Astro2020 Science White Paper

Gravitational-Wave Astronomy in the 2020s and Beyond: A view across the gravitational wave spectrum

Thematic Areas:

☐ Planetary Systems	☐ Star and Planet Formation
☒ Formation and Evolution of Compact Objects	☒ Cosmology and Fundamental Physics
☒ Stars and Stellar Evolution	☐ Resolved Stellar Populations and their Environments
☒ Galaxy Evolution	☒ Multi-Messenger Astronomy and Astrophysics

by

The Gravitational Wave International Committee (GWIC)

https://gwic.ligo.org

Edited by David Shoemaker, MIT, dhs@mit.edu, 617-283-5362

Maura McLaughlin, West Virginia University

James Ira Thorpe, NASA Goddard Space Flight Center

Context:

One of the most notable developments since the 2010 Decadal Survey is the addition of gravitational waves (GW) to the astronomers' suite of tools for understanding the Universe. LIGO's 2015 detection of gravitational waves (Abbott et al. 2016) from the merger of a pair of black holes roughly 30 times the mass of our Sun garnered tremendous excitement from both the public and the scientific community and raised interesting questions as to the origin of such systems. To date a total of 11 confirmed detections have been announced, including the first GW signals from the merger of neutron stars in 2017 seen by LIGO and Virgo (Abbott et al. 2017). That event was associated with a gamma ray burst; the subsequent kilonovae and afterglow was perhaps the most thoroughly-observed astronomical event of all time (Abbott et al. 2017b). In the coming decades, with continued investment, the ground-based network will continue to improve in both the number and sensitivity of detectors at high frequencies, pulsar timing arrays such as NANOGrav will uncover stochastic sources of gravitational waves and then single sources at low frequencies, and LISA will begin to probe the mid-frequency band from space. In this white paper, we present a broad outline of the scientific impact of these facilities in the coming decade and the 2030s, emphasizing the ways in which they complement one another as well as other, more traditional astronomical resources[1].

[1]While the search for primordial gravitational waves through polarization of the Cosmic Microwave Background is an exciting and promising technique, it is not in the scope of GWIC and is not discussed here.

1. Introduction

Gravitational waves will allow us to pursue, with a new and unique probe, some of the most enigmatic questions in fundamental physics, astrophysics and cosmology; among the questions:

- What is the nature of black holes? Are there compact objects of tens of solar masses that are *not* black holes? How do binary black holes of tens of solar masses form and evolve?
- What are the signatures of horizon structure and quantum gravity accessible to gravitational-wave observations? Could dark matter be composed of primordial black holes?
- What is the physics of core collapse? What is the equation-of-state of ultra-high density matter and how large and massive are neutron stars?
- What is the expansion rate of the Universe? What is the nature of dark energy? What phase transitions occurred in the early Universe; what is their energy scale and gravitational-wave stochastic background signature? Do we live in a Universe with large extra dimensions? Is (classical) gravity described by General Relativity?
- How did supermassive black holes at the cores of galactic nuclei form and evolve? What were their seeds and demographics?

Gravitational Waves (GWs) are an independent source of information to electromagnetic and particle signals, and combining observations in these different domains can lead to insights which are otherwise inaccessible. Multi-messenger observations will transform the landscape of astronomy, astrophysics, fundamental gravity and possibly particle physics in the coming decade, with gravitational waves playing a key role. We briefly summarize the potential of gravitational-wave observations in the coming decades, and the complementarity and synergy of the various detectors, to accompany the more detailed white papers on the science possible with a range of GW detectors.

2. Gravitational Wave Astrophysics

The astrophysical discovery potential for Gravitational Waves (GWs) comes from fundamental differences between GWs and electromagnetic radiation. GWs couple directly to mass and provide direct information about dynamics. They propagate freely through dense regions of the Universe, providing insight about environments that are difficult to probe with other messengers. Finally, GWs can provide direct measurements of luminosity distance at large scales using our knowledge of General Relativity as calibration.

End States of Stellar Evolution: Binaries formed from pairs of compact stellar remnants such as White Dwarfs (WDs), Neutron Stars (NSs), or Black Holes (BHs) sweep up in frequency through first the millihertz band of space-based detectors and eventually into the Hz to kHz band of ground-based interferometers, providing information about the component masses, spins, distance, sky location, and orientation. Such measurements can yield clues as to the likely progenitor systems and their evolution. As ground-based instruments continue to operate and improve, we can expect

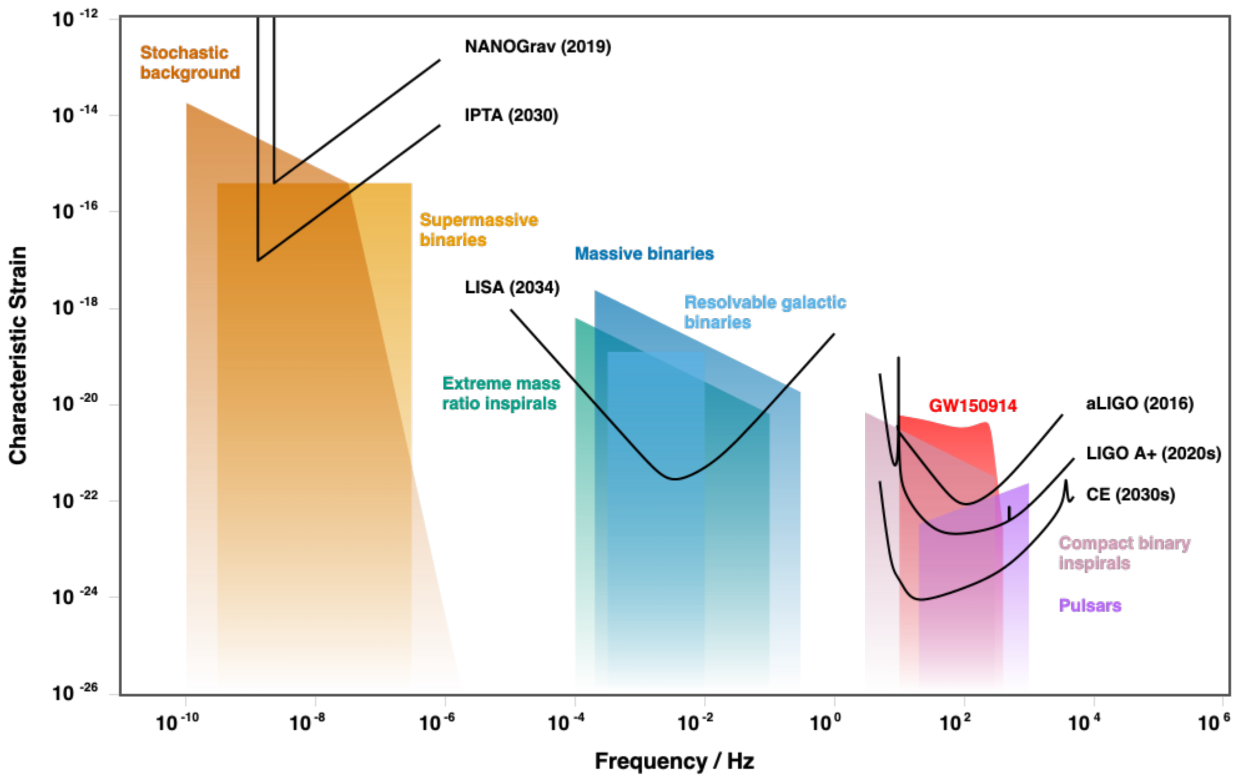

Fig. 1.— The Universe emits gravitational radiation from a variety of sources across the gravitational wave spectrum. Ground-based interferometers (e.g., LIGO, Cosmic Explorer shown here; Virgo, KAGRA, LIGO-India, and Einstein Telescope are other present and future instruments), space-based interferometers (e.g., LISA), and pulsar timing arrays (e.g., NANOGrav and the International Pulsar Timing Array (IPTA)) provide access to a wide swath of this spectrum. Produced with http://gwplotter.com/.

better statistics, more precise measurements, and ultimately reach to the edge of the universe for $\mathcal{O}(100)\,M_\odot$ systems.

With the arrival of LISA, tens of thousands of individual systems will be discovered, many of which with masses inaccessible to ground-based detectors. The population of WD-WD binaries in the Milky Way will enable investigations from the structure of our own galaxy, to the connection between WD-WD binaries and type Ia SNe (Adams et al. 2012). Beyond the Milky Way, hundreds of heavy stellar-mass BH binaries far from coalescence will provide precious complementary information to that gathered by ground-based detectors. Systems such as GW150914 will first sweep through the LISA band, crossing to the ground-based frequency band a few years later (Sesana 2017). LISA will allow precise determination of the sky location and time of coalescence weeks or more in advance, making it possible to schedule massive and deep EM coverage of the sky at the time of merger. Current ground-based detectors can offer minutes of advance warning for e.g., binary neutron star systems to help capture the first post-coalescence EM emission.

Massive Black Hole Growth and Evolution: MBHs inhabiting the centers of galaxies also frequently form binaries by pairing with other compact objects, either with other MBHs or with the capture of a stellar remnant (BH, NS or WD), initiating a so-called extreme mass ratio inspiral (EMRI). Both classes of sources are of capital importance in piecing together the puzzle of cosmic structure formation. LISA has the capability to detect mergers of black holes in the mass range $10^3 - 10^7$ $M_\odot$ out to whatever redshift at which they may have begun forming, even beyond $z = 20$ (Klein et al. 2016). LISA can follow the evolution of large-scale structure over time and, by exploring the demographics of black hole seeds (their masses and spins), can test models of how early black holes grow. At the supermassive ($10^8 - 10^9$ $M_\odot$) end of the mass spectrum, pulsar timing arrays unveil the cosmic population of inspiralling MBHBs that inhabit the largest galaxies in the Universe. These objects are invisible to LISA and ground-based detectors. Outstanding questions such as the fraction of MBHs in galaxies, the merger rate of galaxies, the relation between galaxy masses and the masses of the MBHs they host, the efficiency of pairing of MBHs, and the nature of their dynamical interaction with the local environments, will be answered by deciphering the information encoded in the amplitude and shape of the stochastic GW background (SGWB) spectrum, with upper limits already providing constraints on the physics of galaxy mergers (Arzoumanian et al. 2018). The detection of the SGWB will prove that dynamical interactions in the cores of galaxies solve the "final parsec problem", allowing SMBHs to merge. PTAs probe frequencies at the interface between the environment-driven (when the MBHs are far apart) and GW-dominated (when the MBHs separations are below a milliparsec) regimes.

3. Multi-messenger Astronomy

The era of multi-messenger astronomy with gravitational waves began with the detection of GW170817, the first gravitational-wave observation from the inspiral and merger of a binary neutron-star system (Abbott et al. 2017; Abbott et al. 2017b). The observations are consistent with the basic predictions of kilonovae and short off-axis GRB models. With the improvements in EM, particle, and GW detectors in the coming decade it will become possible to understand e.g., the equation of state of the neutron stars, the nuclear physics involved in the formation of heavy elements, and the physics behind the formation of relativistic jets from such binary coalescences. Other potential sources of MMA events are supernovae, where the expected GW emissions limit detection to the Milky Way Galaxy and a consequent low event rate; and continuous waves from slightly eccentric pulsars. Both are yet to be seen but would be rich sources of physics when observed either in GWs alone, or yet more rewarding with multiple messengers.

Massive black-hole coalescences (MBHC) resulting from the collision and merger of galaxies are expected to take place in environments with significant amounts of gas (Barnes & Hernquist 1991) and thus the possibility of electromagnetic signals associated with LISA detections. This could shed light on formation and evolution of MBHs and their galaxies, allowing detailed studies of accretion physics on MBHs of known masses and spins (extracted from the GW signal) for the first time. Simultaneous determination of redshift and the GW luminosity distance will enable measurements of the Hubble constant up to high redshift, and to infer bounds on the dark matter and dark energy content of the Universe (Tamanini et al. 2016).

At nanohertz frequencies, PTAs will enable individual detection of SMBHBs of $M > 10^9\,M_\odot$ at $z < 1$ (Sesana et al. 2009; Mingarelli et al. 2017) in their inspiral phase. Even with limited position and distance information (Sesana & Vecchio 2010) it will be possible to rank the most likely hosts within the PTA localization area (Mingarelli et al. 2017) and use time domain surveys (such as LSST), and spectroscopic observations to look for AGN variability matching the period of the detected GW, and other spectral signatures indicative of a possible binary (Dotti et al. 2012; Tanaka & Haiman 2013). The secure identification of counterparts will be critical to understand the distinctive signatures of SMBHBs, distinguishing them from regular AGNs. EM counterpart identification for SMBH coalescences will also enable the study of the environments of SMBHs, shedding light on the formation and evolution of black holes and their galaxies.

4. Cosmology

Gravitational waves from merging binary systems are "standard sirens" – the signal contains the information about the luminosity distance to the source (Schutz 1986; Krolak & Schutz 1987). Already LIGO and Virgo have made their first contribution to a measurement of the Hubble constant using the standard siren GW170817 (Abbott et al. 2017a). The current ground-based network, augmented by KAGRA (Aso et al. 2013) and LIGO-India (Unnikrishnan 2013), will improve this to a precision of a few percent in the coming decade. These measurements do not rely on astronomers' distance ladders, can be performed with or without EM observations, and may help resolve the existing tension between the two principal Hubble constant measurement methods (Feeney et al. 2018a,b), clarifying if this is due to measurement issues or new physics.

LISA and third-generation ('3G') ground-based observatories will reach to higher redshifts, enabling them to measure the amount of dark energy and possibly even the dark energy equation of state, even without counterpart identifications. Cosmological isotropy of sources can be tested. On smaller angular scales, these distances will also allow independent estimates of weak lensing, mapping the dark matter. The large variety of sources observed by LISA will provide different classes of standard sirens. Stellar BH binaries at $z \lesssim 0.2$ (Del Pozzo et al. 2018), EMRIs at $z \lesssim 1$ (MacLeod & Hogan 2008) and SMBHBs up to $z \approx 10$ (Tamanini et al. 2016) will enable precision cosmology across the whole astrophysically relevant redshift range, mapping H_o over distance and position.

The SGWB that will be detected by PTAs contains much cosmological information. The properties of the SGWB depend on the formation and evolution of cosmological source populations. PTA measurements of the SGWB produced by SMBHBs, the most promising GW source in that band, will constrain the evolution of the supermassive black holes that become QSOs and AGNs. In addition, PTAs are sensitive to GWs produced by fundamental physical phenomena such as phase transitions in the early universe, cosmic strings, and inflation, all of which would provide unique windows into high-energy and early-Universe physics. Finally, as for both ground- and space-based detectors, EM counterparts to SMBHB systems will allow for new measurements of the Hubble constant and a deeper understanding of the physics of galaxy mergers.

5. Fundamental Physics

While some aspects of general relativity can be tested to high-precision with systems losing energy due to gravitational-wave emission (Taylor & Weisberg 1982; Kramer et al. 2005), other deeper probes require the direct detection (delivering the time series of GW-induced strain) of gravitational waves (Sathyaprakash & Schutz 2009). Further more stringent tests of GR and of alternative theories can be made with higher signal-to-noise ratio detections, and over a broader range of frequencies – millihertz to kHz. For example, the detailed nature of black holes can be inferred, and theories tested, via the GW signal ringdown (Hughes et al. 2019). Upper limits – or a detection – of stochastic backgrounds can inform models of inflation and phase transitions including cosmic strings, and extra dimensions. The nuclear physics of neutron stars, and other compact objects, can be measured via coalescing binaries of various pairs of objects (Annala et al. 2018). Pulsar timing arrays are sensitive to a stochastic background of gravitational waves from cosmic strings, topological defects in spacetime, and have thus far set the most constraining limits on their tensions and reconnection probabilities (Arzoumanian et al. 2018).

Clearly there is also potential for GWs from sources not yet imagined. Having exquisitely sensitive detectors whose data are searched with a wide range of analysis techniques may pay off very richly with new science.

6. Summary

There is a great deal of exciting science to be done via both stand-alone observations of gravitational waves over a wide range of frequencies, and in concert with other astrophysical observations. Higher sensitivity radio telescopes for pulsar timing, a space-borne low-frequency gravitational antenna for very massive systems, and a new class of ground-based gravitational-wave antennas for stellar-mass sources will all be important elements of astronomy in the coming decades. Combined with observations across the electromagnetic spectrum, a new era of multi-messenger astronomy will reveal unique information about the Universe not accessible through any other means.

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