Connecting Phases of the Strong Force

Thermodynamic phases governed by the strong nuclear force have been linked together using multiple theoretical tools.

By Andreas Schmitt

Quantum chromodynamics (QCD) is the theory of the strong nuclear force. On a fundamental level, it describes the dynamics of quarks and gluons. Like more familiar systems, such as water, a many-body system of quarks and gluons can exist in very different thermodynamic phases depending on the external conditions. Researchers have long sought to map the different corners of the corresponding phase diagram. New experimental probes of QCD—first and foremost the detection of gravitational waves from neutron-star mergers—allow for a more comprehensive view of this phase structure than was previously possible. Now Tuna Demircik at the Asia Pacific Center for Theoretical Physics (APCTP), South Korea, and colleagues at APCTP and at Goethe University Frankfurt, Germany, have put together models originally used in very different contexts to push forward a global understanding of the phases of QCD [**1**].

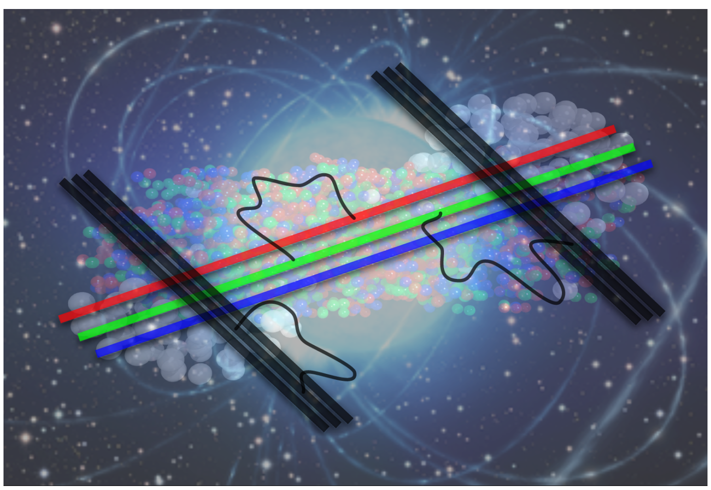

Figure 1: Data from neutron stars and heavy-ion collisions (background) are used to study thermodynamic phases governed by the strong nuclear force. Demircik and colleagues have combined multiple theoretical methods, including string-theory techniques (foreground), to obtain a global view of the phase structure [**1**].
Credit: A. Schmitt/University of Southampton (foreground); ESO/L. Calçada (neutron star); CERN/Henning Weber (heavy-ion collision)

Phase transitions governed by the strong force require extreme conditions such as high temperatures and high baryon densities (baryons are three-quark particles such as protons and neutrons). The region of the QCD phase diagram corresponding to high temperatures and relatively low baryon densities can be probed by colliding heavy ions. By contrast, the region associated with high baryon densities and relatively low temperatures can be studied by observing single neutron stars. For a long time, researchers lacked experimental data for the phase space between these two regions, not least because it is very difficult to create matter under neutron-star conditions in the laboratory. This difficulty still exists, although collider facilities are being constructed that are intended to produce matter at higher baryon densities than is currently possible. However, the past few years have seen progress in the other direction: the detection of gravitational waves reveals information about neutron-star mergers [**2**], and the temperatures reached in such events can be much higher than those in isolated neutron stars—and not far from those in heavy-ion collisions. This new experimental window is a strong motivation to bring together the different theoretical approaches to understand disparate regions of the QCD phase diagram.

The theoretical problem of determining the phase structure of QCD is well defined: scientists know, in principle, how to calculate the properties of statistical ensembles within the rules of quantum field theory. If the energies involved are asymptotically high, quarks and gluons are weakly coupled [**3**, **4**], and techniques based on perturbation theory can be used to this end [**5**, **6**]. However, matter in experimentally accessible conditions is strongly coupled and thus requires other methods that are difficult to implement. For instance, arbitrary coupling strengths can be treated using first-principles methods by evaluating QCD essentially by brute force on a lattice of points in space and time. But this approach cannot be applied to dense matter in neutron stars [**7**]. Therefore, theoretical efforts necessarily resort to less rigorous and less fundamental descriptions, such as effective theories and phenomenological models. Even after giving up some rigor, the various approaches are typically valid only in a certain corner of the phase diagram, for instance, because they work with hadrons—particles containing two or more quarks—rather than deconfined quarks and gluons [**8**].

A relatively novel theoretical tool that has been added to the mix is the so-called gauge-string correspondence [**9**], which is a core ingredient of Demircik and colleagues' work (Fig. **1**). Through the gauge-string correspondence, properties of gauge theories can be calculated in the strongly coupled limit relatively simply by solving classical equations of motion for an equivalent string theory in a higher-dimensional space. The gauge theory of interest is defined on the boundary of the higher-dimensional space, so this approach is also referred to as holography. As an equivalent string theory for the relevant gauge theory—QCD—is not yet known, researchers need to work with theories that share properties with, but are ultimately different from, QCD. An advantage of the holographic model used by Demircik and colleagues is that nuclear matter (at zero temperature) and quark matter (at all temperatures) are treated consistently in the same approach.

Overcoming the obstacles of strongly coupled QCD by combining different theoretical tools is not a new strategy. For instance, in the context of cold and dense matter, models for nuclear and quark matter are often patched together. This construction typically results in the presence of an abrupt (first-order) quark-hadron transition, but it cannot predict whether and at which baryon density such a transition occurs in the real world. Another example involves taking two limiting cases—low-density nuclear matter described using an effective field theory and extremely dense quark matter described using perturbative QCD—and then exploring all experimentally constrained interpolations between them [**10**]. This technique reveals nothing about the microscopic composition of moderately dense quark matter, but it provides a very powerful way to constrain its thermodynamic properties.

The main idea of Demircik and colleagues' work is to take these hybrid methods a step further and attain a global view of the QCD phase diagram. The researchers have combined a holographic model, a low-temperature nuclear-matter description, and a high-temperature hadron-gas model, which all constrain each other through how they are matched. This approach necessarily involves many simplifications and assumptions, and the results depend on the chosen matching procedures. For instance, if a first-order transition is observed between two homogeneous phases, it is natural to ask whether the transition is associated with an inhomogeneous phase—for instance, a mixed phase comprising bubbles of one phase immersed in the other phase forming a periodic structure. In turn, a realistic description of this inhomogeneous phase is needed to check at which temperatures such a periodic structure is broken, similar to the melting temperatures of crystalline structures in solids. In the current study, many of these aspects are treated with simple approximations and improvements will be necessary.

Nevertheless, this work nicely makes the point that, at least in principle, seemingly disparate QCD phenomena can be related. For example, the tidal deformability of a neutron star might inform understanding about a possible critical endpoint in the QCD phase diagram at high temperatures. And the properties of the crossover between quark confinement and deconfinement at zero baryon density could reveal details about a possible quark-hadron transition inside a neutron star.

Current progress in lattice QCD, in effective field theories for nuclear matter, and in perturbative QCD—combined with more data from heavy-ion collisions, isolated neutron stars, and neutron-star mergers—is setting more and more constraints on QCD phases in more and more regions of the phase diagram. Therefore, global approaches, such as that of Demircik and colleagues, are very timely and will be an important tool in future studies to increase understanding of the strong nuclear force.

Andreas Schmitt: Mathematical Sciences and STAG Research Centre, University of Southampton, Southampton, UK

REFERENCES

1. T. Demircik *et al.*, “Dense and hot QCD at strong coupling,” **Phys. Rev. X 12, 041012 (2022).**
2. B. P. Abbott *et al.*, “Properties of the binary neutron star merger GW170817,” **Phys. Rev. X 9, 011001 (2019).**
3. D. J. Gross and F. Wilczek, “Ultraviolet behavior of non-abelian gauge theories,” **Phys. Rev. Lett. 30, 1343 (1973).**
4. H. D. Politzer, “Reliable perturbative results for strong interactions?” **Phys. Rev. Lett. 30, 1346 (1973).**
5. A. Ipp *et al.*, “Pressure of deconfined QCD for all temperatures and quark chemical potentials,” **Phys. Rev. D 74, 045016 (2006).**
6. A. Kurkela *et al.*, “Cold quark matter,” **Phys. Rev. D 81, 105021 (2010).**
7. P. de Forcrand, “Simulating QCD at finite density,” **Proc. Sci. LAT2009 010 (2010).**
8. I. Tews *et al.*, “Neutron matter at next-to-next-to-next-to-leading order in chiral effective field theory,” **Phys. Rev. Lett. 110, 032504 (2013).**
9. J. Maldacena, “The large *N* limit of superconformal field theories and supergravity,” **Adv. Theor. Math. Phys. 2, 231 (1998).**
10. E. Annala *et al.*, “Evidence for quark-matter cores in massive neutron stars,” **Nat. Phys. 16, 907 (2020).**