Joint Institute for Nuclear Research

BOOK OF ABSTRACTS

Compact stars in the QCD phase diagram VI

(Cosmic matter in heavy-ion collision laboratories?)

26-29 September 2017

Dubna, Russia

General Information

The Joint Institute for Nuclear Research (JINR) organizes the conference ”Compact stars in the QCD phase diagram VI”, in Dubna, September 26 - 29, 2017. It will be devoted to the question whether there is ”Cosmic matter in heavy-ion collision laboratories?”
The aim of the conference is to bring together experts in fields of the heavy-ion collisions, QCD phase diagram, compact stars and on related phenomena.
The conference will cover the following main topics:

- QCD phase diagram for HIC vs. astrophysics,
- Quark deconfinement in HIC vs. supernovae, neutron stars and their mergers,
- Strangeness in HIC and in compact stars,
- Equation of state and QCD phase transitions.

The presentations will be videostreamed http://theor.jinr.ru/videolive/
Previous meetings could be found on the website:
http://www.quarknova.ca/CSQCD.html
This conference is supported by different organizations and programs, among them in particular: the JINR Dubna with research themes on ”Fundamental interactions”, ”Nuclear Structure” and ”NICA”, the Bogoliubov-Infeld program, the Heisenberg-Landau program and the COST actions ”NewCompStar” (MP1304) and ”THOR” (CA15213).
We invite research papers devoted to the topic of this conference to be included into a special issue of the MDPI journal ”Universe”. Details are given at the end of this booklet.

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Dubna, September 2017

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Contents

Supporting the existence of the QCD critical point by compact star observations

ALVAREZ CASTILLO, David Edwin[1]
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In order to prove the existence of a critical end point (CEP) in the QCD phase diagram it is sufficient to demonstrate that at zero temperature $T = 0$ a first order phase transition exists as a function of the baryochemical potential μ, since it is established knowledge from ab-initio lattice QCD simulations that at $\mu = 0$ the transition on the temperature axis is a crossover. We present the argument that the observation of a gap in the mass-radius relationship for compact stars which proves the existence of a so-called third family (implying the existence of "mass twins") is caused by the fact that the $T = 0$ equation of state of compact star matter exhibits a strong first order transition with a latent heat that satisfies $\Delta\epsilon/\epsilon_c > 0.6$. Since such a strong first order transition under compact star conditions will remain first order when going to symmetric matter, the observation of a disconnected branch (third family) of compact stars in the mass-radius diagram proves the existence of a CEP in QCD. Modeling of such compact star twins is based on a QCD motivated NJL quark model with high order interactions together with the hadronic DD2-MEV model fulfilling nuclear observables. Furthermore we show results of a Bayesian analysis (BA) using disjunct M-R constraints for extracting probability measures for cold, dense matter equations of state. In particular this study reveals that measuring radii of the neutron star twins has the potential to support the existence of a first order phase transition for compact star matter.

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Bayesian Analysis of Hybrid EoS Models Using Mass and Radius Data from Compact Star Observations

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A Bayesian analysis for a new class of realistic models of hybrid equations of state (EoS) with mixed phase is performed. The mixed phase is described by a one parameter simple model. The parameter represents the impact of the mixed phase structure to the pressure. It is demonstrated that the observation of a possible pair of high-mass twin stars would have a sufficient discriminating power to favour hybrid EoS with a strong first-order phase transition over alternative EoS.

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Prospects of constraining the dense matter equation of state from observations and data analysis of radio pulsars in binaries

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Binary radio pulsars have the potential to constrain the dense matter equation of state. In the present talk, I will discuss a few observable effects that can enable us for different types of binaries. I will emphasise the potential of such studies, especially in the view of upcoming SKA and one of the existing SKA pathfinder - GMRT.

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The effect of quantum fluctuations in compact star observables

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Astrophysical measurements regarding compact stars are becoming more and more accurate. The NICER experiment deployed on ISS on 14 June 2017 NASA (2017) will provide data that will enable the determination of compact star radius with less than 10% error Ozel et al. This poses new challenges to nuclear models aiming to explain the structure of super dense nuclear matter found in neutron stars, because effects which earlier measurements was not able to resolve may became detectable. In the same time detailed studies of the QCD phase diagram shows the importance of bosonic quantum fluctuations in the cold dense matter equation of state. In this talk we build on our earlier work which introduced a new technique to calculate the effect of bosonic quantum fluctuations on the equation of state and thermodynamical quantities. Using a demonstrative model of one bosonic and one fermionic degree of freedom coupled by Yukawa coupling we show the effect of bosonic quantum fluctuations on compact star observables such as mass, radius and compactness. We have also calculated the difference in the value of compressibility which is caused by quantum fluctuations. The above mentioned quantities are calculated in mean field, one-loop and in high order many loop approximation. The results show that the magnitude of these effects is in the range of 4-5%, which place it into the region where modern measurements may detect it. This forms a base for further investigations that how these results carry over to more complicated (e.g. Walecka-like) models.

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Towards a unified quark-hadron equation of state for neutron stars, supernovae and heavy-ion collisions

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The aim of our work is to develop a unified equation of state (EoS) for nuclear and quark matter for a wide range in temperature, density and isospin so that it becomes applicable for heavy-ion collisions as well as for the astrophysics of neutron stars, their mergers and supernova explosions. As a first step, we use improved EoS for the hadronic and quark matter phases and join them via Maxwell construction. For this we work with a generalized density functional approach for the self energies in a quasi particle picture, which gives us the possibility to start with a reasonable physical basis and apply improvements to fit certain constraints from lattice QCD and neutron star measurements.

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Simulation of NICA/MPD with Three-fluid Hydrodynamics-based Event Simulator Extended by UrQMD final State interactions (THESEUS) as an attempt to investigate effects of a QCD phase transition in the EoS on HIC observables

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We present preliminary results obtained in course of simulation of the NICA/MPD detector using input from the program (THESEUS) that has the unique feature to describe a hadron-to-quark matter transition which proceeds in the baryon stopping regime that is not accessible to previous simulation programs designed for higher energies. Influence of the detector effects and reconstruction procedure on HIC observables (flow, net-baryon spectra, femtoscopy...), comparing with pure information obtained directly from THESEUS, is considered.

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EoS for dense matter with a QCD phase transition

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We construct a dense matter EoS starting from a DD2 model with excluded volume corrections at low densities. The high density part is given by a NJL model with multi-quark interactions. This EoS is characterized by increasing speed of sound below and above the phase transition region. The first order transition region has a large latent heat leaving a distinctive signature in the M-R relations in terms of twin stars. We will show how present mass measurements and fictitious radii data constrain model parameters.

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Non-extensive Fokker-Planck transport coefficients of heavy quarks

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In presence of the non-ideal plasma effects, Heavy Quarks (HQs) carry out non linear random walk inside Quark-Gluon Plasma (QGP) and in the small momentum transfer limit, the evolution of the HQ distribution is dictated by the Non Linear Fokker-Planck Equation (NLFPE). Using the NLFPE, we calculate the transport coefficients (drag and diffusion) of heavy quarks travelling through QGP. We observe substantial modification in the momentum and temperature variation of the transport coefficients; and this will modify the physical picture we are having about the transport of heavy quarks inside QGP, and hence, about the characterisation of the plasma.

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Quark exchange effects in the nuclear equation of state at high-densities

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We investigate the effectve repulsive interaction of Pauli blocking due to quark exchange among nucleons in nuclear matter within a nonrelativistic potential model for the nucleons. In order to describe nuclear saturation properties the nucleons are coupled to scalar and vector meanfields in the spirit of a linear Walecka model. The effects of chiral symmetry restoration is studies by adopting density-dependent quark masses that follow either the Brown-Rho scaling or the behaviour of a NJL model with 8-quark interaction terms (hNJL). When compared to the results for density-independent quark masses a strong density-dependent stiffening of the nuclear matter is obtained. The resulting symmetric nuclear matter equation of state is compared with results for the excluded-volume corrected density-dependent relativistic mean-field model DD2. Applications to neutron matter as well as to neutron star matter in beta-equilibrium are studied. The phase transition to quark matter described by the hNJL model is constructed and hybrid star sequences are obtained that form a third family of compact stars at high mass.

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Vector interaction enhanced bag model

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The current state-of-the-art quark matter model in astrophysics is the thermodynamic bag model (tdBAG). This model approximates the effect of quark confinement, but it lacks other important properties of Quantum Chromodynamics. The vector enhanced bag model (vBAG) improves the tdBAG approach by taking into account dynamical chiral symmetry breaking and repulsive vector interactions. The latter is of particular importance to studies of dense matter in beta-equilibrium in order to explain the 2 solar mass maximum mass constraint for neutron stars. Another important feature of this model is the assumption of simultaneous chiral symmetry breaking and confinement. The model can be derived from the QCD based framework of Dyson-Schwinger equations by assuming a simple quark-quark contact interaction. This work will focus on the resulting phase diagram and neutron star equations of state.

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Explosions of massive stars triggered from the 1st-order hadron-quark phase transition at high density

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Any reliable equation of state (EOS) for astrophysical applications faces recently sever constraints, in particular associated with the high-precision observations of massive pulsars. Within the development of a novel phenomenological EOS for quark matter we realize the required stiffness at high density due to the inclusion of repulsive vector interactions. The extension of this model EOS to finite temperatures and arbitrary isospin asymmetry enables us to study the hadron-quark phase transition in simulations of core-collapse supernovae.

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Phase diagram in effective QCD models

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The QCD phase diagram and transitions between quark and hadron phases are in the focus of recent investigations in both theoretical and experimental fields of heavy energy physics. For a description of matter at high temperature and density effective models of Nambu-Jona-Lasinio type have proven most useful. On the basis of NJL-type models it is possible to describe the chiral restoration transition and to describe the quark-gluon coupling and confinement transition, when the Polyakov loop is included. The Polyakov loop extended NJL (PNJL) model can reproduce results of lattice QCD at zero and imaginary chemical potential, where LQCD has no sign problem. In this poster contribution we present the dependence of the first-order phase transition line and its critical endpoint in the PNJL model phase diagram when the following aspects are taken into account: the parametrization of the effective potential $U(\Phi, \bar{\Phi}; T)$; including of the quarks repulsion (vector interaction); an additional interaction between quarks and gluons.

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Cooling of massive neutron stars

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The existence of the high mass pulsars PSR J1614-2230 and PSR J0348-0432 with masses of about 2 M_sun requires a sufficiently stiff equation of state (EoS) of the stellar matter to fulfil this constraint. We succeeded to explain the thermal evolution of compact stars with stiff hadronic EoS in the framework of the “nuclear medium cooling" scenario. We have also investigated the case when due to phase transition to quark matter the third family of compact stars for higher densities can exist. In this case high-mass twin stars could show different cooling behaviour. The cooling scenarios have a discriminating power for selection of optimal EoS models for compact stars.

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Binodal Layer and Phase Freezeout in Adiabatically Expanded Hot Dense Matter

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Binodal layer ("Phase Freezeout") and rarefaction shock in Hot Dense Matter (HDM), adiabatically expanded trough two-phase region of entropic phase transition are under discussion. For example it could be Quark-Hadron Phase Transition (QHPT) or any other "delocalization-driven" phase transition (pressure-ionization PT, pressure-dissociation PT in electromagnetic HDM etc) when equilibrium thermodynamic path of such adiabatic expansion crosses the two-phase region of considered entropic phase transition. Binodal layer appears at the entering of the two-phase region, while rarefaction shock appears at the stage of leaving the two-phase region of entropic PT.

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Directed flow in heavy-ion collisions and its implications for astrophysics

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Analysis of directed flow (v1) of protons, antiprotons and pions in heavy-ion collisions is performed in the range of collision energies $\sqrt{s_{NN}}$ = 2.7-39 GeV. Simulations have been done within a three-fluid model employing a purely hadronic equation of state (EoS) and two versions of the EoS with deconfinement transitions: a first-order phase transition and a smooth crossover transition. The crossover EoS is unambiguously preferable for the description of the most part of experimental data in this energy range. The directed flow indicates that the crossover deconfinement transition takes place in semicentral Au+Au collisions in a wide range of collision energies $4 < \sqrt{s_{NN}} < 30$ GeV. The obtained results suggest that the deconfinement EoS?s in the quark-gluon sector should be stiffer at high baryon densities than those used in the calculation. The latter finding is in agreement with that discussed in astrophysics.

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Nonequilibrium meson production in strong fields

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We develop a kinetic equation approach to nonequilibrium pion and sigma meson production in a time-dependent, chiral symmetry breaking field (inertial mechanism) We investigate the question to what extent the low-momentum pion enhancement observed in heavy- ion collisions at CERN - LHC can be addressed within this formalism. In this preliminary study, we consider the inertial mechanism for nonequilibrium production of sigma-mesons and their simultaneous decay into pion pairs. The resulting pion distribution shows a low-momentum enhancement.

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J-PARC heavy-ion program and search of the QCD critical point

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Recent status of J-PARC heavy-ion program will be reviewed. Then, I will talk on the search for the QCD critical point using event-by-event fluctuations of conserved charges in beam-energy scan.

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QCD equations of state in hadron-quark continuity

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We discuss QCD equations of state for neutron star matter, based on a picture of hadron-quark continuity.

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Charged ρ-meson condensate in neutron stars within RMF models

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Knowledge of the equation of state (EoS) of cold and dense baryonic matter is essential to describe the properties of neutron stars (NSs). With an increase of the density new baryon species can appear in NS matter, as well as various meson condensates. In previous works we developed relativistic mean-field (RMF) models with hyperons and Δ-isobars, which passed the majority of known experimental constraints, including the existence of a $2\,M_{\odot}$ neutron star. In this contribution we present results of inclusion of ρ^{-}-meson condensation into these models. We have shown that in one class of the models (so-called KVOR-based models, in which the additional stiffening procedure is introduced in isoscalar sector) the condensation gives only a small contribution to the EoS. In other class (MKVOR-based models with additional stiffening in isovector sector) models the condensation can lead to a first-order phase transition and a substantial decrease of the NS mass. Nevertheless, in all resulting models the condensation does not spoil the description of the experimental constraints.

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Finite density equation of state of the quark-gluon plasma via resummed perturbation theory

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In thermal quantum chromodynamics, both the poor convergence of the perturbative evaluations and the sign problem encountered by Monte-Carlo simulations at finite baryon density are well known issues. At temperature and chemical potentials just above the deconfinement transition, neat theoretical investigations become then difficult. I shall start by presenting two different perturbative frameworks for addressing this problem. Both entail resummations of important higher order contributions and allow for first principle calculations. The first one, physically motivated, is a systematic, consistent and gauge invariant framework known as Hard-Thermal-Loop perturbation theory. The second one, inspired by the Dimensional Reduction taking place in QCD at very high temperature, relies on effective field theory methods. I will then report on finite density equation of state investigations within these frameworks, by comparing their results to state-of-the-art lattice data. Namely, I will present the pressure at non-zero baryon density as well as various cumulants at vanishing densities, obtained from successive derivatives of the pressure respect to the quark chemical potentials.

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Fully self-consistent thermal evolution studies of rotating neutron stars

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In this work we study the thermal evolution of rotating, axis-symmetric neutron stars, which are subjected to atructural and compositional changes during spin-down. Our aim is to go beyond standard thermal evolution calculations where neutron stars are considered spherically-symmetric and with a static, "frozen-in" composition. Building on previous work, we carry out fully self-consistent thermal evolution calculations where the neutron star has an axis-symmetric, time-dependent structure. Such an approach allows us to consider, during the thermal evolution, changes of the star's geometry as well as its microscopic particle population. As a proof-of-concept, we study the thermal evolution of a neutron star subjected to magnetic braking spin-down. We show that the spin-evolution, combined with the accompanying structural and compositional changes lead to a substantially distinct thermal evolution scenario.

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Fast radio bursts and neutron stars

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Fast radio bursts are enigmatic millisecond radio flares observed since 2007, however, there origin is still unknown. Many models have been proposed. At the moment all leading hypothesis are related to neutron stars: magnetar bursts, supergiant pulses of PSRs, NS coalescence, supramassive NSs and so on. I briefly review these ideas, and then focus on magnetars and young radio pulsars as potential sources of FRBs.

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Correlations and bound states in nuclear matter

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The composition of nuclear matter is investigated, in particular the region of phase instability. As application, the inner crust of neutron stars is considered.

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Baryon rich matter research at NICA

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The NICA (Nuclotron-based Ion Collider fAcility) project is now under active realization stage at the Joint Institute for Nuclear Research (JINR, Dubna). The main goal of the project is an experimental study of hot and dense baryon rich QCD matter in heavy ion collisions at centre of-mass energies $\sqrt{s_{NN}} = 4$ - 11 GeV (NN-equivalent) and the average luminosity of $10^2 7$ cm^{-2} s^{-1} for Au(79+) in the collider mode (NICA collider). In parallel, the fixed target experiment BM@N (Baryonic Matter at Nuclotron) at the upgraded JINR superconducting synchrotron Nuclotron are carried out with extracted beams of various nuclei species up to Au(79+) with maximum momenta 13 GeV/c (for protons). The project also foresees a study of spin physics with extracted and colliding beams of polarized deuterons and protons at the energies up to $\sqrt{s} = 27$ GeV (for protons). The proposed program allows to search for possible signs of the phase transitions and critical phenomena as well as to shed light on the problem of nucleon spin structure. General design and construction status, physical program of the NICA complex is presented.

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Strangeness production in nucleus-nucleus collisions at SIS energies

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SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) is a new hadronic transport model designed to describe the non-equilibrium evolution of heavy-ion collisions. We discuss two different strangeness production mechanisms: one based on resonances and another one using forced canonical thermalization. Comparisons to experimental data from elementary and heavy-ion collisions are shown.

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Looking for the phase transition - recent NA61/SHINE results

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The fixed target NA61/SHINE experiment (SPS CERN) looks for the critical point of strongly interacting matter and the properties of the onset of deconfinement. It is a two dimensional scan of measurements of particle spectra and fluctuations in proton-proton, proton-nucleus and nucleus-nucleus interactions as a function of collision energy and system size, corresponding to a two dimensional phase diagram ($T - \mu_B$). New NA61/SHINE results would be presented, such as transverse momentum and multiplicity fluctuations in Ar+Sc collisions compared to NA61 p+p and Be+Be data, as well as to earlier NA49 A + A results. Recently, a preliminary signature for the new size dependent effect rapid changes in system size dependence was observed in NA61/SHINE data, labeled as "percolation threshold" or "onset of fireball". This would be closely related to the vicinity of the hadronic phase transition region.

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On manifestation of in-medium effects in NS and HIC

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Important role played by in-medium polarization effects in hadron matter of neutron stars and heavy-ion collisions will be demonstrated.

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The High-Density Symmetry Energy in Heavy Ion Collisions and Compact stars

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The high-density nuclear equation-of-state determines much of the structure of compact objects in the cosmos, which concerns especially neutron rich matter, i.e. the nuclear symmetry energy. Microscopic many-body theories still differ considerably in their predictions, due to the difficulties from short-range tensor interactions. Thus heavy ion collisions at relativistic and ultra-relativistic energies are an important method to obtain information here. Due to their non-equilibrium nature they have to be interpreted by transport approaches. I will discuss the Boltzmann-Vlasov and molecular dynamics approaches used in the hadronic regime and actual developments and challenges. The status of the knowledge of the symmetry energy from the most commonly used observables, like elliptic flow and particle production, will be reviewed and compared to the constraints derived from neutron star observations.

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Exotic convection inside hybrid stars

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We show that the unusual thermodynamic properties of matter within the region of two phase coexistence in hybrid stars result in a change of the standard condition for beginning of convection. In particular, the thermal flux transported by convection may be directed towards the stellar center in this region. We consider favourable circumstances leading to such an effect of "inverse convection" and its influence on the thermal evolution of hybrid stars.

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Numerical configurations of differentially rotating quark stars

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It's widely known that there is an X-ray plateau phase following sGRBs. This phase is supposed to be related to the hyper-/supra-massive NS formed after the merger in many sGRB models. The evolution of this hyper-/supra-massive neutron star mainly depends on the total mass of the binary and the EoS, which will also significantly affect the gravitational wave and electromagnetic emissions in the post merger phase. We have built models of both uniform and differential rotating compact stars with quark star EoSs. Comparisons with neutron star models are made, possible way to distinguish between EoSs by future observations are also discussed.

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