# First direct detection of Gravitational waves and the amazing event that produced them

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### Introduction

The theory of general relativity was proposed by Albert Einstein between 1915 and 1916 and even after more than one hundred years we are still confirming his predictions through direct observations of physical phenomena. In this essay we discuss two remarkable confirmations of his predictions through the first direct detection of gravitational waves.

Einstein's general relativity explains gravity as a consequence of the curvature of space time (instead of a force as it was previously believed to be). The distortion of space time is produced by massive objects so their motion through space time should perturb it in such a way that they produce waves that propagate supposedly at the speed of light. These waves are weak thus difficult to detect and only very massive objects can produce gravitational waves detectable with our current technology.

The direct detection of these perturbations of the fabric of space time had been anticipated for a long time (Thorne 1987; Schutz 1989), they suggested that these "ripples" can be detected by measuring the stretch and contraction that they produce in light beams that are perpendicular to each other, which is the basic principle of the detection of gravitational waves. A very extensive effort has been put into the construction of a laboratory able to detect gravitational waves but the precision of the instruments needed for these detections is such that is was only achieved when we created the most precise detector that mankind has created so far at LIGO which can detect spatial deviations of the order of 1 part in a thousand of the width of a proton.

But why was it necessary to put so much effort in finding gravitational waves?. The importance of their detection is that it provides a much deeper understanding of the Universe in different ways. They can in principle provide information of physical phenomena beyond light detection since they don't have an electromagnetic interaction. They provide verifications of general relativity predictions. They can give us more accurate measurements of distances and put constraints on the Hubble constant. They put constraints on modified gravity models that deal with scalar-tensor theories. They can give us a better understanding of the early Universe through the polarization of Cosmic microwave background. They don't get easily absorbed and that gives an advantage in detecting them at high redshifts so they could teach a lot about the early universe by opening the gate for new and exciting discoveries.

Another consequence of the distortion of space time is that if an object surpasses certain mass it could distort it so much that not even light could escape as predicted by Einstein and later on calculated by Schwarzschild. In principle, if two of these dark objects were to encounter, they could merge to an even more massive object. But until the first detection of GW, we didn't have a direct observation of this merging event. So the other remarkable verification of GR predictions that came from the first detection was the confirmation of the first collision and merger of a pair of black holes and that they merge within the age of the Universe.

## The detection

The concept of using physical properties of light and space itself to detect gravitational waves was first proposed in the early 1960's and 1970's. For this purpose, LIGO (Laser Interferometer Gravitational-Wave Observatory) was created. It consists of two giant laser interferometers located thousands of kilometers apart, one in Livingston, Louisiana and the other in Hanford, Washington. Each interferometer consists of two vacuum "arms" (each one 4km long) perpendicular to each other where a laser beam is shone and reflected by mirrors (suspended as test masses) at each end.

If there is no gravitational wave passing through, the two beams will be in phase when arriving to the detectors. But if there is a small deviation produced by the gravitational wave affecting one arm more than the other as a consequence of it's direction of propagation, the two beams will no longer be in phase and an interference pattern is produced (this is why they are called interferometers). Even though the basic principle of this detection appears to be simple, there are major complications on its real implementation which meant a great challenge for the scientific community for many years.

After undergoing major necessary upgrades, in 2015 the LIGO detectors began operation as "Advanced LIGO" which is the first of a significantly more sensitive global network of advanced detectors. There are several techniques used to multiply the effect of the gravitational wave on the phase of the laser light, such as an optical cavity that reflects the laser light back and forth many times in each arm and a power recycling mirror that increases the power of the laser in the interferometer and a signal recycling mirror that optimizes the signal extracted at the detector. These enhancements boost the power of the laser in the optical cavity by a factor of 5000, and increase the total amount of time that the signal spends circulating in the interferometer which is necessary for a clear detection.

The difference between the two arm lengths that produces the interference pattern is proportional to the strength of the passing gravitational wave, which is commonly referred to as the gravitational-wave strain, that in the case of the sensitivity required in LIGO is 1/10,000th the width of a proton. Making it the most precise detector in the world. There are other challenges in the detection of gravitational waves apart from the required sensitivity and the quantum effects. Some of them have to with the ability to isolate real signals from sources of instrument noise since there are constant small disturbances due to environmental effects or the behavior of the instruments themselves.

These sources of noise could mimic the signature strain pattern of a real gravitational wave. In order to solve this issue, there have to be two detectors separated by a long distance on earth so that they allow us to distinguish gravitational waves from these noise effects. Only a real gravitational wave signal would be detected in the two detectors and the detections must be separated by a few thousandths of a second, (the time taken for light (or a gravitational wave) to travel between the two interferometers. Having more than one detector also lets us trace the direction on the sky from which a gravitational wave arrives, by studying the difference in arrival time at each detector, although the error bars are very significant.

After all of these efforts, after 100 years of Einstein's general relativity, on September 14, 2015 the LIGO Hanford and Livingston Observatories both detected a gravitational wave signal that was named GW150914 and marked the start of a new era of exploration of the Universe. As shown in Figure [1], there is a remarkable agreement of the strain signal with the prediction from the numerical relativity simulations of the merging black holes in the inspiral, merger and ringdown stages, suggesting that the model is in good concordance with the observation.

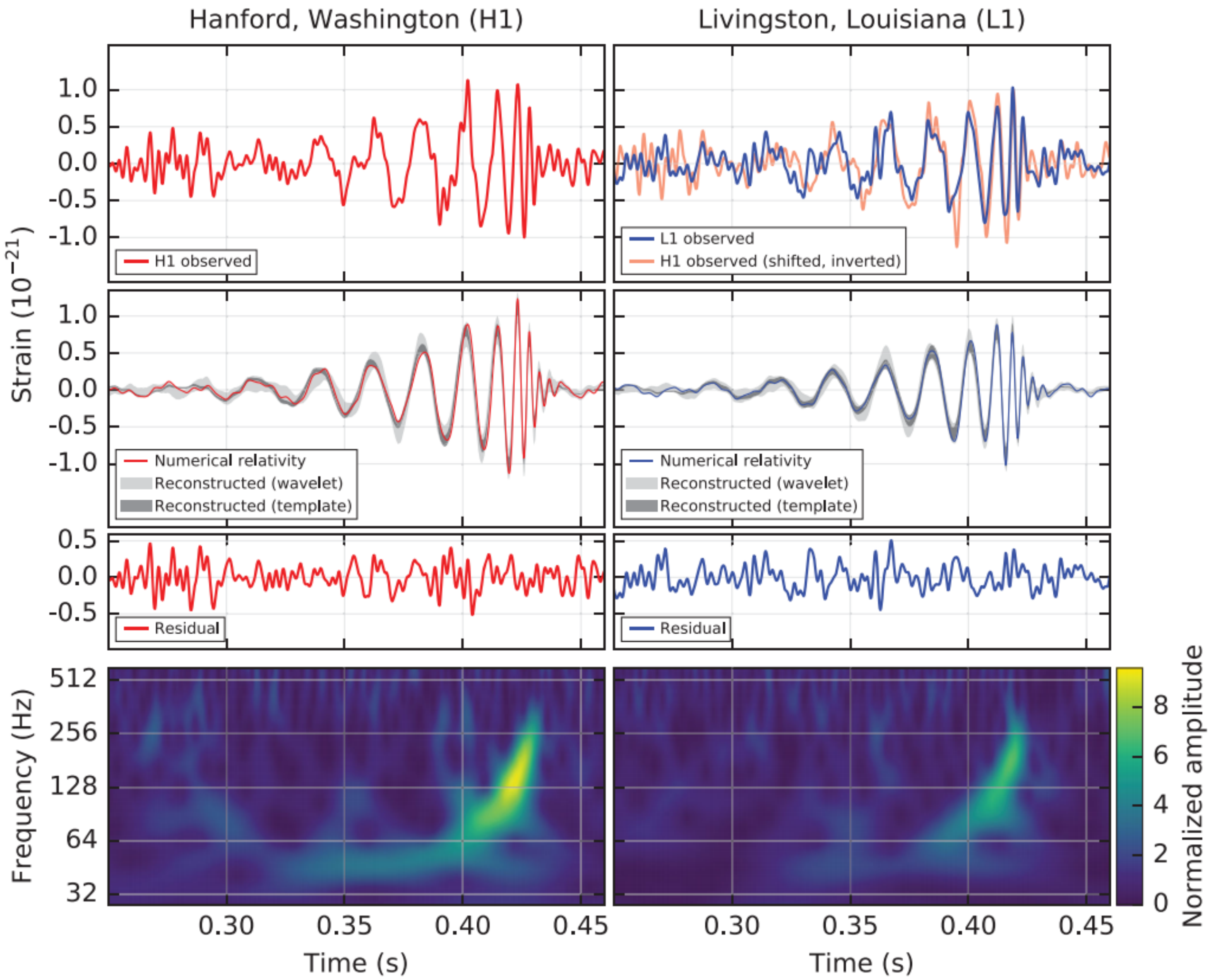


Figure 1: Detection of GW150914 as observed by the LIGO Hanford (left) and Livingston (right) detectors. Top row shows the individual strains for the two interferometers and the comparison between them after the time delay correction. Second row is the comparison between the simulated numerical results using general relativity and the strain signal after reconstruction. Third row shows the residuals and finally bottom row is the time-frequency representation of the strain data where we can see how the signal frequency increases over time. Source: Figure [1] from B. P. Abbott et al. 2016 [2].

### The source and its nature

Given the data and the models, we can estimate the specific physical characteristics of the system that produced GW150914. The Primary black hole mass is $36^{+5}_{-4}$ $M_\odot$, the secondary black hole mass $29^{+4}_{-4}$ $M_\odot$, and the final black hole mass is $62^{+4}_{-4}$ $M_\odot$. Note that if we compare the masses of the pre and post merger black holes, we see that the coalescence converted about 3 $M_\odot$ into gravitational-wave energy, which was emitted in no more than a fraction of a second. To interpret this number, we have that the gravitational wave power radiated by GW150914 was more than ten times greater than the combined luminosity of every star and galaxy in the observable Universe.

Additionally, it is inferred that the final black hole is spinning (Kerr-type black hole) with a spin of $0.67^{+0.05}_{-0.07}$. It's luminosity distance is $410^{+160}_{-180}$ Mpc, and a calculated source redshift of $z = 0.09^{+0.03}_{-0.04}$. All the parameter uncertainties include statistical errors and systematic errors from averaging the results of different wavefront models as discussed by B. P. Abbott et al. 2016 [2].

All the data results strongly suggest that they are both black holes, in particular, by looking at the tiny separation of the two components which is is shown to be just a few times the characteristic size of a black hole (Schwarzschild radius). Black holes are the only known objects compact enough to get this close together without merging. Moreover, we must also consider the enormous velocity that they reach which is a significant fraction of the speed of light.

Is it possible that the event wasn't an astrophysical event?. In principle yes, but first, the time delay between the observations made at each of the two LIGO detectors was consistent with the light travel time between them and second, the Hanford and Livingston signals showed a very similar pattern, as expected with the alignment of the two interferometers. Additionally the two patterns in both interferometers were strong enough to be discarded as background noise. The possibility that GW150914 was an unfortunate noise fluctuation was highly rejected by doing a statistical analysis that gives the false alarm rate. This analysis calculates how often we could expect to measure such a noise fluctuation and the results identify GW150914 as a real event, with a significance of more than 5 sigma.

It is important to study the origin of BBH and what are the needed conditions for their existence. As discussed by B. P. Abbott, 2016 [3], there are two main channels to form the observed BBH.

1) *BBH masses from isolated binary systems*: Observations show that the vast majority of massive stars are members of binary systems with a roughly flat mass-ratio distribution. This suggests that isolated binary systems can form BBH through some typical steps which can be summarized as: (i) stable mass transfer between two massive stars, (ii) the first core collapse and BH formation event, (iii) a second mass transfer phase that is dynamically unstable, (iv) the second core-collapse event leading to BBH formation, and (v) inspiral due to GW emission and merger.

Different models of BBH formation that follow these steps predict a range of metallicity and massive-star winds and in the case of GW150914, is consistent with weak stellar winds and metallicities bellow $z_\odot$.

2) *BBH masses from dense stellar environments*: In this "channel", black holes form in clusters from massive stars and mass segregates to the center through dynamical friction. In these high-density conditions, BHs can form binaries, and often are ejected from the cluster. These dynamical interactions preferentially keep the heaviest objects in binaries and eject the lightest, producing heavier binaries and driving mass ratios closer to unity. Star clusters that have typical metallicities lower than $z_\odot$ can form sufficiently massive merging BBH so in [3] they conclude that BBH forma-

tion in dense star clusters is consistent with GW150914 and that most of these mergers occur outside the clusters following dynamical BBH ejection as predicted by the theory.

The detection of GW150914 shows that BBH mergers indeed occur in nature, so that we can exclude models which don't predict their existence within the age of the Universe. The possible future observation of more of these events and other mergers such as the two neutron stars for which we also obtained the electromagnetic counterpart can put even more constraints on the models that do not predict their existence.

# References


[1] Observation of gravitational waves from a binary black hole merger `https://www.ligo.org/science/PublicationGW150914/index.php`

[2] B. P. Abbott et al. 2016, "*Observation of Gravitational waves from a binary black hole merger*" `https://arxiv.org/pdf/1602.03837.pdf`

[3] B. P. Abbott et al. "*Astrophysical implications of the binary black-hole merger GW150914*" 2016`https://arxiv.org/pdf/1602.03846.pdf`