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INFERENCE OF PROTO-NEUTRON STAR PHYSICAL PARAMETERS IN CORE-COLLAPSE SUPERNOVAE FROM GRAVITATIONAL WAVE DATA ANALYSIS

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Abstract. Core-collapse supernovae are expected to emit gravitational waves. Hydrodynamic simulations predict the existence of universal relations linking the gravitational wave frequency evolution and some physical parameters of the proto-neutron star. We develop a method to coherently analyse data within the LIGO-Virgo-KAGRA interferometer network and extract from it the dominant g_2-mode of the gravitational wave signal. Using the universal relation we infer the time evolution of a combination of mass and radius of the proto-neutron star. We estimate the performance of the method using waveforms generated by 2D and 3D simulations of core-collapse supernovae for the LIGO-Virgo-KAGRA network as well as 3rd generation detectors Cosmic Explorer and Einstein Telescope.

Keywords: core-collapse supernovae, gravitational waves

1 Introduction

Stars more massive than $8M_\odot$ end their lives with the gravitational collapse of their iron core leading to a supernova explosion. These core-collapse supernovae (CCSNe) are expected to be sources of gravitational waves (GWs) that could be detected with the ground-based interferometers of the LIGO-Virgo-KAGRA network in the case of galactic events (Gossan et al. 2016; Szczepańczyk et al. 2021). The analysis of such a GW signal would play an important role in our understanding of the physical mechanisms that drive the explosions of massive stars.

Hydrodynamic numerical simulations of CCSNe show the existence of a dominant mode in the GW signal clearly visible in a time-frequency plane. The so called gravity mode (or g_2-mode) is characterised by a monotonic increase in frequency from $\sim$ 100Hz up to a few kHz in about 1s and is related to the contraction of the newly formed proto-neutron star (PNS). Torres-Forné et al. (2019) showed the existence of a universal relation between the frequency of this g_2-mode and the ratio $r = M_{PNS}/R^2_{PNS}$. It makes it possible to do asteroseismology from the GW signal of a CCSN and to infer the evolution of some of the PNS physical parameters. In this proceeding we present the practical application of this asteroseismology procedure and highlight some of the observational perspectives. We fist give a brief description of the coherent analysis of data in a network of GW detectors. We use CCSN waveforms to estimate the performance of our method and to quantify the observational prospects of the Advanced LIGO-Virgo-KAGRA network. The 2D hydrodynamic simulations of CCSN from which the waveforms are extracted are described in Bizouard et al. (2021). We finally give a brief overview of the results expected with 3rd generation interferometers Einstein Telescope (Punturo et al. 2010) and Cosmic Explorer (Reitze et al. 2019).

2 Coherent analysis method

Following Bizouard et al. (2021) we aim here to generalize the data analysis method to a network composed of several interferometers. Assuming that we know accurately the true sky location of the CCSN from its neutrino and optical counterparts, the time series of each interferometer is first shifted to account for the time delays induced by the GW propagation between interferometers. The data is then segmented and Fourier-transformed

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before it is coherently summed into a single time-frequency (TF) map of maximum likelihood (see Sutton et al. (2010) for more details on the maximum likelihood statistic derivation). This operation takes into account both the antenna patterns of each interferometer and its sensitivity. The left panel of Figure 1 shows the TF map of maximum likelihood obtained from the coherent analysis of a CCSN GW signal added to the noise of the network LIGO-Virgo-KAGRA for a source at 5kpc. The dominant g_2-mode is clearly visible on this representation. To get the temporal evolution of the g_2-mode frequency we store, for each time bin, the pixel of maximum energy and then we fit a polynomial regression to those points. The fitting algorithm follows a Least Absolute Shrinkage and Selection Operator (LASSO) procedure (Tibshirani (1996)). An example of g_2-mode tracking is shown in the right panel of Figure 1.

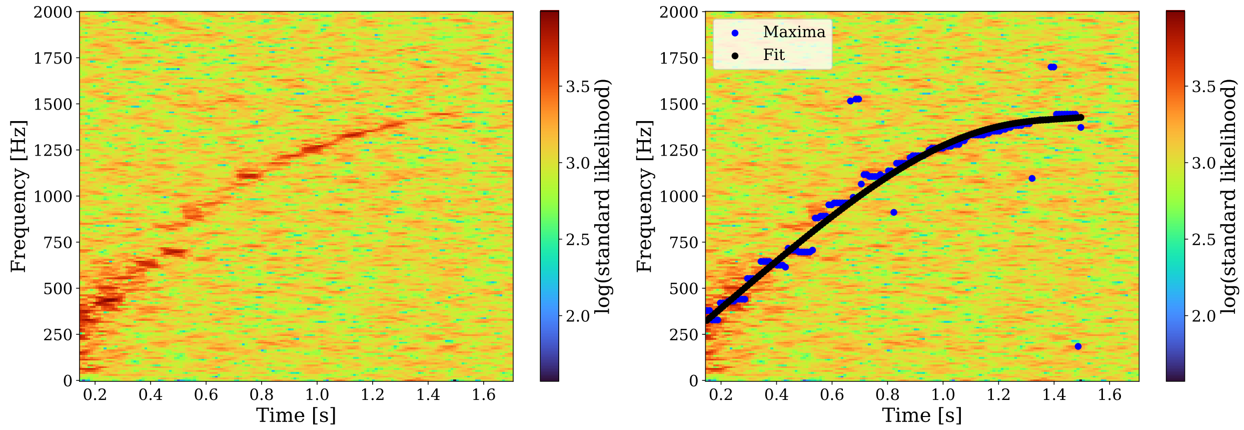


Fig. 1. Left: Time-frequency map of standard likelihood for $\sim$ 2s of LIGO, Virgo and KAGRA noise containing the CCSN GW signal s20.0–LS220 for a source at 5kpc in the direction RA=18.34h, dec=-16.18° and a GPS time of arrival on Earth t_0=1325048418. **Right:** Application of the tracking algorithm to the left panel TF map. The blue circles show the pixel of maximum intensity at each time index. The black dots show the results of the LASSO regression.

With the frequency evolution of the g_2-mode $f(t)$ and the universal relation from Torres-Forné et al. (2019), which we write in the form $r = M_{PNS}/R^2_{PNS} = \beta_1 f + \beta_2 f^2 + \beta_3 f^3 + \epsilon$ where f is the GW frequency and ϵ is a zero-mean Gaussian error term with a frequency dependant variance, it is now possible to estimate the time evolution of the ratio $r(t)$ using the method developed in Bizouard et al. (2021). We apply this procedure to the same simulated GW data as the one used to create the TF map in Figure 1 and we compare our estimated ratio to the true ratio M_{PNS}/R^2_{PNS} in the 2D hydrodynamic simulation. The results are shown in Figure 2. In this case all the true ratios (in red) are inside the 95% band of the reconstructed ratios (in black). Defining the *coverage* as the fraction of true values that lie within the 95% confidence interval of the inferred values, we obtain here a *coverage* equal to 1. We use the *coverage* to estimate the reconstruction quality of the evolution of the ratio M_{PNS}/R^2_{PNS}.

3 Detectability prospects

We now use the coherent analysis method to estimate the range of sources that can be detected with the network of ground-based interferometers LIGO-Virgo-KAGRA and with the 3rd generation detectors Einstein Telescope and Cosmic Explorer. To simulate a source, we first set a sky direction, a distance to Earth and a time of arrival of the GW signal on Earth. This allows us to compute the antenna patterns of each detector at the time of arrival in each detector. Then we add 2D CCSN waveforms (see the list in Bizouard et al. 2021) in Gaussian colored noise simulated according to each detector power spectral density (Barsotti et al. 2018). The coherent analysis method can now be applied to the realistic time series obtained for each interferometer and, with the use of the *coverage* defined above, we can measure the accuracy of the inferred ratio M_{PNS}/R^2_{PNS} for that simulated source.

We start by estimating the typical distance of inference that we can achieve with the LIGO-Virgo-KAGRA network. Fixing a source direction and a time of arrival on Earth, the distance of the source is progressively increased. At each distance step the inferred ratio evolution is compared to the true ratio given by the hydrodynamic simulation and the *coverage* is computed. We repeat the process with 100 different noise realisations

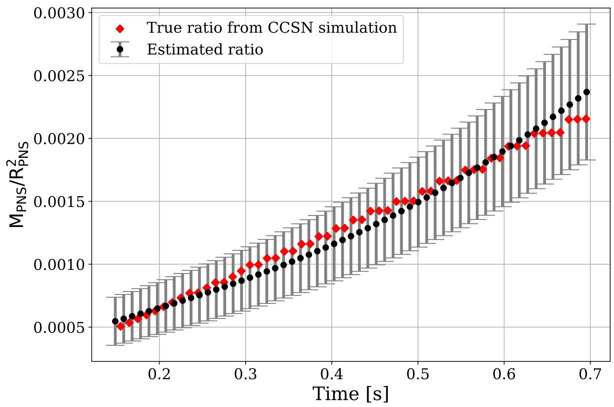
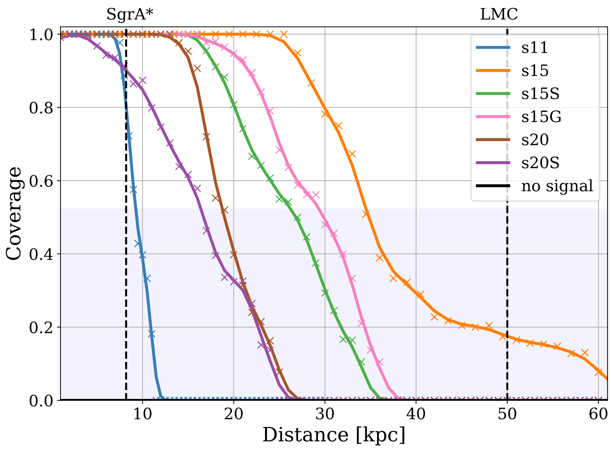


Fig. 2. Time evolution of the ratio M_{PNS}/R^2_{PNS} estimated from the g_2-mode in the GW signal (black circles). The grey band shows the 95% confidence intervals. The red diamonds show the time evolution of this ratio directly derived from the evolution of the PNS mass and radius in the 2D simulation.

for each distance step and each waveform and we consider the median of the *coverage*. The results obtained are shown in the left panel of Figure 3. For all waveforms the *coverage* remains greater than 0.8 at a distance of 10 kpc. This range matches the size of the Milky Way and the Advanced LIGO-Virgo-KAGRA network at their design sensitivity will make it possible to infer from the GW signal of a galactic CCSN the evolution of some physical parameters of the PNS.

Cosmic Explorer (CE) and Einstein Telescope (ET) are projects of next generation GW detectors that would operate with sensitivities roughly 10 times better than the second generation of ground-based interferometers Advanced LIGO-Virgo-KAGRA. Using theoretical expected sensitivities from Hild et al. (2011) and Srivastava et al. (2022), we repeat the same analysis as described above for the second generation detectors and the results obtained are shown in the right panel of Figure 3. These next generation detectors would allow us to extend the reach to a large number of nearby dwarf galaxies around the Milky Way for the asteroseismology of CCSNe.



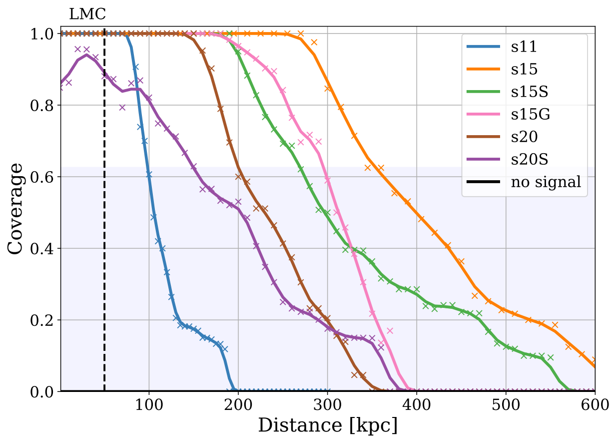


Fig. 3. Left: Evolution of the median *coverage* as a function of the distance to the source. The sky position of the source is set in the direction (RA=18.34h, dec=-16.18°) inside the Sagittarius constellation. The solid lines show the smoothing splines of the median of the *coverage* for the six 2D CCSN waveforms aadded to the LVK network. The "no signal" line shows the median *coverage* in the case where no signal is injected in the detectors. Here it is strictly equal to 0. The blue band boundaries represent the 5^{th} and 95^{th} percentiles of *coverage* for the "no signal" case. **Right:** Same analysis performed with the network of 3rd generation detectors CE+ET. The sky position of the source is set in the direction of the Andromeda Galaxy (RA=0.71h, dec=41.27°).

4 Conclusions

The detection of a GW signal emitted during a CCSN could potentially be the next big breakthrough in GW astronomy. It would give us new hints on the physical mechanisms that drive the explosion of a massive star which is still challenging to fully simulate. We presented here a new coherent analysis method designed to apply the theory of PNS asteroseismology on actual GW data. This study confirms the feasibility of such an approach and constrains its range to a CCSN in the Milky Way with the LIGO-Virgo-KAGRA network of ground-based interferometers. The implementation of 3rd generation detectors allows to us to extend this range to CCSNe in a large number of dwarf galaxies nearby.
Recent results obtained with a 3D hydrodynamic simulation of a CCSN confirm the significance of the work presented here and encourage us to further develop the analysis method. For instance the construction of the TF map as well as the g_2-mode tracking algorithm could be improved to make the inference of the ratio M_{PNS}/R^2_{PNS} more robust.

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