

Title: Black holes in String Theory

Date: Jul 05, 2005 02:30 PM

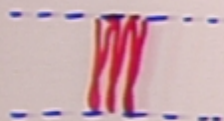
URL: <http://pirsa.org/05070073>

Abstract:

LAST TALK

1-CHARGE

NSI



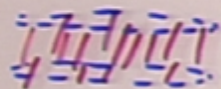
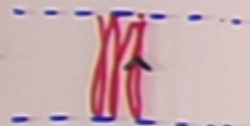
$$S_{\text{micro}} = \ln[256] \\ \approx 0$$



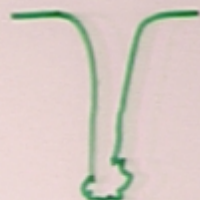
$$S_{\text{Bek}} = \frac{A}{4G} = 0$$

2-CHARGES

NSI-P



Naive
geometry
 $A=0$



"Actual" geometries
Strands separate,
nontrivial in some

NS1-P $\xrightarrow{\text{Dualities}}$ D1-D5

2

D1-D5:

$$ds_{\text{string}}^2 = \sqrt{\frac{H}{1+K}} \left[-(dt - A_i dx^i)^2 + (dy + B_i dx^i)^2 \right] \\ + \sqrt{\frac{1+K}{H}} dx^i dx^i + \sqrt{H(1+K)} dz_a dz_a$$

$$[dB = -\star_4 dA]$$

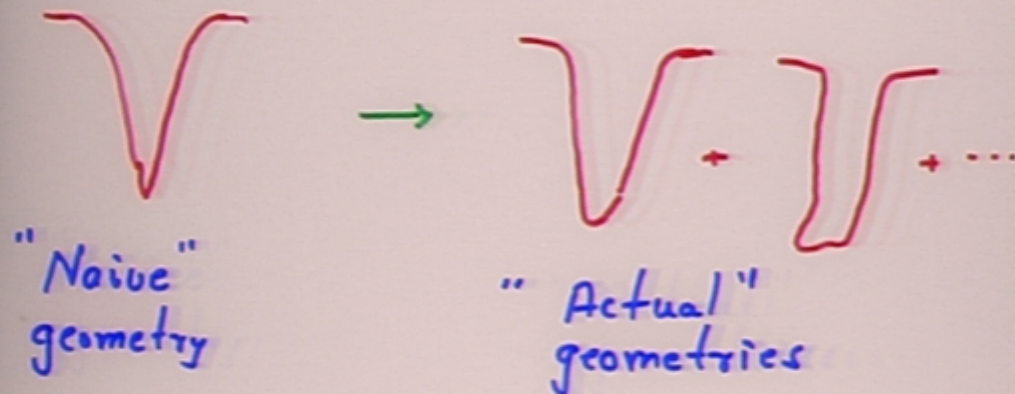
$$H^{-1} = 1 + \frac{Q_1}{L_T} \int_0^{L_T} \frac{dv}{|\vec{x} - \vec{F}(v)|^2}$$

$$K = \frac{Q_1}{L_T} \int_0^{L_T} \frac{dv |\dot{\vec{F}}|^2(v)}{|\vec{x} - \vec{F}(v)|^2}$$

$$A_i = -\frac{Q_1}{L_T} \int_0^{L_T} \frac{dv \dot{F}_i(v)}{|\vec{x} - \vec{F}(v)|^2}$$

Two important properties of these
D1-D5 geometries:

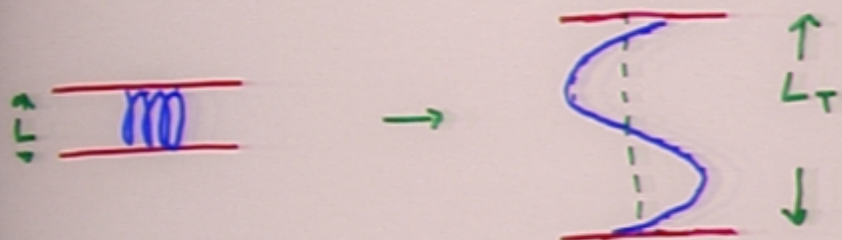
- A) No horizons
- B) No singularity



To understand this, we will make
explicitly a particular D1-D5
geometry.

Profile function $\vec{F}(u) \rightarrow$ geometry ^{4.}

$\vec{F}(u)$: Uniform helix with single turn in covering space



Noncompact (transverse) directions

$x_i, i = 1, 2, 3, 4$

$$F_1 = a \cos(\omega u), \quad F_2 = a \sin(\omega u)$$

$$F_3 = 0, \quad F_4 = 0$$

$$\boxed{\omega = \frac{2\pi}{L_T}}$$

$$\begin{aligned}
 H^{-1} &= 1 + \frac{Q_1}{L_T} \int_0^T \frac{d\nu}{|\vec{x} - \vec{F}(\nu)|^2} \\
 &= 1 + \frac{Q_1}{2\pi} \int_0^{2\pi} \frac{d\zeta}{(x_1 - a \cos \zeta)^2 + (x_2 - a \sin \zeta)^2 + x_3^2 + x_4^2}
 \end{aligned}$$

Use polar coordinates in x_i space

$$x_1, x_2, x_3, x_4 \rightarrow r, \theta, \phi, \psi$$

$$H^{-1} = 1 + \frac{Q_1}{r^2 + a^2 \cos^2 \theta}$$

We have chosen a profile function with axial symmetry, so ϕ, ψ do not appear

Similarly compute K, A_i

$$\begin{aligned}
 ds_{\text{string}}^2 = & -\frac{1}{h} [dt^2 - dy^2] + hf \left[d\theta^2 + \frac{dr^2}{r^2 + a^2} \right] \\
 & - \frac{2a \sqrt{Q_1 Q_5}}{hf} [\cos^2 \theta dy d\psi + \sin^2 \theta dt d\phi] \\
 & + h \left[r^2 + \frac{a^2 Q_1 Q_5 \cos^2 \theta}{h^2 f^2} \right] \cos^2 \theta d\psi^2 \\
 & + h \left[r^2 + a^2 - \frac{a^2 Q_1 Q_5 \sin^2 \theta}{h^2 f^2} \right] \sin^2 \theta d\phi^2 \\
 & + \sqrt{\frac{Q_1 + f}{Q_5 + f}} dz_a dz_c
 \end{aligned}$$

$$f = r^2 + a^2 \cos^2 \theta, \quad h = \left[\left(1 + \frac{Q_1}{f} \right) \left(1 + \frac{Q_5}{f} \right) \right]^{\frac{1}{2}}$$

$$NS1 - P \longrightarrow DS - D1$$

$$Q_1 \longrightarrow Q_5$$

$$Q_P \longrightarrow Q_1$$

For $r \rightarrow \infty$, Flat spacetime

For $r \ll \sqrt{Q_1 Q_5}$;

$$\begin{aligned} ds_{\text{string}}^2 &\approx - \frac{(r^2 + a^2) dt^2}{\sqrt{Q_1 Q_5}} + \frac{r^2 dy^2}{\sqrt{Q_1 Q_5}} \\ &+ \sqrt{Q_1 Q_5} \frac{dr^2}{r^2 + a^2} \\ &+ \sqrt{Q_1 Q_5} \left[d\theta^2 + \cos^2 \theta \left[d\psi - \frac{a dy}{\sqrt{Q_1 Q_5}} \right]^2 \right. \\ &\quad \left. + \sin^2 \theta \left[d\phi - \frac{a dt}{\sqrt{Q_1 Q_5}} \right]^2 \right] \\ &+ \sqrt{\frac{Q_1}{Q_5}} dz_a dz_a \end{aligned}$$

Change coordinates:

$$\psi' = \psi - \frac{a}{\sqrt{Q_1 Q_5}} y$$

$$\phi' = \phi - \frac{a}{\sqrt{Q_1 Q_5}} t$$

For $r \rightarrow \infty$, Flat spacetime

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Change coordinates:

$$\psi' = \psi - \frac{a}{\sqrt{Q_1 Q_5}} y$$

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Define:

$$r' = r/a, \quad t' = \frac{2\pi t}{L} \quad \left[a = \sqrt{Q_1 Q_5} \frac{2\pi}{L} \right]$$

$$ds_{\text{string}}^2 = \sqrt{Q_1 Q_5} \left[-(r'^2 + 1) dt'^2 + r'^2 dy'^2 + \frac{dr'^2}{r'^2 + 1} \right]$$

$$+ \sqrt{Q_1 Q_5} \left[d\theta^2 + \cos^2 \theta d\psi^2 + \sin^2 \theta d\phi'^2 \right]$$

$$+ \sqrt{\frac{Q_1}{Q_5}} dz_a dz_a$$

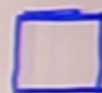
$$= \text{AdS}_3 [\text{global}] \times S^3 \times T^4$$



x



x



→ No singularity, no horizon

This metric was earlier found by
Cvetič + Youm '95, Balasubramanian + de Boer +
Keski-Vakkuri + Ross '00, Maldacena + Maoz '00
in some related contexts

We now see that it is one of
a general family parametrized by
 $\vec{F}(0) \rightarrow$ All 2-charge metrics

Maldacena + Maoz '02: All the
metrics are nonsingular:

$|\vec{x} - \vec{F}(0)|^2$ → coordinate singularity
like that of

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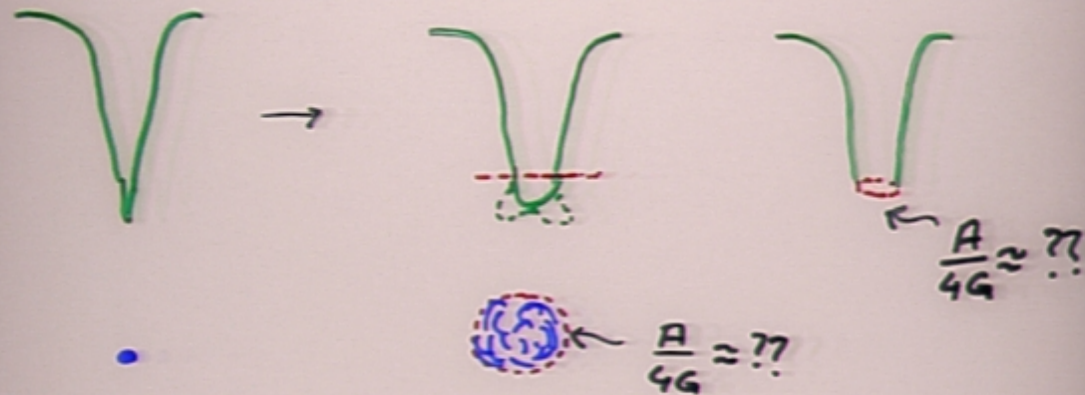
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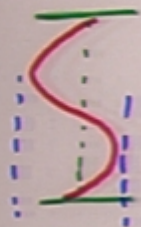
SIZE OF THE BOUND STATE

10.



This truncation is a kind of "coarse-graining", since we keep that part which is common to all metrics, and discard the one which differs from microstate to microstate

Limit (A) : All the momentum is in the lowest harmonic



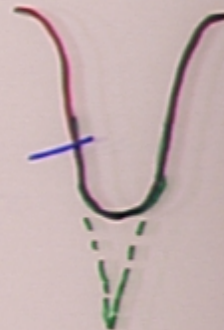
BIG
SIZE

$$\sum_i m_i k_i = n_i n_p :$$

$$k_i = 1$$

$$m_i = n_i n_p$$

SHORT
THROAT

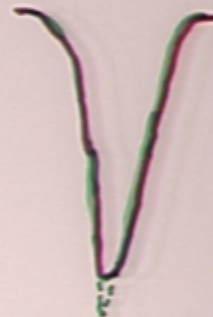


Limit (B) : 1 quantum of highest harmonic

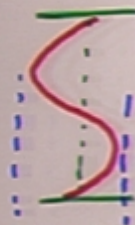
$$k_i = n_i n_p, m_i = 1$$



SMALL
SIZE



Limit (A) : All the momentum is in
the lowest harmonic



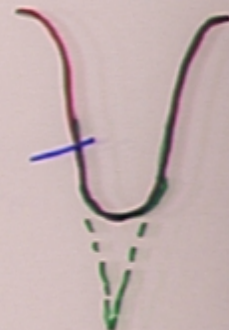
BIG
SIZE

$$\sum_i m_i k_i = n, n_p :$$

$$k_i = 1$$

$$m_i = n, n_p$$

SHORT
THROAT

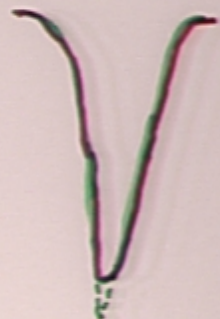


Limit (B) : 1 quantum of highest harmonic

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SMALL
SIZE



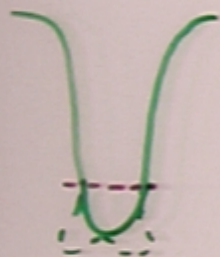
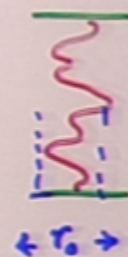
BUT ONLY 1 STATE OF EACH KIND

Generic state: $\sum_i m_i k_i = n, n_p$

12

$$k_i \sim \sqrt{n, n_p}$$

$$m_i \sim \sqrt{n, n_p}$$



$$\frac{A^E}{4G} \sim \frac{\sqrt{Q, Q_p} L V \alpha'^{\frac{1}{2}}}{g^2 \alpha'^4} \sim \sqrt{n, n_p}$$

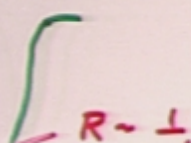
$$\sim S_{\text{micro}}$$

All moduli cancel out.

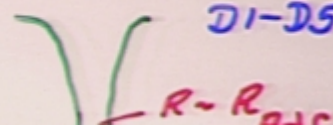
$\frac{A^E}{G}$ is invariant under dualities,
so this works for NS1-P, D1-D5, D1-D9
Supertube, etc

Other effects are duality dependent:

NS1-P



D1-D5

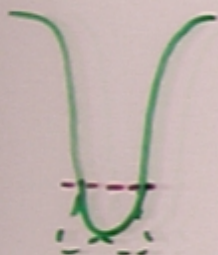
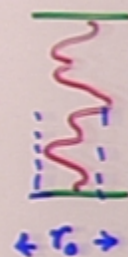


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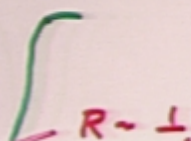
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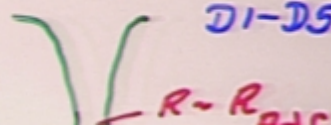
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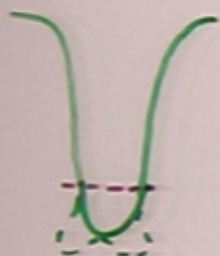
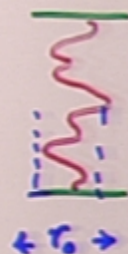


Generic state: $\sum_i m_i k_i = n, n_p$

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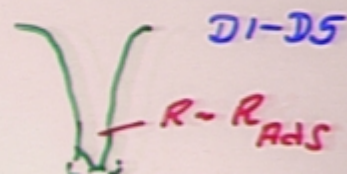
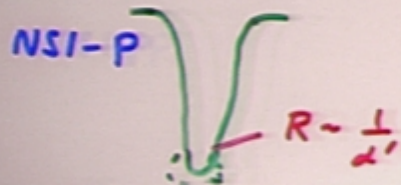
$$\frac{A^E}{4G} \sim \frac{\sqrt{Q, Q_p} L V \alpha'^{\frac{1}{2}}}{g^2 \alpha'^4} \sim \sqrt{n, n_p}$$

$\sim S_{\text{micro}}$

All moduli cancel out.

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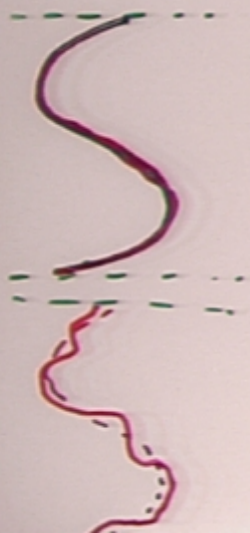
2-CHARGE WITH ROTATION:

12'

SO FAR WE COUNTED ALL STATES
OF THE EXTREMAL 2-CHARGE SYSTEM

WE CAN ALSO TRY TO COUNT STATES
WITH A GIVEN ANGULAR MOMENTUM
 J

$$S_{\text{micro}}: 2\pi\sqrt{2}\sqrt{n_1 n_5} \rightarrow 2\pi\sqrt{2}\sqrt{n_1 n_5 - J}$$

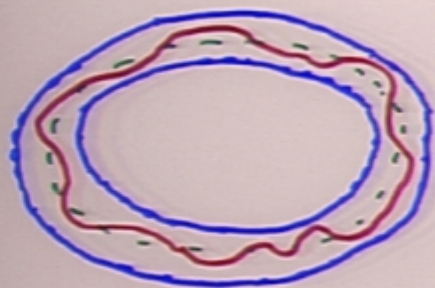


$$J = J_{\text{max}} = n_1 n_5:$$

1 turn of uniform
helix

$J < J_{\text{max}}$: have some
extra energy to "wiggle"
around circular profile

Profile in actual space:



Surround the region where the geometries differ by a surface:

→ Toroidal "horizon"

$$\frac{A^E}{4G} \sim \sqrt{n_1 n_5 - J} \sim S_{\text{micro}}$$

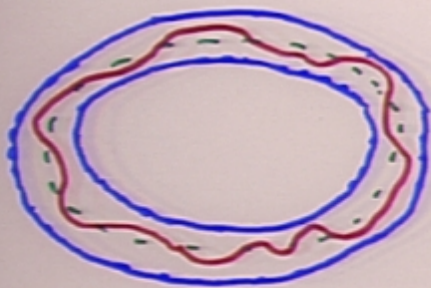
Gravity: $J < (n_1 n_5)^{1/4}$: spherical "horizon"

$J > (n_1 n_5)^{1/4}$: toroidal "horizon"

CFT: $J < (n_1 n_5)^{1/4}$: All modes carry J

$J > (n_1 n_5)^{1/4}$: BOSE CONDENSATION

Profile in actual space:



Surround the region where the geometries differ by a surface:

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$$\frac{AE}{4G} \sim \sqrt{n_1 n_5 - J} \sim S_{\text{micro}}$$

Gravity: $J < (n_1 n_5)^{1/4}$: spherical "horizon"
 $J > (n_1 n_5)^{1/4}$: toroidal "horizon"

CFT: $J < (n_1 n_5)^{1/4}$: All modes carry J

$J > (n_1 n_5)^{1/4}$: BOSE CONDENSATION
 J IN LOWEST HARMONIC

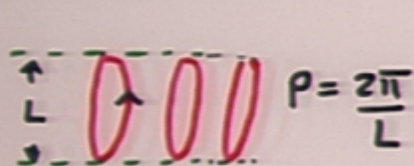
Understanding the D1-D5 CFT

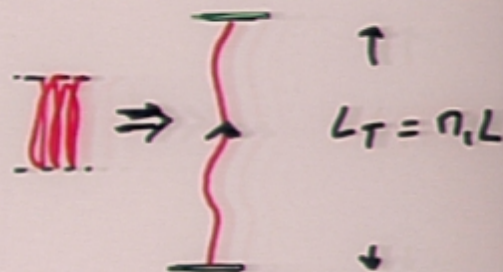
13

$$AdS_5 \times S^5 (D3): \quad D=4 \quad N=4 \text{ SYM}$$

$$AdS_3 \times S^3 \times T^4 (D1D5): \quad D=2 \quad \text{CFT}$$

Fractionation


$$P = \frac{2\pi}{L}$$


$$L_T = n_1 L$$

$$P = \frac{2\pi n_p}{L} = \frac{2\pi n_1 n_p}{L_T}$$

n_p units of strength

$$\frac{2\pi}{L_T} = \frac{1}{n_1} \left(\frac{2\pi}{L} \right)$$

When you BIND
 n_1 NS1 branes
together, the P
charge comes in
fractional units!

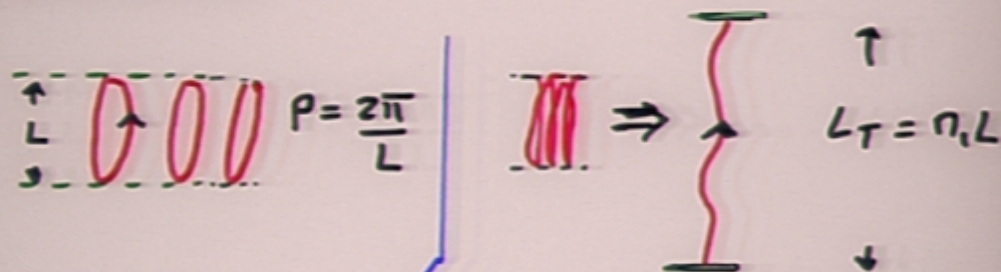
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Fractionation



$$P = \frac{2\pi n_p}{L} = \frac{2\pi n_1 n_p}{L_T}$$

$n_1 n_p$ units of strength

$$\frac{2\pi}{L_T} = \frac{1}{n_1} \left(\frac{2\pi}{L} \right)$$

When you BIND
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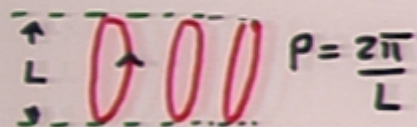
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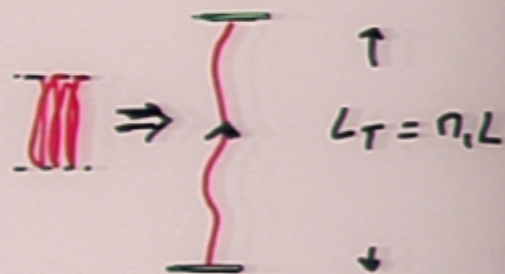
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Fractionation



$$p = \frac{2\pi}{L}$$



$$p = \frac{2\pi n_p}{L} = \frac{2\pi n_1 n_p}{L_T}$$

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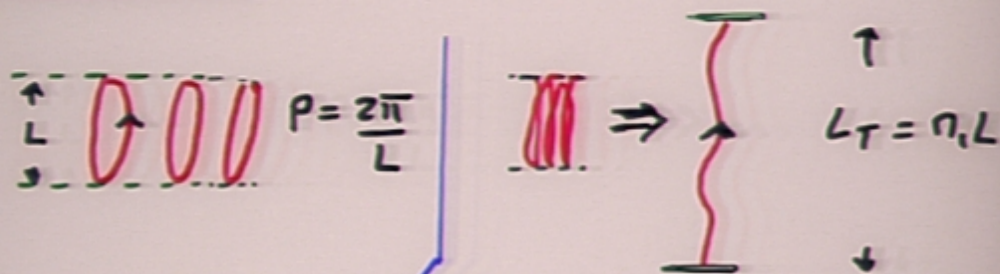
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n_p units of strength

$$\frac{2\pi}{L_T} = \frac{1}{n_1} \left(\frac{2\pi}{L} \right)$$

Duality

14

NS1 (n_1)



D5 (n_5)

P (n_p)



D1 (n_1)

↳ $n_1 n_p$ units
of fractional P

↳ $n_1 n_5$ units
of fractional D1



$n_5 = 1$
 n_1 D1 branes



$n_5 > 1$

$n_1 n_5$

fractional components
of an "effective
string"

4 (BOSONIC) VIBRATIONS,

4 FERMIONS

$C = 4 + 2 = 6$ FOR EACH COMPONENT

Duality

19

$NS1 (n_1)$



$D5 (n_5)$

$P (n_p)$



$D1 (n_1)$

↳ n_1, n_p units
of fractional P

↳ n_1, n_5 units
of fractional $D1$



$n_5 = 1$
 n_1 $D1$ branes



$n_5 > 1$

n_1, n_5

fractional components
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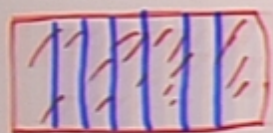
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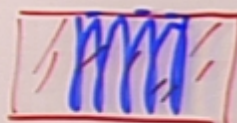
$C = 4 + 2 = 6$ FOR EACH COMPONENT
STRING

FIRST APPLICATION

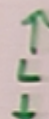
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$n_1 n_5$



$L_T = n_1 n_5 L$



2-CHARGE:

$$S = 2\pi \sqrt{\frac{c}{6} n_1 n_p}$$

$$L_T = n_1 L$$

momentum

3-CHARGE:

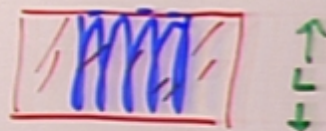
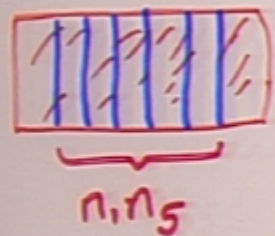
$$S = 2\pi \sqrt{\frac{c}{6} (n_1 n_5) n_p}$$

$(c=6)$

$$2\pi \sqrt{n_1 n_5 n_p}$$

Entropy of 3-charge black hole

FIRST APPLICATION



$$L_T = n_1 n_5 L$$

2-CHARGE:

$$S = 2\pi \sqrt{\frac{c}{6} n_1 n_p}$$

$$L_T = n_1 L$$

momentum

3-CHARGE:

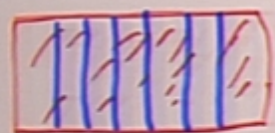
$$S = 2\pi \sqrt{\frac{c}{6} (n_1 n_5) n_p}$$

$(c=6)$

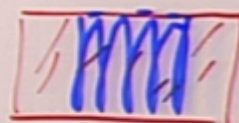
$$\longrightarrow 2\pi \sqrt{n_1 n_5 n_p}$$

Entropy of 3-charge black hole

FIRST APPLICATION



$n_1 n_5$



$$L_T = n_1 n_5 L$$

2-CHARGE:

$$S = 2\pi \sqrt{\frac{c}{6} n_1 n_p}$$

$$L_T = n_1 L$$

momentum

3-CHARGE:

$$S = 2\pi \sqrt{\frac{c}{6} (n_1 n_5) n_p}$$

$(c=6)$

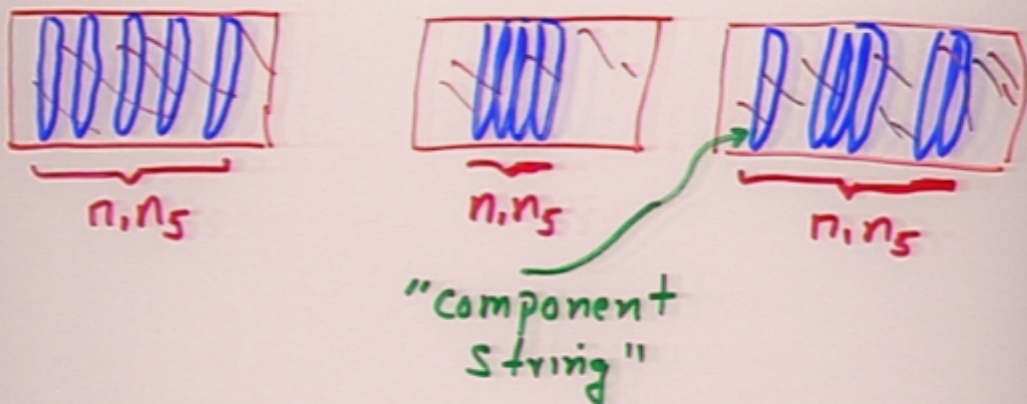
$$\longrightarrow 2\pi \sqrt{n_1 n_5 n_p}$$

Entropy of 3-charge black hole

SECOND APPLICATION

16

D1-D5 [NO P]



Each component string has 4 left
and 4 right fermion zero modes

→ 4 BOSONIC + 4 FERMIONIC STATES

COUNT STATES: PARTITIONS OF $n_1 n_5$

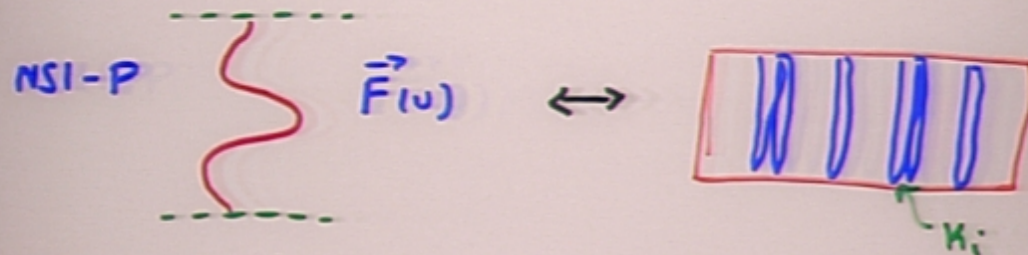
(4 BOSONIC, 4 FERMIONIC
FLAVORS)

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

$$S = 2\pi\sqrt{2}\sqrt{n_1 n_5}$$

WHAT IS THE GEOMETRY FOR A
GIVEN **D1-D5** MICRO STATE?

17.



$$\sum_i m_i k_i = n_1 n_p$$

m_i units of harmonic
 k_i

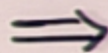
$$\sum_i m_i k_i = n_1 n_5$$

m_i component strings
with winding k_i



NS1-P
geometry

Dualities

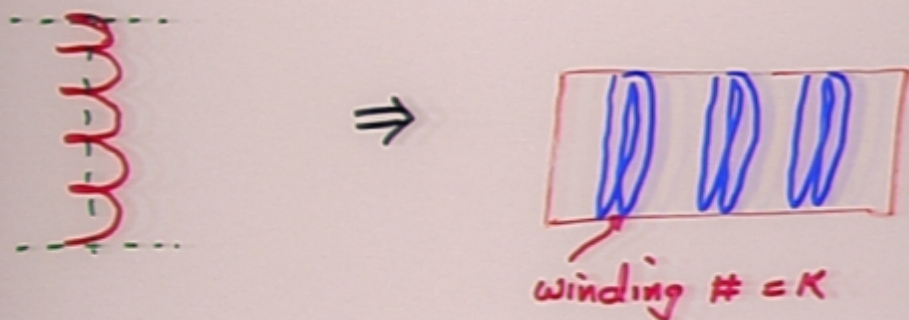


D1-D5
geometry

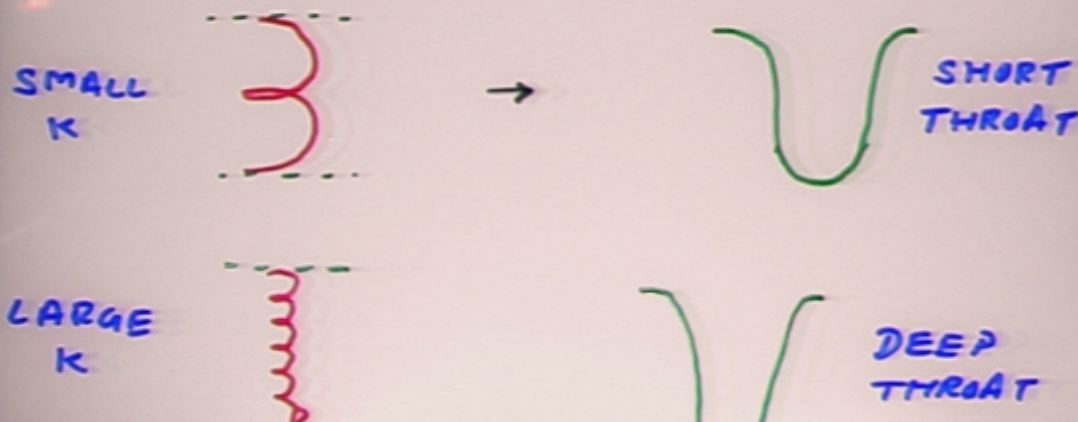


18
CONSIDER A SPECIAL SUBCLASS
OF STATES :

$\vec{F}_{(u)}$: K turns of a uniform helix

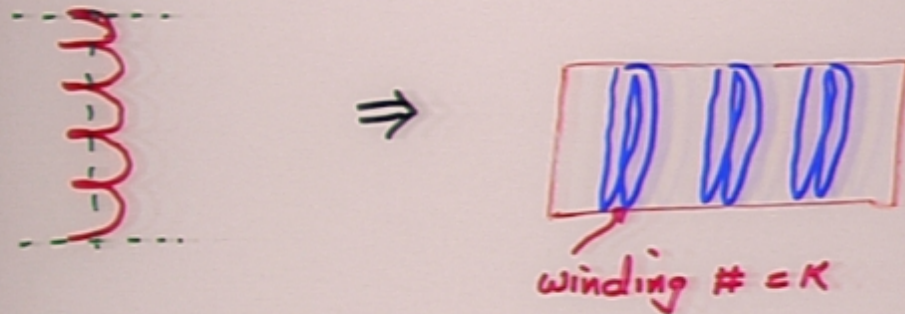


Axially symmetric geometries

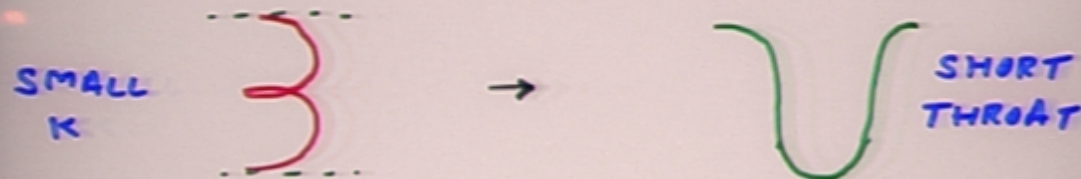


18
CONSIDER A SPECIAL SUBCLASS
OF STATES :

$\vec{F}_{10}$: K turns of a uniform helix

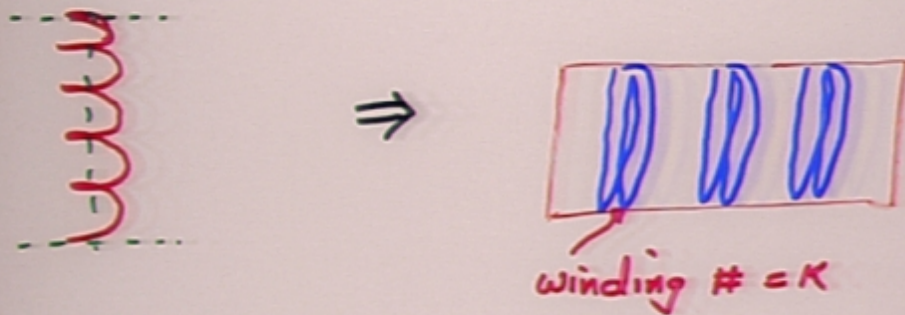


Axially symmetric geometries

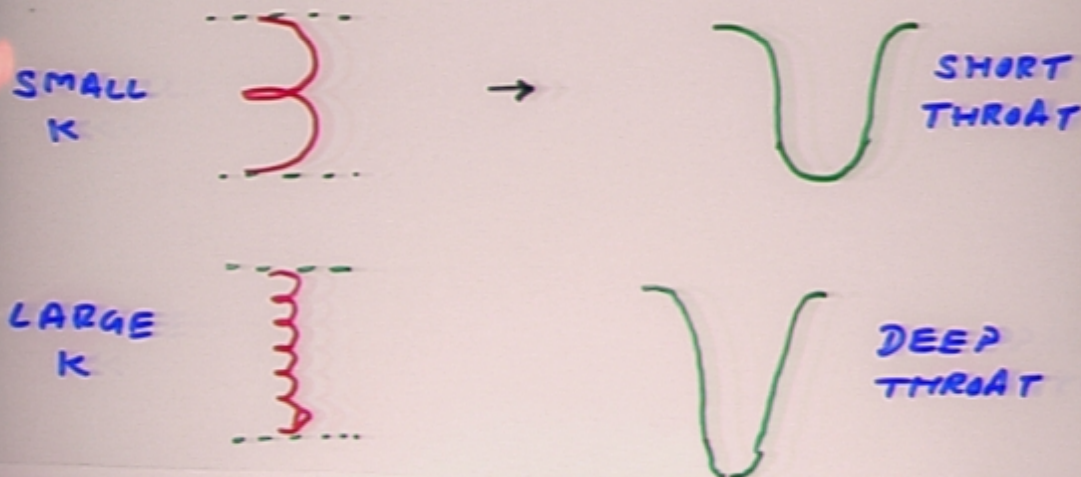


18
CONSIDER A SPECIAL SUBCLASS
OF STATES :

$\vec{F}_{(0)}$: K turns of a uniform helix

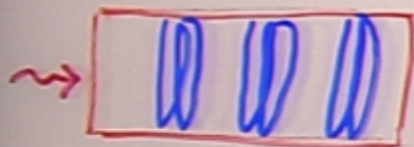


Axially symmetric geometries

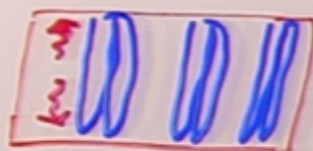


GEDANKEN EXPERIMENT:

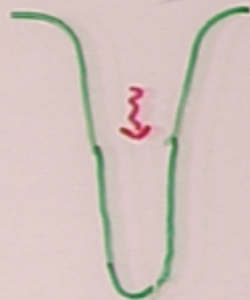
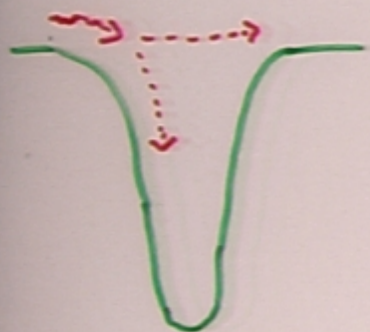
19



A GRAVITON IS
INCIDENT ON
MICROSTATE



Probability P_{CFT} :
graviton absorbed
→ vibrations of
component string



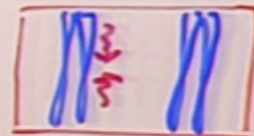
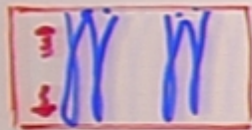
Probability that graviton
enters throat: P_{SUGRA}

Find:

$$P_{\text{CFT}} = P_{\text{SUGRA}}$$

CFT :

20



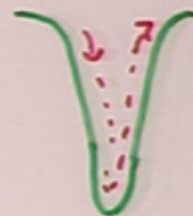
GRAVITON CAN BE
RE-EMITTED AFTER
TIME Δt_{CFT}

Naive geometry:



Graviton does not
return .

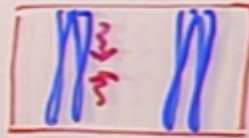
Actual geometry



Graviton bounces
off "cap" and
returns in time

Δt_{SUGRA}

CFT :



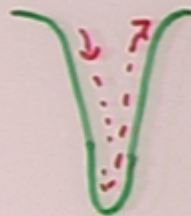
GRAVITON CAN BE
RE-EMITTED AFTER
TIME Δt_{CFT}

Naive geometry:



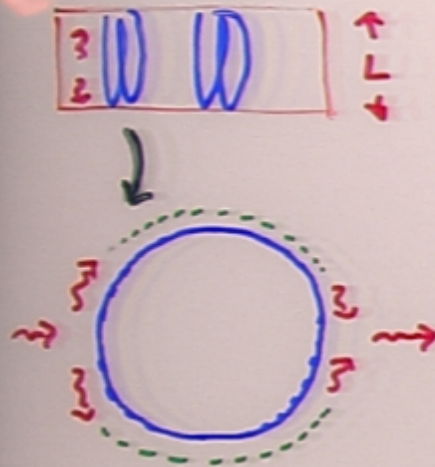
Graviton does not
return .

Actual geometry



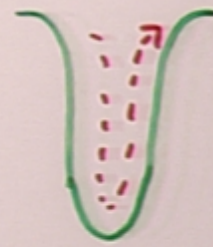
Graviton bounces
off "cap" and
returns in time

 Δt_{supRA}



Length of component
string KL

$$\Delta t_{\text{CFT}} = \frac{KL}{2}$$



Solve wave equation
 $\Delta\phi=0$ in geometry:

Find when
wavepacket returns

$$\begin{aligned}\Delta t_{\text{SUGRA}} &= \frac{\pi\sqrt{4\alpha'}a}{a} \\ &= \frac{KL}{2}\end{aligned}$$

$$\Delta t_{\text{CFT}} = \Delta t_{\text{SUGRA}}$$

(for each value of K)

A COMMENT ON AdS/CFT DUALITY

12

Einstein's picture

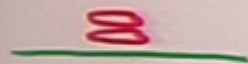


Flat space
(no matter)

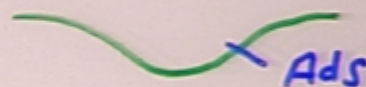


↑ matter
curves space

Maldacena: Branes are dual to supergravity

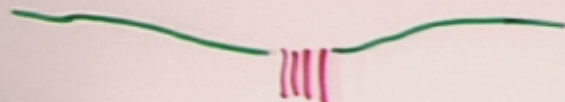


OR



Branes on flat space:

Put a stack of branes at $r=0$:



WHERE
DO THE

A COMMENT ON AdS/CFT DUALITY

22

Einstein's picture

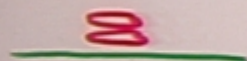


Flat space
(no matter)

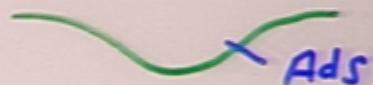


matter
curves space

Maldacena: Branes are dual to supergravity

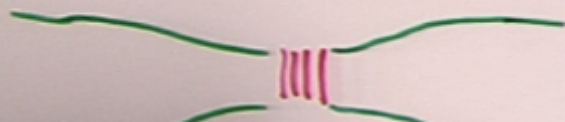


OR



Branes on flat space:

Put a stack of branes at $r=0$:



WHERE
DO THE

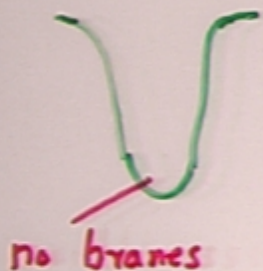
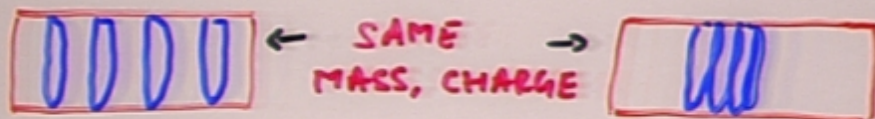
WITTEN:

23



BRANE THEORY
(CFT) LIVES ON
BOUNDARY, PURE
SUPERGRAVITY IN
BULK

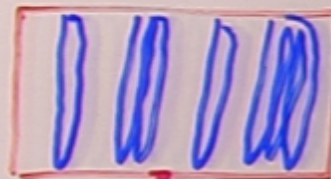
- What happened to the branes?
- What if there were many possible ground states for the branes?



WHAT IS "BLACK" ABOUT THE
2-CHARGE BLACK HOLE?

24

Generic microstate:



Distribution of lengths
is like distribution
of energy in a 1+1
dim. gas. of photons

Component strings
have unequal
length



$\vec{F}(u)$ is composed
of many harmonics

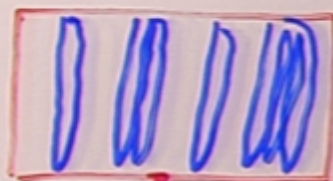
$$\sum_i m_i x_i = n, n_p \leftrightarrow$$

$$\sum_i m_i x_i = n, n_g$$

WHAT IS "BLACK" ABOUT THE
2-CHARGE BLACK HOLE?

24

Generic microstate:



Distribution of lengths
is like distribution
of energy in a $(+1)$
dim. gas. of photons

Component strings
have unequal
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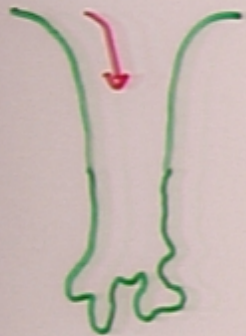


$\vec{F}(u)$ is composed
of many harmonics

$$\sum_i m_i \kappa_i = n, n_p \leftrightarrow$$

$$\sum_i m_i \kappa_i = n, n_g$$

No axial symmetry for generic
microstate: very complicated
geometry at end of throat:



Quanta falling in:

does not return
immediately:

trapped for a long time
in "complicated" region

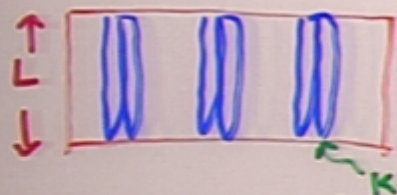
Geodesic approx: $\Delta t_{\text{trapping}} \sim \Delta t_{\text{crossing}} \times \sqrt{S}$

$\sqrt{S} \sim \frac{1}{\hbar}$, $\rightarrow \infty$ in classical
limit

Wavefunction computation: Wavelets
reflecting from different regions

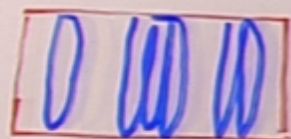
CFT:

2c



All component strings equal

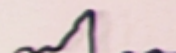
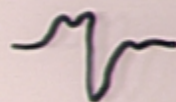
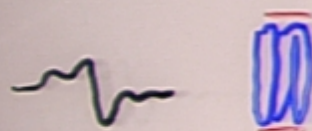
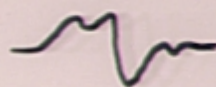
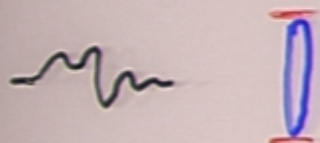
$$\Delta t_{\text{CFT}} = \frac{KL}{2}$$



Component strings unequal:

$$\Delta t_{\text{CFT}} \sim \langle K \rangle \frac{L}{2} ??$$

No! Phase interference kills emitted wave



Add a waveform to all its time translates

$$f(t) \rightarrow \int_{-\infty}^{\infty} f(t) dt \rightarrow \tilde{f}(0) = 0$$

[massless wave moving inwards]

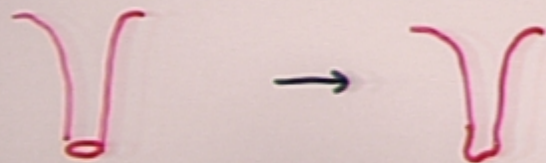
So $\Delta t_{\text{CFT}} \gg \langle k \rangle \frac{L}{2}$, CFT state looks "BLACK"

So "blackness" arises from disorder, just as in ordinary physical systems.

28.
How do these microstate geometries
relate to the traditional black
hole geometry?

No hair "theorem": If you
have a horizon, then you cannot
find smooth deformations of it.

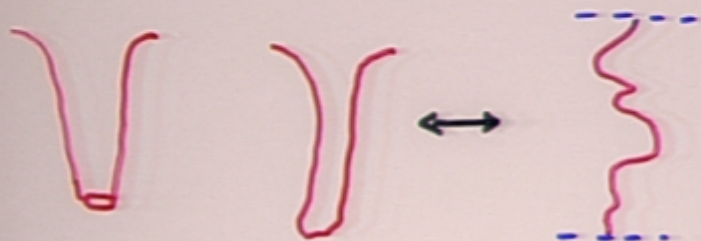
But: In the microstate
geometries we never form a horizon:
 g_{tt} becomes small but does not
vanish, (cap forms instead)



Horizon formation:

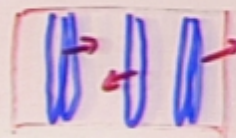
If you take a spherically symmetric ansatz for the solution to supergravity, you get a horizon [with R^2 terms, for the 2-charge case]

But: All microstates break spherical symmetry



D1-D5 CFT STATE:

FERMION ZERO MODES



What about the traditional
black hole geometry ??

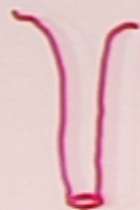
so.

If it was a smooth solution to
Supergravity, then we had to
find it somewhere in the dual
CFT

BUT: It is not smooth; once you
have a horizon, there must be a
singularity inside



NOT
SMOOTH



NOT



SMOOTH

