Astro2020 Science White Paper

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

Thematic Areas:

☐ Planetary Systems
☒ Formation and Evolution of Compact Objects
☐ Stars and Stellar Evolution
☐ Galaxy Evolution

☐ Star and Planet Formation
☒ Cosmology and Fundamental Physics
☐ Resolved Stellar Populations and their Environments
☒ Multi-Messenger Astronomy and Astrophysics

by
The Gravitational Wave International Committee (GWIC)
`https://gwic.ligo.org`

Temporarily in LIGO-P1900065-v1

[1] Addresses

ToDo and Worry About:

- **5 Pages Max** for the text per se; cover page and references do not count. Good ideas for new material must come with good ideas to slim text.
- do we have enough specificity on projects – LISA, yes; 3G? VLA upgrades?
- CW and Burst sources (SN, cosmic strings, etc.) are given very short shrift
- Instructions say "White papers should identify a primary thematic science area (and, if relevant, a secondary area) from the list below," – we have many checked (I removed a few)
- Figure: Ira writes...: I tried to keep the number of facilities plotted as notional, with an emphasis on what we have now (nothing for space unfortunately) and what we might hope to have on the time scale of the Survey. I also tried to emphasize US resources, which might initially raise some hackles at GWIC, but I think they should be understanding when they realize that this is for a US prioritization exercise. So for example, I re-labeled the EPTA curve as NANOGrav, figuring that on this scale, and for this audience, the performance was similar enough. I also added notional dates for the facilities, which should be checked. Again, there is some risk there, but I think for this kind of audience, it would be helpful.
- References. We need to get many more references. Some sections are well-referenced while others are not. A simple solution would be to minimize references and just point to a few key summary docs (e.g., the Gravitational Universe WP for LISA science). A nicer way to do it might be to beef up the references everywhere (there is some cost to length for the citations in the text, but not the References themselves). That would require some people who really know the subject to help identify the correct references.
- White papers should: 1. Identify scientific opportunities and compelling scientific themes for the coming decade, particularly those that have arisen from recent advances and accomplishments in astronomy and astrophysics; 2. Describe the scientific context of the importance of these opportunities, including connections to other parts of astronomy and astrophysics and, where appropriate, to the advancement of our broader scientific understanding; 3. While focusing on science, not specific missions or projects, describe and quantify the key advances in observation, measurement, theory, and/or computation necessary to realize the scientific opportunities within the decade 2020-2030 and beyond.

Summary: 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 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. 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. 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 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, emphasizing the ways in which they compliment one another as well as other, more traditional astronomical resources[1].

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; e.g.,

- What is the nature of black holes? Are there massive 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?
- Do we live in a Universe with large extra dimensions? 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?
- How did supermassive black holes at the cores of galactic nuclei form and evolve? What were their seeds and demographics?

Gravitational waves 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 astrophysics will transform the landscape of the coming decade, with gravitational waves playing a key role. We briefly summarize the potential of

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[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.

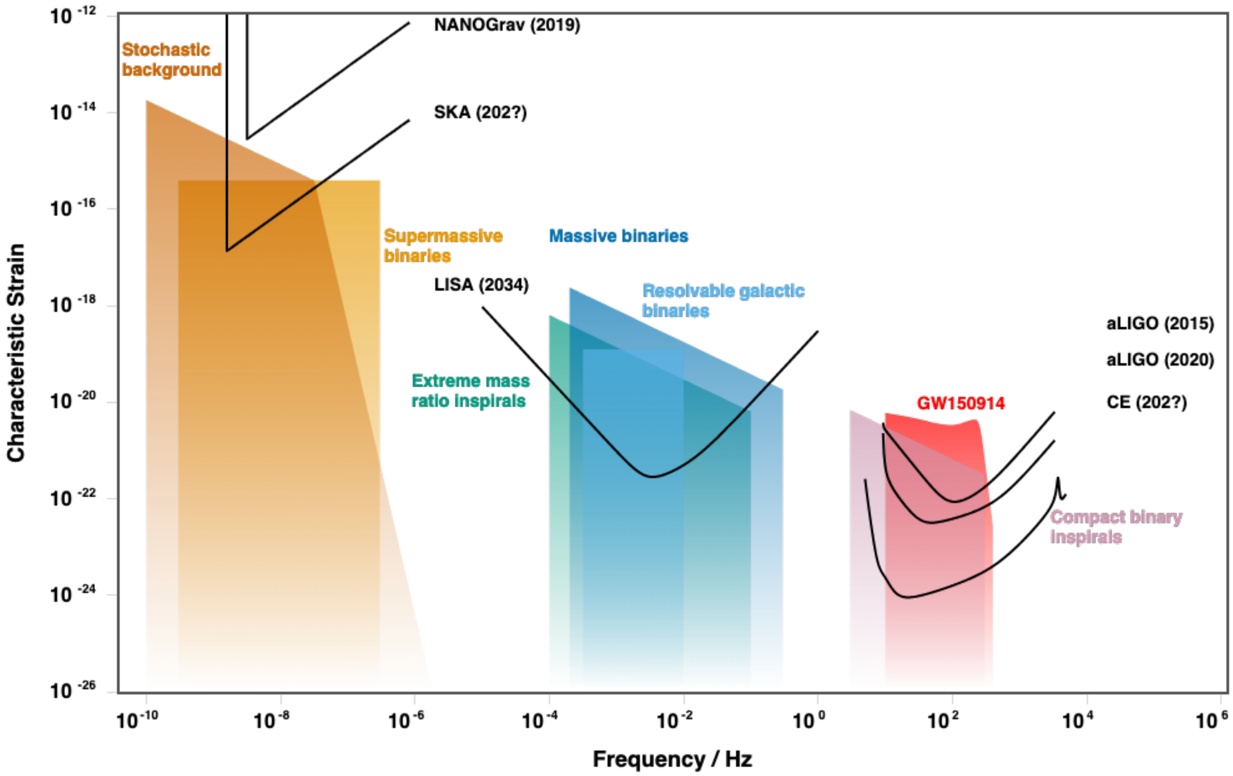

Fig. 1.— The Universe emits gravitational radiation from a variety of sources across the gravitational wave spectrum. Ground-based interferometers, space-based interferometers, and pulsar-timing arrays combine to provide access to a wide swath of this spectrum. Produced with http://gwplotter.com/. [Do we need to define all the projects here, maybe with URLs?]

gravitational-wave observations, and the complementarity and synergy of the various detectors, to accompany the more detailed white papers oriented around detector capabilities.

2. Fundamental Physics

While some aspects of general relativity can be tested to high-precision with objects losing energy due to gravitational-wave emission, other tests require the direct detection (delivering the time series of $h(t)$) of gravitational waves. 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. The quantitative nature of black holes can be seen in the GW signal ringdown. 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. 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).

3. 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 better statistics, more precise measurements, and ultimately reach to the edge of the universe for $\mathscr{O}(100)\mathrm{M}_\odot$ 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. Beyond the Milky Way, hundreds of 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. 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.

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) by a MBH initiates 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 $10^3 - 10^7\mathrm{M}_\odot$ 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), LISA can test models of how early black holes grow. At the supermassive ($10^8 - 10^9$ $\mathrm{M}_\odot$) 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 occupation 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 environments at the cores of galaxies, 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.

4. 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 confirmed the basic predictions of kilonovae and short off-axis GRB models. With the improvements in EM, particle, and GW detectors in the coming decade will come further understanding of e.g., the equation of state of the neutron stars, the ejected mass, the nuclear physics involved in the formation of heavy elements, and the physics behind the formation of the relativistic jet from such binary coalescences. Other potential sources of MMA events are supernovae, for which the limited GW emission limits 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 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 $M > 10^9 \mathrm{M}_\odot$ at $z < 1$ (Sesana et al. 2009; Mingarelli et al. 2017) in their adiabatic 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 all available spectroscopic observations to look for periodic AGN 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 of study the host environments of SMBHs shedding light on the formation and evolution of black holes and their galaxies.

5. 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 and LIGO-India, will improve this to a precision of a few percent in the coming decade. These measurements do not rely on astronomers' distance ladders, 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.

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, just like for ground-based and spaced based detectors, EM counterparts to individual SMBHB systems will allow for new measurements of the Hubble constant and a deeper understanding of the physics governing galaxy mergers.

6. Summary

There is a great deal of exciting science to be done via both stand-alone observations of gravitational waves in a wide range of frequencies, and in concert with other astrophysical observations. Higher sensitivity radio arrays 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. In concert 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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