Perturbative moduli stabilisation in type IIB/F-theory

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Outlines

Moduli Fields

- In string theory, all scales, particle spectra and couplings come from the geometry of the extra dimensions.
- The geometry of the extra dimensions is parameterised by complex scalar fields: Moduli fields.
- Massless moduli generate long-range fifth forces and lead to theory outside the regime of validity.
- Moduli stabilisation: stabilise the geometry of the extra dimensions which leads to a vacuum that can embed Standard Model matter spectrum in four dimensions.

Type IIB Moduli Stabilisation

In IIB string theory, the moduli definitions are

- Axion-dilaton (String coupling): $S = C_0 + ie^{-\phi} \equiv C_0 + i/g_s$,
- Complex structure (Shape) Moduli: z_a,
- Kähler (Size) Moduli: complexified 4-cycle volumes T_i.

One can turn on the 3-form fluxes in the superpotential:

$$\mathcal{W}_0 = \int G_3 \wedge \Omega,$$

where $G_3 = F_3 - SH_3$, Ω contains z_a.

- Supersymmetric condition fixes the first two:

$$D_S \mathcal{W}_0 = D_{z_a} \mathcal{W}_0 = 0.$$

No Scale-Structure

After fixing all the complex moduli and axion-dilaton, only Kähler moduli left…Tree level Kähler potential is:

$$\mathcal{K}_0(T_i) = -\sum_{i=1}^{3} \ln(-i(T_i - \bar{T}_i))$$

which leads to:

$$V = e^{\mathcal{K}} \left(\sum_{I,J \neq T_i} D_I \mathcal{W} \mathcal{K}^{-1}_{I\bar{J}} D_{\bar{J}} \mathcal{W} + \sum_{T_i} D_i \mathcal{W} \mathcal{K}^{-1}_{i\bar{j}} D_{\bar{j}} \mathcal{W} - 3|\mathcal{W}|^2 \right) = 0.$$

- Vanishing vacuum energy with T_i unstabilised,
- Broken SUSY in T_i.

Breaking No Scale-Structure

- KKLT: Non-perturbative effects

$$\mathcal{W} = \mathcal{W}_0 + \sum_{i=1}^{h_+^{1,1}} \Lambda_i e^{-\lambda_i T_i} \quad .$$

Supersymmetric AdS minimum, uplifted by $\overline{D3}$-branes.

- LVS: Non-perturbative effects + α' corrections

$$\begin{aligned} \mathcal{K}_{LVS} &= -2\ln(\tau_b^{\frac{3}{2}} - \tau_s^{\frac{3}{2}} + \xi), \\ \mathcal{W}_{LVS} &= \mathcal{W}_0 + \Lambda e^{-\lambda \tau_s}. \end{aligned}$$

F-term spontaneous supersymmetry breaking, uplifted by D-term.

Perturbative Corrections

α' corrections $\hat{\xi}$ and string one-loop corrections $\hat{\delta}$ arise both in the string frame as corrections to the Einstein kinetic terms:

$$\left[e^{-2\phi}(\mathcal{V}+\hat{\xi})+\hat{\delta}\right]\mathcal{R},$$

which can be accounted by the shifts:

$$\mathcal{V}\to\mathcal{V}+\hat{\xi} \qquad ; \qquad e^{-2\phi_4}=e^{-2\phi}\mathcal{V}\to e^{-2\phi_4}+\hat{\delta}.$$

The radiative corrected Kähler potential reads:

$$\begin{aligned}\mathcal{K} &= -2\ln\left[e^{-2\phi}(\mathcal{V}+\hat{\xi})+\hat{\delta}\right]\\ &= -\ln(S-\bar{S})-2\ln\left(\hat{\mathcal{V}}+\xi+\delta\right),\end{aligned}$$

String One-Loop Corrections with $D7$-Branes

- Logarithmic divergence is common in 2D systems. e.g, Green function of 2D QED.
- In IIB string theory, graviton vertices from the 4d Einstein action localised in the internal space emit closed strings in the bulk towards another boundary.
- The transverse momentum $p_\perp$ of the closed string is not conserved and can flow on the other boundary because there are local tadpoles. These contribute to the amplitude in the large transverse volume $V_\perp$ limit:

$$\mathcal{T}(\mathcal{A}) \sim \frac{1}{V_\perp} \sum_{|p_\perp|<M_s} \frac{1}{p_\perp^2} F(\vec{p}_\perp),$$

  where the $F(\vec{p}_\perp)$ are the local tadpoles in the momentum space and

$$\vec{p}_\perp = \left(\frac{n_1}{R}, \cdots, \frac{n_d}{R}\right)$$

- 2D summation leads to logarithmic divergence.

A Single D7-Brane

Single $D7$-brane

- Kähler modulus: the world volume part τ and the transverse part u:

$$\mathcal{K} = -2\ \ln(\tau\sqrt{u} + \xi + \eta\ln(u)).$$

- Perturbative region:

$$|\eta\ln(u)| < \tau\sqrt{u}.$$

- Large volume expansion of the derivative with respect to u:

$$\frac{dV_F(\tau, u)}{du} = -\eta\mathcal{W}_0^2\frac{3(-10 + 3\ln(u))}{4\tau^3 u^{5/2}} + O(\eta^2) + O(\xi).$$

- For $\eta < 0$, the transverse direction u can have a minimum, while world volume part τ not.

Three Intersecting D7-Branes

Three Intersecting $D7$-Branes

- Now the Kähler potential reads:

$$\begin{aligned}\mathcal{K} &= -2\ln\left(\sqrt{\tau_1\tau_2\tau_3} + \sum_i 2\eta_i \ln\left(\frac{\mathcal{V}}{\tau_i}\right)\right) \\ &= -2\ln\left(\sqrt{\tau_1\tau_2\tau_3} + \sum_i \eta_i' \ln(\tau_i)\right), \qquad \eta_a' = \sum_i \eta_i - 2\eta_a.\end{aligned}$$

- The derivative with respect to either τ_a:

$$\frac{dV_F(\tau_i)}{d\tau_a} = \mathcal{W}_0^2 \frac{3\left(\sum_{i\neq a}(8\eta_i' - 3\eta_i'\ln(\tau_i)) + 10\eta_a' - 3\eta_a'\ln(\tau_a)\right)}{4\prod_{i\neq a}\tau_i^{\frac{3}{2}}\tau_a^{\frac{5}{2}}} + O(\eta'^2).$$

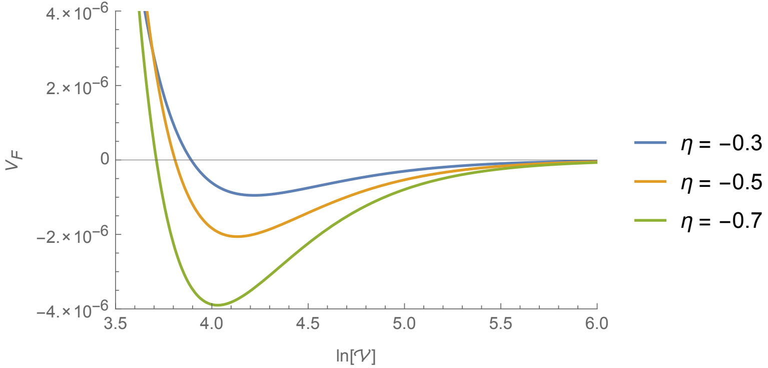
- Minimisation condition:

$$\eta_1 = \eta_2 = \eta_3 = \eta_\tau < 0,$$

- But the minimum is only for the total volume, since:

$$\mathcal{K} = -2\ln(\mathcal{V} + 2\eta_\tau \ln(\mathcal{V})).$$

$$V_F(\mathcal{V}) = \frac{\eta_\tau \mathcal{W}_0^2}{\mathcal{V}^3}(3\ln(\mathcal{V}) - 12) + O(\eta_\tau^2)$$



The minimum is inside the perturbative region and SUSY is spontaneously broken!

D-term from $D7$-Branes

- There remain two moduli, the ratios, unfixed.
- A deviation from the condition $\eta_1 = \eta_2 = \eta_3$ will destabilise the vacuum.
- Solution: Introduce world-volume dependent D-term from each $D7$-brane for both uplifting and ratios stabilisation.

$$V_{D_a} = \frac{d_a}{\tau_a}\left(\frac{\partial K}{\partial_{\tau_a}}\right)^2 = \frac{d_a}{\tau_a^3} + O(\eta_i),$$

- The sum of the potential leads to a GUT scale compactification volume and stabilise the ratios:

$$\ln(\mathcal{V}_0) \simeq 5 \qquad \tau_a = \left(\frac{d_a^3}{d_1 d_2 d_3}\right)^{\frac{1}{9}} \mathcal{V}_0^{\frac{2}{3}}.$$

Conclusion

- Moduli stabilisation is a long-standing issue in string theory. Since we can use fluxes to fix the complex moduli, the rest problems are mainly about the Kähler (size) moduli.
- The string loop corrections display logarithmic dependence on the size of the moduli transverse to $D7$-branes. With 3 intersecting $D7$-branes, one can stabilise the total extra volume.
- Magnetised $D7$-branes, which can generate D-terms that depend on the world-volume of the corresponding $D7$-branes, can stabilise the ratios and uplift the potential to de-Sitter minima where both F-term and D-term supersymmetry are spontaneously broken.
- In this scenario, non-perturbative corrections are not necessary.
- The realisation of this geometric stabilisation mechanism and the uplifting is a viable scenario in F-theory. Thus one can use the F-theory model building to realise the Standard Model.

Thanks!

Backup

Three Intersecting $D7$-Branes

- The whole 6-dimensional volume as triple products of 2-cycle moduli:

$$\mathcal{V} = \frac{1}{6}\kappa_{abc} v^a v^b v^c,$$

- In the framework of 3 intersecting $D7$-branes, take 2-cycle v^a as the transverse volume modulus of each $D7$-brane with world-volume τ_a:

$$v_a = \frac{\mathcal{V}}{\tau_a},$$

- Take κ_{abc} as ϵ_{abc} for simplicity. Then the volume can be expressed as

$$\mathcal{V} = v_1 v_2 v_3 = \sqrt{\tau_1 \tau_2 \tau_3}$$