



GW190814: Spin and Equation of State of a Neutron Star Companion

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Abstract

The recent discovery by LIGO/Virgo of a merging binary having a $\sim 23 M_{\odot}$ black hole and a $\sim 2.6 M_{\odot}$ compact companion has triggered a debate regarding the nature of the secondary, which falls into the so-called mass gap. Here we explore some consequences of the assumption that the secondary was a neutron star (NS). We show with concrete examples of heretofore viable equations of state (EOSs) that rapid uniform rotation may neither be necessary for some EOSs nor sufficient for others to explain the presence of an NS. Absolute upper limits for the maximum mass of a spherical NS derived from GW170817 already suggest that this unknown compact companion might be a slowly or even a nonrotating NS. However, several soft NS EOSs favored by GW170817 with maximum spherical masses $\lesssim 2.1 M_{\odot}$ cannot be invoked to explain this object, even allowing for maximum uniform rotation. By contrast, sufficiently stiff EOSs that yield $2.6 M_{\odot}$ NSs that are slowly rotating or, in some cases, nonrotating, and are compatible with GW170817 and the results of the Neutron Star Interior Composition Explorer (NICER), can account for the black hole companion.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Compact objects (288); Black holes (162); LIGO (920)

1. Introduction

On 2019 August 14 the LIGO/Virgo Scientific Collaboration (LVC) made one of the most intriguing gravitational-wave detections to date (Abbott et al. 2020b). The designated event, GW190814, involved a binary coalescence that had the most asymmetric mass ratio to date, $0.112^{+0.008}_{-0.009}$. The binary contained a primary component with mass $m_1 = 23.2^{+1.1}_{-1.0} M_{\odot}$ and dimensionless spin $\chi_1 \leq 0.07$, presumably making it a very low-spinning black hole (BH). The mass of the secondary was $m_2 = 2.59^{+0.08}_{-0.09}$, placing it at the boundary of the so-called “mass gap” (Bailyn et al. 1998; Özel et al. 2010), and therefore making its identification difficult (Hannam et al. 2013; Littenberg et al. 2015; Mandel et al. 2015; Yang et al. 2018). The absence of an electromagnetic (EM) counterpart and measurable tidal deformation add further uncertainty to the nature of this compact object and allows the secondary to be a BH, an NS, or something more exotic. Preliminary arguments based on estimates of the maximum spherical mass of an NS, the Tolman–Oppenheimer–Volkoff (TOV) limit, suggest that the unknown compact object was too heavy to be an NS (Abbott et al. 2020b).

The TOV limit, $M_{\text{max}}^{\text{sph}}$, is associated with the ground state of matter at zero temperature. Setting constraints on $M_{\text{max}}^{\text{sph}}$ is a long-standing pursuit (see reviews by Lattimer & Prakash 2016; Oertel et al. 2017; Baym et al. 2018) but the detection of a low-mass binary coalescence, GW170817, by LIGO/Virgo (Abbott et al. 2017) has played a significant role recently. This binary system had total mass of $2.74^{+0.04}_{-0.01} M_{\odot}$ or $2.82^{+0.47}_{-0.09} M_{\odot}$ depending on the assumed priors for its dimensionless spin. The low mass estimate assumed that the NSs had spin $|\chi| \leq 0.05$, while the high mass estimate assumed spin $|\chi| \leq 0.89$. Coincident with the detection of the gravitational waves and 1.734 ± 0.054 s after the GW170818 inferred binary coalescence time, there was a short γ -ray burst, GRB 170817A, of duration 2 ± 0.5 s detected by the Fermi

Gamma-Ray Burst Monitor (von Kienlin et al. 2017; Kozlova et al. 2017) and INTEGRAL (Savchenko et al. 2017, 2017).

Following event GW170817 a large number of studies appeared in an effort to elucidate the properties of NSs and their supranuclear density regime (Shibata et al. 2017; Margalit & Metzger 2017; Bauswein et al. 2017; Ruiz et al. 2018; Rezzolla et al. 2018; Annala et al. 2018; Radice et al. 2018; Most et al. 2018; De et al. 2018; Abbott et al. 2018; Raithel et al. 2018; Tews et al. 2018; Malik et al. 2018; Landry & Essick 2019; Baym et al. 2019; Shibata et al. 2019; Abbott et al. 2020a). Quantities rigorously investigated included the NS radius and its tidal deformability. For example, Tews et al. (2018) employed models constrained by calculations of the neutron-matter EOS, which employed chiral effective-field theory Hamiltonians to predict that a $1.4 M_{\odot}$ NS must have a radius $9.0 \text{ km} < R_{1.4} < 13.6 \text{ km}$, similar to Annala et al. (2018). In addition they showed that NSs with $M_{\text{max}}^{\text{sph}} \sim 2.5 M_{\odot}$ could be possible candidates for GW170817.

Independent of the LIGO/Virgo results, NS properties have been reported recently by the Neutron Star Interior Composition Explorer (NICER) team. In particular, estimates of the mass and radius of the isolated 205.53 Hz millisecond pulsar PSR J0030 + 0451 were obtained using a Bayesian inference approach to analyze its energy-dependent thermal X-ray waveform. It was shown that $R = 13.02^{+1.24}_{-1.06} \text{ km}$ and $M = 1.44^{+0.15}_{-0.14} M_{\odot}$ (Miller et al. 2019; Riley et al. 2019), which indicate a stiffer EOS than those mostly favored by the LVC.

Since the detection of GW190814 (Abbott et al. 2020b) one scenario that could explain the BH companion was that of a rapidly spinning NS. Well-known studies by Cook et al. (1994a, 1994b) were the first to show that spinning up an NS uniformly can increase its mass by $\sim 20\%$. Therefore, uniform rotation could provide a means of explaining a heavier compact object, at least in principle. This scenario also has been proposed by Most et al. (2020), who estimated the dimensionless spin of the secondary to be $0.49 \lesssim \chi \lesssim 0.68$. Here we further consider the idea of an NS as the black hole companion

of GW190814 and explore its consequences. By employing concrete examples we show that rapid uniform rotation may neither be necessary nor sufficient to explain the presence of a $2.6 M_{\odot}$ NS in GW190814. Soft EOSs consistent with GW170817, such as SLy (Douchin & Haensel 2001), are unable to provide enough mass to explain the secondary in GW190814, even for an NS endowed with maximum uniform rotation. On the other hand, we argue that well-known absolute mass upper limits derived from GW170817 can be invoked to show that a slowly or even a nonrotating NS can account for the secondary for viable stiff EOSs, such as DD2 (Hempel & Schaffner-Bielich 2010). To put it differently, there are *two* ways to connect events GW170817 and GW190814, and the scenario that the secondary object of the latter is an NS: The first way is to assume low spin priors for GW170817, which then would imply that the NS in GW190814 must be rapidly rotating and supported by a soft EOS like SLy. In the second way one can assume high spin priors in GW170817, which then can explain the secondary in GW190814 as a slowly or even nonrotating NS supported by a stiff EOS like DD2.

2. Assumptions

In this work we assume that the companion of the BH in event GW190814 is a *uniformly* rotating NS, i.e., an NS rotating at a frequency below the mass-shedding (Keplerian) limit, whose maximum mass we will denote by $M_{\max}^{\text{sup}}$. Rotating NSs beyond that limit are called *hypermassive* (HMNS; Baumgarte et al. 2000) and are supported in part by differential rotation. HMNSs are transient objects that typically collapse to a BH on timescales of 10–1000 ms due to the redistribution or loss of angular momentum by viscosity, magnetic field winding and turbulence, and/or (if nonaxisymmetric) gravitational waves. Uniformly rotating NSs with mass less than the Keplerian limit $M_{\max}^{\text{sup}}$ but larger than the maximum spherical limit, $M_{\max}^{\text{sph}}$, are called *supramassive* (Cook et al. 1992) and may also eventually collapse to BHs due to magnetic dipole radiation or gravitational waves, but on much longer time-scales. If the rotating star has mass less than the maximum spherical limit it will remain forever as an NS.

In principle our analysis can hold true even for hybrid (nuclear plus quark matter) stars (Paschalidis et al. 2018).

3. GW170817 and the Maximum Mass

The GW170817 detection has triggered different techniques to estimate $M_{\max}^{\text{sph}}$. Based on information inferred from the EM and gravitational-wave spectra Margalit & Metzger (2017) conclude that $M_{\max}^{\text{sph}} \leq 2.17 M_{\odot}$ at 90% confidence. They also argue that most probably the remnant was an HMNS or a very short-lived supramassive remnant. Using different arguments for the kilonova, together with quasi-universal relations between $M_{\max}^{\text{sph}}$ and the supramassive mass limit $M_{\max}^{\text{sup}}$, Rezzolla et al. (2018) found $2.01_{-0.04}^{+0.04} M_{\odot} \leq M_{\max}^{\text{sph}} \leq 2.16_{-0.15}^{+0.17} M_{\odot}$, yielding an absolute upper bound of $M_{\max}^{\text{sph}} \leq 2.33 M_{\odot}$. They assumed that the core collapsed exactly at the maximum mass-shedding limit. Another set of studies by Shibata et al. (2017, 2019) concluded that this upper limit can be only weakly constrained to be $M_{\max}^{\text{sph}} \lesssim 2.3 M_{\odot}$.

Based on numerical GRMHD simulations Ruiz et al. (2018) have shown that the event GW170817 and its associated short γ -ray burst GRB 170817A can be explained if the remnant

object was a, HMNS, i.e., whereby

$$\beta M_{\max}^{\text{sph}} \approx M_{\max}^{\text{sup}} \lesssim M_{\text{GW170817}} \lesssim M_{\text{thresh}} \approx \alpha M_{\max}^{\text{sph}}, \quad (1)$$

where $\alpha \approx 1.3$ – 1.7 is the ratio of the HMNS threshold mass limit (the limit that distinguishes prompt versus delayed collapse for the postmerger object) to the NS spherical maximum mass as calculated by various numerical experiments (Shibata 2005; Shibata & Taniguchi 2006; Baiotti et al. 2008; Hotokezaka et al. 2011; Bauswein et al. 2013). The important factor that bounds the NS mass from above is the β parameter, which for different realistic EOSs has been found to be $\beta \approx 1.20$ (Cook et al. 1994b, 1994a; Lasota et al. 1996; Breu & Rezzolla 2016), while a general Rhoades–Ruffini causality argument yields $\beta \approx 1.27$ (Friedman & Ipser 1987; Koranda et al. 1997). Depending on the mass of the remnant and the β parameter we were able to set upper limits on $M_{\max}^{\text{sph}}$ (Ruiz et al. 2018) as follows:

Low-spin priors, $|\chi| \leq 0.05$,

$$M_{\max}^{\text{sph}} \lesssim \begin{cases} 2.16 \pm 0.23 & \text{if } \beta \approx 1.27 \\ 2.28 \pm 0.23 & \text{if } \beta \approx 1.20 \end{cases} \quad (2)$$

while for high-spin priors, $|\chi| \leq 0.89$,

$$M_{\max}^{\text{sph}} \lesssim \begin{cases} 2.22 \pm 0.66 & \text{if } \beta \approx 1.27 \\ 2.35 \pm 0.66 & \text{if } \beta \approx 1.20 \end{cases} \quad (3)$$

A hard lower bound on $M_{\max}^{\text{sph}}$ is set by measurements of pulsar masses, which to date are $2.01_{-0.04}^{+0.04} M_{\odot}$ for J0348+0432 (Antoniadis et al. 2013), $1.928_{-0.017}^{+0.017} M_{\odot}$ for J1614–2230 (Demorest et al. 2010), and $2.14_{-0.18}^{+0.20} M_{\odot}$ for J0740+6620 (Cromartie et al. 2019). These measurements suggest that $M_{\max}^{\text{sph}} \gtrsim 2.0 M_{\odot}$, while Equations (2) and (3) suggest that the absolute limit for the maximum mass of spherical NSs, for the majority of the EOSs ($\beta \approx 1.20$), is $M_{\max}^{\text{sph}} \lesssim 2.51$ if GW170817 was composed of low-spin NSs and $M_{\max}^{\text{sph}} \lesssim 3.01$ if it was composed by high-spin ones. These absolute NS upper limits can be invoked already to suggest a straightforward explanation for “heavy” compact objects like the ones in GW190814 or GW190425 (Abbott et al. 2020a, 2020b) without having to identify specific nuclear models or, more significantly, resort to extreme physics.

4. Consequences for the EOS of GW190814

To assess the possibility that GW190814 contains a uniformly rotating NS a choice for an EOS necessarily has to be made. Although the correct EOS that describes supranuclear densities is not currently known, here we choose the SLy (Douchin & Haensel 2001) and the DD2 (Hempel & Schaffner-Bielich 2010) EOSs. These EOSs, which are broadly compatible with GW170817 data, are chosen not because they are more viable than others but rather because they exhibit “opposite” behaviors that will help us illustrate a point. In particular, the low-spin prior prediction for the GW170817 mass is $2.73_{-0.01}^{+0.05} M_{\odot}$ (Abbott et al. 2019),³ a value that is easily accommodated by a transient HMNS with the SLy EOS. On the other hand, the high-spin prior mass prediction of GW170817, $2.79_{-0.06}^{+0.30} M_{\odot}$, is closer to the prompt collapse threshold for the SLy EOS, $\sim 2.9 M_{\odot}$

³ Here we report the TaylorF2 values. The estimates from SEOBNRT and PhenomDNRT (Abbott et al. 2019) are similar, and do not change the argument we put forward.

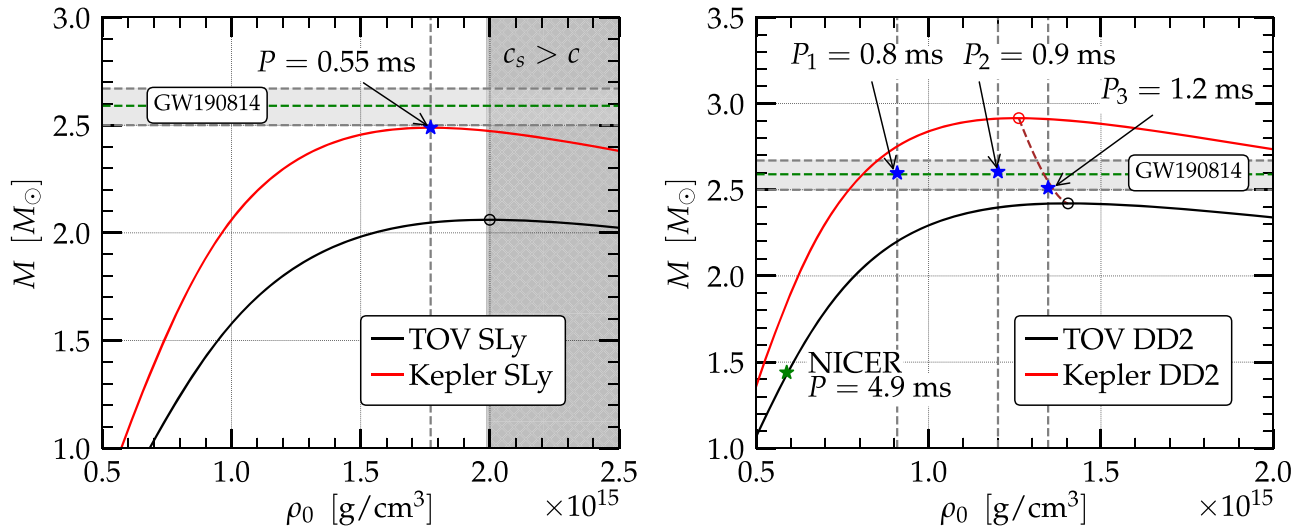


Figure 1. Two possibilities for the EOS of an NS secondary in GW190814. The left panel employs the soft SLy EOS and fails to provide a model of a viable uniformly rotating star. By contrast, the right panel employs the moderately stiff DD2 EOS and is successful.

(Bauswein et al. 2013). Binary NS simulations suggest that the lifetime of the HMNS remnant close to the prompt collapse limit is smaller than its lifetime when it is close to the supramassive limit. Given the fact that the HMNS remnant of GW170817 must have survived for ~ 1 s (Gill et al. 2019) before collapse to a BH, the high-spin prior case ($2.79M_\odot$ remnant mass) is not as probable as the low-spin one ($2.73M_\odot$ remnant mass) for the SLy EOS. This picture differs significantly in the DD2 EOS. In fact, DD2 is incompatible with the low-spin prior estimate of GW170817 and the requirement of Equation (1) that it be hypermassive, given that $M_{\text{max}}^{\text{sup}} = 2.92M_\odot$. Assuming instead high spins for GW170817, Equation (1) now requires $M_{\text{max}}^{\text{sup}} \lesssim 3.09M_\odot$ ($(2.79 + 0.30)M_\odot$), which is compatible with the $M_{\text{max}}^{\text{sup}}$ of DD2.

In Figure 1 we plot the mass versus rest-mass density for the SLy (Douchin & Haensel 2001) and the DD2 (Hempel & Schaffner-Bielich 2010) EOSs. In these plots we denote by a black solid line spherical, TOV NS models, while with a red solid line we show models at the mass-shedding (Kepler) limit. The models were computed using the relativistic rotating equilibrium code of Cook et al. (1994a, 1994b). The maximum of these curves represents $M_{\text{max}}^{\text{sph}}$ and $M_{\text{max}}^{\text{sup}}$, respectively. No *uniformly* rotating star can exist above the red lines in Figure 1. This means that the compact object in GW190814 *cannot be explained by an EOS like SLy*, although it is favored by the event GW170817 (Abbott et al. 2018). Such EOSs must now be rejected because their mass-shedding limit is below the lower limit mass of the compact object in GW190814, i.e.,

$$M_{\text{max}}^{\text{sup}} < 2.59_{-0.09}^{+0.08} M_\odot. \quad (4)$$

These EOSs they all share a relatively low maximum spherical mass, $M_{\text{max}}^{\text{sph}} \lesssim 2.1$, and thus they are called *soft* (see Read et al. 2009 for a list of various mass limits). Notice the supramassive limit for SLy, denoted by a blue star in Figure 1, has a dimensionless spin of $\chi = 0.7$ and a rotational period $P = 0.55$ ms. Hence *the fact that the NS is rapidly spinning and reaches a high χ* does not mean that it can necessarily explain GW190814. A glance at Read et al. (2009) reveals that a great number of these soft EOSs are ruled out based on this simple

observation. In addition, the model at the supramassive limit, is both dynamically and secularly unstable since both the dynamical and secular stability points reside slightly to the left of the turning point at lower rest-mass densities (Takami et al. 2011; Friedman et al. 1988).

In light of GW170817 the above conclusions can be interpreted in either of two ways. One way suggests that there is a tension between the EOSs that are favored by GW170817 and those that can be used to explain the NS companion in GW190814. This does not imply that *all* EOSs favored by GW170817 are nonviable candidates for GW190814, but there is certainly a gap between the two sets. The other way acknowledges that GW170817 is a binary NS system subject to well-established EOS restrictions that lead one to favor certain EOSs, while the nature of the secondary in GW190814 is uncertain. Hence, we might conclude that the likelihood of the secondary in GW190814 being a rotating NS may be small.

A second scenario is depicted in the right plot of Figure 1 where we invoke the DD2 EOS to represent a different class of models. Here the GW190814 limits are easily accommodated within the supramassive regime $[M_{\text{max}}^{\text{sph}}, M_{\text{max}}^{\text{sup}}]$. In the spirit of Equation (1), for the GW190814 secondary to be a uniformly rotating NS we must have

$$2.59_{-0.09}^{+0.08} M_\odot \lesssim M_{\text{max}}^{\text{sup}} \approx \beta M_{\text{max}}^{\text{sph}}, \quad (5)$$

which for $\beta \sim 1.20$ gives immediately $M_{\text{max}}^{\text{sph}} \gtrsim 2.1M_\odot$, consistent with modern pulsar observations (Cromartie et al. 2019). In Most et al. (2020) the same bound was found using more complicated arguments based on universal relations emerging from numerical fits. Three models are depicted with blue stars having periods around 1 ms. All of them reside on the left of the turning point line (maxima on constant angular momentum curves) depicted by a brown dashed line and therefore are dynamically and secularly stable with respect to axisymmetric perturbations, which include radial modes (Friedman et al. 1988; Takami et al. 2011). In addition they are all dynamically and secularly stable with respect to nonaxisymmetric $m = 2$ (bar) modes (all models have $T/W \leq 0.1$ where T is the rotational kinetic and W is the

gravitational binding energy). Although these stars are highly rotating from an astrophysical point of view, not all of them are considered rapidly rotating NSs in a general relativistic context. In particular the third model with period $P_3=1.2$ ms has $\chi_3 = 0.34$, $T/W = 0.03$, and deformation $R_p/R_e = 0.91$, where R_p and R_e are the polar and equatorial radii, respectively. In general relativity this model is considered a slowly rotating star for which even the slow-rotation approximation for equilibria (Hartle 1967) can provide an accurate description. By contrast, the model with maximum supramassive mass at the Keplerian limit (shown with a red circle) has $\chi = 0.7$, $T/W = 0.13$, $R_p/R_e = 0.56$, and $P = 0.7$ ms.

We note that while the periods quoted above may be short astrophysically, they are not unduly so. The fastest-spinning observed pulsar PSR J1748–2446ad has a period of ~ 1.4 ms (Hessels et al. 2006), which resides in the neighborhood of the above values. Short periods are consistent with the requirement that pulsars must have sufficiently small exterior B-fields to avoid spin-down over a reasonable lifetime. This is typically the case for recycled pulsars. Small fields generate small EM dipole emission and, if the radio luminosity is correspondingly low, this may explain why we have not observed the most rapidly rotating NSs with periods below $\sim$ millisecond as radio pulsars. Regarding compact binary systems, approximately 20 binary NSs have been detected (Tauris et al. 2017; Zhu et al. 2018), while there are no robust detections of a binary BH–NS so far. The NS in J1807–2500B has a period of 4.2ms, or $\chi \sim 0.12$, while others typically have longer periods (smaller χ). While the above set of observations is small and one cannot draw definitive conclusions, one might safely argue that if spin-down due to EM emission is as efficient as in the currently known binaries, then any scenario involving a highly spinning NS either in a binary NS or in a binary BH–NS system is not probable. Finally, for these reasons and others we also note that it has been argued that GW190814 is more likely a binary BH (Abbott et al. 2020b).

The major point of the right panel of Figure 1 is demonstrating with a concrete example that *with a relatively stiff EOS* (Tews et al. 2018; Annala et al. 2018; Tan et al. 2020; Alsing et al. 2018) *the secondary in GW190814 can be a slowly rotating NS*. Moreover, *if the EOS was only slightly stiffer, the secondary could even be a nonrotating companion*. Indeed, GW170817 and the maximum mass limits that it has spawned (Section 4) show that a slowly or even nonrotating NS for the secondary in GW190814 can be realized in principle. For nonrotating priors in GW170817 the absolute upper limit for $M_{\text{max}}^{\text{sph}}$ is 2.51, while for highly spinning priors it is 3.01. Models like those depicted in the right panel of Figure 1 can thus be accommodated even if we assume that the NSs in GW170817 had essentially no spins. In this way the limits presented in Ruiz et al. (2018) not only explain both events GW170817 and GW190814 but even allow for a secondary in GW190814 that is a slowly or nonrotating NS. The end result is that we never have to resort to any exotic physics to explain GW190814. We also remark that the representative DD2 stiff EOS yields a radius of $R = 13.3$ km for a mass $M = 1.44 M_\odot$ and period $P = 4.9$ ms, which is consistent with the results of NICER. This model resides slightly above the TOV curve for this EOS (green star in Figure 1).

The fact that rapid rotation is not necessary to explain the lighter object in GW190814 is also consistent with the

dimensionless spin diagnostics (Abbott et al. 2020b). Assuming that m_1 corresponds to the BH and m_2 to the NS the effective inspiral spin parameter χ_{eff} is

$$\chi_{\text{eff}} = \frac{\chi_1 + q\chi_2}{1 + q} \leq 0.063 + 0.1\chi_2, \quad (6)$$

where $q = m_2/m_1 = 0.112$ and $\chi_1 \leq 0.07$ from (Abbott et al. 2020b). Given that $\chi_{\text{eff}} = -0.002^{+0.060}_{-0.061}$ (Abbott et al. 2020b), Equation (6) yields $\chi_2 \geq -0.05$ or $\chi_2 \geq -1.26$, both of which accommodate nonrotating NSs.

Finally, we recognize that alternative models for the secondary in GW190814 include low-mass BHs (Gupta et al. 2020), or even an accreting NS in a circumbinary accretion disk (Safarzadeh & Loeb 2020). Several viable formation scenarios exist for $2.6 M_\odot$ BHs, such as binary NS or NS–white dwarf coalescence (Paschalidis et al. 2011a, 2011b), whose merger remnants may collapse to form BHs in both cases. The key point is that explaining the secondary in GW190814, whether as an NS or a BH, does not require unconventional or exotic physics (Vattis et al. 2020), although such a possibility cannot be ruled out.

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References

- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, *PhRvL*, **119**, 161101
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2018, *PhRvL*, **121**, 161101
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2019, *PhRvX*, **9**, 011001
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2020a, *CQGra*, **37**, 045006
- Abbott, R., Abbott, T. D., Abraham, S., et al. 2020b, *ApJL*, **896**, L44
- Alsing, J., Silva, H. O., & Berti, E. 2018, *MNRAS*, **478**, 1377
- Annala, E., Gorda, T., Kurkela, A., & Vuorinen, A. 2018, *PhRvL*, **120**, 172703
- Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, *Sci*, **340**, 448
- Bailyn, C. D., Jain, R. K., Coppi, B., & Orosz, J. A. 1998, *ApJ*, **499**, 367
- Baiotti, L., Giacomazzo, B., & Rezzolla, L. 2008, *PhRvD*, **78**, 084033
- Baumgarte, T. W., Shapiro, S. L., & Shibata, M. 2000, *ApJL*, **528**, L29
- Bauswein, A., Baumgarte, T., & Janka, H. T. 2013, *PhRvL*, **111**, 131101
- Bauswein, A., Just, O., Janka, H.-T., & Stergioulas, N. 2017, *ApJ*, **850**, L34
- Baym, G., Furusawa, S., Hatsuda, T., Kojo, T., & Togashi, H. 2019, *ApJ*, **885**, 42
- Baym, G., Hatsuda, T., Kojo, T., et al. 2018, *RPPh*, **81**, 056902
- Breu, C., & Rezzolla, L. 2016, *MNRAS*, **459**, 646
- Cook, G. B., Shapiro, S. L., & Teukolsky, S. A. 1992, *ApJ*, **398**, 203
- Cook, G. B., Shapiro, S. L., & Teukolsky, S. A. 1994a, *ApJ*, **424**, 823

- Cook, G. B., Shapiro, S. L., & Teukolsky, S. A. 1994b, *ApJ*, **422**, 227
- Cromartie, H. T., Fonseca, E., Ransom, S. M., et al. 2019, *NatAs*, **4**, 72
- De, S., Finstad, D., Lattimer, J. M., et al. 2018, *PhRvL*, **121**, 091102
- Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T. 2010, *Natur*, **467**, 1081
- Douchin, F., & Haensel, P. 2001, *A&A*, **380**, 151
- Friedman, J. L., & Ipser, J. R. 1987, *ApJ*, **314**, 594
- Friedman, J. L., Ipser, J. R., & Sorkin, R. D. 1988, *ApJ*, **325**, 722
- Gill, R., Nathanail, A., & Rezzolla, L. 2019, *ApJ*, **876**, 139
- Gupta, A., Gerosa, D., Arun, K., et al. 2020, *PhRvD*, **101**, 103036
- Hannam, M., Brown, D. A., Fairhurst, S., Fryer, C. L., & Harry, I. W. 2013, *ApJ*, **766**, L14
- Hartle, J. B. 1967, *ApJ*, **150**, 1005
- Hempel, M., & Schaffner-Bielich, J. 2010, *NuPhA*, **837**, 210
- Hessels, J. W. T., Ransom, S. M., Stairs, I. H., et al. 2006, *Sci*, **311**, 1901
- Hotokezaka, K., Kyutoku, K., Okawa, H., Shibata, M., & Kiuchi, K. 2011, *PhRvD*, **83**, 124008
- Koranda, S., Stergioulas, N., & Friedman, J. L. 1997, *ApJ*, **488**, 799
- Kozlova, A., Golenetskii, S., Aptekar, R., et al. 2017, *GCN*, **21517**, 1
- Landry, P., & Essick, R. 2019, *PhRvD*, **99**, 084049
- Lasota, J.-P., Haensel, P., & Abramowicz, M. A. 1996, *ApJ*, **456**, 300
- Lattimer, J. M., & Prakash, M. 2016, *PhR*, **621**, 127
- Littenberg, T. B., Farr, B., Coughlin, S., Kalogera, V., & Holz, D. E. 2015, *ApJL*, **807**, L24
- Malik, T., Alam, N., Fortin, M., et al. 2018, *PhRvC*, **98**, 035804
- Mandel, I., Haster, C.-J., Dominik, M., & Belczynski, K. 2015, *MNRAS*, **450**, L85
- Margalit, B., & Metzger, B. D. 2017, *ApJL*, **850**, L19
- Miller, M. C., Lamb, F. K., Dittmann, A. J., et al. 2019, *ApJL*, **887**, L24
- Most, E. R., Papenfort, L. J., Weih, L. R., & Rezzolla, L. 2020, arXiv:2006.14601
- Most, E. R., Weih, L. R., Rezzolla, L., & Schaffner-Bielich, J. 2018, *PhRvL*, **120**, 261103
- Oertel, M., Hempel, M., Klähn, T., & Typel, S. 2017, *RvMP*, **89**, 015007
- Özel, F., Psaltis, D., Narayan, R., & McClintock, J. E. 2010, *ApJ*, **725**, 1918
- Paschalidis, V., Etienne, Z., Liu, Y. T., & Shapiro, S. L. 2011a, *PhRvD*, **83**, 064002
- Paschalidis, V., Liu, Y. T., Etienne, Z., & Shapiro, S. L. 2011b, *PhRvD*, **84**, 104032
- Paschalidis, V., Yagi, K., Alvarez-Castillo, D., Blaschke, D. B., & Sedrakian, A. 2018, *PhRvD*, **97**, 084038
- Radice, D., Perego, A., Zappa, F., & Bernuzzi, S. 2018, *ApJL*, **852**, L29
- Raithel, C. A., Özel, F., & Psaltis, D. 2018, *ApJ*, **857**, L23
- Read, J. S., Lackey, B. D., Owen, B. J., & Friedman, J. L. 2009, *PhRvD*, **79**, 124032
- Rezzolla, L., Most, E. R., & Weih, L. R. 2018, *ApJL*, **852**, L25
- Riley, T. E., Watts, A. L., Bogdanov, S., et al. 2019, *ApJL*, **887**, L21
- Ruiz, M., Shapiro, S. L., & Tsokaros, A. 2018, *PhRvD*, **97**, 021501
- Safarzadeh, M., & Loeb, A. 2020, *ApJL*, **899**, L15
- Savchenko, V., Ferrigno, C., Kuulkers, E., et al. 2017, *ApJL*, **848**, L15
- Savchenko, V., Mereghetti, S., Ferrigno, C., et al. 2017, *GCN*, **21507**, 1
- Shibata, M. 2005, *PhRvL*, **94**, 201101
- Shibata, M., Fujibayashi, S., Hotokezaka, K., et al. 2017, *PhRvD*, **96**, 123012
- Shibata, M., & Taniguchi, K. 2006, *PhRvD*, **73**, 064027
- Shibata, M., Zhou, E., Kiuchi, K., & Fujibayashi, S. 2019, *PhRvD*, **100**, 023015
- Takami, K., Rezzolla, L., & Yoshida, S. 2011, *MNRAS*, **416**, L1
- Tan, H., Noronha-Hostler, J., & Yunes, N. 2020, arXiv:2006.16296
- Tauris, T. M., Kramer, M., Freire, P. C. C., et al. 2017, *ApJ*, **846**, 170
- Tews, I., Margueron, J., & Reddy, S. 2018, *PhRvC*, **98**, 045804
- Vattis, K., Goldstein, I. S., & Koushiappas, S. M. 2020, *PhRvD*, **102**, 061301
- von Kienlin, A., Meegan, C., & Goldstein, A. 2017, *GCN*, **21520**, 1
- Yang, H., East, W. E., & Lehner, L. 2018, *ApJ*, **856**, 110
- Zhu, X., Thrane, E., Oslowski, S., Levin, Y., & Lasky, P. D. 2018, *PhRvD*, **98**, 043002