New families of scale separated vacua

Thibaut Coudarchet
Institut für Theoretische Physik, Heidelberg University

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Based on 2309.00043 [R. Carrasco, TC, F. Marchesano and D. Prieto] and review 2311.12105 [TC]

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10d spacetime $=$  $\times$ 

4d world — Compact X^6

- Cosmological constant Λ

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- Kaluza-Klein scale $M_{\mathrm{KK}} \sim \frac{M_{\mathrm{s}}}{\mathrm{Vol}_{X_6}^{1/6}}$ (and winding scale)

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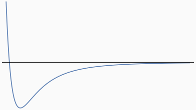

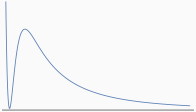

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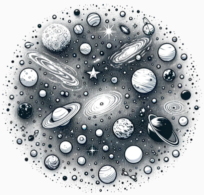
10d spacetime $=$  $\times$ 

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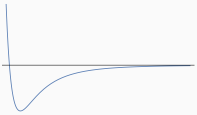

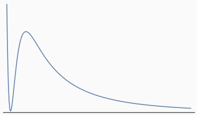

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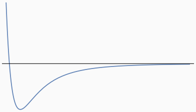

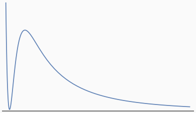

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DGKT in type IIA [DeWolfe, Giryavet, Kachru, Taylor, '05]

- $X_6 = T^6/(\mathbb{Z}_3 \times \mathbb{Z}_3) \Longrightarrow h^{2,1} = 0$ & let us forget twisted moduli

$$t^a \propto \frac{\sqrt{|\hat{e}_1 \hat{e}_2 \hat{e}_3|}}{|\hat{e}_a|\sqrt{m}} \quad \text{with} \quad \hat{e}_a \equiv e_a - \frac{1}{2}\frac{\mathcal{K}_{abc} m^b m^c}{m}$$

Tadpole: $\mathrm{d}G_2 = G_0 H + Q_{\mathrm{O6}}\delta_{\mathrm{O6}}$

$\Longrightarrow$ Flux quanta e_a, m^a unconstrained

$$\boxed{\hat{e}_a \sim n}$$

$$t^a \sim n^{\frac{1}{2}}\,, \quad \mathrm{Vol}_{X_6} \sim n^{\frac{3}{2}}\,, \quad e^{\phi} \propto (\mathcal{K}_{abc} t^a t^b t^c)^{-\frac{1}{2}} \sim n^{-\frac{3}{4}}\,, \quad e^{\phi_4} \sim n^{-\frac{3}{2}}$$

Good control: $n \to \infty \Longrightarrow$ large volume/weak coupling

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$$\Lambda \propto -3e^K|W|^2 \sim n^{-\frac{9}{2}}$$

$$R_{\rm AdS}M_{\rm KK} \sim n^{\frac{1}{2}}\,, \quad \text{and} \quad R_{\rm AdS}M_{\rm W} \sim n$$

Susy AdS:

- Moduli stabilised
- Controlled regime
- Scale separation
- Pert. stable

Generalisable:

- Metric fluxes [Camara, Font, Ibáñez '05] [Derendinger, Kounnas, Petropoulos, Zwirner '05] [Villadoro, Zwirner '05]
- Arbitrary CY, Non-susy [Narayan, Trivedi '10] [Marchesano, Quirant '19]
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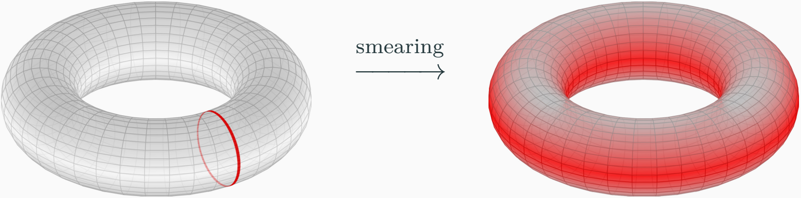
Smearing

10d uplift of DGKT cannot be CY

O6-planes are diluted in compact space [Acharya, Benini, Valandro '07]



$$\delta_{O6}(\vec{y}) \propto \sum_{\vec{k}} e^{i\vec{k}\cdot\vec{y}} = 1 + \sum_{\vec{k}\neq\vec{0}} e^{i\vec{k}\cdot\vec{y}} \longrightarrow 1$$

DGKT lifts to 10d with smeared sources

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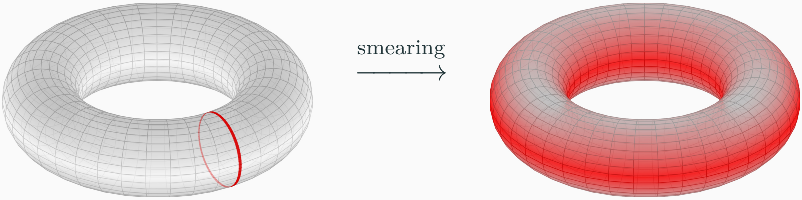

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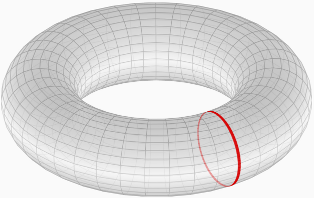
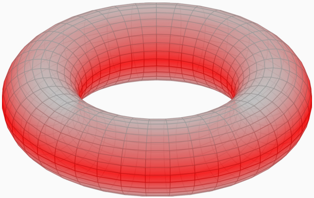


$\xrightarrow{\text{smearing}}$



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Status of scale separation

Status of scale separation [DeWolfe, Giryavets, Kachru, Taylor '05]

Status of scale separation [Banks, van den Brock '07][McOrist, Sethi '12]

Status of scale separation [Junghans '20]

[Marchesano, Palti, Quirant, Tomasiello '20]

Status of scale separation [D. Lust, Palti, Vafa ’19]

Status of scale separation [Buratti, Calderon, Mininno, Uranga '20]

Status of scale separation [Polchinski, Silverstein '09] [Montero, Rocek, Vafa '23] [Collins, Jafferis, Vafa, Xu, Yau '22] [Apers, Conlon, Ning, Revello '22] ...

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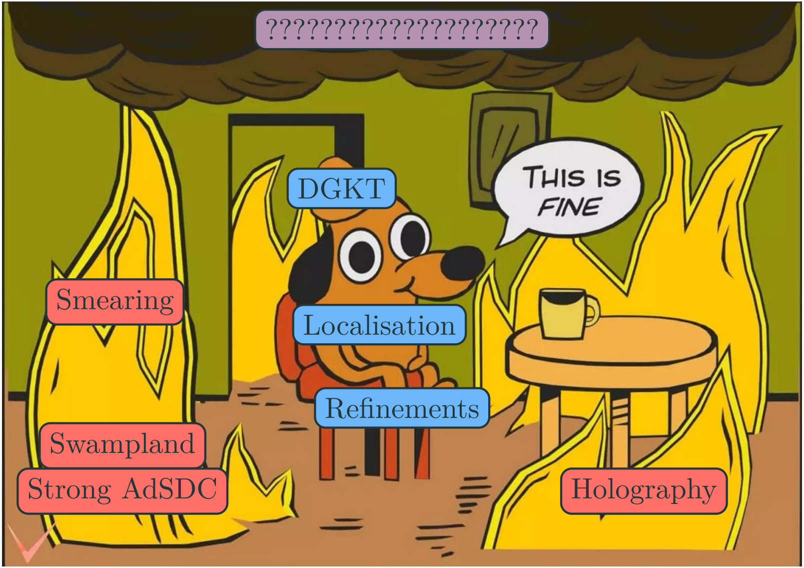

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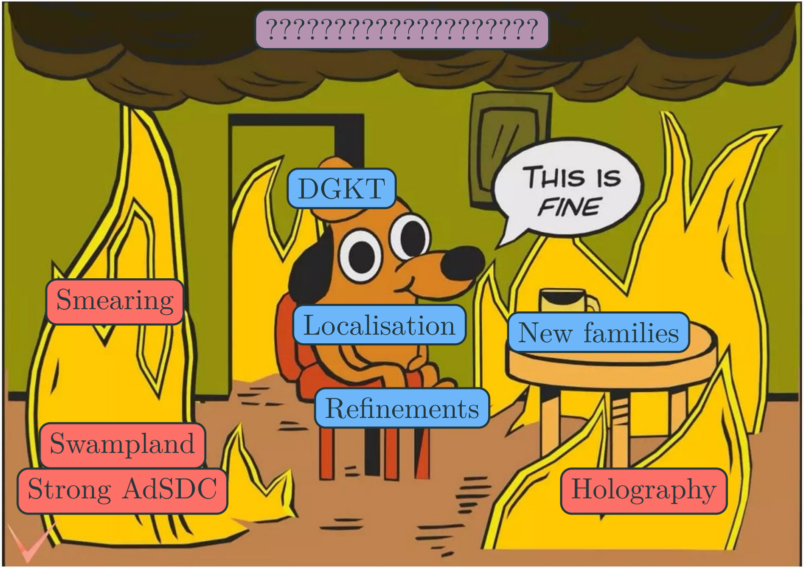

New families: Motivations

New families: Double T-duality [Banks, Van Den Broek '06]

- We consider $(T^2)^3/\Gamma$

$\hat{e}_1 \sim n^{2r}\,, \qquad \hat{e}_2, \hat{e}_3 \sim n^{r+s}$ (DGKT was $r = s = \frac{1}{2}$)

$\implies t^1 \sim n^s \quad t^2, t^3 \sim n^r$

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- Weak coupling: $r + \frac{s}{2} > 0$

Can be satisfied even when $s < 0 \longleftrightarrow$ shrinking torus factor

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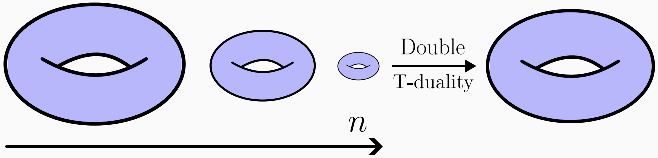

Where T-duality brings us

- $K_K = -\log\left(i\kappa(T^1 - \bar{T}^1)(T^2 - \bar{T}^2)(T^3 - \bar{T}^3)\right), \qquad \kappa = \mathcal{K}_{123}$
- $K_Q(\cancel{T^a})$

Double T-duality for $a = 1$: $T^1 \mapsto -\frac{1}{T^1}$

$K_K \mapsto K_K + \log|T^1|^2$

Kähler transf.: $K_K \mapsto K_K - F - \bar{F}$, $W \mapsto e^F W$, $\qquad F = \log T^1$

$$W_{\mathrm{RR}} = e_0 + e_a T^a + \tfrac{1}{2}\mathcal{K}_{abc} m^a T^b T^c + \tfrac{m}{6}\mathcal{K}_{abc} T^a T^b T^c$$

$$\downarrow$$

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Where T-duality brings us

$$W_{\text{NS}} = h_\mu U^\mu$$

$$\downarrow$$

$$W_{\text{NS}} = h_\mu U^\mu T^1$$

- Quadratic term mixing U^μ and T^1

H-flux $\mapsto$ Metric fluxes (rank-one)

Lost Romans mass but price to pay: Depart from CY

Back to 4d setup

$W_{\mathrm{RR}}, W_{\mathrm{NS}} = h_\mu U^\mu + f_{a\mu} T^a U^\mu$

$f_{a\mu} \in \mathbb{Z} \longleftrightarrow$ metric fluxes:

$$\mathrm{d}\omega_a = -f_{a\mu}\beta^\mu, \qquad \mathrm{d}\alpha_\mu = -f_{a\mu}\tilde{\omega}^a$$

Tadpole: $[m^a f_{a\mu} + m h_\mu + m f_{a\mu} b^a]\, \beta^\mu + N_\alpha \delta^\alpha_{\mathrm{D6}} - 4\delta_{\mathrm{O6}} = 0$

$\Longrightarrow$ e fluxes (G_4 and G_6) are not constrained
$\Longrightarrow$ the m^a's (G_2) not involved in $m^a f_{a\mu}$ either

Generalizes the toroidal construction of [Cribiori, Junghans, Van Hemelryck, Van Riet, Wrase '21]: Iwasawa $\longrightarrow$ Ell. fibred CY

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4d setup: Bilinear magic

$$V_{\mathrm{F}} = \rho_{\mathcal{A}} Z^{\mathcal{A}\mathcal{B}} \rho_{\mathcal{B}}$$

[Bielleman, Ibañez, Valenzuela '15][Carta, Marchesano, Staessens, Zoccarato '16][Herraez, Ibañez, Marchesano, Zoccarato '18]

- $Z^{\mathcal{A}\mathcal{B}}$ depends only on saxions
- The $\rho_{\mathcal{A}}$'s are flux-axion polynomials

$\longrightarrow$ depend on fluxes and axions

Facilitates systematic search for vacua [Escobar, Marchesano, Staessens '18][Escobar, Marchesano, Staessens '19][Marchesano, Quirant '19][Marchesano, Prieto, Quirant, Shukla '20][Marchesano, Prieto, Wiesner '21]

New families: More details

4d setup: Bilinear magic

F-term ansatz [Marchesano, Prieto, Quirant, Shukla '20]:

$$\langle D_{T^a} W, D_{U^\mu} W \rangle_{\text{vac}} = \langle \lambda_K \partial_{T^a} K, \lambda_Q \partial_{U^\mu} K \rangle_{\text{vac}}$$

$$\begin{aligned} \rho_a &= \ell_s^{-1} \mathcal{P}\, \partial_a K \,, \\ \mathcal{K}_{ab}\tilde{\rho}^b + \rho_{a\mu} u^\mu &= \ell_s^{-1} \mathcal{Q}\, \partial_a K \,, \\ \rho_\mu &= \ell_s^{-1} \mathcal{M}\, \partial_\mu K \,, \\ t^a \rho_{a\mu} &= \ell_s^{-1} \mathcal{N}\, \partial_\mu K \,, \end{aligned}$$

Branch \ Parameters	$\mathcal{P}$	$\ell_s \rho_0$	$\mathcal{Q}$	$\ell_s \tilde{\rho} = m$	$\mathcal{M}$
SUSY	Free	$-\frac{3}{2}\mathcal{N}$	$\mathcal{N}$	$-10\frac{\mathcal{P}}{\mathcal{K}}$	$-\frac{2}{3}\mathcal{P}$
non-SUSY	0 $+\frac{\mathcal{N}}{2}$ $-\frac{\mathcal{N}}{2}$	$-\frac{\mathcal{N}}{2}\left(1 - \frac{12}{\mathcal{S}}\right)$	$\mathcal{N}$	0	$\frac{4\mathcal{P}}{\mathcal{S}}$

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Parameters / Branch	$\mathcal{P}$	$\ell_s\rho_0$	$\mathcal{Q}$	$\ell_s\tilde{\rho} = m$	$\mathcal{M}$
SUSY	Free	$-\frac{3}{2}\mathcal{N}$	$\mathcal{N}$	$-10\frac{\mathcal{P}}{\mathcal{K}}$	$-\frac{2}{3}\mathcal{P}$
non-SUSY	0 / $+\frac{\mathcal{N}}{2}$ / $-\frac{\mathcal{N}}{2}$	$-\frac{\mathcal{N}}{2}\left(1-\frac{12}{\mathcal{S}}\right)$	$\mathcal{N}$	0	$\frac{4\mathcal{P}}{\mathcal{S}}$

4d setup: Bilinear magic

F-term ansatz [Marchesano, Prieto, Quirant, Shukla '20]:

$$\langle D_{T^a} W, D_{U^\mu} W \rangle_{\text{vac}} = \langle \lambda_K \partial_{T^a} K, \lambda_Q \partial_{U^\mu} K \rangle_{\text{vac}}$$

$$\begin{aligned} \rho_a &= \ell_s^{-1} \mathcal{P}\, \partial_a K\,, \\ \mathcal{K}_{ab} \tilde{\rho}^b + \rho_{a\mu} u^\mu &= \ell_s^{-1} \mathcal{Q}\, \partial_a K\,, \\ \rho_\mu &= \ell_s^{-1} \mathcal{M}\, \partial_\mu K\,, \\ t^a \rho_{a\mu} &= \ell_s^{-1} \mathcal{N}\, \partial_\mu K\,, \end{aligned}$$

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Massless solutions

$$\text{SUSY:} \qquad \mathcal{Q} = \mathcal{N}\,, \qquad \ell_s \rho_0 = -\frac{3}{2}\mathcal{N}\,,$$
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AdS vacua with $V|_{\text{vac}} = -12 e^{K} \mathcal{Q}^2$

10d interpretation:

- Half-flat $(\mathcal{W}_1, \mathcal{W}_2, \mathcal{W}_3)$ with $\mathcal{W}_3 = 0$
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Vacuum equations

Metric flux Ansatz: $f_{a\mu} = \sigma_a \sigma_\mu \longrightarrow$ rank 1

$\Longrightarrow$ Closed expr. for stabilised axions and Q(fluxes), which sets vacuum energy

Saxions:

$$J_{ab}t^b|_{\rm vac} = \mathcal{Q}\left[4\frac{\sigma_a}{\sigma_a t^a} - 3\frac{\mathcal{K}_a}{\mathcal{K}}\right], \qquad \mathcal{Q}\partial_\mu K|_{\rm vac} = \sigma_\mu \sigma_a t^a$$

$$\mathcal{K}_a \equiv \mathcal{K}_{abc}t^b t^c$$

- To generate infinite families of sol.: Scaling symmetries

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Exact scaling symmetries

$$\text{If } \mathcal{K}_{abc} = \sigma_{(a}\eta_{bc)}, \quad \eta_{ab} = \eta_{ba}, \quad \sum_a \sigma_a \eta_{ab} = 0$$

$Q \sim n^{2r}, \quad m^b \eta_{bc} \sim n^{r-s}, \quad m^a \sigma_a \sim \text{const.}, \quad \text{with } r \geq s \geq 0$

$\Longrightarrow t^b \eta_{bc} \sim n^r, \quad t^a \sigma_a \sim n^s$

And scale separation $\underline{R_{\text{AdS}} M_{\text{KK}} \sim n^{\frac{1}{2}(r-s)}}$ $\quad (g_{\text{s}} \sim n^{-r+\frac{3}{2}s})$

- $X_6 = (T^2 \tilde{\times} X_4)/\Gamma$

$X_4 = T^4$ [Cribiori, Junghans, Van Hemelryck, Van riet, Wrase '21]

or $X_4 = K3$ [Caviezel, Koerber, Kors, Lurs, Tsimpis, Zagermann '09]

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Ell. fibred: Approximate scaling symmetries

$\mathcal{K}_{abc}$ more involved, scale sep. still possible?

$$\mathcal{K}_{Lab} = \eta_{ab}\,, \quad \mathcal{K}_{LLa} = \eta_{ab}c^b\,, \quad \mathcal{K}_{LLL} = \eta_{ab}c^a c^b\,, \quad \mathcal{K}_{abc} = 0$$

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$$m^a \sim n^{r-s}\,, \quad m^L \sim \text{const.}\,, \quad Q \sim n^{2r}\,, \quad c^a \sim n^{r-s}$$

- Hint for approx. scaling corrected by $\epsilon^a \equiv \frac{c^a}{m^a} \sim n^{s-r}$

$\longrightarrow$ Saxions as expansions in ϵ

$$t^L = t^L_{(0)}\left(1 + \Delta^L + \mathcal{O}(\epsilon^2)\right)\,, t^a = t^a_{(0)} - \frac{5}{3}\frac{t^L_{(0)}}{m^L}\left(\Delta^a + m^a\Delta^L + \mathcal{O}(\epsilon)\right)$$

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Perturbative stability

Compute Hessian ($\partial\partial V$) and diagonalize

$\longrightarrow$ very involved computation!!

But analytical expression is found!

$\longrightarrow$ Diagonal complex structure sector

Factorised cases:

$$\frac{m_s^2}{|m_{BF}|^2} = \left(8, \frac{280}{9}, 8, -\frac{8}{9}\right), \begin{cases} \text{SUSY:} & \frac{m_a^2}{|m_{BF}|^2} = (\frac{40}{9}, \frac{352}{9}, \frac{40}{9}, 0) \\ \text{non-SUSY:} & \frac{m_a^2}{|m_{BF}|^2} = (-\frac{8}{9}, \frac{160}{9}, \frac{160}{9}, 0) \end{cases}$$

Multiplicities $(1, 1, h_-^{1,1}(X_6), h^{2,1}(X_6))$

Universal DGKT spectrum [Marchesano, Quirant '19]

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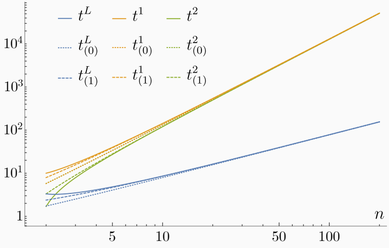
Some numerics

Simple elliptically fibered models:

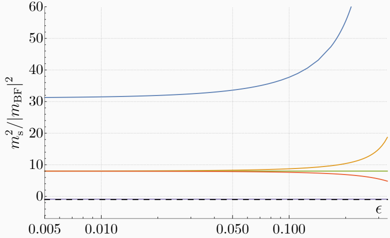
$\longrightarrow$ T-duals of $\mathbb{P}_{(1,1,1,6,9)}$ ($h^{1,1} = 2$) and $\mathbb{P}_{(1,1,2,8,12)}$ ($h^{1,1} = 3$)

- Confirm the existence of infinite families
- Check analytics of approximate scaling symmetry
- Compute masses when not possible analytically
- Crosscheck of our analytical Hessian

Some numerics



(a)



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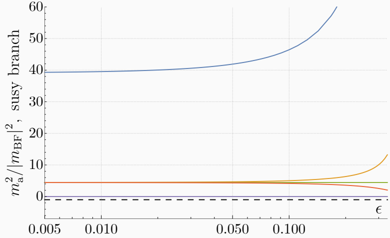

(b)

Conclusions

- Scale separation needed to justify 4d EFT  $\times$ 

- Status uncertain in string theory

$\longrightarrow$ Progress on source localisation and past worries

$\longrightarrow$ Bottom-up constructions clashes with Swampland and holography

- We proposed new families of sol. in massless type IIA based on elliptically fibered CY with metric fluxes

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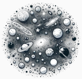
- Scale separation needed to justify 4d EFT  $\times$ 

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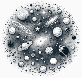
- Scale separation needed to justify 4d EFT  $\times$ 

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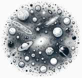
- Scale separation needed to justify 4d EFT  × 

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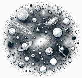
- Scale separation needed to justify 4d EFT  × 

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Outlooks

- O-plane backreaction [Junghans '20][Marchesano, Palti, Quirant, Tomasiello '20]

- Strong coupling regime to study M-theory uplift

$R_{\rm AdS} M_{\rm KK} \sim n^{\frac{1}{2}(r-s)}$ and $g_{\rm s} \sim n^{-r+\frac{3}{2}s}$

So $r > s$ while $r < \frac{3}{2}s \implies$ Scale sep. and strong coupling

- In [Cribiori, Junghans, Van Hemelryck, Van Riet, Wrase '21] backreaction makes F_2 closed and suggest a sourceless M-theory uplift geometry

See also recently: [Van Hemelryck '24]

- Interesting to challenge conjecture in [Collins, Jafferis, Vafa, Xu, Yau '22]: "KK scale cannot be decoupled from internal curvature"

$\longrightarrow$ But sourceless scale sep. only possible if it is the case

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

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