Progress in Particle and Nuclear Physics 75 (2014) 86–132

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Heavy ions and string theory

Oliver DeWolfe [a], Steven S. Gubser [b,*], Christopher Rosen [c], Derek Teaney [d]

[a] Department of Physics, 390 UCB, University of Colorado, Boulder, CO 80309, USA
[b] Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, USA
[c] Crete Center for Theoretical Physics, University of Crete, PO Box 2208, 71003 Heraklion, Greece
[d] Department of Physics & Astronomy, SUNY at Stony Brook, Stony Brook, NY 11794, USA

ARTICLE INFO

Keywords:
Quark-gluon plasma
String theory

ABSTRACT

We review a selection of recent developments in the application of ideas of string theory to heavy ion physics. Our topics divide naturally into equilibrium and non-equilibrium phenomena. On the non-equilibrium side, we discuss generalizations of Bjorken flow, numerical simulations of black hole formation in asymptotically anti-de Sitter geometries, equilibration in the dual field theory, and hard probes. On the equilibrium side, we summarize improved holographic QCD, extraction of transport coefficients, inclusion of chemical potentials, and approaches to the phase diagram. We close with some possible directions for future research.

Contents

* Corresponding author.
E-mail address: ssgubser@Princeton.EDU (S.S. Gubser).

0146-6410/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ppnp.2013.11.001

1. Introduction

1.1. Gauge-gravity duality and the strong force

Quantum chromodynamics (QCD) has been understood to be the correct theory of the strong interaction for four decades. However, because the theory is strongly coupled at low energies, many strong interaction phenomena remain difficult to successfully characterize theoretically. Lattice QCD is a powerful method that has had numerous successes, but certain kinds of phenomena, notably real-time and finite density physics, are not so easily accessible using lattice techniques. The physics of heavy ion collisions is both real-time and apparently strongly coupled, and as a result alternate theoretical tools to help in understanding heavy ion physics are welcome.

The idea that QCD might simplify in the limit of a large number of colors N_c is almost as old as the theory itself [1], and has led to significant conceptual progress. Non-planar diagrams drop out of perturbative calculations when the 't Hooft coupling $\lambda \equiv g^2 N_c$ is kept finite, and meson and glueball states become stable as the large-N_c limit is approached. Calculations of real-time processes remained difficult to address even in the large-N_c context until a fundamental breakthrough took place in 1997, with the formulation of the AdS/CFT, or gauge/gravity, correspondence [2–4]; for reviews see for example [5–8]. Motivated from calculations in string theory involving the dynamics of D-branes, the correspondence states that certain non-Abelian gauge theories can be described in a wholly different way, as theories of quantum gravity living in a higher-dimensional space–time, in particular a space–time with the asymptotic behavior of anti-de Sitter space (AdS). The AdS/CFT correspondence provides a concrete realization of the holographic principle, the idea – motivated by the scaling of the entropy of black holes as the surface area rather than the volume – that quantum gravitating theories are in some sense hugely redundant, and can be described by a non-gravitational theory in fewer dimensions ([9,10]; for a review see [11]).

The AdS/CFT correspondence relies essentially on the asymptotic properties of anti-de Sitter space. In AdS space, massive particles must stay at finite spatial values (the "bulk") but massless trajectories can reach spatial infinity, called the "boundary". As a result, describing physics in an asymptotically AdS space requires more than ordinary initial conditions: it requires boundary conditions as well, fixing the behavior of the various dynamical fields at infinity. The geometry of the boundary has one less dimension than the bulk,[1] and is identified with the space on which the dual quantum field theory lives. The precise statement of the AdS/CFT correspondence is then that for every field $\phi(r, \vec{x})$ in the bulk, there is an associated "dual" operator $\mathcal{O}_\phi(\vec{x})$ in the quantum field theory, and that the suitably-defined boundary conditions $\phi_0(\vec{x})$ on the field ϕ correspond to sources in the Lagrangian for the dual operator. Schematically, this may be thought of as an equality between path integrals:

$$Z_{\rm grav}[\phi \to \phi_0] = \langle e^{i\int \phi_0 \mathcal{O}} \rangle_{\rm QFT}. \tag{1}$$

As part of the correspondence, an identification exists between the isometries of the geometry of the gravity theory, and the symmetries of the dual quantum field theory. Five-dimensional anti-de Sitter space may be described by the metric

$$ds^2 = \frac{r^2}{L^2}\left(-dt^2 + d\vec{x}^2\right) + \frac{L^2}{r^2}dr^2, \tag{2}$$

where slices of constant radial coordinate r are four-dimensional Minkowski space, with the boundary at $r \to \infty$, and L is the radius of curvature, related to the number of degrees of freedom in the dual field theory.[2] The AdS_5 geometry has

[1] Neglecting additional compact space factors, such as the five-sphere in $AdS_5 \times S^5$.

[2] When the dual is $\mathcal{N} = 4$ super-Yang–Mills, the radius of curvature is related to the number of colors by $L^3/\kappa^2 = (N_c/2\pi)^2$, where $\kappa^2 = 8\pi G_5$ and G_5 is the five-dimensional gravitational coupling.