Possible Connections to String Theory

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Plan of the talk

- What is the AdS/CFT correspondence?
- Applications of AdS/CFT and gauge gravity duality
- Had AdS/CFT been useful to QCD and RHIC physics?
- What are the future prospects?

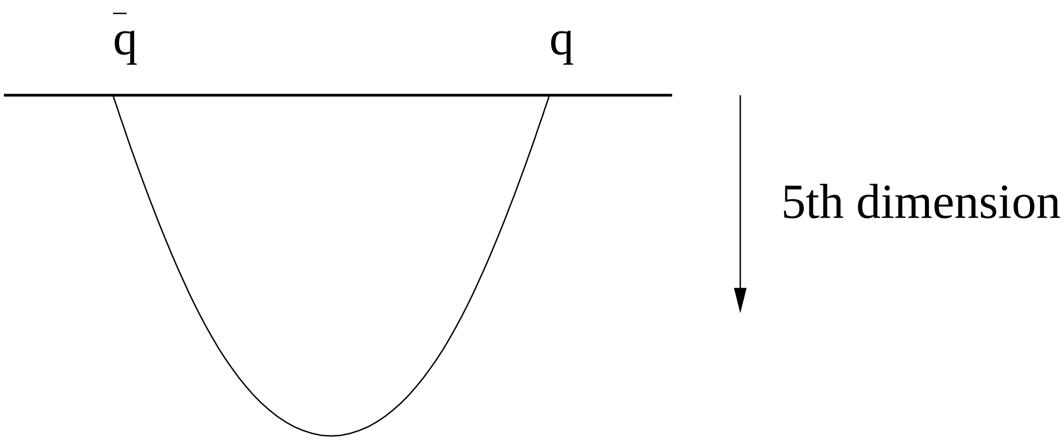
AdS/CFT correspondence

- Original (as suggested by Maldacena): between a field theory, $\mathcal{N}=4$ super symmetric Yang-Mills theory and type IIB string theory on a curved 10D spacetime called AdS$_5\times$S^5
- Strong coupling limit of field theory $\lambda = g^2 N_c \gg 1$ corresponds to the limit of large curvature radius: string theory reduces to supergravity
- Therefore both $\lambda \to 0$ and $\lambda \to \infty$ limit of $\mathcal{N}=4$ SYM are tractable analytically. $\lambda \sim 1$ is not.
- It was surprising because
  - Everyone expected string theory duals of confining theories with flux tubes, but not of a conformal field theory with Coulomb law
  - The string theory lives in 5d

Rules of AdS/CFT correspondence

Each object in field theory corresponds to an object in string theory

- Operator $\Leftrightarrow$ field
  - $F_{\mu\nu}^2 \Leftrightarrow$ dilaton
  - $T_{\mu\nu}$ (stress energy tensor) $\Leftrightarrow$ graviton
  - etc.
- Finite temperature plasma $\Leftrightarrow$ black hole (with Hawking temperature)
- Wilson loop $\Leftrightarrow$ fundamental string



Applied AdS/CFT

The applications of AdS/CFT correspondence can be roughly divided into two types

- Finite-temperature applications
  - Hydrodynamics (will talk about later)
  - Photon, dilepton emission Caron-Huot, Kovtun, Starinets, Moore, Yaffe
  - Energy loss, jet quenching (will talk about)
- Zero-temperature applications (will only touch upon)

Finite temperature

Entropy: from area of the horizon

$$S = \frac{A}{4G} = \frac{3}{4} \times \text{(free gas)}$$

Viscosity: there exist several calculations

- From graviton absorption cross section

$$\eta = \lim_{\omega \to 0} \frac{\sigma_{\rm abs}(\omega)}{16\pi G} \Longrightarrow \frac{\eta}{s} = \frac{1}{4\pi}$$

- From black hole quasinormal frequencies (ringtones)
- From the condition that the gravitational counterpart of Bjorken expansion does not contain naked singularity (Janik)

All different calculations give the same result: consistency!
Universal η/s ratio, reveals deep connection to gravity

Two approaches to the energy loss problem

First approach:
Energy loss by a heavy quark moving in $\mathcal{N} = 4$ SYM plasma $=$ energy rate needed to drag a fundamental string along the horizon
Herzog, Karch, Kovtun, Kozkaz, Yaffe; Gubser et al. Related work by Teaney

Second approach Liu, Rajagopal and Wiedemann

- Use perturbative QCD argument to map the problem to that of finding a $\hat{q}$ parameter
- Define $\hat{q}$ parameter nonperturbatively in terms of lightlike Wilson loop
- Find the expectation value of the Wilson loop geometrically (minimal area surface stretched on the loop).

Result: consistence with each other at the level of parametric dependence on λ and N_c.
Different numerical coefficients.
But the objects computed are different in field theory (although possibly related).

How relevant are these calculations to QCD?

Differences between $\mathcal{N} = 4$ SYM theory and QCD:

- $\mathcal{N} = 4$ SYM is drastically different from QCD: coupling does not run, no Λ_{QCD}.
- All particles are of adjoint color ($\sim$ gluons in QCD), not of fundamental color ($\sim$ quarks in QCD)

On the other hand, the similarities are encouraging:

- At finite T, $\mathcal{N} = 4$ SYM similar to strongly coupled regime of deconfined QGP. May explain why results of AdS/CFT calculations are phenomenologically reasonable?
- Confinement, chiral symmetry breaking can be included into theories with gravity duals

  Example: the Sakai-Sugimoto model ($\mathrm{D4}$ and $\mathrm{D8}/\overline{\mathrm{D8}}$ branes) with the same pattern of chiral symmetry breaking as QCD

The most serious problem: Λ_{QCD} of the same order of magnitude as “non-QCD” degrees of freedom: no decoupling of QCD at low enegy.
Solving this problem requires understanding of string quantization in highly curved space and RR background. Considered a very hard problem by string theorists.

Physical insights from AdS/CFT

Nevertheless, AdS/CFT has already given interesting insights on the strong-coupling regime of gauge theories.
These insights are sometimes complementary to the insights obtained from more tranditional approaches.
One example: viscosity at strong coupling

$$\frac{\eta}{s} > C_0 \sim 1$$

can be understood from uncertainty principle:

mean free path $\gtrsim$ de Broglie wavelength

What we realized from AdS/CFT

- η needs to be divided by by s (clear after the fact, by dimensionality)
- Lower bound is probably universal: $C_0 = 1/(4\pi)$ independent of spatial dimension while kinetic theory reasoning + uncertainty principle normally gives a D dependence, e.g.,

$$\frac{\eta}{s} > \frac{1}{D(D+1)}$$

We seem to be missing something in the kinetic reasoning!

Summary

- AdS/CFT is a huge step toward understanding of strong-coupling dynamics in gauge theory
- Its application to QGP physics has been quite succesful, giving numbers which are not too far off
- But many uncertainties (e.g., estimate of η depends on initial condition)
- The most valuable contributions have been not numbers, but insights, concepts.
- Reveals deep connections to classical gravity and black hole physics.
- Future is hard to predict, but it is clear that we need to further investigate these connections
- Encourage people (especially young) from other communities (string, gravity) to learn and contribute to heavy ion physics. We also learn from them.