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 interferometric 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, the redshift and the system mass are 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

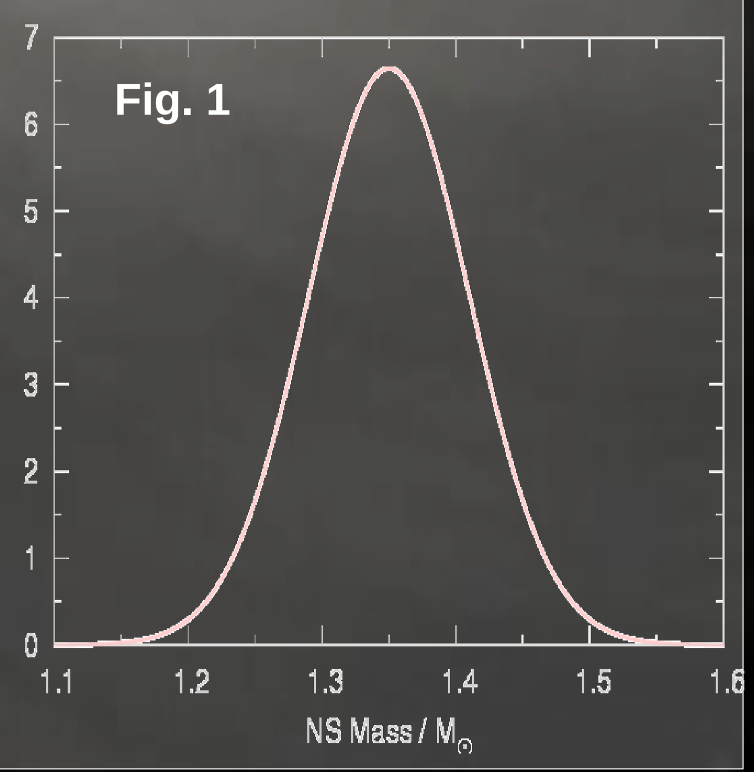
- Gravitational waves from the coalescences of double neutron-star (DNS) binaries are among the most promising sources for LIGO [1] and Virgo [2].
- Advanced detectors such as AdLIGO (due to come online in ~2015) will probe a thousand times the cosmological volume of Initial LIGO [3, 4].
- With this 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(10^5-10^6) 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 simply (1+z) times the chirp mass, which is itself a combination of the two NS masses, defined as,

$$\mathcal{M}_z = (1+z)\left(\frac{m_1 m_2}{(m_1+m_2)^2}\right)^{3/5}(m_1+m_2)$$

- 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 ~(300/SNR) % (e.g., [7-9]). The threshold network SNR we adopt for GW detection is 8.

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 $M_\odot$ and standard deviation of ~ 0.06 $M_\odot$ (see **Fig. 1**) [10-11].



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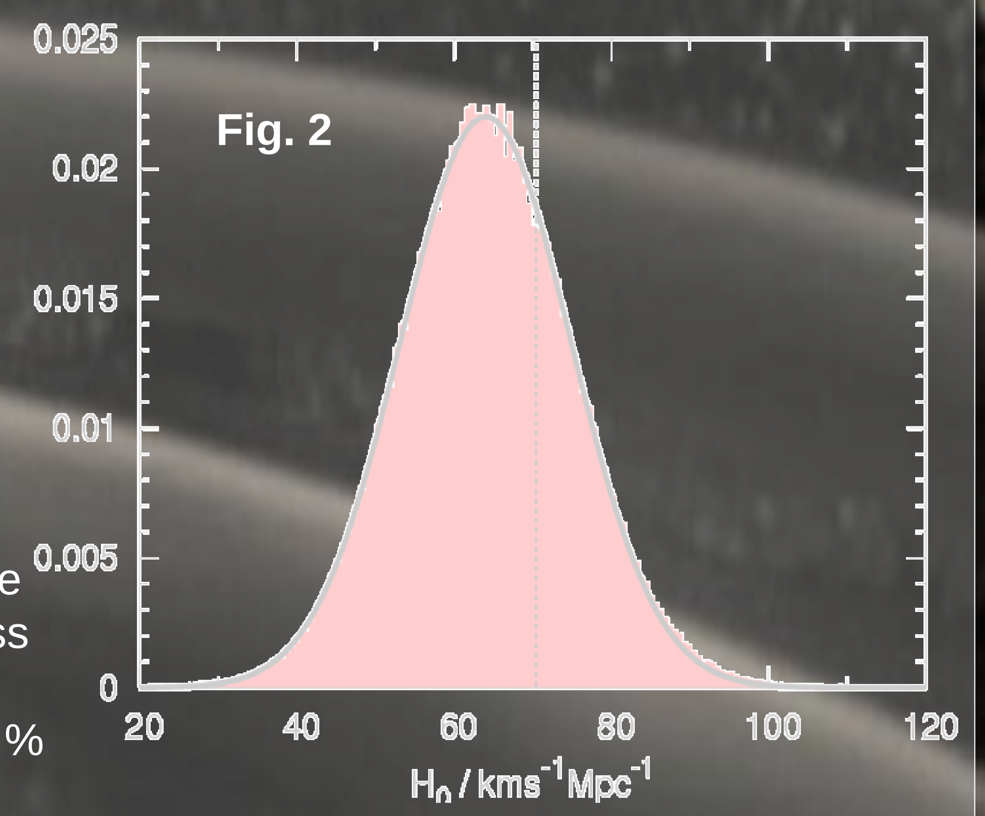
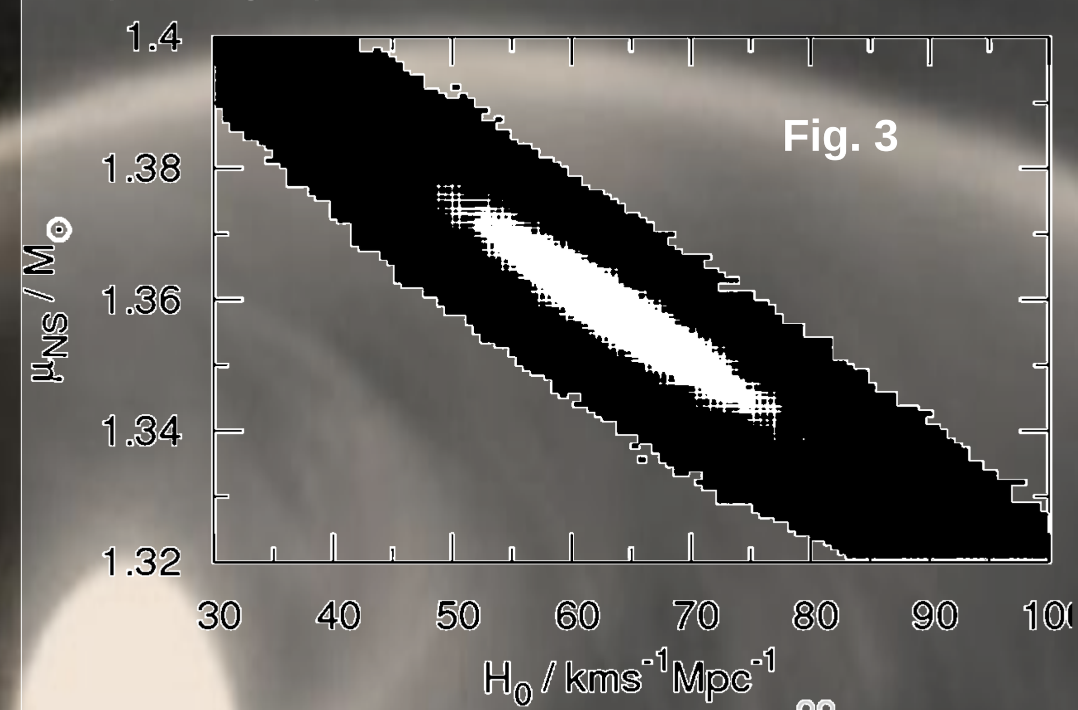
Results 1 – Advanced Era

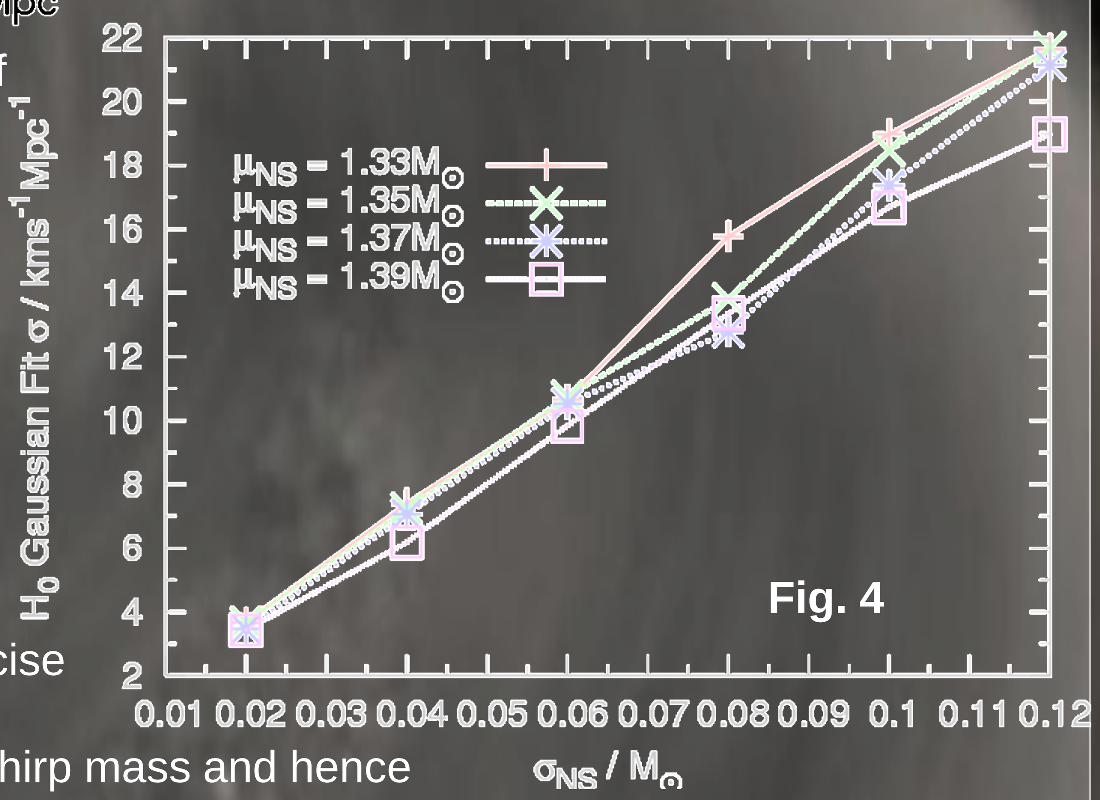
S. R. Taylor, J. R. Gair and I. Mandel, "*Cosmology using advanced gravitational-wave detectors alone*", Phys. Rev. D 85, 023535 (2012), arXiv:1108.5161

- We assume a catalog containing 100 DNS detections (corresponding to 1 - 2 yrs of an advanced-era network operation, assuming the realistic rate-density [5]).
- 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**).





- **Fig. 3** shows the recovered 2D posterior distribution between H_0 and the mean of the NS mass distribution.
- Correlation is negative since a low-H_0 infers a low redshift from a measured distance. This low redshift implies an intrinsic chirp (and hence NS) mass distribution centered around larger values.
- The measurement precision of H_0 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 H_0 (± 3 $kms^{-1}Mpc^{-1}$ with σ_{NS} = 0.02 $M_\odot$).
- 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.



Results 2 – Einstein Telescope era

S. R. Taylor and J. R. Gair, "*Cosmology with the lights off: Standard sirens in the Einstein telescope era*", Phys. Rev. D 86, 023502 (2012), arXiv:1204.6739

- We repeat and extend the analysis for a third-generation network, including the Einstein Telescope. Dark-energy EOS parameters are w_0/w_a, α is the power-law index of the DNS delay-time distribution, and β_1/β_2 parametrize the star-formation rate density (SF2, see [12]). Dark-energy constraints are similar to forcecasts using conventional techniques i.e. CMB, BAO [13].

TABLE 1 : The 95% confidence intervals on a catalog of 10^5 DNS detections in a 3rd generation network.

Parameter	Reference value	95% conf. interval	ΔX
$\sigma_{NS}/M_\odot$	0.06	0.059688 – 0.060254	0.000566
$\mu_{NS}/M_\odot$	1.35	1.347408 – 1.351789	0.00438
w_0	-1.0	-1.036403 – -0.949623	0.0869
w_a	0.0	-0.195630 – 0.073602	0.269
α	-1.0	-1.026691 – -0.961659	0.0650
β_1	3.4	3.318136 – 3.605810	0.288
β_2	3.4	3.310287 – 3.582895	0.273

- **Fig. 5** shows the variation of the precision of parameter recovery with the width of the underlying NS mass distribution, as in **Fig. 4**.
- As before, the constraints on NS mass distribution and cosmological parameters improves with a narrower NS mass distribution.
- All curves are posterior distribution widths with respect to a catalog of DNS detections with σ_{NS} = 0.06 $M_\odot$.