Black holes and fuzzballs

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Giusto–OL–Mathur–Turton, 1211.0306
OL–Mathur, 1211.5830
Black hole information paradox

- Black holes and Hawking radiation
- Classical theory: no-hair theorem
Black hole information paradox

- Black holes and Hawking radiation
- classical theory: no-hair theorem
- QFT: pair creation

Hawking '74
Black hole information paradox

- Black holes and Hawking radiation
  - classical theory: no-hair theorem
  - QFT: pair creation
  - non–unitary evolution

Hawking '74
Black hole information paradox

- Black holes and Hawking radiation
  - classical theory: no-hair theorem
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  - non–unitary evolution
- Entropy and information loss
  - large number of microstates: \( S = \frac{A}{4} \)
  - paradox: pure state \( \Rightarrow \) mixed state
Black hole information paradox

- **Black holes and Hawking radiation**
  - classical theory: no-hair theorem
  - QFT: pair creation
  - non–unitary evolution

- **Entropy and information loss**
  - large number of microstates: \( S = \frac{A}{4} \)
  - paradox: pure state \( \Rightarrow \) mixed state

- **Options for resolving the paradox**
  - information is lost
  - loophole in Hawking’s argument
Outline

- Information paradox and AdS/CFT
  - evolution is unitary
  - paradox is not eliminated
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- Fuzzball proposal
  - geometries for individual microstates
  - corrections to Hawking radiation
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New classes of microstates
- D1–D5–P states localized at the “horizon"
- momentum modes on the torus
- energy spectrum and CFT
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  - D1–D5–P states localized at the “horizon"
  - momentum modes on the torus
  - energy spectrum and CFT
- Hawking radiation from the orbifold CFT
- Open questions
Options for resolving the information paradox

A  information is lost
B  loophole in Hawking’s argument
Black holes in AdS/CFT

Options for resolving the information paradox
A information is lost
B loophole in Hawking’s argument

AdS/CFT correspondence

Maldacena ‘97
Black holes in AdS/CFT

- Options for resolving the information paradox
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- AdS/CFT correspondence
  - unitary QFT $\Rightarrow$ option B
  - What is the problem with Hawking’s argument?
Black holes in AdS/CFT

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- Geometry must change at the horizon
Entropy and microscopic states

D1–D5–P system

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Entropy and microscopic states

D1–D5–P system

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Number of states at weak coupling:

\[ S = k \ln \Gamma = \frac{A}{4\hbar G_N} \]

Strominger–Vafa ’96
Entropy and microscopic states

State counting

$g N$

Strominger–Vafa '96
Entropy and microscopic states

State counting

Individual states

Strominger–Vafa '96
Fuzzballs

Basic idea

Diagram showing a process involving a black hole and a fuzzball.
Fuzzballs

Basic idea

- individual horizon–free metric for every state
- distinctive features extending to the horizon
- corrections to Hawking radiation

Lunin–Mathur ’01-02; Mathur ’04
Fuzzballs

Basic idea

- individual horizon–free metric for every state
- distinctive features extending to the horizon
- corrections to Hawking radiation

Correspondence

- semiclassical state \(\leftrightarrow\) solution to SUGRA
- generic state \(\leftrightarrow\) stringy geometry

Lunin–Mathur ’01-02; Mathur ’04
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Basic idea

- individual horizon–free metric for every state
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- semiclassical state ⇔ solution to SUGRA
- generic state ⇔ stringy geometry

Horizon – coarse graining over geometries
Fuzzballs for D1–D5 system

- Microstates and regular geometries
Fuzzballs for D1–D5 system

Microstates and regular geometries

$g N$
Fuzzballs for D1–D5 system

Microstates and regular geometries

\[ g N \]

vibrating string: \( F(v) \) ⇔ geometry with

\[ H_5 = 1 + \int \frac{dv}{(x-F)^2}, \ldots \]

vibration in 10D ⇔ regular solution of SUGRA

OL–Mathur ’01

OL–Maldacena–Maoz ’02
Fuzzballs for D1–D5 system

Microstates and regular geometries

Vibrating string $F(v) \iff$ regular solution of SUGRA

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$r, S^3$
Fuzzballs for D1–D5 system

Microstates and regular geometries
vibrating string $F(v) \iff$ regular solution of SUGRA
Fuzzballs for D1–D5 system

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Fuzzballs for D1–D5 system

- Microstates and regular geometries
  - vibrating string $F(v) \iff$ regular solution of SUGRA

- Horizon as coarse graining
  - D1–D5: stretched horizon with Planckian area
  - size of the fuzzball $\sim$ size of the horizon

Sen ’95
Lunin–Mathur ’02
D1–D5–P and spectral flow

- D1–D5 system
- geometries for all microstates
- Planckian horizon
D1–D5–P and spectral flow

- D1–D5 system
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- Momentum and spectral flow in $\mathcal{N} = (4, 4) \text{ SCFT}_2$
D1–D5–P and spectral flow

- D1–D5 system
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- Momentum and spectral flow in $\mathcal{N} = (4, 4)$ SCFT$_2$
  - spectral flow: symmetry of SC algebra
    $$T(z), \quad J^a(z), \quad G^{1,2}(z), \quad \bar{G}_{1,2}(z)$$
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Momentum and spectral flow in $N = (4, 4)$ SCFT$_2$

- spectral flow: symmetry of SC algebra

$$T(z), \quad J^a(z), \quad G^{1,2}(z), \quad \bar{G}_{1,2}(z)$$

- boundary conditions for fermions

$$G(z) = -e^{i\pi \eta} G(e^{2\pi i} z), \quad J^\pm(z) = e^{\mp 2\pi i \eta} J^\pm(e^{2\pi i} z)$$

Schwimmer–Seiberg ’87
D1–D5–P and spectral flow

- D1–D5 system
  - geometries for all microstates
  - Planckian horizon
- Momentum and spectral flow in $N = (4, 4)$ SCFT$_2$
  - spectral flow in CFT $\iff$ diff in AdS
  - mixture between $AdS_3$ and $S^3$ ($\psi \rightarrow \psi + \eta(t - y), \ldots$)

$$ds^2 = L^2 \left[-(r^2 + 1)dt^2 + \frac{dr^2}{r^2 + 1} + r^2 dy^2 + d\theta^2 + \cos^2 \theta d\psi^2 + \sin^2 \theta d\phi^2 \right]$$

- momentum charge is generated
- Integer spectral flow is a regular diffeomorphism
D1–D5–P and spectral flow

- Momentum and spectral flow in $N = (4, 4) \text{ SCFT}_2$
- Spectral flow in CFT $\iff$ diff in AdS
- Momentum charge is generated

Adding momentum to D1–D5 system
- Remove flat asymptotics
- Perform spectral flow
- Attach flat asymptotics

OL ’04; Giusto–Mathur–Saxena ’04
D1–D5–P and spectral flow

- Momentum and spectral flow in $\mathcal{N} = (4, 4)$ SCFT$_2$
  - spectral flow in CFT $\Leftrightarrow$ diff in AdS
  - momentum charge is generated
- Adding momentum to D1–D5 system
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More states of D1–D5–P system
- general solution in terms of 4D hyper–Kähler base
  - Gutowski–Martelli–Reall ’03
- special regular solutions
  - Bena–Warner–Bobev–Wang–…’05-11

OL ’04; Giusto–Mathur–Saxena ’04
D1–D5–P and spectral flow

- Momentum and spectral flow in $N = (4, 4)$ SCFT $\mathbb{C}$
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- More states of D1–D5–P system
  - general solution in terms of 4D hyper–Kähler base
  - special regular solutions
  - microscopic interpretation?

OL ’04; Giusto–Mathur–Saxena ’04
Gutowski–Martelli–Reall ’03
Bena–Warner–Bobev–Wang–… ’05-11
Fractional spectral flow

- CFT dual of the D1–D5 system
- marginal deformation of the free CFT on orbifold
- orbifold point: \((T^4)^N/S^N, N = n_1n_5\)

\[\text{de Boer '98; Seiberg–Witten '99; . . . .} \]

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- CFT dual of the D1–D5 system
- marginal deformation of the free CFT on orbifold
- orbifold point: \((T^4)^N/S_N, N = n_1 n_5\)
- Twisted sectors
- chiral primaries: twist operators \(\sigma_k(z)\)

\[ X_1 \rightarrow X_2 \rightarrow \ldots X_k \rightarrow X_1 \]
Fractional spectral flow

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\[
X_1 \rightarrow X_2 \rightarrow \ldots \rightarrow X_k \rightarrow X_1
\]

- functions are single–valued on the covering space
- microstate with \(\sigma_k \Rightarrow \text{SF on the cover} \Rightarrow \text{FSF}\)

\[
\psi(z) = -e^{i\pi \eta} \psi(e^{2\pi ik} z)
\]

- gravity: \([\sigma_k]^N/k \Rightarrow \text{conical singularity}\)
Fractional spectral flow

- CFT dual of the D1–D5 system
  - marginal deformation of the free CFT on orbifold
  - orbifold point: \((T^4)^N/S_N\), \(N = n_1 n_5\)

- Twisted sectors
  - functions are single–valued on the covering space
  - microstate with \(\sigma_k \Rightarrow SF\) on the cover \(\Rightarrow FSF\)

- Fractional spectral flow in gravity
  - AdS region:

\[
\psi \rightarrow \psi + \frac{s}{k}(t - y), \quad \phi \rightarrow \phi - \frac{s}{k}(t - y)
\]

- flat asymptotics – GMR or limit of a black hole
- conical singularity associated with \(\sigma_k\) softens
Properties of “fractional microstates"

Geometry is modified in the “cap"
Properties of “fractional microstates"

- Geometry is modified in the “cap"
- Excitations of microstates
- CFT picture — multiwound string
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![Diagram of multiwound strings]
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  - gravity: wave equation
Properties of “fractional microstates"

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  - CFT picture — multiwound string
  - gravity: wave equation
- Contributions to the energy
  - fermions on a longer string $\Rightarrow \Delta h_f = -\frac{ls}{k}$
  - bosons from the vertex operator $\Rightarrow \Delta h_b = \frac{1}{k}$
  - ang. mom. from the vertex operator: $\Delta h_J = \frac{m(2s+1)}{k}$
  - momentum of the excitation: $n_p = \bar{h} - h$

Giusto–OL–Mathur–Turton ’12
Properties of “fractional microstates"

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  - momentum of the excitation: $n_p = \bar{h} - h$
- Agreement with SUGRA

\[
\omega = \frac{l + 2 + 2(2s + 1)m}{k} - n_p
\]
Excitations on the torus

- Adding momentum to D1–D5
  - spectral flow involves $S^3 \Rightarrow$ solution of 6D SUGRA
  - analog of spectral flow for the torus $\Rightarrow$ 10D SUGRA
Excitations on the torus

- Adding momentum to D1–D5
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  - analog of spectral flow for the torus $\Rightarrow$ 10D SUGRA

- Method for constructing the solution
  - start with known microstate
  - solve for linear perturbation
  - guess the solution
  - check the eqns for Killing spinors
Excitations on the torus

Adding momentum to D1–D5

- spectral flow involves $S^3 \Rightarrow$ solution of 6D SUGRA
- analog of spectral flow for the torus $\Rightarrow$ 10D SUGRA

Method for constructing the solution

- guess the solution
- check the eqns for Killing spinors

Deformation of GMR:

$$ds^2 = -e^\hat{v} e^\hat{u} + HDs_4^2 + dz^\alpha dz^\alpha,$$

$$C^{(2)} = \frac{1}{2} e^\hat{v} \wedge e^\hat{u} + e^\hat{v} \wedge A + \sigma_2,$$

$$e^\hat{v} = H^{-1}(dv + \beta), \quad e^\hat{u} = du + \omega + \frac{FH}{2} e^\hat{v} + \Phi_\alpha(v, x) dz^\alpha.$$
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  \[
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  \]

  \[
  d \left( *_6 \left[D\Phi_\alpha + \partial_v \Phi_\alpha He^\hat{v}\right]\right) = 0
  \]
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- Deformation of GMR:
  - linear equation for the deformation
    \[ d \left( *_6 \left[ D\Phi_\alpha + \partial_v \Phi_\alpha H e^{\hat{v}} \right] \right) = 0 \]
  - regular GMR geometry $\Rightarrow$ regular deformation
  - CFT excitation on the boundary $\Rightarrow$ unique solution

OL–Mathur–Turton '12
Relation to other constructions

- **Deformation of GMR:**
  - linear equation for the deformation
  - regular GMR geometry $\Rightarrow$ regular deformation
  - explicit solutions for special cases
Relation to other constructions

- Deformation of GMR:
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- Plane wave on static black hole
  - Garfinkle–Vachaspati transform: $g_{\mu\nu} \rightarrow g_{\mu\nu} + \Phi k_\mu k_\nu$
  - application to black holes $\Rightarrow$ singularity
    - Horowitz–Marolf ’96
  - GV is extended to some non–static geometries
Relation to other constructions

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- **Pp–wave on D1–D5–P via dualities**

\[
\begin{align*}
    ds^2 &= -e_0^\hat{v} e_0^\hat{u} - \frac{1}{4} \Phi_\alpha \Phi_{\alpha} (e_0^\hat{v})^2 + H ds_4^2 + dz^\alpha dz^\alpha, \\
    B &= -\frac{1}{2} \Phi_\alpha e_0^\hat{v} \wedge dz^\alpha, \\
    C^{(4)} &= \frac{1}{24} \left[ e_0^\hat{v} \wedge \varepsilon_{\alpha \beta \gamma \delta} \Phi_\alpha dz^\beta \wedge dz^\gamma \wedge dz^\delta + \text{dual} \right], \\
    C^{(6)} &= \left[ \frac{1}{2} e_0^\hat{v} \wedge e_0^\hat{u} + e_0^\hat{v} \wedge \mathcal{A} + \sigma_2 \right] dz_1 \wedge dz_2 \wedge dz_3 \wedge dz_4.
\end{align*}
\]
Hawking radiation from CFT

- Non–extremal BH: radiation in probe approximation
Hawking radiation from CFT

- Non–extremal BH: radiation in probe approximation
- Hawking from near–extremal fuzzballs
  - excitation of the microstate
  - transition to a different microstate via emission
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- Toy S–matrix in the CFT
  - special class of in and out microstates
  - one outgoing particle
  - orbifold CFT with spin operators (R–sector)
Hawking radiation from CFT

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- Results for the S–matrix
  - explicit scattering amplitudes
  - transitions to “nearby” states are preferred

Lunin–Mathur ’12
Hawking radiation from CFT

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- Open questions
  - several outgoing particles/general microstates
  - gravity counterpart of the calculation

Lunin–Mathur ’12
Summary

- Fuzzball proposal for black holes
  - individual microstate ⇔ regular (stringy) geometry
  - interior of the “horizon" is not empty
  - horizon as a result of the coarse graining
  - complete picture for D1–D5 system
Summary

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- Hawking radiation from the orbifold CFT
  - prediction for the transition between microstates
Summary

- Fuzzball proposal for black holes
  - individual microstate ⇔ regular (stringy) geometry
  - horizon as a result of the coarse graining

- New classes of microstates
  - D1–D5–P states localized at the “horizon"
  - momentum modes on the torus
  - explicit non–singular solutions
  - energy spectrum agrees with CFT

- Hawking radiation from the orbifold CFT
  - prediction for the transition between microstates

- Open questions
  - generic microstates, Hawking radiation in gravity...