Moduli stabilization, scale separation, holography,…

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Disclaimer

Too little love for Large Volume Scenario & KKLT & M-theory on G2 or heterotic model building. Partially covered by some of the research talks.

No de Sitter in this talk. See overview-talk Severin (or the review [Bena, Graña, VR 2023])

Outline

1. Motivation
2. IIA flux vacua
3. Holography
4. Swampland

Motivation

String phenomenology "in the conventional way" (…) requires small enough extra dimensions *and* stabilization of moduli.

→ Can we get these features? If so, *how* small and *how* stabilized?

→ To get maximal computational control over this question we can study this in **AdS** .

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Vanilla top-down (understood) AdS/CFT pairs seem to feature

$$AdS_d \times X_n$$

With d>2 and X a compact 11-d or 10-d dimensional space with same size radius as AdS.

Can we make X small as we want in AdS units? If so, what is the dual CFT?
In other words: **How many large bulk dimensions does a holographic CFT in D dimensions reproduce? 10, 11, or less?**

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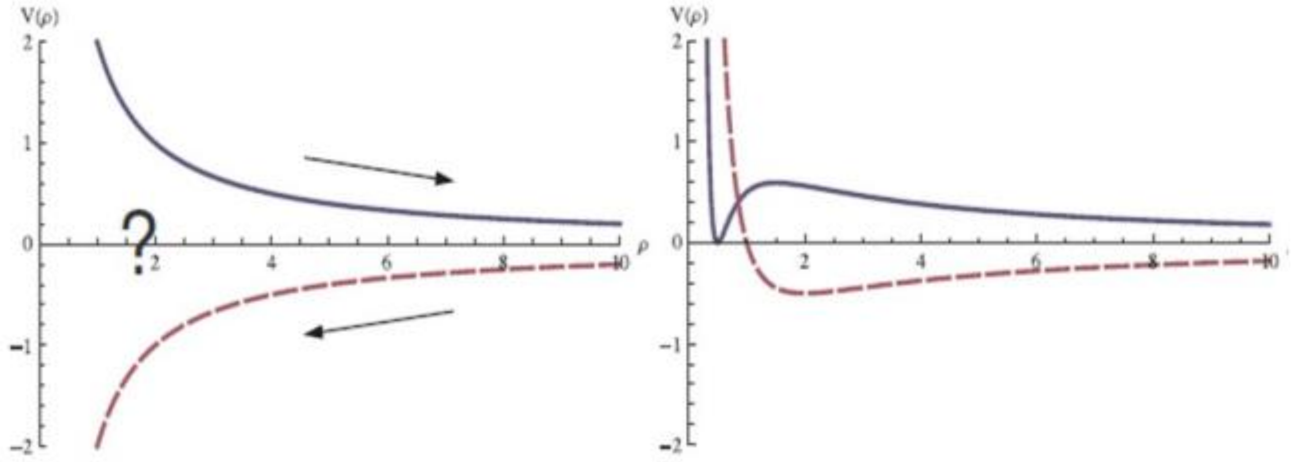
When SUSY is broken one cannot expect massless fields. Generic expectation is moduli fields at SUSY breaking scale? So what is our worry?→ It is **a computational worry** aka Dine-Seiberg problem:



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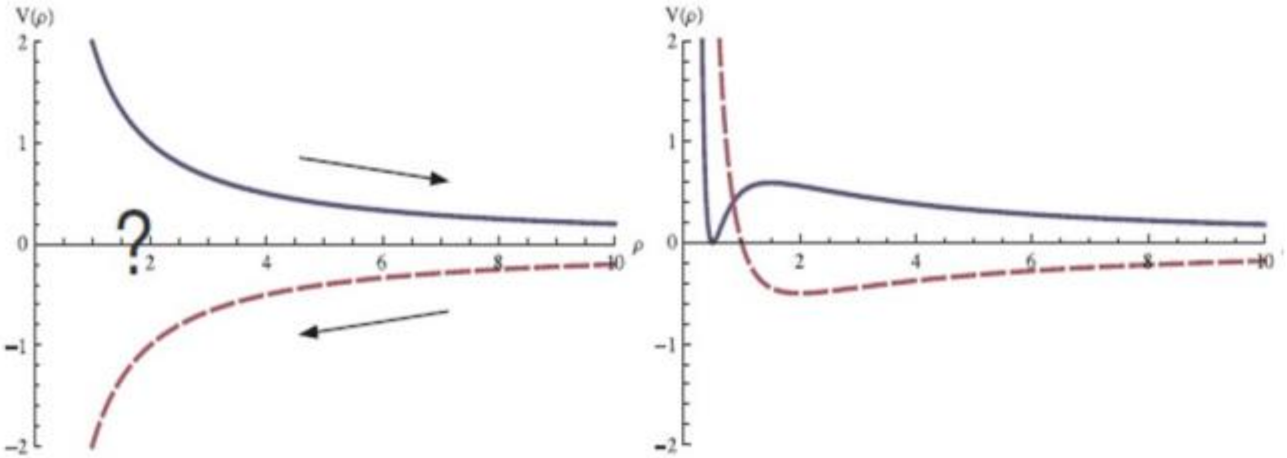

Before uplift, (SUSY?) AdS vacuum with moduli stabilization is dual to **isolated CFT** with sparse spectrum of low-lying single trace scalar operators.
Bizar CFTs. See [Polchinski&Silverstein 2009, Alday&Perlmutter 2019].

Scale separation: extra dimensions "small enough?"

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

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

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

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

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4D QFT predicts "large cc", but 4D QFT is only valid whenever: $\frac{m_{\Lambda}}{m_{KK}} \to 0$

But, there are **nogos** and **conjectures** against scale separation **on the gravity side**.

Nogo-Example for 11d compactifications.

Assume no warping for simplicity, then one easily finds;

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

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

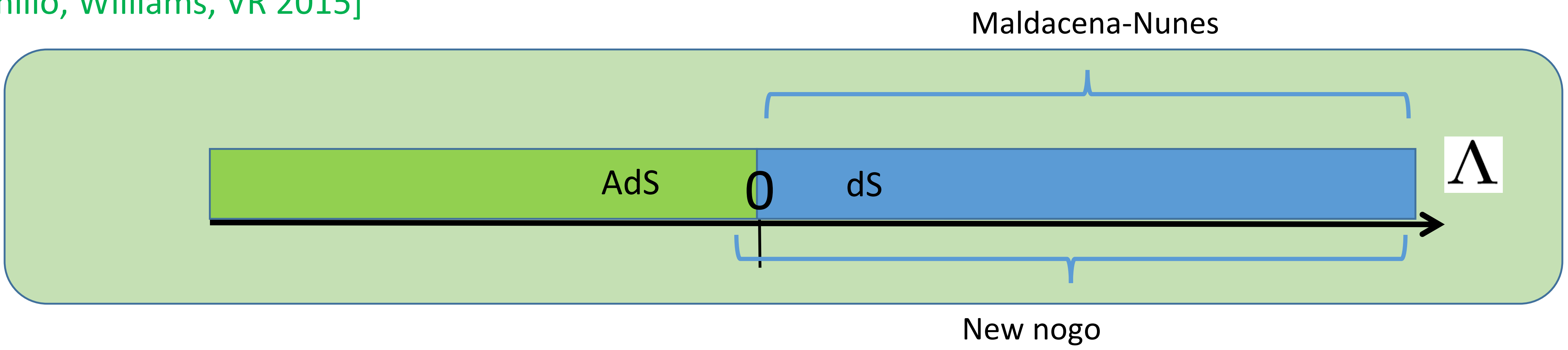
Taking the integrated ratio we find:

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

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 → nogo for scale separation.

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



Precise & complete treatment, see [De Luca, Tomasiello, 2104.12773]

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Scale separation MUST be build on for consistency, if solutions are obtained within the framework of (N=1) EFTs. Means not 100% top-down. All scale sep vacua are found within framework. <u>This is the reason we have debates and conferences and this talk</u>.

(*) Not always: bottom-up AdS duals to isolated CFTs. Eg AdS7 x S^4. But these are the examples with extended SUSY.

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- For the “classical solutions” (fluxes + orientifold) and the Casimir-supported ones, scale separation can be made **arbitrarily large. Infinite landscape because of unbounded flux quantum N.**

- The others in IIB: LVS, KKLT,… have bounded fluxes. But scale separation claimed to be exponentially strong, see impressive advances Cornell group on KKLT.

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Abbreviation invented by **E. Perlmutter**

AdS Scale Separation (ASS) classical?

For a review see [Coudarchet 2023]

Quick and dirty method

→ Just focus on volume and string coupling.

Metric in 10d string frame: $ds_{10}^2 = \tau_0^2 \tau^{-2} ds_D^2 + \rho \, ds_{10-D}^2 \, .$

where $\tau^{8-D} = \rho^{D/2} e^{-2\phi}$ in order to get D-dimensional Einstein frame Lagrangian:

$$S_D = \int d^D x \sqrt{-g_D} \left[\tau_0^{D-2} R_D - \tau_0^D V + \ldots \right] \, .$$

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So we read of that $M_P = \tau_0$. To estimate KK scale we simply take $L_{KK}^2 \sim \rho_0$

The AdS scale we get from the Einstein equation:

$$R_D = \frac{D}{D-2} M_P^2 V \,, \quad \text{where} \quad L_{\rm AdS}^{-2} = M_P^2 V .$$

→

$$\frac{L_{KK}^2}{L_{\rm AdS}^2} \sim \rho_0 \, \tau_0^2 \, V .$$

Knowing the volume and dilaton dependence in the scalar potential can tell us much!

At string tree-level we find

$$
\begin{aligned}
V_R &= U_R \rho^{-1} \tau^{-2} \, , \\
V_H &= U_H \rho^{-3} \tau^{-2} \, , \\
V_n^{RR} &= U_n \tau^{-4} \rho^{3-n} \, , \\
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Eg, take IIA string theory on a Ricci-flat background with O6 planes, F_4-, H_3- and F_0-flux:

$$V = U_H\rho^{-3}\tau^{-2} + U_0\tau^{-4}\rho^{3} + U_4\tau^{-4}\rho^{-1} + U_{O6}\tau^{-3}\,.$$

$$\rho\,\partial_\rho V = 0\,, \qquad \Longrightarrow \qquad -3V_H + 3V_0 - V_4 = 0\,,$$
$$\tau\,\partial_\tau V = 0\,, \qquad \Longrightarrow \qquad -2V_H - 4(V_0 + V_4) - 3V_{O6} = 0\,.$$

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$$V = V_H + V_0 + V_4 + V_{O6} = -\frac{4}{9} V_4 < 0 .$$

Only F4 flux is unconstrained by tadpoles: $N = \int F_4 \,,$

We will consider the large N limit. The only way all terms in the potential can balance against each other is if:

$$\rho \sim N^B \qquad \tau \sim N^A$$

Then: $V \sim U_H \, N^{-2A-3B} + U_0 \, N^{-4A+3B} + N^{2-4A-B} + U_{O6} \, N^{-3A} \,.$

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If we take $B = 1/2$ and $A = 3/2$ *all components scale in the same fashion with* N.

- V goes like $N^{-9/2} \rightarrow 0$
- Scale separation: $\rho_0 \tau_0^2 V \sim N^{-1} \rightarrow 0$
- Weak coupling and large volume: $e^{-2\phi_0} = \tau_0^2 \rho_0^{-3} = N^{3/2} \rightarrow \infty.$ $\quad \rho_0 \sim N^{\frac{1}{2}} \rightarrow \infty$

Do better: using N=1 SUGRA from 10d reduction

[2004-2005: DeWolfe et al, Derendinger et al, Camara et al, Villadoro et al]

[Grimm& Louis 2004] Formulas for N=1 CY_3 orientifolds in IIA with fluxes. In memory of the late [Kounnas] who passionately complained about CY with fluxes not being CY. → See below

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Kahler sector:

$$J_c \equiv B_2 + iJ\,, \qquad K^K(t_a) = -\log(\frac{4}{3}\int J\wedge J\wedge J)$$

$$W^K(t_a) = e_0 + \int J_c \wedge F_4 - \frac{1}{2}\int J_c\wedge J_c\wedge F_2 - \frac{m_0}{6}\int J_c\wedge J_c\wedge J_c\,,$$

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Complex structure sector:

$$\Omega_c \equiv C_3 + 2i\mathrm{Re}\,(C\Omega)\,, \qquad K^{cs} = -\log\left(i\int \Omega\wedge\overline{\Omega}\right)$$

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→ Minimize V, either from solving F-term (and D-term) equations for SUSY vacua: indeed scale separation. But also non-SUSY scale separated vacua, from eg flipping sign of F_4.

Do even better: 10d solutions?

"Solution" in 10D picture [Grana, et al 2006; Lust, Tsimpis et al 2006-…; Acharya et al 2006]

$$e^{\phi} F_0 = 5m \,,$$
$$e^{\phi} F_4 = \frac{3}{2} m J \wedge J \,,$$
$$H = 2m\Omega_R \,,$$
$$e^{-\phi} j_{O6} = -10m^2 \Omega_R$$

$$\Lambda = -6M_p^2 m^2$$

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$$J = \rho^2\left(\mathrm{d}x^1\wedge\mathrm{d}x^2 + \mathrm{d}x^3\wedge\mathrm{d}x^4 + \mathrm{d}x^5\wedge\mathrm{d}x^6\right),$$
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Backreaction of O6 planes not well understood and so contrived. [Kounnas 2004; Banks, Van den Broek 2006; McOrist, Sethi 2012].

→ ***Not yet the real deal?***

Solving the dimensionally reduced theory, means solving the integrated EOM.

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

Then 1-1 relation between effective action and 10D solutions.

Is smearing bad?

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Is smearing bad?

- Wilsonian viewpoint: Since when is course graining evil?
- For IIB with 3-form fluxes and O3/O7 [GKP 2001] the backreaction, ie localization, just means "dressing with warping" and that does not affect the moduli positions.
- Even in IIA with F_0 and O6 branes, no worries in large volume, weak coupling limit [Baines, VR 2020] for *non-intersecting* O6 planes.

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Note the analogy with the attempts to understand KKLT AdS in 10 dimensions: [cite half the audience] (backreaction of the gaugino condensates and the effect in 4d).

However, now O6 planes intersect. Unlike GKP, backreaction of orientifold planes not well understood.

[Junghans 2023]: *the O6 plane don’t need to intersect. Depends on details toroidal orbifold.*

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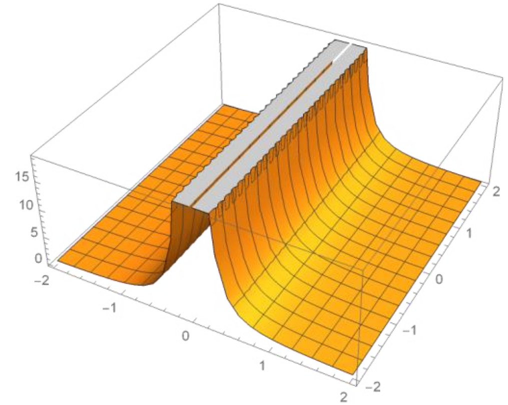
Progress backreaction

1) General results: [Saracco, Tomasiello 2012; DeLuca, Tomassielo 2021]

2) At first order in perturbation (1/N, or g_s) [Junghans 2020; Marchesano et al 2020]. Although it ignores "*intersection*": a linearization in backreaction:



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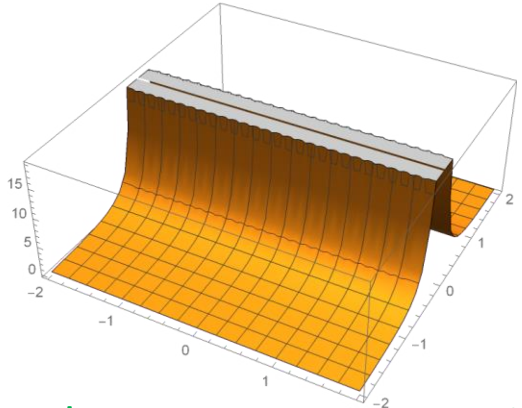

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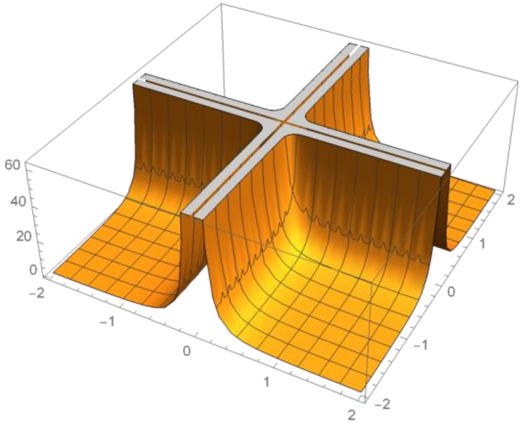

See also: [Cribiori, Junghans,Van Hemelryck,VR,Wrase; 2021 Cribiori,Emelin, Farakos, Tringas 2022; Andriot, Tringas 2023]

More solutions than the original ones of [2004-2005: DeWolfe et al; Derendinger et al; Camara et al, Villadoro et al; Acharya et al]

1. General classification results within IIA on (generalized) CY_3 with O6 planes. [Marchesano, Prieto, Quirant, Shukla 2020; Carrasco, Coudarchet, Marchesano, Prieto 2023; Tringas 2023]

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4. AdS_3 vacua in massive IIA on G2 spaces with O6 planes [Farakos, Tringas, VR 2020; Van Hemelryck 2022; Emelin, Farakos, Tringas 2022, Farakos, Morittu, Tringas 2023;]

AdS/CFT?

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

$$\Delta = \frac{d}{2} + \sqrt{\frac{d}{2} + m^2 L_{AdS}^2} \gg 1$$

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1) "The holographic gap", which is the gap to the higher spin operators (dual to string states.) This gap should be large in case one wants to recover weakly coupled gravity in the bulk. Somewhat enforced by large N.

2) In the spectrum of single trace scalar operators, dual to supergravity scalars, one expects only a few low lying operators and then a gap, dual to the KK spectrum.

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

General **beliefs** [Silverstein, Polchinski 2009, Alday, Perlmutter 2019]:

- R-symmetry gives protected operators, $\Delta \sim q_R$ hence we need minimal susy and no isometries of internal space. Yet, no clean proof of this fact! Why would chiral primaries be the start of a whole tower of single trace operators?

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→ Example: [Alday, Chester 2022] considered holographic dual to pure N = 8 SUGRA in AdS_5 in the large AdS limit, which is dual to the N = 4 stress-energy tensor superconformal multiplet (and multi-trace descendants of it); Model satisfies (saturates) certain bootstrap constraints.

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[Montero, Rocek, Vafa 2023]: pure supergravity theories in AdS with enough SUSY lead, in the large radius limit, to flat space quantum gravities with a nonperturbatively exact global symmetry, so in the Swampland.

[Alday, Perlmutter 2019] loop diagrams in the bulk are sensitive to scale separation since they are affected by all KK modes. Such diagrams are dual to certain non-planar CFT correlators and the main idea is then that there exists a way to define the number of large bulk dimensions purely from CFT data.

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[Collins, Jafferis, Vafa, Xu, Yau, 2201.03660] Studies large set of holographic CFTs from branes probing singularities in Sasaki-Einstein, sphere quotients: *a universal upper bound for dimension of first non-trivial spin 2 operator. Hence, the internal space for the CFT dual has minimal diameter in AdS units.* → Conjecture it holds for all CFTs

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→The 11D lift of the scale separated IIA vacua without Romans mass would provide a counter-example since 11D geometry is AdS_4 x $Einstein_7$ with $Einstein_7$ some generalized G2 structure.

Curious features of would-be CFT duals to IIA vacua.

Early investigation on CFT_3 dual to AdS_4 IIA vacua [Aharony et al 2008]: The scaling of the central charge $c \sim N^{9/2}$. The AdS_3 vacua have $c \sim N^{4}$.

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Recent investigation [Conlon, Ning Revello, 2021] shows all scalar operator dimensions in [DeWolfe at al, 2005] model are integer?!

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

This was then generalized to other orbifolds [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])

Also true for non-SUSY 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
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Explanation? See [Apers 2022] for comments: polynomial shift symmetries in large N limit on AdS side.

$$\phi \to \phi + c_{\mu_1 \ldots \mu_k} X^{\mu_1} \ldots X^{\mu_k}|_{AdS}, \quad \text{if} \quad m_\phi^2 = \frac{k(k+d)}{R_{AdS}^2}, \quad \Delta_+ = k + d.$$

The AdS_3 vacua have no integer dimensions, Also no discrete Z_N higher form symmetry, which was argued to be the deeper reason for scale separation in AdS4 [Buratti, Calderon, Minnino, Uranga 2020]. Is the discrete symmetry related to polynomial shift symmetries?

Further observations from [Fien Apers, 2023]

Replace large N fluxes in IIA AdS4 vacua with branes and backreact them (domain wall-flux correspondence)

	t	x^1	x^2	x	y_1	y_2	y_3	y_4	y_5	y_6
N_1 **D4**	$\otimes$	$\otimes$	$\otimes$		$\otimes$	$\otimes$				
N_2 **D4**	$\otimes$	$\otimes$	$\otimes$				$\otimes$	$\otimes$		
N_3 **D4**	$\otimes$	$\otimes$	$\otimes$						$\otimes$	$\otimes$

→ Reproduces perfectly the N-dependence of the AdS-length, string coupling, volume, and thus the central charge scaling with N.

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→ But this fails for the IIA AdS3 vacua

	t	x^1	x	y_1	y_2	y_3	y_4	y_5	y_6	y_7
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N_2 **D4**	$\otimes$	$\otimes$				$\otimes$	$\otimes$			$\otimes$
N_3 **D4**	$\otimes$	$\otimes$						$\otimes$	$\otimes$	$\otimes$
N_4 **D4**	$\otimes$	$\otimes$		$\otimes$		$\otimes$			$\otimes$	
N_5 **D4**	$\otimes$	$\otimes$			$\otimes$	$\otimes$		$\otimes$		
N_6 **D4**	$\otimes$	$\otimes$		$\otimes$			$\otimes$	$\otimes$		
N_7 **D4**	$\otimes$	$\otimes$			$\otimes$		$\otimes$		$\otimes$	

LVS, KKLT and the holographic Swampland

[De Alwis, Gupta, Quevedo, Valandro 2015;
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Lust, Vafa, Wiesner, Xu, 2022]

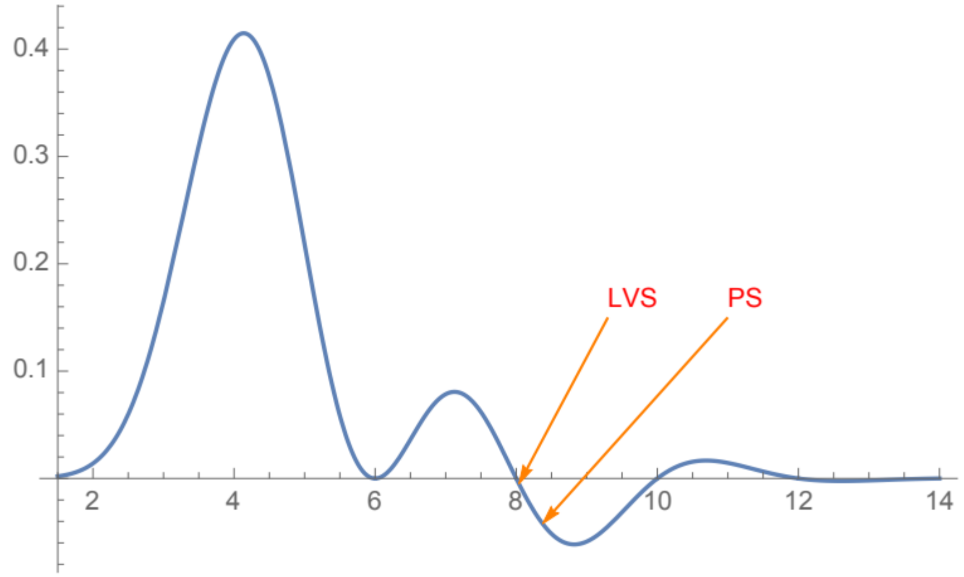
Some swampland consistency constraints are equivalent to a negativity condition on the sign of certain mixed anomalous dimensions.

$$\mathcal{L} \supset e^{-\sqrt{\frac{8}{3}}\frac{\varphi}{M_P}} \partial_\mu a \partial^\mu a,$$

$$f_a S \lesssim M_P,$$

Similar to known CFT positivity bounds arising from causality and unitarity.

Interestingly, the LVS vacuum (with Δϕ=8.038) close to a critical value (Δϕ=8) where anomalous dimensions change sign.



[Lust, Vafa, Wiesner, Xu, 2022]

→ KKLT AdS inconsistent with holography!

Using the c-theorem an overcounting of degrees of freedom is achieved: The tree-level fluxes are traded for domain wall 5-branes and the dof of these branes are counted. One finds:

$$l^2_{\mathrm{AdS}} \lesssim \chi(CY_4).$$

No parametrically large AdS vacua! Even worse:

$$l^2_{\mathrm{species}} \gtrsim \chi(CY_4)$$

So no control: $l_{\mathrm{AdS}}/l_{\mathrm{species}} \lesssim 1$

Hot from the press; [Bobev, David, Hong, Reys, Zhang, to appear]

4d Euclidean N=2 gauged SUGRA with SUSY AdS vacuum, containing N_H hyper- and N_V vector-multiplets *considered as an EFT with some cut-off scale Λ*. Look at SUSY black saddles, ie Euclidean KN black holes (or AdS TN,…) The partition function Z, computed *using heat-kernel techniques* (assumption EFT!) produces a log(L^2)-term:

$$\mathcal{Z} = \ldots + c \log(L^2/G_N) + \ldots$$

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→ **Ways out?**

1) Holography does not work.
2) There is no N=2 AdS EFT. UV modes (KK modes,…,) do not decouple. There is no heat kernel computation in the usual sense, as we have in flat space (Sen et al,…)

- Top-down examples use 2) by having all KK modes contribute such that c-coefficient needs regularization, after which a finite constant number independent of the continuous parameters appears.

- The same gravity statement is true also with minimal or no SUSY. But less understanding of 3d path integrals.

(*) N is something that counts # of dof and C_T is the usual coefficient in the 2pt function of the energy momentum tensor.

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- **Implication:** if EFT+gravity in AdS_4 exists (finitely many fields of spin up to 2) then C_T of dual 3d CFT will contain a log(N) term (in large N expansion) (*). No known CFTs have such C_T & log-terms in local correlation functions. They are not compatible with the usual 't Hooft large N diagramatics. Loopholes?

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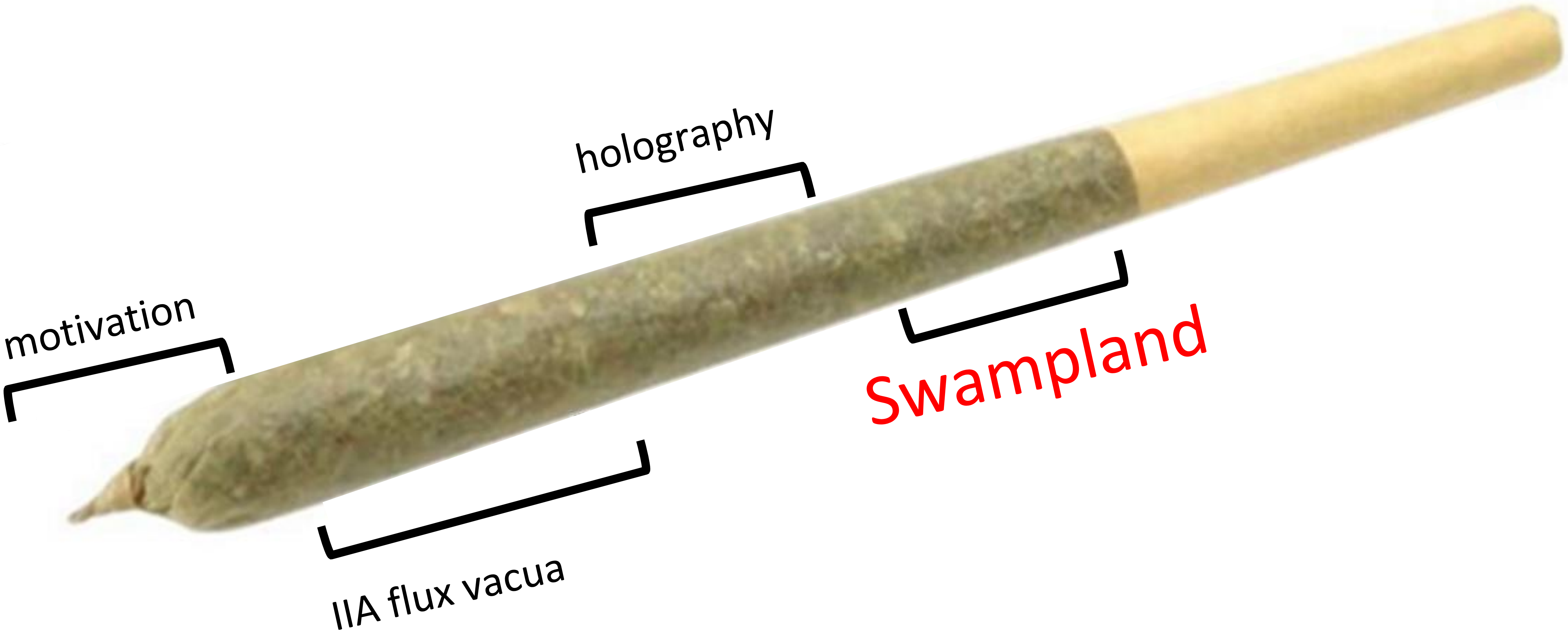
motivation
holography
IIA flux vacua
Swampland

Conjectures

AdS Distance conjecture (ADC) [Palti, Lust, Vafa 2019]: Consider AdS_d space with cc Λ. There exists an infinite tower of states with mass scale m which, as Λ → 0, behaves (in Planck units) as (alpha is O(1))

$$\boxed{m \sim |\Lambda|^{\alpha}}$$

Strong ADC: For SUSY AdS vacua α = ½ → No scale separation.

So non-SUSY scale separation is ok? (See Casimir-supported solutions). No CFT dual?

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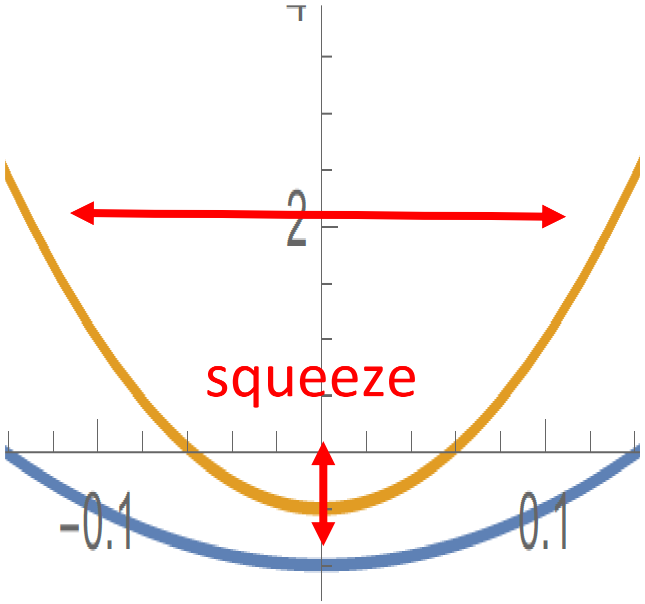
AdS moduli conjecture [Gautason, Van Hemelryck, VR 2018] :
AdS vacua for which *the mass of the lightest scalar obeys*

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

Are in the Swampland.



(Dual "dead-end" CFTs with parametric gap in the Swampland.)

AdS Distance Conjecture (ADC) from **ordinary *distance conjecture*** *[Ooguri, Vafa, 2006]*:

Much evidence, even outside string theory [Stout 2022]

At large geodesic distance Δ in field space from the original vacuum, the mass scale m of a tower of modes becomes lighter as

$$m \sim m_0 \, \mathrm{e}^{-\beta \Delta}$$

with β an order-one number.

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In any case, goal is to compute distances between vacua. Can we interpolate between vacua using scalar fields→ If so we can apply ordinary distance conjecture and compute distances using moduli metric.

→ **Reids-type fantasy** for the whole string landscape: all CY spaces can be deformed into another, *still holds after moduli-stabilization*. Flux numbers can jump continuously without think domain walls. [Shiu, Tonioni, Van Hemelryck, VR 2022, 2023]

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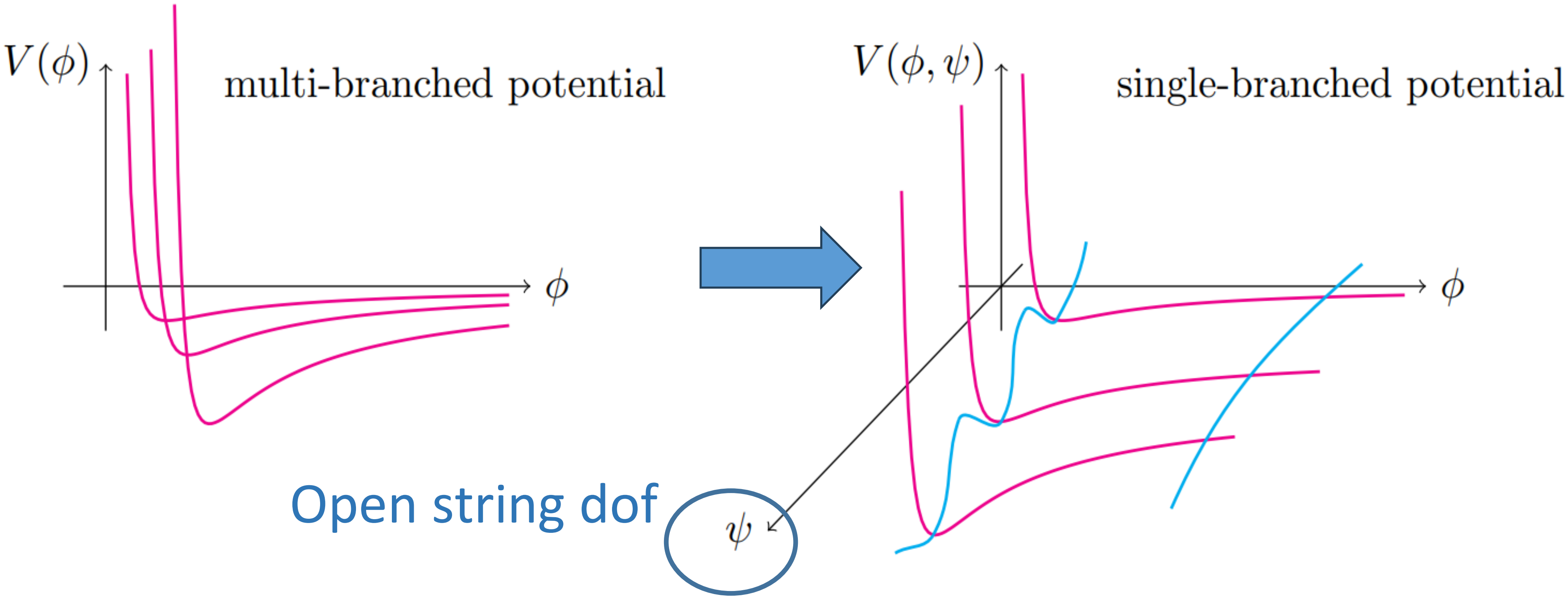

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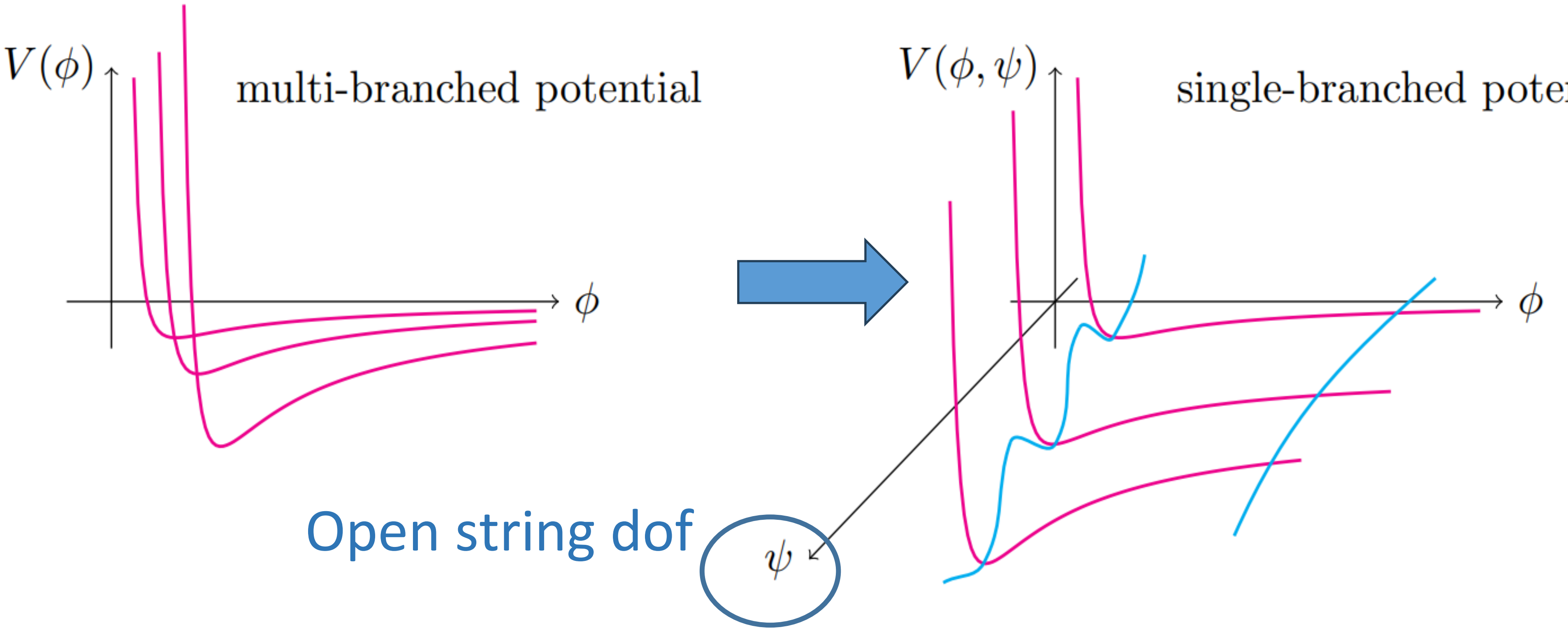

Changing flux quanta without thin domain walls. **Ordinary distance conjecture obeyed** for Freund-Rubin vacua AND scale-separated examples

Why the strong ADC? Mostly from example with **extended SUSY**, or **orbifolds** thereof.

→ **Orbifolding** does not help. Think of S^n/Z_k. You lower the volume at fixed curvature but not the lowest eigenvalue of the Laplacian. You only change degeneracy. So here volume is a bad measure of L_{KK}

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For SUSY 4d AdS vacua preserving Q>4, no scale separation if magnetic WGC holds (*).
[Cribiori, Dall' Agata 2022]

Probably extends to all (any d) SUSY AdS vacua with more than 4 Q's. If so, no scale separation for SUSY vacua in D>4 [Cribiori, Montella 2023]

(of course it holds)*

Outlook

Summary

- Scale separated vacua under control is debated from the bulk viewpoint. Mainly because of orientifold backreaction, or a general lack of proper 10d treatment. But is it needed?

- A holographic understanding/proof of scale separation equally difficult?

- There seems much evidence that supports absence of SUSY AdS scale separation (SASS) with more than 4 real supercharges from WGC and log N correction in Z computed from dual CFT. This also excludes SASS in D>4. So D=4 is special!