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First Interim Report: Studying Effective and Component Spin of Binary Black Hole Mergers

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1. BACKGROUND AND MOTIVATION

In this project, I will be exploring the component and effective spins of gravitational wave (GW) data from binary black hole (BBH) mergers. Specifically, we aim to answer the question: if we simulate two different populations of BBH mergers with the same effective spin distribution but different component spin distributions, will we be able to measure that they are different populations?

Effective spin, $\chi_{\rm eff}$, is an average of the BBH component spins in the direction of the angular momentum, weighted by each black hole's mass.

$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot\hat{L}}{m_1+m_2}$$

Effective spin is a well measured parameter in LIGO data that shows up at leading order in gravitational waveforms, while the individual component spins show up much less strongly in GW signals. Figure 1 provides a visual for the component spins of a BBH.

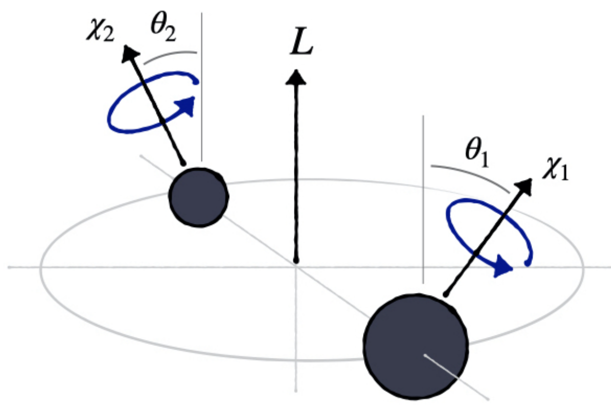

Figure 1. The component spins of a BBH. The effective spin is the mass-weighted average of component spins in the direction of angular momentum (L).

We are interested in exploring component spin distributions of BBH systems to gain insight into their formation channels. BBH mergers that formed through the isolated evolution channel are commonly believed to have spins that line up with the axis of the orbit, while the mergers formed through the dynamical formation channel have spins with random orientations.

2. EXISTING WORK

Using the data from the first and second runs of LIGO and Virgo, the effective spin of BBH systems was found to be very small, with average spin, $\mu \sim 0$ and a narrow distribution (Miller et al. 2020). Miller et al. (2020) make three hypotheses on the component spins based on the near-zero effective spin: the component spins are generally perpendicular to the binary's orbital angular momentum, the component spins are generally anti-aligned, or the component spins are simply very small (Miller et al. 2020).

Using LIGO's third observing run, Abbott et al. (2021) updated the posterior distributions of $\chi_{\rm eff}$ and $\chi_{\rm p}$, finding $\chi_{\rm eff}$ to be centered around 0.06, suggesting that spin-tilt misalignments do not cancel out. They found $\chi_{\rm p}$ to be either centered around 0 with a broad distribution or centered around 0.2 with a narrow distribution.

Using existing data from past LIGO observing runs, we want to judge how informative the LIGO measurements are and see how these measurements could improve as we approach LIGO's fourth observing run.

3. METHODS

We currently have data on 70 BBH mergers that have been detected by LIGO with relatively uninformative posterior distributions of component spins for each event. We will look at the full population of BBHs to obtain information that each posterior on its own cannot by using hierarchical Bayesian inference.

I will generate three different distributions of component spins that add up to the same effective spin distribution. Each distribution will have varying levels of spin precession. There will be three different samples of artificial LIGO data, each with spin magnitudes and alignment angles drawn from a different distributions.

My project will entail analyzing the two samples of artificial LIGO data and to recover individual posterior distributions of the component spins. I will add these posterior distributions together to see if I am able to recover the original distributions that were initially detected, with different component spins but the same effective spins. If I am able to recover the original distributions, I can show that we are able to differentiate between BBH mergers with different component spins, whereas if I am unable to differentiate between the two samples, I can show that we are unable to differentiate between BBH mergers with different component spins at current LIGO sensitivity. This study will provide insight into how informative the LIGO data on component spin is, or if studies should only use effective spin as a parameter of interest.

4. CURRENT PROGRESS

I am currently working through a tutorial written by Simona Miller that is largely based off Callister et al. (2021), which generates mock BBH populations with the same effective spin distributions but different component spin distributions. I first generated 50,000 detected events and then began choosing smaller subsets to actually inject into the LIGO data. Eventually, we will want to inject around 230 events to observe how our analysis will improve if we have more than our current pool of 70 events. However, because these runs require high computational power, I began by injecting ten events into each of my the three different mock populations. From this smaller subset of injections, we picked up a few bugs in the code.

Challenges that have risen primarily involve small bugs in the code that require us to re-run the parameter estimation again, which takes up to several days. The first issue we ran into dealt with the inconsistency with the detector mass and the actual mass. After resolving this issue, we ran into a different issue with incorrect spin injections in the x and y directions (see Figure 2).

We have resolved this issue and our latest run yields correct results (see Figures 3, 4, and 5).

After confirming that our injection and recovery procedure works as expected, I increased the number of injections to 100 and am currently waiting on the results.

I have also been following the tutorials from Callister et al. (2022) to replicate their results. I have replicated their results for one of their effective spin models and another for one of their component spin models. We are primarily interested in the component spin model parameter estimation, as this code will be similar to what we intend to run on our mock populations.

We are interested in the approach that models spin magnitudes as a beta distribution and the cosines of the spin tilt angles as a truncated mixture between aligned and isotropic subpopulations. We are interested in this truncated model for spin tilt to explore whether or not there is a cutoff in the tilt distribution. If there is no truncation, the distribution is bounded by $\cos\theta = -1$ (spin aligned with angular momentum) and $\cos\theta = 1$ (spin aligned with angular momentum). However, if the lower bound is not consistent with -1, this would imply that spin tilt angles prefer aligned orientations. For example, if the truncation bound is 0, this would indicate that the data contains no anti-aligned systems. Following the tutorial, we run an MCMC sampler to explore the parameters and inspect our results.

We first look at the chains to confirm that all the walkers converged (see Figure **??**). We then look at the corner plot of all the parameters of interest (see Figure **??**). Finally, we make a trace plot corresponding to the spin magnitudes and tilt angles from Figure **??** (see Figure 8.

These figures match the figures published in Callister et al. (2022). We are also interested in excluding two events, GW 190911 and GW 200129, rerunning the parameter estimation, and observing how our posterior distributions change.

I will also begin exploring another model for our component spin parameter estimation. Instead of assuming a specific distribution, such as a Gaussian or Beta distribution, I will not assume the shape of the underlying distribution. I

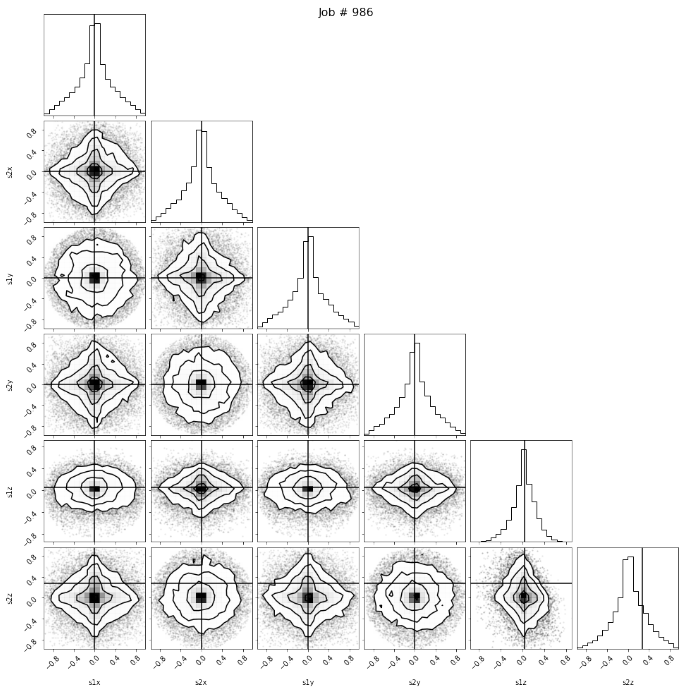

Figure 2. Posterior distributions of the component spins. The x and y spin components are centered around zero, which is incorrect.

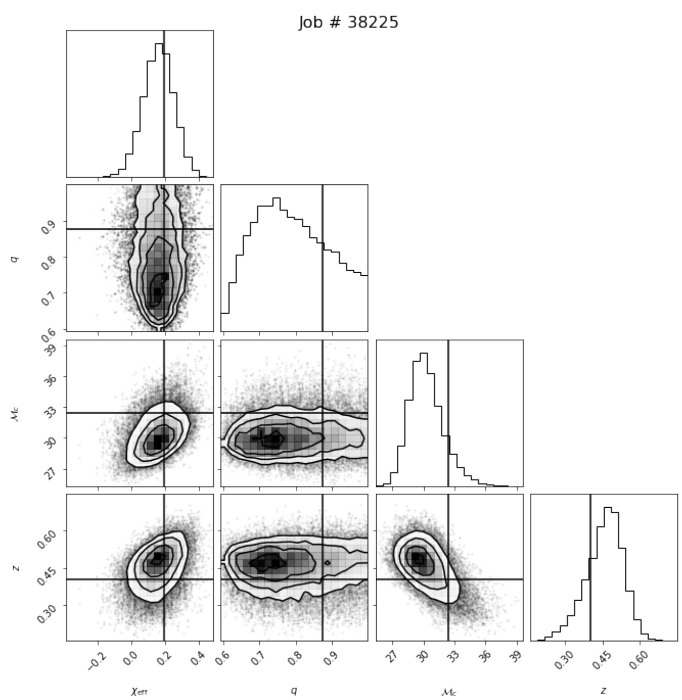

Figure 3. Posterior distributions of our parameters of interest.

will use a binned model, where I will break the population down into separate bins and measure what fraction of the population wants to fall into each bin. I plan to first explore a simple toy model before implementing this four our actual data.

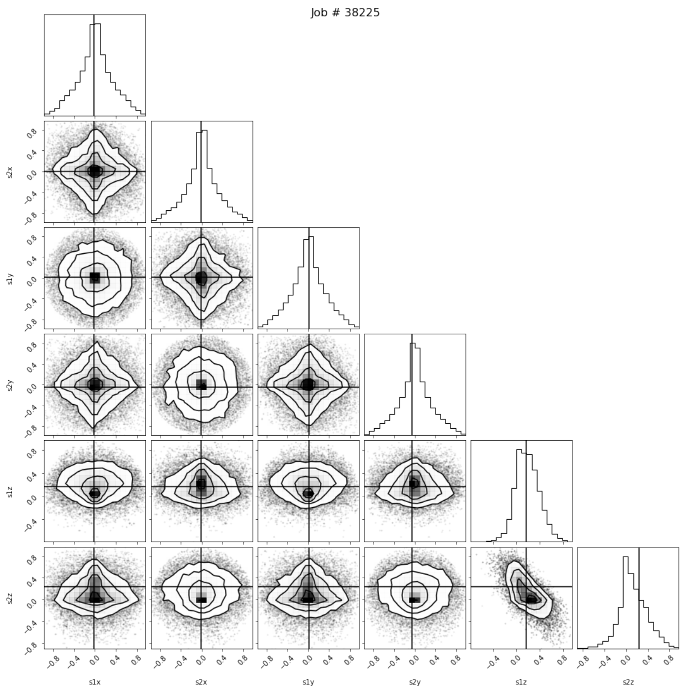

Figure 4. Posterior distributions of the component spins.

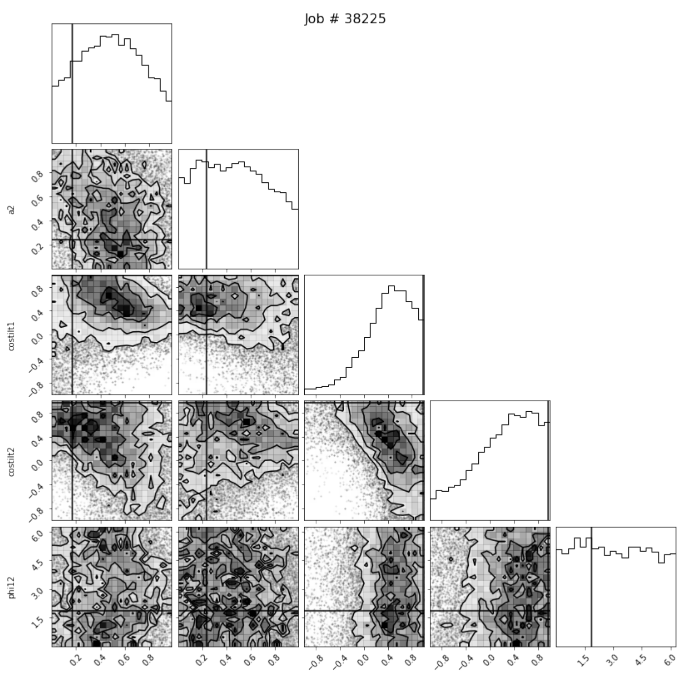

Figure 5. Posterior distributions of additional parameters.

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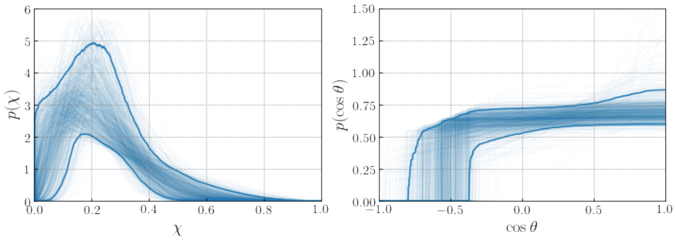

Figure 8. Trace plot showing the set of spin magnitude and tilt angle distributions.