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Nuclear Physics B 913 (2016) 852–876

NUCLEAR PHYSICS B

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Field theories without a holographic dual

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Received 6 July 2016; received in revised form 11 October 2016; accepted 21 October 2016

Available online 26 October 2016

Editor: Stephan Stieberger

Abstract

In applying the gauge–gravity duality to the quark–gluon plasma, one models the plasma using a particular kind of field theory with specified values of the temperature, magnetic field, and so forth. One then assumes that the bulk, an asymptotically AdS black hole spacetime with properties chosen to match those of the boundary field theory, can be embedded in string theory. But this is not always the case: there are field theories with no bulk dual. The question is whether these theories might include those used to study the actual plasmas produced at such facilities as the RHIC experiment or the relevant experiments at the LHC. We argue that, *provided* that due care is taken to include the effects of the angular momentum associated with the magnetic fields experienced by the plasmas produced by peripheral collisions, the existence of the dual can be established for the RHIC plasmas. In the case of the LHC plasmas, the situation is much more doubtful.
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1. String theory in the bulk

Attempts to apply gauge–gravity duality to the Quark–Gluon Plasma [1–3] have always to reckon with the fact that QCD itself certainly does not have any *known* description of this kind; if it has one at all, the dual is, to put it very mildly, not simple [4]. Instead, one confines attention to greatly simplified versions of string theory in the bulk — the string coupling should be very small, the string length scale should be small relative to the bulk curvature length scale — and accepts that the corresponding simplified boundary field theories differ, in important ways, from

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http://dx.doi.org/10.1016/j.nuclphysb.2016.10.015
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QCD. The hope is nevertheless that all of these theories, including QCD, have some universal features in common [5].

In practice, one studies a field theory of this general type, with prescribed parameters (temperature, chemical potential, and so on) chosen to match those of the QGP, and then constructs the appropriate bulk geometry. When using this simplification, one should however bear in mind that the true bulk physics is still *string* physics [6]. The procedure implicitly assumes that arbitrary boundary field theories with specific prescribed parameter values are dual to stringy bulk configurations that actually exist. *But this is a very non-trivial assumption*. For it is clear that, for a holographic description be possible at all, the bulk physics must be extremely strongly constrained; there must be severe additional restrictions, beyond those imposed by classical General Relativity, if it is to be fully equivalent to a lower-dimensional dual. In particular, many candidate bulk geometries, supposedly dual to a constructed boundary field theory, must in fact be mathematically inconsistent when embedded in string theory.

In summary: not every boundary field theory system can have a gravitational dual; one will find in some cases that the field theory is "dual" to a system which does not actually exist in full string theory, even if it *appears* to do so in an incautious application of the standard holographic procedure.

All this is of considerable theoretical interest, since, as we shall see, recent advances make it rather easy to exhibit explicit examples of this phenomenon. More importantly, however, it prompts the question: are there field theory systems, corresponding (as above) to *physical, experimentally attainable QGP states*, such that the purported bulk dual spacetime simply does not exist in a full string-theoretic treatment? Are there, in short, actual plasmas with no holographic description?

Our objective in this work is to bring together some recent important developments in string theory [7–10] with new phenomenological findings (particularly [11]), in order to argue that there is a real possibility that such systems might indeed exist; the QGP arising in certain heavy-ion collisions (involving extremely intense magnetic fields) corresponds to a field-theory configuration which appears to be dual to a bulk system that is not mathematically consistent in string theory. That is, the holographic duals of certain specific quark plasmas indeed (apparently) do not exist.

Remarkably, the boundary between plasmas with a consistent holographic description and those (possibly) without one lies between the regimes explored by the main experimental facilities: on the one hand, the plasmas which are the concern of the RHIC experiment and the allied beam energy scans do have such a description, while, on the other, the QGP produced in certain peripheral heavy-ion collisions at the LHC (and potentially in future facilities such as the Future Circular Collider) apparently do not. We will see, in fact, that it is not trivial to establish the existence of such a description even in the case of certain RHIC plasmas; this can be done, but only by explicitly including certain effects (the shearing and vorticity of the plasma) associated with the magnetic fields.

2. The consistency condition vs. magnetic fields

The argument proceeds as follows. In [7–10] the authors argue that, in an extremely broad class of dual bulk-boundary pairs, a mathematically consistent string-theoretic bulk must satisfy a simple relation between the (on-shell) Euclidean spacetime action and the (on-shell) action of probes such as branes. This is argued to be related to very deep and general thermodynamic

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