LIGO SURF 2021 Proposal: Marginalizing over the noise properties in parameter estimation

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The traditional gravitational wave parameter estimation process relies on sequential estimation of noise properties and binary parameters. Using new capabilities of the `BayesWave` algorithm and recent developments in noise uncertainty modeling, we will simultaneously estimate the noise and binary parameters, which will mitigate the assumption of known noise variance in the fitting process. We will quantify any differences between these methods on parameter recovery and analyze the impact for astrophysical inference.

I. INTRODUCTION

Gravitational wave (GW) data analysis requires models of both the genuine GW signal and the frequency-dependent noise in the raw data. Accurate parameter estimation of black hole and neutron star properties from compact binary coalescence (CBC) signals depends on the robustness of both of these models [1]. While creating waveform templates by numerically solving Einstein's equations has been the subject of many research operations over the last decades [2], noise models have not been traditionally given the same amount of attention.

The traditional parameter estimation process uses sequential estimation of the noise properties and the binary parameters. First, the noise is modeled using the `BayesWave` (BW) algorithm [1], a variable dimension, parameterized model to separate transient GW signals from detector noise that incorporates non-Gaussianity in the data. Integrated into BW is the `BayesLine` algorithm [3] for the noise power spectral density, which selects model parameters via a Markov Chain Monte Carlo method.

The resultant noise model is given to `LALInference` (LI), the primary parameter estimation pipeline used by the LIGO and Virgo collaborations [4]. LI and its successor `Bilby` use a provided fixed noise model in their Bayesian estimation of binary parameters.

Consequently, analyses of CBC signals make three explicit assumptions about the noise properties: first, that the noise is Gaussian; second, that it is stationary in time; and third, that its frequency-dependent variance is known [5]. In practice, all three assumptions break down. The third is invoked in the sequential estimation of noise and parameters, which will address by simultaneously inferring noise properties and binary parameters.

The likelihood function $\mathcal{L}(d|h')$ computes the probability density of measuring the detector data d under the condition of a true GW signal h'. This likelihood is explicitly dependent on $S_n(f)$, the power spectral density (PSD) of the noise. Chatziioannou *et al.* [5] provides and compares two methods of computing $S_n(f)$ to robustly estimate the noise variance in GW data.

The "on-source" spectral estimation method was found to produce whitened data more consistent with a Gaussian likelihood. In addition, both methods for estimating $S_n(f)$ were tested on simulated CBC signals injected into observational data from the Advanced gravitational-wave detector network. Quantitative differences between the resultant parameter estimations demonstrated the importance of the chosen model for the noise variance and further confirmed the comparative strength of the on-source method. Figure 1 depicts an example data spectrum in gray with the extracted signal in purple and noise with uncertainty in black.

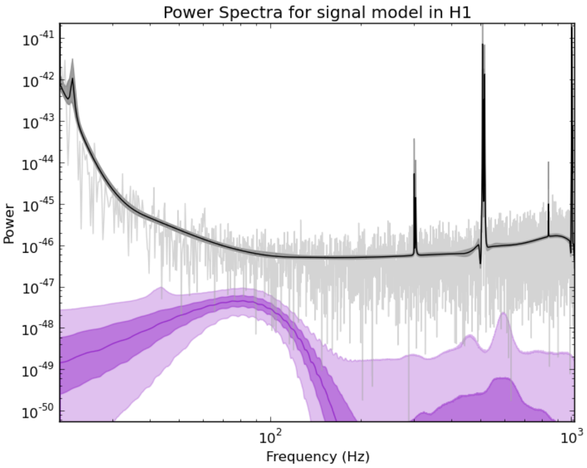

FIG. 1. Example spectra with uncertainty in noise (black, uncertainty in dark gray). The raw data are in gray and the signal with uncertainty is in purple.

As described, the standard process is for BW to compute the noise PSD that is then is fed to LI to estimate binary parameters. A recent development in the capability of BW, described in detail in [6], enables it to compute binary and noise parameters in concert. The simultaneous likelihood estimation mitigates the third assumption in prior analyses that was noted above. As of yet, the new model for uncertainty in the noise PSD, as shown in Fig. 1 and method of marginalizing over the noise properties in parameter estimation have not been applied to actual CBC events, only to injected signals. As such, exploring the impact of these methods is an active area of research to which we aim to contribute.

II. PROJECT OBJECTIVES

We aim to study the effect of including uncertainty in noise on parameter estimation of the confirmed LIGO and Virgo CBC events. We will use `BayesWave` to simultaneously model the noise $S_n(f)$, obtained using the on-source estimation method described above, and the signal so as to infer its parameters. In addition, we will compare our results with those obtained using the sequential estimation method, which first models the noise then extracts binary parameters assuming that noise model, and quantify any differences.

We will draw CBC events from the Gravitational-Wave Transient Catalog for the first and second observing runs (O1, O2) of the Advanced gravitational-wave detector network as well as the catalog for the first half of the third observing run (O3a) (Abbott *et al.* 7, Abbott *et al.* 8). Combined, these catalogs compose GWTC-2. The network comprises the two Advanced LIGO detectors and, since August 1, 2017, the Advanced VIRGO detector. In total, the combined catalogs for O1, O2, and O3a contain over 60 confident and candidate CBC events.

We will perform this new method of parameter estimation on all CBC candidate events and analyze the credible regions for two of the parameters of interest, the total mass M and the mass ratio q. Fig. 2, which is Figure 6 from Abbott *et al.* [8], plots the 90% credible regions for all CBC candidate events in GWTC-2 in M-q space, with events published prior to that study highlighted. The primary objective of our analysis is to quantify differences in the parameter estimates when the noise and signal are modeled in concert, which we will do by using credible regions as in Fig. 2. In doing so, we will quantify the impact of this spectral estimation method on parameter recovery and inferences drawn from GW data.

III. TIMELINE

A general timeline for the project is as follows.

1. Familiarize myself with BW and runs on real data.
2. Analyze the data from GW150914, the first BBH detection, by doing the sequential (first PSD then PE) and joint (PSD+PE) analyses and comparing results.
3. Explore the results from GW150914 in detail, as it is a loud and very well analyzed event.
4. Once all the details are ironed out, analyze the remaining events. The goal is an update plot like Fig. 2.
5. Time permitting, analyze simulated data, as expected from upcoming observing runs, for example O4 [9].

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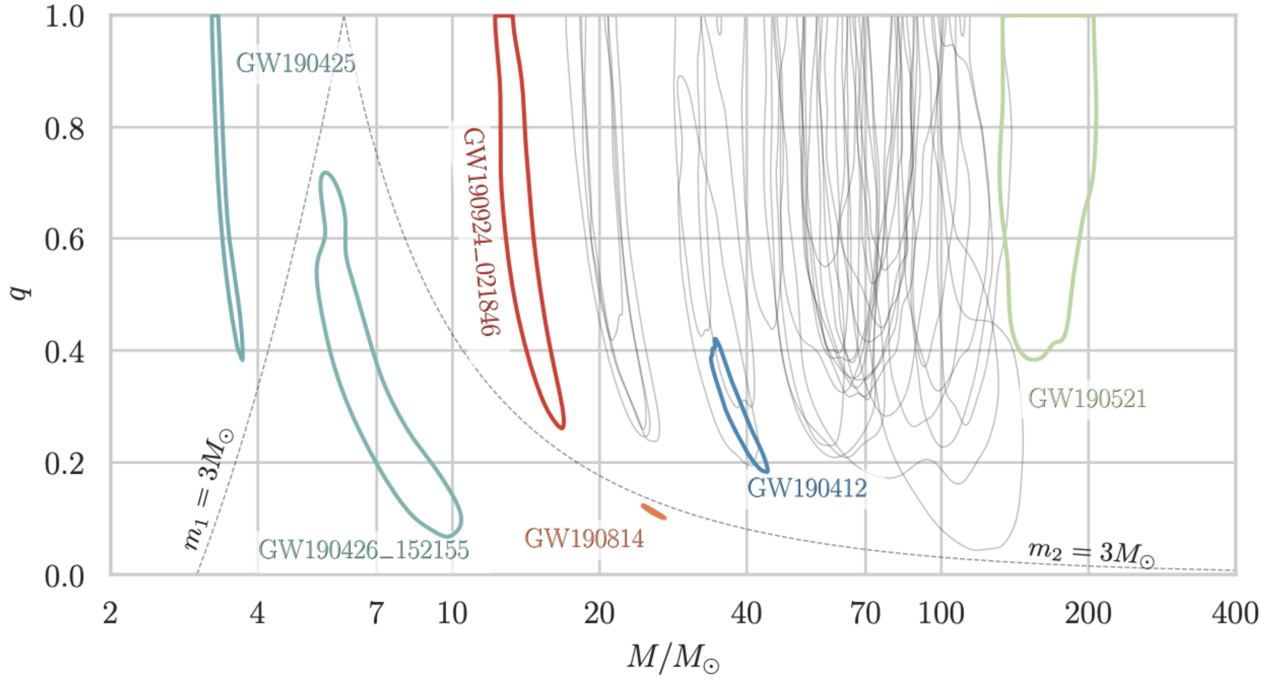

FIG. 2. 90% credible regions for all candidate events in total mass M and mass ratio q space, with previously published events highlighted. Dashed lines delineate where one of the objects can have a mass $< 3\,M_\odot$.