Evidence for a String Emergence Conjecture

- to appear with Seung-Joo Lee and Wolfgang Lerche
- 1808.05958, 1810.05169, 1901.08065
  w/ Seung-Joo Lee and Wolfgang Lerche

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Introduction

Swampland Distance Conjecture: [Ooguri,Vafa'06]

At infinite distance in the moduli space of a gravitational theory, an infinite tower of states becomes asymptotically massless w.r.t. $M_{\rm Pl}$.

- Goes far beyond low-energy effective theory expectations.
- Contains information about content of theory at fundamental scale.
- Related to various other QG conjectures such as
  $\rightsquigarrow$ Weak Gravity Conjecture
  $\rightsquigarrow$ dS/AdS conjecture [Palti,Shiu,Ooguri,Vafa'18]/[Lüst,Palti,Vafa'19]

Explicit confirmation in string compactifications:

[Kläwer,Palti'16] [Heidenreich,Reece,Rudelius'16,'18'19] [Montero,Shiu,Soler'16] [Palti'17]

[Grimm,Palti,Valenzuela'18] [Lee,Lerche,TW'18/19] [Hebecker et al. 16,'19]

[Andriolo,Junghans,Noumi,Shiu'18] [Blumenhagen,Kläwer,Schlechter,Wolf'18], [Lüst,Palti'18],

[Grimm,Li,Palti'18] [Corvilain,Grimm,Valenzuela'18] [Marchesano,Wiesner'19]

[Font,Herraez,Ibanez'19] [Erkinger,Knapp'19] [Joshi,Klemm'19][Grimm,V.d.Heisteeg'19] . . .

Introduction

What is the nature of the light states?

Which type of physics is encountered at boundary of moduli space?
Do they signal exotic new physics as in QFT at finite distances?

Example:

Compactification of higher-dim. gravity theory to d dimensions

- In many infinite distance limits find tower of KK states.
  in particular: [Blumenhagen,Kläwer,Schlechter,Wolf'18] [Font,Herraez,Ibanez'19]
- KK scaling behaviour:

$$M_n^2 \sim n^2 M_0^2 \qquad \text{for large} \quad n$$

- Mimicked also by particles form wrapped branes - see later
  particle towers in Type IIB: [Grimm,Palti,Valenzuela'18] [Grimm,Li,Palti'18] [Joshi,Klemm'19]
  Type IIA: [Corvilain,Grimm,Valenzuela'18] [Font,Herraez,Ibanez'19]

$\Longrightarrow$ effective decompactification unless exists competing tower

Introduction

For **equi-dimensional limits**, need 'denser' tower at same scale:

$$\exists ? \; M_n^2 \sim n^\alpha M_0^2 \,, \qquad \alpha < 2$$

Example: **String tower** $\alpha = 1$

- Emergent weakly coupled heterotic string in F-theory in 6d [Lee,Lerche,TW'18] and 4d [Lee,Lerche,TW'19]
- Emergent weakly coupled Type II string in Type IIB on K3 [Lee,Lerche,TW'19]
- Importance of strings and domain walls from wrapped branes stressed in [Font,Herraez,Ibanez'19][Grimm,V.d.Heisteeg'19]

Suspicion:
Unlike in QFT at finite distance boundaries no strong coupling phenomena occur at infinite distance
emergent Type II or heterotic string as only candidate for denser spectrum?

Introduction

Conjecture [Lee,Lerche,TW - to appear]

String emergence at infinite distance

Any equi-dimensional infinite distance limit in the moduli space of a d-dimensional theory of quantum gravity reduces to a weakly coupled string theory. In particular, there appears an infinite tower of asymptotically massless states which form the particle excitations of a weakly coupled, asymptotically tensionless Type II or heterotic string in d dimensions.

If no weakly coupled string emerges at infinite distance, then

- KK tower is dominant and signals (partial) decompactification: Gravity does not remain dynamical in d dimensions, or
- quantum obstructions forbid taking the limit
  as e.g. in [Gonzalez,Ibanez,Uranga'18] [Marchesano,Wiesner'18]

Summary of results

[Lee,Lerche,TW - to appear]

Provide evidence in Kähler moduli space of CY 3-folds Y probed by

M-theory on CY3	$\longleftrightarrow$	Type IIA on CY3
classical moduli space		quantum moduli space

Necessary condition for equi-dimensional limits:
finite volume (otherwise KK tower obviously wins)

1) Geometric analysis:
Classification of finite volume infinite distance limits in classical Kähler moduli space of CY3

1. CY3 is T^2**-fibration**
2. CY3 is **K3-fibration**
3. CY3 is T^4**-fibration**

In presence of several fibrations, a **unique fiber** vanishes at **fastest** rate

Summary of results

[Lee,Lerche,TW - to appear]

2) M-theory at infinite distance (finite volume)

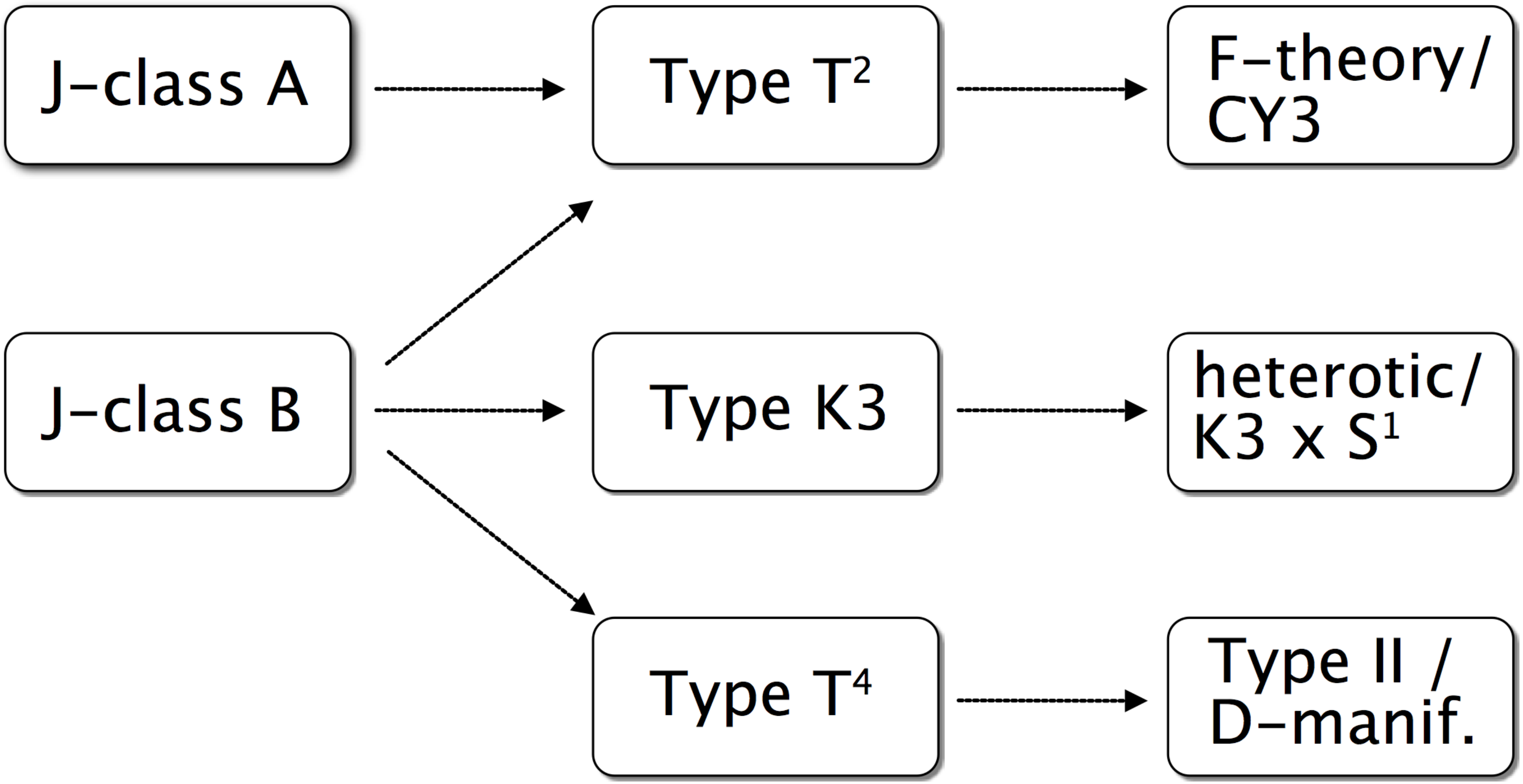
Limit of Type T^2	F-theory limit (decompactification to 6d)
Limit of Type K3	Emergence of heterotic string in 5d
Limit of Type T^4	Emergence of Type II string in 5d

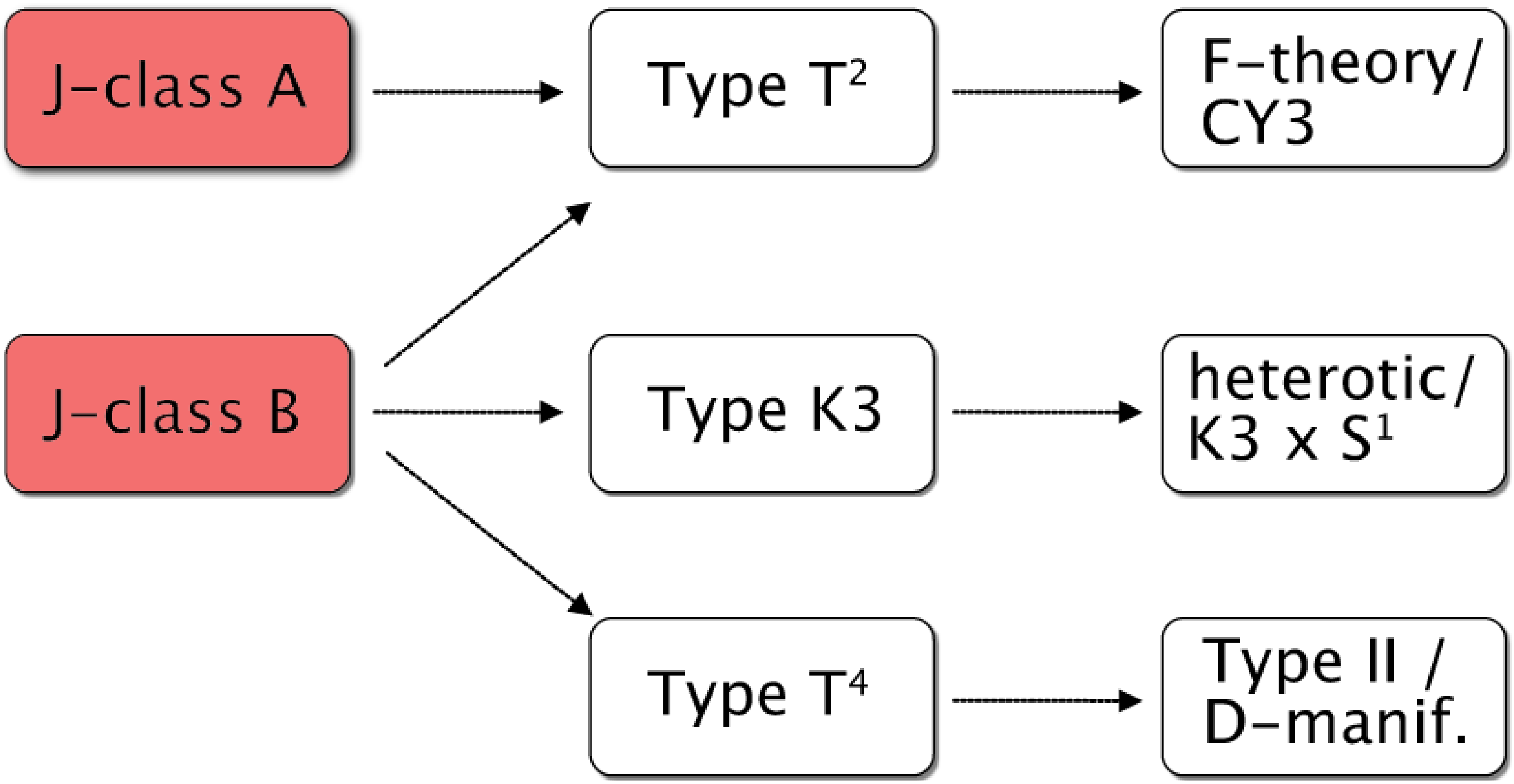
3) Type IIA at infinite distance

Quantum geometry obstructs all finite volume limits

$\Longrightarrow$ No equi-dimensional limits possible in Type IIA on Kähler moduli space

Summary of results




J-class A
J-class B
Type T2
Type K3
Type T4
F-theory/
CY3
heterotic/
K3 x S1
Type II /
D-manif.

Classial finite volume limits

CY 3-fold Y classical Kähler form $J' = \sum_{i\in\mathcal{I}} T'^i J_i$, $T'^i \geq 0$

$$\mathcal{V}'_Y = \frac{1}{3!}\int_Y J'^3$$

Infinite distance limit:

- (some) $T'^i \to \infty$ $\Rightarrow \mathcal{V}'_Y \sim \mu \to \infty$
- rescale $J = \mu^{-1/3} J' =: \sum T^i J_i$ $\Rightarrow \mathcal{V}_Y = \mu^{-1}\mathcal{V}'_Y$ $\mathcal{V}_Y$ finite

If all T^i finite $\Longrightarrow$ no further inf. distance limit

If some $T^i \to \infty$ others to zero $\Longrightarrow$ residual finite volume infinite distance limit

Classical finite volume limits

$$J = \sum_i T^i J_i \,, \qquad \mathcal{V}_Y = \frac{1}{3!} \int_Y J^3$$

Classify finite volume limits via refinement of analysis in

[Lee,Lerche,TW'18/'19]

$$T^i \sim \lambda \to \infty \qquad \forall i \in \mathcal{I}_\lambda \,, \qquad T^j \prec \lambda \qquad \forall j \in \mathcal{I} \setminus \mathcal{I}_\lambda$$

Finite volume requires: $J_i^3 = 0 \qquad \forall\, i \in \mathcal{I}_\lambda$ [Lee,Lerche,TW - to appear]

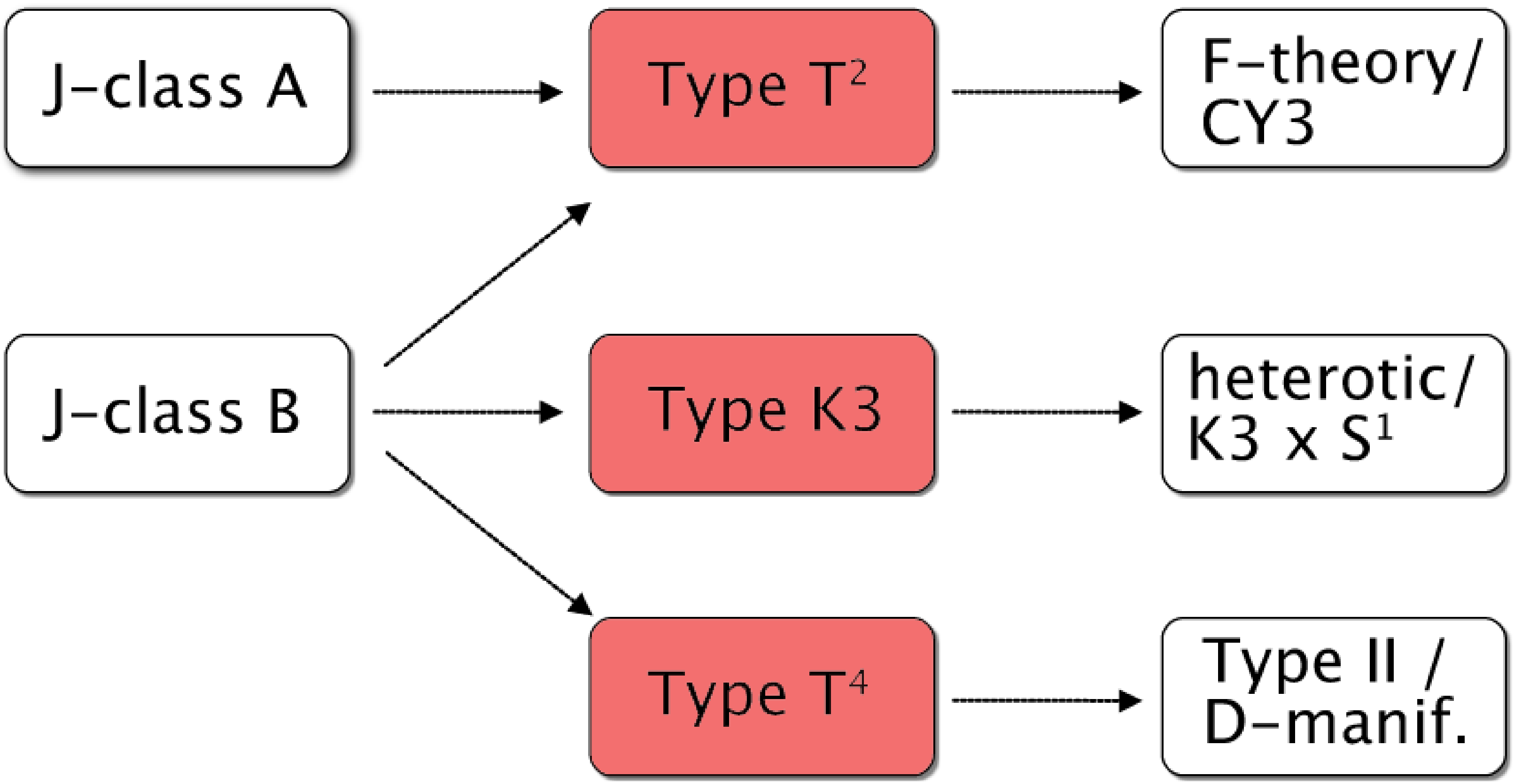
***J*-class A**: $J_i^2 \neq 0$ for some $i \in \mathcal{I}_\lambda$ ***J*-class B**: $J_i^2 = 0 \; \forall\, i \in \mathcal{I}_\lambda$

independent classification: [Corvilain,Grimm,Valenzuela'18]

via mirror symmetry to [Grimm,Palti,Valenzuela'18]

Key to understand the physics: [Lee,Lerche,TW - to appear]

By Ooguiso's theorem each such limit implies a **fibration structure**


J-class A
Type T^2
F-theory/
CY3
J-class B
Type K3
heterotic/
K3 x S^1
Type T^4
Type II /
D-manif.

Classical finite volume limits

1. **Type T^2** [Lee,Lerche,TW - to appear]

   Y is a genus-one fibration over a base B_2

   $$\mathcal{V}_{T^2} \sim \lambda^{-2}\,, \qquad \mathcal{V}_{B_2} \sim \lambda^{2}\,, \qquad \lambda \to \infty$$

   If Y admits in addition a compatible K3- or T^4-fibration over $\mathbb{P}^1_b$

   $$\mathcal{V}_{T^2} \sim \lambda^{-2}\,, \qquad \lambda^{-4} \prec \mathcal{V}_{K3/T^4} \qquad \lambda^{4} \succ \mathcal{V}_{\mathbb{P}^1_b}$$

2. **Type $K3$**

   Y is a K3-fibration over a base $\mathbb{P}^1_b$

   $$\mathcal{V}_{K3} \sim \lambda^{-1}\,, \qquad \mathcal{V}_{\mathbb{P}^1_b} \sim \lambda\,,$$

   $$\mathcal{V}_{C} \sim \lambda^{-1/2} \qquad \text{for every curve in K3 with } C \cdot_{K3} C \geq 0$$

3. **Type T^4**

   Y is a T^4-fibration over a base $\mathbb{P}^1_b$ and replace K3 by T^4

Classical finite volume limits

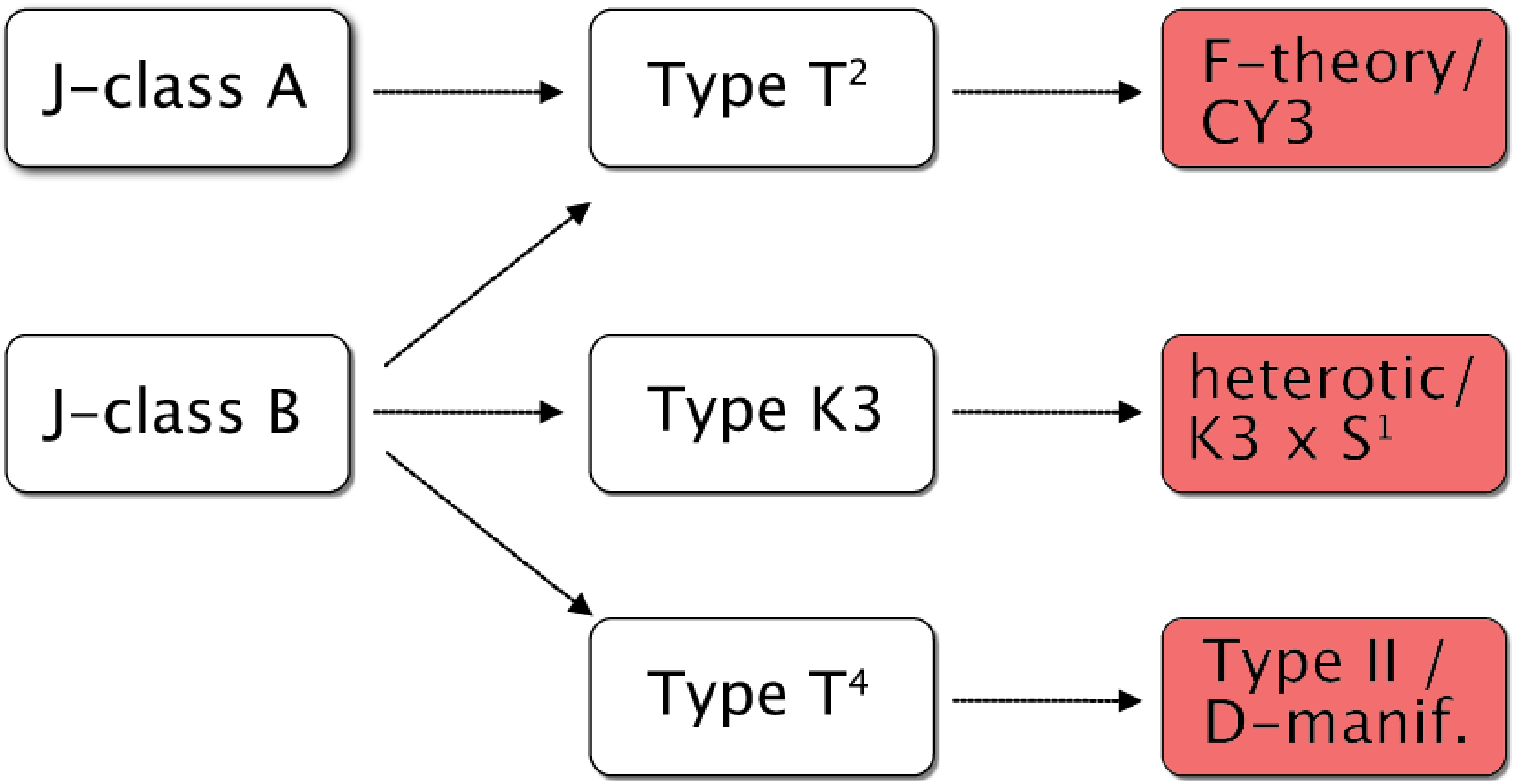
Every classical finite volume limit uniquely falls into one of these classes

- There always exists a **unique fiber** whose volume scales to zero at the **fastest rate**
- no ambiguity in identification of fastest shrinking curve possible

In context of M-theory on Y:

Each limit is a **weak coupling limit for some U(1) gauge field** at Planck scale

$$\frac{M_{\mathrm{Pl}}^3}{M_{11}^3} = 4\pi\mathcal{V}_Y$$


J-class A
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Limit of Type T^2

$$\mathcal{V}_{T^2} \sim \lambda^{-2}\,, \qquad \mathcal{V}_{B_2} \sim \lambda^{2}\,, \qquad \lambda \to \infty$$

M-theory on $Y \Longrightarrow$ **6d F-theory limit** (**partial decompactification**)

Infinite tower of M2-branes along T^2 as effective KK tower from 5d to 6d

cf [Corvilain,Grimm,Valenzuela'18][Lee,Lerche,TW 04/19]

$$\frac{M_n^2}{M_{11}^2} \sim \mathcal{V}_{n\,T^2}^2 \sim \frac{n^2}{\lambda^4}\,, \qquad \lambda \to \infty$$

1. The tower of BPS states are charged under an asymptotically weakly coupled abelian U(1) gauge symmetry = KK U(1).
2. The multiplicities of the states at every level n are equal: BPS invariants $N_{nT^2} = \chi(Y)$
3. The BPS tower from M2-branes on T^2 is *parametrically leading* as $\lambda \to \infty$ compared to any other tower of light BPS states *coupling only to a weakly coupled gauge sector.*

Limit of Type K3

$$\mathcal{V}_{K3} \sim \lambda^{-1}\,, \qquad \mathcal{V}_{\mathbb{P}^1_b} \sim \lambda\,,$$

true equi-dimensional limit with **emergent light heterotic string**

Three towers of massless states: [Lee,Lerche,TW - to appear]

1. M5 on K3 $\leftrightarrow$ emergent heterotic string excitations

$$\frac{M_n^2}{M_{\rm Pl}^2} \sim n\,\frac{T_{\rm het}}{M_{\rm Pl}^2} \sim n\,\mathcal{V}_{\rm K3}\,\frac{M_{11}^2}{M_{\rm Pl}^2} \sim \frac{n}{\lambda}\,\mathcal{V}_{\rm Y}^{1/3}$$

2. M2-branes nC_0 with $C_0 \subset K3$ and $C_0 \cdot_{K3} C_0 \geq 0$

$$\frac{M_n^2}{M_{\rm Pl}^2} \sim n^2 \mathcal{V}_{C_0}^2\,\frac{M_{11}^2}{M_{\rm Pl}^2} \sim \frac{n^2}{\lambda}\,\mathcal{V}_{\rm Y}^{2/3}$$

3. Kaluza-Klein states on $\mathbb{P}^1_b$

$$\frac{M_{\rm KK}^2}{M_{\rm Pl}^2} \sim \frac{1}{\lambda}\,\frac{1}{\mathcal{V}_{\rm Y}^{4/3}}$$

Limits of Type K3

[Lee,Lerche,TW - to appear]

As $\mathcal{V}_{K3} \to 0$ string becomes fundamental string of dual heterotic frame

M-theory on Y		**Heterotic on $\widehat{K}3 \times S^1_A$**
M5 on K3-fiber	$\longleftrightarrow$	fundamental het. string
M2 on $C_0 \subset K3$		winding and KK modes of
$C_0 \cdot_{\mathrm{K3}} C_0 \geq 0$		het string on S^1_A

BPS index for M2-brane on $C \subset K3$: [Harvey,Moore'99], ...

$$N_C = c(\frac{C^2}{2}) \qquad f(q) = \sum_{n=-1}^{\infty} c(n) q^n \quad \text{modular form}$$

Infinite tower on $nC \leftrightarrow C \cdot C \geq 0 =$ non-contractible curves inside K3

✓ Explains why there is an infinite tower of M2-brane wrappings

✓ Links their nature to light heterotic string

Limits of Type T^4

$$\mathcal{V}_{T^4} \sim \lambda^{-1}\,, \qquad \mathcal{V}_{\mathbb{P}^1_b} \sim \lambda\,,$$

true equi-dimensional limit with emergent light Type II string

Three towers of massless states:

1. M5 on $T^4 \leftrightarrow$ emergent Type II string
2. M2-branes nC_0 with $C_0 \subset K3$ and $C_0 \cdot_{K3} C_0 \geq 0$
3. Kaluza-Klein states on $\mathbb{P}^1_b$

Emergent Type II string probes (non-geometric) D-manifold

M-theory on Abelian surface fibration Y	$\longleftrightarrow$	Type IIB theory $Z \times S^1_A$

Limits of Type T^4

Special case:
fiber $T^4 = T^2 \times T^2$
$=$ Schoen manifold

$$\begin{array}{rccc} \pi : & \mathcal{S} \simeq \mathcal{E}_1 \times \mathcal{E}_2 & \rightarrow & Y \\ & & & \downarrow \\ & & & \mathbb{P}^1_b \end{array}$$

$$\mathcal{V}_{\mathcal{E}_1} \sim \lambda^{-1/2}\,, \qquad \mathcal{V}_{\mathcal{E}_2} \sim \lambda^{-1/2}\,, \qquad \mathcal{V}_{\mathbb{P}^1_b} \sim \lambda \qquad \lambda \rightarrow \infty$$

Step 1:

$$\mathcal{V}_{\mathcal{E}_1} \sim \lambda^{-\frac{1}{2}-x}\,, \quad \mathcal{V}_{\mathcal{E}_2} \sim \lambda^{-\frac{1}{2}+x} \quad \Longrightarrow \quad \textbf{F-theory on } \mathcal{B}_1 \ (\mathbf{dP}_9)$$

in 6d frame:

$$\mathcal{V}'_{\mathcal{E}_2} \sim \mu^{-1}\,, \qquad \mathcal{V}'_{\mathbb{P}^1_b} \sim \mu \qquad \mu = \lambda^{3/4 - x/2}$$

$$\begin{array}{rccc} \pi_1 : & \mathcal{E}_1 & \rightarrow & Y \\ & & & \downarrow \\ \rho_1 : & \mathcal{E}_2 & \rightarrow & \mathcal{B}_1 \\ & & & \downarrow \\ & & & \mathbb{P}^1_b \end{array}$$

- 7-branes on 12 copies of $\mathcal{E}_2$
- D3 on shrinking $\mathcal{E}_2$:
  light Type IIB string

Limits of Type T^4

T-duality along $\mathcal{E}_2$

$\hat{\mathcal{V}}'_{\mathcal{E}_2} = \mu \to \infty \qquad \mathcal{V}'_{\mathbb{P}^1_b} = \mu \to \infty$

$g_{\text{IIB}} = \mu\, g^{(0)}_{\text{IIB}}$

$$\rho_1 : \; \mathcal{E}_2 \;\to\; \mathcal{B}_1$$
$$\downarrow$$
$$\mathbb{P}^1_b$$

F-theory on Y		Type IIB on D-manifold Z
D3 on $\mathcal{E}_2$	$\longleftrightarrow$	unwrapped D1 string $\frac{T}{M_s^2} \sim g_{\text{IIB}}^{-1} \sim \mu^{-1}$
(p,q) 7-brane on $\rho_1^{-1}(Q_a)$		(p,q) 5-branes on $\sum_{a=1}^{12} Q_a$

Step 2: $\quad \mathcal{V}_{\mathcal{E}_1} \sim \lambda^{-1/2}\,, \qquad \mathcal{V}_{\mathcal{E}_2} \sim \lambda^{-1/2}$

M-theory on Y		Type IIB string on $Z \times S^1_A$
BPS particle in M-theory		Type IIB string on S^1_A
M2-brane on $l\mathcal{E}_2 + k\mathcal{E}_1$	$\longleftrightarrow$	wrapping number l
$N_{n\mathcal{E}_2} = N_{n\mathcal{E}_1} = \chi(Y)$		KK momentum k

Type IIA - Quantum Geometry

As classical $\mathcal{V}_C \to 0$ quantum effects become important in Type IIA

- $\mathcal{V}_C = 0$ may not be in quantum moduli space
  problematic for K3 fiber, but not for T^2 or T^4 fiber
- Quantum volume $\mathcal{V}_Y = \int_Y J^3 +$ corrections
  problematic also for Type T^2/T^4 Limits

Well-known strategy: at large volume point L_1 can match

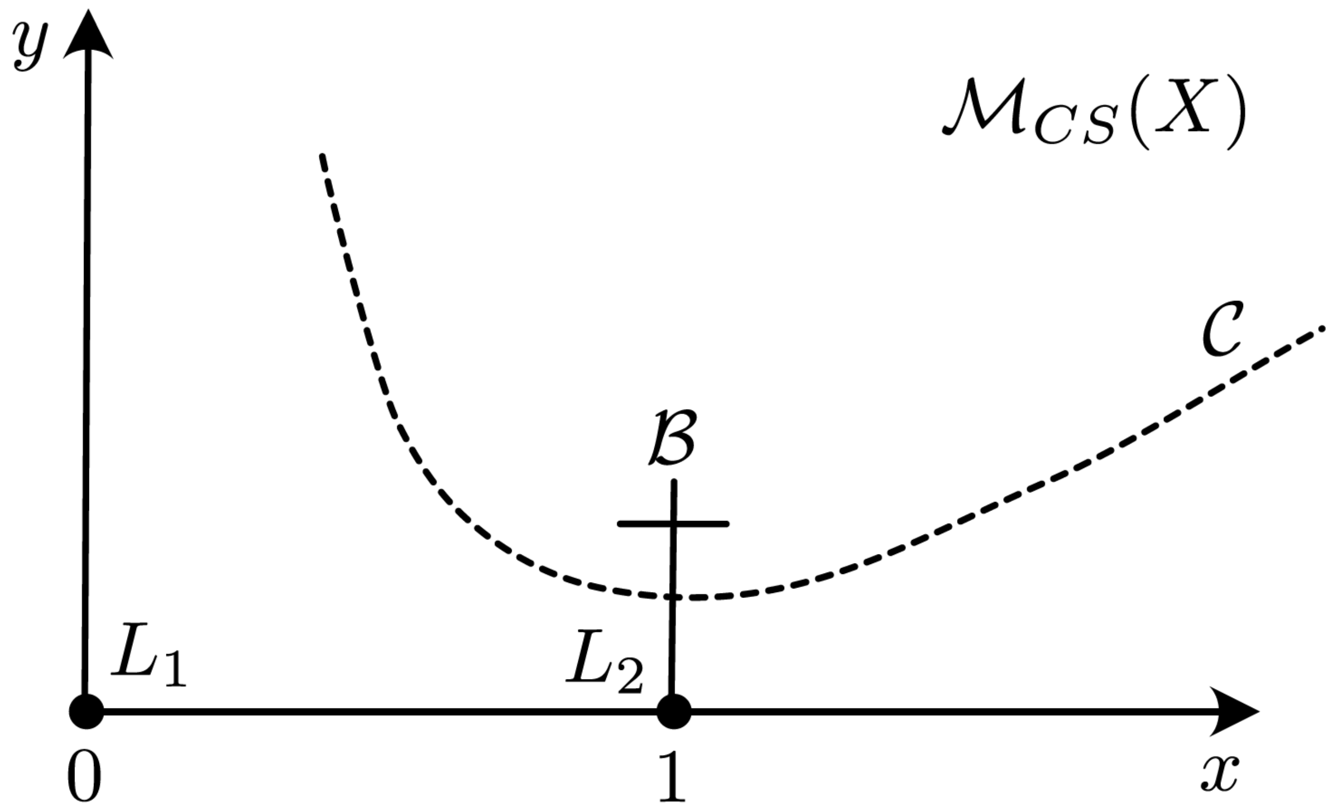
Kähler moduli Y		complex structure on X
2-cycles C_a	$\overset{\text{mirror}}{\underset{\text{map}}{\longleftrightarrow}}$	3-cycles γ_a
$t^a = \int_{C_a} B + iJ_Y$		$z^a = \frac{\int_{\gamma_a} \Omega_X}{X^0}$, $X^0 = \int_{\gamma_0} \Omega_X$
$\mathcal{V}_Y(t^a)$		$\frac{1}{8}\frac{i\int_X \Omega_X \wedge \bar{\Omega}_X}{\lvert X^0\rvert^2}(z)$

Analytically continue from LCS point L_1 to point L_2 in question

Type IIA - Quantum Geometry

L_1: mirror to
large volume regime

L_2: mirror to
(classically) vanishing fiber point



Type IIA - Limit T^2

$\mathcal{V}_{T^2} = 0$ is part of moduli space, but decompactification limit

Clear already by T-duality along T^2 see also [Corvilain,Grimm,Valenzuela'18]

$$\text{at } L_2: \qquad \mathcal{V}_{T^2} = \frac{1}{\lambda^2}\,, \qquad \mathcal{V}_{B_2} = \mathcal{V}'_{B_2}\lambda^2\,, \qquad g_{\rm IIA} = g^{(0)}_{\rm IIA}\,, \qquad \lambda \to \infty$$

T-duality along T^2 fiber:

$$\text{at } L_1: \qquad \mathcal{V}_{T^2} = \lambda^2\,, \qquad \mathcal{V}_{B_2} = \mathcal{V}'_{B_2}\lambda^2\,, \qquad g_{\rm IIA} = g^{(0)}_{\rm IIA}\lambda^2 \;\Rightarrow \mathcal{V}_Y \sim \lambda^6$$

$\Longrightarrow$ Pert. Type IIA at L_2 = Strongly coupled Type IIA at L_1 (M-theory!)

Reevaluate volumes in 5d M-theory frame $J_{\rm M} = \frac{J_Y}{{g_{\rm IIA}}^{2/3}}$

$$\mathcal{V}_{T^2,{\rm M}} = \lambda^{2/3}\,, \qquad \mathcal{V}_{B_2,{\rm M}} = \lambda^{-2/3}\,\mathcal{V}'_{B_2,{\rm M}}\,, \qquad \mathcal{V}_{Y,{\rm M}} = a\,\lambda^2 + S + c\,\mathcal{V}'_{B2,{\rm M}} + \ldots$$

Upshot: [Lee,Lerche,TW - to appear]

Type IIA at L_2 = M-theory in further decompactification limit

Similar for T^4 fiber limits but without further decompactification

Type IIA - Limit K3

Quantum volume of K3-fiber never vanishes in moduli space:

- (D4 - 1 D0) on K3 = M5 on $K3 \times S^1$ = heterotic string on S^1
- Vacuum energy $E_0 = -\frac{\chi(K3)}{24} = -1$ gives offset

$\Rightarrow$ Quantum obstruction to vanishing cycle volume

$\Rightarrow$ Decompactification limit with leading tower given by KK tower

Explicit computation: L_2: $\hat{z}_1 \to 0$, $\hat{z}_2 \to 0$

$$\text{KK scale}: \quad \frac{M}{M_{\rm Pl}} \sim \frac{g_{\rm IIA}}{-\ln(\hat{z}_2 \hat{z}_1^2)} \to 0 \qquad \frac{M}{\Lambda} \sim \hat{z}_2^{-\alpha} \to \infty$$

$$\text{heterotic scale}: \quad \frac{M}{M_{\rm Pl}} \sim \frac{1}{\sqrt{-\ln(\hat{z}_2 \hat{z}_1^2)}} \to 0 \qquad \frac{M}{\Lambda} \sim g_{\rm IIA}^{-1} \sqrt{-\ln(\hat{z}_2 \hat{z}_1^2)}\, \hat{z}_2^{-\alpha} \to \infty$$

Seiberg-Witten W boson:

$$-2\mathrm{D0} + \mathrm{D4} \ \text{ on K3}: \quad \frac{M}{M_{\rm Pl}} \sim \frac{\sqrt{\hat{z}_1}}{\sqrt{-\ln(\hat{z}_2 \hat{z}_1^2)}} \to 0 \qquad \frac{M}{\Lambda} \sim g_{\rm IIA}^{-1} \sqrt{-\ln(\hat{z}_2 \hat{z}_1^2)}\, \hat{z}_2^{-\alpha} \hat{z}_1^{1/2}$$

Conclusions

String Emergence Conjecture

At infinite distance a weakly coupled string becomes light
- or the theory decompactifies

✓ M-theory on CY 3-fold in classical Kähler moduli space:

Classification of finite volume limits

- vanishing T^2 fiber: decompactification to 6d F-theory
- vanishing K3/T^4 fibers: emergent heterotic/type II string in 5d

✓ Type IIA on CY3 in quantum Kähler moduli space:
Always decompactification

By mirror symmetry for Type IIB in complex structure:
towers from T^3 fibers indicate decompactification - mirror to T^2/T^4 fibers

Hypermultiplet moduli space:
∃ candidate for light fundamental string - but quantum corrections

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Mainz Institute for Theoretical Physics

Mathematical Foundations of the Swampland Program

17 August 2020 to 4 September 2020
Mainz Institute for Theoretical Physics, Johannes Gutenberg University
Europe/Berlin timezone

- Overview
- Scientific Program
- General Information
- Travel Information
- Timetable
- Application

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Recently, there has been great interest in determining criteria which differentiate between effective low-energy field theories which can be consistently completed in the ultraviolet into quantum gravity, said to be in the 'Landscape', from theories which appear consistent but nonetheless defy such a coupling to quantum gravity, the so-called 'Swampland'. A number of such criteria, or Swampland Conjectures, have been proposed in the literature and attracted considerable interest in the high energy physics community. If confirmed, they have far-reaching consequences for physics and cosmology, such as for the structure of large field inflation in early time cosmology or for the mechanism responsible for the observed late-time acceleration of the universe, to name but the most striking ones. On the other hand, the Swampland Conjectures translate, in the context of string theory, into conjectures regarding the structure of possible compactifications, or string geometries.

String theory is therefore in a unique position to quantitatively test - and possibly refine - such general Swampland Conjectures. This Scientific Program proposes to study these intriguing connections between general properties of quantum gravity and the geometry of string compactifications. It aims to bring together world experts working at the forefront of research in string theory, field theoretic aspects of quantum gravity, and geometry at this unique time in which our understanding of the Swampland is quickly evolving.