On the origin of GW190425

Isobel M. Romero-Shaw\textsuperscript{1,2}, Nicholas Farrow\textsuperscript{1,2}, Simon Stevenson\textsuperscript{2,3}, Eric Thrane\textsuperscript{1,2}, Xing-Jiang Zhu\textsuperscript{1,2}⋆

\textsuperscript{1}School of Physics and Astronomy, Monash University, Clayton, VIC 3800, Australia
\textsuperscript{2}OzGrav: The ARC Centre of Excellence for Gravitational Wave Discovery, Clayton, VIC 3800, Australia
\textsuperscript{3}Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

ABSTRACT

The LIGO/Virgo collaborations recently announced the detection of a likely binary neutron star merger, GW190425. The total mass of GW190425 is significantly larger than the masses of Galactic double neutron stars known through radio astronomy. This suggests that GW190425 formed differently from Galactic double neutron stars. We hypothesize that GW190425 formed via unstable “case BB” mass transfer. According to this hypothesis, the progenitor of GW190425 was a binary consisting of a neutron star and a \( \sim 4 - 5 M_\odot \) helium star, which underwent a common-envelope process. Following the supernovae of the helium star core, a tight, eccentric, double neutron star was formed, which merged in \( \lesssim 10 \) Myr. The helium star progenitor may explain the unusually large mass of GW190425, while the short time to merger may explain why we do not see similar systems in radio. In order to test this hypothesis, we measure the eccentricity of GW190425 using publicly available LIGO/Virgo data. We constrain the eccentricity at 10 Hz to be \( e \lesssim 0.007 \) with 90% confidence. This result provides no evidence for or against the unstable mass transfer scenario because the binary is likely to have circularized to \( e \lesssim 10^{-4} \) by the time it entered the LIGO/Virgo band. Future detectors operating in lower frequency bands will enable us to discern the formation channel of mergers similar to GW190425 using eccentricity measurements.

Key words: gravitational waves – stars: neutron – binaries: general – pulsars: general

1 INTRODUCTION

Gravitational waves produced by a binary neutron star (BNS) merger have been detected for the second time (Abbott et al. 2017b, 2019a, 2020) by Advanced LIGO (Abbott et al. 2018) and Virgo (Acernese et al. 2015). The binary GW190425 is remarkable because it is significantly more massive than Galactic BNS (Abbott et al. 2020). Of the 17 known Galactic BNS with reported mass measurements (see Table 1 in Farrow et al. 2019, and references therein), the most massive one has total mass \( M = 2.886 \pm 0.001 M_\odot \) (Lazarus et al. 2016; Ferdman 2017). The total mass of GW190425 is \( 3.4^{+0.3}_{-0.1} M_\odot \), which is clearly inconsistent with the observed Galactic population (Abbott et al. 2020). The unusual mass of GW190425 invites speculation about its formation channel.

Double neutron stars may be formed as a result of isolated binary evolution (Smarr & Blandford 1976; Srinivasan 1989; Portegies Zwart & Yungelson 1998a; Canal et al. 1990; Kalogera et al. 2007; Postnov & Yungelson 2014; Beniamini & Piran 2016; Vigna-Gomez et al. 2018; Giacobbo & Mapelli 2018, 2019a,b; Mapelli & Giacobbo 2018) or through dynamical interactions (Phinney & Sigurdsson 1991; Sigurdsson & Phinney 1995; Kuranov & Postnov 2006; Ivanova et al. 2008; Kiel et al. 2010; Benacquista & Downing 2013; East & Pretorius 2012; Palmese et al. 2017; Andrews & Mandel 2019). The dominant formation channel for Galactic BNS is thought to be isolated evolution: a stellar binary in the field experiences successive supernovae, and the stellar remnant of each binary component is a neutron star (Tauris et al. 2017; Vigna-Gomez et al. 2018). The discrepancies between the mass of GW190425 and the observed Galactic BNS suggest two different formation channels. While many neutron stars not in BNS are known to have masses consistent with the components of GW190425 (Özel & Freire 2016; Alsing et al. 2018), it is challenging to explain the high mass of this system through standard isolated evolution, since the large supernova kicks associated with the formation of massive neutron stars are expected to disrupt binaries; see Michaela et al. (2016) and references therein.

In the dynamical formation scenario, BNS form as a result of interactions inside dense stellar environments, such as star clusters, galactic nuclei, and tidal fields. These interactions can perturb the orbits of binary systems, leading to mass transfer and the formation of a binary neutron star. The LIGO/Virgo detection of GW190425 provides a unique opportunity to test these scenarios and gain insights into the formation and evolution of neutron stars.
as globular clusters. A neutron star, which may have a stellar companion, sinks to the cluster core through dynamical friction. This can only occur once the number of black holes in the core has been depleted, either due to merger-induced kicks or because they gain velocity through dynamical interactions (e.g. Breen & Heggie 2013). In the core, the neutron star preferentially swaps any existing stellar companion for another neutron star, forming a BNS with a short merger time (Zevin et al. 2019). However, the merger rate of dynamically-formed BNS is expected to be low relative to the total local BNS merger rate (Grindlay et al. 2006; Bae et al. 2014; Belczynski et al. 2018; Ye et al. 2020). While the dynamical hypothesis provides a natural explanation for the large mass of GW190425, it is difficult to reconcile the merger rate implied by GW190425 with the predicted dynamical merger rate from N-body simulations. However, Andrews & Mandel (2019) point out that several Galactic-field BNS with small orbital separations and high eccentricities may form dynamically inside globular clusters, provided that these clusters have sufficiently high central densities.

We argue that unusually massive BNS like GW190425 may evolve in isolation if they undergo a process known as unstable “case BB” mass transfer (Delgado & Thomas 1981; Tutukov & Yungelson 1993a,b; Portegies Zwart & Verbunt 1996; Portegies Zwart & Yungelson 1998b; Belczynski et al. 2002b,a; Dewi et al. 2002; Ivanova et al. 2003; Zevin et al. 2019). We illustrate the formation of a BNS through unstable case BB mass transfer in Fig. 1. During this process, the helium star companion of a neutron star (panel A) fills its Roche lobe after the end of its helium core burning phase (panel B), initiating common envelope evolution (panel C). The helium envelope is ejected, leaving behind a NS-CO core binary (panel D) that is tight enough to survive the supernova of the helium star (panel E). The resulting BNS inspirals due to emission of gravitational waves (panel F) and eventually merges, leaving behind a merger remnant, which may be a neutron star or black hole (panel G). Unstable case BB mass transfer may produce heavy BNS with unequal masses (Ivanova et al. 2003; Müller et al. 2016). The supernova kick can also leave the binary with significant eccentricity, which can act as an identifier for this formation channel.

Supernova kicks during isolated evolution impart significant momentum to binary components, leaving the binary with high eccentricity (Brandt & Podsiadlowski 1995). During standard isolated evolution, gravitational radiation gradually circularizes binaries before they get close to merger (Peters 1964; Hinder et al. 2008). However, unstable case BB mass transfer may produce an eccentric binary that merges before it has time to completely circularize. In Section 2 of this work, we show that binaries from this channel have eccentricities $10^{-6} \lesssim e \lesssim 10^{-3}$ at 10 Hz when they enter the LIGO/Virgo band, with the peak of the distribution at $e \sim 10^{-4.5}$.

The properties of GW190425 as presented in Abbott et al. (2020) were inferred by matched-filtering data against quasi-circular waveform models. The signal was detected by a search algorithm that assumes quasi-circular compact binary orbits. Burst searches such as Abbott et al. (2019b) may flag eccentric signals, but cannot measure their eccentricity. Recently, Nitz et al. (2019) performed a matched-filtering search for eccentric BNS signals using

Figure 1. Illustration of unstable case BB mass transfer leading to a BNS merger. Credit: Carl Knox.
inspiral-only eccentric waveform models. Computationally efficient, inspiral-merger-ringdown models of eccentric waveform models are not yet available, although development is ongoing (e.g., Huerta et al. 2018; Tiwari et al. 2019). Computationally inefficient models (e.g., Cao & Han 2017) take too long to generate to be used for straightforward Bayesian inference, which often relies on O(100) waveform computations per iteration of its sampling algorithm. We can, however, use such models to efficiently obtain eccentricity measurements by post-processing the posterior probabilities for quasi-circular waveform models, as demonstrated in Romero-Shaw et al. (2019); see also Lower et al. (2018).

In this Letter, we take steps towards identifying the formation channel of GW190425 using measurements of binary eccentricity. We simulate BNS evolving through unstable case BB mass transfer and compare the resulting eccentricity distribution to the posterior probability on eccentricity obtained for GW190425. The remainder of this work is structured as follows. In Section 2, we outline the process of unstable case BB mass transfer and describe our method for simulating the expected eccentricity distribution at 10 Hz from this channel. We present upper limits on the orbital eccentricity of GW190425 when its gravitational radiation has a frequency of 10 Hz in Section 3, comparing the measured posterior probability distribution to the expected eccentricity distribution from supernova kicks. We discuss the implications of our results for the formation pathway of GW190425 in Section 4.

2 THE ISOLATED EVOLUTION OF GW190425

2.1 Unstable mass transfer in the isolated binary evolution channel

The immediate progenitor of an isolated BNS system is a binary comprising a neutron star and a helium (He) star with orbital period \( \sim 0.1 \) – 2 days, which has evolved to its current state via common envelope evolution (Bezegunski et al. 2002b; Dewi et al. 2002; Ivanova et al. 2003, 2013; Zevin et al. 2019). The He star then expands, filling its Roche lobe, and transferring mass onto the neutron star. If the mass transfer process is unstable, it can lead to a second CE (2CE) phase (Ivanova et al. 2003; Dewi & Pols 2003). The surviving post-2CE system consists of the carbon-oxygen (CO) core of the He star and the original neutron star. The latter has accreted only a small amount of mass (\( \sim 0.05 \) – 0.1\( M_\odot \)) (MacLeod & Ramirez-Ruiz 2015) during the 2CE phase. The binary can be tight enough that its orbital period is \( < 1 \) hr, making it likely to survive the subsequent supernova explosion of the CO core.

This asymmetric supernova explosion gives the compact object a kick. In population synthesis studies, kick velocities are frequently assumed to follow a Maxwellian distribution, and the kick velocity depends on the type of supernova. Core collapse supernovae (CCSN) are thought to produce large kicks, with a one-dimensional standard deviation of \( \sigma \approx 265 \text{ km s}^{-1} \) (Hobbs et al. 2005), while ultra-stripped supernovae and electron-capture supernovae are thought to produce small kicks, \( \sigma \approx 30 \text{ km s}^{-1} \) (Vigna-Gomez et al. 2018; Giacobbo & Mapelli 2019b,a).

The relationship between the final He star mass (CO core mass) and the neutron star remnant mass is uncertain, but Müller et al. (2016) predict that a \( \sim 4 \) – 5\( M_\odot \) He star (with a \( \sim 3M_\odot \) CO core) corresponds to a \( \sim 2M_\odot \) NS (see also Tauris et al. 2015). It is assumed that there is an instantaneous mass loss of \( \sim 1M_\odot \) during supernova. If the pre-2CE binary consists of a \( \sim 1.4M_\odot \) neutron star and a \( \sim 4 \) – 5\( M_\odot \) He star, then the post-2CE, post-supernova binary is a \( \sim (1.4 + 2.0)M_\odot \) BNS which merges in \( < 10 \) Myr. BNS with this lifespan are far less likely to be detected in radio pulsar surveys than their longer-lived counterparts. Furthermore, BNS with orbital periods \( < 1 \) hr are effectively invisible in current pulsar searches. For example, the acceleration search of Cameron et al. (2018), which found the most accelerated pulsar observed to date, was sensitive to binary pulsars with orbital periods down to 1.5 hr. We discuss the selection effects further in Appendix A.

2.2 Eccentricity distribution

Following Brandt & Podsiadlowski (1995), we calculate the eccentricity introduced by the supernova kick in this formation scenario. We define the dimensionless mass \( \tilde{m} \) as

\[
\tilde{m} = \frac{M_{1}^{\text{CO}} + M_{2}^{\text{NS}}}{M_{1}^{\text{NS}} + M_{2}^{\text{NS}}},
\]

where \( M_{1}^{\text{CO}} \) is the mass of the progenitor CO core, \( M_{1}^{\text{NS}} \) is the mass of the neutron star remnant, and \( M_{2}^{\text{NS}} \) is the mass of the companion NS. We define the dimensionless kick velocity \( \tilde{v} \) as

\[
\tilde{v} = \frac{v_{\text{kick}}}{v_{\text{orbit}}}.
\]

The resultant orbital eccentricity is

\[
e = [1 - \tilde{m} (2 - \tilde{m} (1 + 2\tilde{v} \cos \phi \cos \theta + \tilde{v}^2))]
\times [(1 + \tilde{v} \cos \phi \cos \theta)^2 + (\tilde{v} \sin \theta)^2)]^{1/2},
\]

where \( \phi \) is the angle between the direction of the star’s velocity vector and the kick vector, and \( \theta \) is the angle between the orbital plane and the kick. The orbit acquires a new semimajor axis \( a' \) from the supernova kick, which is given by

\[
a' = \left[ \frac{1}{a} (2 - \tilde{m} (1 + 2\tilde{v} \cos \phi \cos \theta + \tilde{v}^2)) \right]^{-1}. \]

We simulate binaries with \( M_{1}^{\text{CO}} = 3.0M_\odot \), \( M_{1}^{\text{NS}} = 2.0M_\odot \), \( M_{2}^{\text{NS}} = 1.4M_\odot \), and orbital periods drawn from a log-uniform distribution between 0.1 hr and 1 hr at time of supernova (see Fig. 8 from Vigna-Gomez et al. 2018). Kick velocities are drawn from Maxwellian velocity distributions, with \( \sigma_{v} = 265 \text{ km s}^{-1} \) for large supernova kicks and \( \sigma_{v} = 30 \text{ km s}^{-1} \) for small supernova kicks. For simplicity, we simulate isotropic kicks with no preference for any particular direction. Some NS receive kicks sufficient to disrupt the binary, and hence are discarded. Each binary is then evolved until it has a period of 0.2 s, corresponding to a gravitational-wave frequency of \( f_{\text{gw}} = 10 \text{ Hz} \). The eccentricity decreases due to gravitational radiation, according to the orbital evolution equations from Peters (1964).

We present the distributions of \( \log_{10} \) eccentricities obtained from supernova kicks in this scenario in Fig. 2.
is a slight preference for higher eccentricities from high-velocity kicks. Supernovae with large kicks lead to a log$_{10}$ eccentricity distribution with a mean of $-4.30$, while the log$_{10}$ eccentricity distribution arising from smaller kicks has a mean of $-4.46$. The 90% confidence interval on log$_{10}$ eccentricity spans $-4.94 \leq \log_{10} e \leq -3.98$ for small kick velocities, and $-4.89 \leq \log_{10} e \leq -3.79$ for large kick velocities.

3 ECCENTRICITY OF GW190425

In order to compare GW190425 to the model described in Section 2, we measure the eccentricity of this system when it enters the sensitive frequency range of LIGO/Virgo. Romero-Shaw et al. (2019) demonstrated the calculation of Bayesian posterior probability distributions for the eccentricity of binary systems detected in gravitational waves; see also Payne et al. (2019) for detailed formulation of the reweighting procedure that underlies such post-processing techniques. Following the same method, we use circular waveform model IMRPhenomD (Khan et al. 2016) to compute “proposals” posterior probability distributions for the binary parameters, and eccentric waveform model SEOBNRE (Cao & Han 2017) to reweight to our “target” distribution. We use the Bayesian inference library bilby (Ashton et al. 2019) to fit the data to the proposal model. Our prior on chirp mass $\mathcal{M}$ is uniform between 1.42 and 2.60 $M_\odot$, and our prior on mass ratio $q$ is uniform between 0.125 and 1. Our prior on source luminosity distance $d_L$ is uniform in comoving volume between 1 and 500 Mpc. For dimensionless aligned component spins $\chi_1$ and $\chi_2$, we use priors that are uniform between $-1$ and 0.6 due to limitations of the SEOBNRE waveform model. For the remaining sampled parameters – right ascension, declination, source inclination angle $\theta_\mu$, polarisation angle $\psi$ and reference phase $\phi$ – we use standard priors.

At present, evaluating SEOBNRE waveforms is computationally expensive. To reduce the time taken to post-process our initial IMRPhenomD posterior samples, we generate eccentric waveforms with reference frequencies of 20 Hz. To obtain measurements of orbital eccentricity at the conventional reference frequency of 10 Hz, we use the equations of Peters (1964) to evolve the system backward in time. We use a log-uniform prior on eccentricity, with a resolution of 30 eccentricity bins per sample. At 20 Hz, our prior is in the range $10^{-6} \leq e \leq 0.1$. This corresponds to a range of $10^{-6.68} \leq e \leq 0.197$ at 10 Hz.

We constrain the eccentricity of GW190425 to be $e \leq 0.007$ at 10 Hz with 90% confidence. We present our posterior distribution on eccentricity at 10 Hz for GW190425 in Fig. 2. Our reweighting efficiency is 0.386, giving us 7718 effective samples; see Romero-Shaw et al. (2019) for a discussion of efficiency. Reweighted posterior distributions for intrinsic and extrinsic parameters (plotted in the Appendix) are consistent with results from Abbott et al. (2020).

We compare the eccentricity posterior for GW190425 to the eccentricity distribution expected from supernova kicks during unstable case BB mass transfer in Fig. 2. All distributions are shown at a reference frequency of 10 Hz. The posterior probability distribution for the eccentricity of GW190425 is consistent with our log-uniform prior for eccentricities $e \leq 10^{-2}$, implying that we are unable to resolve differences between eccentricities lower than this. The eccentricity of GW190425 is consistent with the eccentric binaries produced in unstable case BB mass transfer.

4 DISCUSSION

It is possible that GW190425 is formed through unstable case BB mass transfer. However, it is not possible for us to distinguish the small residual eccentricity expected from this channel at 10 Hz with the sensitivity of the current generation of gravitational-wave observatories. Proposed third-generation observatories such as Cosmic Explorer (Abbott et al. 2017a) and the Einstein Telescope (Punturo et al. 2010) will detect binaries like GW190425 with higher signal-to-noise ratio with superior low-frequency sensitivity. These improvements may prove sufficient to find hints of BNS eccentricity that could support the unstable case BB hypothesis. The future space-based gravitational-wave detector LISA (Amaro-Seoane et al. 2017) will provide heightened low-frequency sensitivity down to $10^{-4}$ Hz, enabling us to distinguish between various sub-categories of both isolated and dynamical mergers (Breivik et al. 2016; Nishizawa et al. 2017; D’Orazio & Samsing 2018; Samsing & D’Orazio 2018; Lau et al. 2020).

The inferred merger rate for systems like GW190425 is high compared to lighter BNS systems (Abbott et al. 2020). Since GW190425 is only the second BNS merger to be observed in gravitational waves, roughly half of all BNS mergers may form by the same means. This could imply that unstable case BB mass transfer is a common pathway to BNS formation. Any proposed formation channel for this merger must also explain the relatively high formation rate of similar BNS.
Neutron star spins, which are primarily measurable through the effective spin parameter ($\chi_{\text{eff}}$) of the gravitational waveform, can provide additional clues to the formation channel of BNS. The $\chi_{\text{eff}}$ of Galactic-field BNS, thought to have formed via the standard isolated evolution channel, are predicted to range from 0.00 to 0.02 at merger (Zhu et al. 2018). BNS formed in globular clusters can have a wider range of spins than their isolated counterparts (see East et al. 2015, and references therein). Therefore, a binary with measurably negative $\chi_{\text{eff}}$ would be difficult to explain through anything other than dynamical formation. The $\chi_{\text{eff}}$ of BNS formed through unstable case BB mass transfer depends critically on the amount of angular momentum transferred onto the first-born NS during two common-envelope stages, since the second-born NS is expected to spin down to effectively zero spin in a timescale comparable to the binary merger time ($\lesssim 10$ Myr). De et al. (2019) recently suggested that black holes tend to preserve their natal masses and spins during the common-envelope evolution. If this holds up for BNS, it might imply that all BNS formed through unstable case BB mass transfer are expected to have low dimensionless component spins of $\chi < 0.05$ at merger. While we are unable to measure NS spins in GW190425 (and in GW170817), it may be possible to do so for future discoveries, allowing stronger constraints to be placed on the system origin.

5 ACKNOWLEDGMENTS

This work is supported by Australian Research Council grants CE170100004 and FT150100281. This research has made use of data, software and/or web tools obtained from the Gravitational Wave Open Science Center (https://www.gw-openscience.org), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration.

Note added.– While preparing this manuscript, we became aware of a recent pre-print which claims that the merger rate implied by GW190425 is inconsistent with population synthesis results for the merger rate of Galactic-field BNS, thought to have formed via the standard isolated evolution channel (Canal R., Isern J., Labay J., 1990, ARA&A, 28, 183). We therefore believe that we cannot rule out the formation of GW190425 through unstable case BB mass transfer based solely on the inferred BNS merger rate.

REFERENCES

Abbott B. P., et al., 2017a, Class. Quant. Grav., 34, 044001
Abbott B., et al., 2017b, Phys. Rev. Lett., 119
Abbott B. P., et al., 2018, Living Rev. Rel., 21, 3
Abbott B., et al., 2019a, Phys. Rev. X, 9
Abbott B. P., et al., 2019b, Phys. Rev. D, 100, 064064
Abbott B. P., et al., 2020, arXiv e-prints, p. arXiv:2001.01761
Acernese F., et al., 2015, Class. Quant. Grav., 32, 024001
Alsing J., Silva H. O., Berti E., 2018, MNRAS, 478, 1377
Amaro-Seoane P., et al., 2017, arXiv e-prints, p. arXiv:1702.00786
Andrews J. J., Mandel I., 2019, ApJ, 880, L8
Ashton G., et al., 2019, ApJS, 241, 27
Bae Y.-B., Kim C., Lee H. M., 2014, MNRAS, 440, 2714
Belczynski K., Bulik T., Kalogera V., 2002a, ApJ, 571, L147
Belczynski K., Kalogera V., Bulik T., 2002b, ApJ, 572, 407
Belczynski K., et al., 2018, A&A, 615, A91
Benaquista M. J., Downing J. M. B., 2013, Living Rev. Rel., 16, 4
Beniamini P., Piran T., 2016, MNRAS, 456, 4089
Brandt N., Podsiadlowski P., 1995, MNRAS, 274, 461
Breen P. G., Heggie D. C., 2013, MNRAS, 436, 584
Breivik K., Rodriguez C. L., Larson S. L., Kalogera V., Rasio F. A., 2016, ApJ, 830, L18
Cameron A. D., et al., 2018, MNRAS, 475, L57
Canal R., Isern J., Labay J., 1990, ARA&A, 28, 183
Cao Z., Han W.-B., 2017, Phys. Rev. D, 96, 044028
Chruslinska M., Belczynski K., Klencki J., Benaquista M., 2018, MNRAS, 474, 2937
Chruslinska M., Nelemans G., Belczynski K., 2019, MNRAS, 482, 5012
D’Orazio D. J., Samsing J., 2018, MNRAS, 481, 4775
De S., MacLeod M., Eversoon R. W., Antoni A., Mandel I., Ramirez-Ruiz E., 2019, arXiv e-prints, p. arXiv:1910.13333
Delgado A. J., Thomas H. C., 1981, A&A, 96, 142
Dewi J. M. D., Pols O. R., 2003, MNRAS, 344, 629
Dewi J. M. D., Pols O. R., Savonije G. J., van den Heuvel E. P. J., 2002, MNRAS, 331, 1027
East W. E., Pretorius F., 2012, ApJ, 760, L4
East W. E., Pschaldilis V., Pretorius F., 2015, ApJ, 807, L3
Farrow N., Zhu X.-J., Thrane E., 2019, ApJ, 876, 18
Ferdman R. D., 2017, Proceedings of the International Astronomical Union, 13, 146
Giacobbo N., Mapelli M., 2018, MNRAS, 480, 2011
Giacobbo N., Mapelli M., 2019a, arXiv e-prints, p. arXiv:1909.06385
Giacobbo N., Mapelli M., 2019b, MNRAS, 482, 2234
Grindlay J., Portegies Zwart S., McMillan S., 2006, Nature Phys., 2, 116
Hinder I., Vaishnav B., Herrmann F., Shoemaker D. M., Laguna P., 2008, Phys. Rev. D, 77, 081502
Hobbs G., Lorimer D. R., Lyne A. G., Kramer M., 2005, MNRAS, 360, 974
Huerta E. A., et al., 2018, Phys. Rev. D, 97, 024031
Ivanova N., Belczynski K., Kalogera V., Rasio F. A., Taam R. E., 2003, ApJ, 592, 475
Ivanova N., Heinke C. O., Rasio F. A., 2008, IAU Symp., 246, 316
Ivanova N., et al., 2013, A&ARv, 21, 59
Kalogera V., Belczynski K., Kim C., O’Shaughnessy R. W., Willems B., 2007, Phys. Rept., 442, 75
Khan S., Husa S., Hannam M., Ohme F., Pürrer M., Forteza X. J., Bohé A., 2016, Phys. Rev. D, 93, 044007
Kiel P., Fregeau J., Umbricht S., Chatterjee S., Rasio F., 2010, AIP Conference Proceedings, 1341, 367
Kowalska I., Bulik T., Belczynski K., Dominik M., Gondek-Rosinska D., 2011, A&A, 527, A70
Kuranov A. G., Postnov K. A., 2006, Astronomy Letters, 32, 393
Lau M. Y. M., Mandel I., Vigna-Gómez A., Neijssel C. J., Stevenson S., Sesana A., 2020, MNRAS, 492, 3061
Lazarus P., et al., 2016, ApJ, 831, 150
Lower M. E., Thrane E., Lasky P. D., Smith R., 2018, Phys. Rev. D, 98, 083028
MacLeod M., Ramirez-Ruiz E., 2015, ApJ, 798, L19
Mapelli M., Giacobbo N., 2018, MNRAS, 479, 4391
Michaely E., Ginzburg D., Perets H. B., 2016, arXiv e-prints, p. arXiv:1909.06385
Müller B., Heger A., Liptai D., Cameron J. B., 2016, MNRAS, 460, 742

MNRAS 000, 000–000 (0000)
Neijssel C. J., et al., 2019, MNRAS, 490, 3740
Nishizawa A., Sesana A., Berti E., Klein A., 2017, MNRAS, 465, 4375
Nitz A. H., Lenon A., Brown D. A., 2019, arXiv e-prints, p. arXiv:1912.05464
Özel F., Freire P., 2016, ARA&A, 54, 401
Palmese A., et al., 2017, ApJ, 849, L34
Payne E., Talbot C., Thrane E., 2019, Phys. Rev. D, 100, 123017
Peters P. C., 1964, Phys. Rev., 136, B1224
Phinney E. S., Sigurdsson S., 1991, Nature, 349, 220
Portegies Zwart S. F., Verbunt F., 1996, A&A, 309, 179
Portegies Zwart S. F., Yungelson L. R., 1998a, A&A, 332, 173
Portegies Zwart S. F., Yungelson L. R., 1998b, A&A, 332, 173
Postnov K. A., Yungelson L. R., 2014, Living Rev. Rel., 17, 3
Punturo M., et al., 2010, Class. Quant. Grav., 27, 194002
Romero-Shaw I. M., Lasky P. D., Thrane E., 2019, MNRAS, 490, 5210
Safarzadeh M., Ramirez-Ruiz E., Berger E., 2020, arXiv e-prints, p. arXiv:2001.04502
Samsing J., D’Orazio D. J., 2018, MNRAS, 481, 5445
Sigurdsson S., Phinney E. S., 1995, ApJS, 99, 609
Smarr L. L., Blandford R., 1976, ApJ, 207, 574
Srinivasan G., 1989, Astronomy and Astrophysics Review, 1, 209
Tang P. N., Eldridge J. J., Stanway E. R., Bray J. C., 2020, MNRAS, 493, L6L10
Tauris T. M., Langer N., Podsiadlowski P., 2015, MNRAS, 451, 2123
Tauris T. M., et al., 2017, ApJ, 846, 170
Tiwari S., Gopakumar A., Haney M., Hemantakumar P., 2019, Phys. Rev. D, 99, 124008
Tutukov A. V., Yungelson L. R., 1993a, Astronomy Reports, 37, 411
Tutukov A. V., Yungelson L. R., 1993b, MNRAS, 260, 675
Vigna-Gomez A., et al., 2018, MNRAS, 481, 4009
Ye C. S., Fong W.-L., Kremer K., Rodriguez C. L., Chatterjee S., Fragione G., Rasio F. A., 2020, ApJ, 888, L10
Zevin M., Kremer K., Siegel D., Coughlin S., Tsang B., Berry C., Kalogera V., 2019, ApJ, 886, 4
Zhu X., Thrane E., Osłowski S., Levin Y., Lasky P. D., 2018, Phys. Rev. D, 98, 043002

APPENDIX A: SELECTION EFFECTS

There are several selection effects that can lead to a discrepancy between the mass distribution of Galactic BNS observed in radio and that of extra-galactic BNS mergers measured through gravitational waves. First, more massive binary mergers are detectable at further distances with gravitational waves. Assuming a uniform-in-comoving-volume source distribution, the observed chirp mass distribution differs from the true distribution by the scaling of $M^{5/2}$. Second, more massive BNS live shorter lives and thus are less likely to be discovered in radio pulsar surveys. However, the binary lifetime scales more strongly with its initial orbital period and eccentricity. If the binary mass does not correlate with initial orbital period or eccentricity, the mass distribution of BNS observed in radio is a good representation of the birth distribution. Third, the binary total masses ($M$) of Galactic BNS are known from measurements of the advance of periastron, which is proportional to $M^{2/3}$. This leads to a slight preference within the observed Galactic BNS sample towards higher total masses as well as shorter orbital periods, which make periastron advance and orbital decay rates easier to measure. Taken altogether, the fact that GW190425 is significantly more massive than all 17 Galactic BNS may suggest an invisible Milky Way BNS population that is formed in ultra-tight and possibly highly eccentric orbits, as produced in the unstable case BB mass transfer scenario.

APPENDIX B: RECOVERED POSTERIOR PROBABILITY DISTRIBUTIONS FOR GW190425

We present the posterior probability distributions obtained for a selection of intrinsic and extrinsic parameters for GW190425 in Fig. B.

---

1 This argument is robust against the mild correlation between the mass of second-born neutron star and orbital eccentricity for Galactic BNS (see, e.g., Fig. 17 of Tauris et al. 2017).
Figure B1. Recovered posterior probability distributions for GW190425. Intrinsic parameters chirp mass $M$, mass ratio $q$, effective aligned spin $\chi_{\text{eff}}$, and log eccentricity $\log_{10}(e)$ are plotted on the left. Extrinsic parameters luminosity distance $d_L$, binary inclination angle $\theta_{\text{in}}$, polarisation angle $\psi$, and orbital phase $\phi$ are plotted on the right. We plot the proposal posteriors in turquoise and the reweighted posteriors in gray.