Is There a 6D F-theory Swampland?

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Based On

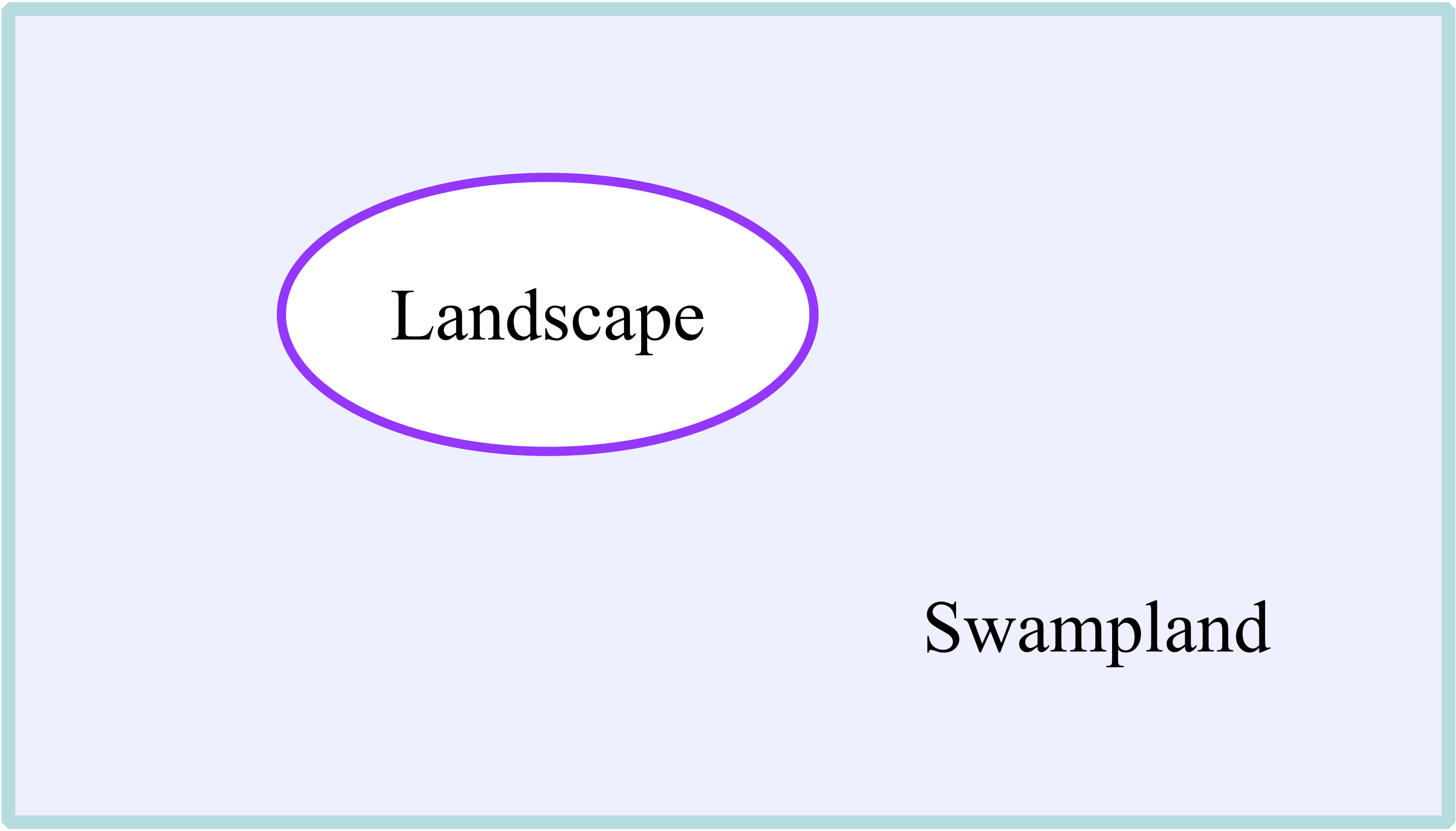
- 1502.05405/hep-th, 1511.05565/hep-th, 1605.08045/hep-th
  - with Lakshya Bhardwaj, Michele Del Zotto, Jonathan Heckman, David Morrison, and Cumrun Vafa
- see also 1201.1943/hep-th, 1604.01030/hep-th 1605.08052/hep-th, by Taylor et al.

Outline

I. The Landscape and the Swampland
II. The Classification of 6D Gauge Theories
    I. SCFTs
    II. LSTs
    III. SUGRAs
III. Unpaired Tensors in 6D
IV. Open Questions

The Landscape and the Swampland

The Big Picture



Vafa ’06, Ooguri, Vafa ‘06

Some Swampland Criteria

- For gravitational theories:
  - "No global symmetries"
  - The Weak Gravity Conjecture Arkani-Hamed et al., 2006
  - Moduli spaces infinite in length Ooguri, Vafa '06
  - Gauge group rank bounded Vafa '05
  - No super-Planckian spatial field variations
    c.f. Eran Palti's talk

- Non-gravitational theories less constrained

Classification of
6D Gauge Theories

6D Theories and F-theory

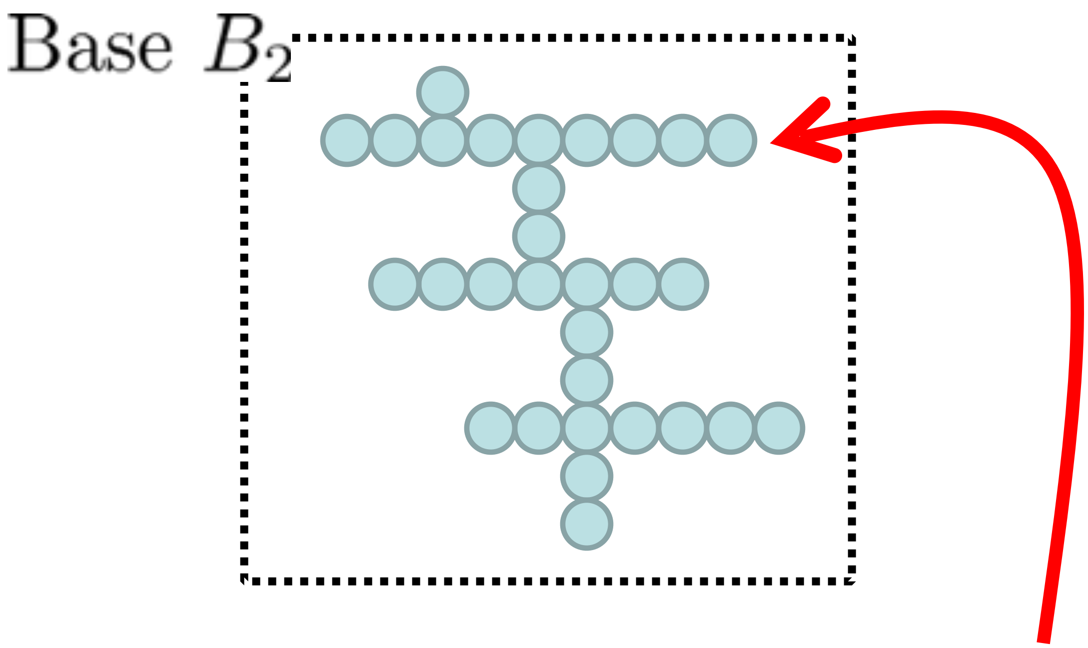
Vafa '96, Vafa Morrison, I/II '96

IIB: $\mathbb{R}^{5,1} \times B_2$ with pos. dep. coupling $\tau(z_B)$

F-theory on $\mathbb{R}^{5,1} \times CY_3$

$$\begin{array}{ccc} T^2 & \rightarrow & CY_3 \\ & & \downarrow \\ & & B_2 \end{array}$$

Geometric Picture



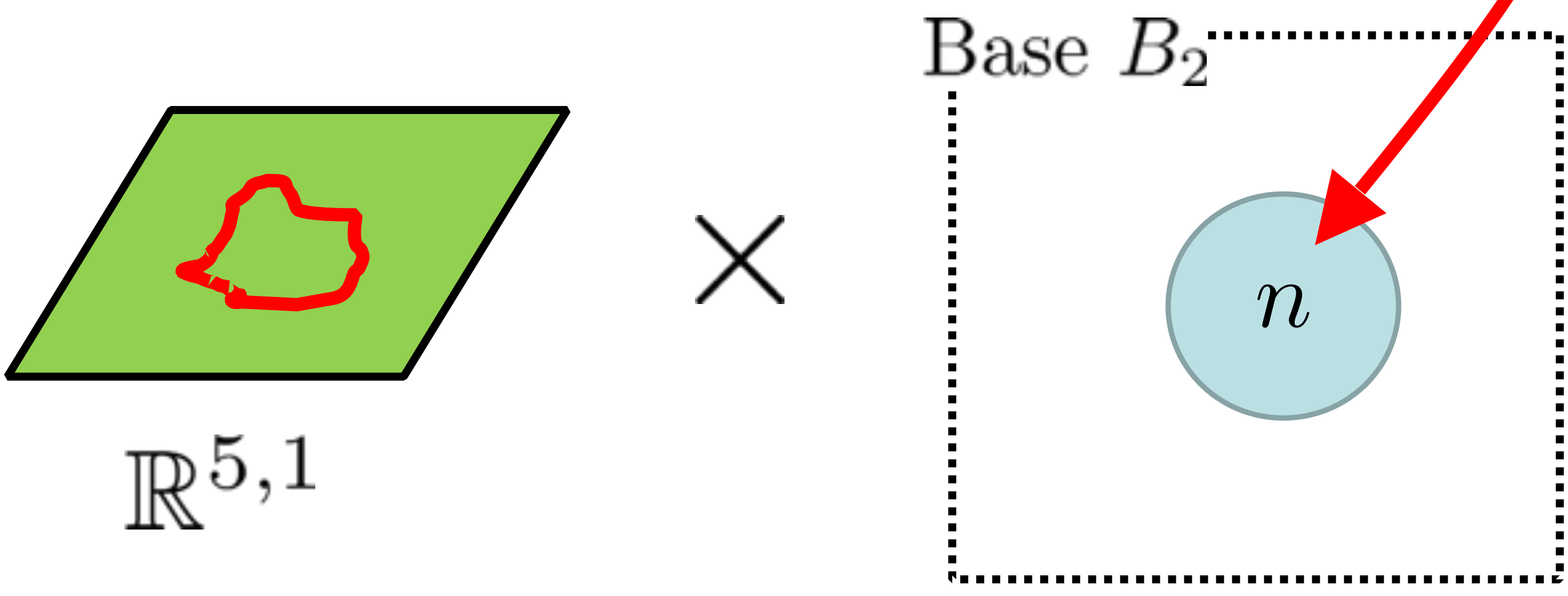
Curves in base $\Rightarrow$ strings (D3 / $\mathbb{P}^1$)

Singularities in fiber $\Rightarrow$ particles (7-brane on $\mathbb{P}^1$)

Strings from D3 on a $\mathbb{P}^1$

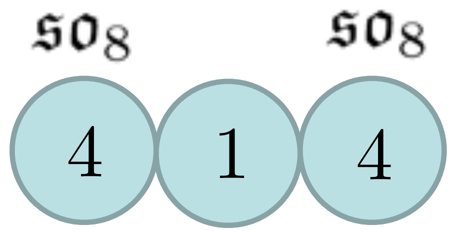
$$-\Sigma \cap \Sigma = \text{String Charge}$$

(which must be integer > 0 for SCFTs,
≥ 0 for LSTs)



Dirac Pairing for String Charge Lattice

Intersection Matrix $\longleftrightarrow$ Dirac Pairing



$$\Omega_{IJ} = \begin{pmatrix} -4 & 1 & 0 \\ 1 & -1 & 1 \\ 0 & 1 & -4 \end{pmatrix}$$

SCFTs vs. LSTs vs. SUGRA

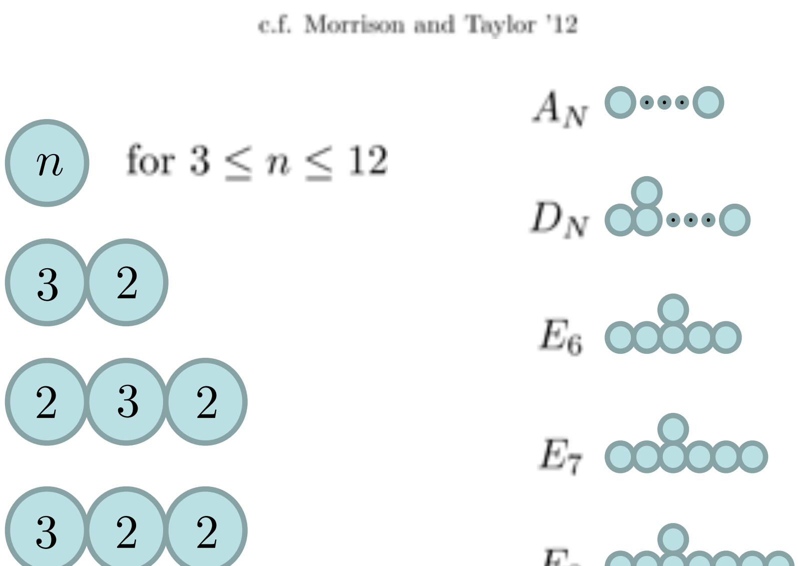
Dirac pairing on string charge lattice Ω_{IJ}

6D SCFT	LST	6D SUGRA
$\Omega_{IJ} < 0$	$\Omega_{IJ} \leq 0$ $\text{Nullity}(\Omega_{IJ}) = 1$	Ω_{IJ}: 1 + eigenvalue

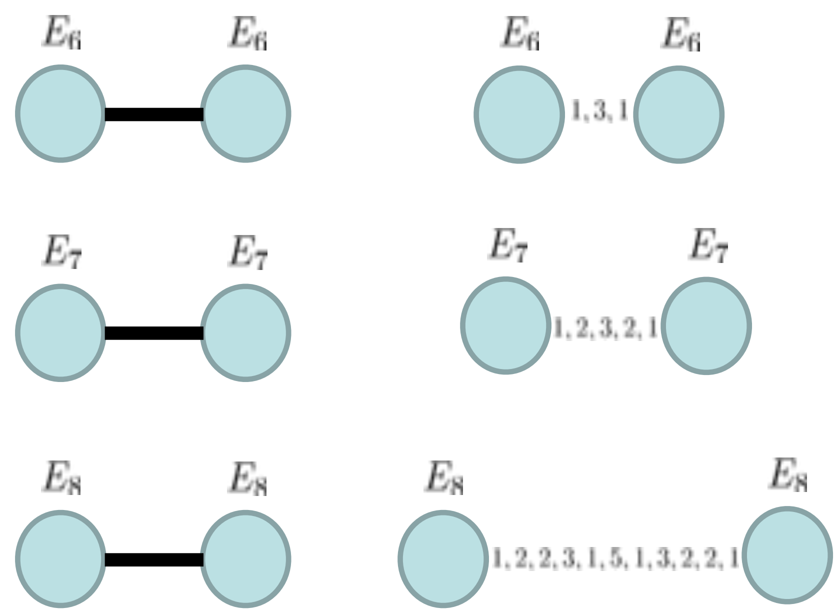
Classification of 6D Theories

- Looks like chemistry

"Atoms"

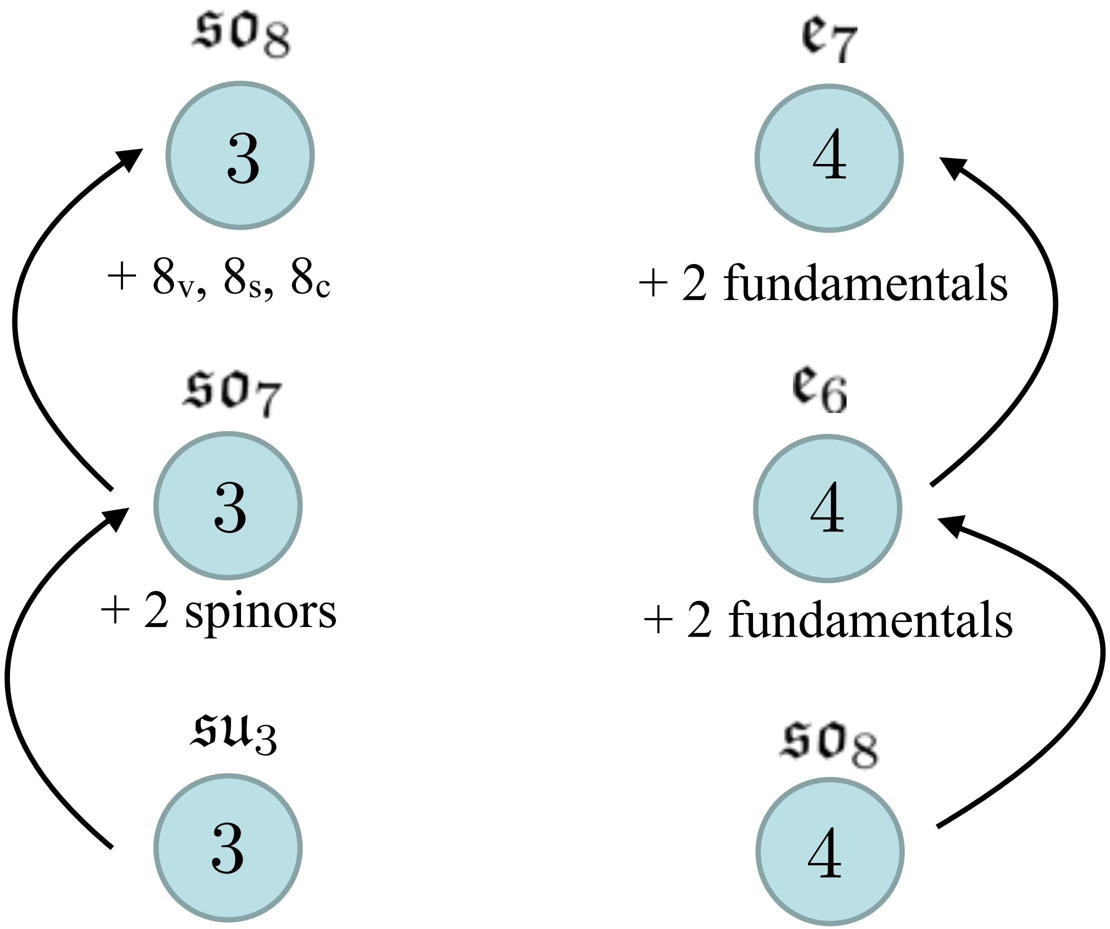


"Radicals"



Minimal Gauge Algebras

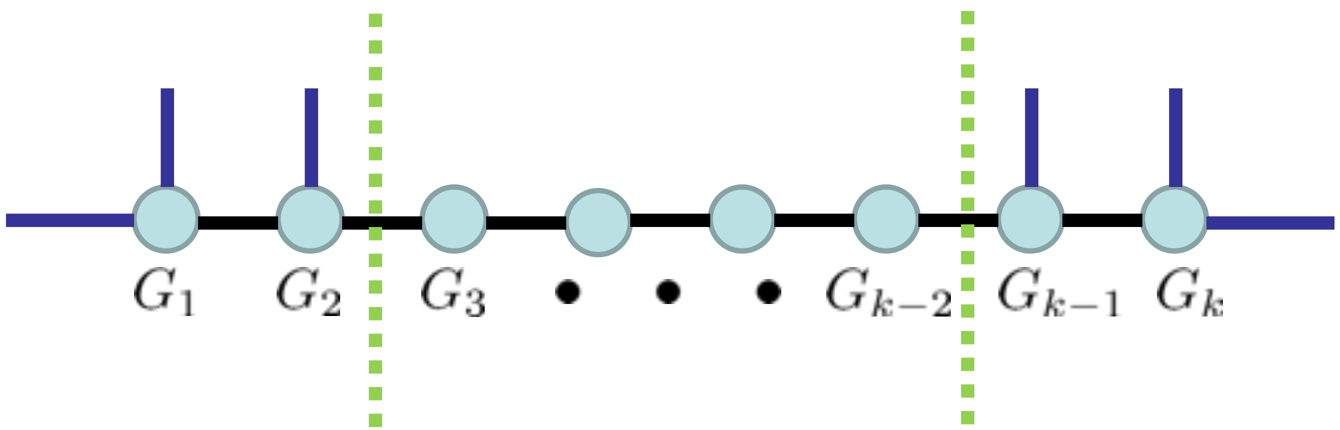
Fiber Enhancements



Classification of 6D SCFTs

Heckman, Morrison, Vafa '13
Heckman, Morrison, TR, Vafa '15

- 6D SCFTs can be classified via F-theory
- Nearly all F-theory conditions can be phrased in field theory terms
- 6D SCFTs = Generalized Quivers



Example: All $(2,0)$ Theories

Witten '95, Strominger '95

Type IIB on $\mathbb{C}^2/\Gamma_{ADE}$

Resolution Involves:

Bouquet of $\mathbb{CP}^1$'s

$\mathbb{CP}^1_i \cap \mathbb{CP}^1_j = -\mathrm{Dynkin}_{ij}$

Note: $\mathbb{CP}^1_i \cap \mathbb{CP}^1_i = -2$

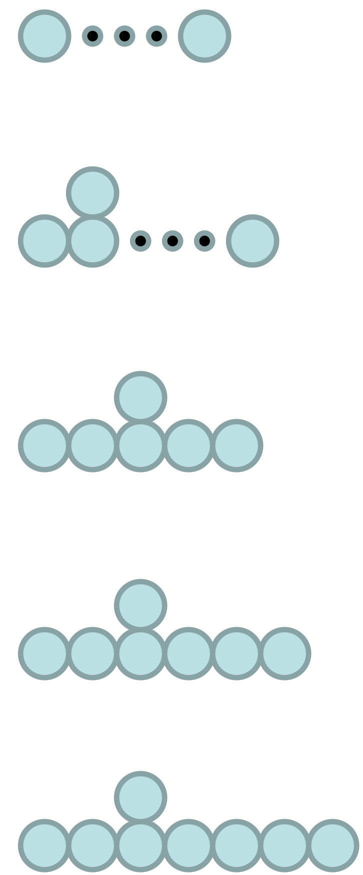
A_N

D_N

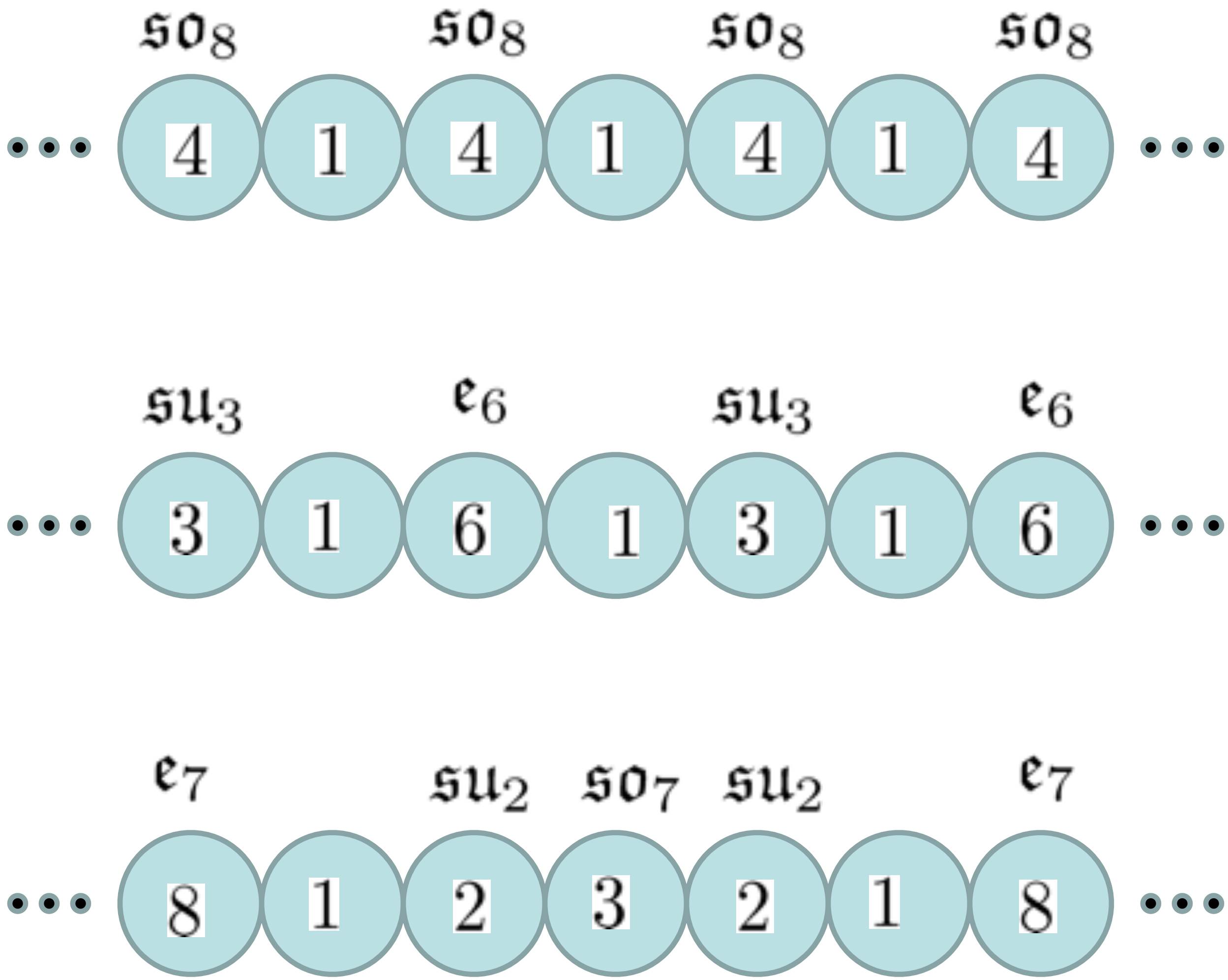
E_6

E_7

E_8



Examples



c.f. Alessandro Tomasiello's talk

Classification of LSTs

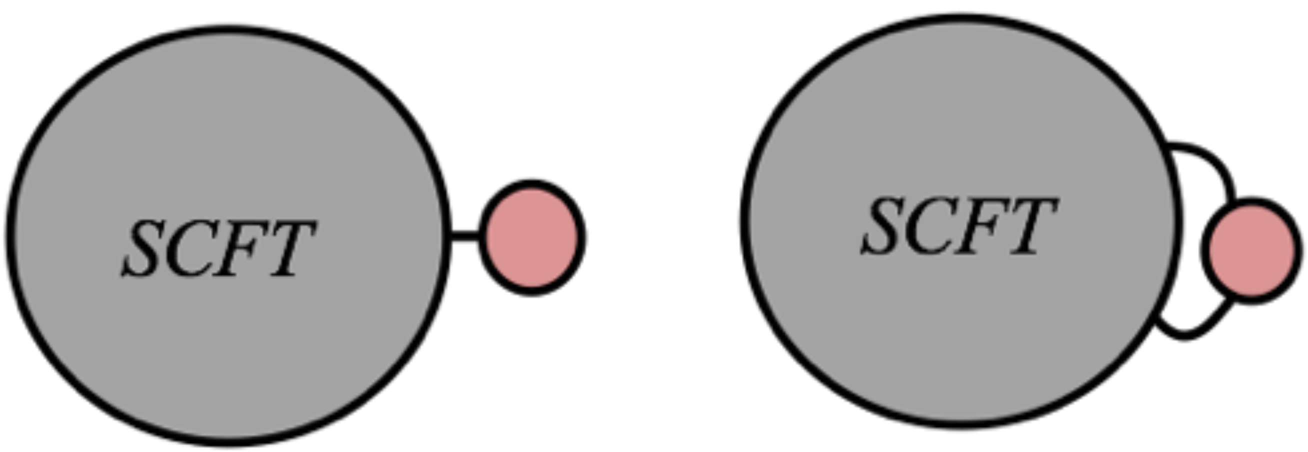
LSTs are UV complete, non-local 6D theories with gravity decoupled and an intrinsic string scale

They are characterized by the presence of a non-dynamical tensor

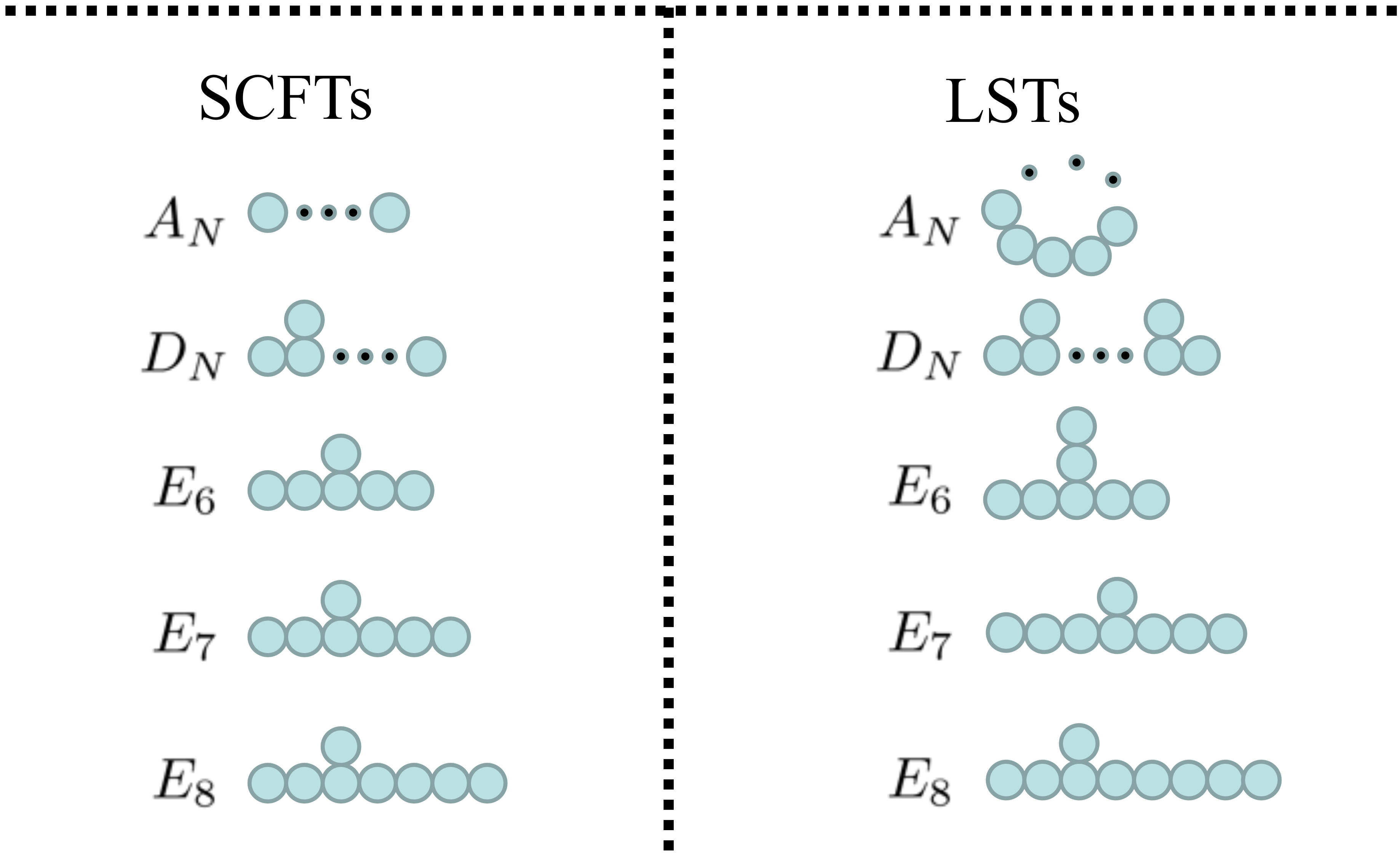
Classification of LSTs

Bhardwaj et al. '15

LSTs are simply "affinizations" of 6D SCFTs in which a single node is added to the quiver!

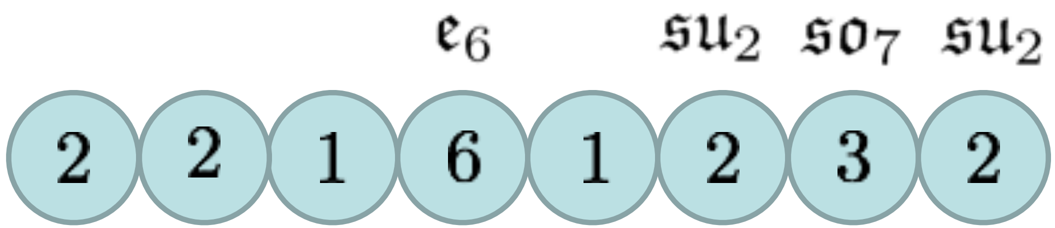


Example: (2,0) LSTs

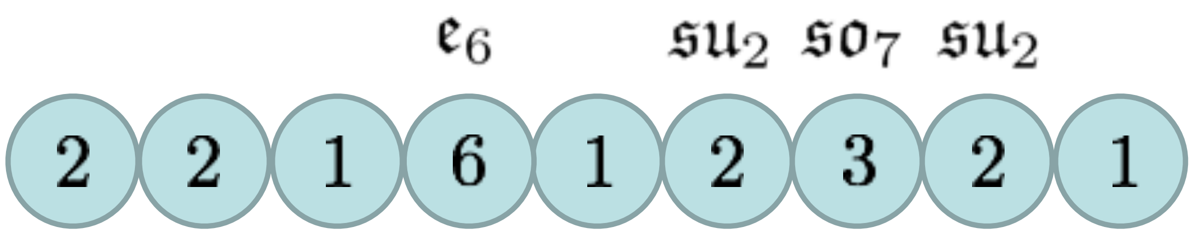


A (1,0) Example

SCFT



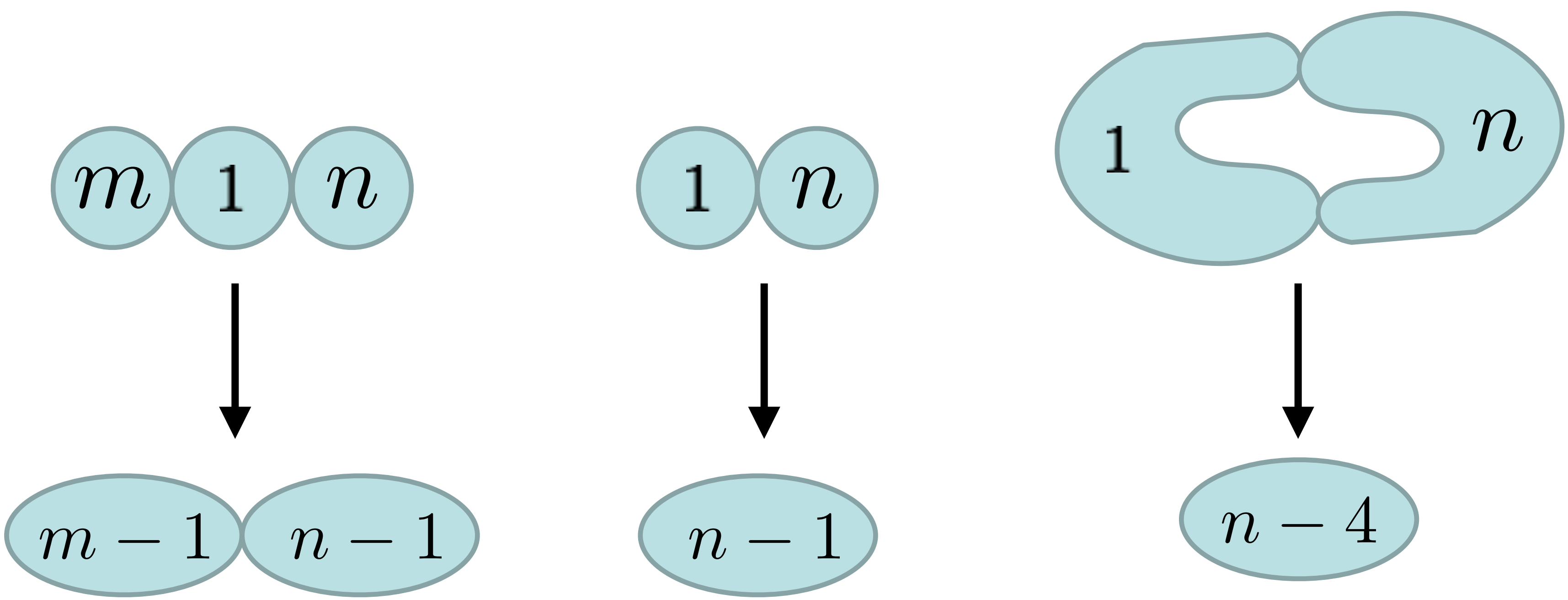
LST



Classification of 6D SUGRAs

Aspinwall, Morrison '97
Kumar, Morrison, Taylor '09, '10
Morrison, Taylor '12
Grimm, Taylor '12
Martini, Taylor '14
Johnson, Taylor '14
Taylor, Wang '15

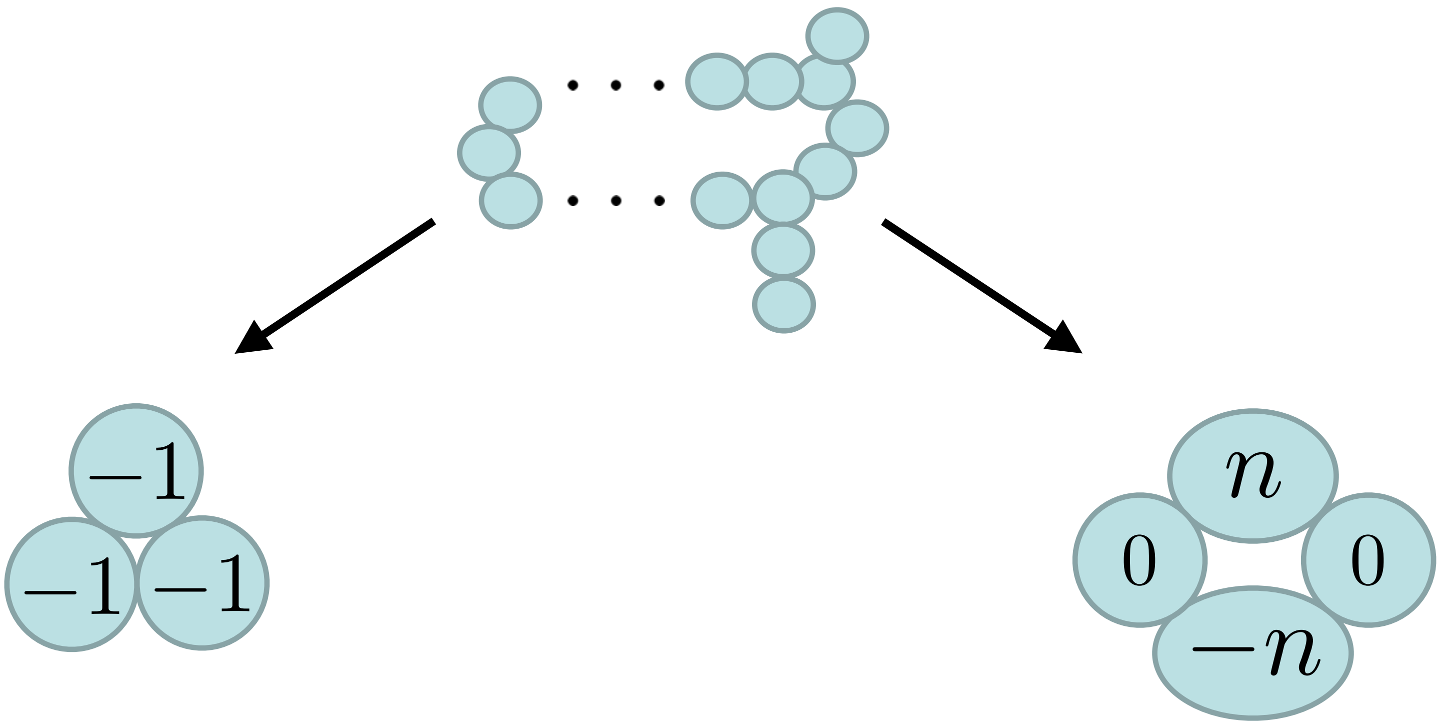
Blow-down operations:



Classification of 6D SUGRAs

All 6D SUGRAs blow down to $\mathbb{P}^2$ or $\mathbb{F}_n$!*

Grassi '91



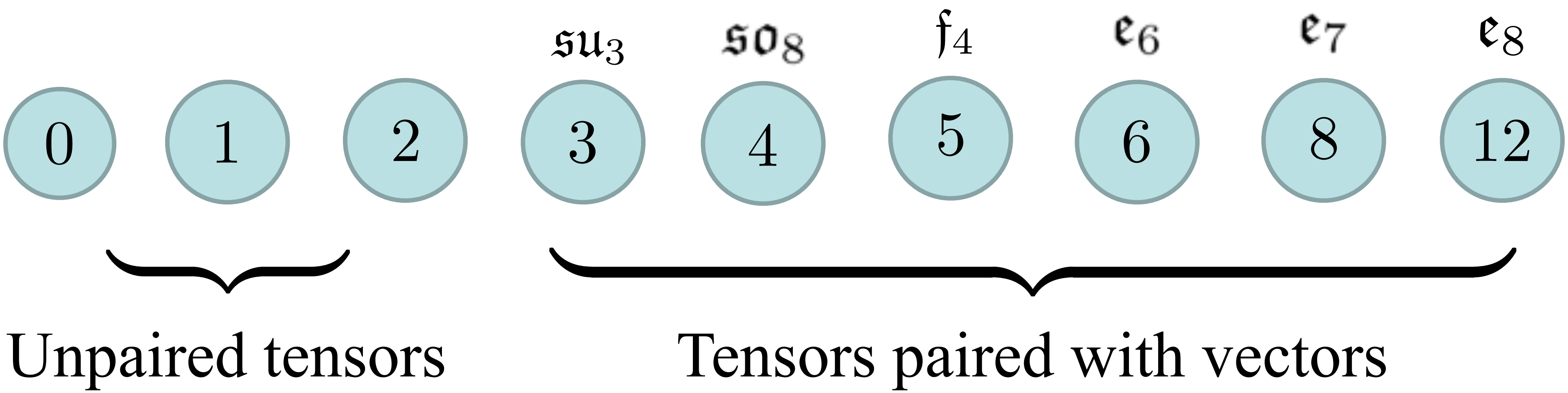
$\mathbb{P}^2$

$\mathbb{F}_n$

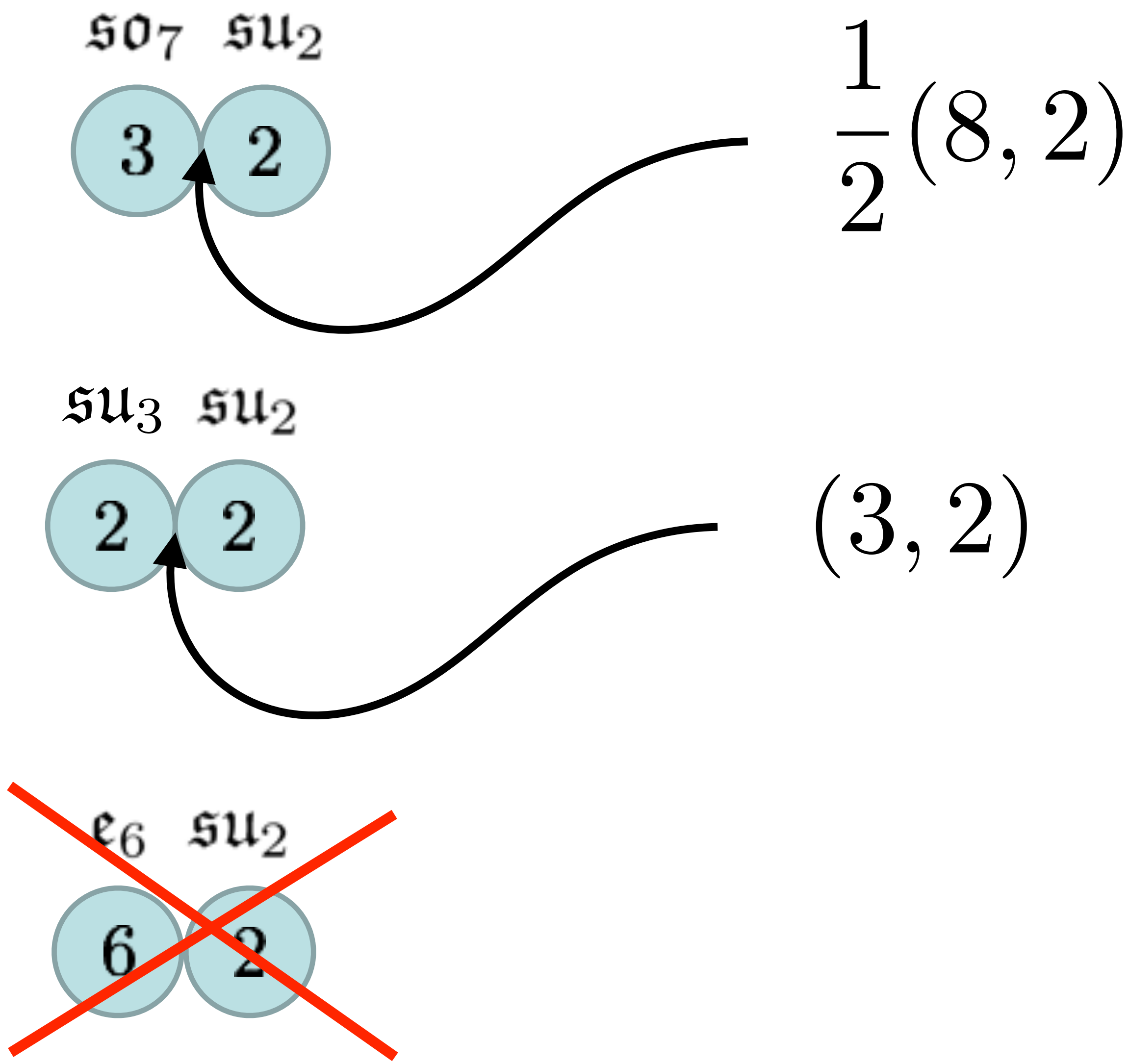
*except the Enriques surface

Unpaired Tensors in 6D

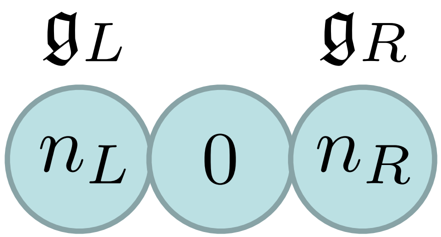
Minimal Gauge Algebras



Mixed Anomalies and Adjacencies

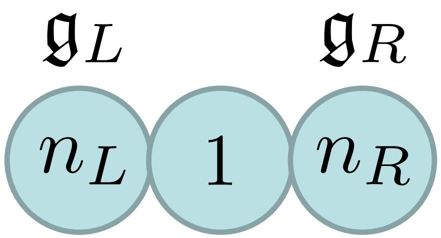


Unpaired Tensors and Adjacencies

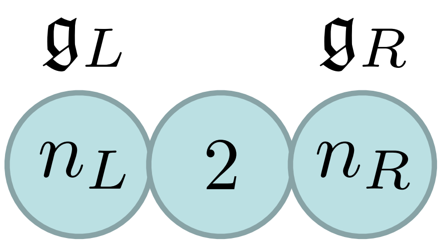


$\Rightarrow \mathrm{rk}\ \mathfrak{g}_L + \mathrm{rk}\ \mathfrak{g}_R \leq 16$

Johnson, Taylor '16

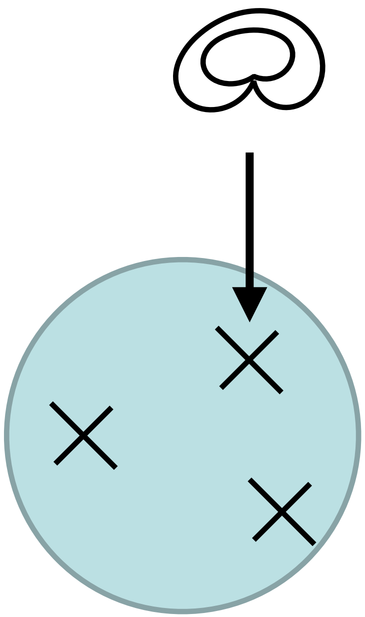


$\Rightarrow \mathfrak{g}_L \oplus \mathfrak{g}_R \subset \mathfrak{e}_8$



$\Rightarrow \mathfrak{g}_L \oplus \mathfrak{g}_R \subset \mathfrak{su}_2$

Unpaired Tensors and Adjacencies



$$\Sigma = \{z = 0\}$$

$$\mathrm{Ord}(f, g, \Delta) = (a, b, d)$$

$$\tilde{f} := \frac{f}{z^a} \in \mathcal{O}(-4K_B - a\Sigma)$$

$$\tilde{g} := \frac{g}{z^b} \in \mathcal{O}(-6K_B - b\Sigma)$$

$$\tilde{\Delta} := \frac{\Delta}{z^d} \in \mathcal{O}(-12K_B - d\Sigma)$$

c.f. Bertolini, Merkx, Morrison '15

Unpaired Tensors and Adjacencies

Define residual vanishings

$$\tilde{a} = (-4K_B - a\Sigma) \cdot \Sigma = -4(m-2) + ma$$

$$\tilde{b} = (-6K_B - b\Sigma) \cdot \Sigma = -6(m-2) + mb$$

$$\tilde{d} = (-12K_B - d\Sigma) \cdot \Sigma = -12(m-2) + md$$

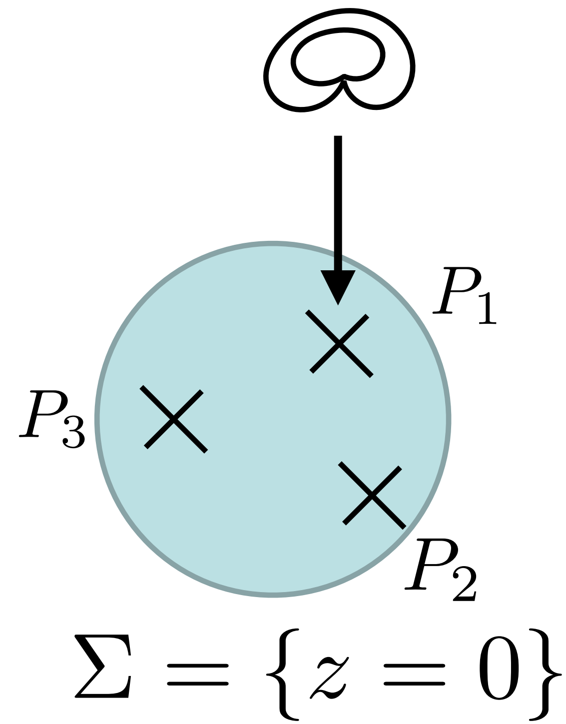
$$(\Sigma^2 = -m)$$

Unpaired Tensors and Adjacencies

Define $\tilde{a}_{P_k} = \mathrm{ord}_{P_k} \tilde{f}$

$\tilde{b}_{P_k} = \mathrm{ord}_{P_k} \tilde{g}$

$\tilde{d}_{P_k} = \mathrm{ord}_{P_k} \tilde{\Delta}$



$$\tilde{a} \geq \sum_k \tilde{a}_{P_k} \,, \qquad \tilde{b} \geq \sum_k \tilde{b}_{P_k} \,, \qquad \tilde{d} \geq \sum_k \tilde{d}_{P_k}$$

Maximal Intersections for -1 Curves

Kodaira Types	Symmetry Algebras
II^*	$\mathfrak{e}_8$
$III^* \oplus III$	$\mathfrak{e}_7 \oplus \mathfrak{su}(2)$
$IV^* \oplus IV$	$\mathfrak{e}_6 \oplus \mathfrak{su}(3)$
I_9	$\mathfrak{su}(9)$
I_4^*	$\mathfrak{so}(16)$
$I_0^* \oplus I_0^*$	$\mathfrak{so}(8) \oplus \mathfrak{so}(8)$
$I_2^* \oplus I_2$	$\mathfrak{so}(12) \oplus \mathfrak{su}(2)$
$I_1^* \oplus I_4$	$\mathfrak{so}(10) \oplus \mathfrak{su}(4)$

Type I_0

Persson '90
Miranda '90

Kodaira Types	Symmetry Algebras
$IV^{*,ns} \oplus I_3$	$\mathfrak{f}_4 \oplus \mathfrak{su}_3$
I_4^*	$\mathfrak{so}(16)$
$I_0^{*,ns} \oplus I_1^{*,ns}$	$\mathfrak{so}(7) \oplus \mathfrak{so}(9)$
I_7	$\mathfrak{su}(7)$
$I_N^{*,ns} \oplus I_M,\, M+N \leq 4$	$\mathfrak{so}(2N+7) \oplus \mathfrak{su}(M)$

Type I_1

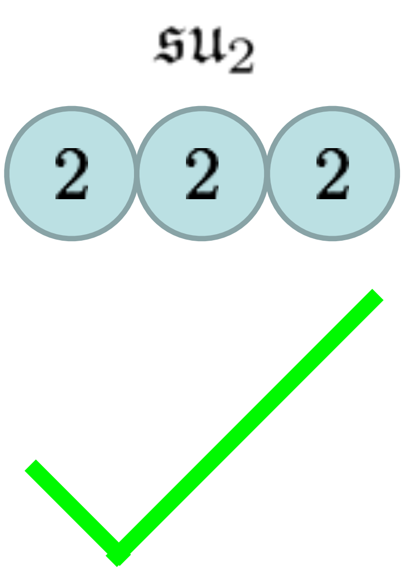
Kodaira Types	Symmetry Algebras
$IV^{*,ns} \oplus I_0^{*,ns}$	$\mathfrak{f}_4 \oplus \mathfrak{g}_2$
$I_1^{*,ns} \oplus I_0^{*,ns}$	$\mathfrak{so}(9) \oplus \mathfrak{g}_2$
$I_0^{*,ns} \oplus I_6^{ns}$	$\mathfrak{g}_2 \oplus \mathfrak{sp}(3)$
$I_6^{ns} \oplus I_3^{s}$	$\mathfrak{sp}(3) \oplus \mathfrak{su}(3)$
$\leq I_9^{ns} \oplus I_0^{*,ns}$	$\leq \mathfrak{sp}(4) \oplus \mathfrak{g}_2$

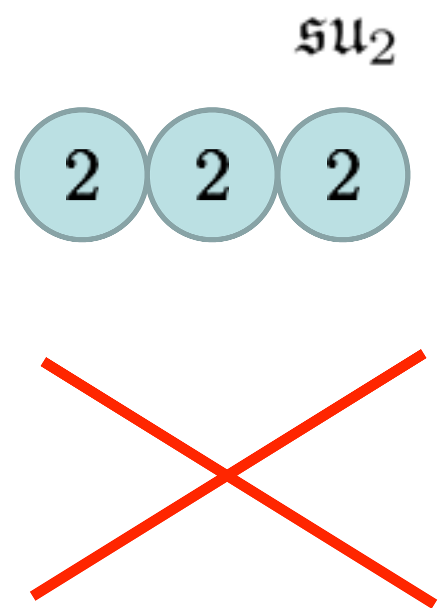
Type II

Maximal Intersections for -2 Curves

Type I_0: $\emptyset$ Type I_1: $\mathfrak{su}_2$ Type II: $\mathfrak{su}_2$

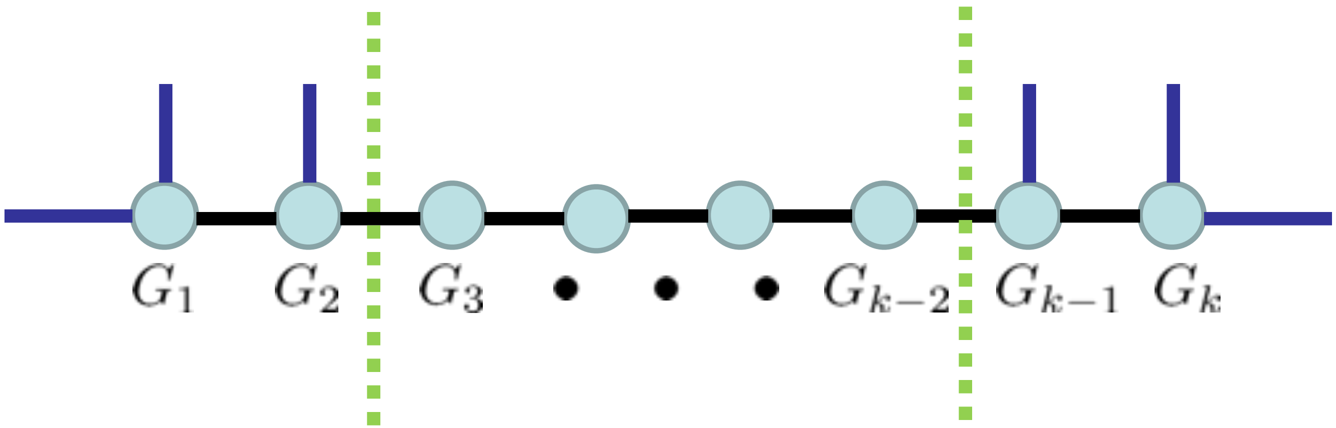
But…





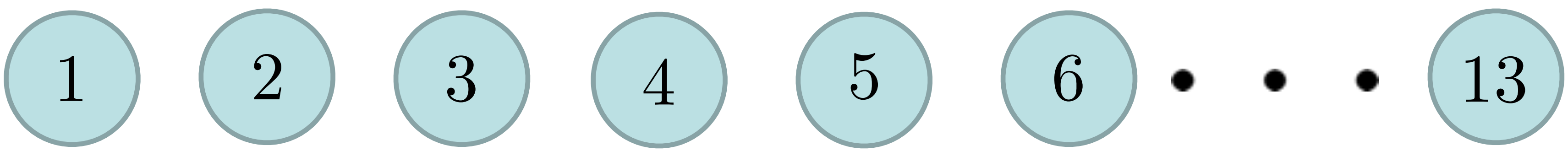
Open Questions

Do all 6D SCFTs admit a tensor branch description?



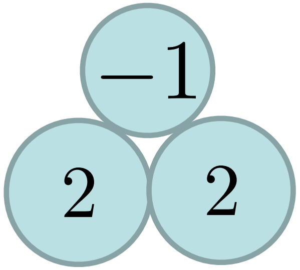
c.f. Antonella Grassi's talk, perhaps?

What about $\Sigma^2 \leq -3$ unpaired tensors?

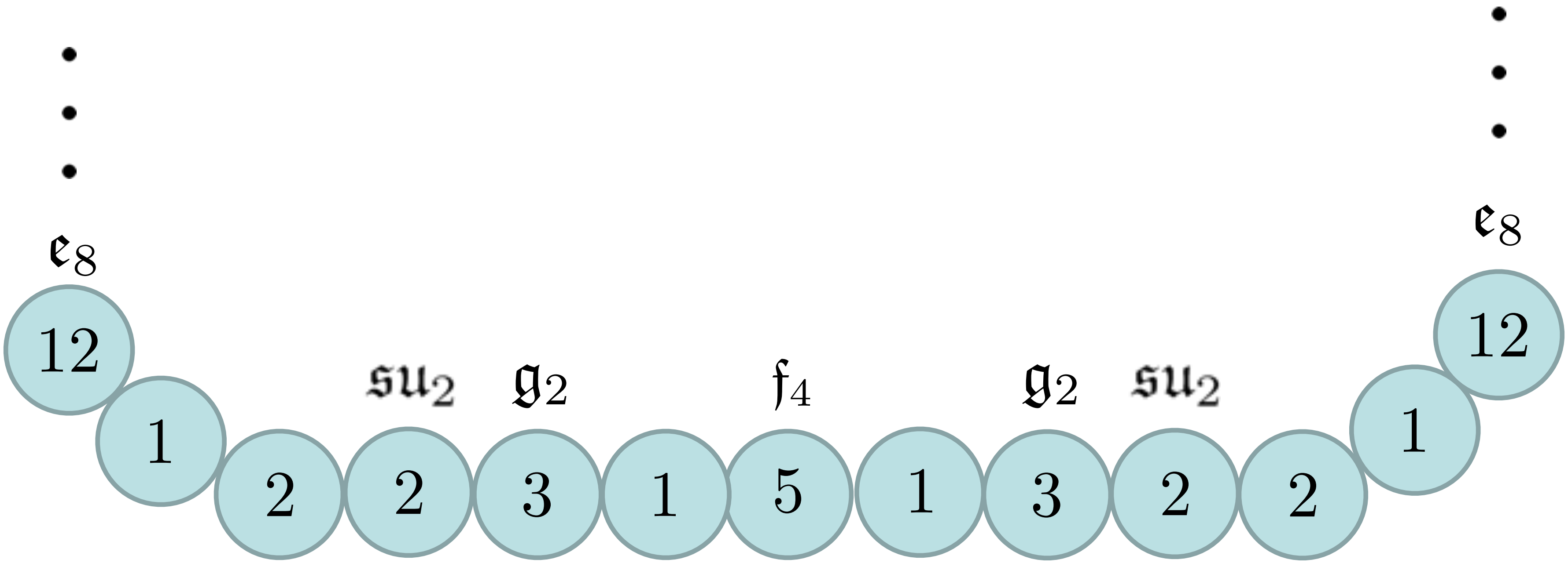


c.f. Timo Weigand's talk

What about lattices that don't admit a geometric realization?



Can we bound $h^{1,1} \leq 491$, $T \leq 193$?



Aspinwall Morrison '97

Can we prove positivity of SUGRA couplings?

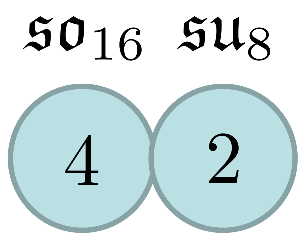
Kumar, Morrison, Taylor '10

$$\mathcal{L} \supset \frac{1}{2} a \ \mathrm{tr}\ R \wedge *R + \frac{2}{\lambda_A}(b_A) \ \mathrm{tr}\ F^A \wedge *F^A$$

$$a > 0$$ Cheung, Remmen '16

$$12a + \sum_A \nu_A b_A > 0$$

What about $4-2$ intersections?



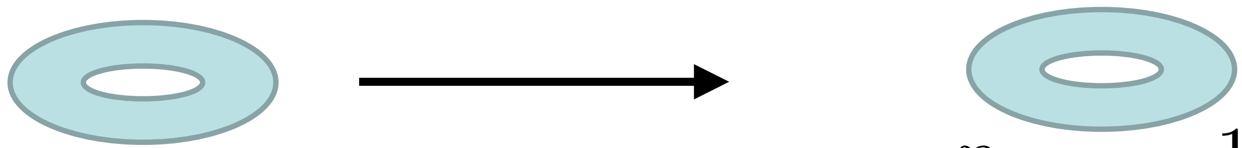
c.f. Hanany, Zaffaroni ’97, Tachikawa ’15
+ work in progress by Bhardwaj, Morrison, Tachikawa, Tomasiello

What about “exotic” matter?

c.f. Wati Taylor’s talk

LSTs/SUGRAs

$\mathfrak{su}_N$ $\quad\quad$ $\mathfrak{su}_N$



$n_{\mathrm{adj}} = 1$

$n_{sym} = 1$
$n_{\Lambda^2} = 1$

SCFTs/LSTs

$\mathfrak{su}_N$ $\quad\quad$ $\mathfrak{su}_N$

$n_F = N + 8$
$n_{\Lambda^2} = 1$

$n_F = N - 8$
$n_{sym} = 1$

Conclusions

- There seems to be an F-theory swampland in 6D
- But, it seems to be be small
- Future top-down work or bottom-up work could eradicate it entirely
- We have made some progress, via understanding unpaired tensors in F-theory
- (Finite) work still to be done!