SCAPEZILLA: the backreaction of anti-branes in flux compactifications

Iosif Bena, Johan Blåbäck, Alex Buchel, Ulf Danielsson, Oscar Dias, Gregory Giecold, Mariana Graña, Nick Halmagyi, Stanislav Kuperstein, Stefano Massai, Andrea Puhm, Bert Vercnocke, Thomas Van Riet
Metastable vacua

- Exist in gauge theories
- $N=1$ SQCD  
  Intriligator, Seiberg, Shih
- Lots of other theories  
  everybody and their brother
- No type IIA realizations of metastable vacua  
  Bena, Gorbatov, Hellerman, Seiberg, Shih
- Why?
No IIA brane realization

- $N=1$ engineered with $D4 + \text{NS5}$
- $D4$ ends on codimension 2 line inside $\text{NS5}$
- End of $D4$ branes sources log mode on $\text{NS5}$
- $\text{NS5}$ brane bending
  $\leftrightarrow$ Log running of $N=1$ coupling constant
- Tiny IR perturbation $\Rightarrow$ log $\Rightarrow$ UV messed up

different UV $\leftrightarrow$ not vacua of the same theory

Bena, Gorbatov, Hellerman, Seiberg, Shih
What about AdS-CFT

- No $\text{asmpt-AdS}_5$ metastable solutions
- One candidate: Kachru Pearson Verlinde
  - Anti-D3 branes in Klebanov Strassler
  - Codimension 6 $\Rightarrow$ modes $\sim 1/r^4$
  - Normalizable $\Rightarrow$ metastable vacuum
  - Much used in string cosmology
Klebanov-Strassler

\[ \frac{1}{4\pi^2 \alpha'} \int_{S^3} F^{(3)} = M \]

3-sphere

2-sphere

\[ r = 0 \]

\[ r = \infty \]

UV

IR

D3 charge dissolved in fluxes

\[ H_3 \times F_3 \rightarrow F_5 \]

\[ F_5 \times F_3 \rightarrow H_3 \]
Metastable proposal

Add anti-D3 at tip

D3 charge in flux

anti-D3 tunnel and annihilate D3 charge in flux

decay to BPS solution

Metastable vacuum

brane polarization (Myers effect)

Kachru Pearson Verlinde
AdS-CFT modes

- Normalizable modes (NM)
  - dual to vevs
  - Finite energy, IR
- Non-normalizable (NNM)
  - deformations of Lagrangian
  - Infinite energy, UV
- Different NNM $\Rightarrow$ different theories
- Same NNM $\Rightarrow$ different vacua, same theory

\[ r = 0 \quad \text{Normalizable} \]
\[ r = \infty \quad \text{Non-Normalizable} \]

metastable $\iff$ NNM$=0$
Big Question

Anti-D3 ⇒ normalizable or non-normalizable modes?

- Fluxes ⇒ KS field \( \sim \log r \)
- encodes \( \log \) running of coupling constant
  \[
  \frac{1}{g_1^2} - \frac{1}{g_2^2} \sim \int_{S^2} B_2 \sim \log r
  \]
- Anti-D3 couple to this field
- IIA intuition: \( \log \) messed up ⇒ non-normalizable
- every dual of non-conformal 4D theory ⇒ \( \log \) modes
Big Implications if NNM

- No AdS-CFT metastable 4D vacua

- String cosmology/landscape:

  anti-D3 down long KS throats →
  redshift → tunably-small energy →
  lift AdS to dS
  anti-D3 non-normalizable
  energy not tunably-small
  moduli stabilization messed up

\[
V = \frac{a A e^{-a \sigma}}{2 \sigma^2} \left( \frac{1}{3} a A e^{-a \sigma} + W_0 + A e^{-a \sigma} \right) + \frac{D}{\sigma^3}
\]

\[3 \times 10^{-9} \sim 1\]
**Scape-zilla**

- 4D $N=1$ gauge theories - log running - generic phenomenon, not restricted to KS
- Same happens in LARGE volume scenarios
- No vacuum uplift by small-energy !
  - anti-D3 give $O(1)$ contribution !
- Landscape of AdS vacua

Landscape of dS vacua
Can we find Scapezilla?

\[ 3\text{-sphere} \rightarrow 2\text{-sphere} \rightarrow r = 0 \rightarrow r = \infty \]

Smear anti-D3's

\[ SU(2) \times SU(2) \times \mathbb{Z}_2 \]

Solution (\pi)
Perturbation theory in anti-D3 number

- 8 modes satisfying second-order eqs.
- 16 integration constants
- expanded around BPS solution ⇒ first-order system:

\[
\begin{align*}
\frac{d\xi_a}{d\tau} + \xi_b M^b_a(\phi_0) &= 0, \\
\frac{d\phi_1^a}{d\tau} - M^a_b(\phi_0)\phi_1^b &= G^{ab}\xi_b
\end{align*}
\]

Papadopoulos, Tseytlin 2000
Borokhov, Gubser 2002
Kuperstein, Sonnenschein 2003
The Hunting Method

- Solve first 8 equations for $\xi$. Integration constants $X$.
- Use $\xi$ + other 8 eqs. to get $\phi$. Integration constants $Y$

<table>
<thead>
<tr>
<th>dim $\Delta$</th>
<th>non-norm/norm</th>
<th>int. constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>$r^4/r^{-8}$</td>
<td>$Y_4/X_1$</td>
</tr>
<tr>
<td>7</td>
<td>$r^3/r^{-7}$</td>
<td>$Y_5/X_6$</td>
</tr>
<tr>
<td>6</td>
<td>$r^2/r^{-6}$</td>
<td>$X_3/Y_3$</td>
</tr>
<tr>
<td>5</td>
<td>$r/r^{-5}$</td>
<td>$-$</td>
</tr>
<tr>
<td>4</td>
<td>$r^0/r^{-4}$</td>
<td>$Y_7, Y_8, Y_1/X_5, X_4, X_8$</td>
</tr>
<tr>
<td>3</td>
<td>$r^{-1}/r^{-3}$</td>
<td>$X_2, X_7/Y_6, Y_2$</td>
</tr>
<tr>
<td>2</td>
<td>$r^{-2}/r^{-2}$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

$X_2$ and $X_7 \sim 1/r$ non-normalizable
The hard work

- Implicit solution - 8 nested integrals
- Smart grad students → nested integrals can be simplified:
  - $\xi$ - solved in terms of one integral!
  - $\phi$ - 2 or 3 nested integrals!
- Easy to find all mode profiles numerically
The silver bullet !!!

- 16 constants - 14 physical ones
- Probe D3 brane attracted by anti-D3's
- Force is universal: $F_r \sim \frac{N_{D3}}{r^5}$
- We get
  $$F_r \sim \frac{X_1}{r^5} + O \left( \frac{1}{r^{11}} \right)$$
- Only depends on 1 of the 14 constants !!!
- Only force-mode is $\xi_1$
Look in the infrared

- Kill very divergent guys + $\xi_1$ must be nonzero !!!
- Physical divergence: anti-D3 smeared on $S^3$
- Warp factor diverges $\sim \tau^{-1}$
- Curvature diverges: $R \sim F_{(5)}^2 \sim \tau^{-4}$
- Another divergence - no obvious reason

$$H_{(3)}^2 \sim F_{(3)}^2 \sim \tau^{-2}$$
- Subleading singularity $\sim \xi_1$

Everything depends on it !!!

Must be there !!!
If singularity physical:

- Anti-D3 in KS is normalizable
- Dual to gauge theory metastable vacuum
- Nice physics - vev's etc.
- Hunt for gauge theory dual

- AdS can be uplifted to dS
- Landscape of dS vacua alive and frisky
- No Scapezilla

Dymarsky
Klebanov
Seiberg
If singularity unphysical:

- anti-D3 sources non-normalizable modes
- IR couplings to log mode \((H_3)\) - mess up UV
- No more dS landscape - **SCAPEZILLA**

Reminder - BPS solution:

- \(F_5 \times F_3 \rightarrow H_3\)
- \(H_3 \times F_3 \rightarrow F_5\)
If singularity unphysical:

- \((-F_5) \times F_3 \rightarrow -H_3\)
- \((-H_3) \times F_3 \rightarrow -F_5\)
- Sign of D3 charge dissolved in flux not fixed !!!
- Only F3 flux on S^3 fixed.

Only physical solution with anti-D3 is anti-KS !!!
Is this generic?

- Do anti-branes always hate charge dissolved in flux?
- I hope not...
- M-theory version of Klebanov-Strassler - CGLP
  Cvetic, Gibbons, Lu, Pope
- M2 + transverse 8D Stenzel Space, magnetic $F_4 + F_4$
- M2 charge in fluxes
- add anti-M2 $\rightarrow$ metastable
  Klebanov, Pufu
- Perturbative solution $=$ singular!
- Idem for anti-D2 in CGLP, A8
- Insane antibranes Giecold, Orsi, Puhm
What about non-extremal fuzzballs?

We have many many many BPS or extremal horizonless microstate geometries (fuzzballs):

Bena, Bobev, Bossard, Dall’Agata, deBoer, Giusto, Niehoff, Ruef, Shigemori, Vasilakis, Warner & friends
Common in String Theory

Non-Extremal

Extremal Black Hole

Resolution "backwards in time" !!!
Non-extremal microstates?

Add metastable supertube wrapping GH fiber:

Bena, Puhm, Vercnocke

Decays via brane-flux annihilation

May be only way to construct stationary non-extremal microstate geometries

Gibbons, Warner
Is singularity physical?

- If not physical:
  - antibranes cannot coexist with charge in fluxes
  - maybe no more dS landscape 😞
  - maybe no systematic way to build non-extremal stationary microstate geometries (fuzzballs) 😞
  - brane of codimension 6 + fluxes → log modes

So it must be physical !!!

Proof by wishful thinking
Is singularity physical?

- One should a-priori take only normalizable modes in UV, and accept whatever exists in the IR.
- Maybe, but not in AdS-CFT.
- IR regularity crucial to relate NNM with NM. Otherwise, get wrong physics:
  - AdS-QCD-CMT without incoming b.c. at black hole.
  - Confinement from Klebanov-Tseytlin.

Scapezilla not easy to kill.
Is singularity physical?

- Anti-D3 singularity @ first-order backreaction
- May go away at full backreaction  
  Dymarsky

- No intention:  
  Bena, Grana, Kuperstein, Massai
  1. Eliminate IR singularity
  2a. Find full solution in an IR expansion to order $\tau^{10}$
  2b. Examine r.h.s. of nonlinear equations
- Only possible solution with anti-D3

Anti-D3's are singular to the bitter end

Anti-M2's as well
Is singularity physical?

- Integral of divergent energy density is finite!
- We can be agnostic about origin of singularity
- Accept everything with finite IR action
- After all, AdS-CFT relates bulk and boundary actions

- Negative-mass Schwarzschild
- Integral of divergent energy density is finite
- Must be eliminated if AdS-CFT is to make any sense

- Furthermore, anti-M2 and anti-D2 singularities have divergent IR action

Klebanov (Dymarsky)

Counter-argument: Horowitz-Myers

GRAVITY PEOPLE WILL KILL YOU & DRINK YOUR BLOOD!!!
Is singularity physical?

- Singularity indicates new physics
  - Instabilities
  - Polarization:
    - Probe anti-D3’s polarize into NS5 branes/$S^2 \subset S^3$
    - this could resolve singularity à la Polchinski-Strassler
- Smearing wipes out this polarization channel:
- PS has many channels: D5 branes/$S^2 \subset T^{1,1}$ survive smearing
- No smeared anti-D3+D5 $\rightarrow$ no localized anti-D3+D5 $\Rightarrow$
  no localized anti-D3+NS5 branes either !!!
Why Polchinski-Strassler does not save the landscape

Same potential terms as in PS!

\[ V(\tau) \sim (2\pi n) a_2 \tau^2 - a_3 \tau^3 + \frac{1}{2\pi n} a_4 \tau^4 \]

No polarization if:

\[ (a_3)^2 < \frac{32}{9} a_2 a_4 \]

Long calculation:

\[ a_2 = \frac{1}{3p^2} \left( 4\lambda_f^2 + 3\lambda_F^2 \right), \quad a_3 = \frac{2}{3p} \lambda_f, \quad a_4 = \frac{1}{8} \]

Could have worked, but it does not!!!

revenge on Bousso-Polchinski 😊
Is singularity physical?

- Maybe we are not smart-enough to understand resolution
- "Good, Bad, Ugly" criterion: Gubser
  Good singularities can be cloaked by horizon
- If physical \( \Rightarrow \exists \) BH in KS/KT with negative charge

All KS/KT black holes must have positive charge:
Bena, Buchel, Dias

Black hole in Klebanov-Strassler/Tseytlin
Aharony, Buchel, Kerner; Buchel
Is singularity physical?

- Maybe artifact of smearing
- **Localized** anti-branes may not have this problem
- $\iff$ Localized BH with anti-D3 charge in KS exists

---

Can be anywhere on $S^3$

Could be smeared

---

Smeared BH with negative charge does not exist

Bena, Buchel, Dias
Is singularity physical?

- Nobody could have predicted it a-priori!
- No a-posteriori physical reason for accepting it
- Several highly nontrivial calculations that could have worked either for or against - all worked against
What would help

- Localized anti-D3 in KS
- Localized BH in KS
  - Non-BPS solution, 2 variables
  - Separation of scales
- No smeared BH solution → no localized BH solution
  - Is this always true? If not why?
- Solution for smeared anti-M2, anti-D2 black holes in CGLP, A8
  - Would confirm whether anti-D3 story is generic or not
- One variable - shooting or relaxation - straightforward.
What would help

- Metastable supertube solution
  - cannot smear → 2 variables!
  - supertube charges: (-,-) or (+,-)
- Numerics? ... BlackFold? ...

Separation of scales? ... Inverse scattering? ... Perturbative?

- first fully-backreacted microstate geometry of a non-extremal BH with macroscopic horizon
- existence of gazillions of microstates - resolve info paradox
- mechanism that keeps them from collapsing into BH (which nobody else has 😁)
Conclusions

- Probe antibranes uplift $\text{AdS}$ to $\text{dS}$
- Probe antibranes give stationary near-extremal fuzzballs
- Backreacted antibranes have singularity
- No reason to accept it. So far all evidence against.

If unphysical:

- A lot of string cosmology and phenomenology to be revisited.
- **SCAPEZILLA**: $\text{AdS}$ landscape $\neq$ $\text{dS}$ landscape
- Find other ways to uplift $\text{AdS}$ to $\text{dS}$ (Kahler uplifting? nonperturbative effects? nothing?)
- Find other ways to build non-extremal fuzzballs (JMaRT-type centers? motion on moduli space? inverse scattering? numerics?)