

# Applications of Exceptional Field Theory to the AdS/CFT correspondence

Emanuel Malek

Humboldt-Universität zu Berlin

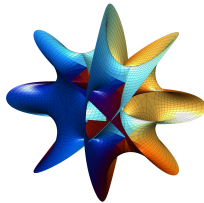


28th June 2022

with Bobev, Galli, Giambrone, Guarino, Josse, Nicolai, Petrini, Robinson, Samtleben, Sterckx, Trigiante, van Muiden, Waldram

# Geometry of Compactification = Physics

10-dimensional String Theory



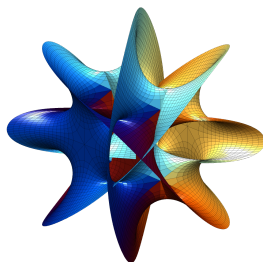
4-dimensional theory

E.g.

- ▶ Moduli  $\rightarrow$  massless scalar fields
- ▶ Kaluza-Klein modes  $\rightarrow$  massive fields

# Ricci-flat vs flux compactifications

## Ricci-flat

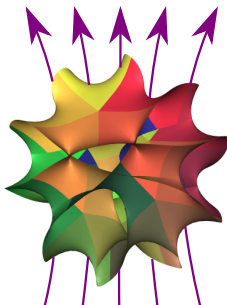


- ▶ Moduli ✓
- ▶ Uplift 4-d theory  $\rightarrow$  Calabi-Yau data ✓
- ▶ Quantum corrections (some control) ✓

SUSY  $\rightarrow$  “Special holonomy” spaces, Calabi-Yau

# Ricci-flat vs flux compactifications

## Flux compactification



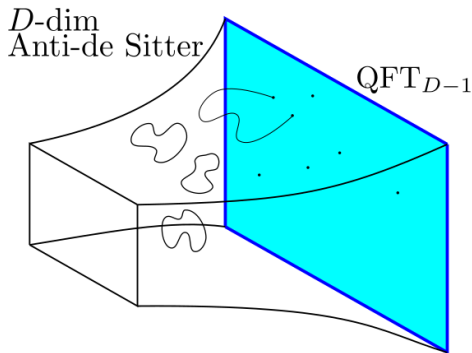
- ▶ Moduli ✗
- ▶ Uplift 4-d theory  $\rightarrow$  Geometric data ✗
- ▶ Quantum corrections ✗

Not “special holonomy” spaces: Fluxes  $\rightarrow$  torsion

Exceptional Field Theory

# AdS/CFT correspondence

All known AdS vacua of String Theory are flux compactifications!

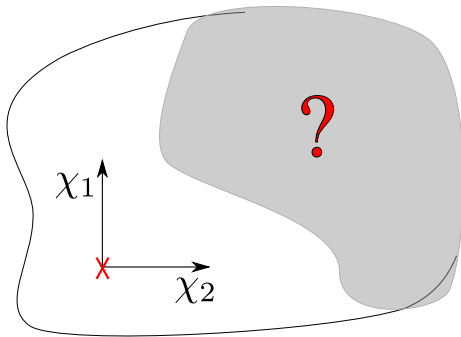


Crucial *quantitative* tool for strongly-coupled CFTs

## Conformal manifold & anomalous dimensions

Moduli  $\Leftrightarrow$  (exactly) marginal deformations

$$L_{\text{CFT}} \rightarrow L_{\text{CFT}} + \chi_i \mathcal{O}^i$$



Kaluza-Klein masses  $\Leftrightarrow$  anomalous dimensions

# Lower-dimensional “toy models” vs String Theory

Use lower-dimensional gauged supergravity to study AdS

- ▶ Only subset of fluctuations and masses
- ▶ (Misleading?) subset of conformal manifold

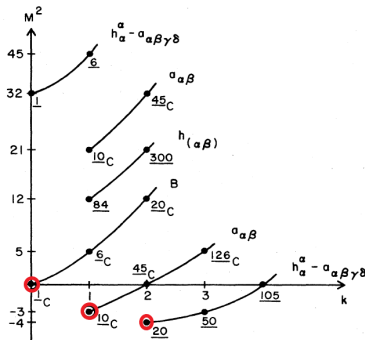
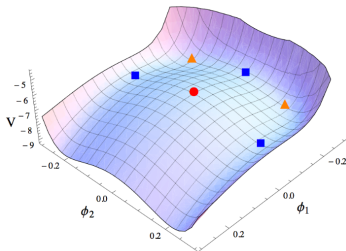


FIG. 2. Mass spectrum of scalars.

Two goals:

Uplift  $D$ -dim gauged supergravity to String Theory

Spectrum of masses  $\Leftrightarrow$  anomalous dimensions

Two goals:

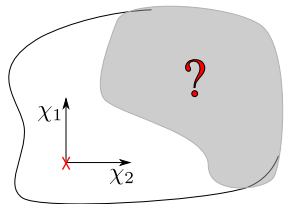
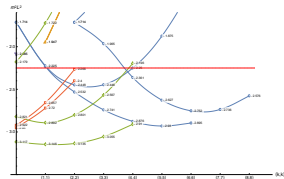
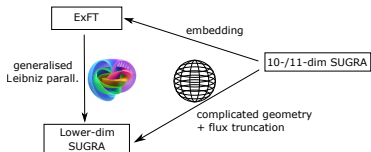
Uplift  $D$ -dim gauged supergravity to String Theory

Spectrum of masses  $\Leftrightarrow$  anomalous dimensions

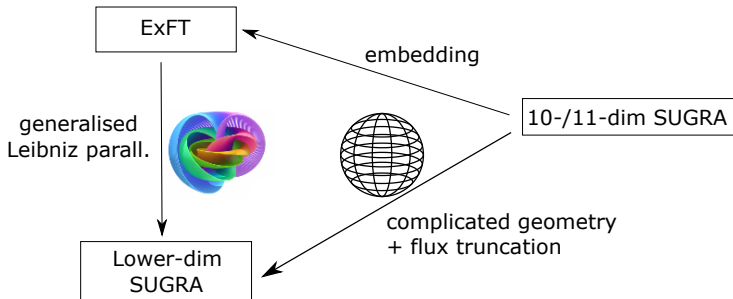


Dangers of trusting lower-dimensional supergravity!

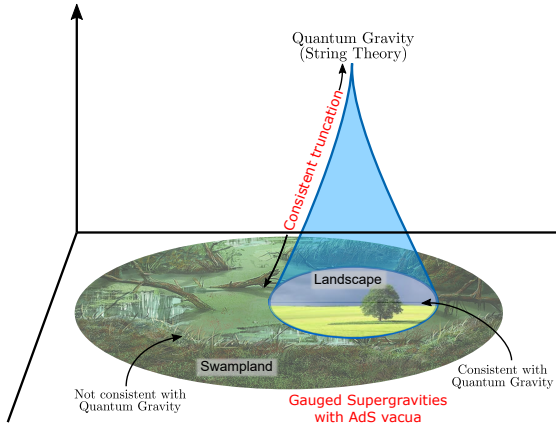
## Kaluza-Klein spectroscopy



# Exceptional field theory & consistent truncations



# Which gauged supergravities actually arise from String Theory?



## Consistent truncation

No well-controlled AdS vacua of String Theory have scale separation

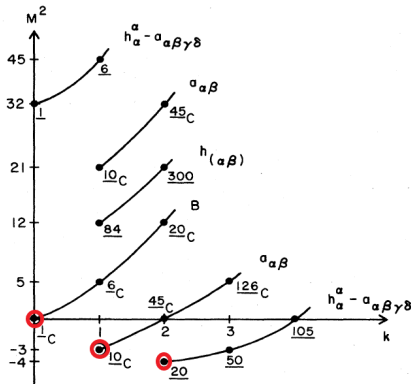


FIG. 2. Mass spectrum of scalars.

### Consistent truncation:

All solutions of lower-dim. theory  $\rightarrow$  solutions of  
10-d/11-d SUGRA

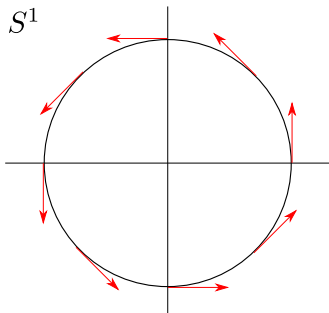
## Consistent truncation

Non-linear embedding of lower-dimensional  
supergravity into 10-/11-d supergravity

- ▶ All solutions of lower-d SUGRA  $\rightarrow$  solutions of 10-/11-d SUGRA
- ▶ Non-linearity: highly non-trivial!
- ▶ Symmetry arguments crucial for consistency & construction

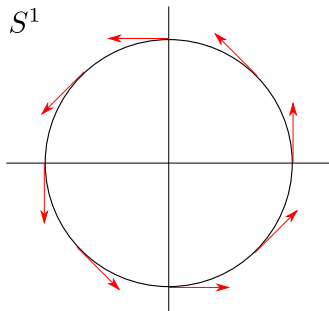
## Consistent truncation on group manifold

Symmetry arguments crucial for consistency, e.g.  
group manifold



# Consistent truncation on group manifold

Symmetry arguments crucial for consistency, e.g.  
group manifold



$$U_m{}^\mu \in \mathrm{GL}(D)$$

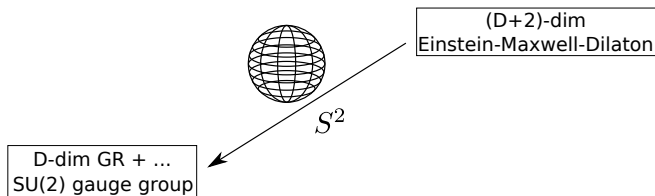
$$L_{U_m} U_n = f_{mn}{}^p U_p$$

$$g_{\mu\nu}(x, y) = g_{mn}(x) (U^{-1})_\mu{}^m(y) (U^{-1})_\nu{}^n(y)$$

# Larger symmetry groups from generalising geometry

Symmetry argument for other consistent truncations?

$$S = \int d^{D+2}x \sqrt{|g|} \left( R_g - (\nabla\phi)^2 - e^{\alpha\phi} F^2 \right)$$



$$ds_{D+2}^2 = Y^{\frac{1}{D}} \left( \Delta^{\frac{1}{D}} ds_D^2 + g^{-2} \Delta^{-\frac{D-1}{D}} T_{ij}^{-1} \mathfrak{D}\mu^i \mathfrak{D}\mu^j \right),$$

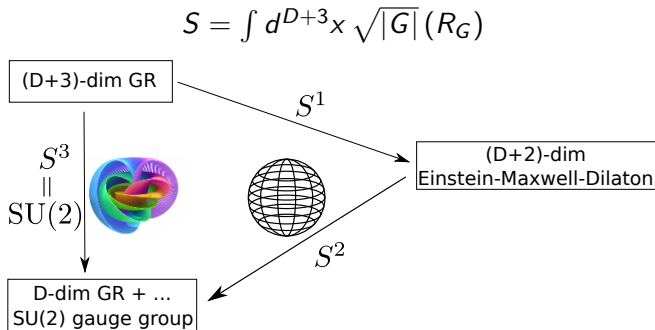
$$e^{\sqrt{\frac{2(D)}{D+1}} \hat{\phi}} = \Delta^{-1} Y^{\frac{D-1}{D+1}},$$

$$\hat{F}_2 = \frac{1}{2} \epsilon_{ijk} \left( g^{-1} \Delta^{-2} \mu^i \mathfrak{D}\mu^j \wedge \mathfrak{D}\mu^k - 2g^{-1} \Delta^{-2} \mathfrak{D}\mu^i \wedge \mathfrak{D} T_{jl} T_{km} \mu^l \mu^m - \Delta^{-1} F_{(2)}^{ij} T_{kl} \mu^l \right).$$

[Cvetic, Lü, Pope '00]

# Larger symmetry groups from generalising geometry

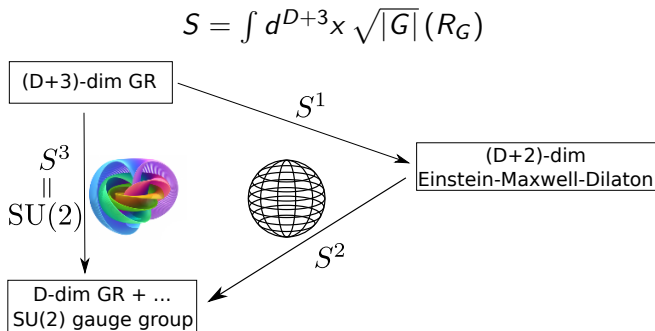
Symmetry argument for other consistent truncations?



$$U_m{}^\mu \in \text{GL}(3)$$
$$L_{U_m} U_n = f_{mn}{}^p U_p$$

# Larger symmetry groups from generalising geometry

Symmetry argument for other consistent truncations?



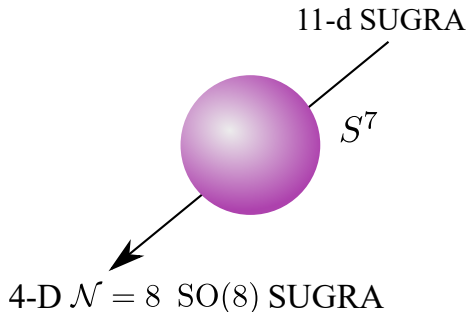
$$U_m{}^\mu \in \text{GL}(3)$$

$$L_{U_m} U_n = f_{mn}{}^p U_p$$

$$g_{\mu\nu}(x, y) = g_{mn}(x) (U^{-1})_\mu{}^m(y) (U^{-1})_\nu{}^n(y)$$

# Consistent truncations beyond group manifolds

Consistent truncations of 10-d/11-d SUGRA beyond group manifolds?



[de Wit, Nicolai '82]

# Exceptional Field Theory

[Berman, Perry '10], [Coimbra, Strickland-Constable, Waldram '11],  
[Hohm, Samtleben '13], ...

Exceptional Field Theory: Unify metric + fluxes of  
supergravity

11-d SUGRA on  $M_4 \times C_7$ :

$$\{g, C_{(3)}, C_{(6)}, \dots\} = \mathcal{M}_{MN} \in \frac{E_{7(7)}}{\mathrm{SU}(8)}.$$

Diffeo + gauge transf  $\rightarrow$  generalised vector field  $V^M \in \mathbf{56}$  of  $E_{7(7)}$   
Lie derivative  $\rightarrow$  generalised Lie derivative

$$\mathcal{L}_V = V^M \partial_M - (\partial \times_{\text{adj}} V) = \text{diffeo} + \text{gauge transf},$$

with  $\partial_M = (\partial_i, \partial^{ij}, \partial^{ijklm}, \dots) = (\partial_i, 0, \dots, 0)$ .

# Exceptional Field Theory = reformulation of supergravity

Exceptional Field Theory: Reformulation of 10-/11-d  
supergravity

$$\{g, C_{(3)}, C_{(6)}, \dots\} = \mathcal{M}_{MN}$$

$$L = R - \frac{1}{48} F_{\mu\nu\lambda\rho} F^{\mu\nu\lambda\rho} + \dots$$

with  $F_{\mu\nu\rho\lambda} = 4\partial_{[\mu} C_{\nu\rho\lambda]}$ .

# Exceptional Field Theory = reformulation of supergravity

Exceptional Field Theory: Reformulation of 10-/11-d  
supergravity

$$\{g, C_{(3)}, C_{(6)}, \dots\} = \mathcal{M}_{MN}$$

$$\begin{aligned} L &= R - \frac{1}{48} F_{\mu\nu\lambda\rho} F^{\mu\nu\lambda\rho} + \dots \\ &= \mathcal{M}^{MN} \partial_M \mathcal{M}^{PQ} \partial_N \mathcal{M}_{PQ} + \dots \end{aligned}$$

# Exceptional Field Theory = reformulation of supergravity

Exceptional Field Theory: Reformulation of 10-/11-d  
supergravity

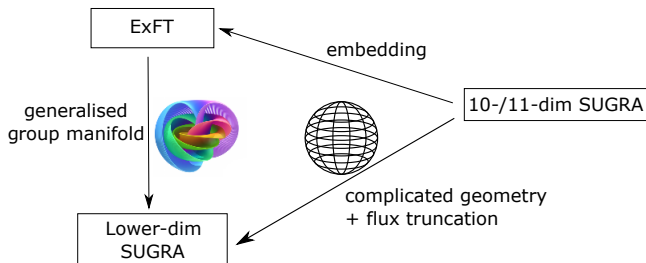
$$\{g, C_{(3)}, C_{(6)}, \dots\} = \mathcal{M}_{MN}$$

$$\begin{aligned} L &= R - \frac{1}{48} F_{\mu\nu\lambda\rho} F^{\mu\nu\lambda\rho} + \dots \\ &= \mathcal{M}^{MN} \partial_M \mathcal{M}^{PQ} \partial_N \mathcal{M}_{PQ} + \dots \end{aligned}$$

Generalised Lie derivative  $\Rightarrow$  generalised Ricci scalar

# Exceptional Field Theory and consistent truncations

Consistent truncations captured by  
“generalised group manifolds” in ExFT



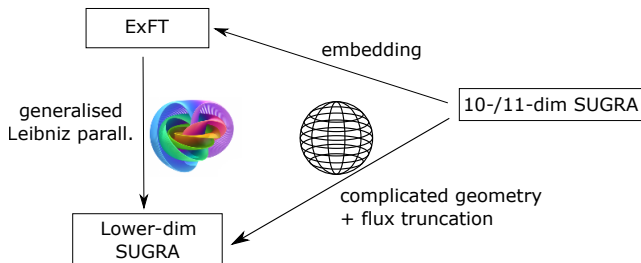
$$U_A{}^M \in E_{7(7)}$$

$$\mathcal{L}_{U_A} U_B = X_{AB}{}^C U_C$$

$$\mathcal{M}_{MN}(x, Y) = M_{AB}(x) (U^{-1})_M{}^A(Y) (U^{-1})_N{}^B(Y)$$

# Exceptional Field Theory and consistent truncations

Consistent truncations captured by  
“generalised Leibniz parallelisable manifolds” in ExFT



$$U_A{}^M \in E_{7(7)}$$

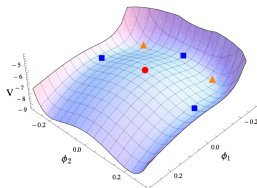
$$\mathcal{L}_{U_A} U_B = X_{AB}{}^C U_C$$

$$\mathcal{M}_{MN}(x, Y) = M_{AB}(x) (U^{-1})_M{}^A(Y) (U^{-1})_N{}^B(Y)$$

# Uplifting AdS vacua to string theory

Consistent truncations on  $S^p$ ,  $H^{p,q}$ ,  $S^p \times S^q$ , ...  
to maximal gSUGRA

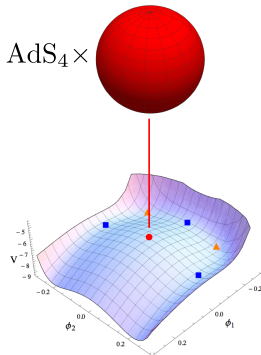
$$\mathcal{M}_{MN}(x, Y) = M_{AB}(x)(U^{-1})_M{}^A(Y)(U^{-1})_N{}^B(Y)$$



# Uplifting AdS vacua to string theory

Consistent truncations on  $S^p$ ,  $H^{p,q}$ ,  $S^p \times S^q$ , ...  
to maximal gSUGRA

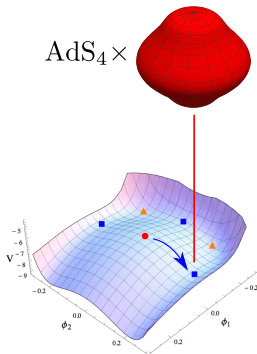
$$\mathcal{M}_{MN}(x, Y) = \delta_{AB} (U^{-1})_M{}^A(Y) (U^{-1})_N{}^B(Y)$$



# Uplifting AdS vacua to string theory

Consistent truncations on  $S^p$ ,  $H^{p,q}$ ,  $S^p \times S^q$ , ...  
to maximal gSUGRA

$$\mathcal{M}_{MN}(x, Y) = M_{AB}(x) (U^{-1})_M{}^A(Y) (U^{-1})_N{}^B(Y)$$

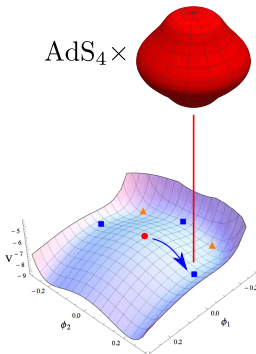


Warped compactifications with few/no remaining (super-)symmetries

# Uplifting AdS vacua to string theory

Consistent truncations on  $S^p$ ,  $H^{p,q}$ ,  $S^p \times S^q$ , ...  
to maximal gSUGRA

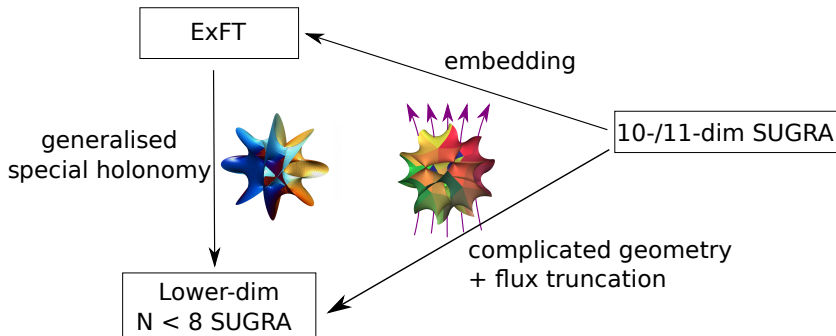
$$\mathcal{M}_{MN}(x, Y) = M_{AB}(x) (U^{-1})_M{}^A(Y) (U^{-1})_N{}^B(Y)$$



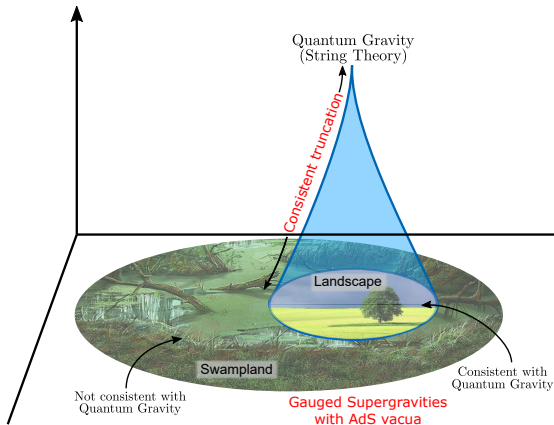
Multiplication by  $E_{7(7)}$  matrix!

Less SUSY consistent truncation  $\longleftrightarrow$  “generalised special holonomy”

[Cassani, Galli, Josse, EM, Petrini, Samtleben, Vall Camell, Waldram, ...]



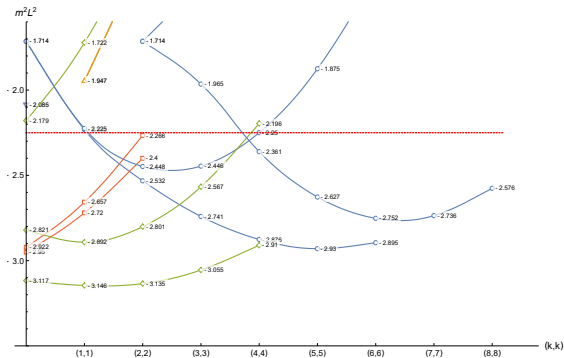
## String Theory origin $\Rightarrow$ Constraints on lower-dim theories



E.g.

- ▶ Symmetric scalar manifolds
- ▶ Small number of matter multiplets
- ▶ No-go theorems for gauge groups

# Kaluza-Klein spectroscopy



# Kaluza-Klein spectroscopy

Consistent truncation:

- ▶ Lower-dimensional theory
- ▶ Compute subset of masses for any vacuum!

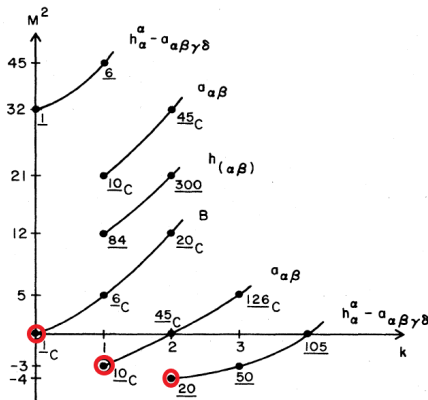
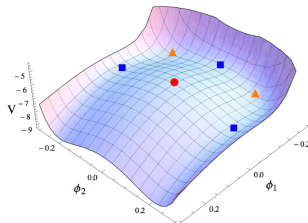


FIG. 2. Mass spectrum of scalars.



# Kaluza-Klein spectroscopy

Consistent truncation:

- ▶ Lower-dimensional theory
- ▶ Compute subset of masses for any vacuum!

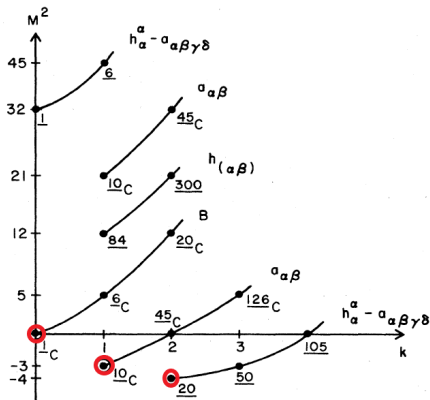
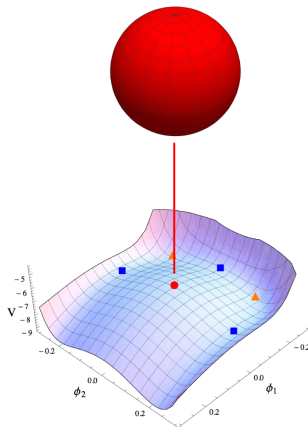


FIG. 2. Mass spectrum of scalars.



# Kaluza-Klein spectroscopy

Consistent truncation:

- ▶ Lower-dimensional theory
- ▶ Compute subset of masses for any vacuum!

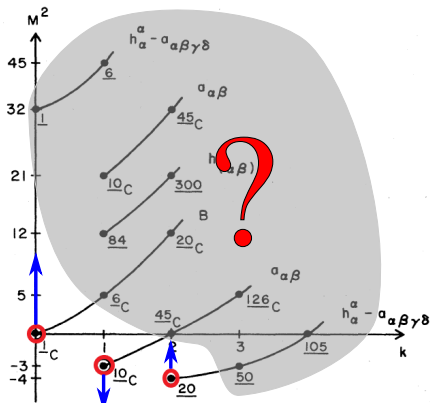
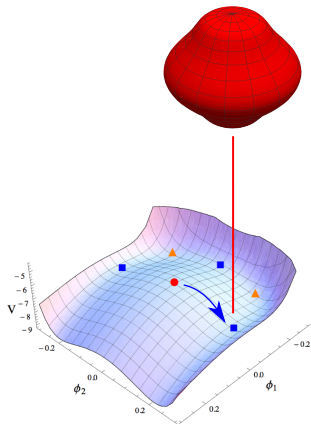


FIG. 2. Mass spectrum of scalars.



# Kaluza-Klein spectroscopy

Consists

- Low
- Com

[EM, Samtleben Phys. Rev. Lett. 2020]

Extend this to full KK spectrum using ExFT!

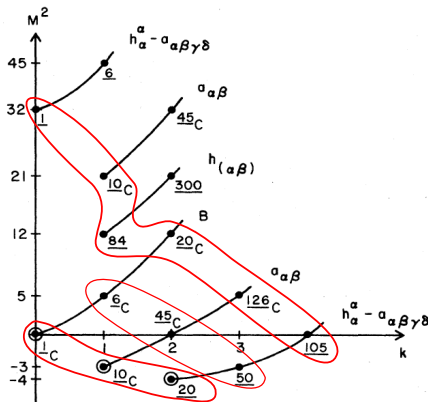
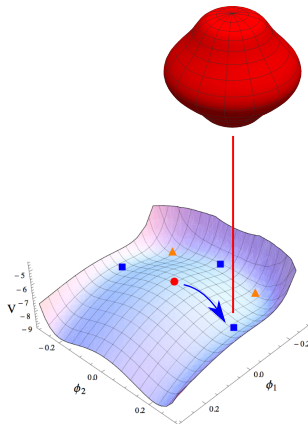


FIG. 2. Mass spectrum of scalars.



# Traditional Kaluza-Klein spectroscopy

Traditionally:

- ▶ Spin-2 fields [Bachas, Estes '11] ✓
- ▶  $M_{int} = \frac{G}{H}$  ✓

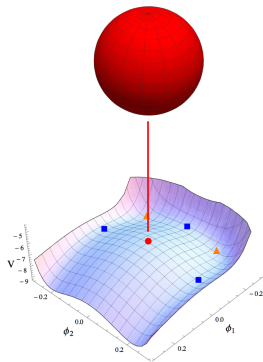
Here: [EM, Samtleben Phys. Rev. Lett. 2020]

- ▶ Warped compactifications with few or no remaining (super-)symmetries!
- ▶ Spectrum along RG flow

# KK spectroscopy strategy

First at max symmetric point:

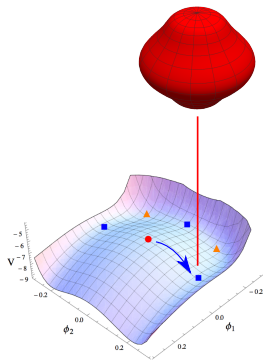
$$\mathcal{M}_{MN}(x, Y) = \delta_{AB}(U^{-1})_M^A(Y)(U^{-1})_N^B(Y)$$



# KK spectroscopy strategy

Then at less symmetric point:

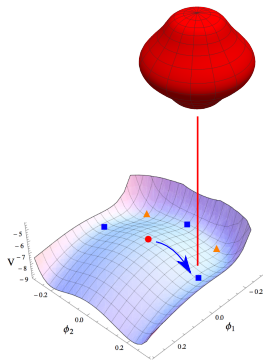
$$\mathcal{M}_{MN}(x, Y) = M_{AB}(x)(U^{-1})_M^A(Y)(U^{-1})_N^B(Y)$$



## KK spectroscopy strategy

Then at less symmetric point:

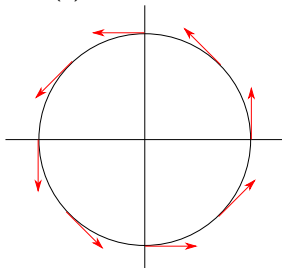
$$\mathcal{M}_{MN}(x, Y) = M_{AB}(x)(U^{-1})_M^A(Y)(U^{-1})_N^B(Y)$$



Multiplication by  $E_{7(7)}$  matrix,  $M_{AB}(x)$ !

## KK spectroscopy at max. symmetric point

$U_A^M \in E_{7(7)}$  give basis for all fields

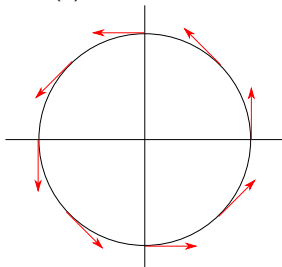


Only need scalar harmonics:  $\mathcal{Y}_\Sigma$

$$\text{c.f. } h_{ij}(x, y) = \sum_{\ell} h^{(\ell)}(x) \mathcal{Y}_{(ij)}^{(\ell)}(y), \quad b_{ij}(x, y) = \sum_{\ell} b^{(\ell)}(x) \mathcal{Y}_{[ij]}^{(\ell)}(y)$$

## KK spectroscopy at max. symmetric point

$U_A^M \in E_{7(7)}$  give basis for all fields

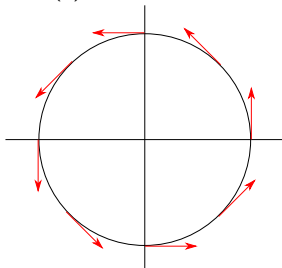


Only need scalar harmonics:  $\mathcal{Y}_\Sigma$

$$\mathcal{M}_{MN}(x, Y) \in E_{7(7)}/\mathrm{SU}(8)$$

## KK spectroscopy at max. symmetric point

$U_A^M \in E_{7(7)}$  give basis for all fields



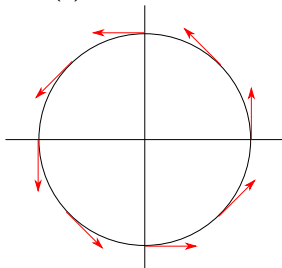
Only need scalar harmonics:  $\mathcal{Y}_\Sigma$

$$\mathcal{M}_{MN}(x, Y) = (\delta_{AB} + j_{AB}{}^\Sigma(x) \mathcal{Y}_\Sigma) (U^{-1})_M{}^A(Y) (U^{-1})_N{}^B(Y)$$

$$j_{AB}{}^\Sigma \in \mathfrak{e}_{7(7)} \ominus \mathfrak{su}(8)$$

## KK spectroscopy at max. symmetric point

$U_A{}^M \in E_{7(7)}$  give basis for all fields



Only need scalar harmonics:  $\mathcal{Y}_\Sigma$

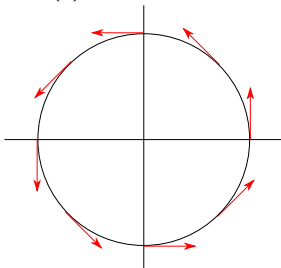
$$\mathcal{M}_{MN}(x, Y) = (\delta_{AB} + j_{AB}{}^\Sigma(x) \mathcal{Y}_\Sigma) (U^{-1})_M{}^A(Y) (U^{-1})_N{}^B(Y)$$

$$j_{AB}{}^\Sigma \in \mathfrak{e}_{7(7)} \ominus \mathfrak{su}(8)$$

KK Ansatz = consistent truncation  $\otimes$  scalar harmonics

## KK spectroscopy at max. symmetric point

$U_A^M \in E_{7(7)}$  give basis for all fields



Only need scalar harmonics:  $\mathcal{Y}_\Sigma$

$$\mathcal{M}_{MN}(x, Y) = (\delta_{AB} + j_{AB}{}^\Sigma(x) \mathcal{Y}_\Sigma) (U^{-1})_M{}^A(Y) (U^{-1})_N{}^B(Y)$$

$$j_{AB}{}^\Sigma \in \mathfrak{e}_{7(7)} \ominus \mathfrak{su}(8)$$

Immediate mass diagonalisation!

## Mass matrix

- ▶ Lower-dim info:

$$\mathcal{L}_{U_A} U_B = X_{AB}{}^C U_C ,$$

- ▶ Higher-dim info:

$$\mathcal{L}_{U_A} \mathcal{Y}_\Sigma = L_{K_A} \mathcal{Y}_\Sigma = \mathcal{T}_{A\Sigma}{}^\Omega \mathcal{Y}_\Omega .$$

**Algebraic** mass matrix:

$$\mathbb{M}_{I\Sigma,J\Omega}^{(\text{scalar})} = \mathbb{M}_{IJ}^{(0)} \delta_{\Sigma\Omega} + \delta_{IJ} \mathbb{M}_{\Sigma\Omega}^{(\text{spin}-2)} + \mathcal{N}_{IJ}{}^C \mathcal{T}_{C,\Omega\Sigma}$$

## Mass matrix

- ▶ Lower-dim info:

$$\mathcal{L}_{U_A} U_B = X_{AB}{}^C U_C ,$$

- ▶ Higher-dim info:

$$\mathcal{L}_{U_A} \mathcal{Y}_\Sigma = L_{KA} \mathcal{Y}_\Sigma = \mathcal{T}_{A\Sigma}{}^\Omega \mathcal{Y}_\Omega .$$

**Algebraic** mass matrix:

$$\mathbb{M}_{I\Sigma, J\Omega}^{(\text{scalar})} = \mathbb{M}_{IJ}^{(0)} \delta_{\Sigma\Omega} + \delta_{IJ} \mathbb{M}_{\Sigma\Omega}^{(\text{spin}-2)} + \mathcal{N}_{IJ}{}^C \mathcal{T}_{C, \Omega\Sigma}$$

- ▶ Lower-dim SUGRA mass matrix  $\mathbb{M}_{IJ}^{(0)}$

## Mass matrix

- ▶ Lower-dim info:

$$\mathcal{L}_{U_A} U_B = X_{AB}{}^C U_C ,$$

- ▶ Higher-dim info:

$$\mathcal{L}_{U_A} \mathcal{Y}_\Sigma = L_{K_A} \mathcal{Y}_\Sigma = \mathcal{T}_{A\Sigma}{}^\Omega \mathcal{Y}_\Omega .$$

**Algebraic** mass matrix:

$$\mathbb{M}_{I\Sigma, J\Omega}^{(\text{scalar})} = \mathbb{M}_{IJ}^{(0)} \delta_{\Sigma\Omega} + \delta_{IJ} \mathbb{M}_{\Sigma\Omega}^{(\text{spin}-2)} + \mathcal{N}_{IJ}{}^C \mathcal{T}_{C, \Omega\Sigma}$$

- ▶ Lower-dim SUGRA mass matrix  $\mathbb{M}_{IJ}^{(0)}$

$$\begin{aligned} \mathbb{M}_{IJ}^{(0)} = & \frac{1}{7} \left( X_{AE}{}^F X_{BE}{}^F + X_{EA}{}^F X_{EB}{}^F + X_{EF}{}^A X_{EF}{}^B + 7 X_{AE}{}^F X_{BF}{}^E \right) \mathcal{P}_{AD}{}^I \mathcal{P}_{BD}{}^J \\ & + \frac{2}{7} \left( X_{AC}{}^E X_{BD}{}^E - X_{AE}{}^C X_{BE}{}^D - X_{EA}{}^C X_{EB}{}^D \right) \mathcal{P}_{AB}{}^I \mathcal{P}_{CD}{}^J \\ & + \frac{1}{6} \mathcal{P}_{AB}{}^I \mathcal{P}_{CD}{}^J X_{FA}{}^B X_{FC}{}^D . \end{aligned}$$

## Mass matrix

- ▶ Lower-dim info:

$$\mathcal{L}_{U_A} U_B = X_{AB}{}^C U_C ,$$

- ▶ Higher-dim info:

$$\mathcal{L}_{U_A} \mathcal{Y}_\Sigma = L_{KA} \mathcal{Y}_\Sigma = \mathcal{T}_{A\Sigma}{}^\Omega \mathcal{Y}_\Omega .$$

**Algebraic** mass matrix:

$$\mathbb{M}_{I\Sigma, J\Omega}^{(\text{scalar})} = \mathbb{M}_{IJ}^{(0)} \delta_{\Sigma\Omega} + \delta_{IJ} \mathbb{M}_{\Sigma\Omega}^{(\text{spin}-2)} + \mathcal{N}_{IJ}{}^C \mathcal{T}_{C, \Omega\Sigma}$$

- ▶ Lower-dim SUGRA mass matrix  $\mathbb{M}_{IJ}^{(0)}$
- ▶ Spin-2 mass matrix  $\mathbb{M}_{\Sigma\Omega}^{(\text{spin}-2)} = \mathcal{T}_{A, \Sigma\Lambda} \mathcal{T}_{A, \Lambda\Omega}$

## Mass matrix

- ▶ Lower-dim info:

$$\mathcal{L}_{U_A} U_B = X_{AB}{}^C U_C ,$$

- ▶ Higher-dim info:

$$\mathcal{L}_{U_A} \mathcal{Y}_\Sigma = L_{K_A} \mathcal{Y}_\Sigma = \mathcal{T}_{A\Sigma}{}^\Omega \mathcal{Y}_\Omega .$$

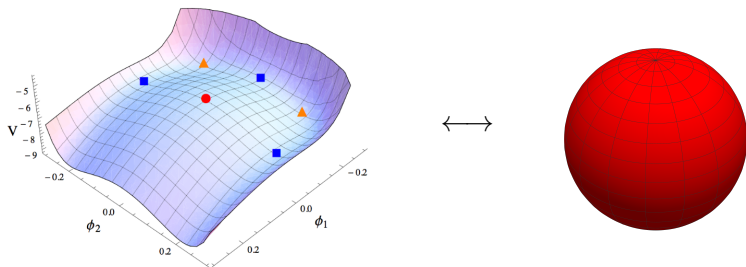
**Algebraic** mass matrix:

$$\mathbb{M}_{I\Sigma, J\Omega}^{(\text{scalar})} = \mathbb{M}_{IJ}^{(0)} \delta_{\Sigma\Omega} + \delta_{IJ} \mathbb{M}_{\Sigma\Omega}^{(\text{spin}-2)} + \mathcal{N}_{IJ}{}^C \mathcal{T}_{C, \Omega\Sigma}$$

- ▶ Lower-dim SUGRA mass matrix  $\mathbb{M}_{IJ}^{(0)}$
- ▶ Spin-2 mass matrix  $\mathbb{M}_{\Sigma\Omega}^{(\text{spin}-2)} = \mathcal{T}_{A, \Sigma\Lambda} \mathcal{T}_{A, \Lambda\Omega}$
- ▶ Key object:

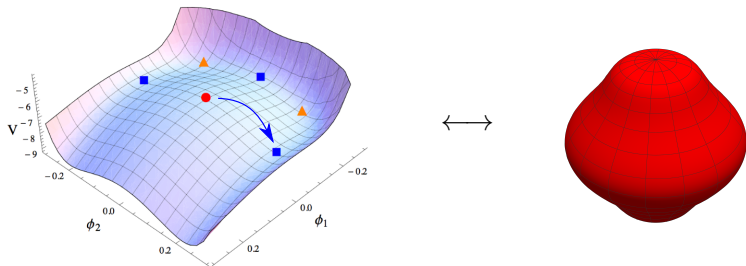
$$\mathcal{N}_{IJ}{}^C = -4(X_{CA}{}^B + 12 X_{AB}{}^C) \mathcal{P}^{AD}{}_{[I} \mathcal{P}^{BD}{}_{J]} .$$

## KK spectroscopy at less symmetric point



KK Ansatz = consistent truncation  $\otimes$  scalar harmonics

## KK spectroscopy at less symmetric point



KK Ansatz = consistent truncation  $\otimes$  scalar harmonics

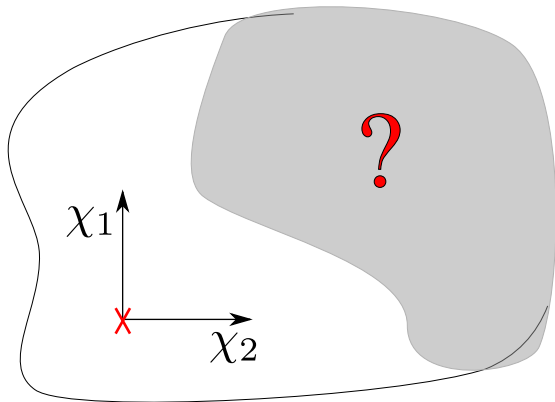
Multiplication by  $E_{7(7)}$  matrix,  $M_{AB}(x)$ !

Use same harmonics as for max. symmetric point

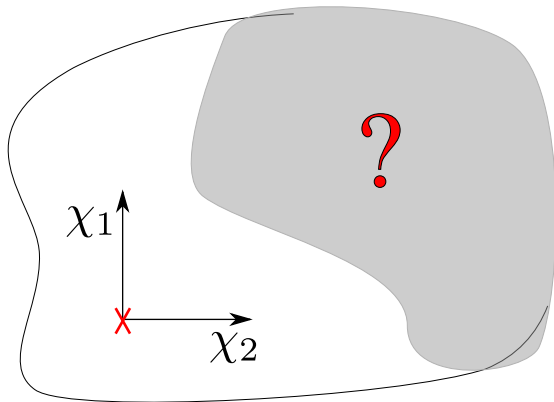
# KK Spectroscopy Summary

- ▶ No need for explicit metric
- ▶ Only scalar harmonics of maximally symmetric point (round sphere)
- ▶ ExFT KK Ansatz  $\implies$  Differential problem  $\rightarrow$  algebraic problem
- ▶ Compute full spectrum for any vacuum in consistent truncation
- ▶ Spectrum for compactifications with few/no remaining (super-)symmetries

# Applications

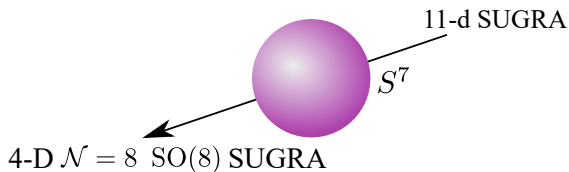


# Applications

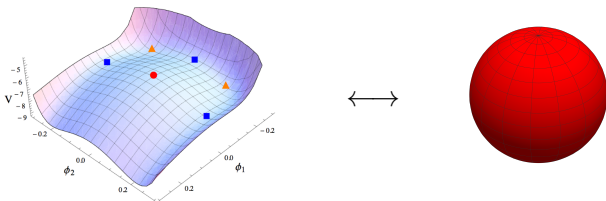


1. Stability of non-SUSY AdS
2. Global properties of conformal manifold

## Ex 1. Non-SUSY $SO(3) \times SO(3)$ $AdS_4$ vacua

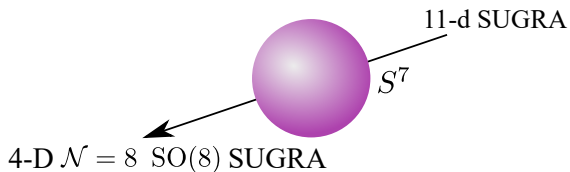


- ▶ Only one non-SUSY vacuum that is stable in 4-d! [Fischbacher, Pilch, Warner '10], [Comsa, Firsching, Fischbacher '19]
- ▶ Non-SUSY  $SO(3) \times SO(3)$   $AdS_4$  vacuum [Warner '83]

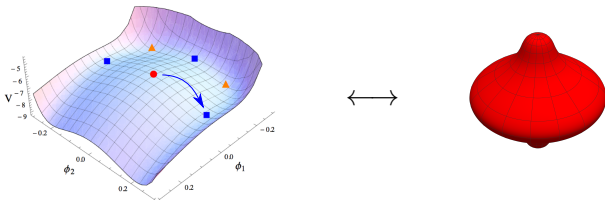


- ▶ Instability?

## Ex 1. Non-SUSY $SO(3) \times SO(3)$ $AdS_4$ vacua



- ▶ Only one non-SUSY vacuum that is stable in 4-d! [Fischbacher, Pilch, Warner '10], [Comsa, Firsching, Fischbacher '19]
- ▶ Non-SUSY  $SO(3) \times SO(3)$   $AdS_4$  vacuum [Warner '83]



- ▶ Instability?

## Ex 1. Perturbative stability?

4-d “zero-mode” stability enough for 11-d perturbative stability?

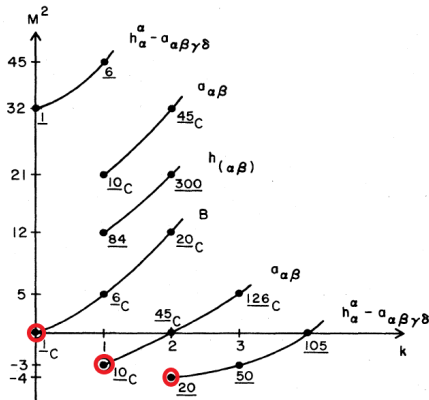
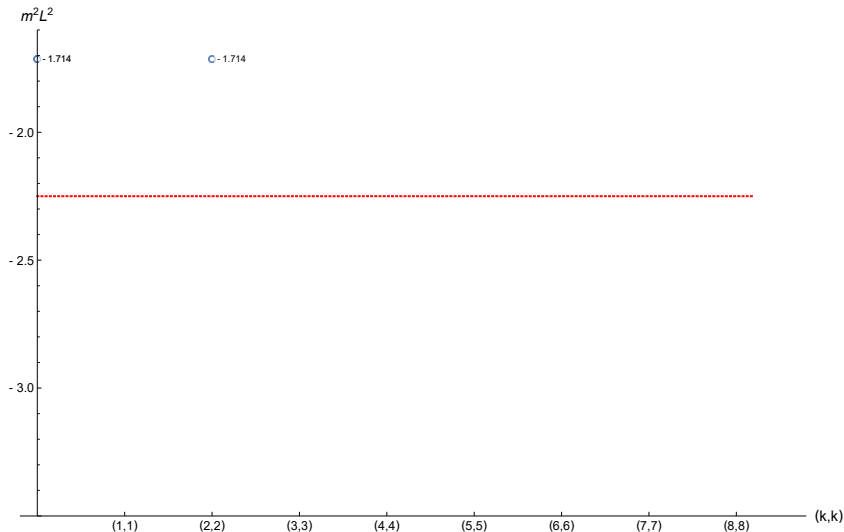


FIG. 2. Mass spectrum of scalars.

## Ex 1. Tachyonic KK modes

Modes  $\ell = 0$ :  $\mathcal{N} = 8$  supergravity multiplet

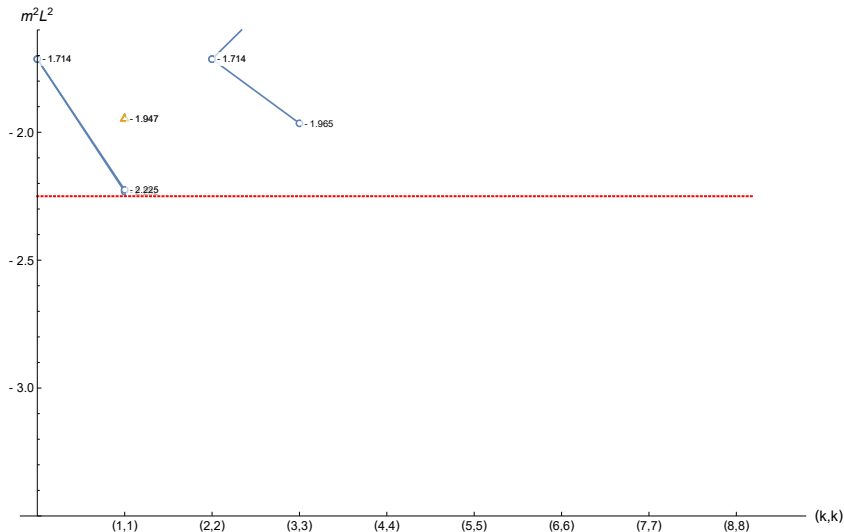
[Fischbacher, Pilch, Warner '10]



# Ex 1. Tachyonic KK modes

Modes  $\ell \leq 1$ : still stable!

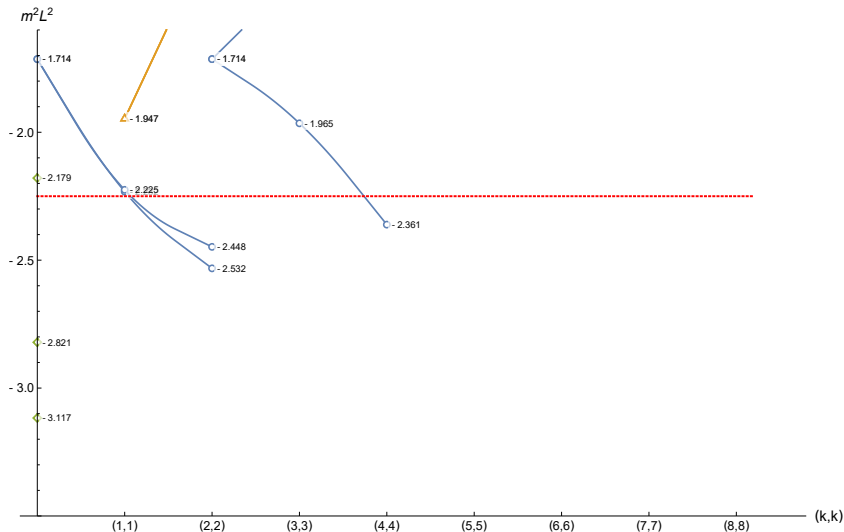
[EM, Nicolai, Samtleben '20]



# Ex 1. Tachyonic KK modes

Modes  $\ell \leq 2$ : **tachyons!**

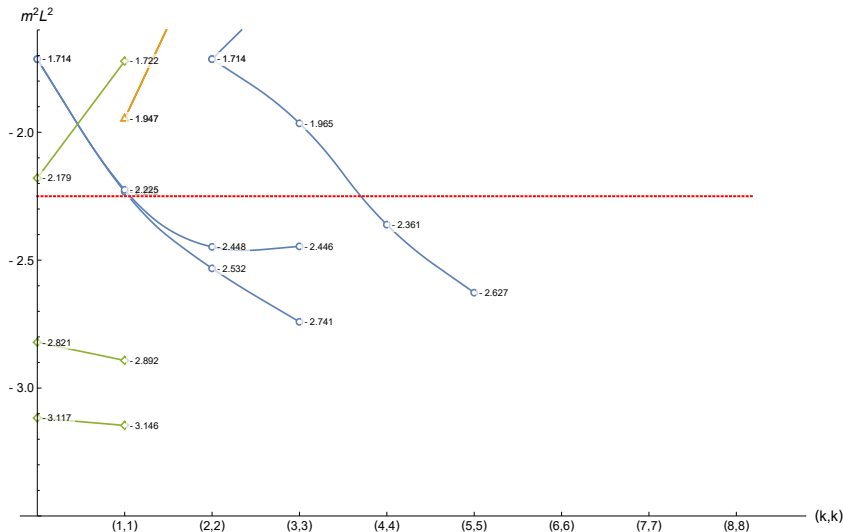
[EM, Nicolai, Samtleben '20]



# Ex 1. Tachyonic KK modes

Modes  $\ell \leq 3$

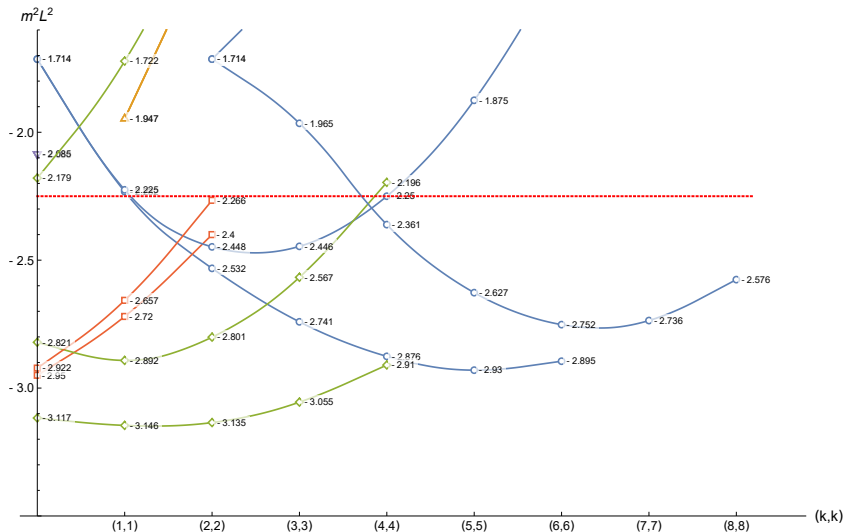
[EM, Nicolai, Samtleben '20]



# Ex 1. Tachyonic KK modes

Modes  $\ell \leq 6$

[EM, Nicolai, Samtleben '20]



## Ex 1. Kaluza-Klein instability

Higher KK modes are tachyonic!

[EM, Nicolai, Samtleben '20]

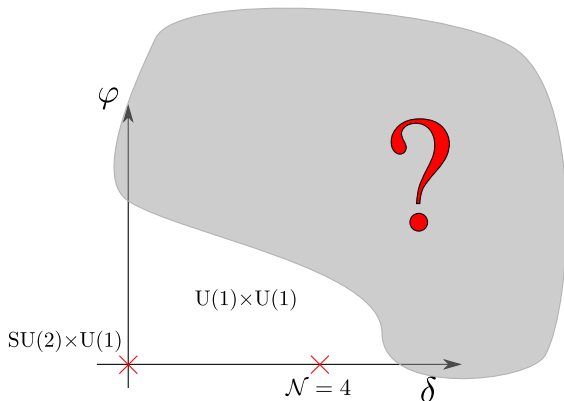
- ▶ Non-SUSY  $SO(3) \times SO(3)$   $AdS_4$  [Warner '83] is perturbatively unstable
- ▶ “Zero-mode” stability does not guarantee perturbative stability in higher dimensions
- ▶ Related to brane-jet instability [Bena, Pilch, Warner '20]?
- ▶ Examples of perturbatively stable non-SUSY  $AdS_4$  vacua in 10-d  
[Guarino, EM, Samtleben '20]  
Non-SUSY exactly marginal deformation?  
[Giambrone, Guarino, EM, Samtleben, Sterckx, Trigiante '21]

## Ex 2. $\mathcal{N} = 2$ AdS<sub>4</sub> family

$[\mathrm{SO}(6) \times \mathrm{SO}(1,1)] \ltimes \mathbb{R}^{12}$  supergravity

2 moduli  $(\varphi, \delta) \in \mathbb{R}_{\geq 0}^2$  in 4-d theory  $\Leftrightarrow \mathcal{N} = 2$  conformal manifold

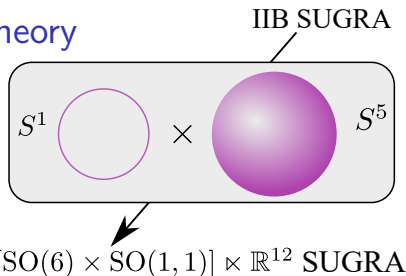
[Guarino, Sterckx, Trigiante '20], [Bobev, Gautason, van Muiden '21]



Expected to be compact e.g. [Perlmutter, Rasteli, Vafa, Valenzuela, '20]

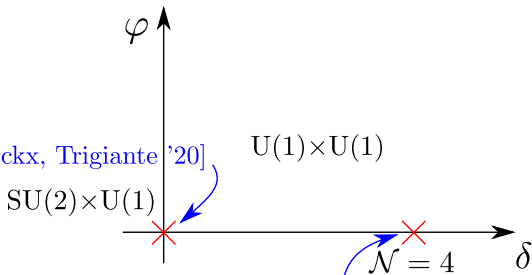
## Ex 2. Uplift to IIB string theory

[Inverso, Samtleben, Trigiante '16]



$AdS_4 \times S^5 \times S^1$  “S-fold” of IIB

[Guarino, Sterckx, Trigiante '20]

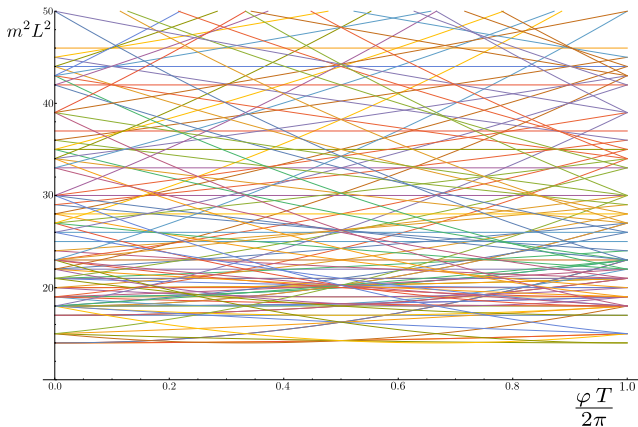


[Inverso, Samtleben, Trigiante '17]

## Ex 2. Global properties of the $\mathcal{N} = 2$ conformal manifold

$\text{AdS}_4 \times S^5 \times S^1$  KK spectrum along  $\varphi$  direction

[Giambrone, EM, Samtleben, Trigiante '21]

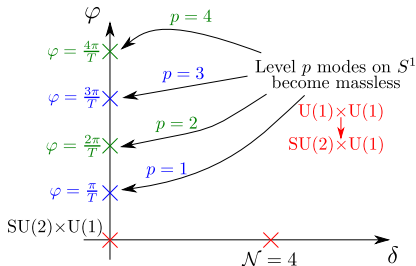


$$\varphi \sim \varphi + \frac{2\pi}{T}, \quad T \text{ radius of } S^1$$

## Ex 2. Space invaders

Higher KK modes become massless when  $\varphi = \frac{p\pi}{T}$ ,  $p \in \mathbb{Z}$

[Giambrone, EM, Samtleben, Trigiante '21]



Spectrum identical for  $\varphi = \frac{2p\pi}{T}$ ,  $p \in \mathbb{Z}$

Spectrum differs for  $\varphi = \frac{(2p+1)\pi}{T}$ ,  $p \in \mathbb{Z}$

## Ex 2. KK spectrum along $\mathcal{N} = 2$ conformal manifold

[Giambrone, EM, Samtleben, Trigiante '21]

- ▶  $\varphi \in \mathbb{R}^+$  is a 4-d artefact
- ▶  $\varphi \in [0, \frac{2\pi}{T})$  in 10 dimensions
- ▶ KK spectrum as fct of  $\varphi$ :

$$\Delta = \frac{1}{2} + \sqrt{\frac{17}{4} + \frac{1}{2}R^2 - J(J+1) - 2k(k+1) + \ell(\ell+4) + 4\left(\frac{\pi n}{T} - j\varphi\right)^2}.$$

Lorentz spin:  $J$

SU(2) spin:  $k$

U(1)<sub>R</sub> charge:  $R$

U(1)  $\subset$  SU(2) Cartan:  $j$

$S^5$  level:  $\ell$

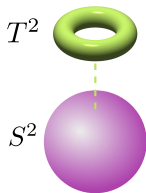
$S^1$  level:  $n$

- ▶ KK spectrum as fct of  $\delta$ : non-compact? [Bobev, Gautason, van Muiden '21], [Cesàro, Larios, Varela '21]

## Ex 2. $\varphi$ as complex structure deformation

[Giambrone, EM, Samtleben, Trigiante '21]

- ▶  $\varphi$ -family:  $\text{AdS}_4 \times S^5 \times S^1_\eta$ :  $S^5 \rightarrow S^3 \times S^2$
- ▶  $S^3$  Hopf fibre &  $S^1_\eta$ :



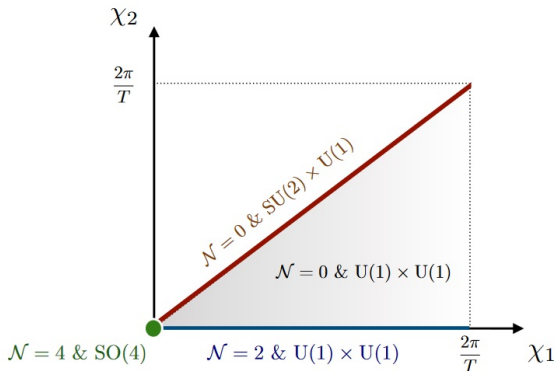
$$\tau = \frac{i}{4\pi} - \frac{\varphi T}{2\pi}$$
$$\varphi \rightarrow \varphi + \frac{2\pi}{T} \implies \tau \rightarrow \tau - 1$$

- ▶  $\varphi$  deformation: locally  $\rightarrow$  coordinate transformation

Similar in other S-fold vacua [Cesàro, Larios, Varela '22]

### Ex 3. Non-SUSY flat deformations

2 new flat directions  $\chi_1, \chi_2$  of 4-D supergravity [Guarino, Sterckx '21]



Non-supersymmetric conformal manifold?

## Ex 3. Evidence for non-SUSY exactly marginal deformations

Non-SUSY exactly marginal deformations not expected to exist

Evidence for a miracle

[Giambrone, Guarino, EM, Samtleben, Sterckx, Trigiante '21]

- ▶ Perturbative stability
- ▶ Non-perturbative stability
- ▶  $\frac{1}{N}$  corrections

$\chi_1, \chi_2$  deformations are locally coordinate transformations!

## Ex 3. KK Spectroscopy

[Giambrone, Guarino, EM, Samtleben, Sterckx, Trigiante '21]

KK spectroscopy  $\rightarrow$  full KK spectrum

Perturbatively stable!

$$\Delta = \frac{3}{2} + a + \frac{1}{2} \sqrt{9 + 2\ell(\ell + 4) + 4\ell_1(\ell_1 + 1) + 4\ell_2(\ell_2 + 1) + 2 \left( \frac{2n\pi}{T} + j_1\chi_1 + j_2\chi_2 \right)^2}.$$

Position within  $\mathcal{N} = 4$  multiplet:  $a$

SO(4) spin:  $\ell_1, \ell_2$

Charges under  $U(1) \times U(1)$  Cartan:  $j_1, j_2$

$S^5$  level:  $\ell$

$S^1$  level:  $n$

## Ex 3. Non-perturbative stability?

[Giambrone, Guarino, EM, Samtleben, Sterckx, Trigiante '21]

- ▶ Probe-brane analysis:  $T > Q$   
Branes more stable than in SUSY case!
- ▶ No Ooguri-Vafa instability [Ooguri, Vafa '16]
- ▶  $S^1$  and  $S^5$  protected against “bubble of nothing” [Witten '82]
- ▶ D3-brane bubble of nothing [Bomans, Cassani, Dibitetto, Petri '21] ??

### Ex 3. $\frac{1}{N}$ corrections

[Giambrone, Guarino, EM, Samtleben, Sterckx, Trigiante '21]

Flat directions lifted by  $\frac{1}{N}$  corrections?

Protection by diffeomorphism symmetry

- ▶  $\chi_1, \chi_2 \rightarrow$  coordinate transformations (locally)
- ▶  $\chi_1, \chi_2$  do not appear in diffeo-invariant quantities

Also applies to  $\mathcal{N} = 1$  exactly marginal deformations

[Bobev, Gautason, van Muiden '21]

### Ex 3. $\frac{1}{N}$ corrections

[Giambrone, Guarino, EM, Samtleben, Sterckx, Trigiante '21]

Flat directions lifted by  $\frac{1}{N}$  corrections?

Protection by diffeomorphism symmetry

- ▶  $\chi_1, \chi_2 \rightarrow$  coordinate transformations (locally)
- ▶  $\chi_1, \chi_2$  do not appear in diffeo-invariant quantities

Also applies to  $\mathcal{N} = 1$  exactly marginal deformations

[Bobev, Gautason, van Muiden '21]

Corrections from D5-instantons?

$vol_{S^5 \times S^1}$  independent of  $\chi_1, \chi_2$

# Conclusions

Using ExFT:

- ▶ Embedding of lower-dimensional AdS vacua into string theory
- ▶ Anomalous dimensions of operators
- ▶ Higher KK modes crucial for physics, e.g. compactness, stability
- ▶ Non-supersymmetric AdS/CFT?
- ▶ Non-supersymmetric exactly marginal deformations?

Open questions

- ▶ Correlation functions?
- ▶ Vacua of less SUSY gSUGRA?
- ▶ Spectrum along RG flow without consistent truncation?
- ▶  $\Lambda \geq 0$ ?

Thank you!