A lower bound on the maximum mass if the secondary in GW190814 was once a rapidly spinning neutron star

ELIAS R. MOST,1,2 L. JENS PAPENFORT,2,3 LUKAS R. WEIH,1 AND LUCIANO REZZOZZA1,2,3

1Institut für Theoretische Physik, Goethe Universität, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany
2School of Mathematics, Trinity College, Dublin 2, Ireland
3Helmholtz Research Academy Hesse for FAIR, Max-von-Laue-Str. 12, 60438 Frankfurt am Main, Germany

(Received June 1, 2019; Revised January 10, 2019; Accepted June 26, 2020)

ABSTRACT

The recent detection of GW190814 featured the merger of a binary with a primary having a mass of \( \sim 23M_\odot \) and a secondary with a mass of \( \sim 2.6M_\odot \). While the primary was most likely a black hole, the secondary could be interpreted as either the lightest black hole or the most massive neutron star ever observed, but also as the indication of a novel class of exotic compact objects. We here argue that the secondary in GW190814 needs not be an ab-initio black hole nor an exotic object; rather, based on our current understanding of the nuclear-matter equation of state, it can be a rapidly rotating neutron star that collapsed to a rotating black hole at some point before merger. Using universal relations connecting the masses and spins of uniformly rotating neutron stars, we estimate the spin, \( 0.49 \lesssim \chi \lesssim 0.68 \), of the secondary – a quantity not constrained so far by the detection – and a novel strict lower bound on the maximum mass, \( M_{\text{TOV}} > 2.08_{-0.04}^{+0.04} M_\odot \), of nonrotating neutron stars, consistent with recent observations of a very massive pulsar. The new lower bound also remains valid even in the less likely scenario in which the secondary neutron star never collapsed to a black hole.

Keywords: transients: black hole - neutron star mergers — gravitational waves — stars: neutron

1. INTRODUCTION

With the detection of gravitational waves (GW) from a binary black hole (BBH) merger GW190412 (The LIGO Scientific Collaboration & the Virgo Collaboration 2020) with mass ratio of \( q = 0.28^{+0.08}_{-0.12} \) by the LIGO/Virgo collaboration, it has been shown that even for more massive BBH a significant mass ratio can be acquired. While the lower mass companion with a mass of \( m_2 = 8.4^{+1.8}_{-1.0} M_\odot \) is definitely a black hole (BH) in this case, it gave an interesting prospect for the possibility of even more asymmetric binary mergers in the future.

The most recent detection GW190814 (The LIGO Scientific Collaboration et al. 2020) belongs to a binary merger featuring a much lower mass ratio of \( q = 0.112^{+0.008}_{-0.009} \) with a massive primary companion of \( m_1 = 23.2^{+1.1}_{-1.0} M_\odot \) and a secondary of \( m_2 = 2.59^{+0.08}_{-0.09} M_\odot \), which falls in the possible mass gap between neutron stars (NSs) and stellar BHs.

Being the source of the most asymmetric binary compact object merger to date GW190814 seems to challenge the established binary formation channels. It is argued in The LIGO Scientific Collaboration et al. (2020) that the formation of such a high mass ratio system as an isolated binary is strongly suppressed in population synthesis simulations. This is certainly true at Milky-Way metallicity where stellar winds are much stronger and progenitors lose more mass throughout the binary evolution. This leads to lower maximum BH masses and subsequently limits the maximum mass ratio for either BBH and BH-NS systems (Kruckow et al. 2018). However, this already posed a challenge for previous detection of BBH with large total mass. It is assumed that these systems have to originate from a lower metallicity environment (see, e.g., Stevenson et al. 2017). Especially Kruckow et al. (2018) have shown that there is a significant population of BBH as well as BH-NS systems with low mass ratios at low metallicity which match the source of GW190814. Together with the broad range of resulting merger times the birth as an isolated binary constitutes still a viable formation channel.

Both, BBH and BH-NS systems, with strong asymmetry are nonetheless suppressed compared to equal mass BBH binaries of the same total mass, due to mass transfer during the binary evolution equalising the companion masses to less asymmetric configurations. Additional alternative channels through dynamical captures or hierarchical binary systems are presented in The LIGO Scientific Collaboration et al. (2020). While the formation rates through these processes are not well known, they all need dense stellar environments to work and the probability to form such a system is independent of the low mass companion being a BH or a NS in these cases.
Assuming a mass gap between NSs and BHs at approximately $5M_\odot$, the progenitor of the secondary companion has to be a NS. For both possibilities of forming the system in isolation or through dynamical processes, accretion of significant amounts of matter onto the NS or gaining angular momentum afterwards is very unlikely. Either due to the fact that the primary companion is evolving faster and thus collapses to a BH before the NS is formed, or because formation in dense stellar systems is only significant in mass segregated regions for which the timescale is much larger than the stellar evolution up to formation of the compact object.

Combining these implications, we conclude that the NS companion has to be born already with an approximate mass of $2.59 M_\odot$ which is above the upper limit for the maximum mass for a nonrotating NS, $2.33 M_\odot$ (Rezzolla et al. 2018; Shibata et al. 2019). Consequently, such a NS has to be supported by rotation against gravitational collapse for a significant time after its birth. Long-term electromagnetic spin-down might lead to its collapse to a BH if a significant fraction of the spin has been removed. Such a BH would then inherit its characteristics, i.e. mass and spin, from the NS.

For the rest of the paper, we will assume that the secondary in GW190814, hence, was either a rapidly rotating NS or a BH formed by the gravitational collapse of such with the same properties. Given the well constrained mass of the low mass companion, we are able to use the universal relations between maximum supportable mass $M_{\text{crit}}$ and the ratio of the stars dimensionless spin to its maximum dimensionless spin at the mass shedding limit found by Breu & Rezzolla (2016) to find a new lower bound on the maximum mass $M_{\text{TOV}}$ a nonrotating NS must be able to support. Such a constraint can help to constrain the equation of state (EOS) of nuclear matter at densities beyond the reach of earth-based experiments. Indeed, in the recent past a number of studies have used the multimessenger signal of the event GW170817 (The LIGO Scientific Collaboration & The Virgo Collaboration 2017) in order to derive astrophysical constraints and/or translate them into constraints on the EOS (Margalit & Metzger 2017; Bauswein et al. 2017; Rezzolla et al. 2018; Ruiz et al. 2018; Annala et al. 2018; Radice et al. 2018; Most et al. 2018b; De et al. 2018; Abbott et al. 2018; Montaña et al. 2019; Raithel et al. 2018; Tews et al. 2018; Malik et al. 2018; Koeppel et al. 2019; Shibata et al. 2019). The present work falls in line with these studies by deriving a new lower limit on $M_{\text{TOV}}$.

Additionally, we can give a lower bound on the dimensionless spin for the secondary companion, using the upper maximum mass constraints from the GW170817 event (Rezzolla et al. 2018; Shibata et al. 2019), and show that the allowed range in dimensionless spins correspond to rotational frequencies much higher than the fastest spinning pulsars known (Hessels et al. 2006).

2. RAPIDLY SPINNING NEUTRON STARS: THE BASIC PICTURE

A binary system of two compact objects can be described in terms of their masses $m_1$ and $m_2$ ($< m_1$) and corresponding dimensionless spins $\chi_1 = S_1/m_1^2$ and $\chi_2 = S_2/m_2^2$, where $S_1$ and $S_2$ are the spin angular momentum of the two compact objects. For simplicity, we will consider only the component of the spins aligned with the orbital angular momentum, which is usually extracted from gravitational wave observations (The LIGO Scientific Collaboration et al. 2020).

The effective spin is defined as

$$\tilde{\chi} := \frac{m_1 \chi_1 + m_2 \chi_2}{m_1 + m_2} = \frac{\chi_1}{1 + q} \left(1 + \frac{\chi_2}{\chi_1}\right),$$

where $q := m_2/m_1 \leq 1$ is the mass ratio of the binary system.

If one of the objects in the system is a NS, its maximally allowed mass $M_{\text{crit}}$ will depend on its spin $\chi_1$. In particular, for a non-spinning NS $m_1 < M_{\text{TOV}}$, where $M_{\text{TOV}}$ is the maximum mass of a nonrotating NS. Observations indicate that $M_{\text{TOV}} > 2.01 M_\odot$ (Antoniadis et al. 2013), with a recent observation indicating that $M_{\text{TOV}} > 2.14 M_\odot$, although with a larger uncertainty (Cromartie et al. 2020). The use of different multi-messenger observations of GW170817 (Abbott et al. 2017; The LIGO Scientific Collaboration et al. 2017) has also led to upper constraints on the maximum mass of $M_{\text{TOV}} \lesssim 2.3 M_\odot$ (see, e.g., Margalit & Metzger 2017; Rezzolla et al. 2018; Ruiz et al. 2018; Shibata et al. 2019), although the latter value could be higher in the less likely case that GW170817 did not result in a BH (Ai et al. 2019). Note that different estimates set different strict upper limits, namely, $2.17 M_\odot$ (Margalit & Metzger 2017), $2.28 M_\odot$ (Ruiz et al. 2018), $2.3 M_\odot$ (Shibata et al. 2019), and $2.33 M_\odot (= 2.16 M_\odot + 0.17 M_\odot)$ (Rezzolla et al. 2018). For simplicity, hereafter we will take $M_{\text{TOV}} \lesssim 2.3 M_\odot$.

If the NS is spinning, its maximum mass can be higher than $M_{\text{TOV}}$ due to the additional rotational support against gravitational collapse to a BH. In particular, Breu & Rezzolla (2016) have found that the critical mass $M_{\text{crit}}$, that is, the mass of uniformly rotating NSs on the mass stability line, can be expressed in a (quasi-) universal relation through the dimensionless spin on the stability line $\chi_{\text{crit}}$ (Friedman et al. 1988; Takami et al. 2011), and the maximum dimensionless spin at the mass shedding limit $\chi_{\text{cep}}$, i.e., (see also Fig. 1)

$$M_{\text{crit}}(\chi_{\text{crit}}, \chi_{\text{cep}}, M_{\text{TOV}}) := M_{\text{TOV}} \left(1 + a_1 \left(\frac{\chi_{\text{crit}}}{\chi_{\text{cep}}}\right)^2 + a_2 \left(\frac{\chi_{\text{crit}}}{\chi_{\text{cep}}}\right)^4\right),$$

where $a_1 = 0.132$, $a_2 = 0.071$. This directly implies that the maximum mass for any uniformly rotating NS is limited by the spin at the mass-shedding limit, $\chi_{\text{crit}} = \chi_{\text{cep}}$. 
Figure 1. Schematic representation of the universal relation for uniformly rotating NSs along the stability line. (Breu & Rezzolla 2016). The solid black line reports the (quasi-)universal relation between $M_{\text{crit}}/M_{\text{TOV}}$ and the dimensionless angular momentum of the star when normalised to its maximum value $\chi/\chi_{\text{Kep}}$, while the blue-shaded area are the constraints on the mass from a given GW event. For any chosen $M_{\text{TOV}}$, the intersections of the blue-shaded area with the solid line will select the rotating stars having the smallest and the largest angular momentum.

where $M_{\text{max}} = M_{\text{crit}}(\chi_{\text{crit}} = \chi_{\text{Kep}}) = \xi_{\text{max}} M_{\text{TOV}}$ with $\xi_{\text{max}} = 1.203 \pm 0.022$ (Breu & Rezzolla 2016). Note that this result, combined with the present estimates on $M_{\text{TOV}}$ implies a strict upper limit on the mass of a NS supported via uniform rotation, i.e., $M_{\text{max}} \leq 2.85 M_{\odot}$, which is clearly larger than the mass inferred for the secondary in GW190814. Based on the results of Koliogiannis & Moustakidis (2020), it is possible to express $\chi_{\text{Kep}}$ in terms of the compactness $C_{\text{TOV}} = M_{\text{TOV}}/R_{\text{TOV}}$, i.e., (Breu & Rezzolla 2016; Shao et al. 2020)

$$\chi_{\text{Kep}} \simeq \frac{\alpha_1}{\sqrt{C_{\text{TOV}}}} + \alpha_2 \sqrt{C_{\text{TOV}}} \quad (3)$$

where $\alpha_1 = 0.045 \pm 0.021$ and $\alpha_2 = 1.112 \pm 0.072$ (Most et al. 2020). From these coefficients, we find an average value of $\chi_{\text{Kep}} = 0.682$, and since the relative difference over a large set of EOSs is only $\Delta \chi_{\text{Kep}}/\chi_{\text{Kep}} \sim 2.9\%$, we will use this average value hereafter.

Given a mass $M_{\text{crit}}$ of a rapidly rotating NS it is possible to set bounds on its spin $\chi$ and the maximum mass $M_{\text{TOV}}$ of a nonrotating NS. This is shown schematically in Fig. 1, which reports the universal relation for the masses of NSs along the stability line of uniformly rotating models $M_{\text{crit}}$ (Breu & Rezzolla 2016). More specifically, the solid black line reports the (quasi-)universal relation between $M_{\text{crit}}/M_{\text{TOV}}$ and the dimensionless angular momentum of the star when normalised to its maximum value $\chi/\chi_{\text{Kep}}$, i.e., Eq. (2). One can see, for instance, that the largest possible mass for a rotating star $M_{\text{max}}$ is $\sim 1.2$ times that of the corresponding nonrotating model for any EOS. Shown instead with a blue-shaded area are the constraints on the mass from a given GW event. This area will depend not only on the GW measurement, but also on $M_{\text{TOV}}$. The intersections of the blue-shaded area with the solid line will then select the rotating star on the stability limit having the smallest and the largest angular momentum that is still in agreement with the observation. The red-shaded area will therefore represent the allowed range in spin for a massive NS that has collapsed to a BH.

Since $\chi \leq \chi_{\text{Kep}}$, it is also possible to determine a lower bound on $M_{\text{TOV}}$ when $M_{\text{crit}} = M_{\text{max}}$, that is, when the lower limit of the observed mass range (lower edge of blue-shaded area) is reached by a star with $\chi = \chi_{\text{Kep}}$.

3. APPLICATION TO GW190814

Recently the LIGO/Virgo collaboration has reported the detection of the merger of a $\sim 23 M_{\odot}$ BH with another $\sim 2.6 M_{\odot}$ compact object (The LIGO Scientific Collaboration et al. 2020). Following the scenarios outlined in Sec. 1 we assume that either we have the merger of a very massive BH with a light BH that was produced by the collapse of a rapidly spinning NS prior to merger. We can then use the universal relations summarised in Sec. 2 to extract bounds on the spin $\chi_2$ and $m_2$ of the secondary companion. Indeed, as we will comment later on, our bounds apply unchanged even if the rapidly spinning NS never collapsed to a BH.

In Fig. 2 we show the universal relation (2) of the mass $m_2$ of a rapidly spinning NS with its spin $\chi_2$. In addition, we also shade the allowed region of masses of the secondary from the GW190814 event in blue (The LIGO Scientific Collaboration et al. 2020), i.e., $m_2 = 2.59^{+0.08}_{-0.08}$, and mark the maximally allowed spin $\chi_2 = \chi_{\text{Kep}}$ approximated as a constant with a red vertical line. Note that for different values for the maximum mass $M_{\text{TOV}}$, Eq. (2), generates a sequence of rotating stars starting at $m_2 = M_{\text{TOV}}$ and terminating at their maximum value when $\chi_2 = \chi_{\text{Kep}}$. If the secondary binary companion in GW190814 was at some point a NS (and since then did not change its mass significantly), it will have to lie on or below one of these sequences. As outlined in Sec. 2, the sequence with the lowest $M_{\text{TOV}}$ that still intersects with the measurement of GW190814 marks (green diamond in Fig. 2) a lower limit on $M_{\text{TOV}}$, i.e., $M_{\text{min}}^{\text{TOV}}$. In order for the NS to have been stable initially, it could not have been more massive than the heaviest rotating configuration, i.e.,

$$m_2 \leq M_{\text{crit}}(\chi_{\text{crit}} = \chi_{\text{Kep}}, M_{\text{TOV}} = M_{\text{min}}^{\text{TOV}}) \simeq \xi_{\text{max}} M_{\text{min}}^{\text{TOV}} \quad (4)$$
Hence, we find that if the secondary in GW190814 was either a BH formed by the collapse of a rapidly rotating NS or a stable rapidly rotating NS, this yields a lower bound on the maximum mass of nonrotating stars, i.e.,

$$M_{\text{TOV}} \gtrsim M_{\text{TOV}}^{\min} = m_2^{\text{GW190814}} / \chi_{\text{max}} \approx 2.08 \pm 0.04 \, M_\odot,$$

(5)

where we have taken the most conservative lower limit on the companion mass $m_2^{\text{GW190814}} = 2.51 \, M_\odot$ (The LIGO Scientific Collaboration et al. 2020). The corresponding sequence of critical masses of rotating NSs with spin $\chi_2$ is given by the lower black line in Fig. 2, which terminates at $\chi_2 = \chi_{\text{Kep}} \approx 0.68$.

On the other hand, in accordance with the maximum mass constraints described in Sec. 2 we can consider the same logic and draw lines for any value of $M_{\text{TOV}} \lesssim 2.3 \, M_\odot$, which is shown with different black lines in Fig. 2. From the intersection of the line corresponding to $M_{\text{TOV}} = 2.3 \, M_\odot$ with $m_2^{\text{GW190814}} = 2.51 \, M_\odot$ we deduce a lower bound of the spin $\chi_2 \gtrsim 0.49$. Combining the two results, we conclude that, for the secondary in GW190814 to be a NS, its spin must have been in the range

$$0.49 \lesssim \chi_2 \lesssim 0.68 = \chi_{\text{Kep}}.$$

(6)

We can check the consistency of $\chi_2$ by computing the spin $\chi_1$ of the primary BH binary component by considering Eq. (1),

$$\chi_1 (\chi_2) = -q \chi_2 + \tilde{\chi} (1 + q),$$

(7)

and using $\tilde{\chi} = -0.002 \pm 0.006$ and $q = 0.112^{+0.008}_{-0.006}$ (The LIGO Scientific Collaboration et al. 2020). We find that the values obtained here are all consistent with those inferred by The LIGO Scientific Collaboration et al. (2020), i.e., $|\chi_1| < 0.07$. The finally allowed range of binary component spins is then shown in Fig. 3.

Using the fit given in Barausse & Rezzolla (2009) we can also derive an estimate on the final BHs spin, $\chi_{\text{fin}}$. Assuming the spins of the primary and secondary are anti-aligned, we derive $0.24 < \chi_{\text{fin}} < 0.29$.

Finally, this range for $\chi_2$ can be translated into a rotation frequency of the NS, $\Omega_2 = S_2 / I_2$, that can easily computed for a given moment of inertia $I_2$, which can be expressed in terms of the NS mass and radius. Using the fit for $\chi \approx 0.4$ from Breu & Rezzolla (2016), we can compute the moment of inertia as

$$I_2 / m_2^3 = (\bar{a}_1 C^{-1} + \bar{a}_2 C^{-2} + \bar{a}_3 C^{-3} + \bar{a}_4 C^{-4}) / \chi_2,$$

(8)

with the compactness $C := m_2 / R_2$ and $\bar{a}_1 = 9.50 \times 10^{-7}$, $\bar{a}_2 = 1.44 \times 10^{-2}$, $\bar{a}_3 = 1.22 \times 10^{-2}$, and $\bar{a}_4 = -7.61 \times 10^{-4}$. Assuming a typical NS radius of $R_2 = 12.5 (13 \, \text{km})$ (Most et al. 2018b) and $S_2 = \chi_2 m_2^2$, we find a rotation frequency $f = \Omega / 2\pi$ of 1.21 (1.14) kHz for $\chi_2 = 0.49$. This frequency is considerably higher than the fastest known pulsar PSR J1748–2446ad (Hessels et al. 2006), with a frequency of 716 Hz, thus making – at least in this hypothetical scenario – the secondary of GW190814 the fastest known NS.

4. CONCLUSION

We have investigated how a lower bound on the maximum mass $M_{\text{TOV}}$ of a nonrotating NS can be derived from the recent observation of the merger of a $\sim 2.6 \, M_\odot$ compact object with a $\sim 23 \, M_\odot$ BH (The LIGO Scientific Collaboration et al. 2020). More specifically, since the maximum-mass constraints from GW170817 (Margalit & Metzger 2017; Rezzolla et al. 2018; Ruiz et al. 2018; Shibata et al. 2019) and the observations of very massive pulsars (Cromartie et al. 2020) indicate that the maximum mass of nonrotating NSs is lower than the measured mass of the secondary $m_2$, rotation is needed to allow for the secondary compact object in GW190814 to have been a NS at some point in the inspiral. Using universal relations for the maximum mass of uniformly rotating NSs (Breu & Rezzolla 2016), we infer a lower limit on the maximum mass of nonrotating NSs, $M_{\text{TOV}} > 2.08^{+0.04}_{-0.04} \, M_\odot$. In combination with the upper limit $M_{\text{TOV}} \leq 2.3 \, M_\odot$ (Rezzolla et al. 2018; Shibata et al. 2019), we are also able to provide an estimate of $0.49 \leq \chi_2 \leq 0.68$. 

![Figure 2. Mass over spin of the secondary in GW190814. The black lines show the Eq. (2) assuming that the secondary was a critically spinning NS at some point. The red-shaded area marks the allowed spin range given the mass measurement (blue shaded). The green diamond selects the curve with the minimal possible value of $M_{\text{TOV}}$.](image-url)
A LOWER BOUND ON THE MAXIMUM MASS FROM GW190814

Figure 3. Allowed range (red-shaded area) of primary and secondary spins $\chi_1$ and $\chi_2$, in case the secondary was a NS at some point before merger.

for the spin of the secondary object, a quantity that has not been constrained by the observations of GW190814.

While these results already are very promising, especially since the scenario considered here is in complete agreement with the present understanding of the EOS of nuclear matter, they can be improved in several ways. First, and for simplicity, our current analysis has used the most conservative lower values in all quantities consistent with the observation. Any improvement on these errors, or a careful re-analysis of the universal relations presented in (Breu & Rezzolla 2016), promise an immediate reduction of the uncertainty on this lower bound. Second, improved estimates on the spin of the primary of GW190814 could potentially reduce our estimates on the spin of the secondary. Interestingly, since the rotational collapse of a magnetised NS to a BH can be accompanied by the emission of a radio signal similar to that measured in fast radio bursts (FRB) (Falcke & Rezzolla (2014) and also Most et al. (2018a)), there could be a potential connection between the location of an FRB and of a massive binary merger of the type discussed here.

ACKNOWLEDGEMENTS

ERM and LRW acknowledge support through HGS-HIRe. Support comes in part from HGS-HIRe for FAIR; the LOEWE-Program in HIC for FAIR; “PHAROS”, COST Action CA16214 European Union’s Horizon 2020 Research and Innovation Programme (Grant 671698) (call FETHPC-1-2014, project ExaHyPE); the ERC Synergy Grant “Black-HoleCam: Imaging the Event Horizon of Black Holes” (Grant No. 610058);

REFERENCES

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, Phys. Rev. Lett., 119, 161101
—. 2018, Physical Review Letters, 121, 161101
Ai, S., Gao, H., & Zhang, B. 2019, arXiv e-prints, arXiv:1912.06369
Annala, E., Gorda, T., Kurkela, A., & Vuorinen, A. 2018, Phys. Rev. Lett., 120, 172703
Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, Science, 340, 448
Barausse, E., & Rezzolla, L. 2009, Astrophys. J. Lett., 704, L40
Bauswein, A., Just, O., Janka, H.-T., & Stergioulas, N. 2017, Astrophys. J. Lett., 850, L34
Breu, C., & Rezzolla, L. 2016, Mon. Not. R. Astron. Soc., 459, 646
Cromartie, H. T., Fonseca, E., Ransom, S. M., et al. 2020, Nature Astronomy, 4, 72
De, S., Finstad, D., Lattimer, J. M., et al. 2018, Physical Review Letters, 121, 091102
Falcke, H., & Rezzolla, L. 2014, Astron. Astrophys., 562, A137
Friedman, J. L., Ipser, J. R., & Sorkin, R. D. 1988, Astrophys. J., 325, 722
Hessels, J. W., Ransom, S. M., Stairs, I. H., et al. 2006, Science, 311, 1901
Koeppel, S., Bovard, L., & Rezzolla, L. 2019, Astrophys. J. Lett., 872, L16
Koliogiannis, P. S., & Moustakidis, C. C. 2020, Phys. Rev. C, 101, 015805
Kruckow, M. U., Tauris, T. M., Langer, N., Kramer, M., & Izzard, R. G. 2018, Mon. Not. R. Astron. Soc., 481, 1908
Malik, T., Alam, N., Fortin, M., et al. 2018, Physical Review C, 98, 035804
Margalit, B., & Metzger, B. D. 2017, Astrophys. J. Lett., 850, L19
Montaña, G., Tolós, L., Hanuske, M., & Rezzolla, L. 2019, Phys. Rev. D, 99, 103009
Most, E. R., Nathanail, A., & Rezzolla, L. 2018a, Astrophys. J., 864, 117
Most, E. R., Weih, L. R., & Rezzolla, L. 2020, Mon. Not. R. Astron. Soc., 496, L16
Most, E. R., Weih, L. R., Rezzolla, L., & Schaffner-Bielich, J. 2018b, Phys. Rev. Lett., 120, 261103
Radice, D., Perego, A., Zappa, F., & Bernuzzi, S. 2018, Astrophys. J. Lett., 852, L29
Raithel, C., Özél, F., & Psaltis, D. 2018, Astrophys. J., 857, L23
Rezzolla, L., Most, E. R., & Weih, L. R. 2018, Astrophys. J. Lett., 852, L25

Figure 3. Allowed range (red-shaded area) of primary and secondary spins $\chi_1$ and $\chi_2$, in case the secondary was a NS at some point before merger.
Ruiz, M., Shapiro, S. L., & Tsokaros, A. 2018, Phys. Rev. D, 97, 021501
Shao, D.-S., Tang, S.-P., Sheng, X., et al. 2020, Phys. Rev. D, 101, 063029
Shibata, M., Zhou, E., Kiuchi, K., & Fujibayashi, S. 2019, Phys. Rev. D, 100, 023015
Stevenson, S., Vigna-Gómez, A., Mandel, I., et al. 2017, Nature Communications, 8, 14906
Takami, K., Rezzolla, L., & Yoshida, S. 2011, Mon. Not. R. Astron. Soc., 416, L1
Tews, I., Margueron, J., & Reddy, S. 2018, Physical Review C, 98, 045804
The LIGO Scientific Collaboration, & The Virgo Collaboration. 2017, Phys. Rev. Lett., 119, 161101
The LIGO Scientific Collaboration, & the Virgo Collaboration. 2020, arXiv e-prints, arXiv:2004.08342
The LIGO Scientific Collaboration, the Virgo Collaboration, Abbott, B. P., et al. 2017, Astrophys. J. Lett., 848, L12
The LIGO Scientific Collaboration, the Virgo Collaboration, Abbott, R., et al. 2020, arXiv e-prints, arXiv:2006.12611