METASTABLE ANTIBRANES

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Introduction

Why care about metastable antibranes? String theory is our most prominent theory of quantum gravity. In establishing connections between string theory and our physical world, a necessary challenge is the introduction of controlled supersymmetry (SUSY) breaking. A canonical method for doing so involves balancing antibranes in warped, fluxed throats to form a metastable non-SUSY configuration. These metastable antibranes configurations have a wide range of applications. For example, they play a crucial role in the Kachru-Kallosh-Linde-Trivedi (KKLT) construction of de Sitter vacua from string theory.

Overview of poster The goal of this poster is to tell stories about metastable antibranes. As a concrete example, I will focus on the Kachru-Pearson-Verlinde (KPV) state, which is a metastable state of anti-D3 branes in the Klebanov-Strassler throat, but much of the discussion applies to other configurations, too. Our story will mostly flow chronologically in time starting with the first ingredient, which is the discovery of the Klebanov-Strassler throat in 2000, to the latest piece of development, which is a matched asymptotic solution of metastable antibranes backreaction in 2022.

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The Kachru-Pearson-Verlinde state

The Klebanov-Strassler throat Let us begin our metastable antibranes story from around 2000 when explorations of AdS/CFT are very much the talk of the town. The classic AdS/CFT duality comes from considering a stack of D3 branes in a flat space. Interesting generalisations of this classic AdS/CFT can be obtained by considering a stack of branes that is instead at the tip of a conifold. Thinking along this line, Klebanov and Tseytlin put N D3 branes and M wrapped D5 branes at the tip of a conifold whose base is topologically an $S^3 \times S^2$. In the supergravity regime, this results in a warped, fluxed conifold solution called Klebanov-Tseytlin. The Klebanov-Tseytlin solution is expected to be dual to an $SU(N+M) \times SU(N)$ gauge theory. However, an unfortunate feature of the Klebanov-Tseytlin is that it contains naked singularities. Later, Klebanov and Strassler realised that by deforming the pointy tip of the conifold to an S^3, one can get rid of these singularities. This supergravity solution is unsurprisingly called Klebanov-Strassler. A pictorial depiction of this story can be found in Figure 1.

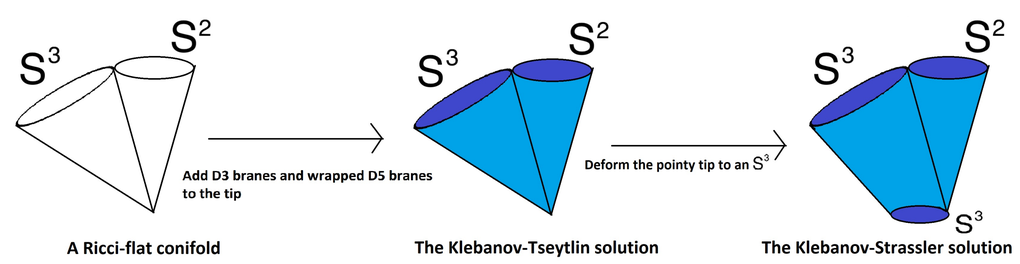

Fig. 1: Pictorial description of the Klebanov-Strassler throat.

Anti-D3 branes in the Klebanov-Strassler background In around 2003, Karchu, Pearson, and Verlinde looked at the dynamics of p probe anti-D3 branes in the Klebanov-Strassler background. It's interesting to note that, naively, they are putting anti-D3 branes into a background of D3 branes. A prerequisite for this to make sense is the observation that there are no physical branes in the Klebanov-Strassler solution, i.e. they have dissolved into fluxes. Thus, there is no direct analogue of the brane/antibrane annihilation story of Sen where the open strings connecting the two branes have a tachyon that rolls down and annihilates the branes into a pressureless gas. Instead, it has to go through a brane/flux annihilation where the background fluxes must first drop by some units and form actual branes before the annihilation can happen. A key claim of KPV is that this process can be exponentially suppressed.

Back to the dynamics of the p probe anti-D3 branes. It's obvious that these antibranes are attracted to the tip of the Klebanov-Strassler throat via gravitational and "electromagnetic" (i.e. brane/antibrane attraction) forces. At the tip, due to the non-trivial background H_3 flux, the stack of anti-D3 branes polarise via the Myers effect to a spherical NS5 brane carrying dissolved anti-D3 brane charge. For those who are less familiar, the Myers effects come essentially from the fact that branes in string theory can interact with not only the flux they carry but other fluxes, too. In particular, the stack of D3 branes here can interact with the non-trivial H_3 flux of the Klebanov-Strassler background and puff into a sphere. In supergravity, one can view it as a spherical NS5 brane with dissolved anti-D3 brane charge (denoted anti-D3-NS5 brane).

The polarised anti-D3 branes, i.e. a spherical anti-D3-NS5 state, wrap an S^2 of the S^3 at the tip of the Klebanov-Strassler throat. By plotting the effective potential for this polarised state, Karchu, Pearson, and Verlinde discovered that when $p/M \lesssim 0.08$ (p is the number of anti-D3 branes and M the units of background F_3 flux), it can balance its own "weight" with "electromagnetic" forces from the fluxes to form a metastable configuration at a non-podal azimuthal angle ψ on the S^3 at the tip of Klebanov-Strassler throat, i.e. $\psi_{metastable} \neq 0, \pi$. This metastable anti-D3-NS5 state is **the KPV state**. A pictorial depiction of this story can be found in Figure 2.

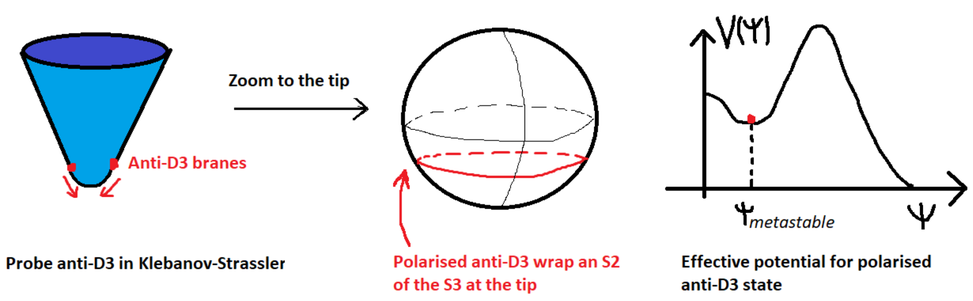

Fig. 2: Pictorial description of the Karchu-Pearson-Verlinde state.

Existence of the KPV state beyond probe?

Does the KPV state exist beyond probe? Discussions on the existence of the KPV state beyond probe started around 2010 due to an observation by Bena, Grana, and Halmagyi. In particular, by studying the linearised backreaction of smeared anti-D3 branes (the anti-D3 branes are smeared homogeneously across the S^3 at the tip of the Klebanov-Strassler throat), they observed that the backreacted supergravity description of the smeared anti-D3 branes must have unphysical singularities in the 3-form flux. Various later works, which dated around 2010 to 2015, showed that the unphysical flux singularities in the anti-D3 branes supergravity description persist even when one gets rid of all the approximations, e.g. linearisation of the antibranes backreaction and smearing of the anti-D3 branes. Thus, one has to ask: Does the KPV state exist beyond probe? Or stated differently, is there a well-behaved supergravity solution of the backreacted KPV state? In this poster, I will argue that the answer to this question is probably yes by outlining three recent observations.

No-go and lifting of no-go In around 2015, Cohen-Maldonado, Diaz, Van Riet, and Vercnocke observed that the arguments for unphysical singularities in the supergravity description of smeared/localised anti-D3 branes do not extend to the case of spherical anti-D3-NS5 branes. In particular, the IR and UV gluing condition, which is the key to previous observations of unphysical singularities, can be expressed in terms of a Smarr relation. While localised/smeared anti-D3 branes cannot satisfy this Smarr relation with a regular horizon, spherical anti-D3-NS5 branes can because of their non-trivial horizon geometry. As the KPV state is the polarised state of anti-D3 branes and, at least in some regime of parameters, can be considered in supergravity as spherical anti-D3-NS5 branes, the observation effectively found the KPV state a possible way out of the unphysical singularities that plagued backreacting antibranes.

As a lifting of no-go only provides the necessary conditions, supplementary positive evidence for the existence of a well-behaved KPV supergravity solution is needed. This brings us to our second observation.

Positive evidence exactly where no-go is lifted Through a thermal blackfold analysis, in a work with Armas, Niarchos, Obers, and Van Riet in 2019, we provided complementary positive evidence for the existence of the KPV state exactly when no-go is lifted. In particular, in the extremal limit, we recovered the KPV state. Away from extremality, we uncovered a metastable black anti-D3-NS5 state and observed, in agreement with expectations, that its metastability is lost when its horizon geometry resembles that of a localised black anti-D3 state.

For those who are less familiar with the blackfold approach, the underlying idea of the technique is to extract information about a configuration by examining a subset of the matched asymptotic equations, which in our case connect the anti-D3-NS5 brane in the near asymptotic to the Klebanov-Strassler solution in the far asymptotic. A potential worry of the approach is that it relies on the blackfold conjecture, which states that satisfying only the blackfold equations guarantees a regular matched asymptotic solution. This conjecture is well supported in Einstein gravity, however, in supergravity, especially the highly-nontrivial situations of antibranes in a warped, fluxed throat, it is not known whether this conjecture is valid. This brings us to our third and final observation.

A well-behaved matched asymptotic solution of antibranes backreaction In 2022, in a work with Niarchos, we provided analytically a leading-order matched asymptotic solution that perturbatively captures the backreaction of a metastable spherical anti-D3-NS5 state at the tip of a warped, fluxed throat that closely resembles the Klebanov-Strassler solution. Our matched asymptotic solution is well-behaved everywhere and, thus, a highly-nontrivial example for the blackfold conjecture in supergravity, especially in cases of backreacting antibranes in warped, fluxed throats. Moreover, as our matched asymptotic solution closely resembles the backreacted KPV state, it also acts as direct evidence for the existence of a well-behaved KPV supergravity solution.

Classical stability of the KPV state?

Why do we discuss the stability of the KPV state? The original claim of metastability of the KPV state only refers to a balance of force felt by the polarised anti-D3 branes in the azimuthal angle ψ of the S^3 at the tip of the Klebanov-Strassler throat. It is not a statement of the robustness of the state under generic perturbations. In using metastable antibranes for one's purpose, e.g. cosmological construction, he/she might be worried that a slight deformation of the polarised sphere or an inhomogeneous ripple of the dissolved antibrane charge might destroy his/her beloved configuration. Therefore, it is important for us to ask whether these antibranes states can withstand generic perturbations. Here, I will briefly outline some discussions on this topic.

Is the KPV state classically stable? By studying the backreacted profile of localised anti-D3 branes at the tip of the Klebanov-Strassler throat, Bena, Grana, Kuperstein, and S. Massai observed in 2015 that a test anti-D3 brane in such a background would feel a repulsive force away from the localised branes. This tachyonic behaviour is subsequently used to argue that the polarised state of anti-D3 branes has classical instabilities. On the other hand, by studying generic deformations of the KPV state using the blackfold approach, I observed in 2020 that the blackfold equations (a subset of the matched asymptotic equations connecting anti-D3-NS5 branes and Klebanov-Strassler throat) prohibit the existence of a tachyonic mode.

The disparity between the two results could be due to the fact that these works are applicable in complementary regimes of validity. In particular, while the technique employed by Bena and other in 2015 is reliable when the spherical polarised state has a small/finite radius, i.e. when M is small, the blackfold technique is reliable when the spherical polarised state has a very large radius, i.e. when M is large. Thus, it is possible that instabilities observed for the KPV state in the small/finite radius regime (small M) do not persist in the large radius regime (large M). An analogous example of this picture can be found in the study of black rings where an instability (i.e. elastic mode instability) is observed for rings with small curvature radius but is not for rings with large curvature radius.