RESULTS FROM THE FIRST SCIENCE RUN OF ADVANCED GW DETECTORS

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On September 14$^{\text{th}}$, 2015 at 09:50:45 UTC the two LIGO detectors simultaneously observed a transient gravitational-wave signal. The signal matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. This observation demonstrates the existence of binary stellar-mass black hole systems and it represents the first direct detection of gravitational waves and the first observation of a binary black hole merger. The methods to assess the statistical significance of the event and to estimate the source parameters will be summarized here. Finally, the results of the comparison between the measured waveform and the predictions of general relativity will be described, together with the astrophysical implications of this detection and the outcome of the broadband campaign to search for electromagnetic or neutrino counterparts.

1 Introduction

A century after the fundamental predictions of Einstein [1] and Schwarzschild [2], the LIGO Scientific Collaboration and the VIRGO Collaboration recently reported the first direct detection of gravitational waves [3] (GWs) and the first direct observation of the merger of a binary black hole system into a single black hole. This mesurement has given the possibility to study the properties of space-time in the strong-field regime and confirm predictions of general relativity for the nonlinear dynamics of highly disturbed black holes [4].

2 The GW signal

The Advanced LIGO detectors [5] (in Hanford, WA, and Livingston, LA), on September 14$^{\text{th}}$ 2015 at 09:50:45 UTC, reported the conicident observation of a signal, initially detected by a low-latency search for generic gravitational-wave transients [6]. The signal reached first Livingston and, after about 6.9 ms, arrived at Hanford. The signal has been then analysed with a matched-filter, constructed from relativistic models of compact binary objects [7] and found to be the most significant event in each detector in the first part of the observing run, with a combined signal-to-noise ratio (SNR) of 24 [8]. The time evolution of GW150914, shown in figure 1, suggests that this signal has been produced by the coalescence of a binary black hole system: the inspiral and merger, and subsequent final black hole ringdown. In about eigth cycles, lasting 0.2 seconds, the frequency increases from 35 to 150 Hz, where also the amplitude is maximum. The evolution of two inspiralling masses, m_1 and m_2, is characterized by the chirp mass [9]:

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5} \tag{1}$$

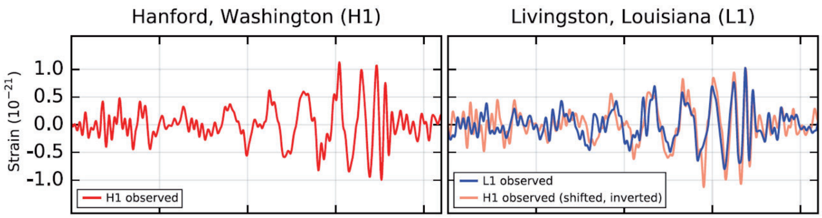

Figure 1 – Times relative to September 14, 2015 at 09:50:45 UTC. Left: H1 strain. Right: L1 strain and, for a visual comparison, the H1 data are also shown, shifted in time by the arrival time difference and inverted (to account for the detectors relative orientations). Figure from [3].

Table 1: Source parameters for GW150914, given in the source frame; to convert to the detector frame multiply by $(1+z)$ [10] . The evaluation of the source redshift assumes standard cosmology [11].

Primary black hole mass	36^{+5}_{-4} M$_\odot$
Secondary black hole mass	29^{+4}_{-4} M$_\odot$
Final black hole mass	62^{+4}_{-4} M$_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

where G and c are the gravitational constant and the speed of light. f and $\dot{f}$ are the observed frequency and its time derivative and can be both estimated from the data. This yelds the result $M_c \simeq 30$ M$_\odot$, which implies that, in the detector frame, the total mass $M = m_1 + m_2$ is larger than 70 M$_\odot$. While this rules out the possibility that the signal may have been generated by a binary neutron star system, the idea that the source could have been a neutron star orbiting around a black hole cannot be excluded. However, in this case, to reach a chirp mass of 30 M$_\odot$, the mass of the black hole must have been of the order of 3000 M$_\odot$ and the coalescence would have occurred at much lower frequencies, unobservable by ground based detectors. To evaluate the source parameters, general relativity-based models [12,13,14,15] have been used, in some cases including also spin precession, and, for each model, a coherent Bayesian analysis has been performed to derive the distributions of the source parameters [16], discussed in detail in [17] and shown in table 1, in the source frame. The uncertainties include statistical and systematic errors deriving from the average of the results of different waveform models. Using the fits to numerical simulations of binary black hole mergers provided in [18,19], the mass and spin of the final black hole, the total energy radiated in gravitational waves, and the peak gravitational-wave luminosity [17] have been computed. The total energy estimated to be radiated in gravitational waves is $3.0^{+0.5}_{-0.5}$ M$_\odot c^2$, and the peak gravitational-wave luminosity has been $3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s, equivalent to 200^{+30}_{-20} M$_\odot c^2$/s.

Around the time of the event, both detectors were in steady state operation since several hours. Instrumental and environmental disturbances have been investigated to rule out the possibility that GW150914 could be an instrumental artefact [20]. The detectors' sensitivity to environmental disturbances was measured by evaluating their response to magnetic, radio-frequency, acoustic, and vibration excitations. Finally, there is no evidence for instrumental transients that are temporally correlated between the two detectors.

Sixteen days of coincident observations between the two LIGO detectors, from September 12$^{\text{th}}$ to October 20$^{\text{th}}$, 2015, have been analysed to assess the statistical significance of GW150914. This is a portion of the first science run of Advanced LIGO, that ended on January 12$^{\text{th}}$, 2016. GW150914 has been independently detected by two different types of searches. One is targeted to the search of signals from coalescing compact objects, using optimal matched filtering with waveforms predicted by general relativity. The other search is optimized for generic transient signals, with minimal assumptions about waveforms. The methods used by the two searches are independent, thus their response to detector noise results different, uncorrelated, events. However, strong signals are expected to be detected by both searches.

The results of the unmodelled search are deeply presenter in [6] and will not be further discussed here. We shall focus on the results from the binary coalescence method [7].

This search has targeted gravitational-wave signal from binary systems with individual masses ranging between 1 and 99 $M_\odot$, total mass smaller than 100 $M_\odot$, and dimensionless spins up to 0.99 [7]. The effective-one-body formalism [21], combining the post-Newtonian approach [9,22] with black hole perturbation theory and numerical relativity, has been used for modelling systems with total mass larger than 4 $M_\odot$. In the waveform model [12,13], the spins of the coalescing objects are assumed to be aligned with the orbital angular momentum, nonetheless, systems with misaligned spins in the parameter space of GW150914 [7] can be effectively recovered. About 250000 template waveforms have been used to cover the whole parameter space. For each template in each detector, the matched-filter signal-to-noise ratio $\rho(t)$ is evaluated and the maxima of $\rho(t)$ with respect to the time of arrival of the signal is identified [23,24,25]. The lists of events in each detector are then compared looking for coincidences within a time window of 15 ms: 10 ms due to the intersite travel time plus 5 ms for uncertainty in arrival time of low SNR signals. The coincident events have been ranked on the basis of the quadrature sum $\hat{\rho}_c$ of the ρ from both detectors [8]. To estimate the background of this search the list of events of one detector are time shifted with respect to the list of the other detector and a new set of coincident events is computed. This procedure has been repeated $\sim 10^7$ times, equivalent to an observation time of about 608000 years. Both candidate and background events are divided into three search classes according to the template length. The background for the search class of GW150914 is shown in figure 2.

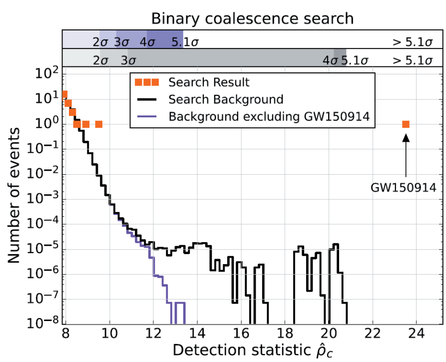

Figure 2 – Search results from the binary coalescence search. The histogram shows the number of candidate events (orange markers) and the mean number of background events (black lines) in the search class where GW150914 was found. The scales on the top give the significance of an event in Gaussian standard deviations based on the corresponding noise background. The tail in the black-line background is due to random coincidences of GW150914 in one detector with noise in the other detector. The purple curve is the background excluding those coincidences. Figure from [3].

Since the GW150914 detection statistic, $\hat{\rho}_c = 23.6$, is larger than any background event, only an upper limit on its false alarm rate can be placed. Considering all the three search classes, this bound is 1 in 203000 years, which corresponds to a false alarm probability $< 2 \times 10^{-7}$, or a detection probability larger than 5.1 σ.

3 Tests of General Relativity

The detection of GW150914 provides an unprecedented opportunity to study the motion of a compact binary system in the large velocity, highly nonlinear regime, and to observe the final merger of the binary and the excitation of relativistic modes of the gravitational field. Several investigations have been carried on to determine whether GW150914 is consistent with the merger of a binary black hole system in general relativity [4].

The first consistency check performed concerns the mass and spin of the final black hole. In the general relativity framework, the product of a black hole binary coalescence is a Kerr black hole, completely described by its mass and spin. For this family of inspirals, these quantities can be evaluated with Einstein's equations and are a function of the masses and spins of the progenitor black holes. Using the relations between the initial black holes and final black hole masses and spins evaluated through numerical relativity simulations [18], the estimates of the final mass and spin obtained from the low-frequency part of the waveform have been compared to those retrieved from the high-frequency component of the waveform. The test of the inspiralmergerringdown consistency shows no evidence of discrepancies with the predictions of general relativity.

Within the post-Newtonian formalism, the phase of the gravitational signal during the inspiral can be expressed as a power series in $f^{1/3}$. The values of these coefficients can also be computed in general relativity. Thus, a test of consistency with general relativity [26,27] can be performed. The coefficients have been made to deviate from the nominal values and it has been checked whether the resulting waveform was consistent with the data. Thus, empirical bounds on several high-order post-Newtonian coefficients have been determined in the dynamical regime [4].

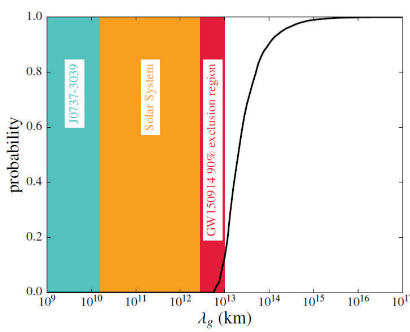

Figure 3 – Cumulative posterior probability distribution for λ_g (black curve) and the 90% (crimson) exclusion region for λ_g from GW150914. The shaded areas show exclusion regions from the double pulsar observations (turquoise), the static Solar System bound (orange).Figure from ref. [4].

Finally, the data from GW150914 have been used to constrain the Compton wavelength of the graviton, λ_g. General relativity assumes massless gravitons that travel at the speed of light $v_g = c$. On the contrary, if the graviton has a (small) mass, the dispersion relation becomes $E^2 = p^2c^2 + m_g^2c^4$, where E is the energy, p the momentum, and m_g is the graviton rest mass related to its Compton wavelength as $\lambda_g = h/(m_g c)$, where h is the Planck constant. Thus, the ratio v_g^2/c^2 becomes equal to $c^2p^2/E^2 = 1 - h^2c^2/(\lambda_g^2 E^2)$, and a massive graviton would propagate at a speed dependent on energy (or frequency). Or, in other words, the lower frequencies propagate slower compared to higher frequencies. This dispersion can be included in the phase of the gravitational wave signal from a coalescing binary as [28] $\Phi_{MG} = -(\pi D c)/[\lambda_g^2(1+z)f]$, where z is the redshift and D a cosmological distance defined in [28]. The signal from GW150914 shows no evidence for dispersion, thus it has been possible to constrain the Compton wavelength of the graviton to be $\lambda_g > 10^{13}$ km, which is equivalent to a bound on the graviton mass $m_g < 1.2 \times 10^{-22}$ eV/c^2

at 90% confidence level. The cumulative posterior probability distribution for λ_g is shown in figure 3. This observation improves the Solar System bound [29] by a small factor and that from binary pulsar observations [30] by a factor of a thousand.

To summarize, all these tests are consistent with general relativity in the strong-field regime.

4 Astrophysics with GW150914

This observation provides the first robust confirmation of several theoretical predictions: "heavy" black holes do exist, binary black hole systems form in nature and merge within the age of the universe at a detectable rate [31]. Two main types of formation models, involving isolated binaries in galactic fields [32] or dynamical interactions in young and old dense stellar environments [33], predict such mergers. The progenitor black holes of the GW150914 coalescence are more massive than the those in known XRBs with reliably measured masses: this discovery provides the most robust evidence for the existence of "heavy" ($\geq$25 $M_\odot$) stellar-mass black holes. This discovery implies relatively weak massive-star winds and thus the formation of GW150914 in a low-metallicity environment [34]: below $\simeq 1/2\ Z_\odot$ and possibly below $\simeq 1/4\ Z_\odot$. The rate of binary black hole mergers inferred from this observation is consistent with the higher end of rate predictions ($\geq$1 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$) from both types of formation models. The low measured redshift ($z \simeq 0.1$) and the low inferred metallicity of the stellar progenitors imply two different scenarios for the formation of binary black hole systems:

- in a low-mass galaxy in the local universe and a prompt merger;
- at high redshift with a time delay between formation and merger of the order of several Gyr.

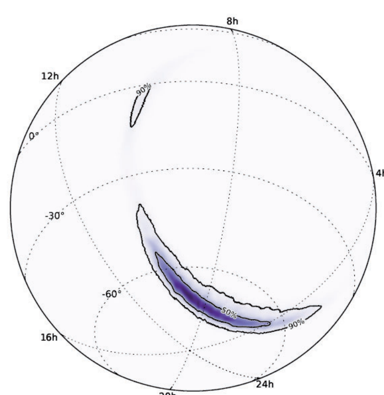

Figure 4 – An orthographic projection of the posterior probability density function (PDF) for the sky location of GW150914 showing contours of the 50% and 90% credible regions plotted over a colour-coded PDF. The sky localization forms part of an annulus, set by the time delay of $6.9^{+0.5}_{-0.4}$ ms between the two advanced LIGO detectors. Figure from [17].

Ground-based gravitational waves detectors are all-sky monitors with no intrinsic capability to determine the direction of incoming transient signals. Thus, a network of instruments is required to reconstruct the location of a source in the sky, through the time-of-arrival, and the relative amplitude and phase at different detectors [17]. The measured time-delay of GW150914 between the Livingston and Hanford sites was $6.9^{+0.5}_{-0.4}$ ms. Since at the time of the event, only the two LIGO instruments were in observational mode, the source location could only be reconstructed to approximately an annulus, due to this time-delay [35,36]. Figure 4 shows the sky map for GW150914: it corresponds to a projected 2-dimensional credible region 590 deg^2 wide at 90% confidence level. The associated 3-dimensional comoving volume probability region is $\sim 10^{-2}$ Gpc^3, that can be compared to the comoving density of Milky Way-equivalent galaxies ($\sim 10^7$ Gpc^{-3}). This area of the sky was targeted by follow-up observations covering radio, optical, near infra-red, X-ray, and gamma-ray wavelengths [37] and searches for coincident high energy neutrinos [38].

Neutrino candidates coincident with GW150914 were searched within the data recorded by the IceCube[39] and Antares[40] detectors. No neutrino candidate was found to be in both temporal and spatial coincidence with the gravitational wave event. Within ± 500 s of the gravitational wave event, three neutrino candidates were detected by IceCube and zero by Antares. This result is consistent with the expected atmospheric background. Furthermore, none of the neutrino candidates was spatially coincident with GW150914.

Since this event was due to a binary black hole merger, there was little expectation of detectable electromagnetic or neutrino signatures.

5 Conclusions

Gravitational waves from the merger of two stellar-mass black holes have been observed for the first time. The detected signal is consistent with the predictions of general relativity for the inspiral and merger of a binary black hole system and the ringdown of the resulting single black hole. GW150914 demonstrates the existence of binary stellar-mass black hole systems.

The implications of the first gravitational wave signal detection, due to the merger of a binary black hole system, have been examined in the context of the existing literature and several astrophysical conclusions have been drawn. The measured masses of the initial black holes are higher than any of the masses dynamically and reliably measured from XRBs. Such "heavy" black holes, for their formation, require massive stars progenitors in low-metallicity environments (1/2 $Z_\odot$ or less). Rate predictions from formation models are broadly consistent with the merger rate implied by GW150914.

Even if GW150914 has been a loud gravitational wave signal, any electromagnetic or neutrino counterpart was expected to be absent. Nevertheless, thorough follow-up observations were pursued to check for possible electromagnetic and neutrino emissions and this first broadband campaign represents a milestone. Future follow-ups of gravitational wave sources will shed light on the presence or absence of electromagnetic and neutrino counterparts and astrophysical processes that may trigger emissions from these systems.

Efforts are under way to enhance significantly the global gravitational-wave detector network [41]. Further commissioning of the Advanced LIGO detectors is ongoing to reach design sensitivity, allowing the detection of GW150914-like signals with a SNR three times higher. The addition of Advanced Virgo [42] will improve the network capability to reconstruct the position and the parameters of sources.

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8.
Summary