Draft version August 15, 2024
Typeset using LATEX **RNAAS** style in AASTeX631

Characterizing Compact Object Binaries in the Lower Mass Gap with Gravitational Waves

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ABSTRACT

The gravitational wave observation GW230529 has provided new insight into the ways compact objects form and interact in the universe. The source binary of GW230529 was inferred to contain a compact object with a mass between the most massive observed neutron stars and least massive observed black holes. However, the properties of the mass-gap object, such as its exact mass and spin, remain uncertain. To investigate the properties of this compact object, we perform parameter estimation on gravitational wave systems with parameters similar to GW230529. We find that the low signal-to-noise ratio of GW230529 is the key reason for the ambiguity in determining whether the mass of the primary object in the binary is consistent with a light black hole or a heavy neutron star. Due to the weakness of the signal, the impact of the priors for the masses and spins on the posterior distribution is significant, and a precise measurement of the system properties cannot be obtained.

Keywords: Gravitational wave sources(677) — Black holes(162) — Neutron stars(1108) — LIGO(920)

INTRODUCTION

When two compact objects (e.g., black holes, neutron stars) are in a close enough orbit, ripples in space-time called gravitational waves are efficiently emitted, causing the binary to lose orbital energy and eventually merge. Gravitational waves give us valuable insight into elements of the cosmos that we cannot always detect with light, like black holes. The LIGO-Virgo-KAGRA (LVK) Collaboration uses laser interferometers to detect incredibly weak gravitational wave signals. During the third observing run, LVK reported nearly 100 significant compact binary coalescence candidates (Abbott et al. 2023).

The ongoing fourth observing run of the international gravitational wave detector network began in May of 2023. The first significant candidate observed during this run was GW230529 (Abac et al. 2024), observed by the LIGO-Livingston detector (Aasi et al. 2015) on 2023 May 29. Due to the unique nature of the objects involved in the source binary, GW230529 has impacted our understanding of the formation and behavior of compact objects, including the masses at which they can exist. GW230529 is the first observed merger event whose primary object resides in the lower mass gap (Abac et al. 2024) between the heaviest neutron stars ($\sim 3\ M_\odot$; Rhoades & Ruffini 1974; Kalogera & Baym 1996) and the lightest black holes ($\sim 5\ M_\odot$; Bailyn et al. 1998; Ozel et al. 2010; Farr et al. 2011). Previously, a lack of observations led some to propose that compact objects could not form in this mass gap (Fryer et al. 2012; Belczynski et al. 2012; Fryer & Kalogera 2001); however, the discovery of GW230529 suggests that this may not be the case.

The properties of the mass-gap object in the GW230529 system remain unclear due to uncertainty in the measured masses and in the neutron star equation of state. Although the bulk of the posterior supports a mass-gap black hole merging with a neutron star, we cannot exclude the possibility that the two compact objects are heavy ($\gtrsim 2\ M_\odot$), near-equal-mass neutron stars (Abac et al. 2024).

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In this work, we explore the measured uncertainties in the parameters of the binary system by performing parameter estimation on synthetic signals to determine how well we can characterize GW230529-like systems. We also discern whether we may be able to better distinguish between these types of systems (heavy binary neutron star versus neutron star and low-mass black hole) in future gravitational wave detections. GW230529 and similar events are key for expanding the current knowledge base about the properties of objects existing in the universe and their potential for forming compact binary coalescences.

METHODS

We perform parameter estimation on simulated gravitational wave signals to investigate how the true parameters of the system, specific noise realization, and signal-to-noise ratio (SNR) affect uncertainties in the results. We use the `IMRPhenomPv2_NRTidalv2` (Dietrich et al. 2019) waveform model with standard low secondary-spin priors, concordant with the framework used in the original GW230529 analysis (Abac et al. 2024). We perform nested sampling (Skilling 2006) and Bayesian inference to sample posterior distributions for the simulated signals using the Bilby (Ashton et al. 2019; Romero-Shaw et al. 2020) software package.

We choose true parameter values corresponding to discrete samples of the posterior obtained in the original `IMRPhenomPv2_NRTidalv2` analysis of GW230529 (Collaboration et al. 2024). Some key parameters associated with each chosen sample, along with the optimal SNR using the L1 detector, are shown in Table 1. For our various simulations, we consider three sets of intrinsic parameters for the system: Max Likelihood has parameters corresponding to the maximum-likelihood posterior sample, Equal Mass has parameters corresponding to the sample of the posterior with the greatest mass ratio, and Secondary Peak is the maximum-likelihood sample out of the subset of samples in which the primary mass is less than 3 solar masses, to capture the secondary mode in the original parameter estimation primary mass distribution.

For each of the three sets of intrinsic parameters in Table 1, we run multiple simulations with different detector configurations and noise realizations. Our fiducial set of simulations includes the L1 detector only and a zero-noise realization. We also investigate a two-detector configuration (L1 and H1) with zero noise, as well as 10 different realizations of Gaussian noise with only the L1 detector. For the Max Likelihood and Equal Mass samples, we also explore the effects of varying the SNR (15, 25, 35, 50) by decreasing the luminosity distance (for Max Likelihood, in Mpc: 204.87, 122.92, 87.80, 61.46; for Equal Mass, in Mpc: 190.26, 114.16, 81.54, 57.08).

Table 1. True parameter values corresponding to the posterior sample chosen for each simulation.

Sample Name	$m_1/M_\odot$	$m_2/M_\odot$	q	$\chi_{\rm eff}$	$D_{\rm L}/{\rm Mpc}$	SNR
Max Likelihood	4.03	1.28	0.32	-0.02	259.8	11.83
Equal Mass	2.21	2.21	1.00	-0.21	250.72	11.38
Secondary Peak	2.77	1.73	0.63	-0.2	317.39	10.47

Note—m_1 and m_2 represent the source-frame masses. The optimal SNR listed is for a L1-only detector configuration.

RESULTS

In Fig. 1, we show the posterior probability distributions of the primary mass, mass ratio, and effective inspiral spin inferred from parameter estimation on the simulated GW230529-like signals.

In the left panel of Fig. 1, we compare the distributions obtained from zero-noise simulations using each of the three sets of intrinsic parameters: Max Likelihood, Equal Mass, and Secondary Peak. Equal-mass heavy neutron star mergers seem to produce similar gravitational wave signals as a low-mass black hole and neutron star merger, so they are difficult to distinguish from each other without a strong enough signal. The posterior distributions are largely influenced by the priors on the specified parameters, which are overwhelming the likelihood and causing this parallel behavior between simulations.

In the right panel of Fig. 1, we show the distributions obtained from varying the signal-to-noise ratio with the Max Likelihood parameter values and a zero-noise realization. We find that increasing the SNR by either decreasing the distance or adding a second detector improves the precision of our parameter estimation results and eliminates the multimodality of the posterior probability distributions. An SNR of 20 or more is needed to achieve a unimodal distribution for the key parameters in the Max Likelihood simulation. For the Equal Mass simulation, a higher SNR, around 30, is needed to overcome the priors and produce a distribution that is consistent with the true values for the parameters.

Furthermore, the particular noise realization does not appear to be the main factor responsible for significantly affecting measurement uncertainty and causing ambiguity in the nature of the GW230529 source, since different realizations of Gaussian noise in our simulations result in similar distributions compared to simulations with zero noise. The distribution is still bimodal when a zero-noise realization is used, indicating that noise is not the cause for the bimodality in the posterior.

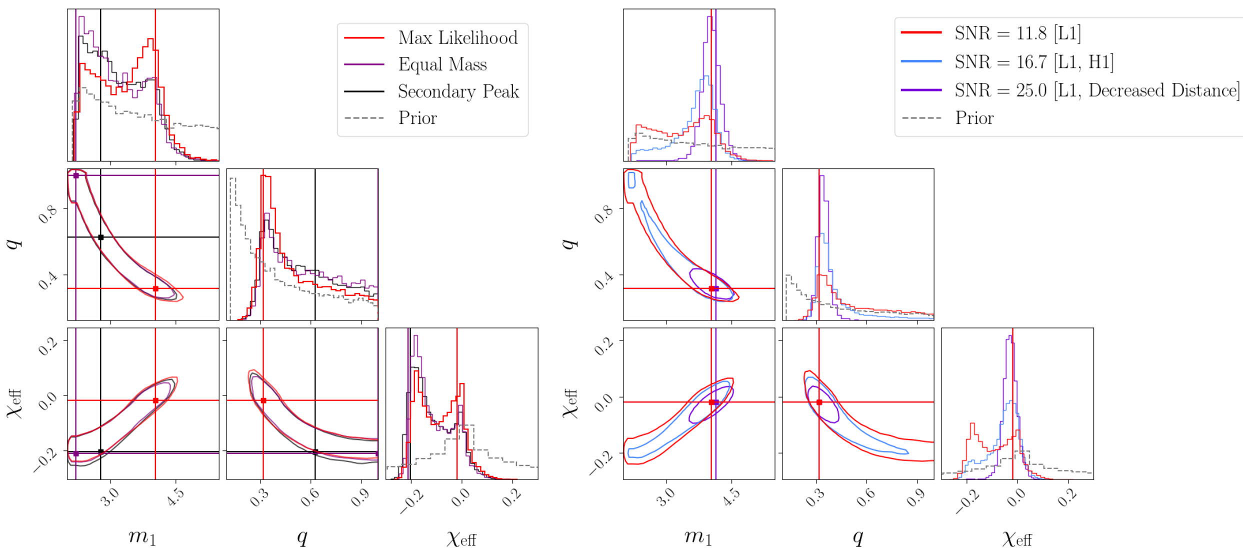

Figure 1. Posterior probability distributions of the primary mass, mass ratio, and effective inspiral spin inferred from parameter estimation on GW230529-like events simulated with zero noise. In the left panel, we show the results from simulating events with different masses, chosen from the GW230529 LVK parameter estimation samples. In red, we simulate a binary with intrinsic parameters corresponding to the Max Likelihood sample (unequal masses characteristic of a mass-gap black hole and a neutron star). In purple, we simulate a binary corresponding to the Equal Mass sample (characteristic of two heavy neutron stars). In gray, we use the Secondary Peak sample. In the right panel, we plot the results of using the Max Likelihood sample but varying the signal-to-noise ratio (SNR) and network configuration. In red, we use the LIGO-Livingston (L1) detector only, as in the GW230529 LVK analysis. In blue, we include the LIGO-Hanford (H1) detector. In black, we simulate a L1-only event with a higher SNR by decreasing the luminosity distance. In both panels, the true values used for each simulation are represented by the solid lines in the corresponding color.

DISCUSSION

The primary reason for the uncertainty and the multimodality in the posterior distributions for the parameters, especially the component masses and effective inspiral spin, is the low SNR of the signal. In other words, the SNR of the GW230529 signal is not strong enough to fully overcome the prior on the parameters of interest. Given the SNR of this event, the original measured uncertainty in the masses and spins of GW230529 is expected. This leads to an ambiguity in the true nature of mass-gap black hole sources at lower SNR.

With upgraded detectors that are more sensitive to quieter signals and with multiple active detectors, we will be able to achieve tighter constraints on parameters of the system and better resolve the true nature of the compact object sources. Hence, better network sensitivity or a louder event should allow us to distinguish whether a compact object in a system similar to GW230529 is consistent with a neutron star or a low-mass black hole. Knowing if the primary object in these types of mass-gap systems is a black hole or a heavy neutron star will not only deepen our understanding of the lower mass gap and at which masses compact objects can exist, but also expand our knowledge of how these compact objects form.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. AST2149425, a Research Experiences for Undergraduates (REU) grant awarded to CIERA at Northwestern University. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

This research was supported in part through the computational resources and staff contributions provided for the Quest high performance computing facility at Northwestern University which is jointly supported by the Office of the Provost, the Office for Research, and Northwestern University Information Technology.

A special thank you to Drs. Michael Zevin, Sylvia Biscoveanu, Chase Kimball, and Vicky Kalogera for their expert guidance and support. Also, thank you to Aaron Geller and all of CIERA for helping to make this REU such a valuable and rewarding experience.

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