How can LISA test the fast-merging hypothesis of GW190425?

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ABSTRACT

The nature of GW190425, a binary neutron star (BNS) merger detected by the LIGO/Virgo Scientific Collaboration (LVC) with a total mass of $3.4^{+0.3}_{-0.1}$ $M_\odot$ remains a mystery. With such a large total mass, GW190425 stands at five standard deviations away from the total mass distribution of Galactic BNSs of $2.66 \pm 0.12$ $M_\odot$. LVC suggested that this system could be a BNS formed from a fast-merging channel rendering its non-detection at radio wavelengths due to selection effects. BNSs with orbital periods less than a few hours -- progenitors of LIGO/Virgo mergers -- are prime target candidates for the future Laser Interferometer Space Antenna (LISA). If GW190425-like binaries exist in the Milky Way, LISA will detect them within the volume of our Galaxy and will measure the chirp masses to better than 10 per cent for those binaries with gravitational wave frequencies larger than 2 mHz. This work explores how we can test the fast merging channel hypothesis using BNSs observed by LISA. We assume that the Milky Way’s BNS population consists of two distinct sub-populations: a fraction $w_1$ that follows the observed Galactic BNS chirp mass distribution and $w_2$ that resembles GW190425. We show that LISA’s accuracy on recovering the fraction of GW190425-like binaries depends on the BNS merger rate. For the merger rates reported in the literature, 21 – 212 Myr$^{-1}$, the error on the recovered fractions varies between ~ 30 – 5 per cent.

Key words: gravitational waves -- binaries (including multiple): close -- stars: neutron

1 INTRODUCTION

GW190425 is a compact object merger with a total mass of $3.4^{+0.3}_{-0.1}$ $M_\odot$ that was recently detected by the LIGO/Virgo Collaboration (LVC, Abbott et al. 2020). If GW190425 is a binary neutron star (BNS) merger, its total mass is inconsistent with the observed Galactic BNS population that shows a narrow range in the total mass of $\approx 2.66\pm0.12$ $M_\odot$ (Farrar et al. 2019). LVC suggests that GW190425 might belong to a class of BNSs born from a fast-merging channel. In this scenario, BNSs are preferentially born massive and with short orbital periods corresponding to inspiral times of 10 - 100 Myr (e.g. Romero-Shaw et al. 2020; Galaudage et al. 2020). Such short lifetimes and severe Doppler smearing that affects short-period systems make these binaries invisible to radio telescopes (Cameron et al. 2018; Pol et al. 2020).

However, the comparable merger rates of GW190425 with $R_{\text{GW190425}} = 460^{+1050}_{-290}$ yr$^{-1}$ Gpc$^{-3}$ and that of GW170817 with $R_{\text{GW170817}} = 760^{+1740}_{-450}$ yr$^{-1}$ Gpc$^{-3}$ derived by LVC can be challenging to account for through a fast-merging channel hypothesis for two reasons. First, massive neutron stars are expected to form from more massive progenitor stars, thus if adopting the initial mass function of Salpeter (1955), the expected merger rate of GW190425-like systems should result in a lower merger rate for GW190425 compared to GW170817 (for a more detailed discussion see Safarzadeh et al. 2020). Second, if fast merging BNSs form through unstable case-BB mass transfer (Ivanova et al. 2003; Dewi & Pols 2003), they should constitute to $\lesssim 10$ per cent of the total number of BNS systems according to a suite of simulations studied in Safarzadeh et al. (2019). In addition, a large fraction of the BNSs formed through fast-merging channels could challenge the BNS origin for the r-process enrichment of the ultra-fair dwarf galaxies (e.g. Komiya et al. 2014; Matteucci et al. 2014; Safarzadeh & Scannapieco 2017).

Many binary population synthesis studies investigated the observed properties of Galactic BNSs (for an overview see Tauris et al. 2017). Although these studies are able to reproduce the broad characteristics of the BNS population, they seem to have difficulties in matching the mass distribution of the radio population and simultaneously account for the unusually high mass of GW190425 (e.g. Tauris et al. 2017; Vigna-Gómez et al. 2018; Kruckow 2020, see also Fig. 3). However, binary population synthesis models using probabilistic remnant mass and kicks prescriptions form heavier BNSs, still half of their population have masses larger than those of known Galactic BNSs (Mandel et al. 2021). Thus, it is not yet clear if more massive BNS like GW190425 could be associated with the fast merging channel or if they require different explanations. For example, the lack of radio detections could be attributed to a weak magnetic dipole moment. If pulsars are born either with a very strong or extremely weak magnetic dipole moment, they will migrate into the graveyard of pulsars and become invisible to radio telescopes (Safarzadeh et al. 2020).

In this work, we propose a test for the hypothesis of fast-merging origin of GW190425-like systems. If fast-merging channels lead to the formation of massive short-period binaries, the Laser Interferometer Space Antenna (LISA, Amaro-Seoane et al. 2017) will be able to detect them and - for sufficiently short orbital periods - accurately measure their chirp masses. We assume that two distinct populations

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of BNSs reside in the Milky Way: one that follows the chirp mass distribution of known Galactic BNSs, and another one that resembles GW190425. The question at hand is that given the expected merger rate of BNSs in the Milky Way, can LISA detect short period massive BNSs and recover their true fraction?

The idea that LISA can study the existence of fast-merging channel BNS system has been introduced in other works. Recently, Andrews et al. (2020) showed that even by adopting a pessimistic Milky Way merger rate for Galactic BNS systems, LISA would detect tens of such BNSs within four years of continuous observations. Lau et al. (2020) arrived at similar conclusions suggesting that with the achievable high accuracy on the chirp mass and eccentricity, one can constrain BNS formation scenarios such as the natal kicks imparted to neutron stars at birth. In this work, we test the hypothesis that all the fast-merging BNSs are born with a total mass similar to GW190425, and we test the idea of how many events it would take for LISA to set bounds on the fraction of such systems in the Milky Way. It is important to mention that in this work, we do not make any assumptions regarding the frequencies of fast-merging BNSs. This effectively means that they form at similar frequencies as Galactic binaries. It is possible that fast-merging BNSs are born at higher frequencies in the LISA band compared to the bulk of the Milky Way population, and therefore would appear as a sub-population at high frequencies.

The structure of this work is as follows. In Section 2, we analyze LISA’s capability to determine the fractional error on the chirp mass of binaries as a function of the gravitational wave (GW) frequency. In Section 3, we set up a multivariate Gaussian distribution for the binaries detectable by LISA, one following the chirp mass distribution of the Galactic binaries and the other resembling GW190425. We study how LISA can recover the relative fraction of the two sub-populations. In Section 4, we discuss our results and conclude.

2 METHODS

2.1 Chirp mass measurement

To start, we have to quantify the accuracy within which LISA can measure the chirp mass. The chirp mass of a binary system is defined as

$$M = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}},$$

where $m_1$ and $m_2$ are the primary and secondary neutron star masses. It determines how fast the binary with a given GW frequency, $f = 2/P$ with $P$ being binary orbital period, moves through the frequency space during the in-spiral phase

$$f = \frac{96}{5} \pi^{8/3} \left(\frac{G M}{c^3} \right)^{5/3} f^{11/3},$$

where $G$ and $c$ are respectively the gravitational constant and the speed of light. Therefore, chirp mass can be derived from GW data when both frequency ($f$) and its time derivative ($\dot{f}$) are measured. The limiting frequency allowing the chirp mass measurement for a typical BNS is of $\sim 1.75 \text{ mHz}$ (cf. Fig. 2). At lower frequencies, BNS will be seen as monochromatic over the whole duration of the mission, meaning that their chirp mass will be degenerate with the distance (cf. Eq. 7).

In the case of a circular binary, the measurement of the chirp depends only on $f$ and $\dot{f}$. The fractional error on the chirp mass can be estimated as

$$\frac{\sigma_M}{M} \approx \frac{11}{5} \frac{\sigma_f}{f} + \frac{3}{5} \frac{\sigma_{\dot{f}}}{f},$$

where

$$\frac{\sigma_f}{f} = 8.7 \times 10^{-7} \left(\frac{f}{2 \text{ mHz}}\right)^{-1} \left(\frac{\rho}{10}\right)^{-1} \left(\frac{T}{4 \text{ yr}}\right)^{-1}$$

and

$$\frac{\sigma_{\dot{f}}}{f} = 0.26 \left(\frac{f}{2 \text{ mHz}}\right)^{-11/3} \left(\frac{M}{1.2 \text{ M}_\odot}\right)^{-5/3} \left(\frac{\rho}{10}\right)^{-1} \left(\frac{T}{4 \text{ yr}}\right)^{-1}$$

with $\rho$ being the signal-to-noise ratio for the mission time $T = 4 \text{ yr}$ (e.g., Lau et al. 2020). Averaging over sky location, polarisation, and inclination, one can write down the signal-to-noise ratio as (e.g. Robson et al. 2019):

$$\rho^2 = \frac{24}{25} |A|^2 \frac{T}{S_n(f) R(f)},$$

where $A$ is the amplitude of the signal

$$A = \frac{2 (G M)^{5/3} (\pi^2)^{2/3}}{c^3 d},$$

$S_n(f)$ is the power spectral density of the detector noise in the low-frequency limit that also accounts for unresolved Galactic background, $d$ is the luminosity distance to the binary and $R(f)$ is a transfer function encoding finite-arm length effects at high frequencies that computed numerically in Korol et al. (2020).

Figure 1 shows the signal-to-noise ratio (cf. Eq. 6) for a circular BNS placed at the distance of $10 \text{ kpc}$ and observed over the nominal four years of the LISA mission. For comparison, we show the sub-sample of shortest orbital period Galactic BNSs detected through the radio emission (orange stars) with measured masses (Ferdman et al. 2014; van Leeuwen et al. 2015; Kramer et al. 2006; Cameron et al. 2018; Stovall et al. 2018; Farrow et al. 2019). By plugging in their true distances in Eq. (6), we find that all of the known BNS lay under the LISA detection threshold of $\rho = 7$. The chirp masses of extra-galactic BNS mergers detected through GW emission by LVC are delimited by grey horizontal bands. In Fig. 2 we zoom-in on frequencies $> 1 \text{ mHz}$ and show the expected fractional error on the chirp mass.

The eccentricity is another parameter that – when sufficiently high – can impact BNS detectability and, consequently, the chirp mass measurement. In the isolated binary evolution, BNSs are expected to form with non-zero eccentricity due to the supernova kicks associated with the formation of the last-born neutron star or Blaauw kicks produced by symmetric mass loss accompanying supernovae (Blaauw 1961; Tauris et al. 2017). The GW radiation quickly circularises BNS orbits so that they become almost circular (e.g., when the Hulse-Taylor pulsar will evolve to $2 \text{ mHz}$ its eccentricity will decrease from 0.61 to 0.03) by the time they move to the LISA band. However, if the binary is born right in or at the edge of the LISA’s frequency window, it will retain the original eccentricity. In this work, we will explore two limiting cases: the case in which all binaries are circular and the case all in which all binaries are eccentric. We anticipate that assuming all binaries to be eccentric does not significantly change our results. Thus, we defer the description of how the chirp mass measurement changes in the eccentric case to Appendix A.

2.2 Mock Galactic BNS population

To assemble a mock Galactic population we assume that the BNSs’ chirp mass distribution is described by a mixture of two Gaussian
where.

for a circular BNS placed at the distance of 10 kpc after nominal four years of LISA mission. Dotted contours show SNR=1 representing the instrument noise, SNR=7 representing the nominal detection threshold, and SNR=30. Orange stars represent known binaries detected through radio emission. grey horizontal bands represent chip masses of BNS detected to date through GW emission, GW170817 and GW190425.

Figure 1. Detectability of Galactic BNSs in the chirp mass-frequency parameter space. In colour, we show the sky-, inclination- and polarisation-averaged SNR for a circular BNS placed at the distance of 10 kpc after nominal four years of LISA mission. Dotted contours show SNR=1 representing the instrument noise, SNR=7 representing the nominal detection threshold, and SNR=30. Orange stars represent known binaries detected through radio emission. grey horizontal bands represent chip masses of BNS detected to date through GW emission, GW170817 and GW190425.

distributions: one centered on the value characteristic of the known Galactic population that has been detected at radio wavelengths and another centered on the chirp mass of GW190425. We therefore write

\[
P_{\text{pop}}(M) = \frac{w_1}{\sigma_1 \sqrt{2\pi}} \exp \left( \frac{-(M - \mu_1)^2}{2\sigma_1^2} \right) + \frac{w_2}{\sigma_2 \sqrt{2\pi}} \exp \left( \frac{-(M - \mu_2)^2}{2\sigma_2^2} \right),
\]

where \( w_1 \) and \( w_2 \) are the relative weights of the two Gaussian distributions normalised such that \( w_1 + w_2 = 1 \). We obtain \( \mu_1 = 1.17 M_\odot \) with a standard deviation of \( \sigma_1 = 0.04 \) by combining individual chirp mass measurements of known Galactic BNS reported in Farrow et al. (2019). We set \( \mu_2 = 1.44 M_\odot \) and \( \sigma_2 = 0.02 \) according to the posterior distribution reported in Abbott et al. (2020). We show our model chirp mass distribution in Fig. 3 with the blue solid line. We note that our choice is supported by studies analysing available GW and/or radio observations of BNSs that found evidence for a broad secondary peak at high masses in the birth mass distributions of second-born neutron stars (Farrow et al. 2019; Galaudage et al. 2020). In addition, population studies of binary white dwarf detectable with LISA also show bi-modality in the chirp mass distribution (Korol et al. 2017).

To model the frequency distribution we assume that the Galactic BNSs population is stationary on the time-scale of interest. Consequently, their distribution in frequency is given by

\[
dN = \frac{5c^5 R_{\text{MW}}}{96\pi^{8/3}(GM)^{5/3}f^{11/3}} \frac{dN}{df}
\]

where \( R_{\text{MW}} \) is the merger rate of BNSs in the Milky Way. Note, however, that this assumption does not account for possible significant recent star formation episodes that could add BNS systems directly in the LISA band. We can then compute the total number of BNS at frequencies above \( f \) by integrating Eq. (9)

\[
N(> f) = \frac{5c^5 R_{\text{MW}}}{256\pi^{8/3}(GM)^{5/3}f^{8/3}} \approx 33 \left( \frac{M_\odot}{1.2 M_\odot} \right)^{-5/3} \left( \frac{f}{2 \text{ mHz}} \right)^{-8/3} \left( \frac{R_{\text{MW}}}{140 \text{ Myr}^{-1}} \right),
\]

where we use \( R_{\text{MW}} = 140 \text{ Myr}^{-1} \) (Seto 2019). We note that the Galactic BNS merger rate is still uncertain: based on extra-galactic BNS merger rates reported by LVC in the first two observing runs Andrews et al. (2020) arrives at \( 210 \text{ Myr}^{-1} \), Pol et al. (2019) arrives at \( 24 \text{ Myr}^{-1} \) using available radio observations, and Vigna-Gómez et al. (2018) predicts at \( 24 \text{ Myr}^{-1} \) based on the COMPAS binary population synthesis code. We note that the updated merger rate of \( 320^{+490}_{-280} \text{ Gpc}^{-3} \text{ yr}^{-1} \) based on the second LVC GW Transient Catalog (The LIGO Scientific Collaboration et al. 2020) corresponds to \( 32^{+49}_{-24} \text{ Myr}^{-1} \) (assuming the number density of the Milky Way-like galaxies of 0.01 Mpc\(^{-3}\)), and thus agrees better with the rates estimated from the population of Galactic BNSs. Moreover, in the next decades, the differences in estimated merger rates should further decrease as more observations will become available from radio and GW observatories.

Finally, we assume that BNS are distributed in the Galactic disc with an exponential radial stellar profile with an isothermal vertical distribution

\[
P(R,z) \propto e^{-R/R_d} \sech^2(z/z_d)
\]
\[ \text{Figure 2. Expected fractional error on the chirp mass as a function of GW frequency (x-axis) and chirp mass (y-axis) for a circular binary. Here we fixed the distance to the binary to } d = 10 \text{kpc and the observation time with LISA to } T = 4 \text{ yr. Overlaid are lines of constant fractional measurement error on the chirp mass; their slope indicates that at a given GW frequency, higher chirp masses lead to a smaller error on the measurement.} \]

\[ \text{Figure 3. Chirp mass distribution of our mock BNS population (blue solid). For comparison we show the chirp mass distribution from Vigna-Gomez et al. (2020) formed at } Z = 0.0142 \text{ (orange dashed). Vertical shaded bands represent the range of chirp masses of known Galactic BNSs in grey and that of GW190425 in red colours.} \]

\[ \text{where } 0 \leq R \leq 20 \text{kpc is the cylindrical radius measured from the Galactic centre, } z \text{ is the height above the Galactic plane, } R_0 = 2.5 \text{kpc is the characteristic scale radius, and } z_d = 0.4 \text{kpc is the vertical scale height of the observed Galactic BNSs (Pol et al. 2019). Finally, when converting BNS positions } (R, z) \text{ into heliocentric distances } d \text{ we assume the position of the Sun to be at } (8.1, 0) \text{ according to Gravity Collaboration et al. (2019).} \]

\[ \text{2.3 Bayesian inference} \]

Given \( N \) measurements of the BNS chirp masses with associated errors, we now would like to reconstruct the shape of the underlying true chirp mass distribution. Here we have chosen to model the chirp mass of Galactic BNSs as a mixture of two Gaussian distributions (cf. Eq. 8), thus the distribution is fully described by 6 parameters \( \lambda \in \{ w_1, w_2, \mu_1, \mu_2, \sigma_1, \sigma_2 \} \). We follow the Bayesian approach as outlined in Mandel et al. (2019) ignoring selection effects because we are only interested in a sub-sample of detections with \( f > 2 \text{ mHz} \) – that allows the measurement of the chirp mass – across which we find the detection probability with LISA to be \( \sim 1 \).

To simulate the instrumental noise, we displace each chirp mass from its true value by re-sampling it from a Gaussian centered on the true value and standard deviation determined by the LISA’s measurement error \( \sigma_M \) (cf. Eq. 3). We will denote this displaced chirp mass with \( \tilde{M} \).

Using Bayes’ theorem, we can write the posterior as

\[ P(\lambda | \tilde{M}) \propto \pi(\lambda) \prod_{i=1}^{N} \int dM_i P(\tilde{M}_i | M) P_{\text{pop}}(M_i | \lambda), \tag{12} \]

where \( \pi(\lambda) \) are priors on \{ \( w_1, w_2, \mu_1, \mu_2, \sigma_1, \sigma_2 \) \}, \( P(\tilde{M}_i | M) \) is the probability of observing the event \( i \) given the assumed underlying distribution (likelihood), \( P_{\text{pop}} \) is the probability of individual chirp mass given the underlying population distribution (Eq. 8). We assume that the likelihood follows a Gaussian distribution. We adopt uniform priors for \( w_1, w_2 \in [0, 1] \), \( m_1 \in [1 - 1.3] M_\odot \) and for \( m_2 \in [1.3 - 1.5] M_\odot \), and a log-uniform prior for \( \sigma_1, \sigma_2 \in [-3, -1] \).

\[ \text{3 RESULTS} \]

We start by assuming the fraction of BNSs that resemble GW190425 to be \( w_2 = 0.2 \) and we set the Galactic merger rate to be \( 140 \text{ Myr}^{-1} \), which corresponds to 33 BNS with frequencies higher than \( 2 \text{ mHz} \) in the Galaxy. We recover the parameters of the chirp mass distribution in the the framework of probabilistic programming package pyMC3 (Salvatier et al. 2016) and sample the posterior (Eq. 12) using the No U-turn Sampler. Figure 4 shows two examples of posterior distributions for \( w_2, \mu_1, \mu_2, \sigma_1 \) and \( \sigma_2 \). We have chosen to display only one of the two weights \( w_2 \), since the other can be recovered as \( 1 - w_2 \). We present our results for two assumptions on the merger rate: \( \mathcal{R}_{\text{MW}} = 42 \text{ Myr}^{-1} \) in yellow and \( \mathcal{R}_{\text{MW}} = 212 \text{ Myr}^{-1} \) in blue colours. The true values are marked by black dashed lines. It is immediately evident that the higher merger rate leads to more constrained results because the number of detectable BNSs by LISA is higher. Moreover, in the case of the lower merger rate the small number statistics leads to bias in some of the parameters, although the true value is recovered to within the \( 1 - \sigma \) of the derived posteriors. Importantly, Fig. 4 shows that we can constrain the relative weights of the two BNS sub-populations \( w_1 \) and \( w_2 \).

We now focus on how well our inference machinery can recover \( w_2 \) (or equivalently \( w_1 \)). We fix the Galactic merger rate and vary \( w_2 \). We find that for \( \mathcal{R}_{\text{MW}} = 140 \text{ Myr}^{-1} \) the weight of GW190425-like sub-population is recovered with \( 1\sigma \) error of 0.1–0.04, where the largest error is obtained for \( w_2 = 0.1 \) while the smallest for \( w_2 = 0.9 \). This trend can be explained by remembering that the error on the chirp mass is mainly dominated by \( \sigma_f \propto M^{-5/3} \) (cf. Eq. 5 for the circular case; for the eccentric case this is true only up to \( \sim 3 \text{ mHz} \) where \( \sigma_f \) and \( \sigma_e \) start to be comparable, see Appendix A). Thus, the population with \( w_2 = 0.9 \) has overall better measured chirp masses than a population with \( w_2 = 0.1 \). Next, we fix \( w_2 \) and vary
How can LISA test the fast-merging hypothesis of GW190425?

\[
\mathcal{R}_{\text{MW}} = 42 \, \text{Myr}^{-1} \\
\mathcal{R}_{\text{MW}} = 212 \, \text{Myr}^{-1}
\]

**Figure 4.** Results of the MCMC simulation in recovering input parameters of the adopted model with \( w_2 = 0.2 \) and the other four variables that enters Eq. (8): for \( \mathcal{R}_{\text{MW}} = 42 \, \text{Myr}^{-1} \) in yellow and for \( \mathcal{R}_{\text{MW}} = 212 \, \text{Myr}^{-1} \) in blue. The true values are marked by black dashed lines. The dark and light shaded regions indicate the 68 per cent, and 95 per cent confidence region in the derived posteriors. The top left panel shows that the fraction of GW190425-like binaries is constrained in both cases.

The merger rate in the range between 21 – 212 Myr\(^{-1}\). We find that the error on the recovered fraction decreases with increasing merger rate as more LISA observations becomes available. Specifically, for \( w_2 = 0.2 \) we recover \( 0.34^{+0.34}_{-0.22} \) for \( \mathcal{R}_{\text{MW}} = 21 \, \text{Myr}^{-1} \), \( 0.22^{+0.08}_{-0.07} \) for \( \mathcal{R}_{\text{MW}} = 140 \, \text{Myr}^{-1} \), and \( 0.19^{+0.06}_{-0.05} \) for \( \mathcal{R}_{\text{MW}} = 212 \, \text{Myr}^{-1} \).

The summary of the recovered weight of GW190425-like BNSs \( w_2 \) as a function of the true (input) \( w_2 \) is represented in Fig. 5. It shows that chirp mass measurement errors allow the recovery of the two sub-populations’ weights with no bias regardless of its true value. In colour we show that our ability to recover \( w_2 \) for different Galactic merger rates of 42, 140, 212 Myr\(^{-1}\), which corresponds to the total number of observed binaries at \( f > 2 \) mHz of 10, 33, 50 respectively.

Finally, for comparison, we perform the same set of simulations for an extreme case in which all binaries in the LISA band are eccentric. For example, using different natal kick prescriptions Lau et al. (2020) reports median eccentricity of the population ranging from 0.36 to 0.071, with a median of 0.1 for their fiducial model. For simplicity, as an example here, we set the eccentricity of all binaries to 0.3. We do not find any significant deviations in re-covering \( w_2 \) from the results of the circular case presented above. We can attribute this to the fact that the chirp mass error distribution does not differ significantly between the circular and eccentric cases (see also Appendix A).

4 DISCUSSION AND CONCLUSIONS

In this paper, we have investigated whether future observations of Galactic BNS with LISA and specifically LISA’s chirp mass measurement can elucidate the nature and origin of heavy BNS like
GW190425. First, we showed that if GW190425-like binaries populate frequencies > 2 mHz, they can be detectable by LISA within the volume of our Galaxy. Moreover, their chirp masses can be measured to better than 10 per cent. Then, we constructed a toy model for Galactic BNSs consisting of two distinct sub-populations: one that follows the chirp mass distribution of known BNSs detected through radio observations and another one that resembles GW190425. Since the relative fraction of the two sub-population depends on the BNS formation model and the treatment of the fast-merging channel in modeling the total population in the Galaxy (e.g. Vigna-Gómez et al. 2018; Mandel et al. 2021), here we considered the weights of the two sub-population as free parameters. As the Galactic BNS merger rate is still uncertain, we repeat our study for a range of merger rates between 24 – 212 Myr$^{-1}$ quoted in the literature (Abbott et al. 2017; Vigna-Gómez et al. 2018; Pol et al. 2019; Andrews et al. 2020). We demonstrated that if GW190425-like binaries constitute a fraction larger than 0.1, LISA should be able to recover the fraction with better than ~ 15 per cent accuracy assuming the merger rate of $R_{MW} = 42$ Myr$^{-1}$ (corresponding to 10 detected binaries with $f > 2$ mHz); the accuracy increases to ~ 5 per cent for $R_{MW} = 212$ Myr$^{-1}$ (corresponding to 50 detected binaries with $f > 2$ mHz). We note that with more upcoming radio and GW observations, the BNS merger rate is expected to be better constrained, such that we will have a more precise estimate on the expected number of BNS sources detectable by LISA. The results of this work can then be used to access what fractions of more massive GW190425-like binaries can be constrained by LISA. Finally, our results show that even if all Galactic BNSs come with large eccentricities, then the errors on the measured chirp masses stay within the limits where our recovered fractions, assuming circularized orbits, remain applicable.

We also mention an important caveat in our underlying assumptions: we have assumed that massive BNSs come from the fast-merging formation channel, but we did impose any specific assumption on their GW frequencies. Population synthesis studies suggest a broad distribution of delay times between BNS formation and merger even under the assumption that case-BB mass transfer is dynamically stable (e.g. Vigna-Gómez et al. 2018). However, if the case-BB mass transfer is occasionally dynamically unstable, it is possible that fast-merging BNSs are born within the LISA band at higher frequencies than the rest of the Galactic population. Therefore, if their merger timescales are sufficiently long to be observed with LISA, it is also possible that they would exhibit an excess in the frequency distribution. As we do not model this possibility in the present work, we are effectively assuming that fast-merging binaries are predominantly formed at low enough frequencies such that they do not disturb or modify the frequency distribution. On the other hand, LISA’s frequency measurement is expected to be very accurate (ideally $\sigma_f/f \propto 1/T \sim 10^{-8}$), thus identifying a sub-population in frequency should not be a problem.

While radio observatories are sensitive to the intermediate stages of BNS evolution and ground-based GW detectors can see only the very last seconds of a BNS’s life and the final merger, LISA will be crucial for bridging the gap between these two regimes. Here we argued that the BNS chirp mass distribution measured by LISA could be a useful tool for testing the fast-merging formation channel of GW190425-like BNSs. Other studies have established the importance of the LISA’s eccentricity measurement for understanding the BNS formation pathways (Andrews et al. 2020; Lau et al. 2020). In addition, LISA will also provide sky positions for Galactic BNS enabling radio follow-up and the discovery of radio-faint pulsars with all-sky surveys such as the Square Kilometre Array (Kiyotoku et al. 2019).

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**DATA AVAILABILITY**

No new data were generated or analysed in support of this research.

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Differently from circular binaries, eccentric binaries emit GWs at multiple harmonics. Each harmonic can be thought as a collection 
of a binary at the distance of $d = 10\text{kpc}$ and emitting at $2\text{mHz}$. Bottom panel: Fractional error of the chirp mass (black) for a binary 
with $e = 0.3$ split into the contributions due to $f$ and $e$; we do not represent the 
contribution due to the uncertainty in $f$ as it remains negligible at all frequencies.

of any two harmonic is proportional to the eccentricity. Therefore, detection of at least two harmonics is required to measure binary’s 
eccentricity (e.g. Seto 2016). For relatively moderate eccentricities that we have considered in this work ($\varepsilon \leq 0.3$), $f_2$ and $f_3$ are the 
strongest harmonics and 

$$\frac{\sigma_e}{\varepsilon} \approx \left( \frac{1}{\rho_2^3} + \frac{1}{\rho_3^3} \right)^{-1/2}. \tag{A4}$$

Finally, the contribution to chirp mass error due to eccentricity $\sigma_{F(e)}$ can be calculated directly for known $\sigma_e$ using Eq. (A2).

In the top panel of Fig. A1 we show how the fractional error on the chirp mass changes as a function of the eccentricity for a binary 
at the distance of $d = 10\text{kpc}$ and emitting at $2\text{mHz}$. In the bottom panel of Fig. A1 we fix binary’s eccentricity to $\varepsilon = 0.3$ and split 
fractional error of the chirp mass (black) into the contributions due to $f$ (blue) and $e$ (orange); we do not represent the contribution due 
to the uncertainty as it remains negligible at all frequencies. For $f \lesssim 3\text{mHz}$ the error on the chirp mass is dominated by the error on

Figure A1. Top panel: Fractional error on the chirp mass as a function of the eccentricity for a binary at the distance of $d = 10\text{kpc}$ and emitting at $2\text{mHz}$. Bottom panel: Fractional error of the chirp mass (black) for a binary with $e = 0.3$ split into the contributions due to $f$ and $e$; we do not represent the 
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\( \dot{f} \), which scales with \( \rho \) and thus \( \sigma_M/M \) is smaller compared to in the circular case (see upper panel). At 3 – 4 mHz, the contribution of the eccentricity limits the chirp mass measurement, so at higher frequencies the chirp mass is better for the circular binaries.

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