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Opening remarks

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 nonzero 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 book. 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. Now, this case is further strengthened by data from the CERN Large Hadron Collider (LHC). 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-principles calculations in non-Abelian field theories at nonzero temperature.

This book aims to provide an introductory exposition of the results obtained from the interplay between gauge/string duality, lattice QCD and heavy ion phenomenology within the past decade. It is written in a form accessible to graduate students seeking to enter this field of research from any direction. At the same time, it includes a comprehensive coverage that will be beneficial to established researchers from either community. It is a book about a newly emerging research field at the intersection of two domains that were until recently completely separate. As such, it does not attempt to cover the many aspects of these research fields that are of interest in their own terms, focusing on those aspects of each field that are relevant for understanding their new interplay. The introductions to heavy ion phenomenology (Chapter 2) and lattice QCD (Chapter 3) are thus written for beginners in these fields (whether graduate students or experienced string theorists) and they focus mainly on topics that have recently made contact with techniques from gauge/string duality. Analogously, Chapters 4 and 5 provide a targeted introduction to the principles behind the gauge/string duality with a focus on those aspects relevant for calculations at nonzero temperature. These chapters are for beginners too, again whether these beginners are graduate students or experts in heavy ion physics or lattice QCD. With the groundwork on both sides in place, we then proceed with a comprehensive exposition of gauge/string calculations of bulk thermodynamic and hydrodynamic properties (Chapter 6); of far-from-equilibrium dynamics and its late-time evolution to hydrodynamics (Chapter 7); of 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 (Chapter 8); and a detailed analysis of mesonic bound states and spectral functions in a deconfined plasma (Chapter 9).

This book aims at covering the main developments of the interplay between hot QCD, heavy ion phenomenology and the gauge/string duality in a way that enables the reader to follow also other parts of the literature on applications of gauge/string duality to heavy ion phenomenology and hot QCD. We aimed at a comprehensive exposition but we had to make choices on what to cover. One important decision was to focus 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 [343, 304, 518, 55, 201, 415, 416, 417, 508, 115, 689, 181, 182]. We are confident, however, that a reader of this book will be well-positioned to understand the motivations for research in this vast subject, as well as the main tools and techniques used in this research. Similarly, a reader of this book will have learned the tools needed to follow the broad and rapidly expanding range of string theory approaches in which dual gravitational descriptions are being developed not just for the strongly coupled plasma and its properties, that we focus on in this book, but also for the dynamics of how the plasma forms, equilibrates, expands, and cools after a collision. Our discussion of this vast topic in Chapter 7 highlights only a fraction of the many developments. Last but not least, we have omitted any discussion of the physics of saturation in QCD and its application to understanding the initial conditions for heavy ion collisions [374, 431, 432, 630, 128, 34, 300]. Here, our main reason was that a self-contained introduction to this subject in QCD would have required significant space, while its connection to the gauge/string duality rests at present on relatively few tentative, albeit very interesting, works. In short, neither this book, nor the list of omissions presented in this paragraph, should be regarded as being complete.

The existence of a textbook is a hallmark for the development of a research topic into a research field. There are several good textbooks in the field of finite temperature and lattice QCD, the field of heavy ion phenomenology and the field of gauge/string duality. However, aspects of the intersection between these fields have been covered so far only in scientific reviews, for example focussing on the techniques for calculating finite-temperature correlation functions of local operators from the gauge/string duality [749], or 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 [730]. There are also a number of shorter topical reviews that provide basic discussions of the duality and its most prominent applications in the context of heavy ion phenomenology [672, 601, 340, 398, 410]. We hope that beyond serving as an overview of what has been achieved already in this newly emerging field, our book will serve as a springboard for great achievements yet to come, in particular from its readers.