Some thoughts on black hole microstates

Jan de Boer, Amsterdam

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See also talks by Mathur, Warner

Ideas developed in:

arXiv:0802.2257 - JdB, Denef, El-Showk, Messamah, van den Bleeken
arXiv:0807.4456 - JdB, El-Showk, Messamah, van den Bleeken
arXiv:0811.2263 - Balasubramanian, JdB, El-Showk, Messamah
arXiv:0906.0011 - JdB, El-Showk, Messamah, van den Bleeken
arXiv:1004.2521 - JdB, Shigemori
arXiv:1107.2650 - Bena, JdB, Shigemori, Warner
arXiv:1205.5023 - Bena, Berkooz, JdB, El-Showk, van den Bleeken

Outline

1. General remarks
2. Microstates for large supersymmetric black holes
3. Issue 1: A bound on the number of smooth supergravity solutions
4. Issue 2: The Higgs-Coulomb map
5. Beyond Geometry?
6. Conclusions

The black hole microstate/fuzzball program is aimed at finding a closed string description of the microscopic degrees of freedom of a black hole.

If you believe open-closed string duality, such a description must exist.

In particular, it would be great if one could obtain all microstates by quantizing families of smooth, horizonless supergravity solutions (aka fuzzball geometries of microstate geometries) with the same quantum numbers as a black hole.

In that case, the entire phase space of the black hole would be explicitly visible and accessible in supergravity.

In particular, one could then construct wave packets to mimic local observers and address many confusing questions.

Notice that even in this case, individual geometries would be coherent and atypical states in the theory. Typical states will have a wavefunction that spreads over the entire phase space and the resulting “average” geometry would be the black hole geometry plus small (and computable) corrections.

But perhaps this is all too much to ask for: it would imply that canonical quantization of supergravity could explain black hole entropy. No need for string theory!

The alternative is that the relevant closed string states involve massive string modes. Requires closed string field theory. Aaargggh.

Is it still possible to say anything quantitative in that case? Can we study these states using low-energy probes and see any substructure? Non-locality?

Microstates for large supersymmetric black holes

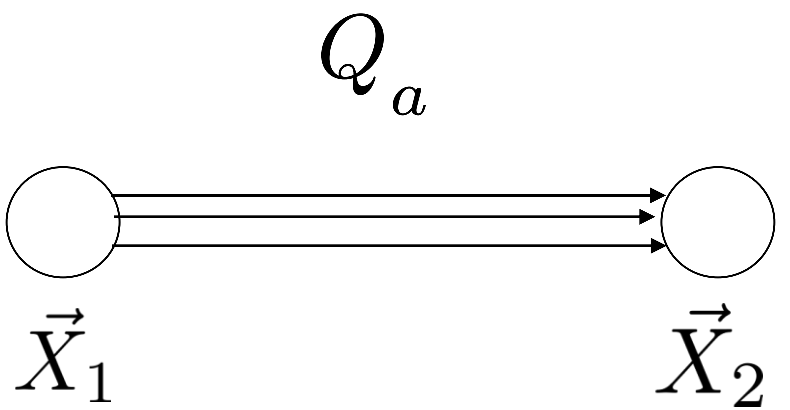
Main example:

Wrap D0-D2-D4-D6 branes on 0,2,4,6-cycles in a CY in IIA string theory. They can form heavy BPS bound states which look like a large supersymmetric black hole in four dimensions.

Relevant gauge theory is the theory on the D-branes. After dimensional reduction over the cycles in the CY, it can be described by various 0+1 dimensional supersymmetric gauge theories. Black hole states live in the Higgs branch of such a gauge theory.

Denef; Balasubramanian, Gimon, Levi; Denef, Moore

Simplest case: $U(1) \times U(1)$ gauge theory with N bifundamentals. Field content:



The theory has a gauge coupling g_{YM} and a FI parameter θ.

The Higgs branch of the theory is

$$\mathcal{M}_H = \{\sum |Q_a|^2 = \theta\}/U(1)$$

This is equal to $\mathbb{CP}^{N-1}$. Ground states correspond to cohomology classes and the total number is N.

The Coulomb branch of the theory is a two-sphere

$$\mathcal{M}_C = |\vec{X}_1 - \vec{X}_2| = \frac{N}{\theta}$$

Ground states are Landau levels due to an effective magnetic field. There are N of these.

The Coulomb and Higgs branch are not independent. They are (in this case) equivalent descriptions of the same set of supersymmetric ground states of the quiver theory.

The Coulomb branch is described by well-separated branes and the relevant configurations can be directly mapped into supergravity solutions by backreacting the branes.

Equations for the Coulomb branch = Equations for multicentered supergravity solutions in N=2 supergravity.

Under suitable conditions, the relevant solutions of supergravity can be smooth and horizonless: the individual centers must have exactly zero entropy.

So here there is a concrete way to connect the open string description (Higgs branch) to a closed string description (Coulomb branch/supergravity).

But does this work for all states on the Higgs branch and more generally for all black hole microstates?

Issue 1: A bound on the number of smooth supergravity solutions

Try to find upper bound: count the number of states in a gas of BPS supergravitons. Idea is that all smooth BPS solutions are obtained by taking a superposition of free BPS supergravitons and letting the system backreact. Because of the BPS bound, the energy of the system cannot become be lowered.

After all, classical solutions can be thought of as coherent superpositions of gravitons…

Important: keep track of stringy exclusion principle

Result: number of states grows (in 2d CFT language) as:

found such a family

	$L_0 \ll c$	$L_0 \gg c$
$d = 5$	$L_0^{2/3}$	$c^{1/3} L_0^{1/3}$
$d = 6$	$L_0^{3/4}$	$c^{1/2} L_0^{1/4}$

This is much less than Cardy: does not reproduce black hole entropy

Caveat:

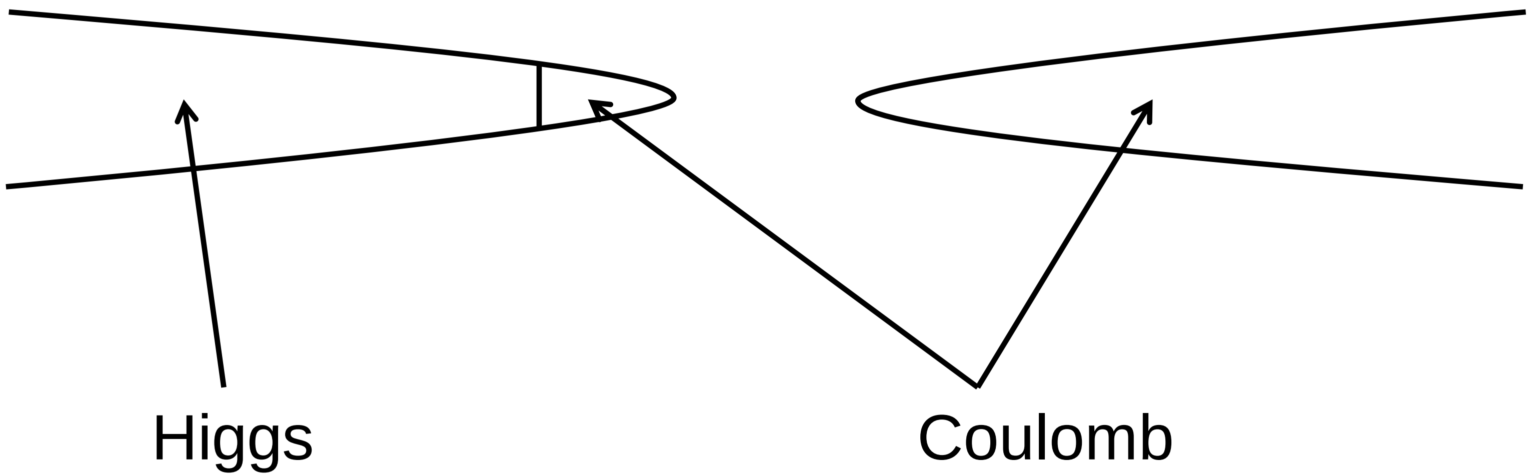
Aminneborg, Begtsson, Brill, Holst, Peldan

In d=3 there are many solutions which are identical to a black hole outside the horizon but have structure behind it. There may even be enough solutions of this type to account for the black hole entropy (Maloney). Not clear whether these solutions should be viewed as pure states though.

Such solutions cannot obviously be made by throwing gravitons in global AdS.

There may be other solutions with a different topology which cannot be viewed as “small” deformations of AdS.

Issue 2: the Coulomb-Higgs map



The decoupling limit, relevant for AdS/CFT, removes the right part, and what is left is the “conformal field theory of the Higgs branch”.

Witten; Aharony, Berkooz

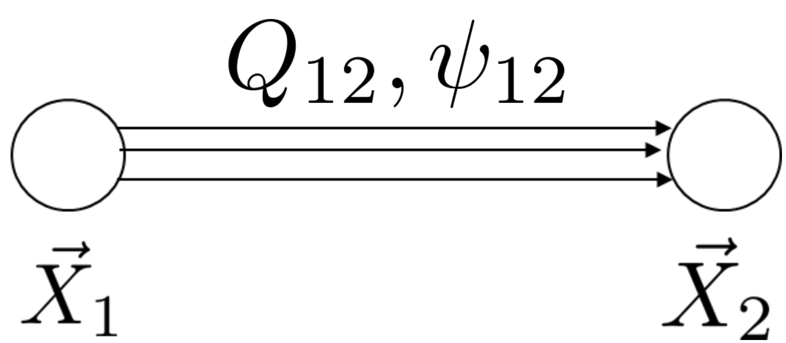
A bit of Coulomb branch remains, however, but not with Independent information.

The decoupling limit removes the kinetic term of the vector multiplet. The vector multiplet scalars obey algebraic equations: can solve explicitly, involves fermion bilinears.

Berkooz, H. Verlinde

In our case the same happens but the equations are more complicated. Schematically

$$X_p^i - X_q^i \sim \frac{\psi_{pq}\sigma^i\psi_{pq}}{2|Q_{pq}|^2}$$

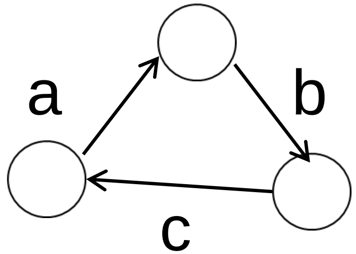


In general, not all states on the Higgs branch are accessible on the Coulomb branch.

This happens when the quiver has a closed loop and a few extra conditions are met.

In space-time, this happens whenever the centers of the multi-centered solution can approach each other arbitrarily closely (so-called scaling solutions).

One can explicitly count the number of missing states for a quiver with three nodes. Their number grows exponentially.



$$\sum_{a,b,c} \chi(a,b,c) x^a y^b z^c = \frac{x^2 y^2 z^2}{(1-xy)(1-yz)(1-zx)(1-xy-yz-zx-2xyz)}$$

The missing Higgs branch states have no obvious description in terms of Coulomb branch variables and hence in supergravity.

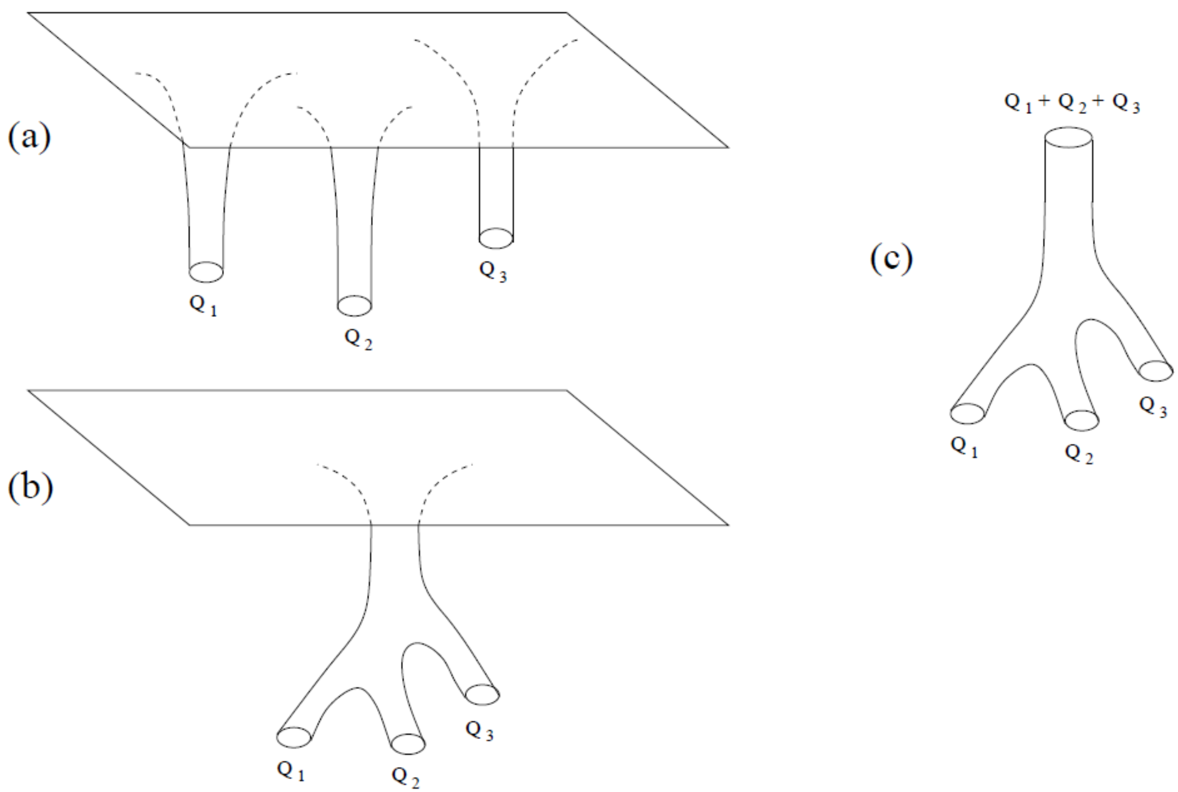
Can we probe them? By the Lefshetz hyperplane theorem, they all live in middle cohomology, and the Lefshetz SU(2) action on cohomology is the same as rotations in spacetime.

Therefore, all these states are rotationally invariant from a space-time point of view: will most likely look exactly like the single center black hole.

One can also use the Coulomb-Higgs map to compute non-local observables: two-point functions of the metric are not obviously those of the single center black hole.

Near the scaling point, where the centers meet each other, the geometry looks like a fragmented AdS2.
There is a conjectured superconformal quantum mechanics there. What happened to that? Michelson, Strominger

Answer: the theory has a mass gap. No strict SCQM limit.

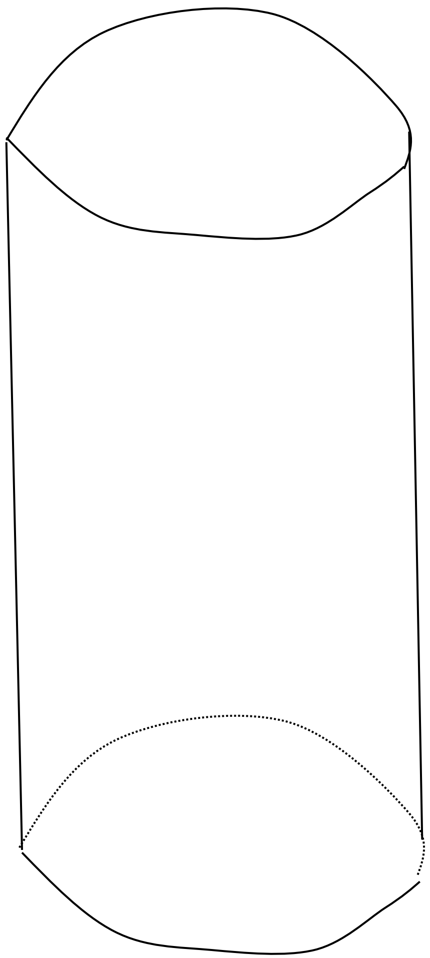


Beyond geometry?

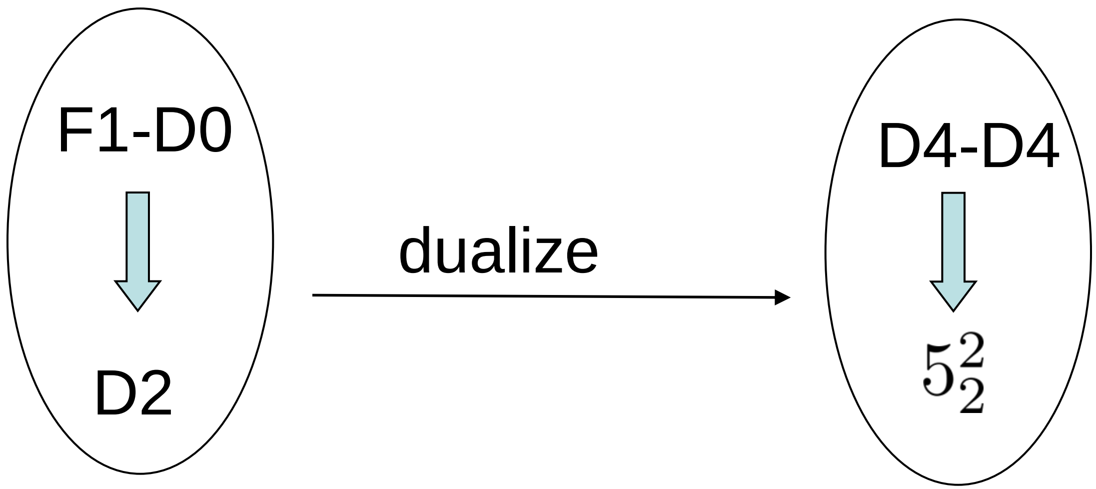
Can we find solutions which are not in supergravity, but do not require full closed string field theory?

Two-charge geometries of Lunin-Mathur presumably also have a Coulomb-Higgs interpretation:

Recall that the F1-D0 system can puff up into a supertube, a D2-brane whose cross section can be an arbitrary curve. This is like the Coulomb branch picture of the system



If we dualize the F1-D0 system, many other systems can be shown to puff up into supertubes.



These exotic objects also appear when U-dualizing conventional branes in three dimensions. Their tensions can involve strange powers of g_s such as g_s^{-3}, and strange powers of the radii. Elitzur, Giveon, Kutasov, Rabinovici; Obers, Pioline

Above reasoning suggests such exotic branes may play an important role in understanding microstates.

JdB, Shigemori

What do such exotic branes correspond to?

In three-dimensions, they are point-particles. Their charges are given by monodromies of the scalars of 3d supergravity. Those scalars take values in $SO(16)\backslash E_8(\mathbb{R})/E_8(\mathbb{Z})$

Charges are not additive: they take values in $E_8(\mathbb{Z})$.

From a higher dimensional point of view, one undergoes a U-duality as one encircles these exotic branes, just as in non-geometric backgrounds.

One can construct explicit examples.

There are many non-geometric solutions that should exist. Nothing we said rules out such solutions. If they have lots of degrees of freedom a la superstrata, perhaps still hope to find the entropy without full closed string field theory?

Conclusions

- Evidence that most microstates have no gravitational description beyond that of the black hole – highly nonlocal in spacetime
- Gap in superconformal quantum mechanics implies nonlocal breakdown of LQFT while curvatures are small: too little gravitational phase space.
- Can obtain rotationally invariant states from supergravity by smearing but not sufficiently many.
- Can in principle use Higgs-Coulomb to probe states with non-local quantities like 2pt functions.
- Perhaps interesting to consider other probes like Brownian motion?
- Can one do anything away from extremality?
- Is it possible to find a more detailed description using non-geometrical solutions?