D3-D5 theories with unquenched flavors

José Manuel Penín Ascariz

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E. Conde, H. Lin, A.V. Ramallo and D. Zoakos

AdS/CFT (Maldacena, 1997): relates gravity and field theory

Observation: S.T. D-brane=SUGRA extremal p-brane $\Rightarrow$ Two p.o.v.

D-BRANES

$$\left\{ \begin{array}{l} \text{open str. on D3 wv} \\ \text{closed str. in the bulk} \\ \text{interactions between them} \end{array} \right\} \xrightarrow{\text{low } E,\ \alpha' \to 0} \left\{ \begin{array}{l} \mathcal{N} = 4 \text{ gauge th. on the D3s} \\ \text{free gravity in the bulk} \end{array} \right\}$$

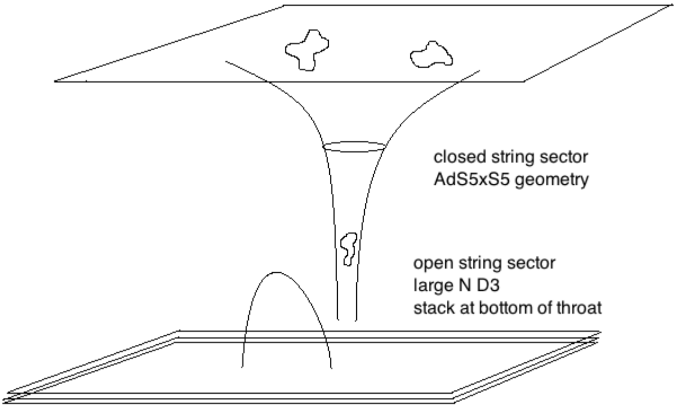
p-BRANES

$$\left\{ \begin{array}{l} r \to \infty,\ E \to 0, \text{ free gravity} \\ r \to 0, \text{ also } E \to 0 \text{ observed at } r \to \infty \\ \text{systems decoupled} \end{array} \right\}$$

Conjecture: identify the low E system in the two p.o.v.

$$\{\ \mathcal{N} = 4 \text{ SYM, gauge SU(N), N} >> 1\ \} = \{\ \text{SUGRA,r} \to 0, \text{ in D-brane bckg.}, \alpha' \to 0\ \}$$

$\Rightarrow$ Duality: ($\lambda >> 1$,grav.) & ($\lambda << 1$,FT)


closed string sector
AdS5xS5 geometry
open string sector
large N D3
stack at bottom of throat

Motivation: d.o.f. of $\mathcal{N}=4$, SYM in adjoint rep. QCD: fundamental rep.!

Fundamentals: how to...? $N_f << N_c \Rightarrow$ probe Dp branes on D3 bckg.
Correspondence now...?
$\Rightarrow$ two p.o.v.

$g_s N_c << 1$ closed & open str. in flat space:

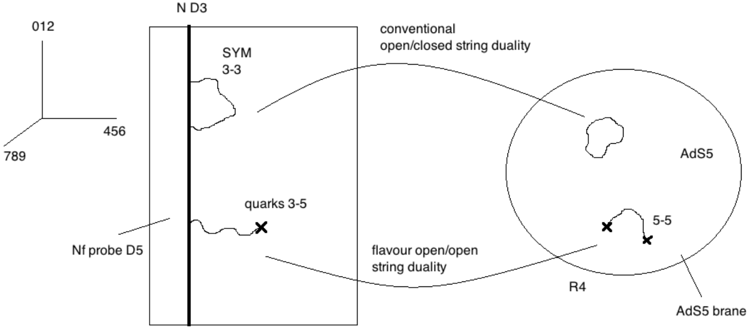
$$\left\{ \begin{array}{l} \text{3-3: } \mathcal{N}{=}4 \text{ SYM}, [g]=0 \\ \text{p-p: coupling} \propto E^{p-3} \\ \text{3-p: bifund. SU(N}_c) \times \text{SU(N}_f) \end{array} \right\} \begin{array}{c} \text{low } E \\ \text{2 sect.} \\ \longrightarrow \end{array} \left\{ \begin{array}{l} \text{1: closed str. in 10d flat \& pp in Dp wv} \\ \text{2: } \mathcal{N}=4 \text{ adj. SU(N}_c) \text{ coupled} \\ \text{to 3-p in fund SU(N}_c) \times \text{SU(N}_f) \end{array} \right\}$$

$g_s N_c >> 1$:

$$\left\{ \begin{array}{l} \text{closed str. \& open p-p in throat of } AdS_5 x S^5. \text{ Non interacting} \\ \text{closed str. \& open p-p in asymptotically flat region. Interacting} \end{array} \right\}$$

Conjecture: identify low E system:

{ $\mathcal{N}$=4 SYM, gauge SU(N), N >>1, coupled to fundamentals }= { type IIB closed str. on $AdS_5 \times S^5$, coupled to open str. on wv of Dp-probes}

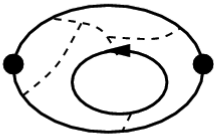

N D3
012
456
789
SYM
3-3
quarks 3-5
Nf probe D5
conventional
open/closed string duality
flavour open/open
string duality
AdS5
5-5
R4
AdS5 brane

Quenched gravity:

- $N_f \to 0 \Rightarrow$ 't Hooft limit
- No backreaction

Quenched field theory:

- mass of fundamentals $= \infty$
- quarks not running into loops
- not dynamical



... beyond the quenched approximation?

Real life $N_f \sim N_c$

$\Rightarrow$ Go to Veneziano limit:

$$N_c \to \infty, N_f \to \infty, \frac{N_c}{N_f} \text{ finite}$$

Captures more physics than 't Hooft limit.

D3-D5 system:

	0	1	2	3	4	5	6	7	8	9
D3	x	x	x	x	-	-	-	-	-	-
D5	x	x	x	-	x	x	x	-	-	-

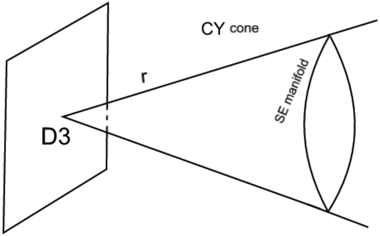
- defect in (x^0, x^1, x^2) where fundamentals live
- 2+1 dim. fundamental matter coupled to gauge theory in 3+1 dim.
- addition of massless hypermultiplete preserves conformality $\Rightarrow$ dCFT

D3 on the tip of a CY cone:

$$ds^2_{CY} = dr^2 + r^2 ds^2_{SE}$$
$$ds^2_{SE} = ds^2_{KE} + (d\tau + A)^2$$

SE: 5d Sasaki-Einstein
KE: 4d Kähler-Einstein base
fiber: $(d\tau + A)$

Examples: S^5, $T^{1,1}$



Ansatz:

$$ds^2 = h^{-\frac{1}{2}}[-(dx^0)^2+(dx^1)^2+(dx^2)^2+e^{2m}(dx^3)^2]+h^{\frac{1}{2}}[dr^2+e^{2g}ds^2_{KE}+e^{2f}(d\tau+A)^2]$$

Problem to solve?

$$S = S_{IIB} + S_{BRANES}$$

$$S_{BRANES} = S_{DBI} + S_{WZ}$$

D3 $\Rightarrow$ coupled to RR $F_{(5)}$

$$F_5 = Q_c(1+*)\epsilon(\mathcal{M}_5)$$

Qc? $\Rightarrow$ charge quantization: $Q_c = \frac{(2\pi)^4 g_s \alpha'^2 N_c}{\mathrm{Vol}(\mathcal{M}_5)}$
D5 $\Rightarrow$ coupled to RR $F_{(3)}$

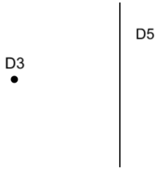
$$S_{WZ} = T_5 \sum_{N_f} \int_{\mathcal{M}_6} \hat{C}_6$$

$$\Rightarrow S_{IIB} = \frac{1}{2\kappa_{10}^2} \int d^{10}x \sqrt{g_{10}} \left[R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}\frac{1}{3!} e^{\phi} F_{(3)}^2 - \frac{1}{2}\frac{1}{5!} e^{2\phi} F_{(5)}^2 \right]$$

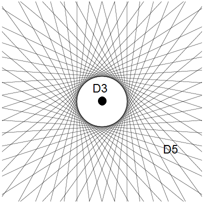
$\Rightarrow$ violation of Bianchi id. for $F_{(3)}$: $dF_{(3)} \sim \delta^{(2)}(\mathcal{M}_6)$. (Challenging to solve)

We use a different approach!!!

Localized embedding



Smeared embedding (massive case)



$$T_5 \sum_{N_f} \int_{\mathcal{M}_6} \hat{C}_6 \rightarrow T_5 \int_{\mathcal{M}_{10}} \Xi \wedge C_{(6)}$$

$$\Rightarrow dF_{(3)} = 2\kappa_{10}^2 T_5 \Xi$$

$\Xi \sim$ charge distribution

Features of smearing:

- no δ-function sources
- still SUSY
- $U(N_f) \rightarrow U(1)^{N_f}$

Ansatz for $F_{(3)}$ (massless flavor)

Kähler form of the KE manifold:

$$J_{KE} = e^1 \wedge e^2 + e^3 \wedge e^4 \Rightarrow J_{KE} = \frac{dA}{2}$$

Define:

$$\hat{\Omega}_2 = e^{i3\tau}(e^1 + ie^2) \wedge (e^3 + ie^4)$$

Ansatz:

$$F_{(3)} = Q_F dx^3 \wedge \mathrm{Im}(\hat{\Omega}_2)$$

$$\Rightarrow dF_{(3)} = -3Q_f dx^3 \wedge \mathrm{Re}(\hat{\Omega}_2) \wedge (d\tau + A) = 2\kappa_{(10)}^2 T_5 \Xi$$

$\Rightarrow$ Dictates smearing form

Bosonic SUSY background in type IIB SUGRA?

$$\Rightarrow \text{BPS equations:} \left\{ \begin{array}{l} \delta\lambda = 0 \ (\textit{dilatino}) \\ \delta\psi_\mu = 0 \ (\textit{gravitino}) \end{array} \right\}$$

Leads to:

$$\left\{ \begin{array}{l} h' = -Q_c e^{-4g-f} - Q_f e^{\frac{\phi}{2}-m-2g} h \\ \phi' = Q_f e^{\frac{\phi}{2}-m-2g} \\ g' = e^{f-2g} \\ f' = 3e^{-f} - 2e^{f-2g} + \frac{Q_f}{2} e^{\frac{\phi}{2}-m-2g} \end{array} \right.$$

Unflavored solution:

$$\Rightarrow ds^2_{unflav} = h^{-\frac{1}{2}} dx^2_{1,3} + h^{\frac{1}{2}} \left[\frac{d\xi^2}{F(\xi)} + \xi^2 ds^2_{KE} + \xi^2 F(\xi)(d\tau + A)^2 \right]$$

where $F(\xi) = 1 - \frac{b^6}{\xi^6}$, $b^6 = \frac{g_3}{4}$ Case $g_3 = 0 \Rightarrow$ Conformal $AdS_5 \times S^5$

Flavored scaling solution:

$$ds^2_{\rm scaling} = ds^2_5 + d\hat{s}^2_5$$

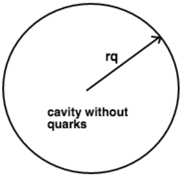
$$ds^2_5 = \frac{r^2}{R^2} \left[dx^2_{1,2} + \left(\frac{4Q_f}{3} \right)^{\frac{4}{3}} \frac{(dx^3)^2}{r^{\frac{4}{3}}} \right] + R^2 \frac{dr^2}{r^2},$$

$$d\hat{s}^2_5 = \bar{R}^2 \left[ds^2_{KE} + \frac{9}{8}(d\tau + A)^2 \right]$$

$\Rightarrow$ Anisotropic scale transf. invariance:

$$r \to \frac{r}{\lambda}, \quad x^{0,1,2} \to \lambda x^{0,1,2}, \quad x^3 \to \lambda^{\frac{1}{3}} x^3, \quad e^{\phi} \to \lambda^{-\frac{2}{3}} e^{\phi}$$

Massive flavors: Cavity $r < r_q$ without charge. $r_q \sim m_q$



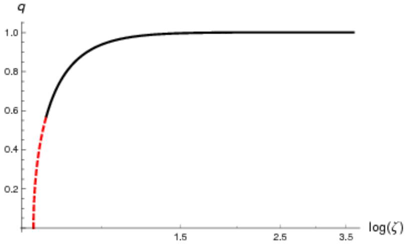
Modified ansatz: $Q_f \to Q_f\, p(r)$

$p(r)$ profile $\begin{cases} p(r \to \infty) = 1 \\ p(r < r_q) = 0 \end{cases}$

Solution for step function:

$$p(r) = \Theta(r - r_q)$$

$\left.\begin{cases} r < r_q \Rightarrow \text{unflavored} \\ r > r_q \Rightarrow \text{massless flavored} \end{cases}\right\}$ Interpolation



What about $T \neq 0$?

- Finite temperature $\rightarrow$ blackening factor
- Breaks SUSY $\rightarrow$ deal directly with 2nd order EOMs

$\Rightarrow$ black hole for D3-D5:

$$ds^2 = \frac{r^2}{R^2}\left[-bdt^2+(dx^1)^2+(dx^2)^2+\left(\frac{4Q_f}{3}\right)^{\frac{4}{3}}\frac{(dx^3)^2}{r^{\frac{4}{3}}}\right]+R^2\frac{dr^2}{br^2}+\bar{R}^2\left[ds^2_{CP^2}+\frac{9}{8}(d\tau+A)^2\right]$$

$$b(r) = 1-\left(\frac{r_h}{r}\right)^{\frac{10}{3}}$$

$r_h \rightarrow$ horizon radius $\rightarrow$ related to the temperature.

- Addition of flavor branes necessary for modelling fundamental matter
- Beyond the probe approximation =more physics+control on the flavor dynamics
- Generic case with color D3 branes placed on the tip of a CY cone with a general SE space
- BPS equations integrated in the unflavored case
- Particular solution with anisotropic invariance
- Extended ansatz for the case of massive flavor, numerically solved
- Construction of black hole

Thank you!