Inferring the Population of Merging Black Holes with Astrophysically Motivated Models

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Proposal

Gravitational waves 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 Laser Interferometer Gravitational-wave Observatory (LIGO). 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. 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 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, the evolution of merger rate with redshift, correlations between properties such as mass and spin, and even branching fractions between different BBH formation channels.

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 leading-order term is governed by a combination of the two masses called the chirp mass, and 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.

The goal of this project is to investigate a novel approach in BBH population modelling. In particular, we are interested in correlations between the spins and masses of the BBH population. Due to limitations in the number and quality of our current detections, we will likely take a heuristic approach, looking for a simple, perhaps linear, correlation. Exploring how this correlation evolves within a third dimension, redshift, gives cosmological implications on the BBH population. From studies of mass-spin correlations in the existing literature, we do not expect to be able to draw robust conclusions from GWTC-3 data. However, making projections for 3rd-generation (3G) detectors (e.g. Cosmic Explorer, Einstein Telescope) could provide exciting implications for what we can expect in coming decades in GW astrophysics.

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