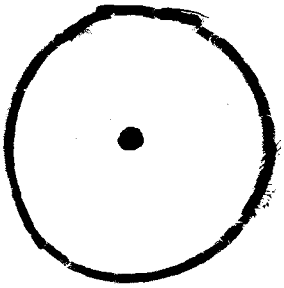
WHAT IS INSIDE A BLACK HOLE?

THE ENTROPY PROBLEM:



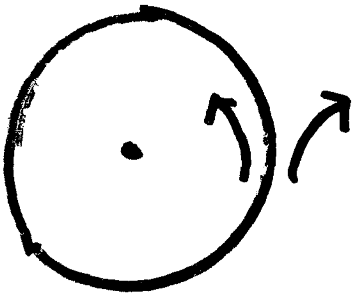
$$S = \frac{A}{4G}$$

But black holes have no hair

$$S = \ln 1 = 0 \quad ??$$

WHERE ARE THE STATES OF A BLACK HOLE?

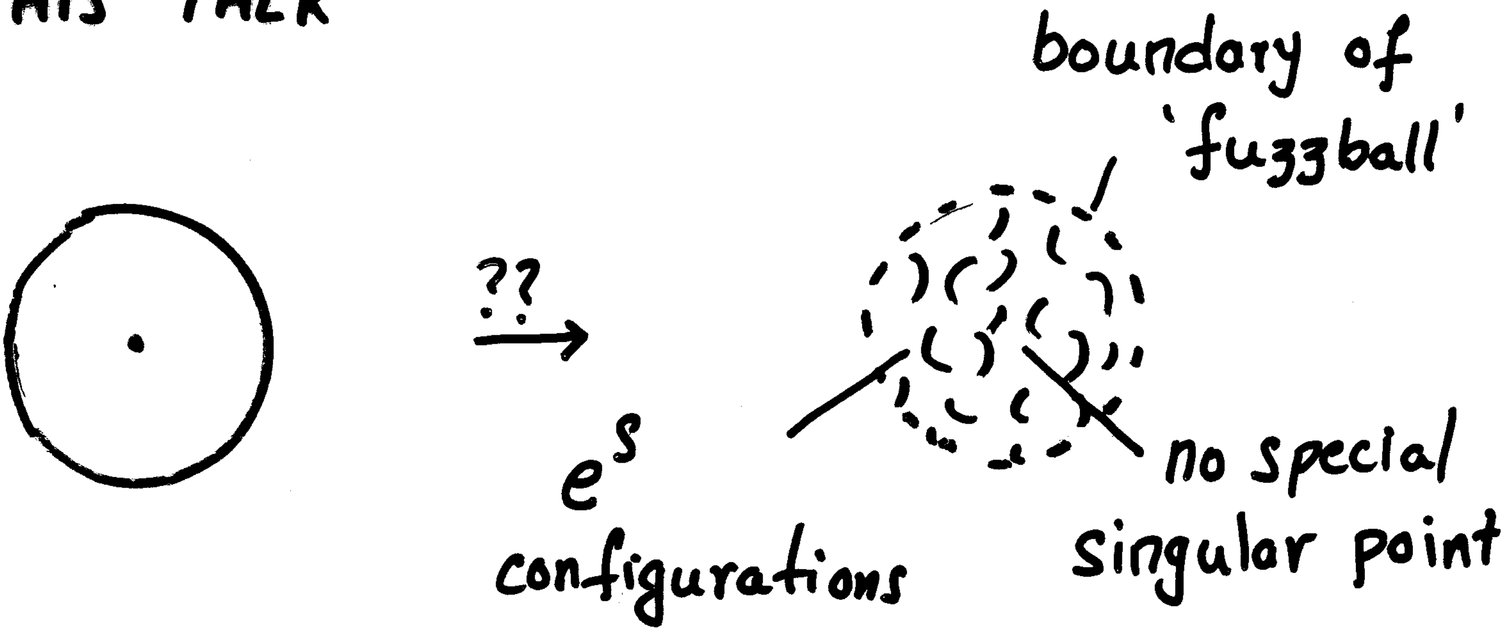
THE INFORMATION PROBLEM:



HAWKING RADIATION

→ INFORMATION LOSS ??

THIS TALK



D-p branes: Extremal bound state

$$S = \ln 1 = 0$$

2 charge: D1-D5 : $S = 2\pi\sqrt{2}\sqrt{n_1 n_5}$

3 charge: D1-D5-P: $S = 2\pi\sqrt{n_1 n_5 n_p}$

When we make a bound state of N quanta, the nonlocality length scale is $\sim N^\alpha l_p$

[Not $\sim l_p$ or $\sim l_s$]

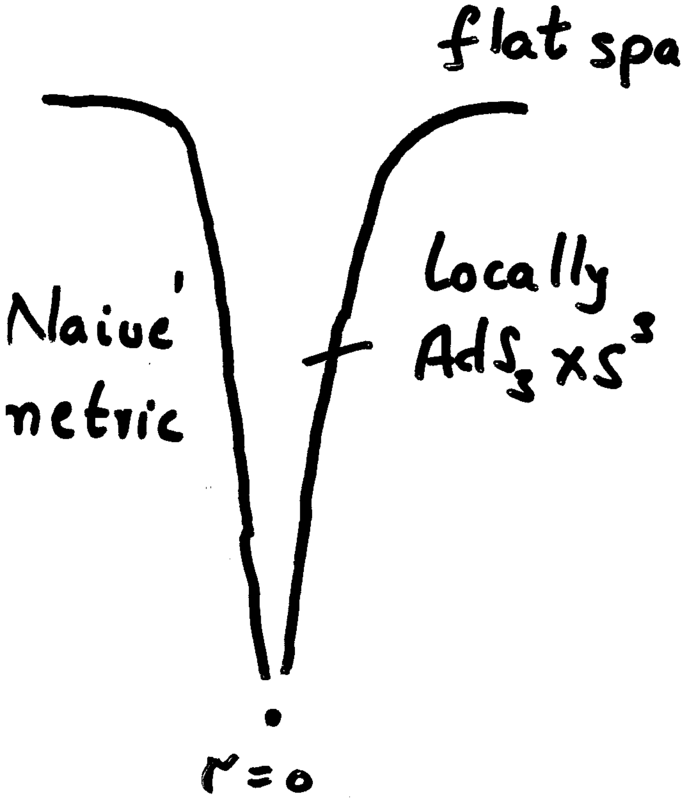
2 CHARGES: THE EXTREMAL D1-D5 SYSTEM

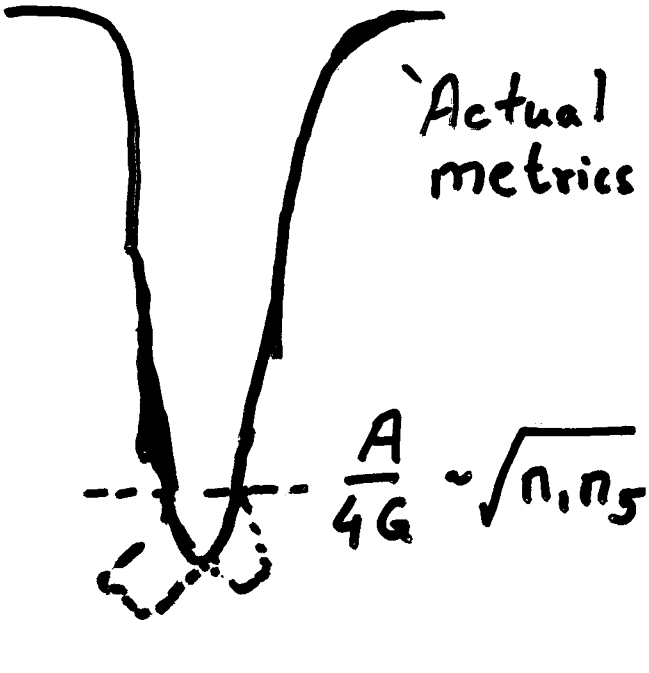
$$M_{9,1} \to \underset{t,\,r,\,\theta,\,\psi,\,\phi}{M_{4,1}} \times \underbrace{\underset{z_1 \cdots z_4}{T^4}}_{D5} \times \underbrace{\underset{y}{S^1}}_{D1}$$

$$ds^2_{\text{naive}} = \frac{1}{\sqrt{\left(1+\frac{Q_1}{r^2}\right)\left(1+\frac{Q_5}{r^2}\right)}}\left[-dt^2+dy^2\right]$$

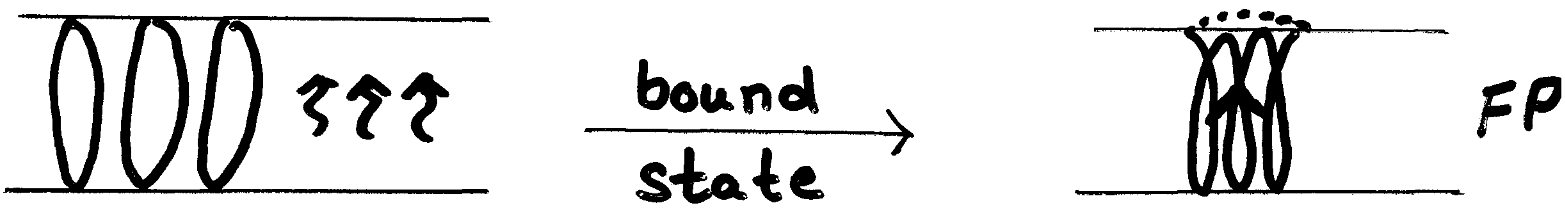
$$+\sqrt{\left(1+\frac{Q_1}{r^2}\right)\left(1+\frac{Q_5}{r^2}\right)}\left[dr^2+r^2 d\Omega_3^2\right]+\sqrt{\frac{1+\frac{Q_1}{r^2}}{1+\frac{Q_5}{r^2}}}\, dz_a dz_a$$

But there should be $e^S = e^{2\pi\sqrt{2}\sqrt{n_1 n_5}}$ states





$$\text{D5-D1} \xrightarrow{S} \text{NS5 F} \xrightarrow{T_y T_{z_1}} \text{NS5 P}$$
$$\downarrow S$$
$$\text{F-P} \xleftarrow[S]{} \text{D1 P} \xleftarrow[T_{z_1} T_{z_2} T_{z_3} T_{z_4}]{} \text{D5 P}$$



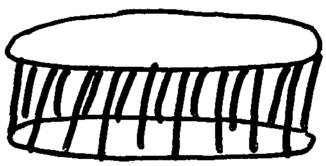
$\vec{F}(v)$

$v = t - y$

F string has no longitudinal vibration mode

So F must bend away from central axis to carry P

$\downarrow$



$\rightarrow$ FP geometry by superposing strands

$\downarrow$ S, T dualities

D1-D5 geometries

[Classical limit: Continuous family labelled by $\vec{F}$]

$$\boxed{\begin{aligned} ds^2 = \sqrt{\frac{H}{1+K}}[-(dt - A_i dx^i)^2 + (dy + B_i dy)^2] \\ + \sqrt{\frac{1+K}{H}} d\vec{x} d\vec{x} + \sqrt{H(1+K)} d\vec{z} d\vec{z} \end{aligned}}$$

$$e^{2\Phi} = H(1+K), \quad C_{ti} = \frac{B_i}{1+K}, \quad C_{ty} = -\frac{K}{1+K}$$

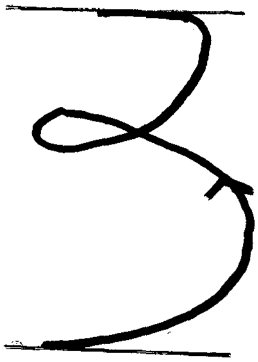
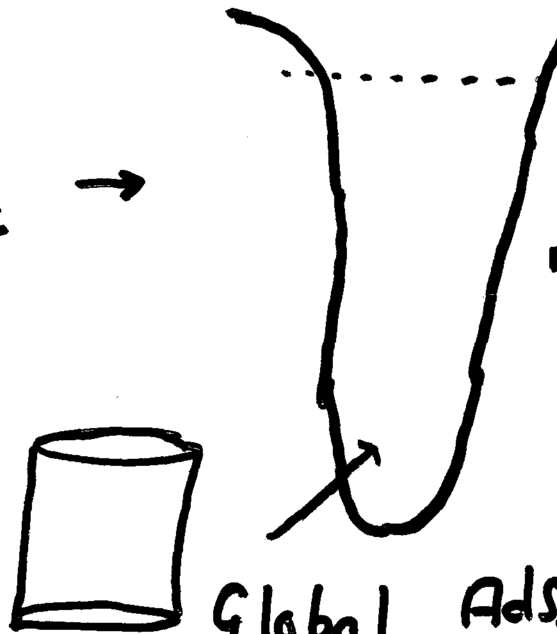
$$C_{iy} = -\frac{A_i}{1+K}, \quad C_{ij} = \tilde{C}_{ij} + \frac{A_i B_j - A_j B_i}{1+K}$$

$$\boxed{\begin{aligned} H^{-1} = 1 + \frac{Q}{L}\int_0^L \frac{dv}{|\vec{x} - \vec{F}(v)|^2}, \quad K = \frac{Q}{L}\int_0^L \frac{dv (\dot{F})^2}{|\vec{x} - \vec{F}(v)|^2} \\ A_i = -\frac{Q}{L}\int_0^L \frac{dv \dot{F}_i}{|\vec{x} - \vec{F}(v)|^2} \end{aligned}}$$

$$dB = - * dA, \quad d\tilde{C} = - * dH^{-1}$$

Lunin + SDM, hepth 0109154

A SIMPLE EXAMPLE

FP  → FP metric → 

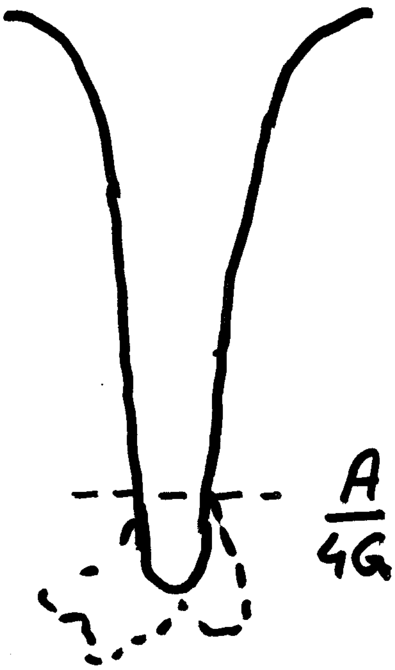
flat space

D1-D5 metric

Single turn uniform helix in covering space

Global $AdS_3 \times S^3$ after coordinate change

[Balasubramanian, de Boer, Keski-Vakkuri, Ross '00; Maldacena-Maoz '00]



$\frac{A}{4G} \sim S$

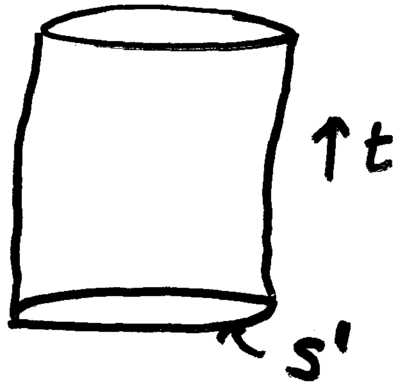
- $\text{Radius}_{5\text{-}d\text{-}Einstein} \sim \left[g^2 \frac{\alpha'^4 \sqrt{n_1 n_5}}{V_4 \, R} \right]^{1/3} \gg l_p, l_s$

- No horizon, no singularity

[$\vec{x} = \vec{F}(v)$ is a COORDINATE SING: Lunin, Maldacena, Maoz]

THE D1-D5 CFT

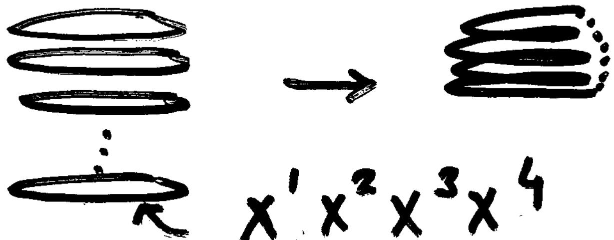
$$M_{9,1} \to M_{4,1} \times \underbrace{T^4 \times \underbrace{S^1}_{D1}}_{D5}$$



1+1 dim CFT : σ model with target space $(T_4)^N / S^N$

$N = n_1 n_5$

Twist operators σ_K : Link together K copies of free $c=6$ CFT

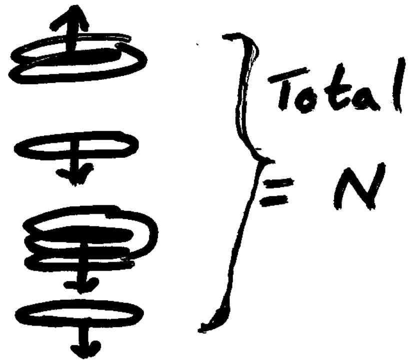


$X^1 X^2 X^3 X^4$

$\psi^1 \psi^2 \psi^3 \psi^4, \ \bar\psi^1 \bar\psi^2 \bar\psi^3 \bar\psi^4$

Ramond ground states:

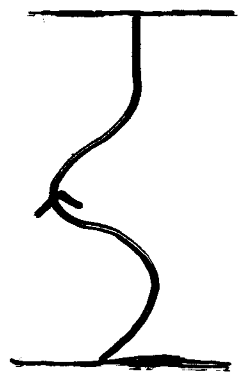
$$\sigma^{\pm}_{K_1} \cdots\cdots \sigma^{\pm}_{K_n} |0\rangle \Big|_{NS \to R}$$



$$\sum K_i = N$$

$$\to e^{2\pi\sqrt{2}\sqrt{n_1 n_5}} \text{ states}$$

THE CFT STATE $\longleftrightarrow$ GEOMETRY MAP



$$\vec{F}(v) \longleftrightarrow (a^{i_1}_{K_1})^{\dagger} \cdots\cdots (a^{i_n}_{K_n})^{\dagger}|0\rangle$$

$\updownarrow$

FP geometry

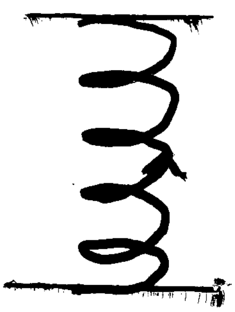
$\updownarrow$

D1-D5 geometry $\Longleftrightarrow$ $\sigma^{\pm\pm}_{K_1} \cdots \sigma^{\pm\pm}_{K_n}|0\rangle$

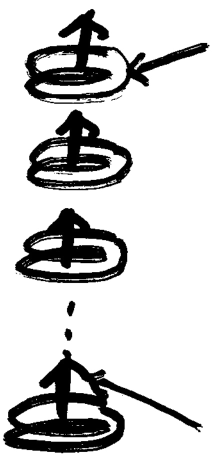
[Classical Geometries : many quanta in the same harmonic]

<u>Example:</u>

FP



$\longrightarrow$



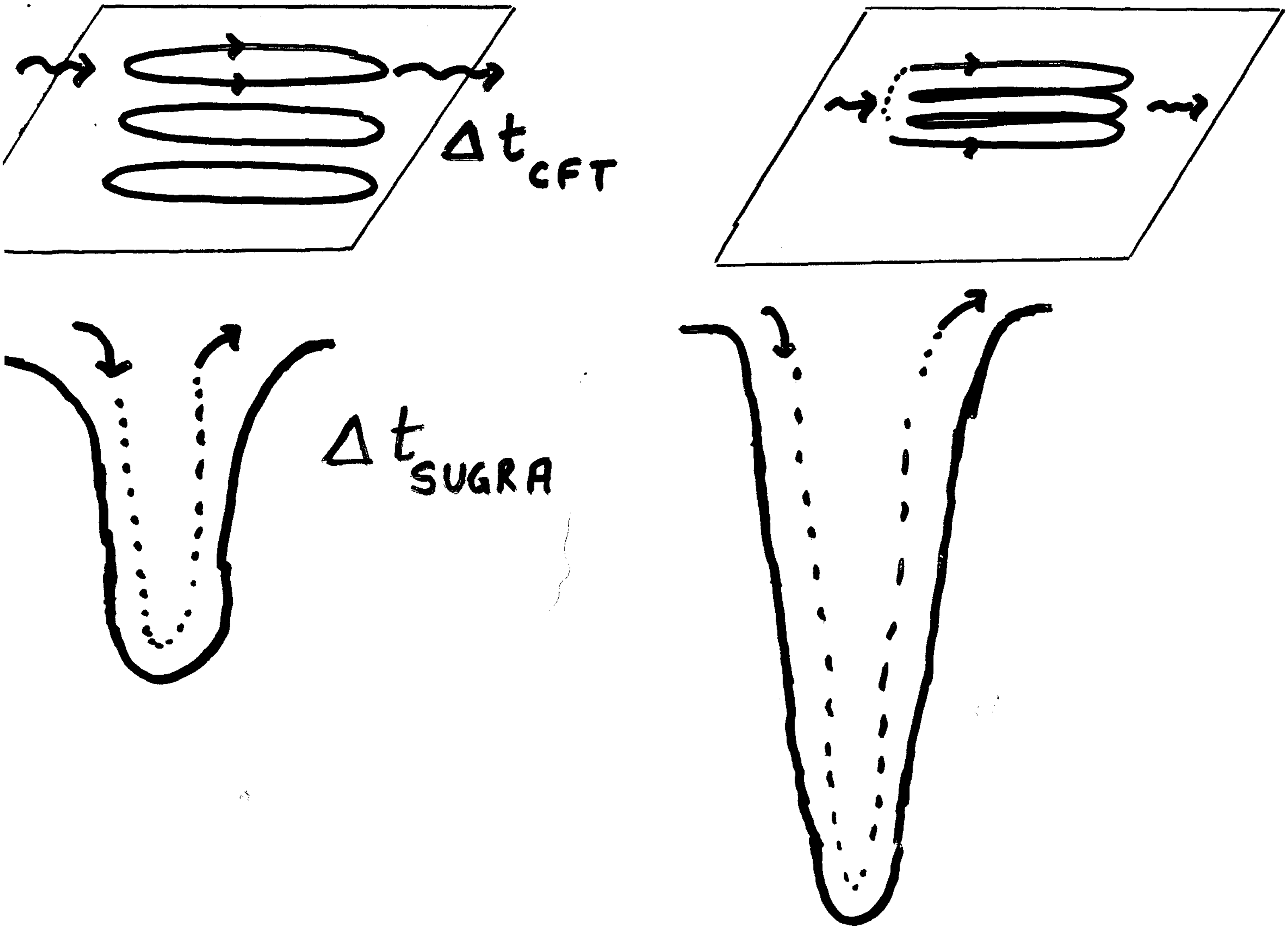
K circles linked by σ_K

All spins aligned

K turns of uniform helix

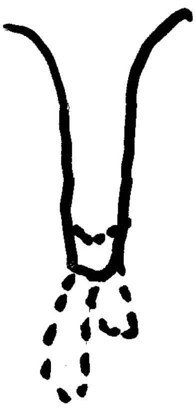
CFT state

A DYNAMICAL EXPERIMENT



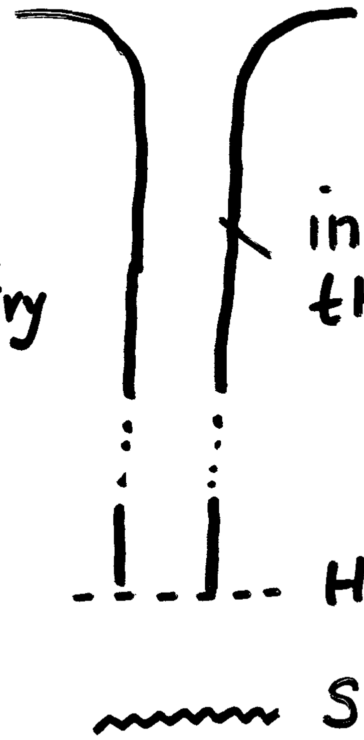
$\Delta t_{CFT} = \Delta t_{SUGRA}$ FOR EACH STATE

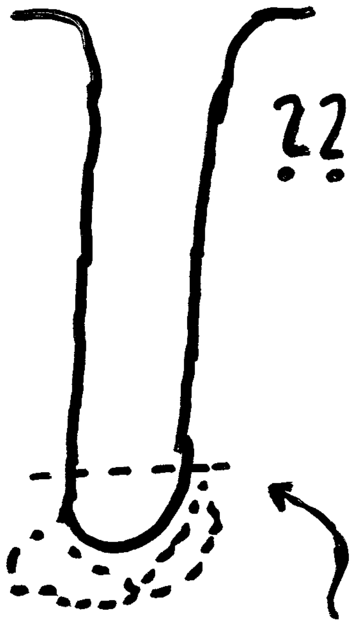
Backreaction $\sim (n_1 n_5)^{-\frac{1}{2}}$ for generic state



'Hair' makes sense since geometries can be distinguished by experiments

3 CHARGES: THE EXTREMAL D1-D5-P SYSTEM'





Throat diameter saturates, so we get exactly $\frac{A}{4G} = 2\pi\sqrt{n_1 n_5 n_p}$

We cannot as yet make all 3-charge geometries; We make a few subfamilies

These subfamilies are all "capped" geometries, with no horizon or closed timelike curves.

Microstates should have no horizon, otherwise, they would have degeneracy $e^S = e^{A/4G}$

SUBFAMILIES OF EXTREMAL D1-D5-P

(A) $J^-_{-1}|\psi\rangle_R$, $|\psi\rangle_R = \sigma_2|0\rangle\Big|_{NS\to R}$

(RR ground state)

$n_1,\ n_5,\ n_p = L_0 - \bar{L}_0 = 1$

Match outer, inner solutions to many orders

(B) Spectral flow Left sector Ramond $\longrightarrow$ Ramond

$$L_0 - \bar{L}_0 = n_p = \frac{N}{K} n(nK+1) \quad \left[\frac{N}{K} \in Z,\ n \in Z\right]$$

$$|\psi\rangle = \left[\Pi\left(J^-_{-2n} J^-_{-2n+\frac{2}{K}} \cdots J^-_{-\frac{4}{K}} J^-_{-\frac{2}{K}}\right)\right]\left[\sigma_K^{N/K}|0\rangle_{NS\to R}\right]$$

(C) $D1 \longleftrightarrow P$ ON (B)

$|\psi\rangle$ similar, with $K \to K' = n_5 n(nK+1)$.

$L_0 - \bar{L}_0 = n_p' = n_1$

(D) $(J^-_{-1})^n|\psi\rangle_R$, $|\psi\rangle_R$ arbitrary 2-charge extrem

$\rightarrow n_1, n_5, n_p \sim 1$, J arbitrary

$n_1 n_5 n_p - J^2 > 0$ [in progress]

(Giusto, SDM, Srivastava)

$$
\begin{aligned}
|-k\rangle^{total} &= (J^{+,total}_{-(2k-2)})^{n_1 n_5} (J^{+,total}_{-(2k-4)})^{n_1 n_5} \dots (J^{+,total}_{-2})^{n_1 n_5} (J^{+,total}_{0})^{n_1 n_5} \, |1\rangle^{total}, \quad & k \geq 0 \\
|k\rangle^{total} &= (J^{-,total}_{-(2k-2)})^{n_1 n_5} (J^{-,total}_{-(2k-4)})^{n_1 n_5} \dots (J^{-,total}_{-2})^{n_1 n_5} \, |1\rangle^{total}, & k > 1
\end{aligned}
$$

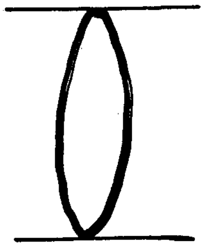
$$
\begin{aligned}
ds^2 &= -\frac{1}{h}(dt^2 - dy^2) + \frac{Q_p}{hf}(dt-dy)^2 + hf\left(\frac{dr_N^2}{r_N^2 + a^2\eta} + d\theta^2\right) \\
&+ h\left(r_N^2 + (n+1)a^2\eta - \frac{(2n+1)a^2\eta Q_1 Q_5 \cos^2\theta}{h^2 f^2}\right)\cos^2\theta d\psi^2 \\
&+ h\left(r_N^2 - na^2\eta + \frac{(2n+1)a^2\eta Q_1 Q_5 \sin^2\theta}{h^2 f^2}\right)\sin^2\theta d\phi^2 \\
&+ \frac{a^2\eta^2 Q_p}{hf}\left(\cos^2\theta d\psi + \sin^2\theta d\phi\right)^2 \\
&+ \frac{2a\sqrt{Q_1Q_5}}{hf}\left[-(n+1)\cos^2\theta d\psi + n\sin^2\theta d\phi\right](dt-dy) \\
&- \frac{2a\eta\sqrt{Q_1Q_5}}{hf}\left[\cos^2\theta d\psi + \sin^2\theta d\phi\right] dy \sqrt{\frac{H_1}{H_5}} \sum_{i=1}^{4} dz_i^2 \\
C_2 &= \frac{a\sqrt{Q_1Q_5}\cos^2\theta}{H_1 f}(ndt - (n+1)dy) \wedge d\psi \\
&+ \frac{a\sqrt{Q_1Q_5}\sin^2\theta}{H_1 f}(-(n+1)dt + ndy) \wedge d\phi \\
&+ \frac{a\eta Q_p}{\sqrt{Q_1Q_5}H_1 f}(Q_1 dt + Q_5 dy) \wedge \left(\cos^2\theta d\psi + \sin^2\theta d\phi\right) \\
&- \frac{Q_1}{H_1 f} dt \wedge dy - \frac{Q_5\cos^2\theta}{H_1 f}\left(r_N^2 - na^2\eta Q_1\right) d\psi \wedge d\phi \qquad (0.1) \\
e^{2\Phi} &= \frac{H_1}{H_5}
\end{aligned}
$$

$$
\begin{aligned}
f &= r_N^2 + a^2\eta\,(n+1)\sin^2\theta - a^2\eta\, n\cos^2\theta \\
h &= \sqrt{H_1 H_5}, \; H_1 = 1 + \frac{Q_1}{f}, \; H_5 = 1 + \frac{Q_5}{f}
\end{aligned}
$$

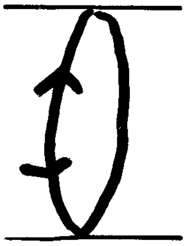
[Giusto, SDM, Saxena '04]

FRACTIONATION

L

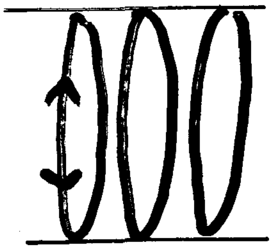


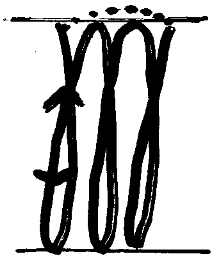
$\rightarrow$



$$\Delta E_{min} = \frac{2\pi}{L} + \frac{2\pi}{L} = \frac{4\pi}{L}$$

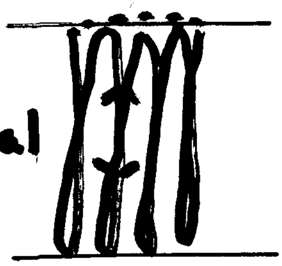
$$\Delta E_{min} = \frac{4\pi}{L}$$





$$\Delta E_{min} = \frac{2\pi}{L_T} + \frac{2\pi}{L_T} = \frac{4\pi}{L_T} = \frac{4\pi}{NL}$$

4+1 dim
near extremal
black hole

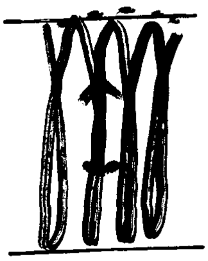


$D1 - D5 - \frac{P}{\bar{P}}$

$$S = 2\pi\sqrt{n_1 n_5}\left(\sqrt{n_p} + \sqrt{\bar{n}_p}\right)$$

$$\Delta E_{min} = \frac{4\pi}{n_1 n_5 L}$$

3+1 dim
near extremal
black hole



$D1 - D5 -$ KK monopoles $+ \frac{P}{\bar{P}}$

$$S = 2\pi\sqrt{n_1 n_5 n_{KK}}\left(\sqrt{n_p} + \sqrt{\bar{n}_p}\right)$$

$$\Delta E_{min} = \frac{4\pi}{n_1 n_5 n_{KK} L}$$

Charges permute under S, T, dualities

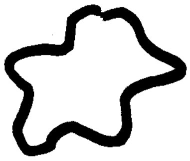
$D1 - D5 - P$, $D1 - D5 - KK - P$

$\Rightarrow$ FRACTIONAL MOM $\rightarrow$ FRACTIONAL BRANES

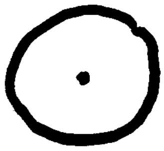
THE 'CORRESPONDENCE PRINCIPLE'

$g < g_c$

$S = S_{string}$



$\longrightarrow$



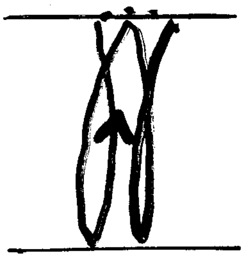
$g > g_c$

$S = S_{Bek} = \frac{A}{4G}$

At $g \sim g_c$, $S_{string} \sim S_{Bek}$

But greybody factors <u>don't</u> agree ...

$M_{9,1} \longrightarrow M_{4,1} \times T^4 \times S^1$



$F: n_1$

$P: n_2$

Add ΔE

Where does ΔE go?

(A)

$$FP \longrightarrow FP + \frac{P}{\bar{P}}, \quad \Delta E = \frac{4\pi}{n_1 L}$$

$$\Delta S = 2\pi\sqrt{2}\sqrt{n_1}\sqrt{\bar{n}_p}$$

(B) $\quad D1\text{-}D5 \left\{ \begin{matrix} P \\ \bar{P} \end{matrix} \right. \longrightarrow D1\text{-}P \left\{ \begin{matrix} D5 \\ \bar{D5} \end{matrix} \right. \xrightarrow{S} FP \left\{ \begin{matrix} NS5 \\ \overline{NS5} \end{matrix} \right.$

$\downarrow$

$$\Delta E = \frac{4\pi}{n_1 n_5 L}$$

$\downarrow$

$$\Delta E = \frac{V_4 L}{n_1 n_2 g^2}$$

$$\Delta S = 2\pi\sqrt{n_1 n_2}\left(\sqrt{n_5} + \sqrt{\bar{n}_5}\right)$$

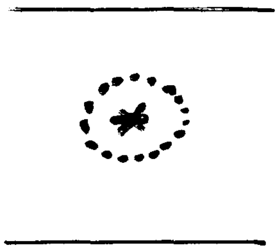
$g < g_c \Rightarrow$ (A), $\quad g > g_c \Rightarrow$ (B)

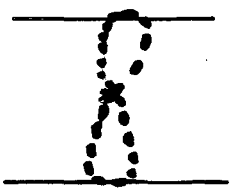
FRACTIONAL BRANES: ANOTHER EXAMPLE

$$M_{9,1} \rightarrow M_{3,1} \times \underset{V_4}{T^4} \times \underset{L}{S^1} \times \underset{\tilde{L}}{\tilde{S}^1}$$

$$D1 + D5 + P + \Delta E$$

$\tilde{S}^1$





$$D1 - D5 - P \begin{cases} P \\ \bar{P} \end{cases}$$

$$\Delta E_{min} = \frac{4\pi}{n_1 n_5 L}$$

$$\Delta S \simeq 2\pi \sqrt{n_1 n_5 \bar{n}_p}$$

$$\tilde{L} < L_{crit}$$

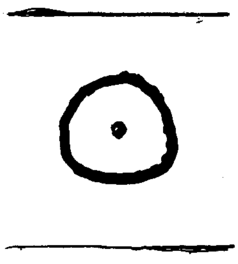
$$D1 - D5 - P \begin{cases} KK \\ \overline{KK} \end{cases}$$

$$\Delta E_{min} = \frac{2 L \tilde{L}^2 V_4}{n_1 n_5 n_p g^2 (2\pi)^4}$$

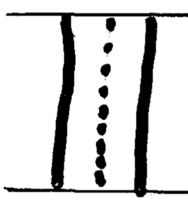
$$\Delta S = 2\pi \sqrt{n_1 n_5 n_p} \left(\sqrt{n_{KK}} + \sqrt{n_{\overline{KK}}} \right.$$

$$\tilde{L} > L_{crit}$$

$$L_{crit} \sim \frac{\Delta E \, g^2}{L \tilde{L} V_4} \qquad (L_{crit} \gg l_s, l_p$$



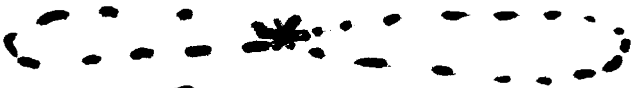
Gregory - Laflamme
$\longrightarrow$
Transition



What is the size of an extremal D1-D5-P bound state? [crude estimat

D1-D5-P
extremal

$\Delta E \gtrsim \frac{1}{D}$ (A)

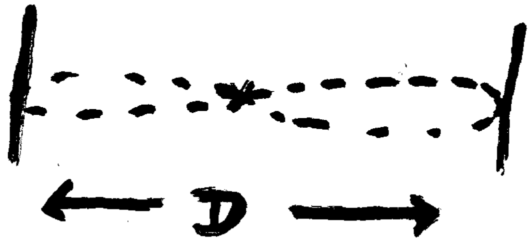


D1-D5-P
+ excitations

?? (B)

Toy problem:

D1-D5-P + $\begin{matrix} KK \\ \overline{KK} \end{matrix}$



(i) $\Delta E \sim \frac{1}{D}$

(ii) Demand $\Delta S \gtrsim 1$

S = log [Volume of phase space]

$\Delta S = 1$; $D = D_{crit} = ?$

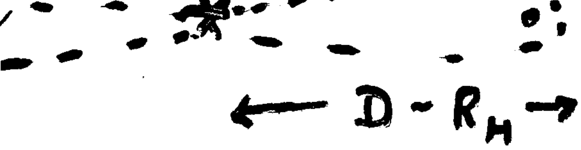
$$\Delta S = 2\pi\sqrt{n_1 n_5 n_p f} + 4\pi\sqrt{n_1 n_5 n_p (1-f) n_{KK}} - 2\pi\sqrt{n_1 n_5 n_p}$$

Extremise over f $\Rightarrow$ $f = \dfrac{1}{4\pi\sqrt{n_1 n_5 n_p}}$

$$D_{crit} \sim \left[\frac{g^2 \alpha'^4 \sqrt{n_1 n_5 n_p}}{V_4 L}\right]^{\frac{1}{3}}$$

Horizon radius of D1-D5-P extremal:

$$R_H = \left[\frac{32\pi^5 g^2 \alpha'^4 \sqrt{n_1 n_5 n_p}}{V_4 L}\right]^{\frac{1}{3}}$$



The energy $\dfrac{1}{R_H}$ causes fractional brane excitations on extremal D1-D5-P which stretch upto $r \sim R_H$

What about Schwarzschild holes?

4+1 nonextremal (including Schwarzschild)

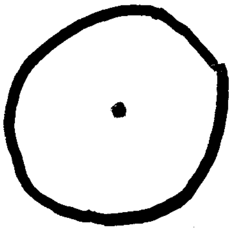
$$S = 2\pi\left(\sqrt{n_1}+\sqrt{\bar{n}_1}\right)\left(\sqrt{n_5}+\sqrt{\bar{n}_5}\right)\left(\sqrt{n_p}+\sqrt{\bar{n}_p}\right)$$

[Horowitz, Maldacena, Strominger '96]

Same size estimate from fractional branes

Large quantum fluctuations

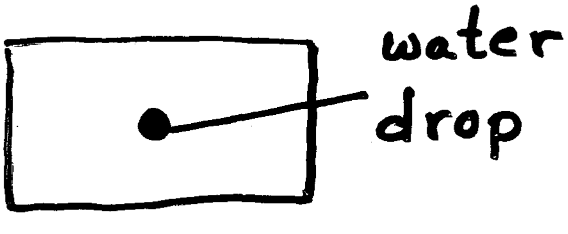
What is wrong with the usual picture?

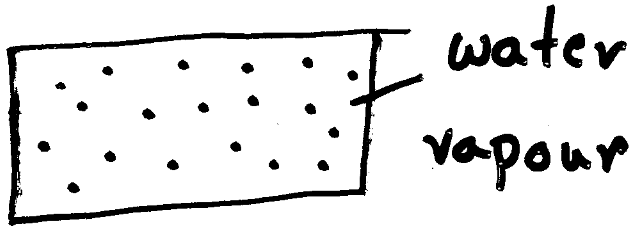


only g_{ab} nontrivial
nongeneric state

fractional branes/anti-branes account for full entropy

$$t_{\text{crossing}} \underset{?}{<} t_{\text{eq}} \underset{?}{<} t_{\text{Hawking}}$$





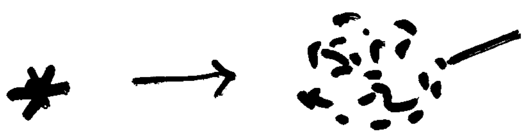
Summary

- Hawking argument
  - (i) Nonlocality $\lesssim l_p, l_s$
  - (ii) Vacuum unique

  $\Rightarrow$ Information loss

- Fractionation suggests nonlocality over $\sim N^{\alpha} l_p$

- 2 charge, some 3 charge, explicity constructed



$\frac{A}{4G} \sim S$

- Nonextremal case appears to be qualitatively similar