On the vacuum structure of F-theory flux compactifications

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Introduction ~ Flux compactification ~

- Flux compactification is a simple idea of achieving the stabilization of extra massless (moduli) fields in spacetime compactifications

- For example, in the Maxwell's theory in $\mathbb{R}^{1,3} \times X$, turning on a magnetic flux threading a non-trivial cycle in the extra dimensions

$$\int_{S^2} F_2 = n$$

- This flux does not break the 4D Lorentz invariance, but there will be an energy cost depending on the metric on extra dimensions

$\longrightarrow$ generate a potential on moduli fields

- String theory has enough preferred gauge fields to realize this scenario

Introduction ~ 4D effective theory ~

- After the Kaluza-Klein reduction, 10D superstring theory on CY 3-folds or 12D F-theory on CY 4-folds reduce to a class of 4D $\mathcal{N}=1$ effective theories with scalar potential

$$V = e^K \left(K^{a\bar{b}} D_a W D_{\bar{b}} \overline{W} - 3|W|^2 \right)$$

$a, \bar{b}$: label of moduli fields

(technically we impose no-scale structure such that $-3|W|^2$ will be cancelled)

- The scalar potential is fixed by Kähler potential K and superpotential W, which can be specified by choosing the background geometry and fluxes

We examined vacuum structure of a model based on the F-theory flux compactification, and also confirmed interesting phenomena

Effective theory for moduli fields

- F-theory on a Calabi-Yau fourfold X_4 is dual to the 11D M-theory on the same fourfold X_4 (with vanishing torus)

[Becker-Becker '96], [Dasgupta-Rajesh-Sethi '99], [Gukov-Vafa-Witten '99]

- By using the mirror symmetry techniques with D-branes, one can derive 4D $\mathcal{N}=1$ effective potential arising from F-theory compactifications

[Honma-Otsuka '17], [Jockers-Mayr-Walcher '09], [Grimm-Ha-Klemm-Klevers '09]

$$K = -\ln\left[-i(S-\overline{S})\right] - \ln\left[\frac{5i}{6}(z-\bar{z})^3 + \underline{\frac{i}{S-\overline{S}}\left(\frac{5}{12}(z-\bar{z})^4 - \frac{1}{6}(z_1-\bar{z}_1)^4\right)}\right]$$

NLO in string coupling ($2\mathrm{Im}S = S - \overline{S} = 1/g_s$)

$$W = \underline{n_{11}} + \underline{n_{10}}S - \underline{n_9}z_1 + \underline{n_8}z - \frac{\underline{n_7}}{2}z_1^2 + \underline{n_6}Sz + \frac{5}{2}\left(\frac{\underline{n_5}}{5} + \frac{2\underline{n_6}}{5}\right)z^2$$
$$-\frac{5\underline{n_4}}{6}z^3 - \underline{n_2}\left(\frac{5}{2}Sz^2 + \frac{5}{3}z^3\right) - \frac{2\underline{n_3}}{3}z_1^3 + \underline{n_1}\left(\frac{5}{6}Sz^3 + \frac{5}{12}z^4 - \frac{1}{6}z_1^4\right)$$

become input data

S : dilaton z : quintic 3-fold modulus inside CY4 z_1 : D7-brane modulus

F-theory flux vacua

- Here we focus on self-dual G_4 fluxes on the CY fourfold X_4 which simplifies the form of flux superpotential of the model as

$$W = n_{11} + n_6 S z + \frac{1}{2}\left(n_5 + 2n_6\right) z - \frac{n_7}{2} z_1^2 + n_1 \left(\frac{5}{6} S z^3 + \frac{5}{12} z^4 - \frac{1}{6} z_1^4\right)$$

(with a tadpole cancellation condition ensuring the global conservation of fluxes n_i)

- In this setup, 4D $\mathcal{N}=1$ effective theory has Minkowski vacua with $V=0$

<u>F-term condition</u>

$$F^I \equiv K^{I\bar{J}} D_{\bar{J}} \overline{W} = 0 \quad \longrightarrow \quad \left\{ \begin{aligned} &\mathrm{Re}z = \mathrm{Re}z_1 = \mathrm{Re}S = 0, \\ &\mathrm{Im}z = \left(\frac{6n_{11}}{5n_1}\right)^{1/4} \frac{2\sqrt{n_6}}{(8n_6(n_5+n_6) - 5n_7^2)^{1/4}}, \\ &\mathrm{Im}z_1 = \left(\frac{30n_{11}}{n_1}\right)^{1/4} \frac{\sqrt{n_7}}{(8n_6(n_5+n_6) - 5n_7^2)^{1/4}}, \\ &\mathrm{Im}S = \left(\frac{6n_{11}}{5n_1}\right)^{1/4} \frac{n_5}{\sqrt{n_6}(8n_6(n_5+n_6) - 5n_7^2)^{1/4}} \end{aligned} \right.$$

- Later we will revisit and utilize this analytic solution in a different context

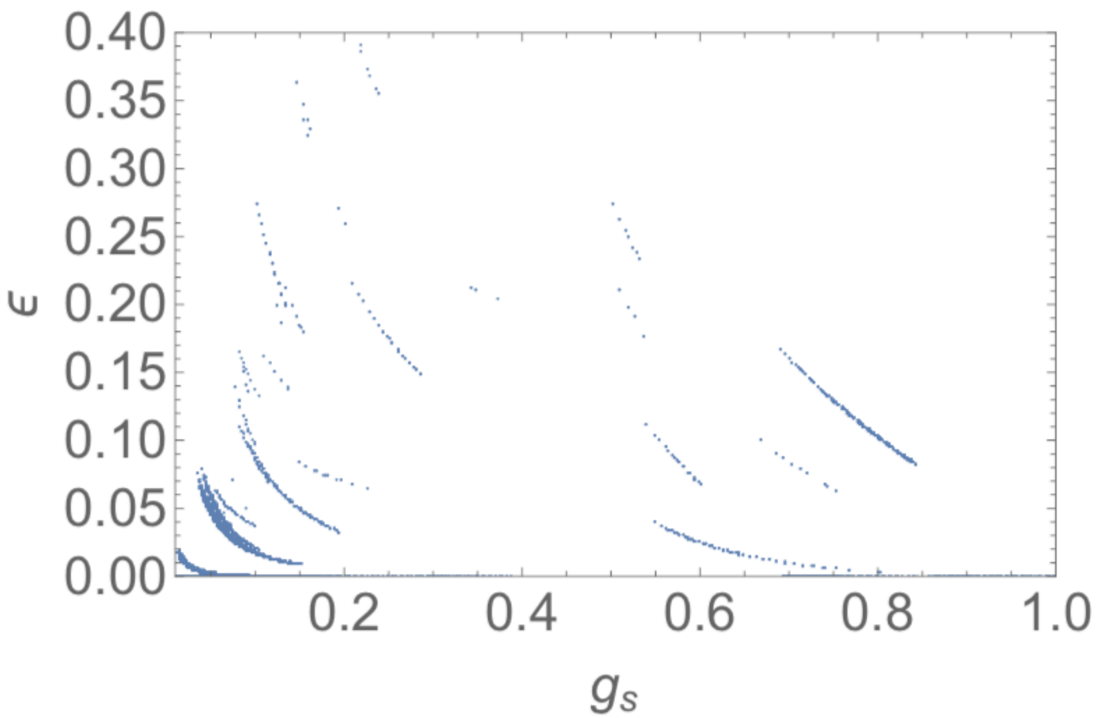
Non-SUSY F-theory flux vacua

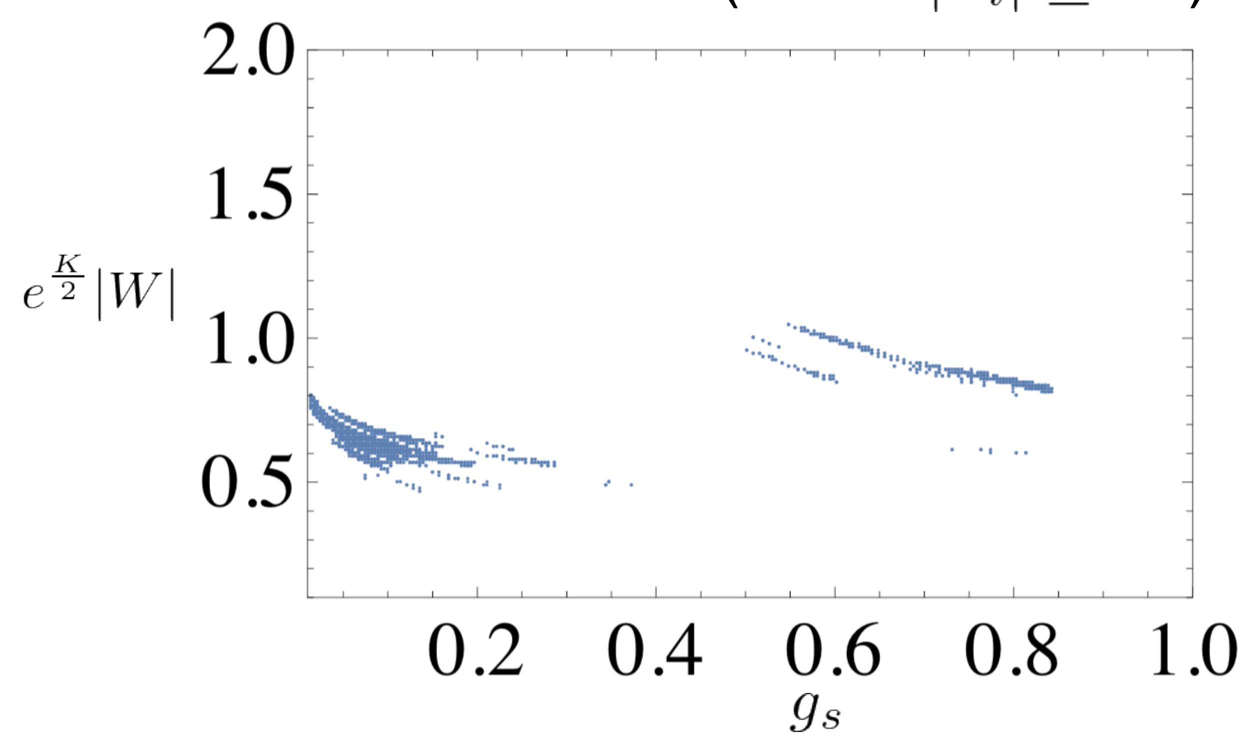
- Non-supersymmetric vacua is defined by

$$\partial_I V = 0, \qquad V : \text{non-zero}, \qquad \partial_I \partial_J V > 0$$

- By using “FindMinimum” function in Mathematica, we numerically found

(within $|n_i| \leq 10$)





- Not completely random. Seemingly monotonic, non-increasing behavior
- Larger string coupling g_s prefers smaller vacuum energy?

What’s been going on? Indicating some physics behind?

Flux vacua/Attractor correspondence

- This can be deeply connected with another topic in SUGRA referred to as the attractor mechanism, where the normalized flux superpotential $\mathcal{Z} = e^{K/2}W$ of a BH system is subject to a monotonic gradient flow along radial direction of a background

<u>Attractor mechanism</u> [Ferrara-Kallosh-Strominger '95]

> In a class of extremal black holes in $\mathcal{N}=2$ theories, moduli fields are drawn to fixed values at the horizon, regardless of initial conditions at asymptotic infinity

- There the fixed values of moduli are determined by attractor equation

$$n_i = 2\mathrm{Re}\left[\overline{\mathcal{Z}}\hat{\Pi}_i\right] \qquad \left(\hat{\Pi}_i \equiv e^{\frac{K}{2}}\int_{\gamma_i}\Omega\right)$$

- In fact, a possible existence of this kind of correspondence has been pointed out before (for Type IIB Minkowski vacua), but still unproven

[Kallosh '05], [Giryavets '05], [Larsen-O'Connell '09]

Attractor equations

- From this perspective, the suggestive behavior of on-shell quantities we observed may reflect the dynamics of a corresponding attracting object, if this kind of correspondence truly exists ALSO IN F-THEORY

- As a nontrivial supporting evidence for this conjecture, we first confirmed that the Minkowski solution we obtained before indeed satisfy the suitably generalized (going beyond SKG) attractor equations simultaneously

$$\mathrm{Re}z = \mathrm{Re}z_1 = \mathrm{Re}S = 0,$$

$$\mathrm{Im}z = \left(\frac{6n_{11}}{5n_1}\right)^{1/4} \frac{2\sqrt{n_6}}{(8n_6(n_5+n_6)-5n_7^2)^{1/4}},$$

$$\mathrm{Im}z_1 = \left(\frac{30n_{11}}{n_1}\right)^{1/4} \frac{\sqrt{n_7}}{(8n_6(n_5+n_6)-5n_7^2)^{1/4}},$$

$$\mathrm{Im}S = \left(\frac{6n_{11}}{5n_1}\right)^{1/4} \frac{n_5}{\sqrt{n_6}(8n_6(n_5+n_6)-5n_7^2)^{1/4}}$$

satisfy $\longrightarrow$

<u>F-theory Attractor Equation</u>

$$n_i = 2\mathrm{Re}\left[\overline{\mathcal{Z}}\hat{\Pi}_i + C^{IJ} D_I D_J \hat{\Pi}_i\right]$$

where C^{IJ} are determined to satisfy

$$\overline{D}_{\bar{K}}\overline{D}_{\bar{L}}\overline{Z} = C^{IJ}\left[R_{I\bar{K}J\bar{L}} + K_{I\bar{K}}K_{J\bar{L}} + K_{I\bar{L}}K_{J\bar{K}}\right] + \overline{C}^{\bar{I}\bar{J}} e^{K} \overline{Y}_{\bar{I}\bar{J}\bar{K}\bar{L}}$$

arising from Hodge structure analysis

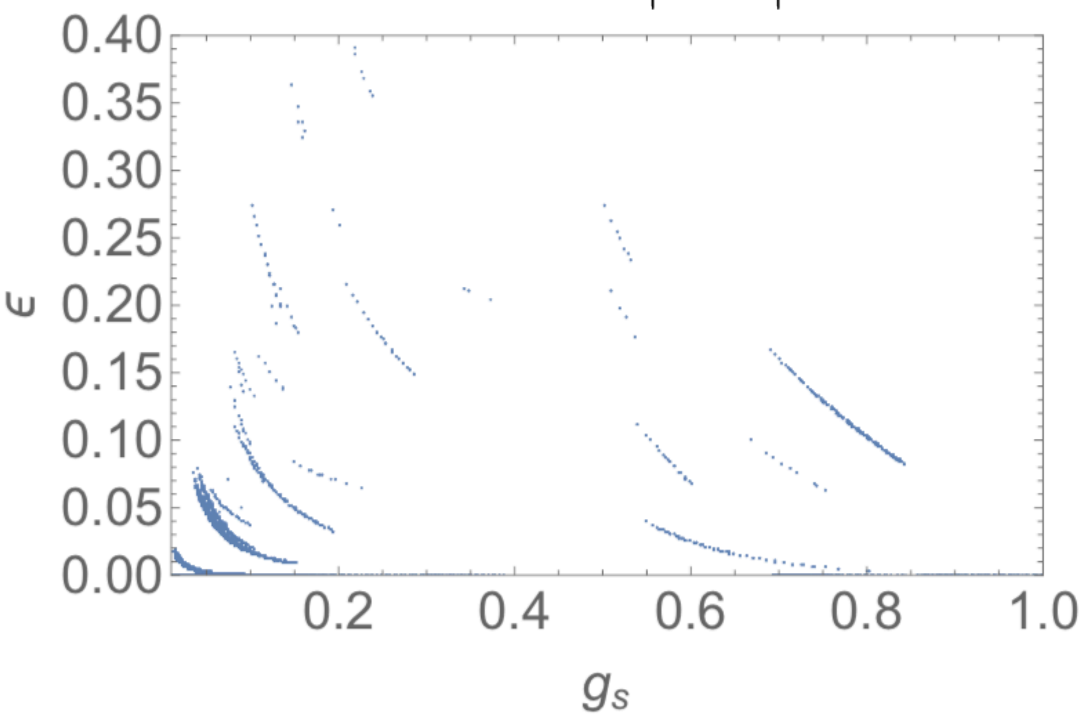
Non-SUSY F-theory flux attractors

- Moreover, we numerically check that, up to the accuracy $\mathcal{O}(10^{-20})$, the non-SUSY F-theory flux vacua we obtained also satisfy the equation

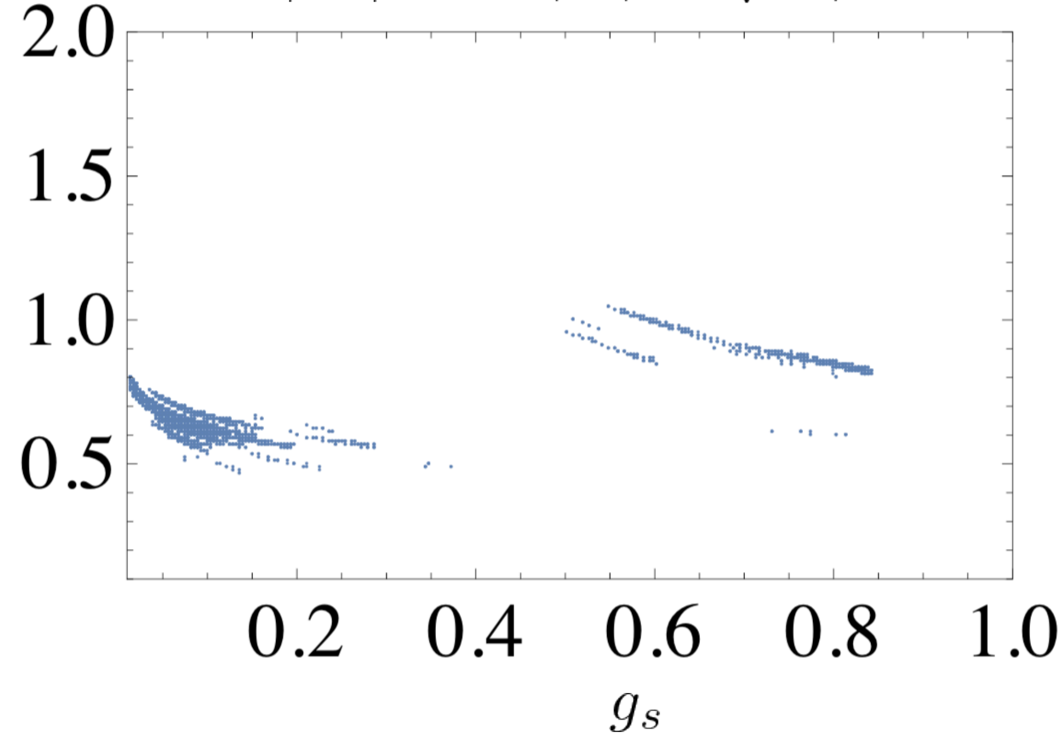
$$n_i = 2\mathrm{Re}\left[\overline{\mathcal{Z}}\hat{\Pi}_i - \overline{D}^I\overline{\mathcal{Z}}D_I\hat{\Pi}_i + C^{IJ}D_ID_J\hat{\Pi}_i\right]$$

- Our demonstrations should be regarded as a prediction: if there exist an attracting black object in the framework of F-theory, its on-shell quantities would exhibit the same characteristics as below

$V \leftrightarrow |D\mathcal{Z}|^2$



$e^{\frac{K}{2}}|W| \leftrightarrow |\mathcal{Z}| = \sqrt{A/4\pi}$



Conclusions and Discussions

- We examined the vacuum structures of 4D N=1 effective theories of moduli fields in F-theory compactification
- Especially, we analytically/numerically investigated the distributions of SUSY/non-SUSY flux vacua and confirmed a possible connection to the attractor mechanism

The main future directions are

- Further investigate the “Flux vacua/Attractor correspondence”
- Other TypeIIB/F-theory/M-theory models?
- Kahler moduli stabilization? De Sitter Swampland conjecture?
- Statistics of flux landscape?

[Obied-Ooguri-Spodyneiko-Vafa ’18], [Garg-Krishnan ’18], [Ooguri-Palti-Shiu-Vafa ’18]

Appendix

Introduction

- String theory indicates that space-time must be higher dimensional and therefore extra dimensions should be compactified

$$\mathbb{R}^{1,3} \times X \qquad (X: \text{some compact space})$$

- The details of the geometry of extra dimensions fix the characteristics of low energy physics in our 4D spacetime

- Use as much 4D SUSY as we can while keeping the problem nontrivial

  → X must be a special type of geometry called Calabi-Yau manifold

  [Candelas-Horowitz-Strominger-Witten '85]

- However, suffer from the appearance of extra massless scalar fields from metric deformations: $\delta g_{a\bar{b}}$ (Kähler moduli) & $\delta g_{\bar{a}\bar{b}}$ (complex structure moduli)

  (no preferred value for them, can create new long-range force)