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Concluding remarks and outlook

Since the purpose of heavy ion collisions is to study the properties of Quantum Chromodynamics at extreme temperature and energy density, any successful phenomenology must ultimately be based on QCD. However, as discussed in Chapter 2, heavy ion phenomenology requires strong coupling techniques not only for bulk thermodynamic quantities like the QCD equation of state, but also for many dynamical quantities at nonzero temperature, such as transport coefficients, relaxation times and quantities accessed by probes propagating through a plasma. By now, lattice-regularized QCD calculations provide well controlled results for the former, but progress on all the latter quantities is likely to be slow since one needs to overcome both conceptual limitations and limitations in computing power. Alternative strong coupling tools are therefore desirable. The gauge/string duality provides one such tool for performing nonperturbative calculations for a wide class of non-Abelian plasmas.

In this book we have mostly focused on results obtained within one particular example of a gauge/string duality, namely the case in which the gauge theory is $\mathcal{N} = 4$ SYM or a small deformation thereof. One reason for this is pedagogical: $\mathcal{N} = 4$ SYM is arguably the simplest and best understood case of a gauge/string duality. By now many examples are known of more sophisticated string duals of non-supersymmetric, nonconformal QCD-like theories that exhibit confinement, spontaneous chiral symmetry breaking, thermal phase transitions, etc. However, many of these features become unimportant in the deconfined phase. For this reason, for the purpose of studying the QCD quark–gluon plasma, the restriction to $\mathcal{N} = 4$ SYM not only yields a gain in simplicity, but also does not imply a significant loss of generality, at least at the qualitative level. Moreover, none of these "more realistic" theories can be considered in any sense a controled approximation to QCD. Indeed, many differences remain including the presence of adjoint fermions and scalar fields, the lack of asymptotic freedom, the large-N_c approximation, etc. Some of these differences may be overcome if string theory in asymptotically AdS spacetimes becomes better understood. However, in the supergravity (plus classical strings and branes) limit currently accessible these caveats remain important to bear in mind when comparing to QCD.

In this context, it is clearly questionable to assess the interplay between heavy ion phenomenology and the gauge/string duality correspondence solely on the basis of testing the numerical agreement between theory and experiment. Rather, one should view this interplay in light of the standard scientific strategy that to gain significant insight into problems that cannot be addressed within the current state of the art, it is useful to find a closely related theory within which such problems can be addressed with known technology and which encompasses the essential features of interest. For many dynamical features of phenomenological interest in heavy ion physics, controlled strong coupling calculations in QCD are indeed not in immediate reach with the current state of the art. In contrast, within the gauge/string correspondence, it has been possible to formulate and solve the same problems in the strongly coupled plasmas of a large class of non-Abelian quantum field theories. Among these, strongly coupled $\mathcal{N} = 4$ SYM theory at large-N_c turns out to provide the simplest model for the strongly coupled plasma being produced and probed in heavy ion collisions. Very often in the past, when theoretical physicists have introduced some model for the purpose of capturing the essence of some phenomenon or phenomena involving strongly coupled dynamics, the analysis of that model has then required further uncontrolled approximations. (Examples abound: Nambu–Jona-Lasinio models in which the QCD interaction is first replaced by a four-fermi coupling but one then still has to make a mean-field approximation; linear sigma models, again followed by a mean-field approximation; bag models; . . .). A great advantage of using a quantum field theory with a gravity dual as a model is that once we have picked such a theory, the calculations needed to address the problems of interest can be done rigorously at strong coupling, without requiring any further compromise. In some cases, the mere formulation of the problem in a way suitable for a gravitational dual calculation can lead to new results within QCD [107, 564, 240]. In many others, as we have seen, the existence of these solutions allows one to examine and understand the physics responsible for the processes of interest. The most important output of a successful model is understanding. Controlled quantitative calculations come later. Understanding how the dynamics works, what is important and what is extraneous, what the right picture is that helps one to think about the physics in a way that is both insightful and predictive, these must all come first.

At the least, the successes to date of the applications of gauge/string duality to problems arising from heavy ion collisions indicate that it provides us with a successful model, in the sense of the previous paragraph. However, there are many indications that it provides more. In solving these problems, some regularities have emerged in the form of universal properties, by which we mean properties common to all strongly coupled theories with gravity duals in the large-N_c, strong coupling limit. These include both quantitative observables, such as the ratio of the thermodynamic potentials at strong and weak coupling (Section 6.1) and the value $\eta/s = 1/4\pi$ at strong coupling (Section 6.2), and qualitative features, such as the observation that the maximal stopping distance of a jet-like excitation made of energetic light quanta scales with its energy E like $E^{1/3}$ (Sections 8.4 and 8.6) or the familiar fact that heavy quarkonium mesons remain bound in the plasma as well as the discovery that the dissociation temperature for quarkonium mesons drops with increasing meson velocity v like $(1 - v^2)^{1/4}$ (Sections 8.7 and 9.4) and that high-momentum dispersion relations become spacelike (Section 9.4). The discovery of these generic properties is important in order to extract lessons for QCD. Indeed, the fact that some properties are valid in a class of gauge theory plasmas so broad as to include theories in different numbers of dimensions, with different field content, with or without chemical potentials, with or without confinement and chiral symmetry breaking, etc., leads one to suspect that such properties might be universal across the plasmas in a class of theories that includes QCD – whether or not a string dual of QCD itself exists. The domain of applicability of this putative universality is at present unknown, both in the sense that we do not know to what theories it may apply and in the sense that we cannot say *a priori* which observables and phenomena are universal and which others are theory-specific details. One guess as to a possible characterization in theory space could be that these universal features may be common across all gauge theory plasmas that have no quasiparticle description (Section 6.3).

Even results obtained via the gauge/string duality that are not universal may provide guidance for our understanding of QCD at nonzero temperature and for heavy ion phenomenology. In many cases, these are strong coupling results that differ parametrically from the corresponding weak coupling results and therefore deliver valuable qualitative messages for the modeling of heavy ion collisions. In particular, the small values of the ratio η/s, of the heavy quark diffusion constant (Section 8.2), of the relaxation time τ_π (Section 6.2) showed that such small values can be realized in a gauge theory plasma. Similarly, the speed with which a near-equilibrium plasma described by hydrodynamics can form from far-from-equilibrium initial conditions (Chapter 7) teaches us that the hydrodynamization times indicated in analyses of heavy ion collision data need not be thought of as unexpectedly rapid. And, via seeing it happen in a large number of examples in which we can use the dual gravitational description to watch hydrodynamization happening, we have learned that strongly coupled plasma is typically locally anisotropic when it hydrodynamizes, with isotropization happening only significantly later. Furthermore, the result for η/s in $\mathcal{N}=4$ theory, combined with the results for the entropy density, pressure and energy density (Section 6.1) have taught us that a theory can have almost identical thermodynamics at zero and infinite coupling and yet have radically different hydrodynamics. The lesson that this provides for QCD is that the thermodynamic observables, although they are available from lattice simulations, are not good indicators of whether the quark–gluon plasma is weakly or strongly coupled, whereas the transport coefficients are.

Important lessons have also been extracted from the strong coupling calculations of the jet quenching parameter $\hat{q}$ and the heavy quark drag coefficient η_D and momentum broadening κ (Sections 8.1, 8.2 and 8.5). These showed not only that these quantities can attain values significantly larger than indicated by perturbative estimates but also that while in perturbation theory both $\hat{q}$ and κ are proportional to the entropy density, this is not the case at strong coupling, where both these quantities and η_D scale with the square root of the number of degrees of freedom. This result, which is valid for a large class of theories, corrected a naïve physical expectation that was supported by perturbation theory.

The strong coupling calculation of the jet quenching parameter $\hat{q}$ also serves as an example of an approach (in this case to jet quenching) in which a part of the story where the QCD physics is likely weakly coupled is treated with conventional calculational methods and only that part of the story where the strongly coupled physics of the quark-gluon plasma in QCD enters is treated via gauge/string duality. It may well be worth developing approaches to other phenomena in heavy ion collisions along these lines.

Perhaps most fundamentally, the availability of rigorous, reliable results for any strongly coupled plasma (let alone for a large class of them) can alter the very intuition we use to think about the dynamics of the quark–gluon plasma. In perturbation theory, one thinks of the plasma as being made of quark and gluon quasiparticles. However, gravity calculations of correlation functions valid at strong coupling show no evidence of the existence of any quasiparticle excitations composed from gluons and light quarks (Section 6.3). (Heavy, small, quarkonium mesons do survive as quasiparticles up to some dissociation temperature (Sections 9.5.2 and 9.6).) The presence or absence of quasiparticles is a major qualitative difference between the weak and strong coupling pictures of the plasma which is largely independent of the caveats associated with the use of gauge/string duality that we have described above. Indeed, the new way of thinking about strongly coupled plasma that originated in a synthesis of insights from heavy on collision data, hydrodynamic calculations and analyses done via gauge/string duality poses a central challenge that must be addressed if in future we are to claim a deep understanding of quark-gluon plasma in QCD: how does a strongly coupled plasma with no quasiparticle description emerge (at length scales $\sim T$) from an asymptotically free gauge theory that describes weakly coupled quarks and gluons at length scales $\ll T$?

Finally, two important roles played by the gauge/string duality are that of a testing ground of existing ideas and models relevant for heavy ion collisions, and that of a source of new ones in a regime in which guidance and inspiration from perturbation theory may be inapplicable or misleading. In its first role, the duality provides a rigorous field-theoretical framework within which to verify our intuition about the plasma. For example, explicit calculations gave support to previously suggested ideas about the hydrodynamical response of the plasma to high energy particles (Section 8.3) or the possibility that heavy quarkonium mesons survive deconfinement (Section 9.3.1). In its second role, the duality has generated qualitatively new ideas which could not have been guessed from perturbation theory. Examples of these are the non-trivial velocity dependence of screening lengths (Section 8.7), the in-medium conversion of mesons into photons (Section 9.6), the energy loss of heavy quarks via Cherenkov emission of mesons (Section 9.6.2), and the appearance of a phase transition associated with the dissociation of heavy quarkonium bound states (Section 9.3.2).

In summary, while it is true that caution and a critical mind must be exercised when trying to extract lessons from any gauge/gravity calculation, paying particular attention to its limitations and range of applicability, it is also undeniable that over the past few years a broad suite of qualitatively novel insights relevant for heavy ion phenomenology have emerged from detailed and quantitative calculations in the gravity duals of non-Abelian field theories. As the phenomenology of heavy ion collisions moves to new, more quantitative and more incisive, studies in the RHIC program, and as it moves to novel challenges at the LHC, we have every reason to expect that experimental information about additional properties of hot QCD matter will come into theoretical focus. Understanding properties of the QCD plasma, as well as its response to and its effects on probes, at strong coupling will therefore remain key issues in future analyses. We expect that the gauge/string correspondence will continue to play an important role in making progress on these issues.