Are fast radio bursts the most likely electromagnetic counterpart of neutron star mergers resulting in prompt collapse?

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Inspiraling and merging binary neutron stars (BNSs) are important sources of both gravitational waves and coincident electromagnetic counterparts. If the BNS total mass is larger than a threshold value, a black hole ensues promptly after merger. Through a statistical study in conjunction with recent LIGO/Virgo constraints on the nuclear equation of state, we estimate that up to $\sim 25\%$ of BNS mergers may result in prompt collapse. Moreover, we find that most models of the BNS mass function we study here predict that the majority of prompt-collapse BNS mergers have $q \gtrsim 0.8$. Prompt-collapse BNS mergers with mass ratio $q \gtrsim 0.8$ may not be accompanied by either kilonovae or short gamma-ray bursts, because they unbind a negligible amount of mass and form negligibly small accretion disks onto the remnant black hole. We call such BNS mergers “orphan”. However, recent studies have found that $10^{41-43} (B_p/10^{12} G)^2 \text{erg s}^{-1}$ electromagnetic signals can be powered by magnetospheric interactions several milliseconds prior to merger. Moreover, the energy stored in the magnetosphere of an orphan BNS merger remnant will be radiated away in $O(1 \text{ ms})$. Through simulations in full general relativity of BNSs endowed with an initial dipole magnetosphere, we find that the energy in the magnetosphere following black hole formation is $E_B \sim 10^{40-42} (B_p/10^{12} G)^2 \text{ erg}$. Radiating $\sim 1\%$ of $E_B$ in $1 \text{ ms}$, as has been found in previous studies, matches the premerger magnetospheric luminosity. These magnetospheric signals are not beamed, and their duration and power agrees with those of non-repeating fast radio bursts (FRBs). These results combined with our statistical study suggest that a non-repeating, precursor FRB may be the most likely electromagnetic counterpart of prompt-collapse BNSs. Detection of a non-repeating FRB coincident with gravitational waves from a BNS merger may settle the extragalactic origin of FRBs and place constraints on the nuclear equation of state. FRBs can also initiate triggered searches for weak signals in the LIGO/Virgo data.

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I. INTRODUCTION

The LIGO and Virgo collaborations have already reported the direct detection of gravitational waves (GWs) from the inspiral and merger of five binary black holes [1,9] and one binary neutron star (BNS) [6] (event GW170817), that was accompanied by multiple electromagnetic (EM) counterparts [7,8]. The consequences for astrophysics and fundamental physics from these observations are far reaching, and it is a matter of time until the detection of such compact binaries becomes routine.

Merging BNSs are not only important sources of GWs, but also sources of coincident EM counterparts. These systems had long been suspected as the progenitors of short gamma-ray bursts (sGRBs) [9,19]. The detection of the GW170817-counterpart GRB170817A [7] has provided the best evidence, yet, that some sGRBs are powered by BNSs. BNSs are also sources of kilonova/macronovae [20,21]. The association of kilonova AT 2017gfo/DLT17ck with GW170817 [8] has verified this expectation, too.

Merging BNSs may also be progenitors for fast radio bursts (FRBs) – a new class of radio transients lasting between a few to a couple of tens of milliseconds [22,23]. So far 36 FRBs have been detected [24]. The discovery of the repeating FRB “FRB121102” [25] points to a non-catastrophic origin as opposed to a collapse or merger, which suggests that there may be at least two different classes of FRB progenitors. Several models have been proposed to explain FRBs including magnetar giant flares, coherent radiation from magnetic braking at BNS merger, blitzars, dark-matter induced collapse of neutron stars, axion-miniclusters, newborn highly magnetized neutron stars in supernova remnants, black hole–neutron star batteries, charged black hole (BH) binaries, black hole current sheets, black hole superradiance induced by plasma [26-38].

Kilonovae from BNS mergers require dynamical ejection of matter during merger and/or from an accretion disk by neutrino irradiation, see e.g. [39] for a review. It is also widely accepted that BNSs can generate sGRBs, if a jet is launched by the BH-disk engine that forms following merger. Thus, in a scenario where a negligibly small disk forms, and a negligible amount of mass escapes, one may expect no sGRB and an undetectable kilonova from the BNS event. We call such “kilonova-free” and “sGRB-free” BNS mergers “orphan”. But, are there any scenarios where such orphan BNS mergers arise?

Numerical relativity simulations have shown that when the BNS total mass ($M_{\text{tot}}$) is greater than a threshold mass ($M_{\text{thres}}$), a BH ensues in the first millisecond after merger. In this prompt-collapse scenario a negligible amount of matter is ejected dynamically [40] (see also [41]) and a negligible amount of matter is available to form a disk [40,42-45]. Negligibly small disks were also reported in [46], where it was demonstrated that in prompt-collapse BNS mergers a jet cannot be launched as opposed to the “delayed” collapse scenario [47]. For illustration we also note that ejecta masses $\sim 0.025 - 0.05 M_{\odot}$ are required to explain the kilonova associated with GW170817 [48,58], while typical ejecta from equal-mass, prompt-collapse BNS mergers are
Note that when two NSs merge and collapse to a BH promptly, the total energy stored in the magnetosphere is likely about the same order of magnitude as in Eq. (2), because there is little time available to amplify the surface magnetic field through hydromagnetic instabilities as in a delayed collapse scenario [75]. However, compression due to the collision can amplify the magnetic field because of magnetic flux freezing. On the other hand, a large amount of the energy will quickly fall into the remnant BH. Thus, a detailed numerical relativity study of prompt-collapse BNS mergers is necessary to assess the post-merger magnetospheric energy of BNSs resulting in prompt collapse.

To confirm the expectation from Eq. (2), we perform fully general relativistic, ideal magnetohydrodynamics simulations of prompt-collapse BNS mergers. At BH formation we compute the energy stored in the magnetosphere. Assuming a 0.8% radiation efficiency [72] and a millisecond emission time, we estimate an outgoing burst with luminosity $L_{\text{EM}} \sim 10^{41} \text{ erg/s}$, which is not very well constrained, yet. A number of studies have recently placed constraints on the nuclear EOS using FRBs [31]. Thus, our simulations provide support to the idea that prompt-collapse BNSs are promising FRB sources in addition to being GW sources.

To sum, BNS mergers are promising candidates for non-repeating, precursor FRBs, and such FRBs may be the most promising EM counterpart of orphan BNS mergers. The outgoing magnetospheric burst is rather isotropic [63–64, 72], in contrast to a sGRB which is beamed, making the detection of such FRB signatures largely independent of the binary orientation. Detection of an FRB can trigger searches in LIGO/Virgo data. The discovery of coincident GWs with an FRB may settle the extragalactic origin of FRBs. Moreover, detection of an FRB from an orphan BNS merger could provide strong evidence that the merger resulted in prompt collapse to a BH, and could place constraints on the nuclear EOS, see e.g. [76].

The remainder of the paper is organized as follows. In Sec. II prompt-collapse BNS mergers are motivated through a study of the BNS $M_{\text{tot}}$ and $q$ distribution. A description of our simulations and results are presented in Sec. III. Our conclusions are provided in Sec. IV. Geometrized units ($G = c = 1$) are adopted throughout, unless otherwise specified.

II. PROBABILITY ESTIMATES FOR BNS MERGERS

To assess whether prompt-collapse BNS mergers are astrophysically relevant, and in particular whether orphan BNS mergers are likely, we need to know the value of $M_{\text{thres}}$, and the BNS $M_{\text{tot}}$ and $q$ distribution. We address these topics in this section.

A. Constraints on the threshold mass for prompt collapse

While $M_{\text{thres}}$ has been found to be independent of the mass ratio [77], it is sensitive to the nuclear EOS [42–43, 76, 78], which is not very well constrained, yet. A number of studies have recently placed constraints on the nuclear EOS using the observation of GW170817 (see, e.g., [79] and references

$O(10^{-4} M_\odot)$ [40, 59], and disk masses $O(10^{-3} M_\odot)$ [45]. According to [60] ejecta masses $O(10^{-3} M_\odot)$ or greater are required for detectable kilonovae at the depth and cadence of the normal LSST survey with current or planned telescopes. Therefore, prompt-collapse BNS mergers may be orphan unless they take place nearby. But, are all such mergers expected to be orphan?

If the binary mass ratio $q$ (defined here to be less than unity) is smaller than 0.8, then both appreciable matter may become unbound and a sizable disk onto the remnant BH may form [40, 41, 61]. This is because for substantially asymmetric BNSs the lighter companion is tidally disrupted before merger, in contrast to near equal-mass binaries. Thus, sufficiently asymmetric, prompt-collapse BNS mergers may power both sGRBs and kilonovae.

In this work we perform a statistical study to assess the astrophysical relevance of prompt-collapse BNSs, and the likelihood of orphan BNS mergers. In particular, we compute the $M_{\text{thres}}$ and $q$ distribution of BNSs using the Galactic NS mass function and population synthesis models in conjunction with GW170817 constraints on the nuclear equation of state (EOS). We estimate that up to $\sim 25\%$ of all BNSs may result in prompt collapse. We also find that most models of the BNS mass function we treat predict that the majority of prompt-collapse BNSs have $q \gtrsim 0.8$. Furthermore, the larger $M_{\text{thres}}$ is, the more skewed toward $q = 1$ the distribution of binaries with $M_{\text{tot}} > M_{\text{thres}}$ becomes. Thus, most prompt-collapse BNSs may be orphan. But, does this imply no EM counterparts from such mergers?

Recent work found that interactions in compact binary magnetospheres [62–66] (see also [67–70] for related discussions) can power $\sim 10^{41} \text{ erg/s}$ for a millisecond prior to merger. Here $B_p$ is the magnetic field strength at the pole of the neutron star. Moreover, following BH formation there is a significant amount of energy stored in the magnetosphere of the remnant. Studies of magnetospheres of stars collapsing to BHs [71, 72] have shown that a fraction on the order of $\epsilon = 1\%$ [74] of the total energy stored in a for a free-magnetosphere is radiated away on a collapse timescale $\tau_{\text{FRB}}$. This timescale is $O(1 \text{ ms})$ for a NS. For a magnetic dipole in flat spacetime the total magnetic energy in the magnetosphere is

$$E_B \sim \int_0^{10^{12}} \left(\frac{B}{10^{12} \text{ G}}\right)^2 \frac{\sin \theta d\theta}{4 \pi} \left(\frac{\epsilon}{0.01}\right)^{1/2} \frac{1}{(1 + \epsilon)^{1/2}} B_{12}^2 R_{10}^3 \text{ erg},$$

(1)

implying an outgoing EM luminosity of

$$L_{\text{FRB}} \sim 10^{42} \epsilon_{0.01} B_{12}^2 R_{10}^3 \tau_{\text{FRB}}^{-1} \text{ erg s}^{-1}.$$  

(2)

Here, $B_{12} = B_p/10^{12} \text{ G}$, $R_{10}$ the stellar radius in units of 10 km, $\epsilon_{0.01}$ the efficiency $\epsilon$ normalized to 0.01, and $\tau_{\text{FRB}}$ the emission time in units of 1 ms. This outgoing luminosity matches the premerger magnetospheric luminosity. Moreover, the power and duration of these magnetospheric signals match those of observed FRBs [31]. Thus, BNSs are candidates for non-repeating, precursor FRBs.
In this work we adopt CM among the softest EOSs with smaller namely, among the EOSs that respect investigated the masses and radii of cold nuclear EOSs listed WFF1 [88] yields a smallest value for $M$ how small the lower bound on the EOSs that are favored by GW170817 [85] to explore finitely separated. We can use Eq. (3) in conjunction with $R$ a $\text{M}$ tic, finite temperature EOSs, and was found that $M$ the upper bound on $M$ here is defined as the Arnowitt-Deser-Misner (ADM) mass of the binary, if the binary companions were infinitely separated. We can use Eq. (3) in conjunction with the EOSs that are favored by GW170817 [85] to explore how small the lower bound on $M$ can become. We investigated the masses and radii of cold nuclear EOSs listed in [86]. Among the EOSs that respect $1.97M_\odot \lesssim M_{\text{TOV}} \lesssim 2.2M_\odot$ [87], the mass-radius constraints of [85], the EOS WFF1 [88] yields a smallest value for $M$ through Eq. (3); namely, $M_{\text{thres}} \approx 2.75M_\odot$. This is not unexpected because Eq. (3) predicts that the softer the EOS (larger $C_{\text{1.6}}$) and the smaller $M_{\text{TOV}}$ are, the smaller $M_{\text{thres}}$ becomes. WFF1 is among the softest EOSs with $M_{\text{TOV}} \sim 2.0M_\odot$. Thus, in this work we adopt [2.75, 3.25]$M_\odot$ as a reasonable range for $M$ respecting current constraints on the nuclear EOS.

B. Binary neutron star total mass and mass-ratio distributions

The NS mass function for Galactic BNSs has been modeled in [89,90]. As in [91], in our analysis below we use the Gaussian mass function of [90], because it is simpler to work with and because the skewed Gaussian of [89] is consistent with 0 skewness parameter, and hence agrees very well with the distribution of [90]. In [90] the probability distribution function of NS masses ($M_{\text{NS}}$) in Galactic BNSs is modeled as

$$P(M_{\text{NS}}; M_0, \sigma) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{(M_{\text{NS}} - M_0)^2}{2\sigma^2}\right)$$

with $M_0 = 1.33M_\odot$, and $\sigma = 0.09M_\odot$. Assuming that the masses of the two NSs in a BNS are independent random variables, we can use Eq. (4) to derive the distribution of the BNS $M_{\text{tot}}$ and that of $q$. The $M_{\text{tot}}$ distribution is again given by Eq. (4), but with $M_0 = 2.66M_\odot$, $\sigma = 0.09\times \sqrt{2}M_\odot$, and $M_{\text{NS}}$ replaced with $M_{\text{tot}}$. Using the $M_{\text{tot}}$ distribution we can compute the probability that $M_{\text{tot}}$ is greater than a certain value. In the left panel of Fig. 1 this is shown by the curve labeled “Galactic”, which demonstrates that if $M_{\text{thres}} = 2.75M_\odot$, as in the WFF1 EOS, then $\sim 25\%$ of all binaries result in prompt collapse. However, if $M_{\text{thres}} = 3.25M_\odot$ (the upper value in the range we discussed in the previous subsection), then the Galactic NS mass function predicts that there are practically no BNSs resulting in prompt collapse. If we use $M_{\text{thres}} \approx 2.8$ [45], which corresponds to the SLy [92] and APR4 [93] EOSs, also favored by GW170817 [85], then the Galactic NS mass function predicts that $\sim 13.5\%$ of all BNSs result in prompt collapse.

The Galactic mass function may not be representative of all BNSs. Thus, we also use results from population synthesis studies [94]. In the left panel of Fig. 1 we show the probability that $M_{\text{tot}} > M_{\text{thres}}$ for one of the standard models of [94] labeled “Standard”, and several variations of the stan-

![Image](image_url)
dard models labeled “##-NSNS,###” (see [94, 95] for the labeling and what parameters are varied). The conclusion from the plot is that there are realizations with a wide tail at large $M_{\text{tot}}$, for which a significant fraction of BNSs result in prompt collapse (even for $M_{\text{thres}} = 3.25M_\odot$). However, there exist realizations for which there are practically no BNSs with $M_{\text{tot}} > M_{\text{thres}}$ (even for $M_{\text{thres}} = 2.75M_\odot$). But, the fact that GW170817 favors softer EOSs, makes prompt-collapse BNS mergers potentially relevant.

Next we address whether any orphan prompt-collapse mergers are expected. As mentioned above, we anticipate that prompt-collapse BNS mergers will eject appreciable matter and form disks for $q < 0.8$. Using Eq. (4) for the Galactic NS mass distribution in BNSs we can compute the $q$ distribution of BNSs. In the right panel of Fig. 1 we show the cumulative distribution of $q$ for Milky-way like BNSs labeled “Galactic”. Thus, for the Galactic mass function more than $\sim 80\%$ of BNSs have $q > 0.9$. We have also checked that this result holds even when restricting to binaries with $M_{\text{tot}}$ greater than $M_{\text{thres}} \in [2.75M_\odot, 3.25M_\odot]$. Moreover, we find that for larger $M_{\text{thres}}$, the distribution of $M_{\text{tot}} > M_{\text{thres}}$ binaries is skewed even more toward $q = 1$. This result is expected because the number of very high mass NSs is very low, and achieving $M_{\text{tot}}$ more than $\sim 3.00M_\odot$ requires $q \sim 1$ binaries.

The $q$ distribution from select population synthesis models is also shown in the right panel of Fig. 1. It is clear that $q \gtrsim 0.8$ in most cases, and there exist realizations where more than $\sim 90\%$ of BNSs have $q > 0.95$. We have also checked that these results hold, even when restricting to binaries with $M_{\text{tot}} > M_{\text{thres}}$. As in the Galactic case, we find in the population synthesis results, too, that the larger $M_{\text{thres}}$ is, the more symmetric binaries with $M_{\text{tot}} > M_{\text{thres}}$ become. In particular, of all 60 variations of population synthesis models available in [95], we find that for $M_{\text{tot}} > M_{\text{thres}}$ only 17, 15 and 3 variations have 20% or more binaries with $q < 0.8$, for $M_{\text{thres}} = 2.75, 2.95,$ and $3.25M_\odot$, respectively.

These results and the discussion in the previous section suggest that the majority of prompt-collapse BNS mergers may be orphan, and hence their most promising EM counterpart may be a non-repeating FRB.

### III. SIMULATIONS AND RESULTS

We performed fully general relativistic, ideal magnetohydrodynamic simulations of BNSs endowed with an initial dipole magnetosphere to assess whether prompt-collapse BNSs have enough energy stored in the remnant magnetosphere to power an FRB. We adopt the code of [96–98]. Our evolution methods and grid set up are the same as those described in [46]. The initial data we adopt are publicly available, have been generated with the LORENE library [99] and correspond to cases P-Prompt-1, P-Prompt-2, and P-Prompt-3 of [46]. These are $\Gamma = 2$ polytropic [100], irrotational BNS initial data. We seed an initial dipole magnetic field in each NS by use of Eq. (2) of [64]. The resulting magnetic field configuration is the same as in [46], but we set the initial polar magnetic field (as measured by comoving observers) to $B_p = 10^{12} \text{G}$. This initial magnetic field is dynamically unimportant, thus our simulations scale with $B_p$. In our results below we show the scaling with $B_{12} = B_p/10^{12} \text{G}$.

The basic dynamics of these systems has been described in [46] where it was shown that these systems form negligibly small disks onto the remnant BH and no jets are launched. We terminate our simulations at the moment a BH apparent horizon appears and compute the energy stored in the magnetosphere as measured by comoving observers in Eq. (9) of [46]. At that time there still exists matter in the BH exterior, thus we compute the magnetospheric energy ($E_B$) only below a certain density which we set to $10^{-3}$ of the maximum density on the grid at that time. We list the measured energy in Table I. As is clear from the table the energy matches well the predictions of Eq. (1).

To estimate the outgoing EM luminosity that is expected to be produced by the “release” of the magnetosphere, we assume that a fraction $\epsilon = 0.8\%$ of $E_B$ is radiated away in $\tau_{\text{FRB}} = 1\text{ms}$. The efficiency $\epsilon$ we adopt is motivated by [72]. The outgoing EM luminosity is estimated as

$$L_{\text{FRB}} \sim \epsilon \frac{E_B}{\tau_{\text{FRB}}} \zeta 10^{43} \epsilon_{0.008} B_{12}^2 \tau_{\text{FRB,1}} \text{erg s}^{-1}.$$ (5)

The $L_{\text{FRB}}$ estimate for each case we simulate is listed in Table I. Thus, the expected burst of the EM radiation $L_{\text{FRB}} \sim 10^{43} \text{erg s}^{-1}$ is fully consistent with FRBs.

We stress that the FRB in the model discussed here is not coming from the collapse only. The inspiral magnetospheric interactions contribute, making it possible to match the observed durations of FRBs, the longest of which are challenging to match by the collapse alone.

### IV. CONCLUSIONS

In this paper, we performed a statistical study of the total mass and mass ratio distribution of BNSs using the Galactic NS mass function and population synthesis models in conjunction with recent constraints on the nuclear EOS from GW170817. We find that up to $\sim 25\%$ of all BNS mergers may result in prompt collapse. Moreover, our analysis shows that most of the considered models of the BNS mass function predict that the majority of prompt-collapse BNS

| Case Model | $E_B/B_{12}$ [erg] | $L_{\text{FRB}}/(B_{12}^2\tau_{\text{FRB,1}})$ [erg s$^{-1}$] |
|-----------|-------------------|---------------------------------|
| P-Prompt-1 | $10^{42.5}$ | $10^{43.4}$ |
| P-Prompt-2 | $10^{40.4}$ | $10^{43.3}$ |
| P-Prompt-3 | $10^{42.5}$ | $10^{43.4}$ |
mergers have $q \gtrsim 0.8$, and that the larger $M_{\text{thres}}$ is, the closer to unity the $q$ distribution of prompt-collapse binaries approaches. Prompt-collapse BNSs with $q > 0.8$ are likely to unbind a negligible amount of mass, and form negligibly small disks onto the remnant black holes. Thus, neither detectable kilonovae nor sGRBs may accompany the GWs from such prompt collapse BNSs. We call these kilonovae- and sGRB-free BNS mergers orphan. Our statistical study suggests that most prompt-collapse BNS mergers may be orphan.

We argued that premerger magnetospheric interactions and the release of energy stored in the magnetosphere of the merger remnant can match the *duration and power* of FRBs. Thus, BNS mergers are promising sources of detectable, non-repeating, *precursor* FRBs, and FRBs may be the most promising electromagnetic counterpart of orphan BNS mergers. The outgoing magnetospheric burst in these cases is rather isotropic, making the detection of coincident FRB and GW signatures possible.

We have also performed magnetohydrodynamic simulations in full general relativity of different BNS configurations that undergo *prompt* collapse. The stars are initially seeded with a dipolar magnetic field that extends from the NS interior into the exterior. We computed the energy stored in the magnetosphere at black hole formation, and estimated the outgoing electromagnetic luminosity produced. We find a luminosity that matches those of FRBs $L_{\text{FRB}} \sim 10^{41} - 10^{43}$ erg s$^{-1}$.

We close with a few caveats: First, our statistical analysis can be refined as soon as ground based GW interferometers unveil the NS mass function in BNSs; second if one is interested in the LIGO/Virgo *observed* mass function, the delay-time distribution should be considered, which we do not account for here; third, some conclusions in our work are based on the size of ejecta and black hole disks found in numerical relativity simulations of prompt-collapse BNS mergers. The number of such simulations is small compared to simulations of BNS mergers resulting in delayed collapse. Therefore, more high resolution simulations in full general relativity of BNSs resulting in prompt collapse are necessary to solidify the results that such mergers unbind negligible amounts of mass and form negligibly small disks onto the remnant black hole, and to find the “critical” mass ratio below which appreciable mass ejection and disks occur. This critical mass ratio is also likely to be equation-of-state dependent. Fourth, whether the FRB signature will be luminous enough depends on the NS surface magnetic field. We adopted a value of $\sim 10^{12} \text{ G}$, but we note that FRB-level luminosities from magnetospheric interactions are possible even from $\sim 10^{11} \text{ G}$ [62]. Finally, with our code we are able to obtain only crude estimates of the energy in the magnetosphere. To assess the full FRB signature in the model considered here requires a code (such as that of [62] [63]) that can evolve through inspiral, merger and prompt collapse to magnetosphere release, while smoothly matching the ideal magnetohydrodynamic stellar interior to a force-free exterior. Such a simulation is currently lacking and will be the subject of future work of ours.

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