Astro2020 Science White Paper

MULTIMESSENGER UNIVERSE with GRAVITATIONAL WAVES from BINARY SYSTEMS

Thematic Areas:

- Formation and Evolution of Compact Objects
- Stars and Stellar Evolution
- Multi-Messenger Astronomy and Astrophysics

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Multimessenger Universe with Gravitational Waves from Binaries

The discovery of GW170817 [1] was a watershed moment in astronomy. Gravitational wave (GW) and electromagnetic (EM) observations of this event provided incontrovertible evidence that binary neutron star (BNS) mergers are connected to short gamma-ray bursts [2] and the precise optical localization [3] unveiled that these are prolific sites of heavy element nucleosynthesis. Furthermore, they showed that to an outstanding accuracy the speed of gravitational waves is identical to the speed of light and allowed the first measurement of the Hubble constant using GW standard sirens [4, 5], ushering in a new era in cosmology. Observations of the event in the entire EM window [6] have accumulated a treasure trove of data that will have a lasting impact on our understanding of some of the most energetic phenomena in the Universe and matter in extreme environs.

Future GW detector networks and EM observatories will provide a unique opportunity to observe the most luminous events in the Universe involving matter in extreme environs. The observations will address some of the key questions in physics and astronomy:

- **Formation and Evolution of Compact Binaries.** How do double neutron star and neutron star-black hole binaries form and evolve; what are their demographics, merger rates, and mass and spin distributions as a function of redshift?
- **Sites of Formation of Heavy Elements.** What is the role of neutron star mergers in the production of heavy elements in the Universe? Are they able to explain abundances in the Solar System and stars?
- **Jet physics.** What is the physics of central engines in mergers, and how do they relate to short gamma-ray bursts? How do the jet properties vary with progenitor binary parameters?
- **Multi-band GW Astronomy.** What can joint observations by the Laser Interferometer Space Antenna and the 3G network tell us about the origin and evolution of black holes?

Capabilities of Next Generation Detector Networks: The next generation of GW detectors (3G, see Table 1) will compile surveys of the Universe for close binary coalescence events in which one of the companions is a neutron star and the other is either a stellar mass black hole or also a neutron star. The Table shows the capability of a third generation detector network (3G) compared to the current network of advanced detectors at their design sensitivity.

For this simulation, source redshifts were sampled from a merger redshift distribution of binary neutron stars, assuming the Madau-Dickinson star formation rate, with an exponential time delay between formation and merger with e-fold time of 100 Myr (see [7]) and a local co-moving BNS merger rate of 1000 Gpc^{-3} yr^{-1}. It is clear that the 3G network will provide ample opportunity for EM follow-up of BNS mergers. Key science questions addressed by the detected population in the 3G era is very rich and diverse. Localizing the EM counterpart to such events will allow us to characterize matter in extreme environments. The redshift of the host galaxy enables cosmological applications, whilst the sub-arcsecond localization of the

Table 1: Expected detections per year (N), number detected with a resolution of < 1, < 10 and < 100 sq. deg. (N_1, N_{10} and N_{100}, respectively) and median localization error (M in sq. deg.), in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV plus KAGRA and LIGO-India (HLVKI) and 1 Einstein Telescope and 2 Cosmic Explorer detectors (1ET+2CE).

Network	N	N_1	N_{10}	N_{100}	M
HLV	48	0	16	48	19
HLVKI	48	0	48	48	7
1ET+2CE	990k	14k	410k	970k	12

kilonova provides information about the nucleosynthesis, environment of the event, jet physics and formation scenarios.

Demographics of Compact Binary Mergers

A key question about compact binary mergers is their demographics, as this could reveal their formation mechanism. Localization of merger events to less than galactic scales ($\sim$ 30 kpc) is essential to unambiguously infer associations of mergers with their host galaxies. Without an EM counterpart the vast majority of events will have error boxes that greatly exceed the typical radii of potential host galaxies. The merger fraction split between early type and star-formation galaxies will provide a fascinating insight into the fraction of mergers that are created with short gravitational "fuses" [8] that are comparable to the evolutionary timescales of massive stars and those that extend out to a Hubble time. Their locations [9, 10] within the hosts will give insights into the kick velocities imparted to the binaries during their supernova explosions.

EM follow-up of BNS mergers will be critical in pinning down host galaxies. Binary black hole (BBH) mergers, not believed to produce any EM counterparts, will not be resolved well enough to unambiguously identify their hosts. The situation is more optimistic for neutron star-black hole (NSBH) mergers. Theoretical predictions suggest that when the mass ratio is not too extreme depending on the BH spin, conditions could be favorable for the creation of an accretion disk around that might rival the absolute visual magnitude of the GW170817 kilonova, and, therefore, be detectable out to $z = 0.5$ in the reddest filters. If such mergers occur in the globular cluster cores it will be difficult to identify host clusters much beyond Virgo, and those in Virgo do not require a 3G GW detector for discovery.

In the modern paradigm, galaxies are assembled by the merger of smaller proto-galaxies and star formation peaks near $z \sim 2$ [11]. Identification of kilonovae beyond $z \sim 0.5$ requires hour-long integrations on 8m class facilities like LSST or Subaru and therefore determining the host galaxies of BNS mergers near the peak of star formation will not be routine in the absence of a gamma-ray burst jet pointing towards the Earth, even with ELTs. Nevertheless, at redshifts $z < 0.5$ 3G detectors will work in concert with astronomy facilities to enable thousands of host galaxy identifications from BNS and NSBH mergers thanks to the identification of a kilonova. At larger distances, the identification will be possible only through the detection of an associated gamma-ray burst afterglow, which can be much more luminous than a kilonova if the jet is directed towards the Earth.

Nucleosynthesis in Binary Neutron Star Mergers

A long standing puzzle in astrophysics is how the elements heavier than iron came into being. About half of these elements are believed to have been created by a process of rapid neutron capture (the "r-process"), but it is unclear which astrophysical sites are the main contributors. Neutron star mergers have long been proposed as a possible site[12]. GW170817 and its associated thermal EM counterpart provided the first direct identification of a prolific site of r-process nucleosynthesis [6]. However, determining the degree to which BNS mergers contribute to cosmic chemical abundance and evolution will require a more extensive determination of the rates, locations, timescales, and nucleosynthetic yields of the various types of merger events. Even the basic question of whether all three r-process abundance peaks were synthesized by GW170817 is debated [13, 14].

Heavy elements can be synthesized in BNS or NSBH mergers when clouds of neutron-rich material are expelled, either dynamically during the merger or later in the form of winds blown off the remnant accretion disk. The subsequent radioactive decay of the freshly synthesized elements powers a thermal optical/infrared transient known as a “kilonova”. Theoretical modeling has demonstrated how measurements of the brightness and color of the kilonovae are diagnostic of both the total mass of r-process elements and the relative abundance of lighter to heavier elements [15].

Whereas historical studies of chemical evolution have relied on observing fossil traces of r-process elements mixed into old stars, multi-messenger observations (MMOs) provide the unique opportunity to study heavy element formation at its production site and to determine how the initial conditions of an astrophysical system map to the final nucleosynthetic outcome. Answering the basic question of the extent to which BNS and NSBH mergers are the dominant site of r-process production will require MMOs of a large sample of events. GW measurements would pin down the rate of mergers and the binary properties, such as the binary type (BNS or NSBH), companion masses, the merged remnant lifetime and the spin-orbit alignment, while optical/infrared photometry of the associated kilonovae would determine the average r-process yields. Detailed infrared characterization would probe the relative abundance distribution and how similar or different it is from the solar abundance distribution of heavy elements. These observations would also illuminate the key physics driving the r-process and kilonova, such as the equation of state of dense matter, the fundamental interactions of neutrinos and the magneto-hydrodynamics of accretion.

Statistical studies of MMOs will reveal how r-process production in BNS and NSBH mergers depends on host galaxy type, location and redshift, allowing us to piece together the history of when and where the heavy elements were formed over cosmic time. Such studies can determine the distribution of delay times between star formation and merger, thereby addressing whether some BNS and NSBH mergers occurred promptly enough to explain the enrichment of the oldest metal poor stars and the extent to which compact binaries receive strong kicks that move them within, or expel them from, their host galaxies, a factor that is important for understanding whether mergers can explain the unusually high r-process enhancement seen in some dwarf galaxies [16].

In addition to discovering BNS and NSBH mergers beyond the peak of star formation, 3G detectors, because of their wide band sensitivity, will track the full inspiral, merger and ringdown signal. This could enable exquisite measurements of the intrinsic masses prior to coalescence, and determine companion spins and the nature of the remnant, key parameters to fully determine the dynamics of the merger, the nature of the relic star, and the type of debris responsible for panchromatic emission of radiation. State of the art numerical magneto-hydro-dynamical simulations will provide key insight into the geometry and physical state of the debris, in the form of ejecta, winds and discs that can be used to model the EM signal. Thus, the combination of information derived independently from the EM and GW signals will be immensely powerful to build a complete, self-consistent astrophysical picture.

In the era of 3G detectors, optical kilonovae will be detectable by LSST out to 3 Gpc and infrared characterization photometrically by WFIRST/Euclid and spectroscopically by JWST/GMT/TMT/E-ELT would be out to 1 Gpc ($z<0.2$). In summary, building the necessary sample size of a thousand kilonovae with detailed ultraviolet-optical-infrared follow-up to probe the nucleosynthesis and ejecta properties is a realistic goal in the 3G era.

Jet Physics in BNS and NSBH Mergers

Relativistic explosions and compact-object mergers can generate collimated, energetic jets of material and radiation. Our understanding of jet physics thus far comes from studies of gamma-ray bursts, active galactic nuclei and X-ray binaries. Multi-messenger observations provide an entirely new perspective on this topic.

The panchromatic study of GW170817 revealed that there was both a wide-angle mildly relativistic cocoon [17–19] as well as a narrow ultra-relativistic jet [5, 20–22]. This was not seen in previous studies of cosmological short-hard gamma-ray bursts. Combining the EM and GW allowed to directly constrain system parameters with unprecedented precision. GW170817 opened up many questions for future events to answer. Specifically, what is the connection to the class of cosmological short hard gamma-ray bursts? Does a wide-angle mildly relativistic cocoon always accompany a BNS merger? Does the jet always successfully escape the cocoon or is it sometimes choked? How do the observed jet properties vary as a function of viewing angle, mass ratio, hypermassive neutron star lifetime, remnant spin, and ejecta mass? Do mergers produce prompt EM signals? What is the distribution of the time delays between the EM and GW signal arrival times? What are the characteristics of a jet from a NSBH merger? With the first census of BNS and NSBH coalescences, and full GW and EM coverage of the signals, joint multi-messenger Bayesian parameter inference will be key in understudying the physical origin of jets, ubiquitous around relativistic sources [23–26]. For the first time, a direct measurement of the BH spin in a source emitting a collimated jet, will enable to establish the close correlations between the jet power, the spin and the inflow rate from the debris disk, which determines the conditions for launching the jet.

The 3G GW network combined with new, powerful EM facilities can further revolutionize our understanding of the physics of jets. 3G network will enable the detection of neutron-star mergers out to redshifts of $z \sim 10$. Even with the planned upgrades, we are limited by the sensitivity of gamma-ray, X-ray and radio telescopes to study jet physics to only out to 500 Mpc. To build a sample large enough to map the full parameter space, we would need $\sim$ thousand events localized to better than few sq deg. This is a realistic goal with the proposed 3G network.

Cosmology

Joint GW and EM observations provide a completely independent tool for measuring the dynamics of the universe and to constrain cosmological parameters such as the Hubble parameter, dark matter and dark energy densities, and the equation of state of dark energy [4, 27–30]. It is estimated that about 10 compact BNS or NSBH mergers with EM counterparts are required to reach H_0 measurements at the 5% level, and 200 to reach 1% [31–33]. While BNS events are promising based on GW170817, NSBH mergers, due to precession of the orbital plane because of spin-orbit coupling, can break the degeneracy between the orbital inclination and luminosity distance, and provide accurate distance measurements [34]. In addition, EM observations could also break this degeneracy [35]. There is significant potential in statistical methods as well, where sources without EM counterparts are combined with galaxy catalogs to make inferences [36]. For example, 3G detectors will localize some BBHs within a volume where on average only one galaxy is present [37, 38], although the method is limited by the peculiar velocity at the redshift of interest and the distance uncertainty from GW observations ($\approx 1\%$).

Multi-band GW astronomy with LISA

Joint observations of GW events by the Laser Interferometer Space Antenna (LISA) at milli-Hertz frequencies and 3G detectors at audio frequencies could maximise their science potential. If LISA had been observing in 2010, it would have detected GW150914 years before it was observed by LIGO [39]. Indeed, LISA will see up to thousands of stellar-mass BBH mergers of $M > 20-30 M_{\odot}$, up to $z \approx 0.3$ [39, 40]. A small fraction of them will sweep across the detector band within few years

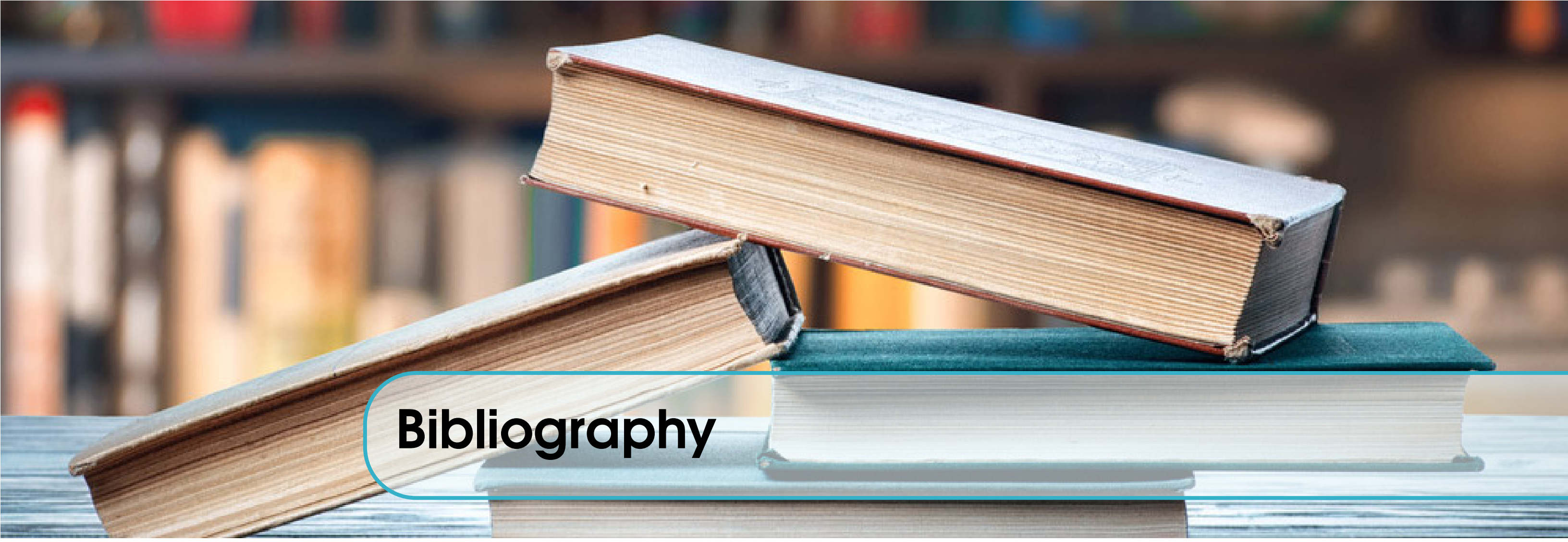
Table 2: Present (P) and future (F) electromagnetic facilities that are able to observe faint/distant counterparts to GWs. Detection Limit (**DL**, 1 hr exposure time) for UV, optical, and near-IR facilities are expressed in AB magnitudes, for X-rays in $10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{2}}$, and for radio in μJy. Distance reach (**D** in Mpc) of facilities for GW170817-like events are shown.

	Facility	**DL**	**D**
Gamma-rays	*Fermi P*	S/N 5	80
	AMEGO *F*	S/N 5	130
X-rays	*Swift P*	S/N 5	$\sim$80
	Chandra P	30	150
	ATHENA *F*	3	480
	Lynx F	6	450
	STROBE-X *F*	S/N 5	120
UV	HST (im) *P*	26	2000
	HST (spec) *P*	23	400
Optical Imaging	Subaru *P*	27	3200
	LSST *F*	27	3200
Optical Spec.	Keck/VLT *P*	23	500
	GMT *F*	25	1265
	TMT *F*	25.5	1592
	E-ELT *F*	26	2005
Infrared Imaging	WFIRST *F*	27.5	4800
	Euclid *F*	25.2	1700
Infrared Spec.	Keck/VLT	21.5	481
	GMT *F*	23.5	762
	TMT *F*	24	960
	E-ELT *F*	24.5	1208
Radio	VLA (S) *P*	5	91
	ATCA (CX) *P*	42	51
	ngVLA (S) *F*	1.5	353
	SKA-mid (L) *F*	0.72	634

that will eventually be detected by ground-based detectors. The benefit of multi-band observations of such events will be quite significant.

LISA would provide a precise measurement of the system's eccentricity (to a precision of $\Delta e < 0.001$ [41]), sky localization to 0.1 sq. deg and time to coalescence within few seconds, several weeks prior to coalescence [39]. This will help point an EM telescope in the right direction *before* the merger, providing a much deeper coverage from radio to gamma-ray than what might be possible without any early warning alert. This could also allow real time optimization of 3G detectors to tune their sensitivity to observe the ringdown signal, thus enhancing the potential of BH spectroscopy [42]. On the other hand, one can use the information extracted by 3G network to dig out sub-threshold LISA events [43]. From an astrophysical standpoint, the eccentricity information delivered by LISA can be combined with the spin measurement obtained from 3G detectors to better constrain different formation channels [44–46]. Multi-band observations will also facilitate tests of GR [47] by enhancing the sensitivity to specific deviations arising in the long adiabatic inspiral as predicted, for example, from dipole radiation [48].

The future of multi-band GW astronomy lives in the observation of intermediate-mass black holes [49, 50], the most elusive sources that might form at the center of dense clusters as the end-product of runaway collisions [51], or result from the death of very massive, low metallicity stars [52]. Multi-band GW astronomy will also be realized by complementary observations of different samples of the same population of sources. Seed black holes are a case in point [53]: While LISA will be sensitive to mergers of $M \geq 10^3 M_\odot$ binaries out a redshift of $z > 20$, 3G detectors can access $M \sim 100 M_\odot$ population at comparable redshifts. If 3G detectors see a $\sim 100 M_\odot$ merger at high z, one question that arises is whether those are the seeds of massive black holes (MBHs) or a different population that will not evolve into MBHs. Multi-band GW observations will likely solve this issue by quantifying the continuity between the two populations.



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