Holography for Black Hole Microstates

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(with I. Bena, E. Moscato, R. Russo, M. Shigemori, N. Warner)

Outline

- A quick overview of black hole paradoxes:
  - the information and entropy problems
  - the Strominger-Vafa “solution”
- The dual CFT side:
  - microstates of the D1-D5 CFT
- Supergravity construction of D1-D5-P microstates:
  - superstrata
- Holography:
  - deriving geometry from the CFT

The information paradox

- Hawking: classical horizons coupled to quantum matter emit particle pairs in an entangled state
- When the black hole has completely evaporated the outside radiation is entangled with nothing
  $\Rightarrow$ one cannot associate to it a definite quantum state
- Mathur, AMPS: to restore unitarity one has to either
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  - introduce non-localities (ER=EPR, Papadodimas-Raju)
  - modify the classical horizon (fuzzballs, firewalls)

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The entropy problem

- Only non-susy black holes evaporate
- One aspect of the information paradox survives in the susy limit: an entropy can be associated to the black hole

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$$S_{BH} = \frac{A_H}{4\,G} \stackrel{?}{=} \log(\#\text{microstates})$$

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Strominger-Vafa counting

- In string theory microstates can be counted by representing black holes as bound states of N D-branes ($N \gg 1$)
- Example:

$$\boxed{\text{D1-D5-P on } \mathbb{R}^{4,1} \times S^1 \times T^4}$$

- At small gravitational coupling ($g_s \to 0$) the bound state of D-branes is described by a CFT
- Microstates of the CFT can be counted

$$\log(\#\text{microstates}) = 2\pi\sqrt{n_1 n_5 n_p} = S_{BH}$$

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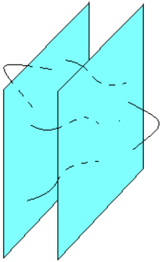
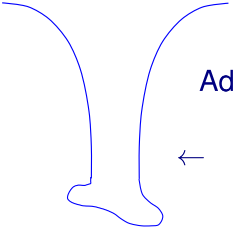
Microstate geometries

- For large $g_s N$, D-branes backreact on spacetime
- For particular microstates (coherent states), the backreaction is well described by supergravity

$g_s N \sim 0$ $\qquad$ $g_s N \gg 1$



$\rightarrow$



$\mathbb{R}^{4,1} \times S^1$

$AdS_3 \times S^3$

$\leftarrow \quad r \sim R_{\text{Hor}}$

no horizon!

D-brane microstate $\qquad$ microstate geometry

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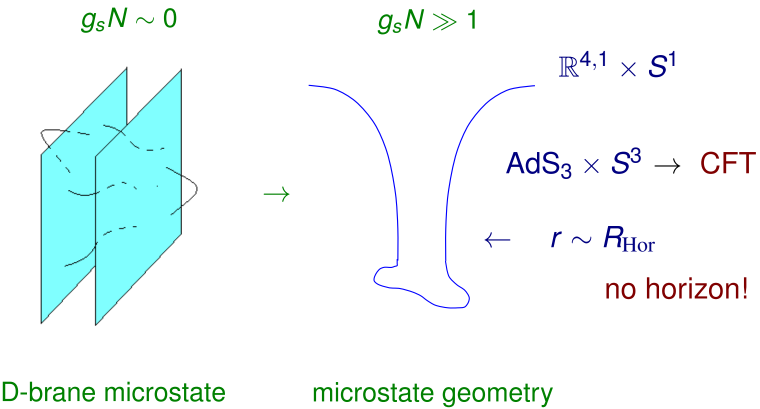


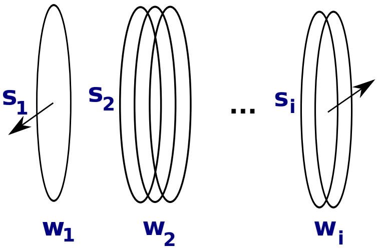
The D1-D5 CFT

- At a special point in moduli space, the low energy limit of the D1-D5 system is described by the

$$(T^4)^N/S_N \text{ orbifold with (4,4) susy}$$

  where $N = n_1 n_5$

- States carrying D1-D5 charges are RR ground states



$\sum_i N_i w_i = N$

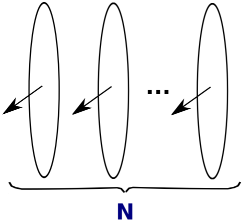
N_i # strands of winding w_i and "spin" s_i

$\Leftrightarrow \quad \prod_i (|s_i\rangle_{w_i})^{N_i}$

Examples

- The simplest D1-D5 state is the maximally rotating one

$$|+,+\rangle_1^N \quad \leftrightarrow$$



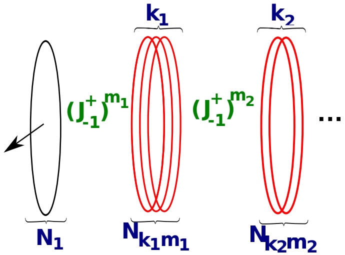
- Spectral flow maps this state into the SL(2,$\mathbb{C}$) invariant vacuum
- The dual geometry is (in appropriate coordinates)

$$\mathrm{AdS}_3 \times S^3$$

- Adding “strands” with different lengths and spins produces on the gravity side deformations of $\mathrm{AdS}_3 \times S^3$
(Lunin, Mathur; Kanitschieder, Skenderis, Taylor)

Adding momentum

- The D1-D5 black hole has vanishing horizon area in classical supergravity $\Rightarrow$ need to add momentum
- Momentum is carried by left-moving excitations on the CFT
- For example, one can act with modes of the R-current



Note:

$J^+_{-1}|+,+\rangle_1 = 0$

$(J^+_{-1})^m|0,0\rangle_k = 0$ for $m > k$

- If $N_{k_i m_i} \gg 1$ the states backreact semi-classically on spacetime

How to construct the dual geometries?

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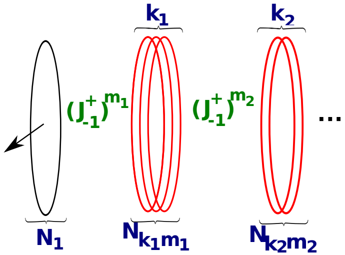

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General susy ansatz

- The most general geometry preserving the same supercharges as the D1-D5-P black hole and T^4-invariant is

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\Big(du+\omega+\frac{\mathcal{F}}{2}(dv+\beta)\Big)+\sqrt{\mathcal{P}}ds_4^2\,,\ \mathcal{P} = Z_1 Z_2 - Z_4^2$$

where $v = \frac{t+y}{\sqrt{2}}$, $u = \frac{t-y}{\sqrt{2}}$

- It is encoded by

  0) ds_4^2 (4D euclidean metric), β (1-form in 4D)

  1) Z_1 , Z_2 , Z_4 (0-forms)

  2) ω (1-form in 4D), $\mathcal{F}$ (0-form)

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1) Z_1 , Z_2 , Z_4 (0-forms) $\Rightarrow$ linear and homogeneous eqs.

2) ω (1-form in 4D), $\mathcal{F}$ (0-form)

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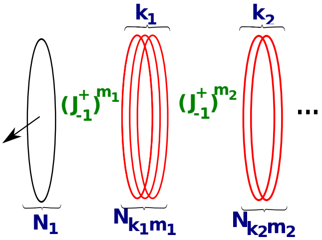
A class of D1-D5-P geometries

- Remember we look for the geometry dual to



- Strands of type $(J^+_{-1})^m|0,0\rangle_k$ contribute linearly to Z_4

$$Z_4 = \sum_{k,m} b_{k,m}\, Z_4^{(k,m)} \quad \text{with} \quad b^2_{k,m} \propto N_{k,m}$$

- Regularity implies that Z_1 has terms quadratic in $b_{k,m}$

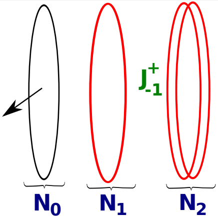
Holographic 1-point functions

- Can we test the connection between geometries and states?
- Terms of order r^{-2-d} in the asymptotic expansion of the geometry are related to vevs of dimension d operators in the microstate
- The vevs of chiral primary operators (and their descendants) in 1/4 and 1/8 BPS states are protected
- Examples: operators of dimension 1
  - O: $O|++\rangle_k = |00\rangle_k \quad \Rightarrow \quad Z_4 \sim \frac{\langle O\rangle Y^1}{r^3}$
  - Σ_2: $\Sigma_2\,(|++\rangle_{k_1} \otimes |++\rangle_{k_2}) = |++\rangle_{k_1+k_2} \quad \Rightarrow \quad Z_1 \sim \frac{\langle \Sigma_2\rangle Y^1}{r^3}$

(Y^1 : S^3 scalar spherical harmonic of order 1)

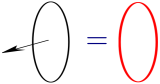
A D1-D5-P example

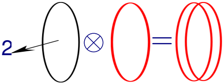
- Consider the state: $|s\rangle =$



$b_1^2 \propto N_1$

$b_2^2 \propto N_2$

O  $\Rightarrow \quad \langle s|O|s\rangle \propto b_1 \quad \leftrightarrow \quad Z_4 \propto b_1$

Σ_2  $\Rightarrow \quad \langle s|\Sigma_2|s\rangle \propto e^{iv}\, b_1 b_2 \quad \leftrightarrow \quad Z_1 \propto e^{iv}\, b_1 b_2$

- Gravity and CFT match (including numerical coefficients)
- The CFT implies the regularity of spacetime

Summary

- We have constructed a family of regular and horizonless D1-D5-P geometries
- We have identified their CFT dual states
- We have checked the gravity-CFT map by computing 1-point functions (and entanglement entropy)

Outlook

- The states we have are still insufficient to produce an entropy which scales like $(n_1 n_5 n_p)^{1/2}$ (fractional modes are missing)
- How well can one resolve typical states in supergravity? (need to know the vevs of operators of high enough dimension)
- What can one say about non-BPS microstates?