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Mass Ratios of Merging Double Neutron Stars as Implied by the Milky Way Population

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Abstract

Of the seven known double neutron stars (DNSs) with precisely measure masses in the Milky Way that will merge within a Hubble time, all but one has a mass ratio, q, close to unity. Recently, precise measurements of three post-Keplerian parameters in the DNS J1913+1102 constrain this system to have a significantly non-unity mass ratio of 0.78 ± 0.03. One may be tempted to conclude that approximately one out of seven (14%) DNS mergers detected by gravitational-wave observatories will have mass ratios significantly different from unity. However J1913+1102 has a relatively long lifetime (pulsar characteristic age plus the system's merger time due to gravitational-wave radiation) of $\approx$3 Gyr. We show that when system lifetimes and observational biases are taken into account, the population of Galactic DNSs implies that $\simeq$98% of all merging DNSs will have $q > 0.9$. We then apply two separate fitting formulas informed by 3D hydrodynamic simulations of DNS mergers to our results on Galactic DNS masses, finding that either $\simeq 0.004\,M_{\odot}$ or $\simeq 0.009\,M_{\odot}$ of material will be ejected at merger, depending on which formula is used. These ejecta masses have implications for both the peak bolometric luminosities of electromagnetic counterparts (which we find to be $\sim 10^{41}$ erg s^{-1}) as well as the r-process enrichment of the Milky Way.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Binary pulsars (153); Gravitational wave sources (677); Compact objects (288)

1. Introduction

The characteristics of those merging double neutron stars (DNSs) that are detected by the LIGO/Virgo gravitational-wave observatories (Abbott et al. 2017a, 2020) are the result of a combination of nonlinear processes such as mass transfer and core collapse (for a review, see Tauris et al. 2017). The masses of DNSs are particularly sensitive to these physical processes. As such they have been the subject of many studies since Hulse & Taylor (1975) discovered the first system, and it was realized that post-Keplerian parameters (e.g., Shapiro delay; Shapiro 1964) could be used to measure the component masses (for a review, see Özel & Freire 2016). One can use binary population synthesis to simulate the masses and mass ratios, q, of the subset of DNSs that will merge due to gravitational-wave emission (e.g., Osłowski et al. 2011; Dominik et al. 2012; Chruslinska et al. 2018; Vigna-Gómez et al. 2018; Kruckow 2020). However, much of the physics involved in DNS formation, in particular the masses, still lack complete, satisfactory descriptions.

Alternatively, one can extrapolate the sample of known DNSs in the Milky Way as an indication of the mass ratios of merging DNSs in the local universe. Initial models used maximum-likelihood or Bayesian methods to fit the NS mass distribution with Gaussian distributions (Thorsett & Chakrabarty 1999; Valentim et al. 2011; Özel et al. 2012; Kiziltan et al. 2013). In the past five years, several studies have built upon these earlier works, adding sophistication and leveraging a progressively expanding observational data set (Antoniadis et al. 2016; Alsing et al. 2018; Huang et al. 2018; Farrow et al. 2019; Keitel 2019; Zhang et al. 2019; Farr & Chatziioannou 2020; Zhu & Ashton 2020).

Most of these studies (Zhu & Ashton 2020 is the only exception) use the entire available population of DNSs with mass measurements to place their constraints. However, if one wants to extrapolate to the sample of merging DNSs, this approach is problematic for two reasons. First, as previously argued by Andrews & Mandel (2019), the population of Galactic DNSs in the field likely evolved from at least three separate formation scenarios, one of which will not merge within a Hubble time. Since they form through different evolutionary pathways, these subpopulations are likely to have different underlying mass distributions. If one is interested in deriving mass constraints for LIGO/Virgo sources, the systems that do not merge in a Hubble time ought to be excluded from any analysis.

Second, not all systems ought to be weighted equally. Of the seven Galactic DNSs with well-measured masses that will merge in a Hubble time, only one system, J1913+1102 (hereafter J1913; Lazarus et al. 2016; Ferdman & PALFA Collaboration 2018) has $q < 0.9$. Recently, Ferdman et al. (2020) precisely measured the masses of the NSs in J1913 to be 1.62 ± 0.03 and $1.27 \pm 0.03\,M_{\odot}$, leading to $q = 0.78 \pm 0.03$. These authors argue the existence of J1913 implies that $\simeq$11% of merging DNSs ought to have $q < 0.9$. As we show below, this argument is flawed as it fails to take into account the differing lifetimes of each Galactic DNS. Throughout this work, we consider a system's lifetime to be the sum of the pulsar's characteristic age and the system's merger time due to gravitational-wave radiation.

This Letter is outlined as follows. In Section 2, we describe our straightforward method, which is nonparametric, accounts for observational biases and merger times, and produces robust estimates under the assumption that the population of Galactic DNSs are representative of the population of DNSs in the local universe. We then apply fitting formulas to these masses to calculate the distribution of ejecta masses at merger and associated electromagnetic counterpart luminosities in Section 3. Finally, we discuss our results and conclude in Section 4.

Table 1
The List of Galactic DNSs with Well-measured Masses that Will Merge in a Hubble Time

System	M_1 ($M_\odot$)	M_2 ($M_\odot$)	$N_{\rm pop}$	$\mathcal{R}$ (Myr^{-1})	$\tau_{\rm life}$ (a) (Myr)
J0737−3039 (b)	1.338	1.249	1380^{+1330}_{-800}	$4.8^{+4.6}_{-2.8}$	290
B1534+12 (c)	1.346	1.333	1690^{+1630}_{-980}	$0.6^{+0.5}_{-0.3}$	2980
J1756−2251 (d)	1.341	1.230	1270^{+1210}_{-740}	$0.6^{+0.6}_{-0.4}$	2100
J1906+0746 (e)	1.322	1.291	690^{+660}_{-400}	$2.2^{+2.1}_{-1.3}$	310
J1913+1102 (f)	1.62	1.27	1580^{+1540}_{-910}	$0.5^{+0.5}_{-0.3}$	3160
J1757−1854 (g)	1.395	1.338	1630^{+1600}_{-940}	$7.8^{+7.6}_{-4.5}$	210
B1913+16 (h)	1.440	1.389	2670^{+2600}_{-1540}	$6.5^{+6.3}_{-3.8}$	410

Note. We provide the component masses, M_1 and M_2, where M_1 is always the more massive of the two. We ignore measurement uncertainties, as these are typically $\lesssim 0.01\ M_\odot$.
References. (a) Tauris et al. (2017); (b) Kramer et al. (2005); (c) Fonseca et al. (2014); (d) Ferdman et al. (2014); (e) van Leeuwen et al. (2015); (f) Ferdman et al. (2020); (g) Cameron et al. (2018); (h) Weisberg et al. (2010).

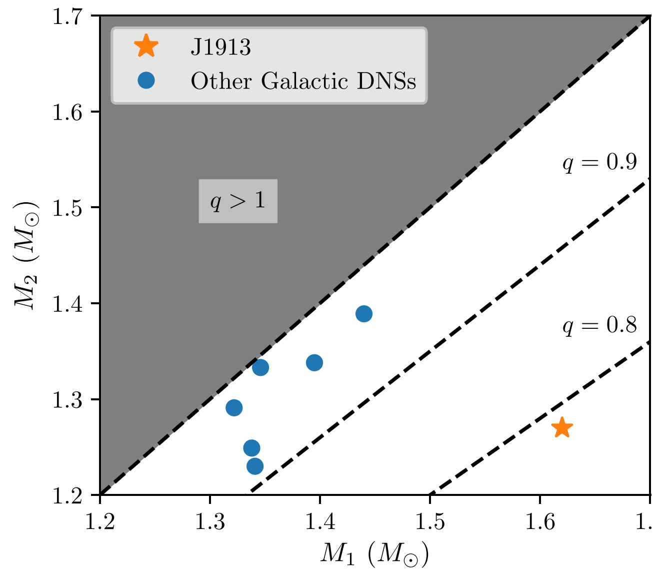

Figure 1. The mass distribution of DNS components for Galactic systems that will merge in a Hubble time. The mass of the more massive NS in the system is designated as M_1. J1913 is the only system of the seven with $q < 0.9$.

2. Method

Of the 20 or so known Galactic DNSs, we focus on the seven systems in the field with precisely measured masses that will merge within a Hubble time.[1] Listed in Table 1, these include the six merging systems in Tauris et al. (2017) as well as J1757−1854 (Cameron et al. 2018). The recently detected DNSs J1946+2052 (Stovall et al. 2018) and J0509+3801 (Lynch et al. 2018) still lack sufficiently precise mass measurements. In Figure 1, we compare the NS masses in these systems; the difference between J1913 and its Galactic counterparts is glaringly apparent. However, to extrapolate from the q distribution of the Galactic DNSs to the q distribution of merging systems, two effects need to be accounted for: the observability through radio-pulsar surveys and the lifetime of each system.

The observability of a DNS is affected by several factors, including the pulsar's luminosity, beaming factor, position in the Milky Way, Doppler smearing due to orbital motion, and the selection function of pulsar surveys. Depending on its observability, a single detected system may comprise the only one of its kind in the Milky Way, or it may represent the tip of an iceberg, implying a much larger, underlying population waiting to be identified with future, deeper pulsar surveys. Using the method pioneered by Kim et al. (2003), one can quantify these effects for each system related to large-scale radio-pulsar surveys and calculate $N_{\rm pop}$, the number of DNSs in the Milky Way implied by each observed system. We refer to these as "like" systems.

As discussed in detail by Kim et al. (2003), the differing systems' lifetimes also affect our understanding of the underlying population in a similar way. To see this effect explicitly, consider two separate DNSs, one with a merger time of 10 Myr and one with 100 Myr. The system with a lifetime of 10 Myr ought to be weighted 10 times its counterpart, since its detection implies that nine others have formed and merged during the lifetime of the longer-lived system. Note this bias only needs to be included when converting from $N_{\rm pop}$ into $\mathcal{R}$, the contribution to the overall Galactic DNS merger rate for each system. This bias is accounted for by weighting each system by the inverse of its lifetime, $\tau_{\rm life}$, listed in the last column of Table 1.

We use the code provided by Pol et al. (2019a, 2019b),[2] which incorporates the latest descriptions of the pulsar surveys, to calculate $N_{\rm pop}$ and $\mathcal{R}$ for each system. Table 1 provides the median and 1σ confidence intervals for both of these parameters. Typical values of $N_{\rm pop}$ are 10^3 while $\mathcal{R} \sim 1\,{\rm Myr}^{-1}$.

We obtain numerical estimates of the relative rates of J1913-like systems in the Milky Way at any one time, $f_{\rm J1913,Milky\ Way}$, accounting for uncertainties using a Monte Carlo method:

$$f_{\rm J1913,Milky\ Way} = \frac{\sum_{j=1}^{N} N_{{\rm pop,J1913},j}}{\sum_{i\in{\rm sys}} \sum_{j=1}^{N} N_{{\rm pop},i,j}} = 15\%. \tag{1}$$

The summations over j are to propagate the errors on $N_{\rm pop}$ using Monte Carlo sampling. So for each of the i systems, we draw $N = 100$ values of $N_{{\rm pop},i,j}$ from the likelihood distribution we calculated using the code from Pol et al. (2019a). The summation in the denominator is a normalization factor to account for each of the i systems in our sample. Our resulting prevalence of J1913-like systems in the Milky Way is 15%, consistent with the rate of $11^{+21}_{-9}\%$ derived by Ferdman et al. (2020). However, if we want to derive the relative contribution of J1913-like systems to the merger rate of Galactic DNSs, we need to instead weigh each system by $\mathcal{R}$:

$$f_{\rm J1913,merging\ DNS} = \frac{\sum_{j=1}^{N} \mathcal{R}_{{\rm J1913},j}}{\sum_{i\in{\rm sys}} \sum_{j=1}^{N} \mathcal{R}_{i,j}} = 2\%, \tag{2}$$

where $\mathcal{R}_{i,j}$ are samples randomly drawn from the likelihood distribution over each of the i systems. We find that since J1913 contributes so little to the overall merger rate, only $\simeq 2\%$

[1] Throughout this work we ignore systems associated with globular clusters, as these suffer from substantially different selection effects and are generally thought to comprise a minority of the overall population of Galactic DNSs (Ye et al. 2020).

[2] https://github.com/devanshkv/PsrPopPy2 (Bates et al. 2014; D. Agarwal et al. 2020, in preparation); https://github.com/NihanPol/2018-DNS-merger-rate.

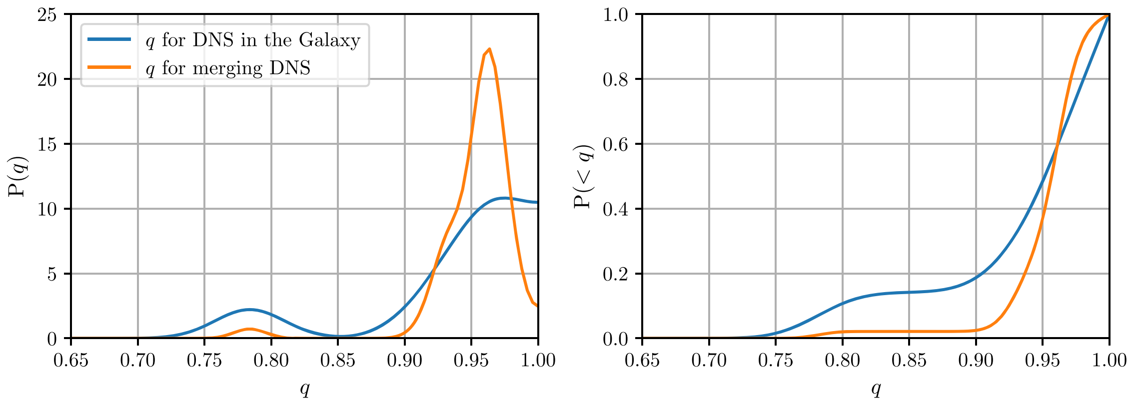

Figure 2. A KDE representation of the mass ratio of merging DNSs in the Milky Way with measured masses. The left panel shows the probability distribution for both the population expected to reside in the Milky Way at any one time (blue) as well as those DNSs that merge (orange). The right panel shows the corresponding cumulative distributions. If the population of Milky Way DNSs are representative of the sources that LIGO/Virgo detects, then ≃98% of systems have $q > 0.9$.

of merging DNSs in the Milky Way are expected to have such low q.

We represent the q distribution of merging DNSs using a kernel density estimate (KDE)[3] in Figure 2, where individual points are weighted by either $N_{\rm pop}$ (blue) or by $\mathcal{R}$ (orange). The left panel shows the probability density function, while the right panel shows the cumulative distribution. When the distribution is weighed by $N_{\rm pop}$, which represents the distribution of DNSs that exist at any one time in the Milky Way, a nontrivial fraction of systems have $q < 0.9$. However, when weighted by $\mathcal{R}$ so as to represent the distribution of merging DNSs, we find that 98% of all merging DNSs have $q > 0.9$, in agreement with Equation (2). While the exact details of the distribution are dependent upon specifics of how the KDE representation is computed, using any set of reasonable values our main conclusion that nearly all merging DNSs have $q > 0.9$ is robust.

We reemphasize that an extrapolation to the sample of LIGO/Virgo sources relies on the assumption that the Galactic systems are representative of the DNS population in the local universe. While the method of Kim et al. (2003) attempts to account for observational biases, imperfections may persist. Furthermore, our conclusions are based on the mere seven known merging systems with measured masses. Because of the weighting scheme, the detection by pulsar surveys of even one new system with a sufficiently short merger time (and therefore large $\mathcal{R}$) can significantly alter the derived q distribution. Clearly, the radio detection of new DNSs in the Milky Way with properties substantially different from those already known will further refine the q distribution of merging DNSs.

3. Ejecta Masses and Luminosities

We can further use the population of Galactic DNSs to derive expectations for the ejecta masses of DNS mergers. We first use `kalepy` to produce a KDE representation[4] of the 2D $q - M_{\rm tot}$ distribution (previously we fit the 1D distribution of q). We show the resulting distribution, transformed into $M_1 - M_2$ space and weighted by $\mathcal{R}$, as 1σ, 2σ, and 3σ contours in the top panel of Figure 3. The outlier, J1913, only contributes at the 3σ level.

Using `kalepy` we obtain random variates of M_1 and M_2 drawn from this KDE representation. For each NS, we further calculate its baryonic mass M^* using the formula $M_x^* = M_x + 0.075 M_x^2$ (Lattimer & Yahil 1989), and its compactness $C_x = \mathcal{G} M_x / c^2 R_x$. For simplicity, we assume all NSs have a radius, R_x, of 11 km. Using these parameters, we calculate the ejecta masses expected from a DNS merger employing the fitting formula from Dietrich & Ujevic (2017):

$$\frac{M_{\rm ej}}{10^{-3} M_\odot} = \left[\alpha \left(\frac{M_a}{M_b}\right)^{1/3} \left(\frac{1 - 2C_a}{C_a}\right) + \beta \left(\frac{M_b}{M_a}\right)^n + \gamma \left(1 - \frac{M_a}{M_a^*}\right)\right] M_a^* + (a \leftrightarrow b) + \delta. \quad (3)$$

By running a broad array of 3D hydrodynamic simulations of DNS mergers, where the NS masses are varied, and then fitting the coefficients, Dietrich & Ujevic (2017) find values for the parameters of: $\alpha = -1.94315$, $\beta = 14.9847$, $\gamma = -82.0025$, $\delta = 4.75062$, and $n = -0.87914$. Radice et al. (2018) generate a similar suite of simulations, finding values of $\alpha = -0.657$, $\beta = 4.254$, $\gamma = -32.61$, $\delta = 5.205$, and $n = -0.773$.

The middle panel of Figure 3 shows the resulting distribution of ejecta masses. The near-unity mass ratios imply relatively low ejecta masses of ≃0.009 and ≃0.004 $M_\odot$ for the fits from Dietrich & Ujevic (2017) and Radice et al. (2018), respectively. Both distributions show a slight secondary peak with somewhat higher ejecta masses designating the contribution from J1913. Due to its relatively small $\mathcal{R}$ value, J1913's contribution to the ejecta mass distribution is at the 2% level.

Radioactive heating of this ejecta causes an electromagnetic transient (Li & Paczyński 1998) that can be observed with targeted follow-up of a gravitational-wave event (Abbott et al. 2017b). The "Arnett rule" (Arnett 1982) provides an estimate of the dependence between ejecta mass and the corresponding bolometric luminosity (Metzger et al. 2010; Metzger & Fernández 2014; Tanaka 2016):

$$L_{\rm peak} \simeq 1.4 \times 10^{41}\ {\rm erg\ s^{-1}} \left(\frac{f}{3 \times 10^{-6}}\right) \left(\frac{v_r}{0.1c}\right)^{1/2} \times \left(\frac{M_{\rm ej}}{0.01\ M_\odot}\right)^{1/2} \left(\frac{\kappa}{10\ {\rm cm\ g^{-1}}}\right)^{-1/2}, \quad (4)$$

[3] To compute our KDEs, we use `kalepy`; https://github.com/lzkelley/kalepy. We use a Gaussian kernel, with a bandwidth of 0.4 and a reflecting boundary at $q = 1$.

[4] We again use a Gaussian kernel with a bandwidth of 0.4 and a reflecting boundary at $q = 1$.

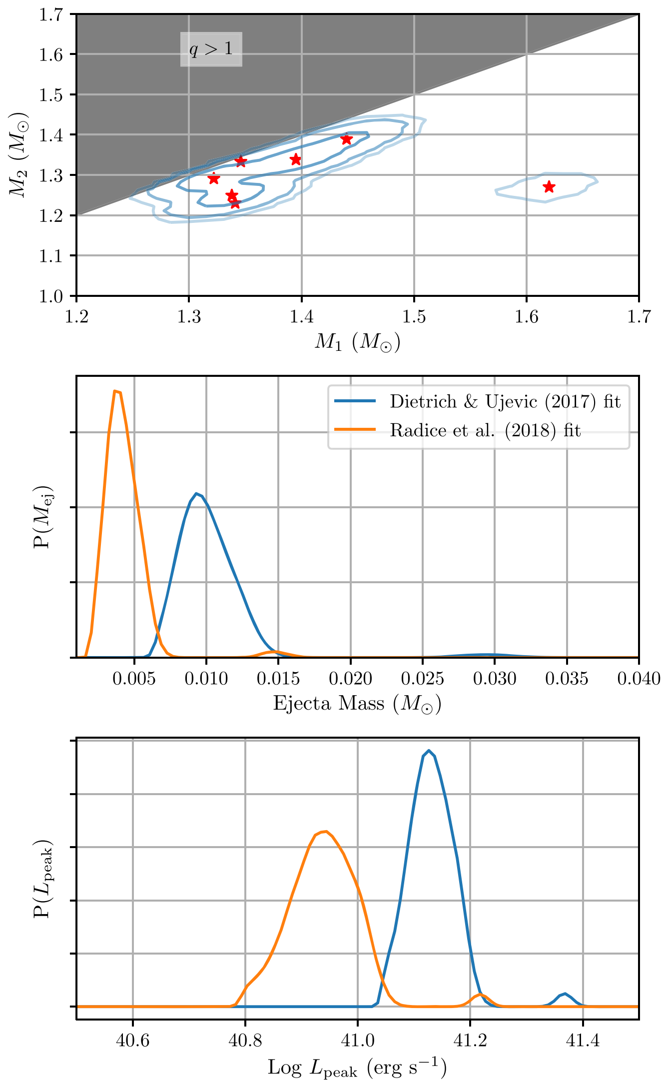

Figure 3. The top panel shows the 1σ, 2σ, and 3σ contours of the component masses of DNS mergers, taken from the KDE representation of the Galactic DNS population (red stars) weighted by their relative merger rates. In the middle panel, we calculate the distribution of ejecta masses from DNS mergers, derived from a fitting formula, from both Dietrich & Ujevic (2017) and Radice et al. (2018), applied to our KDE representations of merging DNS masses. Both fitting formulas show ejecta masses dominated by a single peak, with J1913 contributing a nearly insignificant higher-mass second peak. From the ejecta masses, we use the "Arnett rule" to estimate the peak luminosity of an associated electromagnetic counterpart. Depending on the parameters chosen, we find peak luminosities of $\sim 10^{41}$ erg s^{-1}.

where f quantifies the fraction of radioactive energy deposited in the material, v_r is the expansion velocity, and κ is the opacity. The bottom panel of Figure 3 shows the distribution of electromagnetic luminosities, calculated using Equation (4) and the distribution of ejecta masses displayed in the middle panel of Figure 3. Due to the weak dependence on ejecta mass, the model in Equation (4) for L_{peak} produces a distribution narrowly focused around 10^{41} erg s^{-1}. However, one ought to take these results as only an order-of-magnitude estimate, since these luminosities are produced from a simplified description assuming spherical symmetry. For instance, they do not account for variations in v_c and κ as a function of viewing angle.

4. Discussion and Conclusions

Recently, Ferdman et al. (2020) measured a mass ratio of 0.78 for the DNS J1913+1102. Since this is one of eight merging DNSs in the Milky Way, these authors argue that their observation implies that $\simeq$11% of DNS mergers will have mass ratios significantly different from unity. Given its low mass ratio, Ferdman et al. (2020) suggest that J1913 could be a Milky Way analog to the DNS merger forming GW170817, as its electromagnetic counterpart implies significant mass loss (Cowperthwaite et al. 2017; Kasen et al. 2017), and therefore potentially a non-unity mass ratio. Interestingly, Ramirez-Ruiz et al. (2019) also suggested that J1913+1102 was a Galactic analog to the progenitor of GW170817, albeit for entirely different reasons, based on the X-ray afterglow time delay.

However, the prevalence of low mass ratio systems calculated by Ferdman et al. (2020) does not take into account the different lifetimes of each system. Our analysis suggests that once you properly include this effect, nearly all ($\simeq$98%) of the merging DNSs in the Milky Way have mass ratios larger than 0.9. We additionally apply fitting formula to our KDE representation of NS masses to determine the distribution of ejecta masses during the DNS merger. We find that typical masses ejected are $\simeq 0.004\,M_\odot$ and $0.009\,M_\odot$ using the fitting formulas from Radice et al. (2018) and Dietrich & Ujevic (2017), respectively.

We use the "Arnett rule" to estimate peak luminosities of the electromagnetic counterparts to our derived population of merging DNSs (Metzger & Fernández 2014). As an order-of-magnitude estimate, we find peak luminosities $\sim 10^{41}$ erg s^{-1}. Alternatively, one could use these ejecta masses to compute a series of lightcurves corresponding to the sample of DNS merger events detected by LIGO/Virgo (Barnes & Kasen 2013). When combined with the sensitivities and field of view of a particular telescope, these synthetic lightcurves could be used to optimize a search strategy for a putative electromagnetic counterpart.

At the same time, the ejecta masses we calculate have implications for the r-process enrichment of the Milky Way (Rosswog et al. 1999; Hotokezaka et al. 2018). For instance, Macias & Ramirez-Ruiz (2018) find that, whatever the origin of r-process material is, it must produce $\gtrsim 10^{-3}\,M_\odot$ per event to explain the r-process abundances of halo stars in the Milky Way. This lower limit would fit with our distribution of ejecta masses shown in the middle panel of Figure 2. However, there is disagreement in the literature, as some authors (e.g., Siegel 2019) have argued that collapsar models may have less difficulty explaining the details of r-process observations.

Our analysis differs from recent previous studies that focus on the masses of NSs in DNS systems (e.g., Farrow et al. 2019) in three important ways. First, whereas previous studies fit all DNSs with mass measurements, we focus only on those DNSs in the field that merge within a Hubble time. This choice is motivated by our interest in the progenitors to gravitational-wave merger events. Second, we weigh each system by its individual merger rate (calculated using the method of Kim et al. 2003), such that systems with short lifetimes are more heavily weighted; for every system we observe, there are many more that have been formed and already merged. This quantitative analysis also takes into account observational biases associated with the detection of pulsar binaries. Third, rather than confining ourselves to a parametric model, which will suffer if the model chosen proves to be an inaccurate representation of the underlying distribution (e.g., trying to fit a non-Gaussian distribution with a Gaussian model), we use a nonparametric method to describe the mass distribution of merging DNSs in the Milky Way.[5] As a result of these three differences, our model produces more stringent limits. For example, using Gaussian models separately fit to the recycled pulsar and its companion Farrow et al. (2019) find that 73.6% of all DNSs have $q > 0.9$ under their best-fit hypothesis (compared with our finding that $\simeq$98% have $q > 0.9$).

Can these results be extrapolated to the local universe to infer the properties of LIGO/Virgo detections? There are reasons to think not. Pankow (2018) suggests that GW170817, the first DNS merger detected by LIGO/Virgo, has a mass ratio too low to be represented by the Galactic DNS population. Furthermore, the second LIGO/Virgo detection of a DNS merger (GW190425; Abbott et al. 2020) has a total mass significantly larger than any known system in the Milky Way. Yet, a resolution may be possible; the strong weighting by system lifetime implies that the detection of a single DNS with a short merger time can significantly alter the census of merging DNSs in the Milky Way. If future observations, both by radio telescopes and gravitational-wave observatories cannot resolve this discrepancy, we may be forced to admit the possibility that the Milky Way DNS population forms a poor representation of the local universe.

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Software: `kalepy`, `PsrPopPy2` (Bates et al. 2014; D. Agarwal et al. 2020, in preparation), `2018-DNS-merger-rate` (Pol et al. 2019a).

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[5] Of course, our KDE approach has its own limitations, as it introduces hyperparameters associated with the shape and bandwidth of the kernel used. Nevertheless, our main conclusions are robust for any reasonable set of hyperparameters.