Next-generation dense matter science with binary neutron star inspirals

SUMMARY

A central objective of nuclear physics is to understand the phase structure of dense matter, such as that found in neutron star cores, and the nuclear interactions that support it. Gravitational waves from binary neutron star inspirals can address these questions because they are sensitive probes of the stellar interior. A next-generation observatory that can survey the complete nearby population of binary neutron star mergers, detecting hundreds of coalescences with a signal-to-noise ratio of 100 or more, will be a powerful probe of matter across the density range realized in neutron stars.

Key questions and scientific context in brief

The matter that makes up the cores of neutron stars is extraordinarily dense, exceeding nuclear saturation density by as much as a factor of eight. It is also very asymmetric in isospin, in contrast to matter in atomic nuclei. Because such conditions are too extreme to reproduce directly in laboratory experiments, the properties and structure of neutron star matter are very uncertain. *In situ* probes of neutron star matter, like gravitational waves from binary neutron star coalescences, can shed light on the interactions that characterize the high-density, low-temperature region of the quantum chromodynamics phase diagram, and may reveal its fundamental degrees of freedom. Achieving a more complete understanding of the phase diagram is a longstanding goal of nuclear physics.

Gravitational radiation from inspiralling neutron star binaries encodes information about internal structure via matter signatures in its phase evolution. The cleanest signature is produced by the adiabatic, quadrupolar tidal deformation of the neutron star, which depends sensitively on the dense-matter equation of state at zero temperature. The first multimessenger binary neutron star discovery, GW170817 (B. P. Abbott et al. 2017), yielded a measurement of tidal deformability that disfavors the stiffest models for dense matter, i.e. those that predict less compact neutron stars. This constraint complements dense-matter equation of state knowledge from *ab initio* calculations using, e.g., chiral effective field theory, from laboratory experiments with heavy atomic nuclei and heavy-ion collisions, and from other astrophysical sources, such as radio pulsar mass measurements and neutron star radius measurements from x-ray astronomy (see Kumar et al. 2023 for a recent review). Together, these observations paint an ever-improving picture of neutron star matter, one that may come into better focus with new LIGO, Virgo and KAGRA discoveries.

However, many questions about dense matter are likely to remain unanswerable with current-generation gravitational-wave observations due to their sizeable statistical uncertainties (Finstad, White, and Brown 2022). Besides its equation of state, neutron star matter's composition, phase structure, and fundamental interactions are important science targets for nuclear physics (Lovato et al. 2022). **What are the nuclear interactions that support neutron star cores against gravitational collapse? Does cold nuclear matter undergo a phase transition at densities realized in neutron stars?** These are two key questions that next-generation (XG) gravitational-wave observatories can address with compact binary inspirals.

Potential scientific impact of XG detectors on the key questions

An XG observatory with roughly ten times the broadband strain sensitivity of LIGO A+ will increase the binary neutron star detection rate by nearly a factor of a thousand, make informative measurements of tidal deformability, and explore the entire neutron star mass spectrum in compact binary coalescences. These observations will have a transformative impact on dense matter science, providing insight into nuclear interactions at high densities and possibly revealing the composition of the heaviest neutron star cores.

Haster et al. 2020 has shown that the loudest binary neutron star signals and the more numerous distant ones both contain significant dense matter information via the tidal deformability. We can expect hundreds of XG binary neutron star detections to have a signal-to-noise ratio (SNR) above 100 (Borhanian and Sathyaprakash 2022), leading to an $O(10\%)$-level measurement of the binary tidal deformability for typical mergers (Gamba et al. 2021; Puecher, Samajdar, and Dietrich 2023), although tides in the heaviest binaries may remain difficult to resolve (Chen et al. 2020). This ensemble of measurements will have the constraining power to determine the importance of three-nucleon forces for neutron star structure via model selection on the nuclear Hamiltonian (Rose et al. 2023), and to infer the breakdown scale for chiral effective field theory (Essick, Tews, et al. 2020), possibly an indication of the density at which new degrees of freedom are important for the description of dense nuclear matter.

Provided that the observations probe the full neutron star mass spectrum, they will constrain the dense-matter equation of state and its density derivative—the sound speed—up to the supranuclear densities realized in some of the heaviest neutron stars, although the best constraints are likely to be made at 2–3 times nuclear saturation. If the violation of the conjectured conformal sound speed bound is confirmed, it would indicate that the phases of matter in neutron star cores are strongly coupled (Bedaque and Steiner 2015). If sharp features are discovered in the sound speed profile, it could similarly signal the occurrence of a phase transition to exotic forms of matter (Legred et al. 2021); $O(100)$ XG detections might even permit the characterization of the transition's onset density and latent energy (Essick, Legred, et al. 2023).

We can also expect an XG binary neutron star survey to be complete out to cosmological distances, potentially as far as redshift $z \approx 0.5$ (Borhanian and Sathyaprakash 2022). The huge number of binary neutron star mergers captured by the survey will ensure that population-level signatures of phase transitions in neutron star matter will be resolved, if they are present. For instance, twin star configurations that result from the strongest phase transitions can be identified from gaps in the distribution of binary tidal deformability vs chirp mass; these gaps may be resolvable after $O(100)$ XG detections (Landry and Chakravarti 2022).

Benchmarks for XG detectors to enable the scientific impact

Achievement of these science targets will depend on an XG detector network's capacity to precisely measure the binary tidal deformability for many binary neutron star coalescences from across the merging population. This is essentially a function of the detector's broadband sensitivity up to the ~ 1.5 kHz contact frequency, and it does not require a network of multiple detectors. An SNR threshold of 100 provides a good benchmark for an $O(10\%)$-level binary tidal deformability measurement in a canonical 1.4 $M_{\odot}$-1.4 $M_{\odot}$ merger. Similarly, the survey completeness for such canonical mergers provides a good proxy for the ability to probe the full neutron star mass spectrum. Thus, appropriate metrics to gauge detector performance for dense matter science are as follows: **the yearly number of binary neutron star coalescences detected with SNR $>$ 100, and the redshift out to which the binary neutron star survey is complete.** Based on the available estimates in the literature, we assess that $O(100)$ SNR > 100 detections from a survey complete past $z = 0.2$ would enable new ground to be broken on the key questions described in this letter. The completeness benchmark is chosen such that the volume-limited sample numbers about 1000 coalescences per year, according to the astrophysical rate estimate of R. Abbott et al. 2023.

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