# Snowmass2021 - Letter of Interest

# *Probing the expansion history of the Universe with Gravitational Waves*

**Thematic Areas:** (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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**Abstract:** (maximum 200 words)

Gravitational waves are a novel probe of the Universe. Compact binaries observed via gravitational waves are self-calibrating distance indicators, known as 'standard sirens'. This property makes them an excellent probe of the expansion history of the Universe, and its underlying physics, without the need for additional distance anchors in either the local or early-Universe. Observations from Advanced LIGO and Virgo have already given a first measurement of the Hubble constant. Ground-based and space-based gravitational-wave observations in the coming decade aspire to start constraining the parameters of cosmic acceleration, giving us insight into the nature of dark matter and dark energy. Existing tensions in cosmological observations, including the "Hubble tension", further increase the merit and relevance of independent measurements of cosmological parameters in the gravitational-wave sector. The current program of using electromagnetic counterparts and galaxy catalogues for these measurements will, over the coming years, be augmented with methods involving cross-correlations with large-scale structure taking into account the clustering of matter. Knowledge of internal physics of neutron stars and astrophysical mass distribution of observed compact binaries will also subsequently advance gravitational waves as a truly independent probe of cosmology.

**Motivation.** The discovery of gravitational waves (GWs) has opened up several remarkable avenues to understanding fundamental physics and cosmology [1–11]. Compact binary mergers are driven by Einstein's equations and as such the GW signals emitted in the process, both the amplitude and phase, are precisely modeled in terms of the parameters of the source. Since the signal's amplitude and phase determine the observed GW flux and source's absolute luminosity, respectively, it is possible to directly infer the luminosity distance, circumventing the need to independently calibrate the source—a unique feature that has earned them the name *standard sirens* [12, 13]. With an independent measurement of the cosmological redshift, GW observations can be used to constrain the parameters of the redshift-luminosity distance relationship, namely, the Hubble constant, $H_0$, the matter, curvature, and dark energy density fractions $\{\Omega_m,\,\Omega_K,\,\Omega_\Lambda\}$, as well as the parameters of the dark energy equation of state $\{w_0, w_a\}$. The redshift information can come from an electromagnetic (EM) counterpart [14–16], potential hosts in a galaxy catalogue [12, 17], the spatial correlation of GW events with the redshift distribution of galaxies [18, 19], the observed distribution of compact object masses (which are redshifted) relative to the source-frame distribution [20–23], or purely from the internal physics of neutron stars [24–27].

The multimessenger detection of the binary neutron star (BNS) merger GW170817 led to the first GW standard-siren measurement of $H_0$ [7, 28, 29], and paved the way for a rapid progress in standard-siren science. In light of the "Hubble tension," an increasing discrepancy between the local and early-universe measurements of $H_0$ [30, 31], GWs provide a completely independent measurement, and can potentially resolve the discrepancy or reveal new physics beyond the standard Λ-CDM model of cosmology. Over the coming decade and beyond, GWs will establish an alternate pathway to probe the cosmic expansion and acceleration, giving us insight into the nature of dark matter, dark energy, and large-scale structure of matter in the Universe.

**Sources with electromagnetic counterparts** Compact binary mergers in which at least one of the companions is a neutron star could generate coincident GW and EM signals. Observations of EM counterparts provide better sky localization of the sources, facilitating the search for the host galaxies and their redshifts. A short gamma-ray burst GRB 170817A, as well as a kilonova AT 2017gfo, were observed concurrently with GW170817 [7, 28]. This led to a prompt identification of the host galaxy and the first GW standard siren measurement of $H_0$ [29].

The current GW detector network will expand with inclusion of more detectors and improve as detectors are upgraded to "A+" sensitivities over the coming decades [32–38]. With a target BNS range of $\gtrsim 500\,\mathrm{Mpc}$, $\mathcal{O}(10\text{–}100)$ BNS events are expected over the upcoming observing runs [32]. A precision of $\sim 5\%$ $(1\%)$ in the measurement of $H_0$ is expected with about 10 (200) joint GW-EM observation of BNS mergers [39–43]. In addition to BNSs, neutron star-black hole mergers are also potential sources with EM counterparts [44–46] that could serve as powerful probes of cosmology. The next generation of ground-based GW observatories (3G), e.g. the Cosmic Explorer [47,48] and Einstein Telescope [49–54], will detect BNSs out to a redshift of $z \sim$ 2–3 [55]. Along with their precise measurement of the luminosity distance, sub-percent $H_0$ and percent-level $\{\Omega_m, w_0\}$ measurements are possible with $\mathcal{O}(1000)$ BNS with EM joint detections [56–58].

In addition to the ground-based GW observatories, the Laser Interferometer Space Antenna (LISA) targets GW signals in the 0.1 mHz to 1 Hz frequency range [59]. Among the potential GW sources detectable by LISA, supermassive black hole binary mergers are expected to produce EM counterparts observable up to $z \sim 8$ [60]. This allows for a unique measurement of their redshift, and hence yield constraints of the cosmological parameters that can complement and expand those from both EM probes, e.g. type Ia SNe and ground-based GW observatories [61–63].

**Use of galaxy catalogues** In the absence of an EM counterpart, galaxy catalogues can identify a set of potential hosts from the GW sky localization and provide possible source redshifts [11,12,14,17,41,64–70].

Although the precision of the measurement in this approach is expected to be a factor of a few worse than that with EM counterparts [41,67], the use of galaxy catalogues is a good alternative when the observations of EM counterparts are unfeasible. The most promising sources are the well-localized GW sources followed up by a deep EM survey [11, 41, 66, 68, 69]. The true power of the method comes from combining the available information from multiple detections, and coordinated efforts of GW and EM communities towards addressing systematic effects in this measurement [66,68].

Indeed, planned upgrades to LIGO (A+) and 3G ground-based observatories will allow for a precise sky localization of black hole binary coalescences so as to uniquely identify the host galaxies for nearby GW sources [71,72]. One or two such events would be sufficient to determine the Hubble constant to within a few percent [71,72]. LISA sources for which EM counterparts are not expected, such as extreme mass ratio inspirals, stellar mass binary black holes and intermediate mass binary black holes, can be well localized, providing a reduced number of potential host galaxies for the GW sources (if not uniquely identified) and allow for the galaxy catalogue approach of the standard siren measurement, at least at lower redshift ($z \lesssim 1$) [14,18,19,73,74]. Especially, the combination of low and high redshift measurements makes LISA a unique cosmological probe able to map the expansion of the universe from $z \sim 0.1$ to $z \sim 10$ [75].

**Application of Astrophysical distribution** The masses of binaries measured by GW detectors are redshifted by the cosmic expansion. With a knowledge of the astrophysical mass distribution of the GW sources, the redshifts of the sources can be estimated. For BNS mergers observed with Advanced LIGO-Virgo at design sensitivity, it will be possible to measure $H_0$ with a $\sim 20\%$ precision using $\mathcal{O}(100)$ detections and jointly infer the BNS population parameters to a level of 1–10% [21]. With the extended detection range for BNS mergers of 3G observatories, it will be possible to measure $w_0$, $w_a$ and the population parameters to the level of $\sim 2\%$ using $\mathcal{O}(100)$ observations [22]. Robust features of BBH mass distribution, such as the upper mass gap of the pair-instability supernova process, can also be similarly used to measure the redshift-dependent Hubble parameter $H(z)$, yielding a percent-level measurement within a few years of operation of the LIGO-Virgo-KAGRA network at design sensitivity [23,76].

**Neutron star tidal effect as a probe of the source-frame mass** Tidal effects in the GW waveform of a BNS or NSBH merger can break the degeneracy between the source redshift and masses with the knowledge of the neutron star equation-of-state. 3G observatories are expected to tightly constrain the neutron star equation of state [77], allowing for a GW-based redshift measurement accuracy of $\sim 8\%$–$40\%$ [24–27]. With $\mathcal{O}(10^{6-7})$ BNS detections per year, 3G observatories will constrain cosmological parameters with the same accuracy as Planck [27]. This completely independent approach can confirm established wisdom and more importantly has the potential to unveil hitherto unknown physics.

**GWs as probes of dark matter distribution** The spatial distribution of the GW sources with respect to the underlying dark matter distribution is currently unknown, but can be scrutinised in terms of the *GW bias parameter* [18]. With the availability of a large sample of multi-messenger tracers, such as GW sources and galaxies, we will be able to measure the GW bias parameter, its redshift dependence and scale dependence using cross-correlation between the multi-messenger probes [18, 19, 78, 79]. The cross-correlation will also provide interesting information regarding the origin of compact-object binaries and their association with dark matter. Also, auto-correlation [80, 81] between GW sources will also probe the bias parameter in the longer time-scale using GW sources with better sky-localization. Besides the bias parameter, the *gravitational lensing* of GW strain [82, 83] by the intervening matter distribution is also a powerful probe to explore its spatial distribution [84] and for testing different theories of gravity [85, 86].

**Summary.** LIGO/Virgo observations have paved a path towards establishing gravitational waves as a parallel, independent probe of late-time cosmology. With planned upgrades of the current detectors and expansion of the detector network, as well as new ground- and space-based observatories, gravitational-wave observations will provide novel insights into key questions in cosmology.

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