Research Project

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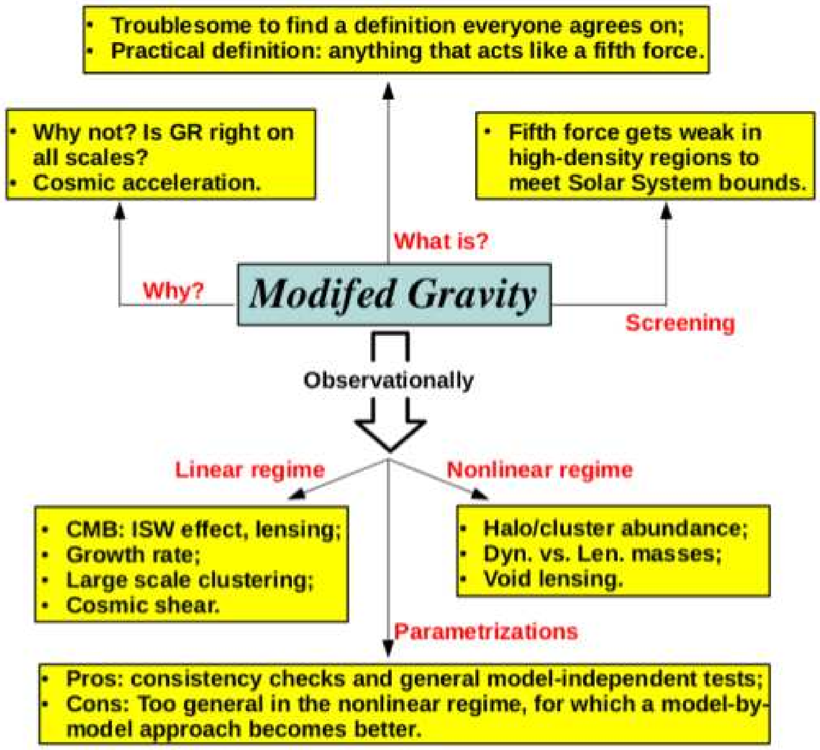
# *Modified Gravity and Cosmology*

## 1 Cosmology and Dark Energy

The standard $\Lambda$ cold dark matter model ($\Lambda CDM$) of cosmology is based on a wealth of cosmological observation, ranging from temperature anisotropies in the cosmic microwave background (CMB), to supernovae type Ia (SNIa) light curves, baryonic acoustic oscillations (BAO) imprinted in the galaxy distribution, galaxy cluster abundances, gravitational lensing. This model assumes the cosmological principle (statistical homogeneity and isotropy on large scales), that derives from the Copernican Principle and has no foundation in any particular physical model or theory; i.e. it can not be "proved" in a mathematical sense. However, it has been supported by numerous observations of our Universe and has great weight from purely empirical grounds.
The standard $\Lambda CDM$ model can be devided into four main ingredients:

1. the standard model of particle physics (SMPP);
2. cold dark matter (CDM);
3. a cosmological constant, $\Lambda$;
4. general relativity (GR) as the theory of gravity.

The SMPP corresponds to all stable known particles that are predicted by this model (including their electroweak and strong force interactions) for after matter/antimatter annihilation (the photon era) and for cosmological purposes these include photons, neutrinos and baryons. The CDM particle does not interact (or interacts only very weakly) electromagnetically and its existence was postulated to explain a number of observational puzzles. The most famous of these is related to the flattening of galaxy rotation curves at large radii, which could not be explained solely by the gravitational field originating from the visible components. This led to explanations in which the galaxies are embedded in larger Dark Matter (DM) haloes. The extra diming of the light emited from SNIa compared to that expected in a Universe containing only matter provided the first concrete evidence for the existence of dark energy - a mysterious energy source with negative background pressure that is causing the expansion of the Universe to accelerate. In the $\Lambda CDM$ model, the role of dark energy is played by vacuum energy, which acts as a cosmological constant, Λ. Despite its simplicity, Λ is responsible for the most serious shortcomings of $\Lambda CDM$ model. We encounter two problems: the cosmological constant problem: *"Why is the observed value of the cosmological constant so small in Planck units ?"* and the coincidence problem: *"Why is the energy density of the cosmological constant so close to the present matter density ?"*.




The theory of gravity in the $\Lambda CDM$ model is Einstein's theory of General Relativity (GR). This theory is in remarkably good agreement with a wealth of precision tests performed in the Solar system (SS). These include the classical tests of gravitational redshift, the lensing of the light from background stars by the Sun and the anomalous perihelion of Mercury, as well as other tests such as the Shapiro time-delay effect measured by the Cassini spacecraft and Lunar laser ranging experiments which meausure the rate of change of the gravitational strength in the SS. Outside of the SS, GR is also in good agreement with the tests that involve changes in the orbital period of binary pulsars due to the emission of gravitational waves. The field equation of General Relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

are thought to govern the expansion of the Universe, the behaviour of black holes, the propagation of gravitational waves, and the formation of all structures in the Universe from planets and stars all the way up to the clusters and super-clusters of galaxies that we are discovering today. From a theoretical point of view, GR is a purely classical theory. GR is not renormalizable in the standard quantum field theory sense; on the other hand, from an observational point of view, cosmological measurements are usually interpreted as providing evidence for dark matter and a nonzero cosmological constant ("dark energy"). The concordance cosmological model describes a universe consisting of approximately 5% ordinary matter, 25% dark matter, and 70% dark energy. While it fits a wide variety of data, this model relies heavily on the existence of a "dark sector" comprising 95% of the universe. The standard model of cosmology is based on a huge extrapolation of our limited knowledge of gravity. All tests only probe length scales that are much smaller than those relevant for cosmology. This therefore motivates research on the observational signatures that alternative gravity models can leave on cosmological observables. Einstein developed his General Theory of Relativity a century ago, and, although it remains a cornerstone of modern physics, one could argue that of all the fundamental forces of nature it is gravity that remains the least well understood. This is almost certainly due to the weakness of the gravitational interaction, which makes it incredibly difficult to test in the lab experimentally. Inevitably, experiments on the scale of planets, stars, galaxies, and beyond cannot be performed with the same level of precision and control as those conducted for the other forces on Earth. Now given the mysterious nature of dark matter and dark energy, and the fact that their existence is inferred exclusively through their gravitational effects, it is natural to wonder whether the apparent need for these components could be a sign that gravity is deviating from conventional general relativity (GR) on large scales. Einstein's equations are the only second-order local equations of motion for a metric derivable from the action in 4D (Lovelock's theorem); so if we modify GR, we need to have one or more of these:

- Extra degrees of freedom
- Higher derivatives
- Higher dimensional spacetime
- Non-locality

The modified theories of gravity represent a generalization of Einstein's gravity, where some combination of curvature invariants (the Riemann tensor, the Weyl tensor, the Ricci tensor and so on) replaces or is added into the classical Hilbert-Einstein action formed by the Ricci scalar term $R$. One of the challenges for modified gravity models is to satisfy the stringent Solar System constraints whilst modifying gravity significantly on cosmological scales. Screening mechanisms have been developed to hide modifications of gravity on small scales. The screening mechanisms enable us to modify gravity significantly on cosmological scales while satisfying the stringent Solar System constraints. Despite the arena of modified gravity-models is in principle infinite, the very accurate data arisen from observation of our universe, restrict the field of viable models. In any case the project of modifying gravity leads immediately to two defining questions:

1. What does a good theory of modified gravity look like ?
2. How can we test such theories against General Relativity ?

## 2 LSST and Euclid

The comparison between observational data and theoretical models of the Universe is not a straightforward process. Besides the ever more complex procedures required to reduce raw data, quantify systematic errors, and extract meaningful cosmological information from direct observations, one also needs to take into account the corresponding difficulty of providing reliable theoretical predictions for the same observable quantities. In any case understanding the origin "dark sector" will require simultaneous progress in both particle physics and cosmology, in both theory and experiment; an interplay between theoretical physics, numerical astrophysics, and cosmological and astrophysical observations. Most astronomical investigations have focused on small samples of cosmic sources or individual objects because our largest telescope facilities typically had rather small fields of view, and those with large fields of view could not detect very faint sources. Now advances in technology have made it possible to move beyond the traditional observational paradigm and to undertake large-scale sky surveys. In the future are scheduled two important programs: the Large Synoptic Survey Telescope (LSST) and Euclid. Euclid and LSST are poised to dramatically change the astronomy landscape early in the next decade. The combination of high cadence, deep, wide-field optical photometry from LSST with high resolution, wide-field optical photometry and near-infrared photometry and spectroscopy from Euclid will be powerful for addressing a wide range of astrophysical questions.

Dark energy affects the cosmic history of both the Hubble expansion and mass clustering. Distinguishing competing models for the physical nature of dark energy, or alternative explanations involving modifications of the General Theory of Relativity, will require percent level measurements of both the cosmic expansion and the growth of dark matter structure as a function of redshift. Any given cosmological probe is sensitive to, and thus constrains degenerate combinations of, several cosmological parameters. Therefore the most robust cosmological constraints are the result of using interlocking combinations of probes. The most powerful probes include weak gravitational lens cosmic shear (WL), baryon acoustic oscillations (BAO), photometry of type Ia supernovae (SN), all as functions of redshift. In addition, strong galaxy and cluster lensing as a function of cosmic time probes the physics of dark matter, because the positions and shapes of multiple images of a source galaxy depend sensitively on the total mass distribution, including the dark matter, in the lensing object. Weak lensing (WL) techniques can be used to map the distribution of mass as a function of redshift and thereby trace the history of both the expansion of the Universe and the growth of structure. Measurements of cosmic shear as a function of redshift allow determination of angular distances versus cosmic time, providing multiple independent constraints on the nature of dark energy. The two main probes, redshift clustering and weak lensing, are complemented by a number of additional cosmological probes: cross correlation between the cosmic microwave background and the large scale structure; abundance and properties of galaxy clusters and strong lensing and possible luminosity distance through supernovae Ia. To extract the maximum of information also in the nonlinear regime of perturbations, these probes will require accurate high-resolution numerical simulations. The use of numerical simulations to investigate the evolution of the Universe and the formation of cosmic structures beyond the linear regime that is readily accessible to analytical computations has proven to be an extremely valuable tool for the development of our understanding of the Cosmos. Significant progress has been made in the field of cosmological numerical simulations over the last decades, both due to the increase of the available computational power and to the development of efficient and sophisticated algorithms. The growing role played by numerical $N$-body simulations in cosmological studies as a fundamental connection between theoretical modeling and direct observations has led to impressive advancements in the development and application of specific algorithms designed to probe a wide range of "dark sector".

# 3 Conclusion

In the coming years the study of cosmology will increasingly be a field of exciting research and full of new ideas. Judging from the theoretical developments in modified gravity over the past few years, it is reasonable to anticipate that novel models will keep being proposed in the literature. It is essential to ensure that we understand the physics of $\Lambda CDM$ and competing models to the same extent. This should serve to improve current techniques in the theoretical modeling and data analysis to design new observational tests and avoid catastrophic systematic errors in the interpretation of these upcoming surveys.
We must answer to the question: *"Could the acceleration of the Universe be a sign of the break down of General Relativity at large scales?"*, and the possible fields of research that we can investigate for this purpose are:

- the properties of General Relativity and its extensions and studies at interface between numerical and analytical relativity;
- the relation between cosmological and local observational constraints;
- understanding the interplay between gravity and expansion history and structure;
- experimental gravity, in particular tests of general relativity: the development of tests that can probe the validity of General Relativity itself on cosmological scale and the techniques needed to distinguish different candidate models.

This project is focused on the study of modified gravity models as an explanation of the accelerated expansion of the Universe and in order to achieve such objective I aim to confront predictions from theoretical models of alternative gravity theories against astronomical data. We can constrain these models via the most recent cosmological observations, especially thanks to a different growth of the cosmic structures compared to the case of General Relativity and it will be interesting the study of the forecasts for experiments concerning large weak lensing surveys, as EUCLID or LSST, in order to see what will be the potentiality of these in testing modified gravity.

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