Post-merger gravitational-wave signatures of phase transitions in binary mergers

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With the first detection of gravitational waves from a binary system of neutron stars (BNS), GW170817, a new window was opened to study the properties of matter at and above nuclear saturation density. Reaching densities a few times that of nuclear matter and temperatures up to 100 MeV, such mergers also represent potential sites for a phase transition (PT) from confined hadronic matter to deconfined quark matter. While the lack of a post-merger signal in GW170817 has prevented us from assessing experimentally this scenario, two theoretical studies have explored the post-merger gravitational-wave signatures of PTs in BNS mergers. We here extend and complete the picture by presenting a novel signature of the occurrence of a PT. More specifically, using fully general-relativistic hydrodynamic simulations and employing a suitably constructed equation of state that includes a PT, we present the occurrence of a "delayed PT", i.e., a PT that develops only some time after the merger and produces a metastable object with a quark-matter core, i.e., a hypermassive hybrid star. Because in this scenario, the post-merger signal exhibits two distinct fundamental gravitational-wave frequencies – before and after the PT – the associated signature promises to be the strongest and cleanest among those considered so far, and one of the best signatures of the production of quark matter in the present Universe.

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Introduction. The first detection of gravitational waves from a merging binary system of neutron stars [1], GW170817, and of its electromagnetic counterpart [2] has provided a wealth of information not only on the nature of gravity, but also on the properties of the equation of state (EOS) of nuclear matter [3–11]. The understanding of all the information extracted from this event was aided by numerical simulations that predicted the properties of the gravitational-wave signal [12–19] and the kilonova resulting from radioactive decay of heavy elements that are produced via r-process in the merger’s ejected material [20–26]. These simulations have shown that after the inspiral and merger, a hypermassive neutron star (HMNS) is formed. The fate of the HMNS depends on a number of factors, such as the mass, mass ratio, strength of the magnetic field, and, of course, the underlying EOS. An important degree of freedom associated with the EOS is the possibility of a phase transition (PT) from hadronic to quark matter. Indeed, considering the high densities in neutron-star cores (up to $\rho \sim (6 - 7) \rho_0$, where $\rho_0$ is the nuclear-saturation density [27]), EOSs that allow for a PT have received increasing attention in the recent past [9, 28–31].

However, the lack of the detection of a post-merger signal from merging BNSs leaves the issue of the occurrence of a PT still unsettled, but it also motivates all those theoretical studies that can highlight the various manifestations in which this process will reveal itself [32–34]. In this Letter, we introduce a novel signature in which a PT can be detected from the post-merger gravitational-wave signal of a BNS system. This new signature, besides extending and completing our understanding of the occurrence of a PT in BNS mergers, also promises to be the signature that, better than those considered so far, will signal the production of quark matter in the present Universe.

Before discussing the results of our simulations, it is useful to describe on general grounds the different manifestations in which a PT from hadronic to quark matter can take place in a BNS merger. These manifestations are best understood when looking at the instantaneous characteristic frequency of the gravitational-wave signal, $f_{\text{GW}}$, as normally shown in spectrograms. To this scope, Fig. 1 shows schematically the evolution of $f_{\text{GW}}$ and identifies four different scenarios:

- No phase transition (NPT; light-blue line): this is the standard case considered so far in BNS simulations, where no PT sets in after merger and the stars are always fully hadronic (see, e.g., [35, 36] for some reviews).
- Prompt phase transition (PPT; green line): the PT sets in right after the merger. As in the NPT-scenario, the dominant frequency settles down to a constant value which is significantly higher than it would be in the absence of a PT and can violate universal relations [12–16, 18], thus providing a signature of the PT [34].
- Phase-transition triggered collapse (PTTC; dark-blue line): after the merger, the remnant’s core does not immediately undergo the PT, which sets in later on, when the density in the remnant’s core reaches a critical value. The prompt softening of the EOS and the consequent increase in density leads to the collapse to a black hole (BH). The premature ringdown signal represents a signature of the occurred PT [33].
- Delayed phase transition (DPT; light-red line): similar to the PTTC-scenario, the PT sets in only some time after the merger. In contrast to the PTTC-scenario, the softening of the EOS does not lead to a collapse, but to a metastable hypermassive hybrid star (HMHS) emitting gravitational waves at higher frequencies. The presence of two distinct and clear characteristic frequencies represents a strong signature of the occurred PT.

While the NPT scenario has been studied extensively and the PTTC and PPT scenarios have been discussed recently [33, 34], in what follows we illustrate the new DPT scenario.
Methods and setup. For the hadronic phase of the cold EOS, the FSU2H relativistic mean-field model has been used [37, 38]. Similar to the Model–2 of Ref. [28], a first-order transition from hadronic to a quark matter has been incorporated by assuming a moderate value of the surface tension of deconfined quark matter droplets within the mixed phase. At zero temperature, this mixed phase follows the Gibbs conditions [39] leading to hadron-quark pasta phase structures [40]. The softening of the EOS within the mixed phase and its stiffening in the pure quark-matter phase has been modeled by two additional pieces of the EOS, following a polytropic dependence. The overall cold EOS used within our numerical approach (FSU2H-PT) consists of a piecewise polytropic representation [41] of the hadronic FSU2H model, a soft mixed phase region which starts at $2.085 \rho_0$ (polytropic index $\Gamma = 1.04$) and a stiff pure quark-matter part for densities above $4.072 \rho_0$ (polytropic index $\Gamma = 5.1$). In order to ensure that the sound speed of deconfined quark matter is always below the speed of light, three additional piecewise polytropes have been added for ultra-high densities ($\rho/\rho_0 = 4.823, 4.969, 5.289; \Gamma = 4.7, 4.1, 3.1$). The specific value of the EOS results in a hybrid star model with a small twin-star branch belonging formally to the twin-star Category III (for details see [28]). We should note that the EOS considered here is not necessarily the most realistic one and a different choice of EOS parameters would increase the range in mass between the DPT and PTTC scenarios. However, as in previous studies [33, 34], the EOS has been constructed mostly to highlight the impact that a PT would have on the gravitational-wave signal.

To account for additional shock heating during the merger and post-merger phase, thermal effects are included by adding an ideal-fluid thermal component to the cold EOS. The total pressure $p$ and the specific internal energy $\epsilon$ are therefore composed of the cold part ($p_c, \epsilon_c$) and a “thermal” ideal-fluid component ($p_{th}, \epsilon_{th}$) where $p = p_c + p_{th} = K \rho^\Gamma + \rho \epsilon_{th} (\Gamma_{th} - 1)$, $\epsilon = \epsilon_c + \epsilon_{th}$, where $p$ is the rest-mass density, $K$ the polytropic constant and $\Gamma_{th} = 1.75$. The effective temperature obtained within this ideal-gas approach can be roughly approximated as $T = (m_n p_{th})/(k_n \rho)$, where $m_n$ is the nucleonic mass and $k_n$ the Boltzmann constant.

The simulations are performed by solving the coupled Einstein-hydrodynamic equations [41] implemented within the general framework of the Einstein Toolkit [42]. The spacetime is evolved by the thorn McLachlan [43], which implements the conformal and covariant CCZ4 formulation of the Einstein equations [44] using the same gauge conditions as in [22, 45]. The equations of general-relativistic hydrodynamics are solved by the WhiskyTHC code [46, 47] via a high-order finite-differencing scheme using the HLLE approximate Riemann solver, the MP5 reconstruction scheme and a positivity-preserving limiter. For the time integration, we use the method-of-lines with a third-order Runge-Kutta scheme and a CFL number of 0.15 [41].

The initial irrotational binary configuration is computed with the LORENE code [48], using an initial separation of 45 km. The grid is handled by the thorn Carpet [49], which implements box-in-box adaptive mesh refinement. We use six refinement levels with the finest level having a resolution of $dx = 0.16 M_\odot (\approx 237 \text{ m})$, while the outer boundary is placed at a distance of $\sim 1500 \text{ km}$ (simulations at higher and smaller resolutions have also been performed yielding consistent results; for compactness, we will omit their discussion here). Furthermore, we reflect the grid across the $z = 0$ plane to reduce the computational cost.

Results. Hereafter, we concentrate on two different and representative equal-mass irrotational BNSs with $M = 2.64 M_\odot$ (low-mass) and $2.68 M_\odot$ (high-mass) for each of the two
EOSs, i.e., with (FSU2H-PT) and without (FSU2H) a PT, for a total of four simulations (the radii of the initial stars are 13.11 and 13.13 km, respectively). Figure 2 shows the evolution of the maximum rest-mass density, $\rho_{\text{max}}$, which is representative of the density within the core of the merged object. As the evolution of BNSs without PT is relatively well studied (see [35, 36] for recent reviews) and the matter in the NPT case is always purely hadronic we here focus on describing the two simulations with PT and show the two simulations without PT only for comparison as light-red and -blue lines in Fig. 2.

During the inspiral all models have densities below the onset of the PT, so that the stars in this stage consist of purely hadronic matter. After merger, the densities increase to values above the threshold for the mixed phase of the cold EOS, but then quickly fall back below this threshold. This local increase is simply due to the large compression experienced by the stellar cores at the time of the merger and unless a PT is triggered promptly (PPT case), $\rho_{\text{max}}$ returns to the typical values of the inspiral, so that the HMHS consists of purely hadronic matter.

The large oscillations of the merged object cause the density in its core to increase gradually and to reach values above the threshold of the mixed phase. Under these conditions, the EOS softens significantly which, in turn, amplifies the increase in density and leads to a considerable conversion of hadrons to quarks. The latter are mostly concentrated in the core of the merged object, which comprises $\sim 20\%$ of the mass of the binary, as already found in [33, 34]. The subsequent evolution of the merged object will depend on the total mass of the binary. More specifically, in the case of the high-mass binary ($M = 2.68 M_\odot$, dark-blue line in Fig. 2), the density experiences large oscillations, increasing considerably so as to reach values $\rho_{\text{max}} \approx (5 - 7) \rho_0$ and entering the pure-quark phase. Once the PT is complete, the resulting EOS is considerably softer in the mixed phase but also stiffer in the pure-quark phase. However, the mass is sufficiently large so that gravity prevails and hence the HMHS collapses rapidly to a BH. Despite the short time that the quark core survives prior to collapse, the fact that the collapse is still a direct cause of the PT essentially categorizes this evolution as PTTC scenario which was already encountered in [33]. Instead, in the case of the low-mass binary ($M = 2.64 M_\odot$, red line in Fig. 2), the density also increases again entering the pure-quark phase via large – but comparatively smaller – oscillations, and thus marking the occurrence of the PT. However, quite differently from the PTTC case, the new HMHS settles down to a new metastable configuration with higher central density, $\rho_{\text{max}} \approx (4 - 5) \rho_0$, and thus becomes a steady emitter of gravitational waves with a new and higher characteristic frequency. This new equilibrium is again the result of the subtle balance between a softening of the EOS in the mixed phase and a stiffening in the quark core. However, in contrast with the high-mass binary that collapses to a BH, for the low-mass binary, the stiffening is sufficient to prevent the collapse and yield a metastable equilibrium.

Much of what was illustrated above for $\rho_{\text{max}}$ is faithfully reproduced by the gravitational-wave signal. This is shown in Fig. 3, which reports in the top panels the $\ell = 2 = m$ component of the strain in the $+$ polarization, $h_{+}^{22}$, for the four simulations (the blue shadings marking the various phases of matter use the same convention as in Fig. 2). The bottom panels, instead, show the corresponding spectrograms together with the instantaneous maximum of the power spectral density (white line) and the instantaneous gravitational-wave frequency (red line).

From left to right, the four panels show first the cases of the high-mass binaries (without and with a PT) and subsequently those of the low-mass binaries (without and with a
PT). The properties of the waveforms in the absence of a PT (NPT cases; first and third columns) have been described many times in the literature [12–17] and basically exhibit the transition at merger from a chirping frequency over to a triplet of peaks, i.e., \( f_1, f_2, f_3 \) [13], with the highest and lowest frequencies disappearing after \( \sim 5 \text{ ms} \) when the transient phase of the merger is complete (see [14] for a simple explanation).

The second column reports instead the case of a PTTC and shows that after the PT has started developing, a sudden jump is measured in the spectrogram, with the HMHS emitting gravitational waves at higher and increasing frequencies as the collapse proceeds and ends with the formation of a BH. While a strong signature of the occurred PT, this scenario may be difficult to detect because the emission at higher frequencies is rapidly replaced by the incipient collapse to black hole.

Finally, the fourth column reports the new case of a DPT and shows that after the PT has started developing, a progressive transition to a signal at higher frequencies can be measured as the HMHS moves to a new metastable equilibrium characterised by a pure-quark core, which is more compact and hence emitting gravitational waves at higher frequencies. This transition can be easily appreciated both in the time domain through the different shadings but, more transparently, from the evolution of the maximum frequency in the spectrogram. In the specific case considered here, this transition takes place between 4 and 7 ms, but this is mostly the result of our specific setup and could be made to take place at different times after suitable tuning of the parameters that define the EOS. What is important is that the post-merger signal in a DPT scenario will exhibit a spectrogram moving from a quasi-stationary low-frequency \( f_2 \), over to a new quasi-stationary high-frequency \( f_2 \), where the relative difference \( \Delta f_2/f_2 \sim 25\% \) is robust at different resolutions. Because emission at constant frequencies leads to distinctive peaks in the post-merger gravitational-wave spectrum [13], the signature of a DPT promises to be the strongest of those considered so far.

Finally, Fig. 4 shows a comparison of the rest-mass density (left panel) and temperature (right panel) distributions on the \((x, y)\) plane for the low-mass binary at a representative time during the post-merger evolution (\( t = 12.85 \text{ ms} \)). In particular, for each panel, the left portion refers to the binary experiencing the PT, while the right portion illustrates the corresponding quantities in the absence of a PT. It is interesting to note that the BNS undergoing the PT exhibits a much denser core, with densities that are almost twice as large as in the absence of a PT. Such a core occupies a considerable fraction of the central regions of the HMHS, while the mixed phase is concentrated on a rather thin shell of \( \sim 1 \text{ km} \) thickness. Marked differences can be found also in the temperature, which is considerably higher in the binary with a PT. In both cases, however, the central region is comparatively colder and the largest values in temperature are concentrated in two opposite hot spots, which later evolve into a ring-like structure [45, 50]. Furthermore, in the case of a PT, these two hot-spots on either side of the core appear together with a “hot-ring”. While the two hot-spots mark the highest temperatures for the purely hadronic regions of the HMHS, the hot-ring falls within the mixed-phase region. Indeed, the formation of this hot-ring takes place a few milliseconds after the core underwent the PT and was therefore not visible in the simulations reported in [33].

**Conclusions.** Exploiting the recent advances in the simulation of BNSs with an EOS that allows for a PT [33, 34], we have introduced the first classification of the post-merger gravitational-wave signatures of the occurrence of a PT. The picture that emerges from this classification was completed by the discussion of a novel scenario, which we refer to as
that of a delayed phase transition (DPT). In this scenario, the softening of the EOS resulting from the PT does not lead to the rapid collapse to a BH, but to a metastable HMHS emitting gravitational waves at higher frequencies. As a result, the post-merger signal in a DPT will be characterised by an initial quasi-stationary low-frequency emission corresponding to a (mostly) hadronic HMHS, which then increases over a timescale of a few milliseconds – to reach a new quasi-stationary high-frequency emission corresponding to a HMHS with a significant quark core. Since a post-merger gravitational-wave emission with marked peaks is comparably easier to characterise, the signature of the novel DPT promises to be the strongest in the proposed classification and hence the optimal signature to witness the creation of quark matter in the present Universe.

As a concluding remark, we note that our classification of the occurrence of a PT refers to the post-merger only since this is when the critical densities (and temperatures) for the onset of a PT are more likely to be reached. However, depending on the mass and mass ratio in the binary system, a PT might take place already during the inspiral (e.g., in systems comprising a hybrid and a hadronic star or two hybrid stars), thus enriching the range of manifestations in which a PT may appear. We plan to explore these scenarios in future studies.

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