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Spring School on Superstring Theory and Related Topics

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Holography and strongly coupled model building

Lecture 1

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"Holography and Strongly Coupled Model Building"

Plan (Main refs for III, IV: 0801.1520, 0903.0619)

I: AdS/CFT & RS

II: Branes at the conifold

III: Gravity dual of DSB

IV: Holographic gauge mediation & composite models

Basic theme:

* Historically, one good place to think about strings when doing model building, has been in study of phenomena where $\frac{1}{M_P}$ suppressed operators are crucial.

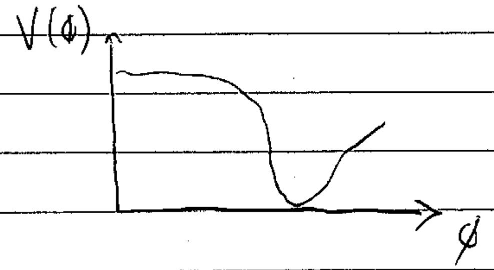
  - Gravity mediation $\int d^4\theta \, \frac{1}{M_P^2} X^+ X \, c_{ij} Q^i Q^{j+}$

    $\rightarrow$ squark/slepton masses. UV physics of flavor??

- Anomaly mediation

Need tiny coefs for those $\Delta = 6$ ops in K that dominate in gravity mediation. Sequestering?

- Inflation



$$\epsilon = \frac{1}{2} M_P^2 \left(V'/V \right)^2$$

$$\eta = M_P^2 \, V''/V$$

So $\Delta = 6$ operators can $\Rightarrow$ eg $O(1)\ \eta$; but slow roll inflation requires $\eta \ll 1$.

"Large field" models where $\Delta\phi \gg M_P$ during inflation are even more sensitive to UV physics.

These are great issues to think about, but we're going to take a different attitude: those examples use string theory as a UV completion. We will instead use string theory as a computational tool. D-branes & AdS/CFT allow us to geometrize strongly coupled field theory dynamics. Some model building or other questions require analysis of such theories:

- Strongly correlated e^- systems (→ Holographic Condensed Matter)
- QCD & QCD phase transition (→ Hol. QCD)
- Strongly Coupled Particle Physics Models

↑ My focus here

a) ∃ strongly coupled DSB models visible only via gauge/gravity duality

b) Composite models (SUSY or not) can be geometrized. Can explain $\left\{ \begin{array}{l} \text{Yukawa} \\ \text{Soft mass} \end{array} \right.$ hierarchies along w/ the main hierarchy problem

I. Hierarchies from (a slice of) AdS_5

a. Trapping gravity in AdS_5

We can obviously live in a higher D world if the extra dims. are compact.

Eg $$ds^2 = \eta_{\mu\nu}\, dx^\mu dx^\nu + R^2 dx_5^2$$

5D Einstein Action $$S_5 = \int d^5x \sqrt{-G}\, M_5^3 R_5$$

"Integrating out" x_5 dim $\rightarrow$

$$M_4^2 \sim M_5^3 R \Rightarrow$$ 4D gravity w/ G_N fixed by this.

Small enough circle $\rightarrow$ ok w/ experiment.

<u>More general</u>: Metric can be <u>warped</u>.

Consider:

$$S = \int d^5x \sqrt{-G}\,(R - \Lambda) \; +$$

$$\int d^4x \sqrt{-g}\,(-V_{brane})$$

$$g_{\mu\nu} = \delta^M_\mu\, \delta^N_\nu\, G_{MN}(x_5 = 0) \qquad \begin{array}{l}\mu = 1..4\\ M = 1..5\end{array}$$

Following RS, we take the most general $SO(3,1)$ symmetric ansatz:

$$ds^2 = e^{2A(x_5)} \eta_{\mu\nu} dx^\mu dx^\nu + dx_5^2$$

Then, Einstein's equations $\Rightarrow$

$$(\star) \quad 6(A')^2 + \tfrac{1}{2}\Lambda = 0 \qquad {}' = \frac{d}{dx_5}$$

$$(\surd) \quad 3A'' + \tfrac{1}{2} V \delta(x_5) = 0$$

Choosing $\Lambda < 0$, can solve $(\star)$ $\Rightarrow$

$$A = \pm k x_5 \qquad k = \sqrt{\frac{-\Lambda}{12}}$$

Integrating $(\surd)$ from $x_5 = -\epsilon$ to $x_5 = \epsilon$ $\Rightarrow$

$$3 \underbrace{\Delta(A')}_{\text{discont. at } x_5 = 0} = -\tfrac{1}{2} V$$

Then we need: $A = \begin{cases} -kx_5 & x_5 > 0 \\ kx_5 & x_5 < 0 \end{cases}$

and $\boxed{V = 12k = 12\sqrt{\frac{-\Lambda}{12}}}$ } tuning of 4D c.c.

Then we have a solution where:

$$ds^2 = e^{-2k|X_5|} \eta_{\mu\nu} dX^\mu dX^\nu + dX_5^2 \qquad (0)$$

- Warp factor is sharply peaked at $X_5 = 0$ where the "Planck brane" is located
- X_5 is noncompact, but $\exists$ 4D gravity!

$$M_4^2 = M_5^3 \int dX_5 \, e^{-2k|X_5|} < \infty$$

(contrast S^1 compactification as $R \to \infty$).

The metric (0) is just a slice of AdS_5 ... (up to a $\mathbb{Z}_2$).

b. Relation to D3 metrics

The solution for a stack of N D3s in IIB SUGRA is:

$$ds^2 = h^{-1/2} dX_{\parallel}^2 + h^{1/2} (dr^2 + r^2 d\Omega_5^2)$$

$$\left. h(r) = 1 + \frac{4\pi g_s N (\alpha')^2}{r^4} \right\} + \text{5-form flux}$$

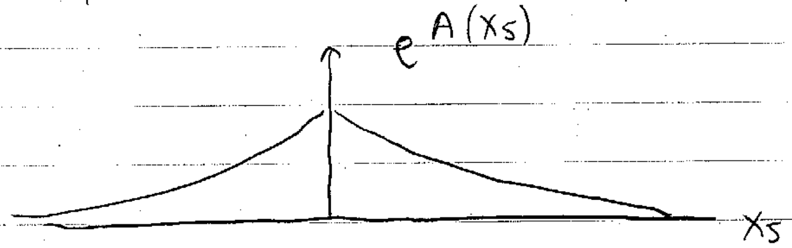
Defining $u = \frac{r}{\alpha'}$ & taking $\alpha' \to 0$ w/ u fixed $\Rightarrow$

$$ds^2 = \alpha' \left[\frac{u^2}{\sqrt{4\pi g_s N}} dx_{\parallel}^2 + \sqrt{4\pi g_s N} \frac{du^2}{u^2} + \sqrt{4\pi g_s N}\, d\Omega_5^2 \right]$$

This is just $AdS_5 \times S^5$ with

$$R_{AdS}^2 = R_{S^5}^2 = \sqrt{4\pi g_s N}\, \alpha'.$$

CHECK: RS metric is same as this, if you ignore S^5, cut-off at U_{max}, & insert a $\mathbb{Z}_2$ image:



C. Hierarchies from IR branes

Consider now a case with 2 branes, located at $x_5 = 0$ & $x_5 = \pi$. ($x_5 \in [0,\pi]$ now)

Then:
$$S = \int d^5x \sqrt{-G}\,(R_5 - \Lambda) + \underbrace{S_{IR}}_{x_5 = \pi} + \underbrace{S_{UV}}_{x_5 = 0}$$

(8)

$$S_{IR} = \int d^4x \sqrt{-g_{IR}} \left(\mathcal{L}_{IR} - V_{IR} \right)$$

$$S_{UV} = \int d^4x \sqrt{-g_{UV}} \left(\mathcal{L}_{UV} - V_{UV} \right)$$

This $S \Rightarrow$ hierarchies of scales in a natural way! Again, consider

$$dS_5^2 = e^{-2A(X_5)} \eta_{\mu\nu} dX^\mu dX^\nu + r^2 dX_5^2$$

($\to$ physical size of X_5 interval is πr)

Einstein Eqns:

$$(\square) \quad 6 \frac{(A')^2}{r^2} + \frac{1}{2}\Lambda = 0$$

$$(\Delta) \quad 3 \frac{A''}{r^2} + \frac{1}{2}\frac{V_{UV}}{r}\delta(X_5) + \frac{1}{2}\frac{V_{IR}}{r}\delta(X_5 - \pi) = 0$$

Defining $k = \sqrt{\frac{-\Lambda}{12}} \Rightarrow A(X_5) = kr|X_5|$

from $(\square)$. (Together w/ jump in A' @ $X_5 = 0$).

- lets extend $X_5 \in [-\pi, \pi]$ & find $\mathbb{Z}_2$ symmetric sol'n.

(9)

$$A = kr|x_5| \rightarrow$$

$$A'' = 2kr\left[\delta(x_5) - \delta(x_5 - \pi)\right]$$

So to solve (Δ) we need

$$V_{UV} = -V_{IR} = 12k$$

Now,

$$ds^2 = e^{-2krx_5}\eta_{\mu\nu}\,dx^\mu dx^\nu + r^2 dx_5^2$$

$$0 \leq x_5 \leq \pi$$

Computing M_4:

$$M_4^2 = \frac{M_5^3}{k}\left(1 - e^{-2kr\pi}\right)$$

→ depends very weakly on r. The 4D graviton must be localized on the UV brane...

Now, also notice

$$g_{\mu\nu}^{UV} = \eta_{\mu\nu} \quad ; \quad g_{\mu\nu}^{IR} = \eta_{\mu\nu}\,e^{-2kr\pi}$$

In particular, a scalar on IR brane w/ cut-off scale mass M_* has:

$$\mathcal{L} \sim \int d^4x \left(g^{\mu\nu}_{IR} \partial_\mu \varphi \partial_\nu \varphi - \frac{1}{2} M_*^2 \varphi^2 \right) \sqrt{-g_{IR}}$$

$$\sim \int d^4x \left(e^{-2kr\pi} \partial_\mu \varphi \partial_\nu \varphi \, \eta^{\mu\nu} - \frac{1}{2} e^{-4\pi kr} M_*^2 \varphi^2 \right)$$

And defining canonical field $\tilde{\varphi} = e^{-kr} \varphi \rightarrow$

$$\mathcal{L} \sim \int d^4x \left(\partial_\mu \tilde{\varphi} \, \partial^\mu \tilde{\varphi} - \frac{1}{2} e^{-2\pi kr} M_*^2 \tilde{\varphi}^2 \right)$$

$$\Rightarrow \quad \boxed{M_{\tilde{\varphi}} = e^{-\pi kr} M_*}$$

So the "natural" energy scale at the IR brane is $M_{\tilde{\varphi}} << M_* \Rightarrow$ light scalars are natural for $kr \sim$ a few.

We'll see that this is a gravity dual of <u>dimensional</u> <u>transmutation</u>. (light scalar mesons of QCD are perfectly natural...).

d. AdS / CFT duality

IIB string theory on $AdS_5 \times S^5$ $\cong$ $\mathcal{N}=4$ $SU(N)$ gauge theory

$$\frac{R_{AdS}^4}{l_s^4} \simeq 4\pi g_{ym}^2 N$$

Precise map:

- Bulk field $\Phi \in AdS \Leftrightarrow$ Operator $\mathcal{O}$ in CFT

Say $ds^2 = e^{-2ky} dx^\mu dx^\nu + dy^2$

$$k = 1/R_{AdS}$$

Then given a ∂ value

$$\Phi(x^\mu, y=-\infty) \equiv \Phi_0(x^\mu)$$

No "UV brane" chopping off $y=-\infty$ here!

the correspondence asserts

$$\left\langle e^{-\int d^n x\, \Phi_0 \mathcal{O}} \right\rangle_{CFT} = e^{-\Gamma(\Phi_0)}$$

$\Gamma(\Phi_0)$ = SUGRA action of sol'n w/ BC Φ_0

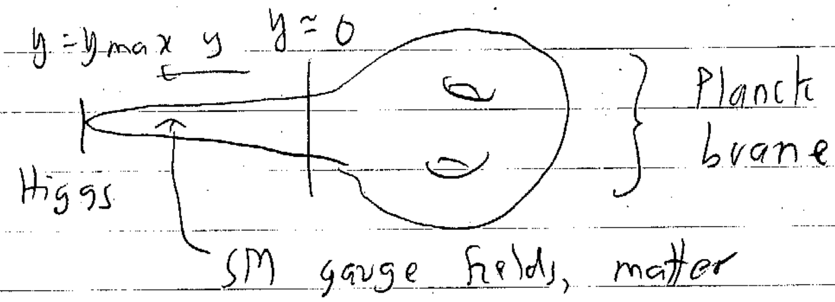
What do cutoffs at UV + IR brane correspond to?

We saw in c) that natural energy scales redshift like e^{-ky}.

- Cutoff at y_{max} (IR) → minimal energy scale $\sim e^{-ky_{max}}$ → CFT develops a mass gap at y_{max}!
- Cutoff at $y_{min} = 0$ ⇒ maximal energy scale. CFT is cutoff in the UV + is coupled to strings / quantum gravity.

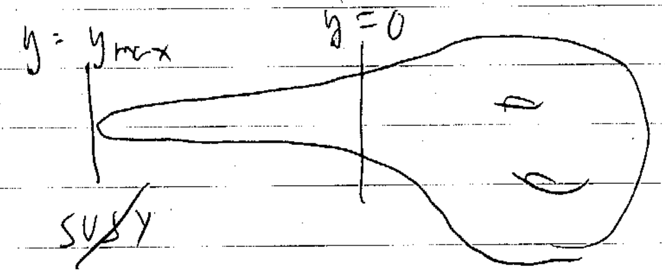
In the next few lectures, we'll try to use this picture. Two obvious ideas:

Ambitious: Forget SUSY



We will see that varying matter field properties in throat geometry can explain Yukawa hierarchies.

Still Interesting:



Use gauge/gravity duality to geometrize DSB!
$\Lambda_{\cancel{SUSY}} \ll M_P$ via warping.

We'll focus on SUSY case. We'll describe simple metastable DSB states, a model of strongly coupled gauge mediation, + finally ideas about SUSY composite models that could explain aspects of flavor structure.