Minimal matter supergravity and asymmetric orbifold

Yuta Hamada 하마다 유타 (KEK)

Based on the work in progress
w/ Zihni Kaan Baykara, Houri-Christina Tarazi, Cumrun Vafa (Harvard)

2023/07/03 String Phenomenology 2023

Supergravity without universal hypermultiplet

~~Minimal matter supergravity~~

and asymmetric orbifold

素粒子原子核研究所
Institute of Particle and Nuclear Studies

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We want to identify theories in the Landscape and the Swampland.

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This seems to be understood for minimal supersymmetric $d > 6$ theories.

10d, 16 SUSY

For $d > 6$, the minimal number of SUSY is 16.

The anomaly-free gauge groups are

$SO(32)$, $E_8 \times E_8$, $E_8 \times U(1)^{248}$, $U(1)^{496}$ [e.g. Green-Schwarz-Witten].

$SO(32)$ and $E_8 \times E_8$ are in the Landscape (Heterotic/Type I).

while $E_8 \times U(1)^{248}$ and $U(1)^{496}$ are in the Swampland.

However, the anomaly can not be cancelled in a supersymmetric way for $E_8 \times U(1)^{248}$ and $U(1)^{496}$ [Adams-DeWolfe-Taylor '10].

Also ruled out by 1-brane argument [Kim-Shiu-Vafa '19].

9d, 8d, 7d

All vacua can be understood geometrically (with frozen singularities) in terms of M/F-theory. [..., de Boer+ '01, ... , Font+ '20, Font+ '21, Fraiman+ '21, Cvetic+ '22, Parra De Freitas '22, Montero+ '22]

9d → IIA on $S^1/\mathbb{Z}_2$

8d → F-theory on elliptic K3.

7d → M-theory on K3.

Swampland argument based on brane probe suggests this is indeed all the vacua [YH, Vafa '21, Bedroya, YH, Montero, Vafa '21] (Note: for 7d, classification of 3d SCFT is assumed)

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Let's go to $d \leq 6$ theories.

Talk Plan

1. $d = 6$ supergravity and the Swampland
2. $d = 5$ supergravity and the Swampland

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6d Supergravity

6d gravity theories with minimal supersymmetry (8 SUSY).

Multiplets are

- Gravity multiplet $(g_{\mu\nu}, \psi_\mu, B^-_{\mu\nu})$.
- Tensor multiplet $(B^+_{\mu\nu}, \phi, \psi)$.
- Vector multiplet (A_μ, λ).
- Hyper multiplet (ϕ, ψ).

Moduli

Anomaly Cancellation

Anomaly cancellation conditions: Gauge group $G_1 \times \cdots \times G_k$.

The anomaly polynomial for 6d theory is 8-form.

$\mathrm{Tr}(R^4)$ and $\mathrm{Tr}(F^4)$ cancels w/o Green-Schwarz-Sagnotti mechanism.

$H - V = 273 - 29T,$ ⟵ $\mathrm{Tr}(R^4)$

$0 = \sum_R n_R^i B_R^i - B_{\mathrm{adj}}^i,$ ⟵ $\mathrm{Tr}(F^4)$ with $\mathrm{tr}_R(F^4) = B_R \mathrm{tr}_F(F^4) + C_R[\mathrm{tr}_F(F^2)]^2$,

n_R^i: #(hyper in rep. R of G_i).

There are other conditions for GSS mechanism to work.

The cancellation of perturbative anomaly implies the absence of the global anomaly [Lee, Tachikawa '20; Davighi, Lohitsiri '20].

Bottom-up

The number of consistent (at the level of EFT) 6d SUGRA is finite for $T < 9$ [Kumar, Morrison, Taylor '10].

The infinite series appear for $T \geq 9$.

The Swampland bounds using brane probe [Kim-Shiu-Vafa '19; Tarazi-Vafa '21] explains the finiteness.

We try to do explicit enumeration using ideas from graph theory [YH, Loges, WIP].

Talk by Gregory Loges on Tuesday.
Session1-B.

[Vafa ‘96, Morrison-Vafa '96, Morrison-Vafa '96]

Top-down

A large class of 6d $\mathcal{N} = (1{,}0)$ vacua is obtained from F-theory compactified on the elliptic Calabi-Yau threefold.

Q: Given an experience at higher dimensions, is this all vacua (with possibly frozen singularities?)

[Vafa ‘96, Morrison-Vafa '96, Morrison-Vafa '96]

F-theory vacua

The number of neutral hypermultiplets:

$$H^0 = h^{2,1}(X) + 1$$

Universal hypermultiplet

The number of tensor hypermultiplets:

$$T = h^{1,1}(B) - 1$$

The rank of gauge group is

$$r(T) = h^{1,1}(X) - h^{1,1}(B) - 1.$$

If these are all consistent vacua, we have the Swampland condition:

All consistent 6d SUGRA must contain at least one neutral hyper.

Otherwise it is in the Swampland.

[Narain-Sarmadi-Vafa ‘87, Narain-Sarmadi-Vafa ‘91]

Asymmetric Orbifold

The left-mover and right-mover live in different spaces.

→ Non-geometric.

Modular invariance is key to constructing consistent models.

The level-matching condition is

$$N\,(E_L - E_R) \in \mathbb{Z}$$

Order of orbifold. Left-moving mass Right-moving mass

Imposing the level-matching condition for the twisted sector provides non-trivial constraints.

[Baykara, Tarazi, YH, Vafa, WIP]

$E_8 \times E_8$ Heterotic on $T^4/\mathbb{Z}_2$

Heterotic string on T^4. The special point in the Narain moduli space, the Lie algebra lattice is realized as a momentum lattice:

$\Gamma^{20,4} = 2\Gamma^{8,0}(E_8) + \Gamma^{4,4}(D_4)$.

$\Gamma^{4,4}(D_4) = \{(p_L, p_R) \,|\, p_L \in \Lambda_W(D_4), p_R \in \Lambda_W(D_4), p_L - p_R \in \Lambda_R(D_4)\}$.

$(n_1, \cdots, n_4)$, or

$\left(n_1 + \frac{1}{2}, \cdots, n_4 + \frac{1}{2}\right)$.

$(n_1, \cdots, n_4)$,

$\sum n_i \in 2\mathbb{Z}$

$\mathbb{Z}_2$ twist: $p_L \to p_L, \quad p_R \to -p_R$.

Shift vector in $E_8 \times E_8$: $V_L = \frac{1}{2}(1,1,0,0,0,0,0,0;\, 1,1,0,0,0,0,0,0)$.

[Baykara, Tarazi, YH, Vafa, WIP]

Spectrum

From $E_8 \times E_8$ heterotic asymmetric orbifold on $T^4/\mathbb{Z}_2$, we obtain the specturm

$$G + T + 300V + 544H.$$

The gauge group is

$$E_7 \times SU(2) \times E_7 \times SU(2) \times SO(8).$$

All hypers are charged:

$$2(\mathbf{56}, \mathbf{2}, \mathbf{1}, \mathbf{1}, \mathbf{1}) + 2(\mathbf{1}, \mathbf{1}, \mathbf{56}, \mathbf{2}, \mathbf{1}) + (\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{2}, \mathbf{8}_V) + (\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{2}, \mathbf{8}_S) + (\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{2}, \mathbf{8}_C).$$

No neutral hypers.

Anomaly Cancellation

The anomaly polynomial for 6d theory is 8-form.

$\mathrm{Tr}(R^4)$ and $\mathrm{Tr}(F^4)$ cancels w/o Green-Schwarz-Sagnotti mechanism.

$\mathrm{Tr}(R^4)$: $H - V = 273 - 29T$.

$\mathrm{Tr}(F^4)$: $\sum_R n_R^i B_R^i - B_{\mathrm{Adj}}^i = 0$. with $\mathrm{tr}_R(F^4) = B_R \mathrm{tr}_F(F^4) + C_R[\mathrm{tr}_F(F^2)]^2$.

The heterotic asymmetric orbifold $T^4/\mathbb{Z}_2$ satisfies the anomaly-free conditions.

[Baykara, Tarazi, YH, Vafa, WIP]

Type IIB on $T^4/\mathbb{Z}_2$

Take IIB on T^4. The special point in the Narain moduli space, the Lie algebra lattice is realized:

$$\Gamma^{4,4}(D_4) = \{(p_L, p_R)\,|\,p_L \in \Lambda_W(D_4), p_R \in \Lambda_W(D_4), p_L - p_R \in \Lambda_R(D_4)\}.$$

$\mathbb{Z}_2$ twist: Left $p_L \to -p_L$, Right $(-1)^{F_R}$.

The spectrum is

$$G + 9T + 12V + 24H.$$

All vectors are $U(1)$ gauge bosons, and charges of hyper are

$$\left(\underline{\pm 1,0,0,0},0^8\right)+\left(\pm\frac{1}{2},\pm\frac{1}{2},\pm\frac{1}{2},\pm\frac{1}{2},0^8\right)+\left(\underline{\pm\frac{1}{2},\mp\frac{1}{2},\mp\frac{1}{2},\mp\frac{1}{2}},0^8\right)+\left(\underline{-\frac{1}{2},-\frac{1}{2},\frac{1}{2},\frac{1}{2}},0^8\right).$$

6d $\mathscr{N} = (1,0)$ supergravity theories without neutral hypermultiplets are in the Landscape.

[Baykara, Tarazi, YH, Vafa, WIP]

Moduli space

We have seen two models without neutral hypermultuplets.

Are these models disconnected to F-theory vacua?

Not necessary. The models can be Higgssed.

Heterotic $T^4/\mathbb{Z}_2$ orbifold $\xrightarrow{\text{Higgsing}}$ $G + T + 244H$.

All hypers are neutral. Maybe dual to F-theory on elliptically fibered $\mathbb{F}_n$ ($n = 0, 1, 2$).

[Baykara, Tarazi, YH, Vafa, WIP]

Moduli space in IIB model

IIB $T^4/\mathbb{Z}_2$ orbifold $\xrightarrow{\text{Higgsing}}$ $G + 9T + 8V + 20H.$

All hypers are neutral. The same can be obtained by F-theory on

$$\frac{T^2 \times T^2 \times T^2}{\mathbb{Z}_2 \times \mathbb{Z}_2'}$$

$\mathbb{Z}_2$: $(-1, -1, 1)$ twist. Half shift on the third torus.

$\mathbb{Z}_2'$: $(1, -1, -1)$ twist. No shift.

This suggests the following picture:

In the context of F-theory compactification when the base volume becomes stringy size, all hypers (including volume modulus of base) are charged.

Talk Plan

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2. $d = 5$ supergravity and the Swampland

S^1 compacfitication

S^1 compactifications of 6d models.

6d		5d
gravity multiplet	$\xrightarrow{S^1}$	gravity multiplet + vector multiplet
tensor multiplet	$\xrightarrow{S^1}$	vector multiplet
vector multiplet	$\xrightarrow{S^1}$	vector multiplet
hypermultiplet	$\xrightarrow{S^1}$	hypermultiplet

5d SUSY multiplets are

gravity, vector, hyper.

contains scalar field.

5d hyper-free models

Let us compactify 6d models w/o neutral hypermultiplets.

$\xrightarrow{S^1}$ 5d theory without neutral hypers.

5d vector multiplet has a real scalar ϕ.

The VEV $\langle \phi \rangle$ is mass of charged hypers.

By turning on $\langle \phi \rangle \neq 0$, all hypers become massive. We obtain 5d theory without hypers [Gkountoumis+ '23].

This is again non-geometric. M-theory on CY_3 has at least one universal hyper.

Open question

- As pointed out in [Gkountoumis+ ‘23], all no-hyper models have even rank.

Is this a Swampland condition, or just a lamppost of orbifold construction here?

Anomaly may not be helpful to explain evenness.

If there is one hyper, then both rank and even rank theories appear.

[Candelas+ ‘16] provides CY_3 with $h^{1,1} = 13, h^{2,1} = 0$ → $H = 1, V = 12.$

and with $h^{1,1} = 2, h^{2,1} = 0$ → $H = 1, V = 3.$

- The maximal rank is 22. Similar to the rank bound in 16Q model, (rank) $\leq 26 - d$

[Kim-Tarazi-Vafa ’19].

Any argument for maximal rank?

Summary&Future direction

- We investigate $d \leq 6$ non-geometric compactifications.
- Non-geometric compactifications provide models without universal hypermultiplets.
- These models seem to follow some patterns. Can we explain it using the Swampland principles?