MEASURING COSMIC EXPANSION WITH DARK STANDARD SIREN GW190814

The Expanding Universe

In the 1920s Georges Lemaître and Edwin Hubble made the discovery that our universe is expanding. This breakthrough revolutionised our understanding of the cosmos and underpins the Big Bang Theory, one of the cornerstones of modern cosmology.

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. (A parsec is a unit of distance equal to about three and a quarter light years or 3.086×10^{16} metres.) However, even after more than 90 years, 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 in the above units) using different methods. This so-called "Hubble tension" is a serious problem for cosmology, and in this context there is growing interest in gravitational-wave observations as a completely novel approach to measuring this crucial number for understanding the cosmic expansion.

Standard Sirens

If we observe the gravitational-wave emission from the merger of a compact binary system containing black holes or neutron stars, analysis of the merger waveform and how it evolves allows us to directly measure the distance to the binary system. This is in stark contrast to most other, more traditional, methods to measure cosmological distances, 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 gravitational-wave 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 recession velocity away from us – which we can deduce from the "redshift" of the source's host galaxy – we can measure the Hubble constant.

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

Turning to the Dark Side

For a neutron star 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 gravitational waves, 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 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 signposting the host galaxy directly, we can still use the gravitational-wave observations to give us information about 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 from all of these possible host galaxies then allows us to measure H_0 *statistically* – as was first outlined in a seminal 1986 paper by Bernard Schutz. Our gravitational-wave observations, even without electromagnetic counterparts, can thus serve as "dark standard sirens".

Just three days before the detection of GW170817, the first BBH merger detected by three observatories (LIGO Hanford, LIGO Livingston and Virgo) was observed, allowing the merger to be well-localized in a narrow region of the sky. That region was also within the "sensitive spot" of the Dark Energy Survey (DES) – an optical and near-infrared galaxy survey – and it contained about 77,000 DES galaxies. Using redshift information from these DES galaxies allowed the first dark standard siren measurement of H_0. This approach was then extended to the other binary black holes observed during the first and second Advanced LIGO and Virgo observing runs. In combination with GW170817, these dark sirens gave a marginal improvement over the first standard siren measurement of H_0 obtained from GW170817 alone.

Measuring H_0 with GW190814

On August 14, 2019 the LIGO-Virgo network observed a gravitational-wave signal from a black hole and another object of undetermined nature: either the lightest black hole or the heaviest neutron star ever discovered in a system of two compact objects. Named GW190814, this intriguing gravitational-wave source is the best localized dark standard siren observed to date. **Figure 2** shows the two sky regions (about 20 square degrees) within which the LIGO-Virgo analysis found that GW190814 was most probably located. These sky regions were then cross-referenced with GLADE (or Galaxy List for the Advanced Detector Era – a catalog constructed to help identify host galaxies of gravitational-wave events). A total of 472 galaxies listed in the GLADE catalog were found in these regions.

The redshift information compiled in the GLADE catalog, weighted by how probable each galaxy was to be the GW190814 host (see **Figure 3**), gives our estimate of H_0. We measured a value of about 75 km per second per Megaparsec (with an uncertainty of about 36 km/s/Mpc) which is as precise as was possible with any previously observed dark standard siren.

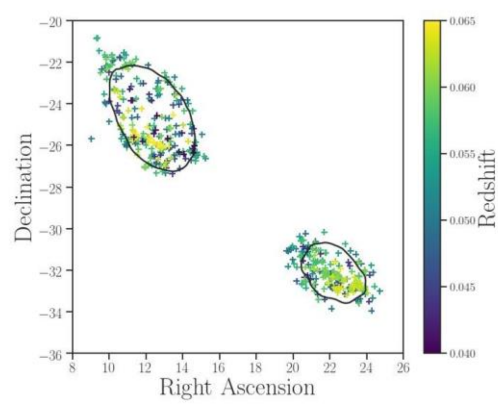

***Figure 2**. Map showing the possible regions on the sky within which GW190814 was located by the LIGO-Virgo network. The crosses show the positions of galaxies in the GLADE catalog that lie within these regions, with the redshift of these galaxies indicated by their color. (Credit: LIGO Scientific Collaboration and Virgo Collaboration)*

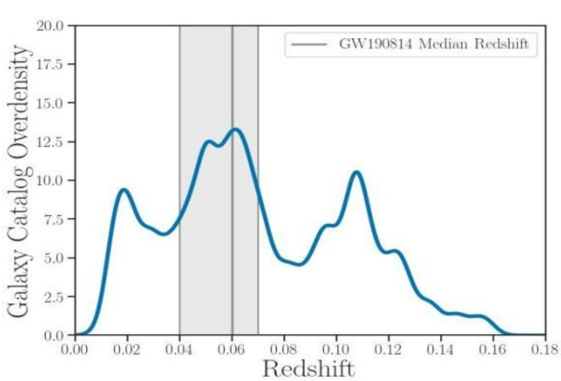

***Figure 3**. Graph showing the redshift distribution of the GLADE galaxies within the possible sky regions where GW190814 was located. The grey vertical band indicates the most likely range of redshifts for the host galaxy of GW190814. (Credit: LIGO Scientific Collaboration and Virgo Collaboration)*

Although the large uncertainty on our GW190814 measurement of H_0 means that it is not currently competitive with other values based on more traditional methods, our result nonetheless provides a valuable proof-of-concept test.

The global network of ground-based detectors is set to improve dramatically over the next decade, with the addition of Kagra, LIGO India and Advanced LIGO+ upgrades. Consequently, the number of well-localized binary black hole mergers can be expected to grow substantially – offering much improved prospects for measuring the Hubble constant by this completely novel approach. Hence, we can be confident that dark standard sirens have a very bright future!