Cosmology Without EM Counterparts: Standard Sirens In The Advanced Era & Beyond

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Abstract

We investigated a novel approach to measuring cosmological parameters using only gravitational-wave signals from merging binary neutron stars. Gravitational-wave observations with a global network of advanced detectors will permit a direct, independent measurement of the luminosity distance to the source systems. If the redshift of the source is known, these inspiraling double-neutron-star binary systems can be used to calibrate the distance-redshift relation and extract cosmological information. Unfortunately, a redshift to a distant system is degenerate in gravitational-wave (GW) observations. Thus, most previous work has assumed that the source redshift is obtained from electromagnetic counterparts (e.g. short gamma ray bursts). In our work, we exploit the narrowness of the distribution of masses of the underlying neutron-star population to probe the background cosmology using only GWs.

Introduction

- Gravitational waves from the coalescences of double neutron-star (DNS) binaries are among the most promising sources for LIGO [1] and Virgo [2].
- Advanced detectors such as AdLIGO (due to come online in 2015) will probe a thousand times the cosmological volume of Initial LIGO [3, 4].
- With this huge gain in sensitivity, the rate of DNS inspiral detection is expected to be ~40 yr⁻¹, but may range from 0.4 yr⁻¹ to 400 yr⁻¹ [5].
- Proposed 3rd generation detectors, such as the Einstein Telescope (e.g., [6]), may be operational in the late 2020s and could detect DNS systems at a rate of ~O(10³⁻¹⁰) yr⁻¹.
- The amplitude of the GWs emitted by these systems directly encodes their distance from us, as well as the redshifted chirp mass. This latter quantity is simple (i.e.) twice the chirp mass, which is itself a combination of the two NS masses, defined as

\[ M_z = (1+z)\left(\frac{m_1m_2}{(m_1+m_2)^2}\right)^{3/5} \]

- The redshifted chirp mass can be measured from the GW phase evolution, using even a single interferometer, to within ~0.1% for a source detected with a signal-to-noise ratio (SNR) of 10.
- Distance measurement requires a network of at least three separated interferometers, giving a typical measurement error of ~0.06 M☉ (see Fig. 1) [10-11].

Methodology

- We assume data for each detected DNS system in the form of a measured redshifted chirp mass and luminosity distance.
- With a narrow intrinsic NS mass distribution, we already have a good idea of the intrinsic chirp mass...
- Hence, we can produce candidate redshift distributions from the redshifted chirp mass measurement.
- Combining these candidate redshift distributions with distance measurements allows us to extract cosmological parameters.
- Recent analysis of Galactic DNS systems suggests the intrinsic NS mass distribution is approximately Gaussian with a mean of ~1.35 M☉ and standard deviation of ~0.06 M☉ (see Fig. 1) [10-11].

Exponential fit to intrinsic NS mass distribution, showing redshift to be 

Results 1 – Advanced Era


- We assume a catalog containing 10⁵ DNS detections (corresponding to 1 - 2 yrs of an advanced-era network operation, assuming the realistic rate-density [6]).
- We model the luminosity distance posterior PDF as a Gaussian, possibly offset from the true value, and with a standard deviation of (300/SNR) %.
- Bayesian analysis via MCMC, exploring parameter space of Hubble constant and mean/width of NS mass distribution.
- Hubble constant constrained to ~20 % (see Fig. 2).

Results 2 – Einstein Telescope era


- We repeat and extend the analysis for a third-generation network, including the Einstein Telescope. Dark-energy EOS parameters are w, w, which are the power-law index of the DNS delay-time distribution, and [M], which parametrizes the star-formation rate density (SF2, see [12]). Dark-energy constraints are similar to forecasts using conventional techniques i.e. CMB, BAO [13].

References


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Fig. 1 - Approximation to the intrinsic NS mass distribution.

Fig. 2 - The measurement precision of H₀ is plotted against the width of the underlying NS mass distribution in Fig. 4. With a narrower underlying NS mass distribution, we achieve better precision on H₀ (10⁻³ kmps⁻¹/µc⁻¹ with SNR = 0.02 M☉). This behaviour is expected since a narrower NS mass distribution allows a more precise estimate of the redshift to be obtained from the measured chirp mass and hence an improved estimate of cosmological parameters.

Fig. 3 - Panel a) shows the evolved 2D posterior distribution between H₀ and the mean of the NS mass distribution, and the best fit redshift obtained from the measurement. This low redshift implies an intrinsic chirp (and hence NS mass distribution) centered around larger values.

Fig. 4 - The measurement precision of H₀ is plotted against the width of the underlying NS mass distribution in Fig. 4. With a narrower underlying NS mass distribution, we achieve better precision on H₀ (10⁻³ kmps⁻¹/µc⁻¹ with SNR = 0.02 M☉). This behaviour is expected since a narrower NS mass distribution allows a more precise estimate of the redshift to be obtained from the measured chirp mass and hence an improved estimate of cosmological parameters.

Fig. 5 - The posterior distribution of Mₚ and Aₓ with respect to a catalog of DNS detections in a 3rd generation network.