# The 6D supergravity swampland and massless charge universality

Navigating the Swampland
IFT, Madrid

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Washington (Wati) Taylor, MIT

Based on work with many collaborators, including:

L. Anderson, M. Cvetic, J. Gray, Y. Huang, S. Johnson, D. Klevers, V. Kumar, G. Martini, D. Morrison, D. Park, H. Piragua, N. Raghuram, N. Seiberg, A. Turner, Y. Wang

in particular, arXiv: 1803.04447, 1901.02012, 19mm.nnnnn WT, A. Turner
arXiv: 1910.nnnnn D. Morrison, WT

# Outline

## 6D supergravity: F-theory and the swampland

6D SUGRA is an ideal framework for precise analysis of the "swampland" and discovery of UV constraints and/or new vacua

- Strongly constrained from gravitational anomalies
- Essentially one big moduli space: connected branches w/ discrete labels [Different $T$ (tensor), $G$ (vector), matter (hyper) branches connected by tensionless string, Higgs, and matter transitions]
- 6D = largest dimension with non-adjoint supersymmetric matter
- F-theory covers virtually all known 6D $\mathcal{N} = (1, 0)$ string vacua [cf. Heckman talk]

Goals: 1) identify "swampland" theories that are apparently consistent but not realized in F-theory/string theory; 2) Find inconsistencies or new vacuum constructions for all these theories

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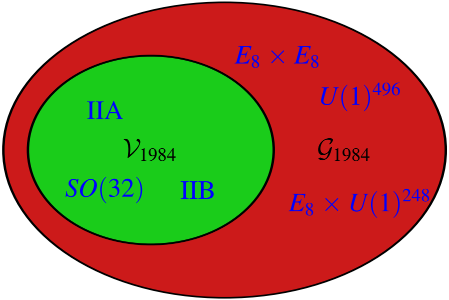
## Example: supergravity/string theory in 10 dimensions




1984: Green-Schwarz anomaly cancellation

1985: Heterotic string discovered [Gross/Harvey/Martinec/Rohm]

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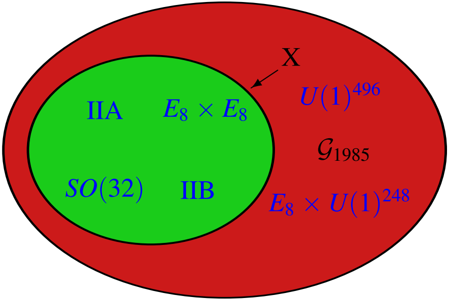


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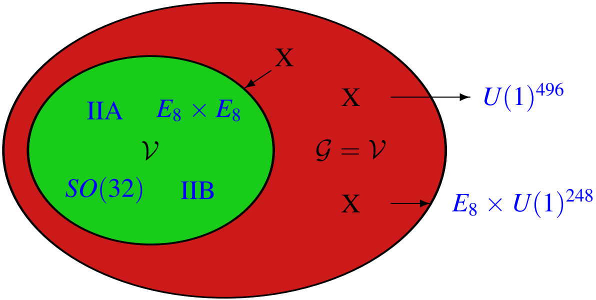


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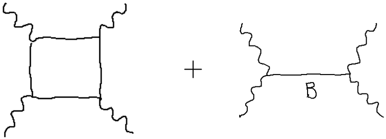
## 6D supergravity: field content (+ SUSY)

Gravity (metric $g_{\mu\nu}$)
$T$ antisymmetric tensor fields $B_{\mu\nu}$
$G$ gauge symmetry (gauge bosons $A_\mu$)
$H$ matter fields (charged under $G$ or not)

Green-Schwarz mechanism from couplings $a \cdot B \wedge R \wedge R$ and $b_i \cdot B \wedge F_i \wedge F_i$

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e.g. $H - \dim G = 273 - T$;  $a \cdot b_i, b_i \cdot b_j, \ldots$ determined by matter content

Strong constraints on {consistent theories}:
$T < 9 \Rightarrow$ finite NA $G, M$ spectra [Kumar/Taylor, Kumar/Morrison/Taylor]

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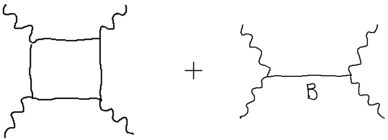


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## F-theory models of 6D supergravity

Based on *elliptic* CY3 $X$:

A torus (fiber) at each $p \in B_2$

$\pi : X \to B_2$, $B_2$ complex surface

Elliptic: $\exists$ section $\sigma : B_2 \to X, \pi\sigma = \text{Id}$


Defined by Weierstrass model (fiber $\tau$ = 10D IIB axiodilaton)

$$y^2 = x^3 + fx + g, \quad f, g \text{ 'functions' on } B_2$$

Fiber singularities over complex curves (7-branes) $\to$ gauge group $G$ (Kodaira)

Singular fibers at codimension two: massless matter (incomplete story)

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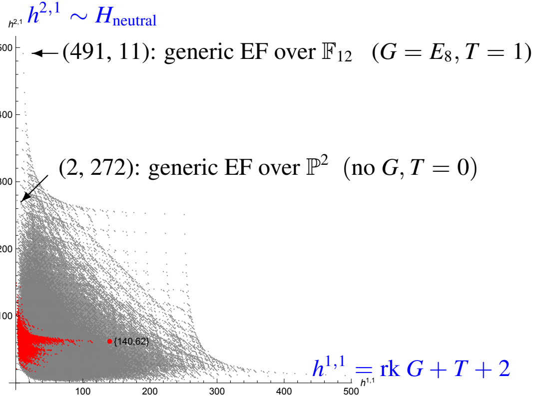
## Global picture of space of F-theory models

Known Calabi-Yau threefolds mostly elliptic

[Huang/WT, Anderson/Gao/Gray/Lee]

(KS: all but red ones [$\sim$ 30k/400M] admit elliptic/g1 fibration )




Set of elliptic Calabi-Yau threefolds bounded, finite, well-described

Useful to distinguish: "generic" vs. exotic matter representations [WT/Turner]

Fix gauge group $G$ (generally tuned/Higgsable)

6D SUGRA: generic matter (for fixed, not large anomaly coefficients $a, b$)

Defined as matter on moduli branch of greatest dimension

Note: Many branches have generic ("non-Higgsable") $G$ [Morrison/WT]
Non-generic gauge groups lie on subspaces,
Non-generic matter lies on distinct branches reached by "matter transitions"
[Anderson/Gray/Raghuram/WT: 1512.05791]

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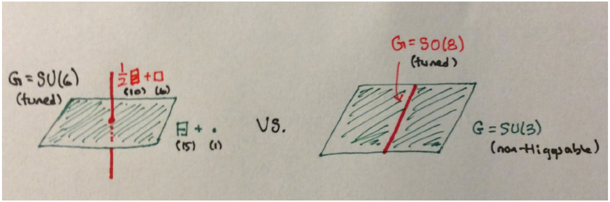


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Look at simplest class of theories

— $T = 0$ (no tensors, F-theory on $\mathbb{P}^2$)

— Generic matter

Generally, F-theory gives all anomaly-free theories in this class
(some minor subtleties, edge cases)

Example: $G = \mathrm{U}(1)$; generic matter $q = 1, 2$.
Anomaly-free spectrum: $\tilde{b}(24 - \tilde{b}) \times (\pm \mathbf{1}) + \tilde{b}(\tilde{b} - 6)/4 \times (\pm \mathbf{2})$
Realized in F-theory by Morrison-Park Weierstrass models
(subtlety at $\tilde{b} = 24$: 108 "charge 2", cf. later)

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## 6D swampland II: exotic matter

Consider $T = 0$, non-generic (exotic) matter

U(1): Exist infinite families of anomaly-free solutions. Infinite swampland!
[WT/Turner]

$$54 \times (\pm q) + 54 \times (\pm r) + 54 \times (\pm (q+r)), \quad \tilde{b} = 6\left(q^2 + qr + r^2\right), \quad q, r \in \mathbb{Z}$$

Another family:

$$54 \times (\pm a) + 54 \times (\pm b) + 54 \times (\pm c) + 54 \times (\pm d), \quad \tilde{b} = 12\left(m^2 - mn + n^2\right)^2$$

$$\begin{aligned} a &= m^2 - 2mn\,, \\ b &= 2mn - n^2\,, \\ c &= m^2 - n^2\,, \\ d &= 2\left(m^2 - mn + n^2\right)\,. \end{aligned}$$

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## What is the largest U(1) charge in F-theory?

– Must be finite, since finite # F-theory models, elliptic CY3's

– No U(1) analogue of Kodaira bound ($-12a \geq Nb$ for SU(N)) on anomaly coefficient $\tilde{b}$.

Explicit Weierstrass models: only up to $q = 4$ [Raghuram]

Some suggestions: standard F-theory constructions bounded at $q = 6$
[Collinucci/Fazzi/Morrison/Valandro]

Indirect construction: [Raghuram/WT]

Tune Weierstrass $SU(5) \times SU(4)$ on genus 2 curve in $\mathbb{F}_3$,
matter content including (10, 4) + (5, 6) + (5, $\bar{4}$) hypermultiplets

Higgs on adjoint fields $\rightarrow U(1) \times U(1)$,
Higgs on (4, -3) $\rightarrow$ charge $q = 3q_1 + 4q_2 = 21$

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$A_{N-1} \to A_N : \ydiagram{1}, \to D_N : \ydiagram{1,1}$

### Exotic matter types in conventional F-theory

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$$\ydiagram{3} : SU(2)$$

Organizing principle: $1 + \frac{1}{2}(a \cdot b + b \cdot b) = \sum(g_R = \frac{1}{12}(2C_R + B_R - A_R))$ [KPT]
(From anomalies; F-theory: arithmetic genus contribution of singular curve)

$g > 0$ realized by singularities over singular 7-branes
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## 6D swampland III

### Various further swampland theories

• Theories violating Kodaira bound ($-12a \geq Nb$ for SU($N$)) ($a = -3$ for $T = 0$); Corresponds to lower bound on coefficient of $R^2$ term (related by SUSY to $a \cdot B \wedge R \wedge R$) [Kumar/Morrison/WT]
(Stronger condition than $a < 0$ [Cheung/Remmen])

• Theories with $T > 0$ and $k$ U(1) factors where $16 < k \leq 20$ [Lee/Weigand]

## 6D swampland IV

### Additional constraints beyond anomalies

- String charge $\Gamma$ lattice w/ Dirac pairing is unimodular [Seiberg/WT]
- $a$ is a characteristic vector of $\Gamma$ [Monnier/Moore]
- Certain infinite classes at large $T$ ruled out by anomaly inflow on strings [Kim/Shiu/Vafa]
- Number of U(1) factors when $T > 0$ satisfies $k \leq 20$ [Lee/Weigand]

## 3. Charge completeness and massless charge universality

**Charge completeness hypothesis for 6D SUGRA**
([Banks/Seiberg; Harlow/Ooguri])

*Consider any 6D supergravity theory with gauge group G. States exist with all possible values in the charge lattice of G.*

**Massless charge universality for 6D SUGRA** ([Morrison/WT])

*Consider any consistent 6D $\mathcal{N} = (1,0)$ supergravity theory. The set of massless states in the theory with nontrivial charges under the gauge group generates a charge lattice $\Lambda$. The global structure of the gauge group is such that the group acts effectively on $\Lambda$, with the exception of U(1) factors that carry no massless charged states.*

We can prove both of these statements for all 6D F-theory models where $G$ is a connected (Lie) group (but not yet for discrete gauge factors; cf. IGG talk).

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## Outline of proof

These results basically follow from Poincaré duality and the observation that for any Calabi-Yau threefold $X$ every curve in $H_{1,1}(X)$ is an integer linear combination of holomorphic and antiholomorphic curves.

For charge completeness:

Every gauge boson is associated with the M-theory 3-form reduced on a divisor $D$ in $H^{1,1}(X)$. By Poincaré duality there is a curve $C$ in $H_{1,1}(X)$ with $D \cdot C = 1$. More generally, the divisors generate the fundamental group of the Cartan torus of $G$, and the curves give all weights in the dual charge lattice $\Lambda$.

For massless charge universality:

Except for the case of non-Higgsable U(1) factors that carry no massless charges, which are dual to curves $C =$ fiber, the curves in the weight lattice are linear combinations of holomorphic and antiholomorphic curves that contract to 0 volume in F-theory, so the full charge lattice is generated by massless charged states.

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## Comments and examples:

• Corollary: All (massive or massless) charged states in the theory lie in the weight lattice $\Lambda$ generated by the massless states, except for U(1) factors under which no massless states are charged.

• Corollary: $\pi_1(G)$ = Mordell-Weil group of $X$.

• Example: SU(2) with only massless adjoints is really SO(3) in F-theory
$\Rightarrow$ SU(2) with only adjoints is in the swampland

• Example: U(1) with only charge $\pm$ **2** (or any $q > 1$) is in the swampland
(MP model w/ only $q = 2$ has hidden generating section, $\sim q = 1$ model)

• Further examples:
— $SU(2) \times SU(2)$ with only bifundamental matter $\Rightarrow (SU(2) \times SU(2))/\mathbb{Z}_2$,
— $SU(24)$ with $T = 0, b = 1$: matter only $\square$'s $\Rightarrow SU(24)/\mathbb{Z}_2, \ldots$

• Conjecture: Completeness and massless charge universality hold for all 6D SUGRA theories

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• Conjecture: Completeness and massless charge universality hold for all 6D SUGRA theories

## Comments and examples:

• Corollary: All (massive or massless) charged states in the theory lie in the weight lattice $\Lambda$ generated by the massless states, except for U(1) factors under which no massless states are charged.

• Corollary: $\pi_1(G) =$ Mordell-Weil group of $X$.

• Example: SU(2) with only massless adjoints is really SO(3) in F-theory
$\Rightarrow$ SU(2) with only adjoints is in the swampland

• Example: U(1) with only charge $\pm$ **2** (or any $q > 1$) is in the swampland
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• Further examples:
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## Conclusions

6D supergravity and 6D F-theory models are both under good control, giving very precise classes of theories in “swampland”

- Theories violating massless charge universality/completeness
- Theories with arbitrarily large U(1) charges
- Theories with exotic nonabelian matter (e.g.  of SU(4), . . . )
- Infinite families of theories at large $T$
- Theories violating Kodaira condition, e.g. $-12a < Nb$ for $SU(N)$, which gives lower bound on $R^2$ term magnitude

For each class of theories, would like to find quantum consistency constraint for general gravity theory or find new string vacua. Otherwise truly stringy constraints.

Underlying geometric structure of 4D F-theory models remarkably similar; many similar swampland questions and issues to explore

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