Simulation of chirp mass distribution of neutron star and black hole merger events for gravitational-wave radiation

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The gravitational waves (GWs) from the merger events of binary black hole (BH-BH) and binary neutron star (NS-NS) have been detected by LIGO-Virgo (O1 and O2). Besides, GWs from the NS-BH mergers have been recently reported and might be hopefully confirmed in the near future. The mass distributions of these merger events are poorly understood now; thus, LIGO-Virgo adopted a simple cut rule for chirp mass ($\mathcal{M}$) to distinguish the GW event candidates: $\mathcal{M} < 2.1\ M_{\odot}$ for NS-NS, $2.1\ M_{\odot} < \mathcal{M} < 4.35\ M_{\odot}$ for NS-BH, and $\mathcal{M} > 4.35\ M_{\odot}$ for BH-BH. We tested its validity by simulating the chirp mass ($\mathcal{M}$) distributions in two synthetic models, i.e., Model Galaxy and Model LIGO, in which the masses of BHs and NSs are observed by the electromagnetic spectrum observations in our Galaxy and inferred by LIGO-Virgo detection (O1 and O2), respectively. The simulation shows that it is unsuitable for Model LIGO due to the BHs inferred by LIGO-Virgo are usually bigger than those in our Galaxy, and $\mathcal{M}$ of NS-BH events would distribute in the range of $2.1\ M_{\odot} < \mathcal{M} < 7.3\ M_{\odot}$, which partially overlaps with those of BH-BH events. Therefore, we suggest that the new searching round of LIGO-Virgo (e.g., O3) should carefully seek out the underlying NS-BH candidates in the range of $2.1\ M_{\odot} < \mathcal{M} < 7.3\ M_{\odot}$.

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I. INTRODUCTION

During the first and second observing runs (O1 and O2) of the gravitational-wave (GW) detector network—Advanced LIGO [1] and Virgo [2] (LIGO-Virgo)—a total of ten binary black hole (BH-BH) and one binary neutron star (NS-NS) merger events were detected; however, no neutron star-black hole (NS-BH) mergers were detected [see [3] and references therein]. The third observing run (O3) of LIGO-Virgo began on April 1, 2019 with higher sensitivity detectors,[1] expected to bring more GW observations, even the NS-BH mergers. Excitingly, the LIGO-Virgo (O3) discovered two interesting GW signals on April 26[2] and August 14, 2019,[3] which may have resulted from the collision of the NS-BH systems, but it will take some time to get the result due to its difficulty. Several possible formation scenarios of NS-BH mergers have been proposed, which include binary stellar evolution [4], mergers in triple systems [5,6], mergers via cluster dynamics [7], and so on. Significantly, investigating these GW events cannot only test the theories on gravitation and astrophysics, such as general relativity (GR) [8], but also present us the whole pictures of various combinations of compact objects in binary systems that should bring out the new insights into the Universe.

Until now, we are still not clear about the actual populations of NS-NS, NS-BH, and BH-BH merger events, as well as the mass distributions of them. However, several researches [e.g., [9–11]] claimed that there exists a mass gap between the heaviest neutron stars (2.1–2.5 $M_{\odot}$) [12–15] and the lightest stellar-mass black holes (5 $M_{\odot}$) [9,10,16], but the nature of this gap is also unknown [17]. Despite poor knowledge about the above questions, LIGO-Virgo used a simple cut rule [3] for chirp mass [$\mathcal{M} = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$] [18–20], where m_1 and m_2 are the component masses of the compact binary system (NS-NS, NS-BH, or BH-BH) to classify the set of GW events: events with $\mathcal{M} < 2.1\ M_{\odot}$ are considered as NS-NS candidates, those with $2.1\ M_{\odot} < \mathcal{M} < 4.35\ M_{\odot}$ as NS-BH candidates, and those with $\mathcal{M} > 4.35\ M_{\odot}$ as BH-BH candidates, while using the search pipeline (i.e., PyCBC) to analyze the GW observational data.

However, none of the previous studies have tested the validity of this cut rule of identifying the merger binary

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[1]https://www.ligo.caltech.edu/news/ligo20190320
[2]https://www.ligo.caltech.edu/news/ligo20190502
[3]https://www.sciencemag.org/news/2019/08/scientists-may-have-spotted-black-hole-and-neutron-star-colliding

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components, so the aim of this work is to test it by constructing the synthetic models based on the current observations of NS and BH masses, in which we simulate the distribution of the chirp mass ($\mathcal{M}$) for different GW merger events (i.e., NS-NS, NS-BH, and BH-BH) using the Monte Carlo method. This paper is organized as follows: in Sec. II, the process of model construction is described. Then, the results of our random sampling process are shown in Sec. III. And we present a short conclusion in Sec. IV.

II. MODEL CONSTRUCTION

In this section, we built the models according to the current observations as much as possible to avoid introducing the external uncertainty caused by the theoretical unknown, as mentioned in Sec. I. We remarked the following observational facts: (i) in general, the masses of neutron stars observed in our Galaxy follow a Gaussian distribution with the mean value $\mu = 1.4\ M_\odot$ and one standard deviation $\sigma = 0.2\ M_\odot$, written as $N(1.4, 0.2)$ [14,21–25]; (ii) the masses of stellar-mass black holes located in our Galaxy can be represented by a Gaussian distribution, as $N(7.8, 1.2)$ [9,10,16,26]; (iii) the values of m_1 and m_2 for NS-NS merger event (GW170817) observed by LIGO-Virgo (O2) are $1.46^{+0.12}_{-0.10} M_\odot$ and $1.27^{+0.09}_{-0.09} M_\odot$ [3,27,28], respectively, which are similar to those of our Galaxy [29]; (iv) the masses of stellar-mass black holes (N = 20) hunted by LIGO-Virgo (O1 and O2) span a wide range of about 7–50 $M_\odot$ [see [3] and references therein], as shown in Fig. 1, which is obviously inconsistent with the observed samples of our Galaxy. Although the origins of these big black holes (e.g., BHs in GW150914, GW170104, GW170729, GW170823) have been extensively investigated by several studies in recent years, they are still not yet settled down.

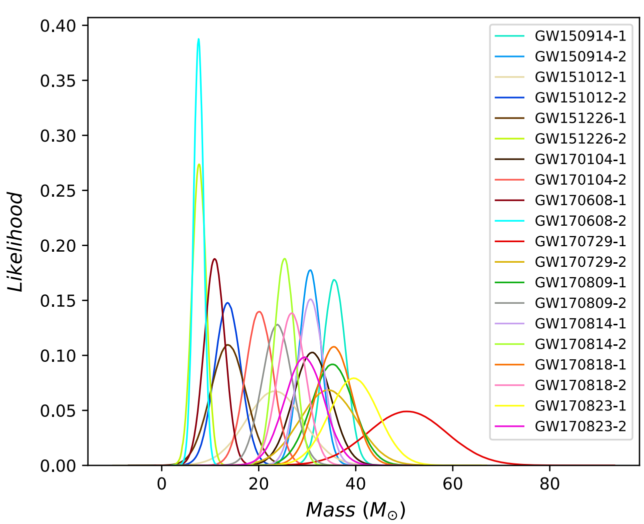

FIG. 1. Mass likelihoods for the BHs (N = 20) inferred by LIGO-Virgo (O1 and O2) as shown in Table I, where the primary BHs and secondary BHs are suffixed by "1" and "2," respectively. All likelihoods are normalized to 1, so that the enclosed area of each likelihood is same.

According to above facts, it is noted that the chirp mass distribution in the framework of our Galaxy observations and LIGO-Virgo detection should exhibit a significant difference. In order to compare both, we constructed two independent synthetic models, i.e., Model Galaxy and Model LIGO, as shown in Table I. In each model, we created 1 000 000 synthetic systems for each type of binary systems (NS-NS, NS-BH, BH-BH) through Monte Carlo random sampling [30,31] and then analyzed the chirp mass distribution of them; the details of the random sampling are described as below.

In Model Galaxy, for NS-NS system, two NSs were randomly sampled from $N(1.4, 0.2)$; for NS-BH system, NS was sampled from $N(1.4, 0.2)$, while BH was sampled from $N(7.8, 1.2)$; for BH-BH system, two BHs were sampled from $N(7.8, 1.2)$.

In Model LIGO, for NS-NS system, two NSs were randomly sampled from $N(1.4, 0.2)$, which is the same as that of Model Galaxy. However, for NS-BH system, NS was sampled from $N(1.4, 0.2)$, while BH was sampled

TABLE I. Comparison of Model Galaxy and LIGO.

Component	Mass ($M_\odot$)
Model Galaxy	
Neutron stars	$N(1.4, 0.2)$
Black holes	$N(7.8, 1.2)$
Model LIGO	
Neutron stars	$N(1.4, 0.2)$
	GW150914-1: $N(35.6, 2.36)$
	GW150914-2: $N(30.6, 2.24)$
	GW151012-1: $N(23.3, 5.90)$
	GW151012-2: $N(13.6, 2.69)$
	GW151226-1: $N(13.7, 3.63)$
	GW151226-2: $N(7.7, 1.45)$
	GW170104-1: $N(31.0, 3.87)$
	GW170104-2: $N(20.1, 2.84)$
	GW170608-1: $N(10.9, 2.12)$
Black holes	GW170608-2: $N(7.6, 1.03)$
	GW170729-1: $N(50.6, 8.12)$
	GW170729-2: $N(34.3, 5.81)$
	GW170809-1: $N(35.2, 4.33)$
	GW170809-2: $N(23.8, 3.12)$
	GW170814-1: $N(30.7, 2.63)$
	GW170814-2: $N(25.3, 2.12)$
	GW170818-1: $N(35.5, 3.69)$
	GW170818-2: $N(26.8, 2.87)$
	GW170823-1: $N(39.6, 5.03)$
	GW170823-2: $N(29.4, 4.06)$

Note: For brevity, we transfer the original 90% credible interval for BH masses by LIGO-Virgo (O1 and O2) [3] to one-sigma level (68% credible interval), and the primary and secondary BHs are suffixed by "1" and "2," respectively.

from 20 BHs inferred by LIGO-Virgo (O1 and O2) (see Fig. 1), and we assumed that the weight of each BH is equal in our random sampling process. For BH-BH system, the first BH was sampled from the 10 primary BHs inferred by LIGO-Virgo (O1 and O2) (suffixed by "1" in Fig. 1 and Table I), and then the second matched BH was sampled from its corresponding secondary BH (suffixed by "2" in Fig. 1 and Table I). That is to say, if the first BH was sampled from $N(13.7, 3.63)$ (the primary BH of GW151226), then the second matched BH would be sampled from $N(7.7, 1.45)$ (the secondary BH of GW151226), where we did not select the BHs from the other BH-BH systems. Because in the view of conservative, we only adopted the combinations of BHs that actually occurred in observations to avoid the offset. Moreover, [32] argued that the probability of the combination of a big black hole (e.g., 50 $M_{\odot}$) and a small one (e.g., 10 $M_{\odot}$) is very small, which is consistent with our sampling process.

III. RESULTS

The simulation results for chirp mass $\mathcal{M}$ distribution of Model Galaxy and Model LIGO are shown in Fig. 2; we can visually find that the original cut rule used by [3], represented by the cut line 1 and 2 in Fig. 2, is roughly suitable for Model Galaxy, however, obviously unsuitable for Model LIGO. In both models, $\mathcal{M}$ of NS-NS GW events is mainly distributed in the range of $0.84\ M_{\odot} < \mathcal{M} < 1.58\ M_{\odot}$, which is consistent with the original cut rule of $\mathcal{M} < 2.1\ M_{\odot}$ for NS-NS events. And the predominant range of $\mathcal{M}$ for NS-BH events in Model Galaxy is $1.82\ M_{\odot} < \mathcal{M} < 3.53\ M_{\odot}$, which is roughly in agreement with the original cut rule (i.e., $2.1\ M_{\odot} < \mathcal{M} < 4.35\ M_{\odot}$ for NS-BH events), and only a few NS-BH events (about 2%) are out of this range. However, $\mathcal{M}$ of the NS-BH events would mainly fall in the range of $1.82\ M_{\odot} < \mathcal{M} < 7.30\ M_{\odot}$ in Model LIGO, implying that there are about 70% events that go beyond the range of the LIGO-Virgo cut rule of $2.1\ M_{\odot} < \mathcal{M} < 4.35\ M_{\odot}$. In addition, $\mathcal{M}$ of the BH-BH events in Model Galaxy is mainly distributed in the ranges of $4.5\ M_{\odot} < \mathcal{M} < 9.0\ M_{\odot}$, but distributed in a wide range of $4.5\ M_{\odot} < \mathcal{M} < 45\ M_{\odot}$ in Model LIGO, and the original cut rule (i.e., $\mathcal{M} > 4.35\ M_{\odot}$ for BH-BH events) is applicable in both models for BH-BH events.

The main reason for the difference between the results of two models (i.e., Model Galaxy and LIGO, as shown in Fig. 2) is that the existence of some heavy BHs ($>20\ M_{\odot}$) detected by the LIGO-Virgo observing runs (O1 and O2) via GW emission that generate at mergers, e.g., the two BHs of GW150914 had masses of $35.6^{+4.8}_{-3.0} M_{\odot}$ and $30.6^{+3.0}_{-4.4} M_{\odot}$ [3,33,34], which both go beyond the mass range of BHs in our Galaxy inferred from x-ray binaries, mostly via dynamical measurements, with masses in the range between $\sim$5 and 20 $M_{\odot}$. In order to produce these heavy LIGO-Virgo BHs, several possible evolution

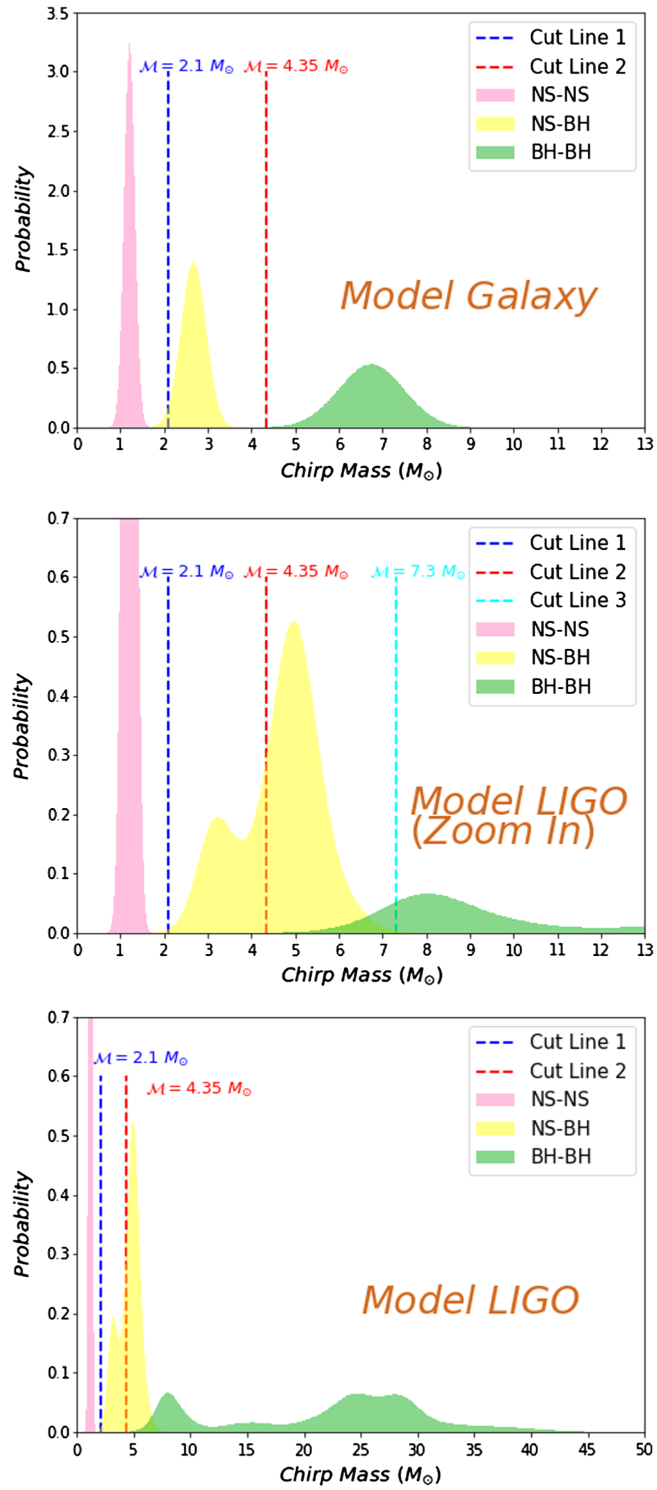

FIG. 2. The comparison for chirp mass distribution of Model Galaxy and LIGO after Monte Carlo random sampling, where cut line 1 and 2 represent the original cut rule used by [3], and cut line 3 is the newly added rule based on our simulation.

scenarios have been proposed, which include binary evolution channel with a failed supernova model [35,36] or via chemically homogeneous evolution [37,38], mergers of primordial BHs in the early Universe [39,40], dark matter accretion onto BHs [41], and so on. For more detailed discussions, please refer to [32] and references therein.

Thus, we prefer using Model LIGO to predict $\mathcal{M}$ distribution of various GW events due to the fact that we really have such assured observations of these big BHs, and we suggested that in order to separate the set of GW events in Model LIGO, an additional cut line 3 ($\mathcal{M} = 7.3\ M_\odot$) should be added upon the original cut line 1 and 2, as shown in the middle panel of Fig. 2. We state the new cut rule as bellow.

(1) $\mathcal{M} < 2.1\ M_\odot$:
NS-NS candidate.
(2) $2.1\ M_\odot < \mathcal{M} < 4.35\ M_\odot$:
NS-BH candidate.
(3) $4.35\ M_\odot < \mathcal{M} < 7.3\ M_\odot$:
NS-BH or BH-BH candidate.
(4) $\mathcal{M} > 7.3\ M_\odot$:
BH-BH candidate.

We note that the chirp mass distribution of NS-BH and BH-BH GW events seems to exist bimodality or multimodality (see Fig. 2), which indicates that they may have various formation channels. However, our results cannot be applied to study this question due to the limitation of both observation and theory, since it may be misleading by the overfitting. And we are expected to investigate the detailed population information of GW events in the future with more GW observational samples (e.g., LIGO-Virgo O3).

IV. CONCLUSIONS

As a short conclusion, our results would play an important role in predicting the chirp mass ($\mathcal{M}$) distribution of the compact binary systems (i.e., NS-NS, NS-BH, and BH-BH) in the oncoming GW hunting (e.g., O3), and we suggest that the potential NS-BH candidates may be overlapped with some BH-BH candidates in the LIGO-Virgo detection data. Therefore, we should focus on the range of $2.1\ M_\odot < \mathcal{M} < 7.3\ M_\odot$ carefully to find out the possible NS-BH candidates on the following hunting round of LIGO-Virgo (e.g., O3).

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