

MAGIC - how Matter's extreme phases can be revealed in Gravitational wave observations and in relativistic heavy Ion Collision experiments

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Abstract. Nearly one hundred years after Albert Einstein developed the field equations of general relativity and predicted the existence of gravitational waves, a gravitational wave event from a binary neutron star merger (GW170817) was detected in August 2017 by the LIGO/VIRGO collaboration. During the thereon analysis of the gravitational wave data, the equation of state of elementary matter could be constrained in the regime of high densities/temperatures. Recent simulations show, that the appearance of a hadron to quark phase transition in the interior region of a hybrid star merger remnant might change the overall properties of the merger event and could be detectable in future. On the one hand, 4D-simulations of binary neutron star mergers show that these astrophysical systems represent optimal laboratories to investigate the phase structure of quantum chromodynamics. On the other hand, accelerators like the FAIR facility at GSI Helmholtzzentrum allow one to study the properties of the quark-gluon plasma produced in relativistic collisions of heavy ions. This article combines a survey of recent advancements in two rather distinct fields, which reveal - on first sight - a surprising similarity of both, namely relativistic collisions of nuclei and of neutron star mergers.

1. Introduction

Neutron stars are, beside white dwarfs and black holes, the potential final states of the evolution of a normal star. These extremely dense astrophysical objects, which are formed in the center of supernova explosions, represent the last stable state before matter collapses to a black hole. In our galaxy, we currently know about 3000 of these exotic objects, which are mainly observed as pulsars by radio telescopes. Among the known neutron stars, there are some which are in binary systems where the companion of the neutron star is either a normal star, a planet, a white dwarf or again a neutron star.

New observational results have made it possible to study strongly interacting elementary matter in extreme astrophysical objects. The detection of a gravitational wave (GW) from a binary neutron star (BNS) merger by the LIGO/VIRGO collaboration (GW170817, [1]) marked the beginning of a new era in observational astrophysics. In August 2017, the GWs and a 1.7 seconds delayed gamma-ray burst (GRB 170817A, [2]) had been detected and, additionally, the electromagnetic counterparts of an associated kilonova [3] have been tracked by numerous observatories around the world. In contrast to electromagnetic waves, GWs travel almost unaffected with the speed of light through our universe. The little space-time oscillations (GWs) of GW170817, for example, had been traveled about 130 million



years through space until they were detected in 2017. Right after the neutron stars merge, a remnant is formed, which could be stable for longer times (supramassive neutron star, SMNS) or collapse within less than one second (hypermassive neutron star, HMNS) to a rotating Kerr black hole. During this process a short gamma ray burst is emitted, releasing in less than one second the energy emitted by our Galaxy over one year [4]. Space-based gamma-ray telescopes (e.g., the Fermi's gamma-ray burst monitor or the Swift gamma-ray burst mission) detect on average approximately one gamma-ray burst per day - however, the gamma-ray burst [2], which had been associated with GW170817, is an outstanding event and in addition with the observations of the electromagnetic counterparts of the associated kilonova, provides a conclusive picture of the whole merger event.

General relativistic astrophysics of neutron stars and nuclear/elementary particle physics are strongly connected and numerical simulations in both fields strongly depend on the equation of state (EOS) of fundamental elementary matter [5]. Hot and dense matter created in high energy heavy ion collisions and mergers of a binary system of two neutron stars reach such extreme conditions, that the strongly interacting matter created is expected to undergo the deconfinement phase transition. Recently, a joint group at FIAS, the Goethe University and Kent State University discovered that the emitted gravitational waves, as predicted from general relativistic magneto- hydrodynamics from BNS merger - calculations, are extremely sensitive to the appearance of quark matter and the stiffness of the EOS of matter described by the interaction of quantum chromodynamics (QCD). The inner core of a HMNS, as well as its behavior during the gravitational collapse to a black hole depends strongly on the high density/temperature regime of the EOS [6]. This is a new observable messenger from outer space, which does provide direct signals for the phase structure of strongly interacting QCD matter at high baryon density and high temperature. Those astrophysically created extremes of thermodynamics do match, to within 20%, the values of temperatures which we find in relativistic hydrodynamics and transport theory of heavy ion collisions at the existing laboratories like LHC, SpS at Cern, RHIC at Brookhaven, and HaDes - SiS18 at GSi and at the NICA and FAIR accelerators under construction, if though at quite different rapidity windows, impact parameters and bombarding energies of the heavy nuclear systems. In this article, the simulations of BNS and binary hybrid star mergers will be presented and the different density/temperature regions within the QCD phase diagram will be visualized in order to compare it with the present and future projects of the heavy nuclear experiments.

The paper is structured as follows: After this introduction, Section 2 summarizes briefly the theoretical groundings of a BNS merger simulation. In order to motivate, that the temperature and density values reached inside a BNS merger product requires an incorporation of a hadron-quark phase transition (HQPT), Sec. 3 discusses a BNS merger in the context of the HQPT. The interior temperature and density structure of a neutron star merger product and the evolution of the hot and dense matter inside the HMNS will be analyzed and visualized in a $(T-\rho)$ QCD phase diagram. In addition to former publications [7, 8, 9, 10, 11, 12], the different phases of a BNS merger scenario will be explained using the analogy of a variety of different dances. A brief overview about the astrophysical observables of the HQPT in a binary hybrid star merger event will be given in Section 4. Finally, a summary and outlook will be presented in Sec. 5.

2. Relativistic hydrodynamics and numerical relativity of compact star mergers

In order to calculate the properties of a BNS merger, the gravitational force needs to be implemented in the model of elementary particle physics. We used Einstein's theory of general relativity in connection with the conservation laws for energy-momentum and rest mass as the groundings of the differential equations which we solve numerically on a spatial grid using high performance supercomputers. The Einstein equation and the conservation laws are summarized in the following set of highly non-linear differential equations:

$$G_{\mu\nu} := R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi T_{\mu\nu}, \quad \nabla_\mu T^{\mu\nu} = 0, \quad \nabla_\mu(\rho u^\mu) = 0, \quad (1)$$

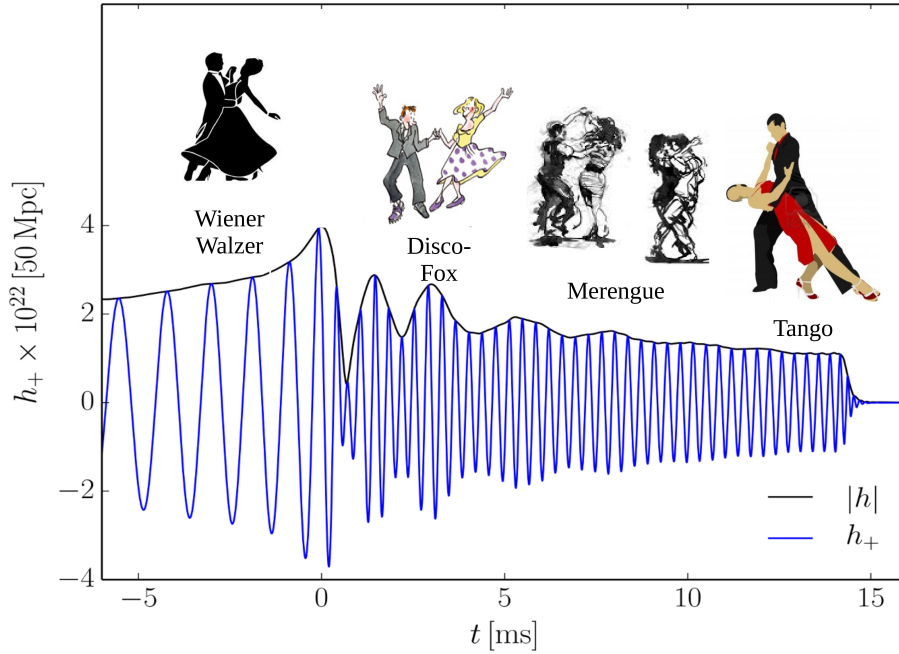


Figure 1. Illustration of the different dances within a BNS merger simulation: Gravitational-wave amplitude $|h|$ (black line) and strain amplitude in the $+$ polarization h_+ (blue line) for the ALF2-M135 binary at a distance of 50 Mpc.

where $G_{\mu\nu}$ is the Einstein tensor, $T_{\mu\nu}$ is the energy-momentum tensor, $R_{\mu\nu}$ is the Ricci tensor, which contains first and second derivatives of the space-time metric $g_{\mu\nu}$, ∇_μ is the covariant derivative and u^μ is the four velocity of the star's fluid. The Einstein equation (first equation in (1)) describes describe on the one hand how matter moves in a curved space-time and on the other hand formulates in which way the amounts of energy-momentum curves the space-time structure. In the energy-momentum tensor $T_{\mu\nu} = (e + p) u_\mu u_\nu + p g_{\mu\nu}$ enters the energy and pressure densities of the nuclear and elementary particle physics contributions of the underlying neutron star matter and $u^\mu = dx^\mu/d\tau$ describes the four velocity of the star's fluid which is defined as the derivative of the coordinates $x^\mu = (t, x, y, z)$ by the proper time τ . In order to solve the evolution of a merging neutron star binary system numerically, equation 1 need to be reformulated, because its structure is not well posed. To reformulate equation 1, the so called $(3 + 1)$ -split is used, which starts by slicing the 4-dimensional manifold $\mathcal{M}$ into 3-dimensional space-like hypersurfaces Σ_t . The space-time metric $g_{\mu\nu}$ is then sub-classified into a purely spatial metric γ_{ij} , a lapse function α and a shift vector β_i . In addition, to perform a BNS merger simulation an EOS of the compact star matter is needed.

In the following the numerical setup of the simulation of Sec. 3 will be briefly described (for details see [7, 8, 9, 10, 11, 12]). To solve the conformal traceless formulation of the Einstein equations [13, 14, 15] the McLachlan-thorn [16, 17] of the publicly available Einstein Toolkit [18] has been used. Simultaneously, the general-relativistic hydrodynamics equations are solved using the finite-volume code Whisky [19]. An adaptive-mesh refinement (AMR) approach had been employed using the Carpet mesh-refinement driver [20]. The grid hierarchy consists of six refinement levels, whose outer boundary is at $514 M_\odot$ (i.e., $\simeq 759$ km). In contrast to [8] no π -symmetry condition across the $x = 0$ plane has been adopted. The initial configuration for the quasiequilibrium irrotational BNSs has been generated with the use of the LORENE-code [21] and an initial coordinate separation of the stellar centers of 45 km had been used. With the exception of Fig. 1, we have used the LS220 EOS in our simulations and considered a equal-mass binary with a mass of $M_\odot$ ($1.35 M_\odot$ for each star).

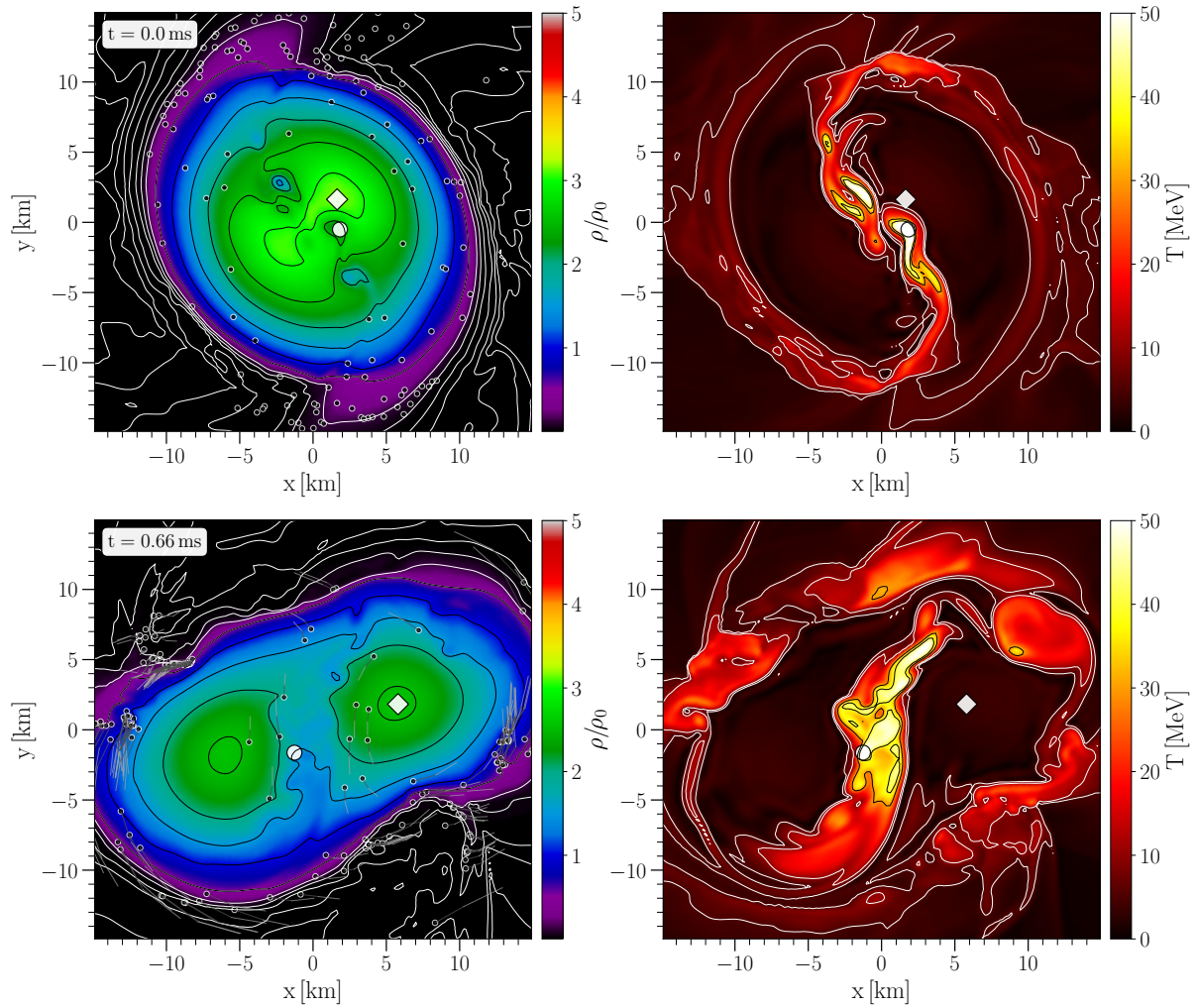


Figure 2. Distributions of the rest-mass density (left pictures) and temperature (right pictures) within the early Disco-fox phase at merger time $t = 0$ (upper panel) and at $t = 0.66$ ms (lower panel). The circles mark the maximum value of the temperature while the diamond symbols indicate the maximum of the density. Additionally, several tracer particles that remain close to the equatorial plane are visualized with small black dots.

3. The different phases of a binary neutron star merger

A BNS merger can be regarded as a great love story (see Fig. 1), ranging from the first moment of perception, the closer approach, the moment of coalescence and fusion, and can be separated in different phases. It begins with the first face-to-face encounter of the two lovers (neutron stars), which is possibly the greatest serendipity. During this inspiral phase (Viennese waltz phase) the two stars are separated by a certain distance and orbit around each other. Additionally, each neutron star rotates around its rotational axis and the whole movement looks similar to a Viennese waltz dance, where each neutron star corresponds to an individual dancer who dances with an invisible companion. Due to the emission of GWs, their separating distance decreases with time. One of the most impressive binary neutron star system is the so called *Double Pulsar*: *PSR J0737-3039A/B*, which has been discovered in 2003 [22, 23, 24]. The two neutron stars in this binary system, which are only separated by 800,000 km, orbit around each other with an orbital period of 147 minutes and mean velocities of one million km/h. The

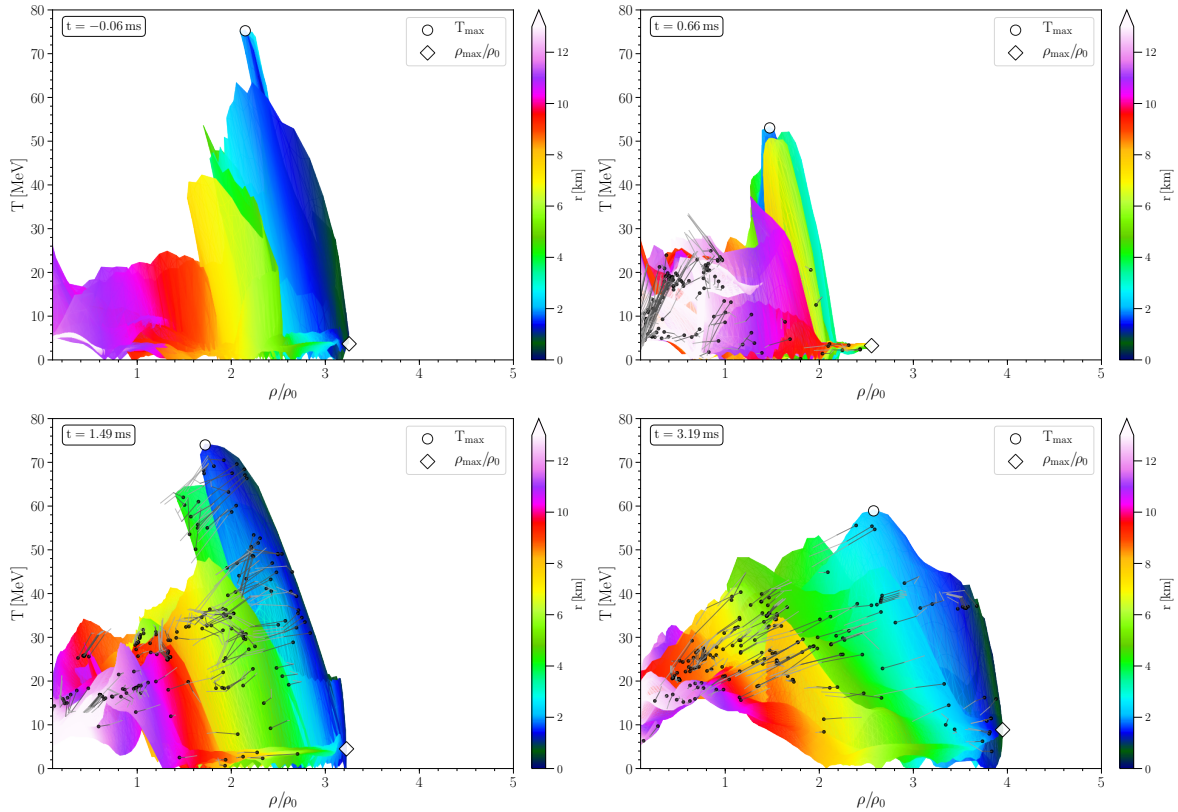


Figure 3. Density-temperature profiles (normalized to saturation density ρ_0) inside the inner region of the HMNS of the LS220–M135 simulation in the style of a $(T-\rho)$ QCD phase diagram plot during the Disco-fox phase. The color-coding indicates the radial position r of the corresponding fluid element inside the HMNS.

distance between the two neutron stars decreases with time and, finally, the two objects need to merge and the two lovers touch each other and become a couple [8]. In this inspiral phase, the temperature effects can be neglected in good approximation and only at the stars surfaces the temperature reaches non-neglectable values. During the last orbits, the stars become tidally deformed and the temperature in the low density regime, near to the region where the two NSs touch each other, increases rapidly. During the last orbits, the stars become tidally deformed and the temperature in the low density regime, near to the region where the two NSs touch each other, increases rapidly [11, 12].

At merger time ($t = 0$ ms), where the emitted gravitational wave of the newly born remnant reaches its maximum value, the hot temperature spot of the newly born remnant reaches values up to $T \approx 75$ MeV (see white circles in the upper panel of Fig. 2). The density maximum (see white diamonds in the upper panel of Fig. 2) are almost at the center and the high temperature regions are placed between them (for details see [8, 11]). The following violent, early post-merger phase (Disco-fox phase) is characterized by a pronounced density double-core structure and hot temperature regions which are smeared out in areas between the double-core density maxima (see lower panel in Fig. 2). The movement of advanced Disco-fox dancers consist of two separate motions: A coming closer and a subsequently removing of the two bodies and a shared rotation with respect to the static dance floor. The two dancers correspond now to the two, still separately visible double-core density maxima of the HMNS (see left picture in the lower panel of Fig. 2) and the movement of the double-core structure, within the first ≈ 2 ms after the merger, looks therefore quite similar to a Disco-fox dance.

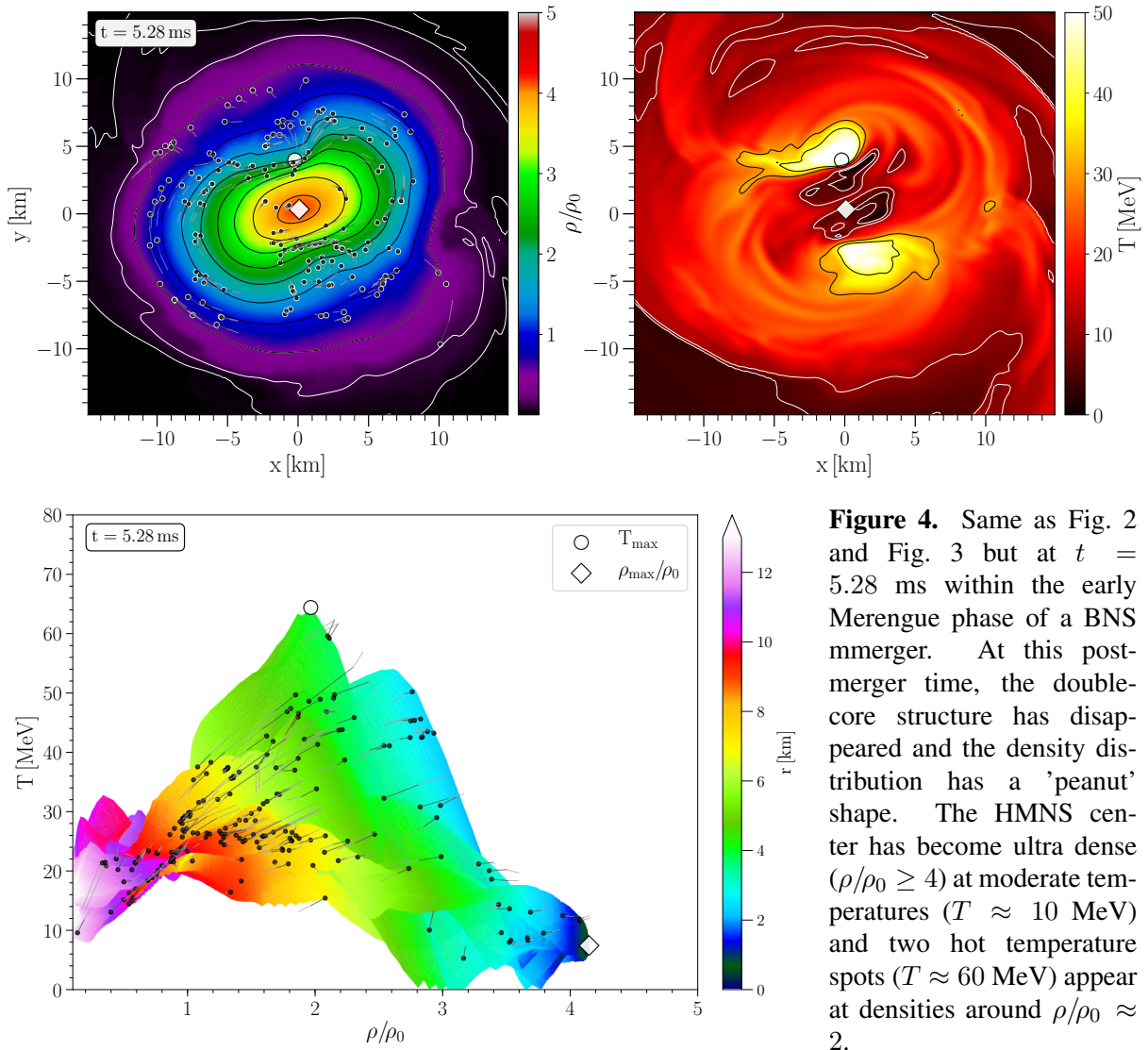


Fig. 3 illustrates the spatial allocation of the density and temperature values reached in a $(T-\rho/\rho_0)$ plot during the early post-merger phase (Disco-fox phase). The color of a density/temperature point ($(T-\rho)$ -fluid element) indicates its radial position r measured from the origin of the simulation $(x, y) = (0, 0)$ on the equatorial plane ($z = 0$). In order to track the motion of individual fluid cells, tracer particles have been used within the LS220-M135 simulation (for details see [25, 26]). Initially placed at $t = 0$ near to the surface of the newly born remnant (see left picture in the upper panel of Fig. 2) the tracer particles diffuse both spatially and in the $(T-\rho)$ -plane, however, in the following, only the tracers that stay in the inner region of the HMNS will be shown. The flowlines of these tracer particles can be visualized using the method of a “corotating frame”. In a corotating frame, each grid point is rotating at a frequency that is half the angular frequency of the instantaneous emitted gravitational waves, Ω_{GW} and it corresponds to the collective rotation of the whole HMNS. In a “corotating frame” the observer is transformed within the rotating frame of the dancing couple and the movement of the two density double-cores (dancers) takes place on a straight line. In a corotating frame the Disco-fox looks more like a West Coast Swing dance and the merger snapshot (see upper panel of Fig. 2) can be regarded as the first “sugar push” of the West Coast Swing couple.

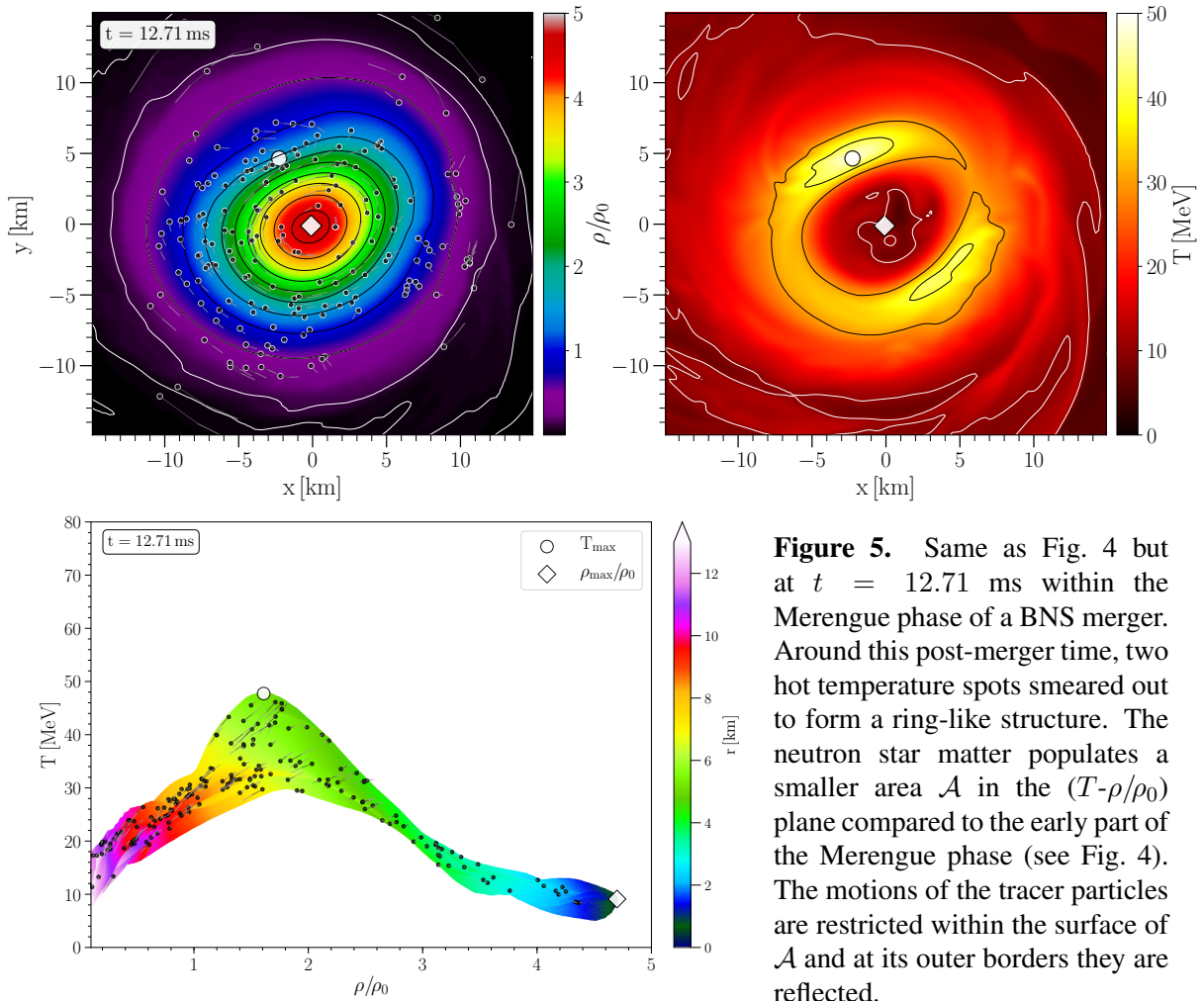


Figure 5. Same as Fig. 4 but at $t = 12.71$ ms within the Merengue phase of a BNS merger. Around this post-merger time, two hot temperature spots smeared out to form a ring-like structure. The neutron star matter populates a smaller area $\mathcal{A}$ in the $(T-\rho/\rho_0)$ plane compared to the early part of the Merengue phase (see Fig. 4). The motions of the tracer particles are restricted within the surface of $\mathcal{A}$ and at its outer borders they are reflected.

After the violent and transforming, early post-merger phase, a new phase begins (the Merengue phase). In the time interval $2 \text{ ms} < t < 4 \text{ ms}$, the double-core structure disappears and the maximum density value shifts to the central region of the HMNS. The high temperature regions transform into two hot temperature spots and they move further out. The density distribution at this post-merger time has been named 'peanut' shape but the highest value of the density ρ is located in the center of the HMNS. In a Merengue dance, the dancers are so close together that distinguishing the individuals is difficult (no double-core structure). In close embrace, the united couple quickly rotates around each other and this movement describes in a clear way the motion of the HMNS at $t > 4 \text{ ms}$. The high temperature values ($T > 40 \text{ MeV}$) are reached now in regions where the density is in a range of $1 - 2.5\rho_0$, while the maximum density values are always at moderate temperatures $T < 20 \text{ MeV}$. The hot temperature spots have moved further out and the interior of the HMNS, where the maximum of the density is located. The tracer particles have diffused over the entire inner region of the HMNS and populate almost the whole area of the $(T-\rho/\rho_0)$ plane. Some of these tracers circulate around the high temperature hot spots, others populate the low temperature high dense inner region, and some are moving in the outer surface of the HMNS within the low density regime (see Fig. 4).

Fig. 5 shows a snapshot at later times in the Merengue phase ($t = 12.71 \text{ ms}$). The two pronounced temperature maxima at $t = 5.94 \text{ ms}$ have almost merged to one maximum at this post-merger time (see lower left picture in Fig. 5). At these post-merger times, the temperature hot spots have smeared out to

become a ring like structure, the 'peanut' shape has been dissolved and the area populated in the $(T-\rho)$ -plane has been constricted to a small quasi stable region. The central region of the HMNS consists of high dense matter ($\rho/\rho_0 \approx 5$) at moderate temperature values $T \approx 10$ MeV, while the maximum of the temperature is reached at the highest point of the temperature ring like structure at $r \approx 6$ km at moderate density values ($\rho/\rho_0 \approx 2$). The unusual temperature ring-like structure (see right picture in the upper panel of Fig. 5) is closely related with the rotation profile Ω of the differentially rotating HMNS ($\Omega = \alpha v^\phi - \beta^\phi$, where v^ϕ and β^ϕ describes the ϕ -component of the three-velocity and shift vector, see [7] for details).

The results of the LS220-M135 simulation presented so far show that within the first 20 ms the matter inside the HMNS populate areas in the QCD phase diagram where an inclusion of the quark degrees of freedom in the EOS is necessary. Especially in the interior region of the HMNS for $t > 10$ ms, the density reaches values where a non neglectable amount of deconfined quark matter is expected to be present. If the total mass of the BNS merger system is above a certain value or the EOS behaves differently in its ultra high density regime, the HMNS will collapse to a black hole and this last dance of the two lovers can be understood by a Tango dance, where the motion of the dancers is suddenly freezing and the emission of gravitational wave stops. Fig. 1 summarizes the different dances of a BNS merger simulation and connects them with the emitted gravitational-wave amplitude of a BNS merger simulation (ALF2-M135 run, for details see [7]). During the collapse of the HMNS to a black hole, the density in the inner region increases rapidly, the quarks get free and the color charge of the deconfined pure quark phase becomes visible - however, the formation of the event horizon prevents that this new degree of color can be observed from the outside and the whole deconfined quark phase gets macroscopically confined by general relativity (see p.186-188 in [27]). The event horizon of a black hole marks a certain threshold and the collapse of a neutron star to a black hole looks for an outside observer looks like a frozen picture of the collapsing star - however, the color of this frozen picture will be infinitely gravitationally red-shifted quite rapidly.

4. Binary hybrid star mergers

The thermodynamical origin of the transition from hadronic matter to quark matter is still not known. The appearance of deconfined quarks with increasing chemical potential and/or temperature is determined by the type of the transition. In case of the first order phase transition the quarks appear jump-like, so with increasing chemical potential the number of quarks increases discontinuously. The construction of the phase transition can be done in different ways, using a Gibbs construction between the hadron and quark models or, assuming a large surface tension of the first deconfined quark bubbles, in a sharp discontinuous way, using a Maxwell construction between the two separate models. Within this work we concentrate on the assumption of first order phase transition associated with appearance of the quarks. The crossover type of deconfinement transition is also possible, then quarks appear smoothly without separation into confined/deconfined phases. This mechanism is developed in [28, 29] where the approach that also reproduces the properties of QCD at high temperatures is applied to model the neutron stars where the QCD matter is cold and dense.

The astrophysical observables of the QGP, which are connected with compact stars can be grouped in the following way [27]: Evidence of the HQPT based on mass and radius properties, rotational behaviors, twin star properties and by means of a future gravitational wave detection. The effects of a strong HQPT have been already investigated in the context of static [30, 31, 32] and uniformly rotating hybrid stars [33, 34] and the results show that tremendous changes in the star properties might occur including the existence of a third family of compact stars - the so called "twin stars" [35]. In general, the GW-frequency at the moment of collision in a neutron star merger (f_{peak}) is lower than in a hybrid or quark star merger [27, 36].

With the use of the observed tidal deformations of the two neutron stars from the late inspiral phase and other properties of GW170817, the EOS of dense matter could be severely constrained [37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48]. Unfortunately the ultra dense and high temperature regime

of the EOS, which is only reached within the post-merger phase, has not been observed in GW170817. However, in prospecting merger events within the next observing run, these extreme conditions will be possibly detected [49]. During the post-merger time of a BNS merger, the value of central rest-mass density can increase to several times of normal nuclear matter. For such high densities, the EOS is still poorly constrained by observations from heavy-ion collisions. By analyzing the power spectral density profile of the post-merger emission of a future event within the next observing run of the LIGO/VIRGO collaboration, the GW signal can set tight constraints on the high density regime of the EOS of elementary matter [50]. Numerical simulations which includes a density/temperature and composition dependent EOS with a HQPT, the so called hybrid star merger simulations, have only been performed recently.

In [51] a temperature-dependent EOS [52] with a strong HQPT has been used for the first time in a binary hybrid star merger simulation. Within this model it was shown that the phase transition, which happens during the post-merger phase, leads to a hot and dense quark core that, when it collapses to a black hole, produces a ringdown signal different from the hadronic one. The formation of a hot and dense quark core for later post-merger times changes the evolution of the hypermassive hybrid star. In contrast to the numerical results performed within a purely hadronic model, the temperature in the inner core of the merger remnant increases, resulting in a different evolution of the temperature profile. In [36] a different temperature-dependent EOS for a hybrid star model was used in a merger simulation and it was shown that the dominant post-merger GW frequency f_{peak} exhibit a significant deviation from the empirical relation between f_{peak} and the tidal deformability Λ , if a strong first-order phase transition leads to the formation of a gravitationally stable quark matter core in the hypermassive hybrid star. In [53] the numerical results of binary compact star merger simulations have been presented within a two-family scenario assuming the Bodmer-Witten "strange matter" hypothesis'. Especially, within an EOS that includes the possibility of a twin star behavior, the astrophysical observables of a HQPT might be detectable by future detection of compact star merger events [9, 11, 45, 46, 12].

5. Summary and outlook

The possible appearance of a transition from confined hadronic to deconfined quark matter (hadron-quark phase transition, HQPT), and the formation of regions of deconfined quark matter in the interior of a compact star merger product have been discussed within this article. The temperature and density structure of a neutron star merger product and the evolution of hot and dense matter inside the produced HMNS/SMNS advises an incorporation of a HQPT in the EOS. The occurrence of hot temperature regions and their spatial location is closely connected with the rotational properties of the HMNS/SMNS [7]. Additionally, the possibility of a viscousless superfluid quark phase might change the overall properties as viscous dissipation and energy transport can play a significant role in the survival time of the post-merger object [10]. Binary hybrid star mergers represent therefore optimal astrophysical laboratories to investigate the phase structure of QCD and in addition with the observations from heavy-ion collisions will possibly provide a conclusive picture on the QCD phase structure at high density and temperature [8]. We demonstrated how the gravitational wave signals from future advanced LIGO-Virgo - to radiowave signals from SKA-events can be combined with the high multiplicity fluctuation - and flow measurements in heavy ion detectors in the lab to pin down the EOS and the phase structure of dense matter.

Acknowledgments

We would like to thank Luciano Rezzolla. Without his profound knowledge and his comprehensive expertise in the field of numerical relativity and general relativistic hydrodynamics the presented simulations and the whole article would not have been possible. MH gratefully acknowledges support from the Frankfurt Institute for Advanced Studies (FIAS) and the Goethe University Frankfurt, VD acknowledges support from the National Science Foundation under grant PHY-1748621, while HS acknowledges the Judah M. Eisenberg laureatus Professur endowment.

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