which the cosmological constant undergoes a *self-tuning* mechanism: the vacuum energy of the quantum fields on the 3-brane is compensated by a dynamical adjustment of the bulk geometry, resulting in a vanishing cosmological constant as seen by an observer on the brane. This class of models therefore allows a large vacuum energy to be compatible with observation. At the same time, at large distances these models behave similarly to massive gravity theories discussed in earlier sections and may therefore be relevant for explaining late-time acceleration. They also offer new directions to construct de Sitter and inflationary spacetimes in string theory [11, 12]

3 Observational aspects

All theoretical frameworks described above imply both a time-dependence (which translates in a red-shift dependence) of the dark energy parameters and a deviations from GR in a certain range of scales. These deviations can potentially be detected by probes of dark energy on cosmological scales, but also by future gravitational wave observation. Among the first class of experiments, one may cite the LSST telescope and the Euclid satellite, which will give an improved measurement of dark energy parameters, and potentially detect deviations from a plain cosmological constant. A full-sky census of the build-up of structures (distribution of mass and velocity flows across the Hubble volume) as proposed in the ESA Voyage 2050 process [13, 14] is also potentially a very powerful probe of dark energy and modifications to GR.

In the context of gravitational wave observation, evidence of deviations from GR can come from multiple directions. We have already mentioned the tight constraints on scalar-tensor theories which came from just a single event, GW170817. More generally, any modification of GR will necessarily modify the details of the solutions describing coalescing compact objects, affecting the waveform of the corresponding gravitational wave signal. Finally, the addition of new GW interferometers (LIGO-India, Kagra) to the LIGO/VIRGO network, will potentially allow to reveal the presence of extra polarizations, beyond the two transverse modes of GR, in the gravitational wave signal. As we have discussed above, these extra polarizations are a feature of virtually all modified gravity theories.

All these potential observations with future probes give a concrete chance of observing deviations from GR. This makes it essential to continue the theoretical effort to classify and understand consistent modified gravity theories and their phenomenology.

References

[1] C. Brans and R. H. Dicke, *Mach's principle and a relativistic theory of gravitation*, *Phys. Rev.* **124** (1961) 925–935.

[2] G. W. Horndeski, *Second-order scalar-tensor field equations in a four-dimensional space*, *Int. J. Theor. Phys.* **10** (1974) 363–384.

[3] D. Langlois and K. Noui, *Degenerate higher derivative theories beyond Horndeski: evading the Ostrogradski instability*, *JCAP* **1602** (2016) 034, [`1510.06930`].

[4] J. Ben Achour, M. Crisostomi, K. Koyama, D. Langlois, K. Noui and G. Tasinato, *Degenerate higher order scalar-tensor theories beyond Horndeski up to cubic order*, *JHEP* **12** (2016) 100, [`1608.08135`].

[5] M. Fierz and W. Pauli, *On relativistic wave equations for particles of arbitrary spin in an electromagnetic field*, *Proc. Roy. Soc. Lond.* **A173** (1939) 211–232.

[6] C. de Rham, G. Gabadadze and A. J. Tolley, *Resummation of Massive Gravity*, *Phys. Rev. Lett.* **106** (2011) 231101, [`1011.1232`].

[7] D. Langlois, *Brane cosmology: An Introduction*, *Prog. Theor. Phys. Suppl.* **148** (2003) 181–212, [`hep-th/0209261`].

[8] E. Kiritsis, *D-branes in standard model building, gravity and cosmology*, *Phys. Rept.* **421** (2005) 105–190, [`hep-th/0310001`].

[9] E. Kiritsis, *Gravity and axions from a random UV QFT*, *EPJ Web Conf.* **71** (2014) 00068, [`1408.3541`].

[10] C. Charmousis, E. Kiritsis and F. Nitti, *Holographic self-tuning of the cosmological constant*, *JHEP* **09** (2017) 031, [`1704.05075`].

[11] J. K. Ghosh, E. Kiritsis, F. Nitti and L. T. Witkowski, *De Sitter and Anti-de Sitter branes in self-tuning models*, *JHEP* **11** (2018) 128, [`1807.09794`].

[12] A. Amariti, C. Charmousis, D. Forcella, E. Kiritsis and F. Nitti, *Brane cosmology and the self-tuning of the cosmological constant*, `1904.02727`.

[13] e. a. Basu, K., *A Space Mission to Map the Entire Observable Universe using the CMB as a Backlight*, `1909.01592`.

[14] e. a. Delabrouille, J., *Microwave Spectro-Polarimetry of Matter and Radiation across Space and Time*, `1909.01591`.