Feeling fivebranes in matrix models

by Monte Carlo Simulation

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1. Introduction

M(atrix) Theory (BFSS model)

[de Wit-Hoppe-Nicolai '88,
Banks-Fischler-Shenker-Susskind '96]

Defined by

- D0-brane quantum mechanics
- Matrix regularization of super-membrane theory

$$X_M(\tau,\sigma_1,\sigma_2) \to \underbrace{\hat{X}_M(\tau)}_{N_c\times N_c \text{ matrix}}$$

Non-perturbative formulation of M-theory

- Correct supergraviton interactions
- M2 is realized as a classical configuration.

1. Introduction

Gauge/gravity duality for BFSS

[Itzhaki–Maldacena–Sonnenschein–Yankielowicz '98]

Thermal BFSS (D0 QM) ⟷ **IIA SUGRA around black 0-branes**

$$\frac{\lambda}{U^3 N_c^{\frac{4}{7}}} \sim \langle e^{\phi} \rangle^{\frac{4}{7}}$$

$$\frac{U^3}{\lambda} \sim \left(\frac{\alpha'}{R^2}\right)^2$$

U: energy scale

R: curvature radius

$\lambda = g_{YM}^2 N_c$

Hawking temperature: $T \sim \frac{1}{L}\left(\frac{u_0}{L}\right)^{\frac{5}{2}}$

L: length scale

1. Introduction

Gauge/gravity duality for BFSS

Success in computational simulation:

Hanada–Hyakutake–Ishiki–Nishimura ’14

Correct T and g_s expansion with α' correction from BFSS

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When we go back to M-theory description,

How does M5 play a role in Matrix model?

cf) transverse M5 $\cdots$ M5 charges in BMN model

[Maldacena-Sheikh Jabbari-Raamsdonk '02]

longitudinal M5 $\cdots$ BD model [Berkooz-Douglas '96]

($\rightarrow$ D4 in IIA)

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longitudinal M5 $\cdots$ BD model [Berkooz–Douglas '96]
(→ D4 in IIA)

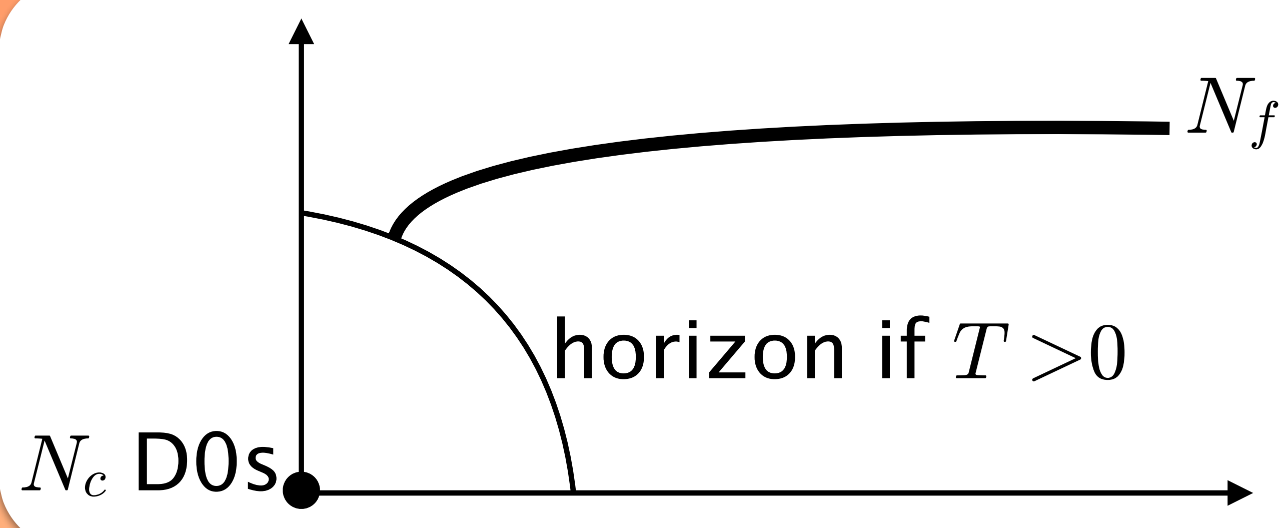
Let's compute BD model
by Monte Carlo simulation.

2. BD model

D0 quantum mechanics with probe D4

[Berkooz–Douglas '96]

$SO(9)$ symmetry breaks down to $SO(5)\times SO(4)$.



quench approx.
$N_f \ll N_c$

field contents:

D0–D0 strings

X^M: $N_c\times N_c$ Hermitian

Ψ: 2 $N_c\times N_c$ symplectic Majoranas

D0–D4 strings

Φ_ρ: $N_c\times N_f$ complex

χ: $N_c\times N_f$ Weyl

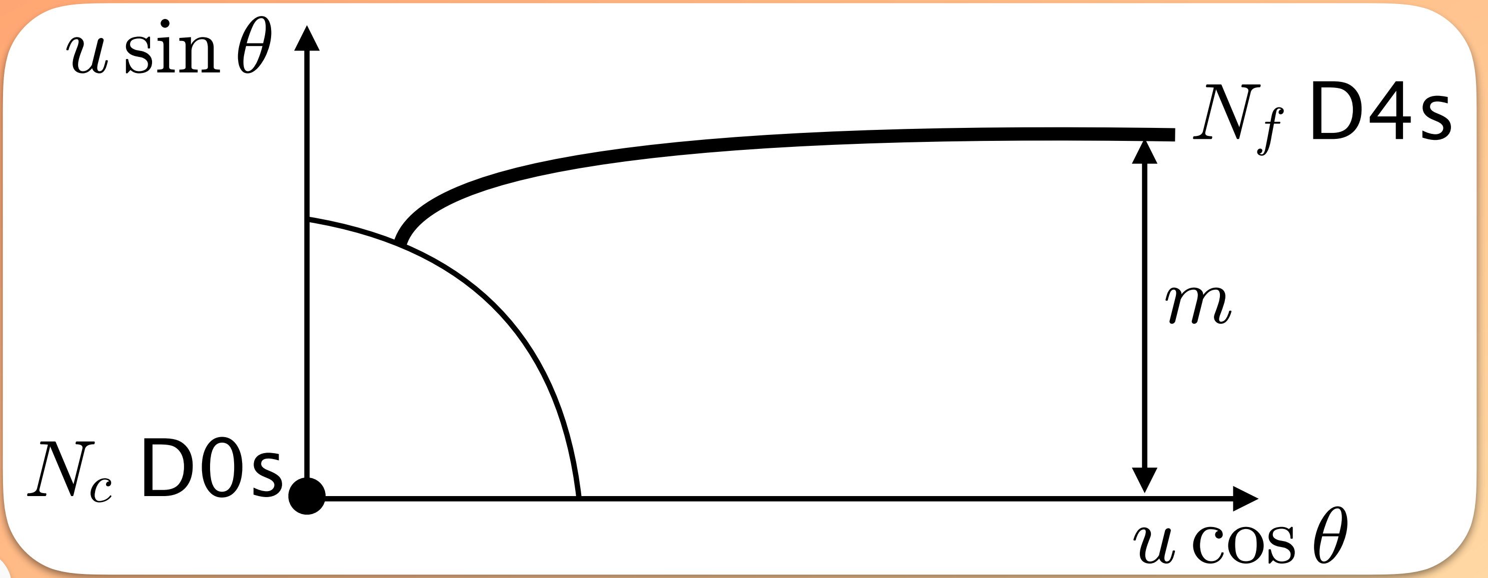
(in the meaning of SO(5) spinor)

$M=\underbrace{1,\ldots,5}_{SO(5)},\underbrace{6,\ldots,9}_{SO(4)}$ $\qquad$ $\rho,\dot{\rho}=1,2\ :\ SU(2)\times SU(2)\sim SO(4)$ sym.

3. Monte Carlo simulation of BD model

[Filev-O'Connor '15]

Gauge/gravity agreement in Mass-Condensate plot



Gauge theory side

$$c = \frac{\partial F}{\partial m} \qquad (F = -\beta^{-1} \ln Z)$$

Gravity side

classical sol. of DBI eom:

$$\sin[\theta(u)] = \tilde{m}\frac{u_0}{u} + \tilde{c}\frac{u_0^3}{u^3} + \cdots$$

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[Filev-O'Connor '15]

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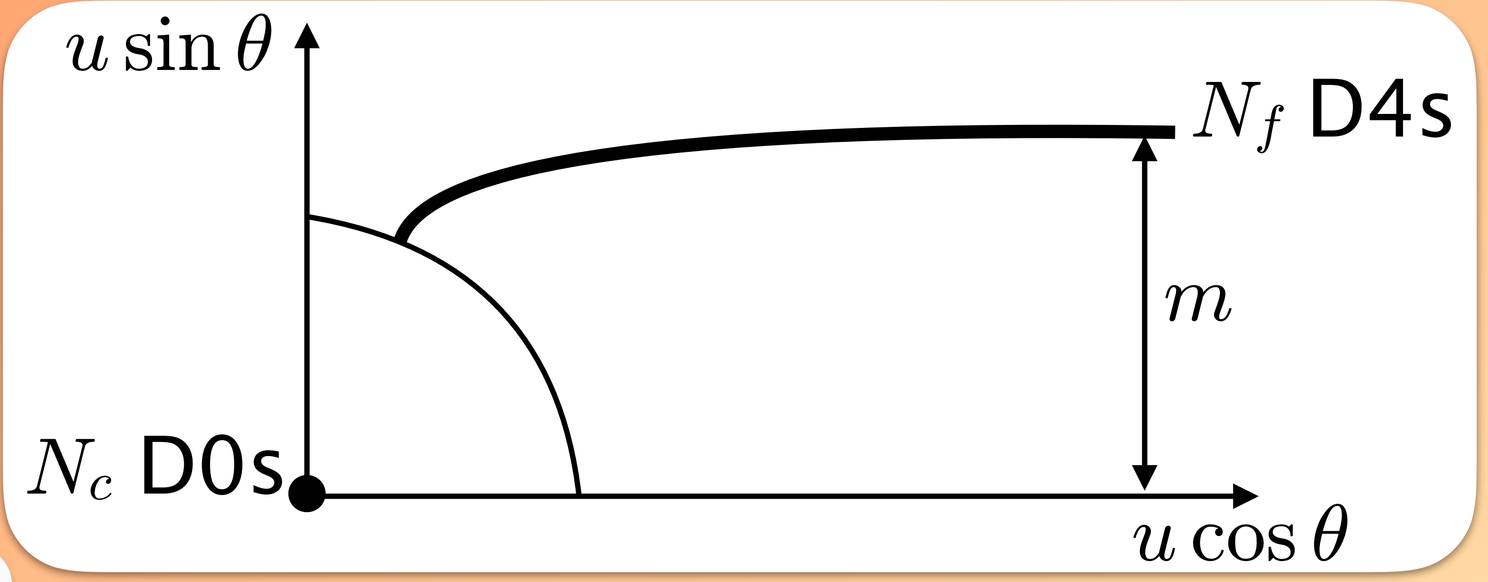

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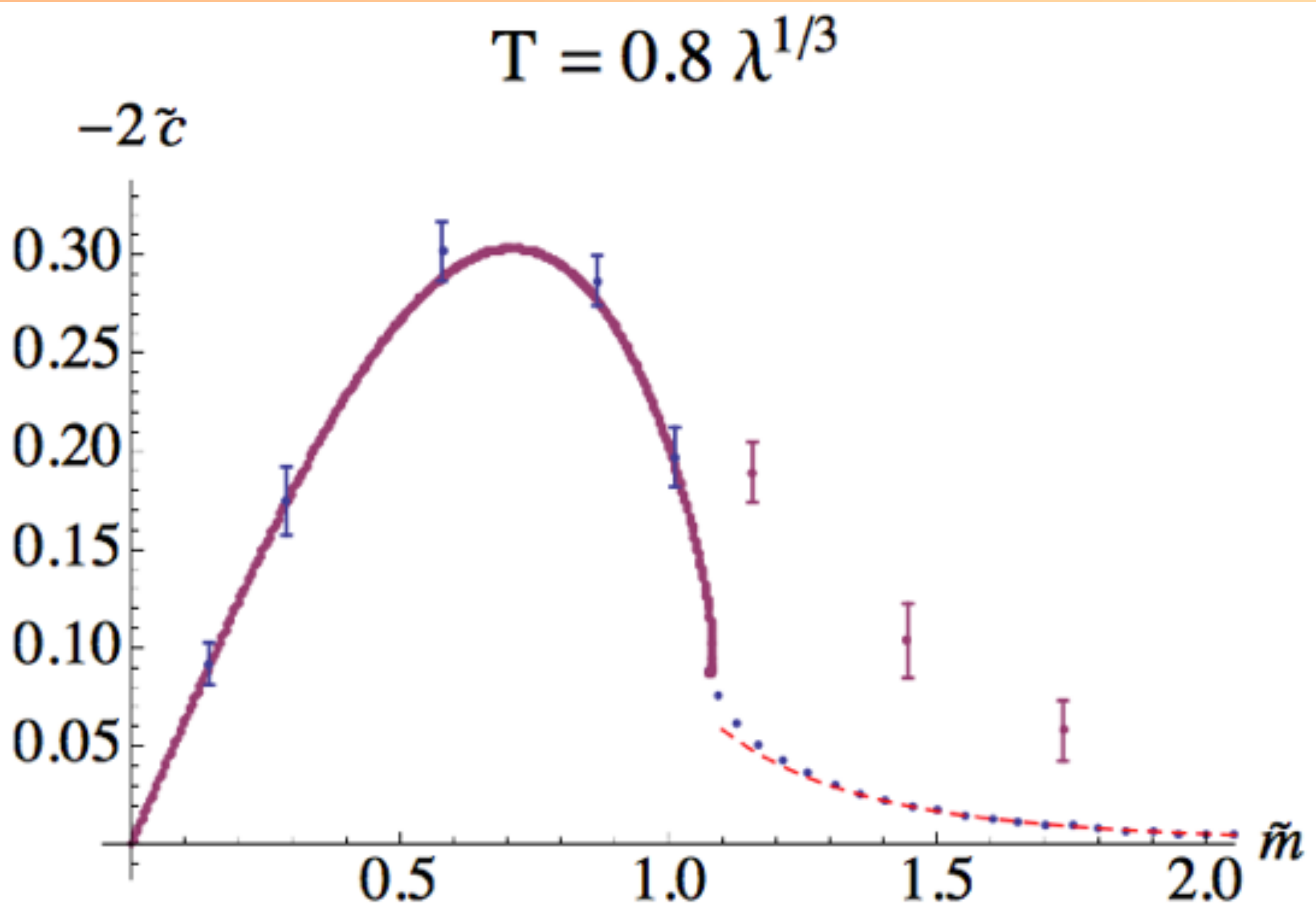


Agreement at small mass!
(deconfined phase)

solid red line: gravity side
points w/ error bars: BD model

[Filev-O'Connor '15]

4. More BD model simulation

– High temperature expansion

[YA–Filev–Kovacik–O'Connor to appear]

- Able to analyze BD model by 0–mode dynamics
- Further check in high temperature regime

– Deformed BD model (KLY model) [Kim–Lee–Yi '02]

- M–theory with M5 in pp–wave background

(analog of BMN model)

→ # of SUSY in KLY model is same as BD model.

- Difficulty in BFSS and BD model would be gone.

(due to flat–direction)

→ smaller N_c can be investigated more easily

5. Summary

- Monte Carlo simulation of
  BD model (D0 QM with probe D4)

- Agreement between gauge & gravity sides
  for condensate c

- We are working on
  BD model and the deformed one
  to get more (nontrivial) gauge/gravity evidence.

Backups

1. Introduction

Gauge/gravity duality for BFSS

IIA SUGRA around black 0-branes $\longleftrightarrow$ Thermal BFSS (D0 QM)

$$\langle e^{\phi} \rangle^{\frac{4}{7}} \sim \frac{\lambda}{U^3 N^{\frac{4}{7}}}$$

$$\left(\frac{\alpha'}{R^2}\right)^2 \sim \frac{U^3}{\lambda},$$

U: energy scale

R: curvature radius

$\lambda = g_{YM}^2 N$

near-horizon black 0-brane solution:

$$ds^2 = -\left(\frac{u}{L}\right)^{\frac{7}{2}} \left(1 - \left(\frac{u_0}{u}\right)^7\right) dt^2 + \left(\frac{L}{u}\right)^{\frac{7}{2}} \left\{ \frac{du^2}{1 - \left(\frac{u_0}{u}\right)^7} + u^2 d\Omega_8^2 \right\}$$

Hawking temperature: $T \sim \frac{1}{L} \left(\frac{u_0}{L}\right)^{\frac{5}{2}}$

L: length scale

1. Introduction

My motivation:

Matrix model as
a non-perturbative formulation of string/M theory

How about M5 in BFSS?

longitudinal M5

transverse M5

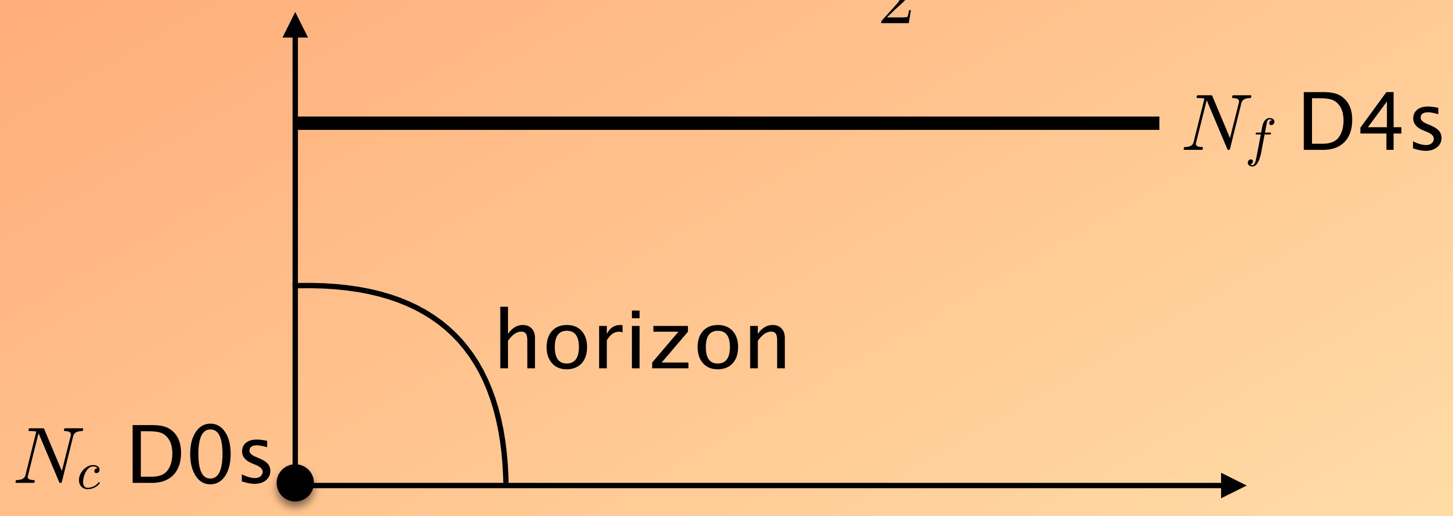
D0 quantum mechanics	$\longrightarrow$	light-front M-theory (BFSS matrix model)
with flavors from D4		with BG M5
		M2 as classical config.

2. BD model

D0 quantum mechanics in background D4

$SO(9)$ symmetry breaks down to $SO(5)\times SO(4)$.

$$S = N_c \int_0^\beta d\tau \Big[\mathrm{Tr}\left(\frac{1}{2}D_\tau X^M D_\tau X^M + \frac{1}{4}[X^M, X^N]^2\right) + \mathrm{tr}\Big(D_\tau \bar{\Phi}^\rho D_\tau \Phi_\rho + \bar{\Phi}^\rho (X^a - m^a)^2 \Phi_\rho - \bar{\Phi}^\rho [\bar{X}^{\sigma\dot{\rho}}, X_{\rho\dot{\rho}}]\Phi_\sigma - \frac{1}{2}\bar{\Phi}^\rho \Phi_\sigma \bar{\Phi}^\sigma \Phi_\rho + \bar{\Phi}^\rho \Phi_\rho \bar{\Phi}^\sigma \Phi_\sigma \Big) + \text{fermions} \Big]$$



$N_f \ll N_c$

X^M: $N_c\times N_c$ matrix field
M=1,…,9
a=1,…,5 : $SO(5)$ sym.

Φ_ρ: $N_c\times N_f$ matrix field
$\rho, \dot{\rho} = 1, 2$: $SU(2)\times SU(2) \sim SO(4)$ sym.

2. BD model

D0 quantum mechanics in background D4

$$S = N_c \int_0^\beta d\tau \Bigg[\mathrm{Tr}\left(\frac{1}{2}D_\tau X^a D_\tau X^a + \frac{1}{2}D_\tau \bar{X}^{\rho\dot{\rho}} D_\tau X_{\rho\dot{\rho}} + \frac{1}{2}\lambda^{\dagger\rho} D_\tau \lambda_\rho + \frac{1}{2}\theta^{\dagger\dot{\rho}} D_\tau \theta_{\dot{\rho}}\right)$$

$$+ \mathrm{tr}\left(D_\tau \bar{\Phi}^\rho D_\tau \Phi_\rho + \chi^\dagger D_\tau \chi\right)$$

$$+ \mathrm{Tr}\left(\frac{1}{4}[X^a, X^b]^2 + \frac{1}{2}[X^a, \bar{X}^{\rho\dot{\rho}}][X^a, X_{\rho\dot{\rho}}]\right)$$

$$+ \frac{1}{2}\,\mathrm{Tr}\sum_{A=1}^{3} \mathcal{D}^A \mathcal{D}^A + \mathrm{tr}\left(\bar{\Phi}^\rho (X^a - m^a)^2 \Phi_\rho\right)$$

$$+\text{fermion coupling terms}\Bigg]$$

$$\mathcal{D}^A = \sigma^{A\ \sigma}_{\rho} \left(\frac{1}{2}[\bar{X}^{\rho\dot{\rho}}, X_{\sigma\dot{\rho}}] - \Phi_\sigma \bar{\Phi}^\rho\right)$$