Snowmass2021 - Letter of Interest

Compact binaries as probes of dense matter and QCD phase transitions

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (EF7) QCD and strong interactions: Heavy Ions

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Abstract: Compact binary mergers that include at least one neutron star have opened the opportunity to study the dense-matter equation of state through gravitational-wave and electromagnetic observations. Combined with theoretical nuclear-physics calculations, we can use such observations to extract crucial astrophysical information about the phase diagram of quantum chromodynamics and matter at the most extreme conditions in our Universe. Here, we elucidate a number of science frontiers enabled by these observations, which are transforming how we understand dense matter, astronomical systems, and cosmology.

Motivation. Neutron stars (NSs) probe matter at the highest densities in our cosmos, yielding insights into the strong interactions described by quantum chromodynamics (QCD). Observations of compact binary mergers consisting of two neutron stars (BNS) or a NS and a black hole (BH) encode information about both fundamental physics and the behaviour of dense matter. The Advanced LIGO [1] and Advanced Virgo [2] gravitational-wave (GW) detectors' discovery of a BNS merger in 2017, GW170817 [3], ushered in a new era of multimessenger astronomy. Electromagnetic (EM) facilities observed a coincident short gamma-ray burst [4–6] and subsequent kilonova [7–13], demonstrated that BNSs are prolific formation sites for many of the heavy elements found in nature [14, 15]. Analyses of the GW data provided limits on the size of NSs [16–25], and joint GW/EM analyses enabled an independent measurement of cosmological parameters [25–28]. The most recent LIGO-Virgo observing run produced very likely another BNS merger [29] as well as NS-BH candidates [30, 31].

The current network of LIGO, Virgo, and KAGRA [32] will continue commissioning and observing runs through to c. 2023. Planned upgrades in c. 2025, including the addition of a fifth observatory (LIGO-India [33]), will extend their reach for binary neutron star detections from ∼100 Mpc (in 2020) to ∼300 Mpc [34]. Third generation (3G) observatories, [35–38], currently in the design stage, may observe BNSs and BHNSs out to the era of peak star formation in our Universe. At the same time, EM surveys such as the Vera C. Rubin Observatory's (VRO) Legacy Survey of Space and Time (LSST) [39] and the Dark Energy Spectroscopic Instrument (DESI) [40], as well as the advent of 30 m class telescopes, will push the boundaries of depth and cadence. The combined operation of GW and EM observatories in the next decade will provide a unique opportunity to resolve long-standing questions such as the nature of the NS *equation of state* (EOS) including possible *phase transitions* to exotic matter, an independent measurement of the *expansion rate of the Universe*, and a possibility to reveal the nature of *dark matter* (DM).

Dense matter in NS interiors. GW and EM observations constraining NS properties are sensitive to the dense matter EOS due to the strong connections between astrophysical observables and microphysical interactions. The presence of a NS imprints information about cold, dense matter up to a few times nuclear saturation density on to gravitational-wave inspiral. Analyses of GW170817 already provide stringent constraints of the radius of typical $1.4 M_{\odot}$ NSs [16–25, 41]. Several of these estimates included multi-messenger input, combining GW and EM observations of BNS mergers, radio observations of massive pulsars [42–44], X-ray observations by NASA's Neutron Star Interior Composition Explorer (NICER) mission [45, 46], and nuclear-physics constraints [22, 47] (see also, e.g., [48–56]).

In the next decade, stronger constraints from combining information from multiple events [24, 57, 58] will enable percent-level measurements of the NS radius and the fundamental interactions of dense neutron-rich matter [53, 56, 59–72]. It will be increasingly important to control systematic errors from prior assumptions about the EOS and the mass distribution of NSs in merging binaries [73], emphasizing the need to understand the population of sources as a whole. Nuclear physics may imprint on the GW source mass distribution itself [74]. Precise knowledge of the EOS or the mass distribution, particularly any sharp features therein, may enable GW observations alone to constrain the local expansion rate of the universe [75–78] and directly calibrate standard candles such as type Ia SNe [79]. Going beyond the equilibrium EOS, future BNS signals may reveal dynamical processes, e.g. stellar oscillations, that probe transport properties of normal matter or exotica such as boson condensates, hyperons, and quarks [49, 80–82].

New regions of the QCD phase space, black hole formation. Both density and temperature increase dramatically after two NSs collide. Therefore, observing merging NSs enables us to probe not only the low-temperature QCD phase diagram, but provides a window on the most extreme conditions in the universe, which will shed additional light on the existence of phase transitions or exotic forms of matter. While these transitions or the breakdown of purely hadronic models could be detected during the inspiral phase under certain conditions [56, 83–85], their existence may be more apparent during the post-merger phase when densities are higher [86–92]. The required sensitivity to detect the post-merger GW signal from a

GW170817-like event is likely to be achieved with future GW detector upgrades [67,68] and high detection rates are expected with the planned 3G facilities or with the proposed dedicated high-frequency GW detectors [93,94]. Increasing detector sensitivity allows us to observe post-merger GW signatures and determining the threshold mass for prompt collapse of the merger remnant to a BH will provide stringent constraints on the EOS and verify possible strong phase transitions in the NS EOS [95–98]. In addition, knowledge of the exact threshold mass can inform future EM counterpart searches, as systems undergoing prompt collapse are most often not connected to bright, detectable EM signals, e.g., [99,100], and can be used to distinguish between different types of compact binary progenitors [101], possibly resolving long-standing issues associated with the lower "mass gap" between observed NSs and BHs, as well as uncertainties in the core-collapse supernova (CCSN) explosion mechanism (e.g., [102,103]) and the nucleosythesis therein.

Matter outflows and r-process nucleosynthesis. Postmerger GW and EM observations trace the dynamic aftermath in the extreme environments created by compact binary mergers. The successful search and detection of the *kilonova* associated with GW170817 revealed NS mergers as a critical site of rapid neutron-capture process (r-process) nucleosynthesis. Combined with the inferred BNS merger rate [29, 104] and detailed nucleosynthesis simulations, future multimessenger observations of NS mergers will elucidate the processes that make the heavy elements [105,106]. An interdisciplinary effort implicating GW and EM observations, numerical relativity (NR) simulations, and nuclear theory calculations will enable detailed predictions of the abundances of individual elements. In the future, we expect that wide field-of-view, optical survey instruments are most likely to find fast-fading kilonovae. While today's searches for these counterparts are difficult due to their large sky localizations [107–109], 3G detectors will significantly improve the localizability. Information from the inspiral GWs together with NR simulations can inform EM follow-up campaigns by making robust predictions about potential matter outflows and light curves [100, 110]. Together, GW and EM observations may reveal exotic components like primordial black holes [111–115].

Dark matter in neutron stars and exotic compact objects. Because of their strong gravity and extreme core densities, NSs may accumulate DM from their environment by capturing DM particles after they scatter off of nucleons [116,117]. Depending on the DM-nucleon interaction cross-section and the DM particle mass, the DM could form a core [118–120] or become admixed with the baryonic matter [121, 122]. DM could even be produced during the merger of two NSs [123]. For certain DM models, a configuration of baryonic and non-baryonic matter is gravitationally stable [124–126]. The DM concentration is then sensitive to the NS's age, mass and environment, producing diversity in the EOS-dependent observables, like tidal deformabilities, measured for the population. In other cases, DM may implode the stars [127]. Alternatively, DM that is formed out of ultra-light scalar field could agglomerate on its own, forming compact objects that mimic true NSs and BHs [128–131]. GW observations over the next decade, especially in the 3G detector era, combined with EM searches will give access to the full population of compact binary mergers, allowing us to search for "smoking-gun" EOS variability due to DM.

Requirements for the coming decade. We call upon the community to build the multidisciplinary ingredients necessary for multi-messenger astronomy of compact binary systems. This includes the installation of highly-sensitive observatories, such as 3G GW detectors and the next generation of EM telescopes, and the development of an efficient, reliable, and interdisciplinary hierarchical Bayesian framework for the interpretation of the growing number of upcoming multi-messenger sources. Such a framework must account for selection effects within both GW and EM observations while considering all aspects of the source population simultaneously, including the fundamental aspects of strong interactions that govern their formation, composition, and internal properties. By reliably extracting source properties (masses, radii, dynamical states, magnetic field structures, ejecta properties, etc.), this framework will enable reliable measurements of the dense matter EOS, the QCD phase diagram, and r-process nucleosynthesis. Ultimately, future observations of these astronomical systems at the extremes of gravity and density have the potential to reveal physics beyond the Standard Model.

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