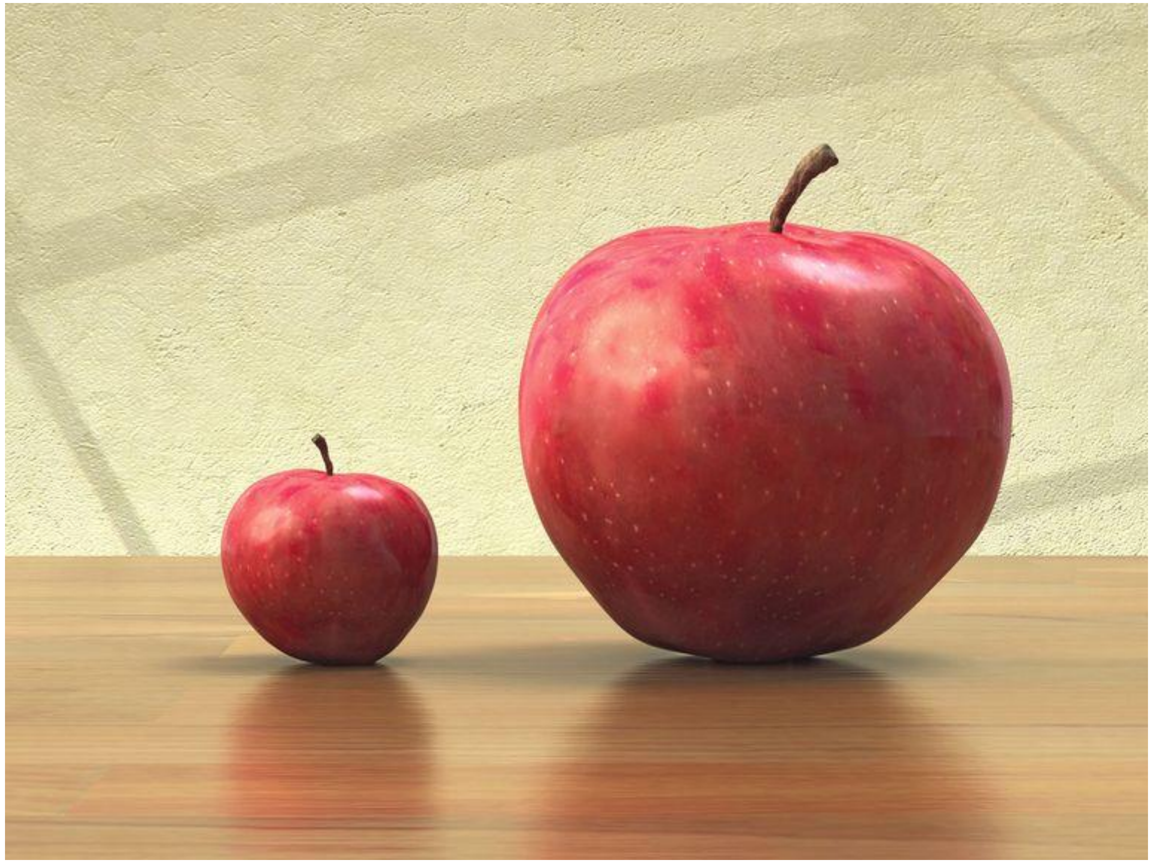
Comments on AdS/KK scale separation



Thomas Van Riet, Leuven (Belgium)

String pheno, Liverpool, 2022

Based on

- *Scale separated AdS_4 vacua of IIA orientifolds and M-theory*, arXiv 2107.00019, with N. Cribiori, D. Junghans, V. Van Hemelryck and T. Wrase.
- *Comments on classical AdS flux vacua with scale separation*, arXiv 2202.00682, with F. Apers, M. Montero and T. Wrase.

Motivation

If the critical superstring is useful for phenomenology then there is a laundry list of requirements on its vacuum structure. We need (many?) vacua of the form

$$ds_{10}^2 = ds_4^2 + ds_6^2$$

where

1. Six extra dimensions are compact and “small enough”

2. All moduli are stabilized.

3. The 4D dimensions can be de Sitter like.

4. With appealing particle pheno.

5….

4d de Sitter? Let's not go there.

4d Minkowski? With less than 8 supercharges unclear whether it exist (cc problem). With 8 or more supercharges, always with moduli space [Palti, Vafa, Weigand 2020].

We settle for Anti-de Sitter space. Interesting as a steppingstone towards de Sitter after "uplift" or for holography.

Extra dimensions "small enough?"

Two length scales $$L_{KK} = \text{Volume}^{1/6} = \frac{1}{M_{KK}}$$ and $$L_{\text{Hubble}} = \frac{1}{M_\Lambda}$$

$$L_{\text{Hubble}} \gg L_{KK} \leftrightarrow M_\Lambda \ll M_{KK}$$

The EFT expectation is that the "typical" cc is order cut-off. The "typical" string flux solution **indeed** obeys:

$$\frac{m_\Lambda}{m_{KK}} = \mathcal{O}(1)$$

The failure of the solution to look 4D is the same as not having a cc hierarchy.

4D QFT predicts "large cc", but 4D QFT is only valid whenever:

$$\frac{m_\Lambda}{m_{KK}} \rightarrow 0$$

Danger of circular reasoning?

Nogos and conjectures

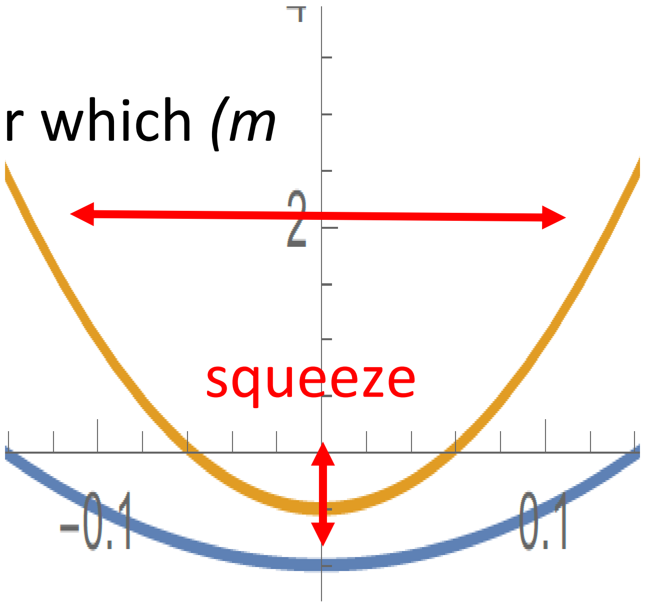
Conjectures?

Strong AdS scale separation conjecture *of* [Lust, Palti, Vafa 2019] claiming ratio of lengthscales is order 1 for **SUSY** AdS vacua. However beautiful refinement by [Buratti et al 2020]: (k is from discrete Z_k 3-form symmetry)

$$L_{KK} = \mathcal{O}(1)\frac{L_{AdS}}{\sqrt{k}} \,.$$

AdS moduli conjecture [Gautason, Van Hemelryck, VR 2018] : AdS vacua for which *(m is mass of lightest scalar)*

$$m_\phi L_{AdS} \gg 1$$



Are in the Swampland. (Difference is that it is a single scalar, not a tower). Dual “dead-end” CFTs with parametric gap in the Swampland.

- **Counter example** to strong AdS distance conjecture by [Lust, Palti, Vafa 2019]

  KKLT & LVS in parametric regimes but especially ***DGKT vacua*** [DeWolfe, Girvayets, Kachru Taylor, 2005]. Focus of this talk**. (**& AdS3 vacua in IIA mimicking DGKT but with G2 space[Farakos, Tringas, VR 2020])

- **Counter example** to refined strong AdS distance conjecture by [Buratti et al 2020]

  AdS3 vacua from massive IIA on G2 space with 06 planes [Farakos, Tringas, VR, 2020] as pointed out in [Apers, Montero, VR, Wrase, 2022]

- **Counter example** to AdS moduli conjecture by [Gautason, Van Hemelryck, VR 2018]

  Linde-Kallosh racetrack finetuning [Kallosh, Linde 2004].

Nogos?

Maldacena-Nunes nogo: Consider a general warped product with a static internal space. Assume higher-dimensional theory obeys Strong Energy Condition. No 4D de Sitter. Also no 4D Minkowski if fluxes are present.

Example for 11d compactifications.

Assume no warping for simplicity, then one easily finds;

$$R_4 = -\frac{4}{3}|F_4|^2 - \frac{8}{3}|F_7|^2 \ ,$$
$$R_7 = \frac{5}{3}|F_4|^2 + \frac{7}{3}|F_7|^2 \ .$$

We only make use of magnetic fluxes, i.e. field strengths with legs entirely along the internal space.

We recognise that $R_4 < 0$ as we expect from Maldacena-Nunez and $R_7 > 0$ [Douglas-Kallosh].

Taking the integrated ratio we find:

$$\left|\frac{\int R_7}{\int R_4}\right| = \frac{5\int|F_4|^2 + 7\int|F_7|^2}{4\int|F_4|^2 + 8\int|F_7|^2} \leq \frac{5}{4}$$

Now define the curvature radius as;

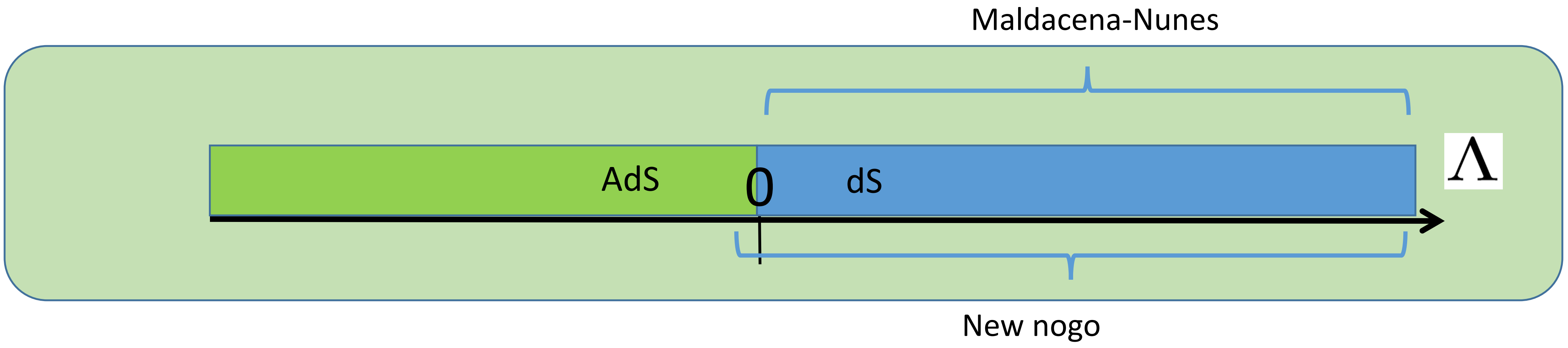
$$L_R^{-2} = \mathrm{vol}_d^{-1} \int \mathrm{d}^d y \sqrt{g_d}\, R_d\,,$$

- For the external dimensions this defines the Hubble length, aka AdS radius L_{AdS}

- **If we assume that L_{KK} cannot be taken to zero at fixed L_R** then we have a nogo for scale separation since we cannot take the ratio L_{KK}/L_{AdS} to be parametrically small. More precise treatment, see [De Luca, Tomasiello, 2104.12773]

- Without sources, internal manifold always has positive curvature [Douglas&Kallosh 2010]

We arrive at an extension of the MN nogo to AdS vacua with scale separation [Gautason, Schillo, Williams, VR 2015]



Important assumption: at fixed positive curvature one cannot shrink L_{KK}

→ Easiest way out: **include negative tension objects** (orientifolds).

Related other recent nogo [Cribiori, Dall' Agata 2022]:

For SUSY 4d AdS vacua preserving more than 4 supercharges, generically absence of scale separation if magnetic WGC holds.

→Probably extends to all SUSY AdS vacua with more than 4 Q's.
→ If so, no scale separation for SUSY vacua in D>4
→ AdS/CFT proof using charge bounds?

Scale separated AdS vacua from 10D IIA orientifolds

Remarkable: In IIA Romans supergravity on CY with fluxes and O6 planes we can achieve moduli stabilization& scale separation with arbitrary good control! [DeWolfe et al 2005]. No alpha' corrections or quantum corrections.

$$\mathrm{vol}_6 \sim n^{3/2} \qquad g_s \sim n^{-3/4} \qquad \boxed{\frac{L^2_{\mathrm{KK}}}{L^2_{\mathrm{AdS}}} \sim n^{-1} \to 0.}$$

n is F4 flux quantum and is **not** bounded by tadpoles.

Backreaction of **<u>intersecting</u>** O6 planes not well understood. No worries in large volume, weak coupling limit [Baines, VR 2020]? *However, now O6 planes intersect:*

⊗	⊗	⊗	—	—	—
⊗	—	—	⊗	⊗	—
—	⊗	—	—	⊗	⊗
—	—	⊗	⊗	—	⊗

Despite certain beliefs intersecting brane solutions in SUGRA are **not known**, only upon partial smearing.

Solution has always been contrived [Banks, Van den broek 2006, Sethi, McOrist 2012]. Recent progress: backreaction understood at "first order" in perturbation [Junghans 2020, Marchesano et al 2020]. Although it ignores intersection ☹

Our goal: can we lift the solution to 11D such that sources ``geometrize"? Recall: D6 branes lift to Taub-Nut and (simple) O6 configuration to Atyah-Hitchin [Seiberg-Witten 1996]. All smooth and no sources in 11D.

Obstacle: Romans mass F_0. But is it really required?

→ Only for geometries that are CY in smeared limit. [Lüst-Tsimpis-Koerber-Caviezel-Zagermann,-… 2004-2009]. General solution on *SU(3)-structure* fluxes

$$H_3 = 2m\,\mathrm{Re}\,\Omega,$$
$$g_sF_0 = 5m,$$
$$g_sF_2 = \frac{\tilde{m}}{3}J + \mathrm{i}\mathcal{W}_2,$$
$$g_sF_4 = \frac{3}{2}mJ\wedge J,$$
$$g_sF_6 = 3\tilde{m}\,\mathrm{dvol}_6.$$

geometry

$$\mathrm{d}J = 2\tilde{m}\,\mathrm{Re}\,\Omega\,,$$
$$\mathrm{d}\Omega = -\frac{4}{3}\mathrm{i}\,\tilde{m}J\wedge J + \mathcal{W}_2\wedge J\,,$$
$$\frac{1}{L_H^2} = m^2 + \tilde{m}^2\,.$$

Sources

$$g_s j_3 = \mathrm{i}\,\mathrm{d}\mathcal{W}_2 + \left(\frac{2}{3}\tilde{m}^2 - 10m^2\right)\mathrm{Re}\,\Omega.$$

This source term represents the O6: $dF_2 = F_0H_3 + j_3$

- We can m=0 and keep $\tilde{m}$. Iwasawa space is a **concrete** example, which can be obtained from double T-duality of torus solution [Lust et al 2008].

- **Easiest to present solution in terms of 3 T^2s** and scale their volumes *separately*.

- F_6 fluxes and parts of F_2, not constrained by RR tadpoles:
  A. F_6 scales like n^a,
  B. F_2 along e_{35} scales as n^b,
  C. F_2 along e_{24} scales as n^c .

  When (a,b,c>0), one can show that "second torus" determines KK scale and:

$$\boxed{\frac{L_{\mathrm{KK}}^2}{L_H^2} \sim n^{-b}}$$

For simplicity we take b=c

When: $a = 1,\ b = c = \frac{1}{4}$:

$$L \sim n^{\frac{1}{4}}, \qquad L_H \sim n^{\frac{3}{8}}, \qquad g_s \sim n^{-\frac{1}{8}}.$$

→ **Weakly coupled & curved solution in massless IIA.**

When: $a = 1,\ b = c = \frac{1}{8}$:

$$L \sim n^{\frac{1}{4}}, \qquad L_H \sim n^{\frac{5}{16}}, \qquad g_s \sim n^{\frac{1}{16}}.$$

→ **Strongly coupled IIA but weakly curved solution in 11D without explicit sources?**

O6 plane does need to backreact heavily at large g_s if ratio g_s/L goes to zero, with L size of space transverse to O6.

Scale separated AdS vacua from 11D fluxes?

Going from 11D to 10D string frame proceeds via the Ansatz:

$$\mathrm{d}s_{11}^2 = \mathrm{e}^{-\frac{2}{3}\phi}\mathrm{d}s_{10}^2 + \mathrm{e}^{\frac{4}{3}\phi}(\mathrm{d}z + C_1)^2$$

F_2 closed, *up to a localized source,* is necessary requirement to lift. *Not true for smeared solutions: $dF_2 = j_3$.   What now?*

First-order backreaction [Junghans 2020, Marchesano, Palti, Quirant, Tomasiello 2020]

For massive IIA solutions. Do perturbation theory in g_s or in 1/n and keep first-order correction to smeared solution. See also [Tomasiello&Sarraco 2012]

We repeated this for our massless IIA solutions. Here is a rough sketch of the idea:

$$e^{-\phi} \equiv \mathcal{T} = n^{(3b+3c-a)/4}\left[\mathcal{T}^{(0)} + \mathcal{T}^{(1)} n^{-b} + \mathcal{O}(n^{-2b})\right],$$
$$L_H e^{A} \equiv w = n^{(a+b+c)/4}\left[w^{(0)} + w^{(1)} n^{-b} + \mathcal{O}(n^{-2b})\right].$$

…and so on, for all bosonic sugra fields.

After quite some pain "we" obtained something like

$$\nabla^2 \mathcal{T}^{(1)} = -\frac{3}{2}\sum_i \left(j_{\pi_i} - \delta(\pi_i)\right),$$
$$\nabla^2 w^{(1)} = \frac{1}{2}\frac{w^{(0)}}{\mathcal{T}^{(0)}}\sum_i \left(j_{\pi_i} - \delta(\pi_i)\right),$$

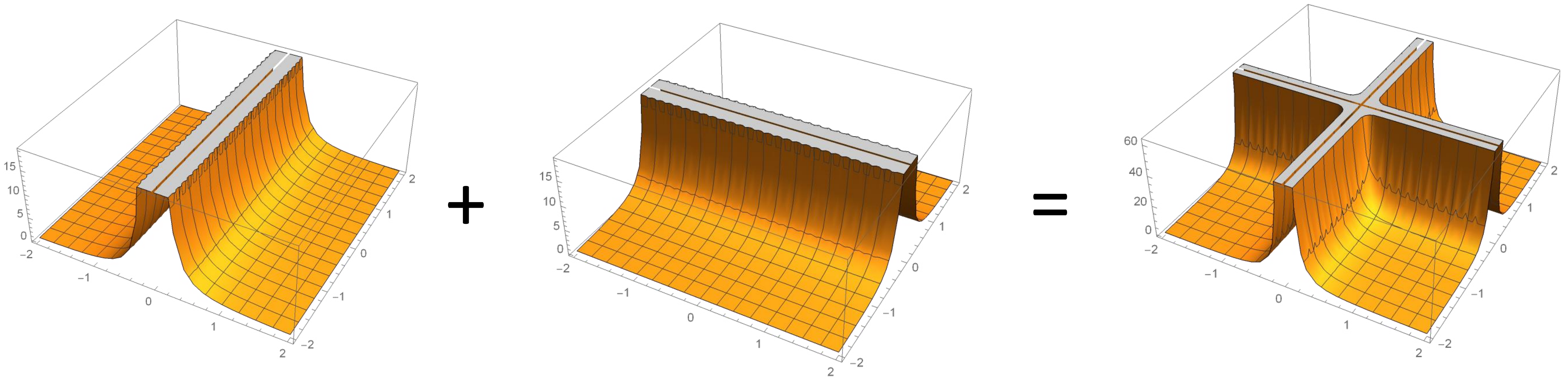
where

$$w^{(1)} = w^{(0)}\beta_i$$
$$\mathcal{T}^{(1)} = -3\mathcal{T}^{(0)}\beta_i\,;$$

obeying

$$\boxed{\nabla^2 \beta_i = \frac{1}{2\mathcal{T}^{(0)}}\left(j_{\pi_i} - \delta(\pi_i)\right)}$$

Intuitive picture;



Without backreaction effects (ie beyond smearing) one would get inconsistent results. Example:

$$\hat{R}_7 = \frac{R_6}{\mathcal{T}^{2/3}} - \frac{|F_2|^2}{2\mathcal{T}^{8/3}} \,,$$

→ Strictly negative since $R_6<0$

We indeed find;

$$\hat{R}_7 = \frac{R_6}{\mathcal{T}^{2/3}} - \frac{|F_2|^2}{2\mathcal{T}^{8/3}} + backreaction\ \ corrections > 0$$

We find no warping in 11D, indeed source-less solution. But O6 resolution unclear at intersections. SUSY analysis in 11d not fully understood in general.

Even more, our solution seems of the Freund-Rubin type in 11d! Is this the wanted "strange" (Einstein) space for which we can shrink the KK scale at fixed curvature? Direct clash with CFT conjecture of [Collins, Jafferis, Vafa, Xu, Yau, 2201.03660]

AdS/CFT?

- Dual CFTs have only few low lying single trace scalar operators, then a parametric gap!

$$\Delta = \frac{3}{2} + \frac{1}{2}\sqrt{9 + 4\kappa^2} \gg 1 \qquad mR = \kappa \gg 1$$

- Even more special: scale separated AdS vacua suited for uplifting have no tachyons, so no relevant deformations: **Dead-end CFTs with huge gap.** This gets close to understanding whether pure AdS gravity has a dual?

- Early investigation on CFT dual to IIA vacua [Aharony et al 2008], but new investigation [Conlon, Ning Revello, 2021] shows **all such operator dimensions in DGKT are integer**! This was then generalized to other orbifolds and non-SUSY vacua [Apers, Montero, VR, Wrase 2022]. Full proof for **any CY** was then given in [Apers, Conlon, Ning, Revello, 2022] based on formalism of [Marchesano, Quirant 2019]. However, there is a class of non-SUSY vacua that has non-integers [Quirant 2022].

Modulus	Operator dimension Δ
1. $h_-^{1,1}$ saxionic Kähler moduli from J	6
1. $h_-^{1,1}$ axionic Kähler moduli from B_2	5
2. The dilaton direction	10
2. The C_3-axion appearing in W	11
3. $h^{2,1}$ saxionic complex structure moduli from $Re(\Omega)$	1 or 2
3. $h^{2,1}$ massless C_3-axions	3

Table 2: Summary of integer operator dimension of a putative CFT_3 dual for generic supersymmetric DGKT type AdS_4 vacua.

Modulus	Operator dimension Δ
1. $h_-^{1,1}$ saxionic Kähler moduli from J	6
1. $h_-^{1,1}$ axionic Kähler moduli from B_2	8
2. The dilaton direction	10
2. The C_3-axion appearing in W	1 or 2
3. $h^{2,1}$ saxionic complex structure moduli from $Re(\Omega)$	1 or 2
3. $h^{2,1}$ massless C_3-axions	3

Table 3: Summary of integer operator dimension of a putative CFT_3 dual for non-supersymmetric DGKT type AdS_4 vacua obtained by flipping the signs of F_4-flux quanta. Note that all non-flat axionic directions have different masses now.

[Collins, Jafferis, Vafa, Xu, Yau, 2201.03660]

Large set of holographic CFTs checked from branes probing singularities in general geometries: Sasaki-Einstein, sphere quotients.

There is universal upper bound for dimension of first non-trivial spin 2 operator.
The internal space for the CFT dual has minimal diameter in AdS units.

→ Conjecture it holds for all CFTs

→ Our 11D lift would provide counter-example since 11D geometry is AdS_4 x $Einstein_7$ with $Einstein_7$ some generalized G2 structure.

Outlook

Summary

Flux compactifications with sources work such that

integrated equations of motion = zero KK mode truncation =smearing

At that level we have :

- solutions **beyond** DGKT with moduli stab. & scale sep. & param. control in **massless** IIA.
- Strongly coupled but weakly curved solutions in massless IIA suited for lifting to 11D.
- Lift required a first-order backreaction computation and then behaves well. Seems a sourceless (smooth) Freund Rubin geometry → **an Einstein geometry for which *at fixed positive curvature one can shrink the KK length scale?*** Goes against [Collins, Jafferis, Vafa, Xu, Yau, 2201.03660]

Future?

- Go beyond first-order backreaction. Can we see intersection at second order?
- Study M theory directly. General properties 7D space: how does it shrink KK scale at fixed curvature? Any relation with M-theory moduli stabilization scenario's of [Acharyah 2002]?
- **Holographic duals to scale separated AdS?! First tackle D>4 and Q>4?**

EXTRA SLIDES

We can m=0 and keep m̃ . Iwasawa space is a **concrete** example, which can be obtained from double T-duality of torus solution [Lust et al 2008].

$$ds_6^2 = (L_1^{-1}e^1)^2 + (L_2 e^2)^2 + (L_3 e^3)^2 + (L_2 e^4)^2 + (L_3 e^5)^2 + (L_1^{-1}e^6)^2,$$

$$de^1 = -e^{23} - e^{45}, \qquad de^6 = -e^{34} - e^{25}. \qquad L_T \equiv L_1^{-1}$$

$$\begin{aligned} J &= -L_T^2 e^{16} - L_2^2 e^{24} + L_3^2 e^{35}, \\ \mathrm{Re}\,\Omega &= L_T L_2 L_3 \left(e^{456} + e^{236} - e^{134} - e^{125}\right), \\ \mathrm{Im}\,\Omega &= L_T L_2 L_3 \left(e^{123} + e^{145} + e^{256} + e^{346}\right), \\ \mathcal{W}_2 &= \frac{8\tilde{m}}{3}\mathrm{i}\left(-2L_T^2 e^{16} + L_2^2 e^{24} - L_3^2 e^{35}\right), \end{aligned}$$

Fluxes as in previous formulae with m=0.

Smearing: replace delta with “1” and then S=1, etc and one obtains “smeared solution”.
Then 1-1 relation between effective action and 10D solutions.

$$\delta(\vec{x}) = \sum_{\vec{n}} e^{i\vec{n}\cdot\vec{x}} \qquad \to \qquad 1$$

Your standard way of truncating KK modes.

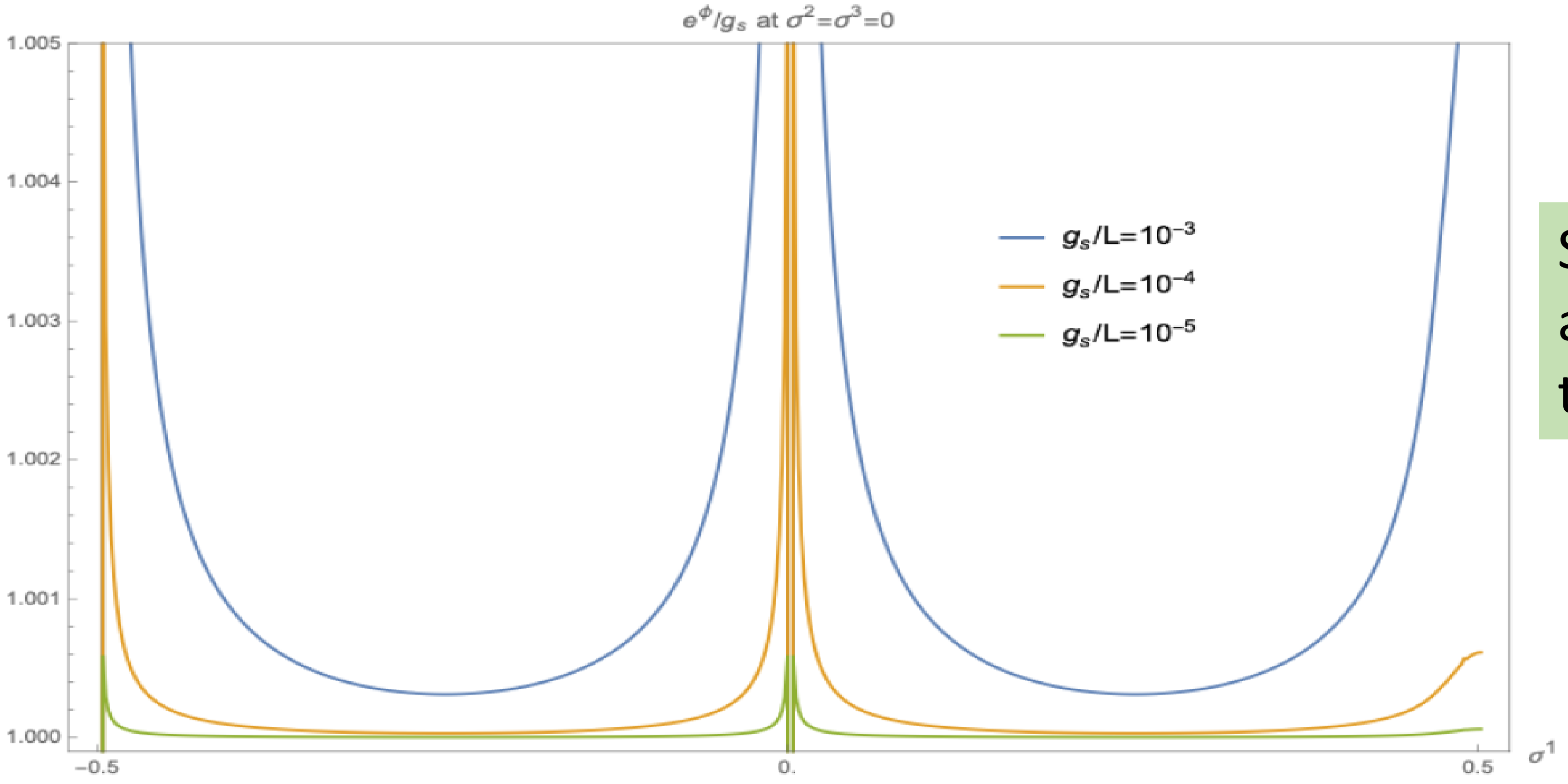
Is smearing bad?

→The “dressing with warping” does not affect the moduli positions.
→The model can be solved exactly and helps understanding

Eg the dilaton:

$$e^{\phi} = e^{\phi_0}\left[1 + 2\frac{1}{L}g_s\sum_{i=1}^{8}\int_0^{\infty} dt\left(1 - \prod_{m=1}^{3}\theta_3\left(\sigma^m - \sigma_i^m|4\pi i t\right)\right)\right]^{-3/4}$$

Where L^3 is volume 3-torus. *Small g_s, large L limit is possible and makes deviations from smeared solution confined to arbitrary small regions.*



Smearing is really good approximation in exactly the parametric regime.