galaxies

MDPI

Editorial

Present and Future of Gravitational Wave Astronomy

Gabriele Vajente

LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA; vajente@caltech.edu

Gravitational waves (GW) are propagating perturbations of the space-time metric, generated by time-varying mass distributions. Their existence was predicted more than 100 years ago, in 1916, as a consequence of the General Relativity theory of gravitation [1]. The most intense sources of gravitational waves are astrophysical objects such as neutron stars and black holes. Despite the large amount of energy emitted in the form of gravitational waves by the coalescence of compact binary systems, the radiation has to travel tens or thousands of Mpc before reaching earth, where it can be detected. This, and the weakness of the coupling to matter, are the reasons why the direct observation of gravitational waves has been such a challenging scientific endeavor, and why the signal from the first binary black hole coalescence, detected in 2015, produced a relative change in the local earth space-time metric of only about 10^{-21} [2], see Figure 1. Many sources of noises had to be understood and overcome [3], so that the two Advanced LIGO observatories [4,5] were sensitive enough to detect this event with high signal-to-noise ratio, opening the era of gravitational-wave astronomy and astrophysics. This event was the first demonstration of the existence of binary black holes, and the first confirmation that General Relativity is still valid in the intense-field regime involved in the collision of two compact objects such as black holes.

The first detection, dubbed GW150914, was only the first step of the newly-born gravitational-wave astronomy. The second major milestone was the detection of the first binary neutron star merger, GW170817 [6], only two years after the first event, see Figure 2. By then, the LIGO and Virgo [7,8] detectors had joined forces, and had already detected several more binary black hole events. However, the importance of the detection of two neutron stars colliding was on par with the first discovery. Not only we could detect gravitational waves from the two objects, proving without a doubt that they had masses compatible with neutron stars, but we also observed a short gamma-ray burst in coincidence with the event, proving the connection between the two phenomena. The sky localization provided by the gravitational wave observation by multiple detectors, LIGO and Virgo, allowed optical telescopes to identify the aftermath of the collision, and subsequently follow up in the entire electromagnetic spectrum. The promise of multi-messenger astronomy was indeed fulfilled.

The network of instruments actively observing the gravitational-wave universe is going to grow with the KAGRA detector [9,10]. As a first step, KAGRA operated in conjunction with the GEO 600 observatory [11] after the LIGO and Virgo O3 run ended [12]. In the three main observing runs carried out so far, the LIGO and Virgo collaborations have reported a total of 90 events with high probability of being of astrophysical origin [13], see Figure 3, an average of one event every five days in the last run.

Signals from coalescing binary systems [14] are just the beginning of the discoveries that gravitational-wave detectors will bring. Short-duration signals are expected to be produced by other sources, the most important being core-collapse supernovae [15]: both modeled and unmodeled searches are ongoing for such signals. Additionally, continuous-wave signals are expected to be produced by rotating pulsars [16]. Although they have not been detected yet, the upper limits obtained so far are already more stringent that the spin-down limits for many systems. With improved sensitivities, ground-based gravitational-wave observatories might be finally able to detect stochastic backgrounds [17] either from the confusion noise of coalescing binary systems, of from a cosmological origin.

Citation: Vajente, G. Present and Future of Gravitational Wave Astronomy. *Galaxies* **2022**, *10*, 91. https://doi.org/10.3390/galaxies10040091

Received: 27 May 2022
Accepted: 30 May 2022
Published: 19 August 2022

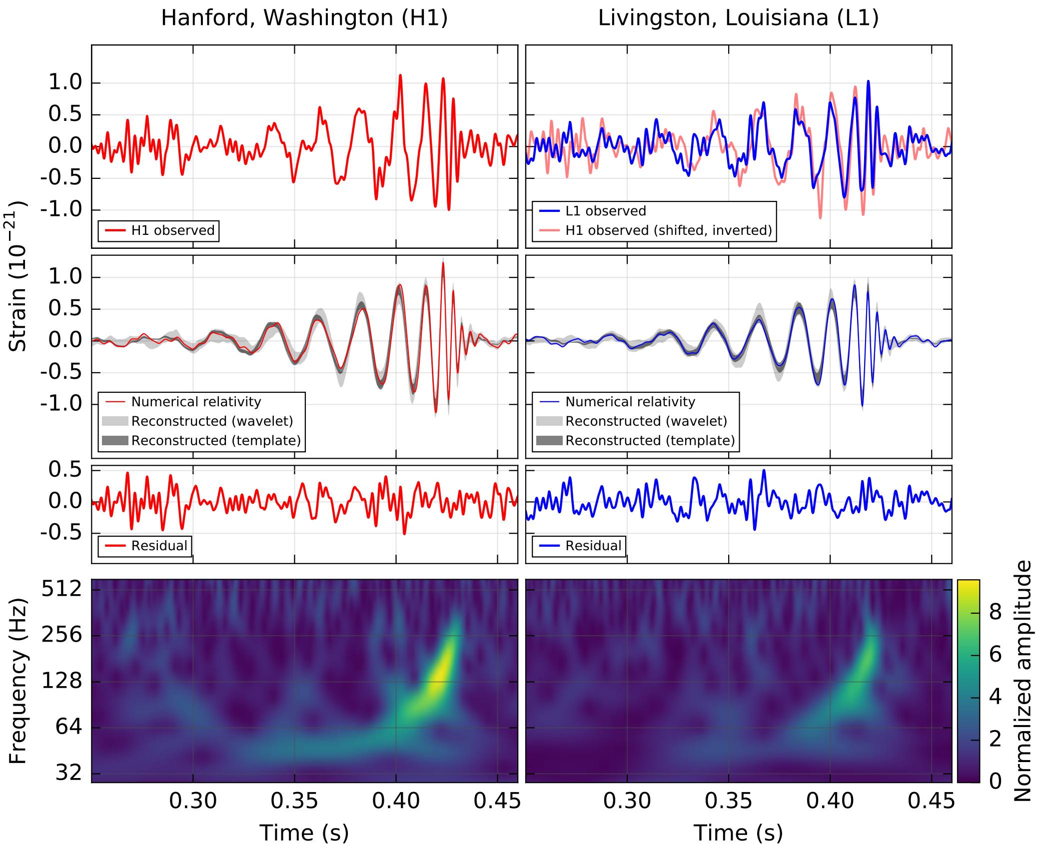

Figure 1. Strain data for the gravitational-wave event GW150914, produced by the collision of two black holes, and observed by the LIGO Hanford and LIGO Livingston detectors. The top row shows the band-passed strain output of the two detectors. In the right panel the LIGO Hanford signal is superimposed to the LIGO Livingston signal, with a time shift, to show the agreement between the two waveforms. The second row shows the comparison between the numerical relativity model of the event and the reconstructed signals. The residual difference between model and measurement in the third row shows the good agreement between theory and experiment. Finally, the bottom row shows time-frequency representations of the signals, where the characteristic chirp waveform is evident. Graphics reproduced from [2] under Creative Commons License.

The increasingly large number of gravitational wave detections made it possible to study the astrophysics of the sources [18] and the behavior of gravity in the intense field regime [19]. To be able to infer precise information on those fundamental topics, it is crucial to continuously increase the detector sensitivity, to improve the signal-to-noise ratio of the events, but it is also of the utmost importance to calibrate the detector output with high precision [20] and to remove any additional spurious disturbance that might mimic astrophysical signals [21].

The instruments that allowed all those scientific discoveries are laser Michelson interferometers [22]. The phase of two coherent laser beams propagating along orthogonal directions is changed by the passage of gravitational waves, modifying the interference condition at the beam recombination. The phase change is proportional to the differential fluctuation in the length of the two arms, due to the strain induced by gravitational-wave signals. Therefore, the detector sensitivity is directly proportional to the baseline length of the Michelson interferometer: this is the main reason to build km-scale detectors. Even with such large scale Michelson interferometers, the fundamental limitation due to laser quantum noise would not have allowed the sensitivity needed to detect gravitational waves. Over the years, the initial design of the detectors evolved to include more and more complex techniques aimed at increasing the sensitivity. The Michelson interferometer arms were replaced by resonant Fabry–Perot cavities to increase the phase accumulation by the laser beam in response to gravitational-wave signals. Power-recycling cavities were added to increase the circulating laser power. Signal-recycling cavities were added to shape the detector bandwidth. Quantum-measurement techniques such as squeezed vacuum injections were implemented [23] to beat the laser shot-noise limit. Sophisticated seismic isolation and suspension systems were developed to reduce noise from ground motion [24]. Cryogenic operation of the interferometer test masses was implemented [10] to reduce thermal noise. The result of all those efforts are the currently operating Advanced Virgo [8], Advanced LIGO [5] and KAGRA observatories [10].

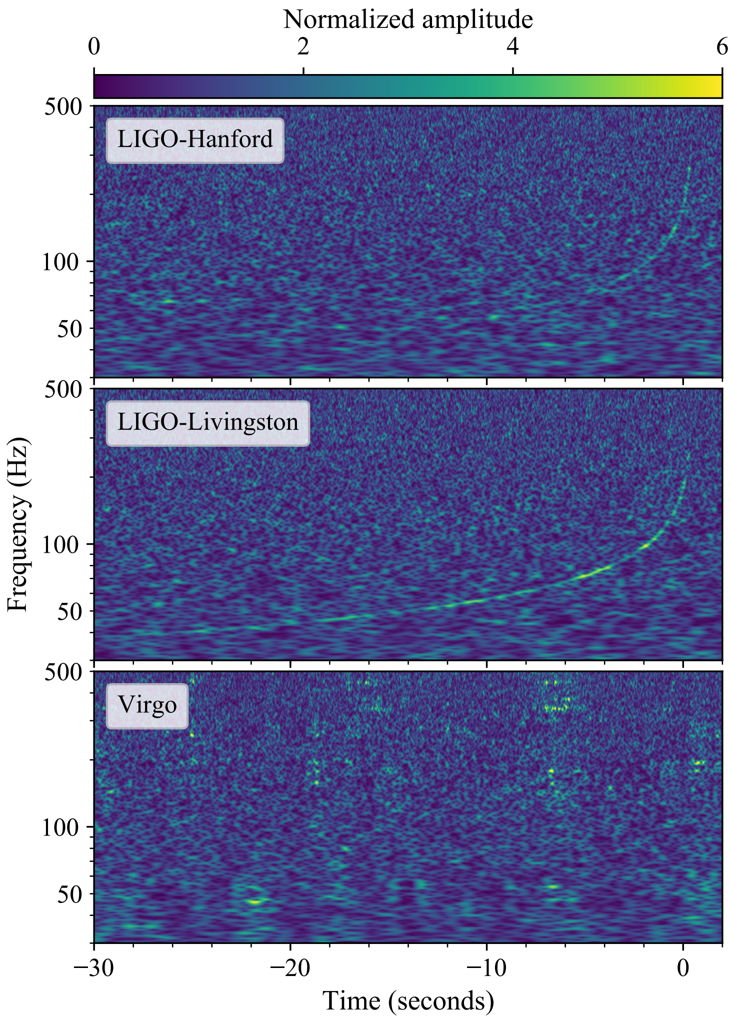

Figure 2. Time-frequency maps of the LIGO and Virgo detector outputs during the gravitational-wave event GW170817, created by the collision of two neutron stars. The signal stayed in the detector bandwidth for several tens of seconds, increasing in frequency following a characteristic chirp-like pattern. Graphics reproduced from [6] under Creative Commons License.

At the time this special issue is being published, the major ground-based detectors are undergoing an upgrade period. They are expected to be back in observation in 2023, with improved sensitivity to all kind of gravitational-wave sources. Further improvements are planned in the coming years for those detectors [25], and design studies are well underway for the next generation observatories. The next decades will see the European project Einstein Telescope [26] and the US project Cosmic Explorer [27] move from the drawing board to construction and operation. The currently existing detector will undergo upgrades, to move to silicon test masses operated at cryogenic temperatures [25], providing not only a significant improvement in sensitivity, but also serving as a crucial research and development platform for Einstein Telescope and Cosmic Explorer. Together with the planned space-borne gravitational-wave detectors LISA [28] and DECIGO [29], they hold the promise of detecting signals from the coalescence of compact binary systems from the entire observable universe, many of those events with very large signal-to-noise ratio, opening the era of high precision gravitational-wave physics, astrophyisics and cosmology.

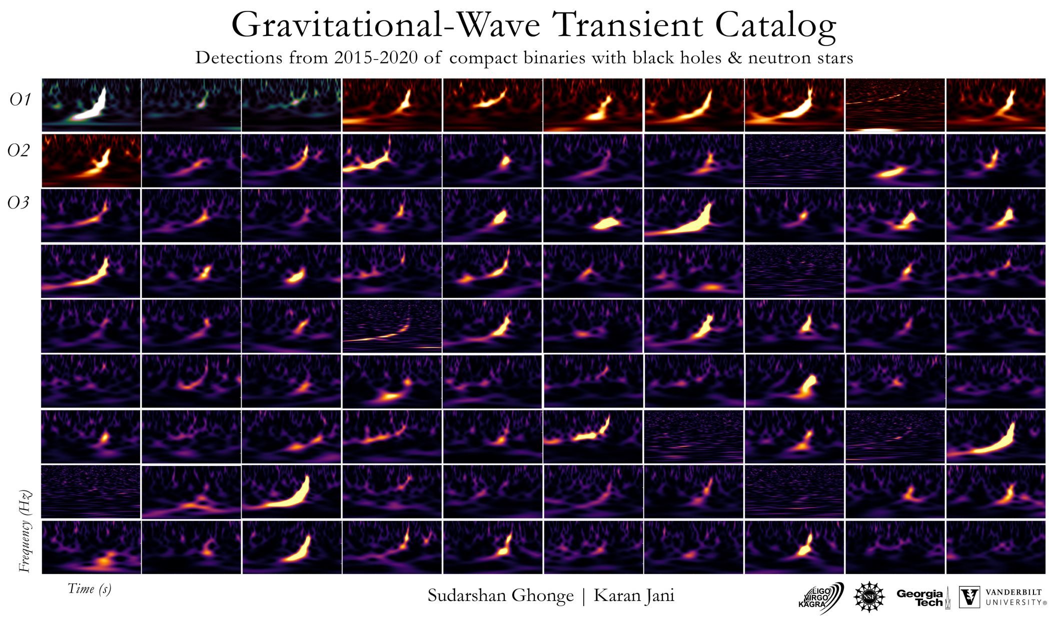

Figure 3. Collection of time-frequency maps of all the LIGO and Virgo detections in the first three observation runs. Graphics reproduced from [30].

Funding: LIGO was constructed by the California Institute of Technology and Massachusetts Institute of Technology with funding from the National Science Foundation, and operates under cooperative agreement PHY-1764464. Advanced LIGO was built under award PHY-0823459.

Acknowledgments: This material is based upon work supported by NSF's LIGO Laboratory, which is a major facility fully funded by the National Science Foundation. The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO, as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, and the Max-Planck-Society (MPS) for support of the construction of Advanced LIGO. Additional support for Advanced LIGO was provided by the Australian Research Council.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Einstein, A. Naeherungsweise Integration der Feldgleichungen der Gravitation. *Sitzungsber. Preuss. Akad. Wiss.* **1916**, *1*, 688.
2. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Abernathy, M.R.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; et al. Observation of Gravitational Waves from a Binary Black Hole Merger. *Phys. Rev. Lett.* **2016**, *116*, 061102. [CrossRef] [PubMed]
3. Whitcomb, S. Making LIGO Possible: A Technical History. In Proceedings of the APS April Meeting 2019, Denver, Colorado, 13–16 April 2019. Available online: https://dcc.ligo.org/public/0157/G1802281/001/G1802281-v1.pdf (accessed on 1 June 2022).
4. Aasi, J.; Abbott, B.P.; Abbott, R.; Abbott, T.; Abernathy, M.R.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; et al. Advanced LIGO. *Class. Quantum Grav.* **2015**, *32*, 074001.
5. Cahillane, C.; Mansell, G. Review of the Advanced LIGO Gravitational Wave Observatories Leading to Observing Run Four. *Galaxies* **2022**, *10*, 36. [CrossRef]
6. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.* **2017**, *119*, 161101. [CrossRef]
7. Acernese, F.A.; Agathos, M.; Agatsuma, K.; Aisa, D.; Allemandou, N.; Allocca, A.; Amarni, J.; Astone, P.; Balestri, G.; Ballardin, G.; et al. Advanced Virgo: A second-generation interferometric gravitational wave detector. *Class. Quantum Grav.* **2015**, *32*, 024001. [CrossRef]
8. Nardecchia, I. Detecting Gravitational Waves with Advanced Virgo. *Galaxies* **2022**, *10*, 28. [CrossRef]

9. Akutsu, T.; Ando, M.; Arai, K.; Arai, Y.; Araki, S.; Araya, A.; Aritomi, N.; Aso, Y.; Bae, S.; Bae, Y.; et al. Overview of KAGRA: Detector design and construction history. *Prog. Theor. Exp. Phys.* **2021**, *2021*, 05A101. [CrossRef]
10. Abe, H.; Akutsu, T.; Ando, M.; Araya, A.; Aritomi, N.; Asada, H.; Aso, Y.; Bae, S.; Bajpai, R.; Cannon, K.; et al. The Current Status and Future Prospects of KAGRA, the Large-Scale Cryogenic Gravitational Wave Telescope Built in the Kamioka Underground. *Galaxies* **2022**, *10*, 63. [CrossRef]
11. Dooley, K.L.; Leong, J.R.; Adams, T.; Affeldt, C.; Bisht, A.; Bogan, C.; Degallaix, J.; Gräf, C.; Hild, S.; Hough, J.; et al. GEO 600 and the GEO-HF upgrade program: successes and challenges. *Class. Quantum Grav.* **2016**, *33*, 075009. [CrossRef]
12. Abbott, R.; Abe, H.; Acernese, F.; Ackley, K.; Adhikari, N.; Adhikari, R.X.; Adkins, V.K.; Adya, V.B.; Affeldt, C.; Agarwal, D.; et al. First joint observation by the underground gravitational-wave detector, KAGRA, with GEO600. *arXiv* **2022**, arXiv:2203.01270.
13. Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adhikari, N.; Adhikari, R.X.; Adya, V.B.; Affeldt, C.; Agarwal, D.; et al. GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run. *arXiv* **2021**, arXiv:2111.03606.
14. Spera, M. Compact Binary Coalescences: Astrophysical Processes and Lessons Learned, *Galaxies* **2022**, *10*, 76. [CrossRef]
15. Szczepańczyk, M.; Zanolin, M. Gravitational Waves from a Core-Collapse Supernova: Perspectives with detectors in the late 2020s and early 2030s. *Galaxies* **2022**, *10*, 70. [CrossRef]
16. Piccinni, O.J. Status and perspectives of Continuous Gravitational Wave searches. *Galaxies* **2022**, *10*, 72. [CrossRef]
17. Renzini, A.I.; Goncharov, B.; Jenkins, A.C.; Meyers, P.M. Stochastic Gravitational-Wave Backgrounds: Current Detection Efforts and Future Prospects. *Galaxies* **2022**, *10*, 34. [CrossRef]
18. Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adhikari, N.; Adhikari, R.X.; Adya, V.B.; Affeldt, C.; Agarwal, D.; et al. The population of merging compact binaries inferred using gravitational waves through GWTC-3. *arXiv* **2021**, arXiv:2111.03634. [CrossRef]
19. Abbott, R.; Abe, H.; Acernese, F.; Ackley, K.; Adhikari, N.; Adhikari, R.X.; Adkins, V.K.; Adya, V.B.; Affeldt, C.; Agarwal, D.; et al. Tests of General Relativity with GWTC-3. *arXiv* **2021**, arXiv:2112.06861. [CrossRef]
20. Karki, S.; Bhattacharjee, D.; Savage, R.L. Toward Calibration of the Global Network of Gravitational Wave Detectors with Sub-Percent Absolute and Relative Accuracy. *Galaxies* **2022**, *10*, 42. [CrossRef]
21. Davis, D.; Walker, M. Detector Characterization and Mitigation of Noise in Ground-Based Gravitational-Wave Interferometers. *Galaxies* **2022**, *10*, 12. [CrossRef]
22. Vajente, G.; Gustafson, E.K.; Reitze, D.H. Precision interferometry for gravitational wave detection: Current status and future trends. In *Advances in Atomic, Molecular, and Optical Physics*; Academic Press: Cambridge, MA, USA, 2019; Chapter 3, Volume 68, pp. 75–148.
23. Dwyer, S.E.; Mansell, G.L.; McCuller, L. Squeezing in Gravitational Wave Detectors. *Galaxies* **2022**, *10*, 46. [CrossRef]
24. Trozzo, L.; Badaracco, F. Seismic and Newtonian Noise in the GW Detectors. *Galaxies* **2022**, *10*, 20. [CrossRef]
25. Adhikari, R.X.; Arai, K.; Brooks, A.F.; Wipf, C.; Aguiar, O.; Altin, P.; Barr, B.; Barsotti, L.; Bassiri, R.; Bell, A.; et al. A Cryogenic Silicon Interferometer for Gravitational-wave Detection. *arXiv* **2020**, arXiv:2001.11173. [CrossRef]
26. Di Pace, S.; Mangano, V.; Pierini, L.; Rezaei, A.; Hennig, J.S.; Hennig, M.; Pascucci, D.; Allocca, A.; Tosta, e Melo, I.; Nair, V.G.; et al. Research Facilities for Europe?s Next Generation Gravitational-Wave Detector Einstein Telescope. *Galaxies* **2022**, *10*, 65. [CrossRef]
27. Hall, E. Cosmic Explorer: A next-generation ground-based gravitational-wave observatory, *Galaxies* **2022**, *10*, 90. [CrossRef]
28. Danzmann, K.; LISA Study Team. LISA: Laser interferometer space antenna for gravitational wave measurements. *Class. Quantum Grav.* **1996**, *13*, A247. [CrossRef]
29. Kawasaki, Y.; Shimizu, R.; Ishikawa, T.; Nagano, K.; Iwaguchi, S.; Watanabe, I.; Wu, B.; Yokoyama, S.; Kawamura, S. Optimization of Design Parameters for Gravitational Wave Detector DECIGO Including Fundamental Noises. *Galaxies* **2022**, *10*, 25. [CrossRef]
30. GWTC-3 Poster. Available online: https://dcc.ligo.org/LIGO-G2102338/public (accessed on 1 June 2022) .