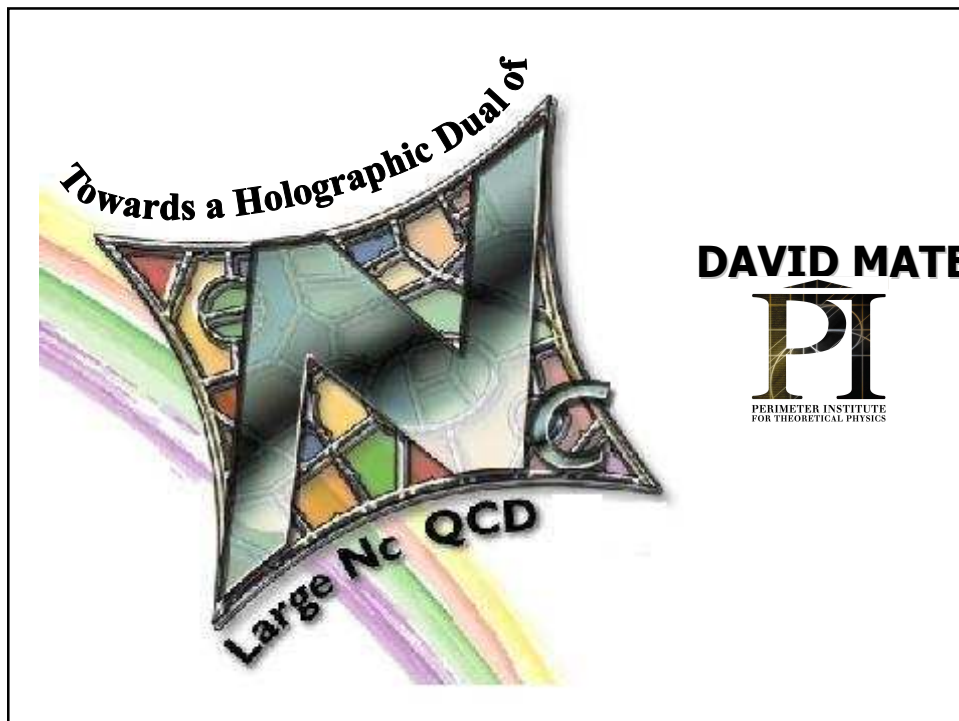


## Towards a Holographic Dual of Large-N QCD



### Based on:

- Towards the Holographic Dual of Large  $N_c$  QCD (hep-th/0311270)

M. Kruczenski, DM, R. Myers and D. Winters

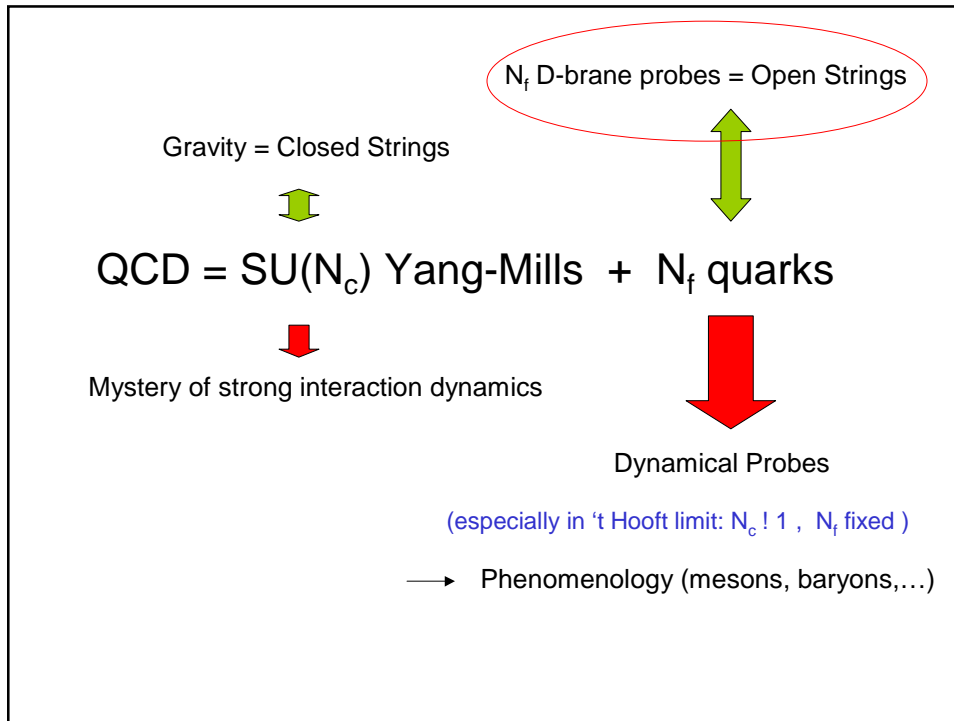
- The Holographic Life of the  $\eta'$  (hep-th/0404260)

J. Barbon, C. Hoyos, DM and R. Myers

### Related work:

- Meson Spectroscopy in AdS/CFT with Flavour (hep-th/0304032)

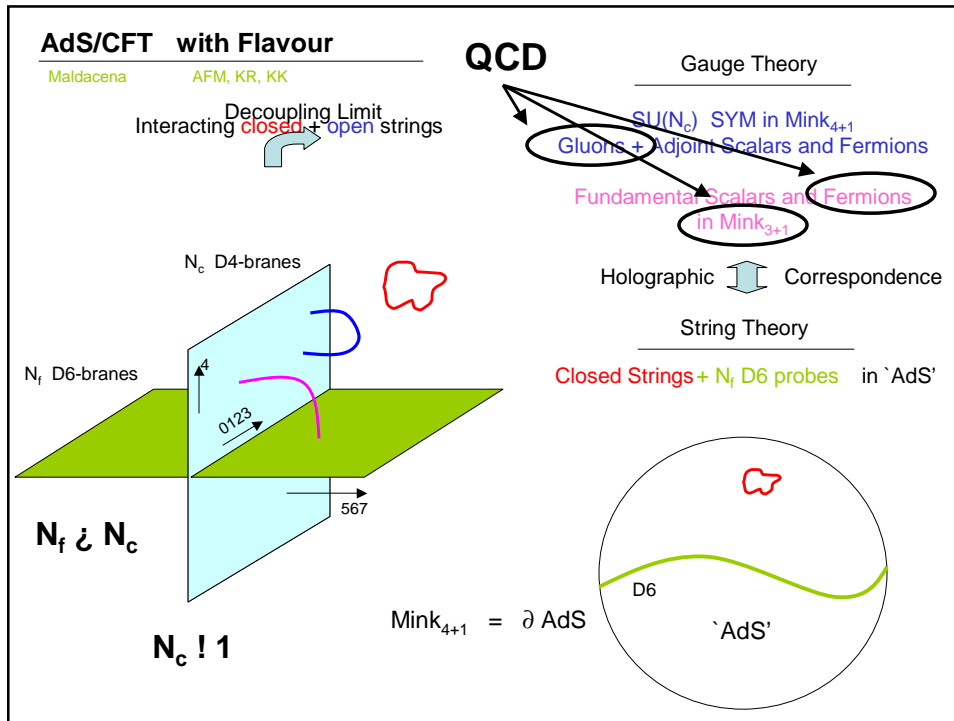
M. Kruczenski, DM, R. Myers and D. Winters



## Plan

- AdS/CFT with Flavour
- QCD from D4/D6
- $N_c=1$ ,  $N_f=1$ :  $S\chi$ SB and meson spectrum  
(goldstone boson)
- $N_c=1$ ,  $N_f > 1$ : Holographic Vafa-Witten
- $N_c$  finite:  $\eta^0$  physics
- Baryons and Skyrmions

# Towards a Holographic Dual of Large-N QCD



**QCD from D4/D6**

$N_c$  D4: 0 1 2 3 4 \_ \_ \_ \_ \_  
 $N_f$  D6: 0 1 2 3 \_ 5 6 7 \_ \_  
 U(1)<sub>A</sub>

On D4-branes: 4+1  $SU(N_c)$  SYM = Gluons + Adjoint Scalars and Fermions

Compactify 4-direction with antiperiodic boundary conditions for Adjoint Fermions Witten

- Renders theory four-dimensional at  $E \zeta M_{KK} = 1 / R_{KK}$
- Breaks SUSY: Gives masses to Adjoint Fermions (tree level) and Adjoint Scalars (one-loop)

With D6-branes:  $N_f$  flavours of 3+1 Fundamental Scalars + Dirac Fermions  $\psi_L + \psi_R$

- Fundamental Scalars acquire one-loop mass
- Fundamental Fermions remain massless because protected by chiral  $U(1)_A$

**So do we have QCD at  $E \zeta M_{KK}$  ?**

**So do we have strictly QCD ?** No, but many features are captured, and confining theory in its own right.

Energy scale  $E$  with markers  $M_{KK}$  and  $\Lambda_{QCD}$ .

Region  $\Lambda_{QCD} < E < M_{KK}$ : Weakly coupled gluons + quarks

But:  $\Lambda_{QCD} \gg M_{KK} e^{-\frac{\#}{g_{YM}^2 (M_{KK}) N_c}}$

Decoupling  $\rightarrow g_{YM}^2 N_c < 1$

String description has: Curvature  $\gg 1/g_{YM}^2 N_c$

Supergravity approximation  $\rightarrow g_{YM}^2 N_c \ll 1$

**The Vacuum: D6-brane Embedding and  $S\chi SB$**

D6-brane probe in D4-brane background:

$N_c$  D4: 0 1 2 3 4 \_ \_ \_ \_ \_

$N_f=1$  D6: 0 1 2 3 \_ 5 6 7 \_ \_

$\lambda$        $r, \phi$

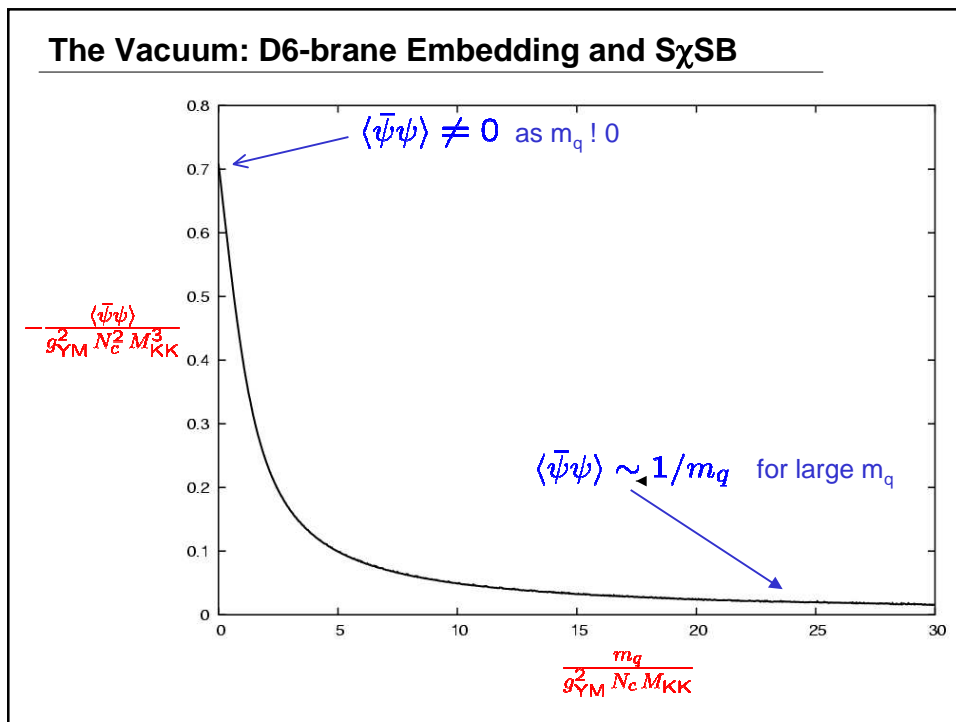
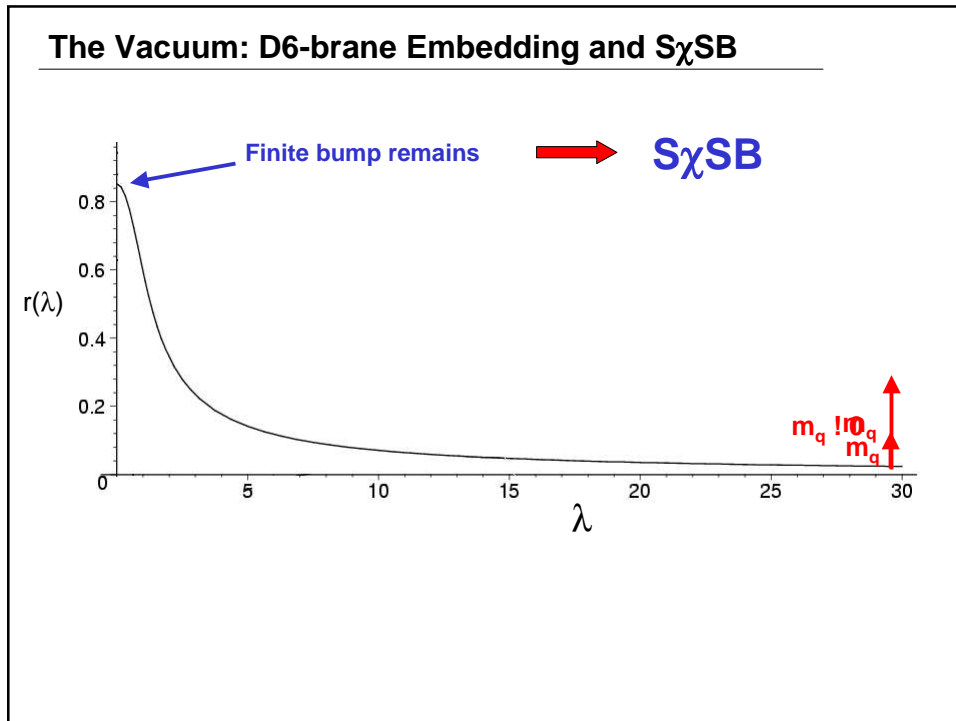
Minimum energy  $\rightarrow \phi = \text{const}, r = r(\lambda)$

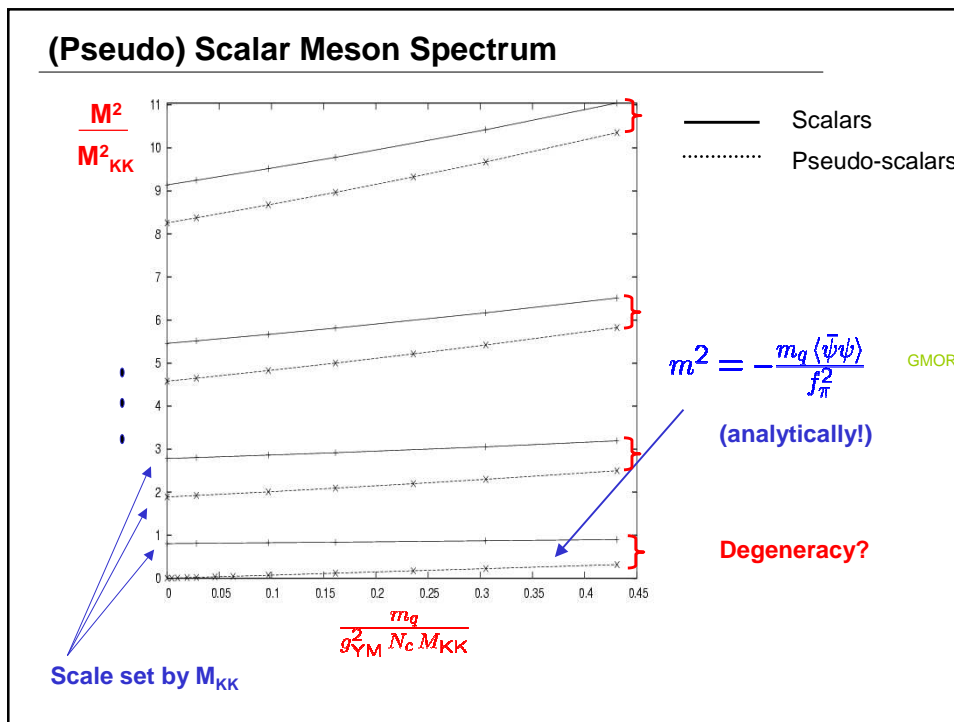
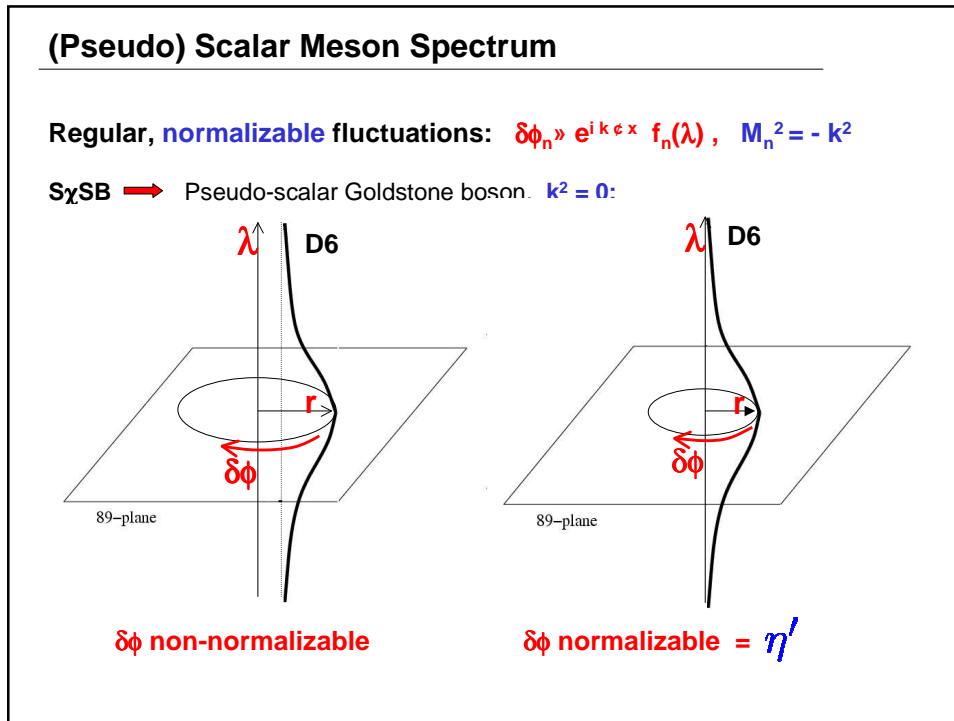
Asymptotically ( $\lambda \rightarrow 1$ ):  $r = a + b / \lambda + \dots$

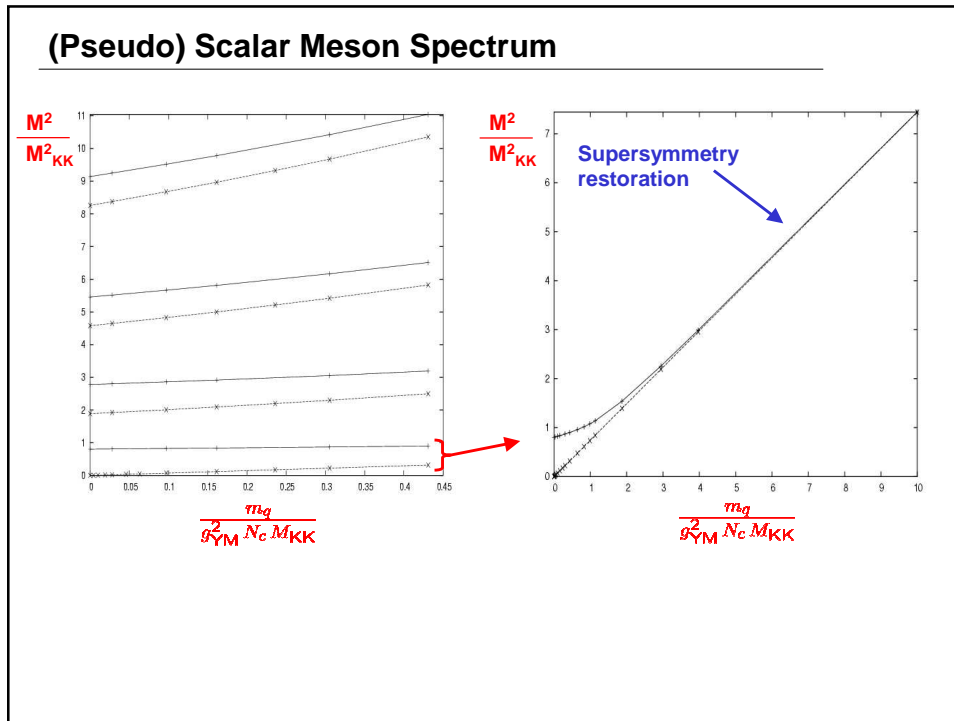
$m_q$   $\swarrow$  Proportional  $\searrow$   $\langle \bar{\psi}\psi \rangle$

Field/Operator Correspondence:  $r(\lambda) \leftrightarrow \mathcal{O} = \bar{\psi}\psi$

Vacuum embedding: Choose  $a$  and adjust  $b$  for regularity  $\rightarrow \langle \bar{\psi}\psi \rangle(m_q)$







### Holographic Vafa-Witten Theorem and $N_f > 1$ Spectrum

QCD with  $N_f$  flavours of mass  $m_q > 0 \rightarrow U(N_f)_V$  is not spontaneously broken

In brane picture  $U(N_f)_V$  is gauge symmetry:

**Unbroken**

~~Spectrum  $\propto N_f^2$  masses pseudo-scalars~~

~~Goldstone Bosons of  $U(N_f)_V \times U(N_f)_A \rightarrow U(N_f)_V$  ?~~

~~Not clear~~

- Gauge theory contains  $\bar{\psi}_i X \psi^i$
- Non-derivative interactions (from D6s action)

~~String gauge theory = based on Gauge Invariance~~

~~NA DBI = A DBI +  $[X_i, X_j]$   $\leftarrow$   $F_{ij} = \partial_{[i} A_{j]} + [A_i, A_j]$  on D9-brane~~

~~Spontaneously Broken~~





### Generation of $\eta'$ mass

String corrections to  $\eta'$  propagator:

**Gauge theory**

**String analog of de Rujula-Georgi-Glashow:**  
Splits  $U(N_f)$  singlet from non-singlets...

**Provided  $\eta'$ -glueball coupling is non-zero at  $p=0$  !**    **Shown in SUGRA limit from D6 couplings**

### A quantitative test: the tadpole

Master substitution  $\theta \rightarrow \theta + N_f \phi$  implies

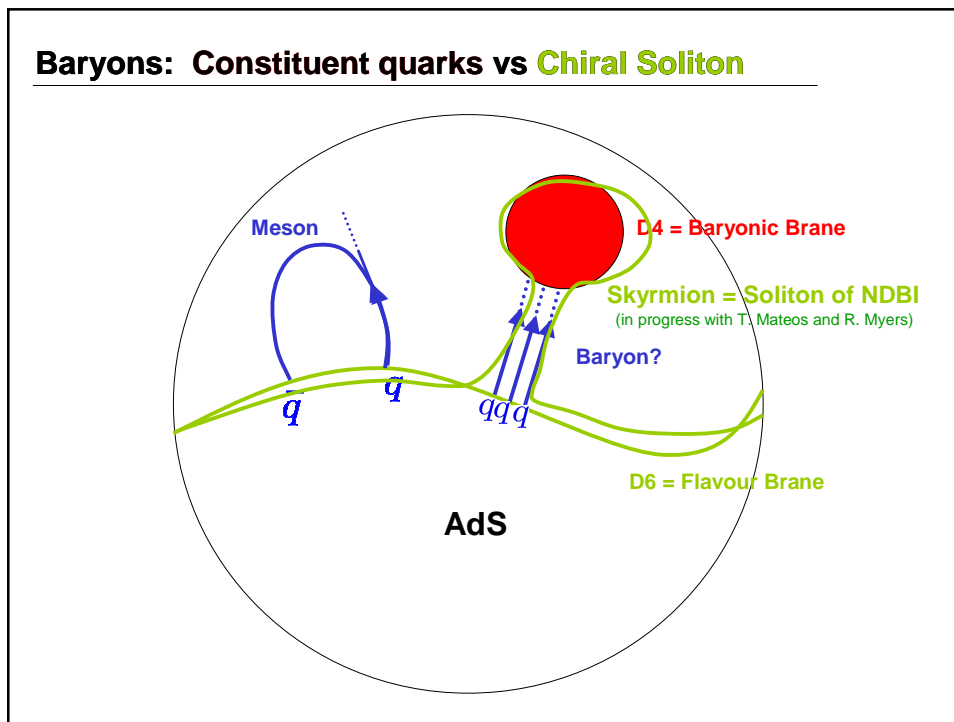
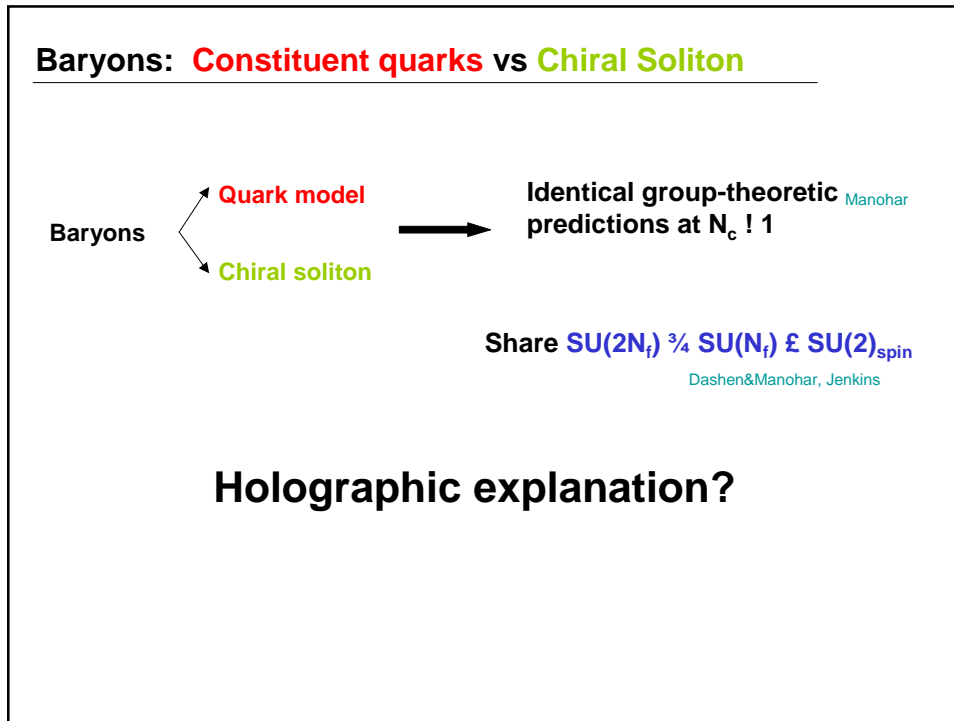
$$V(\phi) = \chi_{YM} \theta N_f \phi + \dots$$

Open string calculation (D6-branes):

- $\rightarrow *F_2 = F_8 = dC_7 \neq 0$
- $\rightarrow S_{D6} = \int_{D6} C_7$
- $\rightarrow V(\phi) = \chi_{YM} \theta N_f \phi$

Closed string calculation (no D6-branes):

- $\theta = \int_{S^1} C_1 \rightarrow 0 \neq F_2 \propto \theta$
- $\rightarrow \delta E_{vac} = \int_{Spacetime} |F_2|^2 = \frac{1}{2} \chi_{YM} \theta^2$
- $\rightarrow \chi_{YM} = \frac{(g_{YM}^2 N_c)^3}{4 \cdot (3\pi)^6} M_{KK}^4$



**Conclusions**

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**How close string theory  
can get to QCD remains to be seen...**

**But at the very least it provides a new, geometric way  
of looking at old problems.**