Summary of the Doctoral Thesis

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PhD Thesis entitled: **Lensing of gravitational waves as a cosmological and astrophysical probe**

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In light of the recently opened and rapidly growing gravitational waves window on multi-messenger astronomy, new ideas are required in order to fully take advantage of the fresh opportunities we are provided with these new probes. Following this goal, in this thesis we describe and exploit the fact that the lensing of gravitational wave radiation can leave a clear imprinting in the corresponding waveform, and we try to find out if this kind of measurements can be successfully employed to better constrain the cosmological background or to infer unbiased and precise astrophysical information.

In the first part, we use the wave optics formalism for the gravitational wave lensed signal, and the standard geometrical optics approximation for the electromagnetic one, to study the impact of different cosmological parameters (the Hubble constant in particular) on the arrival time delay due to gravitational lensing. We show that even one single lensing event in a "pessimistic" scenario (namely with a pulsar population similar to currently achieved Pulsar Timing Array state),

combined with a prior on Ω_m from *Planck*, could provide an uncertainty on H_0 comparable with present independent probes. In an "optimistic" scenario, with a number of observed pulsars as large as that expected in the next future from the Square Kilometer Array, we can achieve errors two orders of magnitudes smaller. Thus, the role played by gravitational lensing of gravitational waves in the solution of the Hubble tension could be decisive.

Since such results may still be affected by one of the most important lensing problems, the mass-sheet degeneracy, in the second part we focus on this problem more specifically. The mass-sheet degeneracy is a well-known problem in gravitational lensing which limits our capability to infer astrophysical lens properties or cosmological parameters from observations by bringing large degeneracies between the position and the mass of the lens. We thus study the effects of this degeneracy on the lensing of gravitational waves. We differentiate between different optical regimes, and we focus on ground-based gravitational waves detectors. We find that in the interference regime, and in part in the wave-optics regime, the mass-sheet degeneracy can be broken with only one lensed waveform thanks to the characteristic interference patterns of the signal. We also quantify, through template matching, how well the mass-sheet degeneracy can be broken. We find that within present gravitational waves detectors' sensitivities, and considering signals as strong as those which have been detected so far, the mass-sheet degeneracy can lead to a 1σ uncertainty on the lens mass of $\sim 12\%$. With these values the mass-sheet degeneracy might still be a problematic issue. But in case of signals with higher signal-to-noise ratios, the uncertainty can drop to $\sim 2\%$, which is much less than the current indeterminacy achieved by dynamical mass measurements.

Finally, in the last part we study how much efficiently gravitational wave lensing events can be recognized and if we are able to use them to differentiate between different lens mass models. We study the lensing of gravitational waves in the context of LISA sources and wave-optics regime. We focus on frequency (time) dependent phase effects produced by one lens and that will be visible with only one lensed image. We show how in the interference regime we are able to distinguish a lensed waveform from an unlensed one, and to differentiate between different lens models. In pure wave-optics the feasibility of the study depends

on the signal-to-noise ratio and on the magnitude of the lensing effect. In order to achieve these goals, we study the phase of the amplification factor of the different lens models and the effects on the unlensed waveform, and we exploit the signal-to-noise calculations to provide some quantitative examples.

Keywords: gravitational waves, gravitational lensing, cosmology, dark matter, dark energy

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