Geometry of Type IIA compactifications with (non-)geometric fluxes

David Prieto

Based on **2309.00043** [R. Carrasco, T. Coudarchet, F. Marchesano, DP]
and **2402.13899** [DP, J. Quirant, P. Shukla]

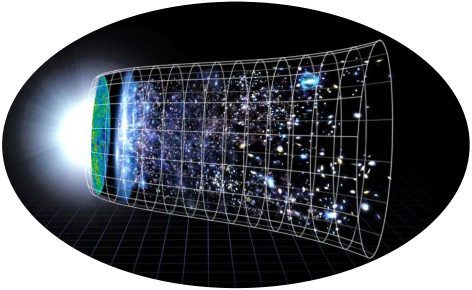
String Pheno 2024

Contents

Motivation and context

Motivation

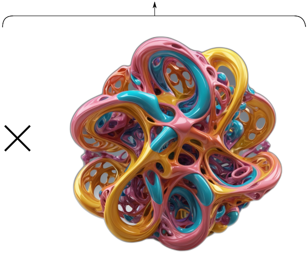
de Sitter?



X_4

×

Scale Separation?



X_6

Swampland Conjectures

- **AdS Distance Conjecture**: Any AdS vacuum has an infinite tower of states that becomes light in the limit $\Lambda \to 0$, satisfying $m \sim |\Lambda|^{\gamma}$. D. Lust, E. Palti, C. Vafa '19

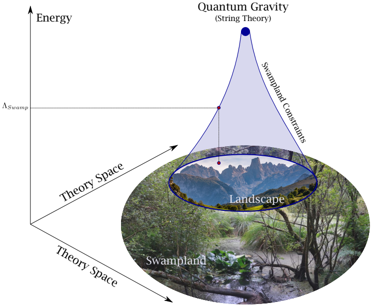
Strong version: $\alpha = 1/2$ for SUSY and $\alpha \geq 1/2$ for non-SUSY $\Rightarrow$ no scale separation.

- **AdS/KK scale separation conjecture**: In AdS vacua there is no separation between the AdS and the lightest KK scales.

  D. Tsimpis '12

Compactifications in $AdS_4 \times X_6$, with Romans mass and membranes in the smearing approximation remain elusive.

O. DeWolfe, A. Giryavets, S. Kachru and W. Taylor '05
P. G. Cámara, A. Font, L.E. Ibáñez '05



- **De Sitter Conjecture**: No dS vacua consistent with quantum gravity. A scalar potential of an EFT weakly coupled to gravity must satisfy $M_P \frac{|\nabla V|}{V} \geq c\,, \quad c \sim \mathcal{O}(1)\,.$

G. Obied, H. Ooguri, L. Spodyneiko, C. Vafa '18

Current goal

- Test these conjectures in DGKT-like settings including geometric and non-geometric fluxes. F. Marchesano, D. Prieto, J. Quirant and P. Shukla '20

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- We find:
  - Families of vacua displaying **scale separation**. Ingredients: elliptically fibered CY + geometric fluxes (no Romans mass). 🎉
  - Several **dS no-go's** including RR, NSNS, geometric and non-geometric fluxes. 😔

Type IIA and the bilinear formulation

Manifold, moduli and flux quanta

- Y_6 Type IIA CY orientifold with fluxes and smeared D6/O6 characterized by

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  - Geometric Fluxes: $\quad f \triangleleft \omega_a = f_{aK}\beta^K - f_a{}^\Lambda\alpha_\Lambda$
  - Non-geometric fluxes $\quad \begin{cases} Q \triangleright \alpha_K = Q^a{}_K\omega_a \quad Q \triangleright \beta^\Lambda = Q^{a\Lambda}\omega_a \\ R \bullet (\alpha_K + \beta^\Lambda) = R_K + R^\Lambda \end{cases}$

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- Fluxes induce a superpotential

$$W = \int_{Y_6} e^{-J_c} \wedge \bar{\mathbf{G}} + \int_{Y_6} \Omega_c \wedge \mathcal{D}(e^{-J_c})\,, \qquad \text{with} \qquad \mathcal{D} = d - H + f\triangleleft + Q\triangleright + R\bullet\ .$$

S. Gukov, C. Vafa and E. Witten '00; G. Aldazabal, P. G. Cámara, A. Font and L. Ibáñez '06

F-term flux potential

- Bilinear formulation for the F-term moduli scalar potential: $V = \underbrace{\rho_{\mathcal{A}} \quad \overset{\text{saxions}}{\overset{\uparrow}{Z^{\mathcal{A}\mathcal{B}}}} \quad \rho_{\mathcal{B}}}_{\text{axions+fluxes}}$

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$$
\begin{aligned}
\rho_0 &= e_0 + e_a b^a + \frac{1}{2}\mathcal{K}_{abc} m^a b^b b^c + \frac{m}{6}\mathcal{K}_{abc} b^a b^b b^c + \rho_\mu \xi^\mu \, , \\
\rho_a &= e_a + \mathcal{K}_{abc} m^b b^c + \frac{m}{2}\mathcal{K}_{abc} b^b b^c + \rho_{a\mu}\xi^\mu \, , \\
\tilde{\rho}^a &= m^a + m b^a + \tilde{\rho}^a_\mu \xi^\mu \, , \\
\tilde{\rho} &= m + \tilde{\rho}_\mu \xi^\mu \, , \\
\rho_\mu &= h_\mu + f_{a\mu} b^a + \frac{1}{2}\mathcal{K}_{abc} b^b b^c Q^a_\mu + \frac{1}{6}\mathcal{K}_{abc} b^a b^b b^c R_\mu \, , \\
\rho_{a\mu} &= f_{a\mu} + \mathcal{K}_{abc} b^b Q^c_\mu + \frac{1}{2}\mathcal{K}_{abc} b^b b^c R_\mu \, , \\
\tilde{\rho}^a_\mu &= Q^a_\mu + b^a R_\mu \, , \\
\tilde{\rho}_\mu &= R_\mu \, .
\end{aligned}
$$

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$$
Z^{\mathcal{A}\mathcal{B}} = e^{K} \begin{bmatrix} \mathbf{B} & \mathcal{O} \\ \mathcal{O}^{\,t} & \mathbf{C} \end{bmatrix} ,
$$

$$
\mathbf{B} = \begin{pmatrix} 4 & 0 & 0 & 0 \\ 0 & g^{ab} & 0 & 0 \\ 0 & 0 & \frac{4\mathcal{K}^2}{9} g_{ab} & 0 \\ 0 & 0 & 0 & \frac{\mathcal{K}^2}{9} \end{pmatrix} , \quad \mathcal{O} = \begin{pmatrix} 0 & 0 & 0 & -\frac{2\mathcal{K}}{3} u^{\nu} \\ 0 & 0 & \frac{2\mathcal{K}}{3} u^{\nu} \delta^{a}_{b} & 0 \\ 0 & -\frac{2\mathcal{K}}{3} u^{\nu} \delta^{b}_{a} & 0 & 0 \\ \frac{2\mathcal{K}}{3} u^{\nu} & 0 & 0 & 0 \end{pmatrix} ,
$$

$$
\mathbf{C} = \begin{pmatrix} c^{\mu\nu} & 0 & -\tilde{c}^{\mu\nu} \frac{\mathcal{K}_b}{2} & 0 \\ 0 & \tilde{c}^{\mu\nu} t^a t^b + g^{ab} u^{\mu} u^{\nu} & 0 & -\tilde{c}^{\mu\nu} t^a \frac{\mathcal{K}}{6} \\ -\tilde{c}^{\mu\nu} \frac{\mathcal{K}_a}{2} & 0 & \frac{1}{4} \tilde{c}^{\mu\nu} \mathcal{K}_a \mathcal{K}_b + \frac{4\mathcal{K}^2}{9} g_{ab} u^{\mu} u^{\nu} & 0 \\ 0 & -\tilde{c}^{\mu\nu} t^b \frac{\mathcal{K}}{6} & 0 & \frac{\mathcal{K}^2}{36} c^{\mu\nu} \end{pmatrix} .
$$

Stability, F-terms and Ansatz

- Look for a criterion that simplifies the equations of motion while favoring the solutions that are stable.
- Simple criterium to analyse vacua metastability for F-term potentials in 4d supergravity: sGoldstino direction in field space is the one more likely to become tachyonic.

M. Gomez-Reino , C. A. Scrucca '06

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- Maximum vev of the sGoldstino is achieved by

$$\boxed{\{D_a W, D_\mu W\} \propto \{\partial_a K, \partial_\mu K\}}$$

- This leads to the following ansatz

$$\rho_a - \mathcal{K}_{ab}\tilde{\rho}^b_\mu u^\mu = \ell_s^{-1}\mathcal{P}\,\partial_a K\,, \qquad \mathcal{K}_{ab}\tilde{\rho}^b + \rho_{a\mu}u^\mu = \ell_s^{-1}\mathcal{Q}\,\partial_a K\,,$$

$$\rho_\mu - \frac{1}{2}\mathcal{K}_a\tilde{\rho}^a_\mu = \ell_s^{-1}\mathcal{M}\,\partial_\mu K\,, \qquad t^a\rho_{a\mu} - \frac{1}{6}\mathcal{K}\tilde{\rho}_\mu = \ell_s^{-1}\mathcal{N}\,\partial_\mu K\,,$$

Scale Separation with Metric Fluxes

Equations of motion and refined ansatz

- Turn off non-geometric fluxes. Equations of motion in the Ansatz become

$$
\begin{gathered}
8\,(\rho_0\mathcal{M}-\mathcal{P}\mathcal{N})\,\partial_\mu K=0\,,\\
\left[8\mathcal{P}(\rho_0-\mathcal{Q})-\frac{1}{3}\tilde{\rho}\mathcal{K}\,(-2\mathcal{Q}+8\mathcal{N})\right]\partial_a K+\left[\frac{4}{3}\mathcal{K}\tilde{\rho}+8\mathcal{P}-8\mathcal{M}\right]\rho_{a\mu}u^\mu=0\,,\\
\left(4\rho_0^2+12\mathcal{P}^3+3\mathcal{Q}^2+8\mathcal{M}^2+8\mathcal{N}^2+\frac{\mathcal{K}^2}{9}\tilde{\rho}^2-20\mathcal{Q}\mathcal{N}-4\mathcal{M}\mathcal{K}\tilde{\rho}\right)\partial_\mu K=0\,,\\
\left[4\rho_0^2+4\mathcal{P}^2-\mathcal{Q}^2-8\mathcal{Q}\mathcal{N}+16\mathcal{M}^2-\frac{\mathcal{K}^2}{9}\tilde{\rho}^2\right]\partial_a K+\Big[8\mathcal{Q}-8\mathcal{N}\Big]\rho_{a\mu}u^\mu=0\,.
\end{gathered}
$$

- When brackets do not vanish independently ⇒ **AdS vacua**, generically **without scale separation** (nearly-Kähler manifolds). F. Marchesano, D. Prieto, J. Quirant and P. Shukla '20

New families of vacua

- Demanding blue brackets to vanish independently → 4 new families of vacua.

Parameters Branch	$\mathcal{P}$	$\mathcal{S}$	ρ_0	$\mathcal{Q}$	m	$\mathcal{M}$
SUSY	Free	$3+4\frac{\mathcal{P}^2}{\mathcal{N}^2}$	$-\frac{3}{2}\mathcal{N}$	$\mathcal{N}$	$-10\frac{\mathcal{P}}{\mathcal{K}}$	$-\frac{2}{3}\mathcal{P}$
non-SUSY	0	3	$-\frac{\mathcal{N}}{2}\left(1-\frac{12}{\mathcal{S}}\right)$	$\mathcal{N}$	0	$\frac{4\mathcal{P}}{\mathcal{S}}$
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- $V_{vac} = -12 e^{K}\mathcal{Q}^2 \Rightarrow$ **AdS**.

- 10d-perspective $\Rightarrow$ **Half-flat manifold**.

  $\left(\mathcal{W}_1 = -i\frac{4\mathcal{Q}}{\mathcal{K}\ell_s}e^{\phi}\, , \, \mathcal{W}_2 = -iG_2^{\mathrm{P}}\, e^{\phi}\, , \, \mathcal{W}_3 = \mathcal{W}_4 = \mathcal{W}_5 = 0\right)$

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- Study Scale Separation with **vanishing Romans mass** $m = 0$ and **rank-one metric fluxes**.

  N. Cribiori, D. Junghans, V. Van Hemelryck, T. Van Riet and T. Wrase '21

- Focus on first two branches and set $\mathcal{P} = 0$ and $f_{a\mu} \equiv \sigma_a\sigma_\mu$.

Twisted Factorized Geometries

- Consider $Y_6 = (T^2 \tilde{\times} Y_4)/\Gamma$, with Y_4 a CY 2-fold. Geometric flux along the torus fibre induces twist. The intersection numbers simplify to

$$\mathcal{K}_{LAB} = \sigma_L \eta_{AB} \, , \quad \mathcal{K}_{ABC} = \mathcal{K}_{LLA} = \mathcal{K}_{LLL} = 0 \, .$$

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- Exact solution for the saxions:

$$\underbrace{t^A = -\frac{5}{3}\frac{m^A}{m^L}t^L}_{Y_4 \text{ Kähler saxions}} \,,$$

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- Scaling the fluxes asymmetrically leaves the eoms invariant.

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

$$e_0 \sim n^{2r}\,, \quad e_A \sim n^r\,, \quad e_L \sim n^{2r-s}\,, \quad h_\mu \sim n^s\,.$$

- D6 tadpole contribution

$$N_{\text{flux}} = m h_\mu + m^a f_{a\mu} = m^L \sigma_L \sim \text{const.}$$

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$$N_{\text{flux}} = m h_\mu + m^a f_{a\mu} = m^L \sigma_L \sim \text{const.}$$

- Tuning the exponents one can find parametric scale separation.

$$\left.\begin{aligned} &L_{\text{KK}} \sim \sqrt{t^A} \sim n^{r/2} \implies \frac{M_{\text{KK}}^2}{M_{\text{P}}^2} \sim \frac{g_s^2}{\text{Vol}_{X_6}\, t^A} \sim n^{-5r+2s} \\ &\Lambda = (R_{\text{AdS}}M_{\text{P}})^{-2} \sim e^K \mathcal{Q}^2 \sim n^{-6r+3s} \end{aligned}\right\} \to R_{\text{AdS}}M_{\text{KK}} \sim n^{\frac{1}{2}(r-s)}$$

N. Cribiori, D. Junghans, V. Van Hemelryck, T. Van Riet and T. Wrase '21

Elliptically fibered Calabi-Yau

- Elliptically fibered CY Y_6 with base B_4 and $c_1(B_4) = c^A\omega_A \neq 0$. The intersection numbers become

$$\mathcal{K}_{LAB} = \eta_{AB}\,, \quad \mathcal{K}_{LLA} = \eta_{AB}c^B\,, \quad \mathcal{K}_{LLL} = \eta_{AB}c^Ac^B\,, \quad \mathcal{K}_{ABC} = 0\,.$$

- Turning on a rank-one metric flux along fibre direction, the scaling symmetry remains if we allow the Chern Class of the base to grow

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- In general we have the approximate scaling symmetry with corrections $\epsilon^A \equiv \frac{c^A}{m^A} \sim n^{s-r}$.

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

$$\Delta^L = -\frac{\eta_{AB}c^Am^Bm^L}{2M}\,, \qquad \Delta^A = \frac{4}{5}c^Am^L\,.$$

Up to ϵ corrections we find the same **parametric scale separation** as in the factorized geometry.

Stability and examples

- Test stability studying the Hessian in $T^2 \tilde{\times} T^4$ and $T^2 \tilde{\times} K_3$ analytically.
- For the elliptic fibration we perform numerical evaluation in specific examples (e.g. two parameter hypersurface of $\mathbb{P}^4_{(1,1,1,6,9)}$).

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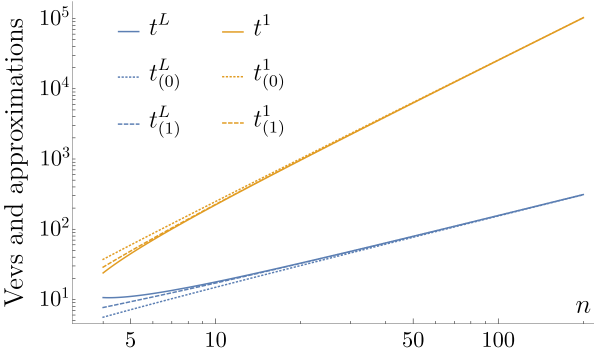

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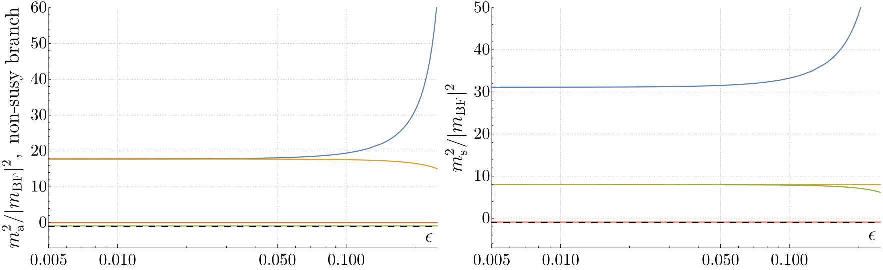

Searching de Sitter with Non-Geometric Fluxes

General Picture

- Many dS no-go's have been found in Type IIA, some even including geometric fluxes.

  J. M. Maldacena and C. Nunez '01

- Geometric & non-geometric fluxes together still have potential.

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- Go back to the eoms without assuming any Ansatz. First check: SUSY.

$$\langle V_{\mathrm{SUSY}}\rangle = -3e^{K}\left[\left(\rho_0 - \frac{1}{2}\mathcal{K}_a\tilde{\rho}^a\right)^2 + \left(\rho_a t^a - \frac{\mathcal{K}}{6}\tilde{\rho}\right)^2\right] \Rightarrow \text{SUSY dS is not possible.}$$

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General dS no-go conditions

- General eoms are very involved. Use simplifying combinations of $t^a\partial_{b^a}V$, $t^a\partial_{t^a}V$, $u^\mu\partial_{\xi^\mu}V$ and $u^\mu\partial_{u^\mu}V$ to extract relevant information.
- Focusing on the NSNS sector we find **4 no-go conditions** for dS vacua.

$$\begin{aligned}
\frac{\mathcal{K}^2\tilde{\rho}^2}{9}+\tilde{\mathcal{R}}-\frac{\tilde{\mathcal{S}}}{3}+\frac{\mathcal{K}^2}{18}c^{\mu\nu}\tilde{\rho}_\mu\tilde{\rho}_\nu-c^{\mu\nu}\rho_\mu\rho_\nu &\leq 0\,,\\
\mathcal{R}-\mathcal{S}+4\rho_0^2+2c^{\mu\nu}\rho_\mu\rho_\nu-\frac{\mathcal{K}^2}{36}c^{\mu\nu}\tilde{\rho}_\mu\tilde{\rho}_\nu &\leq 0\,,\\
\frac{\mathcal{R}}{2}-\frac{\mathcal{S}}{2}+\tilde{\mathcal{R}}-\frac{\tilde{\mathcal{S}}}{3}+\frac{\mathcal{K}^2}{24}c^{\mu\nu}\tilde{\rho}_\mu\tilde{\rho}_\nu &\leq 0\,,\\
2\mathcal{R}-2\mathcal{S}+\tilde{\mathcal{R}}-\frac{\tilde{\mathcal{S}}}{3}+3c^{\mu\nu}\rho_\mu\rho_\nu &\leq 0\,.
\end{aligned}$$

$$\begin{aligned}
\mathcal{R} &\equiv \left(\tilde{c}^{\mu\nu}t^a t^b+g^{ab}u^\mu u^\nu\right)\rho_{a\mu}\rho_{b\nu}-\frac{4\mathcal{K}^2}{9}\tilde{\rho}^a\tilde{\rho}^b g_{ab}\,, & \mathcal{S} &\equiv \tilde{c}^{\mu\nu}\mathcal{K}_a\rho_\mu\tilde{\rho}^a_\nu\,,\\
\tilde{\mathcal{R}} &\equiv \left(\tilde{c}^{\mu\nu}\frac{\mathcal{K}_a}{2}\frac{\mathcal{K}_b}{2}+\frac{4\mathcal{K}^2}{9}g_{ab}u^\mu u^\nu\right)\tilde{\rho}^a_\mu\tilde{\rho}^b_\nu-g^{ab}\rho_a\rho_b\,, & \tilde{\mathcal{S}} &\equiv \mathcal{K}\tilde{c}^{\mu\nu}t^a\rho_{a\mu}\tilde{\rho}_\nu\,.
\end{aligned}$$

- Whenever one of these inequalities is verified, de Sitter vacua is ruled out.

Ansatz dS no-go conditions

- We obtain much more analytical control once we introduce the stability motivated ansatz.

$$\boxed{\{D_aW, D_\mu W\} \propto \{\partial_a K, \partial_\mu K\}}$$

Non-geo					
local	global	Geo	NSNS		
$\tilde{\rho}_\mu$	$\tilde{\rho}^a_\mu$	$\rho_{a\mu}$	ρ_μ	dS	No-go
0	0	0	0	✗	
			-	✗	
		-	0	✗	
			-	✗	
	-	0	0	✗	
			-	?	$\tilde{\rho} = 0$
		-	0	✗	
			-	?	$\tilde{\rho} = 0$

Non-geo					
local	global	Geo	NSNS		
$\tilde{\rho}_\mu$	$\tilde{\rho}^a_\mu$	$\rho_{a\mu}$	ρ_μ	dS	No-go
-	0	0	0	✗	
			-	?	
		-	0	?	$\rho_0 = 0$
			-	?	
	-	0	0	✗	
			-	?	
		-	0	?	$\rho_0 = 0$
			-	?	

Refining the analysis in the Ansatz

- Scalar potential can be written in terms of 8 quantities.

$$\gamma_1 = \rho_0, \qquad \gamma_2 = \rho_a t^a, \quad \gamma_3 = \frac{1}{2}\mathcal{K}_a\tilde{\rho}^a, \quad \gamma_4 = \frac{\mathcal{K}}{6}\tilde{\rho},$$
$$\lambda_1 = \rho_\mu u^\mu, \quad \lambda_2 = \rho_{a\mu} t^a\, u^\mu, \quad \lambda_3 = \frac{1}{2}\mathcal{K}_a\tilde{\rho}^a_\mu u^\mu, \qquad \lambda_4 = \frac{\mathcal{K}}{6}\,\tilde{\rho}_\mu u^\mu.$$

- Use this to account for the RR sector contribution and perform a complete study of the 256 cases. 227 of the are excluded (most of the simplest ones).

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- Use this to account for the RR sector contribution and perform a complete study of the 256 cases. 227 of the are excluded (most of the simplest ones).
- Simplest non-excluded case:

$$\gamma_1 = \gamma_2 = \gamma_3 = \lambda_2 = \lambda_4 = 0\,, \qquad \lambda_1 = -\frac{\gamma_4}{4}\,, \qquad \lambda_3 = -\frac{9}{4}\gamma_4\,, \qquad \gamma_4 \geq 0\,,$$
$$\mathcal{N} = \mathcal{Q} = 0\,, \qquad \mathcal{P} = -\frac{3}{2}\gamma_4\,, \qquad \mathcal{M} = -\frac{9}{16}\gamma_4\,.$$

Conclusions

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- Bilinear formalism is a powerful tool to systematically study phenomenological properties of flux vacua.
- Scale separation found in Type IIA orientifolds with no Romans mass and rank-one metric fluxes. Generalizes the model built by *Cribiori et al. '21* to elliptic fibrations.
- Still need better understanding of 10d uplift and localized sources.
- To avoid dS no-go's a complex interplay between RR, NSNS, geometric and non-geometric fluxes in very generic configurations is needed.
- Flux quantization and tadpole bound will impose additional constraints.
- There are some particularly simple configurations that are good candidates for a detailed numerical analysis.

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Thanks for your attention!!