Exploring LIGO sensitivity across binary black hole parameter space

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Introduction to GW detector sensitivity

LIGO (Laser Interferometer Gravitational-Wave Observatory) is designed to detect gravitational waves (GWs), which were predicted by Einstein's general theory of relativity. GWs are ripples in space and time and are very weak, so only GWs from events involving massive objects can be detected, such as binary systems with black holes and neutron stars (Abbott et al., 2009).
GW detectors are biased towards detecting loud signals, which are either nearby signals and/or high masses. This project's goal is to correct for it by computing the dependence of the detection efficiency η on source distance and mass $\eta(D_L; \vec{\lambda})$. For this, we will compute the time-volume sensitivity of LIGO, both for O4, observation run that is set to start running in mid-December, as well as to future GWs observatories.
The volume we are interested in is the comoving volume, which takes in account the expansion of the universe, and not the Euclidean one. Ultimately, we are interested in learning the rate density, which can be described by:

$$R = \frac{N}{VT} \quad [1]$$

where the N is the number of events observed and VT is the sensitive time-volume. In specific, this project will access the denominator of this rate density function. Solving the rate density function will eventually help us to understand the cosmic population.

Objectives

The main equation of this study is the average time-volume equation:

$$< VT >= T\int d\Omega \int \eta(D_L; \vec{\lambda}) C(D_L) D^2_L dD_L \quad [2]$$

Where

$$C(D_L) = \frac{1}{(1 + z(D_L))^4} \frac{1}{1 + \frac{E(z(D_L))}{(1+z)} \int_0^z \frac{dz'}{E(z'(D_L)}} \quad [3]$$

The sensitive time-volume depends on different parameters, which are the variables and are the described in $\vec{\lambda}$. Those parameters are both intrinsic (the masses, spins, tidal parameters and eccentricity) and extrinsic (RA and Dec, luminosity distance, inclination, phase polarization, time

of coalescence). In general, we are interested in the masses (m_1 and m_2) and the spins of the black holes in the binary system, so all the other parameters are marginalized over.
In figure 1, the plot shows the sensitive hypervolumes in function of the masses m_1 and m_2. Those were produced by Richard Udall, and this code will be used as the starting point of this project.

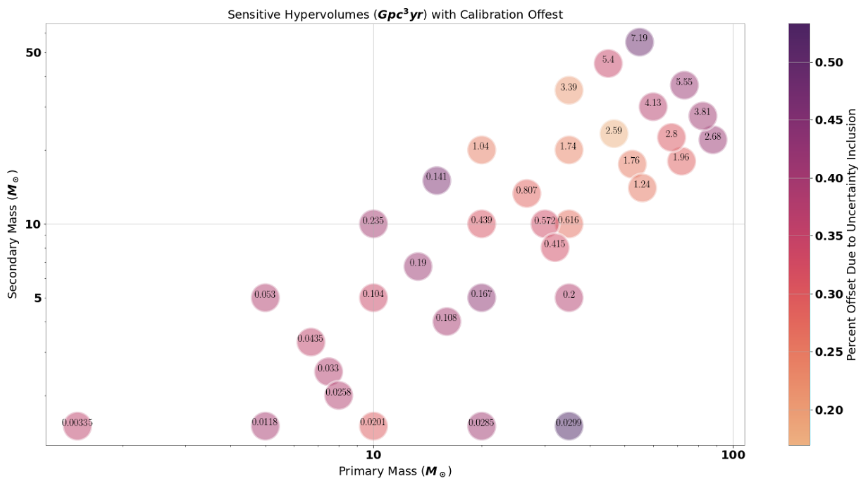

Figure 1. Adapted from “Impacts of Calibration Uncertainty on Astrophysical Sensitivity of the LVK Network” by R. Udall.

In this specific plot, the sensitivity volumes were calculated for specific masses, allowing the spins to vary. During the summer, I will be exploring using Udall’s code with different parameters. The goal is to understand how the sensitivity is affected by those changes.

Approach

The starting point of the project is the SIFCE (Simple Injection Framework for Computational Estimates), which is a package that was written by Richard Udall. The code was written in Python and calculates the sensitivity for simulated populations. For this, the package first creates a population, which can be drawn from a model or fixed parameters. Then, the population is cloned and for one of the versions calibration is taken into account. Equation [2] is used to compute the time-volume sensitivity average for both sets, and the results are compared to assess the sensitivity and efficiency.
I will start the summer by experimenting with the package. The first milestone of the project is determining the experiments we want to run with the code, as there are a few options we are currently considering. The first option would be to change the cosmological parameters and see how the sensitivity is affected, comparing the versions with the current cosmological parameters and new ones. This would allow us to explore what we may be missing out if the cosmological parameters are incorrect. The second option is to change the independent variables, for example the spins, and calculate the sensitive time-volume for binary systems with different spins and compare the change in the sensitivity.

The second milestone is having a robust set of results from the simulations, so that we can draw conclusions about the sensitivity. As necessary, I will also be working with implementing new functionalities to the code. Some possible challenges is the time taken to run the code, as currently it takes hours for each simulation. This limits the number of runs/experiments that can be performed. If the time constraints are limiting the advance of the project, I will also work in the optimization of the code. The materials needed for this project are a computer with internet access. The computational complexity of the program does not allow it to be run on a laptop, so access to a cluster with a greater computational power is necessary.

Work Plan

The SURF LIGO will last 10 weeks, and starts on June 14th and ends on August 19th. During Weeks 1 and 2, the goal is to get started both with the scientific part of the project and the technical skills. For the scientific part, the focus will be on studying cosmology and doing readings about the LIGO and sensitivity. For the technical part, I will have meetings with Richard Udall to learn more about the existing code and learn its functionalities. During those two weeks, I will also have meetings with the mentors to decide the specific parameters I will start working on.

For the next two weeks, I will be running the code, experimenting with different inputs for the parameters, as well as work on the first interim report. The goal is to have initial results that can be studied during Weeks 5 and 6. During those two weeks, I will prepare, analyze the results obtained, produce relevant plots and have meetings with the mentors to discuss the findings. Week 7 will be dedicated to writing the abstract and the interim report, and to running the code to further investigate the desired parameters/confirm results. Week 8 and Week 9 will be dedicated to finish running the code if necessary, and to the interpretation of the results obtained during the past weeks. Finally, Week 10 will be dedicated to the preparation for the final presentation.

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