HOLOGRAPHIC CONSTRAINTS ON SCALE SEPARATION

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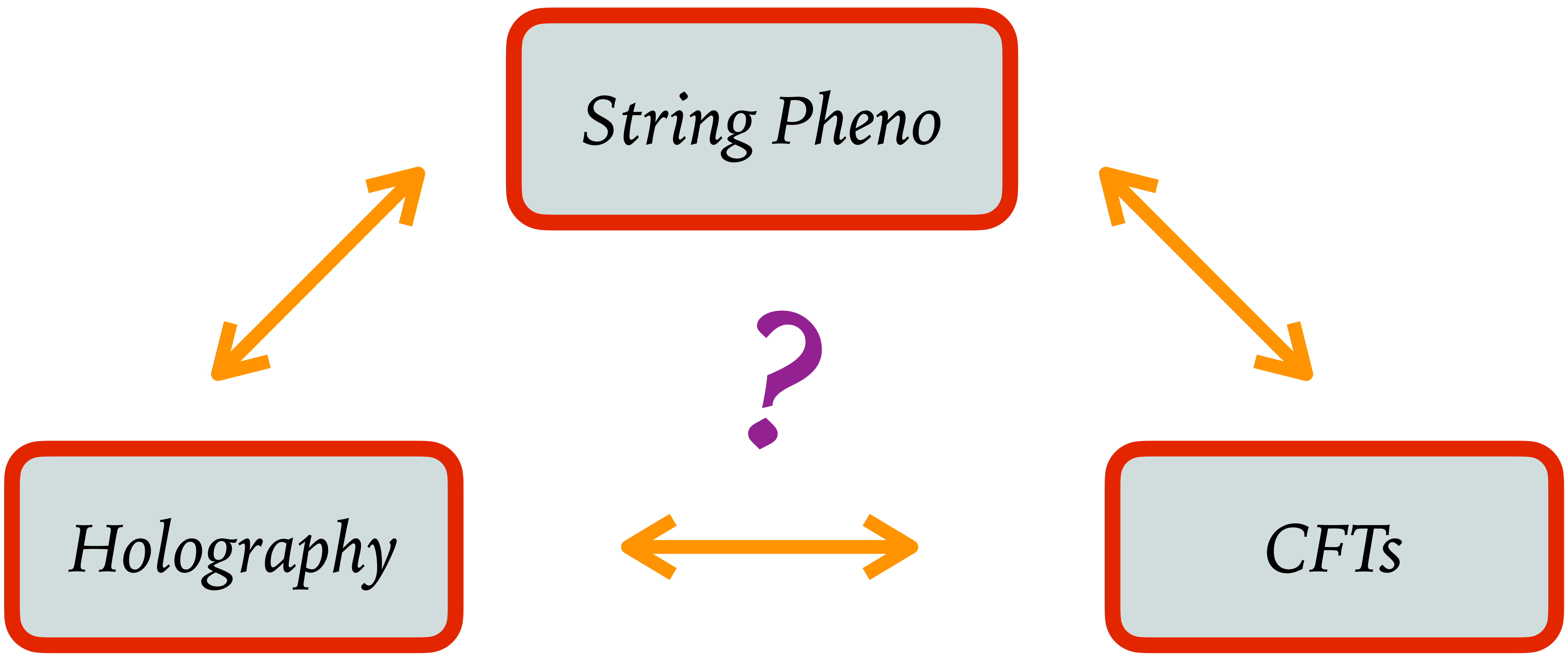
Based on: 2512.11031 [Bobev,Paul,FR] + WiP [FR,Van Hemelryck]

GENERAL PICTURE - SCALE SEPARATION

AdS vacua in String Theory (SUGRA) with $R_{\rm int} \ll R_{\rm AdS}$

schematic - many subtleties

Genuine low-dim vacua: $m_{KK} \gg R_{\rm AdS}^{-1}$



Small compact factor in $AdS_{d+1} \times \mathcal{M}$

Gapped spectrum: $\Delta_{KK} \gg 1$

PLAN OF THE TALK

(Lengthy) Introduction

I) Holographic constraint on scale sep.

II) Application to a specific model: DGKT

Outlook & future directions

SCALE SEPARATION AND STRING THEORY

Scale separation: *stepping stone towards de Sitter*

Classical No-go's: Flux + curvature + positive tension objects (branes)

Ex: *M-Theory*

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

à la Maldacena-Nunez

$\sim R^2_{\mathrm{KK}}$ $\qquad \sim R^2_{\mathrm{AdS}}$

[Gautason, Schillo, Van Riet, Williams '15]

Violated by higher derivative corrections, negative tension objects

Connection to Geometry $\qquad R_{ab} = \frac{1}{L_R^2} g_{ab} \qquad \Box_g \phi_i = \lambda_i \phi$

Cannot push $\quad \lambda_1 \gg 1$

[Collins, Jafferis, Vafa, Xu, Yau '22]

SCALE SEPARATION AND THE LANDSCAPE

Candidates:

Type IIB: ***KKLT, LVS*** *"Quantum": α' + NP corrections*

[Kachru,Kallosh,Linde,Trivedi '03] [Conlon,Quevedo,Suruliz '05]
[Balasubramanian,Berglund,Conlon,Quevedo '05]

Type IIA: ***DGKT*** *"Classical": only flux (incl. Romans mass)*

[DeWolfe,Giryavets,Kachru,Taylor '05]

Negative tension objects

Recent progress in 3d [Apers,Arboleya,Cribiori,Farakos,Guarino, Emelin,Miao, Montero,Morittu,Rajaguru,Tringas,Van Hemelryck,Van Riet,Wrase +… '20-'25]

Main criticism: *smeared* *and* *intersecting* *O-planes, no 10d picture*

Backreaction OK at leading order, but hard to be conclusive *[Junghans '20]*

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SCALE SEPARATION AND THE SWAMPLAND

AdS distance conjecture [Lust,Palti,Vafa '19]

String theory on AdS, with $\Lambda \to 0$

SUSY case

$\exists$ *a tower* $\mid$ $m_t \sim |\Lambda|^\alpha$ $\alpha = \frac{1}{2}$

Forbids scale separation…

Refined in [Buratti,Calderon,Mininno,Uranga '19]

$\Lambda \sim \frac{m_{KK}^2}{k}$ k *order of* $\mathbb{Z}_k$ *higher form symmetry*

Allows scale-separated DGKT!

SCALE SEPARATION AND HOLOGRAPHY

No (established) top-down examples

Incompatible with constraints on Log(N) term of partition function

[Bobev,David,Hong,Reys,Zhang '24]

Unusual CFT spectrum

$$\Delta(\Delta - d) = m^2 R^2_{\text{AdS}}$$

No such CFT is known!

Large Gap

No relevant operators?

Dead-end CFT

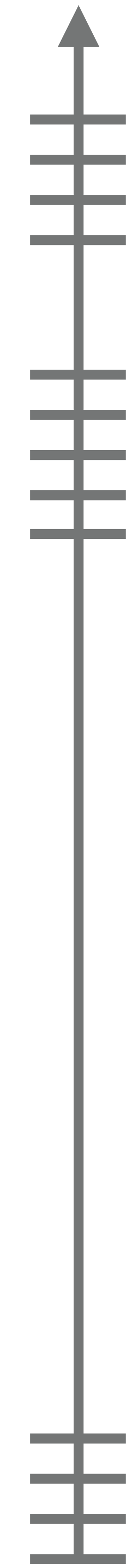
DGKT (+ many 3d examples): only integers

[Conlon,FR, Ning '21][Apers,Conlon,FR,Ning '22]+....

$\Delta_S \gg 1$

$\Delta_{KK} \gg 1$

$\Delta \sim \mathcal{O}(1)$



PART I

Holographic constraints on scale separation

THE SETUP

Consider a (scale-separated) AdS vacuum, dual to holographic CFT

$$S_{\text{eff}} = \eta \int_{\text{AdS}_{d+1}} d^{d+1}x\sqrt{g}\mathcal{L}_{\text{eff}}\,, \qquad \eta = \frac{1}{16\pi G}$$

Implicit (but crucial): *genuine EFT* $\begin{cases} \textit{Finite \# fields, } s \leq 2 \\ \textit{A single cutoff} \end{cases}$

$$\mathcal{L}_{\text{eff}} = -R - d(d-1) + \frac{1}{2}(\partial_\mu\phi_i)^2 + \frac{1}{2}m_i^2\phi_i^2$$
$$+ d_{ijk}\phi_i\partial_\mu\phi_j\partial^\mu\phi_k + c_{ijk}\phi_i\phi_j\phi_k + \ldots$$

Focus on cubic couplings

THE CLAIM

Extremal arrangements:

$$\{\phi_1, \phi_2, \phi_3\} \longleftrightarrow \{\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3\} \qquad \Delta_1 + \Delta_2 = \Delta_3$$

Would seem fine-tuned - but often the case for integer dimensions!

$$\langle \mathcal{O}_i \mathcal{O}_j \mathcal{O}_k \rangle \sim c_{ijk} + \left[\Delta_j \Delta_k + \frac{1}{2}(d - \Delta_i - \Delta_j - \Delta_k)(\Delta_j + \Delta_k - \Delta_i)\right] d_{ijk}$$

$$\equiv c'_{ijk} = 0$$

Extremal 3-pt couplings must vanish !

A FEW COMMENTS

- *Applies to **any** AdS vacuum, not just scale-separated* *(E.g. consistent truncation, non-geometric…)*

- *Can always perform field redefinitions s.t.* $c'_{ijk} = c_{ijk}, \quad d_{ijk} = 0$
  [Bobev,Paul '25]

- *Trivially verified in maximally SUSY examples:* $c_{ijk} = d_{ijk} = 0$

- *Cancellation occurs in examples with* $c_{ijk}, d_{ijk} \neq 0$ *(E.g. Leigh-Strassler SCFT)*
  [Bobev,Paul '25]

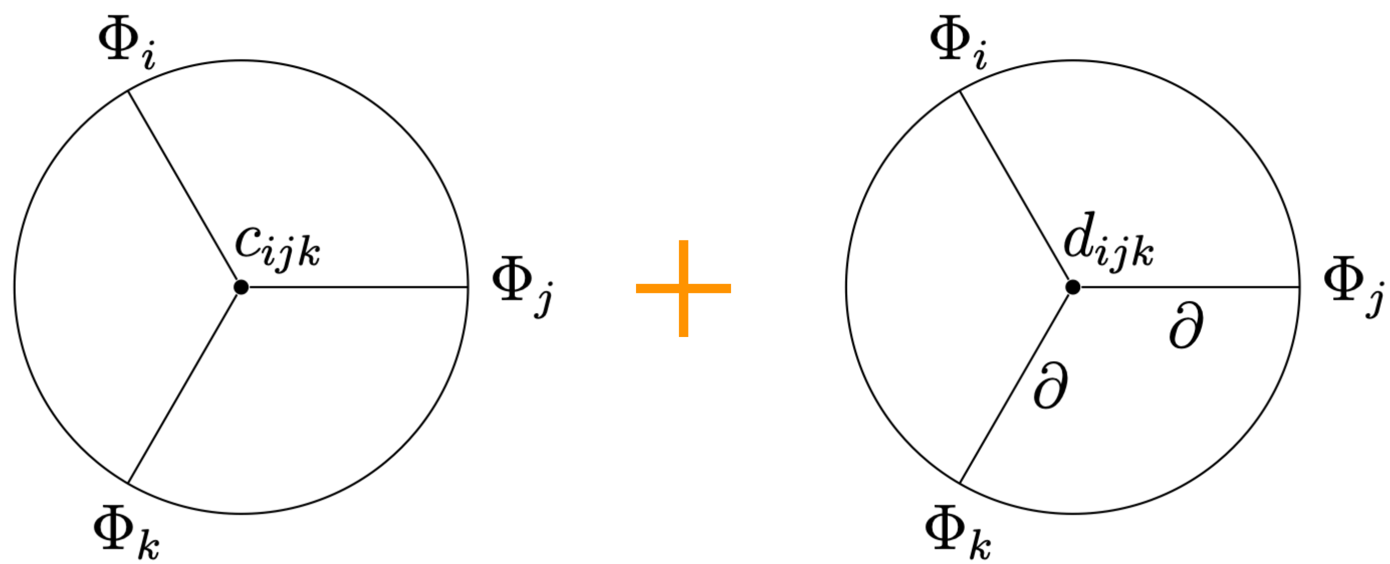
- *Not true if "EFT" assumptions violated* *(E.g. open + closed string modes present)*
  [Chester,Mouland,Van Muiden '25 x 2]

A FIRST HINT

3-pt couplings

$$C_{ijk} = \eta\, c'_{ijk}\, A_{\Delta_i \Delta_j \Delta_k}$$

CFT *kinematics*



$$A_{\Delta_i \Delta_j \Delta_k} = \frac{\Gamma\left(\frac{\Delta_i + \Delta_j - \Delta_k}{2}\right)\Gamma\left(\frac{\Delta_j + \Delta_k - \Delta_i}{2}\right)\Gamma\left(\frac{\Delta_k + \Delta_i - \Delta_j}{2}\right)\Gamma\left(\frac{\Delta_i + \Delta_j + \Delta_k - d}{2}\right)}{2\pi^d \Gamma\left(\Delta_i - \frac{d}{2}\right)\Gamma\left(\Delta_j - \frac{d}{2}\right)\Gamma\left(\Delta_k - \frac{d}{2}\right)}$$

Extremal case: *Pole at zero leads to a divergence unless* $c'_{ijk} = 0$

Similar story for other poles - super-extremal and shadow arrangements

A FEW SUBTLETIES

Can we quantify the divergence?

Two aspects: operator mixing + central charge scalings as $c \to \infty$

$\Delta_i = \Delta_j + \Delta_k$ *degeneracy for* $\mathcal{O}_i$ *and* $[\mathcal{O}_j \mathcal{O}_k]$

Ambiguity: $\phi_i \quad \leftrightarrow \quad \mathcal{O}'_{\phi_i} = \mathcal{O}_{\phi_i} + f(c)\mathcal{O}_{\phi_j,\phi_k} + \dots$

Proposal: Single Particle Operator *[Aprile,Drummond,Heslop,Paul '18-'19][Bobev,Paul '25]*

SPO

$\phi_i \longleftrightarrow \mathcal{O}^{(s)}_{\phi_i}$

$$\left\langle \mathcal{O}^{(s)}_{\Phi}(x)\left[\mathcal{O}_{\Phi_1}\cdots\mathcal{O}_{\Phi_k}\right](y)\right\rangle = 0, \quad k \geq 2$$

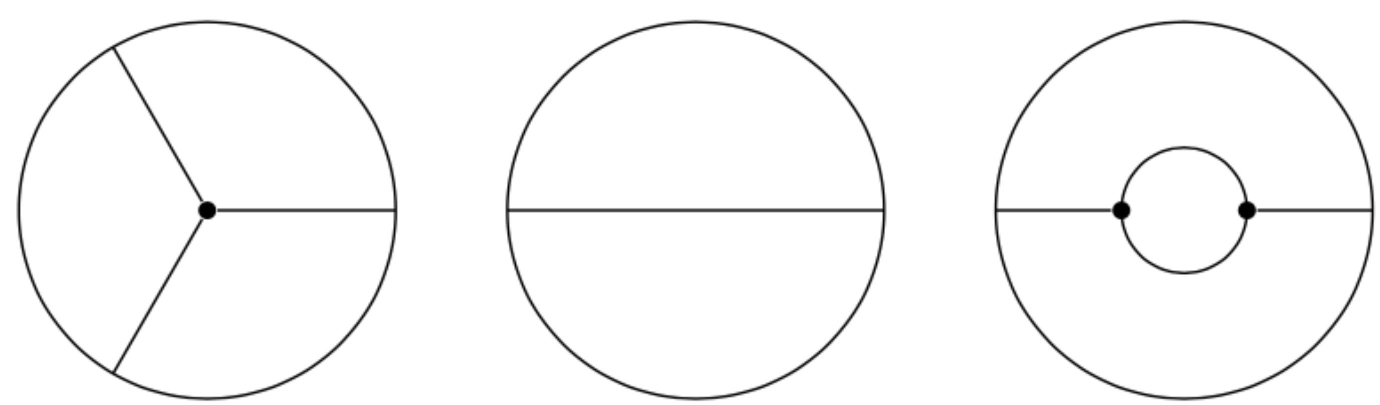
VIEWPOINT FROM THE BULK

SPOs $\mathcal{O}^{(s)}_{\phi_i}$ *of dimensions* $m_i^2 = \Delta_i^{(0)}\left(\Delta_i^{(0)} - d\right)$

Power counting in c

$\sim \frac{1}{c}$

$\sim c$



$$\left\langle \mathcal{O}^{(s)}_{\phi_i}\mathcal{O}^{(s)}_{\phi_i}\right\rangle \sim \frac{1}{c}, \quad \left\langle \mathcal{O}^{(s)}_{\phi_i}\mathcal{O}^{(s)}_{\phi_j}\mathcal{O}^{(s)}_{\phi_k}\right\rangle \sim \frac{1}{c^2}, \quad \Delta_i = \Delta_i^{(0)} + \frac{\gamma_i}{c} + \ldots$$

VIEWPOINT FROM THE BOUNDARY

CFT with large central charge:

$$\underbrace{\mathcal{O}^{DT}_{i,j}}_{\text{double trace}} \equiv [\underbrace{\mathcal{O}^{ST}_i}_{\text{single trace}} \mathcal{O}^{ST}_j]$$

Scaling of correlators with c determines notion of single vs double trace

$$\langle \mathcal{O}^{\mathrm{ST}}_i \mathcal{O}^{\mathrm{ST}}_i \rangle \sim 1, \qquad \langle \mathcal{O}^{\mathrm{DT}}_{i,j} \mathcal{O}^{\mathrm{DT}}_{i,j} \rangle \sim 1,$$

arbitrary normalisation

"Large-N" factorisation implies:

$$\langle \mathcal{O}^{\mathrm{ST}}_i \mathcal{O}^{\mathrm{ST}}_j \mathcal{O}^{\mathrm{ST}}_k \rangle \sim \frac{1}{\sqrt{c}}, \qquad \langle \mathcal{O}^{\mathrm{ST}}_i \mathcal{O}^{\mathrm{ST}}_j \mathcal{O}^{\mathrm{DT}}_{i,j} \rangle \sim 1$$

THE DICTIONARY

Dictionary

$$\mathcal{O}^{(s)}_{\phi_k} = \frac{1}{\sqrt{c}}\left(\mathcal{O}^{\mathrm{ST}}_k + \frac{B}{c^\beta}\,\mathcal{O}^{\mathrm{DT}}_{i,j} + \dots\right)$$

bulk

boundary

$$\langle \mathcal{O}^{(s)}_{\phi_i}\mathcal{O}^{(s)}_{\phi_j}\mathcal{O}^{(s)}_{\phi_k}\rangle = \frac{1}{c^{3/2}}\left[\langle \mathcal{O}^{\mathrm{ST}}_i\mathcal{O}^{\mathrm{ST}}_j\mathcal{O}^{\mathrm{ST}}_k\rangle + \frac{B}{c^\beta}\langle \mathcal{O}^{\mathrm{ST}}_i\mathcal{O}^{\mathrm{ST}}_j\mathcal{O}^{\mathrm{DT}}_{i,j}\rangle\right]$$

$$= \frac{1}{c^{3/2}}\left[\frac{A}{\sqrt{c}} + \frac{B}{c^\beta}\cdot D + \dots\right]$$

$$\sim \frac{1}{c^2}$$ *from bulk Witten diagrams*

$$\boxed{\beta \geq \frac{1}{2}}$$

THE ARGUMENT

Extremal arrangement $\langle \mathcal{O}^{(s)}_{\phi_1} \mathcal{O}^{(s)}_{\phi_2} \mathcal{O}^{(s)}_{\phi_3} \rangle \sim \eta \, c'_{ijk} \, A_{\Delta_1 \Delta_2 \Delta_k}$

expand kinematic divergence at large c

CFT

$$\frac{1}{c^{3/2}} \left[\frac{A}{\sqrt{c}} + \frac{B}{c^{\beta}} \cdot D + \dots \right]$$

AdS bulk theory

$$\frac{1}{c} \cdot c_{ijk} \, \frac{\hat{a}_{\Delta_i^{(0)} \Delta_j^{(0)} \Delta_k^{(0)}}}{(\gamma_i + \gamma_j - \gamma_k)}$$

Contradiction: $\beta = -\frac{1}{2}$ *Unless* $c'_{ijk} = 0$

Application to DGKT

THE DGKT SCENARIO

Setting: *Flux compactifications in massive type IIA*

$AdS_4 \times \mathcal{M}_6$ → *Calabi-Yau orientifold* $\mathcal{N} = 1 \quad / \quad \mathcal{N} = 0$

no R-symmetry

Ingredients: fluxes + orientifold planes (O6) *[DeWolfe,Giryavets,Kachru,Taylor '05]*

All moduli stabilised

$$\begin{cases} F_0, \quad (F_2), \quad H_3, \quad F_4 & \text{unconstrained} \\ m_0, \quad (m_i), \quad p_i, \quad e_i & e_i \to \infty \end{cases}$$

Scale-separated

$$V_{\rm AdS} \equiv -\frac{3}{R^2_{\rm AdS}} \sim \bar{e}^{-9/2} \qquad R_{\rm KK} \sim \bar{e}^{7/2}$$

THE TOROIDAL ORENTIFOLD

Simplest example: $T^6/(\mathbb{Z}_3 \times \mathbb{Z}_3)$ [DeWolfe,Giryavets,Kachru,Taylor '05]

Kahler moduli

$v_i \sim \int_{\Sigma_{2,i}} J$ *volumes of the three 2-tori*

$\mathcal{N}=1$

$i = 1, 2, 3$

$b_i \sim \int_{\Sigma_{2,i}} B_2$ *B-field axions*

Complex structure moduli

~~*expansion of* Ω, C_3~~

projected out by orientifold

dilaton $\phi + \xi \sim \int_{\Sigma_3} C_3$

$\mathcal{N}=1$

Simple EFT, with 8= 6+2 scalars

4D N=1 SUPERGRAVITY DESCRIPTION

Kahler moduli: t_i $\quad i = 1, 2, 3$ *Axio-dilaton:* S

volumes of the three tori

$$K = -4\log\left[\sqrt{2}\,\mathrm{Im}(S)\right] - \log\left[8\kappa\,\mathrm{Im}(t_1)\,\mathrm{Im}(t_2)\,\mathrm{Im}(t_3)\right].$$

$$W = e_0 + e_a t^a - \kappa m_0 t_1 t_2 t_3 - 2pS$$

Effect of fluxes

[Grimm, Louis '04]+….

$$\frac{\mathcal{L}_K}{2} = -\underbrace{K_{I\bar{J}}}_{d_{ijk}}\partial_\mu \Phi^I \partial^\mu \bar{\Phi}^{\bar{J}} + e^K\left(\sum_I \underbrace{K^{I\bar{J}}}_{c_{ijk}} D_I W D_{\bar{J}}\bar{W} - 3|W|^2\right)$$

THE HOLOGRAPHIC DUAL

"Saxions" $\{\varphi_0, \varphi_i\}$ *"Axions"* $\{a_0, a_i\}$

$$\mathcal{L}^{(2)} = \frac{1}{2}(\partial\varphi_0)^2 + \frac{1}{2}\sum_{i=1}^{3}(\partial\varphi_i)^2 + \frac{35}{L^2}\varphi_0^2 + \frac{9}{L^2}\sum_{i=1}^{3}\varphi_i^2$$

$$\frac{1}{2}(\partial a_0)^2 + \frac{1}{2}\sum_{i=1}^{3}(\partial a_i)^2 + \frac{43-45s}{2L^2}\varphi_0^2 + \frac{25+15s}{2L^2}\sum_{i=1}^{3}a_i^2$$

SUSY case $s = -1$

CFT SPO spectrum at leading order in c

$$\begin{cases} \Delta_\varphi = \{10, 6, 6, 6\} \\ \Delta_a = \{11, 5, 5, 5\} \end{cases}$$

Independent of fluxes, geometric data

$$|\Delta_\varphi - \Delta_a| = 1$$

Still true for arbitrary orientifold

[Conlon,FR, Ning '21][Apers,Conlon,FR,Ning '22]+....

EXTREMAL ARRANGEMENTS IN DGKT

"$11 = 6+5$" $\langle 11\, 6_i\, 5_j \rangle$

$$d_{\varphi_j a_i a_0} = -\frac{4}{3\sqrt{13}} M_{ij}$$

$$c_{\varphi_0 a_i a_j} = \frac{100}{3\sqrt{13}} M_{ij}$$

"$10 = 5+5$" $\langle 10\, 5_i\, 5_j \rangle$

$$d_{\varphi_j a_i a_0} = -\frac{4}{3\sqrt{13}} M_{ij}$$

$$c_{\varphi_j a_i a_0} = \frac{160}{3\sqrt{13}} M_{ij}$$

Exact Cancellation!

$$\boxed{c_{0ij} + \left[\Delta_i \Delta_j + \frac{1}{2}(d - \Delta_0 - \Delta_i - \Delta_j)(\Delta_i + \Delta_j - \Delta_0)\right] d_{0ij} = 0}$$

NON-SUSY VACUA

Non susy-vacua *different sign choices* $s_i \equiv \mathrm{sgn}(m_0 e_i)$

CFT spectrum
at leading order in c

$$\begin{cases} \Delta_\varphi = \{10, 6, 6, 6\} \\ \Delta_a = \{8, 8, 8, 2\} \end{cases}$$

1 *in alternative quantisation*

All extremal + superextremal couplings vanish

Extremal: $\Delta_i = \Delta_j + \Delta_k$

$c'_{\varphi_0 a_i a_0} \sim \langle 10\, 8_i\, 2 \rangle = 0$ $\quad$ $c'_{a_i \varphi_j a_0} \sim \langle 8_i\, 6_j\, 2 \rangle = 0$

Super-extremal: $\Delta_i = \Delta_j + \Delta_k + 2n$

$c'_{\varphi_i a_0 a_0} \sim \langle 6_i\, 2\, 2 \rangle = 0$ $\quad$ $c'_{\varphi a_0 a_0} \sim \langle 10\, 2\, 2 \rangle = 0$

(alternative quantisation) $\langle 6_i\, 1\, 1 \rangle = 0$ $\quad$ $\langle 10\, 1\, 1 \rangle = 0$

A BULK INTERPRETATION

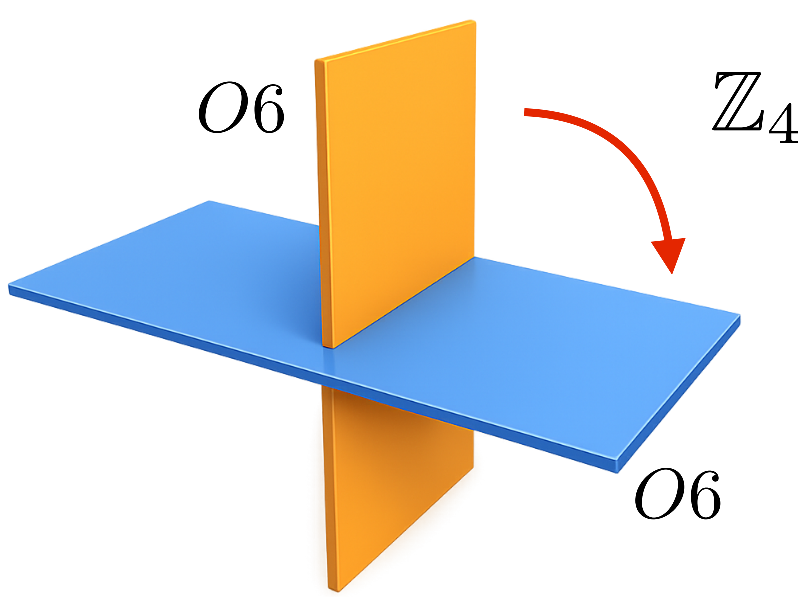
Preliminary result:

- *DGKT vacua w/ complex structure moduli*
  - *e.g. from different orientifold*
- *Analogous 3d vacua on G2 manifolds*
  - *[Van Hemelryck '25]+...*

Constraint is (superficially) violated ?! *[FR, Van Hemelryck WiP]*

Satisfied if certain fields are identified

Quotienting extra direction(s) in the orbifold!



O6-planes are identified

Connected to O-plane intersections?

CONCLUSIONS

- *Holographic, consistency constraint for "genuine" EFTs in AdS*

Finitely many (s<2) fields below a fixed cutoff

Extremal arrangements — ***cubic couplings must vanish !***

$$\Delta_1 + \Delta_2 = \Delta_3 \qquad\qquad c'_{ijk} = 0$$

- *The constraint is satisfied non-trivially for vacua in the DGKT class*

$$c_{ijk} \neq 0 \qquad d_{ijk} \neq 0 \qquad\qquad c'_{ijk} \equiv c_{ijk} + \# d_{ijk} = 0$$

For all (super)extremal arrangements, in both susy and non-susy vacua

Putative dual to DGKT looks like well-behaved large-c CFT?

- *Calculated all 3-pt functions for low-lying scalars in DGKT*

Bottom up understanding of the dual CFT?

OUTLOOK

- *Can we push this further? E.g. 4-pt functions (or higher)?*

  And implications for DGKT

- *Straightforward: does the constraint hold for similar flux vacua ?*

  DGKT for different orientifolds?

  [Apers,Conlon,FR,Ning'22]

  G2 vacua in 3d

  [Apers,Arboleya,Cribiori,Farakos,Guarino, Emelin,Miao,Montero,Morittu,Rajaguru,Tringas, Van Hemelryck,Van Riet,Wrase +… '20-'25]

- *More ambitious: KKLT/LVS?*

  Difficulty: no integer dimensions or extremal arrangements, no "large-c" parameter

- *Interplay with symmetries and other Swampland conjecture*

  Generalised shift symmetries/ higher form symmetries/ Weak Gravity Conjecture

  [Apers '22][Montero,Valenzuela '24]

Long term: *qualitatively new holography/fate of scale separation*

THANK YOU FOR YOUR ATTENTION!

NON-EXTREMAL COUPLINGS

$$c'_{\varphi_0 a_0 a_0} \sim \langle 10\,11\,11 \rangle = \frac{11\sqrt{\frac{7}{26}}}{36\pi}$$

$$c'_{\varphi_0 \varphi_0 \varphi_0} \sim \langle 10\,10\,10 \rangle = -\frac{437\sqrt{\frac{5}{22}}}{728\pi}$$

$$c'_{\varphi_0 \varphi_i \varphi_j} \sim \langle 10\,6_i\,6_j \rangle = 0$$

related to extremal

$$c'_{\varphi_i a_0 a_0} \sim \langle 6\,11\,11 \rangle = 11\,x_i$$

non-zero vector

$$c'_{\varphi_0 \varphi_0 \varphi_i} \sim \langle 10\,10\,6_i \rangle = 14 x_i$$

$$c'_{\varphi_0 a_0 a_i} \sim \langle 10\,11\,5_i \rangle = 4\,x_i$$

$$c'_{\varphi_i \varphi_j \varphi_k} \sim \langle 6_i\,6_j\,6_k \rangle = 3\,T_{ijk}$$

$$c'_{\varphi_i a_j a_k} \sim \langle 6_i\,5_j\,5_k \rangle = T_{ijk}$$

non-zero, fully symmetric tensor

Many relations due to superconformal Ward identities

Only a few numbers to specify