Type IIA Scale Separation and Moduli Stabilization

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Based on ongoing work with R. Carrasco and F. Marchesano

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21st STRING PHENOMENOLOGY

Contents

Introduction

Swampland Conjectures

- **AdS/KK scale separation conjecture**[1]: In any AdS vacua there is no separation between the AdS and the lightest KK scales.

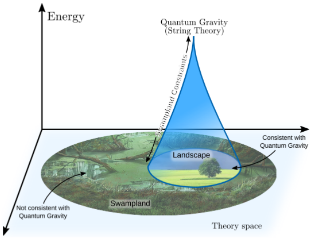


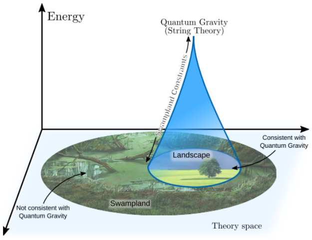
Figure: Swampland and Landscape of EFTs. [Van Beest, Calderon-Infante, Mirfendereski, Valenzuela '21].

[1] D. Tsimpis, *Supersymmetric AdS vacua and separation of scales*, 2012

Swampland Conjectures

- **AdS/KK scale separation conjecture**[1]: In any AdS vacua there is no separation between the AdS and the lightest KK scales.
- **AdS Distance Conjecture**[2]: Any AdS vacuum has an infinite tower of states that becomes light in the flat space limit $\Lambda \to 0$, satisfying $m \sim |\Lambda|^{\alpha}$.

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



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[2] D. Lüst, E. Palti and C. Vafa, *AdS and the Swampland*, 2019

Swampland Conjectures

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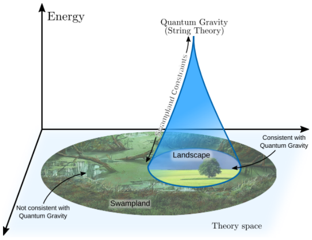
Strong version: $\alpha = 1/2$ for SUSY and $\alpha \geq 1/2$ for non-SUSY $\Rightarrow$ no scale separation.

Tested in different contexts. Compactifications in $AdS_4 \times X_6$, with Romans mass and membranes in the smearing approximation[3] remain elusive.



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2 D. Lüst, E. Palti and C. Vafa, *AdS and the Swampland*, 2019

3 O. DeWolfe, A. Giryavets, S. Kachru and W. Taylor, *Type IIA moduli stabilization*, JHEP 07 (2005) 066

Scale-separated AdS4 vacua of IIA orientifolds

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Scale-separated AdS4 vacua of IIA orientifolds

- Main complains to these models: Romans mass and the backreaction of the orientifold planes.
- These problems were circumvented recently[1] by T dualising DGKT solutions on a factorized torus.

$$
\begin{aligned}
J &= -L_1^2 v^{16} - L_2^2 v^{24} + L_3^2 v^{35} \\
H_3 &= 2m \mathrm{Re}\,\Omega\,, \\
g_s F_0 &= 5m\,, \\
g_s F_2 &= 0\,, \\
g_s F_4 &= e_a \tilde{\omega}^a\,, \\
g_s F_6 &= 0 \\
dv^1 &= dv^6 = 0
\end{aligned}
\quad \xRightarrow{\text{T-duality}} \quad
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g_s F_2 &= m\omega_1 + e_3\omega_2 + e_2\omega_3\,, \\
g_s F_4 &= 0\,, \\
g_s F_6 &= e_1 \mathrm{dvol}_6 \\
dv^1 &= -v^{23} - v^{45}\,, \quad dv^6 = -v^{34} - v^{25}
\end{aligned}
$$

[1] N. Cribiori, D. Junghans, V. Van Hemelryck, T. Van Riet and T. Wrase *Scale-separated AdS4 vacua of IIA orientifolds and M-theory*, 2021

Scale-separated AdS4 vacua of IIA orientifolds

- Take a particular scaling for the fluxes, respecting the constraints of the Bianchi identity (m cannot scale).

$$e_1 \sim n^a\,, \quad e_2 \sim n^b\,, \quad e_3 \sim n^c\,,$$

  with $a, b, c \geq 0$.

- If we choose $c \geq b$ and $b > 0$, $L_{KK} \sim L_2$ and

$$\frac{L_{KK}^2}{L_H^2} \sim n^{-b}\,.$$

- Two interesting regimes with parametrically small backreaction[1]: a weakly coupled regime admitting a family of solutions in perturbative type IIA and a strongly coupled regime with a family of solutions that can be lifted to M-theory.

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Previous work and current goal

- In a previous paper[1] we tried to provide a unified treatment of moduli stabilisation in massive type IIA using the bilinear formalism of the scalar potential and including metric fluxes.
- We classified the solutions to the equations of motion. We did not find scale separation.

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- We classified the solutions to the equations of motion. We did not find scale separation.
- In this project we aim to
  - Provide a new family of solutions that contains the one described in *Cribiori et al. '21*.
  - Study scale separation in more general settings beyond the factorized torus.

[1] F. Marchesano, D. Prieto, J. Quirant and P. Shukla *Systematics of type IIA moduli stabilisation*, 2020

Systematics of Type IIA moduli stabilisation

Manifold and Moduli

- Type IIA string theory compactified on an orientifold of $X_4 \times X_6$ with X_6 a compact Calabi-Yau three-fold.
- Standard orientifold quotient by $\Omega_p(-)^{F_L}\mathcal{R}$ with $\mathcal{R}$ an involution of the Calabi–Yau metric.
- Complexify and decompose in terms of the moduli and a basis of harmonic 2-forms (ω_a) and symplectic 3-forms $(\alpha_\Lambda, \beta^K)$.

$$J_c \equiv B + i\, e^{\frac{\phi}{2}} J = (b^a + it^a)\, \omega_a = T^a \omega_a$$

$$\Omega_c \equiv C_3 + i\, \mathrm{Re}\,(\mathcal{C}\Omega) \longrightarrow \begin{cases} N^K & = \xi^K + in^K = \ell_s^{-3} \int_{X_6} \Omega_c \wedge \beta^K \\ U_\Lambda & = \xi_\Lambda + iu_\Lambda = \ell_s^{-3} \int_{X_6} \Omega_c \wedge \alpha_\Lambda \end{cases}$$

Flux superpotential

- Expand the p-form field strengths in the basis of quantised forms

$$F_0 = -m, \quad F_2 = m^a\,\omega_a, \quad F_4 = -e_a\,\tilde{\omega}^a, \quad F_6 = e_0\,\Phi_6\,, \quad H = h_K\beta^K - h^\Lambda\alpha_\Lambda\,.$$

- The flux superpotential including RR and NS fluxes is described in terms of a twisted differential operator:

$$\mathcal{D} = d + H\wedge + \underbrace{f\triangleleft}_{geometric}\,,$$

$$f\triangleleft\omega_a = f_{aK}\beta^K - f_a^{\Lambda}\alpha_\Lambda\,.$$

- Leads to the following superpotential

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

$$\ell_s W_{\mathrm{NS}} = U^\mu\left[h_\mu + f_{a\mu}T^a\right].$$

F-term flux potential

- From standard supergravity expression

$$\kappa_4^2\, V_F = e^K \left(K^{\mathcal{A}\overline{\mathcal{B}}}\, D_{\mathcal{A}} W\, \overline{D}_{\overline{\mathcal{B}}'}\, \overline{W} - 3\,|W|^2 \right) \longrightarrow V_F = \rho_{\mathcal{A}}\, Z^{\mathcal{A}\mathcal{B}}\, \rho_{\mathcal{B}}\,.$$

- Flux and axion polynomials $\rho_{\mathcal{A}} = \{\rho_0, \rho_a, \tilde{\rho}^a, \tilde{\rho}, \rho_\mu, \rho_{a\mu}\}$:

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

Stability, F-terms and Ansatz

- Criterium to analyse vacua metastability for F-term potentials in 4d supergravity[1] leads to

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

$$\rho_\mu = \ell_s^{-1}\mathcal{M}\,\partial_\mu K\,, \qquad t^a\rho_{a\mu} = \ell_s^{-1}\mathcal{N}\,\partial_\mu K\,.$$

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- The equations of motion for the axions are

$$8\,(\rho_0\mathcal{M} - \mathcal{P}\mathcal{N})\,\partial_\mu K = 0\,,$$
$$\left[8\mathcal{P}(\rho_0 - \mathcal{Q}) - \frac{1}{3}\tilde{\rho}\mathcal{K}\,(10\mathcal{Q} - 8\mathcal{N})\right]\partial_a K + [\mathcal{K}\tilde{\rho} + 8\mathcal{P} - 8\mathcal{M}]\,\rho_{a\mu}u^\mu = 0\,.$$

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- As long as the terms in brackets do not vanish independently $\rho_{a\mu}u^\mu \propto \partial_a K$ and so

$$\ell_s\rho_0 = A\mathcal{K}\,, \qquad \ell_s\rho_a = B\mathcal{K}\partial_a K\,, \qquad \ell_s\tilde{\rho}^a = Ct^a\,, \qquad \ell_s\tilde{\rho} = D\,,$$

$$\ell_s\rho_\mu = E\mathcal{K}\partial_\mu K\,, \qquad \ell_s\rho_{a\mu}t^a = \frac{F}{4}\mathcal{K}\partial_\mu K\,, \qquad \ell_s\rho_{a\mu}u^\mu = \frac{F}{3}\mathcal{K}\partial_a K\,.$$

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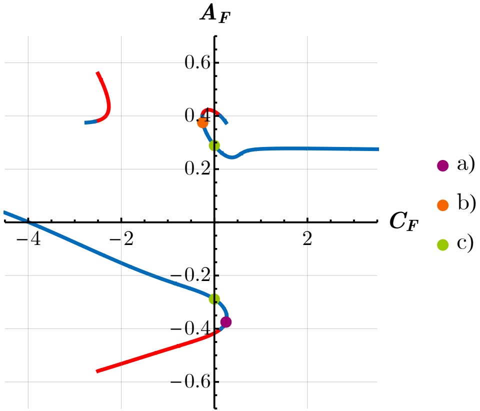
Branches of vacua

Branch	A_F	B_F	C_F	D_F
SUSY	$-\frac{3}{8}$	$-\frac{3}{2}E_F$	$\frac{1}{4}$	$15E_F$
non-SUSY	fig.	$4A_F E_F$	fig.	$\sqrt{\frac{\Delta_F}{C_F^2} + (4A_F^2+1)}\,12E_F$



Vacuum energy and KK scale

- Imposing the extremisation of the potential we obtain

$$4\pi\kappa_4^4 V|_{\rm vac} = -\frac{4}{3}e^K\mathcal{K}^2F^2\underbrace{\left(2A_F^2 + 64A_F^2E_F^2 + \frac{1}{18}C_F^2 + \frac{5}{18}\right)}_{\chi}$$

- Assuming all Kähler saxions scale equally, we compare the AdS scale with KK scale and arrive to

$$\frac{\Lambda_{\rm AdS}^2}{M_{\rm KK}^2} \sim e^{2D}V_{X_6}^{4/3}F^2 \sim \frac{t^4}{u^2}F^2\chi\,.$$

- Scale separation very difficult since generally $u \sim t^2$.

Moduli Stabilization and Scale speration

Merging approaches

- *Cribiori et al. '21* example is not described by the refined ansatz of systematics. We go back to our original proposal and set

$$\rho_a = 0\,, \qquad \rho_\mu = 0\,, \qquad \tilde{\rho} = 0\,,$$

$$\mathcal{K}_{ab}\tilde{\rho}^b + \rho_{a\mu}u^\mu = \ell_s^{-1}\mathcal{Q}\,\partial_a K\,, \qquad t^a\rho_{a\mu} = \ell_s^{-1}\mathcal{N}\,\partial_\mu K\,.$$

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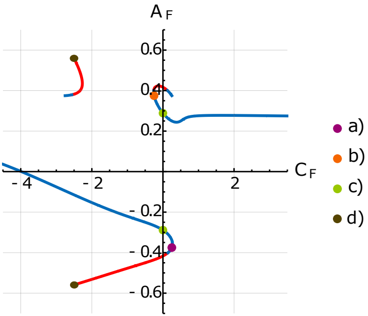
- We obtain four different families of vacua:

$$\mathcal{Q} = \mathcal{N}, \quad \rho_0 = \pm\frac{3}{2}\mathcal{Q}, \quad - : a), \;\; + : b)$$

$$\mathcal{Q} = \frac{14}{3}\mathcal{N}, \quad \rho_0 = \pm\sqrt{5}\mathcal{Q} \qquad d)$$



Factorized Torus with rank-two metric fluxes

- Take factorized 6-torus $T^6 = \otimes_{i=1}^3 T^2$, with $F_4 = H_3 = 0$. Fluxes constraint by the tadpole

$$\mathcal{D}F_{RR} = m^a f_{a\mu}\beta^\mu = (m^1 f_{1\mu} + m^2 f_{2\mu} + m^3 f_{3\mu})\beta^\mu .$$

- Try rank-two metric fluxes $(f_{1\mu}, f_{2\mu})$.

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- Try rank-two metric fluxes $(f_{1\mu}, f_{2\mu})$.
- From the results of moduli stabilization we deduce

$$(t^1)^2 \sim \frac{e_0}{m^3}, \quad (t^2)^2 \sim \frac{e_0}{m^3}, \quad (t^3)^2 \sim e_0 m^3, \quad (u^0)^2 \sim e_0 m^3.$$

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- Take $e_0 \sim n^a$ and $m^3 \sim n^b$. No scale separation. The strong distance conjecture is verified.

$$\frac{M_{\text{KK}}^2}{\Lambda} \sim \frac{L_{\text{H}}^2}{L_{\text{KK}}^2} \sim 1 \to M_{\text{KK}} \sim \Lambda^{1/2} .$$

Factorized Torus with rank-one metric fluxes

- Set $f_{20} = 0$. We get more freedom to scale the flux quanta. From the results of moduli stabilization we deduce

$$(t^1)^2 = \frac{3}{5}\frac{e_0 m^1}{m^2 m^3}, \quad (t^2)^2 = \frac{5}{3}\frac{e_0 m^2}{m^1 m^3}, \quad (t^3)^2 = \frac{5}{3}\frac{e_0 m^3}{m^1 m^2}, \quad (u^0)^2 = \frac{20}{27}\frac{e_0 m^2 m^3}{f_{10}^2 m^1}.$$

- Taking $e_0 \sim n^a$, $m^2 \sim n^b$ and $m^3 \sim n^c$, the scalings read

$$t^1 \sim n^{(a-b-c)/2}, \quad t^2 \sim n^{(a+b-c)/2}, \quad t^3 \sim n^{(a-b+c)/2}, \quad u^0 \sim n^{(a+b+c)/2}.$$

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- Choosing $b > c$ we observe

$$(L_H M_P)^{-2} \sim n^{-\frac{3}{2}(a+b+c)}, \quad (L_{\rm KK} L_{\rm Pl})^{-2} \sim n^{-\frac{3}{2}(a+b)-\frac{1}{2}c}.$$

- Hence we obtain scale separation.

$$\frac{M_{KK}^2}{\Lambda} \sim \frac{L_{\rm H}^2}{L_{\rm KK}^2} \sim n^c \to M_{\rm KK} \sim n^c \Lambda^{1/2}.$$

Moduli Stabilization with rank-one metric fluxes

- If $f_{a\mu}$ is a rank-one $\Rightarrow f_{a\mu} = \sigma_a \sigma_\mu$.
- From $\rho_\mu = 0$ we derive $h_\mu = \sigma\sigma_\mu \Rightarrow \sigma_a b^a|_{\rm vac} = -\sigma$.
- Let J^{ab} to be the inverse of $\mathcal{K}_{abc} m^c$. The vacuum condition $\rho_a = 0$ means

$$b^a|_{\rm vac} = -J^{ab} e_b - J^{ab} \sigma_b \sigma_\mu \xi^\mu|_{\rm vac} \, .$$

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- Relation $\mathcal{K}_{ab} \tilde{\rho}^b + \rho_{a\mu} u^\mu = \ell_s^{-1} \mathcal{Q}\, \partial_a K$ allows us to fix the Kähler saxions

$$t^a|_{\rm vac} = -3 \frac{\mathcal{Q}}{\mathcal{K}} J^{ab} \mathcal{K}_b - J^{ab} \sigma_b \sigma_\mu u^\mu|_{\rm vac} \,.$$

- And together with $t^a \rho_{a\mu} = \ell_s^{-1} \mathcal{N}\, \partial_\mu K$ we fix the complex structure saxions

$$-\left(3 \frac{\mathcal{Q}}{\mathcal{K}} J^{ab} \sigma_a \mathcal{K}_b + J^{ab} \sigma_a \sigma_b\, \sigma_\mu u^\mu \right) \sigma_\mu = \mathcal{Q}\, \partial_\mu K \,.$$

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- We use the last equation of our anasatz to fix the parameter $\mathcal{Q}$:

$$\rho_0|_{\mathrm{vac}} = e_0 - \frac{1}{2} J^{ab} e_a e_b + \frac{1}{2} \frac{(\sigma - J^{ab} \sigma_a e_b)^2}{J^{ab} \sigma_a \sigma_b} = \pm \frac{3}{2} Q \, .$$

Scale separation in Elliptic Fibrations

- Let η_{ij} be the intersection numbers of the base and $c_1 = c^i\omega_i$ its first Chern class.

$$\mathcal{K}_{ijk} = 0\,, \quad \mathcal{K}_{Lij} = \eta_{ij}\,, \quad \mathcal{K}_{LLi} = \eta_{ij}c^j\,, \quad \mathcal{K}_{LLL} = \eta_{ij}c^i c^j\,.$$

- Choose metric fluxes along the torus fibre. Tadole condition constraints m^L.
- Consider $r > s > 0$. We are free to scale

$$m^i \sim n^{r-s}\,, \quad m^L \sim 1\,, \quad e_0 \sim n^{2r}\,, \quad e_i \sim n^r\,, \quad e_L \sim n^{2r-s}\,, \quad h_\mu \sim n^s$$

We obtain $t^i \sim n^r$, $t^L \sim n^s$ and $u^\mu \sim n^{2r-s}$, which behaves the same as the example from *Cribiori et al. '21*.

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- For a trivial fibration (like $K_3 \times T^2$) $c^i \to 0$ and we have an exact symmetry.

Conclusions

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- We have extended the study of moduli stabilization to a new family of solutions that was overlooked in *Marchesano et al. '20*.
- 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.
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Conclusions

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Thanks for your attention!!