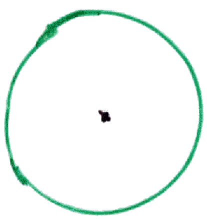
I·1

WHERE ARE THE STATES OF A BLACK HOLE ?

PROBLEMS WITH BLACK HOLES :



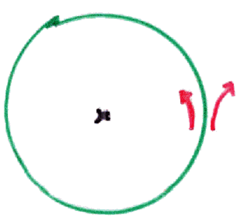
$S = \frac{A}{4G}$

$\overset{?}{\Rightarrow}$ e^S states?

[Bekenstein '72]

But : Black holes have no 'hair'

Unique metric, $S = \ln 1 = 0$??



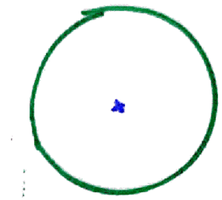
Related problem :

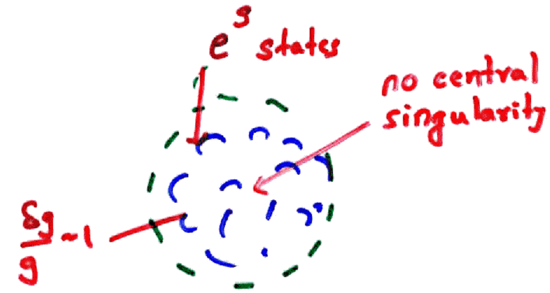
Information loss in Hawking radiation, violation of quantum mechanics

[Hawking '74]

I·2

THIS TALK





- 2-CHARGE EXTREMAL D1-D5 (Black hole ?)

"Naive" metric

Actual metrics

- D1-D5 + 1 unit of P : similar structure
- Physical basis : "Fractionation"

N quanta $\Rightarrow$ nonlocality $\sim N \ell_p$ [not $\sim \ell_p$]

T:1

THE 2-CHARGE D1-D5 SYSTEM

$M^{9,1}$: IIB STRING THEORY

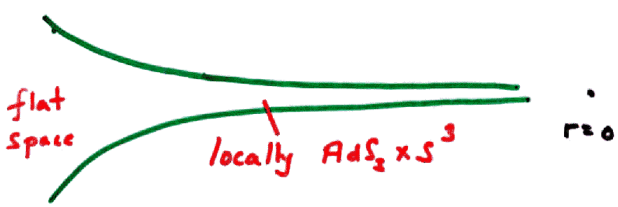
$$\underbrace{x^0\quad x^1\quad x^2\quad x^3\quad x^4}_{4+1\ \text{noncompact}}\qquad \underbrace{x^5}_{S^1}\qquad \underbrace{x^6\ x^7\ x^8\ x^9}_{T^4}$$

t, r, θ, ψ, ϕ $\quad y \quad$ $z_1\ z_2\ z_3\ z_4$

n_1 - D1 branes (along y)

n_5 D5 branes (along y and T^4)

"Naive geometry"



$$ds^2 = (f_1 f_5)^{-\frac{1}{2}}[-dt^2 + dy^2] + (f_1 f_5)^{\frac{1}{2}}[dr^2 + r^2 d\Omega_3^2] + \sqrt{\frac{f_1}{f_5}}\, dz_a dz_a$$

$$f_1 = 1 + \frac{Q_1}{r^2}, \qquad f_5 = 1 + \frac{Q_5}{r^2}$$

T:2

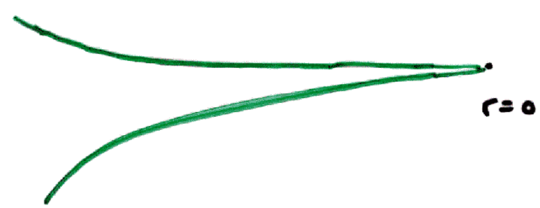
THE 2-CHARGE FP SYSTEM

$$\underset{(IIB)}{D1\text{-}D5} \xrightarrow{S} \underset{(IIB)}{F\ NS5} \xrightarrow{T_5} \underset{(IIA)}{P\ NS5} \xrightarrow{T_6} \underset{(IIB)}{P\ NS5} \xrightarrow{S} \underset{(IIB)}{P\text{-}D5} \xrightarrow{T_{6789}} \underset{(IIB)}{P\ D1} \xrightarrow{S} \underset{(IIB)}{FP}$$

FP : fundamental string (F) wrapped n_5 times around y, carrying n_1 units of momentum (P) along y.

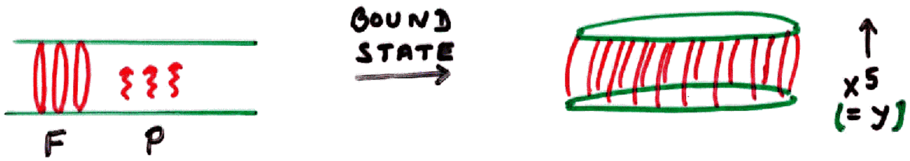
FP. "Naive metric"

$$ds^2 = -\left(1 + \frac{Q}{r^2}\right)^{-1}\left[du\,dv + \frac{Q'}{r^2}dv^2\right] + dx_i dx_i + dz_a dz_a$$



T3

ACTUAL GEOMETRY OF FP BOUND STATE



COVERING SPACE

$\vec{F}(v)$

$v = t - y$

CLASSICAL LIMIT :

$n_1 \to \infty, \quad n_5 \to \infty$

- Classical profile $\vec{F}(v)$

  [Quantize, amplitude $\vec{F}(v)$ "discrete", $e^{2\sqrt{2}\pi\sqrt{n_1 n_5}}$ states]

- Generic profile has wavelength

  $\sqrt{n_1 n_5}\, L \gg L$

  Thus each strand is "straight" (no t, y dependence in result)

- Strands → continuous "ribbon"

T4

CONSTRUCTING METRIC FOR FP BOUND STATES

Metric known for 1 strand

[Dabholkar, Gauntlett, Harvey, Waldram, '95

Callan Maldacena Peet '95]

Many strands: Superpose harmonic fns.

$$ds^2 = H\left[-du\,dv + K\,dv^2 + 2A_i\,dx^i\,dv\right] + dx_i\,dx_i + dz_a\,dz_a$$

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

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

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

[Lunin + SDM hep-th/0105136]

Dualize back: FP → D1-D5

8.

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

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

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

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

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

Lunin + SDM, hepth 0109154

15

SMOOTHNESS OF D1-D5 GEOMETRIES

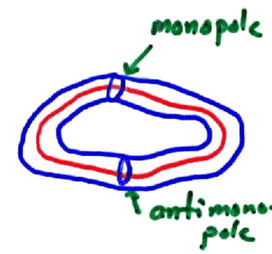
$\frac{1}{|\vec{x} - \vec{F}(v)|^2} \rightarrow$ singularity on curve $\vec{x} = \vec{F}(v)$??

Generically; simple closed curve  in 4 Euclidean dimensions $x_1 x_2 x_3 x_4$

Lunin, Maldacena, Maoz, hepth/0212210 :
'Singularity' is only a Co-ordinate singularity, like the one at center of a Kaluza-Klein monopole

$\rightarrow$ KK monopole $\times S^1$

$\boxed{\text{No net KK monopole charge}}$



Similar to 'Supertubes'
In fact D1-D5 $\rightarrow$ F-D0 supertubes by duality

[Ang mom. bound, FP metric Lunin + SDM hepth 0105136]

7.6

'AREA ENTROPY'

Individual D1-D5 microstates have no horizon and no singularity

$$\frac{A}{4G} \sim \sqrt{n_1 n_5} \sim S_{micro} = 2\sqrt{2}\pi\sqrt{n_1 n_5}$$

"Area Entropy" from a "coarse graining" over microstates.

States with angular momentum :

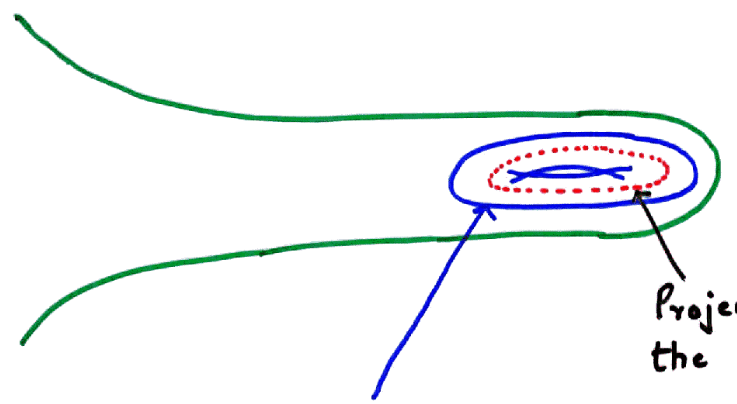
$$S_{micro} = 2\sqrt{2}\,\pi\sqrt{n_1 n_5 - J}$$

Geometry [FP] : 

F string swings around in a helix to get ang mom J, plus some additional vibrations

7.7

Metrics differ from each other in a doughnut shaped region around the projection of the helix



$$\frac{A}{4G} \sim \sqrt{n_1 n_5 - J} \sim S_{micro} = 2\sqrt{2}\pi\sqrt{n_1 n_5 - J}$$

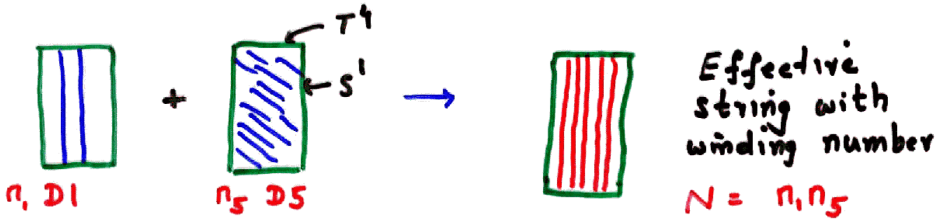
[Lunin + SDM hep-th/0202072]

T.8

THE D1-D5 CFT

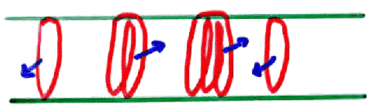
$M_{9,1} \rightarrow M_{4,1} \times S^1 \times T^4$

$\uparrow$ $SO(4) \approx SU(2) \times SU(2)$



Effective string with winding number $N = n_1 n_5$

[Maldacena-Susskind '96]



- Total winding # $= N$
- Each "component string" has spin $(\frac{1}{2}, \frac{1}{2})$ under $SU(2) \times SU(2)$

Orbifold CFT: T_4^N / S_N 4 bosons + 4 fermions $\hookrightarrow \phi_1, \phi_2$

$\boxed{\text{D1-D5 system is in Ramond (R) sector}}$

$J_z^3 = i \partial_z [\phi_1 - \phi_2]$

$J_{\bar{z}}^3 = i \partial_{\bar{z}} [\phi_1 - \phi_2]$

Spin fields: $e^{\pm \frac{i}{2} \phi_1 \pm \frac{i}{2} \phi_2}$

[Lunin + SDM, to appear]

T.9

THE FP $\leftrightarrow$ D1-D5 MAP

FP

$\vec{F}(v) \longrightarrow$

$(a^{i_1}_{n_1})^\dagger \cdots (a^{i_k}_{n_k})^\dagger |0\rangle$

$\sum n_i = N$

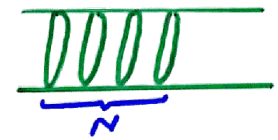
$i = 1, 2, 3, 4$

$\rightarrow$ 4 of $SO(4)$

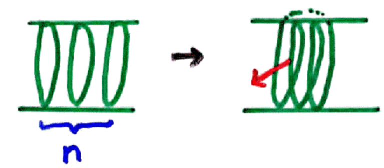
$S = 2\sqrt{2}\pi\sqrt{n_1 n_5}$

D1-D5

$|0\rangle_{NS}$



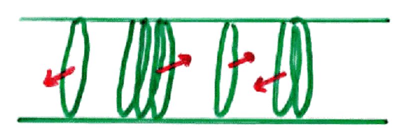
$\sigma_n^{\pm\pm}$:



$(\pm\pm) = (\frac{1}{2}, \frac{1}{2})$ of $SU(2) \times SU(2) \rightarrow$ 4 of $SO(4)$

$\sigma_{n_1}^{\pm\pm} \cdots \sigma_{n_k}^{\pm\pm} |0\rangle_{NS}$

$\sum n_i = N$



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

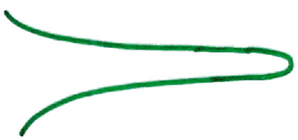
T.10

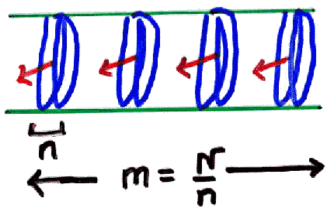
A DYNAMICAL EXPERIMENT

A special subfamily of geometries:

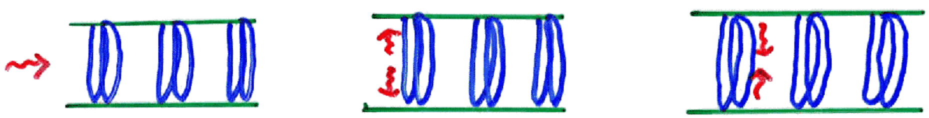
FP:  + . . .

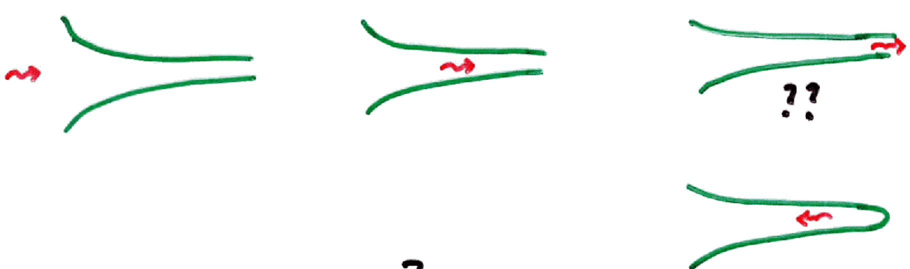
Uniform helixes, n turns in covering space





Experiment

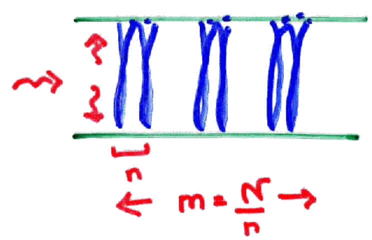




TIMES AGREE ?

T.11

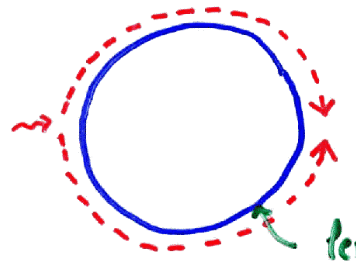
THE CFT COMPUTATION



$S_{int} = \partial x^i \partial x^j h_{ij}$

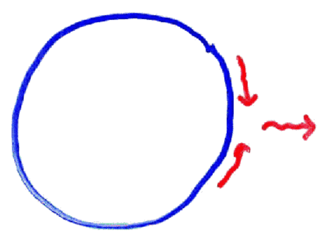
$\rightarrow$ Probability of absorption P_{CFT}

[Das + SDM '96]



length $= \dfrac{2\pi R\, n_1 n_5}{m}$

$$\Delta t_{CFT} = \frac{2\pi R\, n_1 n_5}{m} \times \frac{1}{2} = \frac{\pi R\, n_1 n_5}{m}$$



Probability of emission per unit time

$$R_{CFT} = \frac{P_{CFT}}{\Delta t_{CFT}}$$

T.12

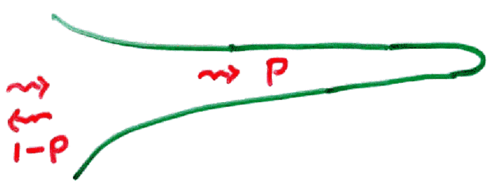
THE SUPERGRAVITY COMPUTATION

Scalar wave equation $\Box\phi = 0$

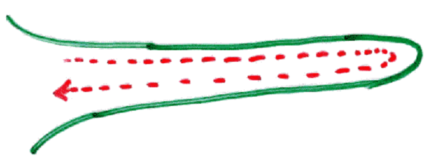
$$\phi = e^{-i\omega t}\, Y(\theta,\psi,\phi)\, f(r)$$

$$4\frac{d}{dx}\left[(x+\gamma^2)\frac{df}{dx}\right] + \left[(\omega^2-\lambda^2)\left[\frac{Q_1Q_5}{R^4}x + \frac{Q_1+Q_5}{R^2}\right] + \frac{(\omega-n_1\gamma)^2}{x+\gamma^2} - \frac{(\lambda+n_2\gamma)^2}{x}\right]f - \Lambda f = 0$$

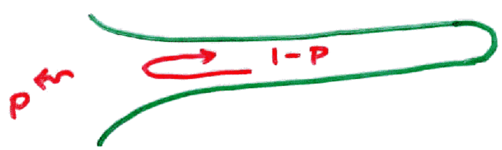
$$x = r^2\frac{R^2}{Q_1Q_5}, \qquad \gamma = \frac{m}{n_1 n_5}$$



$$P = 4\pi^2\left[\frac{Q_1Q_5\,\omega^4}{16}\right]^{l+1}\left[\frac{1}{(l+1)!\,l!}\right]^2$$



$$\Delta t = \frac{\pi R n_1 n_5}{m}$$

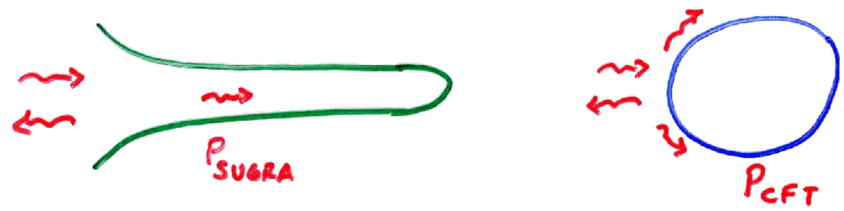


Prob. of emission per unit time

$$R = \frac{P}{\Delta t} = \frac{\pi^2\omega^4 g^2}{V}\frac{1}{2\pi R}\frac{m}{2}$$

T.13

THE DUALITY MAP



$$P_{SUGRA} = P_{CFT}$$

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

$$R_{SUGRA} = R_{CFT}$$

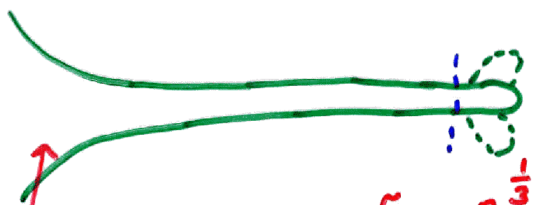
$\Delta t \gg$ radius of AdS

$\downarrow$ $(n_1 n_5)^{\frac{1}{2}} R$ $\qquad$ $\downarrow$ $g^{\frac{1}{2}}(n_1 n_5)^{1/4}\sqrt{\alpha'}$

Δt probes the essential physics with Lorentzian signature

THE D1-D5-P SYSTEM

Th.1'



D1-D5

$n_1 \sim n_5 \sim n$

$r_H \sim n^{\frac{1}{3}} l_p \sim n^{\frac{1}{3}} l_s$

not small !

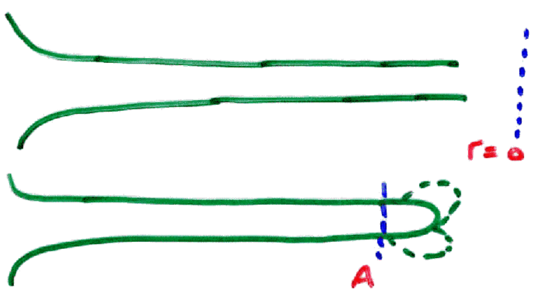
$1+\frac{Q_1}{r^2}$, $1+\frac{Q_5}{r^2}$

$r \sim \sqrt{Q} \sim n^{\frac{1}{2}}$

"Charge radius"

Classical limit : $n \to \infty$: 'horizon' not seen

D1-D5-P



"interior"

"singularity"

Throat radius saturates, so we will get

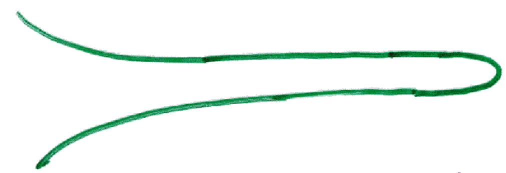
$A/4G = 2\pi\sqrt{n_1 n_5 n_p} = S_{micro}$

D1 + D5 + 1 UNIT OF P

Th.2

Start with a particular D1-D5 geometry

FP : Uniform helix with 1 turn in covering space $\longrightarrow$ D1-D5



{ · Cvetic-Youm, Balasubramanian, deBoer, Keski-Vakkuri, Ross, · Maldacena-Moore

Look for a supergravity perturbation :

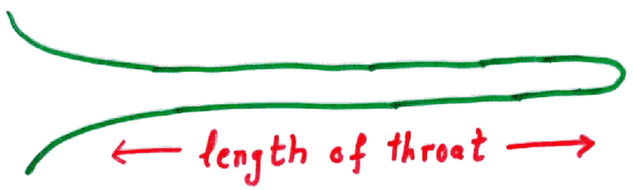
- $\Psi \sim e^{i\frac{p y}{R}}$, $p = -1$
- $\Psi \sim e^{-i\omega t}$, $\omega = \frac{|p|}{R}$

[Energy = |momentum| , BPS]

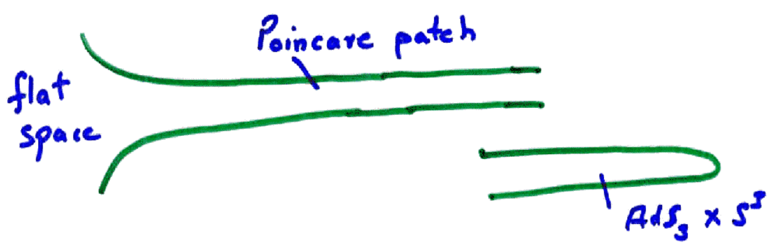
- Ψ is regular everywhere, normalizable at infinity

FINDING THE PERTURBATION Ψ Th.3

Solve for Ψ by a "matching" technique:



Expand in powers of $\frac{1}{\text{length of throat}}$



$|0\rangle_{NS} \longrightarrow |0\rangle_R$

Maldacena Strominger '97 — Chiral primary — $|\psi\rangle_{NS} \longrightarrow |\psi\rangle_R$ — R ground state

$J_0^- |\psi\rangle_{NS} \longrightarrow J_{-1}^+ |\psi\rangle_R$

$L_0 - \bar{L}_0 = 1, \quad \rightarrow e^{i/R(t+y)}$

Does this continue to a normalizable Ψ outside?

Field equations: $B_{MN},\ w$

$(F_{MNP} = \partial_M B_{NP} + \partial_N B_{PM} + \partial_P B_{MN})$

$$F_{ABC} + \frac{1}{3!}\epsilon_{ABCDEF}F^{DEF} + w\bar{H}_{ABC} = 0$$

$$w_{;A}{}^{;A} - \frac{1}{3}\bar{H}^{ABC}F_{ABC} = 0$$

Inner region solution, leading order

$$
\begin{aligned}
w &= \frac{1}{Q}\frac{e^{-i\frac{a}{Q}u}}{(r^2+a^2)^l}Y^{(l)}\\
B_{\theta\psi} &= \frac{1}{4l}\frac{e^{-i\frac{a}{Q}u}}{(r^2+a^2)^l}\cot\theta\partial_\phi Y^{(l)}\\
B_{\theta\phi} &= -\frac{1}{4l}\frac{e^{-i\frac{a}{Q}u}}{(r^2+a^2)^l}\tan\theta\partial_\psi Y^{(l)}\\
B_{\psi\phi} &= \frac{1}{4l}\frac{e^{-i\frac{a}{Q}u}}{(r^2+a^2)^l}\sin\theta\cos\theta\partial_\theta Y^{(l)}\\
B_{t\theta} &= -\frac{a}{4l}\frac{e^{-i\frac{a}{Q}u}}{Q(r^2+a^2)^l}\tan\theta\partial_\psi Y^{(l)}\\
B_{t\psi} &= \frac{a}{4l}\frac{e^{-i\frac{a}{Q}u}}{Q(r^2+a^2)^l}\sin\theta\cos\theta\partial_\theta Y^{(l)}\\
B_{y\theta} &= \frac{a}{4l}\frac{e^{-i\frac{a}{Q}u}}{Q(r^2+a^2)^l}\cot\theta\partial_\phi Y^{(l)}\\
B_{y\phi} &= -\frac{a}{4l}\frac{e^{-i\frac{a}{Q}u}}{Q(r^2+a^2)^l}\sin\theta\cos\theta\partial_\theta Y^{(l)}\\
B_{ty} &= -\frac{1}{2Q^2}\frac{r^2e^{-i\frac{a}{Q}u}}{(a^2+r^2)^l}Y^{(l)}\\
B_{yr} &= \frac{i}{2Q}\frac{re^{-i\frac{a}{Q}u}}{(r^2+a^2)^{l+1}}Y^{(l)}
\end{aligned}
$$

$$Y^{(l)} = -\frac{\sqrt{l(2l+1)}}{\pi}e^{i(-2l+1)\phi+i\psi}\sin^{2l-1}\theta\cos\theta, \quad u = t+y$$

1

Outer region solution, leading order

$$
\begin{aligned}
w &= \frac{e^{-i\frac{a}{Q}u}}{(Q+r^2)r^{2l}}Y^{(l)} \\
B_{\theta\psi} &= \frac{1}{4l}\frac{e^{-i\frac{a}{Q}u}}{r^{2l}}\cot\theta\partial_\phi Y^{(l)} \\
B_{\theta\phi} &= -\frac{1}{4l}\frac{e^{-i\frac{a}{Q}u}}{r^{2l}}\tan\theta\partial_\psi Y^{(l)} \\
B_{\psi\phi} &= \frac{1}{4l}\frac{e^{-i\frac{a}{Q}u}}{r^{2l}}\sin\theta\cos\theta\partial_\theta Y^{(l)} \\
B_{ty} &= -\frac{1}{2(Q+r^2)^2}\frac{e^{-i\frac{a}{Q}u}}{r^{2l-2}}Y^{(l)} \\
B_{tr} &= \frac{ia}{r^{2l+1}}\frac{1}{4lQ}e^{-i\frac{a}{Q}u}Y^{(l)} \\
B_{yr} &= \frac{ia}{r^{2l+1}}\frac{1}{4lQ}e^{-i\frac{a}{Q}u}Y^{(l)}
\end{aligned}
$$

Agreement in region

$$a << r << Q$$

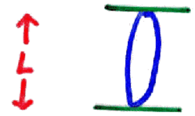
$$
\begin{aligned}
w &= \frac{e^{-i\frac{a}{Q}u}}{Qr^{2l}}Y^{(l)} \\
B_{\theta\psi} &= \frac{1}{4l}\frac{e^{-i\frac{a}{Q}u}}{r^{2l}}\cot\theta\partial_\phi Y^{(l)} \\
B_{\theta\phi} &= -\frac{1}{4l}\frac{e^{-i\frac{a}{Q}u}}{r^{2l}}\tan\theta\partial_\psi Y^{(l)} \\
B_{\psi\phi} &= \frac{1}{4l}\frac{e^{-i\frac{a}{Q}u}}{r^{2l}}\sin\theta\cos\theta\partial_\theta Y^{(l)} \\
B_{ty} &= -\frac{1}{2Q^2}\frac{r^2e^{-i\frac{a}{Q}u}}{r^{2l}}Y^{(l)}
\end{aligned}
$$

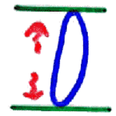
2

[SDM, Saxena, Srivastava, 2003]

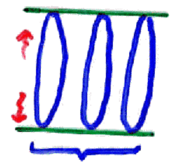
F.1

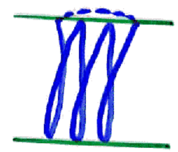
FRACTIONATION





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





Total length

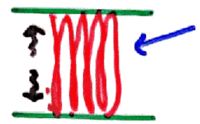
$L_T = NL$

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

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

[Das + SDM '96]

3-charge system:

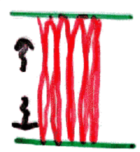


"Effective string"

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

[Maldacena + Susskind '96]

4 charge black hole [3+1 d]



$$\Delta E_{min} = \frac{4\pi}{n_1 n_5 n_3}$$

F·2

PHYSICAL CONSEQUENCE OF FRACTIONATION

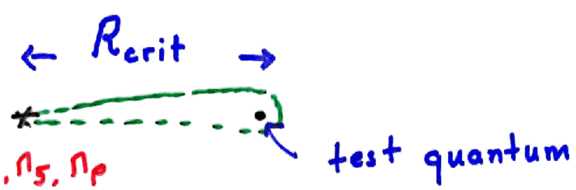
Many quanta in bound state

→ very light fractional excitations exist

→ extend far out from $r=0$

→ reach upto $r \sim R_H$, horizon radius

[S.D.M. '97]



$$R_{crit} \sim \left[\frac{(n_1 n_5 n_p)^{\frac{1}{2}} g^2 \alpha'^4}{V_4 R} \right]^{\frac{1}{3}} \sim R_H$$

[parameters $n_1, n_5, n_p, R, g, \alpha', V_4$ all cancel out in ratio $\frac{R_{crit}}{R_H} \sim 1$]

F2

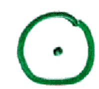
STRINGS → BLACK HOLES

$g < g_c$ $\qquad$ $g > g_c$

Entropy S matches at g_c [Horowitz + Polchinski '96]

greybody factors don't quite agree

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



$FP + \frac{P}{\bar{P}}$]

$T_L \gg T_R$

$T_L = T_R$

[FP → D1-D5]

[Emparan '97]

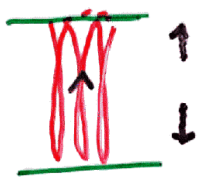
Emitted spins not correct

h_{ij} $[T^4]$, h_{ab} $[R^4]$ $\qquad$ h_{ij} $[T^4]$ (scalars)

PHASE TRANSITIONS

F3'

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



$\Delta E \Rightarrow P\bar{P}$ pair

$$(\Delta E)_{min} = \frac{4\pi}{n_1 L}$$

Ⓐ

FP: n_1, n_p

BUT

$$\underline{D1-D5}-P \longrightarrow D1-P-D5 \xrightarrow{S} \underline{F-P}-NS5$$

$D1D5$ $\quad P, \bar{P}$ $\qquad\qquad$ FP $\quad NS5, \overline{NS5}$

$$\Delta E = \frac{4\pi}{n_1 n_5 L} \qquad\qquad \Delta E = \frac{2\,V_4\,L}{(2\pi)^4 g^2 n_1 n_5}$$

Ⓑ

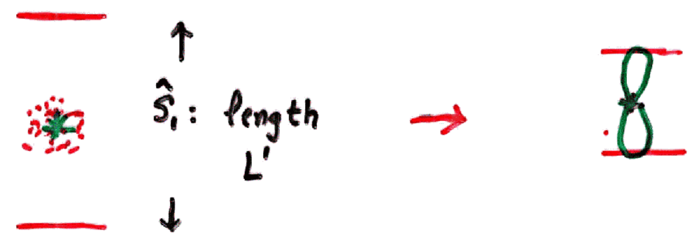
$$\boxed{g < g_c \Rightarrow Ⓐ, \quad g > g_c \Rightarrow Ⓑ}$$

Dynamical degrees of freedom change at $g \sim g_c$

THE 'CRUSHING' TRANSITION

F4

$$M_{4,1} \to M_{3,1} \times \underbrace{T^4 \times S^1}\times \hat{S}_1$$



$n_1 n_5 n_p + (P\bar{P})$ $\qquad$ $n_1 n_5 n_p + (K\bar{K})$

$$\delta M = M - M_{extremal} \approx \frac{(2\pi)^5 L L' V_4 \boxed{r_0}}{2 g^2 \alpha'^4}$$

Similar to Gregory-Laflamme instability

$L' > r_0$ $\qquad\qquad$ $L' < r_0$

F·5

`SIZE' OF EXTREMAL D1D5P BOUND STATE

① * Extremal

$n_1\; n_2\; n_3 \quad (= n_1, n_5, n_p)$

Size: If we place it in a box of length L', then will it be entropically favorable for brane-antibrane pairs to "reach out and wrap around" the box?

②

Energy budget: $\Delta E \sim \frac{1}{R}$

③

$S_{non-wrap} = 2\pi\sqrt{n_1 n_2 n_3}$

$S_{wrap} = 2\pi\sqrt{n_1 n_2 n_3\, \mu} + 4\pi\sqrt{n_1 n_2 n_3 (1-\mu)}\; n_4$

F·6

④ Require that

$$\Delta S = S_{wrap} - S_{non-wrap} \gtrsim 1$$

So that phase space for wrapped brane-antibrane pairs is e [2.7] times phase space of not wrapping pairs

Optimise over μ:

$$\mu = \frac{1}{1+4n_4}, \quad \Delta S \simeq 4\pi\sqrt{n_1 n_2 n_3}\; n_4,$$

$$\Delta S = 1 \rightarrow n_4 = \frac{1}{4\pi\sqrt{n_1 n_2 n_3}}$$

⑤ Mass of $K\bar{K}$ ~~f~~ pair is

$$M_{K\bar{K}} = \frac{2LR^2 V_4}{g^2 (2\pi)^4 \alpha'^4}$$

Thus we need energy

$$E_{needed} = \frac{2LR^2 V_4}{g^2 \alpha'^4 (2\pi)^5\, 4\pi\sqrt{n_1 n_2 n_3}}$$

F.7

⑥ Set $E_{needed} = \frac{1}{R}$

$$\frac{2LR^2V_4}{g^2\alpha'^4(2\pi)^5 4\pi\sqrt{n_1 n_5 n_p}} = \frac{1}{R}$$

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

Thus the 'size' of the Extremal D1-D5-P bound state is of order R_H, the radius of its classical black hole horizon.

S.1

NONEXTREMAL SYSTEMS

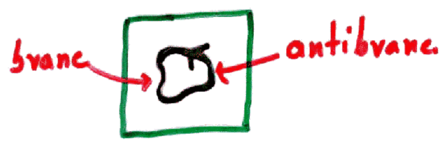
Nonextremality → Brane - Antibrane pairs

- Entropy of Schwarzschild hole in 4+1 dim

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

[Horowitz Maldacena Strominger '96]

- Entropy of near extremal 5-brane



Exact agreement
[Maldacena '96]

- Hawking radiation agrees exactly for near-extremal 5-brane
[Klebanov + SDM '97]

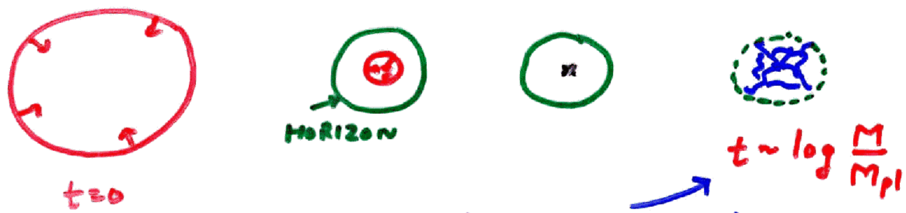
Fractionation : Size of bound state
$R \sim R_H$ (as before)

5·2

DYNAMICAL INFALL

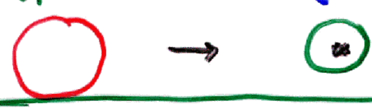
Possibility 1

Possibility 2.



time when source quanta for Hawking radiation become transplanckian

There is much more phase space $[e^S]$ for brane-antibrane pairs than for configurations of just $g_{\mu\nu}$. If we ignore these pairs we get



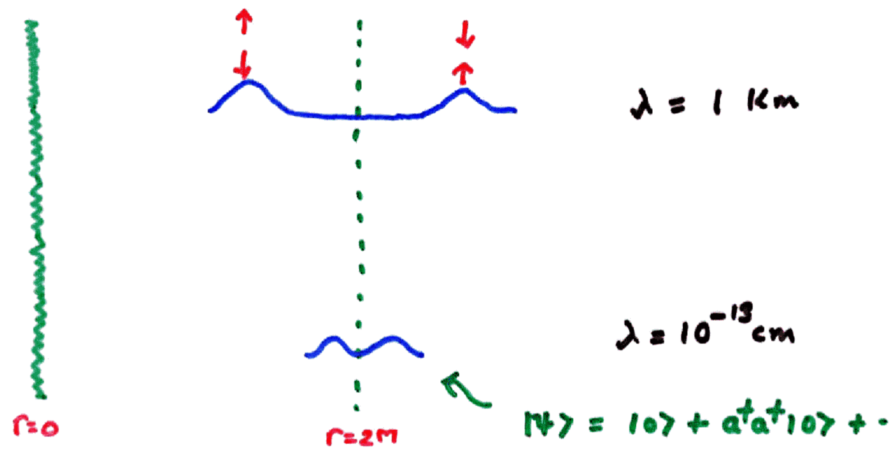
M·1

HAWKING "THEOREM"

Nonlocality $\lesssim l_p$

Vacuum unique

→ Will have information loss



$$i \frac{d\psi}{dt} = [H + H_{New}]\psi; \quad \boxed{H_{New} \sim H}$$

Cannot have "Empty space with information transfer through small subtle quantum gravity effects.

C.1

CONCLUSION

- Resolving information paradox needs nonlocality on macroscopic length scales.

- D1-D5-P : Estimate of 'size' gives $R \sim R_H$ [long floppy objects from fractionation]

- Abstract argument on hair says that "microstates have no horizons"

- Explicit construction for D1-D5, "fuzzball radius gives entropy"

- Subfamilies of D1-D5-P give similar "capped" geometries

[+ Bena, Kraus, Marolf, . . .]