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Exploring the quark-hadron phase transition with gravitational waves

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We present a detectable and unambiguous feature of a strong first-order phase transition (PT) from hadronic to deconfined quark matter encoded in the gravitational wave (GW) signal of a binary neutron star merger. If the PT takes places after the merger it can increase the dominant postmerger frequency relative to the tidal deformability, a quantity, inferred from the premerger signal. We also observe a tight correlation between the dominant postmerger GW frequencies and the largest densities in the system shortly after the merger. By combining both findings we demonstrate that a single, accurate measurement of pre- and postmerger gravitational waves has the potential to yield constraints on the onset density of quark deconfinement.

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1. Introduction

Neutron stars (NSs) offer a unique possibility to study matter above nuclear saturation density. Currently, the state of matter in this environment is still not completely understood. With increasing density, a PT from hadronic to deconfined quark matter is expected to occur eventually. However, the exact onset density of quark deconfinement remains unknown. It is hence unclear, whether this PT is present in the interiors of NSs.

A new possibility to investigate the properties of dense matter has come with the advent of GW astronomy. The first GWs from a binary NS merger were observed in 2017 in the famous GW170817 event [1]. With many more similar observations anticipated in the coming years major advancements in our understanding of NS matter are expected.

In this work we use results from simulations to present a procedure that unambiguously identifies a strong PT taking place in the merger remnant. We also present a scheme to estimate the largest densities occurring in the remnant shortly after the merger. The combination of both findings can provide constraints on the onset density of the quark-hadron PT from a single, sufficiently accurate measurement of pre- and postmerger GWs. More details on this can be found in Ref. [2].

2. Identifying a strong phase transition with gravitational waves

In Refs. [2, 3] we performed several numerical NS merger simulations with a large group of purely hadronic equations of state (EoSs) as well as the hybrid EoS models of Ref. [4], where the latter feature a strong first-order PT to deconfined quark matter.

For purely hadronic EoSs we find a tight relation between the combined tidal deformability $\tilde{\Lambda}$ of the inspiraling NSs and the dominant postmerger gravitational wave frequency f_{peak}.

$\tilde{\Lambda}$ describes finite-size effects in waveform models and is defined as

$$\tilde{\Lambda} = \frac{16}{13}\frac{(M_1 + 12M_2)M_1^4\Lambda_1 + (M_2 + 12M_1)M_2^4\Lambda_2}{(M_1 + M_2)^5} \,. \tag{1}$$

Here, $\Lambda_{1,2}$ refer to the tidal deformabilities of the individual stars with masses $M_{1,2}$. The tidal deformability of a single neutron star $\Lambda = \frac{2}{3}k_2\left(\frac{R}{M}\right)^5$ with the stellar mass M, the stellar radius R and the tidal love number k_2 [5] quantifies the quadrupolar deformation of this star in an external tidal field.

We show the relation between $\tilde{\Lambda}$ and f_{peak} for hadronic EoSs (black crosses) in Figure 1 for 1.35-1.35 $M_{\odot}$ binaries. The black line is a least squares fit with a second order polynomial and the grey-shaded area visualizes the maximum deviation of the crosses from the fit.

Results from hybrid EoS models featuring a strong PT to deconfined quark matter (green plus signs) violate this relation as they have larger f_{peak} than hadronic EoSs for similar $\tilde{\Lambda}$. This is because no deconfined quark matter present before the merger in our hybrid models. Once the stars have collided, the transition sets in softening the EoS and hence increasing the densities in the remnant. This shifts f_{peak} but $\tilde{\Lambda}$, which is inferred from the inspiral signal, is not affected by the PT. Hence the hybrid EoSs violate the f_{peak}–$\tilde{\Lambda}$ relation. This deviation is an unambiguous feature of a strong PT as all hadronic models behave differently. We emphasize however, that the PT has to be strong for this method. A weak PT only leading to a minor shift in f_{peak} will likely not be distinguishable

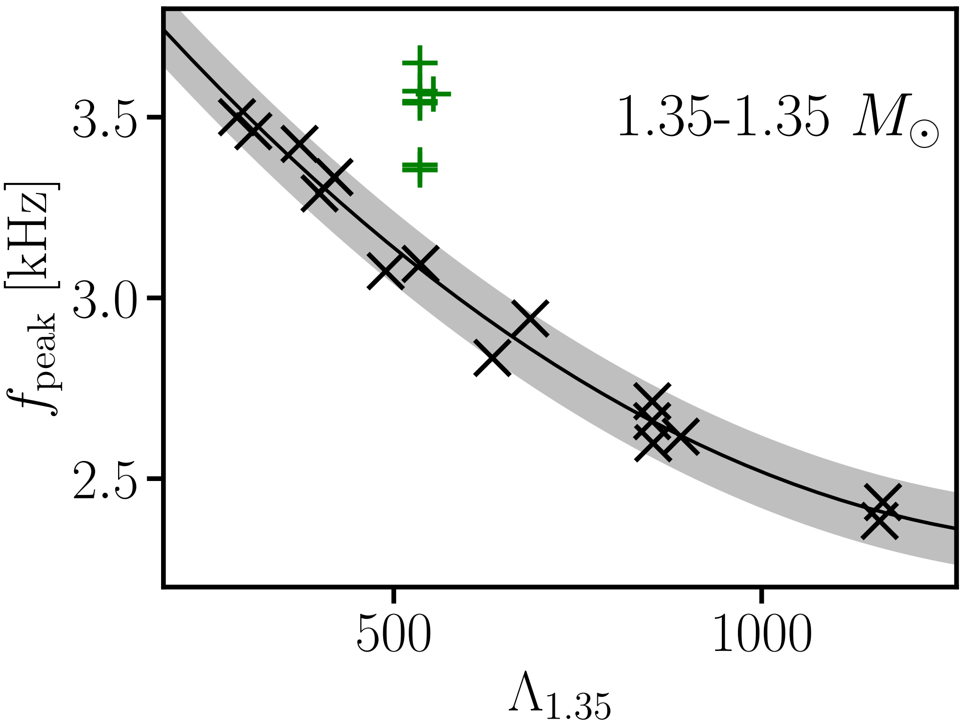

Figure 1: Dominant postmerger GW frequency $f_{\rm peak}$ as a function of the combined tidal deformability $\tilde{\Lambda}$ for 1.35-1.35 $M_\odot$ mergers with different microphysical EoSs. Black crosses show results with purely hadronic EoSs, green plus signs are results with the hybrid DD2F-SF models. Figure adopted from Ref. [2].

from a system with no PT.
We provide similar plots and relations for other binary mass configurations in Ref. [2].

3. Constraining the onset density

In Ref. [2] we further investigate a finding of Ref. [3] that for purely hadronic EoSs the maximum density occurring in the system within the first 5 ms after the merger $\rho_{\rm max}^{\rm max}$ also scales with $f_{\rm peak}$. This means that a precise measurement of $f_{\rm peak}$ can provide an estimate on the largest densities appearing in the remnant while the emission of GWs is strongest.
By combining this finding with our method to identify a PT we provide a constraint on the onset density $\rho_{\rm onset}$ of the hadron-quark PT once $f_{\rm peak}$ and $\tilde{\Lambda}$ are measured simultaneously. For this we combine the $f_{\rm peak}$–$\tilde{\Lambda}$ and the $\rho_{\rm max}^{\rm max}$–$f_{\rm peak}$ relations into a single $\rho_{\rm max}^{\rm max}$–$\tilde{\Lambda}$ relation. If the inferred $f_{\rm peak}$ and $\tilde{\Lambda}$ are consistent with our empirical relation we conclude that no strong PT took place in the system. In this case the $\rho_{\rm max}^{\rm max}$–$\tilde{\Lambda}$ relation can be used to estimate the maximum density in the system. This density then serves as a lower limit on $\rho_{\rm onset}$. On the other hand if $f_{\rm peak}$ clearly exceeds our relation at the measured $\tilde{\Lambda}$ we conclude a strong PT took place in the system. The result from the $\rho_{\rm max}^{\rm max}$–$\tilde{\Lambda}$ relation then provides an estimate on the density a purely hadronic system with this $\tilde{\Lambda}$ would have. Since the PT already took place at this density, the inferred $\rho_{\rm max}^{\rm max}$ serves as an

upper limit on ρ_{onset}. Details on the used numerical framework, the microphysical EoS models, the formulas for the empirical relations and potential caveats of our procedure can be found in Ref. [2].

4. Summary and outlook

We have presented a procedure to unambiguously identify a sufficiently strong first-order PT in NSs mergers. This procedure relies on the simultaneous measurement of pre- and postmerger GWs. It compares the inferred $\tilde{\Lambda}$ and f_{peak} with tight, empirical relations valid for purely hadronic EoSs. Using an additional relation between f_{peak} and $\rho_{\mathrm{max}}^{\mathrm{max}}$ we also provide a framework to constrain ρ_{onset} of the hadron-quark PT. This framework can provide an upper (lower) limit on ρ_{onset} depending on whether a clear indication of a strong PT is present (absent). Hence, a single, precise measurement of postmerger GWs will already yield further insights into the density range of deconfinement PT. With the ongoing enhancement of existing GW detectors and the advent of new third generation detectors we expect such a measurement to be possible within the next few years.

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References

[1] B.P. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration), *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, *Physical Review Letters* **119** (2017) 161101 [1710.05832].

[2] S. Blacker, N.-U.F. Bastian, A. Bauswein, D.B. Blaschke, T. Fischer, M. Oertel et al., *Constraining the onset density of the hadron-quark phase transition with gravitational-wave observations*, *Physical Review D* **102** (2020) 123023 [2006.03789].

[3] A. Bauswein, N.-U.F. Bastian, D.B. Blaschke, K. Chatziioannou, J.A. Clark, T. Fischer et al., *Identifying a first-order phase transition in neutron-star mergers through gravitational waves*, *Physical Review letters* **122** (2019) 061102 [1809.01116v2].

[4] N.-U.F. Bastian, *Phenomenological quark-hadron equations of state with first-order phase transitions for astrophysical applications*, *Physical Review D* **103** (2021) 023001 [2009.10846].

[5] T. Hinderer, *Tidal Love Numbers of Neutron Stars*, *Astrophys. J.* **677** (2008) 1216 [0711.2420].