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Searching for Landscape/CFT Duals

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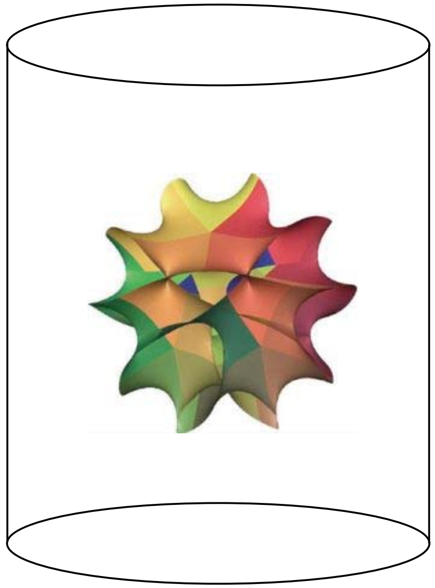
Lecture 3, 2009 ICTP Spring School: Searching for Landscape/CFT Duals



Joseph Polchinski

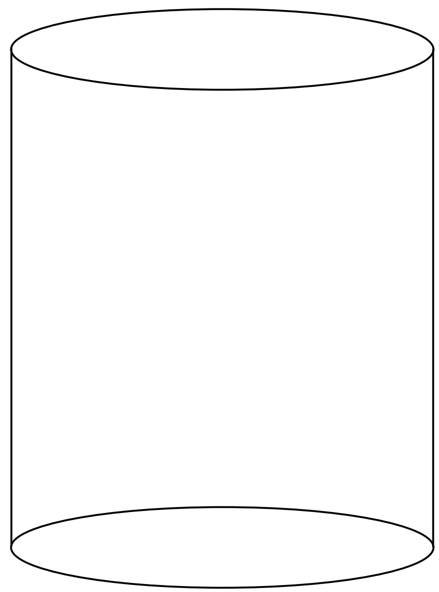
Work in progress with Eva Silverstein

Long-term goal: a nonperturbative construction of string theory.

Presumably this will be based on the *holographic principle,* where the basic degrees of freedom live on the boundary of spacetime.

However, for our expanding universe, and for the universe of eternal inflation that seems to arise in string theory, it is not clear what the relevant boundary is. This clearly requires new concepts… and is left for a future talk.

A more immediate goal: Most realistic (e.g. positive$-\Lambda$) string vacua are constructed as excited states of negative$-\Lambda$ AdS vacua. For AdS vacua we know the framework for a non-perturbative construction, AdS/CFT duality:



If we can identify the CFT (i.e. its Lagrangian), this provides a precise construction of theory.

The constructions that suggest the existence of 10^{500} vacua (or 10^{10000}) suggest a similar number of 4d *AdS* vacua. So where are all the dual 3d CFTs? (e.g. Banks, Dine, Gorbatov hep-th/0309170).

Outline

I. Lots of 3d CFTs
II. Matching CFTs to `landscape' vacua: why is it so hard?
III. Some attempts
IV. New AdS_5/CFT_4 duals based on intersecting branes

I,II,III with Eva Silverstein. IV with Gonzalo Torroba.

I. Lots of 3d CFTs

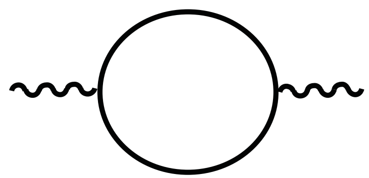
Consider a $U(1)$ gauge theory with N_f charge-1 fermions. First in d=4 the RG is

$$\mu\partial_\mu e^2 \sim N_f e^4 \qquad \text{(d=4)}$$

(coupling goes to 0 in IR, diverges at high energy).
In d=3, e^2 has units of mass so define the dimensionless $\varepsilon^2 = e^2/\mu$. The RG is

$$\mu\partial_\mu \varepsilon^2 \sim -\varepsilon^2 + N_f \varepsilon^4 \qquad \text{(d=3)}$$

There is an IR fixed point at $\varepsilon^2 \sim 1/N_f$. For large N_f this is reliable (Applequist & Heinz, 1981), just like the Wilson-Fisher fixed point for $\lambda\phi^4$.
SUSY is not needed.



This has an infinite number of generalizations: take any gauge group G with enough matter to give a large positive one-loop β-function.

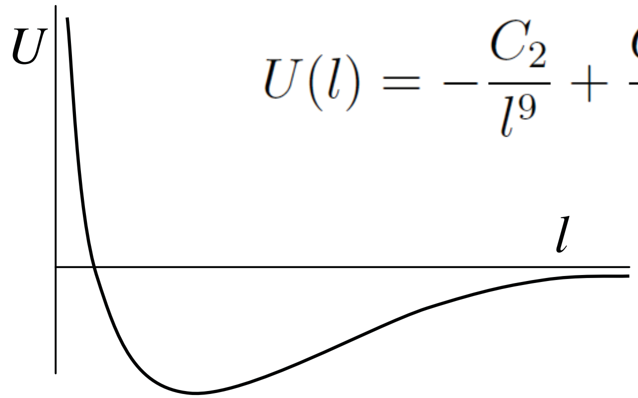
These fixed points are weakly coupled, so any gravity dual would have stringy curvature, but as the number of matter fields is reduced the coupling grows, and in many cases we will be able to identify a small-curvature gravitational dual.

II. Matching CFTs to `landscape' vacua: why is it so hard?

Simple example of AdS_4 dual: $AdS_4 \times S^7$ with 7-form flux on S^7. 4d effective theory, reducing on S^7 (radius l):

$$\begin{aligned} S &= \frac{1}{l_M^9}\int d^{11}x\sqrt{-g}(\mathcal{R} - H^2) \\ &= \frac{1}{l_M^9}\int d^4x\sqrt{-g_4}\,l^7\left(C_1\mathcal{R}_4 + \frac{C_2}{l^2} - \frac{C_3 N^2 l_M^{12}}{l^{14}}\right) \\ &= \frac{1}{l_P^2}\int d^4x\sqrt{-g_4'}\left(C_1\mathcal{R}_4' + \frac{C_2}{l^9} - \frac{C_3 N^2 l_M^{12}}{l^{21}}\right) \end{aligned}$$

4d potential: $U(l) = -\frac{C_2}{l^9} + \frac{C_3 N^2 l_M^{12}}{l^{21}}$

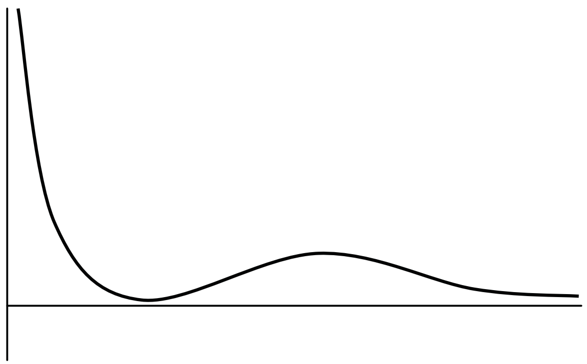


$$U(l) = -\frac{C_2}{l^9} + \frac{C_3 N^2 l_M^{12}}{l^{21}}$$

AdS minimum at

$$l \sim N^{1/6} l_M$$

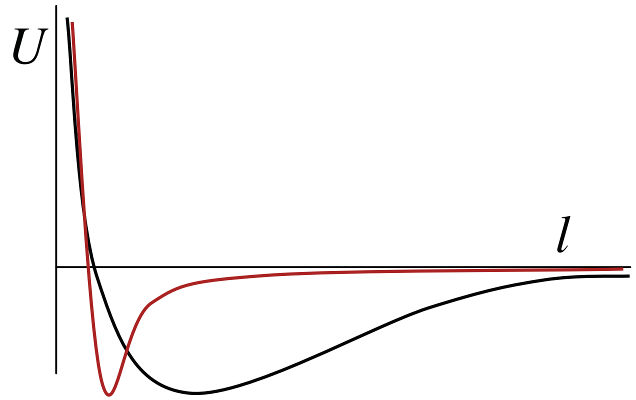
To get dS vacuum, *uplift* by adding (anti)branes, etc:



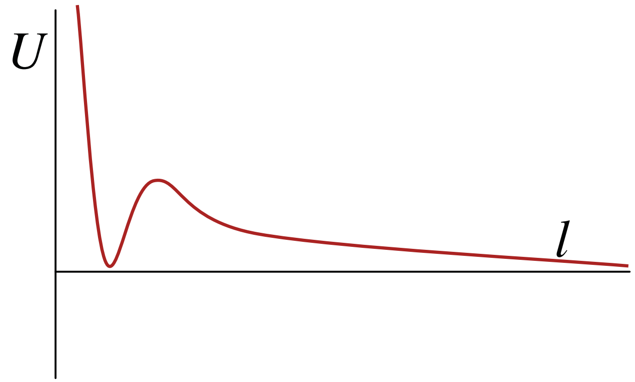
(add $+1/l^n$ to U, with $n < 9$).

Problem: negative term (from positive curvature) dominates all other terms at large l. True for all known gravity duals: can't be uplifted.

In KKLT, for example, the negative term in U is from instantons, and falls much more rapidly at large radius, $\sim \exp(-O(l^4))$.



It is then straightforward to uplift:



In all known AdS duals, the curvature is an $O(1)$ contribution to the potential (a.k.a. Freund-Rubin), and it is not possible to uplift.

Another problem: when negative curvature is an O(1) contribution to the potential, Einstein's equations imply that the curvature of the compact dimensions is of the same order as the AdS curvature. E.g., the S^7 radius is comparable to the AdS_4 radius. (One can reduce to three large dimensions but no fewer by orbifolding on $Z_n^4 \subset U(1)^4 \subset SO(8)$).

In KKLT, $l_{\rm AdS} \sim W_0$, while $l_{\rm comp} \sim \ln(1/W_0)$, so there is a large hierarchy when W_0 is small. Thus, there is a large number of landscape vacua with $l_{\rm AdS} >> l_{\rm comp}$.

Goal: find AdS duals with $l_{\rm AdS} >> l_{\rm comp}$ (none are known).

General considerations:

Goal: $l_{\text{AdS}} >> l_{\text{comp}} \geq l_{\text{s}} \geq l_{\text{P}}$

A necessary condition, from the AdS black hole entropy, is

$$N_{\text{dof}} \sim S/T^2 \sim (l_{\text{AdS}}/l_{\text{P}})^2 >> 1$$

Thus, we need a CFT with many fields (not a surprise).

The AdS/CFT dictionary gives

$$(m l_{\text{AdS}})^2 = \Delta(\Delta - 3) \; ,$$

relating the 4d mass of a particle to the dimension of the dual operator. A large hierarchy implies only a small number of fields with Δ of order one, so many operators must get large anomalous dimensions. Thus the CFT must be strongly coupled, again not a surprise.

The masses of the KK modes are of order $1/l_{\text{comp}}$, so our goal $l_{\text{AdS}} >> l_{\text{comp}}$ means that all of these have large Δ. In all known examples there is a large tower of operators with dimensions $O(1)$.

If there is an R symmetry, there will be a large number of protected operators in the bulk. Thus we must have at most d=3, $\mathcal{N}$=1 in the CFT (which implies d=4, $\mathcal{N}$=1 in the bulk). (Possible exception: d=3, $\mathcal{N}$=2 has a *U*(1) R symmetry, which might allow reduction by orbifolding).

Examples: $AdS_3 \times S^3 \times T^4$ (T^4 can be small); DGKT models (hep-th/0505160) have large hierarchy, $\mathcal{N}$=1, but no known dual.

Also, $\mathcal{N}$=0 has potential instabilities, so $\mathcal{N}$=1 seems the best place to look.

Conjecture: a large number of fields, strong coupling, and $\mathcal{N}$=1 are sufficient conditions to produce the desired hierarchy. (Omitting trivial exceptions, like breaking SUSY via orbifolding).

III. Some attempts

Simple way to obtain such an AH gauge theory on branes: N_c D2-branes (012) plus k D6-branes (0126789). Gives $\mathcal{N}$=4 $U(N_c)$ gauge theory with $2k$ hypermultiplets in fundamental. RG for $\gamma^2 = g^2/\mu$:

$$\mu\partial_\mu\gamma^2 \sim -\gamma^2 + k\gamma^4$$

Fixed point at $\gamma^2 = 1/k$, dimensionless 't Hooft coupling $\lambda = N_c/k$. Effective descriptions:

- $k >> N_c$: weakly coupled gauge theory
- $k^5 >> N_c >> k$: IIA geometry: D6s wrapped on S^3 in S^6
- $N_c >> k^5$: C^2/Z_k orbifold of the $AdS_4 \times S^7$ solution

Still of Freund-Rubin type, no hierarchy.

From this starting point we can deform in various ways:

- Further RG flow
- Orbifolding
- Adding fluxes/fractional branes
- T-dualing

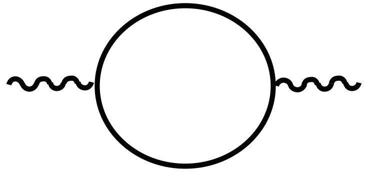
(Recall goals --- examples with hierarchy, investigate conjecture.)

Further RG flow:

Bosonic fields of D2-D6 model:

$U(N_c)$ adjoint: A_μ, $\mu=0,1,2$; Φ_i, $i=3,4,5$; Φ_m, $m=6,7,8,9$

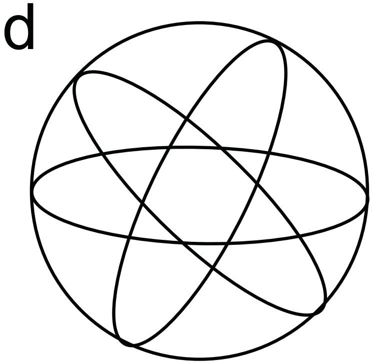
$U(N_c)$ fundamental: Q_r, $\bar{Q}_r$, $r=1,\ldots,k$



All have canonical dimension $1/2$, but A_μ and Φ_i get dimension 1 at the fixed point.

Relevant superpotential perturbation $g_{rm}\bar{Q}_r\Phi_m Q_r$ leads to many new AH fixed points. Simple geometric interpretation: rotating D6-branes (indexed by r) to wrap on different S^3's in S^6:

$\mathcal{N}$=2,1,0 SUSY depending on angles.



Many new geometries (Gukov & Tong '02). E.g. C^2/Z_k x C^2 flows to conifold x C with two stacks of branes.

Estimate scaling via potential:

$$U(l,\phi) = -\frac{C_2 e^{2\phi} l_s^4}{l^8} + N^2 \frac{C_3 e^{4\phi} l_s^{14}}{l^{18}} + k \frac{C_4 e^{3\phi} l_s^5}{l^9}$$

curvature $\quad$ F_6 flux $\quad$ D6 tensions

Unique extremum at

$$l \sim N^{1/4}/k^{1/4}\ , \qquad e^{\phi} \sim N^{1/4}/k^{5/4}$$

This agrees with explicit solutions where known.
All terms are of the same order as each other and as the sum, so no hierarchy (can't even tune).

Crude method, assumes rough homogeneity…

Other flows, e.g $\bar{Q}\Phi\Phi Q$?

Orbifolding:

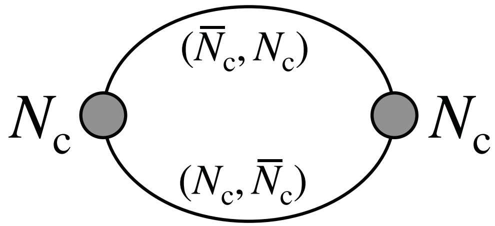
Can orbifold by additional Z_n acting in 6789 directions, to get $U(N_c)^n$ quiver theory. Total M theory space is Z_n x Z_k orbifold of AdS_4 x S^7, still no hierarchy.

Interesting feature: for large enough n the fiber direction becomes small and we must T-dual to a IIA description. Also, the possibility of fractional branes (next).

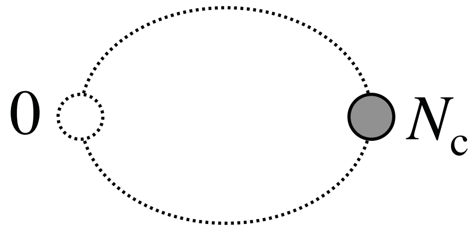
Fractional branes:

Models thus far are all related to $\mathcal{N}$=8 theory, in that the total contribution of the adjoints (or their orbifold descendants) to the β-function vanishes. To get a different set of theories with fewer adjoints, introduce fractional D2-branes at the orbifold fixed point.

whole D2's:



fractional D2's:



Now

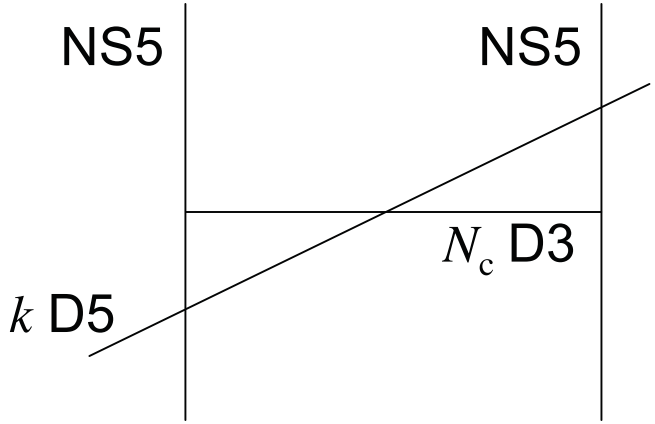
$$\mu\partial_\mu \gamma^2 \sim -\gamma^2 + (k-2N_c)\gamma^4$$

$k<2N_c$ no longer has a fixed point, theory confines.
$k>2N_c$ has fixed point with ‘t Hooft parameter $N_c/(k-2N_c)$:
small for $k>>2N_c$, large for $k-2N_c << 2N_c$

(Still $\mathcal{N}$=4, can get less SUSY by rotating branes).

Dual solution known (DiVecchia, Enger, Imeroni, Lozano-Tellechea ‘01) but even at strong coupling curvature is stringy. Also, B-flux at fixed point ~ 0 (as opposed to π in orbifold theory): suggests T-dual along fiber.

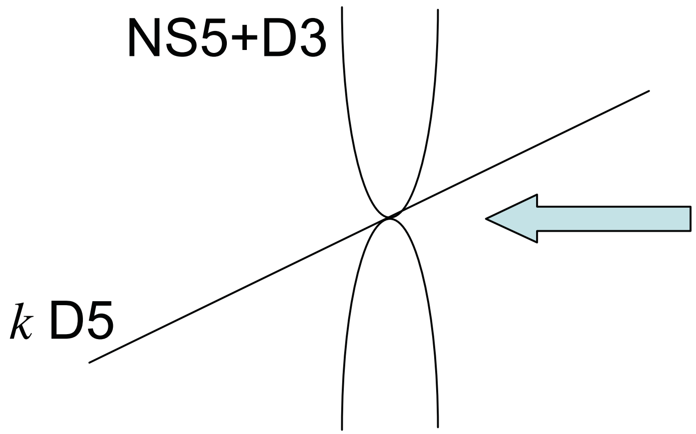
T-dual IIB geometry (Ooguri & Vafa ‘95):



D3: 0126
NS5: 012345
D5: 012789

Hanany-Witten setup

with brane bending:



Near-horizon AdS geometry

Scaling argument shows that curvatures are still stringy, in spite of the strong coupling. It appears that there is *no* weakly curved dual. There are some calculable properties at strong coupling because the NS5 throat becomes long. However, there is no hierarchy between any of $l_{\rm AdS}$, $l_{\rm comp}$, $l_{\rm s}$, and no large anomalous dimensions: conjecture seemingly falsified.

Another general lesson: to get 4d curvature << internal curvature will apparently require fine-tuning, canceling large + and – terms without a symmetry. This is consistent with the landscape constructions: in KKLT, W_0 is the sum of $O(1)$ terms, and so small W_0 solutions are sporadic. GVW superpotential:

$$W_0 = \int_{\mathcal{M}} G_{(3)} \wedge \Omega = (2\pi)^2 \alpha' \left(M \int_B \Omega - K\tau \int_A \Omega \right)$$

New goal: (1) Find a large space of CFT's that allows such cancellation. (2) Identify a holomorphic analog of W_0 to quantify this.

Potentially interesting ingredient: [p,q]7-branes: same scaling as curvature with opposite sign, e.g. in Sen's (S^2 with 24 7-branes) x 8d Minkowski. In the limit that the 7-branes coincide to give O7-planes, the dual can be identified, and more general configurations by perturbing. We expect that we will be able to find examples where the curvature is *almost* exactly canceled, leaving a large hierarchy.

Conclusions:

No success yet, but we have some lessons:

- Duals with a hierarchy are likely to be sporadic, as a consequence of discrete fine tuning.
- We should look for a large set of duals that allows such tuning, and identify the CFT parameter corresponding to W_0.
- Some features of familiar AdS/CFT duals, like large anomalous dimensions, may not be universal - need to understand this better.