Smooth horizonless geometries deep inside the black hole regime

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The String Theory Universe

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Based on

Bena, Giusto, Martinec, Russo, Shigemori, DT, Warner

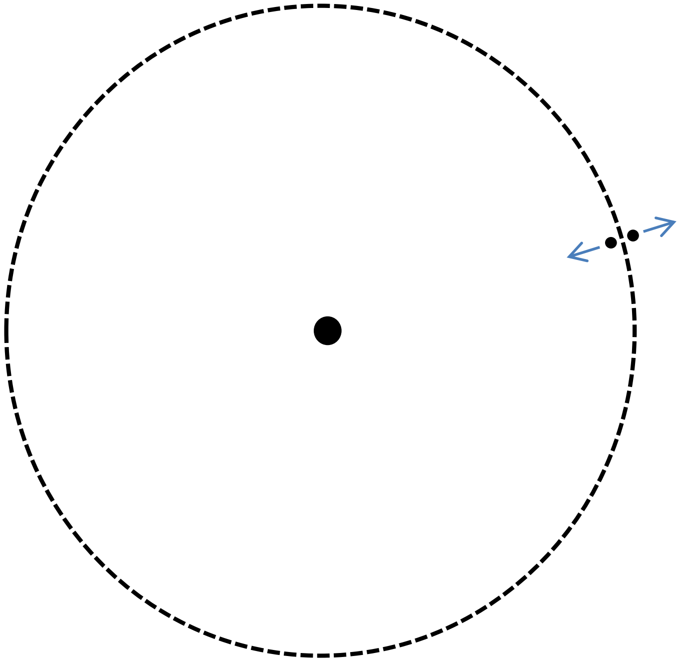
arXiv:1607.03908, PRL 117, 201601 (2016)

Outline

1. The Black Hole Information Paradox
2. The D1-D5 system
3. Smooth horizonless geometries deep inside the black hole regime
4. Falling into a black hole

The Information Paradox

Classical BH horizon:
normal lab physics
(small curvature)

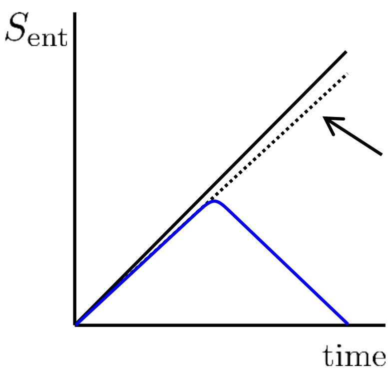


Hawking radiation:
pair creation

$\rightarrow$ entangled pair

$\rightarrow$ Final state not pure?

- Endpoint of process: violation of unitarity or exotic remnants.
  Hawking '75
- Conclusions robust including small local corrections
  Mathur '09
- Much recent interest in implications for physics of infalling observer
  Almheiri, Marolf, Polchinski, Sully '12



Black Hole Hair

- Bekenstein-Hawking entropy $S \rightarrow e^S$ microstates
- Can physics of individual microstates modify Hawking's calculation?
- Many searches for Black hole 'hair': deformations at the horizon.
- In classical gravity, many 'no-hair' theorems resulted

Israel '67, Carter '71, Price '72…

Black Hole Quantum Hair

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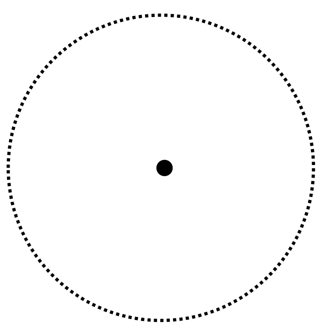
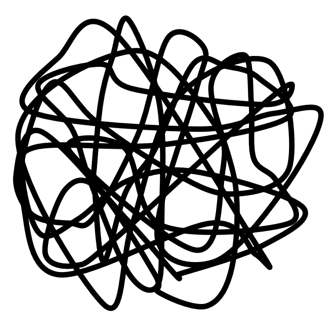
However, in String Theory, we find examples of Quantum Hair. This suggests that

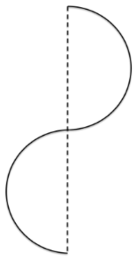
- Quantum effects important at would-be-horizon (fuzz)
- Bound states have non-trivial size (ball)





"Fuzzball"

Two-charge Black hole



- Multiwound fundamental string + momentum
- Entropy: exponential degeneracy of microscopic states

Sen '94

- For classical profiles, string sources good supergravity background

  Classical profiles $\leftrightarrow$ coherent states

Dabholkar, Gauntlett, Harvey, Waldram '95
Lunin, Mathur '01

- No horizons; string source
- Transverse vibrations only $\rightarrow$ non-trivial size

- F1-P is U-dual to D1-D5 bound state

Lunin, Mathur '01

- Configurations are everywhere smooth in D1-D5 frame

Lunin, Maldacena, Maoz '02

- Can study precision holography in this system

Skenderis, Taylor '06, '07

- Caveat: two-charge Black hole is string-scale sized.

D1-D5-P: Large BPS black hole

- D1-D5-P black hole: large BPS black hole in 5D / black string in 6D

- Entropy reproduced from microscopic degrees of freedom

Strominger, Vafa ’96

Breckenridge, Myers, Peet, Vafa ’96

- Certain microstates admit classical descriptions as supergravity solitons; large classes of such ‘microstate geometries’ constructed & studied

Mathur, Lunin, Bena, Warner, de Boer, Ross, Giusto, Russo, Shigemori, DT,…

- Supergravity solitons are interesting in their own right, for holography, and for the classification of solutions to supergravity theories

Large BPS, Non-BPS & non-extremal

Despite much progress, important questions remain:

1. Can one construct & study (many) solutions which have large near-horizon throats and general values of angular momenta?
2. Can one identify the holographic description of such solutions?

These questions are key to understanding more typical states of large BPS black holes.

Big Question!

3. What is the gravitational description of non-extremal black hole microstates?

This is crucial for studying Hawking radiation, but only a handful of solutions known to date

Jejjala, Madden, Ross, Titchener '05,…

– Recent progress in this direction, however.

Bena, Bossard, Katmadas, DT '15, '16,…

4. If there is new physics at the horizon, what does an infalling observer experience?

The D1-D5 system

D1-D5 system: setup

Consider type IIB string theory on T^4 or $K3$ (take T^4 for concreteness)

$$\begin{array}{ccccc} \mathbb{R}^{1,4} & \times & S^1 & \times & T^4 \\ t, x^\mu & & y & & z^i \end{array}$$

- Radius of S^1 : R_y
- n_1 D1 branes on S^1
- n_5 D5 branes on $S^1 \times T^4$
- n_P units of momentum along S^1

For states which have geometrical descriptions, the geometry has charges

$$Q_1 = \frac{g_s \alpha'^3}{V} n_1 \,, \qquad Q_5 = g_s \alpha' \, n_5 \,, \qquad Q_P = g_s^2 \alpha'^4 \, n_P \,.$$

D1-D5 CFT & Holography

- Worldvolume gauge theory on D1-D5 bound state flows in IR to an (1+1)-dimensional $\mathcal{N} = (4,4)$ SCFT.

- Deformation of symmetric product orbifold SCFT with target space $(T^4)^N/S_N$, $N = n_1 n_5$.

Vafa '95, Douglas '95

- Decoupling limit of asymptotically-flat configurations results in asymptotically $AdS_3 \times S^3 \times T^4$ solutions

- One of the original examples of holographic duality.

Maldacena '97

Smooth horizonless geometries

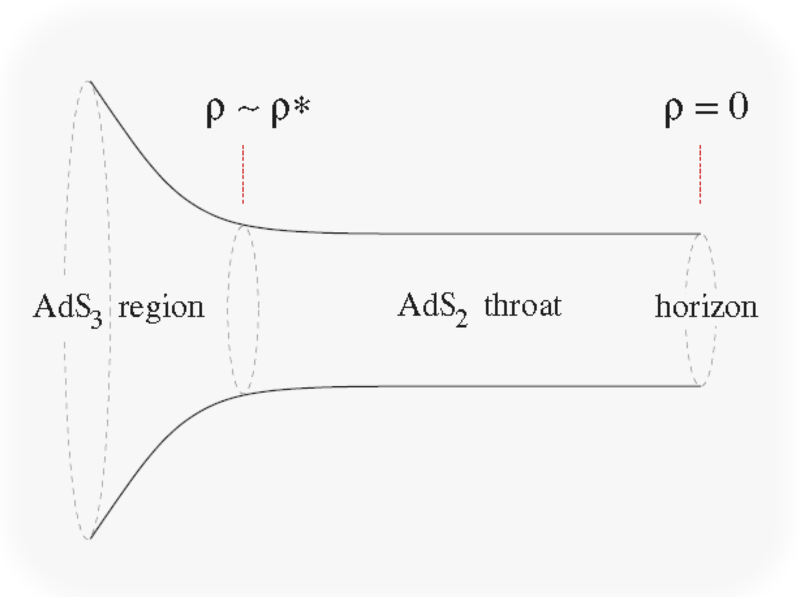
deep inside the black hole regime

D1-D5-P black holes

D1-D5-P BPS black string in 6D: NH geometry is S^3 fibered over extremal BTZ

$$ds^2_{\rm BTZ} = \ell^2_{\rm AdS}\left[\rho^2(-dt^2+dy^2) + \frac{d\rho^2}{\rho^2} + \rho_*^2(dy+dt)^2\right]$$

$$\ell^2_{\rm AdS} = \sqrt{Q_1 Q_5}\,, \qquad \rho^2 = \frac{r^2}{Q_1 Q_5}\,, \qquad \rho_*^2 = \frac{Q_{\rm P}}{Q_1 Q_5}\,.$$



- BTZ solution is locally AdS_3 everywhere, with global identifications
- "Very-near-horizon" throat: S^1 fibered over AdS_2

Strominger '98

The black hole regime

- The angular momentum of rotating D1-D5-P black string/BMPV black hole is bounded above by the charges:

$$j_L < \sqrt{n_1 n_5 n_{\mathrm{P}}}$$

- Desire solutions with microstructure inside large AdS_2 throat.

- Previous such examples ("scaling solutions") known only in the range

$$0.85 \lesssim \frac{j_L}{\sqrt{n_1 n_5 n_{\mathrm{P}}}} \leq 1$$

Bena, Wang, Warner '06

and CFT description not known.

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Bena, Wang, Warner '06

and CFT description not known.

- Our new solutions have large AdS_2 throats, probe the entire range of values of j_{L}, & we give a proposal for the dual CFT states.

BPS D1-D5-P solutions in 6D

- IIB sugra on T^4. 6D theory: minimal sugra coupled to two tensor multiplets
- For BPS solutions, the 6D metric takes the form:

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\left[du+\omega-\frac{Z_3}{2}(dv+\beta)\right]+\sqrt{\mathcal{P}}\,ds_4^2$$

$$\mathcal{P} = Z_1 Z_2 - Z_4^2$$

$$v = t+y\,,\quad u = t-y$$

The BPS eqns have an almost-linear structure: (Step 1 is non-linear, the rest are linear)

Giusto, Martucci, Petrini, Russo '13

1. Base metric ds_4^2 , one-form β
2. Scalars $Z_1,\, Z_2,\, Z_4$, two-forms $\Theta_1,\, \Theta_2,\, \Theta_4$
3. Scalar Z_3 , one-form ω

ds_4^2 (flat R^4) and β are those of a two-charge seed:

$$\beta = \frac{R_y}{\sqrt{2}}\frac{a^2}{\Sigma}(\sin^2\theta\, d\phi - \cos^2\theta\, d\psi)$$

$$ds_4^2 = \frac{\Sigma\, dr^2}{r^2+a^2} + \Sigma\, d\theta^2 + (r^2+a^2)\sin^2\theta\, d\phi^2 + r^2\cos^2\theta\, d\psi^2$$

$$\Sigma = r^2 + a^2\cos^2\theta$$

The tensor fields depend explicitly on the angular and S^1 directions, via the phase

$$\hat{v}_{k,m,n} \equiv \frac{\sqrt{2}}{R_y}\,(m+n)\,v + (k-m)\phi - m\psi$$

"Superstratum"

- The metric is however independent of $u,\ v,\ \psi,\ \phi$.
- We have

$$Z_1 = \frac{Q_1}{\Sigma} + \frac{R_y^2}{2Q_5} b_{k,m,n}^2 \frac{\Delta_{2k,2m,2n}}{\Sigma} \cos \hat{v}_{2k,2m,2n}\,, \qquad Z_2 = \frac{Q_5}{\Sigma}\,,$$

$$Z_4 = b_{k,m,n} R_y \frac{\Delta_{k,m,n}}{\Sigma} \cos \hat{v}_{k,m,n}$$

$$\mathcal{P} = Z_1 Z_2 - Z_4^2$$

$$\Delta_{k,m,n} \equiv \frac{a^k r^n}{(r^2+a^2)^{(k+n)/2}} \cos^m\theta\, \sin^{k-m}\theta$$

- Z_3 and ω can then be solved for. Smoothness imposes the condition:

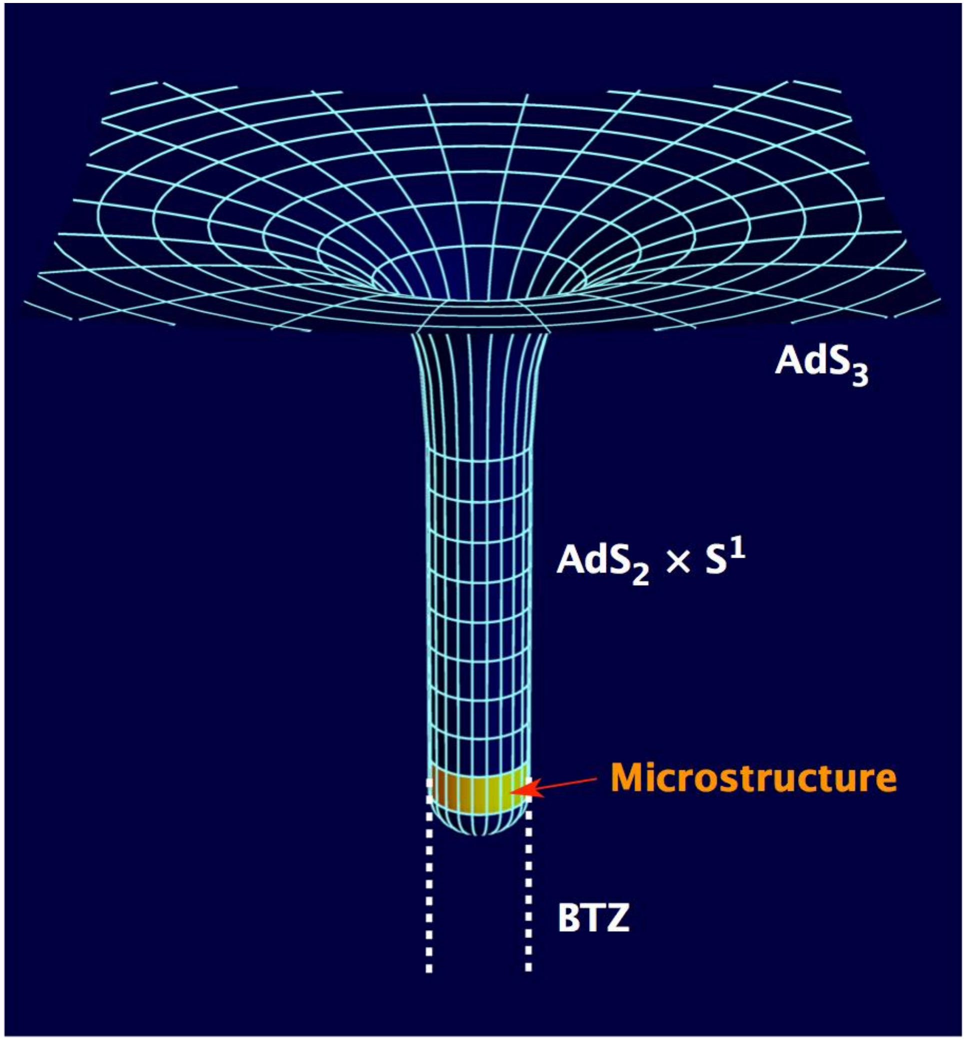
$$\frac{Q_1 Q_5}{R_y^2} = a^2 + \frac{b^2}{2}\,, \qquad b^2 = x_{k,m,n}\, b_{k,m,n}^2\,, \qquad x_{k,m,n}^{-1} \equiv \binom{k}{m}\binom{k+n-1}{n}$$

Bena, Giusto, Martinec, Russo, Shigemori, DT, Warner 1607.03908, PRL

Structure of the solutions

- Solutions are asymptotically $AdS_3 \times S^3$.

- For $a \ll b$, the geometry has the following structure:



CFT description

Fields & Twist operators

- Orbifold CFT on $(T^4)^N/S_N$: N copies of $c=6$ T^4 sigma model, fields:

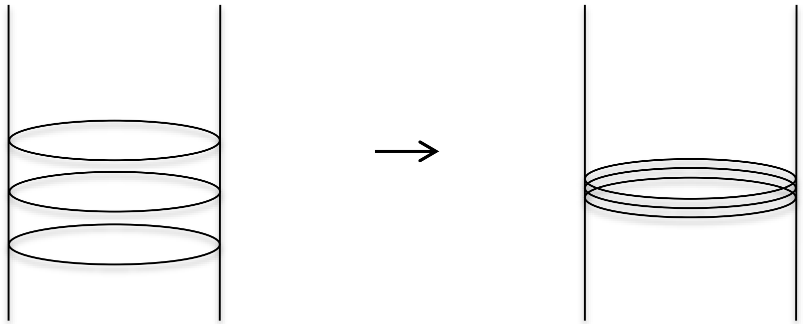
$$X_{A\dot{A}} \qquad \psi^{\alpha A} \qquad \bar{\psi}^{\dot{\alpha} A} \qquad\qquad \mathcal{N}=(4,4)$$

- Twist operators: permute fields, 'link together' different copies:

$$\sigma_k : \qquad \begin{array}{l} X^{(1)} \to X^{(2)} \to \cdots \to X^{(k)} \to X^{(1)} \\ \psi^{(1)} \to \psi^{(2)} \to \cdots \to \psi^{(k)} \to -\psi^{(1)}. \end{array}$$

- The operator σ_k links together k copies of the sigma model to effectively make a single CFT on a circle k times longer.

σ_3 :



'Strand' of length k

- There are five T^4-invariant, bosonic R-R ground states in each twist sector

- We label them by their charges under $SU(2)_L \times SU(2)_R$ $\quad (+\frac{1}{2}\,, -\frac{1}{2}\,, \quad \text{or} \quad 0)\,,$

$$|\pm\pm\rangle_k \;, \qquad\qquad |00\rangle_k \;.$$

- On each strand, there are L and R-moving small $N = 4$ superconformal algebras. L-moving bosonic generators:
  - Virasoro symmetry L_n
  - SU(2) R-symmetry $J^{\pm}_n\,,\; J^3_n$

CFT description

- Our proposed CFT description involves a particular coherent superposition of states of the form:

$$\Big(|{+}{+}\rangle_1\Big)^{N_1}\left((J^+_{-1})^m(L_{-1}-J^3_{-1})^n|00\rangle_k\right)^{N_{k,m,n}}$$

for all values of N_1 such that $N_1 + kN_{k,m,n} = N\,.$

The coefficients of the superposition are determined by the gravity parameters a, $b_{k,m,n}$.

- Recall: $$a^2+\frac{b^2}{2} = \frac{Q_1Q_5}{R_y^2}$$

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The coefficients of the superposition are determined by the gravity parameters a, $b_{k,m,n}$.

- Recall: $$a^2+\frac{b^2}{2} = \frac{Q_1 Q_5}{R_y^2}$$

- The conserved charges match precisely between gravity and CFT

Bena, Giusto, Martinec, Russo, Shigemori, DT, Warner 1607.03908, PRL

- Further holographic tests are possible

Kanitscheider, Skenderis, Taylor '06, '07

Giusto, Moscato, Russo '15

Some comments

- These microstates are atypical.

- The bulk description of typical microstates is an open question.

- However, this is the first family of microstate geometries with large AdS_2 throats, general values of angular momentum, and identified dual CFT states.

- Generalizations in progress.

Falling into a black hole

The Black Hole Interior

- Black hole complementarity: Different observers could have different low-energy EFT descriptions of their observations

Susskind, Thorlacius, Uglum ’93

- As originally postulated, this has been argued to be inconsistent
- Suggestion that infalling observer experiences a “Firewall” of Planck-scale radiation at the horizon

Almheiri, Marolf, Polchinski, Sully ’12

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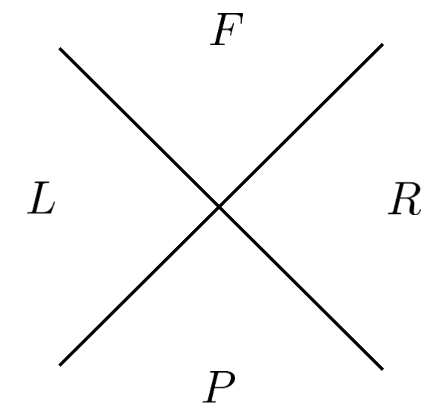
- From a string theory point of view, if Quantum Hair is present, question becomes: what is the interaction of an infalling observer with the hair?

- Fuzzball Complementarity conjecture: for coarse, high energy ($E \gg T$) physics, strong interaction with Quantum Hair has a dual description as infall on the empty black hole interior spacetime.

Mathur, DT 1208.2005, JHEP

Mathur, DT 1306.5488, NPB

Correlators in Rindler space



Rindler space:

- Accelerated observer in Minkowski space
- Near-horizon region of a far-from-extremal BH

- Minkowski space decomposes into four Rindler wedges

- Consider a free scalar field theory
- Minkowski vacuum restricted to right Rindler wedge is a thermal state

$$|0\rangle_M = C \sum_k e^{-\frac{E_k}{2}} |E_k\rangle_L |E_k\rangle_R, \qquad C = \Big(\sum_k e^{-E_k} \Big)^{-\frac{1}{2}}$$

Correlators in Rindler space

- Consider the right Rindler wedge, in a particular typical pure state.

Divide correlators into those which

1. Are well approximated by the canonical ensemble (coarse)
2. Are not well approximated by the canonical ensemble (fine).
   (sensitive to some details of typical microstates)

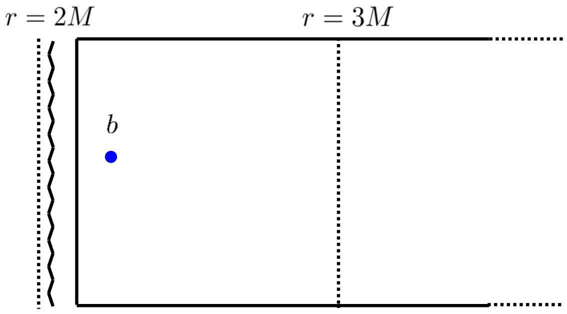
- Minkowski space $\leftrightarrow$ canonical ensemble,
  so accurately describes coarse correlators:

$$ {}_R\langle E_k|\hat{O}_R|E_k\rangle_R \;\approx\; \frac{1}{\sum_l e^{-E_l}} \sum_i e^{-E_i}\, {}_R\langle E_i|\hat{O}_R|E_i\rangle_R \;=\; {}_M\langle 0|\hat{O}_R|0\rangle_M $$

- Suggests correct role of classical black hole metric.

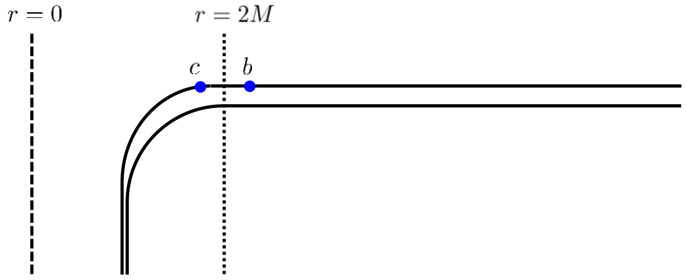
Fuzzball Complementarity

- **Picture 1**: space-time is cut off at the horizon by the Quantum Hair/Fuzzball; state is a solution of string theory.
  - This description is appropriate for all physical processes**.**



Stretched horizon model of a typical fuzzball state

- **Picture 2**: Traditional black hole metric.
  - This description is appropriate for coarse, high energy ($E \gg T$) processes



- Consistent with AMPS thought experiments.

Mathur, DT 1208.2005, JHEP

Mathur, DT 1306.5488, NPB

Summary

- Smooth horizonless supergravity solitons constructed, that have large near-horizon AdS_2 throats and general values of angular momentum

- Dual CFT description identified

- Quantum Hair in String Theory offers the potential of reproducing the physics of the classical black hole, for coarse infall processes.

Future

- More general microstates of supersymmetric black holes
- Extremal non-supersymmetric & non-extremal black hole microstates
- Instabilities & dynamics of evolution to typical microstates
- Role of exotic branes & non-geometric solutions
- Observability of black hole quantum structure?

Thanks!