Geometry and Physics of Degenerating Calabi-Yau three- and fourfolds

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Universität Hamburg
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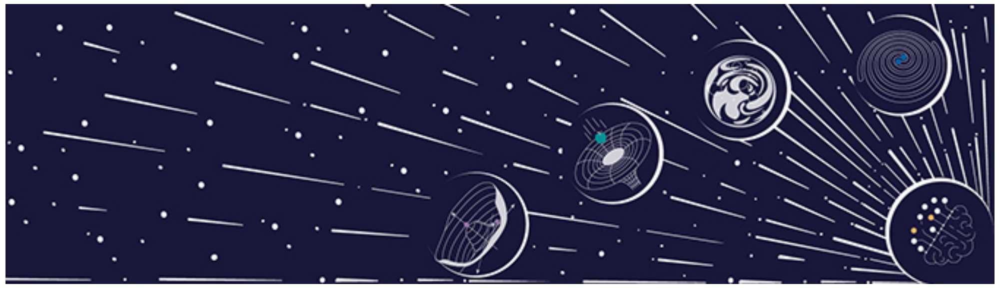
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE



based on work with

Lukas Kaufmann, Jeroen Monnee, and Timo Weigand
2603.13470

Jeroen Monnee and Timo Weigand
2509.07056

Björn Hassfeld, Jeroen Monnee, and Timo Weigand
2504.01066

See also:
2603.12315 w/ **Kaufmann, Monnee, Weigand**
2510.02435 w/ **Monnee, Weigand**
2604.25988 w/ **Kaufmann, Weigand**

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Emmy Noether-Programm
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Motivation

- Geometric string compactifications have given much insight into quantum field theory and quantum gravity theory.

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- Of particular interest are, of course, **Calabi-Yau manifolds** for which the physics at **local singularities** is very well understood
  (see e.g. [Strominger '95; Ooguri, Vafa '96] for conifolds in CY3-folds)

- Local singularities $\leftrightarrow$ field theory subsector

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- For quantum gravity: more severe singularities are interesting.

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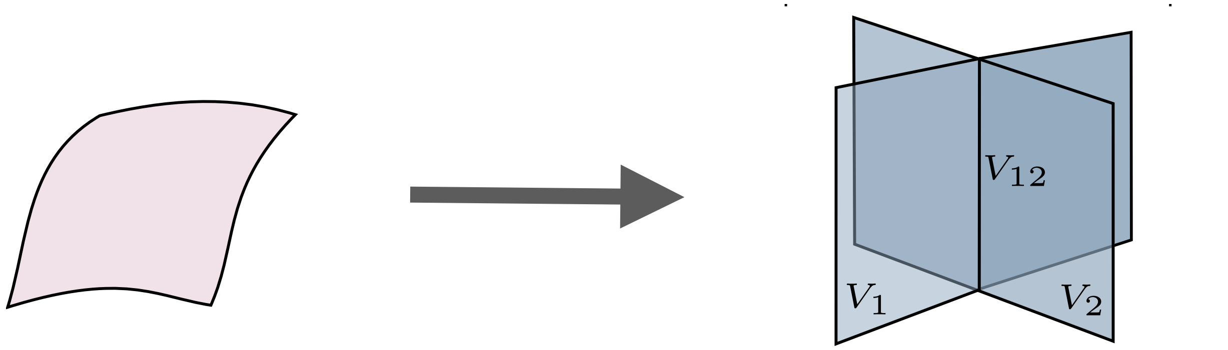
- To test string theory implications for quantum gravity, have to study compactifications on severely degenerating manifolds



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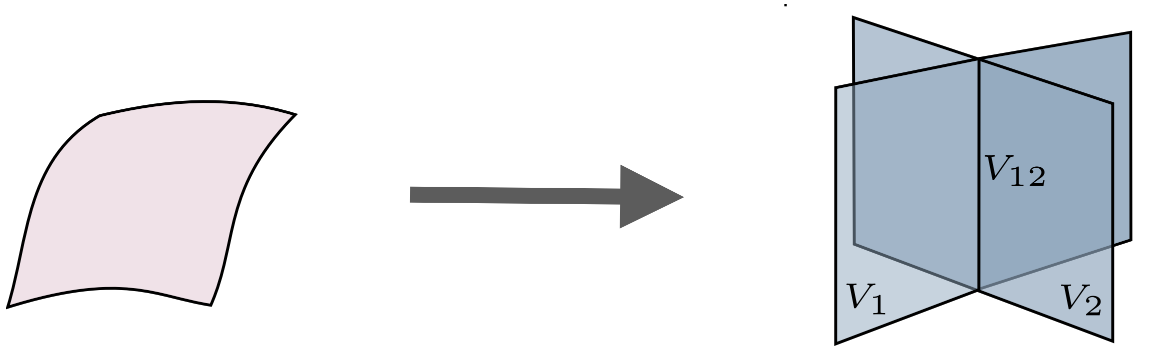

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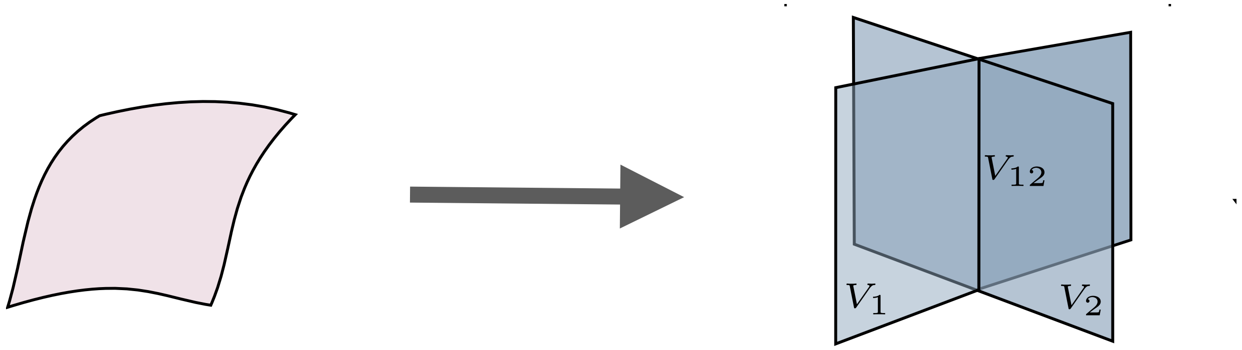

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- Infinite distance limits in c.s. moduli space have been studied extensively studied in the context of Distance and Emergent String Conjecture

[Ooguri, Vafa '06; Lee, Lerche, Weigand '19]

see [Grimm, Palti, Valenzuela '18; Grimm, Li, Palti '18; Joshi, Klemm '19; Grimm, v.d. Heisteeg '19; Grimm, Li, Valenzuela '19; Grimm, Ruehle, v.d. Heisteeg '19; Grimm, Monnee, v.d. Heisteeg '21; Alvarez-Garcia, Kläwer, Weigand '21; Lee, (Lerche), Weigand '21; Calderon-Infante, Ruiz, Valenzuela '22; v.d. Heisteeg, Vafa, MW, Wu '22; Alvarez-Garcia, Lee, Weigand '23; v.d. Heisteeg '24; Hattab, Palti '24-'26; Grimm, v.d. Heisteeg, Revello '25; ...]

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Here: study compactifications to 4d and use the relation

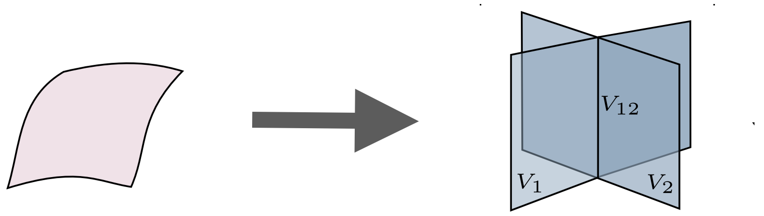
geometry of semi-stable degenerations $\leftrightarrow$ string solutions

to infer information about QG theory!

General Logic

[(Hassfeld), Monnee, Weigand, MW '25, Kaufmann, Monnee, Weigand, MW '26]

Geometry of Degenerations of Calabi-Yau 3- or 4-fold



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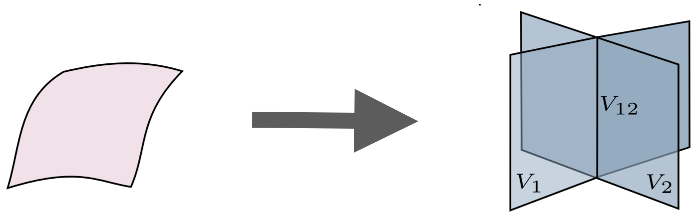

↓

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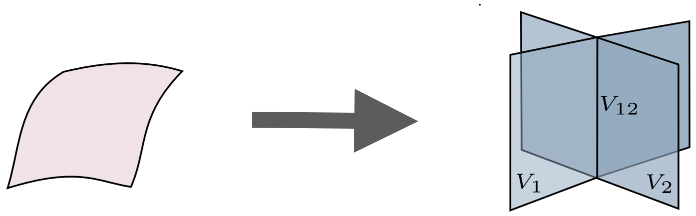

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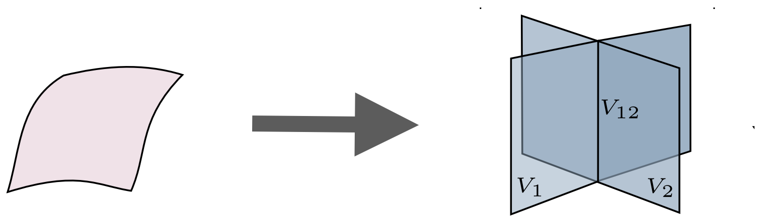

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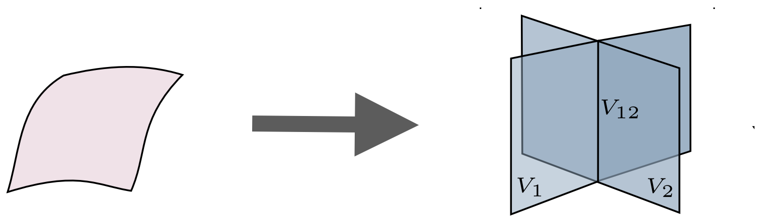

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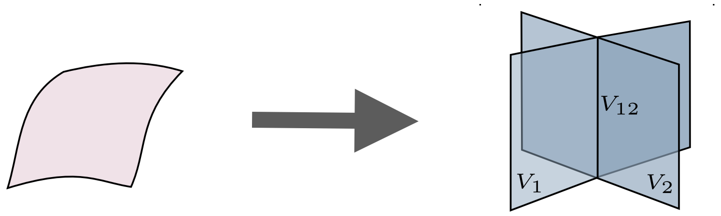

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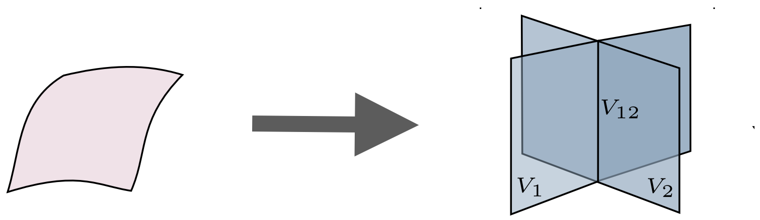

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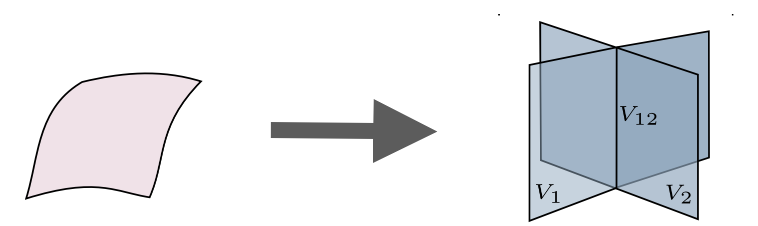

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Geometry of Calabi-Yau Degenerations

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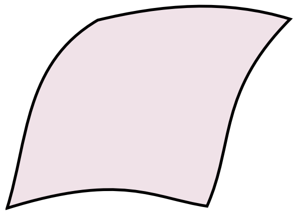

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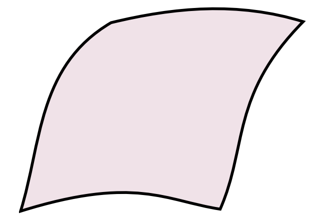
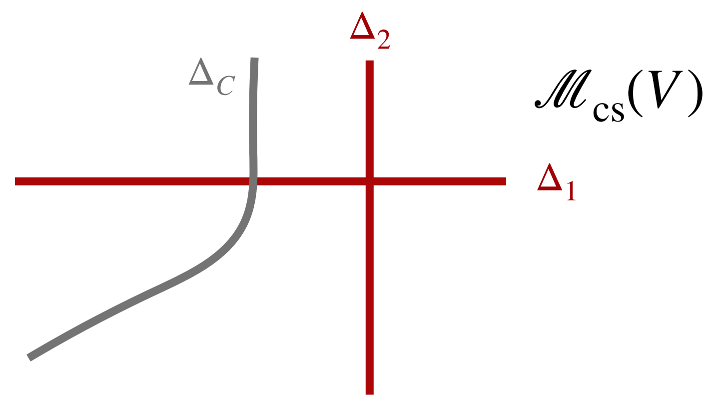


- The complex structure moduli space $\mathscr{M}_{\text{c.s.}}$ of V contains loci at which V is singular



$$\dim_{\mathbb{C}}(\mathscr{M}_{\text{c.s.}}(V)) = \begin{cases} h^{2,1} & \text{CY threefolds} \\ h^{3,1} & \text{CY fourfolds} \end{cases}$$

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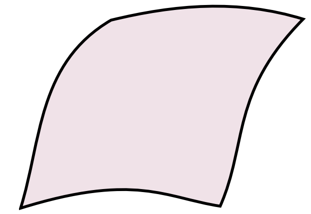

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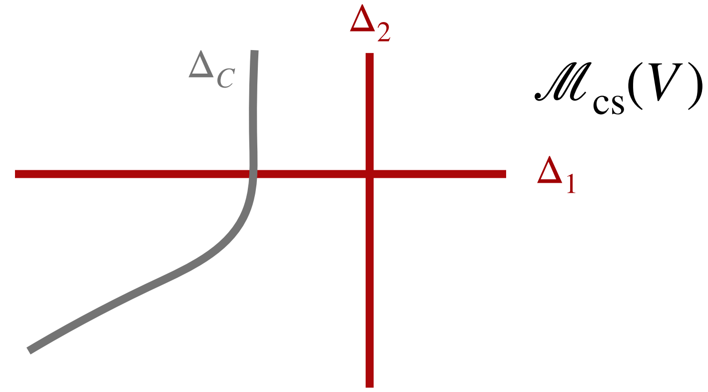

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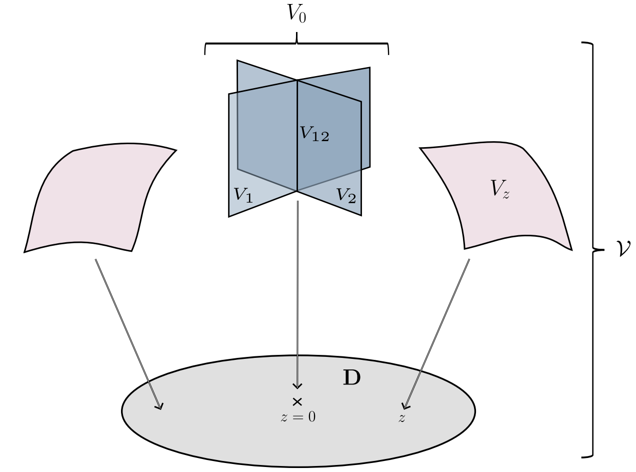
- Here: interested in loci $\Delta = \{z = 0\} \subset \mathcal{M}_{\text{c.s.}}$ where V undergoes

semi-stable degeneration

$$V_z \to V_0 = \bigcup_{i=1}^{m} V_i$$

$$V_i \hat{=}\, n - \text{folds}$$



c.f. [Kulikov '77, '81; Persson, Pinkham '81; Lee, (Lerche,) Weigand '21] for K3 degenerations.

Classification of Semi-Stable Calabi-Yau Degenerations

[Monnee, Weigand, MW '25 (1)]

- Properties of the degeneration encoded in the intersection pattern of V_i in

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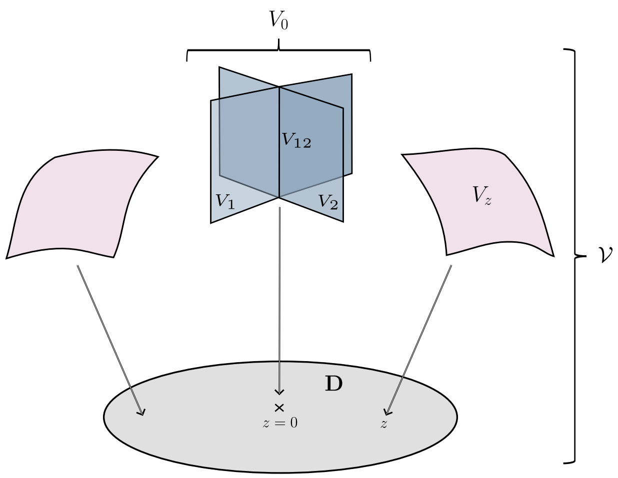

- Simplest case: - $m = 2 \to$ only one non-trivial double $(n-1)$-fold

$$V_{12} = V_1 \cap V_2$$

Tyurin degeneration of n=3
[Tyurin '03]

- Calabi-Yau condition for V_z implies that V_{12} is CY $(n-1)$-fold

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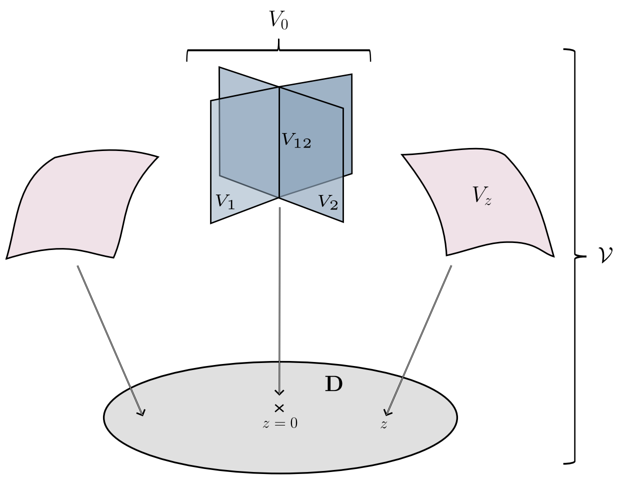

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- Coarse classification of degeneration now depends highest co-dimension of non-trivial intersection:
  $\to$ can define an integer d such that for given degeneration

$$V_{i_0,\ldots,i_d} = V_{i_0} \cap \ldots \cap V_{i_d} \neq \varnothing\,, \quad \text{for } \textbf{some} \quad i_0 < \ldots < i_d$$

$$V_{i_0} \cap \ldots \cap V_{i_{d+1}} = \varnothing\,, \quad \text{for } \textbf{all} \quad i_0 < \ldots < i_{d+1}$$

($d = 1$ in the above $m = 2$ example)

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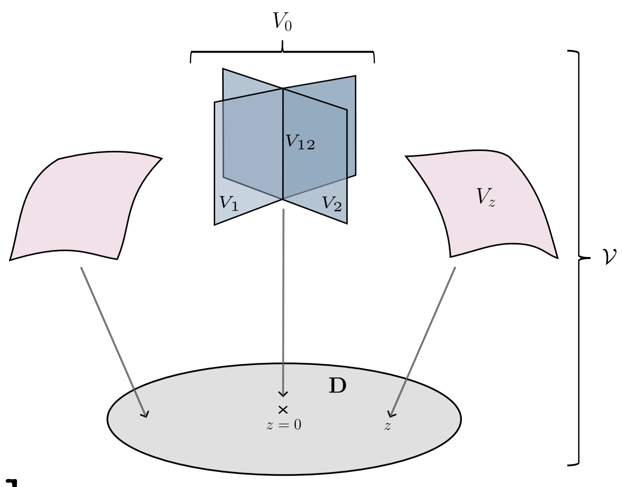

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- Calabi-Yau condition of $V_z \Rightarrow V_{i_0\ldots i_d}$ are Calabi-Yau $(n-d)$-folds.

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- for Calabi-Yau n-fold have $d \in \{1,\ldots,n+1\}$

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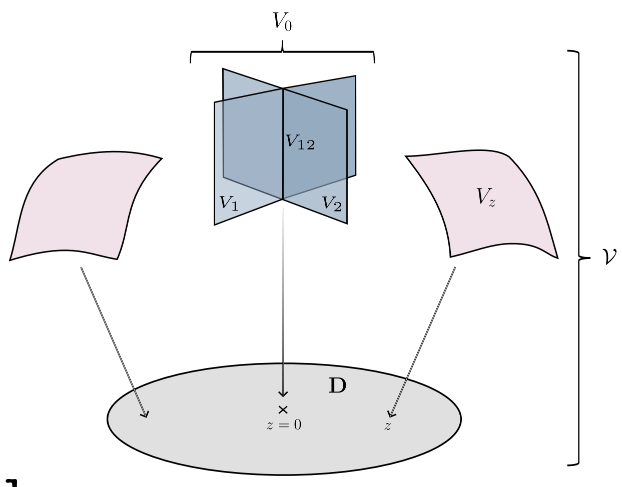

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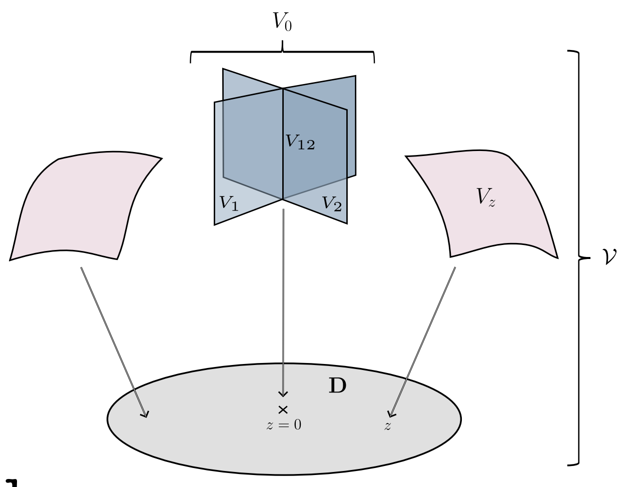

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see [Grimm, Palti, Valenzuela '18; Grimm, Li, Palti '18; Grimm, Li, Valenzuela '19]

- To match nomenclature in the literature we define primary degeneration type for Calabi-Yau three- and fourfolds:

	CY 3-fold V	**CY 4-fold** V
Type II $(d=1)$	**Double** surfaces $V_{i_0i_1}$ are K3s	**Double** threefolds $V_{i_0i_1}$ are CY3
Type III $(d=2)$	**Triple** curves $V_{i_0i_1i_2}$ are T^2s	**Triple** surfaces $V_{i_0i_1i_2}$ are K3s
Type IV $(d=3)$	**Quadruple** points V_{i_0,i_1,i_2,i_3} exist	**Quadruple** curves V_{i_0,i_1,i_2,i_3} are T^2s
Type V $(d=4)$	**N/A**	**Quintuple** points V_{i_0,i_1,i_2,i_3,i_4} exist

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Worldsheet theory of String Solutions

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Semi-Stable Degenerations and String Solutions

[(Hassfeld), Monnee, Weigand, MW '25]
[Kaufmann, Monnee, Weigand, MW '26 (2)]

- Consider Calabi-Yau n-fold V as compactification manifold of string/F-theory to four dimensions:

Here: **Type IIB string theory on** V $(n = 3)$

F-theory on V $(n = 4)$

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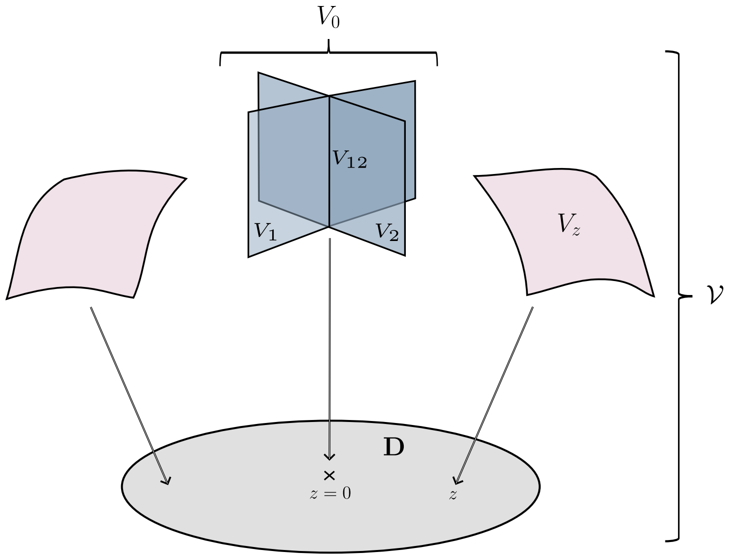

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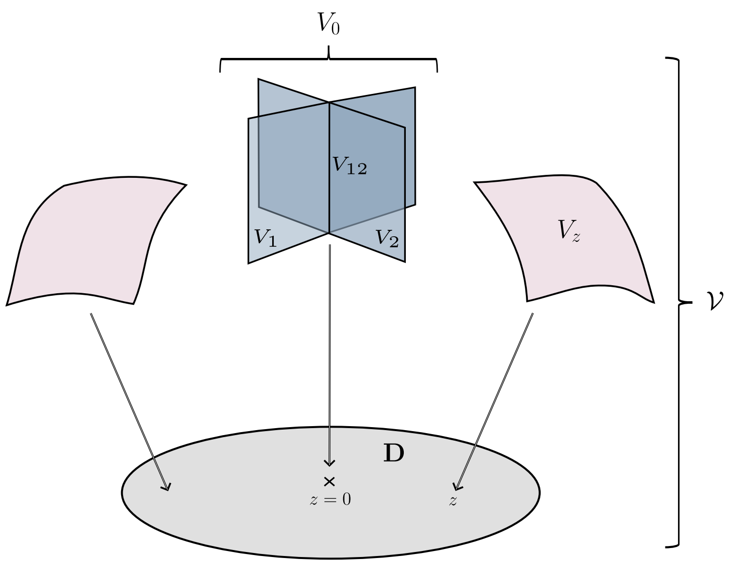

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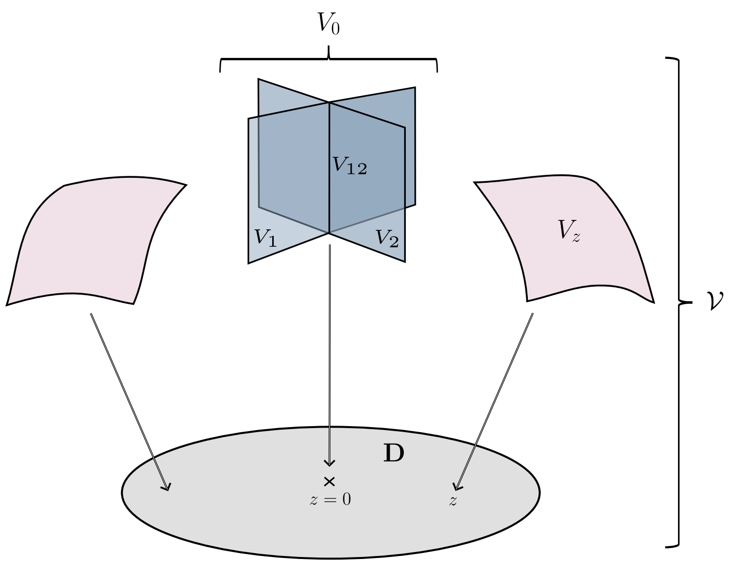

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- The string solution is such that it realizes the degeneration limit
  $V_z \to V_0$ at the core of the string $\to$ candidate for the "EFT-strings" introduced by

[Lanza, Marchesano, Martucci, Valenzuela '21]

Candidate EFT Strings and CY Degenerations

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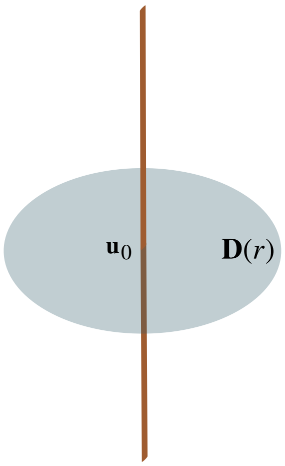

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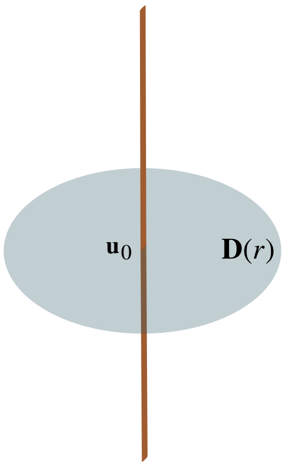

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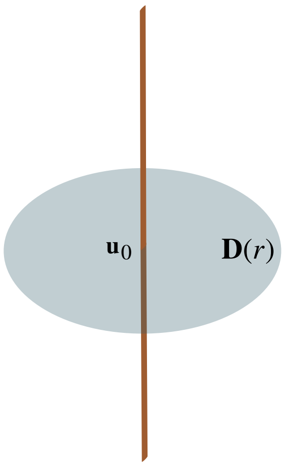

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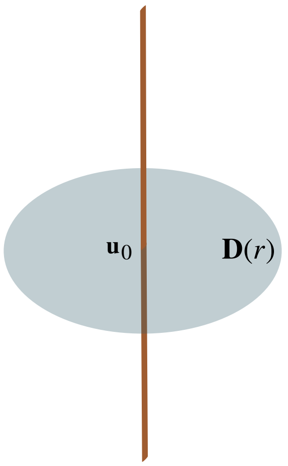

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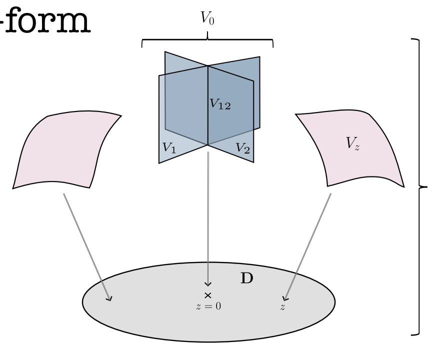

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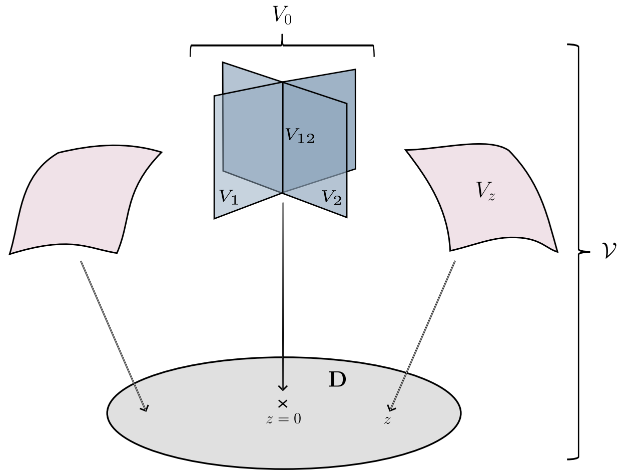

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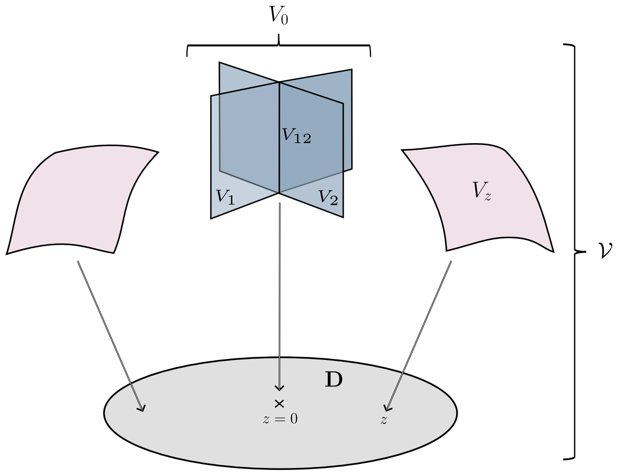

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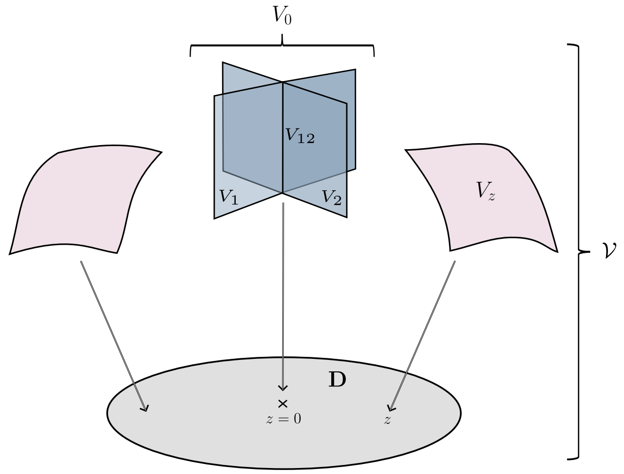

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- Generally: **two origins** for massless modes

  1. Geometric zero modes → position of the string in **D** + geometric moduli of $V_{i_0,i_1} \subset V_0$
  2. Localized modes of p-forms of 10d supergravity to V_0.

Mode Counting: Type IIB on CY3

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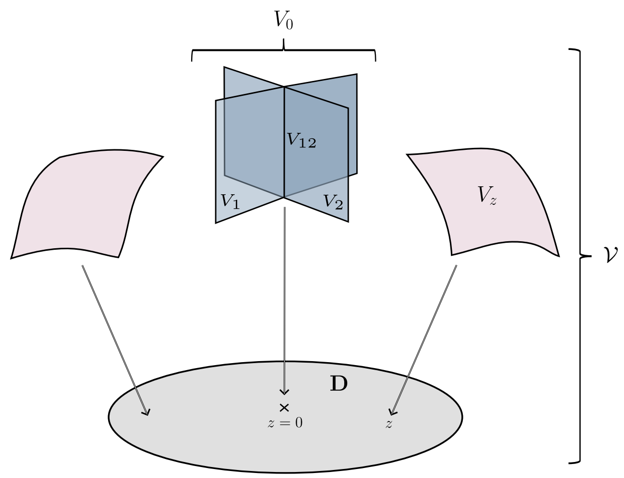

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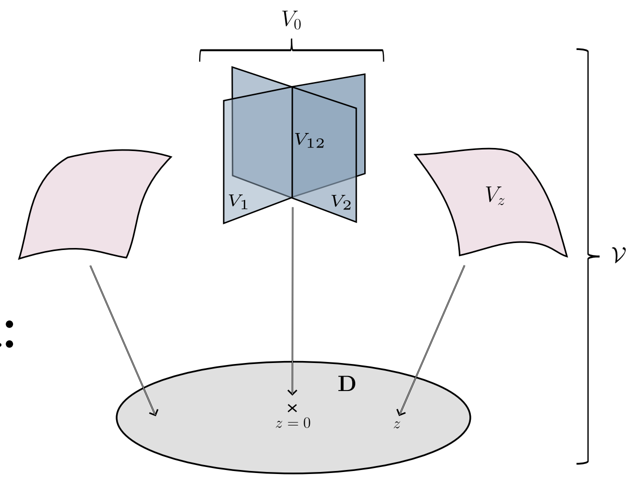

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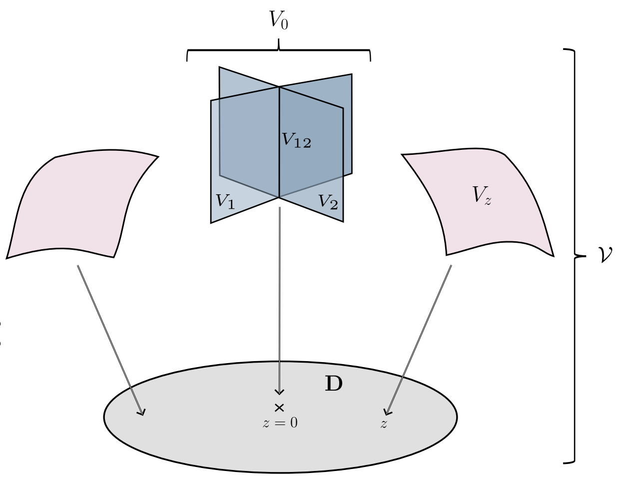

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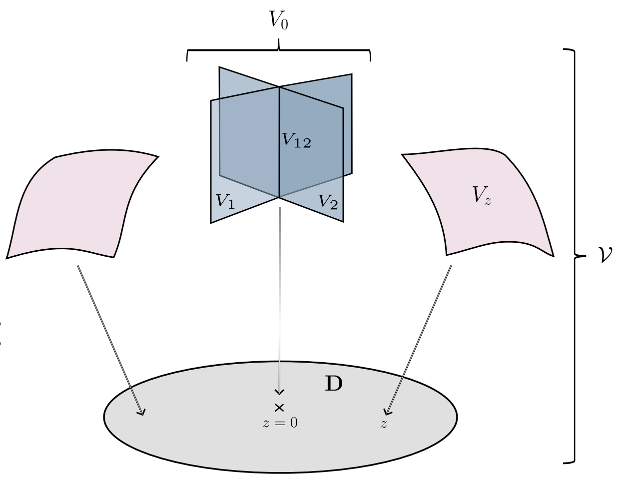

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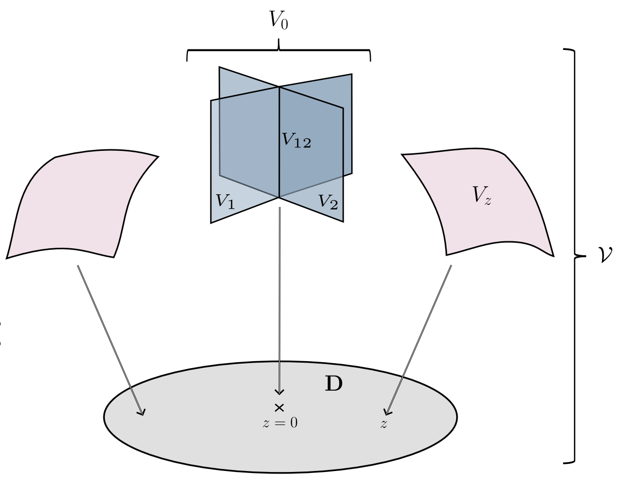

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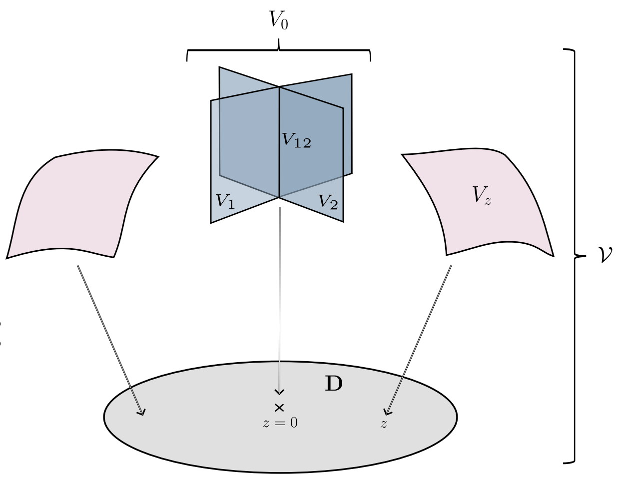

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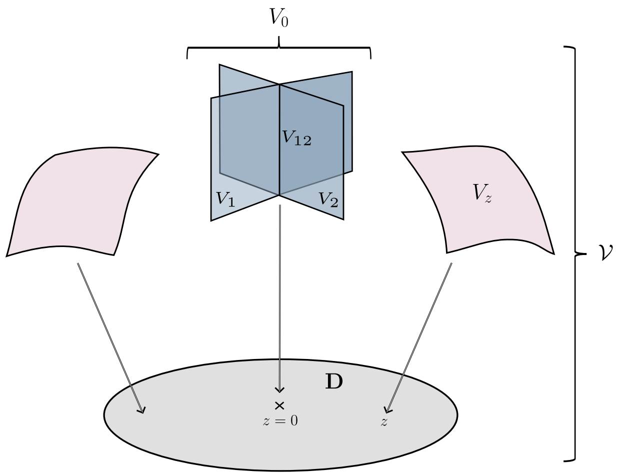

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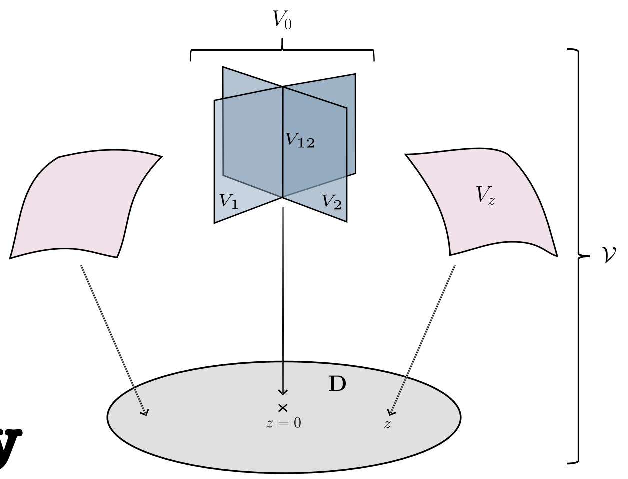

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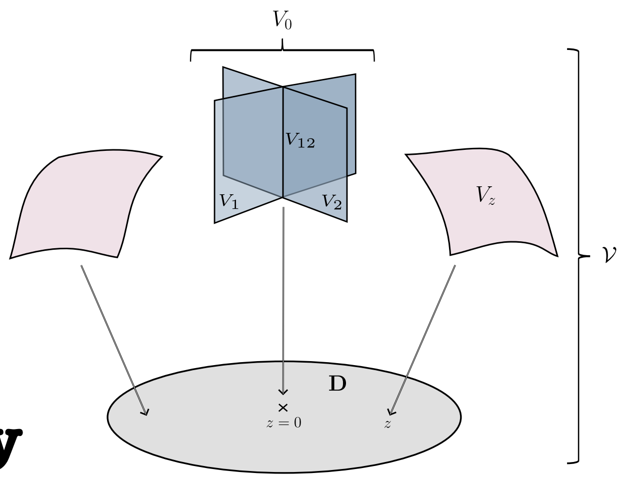

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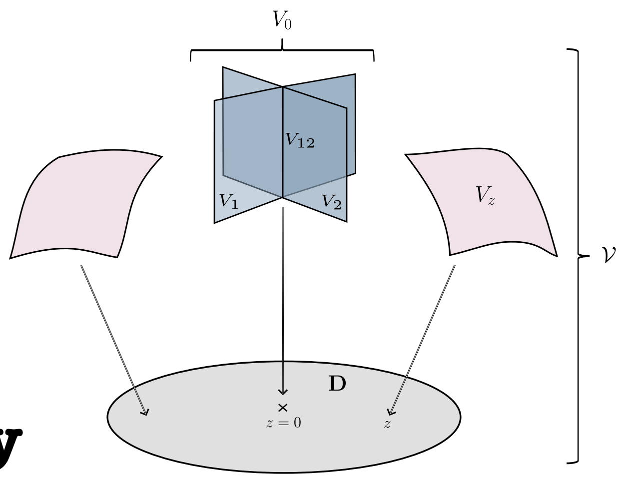

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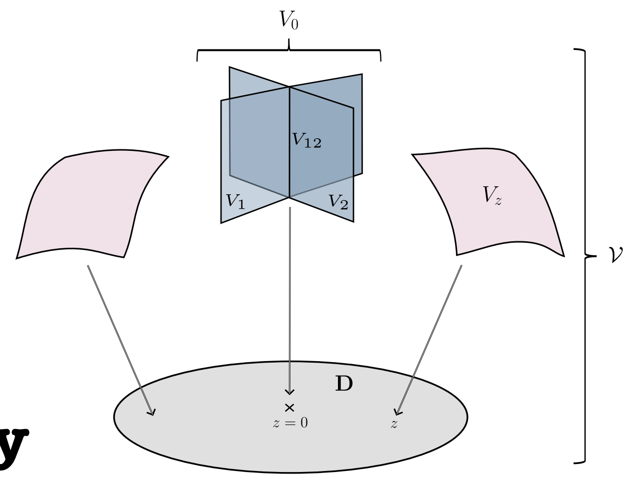

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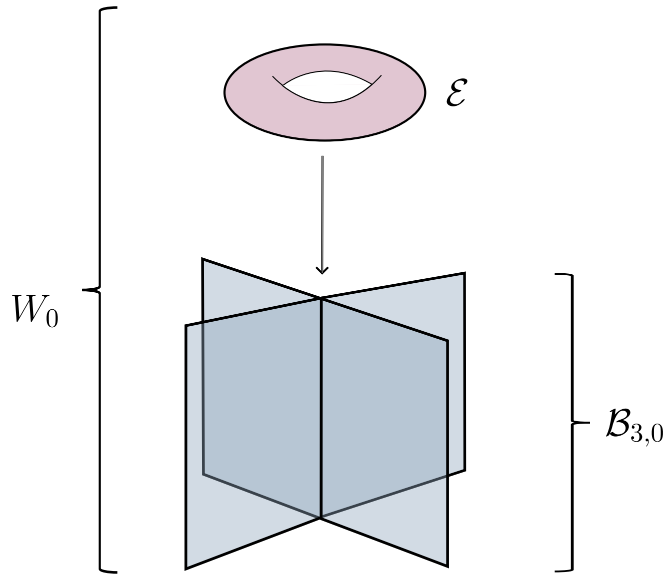

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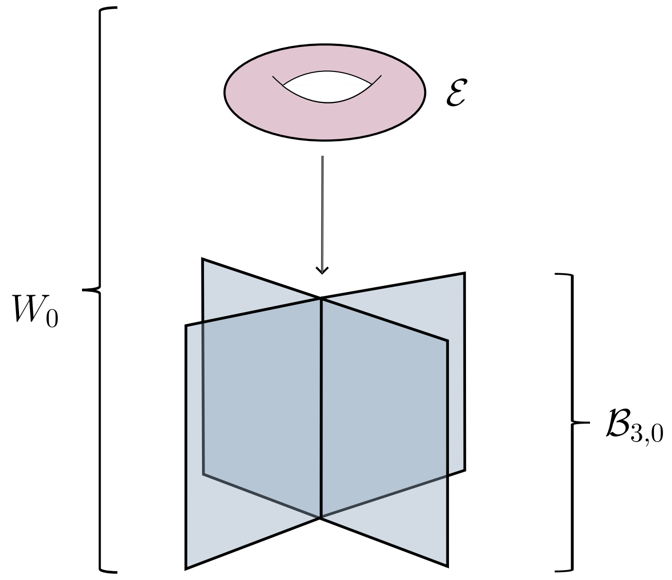

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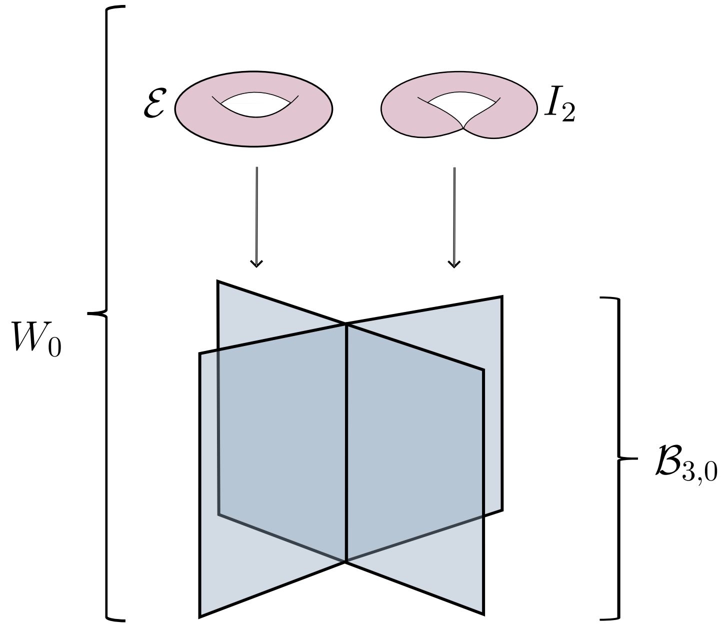

I_n-Type Limit

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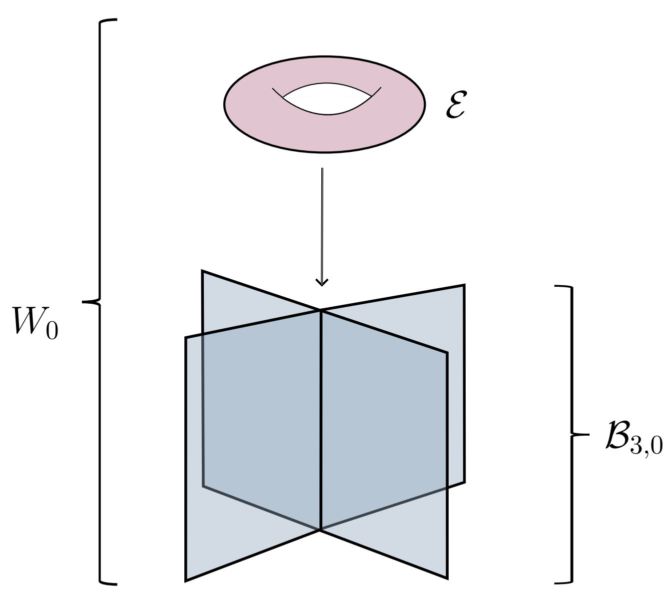
[Kaufmann, Monnee, Weigand, MW ’26 (2)]

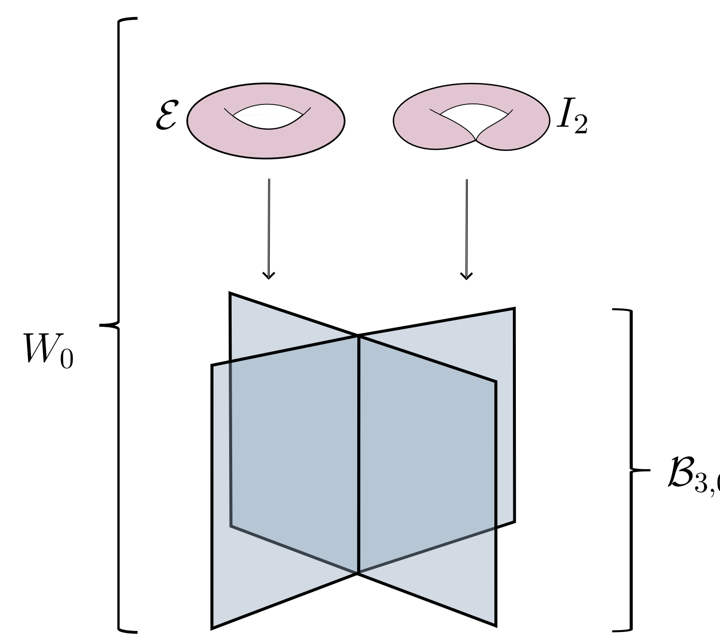
- Now consider the uplift of the SQM to a string in the 4d SUGRA theory.

- Can distinguish **two types** of fourfold **degenerations**
  → does the elliptic fiber degenerate or not?

Definition: – A limit is of **regular-fiber type** if each double surface V_{i_0,i_1} is itself elliptically fibered with general fiber $\mathscr{E}$.
– Instead for I_n**-type degenerations** the generic fiber over at least one component of $B_{3,0}$ is of Kodaira type I_n.



Regular Fiber Limit



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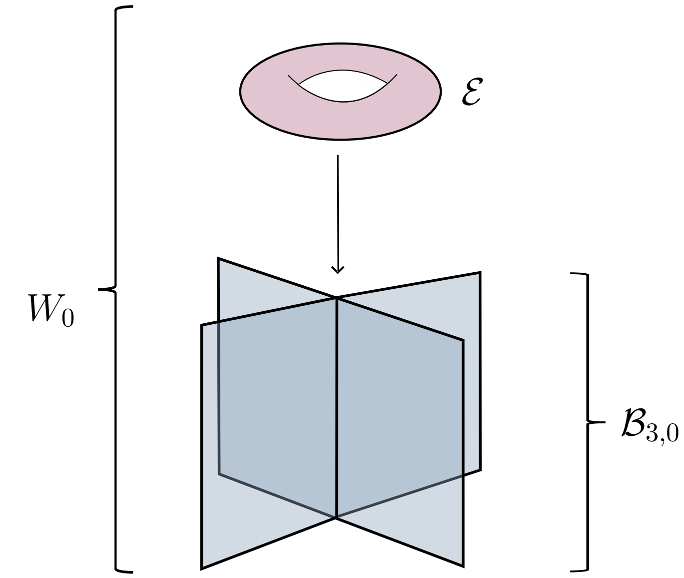

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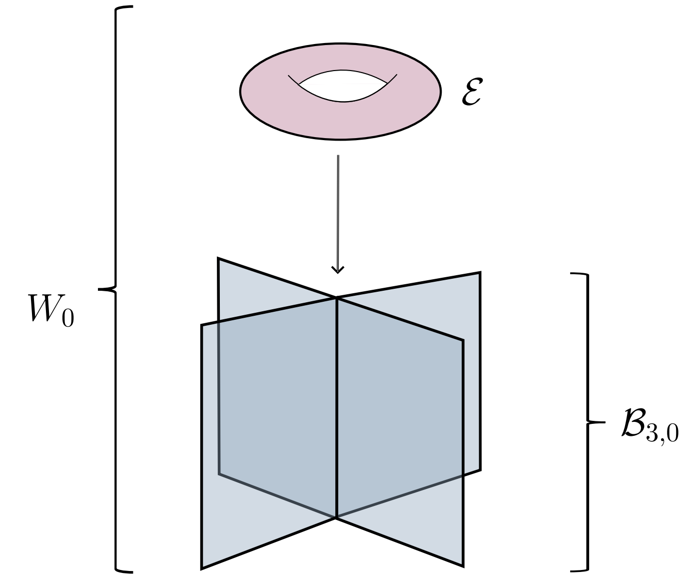

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    $\gamma_\alpha \in H^1(V_{ij}) \oplus H^1(V_{ijk}) \oplus H^1(V_{ijkl})$
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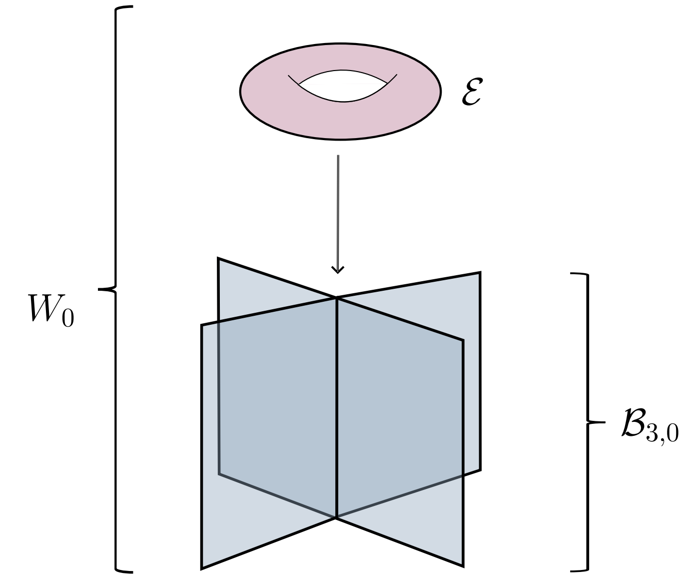

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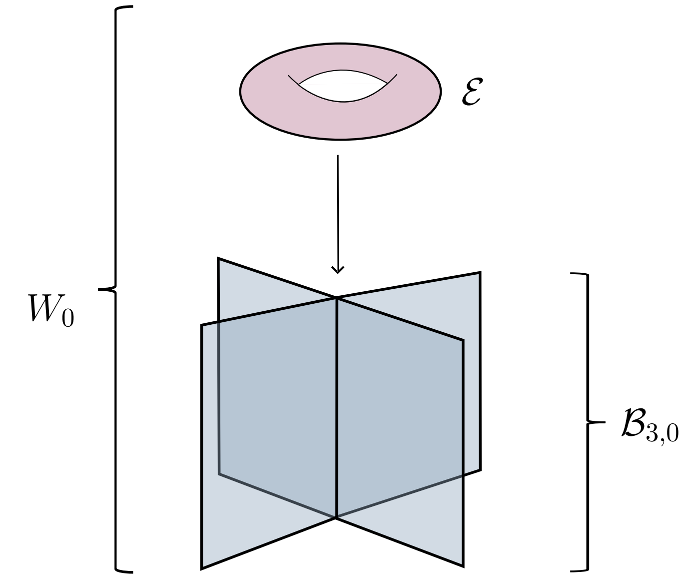

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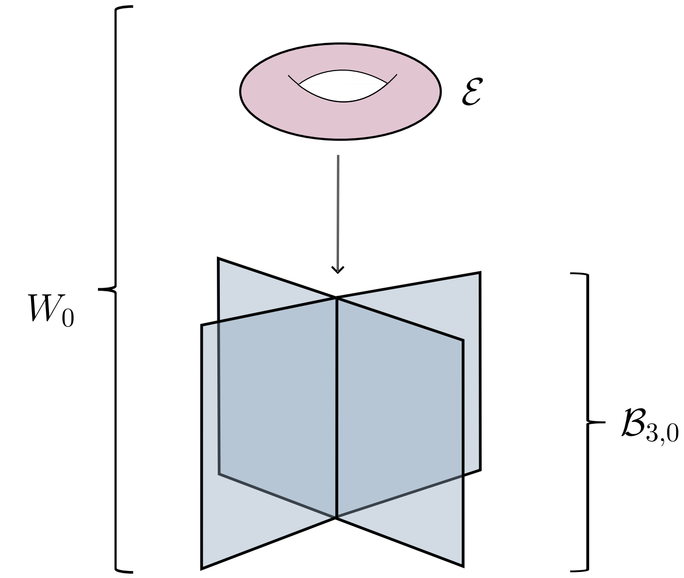

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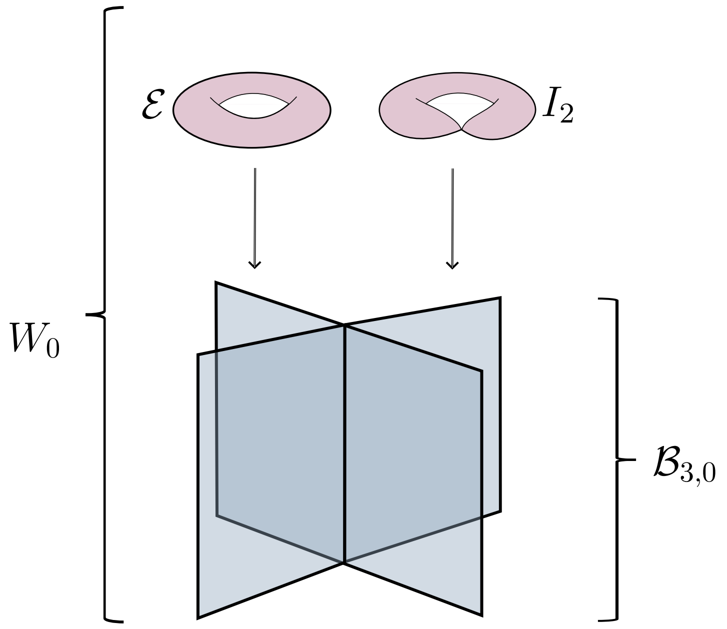

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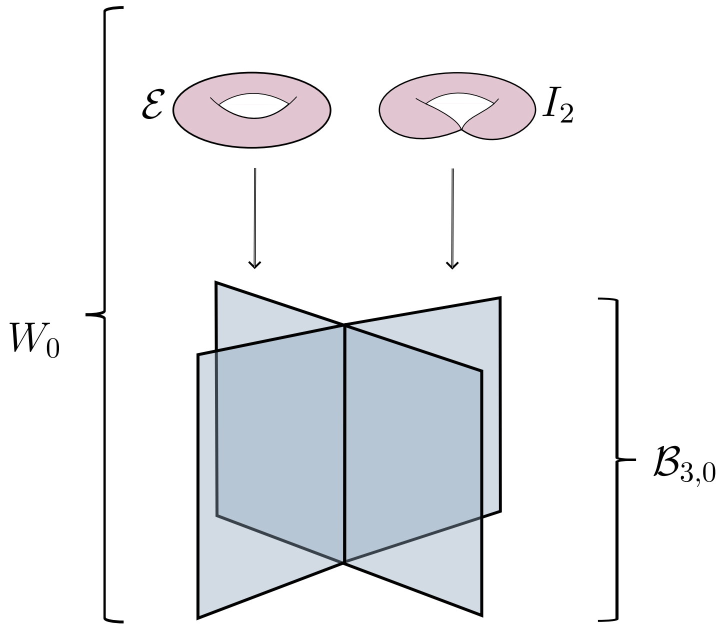

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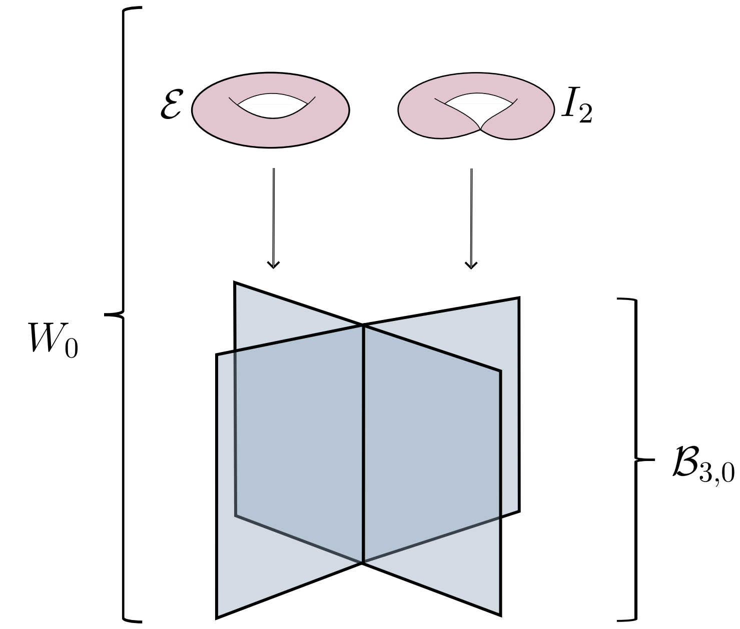

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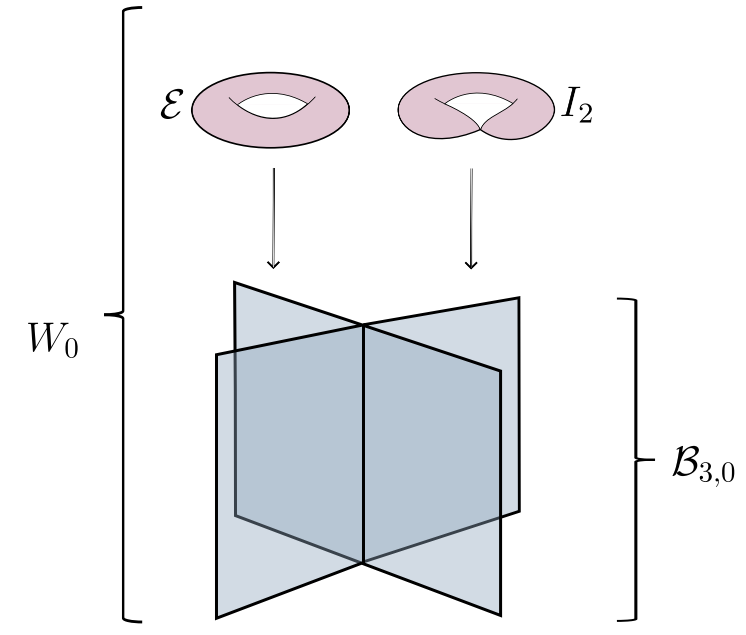

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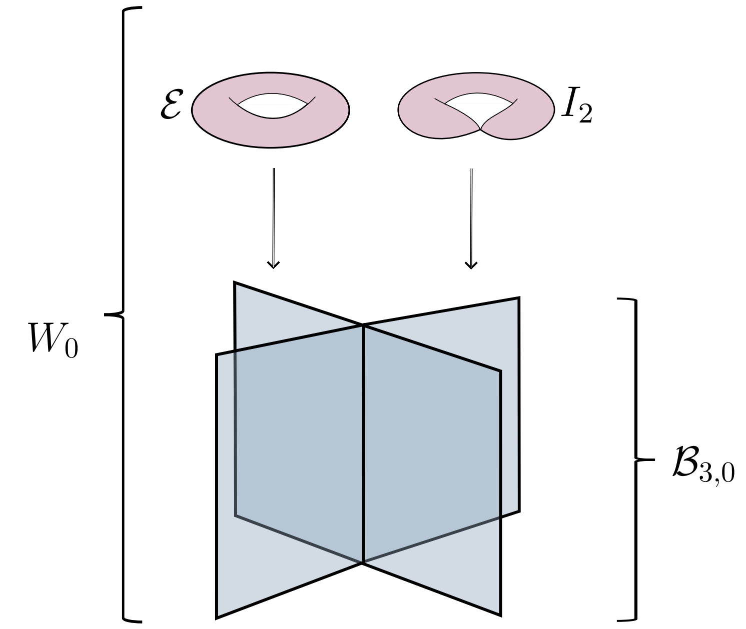

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General Logic

Geometry of Degenerations of Calabi-Yau 3- or 4-fold

↓

Worldsheet theory of String Solutions

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Non-perturbative Physics of the effective 4d action

Classical effective Action — WS theory on String Solutions

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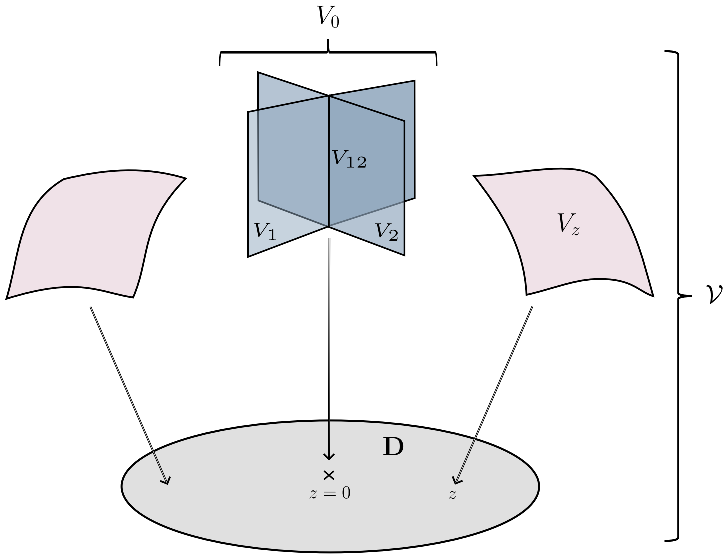

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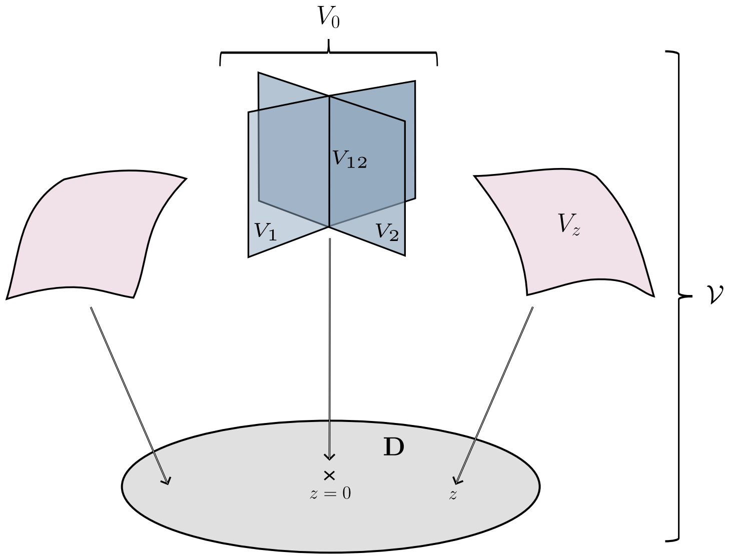

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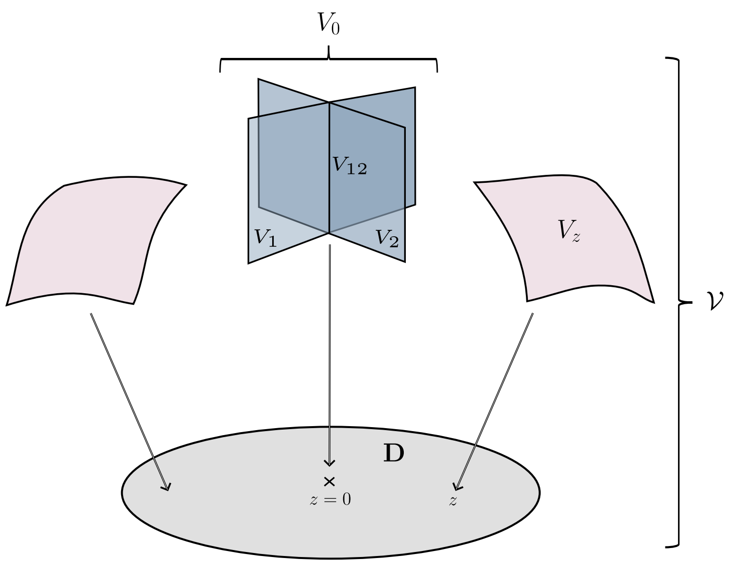

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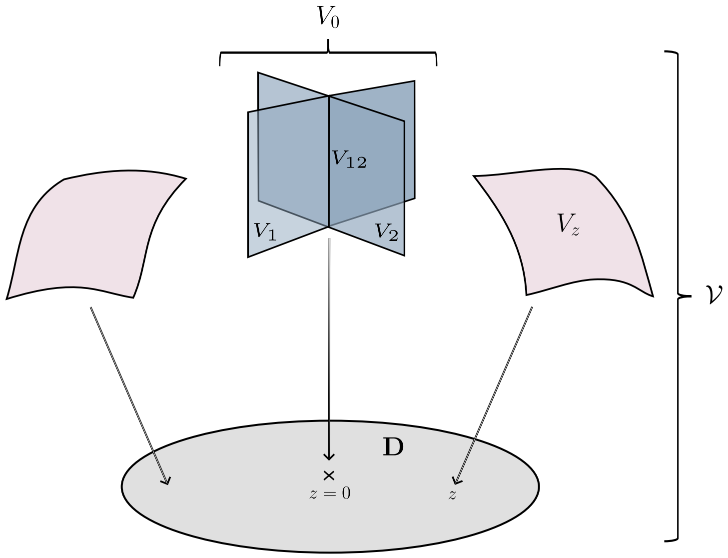

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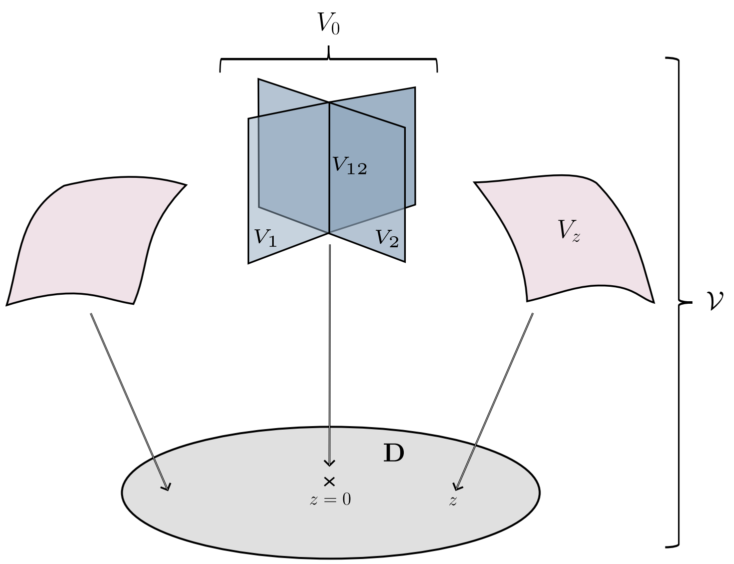

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- Test of the **Distance Conjecture** and **Emergent String Conjecture**
  [Ooguri, Vafa '06] [Lee, Lerche, Weigand '19]

At **infinite distance in moduli space** (here degeneration of CY3) there is **a tower of asymptotically massless states** that is either a **KK-tower or the tower of excitations of a critical string**

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Type IV limit: KK U(1)s from decompactification to 5d

- Test of the **Distance Conjecture** and **Emergent String Conjecture**
  [Ooguri, Vafa '06] [Lee, Lerche, Weigand '19]

> At **infinite distance in moduli space** (here degeneration of CY3) there is **a tower of asymptotically massless states** that is either a **KK-tower or the tower of excitations of a critical string**

Large complex structure limits in F-theory

[Kaufmann, Monnee, Weigand, MW '26 (2)]

- Consider now the analog degenerations for F-theory compactified on an elliptically fibered CY4-fold $\mathcal{E} \hookrightarrow W \to B_3$.

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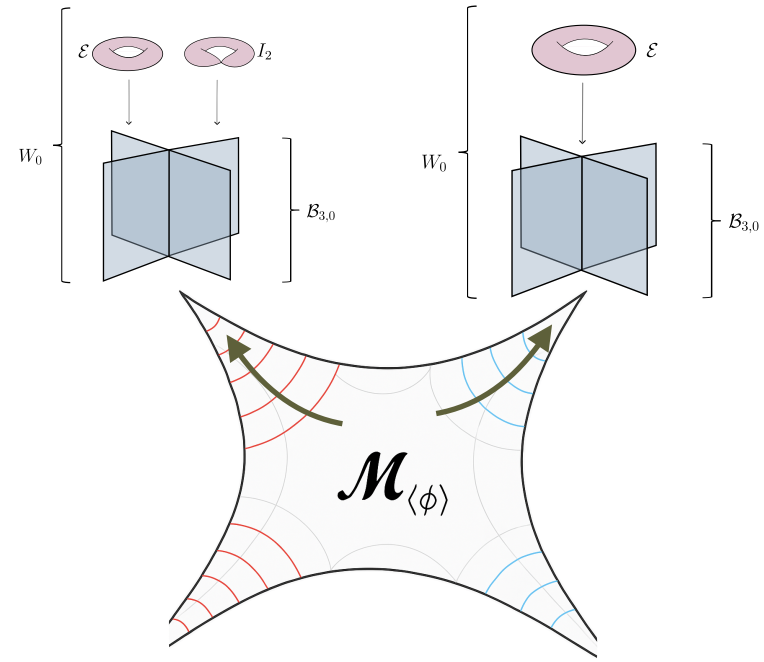

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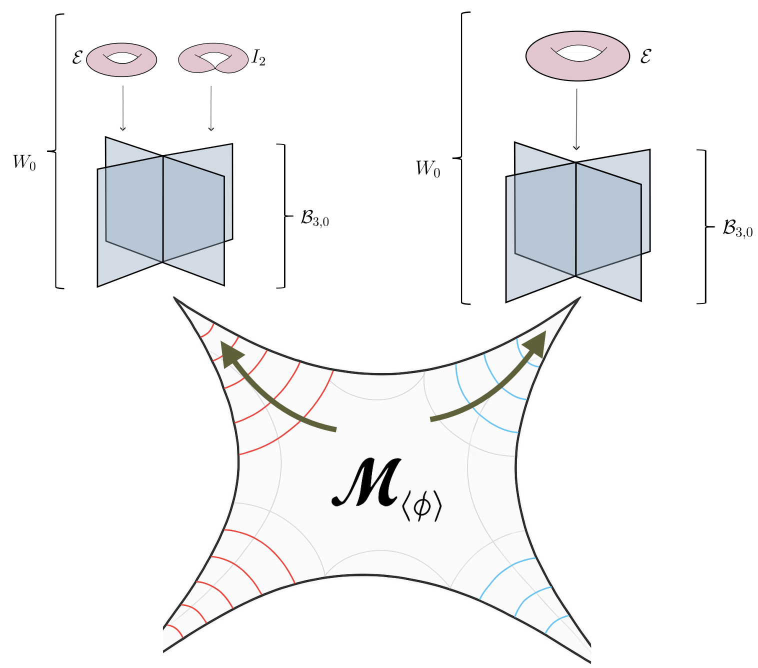

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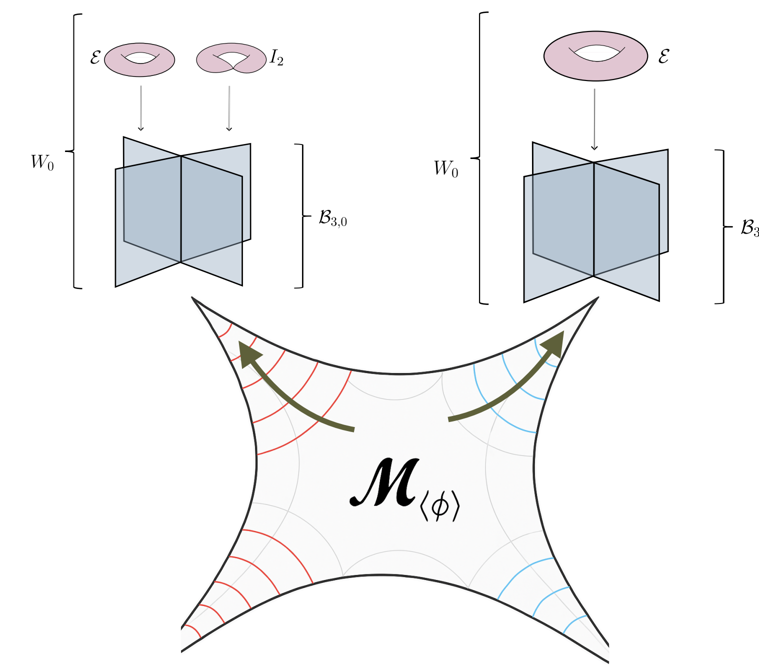

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- **Question**: Are the candidate EFT strings associated with degeneration **supergravity** strings of higher-dimensional theory or **critical strings?**

Candidate EFT strings for I_n-type degenerations

[Kaufmann, Monnee, Weigand, MW '26 (2)]

- **Upshot:** candidate EFT strings for CY4-fold degenerations are **neither** *
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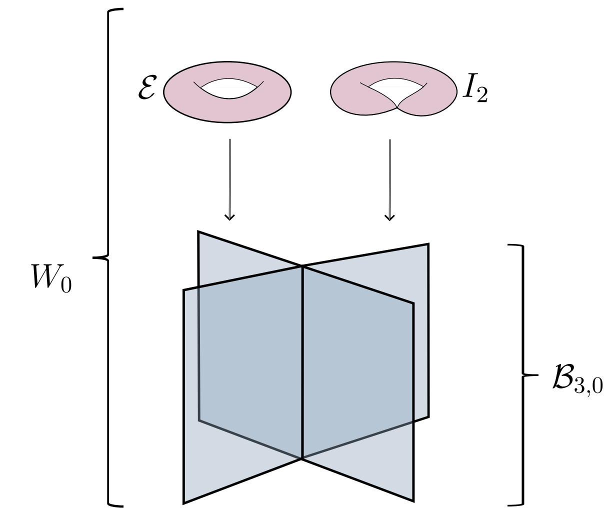

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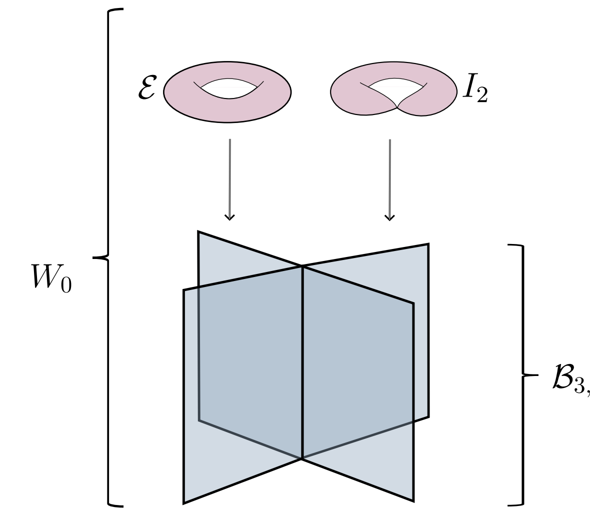

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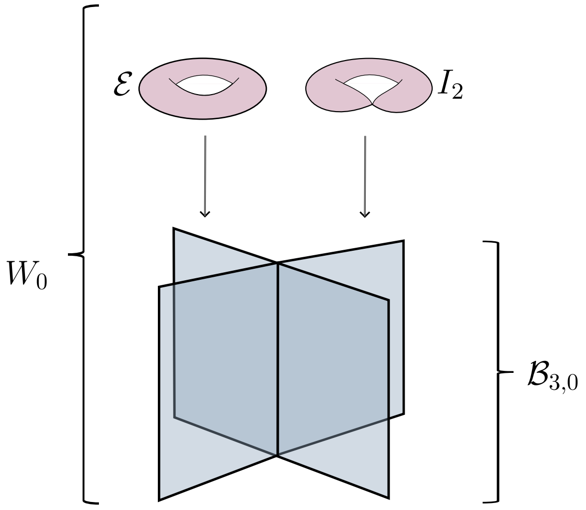

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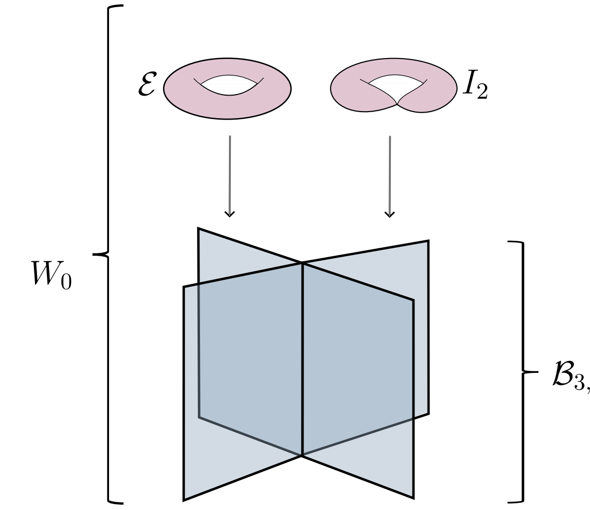

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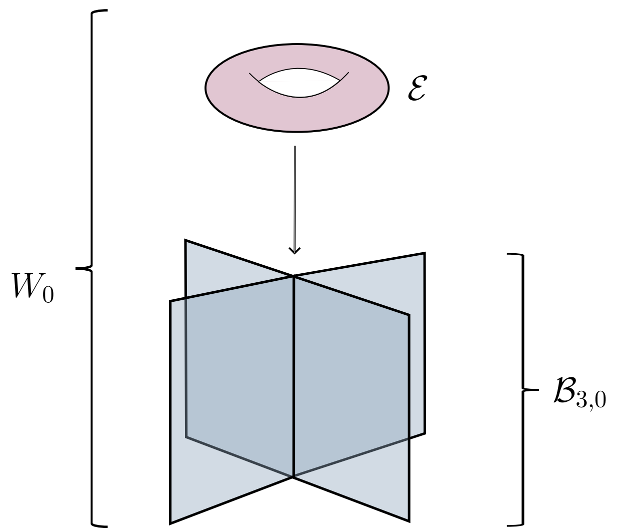

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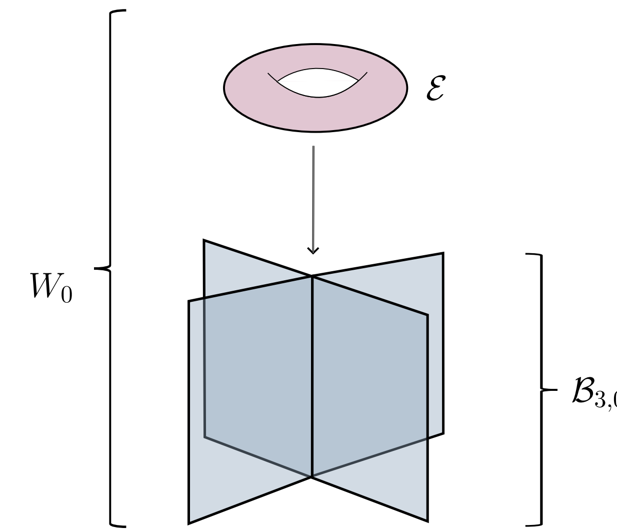

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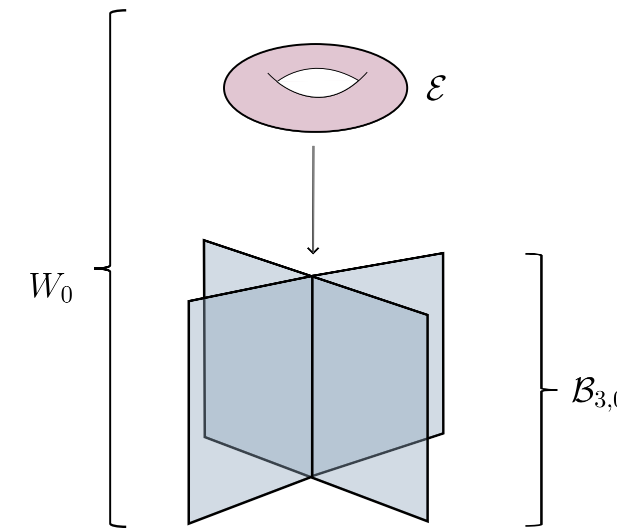

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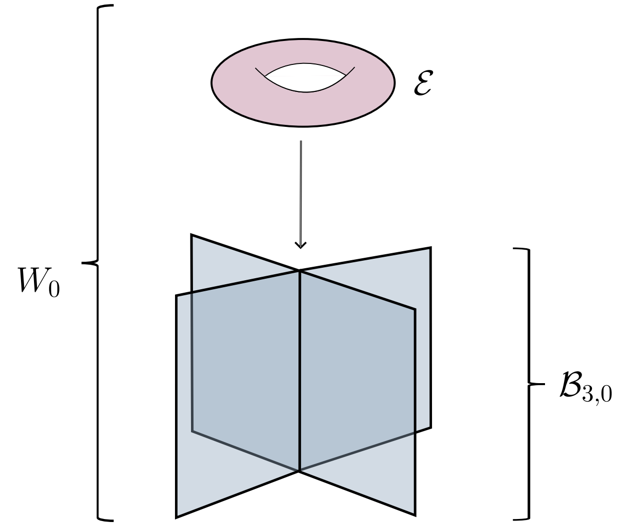

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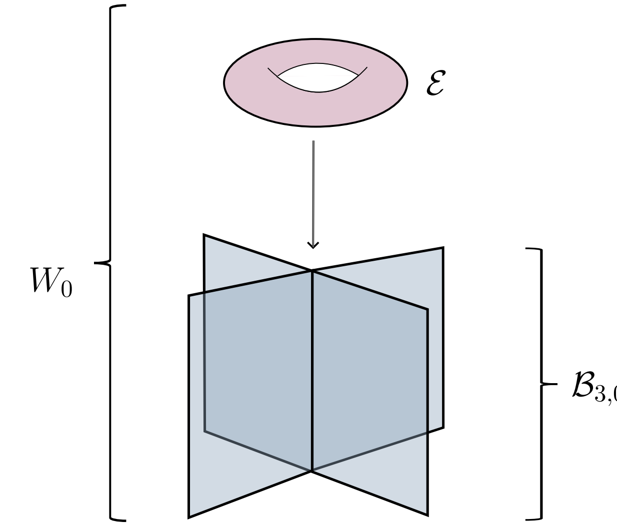

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Using dualities (F-theory in 6d, Heterotic String, …) we explicitly demonstrate that:

$$\mathscr{V}_D = \mathscr{V}_D^{(0)} + az^\alpha\,, \quad 0 \neq a \in \mathbb{R}\,,\ 1 \leq \alpha \in \mathbb{Z}$$

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Comparison with dual **M-theory on G_2-manifold** reveals that quantum corrections **completely remove infinite distance**
→ **compactify moduli space** in $z^i \to \infty$ limit at finite Kähler moduli

[Kaufmann, Weigand, MW '26]

Summary

Geometry of Degenerations of Calabi-Yau 3- or 4-fold

↓

Worldsheet theory of String Solutions

↓

Non-perturbative Physics of the effective 4d action

Type IIB on CY3:

Classical effective Action 🤝 WS theory on String Solutions

Weakly-coupled duality frame

F-theory on CY4:

Classical effective Action ❌🤝 WS theory on String Solutions

Non-perturbative corrections to effective action

Thank you!