Using the Binary Black Hole Population to Study Cosmology and the Stochastic Gravitational Wave Background

Jake Summers
*School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA**

Mentors: Jacob Golomb and Alan Weinstein
LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA
(Dated: May 7, 2024)

Research Proposal for the 2024 LIGO SURF Program — v20240507

I. INTRODUCTION TO GRAVITATIONAL WAVES AND THE ASTROPHYSICAL GRAVITATIONAL WAVE STOCHASTIC BACKGROUND

In 2015 the Laser Interferometer Gravitational-Wave Observatory (LIGO) made its first detection of a binary black hole merger through the detection of gravitational waves [1]. Since then, the LIGO–Virgo–KAGRA (LVK) collaboration has accumulated a catalog of some ∼90 compact binary coalescences (CBCs) [2]. This catalog of CBCs includes many binary black hole (BBH) events, along with a few binary neutron star (BNS) and neutron star–black hole (NSBH) events. With such a large collection of CBCs to analyze, it is possible—and extremely useful—to analyze the population of CBCs as a whole, to obtain deeper insights regarding the set of gravitational wave signals that the LVK detects. In turn, we can learn more about the astrophysical processes that yield these signals.

In particular, population analyses can be used to measure the (observed) mass distribution, merger rate (as a function of mass, redshift, etc.), and spin [2]. Furthermore, these population parameters can be used to predict the *overall* population (both observed and unobserved) of CBCs; this produces the signals that form components of the astrophysical gravitational-wave stochastic background (AGB). While not yet observed, the AGB produced by stellar-mass BBH mergers could provide invaluable information about the mostly unobserved population of stellar-mass black holes in our universe.

In order to accurately measure the AGB, we need an idea about what sort of signal is expected from specifically BBH, BNS, and NSBH mergers. There are numerous contributors to the overall gravitational-wave stochastic background. Among those, terrestrial (*e.g.,* LVK, $20\text{ Hz} \lesssim f \lesssim 10^4\text{ Hz}$) and space-based gravitational-wave detectors ($10^{-5}\text{ Hz} \lesssim f \lesssim 1\text{ Hz}$) may eventually be able to see a stochastic background consisting of a superposition of vacuum fluctuation amplification, cosmic strings, phase transitions, triaxial emission and instabilities due to rotating neutron stars, core-collapse supernovae, supermassive black hole capture, and of course—CBCs [3]. Additionally, there is strong evidence for an AGB in the nanohertz frequency range, believed to be caused by the inspiral of supermassive black hole binaries and observed with pulsar timing data [4].

Using most CBCs from the Gravitational Wave Transient Catalog 3, previous analyses have predicted the AGB from BBH, BNS, and NSBH mergers, under a handful of simplifying assumptions. These predictions are shown in Figure 1 [2]. Given these predictions, it is possible that the AGB from CBCs can be observed at around 30 Hz using the future "A+" LIGO design.

Yet, this analysis has some features that can be improved upon. It used a course-grained model to predict the AGB, using fixed mass distributions for the contribution from binary neutron star and neutron star–black hole mergers. For the contribution from BBHs, the analysis marginalizes over the local merger rate and mass distribution. The prediction takes these mass distributions, combined with empirical models for the time delay (between formation and merger) and star formation rate, in order to estimate the AGB. The goal of this project is to improve upon these models, while also considering any unusual effects that may show up in the AGB.

II. LIGO OBSERVING RUN 4 AND BEYOND

The LVK collaboration underwent their first period of observing run 4 (O4a) from May 24th, 2023 to January 16th, 2024. The second period, O4b, started on April 10th, 2024, and will run for around nine months. This means that there are many more CBCs detected in O4a that can be used to improve predictions of the AGB from CBCs.

* jssumme1@asu.edu

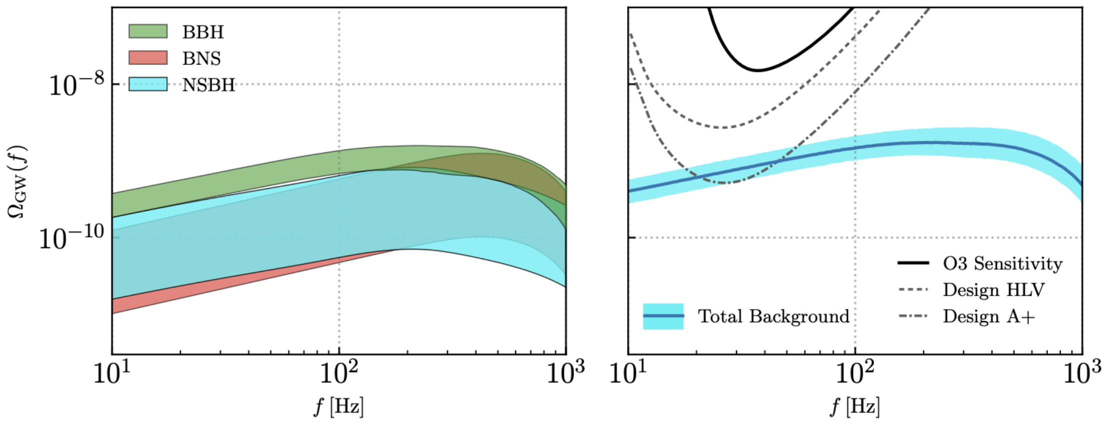

FIG. 1. Prediction of the AGB from CBCs following LVK O3, from Figure 23 of Ref. [2]. The AGB is quantified using $\Omega(f)$, the dimensionless energy density spectra, and is plotted as a function of frequency (f). The individual contributions from BBH, BNS, and NSBH mergers are plotted on the left; the AGB due to BNS and NSBH mergers is determined by Poisson uncertainty, while the AGB from BBH mergers additionally accounts for uncertainty in the mass distribution. The total AGB estimate is plotted on the right, with additional curves depicting the current LVK sensitivity and the sensitivity of future gravitational-wave detectors.

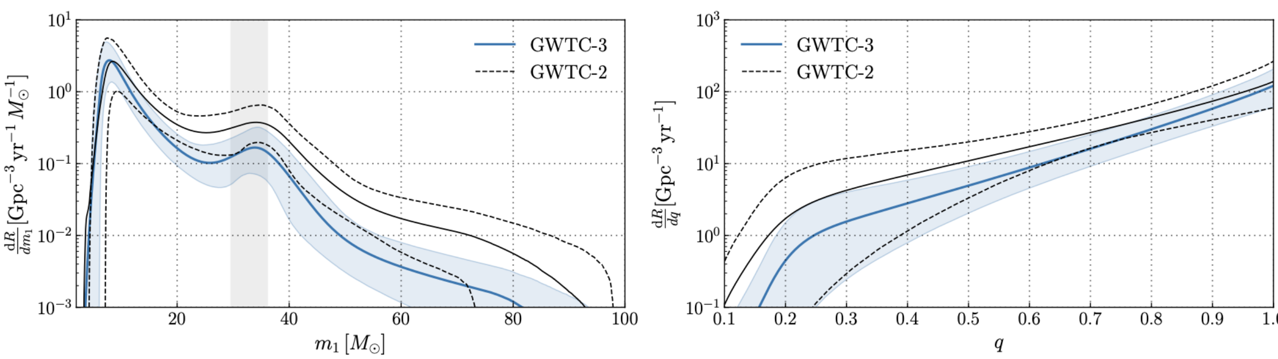

FIG. 2. Population parameters for BBH differential merger rate ($d\mathcal{R}/dm_1$ on the left and $d\mathcal{R}/dq$ on the right) as a function of primary mass (m_1) and mass ratio (q), from Figure 10 of Ref. [2]. These plots show the posterior probability distribution, with the shaded region showing the 90% credible interval. The black curves show the same, but for the prior analysis from O2. These analyses use the POWERLAW+PEAK model, which models the mass distribution as a power law with a gaussian peak (the shaded grey region on the leftmost plot shows the 90% credible interval for the mean of the gaussian peak).

Beyond LVK, plans have been made to build more terrestrial gravitational wave detectors—the Einstein Telescope (ET) and the Cosmic Explorer (CE)—and to begin building space-based detectors—the Laser Interferometer Space Antenna (LISA) [5]. Whereas the LVK collaboration can reach frequencies as low as ∼20 Hz, the ET and CE will be sensitive down to ∼3 Hz. Such improvements will allow for the measurement of coalescences of more massive objects. In fact, while LVK can reach masses of $m \lesssim 200\ M_\odot$, ET and CE could detect masses as large as $m \lesssim 1000\ M_\odot$. Additionally, ET and CE could detect CBCs out to $z \lesssim 20$, compared to LVK at $z \lesssim 1$ [5]. With these drastic improvements in detection ability, it is possible that such next-generation gravitational wave detectors could detect coalescences between BH remnants from Population III stars at $z \approx 5 - 20$ with masses $m \approx 100 - 1000\ M_\odot$. Additionally, it is certain that these detectors could detect hierarchical black hole coalescences, which can produce intermediate mass BHs via mergers from lighter BHs. Other key science questions to be addressed by CE include observing the complete population of stellar-mass BBHs, characterization of the $\sim 60\ M_\odot - 150\ M_\odot$ mass gap caused by pair instability, investigation of the interiors of neutron stars, and the search for new physics [6].

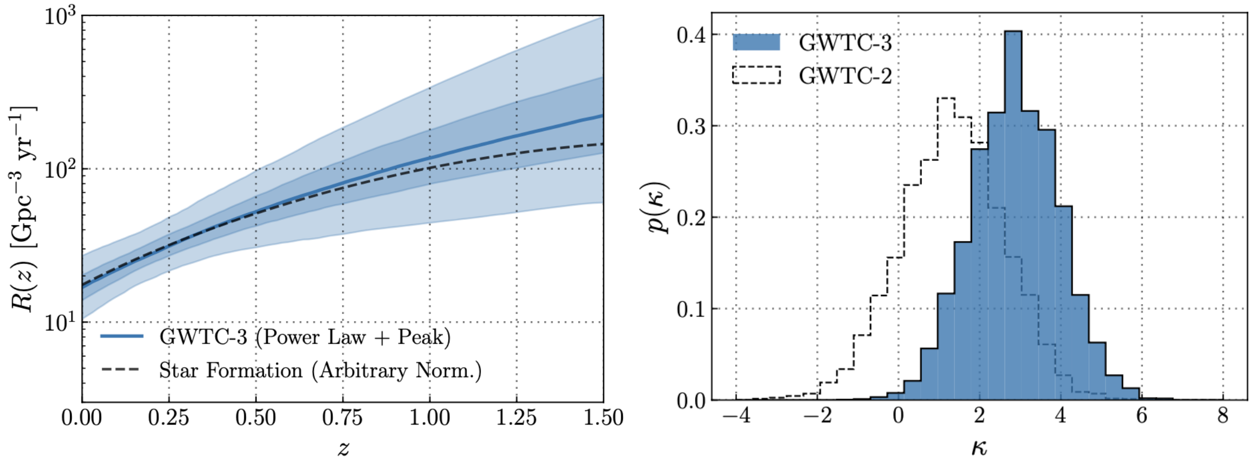

FIG. 3. Redshift evolution of the BBH merger rate, from Figure 13 of Ref. [2]. The leftmost plot shows the merger rate ($\mathcal{R}$) as a function of redshift (z). The dark blue region shows the 50% credible interval, the light blue shows the 90% credible interval, and the dashed line shows the (scaled) cosmic star formation rate. The rightmost plot shows the posterior probability distribution for the power law parameter κ, for a model $\mathcal{R}(z) \propto (1+z)^\kappa$. The blue histogram shows the results from O3, and the dashed histogram shows the results from O2. The O3 results find $\kappa = 2.9^{+1.7}_{-1.8}$, providing very strong evidence for a merger rate that increases with redshift.

III. OBJECTIVES

The primary goal of this project is to improve upon the model in Figure 1 by incorporating models of merger rate as a function of primary mass, mass ratio (*e.g.,* Figure 2), and redshift (*e.g.,* Figure 3); additionally, I will investigate how the predictions for the AGB from CBCs change when these merger rate models are varied. Starting from the posterior probability distributions of mergers observed in O4a and earlier observing runs, I will compute the inferred population merger rate as a function of primary mass, mass ratio, redshift, etc. The initial assumptions will come from population parameters inferred from the Gravitational Wave Transient Catalog 3 (*e.g.,* Ref. [2]). However, one goal of this project is to investigate how our predictions of the AGB change when these assumptions are varied.

Beyond modeling the AGB for the population of CBCs that are observable by LIGO, I will also test how these predictions change if we incorporate unobserved—but physically meaningful—features that could be observed by next-generational gravitational wave detectors such as ET and CE. One example of this could be a bump in mass at $m \gtrsim 100\ M_\odot$ due to hierarchical mergers producing intermediate-mass BHs, or large BHs produced by the collapse of Population III stars with masses above the pair instability mass gap.

The criteria for success would be a multitude of plots similar to Figure 1, which show the expected AGB under various different model assumptions. In particular, we will model how the AGB predictions change by performing the following steps:

1. Perform a population analysis of CBCs observed up to O4a, to create population parameter models similar to those in Figure 2 and 3.

2. By assuming a broken power law distribution of BBH masses, as in Figure 23 of Ref. [2] and Figure 5 of Ref. [7], along with similar assumptions for star formation rate, time delays between formation and merger, spin distribution, and redshift distribution, reproduce these figures, but using all data up to O4a. Compare results to previous models and cross-check results with parallel analyses of O4a.

3. Vary the assumed distributions of merger rate as a function of primary mass, mass ratio, and redshift, in order to model how strongly these assumed distributions affect the predicted AGB from CBCs. Additionally, test out the validity of using a broken power-law model for $\mathcal{R}(z)$, compared to previous calculations of the AGB which rely on an assumed time delay distribution and star formation rate model. I could also consider a time-evolving mass distribution for BBH mergers.

4. Simulate contributions from very massive BBH mergers ($\gtrsim 100\ M_\odot$) to analyze how hierarchical mergers and BHs produced by Population III stars may affect the AGB. This can be done by adding an additional peak at high masses to the assumed mass distribution of BBH mergers.

5. Simulate the stochastic background as seen by CE and other next-generation detectors [5].

IV. APPROACH

The first step of this project would be to perform a population inference of all CBCs observed up to O4a. This can be done using pipelines such as `gwpopulation_pipe`. I will use such pipelines to obtain posterior probability distributions for merger rate as a function of primary mass, mass ratio, redshift, and potentially spin.

I will then take these models and compute the stochastic background that would be caused by them. I will do this by starting from a skeleton code provided by Jacob Golomb, making changes as necessary. In essence, this step will involve computing waveforms produced by the population of CBCs, calculating the energies associated with such waveforms, and translating that into an energy density which can be observed as part of the AGB.

I expect that the most difficult step will be going from the posterior probability distributions and marginalizing over uncertainty for various parameters, in order to calculate the dimensionless energy-density spectra of gravitational waves. This step will be both computationally and intellectually challenging.

Necessary equipment would be an account on a computing cluster, as computations will be quite intensive and not doable on my laptop. However, I will be able to use my personal laptop to use `ssh` and run JupyterLab through the supercomputer. I will also require access to state-of-the-art GPUs and machine-learning-based libraries (*e.g.,* JAX) to speed up computations.

I will possibly be collaborating with Arianna Renzini, Tom Callister, Sterling Scarlett, as well as the LIGO–Virgo–KAGRA Collaboration as a whole. My project will depend on the parameter estimation results from individual events, cataloged in the Gravitational Wave Transient Catalog.

V. WORK PLAN

Date	**Tasks/Deliverables**
May 15th, 2024	Project Plan Due.
June 18th, 2024	Begin research at Caltech.
June 21st, 2024	Perform population inference of CBCs observed up to O4a.
June 28th, 2024	Reproduce Figure 1 from Ref. [2], using new CBCs from O4a. Compare results to O3.
July 5th, 2024	Investigate AGB dependence on mass ratio and primary mass by varying these parameters.
July 8th, 2024	Field trip to LIGO Hanford Observatory.
July 12th, 2024	Investigate dependence on merger rate evolution with redshift.
July 12th, 2024	First Interim report due.
July 19th, 2024	Analyze how very massive BBH mergers affect the AGB prediction.
July 26th, 2024	Simulate the AGB as seen by CE and ET.
August 2nd, 2024	Test other possibilities and see how they influence the AGB.
August 2nd, 2024	Second Interim report due.
August 23rd, 2024	Final presentation.
Septemper 27th, 2024	Final report due.

VI. ACKNOWLEDGEMENTS

JS thanks JG and AW for significant help in introducing him to the world of gravitational wave astronomy. Funded by the National Science Foundation Research Experience for Undergraduates Award #2150027.

[1] B.P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. **116**, 061102 (2016).
[2] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), *Population of Merging Compact Binaries Inferred Using Gravitational Waves through GWTC-3*, Phys. Rev. X **13**, 011048 (2023).
[3] T. Regimbau, *The astrophysical gravitational wave stochastic background*, Res. Astron. Astrophys. **11**, 369 (2011).
[4] G. Agazie *et al.* (The NANOGrav Collaboration), *The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background*, ApJL **951**, L8 (2023).
[5] M. Pieroni, A. Ricciardone, and E. Barausse, *Detectability and parameter estimation of stellar origin black hole binaries with next generation gravitational wave detectors*, Sci. Rep. **12**, 17940 (2022).
[6] M. Evans *et al.*, *A Horizon Study for Cosmic Explorer: Science, Observatories, and Community*, arXiv e-prints (2021).
[7] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), *Upper limits on the isotropic gravitational-wave background from Advanced LIGO and Advanced Virgo's third observing run*, Phys. Rev. D **104**, 022004 (2021).