

# IS GW190425 CONSISTENT WITH BEING A NEUTRON STAR–BLACK HOLE MERGER?

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## ABSTRACT

GW190425 is the second neutron star merger event detected by the Advanced LIGO/Virgo detectors. If interpreted as a double neutron star merger, the total gravitational mass is substantially larger than that of the binary systems identified in the Galaxy. In this work we analyze the gravitational wave data within the neutron star–black hole merger scenario. For the black hole, we yield a mass of  $2.34^{+0.38}_{-0.27} M_{\odot}$  and an aligned spin of  $0.133^{+0.070}_{-0.054}$ . As for the neutron star we find a mass of  $1.18^{+0.13}_{-0.14} M_{\odot}$  and the dimensionless tidal deformability of  $1.7^{+5.5}_{-1.4} \times 10^3$ . The ranges of these parameters are corresponding to the 90% credible intervals. The inferred masses of the neutron star and the black hole are not in tension with current observations and we suggest that GW190425 is a viable candidate of a neutron star–black hole merger event. Benefited from the continual enhancement of the sensitivity of the advanced gravitational detectors and the increase of the number of the detectors, similar events are anticipated to be much more precisely measured and the presence of black holes below the so-called mass gap will be unambiguously clarified. If confirmed, the mergers of neutron stars with (quickly rotating) low-mass black holes are likely important production sites of the heaviest  $r$ -process elements.

*Keywords:* binaries: close—gravitational wave

## 1. INTRODUCTION

The neutron star (NS)–black hole (BH) binary systems, though not directly observed before, have been widely believed to exist in the Universe (see [Abbott et al. 2018](#), and the references). In addition to giving rise to strong gravitational wave radiation, the NS–BH mergers can also produce electromagnetic transients such as short/long-short Gamma Ray Bursts (GRBs) and macronovae/kilonovae, as long as the merging neutron stars have been effectively tidally-disrupted (e.g., [Narayan et al. 1992](#); [Li & Paczyński 1998](#); [Piran 2004](#); [Metzger 2019](#)). In the absence of Gravitational Wave (GW) observations, the well-measured macronova/kilonova signals in the afterglow of some short/long-short GRBs in principle can shed valuable light on the merger nature (e.g., [Hotokezaka et al. 2013](#); [Kyutoku et al. 2020](#)). Indeed, the NS–BH merger model has been adopted to well reproduce the luminous and relatively blue macronova/kilonova signal of the long-short GRB 060614 ([Yang et al. 2015](#); [Jin et al. 2015](#)). According to the macronova/kilonova modeling of a few events, the NS–BH merger rate was estimated to be  $\sim a \text{ few } \times 100 \text{ Gpc}^{-3} \text{ yr}^{-1}$  and some black holes were speculated to have low masses ([Li et al. 2017](#)). Such arguments are indirect and more solid evidence for the NS–BH mergers is highly needed. Such a purpose can be achieved in the gravitational wave observations.

The data of GW170817, the first neutron star merger event, strongly favor the binary neutron star (BNS) merger scenario ([Abbott et al. 2017, 2019](#)). Though the NS–BH merger possibility has also been examined, the inferred masses of the involved black hole and neutron star are not natural ([Coughlin & Dietrich 2019](#)). Very recently, the LIGO/Virgo collaboration reported the detection of GW190425, the second BNS merger event with a total gravitational mass of  $M_{\text{tot}} \approx 3.4 M_{\odot}$  ([Abbott et al. 2020](#)). These authors concluded that such a massive binary most likely consists of a pair of neutron stars and have intriguing implications on the stellar evolution. The lack of the detection/identification of such massive binaries in the Galaxy, which is unlikely attributed to their quick merging after the birth ([Safarzadeh et al. 2020](#)), motivates us to further examine the possible NS–BH merger origin of GW190425. Since the gravitational wave data alone are known to be unable to pin down the nature of the two compact objects ([Abbott et al. 2020](#)), our main purpose is to check whether the NS–BH merger hypothesis is in agreement with other data or not.

## 2. THE DATA ANALYSIS AND THE TEST OF THE BLACK HOLE HYPOTHESIS

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### 2.1. The data analysis within the NS–BH merger scenario

GW190425 was mainly detected by the LIGO-Livingston (L1) at 2019-04-25 08:18:05.017 UTC (Abbott et al. 2020). LIGO-Hanford (H1) was offline at the time. The signal-to-noise ratio (SNR) of the Advanced Virgo (V1) is low, but it is consistent with the L1 data given the relative sensitivities of the detectors (Abbott et al. 2020). To obtain the source parameters of the GW merger event, we apply the widely used Bayesian parameter inference method. Based on the work of Abbott et al. (2020), we take the cleaned data spanning GPS time (1240215303, 1240215511)s which are open-access and available from the Gravitational Wave Open Science Center<sup>1</sup> (Vallisneri et al. 2015). Due to the low SNR of GW190425, systematic errors caused by the choice of waveform is negligible compared to the large statistical uncertainties. Therefore, we take the spin-aligned waveform template IMRPhenomDNRT (Husa et al. 2016; Khan et al. 2016; Dietrich et al. 2017, 2019) to analyze the data, and use the SEOBNRv4\_ROM (Bohé et al. 2017) with added tidal phase correction (Dietrich et al. 2017) to check the result. We do not consider the calibration errors of the detector which will influence the sky localization but has little effects on mass measurements (Abbott et al. 2016). For the noise power spectral density (PSD), we calculate it by using the Welch’s method (Welch 1967) with 16-second Hann-windowed segments (overlapped by 8s) taken from GPS time 1240215263s to 1240215519s. Then the single detector log-likelihood can be constructed with the GW data  $d(f)$ , one-sided PSD  $S_n(f)$ , and waveform model  $h(\vec{\theta}_{\text{GW}}, f)$ , which reads

$$\log L(d|\vec{\theta}_{\text{GW}}) = -2 \int_{f_{\min}}^{f_{\max}} \frac{|d(f) - h(\vec{\theta}_{\text{GW}}, f)|^2}{S_n(f)} df + C, \quad (1)$$

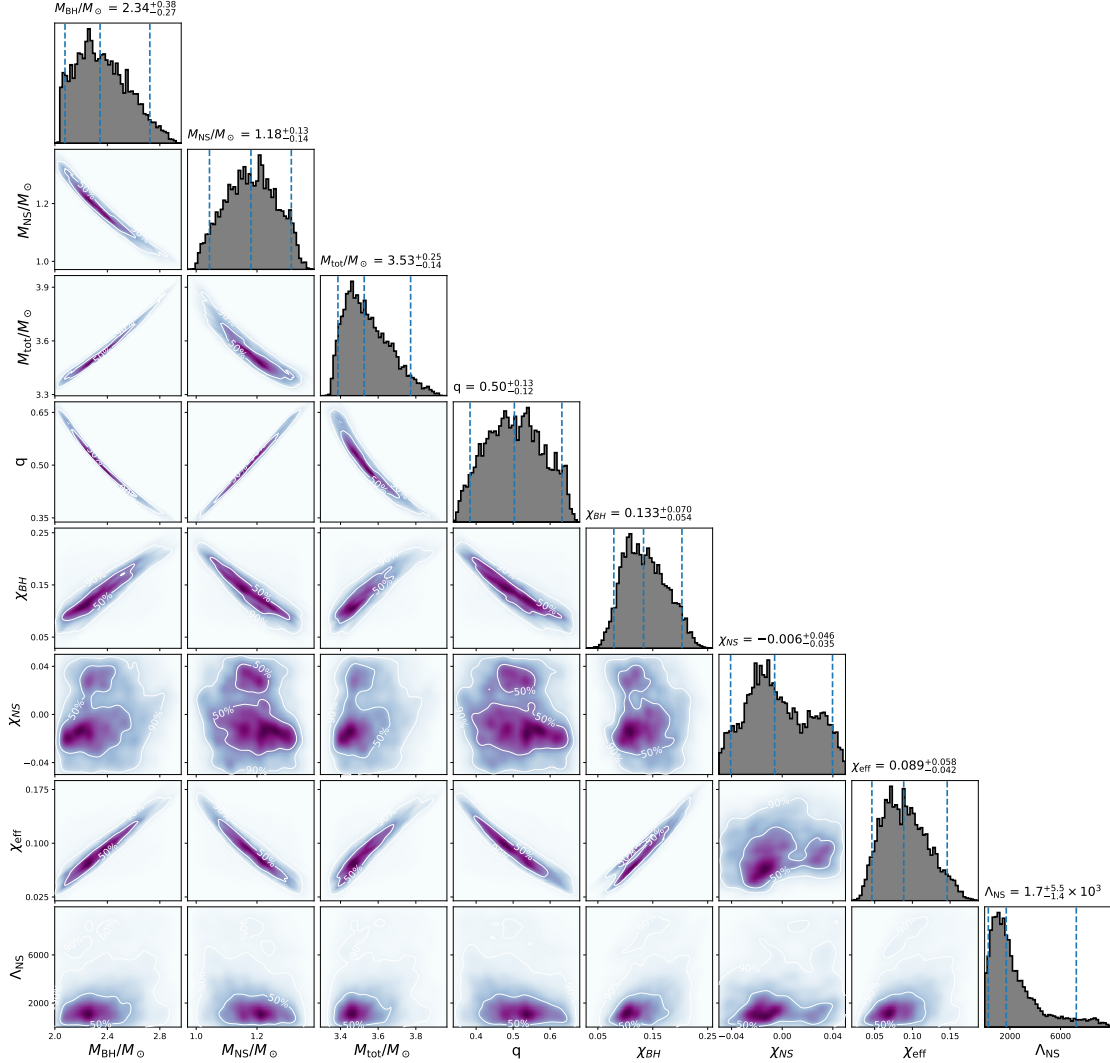
where we take  $f_{\min} = 19.4\text{Hz}$  and  $f_{\max} = 2048\text{Hz}$  following Abbott et al. (2020). With the likelihood in hand, it is convenient to estimate the posterior probability distributions for the source model parameters using the Bayesian stochastic sampling software, we use the PyCBC Inference (Biwer et al. 2019) with the sampler Dynesty (Speagle 2019) for our analysis and the Bilby (Ashton et al. 2019) with the sampler PyMultiNest (Buchner 2016) for checking. To accelerate Nest sampling (Skilling 2004), we marginalize the likelihood over coalescence phase (Allen et al. 2012; Abbott et al. 2019; Radice & Dai 2019; Thrane & Talbot 2019). Thus the parameters of GW can take the form  $\vec{\theta}_{\text{GW}} = \{\mathcal{M}, q, \chi_{\text{BH}}, \chi_{\text{NS}}, D_L, \theta_{\text{jn}}, \text{RA}, \text{DEC}, t_c, \Psi, \Lambda_{\text{BH}}, \Lambda_{\text{NS}}\}$ , where  $\mathcal{M}$ ,  $q$ ,  $\chi_{\text{BH}}(\chi_{\text{NS}})$ ,  $D_L$ ,  $\theta_{\text{jn}}$ , RA, DEC,  $t_c$ ,  $\Psi$ , and  $\Lambda_{\text{BH}}(\Lambda_{\text{NS}})$  are chirp mass, mass ratio, aligned spins, luminosity distance, inclination angle, right ascension, declination, geocentric GPS time of the merger, polarization of GW, and dimensionless tidal deformabilities, respectively.

For the NS–BH merger scenario, we set the prior of  $q = M_{\text{NS}}/M_{\text{BH}}$  to a uniform distribution in range of (0.2, 1) (We also set the prior of  $q^{-1}$  into a log-uniform distribution in the range of (1, 5), and find that the results just change very slightly), and take  $\Lambda_{\text{BH}} = 0$ , while  $\Lambda_{\text{NS}}$  is assumed to lie in a wide range (0, 10000). Meanwhile, it is natural to give a narrow range for the component of the spin aligned with the orbital angular momentum of NS  $|\chi_{\text{NS}}| < 0.05$  (Abbott et al. 2020), and broader for that of BH, i.e.,  $|\chi_{\text{BH}}| < 0.998$  (Thorne 1974). The chirp mass  $\mathcal{M}$  is uniformly distributed in  $(1.42, 2.6)M_{\odot}$  (in the detector frame Abbott et al. 2020), the luminosity distance is uniform in co-moving volume bounded in  $(1, 500)\text{Mpc}$ , and other parameters are all uniformly distributed in their domains. Additionally, we assume the source frame mass  $M_{\text{BH}} > 2.04M_{\odot}$ , i.e., it is above the  $1\sigma$  lower-limit on the mass of PSR J0740+6620 (Cromartie et al. 2019, the uniform rotation of this pulsar can enhance the gravitational mass by  $\sim 0.01M_{\odot}$ , which has been corrected here), and assume  $M_{\text{NS}} > 1.0M_{\odot}$ , as widely anticipated in the literature (see Lattimer 2012, for a review).

Fig. 1 presents the main results of our data analysis. It contains the 2-D density plots and the marginal distributions of some intrinsic parameters and their combinations. For the BH component we have  $M_{\text{BH}} \in (2.07, 2.72)M_{\odot}$  (i.e., the primary mass; in this work the ranges of the parameters represent the 90% credible intervals). While for the mass of the NS component, we have  $M_{\text{NS}} \in (1.04, 1.31)M_{\odot}$ . The total gravitational mass and the mass ratio of the binary are  $3.53^{+0.25}_{-0.14}M_{\odot}$  and  $q \in (0.38, 0.63)$ , respectively. The dimensionless aligned spin of the BH is  $\chi_{\text{BH}} = 0.133^{+0.070}_{-0.054}$ . As for the NS, we have  $\chi_{\text{NS}} = -0.006^{+0.046}_{-0.035}$ . The inferred mass and spin of the NS component are consistent with the observations of the Galactic binary systems. Besides, the effective spin, defined as  $\chi_{\text{eff}} = (M_{\text{BH}}\chi_{\text{BH}} + M_{\text{NS}}\chi_{\text{NS}})/M_{\text{tot}}$ , is found to be  $0.089^{+0.058}_{-0.042}$ . We do not show the results of other extrinsic parameters that are just poorly constrained because of the absence of the electromagnetic counterparts and the non-detection by H1 (the SNR of V1 is very low).

The dimensionless tidal deformability of the NS is constrained to  $\Lambda_{\text{NS}} = (2/3)k_2[(c^2/G)(R_{\text{NS}}/M_{\text{NS}})]^5 = 1.70^{+5.50}_{-1.40} \times 10^3$ , where  $k_2$  is the tidal Love number (Hinderer 2008; Flanagan & Hinderer 2008),  $c$  is the speed of light in vacuum,  $G$  is the gravitational constant, and  $R_{\text{NS}}$  is the radius of NS, respectively. Fig 2 shows the result of the tidal deformability and the mass of NS. In comparison to GW170817, the signal of GW190425 has a considerably lower SNR (partly attributing to the non-observation of the H1 detector) and the constraint on  $\Lambda$  is looser (Abbott et al. 2020). Anyhow, the resulting  $\Lambda$  is consistent with the joint constraints set by GW170817, PSR J0030+0451 and the nuclear data (Jiang et al. 2020). Note that for the signal with a low SNR, the inferred  $\Lambda$  is likely biased to a higher value (Han et al. 2020).

<sup>1</sup> <https://dcc.ligo.org/LIGO-T1900685/public>

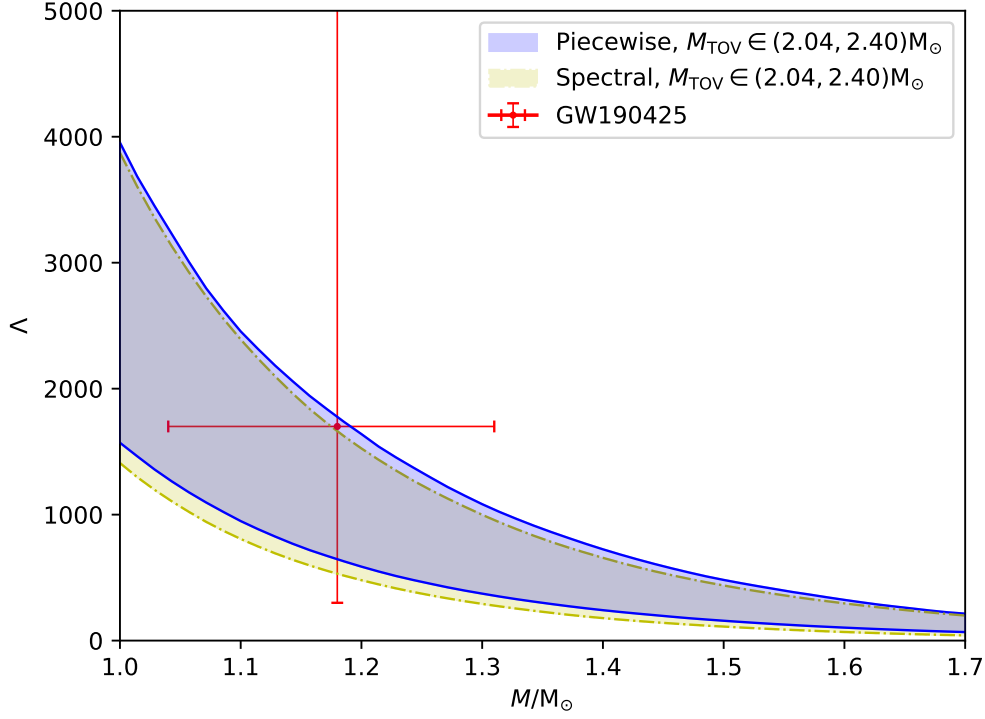


**Figure 1.** Posterior distributions of the physical parameters, including the source frame masses of the two compact objects ( $M_{\text{BH}}$ ,  $M_{\text{NS}}$ ), the source frame total mass  $M_{\text{tot}}$ , the mass ratio  $q$ , the dimensionless spins ( $\chi_{\text{BH}}$ ,  $\chi_{\text{NS}}$ ), the effective spin parameter  $\chi_{\text{eff}}$ , and the dimensionless tidal deformability of the neutron star  $\Lambda_{\text{NS}}$ . The error bars are all for the 90% credible level.

## 2.2. Testing the validity of the black hole hypothesis

In principle, the massive binary neutron star merger model can be distinguished from the NS–BH merger model if the macronova/kilonova emission has been well monitored (Kyutoku et al. 2020). However, GW190425 was only poorly localized and the partial volume covered by macronova/kilonova observations just span up to about 40% (Hosseinzadeh et al. 2019, for AT2017gfo-like macronova/kilonova), which are insufficient to pin down the merger scenarios. In this subsection we concentrate on the possibility that the heavy component is a black hole.

So far, thanks to the long time radio observations of the massive pulsars, the record of observed maximum mass of NS was broken over and over, e.g., from  $2.01 \pm 0.04 M_{\odot}$  (PSR J0348+0432, Antoniadis et al. 2013) to  $2.14^{+0.10}_{-0.09} M_{\odot}$  (PSR J0740+6620, Cromartie et al. 2019). Though the maximum mass of non-rotating neutron star (i.e.,  $M_{\text{TOV}}$ ) still remains unknown, one can



**Figure 2.** The inferred  $M$  and  $\Lambda$  of the neutron star component of GW190425 at the 90% credible level. The shaded regions represent the joint constraints set by GW170817, PSR J0030+0451 and the nuclear data, which are adopted from [Jiang et al. \(2020\)](#).

statistically estimate the probability distribution of NS's maximum mass ( $M_{\max}$ , which can be approximated by  $M_{\text{TOV}}$  since the rotation of all these NSs are slow that do not effectively enhance the gravitational mass) using the mass measurements of dozens of NSs. Such a study has been recently carried out by [Alsing et al. \(2018\)](#), where the authors have found strong evidence for the presence of a maximum mass cutoff. Here we adopt their marginal posterior distribution of the maximum mass of the NSs to evaluate the possibility for the heavy component of GW190425 to be a BH. Using the posterior of  $\mathcal{M}$ ,  $q$ , and  $D_L$  obtained in Sec. 2.1, it is straightforward to calculate the posterior probability distribution of the heavier component's mass with

$$M_{\text{BH}} = \frac{q^{-3/5}(1+q)^{1/5}\mathcal{M}}{1+z(D_L)}, \quad (2)$$

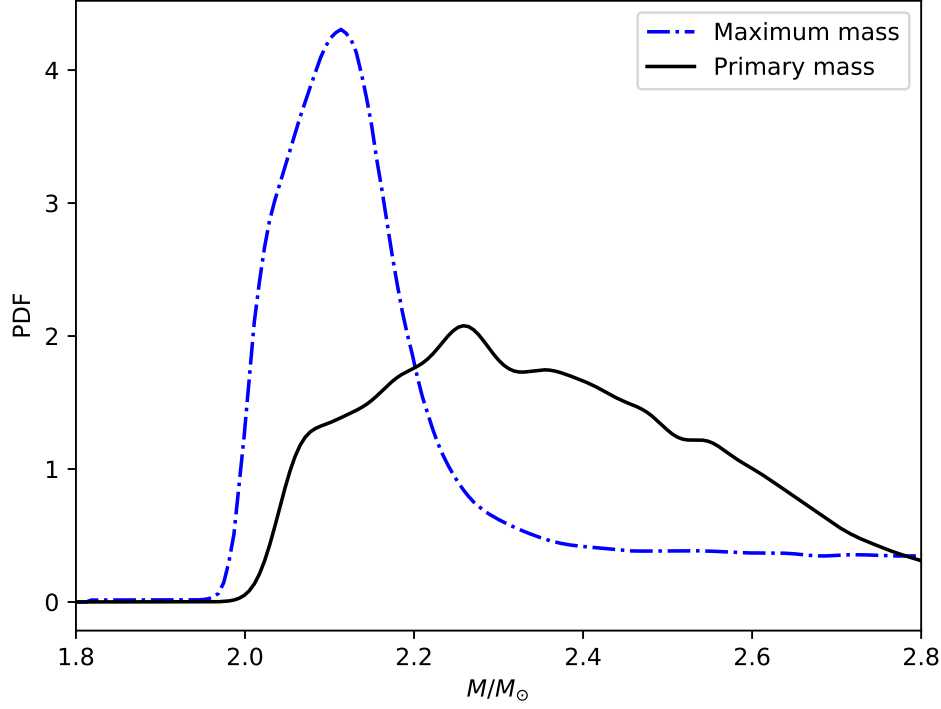
where  $z$  is the cosmic redshift transformed from luminosity distance  $D_L$  assuming the  $\Lambda$ CDM cosmology ([Planck Collaboration et al. 2016](#)). Then we integrate the joint probability distribution of the heavier component's mass  $P(M_{\text{BH}})$  and the maximum NS mass  $P(M_{\max})$  with the condition of  $M_{\text{BH}} > M_{\max}$  through

$$\mathcal{P} = \iint_{M_{\text{BH}} > M_{\max}} P(M_{\text{BH}}) P(M_{\max}) d^2 M, \quad (3)$$

and finally get  $\mathcal{P} = 0.738$ , which indicates that our NS–BH merger assumption is reasonable (This is also evident in Fig. 3). [Abbott et al. \(2020\)](#) found a rate of GW190425-like events of  $460^{+1050}_{-390} \text{ Gpc}^{-3} \text{ yr}^{-1}$ , which is comparable to that suggested in [Li et al. \(2017, see Tab.1 therein\)](#) but may be hard to achieve in some population synthesis calculations (e.g., [Cote et al. 2017](#), in which a local NS–BH merger rate of  $\leq 150 \text{ Gpc}^{-3} \text{ yr}^{-1}$  has been suggested), implying that some new NS–BH binary formation channels may present.

### 3. DISCUSSION

In this work we have examined the possible neutron star–black hole origin of GW190425, the second neutron star merger event detected by the Advanced LIGO/Virgo detectors. In such a specific scenario, the gravitational wave data favor a black



**Figure 3.** The distribution of maximum mass cutoff of neutron stars (the dash-dotted line; adopted from Alsing et al. 2018) and that of the mass of the heavy compact object (i.e., primary mass) involved in GW190425 (the solid line). Clearly, the heavy component of GW190425 is consistent with being a black hole.

hole (neutron star) mass of  $2.34^{+0.38}_{-0.27} M_{\odot}$  ( $1.18^{+0.13}_{-0.14} M_{\odot}$ ) and an aligned spin (a dimensionless tidal deformability) of  $0.133^{+0.070}_{-0.054}$  ( $1.7^{+5.5}_{-1.4} \times 10^3$ ). The inferred parameters are not in tension with current observations and we suggest that GW190425 is a viable candidate of a neutron star–black hole merger event. This is different from the case of GW170817, for which the neutron star–black hole modeling yields unnatural masses of the objects (Coughlin & Dietrich 2019). Therefore, GW190425 may be the first detected neutron star–black hole merger event. The current data however are insufficient to disfavor the double neutron star merger origin (Abbott et al. 2020) because of the low SNR of the signal and the non-detection of the electromagnetic counterparts. GW190425 was just detected by LIGO-Livingston Observatory and the Virgo Observatory, but not the LIGO-Hanford Observatory. Currently, the sensitivity of the Virgo Observatory is considerably lower than that of LIGO-Livingston and LIGO-Hanford Observatories, and hence can not contribute significantly to improving the SNR of the signal (anyhow, the presence of a low-SNR signal in the Virgo Observatory provides a valuable verification). Together with the information reported in <https://gracedb.ligo.org/superevents/public/O3/>, the duty cycle for each detector of current aLIGO is an important issue. The situation will change substantially in the near future. KAGRA will join the O3 run of Advanced LIGO/Virgo network in 2020. The sensitivities of Virgo and KAGRA will be enhanced by a factor of a few in the upcoming O4 run. LIGO-India is anticipated to join in 2025. Therefore, for GW190425-like events taking place in O4 and later runs of LIGO/Virgo/KAGRA, the SNR would be higher by a factor of  $\sim 2 - 6$ , benefited from the enhancement of the sensitivity of the advanced gravitational detectors and the increase of the number of the observatories. With such a high SNR, the gravitational wave data will provide much more accurate classification of the compact objects. The joint observation of multiple detectors will improve the localization of the mergers considerably that is very helpful to catch the macronova/kilonova radiation (and the off-axis afterglow emission), with which the nature of merger can be further revealed.

If the neutron star–black hole merger origin of GW190425-like events has been confirmed, there are some interesting implications: (i) There exists low-mass black hole below the so-called mass gap, which favors the formation of black hole with a continual mass distribution rather than a gap, as suggested for instance in Ebinger et al. (2019) and Burrows et al. (2020). The continual distribution of the BH masses may lead to the misidentification of binary black hole system with light components (e.g.,  $\sim 3 M_{\odot}$ ) into neutron star–black hole systems, which consequently brings difficulty for constructing the black hole mass



function of such systems (Tang et al. 2020; Yang et al. 2018). (ii) The neutron star–quickly rotating low-mass black hole mergers could eject massive sub-relativistic neutron-rich outflow (Lattimer et al. 1974). In comparison to the double neutron star merger scenario, very heavy  $r$ -process elements are likely easier to form because for the former the huge amount of neutrino emission from the pre-collapse massive neutron stars will make the sub-relativistic ejecta less neutron-rich. Therefore, together with a high rate, such mergers can be important sites of the heaviest  $r$ -process nucleosynthesis (see the indication in the macronova/kilonova observations by Yang et al. 2015; Jin et al. 2016).

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*Software:* Bilby (Ashton et al. 2019, version 0.5.5, ascl:1901.011, <https://git.ligo.org/lscsoft/bilby/>), Dynesty (Speagle & Barbary 2018, version 1.0, ascl:1809.013, <https://github.com/joshspeagle/dynesty/tree/v1.0.0>), PyCBC (The PyCBC Team 2018, version 1.13.6, ascl:1805.030, <http://doi.org/10.5281/zenodo.3265452>), PyMultiNest (Buchner 2016, version 2.6, ascl:1606.005, <https://github.com/JohannesBuchner/PyMultiNest>)

## REFERENCES

- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, Phys. Rev. Lett., 116, 241102
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, Phys. Rev. Lett., 119, 161101
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2018, Living Rev. Relativ. 21, 3
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2019, Phys. Rev. X. 9, 011001
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2020, arXiv e-prints, arXiv:2001.01761
- Allen, B., Anderson, W. G., Brady, P. R., Brown, D. A. & Creighton, J. D. E. 2012, Phys. Rev. D, 85, 122006
- Alsing, J., Silva, H. O., & Berti, E. 2018, MNRAS, 478, 1377
- Antoniadis, J., et al., 2013, Sci, 340, 448
- Ashton, G., Hübner, M., Lasky, P. D., et al. 2019, ApJS, 241, 27
- Ashton, G., Hübner, M., Lasky, P. D., et al. 2019, Bilby: Bayesian inference library, ascl:1901.011
- Biwer, C. M., Capano, C. D., De, S., et al. 2019, PASP, 131, 024503
- Bohé, A., Shao, L., Taracchini, A., et al. 2017, Phys. Rev. D, 95, 044028
- Buchner, J. 2016, PyMultiNest: Python interface for MultiNest, ascl:1606.005
- Burrows, A., Radice, D., Vartanyan, D., et al. 2020, MNRAS, 491, 2715
- Cote, B., Belczynski, K., Fryer, C. L., et al. 2017, ApJ, 836, 230
- Coughlin, M. W. & Dietrich, T. 2019, Phys. Rev. D, 100, 043011
- Cromartie, H. T., Fonseca, E., Ransom, S. M., et al. 2019, Nat. Astron., 3, 439
- Dietrich, T., Bernuzzi, S. & Tichy, W. 2017, Phys. Rev. D, 96, 121501
- Dietrich, T., Khan, S., Dudi, R., et al. 2019, Phys. Rev. D, 99, 024029
- Ebinger, K., Curtis, S., Fröhlich, C., et al. 2019, ApJ, 870, 1
- Flanagan, É. É., & Hinderer, T. 2008, Phys. Rev. D, 77, 021502
- Han, M. Z., Jiang, J. L., Tang, S. P., Li, Y. J., & Fan, Y. Z. 2019, arXiv e-prints, arXiv:2001.01892
- Hinderer, T. 2008, ApJ, 677, 1216
- Hosseinzadeh, G., Cowperthwaite, P. S., Gomez, S., et al. 2019, ApJL, 880, L4
- Husa, S., Khan, S., Hannam, M., et al. 2016, Phys. Rev. D, 93, 044006
- Jiang, J.-L., Tang, S.-P., Wang, Y.-Z., et al. 2020, arXiv e-prints, arXiv:1912.07467
- Jin, Z.-P., Li, X., Cano, Z., et al. 2015, ApJL, 811, L22
- Jin, Z. P., Hotokezaka, K., Li, X., et al., 2016, Nat. Commun., 7, 12898
- Hotokezaka, K., Kyutoku, K., Tanaka, M., et al. 2013, ApJL, 778, L16
- Khan, S., Husa, S., Hannam, M., et al. 2016, Phys. Rev. D, 93, 044007
- Kyutoku, K., Fujibayashi, S., Hayashi, K., et al. 2020, arXiv e-prints, arXiv:2001.04474
- Lattimer, J. M. & Schramm, D. N. 1974, ApJL, 192, L145
- Lattimer, J. M. 2012, Ann. Rev. Nucl. Part. Sci., 62, 485
- Li, L.-X. & Paczyński, B. 1998, ApJL, 507, L59
- Li, X., Hu, Y.-M., Jin, Z.-P., Fan, Y. Z. & Wei, D. M. 2017, ApJL, 844, L22
- Metzger, B. D., 2019, Living Rev. Relativ. 23, 1
- Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, A&A, 594, A13
- Piran, T., 2004, Rev. Mod. Phys., 76, 1143
- Narayan, R., Paczynski, B., & Piran, T. 1992, Astrophys. J. Lett., 395, L83
- Radice, D. & Dai, L. 2019, EPJA, 55, 50
- Safarzadeh, M., Ramirez-Ruiz, E., & Berger, E. 2020, arXiv:2001.04502
- Skilling, J. 2004, American Institute of Physics Conference Series, 395
- Speagle, J. S., & Barbary, K. 2018, dynesty: Dynamic Nested Sampling package, ascl:1809.013
- Speagle, J. S. 2019, arXiv e-prints, arXiv:1904.02180
- Tang, S.-P., Wang, H., Wang, Y.-Z., et al. 2020, submitted
- The PyCBC Team 2018, PyCBC: Gravitational-wave data analysis toolkit, ascl:1805.030
- Thorne, K. S. 1974, ApJ, 191, 507
- Thrane, E. & Talbot, C. 2019, PASA, 36, e010
- Vallisneri, M., Kanner, J., Williams, R., Weinstein, A., & Stephens, B. 2015, Journal of Physics Conference Series, 610, 012021
- Welch, P. D. 1967, IEEE Trans. Audio & Electroacoust., 15, 70
- Yang, B., Jin, Z.-P., Li, X., et al. 2015, Nat. Commun., 6, 7323
- Yang, H., East, W. E., & Lehner, L. 2018, ApJ, 856, 110