String theory compactifications with sources

Alessandro Tomasiello

String Phenomenology 2019, CERN

Introduction

Internal D-brane or O-plane sources
important in string theory compactifications

- in AdS/CFT they realize flavor symmetries
- O-planes necessary for de Sitter and for Minkowski beyond CY

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Internal D-brane or O-plane sources
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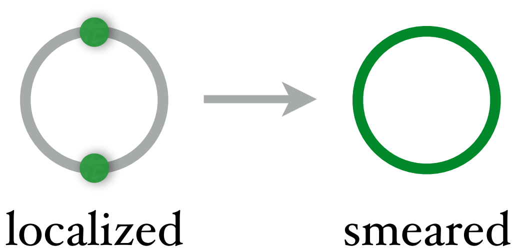
- in AdS/CFT they realize flavor symmetries
- O-planes necessary for de Sitter and for Minkowski beyond CY
- it has been hard to find examples; often people have resorted to 'smearing'



[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.

- They create singularities where supergravity breaks down

backreaction on flat space:

$$ds^2_{10} = \underbrace{H}_{\text{harmonic function in } \mathbb{R}^{9-p}_{\perp}}{}^{-1/2} \overbrace{ds^2_{\parallel}}^{0,\dots,p} + H^{1/2} \overbrace{ds^2_{\perp}}^{p+1,\dots,9}$$

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

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

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

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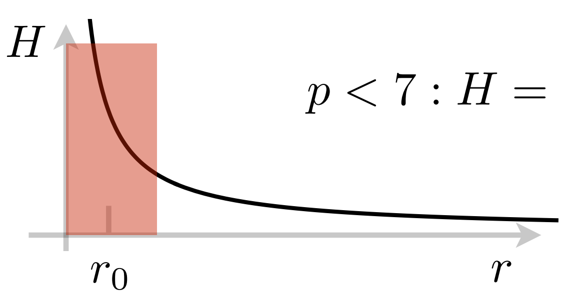
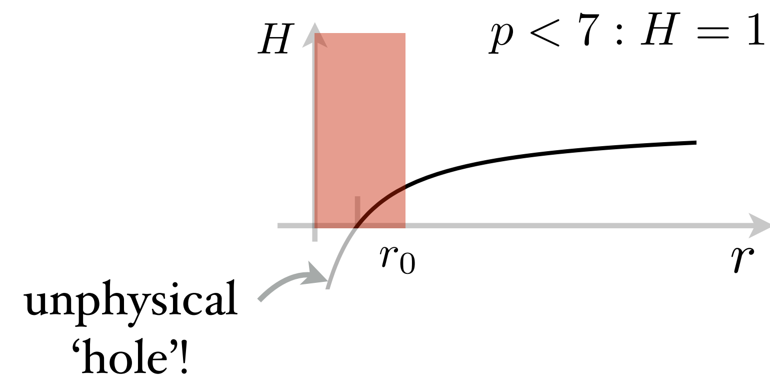
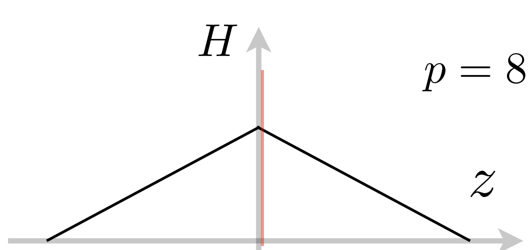
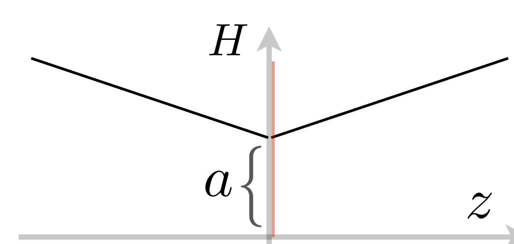
D-branes	O-planes [Op_-: tension=charge=-2^{p-5}]
 $p<7: H = 1 + \left(\frac{r_0}{r}\right)^{7-p}$	$p<7: H = 1 - \left(\frac{r_0}{r}\right)^{7-p}$ 
 $p=8: H = a - \lvert z/z_0 \rvert$	 $p=8: H = a + \lvert z/z_0 \rvert$

This talk:

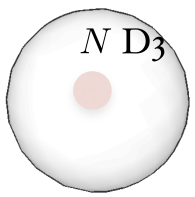
- Recent progress in finding compactifications with sources

- first steps in applying it to de Sitter

AdS solutions with sources

- Rarely: near-horizon limits from brane intersections

D3 dissolve; no source after near-horizon



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

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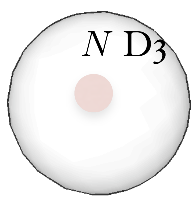
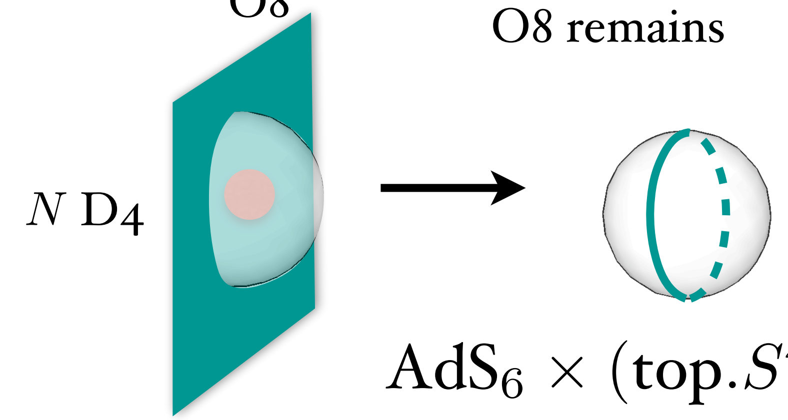


$\longrightarrow$ $\mathrm{AdS}_5 \times S^5$

O8

D4 dissolved, but O8 remains



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

[Youm '99, Brandhuber, Oz '99]

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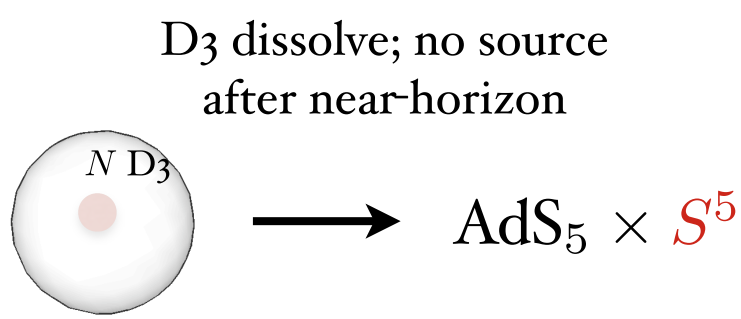
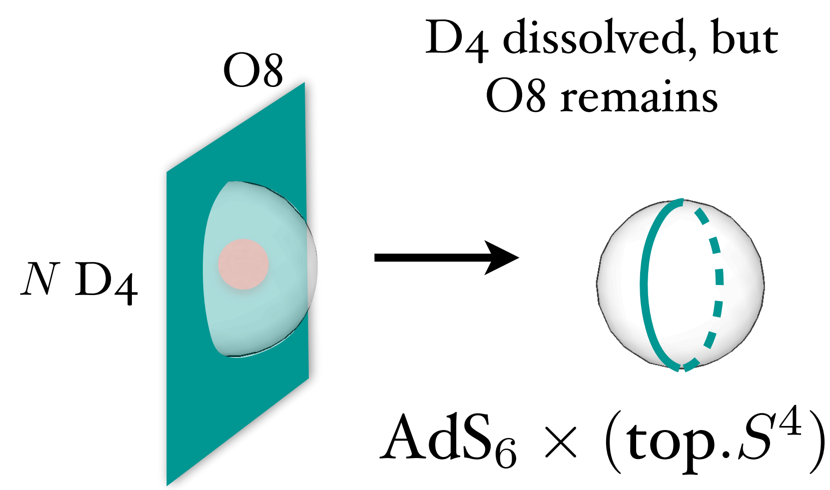
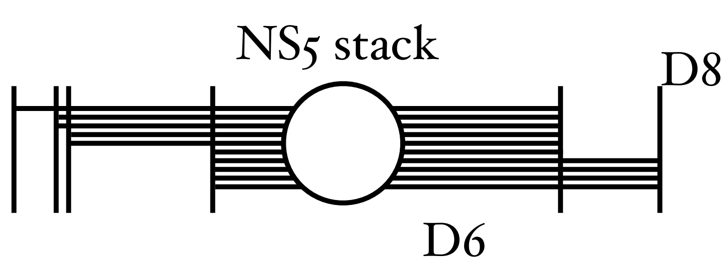




[Youm '99, Brandhuber, Oz '99]

- But brane intersections for more complicated configurations is not known...



- More successful: systematic exploration of BPS conditions
  - old methods: G-structures, pure spinors

    first wave around '04
    eg. [Gauntlett, Martelli, Sparks, Waldram '04]

    [Graña, Minasian, Petrini, AT '05]

  - more recent extensions: pure spinors in odd dimensions, extended susy

    eg. [Apruzzi, Fazzi, Rosa, AT '13]

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- AdS7 in IIA: $S^2 \to I$ 

  sources: D8, D6, O8, O6

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- AdS4 in IIA $M_3 \to H_3$

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- AdS3 in IIA: $S^6 \to I$

  $\mathcal{N} = (0,8), (0,7)$; F_4 and G_3 superalg. ; $\mathcal{N} = (4,4)$

  sources: O8

  [Dibitetto, Lo Monaco, Petri,
  Passias, AT '18; Macpherson '18]

general lessons:

- relations between different cases suggest ‘correct’ coordinates
- classification efforts succeed more often than ad hoc Ansätze
- O8 appears to be particularly ubiquitous

- AdS7 in IIA

[Apruzzi, Fazzi, Rosa, AT '13
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$$\frac{1}{\pi\sqrt{2}}ds^2 = 8\sqrt{-\frac{\alpha}{\ddot{\alpha}}}ds^2_{\mathrm{AdS}_7} + \sqrt{-\frac{\ddot{\alpha}}{\alpha}}\left(dz^2 + \frac{\alpha^2}{\dot{\alpha}^2 - 2\alpha\ddot{\alpha}}ds^2_{S^2}\right)$$

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

α, $\dot{\alpha}$, $\ddot{\alpha}$ continuous

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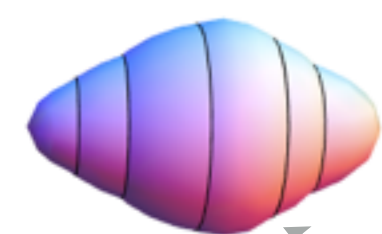
- At endpoint, smoothness: S^2 should shrink, $\frac{\alpha}{\ddot\alpha}$ finite

⇨ $\alpha \to 0, \ddot\alpha \to 0$



smooth endpoint

D8s

[Apruzzi, Fazzi, Rosa, AT '13
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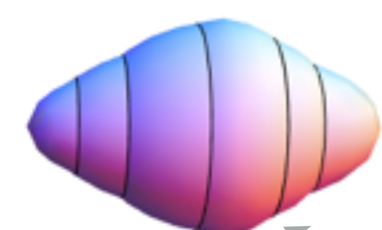

- When F_0 jumps ⇨ D8

[Apruzzi, Fazzi, Rosa, AT '13
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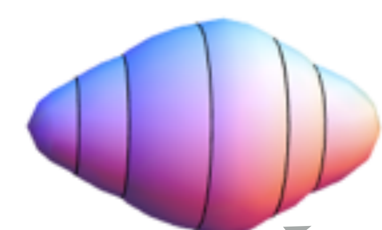

- When F_0 jumps ⇨ D8

what happens with other boundary conditions?

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compare locally with

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

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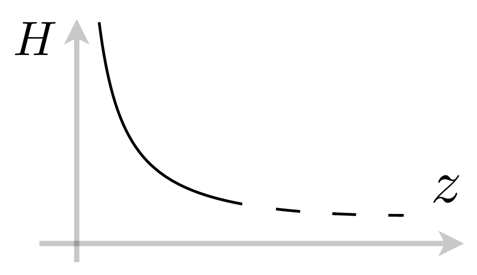
$$ds^2 \sim z^{1/2} ds^2_{\mathrm{AdS}_7} + z^{-1/2} \underbrace{(dz^2 + z^2 ds^2_{S^2})}_{\text{transverse } \mathbb{R}^3}$$

D6



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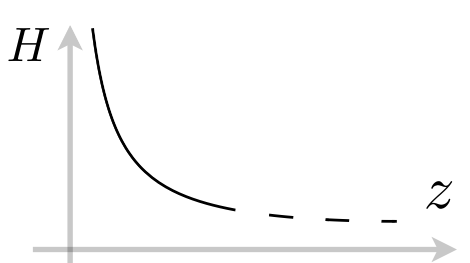

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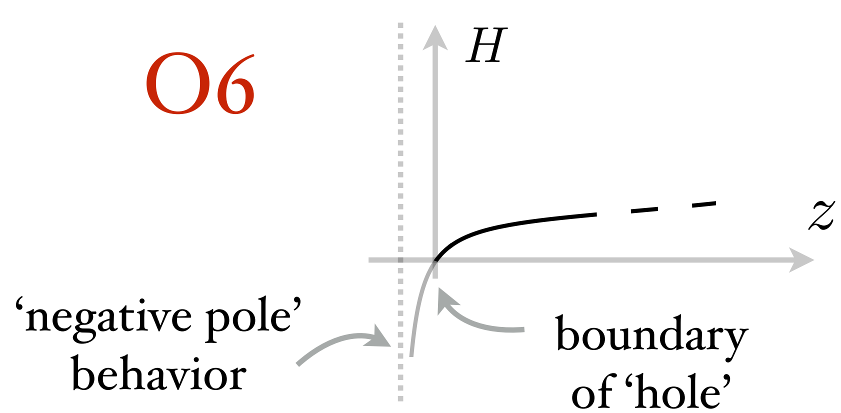

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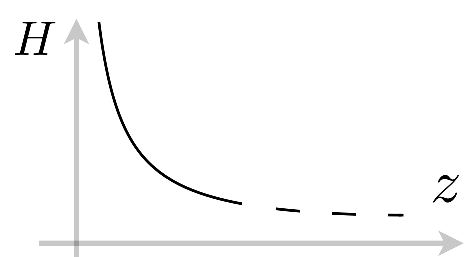

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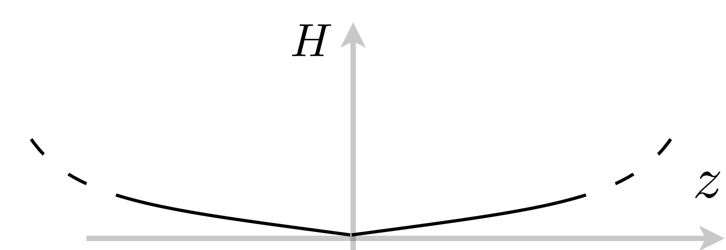
O8



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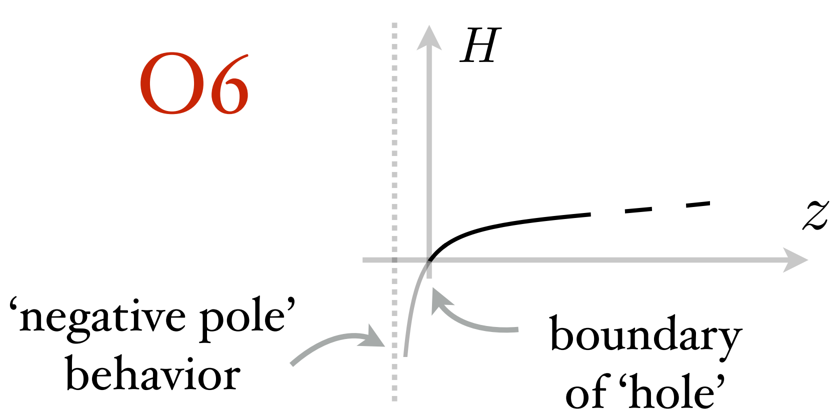

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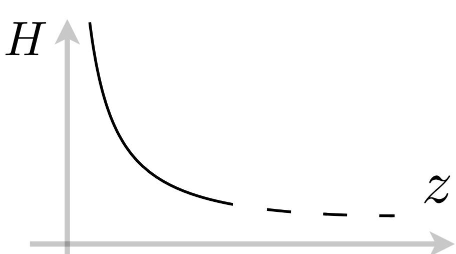

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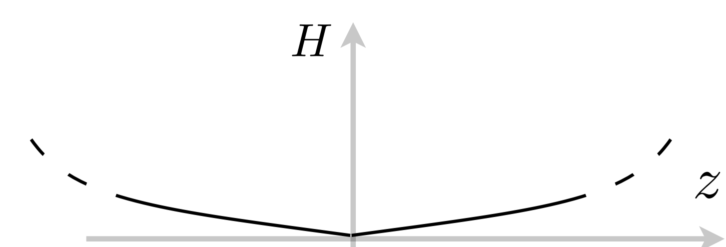

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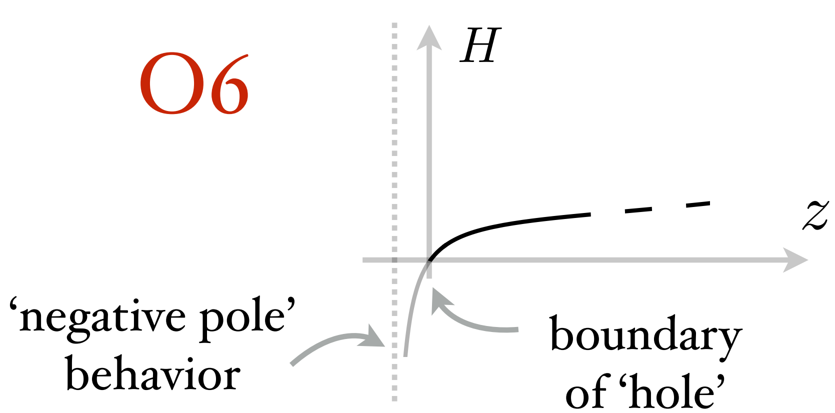

- Sugra artifacts, but same local behavior as solutions in flat space
- Holographic checks work out even in presence of these sources

[particularly impressive for O8]

Non-supersymmetric solutions

- Every AdS7 solution has a non-susy 'evil twin'


established via consistent truncation: some small changes

[Passias, Rota, AT '15]

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

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

some are pert. unstable

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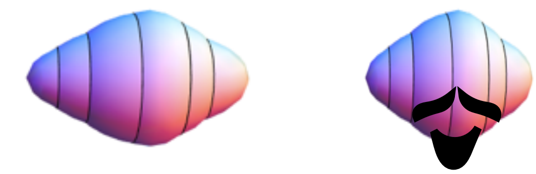
Non-supersymmetric solutions

- Every AdS7 solution has a non-susy ‘evil twin’



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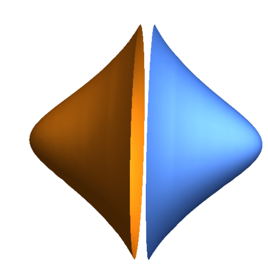
- AdS8 solution with O8_ [direct sol. of EoM] [Córdova, De Luca, AT '18]



dS

- 4d models are practical and nice

but they can leave doubts: have we kept all the relevant modes?

Indeed: current furious debate, notably at this conference. Many solutions, or none?

[KKLT '03, Balasubramanian, Berglund, Conlon, Quevedo '05,...]
versus [Obied, Ooguri, Spodyneiko, Vafa '18; Ooguri, Palti, Shiu, Vafa '18...]

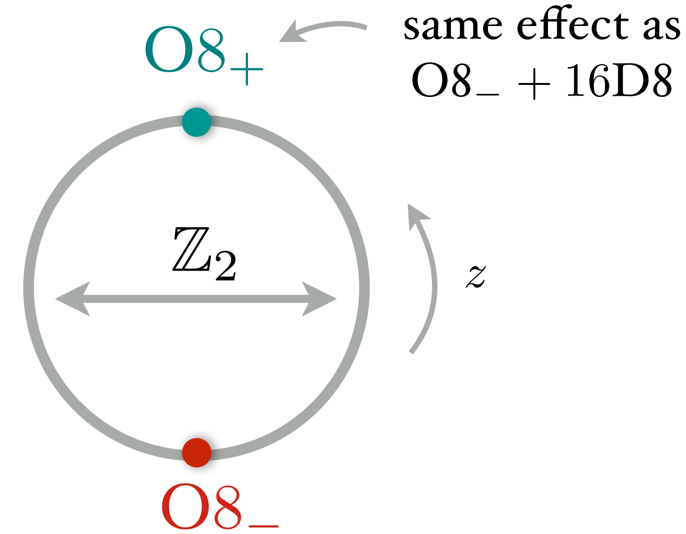
Given the progress just reviewed, let's try directly in ten dimensions.

- A simple Ansatz [Córdova, De Luca, AT '18]

$$ds^2 = e^{2W} ds^2_{dS_4} + e^{-2W}(dz^2 + e^{2\lambda} ds^2_{M_5})$$

compact hyperbolic

"cohomogeneity one": W, λ, ϕ only depend on z



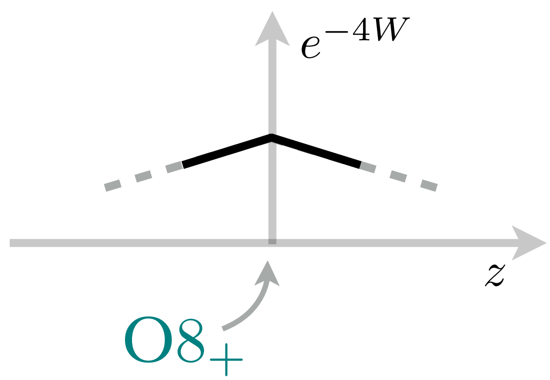
similar to relatively famous $\mathrm{Mink}_9 \times S^1$ model [Dabholkar, Park '96, Witten '97, Aharony, Komargodski, Patir '07]

also similar in spirit to 5d setup described in [Silverstein, Strings 2013 talk]

- The functions won't be diff. at the O8+

$$ds^2 = e^{2W} ds^2_{dS_4} + e^{-2W}(dz^2 + e^{2\lambda} ds^2_{M_5})$$

Jump in first derivatives can be determined: $e^{W-\phi} f_i'|_{z\to 0^+} = -1$ $\quad f_i = \{W, \frac{1}{5}\phi, \frac{1}{2}\lambda\}$



- by comparing with O8+ in flat space, or
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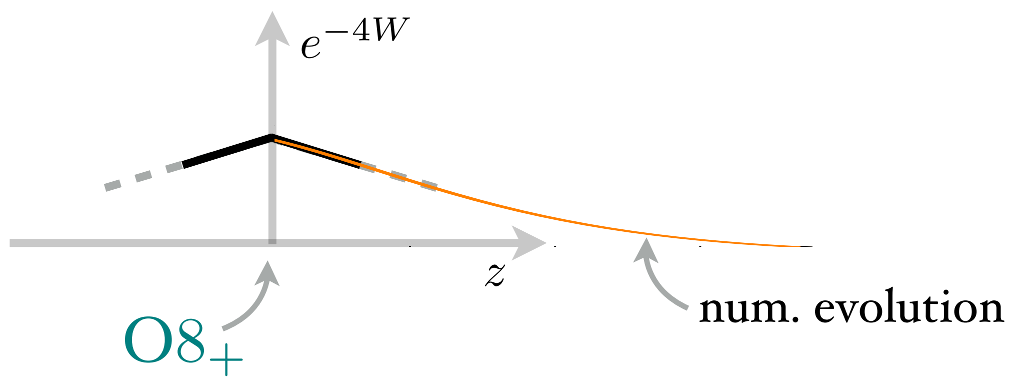

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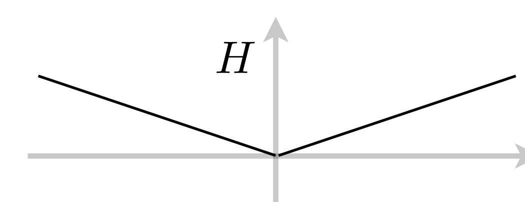
$$p = 8 : H = \cancel{a} + |z/z_0|$$

- Idea: if we make $H \sim e^{-4W}$ hit zero

⇨ same behavior of $\mathrm{O8}_-$ for $a = 0$



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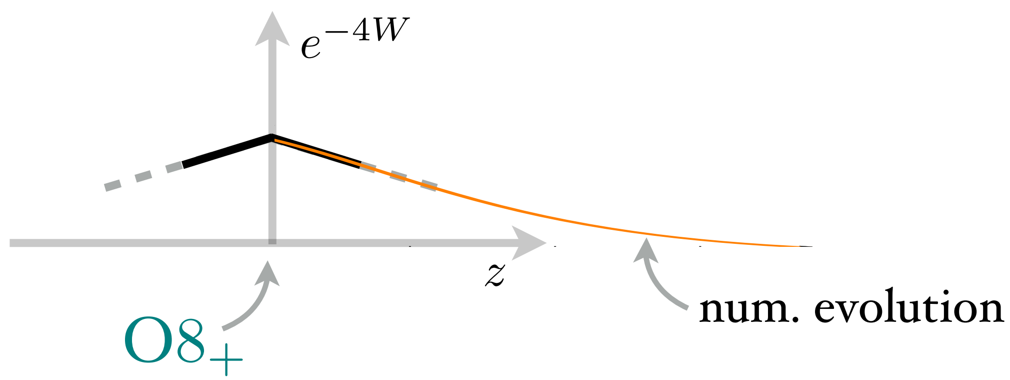

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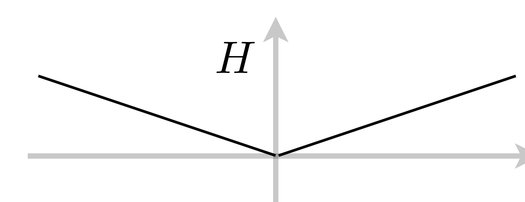
$\Rightarrow$ same behavior of O8$_-$ for $a = 0$

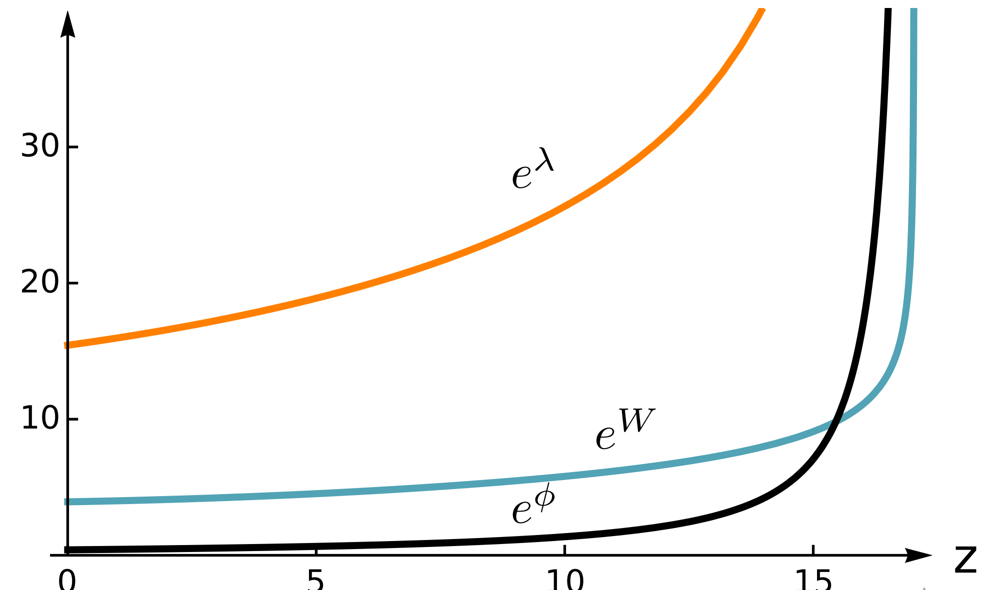


- Notice that $e^{\phi} \sim H^{(3-p)/4} = H^{-5/4}$ diverges

- Indeed we manage to reach the behavior

$$e^{W} \sim e^{\frac{1}{5}\phi} \sim e^{\frac{1}{2}\lambda_i/2} \sim |z - z_0|^{-1/4}$$

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



$O8_+$ $O8_-$

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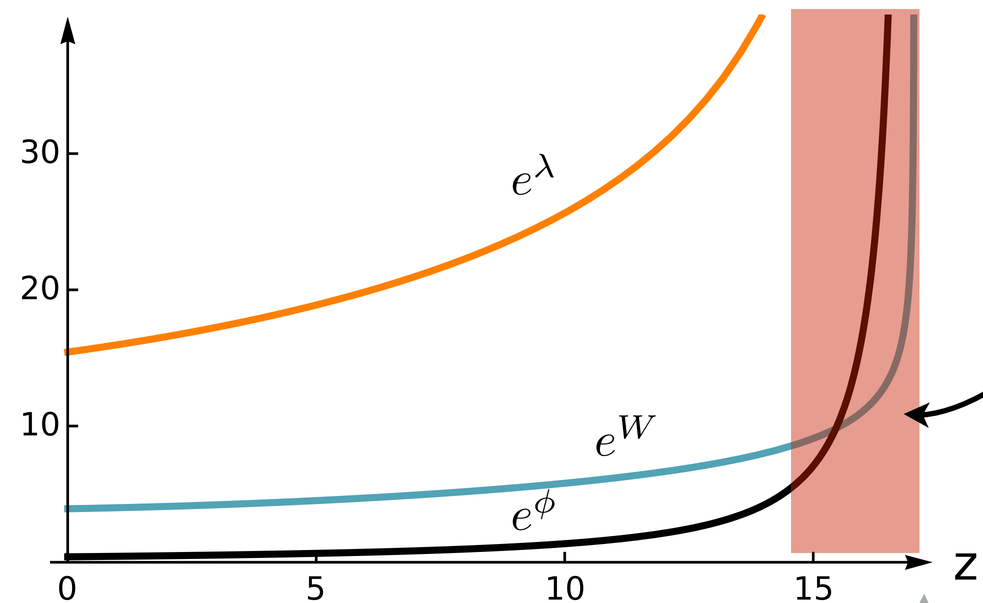
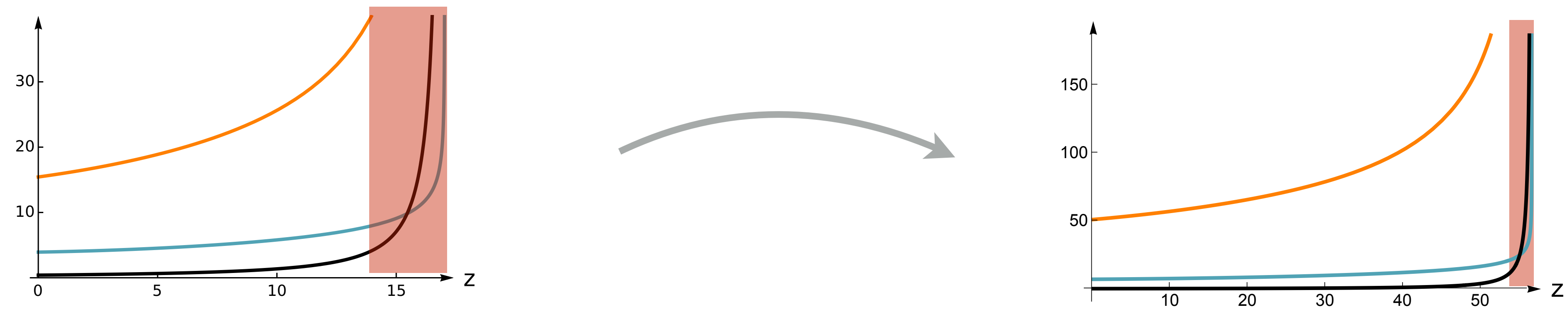


inevitably, O8_ has strongly coupled region

$O8_+$

$O8_-$

- Rescaling symmetry: $g_{MN} \to e^{2c} g_{MN}\ , \quad \phi \to \phi - c\ , \quad F_4 \to e^{4c} F_4$



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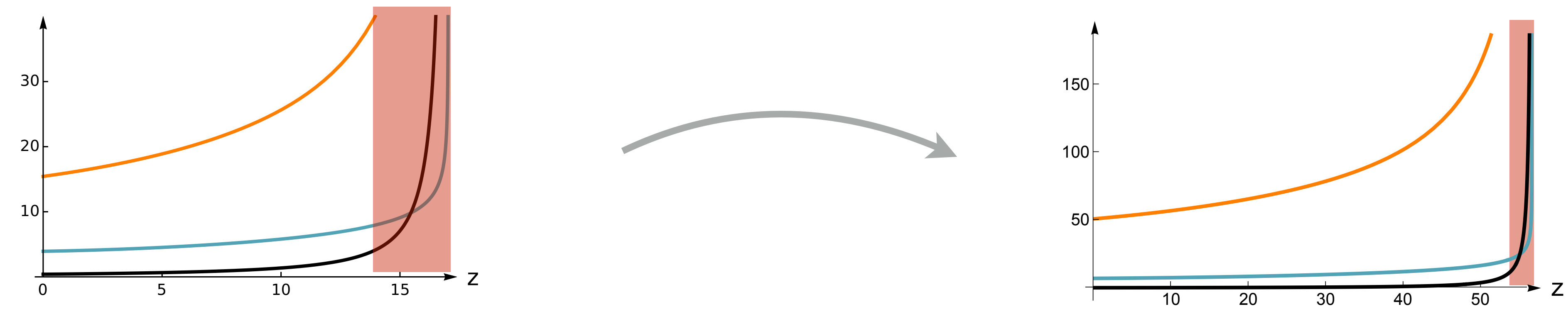

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sugra action is least important term;
ideally in this region we'd switch to another duality frame.

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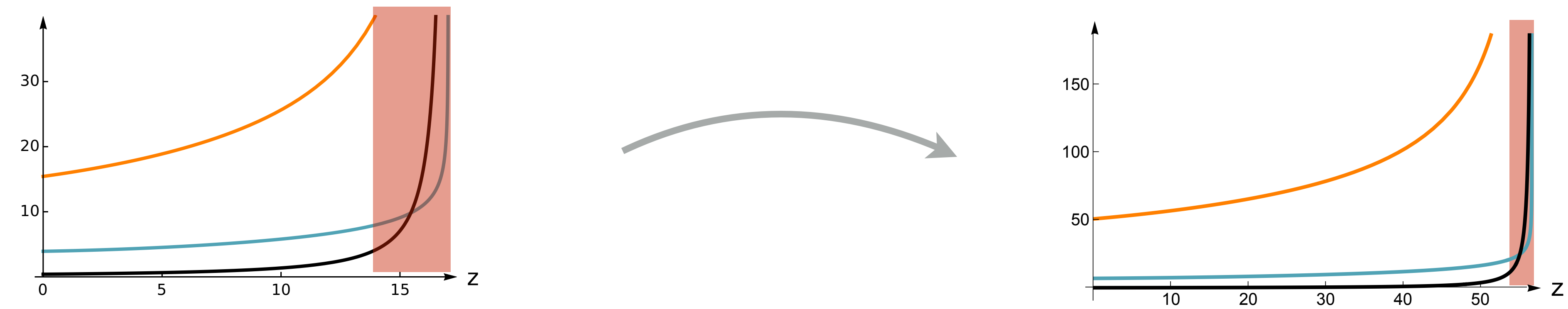

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In other words: string theory generates eff. potential $V(c)$ which should fix c

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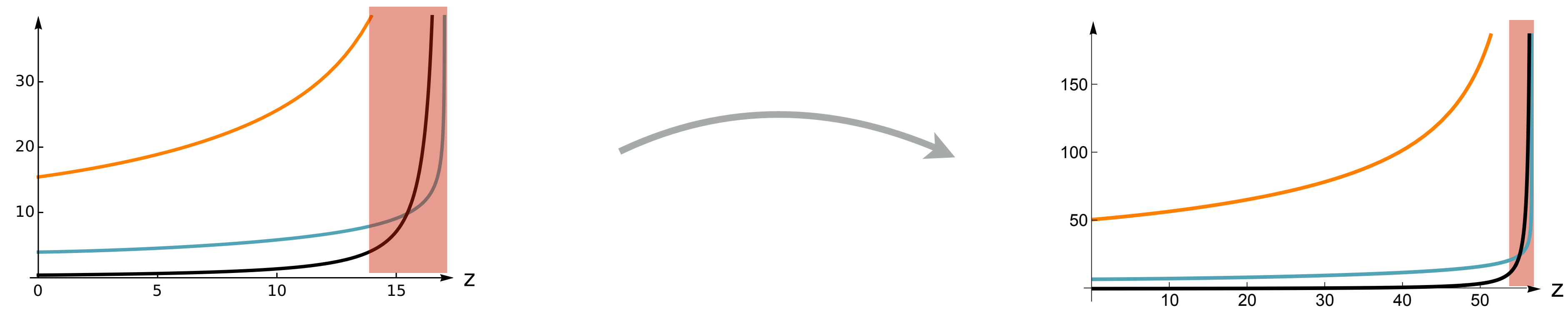

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In other words: string theory generates eff. potential $V(c)$ which should fix c

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- Hope that this solution is sensible comes from similarity with flat-space O8_

- We have also tried to replace $O8_- \to O6_-$ [Córdova, De Luca, AT, work in progress]

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

surrounds the O6

again all functions only dep. on z

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

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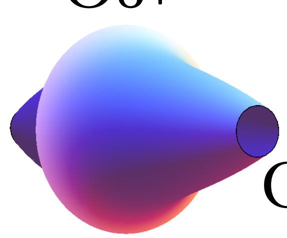
- we already know one such solution for $\Lambda < 0$:

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

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

O8+



O6_

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$$\downarrow$$

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

- we slowly modified it numerically, bringing Λ up

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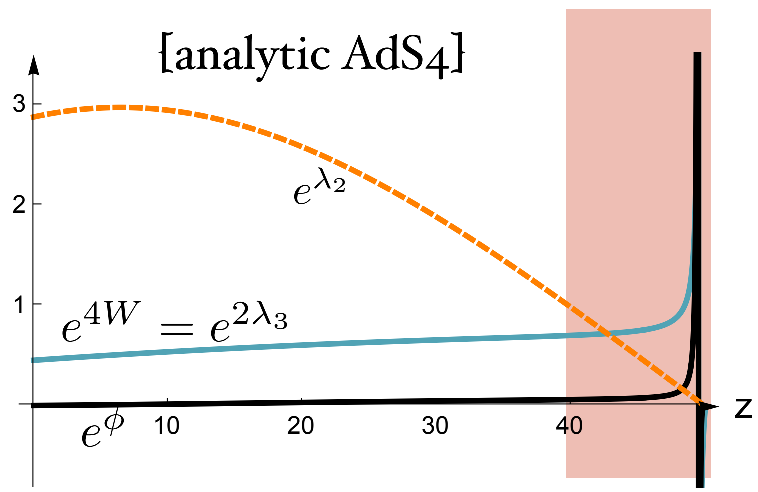
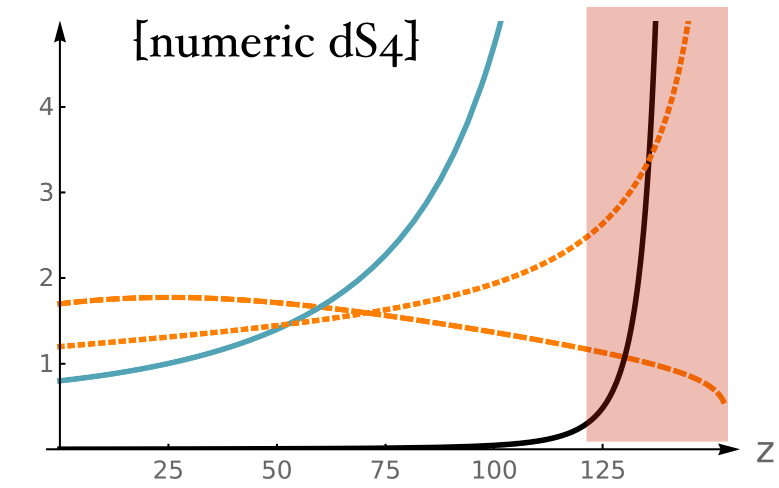
[functions rescaled for clarity]



We still obtain the O6 boundary.



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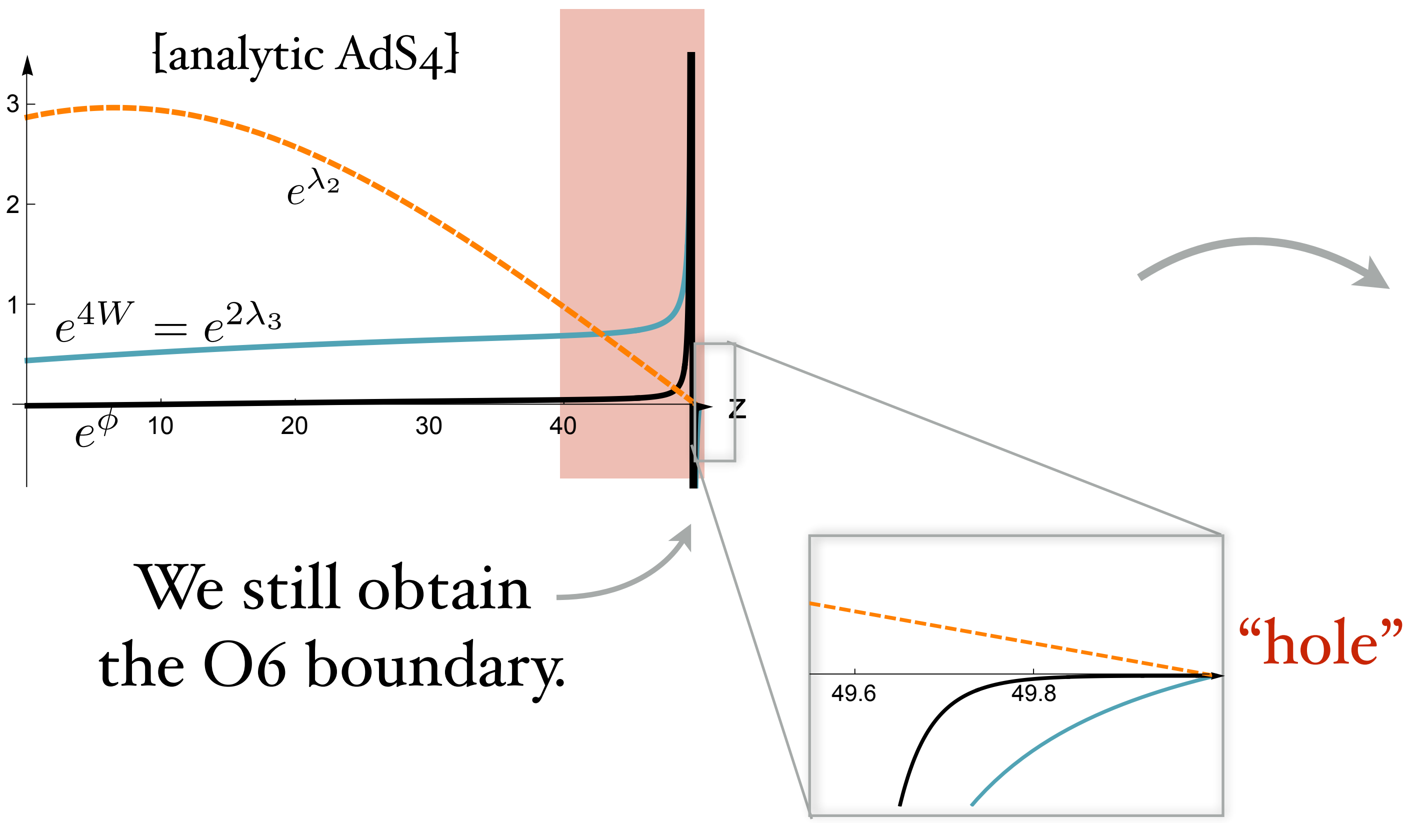

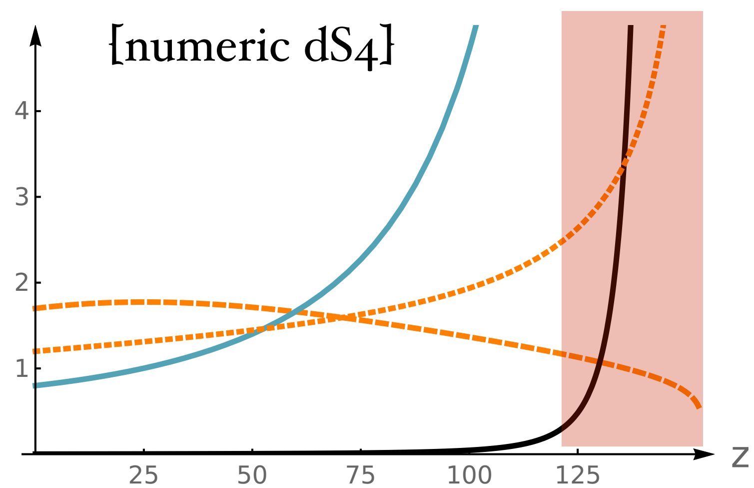

We still obtain the O6 boundary.

- But do we also take the 'hole interior' seriously?

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

there is a sourceless 'pre-O6' metric obtained by 'unwarping'

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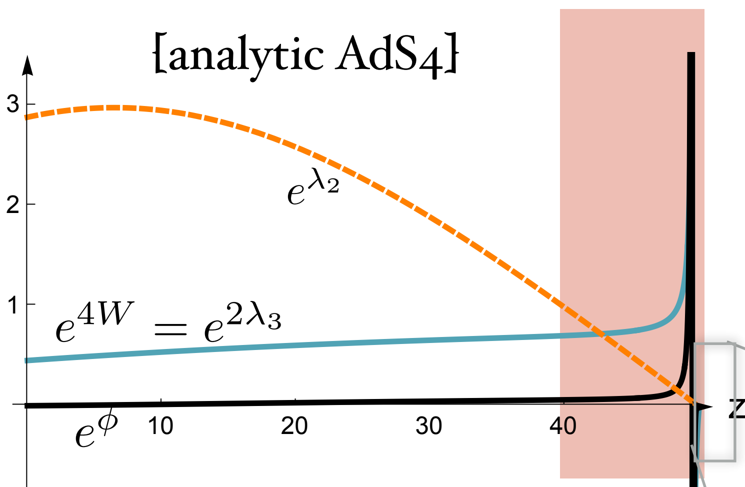

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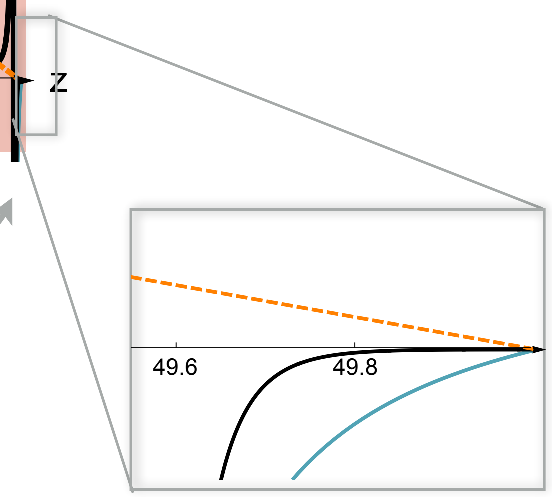
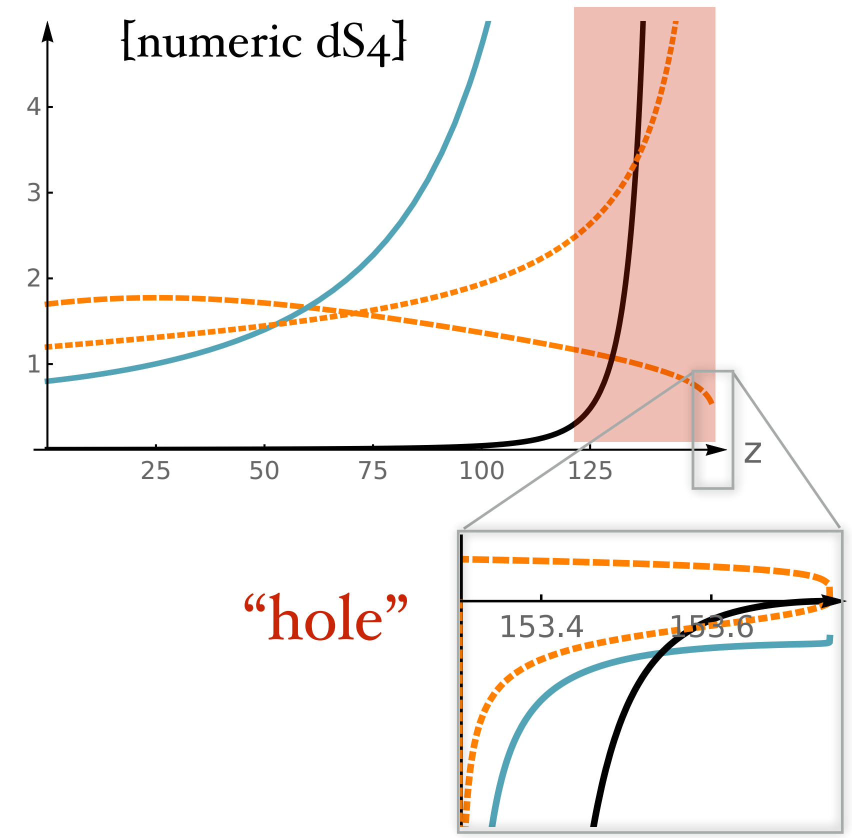


"hole"



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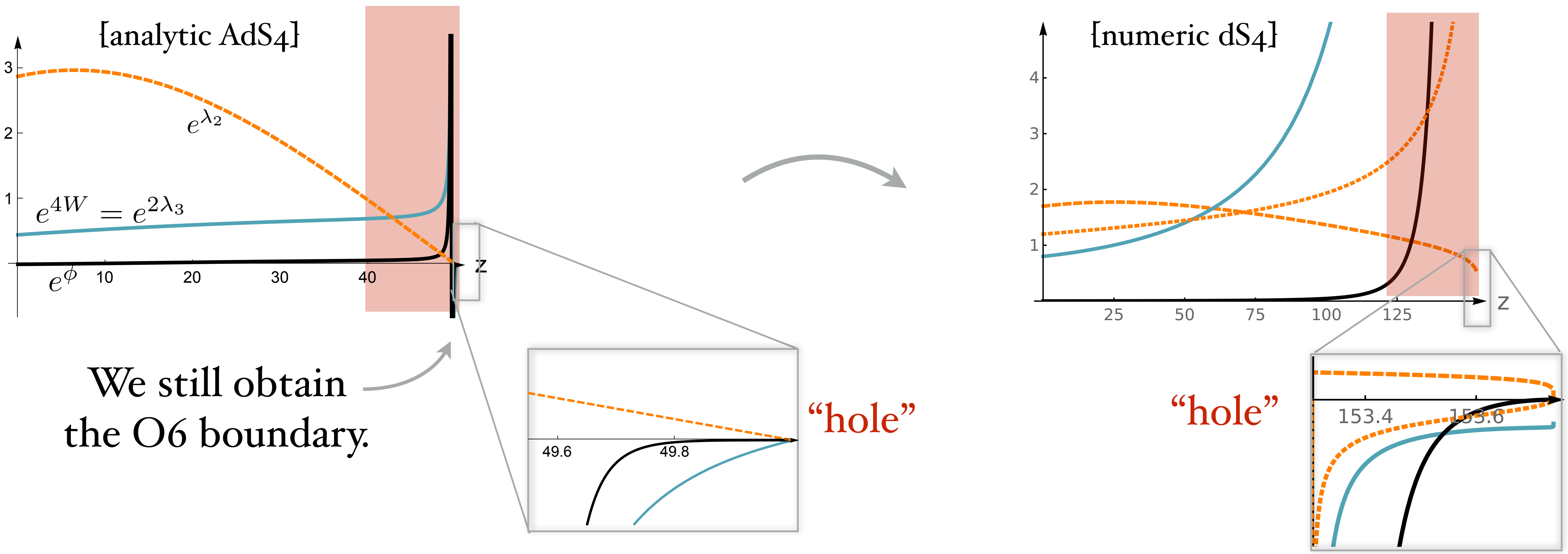

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- A perhaps more physical procedure: probe analysis

perhaps following
[Sen ’96, Saracco, AT, Torroba ’13]

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
  - O8-O6 solutions also promising
  - There are regions where supergravity break down.

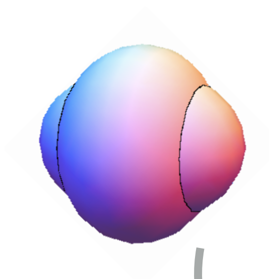
Inevitable! If you want solutions with O-planes.
We better learn how to deal with them.

Backup slides

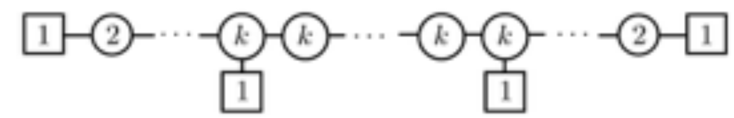
• Holographic checks work with all sources

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

Examples



dual quiver theory [SU gauge groups]

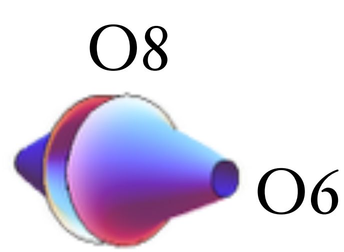


integral over
internal dimensions
[Henningson, Skenderis '98]

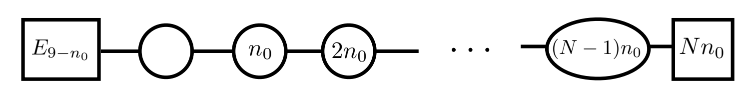
susy, grav. &
R-symmetry anomalies

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

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



[SO-USp gauge groups]

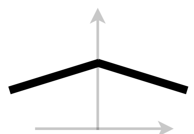


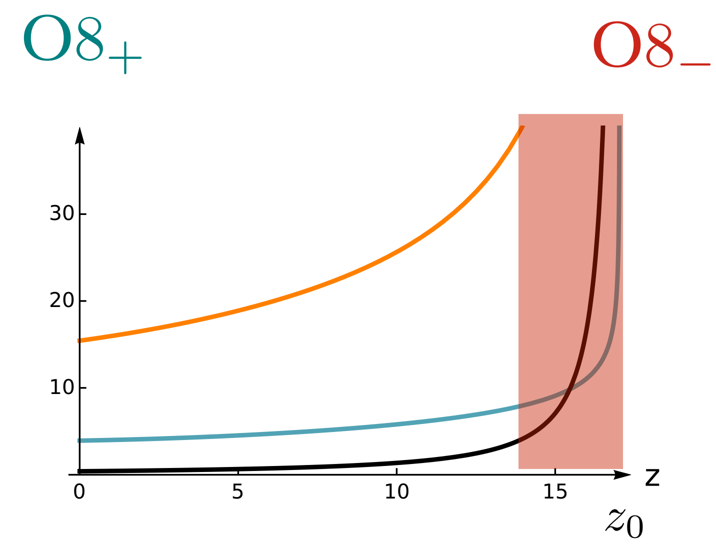
[Bah, Passias, AT '16]
[Apruzzi, Fazzi '17]

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

Possible criticism of the O8–O8 model

- Near sources, EoMs: $e^{W-\phi}\partial_z^2 f_i \sim \mp\delta + \ldots$ $\qquad f_i = \{W, \tfrac{1}{5}\phi, \tfrac{1}{2}\lambda\}$

- O8$_-$: $\partial_z^2\Big($  $\Big) = -\delta \quad \Rightarrow \quad e^{W-\phi} f_i'|_{z\to 0^+} = -1$



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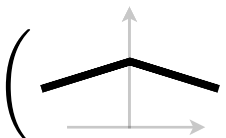
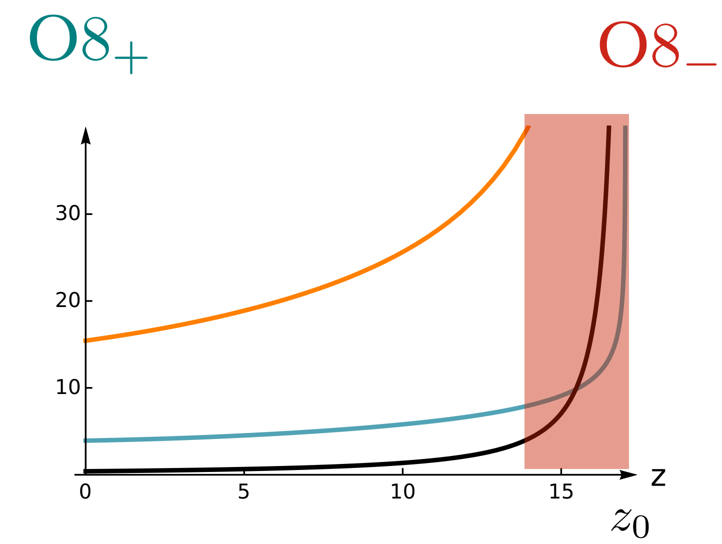
- O8$_-$: $\partial_z^2\Big($  $\Big) = -\delta$ $\;\Rightarrow\;$ $e^{W-\phi} f_i'|_{z\to 0^+} = -1$



- Near O8$_-$, supergravity breaks down;

  we shouldn't take its EoMs seriously.

Possible criticism of the O8–O8 model

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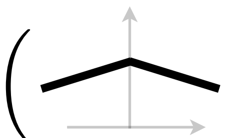
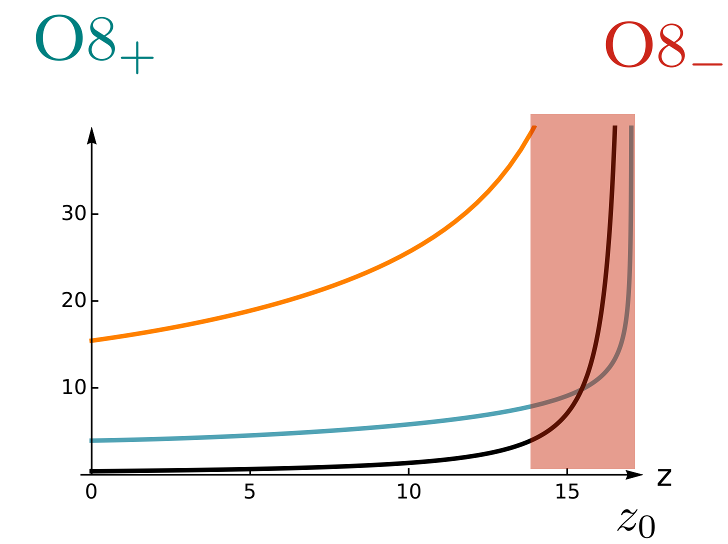
- O8$_-$: $\partial_z^2\Big($  $\Big) = -\delta \quad \Rightarrow \quad e^{W-\phi} f_i'|_{z\to 0^+} = -1$



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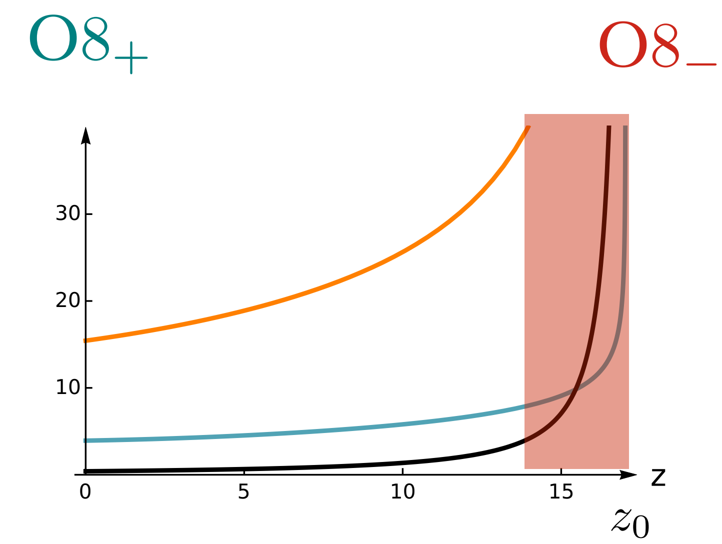
Possible criticism of the O8–O8 model



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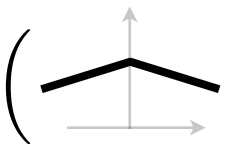
- O8$_-$: $\partial_z^2\Big($  $\Big) = -\delta \;\Rightarrow\; e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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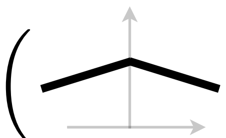
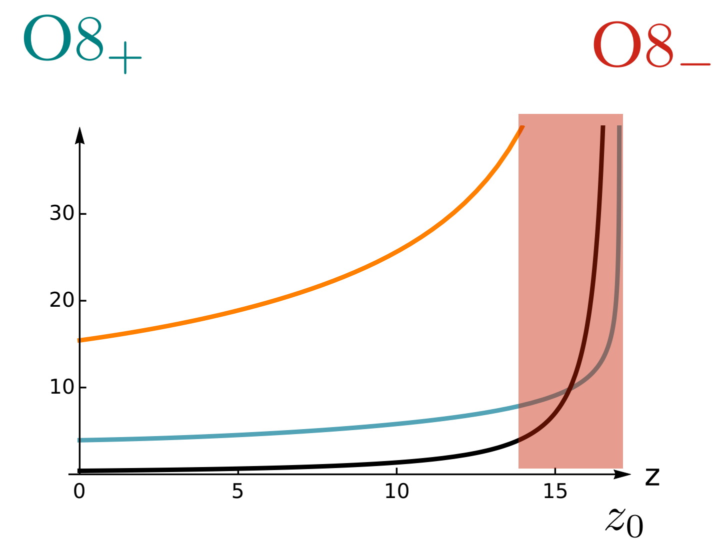
- O8$_-$: $\partial_z^2\Big($  $\Big) = -\delta \quad \Rightarrow \quad e^{W-\phi} f_i'|_{z\to 0^+} = -1$



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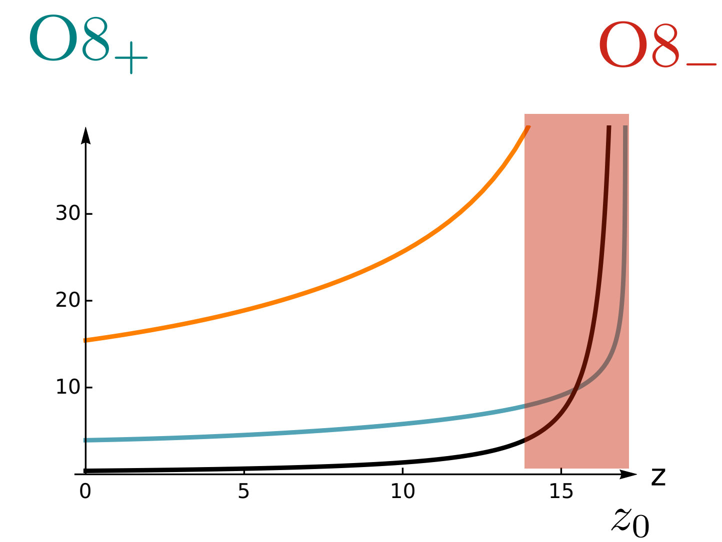

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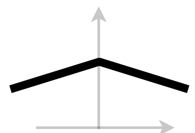
- O8$_-$: $\partial_z^2\Big($  $\Big) = -\delta \quad \Rightarrow \quad e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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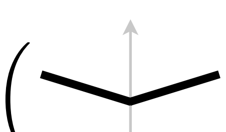
- if we extrapolate from O8$_+$ with $a \neq 0$: $\partial_z^2\Big($  $\Big) = \delta \quad \Rightarrow \quad e^{W-\phi} f_i'|_{z\to z_0^+} = 1$

this works ✓

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To me this confirms understanding sugra EoMs
in strongly coupled region is not a meaningful enterprise.

Of course, this also confirms that the fate of our solutions depends on quantum corrections.