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ABSTRACT
We estimate the properties of the double neutron star (DNS) population that will be observable by the planned space-based interferometer Laser Interferometer Space Antenna (LISA). By following the gravitational radiation-driven evolution of DNSs generated from rapid population synthesis of massive binary stars, we estimate that around 35 DNSs will accumulate a signal-to-noise ratio above 8 over a 4-yr LISA mission. The observed population mainly comprises Galactic DNSs (94 per cent), but detections in the LMC (5 per cent) and SMC (1 per cent) may also be expected. The median orbital frequency of detected DNSs is expected to be 0.8 mHz, and many of them will be eccentric (median eccentricity of 0.11). LISA is expected to localize these DNSs to a typical angular resolution of 2°. We expect the best-constrained DNSs to have eccentricities known to a few parts in a thousand, chirp masses measured to better than 1 per cent fractional uncertainty, and sky localization at the level of a few arcminutes. The orbital properties will provide insights into DNS progenitors and formation channels. The localizations may allow neutron star natal kick magnitudes to be constrained through the Galactic distribution of DNSs, and make it possible to follow up the sources with radio pulsar searches. LISA is also expected to resolve ~10^4 Galactic double white dwarfs, many of which may have binary parameters that resemble DNSs; we discuss how the combined measurement of binary eccentricity, chirp mass, and sky location may aid the identification of a DNS.

Key words: gravitational waves – binaries: close.

1 INTRODUCTION
The LIGO Scientific Collaboration made the first direct detection of gravitational waves (GWs) in 2015 from the binary black hole merger GW150914 (Abbott et al. 2016). Since then, 11 GW events were recorded in the Gravitational-Wave Transient Catalog (GWTC-1; Abbott et al. 2019). The start of the Advanced LIGO and Advanced Virgo third observing run (O3) on 2019 April 1, with improved detector sensitivity has given almost weekly public alerts to credible GW candidates on the Gravitational Wave Candidate Event Database (GraceDB). The exploration of double compact object (DCO) population statistics will be integral to constraining the relative importance of different formation channels and reducing the large uncertainties that characterize key stages of isolated binary evolution.

Double neutron star (DNS) coalescences are of particular interest, as they may produce electromagnetic counterparts, including gamma-ray bursts, their afterglows, and kilonovae. GW170817, detected during the second observing run (O2) of Advanced LIGO and Virgo (Abbott et al. 2017a), was associated with EM counterparts GRB 170817A and AT 2017gfo (Abbott et al. 2017c, b), marking the first multimessenger event involving GWs.

Neutron stars can receive supernova (SN) natal kicks of several hundred km s^{-1} and lose significant fractions of mass during SNe, and so DNSs forming from isolated binaries may possess significant eccentricities at birth. However, by the time these DNSs evolve to the 10–1000 Hz sensitivity window of the LIGO-Virgo advanced detectors, gravitational radiation reaction circularizes the orbit of isolated binaries to eccentricities e \lesssim 10^{-5} regardless of their formation eccentricity if they are formed at orbital frequencies \lesssim 10^{-2} Hz. On the other hand, ESA’s proposed space-based Laser Interferometer Space Antenna (LISA) (Amaro-Seoane et al. 2017) is anticipated to observe inspiral GWs in the 10^{-2}–10^{-3} Hz window,

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and so may detect residual eccentricity in inspiralling DNSs. Eccentricity measurements by LISA may provide constraints on the physics of isolated binary evolution (Nelemans, Yungelson & Portegies Zwart 2001b; Belczynski, Benacquista & Bulik 2010; Tauris 2018; Vigna-Gómez et al. 2018; Kyutoku, Nishino & Seto 2019) or dynamical formation (Kremer et al. 2018; Andrews & Mandel 2019; Hamers & Thompson 2019).

The detection of GW170817 and the selection of LISA as ESA’s third L-class mission in 2017 January has led to recent interest in LISA DNS sources. Seto (2019) estimated the frequency distribution of DNSs in Local Group galaxies by extrapolating the comoving volumetric DNS merger rate inferred from GW170817. Kyutoku et al. (2019) demonstrated that LISA-informed observations can enhance the efficiency of radio pulsar searches with the Square Kilometre Array (SKA). Thrane, Oslowski & Lasky (2019) showed that constraints may be placed on the neutron star equation of state by measuring the Lense–Thirring precession with multimessenger observations with LISA and SKA.

In this paper, we predict the detection rate, distribution of source parameters (eccentricity, signal-to-noise ratio, distance), and uncertainty in source parameters (eccentricity uncertainty, sky-localization accuracy, chirp mass uncertainty) of DNSs in the Milky Way (MW) and in nearby galaxies. We generate a population of synthetic DNSs using the Compact Object Mergers: Population Astrophysics and Statistics (COMPAS) suite (Stevenson et al. 2017; Barrett et al. 2018; Vigna-Gómez et al. 2018; Neijssel et al. 2019), and follow the evolution of these DNSs through the LISA band driven by gravitational radiation reaction, for which we use the leading quadrupole order expressions (Peters 1964). Starting from an initial population of zero-age main sequence (ZAMS) binary stars, COMPAS performs single-star evolution using the fitting formulae in Hurley, Pols & Tout (2000) and calculates changes in stellar and orbital properties due to wind-driven mass-loss, mass transfer, common-envelope events, and SNe, until the formation of a DCO.

This paper is structured as follows. Section 2 describes how the DNS detection rate is calculated; it begins by highlighting important features of COMPAS’s Fiducial model of binary evolution (Section 2.1), then discusses the general procedure for estimating the LISA DNS detection rate (Section 2.2), the DNS formation rate within the detector’s sensitive volume (Section 2.3), and the detector sensitivity (Section 2.4). Section 3 presents our predictions for the distribution of LISA DNS binary parameters and their uncertainties. In particular, we discuss how the eccentricity distribution may constrain binary evolution physics. Section 4 discusses strategies for distinguishing LISA DNSs from resolved Galactic double white dwarfs (DWDs) and neutron star–white dwarf (NS–WD) binaries. We summarize our results and discuss the validity of our assumptions in Section 5.

2 METHODS

2.1 Population synthesis

This work uses a synthetic population of DNSs evolved by Vigna-Gómez et al. (2018) using the rapid population synthesis element of COMPAS. A total of $10^6$ binary stars were evolved, with 0.13 per cent becoming DNSs, of which 73 per cent merge within the age of the Universe. We highlight distinctive features of the assumed Fiducial model of binary evolution, and refer the reader to Stevenson et al. (2017) and Vigna-Gómez et al. (2018) for details.

The mass of the primary star is drawn from the Kroupa initial mass function (Kroupa 2001) in the mass range $[5, 100] \text{M}_\odot$ (the full mass range was used for normalization), while the mass ratio $q = m_2/m_1$ is drawn from a uniform distribution in $[0.1, 1]$ (Sana et al. 2012). All binaries are assumed to be circular at ZAMS with solar metallicity. The binary separation is drawn from a log-uniform distribution in $[0.1, 1000]$ au, following Opik (1924).

A common-envelope phase follows dynamically unstable mass transfer, and is described by the $\alpha\lambda$-formalism (Webbink 1984; de Kool 1990) with $\alpha = 1$ and $\lambda$ determined by the fits of Xu & Li (2010).

The Fiducial model distinguishes between core-collapse, ultra-striped, and electron-capture SNe. The natal kick direction is randomly drawn from the unit sphere, while the kick magnitude follows a bimodal distribution. The core-collapse SN kick magnitude is distributed by a Maxwellian with $\sigma_{\text{high}} = 265 \text{ km s}^{-1}$, following Hobbs et al. (2005). Ultra-striped and electron-capture SN kicks follow a low-kick Maxwellian with $\sigma_{\text{low}} = 30 \text{ km s}^{-1}$ (Pfahl, Rappaport & Podsialowski 2002; Podsialowski et al. 2004; Verbunt, Igoshov & Cator 2017). The ‘rapid’ explosion model in Fryer et al. (2012) is used to calculate the compact remnant mass from the pre-SN core mass.

A discussion of the Fiducial model’s two dominant DNS formation channels (accounting for 91 per cent of all DNSs formed) can be found in Vigna-Gómez et al. (2018).

To illustrate the sensitivity of our results to uncertainties in binary evolution prescriptions, we compare results obtained with the Fiducial model assumptions to the following three variants:

(i) Case BB unstable: Case BB mass transfer from a post-helium-main-sequence star (see Section 3.2.1) is assumed to always be dynamically unstable, whereas it is always stable in the Fiducial model.

(ii) Single SN mode: The distribution of natal kick magnitude is a Maxwellian with $\sigma_{\text{high}} = 265 \text{ km s}^{-1}$ for all types of SNe, as opposed to the bimodal distribution in the Fiducial model.

(iii) $\alpha = 0.1$: The common-envelope efficiency parameter (see Section 3.2.3) is set to $\alpha = 0.1$.

We use the DNS populations simulated with these variation models by Vigna-Gómez et al. (2018).

2.2 Detection rate

In Monte Carlo population synthesis, each DNS synthesized by COMPAS represents a sample population labelled by a set of binary parameters $\theta_i = (e_{i0}, a_{i0}, m_{1i}, m_{2i})$ for $i = 1, 2, ..., N_{\text{DNS}}$, where $e_{i0}$ and $a_{i0}$ are the eccentricity and semimajor axis at the formation of the $i$th DNS, $m_{1i}$ and $m_{2i}$ are the component masses, and $N_{\text{DNS}}$ is the total number of simulated DNSs. For each DNS $\theta_i$, we denote by $f$ its starting orbital frequency, the orbital frequency of the DNS at the start of its observation by LISA. We also denote by $dN(f) = dN(df)/df$ the number of detections this DNS population contributes to the bin $[f, f + df]$ of starting orbital frequencies. The total contribution is therefore

$$N = \sum_{i=1}^{N_{\text{DNS}}} \int_0^{\infty} dN(f) \, df.$$  

1The case BB unstable, single SN mode, and $\alpha = 0.1$ models are the (02), (05), and (10) variations, respectively, in Vigna-Gómez et al. (2018).
where the subscript \( i \) denotes a quantity evaluated for the parameters \( \theta_i \). The integrand can be written in a more explicit form:

\[
N = \sum_{i} \int_{0}^{N_{\text{DNS}}} \frac{dN(t)}{dt} \frac{d\mathcal{N}(f_i)(f)}{df} df.
\]

which involves (i) \( dN(t)/dt \), the formation rate of LISA-detectable DNSs with \( \theta = \theta_i \), and (ii) \( d\mathcal{N}(f_i)/df \), the time taken for these DNSs to increase their orbital frequencies from \( f \) to \( f + df \). The time interval \( df \) is calculated by integrating the orbit-averaged, quadrupole-level expression for \( [(df/dt)^{-1}](e) \) given in Peters (1964):

\[
de = -19 \beta \frac{e^{-20/19}(1 - e^2)^{1/2}}{12 c_0^2 (1 + (121/304)e^2)^{11/181/2299}}
\]

where \( \beta = 2G^3 m_1 m_2 (m_1 + m_2)/c^5 \) and \( c_0 = a_0(1 - e_0^2)^{-1} \). \( e_0 \) are constants that depend only on the initial binary parameters \( \theta_i \). The lower and upper integration limits \( e_{\text{lower}} = e(f) \) and \( e_{\text{upper}} = e(f + df) \) are calculated by inverting the Keplerian expression:

\[
f(e) = \frac{1}{2\pi} \sqrt{\frac{G(m_1 + m_2)}{a(e)^3}}.
\]

The cumulative blue light luminosity \( L_{B}(< d) \) as a function of distance \( d \) is derived from the Gravitational Wave Galaxy Catalogue (GWGC; White, Dar & Dhillon 2011), which contains the extinction-corrected absolute blue magnitude of 53 255 galaxies. In particular, we calculate the MW blue light luminosity from the GWGC to be \( L_{B,\text{MW}} = 1.07 \times 10^{10} L_{B,\odot} \), in units of solar blue light luminosity \( L_{B,\odot} \). For the synthetic DNS population in this study, the MW DNS formation rate is 33 Myr\(^{-1}\) (Vigna-Gómez et al. 2018), assuming continuous star formation at 2.0 M\(_{\odot}\)yr\(^{-1}\) with solar metallicity Z\(_{\odot}\) = 0.0142. In equation (2), the formation rate contributed by the \( i \)th simulated binary is equal to the total formation rate within distance \( d_{\text{max},i} \), \( dN(< d_{\text{max},i})/dt \), re-weighted by the number of simulated DNSs, \( N_{\text{DNS}} \):

\[
dN_i = \frac{\int_{0}^{N_{\text{DNS}}} \frac{dN(t)}{dt} \mathcal{N}(f) df}{\int_{0}^{N_{\text{DNS}}} \mathcal{N}(f) df}.
\]

where \( d_{\text{max},i} \) is the horizon distance of the \( i \)th DNS, the maximum distance the DNS may be located to be detectable by LISA. It is a function of \( \theta_i \) and Section 2.4 explains how it is calculated. This prescription assumes the fraction of massive binary stars that become DNSs in different galaxies is the same as in the MW, neglecting variations in, for example, metallicity, binary fraction, and initial mass function. It also neglects variations in star formation rate over cosmic history. Finally, in the MW, we focus on DNSs produced by isolated binary evolution in the Galactic disc and do not consider dynamical formation in globular clusters. The validity of these assumptions is discussed in Section 5.

We consider two models as limiting cases for the distribution of DNSs within the Galaxy. The first model assumes negligible kicks or dynamical evolution, so that DNSs are distributed in the same way as today’s massive star birth sites. The second assumes the limit of very large kicks, under which the DNSs distribution follows the mass distribution of the dark matter halo.

In the first model, we spatially distribute Galactic DNSs to the plane-projected Galactic disc density profile. We use a disc profile inferred from the disc gravitational potential proposed in Miyamoto & Nagai (1975).

\[
\phi_d(r, z) = -\frac{GM_d}{\sqrt{r^2 + (ad + \sqrt{z^2 + b_d^2})^2}},
\]

where \( M_d \) is the total disc mass, \( a_d \) and \( b_d \) are the radial and vertical scales, and \( (r, z) \) are Galactocentric cylindrical coordinates. The density profile \( \rho_d(r, z) \) is obtained by solving Poisson’s equation \( \nabla^2 \phi_d = 4\pi G \rho_d \) as

\[
\rho_d(r, z) = \frac{b_d^2 M_d}{4\pi} \left[ (ad + \sqrt{z^2 + b_d^2})^{-2} \left( r^2 + (ad + \sqrt{z^2 + b_d^2})^{-2} \right)^{5/2} \right]^{-1}.
\]

Finally, we obtain the plane-projected Galactic disc density profile from the integral \( \int \rho_d(r, z)dz \).
In reality, the DNS distribution will not trace the birth site distribution because of a combination of natal kicks from asymmetric SNe, Blaauw kicks produced by symmetric mass loss accompanying SNe (Blaauw 1961), and subsequent dynamical evolution in the Galaxy’s potential. We therefore also consider the opposite extreme: natal kick magnitudes being large enough to eject DNSs into the dark halo potential. Considering this as a boundary case, we take the extreme limit in which these DNSs are allowed to relax and virialize, and so trace the dark halo mass distribution. For the MW dark halo, we use the density profile in Wilkinson & Evans (1999),

$$\rho_h(R) = \frac{M_h}{4\pi} \frac{a_h^2}{R^2 (R^2 + a_h^2)^{3/2}},$$

(10)

where $M_h$ is the total halo mass, $a_h$ is a characteristic fall-off radius, and $R$ is the Galactocentric distance. We intentionally do not cut-off the halo mass distribution in this model in order to consider it as an extreme limiting case. In equations (9) and (10), we use parameters given in ‘Model II’ of Irrgang et al. (2013), obtained by a $\chi^2$ fit to observational constraints: $M_h = 2829 M_{\odot}$, $a_h = 4.85$ kpc, $b_h = 0.184$ kpc, $M_h = 69, 725 M_{\odot}$, $a_h = 200$ kpc, and the solar displacement $r_0 = 8.35$ kpc from the Galactic Centre, where $M_{\odot} = 2.325 \times 10^7 M_{\odot}$ is the Galactic mass unit. We expect the true distribution of Galactic DNSs to be between the Galactic disc and the dark halo scenarios.

Fig. 1 plots the MW DNS formation rate $dN(<d)/dt$ contained in a spherical detection volume (centred upon the Solar system) as a function of the sphere radius $d$ for our two prescriptions. A third, toy prescription has also been included for comparison, where the MW is modelled as a uniform flat disc of radius 12 kpc. In the toy model, the detection volume contains the entire disc-like ‘MW’ at $d \approx 20$ kpc, beyond which the curve flattens out sharply. The formation rate grows more gently with distance for the Galactic disc potential, where more than 95 per cent of the DNS formation rate is contained in $d < 100$ kpc. In the dark halo prescription, the diffuse halo stretches out to large distances with scale radius $a_h = 2829$ kpc, and only 45 per cent of the DNS formation rate is contained in $d < 100$ kpc.

### 2.4 Signal-to-noise ratio

We use an SNR expression that is averaged over sky location $(\theta, \phi)$, GW polarization $\psi$, and source inclination $i$. Then, the averaged SNR of the $n$th GW harmonic depends only on the total energy per unit frequency carried by GWs emitted in the $n$th harmonic, $dE/d(nf)$ (see e.g. Flanagan & Hughes 1998):

$$\langle \rho_n^2 \rangle = \frac{2G}{\pi c^2 n f^2} \int_{nf}^{n\theta_0} \frac{|dE_d/d(nf)|}{\langle S(nf) \rangle \langle \psi \rangle} d(nf).$$

(11)

Here, $\langle \rho_n^2 \rangle$ is the squared SNR of the $n$th GW harmonic averaged over $(\theta, \phi, i, \psi)$, $d$ is the source distance, and $\langle S(nf) \rangle \langle \psi \rangle$ is the sky-averaged LISA one-sided noise power spectral density. The upper and lower integration limits $n f_1$ and $n f_2$ are the $n$th harmonic GW frequency of the source at the start and end of LISA observation, respectively. In this study, we assume a 4-yr LISA mission duration as put forwards in the LISA ESA L3 mission proposal (Amaro-Seoane et al. 2017).

We approximate the LISA sensitivity curve $S_d(nf)$ with the analytically fitted expression of Robson, Cornish & Liu (2019). This is plotted in Fig. 2, along with a Monte Carlo population of detectable DNSs. Below GW frequencies of 1–3 mHz, the noise spectrum is dominated by confusion noise due to unresolved Galactic binaries, mainly comprising ~10²³ DWDs (Nelemans et al. 2001b; Farmer & Phinney 2003; Ruiter et al. 2010). As the LISA mission progresses, the confusion noise reduces since resolved

5Note that $\langle \rho_n^2 \rangle$ in equation (11) is larger by a factor of 5 compared to the corresponding expression in LIGO literature, because of the convention in LISA to include the signal response function $R$ in the noise spectral density as $1/R_LISA$, rather than in the strain power spectral density as $R_{LISA}$. Converting from the LIGO to the LISA SNR expression requires dividing by a factor of $R_{LIGO} = 1/5$. 

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**Figure 1.** Cumulative fraction of the MW DNS formation within a given distance from the Solar system according to three DNS spatial distribution prescriptions: (i) DNS distributed according to the plane-projected Galactic disc density profile (blue); (ii) DNS distributed according to the MW dark halo density profile (orange); (iii) DNS distributed uniformly on a flat disc with radius 12 kpc (black).

**Figure 2.** Plot of the total LISA noise amplitude spectral density, $\sqrt{\langle S(nf) \rangle}$ (solid line), the amplitude spectral density of the Galactic background confusion noise, $\sqrt{\langle S(nf) \rangle}$ (dashed line) assuming signal subtraction over a 4-yr LISA mission, and $2h(t)\sqrt{\tau_{GW}}$ for 35 Monte Carlo realizations of LISA DNS sources (filled circles) with frequencies drawn from Fig. 3 and distances drawn from Fig. 5. The height of a dot above the solid curve gives the SNR of the DNS. The green circles correspond to LMC sources.
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3 RESULTS

We anticipate that LISA will be able to detect GWs from several tens of local DNS binaries. Evaluating equation (2) yields 35 detectable DNSs assuming Galactic sources distributed according to the plane-projected disc density profile (our default for the rest of the paper) and 8.4 DNSs assuming Galactic sources distributed according to the MW dark matter halo density profile. Fig. 3 shows the cumulative number of DNS detections as a function of the starting orbital frequency $f$.

Although the LISA sensitivity curve is limited by the Galactic confusion noise below GW frequencies of $1–3 \text{ mHz}$, LISA DNSs are detected with a $1 \text{ mHz}$ characteristic orbital frequency (17-min period), or a gravitational-wave frequency of $2f = 2 \text{ mHz}$ for a circular DNS. There are few high-frequency DNSs in the sample due to the shorter time per unit frequency interval at higher frequencies $(df/df \propto f^{-1/2})$. This is shown in Fig. 4, which illustrates how our rate estimate is developed using a circular DNS with $m_1 = m_2 = 1.4M_\odot$. The DNS can be observed at the greatest distance $d = 1160 \text{ kpc}$ (blue curve in the top panel) at 17.5 mHz, yielding the largest DNS formation/merger rate within the sensitive volume at that orbital frequency (orange curve in the top panel – the apparent steps on this curve correspond to additional galaxies coming into view). However, because of the steep decrease in the time spent by binaries at higher frequencies (orange line in the bottom panel), the distribution of expected DNS detections per unit logarithmic frequency peaks at 0.6 mHz (blue curve in the bottom panel).

Fig. 5 shows the distance distribution of the detectable DNSs. We predict 33 (94 per cent) of sources to be Galactic, 1.7 (5 per cent) from the Large Magellanic Cloud (LMC) and 0.3 (1 per cent) from the Small Magellanic Cloud (SMC). The number of detectable DNSs in M31 ($d = 780 \text{ kpc}$) and beyond is negligible ($N < 0.01$), as DNSs spend too little time at orbital frequencies above 10 mHz where they can be observed out to M31 and no significant number of detections in M33. This is broadly consistent with Seto (2019), who finds $\sim 3$ and $\sim 0.5$ detectable DNSs in the LMC and SMC, respectively, using a slightly higher SNR threshold $\rho_{\text{min}} = 10$ but a larger intrinsic DNS merger rate inferred from GW170817. Seto (2019) also expects $\sim 1$ detection in M31 and no significant number of detections in M33.

Below, we discuss how accurately DNS parameters such as sky location, eccentricity, and chirp mass can be measured from LISA observations. In general, parameter estimation improves with the accumulated SNR of a GW source, with the typical uncertainty in individual parameters scaling as $1/\rho$ in a regime where the linear signal approximation is valid (Cutler & Flanagan 1994; Poisson & Will 1995).

Fig. 6 shows the cumulative SNR distribution of LISA DNSs for both the disc and the dark matter halo distribution of Galactic DNSs. For the disc prescription, the median SNR is 16.8, $\sim 15$ DNSs can accumulate $\rho > 20$, 2.5 can accumulate $\rho > 100$, and the highest expected SNR (set by $N(\rho > 1) = 1$) is $\sim 180$. The bottom panel is a log–log plot of dN/d$\rho$ labelled with an approximate slope obtained by a least-squares fit. Because the Galactic disc...
Figure 4. Top: The horizon distance $d_{\text{max}}$ (blue) and the DNS formation rate $dN/dt$ within that distance (orange) as functions of starting orbital frequency $f$, with the horizontal dotted lines marking the distances of four nearby galaxies: the LMC, SMC, M31, and M33. Bottom: The DNS frequency distribution $(dN/dt)(dt/d\log f)$ (blue), which is the DNS formation rate weighted by the time spent by the evolving DNS per frequency bin $dt/d\log f$ (orange), as functions of $f$. This figure assumes a circular DNS with $m_1 = m_2 = 1.4 M_\odot$.

Figure 5. The expected number of LISA DNS detections plotted as a function of the distance $d$ from the Solar system. The vertical dashed lines mark the positions of the Milky Way nucleus, LMC, and SMC, and the bracketed number gives the number of detections expected in each galaxy.

Figure 6. Top: Cumulative SNR distribution of detectable DNSs. Bottom: log–log plot of the SNR distribution labelled with the power-law index obtained by a least-squares fit.

density is centrally concentrated, $dN/d\rho$ falls off more gently than the expected $\rho^{-3}$ scaling for a uniform disc. Likewise, for the MW dark matter halo prescription, $dN/d\rho$ falls off more gently than the expected $\rho^{-4}$ scaling for a uniform sphere. This behaviour also causes the more centrally concentrated Galactic disc prescription to have a lower characteristic DNS frequency in Fig. 3, as closer DNSs produce stronger signals that can be detected at lower frequencies.

3.1 Sky localization

Recent works have discussed the importance of sky localization of LISA DNSs for multimessenger follow-ups of Galactic systems, including radio pulsar observations, to constrain the neutron star equation of state and test general relativity (Kyutoku et al. 2019; Thrane et al. 2019). Accurate sky localisation by LISA can reduce the search time for pulsar surveys such as the SKA Phase 2, which may coincide with LISA’s expected launch in the 2030s. LISA triggers would thus allow a longer signal accumulation time, which leads to higher detection significance and detections of fainter binary pulsars. Kyutoku et al. (2019) show that LISA measurements of orbital frequency and other binary parameters can allow a computationally efficient correction of Doppler smearing associated with tight radio pulsars, where the signal integration time is a significant fraction of the orbital period. Moreover, since our calculations show that a total of $\sim$2 DNSs may be detected in the LMC and SMC, sky localization is also needed for host galaxy identification. Three-dimensional localization is possible if,
since their merger time for a circular binary, orbital frequencies $f$ the source evolves (Fairhurst 2009). However, LISA DNSs with the SNR and the detector frequency bandwidth source observed with a detector network is inversely-proportional to points along its orbit around the Sun. The timing error of a GW accomplished by a single detector observing the source at different time in a detector network. For long-lived GW sources, this may be DNSs kick magnitudes.

For Galactic DNSs, measuring the sky distribution, particularly the normalized cumulative eccentricity distribution for LISA-Fiducial dotted), and a common-envelope efficiency of case BB mass transfer (orange dashed), a single SN kick magnitude (purple of binary evolution, and for variations with: always dynamically unstable $= \alpha 0.1$ (green dash–dotted).

A GW source is triangulated using differences in the signal arrival time in a detector network. For long-lived GW sources, this may be accomplished by a single detector observing the source at different points along its orbit around the Sun. The timing error of a GW source observed with a detector network is inversely-proportional to the SNR and the detector frequency bandwidth $\sigma_{GW}$ through which the source evolves (Fairhurst 2009). However, LISA DNSs with orbital frequencies $f \sim 1 \text{ mHz}$ are approximately monochromatic, since their merger time for a circular binary,

$$\tau_{\text{merge}} = 240 000 \left( \frac{M_1}{1.2 M_\odot} \right)^{-5/3} \left( \frac{f_{\text{GW}}}{0.002 \text{ Hz}} \right)^{-8/3} \text{ yr}, \quad (17)$$

is much longer than the fiducial 4-yr LISA mission duration. Then, following Mandel, Sesana & Vecchio (2018), the timing accuracy instead scales as $1/(\rho f)$, since the GW phase is determined down to $1/\rho$ of the wave cycle. LISA will complete multiple heliocentric orbits as it observes a DNS, and so gives rise to an effective detector baseline of 2 au. The uncertainty $\sigma_\theta$ in the source angular coordinate in one plane is approximately

$$\sigma_\theta \approx 2.9 \left( \frac{\rho}{10} \right)^{-1} \left( \frac{f_{\text{GW}}}{2 \text{ mHz}} \right)^{-1} \left( \frac{L}{2 \text{ au}} \right)^{-1} \text{ deg.} \quad (18)$$

which is just the timing accuracy divided by the light traveltime $L/c$ across the effective detector baseline, and we have used a characteristic SNR of 10. This corresponds to localization within a sky patch of solid angle $\Delta \Omega \sim \sigma_\theta^2 \approx 26.4 \text{ deg}^2$. We use the approximation of equation (18) to plot the distribution of $\sigma_\theta$ (Fig. 7) for our synthetic DNS population, finding that most DNSs can be localized to within $\sigma_\theta \approx 2^\circ$.

An angular resolution of $2^\circ = 0.035 \text{ rad}$ allows the vertical displacement of a Galactic DNS above the Galactic plane at $d = 10 \text{ kpc}$ to be resolved to (0.035 rad)(10 kpc) = 0.35 kpc, roughly the thickness of the old thin stellar disc itself. The size of a pencil beam for a 15 m diameter SKA dish observing at 1.4 GHz is approximately $0.67 \text{ deg}^2$ (Smits et al. 2009; Kyutoku et al. 2019). It then follows from Fig. 7 that $\approx 6$ DNSs, if containing a radio pulsar, can be covered by a single pointing with the SKA.

### 3.2 Eccentricity

Significant orbital eccentricities may be imparted to DNSs by SN kicks (e.g. Tauris et al. 2017) or Blaauw kicks (Blaauw 1961). Short-period DNSs may also be formed through dynamical hardening interactions in globular clusters until the binary is ejected into the field, presents too small of a cross-section for further interactions, or merges through GW emission (Kulkarni, Narayan & Romani 1990; Phinney & Sigurdsson 1991), or in hierarchical triple-star systems (Hamers & Thompson 2019). The typical separation of the ejected DNSs depends on the globular cluster properties, but may fall in the range of a few solar radii, or orbital frequencies of a few times $10^{-3}$ Hz (Andrews & Mandel 2019). These ejected systems sample a thermal eccentricity distribution $p(e) = 2e$ (Heggie 1975), thereby producing high-frequency, eccentric GW sources. However, DCOs typically circularize before reaching the 10–1000 Hz GW sensitivity window of the Advanced LIGO and Virgo detector networks due to gravitational radiation reaction (Peters 1964), though some dynamical channels may yield observable eccentricities in the ground-based detector frequency band (e.g. Samsung, MacLeod & Ramirez-Ruiz 2014). On the other hand, even field DNSs possess measurable residual eccentricities in LISA’s millihertz GW window, giving important insights into DNS formation channels and their progenitor properties.

The blue solid line of Fig. 8 shows the expected eccentricity distribution of the DNS population observed by LISA, assuming the isolated binary evolution channel as predicted by the COMPAS Fiducial model of Vigna-Gómez et al. (2018). We find that this model predicts a significant number of eccentric DNSs in the LISA band with median eccentricity of 0.11 at detection and several highly eccentric systems, e.g. $N(e > 0.6) = 3.6$. To illustrate how binary physics may be imprinted on to the LISA DNS distribution, we also include the eccentricity distributions of DNSs simulated with variations in binary evolution prescription.

![Figure 7](https://example.com/fig7.png)

*Figure 7. Cumulative distribution of the uncertainty in the sky angle (in one plane) of the simulated detectable DNSs.*

![Figure 8](https://example.com/fig8.png)

*Figure 8. Normalized cumulative eccentricity distribution for LISA-detectable DNSs for the COMPAS Fiducial model (blue solid curve) of binary evolution, and for variations with: always dynamically unstable case BB mass transfer (orange dashed), a single SN kick magnitude (purple dotted), and a common-envelope efficiency of $\alpha = 0.1$ (green dash–dotted).*
3.2.1 Case BB mass transfer stability

Case BB mass transfer refers to Roche lobe overflow from a post helium-main-sequence star (a helium Hertzsprung-gap star) (e.g. Delgado & Thomas 1981; Ivanova et al. 2003). In the DNS formation channels identified by Vigna-Gómez et al. (2018), this is initiated by a secondary that has previously been stripped of its hydrogen envelope during a common-envelope event. Case BB mass transfer leads to further stripping of the helium envelope down to a metal core, resulting in an ‘ultra-stripped’ star (Tauris et al. 2013; Tauris, Langer & Podsiadlowski 2015). This stripping may leave a thin carbon and helium layer, which allows the ensuing ultra-stripped SN to receive a low but non-zero SN natal kick, along with the Blaauw kick from symmetric mass-loss. This allows the DNS to become eccentric despite previously going through a common envelope.

The COMPAS Fiducial model assumes that case BB mass transfer is always stable, which is justified a posteriori by the better match to the observed Galactic DNS period–eccentricity distribution. Moreover, all simulated systems undergoing case BB mass transfer meet the mass ratio-period stability criterion of Tauris et al. (2015) and more than 90 per cent meet the mass ratio stability criterion of Claeys et al. (2014).

The orange dashed curve of Fig. 8 shows the eccentricity distribution of DNSs detectable by LISA under the assumption that case BB mass transfer is always dynamically unstable instead. With this model variation, case BB mass transfer always leads to a common-envelope phase, which significantly tightens the orbit and produces DNSs with $\sim 1$ mHz orbital frequencies. This is right in the detectability region of LISA, and so these DNSs undergo little to no circularization by gravitational radiation by the time they are detected. This is reflected by the higher median eccentricity of 0.36. However, unstable case BB mass transfer leads to fewer overall detections (see the Appendix). Although the total DNS merger rate in the unstable case BB variation is similar to that in the Fiducial model with stable case BB mass transfer, unstable case BB produces tighter, higher frequency binaries that evolve rapidly through the LISA sensitive frequency window, leading to fewer observable systems at a given time. Both stable and unstable case BB mass transfer could occur in reality, so the Fiducial (blue solid curve) and case BB unstable (orange dashed curve) models represent boundary cases.

3.2.2 Natal kick magnitude distribution

The distribution of neutron star natal kicks is another uncertainty in binary population synthesis. Hobbs et al. (2005) proposed a Maxwellian distribution with scale parameter $\sigma = 265$ km s$^{-1}$ based on the observed 2-d pulsar velocity distribution, while Verbunt et al. (2017) suggest that a bimodal Maxwellian produces a better agreement because it better fits the low-speed pulsar subpopulation. Population synthesis studies also suggest that the bimodal distribution is needed to match the observed wide Galactic DNSs, which are overwhelmingly disrupted by a natal kick drawn from a single, high-velocity mode.

Fig. 8 shows that the single high SN natal kick variation (dotted purple curve) produces a moderately more eccentric population than the Fiducial bimodal distribution, with median $e = 0.23$. However, the most significant difference relative to the Fiducial model is an overall decrease in the number of detectable DNS systems by almost a factor of 3, as more binaries are disrupted by the greater SN natal kicks (see Fig. A1).

3.2.3 Common-envelope efficiency

The common-envelope efficiency parameter $\alpha$ (Webbink 1984; de Kool 1990) is the ratio of the binding energy of the common envelope to the difference in orbital energy before and after the common-envelope phase. The Fiducial model’s default value of $\alpha = 1$ assumes perfectly efficient transfer of orbital energy into unbinding the envelope, while $0 < \alpha < 1$ assumes that this energy transfer is not fully efficient. We consider a variation with $\alpha = 0.1$. The green dash–dotted curve of Fig. 8 shows the corresponding eccentricity distribution, which has a moderately less eccentric population than the Fiducial model, with a median eccentricity of 0.071.

The examples above highlight the value of LISA eccentricity measurements to constraining the physics of binary evolution. Fig. A1 shows that the same model variations do not significantly affect the frequency distribution of DNSs at the moment of detection by LISA, which is mainly driven by the LISA sensitivity; it also highlights the differences in the overall rates between variations.

3.2.4 Eccentricity measurement

We consider a conservative threshold for the detection of multiple harmonics by testing whether individual harmonics pass the SNR detection threshold (e.g. Willems et al. 2007); in practice, this condition may be relaxed with the aid of a matched-filtering search for eccentric signals. The uncertainty in measured eccentricity depends strongly on whether two or more harmonics are individually detected, or only a single harmonic is detected, and so we consider these cases separately.

If two or more harmonics are detected, the source eccentricity can be determined from the ratio of GW amplitudes of these harmonics. We denote the SNR and harmonic number of the loudest (largest SNR) harmonic by $\rho_\alpha$ and $\alpha$, respectively, and denote the respective quantities for the second-lowest harmonic by $\rho_\beta$ and $\beta$. The harmonic numbers $\alpha$ and $\beta$ and the orbital frequency $f$ can be determined from the observed harmonic frequencies $f_\alpha$ and $f_\beta$ with the additional knowledge that the two lowest harmonics are neighbouring, $\beta = \alpha \pm 1$. Then the SNR ratio $\rho_\beta/\rho_\alpha$ can be mapped uniquely to the source eccentricity $e$. We plot $\rho_\beta/\rho_\alpha$ as a function of $e$ in Fig. 9 for a typical DNS ($f = 1$ mHz and $m_1 = m_2 = 1.4 M_\odot$) observed by LISA. The upward trend in $\rho_\beta/\rho_\alpha$ with increasing eccentricity reflects the dispersal of GW luminosity across a larger range of frequency harmonics for a more eccentric source. However, there are also spiked structures in the plot originating from $\alpha$ and $\beta$ interchanging values as a DNS’s eccentricity decreases.

In Fig. 9, $\alpha$ and $\beta$ drop abruptly at $e = 0.93$ to $\alpha = 4$ and $\beta = 3$. This occurs because although the peak GW luminosity shifts to higher harmonics as eccentricity increases, it is also emitted at increasingly larger frequencies away from the trough of the LISA noise curve and so is suppressed. For the 1 mHz orbital frequency chosen for this example, this suppression becomes sufficiently large at $e = 0.93$ that the $n = 4$ harmonic becomes loudest because its frequency falls in the region of minimum noise, $\sim 4$ mHz. This shows that very eccentric DNSs may be detected as systems with dominant harmonics that have similar SNRs but small harmonic numbers.

Meanwhile, for a DNS with only one detectable GW harmonic, an upper constraint may be placed on the eccentricity based on the fact that the harmonic with the second-largest SNR is below the detection threshold: $\rho_\beta < \rho_{\text{min}} \Rightarrow \rho_\beta/\rho_\alpha < \rho_{\text{min}}/\rho_\alpha$. This maximum
SNR ratio can then be mapped to a maximum eccentricity. For example, in Fig. 9, constraining the eccentricity to \( e < 0.1 \) requires \( \rho_\beta / \rho_\alpha < 0.5 \), i.e. the SNR in the \( n = 2 \) harmonic would need to be at least a factor of 2 above the detection threshold. Therefore, eccentricity is relatively poorly constrained for DNSs with only one detectable harmonic.

The uncertainty in measured eccentricity \( e \) is further compounded by fluctuations in the SNR due to noise. While Fig. 9 shows the ratio of expected SNRs, actual SNRs fluctuate at the level of \( \pm 1 \) for different noise realizations. Consequently, in the limit of large SNR, the uncertainty on the SNR ratio \( \rho_\beta / \rho_\alpha \) is at the level \( 1/\rho_\beta + 1/\rho_\alpha \).

Fig. 10 shows the distribution of eccentricity uncertainties based on \( \rho_\beta / \rho_\alpha \) versus \( e \) such as Fig. 9 for each starting DNS frequency. We

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detectable harmonics only have marginally tighter mass constraints (median $\Delta M_\text{c}/M_\text{c} \approx 0.02$) than those with only one detectable harmonic (median $\Delta M_\text{c}/M_\text{c} \approx 0.05$). Although DNSs with only one detectable harmonic have poorer constrained absolute values of eccentricity (see Fig. 10), they tend to be less eccentric compared to sources with two detectable harmonics, and $\Delta F/e/F(e) \propto e \Delta e$ for $e \to 0$, so the contribution of the eccentricity uncertainty to the chirp mass measurement error is small for low-eccentricity sources. A total of $\sim 8$ DNSs in our simulated population will have chirp masses constrained to better than 10 per cent in fractional uncertainty, which should be sufficient for the purpose of identifying the GW source. The best-measured LISA DNSs will yield chirp masses with $\lesssim 1$ per cent fractional uncertainty.

4 IDENTIFYING A DNS WITH LISA

Binary population synthesis studies estimate a population of $\sim 10^8$ DWDs to exist in the MW (Marsh 2011, and references therein), most of which are expected to be detached DWDs (Nelemans et al. 2001b). As discussed in Section 2.4, GWs emitted by unresolved Galactic DWDs form a confusion noise below 1–2 mHz, which has been included in the sensitivity curve used in this study (Robson et al. 2019). However, $\sim 10^7$ binaries from this Galactic DWDs population are estimated to be detectable by LISA (Nelemans et al. 2001a; Farmer &phinney 2003; Ruiiter et al. 2010; Korol et al. 2017), significantly outnumbering our estimated $\sim 30$ Galactic DNSs. Here, we discuss methods of positively identifying a DNS with LISA observations.

The chirp mass is the primary means of differentiating DWD and DNS systems, with chirp masses above $\sim 1.2 M_\odot$ indicating that at least one component exceeds the Chandrasekhar limit for the maximum WD mass. However, given the size of the DWD population, a high-mass tail of $M_\odot \lesssim 1.2 M_\odot$ (but sub-Chandrasekhar) DWD binaries could still cause confusion with DNSs, as could neutron star-WD binaries.

The detection of a source with non-zero eccentricity favours a DNS interpretation. The disc population of DWDs is thought to have formed via isolated binary evolution, where the progenitors are expected to have tidally circularized from multiple mass transfer episodes (Nelemans et al. 2001b). Observationally, there are no known eccentric Galactic DWDs, although there are observations of an eccentric Galactic pulsar–WD binary (Antoniadis et al. 2016) and a WD-main sequence (Siess, Davis & Jorissen 2014) binary in the MW. On the other hand, DNSs may have significant eccentricities from SN and Blaauw kicks: in our model, half of LISA DNSs will have $e > 0.1$, and $\sim 10$ will have measurable second GW harmonics, which allow eccentricity to be measured with $\Delta e \lesssim 0.02$ accuracy. Yet, dynamical formation channels in MW globular clusters (Willems et al. 2007) or Lidov–Kozai oscillations in hierarchical triple systems (Thompson 2011) may produce eccentric DWDs. Kremer et al. (2018) estimate that ejected binaries will only comprise a few MW sources with $\rho \geq 2$, but given the very large DWD population, even rare systems could be responsible for confusion with DNSs.

The identification of an eccentric source as a DNS is even more confident if a chirp mass measurement is possible. Above a chirp mass of $\sim 1.2 M_\odot$, the DWD interpretation becomes highly unlikely. In fact, the chirp mass distribution of eccentric DWDs formed in globular clusters is expected to peak at $0.3–0.4 M_\odot$ (Willems et al. 2007).

Finally, sky localization may also aid source identification. Since eccentric DWDs dynamically formed in MW globular clusters are ejected into the Galactic halo, we expect eccentric disc binaries to be DNSs, though the latter may also be found far from the disc due to dynamical formation or kicks (see e.g. fig. C1 of Vigna-Gómez et al. 2018). Accurate sky localization will also enhance the prospects for electromagnetic follow-up, which could definitely distinguish DNS and DWD systems (Kyutoku et al. 2019; Thrane et al. 2019).

5 CONCLUSIONS AND DISCUSSION

We estimated that around 35 inspiralling DNSs will be detectable over a 4-yr LISA mission with SNR $\rho > 8$ using a mock population of isolated binaries synthesized with COMPAS. Of those, 94 per cent are expected to be Galactic DNSs, with the remainder in the LMC (5 per cent) and SMC (1 per cent). These DNSs are detected when the orbital frequency is typically 1 mHz, despite the presence of confusion-limited noise below GW frequencies of 1–3 mHz from unresolved Galactic DWD binaries.

Half of the detectable DNSs retain significant residual eccentricities, $e > 0.11$, imparted mostly by the Blaauw kick at the second SN in the COMPAS population synthesis models. Around a quarter of the LISA DNSs will have two or more individually detectable GW harmonics and $\sim 40$ per cent have only a single resolvable harmonic, while the remaining third will have GW harmonics that combine to exceed the SNR threshold, but are not individually resolvable. When two or more harmonics are observed, eccentricities may be accurately estimated to $\Delta e \lesssim 0.02$ by measuring SNR ratios of different GW harmonics. If only one GW harmonic is observed for a DNS, only an upper constraint on the eccentricity is placed at a typical level of $e \lesssim 0.1$.

A population of DNSs with well-measured periods and eccentricities places valuable constraints on binary evolution physics. With a merger time of $\sim 2.4 \times 10^9$ yr from a GW frequency of $2f = 2$ mHz, the DNSs evolve slowly in frequency over the 4-yr LISA mission, only changing their frequency by parts in $10^5$. This
makes accurate chirp mass measurements challenging, which is compounded by the correlation between chirp mass and eccentricity in driving orbital frequency evolution. We find that ≈15 DNSs will have useful chirp mass constraints from the LISA signal, with median fractional chirp mass uncertainties of 0.04, dropping to below 1 per cent for the best-measured sources. These chirp mass and eccentricity measurements will make it possible to distinguish at least a fraction of the better-measured eccentric DNSs from the much larger Galactic DWD population. They can also elucidate the origin of the DNS systems: although the isolated binary channel is generally assumed to dominate DNS formation, with globular clusters expected to contribute less than 1 per cent of all merging DNSs (Phinney 1991; Grindlay, Portegies Zwart & McMillan 2006; Ivanova et al. 2008; Kremer et al. 2018), recent work has suggested that dynamical or three-body formation channels may be relevant (Hamers & Thompson 2019; Andrews & Mandel 2019). Moreover, LISA’s measurement of the eccentricity distribution in the early DNS evolutionary history could shed light on uncertainties in models of isolated binary evolution, such as the stability of case BB mass transfer.

LISA’s heliocentric orbit produces an effective detector baseline of 2 AU for source triangulation, allowing for accurate sky localisation. We find that most DNSs will be localised with an angular resolution $\sigma_\theta \lesssim 2$ deg. This is sufficient to measure the height of Galactic DNSs relative to the Galactic plane to within $\sim 0.35$ kpc, which provides a constraint on the DNS natal kick distribution. Around 6 DNSs will be localised sufficiently well to be covered by a single pointing of the SKA, giving rise to an efficient, LISA-informed follow-up of possible radio pulsars.

The best-constrained LISA DNSs—the golden binaries—will be localised to a few arc-minutes with eccentricity inferred at an accuracy of a few parts in a thousand and the chirp mass to better than 1 per cent fractional uncertainty. While this paper was under review, the manuscript of Andrews et al. (2019) (hereafter A19) became available. A19 study the population of LISA DNSs by sampling DNS merger times and positions in the MW. They assume that all systems have periods and eccentricities set by the forward evolution of PSR B1913 + 6. They further assume a MW merger rate of 210 Myr$^{-1}$ inferred from the DNS GW event GW170817 (Abbott et al. 2017a), which is $\approx 6$ times higher than our assumed rate of 33 Myr$^{-1}$ under our fiducial model. Therefore, A19 predict approximately six times more detections over a 4-yr LISA mission than we do. With the larger merger rate, A19 further predict $\sim 1$ detections in M31. A19 also find eccentricity uncertainties that are roughly consistent with ours, based on measuring the SNR ratio of the $n = 2, 3$ harmonics. As shown in Fig. 9, for a typical LISA DNS, the second and third harmonics have the highest SNRs only for $e \lesssim 0.3$. For more eccentric DNSs, A19’s approach overestimates the uncertainty.

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APPENDIX: MODEL VARIATIONS IN THE DNS FREQUENCY DISTRIBUTION

Fig. A1 shows the distribution of the orbital frequencies of detectable DNSs at the start of LISA observation for the Fiducial model and the three model variations discussed in Section 3.2. The characteristic detection frequency is similar across the four models, as it is mainly set by the LISA sensitivity.

The overall normalization is, however, sensitive to changes in the binary evolution prescription. The Fiducial model yields the most DNS detections among the considered variations. The single SN mode causes fewer systems to be detected, as the higher natal kick scale parameter for ultra-stripped SNe, $\sigma_{\text{high}} = 265$ km s$^{-1}$, compared to $\sigma_{\text{low}} = 30$ km s$^{-1}$ in the Fiducial model, is more likely to disrupt the binary. The $\alpha = 0.1$ variation makes it approximately 10 times more difficult to satisfy the global energy criterion for envelope ejection, $E_{\text{bind}} > \alpha E_{\text{orb}}$, compared to the Fiducial model where $\alpha = 1$, thereby decreasing the survivability of the common-envelope phase. On the other hand, the unstable case BB variation actually gives rise to a DNS merger rate that is similar to the Fiducial model with stable case BB mass transfer, but with fewer detections because DNSs are produced at higher frequencies and quickly evolve through the LISA sensitivity window.

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