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Testing General Relativity and modified gravity with gravitational waves – Part II

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Abstract

Gravitational waves, which were detected directly for the first time by the LIGO-Virgo scientific collaboration, can be used to test modified gravity. This letter complements the companion letter titled "Cosmology with gravitational waves" and we describe here 1) theoretical developments in modified gravity/dark energy; 2) Tests of general relativity with GWs. We believe this research will be a frontier of theoretical and gravitational wave physics for next 10 years and beyond.

Theoretical developments in modified gravity/dark energy

The late-time acceleration of the universe — probably one of the most intriguing aspects of modern cosmology — has led to a huge interest in the recent years in theories of gravity which differ from Einstein's General Relativity (GR) on large scales: could this late time acceleration be due to a modification of the theory from GR on large scales, rather than to the existence of a *dark energy* component among what constitutes the energy density of the universe? And if it were not the case, what exactly is the nature of dark energy?

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*, a type of fluid whose energy density is independent of space and time. This however raises new puzzles: the value of the cosmological 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 level (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 (*de Sitter space-time*) faces important theoretical challenges on two fronts: (a) understanding and controlling QFT in de Sitter, (b) having difficulty embedding it in a fundamental theory of gravity like string theory [1].

Faced with these questions, theorists are developing new frameworks to better understand gravity at a fundamental level, which almost universally result in the presence of new degrees of freedom (beyond those of GR) which participate gravitational interactions.

There are many such *scalar-tensor theories*, from simple *quintessence* to more complicated higher-derivative theories: the most general family of viable theories, known as degenerate higher-order scalar-tensor (DHOST) theories, has been developed within the theory group at APC (see [2, 3] and [4] for a recent review). In all these theories dark energy is dynamical, but the CC problem is not addressed.

Another possibility is that late-time acceleration is the result of gravity becoming weaker (than in GR) at large distances. This can be achieved by postulating that, as opposed to GR, excitations describing gravity have a tiny but non-zero mass. The resulting theories of *massive gravity* [5] have received much attention in recent years.

A more radical proposal, which addresses at the same time the large-distance properties of gravity and the fundamental nature of gravity on short-distances (and in particular is relevant for the CC problem) is the idea that gravity may be *emergent*, i.e. it is a low-energy manifestation of more fundamental, non-gravitational degrees of freedom. A concrete implementation of this idea stems from string theory in the form of *holographic duality*, according to which certain gravitational theories may be equivalently described in terms of strongly coupled quantum field theories in a lower-dimensional space-time. In this framework, explicit effective models of emergent gravity have been recently developed at APC [6]. These models display a self-tuning mechanism for the CC (thus explaining why its value is not unacceptably large) and the possibility for dynamical dark energy. At the same time, these models offer a novel possibility for embedding de Sitter space in string theory [7].

All theoretical frameworks mentioned above imply both a time-dependence of the dark energy parameters and deviations from GR in a certain range of scale. All these deviations may be potentially detected by future gravitational wave observation, as discussed in the following sections. 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.

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 the following interconnected steps: (i) continue exploring mathematically consistent theories of modified gravity, compatible with all experimental data to date (from early times such as at the formation of the Cosmic microwave background, to the late time universe); (ii) within existing and future models, focus on constructing BH solutions, (iii) study the ring-down of these modified BHs and how the expected signal at a detector differs from that of GR, and then (iv) working with members of the LIGO-Virgo and LISA collaborations, use data to impose constraints on the models.

Tests of General Relativity with Gravitational Waves

The detection of gravitational waves by Advanced LIGO and Advanced Virgo provides an opportunity to test general relativity in a regime that is inaccessible to traditional astronomical observations and laboratory tests. We are probing strong dynamical gravitational field with (merging NSs) and without (merging BHs) matter [8, 9]. Set of tests was applied to the first catalogue of GW events (from O1 and O2 observational runs) [10, 11].

Detection and characterization of the GW signals from coalescing binaries rely on accurate modelling of those signals, which is a quite challenging problem already within GR. To date, we do not have a model reliably describing GW signal from two merging objects outside GR. Boson stars were proposed as BH mimickers (still a solution consistent with GR), those are objects consisting of a scalar field with the self-interaction. Mass of boson stars could vary from sub-solar to supermassive ($10^6 - 10^7\, M_\odot$) while remaining compact (compactness of solar mass boson stars is comparable to that of neutron stars). The GWs from merging boson stars were recently computed numerically and contain signatures which could distinguish them from black hole systems [12], however, it would require detecting the merger and post-merger signal with a high signal-to-noise ratio (SNR) which is possible with the next generation of ground-based detectors (like Einstein Telescope) and with the space-based observatory LISA.

Most of the current tests of GR are performed in a phenomenological way by introducing deviations in the GW model computed withing GR. Some of those deviations correspond to the additional physical processes which take place in alternative (to GR) theories of gravity, few examples: (i) dipolar radiation would generically lead to the presence of "-1PN" order term in the GW phase (PN - post-Newtonian) while the amplitude and dependence of this term on masses depends on a particular theory (ii) GW propagates with the speed different from the speed of light if graviton has a mass (or if Lorentz invariance is broken), and, the GW dispersion due to massive graviton leads to the appearance of "1PN" term in the GW phase.

Detection of GW signals from coalescing binaries and estimation of parameters is very sensitive to the phase of the GW signal. To test the consistency of the detected GW signal with GR we perturb the GW phase by introducing phenomenological deviations in the inspiral (variation of PN coefficients), merger and ringdown and infer the deviations compatible with the observed data. Another consistency test is performed by splitting the expected signal into two parts (pre-merger and merger-post-merger), each of those parts is analyzed separately. The parameters of the signal inferred from each analysis are checked for mutual consistency and consistency with parameters inferred from the whole signal. Current results show full consistency of the detected GW signals with GR. However, we do not expect any strong deviations from GR and detection of weak features requires a *significant number* of GW signals with *high* SNR. While the number of events can be accumulated by long observational runs (O3, O4), getting high SNR ("golden") events requires better sensitivity similar to Einstein Telescope and LISA (for massive black hole binaries). The importance of high SNR events lies in the non-stationarity of the noise which could be mistaken for deviations in GR. The influence of the noise for loud signals is diminished allowing us to conduct *ultra-precise* tests of GR.

We have already mentioned a possible modification of GR through the emission of the dipolar radiation or, more generally, dissipation of the energy and angular momentum from a binary that is not consistent with GR. The dissipation through a dipolar moment appears in the phase at "-1PN" relative order, which implies that it is most important during the slow inspiral. The best way to detect any possible deviation is to observe the signal for a very long time: inspiral would give us the measurement of the deviation from GR while the merger provides high SNR and, therefore, accurate parameter estimation. The stellar-mass black hole binaries (like those which are being detected weekly by LIGO and Virgo) can be potentially detected by LISA during their early inspiral. Some of those systems will evolve across the high-frequency end of LISA sensitivity and will be detectable with a very high SNR ($\sim 10^3$)

several years later with the ground-based interferometers like Einstein Telescope. It is crucial to start *early planning* of the next generation of the ground-based detectors ensuring that they are fully operational during the LISA mission. Conducting multi-band GW observations will improve the current GW constrains by 4 orders of magnitude.

Another test which will greatly benefit from the multi-band observations is based on testing dispersion of the GW signals. We have already mentioned that the speed of graviton could deviate from the speed of light due to non-zero mass of a graviton and/or in the theories with Lorentz invariance violation. There are two factors which affect dispersion: (i) distance to the object, we expect larger dispersion from binaries which are further away; and (ii) GW bandwidth, observing a GW signal across the very broad frequency band gives a large difference in arrival time between low and high frequencies of a GW signal. LISA's observations of merging massive black holes throughout the Universe with high SNR will fulfil the first condition. The multi-band observations of coalescing binary black holes satisfy the second condition. Besides, we do expect high SNR events with combined LISA-ET observations.

Another test of GR concerns the polarization of GW signal, GR predicts only two (tensorial) polarization of the GW signal, while in general, we could expect four more (two vectorial and two scalar modes). We require more than two GW detectors on the ground to measure the polarization of the GW signal (for the transient GW signal, two not co-located detectors could measure two polarizations and the third checks consistency). LISA will be able to measure "alternative" polarizations at high-frequency end of its sensitivity (where the GW wavelength is comparable to the detector's size). The best detector to measure the polarizations turns out to be Pulsar Timing Array (PTA), there we use millisecond pulsars as ultra-stable clocks and measure the effect of GWs on the propagation of the radio signals from pulsars. PTA can be seen as a multi-arm detector where the electromagnetic signal travells only in one way. It is the multi-arm structure which appears to be sensitive to the alternative polarizations.

Last, but might be the most important test of GR concerns the BH "no-hair" theorem which implies that the perturbed black hole will release all its perturbation in form of GWs and quickly approach stationary state characterized only by its mass and spin (Kerr BH). What is important is that the ring-down GW radiation (releasing perturbations) has a characteristic spectrum consisting of damped sinusoids, where the frequencies and the damping times are characterized by the same two parameters (mass and spin of the stationary solution). The amplitude of these eigen (quasi-normal) modes depends on the physical process which excites a BH. Measuring and identifying one ring-down harmonic provides us with the estimation of mass and spin, and detection and characterization of the second mode allow us to test no-hair theorem. Unfortunately, the ring-down part of the detected by LIGO/Virgo GW signals is very short and has a low SNR. At best, we could (barely) identify the less damped quasi-normal mode. We require ET telescope to make a reliable measurement of several modes, alternatively, the SNR of the GW signals from massive black holes with mass $M > 5 \times 10^6\, M_\odot$ will be dominated by a post-merger part allowing us to perform the no-hair test. However, ET and LISA will see BHs produced by different physical processes, and some fraction of massive BHs might be surrounded by gas breaking "vacuum condition" of the theorem.

Another way of testing no-hair theorem can be done using LISA's observation of extreme mass ratio inspirals (EMRIs). Those are inspirals of a compact solar-mass object (like a BH, NS or a white dwarf) into a massive BH in galactic nuclei. The orbit of a compact object decays very slowly even in very close proximity of massive BH (amplitude of GWs scales as a mass ratio), so the compact object could spend $10^4 - 10^6$ orbits before it plunges into massive BH. The information about the spacetime of a central massive object is encoded in the emitted

GW signal and could be used to test if the central massive object is indeed a Kerr BH of GR. LISA's observation of EMRIs will allow us to measure deviation in the quadrupole moment of a massive object form the Kerr value with accuracy $10^{-4} - 10^{-3}$.

In conclusion of this section, we would like to strongly emphasize the importance of modelling GW signals both within GR and within alternative theories of gravity. For loud GW signals which are expected with LISA and ET, the accuracy in GW modelling will be a constraining factor, lack of accuracy in the GW model could be mistaken for some deviation from GR. Modelling GW singals in alternative theories is extremely challenging but could hint us to search for specific features in the detected GW signals.

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