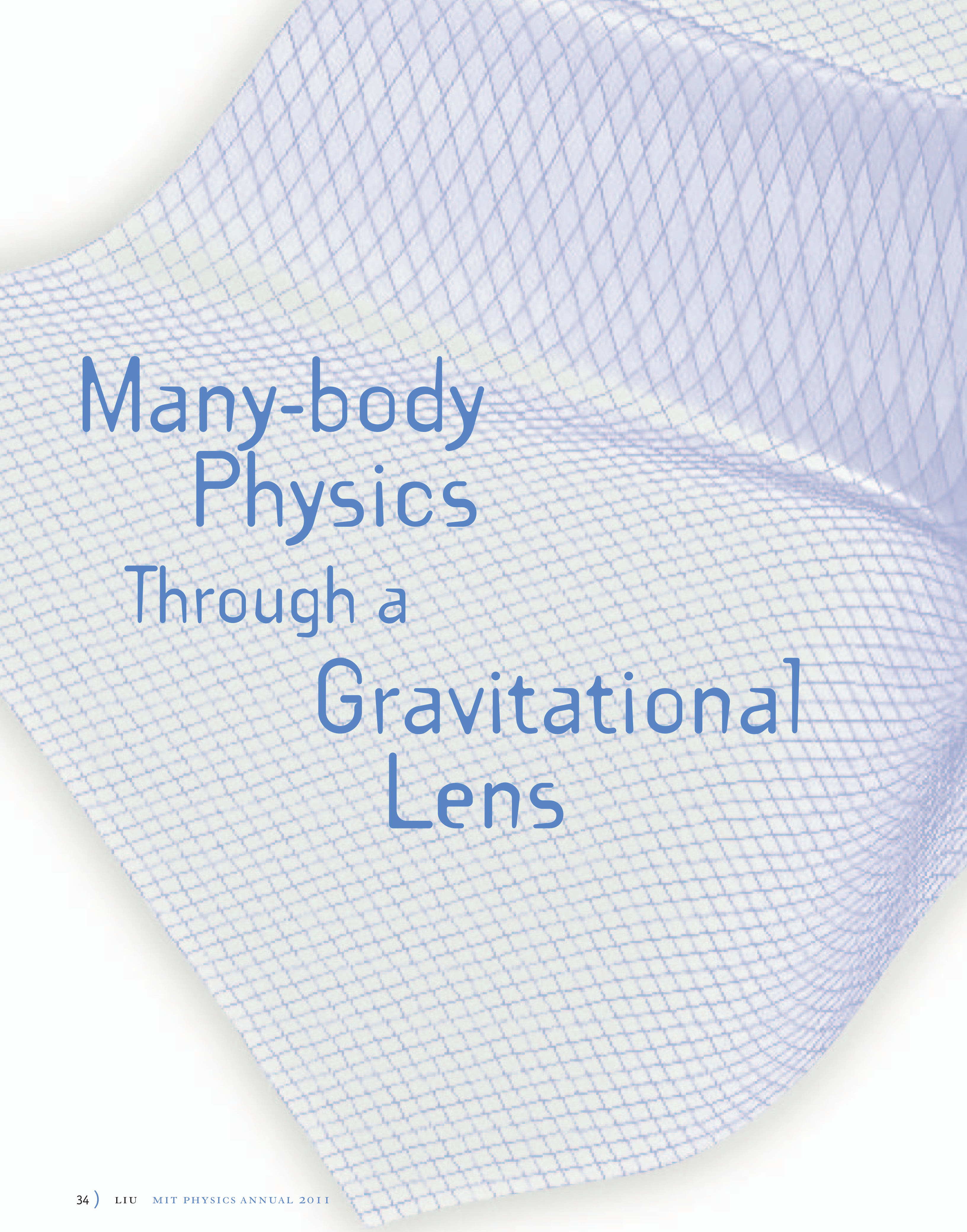
Many-body Physics Through a Gravitational Lens



by **Hong Liu**

The development of physics has largely followed a dichotomy between the frontiers of reduction and emergence. On the one hand, we search for the most fundamental laws that would encompass all phenomena in nature. String theory—an ambitious attempt to marry general relativity and quantum mechanics, and to unify all fundamental interactions—may be considered the epitome of this approach. On the other hand, we also search for new "emergent" principles, arising from the collective behavior of a large number of particles, which cannot be obtained from the simple extrapolation of the dynamics of a few particles. Emergent phenomena are an important theme in almost all areas outside high energy physics, including nuclear and condensed matter physics.

SURPRISINGLY, DURING THE LAST DECADE developments in string theory have shown that these seemingly remote frontiers are in fact fundamentally intertwined. In 1997, Juan Maldacena discovered that certain quantum gravitational systems—string theories—are equivalent to non-gravitational many-body systems defined in spacetimes with one less spatial dimension. [1] This equivalence, known as HOLOGRAPHIC DUALITY, is conceptually startling, with far-reaching implications for our understanding of quantum gravity. It also has practical applications: when the many-body system is strongly coupled, the equivalent string theory reduces to classical gravity and is simple. As a result, difficult questions about strongly coupled many-body systems, which could not be answered with conventional methods, can now be addressed using classical gravity, potentially giving rise to a new paradigm for studying many-body dynamics.

Strongly Coupled Systems

Strongly coupled many-body systems abound in nature, giving rise to some of the most fascinating phenomena in physics, but also presenting some of the most challenging problems. Familiar examples include the liquid state of ordinary matter, such as water. To obtain some intuition regarding strongly coupled systems like liquids, let us first consider a gaseous system such as air. In air, molecules are far apart and intermolecular forces, while present, do not have significant effects on the motion of a particle. In other words, the potential energy due to intermolecular forces is much smaller than the kinetic energy of a particle. It is a good approximation to treat air as an ideal gas of non-interacting particles. The effects of intermolecular interactions can then be incorporated systematically as corrections to the behavior of an ideal gas. The corrections are characterized by a weak "effective coupling," which is the ratio of the potential energy to the kinetic energy of a particle, and are small. In contrast, in a liquid state, which has a much larger density, the potential energy is comparable to a particle's kinetic energy and the motion of a particle is heavily influenced by others around it. In this regime, the effective coupling is not small and corrections to the behavior of an ideal gas are large. This makes it difficult to treat a liquid theoretically. Yet it is precisely this strongly coupled regime that endows a liquid with many special properties that are not shared with gases or solids, including those important for life.

The physics becomes even richer when quantum mechanics comes into play. From the uncertainty principle, the position of a particle has a spread inversely proportional to its momentum, and quantum effects become important when the spread becomes comparable to the average interparticle separation. One fascinating consequence of quantum effects is that a large number of strongly interacting particles can conspire to behave as if the system consists of a gas of weakly-interacting particles, called quasi-particles. One class of such examples is called Fermi liquids. This class includes ordinary metals, which can be regarded as collections of electrons interacting via the repulsion that arises from their electric charges. A quasi-particle carries the same spin and charge as the original electron, but a different mass (sometimes 100 to 1,000 times bigger than the electron mass). By describing the system in terms of the weakly interacting quasi-particles, the properties of a Fermi liquid can be readily understood theoretically despite the potentially strong interactions among the underlying electrons.

Strongly Coupled "Quantum Soups"

While quasi-particles can be a powerful tool for theoretical descriptions, not all strongly coupled quantum systems exhibit quasi-particle behavior. For some systems, the particles (say, electrons) that make up the system can completely lose their individualities due to significant mutual overlap and interactions. As a result, the system behaves as a coherent "quantum soup," with no indication of any particle-like excitations. If an additional electron is added to such a system, then before it can propagate far enough to show its particle-like properties, it will be devoured by the "soup" and "disappear." I will now discuss two examples of such systems, both of which have proven very difficult to understand by conventional methods.

Strange Metals

One example is the electron structure in the strange metal phase of cuprate superconductors. Superconductivity was discovered one hundred years ago by Heike Kamerlingh Onnes when he found that the electrical resistance of mercury suddenly vanished completely when the metal was cooled below 4.2 K (Nobel Prize, 1913). The phenomenon was later found in many other materials, with varying transition temperatures, and would challenge physicists' understanding for almost fifty years. Finally, in 1957, Bardeen, Cooper, and Schrieffer offered a complete microscopic explanation, now known as BCS theory (Nobel Prize, 1972), according to which the transition temperature for a material cannot be greater than 30K. Thus it came as a great surprise when in 1986, Bednorz and Mueller discovered superconductivity in a lanthanum barium copper oxide compound with a transition temperature of 35K (Nobel Prize, 1987), ushering in the era of high temperature superconductors. Since then, many other copper oxide compounds (now collectively called cuprate superconductors or cuprates) were found to be superconducting, with transition temperatures as high as 165K. A precise understanding of the origin of superconductivity in cuprates and why their transition temperatures are much higher than those of ordinary superconductors remains elusive. One major mystery lies in the

Holographic Duality

In holographic duality, a quantum gravity system defined in a (d + 1)-dimensional anti-de Sitter spacetime is equivalent to a many-body system defined on its d-dimensional boundary. Anti-de Sitter spacetime is a curved spacetime of constant negative curvature. It has a radial direction z that runs from 0 to +∞, with a d-dimensional Minkowski spacetime at each constant value of z. z = 0 is the boundary of the whole, or "bulk," spacetime, and is where the many-body system is defined. How can a d-dimensional system be equivalent to a (d+1)-dimensional system? At a heuristic level, the radial direction z in the bulk can be interpreted as corresponding to the size of structures in the boundary many-body system. For example, two objects in the bulk that are identical except for their radial coordinate z correspond in the boundary system to two objects that are identical in all respects except for their size; one can be obtained from the other by magnification. This correspondence, with larger structures on the boundary corresponding to deeper structures in the bulk, is the key to how the boundary system can describe all the physics within the bulk even though it has one dimension less. By analogy, the boundary system is referred to as a "hologram" of the bulk system (since in laser physics a hologram is a two-dimensional representation of a three-dimensional object), and we say that there is a "holographic duality" between the boundary many-body system and the bulk quantum gravity system.

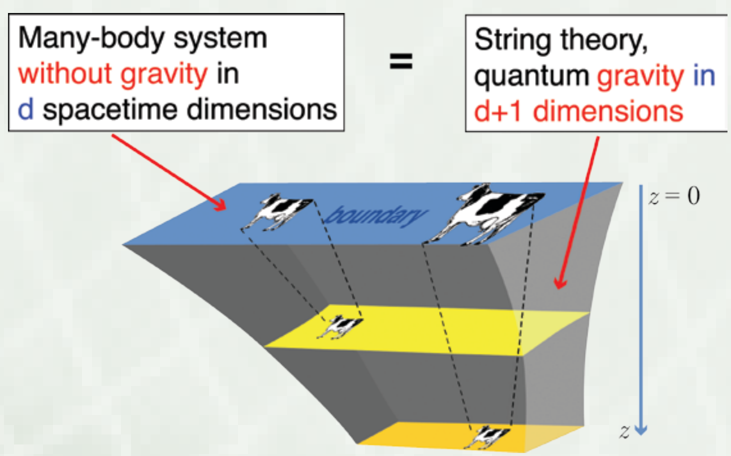


FIGURE I

Black Hole

A black hole is a region of space from which nothing, not even light, can escape. Our understanding of astrophysics, combined with Einstein's theory of general relativity, implies that black holes are ubiquitous; any sufficiently massive object will eventually form a black hole. Classically, a black hole absorbs everything and emits nothing. In 1975, however, Stephen Hawking discovered that quantum mechanically a black hole must radiate like a perfect black body, at a temperature that is inversely proportional to its mass. In fact, a black hole satisfies all the laws of thermodynamics. Thermodynamic properties of a black hole make it a natural object to describe a boundary many-body system at a finite temperature (such as a QGP), or charge density (such as a strange metal), in holographic duality.

phase (called the normal state of a superconductor) just above the transition temperature, from which superconductivity develops. For an ordinary superconductor (which can be explained by BCS theory), the normal state is an ordinary metal, *i.e*, a Fermi liquid. For cuprates, the normal state has been found to have transport properties significantly different from those of an ordinary metal, and has been dubbed a "strange metal." A particularly striking property of a strange metal is that the electrical resistivity increases linearly with temperature, in contrast to the quadratic temperature dependence of an ordinary metal. This remarkably simple behavior is very robust, existing over a wide range of temperatures (sometimes until a material melts), and universal, appearing in all cuprate superconductors. Nonetheless, it has resisted a satisfactory explanation for more than twenty years. Also in contrast with a Fermi liquid, a strange metal does not have any weakly-coupled electron-like excitations, *i.e*, quasi-particles.

Quark-gluon Plasma

Another example is the quark-gluon plasma (QGP) produced by heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory. QGP is a state of matter in which quarks and gluons are not confined inside protons or neutrons, but can freely roam through space. The QGP at RHIC exhibits many surprising properties: it is extremely hot, about 250,000 times hotter than the center of our sun, yet it is close to being a perfect fluid, with a dimensionless measure of viscosity hundreds of times smaller than that of water. It also exhibits a strong quenching of quarks: a high energy quark, even one traveling near the speed of light, would only penetrate on the order of 10^{-15} meters, about the size of a proton. These phenomena cannot be explained using a gas of weakly interacting quarks, gluons, or other quasi-particles, suggesting that the QGP at RHIC is a strongly coupled quark-gluon soup. Since the end of 2010, the Large Hadron Collider (LHC) at CERN started running heavy ion collisions that produce QGP with a temperature roughly twice that of RHIC.

As different as the quark-gluon plasma and a strange metal appear to be, they share the same fundamental feature: these are strongly coupled quantum soups that do not possess particle-like excitations. There is currently no systematic theoretical tool to deal with such systems, and understanding how to do so is one of the most outstanding problems in physics. We will now turn to holographic duality, which provides brand new ideas and techniques for dealing with such systems.

Many-body Physics Through a Gravitational Lens

In holographic duality, certain many-body systems at strong coupling can be described by classical gravity systems in a curved spacetime of one dimension higher, which are solvable. Below, we will refer to such systems as holographic systems. Nature, however, does not give free passes: while many examples of holographic systems are known, real-life systems such as the QGP at RHIC and the electron system underlying the strange metal phase of a cuprate are not among them. Nevertheless, one can ask whether holographic systems can serve as useful models, whether there exist "QGPs" and "strange metals" in these systems sharing properties with real-life systems. In particular, we would like to search for universal characterizations for strongly coupled quantum soups. We are used to the idea that all gases, liquids, and solids have common defining characteristics, even though they may differ very significantly at a microscopic level. Can we find similar defining characteristics for QGPs and strange metals?

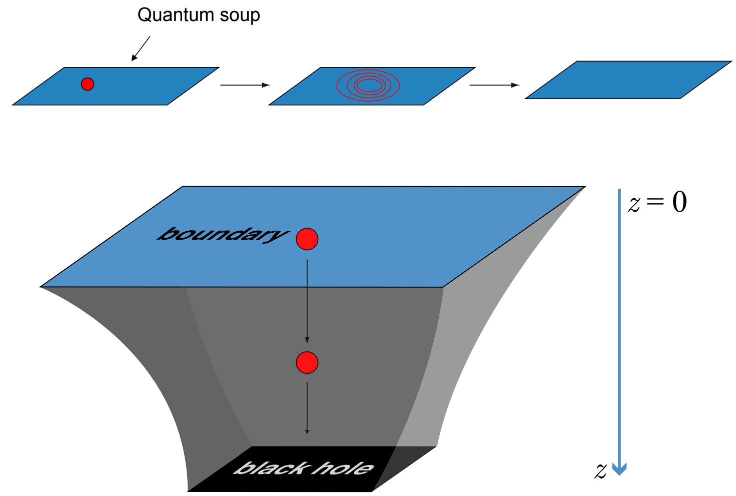


FIGURE 2

(Top) ***When a particle is added*** *to a quantum soup, it will be quickly devoured.*
(Bottom) ***The corresponding gravity picture.*** *A quantum soup is described on the gravity side by a curved spacetime of one higher dimension containing a black hole. Starting from $z = 0$ and going inward along the radial direction, one eventually encounters a black hole no matter where one starts at the boundary. When a particle is added to the quantum soup, in the gravity description, it falls into the black hole before it has time to propagate far enough along the boundary directions to show its particle-like properties.*

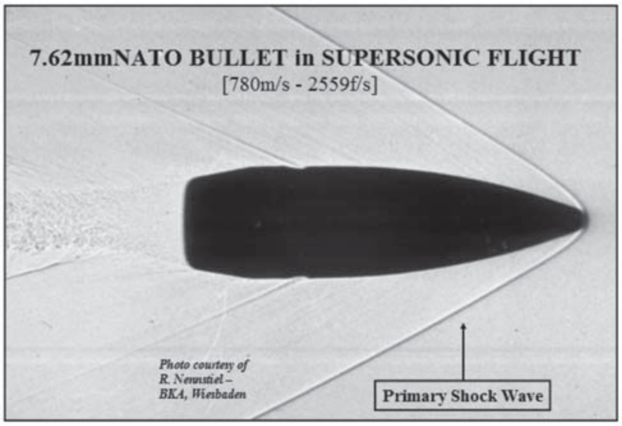
Black Holes as Quantum Soups

It turns out that strongly coupled QGPs and strange metals occur generically in holographic systems, and are related by the holographic equivalence to systems containing black holes. Black holes are known for their simplicity and universality; assuming rotational symmetry, the geometry of a black hole is fully specified by its mass and certain conserved charges such as the electric charge, independent of other details. Moreover, for a given mass, there is a maximal allowed charge. A QGP has almost equal numbers of "quarks" and "anti-quarks," and is described by a black hole of almost zero charge, while a strange metal has only "electrons" but not "positrons," and is described by a black hole of maximal charge. Due to the universality of black holes, holographic QGPs and strange metals have universal properties, independent of the microscopic details of specific systems.

Even though a quantum soup itself does not have any weakly-interacting quasi-particles, its gravity description does contain weakly interacting particles, albeit in a black hole geometry. As a result, dynamical properties of these quantum soups can often be understood from simple features of a black hole. For example, the absence of particle-like excitations in such a system simply follows from the fact that black holes absorb everything (*Figure 2*). The same absorption process can also be used to extract many important physical properties of the many-body system, including its viscosity and conductivity.

Holographic QGPs

It then came as a pleasant surprise that holographic QGPs and strange metals appear to share certain properties of real-life systems. For example, it was found that in all holographic QGPs the dimensionless viscosity (defined by the ratio of viscosity to entropy density) is given by $\frac{1}{4\pi}$. [2] This value is at least an order of magnitude smaller than that of any ordinary matter, including superfluid helium (the value for water is about 50 and for an ideal gas it is infinite), but is rather close to that of the QGP at RHIC, which is less than 0.2. This raises the possibility that a small viscosity may be considered as a defining characteristic of a strongly coupled QGP. Furthermore, thought experiments on "quarks" moving in a holographic QGP show strong quenching, consistent with the QGP of RHIC at both the qualitative and



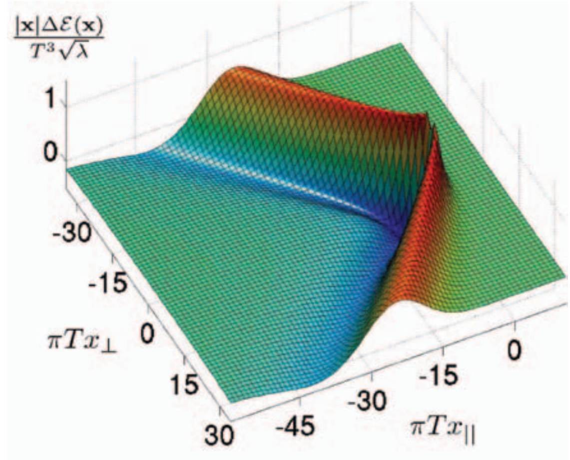


FIGURE 3

(Left) ***Mach cone*** *from a supersonic bullet in water.* (Right) ***The energy density distribution*** *of a supersonic quark moving in a QGP. A Mach cone is clearly visible.* (P. Chesler/MIT and L. Yaffe/University of Washington) [4]

semi-quantitative level. Such "coincidences" boosted the confidence of researchers to make predictions for experiments based on properties of holographic QGPs. Here I mention two examples. The first concerns finding a "smoking gun" to demonstrate that the matter created by heavy ion collisions at RHIC or at the LHC is really QGP. A hallmark of a quark-gluon plasma is that it screens interactions between a heavy quark–antiquark pair immersed in it, just like an electromagnetic plasma screens electric charges. In 2006, Krishna Rajagopal at MIT, Urs Wiedemann at CERN, and I discovered that in a holographic QGP the screening becomes more effective as the velocity of a pair is increased. This behavior is now called the "hot wind effect," because in the rest frame of the quark pair the wind of the passing QGP is seen to weaken their interaction. Based on this observation, we predicted that the production rate of bound states formed from heavy quark–antiquark pairs should be suppressed at large momentum, due to the enhanced probability that the pair will dissociate. [3] This could soon be tested at the LHC.

The second example concerns how a QGP responds to a high energy quark moving through it. When a bullet moves through water (or an airplane through the air) with a supersonic velocity, it excites a hydrodynamic shock wave in the form of a cone, called a Mach cone (*Figure 3, left*). Researchers have been debating for years whether this will happen to a high energy quark moving at supersonic speed through a QGP. Using holographic QGPs, this question has been answered in the affirmative (*Figure 3, right*).

Holographic Strange Metals

Holographic strange metals have also shown properties that bear intriguing resemblance to those of cuprates. For example, consider adding an electron to a strange metal. In cuprates, photoemission experiments showed that the electron would scatter so strongly with its surroundings that it would have already been "devoured" by the electron "soup" before it has time to propagate one wavelength. In a holographic strange metal, the strength of such scatterings can be calculated by considering the absorption of a bulk electron by a black hole. With a specific choice of the bulk electron mass, the scattering rate becomes proportional to the energy of the electron, which agrees with what is seen in cuprates [5]. Furthermore, with the same choice of the bulk electron mass, the electrical resistance of the holographic strange metal is linear in temperature [6], just as it is in cuprates. Recently, graduate students Nabil Iqbal, Márk Mezei, and I argued that holographic strange metals are examples of a universal intermediate-energy phase, which we named a semi-local quantum liquid. [7] The resemblance of holographic strange metals to cuprates hints that the semi-local quantum liquid may underlie the physics of cuprates and possibly other strongly coupled electronic systems.

Concluding Remarks

The black hole description of holographic quantum soups has given us many insights into strongly coupled systems. Heavy ion experiments at the LHC and further connections with condensed matter experiments should soon tell us whether this gravitational lens captures the essence of real-life many-body systems.

In physics we often approximate complicated systems by simple solvable reference systems, which nevertheless capture the essential physics. Well-known examples include the simple harmonic oscillator, the hydrogen atom, and the ideal gas. For strongly coupled systems, the appropriate simple reference system has been hard to come by. Maybe black holes are the answer!

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