String theory compactifications with sources

Alessandro Tomasiello

Strings 2019

Introduction

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

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

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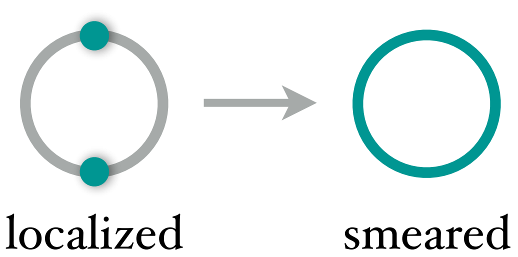
- it has been hard to find examples; often people have resorted to 'smearing'



[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.

Plan:

I. Progress in finding solutions

II. How we introduce localized sources

III. de Sitter?

I. Geometry of solutions

- Systematic classification of BPS solutions: more successful than ad hoc Ansätze

  - old methods: G-structures; gen. complex geometry, pure spinors

    [Strominger '86, Gauntlett, Pakis '02...]

    [Graña, Minasian, Petrini, AT '05...]

  - Conceptual origin: calibrations. Type II, for example:

    'calibration conjecture': [Martucci, Smyth '05, Lüst, Patalong, Tsimpis '10...]

collective D-brane calibration

$$(\mathrm{d} + H\wedge)\Phi = (\iota_K + \tilde{K}\wedge)F$$

[AT '11]

$$\mathrm{d}\Omega = -\iota_K * H + \underbrace{(\Phi, F)_6}_{\text{pairing}}$$

[Legramandi, Martucci, AT '18]

NS5-brane calibration

- practically, the D-brane equation is enough for $d \geq 4$

$$\left.\begin{matrix}\mathrm{AdS}_d \\ \mathrm{Mink}_d\end{matrix}\right] \times M_{10-d}$$

⇨ pure spinor equations

[Graña, Minasian, Petrini, AT '05]

⇨ matrix pure spinor equations for extended susy

[Passias, Solard, AT '17;
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- In general more calibration equations [eg KK-monopole] needed for sufficiency

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• Supersymmetry breaking?

- For Minkowski: sometimes possible to break susy by adding one term to pure spinor equations [Legramandi, AT, in progress]

- Via consistent truncations [Passias, Rota, AT, '15…]

- Direct solution of EoM, with some lessons from the susy case [Cordova, De Luca, AT, '18]

- some recent solution classes:

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  + susy-breaking twins

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

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Almost all analytic.

For ex. $$e^{-2A} ds^2_{M_6} = -\frac{1}{4}\frac{q'}{xq} dx^2 - \frac{q}{xq' - 4q} D\psi^2 + \frac{\kappa q'}{3q' - xq''} ds^2_{\mathrm{KE}_4}$$

$q(x) =$ deg. 6 pol.

[dual to CS-matter theories]

generalizes
[Guarino, Jafferis, Varela '15] (anal.)
[Petrini, Zaffaroni '09; Lüst, Tsimpis '09...] (num.)

formally similar to
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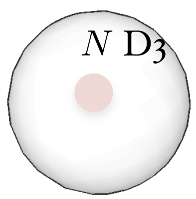
- relations between different cases often suggest 'correct' coordinates

- we will now see that all these admit possible sources...

II. Including sources

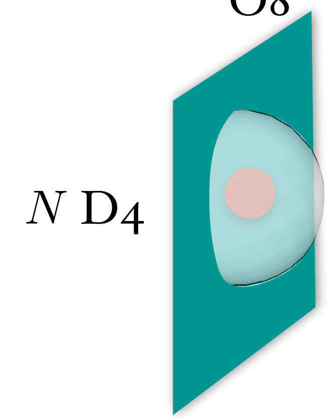
- Many AdS solutions have near-horizon origin

D3 dissolve; no source
after near-horizon



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

D4 dissolved, but
O8 remains



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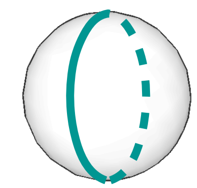

$\mathrm{AdS}_6 \times (\mathrm{top}.S^4)$

[Youm '99,
Brandhuber, Oz '99]

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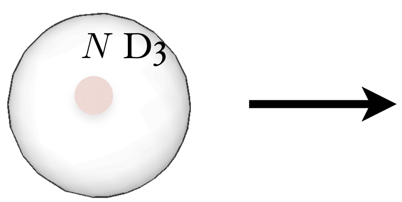

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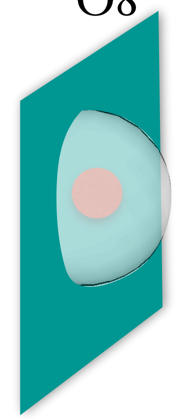
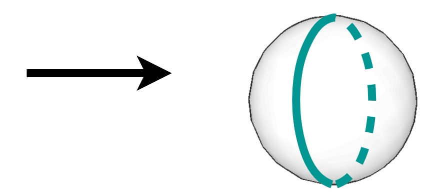
N D4





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

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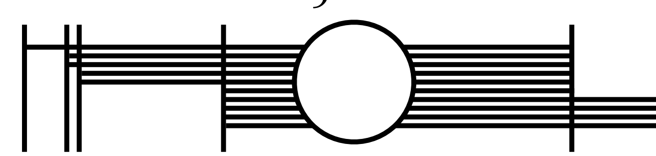
- Unclear if all AdS are near-horizon limits

- Intersecting brane solutions are rare anyway



- Better strategy: start from analytic classes, explore boundary conditions for sources

- Sources create singularities where supergravity breaks down

backreaction on flat space:

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

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

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

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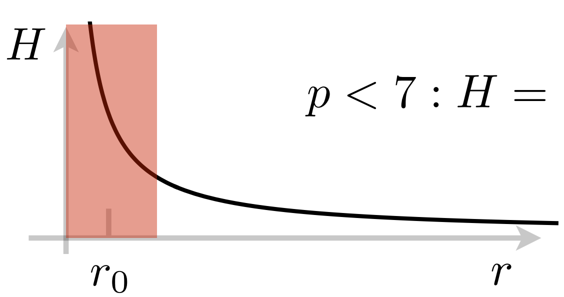
- supergravity artifacts: they should be resolved in appropriate duality frame

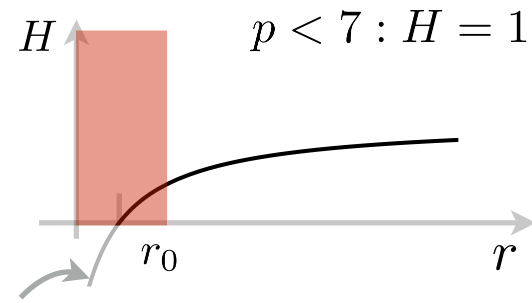
D-branes

O-planes

[Op_-: tension=charge=-2^{p-5}]



$p < 7 : H = 1 + \left(\frac{r_0}{r}\right)^{7-p}$



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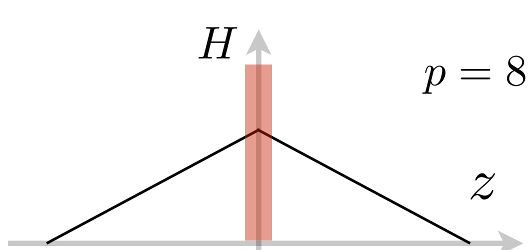
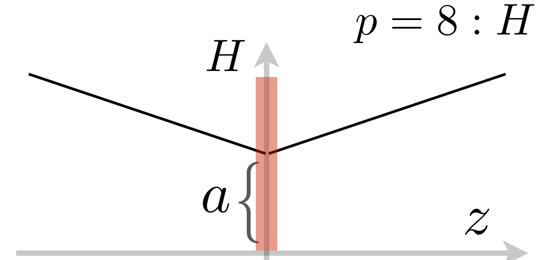
unphysical ‘hole’!



$p = 8 : H = a - |z/z_0|$



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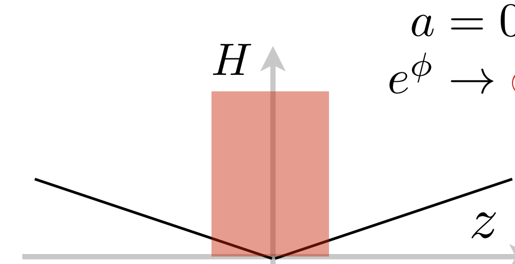

$a = 0$:
$e^\phi \to \infty$

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- Example: AdS7 in IIA. All solutions:

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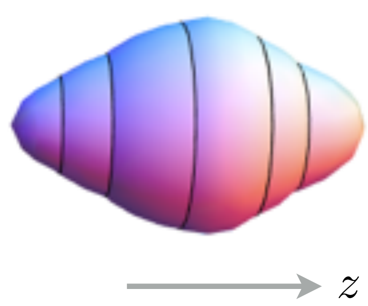
$\dddot\alpha = F_0 \quad \Rightarrow \quad \alpha$ piecewise cubic



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[Passias, Rota, AT '15; Malek, Samtleben, Vall Camell '18]

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some are unstable

[Danielsson, Dibitetto, Vargas '17; Apruzzi,
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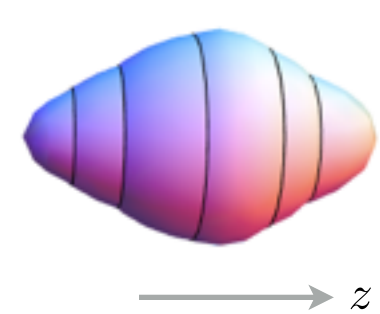

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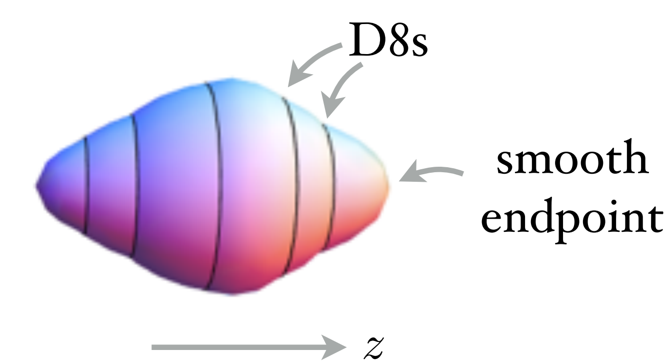
- When F_0 jumps ⇨ D8



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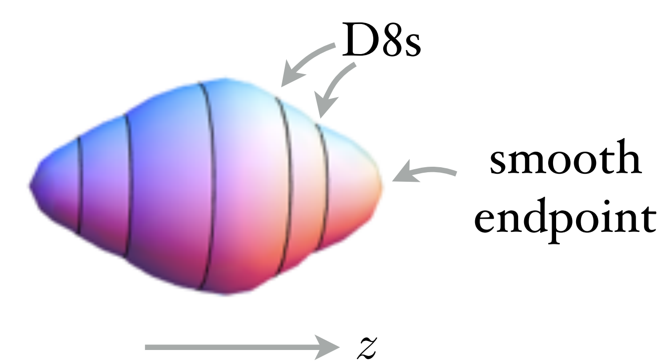

what happens with other boundary conditions?

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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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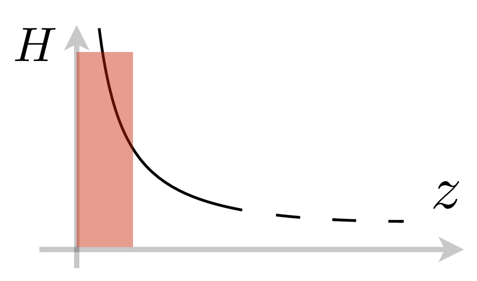
D6



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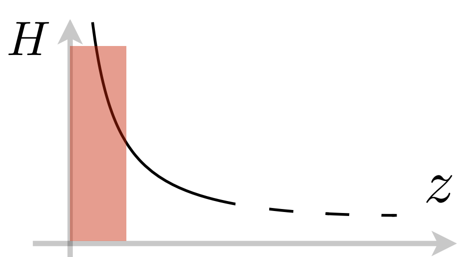
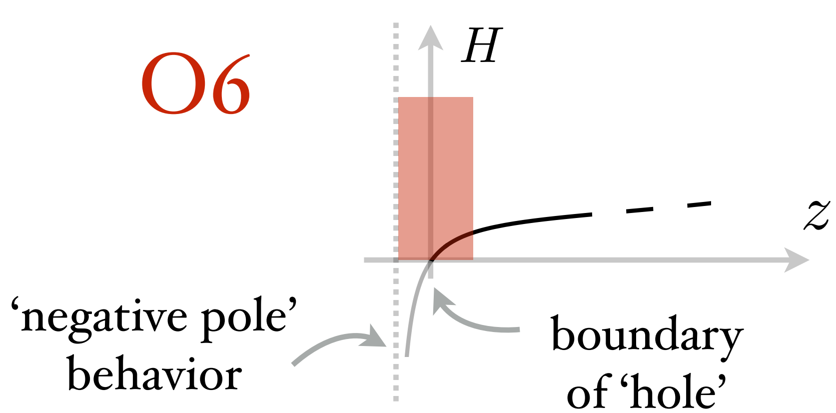


- $\ddot{\alpha} \to 0$

transverse $\mathbb{R}^3$

$$ds^2_{10} \sim z^{-1/2}ds^2_{\mathrm{AdS}_7} + z^{1/2}(dz^2 + ds^2_{S^2})$$

O6



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

compare locally with

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

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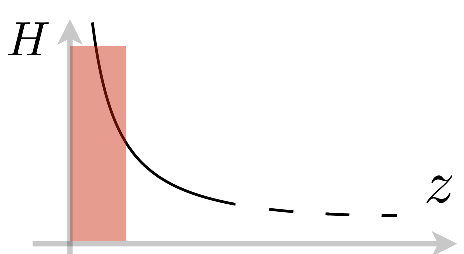
D6



- $\alpha \to 0,\ \dot\alpha \to 0$

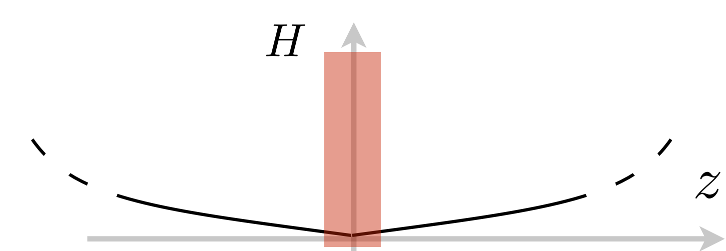
[Bah, Passias, AT '17]

transverse $\mathbb{R}$

$$ds^2_{10} \sim z^{-1/2}(ds^2_{\mathrm{AdS}_7} + ds^2_{S^2}) + z^{1/2}dz^2$$

$$e^{\phi} \xrightarrow[z\to 0]{} \infty$$

O8



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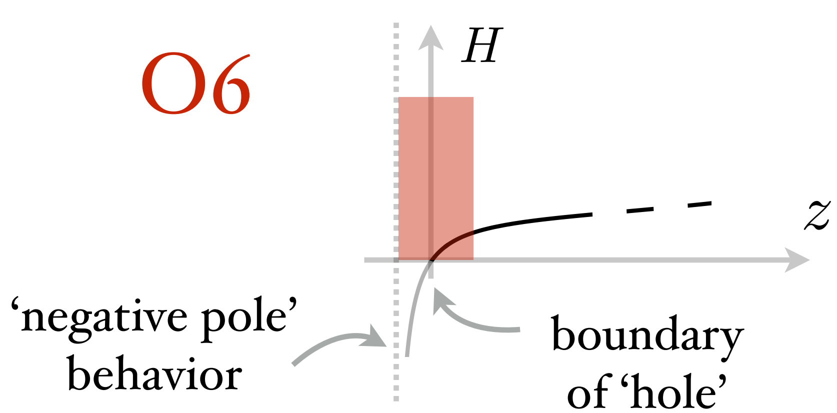

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transverse $\mathbb{R}^3$

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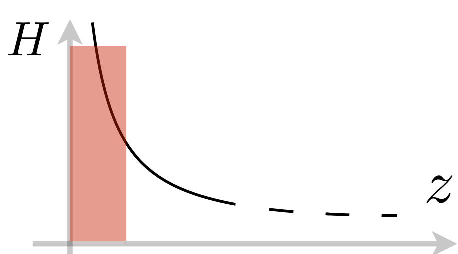
D6



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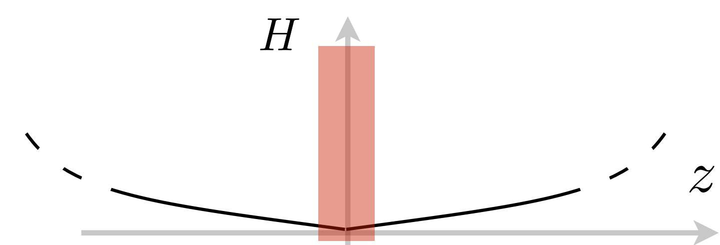

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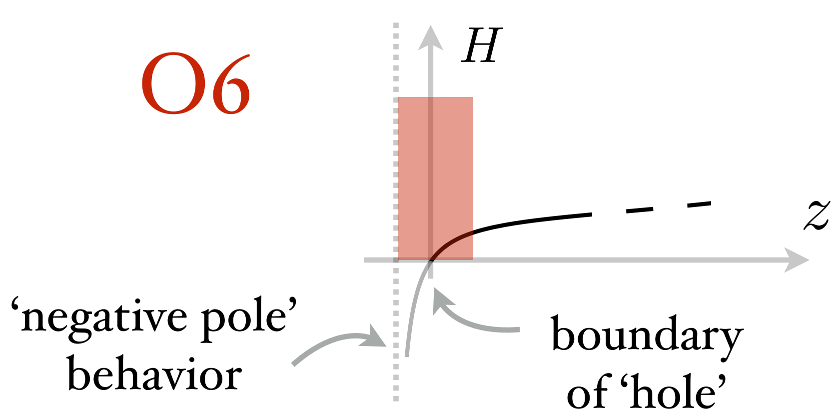


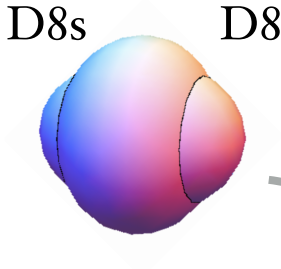
- Not always so easy...
- Supergravity artifacts, but same local behavior as solutions in flat space

Holographic checks work with all sources

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

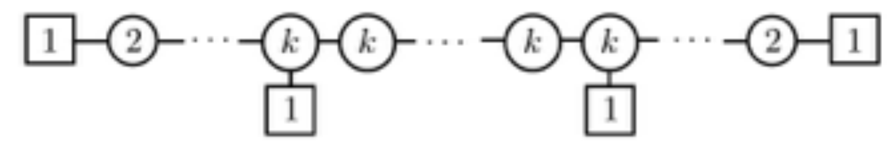
Examples

D8s D8s



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]

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

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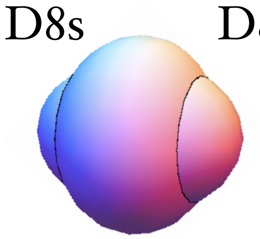

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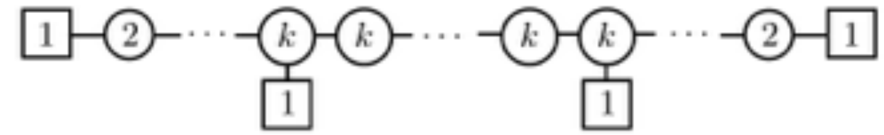

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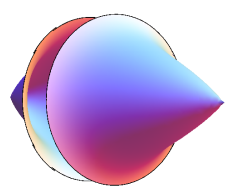
O8+D8



D6

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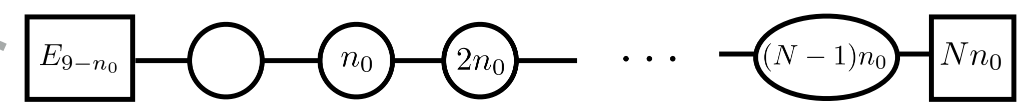

[Bah, Passias, AT '16]
[Apruzzi, Fazzi '17]

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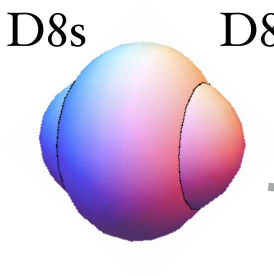
Examples

D8s D8s



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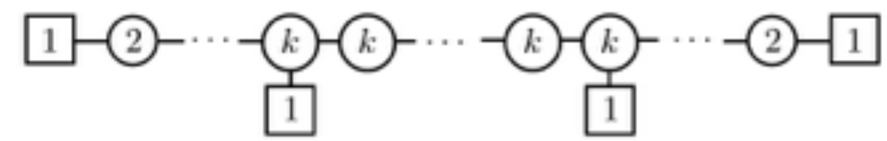

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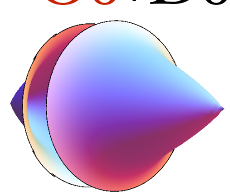

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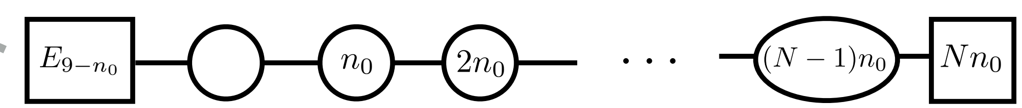


[Bah, Passias, AT '16]
[Apruzzi, Fazzi '17]

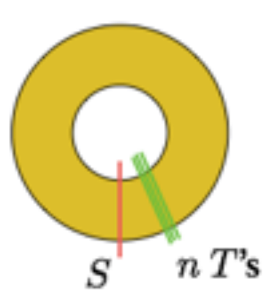
• Holographic check of S-folds:

sort of alternative to sources.
I was skeptical, but:

AdS4 solution: [Inverso, Trigiante, Samtleben '16]

CFT3 dual: [Assel, AT '18]

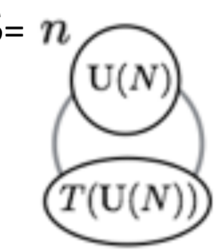
$S^2 \times S^2 \to$



free energy =

$$\frac{1}{2}N^2 \ln\left(\frac{1}{2}\left(n + \sqrt{n^2-4}\right)\right)$$

CS= n



see also [Garozzo, Lo Monaco, Mekareeya '18]

- Sources can be introduced in most classes

• AdS7 in IIA: $S^2 \to I$ sources: D8, D6, O8, O6	• AdS5 in IIA: $(\text{top. } S^3) \to \Sigma_g$ + "punctures" sources: D8, D6, D4, O8, O6
• AdS4 in IIA $(\text{top.} S^3) \to H_3, S^3$ sources: D8, D6, O8, O6 $(\text{top. } S^2) \to \text{KE}_4, \Sigma_g \times \Sigma_{g'}$ O8	• AdS3 in IIA: $S^6 \to I$ $\mathcal{N} = (0,8),\ (0,7)$: F_4 and G_3 superalg. sources: O8

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- Other notable classes that admit sources:
  - AdS_6 in IIB: (p,q)-fivebranes [D'Hoker, Gutperle, Karch, Uhlemann '16...]
  - AdS_5 in 11d: M5 [Gaiotto, Maldacena '09...]
  - AdS_4 $\mathcal{N} = 4$ in IIA: NS5, D5 [...Assel, Bachas, Estes, Gomis '11,'12]
  - AdS_3 in F-theory [Couzens, Lawrie, Martelli, Schäfer-Nameki '17; Haghighat, Murthy, Vandoren, Vafa '15]

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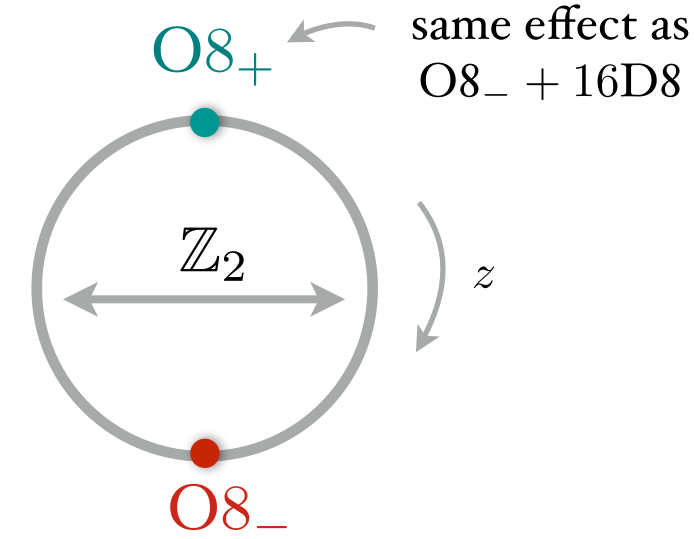
- Let's see if we can use this progress as inspiration for de Sitter...

dS

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

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

compact hyperbolic



Minkowski: [Dabholkar, Park '96, Witten '97, Aharony, Komargodski, Patir '07]

see also [Silverstein, Strings 2013 talk]

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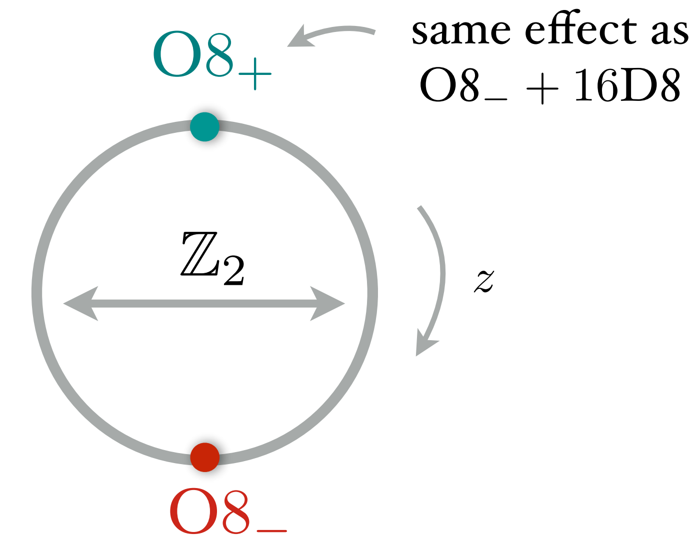
Boundary condition at O8+

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



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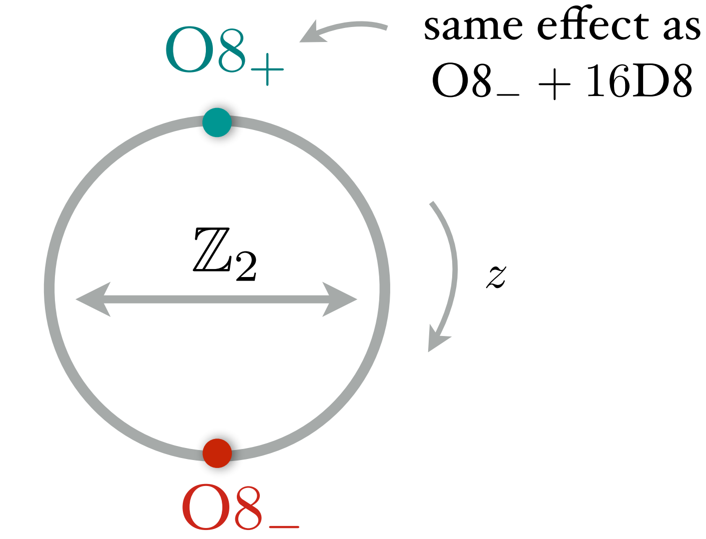

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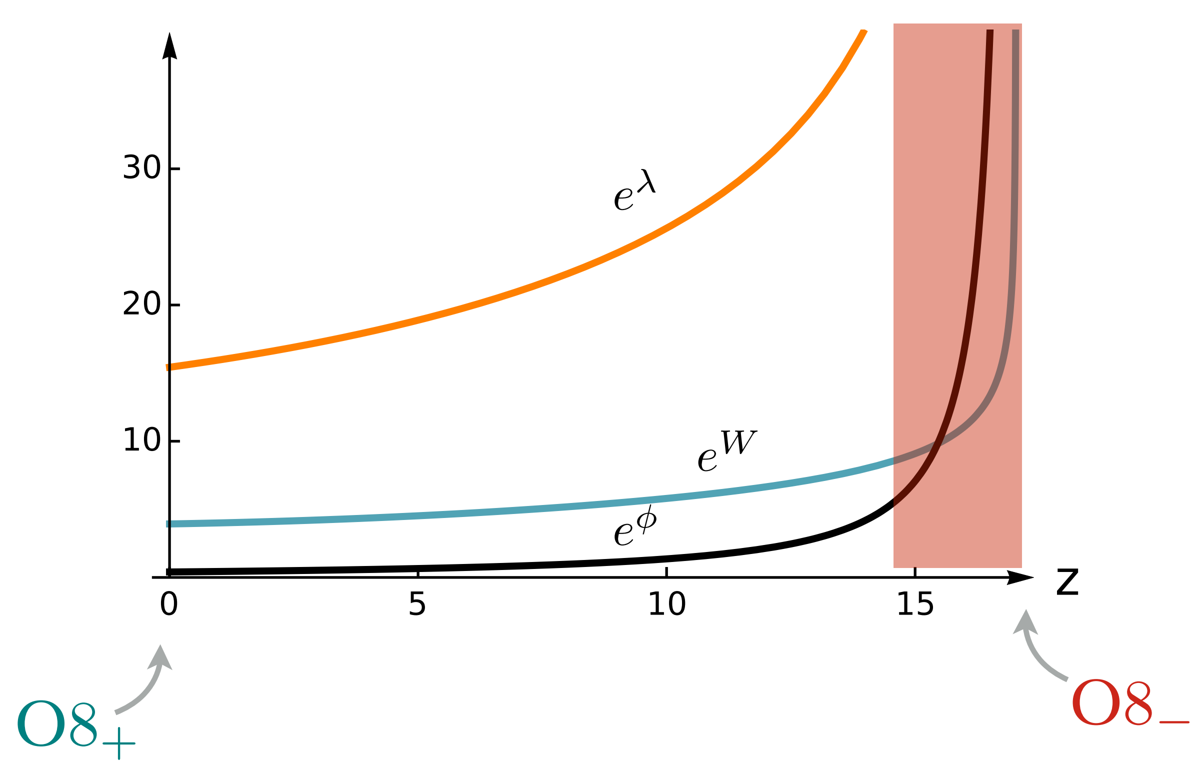
Numerical evolution: we manage to reach $e^{f_i} \sim |z - z_0|^{-1/4}$

same as O8− in flat space
[even the coefficients work]



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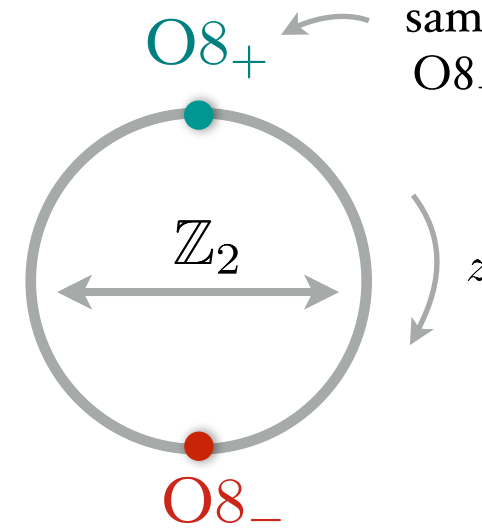

same effect as $O8_- + 16D8$

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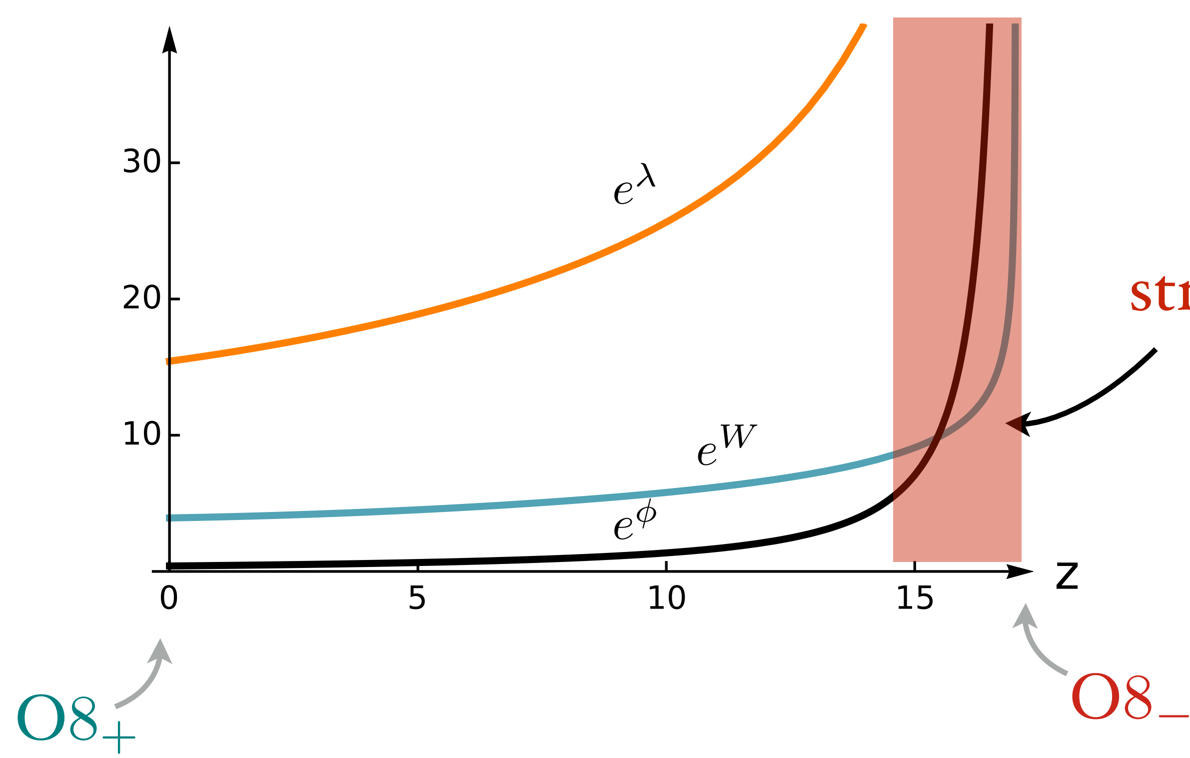
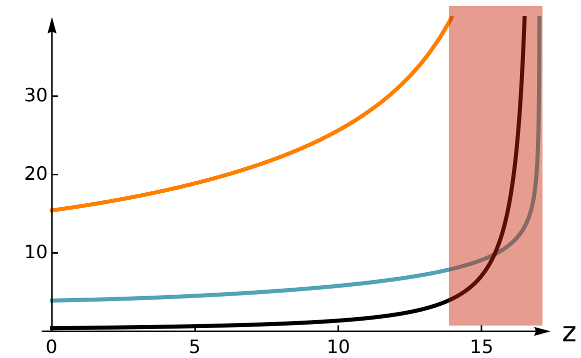
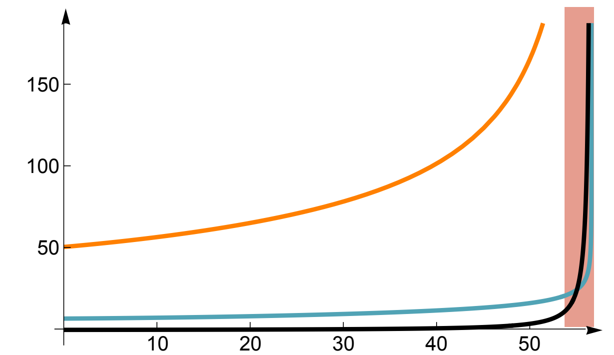


inevitably, O8_ has strongly coupled region

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





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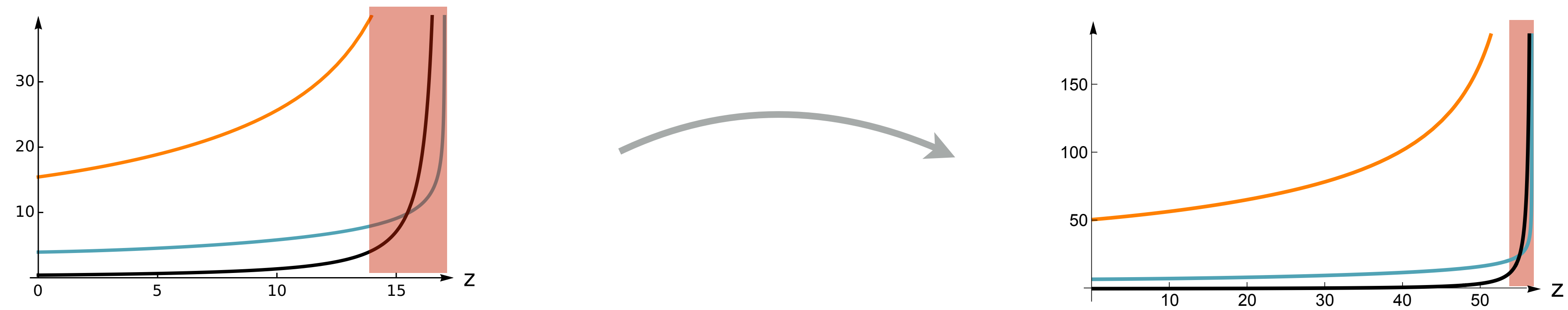

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- In the O8_ region stringy corrections become dominant $\ldots \gg e^{-2\phi} R^4 \gg e^{-2\phi} R$ $\underset{R^4}{\Uparrow}$

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

In other words: full string theory will fix c

it has been $\sim$ argued that supergravity contributes to this [Cribiori, Junghans '19]

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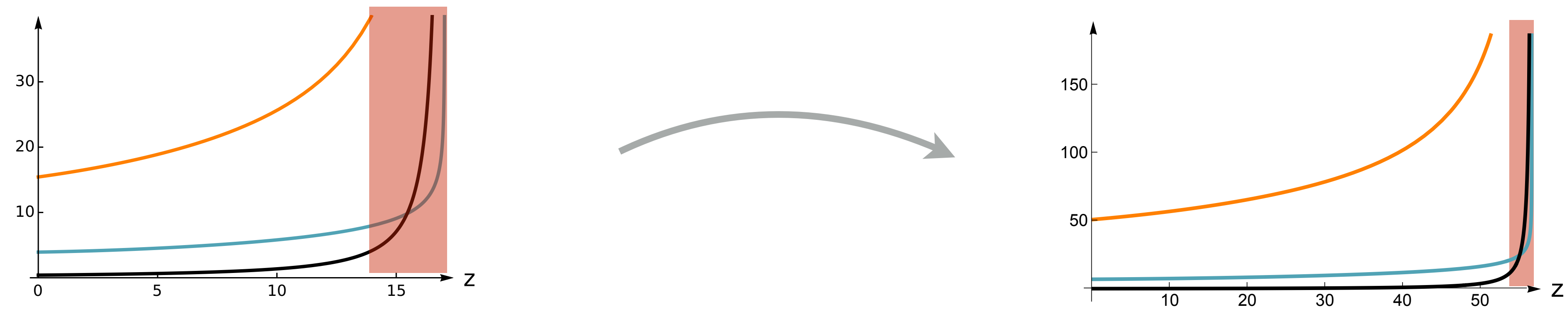

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- Hope that this solution is sensible comes from similarity with flat-space O8_
(which we know to exist in string theory)

- We also tried: $O8_+ - O6_-$

[Córdova, De Luca, AT, work in progress]

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

surrounds the O6

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

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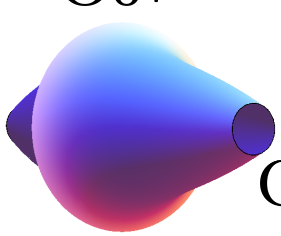
- we already know one such solution for $\Lambda < 0$:

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

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



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

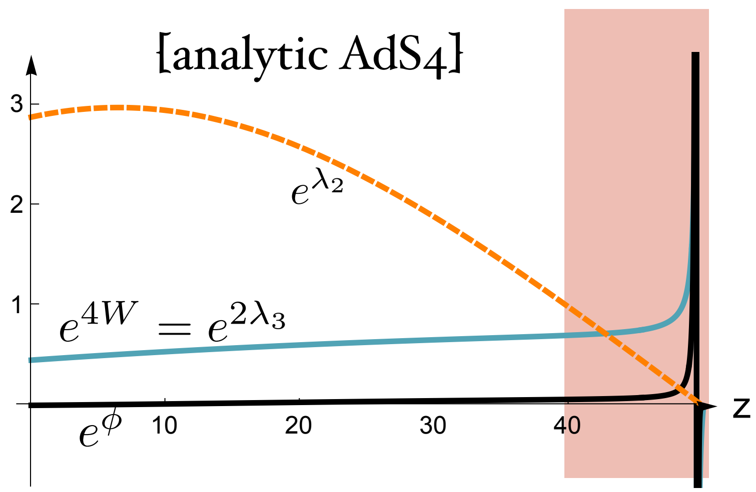
$$\downarrow$$

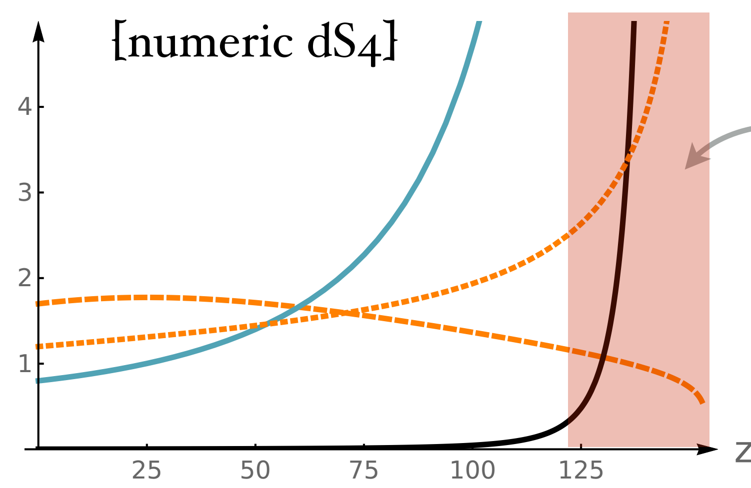
$\mathrm{AdS}_4 \times H_3$ compact hyperbolic

- 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.

- we slowly modified it numerically, bringing Λ up

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

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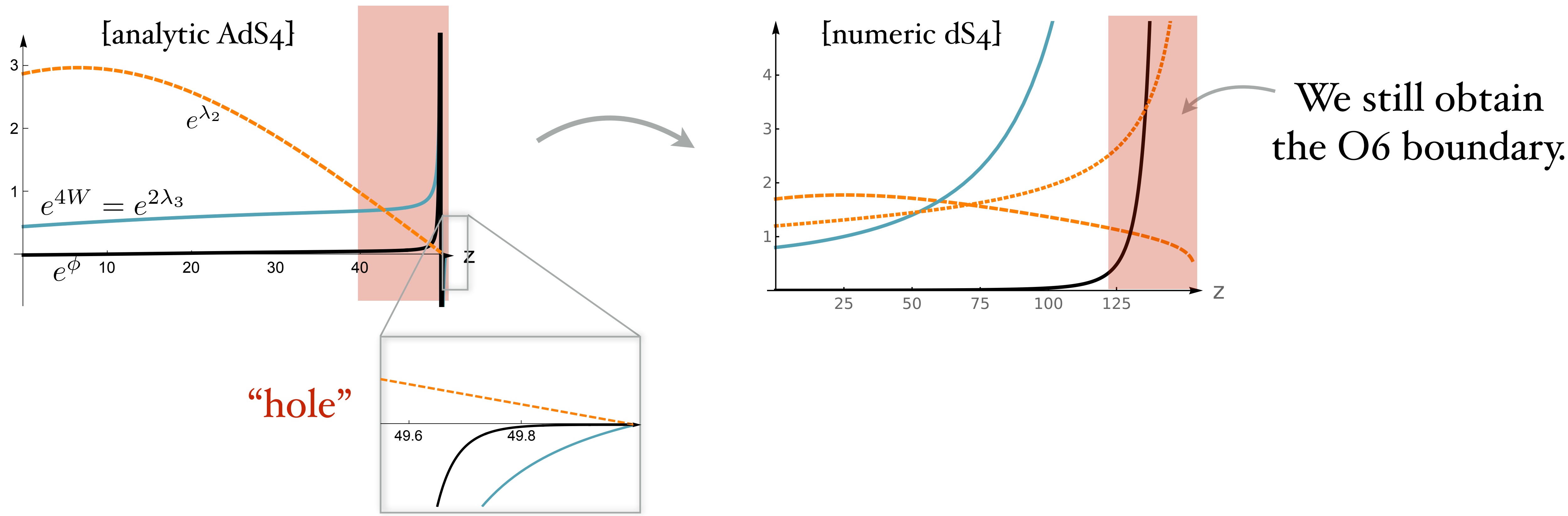

- Recall: for AdS solution we can analytically ‘inside the hole’

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

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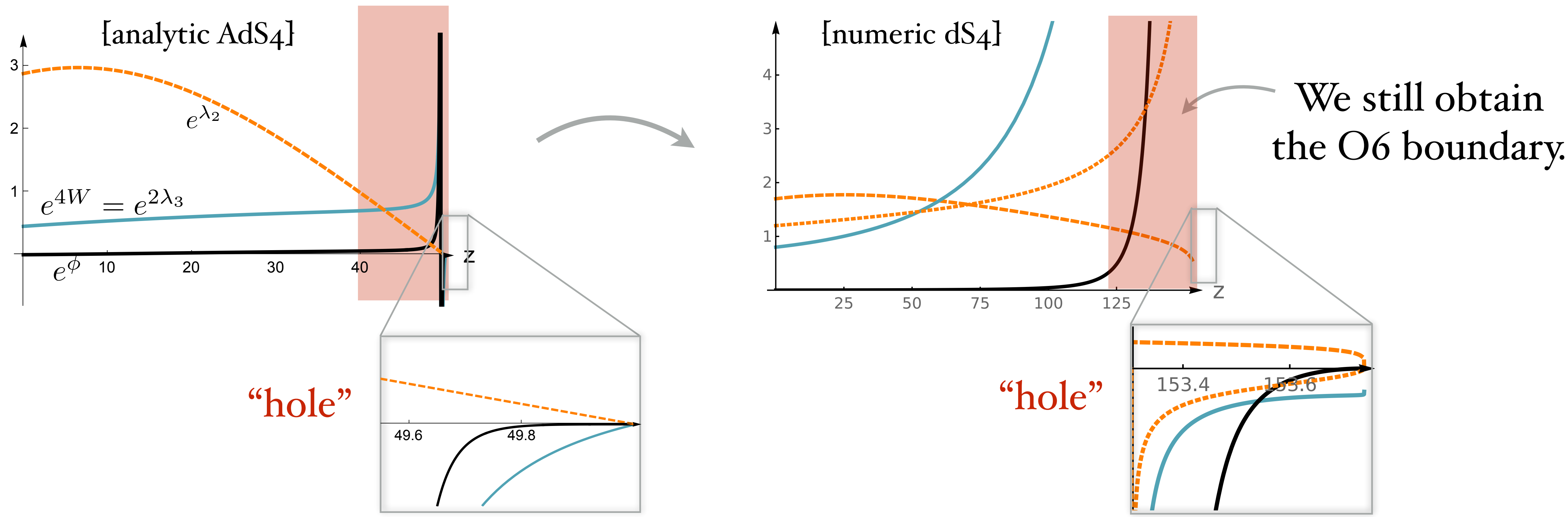
$$ds^2 = e^{2W} ds^2_{dS_4} + e^{-2W}\left(dz^2 + e^{2\lambda_3} ds^2_{M_3} + e^{2\lambda_2} ds^2_{S^2}\right)$$

[functions rescaled for clarity]



- Recall: for AdS solution we can analytically ‘inside the hole’

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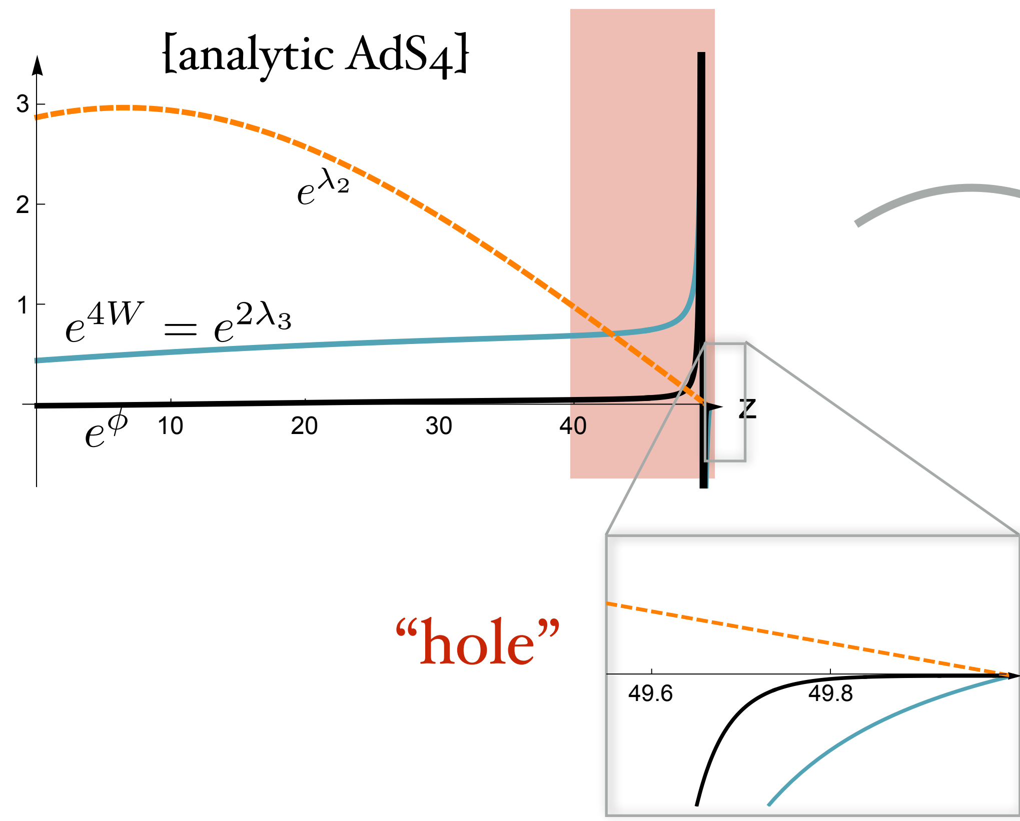

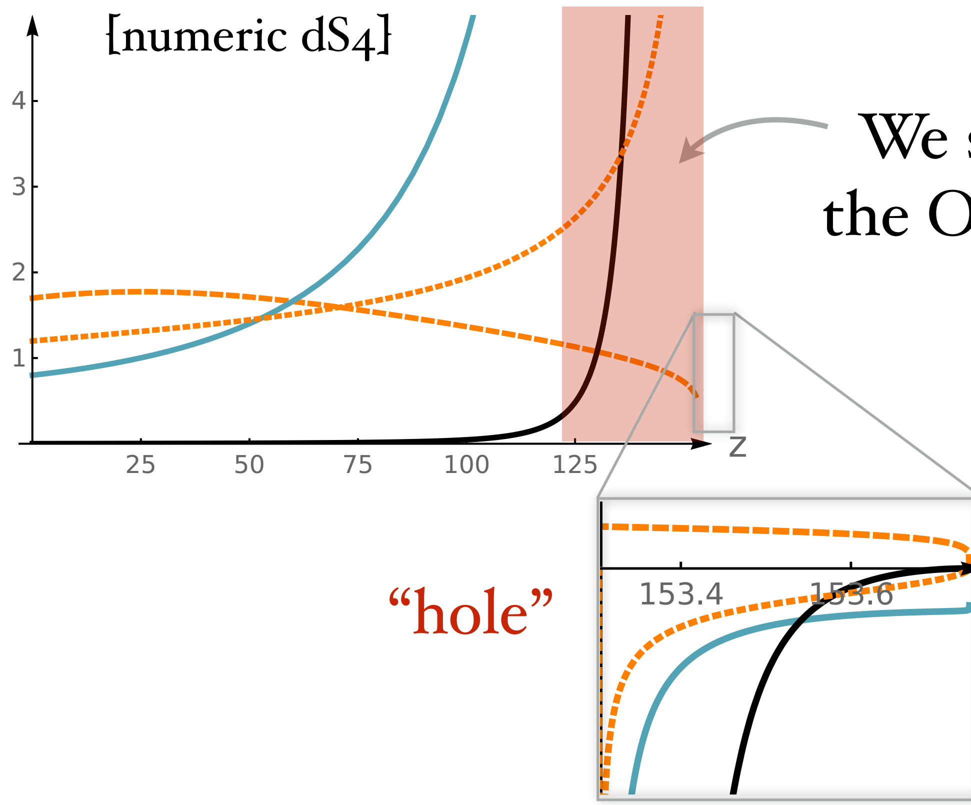

We still obtain the O6 boundary.

- Recall: for AdS solution we can analytically 'inside the hole'

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- Similar request for dS solution introduces many fine-tunings. Numerics unclear [so far]

- A perhaps more physical procedure: probe analysis

perhaps following

[Sen '96, ... Saracco, AT, Torroba '13]

Conclusions

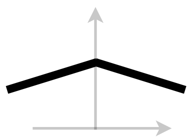
- A lot of progress in AdS solutions
  - often localized O-plane sources are possible
  - holography works even in their presence
  - sometimes non-supersymmetric

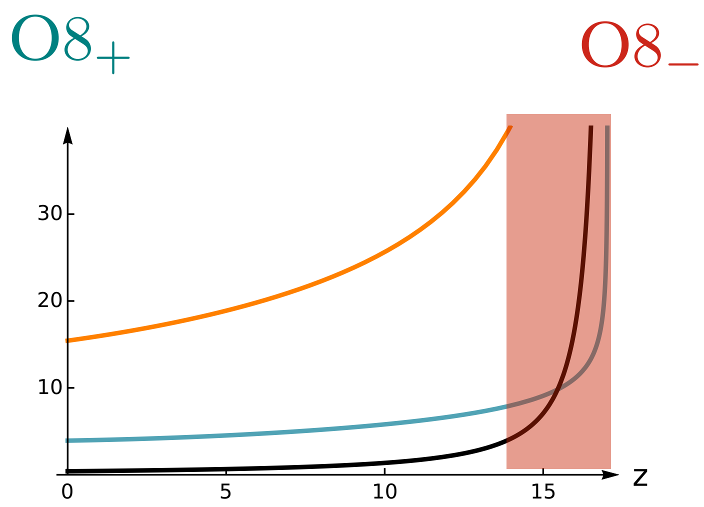
- Time to look for de Sitter
  - Using numerics, we find dS solutions with O8-planes in relatively simple setup
  - Also O8-O6 solutions
  - There are regions where supergravity breaks down.

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

Backup slides

Possible criticism of the O8–O8 model

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



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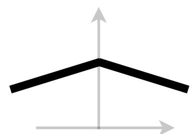
- $\mathrm{O8}_+$: $\partial_z^2\Big($  $\Big) = -\delta$ ⇨ $e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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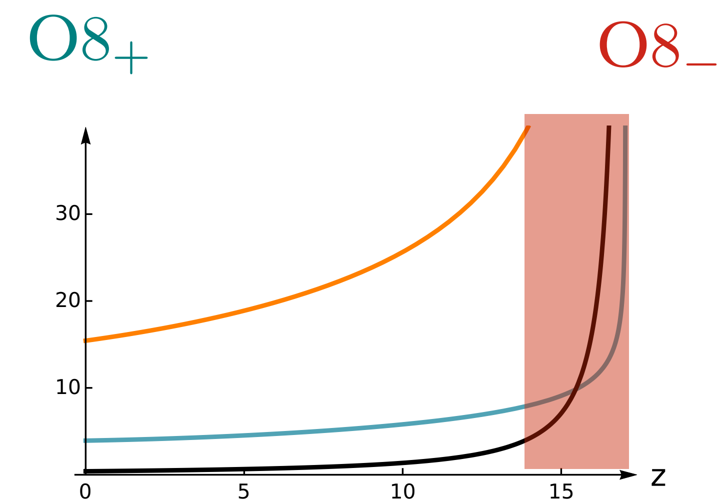

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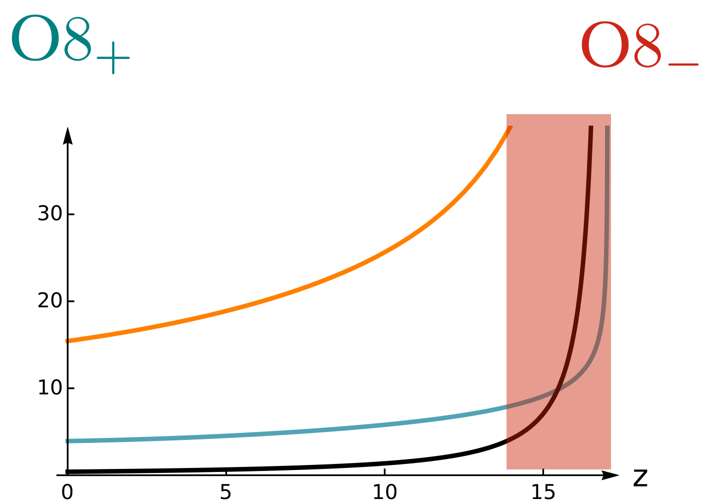
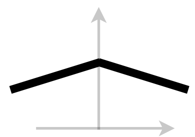


- O8$_+$: $\partial_z^2\Big($  $\Big) = -\delta$ ⇨ $e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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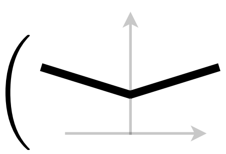
- if we extrapolate from O8$_+$ with $a \neq 0$: $\partial_z^2\Big($  $\Big) = \delta$ ⇨ $e^{W-\phi} f_i'|_{z\to z_0^+} = 1$

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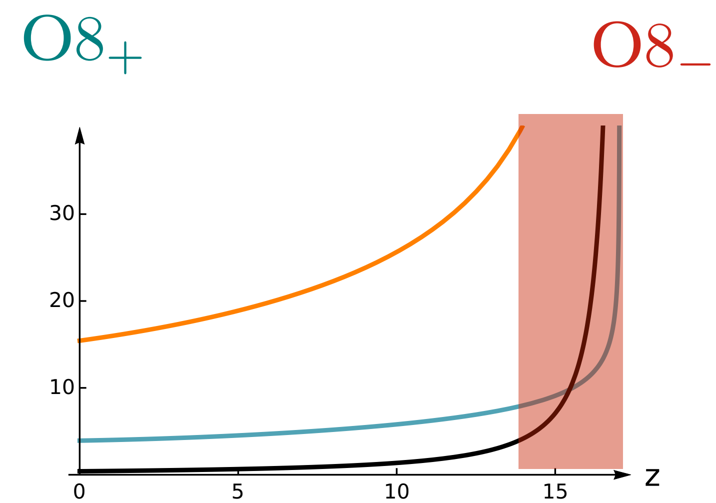
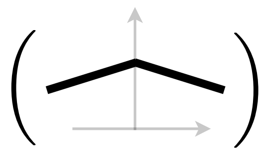


- O8$_+$: ∂_z^2  $= -\delta \quad \Rightarrow \quad e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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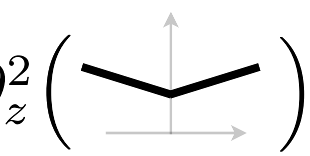
- if we extrapolate from O8$_+$ with $a \neq 0$: ∂_z^2  $= \delta \quad \Rightarrow \quad e^{W-\phi} f_i'|_{z\to z_0^+} = 1$

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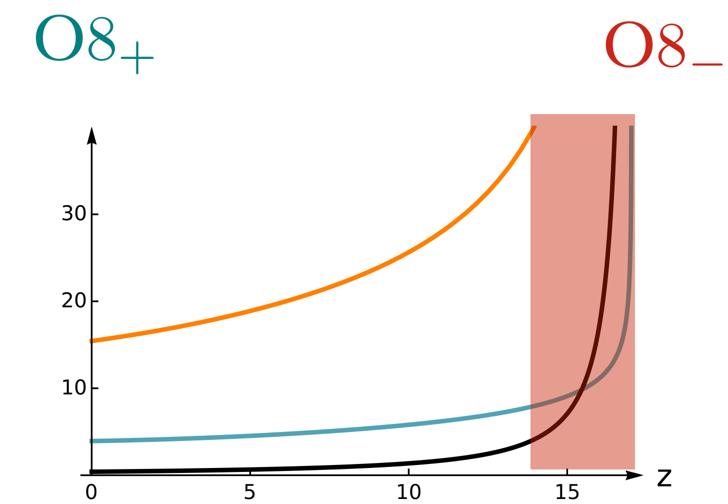
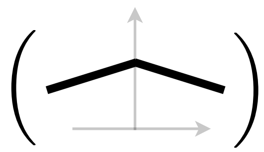


- $O8_+$: ∂_z^2  $= -\delta \quad \Rightarrow \quad e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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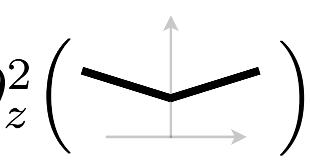
- if we extrapolate from $O8_+$ with $a \neq 0$: ∂_z^2  $= \delta \quad \Rightarrow \quad e^{W-\phi} f_i'|_{z\to z_0^+} = 1$

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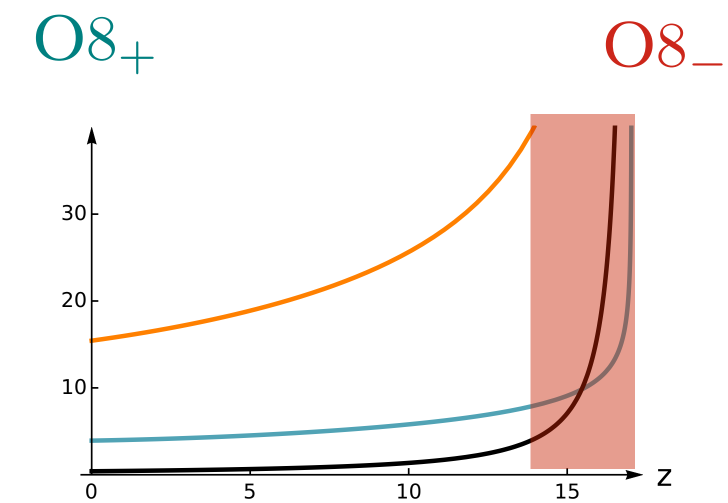
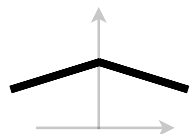


- O8$_+$: ∂_z^2 () $= -\delta$ $\Rightarrow$ $e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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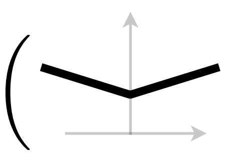
- if we extrapolate from O8$_+$ with $a \neq 0$: ∂_z^2 () $= \delta$ $\Rightarrow$ $e^{W-\phi} f_i'|_{z\to z_0^+} = 1$

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

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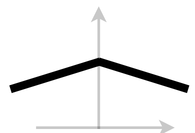
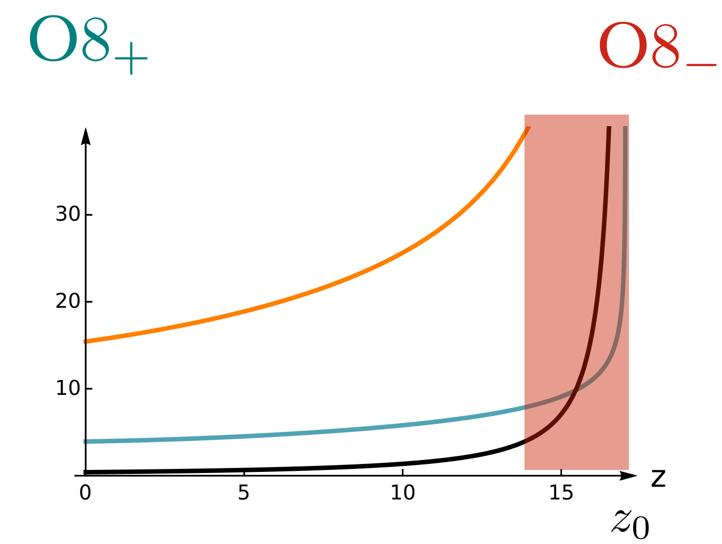
- Near sources, EoMs: $e^{W-\phi}\partial_z^2 f_i \sim \mp\delta + \dots$ $\qquad f_i = \{W, \tfrac{1}{5}\phi, \tfrac{1}{2}\lambda\}$

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



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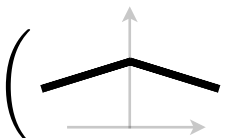
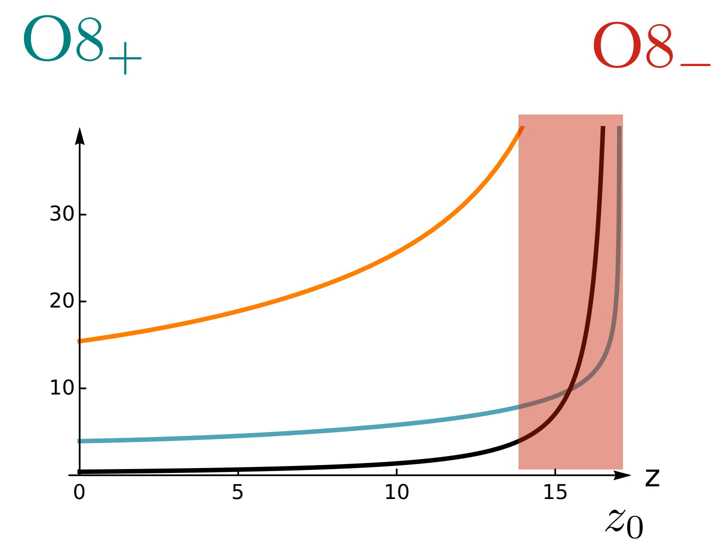
- O8$_+$: $\partial_z^2\Big($  $\Big) = -\delta$ ⇨ $e^{W-\phi} f_i'|_{z\to 0^+} = -1$



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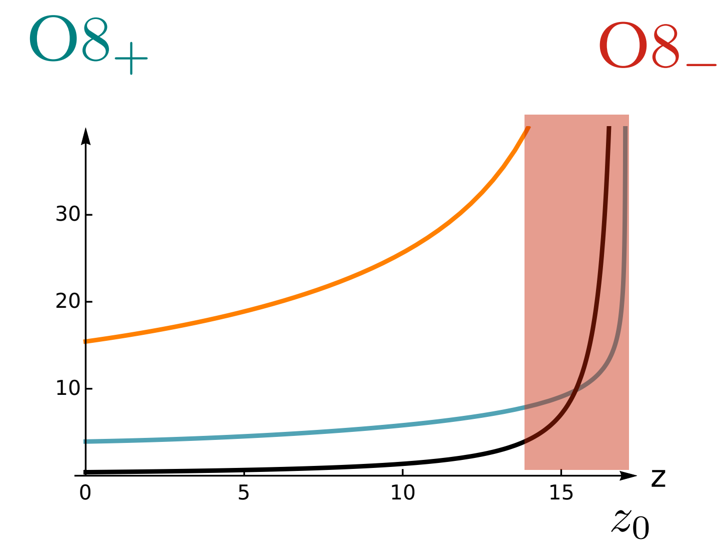

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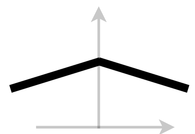
- O8$_+$: $\partial_z^2\Big($  $\Big) = -\delta$ ⇨ $e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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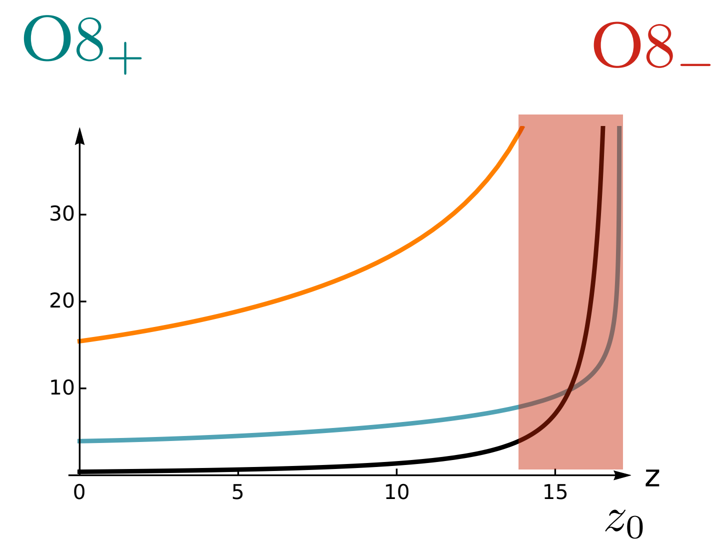

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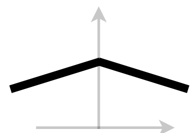
- $O8_+$: $\partial_z^2\Big($  $\Big) = -\delta$ ⇨ $e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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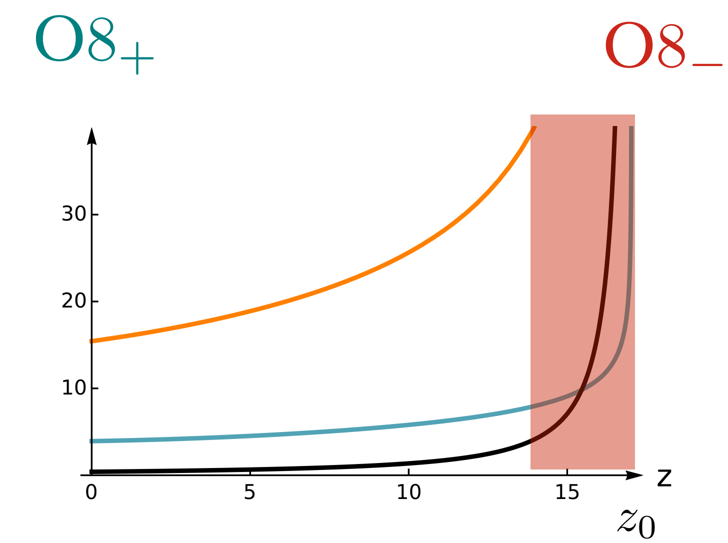
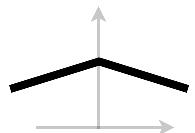


- O8$_+$: $\partial_z^2 \Big($  $\Big) = -\delta$ ⇨ $e^{W-\phi} f_i'|_{z\to 0^+} = -1$

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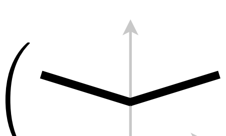
- if we extrapolate from O8$_+$ with $a \neq 0$: $\partial_z^2 \Big($  $\Big) = \delta$ ⇨ $e^{W-\phi} f_i'|_{z\to z_0^+} = 1$

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