New Probes of the Finite-Temperature Dense-Matter Equation of State with Cosmic Explorer

SUMMARY

The exquisite sensitivity of next-generation (XG) gravitational wave (GW) detectors at high frequencies will provide new probes of the dense-matter equation of state (EoS), through the observation of the post-merger phase of binary neutron star (BNS) mergers and core collapse supernovae (ccSN). Given that BNS merger remnants and proto-neutron stars are hot objects, with thermal pressures contributing substantially to their total pressures, the emergent GW peak frequencies can differ by several percent due to uncertainties in thermal physics. Such frequency shifts will enable new constraints on the finite temperature nuclear EoS, probing nuclear physics at temperatures and densities not accessible in the lab.

Key question(s) and scientific context in brief

What is the dense-matter EoS above the nuclear saturation density ($n_{\rm sat}$) at *finite temperature*? The EoS above $n_{\rm sat}$ is uncertain not only for cold matter, but also for matter at finite temperatures, as found in ccSN and BNS mergers. The extreme densities, temperatures, and compositions of these violent astrophysical events probe a unique part of the parameter space, inaccessible in the lab (see Fig. 1). Following a typical BNS merger, the thermal pressure can contribute as much as the cold degenerate pressure, thereby playing an important role in the dynamics and evolution of the remnant (Sekiguchi et al. 2011; Paschalidis, Etienne, and Shapiro 2012). Existing finite-temperature EoSs, which are constructed to satisfy experimental constraints, differ in their thermal-to-cold pressure ratio by a factor of 5 at $n_{\rm sat}$, and a factor of 3 at $2n_{\rm sat}$ already at temperatures of 20 MeV (C. Raithel, Paschalidis, and Özel 2021), indicating significant uncertainties in the thermal physics. For comparison, the temperature following a BNS merger can exceed 50 MeV. Thus, the GW spectrum from a BNS merger remnant (see Baiotti and Rezzolla 2017; Paschalidis and Stergioulas 2017 for reviews) or from a ccSN (see Ott 2009 for a review) can be used to constrain these uncertainties and inform nuclear physics at finite temperature.

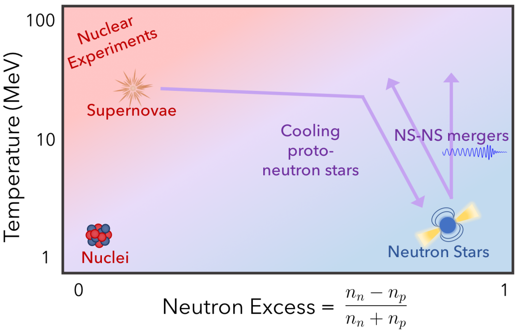

Figure 1: Schematic phase diagram showing various probes of dense matter. BNS mergers contain matter that is not only several times denser, but also more isospin asymmetric (neutron rich) and at more moderate temperatures than is probed in the lab, e.g., in heavy ion collisions. Figure from C. A. Raithel, Ozel, and Psaltis 2019.

Potential scientific impact of XG detectors on the key questions

Following a ccSN or BNS merger, the newly formed proto-neutron (in the ccSN case) or the massive neutron star (in the BNS case) exhibit characteristic oscillations that depend on the nuclear EoS at high densities (see e.g. Baiotti and Rezzolla 2017; Paschalidis and Stergioulas 2017 for reviews). Existing GW detectors are not sensitive enough at the kilohertz frequencies required to detect these post-merger oscillations, unless the merger takes place within $\lesssim 30$ Mpc (Clark et al. 2016).

XG detectors – in particular, in configurations that optimize the sensitivity at high frequencies – are necessary to detect these oscillation modes. For example, depending on the EoS, there is up to $\sim 80\%$ probability of detecting a single post-merger event at signal-to-noise ratio of 5 or more with Cosmic Explorer (CE) within a year of observations (Yang et al. 2018). Using mode stacking, this probability increases significantly, while the statistical accuracy for the determination of the peak GW frequency becomes $\sim$ 20Hz (Yang et al. 2018). For these 2-3.5 kHz oscillations, this implies a determination of the peak frequency to within 1%. The statistical errors become smaller for a network of XG detectors, as the network-combined SNR increases (Evans et al. 2021; Srivastava et al. 2022).

Such exquisite precision can be used to place *novel* constraints on finite temperature nuclear physics, if the cold EoS can be pinned down by the inspiral. In Ref. C. A. Raithel and Paschalidis n.d., a first parameter study of thermal effects using a realistic treatment of finite temperature nuclear physics (based on the M* framework of C. A. Raithel, Ozel, and Psaltis 2019; see also C. Raithel, Paschalidis, and Özel 2021; C. A. Raithel, Espino, and Paschalidis 2022), demonstrates that the peak GW frequency shifts by $\sim$ 190 Hz ($\sim$ 60 Hz) – a fractional shift of 5.5% (2.3%) – for soft (stiff) EoSs, due purely to uncertain *finite temperature* nuclear physics. In other words, for the same cold EoS, differences in the thermal physics can shift the post-merger GW peak frequencies by up to 190 Hz (see also Bauswein, Janka, and Oechslin 2010; Figura et al. 2020; Fields et al. 2023). Such differences are within reach for XG detectors.

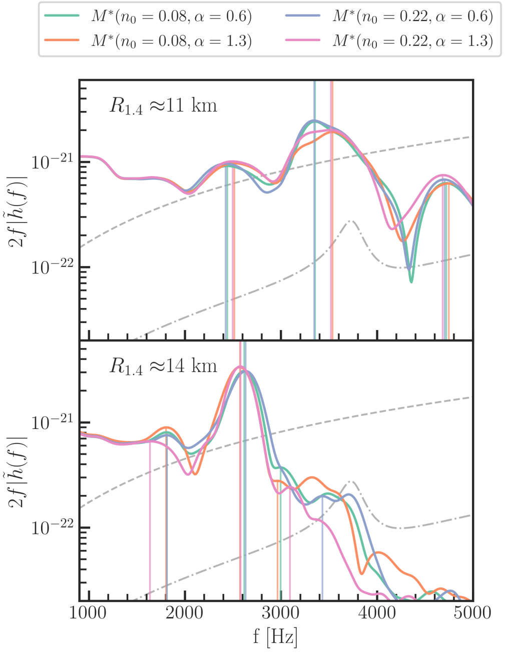

Figure 2: Characteristic strain for a face-on merger at 40 Mpc, for BNS mergers evolved with a cold EoS that predicts 11 km radii (top) or 14 km radii (bottom) for a 1.4 $M_\odot$ neutron star. The colors indicate different thermal prescriptions for the same underlying cold EoS. The dashed gray line represents the *aLIGO Design Sensitivity* n.d., while the dash-dotted line indicates the proposed *Cosmic Explorer Sensitivity Curves* n.d.

Benchmarks for XG detectors to enable the scientific impact

To maximize the science output, i.e., increasing both the detection rate and the SNR of BNS post-merger GW signals, XG detectors must have high sensitivity in the 1-3.5 kHz range. A post-merger tuned CE characteristic strain sensitivity at 2–3kHz of $2.7 - 4.4 \times 10^{-23}$, as described in Srivastava et al. 2022, which is $\sim 1.5\times$ better than the main CE configuration, not only increases the SNR at a given distance, but also the probed volume by more than $3\times$. These enhancements are necessary for precision GW probes of the finite temperature EoS.

SCIENTIFIC IMPACT OF XG DETECTORS

XG detectors will enable precision constraints on the nuclear physics beyond the nuclear saturation density at finite temperature and lead to novel constraints of the QCD phase diagram.

XG DETECTOR AND NETWORK REQUIREMENTS

Achieving precision constraints on the uncertain nuclear physics at finite temperature, requires GW detectors with exquisite sensitivity in the 1-3.5 kHz range. A characteristic strain sensitivy below a few $\times 10^{-23}$ is important to accomplish this task. A promising strategy to achieve this goal is to set up a XG network such that one XG detector is tuned at high-frequencies.

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