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Caltech LIGO SURF Proposal
Constraining Orbital Precession From LIGO Sources

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1. MOTIVATION AND BACKGROUND RESEARCH

Observing the degree of spin alignment of two binary black holes (BBHs) can provide meaningful insight into the formation channel of the system. Aligned spins between the BBHs point to formation through binary stellar evolution, whereas isotropic spin misalignment points to dynamical formation (e.g., Mandel & Farmer 2022). Additional relationships such as the ratio of magnitudes of aligned spins can provide insight into the exact details of the binary evolution that yielded the BBH system (Mandel & Farmer 2022). The alignment of the BBH spins with the angular momentum can be observed through the waveform, gleaning insight into the formation of the system. Most prominently, precession of the orbital angular momentum is characteristic of spin-orbit coupling, hinting at spin misalignment between the BBHs and the orbit.

There is LIGO data for just under 100 BBH mergers (Abbott et al. 2023; Mehta et al. 2023; Nitz et al. 2023). Of these many cases, there is only a small number of candidates which could potentially have noticeable precession. Specifically, LIGO data from GWTC-3 have presented several promising candidates for BBHs which may have measurable precession, and therefore spin misalignment (Abbott et al. 2023). However, the claims of precession in these cases are controversial (Hannam et al. 2022; Payne et al. 2022). There are several potential causes for this low number of candidates and controversy: either a clear way to measure BBH precession does not exist, or BBHs don't typically precess in their orbits, at least on a measurable scale.

Currently, the precession of BBHs is measured by the effective precession spin, χ_p, which is defined as

$$\chi_\mathrm{p} = \max\left[\chi_1 \sin\theta_1, \left(\frac{3+4q}{4+3q}\right) q\chi_2 \sin\theta_2\right], \tag{1}$$

where χ_i is the dimensionless spin parameter of black hole i, and θ_i is the angle between the combined spin of each black hole and the orbital angular momentum, $\vec{L}$ (Schmidt et al. 2015).

There are several problematic elements to note about this parameter, the most important of which is that χ_p does not appear to be well constrained. In most of the cases reported in GWTC-3, the marginal posterior distribution of χ_p is very similar to the marginal prior distribution of χ_p (Abbott et al. 2023); the data are not informative about χ_p. Second, the prior for χ_p goes to zero for $\chi_\mathrm{p} = 0$ (i.e., the posterior is proportional to the prior times the likelihood). With this current system, it is difficult to interpret the results when $\chi_\mathrm{p} = 0$. We would like to implement a parameter that better

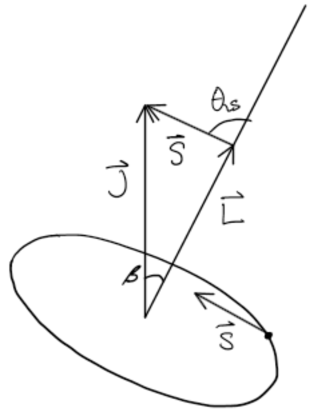

Figure 1. A geometric definition of the parameters of interest for analysis

constrains the precession while also allowing for a nonzero probability of aligned spins. That way, the posterior distribution may be more informative on the spin precession of the BBH system.

Due to these issues with the current measurement of spin precession, it cannot be entirely ruled out that BBH spin precession is unlikely. Finding a better constraint on the precession of BBHs using different parameters in the evaluation of the prior may allow for a better statistical analysis of current LIGO data and may provide stronger evidence for precession. Alternatively, it may show that LIGO has not yet observed a strong candidate for spin precession.

2. PROJECT GOALS

This summer, I would like to accomplish two things: I would like to define a new parameter that more clearly shows spin precession while also accounting for spin alignment, and I would like to run statistical analysis on GWTC-3 data with this new parameter to evaluate the precession of the current LIGO data. There are several contenders for a new parameter to constrain the precession that also align with the expected nonzero $\chi_{\rm p}$ probability for $\chi_{\rm p} = 0$. As described earlier, $\chi_{\rm p}$ depends on the sine of the angle between the total BH spin $\vec{S}$ (where $\vec{S} = \vec{S}_1 + \vec{S}_2$) and the orbital angular momentum $\vec{L}$. However, another quantity that may be better at constraining the precession is β, the angle between $\vec{L}$ and the total angular momentum, $\vec{J}$ (where $\vec{J} = \vec{L} + \vec{S}$). β is often used to control the magnitude of precession, making it a promising candidate to determine the effective precession itself. Alternatively, the cosine of the angle between $\vec{S}$ and $\vec{L}$, $\cos\theta_{\rm LS}$ may be another insightful parameter. This parameter may be more informative because $\cos\theta_{\rm LS} = 1$ when spins are aligned; this is opposite of the current $\chi_{\rm p}$ parameter which goes 0 when the spins are aligned. In particular, it can be more informative of the results when the parameter is equal to zero. These angles are geometrically shown in Figure 1.

Once a parameter has been formulated, we plan to implement a two step process to analyze the LIGO-Virgo data. Before applying our parametrization to real events in LIGO-Virgo data, we will first apply it to artifical BH data in which parameter measurements have been performed and at the same time, the true injected parameters are known. If the parameter can accurately determine the precession of this sample data, then I will apply it to the actual data. Otherwise, I will reconstruct a new parameter which we will use to repeat this process until we have a better match. With a better-constrained precession parameter, we will fit a model for the astrophysical distribution of this parameter to the LIGO-Virgo observations.

3. TIMELINE

My proposed timeline is as follows:

1. **Weeks 1-4:**
   - Download parameter runs on synthetic data
   - Explore suitable choices of parameters to identify precession as possible. I will also diagnose using the injections
   - Interim Report 1
2. **Weeks 5-7:**
   - Familiarize myself with the population inference software
   - Download parameter estimation samples for the real events (for observing runs O1-O3), download pipline injections (used to characterize detector sensitivity)
   - Interim Report 2
3. **Weeks 8-10:**
   - Formulate a population model using our precession parameter in such a way that the predictions from classic formation channels are obtained as limiting cases
   - Constrain the parameter of this population model using the LIGO-Virgo events
   - Final Report

The links for the various aspects of the project are included below:
Synthetic Data:
https://zenodo.org/records/10910135

GW Population Inference Software:
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.100.043030
https://github.com/ColmTalbot/gwpopulation?tab=readme-ov-file

Parameter Estimations Samples on Real Events, Pipeline Injections:
https://zenodo.org/records/5655785

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