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Uplifting Runaways
with I. Bena, E. Dudas, and M. Graña [arXiv:1809.06861]

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de Sitter vacua in string theory

Three-step procedure [Kachru, Kallosh, Linde, Trivedi ’03]:

1. warped IIB with CS-moduli stabilized by three-form fluxes including a region with strong warping [Giddings, Kachru, Polchinski ’01] described by the Klebanov Strassler throat [Klebanov, Strassler ’00] → large hierarchy of scales

2. Stabilize Kähler moduli by non-perturbative effects → supersymmetric AdS-vacuum

3. Supersymmetry breaking by an $\overline{D3}$-brane at the bottom of the throat → exponentially suppressed uplift to dS due to strong warping

(See also many other talks during this conference.)
de Sitter vacua in string theory

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Warped CY

- Metric: \( ds^{2}_{10} = e^{2A} ds^{2}_{4} + e^{-2A} ds^{2}_{CY_3} \)

- Fluxes fix the sizes of the 3-cycles: \( \int_{A_i} F_3 = M^i, \int_{B_i} H_3 = K_i \)

- Choose a configuration such that one cycle is exponentially large.
  \( \rightarrow \) Klebanov-Strassler throat.
Deformed conifold

- In the region of high warping, the six-dimensional geometry is given by the deformed conifold.

- Embedding of the deformed conifold into $\mathbb{C}^4$:
  \[
  \sum_{a=1}^{4} z_a^4 = S .
  \]

- Replace the singularity of the conifold ($S = 0$) by a $S^3$ of size $|S|$

- $S$ is a complex structure modulus of the deformed conifold.

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[Candelas, Ossa '89]
Potential for $S$

- Fluxes $M$ and $K$ along the two three-cycles of the conifold generate a potential $V_{KS}(S)$ [Douglas, Shelton, Torroba ’07, ’08]:

\[ V(S) = V(S) \] (dotted without warping effects)

- (Supersymmetric) minimum at $s_{KS} = \Lambda_0^3 \exp \left( -\frac{2\pi K}{g_s M} \right)$.

- Relative warp factor: $\Lambda_0 / \Lambda_{IR} \sim |s_{KS}|^{1/3}$.

$\rightarrow$ Large hierarchy for suitable values of $K$, $M$, and $g_S$ [Giddings et al. ’01].
Mass of $S$

- The mass of $S$ at the minimum $s_{KS}$ can be computed by

\[
m^2_S \equiv \frac{1}{M_{pl}^2} G^{S\bar{S}} \partial_S \partial_{\bar{S}} V \bigg|_{S=s_{KS}}
\]

- Including the effects of the warping we find:

\[
m^2_S \sim \frac{s_{KS}^{2/3}}{\alpha'^2}
\]

(c.f. [Blumenhagen, Herschmann, Wolf '16] for $m^2_S$ without warping)

→ If $s_{KS}$ is exponentially small, $S$ becomes exponentially light.
→ $S$ cannot be integrated out before uplifting with an anti-brane.

Comparison with Kähler moduli masses: [Blumenhagen, Kläwer, Schlechter '19]
$D3$-brane in the KS throat

- Place an anti-D3 brane at the bottom of the throat

- Positive contribution to the energy $\rightarrow$ uplift to de Sitter
\textbf{$D3$-brane in the KS throat}

- The $D3$-brane gives a contribution to the potential:

$$V_{D3}(S) \propto e^{4A} \propto \frac{|S|^{4/3}}{(\alpha' g_s M)^2}$$

with $e^{4A}$ the warp factor of the Klebanov-Strassler solution.

- Plot of the potential:

(dotted lines represent the KS potential and their superposition)
Stability with one $\overline{D3}$-brane

- A stable minimum of $V_{KS} + V_{\overline{D3}}$ with $S > 0$ exists iff

$$g_s M^2 > M_{min}^2 \quad \text{with} \quad M_{min} \approx 12.$$  

(see also [Blumenhagen, Kläwer, Schlechter '19])

- Superposition of the potentials:

![Diagram showing the superposition of potentials for different values of $g_s M$]
Implications on the maximal hierarchy

- Warping creates a hierarchy of scales

\[ h = 3 \ln \frac{\Lambda_0}{\Lambda_{IR}} = \frac{2\pi K}{g_S M} \]

- Tadpole cancellation:

\[ M^I K_I + Q_3^{loc} = 0, \]

where \( Q_3^{loc} \) is the D3-charge of localized sources.

- Stability of the KS throat + tadpole cancellation:

\[ h = 2\pi \frac{MK}{g_S M^2} < 2\pi \frac{|Q_3^{loc}|}{M_{min}^2} \approx \frac{|Q_3^{loc}|}{23} \]
For CY orientifolds with O3-planes and D3-branes:

$$Q^{loc}_3 = N_{D3} - \frac{1}{4} N_{03}$$

• Largest number of O3-planes: $T^6/\mathbb{Z}_2$: $Q^{loc}_3 \leq 32$

→ No large hierarchy possible.

O7-planes and D7-branes:

$$Q^{loc}_3 = \frac{1}{24} \chi(D7) + \frac{1}{6} \chi(O7) - \text{(gauge)}$$

• $\chi$: Euler number of the 4-cycles wrapped by the D7s/O7s.

→ Large tadpole possible, but D7-moduli need to be stabilized.
Tadpole cancellation in F-theory

- Tadpole cancellation for F-theory on a Calabi-Yau four-fold $CY_4$ with four-form flux $G$:

$$N_{D3} + \frac{1}{2} \int G \wedge G = \frac{\chi(CY_4)}{24}$$

- $\chi(CY_4)$: Euler number of the CY → can be very large
  (largest known example [Klemm et al. '97]: $\chi = 1820448 = 24 \cdot 75852$)

- But: Large $\chi$ implies a lot of moduli:

$$\chi(CY_4) = 6(8 + h^{1,1} + h^{3,1} - h^{2,1})$$

- $h^{3,1}$: complex structure of $CY_4$ must be stabilized by flux:

$$\int G \wedge G = \mathcal{O}(h^{3,1})?$$
Conclusions

• With a large hierarchy the KS-modulus becomes exponentially light.

• One $\tilde{D}3$ makes a Klebanov-Strassler throat unstable unless $g_s^{1/2} M > 12$.

• Due to tadpole-cancellation: Constraints on the hierarchy.
• With a large hierarchy the KS-modulus becomes exponentially light.

• One $\overline{D3}$ makes a Klebanov-Strassler throat unstable unless $g_s^{1/2} M > 12$.

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Thank You!