

Identifying a First-Order Phase Transition in Neutron-Star Mergers through Gravitational Waves

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We identify an observable imprint of a first-order hadron-quark phase transition at supranuclear densities on the gravitational-wave (GW) emission of neutron-star mergers. Specifically, we show that the dominant postmerger GW frequency f_{peak} may exhibit a significant deviation from an empirical relation between f_{peak} and the tidal deformability if a strong first-order phase transition leads to the formation of a gravitationally stable extended quark matter core in the postmerger remnant. A comparison of the GW signatures from a large, representative sample of microphysical, purely hadronic equations of state indicates that this imprint is only observed in those systems which undergo a strong first-order phase transition. Such a shift of the dominant postmerger GW frequency can be revealed by future GW observations, which would provide evidence for the existence of a strong first-order phase transition in the interior of neutron-stars.

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Introduction.—The theory of strong interactions, quantum chromodynamics (QCD), with quarks and gluons as fundamental degrees of freedom predicts a transition from nuclear matter to quark matter. At a vanishing baryonic chemical potential, numerical solutions of QCD are available, which state a smooth crossover transition at a temperature of $T = 154 \pm 9$ MeV [1–3]. At finite baryon densities only phenomenological models of QCD exist, which are benchmarked by nuclear matter phenomenology around nuclear saturation density $\rho_{\text{sat}} \approx 2.7 \times 10^{14}$ g cm⁻³ [4] and by perturbative QCD at asymptotic densities [5]. Those methods, however, are not applicable in the region of the hadron-quark transition. Hence, the nature of the transition to quark matter (crossover or first-order phase transition) remains unclear. Whether the hadron-quark phase transition occurs at conditions which are found in compact stellar objects, e.g., in neutron-stars (NSs) with central densities of several times ρ_{sat} , is presently unknown. The very first detection of gravitational waves (GWs) from a NS merger [6] highlights the prospect to learn about the presence and the nature of the QCD phase transition in stellar objects; see, e.g., Refs. [7–15].

The merger dynamics and the corresponding GW signal can be divided into an inspiral phase before merging and a

postmerger stage [16–19]. The GW signal prior to the merger allows us to measure the tidal deformability of the progenitor stars, which is encoded in the phase evolution of the orbital motion and the corresponding GW signal [20–30]. During merging, densities and temperatures increase, and hence the postmerger phase probes a different equation of state (EOS) regime. The associated GW signal contains information about the stellar structure of the remnant. Postmerger oscillation frequencies are correlated with the size of the remnant and with radii of nonrotating cold NSs [31–35].

In the present work, we describe a compelling example of the complementarity of pre- and postmerger GW signals. We demonstrate that the joint detection of GWs from both phases can provide a unique observable signature of a first-order hadron-quark phase transition. Previous works have focused on comparisons between individual models with and without phase transition and on describing differences between these models [9,36–39]. While these studies have revealed potential indicators of phase transitions, it is not clear whether the differences observed are indeed an unambiguous signature for a phase transition. To identify clear evidence for a phase transition it is indispensable to ensure that a particular signature can *only* be caused by the

presence of a phase transition. Unless this criterion is met, any observational indication of a phase transition would be degenerate with the uncertainty of the hadronic EOS.

The novelty of our work lies precisely in the fact that we describe a scenario that allows us to uniquely discriminate an EOS with a strong first-order phase transition. To this end, we provide evidence that *all* possible hadronic EOS models yield a different observational signature. We achieve this by considering a large, representative sample of hadronic EOSs that exhibit a clearly distinguishable behavior. In this sense we provide here for the first time an observable signature of a first-order phase transition in NS mergers.

Two aspects are critical. First, a potential signature of a phase transition should involve quantities which are measurable with sufficient precision in future experiments. This has been shown for the tidal deformability [6,22,24–30,40–43] and postmerger GW frequencies [44–49]. Second, the observable quantities under consideration should be determined from theoretical models or simulations with sufficient precision to allow for an interpretation of the measurements. In contrast to, for instance, the remnant lifetime and the precise phase evolution in the postmerger phase, the tidal deformability during inspiral and the oscillation frequencies of the postmerger remnant can be determined with relatively high reliability [16–19,50]. We remark that identifying the impact of a phase transition on the tidal deformability in binaries where at least one component contains a quark core would require highly precise measurements of the masses and tidal deformabilities apart from the problem that massive stars with quark core may be less abundant.

Equations of state.—In this work, we present NS merger simulations with the novel temperature-dependent, microscopic hadron-quark hybrid EOS DD2F-SF of Ref. [51]. Among other purely hadronic EOS models, we consider a nucleonic reference EOS (DD2F) [52–54] and corresponding hybrid EOSs with a phase transition to deconfined quark matter (DD2F-SF) of Ref. [51]. The latter employ the classical two-phase construction, which features a strong first-order phase transition within the standard Maxwell approach. The stiffening of the quark phase admits gravitationally stable stellar configurations with extended quark matter cores, so-called hybrid stars. We consider different choices of parameters for the description of the quark phase resulting in seven specific hybrid EOSs, which cover a variety of different models, i.e., with different onset densities and different density jumps. We dub these EOSs DD2F-SF- n with $n \in \{1, 2, 3, 4, 5, 6, 7\}$. Below we use the acronym DD2F-SF to refer to all seven hybrid models. Details of the microphysical model for DD2F and DD2F-SF are provided in the Supplemental Material along with information about 15 other EOSs, which serve as representative samples of purely hadronic models [55]. (The Supplemental Material includes additional Refs. [4,6,32,41,42,53,54,56–89] with

information on the models and some astrophysical and nuclear physics constraints, which are met by DD2F.) Three of these purely hadronic EOSs include a second-order phase transition to hyperonic matter. Additionally, we employ the EOSs ALF2 and ALF4 from Ref. [83], which resemble models with a more continuous transition to quark matter (with vanishing latent heat) [82].

Simulations.—We perform NS merger simulations with a relativistic smooth particle hydrodynamics code, which imposes the conformal flatness condition [90,91] to solve the Einstein equations (see Refs. [37,92,93] for details and, e.g., Refs. [32–34] for a comparison of GW frequencies with grid-based codes solving the full field equations). The calculations start from circular quasiequilibrium orbits with nonspinning stars a few revolutions before merging. The stars are initially in beta equilibrium at zero temperature. During the evolution temperature effects are taken into account self-consistently if provided by the EOS. For some EOSs where the temperature dependence is not available, we employ an approximate treatment of thermal effects, which requires us to choose a coefficient Γ_{th} (see, e.g., Ref. [94]). It regulates the strength of thermal pressure support. We adopt $\Gamma_{\text{th}} = 1.75$, which reproduces results with fully temperature-dependent EOSs relatively well [94].

We focus on merger simulations for equal-mass systems with a total mass of $M_{\text{tot}} = 2.7 M_{\odot}$, which is comparable to the total mass of GW170817 [6,40,41]. This represents a likely binary configuration according to pulsar observations and population synthesis studies [95,96]. We emphasize that in the future the binary component masses will be measured with good precision for events which are sufficiently close to allow an extraction of EOS effects from the GW signal [97,98]. This justifies the focus on fixed binary masses in our investigation.

We start with a exemplary discussion of DD2F-SF-1, noting that the other models of the DD2F-SF class behave similarly. Figure 1 displays the evolution of the maximum rest-mass density as a function of time for $1.35 M_{\odot} - 1.35 M_{\odot}$ simulations with the DD2F-SF-1 (green line) and the purely hadronic counterpart DD2F (black line). The dotted horizontal green lines indicate the onset density ρ_{onset} of the phase transition at $T = 0$ and 20 MeV for beta equilibrium. During the inspiral phase the central density of the stars is below the transition density and the two systems evolve identically. The two stars merge at about 7 ms and form a single central object associated with a steep increase of the maximum rest-mass density. For the quark matter EOS the density rises above the threshold for the hadron-quark phase transition, reaching the pure quark matter phase. A quark core forms in the center of the merger remnant. The mass enclosed inside the quark matter core comprises about 20%–30% of the total mass. The maximum density in the calculation with the purely hadronic EOS always remains below that of DD2F-SF-1. The stronger density increase in the model with quark matter

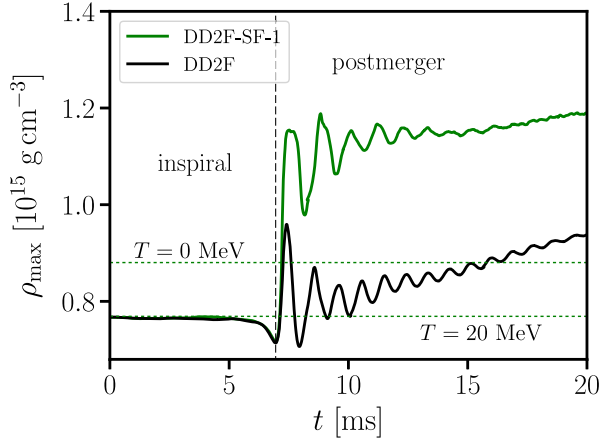


FIG. 1. Evolution of the maximum rest-mass density comparing DD2F-SF-1 (green line) and DD2F (black line) for $1.35 M_{\odot} - 1.35 M_{\odot}$ mergers (solid curves). Horizontal dotted green lines mark the onset density ρ_{onset} of the phase transition for DD2F-SF-1 at $T = 0$ and at 20 MeV.

is a direct consequence of the density jump across the phase transition and the stiffening only at higher densities.

GW spectrum.—The different evolution of the mergers with and without phase transition to quark matter is reflected in the GW signal. Figure 2 shows the GW spectra of the cross polarization at a distance of 20 Mpc along the polar axis comparing the DD2F-SF-1 EOS (green line) and the DD2F EOS (black line). During the premerger phase the GW signals reach a maximum frequency of about 1.7 kHz, and the GW spectra are similar below this frequency. The high-frequency content of the spectra is shaped by the postmerger stage and significant differences between the two simulations are apparent. In particular, the frequency f_{peak} of the dominant oscillation of the postmerger phase is clearly different. This peak is a robust and generic feature that occurs in all simulations which do not directly form a black hole after merging [32,99–103].

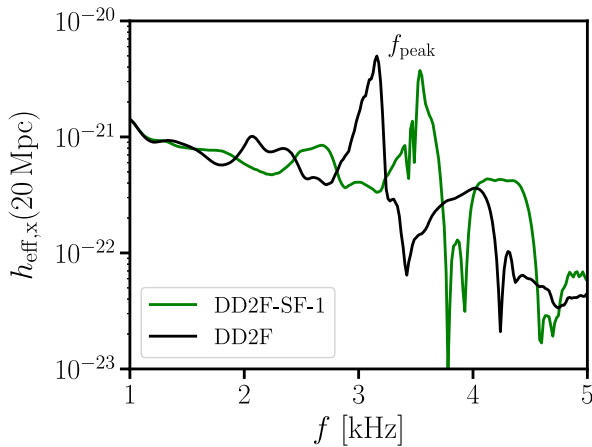


FIG. 2. GW spectrum of the cross polarization at a distance of 20 Mpc along the polar axis comparing the DD2F-SF-1 EOS (green curve) and the DD2F EOS (black curve).

The frequency of the main peak depends sensitively on the EOS [99–101,104]. It has been found [31,32] that f_{peak} scales tightly with radii R of nonrotating cold NSs for different fixed binary masses (cf. Figs. 9–12 and 22–24 in Ref. [32]). In turn, these relations $f_{\text{peak}}(R)$ offer the possibility to determine NS radii from a measurement of the dominant postmerger GW frequency [44–48].

Moreover, during the inspiral phase of NS mergers finite-size effects are measurable and encoded in the tidal deformability $\Lambda = \frac{2}{3} k_2 (R/M)^5$ with the tidal Love number k_2 [21,23]. Considering the strong dependence of Λ on NS radii, it is clear that f_{peak} also correlates with the tidal deformability of NSs (see Fig. 3 and Refs. [105,106] for plots with the tidal coupling constant including different total binary masses). It is conceivable that Λ will be measured with significantly better precision in future observations compared to GW170817, which resulted in a measurement uncertainty on Λ of a $1.4 M_{\odot}$ NS of about 510 at the 90% level [6,40,41]. For instance, an event similar to GW170817 would reduce this error by a factor of about 3 once the detectors reach their design sensitivity [22,24–30]. Similarly, it is expected that the dominant postmerger frequency will be measured to within a few 10 Hz in future nearby events with the projected improvements for the current generation of detectors [44–49].

Observational signature of phase transitions.—In Fig. 3, we show the dominant postmerger frequency f_{peak} as a function of the tidal deformability $\Lambda_{1.35} = \Lambda(1.35 M_{\odot})$ for the $1.35 M_{\odot} - 1.35 M_{\odot}$ mergers for all EOSs of this study. As anticipated, f_{peak} scales tightly with the tidal

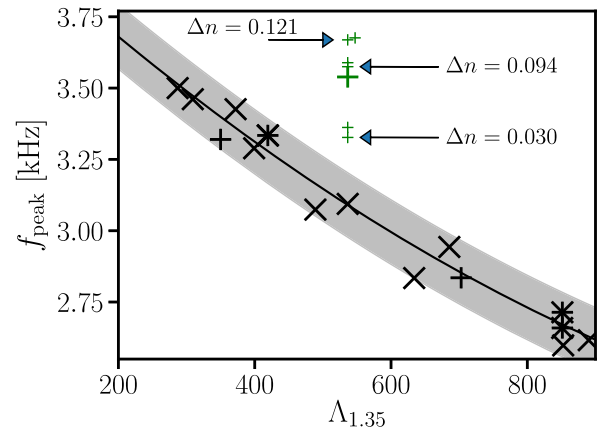


FIG. 3. Dominant postmerger GW frequency f_{peak} as a function of tidal deformability Λ for $1.35 M_{\odot} - 1.35 M_{\odot}$ mergers. The DD2F-SF models with a phase transition to deconfined quark matter (green symbols) appear as clear outliers (big symbol for DD2F-SF-1). Solid curve shows the least-squares fit Eq. (1) for all purely hadronic EOSs (including three models with hyperons marked by asterisks). ALF2 and ALF4 are marked by black plus signs. EOSs incompatible with GW170817 are not shown. Arrows mark DD2F-SF models 3, 6, and 7, which feature differently strong density jumps Δn (in fm^{-3}) with roughly the same onset density and stiffness of quark matter.

deformability for all EOS models (black symbols). There is only one exception: the DD2F-SF EOSs lead to significantly higher peak frequencies of 3.3–3.7 kHz (green symbols). The purely hadronic counterpart of these EOS models without phase transition yields a peak frequency of only 3.098 kHz, while the tidal deformability parameters are identical for both types of EOSs.

Excluding the hybrid models DD2F-SF, ALF2, and ALF4, we obtain a least-squares fit,

$$f_{\text{peak}} = (6.486 \times 10^{-7} \Lambda^2 - 2.231 \times 10^{-3} \Lambda + 4.1) \text{ kHz}, \quad (1)$$

for all purely hadronic EOSs (solid curve in Fig. 3). The maximum deviation between data (black symbols) and the fit Eq. (1) is 113 Hz (gray band in Fig. 3), with an average scatter of 44 Hz [107]. In comparison, for the DD2F-SF-1 model the peak frequency is 448 Hz above the value which is expected from the $f_{\text{peak}}(\Lambda)$ fit for the given tidal deformability of this EOS.

A deviation of nearly 0.5 kHz is significant also if we assume a measurement accuracy of the tidal deformability of 100–200 and of several tens of hertz for the peak frequency. These error bars can be achieved within the next few years for events with distances similar to that of GW170817 [22,24–30,40,44–49,108]. Note that actually the mass ratio $q = M_1/M_2$ and the combined tidal deformability $\tilde{\Lambda}$ are measured during the inspiral (for equal-mass systems $\tilde{\Lambda} = \Lambda$). We also remark that neither $\tilde{\Lambda}$ nor the postmerger frequencies are too strongly affected by small variations of q , which we confirm by additional simulations for $q = 0.8$. These simulations yield $f_{\text{peak}} = 3.79$ kHz and $f_{\text{peak}} = 3.01$ kHz for DD2F-SF-1 and DD2F, respectively, and thus the deviations are even larger. The combined tidal deformability of an asymmetric merger with $q = 0.8$ is to within 5% identical to the one of the equal-mass binary of the same total mass. Hence, small uncertainties in the determination of the mass ratio do not affect our ability to discern models with and without high-density phase transitions.

Three EOSs of our sample include a second-order phase transition to hyperonic matter (BHBLP [68], SFHOY [80], and DD2Y [81]). These EOSs follow closely the $f_{\text{peak}} - \Lambda$ relation similarly to purely nucleonic EOSs. This is in line with the simulations for BHBLP in Ref. [39] showing no significant frequency shift compared to the nucleonic reference model. Similarly, the postmerger frequencies of the calculations with the ALF2 and ALF4 EOSs (involving continuous transitions without density jump) are consistent with the $f_{\text{peak}} - \Lambda$ relation (black plus signs in Fig. 3).

This indicates that only a sufficiently strong first-order phase transition (to deconfined quark matter) with a significant impact on the stellar structure (see Figs. 2 and 3 in the Supplemental Material [55]) can alter the postmerger GW signal in such a way that a measurable deviation from the $f_{\text{peak}} - \Lambda$ relation occurs. In these cases

the formation of a quark matter core in the early postmerger phase leads to a stronger compactification of the remnant and thus to higher oscillation frequencies. The effect is less pronounced for phase transitions which are weaker in the sense that the resulting mass-radius relations deviate less from that of the purely hadronic reference model such as DD2F-SF-4 and DD2F-SF-7 (see Supplemental Material [55]). This is quantitatively supported by considering the increase of f_{peak} as a function of the density jump Δn across the phase transition while approximately fixing other EOS parameters which regulate the onset density and the stiffness of quark matter (symbols marked by arrows in Fig. 3). The deviation from the $\Lambda - f_{\text{peak}}$ relation is stronger for larger density jumps, and weakens for less drastic transitions. We thus explicitly stress that we do not expect that every first-order phase transition would lead to such clearly observable features, but that there is a class of viable hybrid star models that do exhibit the described signature. This would thus be indicative for a transition because the signature cannot result from a purely hadronic EOS, as our representative sample of hadronic models shows. Note that at least in principle, any transition which is formally not first order but which is able to resemble a strong softening of the EOS in a transition region as our DD2F-SF could lead to a similar impact on the stellar structure and thus an increase of f_{peak} .

A measured peak frequency being consistent with the $f_{\text{peak}}(\Lambda)$ fit rules out a strong first-order phase transition as in DD2F-SF and points to either purely hadronic matter or a weak imprint of the phase transition in the probed density regime (cf. Fig. 1). Clearly, an agreement with Eq. (1) cannot inform us about phase transitions at higher densities and about phase transitions which are that strong that they rapidly induce the collapse of the merger remnant (see below).

To understand which density regimes are probed during the postmerger evolution, we extract the largest value $\rho_{\text{max}}^{\text{max}}$ of the maximum rest-mass density $\rho_{\text{max}}(t)$ during the first few milliseconds after merging. In Fig. 1, $\rho_{\text{max}}^{\text{max}}$ is reached at 8.8 ms for DD2F-SF-1 and at 7.4 ms for DD2F. $\rho_{\text{max}}(t)$ can exceed $\rho_{\text{max}}^{\text{max}}$ at later times, but here we are interested in the initial phase when the postmerger GW emission is strongest.

Figure 4 displays $\rho_{\text{max}}^{\text{max}}$ as a function of f_{peak} for all $1.35 M_{\odot} - 1.35 M_{\odot}$ simulations. The figure reveals a correlation between $\rho_{\text{max}}^{\text{max}}$ and f_{peak} , which can be approximated by the least-squares fit,

$$\rho_{\text{max}}^{\text{max}} = (af_{\text{peak}}^2 + bf_{\text{peak}} + c) \text{ g cm}^{-3}, \quad (2)$$

with f_{peak} in kilohertz and $a = 1.89 \times 10^{14}$, $b = -4.13 \times 10^{14}$, and $c = 4.66 \times 10^{14}$ (excluding hybrid models). This result shows that a measurement of f_{peak} can serve as a proxy for the highest rest-mass density which is reached during the initial phase of the postmerger evolution.

If the dominant postmerger GW frequency is in agreement with the $f_{\text{peak}}(\Lambda)$ fit, Eq. (2) approximately

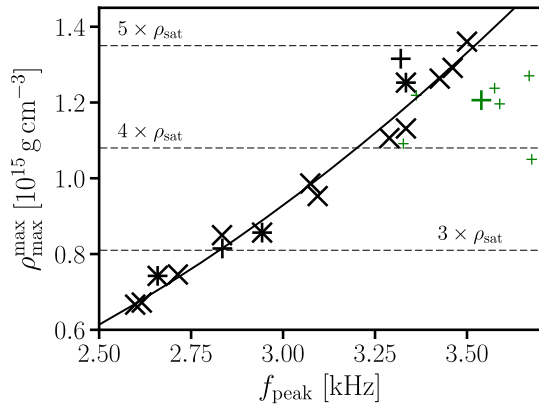


FIG. 4. Maximum rest-mass density $\rho_{\text{max}}^{\text{max}}$ during the first milliseconds of the postmerger phase as a function of the dominant postmerger GW frequency f_{peak} for $1.35 M_{\odot}$ – $1.35 M_{\odot}$ mergers. Green symbols show results for DD2F-SF (big symbol for DD2F-SF-1). Asterisks indicate models with hyperons. Black plus signs indicate ALF2 and ALF4. Solid curve is a second-order polynomial least-squares fit to the data excluding hybrid EOSs.

determines up to which rest-mass density no strong first-order phase transition of similar type as the ones in DD2F-SF occurred for $M_{\text{tot}} = 2.7 M_{\odot}$ (see extended discussion in Supplemental Material [55]).

Relation to other works.—It is instructive to compare our finding with the merger simulations of absolutely stable strange stars [109–112], which do not feature a phase transition at supernuclear densities but a large density jump at the surface. The calculation for the model EOS MIT40 in Ref. [31] yields $f_{\text{peak}} = 2.62$ kHz, while the tidal deformability $\Lambda(1.35 M_{\odot}) = 1161.7$ for this EOS. This model shows a somewhat weaker but similar trend as DD2F-SF in Fig. 3. In principle, a deviation from the fit Eq. (1) may thus also be characteristic for absolutely stable strange quark matter [109,110]. However, this particular model of absolutely stable strange quark matter is incompatible with existing constraints on Λ , and it is likely that a merger of absolutely stable strange stars [37,113] would lead to an electromagnetic counterpart different from that of GW170817 [114]. We thus suspect that such a scenario would be distinguishable from the collision of two hybrid stars as described in this study.

Recently, Ref. [9] used the chiral mean field (CMF) model EOS of Ref. [115] for hadronic and quark matter in merger simulations. Compared to our DD2F-SF, the phase transition of CMF has a very different impact on the stellar structure and consequently on merger simulations (according to Fig. 5 in Ref. [115], this EOS does not yield gravitationally stable hybrid stars with extended quark matter cores). We find a massive gravitationally stable quark matter core with a strong imprint on the postmerger GW frequency for DD2F-SF. In comparison, the CMF EOS leads to a small quark matter fraction during most of the

postmerger evolution. Only at late times the quark matter fraction increases and immediately induces the gravitational collapse of the remnant. Hence, the influence on the GW frequency is significantly weaker compared to our model. In comparison to its purely hadronic reference model, the CMF EOS results in an earlier collapse of the remnant and a dephasing of about 3 rad within 30 cycles. The postmerger frequency is thus shifted only slightly. Such signatures cannot be easily interpreted as being an unambiguous feature for the occurrence of quark matter. A similar phase and frequency shift and a shorter remnant lifetime can as well be expected from a purely hadronic EOS, being somewhat softer at higher densities compared to the CMF hadronic reference model.

In the Supplemental Material [55] we discuss our findings in the context of empirical relations between f_{peak} and radii of nonrotating NSs [31–33].

Summary and conclusions.—In this work, we describe a way to detect a strong first-order phase transition in NSs, complementary to efforts at the future experimental facilities FAIR at GSI and NICA in Dubna dedicated to the study of compressed matter in heavy-ion collisions [116,117]. Our scenario involves quantities which have been shown to be measurable in future GW detections. We provide evidence that the described signature can only be related to a strong first-order phase transition by showing that a representative set of hadronic EOS models behaves differently. These results highlight the complementarity of the information which can be obtained from the inspiral and the postmerger phase of NS mergers. It stresses the importance of kilohertz GW astronomy both with current second-generation [118–121] and proposed third-generation detectors like those in Refs. [122–124]. Future work should consider a larger class of EOS models with a hadron-quark phase transition to determine under which conditions a clearly distinguishable imprint on the GW signal can be identified. We will also investigate other observables like electromagnetic counterparts and secondary features of the GW spectrum.

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- [1] A. Bazavov, H.-T. Ding, P. Hegde, O. Kaczmarek, F. Karsch, E. Laermann, S. Mukherjee, P. Petreczky, C. Schmidt, D. Smith *et al.*, *Phys. Rev. Lett.* **109**, 192302 (2012).
- [2] S. Borsányi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, and K. K. Szabó, *Phys. Lett. B* **730**, 99 (2014).
- [3] A. Bazavov, T. Bhattacharya, C. DeTar, H.-T. Ding, S. Gottlieb, R. Gupta, P. Hegde, U. M. Heller, F. Karsch, E. Laermann *et al.*, *Phys. Rev. D* **90**, 094503 (2014).
- [4] T. Krüger, I. Tews, K. Hebeler, and A. Schwenk, *Phys. Rev. C* **88**, 025802 (2013).
- [5] A. Kurkela, E. S. Fraga, J. Schaffner-Bielich, and A. Vuorinen, *Astrophys. J.* **789**, 127 (2014).
- [6] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), *Phys. Rev. Lett.* **119**, 161101 (2017).
- [7] C. Csáki, C. Eröncel, J. Hubisz, G. Rigo, and J. Terning, *J. High Energy Phys.* **09** (2018) 087.
- [8] V. Paschalidis, K. Yagi, D. Alvarez-Castillo, D. B. Blaschke, and A. Sedrakian, *Phys. Rev. D* **97**, 084038 (2018).
- [9] E. R. Most, L. J. Papenfort, V. Dexheimer, M. Hanauske, S. Schramm, H. Stöcker, and L. Rezzolla, preceding Letter, *Phys. Rev. Lett.* **122**, 061101 (2019).
- [10] S. Han and A. W. Steiner, [arXiv:1810.10967](https://arxiv.org/abs/1810.10967).
- [11] J.-E. Christian, A. Zacchi, and J. Schaffner-Bielich, *Phys. Rev. D* **99**, 023009 (2019).
- [12] M. Sieniawska, W. Turczański, M. Bejger, and J. Leszek Zdunik, [arXiv:1807.11581](https://arxiv.org/abs/1807.11581).
- [13] G. F. Burgio, A. Drago, G. Pagliara, H.-J. Schulze, and J.-B. Wei, *Astrophys. J.* **860**, 139 (2018).
- [14] A. Drago and G. Pagliara, *Astrophys. J. Lett.* **852**, L32 (2018).
- [15] V. Dexheimer, R. de Oliveira Gomes, S. Schramm, and H. Pais, [arXiv:1810.06109](https://arxiv.org/abs/1810.06109).
- [16] J. A. Faber and F. A. Rasio, *Living Rev. Relativity* **15**, 8 (2012).
- [17] L. Baiotti and L. Rezzolla, *Rep. Prog. Phys.* **80**, 096901 (2017).
- [18] V. Paschalidis and N. Stergioulas, *Living Rev. Relativity* **20**, 7 (2017).
- [19] J. L. Friedman, *Int. J. Mod. Phys. D* **27**, 1843018 (2018).
- [20] É. É. Flanagan and T. Hinderer, *Phys. Rev. D* **77**, 021502 (2008).
- [21] T. Hinderer, *Astrophys. J.* **677**, 1216 (2008).
- [22] J. S. Read, C. Markakis, M. Shibata, K. Uryū, J. D. E. Creighton, and J. L. Friedman, *Phys. Rev. D* **79**, 124033 (2009).
- [23] T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, *Phys. Rev. D* **81**, 123016 (2010).
- [24] J. S. Read, L. Baiotti, J. D. E. Creighton, J. L. Friedman, B. Giacomazzo, K. Kyutoku, C. Markakis, L. Rezzolla, M. Shibata, and K. Taniguchi, *Phys. Rev. D* **88**, 044042 (2013).
- [25] W. Del Pozzo, T. G. F. Li, M. Agathos, C. Van Den Broeck, and S. Vitale, *Phys. Rev. Lett.* **111**, 071101 (2013).
- [26] L. Wade, J. D. E. Creighton, E. Ochsner, B. D. Lackey, B. F. Farr, T. B. Littenberg, and V. Raymond, *Phys. Rev. D* **89**, 103012 (2014).
- [27] M. Agathos, J. Meidam, W. Del Pozzo, T. G. F. Li, M. Tompitak, J. Veitch, S. Vitale, and C. Van Den Broeck, *Phys. Rev. D* **92**, 023012 (2015).
- [28] K. Chatziioannou, K. Yagi, A. Klein, N. Cornish, and N. Yunes, *Phys. Rev. D* **92**, 104008 (2015).
- [29] K. Hotokezaka, K. Kyutoku, Y.-i. Sekiguchi, and M. Shibata, *Phys. Rev. D* **93**, 064082 (2016).
- [30] K. Chatziioannou, C.-J. Haster, and A. Zimmerman, *Phys. Rev. D* **97**, 104036 (2018).
- [31] A. Bauswein and H.-T. Janka, *Phys. Rev. Lett.* **108**, 011101 (2012).
- [32] A. Bauswein, H.-T. Janka, K. Hebeler, and A. Schwenk, *Phys. Rev. D* **86**, 063001 (2012).
- [33] K. Hotokezaka, K. Kiuchi, K. Kyutoku, T. Muranushi, Y. I. Sekiguchi, M. Shibata, and K. Taniguchi, *Phys. Rev. D* **88**, 044026 (2013).
- [34] K. Takami, L. Rezzolla, and L. Baiotti, *Phys. Rev. Lett.* **113**, 091104 (2014).
- [35] A. Bauswein and N. Stergioulas, *Phys. Rev. D* **91**, 124056 (2015).
- [36] R. Oechslin, K. Uryū, G. Poghosyan, and F. K. Thielemann, *Mon. Not. R. Astron. Soc.* **349**, 1469 (2004).
- [37] A. Bauswein, R. Oechslin, and H.-T. Janka, *Phys. Rev. D* **81**, 024012 (2010).
- [38] Y. Sekiguchi, K. Kiuchi, K. Kyutoku, and M. Shibata, *Phys. Rev. Lett.* **107**, 211101 (2011).
- [39] D. Radice, S. Bernuzzi, W. Del Pozzo, L. F. Roberts, and C. D. Ott, *Astrophys. J. Lett.* **842**, L10 (2017).
- [40] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), *Phys. Rev. X* **9**, 011001 (2019).
- [41] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya *et al.*, *Phys. Rev. Lett.* **121**, 161101 (2018).
- [42] S. De, D. Finstad, J. M. Lattimer, D. A. Brown, E. Berger, and C. M. Biwer, *Phys. Rev. Lett.* **121**, 091102 (2018).
- [43] M. F. Carney, L. E. Wade, and B. S. Irwin, *Phys. Rev. D* **98**, 063004 (2018).
- [44] J. Clark, A. Bauswein, L. Cadonati, H.-T. Janka, C. Pankow, and N. Stergioulas, *Phys. Rev. D* **90**, 062004 (2014).
- [45] J. A. Clark, A. Bauswein, N. Stergioulas, and D. Shoemaker, *Classical Quantum Gravity* **33**, 085003 (2016).
- [46] K. Chatziioannou, J. A. Clark, A. Bauswein, M. Millhouse, T. B. Littenberg, and N. Cornish, *Phys. Rev. D* **96**, 124035 (2017).
- [47] S. Bose, K. Chakravarti, L. Rezzolla, B. S. Sathyaprakash, and K. Takami, *Phys. Rev. Lett.* **120**, 031102 (2018).
- [48] H. Yang, V. Paschalidis, K. Yagi, L. Lehner, F. Pretorius, and N. Yunes, *Phys. Rev. D* **97**, 024049 (2018).
- [49] A. Torres-Rivas, K. Chatziioannou, A. Bauswein, and J. A. Clark, [arXiv:1811.08931](https://arxiv.org/abs/1811.08931).
- [50] M. D. Duez and Y. Zlochower, *Rep. Prog. Phys.* **82**, 016902 (2019).
- [51] T. Fischer, N.-U. F. Bastian, M.-R. Wu, P. Baklanov, E. Sorokina, S. Blinnikov, S. Typel, T. Klähn, and D. B. Blaschke, *Nat. Astron.* **2**, 980 (2018).
- [52] S. Typel, *Phys. Rev. C* **71**, 064301 (2005).
- [53] S. Typel, G. Röpke, T. Klähn, D. Blaschke, and H. H. Wolter, *Phys. Rev. C* **81**, 015803 (2010).

- [54] D. Alvarez-Castillo, A. Ayriyan, S. Benic, D. Blaschke, H. Grigorian, and S. Typel, *Eur. Phys. J. A* **52**, 69 (2016).
- [55] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.122.061102> for more information on the EOS models used in this study.
- [56] M. Hempel, T. Fischer, J. Schaffner-Bielich, and M. Liebendörfer, *Astrophys. J.* **748**, 70 (2012).
- [57] M. Hempel and J. Schaffner-Bielich, *Nucl. Phys.* **A837**, 210 (2010).
- [58] M. A. R. Kaltenborn, N.-U. F. Bastian, and D. B. Blaschke, *Phys. Rev. D* **96**, 056024 (2017).
- [59] Y. Nambu and G. Jona-Lasinio, *Phys. Rev.* **122**, 345 (1961).
- [60] S. Klevansky, *Rev. Mod. Phys.* **64**, 649 (1992).
- [61] S. B. Rüster, V. Werth, M. Buballa, I. A. Shovkovy, and D. H. Rischke, *Phys. Rev. D* **72**, 034004 (2005).
- [62] D. Blaschke, S. Fredriksson, H. Grigorian, A. M. Öztaş, and F. Sandin, *Phys. Rev. D* **72**, 065020 (2005).
- [63] N.-U. Bastian, D. Blaschke, T. Fischer, and G. Röpke, *Universe* **4**, 67 (2018).
- [64] S. Benic, D. Blaschke, D. E. Alvarez-Castillo, T. Fischer, and S. Typel, *Astron. Astrophys.* **577**, A40 (2015).
- [65] T. Klähn and T. Fischer, *Astrophys. J.* **810**, 134 (2015).
- [66] S. Typel, *Eur. Phys. J. A* **52**, 16 (2016).
- [67] A. Akmal, V. R. Pandharipande, and D. G. Ravenhall, *Phys. Rev. C* **58**, 1804 (1998).
- [68] S. Banik, M. Hempel, and D. Bandyopadhyay, *Astrophys. J. Suppl. Ser.* **214**, 22 (2014).
- [69] S. Goriely, N. Chamel, and J. M. Pearson, *Phys. Rev. C* **82**, 035804 (2010).
- [70] R. B. Wiringa, V. Fiks, and A. Fabrocini, *Phys. Rev. C* **38**, 1010 (1988).
- [71] G. Shen, C. J. Horowitz, and S. Teige, *Phys. Rev. C* **83**, 035802 (2011).
- [72] J. M. Lattimer and F. Douglas Swesty, *Nucl. Phys.* **A535**, 331 (1991).
- [73] G. A. Lalazissis, J. König, and P. Ring, *Phys. Rev. C* **55**, 540 (1997).
- [74] A. W. Steiner, M. Hempel, and T. Fischer, *Astrophys. J.* **774**, 17 (2013).
- [75] F. Douchin and P. Haensel, *Astron. Astrophys.* **380**, 151 (2001).
- [76] Y. Sugahara and H. Toki, *Nucl. Phys.* **A579**, 557 (1994).
- [77] H. Toki, D. Hirata, Y. Sugahara, K. Sumiyoshi, and I. Tanihata, *Nucl. Phys.* **A588**, c357 (1995).
- [78] A. Bauswein, S. Goriely, and H.-T. Janka, *Astrophys. J.* **773**, 78 (2013).
- [79] A. Bauswein, N. Stergioulas, and H.-T. Janka, *Phys. Rev. D* **90**, 023002 (2014).
- [80] M. Fortin, M. Oertel, and C. Providência, *Pub. Astron. Soc. Aust.* **35**, e044 (2018).
- [81] M. Marques, M. Oertel, M. Hempel, and J. Novak, *Phys. Rev. C* **96**, 045806 (2017).
- [82] M. Alford, M. Braby, M. Paris, and S. Reddy, *Astrophys. J.* **629**, 969 (2005).
- [83] J. S. Read, B. D. Lackey, B. J. Owen, and J. L. Friedman, *Phys. Rev. D* **79**, 124032 (2009).
- [84] P. Danielewicz, R. Lacey, and W. G. Lynch, *Science* **298**, 1592 (2002).
- [85] C. Y. Tsang, M. B. Tsang, P. Danielewicz, W. G. Lynch, and F. J. Fattoyev, [arXiv:1807.06571](https://arxiv.org/abs/1807.06571).
- [86] J. M. Lattimer and Y. Lim, *Astrophys. J.* **771**, 51 (2013).
- [87] J. Antoniadis, P. C. C. Freire, N. Wex, T. M. Tauris, R. S. Lynch, M. H. van Kerkwijk, M. Kramer, C. Bassa, V. S. Dhillon, T. Driebe *et al.*, *Science* **340**, 1233232 (2013).
- [88] Z. Arzoumanian, A. Brazier, S. Burke-Spolaor, S. Chamberlin, S. Chatterjee, B. Christy, J. M. Cordes, N. J. Cornish, F. Crawford, H. Thankful Cromartie *et al.*, *Astrophys. J. Suppl. Ser.* **235**, 37 (2018).
- [89] A. Bauswein, O. Just, H.-T. Janka, and N. Stergioulas, *Astrophys. J. Lett.* **850**, L34 (2017).
- [90] J. R. Wilson, G. J. Mathews, and P. Marronetti, *Phys. Rev. D* **54**, 1317 (1996).
- [91] J. Isenberg and J. Nester, in *General Relativity and Gravitation. Vol. 1. One Hundred Years after the Birth of Albert Einstein*, edited by A. Held (Plenum Press, New York, 1980), p. 23.
- [92] R. Oechslin, S. Rosswog, and F.-K. Thielemann, *Phys. Rev. D* **65**, 103005 (2002).
- [93] R. Oechslin, H.-T. Janka, and A. Marek, *Astron. Astrophys.* **467**, 395 (2007).
- [94] A. Bauswein, H.-T. Janka, and R. Oechslin, *Phys. Rev. D* **82**, 084043 (2010).
- [95] M. Dominik, K. Belczynski, C. Fryer, D. E. Holz, E. Berti, T. Bulik, I. Mandel, and R. O’Shaughnessy, *Astrophys. J.* **759**, 52 (2012).
- [96] J. M. Lattimer, *Annu. Rev. Nucl. Part. Sci.* **62**, 485 (2012).
- [97] C. L. Rodriguez, B. Farr, V. Raymond, W. M. Farr, T. B. Littenberg, D. Fazi, and V. Kalogera, *Astrophys. J.* **784**, 119 (2014).
- [98] B. Farr, C. P. L. Berry, W. M. Farr, C.-J. Haster, H. Middleton, K. Cannon, P. B. Graff, C. Hanna, I. Mandel, C. Pankow *et al.*, *Astrophys. J.* **825**, 116 (2016).
- [99] M. Shibata, K. Taniguchi, and K. Uryū, *Phys. Rev. D* **71**, 084021 (2005).
- [100] M. Shibata and K. Taniguchi, *Phys. Rev. D* **73**, 064027 (2006).
- [101] R. Oechslin and H.-T. Janka, *Phys. Rev. Lett.* **99**, 121102 (2007).
- [102] K. Hotokezaka, K. Kyutoku, H. Okawa, M. Shibata, and K. Kiuchi, *Phys. Rev. D* **83**, 124008 (2011).
- [103] A. Bauswein, T. W. Baumgarte, and H.-T. Janka, *Phys. Rev. Lett.* **111**, 131101 (2013).
- [104] X. Zhuge, J. M. Centrella, and S. L. W. McMillan, *Phys. Rev. D* **54**, 7261 (1996).
- [105] S. Bernuzzi, T. Dietrich, and A. Nagar, *Phys. Rev. Lett.* **115**, 091101 (2015).
- [106] L. Rezzolla and K. Takami, *Phys. Rev. D* **93**, 124051 (2016).
- [107] The fit parameters as well as the deviations from the fit depend slightly on the chosen sample of EOS models; employing a large set of EOSs we expect to diminish any bias.
- [108] R. Dudi, F. Pannarale, T. Dietrich, M. Hannam, S. Bernuzzi, F. Ohme, and B. Brügmann, *Phys. Rev. D* **98**, 084061 (2018).
- [109] A. R. Bodmer, *Phys. Rev. D* **4**, 1601 (1971).
- [110] E. Witten, *Phys. Rev. D* **30**, 272 (1984).

- [111] C. Alcock, E. Farhi, and A. Olinto, *Astrophys. J.* **310**, 261 (1986).
- [112] P. Haensel, J.L. Zdukun, and R. Schaefer, *Astron. Astrophys.* **160**, 121 (1986).
- [113] A. Bauswein, H.-T. Janka, R. Oechslin, G. Pagliara, I. Sagert, J. Schaffner-Bielich, M.M. Hohle, and R. Neuhäuser, *Phys. Rev. Lett.* **103**, 011101 (2009).
- [114] B.P. Abbott, R. Abbott, T.D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V.B. Adya *et al.*, *Astrophys. J. Lett.* **848**, L12 (2017).
- [115] V.A. Dexheimer and S. Schramm, *Phys. Rev. C* **81**, 045201 (2010).
- [116] *The CBM Physics Book*, edited by B. Friman, C. Höhne, J. Knoll, S. Leupold, J. Randrup, R. Rapp, and P. Senger, Lecture Notes in Physics Vol. 814 (Springer-Verlag, Berlin, 2011).
- [117] D. Blaschke, J. Aichelin, E. Bratkovskaya, V. Friese, M. Gazdzicki, J. Randrup, O. Rogachevsky, O. Teryaev, and V. Toneev, *Eur. Phys. J. A* **52**, 267 (2016).
- [118] J. Aasi, B.P. Abbott, R. Abbott, T. Abbott, M.R. Abernathy, K. Ackley, C. Adams, T. Adams, P. Addesso *et al.* (LIGO Scientific Collaboration), *Classical Quantum Gravity* **32**, 115012 (2015).
- [119] J. Aasi, B.P. Abbott, R. Abbott, T. Abbott, M.R. Abernathy, K. Ackley, C. Adams, T. Adams, P. Addesso *et al.* (LIGO Scientific Collaboration), *Classical Quantum Gravity* **32**, 115012 (2015).
- [120] F. Acernese, M. Agathos, K. Agatsuma, D. Aisa, N. Allemandou, A. Allocca, J. Amarni, P. Astone, G. Balestri, G. Ballardin *et al.*, *Classical Quantum Gravity* **32**, 024001 (2015).
- [121] LIGO Scientific Collaboration, LIGO Document Control Center, <https://dcc.ligo.org/LIGO-T1700231/public>.
- [122] M. Punturo, M. Abernathy, F. Acernese, B. Allen, N. Andersson, K. Arun, F. Barone, B. Barr, M. Barsuglia, M. Beker *et al.*, *Classical Quantum Gravity* **27**, 084007 (2010).
- [123] S. Hild, M. Abernathy, F. Acernese, P. Amaro-Seoane, N. Andersson, K. Arun, F. Barone, B. Barr, M. Barsuglia, M. Beker *et al.*, *Classical Quantum Gravity* **28**, 094013 (2011).
- [124] J. Miller, L. Barsotti, S. Vitale, P. Fritschel, M. Evans, and D. Sigg, *Phys. Rev. D* **91**, 062005 (2015).