EXPLORING THE HOLOGRAPHIC SWAMPLAND

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(based on JC, Quevedo 1811.06276,
JC, Revello 2006.01021
JC, Ning, Revello 2110.06245)

MODULI: A GENERIC PREDICTION

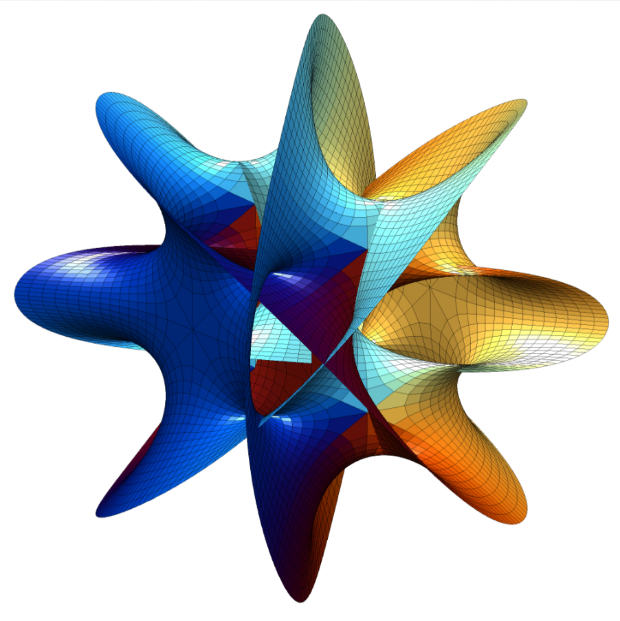
$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{SM} + \mathcal{L}_{BSM}$$

- What is in $\mathcal{L}_{BSM}$?

- Simple concept: *massive scalar* Φ with *gravitationally suppressed couplings* to ordinary matter such as $\frac{\Phi}{M_P} F_{\mu\nu} F^{\mu\nu}$

- Such **moduli** are well motivated from e.g. string theory and extra-dimensional theories

MODULI: WHY?



- String theory is a theory of ***dynamical*** extra dimensions
- In 4d theory, geometry of extra dimensions (size and shape) parametrised by *moduli* - such as Kahler and complex structure moduli.
- Unstabilised, these lead to fifth forces, varying couplings or (fatal) decompactification.
- Essential to develop *moduli potentials* that fix this geometry
- Moduli Stabilisation is a precondition to doing String *Phenomenology*

MODULI STABILISATION

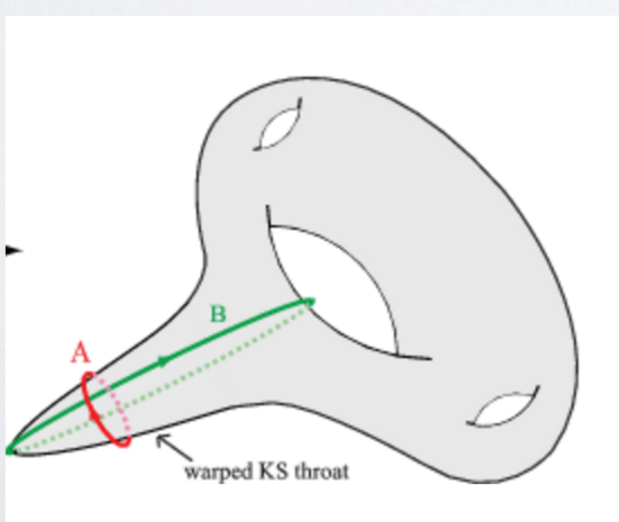
- Much work on developing moduli potentials (LVS, KKLT, DGKT) and studying dynamics in terms of

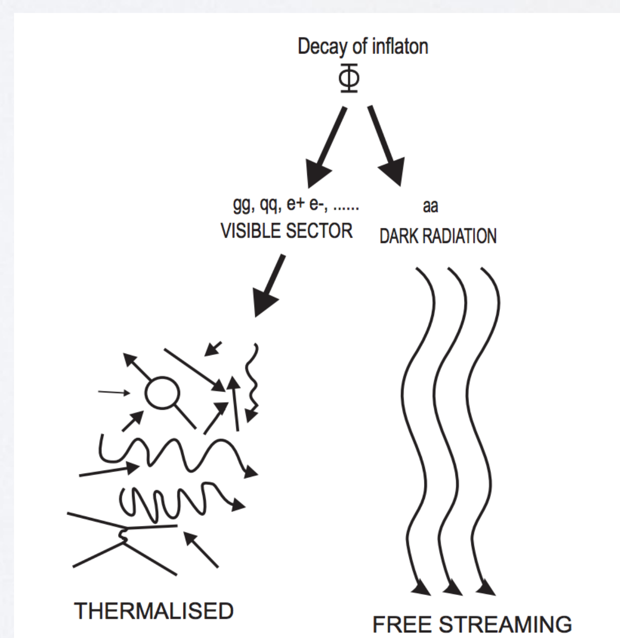
Supersymmetry breaking

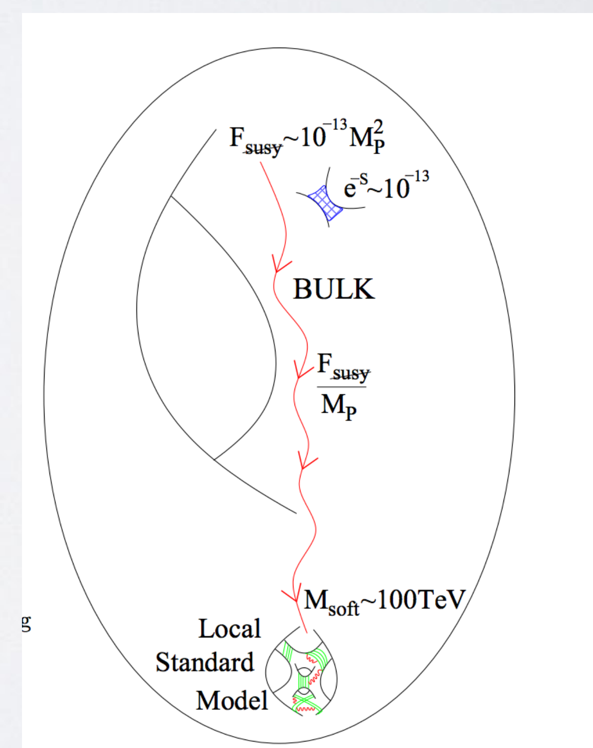
Cosmology - late time de Sitter

Cosmology - inflation

Particle physics







MODULI STABILISATION

- `Natural' vacua arising from moduli stabilisation are often AdS vacua.
- Approaches to making these de Sitter are (in my view) unsatisfactory
- They rely on the observed vacuum energy arising from a fortuitous cancellation to ~50 decimal places and appealing to the Misanthropic Principle.
- This talk focuses on studying and understanding the AdS vacua rather than de Sitter uplifts.

TWO EXAMPLES

- This talk focuses mainly on two examples. These are especially interesting because they are scale-separated vacua *in asymptotic regions of moduli space.*

- LVS (Large Volume Scenario): interplay of α' and non-perturbative effects in IIB flux vacua to give non-susy AdS vacuum with stabilised volume at $\mathscr{V} \sim e^{\frac{c}{g_s}}$ for some constant c

- Type IIA DGKT flux vacua: flux stabilisation can give large volumes and scale separation (Susy / Non-Susy)

LARGE VOLUME SCENARIO

Balasubramanian, Berglund, JC, Quevedo

- Perturbative corrections to K and non-perturbative corrections to W

$$W = \int G_3 \wedge \Omega + \sum_i A_i e^{-2\pi a_i T_i}$$

$$K = -2\ln\left(\mathcal{V} + \xi'\right) + \ln\left(\int \Omega \wedge \bar{\Omega}\right) - \ln(S + \bar{S})$$

- Resulting scalar potential has minimum at *exponentially large* values of the volume

$$V = \frac{A\sqrt{\tau_s}\, e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{B\tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{C}{\mathcal{V}^3}$$

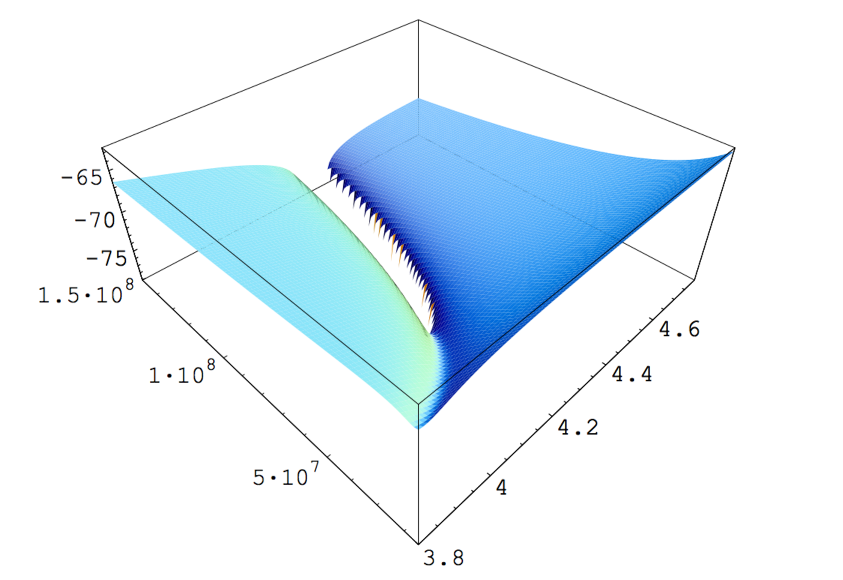


Figure 1: $\ln(V)$ for $P^4_{[1,1,1,6,9]}$ in the large volume limit, as a function of the divisors τ_4 and τ_5. The void channel corresponds to the region where V becomes negative and $\ln(V)$ undefined. As $V \to 0$ at infinite volume, this immediately

LVS PROPERTIES

- In LVS, volume is exponentially large - can easily be

$$\mathcal{V} \sim 10^{50}(2\pi\sqrt{\alpha'})^6$$

- This *generates interesting hierarchies* and ensures *superb parametric decoupling* of heavy modes (KK modes, heavy moduli)

- Decoupling also has a clear geometric origin - large volume

$$\langle \mathcal{V} \rangle \sim e^{\xi/g_s}$$

- $\mathcal{V} \to \infty$ limit of LVS also leads to a unique effective theory

LARGE VOLUME SCENARIO

- LVS effective theory for volume modulus Φ and axion a

$$V_{potential} = V_0 e^{-\lambda\Phi/M_P}\left(-\left(\frac{\Phi}{M_P}\right)^{3/2} + A\right) \qquad \left(\lambda = \sqrt{27/2}\right)$$

$$\mathcal{L}_{kinetic} = \frac{1}{2}\partial_\mu\Phi\partial_\mu\Phi + \frac{3}{4}e^{-\sqrt{\frac{8}{3}}\Phi}\partial_\mu a\partial^\mu a$$

- Solve for minimum and expand about it to determine masses and couplings

DGKT IIA FLUX VACUA

In contrast to type IIB models, fluxes generate a potential for all the moduli, and certain limits give vacua at large volumes with scale separation

- $$V = \frac{p^2}{4}\frac{e^{2D}}{k}e^{-\sqrt{2}\sum_i \phi_i} + \left(\sum_i e_i^2 e^{2\sqrt{2}\phi_i}\right)\frac{e^{4D-\sqrt{2}\sum_i \phi_i}}{2k} + \frac{m_0^2}{2}e^{4D}k e^{\sqrt{2}\sum_i \phi_i} - \sqrt{2}\,|m_0 p|\,e^D .$$

$$\mathscr{L}_{axions} = \frac{1}{4}\sum_{i=1}^{3} e^{-2\sqrt{2}\phi_i}\partial_\mu b_i \partial^\mu b_i + \frac{1}{2}e^{2D}\partial_\mu \xi \partial^\mu \xi - \frac{e^{4D}}{\mathscr{V}}\left(b_1 e_1 + b_2 e_2 + b_3 - p\xi\right)^2$$

$$-\frac{e^{4D}}{2}\sum_{i=1}^{3}\left(m_0^2 e^{-2\sqrt{2}\phi_i}\mathscr{V}\, b_i^2 - 2m_0 e^{2\sqrt{2}\phi_i - \sqrt{2}(\phi_1+\phi_2+\phi_3)} b_1 b_2 b_3 \frac{e_i}{b_i}\right).$$

THE SWAMPLAND (Vafa et al)

- Which low-energy Lagrangians are forbidden by quantum gravity?
- Do de Sitter vacua exist in string theory?
- How to rule scenarios in or out?

MODULI STABILISATION

- String theory

EFT

- 10-dimensional supergravity with alpha' corrections

EFT

- 4-dimensional supergravity of moduli and matter

EFT

- Integrate out heavy modes to get potential for lightest moduli

EFT

- Find vacuum as minimum of effective potential,

MANY STEPS…..WHAT CAN GO WRONG?

- String theory

EFT

- 10-dimensional supergravity with alpha' corrections

EFT

- 4-dimensional supergravity of moduli and matter

EFT

- Integrate out heavy modes to get potential for lightest moduli

EFT

- Find vacuum as minimum of effective potential,

HOLOGRAPHY

- We want to analyse such vacua holographically. Perhaps this will reveal structure / inconsistencies opaque in traditional treatments

- CFT dimensions of dual operators:

$$\Delta(\Delta - 3) = m_{\Phi}{}^{2} R_{AdS}^{2}$$

- In infinite volume / asymptotic limit can classify modes as

heavy $$m_{\Phi}^{2} \gg R_{AdS}^{-2}, \Delta \to \infty \quad \text{as} \quad \mathcal{V} \to \infty$$

light $$m_{\Phi}^{2} \ll R_{AdS}^{-2}, \Delta \to 3 \quad \text{as} \quad \mathcal{V} \to \infty$$

interesting $$m_{\Phi}^{2} \sim R_{AdS}^{-2}, \Delta \to \mathcal{O}(1-10) \quad \text{as} \, \mathcal{V} \to \infty$$

A BAD ARGUMENT

- “You cannot use AdS/CFT arguments when discussing non-susy AdS solutions.

  This is because if AdS is unstable, even to exponentially suppressed processes, then decay is effectively instantaneous and so no CFT can exist:

$$\Gamma_{total} = \int_{AdS} \Gamma_{bubble} \sim \mathrm{Vol(AdS)}\Gamma_{\mathrm{bubble}} \sim \infty \times \Gamma_{\mathrm{bubble}} = \infty$$

  as AdS has infinite volume but a finite travel time from boundary to centre"

A BAD ARGUMENT

- This is a bad physics argument:

  1. It relies on the **infinite volume of exact AdS**, and so preserves the perfect AdS structure all the way to the boundary
  2. A cosmological evolution to AdS will never produce exact AdS.
  3. Holographically, using the infinite volume of AdS is equivalent to exact conformality all the way to the infinite UV.
  3. On this argument, CFT techniques have no applicability to a theory that slowly walks its coupling constant over a hundred orders of magnitude in energy but runs in the infinite UV.
  4. This is not a good physics argument. Such theories *can* be regarded as approximately conformal in a physics sense
  5. One such example is QCD and its friends.

LVS MASS SPECTRUM

- In LVS we have
- **Heavy:** KK modes, complex structure moduli, all Kahler moduli except overall volume
- **Light:** Graviton, overall volume axion
- **Interesting:** overall volume modulus

LVS HOLOGRAPHY

Mode	Spin	Parity	Conformal dimension
$T_{\mu\nu}$	2	+	3
a	0	-	3
Φ	0	+	$8.038 = \frac{3}{2}\left(1+\sqrt{19}\right)$

Table 1. The low-lying single-trace operator dimensions for CFT duals of the Large Volume Scenario in the limit $\mathcal{V} \to \infty$.

In minimal LVS, AdS effective theory has small number of fields which correspond to specific predictions for dual conformal dimensions

No Landscape - properties of low-dimension C FT operators completely fixed!

LVS HOLOGRAPHY

- n-point self interactions of volume modulus

$$\mathcal{L}_{n-pt} = (-1)^{n-1}\lambda^n (n-1)\left(-3\frac{M_P^2}{R_{AdS}^2}\right)\frac{1}{n!}\left(\frac{\delta\Phi}{M_P}\right)^n\left(1+\mathcal{O}\left(\frac{1}{\ln\mathcal{V}}\right)\right)$$

$$\left(\lambda = \sqrt{27/2}\right)$$

- Mixed interactions of volume modulus and axion

$$\mathcal{L}_{\Phi^n aa} = \left(-\sqrt{\frac{8}{3}}\right)^n \frac{1}{2n!}\left(\frac{\delta\Phi}{M_P}\right)^n \partial_\mu a \partial^\mu a$$

- Again, unique form for interactions in large-volume limit: fluxes, W_0, etc all drop out

LVS HOLOGRAPHY

- In asymptotic limit of exponentially large volumes, low-lying CFT data becomes unique

- Conformal dimensions and 3-point couplings of low-dimension primaries reduce to single values and lose all dependence on fluxes, W_0, etc.

- From CFT side, there is no landscape……

DGKT IIA FLUX VACUA

- Interestingly, something similar happens with DGKT vacua in large-volume scale-separated limit
- Again, conformal dimensions and 3-point couplings of low-dimension primaries reduce to single values and lose all dependence on fluxes (up to discrete sign choices which determine whether vacuum is Susy or non-Susy)
- The landscape again disappears……

DGKT IIA FLUX VACUA

- Conformal dimensions for saxion sector of stabilised Kahler moduli are

$$\Delta_\varphi = (10,6,6,6)$$

- For Kahler axions, dimensions depend on flux signs $sgn(m_0 e_i)$ (which change whether vacuum is Susy or non-Susy)

Susy case (-1,-1,-1) and non-Susy (-1,1,1):

$$\Delta_a = (8,8,8,2) \quad \text{or} \quad \Delta_a = (8,8,8,1)$$

Non-Susy cases (1,1,1) and (1,-1,-1)

$$\Delta_a = (11,5,5,5)$$

DGKT IIA FLUX VACUA

- Again, a unique form in the asymptotic region, which `forgets' about all the flux choices.

- The same also holds for the 3-point and higher-point interactions: they can be expressed in terms of R_{AdS} and so take a universal form from the CFT perspective

- Interestingly, in this case all the conformal dimensions are also integers - we do not understand why.

QUESTIONS

- Not many examples of asymptotic scale-separated vacua - LVS, DGKT - any others? (nb KKLT not asymptotic as volume logarithmic in W_0)

- Is this CFT almost-uniqueness a general property of such vacua? Can this be argued from a CFT side?

- Why does DGKT lead to integer conformal dimensions?

CONCLUSIONS

- Holographic studies of moduli stabilisation provides a new perspective on old problems
- They reveal a structure in LVS and DGKT that is opaque in the traditional approach
- Can this structure be used to establish consistency (or inconsistency) of such vacua?

ANOMALOUS DIMENSIONS

- Anomalous dimensions are well-defined; can be related to Mellin amplitude for 2 -> 2 scattering

$$\gamma(0,\ell) = -\int_{-i\infty}^{+i\infty} \frac{ds}{2\pi i} M(s,0)\ {}_3F_2\left(-\ell, \Delta_1+\Delta_3+\ell-1, \frac{s}{2}; \Delta_1, \Delta_3; 1\right)$$
$$\times \Gamma\Big(\Delta_1 - \frac{s}{2}\Big)\Gamma\Big(\Delta_3 - \frac{s}{2}\Big)\Gamma\Big(\frac{s}{2}\Big)^2,$$

where $M(s,t)$ is the Mellin amplitude corresponding to the correlator

$$\langle \mathcal{O}_1(x_1)\mathcal{O}_1(x_2)\mathcal{O}_3(x_3)\mathcal{O}_3(x_4)\rangle.$$

ANOMALOUS DIMENSIONS

$$\gamma^{\varphi a}(0,\ell) = -2 f_{\varphi\varphi\varphi} f_{\varphi aa} \frac{\Gamma(\Delta_a)\Gamma(\Delta_\varphi)^2}{\Gamma\left(\frac{2\Delta_a-\Delta_\varphi}{2}\right)\Gamma\left(\frac{\Delta_\varphi}{2}\right)^3} \frac{1}{\ell^{\Delta_\varphi}} + \mathcal{O}\left(\frac{1}{\ell}\right)$$

Anomalous dimensions are equivalent to binding energies of 2-particle states in AdS

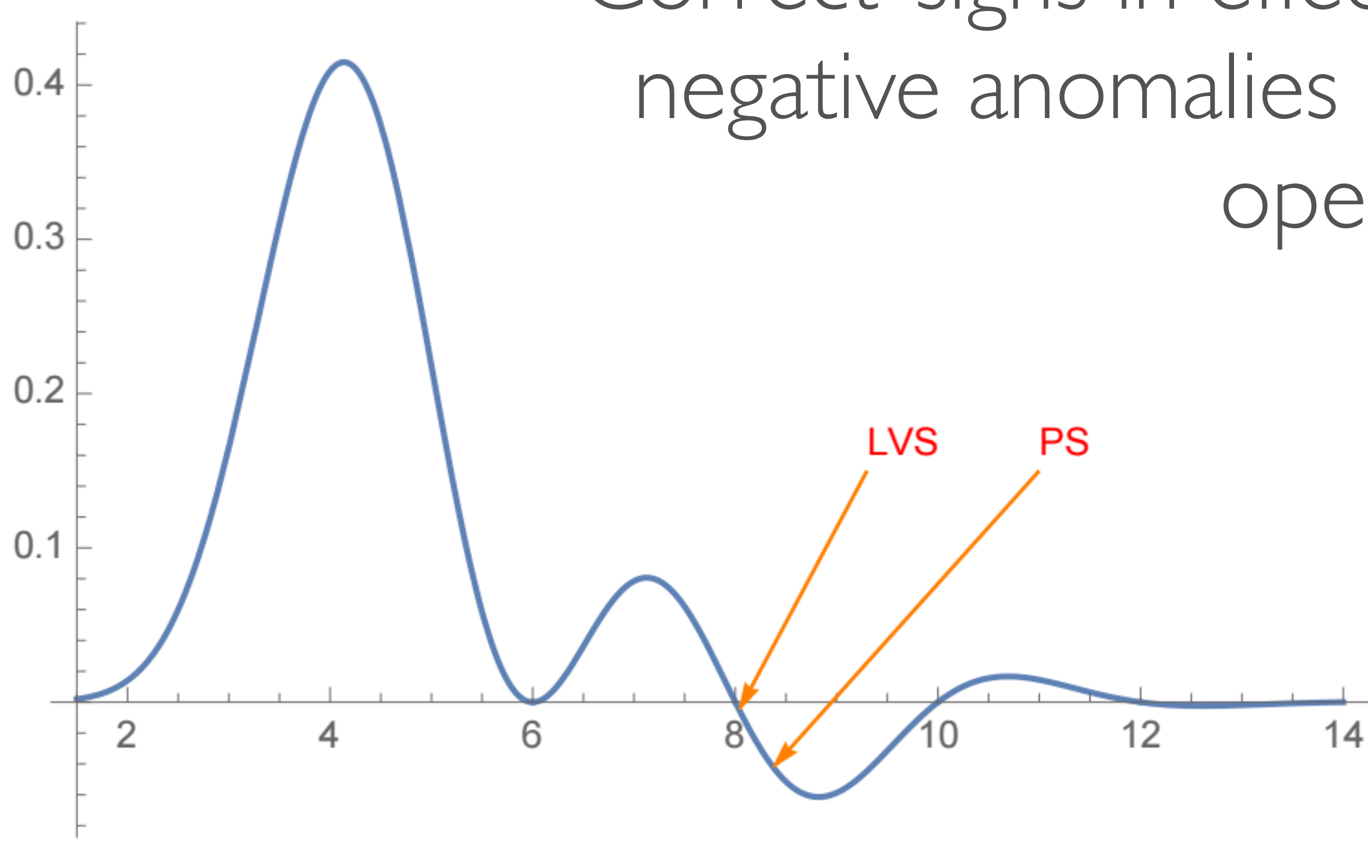
In Mellin amplitude, 'exchange' t-channel diagrams provide dominant contribution at large l

ANOMALOUS DIMENSIONS

LVS 'just' gives a negative anomalous dimension for the mixed volume-axion state

$$\gamma^{\varphi a}(0,\ell) \sim -g\mu \frac{(\Delta_\varphi - 6)}{\Gamma\left(\frac{6-\Delta_\varphi}{2}\right)}.$$

'Correct' signs in effective AdS equivalent to negative anomalies dimension for mixed operator



ANOMALOUS DIMENSIONS

- In LVS context, right signs of 3-pt AdS couplings are equivalent to negative anomalous dimensions for the mixed double-trace operator.

- A similar result holds for perturbative or KKLT stabilisation (qualitatively different as involves a massive axion) - but not for DGKT