Opening up the EFT string limits

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Based on 2207.xxxxx (hep-th)

together with Cesar Fierro Cota, Timo Weigand and Max Wiesner

see also

Opening up the Weak Gravity Conjecture

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

Results

EFT string limits

1. We studied the **EFT string limits** in F-theory Kähler quasi-moduli space.
2. We studied the 4d tower Weak Gravity Conjecture for the EFT strings associated to such limits.

Clash with the tWGC

The tower Weak Gravity Conjecture is satisfied **only** by critical heterotic strings and the gauge groups is **perturbative** gauge theory of the heterotic string.

Species scale argument

1. For all other **quasi-primitive** EFT string limits, the scale set by the tension of the EFT string is necessarily above the **higher** dimensional Planck scale.
2. We do **not** expect the WGC to be satisfied by any would-be excitations of the primitive EFT strings.

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EFT strings in F-theory on Calabi–Yau 4-folds

Let us consider a $\mathcal{N} = 1$ EFT in 4d in type IIB/F-theory set-ups.

1. Complex scalar fields:
$$\mathcal{M}: \qquad T_i = \frac{1}{2}\int_{D_i} J \wedge J + i\int_{D_i} C_4\,, \qquad \mathrm{Eff}^1(B_3) = \mathrm{Span}\{D_i,\, i = 1, \ldots, h^{1,1}(B_3)\}\,.$$
2. Infinite distance in $\mathcal{M}$, we recover a continuous **shift** symmetry: $\mathrm{Im}\, T_i$ can be treated as an **axion**.
3. The axion can be dualized into a 2-form B_2: **EFT strings** are charged under it.[1]
4. The **backreaction** of the strings
$$T_i(z) = T_i^{(0)} - \frac{e_i}{2\pi}\log\left(\frac{z}{z_0}\right),$$
induces the infinite distance limit and the corresponding **instantons** become weakly coupled.

$$\text{Cone of Instanton charges} \quad \Longleftrightarrow \quad \mathrm{Eff}^1(B_3)$$
$$\text{Cone of EFT strings charges} \quad \Longleftrightarrow \quad \mathrm{Mov}_1(B_3)$$

[1] S. Lanza *et al.*, *JHEP* **02**, 006, arXiv: 2006.15154 (hep-th) (2021); S. Lanza *et al.*, *JHEP* **09**, 197, arXiv: 2104.05726 (hep-th) (2021).

Weak coupling limits

5. Effective action:

$$S_{4d} = M_{Pl}^2 \int \frac{1}{2} R \star \mathbb{1} - g^{i\bar{j}} dT_i \wedge \star d\bar{T}_{\bar{j}} + \dots\,, \quad \text{with } g^{i\bar{j}} = \partial_{T_i} \partial_{\bar{T}_{\bar{j}}} K\,.$$

6. D7-branes wrapping effective divisors $\mathcal{S} = a^i D_i$, with $a^i \in \mathbb{R}_{\geq 0}$ give gauge theories whose gauge coupling is

$$\frac{1}{g_{YM}^2} = 2\pi \mathcal{V}_{\mathcal{S}}\,.$$

Weak coupling limits: $\frac{1}{g_{YM}^2} = 2\pi \mathcal{V}_{\mathcal{S}} \Longrightarrow \mathcal{V}_{\mathcal{S}} \to \infty \Longrightarrow T_i \to \infty$ for some i.

DASC:[2] End-points of certain EFT string flows.

EFT strings given by D3-branes on curves $C_i \subset B_3$ with $C_i \in \mathrm{Mov}_1(B_3) = \mathrm{Eff}^1(B_3)^\vee$.

[2] S. Lanza *et al.*, *JHEP* **02**, 006, arXiv: 2006.15154 (hep-th) (2021); S. Lanza *et al.*, *JHEP* **09**, 197, arXiv: 2104.05726 (hep-th) (2021).

EFT string limit

EFT string limit

An EFT string limit in the F-theory Kähler quasi-moduli space is a limit in which the volume of a subset $\mathcal{I} \subset \{D_i\}$ diverges homogeneously, i.e.

$$\mathcal{V}_D \sim \lambda \to \infty\,, \qquad \forall D \in \mathcal{I}\,,$$

while $\mathcal{V}_{\hat{D}} < \infty$ for $\hat{D} \notin \mathcal{I}$. In this case, we call the set $\mathcal{I}$ **homogeneously expandable**.

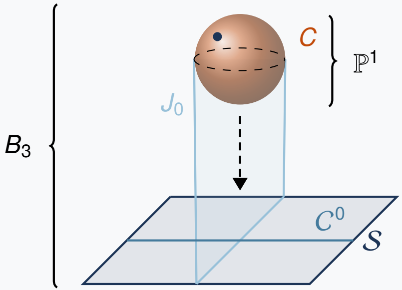
Primitive and Quasi-primitive EFT string limit

1. **Primitive** EFT string limit corresponds to a limit for which $|\mathcal{I}| = 1$.
2. **Quasi-primitive** EFT string limit correspond to an EFT limit in which one minimized $|\mathcal{I}| > 1$.

EFT strings

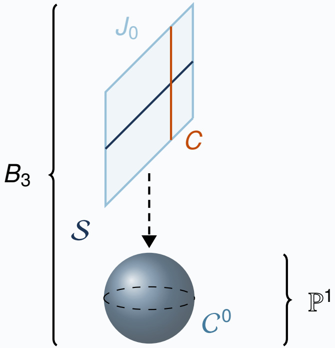
q = 0

$C = J_0^2$, with $J_0^3 = 0$, is a $\mathbb{P}^1$ fiber.



q = 1

$C = J_0 \cdot J_i$ is in a surface fiber of B_3.



q = 2

$C = J_0^2$, with $J_0^3 \neq 0$, is a curve in an expanding B_3.

Repulsive Force Conjecture

The tWGC is fulfilled if the tower of charged excitations satisfies the relation[3]

$$\frac{g_{\rm YM}^2 q_k^2}{M_k^2} \geq \frac{1}{M_{\rm Pl}^2}\left[\left.\frac{d-3}{d-2}\right|_{d=4} + \frac{1}{4}\frac{M_{\rm Pl}^4}{M_k^4} g^{rs}\partial_r\left(\frac{M_k^2}{M_{\rm Pl}^2}\right)\partial_s\left(\frac{M_k^2}{M_{\rm Pl}^2}\right)\right].$$

tWGC for primitive EFT strings

EFT strings have $q = 0, 1, 2$, so the tWGC is satisfied only for primitive EFT strings with $q = 0$.

Claim

We do **not** expect that the tWGC is saved since we do **not** expect the quasi-primitive EFT strings with $q \geq 1$ to have particle-like excitations in 4d.

[3] E. Palti, *JHEP* **08**, 034, arXiv: 1705.04328 (hep-th) (2017); B. Heidenreich *et al.*, *JHEP* **10**, 055, arXiv: 1906.02206 (hep-th) (2019).

Contents

Species scale

Are the D3-brane strings still effective strings in 4d?

Scaling weight:[4]

$$m_*^2 \sim M_{\rm Pl}^2 \left(\frac{T_{\rm EFT}}{M_{\rm Pl}}\right)^w \Longrightarrow q = (0,1,2) \longleftrightarrow w = (1,2,2)$$

Unless $q = 0$, the tension of the string is **always above** the KK-scale. These limits are **decompactification** limits.

Species scale:[5]

$$\Lambda_{\rm sp}^2 = \frac{M_{\rm Pl}^2}{N_{\rm sp}} \overset{N_{\rm sp}\sim k^n}{\Longrightarrow} \Lambda_{\rm sp,KK}^2 = k_{\rm max}^2 M_{\rm KK}^2 \overset{!}{=} \frac{M_{\rm Pl}^2}{k_{\rm max}^n} \Longrightarrow \frac{\Lambda_{\rm sp,KK}^2}{M_{\rm Pl}^2} = \left(\frac{M_{\rm KK}^2}{M_{\rm Pl}^2}\right)^{\frac{n}{n+2}}$$

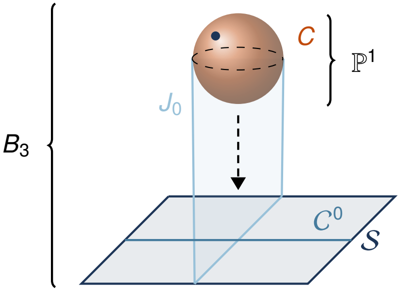
n-decompactifying dimensions

[4] S. Lanza, F. Marchesano, L. Martucci, I. Valenzuela, *JHEP* **09**, 197, arXiv: 2104.05726 (hep-th) (2021).

[5] G. Dvali, *Fortsch. Phys.* **58**, 528–536, arXiv: 0706.2050 (hep-th) (2010); G. Dvali, M. Redi, *Phys. Rev. D* **77**, 045027, arXiv: 0710.4344 (hep-th) (2008); G. Dvali, C. Gomez, arXiv: 1004.3744 (hep-th) (Apr. 2010); M. Montero *et al.*, arXiv: 2205.12293 (hep-th) (May 2022).

Species scale for $q = 0$ EFT strings

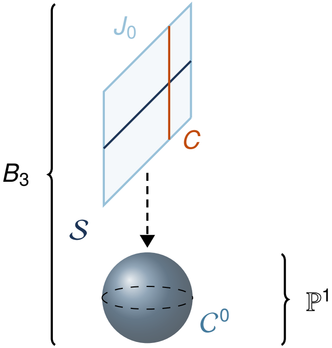
1. $C = J_0^2$, with $J_0^3 = 0$, is a $\mathbb{P}^1$ fiber.
2. $v^0 \sim \lambda \to \infty$:
$$\mathcal{V}_{B_3} \sim \lambda \to \infty$$
3. KK tower:
$$\frac{M_{\rm KK}^2}{M_{\rm Pl}^2} \sim \frac{1}{\lambda^2}$$
4. Species scale with $n = 4$:
$$\frac{\Lambda_{\rm sp,KK}^2}{M_{\rm Pl}^2} \sim \left(\frac{M_{\rm KK}^2}{M_{\rm Pl}^2}\right)^{\frac{2}{3}} \sim \frac{1}{\lambda^{4/3}}$$
5. EFT tension, i.e. WGC scale:
$$\frac{T_{\rm EFT}}{M_{\rm Pl}^2} = \frac{\Lambda_{\rm WGC}^2}{M_{\rm Pl}^2} \sim \frac{1}{{\rm Re}\, T_0} \sim \frac{1}{\lambda^2}$$
6. Species scale set by the EFT string itself $\Longrightarrow$ **4d** limit.



$$\frac{T_{\rm EFT}}{M_{\rm Pl}^2} \ll \frac{\Lambda_{\rm sp,KK}^2}{M_{\rm Pl}^2}$$

Species scale for $q = 1$ EFT strings

1. $C = J_0 \cdot J_i$ is in a surface fiber of B_3.
2. $v^0 \sim \lambda \to \infty$:
$$\mathcal{V}_{B_3} \sim \lambda \to \infty$$
3. KK tower:
$$\frac{M_{\rm KK}^2}{M_{\rm Pl}^2} \sim \frac{1}{\lambda^2}$$
4. Species scale with $n = 2$:
$$\frac{\Lambda_{\rm sp,KK}^2}{M_{\rm Pl}^2} \sim \left(\frac{M_{\rm KK}^2}{M_{\rm Pl}^2}\right)^{\frac{1}{2}} \sim \frac{1}{\lambda}$$
5. EFT tension, i.e. WGC scale:
$$\frac{T_{\rm EFT}}{M_{\rm Pl}^2} = \frac{\Lambda_{\rm WGC}^2}{M_{\rm Pl}^2} \sim \frac{1}{{\rm Re}\, T_0} \sim \frac{1}{\lambda}$$
6. Decompactification to **6d**.



$$\frac{T_{\rm EFT}}{M_{\rm Pl}^2} \sim \frac{\Lambda_{\rm sp,KK}^2}{M_{\rm Pl}^2}$$

Species scale for $q = 2$ EFT strings

1. $C = J_0^2$, with $J_0^3 \neq 0$, is a curve in an expanding B_3.
2. $v^0 \sim \lambda \to \infty$:
$$\mathcal{V}_{B_3} \sim \lambda^3 \to \infty$$
3. KK tower:
$$\frac{M_{\rm KK}^2}{M_{\rm Pl}^2} \sim \frac{1}{\lambda^4}$$
4. Species scale with $n = 6$:
$$\frac{\Lambda_{\rm sp,KK}^2}{M_{\rm Pl}^2} \sim \left(\frac{M_{\rm KK}^2}{M_{\rm Pl}^2}\right)^{\frac{1}{2}} \sim \frac{1}{\lambda^3}$$
5. EFT tension, i.e. WGC scale:
$$\frac{T_{\rm EFT}}{M_{\rm Pl}^2} = \frac{\Lambda_{\rm WGC}^2}{M_{\rm Pl}^2} \sim \frac{1}{\mathrm{Re}\, T_0} \sim \frac{1}{\lambda^2}$$
6. Decompactification to **10d**.

$$\frac{T_{\rm EFT}}{M_{\rm Pl}^2} \gg \frac{\Lambda_{\rm sp,KK}^2}{M_{\rm Pl}^2}$$

Species scale vs. Species scale for (quasi-)primitive EFT string limits

q = 0

$$M_{\rm IIB}^2 \sim M_{\rm Pl}^2 \left(\frac{T_{\rm EFT}}{M_{\rm Pl}^2}\right)^{1/2}$$

- $M_{\rm Pl}^2 \sim 1$
- $\Lambda_{\rm sp,KK}^2 \sim \frac{1}{\lambda^{4/3}}$
- $M_{\rm IIB}^2 \sim \frac{1}{\lambda}$
- $M_{\rm KK}^2 \sim T_{\rm EFT} \sim \Lambda_{\rm sp}^2 \sim \frac{1}{\lambda^2}$

q = 1

$$M_{\rm IIB}^2 \sim M_{\rm Pl}^2 \left(\frac{T_{\rm EFT}}{M_{\rm Pl}^2}\right)$$

- $M_{\rm Pl}^2 \sim 1$
- $\Lambda_{\rm sp,KK}^2 \sim M_{\rm IIB}^2 \sim T_{\rm EFT} \sim \frac{1}{\lambda}$
- $M_{\rm KK}^2 \sim \frac{1}{\lambda^2}$

q = 2

$$M_{\rm IIB}^2 \sim M_{\rm Pl}^2 \left(\frac{T_{\rm EFT}}{M_{\rm Pl}^2}\right)^{3/2}$$

- $M_{\rm Pl}^2 \sim 1$
- $T_{\rm EFT} \sim \frac{1}{\lambda}$
- $\Lambda_{\rm sp,KK}^2 \sim M_{\rm IIB}^2 \sim \frac{1}{\lambda^3}$
- $M_{\rm KK}^2 \sim \frac{1}{\lambda^4}$

Consequences

$$M_{\mathrm{IIB}}^2 \sim M_{\mathrm{Pl}}^2 \left(\frac{T_{\mathrm{EFT}}}{M_{\mathrm{Pl}}^2} \right)^{\frac{q+1}{2}}$$

1. Decompactification limits with $q \neq 0$ are **strict decompactification limits**: no additional, non-critical strings appear before reaching the higher dimensional Planck scale.
2. Limits with $q = 0$ have strings whose tension is always of the order of the KK scale. The species scale is **set** by the string scale itself.
3. For $q \geq 1$, we do **not** expect the tWGC to be satisfied by any would-be excitations of the primitive EFT strings.

4d effective string	$\dim_{\mathrm{eff}}$(gauge theory) for $g_{\mathrm{YM}} \to 0$	Supergravity string exists in
$q = 0$	$d = 4$	$d \leq 8$
$q = 1$	$d = 6$	$d \leq 6$
$q = 2$	$d = 8$	$d = 4$

Non-EFT string limits

Non-EFT string limits

Given a generator D_0 of $\mathcal{V}_{D_0} \to \infty$ **cannot** be realized as a quasi-primitive EFT string limit. The weak coupling limit for a gauge theory on D_0 corresponds to a limit in which either the gauge theory effectively becomes

1. a **defect theory** in either 8d or 10d or
2. a **non-weakly coupled** 6d theory.

1. Gauge theories, **without** a quasi-primitive EFT string limit, reduce to higher dimensional theories in the weak-coupling limit.
2. There **cannot** be any non-critical EFT string with tension between the scale of the KK-tower and the associated species scale.
3. **Caveat**: there can be critical strings appearing between these two scales, taking a decompactification limit and additional limits in 6d.

Combine $q = 1$ quasi-primitive EFT limit with weak coupling limit in 6d

1. Assume a fibration structure $p : \mathbb{P}^1_0 \to \left(\mathbb{P}^1_1 \to \mathbb{P}^1_2\right)$, such that

$$v^0 \sim \lambda^{-1}\,,\ v^1 \sim \lambda\,,\ v^2 \sim \lambda^2\,.$$

2. For the limit $\lambda \to \infty$, we have a **decompactification** to 6d, i.e.

$$\mathcal{V}_{B_3} \sim \lambda^2\,,$$

3. The KK-scale and the species scale are given by

$$\frac{M^2_{\mathrm{KK}}}{M^2_{\mathrm{IIB}}} \sim \lambda^{-2} \qquad \Longrightarrow \qquad \frac{\Lambda^2_{\mathrm{sp,KK}}}{M^2_{\mathrm{Pl}}} \sim \lambda^{-2}\,.$$

4. Using

$$\frac{T_{\mathrm{het}}}{M_{\mathrm{IIB}}} \sim \lambda^{-1} \qquad \Longrightarrow \qquad T_{\mathrm{het}} \lesssim \Lambda_{\mathrm{sp,KK}}\,.$$

5. The species scale is given by M_{IIB}.
6. The resulting 6d limit then corresponds to the **emergent string limits**.[6]
7. A gauge theory on $\mathbb{P}^1_1 \to \mathbb{P}^1_0$ becomes weakly-coupled at the fastest rate, but **effectively 6d**.

[6] S.-J. Lee *et al.*, *Nucl. Phys. B* **938**, 321–350, arXiv: 1810.05169 (hep-th) (2019); S.-J. Lee *et al.*, *JHEP* **10**, 164, arXiv: 1808.05958 (hep-th) (2018).

$\mathbb{P}^1$ fibration over Bl($\mathbb{F}_2$)

1. Let us consider a blow-up in a smooth point of $\mathbb{F}_2$, i.e. $B_2 = \text{Bl}(\mathbb{F}_2)$, with

$$\mathcal{I}(B_2) = 2j_0^2 + j_0 \cdot j_1 + j_2^2 + j_2 \cdot j_1 + 2j_0 \cdot j_2 \,.$$

2. Consider also a $\mathbb{P}^1$ fibration over B_2 with twist given by some bundle $\mathcal{T}$ such that $c_1(\mathcal{T}) = j_0$.
3. The Kähler cone generators,

$$J_0 = p^* j_0 \,, \; J_1 = p^* j_1 \,, \; J_2 = p^* j_2 \,, \; J_3 = S_- + p^* c_1(\mathcal{T}) \,,$$

have the following intersection ring

$$\mathcal{I}(B_3) = 2J_3^3 + 2J_0 \cdot J_3^2 + J_1 \cdot J_3^2 + 2J_2 \cdot J_3^2 + 2J_0^2 \cdot J_3 + J_2^2 \cdot J_3 + J_0 \cdot J_1 \cdot J_3 + 2J_0 \cdot J_2 \cdot J_3 + J_1 \cdot J_2 \cdot J_3 \,.$$

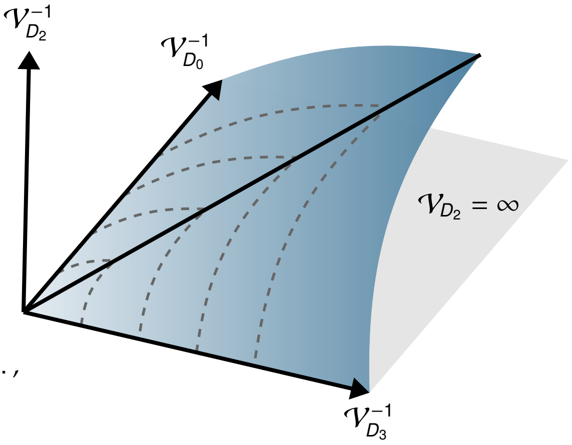
Effective Divisors: $\text{Cone}\,\langle J_3 - J_0, J_0 - 2J_1, J_0 - J_2, J_1 + J_2 - J_0 \rangle \equiv \text{Cone}\,\langle D_0, D_1, D_2, D_3 \rangle$

Movable Curves: $\text{Cone}\,\langle J_0 \cdot J_1, J_1 \cdot J_3, J_2 \cdot J_3, J_0 \cdot J_3 \rangle \equiv \text{Cone}\,\langle C^0, C^1, C^2, C^3 \rangle$

$\mathbb{P}^1$-fibration over Bl($\mathbb{F}_2$)

1. Effective divisors' volumes:

$$\mathcal{V}_{D_0} = v^0\left(v^0 + v^1\right) + v^2\left(2v^0 + v^1 + \frac{1}{2}v^2\right),$$
$$\mathcal{V}_{D_1} = v^3 v^1,$$
$$\mathcal{V}_{D_2} = v^3 v^2,$$
$$\mathcal{V}_{D_3} = \frac{1}{2}v^3\left(2v^0 + v^3\right).$$



2. Primitive EFT limits:

C^0	$q = 0$	$v^0, v^1, v^2 \to \infty\,,\ v^3 \to 0\,,$
C^1	$q = 1$	$v^1 \to \infty\,,\ v^0, v^2 \to 0\,,\ v^3 \simeq \text{const.}\,,$
C^2	?	?
C^3	$q = 2$	$v^3 \to \infty\,,\ v^1, v^2 \to 0\,,\ v^0 \simeq \text{const.}\,.$

3. C^1 limit **shrinks** D_2!

Missing limits

1. We expect that **all** primitive EFT string limits can be reached, even though not necessarily in the same chamber of the Kähler cone.[7]
2. To reach another chamber of the Kähler cone we need to perform a **flop transition** for B_3 by shrinking a curve without shrinking any divisors.
3. We reach a boundary of the initial Kähler cone chamber where we can blow-up another curve in B_3 and traverse into another chamber of the extended Kähler cone.

Flopping C^0 to C^4

$$C^1 \mid q = 1 \mid v^1 \to \infty\,,\ v^2 \to 0$$

Flopping C^0, C^1 to C^4,C^5

$$C^2 \mid q = 2 \mid v^5 \to \infty$$

[7] S. Lanza, F. Marchesano, L. Martucci, I. Valenzuela, *JHEP* **09**, 197, arXiv: 2104.05726 (hep-th) (2021).

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