Neutron stars: birth, structure, and mergers

1. Scientific Goals

Neutron stars, predicted in 1933, waited for their discovery until 1967. This time span has been somehow similar to the neutrino's fate – predicted in 1930, directly detected in 1956. It appears these objects, compact star and elementary particle, are intertwined both in the astrophysical problems of the Universe and in the field of fundamental interactions.
The purpose of this project is the understanding of basic properties of neutron stars, from their birth till their very end in the unified context of astrophysics, fundamental interactions, and newest experimental data.

1A. Birth of massive neutron stars

According to the standard scenario for the birth of a neutron star (NS) it emerges as the compact hot and lepton rich remnant, known as proto-neutron star (PNS), of a core-collapse supernova (CSSN) explosion of a massive star, with zero-age main sequence (ZAMS) mass greater than about 8 $M_\odot$. To study the supernova problem, i.e. explosion of the initially imploding stellar core and the subsequent ejection of the stellar mantle, requires large-scale super-computing tools that are based on detailed neutrino-radiation hydrodynamics (Janka et al. 2007). Successful neutrino-driven supernova explosions are obtained in spherical symmetry only for low-mass progenitors in the range 8–10 $M_\odot$ (Kitaura et al. 2006) while more massive progenitors require multi-dimensional physics, e.g., convection which enhances the neutrino-heating efficiency. Resulting birth masses of NS hardly exceed 1.6 $M_\odot$ (Sukhbold et al. 2016) which raises the problem of the origin of observed pulsars with masses on the order of 2 $M_\odot$. The alternative explanation has been binary system evolution, i.e.. mass transfer from the companion main sequence star to the newly born NS. However, serious doubts have been raised against such a picture (Fortin et al. 2016) since the amount of accreted mass saturates at a maximum of 0.2 $M_\odot$. This situation leaves us with the puzzle of the origin of 2 $M_\odot$ pulsars. A possible solution has been proposed recently in Fischer et al. (2018) where the supernova explosion of a massive supergiant star with ZAMS mass of 50 $M_\odot$ was achieved by means of a deconfinement phase transition, from ordinary nuclear (in general hadronic) matter to the quark-gluon plasma. Such a CCSN explosion produces a NS in the mass range of 2$M_\odot$, now featuring a massive and stable quark-matter core. Necessarily, due to this very mechanism of their birth, these pulsars must consist of deconfined quark matter in their interiors.

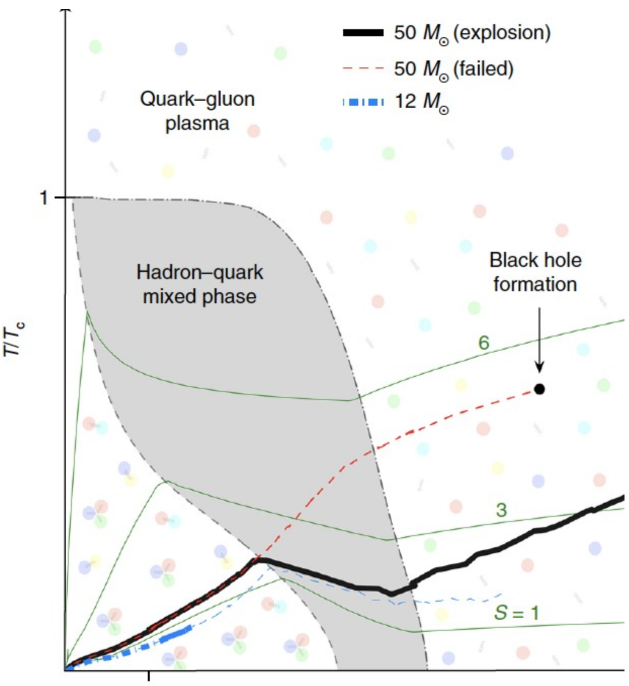


Fig. 1: Phase diagram of QCD (in 2D projection suppressing the isospin density axis) with a hadron-quark matter mixed phase region due to a 1st–order phase transition in the EOS that serves as the engine of successful supernova explosions of massive supergiant stars. Compared to the artistic view of Fig. 6, this phase diagram is a proof-of principle result for the project task to constrain the location and shape of the phase transition region as well as EOS properties in the QCD phase diagram by the criterion of massive supernova explodability.

(figure adopted from Fischer et al. 2018)

Without such deconfinement 1st–order phase transition the fate of such massive progenitors in the

ZAMS mass range of 40–50 $M_\odot$ is the collapse to a black hole, which has long been studied known as failed supernova explosion branch (see Fig. 1).

Naturally, the question arises about a possibly lower progenitor mass limit of the progenitor stars for which the *explodability* could be demonstrated and related: what is the onset mass of the phase transition in the PNS core which would then trigger the explosion? This depends on the yet entirely unknown hadron-quark hybrid EOS properties in terms of onset density for quark matter, the order of the phase transition as well as the latent heat potentially released at the phase transition.

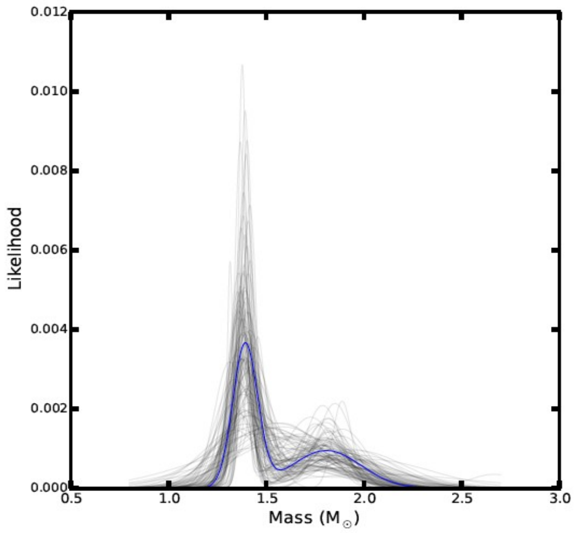


Fig. 2: The likelihood for a NS mass at birth shows a bimodal behaviour according to Antoniadis et al. (2016). Such a NS mass distribution would be supported by the new CCSN explosion mechanism which operates for massive blue supergiants with a ZAMS mass of around 50 $M_\odot$ or more and results in massive NS with ~2 $M_\odot$ while the traditional neutrino driven supernova explosions of stars with up to ~25 $M_\odot$ would produce NS of typically 1.3 – 1.4 $M_\odot$.

1B. Neutron star structure

Starting from the hypotheses that a NS at birth may belong to one of two *families* of compact stellar objects. The family with higher masses necessarily has to consist of hybrid stars due to the very mechanism of their creation, in particular the observed high-mass pulsars J1614-2230 (Demorest et al. 2010; Fonseca et al. 2016; Arzoumanian et al. 2018), J0348+0432 (Antoniadis et al. 2013) and recently J0740+6620 (Cromartie et al. 2019). The nature of the members of the other lower-mass family could be a pure neutron star or a hybrid star or even an exotic hadronic star. Their distinction depends on the yet unknown onset mass (i.e. central energy density) for the corresponding phase transition. The upcoming results for simultaneous measurement of masses and radii by the NICER (Neutron star Interior ExploreR) NASA mission (Arzoumanian 2018) may shed new light on this crucial aspect of dense matter, potentially further constrain the NS matter EOS substantially.

In the present project we will be mainly concerned with those neutron stars that emerge from the supernova explosion of progenitors for which the standard neutrino heating mechanism may potentially not operate and that consist therefore of extended quark matter interior. What will be the internal structure of such a NS? It is well known that the commonly employed Maxwell construction for the phase transition produces a maximal softening of the EOS in terms of vanishing pressure gradient in the hadron-quark mixed phase. It represents one extreme case of such construction with infinite surface tension. In reality this situation cannot be realized in nature. There are other more physical phenomena which modify the hadron-quark phase border at low temperatures and which need to be considered within a systematic investigation. In particular, the occurrence of inhomogeneous condensates (Buballa & Carignano 2014), which may be related to the appearance of structures known as *pasta* phases in the hadron-quark mixed phase (Yasutake et al. 2014, and references therein) and crystalline phases of color superconductivity (Anglani et al. 2014). Within the present project we plan to dwell on the role of pasta phases in the mixed phase, generalizing previous work (Yasutake et al 2014; Ayriyan et al. 2018; Maslov et al. 2018) to finite temperatures.

On the other hand, when due to the pasta-phase formation a finite pressure gradient arises in the mixed phase, the question arises whether the reduced sharpness of the phase border in the hot PNS can still give rise to a second shock that drives the supernova explosion. Within this project we want to systematically explore the limits for the smoothness of the transition that would still be in accord explodability. A maximal smoothing of the transition corresponds to a minimum surface tension of the quark-hadron interface (for vanishing surface tension one would obtain the so-called

Glendenning construction (Glendenning 1992) which maximizes the mixed phase extension and thus the smoothness of the density profile in the PNS. An astrophysical constraint can thus provide a lower limit on this fundamental parameter of non-perturbative dense QCD.

Following the result of Fischer et al. (2018), there can be an explanation for the missing red supergiant problem (Smartt et al. 2009; Adams et al. 2017) which corresponds to SN progenitors that feature the most compact stellar cores (O'Connor et al. 2011) in the progenitor mass range ~25 – 40 $M_\odot$ where the neutrino-driven explosion mechanism does no longer work and the phase transition engine is not yet operative. This would entail an explanation for the indication that the NS mass distribution at birth is bimodal, see Fig. 2, taken from Antoniadis et al. (2016).

1C. Binary system evolution and neutron star mergers

One of the key questions for the compact star community is the quest for the structure and composition of the NS core in dependence on the gravitational mass of the star. Even if we will have found a lower limit for the phase transition onset with the study of the explodability of massive progenitor stars, which could then be translated to an onset mass for NS with quark matter cores, we should be looking for independent confirmation of such an important result in other astrophysical systems. Particularly suitable are binary systems involving a millisecond pulsar (MSP) since they allow in principle precise mass measurements and, due to episodes of mass transfer from a donor star, they would be the sites where to witness the onset of a phase transition in the interior of the accreting star. As an example for a possible "smoking gun" observation we show in Fig. 3 the puzzling effect that MSP in a binary with a helium white dwarf show a strong eccentricity of their orbit only in a narrow window of orbital periods while otherwise the orbits are practically circular (courtesy of John Antoniadis, Antoniadis 2014). It has been shown that this window of orbital periods is particularly suitable for mass transfer (Tauris et al. 2013) and thus one of the viable explanations is accretion induced collapse to a hybrid star (Jiang et al. 2015) with an energy release that would be the origin for a "kick" leading to the eccentric orbit. We aim to address this effect by means of analyzing the energy release and kick mechanism within our systematic study of hybrid star EOS and accretion/spin-down evolution scenarios (cf. Bejger et al. 2017).

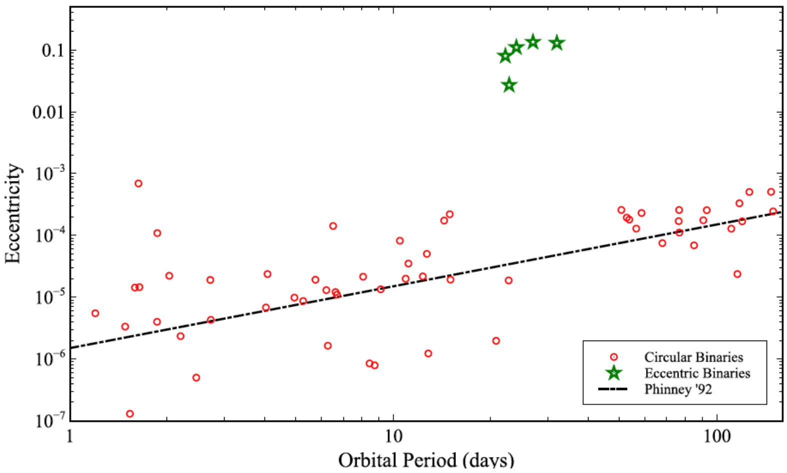


Fig. 3: The puzzling observation has been made that millisecond pulsars in binaries with white dwarf companion show almost circular orbits except for a narrow window of orbital periods of 25-60 days, where eccentricities increase by four orders of magnitude, cf. Antoniadis (2014). One explanation could be a kick that is provided by the accretion induced transition to a strange star as suggested in Jiang et al. (2015).

NS mergers, now accessible in the fascinating era of multi-messenger astronomy opened by the observation of gravitational waves from the first binary NS merger GW170817 by the LIGO-Virgo Collaboration (Abbott et al. 2017) allow further constraints on the cold, dense EOS by measuring the tidal deformability in the inspiral phase and constraints on the hot, dense EOS from the post-merger GW signal (known as ring-down). Our team has suggested a smoking-gun signature for a 1^{st}–order deconfinement phase transition in the NS EOS at 5σ statistical significance when the peak frequency of the ring-down is compared with the tidal deformability of the inspiral phase (Bauswein et al. 2019) as shown in Fig.4.

It will be interesting to generalize this study from the case of merging neutron stars without exotic interior to other cases, involving hybrid stars and a black hole. The preliminary studies of Paschalidis et al. (2018) and Alvarez et al. (2019) followed this strategy in line with the constraints derived from GW170817, however, for which a low onset mass for the phase transition of about

1.35 M⊙ was employed as well as mixed phase effects on the tidal deformability have been studied (Ayriyan 2018; Blaschke et al. 2019).

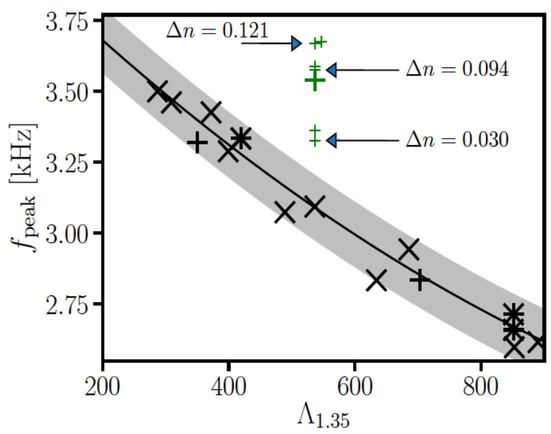


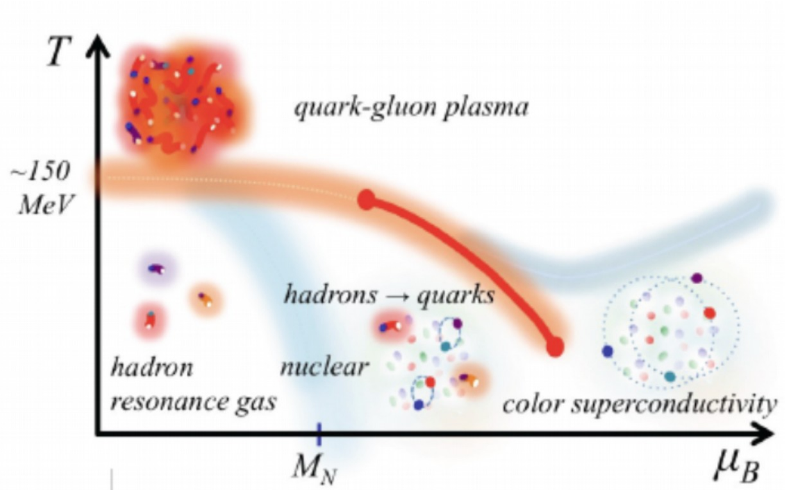
Fig. 4: The signal for a phase transition that strongly interacting matter may undergo in the course of a BNSM event is, according to Bauswein et al. (2019) the significant deviation of the peak frequency f_{peak} (shown by green plusses for first-order phase transitions with different density jumps of size Δn [fm^{-3}]*) from the systematics of purely hadronic EoS models (shown as a grey band).*

1D. Equation of state (EOS) development

As for the construction of the hadron-quark hybrid EOS it is important to go beyond the Maxwell construction scheme and to take into account the possibility of electrically charged localized finite size regions of the phases (known as pasta structures) as developed, in Yasutake et al. (2014). A simplified one-parameter scheme of mixed phase construction has been developed (Ayriyan et al. 2018) which represents the corresponding pasta phase construction as was shown in Maslov et al. (2018). The generalization to finite temperatures will be performed within this project and will allow to explore the robustness of the astrophysical consequences of a first-order phase transition. The key question which derives from this for this project is: how broad is this crossover in the baryon density and will it affect the massive SN explosion mechanism?

Another physical mechanism which changes the first-order transition to a (rapid) crossover is the coexistence of dynamical chiral symmetry breaking with color-superconducting phases of cold dense quark matter. This effect could lead to the existence of a second critical endpoint (CEP) which could be decided, if at all, only by comparison of the appropriate modeling results that will be provided within this project with observations of NS, binary NS mergers and/or galactic supernovae. The smoothing of the transition at the low-temperature end of the phase border could have an influence on the explodability of supernovae in the mass range for which the evolutionary track traverses the vicinity of the 2nd CEP, compare Fig. 5. The details of the sketched QCD phase diagram of Fig. 5 depend crucially on the appearance of the strange quark flavor in the system and the possibility of absolutely stable strange quark matter according to the Bodmer-Witten hypothesis (Bodmer 1971; Witten 1984) which we will explore within our dynamical approach.

Fig. 5: Conjectured phase diagram of QCD illustrating the possible role of color superconductivity in quark matter, which may lead to a coexistence with chiral symmetry breaking which causes the 1st order transition to turn to a crossover at low temperatures, inducing a second critical endpoint; from Baym et al. (2018).



In this way, the supernova explosion problem can be linked to another present-day challenge: the structure of the phase diagram for strongly interacting matter, illustrated in Fig. 6 below. While this phase diagram should be theoretically described by quantum chromodynamics (QCD) as the fundamental gauge field theory of strong interactions with quakrs and gluons as the degrees of freedom, it is notoriously difficult to obtain solutions of this theory in the non-perturbative domain of low energies which corresponds to the region of low temperatures T as well as large baryon and isospin chemical potentials (μ_B, μ_I) that is depicted in Fig. 6.

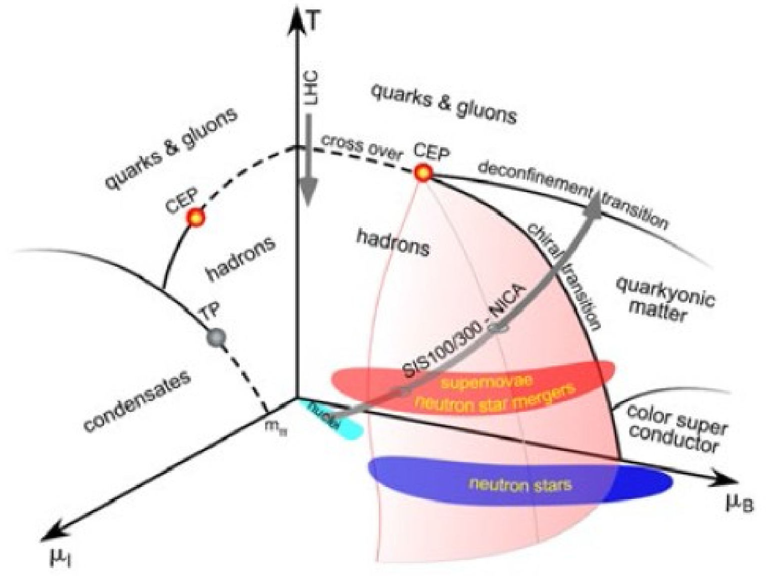


Fig. 6: Conjectured phase diagram of QCD illustrating the role Fig. 2: Conjectured phase diagram of QCD illustrating the role of astrophysical phenomena like supernovae, neutron stars and their mergers for exploring the phase boundary limiting the hadronic matter phase.

(figure adopted from the "NuPECC Long Range Plan 2017" http://www.nupecc.org)

It is characterized by quark and gluon confinement into hadronic bound states and dynamical chiral symmetry breaking which gives the quarks a sufficiently large mass to explain the observed mass spectrum of hadrons. Ab-initio solutions of QCD can be obtained by numerical simulations on space-time lattices (cf. Bazavov et al. 2017) and references therein), but due to the sign problem for simulations with nonzero baryon chemical potential μ_B , their extension away from the T-axis is bound to Taylor expansion techniques which confirm that a conjectured critical endpoint (CEP) of first order transitions cannot lie in the range of $\mu_B/T< 2$ and cannot occur at T>135 MeV (Bazavov et al. 2017). Therefore, the investigation of the phase diagram of QCD and in particular the search for the CEP has to rely on effective field-theoretical models. The test of such models with heavy-ion collision experiments is presently also bound to rather high temperatures and low baryon densities, as long as dedicated facilities like FAIR and NICA are still under construction.

Summarizing, we subdivide the tasks to be tackled within this project into three groups:

A. Developing a unified EoS for proto-neutron stars (PNS), neutron stars (NS), and NS-NS merger,

B. Tests of the massive blue supergiant explosion mechanism and its correlation to corresponding masses of PNS and their structure

C. Upper limit for maximum mass of hybrid compact stars from systematic study of rotating PNS and GW signal from NS-NS merger evolution, including effects of strange quark matter

2. Significance

The theory of core-collapse supernovae with the canonical scenario for the explosion mechanism based on the neutrino-heating mechanism that revives the prompt shock of the iron core collapse is described in detail in Janka et al. (2007). The key feature is 'accurate' neutrino transport, which also defines the computational challenge. The SN explosion mechanism driven by the hadron-quark phase transition has been introduced for progenitors of $\leq 15\ M_\odot$ (Sagert et al. 2009; Fischer et al. 2011). However, the low transition densities ($<\rho_0$) assumed and the maximum masses of neutron stars, being below the current constraint of $2\ M_\odot$, rule out these previously developed hadron-quark hybrid model EOS. It emerges the necessity of more sophisticated hadron-quark hybrid models, consistent with current constraints.

This breakthrough has become possible due to the new class of hybrid quark-hadron EOS that was developed by the University of Wroclaw (UWr) team on the basis of a relativistic density functional (RDF) approach to quark matter which qualitatively differs from other previous approaches. Those were based on either the Nambu—Jona-Lasinio (NJL) type modeling of quark matter that focusses on the dynamical chiral symmetry breaking (DχSB) aspect of interacting quark matter but misses a quark confinement mechanism or on as simple quark matter models as the thermodynamic bag model which has a schematic confining mechanism but no DχSB. The RDF approach to quark matter provides a broad generalization of NJL-type models which are obtained as limiting cases when the density functional is assumed to have a quadratic dependence on quark bilinears (which have corresponding densities as expectation values). Two of these possible generalizations were used in Kaltenborn et al. (2017):

i) a confining term suppressing quarks at low densities, and

ii) a higher order repulsive interaction providing a stiffening of quark matter at high density and thus a sufficiently large maximum mass (~2 $M_\odot$) of hybrid stars.

The RDF approach has another feature which is of utmost interest for our project: it leads to almost simultaneous deconfinement of different quark flavors when the density is increased while the NJL-type approaches show a sequential appearance of quark flavors (Blaschke et al. 2009). Therefore, in NJL type models no stable hybrid stars with strange quark matter (SQM) content could be obtained (cf. Klähn et al. 2007), unless a pressure shift was applied (Bonanno & Sedrakian 2012).

A particularly interesting aspect of the new RDF model is the possibility to obtain absolutely stable SQM according to the Bodmer-Witten hypothesis (Bodmer 1971; Witten 1984). According to the analysis in Klähn & Blaschke (2018) it requires both, a confinement mechanism and light strange quarks to obtain absolutely stable SQM which is not possible in NJL based quark matter models, due to missing confinement and sequential appearance of flavors. The string-flip model (SFM) motivated confinement in Kaltenborn et al. (2017) is flavor-blind (as gluons) and scalar so that parametrizations can be found where the high-density phase consists of absolutely stable SQM. We will therefore extend the RDF approach in this project to include the strange quark degree of freedom in order to be prepared for studying the question of generation of strangeness at the hadron to quark matter phase boundary for static NS solutions as well as during the dynamical evolution of the supernova collapse and PNS evolution. To this end it is necessary to develop the RDF approach to quark matter to include these directions:

i) strange flavor in the scalar and vector bilinears

ii) strange flavor in the scalar diquark bilinear (2SC vs. CFL phase)

iii) ‘t Hooft determinant interaction term (axial anomaly) and its Fierz transform, coupling chiral and diquark condensates

The first two items are rather straightforward and can be implemented along the lines of the corresponding treatment in the NJL model (Ruester et al. 2005; Blaschke et al. 2005; Abuki & Kunihiro 2006). For the third item one can follow Hatsuda et al. (2006) and Abuki et al. (2010), see also Steiner (2005). The main result of this inclusion of the effect of the axial anomaly shall be a coexistence of chiral symmetry breaking with color superconductivity which changes the 1st order phase transition to a crossover and thus induces the appearance of a second CEP at low temperatures or the vanishing of CEPs from the QCD phase diagram. This new situation is illustrated in the phase diagram of Fig. 3 and can be also denoted as BEC-BCS crossover phenomenon in quark matter (Abuki et al. 2010).

For the final task C from the scientific goals listed above we suggest systematic studies with the new class of hybrid EOS which explore the rotational evolution of supramassive NS formed in BNSM, starting at the limit of stability against mass shedding and evolving towards gravitational collapse upon spin-down by GW emission and cooling. In particular we follow up on the possible consequence of an upper limit for the maximum mass of non-rotating, cold compact stars M_{TOV} <2.17 $M_\odot$ (Rezzolla et al. 2018) that is built on the phenomenology of the BNSM GW170817 and the existence of so-called universal relationships between the maximum mass of stars rotating uniformly at the maximal (Kepler) frequency (M_{max}) to that of a non-rotating star sequence (M_{TOV}) which for purely hadronic stars is known to be $\alpha = M_{max}/M_{TOV} \sim 1.20$ (cf. Haensel et al. 2007), and consider now hybrid quark-hadron stars (Bozzola et al. 2019; Blaschke et al. 2019) that may even belong to a third family of compact stars as in Bejger et al. (2017). In an exploratory study using a multi-polytrope EOS we find that the ratio α is not universal but rather depends on the compactness (and thus the central density of the maximum mass configuration). These studies of maximum mass constraints shall be performed in the present project for realistic hybrid star EOS.

Finally, full BNSM simulations will be conducted to test the robustness of the phase transition signal in the gravitational wave spectrum against variations of the EoS model and the type of stars in the binary merger (their masses and composition) analogous to the initial study published in Bauswein et al. (2019). As soon as the first post-merger GW signal will be detected far-reaching consequences for the structure of the phase diagram of QCD at high baryon densities will be possible on the basis of the results from this project. In this manner this project shall have a major impact on the further development of research directions in the Astrophysics of compact objects and its consequences for the microphysics of strongly interacting matter.

3. Concept and work plan

The basis for the success of this project is the fulfillment of tasks serving the goal (A): Developing the class of phenomenological hadron-quark hybrid EOS applicable to SN studies that allows systematic changes in parameters characterizing a-priori unknown in-medium effects of dense QCD. Preliminary results obtained at the Division of Elementary Particle Physics at the Institute of Theoretical Physics of the University of Wroclaw have been published in a series of papers (Benic et al. 2015; Klähn & Fischer 2015; Klähn et al. 2016; Kaltenborn et al. 2017; Blaschke et al. 2014,2017; Bastian et al. 2018). Such effective EOS models are deduced by obeying key criteria for effective QCD approaches, e.g., taking into account DχSB and a description of deconfinement with their medium dependence. Combined with a well selected hadronic EOS (Typel et al. 2010), the main focus is here on the phase transition construction (pasta phases and hadron dissociation), the role of the strange quark flavor and color superconducting phases of quark matter (Blaschke & Chamel 2018).

In fulfilling the goal (B) of this project, a systematic analysis will be performed to study the impact that both types of modifications of the SN explosion mechanism proposed in Fischer et al. (2018) will have on the explodability as the observable criterion for their viability: changes of the hadron-quark first-order phase transition model on the one hand and variations of different stellar models which feature different core structures of the progenitor stars on the other. The "workhorse" of this study will be our spherically symmetric and fully general relativistic SN model built on accurate three-flavor Boltzmann neutrino transport and a flexible EOS module. It was the basis for a large number of EOS studies (cf. Fischer et al. 2009; Sagert et al. 2009; Hempel et al. 2012; Fischer et al. 2014) and improved to capture the long-term cooling evolution of the nascent PNS (cf. Fischer et al. 2010). Besides the decision about the explodability of a given EOS and progenitor star scenario, the accurate prediction of neutrino fluxes and spectra as well as their evolution together with the mass and structure of the resulting PNS will be an outcome of the study. The feasibility we have demonstrated in the breakthrough work by Fischer et al. (2018).

In order to reach goal (C) of this project, full-scale simulations of the GW spectrum from BNSM with the newly developed class of hybrid hadron-quark EoS will be conducted within our established collaboration with GSI Darmstadt, as published in Bauswein et al. (2019). Besides this major line of research, important and significant prerequisite studies will be performed using public codes for rotating compact stars in full general relativity such as LORENE and RNS that have meanwhile been applied by our team members to extreme cases of hybrid EoS with strong phase transitions which produce third families of hybrid stars under fulfillment of the maximum mass constraint for pulsars (Bejger et al. 2017; Paschalidis et al. 2018; Blaschke et al. 2019).

The team at UWr fulfilling the above tasks consists of the PI, two investigators, one postdoc and two Ph.D. students. **The postdoc position** shall on the one hand partially supervise the two Ph.D. students and help introducing them to the effective description of quark-hadron matter under extreme conditions within the flexible RDF approach. On the other hand, this postdoc should be sufficiently familiar with numerical methods to accomplish the preparation of the EoS inputs for the envisaged applications in simulations of supernova explosions (the code is available within our team and has been used in Fischer et al. (2018); the EoS module and the neutrino transport module shall get upgraded within the project), rotating PNS simulations (public codes) and NS merger simulations — the code developed at GSI Darmstadt will be accessible which has been used already for our work described in Bauswein et al. (2019). We have also agreed with the University of Heidelberg to jointly further develop the code on the combustion of a neutron star to a strange star by implementing our hybrid EoS for hadron-strange quark matter. The **two PhD projects** are are devoted to the study of:

(1) Effects of the confining density functional on color superconductivity in the quark matter EoS,

(2) Absolutely stable strange quark matter in the dynamically confining RDF approach,

and the application of the obtained results in the simulations of supernova explosions (test of explodability), rotating PNS sequences (problem of maximum mass, rotation- and accretion induced transitions) and NS merger simulations (testing GW signals against observations). The workplan is summarized in the Table below.

	Topics		Time/months
1	Development of hadron-quark matter EoS with phase transition construction including pasta phases and unified approach	Implementation of color superconductivity	12
		Inclusion of strange quark (SQ) flavor and scenario of absolutely stable SQ matter	24
2	Upper limit for maximum mass of hybrid compact stars from systematic study of rotating PNS and NS-NS merger evolution	Uniform rotation in full general relativity, limits on M_{max}/M_{TOV}	12
		BNSM simulation for the scenarios NS-NS, NS-HS and HS-HS	12
3	Test of the explosion mechanism for massive supernova and corresponding PNS mass and structure	SN simulations and test of explodability for 50 $M_\odot$ progenitor stars & other stellar models	12
		Investigation of PNS mass and structure at birth in dependence on progenitor star and EOS model	12

Both Ph.D. students will be trained in implementing their results on modifications of the EoS properties into the tabulated versions of the hybrid hadron-quark EoS that are then used in tests of the explodability in simulations of CCSN and in studies of the rotational and cooling evolution of hyper(supra-) massive neutron stars emerging from BNSM events.

The UWr team has the documented refereed expertise on these topics. The development of the new class of hybrid EoS capturing dynamical quark confinement within the RDF approach has been documented, e.g., in Blaschke & Chamel (2018) and references therein, Kaltenborn et al. (2017), and Bastian et al. (2018a)-(2018c). The generalization of the confining RDF approach to include color superconductivity will follow the scheme of relativistic 4-fermion coupling models of the NJL-type models using the Nambu-Gorkov formalism, as described in Blaschke et al. (2005) and Blaschke et al. (2014); and the nonlocal generalization used recently to discuss general conditions for the occurrence of the third family of hybrid stars in Alvarez-Castillo et al. (2019). As for the construction of the hadron-quark hybrid EoS it is important to go beyond the Maxwell construction scheme and to take into account the possibility of electrically charged finite size regions of the subphases (pasta structures) as developed, e.g., in Yasutake et al. (2014). We have developed a simplified one-parameter scheme of mixed phase construction (Ayriyan et al. (2018)) which very well represents the corresponding pasta phase construction as shown in Maslov et al. (2018).
The generalization to finite temperatures will be performed within this project and will allow to explore the robustness of the astrophysical consequences of the first-order phase transition (explodability of massive blue supergiant stars and GW signal of the phase transition in BNSM) against physical phenomena that change the strict first-order transition to a rapid crossover.
We have performed such tests of robustness against mixed phase effects for the example of the mass twin phenomenon that accompanies the third family sequences of hybrid stars (Ayriyan et al. (2018)).

4. Methodology

The current tools are at the frontier of research with respect to spherically symmetric SN modeling with Boltzmann neutrino transport and phenomenological hot and dense QCD for applications in astrophysics. An extension of the neutrino transport code is required for adequately dealing with the novel hadron-quark EOS, in particular when color-superconducting quark matter phases and finite-size electrically charged structures (pasta phases) are considered (Berdermann et al. 2016).

Concerning the development of the EoS with a strong phase transition, we will be pursuing a path-integral-based relativistic density functional (RDF) approach for baryonic (hadronic) and quark matter in extension of the formulation given in Kaltenborn et al. (2017). This extension in the hadronic phase shall concern further baryonic states such as Deltas and hyperons as well as the dibaryon d*(2380) (Vidana et al. 2018) and the chiral partner of the nucleon N*(1535) (Marczenko et al. 2018).

For the corresponding density functionals also excluded volume corrections due to the compositeness and finite radii of the hadrons will be included.

On the quark matter side the choice of the effective interaction density functional will be extended by terms depending on quark bilinears responsible for the pairing interaction and a term originating from the Fierz transformed ‘t Hooft interaction (triangle anomaly) which mixes chiral and diquark condensates.

Steps beyond the selfconsistent mean field approximation will be taken along the lines of a cluster virial expansion formulated within the so-called Φ-derivable approach (generalized Luttinger-Ward-Baym formalism), as outlined in Bastian et al. (2018). A generalized Beth-Uhlenbeck approach for the in-medium properties of few-quark and few-nucleon clusters, including their Mott-dissociation will be developed, first by adopting generic medium-dependent phase shift functions for the hadronic correlations and in a final step by using the corresponding Bethe-Salpeter equations for T-matrices in the Nambu-Gorkov formulation.

5. Literature

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