Resolving Phase Transitions in the Neutron Star Equation of State

SUMMARY

Neutron star mergers provide a unique laboratory for studying the densest phases of matter. Certain classes of low-density phase transitions will require the sensitivity of XG detectors to resolve from the inspiral, while higher-density phase-transitions can be probed only with post-merger gravitational waves.

Key question(s) and scientific context in brief

At neutron star densities beyond the nuclear saturation density, $\rho_{\rm sat}$, new phases of matter can be present. These include hyperonic matter (containing net strangeness) or even de-confined quark matter. Understanding at what densities these phase transitions occur, and whether they are of first-order, has the potential to provide novel insights into the different phases of matter under the strong force, and in particular into the phase diagram of quantum chromodynamics. In this Letter, we outline different scenarios for first-order phase transitions occurring at low or high densities above $\rho_{\rm sat}$, which can only be constrained by inspiral and post-merger gravitational wave (GW) signals detected with XG-detectors. These include *tidal deformability doppelgängers* (Raithel and Most 2022b) , equations of state (EoS) with significant stiffening at high-densities, (Raithel and Most 2022a) , and deconfined quark matter in the post-merger (Most, Papenfort, et al. 2019; Most, Jens Papenfort, et al. 2020; Most, Motornenko, et al. 2023) .

Potential scientific impact of XG detectors and required capabilities

Tidal deformability doppelgängers: Current inferences of the neutron star EoS from the inspiral GW signal rely on the robust mapping between tidal deformability, Λ, and the underlying EoS. In a recent work, Raithel and Most 2022b have shown that for a class of phase transitions occurring at significantly different densities, the tidal deformability can be almost identical across the entire neutron star mass range (see top row, Fig. 1). These *tidal deformability doppelgängers* thus predict nearly identical inspiral GW signals, despite having very different nuclear properties. Resolving the small differences in Λ of these *doppelgängers* will require precision measurements, $\Delta\Lambda \lesssim 10$, of the tidal deformability (bottom row, Fig. 1). For these particular types of models, differences in tidal deformability are largest at small masses. Thus, if there exist significant populations of low-mass neutron stars ($M \sim 1.2 M_\odot$), and if the crust EoS is constrained precisely to relatively high densities from nuclear theory, then it may also be possible to resolve these phase transitions with the sensitivity of A+ (bottom row, Fig. 1).

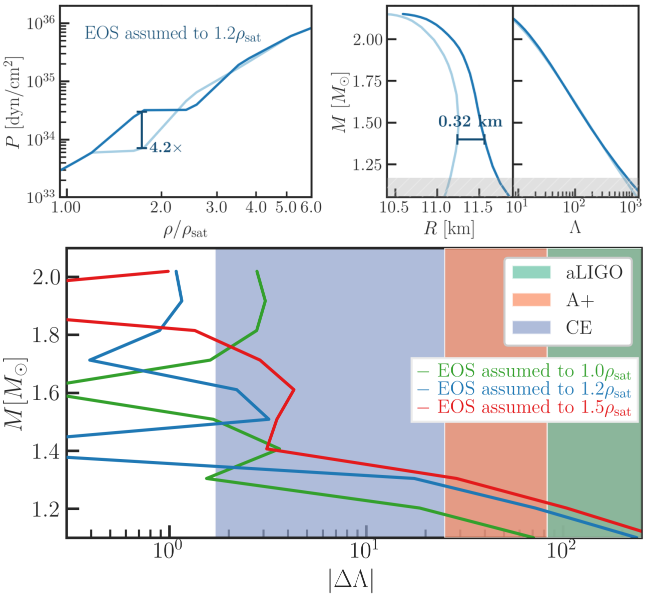

Figure 1: Differences in Λ resolvable with one year of aLIGO (green), A+ (orange), and CE (blue) (Carson et al. 2019) for doppelgänger EoS models. CE sensitivity will be needed to distinguish these models for NS masses $> 1.2\, M_\odot$. Adapted from Raithel and Most 2022b.

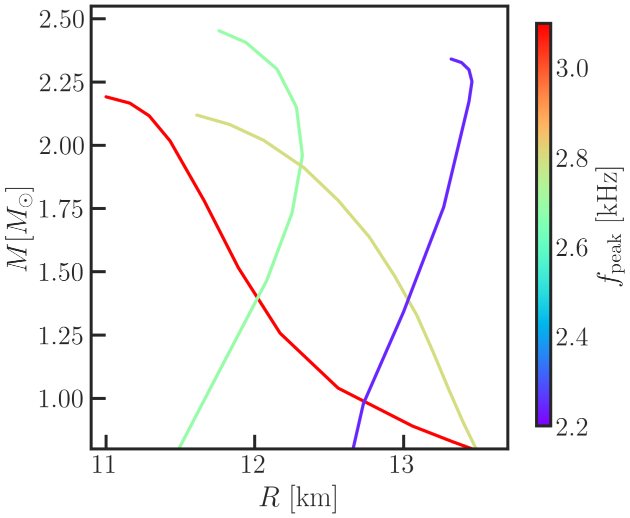

Figure 2: Mass-radius relations for EoSs with significant softening or stiffening at high-densities. The models are colored by $f_{\rm peak}$ for a GW170817-like event. Adapted from Raithel and Most 2022a.

Phase transitions and post-merger GW: On the other hand, other types of phase transitions – e.g., from a high-density softening in the EoS caused by the emergence of new degrees of freedom, or a stiffening caused by a transition to a quarkyonic state of matter – can leave a unique signature in the *post-merger* GWs, even when the inspiral GWs are indistinguishable. Measuring these signatures will require sensitivity at high frequencies, ∼2-3.5 kHz (Shibata 2005) . The frequency at which the spectrum of post-merger GWs peaks for a massive neutron star remnant, $f_{\rm peak}$, has been shown to depend quasi-universally on the radius of intermediate-mass neutron stars (Baiotti and Rezzolla 2017; Bauswein and Stergioulas 2019; Bernuzzi 2020; Radice, Bernuzzi, and Perego 2020; Vretinaris, Stergioulas, and Bauswein 2020) . However, the appearance of strong first-order phase transitions can lead to smaller radii at high NS masses, or for quarkyonic matter to larger radii. As a result, extrapolating properties from the inspiral of intermediate-mass neutron stars to the high-density phase is not entirely universal. Indeed, violation of quasi-universality has been proposed as smoking gun signatures for strong first-order phase transitions (Bauswein, Bastian, et al. 2019) , as well as for significant stiffening in the EoS (Raithel and Most 2022a) , which can be associated with substructure in the speed of sound (Tan et al. 2022) . Differences in $f_{\rm peak}$ can range up to ∼500 Hz depending on the high-density behavior of the EoS (Raithel and Most 2022a) (see Fig. 2).

In addition, the appearance of quarks at finite-temperature in the post-merger is sufficient to cause frequency shifts in the post-merger GW signal, including an early collapse to a black hole (Most, Papenfort, et al. 2019) . This will sensitively depend on the type of phase-transition (Weih, Hanauske, and Rezzolla 2020; Prakash et al. 2021) , and in turn the nuclear matter content (Most, Jens Papenfort, et al. 2020) .

Thus, if the XG network has sufficient sensitivity in the 2-3.5 kHz band to resolve $f_{\rm peak}$, it may be possible to test for new degrees of freedom or exotic phases of matter, such as quarkyonic phases, in the dense-matter EoS, akin to nuclear collider experiments (Most, Motornenko, et al. 2023) .

SCIENTIFIC IMPACT OF XG DETECTORS

1. Distinguishing low-density first-order phase transitions, if present, in inspiral GWs
2. Testing for the emergence of new degrees of freedom or exotic states, such as quarkyonic phases of matter, at high densities, with post-merger GWs

XG DETECTOR AND NETWORK REQUIREMENTS

- Sensivity to measure the tidal deformability to within $\lesssim 10$, from a population of mergers
- High-frequency sensitivity between 2-3.5 kHz to accurately measure $f_{\rm peak}$

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