Compact Stars in the QCD Phase diagram

Monday, October 7, 2024 - Friday, October 11, 2024

YITP

Book of Abstracts

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Current Status of Astronomical Observations of Neutron Stars

I will introduce recent astronomical observations and hot topics of neutron stars and magnetars.

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Neutron stars and Constraints for the Equation of State of Dense Matter

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In this talk I review our current understanding of the interior of neutron stars and modern constraints relevant for dense matter. This includes theoretical first-principle results from lattice and perturbative QCD, as well as chiral effective field theory results. From the experimental side, it includes heavy-ion collision and low-energy nuclear physics results, as well as observations from neutron stars and their mergers. I also discuss the relevance of isospin, strangeness, and magnetic fields on the dense and hot equation of state.

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Astrophysics and Nuclear Physics Informed Interactions in Dense Matter: Inclusion of PSR J0437-4715

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We investigate how vector and isovector interactions can be determined within the density regime of neutron stars (NSs) while fulfilling nuclear and astrophysics constraints. We make use of the Chiral Mean Field (CMF) model, a SU(3) nonlinear realization of the sigma model within the mean-field

approximation, for the first time within a Bayesian analysis framework. We show that neutron-matter EFT constraints at low density are only satisfied if the vector-isovector mixed interaction term is included, e.g., a term. We also show the behaviour of the model with respect to the conformal limit. We demonstrate that the CMF model is able to predict a value for the parameter related to the trace anomaly and its derivative takes values below 0.2 above four times saturation density within a hadronic model that does not include {\blu hyperons or} a phase transition to deconfined matter. We compare these effects with results from other (non-chiral) Relativistic Mean Field models to assess how different approaches to incorporating the same physical constraints affect predictions of NS properties and dense matter equations of state. We also include data from the gravitation wave event GW230529 detected by the LIGO-Virgo-Kagra collaboration and the most recent radius measurement of PSR J0437-4715 from the NASA NICER mission. Our analysis reveals that this new NICER measurement leads to an average reduction of approximately km radius in the posterior of the NS mass-radius relationship.

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Recent NICER Analyses

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X-ray pulses of rapidly rotating neutron stars (NSs) can be used to probe both the properties of heated surface regions of a NS and the equation of state (EoS) of high-density matter inside a NS. Constraints on the EoS are obtained by measuring the mass and radius of the NS based on the relativistic effects when photons travel from the stellar surface to the observer. During the last few years, NICER telescope has been used to study several rotation-powered millisecond pulsars using this technique. I will review our latest analysis for the first published pulsar PSR J0030+0451, the massive pulsar PSR J0740+6620, and the brightest pulsar PSR J0437−4715. In addition, I will discuss our recent progress in applying the pulse profile modeling method to accretion and thermonuclear-powered millisecond pulsars.

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Bayesian inference of hybrid neutron star equation of state from multi-messenger astronomy

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Framework for phase transitions between the Maxwell and Gibbs constructions

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By taking the nucleon-to-quark phase transition within a neutron star as an example, we present a thermodynamically consistent method to calculate the equation of state of ambient matter so that transitions that are intermediate to those of the familiar Maxwell and Gibbs constructions can be described. This method does not address the poorly known surface tension between the two phases microscopically (as, for example, in the calculation of the core pasta phases via the Wigner-Seitz approximation) but instead combines the local and global charge neutrality conditions characteristic of the Maxwell and Gibbs constructions, respectively. Overall charge neutrality is achieved by dividing the leptons to those that obey local charge neutrality (Maxwell) and those that maintain global charge neutrality (Gibbs). The equation of state is obtained by using equilibrium constraints derived from minimizing the total energy density. The results of this minimization are then used to calculate neutron star mass-radius curves, tidal deformabilities, equilibrium and adiabatic sound speeds, and nonradial g-mode oscillation frequencies for several intermediate constructions. The equation of state at finite temperature and off-β-equilibrium, constructed from this framework, can be used to study the impact of first-order phase transitions in neutron star mergers and core-collapse supernovae.

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Lattice results for the speed of sound in dense QCD-like theories

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We review recent works on the Monte Carlo simulations of dense two-color QCD (QCD) by focusing on the phase diagram, the equation of state, and the sound velocity at nonzero quark chemical potential. A possible upper bound of the sound velocity is known as the conformal bound, namely, cs^2/c^2 < 1/3. The sound velocity is below the bound at least in the case of finite-temperature QCD. However, our recent works show the breaking of this bound in dense QCD. This phenomenon was previously unknown from any lattice calculations. We also discuss recent related works including lattice studies on QCD at nonzero isospin chemical potential, some effective model analyses, and an analysis based on recent neutron star observations. These works also suggest the breaking of the conformal bound.

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A study of neutron star property based on the PDM-NJL crossover model

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I will summarize our works in Refs. [1]-[3] in which we studied neutron star property based on the PDM-NJL crossover model. In the low-density region, we construct an EoS using a hadronic model based on the parity doublet structure with the chiral invariant mass of nucleons. In the high density region, an EoS is obtained in an NJL-type quark model. By interpolating two EoSs with assuming the quark-hadron crossover, we construct a unified EoS for dense matter. We then derive the M-R relation of neutron stars from the unified EoS and compare the result with the observational constraints to obtain an allowed range for the chiral invariant mass.

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Establishing connection between neutron star properties and nuclear matter parameters through a comprehensive multivariate analysis

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We have attempted to mitigate the challenge of connecting the neutron star (NS) properties with the nuclear matter parameters that describe equations of state (EOSs). The efforts to correlate various neutron star properties with individual nuclear matter parameters have been inconclusive.
A Principal Component Analysis is employed as a tool to uncover the connection between multiple nuclear matter parameters and the tidal deformability as well as the radius of neutron stars within the mass range of . The essential EOSs for neutron star matter at low densities have been derived using both uncorrelated uniform distributions and minimally constrained joint posterior distributions of nuclear matter parameters. For higher densities (fm), the EOSs have been established through a suitable parameterization of the speed of sound, which consistently maintains causality and gradually approaches the conformal limit. Our analysis reveals that in order to account for over 90\% of the variability in NS properties, it is crucial to consider two or more principal components, emphasizing the significance of employing multivariate analysis. To explain the variability in tidal deformability needs a greater number of principal components compared to those for the radius at a given NS mass. The contributions from iso-vector nuclear matter parameters to the tidal deformability and radius of NS decrease by 25\% with the increase in mass of NS from 1.2 to 1.8.

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Reconciling constraints from the multi-messenger constraints with the parity doublet model

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The recent discovery of a central compact object (CCO) within the supernova remnant HESS J1731-347, characterized by a mass of approximately and a radius of about
km, has opened up a new window for the study of compact objects. This CCO is particularly intriguing because it is the lightest and smallest compact object ever observed, raising questions and challenging the existing theories. To account for this light compact star, a mean-field model within the framework of parity doublet structure is applied to describe the hadron matter. Inside the model, part of the nucleon mass is associated with the chiral symmetry breaking while the other part is from the chiral invariant mass which is insensitive to the temperature/density. The value of affects the nuclear equation of state for uniform nuclear matter at low density and exhibits strong correlations with the radii of neutron stars. We point out that HESS J1731-347 can be explained as the lightest neutron star for \,MeV.

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Reconciling constraints from the multi-messenger constraints with the parity doublet model

Corresponding Author: bikai.gao@gmail.com

The recent discovery of a central compact object (CCO) within the supernova remnant HESS J1731-347, characterized by a mass of approximately 0.77+0.20-0.17 Msun and a radius of about 10.4+0.86-0.78km, has opened up a new window for the study of compact objects. This CCO is particularly intriguing because it is the lightest and smallest compact object ever observed, raising questions and challenging the existing theories. To account for this light compact star, a mean-field model within the framework of parity doublet structure is applied to describe the hadron matter. Inside the model, part of the nucleon mass is associated with the chiral symmetry breaking while the other part is from the chiral invariant mass which is insensitive to the temperature/density. The value of affects the nuclear equation of state for uniform nuclear matter at low density and exhibits strong correlations with the radii of neutron stars. We point out that HESS J1731-347 can be explained as the lightest neutron star for 850 MeV.

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The Effect of Isovector Scalar Meson on Neutron Star Matter Based on a Parity Doublet Model

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We study the effect of the isovector-scalar meson (980) on the properties of nuclear matter and the neutron star (NS) matter by constructing a parity doublet model with including the meson based on the chiral SU(2)L x SU(2)_R symmetry. We also include the - mixing contribution to adjust the slope parameter at the saturation. We find that, when the chiral invariant mass of nucleon is smaller than about 800 MeV, the existence of (980) enlarges the symmetry energy by strengthening the repulsive meson coupling. On the other hand, for large where the Yukawa coupling of (980) to nucleon is small, the symmetry energy is reduced by the effect of omega-rho mixing. We then construct the equation of state (EoS) of a neutron star matter to obtain the mass-radius relation of NS. We find that, in most choices of , the existence of (980) stiffens the EoS and makes the radius of NS larger. We then constrain the chiral invariant mass of nucleon from the observational data of NS, and find that 580 < m_0 < 860 MeV for L0 = 57.7 MeV.

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Two-flavor color superconducting quark stars may not exist

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Large uncertainties in the determinations of the equation of state of dense stellar matter allow the intriguing possibility that the bulk quark matter in beta equilibrium might be the true ground state of the matter at zero pressure. And quarks will form Cooper pairs very readily since the dominant interaction between quarks is attractive in some channels. As a result, quark matter will generically exhibit color superconductivity, with the favored pairing pattern at intermediately high densities being two-flavor pairing. In the light of several possible candidates for such self-bound quark stars, including the very low-mass central compact object in supernova remnant HESS J1731-347 reported recently, we carry out one field-theoretic model, the Nambu–Jona-Lasinio model, of investigation on the stability of beta-stable two-flavor color superconducting (2SC) phase of quark matter, nevertheless find no physically-allowed parameter space for the existence of 2SC quark stars.

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Renormalization Group Consistent treatment of NJL Color Superconductivity (online)

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Constraining Coupling Parameters of NJL Color Superconductivity for Compact Stars

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We study the Nambu-Jona-Lasinio (NJL) model and its extension to color superconductivity (CSC) by incorporating the Renormalization Group (RG)-consistent treatment. This refinement leads to significant updates in the understanding of the CSC phases including an improved speed of sound at higher densities.

For modeling the dense quark matter EoS, we determine and constrain the vector and diquark coupling parameters based on the current astrophysical constraints from various measurements. Varying the vector and diquark couplings shift the stellar configuration from self-bound to mimicking gravitational bound for pure strange stars. Furthermore, we observe both stable 2SC and CFL phases at low vector couplings which change to unstable CFL phases at high values.

We apply these refined couplings to the EoS for the strange stars and hybrid stars, particularly in the context of neutron star mergers to determine the signatures of CSC phases.

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Holographic model for neutron star with color superconductivity in the inner core

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In this model holographic model, we will use the Gauss-Bonnet gravity the baryonic matter correspond to the dilute instanton gas and the color superconductivity (CSC) phase is in deconfinement region. We will calculate this and find the equation of state of the CSC phase

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Equation of state in neutron stars from a bottom-up holographic QCD

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We derived an equation of state for neutron stars using a bottom-up holographic QCD model. Our calculations included mass-radius relationships of neutron stars and the sound velocity in high-density QCD matter.

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Superfluid Band Calculations for Neutron Star Inner Crust

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In the inner crust of neutron stars, a Coulomb lattice of nuclei exists, immersed in a sea of superfluid neutron gas. The interplay between these nuclear crystals and the background neutrons may significantly alter nuclear dynamics, a phenomenon known as the "entrainment" effect, which is crucial for understanding several astronomical phenomena.

In our study, we have developed new self-consistent calculations that fully account for both superfluid effects and band structure effects. We have extracted the "effective mass" of free neutrons through the real-time method.

In this presentation, we will show the formalism and methodology of our calculations, as well as further extensions towards comprehensive simulations of the subnuclear properties of neutron star matter.

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Features of Quarkyonic Matter

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I outline the origin of the hypothesis for Quarkyonic Matter and discuss the generic characteristics of such matter. A specific IdylliQ model is presented corresponding to an ideal gas of nucleons with a constraint that the quark phase space density does not exceed 1, that is the maximal occupancy for quark states, This model is dual between quarks and nucleons, and in the Quarkyonic phase nucleons largely sit on a Fermi surface surrounded by a filled Fermi sea of quarks. The possibility that the transition density to Quarkyonic matter might be as low as nuclear matter density is discussed.

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Which first order phase transitions to quark matter are possible in neutron stars?

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We examine which first order phase transitions are consistent with today's astrophysical constraints. In particular, we explore how a well-constrained mass-radius data point would restrict the admissible parameter space and to this end, we employ the most likely candidates of the recent NICER limits of PSR J0030+0451. To systematically vary the stiffness of the equation of state, we employ a parametrizable relativistic mean field equation of state, which is in compliance with results from chiral effective field theory. We model phase transitions via Maxwell constructions and parametrize them by means of the transitional pressure and the jump in energy density . This provides us with a generic setup that allows for rather general conclusions to be drawn. We outline some regions in the - parameter space that may allow for a phase transition identification in the near future. We also find that a strongly constrained data point, at either exceptionally large or small radii, would reduce the parameter space to such an extent that mass and radius become insufficient indicators of a phase transition.

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Possibility of phase transition on superfluid vortex under Higgs-confinement crossover

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At finite densities of three-flavor QCD, a hadron (confinement) superfluid phase is expected to be realized at low densities, and a color superconducting (Higgs) phase at high densities. It is not well understood whether these two phases are connected with or without a phase transition. In this talk, we consider the Higgs-confinement transition with superfluidity in a U(1)U(1) lattice model as a simple model. We found that a phase transition occurs on a superfluid vortex, although the bulk system does not exhibit a phase transition. We confirm this phase transition through analytical calculations using weak/strong coupling expansion and Monte Carlo simulations. We also discuss possible scenarios for QCD.

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Heavy Hadron Spectroscopy and Quark Confinement in the Quark Model

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I will discuss how multi-quark system confines quarks and propose a new string-type confinement for heavy-tetra-quark systems. It is tested by the fully-heavy tetra-quark (cc c-bar c-bar) system.

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Properties of kaon condensation in hyperon-mixed matter with three-baryon repulsion

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Possibility of kaon-condensed phase (KC) in hyperon-mixed matter is considered in high-density multi-strangeness system, which may be realized in neutron stars.
The interaction model is based on effective chiral Lagrangian for kaon-baryon and kaon-kaon interactions, being combined with the relativistic mean-field theory for two-body baryon-baryon (B-B) interaction. In addition, universal three-baryon repulsive force (UTBR) and three-nucleon attractive force (TNA) are phenomenologically introduced, where relevant parameters are fixed to satisfy the saturation properties of symmetric nuclear matter and causality condition.
It is shown that the equation of state (EOS) with KC in hyperon-mixed matter is stiff enough to be consistent with recent observations of massive neutron stars.
The quark condensates in the presence of KC are also obtained as a function of baryon density, and a role of KC on chiral restoration in the course of hadron-quark transition is discussed.

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Impact of hot and cold dense matter on quasinormal oscillation

modes in compact stars

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A vast ensemble of equations of state (EoSs), developed within the framework of covariant density functional theory pertaining to hadronic matter and accommodating density-dependent couplings, is deployed to scrutinize the polar f- and p-oscillations in both cold and hot compact stars. The interplay between oscillation frequencies of cold purely nucleonic neutron stars (NSs), their global parameters, and the characteristics of nuclear matter (NM) is explored by investigating a spectrum of models, which enforce a series of constraints on the saturation properties of NM, pure neutron matter, and the lower limit of the maximum NS mass within a Bayesian framework. The influences of finite temperature and the presence of exotic particle degrees of freedom, such as hyperons, Δ-resonances, antikaon condensates, or the transition from hadron to quark phase, are addressed through the utilization of a suite of models publicly accessible on compose, assuming idealized profiles of temperature or entropy per baryon and charge fraction. Our analysis reveals that finite temperature effects lead to a reduction in the oscillation frequencies of nucleonic stars, while an opposite trend is observed for stars harbouring exotic particle degrees of freedom. Furthermore, when employing the Γ-law to construct finite temperature EoSs, errors in the estimation of oscillation mode frequencies range from 10% to 30%, contingent upon the stellar mass. Throughout this investigation, the Cowling approximation is consistently applied.

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Analytic Inversion of the TOV Equation and EOS Predictions From M,R Data

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An analytic technique of inverting the TOV equation with accuracies within 1% in both energy density and pressure is presented. In addition, a method using correlations connecting M,R data and energy density,pressure information is presented, giving a method of inferring the EOS from observations that does not contain the usual prior uncertainties stemming from the use of parameterized or non-parametric EOS techniques.

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Twin stars and the QCD phase diagram

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It has been suggested [1] that the observation of pulsars with the same mass but significantly different radii (twin stars) would prove that the existence of a critical endpoint in the QCD phase diagram since this phenomenon requires a strong phase transition in cold neutron star matter [2].
We explore whether such a phase transition in neutron star cores, possibly coupled with a secondary kick mechanism such as neutrino or electromagnetic rocket effect, may provide a formation path for isolated and eccentric millisecond pulsars (MSPs) [3].
We find that in compact binary systems (P_orb = 8 days) the accretion-induced phase transition occurs towards the end of mass transfer, specifically during the spin equilibrium phase. In contrast, in binary systems with wider orbits (P_orb ⊠ 22 days), this transition takes place during the subsequent spin-down phase, leading to a delayed collapse. We find that a gravitational mass loss of approximately ΔM ~ 0.01 M⊠ suffices to produce an eccentricity of the order of 0.1 without the need of a secondary kick mechanism. Wider systems are more prone to yielding highly eccentric orbits and be disrupted, presenting a formation path for isolated MSPs [3].

We show that in hot neutron star matter during supernova and merger events, thermal twin stars can be formed [4], even when in the mass-radius diagram of cold neutron stars the branch of hybrid stars with color superconducting quark matter cores is connected to that of pure neutron stars (no twins). Investigating systematically star sequences for increasing entropy per baryon s/n_B = const, we find a correlation between the transition to normal quark matter in hybrid star cores, the change from enthalpic to entropic character of the transition and the occurrence of thermal twin stars at s/n_B ~ 2. We speculate about a correlation of the thermal twin phenomenon with the supernova explodability of massive blue supergiant stars [4]. The result of these investigations has consequeences for the accessibility of color superconducting quark matter phases in heavy-ion collisions [5].

[1] D. Blaschke, D. E. Alvarez-Castillo and S. Benic, Mass-radius constraints for compact stars and a critical endpoint, PoS CPOD2013 (2013), 063, arXiv:1310.3803 [nucl-th]
[2] S. Benic et al., A new quark-hadron hybrid equation of state for astrophysics –I. High-mass twin compact stars, Astron. Astrophys. 577 (2015) A40
[3] S. Chanlaridis et al., Formation of twin stars in low-mass X-ray binaries. Implications on eccentric and isolated millisecond pulsar populations, in preparation (2024)
[4] J. Carlomagno et al., Hybrid isentropic twin stars, Universe 10 (2024) 336; arXiv:2406.17193
[5] D. Blaschke, F. Sandin, V.V. Skokov and S. Typel, Accessibility of color superconducting quark matter phases in heavy-ion collisions, Acta Phys. Polon. Supp. 3 (2010) 741

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In memory of Prof. Akira Ohnishi: Hyperon puzzle of neutron stars examined through heavy-ion collisions and hypernuclei

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At the beginning of the talk, I will reflect on my memories with my supervisor, Prof. Akira Ohnishi. Then, I will present our research on the Lambda potential strongly repulsive at high densities that is capable of avoiding the hyperon puzzle of neutron stars. The Lambda potential is shown to be consistent with the Lambda binding energies of hypernuclei and the Lambda directed flows in heavy-ion collision. I will also present my recent studies analyzing the Σ potential to constrain the Λ potential at high densities.

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Quark nucleation in compact stars

At the extreme densities reached in the core of neutron stars and related astrophysical phenomena, quark deconfined matter may take place. The formation of this new phase of strongly interacting matter is likely to occur via a first-order phase transition for the typical temperatures reached in astrophysical processes. For example, quark deconfinement could occur within the hot remnant of a neutron star merger or within a newly born proto-neutron star. Also, it could possibly represent the mechanism leading to the explosion of massive blue supergiants.
Within these scenarios, the first seeds of quark matter would form through a process of nucleation within the metastable hadronic phase. I will address the role of the thermal fluctuations in the hadronic composition on the nucleation of two-flavor quark matter and its implication for the phenomenology of compact stars. I will discuss in particular how those fluctuations (up to now disregarded in the literature) could substantially increase the rate of nucleation. Moreover, I will also consider the possibility
of nucleation of absolutely stable three-flavor quark matter that could give birth to stars entirely composed of strange quark matter.

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New modelling for hybrid stars with an elastic quark core

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Current anisotropic star models often overlook the effects of shear modulus and phase transitions. In our study, we propose a new anisotropic model for hybrid stars with an elastic quark matter core and a fluid nuclear matter envelope with a sharp phase transition in between. We incorporate the effects of shear deformation characterized by the shear modulus into the structural equations of anisotropic stars by extending the framework established by Karlovini and Samuelsson (2003). Using this approach, we calculate the anisotropic parameter, , numerically to analyze the impact on the mass-radius relation and the internal structure of hybrid stars. Additionally, we develop a new analytical model for anisotropy, as other phenomenological models cannot describe the internal structure well. The accuracy of our new model is lower than 10%, indicating that the provided analytical form of σ0 is valid across a broad parameter space.

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Constraining Quark Matter in Neutron Stars and the prospects of detecting Quark Stars

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Neutron Stars (NSs) make a unique physical laboratory with extreme physical conditions irreproducible in experiments, capable of producing a hadron-to-quark deconfinement phase transition in their interior. Owing to the high densities reached by the cold nuclear matter at the core of NSs, it is speculated that NS cores may be composed of deconfined quark matter (QM). Using state-of-the-art inputs from multi-disciplinary physics (like the chiral effective field theory, astrophysical observations, and perturbative quantum chromodynamics), we impose new constraints on the widely-accepted phenomenological MIT Bag for deconfined QM in NSs and comment on the phase of matter in NS cores. We include strong interactions to the first order and allow for a mixed phase to model the system realistically. It is known that if this deconfined QM is more stable than ordinary nuclear matter, a hypothesis known as the strange quark matter (SQM) hypothesis, such a phase transition would further lead to the formation of exotic compact objects known as Strange Stars (SSs). We demonstrate that the future next-generation gravitational wave (GW) detectors hold the potential to distinguish SS from NSs using simultaneous f-mode and tidal deformability measurements and can settle the long-standing problem in physics concerning the true ground state of matter.

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Properties of H particle-admixed compact star

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We explore the potential manifestation of a hexaquark, the H particle, as a constituent within neutron stars.
The H particle, characterized by a quark composition of ,
is constructed using the framework of Chromomagnetic Interaction (CMI).
Specifically, we contemplate the flavor-singlet state H with .
Our computations indicate that the three-flavor hexaquark state, the H particle, possesses a lower mass of in comparison to the ,
implying greater stability than the two-flavor .

The analysis involving the H particle is carried out using
the relativistic mean-field (RMF) model.
We investigate the influence of H particle couplings,
a key factor in determining the system stability,
and focus on the potential existence of H particle within neutron stars.
We find that H particle could potentially endure as a stable constituent within neutron stars, and lead to a reduction of the maximum mass.

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3D Pion crystal from the chiral anomaly

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Including the effects of the chiral anomaly within Chiral Perturbation Theory at finite baryon chemical potential, it has been shown that neutral pions form an inhomogeneous phase dubbed the "Chiral Soliton Lattice" (CSL) above a certain critical magnetic field that could possibly be reached in magnetars and heavy-ion collisions. Beyond a second critical field, the CSL becomes unstable to fluctuations of charged pions, implying they condense. I will point out the similarity of this second critical field to the upper critical magnetic field in conventional type-II superconductors, suggesting that an inhomogeneous superconducting charged pion phase exists beyond this point. Applying similar methods originally used by Abrikosov, I will present results where we've constructed such a phase, and show the region where it is preferred in the baryon chemical potential-magnetic field phase diagram at zero temperature. This new phase has a non-zero baryon number density which is periodic in all three spatial dimensions.

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Baryonic Vortex and Magnetic Field Generation

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We propose a vortex carrying baryon number in low energy dense QCD with finite baryon and isospin chemical potentials. The isospin chemical potential is responsible for the charged pion condensate, among which Abrikosov vortex could arise with quantized magnetic flux. Our discovery is that when the winding of neutral pion is added, such a vortex carries a baryon number conserved by the homotopy of Skyrmion. Then the energy is reduced by a finite baryon chemical potential through the gauged Wess-Zumino-Witten term. As a result, we reveal that at high baryon density, a baryonic vortex state features energy lower than the homogeneous pion condensates. Such a vortex bears a self-generated magnetic field indicating applicable scenarios among Magnetar cores.

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IAC meeting

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Progress and open questions in core-collapse supernova theory

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I will outline the current status of core-collapse supernova (CCSN) theory, and then introduce some proposed strategies of how the theory can be tested from multi-messenger observations. After underlining the recent progress, I summarize remaining questions on some microphysical aspects of CCSN theory, paying a special attention to neutrino quantum kinetics or self-induced neutrino flavor conversions.

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Parity violation of the weak interaction and supernovae

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Neutrinos play essential roles in the evolution of core-collapse supernovae. However, the conventional neutrino kinetic theory violates the basic tenet of low-energy effective theories in that it does not respect the symmetry (or parity violation) due to the chirality of neutrinos. In this talk, we discuss the formulation of the chiral radiation transport theory for neutrinos with parity violation and its applications to the physics of supernovae and neutron stars.

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Constraints on dark matter mass-momentum space in light of GW170817 data

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We investigate the effects of dark matter (DM) on neutron star (NS) properties using the relativistic mean-field (RMF) theory. By integrating a DM model, we analyze how DM parameters, specifically DM mass and Fermi momentum, influence nuclear saturation properties, the equation of state (EoS), and the mass-radius relationship of NSs. Our research also examines the universal relation between dimensionless tidal deformability and compactness in the presence of DM. The inclusion of DM significantly alters nuclear saturation properties, resulting in higher incompressibility and symmetry energy values. Higher DM Fermi momenta and masses lead to more compact NS configurations with reduced radii and lower maximum masses, indicating a complex interplay between DM and nuclear matter. Deviations from the universal relation are observed, notably for NSs with lower compactness. Using observational data from PSR J0740+6620, GW170817, and NICER measurements of PSR J0030+0451, we derive stringent constraints on the DM parameter space within NSs. Our findings highlight the necessity of considering DM effects in NS modeling and suggest potential refinements to current theoretical frameworks to accurately predict NS properties under various astrophysical conditions. Future work will focus on further refining these models and exploring additional observational data to tighten constraints on DM properties. Furthermore, we acknowledge the importance of investigating potential decay processes of DM particles and their implications for stellar evolution.

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Gravitational waves from the quark-hadron phase transition

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It is believed that de-confined quark matter is more energetically stable than hadronic matter at extreme densities, such as those occurring in neutron stars. We thus believe that an explosive phase transition between hadronic and quark matter can occur in neutron star cores. Past studies have shown that the interface between hadronic and quark matter can develop wrinkles as the phase transition proceeds outward from the core. These wrinkles could cause gravitational wave emission. This project aims to model that gravitational wave signal using full general relativity.

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quasi normal oscillations in newly born compact star considering effects of phase transition

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The massive stars end their lives by supernova explosions, leaving central compact objects that may evolve into neutron stars. Initially, after birth, the star remains hot and gradually cools down. We explore the matter and star properties during this initial stage of the compact stars, considering the possibility of the appearance of deconfined quark matter in the core of the star. Nonradial oscillation in the newly born compact object is highly possible at the initial stage after the supernova explosion. Non-radial oscillations are an important source of GWs. There is a high chance for GWs from these oscillations, especially the nodeless fundamental (f-) mode, to be detected by next-generation GW detectors. We study the evolution in frequencies of non-radial oscillation after birth, considering the effects due to the presence of deconfined quark matter and predicting the possible signature for different possibilities of theoretical compact star models.

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On the ejecta properties of binary quark star or quark star-black hole mergers

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The Bodmer-Witten conjecture proposes that strange quark matter (SQM) is the true ground state of strong interaction matter, suggesting that self-bound strange quark stars could be the physical nature of all compact stars. However, distinguishing between quark stars and neutron stars remains challenging with current astronomical observations. In this talk, I will explore the properties of the ejecta coming from binary quark star or quark star-black hole mergers and compare these properties to those from binary neutron star mergers.

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Nucleosynthesis with Quark nugget

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During the binary quark star merger, segment quark nuggets could be ripped out. The emission of neutrons and protons from quark nugget makes the environment differ from the standard binary neutron star merger. When temperature drops below 1 MeV, the nucleosynthesis path will be different compare with the well-know r-process nucleosynthesis in binary neutron star merger. here in this talk, I will present the preliminary results on the nucleosynthesis that include the quark nuggets evaporation and some distinguishable results from the r-process yields.

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New alternatives of compact stars and related gravitational-wave signatures

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Due to the nonperturbative QCD dynamics in the density regime of neutron stars, new alternatives of strong matter and related stellar
structure are possible. Recently, we proposed that up-down quark stars, inverted hybrid stars, hybrid strangeon stars can possibly exist, based on the hypothesis that either quark matter or strangeon matter is the ground state of bulk strong matter. They can meet various astrophysical constraints on masses-radii and tidal deformabilities, some with distinct gravitational-wave signatures that may help their discriminations in future observations.

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Neutron Star in Covariant f(Q) Gravity

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In this study, we investigate the structure of neutron stars within the framework of covariant gravity, an extension of general relativity that incorporates non-metricity. By adopting a static and spherically symmetric metric with perfect fluid matter, we derive the modified Tolman-Oppenheimer-Volkoff (TOV) equations specific to three models: quadratic, exponential, and logarithmic. We analyze the structure profiles and properties of neutron stars, such as mass, radius, and compactness, by employing realistic equations of state (EoS) for nuclear matter. Our results indicate deviations in the mass-radius relationship of neutron stars when compared to predictions from general relativity, suggesting that non-metricity affects the interior profile of the star. We also demonstrate how diagrams are compatible with observational constraints from NICER and LIGO.

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Investigating ultra-high-density equations of state through gravitational waves from binary neutron stars mergers

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After an introduction to the status of the field, I present our results on how to discriminate equations of state with a quark-hadron crossover with respect to EOSs with purely hadronic matter or with a first-order quark-hadron transition through gravitational waves emitted in binary neutron star mergers.

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g-mode oscillations in neutron stars with hyperons

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A common alternative to the standard assumption of nucleonic composition of matter in the interior of a neutron star is to include strange baryons, particularly hyperons. Any change in composition of the neutron star core has an effect on g-mode oscillations of neutron stars, through the compositional dependence of the equilibrium and adiabatic sound speeds. Using a variety of relativistic mean field models of dense matter that satisfy observational constraints on global properties of neutron stars, we predict a sharp rise in the g-mode frequencies upon the onset of strange baryons. Should g-modes be observed in the near future, their frequency could be used to test the presence of hyperonic matter in the core of neutron stars.

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Supernova gravitational waves and protoneutron stars

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Supernova gravitational waves are potentially the next candidates to those from the compact binary mergers. The gravitational waves generally depend on the supernova models, such as the progenitor mass and equation of state (EOS) for a higher-density region. So, even if one succeeds in detecting them in the future, it may be difficult to directly extract physical information from them. Up to now, the supernova gravitational waves have mainly been studied via numerical simulations. From such simulations, the gravitational wave signals are shown, whose frequencies increase from a few hundred hertz to kilo-hertz. On the other hand, the origin of this signal has been unclear. To understand the gravitational wave signals appearing in numerical simulations, we are studying them with the approach of asteroseismology. In particular, using the numerical data of simulations we prepare the protoneutron star models and determine the specific oscillation modes on each time step. Then, we successfully identify the gravitational wave signals that come from the fundamental oscillations of protoneutron stars. In this talk, we also show the recent progress in supernova gravitational waves with asteroseismology.

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Long term evolution of binary neutron star merger and nucleosynthesis

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The merger of two neutron stars can form a system composed of a central object (either a neutron star or black hole) and a centrifugally supported disk. Inside the disk, magnetorotational instability generates a turbulent state, which then induces an effective viscosity. The viscous angular momentum transport and heating can evolve the system and trigger mass ejection from the disk on a timescale of seconds. The post-merger mass ejection contributes to the total ejecta in addition to the violent merger phase and to shaping the abundance pattern of heavy nuclei produced via the r-process. In this talk, I will present the results of our numerical simulations of such systems and their implications.

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Damping of density oscillations from bulk viscosity in quark matter

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We study the damping of density oscillations in the quark matter phase that might occur in compact stars. To this end we compute the bulk viscosity and the associated damping time in three-flavor quark matter, considering both nonleptonic and semileptonic electroweak processes. We use two different equations of state of quark matter, more precisely, the MIT bag model and perturbative QCD, including the leading order corrections in the strong coupling constant. We analyze the dependence of our results on the density, temperature and value of strange quark mass in each case. Our results suggest that bulk viscous damping might be relevant in the post-merger phase after the collision of two neutron stars if deconfined matter is achieved in the process.
We also reviewed the value of the bulk viscosity in different quark matter phases.

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Study of correlations of nuclear saturation properties and neutron star f mode oscillations from a machine learning

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We investigate the intricate relationships between the non-radial
⊠ mode oscillation frequencies of neutron stars (NS)s and the corresponding nuclear matter equation of state (EOS) using a machine learning (ML) approach within the ambit of the relativistic mean field (RMF) framework for nuclear matter. With two distinct parameterizations of the Walecka model, namely, (1) with non-linear self interactions of the scalar field (NL) and, (2) a density dependent Bayesian model (DDB), we perform a thorough examination of the ⊠ mode frequency in relation to various nuclear saturation properties. The correlations between the ⊠ mode frequencies and nuclear saturation properties reveal, through various analytical and ML methods, the complex nature of NSs and their potential as the cosmic laboratory for studying extreme states of matter. A principal component analysis (PCA) has been performed using mixed datasets from DDB and NL models to discriminate the relative importance of the different components of the EOS on the ⊠ mode frequencies. Additionally, a {\it Random forest feature importance} analysis also elucidates the distinct roles of these properties in determining the ⊠ mode frequency across a spectrum of NS masses. Our findings are further supported by symbolic regression searches, yielding high-accuracy relations with strong Pearson coefficients and minimal errors. These relations suggest new methodologies for probing NS core characteristics, such as energy density, pressure, and speed of sound from observations of non-radial ⊠ mode oscillations of NSs.

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Probing the QCD phase structure with heavy-ion collisions

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I will discuss the recent developments for the analysis of QCD phase structure with heavy-ion collisions with an emphasis on the QCD critical point search with event-by-event fluctuations. I will discuss the dynamical description of proton number cumulants and put these results in the context of new STAR data from phase II of Beam Energy Scan.

110

The energy budget of fast radio burst: Quake from pulsar-like compact star

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With a growing sample of fast radio bursts (FRBs), we investigate the energy budget of different power sources within the framework of magnetar starquake triggering mechanism.
During a starquake, the energy can be released in any form through strain, magnetic, rotational, and gravitational energies.
{\bf The strain energy can be converted from other three kinds of energy during starquakes.
The following findings are revealed:
1. The crust can store free magnetic energy of erg by existing toroidal fields, sustaining bursts with frequent starquakes occurring due to crustal instability.}
2. The strain energy develops as a rigid object spins down, which can be released during a global starquake accompanied by a glitch. However, it takes a long time to accumulate enough strain energy via spindown.
3. The rotational energy of a magnetar with can match the energy and luminosity budget of FRBs.
4. The budget of the total gravitational energy is high, but the mechanism and efficiency of converting this energy to radiation deserve further exploration.

111

The status of the Compressed Baryonic Matter experiment at FAIR

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The Compressed Baryonic Matter (CBM) experiment is currently under construction at the Facility for Antiproton and Ion Research (FAIR).
Its goal is to explore the phase structure of strongly interacting (QCD) matter at high net-baryon densities and moderate temperatures through heavy-ion
and hadron collisions in the energy range of \sqrt{s_{NN}} = 2.9 - 4.9 GeV using the SIS100 beams.
As a fixed-target experiment, CBM is equipped with fast, radiation-hard detector systems and an advanced trigger-less data acquisition scheme.
CBM will operate at interaction rates of up to 10 MHz by performing online space-time reconstruction and event selection,
enabling the measurement of production rate as well as flow of probes such as multi-strange hadrons and their antiparticles, multi-strange hypernuclei,
and di-leptons, which have not been extensively studied so far.
This presentation will provide an overview of the CBM physics goals, including the investigation of the equation-of-state of compressed nuclear matter,
the potential phase transition from the hadronic to the partonic phase, and chiral symmetry restoration. Experimental data obtained by CBM will have potential to verify
theoretical description of compressed hadronic matter, which is expected to dominate in interior of the compact stars.
The presentation will cover CBM's physics performance in areas such as (multi-)strange particle production, di-lepton spectroscopy and flow phenomena.
Additionally, the status of preparations for CBM's construction will be reviewed, including performance
evaluations of CBM components in FAIR Phase-0 experiments and the latest results from a CBM demonstrator test setup operating with SIS18 beams (mCBM).

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The low-density EoS under core-collapse supernova and heavy-ion collisions conditions

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Light (e.g. deuterons, tritons, helions, particles) nuclei exist in nature in core-collapse supernova matter and neutron star (NS) mergers, where temperatures of the order of 50 to 100 MeV may be attained. These clusters not only form in these astrophysical sites, but also in heavy-ion collisions. The appearance of these clusters can modify the neutrino transport, and, therefore, consequences on the dynamical evolution of supernovae and on the cooling of proto-neutron stars are expected. However, a correct estimation of their abundance implies that an in-medium modification of their binding energies is precisely derived.

In this talk, we will address the low-density equation of state with the inclusion of light clusters. We will consider not only from the theoretical point of view how these light clusters are calculated for warm nuclear matter in the framework of relativistic mean-field (RMF) models with in-medium effects, but also how these models were calibrated to experimental data from heavy-ion collisions, measured by the INDRA Collaboration.

We will also analyze the effect of including an exotic state state, such as the tetraneutron, that was reported in Duer et al, Nature 606, 678 (2022) as a resonant state, on the yields of the other light clusters. We consider in-medium effects in a two-fold way –that is, via the couplings of the clusters to the mesons, that were calibrated to the experimental data, and via a binding energy shift –to compute the low-density equation of state (EoS) for nuclear matter at finite temperature and fixed proton fraction. We calculate the abundances of the light clusters and chemical equilibrium constants with and without the tetraneutron. We also analyze how the associated energy of the tetraneutron would influence such results.

We find that the low-temperature, neutron-rich systems are the ones most affected by the presence of the tetraneutron, making NSs excellent environments for their formation. Moreover, its presence in strongly asymmetric matter may increase the proton and particle fractions considerably. This may have an influence on the dissolution of the accretion disk of the merger of two NSs.

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Polarization of thermal dilepton radiation in high-energy heavy-ion collisions

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Dileptons are one of the most precise probes of the QCD phase diagram in high-energy heavy-ion experiments. Traversing the fireball undisturbed they yield information about the entire space-time history of the collision. Over the last decade, a rather consistent picture has emerged in interpreting the observed inclusive dilepton spectra over a wide range of collision energies. Polarization observables can further elucidate the microscopic emission processes, as they provide independent tests of the longitudinal and transverse components of the virtual photon's selfenergy. In this talk, I will present theoretical predictions of these observables based on a realistic model for the in-medium electromagnetic spectral function. Comparisons to available data from the HADES and NA60 experiments are discussed. They set stage for quantitative polarization studies at FAIR and collider energies in the future.

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Strangeon matter: from stars to nuggets

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We draw an analogy between the materials condensed by the strong interaction (i.e., strong matter) and that by the electromagnetic force (simply, electric matter), both of which are condensed matters with almost continues mass spectrum, if Nature favors the quark-flavor symmetry. While strangeon stars could be manifested in the form of pulsar, gamma-ray bursts and fast radio bursts, strangeon nuggets would be a dark matter candidate in the standard model of particle physics. Observational evidence for strangeon matter is discussed.

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Identifying Viable Inhomogeneous Chiral Phases for Neutron Star Matter

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Spatial inhomogeneous phases of nuclear and quark matter are a feature of the QCD Phase Map at intermediate densities/low temperatures, making them potential candidates for the inner phases of neutron stars. Yet, single-modulated chiral condensates, even when energetically favored over others at zero temperature, are wiped out by thermal fluctuations due to the Landau-Peierls instability. In this work, we discuss a general approach based on simple symmetry arguments to identify a set of single-modulated inhomogeneous chiral phases that can be robust against thermal fluctuations at temperatures compatible with those of neutron stars.

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Effects of charge neutrality and beta equilibrium on the magnetic dual chiral density wave phase in dense QCD

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Recent work has suggested that the magnetic dual chiral density wave (MDCDW), an inhomogeneous condensate that arises in dense QCD in a magnetic field, is an appealing candidate phase for the description of matter in the core of compact stars. For example, the nontrivial topology in its fermion spectrum gives it a high critical temperature and allows it to avoid the Landau-Peierls instability, which destabilizes most other inhomogeneous phases at finite temperatures. However, previous studies have not yet examined this phase under the conditions of charge neutrality and beta equilibrium, which more realistically reflect the environment within compact stars. We are investigating charge neutral, beta equilibrated MDCDW, determining how these conditions affect the order parameters and critical temperature. We also examine the effects of neutrality and beta equilibrium on the small but nonzero remnant mass that persists at large densities in a magnetic field, which may lead to interesting chiral transport behavior.

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Limiting phase transition scenarios in NSs: challenges and opportunities

Since the discovery of a two-solar-mass pulsar back in 2010, the field of neutron-star physics has been revolutionized along with great progress in the theory and modeling of strongly-interacting matter at supra-nuclear densities. In this talk, I will focus on the implications for limiting viable scenarios of high-density hadron-to-quark phase transitions in the inner cores of neutron stars, with the aid of multi-messenger astronomy and theoretical calculations of the low-density matter. Future prospects with more advanced microphysics input as well as upgraded facilities with better sensitivity will be discussed.

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Sound velocity peak driven by chiral partners in dense two-color QCD

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Recently the lattice simulation in two-color QCD at finite density clarified that the squared sound velocity cs2 exceeds the conformal limit 1/3 . We know that at mu -> infinity the conformal limit is realized, thus, a peak structure was numerically observed. Theoretically, on the other hand, the ChPT is known to predict a monotonic increment of cs2 to yield cs2 -> 1 at sufficiently dense regime, and fails in deriving the peak. In this talk, I will show that, based on our linear sigma model in dense two-color QCD, chiral-partner contributions from sigma meson can successfully lead to the peak structure.

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Phase diagram of QCD matter with magnetic field: domain-wall Skyrmion chain in chiral soliton lattice

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Impact of first-principles calculations on the QCD phase diagram and equation of state

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We compare two first-principles calculations of the QCD equation of state (EOS): the weak-coupling results and the recent lattice QCD data at finite isospin density.
Because both finite-baryon-density QCD and finite-isospin-density QCD have the same weak-coupling expansion, we can learn about the former case from the latter, in which the lattice data is available, and in this talk, we particularly discuss the effects on (1) the QCD phase diagram and (2) the EOS of neutron star matter.
Firstly, the weak-coupling results give a small (~ a few MeV) value for the color-superconducting gap at quark chemical potential of a GeV order and this implies that the color-flavor locked phase may not be the ground state even in the perturbative regime of QCD.
Secondly, we discuss the weak-coupling results as the input to the EOS inference for neutron stars. In such weak-copuling input, there is an undetermined constant (the renormalization scale), which gives rise to a large uncertainty. We introduce a new prescription to reduce the ambiguity in

the choice of the renormalization scale and discuss its relevance to neutron-star phenomenology.

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Emulating neutron stars with dipolar supersolids

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In physics, analogies are extremely powerful tools. They give the opportunity to look at physical phenomena from different perspectives, favoring connections between very disparate research fields. In a recent work, we established an intriguing analogy between the inner crust of neutron stars and ultracold dipolar supersolids and used it to investigate the anomalies in the rotation frequency of neutron stars, known as glitches.

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Exploring dense QCD through hamiltonian lattice simulations in (1+1) dimensions

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We study one-flavor SU(2) and SU(3) lattice QCD in (1+1) dimensions at zero temperature and finite density using matrix product states and the density matrix renormalization group. We compute physical observables such as the equation of state, chiral condensate, and quark distribution function as functions of the baryon number density. As a physical implication, we discuss the inhomogeneous phase at nonzero baryon density, where the chiral condensate is inhomogeneous, and baryons form a crystal. We also discuss how the dynamical degrees of freedom change from hadrons to quarks through the formation of quark Fermi seas.

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Opening

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Heavy Hadron Spectroscopy and Quark Confinement in the Quark Model

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I will discuss how multi-quark system confines quarks and propose a new string-type confinement for heavy-tetra-quark systems. It is tested by the fully-heavy tetra-quark (cc c-bar c-bar) system.

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Registration

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New alternatives of compact stars and related gravitational-wave signatures (online)

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Due to the nonperturbative QCD dynamics in the density regime of neutron stars, new alternatives of strong matter and related stellar structure are possible. Recently, we proposed that up-down quark stars, inverted hybrid stars, hybrid strangeon stars can possibly exist, based on the hypothesis that either quark matter or strangeon matter is the ground state of bulk strong matter. They can meet various astrophysical constraints on masses-radii and tidal deformabilities, some with distinct gravitational-wave signatures that may help their discriminations in future observations.

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Award and closing

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Opening