

On the Uses of Antíbranes

SCAPEZILLA

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SACLAY

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;
Ooguri, Ookouchi; Franco, Uranga
Mukhi, Suryanarayana

- ◆ Why?



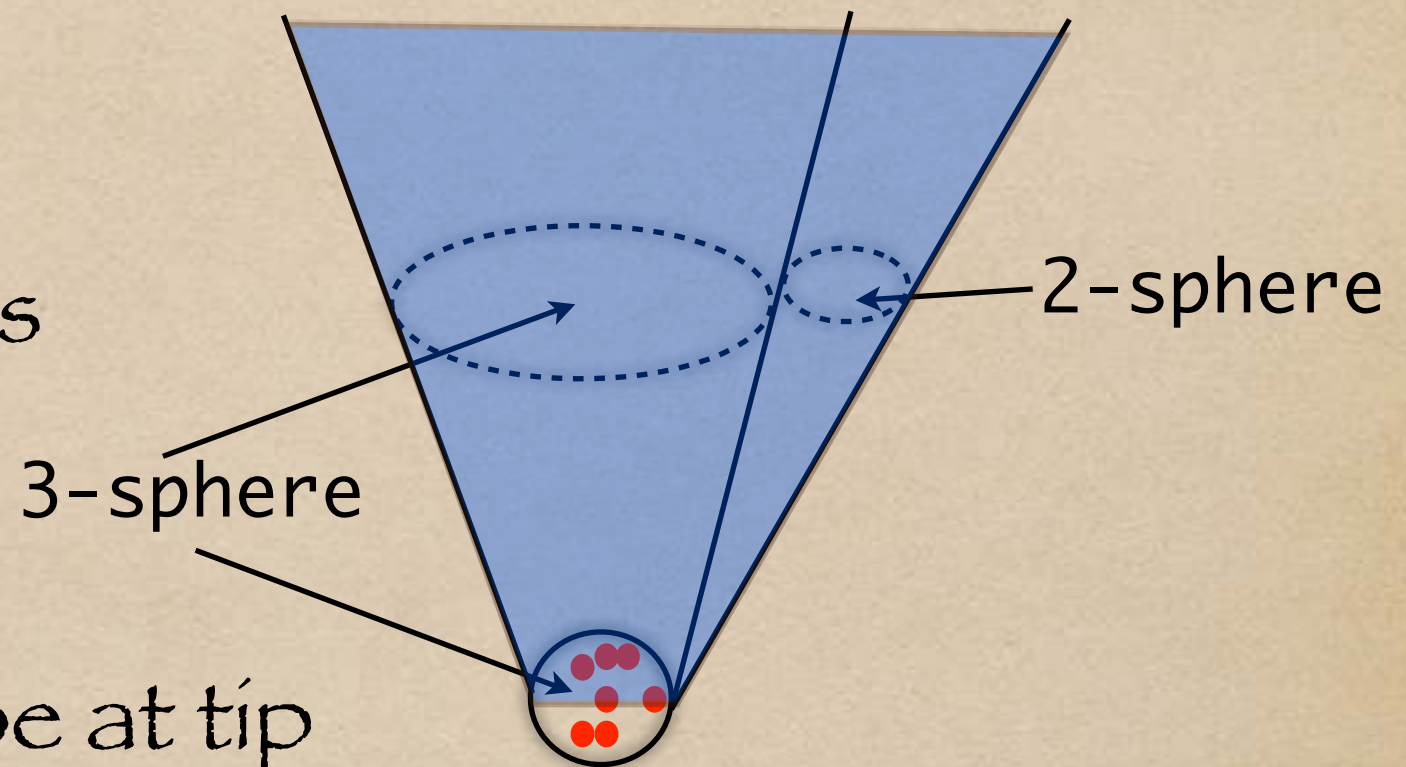
No IIA brane realization

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

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

Klebanov-Strassler (AdS-CFT)

$D3$ charge
dissolved in fluxes



Add $\text{anti-}D3$ probe at tip

$\text{anti-}D3$ tunnel and annihilate $D3$ charge in flux

decay to BPS solution

Ignoring backreaction \Rightarrow Metastable

Kachru Pearson Verlinde

Maldacena Năstase (similar)

Big Question

Is anti-D3 in KS really metastable ?

- ◆ Fluxes \Rightarrow 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 \Rightarrow metastability = artifact of probe approx.
Backreaction $\Rightarrow \log$ messed up \Rightarrow
strong effect at ∞ (non-normalizable) \Rightarrow not metastable

Are any other anti-branes metastable ?

Why important?

Antibranes = Bread & butter for two different fields

- ◆ String Phenomenology and Cosmology
 - ◆ Flux compactifications \rightarrow AdS landscape
 - ◆ Antibranes uplift Λ to get de Sitter, String Inflation
- ◆ Black Hole Information Paradox
 - ◆ Need Structure @ Horizon (Fuzzball, Firewall)
 - ◆ Constructed for extremal (SUSY) black hole
 - \Rightarrow black-hole-like entropy !!!
 - ◆ Antibranes give only systematic method to build structure @ non-extremal horizon

talk by Shigemori

Bena, Puhm, Verhocke; Gibbons, Warner

Anti-branes in String Cosmology

Flux compactifications \rightarrow AdS

anti-D3 down long KS-like throats \rightarrow

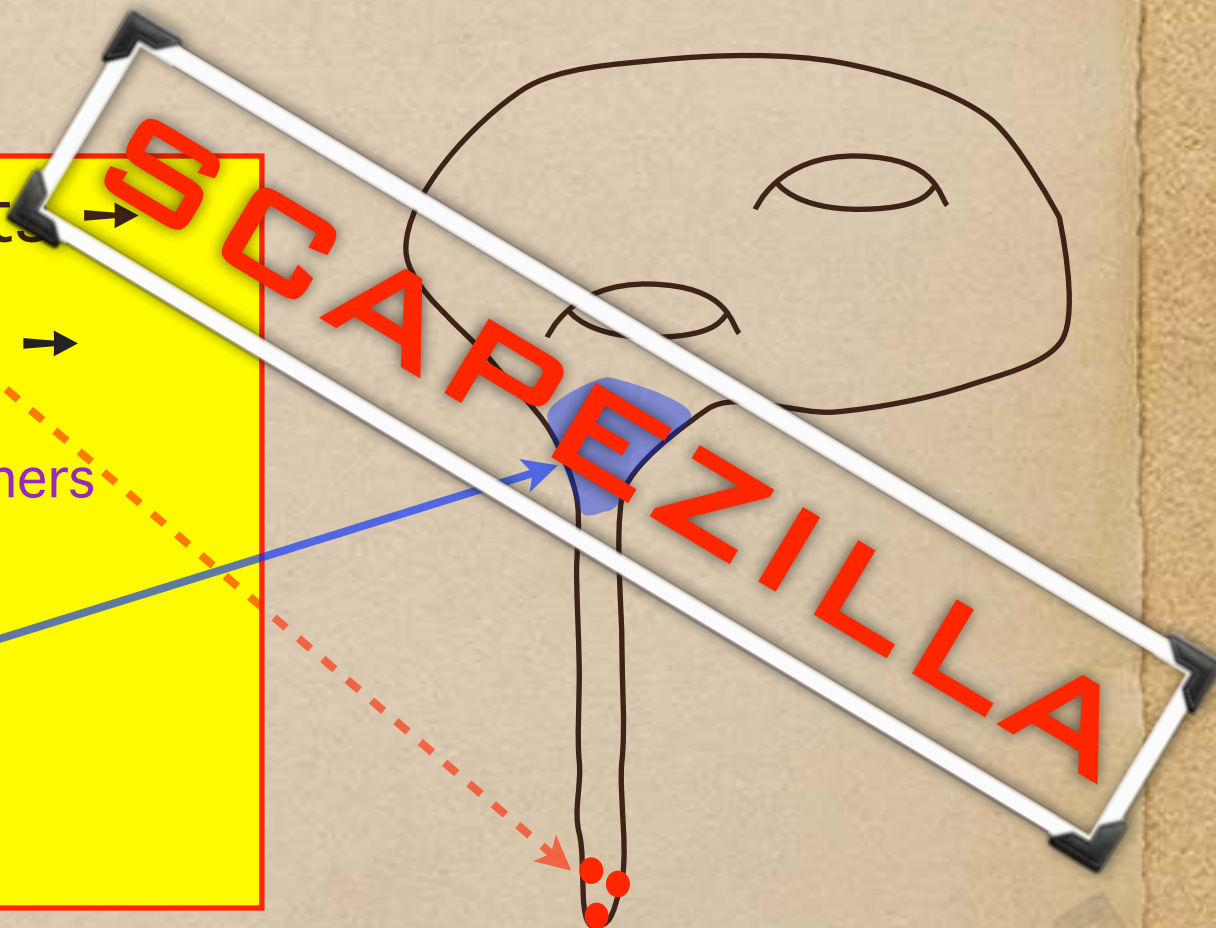
redshift \rightarrow tunably-small energy \rightarrow

lift AdS to dS KKLT, ~2000 others

if anti-D3 non-normalizable \rightarrow

energy not tunably-small \rightarrow

moduli stabilization messed up

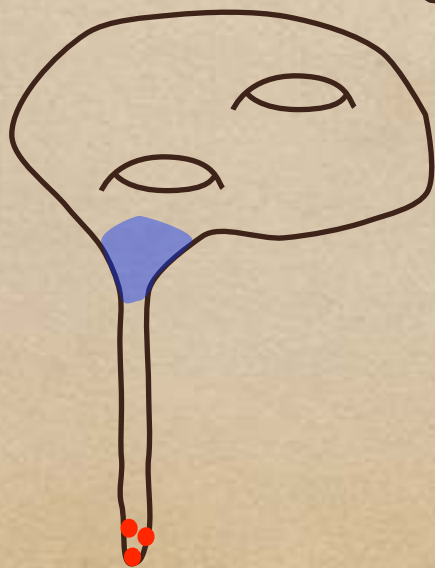


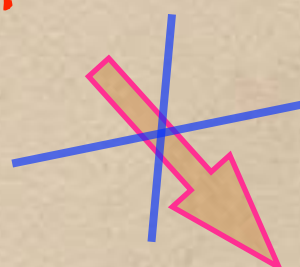
$$V = \frac{aAe^{-a\sigma}}{2\sigma^2} \left(\frac{1}{3}\sigma aAe^{-a\sigma} + W_0 + Ae^{-a\sigma} \right) + \frac{D}{\sigma^3}$$

3×10^{-9}
 ~ 1

SCAPE - ZILLA

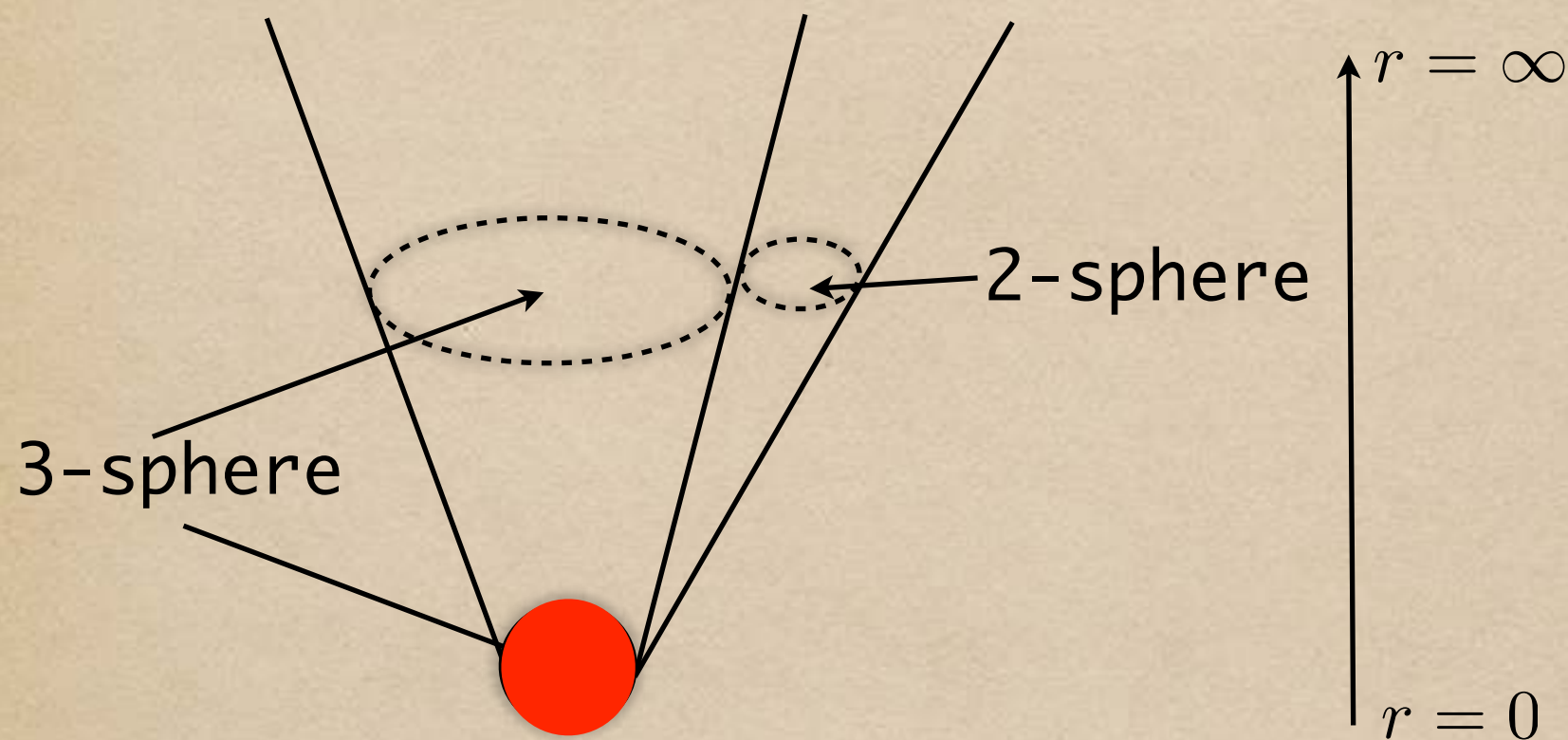
- ◆ 4D $N=1$ gauge theories have \log running \Rightarrow anti-D3 in **any** long throat change NNM
- ◆ No vacuum uplift by **small-energy** !
anti-D3 give $O(1)$ contribution !
- ◆ Similar for **D7 + anti-D3**, other uplifting scenarios
- ◆ String Theory has Land**scape** of AdS vacua




Land**scape** of dS vacua



Can we find **SCAPEZILLA** ?



First step - smear **anti-D3's**

$$SU(2) \times SU(2) \times \mathbb{Z}_2$$

Solution(τ)

Perturbation theory in anti-D3 number

- ◆ 8 modes: second-order nonlinear eqs.
- ◆ Solved them all !!!

Having smart grad students does not hurt

dim Δ	non-norm/norm	int. constant
8	r^4/r^{-8}	Y_4/X_1
7	r^3/r^{-7}	Y_5/X_6
6	r^2/r^{-6}	X_3/Y_3
5	r/r^{-5}	— — —
4	r^0/r^{-4}	$Y_7, Y_8, Y_1/X_5, X_4, X_8$
3	r^{-1}/r^{-3}	$X_2, X_7/Y_6, Y_2$
2	r^{-2}/r^{-2}	— — —

Solution **MUST** have infrared singularity

Other anti-branes - similar singularities

- ◆ **M-theory** version of **KS** - **M2 charge** in flux

Cvetič, Gibbons, Lu, Pope (CGLP)

- ◆ probe anti-M2 \rightarrow metastable

Klebanov, Pufu

- ◆ Backreaction \rightarrow **singularity**!

Bena, Giecold, Grana, Halmagyi, Kuperstein, Massai

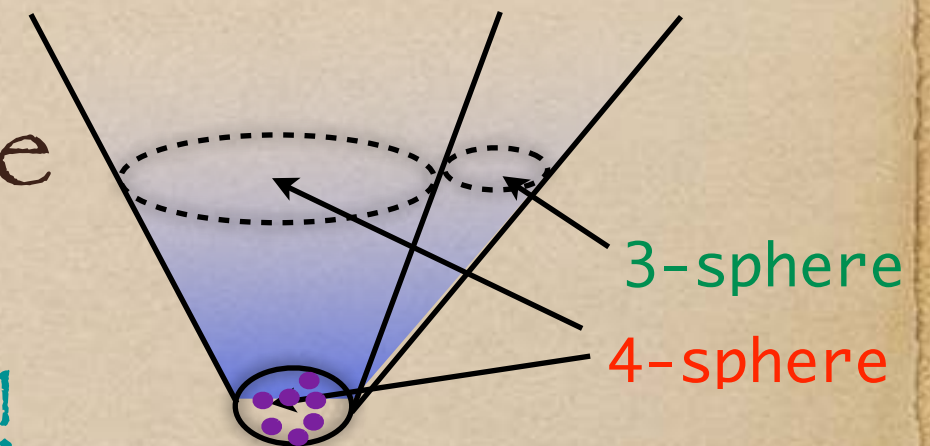
- ◆ **anti-D6** + D6 charge in fluxes

Blåbäck, Danielsson, Junghans, Van Riet, Zagermann

- ◆ **anti-D2** in **CGLP**, **anti-D2** in **A8** Giecold, Orsi, Puhm

- ◆ Localized anti-D3 also singular

Gautason, Junghans, Zagermann



What can we do about singularity

If not physical \rightarrow no (KKLT) uplifting mechanism \rightarrow no dS landscape . . . **so it must be physical**

Proof by wishful thinking

One should a-priori turn off **non-normalizable modes** in UV, and accept **whatever** exists in the IR

Incorrect AdS-CFT

Anti-D3 singularity @ first-order backreaction

Dymarsky

Maybe it goes away at **full backreaction**

It doesn't!

Bena, Grana, Kuperstein, Massai

Singularity

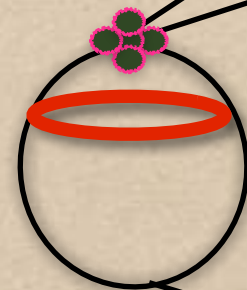
Maybe

IF YOU ACCEPT IT, GRAVITY PEOPLE
WILL KILL YOU & DRINK YOUR BLOOD !!!

incorrect criterion

Singularity may indicate new physics ?

- ◆ Ignored degrees of freedom
 - ◆ Polarization
 - ◆ Tachyons / Other instabilities
-
- ◆ Probe anti-D3's polarize into NS5 branes / $S^2 \subset S^3$
 - ◆ Many anti-D3 near North Pole: solution $\sim \text{AdS}_5 \times S^5$
 - ◆ Singularity could be resolved by brane polarization (à la Polchinski-Strassler)



Polchinski-Strassler in one slide

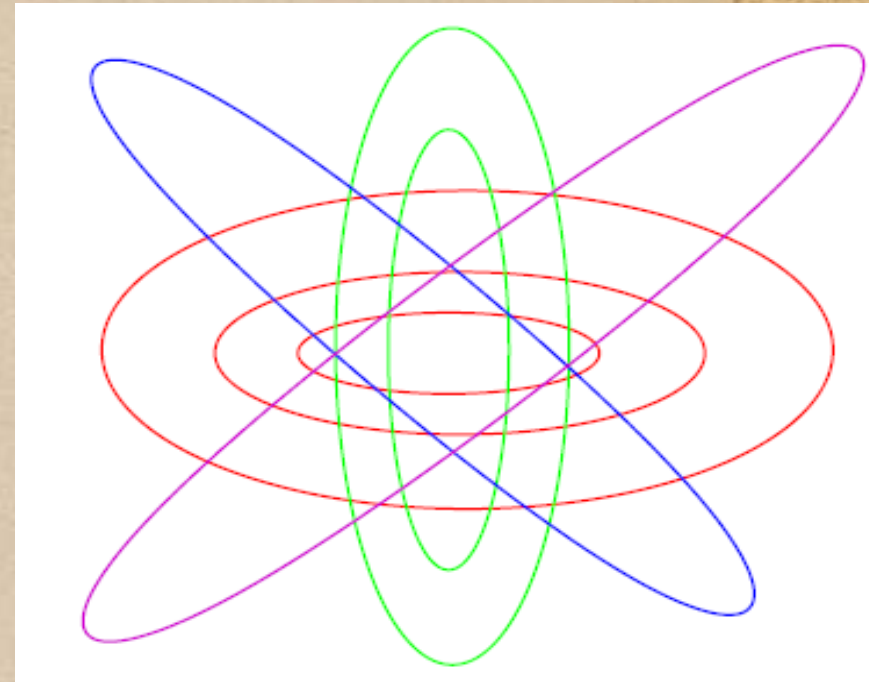
- ◆ $\text{AdS}_5 \times S^5$ perturbed with **3-forms** \Leftrightarrow
 $\text{N}=4 \text{ SYM} + \text{fermion masses}$ ($\text{N}=1^*$)
- ◆ Force D3 branes to polarize: **$D5/S^2 \subset R^3$**
 $NS5/S^2 \subset R^3 \perp$, $(p,q)5/\text{oblique } S^2$

$$V_{D3 \rightarrow D5} = a_4 \frac{\tau^4}{N_3} - a_3 \tau^3 + N_3 a_2 \tau^2$$

M2 in $\text{AdS}_4 \times S^7$ **similar story**

\rightarrow **$M5/S^3 \subset R^4$** or $M5/S^3 \subset R^4 \perp$

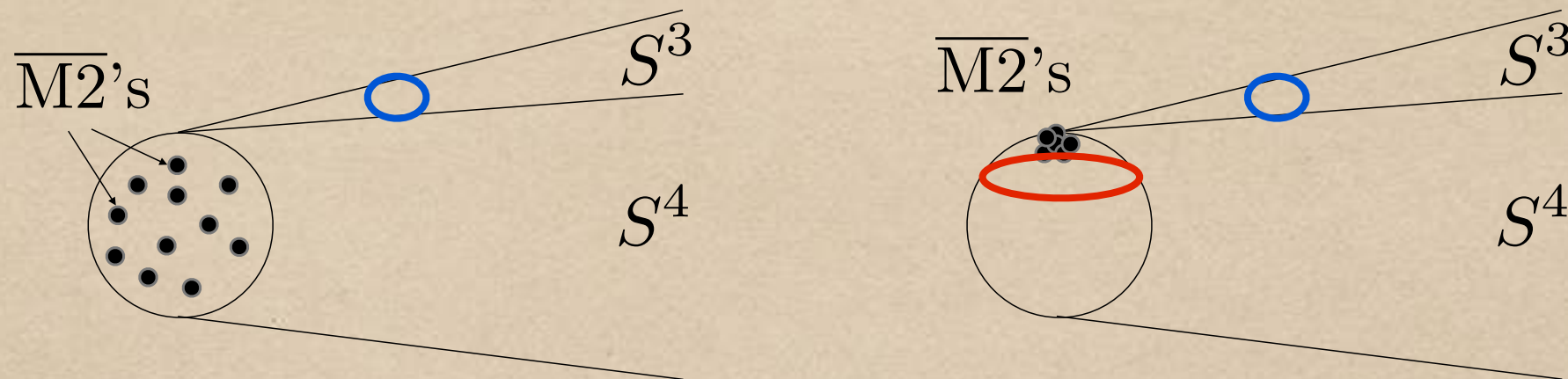
$$V_{M2 \rightarrow M5} = a_6 \frac{r^6}{N_2} - a_4 r^4 + N_2 a_2 r^2$$



**brane-brane
potential**

Bena (2000)

antiM2-M5 polarization in CGLP



Calculate smeared transverse-channel potential ($M5/S^3 \subset \text{Stenzel}$):

$$V^T(\rho) = a_6 \rho^6 - a_4 \rho^4 + a_2 \rho^2 = \left(\sqrt{a_6} \rho^3 - \frac{a_4}{2\sqrt{a_6}} \rho \right)^2 - \left(\frac{a_4^2}{4a_6} - a_2 \right) \rho^2$$

Same as localized transverse-channel potential !!!

SUSY + L=2 part \rightarrow find K-Pufu channel ($M5/S^3 \subset S^4 \subset \text{Stenzel}$)

$$V^{KP}(\theta) = \left(\sqrt{a_6} \theta^3 - \frac{a_4}{2\sqrt{a_6}} \theta \right)^2 + \left(\frac{a_4^2}{4a_6} - a_2 \right) \theta^2 \equiv a_6 \theta^6 - a_4 \theta^4 + \tilde{a}_2 \theta^2$$

$$\tilde{a}_2 = -\frac{3}{4} e^{-6\alpha_0(0)} \cdot \left(b_1 + \frac{4}{3} b_2 \right)^2$$

Bena, Grana, Kuperstein, Massai

anti-M2 branes are tachyonic !!!

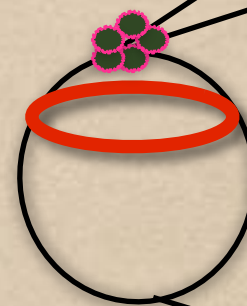
What about anti-D3's

- ◆ Transverse channel: $D5/S^2 \subset T^{1,1}$
- ◆ Potential has 3 contributions
Polchinski, Strassler ; Zamora
 - ◆ susy fermion mass: m
 - ◆ gaugino mass: m'
 - ◆ $L=2$ modes: μ_1 and μ_2

$$V_{\overline{D3} \rightarrow NS5} = a_4 \frac{\theta^4}{N_{\overline{D3}}} - a_3 \theta^3 + N_{\overline{D3}} a_2 \theta^2$$

- ◆ Disentangle (0,3) and (2,1) forms
- ◆ a_2 is exactly zero !!!
- ◆ Other directions negative !!!

Bena, Grana, Kuperstein, Massai, 1410.7776



anti-D3 also
tachyonic !!!

A Last Hope

- ◆ “Good, Bad, Ugly” criterion: Gubser
Good singularities can be cloaked by a horizon
- ◆ If physical $\Rightarrow \exists$ BH in KS/KT with negative D3 charge

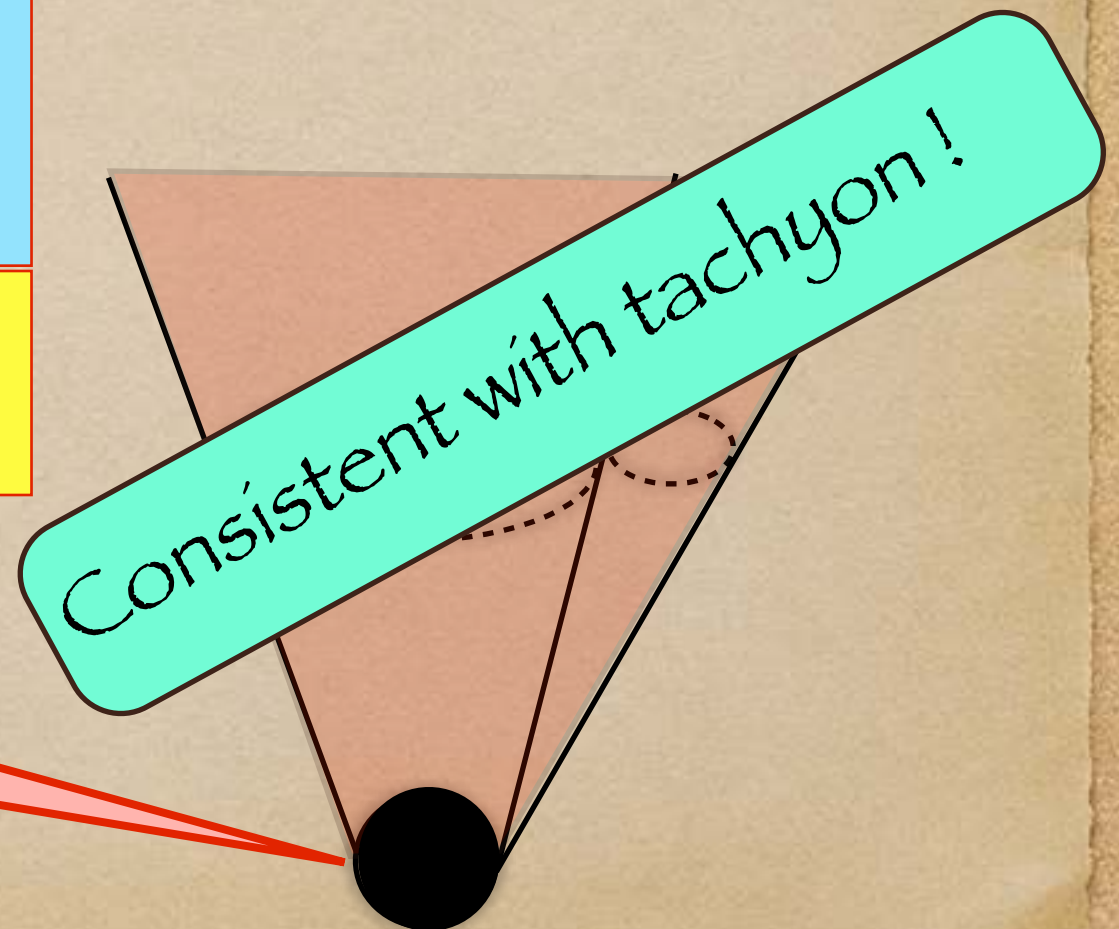
This black hole cannot have
negative D3 brane charge:

Bena, Buchel, Días

Neither can a localized KS black hole
Blåbäck, Danielsson, Junghans, Van Riet, Vargas

Smeared black hole in
Klebanov-Strassler/Tseytlin

Aharony, Buchel, Kerner; Buchel



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**
- ◆ Underlying problem - **brane-brane-repelling tachyon**

Romanian Proverb: if 3 people tell you that you are drunk, go and take a nap !

Physics Version: if 3 calculations tell you that something does not work, maybe it is time to give it up

Caveats

- ◆ Antibranes in Klebanov-Strassler/CGLP
- ◆ Prototypical **long warped throat** - uplifting AdS
- ◆ Other antibranes in other regions **may be OK**
- **irrelevant for uplifting** and deSitter
- ◆ All our calculations so far done for $g_s N \gg 1$
- ◆ KPV probe calculation @ $g_s N \ll 1$ - why not OK?

Hartnett

Junghans, Schmidt, Zag German

Not so fast...

- ◆ Anti-D3 branes in KS polarized into NS5 branes
- ◆ tension of NS5 brane $\sim g_s^{-2}$
- ◆ $R_{\text{polarization}} \sim g_s N \ell_{\text{String}} \rightarrow$ stringy curvature for $g_s N \ll 1$
- ◆ **Correct regime** for metastable anti-D3 in KS is $g_s N \gg 1$!!!

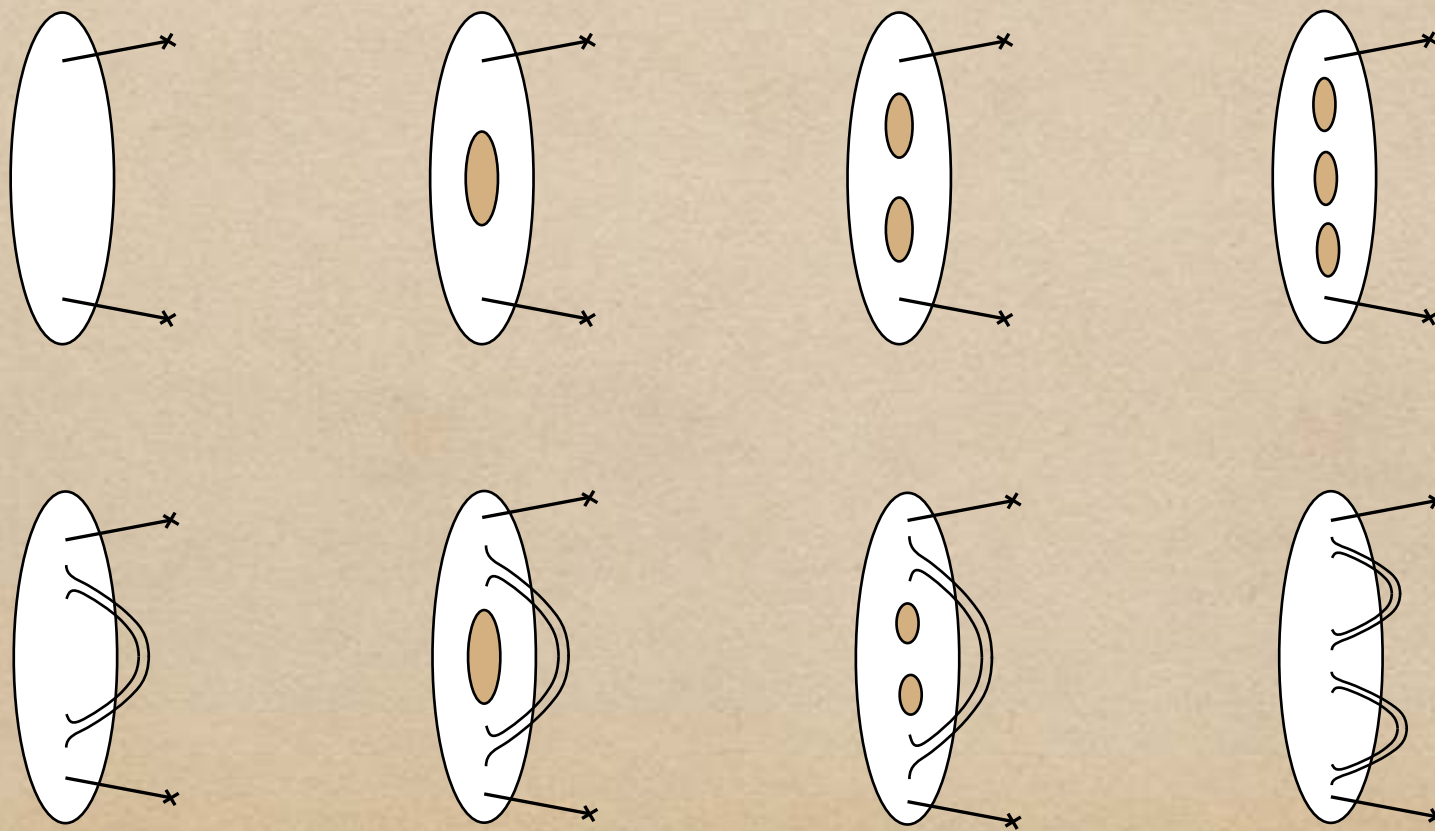
KPV

Bena, Grana, Kuperstein, Massai

Antibranes @ $g_s N \ll 1$

Michel, Mintum, Polchinski, Puhm, Saad; Bena, Blåbäck, Turton (to appear)

- ◆ One or a few antibranes (still OK for dS uplifting)
- ◆ Brane effective action
- ◆ Corrections to brane-brane potential



$$m^2 \phi^2$$

A few anti-D3 branes at the bottom of KS

$$\mathcal{L} = \text{Tr} \left[K_{mn} \phi^m \phi^n + g_{YM}^2 e^{4A_0} \left((\bar{S})_{ij} \psi^i \psi^j + h.c. \right) \right.$$

Tree level:

$$+ g_{YM}^3 e^{4A_0} (G_{lmn} \phi^l \phi^m \phi^n + h.c.)$$

$$+ g_{YM} \epsilon_{ijk} \psi^i [\phi^j, \psi^k] + g_{YM}^2 [\phi^m, \phi^n] [\phi^m, \phi^n] \left. \right]$$

$$S_{\bar{i}\bar{j}} = \frac{1}{2} (\epsilon_{\bar{i}}^{kl} G_{kl\bar{j}} + \epsilon_{\bar{j}}^{kl} G_{kl\bar{i}})$$

$$V_{\text{tree level}}^{\text{quadratic}} = m_F \delta_{ij} \psi^i \psi^j$$

Flat potential along the S^3

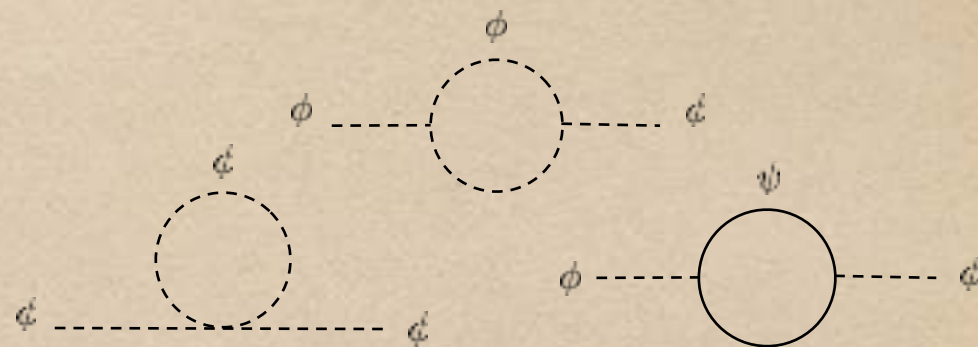
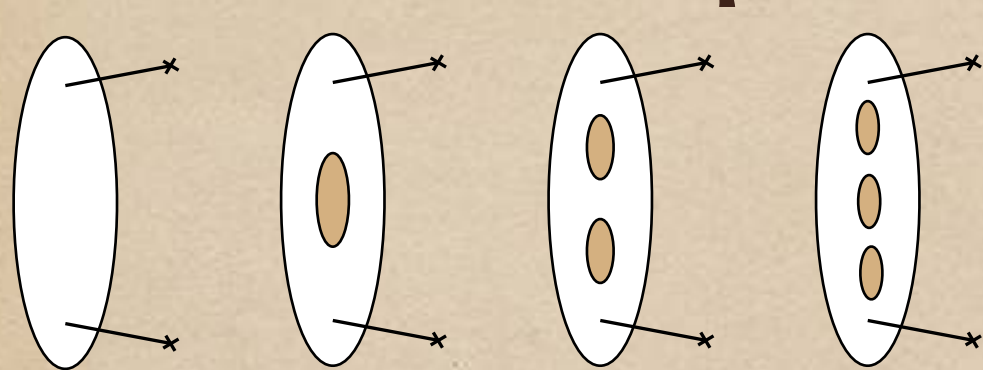
$$+ m_F^2 (X_1^2 + X_2^2 + X_3^2 + Y_1^2 + Y_2^2 + Y_3^2)$$

$$+ m_F^2 (X_1^2 + X_2^2 + X_3^2 - Y_1^2 - Y_2^2 - Y_3^2)$$

$$N=4 \Rightarrow N=1^* \Rightarrow N=0^*$$

Bena, Blåbäck, Turton (to appear)

Loop corrections



Truncation to massless open string states - gauge theory loops

This $N=0^*$ theory = **finite to all orders** in perturbation theory!

Parkes, West; Jack, Jones

Brane-brane potential along S^3 is **flat**!

Bena, Blåbäck, Turton (to appear)

Also flat at $g_s N \gg 1$

Bena, Graña, Kuperstein, Massai

Unlikely to be nonzero at intermediate $g_s N$

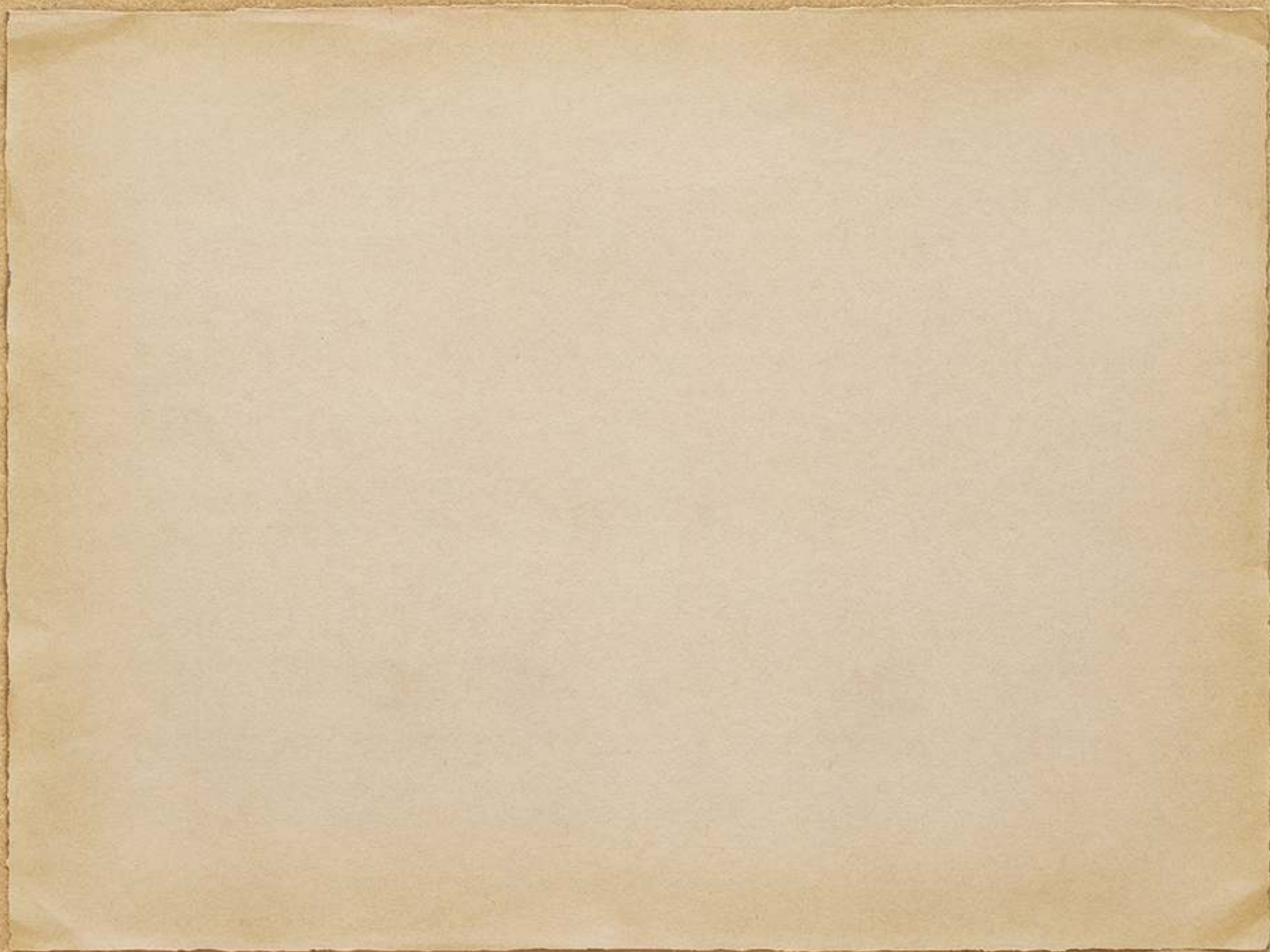
If always flat, **brane-brane repelling tachyon** always there

Conclusions

- ◆ Probe antibranes uplift AdS to dS
- ◆ Probe antibranes give structure at non-extremal horizons
- ◆ Backreacted antibranes have singularity - no horizon cloaking.
- ◆ Brane-brane-repelling tachyon in two regimes
- ◆ No calculation for single anti-D3 yet (in the making, log dynamics)

Looks like ...

- A lot of string cosmology and phenomenology to be revisited
- **SCAPEZILLA:** AdS landscape \neq dS landscape
- Find other ways to uplift AdS to dS (nothing?)
- near-extremal fuzzballs are in fact unstable
 - implications for building firewalls in string theory



Other uplift mechanisms

- ◆ Anything that contains **incarnations** of anti-D3 branes = essentially **doomed**
- ◆ D7 with **anti-D3** charge on their worldvolume
- ◆ Compactifications with **flux-antiflux** \Leftrightarrow geometric transitioned **anti-D3's**
Aganagic, Beem, Seok, Vafa; Aganagic, Beem, Kachru
- ◆ Certain Kähler uplift models \Leftrightarrow **flux-antiflux** in F-theory
Rummel, Westphal

Not too much left ...

Is tachyon really bad?

- ◆ Tachyon favors brane polarization

$$V_{\text{tip}} = r^4 - m r^3 - m_T^2 r^2$$

- ◆ Looks metastable if one considers spherically-symmetric fluctuations only
- ◆ In fact unstable once you consider modes breaking spherical symmetry
- ◆ You can get dS vacua but they are all unstable