How Third Generation Gravitational Wave Detectors Can Unveil the True Degrees of Freedom of Dense Matter

SUMMARY

We argue that a third-generation detector network should have the capability of measuring the effects of transport on the post-merger signal of a binary neutron star merger. This will provide the best chance of detecting exotic phases like quark matter or hyperonic matter, which can be degenerate in the inspiral.

Key question(s) and scientific context

Unveiling the structure of the phase diagram of quantum chromodynamics (QCD) and finding the true degrees of freedom of dense matter at densities achieved in compact stars is one of the great scientific challenges of our time [Bogdanov et al. 2019; Maggiore et al. 2020; Evans et al. 2021a; Evans et al. 2021b; Lovato et al. 2022; Bogdanov et al. 2022]. Neutron star mergers offer a unique opportunity to explore the high-density, low to intermediate temperature regime of the QCD phase diagram. One measurable property of dense matter is the equation of state (EOS), on which much effort has been expended in the last decades, yielding hints at the existence of a first-order phase transition from nuclear to quark matter inside heavy neutron stars [Annala, Gorda, Kurkela, et al. 2020; Annala, Gorda, Hirvonen, et al. 2023]. However, it is well known that the EOS is not the optimal observable for mapping the phase diagram of a material. Different phases are mainly distinguished via their spectrum of low-energy excitations, which are most easily detected via differences in transport or equilibration properties. This is especially true for models subject to the "masquerade problem": For a class of EOS for matter with a weak first-order phase transition from nuclear matter to quark matter, one can find identical mass-radius curves and stellar structures, including tidal deformabilities, that are indistinguishable from a purely nucleonic EOS without quark matter [M. Alford, Braby, et al. 2005; Wei et al. 2018].
Current research shows that a strong first-order phase transition with a large latent heat is unlikely to occur in nature [Gorda et al. 2022], which makes it more likely that the true EOS falls in the "masquerade" parameter space. This implies that constraints on the tidal deformability from the inspiral might be insufficient to truly determine the degrees of freedom of dense matter. However, additional insights can be provided by *dynamical* transport and equilibration properties probed in the post-merger phase, when the material is subject to strong variations in external conditions. In the following, we provide two examples of transport phenomena, both associated with (weak-) interactions acting on timescales comparable to the dynamical time of the post-merger phase [M. G. Alford, Bovard, et al. 2018]. Quark matter in compact stars, if it exists, is most likely in a color superconducting state, since the critical temperatures for the most commonly postulated color superconducting phases are estimated to be tens of MeV. One possible manifestation of the presence of superconducting quark matter would be its flavor equilibration properties such as bulk viscosity and phase conversion dissipation.

Neutrino-driven bulk viscosity: During the merger, the flavor content (e.g., electron fraction) can be driven away from its equilibrium value. Chemical equilibration due to neutrino interactions will establish a new equilibrium, causing bulk-viscous feedback on the matter. The resulting bulk viscosity of quark matter has been studied in various publications [M. G. Alford and Schmitt 2007; Schmitt and Shternin 2018] and shown to be significantly different than the underlying processes in nuclear [M. G. Alford and Harris 2019; M. G. Alford, Haber, et al.

2021; M. Alford, Harutyunyan, and Sedrakian 2022] or hyperonic matter [M. G. Alford and Haber 2021].

Phase conversion dissipation: If nuclear matter is separated from quark matter by a first-order phase transition then in a neutron star there may be regions of quark matter separated from nuclear matter by sharp phase boundaries. In a neutron star merger, there will be strong density oscillations with frequencies in the kHz range which cause these boundaries to move as fluid elements cross the critical pressure. However, the speed at which the phase boundary can move is limited by the rate of weak interaction processes. These are needed because the quark matter phase will have a different flavor content (e.g. more strangeness) than nuclear matter. One of the effects of a phase boundary moving at a limited speed in an oscillatory system is a form of dissipation called "phase conversion dissipation" [M. G. Alford, Han, and Schwenzer 2015]. Especially for masquerading EOS models, this is a potential smoking gun signal for the existence of quark matter in mergers, since other signatures [Most, Papenfort, et al. 2019; Bauswein et al. 2019; Weih, Hanauske, and Rezzolla 2020; Prakash et al. 2021] may be absent in this case. It has been shown that this effect is capable of damping oscillations in isolated stars on short time scales [M. G. Alford, Han, and Schwenzer 2015] and should therefore significantly contribute to dissipation in a merger as well.

Potential scientific impact of XG detectors on the key questions

Transport and equilibration properties are key to distinguishing the phase structure of dense matter. The best chance to see their effects is in the first fraction of a second after the merger. Transport effects like chemical equilibration and the resulting bulk viscosity or phase conversion dissipation might allow us to unambiguously detect exotic phases like quark matter or hyperonic matter in compact stars.

Benchmarks for XG detectors to enable the scientific impact

Bulk viscous damping and phase conversion dissipation can potentially shift the frequency spectrum of post-merger gravitational waves [M. G. Alford, Bovard, et al. 2018; Most, Harris, et al. 2021]. Recent numerical relativity studies have investigated the potential impact of these effects in nuclear matter: Refs. [Hammond, Hawke, and Andersson 2023; Most, Haber, et al. 2022] placed upper bounds on the associated frequency shift ($\Delta f_2 < 100\,\mathrm{Hz}$) of the dominant peak frequency, f_2, in the neutrino-transparent regime. The effect may be smaller in the neutrino-trapped regime[Zappa et al. 2022]. Bulk viscosity in quark matter could also affect the recently reported suppression of the $m = 1$ mode of the post-merger gravitational wave signal [Espino et al. 2023]. To fully clarify these effect, and to also distinguish it from finite-temperature Raithel, Paschalidis, and Özel 2021; Fields et al. 2023; Blacker, Bauswein, and Typel 2023 or magnetic field effects Ciolfi et al. 2017; Chabanov et al. 2023, further numerical relativity simulations at much higher resolution may be required to provide a full assessment. Assessing these effects with Cosmic Explorer will require a high sensitivity for post-merger gravitational wave signals (e.g., strain noise $\lesssim 10^{-24}\mathrm{Hz}^{-1/2}$ in the $2 - 3.5\,\mathrm{kHz}$ band).

SCIENTIFIC IMPACT OF XG DETECTORS

Detecting exotic matter like quark or hyperonic matter in neutron stars via transport phenomena.

XG DETECTOR AND NETWORK REQUIREMENTS

High-frequency sensitivity (e.g., strain noise $\lesssim 10^{-24}\mathrm{Hz}^{-1/2}$) between 2-3.5 kHz to accurately measure the dominant post-merger frequency f_2.

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