Neutron Stars, Gravitational Waves and the QCD equation of state

October 3, 2019

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Abstract

The behavior of strongly interacting matter at high density is one of the main open questions in both theoretical and experimental physics. New data are available or are soon expected from a wide range of observations, from the gravitational observation of binary neutron star mergers to heavy-ion collision experiments. The holographic gauge/gravity duality is a powerful tool to describe strongly coupled systems, and it provides an effective theoretical tool to model dense QCD matter. We plan to bring together aspects of gauge/gravity duality, quantum field theory and neutron star physics and we aim at developing realistic holographic models of the dense QCD medium. These will be used to address the neutron star equation of state, the QCD phase diagram and non-equilibrium properties at finite density and their manifestation in gravitational wave and electromagnetic neutron star merger signals as well as coming relevant collider experiments like FAIR and NICA. They may be also used to probe the anthropic solution to the cosmological constant problem

1 Overview

Gravitational wave detection offers a new tool to investigate strongly interacting matter in extreme conditions, such as those found in neutron stars. We will investigate aspects of high density systems in strongly coupled gauge theories, specifically but not limited to their description using gauge/gravity duality. This is a topic of interest for a broad community of scientists, working on high energy physics, nuclear physics, astrophysics and string theory.

On the observational side, new information about nuclear matter at high densities and the phase diagram of the underlying microscopic theory, Quantum Chromodynamics (QCD), is expected to be collected in the next few years from both astrophysical observations and heavy ion collisions experiments like FAIR and NICA.

On the theoretical side the situation is challenging. The new regions of the QCD phase diagram which will be explored are beyond the regime of validity of effective field theory descriptions. While lattice analysis can be used at zero density, we also lack a first-principles approach in field theory that works at strong coupling and nonzero density. A different approach is sorely needed to scrutinize the incoming observations and experiments.

In contrast to usual field theory methods, gauge/gravity duality is a very well suited framework to study strongly coupled theories at finite density, and more generally in dynamical contexts. Very recent progress in this direction aims at making contact with the new observations and experiments.

This line of research will be one of the goals of the next few years within the APC theory group, which can count on experts in the gauge/gravity duality and its application to QCD. The strong presence in APC of members of the LIGO/VIRGO collaboration will allow direct contact with experiment.

2 Dense strongly interacting matter: observational and theoretical status

2.1 New observations and experiments

The LIGO and Virgo collaborations reported in 2015 the first observation of gravitational waves from binary black hole mergers. As witnessed soon thereafter, gravitational wave observatories are also able to detect signals from mergers of binary neutron star systems.

The properties of the gravitational wave signal depend on the equation of state (EOS) of matter in the neutron star. The first observation of a neutron star merger in August 2017 [1] only included the inspiral phase, but was still enough to rule out some of the stiffest EOS. Future observations are expected to lead to significantly improved constraints. Observing the gravitational wave ringdown after the merger would provide much more detailed information on the EOS even at finite temperature and neutron star structure, but requires greatly improved sensitivity at high frequencies. The dynamical evolution of the hot massive merger remnant will also depend on out-of-equilibrium properties such as transport coefficients. The gravitational wave signal will thus provide invaluable information about the properties of dense nuclear matter in and out of equilibrium in the future.

Other observations can constrain the Neutron Star (NS) structure, too. The main present constraint on the EoS stems from the measurements of two very massive NSs in radio pulsar/white dwarf systems which have been reported with high precision. In addition, there is much effort in measuring neutron star radii, e.g. with the project NICER launched in June 2017. Current standard techniques to determine NS radii rely on *i)* spectroscopic measurements of accreting neutron stars in quiescence or *ii)* on the study of thermonuclear (type I) X-ray bursts, or *iii)* timing observations of surface inhomogeneities of rotating stars. Another possibility might be to determine the moment of inertia for a NS with well known mass as planned by the SKA. All current measurements have large systematic uncertainties, but are expected to become more accurate in the future, setting direct constraints to the mass radius curves of the neutron stars and therefore to the EOS of cold QCD matter.

Another way to probe the neutron star structure are glitches, i.e., small irregularities in the rotation frequency of the stars. The glitches have been argued to reflect superfluidity inside neutron stars, giving a coherent qualitative picture. However, more than 50 years after the first detection of glitches, a quantitative model is still lacking and the detailed mechanism explaining the large variety of observed glitches are still unknown. Improved theoretical understanding of the glitches together with new dedicated observations (e.g. UTMOST, SKA) may help to obtain further information on the neutron star structure in the future. Neutron star cooling is very sensitive to NS structure, too, as well as oscillations, potentially observable via asteroseismology or gravitational waves.

In addition to indirect information through gravitational wave interferometry, a wide range of new data from heavy-ion collision experiments will be available. The ongoing experiments at LHC and RHIC will continue to explore the hydrodynamics of the Quark-Gluon plasma. The Beam Energy Scan program at RHIC will soon enter its second phase, and will provide precision results into the region of high temperature and low to intermediate chemical potential of the QCD phase diagram. The future experiments at the FAIR and NICA facilities (currently under construction) will probe higher values of the chemical potential, into the regime relevant for neutron star physics. With this experimental information,it will be possible to have a precise idea of the QCD and hadronic matter phase diagram, critical points and phase transitions.

2.2 Problems in finite density QCD

At asymptotically large densities, QCD becomes weakly coupled and perturbative methods are applicable. However, uncertainties in the perturbative calculation become very large around values of the quark chemical potential of the order of 1 GeV, two to three times higher than those explored in heavy ion collision experiments or realized in the interior of neutron stars.

For small values of the chemical potential, Lattice QCD can be used outside the weakly coupled regime to predict the properties of the QCD phase diagram. However, for large densities it suffers from the notorious sign problem that impedes the usual importance sampling and Monte Carlo methods. Alternative methods that try to circumvent the sign problem, such as the complex Langevin approach, have their own issues and have not succeeded so far in providing reliable non-perturbative results.

At low temperatures, Chiral Effective Field theory fitted to nuclear physics experiments works well below the saturation density of nuclear matter. However, it breaks down in the regions of the phase diagram corresponding to densities reached at the interior of the neutron stars or close to the critical point.

In the absence of reliable methods at densities present in neutron star cores, the typical approach to estimate the equation of state is by interpolating between known results at smaller and larger densities. This leaves, however, significant uncertainties to the EOS even after applying all known experimental constraints. Moreover, this give no information on transport coefficients, relevant for dynamical processes.

3 Gauge/gravity duality and dense QCD matter

A promising alternative approach to the non-perturbative description of dense QCD matter is the *gauge/gravity duality,* or *holographic correspondence,* the conjectured equivalence between a strongly coupled, large-N quantum gauge theories, and a gravitational theory in a higher-dimensional curved space-time [2]. Although the original formulation of the conjecture was within the context of supersymmetric field theories, the holographic approach has been often used as a tool to model the phenomenology of non-perturbative phenomena of non-susy field theories. It is also believed that qualitatively, and up to small corrections, many features of QCD with three colors are essentially captured in the large-N limit. In this limit, and at strong coupling, the gravity dual theory is described by two-derivative, classical gravity coupled to other fields. It is therefore possible, given the gravity dual, to compute quantities in strongly coupled QCD by a relatively simple classical calculation. The goal is then to construct an appropriate gravity dual theory which can describe properly QCD at high density.

3.1 Phenomenological models for strongly interacting matter

The basic tool to model QCD by a holographic dual is a theory in curved-spacetime which contains dynamical gravity (which may be ten-dimensional string theory, or more phenomenologically, a lower-dimensional Einstein gravity theory) coupled to at least one scalar field dual to the Yang-Mills coupling constant [3, 4]. This class of models was shown to accurately reproduce several properties of thermal Yang-Mills theory at strong coupling [5, 6, 7] and in the linear hydrodynamic regime [8].

The dynamics of flavor degrees of freedom is captured by the addition of gauge fields, which can propagate in the full bulk spacetime, or live on the worldvolume of lower-dimensional objects such as D-branes [9]. Non-zero density states can be realized by turning on gauge fields in the gravity dual. The phase diagram as a function of temperature, chemical potentials, and magnetic field has been studied with great detail in a few models, and many varied phases have been found, with different patterns of spontaneous breaking of global and space symmetries [10, 11]. Those models include also Higgsed phases similar to the Color-Flavor Locking phases described in perturbative QCD, plausible states of matter in the cores of neutron stars. The techniques to study thermodynamics of all kind of theories with a gauge/gravity dual are well developed and understood, and progress is being made on applications to far-from-equilibrium dynamics.

An obstruction to the application of the gauge/gravity duality to QCD at large density has been the absence of theories that could serve as realistic models, as the most commonly studied have equations of state (EOS) which are too soft. It was believed that models with stiffer EOS could not exist, but it has been recently shown that this conjecture is not true [12]. However, finding theories with realistic EOS is still an open question. Beyond equilibrium, the calculation of quantities using linear response, such as transport coefficients using Kubo formulas, has advanced remarkably. Systematic hydrodynamic expansions have also been carried out to a high degree in a framework called the fluid/gravity correspondence [13]. All these methods can be readily applied to study properties of theories with realistic equations of state at non-zero density.

3.2 Modeling neutron stars

We will aim at improving the holographic modeling of dense QCD and neutron stars beyond the current state of the art by combining expertise from holography and neutron star physics, with input from new experiments.

The first step will be finding holographic models with realistic equations of state for neutron stars. Studies of this type have been recently carried out in [14], in a simplified model (maximally supersymmetric Yang-Mills theory) which is quite far from real QCD. Instead, our starting point the realistic models for holographic QCD developed in [3, 4, 10]. One important aspect of this project will be to give a realistic holographic realisation of baryonic matter, which so far has been a challenging aspect of realistic models, alrhough recently some progress in this direction has been made [15].

We will next determining the phase diagram by studying the competition between different solutions of the gravity dual field equations. In particular, this will address the question whether quark matter may be present in the interior of stars and whether the gauge/gravity duality could describe other exotic objects such as quark stars, or neutron star "exotic" (e.g. color superconducting) cores.

Compared with other methods, one of the advantages of the gauge/gravity duality approach to dense QCD matter is the possibility to study properties beyond the zero-temperature equation of state: using the gravitational dual description one can obtain the equation of state and phase diagram at finite temperature, as well as the transport coefficients relevant for dense nuclear matter. In particular, we will address the question whether astrophysical simulations can be improved by departing from ideal hydrodynamics.

Finally, much of the work to obtain explicit solutions for the holographic system, both in and out of equilibrium, will have to be performed numerically. Numerical codes for holography are well developed, and this will give the opportunity to investigate the relationship between numerical holography and numerical relativity: what can they learn from each other?

4 Connection with gravitational wave observations

Having realistic holographic models of high-density QCD matter will move us to the next step, namely confronting these models with gravitational wave observation. For this, it will be necessary to use the data obtained from holography to numerically simulate a neutron star merger and obtain the corresponding gravitational wave signal waveform. A preliminary study along these lines was very recently carried out [16], showing the feasibility of this program. In our case, we will improve on this by developing a realistic implementation of baryonic matter, and especially by the implementation of thermal (development of hot spots) and out-of-equilibrium features during the merger phase. For this, the collaboration with members of the LIGO/VIRGO collaboration and with experts in numerical relativity will be of great importance.

5 Using neutron star dynamics to test the anthropic solution to the cosmological constant problem.

It has been argued recently, [17] if the core of neutron stars belongs to a different phase of cold nuclear matter, then observations may test wether the anthropic solution to the cosmological constant problem is valid in nature. The idea is that the presence of a different phase changes the effective value of the cosmological constant and this affects the properties of neutron stars.

This idea needs to be turned into a set of measurable observables and for this a detailed knowledge of the QCD equation of state at finite density is crucial.

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