String theory compactifications with sources

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Introduction

For de Sitter solutions in string theory, we need to break supersymmetry, and to consider...

- higher-derivative operators e.g. $(\text{Riemann})^k$
- orientifold-planes (O-planes) [Gibbons '84; de Wit, Smit, Hari Dass '87, Maldacena, Nuñez '00] [Bianchi, Pradisi, Sagnotti '91...]

- Most activity: 4d effective actions [Kachru, Kallosh, Linde, Trivedi '03, Silverstein '07... huge list]

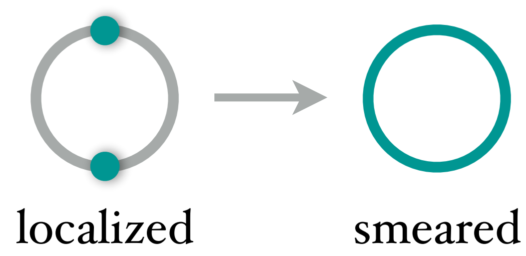
  furious debate! [Bena, Graña, Halmagyi '09, Banks '12, Sethi '17...]

- Finding solutions directly in 10d? still a challenge:

  - O-planes back-react on geometry and create singularities

  - when higher-derivatives get involved, they do so all at once

- it has been hard to find examples; often people have resorted to ‘smearing’



[Acharya, Benini, Valandro ’05,
Graña, Minasian, Petrini, AT ’06,
Caviezel, Koerber, Körs, Lüst, Wrase, Zagermann ’08,
Andriot, Goi, Minasian, Petrini ’10...]

However, O-planes should sit at fixed loci of involutions

⇨ they shouldn’t be smeared by definition.

- several people tried to understand criteria for un-smearing

[Dong, Horn, Silverstein, Torroba ’10;
Blåbäck, Danielsson, Junghans, Van Riet ’14...]

- But: solutions with unsmeared O-plane singularities
  have appeared in the last few years
  for supersymmetric AdS

Maybe time to try again for dS?

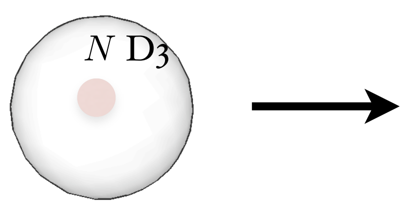
Plan

- Review: Localized sources in AdS
  - some explicit solutions
  - how to find them
  - why one should believe them
- Ideas for supersymmetry breaking
- some simple de Sitter models

AdS with sources

- Sometimes solutions with sources come from near-horizon limits

D3 dissolve; no source after near-horizon

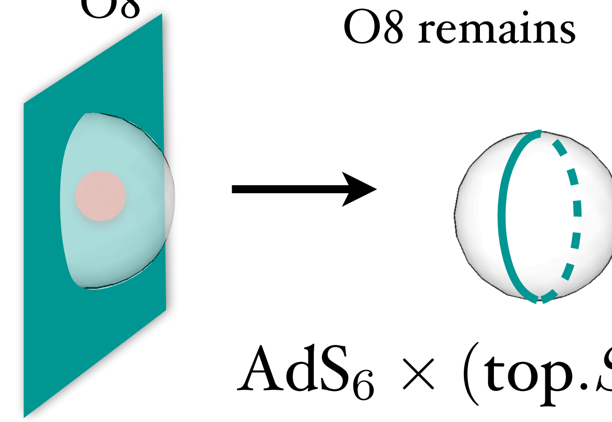


$\mathrm{AdS}_5 \times S^5$

O8

D4 dissolved, but O8 remains

N D4



$\mathrm{AdS}_6 \times (\mathrm{top}.S^4)$

[Youm '99, Brandhuber, Oz '99]

- Unclear if all AdS are near-horizon limits

- Intersecting brane solutions are rare anyway

- Better strategy: work out boundary conditions corresponding to various sources

- Sources create singularities where supergravity breaks down

backreaction on flat space:

$$ds_{10}^2 = H^{-1/2} \underbrace{ds_{\parallel}^2}_{0,\dots,p} + H^{1/2} \underbrace{ds_{\perp}^2}_{p+1,\dots,9}$$

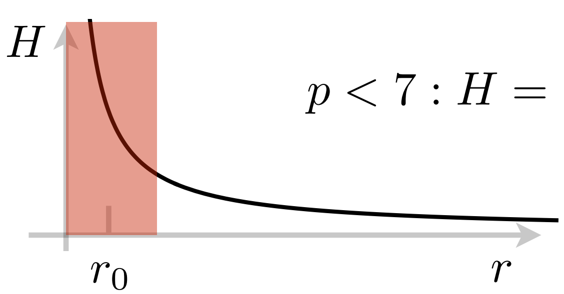
H: harmonic function in $\mathbb{R}_{\perp}^{9-p}$

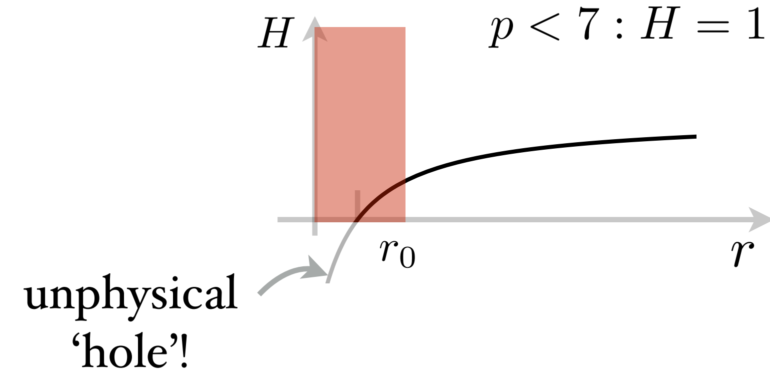
$$e^{\phi} = g_s H^{(3-p)/4}$$

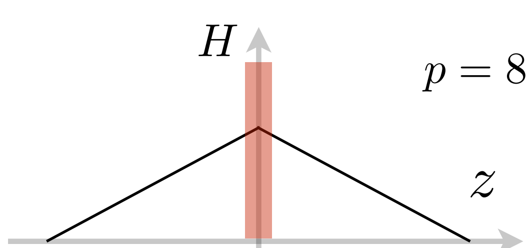
$$ds_{\perp}^2 = dr^2 + r^2 ds_{S^{8-p}}^2$$

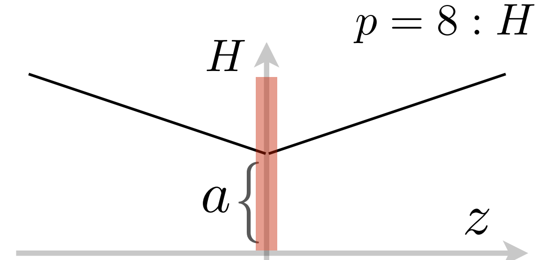
- supergravity artifacts: they should be resolved in appropriate duality frame

D-branes	O-planes [Op_-: tension=charge=-2^{p-5}]
$p<7: H = 1 + \left(\frac{r_0}{r}\right)^{7-p}$	$p<7: H = 1 - \left(\frac{r_0}{r}\right)^{7-p}$
$p=8: H = a - \lvert z/z_0 \rvert$	$p=8: H = a + \lvert z/z_0 \rvert$

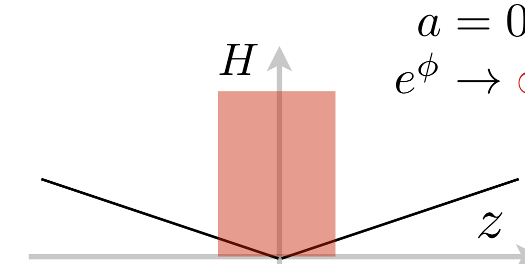








$a = 0$: $e^{\phi} \to \infty$



- **Example**: AdS7 in IIA. All solutions:

[Apruzzi, Fazzi, Rosa, AT '13
Apruzzi, Fazzi, Passias, Rota, AT '15;
Cremonesi, AT '15; Bah, Passias, AT '17]

$$\frac{1}{\pi\sqrt{2}}ds^2 = 8\sqrt{-\frac{\alpha}{\ddot\alpha}}ds^2_{\mathrm{AdS}_7} + \sqrt{-\frac{\ddot\alpha}{\alpha}}\left(dz^2 + \frac{\alpha^2}{\dot\alpha^2 - 2\alpha\ddot\alpha}ds^2_{S^2}\right)$$

interval

$$e^\phi = 2^{5/4}\pi^{5/2}3^4\frac{(-\alpha/\ddot\alpha)^{3/4}}{\sqrt{\dot\alpha^2 - 2\alpha\ddot\alpha}}$$

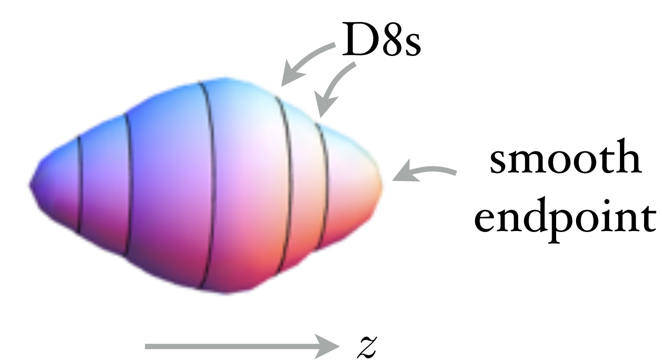
$$B = \pi\left(-z + \frac{\alpha\dot\alpha}{\dot\alpha^2 - 2\alpha\ddot\alpha}\right)\mathrm{vol}_{S^2}$$

$$F_2 = \left(\frac{\ddot\alpha}{162\pi^2} + \frac{\pi F_0\alpha\dot\alpha}{\dot\alpha^2 - 2\alpha\ddot\alpha}\right)\mathrm{vol}_{S^2}$$

$\dddot\alpha = F_0$ $\Rightarrow$ α piecewise cubic

- At endpoint, smoothness: S^2 should shrink, $\frac{\alpha}{\ddot\alpha}$ finite $\Rightarrow$ $\alpha \to 0, \ddot\alpha \to 0$

- When F_0 jumps $\Rightarrow$ D8



what happens with other boundary conditions?

$$\frac{1}{\pi\sqrt{2}}ds^2 = 8\sqrt{-\frac{\alpha}{\ddot{\alpha}}}ds^2_{\mathrm{AdS}_7} + \sqrt{-\frac{\ddot{\alpha}}{\alpha}}\left(dz^2 + \frac{\alpha^2}{\dot{\alpha}^2 - 2\alpha\ddot{\alpha}}ds^2_{S^2}\right)$$

compare locally with

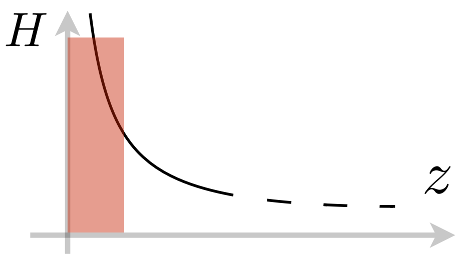
$$ds^2_{10} = H^{-1/2}ds^2_{\parallel} + H^{1/2}ds^2_{\perp}$$

[Blåbäck, Danielsson, Junghans, Van Riet, Wrase, Zagermann '11; Apruzzi, Fazzi, Rosa, AT 13...]

- $\alpha \to 0$

$$ds^2 \sim z^{1/2}ds^2_{\mathrm{AdS}_7} + \underbrace{z^{-1/2}(dz^2 + z^2 ds^2_{S^2})}_{\text{transverse } \mathbb{R}^3}$$

D6



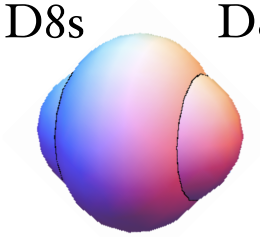
- Other interesting boundary conditions:

$\alpha(z_0)$	$\dot{\alpha}(z_0)$	$\ddot{\alpha}(z_0)$	
0	$\neq 0$	$\neq 0$	D6
$\neq 0$	$\neq 0$	0	O6
0	$\neq 0$	0	regular point
$\neq 0$	0	0	O8

Why should we believe this? Holographic checks:

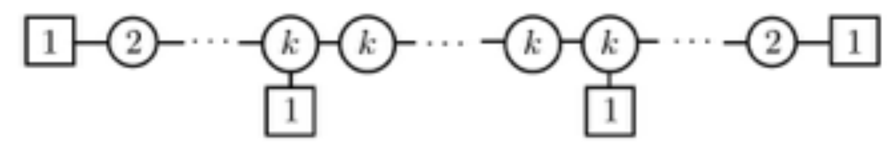
[Cremonesi, AT '15]
[Apruzzi, Fazzi '17]

Examples



integral over
internal dimensions
[Henningson, Skenderis '98]

dual quiver theory [SU gauge groups]

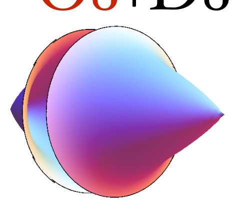


susy, grav. &
R-symmetry anomalies

[Ohmori, Shimizu, Tachikawa, Yonekura '14; Cordova, Dumitrescu, Intriligator '15]

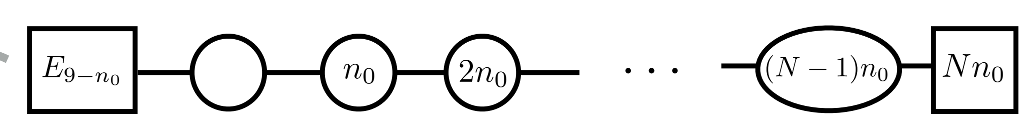
$$a = \frac{16}{7} k^2 (N^3 - 4Nk^2 + \frac{16}{5} k^3)$$

O8+D8



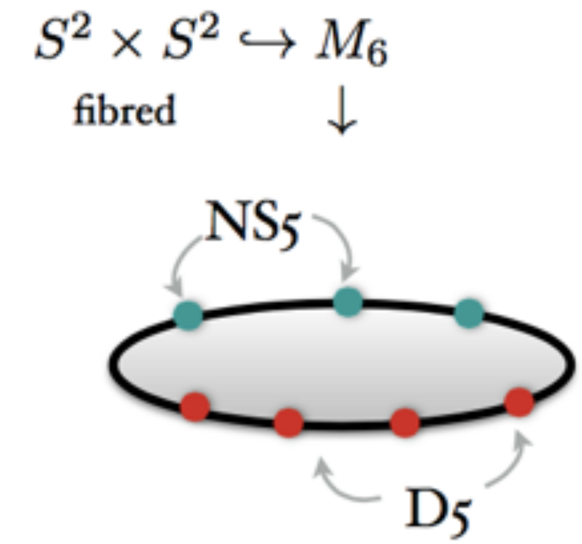
D6

$$a = \frac{16}{7}\frac{3}{10} N^5 n_0^2$$



[Bah, Passias, AT '16]
[Apruzzi, Fazzi '17]

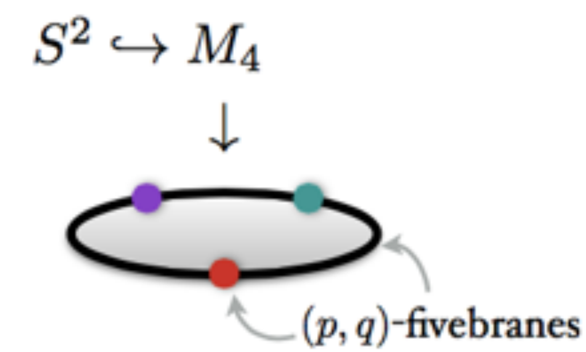
Other examples



- $\mathrm{AdS}_4 \times M_6$ in IIB with $\mathcal{N} = 4$ supersymmetry

  no O-planes so far

  [Assel, Bachas, Estes, Gomis '11]
  building on [d'Hoker, Estes, Gutperle '07]



- Similar $\mathrm{AdS}_6 \times M_4$

  [d'Hoker, Gutperle, Karch, Uhlemann '16]

  also no O-planes. Possible extension with 7-branes?

- AdS_4 in IIA

  $(\text{top.}S^3) \to H_3, S^3$

  sources:
  D8, D6, O8, O6
  O8

  $(\text{top. } S^2) \to \mathrm{KE}_4, \Sigma_g \times \Sigma_{g'}$

  [Rota, AT'15; Passias, Prins, AT '18;
  Bah, Passias, Weck '18]

- AdS_3 in F-theory

  [Couzens, Lawrie, Martelli, Schäfer-Nameki '17;
  Haghighat, Murthy, Vandoren, Vafa '15]

Supersymmetry breaking

- Possible way of breaking susy: consistent truncations

    once rare; now common, although perhaps general theory still lacking

- For ex: every AdS7 solution has a non-susy 'evil twin' [Passias, Rota, AT '15]

    established via consistent truncation: some small changes

$$\frac{1}{\pi\sqrt{\cancel{2}}}ds^2 = \overset{12}{\cancel{8}}\sqrt{-\frac{\alpha}{\ddot{\alpha}}}\,ds^2_{\mathrm{AdS}_7} + \sqrt{-\frac{\ddot{\alpha}}{\alpha}}\left(dz^2 + \frac{\alpha^2}{\dot{\alpha}^2 - \cancel{2}\alpha\ddot{\alpha}}ds^2_{S^2}\right)$$

$$e^{\phi} = 2^{\cancel{5/4}}\pi^{5/2}3^4\frac{(-\alpha/\ddot{\alpha})^{3/4}}{\sqrt{\dot{\alpha}^2 - \cancel{2}\alpha\ddot{\alpha}}}$$

- Most are unstable [Danielsson, Dibitetto, Vargas '17; Apruzzi, De Luca, Gnecchi, Lo Monaco, AT, in progress]

    part of the KK spectrum via 7d trick $\Rightarrow$ pert. instability for all solutions with D8s on top of each other

    NS5 'bubbles' $\Rightarrow$ non-pert. instability for all solutions with a massless region

- More general strategy?

[Legramandi, AT; in progress]

let's start from an easy class:

eg. $\mathrm{Mink}_6 \times M_4$

[Imamura '01; Janssen, Meessen, Ortin '99]

$$ds^2 = S^{-1/2} ds^2_{\mathrm{Mink}_6} + K(S^{-1/2} dz^2 + S^{1/2} ds^2_{\mathbb{R}^3})$$

[motivated by NS5-D6-D8]

$$d_H(e^{3A-\phi}\Phi_+) = 0$$
$$d_H(e^{2A-\phi}\mathrm{Re}\Phi_-) = 0$$
$$d_H(e^{4A-\phi}\mathrm{Im}\Phi_-) = e^{4A} \star \lambda(F)$$

$$\supset \quad \Delta_3 S + \tfrac{1}{2}\partial_z^2 S^2 = 0 \qquad K = -\tfrac{4}{F_0}\partial_z S$$

[Lüst, Patalong, Tsimpis '10;
Graña, Minasian, Petrini, AT '05]

susy breaking $\downarrow$ keep same fluxes; impose Bianchi, but not BPS

$$d_H(e^{3A-\phi}\Phi_+) = 0$$
$$d_H(e^{2A-\phi}\mathrm{Re}\Phi_-) = c\, e^{8A-2\phi}\mathrm{vol}_{M_4}$$
$$d_H(e^{4A-\phi}\mathrm{Im}\Phi_-) = e^{4A} \star \lambda(F)$$

$$\supset \quad \Delta_3 S + \tfrac{1}{2}\partial_z^2 S^2 + c\, z\partial_z^2 S = 0 \qquad K = -\tfrac{4}{F_0}\partial_z S, \quad S = e^{-4A} + cz$$

we checked that this small modification works in several other classes

similar in spirit to adding primitive part to G_3 in conf. CY

[Becker, Becker '96, Dasgupta, Rajesh, Sethi '98,
Graña, Polchinski '00, Giddings, Kachru, Polchinski '01]

dS with O8-planes

- Simplest model [Córdova, De Luca, AT '18]

$$ds^2 = e^{2W(z)} ds^2_{\mathrm{dS}_4} + e^{-2W(z)} \left(dz^2 + e^{2\lambda(z)} ds^2_{M_5}\right)$$

compact hyperbolic

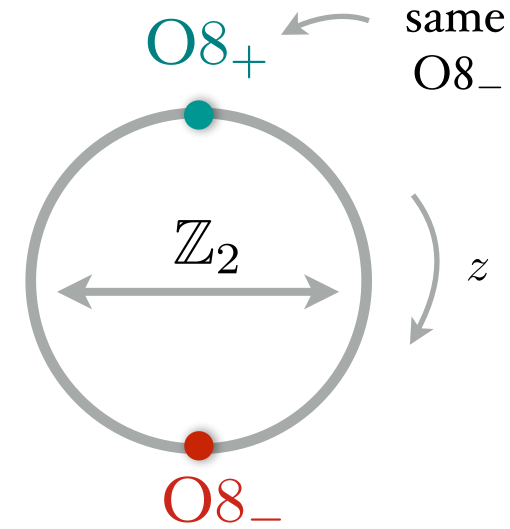
Boundary condition at O8+

$$e^{W-\phi} f_i'|_{z\to 0^+} = 1 \qquad f_i = \{W, \tfrac{1}{5}\phi, \tfrac{1}{2}\lambda\}$$

Numerical evolution: we manage to reach

$$e^{f_i} \sim |z - z_0|^{-1/4}$$

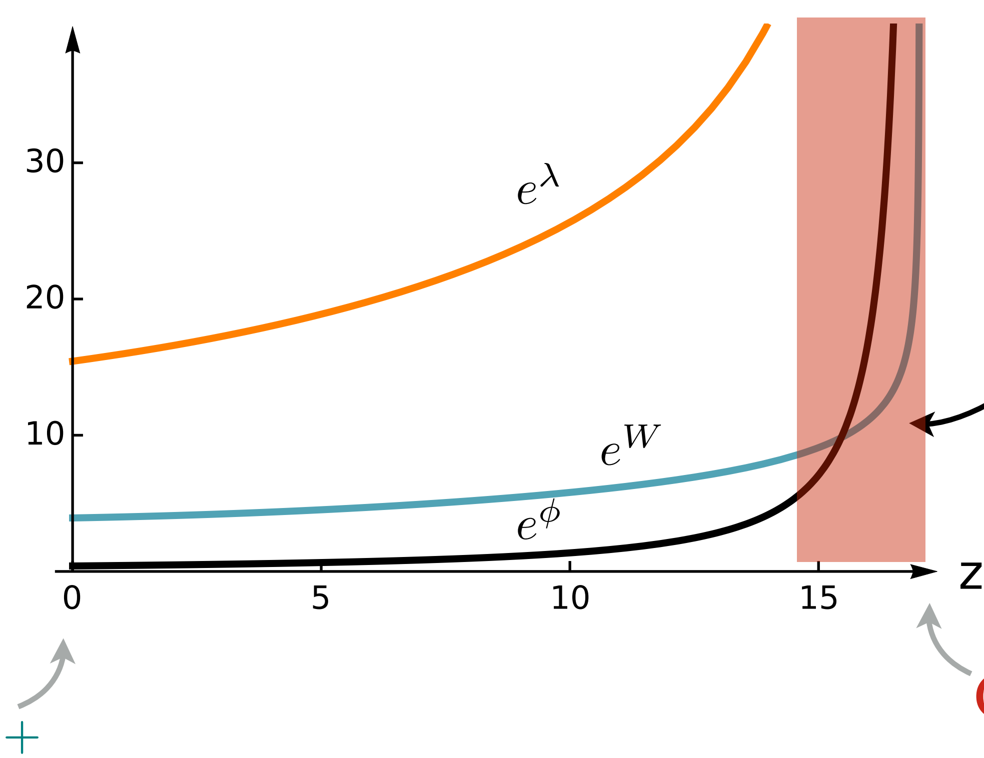
same effect as $O8_- + 16D8$



Minkowski: [Bianchi, Pradisi, Sagnotti '91, Dabholkar, Park '96, Witten '97, Aharony, Komargodski, Patir '07]

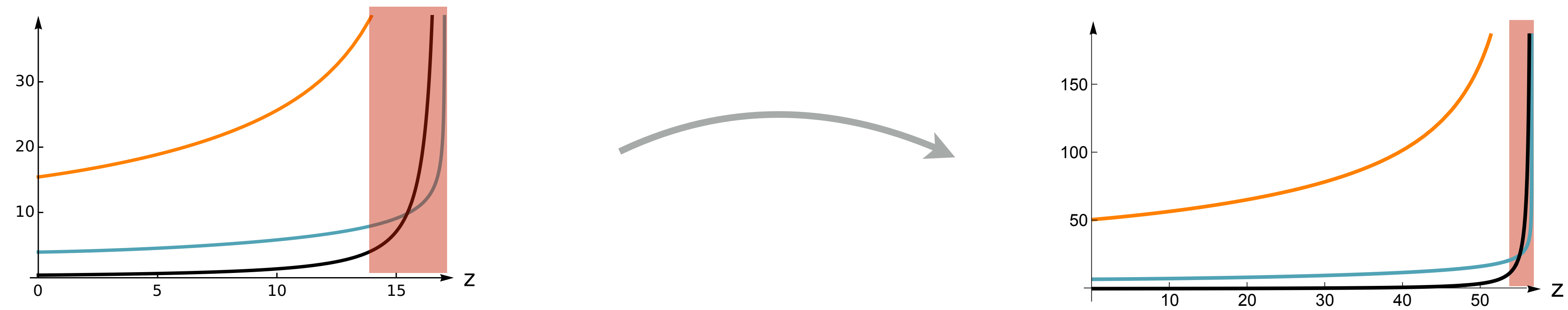
see also [Silverstein, Strings 2013 talk]

same as O8_ in flat space
[even the coefficients work]



inevitably, O8_ has strongly coupled region

- Rescaling symmetry: $g_{MN} \to e^{2c} g_{MN}, \phi \to \phi - c$



it makes strong-coupling region small, but it doesn't make it disappear.

- In the O8_ region stringy corrections become dominant

$$\ldots \gg \underset{\underset{\displaystyle R^4}{\rotatebox{90}{$\gg$}}}{e^{-2\phi} R^4} \gg e^{-2\phi} R$$

supergravity action is least important term;
ideally in this region we'd switch to another duality frame.

Full string theory should then fix c

- Hope that this solution is sensible comes from similarity with flat-space O8_
(which we know to exist in string theory)

dS with O8s and O6s

- We also tried: $\mathrm{O8}_+ - \mathrm{O6}_-$

[Córdova, De Luca, AT, to appear]

$$ds^2 = e^{2W} ds^2_{dS_4} + e^{-2W}(dz^2 + e^{2\lambda_3} ds^2_{M_3} + e^{2\lambda_2} ds^2_{S^2})$$

surrounds the O6

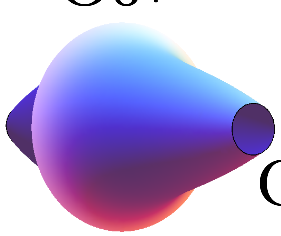
$$\begin{aligned} H &= h_1 dz \wedge \mathrm{vol}_2 + h_2 \mathrm{vol}_3 \\ F_2 &= f_2 \mathrm{vol}_2 \\ F_4 &= f_{41} \mathrm{vol}_3 \wedge dz + f_{42} \mathrm{vol}_4 \\ F_0 &\neq 0 \end{aligned}$$

- we already know one such solution for $\Lambda < 0$:

from a non-susy AdS7 solution with O8+ and O6_

$$\alpha = 3k(N^2 - z^2) + n_0(z^3 - N^3)$$

O8+



O6_

$$\frac{1}{\sqrt{\pi}} ds^2 = 12\sqrt{-\frac{\alpha}{\ddot\alpha}} ds^2_{\mathrm{AdS}_7} + \sqrt{-\frac{\ddot\alpha}{\alpha}}\left(dz^2 + \frac{\alpha^2}{\dot\alpha^2 - \alpha\ddot\alpha} ds^2_{S^2}\right)$$

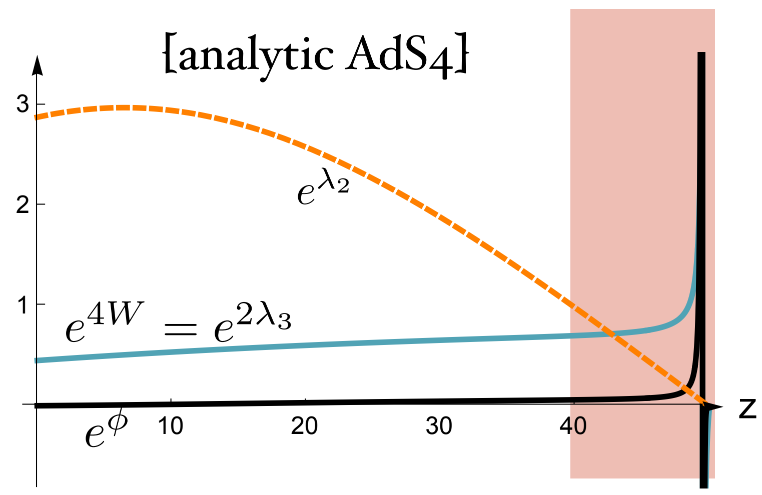
$$\downarrow$$

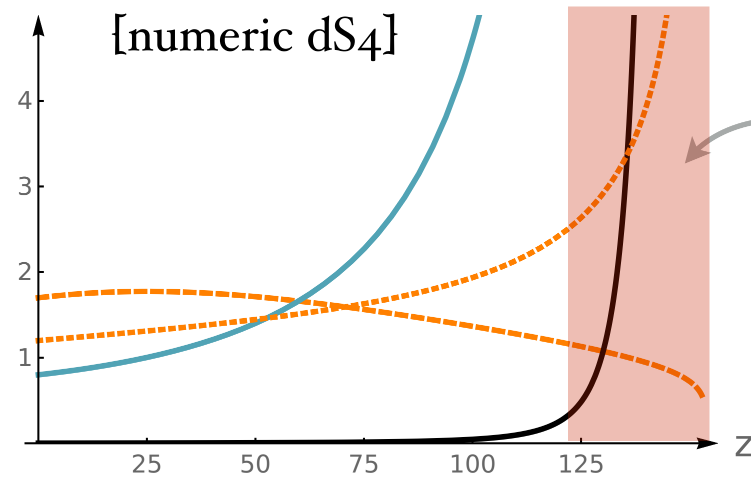
$\mathrm{AdS}_4 \times H_3$ compact hyperbolic

- we slowly modified it numerically, bringing Λ up

$$ds^2 = e^{2W} ds^2_{dS_4} + e^{-2W}(dz^2 + e^{2\lambda_3} ds^2_{M_3} + e^{2\lambda_2} ds^2_{S^2})$$

{functions rescaled for clarity}





We still obtain the O6 boundary.

Conclusions

- A lot of progress in AdS solutions
  - often localized O-plane sources are possible
  - holography works even in their presence
  - sometimes non-supersymmetric

- Time to look for de Sitter
  - Using numerics, we find dS solutions with O8-planes in relatively simple setup
  - Also O8-O6 solutions
  - There are regions where supergravity breaks down.

Inevitable! If you want solutions with O-planes.
We better learn how to deal with them.