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Science opportunities and challenges with current and next-generation ground-based gravitational-wave observations

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Abstract. Since 2015, ground-based gravitational-wave observations have constantly provided new insight into our universe. With successive upgrades to current facilities and the launch of new instruments, and hence a growing number of detections, we are prepared to address some fundamental questions in the Universe. This article gives an overview of the science opportunities provided by current and next-generation gravitational-wave facilities and provides several examples of major challenges in the interface of data, simulations, and theories.

Keywords. Gravitational waves, compact binary mergers

1. Introduction

Since the detection of binary black hole merger GW150914 by the Laser Interferometer Gravitational-Wave Observatory (LIGO), another window to the Universe has been opened (Abbott et al. 2016b). So far, LIGO-Virgo-KAGRA Scientific Collaboration has announced ~ 100 detections of compact binary mergers in the first three observing runs, with another > 100 detection candidates in the ongoing fourth observing run (Abbott et al. 2023b). The science opportunities brought by gravitational-wave (GW) observations lie across diverse areas of physics. The actively planned next-generation ground-based GW observatories (expected to start observing in the late 2030s to early 2040s), such as Cosmic Explorer (Evans et al. 2021) and Einstein Telescope (Maggiore et al. 2020), with the capability to observe stellar-mass compact binary mergers beyond redshift of 20, will further widen the science scope of GW observations.

Stellar-mass compact binary mergers, such as binary black hole, neutron-star black-hole, and binary neutron star mergers, are the most common sources for ground-based GW detectors. The physical properties of the mergers are embedded in the GW waveforms. With the help of theories, numerical simulations, and data analysis, critical properties of the stars, such as their mass, spin, sky location, and distance can be measured (Abbott et al. 2016d). Furthermore, if the compact binary systems also emit electromagnetic (EM) signals or astroparticles, the scientific landscape could be further extended with the complementary information brought by these other messengers (Abbott et al. 2017a).

2. Science opportunities

GW observations will help answer plenty of important questions. For example,

• The population properties of compact binary mergers, such as their component mass, spin, and distance distributions, are affected by stellar physics and the formation history

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of the binaries. With the growing number of detections, the population distributions of stellar-mass compact objects will be better resolved and enable an in-depth study of the evolution history of binary mergers (Abbott et al. 2023a).

• When the redshifts of the GW sources are independently determined, for example, from the galaxies associated with their EM counterparts, the redshifts can be combined with the GW-measured luminosity distances to constrain the Hubble parameter. This method, known as the "standard sirens", provides a tool that is independent of other cosmological experiments (Schutz 1986; Holz & Hughes 2005). These independent measurements may shed light on a few puzzling tensions between different measurements of the cosmic expansion history (Chen et al. 2018).

• The observations of compact binary mergers also provide a distinct opportunity to test general relativity in the highly dynamical, high velocity, and strong-field regime of gravity (Abbott et al. 2016c, 2019b). The increase in GW detector sensitivity and the combination of multiple detections will offer stringent tests of gravity theories.

• The nature of cold and high-density matter in neutron stars currently can not be probed with terrestrial experiments. The observations of matter effects in the GW waveform of a neutron star merger, such as the tidal deformation induced by the companion stars, provide insight into the properties of these extreme matter (Abbott et al. 2018). Precise measurements of neutron star equation-of-state will be available with future binary neutron star and neutron star-black hole merger observations.

• The origins of half of the heavy elements in the Universe are unknown. Neutron star mergers are a promising site for the rapid neutron capture process (r-process), especially after the observations of EM counterpart of the first binary neutron star merger GW170817, which could account for the production of heavy elements (Kasen et al. 2017). GW and EM observations of these mergers will unfold this another mystery in the Universe.

3. Challenges

To achieve the remarkable science goals, various challenges in the interface of data, simulations, and theories will have to be overcome. In the following, we highlight several major challenges:

• *Search for the signals:* With templates of GW waveform, the sensitivity to the GW sources can be greatly enhanced. However, the generation of the template banks can be computationally heavy to cover the large binary parameter space (Abbott et al. 2016a). Incomplete coverage of the parameter space or missing physics can lead to loss of interesting detections. The construction of a sufficiently complete template bank for the search of GW signals is one of the essential tasks.

• *Parameter estimation:* Once the GW signals are found, more complete estimate of the binary physical parameters is done by comparing the data to GW waveform with different parameters (Abbott et al. 2016d, 2019a). The waveform approximations in use were calibrated by numerical relativity simulations. Limitation on the simulations, such as insufficient gridding or missing physics, could lead to bias in parameter estimation and interpretation of the physics.

• *Connection to stellar physics and binary formation history:* The stellar and binary formation history of the GW sources can be revealed by their population distribution, such as the mass, spin, and distance distributions (Abbott et al. 2016e, 2017b). Currently, several interesting features in the observed populations of binary mergers can not be fully explained (Abbott et al. 2023a). Common features shared by different formation histories will also need to be resolved. The developments of theories and simulations will be critical to connect the observed binary population to their origins.

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• *Interpretation of EM signals:* The complimentary information about the GW sources brought by the EM counterpart observations can be remarkably useful, such as the improvements in the measurements of neutron star equation-of-state (Radice et al. 2018) and cosmological parameters (Chen et al. 2019). However, bias introduced by inaccurate constraints on the binary physical parameters from EM observations could induce significant systematic uncertainties (Chen 2020). The modeling complexity of EM emissions for interpretation of the EM signals is another major challenge to overcome.

GW observations open up new horizons and bring in immense exploration space for many areas of physics, marking the importance to address the challenges in the interface of data, simulations and theories. As we lay the groundwork for the infrastructure, the next decades are promised to be an exciting era for GW physics.

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