arXiv:1101.0618v2 [hep-th] 8 Aug 2012

hep-th 1101.0618

August 9, 2012

CERN-PH-TH/2010-316
MIT-CTP-4198
ICCUB-10-202

Gauge/String Duality, Hot QCD and Heavy Ion Collisions

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Abstract

Over the last decade, both experimental and theoretical advances have brought the need for strong coupling techniques in the analysis of deconfined QCD matter and heavy ion collisions to the forefront. As a consequence, a fruitful interplay has developed between analyses of strongly-coupled non-abelian plasmas via the gauge/string duality (also referred to as the AdS/CFT correspondence) and the phenomenology of heavy ion collisions. We review some of the main insights gained from this interplay to date. To establish a common language, we start with an introduction to heavy ion phenomenology and finite-temperature QCD, and a corresponding introduction to important concepts and techniques in the gauge/string duality. These introductory sections are written for nonspecialists, with the goal of bringing readers ranging from beginning graduate students to experienced practitioners of either QCD or gauge/string duality to the point that they understand enough about both fields that they can then appreciate their interplay in all appropriate contexts. We then review the current state-of-the art in the application of the duality to the description of the dynamics of strongly coupled plasmas, with emphases that include: its thermodynamic, hydrodynamic and transport properties; the way it both modifies the dynamics of, and is perturbed by, high-energy or heavy quarks passing through it; and the physics of quarkonium mesons within it. We seek throughout to stress the lessons that can be extracted from these computations for heavy ion physics as well as to discuss future directions and open problems for the field.

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Chapter 1

Preface

The discovery in the late 1990s of the AdS/CFT correspondence, as well as its subsequent generalizations now referred to as the gauge/string duality, have provided a novel approach for studying the strong coupling limit of a large class of non-abelian quantum field theories. In recent years, there has been a surge of interest in exploiting this approach to study properties of the plasma phase of such theories at non-zero temperature, including the transport properties of the plasma and the propagation and relaxation of plasma perturbations. Besides the generic theoretical motivation of such studies, many of the recent developments have been inspired by the phenomenology of ultra-relativistic heavy ion collisions. Inspiration has acted in the other direction too, as properties of non-abelian plasmas that were determined via the gauge/string duality have helped to identify new avenues in heavy ion phenomenology. There are many reasons for this at-first-glance surprising interplay among string theory, finite-temperature field theory, and heavy ion phenomenology, as we shall see throughout this review. Here, we anticipate only that the analysis of data from the Relativistic Heavy Ion Collider (RHIC) had emphasized the importance, indeed the necessity, of developing strong coupling techniques for heavy ion phenomenology. For instance, in the calculation of an experimentally-accessible transport property, the dimensionless ratio of the shear viscosity to the entropy density, weak- and strong coupling results turn out to differ not only quantitatively but parametrically, and data favor the strong coupling result. Strong coupling presents no difficulty for lattice-regularized calculations of QCD thermodynamics, but the generalization of these methods beyond static observables to characterizing transport properties has well-known limitations. Moreover, these methods are quite unsuited to the study of the many and varied time-dependent problems that heavy ion collisions are making experimentally accessible. It is in this context that the very different suite of opportunities provided by gauge/string calculations of strongly-coupled plasmas have started to provide a complementary source of insights for heavy ion phenomenology. Although these new methods come with limitations of their own, the results are obtained from first-principle calculations in non-abelian field theories at non-zero temperature.

The present review aims at providing an overview of the results obtained from this interplay between gauge/string duality, lattice QCD and heavy ion phenomenology within the last decade in a form such that readers from either community can appreciate and understand the emerging synthesis. For the benefit of string theory practitioners, we begin in Sections 2 and 3 with targeted overviews of the data from and theory of heavy ion collisions, as well as of state-of-the art lattice calculations for QCD at non-zero temperature. We do not provide a complete overview of all aspects of these subjects that are of current interest in their own terms, aiming instead for a self-contained, but targeted, overview of those aspects that are keys to understanding the impacts of gauge/string calculations. In turn, Sections 4 and 5 are mainly written for the benefit of heavy ion phenomenologists and QCD practitioners. They provide a targeted introduction to the principles behind the gauge/string duality with a focus on those aspects relevant for calculations at non-zero temperature. With the groundwork on both sides in place, we then provide an in-depth review of the gauge/string calculations of bulk thermodynamic and hydrodynamic properties (Section 6); the propagation of probes (heavy or energetic quarks, and quark-antiquark pairs) through a strongly-coupled non-abelian plasma and the excitations of the plasma that result (Section 7); and a detailed analysis of mesonic bound states and spectral functions in a deconfined plasma (Section 8).

The interplay between hot QCD, heavy ion phenomenology and the gauge/string duality has been a very active field of research in recent years, and there are already a number of other reviews that cover various aspects of these developments. In particular, there are reviews focussing on the techniques for calculating finite-temperature correlation functions of local operators from the gauge/string duality [1]; on the phenomenological aspects of perfect fluidity and its manifestation in different systems, including the quark-gluon plasma produced in heavy ion collisions and strongly coupled fluids made of trapped fermionic atoms that are more than twenty orders of magnitude colder [2] (we shall not review the connection to ultracold atoms here); and also shorter topical reviews [3–7] that provide basic discussions of the duality and its most prominent applications in the context of heavy ion phenomenology. The present review aims at covering a broader range of applications while at the same time providing readers from either the string theory or the QCD communities with the opportunity to start from square one on ‘the other side’ and build an understanding of the needed context.

Since any attempt at covering everything risks uncovering nothing, even given its length this review does remain limited in scope. Important examples of significant advances in this rapidly-developing field that we have not touched upon include: (i) the physics of saturation in QCD and its application to understanding the initial conditions for heavy ion collisions [8–14]; (ii) various field-theoretical approaches to understanding equilibration in heavy ion collisions [15–19]; and (iii) work from the string side on developing dual gravitational descriptions not just of the strongly-coupled plasma and its properties, as we do review, but of the dynamics of how the plasma forms, equilibrates, expands, and cools after a collision. This last body of literature includes the early work of Refs. [20–23], continues in modern form with the discovery of a dual gravitational description of a fluid that is cooling via boost-invariant longitudinal expansion [24] extends to the very recent discovery of the dual description of the collision of two finite-thickness sheets of energy density and the ensuing plasma formation [25], and includes much in between [26–43]. Also, we focus throughout on insights that have been obtained from calculations that are directly rooted in quantum field theories analyzed via the gauge/string duality. Consequently, we have omitted the so-called AdS/QCD approach that aims to optimize ansätze for gravity duals that do not correspond to known field theories, in order to best incorporate known features of QCD in the gravitational description [44–56]. So, while we have high hopes that the material reviewed here will serve in coming years as a pathway into the field for new practitioners with experience in QCD or string theory, we have not aimed for completeness. Indeed, we can already see now that this very active field continues to broaden and that adding new chapters to a review like this will soon be warranted.

Chapter 2

A heavy ion phenomenology primer

What macroscopic properties of matter emerge from the fundamental constituents and interactions of a non-abelian gauge theory? The study of ultra-relativistic heavy ion collisions addresses this question for the theory of the strong interaction, Quantum Chromodynamics, in the regime of extreme energy density. To do this, heavy ion phenomenologists employ tools developed to identify and quantify collective phenomena in collisions that have many thousands of particles in their final states. Generically speaking, these tools quantify deviations with respect to benchmark measurements (for example in proton-proton and proton-nucleus collisions) in which collective effects are absent. In this Section, we provide details for three cases of current interest: (i) the characterization of elliptic flow, which teaches us how soon after the collision matter moving collectively is formed and which allows us to constrain the value of the shear viscosity of this matter; (ii) the characterization of jet quenching via single inclusive hadron spectra and angular correlations, which teaches us how this matter affects and is affected by a high-velocity colored particle plowing through it; and (iii) the characterization of the suppression of quarkonium production, which has the potential to teach us about the temperature of the matter and of the degree to which it screens the interaction between colored particles.

2.1 General characteristics of heavy ion collisions

In a heavy ion collision experiment, large nuclei, such as gold (at RHIC) or lead (at SPS and LHC), are collided at an ultra-relativistic center of mass energy $\sqrt{s}$. The reason for using large nuclei is to create as large a volume as possible of matter at a high energy density, to have the best chance of discerning phenomena or properties that characterize macroscopic amounts of strongly interacting matter. In contrast, in energetic elementary collisions (say electron-positron collisions but to a good approximation also in proton-proton collisions) one may find many hadrons in the final state but these are understood to result from a few initial partons that each fragment rather than from a macroscopic volume of interacting matter. Many years ago Phil Anderson coined the phrase “more is different” to emphasize that macroscopic volumes of (in his case condensed) matter manifest qualitatively new phenomena, distinct from those that can be discerned in interactions among few elementary constituents and requiring distinct theoretical methods and insights for their elucidation [57]. Heavy ion