Evaluating the impact of low-frequency sensitivity difference of LIGO detectors on GW231123

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ABSTRACT

GW231123 is a short duration gravitational wave signal, consistent with a binary black hole merger with a total mass of $240 M_\odot$. It is the most massive binary black hole observed to date. Both components are highly spinning and likely have masses in the mass gap caused by pair-instability supernova processes. The event is challenging to analyze because of its short duration and limited accuracy of waveform models for such a system. Additionally, 2 sigma differences between median total mass and median spin precession arise when parameter estimation is performed using LIGO Hanford-only and LIGO Livingston-only data, raising concerns about the presence of spurious transient noise overlapping with the GW signal. In this project, we will perform the parameter estimation of GW231123 to quantify these differences. Later, we will perform injection simulations to investigate whether the differences between the parameter estimation results can be explained by fluctuations of Gaussian noise, the difference in low-frequency sensitivity of the two LIGO detectors, or if they are related to transient noise.

1. INTRODUCTION

Gravitational waves (GW) are deformations of spacetime traveling at the speed of light. They were predicted by Albert Einstein as a consequence of general relativity in 1916 (Einstein 1916). Since then, multiple experiments have attempted to detect them, with the first successful direct detection made by ground-based LIGO interferometers in 2015 (Abbott et al. 2016).

The first detected transient gravitational wave, GW150914, originated from the merger of a pair of black holes in a binary system (Abbott et al. 2016). Since then, more than 200 events have been observed (Abbott et al. 2023), including, apart from binary black holes, neutron star - black hole mergers (Abbott et al. 2020a, 2021) and binary neutron star mergers (Abbott et al. 2017) (Christensen & Meyer 2022).

GW190521 was a particularly interesting GW event. When it was detected it was the most massive binary black hole merger detected. The masses of the two components were $85^{+21}_{-14} M_\odot$ and $66^{+17}_{-18} M_\odot$, with a total mass of $150^{+29}_{-17} M_\odot$ and a remnant mass of $142^{+28}_{-16} M_\odot$ (90% credible intervals) (Abbott et al. 2020b,c). Due to pair-instability supernova process (Farmer et al. 2019), it is believed that black holes with masses between $65 M_\odot$ and $130 M_\odot$ cannot form as a result of stellar collapse. In GW190521's case, the primary black hole lies in this mass gap and so it may be the result of a previous binary black hole merger. Another important astrophysical implication is that the remnant of GW190521 was the direct first observation of the formation of an intermediate mass black holes, a class of black holes with masses between $10^2 M_\odot$ and $10^5 M_\odot$.

In this project, we will focus on the recently observed event GW231123, detected on 23 November 2023 by the two LIGO detectors. The signal is consistent with the coalescence of a binary black hole system with a total mass of over $240 M_\odot$, with both black holes likely highly spinning. This merger is the most massive to date; the primary is within or above the 65-130$M_\odot$ mass gap produced by the pair-instability supernova process, while the secondary is within the mass gap with a probability of 80%.

2. OBJECTIVES

The analysis of GW231123 is very challenging, as only a few cycles of the signal were observed, and the theoretical waveform models currently available have limited accuracy for such highly spinning black holes. For this project, we will focus on the inference of the source properties of this event, studying in particular the contribution of individual LIGO detectors. Typically, the probability distributions of the source parameters obtained from both LIGO detectors should be consistent. In the case of GW231123, differences between the median values of total mass and spin precession inferred only from the LIGO Livingston data differ by 2 sigma from those inferred only from the LIGO Hanford data. These differences raise concerns about the presence of spurious transient noise overlapping with the GW signal.

As GW231123 is a high-mass event and both black holes are likely highly spinning, the information contained in the low-frequency region (< 50 Hz) is crucial for the inference of its properties. The LIGO Livingston detector has a slightly higher sensitivity in the low frequency region than LIGO Hanford, therefore, it is possible that such differences in the inferred posteriors are to be expected.

The objective of this project is to quantify the differences observed in LIGO Livingston-only and LIGO Hanford-only posteriors. Afterwards, we aim to investigate whether the differing parameter estimation results from both detectors could be explained by the difference in their low-frequency sensitivity, could be expected due to fluctuations of Gaussian noise, or could be related to transient noise.

3. APPROACH

3.1. *Gravitational wave signal*

LIGO interferometers are L-shaped quadrupole detectors that aim to measure the gravitational wave strain:

$$h(t) = F_+(\theta,\phi,\psi)h_+(t) + F_\times(\theta,\phi,\psi)h_\times(t),$$

where h_+ and $h_\times$ are the amplitudes of the two polarizations of the wave, θ is the angle between the propagation direction of the gravitational wave and the axis normal to the detectors' plane, ϕ is the angle between the projection of the propagation direction vector onto the detector plane and one of the detectors, while ψ is the polarization angle. We have:

$$F_+(\theta,\phi,\psi) = \frac{1}{2}(1+\cos^2\theta)\cos 2\phi\cos 2\psi - \cos\theta\sin 2\phi\sin 2\psi$$

and

$$F_\times(\theta,\phi,\psi) = \frac{1}{2}(1+\cos^2\theta)\sin 2\phi\cos 2\psi - \cos\theta\sin 2\phi\cos 2\psi.$$

The detectors' actual measurements $d(t)$, in addition to the potential GW strain $h(t)$, contain significant noise $n(t)$:

$$d(t) = h(t) + n(t).$$

Accurate characterization of the noise is crucial for reliable parameter estimation. This is typically achieved by estimating the power spectral density (PSD) of data segments near (but not containing) the GW signal or by modeling the noise using a mixture of Lorentzians and cubic splines (Littenberg & Cornish 2015) . The PSD is then used in the construction of the likelihood function, allowing the parameter estimation process to adequately account for frequency-dependent noise characteristics (Christensen & Meyer 2022). PSD of both LIGO detectors at the time of registering the GW231123 signal is shown in Figure 1.

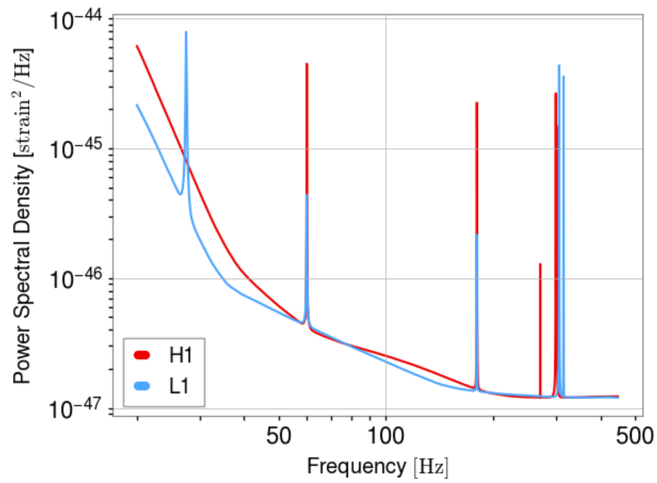

Figure 1. Power spectral density of LIGO Hanford (red) and LIGO Livingston (blue) at the time of registering GW231123 signal.

3.2. *Parameters*

The main difficulty in parameter estimation from binary black hole GW signal comes from the multidimensionality of the data. There are 15 total parameters that impact a binary black hole waveform, namely:

- masses of the two black holes m_1 and m_2 ,
- spins $\vec{\chi_1}$ and $\vec{\chi_2}$, expressed by the dimensionless spin vector $\vec{\chi_i} = \vec{J_i}c/(Gm_i^2)$ $(0 \leq |\vec{\chi_i}| < 1)$, where J_i is the angular moment of black hole,
- luminosity distance D_L,
- inclination angle ι (angle between observer's line of sight and orbital plane of the system),
- coalescence time t_0 and phase ϕ_0,
- polarization angle ψ,
- source sky position θ and ϕ.

Due to the possibility of more precise measurement, often, instead of directly estimating the two masses, the chirp mass $\mathcal{M}$ is used, which is defined as

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

for $m_1 > m_2$.

3.3. *Bayesian statistics*

To infer the properties of GW signals, we use Bayesian statistics. Bayesian statistics is based on an interpretation of probability, where, unlike in the frequentist approach, probability expresses a degree of belief. It is achieved by combining prior knowledge with new data to compute new probabilities ("posterior") according to Bayes' theorem:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

where $P(A)$ is the prior probability, $P(B|A)$ the likelihood, and $P(A|B)$ the posterior probability. In the context of parameter estimation, Bayes' theorem can be rewritten as

$$p(\theta|d) = \frac{L(d|\theta)\pi(\theta)}{\int L(d|\theta)\pi(\theta)\,\mathrm{d}\theta}$$

where observations are denoted by d, unknown parameters are denoted by θ, L is the likelihood function and π is the prior probability density function (Christensen & Meyer 2022). The denominator serves as a normalization constant.

To compare different models $\mathscr{M}_1$ and $\mathscr{M}_2$ in Bayesian statistics, we can introduce the Bayes factor B_{12}, a ratio of the marginal probabilities of the models. We can write:

$$B_{12} = \frac{P(d|\mathscr{M}_1)}{P(d|\mathscr{M}_2)} = \frac{P(\mathscr{M}_1|d)/P(\mathscr{M}_2|d)}{P(\mathscr{M}_1)/P(\mathscr{M}_2)}$$

$$B_{12} = \frac{\int L_1(d|\theta_1, \mathscr{M}_1)\pi(\theta_1, \mathscr{M}_1)\,\mathrm{d}\theta_1}{\int L_2(d|\theta_2, \mathscr{M}_2)\pi(\theta_2, \mathscr{M}_2)\,\mathrm{d}\theta_2}.$$

3.4. *Bilby pipeline*

`Bilby` is a Python library for GW-related Bayesian inference. It allows one to perform parameter estimation for a GW signal using nested sampling (Ashton et al. 2019). `Bilby` will be used to perform parameter estimation of both the GW231123 event and of simulated, injected GW231123-like signals.

4. TIMELINE

- Weeks 1-2: Attend gravitational wave workshops, set up LIGO credentials, and download the necessary libraries. Download the GW231123 data and start getting familiar with `Bilby`.
- Weeks 3-4: Perform parameter estimation for GW231123 and choose a metric to compare posterior distributions.
- Weeks 5-6: Get familiar with techniques for injecting simulated data and prepare scripts to analyze them.
- Weeks 7-8: Perform parameter estimation for the synthetic GW231123-like waveform.
- Week 9: Summarize and visualize the results, start writing the final report.
- Week 10: Finish writing the final report, prepare the presentation.

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