

Impact of pions on binary neutron star mergers

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We study the impact of pions in simulations of neutron star mergers and explore the impact on gravitational-wave observables. We model charged and neutral pions as a noninteracting boson gas with a chosen, constant effective mass. We add the contributions of pions, which can occur as a condensate or as a thermal population, to existing temperature- and composition-dependent equations of state. Compared with the models without pions, the presence of a pion condensate decreases the characteristic properties of cold, nonrotating neutron stars such as the maximum mass, the radius and the tidal deformability. We conduct relativistic hydrodynamical simulations of neutron star mergers for these modified equations of state models and compare to the original models, which ignore pions. Generally, the inclusion of pions leads to a softening of the equation of state, which is more pronounced for smaller effective pion masses. We find a shift of the dominant postmerger gravitational-wave frequency by up to 150 Hz to higher frequencies and a reduction of the threshold binary mass for prompt black-hole formation by up to $0.07M_{\odot}$. These quantitative changes compared with the equation of state model without pions are stronger for smaller effective pion masses and for underlying baryonic models which result in softer equations of state. We evaluate empirical relations between the threshold mass or the dominant postmerger gravitational-wave frequency and stellar parameters of nonrotating neutron stars. These relations are constructed to extract these stellar properties from merger observations and are built based on large sets of equation of state models which do not include pions. Comparing to our calculations with pions, we find that these empirical relations remain valid to good accuracy, which justifies their use although they neglect a possible impact of pions. Pions simultaneously modify merger characteristics and the properties of cold, nonrotating neutron stars. We also address the mass ejection by neutron star mergers and observe a moderate enhancement of the ejecta mass by a few ten percent. While such variations may be within statistical uncertainties of the simulations, the increase is slightly more pronounced than one would have expected from empirical relations predicting the ejecta mass based on stellar parameters of nonrotating neutron stars.

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I. INTRODUCTION

The equation of state (EOS) of high-density matter determines the stellar structure of neutron stars (NSs) and the dynamics and outcome of binary neutron star (BNS) mergers. Therefore, the EOS is particularly important to understand the gravitational-wave (GW) emission, nucleosynthesis and electromagnetic radiation of merger events [1–12].

The EOS of NS matter is not fully known, and various theoretical models have been put forward along with efforts to obtain insights from observations of, for instance, BNS mergers. The theoretical models are based on different methods to solve the nuclear many-body problem and make different assumptions about the constituents of high-density matter, e.g. [13–19]. Apart from neutrons, protons and electrons, some models additionally consider for instance hyperons, deconfined quarks, muons, quarks, pions, kaons, and at finite temperatures positrons, photons, neutrinos and antineutrinos. The finite-temperature regime of the EOS is relevant for phenomena such as core-collapse supernovae and binary

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mergers, which can reach temperatures of several 10 MeV (see reviews above).

Already for decades it has been conjectured that negatively charged pions could form a Bose-Einstein condensate in the cores of NSs [20–28]. If and at which density such a condensate occurs, depends on the detailed interactions between pions and nucleons and is currently not known. One expects that pions are associated with an effective pion mass which differs from its vacuum value of about 140 MeV. At finite temperature one may in addition expect that a population of thermal pions is present, where positively and negatively charged pions as well as neutral pions may play a role [29–35].

The influence of pions (either as condensate or thermal population) in BNS mergers is largely unexplored. But see Refs. [31,32,34], which investigate pions in simulations of core-collapse supernovae. In fact only a few currently available temperature-dependent EOS tables for astrophysical applications include pions [30,33,35,36]. These calculations indicate a softening of the EOS compared with models without pions, which results from a change of the proton fraction if pions are included.

In this study we provide a first assessment of the potential impact of pions in BNS merger simulations. We adopt a relatively simple model describing pions as a noninteracting boson gas with a chosen effective mass, and by this consider both condensate and thermal populations of pions. We add the contributions by pions to existing EOS tables and compute the properties of isolated NSs by considering matter in neutrinoless beta-equilibrium at zero temperature. We then focus on the impact in dynamical simulations of BNS mergers and analyze the influence of pions on the dynamics, on black-hole formation, on the GW signal, and on the mass ejection in these events.

A major motivation of this exploration is to evaluate to which extent neglecting pions in previous studies affects empirical relations for the dominant postmerger GW frequency and the threshold mass for prompt black-hole formation, e.g. [37–55]. These relations have been derived from calculations without pions,¹ and, partly, they are already employed to interpret observations and to infer EOS information, or they may be used in future measurements. We find that most empirical relations also hold for models which include pions although the relations have been built based on calculations that neglect pions. This is because these relations connect properties of isolated, cold, nonrotating NSs with observable properties of the merger. Since the addition of pions modifies both the properties of

isolated stars and of the merger, the empirical relations remain to good accuracy unaltered. We find this to hold for different chosen effective pion masses, which supposedly cover a reasonable range and to some extent reflect the more complicated physics of pions in the dense medium of NSs [57–61], which we do not include here. Based on these findings we conclude that it is safe to employ such relations in existing and upcoming studies.

This paper is organized as follows. In Sec. II we describe the inclusion of pions using in existing EOS models which originally do not consider pions. Section III briefly discusses the impact on the stellar structure of isolated, nonrotating stars and provides technical information on the hydrodynamical simulations. Section IV addresses the dynamics of BNS mergers with pions and the detailed analysis of the simulation results including the GW signal, the threshold binary mass for prompt black-hole formation, and the ejecta. In Sec. V we summarize and discuss the conclusions of our findings. The Appendix briefly assesses stellar equilibrium models which also include muons and neutrinos in addition to pions.

II. PIONIC EQUATION OF STATE

In this section, we discuss our procedure of adding pions in an existing nonpionic EOS. The tabulated Steiner, Fischer, and Hempel (SFHo) EOS [62–64] and the DD2 EOS [62,65,66] are used in this study as base EOSs. These EOSs include neutrons, protons, light nuclei (deuterium, tritium, ³He, etc.), alpha particles, heavy nuclei (charge number $Z \geq 6$), electrons, and positrons as their constituent and assume nuclear statistical equilibrium (NSE) over the whole ranges of density and temperature. The base nonpionic EOSs tabulate various thermodynamic quantities against the baryonic density ρ , temperature T , and number fraction of positively charged particles Y_p . We note that in the absence of pions, the net electron fraction $Y_e = Y_{e^-} - Y_{e^+}$ is equal to Y_p , where Y_{e^-} , Y_{e^+} are the number fractions of electrons and positrons, respectively.

The charged pions π^-, π^+ and the neutral pion π^0 have vacuum rest masses of $m_{\pi^\pm} = 139.57039$ MeV and $m_{\pi^0} = 134.9768$ MeV [67]. We treat pions as a free Bose gas and assume their masses do not change with baryonic density; however, see for instance [58,59,61,68] for detailed discussions about the pion mass variation in dense medium. Pions are in thermal and chemical equilibrium with nucleons through the strong interaction. Therefore, the chemical potentials of the pions follow $\mu_{\pi^\pm} = \mp(\mu_n - \mu_p)$ and $\mu_{\pi^0} = 0$, where $\mu_n, \mu_p, \mu_{\pi^-}, \mu_{\pi^+}$, and μ_{π^0} are the chemical potentials of neutrons, protons, negatively charged pions, positively charged pions, and neutral pions, respectively. Since we assume pions are a noninteracting Bose gas, the chemical potential of negatively charged pions should be equal to or smaller than their

¹Some of these studies do include a few models with pions such as the APR EOS [36,56]. However, the majority of employed EOS models ignore pions, and thus the models with pions have only a negligible impact on the resulting fits. For simplicity, in the following we will refer to such empirical relations as being obtained from models without pions.

vacuum rest mass. Additionally, charge neutrality requires $Y_p = Y_e + Y_\pi = Y_e + Y_{\pi^-} - Y_{\pi^+}$, where Y_π , Y_{π^-} , and Y_{π^+} are the net number fraction of charged pions, the number fraction of negatively charged pions, and the number fraction of positively charged pions.

To add charged pions to a base EOS, we apply the following procedure. For a given baryonic density ρ , temperature T , and net electron fraction Y_e , we iteratively determine Y_p until charge neutrality $Y_p - Y_\pi = Y_e$ is fulfilled. The base EOS provides $\hat{\mu} = \mu_n - \mu_p$ and in case $|\hat{\mu}| < m_{\pi^\pm}$, the net number fraction of pions Y_π is evaluated employing the Bose-Einstein statistics for a given T and $\mu_{\pi^\pm} = \pm\hat{\mu}$ in each iteration.

In neutron-rich conditions when $Y_p < 0.5$, the base EOS can yield $\hat{\mu} > m_{\pi^-}$. However, the maximum allowed value of negatively charged pions' chemical potential $\mu_{\pi^-}^{\max}$ is their rest mass as pions are a Bose gas. Under such thermodynamic conditions when $\hat{\mu} > m_{\pi^-}$, the negatively charged pions can form the Bose-Einstein condensate which, unlike thermal pions, have zero kinetic energy. In such conditions, we iteratively solve the equation $\hat{\mu} = \mu_{\pi^-}^{\max} = m_{\pi^-}$ to find a new value of Y_p under fixed baryonic density, temperature, and electron fraction. Afterward, we employ the charge neutrality condition to obtain the number fraction of negatively charged condensed pions $Y_\pi^c = Y_p - Y_e - Y_\pi^{\text{thermal}}$ where the number fraction of thermal pions Y_π^{thermal} is evaluated from the Bose-Einstein statistics with $\mu_{\pi^-} = m_{\pi^-}$.

This condensed part of π^- does not contribute to the total pressure and the total thermal energy. In proton-rich conditions, a condensate of positively charged pions can form; however, such scenarios are not expected for zero-temperature β -equilibrium NSs and hypermassive neutron stars (HMNSs). The number fraction of neutral pions can be evaluated easily since it only depends on the temperature of the Bose gas. Finally, we determine the contribution of pions to the pressure, the internal energy, and the total entropy per baryon using the Bose-Einstein statistics.

We note that the base SFHo and DD2 EOSs employed in this study include the electronic contributions corresponding to $Y_e = Y_p$ in the total pressure, the total energy, and the total entropy of the gas, and the base EOSs tabulate these thermodynamic quantities against the ρ , T , and Y_p . Therefore, while building our modified EOSs with pions, which tabulate thermodynamic quantities as a function of the ρ , T , and Y_e with $Y_e \neq Y_p$, we first subtract the electronic contributions corresponding to $Y_p = Y_e + Y_\pi$ from the total pressure, the total energy, and the total entropy, and then we add the electronic contributions corresponding to Y_e to the total pressure, the total energy, and the total entropy of the gas.

The base EOS considers the Coulomb interactions between charged particles and includes their contributions to the pressure, the internal energy, and the proton chemical potential. The Coulomb contributions in these mentioned

thermodynamic quantities can be different for pions and electrons as the mean separation length between positive charges and pions can be smaller than the mean separation length between positive charges and electrons. Despite that, we do not modify the Coulomb contributions to thermodynamic quantities in this paper, which is a caveat of our scheme. However, at densities relevant for pion production, i.e., densities above the nuclear saturation density, the nuclear contributions dominate over the Coulomb contributions. Therefore, our approximation regarding the Coulomb interactions may have a minor impact on the structure of NSs and the GWs emitted during merger, which are the two main topics of this paper.

In a dense medium, the effective pion mass may vary with the baryon density, temperature, and composition, due to the pion-pion interaction and the pion-nucleon interaction (see, e.g., [58,59,61,68]). Reference [61] has shown a significant increase in the mass of the negatively charged pions at densities above saturation density and zero temperature. However, the behavior at typical temperatures of a few 10 MeV, which is the relevant regime for postmerger remnants, requires further studies. For simplicity, we use fixed pion masses adopting the vacuum mass, 170 MeV, and 200 MeV. To probe the consequences of the effective pion mass variation on various thermodynamic quantities, we construct and study EOSs with different constant pion masses. We assume that neutral and charged pions have the same masses and already remark that positively charged pions are strongly suppressed under the relevant conditions such that we do not expect major effects by a possible mass splitting between negatively and positively charged pions. Our treatment may not capture all intricacies of how the dense medium may change the pion EOS (see, e.g., [57,60,61,69] for discussions about the medium modification of pionic EOSs); however, it provides a simple way to study the probable impact of pion mass variations on BNS mergers.

In this paper, we use the following notation: ‘‘SFHo’’ for the base SFHo EOS, ‘‘SFHo + π , $m_\pi = \text{Vacmass}$ ’’, ‘‘SFHo + π , $m_\pi = 170 \text{ MeV}$ ’’, ‘‘SFHo + π , $m_\pi = 200 \text{ MeV}$ ’’ for SFHo based EOSs that include pions with effective pion masses equal to the vacuum mass, 170 MeV and 200 MeV, respectively. A similar notation is used for the models based on DD2.

In Fig. 1, we compare the SFHo EOS and the modified SFHo EOS with pion masses equal to their vacuum values at a baryon density of 10^{15} g/cm^3 . The top panels show the net number fraction of the charged pions Y_π (solid lines), the number fraction of the condensed negatively charged pions Y_π^c (dashed lines), the neutral pions Y_{π^0} (dotted lines), and the positive charges Y_p (dotted-dashed lines). The middle and bottom panels show the total pressure and the specific internal energy, respectively, for the SFHo EOS (dashed lines) and the modified SFHo EOS with pion masses equal to their vacuum values (solid lines). The

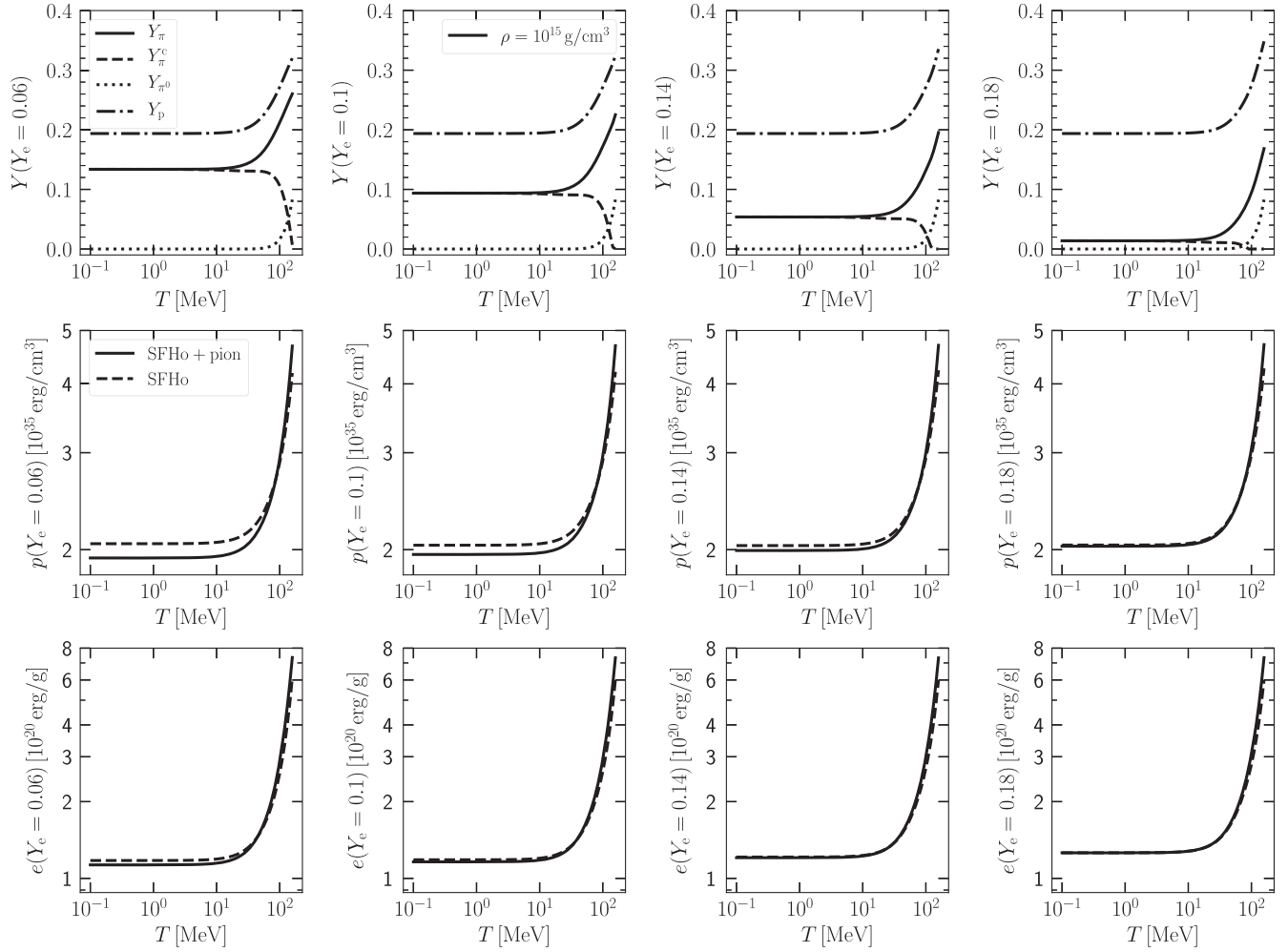


FIG. 1. Comparison between the SFHo EOS and the modified SFHo EOS with pion masses equal to their vacuum values at a baryon density of 10^{15} g/cm 3 . The net number fraction of charged pions (solid lines) and number fraction of condensed negative pions (dashed lines), neutral pions (dotted lines), and positive charges (dotted-dashed lines) are shown in the top row. The total pressure and total specific internal energy are shown for the SFHo EOS (dashed lines) and the modified SFHo EOS with pions (solid lines) in the second and third rows, respectively. Different columns represent different electron fractions.

panels show the aforementioned quantities as functions of the gas temperature, and different columns represent different electron fractions, namely $Y_e = 0.06$ (first column), 0.1 (second column), 0.14 (third column), and 0.18 (fourth column). Such values of the electron fraction and the baryon density of 10^{15} g/cm 3 are representative of conditions in an HMNS (see, e.g., [45,70–73]).

At these thermodynamic conditions, the net number fraction of charged pions and the number fraction of condensed negatively charged pions remain constant below a threshold temperature T_{thres} . Below T_{thres} , pions are predominately in the Bose-Einstein condensate form ($Y_\pi \approx Y_\pi^c$). As the temperature rises beyond T_{thres} , more and more pions go out of the condensate form; moreover, the net number fraction of charged pions grows with the temperature as thermal pions, i.e. pions with nonzero kinetic energies, are produced copiously. We also notice

that the threshold temperature rises with growing baryon density and diminishes with increasing electron fraction as shown in Fig. 2, where T_{thres} are marked by crosses for various densities and electron fractions. We approximate T_{thres} as the temperature where the number fraction of condensed negatively charged pions differs by one percent from the net number fraction of charged pions. We also observe that the neutral pions are only produced copiously at high temperatures, and their number fraction does not depend significantly on the electron fraction since their chemical potential is zero. In contrast, the net number fraction of charged pions decreases with the growing electron fraction. The number fraction of positively charged particles follows the charge neutrality condition $Y_p = Y_e + Y_\pi$. In neutron-rich conditions shown in Fig. 1, the π^- are more abundant than π^+ ($Y_\pi > 0$) which leads to $Y_p > Y_e$; therefore, the inclusion of pion production moves

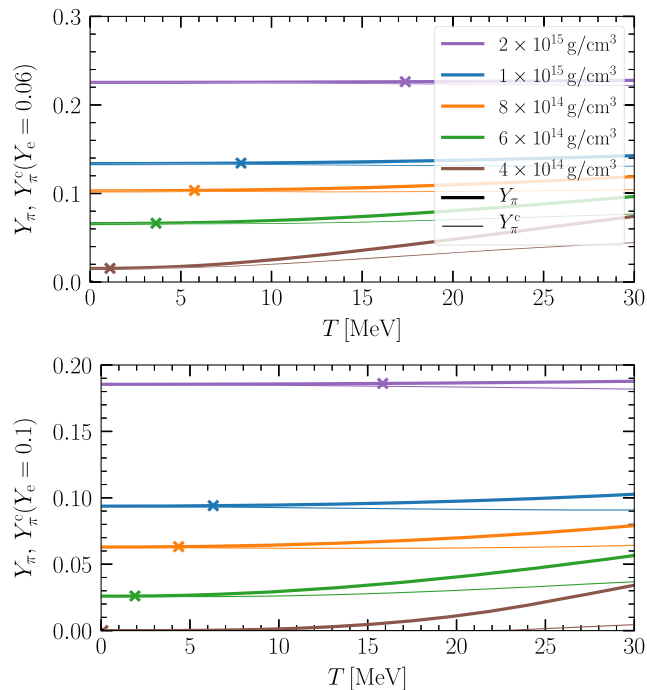


FIG. 2. Net number fraction of charged pions and number fraction of negative pions in the condensate versus temperature at different densities for the modified SFHo EOS with pion masses equal to their vacuum values. The top panel and the bottom panel show these number fractions at electron fractions of 0.06 and 0.1, respectively. The crosses mark the threshold temperatures. We define these threshold temperatures as the points where the number fraction of negative pions in the condensate differs by one percent from the net number fraction of charged pions.

baryonic contribution matter toward a more symmetric condition ($Y_p \rightarrow 0.5$) and thus affects the pressure.

The total pressure shown in the middle row of Fig. 1 contains contributions from baryons, electrons, positrons, and photons for both EOSs and, in addition, includes contributions from thermal charged pions and the neutral pions for the modified SFHo EOS. The bottom panels of Fig. 1 display the specific internal energy, i.e. the relativistic specific internal energies from which the vacuum rest-mass energies of baryons are subtracted. It contains contributions from baryons, electrons, positrons, photons, and, if present, from pions. The condensed negatively charged pions do not contribute to the pressure as they possess zero kinetic energy and only contribute to the specific internal energies.

At temperatures below several 10 MeV the pressure as well as the specific internal energy of the EOS which includes pions, is smaller than those of the base EOS. This is because a fraction of the pions exist in condensed form and do not contribute to the thermal pressure and thermal energy. Furthermore, the difference between the two EOSs becomes smaller with increasing electron fraction because of the decreasing net number fraction of charged pions.

We also notice that the decrease in the pressure due to pion production is more pronounced compared with that of the specific internal energy.

As temperature rises and pions go out of the condensed form, these reductions in the pressure and the specific internal energy vanish, and at temperatures above several 10 MeV, the pressure and the specific internal energy of the modified SFHo EOS become larger than that of the base SFHo EOS due to the contributions from the thermal charged pions and the neutral pions, which are produced abundantly at high temperature.

In Fig. 3, we show the comparison between the DD2 EOS and the modified DD2 EOS with pion masses equal to their vacuum values. The quantities shown in Fig. 3 are the same as in Fig. 1. The qualitative trends discussed above for the modified SFHo EOS are also observed for the modified DD2 EOS. However, there are some quantitative differences between the modified DD2 EOS and the modified SFHo EOS, which are expected since the base EOSs are based on different nuclear models [64–66].

In Fig. 4, we depict the total pressures (top panel) and the net number fractions of charged pions (bottom panel), respectively, versus temperature at a baryon density of 10^{15} g/cm³ and an electron fraction of 0.06 for the SFHo EOS (black lines) and the modified SFHo EOS with various pion masses, namely the vacuum masses (blue lines), 170 MeV (orange lines), and 200 MeV (green lines). For large pion masses, the total pressure of the modified SFHo EOSs approaches that of the base EOS. This reduction in the total pressure difference between the modified SFHo EOSs and the base SFHo EOS is expected since the charged pion production diminishes with increasing pion mass. The reduced pion production is reflected by the shift of the net number fraction of charged pions to smaller values as the pion masses increase (lower panel). Recently, [61] discussed the density dependence of pion mass at $T = 0$. They showed the negatively charged pion mass can be greater than 200 MeV at densities relevant for the pion production, i.e., at densities greater than nuclear saturation density. The net pion fraction will be minuscule for such a high value of negatively charged pion mass, and the impact of pion production on the total pressure, the total energy, etc. will be negligible. The dependence of pion effective mass on the density and temperature and how the pion’s energy-momentum dispersion relation changes in a dense medium require further studies.

In Fig. 5, we show the net number fraction of charged pions color-coded on the baryon density-temperature plane (ρ - T plane) for modified SFHo EOSs with pion masses equal to their vacuum values (top panel), 170 MeV (middle panel), and 200 MeV (bottom panel). Additionally, we mark the ratios of the number fraction of condensed charged pions and the net number fraction of charged pions Y_π^c/Y_π by black lines. Y_π and Y_π^c are evaluated under the assumption that the charged pions are in chemical

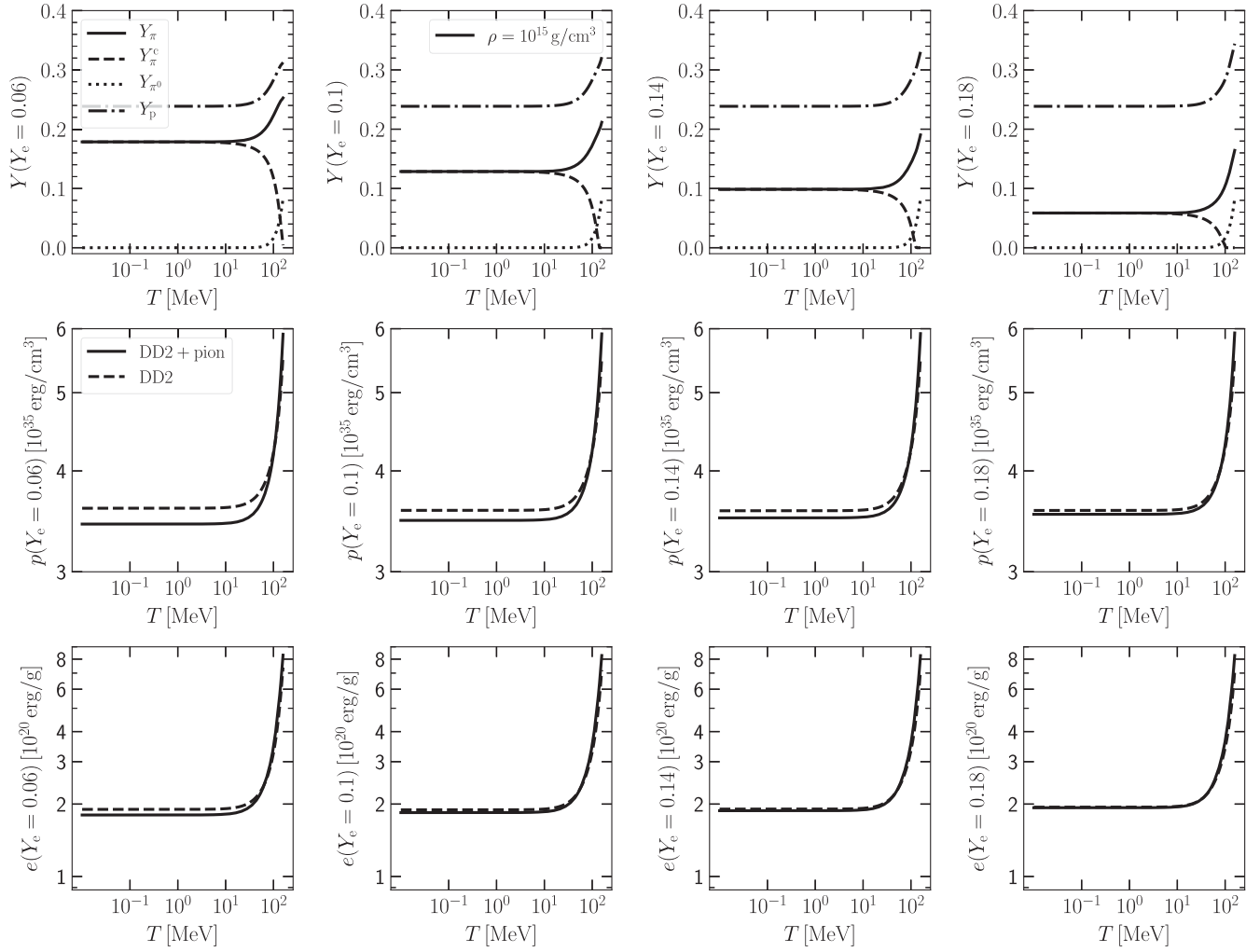


FIG. 3. Comparison between the DD2 EOS and the modified DD2 EOS with pion masses equal to their vacuum values. Quantities shown here are the same as in Fig. 1.

equilibrium with the nucleons and electrons $\mu_{\pi^-} = \mu_n - \mu_p = \mu_e$, where μ_e is the chemical potential of electrons. The $Y_{\pi^c}/Y_{\pi} = 0.99$ line corresponds to the threshold temperature T_{thres} (see also Fig. 2). We notice from Fig. 5 that for a given temperature, the net number fraction of charged pions typically rises with the baryon density; moreover, the ratio between Y_{π^c} and Y_{π} increases with the baryon density for all modified EOSs. A larger fraction of negatively charged pions enter the condensed state as the temperature decreases, which is also evident from Figs. 1 and 2. By comparing the panels for different modified SFHo EOSs, i.e. different assumed pion masses, in Fig. 5, we see that the value of Y_{π} drops with increasing charged pion mass for a given baryon density and temperature. As the charged pion masses grow, a larger density and a lower temperature are needed to achieve the same value of the Y_{π^c}/Y_{π} ratio because a larger value of $\hat{\mu}$ is required to form the pion condensate. Similar qualitative trends in Y_{π} and Y_{π^c}/Y_{π} with varying density, temperature, and pion masses can be observed for the modified DD2 EOSs in Fig. 6.

III. STELLAR STRUCTURE AND MERGER MODELING

To understand the impact of pions in BNS mergers, we conduct a number of simulations using the EOSs discussed in Sec. II with effective pion masses equal to their vacuum masses, 170 MeV, and 200 MeV based on the SFHo and DD2 model, respectively. As a reference, we also consider simulations using the base EOSs without pions.

A. Stellar structure of isolated NS star

Before we describe merger simulations with the new EOS models, we briefly discuss the impact of pions on the stellar structure by considering the zero temperature² neutrinoless beta-equilibrium slices of the EOS models

²For the sake of simplicity we write “zero temperature” although the lowest temperature listed in the EOS tables is 0.1 MeV, and we compute TOV profiles for this temperature.

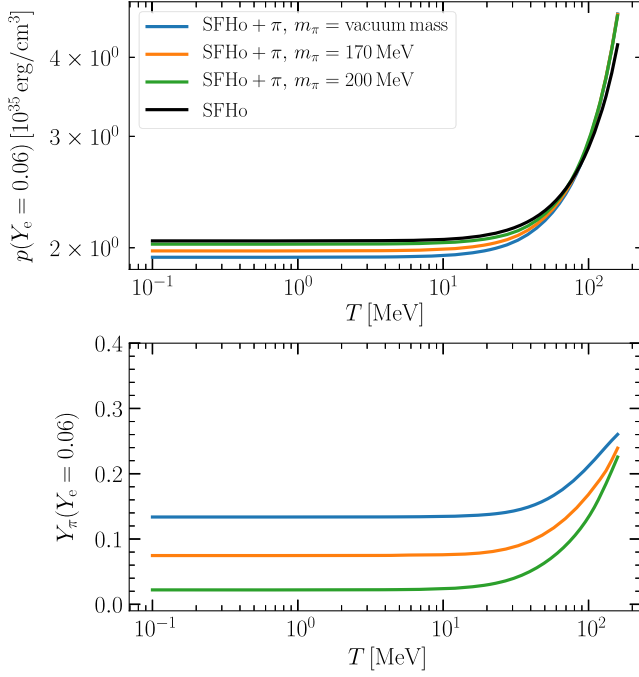


FIG. 4. Total pressure of matter (top panel) and net number fraction of charged pions (bottom panel) versus temperature at a baryon density of 10^{15} g/cm 3 and at an electron fraction of 0.06 for the SFHo EOS (black lines) and the modified SFHo EOSs with different pion masses, namely, vacuum mass (blue lines), 170 MeV (orange lines), and 200 MeV (green lines). The total pressure of matter for the modified EOSs with pions converges toward the SFHo EOS values as the mass of the pion increases. Moreover, the net number fraction of charged pions decreases with the growing pion mass.

and by solving the Tolman–Oppenheimer–Volkoff (TOV) equations [74,75] for these barotropic relations.

Considering pions in NS matter has a strong impact on the conditions for chemical equilibrium, and by this it affects the stellar structure of NSs in equilibrium. It also determines the initial conditions for binary mergers. The conditions for beta-equilibrium at zero temperature are clarified in Fig. 7. The upper panel shows the difference between the chemical potentials of neutrons and protons as a function of density. Once the $\mu_n - \mu_p$ reaches the effective pion mass, the difference remains constant. Hence, the electron chemical potential is constant, which implies that the electron fraction Y_e decreases with density because $\mu_e = \text{const} \propto n_e^{1/3} \propto (\rho Y_e)^{1/3}$ for relativistic electrons. This can be seen in the middle panel, where the thick lines exhibit Y_e . Since the electron chemical potential is given by the effective pion mass, the electron fraction is independent of the nuclear EOS in the regime where $\mu_n - \mu_p$ remains constant. For larger effective pion masses, this behavior sets in at a higher density. Also, at this threshold density the proton fraction starts to deviate from the electron fraction (middle panel) because of the occurrence of condensed pions. In comparison to the base EOS,

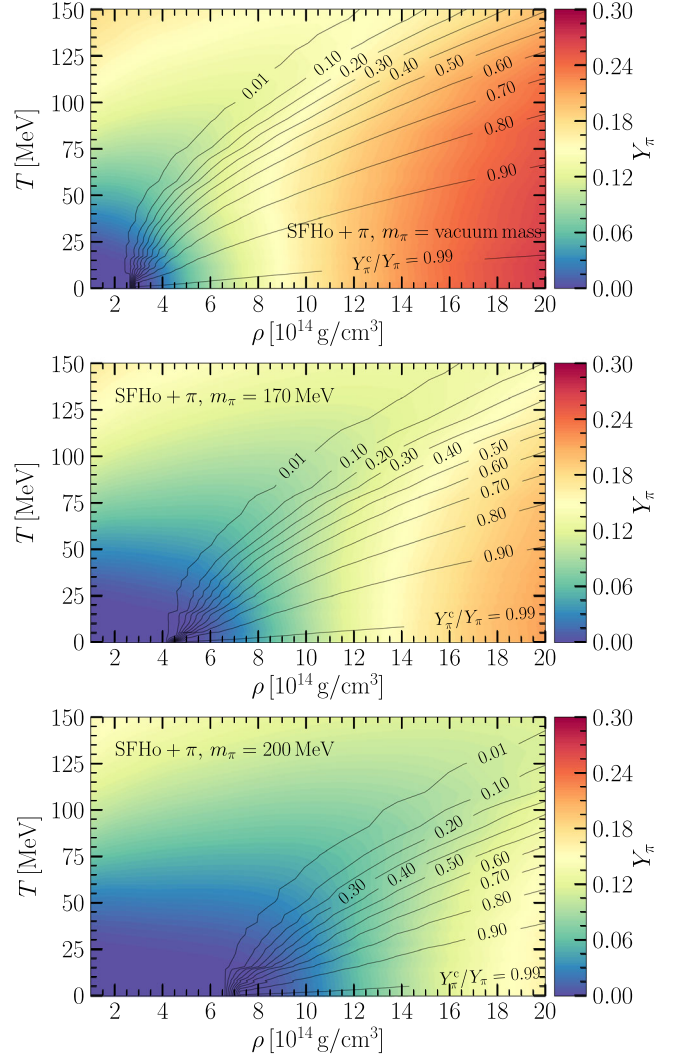


FIG. 5. Equilibrium net number fractions of charged pions, i.e., the net number fraction of charged pions, nucleons, and electrons are in chemical equilibrium, are shown color-coded on the baryon density-temperature plane (ρ - T plane) for the modified SFHo EOSs with pion masses equal to their vacuum values (top panel), 170 MeV (middle panel), and 200 MeV (bottom panel). The ratios of the equilibrium number fraction of negatively charged condensed pions and the equilibrium net number fraction of charged pions are marked by black lines.

Y_p is increased, and charge neutrality is established between protons, electrons and pions.

The proton fraction does show a dependence on the nuclear EOS at all densities, i.e. also in the regime with pion condensation. Hence, the fraction of pions does also depend on the EOS fulfilling charge neutrality.

This behavior can be understood by considering the symmetry energy of the EOS defined as the energy difference between neutron matter and symmetric matter. The symmetry energy is known to determine the proton fraction in beta-equilibrium for matter composed of neutrons, protons and electrons by connecting the difference

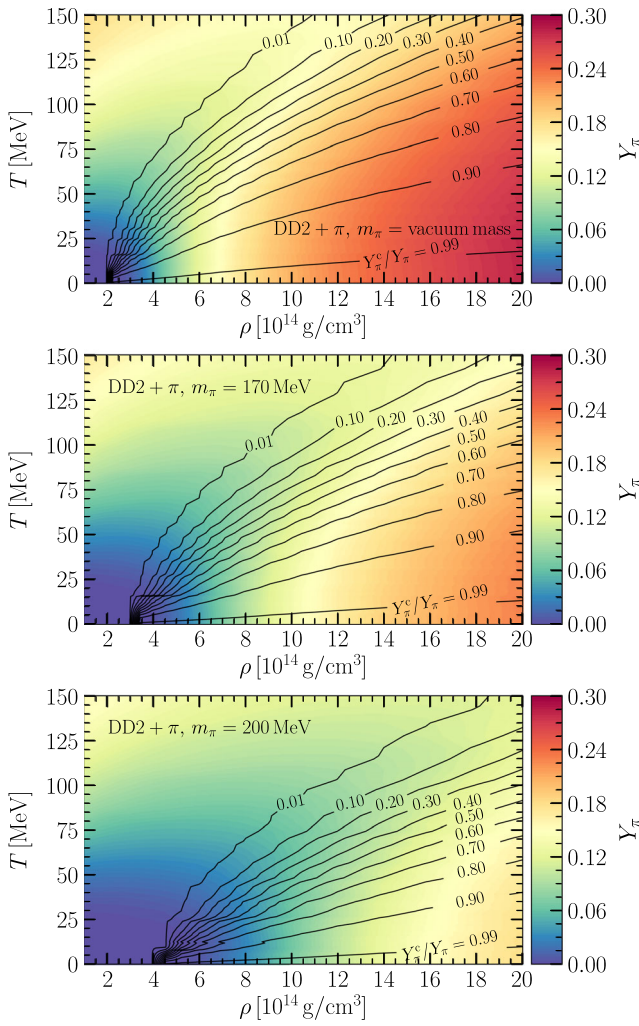


FIG. 6. Same as Fig. 5 but for the EOSs based on the DD2 model.

of chemical potentials between neutrons and protons, $\hat{\mu} = \mu_n - \mu_p$, and Y_p (see e.g. [76,77], noting that slightly different definitions of the symmetry energy are used in the literature). In the regime of pion condensation with $\hat{\mu} = \text{const}$, the proton fraction is thus entirely determined by the symmetry energy. The symmetry energy is given in the bottom panel of Fig. 7. As the symmetry energy increases for constant $\hat{\mu}$, the proton fraction increases, which is clearly visible in the middle panel. The middle panel also shows that the proton fraction is larger for the DD2 based models, which is a consequence of their larger symmetry energy (bottom panel).

In Fig. 8(a), we show the NS gravitational masses versus central densities (top panel) and NS radii (bottom panel) at zero temperature for the SFHo EOS and the modified SFHo EOSs with pions, respectively. Figure 8(b) displays the same relations for the DD2 EOS and modified DD2 EOSs, respectively. The production of condensed pions in a NS lowers the pressure support against gravity and leads to a reduced mass for the same central density as we can notice from the top panel of Figs. 8(a) and 8(b). The maximum

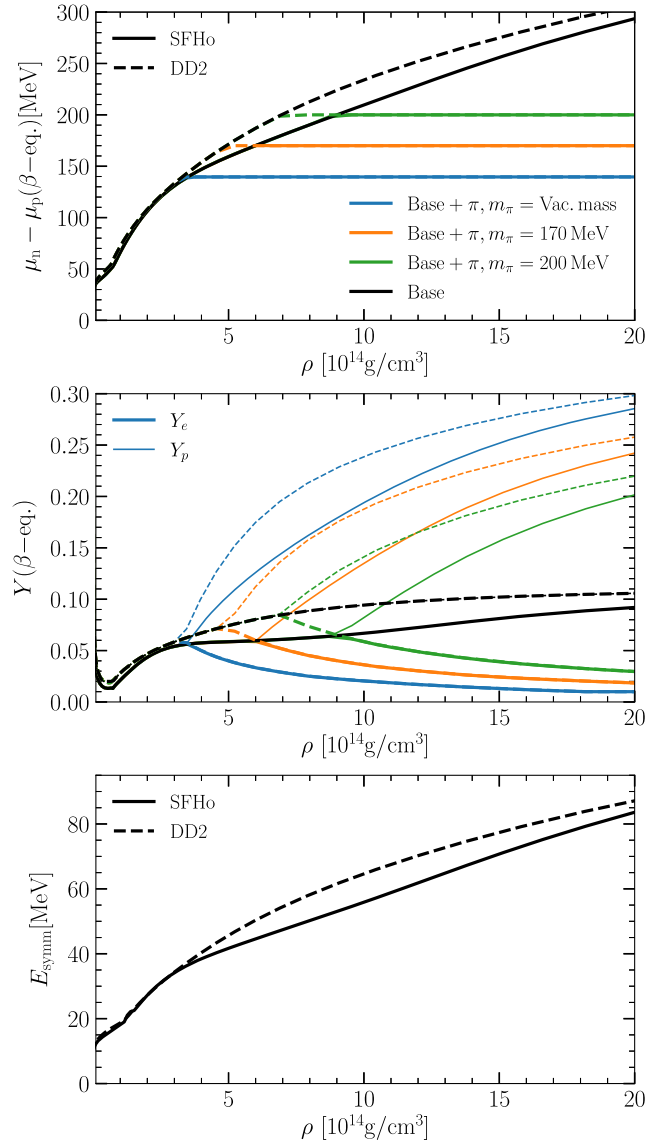


FIG. 7. Top panel shows the difference between neutron and proton chemical potential as a function of density at zero temperature for beta-equilibrium. Middle panel provides the electron fraction and proton fraction in beta-equilibrium. Bottom panel displays symmetry energy of nuclear matter as the energy difference between neutron matter and symmetric matter. In all panels black curves refer to the base EOS without pions. Colored curves show the aforementioned quantities for EOSs with pions assuming different effective pion masses. Solid lines are for SFHo based models, while dashed curves visualize DD2 based models. In the middle panel thin lines display the proton fraction and thick lines indicate the electron fraction. For the base models both coincide.

mass is also reduced by the inclusion of pions for both EOS models. The effect amounts to at most one to two percent for the models adopting the vacuum masses. For higher effective pion masses the impact is smaller. See Tables I and II. Similar trends are found for NS radii, which are reduced by about one percent for models with the pion vacuum masses.

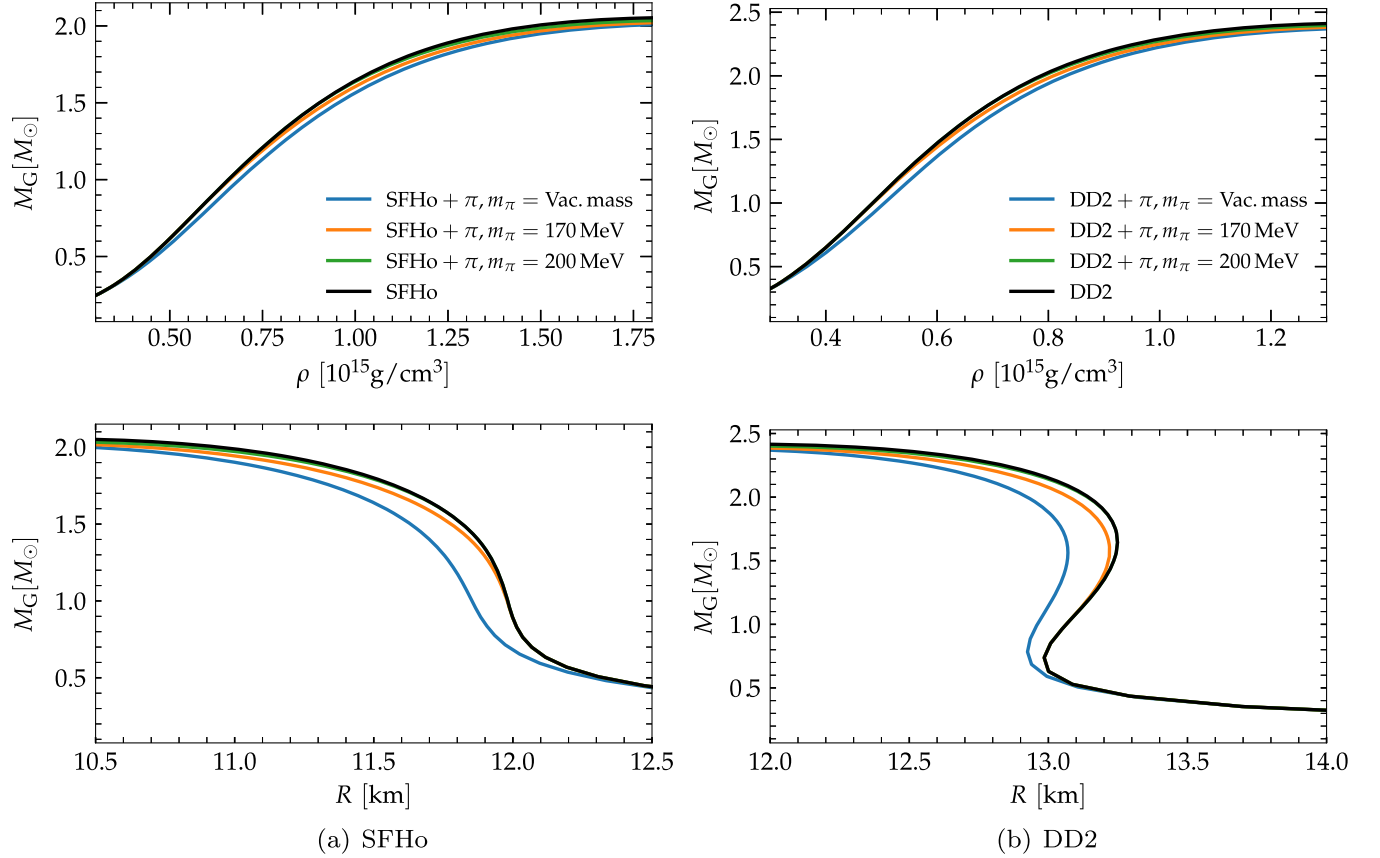


FIG. 8. (a) Gravitational mass versus central baryon density (top panels) and gravitational mass versus the radius of NSs (bottom panels) for the base SFHo EOS and the ones including pions, SFHo, SFHo + π , $m_\pi = \text{Vac. mass}$, SFHo + π , $m_\pi = 170 \text{ MeV}$ and SFHo + π , $m_\pi = 200 \text{ MeV}$. (b) Same plots as in the left panel, but for DD2, DD2 + π , $m_\pi = \text{Vac. mass}$, DD2 + π , $m_\pi = 170 \text{ MeV}$ and DD2 + π , $m_\pi = 200 \text{ MeV}$.

In general, the softening from pions leads to a higher compactness. For a given EOS with fixed effective pion mass, the softening at higher densities is inversely related to the effective mass of the pion used in that EOS. For large effective pion masses, the stellar structure is very similar to the one resulting from the EOSs without pions.

B. Simulation details

We simulate the hydrodynamical evolution of NS mergers using a general relativistic smoothed particle hydrodynamics (SPH) code that employs the conformal flatness condition to solve the general relativistic Einstein field equations [78–82]. The initial data are constructed by imposing neutrinoless β -equilibrium conditions in the respective EOSs where neutrons, protons, electrons and pions (if present) are in chemical and thermal equilibrium. The stars are assumed not to have any intrinsic rotation. Our simulations begin with two NSs in a quasicircular equilibrium orbit with an orbital separation such that the merger takes place after a few revolutions. We advect the initial electron fraction with the fluid i.e. $\frac{dY_e}{dt} = 0$, which represents a rather crude treatment of weak interaction.

In this study we only consider equal mass BNS systems. We choose $1.35 - 1.35M_\odot$ binaries and systems with a total mass close to the threshold binary mass for prompt black-hole formation, which we estimate for the EOSs with pions from empirical relations [52]. We provide a complete list of simulations in Table I for SFHo based models and Table II for DD2 based models.³ These include information on the total mass of the binaries, the mass of pions, the radius of cold, isolated NSs with half of the total mass of the BNS, the tidal deformability of the binary system, and the chirp mass. The tidal deformability is defined as $\Lambda = \frac{2}{3}k_2\left(\frac{R}{M}\right)^5$, where R and M are the radius and the gravitational mass of the individual nonrotating NSs and k_2 is the tidal Love number [83]. The chirp mass is given by $M_{\text{chirp}} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$, where M_1 and M_2 are BNS masses. We also indicate whether the system undergoes a prompt

³In these tables we do not list all simulations performed for this study but provide only those for which we run the same total binary mass for all four versions of the EOS model. For determining the threshold binary mass for the individual EOS models we conducted additional simulations for specific total binary masses.

TABLE I. Properties of the simulated models with the SFHo EOS and the modified SFHo EOSs with pions. First column shows names of the simulated models. Second column shows the gravitational masses of BNSs, m_π is the effective pion mass employed in the modified EOS, R_{ns} and Λ are the radius and the dimensionless tidal deformability of a single NS corresponding to one of the star in the equal-mass BNS system. M_{chirp} represents the chirp mass of the BNS system. The column ‘‘Prompt collapse’’ indicates whether a BH is formed immediately after the merger or not, and f_{peak} denotes the peak frequency of the GW spectrum. The f_{peak} is shown only for the models without prompt collapse.

Model	BNS masses [M_\odot]	m_π [MeV]	R_{ns} [km]	Λ	M_{chirp} [M_\odot]	Prompt collapse	f_{peak} [kHz]
SFHo_Pions_VacMass_1.35_1.35	1.35–1.35	Vacuum mass	11.727	377.902	1.175	No	3.462
SFHo_Pions_170 MeV_1.35_1.35	1.35–1.35	170 MeV	11.872	413.490	1.175	No	3.351
SFHo_Pions_200 MeV_1.35_1.35	1.35–1.35	200 MeV	11.896	420.776	1.175	No	3.318
SFHo_Base_1.35_1.35	1.35–1.35	No pion	11.896	420.813	1.175	No	3.310
SFHo_Pions_VacMass_1.40_1.40	1.40–1.40	Vacuum mass	11.700	296.937	1.219	No	3.599
SFHo_Pions_170 MeV_1.40_1.40	1.40–1.40	170 MeV	11.845	324.561	1.219	No	3.530
SFHo_Pions_200 MeV_1.40_1.40	1.40–1.40	200 MeV	11.874	332.950	1.219	No	3.454
SFHo_Base_1.40_1.40	1.40–1.40	No pion	11.874	332.970	1.219	No	3.419
SFHo_Pions_VacMass_1.42_1.42	1.42–1.42	Vacuum mass	11.687	270.635	1.236	Yes	...
SFHo_Pions_170 MeV_1.42_1.42	1.42–1.42	170 MeV	11.833	296.199	1.236	No	3.621
SFHo_Pions_200 MeV_1.42_1.42	1.42–1.42	200 MeV	11.864	303.134	1.236	No	3.552
SFHo_Base_1.42_1.42	1.42–1.42	No pion	11.864	303.089	1.236	No	3.499
SFHo_Pions_VacMass_1.425_1.425	1.425–1.425	Vacuum mass	11.684	264.060	1.241	Yes	...
SFHo_Pions_170 MeV_1.425_1.425	1.425–1.425	170 MeV	11.830	289.202	1.241	Yes	...
SFHo_Pions_200 MeV_1.425_1.425	1.425–1.425	200 MeV	11.862	295.680	1.241	No	3.622
SFHo_Base_1.425_1.425	1.425–1.425	No pion	11.862	295.619	1.241	No	3.573
SFHo_Pions_VacMass_1.43_1.43	1.43–1.43	Vacuum mass	11.681	257.484	1.245	Yes	...
SFHo_Pions_170 MeV_1.43_1.43	1.43–1.43	170 MeV	11.827	282.205	1.245	Yes	...
SFHo_Pions_200 MeV_1.43_1.43	1.43–1.43	200 MeV	11.859	288.226	1.245	Yes	...
SFHo_Base_1.43_1.43	1.43–1.43	No pion	11.859	288.156	1.245	No	3.614

TABLE II. Properties of the simulated models with the DD2 EOS and the modified DD2 EOSs with pions. Same as Table I but for the models based on DD2.

Model	BNS masses [M_\odot]	m_π [MeV]	R_{ns} [km]	Λ	M_{chirp} [M_\odot]	Prompt collapse	f_{peak} [kHz]
DD2_Pions_VacMass_1.35_1.35	1.35–1.35	Vacuum mass	13.048	796.159	1.175	No	2.681
DD2_Pions_170 MeV_1.35_1.35	1.35–1.35	170 MeV	13.189	854.982	1.175	No	2.642
DD2_Pions_200 MeV_1.35_1.35	1.35–1.35	200 MeV	13.199	871.076	1.175	No	2.597
DD2_Base_1.35_1.35	1.35–1.35	No pion	13.199	871.135	1.175	No	2.608
DD2_Pions_VacMass_1.62_1.62	1.62–1.62	Vacuum mass	13.068	262.744	1.410	No	3.099
DD2_Pions_170 MeV_1.62_1.62	1.62–1.62	170 MeV	13.219	287.197	1.410	No	3.030
DD2_Pions_200 MeV_1.62_1.62	1.62–1.62	200 MeV	13.247	294.408	1.410	No	3.008
DD2_Base_1.62_1.62	1.62–1.62	No pion	13.247	294.465	1.410	No	2.997
DD2_Pions_VacMass_1.64_1.64	1.64–1.64	Vacuum mass	13.066	243.524	1.428	Yes	...
DD2_Pions_170 MeV_1.64_1.64	1.64–1.64	170 MeV	13.217	266.835	1.428	No	3.137
DD2_Pions_200 MeV_1.64_1.64	1.64–1.64	200 MeV	13.248	270.335	1.428	No	3.024
DD2_Base_1.64_1.64	1.64–1.64	No pion	13.248	270.407	1.428	No	3.036
DD2_Pions_VacMass_1.65_1.65	1.65–1.65	Vacuum mass	13.065	234.778	1.436	Yes	...
DD2_Pions_170 MeV_1.65_1.65	1.65–1.65	170 MeV	13.216	256.653	1.436	Yes	...
DD2_Pions_200 MeV_1.65_1.65	1.65–1.65	200 MeV	13.248	260.521	1.436	No	3.127
DD2_Base_1.65_1.65	1.65–1.65	No pion	13.248	260.531	1.436	No	3.047
DD2_Pions_VacMass_1.66_1.66	1.66–1.66	Vacuum mass	13.064	226.031	1.445	Yes	...
DD2_Pions_170 MeV_1.66_1.66	1.66–1.66	170 MeV	13.216	246.472	1.445	Yes	...
DD2_Pions_200 MeV_1.66_1.66	1.66–1.66	200 MeV	13.248	251.637	1.445	Yes	...
DD2_Base_1.66_1.66	1.66–1.66	No pion	13.248	251.658	1.445	No	3.139

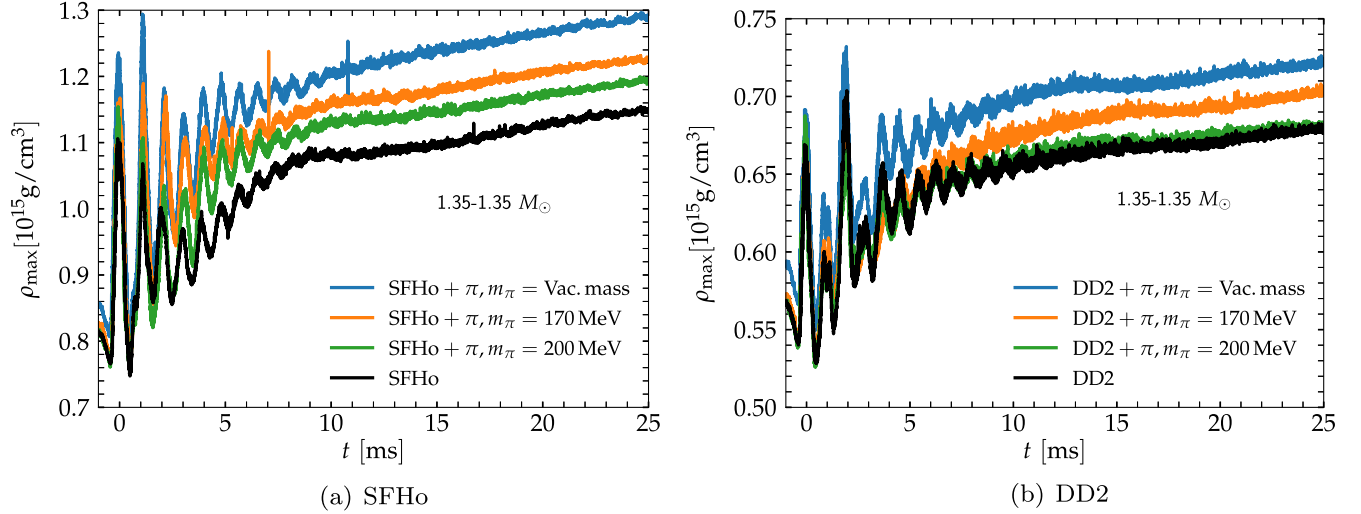


FIG. 9. Time evolution of the maximum baryonic rest-mass density for $1.35 - 1.35M_{\odot}$ BNS systems using SFHo EOS [left panel (a)] and DD2 EOS [right panel (b)]. The time zero corresponds to the instant of the maximum compression during the first bounce after merging (minimum in the lapse function). We evaluate the maximum baryonic rest-mass density on the SPH particle level, which is why some noise is visible.

gravitational collapse and provide the dominant GW frequency of the postmerger phase. The dominant GW frequency is not shown for the models that experience prompt collapse.

IV. SIMULATION RESULTS

In this section we describe the general dynamics and the evolution of the pion contributions in our binary merger simulations. We address the postmerger GW signal and the threshold mass for prompt black-hole formation and discuss to which extent these features are affected by the presence of pions.

A. Dynamics and pion production in NS mergers

Apart from models undergoing a prompt gravitational collapse to a black hole, all BNS merger simulations proceed qualitatively similarly, and we do not recognize any specific differences between the calculations with the base EOSs and those with the modified EOSs with pions. Most of the simulated binaries result in the formation of a rotating NS remnant, and only a few systems with relatively large total binary masses lead to direct black-hole formation after merging (to be discussed below).

In the simulations yielding a NS remnant, the merging stars form a rotating double-core structure, and, while the densities in the postmerger phase increase, the remnant undergoes vivid oscillations. For the $1.35 - 1.35M_{\odot}$ models, the density oscillations can be seen in Fig. 9 showing the evolution of the maximum baryonic rest-mass density. The quantitative behavior is inline with existing literature results, i.e., softer EOSs lead to higher densities. This concerns the comparison between the base EOSs, SFHo and DD2, and also the comparison between the respective

base EOS and the versions with pions. Smaller effective pion masses lead to softer EOSs and more compact stellar configurations and thus higher ρ_{\max} in the merger remnant. Quantitatively, the maximum densities in the merger remnant are consistent with empirical relations for ρ_{\max} found for a large sample of candidate EOSs without pions (see discussion below in Sec. IV C).

As discussed in Sec. II, the production of pions depends on the difference between the chemical potentials of neutrons and protons, and through this on the density and temperature. At typical densities of NSs and NS merger remnants, the contributions from thermal pions become dominant only beyond a threshold temperature of several 10 MeV (see Fig. 2 and discussion in Sec. II). We assess the temperature regime in the merger remnants of $1.35 - 1.35M_{\odot}$ binary simulations in Fig. 10 visualizing the evolution of the maximum temperature and the mass-averaged temperature.⁴ The largest temperatures occur at the collisional interface between the merging NSs with this contact layer having a thickness of typically some 100 meters to km. We note that the exact values of T_{\max} are affected by the numerical resolution with the general trend being an increase in the maximum temperature of a few tens of percent.⁵ Furthermore, we find that relative

⁴We define a mass-averaged quantity by summing the contribution from all SPH particles weighted by the mass of the particle relative to the total mass.

⁵We have investigated the resolution dependence by running additional simulations with about 600,000, 1,200,000 and 2,400,000 SPH particles compared with our default resolution of 300,000 SPH particles. The maximum temperatures show a slight increase with higher resolution by at most a few 10 MeV, which is roughly comparable to the differences between models with and without pions.

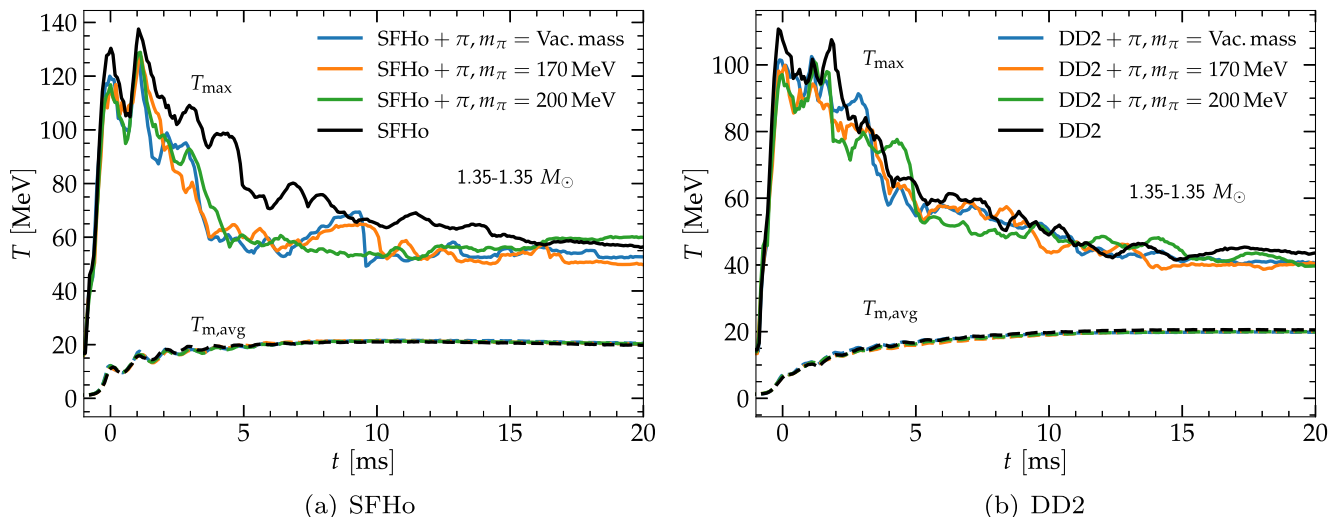


FIG. 10. Time evolution of the maximum and mass-averaged temperature for $1.35 - 1.35M_{\odot}$ BNS systems using SFHo EOS [left panel (a)] and DD2 EOS [right panel (b)].

changes on T_{\max} with time are independent of the resolution. Although the maximum temperatures do reach about 100 MeV, such conditions are only found in a small volume in the remnant and not necessarily at the highest densities. Average temperatures in the merger remnant are significantly lower (of the order of about 20 MeV), which suggests that thermal pions likely play only a subdominant role in the merger remnant of the systems considered here. Hence, we anticipate that the inclusion of pions in BNS merger simulations overall has a softening effect.

In Fig. 10(a), we observe that the models with the softer SFHo EOS lead to slightly higher maximum temperatures, which is understandable given that the stars described by this EOS collide more violently and the compression in the remnant is stronger. There is also the tendency that models with pions result in slightly lower maximum temperatures. Figure 4 clearly shows that at such high temperatures the inclusion of pions leads to a stiffening of the EOSs, which is roughly independent of the effective pion mass. We caution that one should not overinterpret the differences in the maximum temperature between EOSs because we evaluate the temperature on the basis of individual SPH particles, which are affected by noise.⁶

⁶We also run simulations with about 600,000 SPH particles for all SFHo models with and without pions. The evolution of T_{\max} in the first few milliseconds after merging follows approximately the one in the simulations with our default resolution. Only for the model with m_{π} equal to the vacuum mass, we find that T_{\max} is higher (by about 20 MeV) compared with the run with 300,000 particles. Comparing runs with 600,000 particles, the model with pion mass equal to the vacuum mass actually features the highest temperatures in the first milliseconds after merging somewhat in contrast to the finding for the default-resolution simulations, where the base models yield the highest T_{\max} .

Evaluating directly the ratio between the number of thermal pions and pions in the condensate, we do indeed find that thermal pions are subdominant even in the hot merger remnant and that the main effects of pions originate from the condensate (Figs. 13 and 14 except for the case with $m_{\pi} = 200$ MeV).

In this respect, it is also instructive to directly compare the difference $\hat{\mu}$ between the chemical potentials of neutrons and protons for the base model and the calculation including pions. Figure 11 shows $\hat{\mu}$ in the equatorial plane for the DD2 base model and the model with pions adopting the vacuum pion mass. In the latter case, $\hat{\mu}$ is limited by the pion mass (~ 139.6 MeV for this case), whereas $\hat{\mu}$ reaches more than 200 MeV in the remnant's center if pions are ignored. If pions with an effective mass equal to their vacuum mass are included, a pion condensate is found throughout the whole high-density region of the remnant. One may already conclude from the range of $\hat{\mu}$ in the left panel of Fig. 11 that the condensation of pions in the remnant depends on the adopted effective pion mass. $\hat{\mu}$ increases toward the center for the base model and reaches 200 MeV only in the very inner region. Hence, for $m_{\pi} = 200$ MeV, pion condensation only takes place in the center of the remnant at the highest densities. This clearly demonstrates that the effective pion mass has a significant impact on the production of pions in BNS mergers.

These observations and their impact are further illustrated in Fig. 12, which displays snapshots of the electron fraction (upper panel), the pion fraction (middle panel) and the proton fraction (bottom panel) in the equatorial plane for a $1.35 - 1.35M_{\odot}$ BNS merger remnant about (~ 18.95) milliseconds after merging, employing the pionic DD2 EOSs. The columns refer to different m_{π} increasing from left to right.

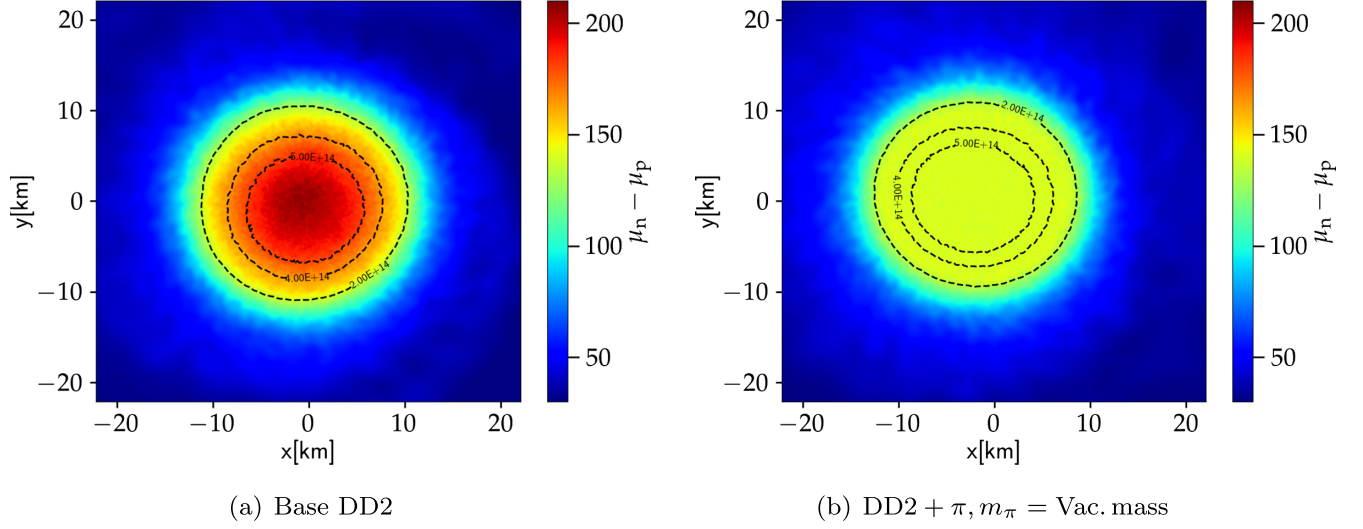


FIG. 11. (a),(b) Snapshots of neutron and proton chemical potential difference $\mu_n - \mu_p$ in the equatorial plane for a $1.35 - 1.35M_\odot$ BNS model after the merger, using the base DD2 EOS without pions and the modified DD2 EOS that includes pions with an effective pion mass equal to their vacuum masses, DD2 + $\pi, m_\pi = \text{Vac. mass}$. Density regions of 2×10^{14} g/cm³, 4×10^{14} g/cm³ and 5×10^{14} g/cm³ are shown by dashed contour lines.

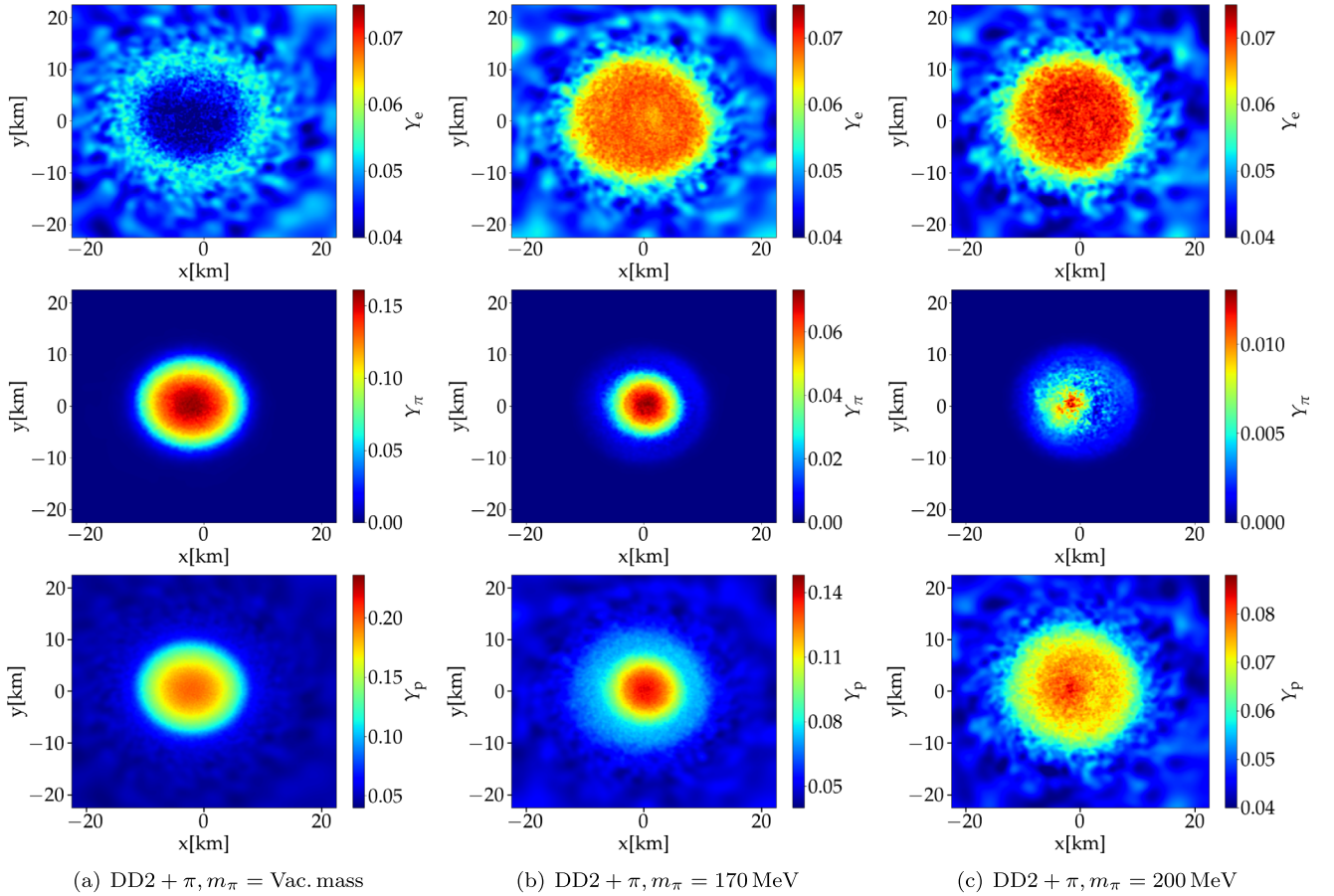


FIG. 12. Y_e distribution (top row panels), Y_π distribution (middle row panels) and Y_p distribution (bottom row panels) in the equatorial plane for $1.35 - 1.35M_\odot$ BNS systems using DD2 + $\pi, m_\pi = \text{Vac. mass}$ [left column panels (a)], DD2 + $\pi, m_\pi = 170$ MeV [middle column panels (b)] and DD2 + $\pi, m_\pi = 200$ MeV [right column panels (c)].

It is obvious that the inclusion of pions and their effective mass have a very strong impact on the electron fraction in the remnant, which is determined by $\hat{\mu}$ and thus by the presence of pions and their properties in the progenitor (see Fig. 7). For relatively small pion masses, the electron fraction in the remnant remains rather small while the proton fraction increases with the produced number of pions [Fig. 12(a)]. For $m_\pi = 200$ MeV [Fig. 12(c)] the highest Y_e and the lowest Y_p are found. We recall that in these simulations we employ a rather simplistic treatment of weak interactions by ignoring neutrinos and only advecting the electron fraction. Hence, the behavior in Fig. 12 can be easily understood by the behavior in Fig. 7. For smaller effective pion masses, Y_e is strongly reduced in the initial stars, which thus yields a lower electron fraction in the remnant. The behavior of the pion fraction and the proton fraction is a consequence of the advected electron fraction. Both follow similar trends as for equilibrium NSs,

i.e. a lower Y_e is accompanied by a larger proton fraction and a larger pion fraction (see Fig. 7). Despite the simple treatment of weak interactions, the panels indicate a potentially significant impact by pions on the microphysics of weak interactions as they affect the conditions for the chemical potentials in the remnant.

The middle row of panels in Fig. 12 visualize the pion content in the remnant depending on the effective pion mass. As expected, the volume of the region inside the HMNS where pions are present, shrinks as the effective pion mass increases. The pion content is strongly suppressed for $m_\pi = 200$ MeV, and only occurs in the center where $\hat{\mu}$ reaches the pion mass. This panel illustrates that the DD2 + π , $m_\pi = 200$ MeV model should behave very similarly to the base EOS.

To address the distribution of thermal and condensed pions in different regions of the merger remnant, we show the distribution of Y_π^c and Y_π^{thermal} in Fig. 13 for

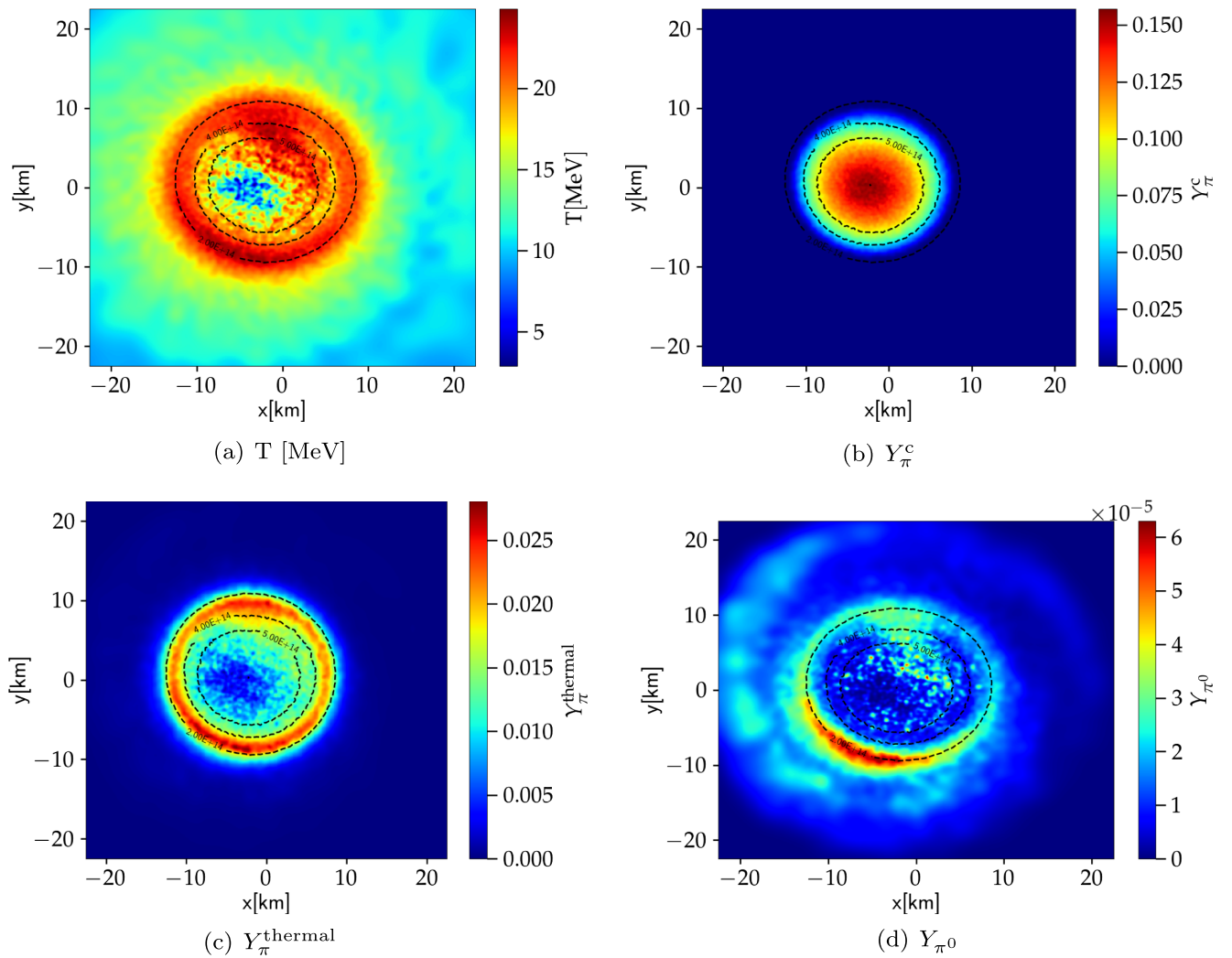


FIG. 13. (a)–(d) temperature, Y_π^c , Y_π^{thermal} and Y_{π^0} distribution in the equatorial plane for a $1.35 - 1.35M_\odot$ BNS system using the DD2 + π , $m_\pi = \text{Vac mass}$ model. Densities of 2×10^{14} g/cm³, 4×10^{14} g/cm³ and 5×10^{14} g/cm³ are shown by dashed contour lines.

the DD2 + π , $m_\pi = \text{Vac}$ mass model along with the corresponding temperature distribution. The correlation between thermal pions and the local temperature is clear from the hot ringlike structure in the merger remnant shown in Figs. 13(a) and 13(c) whereas Y_π^c roughly follows the density in Fig. 13(b). Although the number of neutral pions increases with temperature, the relative magnitude is very low [Fig. 13(d)]. We expect the neutral pion contribution to become noticeable only at high temperatures around ~ 100 MeV (particles with maximum temperature); see Figs. 1 and 3.

As temperatures and densities increase during the dynamical evolution, more pions are produced as compared with the pion content of the initial stars. We quantify the pion production in Fig. 14, which provides the mass-averaged fraction of the total number of pions, condensed pions and thermal pions as a function of time for both SFHo and DD2 EOSs.

One can clearly recognize that the effective pion mass sensitively affects the production of pions. For the pion mass equal to the vacuum mass, there are already a lot of pions present in the initial stars, and the additional increase of the pion fraction during merging is moderate. For $m_\pi = 170$ MeV we see a significant increase of Y_π by about a factor of four. If the effective pion mass is as high as 200 MeV, there are no pions present during the inspiral and only the density and temperature increase after merging leads to the production of pions, which are predominantly thermal.

SFHo is softer than DD2 and thus results in higher densities in the inspiralling stars and in the postmerger remnant. Hence, the pion production is increased for the SFHo based models as compared with the EOSs relying on DD2. Considering this behavior, we anticipate that the softening of the EOS by pions is more pronounced for the softer SFHo model as compared with DD2.

B. Gravitational-wave signal

1. Inspiral

The GW signal reflects the dynamical evolution of BNS mergers and thus carries an imprint of the EOS. The GW inspiral signal is determined by the tidal deformability Λ , where we find a reduction of Λ of up to about 10% by the inclusion of pions comparing the base models without pions and the modified EOSs with an effective pion mass equal to the vacuum mass. As anticipated from the mass-radius relations (Fig. 8), the reduction of the tidal deformability depends on the effective pion mass, and larger effective pion masses have a smaller or even negligible impact on the tidal deformability.

While these findings are not unexpected, they caution that ignoring pions in EOS calculations might potentially introduce a systematic bias if the actual effective pion mass in medium is close to its vacuum mass. This may apply to

cases where microphysical parameters of the EOS as for instance the slope of the symmetry energy are inferred from the GW inspiral signal through microphysical EOS models which consider only the baryonic and leptonic contributions. Neglecting pions and thus an additional unmodeled softening of the EOS model would lead to a systematic bias of these quantities. Clearly, whether these are severe issues, cannot be judged in our present explorative study with the rather crude incorporation of pions and especially freely chosen effective pion masses. One may expect that the actual impact of pions may become stronger for high-mass NSs and BNSs.

2. Postmerger

The GW signal can also contain a high-frequency component originating from the postmerger phase, i.e. the dynamical evolution of the NS remnant, whereas the high-frequency emission from a directly forming black hole in a prompt gravitational collapse is very weak. If a rotating NS merger remnant forms, one may expect a pronounced impact of pions because the postmerger remnant features finite temperatures and higher densities than the inspiralling NSs. The GW emission of a NS postmerger remnant is dominated by a single, roughly constant frequency, f_{peak} , which reflects the main oscillation mode of the central object and occurs as a strong peak in the GW spectrum.

Figure 15 shows the amplitude of the postmerger GW spectra for an observer at 20 Mpc along the polar axis for $1.35 - 1.35M_\odot$ BNS systems with the SFHo EOSs (left panel) and DD2 EOSs (right panel). It is known that the main frequency scales tightly with NS radii as a measure for the softness of the EOS [38]. The DD2 models oscillate at significantly lower frequencies of about 2.6 kHz compared with more than 3 kHz for the SFHo based EOSs.

Considering the impact of pions, we find that their inclusion shifts the main peak to higher frequencies. This effect is more pronounced for smaller effective pion masses, which is not surprising considering for instance the mass-radius relations of these EOSs. The shift appears to be slightly more pronounced for the SFHo based models with a modification of about 200 Hz. For $m_\pi = 200$ MeV, the main peak is hardly affected by the inclusion of pions, which is consistent with the findings in Sec. IV A, namely that there is only a small contribution by pions for this model. We also recognize an impact on the secondary features of the GW spectrum, i.e. subdominant frequency peaks that have for instance been associated with the formation of massive tidal bulges at the surface of the remnant or a nonlinear coupling of the dominant mode and the quasiradial oscillation of the central object (see [5] for a detailed discussion). Interestingly, it seems that at least for the SFHo based models the influence of pions on those features is stronger.

We display the frequency shift of the main peak and the quantitative impact of the chosen effective pion mass in

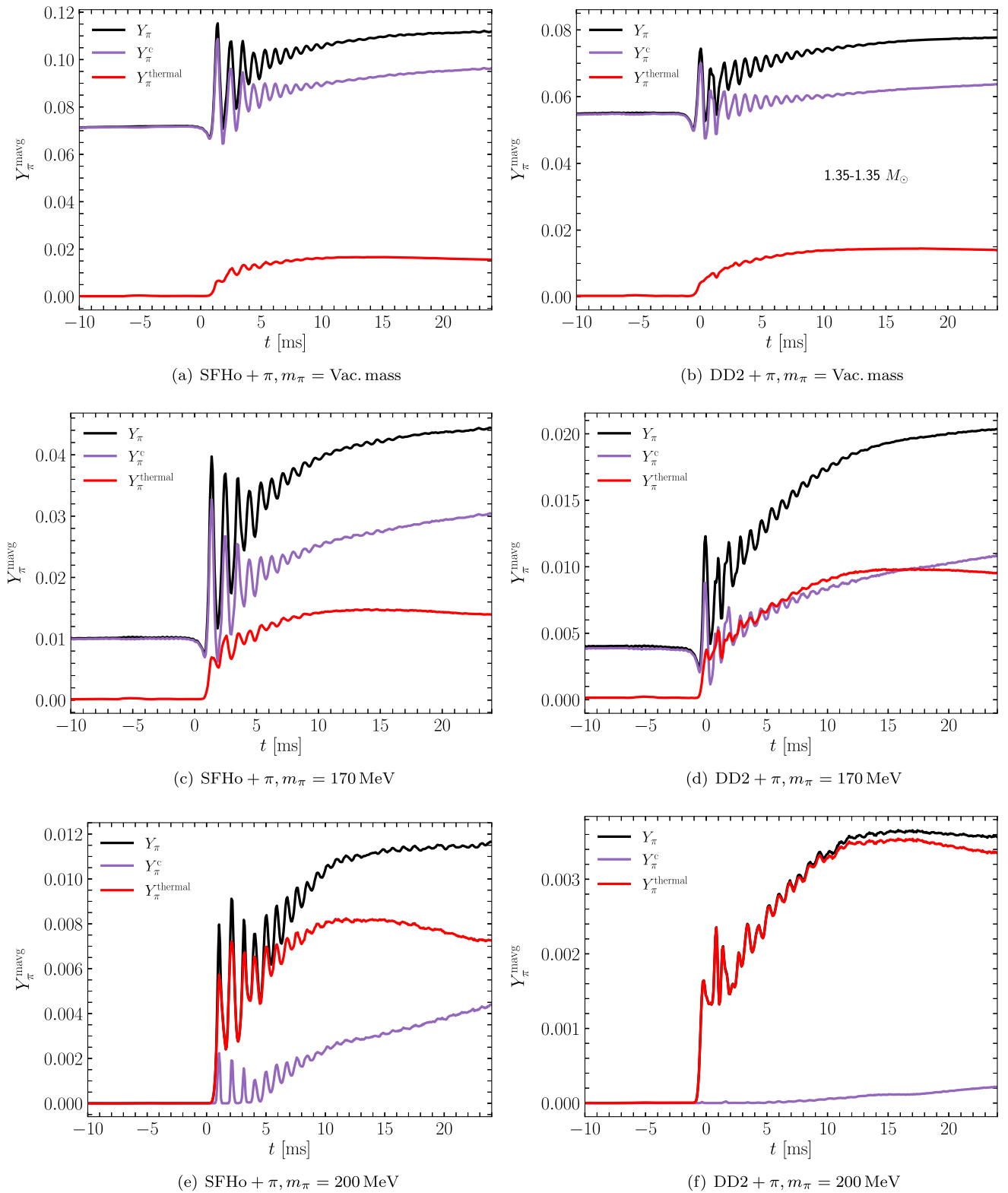


FIG. 14. Time evolution of the mass-averaged pion fraction Y_π^{mavg} of total pion fraction Y_π , condensed pion fraction Y_π^c and thermal pion fraction Y_π^{thermal} for $1.35 - 1.35 M_\odot$ BNS systems. (a), (c), (e) show models of SFHo EOS with Vac. mass, 170 MeV and 200 MeV and (b), (d), (f) show models of DD2 EOS with Vac.mass, 170 MeV and 200 MeV.

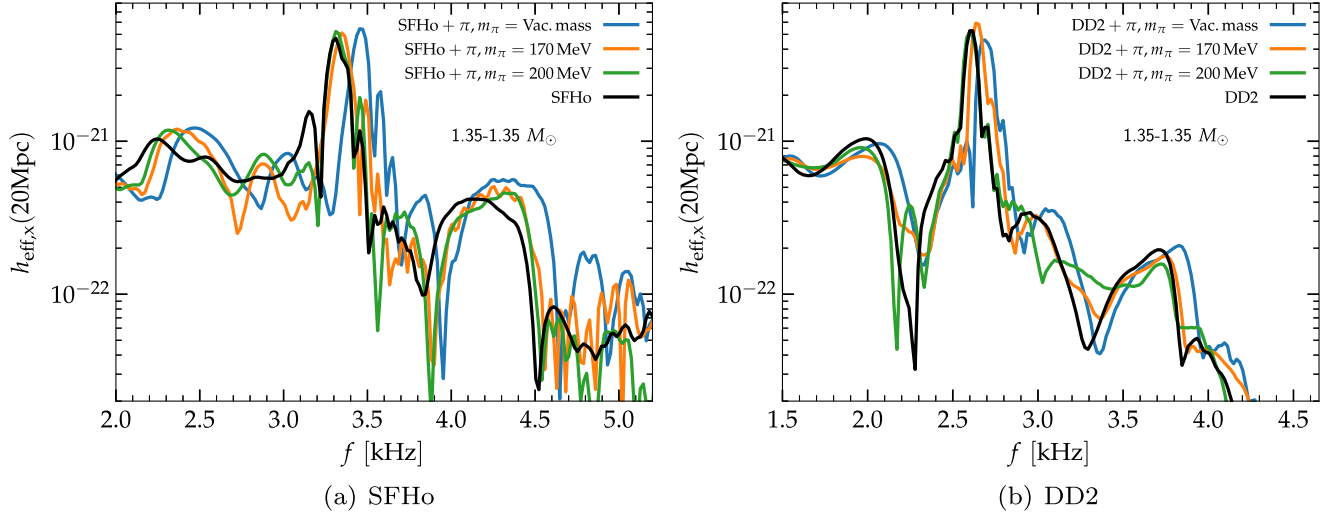


FIG. 15. Comparison of the cross-polarization amplitude of the GW spectra for an observer at 20 Mpc along the polar axis with the SFHo (a) and DD2 (b) EOSs for $1.35 - 1.35 M_\odot$ binaries. The color scheme is the same as in Figs. 9 and 10.

Fig. 16, which reveals a clear dependence on m_π . The shifts also indicate (based on only these two base EOSs) that there may be a stronger impact for softer EOSs. This may not be surprising since such models reach higher densities and temperatures, where pions may lead to a strong impact. We also observe similar trends for the frequency shift for other binary masses (see Tables I and II).

C. Empirical relations for postmerger GW frequencies

By surveying a large sample of EOS models without pions, a number of empirical relations have been identified, which relate the main postmerger frequency to stellar properties of isolated, cold, nonrotating NSs such as their radii

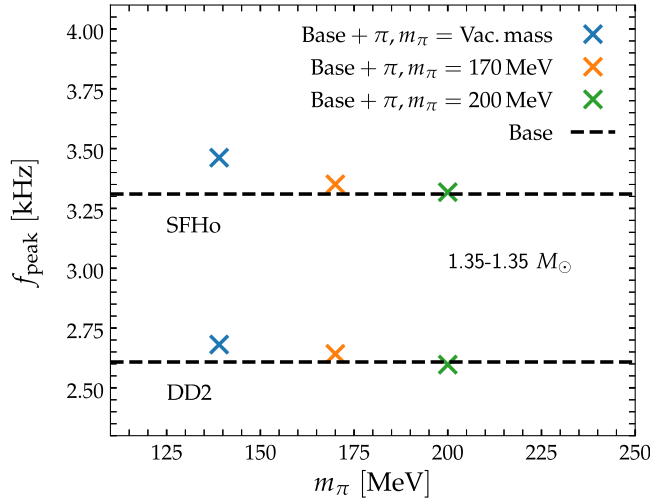


FIG. 16. The dominant postmerger GW oscillation frequency with respect to the pion mass employed in the modified EOSs for $1.35 - 1.35 M_\odot$ simulations. f_{peak} for the respective base EOS is indicated by the black dashed line.

or tidal deformability, e.g. [37,38,40,42–45,47,48,50,51]. These relations are important because they are the basis for inferring these stellar parameters from a measurement of f_{peak} , e.g. [84].

Our results so far showed that the inclusion of pions affects both the stellar parameters of isolated NSs and the properties of the postmerger GW emission. As the empirical relations are built on models ignoring pions, it is thus important to investigate whether models with pions do follow these empirical relations or whether there are deviations. This is relevant because the use of the existing relations could introduce a bias when they are employed for EOS constraints.

We also recall that the impact of pions may be different in different regimes. The analysis in Sec. II shows that including pions can lead to a softening of the EOS compared with a base model without pions or to a stiffening for instance at high temperatures. Hence, the effect of pions is not straightforward to estimate.

We address this aspect by evaluating mass-dependent empirical relations, i.e. relations for a fixed total binary mass, since those yield the tightest relations, and possible deviations can be identified more easily. Specifically, we check the results for $1.35 - 1.35 M_\odot$ binaries.

Figure 17 displays the relation between f_{peak} and the radius $R_{1.6}$ of nonrotating NSs with a mass of $1.6 M_\odot$ [38]. The plot includes results from our new calculations and older data from [50] for a larger set of EOSs none of which considers pions. The solid black line is a least square polynomial fit to the data from [50], i.e. it describes the behavior of EOS models without pions. The band illustrates the maximum scatter in this relation; we choose the width to equal the maximum residual between fit and data.

The figure shows that the inclusion of pions does not lead to strong deviations from the empirical $f_{\text{peak}} - R_{1.6}$

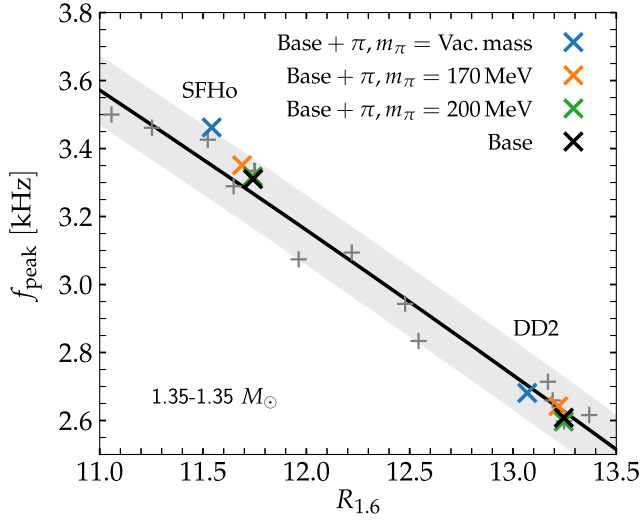


FIG. 17. Dominant postmerger GW frequency, f_{peak} versus the radius of nonrotating $1.6M_{\odot}$ NS for $1.35 - 1.35M_{\odot}$ BNS models using the modified SFHo and DD2 EOSs (crosses) compared with models using different microphysical EOSs which do not include pions (plus signs). The solid curve is a least square fit to the data points of EOSs without pions, with the gray shaded area showing the largest deviation of the data from the least squares fit.

relation. The presence of pions simultaneously changes the properties of the postmerger GW emission and the parameters of nonrotating NSs. The modifications by pions to a large extent cancel each other. Only for the SFHo model with m_{π} equal to the mass in vacuum, f_{peak} is shifted to higher frequencies such that it is marginally compatible with the band defining the inherent scatter of this relation (see also [85] for an extensive discussion of frequency deviations in empirical relations for the postmerger GW signal). These findings indicate that at most there could be a slight bias for very soft EOS models in the sense that the actual relation lies at slightly higher frequencies if the actual effective pion mass is close to its vacuum value.

A similar picture arises for relations which link the dominant postmerger frequency and the tidal deformability [42,43,50]. This is demonstrated in Fig. 18. Again, models with pions are in agreement with relations that are based on models without pions. The SFHo + π , $m_{\pi} = \text{Vac. mass}$ model leads to a somewhat more pronounced frequency shift, and this case is only marginally compatible with the old relation.

We furthermore investigate a relation that connects the dominant postmerger frequency and the maximum rest-mass density, $\rho_{\text{max}}^{\text{max}}$, which occurs during the early evolution in the postmerger remnant, i.e. the highest maximum rest-mass density that occurs during the first five milliseconds after merging [50,86]. This correlation is useful because one can estimate the density regime of the central object. Figure 19 reveals that models with pions also follow this relation with good accuracy and that there do not occur any

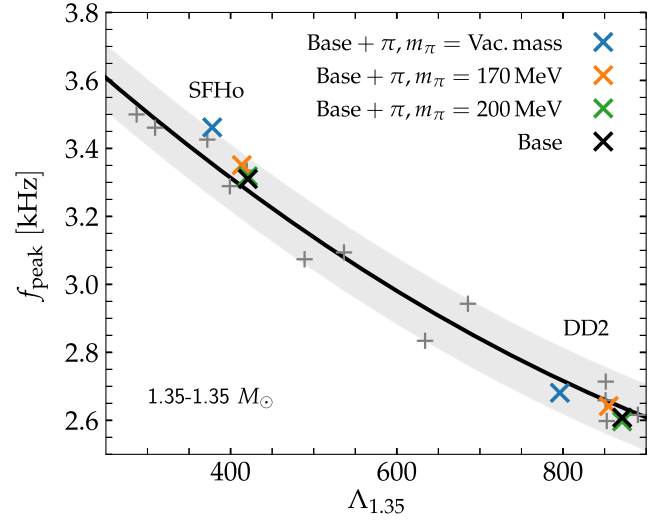


FIG. 18. Dominant postmerger GW frequency, f_{peak} , versus the tidal deformability Λ of $1.35 - 1.35M_{\odot}$ BNSs using modified SFHo and DD2 EOSs (crosses) compared with models using different microphysical EOSs which do not include pions (plus signs). The solid curve is a least square fit to the data points of EOSs without pions, with the gray shaded area showing the largest deviation of the data from the least squares fit.

particularly strong deviations. Compared with the base model, the calculation adopting a pion mass equal to the vacuum mass exhibits a slight increase in $\rho_{\text{max}}^{\text{max}}$. This is consistent with the behavior in Figs. 9(a) and 9(b), which also indicate an increased softening of the EOS by the

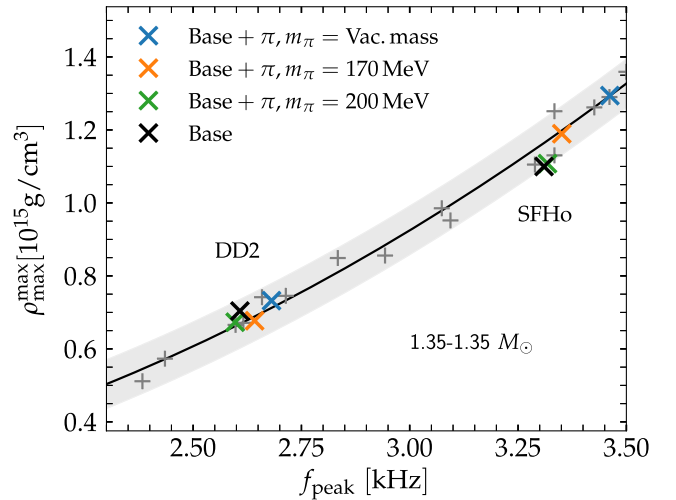


FIG. 19. Maximum rest-mass density $\rho_{\text{max}}^{\text{max}}$ of the early postmerger evolution as a function of the dominant postmerger GW frequency, f_{peak} , for a $1.35 - 1.35M_{\odot}$ BNS using modified SFHo and DD2 EOSs (crosses) compared with models using different microphysical EOSs which do not include pions (plus signs). The solid curve is a least square fit to the data points of EOSs without pions, with the gray shaded area showing the largest deviation of the data from the least squares fit.

TABLE III. Determination of threshold mass. First column gives the different EOSs models used in this paper. M_{thres} is the threshold binary mass for prompt collapse. M_{max} is the maximum mass of the nonrotating NS, $R_{1.6}$ is the radius of a $1.6M_{\odot}$ nonrotating NS, R_{max} is the radius of the nonrotating maximum mass NS. $\Lambda_{1.4}$ and $\tilde{\Lambda}_{\text{thres}}$ are the tidal deformability of a $1.4M_{\odot}$ NS and the tidal deformability of a binary system with a total mass equal to M_{thres} . The last four columns provide an estimated $M_{\text{thres}}^{\text{fit}}$ using available fit formulas [52] of the form $M_{\text{thres}}^{\text{fit}} = M_{\text{thres}}^{\text{fit}}(M_{\text{max}}, Y)$ with Y being either $R_{1.6}$, R_{max} , $\Lambda_{1.4}$ or Λ_{thres} . For the estimate we employ the respective values of M_{max} and Y for the EOS model of the given row. The fit formulas are obtained from models without pions and thus the estimates allow one to assess the performance of these relations for models including pions. The difference, $M_{\text{thres}} - M_{\text{thres}}^{\text{fit}}(M_{\text{max}}, Y)$, between the actual threshold mass (second column) and the estimate by the respective fit formula is given in parentheses. We quote the maximum residuals of the respective fits in parentheses in the third line (see [52]).

Model (Max dev/ M_{\odot})	M_{thres} [M_{\odot}]	M_{max} [M_{\odot}]	$R_{1.6}$ [km]	R_{max} [km]	$\Lambda_{1.4}$	$\tilde{\Lambda}_{\text{thres}}$	$M_{\text{thres}}^{\text{fit}}$ ($Y = R_{1.6}$) (0.042) [M_{\odot}]	$M_{\text{thres}}^{\text{fit}}$ ($Y = R_{\text{max}}$) (0.059) [M_{\odot}]	$M_{\text{thres}}^{\text{fit}}$ ($Y = \Lambda_{1.4}$) (0.056) [M_{\odot}]	$M_{\text{thres}}^{\text{fit}}$ ($Y = \tilde{\Lambda}_{\text{thres}}$) (0.085) [M_{\odot}]
SFHo + π , Vac mass	2.810	2.017	11.542	10.085	296.937	290.362	2.806(0.004)	2.804(0.006)	2.784(0.026)	2.796(0.014)
SFHo + π , 170 MeV	2.845	2.026	11.688	10.212	324.561	292.701	2.835(0.010)	2.832(0.013)	2.811(0.034)	2.816(0.029)
SFHo + π , 200 MeV	2.855	2.038	11.741	10.277	332.950	291.953	2.851(0.004)	2.850(0.005)	2.825(0.030)	2.832(0.023)
SFHo Base	2.870	2.056	11.743	10.285	332.970	282.036	2.861(0.009)	2.859(0.011)	2.835(0.035)	2.830(0.040)
DD2 + π , Vac mass	3.250	2.381	13.069	11.692	639.278	256.841	3.257(-0.007)	3.271(-0.021)	3.271(-0.021)	3.228(0.022)
DD2 + π , 170 MeV	3.290	2.390	13.220	11.791	699.649	261.744	3.287(0.003)	3.294(-0.004)	3.325(-0.035)	3.256(0.034)
DD2 + π , 200 MeV	3.310	2.403	13.246	11.865	700.166	256.079	3.298(0.012)	3.314(-0.004)	3.333(-0.023)	3.259(0.051)
DD2 Base	3.322	2.417	13.246	11.899	700.146	250.548	3.306(0.016)	3.327(-0.005)	3.341(-0.019)	3.263(0.059)

inclusion of pions with this effective mass. This specific model features the largest pion content (mostly condensate pions; see Fig. 14) and leads to the most significant shifts in Figs. 17, 18 and 19, not only parallel to the black solid lines but also perpendicular to it. One may hence not fully exclude that more extreme models with even higher pion content could lead to somewhat stronger deviations from the various empirical relations. However, given that our models provide a decent coverage of the allowed parameter space, substantially stronger deviations seem unlikely.

D. Threshold mass

The high-density EOS determines the outcome of BNS mergers, i.e. the nature, evolution and stability of merger remnants, which can be either a black hole for high total binary masses or a massive, rotating NS if the total mass of the system does not exceed the threshold mass for a prompt gravitational collapse. It is thus important to understand whether pions do have an influence in this context as well.

Specifically, we consider the threshold binary mass M_{thres} for prompt black-hole formation, which can also be regarded as a general measure for the stability of the remnant. As in previous work [39,52,87] we determine M_{thres} by considering simulations with different total binary masses M_{tot} for a given EOS model. Within this set of calculations we identify the model with the highest $M_{\text{tot}} = M_{\text{stab}}$ that does not undergo a direct collapse, and the lightest system with $M_{\text{tot}} = M_{\text{unstab}}$ which directly forms a black hole. The threshold mass is then defined by $M_{\text{thres}} = 0.5(M_{\text{stab}} + M_{\text{unstab}})$. We consider the evolution of the minimum lapse function α_{min} to distinguish

prompt black-hole formation from a delayed gravitational collapse. If α_{min} continuously decreases after the first contact, a prompt collapse occurs. If α_{min} levels off and increases, this indicates a bounce of the merger remnant, and we classify this behavior as a delayed collapse. This procedure and the definition of M_{thres} imply that M_{thres} can only be determined with a finite accuracy apart from other numerical errors in the simulations. For every EOS model in this study we compute the threshold mass to at least within $\pm 0.02M_{\odot}$, i.e. $M_{\text{unstab}} - M_{\text{stab}} = 0.04M_{\odot}$.

Table III lists the threshold mass for all EOS models.⁷ For both base EOS models we find that M_{thres} is systematically reduced by the inclusion of pions. For a given base model the decrease of M_{thres} is stronger for smaller m_{π} and can be as large as $0.08M_{\odot}$ (about two percent of M_{thres}). This is in line with the behavior already found in the analysis of the GW emission, where smaller effective pion masses lead to a generally more pronounced softening of the EOS. Still, this behavior may not be obvious, since the inclusion of pions actually leads to a stiffening of the EOS in the regime of very high temperatures, which is not strongly depending on the pion mass. Apparently, the overall softening has a stronger impact on the stability, which may be explained by the fact that only a very small

⁷The values for M_{thres} for our base models slightly deviate from the ones given in [52] for the same EOS. The reason is that M_{thres} is determined by a bracketing method considering the outcome of binary simulations with different total masses, and in this study we obtain M_{thres} with higher accuracy to within $\pm 0.02M_{\odot}$. We note that the outcomes of the respective simulation data are fully consistent with each other.

volume of the remnant features conditions where a stiffening by pions could occur.

As features of the GW signal, the threshold mass for prompt black-hole formation follows empirical relations, which describe M_{thres} as a function of stellar parameters of cold, nonrotating NSs. A number of such relations have been put forward based on the consideration of a large set of different EOS models without pions [39,41,46,49,52–55,87]. These relations typically depend on two stellar parameters including the maximum mass M_{max} of nonrotating NSs. A bilinear ansatz

$$M_{\text{thres}}^{\text{fit}}(M_{\text{max}}, Y) = aM_{\text{max}} + bY + c \quad (1)$$

works well with fit parameters a , b and c and Y being either the radius $R_{1.6}$ of a $1.6M_{\odot}$ NS or radius R_{max} of a nonrotating neutron star at its maximum mass or tidal deformability $\Lambda_{1.4}$ of a $1.4M_{\odot}$ NS or tidal deformability $\tilde{\Lambda}_{\text{thres}}$ at the threshold mass [52,87]. All these stellar parameters are listed in Table III.

The inclusion of pions in an EOS model changes simultaneously the stellar parameters of cold, nonrotating NSs and the threshold mass for black-hole formation. It is thus important to check if the models with pions do follow these relations which are obtained by fits to EOS models without pions. We note that these relations are for instance employed to establish constraints on NS properties and are generally used to interpret BNS merger observations. Table III provides the estimated threshold mass for all models of this study using empirical relations constructed based on EOSs without pions [52], where we insert the stellar parameters of our modified and the original EOS tables. Specifically, we list estimates based on the fits numbered 1, 15, 29 and 43 in [52], which employ the EOS set labeled “b” therein that contains viable EOS models without phase transition to deconfined quark matter. The EOS models with pions follow these relations with very good accuracy, and one cannot identify significant deviations. The differences between the fits and the actual threshold mass are provided in Table III. The deviations are generally small, especially in comparison to the maximum residuals of the fits (see Table III).

The performance of the fits is also visualized in Fig. 20, which shows $M_{\text{thres}}^{\text{fit}}(M_{\text{max}}, R_{1.6})$. The models with pions (red data points) do not feature any considerable deviations. A similar behavior is found for other empirical relations of [52].

Generally, this comparison shows that such types of empirical relations for $M_{\text{thres}}^{\text{fit}}$ are accurate and can be used although they neglect pions. This is because pions impact the threshold mass and stellar parameters of NSs such that the resulting effects nearly cancel each other. This also implies that EOS constraints based on relations for the threshold mass as in [52,88,89], are not affected by ignoring pions.

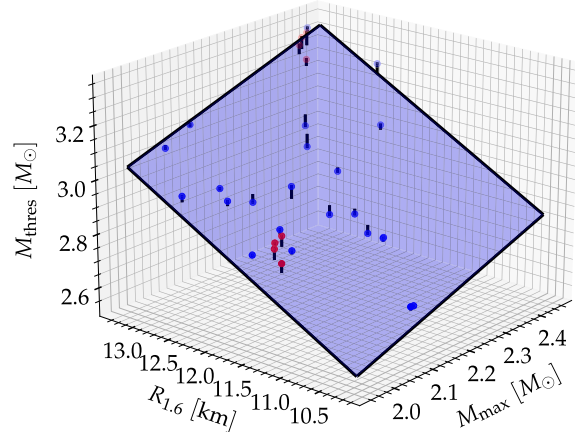


FIG. 20. Threshold binary mass for prompt collapse as a function of the radius $R_{1.6}$ of a $1.6M_{\odot}$ NS and the maximum mass M_{max} of nonrotating NSs. Blue dots display results for EOS models without pions, and the blue plane shows a least square fit to these data (set “b” from [52]). Vertical lines visualize the deviation between the respective data point and the fit (plane). Red dots show the data for the simulations with the EOSs employed in this study.

E. Mass ejection

We finally address the mass ejection of BNS mergers, which is relevant for the nucleosynthesis of heavy elements through the rapid neutron-capture process and electromagnetic counterparts, so-called kilonovae, e.g. [1–7,9,11,12]. Clearly, a key quantity is the ejecta mass M_{ej} , which determines the overall production of heavy elements and the properties of the electromagnetic transient. Mass ejection of BNS mergers includes several phases and with the simulations described here we can only assess the dynamical ejecta, i.e. the material which becomes gravitationally unbound during the first few 10 milliseconds after merging.

Figure 21 shows the amount of unbound material as a function of time for the EOS models based on SFHo (left panel) and DD2 (right panel) considering $1.35 - 1.35M_{\odot}$ binaries. We clearly recognize that dynamical mass ejection is enhanced for models with pions and that smaller effective pion masses tend to produce more unbound matter. This behavior may be expected since softer EOSs yielding smaller NS radii lead to larger ejecta masses based on studies which ignore pions [90,91]. However, the softening by the inclusion of pions is relatively minor, and NS radii do not change by a lot in particular for larger effective pion masses. In this sense the impact of pions visible in Fig. 21 is stronger than expected. Based on previous work one would expect M_{ej} to increase by only a few percent if NS radii decrease by one or two percent, employing fit formulas that link the ejecta mass and NS radii (see e.g. Fig. 22 in [12] based on fits from [92–95]). In Fig. 21 we find an increase of more than 20% in the dynamical ejecta

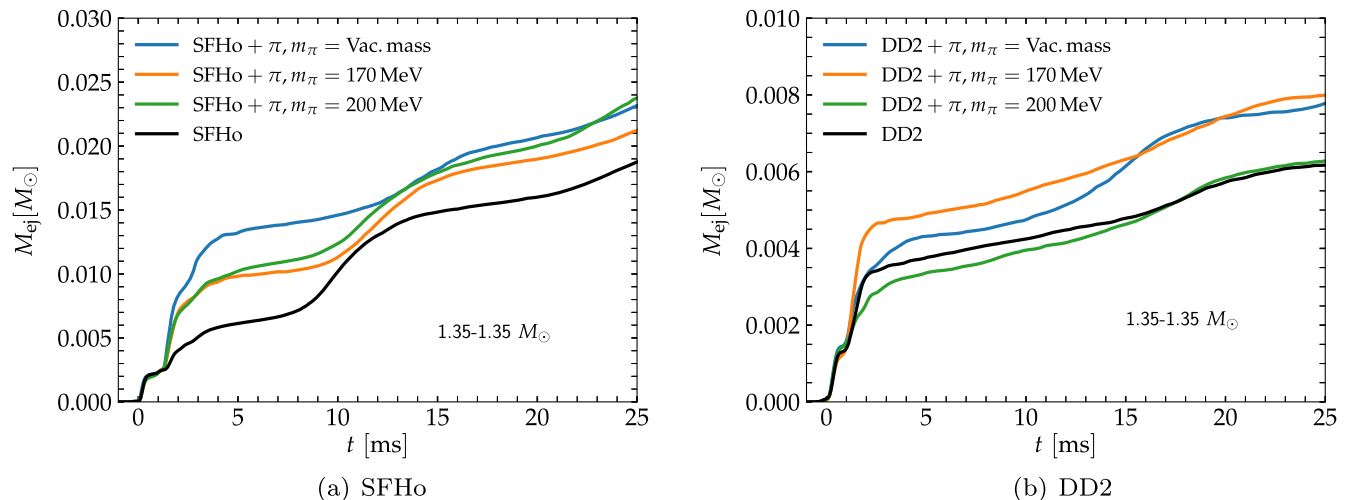


FIG. 21. Time evolution of the ejecta mass for $1.35 - 1.35 M_{\odot}$ BNS mergers using modified SFHo EOSs (a) and DD2 EOSs (b) along with their base EOSs. Time zero corresponds to the instant when the minimum lapse function features a first minimum.

mass for models employ effective pion masses equal to the vacuum values.

The absolute values of the base models in Fig. 21 at about 10 ms after merging are compatible with the results in [90], where M_{ej} is determined at the same time. Also, typical estimates from the existing fit formulas are roughly compatible with M_{ej} at about 10 ms after the collision.

We remark that relations between M_{ej} and NS parameters generally show a large scatter and that the ejecta mass is very sensitive to numerics and is certainly not fully converged in the simulations in addition to missing physics in the calculations (see e.g. discussion in [12]). This may also explain why there is no exact hierarchy with respect to m_{π} . SPH simulations with different particle numbers in [90] (without neutrinos) indicate that the ejecta mass can vary by several 10%, where M_{ej} does not follow a clear trend with particle number but rather seems to fluctuate statistically. The differences in Fig. 21 are hence only tentative⁸ but caution that ignoring pions might have a more pronounced impact on the mass ejection than suggested by the change of stellar properties of cold, nonrotating NSs. This might in particular affect attempts to infer EOS constraints from observed

⁸We perform simulations with about 600,000 SPH particles for the SFHo EOS without pions and with pions following the evolution into the early postmerger phase. Comparing these simulations, we observe very similar trends, namely that the models with pions yield a significant increase of the ejecta mass compared with the run without pions. Similarly, these higher-resolution runs confirm the behavior of the torus mass discussed below, where again the inclusion of pions with relatively small masses leads to an increase compared with the model without pions. Higher resolution tends to increase the torus mass by $\lesssim 10\%$.

kilonovae (e.g. [93]). We note that the inclusion of pions does affect the EOS in a complicated noncontinuous way in different regimes including softening and stiffening with respect to a base model. This may as well contribute to the behavior seen in Fig. 21.

We note that at most a very small fraction of the ejecta ($\sim 1\%$ for SFHo, 0% for DD2) originates from densities beyond the threshold density where pion condensation sets in at about 3×10^{14} g/cm³ in beta-equilibrium (see Fig. 7). Hence, in merger models with pions the initial proton fraction of the ejecta remains basically unaffected compared with the base model. This may suggest that the impact of pions on the composition of the ejecta is only a secondary effect even if weak interactions were taken into account in the simulations.

Figure 22 shows the evolution of the torus mass as function of time, where we define the torus as material with a density below 10^{13} g/cm³ as a coarse estimate. This quantity can serve as a rough estimate of the amount of secular ejecta, which consists of a fraction of a few ten percent of this torus material (see, e.g., [96] for an extensive analysis of torus ejecta). As for the dynamical ejecta, we attempt to assess whether the inclusion of pions affects the torus mass. In Fig. 22, we observe an increase of the torus mass for models which include pions, i.e. for softer EOSs (except for the DD2 based EOS with $m_{\pi} = 200$ MeV). Alternatively, we can consider fit formulas that relate the torus mass to TOV properties, and are based on simulation results (see Fig. 23 in [12] that compiles formulas from [94,95,97]). We notice that these relations are approximate, and different fit formulas show sizeable variations. Nevertheless, they indicate that softer EOSs lead to smaller torus masses. Hence, fit formulas predict that the change of TOV properties induced by the inclusion of pions would lead to a decrease of the torus mass contrary to our findings.

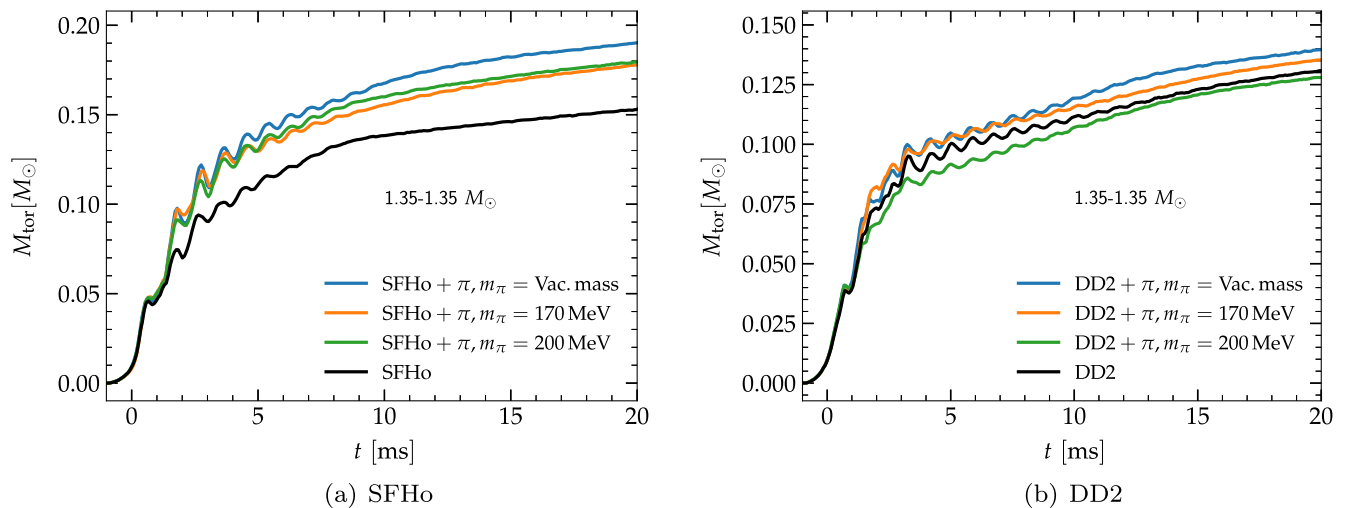


FIG. 22. Time evolution of the torus mass for $1.35 - 1.35 M_{\odot}$ BNS mergers using modified SFHo EOSs (a) and DD2 EOSs (b) along with their base EOSs. Time zero corresponds to the instant when the minimum lapse function features a first minimum.

V. CONCLUSIONS

We study the impact of pions on BNS mergers by considering neutral and charged pions as a free noninteracting boson gas, which we add to an existing base EOS. We use the temperature- and composition-dependent SFHo and DD2 EOSs [62–66]. Although the pion mass may change in a dense medium [58,59,61,68], for this study we assume a constant value of an effective pion mass under all thermodynamical conditions. To assess the impact of changes in the pion mass, we choose different values for a constant effective pion mass. We consider calculations adopting the vacuum values of the pion masses, 170 MeV and 200 MeV.

Pions in dense matter can occur as a condensate, which does not directly add to the pressure, but affects the total pressure at a given Y_e by changing the equilibrium conditions and thus the baryonic contribution. This leads to a softening of the NS EOS. At finite temperature thermal pions occur, which also affect the chemical equilibrium but may overall stiffen the EOS for very high temperatures.

For isolated, cold NSs in neutrinoless beta-equilibrium, the inclusion of pions leads to a softening of the EOS compared with the respective model without pions. This affects the TOV solutions of NSs. The inclusion of pions leads to a decrease of the maximum mass of NSs and to smaller NS radii for a given mass. The magnitude of these effects is inversely related to the adopted pion mass. Radii decrease by at most ~ 200 m for pion masses close to the vacuum value. For $m_{\pi} = 200$ MeV models, changes of the stellar structure are very small since the condensation is largely suppressed.

The tidal deformability can change by about 10 percent for pion masses equal to their vacuum value. This might affect the EOS inference from a GW analysis study of the inspiral if microphysical parameters of nuclear matter are

deduced using microphysical EOS models which neglect pions.

To understand the influence of pions on the BNS mergers, we conduct relativistic hydrodynamical simulations with the different EOS models with and without pions. We focus on $1.35 - 1.35 M_{\odot}$ mergers but also simulate equal-mass binaries with higher total binary mass.

Concerning the general dynamics of the merger there are no qualitative differences comparing simulations with and without pions. However, we find that depending on the adopted pion mass the electron fraction can be significantly altered, albeit we employ a rather crude treatment of weak interactions by simply advecting the initial electron fraction. For a more sophisticated treatment one should also include muons. We briefly estimate the potential impact of muons in the Appendix. In essence, we find that if pions have a sizable impact on the stellar structure for effective pion masses close to the vacuum values, the changes by adding muons are relatively small. For most of our simulated binary configurations we find that pions in the condensate are more abundant than thermal pions. Only for high effective pion masses, thermal pions dominate in the postmerger phase.

We analyze the GW signal in our simulations and observe that the dominant postmerger GW frequency is shifted to higher frequencies by up to 200 Hz compared with the base model without pions. The shift is more pronounced for smaller effective pion masses. We evaluate how these changes compare to empirical relations between stellar parameters of NSs and the dominant postmerger frequency (e.g. [37,38,40–45,47,48,50,51]). These relations have been obtained in the literature considering large sets of EOS models that neglect pions. We find that these relations remain to good accuracy valid because the inclusion of pions changes both the properties of

nonrotating NSs and of postmerger remnants. This justifies using these relations for the EOS inference in GW observations. Only for small pion masses close to their vacuum values slight deviations may occur.

Similarly, we investigate the impact of pions on the threshold binary mass M_{thres} for prompt black-hole formation. Again, we find that the overall softening of the EOS compared with a base model without pions, leads to a reduction of M_{thres} . The reduction can be as large as about $0.07M_{\odot}$ and is more significant for small pion masses. Again, the inclusion of pions does not lead to significant deviations in empirical relations for M_{thres} which have been built using models without pions [52]. Similarly, we find relations for the maximum density in the early postmerger evolution to be fulfilled [50].

We also briefly assess the consequences for mass ejection in NS mergers. We find that the presence of pions leads to enhanced mass ejection by a few ten percent compared with the base models. Also ejecta properties such as their mass have been related to stellar parameters of nonrotating NSs [90,91]. In this respect we observe that the ejecta mass increase in our models with pions is stronger than one would naively expect based on the changes of stellar parameters of cold, nonrotating stars. This might indicate a systematic bias with consequences for attempts to infer stellar parameters from kilonova observations, but we caution that ejecta properties are generally challenging to resolve and that the uncertainties and the intrinsic scatter in relations describing kilonova features as functions of NS properties are rather large.

Future research should improve this first assessment of pion effects in NS mergers in several ways. We describe pions as noninteracting boson gas and choose a constant pion mass, which allows only a coarse description of the impact on the EOS. A more sophisticated treatment of weak interactions is desirable to understand the impact on the ejecta composition, where our crude simulations already indicate a potential influence as pions change the electron fraction. Clearly, more EOS models should be considered in future work.

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APPENDIX: IMPACT OF MUONS

In this study we focus on the impact that pions have on BNS. We do not consider muons, which we also neglected in many currently available EOS tables, although one should expect that muons are also present in NS matter (see [98–100] for the consideration of muons in simulations of core-collapse supernovae and NS mergers). The chemical potential of electrons can reach the rest mass of muons of 105.7 MeV, which can be seen in Fig. 11. Muons are the decay products of pions and should thus in principle be taken into account. We assess the influence of muons by considering stellar equilibrium solutions of isolated stars. We are mostly interested in the impact on the GW signal and the collapse behavior, both of which are determined primarily by the high-density regime of the EOS.

The consideration of muons in EOS tables is in principle straightforward as they can be treated as an ideal Fermi gas similar to electrons. Including muons in the existing tables requires some minor adaptations because the base models determine the contributions of the different constituents by assuming charge neutrality between protons, electrons and positrons. Adding muons and pions thus changes the conditions for charge neutrality. To this end we first remove the contributions from electrons (and positrons for $T > 0$) from the base model as we did for adding pions. We then recalculate at every point of the EOS table the contributions of all considered leptons and pions considering the respective new relation for charge neutrality and chemical equilibrium. We consider stellar configurations at zero temperature and neutrinoless β -equilibrium. Moreover, we investigate stellar models at finite temperature to mimic the behavior of merger remnants. For those we choose a finite temperature of 20 MeV and fix the lepton fraction. At every point of the EOS table with this temperature, we solve the conditions for charge neutrality under the assumption of chemical equilibrium between the nucleons, the leptons (electrons, muons, their antiparticles, and the respective neutrinos and antineutrinos), and the pions. We emphasize that this analysis is meant to estimate the impact on GWs and bulk properties of NSs and BNS mergers, which are mostly determined by the high-density EOS, where these conditions are well justified.

Following the aforementioned procedure we construct different versions of the EOS tables at zero temperature using the SFHo and DD2 base models: the base model with pions only, the base models with muons only, and the base model with muons and pions. For those we determine the beta-equilibrium EOS at zero temperature and compute

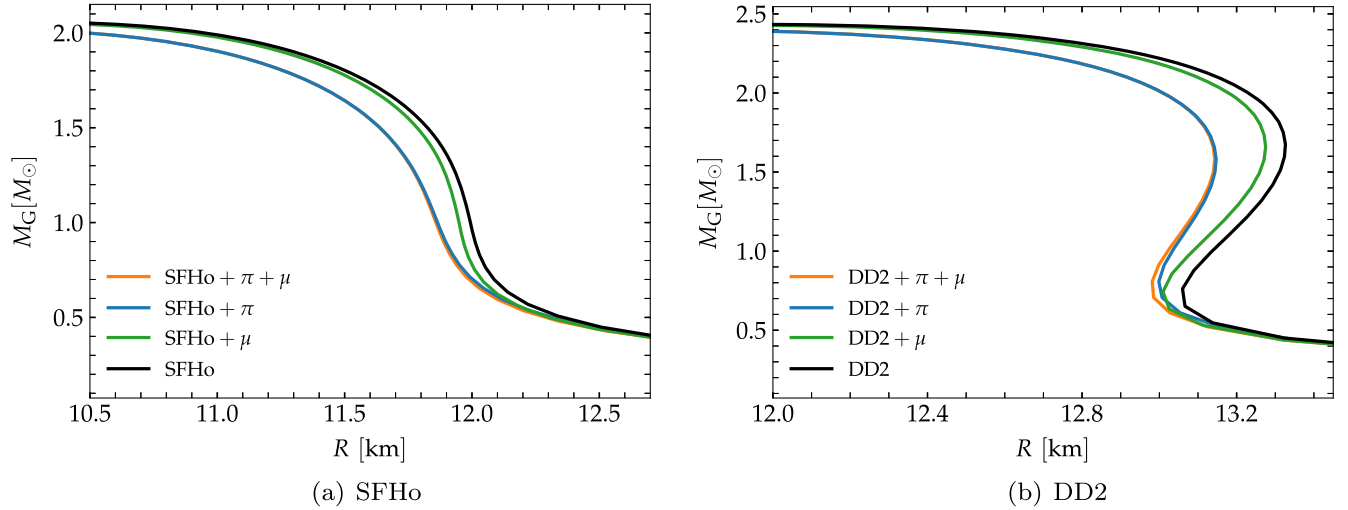


FIG. 23. Gravitational mass versus NS radius for the Base, Base + π , Base + μ and Base + $\pi + \mu$ models with SFHo (a) and DD2 (b) as base model.

TOV solutions, which are shown in Fig. 23 for SFHo (left panel) and DD2 (right panel). Here we only consider an effective pion mass which equals the vacuum mass.

The inclusion of muons without pions leads to a mild softening of the EOS and yields smaller NS radii. The softening induced by pions is in comparison more significant. For instance, the reduction of the radius and the maximum mass is more pronounced. Interestingly, we find that adding muons to an EOS with pions has only a negligible impact. This is understandable because in the presence of pions the difference $\mu_n - \mu_p$ is limited by the pion mass. Hence, under the conditions of neutrinoless

beta-equilibrium, $\mu_n - \mu_p = \mu_e = \mu_\pi = \mu_\mu$, the muon production is suppressed as μ_μ cannot grow a lot. One may thus argue that neglecting muons is a good approximation in our models with relatively small effective pion masses. However, for the models with higher effective pion mass the suppression of muons will be less restrictive. In this case the inclusion of pions does not have a strong impact on the EOS (see Sec. IV A), but modifications by muons may become somewhat more significant (see the case where we consider only muons and the base model).

A similar picture arises for finite-temperature EOS models, where we also consider neutrinos (see Fig. 24). We fix the

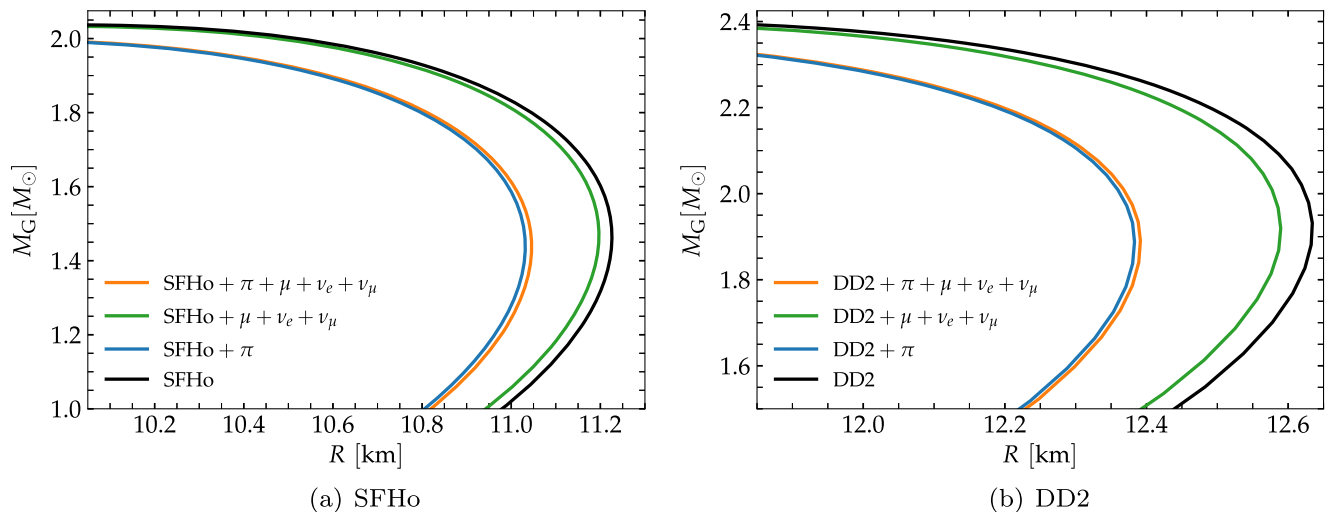


FIG. 24. Gravitational mass versus NS radius for the Base, Base + π , Base + $\mu + \nu_e + \nu_\mu$, Base + $\pi + \mu + \nu_e + \nu_\mu$ for a fixed electronic lepton fraction $Y_{\text{lep},e} = 0.04$, and muonic lepton fraction $Y_{\text{lep},\mu} = 0.015$ (if muon and muon neutrinos are present) at temperature $T = 20$ MeV with SFHo (a) and DD2 (b) as base models. For these calculations the surface of the stars is defined at a rest-mass density of 10^{14} g/cm³.

electronic lepton fraction to $Y_{\text{lep},e} = 0.04$ and the muonic lepton fraction to $Y_{\text{lep},\mu} = 0.015$ (if muon and muon neutrinos are present), which is coarsely representative of BNS merger remnants. Here, we assume that the initial electronic and muonic lepton fractions of the original cold neutron stars are approximately preserved during the merger at the high densities considered here due to neutrino trapping. To better assess the impact on the stellar structure, in the following we consider only the NS core and its radius by computing TOV models for which we disregard densities below 10^{14} g/cm³. In this way, we avoid that the stellar models are inflated by the finite temperature at lower densities.

Again, we find that the impact of muons is nearly negligible if pions are included as can be seen by comparing the blue and orange lines in Fig. 24. The comparison between the different EOS versions also reveals that ignoring neutrinos in our analysis can be justified as they apparently have only a small influence on the stellar structure. We thus conclude that considering only pions and ignoring muons in the BNS merger simulations discussed in the main text is a reasonable approximation for a first study evaluating the bulk properties of mergers like GWs and the conditions for black-hole formation.

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