Detection and Analysis of Gravitational Waves in the era of Multi-Messenger Astronomy: From Mathematical Modelling to Machine Learning

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The Banff International Research Station for Mathematical Innovation and Discovery (BIRS) "Detection and Analysis of Gravitational Waves in the Era of Multi-Messenger Astronomy: From Mathematical Modeling to Machine Learning," took place in Oaxaca, MX, from Monday, November 15 through Friday, November 19. A dozen participants challenged covid travel restrictions and testing requirements to enjoy the hospitality of the Casa Matemática Oaxaca (CMO) and the beautiful hotel Hacienda Los Laureles to attend the workshop in person. Another couple dozen participants attended the hybrid workshop remotely. The focus of the discussions was the latest advances in the development of numerical algorithms for the analysis and interpretation of gravitational-wave (GW) data.

1 Overview

On February 11, 2016, one hundred years and a few months after the publication of the Theory of General Relativity (GR), researchers from the Laser Interferometer Gravitational-wave Observatory (LIGO) [1] Scientific Collaboration (LSC) and the European Virgo [2] Collaboration announced the first direct detection of GWs from a pair of coalescing black holes, confirming once again Einstein's theory and turning GW astronomy into reality [3]. Rather than being the end of a century-long scientific journey, the LIGO-Virgo detection embodied the beginning of a new way of exploring our universe. In 2017, LIGO and Virgo observed GWs from the merger of two neutron stars [4]. This event was rapidly followed by the Fermi Gamma-ray Space Telescope's detection of a gamma-ray flash, and eventually by optical, infrared, radio, and x-ray observations by hundreds of telescopes around the world in what became the most observed event in the history of modern astronomy [5]. Since then, the LSC, the Virgo Collaboration and the KAGRA [6] Collaboration (LVK) have announced the detection of about one hundred binary black hole (BBH), binary neutron star (BNS) and mixed (NSBH) mergers [7]. The third LVK observation run has brought us GW observations on a routine basis, enabling a plethora of novel astrophysical and theoretical investigations.

The next decade will see Multi-Messenger Astrophysics (MMA) and GW astronomy further expand their reach in frontier scientific research. India has finalized plans for the construction of the LIGO-India detector [8]. The European space-based LISA mission [9], slated to launch in 2034, will greatly improve detection capabilities and localization of astrophysical sources. The International Pulsar Timing Array project will detect ultra-low frequency GWs within a few years [10]. Optical, particle and GW astronomy will together explore the universe through complementary physical carriers. The LVK now forms a community of over two thousand members across the world working as one to push the boundaries of our knowledge. This amazing scientific pursuit is made possible thanks to the efforts of numerical relativists developing codes and algorithms to accurately model GW signals, data analysts striving to make LVK detection techniques increasingly efficient, commissioners steadily bringing the detectors to design sensitivity, and instrument scientists developing the next generation of GW interferometric detectors. All these activities are intertwined and play an essential role in developing MMA as a tool to probe our universe.

2 Recent Developments and Open Problems

The first three LVK observing runs have undoubtedly been a huge success story. The first direct detection of GWs from a pair of coalescing black holes [3] and the first observation of a GW signal from a coalescing binary neutron star system [4] established MMA as a new way to explore the universe. The publication of the LVK catalogs of compact binary merger signals [7] has shown that GW astrophysics is a powerful tool for population and source property studies of compact objects, tests of General Relativity, and large-scale cosmological measurements. Yet many open questions remain. For example, the formation channels of black hole binaries are still unclear [11] as is the physics of electromagnetic-bright mergers [12]. Tests of GR have returned a null result [13], the determination of the Hubble constant from GW sirens is still uncertain [14]. Future source property studies and tests of GR will require better reconstructions of GW signals, improved estimates of statistical and systematic errors, and more accurate detector calibration and characterization. Processing and analyzing the increased rate of detections in future runs will require to streamline current search pipelines and develop faster and more efficient methods for detector and signal characterization.

Published GW observations only represent the tip of the iceberg of the MMA universe. While LVK researchers have detected coalescences of compact binary objects, other known sources of multi-messenger signals, such as isolated compact objects [15] and core-collapse supernovae [16], have not yet been observed in the GW domain. Despite the LVK is running all-sky, unmodeled searches [17, 18], no GW signals have been detected which cannot be modeled as a compact binary coalescences. The LVK scientific operations in the next few years will focus not only on improving existing data analysis methods for already-detected classes of events, but also on developing and maintaining the infrastructure to detect new classes of GW sources.

In this context, a consistent fraction of LVK data analysis R&D deals with the application of machine learning (ML) methods to detector data [19]. ML algorithms are designed to perform specific tasks and automatically improve their performance by means of adaptive techniques and iterative procedures. They are powerful tools for the analysis of massive amount of data and pattern recognition. They are flexible, robust and portable to different situations; ML tools designed to solve a specific problem can be adapted to different issues. Therefore, in recent years, algorithms such as Neural Networks, Deep Learning, Support Vector Machine and Random Forest classifiers, and evolutionary algorithms, have been applied to various aspects of LVK detection pipelines. This exploratory phase has reached its mature stage. The challenge is now the development of self-contained algorithms that can be integrated in existing searches or noise investigation procedures. This is an essential step to bring new methods into production and positively impact LVK scientific operations.

In parallel to the above efforts, R&D in numerical relativity [20] is experiencing an unprecedented expansion in the GW community. As more and more refined GW observations become available, the analysis and interpretation of these observations will rely more on accurate signal waveforms which can only be obtained by numerically solving Einstein's equations. Here, open issues are how to accurately model strong, dynamical gravitational fields and the effects of matter present in the systems.

Meeting all these challenges requires close interaction between the whole spectrum of GW researchers. With this in mind, the aim of this workshop was to gather a mix of theorists, numerical analysts and data analysts with a common interest in GW science to discuss recent progress in the field and its future, from mathematical modelling of GW sources to integration of data analysis techniques with ML.

3 Presentation Highlights

The workshop included 21 invited presentations about MMA, numerical relativity, and R&D of techniques for GW searches in detector data, as well as ample time for informal discussions. Presentations focused on mathematical and numerical methods to extract physical information from GW detections, new algorithms to search for GW in detector data, ML techniques to improve data quality, detector characterization and control, and tests of GR or effects beyond Einstein's theory that could soon be within reach of GW detectors.

Deirdre Shoemaker and Pablo Laguna's talks focused on numerical relativity. Shoemaker discussed the role that numerical relativity plays in unveiling the GW sky and how it might improve our understanding of gravity as the detectors improve. Laguna discussed the challenges faced in distinguishing NSBH binaries from BBH mergers for high-mass ratios, when neutron stars could coalesce with black holes without experiencing significant disruption. New results from merger simulations for different mass ratios allow researchers to determine how the degree of disruption of the neutron star impacts the inspiral and merger dynamics, the properties of the final black hole, the accretion disk formed from the circularization of the tidal debris, and the strain spectrum and mismatches.

From the testing GR side of MMA, several talks focused on possible signatures of new physics in future detections. Adam Coogan and Gianfranco Bertone discussed dark matter halos around black holes. As the interplay between black holes and dark matter remains largely unexplored, the latter could accumulate around black holes and modify the rich phenomenology exhibited by these objects. After a brief overview of the status of dark matter searches, Bertone presented the prospects for detecting primordial black holes or ruling them out as dark matter candidates. He then discussed the prospects for characterizing and identifying dark matter using GW. Along the same lines, Coogan discussed dark matter halos around intermediate mass-ratio inspirals as potential sources of distinctive GW signals. Future interferometers could observe and characterize these systems over large swaths of their parameter space.

GW emission from core-collapse supernovae was the subject of Bernard Mueller and Pablo Cerdá-Durán presentations. Muller focused on the importance of magnetic fields both in normal and hyperenergetic explosions. He discussed the progress on 3D magnetohydrodynamic simulations of supernovae and their progenitors, possible implications for hypernovae and magnetar formation, and open issues in the current models. Cerdá-Durán focused on the current understanding of core-collapse GW signals and how they can be modelled in terms of normal oscillations modes of proto-neutron stars excited during the post-bounce phase before the onset of the explosion. The observation of such modes by GW detectors could allow determination of the properties of the proto-neutron stars and the equation of state of nuclear matter.

The physics of black hole ringdown was the subject of Lorena Magaña Zertuche's talk. This phase of a BBH merger is crucial to understand astrophysical black holes, fit detections from GW detectors, and take full advantage of the GW data from third-generation detectors. Leïla Haegel discussed probes of new physics through potential observations of GW dispersion during their propagation. She presented constraints on different alternative theories of gravitation using MMA and BBH detections from the second LIGO-Virgo catalog.

ML techniques for the detection of GWs and the characterization of the detectors were the focus of the rest of the workshop. Discussions and presentations focused on applications of different flavors of ML algorithms to GW astronomy, such as deep learning, neural networks, and support vector machines.

Vasileios Skliris and Javier Antelis discussed GW searches for unmodeled signals. Skliris showed that Convolutional Neural Networks can be used to detect generic unmodeled signals. Tests on data from the second LIGO-Virgo observing run show that the method has sensitivity approaching that of the unmodeled transient searches currently used by the LVK in low-latency, allowing for the possibility of real-time detection of GW transients associated with MMA phenomena. Antelis presented a new use of Linear Discriminant Analysis and Support Vector Machines to distinguish noise and signal events in GW unmodeled searches. Tests on strain data from the third LVK observing run and 3D simulations show an effective enhancement of the statistical significance of current unmodeled searches of GWs from supernovae.

ML techniques applied to detector control and characterization were the subject of several talks. Gabriele

Vajente discussed how ML could also be applied to improve the sensitivity with noise subtraction or to improve the detector robustness with advanced control systems. Ryan Quitzow-James presented NNETFIX, a ML-based algorithm which uses artificial neural networks to estimate the portion of the data lost due to the presence of the glitch. The sky localization of the NNETFIX-denoised signal may be significantly more accurate than the sky localization obtained from the original data or by excising the portion of the data impacted by the glitch. Massimiliano Razzano discussed how ML can help in investigating the time-frequency evolution of glitches and contribute to the low-latency characterization of GW detectors. Jess McIver gave an overview of new approaches to characterize the performance of current and near-future detectors, including novel metrics for detector performance and characterization, new methods for distinguishing between true GW signals and detector noise, and improved techniques for GW signal reconstruction.

The presentations by Christopher Messenger and Deep Chatterjee focused on ML methods for data analysis. Messenger discussed a new conditional variational autoencoder method for the estimation of BBH GW signal source parameters that could replace current computationally costly Bayesian inference approaches. Chatterjee discussed data-driven and ML approaches for near real-time inference of electromagnetic counterparts to GW signals and data products for follow-up of interesting GW candidates.

Alberto Iess, Ik Siong Heng, and Kendall Ackley's presentations focused on MMA data analysis for compact binary coalescences. Iess proposed the application of a new multimodal ML approach to characterize MMA events. Heng presented an analysis of kilonova light curves for joint observations and a hierarchical Bayesian analysis, with a ML-augmented sampler (Nessai), for combining GW and gamma-ray observations to identify plausible models for gamma-ray burst jet structures. Ackley gave an overview of the current strategies of transient classification employed by optical observatories, such as Bayesian Convolution Neural Networks, Photometric Time-Series classification, and improvements on building balanced training sets for large sky-surveys in preparation for future observing runs.

Different aspects of inference for multi-messenger astronomy were the subject of Michael Coughlin and Greg Ashton's presentations. Coughlin discussed two deep-learning algorithms, ”DeepClean” and ”BBH-Net”, which are used for GW data denoising and compact binary source identification, respectively. Subtraction of stationary and non-stationary noise sources followed by identification of candidates for astrophysical transient detections at low latency may be possible at latencies as low as a few hundreds of milliseconds. Ashton reviewed Bayesian inference as the foundational framework used to extract the source properties of binary coalescence signals from GW data and provided insights into the shortcomings and highlights of current approaches.

4 Outcome of the Meeting

In the past decade ML and numerical relativity have played an ever increasing role in GW astronomy and MMA. ML algorithms have been applied to a variety of problems from detector science to data analysis. Numerical relativity codes provide accurate waveforms for follow-up and physical interpretation of GW detections. Both ML algorithms and numerical relativity schemes must confront themselves with large data sets and the need for high accuracy which is required in performing searches at the limit of the instrument sensitivity and extracting the physics from the data. In this context, the BIRS workshop successfully provided a forum to review the latest advances in this field, as well as the challenges and open questions that need to be solved to render these techniques even more robust and widely applicable.

The workshop supported the participation of researchers and students at different stages of their careers and from diverse institutions. Despite the covid-19 travel restrictions drastically reduced the number of in-person participants, a small contingent of enthusiastic students and researchers from Mexico and a few international researchers from the USA were able to attend the workshop in person. The hybrid nature of the workshop allowed several international participants, who otherwise would not have had the chance of attending the workshop, to attend the meeting remotely.

Overall, the workshop was successful in its original intents: put together a balanced program with invited and contributed talks from all main thematic areas of GW science, set up an environment to encourage discussions and facilitate the interaction between scientists with a common interest but different research approaches, and encourage participation of early career researchers.

GW astronomy is just in its infancy. There is no doubt that it will play an ever increasing role in expanding our understanding of the Universe. As this new branch of scientific research will lead to new discoveries, we hope to repeat the success of the "Detection and Analysis of Gravitational Waves in the era of Multi-Messenger Astronomy: From Mathematical Modelling to Machine Learning" workshop some time soon.

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Appendix: List of invited participants

Antelis, Javier M. (Embry-Riddle Aeronautical University)
Arias, Anibal (Universidad Tecnológica de la Mixteca)
Cavaglia, Marco (Missouri Univ. of Science and Technology)
Cuoco, Elena (European Gravitational Observatory)
Coogan, Adam (Université de Montréal and Mila)
Gamboa Castillo, Aldo Javier (UNAM)
Ghosh, Shaon (Montclair State University)
Gracia-Linares, Miguel (The University of Texas at Austin)
Jiménez, Moisés Eduardo (UNAM)
Laguna, Pablo (University of Texas at Austin)
Martìnez Marcelo, Jessica (UNAM)
Morales Martìnez, Jorge Braulio (UNAM)
Shoemaker, Deirdre (University of Texas at Austin)
Ackley, Kendall (University of Warwick)
Ashton, Greg (Royal Holloway, University of London)
Bertone, Gianfranco (University of Amsterdam)
Cerdá-Durán, Pablo (Universidad de Valencia)
Chatterjee, Deep (U. Illinois Urbana-Champaign)
Coughlin, Michael (University of Minnesota)
Haegel, Leïla (University of Paris)
Heng, Ik Siong (University of Glasgow)
Iess, Alberto (Scuola Normale Superiore Pisa)
Khanam, Tanazza (Texas Tech University)
Lange, Jacob (The University of Texas at Austin)
Magana Zertuche, Lorena (University of Mississippi)
McIver, Jess (University of British Columbia)
Messenger, Christopher (Glasgow University)
Mueller, Bernhard (Monash University)
Otten, Sydney (Radboud University & University of Amsterdam)
Parisi, Alessandro (Scuola Normale Superiore di Pisa)
Pham, Kiet (University of Minnesota)
Powell, Jade (Swinburne University of Technology)
Quitzow-James, Ryan (Missouri University of Science and Technology)
Razzano, Massimiliano (University of Pisa)

Shafeeque, Muhammed (Indian Institute of Technology, Guwahati, India)
Skliris, Vasileios (Cardiff University)
Utina, Andrei (Maastricht University)
Vajente, Gabriele (California Institute of Technology)
Valdés, Guillermo (Texas A&M University)

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