Detectability of Spin Precession of BBH Systems in Next Generation Gravitational Wave Detectors

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Binary black hole systems are sources of gravitational wave signals that can be observed by detectors such as LIGO. Their orbits can undergo spin-induced precession, an effect that occurs when the black hole spins are misaligned with the binary's total orbital angular momentum. Spin precession can imprint itself on the detected gravitational waveform, but has not been observed in any gravitational wave detector observing run thus far. The difficulty in measuring spin-induced precession and its impact on source characterization arises due to complicated orbital dynamics, as well as factors such as the binary's orientation and detector polarization. In this project, we analyze the detectability of spin-induced precession in binary black hole systems by exploring precession parameter spaces using the two-harmonic approximation method. We hope to infer the likelihood of observing this signal phenomenon in next generation gravitational wave detectors in order to further probe binary black hole characteristics and astrophysical formation channels.

I. INTRODUCTION

A. Gravitational Waves

Predicted by Einstein in 1915 with his theory of General Relativity [1], the concept of gravitational waves as disturbances of spacetime revolutionized our understanding of gravity beyond standard Newtonian physics. Caused by the acceleration of matter, the existence and possible observation of gravitational waves has been subject to theoretical debate for over 100 years. These highly studied cosmic ripples in spacetime were finally detected in 2015 by the LIGO and Virgo gravitational wave collaborations [2, 3]. Since this landmark achievement, the field of gravitational wave astronomy has undergone massive expansion into the exploration of various origin sources, population studies, and detector physics concerning these highly sought after phenomena. Gravitational wave astronomy enters a new era with highly advanced observatories continuously being developed and further sources being detected as physicists seek to answer the deepest questions prevailing our understanding of gravity and the universe.

B. Gravitational Wave Detectors

The theoretical basis of gravitational wave sources formulated by Einstein establishes gravity as a curvature of spacetime. Einstein's field equations describe the geometry and curvature of spacetime around a gravitating body, as well as the energy and momentum of the source. Following the logic that wave-like solutions are possible for these equations, the existence and propagation of gravitational waves became the subject of much debate [4, 5]. Physicists theorized the detectability of these spacetime disturbances and began developing detectors to hunt for signals carrying gravitational wave energy. A large laser interferometric gravtitational wave detector spearheaded by Rainer Weiss and Kip Thorne evolved into the now well-known Laser Interferometer Gravitational Wave Observatory (LIGO) [6], a joint project by Caltech and MIT with funding from the NSF. Two laboratories, one in Hanford and one in Livingston, could simultaneously detect gravitational wave signals by utilizing the fact that these signals pass through matter while stretching and compressing it in two different directions (signal polarization). Over the next decade, the gravitational wave detector community expanded with other facilities coming online in Germany, Italy, and Japan [7–9]. Success was finally achieved in September 2015 with the first detection of a gravitational wave signal from the merger of two inspiralling black holes passing through the LIGO detectors, consistent with Einstein's theory of relativity [2]. Following this momentous achievement, dozens of signals have been detected since 2015 with continuous upgrades and advancements in detector technology and signal data analysis being developed in tandem to improve sensitivity and accuracy in gravitational wave astronomy.

With the Advanced LIGO, Virgo, and KAGRA detectors operational and functioning, physicists continue to push at the limits of detecting these perturbations of spacetime and simultaneously investigating their origins. The next generation of both ground and space-based detectors hope to further widen the gravitational window into our universe. The third generation detectors Einstein Telescope (ET) [10], Cosmic Explorer (CE) [11], and LISA (Laser Interferometer Space Antenna) [12] are

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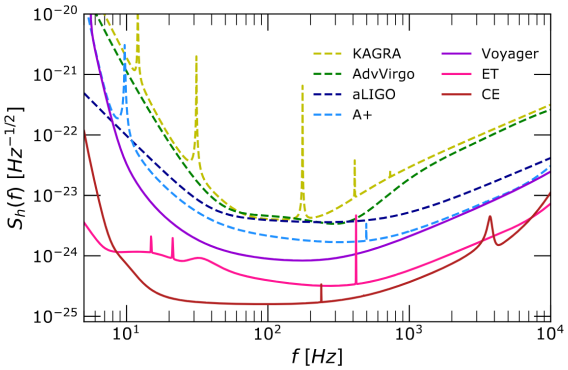

FIG. 1. [Taken from Divyajyoti 2024] Detector sensitivity curves across frequency range. Current detectors are denoted with dashed lines, while Next Generation detectors ET, CE, and LIGO Voyager are in solid lines.

expanding the field of gravitational wave astronomy by reaching an order of magnitude better sensitivity of detection, as well as accessing a wider frequency band to hunt for more sources (See Fig. 1) [10].

Furthermore, better technological advancements such as three nested interferometers in the case of ET will provide better accuracy in bandwidth and noise reduction. This increased 'discovery potential' will open the door to exploring sources of GW signal beyond black hole and neutron star mergers, as well as probe the parameter space for various other astrophysical and cosmological phenomena including the nature of dark matter, dark energy, and the stochastic gravitational wave background [10].

II. SCIENTIFIC MOTIVATION

A. Binary Black Hole Systems

As mentioned above, gravitational waves (GW) are represented by a time-dependent perturbation in flat spacetime. The sources of GW signal detections so far have been black hole-black hole mergers [13], binary neutron star mergers [14], and neutron star-black hole mergers [15]. These signal produced by compact binary systems of two massive objects coalescing is described as a 'chirp' signal [16]. Two black holes in orbit with each other will lose energy and angular momentum as they inspiral and eventually merge, producing gravitational waves. Since the frequency and amplitude of the binary system increases during the final few cycles in this process, the gravitational signal becomes detectable as the system approaches merger [16]. GW signals from compact coalescing binaries such as two back holes have characteristic properties that can be observed by ground-based detectors such as LIGO. Focusing on binary black hole (BBH) systems, there are 15 basic parameters that we can use to describe the GW signal event [16]. These are the masses of the two black holes (m_1 and m_2), spin vector components of each ($S_{1x}, S_{1y}, S_{1z}, S_{2x}, S_{2y}, S_{2z}$), luminosity distance ($d_L$), inclination angle of the binary (ι), time of coalescence (t_c), phase of coalescence (ϕ_c), right ascension and declination (α and δ), and polarization angle (ψ). Characterizing these parameters is paramount to inferring properties of the BBH system in order to understand their astrophysical nature as dictated by the gravitational waves they produce.

B. Parameter Estimation

In order to properly analyze GW signals from BBH systems, performing parameter estimation in an accurate way that matches with what detectors observe as well as our assumptions and limitations of physical modeling allows us to characterize the properties of the binary. Starting with the parameters described above, combining two or more of these properties is usually better suited to the measured properties of a signal due to the fact that all parameters may not be accurately measured simultaneously, and to reduce degeneracy of parameters [16]. For example, a mass ratio of $q = m_1/m_2$ is often used instead of directly sampling individual masses. In defining the spins of binary systems, individual components of spin are additionally difficult to measure, so we utilize a combination of spins and the mass ratio to model in-plane and out-of-plane spin components, as detailed below.

C. Spin Induced Orbital Precession

In a BBH system with two spinning compact objects, it is logical to assume that the individual spins of one or both black holes may not be aligned with the orbital angular momentum of the overall system. When the total spin vector ($\mathbf{S} = \boldsymbol{S_1} + \boldsymbol{S_2}$) becomes misaligned with the orbital angular momentum vector ($\mathbf{L}$), the orbital plane of the binary precesses about the approximately constant total angular momentum vector ($\mathbf{J} = \boldsymbol{S_1} + \boldsymbol{S_2} + \boldsymbol{L}$) (See Fig. 2)[17].

This effect of spin induced precession in a GW signal manifests itself in the form of modulations in amplitude and phase [17–19]. These modulations, and therefore the signal measured, depend on the opening angle β, the inclination angle θ_{JN}, and the precession angle of $\boldsymbol{L}$ around $\boldsymbol{J}$ denoted by α [20]. The spin precession imprints itself on the gravitational wave signal and is thought to occur in many BBH systems, yet no evidence of precession in signals from advanced LIGO or Virgo detectors have been observed [20]. The leading thought on this phenomenon is that the precession feature within a signal is too weak to be inferred due to complications such as parameter degeneracies, when the binary is face-on to the detectors, and when the two black holes are of compara-

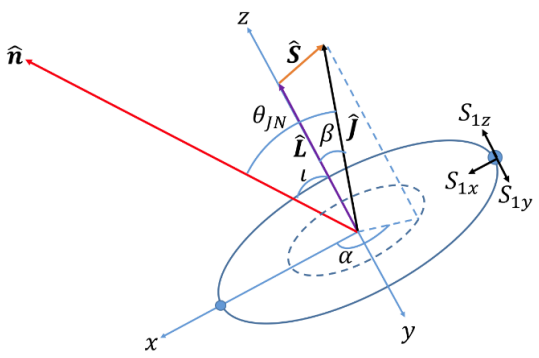

FIG. 2. [Taken from Hoy 2021] A diagram showing the orbital angular momentum $\hat{L}$, total spin $\hat{S}$, and total angular momentum $\hat{J}$ of a binary system. The normal vector $\hat{n}$ indicates the line of sight of the observer. The inclination angle between the total angular momentum and the observer is denoted by θ_{JN}.

ble mass [20]. As a result of this, predicting under which conditions spin precession is observable is ideal for signal detection from binary system sources.

In order to characterize precession, we utilize two spin parameters to model the out-of-plane spin effects ($\chi_{\rm eff}$) and in-plane spin effects ($\chi_{\rm p}$) of the binary. $\chi_{\rm eff}$ describes the spin effects along the direction of the angular momentum axis [21], and is defined as

$$\chi_{\rm eff} = \frac{1}{M}\left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m_2}\right)\cdot\hat{\mathbf{L}}, \tag{1}$$

and takes values between -1 and $+1$ - either maximally anti-aligned or aligned individual spins with the total angular momentum. $\chi_{\rm p}$ describes the spin effects within the orbital plane of the binary [22], and is written as

$$\chi_{\rm p} = \frac{1}{A_1 m_1^2}\max(A_a S_{1\perp}, A_2 S_{2\perp}), \tag{2}$$

where $A_1 = 2 + (3/2q)$ and $A_2 = 2 + (3q/2)$ defined in terms of the mass ratio q. $\chi_{\rm p}$ varies from 0 to 1, indicating how misaligned spins are with the orbital angular momentum vector [16]. A higher $\chi_{\rm p}$ value indicates a more maximally precessing overall system [23].

Using these two spin parameters, we can better estimate characteristics of the BBH system when it is undergoing spin-induced precession. Additionally, the measurement of the spin vectors themselves can provide information regarding the formation channel of the black hole binary [24]. It is predicted that binaries formed in isolated environments tend to have more aligned spins, while those with misaligned spins (and therefore higher precession) formed through dynamical evolution or hierarchical mergers [25]. Finally, based on previous efforts to model the impact of precession on GW signals, it is theorized that precession will be most significant for binaries with large mass ratios and where the total angular momentum of the binary is misaligned with the line of sight to the observer [20]. In this project, we hope to elucidate parameters of spin precession detectability in order to further explore BBH characteristics and formation origins.

III. METHODS

A. Two-Harmonic Approximation

Utilizing parameter estimation of spins in order to detect precession, we employ a two harmonic approximation method introduced in Fairhurst 2020 to apply to detectability in Next Generation detectors. Gravitational wave strain as measured by a detector can be expressed as a linear combination of different modes with a basis of -2 spin-weighted spherical harmonics [26]. This includes the intrinsic parameters of mass and spins of the binary system, as mentioned above. A gravitational waveform from a precessing binary is composed of 5 harmonics which form a natural hierarchy, with the amplitude of the higher harmonics depending on the opening angle between the orbital and total angular momenta [20]. The two harmonic approximation involves using this model and restricting to the two leading harmonics, providing us a with a relatively simple expression for the full waveform [20]. The sub-leading harmonics are expressed as a non-precessing binary waveform with added amplitude and phase modulations that contribute to the complete overall waveform [17, 18, 20]. The strength of the precession itself depends on various factors of the system, namely, the contributions of the in-plane spin vectors, and the line of sight angle between the total angular momentum and the observer.

IV. DATA ANALYSIS AND RESULTS

The primary focus of this project is to test the validity of two harmonic approximation by examining the overlap of a precessing waveform and its harmonics across the parameters spaces of inclination angle θ_{JN} and the in-plane spin vector components $\chi_{\rm p}$. To obtain precessing waveforms with which to analyze, we simulate various waveform parameters using BILBY base prior dictionaries for BBH systems [27]. $\chi_{\rm eff}$ is set to 0 in order to restrict our parameter space exploration to the most precessing systems, i.e. focusing on in-plane spin misalignments. We then employ SIMPLE-PE [28] to convert priors into gravitational wave events with an applicable frequency range and power spectral density of a given detector, as well as polarization parameters. We use the IMRPhenomXPHM phenomenological waveform model presented in Ref. [29], as it includes precession and gravita-

tional wave multipoles other than the dominant 22 mode. We simulate a complete precessing waveform, as well as waveforms with $k = 0$ and $k = 1$ harmonics. The full two-harmonic precessing waveform is defined as a combination of the $k = 0$ and $k = 1$ harmonics within the 22 mode. See Figure 3 for an example of a simulated full precessing waveform including subsets of its harmonics.

In order to infer properties of the simulated waveforms, we use PyCBC [30] and employ a commonly used technique called matched filtering [31, 32], which involves cross-correlating data against a linear filter that serves as a template of the signal within the detector data. Since the form of the gravitational wave signal depends on the source parameters, this method allows us to match a filter which best describes the simulated data. An optimal filter for a given signal can also be used to calculate the intrinsic signal-to-noise ratio (SNR) of the waveform [16].

In each case, we calculate

$$O(h, h') = \frac{max_{\phi_o}(h|h')}{|h||h'|}, \tag{3}$$

where

$$(a|b) = 4\mathrm{Re}\int_{f_o}^{\infty} \frac{a^*(f)b(f)}{S(f)}df, \tag{4}$$

and $S(f)$ is the power spectral density of the detector data.

To test the validity of the two harmonic approximation, we calculate the overlap of the full precessing waveform against subsets of its harmonic - the leading $k = 0$ harmonic, the dominant $k = 1$ harmonic, and the restricted two harmonic waveform (See Figure 4) [20]. The overlap value depends on the power spectral density of the detector data, and varies with the particular sensitivities of each interferometer. Compared to match filtering, the overlap is maximized over the phase of the signal, but not over time or mass and spin parameters. An overlap close to unity indicates similar waveform features and a higher observable SNR [20]. Additionally, the regions where the two harmonic approximation are valid for a precessing waveform in the parameter space of χ_{p} and θ_{JN} vary across polarization of the GW signal. The two harmonic approximation against the full precessing waveform is predicted to hold up fairly well for a 1-overlap value below 0.9. This can be interpreted as regions of darker parameter space in Figure 4. A valid precession approximation is most notable throughout this parameter space when comparing both contributing $k = 0$ and $k = 1$ harmonics against each of them individually to the full waveform, and is particularly pronounced in the cross polarization signal.

V. CONCLUSION

The two harmonic method for precessing binary waveforms simulated within current LIGO and Virgo sensitivities serves as a useful approximation for exploring parameter space of where precession will be detectable by utilizing the two leading harmonics of the GW signal. With this approximation, we have shown regions of parameter space that would indicate a higher observable imprint of precession on the waveform from BBH systems. Future directions involve applying this method to wider signal searches across various other parameters for black hole binaries in order to more conclusively observe precession effects across GW events. While we were not able to complete the full parameter space exploration with the next generation PSD detector data using the two harmonic approximation, this method is an intuitive way of understanding observability of precession within current GW detectors. With the advent of next generation detectors and increased sensitivities to precessing binary systems across a wider frequency range, we hope to elucidate the complex issue of precession detectability to further explore formation channels and astrophysical properties of gravitational wave signal events.

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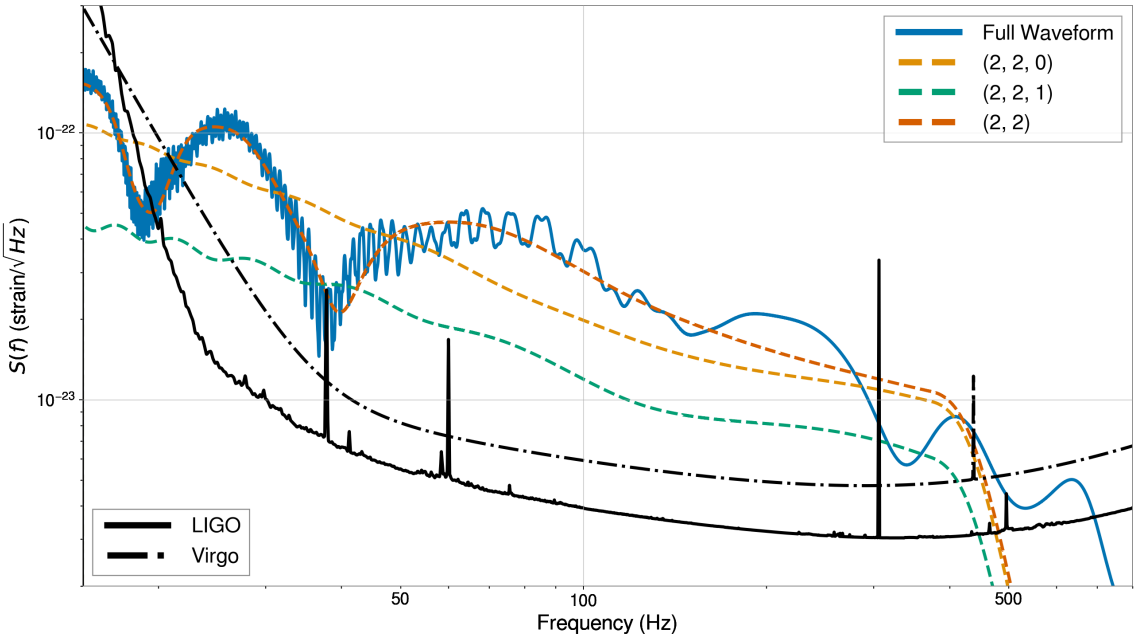

FIG. 3. A plotted simulated waveform with included LIGO and Virgo sensitivity curves for reference. Note that the two harmonic approximation (2, 2) in dotted red is a close match to the full precessing waveform.

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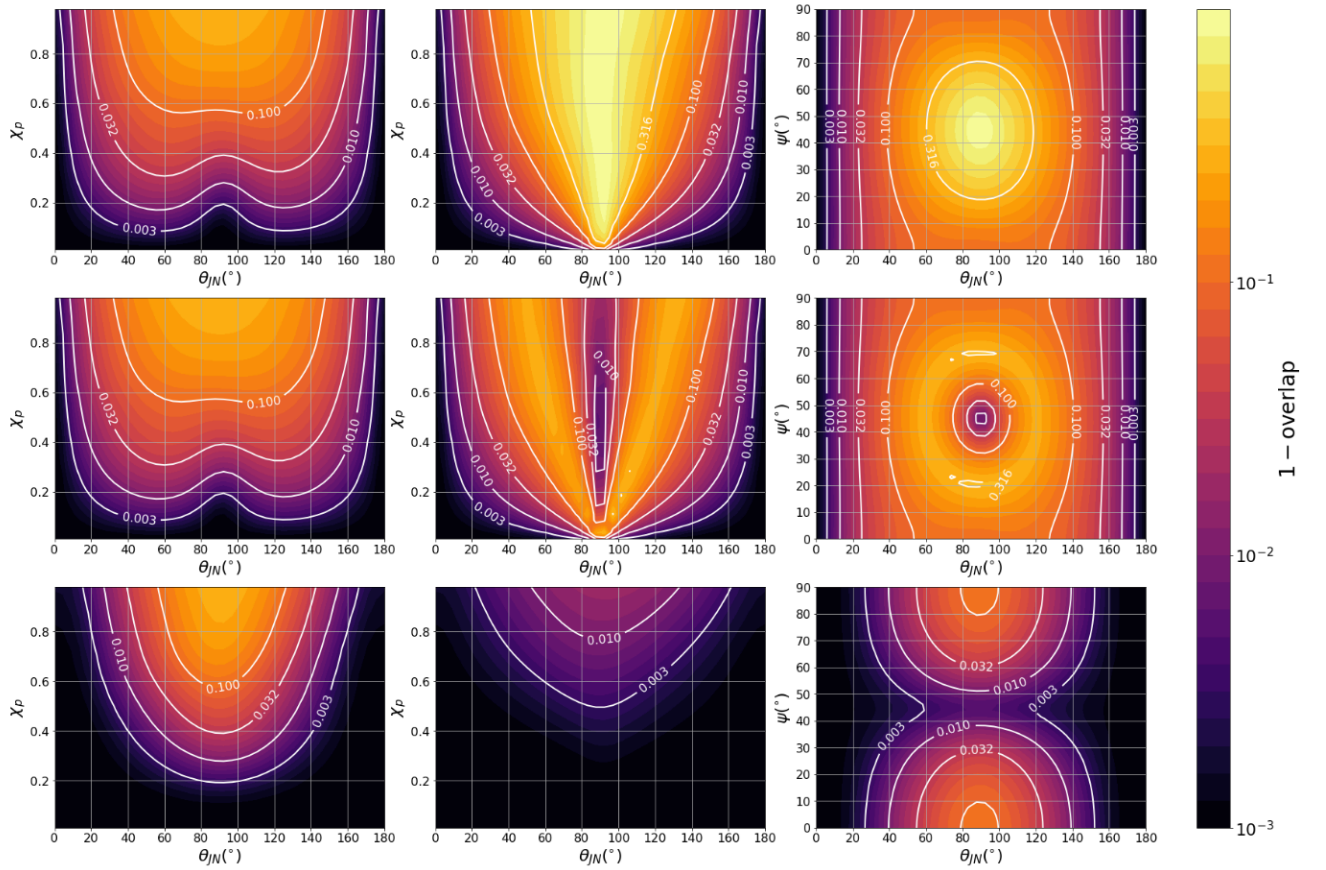

FIG. 4. [Taken from Fairhurst 2020] Overlap values between a full precessing waveform and subsets of its harmonics across parameter space $\chi_{\rm p}$ and θ_{JN}. The top row is the overlap between the leading $k = 0$ harmonic and the full waveform, the middle row is the $k = 1$ harmonic, and the bottom row is the two harmonic combination approximation. The left column is for plus polarization, the middle column is for cross polarization, and the right column is for varying polarization.

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