LSC LIGO Scientific Collaboration

VIRGO

OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE MERGER

Albert Einstein's general theory of relativity, first published a century ago, was described by physicist Max Born as "the greatest feat of human thinking about nature". We report on two major scientific breakthroughs involving key predictions of Einstein's theory: the first direct detection of **gravitational waves** and the first observation of the collision and merger of a pair of **black holes**.

This cataclysmic event, producing the gravitational-wave signal **GW150914**, took place in a distant galaxy more than one billion light years from the Earth. It was observed on September 14, 2015 by the two detectors of the **Laser Interferometer Gravitational-wave Observatory** (LIGO), arguably the most sensitive scientific instruments ever constructed. LIGO estimated that the peak gravitational-wave power radiated during the final moments of the black hole merger was more than ten times greater than the combined light power from all the stars and galaxies in the observable Universe. This remarkable discovery marks the beginning of an exciting new era of astronomy as we open an entirely new, gravitational-wave, window on the Universe.

INTRODUCTION AND BACKGROUND

Gravitational waves are 'ripples' in space-time produced by some of the most violent events in the cosmos, such as the collisions and mergers of massive compact stars. Their existence was predicted by Einstein in 1916, when he showed that accelerating massive objects would shake space-time so much that waves of distorted space would radiate from the source. These ripples travel at the speed of light through the Universe, carrying with them information about their cataclysmic origins, as well as invaluable clues to the nature of gravity itself.

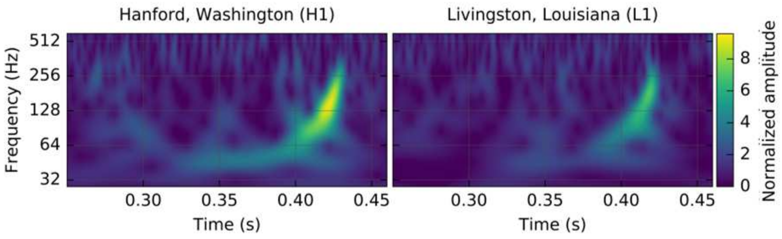

Figure 1*. (Adapted from Figure 1 of our publication). The gravitational wave event GW150914 observed by the LIGO Hanford (H1, left panel) and LIGO Livingston (L1, right panel) detectors. The two plots show how the gravitational wave strain (see below) produced by the event in each LIGO detector varied as a function of time (in seconds) and frequency (in hertz, or number of wave cycles per second). Both plots show the frequency of GW150914 sweeping sharply upwards, from 35 Hz to about 150 Hz over two tenths of a second. GW150914 arrived first at L1 and then at H1 about seven thousandths of a second later – consistent with the time taken for light, or gravitational waves, to travel between the two detectors.*

Over the past few decades astronomers have amassed strong supporting evidence that gravitational waves exist, chiefly by studying their effect on the motions of tightly orbiting pairs of stars in our Galaxy. The results of these indirect studies agree extremely well with Einstein's theory – with their orbits shrinking, exactly as predicted, due to the emission of gravitational wave energy. Nevertheless the *direct* detection of gravitational waves as they reach the Earth has been hugely anticipated by the scientific community as this breakthrough would provide new and more stringent ways to test general relativity under the most extreme conditions and open up an entirely novel way to explore the Universe.

In the same year that Einstein predicted gravitational waves, the physicist Karl Schwarzschild showed that Einstein's work permitted the existence of **black holes**: bizarre objects which are so dense and so compact that not even light can escape their gravitational field. Although by definition we cannot directly 'see' light from a black hole, astronomers have gathered a great deal of circumstantial evidence for their existence by studying the effects of black hole candidates on their immediate surroundings. For example, it is thought that most galaxies in the Universe, including the Milky Way, contain a **supermassive black hole** at their center – with masses millions or even billions of times that of the Sun. There is also evidence of many black hole candidates with much lower masses (ranging from a few, to a few dozen, times the Sun's mass), believed to be the remnants of dead stars that have undergone a cataclysmic explosion known as a **core-collapse supernova**.

Alongside this substantial progress in the indirect *observation* of black holes, there have been dramatic improvements in our *theoretical* understanding of these bizarre objects – including, over the past decade, some remarkable advances in modeling a pair of black holes (referred to as a binary) through several close orbits before they finally merge. These computer models have allowed us to construct precise **gravitational waveforms** – i.e. the pattern of gravitational waves emitted by the black holes as they approach ever closer and finally merge into a single, larger black hole – in accordance with the predictions of general relativity. The direct observation of a binary black hole merger would therefore provide a powerful cosmic laboratory for testing Einstein's theory.

Visit our website at
http://www.ligo.org/

#GravitationalWaves
#BinaryBlackHole
#EinsteinWasRight

THE LIGO DETECTORS

LIGO is the world's largest gravitational wave observatory and one of the world's most sophisticated physics experiments. Comprised of two giant **laser interferometers** located thousands of kilometers apart, one in Livingston, Louisiana and the other in Hanford, Washington, LIGO uses the physical properties of light and of space itself to detect gravitational waves – a concept first proposed in the early 1960's and the 1970's. A set of initial interferometers was completed by the early 2000s, including TAMA300 in Japan, GEO600 in Germany, LIGO in the United States and Virgo in Italy. Combinations of these detectors made joint observations between 2002 and 2011, but did not detect any gravitational wave sources. After undergoing major upgrades, in 2015 the LIGO detectors began operation as **Advanced LIGO**: the first of a significantly more sensitive global network of advanced detectors.

An interferometer like LIGO consists of two "arms" (each one 4km long) at right angles to each other, along which a laser beam is shone and reflected by mirrors (suspended as **test masses**) at each end. When a gravitational wave passes by, the stretching and squashing of space causes the arms of the interferometer alternately to lengthen and shrink, one getting longer while the other gets shorter and then vice-versa. As the interferometers' arms change lengths, the laser beams take a different time to travel through the arms – which means that the two beams are no longer "in step" (or in **phase**) and what we call an **interference pattern** is produced. This is why we refer to the LIGO detectors as "interferometers".

The difference between the two arm lengths is proportional to the strength of the passing gravitational wave, referred to as the **gravitational-wave strain**, and this number is mind-bogglingly small. For a gravitational wave typical of what we can detect, we expect the strain to be about **1/10,000th the width of a proton**! However LIGO's interferometers are so sensitive that they can measure even such tiny amounts.

Figure 2 shows a simplified diagram of an Advanced LIGO detector.

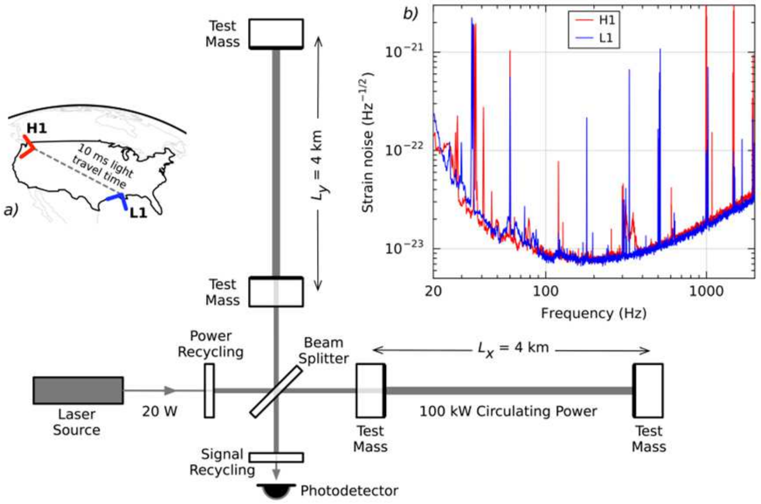

***Figure 2**. Simplified diagram of an Advanced LIGO detector (not to scale), including several of the key enhancements to the basic design: an **optical cavity** that reflects the laser light back and forth many times in each arm, multiplying the effect of the gravitational wave on the phase of the laser light; a **power recycling** mirror that increases the power of the laser in the interferometer as a whole; a **signal recycling** mirror that further optimizes the signal extracted at the **photodetector**. 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.*

*Inset (a), on the left, shows the locations and orientations of the two LIGO observatories, and indicates the light travel time between them. Inset (b) shows how the **instrument strain noise** varied with frequency in each detector near to the time of the event. The lower the instrument noise, the higher the detectors' sensitivity. The tall spikes indicate narrow frequency ranges where the instrument noise is particularly large.*

To successfully detect a gravitational wave event like GW150914 the LIGO detectors need to combine astounding sensitivity with an ability to isolate *real* signals from sources of **instrument noise**: tiny disturbances, due to e.g. environmental effects or the behavior of the instruments themselves, that could mimic – or indeed simply overwhelm – the signature strain pattern we are looking for. This is a key reason why there are *two* Advanced LIGO detectors, as it allows us to distinguish gravitational waves from local instrumental or environmental effects: only a real gravitational wave signal would appear in *both* detectors – albeit separated by a few thousandths of a second, to account for the time taken for light (or a gravitational wave) to travel between the two detector sites.

Inset (b) in Figure 2 shows how the instrument noise in the LIGO detectors depends on frequency. We can see that the instrument noise is lowest in the 'sweet spot' around a few hundred hertz, but increases sharply at both low and high frequencies. There are also a number of narrow spikes where the instrument noise is particularly large, due to e.g. vibration of the fibers that suspend the mirrors and test masses in each interferometer.

Reaching the much greater sensitivity of Advanced LIGO required the upgrading of almost every aspect of the Initial LIGO design. These upgrades included:

- Significantly increasing the laser power, to reduce the main source of high frequency noise
- Redesigning the recycling cavities to better contain the spatial distribution of the laser light
- Using larger, heavier fused silica test masses, to reduce the random motions of the mirrors
- Suspending the test masses using fused silica fibers, to reduce their thermal noise
- Suspending the test masses with a four-stage pendulum, improving their seismic isolation
- Using an active "measure and cancel" strategy for reducing the impact of ground motions

You can read more about the remarkable technology that underpins Advanced LIGO at:

http://tinyurl.com/ALIGO-upgrades-pdf

Operating a network of two or more detectors also lets us 'triangulate' the direction on the sky from which a gravitational wave arrives, by studying the difference in arrival time at each detector. The more detectors in one's network, the better the sky position of a gravitational wave source can be localised. In 2016 the Advanced Virgo detector, in Italy, will join the global network – and other advanced interferometers are planned for the future. For more details see e.g. http://www.ligo.org/science/Publication-ObservingScenario/index.php.

OUR LIGO OBSERVATIONS AND WHAT THEY MEAN

On September 14, 2015 at 09:50:45 Greenwich Mean Time the LIGO Hanford and Livingston Observatories both detected a signal from GW150914. The signal was identified first by what we call *low-latency* search methods that are designed to analyse the detector data very promptly, looking for evidence of a gravitational-wavelike pattern but without modeling the precise details of the waveform. These prompt searches reported the candidate event within only **three minutes** of the signals arriving at the detectors. The gravitational-wave strain data acquired by the LIGO interferometers was then compared with an extensive bank of theoretically predicted waveforms – a process known as **matched filtering** – with the goal of finding the waveform that best matched the data.

Figure 3 presents key results of these detailed analyses – all of which firmly point to GW150914 being produced by the coalescence of two black holes. The middle part of the figure shows our reconstruction of the gravitational-wave strain, as seen by the Hanford detector. Note, in particular, the impressive agreement between this pattern (shown in grey) and (shown in red) a waveform for two coalescing black holes consistent with our data, computed using general relativity.

Images of the black hole horizons at various stages of this computation are shown at the top of the figure: the **inspiral**, as the two black holes approach each other; the **merger** as the black holes join together and the subsequent **ringdown**, as the single black hole that has newly formed briefly oscillates before settling down.

Comparing the strain data with theoretical predictions allows us to test whether general relativity is able to fully describe the event. It passes this test with flying colors: all of our observations are consistent with the predictions of general relativity.

We can also use the data to estimate the specific physical characteristics of the system that produced GW150914, including the masses of its two black holes before the merger, the mass of the single post-merger black hole, and the distance of the event.

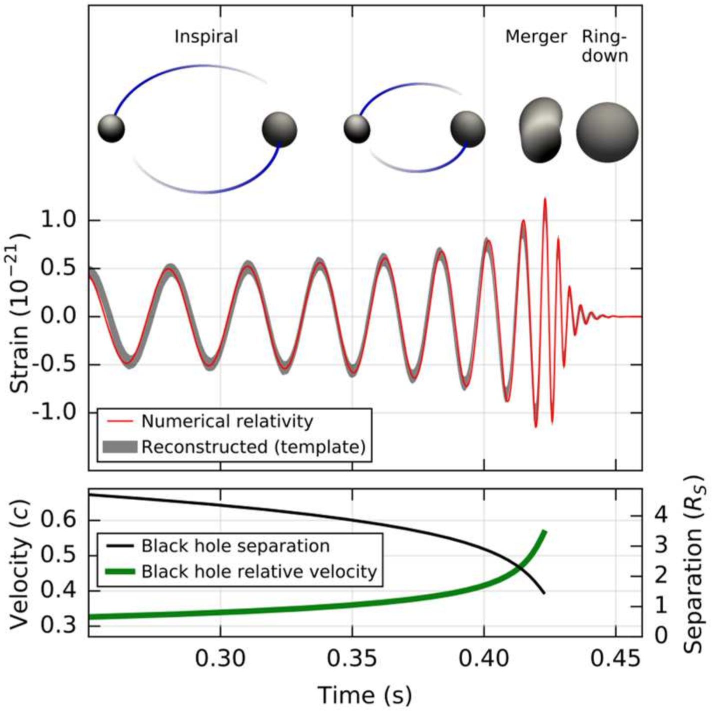

***Figure 3**. Some key results of our analysis of GW150914, comparing the reconstructed gravitational-wave strain (as seen by H1 at Hanford) with the predictions of the best-matching waveform computed from general relativity, over the three stages of the event: inspiral, merger and ringdown. Also shown are the separation and velocity of the black holes, and how they change as the merger event unfolds.*

Our results indicate that GW150914 was produced by the merger of two black holes with masses of about **36 times** and **29 times** the mass of the Sun respectively, and that the post-merger black hole had a mass of about **62 times** the Sun's mass. Moreover, we infer that the final black hole is *spinning* – such rotating black holes were first predicted theoretically in 1963 by mathematician Roy Kerr. Finally, our results indicate that the GW150914 occurred at a distance of more than **one billion light years**. So the LIGO detectors have observed a truly remarkable event that happened a long time ago in a galaxy far, far away!

If we compare the masses of the pre- and post-merger black holes, we see that the coalescence converted about **three times the mass of the Sun** (or nearly **six million trillion trillion kilograms**) into gravitational-wave energy, most of it emitted in a fraction of a second. By contrast the Sun converts a mere *two billionths of one trillionth* of its mass into electromagnetic radiation every second. In fact, the gravitational-wave power radiated by GW150914 was more than ten times greater than the combined *luminosity* (i.e. the light power) of **every star and galaxy in the observable Universe**.

HOW DO WE KNOW GW150914 WAS A *BLACK HOLE* MERGER?

Our estimated pre-merger masses of the two components in GW150914 make a very strong argument that they are *both* black holes – particularly when we also consider the enormous **velocity** and tiny **separation** of the two components, as shown in the lower part of figure 3. In this figure indicative velocities of the two components are seen to be significant fractions of the speed of light. Similarly their approximate separation is shown to be just a few times the characteristic size of a black hole, known as its **Schwarzschild radius**.

These graphs imply that the two components were only a few hundred kilometers apart just before they merged, ie. when the gravitational-wave frequency was about 150 Hz. Black holes are the only known objects compact enough to get this close together *without* merging. Based on our estimated total mass for the two components, a pair of **neutron stars** would not be massive enough, and a black hole-neutron star pair would have already merged at a *lower* frequency than 150 Hz.

ARE WE SURE THAT GW150914 WAS A REAL ASTROPHYSICAL EVENT?

The short answer is "yes", but of course this is a crucial question and the LIGO Scientific Collaboration and Virgo Collaboration have together made a huge effort to address it, carrying out a variety of independent and thorough checks – all of which contribute to strengthening the detection case for GW150914.

Firstly, as we noted already, the time delay between the observations made at each LIGO detector was consistent with the light travel time between the two sites. Also, as seen in figure 1, the Hanford and Livingston signals showed a similar pattern, as would be expected given the near alignment of the two interferometers, and were strong enough to 'stand out' against the background noise around the time of the event – like a burst of laughter heard above the background chatter of a crowded room.

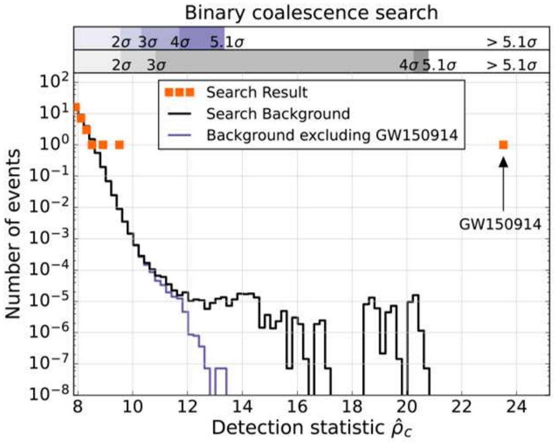

***Figure 4**. (Adapted from figure 4 of our publication). Results from our binary coalescence search quantifying how rare GW150914 was compared with false 'events' resulting from noise fluctuations. This search concluded that a noise event mimicking GW150914 would be extremely rare – less than one occurrence in about 200,000 years of data like this – a value that corresponds to a detection significance of more than 5 'sigma'.*

Understanding this background noise is an essential part of our analysis and involves monitoring a vast array of **environmental data** recorded at both sites: ground motions, temperature variations and power grid fluctuations to name just a few. In parallel, many data channels monitor in real time the **status of the interferometers** – checking, for example, that the various laser beams are properly centred. If any of these environmental or instrumental channels indicated a problem, then the detector data would be discarded. However, despite exhaustive studies, no such data quality problems were found at the time of the event.

But perhaps GW150914 was a rare noise fluctuation, which happened to occur simply by chance with similar characteristics at both sites? To reject this possibility we need to work out just how rare such a fluctuation would be: the less often it could occur by chance, the more confidently we can rule out this scenario in favour of the alternative – that GW150914 was indeed a real gravitational wave event.

To carry out this statistical analysis we used 16 days' worth of stable, high quality detector strain data from the month following the event. GW150914 was indeed by far the strongest signal observed in either detector during that period. We then introduced a series of artificial time shifts between the H1 and L1 data, effectively creating a much longer data set in which we could search for apparent signals that were as strong (or stronger) than GW150914. By using *only* time shifts greater than 10 milliseconds (the light travel time between the detectors) we ensured that these artificial data sets contained *no* real signals, but only coincidences in noise. We can then see, in the very long artificial data set, how often a coincidence mimicking GW150914 would appear. This analysis gives us the **false alarm rate**: how often we could expect to measure such a seemingly loud event that was really just a noise fluctuation (i.e. a 'false alarm').

Figure 4 (adapted from figure 4 of our publication) shows the result of this statistical analysis, for one of the searches carried out on our detector data. The solid black and purple curves represent the 'background': the number of coincidental noise 'events' that we estimate would be produced (under slightly different assumptions) for different strengths of signal. The orange boxes represent what we actually saw, without the artificial time shifts. The key message of this figure is how far away the observed event GW150914 is from the background noise. This means that a noise event mimicking GW150914 would be *exceedingly rare* – indeed we expect an event as strong as GW150914 to appear by chance only once in about 200,000 years of such data! This false alarm rate can be translated into a number of 'sigma' (denoted by σ), which is commonly used in statistical analysis to measure the significance of a detection claim. This search identifies GW150914 as a real event, with a significance of more than 5 sigma.

CONCLUSIONS AND OUTLOOK

The first direct detection of gravitational waves and the first observation of a binary black hole merger are remarkable achievements, but they represent only the first page of an exciting new chapter in astronomy.

The next decade will see further improvements to the Advanced LIGO detectors and extension of the global detector network to include Advanced Virgo in Italy, KAGRA in Japan, and a possible third LIGO detector in India.

This enhanced global network will significantly improve our ability to locate the positions of gravitational-wave sources on the sky and estimate more accurately their physical properties. The nascent field of gravitational-wave astronomy has a very bright future!

FURTHER INFORMATION

LIGO Scientific Collaboration homepage (includes link to our main publication, published in Physical Review Letters): http://www.ligo.org

Advanced Virgo homepage: http://public.virgo-gw.eu/language/en/

Some of the companion papers to our main publication:

- *Observing gravitational-wave transient GW150914 with minimal assumptions:* https://dcc.ligo.org/P1500229/
- *GW150914: First results from the search for binary black hole coalescence with Advanced LIGO:* https://dcc.ligo.org/P1500269/
- *Astrophysical implications of the binary black hole merger GW150914:* https://dcc.ligo.org/P1500262/
- *Localization and broadband follow-up of the gravitational-wave candidate G184098:* https://dcc.ligo.org/P1500227/
- *GW150914: a black-hole binary coalescence as predicted by general relativity:* https://dcc.ligo.org/P1500213/
- *The rate of binary black hole mergers inferred from Advanced LIGO observations surrounding GW150914:* https://dcc.ligo.org/P1500217/
- *Properties of the binary black hole merger GW150914:* https://dcc.ligo.org/P1500218/

LIGO Open Science Center (with access to GW150914 data): https://losc.ligo.org/about/