LIGO SURF First Interim Report:

Inferring the Population of Merging Black Holes with Astrophysically Motivated Models

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Introduction

Gravitational waves (GWs)—first prediced by Einstein shortly after his introduction of General Relativity but at the time predicted to be unobservable—are propagating perturbations in the spacetime metric. In 2015, they were directly detected by the Laser Interferometer Gravitational-wave Observatory (LIGO) [1]. Since gravitational waves are produced by a time-varying mass quadrupole moment, thus far only merging binary compact objects (black holes and neutron stars) have produced gravitational waves detectable by our current gravitational wave experiments LIGO and Virgo. Nonetheless, this has opened up an entirely new field of GW astronomy. With the third LIGO-Virgo GW transient catalog (GWTC-3), we have now $\mathcal{O}(100)$ detections of gravitational waves, most of which are binary black holes (BBHs). It is now possible to not only infer individual source properties, but also to probe the underlying population from which these BBHs arise, placing constraints on models of stellar evolution and astrophysics. Interesting population properties that can be probed with the GW dataset include the shape of the black hole mass distribution [18, 2], the black hole spin distribution [17, 7, 9, 22, 2], the distribution of BBHs across the sky [15], the evolution of merger rate and other properties with redshift [8, 7, 2], correlations between properties such as mass and spin [7, 10, 23, 4, 2, 13], and even branching ratios between different BBH formation channels [24, 12, 21, 16].

Such analyses are usually done with a method called hierarchical Bayesian inference. BBH systems are completely described by 15 parameters: two characterizing the mass of each black hole, 6 characterizing the 3D spin vectors of each black hole, and seven extrinsic parameters that describe the sky location, distance, and orientation of the system. However, these parameters cannot be extracted straightforwardly from the GW strain data; for example, the majority of the spin information we obtain from a detection is from a measurement of the effective dimensionless spin parameter (χ_{eff}), which is a mass-weighted combination of the spin magnitude projected onto the orbital angular momentum, since it is the leading-order spin term in the post-Newtonian expansion of the strain. Furthermore, there exist degeneracies between some of the parameters. In the GW literature, these parameters are extracted for each system using Bayesian inference in a process called parameter estimation (PE). Therefore, what we have for each detection is not an exact measurement of any parameter, but rather a 15-dimensional *posterior distribution* describing the probability that the system has a certain set of parameters, given the detected signal. It is these posterior distributions that are then used to infer properties of the underlying population. One can then choose an astrophysically-motivated parameterization of the population and fit the posterior samples to the model in another layer of Bayesian inference in a process called hierarchical Bayesian analysis, the output of which is a posterior distribution on the value of the population parameters; it is also possible to compare the likelihoods between the models to discern which one is more favored. Analyses using flexible approaches (e.g. splines, Gaussian processes), which have the advantage of not being model-dependent, have also been explored. See [20] for a pedagogical introduction to both PE and hierarchical inference in the context of GW astronomy.

One of the primary goals of hierarchical inference in GW astronomy is to learn about the formation origins of the detected BBHs. Several different formation mechanisms have been explored in the literature, each of which have different signatures in BBH parameter space, subject to modelling uncertainties. These formation channels can be roughly grouped into two categories: dynamical formation channels, which involve BBHs formed via random dynamical capture in dense stellar environments, and field channels, which involve the isolated co-evolution of a binary star system. Recent literature has suggested that BBHs that form via field channels have mass-spin correlations; in particular, there is a negative correlation between the mass and the spin magnitude of the secondary star, which can be spun up via tidal forces [5], although the strength of this correlation is uncertain [14]. Hierarchical mergers in dynamical channels, involving the mergers of merger remnants, also have a mass-spin correlation, as the 2nd-generation component should have both a higher mass and a characteristic high spin-magnitude of around $a \sim 0.7$ [12]. Additionally, there are detections in our current catalog with extreme mass-spin properties that are difficult to explain via isolated evolution [23]. The goal of this project is to employ hierarchical Bayesian inference to fit a spin-mass correlated model, motivated by the astrophysical literature, to gravitational-wave data to learn about the formation mechanisms of BBHs.

Method

Due to limitations in the number and quality of our current detections, we will take a heuristic approach to searching for a mass-spin correlation within the BBH population. My tentative proposal is to model $\chi_{\rm eff}$ as a Gaussian, and allow the mean and width of the Gaussian to vary linearly with the mass of the secondary black hole, or alternatively, the mass of the *highest-spinning* black hole [6]. Assuming that the majority of the detected BBHs originate from the field, this should capture, to first order, the correlation described in the previous section, since $\chi_{\rm eff}$ should act as a proxy for the spin-magnitude of the highest-spinning component, assuming that the other black hole has negligible spin. To capture a possible sub-population of dynamical mergers, we could additionally introduce a second model which has a Gaussian in $\chi_{\rm eff}$ with mean fixed at 0 (as is expected in an isotropic spin distribution) and perhaps width that is allowed to vary with mass, and infer the mixing fraction between the two models.

From similar studies of mass-spin correlations on GWTC-3 data, we do not expect to be able to draw conclusions from inference on GWTC-3 data. However, making projections for 3rd-generation (3G) detectors (i.e. Cosmic Explorer, Einstein Telescope) could provide exciting implications for what we can expect in coming decades in GW astrophysics. We plan on doing an injection study, where we draw from some distribution given by grid simulations of BBHs (i.e. [24, 5, 14]) and see if it is possible to recover a linear correlation with the detection limits of future detectors.

To do the hierarchical inference, we will use the Python inference codes `gwpopulation` [19] and `bilby` [3].

Current Progress

Thus far, most of my time has been spent on reviewing the literature, learning about how hierarchical inference works, brainstorming ideas with my mentor, and learning how `gwpopulation` works. As such, most of the problems I have encountered have been questions regarding the material I have read or specifics on `gwpopulation`, which have been helpfully answered by my mentor. Writing code to create the models and run the inference as outlined above should begin within the next week. I anticipate problems with using `gwpopulation` and `bilby`, as is usually the case when I use a code package that I did not write. I think it is possible that no strong correlation will be found with GWTC-3 data, although this is expected.

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