Gravitational Waves and Black Holes

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Abstract. We summarise the present status of the gravitational wave detectors on the Earth.Then, we discuss some of the most intriguing results obtained during the last data collection O3. We will focus on the statistical distributionof the population of these compact objects and we will discuss a couple of potential tests to be carried on the on the Bekenstein-Hawking thermodynamics using the gravitational wave signals.

1 Introduction

The experimental effort to detect Gravitational Waves (GW) was accomplished in 2015, just 100 years after the first presentation of the Einstein theory of General Relativity. To date, the catalog GWTC-3 of GW signals account for 90 events, the majority of them due to emission of the coalescence of binary black holes (BBH) systems. These are stellar mass black holes (BH) emitting GW in the acoustic frequency band of the LIGO, Virgo and KAGRA detectors. The signals have been collected during three observation runs, the last of which was O3 ended on March 27^{th}, 2020. Towards the end of O3, the KAGRA detector, located in the Mozumi mine of the Kamioka mining of Japan, joined the observing run. This detector continued to operate for other two weeks taking data in coincidence with the German-UK gravitational-wave detector GEO600 near Hannover in Germany. The results from the GEO600-KAGRA run have been published in [1]. KAGRA, the two LIGOs, installed one in the Louisiana and the other in the Washington state, as Virgo, installed in Tuscany (Italy), are currently being upgraded fin preparation of the fourth observing run (O4). The joined data collection of the whole terrestrial network is expected to begin in 2023. We expecte to deal with detectors of higher sensitivity, so that the observation rate of gravitational waves will increase up to three times as often as in O3. The prediction is to have as many as five signals each week. The plans for upgrades in LIGO and Virgo concern different parts of the detectors. Virgo will modify the optical configuration adding the signal recycling mirror at the detector output, a solution already adopted in LIGO during the previous observation runs. Both US and European detectors will run using new high power laser and injecting trough the output port of the interferometer a squeezed electromagnetic (e.m.) vacuum with a frequency dependency. This is a significant novelty compared to the set-ups of LIGO and Virgo during O3. During the last run a phase squeezed vacuum field was injected in the interferometers, obtaining a sensitivity improvement at high frequency, but paying the price of a degrades at low frequency due to the anti-squeezing effect. The simultaneous reduction of the shot noise at high frequencies and quantum radiation pressure noise at low frequencies will be obtained by filtering the e.m.

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vacuum by means of a long Fabry-Perot cavity with low optical losses before to inject it in the output port of the interferometer. The filter cavity acts on the e.m. field like a passive filter in an electric circuit and it rotates the squeezed quadrature of the complex vector representing the e.m. vacuum in the Gauss plane as a function of frequency (see fig. **??**).

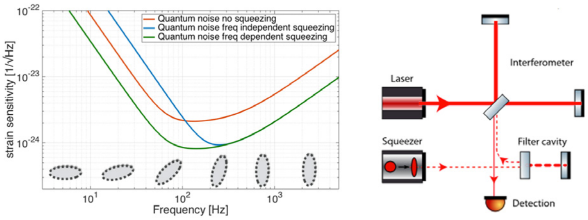

Figure 1. On the right we show a simplified optical scheme, which includes the cavity filtering the e.m. vacuum field (dashed line). On the left the sensitivity curves of the interferometer in he three different configurations: no squeezing, frequency independent and frequency dependent squeezing. On the bottom of the rotation of the vacuum squeezed quadrature in the Gauss plane as a function of frequency.

2 Population studies

The LIGO-Virgo collaborations published companion studies of the underlying population of black holes and neutron stars [2] and the history of the expansion of the Universe[3]. Moreover, the new catalog contains some surprises, such as an unusual neutron-star (NS) merged with a black-hole (BH), a massive BH merger, and BBHs revealing information about their spins. On the base of the 76 compact binary mergers detected with gravitational waves below a false alarm rate of 1 per year, present in the GWTC-3 catalog the LIGO-Virgo collaboration inferred some of the properties of the population of the astrophysical compact objects. The catalog contains three classes of binary mergers: BBH, BNS, and NSBH mergers. The inference on the BNS merger rate is ranging between 13 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ and 1900 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ while the NSBH merger rate is between 7.4 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ and 320 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$, assuming a constant rate density versus comoving volume and taking the union of 90% credible intervals for all the methods used in this analysis. Concerning the BBH merger , the rate interval is 17.3 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ - 45 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ at a redshift (z=0.2), accounting for the evolution of the merger rate to with redshift z

The neutron star mass distribution is broad and it is extended from $1.2^{+0.1}_{-0.2} M_\odot$ to $2.0^{+0.3}_{-0.2} M_\odot$, without evidence of an increase of the merger rate before 10 $M_\odot$. The BBH mass distribution is localised over- and under-densities relative to a power law distribution. While we find the mass distribution of a binary's more massive component strongly decreases as a function of primary mass, we observe no evidence of a strongly suppressed merger rate above $\sim 60 M_\odot$. The rate of BBH mergers seems to increase with redshift at a rate proportional to $(1+z)^\kappa$ with $\kappa = 2.7^{+1.8}_{-1.9}$ for $z \lesssim 1$. Concerning the BH spins, half of spin magnitudes are below $\chi_i \simeq 0.26$; in addition we have evidence of an increase of spin magnitude in systems with more unequal mass ratio and even negative aligned spins in the population [2].

The events of the GWTC-3 catalog have been used also to estimate the current value of the Hubble parameter H_o[3]. The analysis is based on 47 events, providing the luminosity distances to the source. The the redshift associated to each event has been inferred in two modes: a) using the redshifted masses , b) using the galaxy catalog. In the first method based on the BBH redshifted masses we should infer simultaneously the source mass distribution and the Hubble parameter in function of the redshift $H(z)$. Then, assuming that the assigned mass distribution does not evolve with z, the result obtained for H_o is:

$$H_o = 68^{+12}_{-7} \quad \frac{km}{s\ Mpc} \tag{1}$$

The use of the galaxy catalog implies to marginalise, in the statistical sense, over the redshifts of each event's potential hosts. Then, making the assumption that the BBH population is fixed, they conclude that H_o is :

$$H_o = 68^{+8}_{-6} \quad \frac{km}{s\ Mpc} \tag{2}$$

Although the gain to the respect of the values obtained using just the data of the previous catalog GETC-2 is of the order of 42% outcome, we note that it depends significantly on the assumption done on he BBH mass distribution.

3 GR Tests and BH Thermodynamics

There are several good motivation to search for *new* physics beyond the Einstein theory of Gravitation, on which today we are founding our models of the Universe. The matter we know and that makes up all stars and galaxies only accounts for 5% of the content of the universe, while an other kind of matter of unknown origin , the dark matter, seems to complement the Universe mass for about 27 %. In addition, cosmology at present has no explanation for about 68 % of the energy in the Universe that comes in the form of dark energy. Universe is a mystery, but today we have a new way for studying it via the gravitational waves. The GW advanced detectors allows to perform tests of general relativity (GR) in the strong-field regime of gravity. The most recent ones of the LIGO-Virgo-KAGRA collaboration is based on fifteen BBH events with a false alarm rate of $\leq 10^{-3}$ year $^{-1}$ to which a NS-BH event has been added. The test is carried on by computing, for each event ,the power residuals resulting from the subtraction of the waveform best fit of signal to the real data and check that is compatible with the detector noise. To find evidence for possible deviations from GR, we can perform *consistency* or *parameterised* tests. Consistency tests has been done by checking how much the signal shape is consistent with GR; the other category of tests implies the choice of an appropriate parametrisation to search for deviations from GR. Tests based on the post-Newtonian (PN) coefficients are sensitive to the physical effects that appear at different PN orders, while the parameterisation of the dispersion relation can give hints on non-GR wave propagation effects. The list of the GR tests is long and we refer to the article [4] for the details. Here we cite just the results, all null at present:

- the BH quadrupole moments induced by its rotation are consistent with those of Kerr black holes in GR;
- no evidence of dispersion of gravitational waves was found;
- no polarisation modes from GR prediction were evidenced;
- in the events that were analysed, no post-merger echoes were found.

In addition, we report the new upper bound on the graviton mass m_G set at 90% credibility:

$$m_G \leq 1.27 \cdot 10^{-23} \quad \frac{eV}{c^2} \tag{3}$$

GR is classified as a classical theory, leading to many surprising results as the prediction of the BH existence and its singularity inside its horizon. BH define a space volume from which even light can not escape, but we may expect that classical physics breaks down near the singularity. In addition there are good reasons to believe that at least in the proximity of the horizon we could observe deviations from semiclassical physics predictions [5],[6]. In a pure scenario depicted by GR, BH do not emit any radiation, so its absolute temperature is zero. However, in the 70s, S. Hawking and J. Bekenstein [7],[8],[9] theorised that even in a semiclassical framework, including some how quantum mechanics (QM) in the BH description, the compact object should acquires a finite temperature. The first hint that it could exist a connection between BH and Thermodynamics came is dated 1970: it concerns the mathematical result that the value of the BH horizon area always increases when additional matter or radiation falls into the black hole. Moreover, in the case of BBH merger the area of the horizon are of the final BH should be greater than the sum of the areas of the two primary BHs. These properties suggest that there is a resemblance between the BH horizon area and the thermodynamical concept of Entropy. Further, the similarity is extended looking at the change of BH internal energy, which pushes us to assume that a finite temperature of a BH is proportional to its surface gravity. The existence of a finite temperature for BH implies that this object is in thermal equilibrium with its external environment by emitting thermal radiation. Thus, we are ending up with the paradox that in the pure classical description of a BH, this object would absorb any thermal radiation that fell on it but by definition would not be able to emit anything in return. Al these considerations pushed to assume that the Bekenstein-Hawking entropy of a black hole depends on the BH area, the BH has a temperature and emits thermal radiation.

These are all intriguing theoretical consideration; now the GW experimental physics gives us access to a new regime in which the unique properties of BH can be observationally tested. Since the BBH merger is an irreversible process, we expect that the total horizon areas should always increase. The area is in turn a function of BH mass and spin and, using the values given by the GW catalog of events, it is rather an academic exercise to test the entropy increase for the coalescent events of binary black holes [10]. However, a fundamental objection has been raised on this approach to prove that we are really dealing with quantities related to BH thermodynamics: we are extracting data by fitting the GW data with numerical relativity formulas, i.e. in the full assumption of the validity of the classical GR theory. To evade this problem, it has been proposed [11] to avoid GR by using just the initial masses measured using the data of the quasi Keplerian orbit far from the merger phase and for the final BH mass the ring-down part of the signal.

An other way to approach the question of how to check the thermodynamical laws of BHs, is looking at the spin dependence. According to the Bekenstein-Hawking formula, the entropy is smaller in the case of larger spins for a given fixed mass M. The statistics interpretation of the entropy implies that there are fewer micro-states with large spin than with small spin. Thus, it is possible to compare spin data with the models predicting the BH population according to the micro-canonical ensemble. This would be a way to apply the statistical mechanics approach to the BH physics trough its entropy study: an interesting attempt is reported in [12].

The finite temperature of BH thermodynamics implies a thermal emission, i.e. a change of the BH mass and, as consequence, of its entropy. Assuming a statistical point of view, we can state that there is a change in the number of internal configurations accessible to the system or conversely, an amount of information emitted by the system. Bekenstein derived an universal bound for the maximum average rate of information emission achievable by a physical system[13]. Then, Hod noted that this bound applies to the ring-down phase of a BH relaxing towards equilibrium. He quantified the bound by introducing the information loss parameter $\mathcal{H}$, a quantity having an explicit dependence on the relaxation time of a perturbed black hole $\tau = 1/\omega_I$ [14]:

$$\mathcal{H}_{max} = \frac{1}{\pi}\frac{\hbar\omega_I}{k_B T} \leq 1 \tag{4}$$

where T is the BH temperature and k_B the Boltzmann constant. This limit is known as the Bekenstein-Hod universal bound and, using a time-domain ringdown analysis of BBH events of GW catalog of signals, Carullo et al. [15] were able to provide an experimental confirmation of the Bekenstein-Hod bound. This can be regarded as the first experimental verification of a long standing prediction on the dynamical information-emission process of a BH.

4 Conclusions

The accumulation of GW data, produced in the merger phase of astrophysical compact object as BH and NS, increases our chance to shed lights on the dark side of the Universe. 90 signals have been collected in the GWTC-3 and on this base more stringent values on the formation rates of BBH and BHNS have been derived. There is a growing theoretical and experimental evidence that modifications of GR at small and large energies are somehow inevitable and the GW observations allow to perform GR tests in the strong-field regime of gravity. Although no deviations have been observed up to now, significant upper bounds have been set on the deviation of post-Newtonian coefficients of different PN orders and on the parameters giving hints on non-GR wave propagation effects. New data will come soon with the upgraded LIGO-Virgo-KAGRA network that will begin the O4 observation in 2023. The goal is to run the network at a signal to noise ratio higher than in the past, increasing the chance to insight into the origins of the binary compact objects, the extreme conditions inside neutron stars and perform most-stringent tests of GR. We are also confident to detect new categories of GW signals, as those emitted by the asymmetric rotating neutron stars, giving hints on the status of central matter of the neutron star with densities exceeding that of atomic nuclei.

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