Decoding the Universe: Recent Developments in LIGO and LISA

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Introduction

With the monumental advent in our current engineering technologies we are in the age of unravelling the universe's most fundamental mysteries. Gravitational Waves, an astrophysical phenomenon that sends ripples through spacetime were predicted from the theory of General Relativity by Einstein in 1915. These were experimentally confirmed after 100 years by the Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors in 2015. Since then several new observatories and projects such as Laser Interferometer Space Antenna (LISA) have been in construction to increase our understanding of the phenomenon. In this article, we look at the underlying technicalities in these detectors and the recent advancements in their technologies.

LIGO: Enhancing Sensitivity and Broadening Discoveries

LIGO is based on the principle of a Michelson interferometer which is designed to detect very minute changes in the length of its arms which correspond to variations in the interference pattern of the laser beams, to a precision of about 10^{-18} meters. Since 2015, LIGO has undergone several upgrades which were implemented in order to increase it's sensitivity and reduce noise. These enhancements are responsible for increasing the range of sources primarily in the form of compact binary coalescences which refer to the merger of black holes and neutron stars. One of the most recent updates to the LIGO observatory after the observing run O3 includes the implementation of quantum technology which will reduce the quantum noise and give a boost to the laser power. This is done in order to increase the rate of detection of the mergers leading to more science. This is currently being utilised in the fourth observing run O4 [1, 2].

Along with this, several advancements have been made in integrating AI (Artificial Intelligence) and ML (Machine Learning) techniques and pipelines to help with noise reduction and filtering the signal, assisting in the real time detection of these transient events and therefore making the analysis of these mergers relatively easier to follow up by scientists with other telescopes, observatories, and detectors [3]. The most recent advances have been recorded from what we understand to be the lightest and the heaviest black hole and neutron star mergers that have been recorded till date. These data sets and sources will help us in understanding the process of star formation and stellar death in a previously unfathomable detail [4].

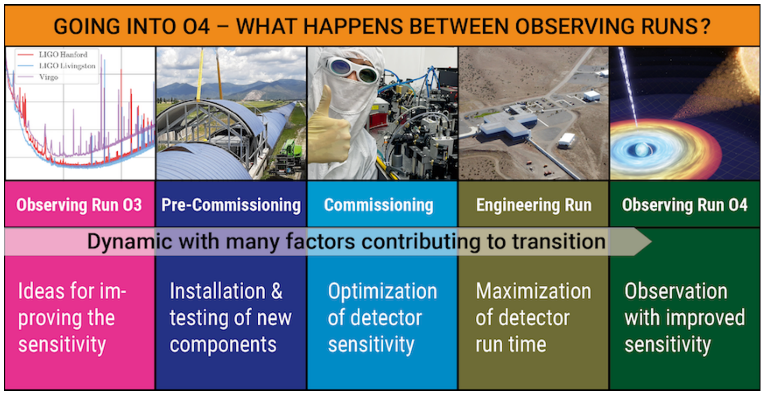

Figure 1: Moving to the LIGO run O4 [Image credit: LIGO/Virgo/KAGRA]

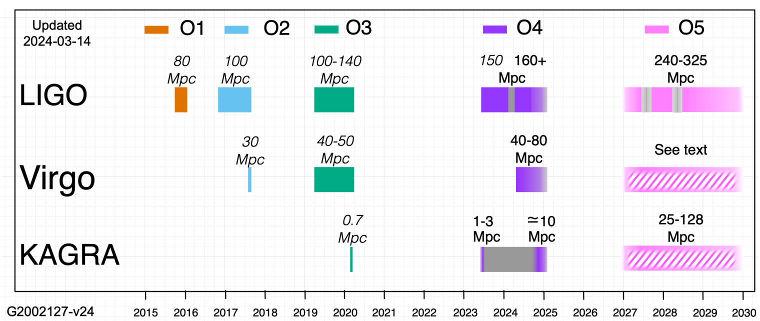

Figure 2: Observing Runs Tentative Timeline [Image credit: LIGO/Virgo/KAGRA]

LISA: Leading the path for Space-Based Gravitational Wave Astronomy

LISA was started as a joint venture between NASA and the ESA (European Space Agency) after the success of the LISA Pathfinder mission which proved that the technological developments for the construction of LISA are feasible. The LISA pathfinder mission demonstrated that picometer level distance measurements can be taken between test masses that are situated millions of kilometers apart where only a single spacecraft with one of the LISA interferometer arms shortened to about 38 cm was used as the testing facility. The current updates for LISA include focus on finalising the design and the technology required for the spacecrafts to function properly. These technologies include the ultra-stable laser system to be used for the interferometers, the micro-propulsion system to point at different source localisations, and drag-free control which is needed to isolate the test masses from all external forces other than gravity [5].

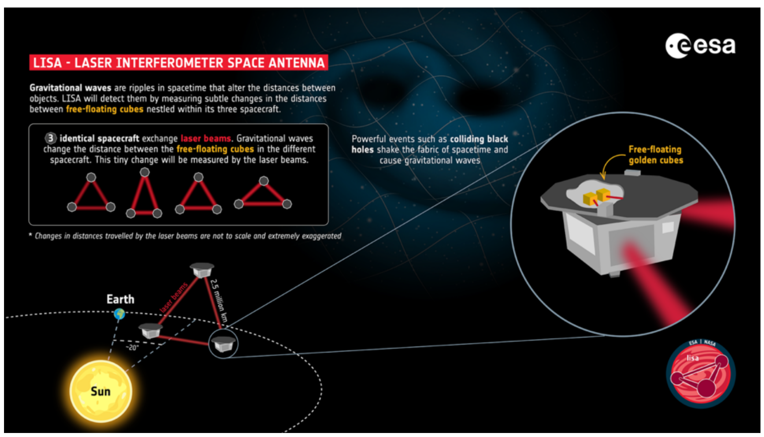

Figure 3: LISA Concept [Image credit: ESA/NASA]

LISA is different from LIGO from the fact that it will operate in space but the core principle of interferometry remains the same. This is highly beneficial as it can operate in the low frequency range, ranging from 0.1 mHz and 1 Hz (which is minuscule compared to LIGO's which ranges from 10 Hz t0 1000 Hz). This lower frequency range will allow LISA to look at much longer wavelengths, and therefore look at sources which are way heavier than the ones detected by LIGO and in much wider orbits than previously detected which is ought to drastically increase our understanding of Gravitational Waves and related science. LISA will include three spaceships that form an equilateral triangle where the edges of the triangles extend upto a million kilometers and therefore act as three arms of the interferometer. This allows LISA to get rid of the noise from Earth and get access to regions previously unknown due to the lack of length of the arms of the current ground based detectors. With these technologies, LISA would be able to discover several ultra-compact binaries, supermassive black hole mergers, and extreme mass ratio in-spirals, amongst several other possibilities.

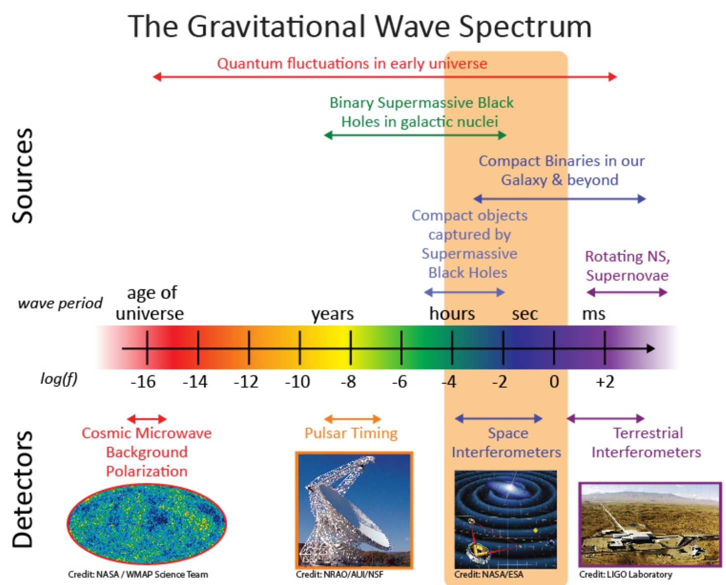

Figure 4: Gravitational Wave Spectrum for different Astrophysical Phenomenon[Image credit: ESA/NASA]

Collaboration and Multi-Messenger Astronomy

Quick follow-ups with telescopes for electromagnetic counterparts to the gravitational waves coming from LIGO, Virgo, Kagra, and upcoming LISA observations are made possible through different collaborations with different observatories and other space telescopes. These collaborations are crucial for the era of multi-messenger astronomy, where gravitational wave detections are combined with observations from electromagnetic telescopes and neutrino detectors. This mixed approach allows scientists to comprehensively understand events like neutron star mergers, which can emit signals across the electromagnetic spectrum and gravitational waves, and have a complete report about the event. These are some of the observatories and space telescopes that collaborate with the Ligo-Virgo-Kagra (LVK) detectors:

Optical and Infrared Observatories

- **Vera C. Rubin Observatory**: The Vera C. Rubin Observatory, previously known as the Large Synoptic Space Telescope (LSST) is currently under construction in Chile. The Rubin Observatory will house the Simonyi Survey Telescope which is a wide-field reflecting telescope with an 8.4 meter primary mirror. The observatory is bound to discover thousands of transients, including kilonovae, which are the visible and infrared counterparts of neutron star mergers [6].

- **Very Large Telescope (VLT) and European Southern Observatory (ESO)**: The Very Large Telescope consists of 4 unit telescopes of 8.2 meters and 4 auxiliary 1.8 meter telescopes. The four unit telescopes can be combined to make an interferometer and thus it can provide powerful optical and infrared observations that can pinpoint electromagnetic counterparts' location and chemical composition [7].

Radio Telescopes

- **Very Large Array (VLA)**: The Very Large Array is located in New Mexico and it can be used to quickly respond to gravitational wave detections, and therefore search for radio emissions arising from the mergers, which can provide insights for the jets and materials ejected from these high energy events.

- **Square Kilometre Array (SKA)**: The Square Kilometer Array is a project being constructed in Australia (low frequency) and South Africa (mid frequency) which will become the world's largest radio telescope. This will help scientists in detecting and studying electromagnetic counterparts to gravitational wave sources.

X-ray and Gamma-ray Observatories

- **Chandra X-ray Observatory**: Chandra is NASA's X-ray observatory in space as Gamma rays can't be detected from ground based observatories. It is specifically designed to detect X-ray emission from very hot regions of the Universe such as exploded stars, clusters of galaxies, and matter around black holes. This can be particularly useful for the detection of sources for binary merger events and their localisation.

- **Fermi Gamma-ray Space Telescope**: The Fermi Gamma-ray Space Telescope is designed to study Gamma ray bursts which are the crucial events related to the mergers and therefore can give us a detailed understanding of kilonovaes as well as cosmic rays arising from the mergers.

Neutrino Detectors

- **Ice-Cube Neutrino Observatory**: The Ice-Cube Neutrino observatory is located at the South Pole and encompasses a cubic kilometer of ice. It is used to detect highly energetic almost mass-less neutrinos. These neutrinos can tell us about the source of the merger events related to the gravitational wave signal detected by the LVK detectors.

The prowess of these collaborations can be understood from the example of the detection of GW170817, the neutron star merger which was detected by LIGO and Virgo. The electromagnetic counterparts were detected in the same way as mentioned above and has contributed immensely in our understanding of these events producing kilonovae and also the synthesis of heavy elements such as gold and platinum in the universe [8].

The Future of Gravitational Wave Astronomy

As we saw in the recent developments of these observatories, the future for gravitational wave science looks very bright. Understanding the mergers that lead to these gravitational waves will increase our understanding of the current and early universe, which will allow us to better refine the standard model of Big Bang Cosmology. With the advances in technology, and a possible collaboration of collaborations, the future holds great prospects, which will enable us to better understand the origins of the universe, and thereby offering a deeper understanding of where we came from. Thus, from this viewpoint of gravitational wave astronomy, we will be able to witness something remarkable and better understand our place in this cosmos.

References

[1] LIGO Scientific Collaboration. Update on ligo, virgo and kagra observing run plans. https://www.ligo.caltech.edu/news/ligo20211115, 2021.

[2] LIGO Scientific Collaboration. Ligo and its partners fast approaching next observing run. https://www.ligo.caltech.edu/news/ligo20230516, 2023.

[3] Vincenzo Benedetto, Francesco Gissi, Gioele Ciaparrone, and Luigi Troiano. Ai in gravitational wave analysis, an overview. *Applied Sciences*, 13(17), 2023.

[4] LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration. Gw230529: Discovery of gravitational waves from a compact binary coalescence. Technical Report P2300352, LIGO Document Control Center, 2024.

[5] M. Armano, H. Audley, G. Auger, J. T. Baird, M. Bassan, P. Binetruy, M. Born, D. Bortoluzzi, N. Brandt, M. Caleno, L. Carbone, A. Cavalleri, A. Cesarini, G. Ciani, G. Congedo, A. M. Cruise, K. Danzmann, M. de Deus Silva, R. De Rosa, M. Diaz-Aguiló, L. Di Fiore, I. Diepholz, G. Dixon, R. Dolesi, N. Dunbar, L. Ferraioli, V. Ferroni, W. Fichter, E. D. Fitzsimons, R. Flatscher, M. Freschi, A. F. García Marín, C. García Marirrodriga, R. Gerndt, L. Gesa, F. Gibert, D. Giardini, R. Giusteri, F. Guzmán, A. Grado, C. Grimani, A. Grynagier, J. Grzymisch, I. Harrison, G. Heinzel,

M. Hewitson, D. Hollington, D. Hoyland, M. Hueller, H. Inchauspé, O. Jennrich, P. Jetzer, U. Johann, B. Johlander, N. Karnesis, B. Kaune, N. Korsakova, C. J. Killow, J. A. Lobo, I. Lloro, L. Liu, J. P. López-Zaragoza, R. Maarschalkerweerd, D. Mance, V. Martín, L. Martin-Polo, J. Martino, F. Martin-Porqueras, S. Madden, I. Mateos, P. W. McNamara, J. Mendes, L. Mendes, A. Monsky, D. Nicolodi, M. Nofrarias, S. Paczkowski, M. Perreur-Lloyd, A. Petiteau, P. Pivato, E. Plagnol, P. Prat, U. Ragnit, B. Raïs, J. Ramos-Castro, J. Reiche, D. I. Robertson, H. Rozemeijer, F. Rivas, G. Russano, J. Sanjuán, P. Sarra, A. Schleicher, D. Shaul, J. Slutsky, C. F. Sopuerta, R. Stanga, F. Steier, T. Sumner, D. Texier, J. I. Thorpe, C. Trenkel, M. Tröbs, H. B. Tu, D. Vetrugno, S. Vitale, V. Wand, G. Wanner, H. Ward, C. Warren, P. J. Wass, D. Wealthy, W. J. Weber, L. Wissel, A. Wittchen, A. Zambotti, C. Zanoni, T. Ziegler, and P. Zweifel. Sub-femto-g free fall for space-based gravitational wave observatories: Lisa pathfinder results. *Phys. Rev. Lett.*, 116:231101, Jun 2016.

[6] Rubin Observatory. Rubin 2024 too workshop final report. Technical report, Rubin Observatory, 2024.

[7] Oskar von der Lühe. An introduction to interferometry with the eso very large telescope. In Francesco Paresce, editor, *Science with the VLT Interferometer*, pages 13–34, Berlin, Heidelberg, 1997. Springer Berlin Heidelberg.

[8] P. S. Cowperthwaite, E. Berger, V. A. Villar, B. D. Metzger, M. Nicholl, R. Chornock, P. K. Blanchard, W. Fong, R. Margutti, and M. Soares-Santos. The electromagnetic counterpart of the binary neutron star merger ligo/virgo gw170817. ii. uv, optical, and near-infrared light curves and comparison to kilonova models. *The Astrophysical Journal Letters*, 848(2):L17, 2017.