Gravitational waves through the cosmic web

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Summary

The direct detection of gravitational waves (GW) is a groundbreaking scientific achievement of the past decade. Among others, it marked the beginning of GW-cosmology: the possibility of studying the Universe, from its primordial phase until today, using this new fascinating probe. Gravitational waves carry valuable information about their sources and the spacetime through which they propagate. For this reason, they have the power of revealing insights into the homogeneous and isotropic Universe, and the cosmic structures that perturb it. While the current technology for their detection is not able to deliver cosmological data of comparable quality as the one gathered through electromagnetic signals, the inherent potential of gravitational waves still remains. Looking ahead to future missions, this Thesis aims at understanding what gravitational waves can tell us about the dynamics of the Universe on cosmological scales, with particular emphasis on dark energy and large-scale structures. After **Chapter 1**, where we introduce all the necessary concepts regarding cosmology and gravitational waves, the rest of the Thesis is divided in three main parts:

1. The first Part seeks to harness the power of *gravitational waves luminosity distance fluctuations* as a robust tool to investigate scalar-tensor theories of gravity. The latter are extended gravitational theories where a scalar field mediates an additional gravitational interaction. The presence of the scalar field leaves traces in the so-called *relativistic effects*: distortions of the GWs due to the presence of cosmic structures along the propagation path. Since the growth pattern of the matter gravitational potentials depends on the gravitational theory, relativistic effects carry information about the scalar field. The analysis is conducted in the geometric optics regime, where the frequency of the gravitational waves greatly exceeds the characteristic energy scale of the encountered obstacles. **Chapter 2** proposes a novel estimator, which exploits GW and Type-Ia Supernovae observation, to detect the distinctive signatures associated with the running Planck's Mass and the clustering of dark energy. According to our analysis, in the most optimistic scenario, a total of 10^{14} effective number of events is needed to pick up such signatures. **Chapter 3** shifts the focus to the weak lensing convergence term, the most prominent relativistic effect. We investigate its potentiality in constraining the parameters of the extended cosmological model, considering GW-missions alone or in combi-

nation with galaxy surveys. We concluded that GWs can help the constraining power if their statistic becomes comparable with the one of galaxies.

2. The second Part of the Thesis formulates additional tests for scalar-tensor theories of gravity. Working again in the high frequency approximation, in **Chapter 4** we introduced the *gravitational wave stress-energy tensor* in the subclass of such theories where tensor modes propagate at the speed of light. From this result, we derived the gravitational wave distances, d_L^{GW} and d_A^{GW}, and showed that both of them can be explicitly modified by the presence of the scalar field. We also proved the validity of the *Etherington's reciprocity law* and investigated the implications of our result in the context of strong lensing time delay. **Chapter 5** explores the direct detection prospect of the scalar field waves in light of two screening mechanisms: *chameleon* and *symmetron*. Indeed, in order for a scalar-tensor theory to be viable, it must be equipped of a mechanism which suppresses the scalar field in high-density regions, such as the Solar System. We show that, in both scenarios, the interaction between the scalar waves and test particles is suppressed. Because of this, we concluded that scalar waves in these theories should not be observable.

3. In the third Part, we investigate the propagation of gravitational waves in the wave-optics regime within General. The reason behind this choice is to demonstrate that certain effects, commonly attributed to additional dynamical field content, may exhibit degeneracy with wave-optics effects. In **Chapter 6** we showed that the propagation effects can produce observable scalar and vector polarization modes even in General Relativity. While the results obtained remain applicable to resolved gravitational wave events, in this part we focused on the *stochastic gravitational wave background* and its polarization content. For the simple case of an unpolarized, Gaussian, statistically homogeneous initial background, we showed that the interaction with matter structures does not generate a net difference in the amount of left- and right-helicity tensor modes. We also observed that, in order to produce Q- and U-polarization modes, a hexadecapole anisotropy is required.