IMPROVING MEASUREMENTS OF THE COSMIC EXPANSION WITH GRAVITATIONAL WAVES

In a new LIGO Virgo KAGRA publication, we use a set of 47 gravitational-wave sources from the newly-published Gravitational-Wave Transient Catalog GWTC-3 to measure the local expansion rate of the Universe. From their waveforms, we estimate the distances of these GWTC-3 sources, which comprise the mergers of binary black hole, binary neutron star and neutron star-black hole systems. We then derive redshift information for these binaries from the measured distribution of their masses, or from the distribution of redshifts mapped by the galaxy catalog GLADE+, and we combine these measurements to infer a new and significantly improved estimate of the Hubble constant. With the promise of many more gravitational-wave (GW) detections to come in the next few years, our novel GW method for probing the cosmic expansion may soon shed some light on the current "Hubble tension": the strong and puzzling disagreement between measurements of the Hubble constant obtained using different methods.

Cosmology and Gravitational Waves in a Nutshell

In the 1920s Georges Lemaître and Edwin Hubble made the discovery that our universe is expanding (see **Figure 1** for a cartoon illustration). This breakthrough revolutionised our understanding of the cosmos and underpins the Big Bang Theory, one of the cornerstones of modern cosmology.

***Figure 1**. Schematic representation of the cosmic expansion, in which galaxies are carried apart from each other on the surface of an expanding balloon. (Credits: Eugenio Bianchi, Carlo Rovelli & Rocky Kolb)*

The local expansion rate of the universe is measured by the Hubble constant, denoted by the symbol H_0 and expressed in units of kilometres per second per Megaparsec (Mpc). However, even after nearly a century, the value of the Hubble constant has not yet been accurately determined. There are clear inconsistencies between 'state of the art' measurements (mostly in the range 65 to 80 km s^{-1} Mpc^{-1}) using different methods. For example, we can infer the Hubble constant indirectly from measurements of the first light of the Universe, when its age was about 380,000 years, known as the cosmic microwave background, or CMB, and this approach yields values very close to H_0 = 68 km s^{-1} Mpc^{-1}. Alternatively, we can determine the Hubble constant more directly from studying the brightness of type Ia supernovae and pulsating stars known as Cepheid variables, which yields values very close to H_0 = 74 km s^{-1} Mpc^{-1}. These values are in serious disagreement, given their very small quoted uncertainties, and the discrepancy is too large to be simply down to the unavoidable random variations we expect from different measurements. This so-called "Hubble tension" has, therefore, become a major problem for cosmology.

Meanwhile, since 2015 we have opened an entirely new window for observing the Universe - based not on electromagnetic waves (i.e. light, produced by displacement of electric charges) but on gravitational waves (produced by acceleration of masses). Gravitational waves are 'ripples', or perturbations, in the fabric of spacetime. They were predicted by Albert Einstein in 1917 and their observation is a beautiful confirmation of his theory of general relativity. Among the strongest known sources of gravitational waves in the Universe are pairs of extremely dense, compact objects known as black holes or neutron stars. As these stars orbit each other, tied by gravity, they lose energy through the emission of GWs and their orbit shrinks until they merge into a single black hole. If we observe the GW emission from the merger of such a compact binary system, analyzing the merger waveform and how it evolves allows us to directly measure the distance to the binary system. This is in stark contrast to many other, more traditional, methods to measure cosmological distances (including the Cepheids and type Ia supernovae mentioned above) which rely on multiple steps of calibration via what astronomers refer to as the cosmic distance ladder.

This exquisite property of being a *self-calibrated* distance indicator, able to bypass the rungs of the cosmic distance ladder, has fuelled great interest in these compact binary GW sources, which are termed "standard sirens". If the direct distance measured to a standard siren can be combined with independent information about the source's velocity away from us – which we can deduce from the redshift of the source's host galaxy – we can measure the Hubble constant.

Turning to the dark side

For a neutron star binary merger with an electromagnetic (e.g. optical) counterpart, the redshift of the host galaxy is easy to measure. The first binary neutron star to be discovered in GWs, GW170817, came with a bright electromagnetic counterpart. This led to prompt identification of the galaxy (NGC4993) hosting the neutron star binary merger, and its redshift was combined with the direct GW distance measured to GW170817 to obtain the first gravitational-wave standard siren measurement of the Hubble constant.

Unfortunately most binary mergers, and in particular binary black hole (BBH) mergers, do not have associated electromagnetic counterparts. However, in the absence of such a counterpart indicating the host galaxy of each source directly, we can still use our GW observations to obtain information about the redshift of the sources.

Firstly, we can exploit the fact that the BBH masses that we *measure*, in the reference frame of our LIGO and Virgo detectors, are redshifted by the cosmic expansion – i.e. the BBH masses appear to be larger than they really are, just like the light from a receding galaxy is similarly stretched to longer (redder) wavelengths. This means that the statistical distribution of BBH masses that we measure can also, in principle, supply information about the statistical distribution of redshifts of our source population. We can combine this information with their measured distances to infer the Hubble constant.

Secondly, we can use the GW observations to constrain the sky position of the source – and in this way narrow down the host galaxy to a set of candidate galaxies in this region. Combining redshift information measured directly for all of these possible host galaxies then allows us to infer H_0 statistically – as was first outlined in a seminal 1986 paper by Bernard Schutz.

So our GW observations, even without electromagnetic counterparts, can thus serve as "dark standard sirens".

How does it work?

To understand in more detail how we can use the redshifted masses of our BBH population to measure the Hubble constant, suppose that the masses of black holes in our universe follow a distribution with a clear peak, due to some physical process related to their formation. (There is, in fact, some support for the existence of just such a peak based on the theoretical prediction that stellar black hole remnants have a maximum allowed mass since more massive stars would explode in such a violent way that nothing is left behind – a phenomenon known as a Pair Instability Supernova). Although we are only able to measure the redshifted masses of each BBH, we can nevertheless expect that the observed distribution of these redshifted masses will also bear an imprint of that peak – albeit also redshifted by the cosmic expansion. So the *observed* peak in the mass distribution tells us about the redshifts of the BBHs, and we can combine that information with our measured BBH distances to infer the expansion rate of the Universe.

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GWTC-3 data release:

https://www.gw-openscience.org/

Our second statistical method for measuring H_0 involves using a galaxy catalog, known as GLADE+, which systematically collates information about the redshift, brightness, color and other properties of (quite literally!) millions of galaxies in our region of the Universe. Since the GW data tells us about the sky position and distance of each standard siren, we can cross-match that information with our GLADE+ catalog to identify possible host galaxies in which the siren could have occurred. In practice this association is expressed as a probability because our determination of the siren's sky location is usually not very precise, so there is not just a single potential host galaxy identified. Instead there may be hundreds, or even thousands, of possible hosts – each with a different probability of being the true one. The association also depends on the value of the Hubble constant since that determines the relationship between distance and redshift. We also need to account for the fact that galaxy surveys are *incomplete* – i.e. they don't contain every galaxy in the surveyed volume since, for example, more distant galaxies which are smaller or less luminous may be too faint to be detected. Nevertheless, by carefully averaging over the redshifts of its possible host galaxies, we can characterize the redshift of each siren – and thus combine that information with the siren's GW distance to again measure the value of H_0.

How did we do?

Our publication presents the results of our analyses using the two approaches described in the previous section: the population-based method and the catalog method, applied to the GW events that we selected from GWTC-3.

For our population-based method, using the distribution of redshifted BBH masses, this is the first time an analysis has constrained simultaneously *both* the properties of the BBH population and the cosmological parameters that determine the expansion of the Universe. In fact, our analysis fitted not just the Hubble constant but also the dimensionless parameters that determine the amount of dark matter and dark energy in the Universe, contributing to what has become known as the 'Standard Model' of cosmology – usually referred to as 'Lambda CDM'.

We found that the GWTC-3 data do not yet place any useful constraints on the dark matter and dark energy content of the Universe. This is not surprising, since those parameters should become more important for BBHs observed at a greater distance (and redshift) than the GWTC-3 sources that we studied. On the other hand, our results do suggest that the future prospects for learning about dark matter and dark energy from the BBH population are encouraging, as our detectors become more sensitive and we observe more distant sirens.

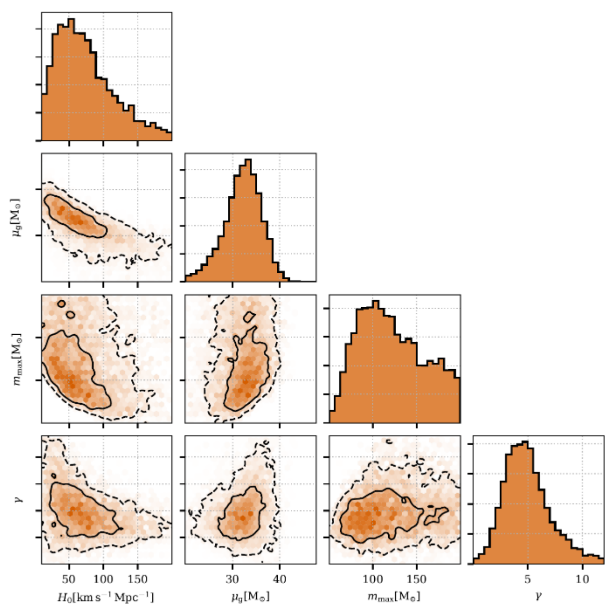

***Figure 2**. (Figure 5 from our publication). Posterior probability distributions for the values of the Hubble constant (H_0) and the parameters of our model for the distribution of masses in the BBH population, jointly inferred from our population-based analysis of the BBH sources we selected from GWTC-3. The rightmost panel in each row shows the probability distribution for a single parameter, with the H_0 distribution shown at the top of the figure. The other panels show the joint probability distribution of each pair of parameters. The solid and dashed lines enclose the regions within which we are, respectively, 90% and 50% confident that the true values of the parameters lie.*

The Hubble constant results from the application of our population-based method are more informative, however. **Figure 2** shows the combined constraints that we obtained on H_0 and the parameters of our population model; this figure indicates that (at least for this particular population model) our data appear to favour somewhat lower values of the Hubble constant. When we combine the population constraints with the H_0 measurement from GW170817 and its electromagnetic counterpart, we estimate a value of $H_0 = 68^{+13}_{-7}$ km s^{-1} Mpc^{-1}, which represents a 13% improvement on our previously-published result using the BBHs from our first Gravitational-Wave Transient Catalog, GWTC-1. (Note that the properties of our GW distance estimates make the uncertainty on H_0 'lopsided').

The results from our second method, using the GLADE+ catalog, are also encouraging. In this case, we first need to assume our model for the properties of the BBH population; we adopt the parameters of the model (which comprises a power law plus a Gaussian peak to describe the distribution of black hole masses) which gives the best fit to the observed BBH population. Combining the information from GLADE+ with these fixed BBH population model parameters, we estimate a value of $H_0 = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}, which represents a 41% improvement on our corresponding GWTC-1 estimate. **Figure 3** shows this new result, where we see that our value of the Hubble constant is consistent with the estimates of H_0 from both the CMB and type 1a supernovae plus Cepheids (shown as the magenta and green vertical bands respectively) although it is not yet precise enough to help to resolve the 'Hubble tension' between those measurements.

Summary and future prospects

While the constraints on the Hubble constant obtained in our publication improve upon previously published results, we recognise that they depend on the details of how we model the BBH population. For almost all of the GWTC-3 events that we analysed using the catalog-based method, our results are strongly affected by the assumptions that we make about this population model. The only event where this was not the case is GW190814, which was much better localized on the sky than the other dark sirens, which means that the match between its localization volume and the GLADE+ data provided some useful information about the Hubble constant.

In the next few years the LIGO and Virgo detectors will undergo further upgrades to improve their sensitivity and will be joined first by KAGRA (for our fourth observing run O4, provisionally planned for late 2022) and later this decade by LIGO India. This enhanced detector network is expected to yield a much-increased number of well-localized bright and dark sirens, so we can anticipate that our constraints on the Hubble constant via application of the catalog method will improve - particularly if new, deeper galaxy surveys that are more complete up to higher redshift are also included in our analyses.

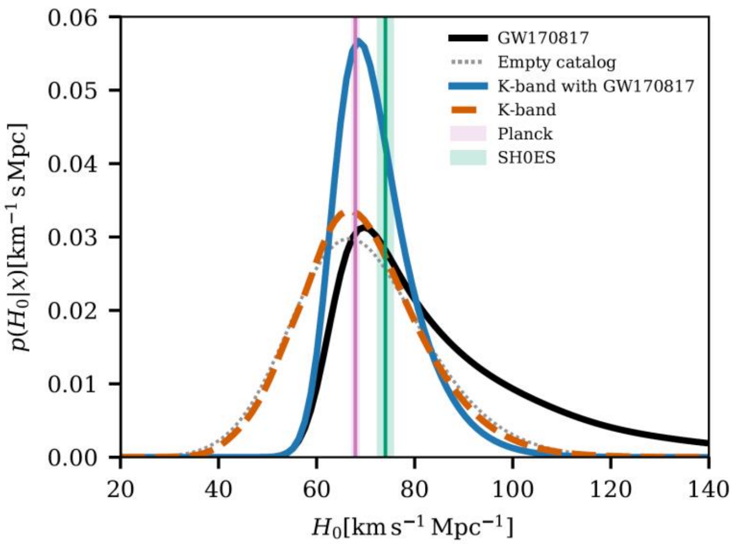

Figure 3. *(Figure 9 from our publication). Posterior probability distributions for the Hubble constant (H_0) corresponding to different analyses. Each probability distribution is a curve representing our best guess for the value of H_0 after carrying out our analysis. The solid black line plots the result using only the BNS event GW170817 and its electromagnetic counterpart. The dotted blue line shows the result of our analysis without using any galaxy catalog information. In solid blue and dashed orange, we plot the results of analyses that consider the galaxy catalog with and without also including the BNS event respectively. (Note that the K-band galaxy catalog is used, which collates galaxy data for a particular range of wavelengths centred in the infrared). Finally, the two vertical bands (magenta and green) show the constraints on H_0 obtained from the CMB (Planck) and Supernovae + Cepheids (SH0ES) respectively.*

With significantly higher rates of BBH detections anticipated in the next few years, we can also expect to improve the results from future application of our population-based method. Within a few years we can look forward to analyses that constrain simultaneously both the properties of the BBH population (taking into account more general population models than those we considered in this publication) and the parameters of our cosmological model – including not only the Hubble constant but also the influence of dark matter and dark energy on the cosmic expansion. The future prospects for GW cosmology with standard sirens are looking bright!

GLOSSARY

GLADE+: new, extended, compilation of galaxy catalogs, containing data for about 22 million galaxies, used to provide redshift information for potential host galaxies of our GW events. A free-to-access scientific paper describing the GLADE+ catalog is available here.

Megaparsec: unit of distance commonly used in cosmology. One megaparsec is equal to one million parsecs, where a parsec is equal to about three and a quarter light years or 3.086×10^{16} metres.

Hubble constant: parameter used to measure the expansion rate of the universe. Its present-day value is denoted by the symbol H_0 and it is measured to be about 70 km s^{-1} Mpc^{-1}

Big Bang theory: explanation for the origin and evolution of the observable universe which describes how the universe began about 14 billion years ago and has expanded from an initially very hot and dense state. The Big Bang theory is widely accepted as explaining many of the observed properties of the universe, including the abundance of the lightest chemical elements and the existence of the cosmic microwave background radiation.

Cosmic Microwave Background (CMB): Electromagnetic radiation coming from an early stage in the evolution of the universe, when it was about 380,000 years old. The CMB is also known as “relic radiation” left over from the Big Bang. For more information see here.

Type Ia supernova: particular explosion mechanism of a white dwarf, accreting material from a red giant companion star, whose mass becomes greater than the Chandrasekhar limit of 1.4 times the solar mass. The distances of Type Ia supernovae can be reliably estimated since they are all found to explode with a quite similar peak intrinsic brightness, or luminosity - making them useful standard candles.

Cepheid: type of pulsating variable star that undergoes periodic changes in radius and temperature, leading to regular, periodic changes in their luminosity. By measuring their pulsation period, astronomers can reliably estimate the distance of Cepheid variable stars.

Cosmic distance ladder: the combination of methods by which astronomers determine the distance of objects in the universe. Distances to remote objects, which are usually based on empirical relationships between their properties, are built upon more direct, geometrical, measurements of distances to nearby objects - usually within the Milky Way galaxy. For more information see here.

Black hole: A region of space-time caused by an extremely compact mass where the gravity is so intense it prevents anything, including light, from leaving.

Neutron star: Remnant of the supernova process undergone by a star with a mass between 10 and 25 times the mass of our Sun. Typical neutron stars have a mass of around 1-2 solar masses and a radius of 10-15 kilometers, being some of the most compact objects ever discovered.

Pair-instability supernova (PISN): type of supernova explosion predicted to occur in a star with a mass greater than about 130 solar masses. The production of electron-positron pairs in the core causes a dramatic drop in the pressure supporting the star, leading to a runaway thermonuclear explosion which leaves behind no stellar remnant.

Redshift: Increase in wavelength (of sound, light, or gravitational waves) due to motion of the source with respect to the observer. Due to the cosmological expansion of the universe, objects such as galaxies are receding from us, and light and other electromagnetic radiation coming from them has a longer wavelength.

Dark matter: mysterious form of matter that makes up about 85% of the mass in the Universe. It is dark because it does not emit light or interact electromagnetically. Many theories of dark matter predict that it is some type of fundamental particle, but it is also interesting to consider the possibility that the darkest objects we know of (black holes!) could be a component of dark matter.

Dark energy: mysterious, unknown, component of the matter and energy content of the cosmos that dominates the behavior of the Universe on its largest scales and is believed to be causing the expansion of the universe to accelerate. The simplest model for dark energy is that of a so-called cosmological constant that exerts a negative pressure, resulting in an accelerated expansion.

Posterior probability distribution: graph or plot showing how likely are different values of a given physical property, after analysing our data, estimated through a process known as Bayesian inference.