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Macroscopic Quantum Fluctuations of Scaling Solutions

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In this short note AdS/CFT techniques are used to argue that certain smooth supergravity solutions cannot, in fact, be thought of as "good" semiclassical states as they suffer from *macroscopic* quantum fluctuations. Such a breakdown of effective field theory intuition is a potentially quite important in resolving information loss.

One of the great difficulties in evading the information paradox is the fact that all the relevant physics occurs at the black hole horizon where the curvature can be made arbitrarily small. This leads us to believe that we can neglect the effects of the underlying quantized gravity and rely on field theory techniques. Recently, however, a program has been initiated [1], within the context of string theory, to show that quantum effects indeed extend all the way to the horizon of a putative black hole. Within this framework it is argued that the need for a large number, N, of quanta to form a black hole introduces a new parameter in determining the "effective Plank scale" and thus quantum effects can become significant even though all curvature scales remain small. This phenomenon has indeed been observed to occur for certain "microscopic" 1/2 and 1/4 BPS black holes in string theory; unfortunately, the latter always have string-scale horizons and thus it is difficult to disentangle stringy effects. An overview of this program, including an extensive list of references, can be found in [2].

More recently, in [3], a large class of smooth supergravity solutions, believed to be related to the "microstates" making up the black hole ensemble, have been quantized. The associated black holes are 1/8 BPS and possess macroscopic horizons with curvatures that can be made arbitrarily small. The "microstate solutions" are smooth BPS solutions of supergravity that share the same asymptotics as the black hole solution and thus form part of the phase space of the theory in the same sector as the black hole. As black holes are believed to be thermal ensembles over the relevant sector of the Hilbert space, the quantization of the "microstate phase space" is argued to generate states that contribute to this ensemble.

A certain class of these solutions, known as *scaling solutions*, posses very deep throats, like the BPS black hole geometry, but, unlike the latter, these throats eventually cap off smoothly and the geometries are everywhere smooth with low curvature. A remarkable discovery in [3] is that, when quantized, these particular geometries (which look most like the actual black hole geometries with infinitely deep throats) exhibit macroscopic quantum fluctuations and are thus not good classical geometries, even though they have no regions of high curvature.

This is perhaps the first instance of macroscopic quantum effects clearly invalidating classical and effective field theory reasoning. As such it would be nice to have an alternative derivation of this result. In this short note we will use AdS/CFT to argue, in an independent way, that these smooth geometries indeed must suffer from large scale quantum effects.

Scaling Solutions and AdS/CFT

The microstate geometries quantized in [3] are multicenter BPS solutions (all possessing a U(1) isometry) of $\mathcal{N} = 1$ supergravity in five dimension, the low-energy limit of M-theory compactified on a Calabi-Yau, X [4–6]. They are sourced by n centers of charge Γ_a located at coordinates $\vec{x}_a$. These sources can, by an appropriate choice of charges, be made smooth and they represent

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the location of the original branes generating the geometry. The asymptotics of these geometries match that of a black hole of charge $\Gamma = \sum_a \Gamma_a$ and indeed the black hole can be described within this class of geometries by using only a single center of charge Γ.

Supersymmetry constrains the $\vec{x}_a$ to satisfy

$$\sum_{b,b\neq a}^{n} \frac{\langle \Gamma_a, \Gamma_b \rangle}{r_{ab}} = \langle h, \Gamma_a \rangle , \quad r_{ab} = |\vec{x}_a - \vec{x}_b| \quad (1)$$

Where $\Gamma_{ab} := \langle \Gamma_a, \Gamma_b \rangle$ is the antisymmetric Mukai pairing on the charge space and h are constants determining boundary conditions (cf. eqn (6)). A simple solution, when $n = 3$, to these constraints are $r_{ab} = \lambda \Gamma_{ab} + \mathcal{O}(\lambda^2)$ for $\lambda \ll 1$ where the order of the subscript ab is fixed by the requirement $\Gamma_{ab} > 0$. As coordinate distances, r_{ab} must satisfy triangle inequalities so such solutions only exists if Γ_{ab} also satisfy these inequalities.

Such solutions are referred to as "scaling solutions" and enjoy the special property that as $\lambda \to 0$ they develop an extremely deep throat outside of which they are essentially indistinguishable from a black hole solution with the same total charge sitting at the end of the throat. Although the coordinate distances $r_{ab} \to 0$ in this limit, the actual metric distance between the centers stays finite (and fixed) as the throat gets deeper and the throat ends, at a *highly λ-dependent* depth, in a smooth cap formed by the centers. For $n > 3$ centers solutions with similar properties exist but are less well studied.

Quantization

In [3] the solution space defined by (1) was shown to be a phase space and quantized accordingly using methods of geometric quantization. The symplectic form (derived via a non-renormalization theorem from a related D-brane system) was shown to have vanishingly small support near $\lambda \sim 0$, implying a very low phase space density in this region.

This is in stark contradiction to the expectation that the phase space should scale with the spacetime volume (recall that $\lambda \sim 0$ corresponds to an extremely deep throat). Moreover, this implies that geometries with arbitrarily deep throats cannot all be good classical solutions. The lack of phase space volume as $\lambda \to 0$ implies that in the quantized phase space there will be some λ_c such that the region $0 \leq \lambda \leq \lambda_c$ comprises only one Plank unit of phase space volume and no states can be localized within this region. Thus throats with $\lambda < \lambda_c$ simply cannot be constructed as semiclassical states.

Intuition, on the other hand, would suggest the existence of quantized fluctuations localized in each Plank sized volume inside the throat, implying a *growth* of the phase space at small λ. The quantization of [3] clearly suggests this is not the case. A simple explanation of this fact is that this quantization applies only to supersymmetric solutions and hence can be continued to the $g_s \to 0$ limit where gravity is weak and no deep throat exists. Thus clearly the BPS phase space density cannot scale with the depth of the throat. For this very reason, however, one might worry that this argument applies only to BPS states and that the non-BPS phase space grows as the throat volume increases.

AdS asymptotics and CFT quantization

To reinforce the claims of [3] we will argue, via AdS/CFT, that the CFT states dual to geometries with $\lambda \sim 0$ are necessarily quite delocalized and hence very quantum. This argument, however, will not depend on supersymmetry but rather on the fact that the solution space is a phase space and hence is parameterized by expectation values of conjugate operators in the dual CFT. Moreover, our argument will not directly use the result of [3] that the supergravity symplectic form has vanishingly small support in the $\lambda \sim 0$ region and is, in this sense, an independent verification.

In [7] a decoupling limit was found for this general set of multicenter solutions which places them in an asymptotically $\mathrm{AdS}_3 \times \mathrm{S}^2$ geometry. Thus we can study these geometries by applying standard AdS/CFT techniques. For instance we can extract the expectation values of operators of the dual conformal field theory in the state associated to the geometry by studying an asymptotic expansion of our solutions near the boundary.

To do this one first writes all the fields, ϕ