Inertial mode excitation of long-lived remnants of binary neutron star mergers

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Abstract

We show that in the post-merger phase of binary neutron star (BNS) merger are present convective instabilities that excite inertial mode oscillations. These oscillations emit gravitational waves in the frequency band where ground-based detectors are within reach of planned third-generation detectors and could be used also as sensitive probes of the rotational and thermal state of matter in the neutron star remnant. Within the limits of the input physics of our simulations (which neglect magnetic fields and neutrino transport) their presence appear to be quite general for remnants that live more than 50 ms and show up for four different equations of state (EoS), parametrized as piecewise polytropics plus a thermal component with $\Gamma = 1.8$. We also analyze the gravitational wave signal emitted by the remnant after the merger for each EoS in order to characterize the rate of change of the frequencies and the damping of the amplitudes for both the main and excited mode.

Motivation

In previous simulations the dynamics of the remnant was followed up to $\sim$ 40 ms after the merger. Here we present the first very long-term simulations of BNS mergers [1] (reaching up to $\sim$ 140 ms after merger) using a piecewise polytropic EoS with a thermal part. Our simulations reveal that $\sim$ 30-50 ms after merger (depending on the model we used), the initial $m = 2$ f-mode oscillation has diminished and parts of the star become convectively unstable. Subsequently, the convective instability triggers the excitation of global, discrete inertial modes, in which the Coriolis force is the dominant restoring force. The inertial modes are sustained up to several tens of ms and will be detectable by the planned third-generation GW detectors at frequencies of a few kHz.

Initial data and methods

Initial data were generated with the `LORENE` code, employing four different equation of state, namely the APR4, SLy, H4 and MS1 EoS, parametrized as piecewise polytropes with 7 pieces plus a thermal component with adiabatic index $\Gamma_{th} = 1.8$. We consider systems of total mass of 2.56 $M_\odot$, with an initial separation of roughly 44.3 km (four full orbits before merger) and an initial angular velocity of $\simeq 1770 s^{-1}$. In particular we consider equal-mass systems characterized by relatively low-mass components, below the range of the inferred masses for GW170817 (total mass between 2.73 and 3.29 $M_\odot$ for conservative spin priors). The compactness of the star is 0.166 for the APR4, 0.161 for the SLy, 0.137 for the H4 and 0.129 for the MS1 EoS. The remnant HMNS survives for more than 100 ms before collapsing to a black hole for the SLy model while it collapses to BH only after 84 ms for the H4 model, developing interesting new dynamics. The simulations were performed using the `EinsteinToolkit` employing the same setting of [2]. We also used π-symmetry to reduce the computational cost by a factor 2 in order to extend the limit of the simulation time up to $\sim$ 160 ms, of which the last 140 ms correspond to the postmerger phase.

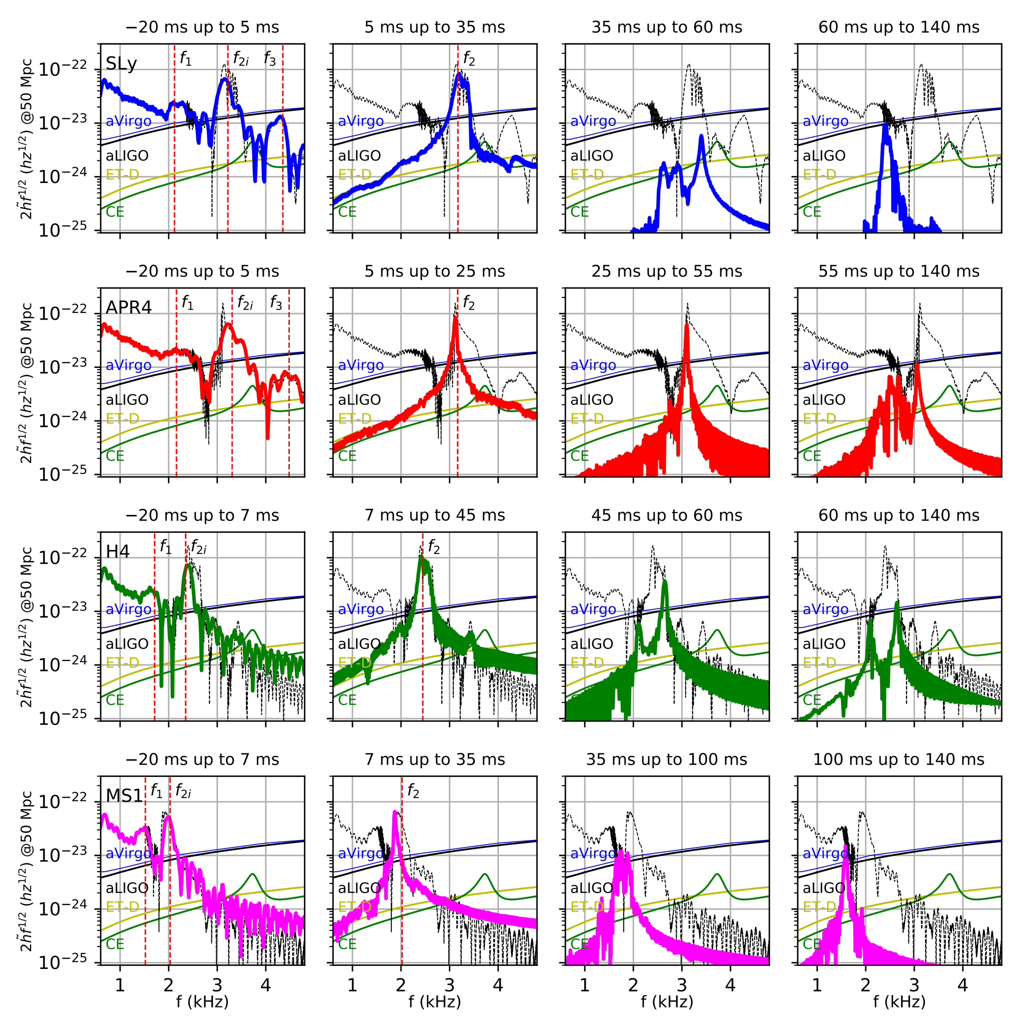
Results

We used the ESPRIT Prony's method, as discussed in [3], to superimpose the frequency of the dominant spectral modes on the time-frequency spectrogram of the h_{22} component of the spherical harmonics decomposition of the GW signal. We note that a few milliseconds after the merger the density profile of the core stops oscillating and a dominant mode becomes visible. This dominant mode in the postmerger phase is the $m = 2$ f-mode, with a frequency above 3 kHz for the APR4 and SLy EoS and lower than 3 kHz for the H4 and a decaying amplitude, while the MS1 only have a dominant frequency around $\sim$ 1.9 kHz which is decreasing constantly. However, we find that a distinct lower-frequency mode appears later in the evolution, at $t - t_{merger} \sim 35$ ms for SLy, ~ 55 ms for APR4 and ~ 45 ms for the H4 while for the MS1 we cannot distinguish any additional mode. At later times the new mode become the dominant emitter of GWs. Moreover, the analysis of the spectra for convenient time windows shows that there is sufficient power in these lower-frequency modes to render them potentially observable by third-generation detectors.

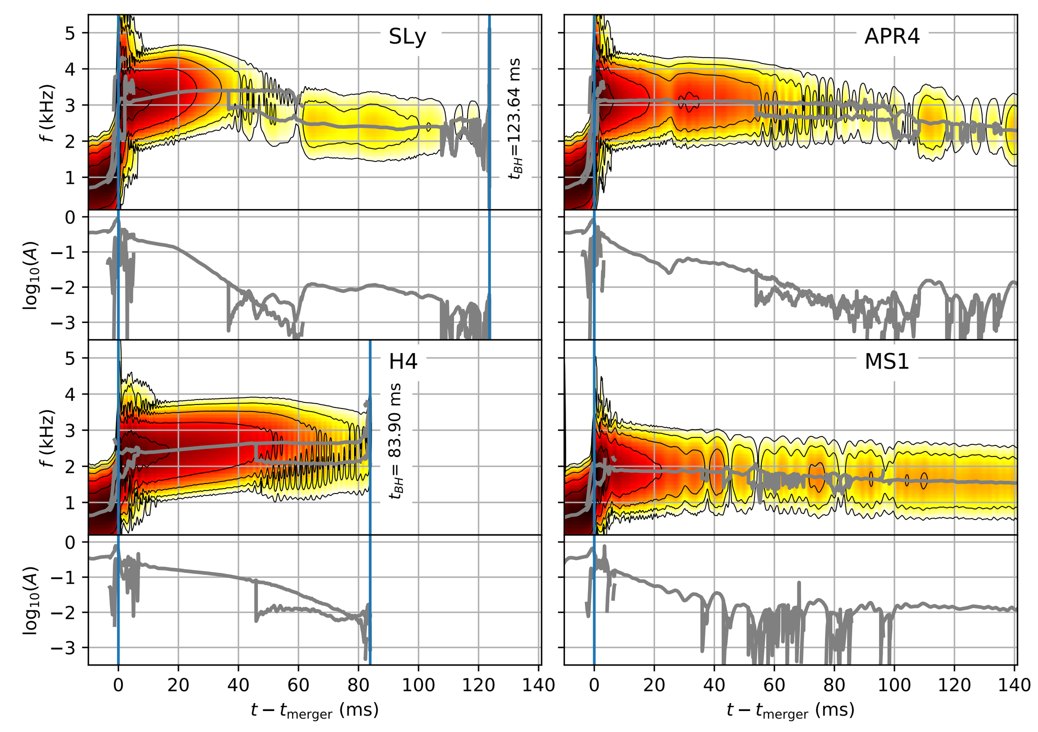
The late-time, lower-frequency modes found in our simulations can be interpreted as inertial modes, for which the Coriolis force is the dominant restoring force. The growth of the inertial modes (up to their saturation amplitude) is triggered by a convective instability that appears shortly before the inertial modes start to grow from a small amplitude. The local convective instability depends on the sign of the Schwarzschild discriminant A_α, which depends on the adiabatic index of linear perturbations about a pseudo-barotropic equilibrium Γ_1 and the energy density ε. Regions with $A_\alpha < 0$ are convective stable, whereas regions with $A_\alpha > 0$ are convectively *unstable*.

We note that for the SLy EoS at an early time most of the star, except for some parts in the low-density envelope, is convectively stable and the $m = 2$ f-mode dominates the GW spectrum. At $t = 36$ ms, a convectively unstable ring appears in the equatorial plane, at $\rho \simeq 8 \times 10^{13}$ g/cm^3, corresponding to the first appearance of the inertial modes. Later, the convective unstable ring has expanded to lower densities and appears fragmented, which coincides with a strong growth of an inertial mode with lower frequency (smaller than twice the maximum angular frequency Ω_{max}) [1, 4]. For the APR4 EoS we still observe the formation of an unstable ring when the excited mode starts growing. However we observe a sudden increase in amplitude at $\sim$ 30 ms, which is not present in any of the other models, corresponding to an increase in GW emission. At this time we note that the spectrum of the GW signal shows a minor peak in the frequency range of $2.70 - 2.80$ kHz which correspond to an excited mode of lower intensity that is not visible using the Prony's method but is easily recognizable from the density eigenfunction profile. For the H4 model we note that the convectively unstable ring starts forming at $\sim$ 40 ms and is followed by the appearance of an excited mode a few milliseconds later with a frequency of $\sim$ 2.1 kHz. The HMNS continue losing energy and will finally collapse to BH $\sim$ 83 ms after the merger. On the other hand, we note that for the MS1 EoS unstable regions appear immediately and keep growing during the simulation leading to the immediate formation of excited modes.

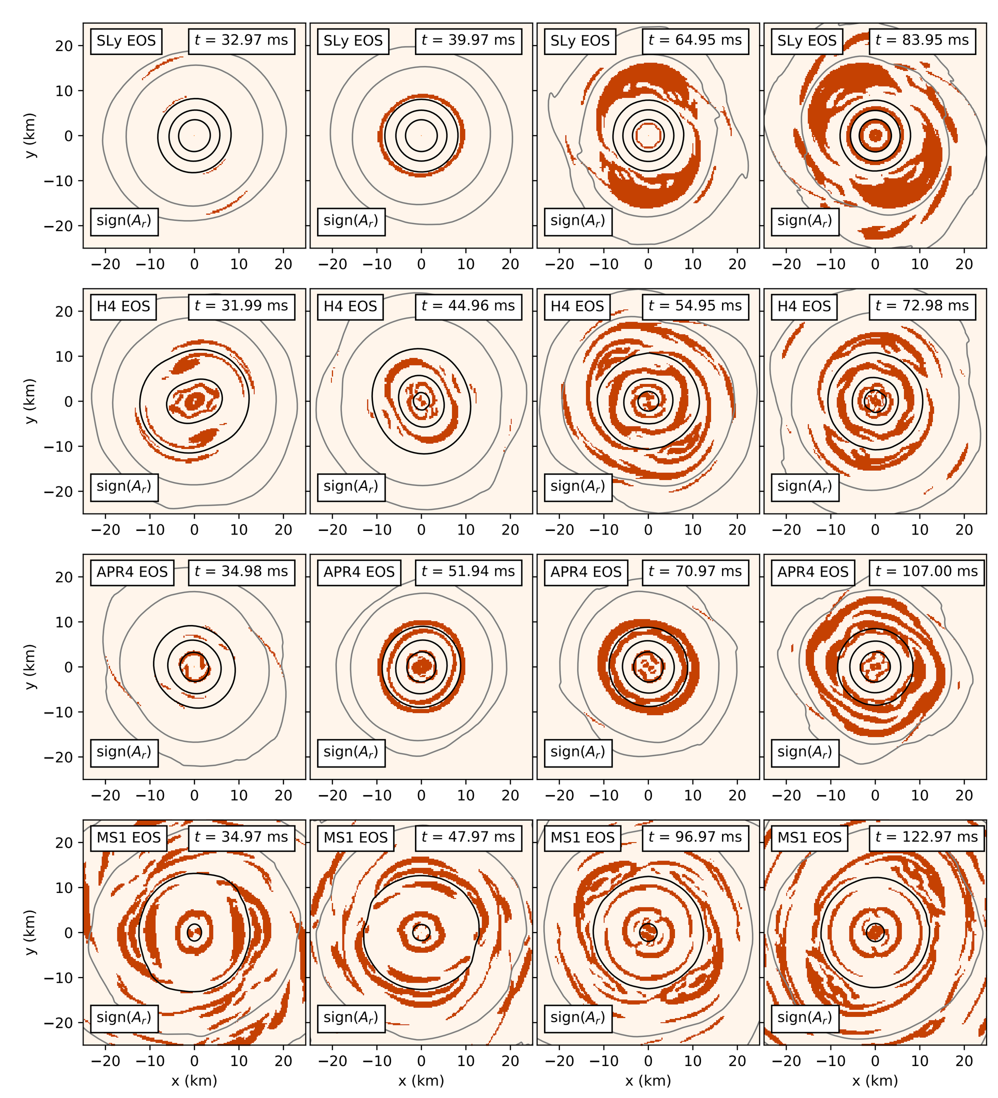
Spectrum of the GW signal



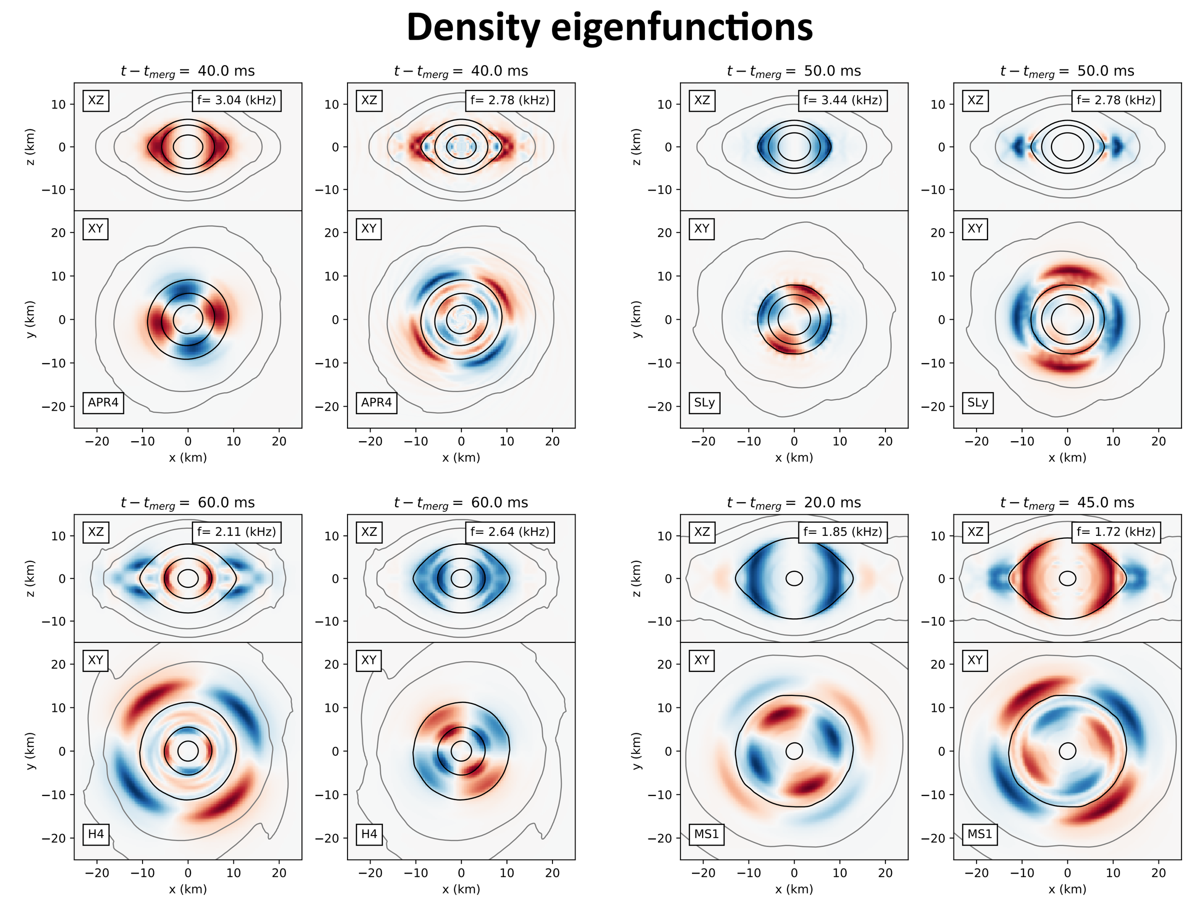
Time-frequency spectrograms and mode amplitudes



Snapshots of A_r



Density eigenfunctions



References

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[3] F. Maione, R. De Pietri, A. Feo and F. Löffler, *Spectral analysis of gravitational waves from binary neutron star merger remnants*, PhysRevD.96.063011 (2017), arXiv:1707.03368 [gr-qc].

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