Holography and Hadron Physics I

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New Trends – Natal
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Plan

1. Holographic engineering
   - String theory and holographic correspondence
   - Gauge sector
   - Matter sector
   - Sakai-Sugimoto model
   - Klebanov-Strassler model
2. Holographic phenomenology
   - Glueballs (spectrum)
   - Mesons (spectrum/couplings)
   - Baryons (couplings/nuclear force/finite density)

String Theory and Holographic Correspondence

String Theory and Holography

Why string theory?

- String theory emerged as a theory of hadrons
- It was found to yield a theory of quantum gravity
- String theory is a theory of everything?
- String theory is a theory of nothing?

String Theory and Holography

String Theory and Holography

Pros

- String theory is very rich and naturally incorporates many physical and mathematical models and methods
- String theory opens a geometrical interpretation of physical phenomena

Cons

- So far string theory does not provide a quantitative description of any realistic physical system

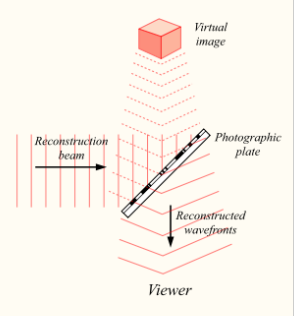
Though string theory cannot be used for a quantitative description of real-life systems it can be a source of intuition about very complicated systems and inspiration for new discoveries

see also lectures by Gary Shiu and Jorge Noronha

String Theory and Holography

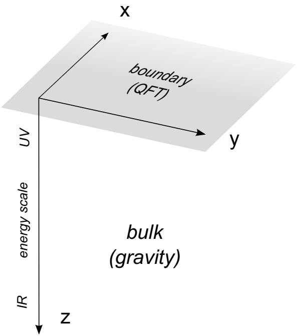
Holography

In real life holography is a technique to store a 3d image in a 2d container. The image changes with the change of the position and the orientation of the viewing system



Holography

In string theory holography is a duality between a $d+1$ and d-dimensional theories. It states the existence of two equivalent descriptions of one theory, where the higher dimensional description should include gravity



String Theory and Holography

Duality

$$Z_{\mathrm{QFT}}\left[J_i\right] = Z_{\mathrm{grav}}\left[g^{\infty}_{\mu\nu}, \Phi^{\infty}_i\right] \qquad \Phi^{\infty}_i \equiv J_i$$

Correlation functions (Jorge's lectures)

$$\langle\, \mathcal{O}_1 \cdots \mathcal{O}_n \,\rangle_{\mathrm{QFT}} = \left.\frac{\delta^n Z_{\mathrm{grav}}}{\delta\Phi^{\infty}_1 \cdots \delta\Phi^{\infty}_n}\right|_{\Phi_i=0}$$

The duality relates a strongly coupled QFT and weakly coupled gravity

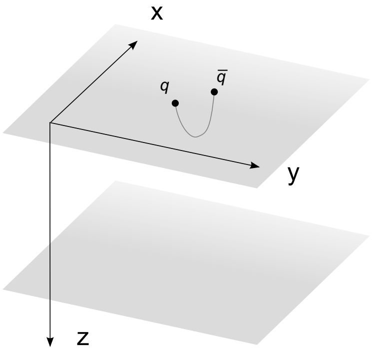
String Theory and Holography

Geometry

Anti-de-Sitter space

$$ds^2 = \frac{L^2}{z^2}\left(-dt^2 + \sum_i dx_i^2 + dz^2\right)$$

Cartoon: quark confinement $\Longrightarrow$



String Theory and Holography

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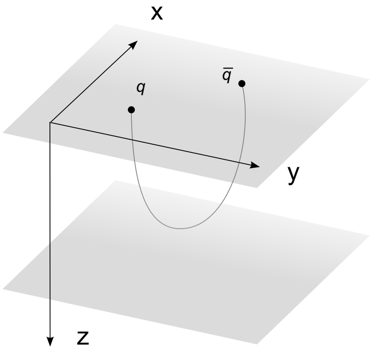

String Theory and Holography

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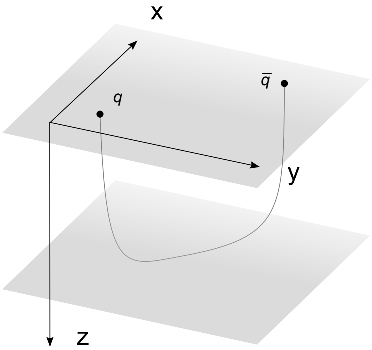


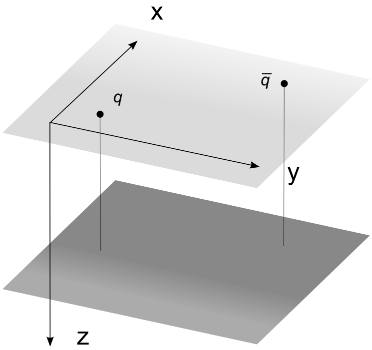
String Theory and Holography

Geometry

Anti-de-Sitter space

$$ds^2 = \frac{L^2}{z^2}\left(-f(z)dt^2 + \sum_i dx_i^2 + \frac{dz^2}{f(z)}\right)$$

Cartoon: quark confinement $\Longrightarrow$



String Theory and Holography

Bottom-up approach

Consider simplified gravity models in AdS-like space. The dual field theory is not exactly known. Good for qualitative analysis and universal properties: example of η/s ratio (see Jorge's lectures)

Top-down approach

Derive the construction from 10d string theory. Technically involved. Limited number of examples. Better control on the QFT side (examples in these lectures)

String Theory and Holography

AdS/CFT correspondence

Maldacena's conjecture: Type IIB string theory on $AdS_5 \times S^5$ with N_c units of the RR flux is dual to the $\mathcal{N} = 4$ SYM theory with gauge group $SU(N_c)$

type IIB		$\mathcal{N} = 4$
Isometries of AdS_5	$\leftrightarrow$	Conformal group
SO(2,4)	=	SO(2,4)
Isometries of S^5	$\leftrightarrow$	R-symmetry
$SO(6)$	=	$SU(4)$

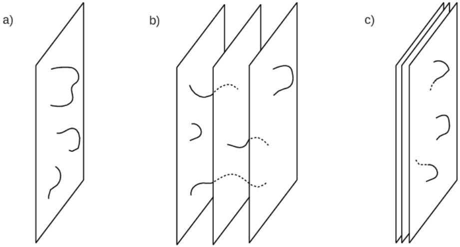
The conjecture has been tested against many non-trivial checks

Nonabelian Gauge Theories from Branes

Gauge Theories from Branes

Strings and D-branes

D-branes are loci for the endpoints of open strings. The effective theories of strings ending on the Dp branes are $p+1$ dimensional gauge theories



single D-brane $\rightarrow U(1)$ theory

N D-branes $\rightarrow U(N)$ theory

Gauge Theories from Branes

Breaking SUSY

- Start from a 5d theory: N_c D4-branes in type IIA
- Compactify 1 dimension
- Impose antisymmetric boundary conditions on fermions

$$
\begin{array}{c}
\quad\;\; 0 \quad 1 \quad 2 \quad 3 \qquad 4 \qquad 5 \qquad 6 \quad 7 \quad 8 \quad 9 \\
D4 \;\; \underbrace{\circ \quad \circ \quad \circ \quad \circ}_{\mathcal{M}^{1,3}} \;\; \underbrace{\circ}_{S^1} \;\; \underbrace{}_{R^+} \;\; \underbrace{}_{S^4}
\end{array}
$$

Antisymmetric bc introduce mass for the fermions $\equiv$ SUSY breaking

Gauge Theories from Branes

KK scale

Radius of the compact dimension (S^1) introduces a scale in the theory

$$M_{KK} = \frac{1}{R}$$

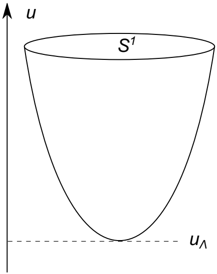
- This is not a conformal theory
- The M_{KK} scale is manifest in the IR geometry
- Theory contains a KK tower of unwanted massive states

Gauge Theories from Branes

IR geometry

$$ds^2 = \left(\frac{u}{R_{D4}}\right)^{3/2}\left[-dt^2 + \delta_{ij}dx^i dx^j + f(u)dx_4^2\right] + \left(\frac{R_{D4}}{u}\right)^{3/2}\left[\frac{du^2}{f(u)} + u^2 d\Omega_4^2\right]$$

$$R_{D4}^3 = \pi g_s N_c l_s^3\,, \qquad f(u) = 1 - \left(\frac{u_\Lambda}{u}\right)^3$$



To avoid singularity one sets

$$2\pi R = \frac{4\pi}{3}\left(\frac{R_{D4}^3}{u_\Lambda}\right)^{1/2}$$

Gauge Theories from Branes

Flux

$$F_4 = \frac{(2\pi)^3 l_s^3 N_c}{V_4} \mathrm{vol}(S^4) , \qquad \int_{S^4} F_4 \sim N_c$$

D-branes are replaced by flux, which backreacts on the metric

Running dilaton

$$e^{\phi} = g_s \left(\frac{u}{R_{D4}} \right)^{3/4}$$

u-dependence of the dilaton leads to a diverging coupling in the UV

Gauge Theories from Branes

Dual theory

- Low-energy theory of this construction is $U(N_c)$ YM+KK modes
- Geometrical parameters are mapped onto the parameters of the dual QFT

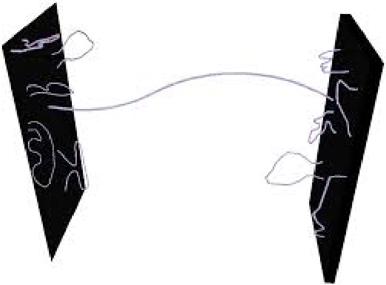
$$R \to \Lambda \sim M_{KK} \,, \qquad g^2_{YM}(\Lambda) = 2\pi \frac{M_{KK}}{M_s} g_s$$

- The theory is not UV-complete

Adding Flavor

Adding Flavor

Matter fields



Add different types of branes (gauge+flavor)

Chiral matter: to have it we need have either branes at singularities, intersecting branes or magnetized branes (see Gary's lectures)

Adding Flavor

Probe limit

Add N_f flavor branes, such that $N_f \ll N_c$. Ignore the backreaction of the geometry

Effective action

$$S_{\mathrm{DBI}} = -(2\pi\alpha')^{-(p+1)/2} \int_{Dp} \mathrm{d}^{p+1}x\, e^{-\phi}\, \mathrm{Tr} \sqrt{-\det(g_{ab} + 2\pi\alpha' \mathcal{F}_{ab})}$$

Chern-Simons actions

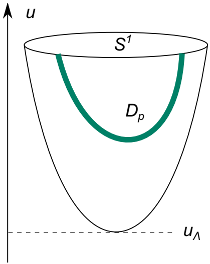
$$S_k = (2\pi\alpha')^{-(p+1)/2} \int_{Dp} \mathrm{e}^{2\pi\alpha' \mathcal{F}} \wedge C_k$$

generalization of the action of a relativistic charged particle

Adding Flavor

Stable embeddings

- Add few flavor branes $N_f \ll N_c$
- Solve for the DBI+CS action to find the geometry of the embedding (profile of the flavor branes)
- Check the spectrum for tachyonic modes



Sakai-Sugimoto Model

Sakai-Sugimoto model

System

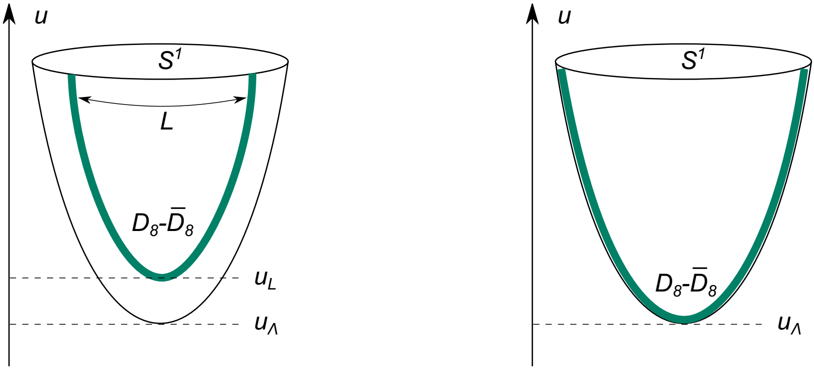
Add N_f probe $D8$ and anti-$D8$-branes

	0	1	2	3	4	5	6	7	8	9
$D4$	○	○	○	○	○					
$D8/\overline{D8}$	○	○	○	○		○	○	○	○	○
	$\mathcal{M}^{1,3}$				S^1	R^+	S^4			

$$S_{\rm CS} = \pm(2\pi\alpha')^{-9/2} \int_{D8} \mathrm{e}^{2\pi\alpha' \mathcal{F}_2} \wedge C_3$$

Sakai-Sugimoto model

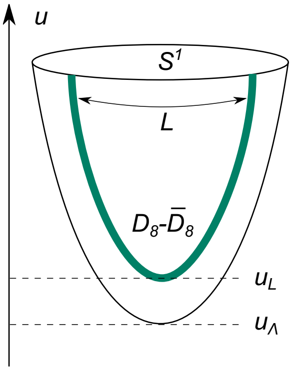
Stable configurations



General stable profiles are classified by a new parameter L, not present in QCD. In the “antipodal" case $L = \pi R$

Sakai-Sugimoto model

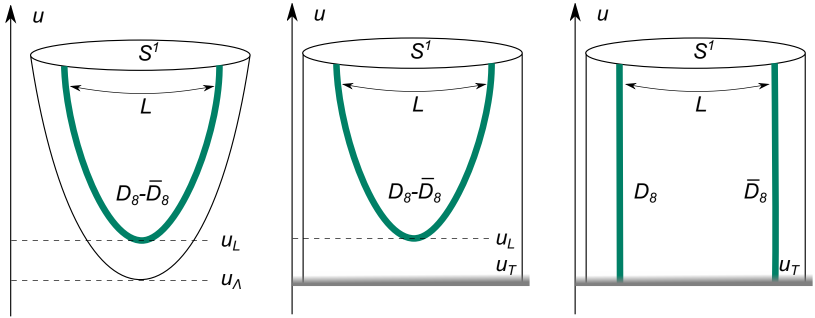
Chiral symmetry



- In these configurations the orientation of the $D8$ changes as the lowest point of the embedding is passed: $D8$-$\overline{D8}$
- Each $D8$ ($\overline{D8}$) has a $U(N_f)$ gauge theory on its worldvolume: $U(N_f)_L \times U(N_f)_R$
- $D8$ and $\overline{D8}$ have no point to end in this geometry. They have to reconnect: chiral symmetry breaking
- This model has massless pions

Sakai-Sugimoto model

Finite temperature phases



$0 \leq T \leq T_\tau$ $\quad$ $T_\tau \leq T \leq T_\chi$ $\quad$ $T_\chi \leq T \leq \infty$

At high T deconfinement and chiral symmetry restoration occur

Sakai-Sugimoto model

Summary of the model

- We expect Sakai-Sugimoto model to be like very strongly coupled version of QCD
- but it has extra stuff ...
- The model provides a geometrical picture of chiral symmetry breaking with many characteristic features

In the next lecture we will review the phenomenology of the model (spectrum, couplings, baryons)

Klebanov-Strassler Model

Klebanov-Strassler model

Keeping some SUSY

AdS/CFT:	$AdS_5 \times S^5$	$SO(6)$	$\Rightarrow$	$\mathcal{N} = 4$
KW:	$AdS_5 \times T^{1,1}$	$SU(2) \times SU(2)$	$\Rightarrow$	$\mathcal{N} = 1$

KW model

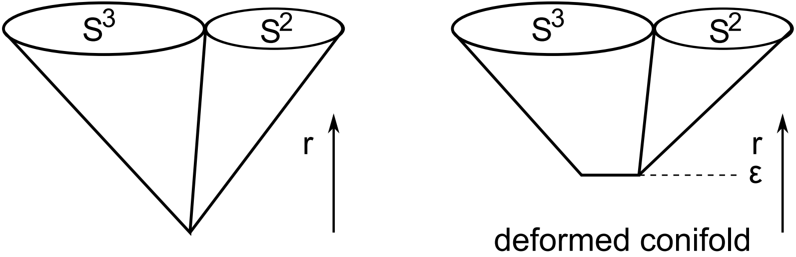
- Conformal symmetry is still preserved
- The space transverse to the Minkowski space-time dimensions is a 6d cone – conifold

$$\sum_{i=1}^{4} z_i^2 = 0$$

- Dual theory is a theory of D3-branes compactified on $T^{1,1}$

Klebanov-Strassler model

Breaking conformal invariance



$$\sum_{i=1}^{4} z_i^2 = \epsilon^2$$

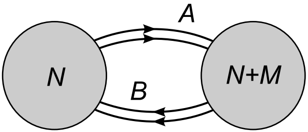
Deformation introduces a scale in the theory

To support such a geometry extra branes need to be added (M fractional D3-branes)

Klebanov-Strassler model

Dual theory

- It is a $\mathcal{N} = 1$ SUSY Yang-Mills theory with extra stuff
- The gauge group is $SU(N+M) \times SU(N)$
- Matter sector contains two doublets of bifundamental fields A_i and B_i



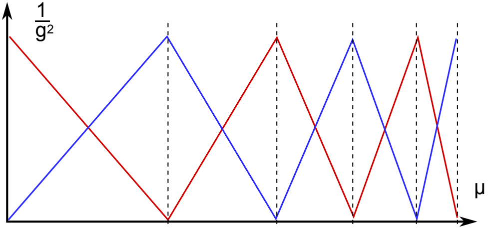
- The theory has a special marginal deformation

$$W = \lambda \, \mathrm{Tr} \, \epsilon^{ik} \epsilon^{jl} A_i B_j A_k B_l$$

Klebanov-Strassler model

Cascade

The theory has two couplings g_1 and g_2 which run in the opposite directions



At strong coupling the theory undergoes a Seiberg duality

$$SU(N_c) \times SU(N_f) \to SU(N_f - N_c) \times SU(N_f) \,, \qquad N_f > N_c$$

,

Klebanov-Strassler model

Cascade

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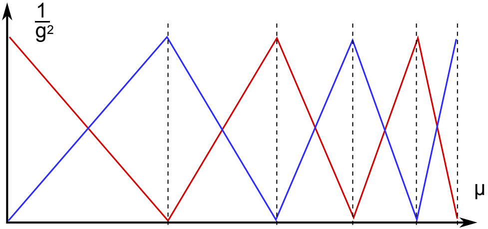

$$SU(M) \leftarrow SU(2M) \times SU(M) \leftarrow \dots$$
$$\dots \leftarrow SU(N-M) \times SU(N) \leftarrow SU(N+M) \times SU(N) \leftarrow \dots$$

Klebanov-Strassler model

Spontaneous breaking of $U(1)_B$

The hope of Klebanov *et al.* was to construct a gravity dual of SYM, but ...

Baryonic operators ($N_c = N_f$)

$$\mathcal{B} = \epsilon_{i_1 i_2 \ldots i_{2M}} (A_1)_1^{i_1} (A_1)_2^{i_2} \cdots (A_1)_M^{i_M} (A_2)_1^{i_{M+1}} \cdots (A_2)_M^{i_{2M}}$$

$$\overline{\mathcal{B}} = \epsilon_{i_1 i_2 \ldots i_{2M}} (B_1)_1^{i_1} (B_1)_2^{i_2} \cdots (B_1)_M^{i_M} (B_2)_1^{i_{M+1}} \cdots (B_2)_M^{i_{2M}}$$

These operators condense in the KS theory and there are Goldstone bosons in the spectrum

Conclusions

Next time we talk about

Phenomenology of the Sakai-Sugimoto and Klebanov-Strassler model

- Spectrum of glueballs (confronting lattice results?)
- Spectrum of mesons in the Sakai-Sugimoto model
- Meson couplings
- Phenomenology of baryons
- Baryons at finite density