Supersymmetric scale-separated vacua were meant IIB

Vincent Van Hemelryck

UPPSALA UNIVERSITET

Based on [VVH, 2502.04791]

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Hiding extra dimensions

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$$10 \neq 4$$

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$$11 \neq 4$$

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Dimensionality of best understood string theories/M-theory $\neq$ Observed dimensionality of the universe

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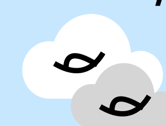
Solution

Compactifications & scale separation

$\times$ $\mathcal{M}_n$



L_{KK}

L_H

$$\mathrm{d}s^2_{d+n} = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu \quad + \quad g_{mn}\mathrm{d}y^m \mathrm{d}y^n$$

Lower-dimensional effective field theory: **scale separation:**

$$L_{\mathrm{KK}} \ll L_H$$

Extra dimensions smaller than cosmological radius

$$\Lambda_d \ll M^2_{\mathrm{KK}}$$

Cosmological constant smaller than the UV cut-off

Moduli stabilisation

with fluxes, branes and O-planes

See e.g. [Van Riet, Zoccarato, 2023]

$$ds_{10}^2 = e^{\frac{2\Phi_d}{d-2}} g_{\mu\nu} dx^\mu dx^\nu \quad + \quad L^2 g_{mn} dy^m dy^n$$

$$\Lambda_n$$

$$S_{10} = \frac{M_{\mathrm{Pl},10}^8}{2} \int \sqrt{-g_{10}}\, e^{-2\phi} \left(R_{10} + \cdots\right) \longrightarrow S_d = \frac{M_{\mathrm{Pl,d}}^{d-2}}{2} \int \sqrt{-g_d} \left(R_d - g_{ij}\partial\phi^i\partial\phi^j - V(L, \Phi_d)\right)$$

schematically $V = -R_n + \sum_k |F_k|^2 + V_{\text{D-branes}} - V_{\text{O-planes}}$

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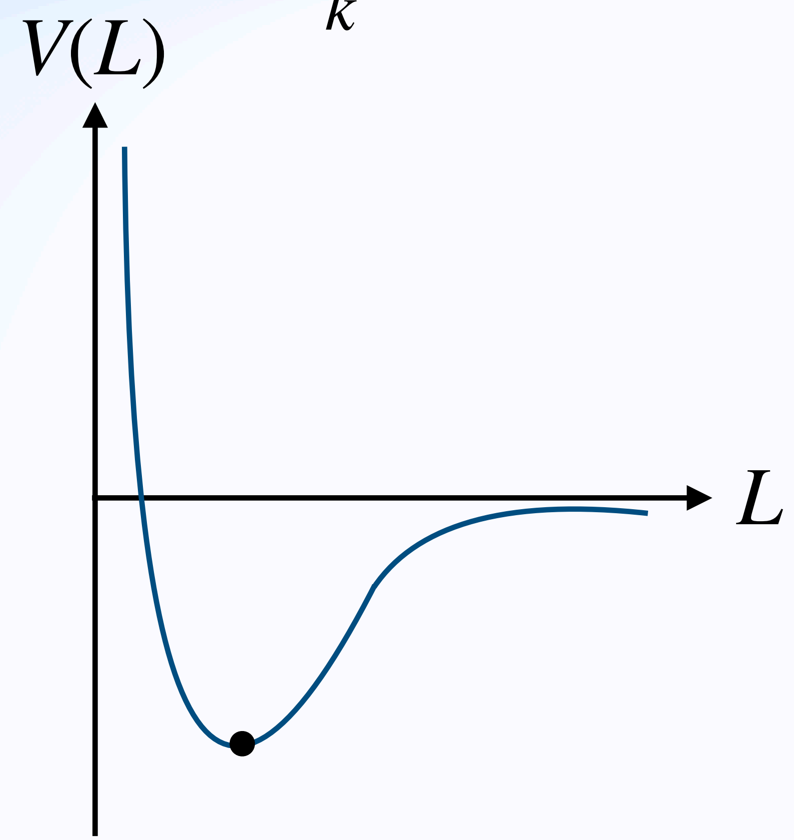
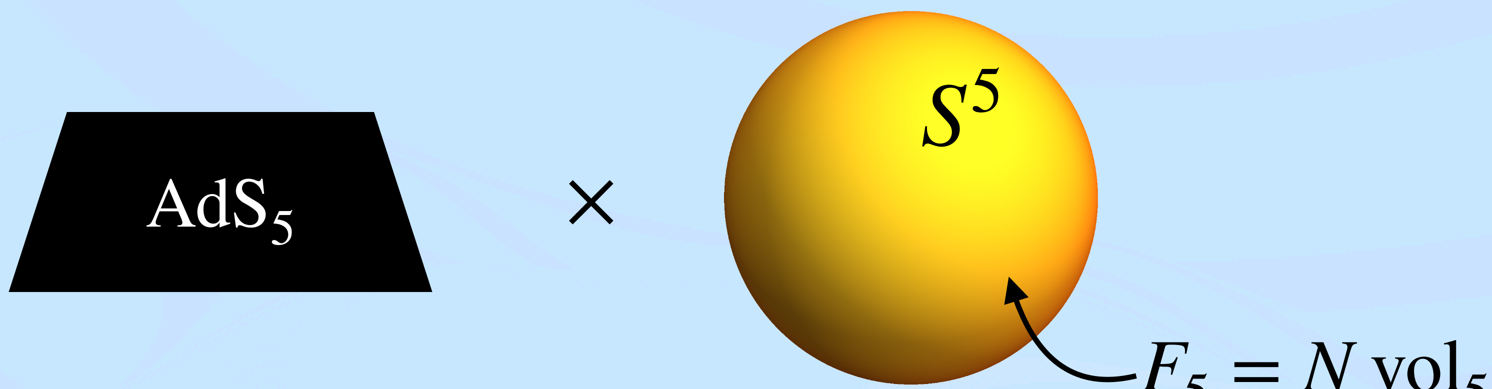
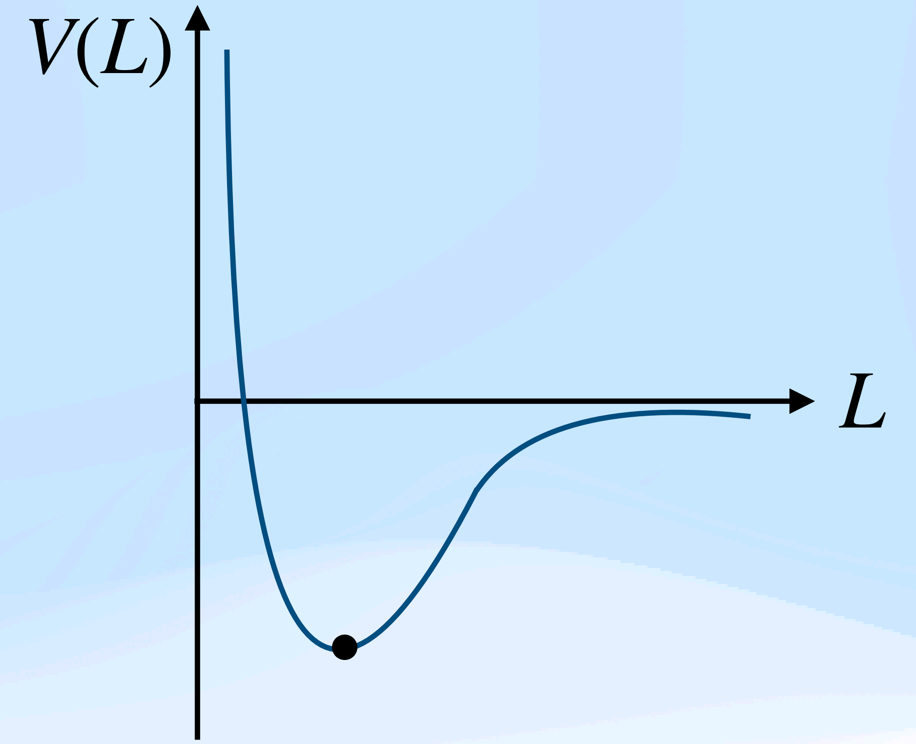


Moduli stabilisation

e.g. $\mathrm{AdS}_5 \times S^5$





Both scales are completely determined by the five-form flux

$$L = (4\pi g_s N)^{1/4} \ell_s = L_{\mathrm{AdS}}$$

So **no scale separation!** It is possible for compactifications with

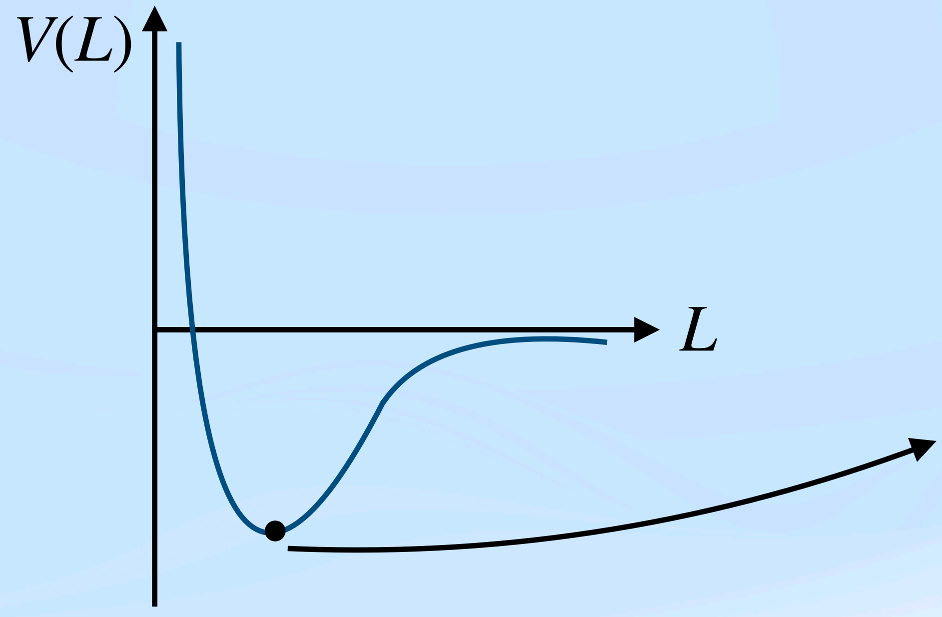
$$L_{\mathrm{KK}} \sim N^{\alpha} \ell_s \quad \text{and} \quad L_{\mathrm{AdS}} \sim N^{\beta} \ell_s$$

with $0 < \alpha < \beta$.

We <u>do</u> have such examples in type IIA string compactifications

DGKT-CFI, 4d & 3d variants by:
Cribiori, Junghans, VVH, Van Riet, Wrase, Andriot, Horer, Marconnet, Farakos, Tringas, Van Riet, Emelin, Morittu, Arboleya, Guarino,…]

No scale separation?



Theorems

[Gautason, Schillo, Van Riet, Williams, 2016],
[De Luca, Tomasiello, 2021], [Tringas, Wrase, 2025]

Strong AdS distance conjecture: with SUSY, $m \sim \Lambda^{1/2}$ [Lüst, Palti, Vafa, 2019]

Arguments against scale separation with extended SUSY and $Q \geq 8$

[Cribiori, Dall'agata, 2022]
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[Perlmutter, 2024],..

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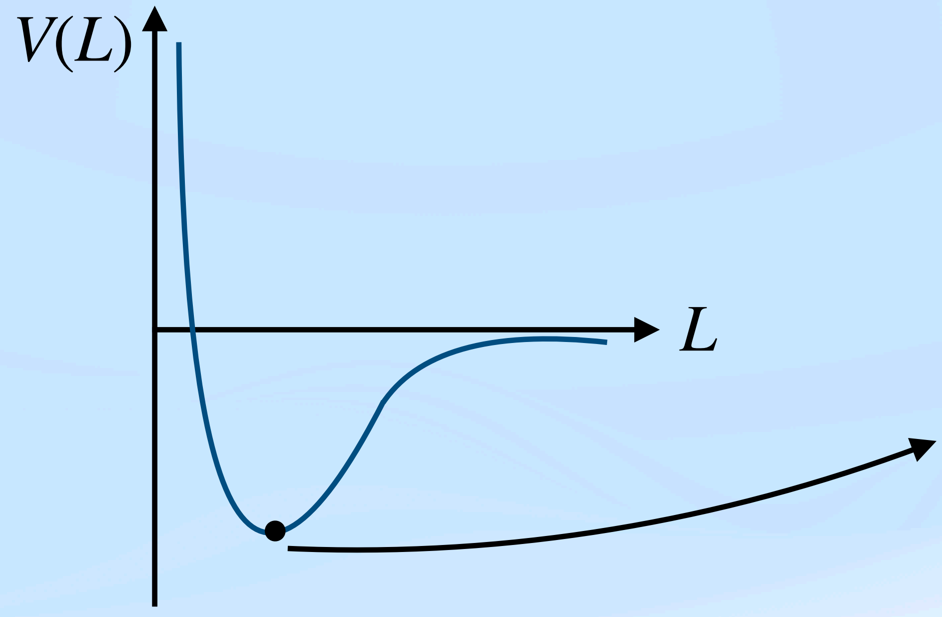

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Option 1: no curvature

$\mathcal{N} = 1$ state of the art with parametric scale separation

O6-planes, H
$F_4 \sim N$

4d: $\mathscr{M}_6 = \mathrm{CY}_3$ [Dewolfe, Giryavets, Kachru, Taylor, 2005], [Camara, Font, Ibañez, 2005], …

3d: $\mathscr{M}_7 = \mathscr{M}_{G_2}$ [Farakos, Tringas, Van Riet, 2020]

✕

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Option 2: curvature

Can the curvature scale decouple?

L_{KK}^{-2} estimated by λ_1 = lowest eigenvalue of scalar Laplacian

$$|R_n| \ll \lambda_1$$

Positively curved manifolds → No examples known

Claimed to be impossible by [Collins, Jafferis, Vafa, Xu, Yau, 2022]
However, see [Cribiori, Junghans, VVH, Van Riet, Wrase, 2021], [VVH, 2024]

Negatively curved manifolds → Nilmanifolds

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Negatively curved manifolds → **Nilmanifolds**

(Negative energy density necessary, such as by O-planes)

The harmonic oscillator of nilmanifolds

$$\mathrm{d}s_3^2 = (L_1 e^1)^2 + (L_2 e^2)^2 + (L_3 e^3)^2 \qquad e^1 = \mathrm{d}x^2 + \omega x^2 \mathrm{d}x^3, \qquad e^{2,3} = \mathrm{d}x^{2,3}$$

$$\mathrm{d}e^1 = \omega e^2 \wedge e^3, \qquad \mathrm{d}e^{2,3} = 0$$

Laplacian spectrum

$$m_{p,q}^2 = p^2 \left(\frac{2\pi}{L_2}\right)^2 + \; q^2 \left(\frac{2\pi}{L_3}\right)^2$$

$$m_{k,l,n}^2 = k^2 \left(\frac{2\pi}{L_1}\right)^2 + (2n+1)\,|\,k\omega\,|\,\frac{2\pi}{L_2 L_3}$$

[Andriot, Tsimpis, 2018]

Curvature

$$R_3 = -\left(\omega \frac{L_1}{L_2 L_3}\right)^2$$

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Take $L_1 \ll L_3 \leq L_2$ and ω fixed

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$$\longrightarrow \quad \lambda_1 = m_{1,0}^2 = \left(\frac{2\pi}{L_2}\right)^2$$

Curvature

$$R_3 = -\left(\omega \frac{L_1}{L_2 L_3}\right)^2$$

$$\longrightarrow \quad |R_3| \ll \left(\frac{\omega}{L_2}\right)^2 \sim \lambda_1$$

$\mathcal{N} = 1$ state of the art with parametric scale separation

O6-planes,
$H = 0, F_6 \sim N^a,$
$F_{2,2} \sim N^b, F_{2,3} \sim N^c$

In 4d only

[Cribiori, Junghans, VVH, Van Riet, Wrase, 2021]
see also [Koerber, Lüst, Tsimpis, 2008], [Caviezel, Koerber, Kors, Lüst, Tsimpis, Zagermann, 2009],…
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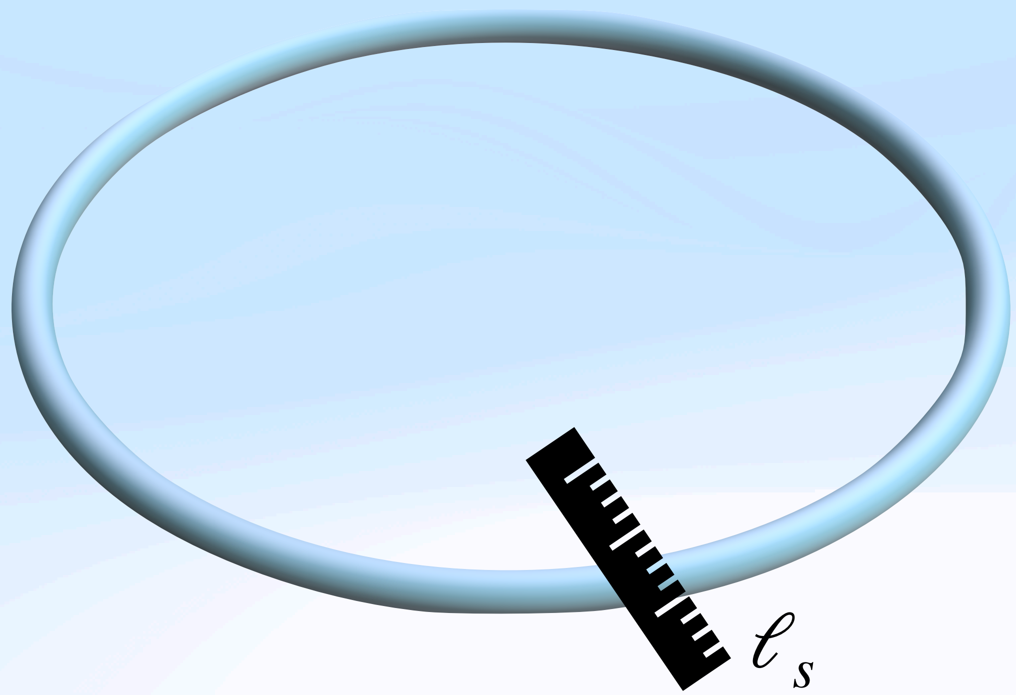
IIB or not IIB?

Supersymmetric history

Efforts only for AdS_4: SU(2)-structures

[Cavaziel, Wrase, Zagermann 2009]
[Petrini, Solard, Van Riet, 2013]

Problem:



[Cribiori, Junghans, VVH, Van Riet, Wrase, 2021]

For AdS_3: co-closed G_2-structures?

[Emelin, Farakos, Tringas, 2021]
[Passias, Prins, 2019]
[VVH, 2022]

$\rightarrow$ If too many O5-planes:

$$\not\leftrightarrow$$

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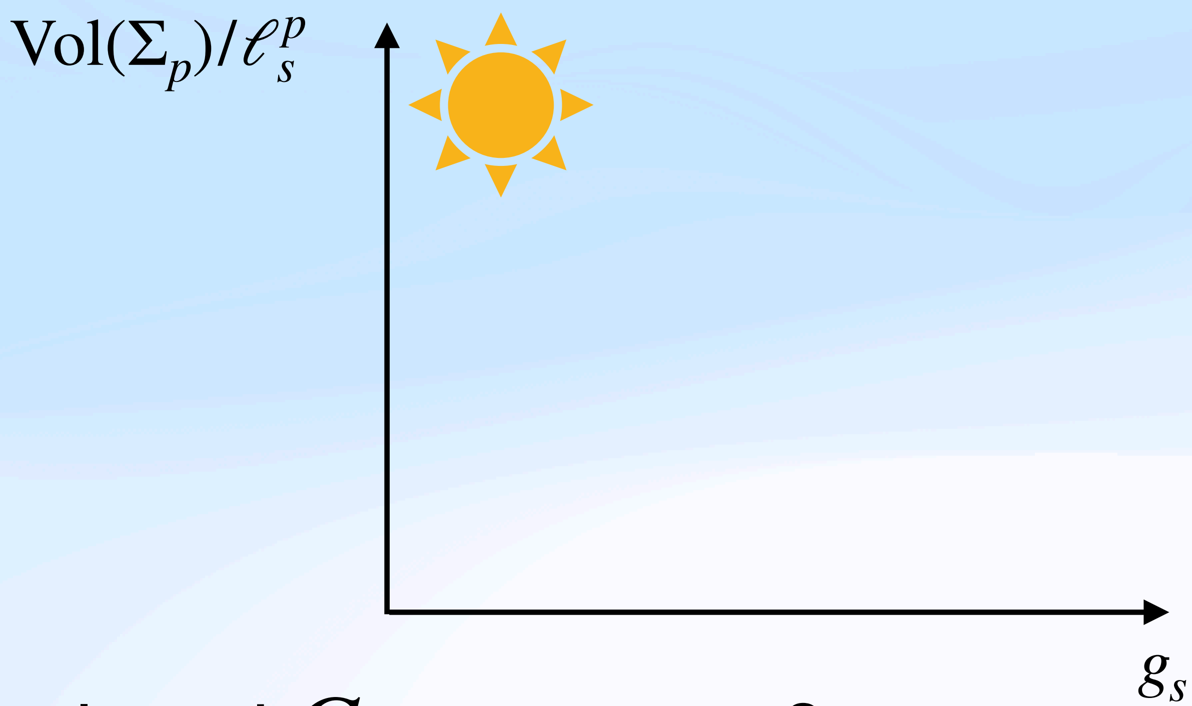

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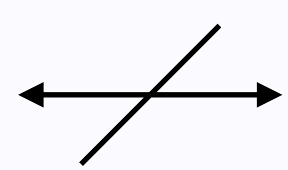

$\mathcal{N} = 1$ scale-separated AdS solutions of type IIB

with nilmanifolds

$\mathcal{N} = 1$ AdS$_3$ solutions of type IIB

On G_2-structure manifolds

[Dibitetto, Lo Monaco, Passias, Tomasiello, 2018]
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Co-closed G_2-structure

$$\mathrm{d}\Phi = W_1 \star \Phi + W_{27}\,, \qquad \mathrm{d} \star \Phi = 0, \qquad W_1 = 12/(7L_{\mathrm{AdS}})$$

SUSY variations imply

$$g_s F_3 = - \star \mathrm{d}\Phi + 2\mu\Phi$$
$$g_s F_7 = - 2\mu \mathrm{vol}_7$$

$$F_1 = 0$$
$$F_5 = 0$$
$$H = 0$$

Non-trivial Bianchi identity

$$\mathrm{d}F_3 = \sum_i j_{\mathrm{D5},i} - \sum_i j_{\mathrm{O5},i}$$

$\mathcal{N}=1$ AdS$_3$ solutions of type IIB

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g_{mn}

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$R^m{}_{nlp}$

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$\mathbb{Z}_2^3$ toroidal orbifolds

[Joyce, 1996][2],…
[Dall'Agata, Prezas, 2005,],
[Emelin, Farakos, Tringas, 2021],…

Joyce orbifolds

$\mathbb{Z}_2^3$ orbifold generators

x^i	1	2	3	4	5	6	7
α	-	-	+	+	-	-	+
β	+	+	-	-	-	-	+
γ	-	+	-	+	-	+	-

+ shifts

Orientifold involution

x^i	1	2	3	4	5	6	7
σ_α	-	-	+	+	-	-	+

Invariant cycles/forms

Σ_3	1	2	3	4	5	6	7
$e^{\cdots}$	127	347	567	145	235	136	426

+ dual 4-cycles/forms

$$\Phi = L_1L_2L_7\, e^{127} + L_3L_4L_7\, e^{347} + L_5L_6L_7\, e^{567} + L_1L_4L_5\, e^{145} + L_2L_3L_5\, e^{235} + L_1L_3L_6\, e^{136} - L_2L_4L_6\, e^{246}$$

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+ shifts

Orientifold involution

x^i	1	2	3	4	5	6	7
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$$\mathrm{d}e^a = \frac{1}{2} f^a{}_{bc}\, e^b \wedge e^c \quad \rightarrow \quad \text{must be invariant}$$

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$f^a{}_{bc} \to W_1, W_{27}$

[Gong, 1998], [Bagaglini, Bazzoni, Conti, Fernandez, Fino, Garvin, Muñoz, …]

The harmonic oscillator: $\mathfrak{n}_2 = \mathrm{Nil}_3 \times \mathbb{T}^4$

$$\mathrm{d}e^7 = \omega e^1 \wedge e^2$$

Σ_3	1	2	3	4	5	6	7
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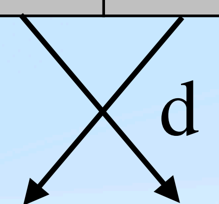
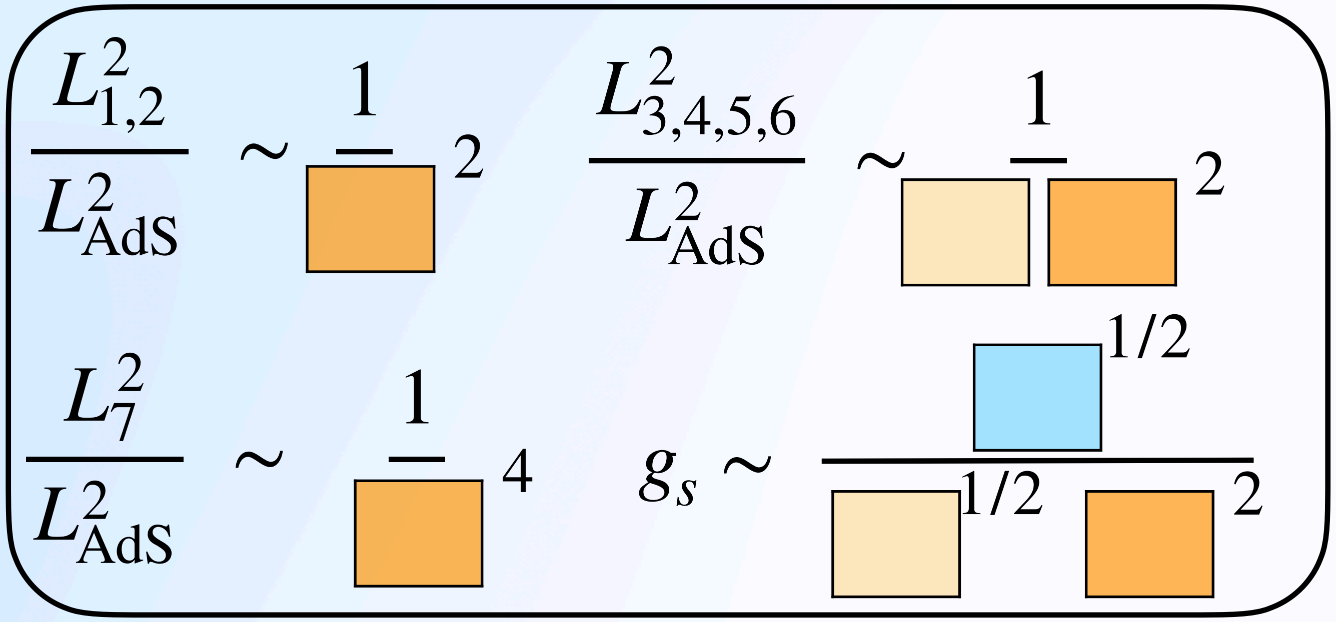
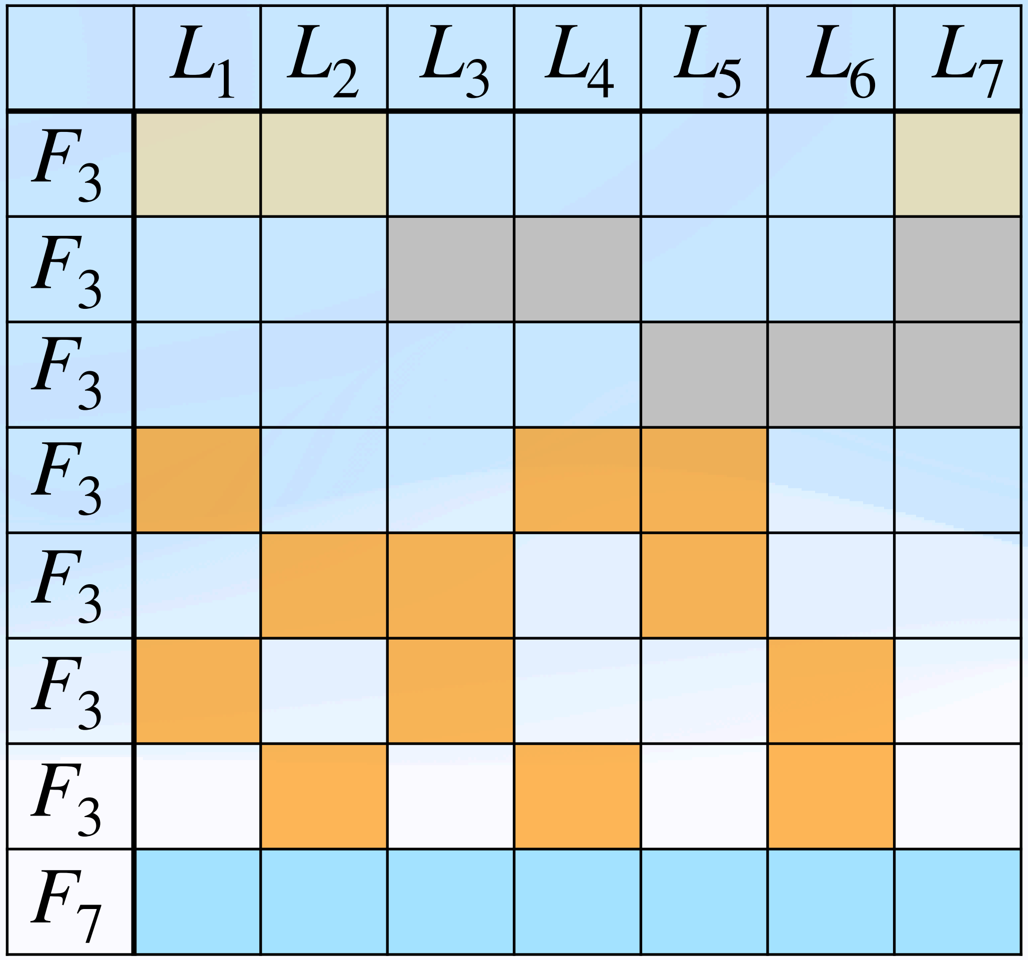
Σ_3	1	2	3	4	5	6	7
F_3							



Σ_4	1	2	3	4	5	6	7
$\perp$ O5		j_{O5}	j_{O5}				





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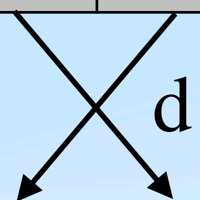

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	L_1	L_2	L_3	L_4	L_5	L_6	L_7
F_3							
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F_3							
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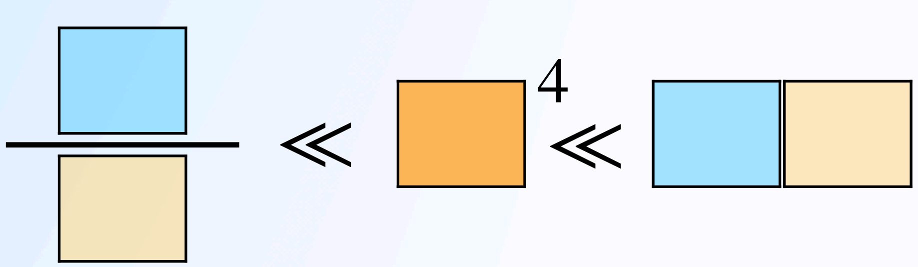
F_7							



$$m^2 L_{\mathrm{AdS}}^2 = \{120, 8^7\}$$

$$\Delta = \{12, 4^7\}$$

[Conlon, Ning, Revello, 2021],…

$37D_1$

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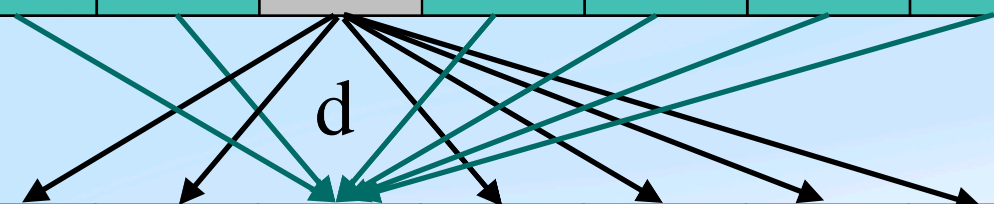

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	L_1	L_2	L_3	L_4	L_5	L_6	L_7
F_3							
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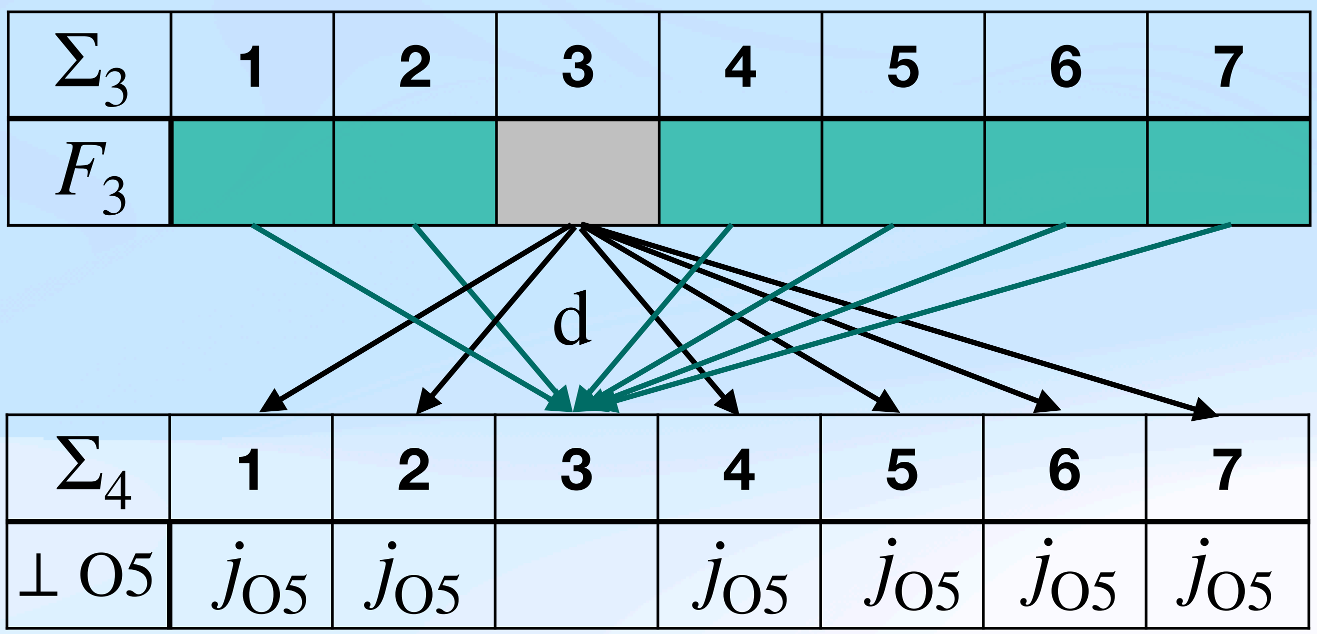
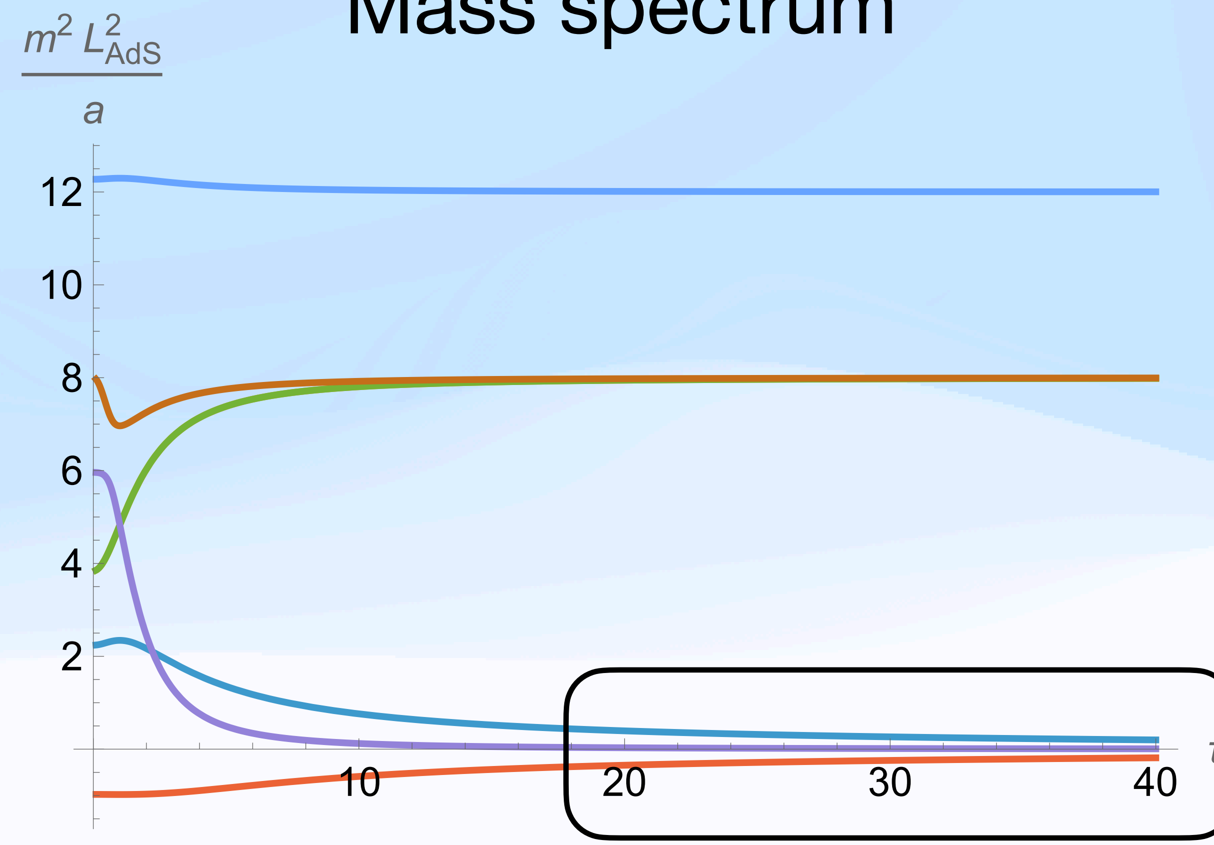
Similar scale separated limit

$37D_1$

Σ_3	1	2	3	4	5	6	7
$e^{\cdots}$	127	347	567	145	235	136	426



Mass spectrum



3 scalars
become light

Similar scale separated limit

Similar as in [Farakos, Tringas, 2025],
related by T-duality

Remark about solvmanifold constructions

Similar solvmanifold constructions on $\mathbb{Z}_2^3$ orbifolds

Hierarchy between cycle volumes and AdS scale:

$$\frac{\mathrm{Vol}(\Sigma_p)}{L_{\mathrm{AdS}}^p} \ll 1 \text{ for } p = 3,4$$

But λ_1 decouples from cycle volumes:

$$L_{\mathrm{KK}} \sim \lambda_1^{-1/2} \nsim \mathrm{Vol}(\Sigma_\mathrm{p})^{1/p}$$

[VVH, 2025]

Also true for non-supersymmetric cousins

[Arboleya, Guarino, Morittu, 2024 & 2025]
[Arboleya, Guarino, Morittu, Sudano, 2025]

Conclusions

First supersymmetric, scale-separated solutions of type IIB

Nilmanifolds with the required property $|R_7| \ll \lambda_1$ (or $|W_1| \ll \lambda_1$)

Co-closed G_2-structure, with only RR fluxes

Simplest example is $\mathrm{AdS}_3 \times (\mathrm{Nil}_3 \times \mathbb{T}^4)/\mathbb{Z}_2^3$ with only 2 sets of O-planes

Outlook

Go beyond $\mathbb{Z}_2^3$ orbifolds

Investigating T-duals in IIA into $\mathrm{SU}(3)$-structures

[Passias, Prins, 2020]

Going beyond the smearing approximation

[Junghans, 2020]
[Marchesano, Palti, Quirant, Tomasiello, 2020]
[Cribiori, Junghans, VVH, Van Riet, Wrase, 2021],
[Junghans, 2023], [VVH, 2024]
[Emelin, Farakos, Tringas, 2022], [Emelin, 2024],…

Formulating the holographic dual field theory?

[Apers, Montero, Valenzuela, 2025]

Thank you!