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Studying Effective and Component Spin of Binary Black Hole Mergers

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1. OVERVIEW

Gravitational wave (GW) observations of binary black hole (BBH) mergers provide measurements of BBH parameters such as mass and spin, which can then shed light on the evolutionary history of these systems. In this project, I will be exploring the component and effective spins of GW data from BBH mergers. Specifically, we aim to answer the question: if we simulate two different populations of binary black hole mergers with the same effective spin distribution but different component spin distributions, will we be able to tell the difference?

2. BACKGROUND INFORMATION

The spins of black holes in binary systems can be parameterized in two ways which are useful in the context of GW data: component spins and effective spin. Component spins are the individual spins of each black hole in the binary. The component spin parameterization includes spin magnitudes and tilt angles, as shown in Figure 1. These quantities can be extracted from LIGO data, but with current sensitivity they are poorly measured, as indicated by wide posterior distributions over the full allowed range of values. This makes it difficult to precisely extract specific magnitudes and the tilt angles. However, LIGO data provides stronger constraints on effective spin, χ_{eff}, an average of the component spins in the direction of the angular momentum, weighted by each black hole's mass.

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

Therefore, effective spin is a more commonly explored parameter of BBH mergers. Figure 1 provides a visual for the component spins of a BBH.

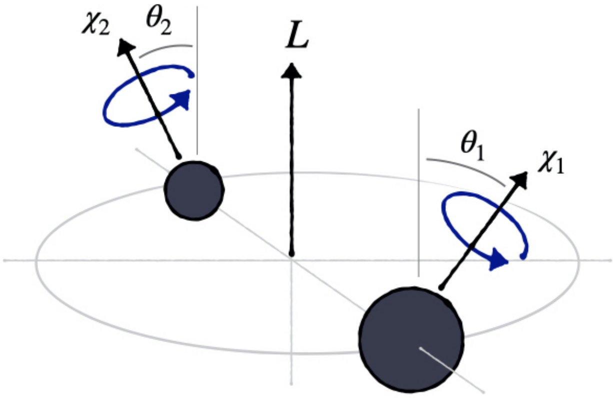

Figure 1. The component spins of a BBH. The effective spin is the mass-weighted average of component spins in the direction of angular momentum (L).

3. MOTIVATIONS

The spin distribution of BBH mergers can provide insight into their evolutionary origins. 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. Therefore, gathering information on component spin distributions of BBH systems can provide insight into these formation channels. However, because of the difficulty of constraining component spin parameters, effective spin is more commonly used. BBHs formed in isolation have spins that are aligned, and therefore, the distribution of effective spins should be centered around a positive value. On the other hand, BBHs formed dynamically have spins that are randomly oriented, and therefore, the distribution of effective spins should be centered around zero. 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 $\mu \sim 0$ with a narrow distribution (Miller et al. 2020). Miller et al. (2020) makes 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). While no conclusions were drawn regarding rates of isolated formation versus dynamical formation, an effective spin of zero points toward dynamically formed BBHs.

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.

4. PROJECT PLAN

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 be given 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. 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.

REFERENCES

Abbott, R., Abbott, T., Acernese, F., et al. 2021, arXiv preprint arXiv:2111.03634

Miller, S., Callister, T. A., & Farr, W. M. 2020, The Astrophysical Journal, 895, 128