Black Hole Microscopy: Conformal Field Theory at the bottom of the throat of the horizon

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What are we talking about?

- The free $\mathcal{N} = (4,4)$ SCFT with target space $(T^4)^N/S_N$ is a very interesting object:
  - It has been the subject of important recent developments in the explicit construction of $\mathrm{AdS}_3/\mathrm{CFT}_2$ holography ([Eberhardt et al., 2019] and others)
  - It famously holds the microstates accounting for the entropy of black holes in string theory [Strominger and Vafa, 1996]
  - It is related to the D1-D5 system, the simplest example of a black hole in string theory
- Goals:
  - Present some new results concerning the deformed theory [Lima et al., 2020a, Lima et al., 2020b, Lima et al., 2020c, Lima et al., 2020d] ,
  - along with a (*utterly*) schematic overview of how the SCFT is related to black holes

With results published in

· Lima, A.A., Sotkov, G., Stanishkov, M. (2020). Dynamics of R-neutral Ramond fields in the D1-D5 SCFT.

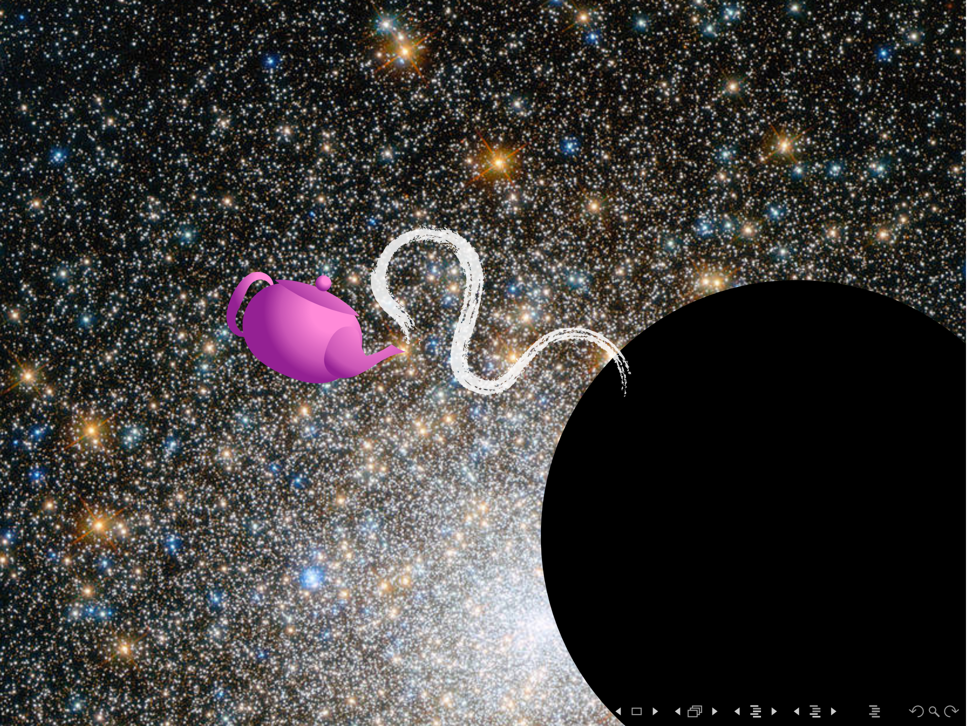
· Lima, A.A., Sotkov, G., Stanishkov, M. (2020). Renormalization of Twisted Ramond Fields in D1-D5 SCFT_2.

· Lima, A.A., Sotkov, G., Stanishkov, M. (2020). Correlation functions of composite Ramond fields in deformed D1-D5 orbifold SCFT_2. *Physical Review D, 102.*

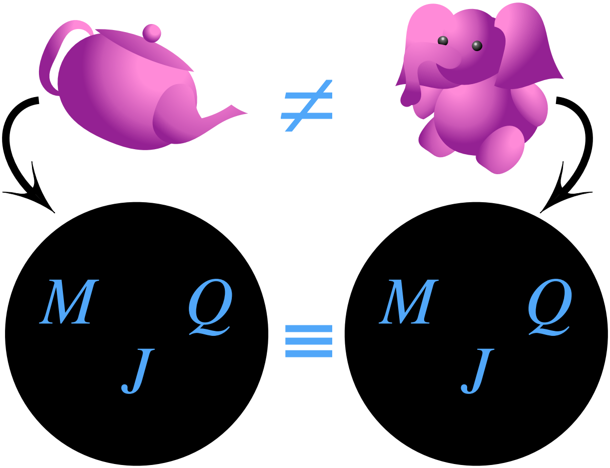
· Lima, A.A., Sotkov, G., Stanishkov, M. (2020). Microstate renormalization in deformed D1-D5 SCFT. *Physics Letters B, 808,* 135630.

Outline

1. A black hole is a black hole



$$S_{BH} = \frac{\text{Area}}{4G_N}$$



What are hairless black holes made of?

2. How to build a quantum black hole

- A quantum black hole needs quantum gravity
  i.e. String Theory.

- In low-energy limit, String Theory becomes SUGRA
- Ingredients:

$$\begin{aligned} \text{NS-NS (Type IIA and IIB):} \qquad & G_{\mu\nu}, \quad \Phi, \quad B^{(2)} \\ \text{R-R (Type IIA):} \qquad & C^{(1)}, \quad C^{(3)} \\ \text{R-R (Type IIB):} \qquad & C^{(0)}, \quad C^{(2)}, \quad C^{(4)} \end{aligned}$$

- Field equations are complicated, but there are techniques
  for building supersymmetric solutions

D1-D5 system

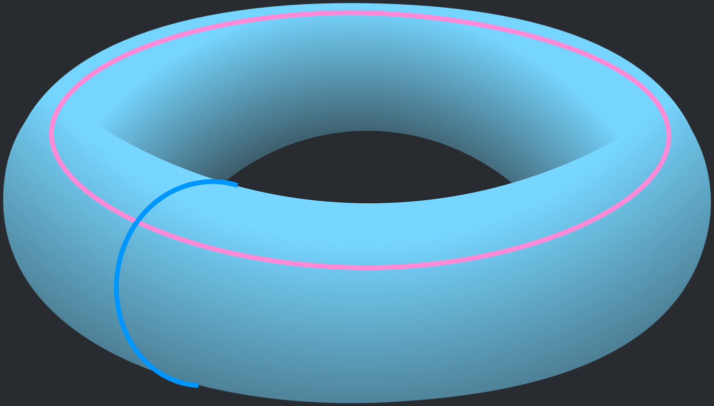
- Type IIB SUGRA
- N_1 D1 branes electrically coupled to $C^{(2)}$
- N_5 D5 branes magnetically coupled to $C^{(2)}$
- Array D1 along circle S^1 with radius R
- Array D5 along torus $T^5 = T^4 \times S^1$
- Wrap!

10 dimensions:	0	1	2	3	4	5	6	7	8	9
D1	–	·	·	·	·	–	·	·	·	·
D5	–	·	·	·	·	–	–	–	–	–

– means "extended"; · means "pointlike"

the compact dimensions of

D1-D5



$$T^4 \times S^1$$

A black hole (rather a black ring) with two charges:

$$e^{\frac{1}{2}\Phi} ds_E^2 = \frac{1}{\sqrt{H_1 H_5}}(-dt^2 + dy^2) + \sqrt{H_1 H_5}(dr^2 + r^2 d\Omega_3^2)$$
$$+ \sqrt{\frac{H_1}{H_5}} \sqrt{\mathrm{Vol}(T^4)} ds^2(T^4)$$
$$e^{\Phi} = \sqrt{H_1/H_5}$$
$$F^{(3)} = dC^{(2)}, \quad F^{(3)}_{rty} = \partial_r \left(\frac{1}{H_1} \right), \quad F^{(3)}_{\theta\phi\varphi} = 2Q_5 \sin^2\theta \sin\phi$$

where y parameterizes S^1, and

$$H_1 = 1 + \frac{Q_1}{r^2}, \qquad H_5 = 1 + \frac{Q_5}{r^2}$$

are *harmonic functions* on the transverse space

Geometry:

$$e^{\frac{1}{2}\Phi}ds_E^2 = \frac{1}{\sqrt{H_1 H_5}}(-dt^2 + dy^2) + \sqrt{H_1 H_5}(dr^2 + r^2 d\Omega_3^2)$$
$$+ \sqrt{\frac{H_1}{H_5}}\sqrt{\mathrm{Vol}(T^4)}ds^2(T^4)$$
$$H_1 = 1 + \frac{Q_1}{r^2}, \qquad H_5 = 1 + \frac{Q_5}{r^2}$$

Asymptotically: $r \to \infty$ geometry is $\boxed{M^{4,1} \times S^1 \times T^4}$

Horizon: $r = 0, \quad g^{rr} = 1/\sqrt{H_1 H_5} = 0$

Near horizon: $H_1 = \frac{Q_1}{r^2}, \qquad H_5 = \frac{Q_5}{r^2}$

Near-horizon geometry:

with $z = \sqrt{Q_1 Q_5}/r$

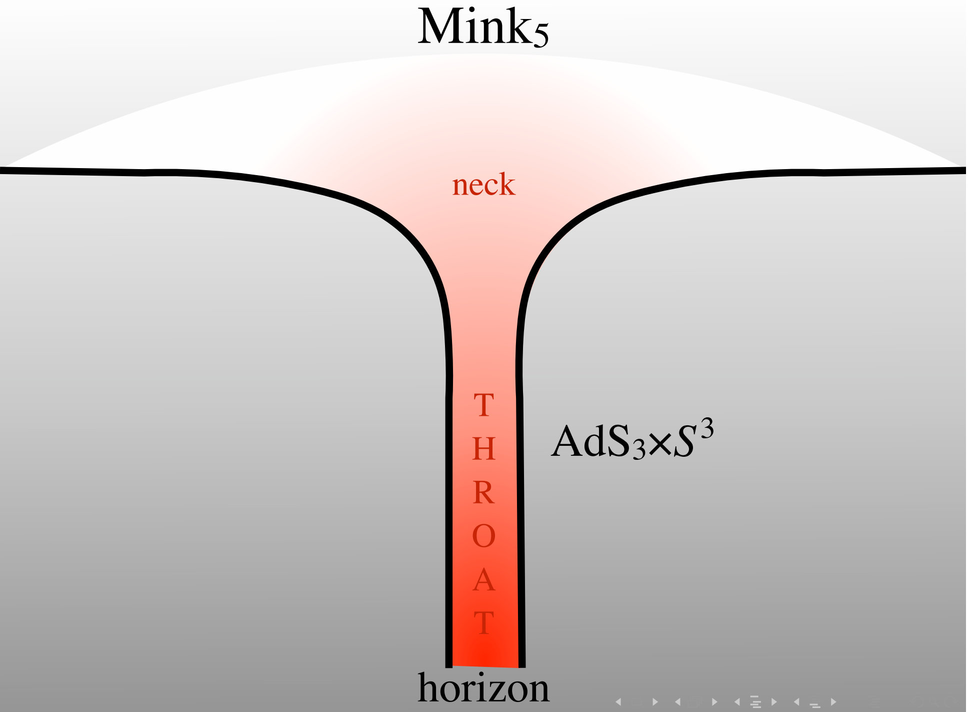
$$e^{\frac{1}{2}\Phi} ds_E^2 = \underbrace{\frac{\sqrt{Q_1 Q_5}}{z^2}(-dt^2 + dz^2 + dy^2)}_{\text{AdS}_3 \text{ with radius } (Q_1 Q_5)^{\frac{1}{4}}}$$

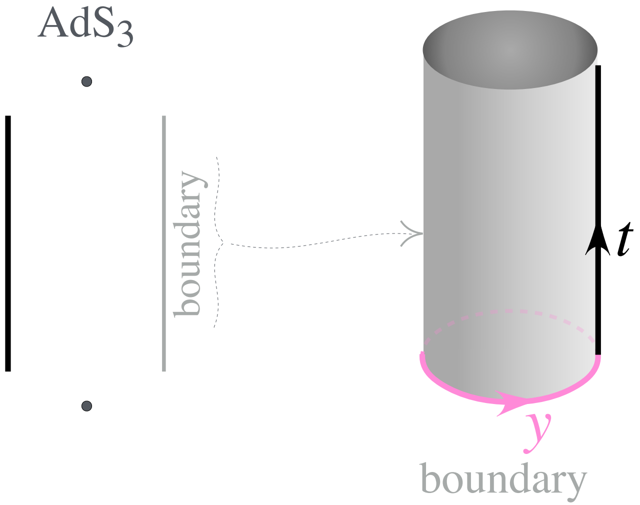
$$+ \underbrace{\sqrt{Q_1 Q_5}\, d\Omega_3^2}_{S^3}$$

$$+ \underbrace{\sqrt{\frac{Q_1}{Q_5}\mathrm{Vol}(T^4)}\, ds^2(T^4)}_{T^4}$$

$$e^{\Phi} = \sqrt{Q_1/Q_5} \qquad \text{(frozen)}$$

Horizon: $r \to 0$ hence $z \to \infty$ so AdS boundary


Mink$_5$
neck
THROAT
AdS$_3\times S^3$
horizon



AdS$_3$
boundary
t
y
boundary

OBS:

Gravity description is good if radius is large and string coupling small:

$$N = N_1 N_5 \gg \frac{1}{g_s} \sim \frac{N_5}{N_1} \gg 1$$

So we need large N

We have found the geometry

$$\mathrm{AdS}_3 \times S^3 \times T^4$$

This is dual to

$$\mathrm{CFT}_2 \quad \text{with} \quad \mathrm{SO}(4)_E \quad \text{R-symmetry}$$

and

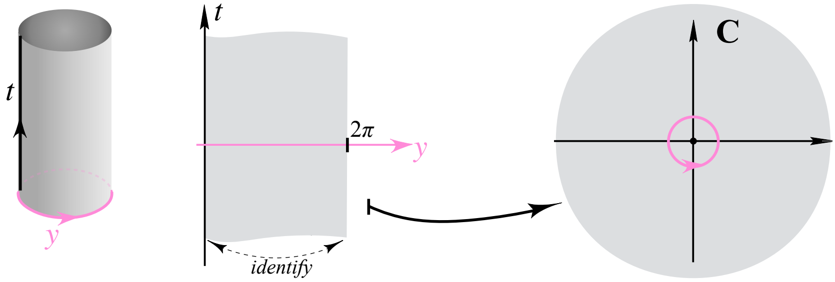
$$\mathrm{SO}(4)_I \quad \text{``internal'' symmetry}$$

The central charge is determined by AdS:

$$c = \frac{3L_{\mathrm{AdS}_3}}{2G_N^{(3)}} = 6N, \qquad N = N_1 N_5$$

The correct CFT is supersymmetric, with 8 supersymmetries, and it is an **orbifold** defined on the target space $(T^4)^N/S_N$

3. The free CFT



t
y
t
2π
y
identify
C

The $\mathcal{N} = (4,4)$ SCFT

Four real bosons and four real fermions: all free
Gather fields into complex bosons and complex fermions

$$X^{\dot{A}A}(z,\bar{z}), \quad \psi^{\alpha\dot{A}}(z), \quad \tilde{\psi}^{\dot{\alpha}\dot{A}}(\bar{z})$$

$$\begin{array}{llll} a = 1,2,3, & \text{triplet of } \mathrm{SU}(2)_L; & \dot{a} = \dot{1},\dot{2},\dot{3}, & \text{triplet of } \mathrm{SU}(2)_R \\ \alpha = +,-, & \text{doublet of } \mathrm{SU}(2)_L & \dot{\alpha} = \dot{+},\dot{-}, & \text{doublet of } \mathrm{SU}(2)_R \\ A = 1,2, & \text{doublet of } \mathrm{SU}(2)_1; & \dot{A} = \dot{1},\dot{2}, & \text{doublet of } \mathrm{SU}(2)_2 \end{array}$$

Bosonize fermions:

$$\psi^{\alpha\dot{1}}(z) = \begin{bmatrix} e^{-i\phi_2(z)} \\ e^{-i\phi_1(z)} \end{bmatrix}, \qquad \psi^{\alpha\dot{2}}(z) = \begin{bmatrix} e^{i\phi_2(z)} \\ -e^{i\phi_1(z)} \end{bmatrix},$$

Central charge: $c = 6$

Currents

Stress-tensor:

$$T(z) = \frac{1}{4}\epsilon_{\dot{A}\dot{B}}\epsilon_{AB}\partial X^{\dot{A}A}\partial X^{\dot{B}B} + \frac{1}{4}\epsilon_{\dot{A}\dot{B}}\epsilon_{\alpha\beta}\psi^{\alpha\dot{A}}\partial\psi^{\beta\dot{B}}$$

Four holomorphic super-currents:

$$G^{\alpha A}(z) = \epsilon_{\dot{A}\dot{B}}\psi^{\alpha\dot{A}}\partial X^{\dot{B}A}$$

R-current:

$$J^3(z) = \frac{1}{2}i[\partial\phi_1(z) - \partial\phi_2(z)]$$

Internal $\mathrm{SU}(2)_2$:

$$\mathfrak{J}^3(z) = \frac{1}{2}i[\partial\phi_1(z) + \partial\phi_2(z)]$$

Quantum numbers: h, j^3, $\mathfrak{j}^3$

OPERATOR ALGEBRA:

$$T(z')T(z) = \frac{c/2}{(z'-z)^4} + \frac{2T(z)}{(z'-z)^2} + \frac{\partial T(z)}{z'-z} + \cdots$$

$$J^a(z')J^b(z) = \frac{c}{12}\frac{\delta^{ab}}{(z'-z)^2} + \frac{i\epsilon^{ab}{}_c J^c(z)}{z'-z} + \cdots$$

$$\begin{aligned} G^{\alpha A}(z')G^{\beta A}(z) &= -\frac{c}{3}\frac{\epsilon^{AB}\epsilon^{\alpha\beta}}{(z'-z)^3} - \epsilon^{AB}\epsilon^{\alpha\beta}\frac{T(z)}{z-z'} \\ &\quad + \epsilon^{AB}\epsilon^{\beta\gamma}[\sigma^{*a}]^{\alpha}{}_{\gamma}\left[\frac{2J^a(z)}{(z'-z)^2} + \frac{\partial J(z)}{z'-z}\right] + \cdots \end{aligned}$$

$$J^a(z)G^{\alpha A}(z') = \tfrac{1}{2}[\sigma^{*a}]^{\alpha}{}_{\gamma}\frac{G^{\gamma A}(z)}{z'-z} + \cdots$$

$$T(z')G^{\alpha A}(z) = \frac{3}{2}\frac{G^{\alpha A}(z)}{(z'-z)^2} + \frac{\partial G^{\alpha A}(z)}{z'-z} + \cdots$$

$$T(z')J^a(z) = \frac{J^a(z)}{(z'-z)^2} + \frac{\partial J^a(z)}{z'-z} + \cdots$$

The correct CFT is the **orbifold** $(T^4)^N/S_N$; make N copies:

$$(T^4)^N = T^4 \otimes \cdots \otimes T^4$$

Copy index: $I = 1, \cdots, N$

$$X_I^{\dot{A}A}(z,\bar{z}), \quad \psi_I^{\alpha\dot{A}}(z), \quad \phi_I^a(z)$$

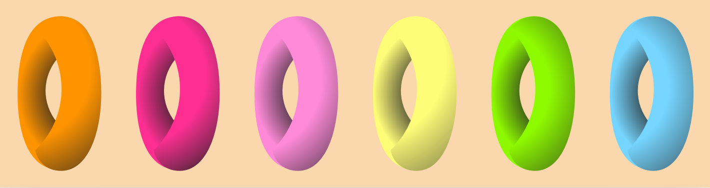
Total currents:

$$T(z) = \sum_{I=1}^{N} \left[\tfrac{1}{4}\epsilon_{\dot{A}\dot{B}}\epsilon_{AB}\partial X_I^{\dot{A}A}\partial X_I^{\dot{B}B} + \tfrac{1}{4}\epsilon_{\dot{A}\dot{B}}\epsilon_{\alpha\beta}\psi_I^{\alpha\dot{A}}\partial\psi_I^{\beta\dot{B}}\right]$$

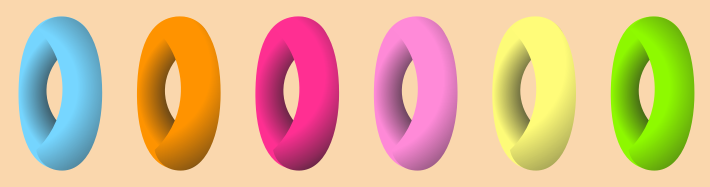
$$J^3(z) = \tfrac{1}{2}i\sum_{I=1}^{N}[\partial\phi_I^1(z) - \partial\phi_I^2(z)]$$

etc. Central charge of orbifold: $c = 6N$

... Now identify permutations



Permute and identify!



What changes when we orbifold?

Answer: New possible boundary conditions permuting the copies.

How to implement?

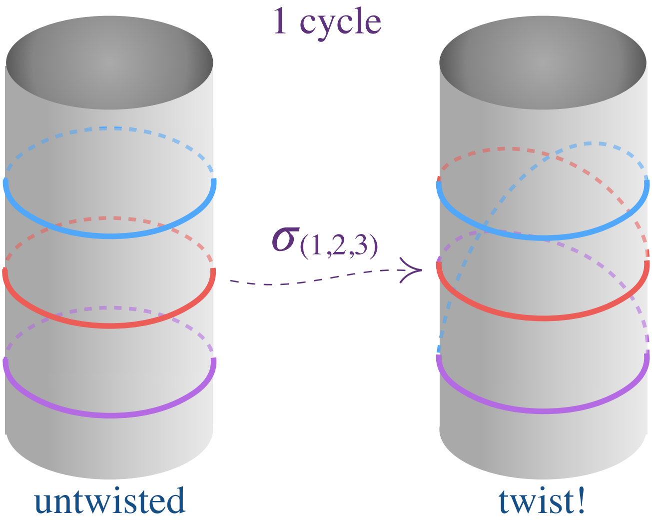
Answer: 'Twist fields' $\sigma_g(z)$, $g \in S_N$

Going around a twist:

$$X^i_I(e^{2\pi i}z, e^{-2\pi i}\bar{z})\sigma_g(z,\bar{z}) = X^i_{g(I)}(z,\bar{z})\sigma_g(z,\bar{z}).$$

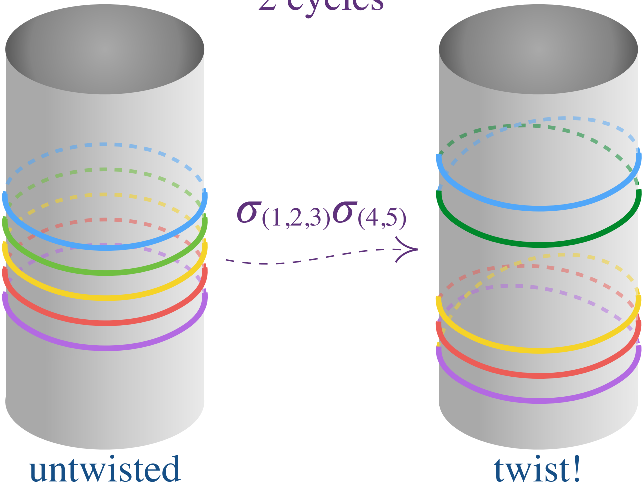
Interpretation in the (t, y) plane:

The twist field $\sigma_{(n)}$ joins n "strings" into a single n-wound string



1 cycle
$\sigma_{(1,2,3)}$
untwisted
twist!

2 cycles



We have found a CFT dual to the AdS throat

We can compute its degeneracy of states Ω, and we find that $\log \Omega = S_{BH}$

This is the famous result of [Strominger and Vafa, 1996]

4. The deformed CFT

The free orbifold is dual to a very singular gravitational solution

To go towards the SUGRA description,
we need an interacting CFT

[Larsen and Martinec, 1999, Seiberg and Witten, 1999, David et al., 2002]

(States corresponding to the black hole are states which do not renormalize under this deformation)

Deformed theory:

$$S_{\rm int} = S_{\rm free} + \lambda \int d^2 z \, O^{(\rm int)}_{[2]}(z, \bar z)$$

defined by the MARGINAL interaction operator

$$O^{(\rm int)}_{[2]}(z, \bar z) = \epsilon_{AB} G^{-A}_{-\frac{1}{2}} \tilde G^{\dot -B}_{-\frac{1}{2}} O^{(0,0)}_{[2]}(z, \bar z)$$

The effect of the deformation on an operator $\mathscr{A}_{[n]}$ can be found from the corrections to the two-point function

$$\left\langle \mathscr{A}^{\dagger}_{[n]}(z_1,\bar{z}_1)\mathscr{A}_{[n]}(z_2,\bar{z}_2)\right\rangle = \underbrace{\frac{C}{|z_1 - z_2|^{2\Delta}}}_{\text{fixed by conf. symm.}}$$

Change in the conformal dimension

$$\Delta(\lambda) = \Delta + \lambda\delta\Delta + \tfrac{1}{2}\lambda^2\delta^2\Delta + \cdots$$

where

$$\delta\Delta \sim \langle \mathscr{A}^{\dagger}_{[n]}(\infty) O^{(\text{int})}_{[2]}(1,\bar{1})\mathscr{A}_{[n]}(0)\rangle$$

$$\delta^2\Delta \sim \frac{\lambda^2}{2}\int d^2z_2 \int d^2z_3 \left\langle \mathscr{A}^{\dagger}_{[n]}(z_1,\bar{z}_1) O^{(\text{int})}_{[2]}(z_2,\bar{z}_2) O^{(\text{int})}_{[2]}(z_3,\bar{z}_3)\mathscr{A}_{[n]}(z_4,\bar{z}_4)\right\rangle$$

The four-point function

$$\left\langle \mathscr{A}^{\dagger}_{[n]}(\infty) O^{(\mathrm{int})}_{[2]}(1,\bar{1}) O^{(\mathrm{int})}_{[2]}(u,\bar{u}) \mathscr{A}_{[n]}(0) \right\rangle$$

is complicated: TWISTS!

Move u around the other points and fields are permuted:

Very non-trivial boundary conditions!

What to do?

For

$$\left\langle \sigma_{[n_1]}(\infty)\sigma_{[n_2]}(1,\bar{1})\sigma_{[n_3]}(u,\bar{u})\sigma_{[n_4]}(0) \right\rangle$$

USE A COVERING SURFACE [Lunin and Mathur, 2001] with coordinates $(t, \bar{t})$

$$\begin{array}{ccccccc} z=0 & z=1 & z=u & z=\infty & \in & S^2_{\text{base}} \\ \downarrow & \downarrow & \downarrow & \downarrow & & \downarrow \\ t=0 & t=t_1 & t=x & t=\infty & \in & S^2_{\text{cover}} \end{array}$$

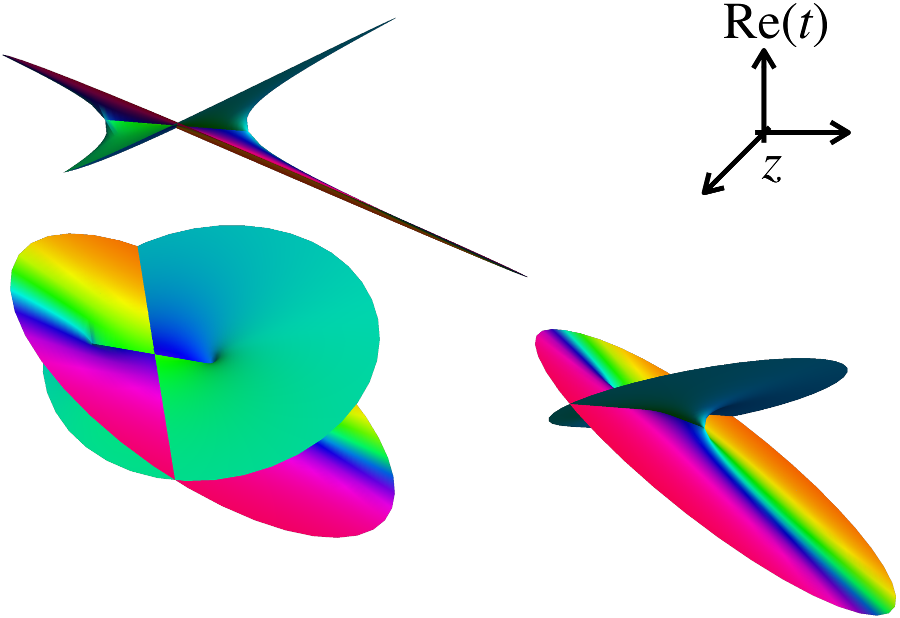
such that

$$\begin{aligned} z(t) &\approx b_1 t^{n_1} && \text{as } z \to 0 \\ z(t) &\approx 1 + b_2(t-t_1)^{n_2} && \text{as } z \to 1 \\ z(t) &\approx u + b_3(t-x)^{n_3} && \text{as } z \to u \\ z(t) &\approx b_4 t^{n_4} && \text{as } z \to \infty \end{aligned}$$

... plus other images of ∞

E.g. for two-point functions $\langle\sigma_2\sigma_2\rangle$

the covering surface looks like


Re(t)
z

Covering Surface:

Its genus and the number of its ramification points determine the large-N scaling of the corresponding correlation function

$$
\Big\langle \mathscr{O}^{1}_{[n_1]}(z_1,\bar{z}_1)\,\mathscr{O}^{2}_{[n_2]}(z_2,\bar{z}_2)\cdots\mathscr{O}^{Q}_{[n_Q]}(z_Q,\bar{z}_Q)\Big\rangle
\sim N^{\mathbf{s}-\frac{1}{2}\sum_{r=1}^{Q} n_r}\Big(1+N^{-1}+\cdots\Big)
= N^{1-\mathbf{g}-\frac{1}{2}Q}\Big(1+N^{-1}+\cdots\Big)
$$

Here $\mathbf{s}$ is the number of distinct copies entering the permutations, and

$$
\mathbf{g} = \frac{1}{2}\sum_{r=1}^{Q}(n_r-1)-\mathbf{s}+1
$$

(Riemann-Hurwitz Formula)

We have therefore the following program:

1. Choose a relevant operator in the CFT
2. Compute the four-point function with $O^{(\mathrm{int})}_{[2]}$
   (Not trivial! Must use covering surface and other paraphernalia)
3. Obtain information about dynamics: structure constants, fusion rules, etc.
4. Integrate the four-point function
   (Also not trivial! There are regularization issues and complex-contour gymnastics)
5. Obtain the correction to conformal dimensions

We have done this for Ramond ground states of the n-twisted sector:

$$R^{\pm}_{[n]} \equiv \frac{1}{\mathscr{S}_n(N)} \sum_{h \in S_N} \exp\left(\pm \frac{i}{2n} \sum_{I=1}^{n} \left[\phi_{1,h(I)} - \phi_{2,h(I)} \right] \right) \sigma_{h^{-1}(n)h}(z)$$

(R-charged doublet of $\mathrm{SU}(2)_E$, neutral under internal $\mathrm{SU}(2)_2$)

$$R^{\dot{1}}_{[n]} \equiv \frac{1}{\mathscr{S}_n(N)} \sum_{h \in S_N} \exp\left(- \frac{i}{2n} \sum_{I=1}^{n} \left[\phi_{1,h(I)} + \phi_{2,h(I)} \right] \right) \sigma_{h^{-1}(n)h}(z)$$

$$R^{\dot{2}}_{[n]} \equiv \frac{1}{\mathscr{S}_n(N)} \sum_{h \in S_N} \exp\left(+ \frac{i}{2n} \sum_{I=1}^{n} \left[\phi_{1,h(I)} + \phi_{2,h(I)} \right] \right) \sigma_{h^{-1}(n)h}(z)$$

(R-neutral doublet of internal $\mathrm{SU}(2)_2$)

Compute the functions

$$\left\langle R^{-}_{[n]}(\infty,\bar{\infty}) O^{(\text{int})}_{[2]}(1,\bar{1}) O^{(\text{int})}_{[2]}(u,\bar{u}) R^{+}_{[n]}(0,\bar{0}) \right\rangle$$
$$\left\langle R^{\dot{2}}_{[n]}(\infty,\bar{\infty}) O^{(\text{int})}_{[2]}(1,\bar{1}) O^{(\text{int})}_{[2]}(u,\bar{u}) R^{\dot{1}}_{[n]}(0,\bar{0}) \right\rangle$$

Genus-zero covering surface:

$$z(t) = \left(\frac{t}{t_1}\right)^n \left(\frac{t-t_0}{t_1-t_0}\right)\left(\frac{t_1-t_\infty}{t-t_\infty}\right)$$

Roaming point on covering is x, its image on base is u; map $z(x) = u$ is

$$u(x) = \frac{x^{n-1}(x+n)^{n+1}}{(x-1)^{n+1}(x+n-1)^{n-1}}$$

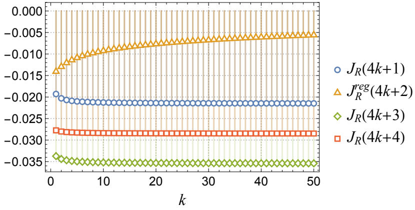


Figure: Correction to dimension – R-charged fields

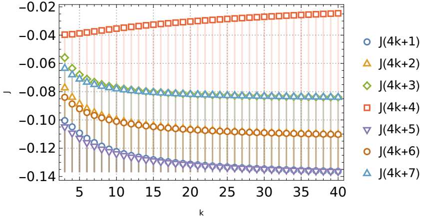


Figure: Correction to dimension – R-neutral fields

We have also analyzed double-cycle operators

$$
\begin{aligned}
&[\![R^{\pm}_{[n_1]} R^{\pm}_{[n_2]}]\!](z,\bar z), \quad [\![R^{\pm}_{[n_1]} R^{\mp}_{[n_2]}]\!](z,\bar z), \\
&[\![R^{\dot 1}_{[n_1]} R^{\dot 1}_{[n_2]}]\!](z,\bar z), \quad [\![R^{\dot 2}_{[n_1]} R^{\dot 2}_{[n_2]}]\!](z,\bar z), \quad [\![R^{\dot 1}_{[n_1]} R^{\dot 2}_{[n_2]}]\!](z,\bar z)
\end{aligned}
$$

Twisted sector corresponding to conjugacy class $(n_1)(n_2)(1)^{N-n_1-n_2}$

Genus-zero covering surface:

$$
z(t) = \left(\frac{t}{t_1}\right)^{n_1} \left(\frac{t-t_0}{t_1-t_0}\right)^{n_2} \left(\frac{t_1-t_\infty}{t-t_\infty}\right)^{n_2}
$$

Roaming map:

$$
u(x) = \left(\frac{x+\frac{n_1}{n_2}}{x-1}\right)^{n_1+n_2} \left(\frac{x}{x-1+\frac{n_1}{n_2}}\right)^{n_1-n_2}
$$

Example:

$$\left\langle [\![R^{\mathrm{i}}_{[n_1]} R^{+}_{[n_2]}]\!]^\dagger(\infty,\bar\infty) O^{(\mathrm{int})}_{[2]}(1,\bar 1) O^{(\mathrm{int})}_{[2]}(u,\bar u) [\![R^{\mathrm{i}}_{[n_1]} R^{+}_{[n_2]}]\!](0,\bar 0) \right\rangle$$
$$= G(u,\bar u)$$
$$= \sum_{\mathfrak{a}} |G(x_{\mathfrak{a}}(u))|^2$$

where

$$G(x) = C\, \frac{x^{1-n_1+n_2}(x-1)^{1+n_1+n_2}(x+\frac{n_1}{n_2})^{1-n_1-n_2}(x-1+\frac{n_1}{n_2})^{1+n_1-n_2}}{(x+\frac{n_1-n_2}{2n_2})^4} \times \left[(x-1)(x-1+\tfrac{n_1}{n_2}) + x(x+\tfrac{n_1}{n_2})\right]$$

and $x_{\mathfrak{a}}(u)$ are inverses of roaming map

$$u(x) = \left(\frac{x+\frac{n_1}{n_2}}{x-1}\right)^{n_1+n_2} \left(\frac{x}{x-1+\frac{n_1}{n_2}}\right)^{n_1-n_2}$$

Results:

· Fusion rules...

$$[O^{(\mathrm{int})}_{[2]}]\times[[\![R^{\mathrm{i}}_{[n_1]}R^{+}_{[n_2]}]\!]],\quad [O^{(\mathrm{int})}_{[2]}]\times[[\![R^{\mathrm{i}}_{[n_1]}R^{\dot{2}}_{[n_2]}]\!]],$$
$$[O^{(\mathrm{int})}_{[2]}]\times[[\![R^{\mathrm{i}}_{[n_1]}R^{\mathrm{i}}_{[n_2]}]\!]]$$

... and structure constants; e.g.

$$\langle (R^{\mathrm{i}}_{m_1}R^{+}_{m_2})^{\dagger}\sigma_3(R^{\mathrm{i}}_{m_1}R^{+}_{m_2})\rangle = 2^{-\frac{25}{3}}3^{-\frac{16}{3}}(m_1^2-m_2^2)^{\frac{2}{3}}m_1^{-\frac{4}{3}}m_2^{-\frac{4}{3}}$$

· Selection rule:

Composite fields renormalize for $2<n_1+n_2<N$ BUT

Fields protected if

$$n_1+n_2=N$$

Consequence:

The most general Ramond field:
$\prod_i (R^{(\zeta_i)}_{(n_i)})^{q_i}$, with $\sum_i n_i q_i = N$
is protected

Proof involves showing that the function

$$\Big\langle \prod_i (R^{(\zeta_i)\dagger}_{[n_i]})^{q_i}(\infty,\bar\infty)\; O^{(\mathrm{int})}_{[2]}(1,\bar 1)\; O^{(\mathrm{int})}_{[2]}(u,\bar u)\; \prod_i (R^{(\zeta_i)}_{[n_i]})^{q_i}(0,\bar 0) \Big\rangle$$

factorizes into the protected double-cycle functions
[Lima et al., 2021] (in preparation)

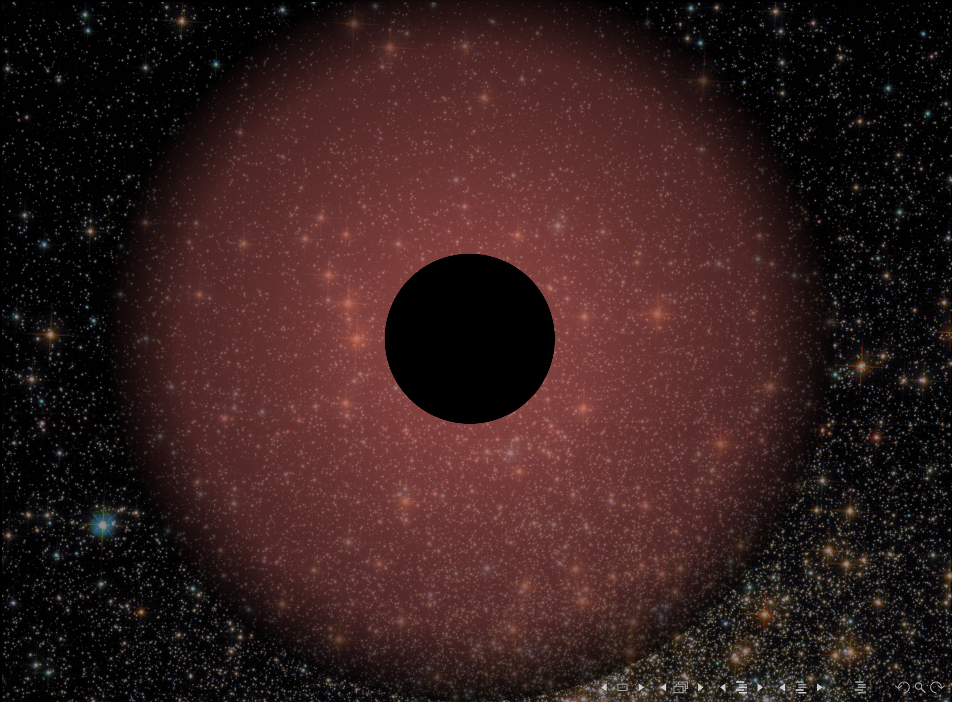
This result was known
based on the relation of the field
to a BPS NS chiral,
but we can give an explicit proof!

5. What *is* a black hole?

Unitarity problem:

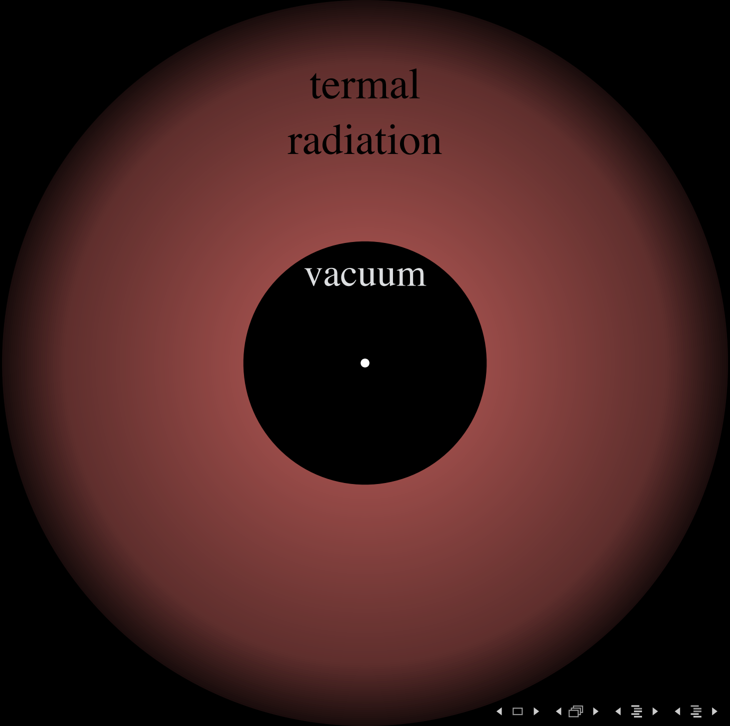
Semi-classically, the black hole radiates as a black body

After the black hole evaporates, where does its information go?



Information must be encoded in the radiation somehow...

but the horizon is empty!


termal
radiation
vacuum

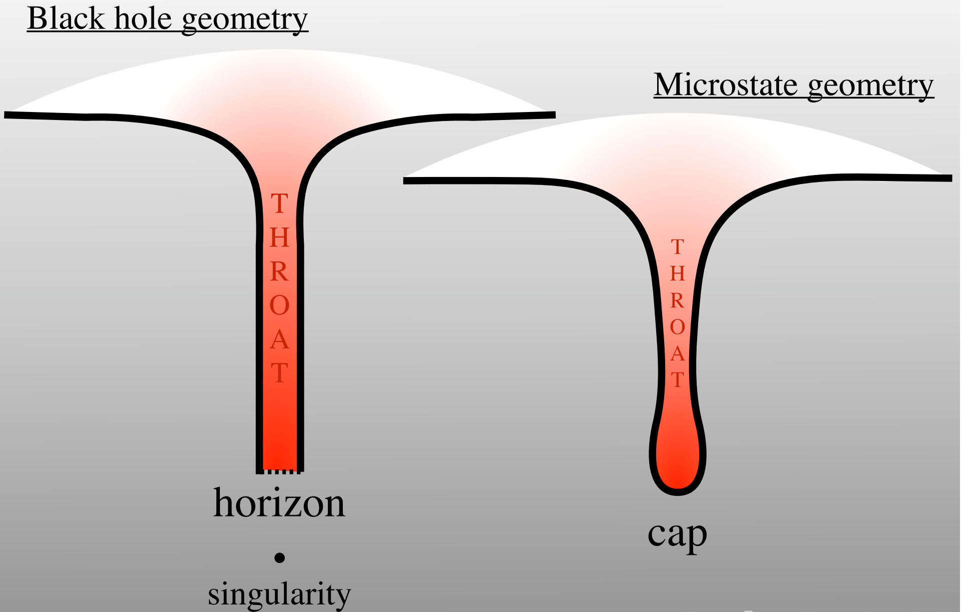
Mathur's theorem:

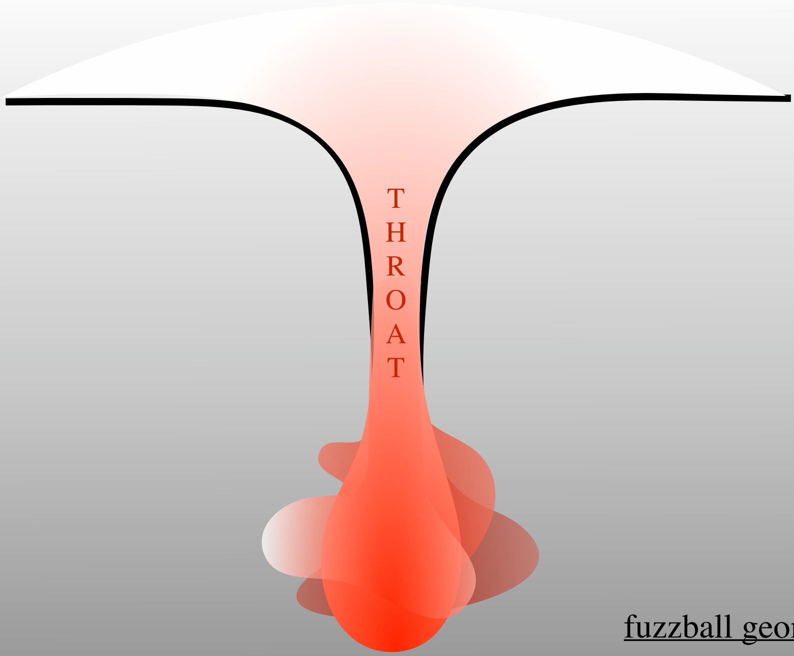
Recovery of information requires
CHANGES OF ORDER ONE AT THE HORIZON SCALE

[Mathur, 2009]

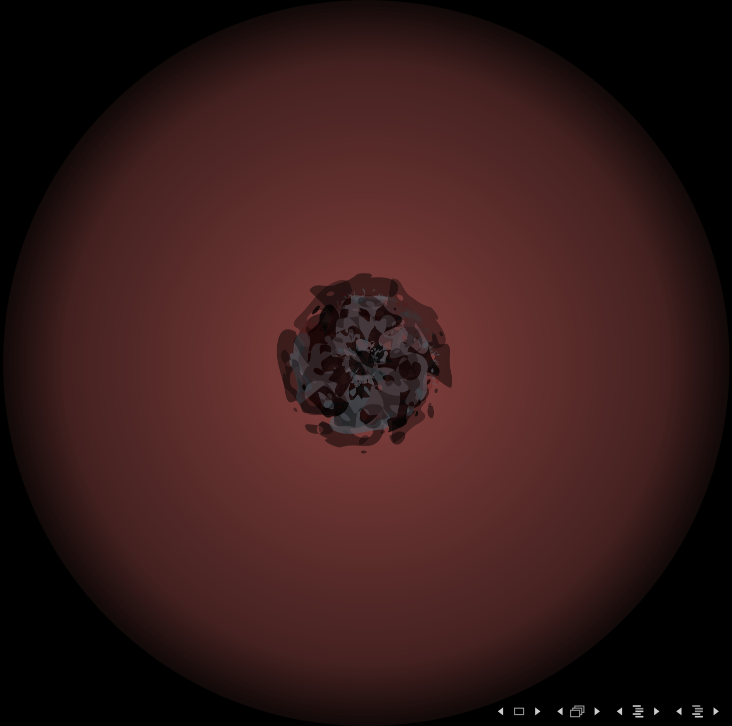
Fuzzball Proposal:
Black holes are superposition of horizonless *'microstate geometries'* [Lunin and Mathur, 2002]

Construction of microstate geometries
is a very active area
[Lunin and Mathur, 2002, Skenderis and Taylor, 2008,
Bena et al., 2011, Giusto et al., 2013, Giusto and Russo, 2014,
Bena et al., 2015, Bena et al., 2016, Warner, 2019]


Black hole geometry
THROAT
horizon
singularity
Microstate geometry
THROAT
cap



fuzzball geometry



Fim

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