Physics: Science as a Human Endeavour Investigation

Do We Need Big Science?

An investigation of the interaction between science and society for the Laser Interferometer Gravitational-Wave Observatory (LIGO)

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Stage 2 Physics: Science as a Human Endeavour Investigation

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Introduction:

The Laser Interferometer Gravitational-Wave Observatory (LIGO) (Figure 1), is a contemporary “Big Science” project that detects gravitational waves to make discoveries. The 2017 Nobel Prize in Physics was awarded to LIGO’s founders, Rainer Weiss, Kip Thorne and Barry Barish, illustrating LIGO’s already profound impact on science (LIGO-Caltech, 2018). LIGO demonstrates the interaction between science and society through collaboration between LIGO’s scientists and other agencies; the development of scientific theories by providing essential evidence for Einstein and Schwarzschild’s revolutionary theories; and LIGO’s potential applications to advance technological fields, offer valid explanations and extend our understanding of the universe.

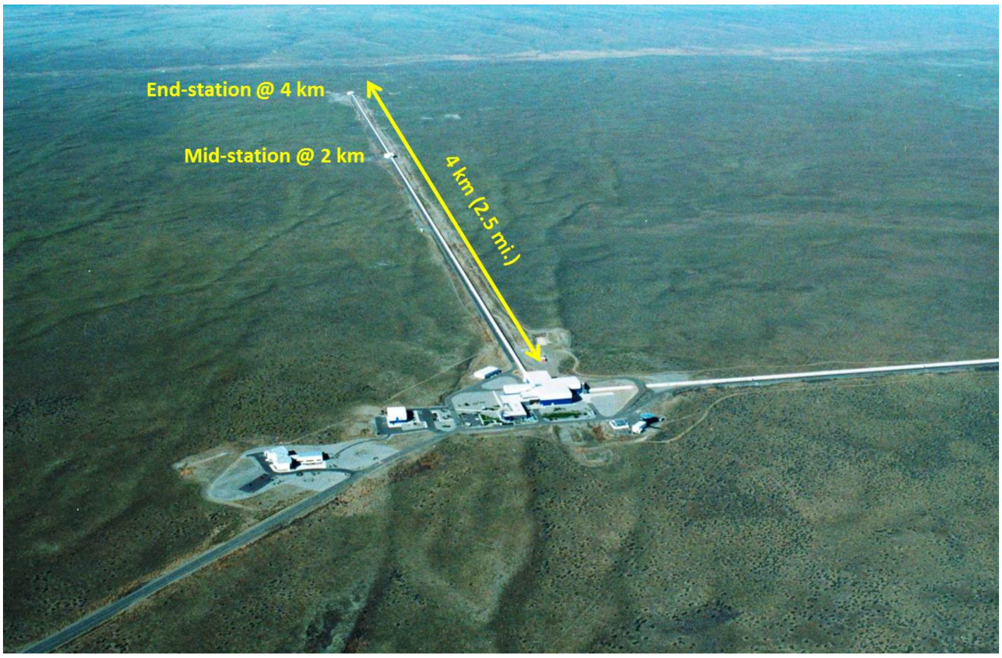

Figure 1: Aerial photograph of a LIGO observatory. (LIGO-Caltech, 2018)

Physics Behind LIGO:

LIGO detects gravitational waves. Einstein’s General Theory of Relativity (Figure 2) predicted the existence of gravitational waves in 1916; the distortion of spacetime occurring in “ripples” emanating at the speed of light and weakening with distance from a source, similar to the phenomenon observed after dropping a stone in water (Figure 3) (LIGO-Caltech, 2018). While all accelerating masses produce gravitational waves, the strongest are generated by astrophysical events involving massive accelerating objects, such as colliding black holes or neutron stars (Daw, 2016). As such events have occurred at great distances, the effects of these gravitational waves on Earth are insignificant. Thus, LIGO’s instruments must have high sensitivity to detect them. (LIGO-Caltech, 2018)

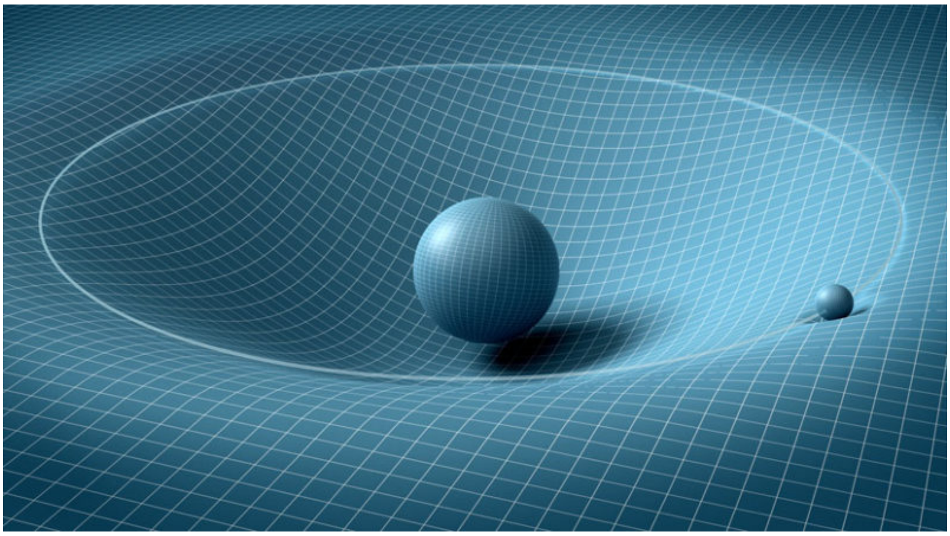

Figure 2: Depiction of Einstein's General Theory of Relativity, essentially that the force of gravity arises from the curvature of space-time. (GoPhysics, 2017)

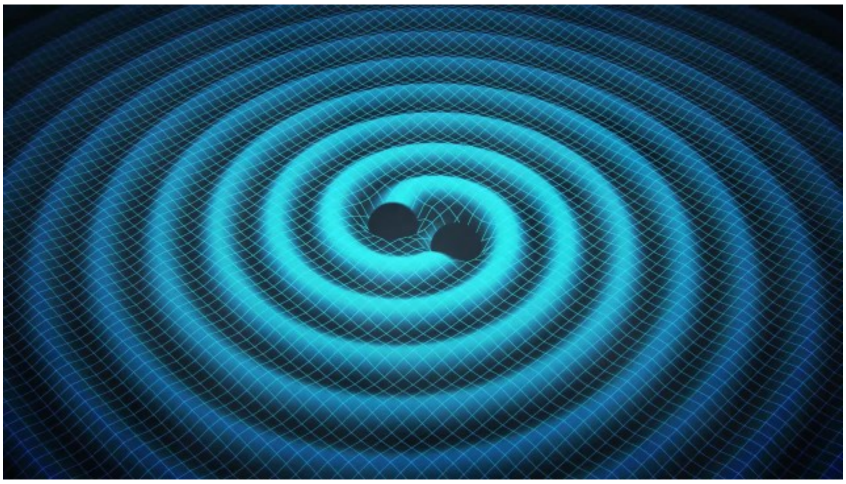

Figure 3: Depiction of gravitational waves emanating from the orbiting of two massive accelerating objects. (Templeton. G, 2016)

LIGO detects gravitational waves through the use of the apparatus in Figure 4. A population inversion is established by absorbing light of wavelength 808nm with power ~400W, producing a 50W 1064nm beam of pure, stable laser light in a laser diode. The laser is split into two identical beams which travel through separate 4km perpendicular arms in a vacuum (pressure 1 trillionth of an atmosphere), to avoid refraction with air molecules and interference by sound waves, as gravitational waves similarly cause vibrations. The light beams are reflected at the end of the arms by fused silica glass mirrors and merge into a single beam upon return (LIGO-Caltech, 2018). In the absence of gravitational waves, the beams travel the same distance (4km) at the same speed (speed of light in a vacuum is an absolute constant (3.00×10^{8} ms^{-1})), upon merging superimpose, undergo total destructive interference and the photodetector detects no light (Figure 5). However, gravitational waves are transverse waves, causing space to stretch in one direction and compress in the perpendicular direction (Daw, 2016). Thus, if a gravitational wave passes, space-time will be distorted so that the length of one arm, and hence distance travelled by one beam, increases, whilst the other perpendicular to this arm decreases. Consequently, the light waves return at varying times and total destructive interference no longer occurs. Instead, the waves are no longer perfectly out of phase and an interference pattern of light is observed by the photodetector, thus detecting a gravitational wave (LIGO-Caltech, 2018) (Overbye, D. 2016). The resulting change in distance detected is of the order of magnitude of one million millionth the width of a human hair. (Hendry, M. 2016)

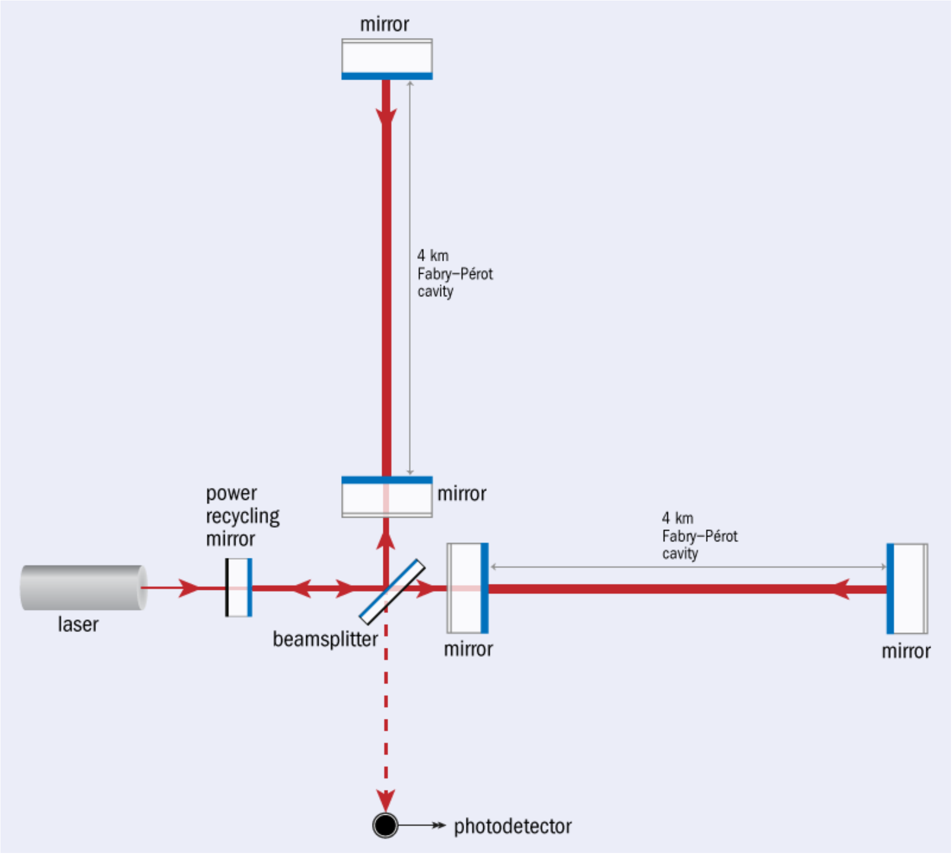

Figure 4: Diagram of LIGO's interferometer conveying the splitting, reflection and merging of laser light. (PhysicsWorld, 2016).

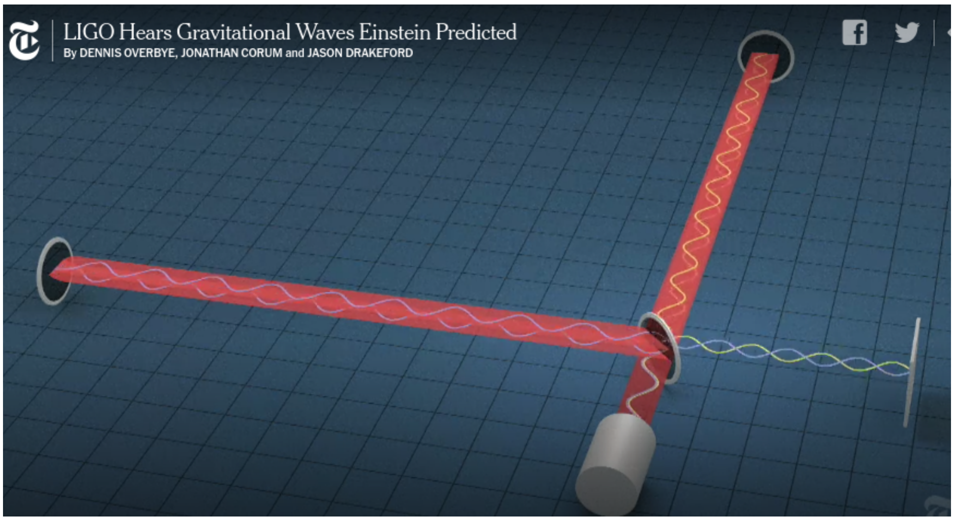

Figure 5: Superposition of light waves in LIGO's interferometer undergoing total destructive interference at the photodetector. (Overbye. D, 2016)

Communication and Collaboration:

Collaboration between scientists and other agencies is often required in scientific research and enterprise. As stated by Dr Riccardo DeSalvo in the Astrophysics Learning from Gravitational Waves lecture transcripts, of the Erice International School of Subnuclear Physics, "*The hunt for gravitational waves is one of the best examples of international scientific collaborations*." (DeSalvo, 2018). Specifically, LIGO's construction and the identification and analysis of gravitational waves with LIGO, strongly illustrate the necessity of such collaborations. Regarding construction, LIGO's mirror systems were primarily developed by an association of UK institutions lead by University of Glasgow, who provided invaluable experience in the field of laser interferometers from their earlier work on the UK/German GEO600 detector (Hendry, M. 2016). Scientists and engineers from the California Institute of Technology, the Massachusetts Institute of Technology and over 80 scientific institutions that are members of the LSC internationally collaborated to construct LIGO (LIGO-Caltech, 2018), allowing for optimal design and efficient construction through the sharing of knowledge and ideas. As big science projects such as LIGO are costly to maintain and construct, international collaboration to provide financial support is often required for their success. LIGO received funding for construction from Australia, Germany, UK and the U.S National Science Foundation (LIGO-Caltech, 2018). According to the interviewed Professor Peter Veitch, Adelaide University's Head of Physics and LSC member, construction of the ~$1.2 billion project (DeSalvo, 2018) would not have occurred without such agencies' support. (Veitch, 2018)

The aforementioned necessary high sensitivity of LIGO's instruments provides another source of integral collaboration between scientists and agencies for gravitational waves to be accurately detected. The extreme sensitivity of LIGO's instruments cause it to be able to detect vibrations from nearby sources such as earthquakes, tides and traffic, which can imitate gravitational wave signals. Thus, LIGO itself consists of two identical interferometers in Hanford and Livingston (Figure 6). While LIGO's interferometers will not detect the same local vibrations, due to being 3002 km apart, they will detect gravitational wave vibrations practically simultaneously (LIGO-Caltech, 2018). Consequently, scientists at LIGO collaborate by comparing data between interferometers to determine whether a gravitational wave was detected. Without such collaboration between observatories, gravitational waves could not be distinguished from local vibrations, significantly impeding LIGO's accuracy. (LIGO-Caltech, 2018) LIGO also collaborates similarly with Virgo, a European gravitational wave interferometer in Pisa. The international collaboration between LIGO and Virgo, comprising of more than 1,500 scientists, allows the analysis and comparison of LIGO and Virgo data, to further confirm and increase confidence in gravitational wave detections (Geant, 2017) (LIGO-Caltech, 2018). Moreover, a third interferometer allows detected events to be triangulated, thus accurately determining their location (DeSalvo, 2018). Hence, it is clearly apparent that LIGO's construction and detection of gravitational waves is heavily reliant on collaboration between scientists and agencies.

Figure 6: Aerial photograph and location of LIGO's Hanford (left) and Livingston (right) interferometers. (LIGO-Caltech, 2018)

Development:

Development of complex scientific theories often requires a wide range of evidence from many sources. LIGO's first detections of gravitational waves provided essential evidence to support Einstein's General Theory of Relativity and Schwarzschild's black hole predictions, thus allowing for the development of such complex scientific theories. Einstein proposed the General Theory of Relativity in 1915; that the force of gravity arises from the curvature of space-time; which included the idea of gravitational waves existing (Overbye, D. Feb 2016). As scientists had previously endorsed Newtonian physics for 200 years prior to Einstein's proposition, evidence was undoubtedly required if Einstein's theory, seemingly against intuition, was to replace that which scientists had accepted. Even Einstein himself was uncertain of gravitational waves, reportedly informing Schwarzschild in 1916 that gravitational waves did not exist (Overbye, D. Feb 2016). However, on September 14, 2015, LIGO recorded the first ever detection of gravitational waves. This momentous achievement was awarded the Physics World 2016 Breakthrough of the Year, providing the first direct evidence for the existence of gravitational waves, verifying Einstein's prediction (LIGO-Caltech, 2018). The detected gravitational waves were from two black holes circling each other before merging into a single black hole, 1 billion light-years away. From this detection scientists were able to determine their distances, masses and spins, all of which supported predictions from Einstein's theory (Figure 7). Schwarzschild himself theorised in 1916 the existence of black holes with size and mass. LIGO's first detection was also the first direct observation of black holes, supporting and providing the first evidence for Schwarzschild's black hole theories (Blair, D. 2016). Consequently, LIGO's first detections were essential in providing evidence for the development of Einstein and Schwarzschild's gravitational wave and black hole theories. Without such evidence, scientists and the wider community are unlikely to accept such complex scientific theories.

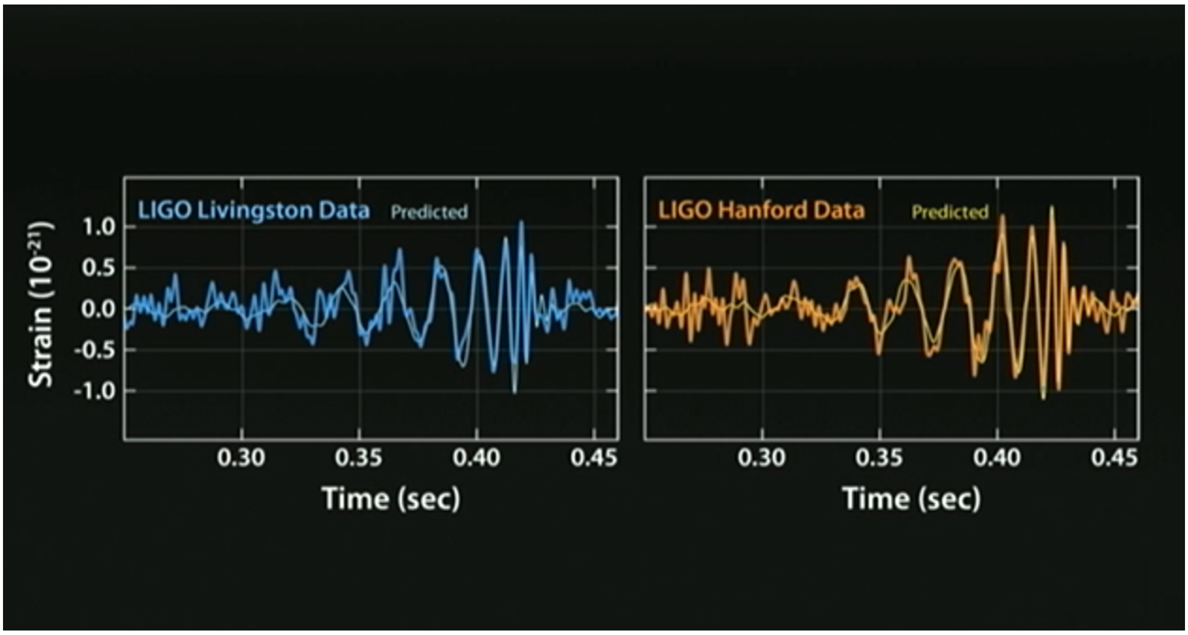

Figure 7: The first detected gravitational waves by LIGO's interferometers compared to the predicted waves (lighter colour) based on Einstein's theory. (Macdonald, F. 2016)

Potential Impact/Application:

LIGO's detection of gravitational waves enables scientists to make discoveries, offer valid explanations and further our understanding of the universe. Previously, the universe could only be observed through the electromagnetic spectrum. However, LIGO allows novel observations from the gravitational wave spectrum (Hendry, M. 2016). As some phenomenon, such as black hole collisions, emit waves in the gravitational but not electromagnetic spectrum, LIGO allows the groundbreaking observation of new astrophysical phenomena. (LIGO-Caltech, 2018). Furthermore, in contrast to electromagnetic radiation, gravitational waves barely interact with matter, allowing for gravitational waves and their sources to be analysed more accurately, without the distortion experienced by electromagnetic waves. (LIGO-Caltech, 2018) Moreover, according to the personally interviewed Dr DeSalvo, LSC member, as a result of LIGO's 2017 detection from the collision of two neutron stars, the cosmic abundance of atoms heavier than iron could finally be explained to have arisen from such collisions (DeSalvo, 2018). Additionally, according to Prof. Veitch this detection by LIGO, "*allowed optical astronomers to examine the resulting electromagnetic radiation in the gamma, X-ray, UV, optical and infrared bands from a known source for the first time [and] created a new field of research: multi-messenger gravitational astrophysics.*" (Veitch, 2018) Thus, as the first successful detector of gravitational waves, LIGO provides unimaginable opportunities to extend our knowledge and understanding of the universe, space and time, whilst offering explanations for the cosmic abundance of heavy atoms and initiating the field of observing astrophysical phenomena through multiple spectra.

Conclusion:

LIGO clearly illustrates the interaction between science and society. The collaboration between LIGO scientists at the Hanford and Livingston interferometers and other agencies, such as Italy's Virgo interferometer, is essential for LIGO's detection and analysis of gravitational waves. Moreover, international collaboration for LIGO's construction and financial resources was vital for its success. Furthermore, LIGO's detections are invaluable for providing direct evidence for the development of Einstein's General Theory of Relativity and Schwarzschild's black hole theories. Additionally, LIGO enhances research in the fields of general relativity and astrophysics, to extend our knowledge of the universe and make discoveries through the previously unexplored gravitational wave spectrum and explain the presence of heavy atoms. Thus, contemporary "Big Science" projects, such as LIGO, form an integral part of future scientific research and enterprise.

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