"Ask not what the extra dimension can do for you..."

(or the successes and challenges of AdS/QCD)

Ami Katz
Boston U.

Lattice2008

Overview

1. What is AdS/QCD?
2. Top-down vs. bottom-up paths.
3. Results/challenges facing the approach.

AdS/QCD

Old Myth: G.T. at large N simplifies $\Rightarrow$ a weakly coupled string theory.

AdS/CFT: An additional simplification occurs for a large hierarchy of anomalous dimension of operators:

a few have $\Delta_O \sim 1$, but most have $\Delta_O >> 1$.

AdS/CFT duality:

G.T. is dual to an extra-dimensional (ED) theory:

Local primary operators of G.T., $O(x)$. $\Longleftrightarrow$ Fields propagating in ED curved space $\phi(x,z)$.

$$\Delta_O \Longleftrightarrow m_\phi$$

Holographic Dictionary

G.T.	ED dual
$\bar{q}q(x)$	$\phi(x,z)$
$J_\mu(x) = \bar{q}\gamma_\mu q(x)$	$A_\mu(x,z)$
$T_{\mu\nu}(x)$	$h_{\mu\nu}(x,z)$
$\bar{q}\gamma_{\mu_1}D_{\mu_2}...D_{\mu_n}q(x)$	$\phi_{\mu_1\mu_2...\mu_n}(x,z)$

$$\Delta_O >> 1 \quad \Rightarrow \quad m_\phi \sim \Delta_O >> 1$$

Most ED dual fields decouple. Only left with duals to currents:

$J_\mu, T_{\mu\nu}$ (+ superpartners) $\Leftrightarrow$ $A_\mu, h_{\mu\nu}$ (+ super)

(The string theory simplifies, becoming a local field theory)

$$g_{ED} \sim \frac{1}{\sqrt{N_c}}$$

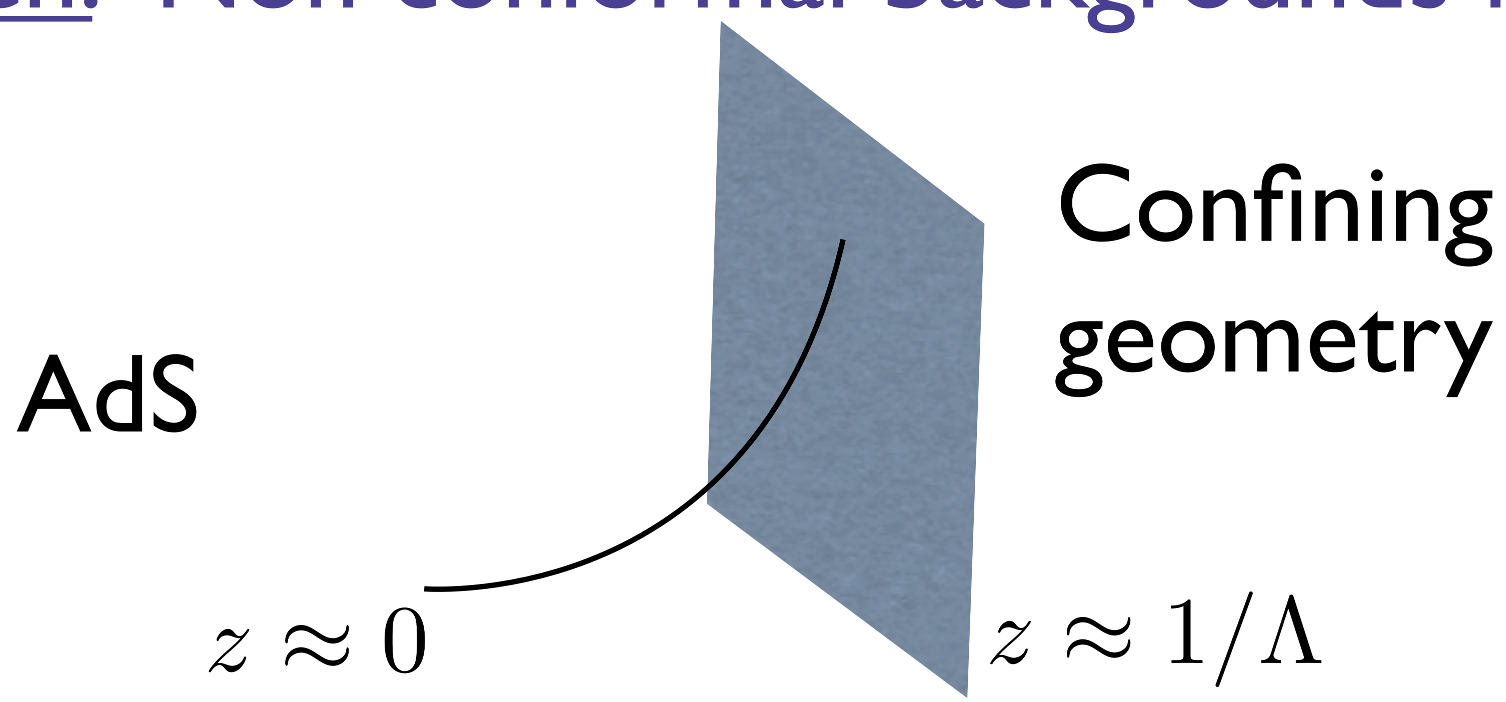
At first: ED duals only for conformal theories were found:

$$ds^2 = \frac{1}{z^2}(dx_\mu dx^\mu - dz^2)$$

Dilatation: $x^\mu \to \lambda x^\mu, \; z \to \lambda z$

UV: $z << 1$, IR: $z >> 1$

Then: Non conformal backgrounds found.



Towards QCD

Top-down approach: Study of particular field theories (mostly SUSY) with known ED duals in an attempt to extract universal/qualitative features.

Bottom-up approach: An attempt to build ED models for certain limited sectors of QCD that make quantitative predictions.

Top-down approach

- Studies of χSB, spectra, DIS, etc in theories with large hierarchies in anomalous dimensions of operators.
- QFT dynamics at finite temperature and chemical potential: Phase diagrams, transport properties, and response to external E & B fields:

1. RHIC physics: small shear viscosity consistent with strong coupling (qualitatively similar to strongly coupled known duals).
2. Condensed matter physics: theories which reflect some properties of superconductors.

- Challenges for top-down:

1. Calculations are under control at large N.
2. All field theories described have a large hierarchy in the dimensions of operators.
3. It is not yet clear how to connect the calculations to QCD data at a more quantitative level.

FT with simple ED duals are Probably rare

1. Generically, a strongly coupled CFT has $\Delta_O \sim 1$.
2. Even for a CFT with a marginal deformation, there is no guarantee that $\Delta_O \sim (def.\ parameter)$.
3. FT with weakly coupled duals have correlation functions with certain polarization structures suppressed (not due to any symmetry).

QCD as a test for ED models

w/ Erlich, Schwartz, Son, and Stephanov.

QCD: $\Delta_O \sim O(1)$ (no hierarchy). →

ED dual contains infinitely many fields.

Conjecture: Lightest states are well described by the lowest dimension operators. →

Might only need to consider a few ED fields.

Evidence for the conjecture:

1. True for G.T. with known ED duals.
2. Suggested by success of ED models for lightest QCD resonances.
3. True in 2D QCD at large N.
4. LATTICE?

Modeling the lightest QCD states

1. Include only lowest dimension operators.
2. Use QCD OPE's as a guide for constructing the 5D metric.
3. Model confinement with a hard wall + b.c.

$$SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$$

QCD	5D dual
$\bar{q}q(x)$	$\phi(x,z)$
$J_\mu^V(x),\ J_\mu^A(x)$	$V_\mu(x,z),\ A_\mu(x,z)$
$T_{\mu\nu}(x)$	$h_{\mu\nu}(x,z)$
$\bar{q}\gamma_{\{\mu_1}D_{\mu_2}...D_{\mu_n\}}q(x),\ G^a_{\nu\{\mu_1}D_{\mu_2}...D_{\mu_{n-1}}G^{a\nu}_{\mu_n\}}(x)$	$\phi_{\{\mu_1\mu_2...\mu_n\}}(x,z)$

$$\int_x e^{iqx}\langle J^a_\mu(x) J^b_\nu(0)\rangle = \delta^{ab}(q_\mu q_\nu - q^2 g_{\mu\nu})\Pi(Q^2)$$

$$\Pi_V(Q^2) = -\frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right)\ln Q^2 + \frac{1}{24\pi}\cdot\frac{\langle\alpha_s G^2\rangle}{Q^4} - \frac{m_q\langle q\bar{q}\rangle}{Q^4} - \frac{14}{9}\pi\frac{\langle\alpha_s \bar{q}q\rangle^2}{Q^6} + \ldots$$

$$\begin{aligned} S = \int d^5x\{ \quad - \quad & \frac{1}{4g_5^2 z}(1+\frac{c_0}{Log(\Lambda z)} + c^{ab}_{4V} z^4 + c^{ab}_{6V} z^6) F^a_V F^b_V \\ - \quad & \frac{1}{4g_5^2 z}(1+\frac{c_0}{Log(\Lambda z)} + c^{ab}_{4A} z^4 + c^{ab}_{6A} z^6) F^a_A F^b_A + \frac{v(z)^{ab}}{2z^3} D\pi^a D\pi^b\}. \end{aligned}$$

$$v(z)_{ab} = (M_q)_{ab}\ z + \langle\bar{q}q\rangle\ \delta_{ab}\ z^3$$

LATTICE - Help find condensates at large N.

QCD-lite Model

Also
Da Rold & Pomarol

$$c_{nV}, \; c_{nA} = 0.$$

$$z_{IR} = 1/(346MeV), \; \langle \bar{q}q \rangle = (308MeV)^3, \; m_q = 2.3MeV, \; m_s = 35MeV.$$

Observable	Measured (MeV)	Model (MeV)	Width (MeV)
m_π	139.6	141	-
m_ρ	775.8	832	146
m_{a_1}	1230±40	1220	250-400
f_π	92.4	84	-
$F_\rho^{1/2}$	345±8	353	-
$F_{a_1}^{1/2}$	433±13	440	-
m_{K^*}	892	897	51
m_ϕ	1020	994	4
m_{K_1}	1272±7	1290	90±2
m_K	498	411	-
f_k	113	117	-
m_{f_2}	1275	1236	185
m_{ω_3}	1667±4	1656	168±10
m_{f_4}	2025±8	2058	225±18
m_{ρ_5}	2330±35	2448	400±100
m_{f_6}	2465±50	2829	255±40
m_η	548	520	-
$m_{\eta'}$	958	867	-
$\Gamma(f_2 \to 2\gamma)$	2.6±.24 KeV	2.71 KeV	-

Additional Progress

1. Baryons as 5D solitons (similar to skyrmions).
   Pomarol & Wulzer
2. Anomaly physics from 5D Chern-Simmons term.
3. Modification of IR geometry away from the hard wall to reproduce Regge physics: $M_J^2 \sim J$.

2D QCD at large N (w/ T. Okui)

The PDF of the n-th excited meson is given by

$$f_q^n(x) = |\phi_n(x)|^2$$

Solutions for highly excited modes are :

$$\phi_n(x) \simeq \sqrt{2}\cos[n\pi x] \quad , \quad m_n^2 \simeq \pi^2\Lambda^2 n \,.$$

In terms of the primary operators, $O_k, \; \Delta_k \sim k$:

$$\phi_n(x) = \sum_k \langle 0|O_k|n\rangle P_{k-1}(2x-1)$$

The lightest states have the biggest overlap with the lowest dimension operators:

$$\langle 0|O_k|n\rangle << 1, \;\; k \gtrsim n$$

Parton-x and the extra dimensional coordinate are related by a transform:

‘t Hooft Eqn $\Longleftrightarrow$ EOM for a scalar in ED.

Conclusions

1. AdS/QCD captures non-perturbative aspects of QCD both quantitatively and qualitatively.
2. Bottom-up models offer a connection between low-energy parameters (of lightest resonances) and the UV theory (via the OPE).
3. These models are a useful tool for the LHC, where we might access only a few resonances. Similar to Randall-Sundrum models.
4. They work better than they should.
5. LATTICE may help clarify the reach and limitations of the approach.