Constraining Quantum Gravity -
in theory and in the lab

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Holography and the Swampland

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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

How to find constraints on quantum gravity?

1) **Idea** guided by theoretical consistency starting with certain assumptions

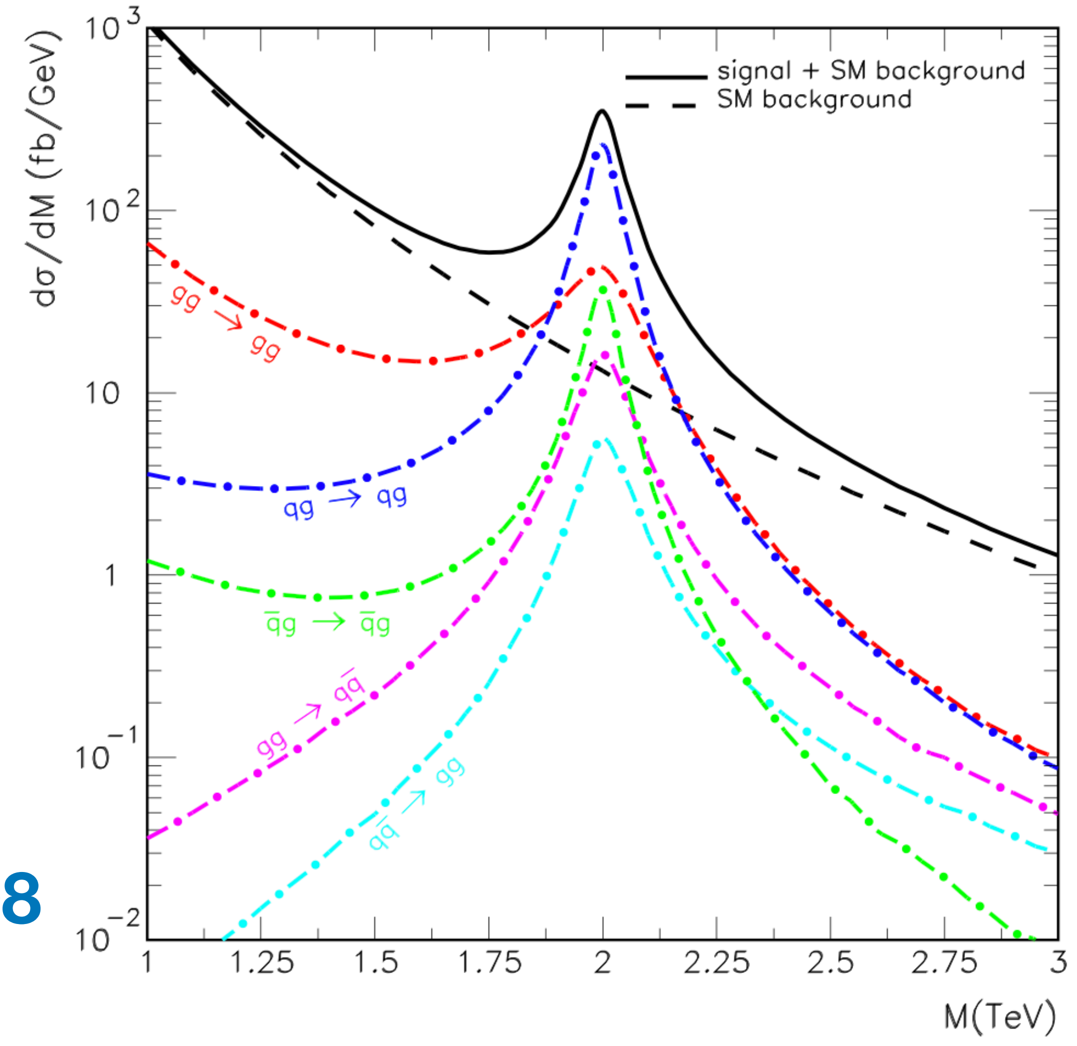
- Successful example: **String Theory**
- **Swampland Program**: attempts to relax assumptions on UV

2) **Laboratory** to test / rule out the idea

- **Theoretical laboratory** (mathematics….)
- Universe (**cosmological observations**) or actual **experiment**

difficult: 4d Planck scale high….

However:
[Anchordoqui, …,
Lüst, Stieberger, …, Taylor] '08



1) We are playing the long game: patience!

2) A negative result can also be a good result.

This talk

Idea 1:

Distance Conjecture **[Ooguri, Vafa'05]**

Emergent String Conjecture **[Lee,Lerche,TW'19]**

Laboratory 1: Geometry of stable degenerations

Evidence that ESC realised in Type IIB string theory on CY 3-folds at infinite distance in the complex structure

[Friedrich, Monnee,TW,Wiesner'25] [Monnee,TW,Wiesner'25]

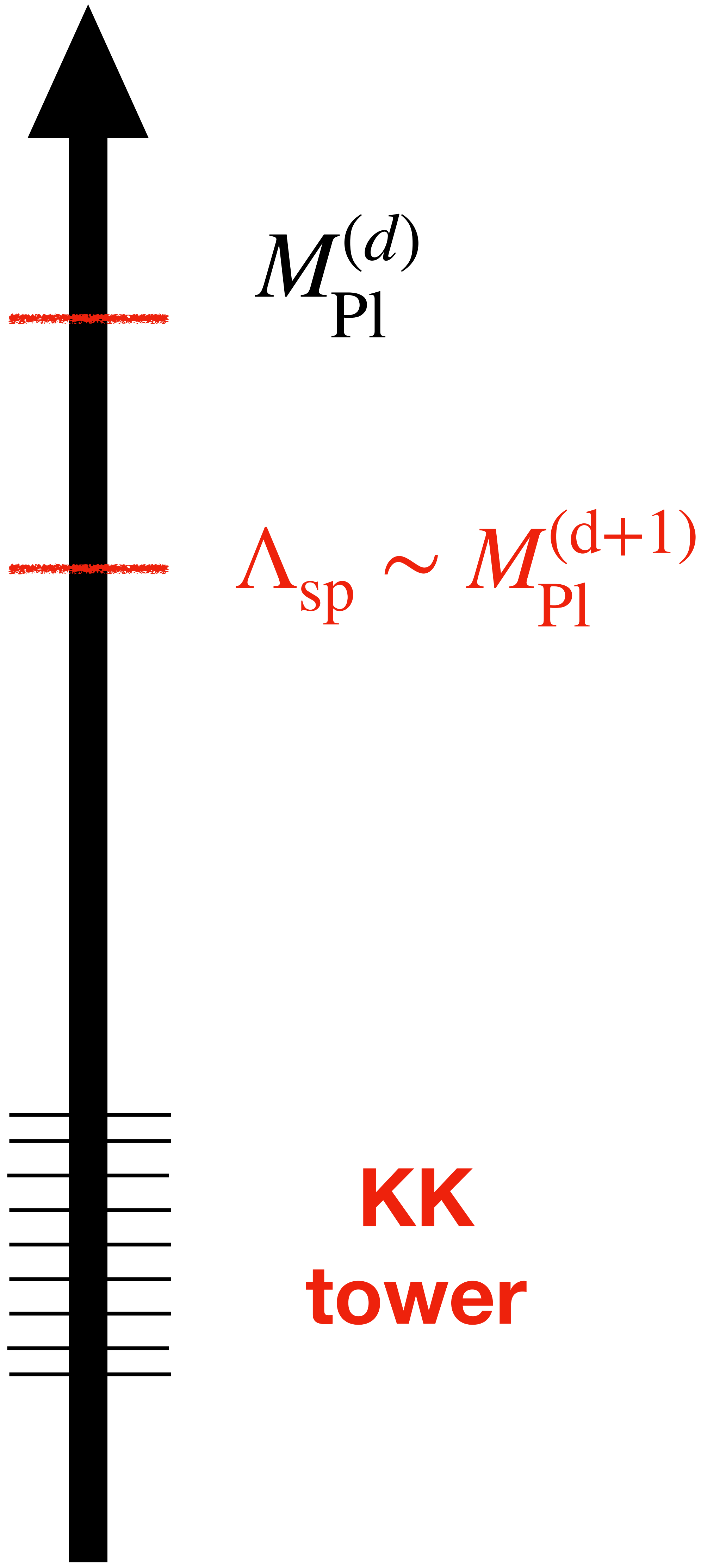
Idea 2:

Perturbative heterotic string

Laboratory 2: Universe or axion experiments

Finding an axion-like particle with a coupling-to-mass ratio far above the QCD line would rule out perturbative heterotic string theory.

[Agrawal,Nee,Reig'22, '24] [Reig,TW'25]



Part 1:

Testing ESC at infinite complex structure in Type IIB CY 3-folds

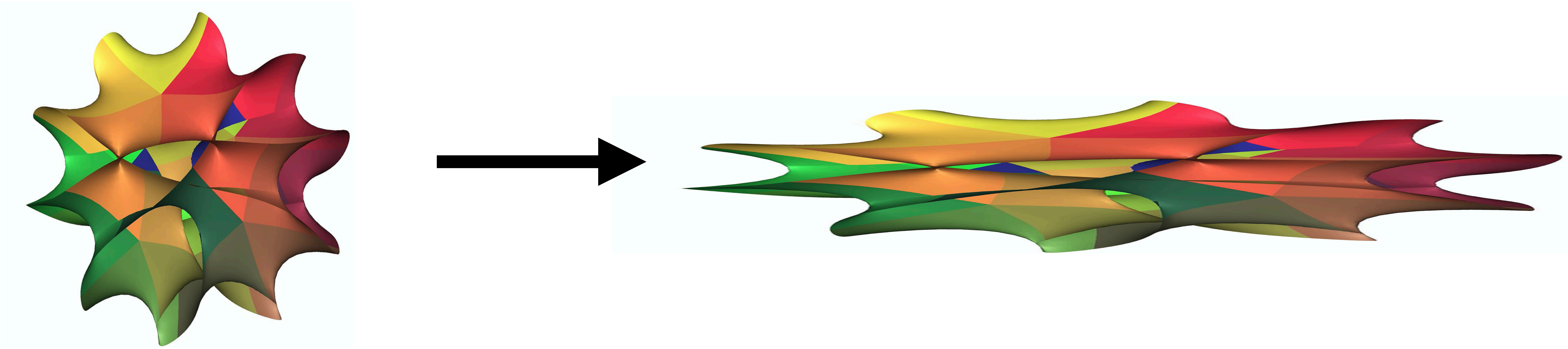
[Friedrich, Monnee,TW,Wiesner'25] [Monnee,TW,Wiesner'25]

The setup

Consider Type IIB string theory on CY 3-fold V.

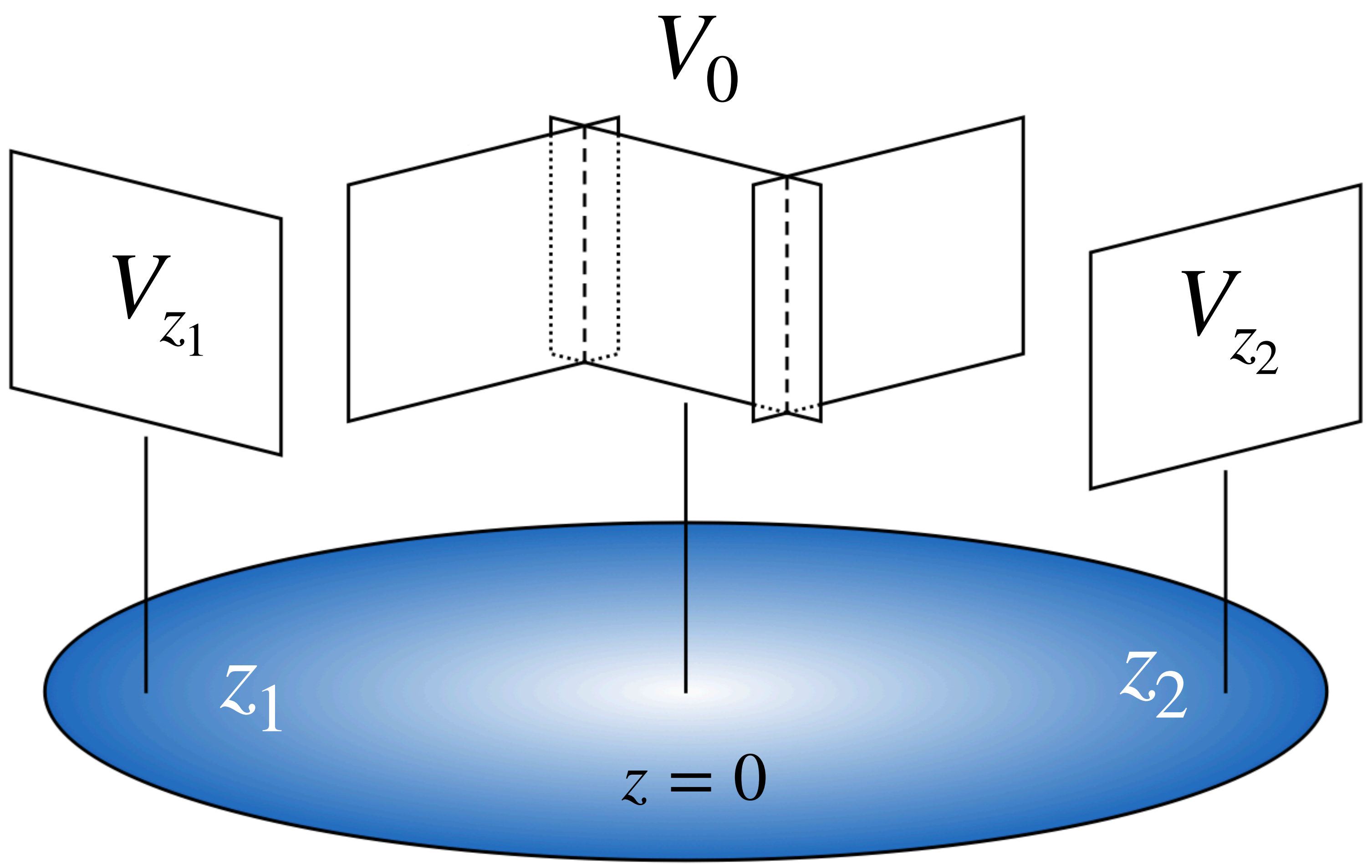
Infinite distance limit in **complex structure moduli** at fixed Kähler moduli:

$\Longrightarrow$ highly anisotropic space with **large and small 3-cycles**



Semi-stable degenerations

CY3 $\xrightarrow[\text{degeneration}]{\text{semi-stable}}$ **normally crossing components** **[Mumford 1972]**



$$V \to V_0 = V_1 \cup V_2 \cup \ldots \cup V_n$$

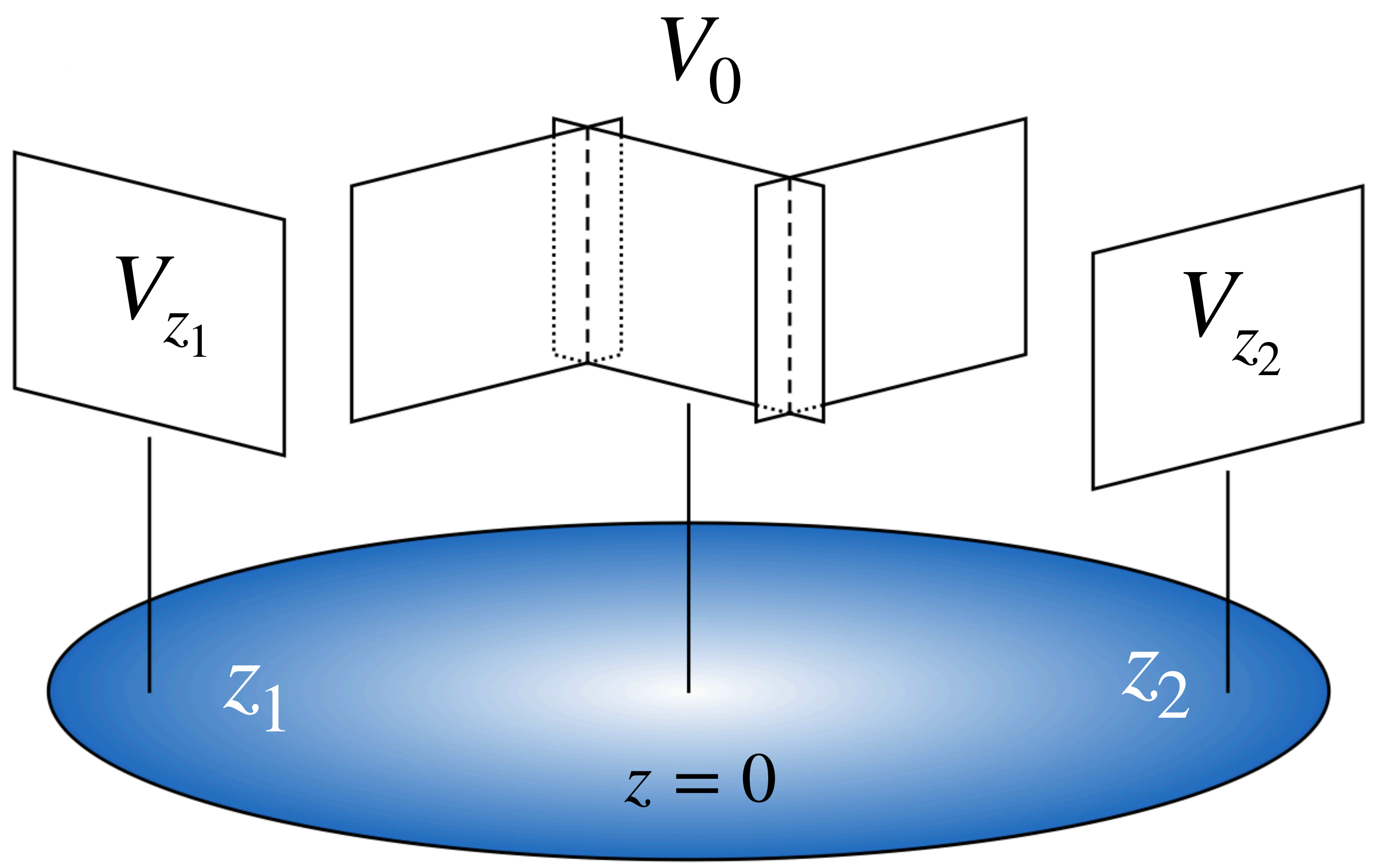
Example:

$$P = x_1^{12} + x_2^{12} + x_3^6 + x_4^6 + x_5^2 - u_1^{-1} x_1 x_2 x_3 x_4 x_5 - u_2^{-1} x_1^6 x_2^6 = 0 \quad \overset{u_2 \to 0}{\Longrightarrow} \quad V_0 = V_1 \cup V_2$$

$$V_1 = \{x_1^6 = 0\}\,, \quad V_2 = \{x_2^6 = 0\}$$

The II, III, IV of infinite distance

CY3 $\xrightarrow[\text{degeneration}]{\text{semi-stable}}$ **normally crossing components**



$$V_{i_1} \cap V_{i_2} \cap \ldots \cap V_{i_n} = V_{i_1 i_2 \ldots i_n}$$

Primary type of degeneration:

Highest complex codimension d of intersection loci:

[Mumford 1972]

type II: $V_{ij} \neq 0$: double surfaces but $V_{ijk} = 0$ $\quad d = 1$

type III: $V_{ij} \neq 0$: double surfaces, $V_{ijk} \neq 0$: triple curves, but $V_{ijkl} = 0$ $\quad d = 2$

type IV: $V_{ij} \neq 0\,,\quad V_{ijk} \neq 0\,,\quad V_{ijkl} \neq 0$ (point) $\quad d = 3$

Vanishing 3-cycles

Primary type of degeneration:

Codimension d of highest-dim intersection locus:

type II: $V_{ij} \neq 0$: double surfaces but $V_{ijk} = 0$ $d = 1$

type III: $V_{ij} \neq 0$: double surfaces, $V_{ijk} \neq 0$: triple curves, but $V_{ijkl} = 0$ $d = 2$

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Vanishing 3-cycles:

fibration $T^d \hookrightarrow \Gamma \to B_{3-d}$

real (3-d) cycle on (3-d) complex dim. intersection locus

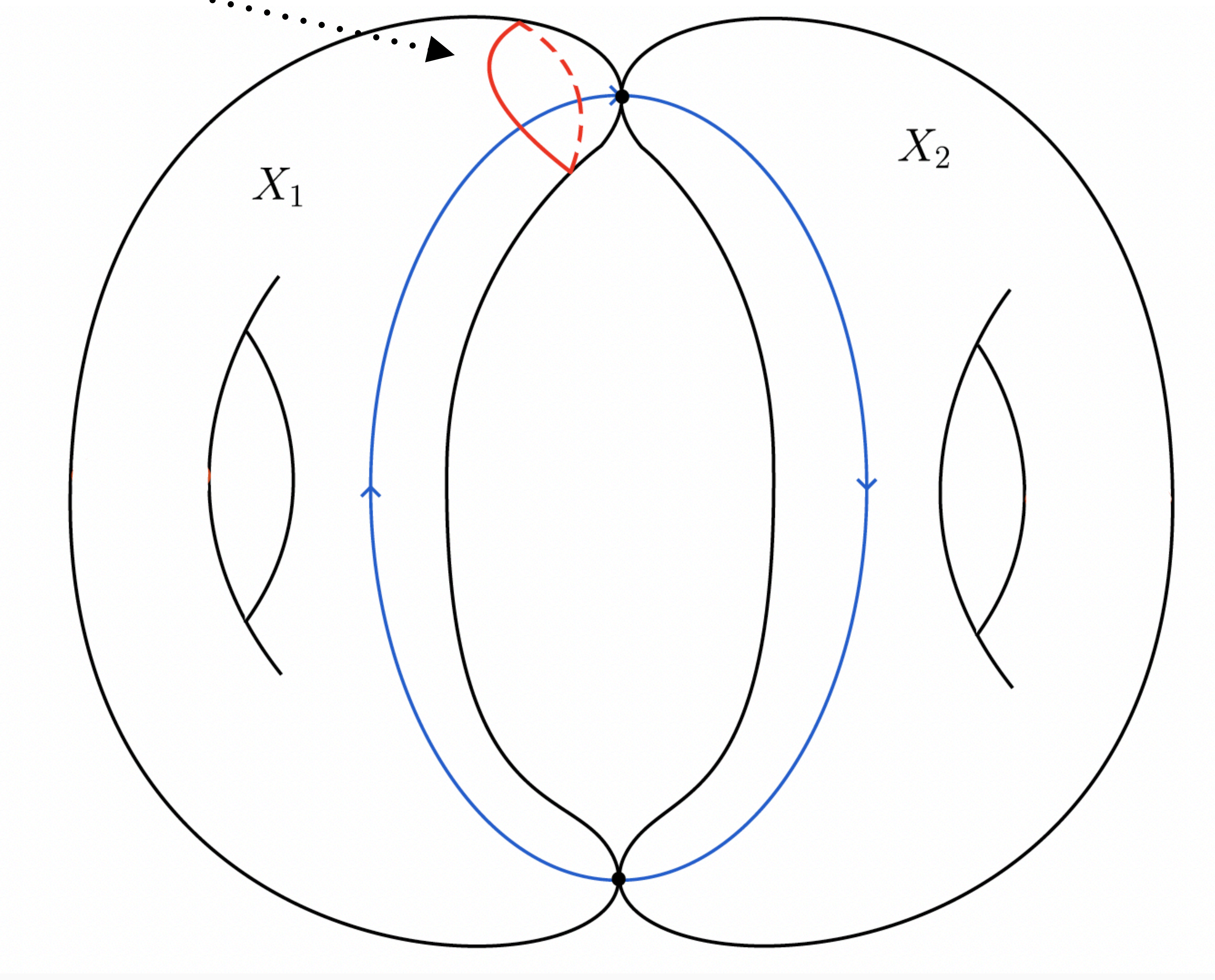
Vanishing 3-cycles

Vanishing 3-cycles:

fibration $T^d \hookrightarrow \Gamma \to B_{3-d}$

real (3-d) cycle on (3-d) intersection locus

$\Gamma =$ vanishing S^1



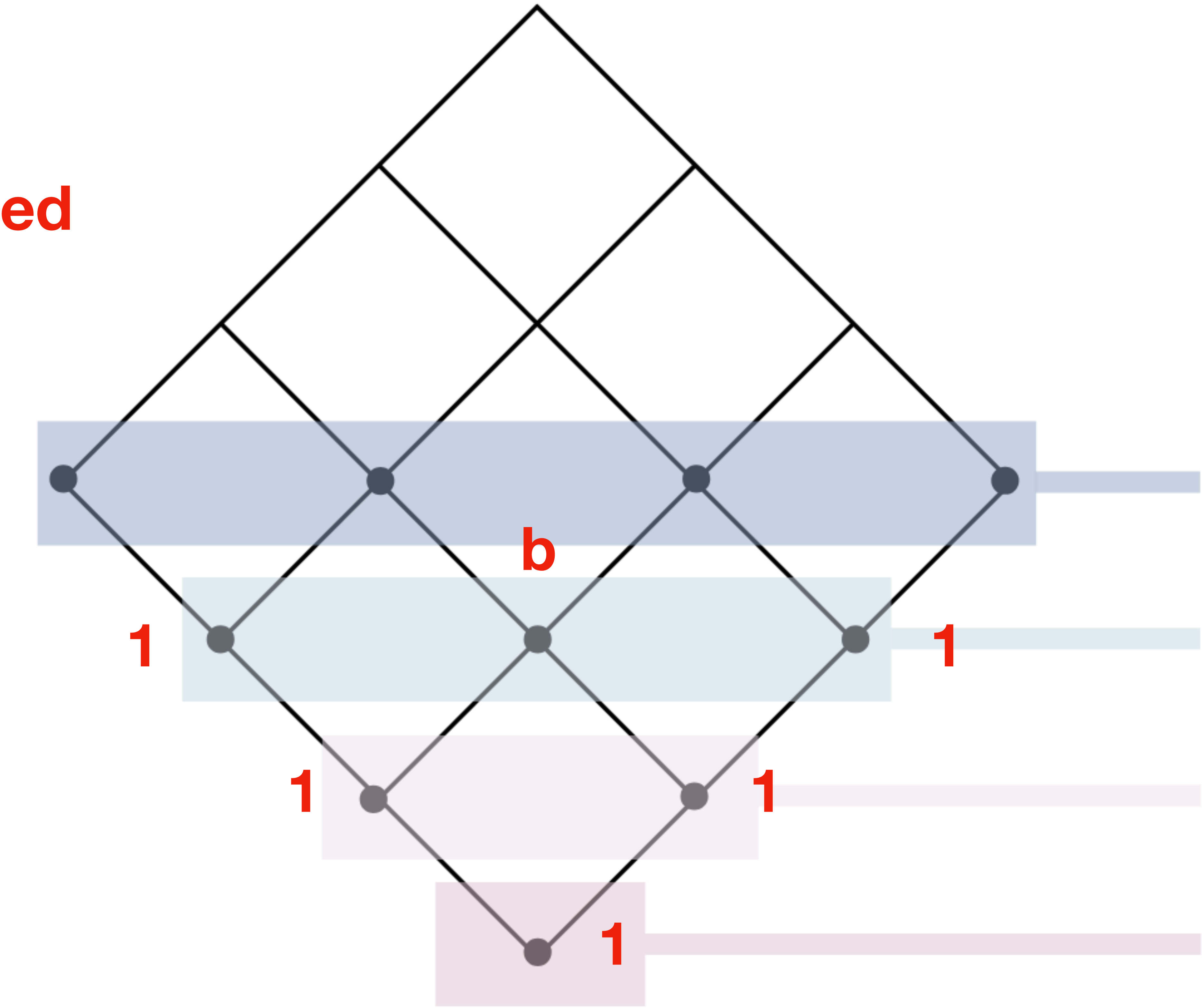
Toy example:
Degeneration of T^2

Vanishing 3-cycles in type II, III, IV

Vanishing 3-cycles: fibration $T^d \hookrightarrow \Gamma \to B_{3-d}$ ← real (3-d) cycle on (3-d) intersection locus

Geometric limiting mixed Hodge structure

[Deligne '71/'74]
[Morrison'84]



[Friedrich, Monnee,TW,Wiesner'25]
[Monnee,TW,Wiesner'25]

type I (finite distance)

type II $S^1 \hookrightarrow \Gamma^a \to C_2^a$

type III $T^2 \hookrightarrow \Gamma^{(A,B)} \to S_1^{(A,B)}$

type IV $\Gamma = T^3$

Vanishing 3-cycles in type II, III, IV

Infinite distance limit in complex structure moduli space of **Type IIB on CY 3-fold V**

$$\frac{\log u^j}{2\pi \mathrm{i}} = a^j + \mathrm{i}s^j \to \mathrm{i}\infty$$

axions **saxions**

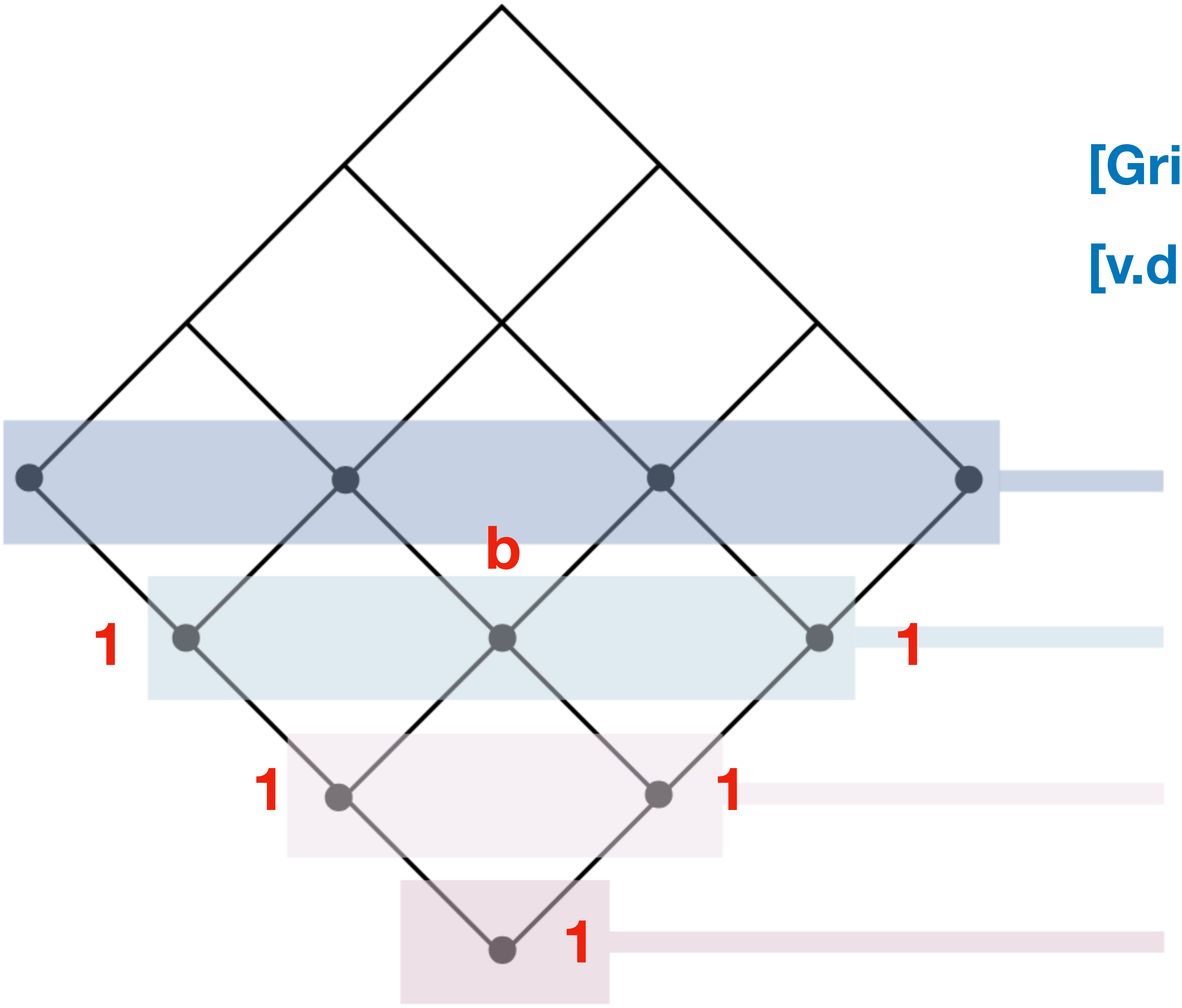
[Grimm,Palti,Valenzuela'18] [Grimm,Li,Palti'18] …

[v.d. Heisteeg'22] [Monnee'24]

Algebraic limiting mixed

Hodge structure

$$H^3(V,\mathbb{C}) = \bigoplus_{\ell=0}^{6} \mathrm{Gr}_\ell$$



type I (finite distance)

$\mathrm{vol}(\Gamma) \sim s^{-1}$ type II $S^1 \hookrightarrow \Gamma^a \to C_2^a$

$\mathrm{vol}(\Gamma) \sim s^{-2}$ type III $T^2 \hookrightarrow \Gamma^{(A,B)} \to S_1^{(A,B)}$

$\mathrm{vol}(\Gamma) \sim s^{-3}$ type IV $\Gamma = T^3$

[Cattani,Kaplan,Schmid'86]

Physics interpretation

Infinite distance limit in complex structure moduli space of **Type IIB on CY 3-fold** V

$$\frac{\log u^j}{2\pi \mathrm{i}} = a^j + \mathrm{i}s^j \to \mathrm{i}\infty$$

axions **saxions**

$\mathrm{vol}(\Gamma) \sim s^{-1}$	type II	$S^1 \hookrightarrow \Gamma^a \to C_2^a$	**Emergent string limits**
$\mathrm{vol}(\Gamma) \sim s^{-2}$	type III	$T^2 \hookrightarrow \Gamma^{(A,B)} \to S_1^{(A,B)}$	**Decompactification 4d → 6d**
$\mathrm{vol}(\Gamma) \sim s^{-3}$	type IV	$\Gamma = T^3$	**Decompactification 4d → 5d**

Algebraic mixed Hodge structure + **Geometric mixed Hodge structure** $\Longrightarrow$ **Physics**

Type IV as decompactification $4d \to 5d$

1 leading vanishing 3-cycle Γ of topology T^3 $\Longrightarrow$ 1 tower of BPS states from wrapped D3-branes

behaving like 1 KK tower

Reason:

$$\boxed{\text{BPS index: } \Omega(n\Gamma) = \Omega(\Gamma)\,, \quad n > 0}$$

[Monnee,TW,Wiesner'25]

From this we can in fact show: $\Omega(\Gamma) = -\chi(V)$

$$\Omega^{(0)}_{\text{BPS,5d}} = -\sum_{j_R} (-1)^{2j_R}(2j_R+1)n^0_{(j_L,j_R)} = -2n^{(0)}_H + 2n^{(0)}_V + 4 \qquad n^{(0)}_H = h^{1,1}(V) + 1\,, \quad n^{(0)}_V = h^{2,1}(V) - 1$$

Known by mirror symmetry for large complex structure points,

but **true more generally for all type IV degenerations and without using mirror symmetry**!

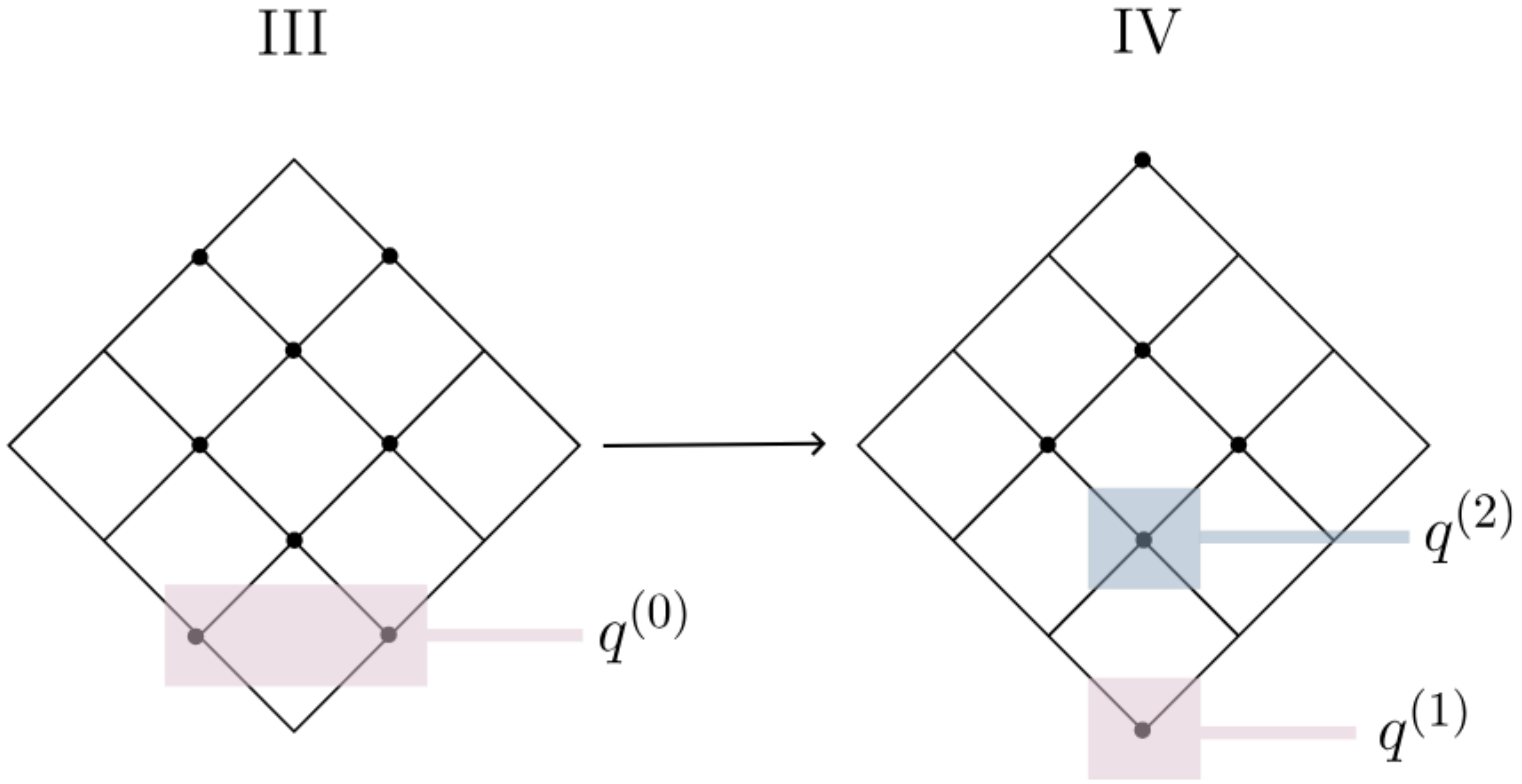
Type III as decompactification $4d \to 6d$

2 leading vanishing 3-cycles $\Gamma^{A,B}$ of topology T^3 $\implies$ 2 towers of BPS states from wrapped D3-branes **behaving as 2 KK towers**

In fact: $\boxed{\text{BPS index: } \Omega(n\Gamma^{(i)}) = \Omega(\Gamma^{(i)}) = -\chi(V)\,, \quad n > 0 \;\; i = A, B}$

[Monnee,TW,Wiesner'25]

By noting that
enhancement
type III to IV
is always possible



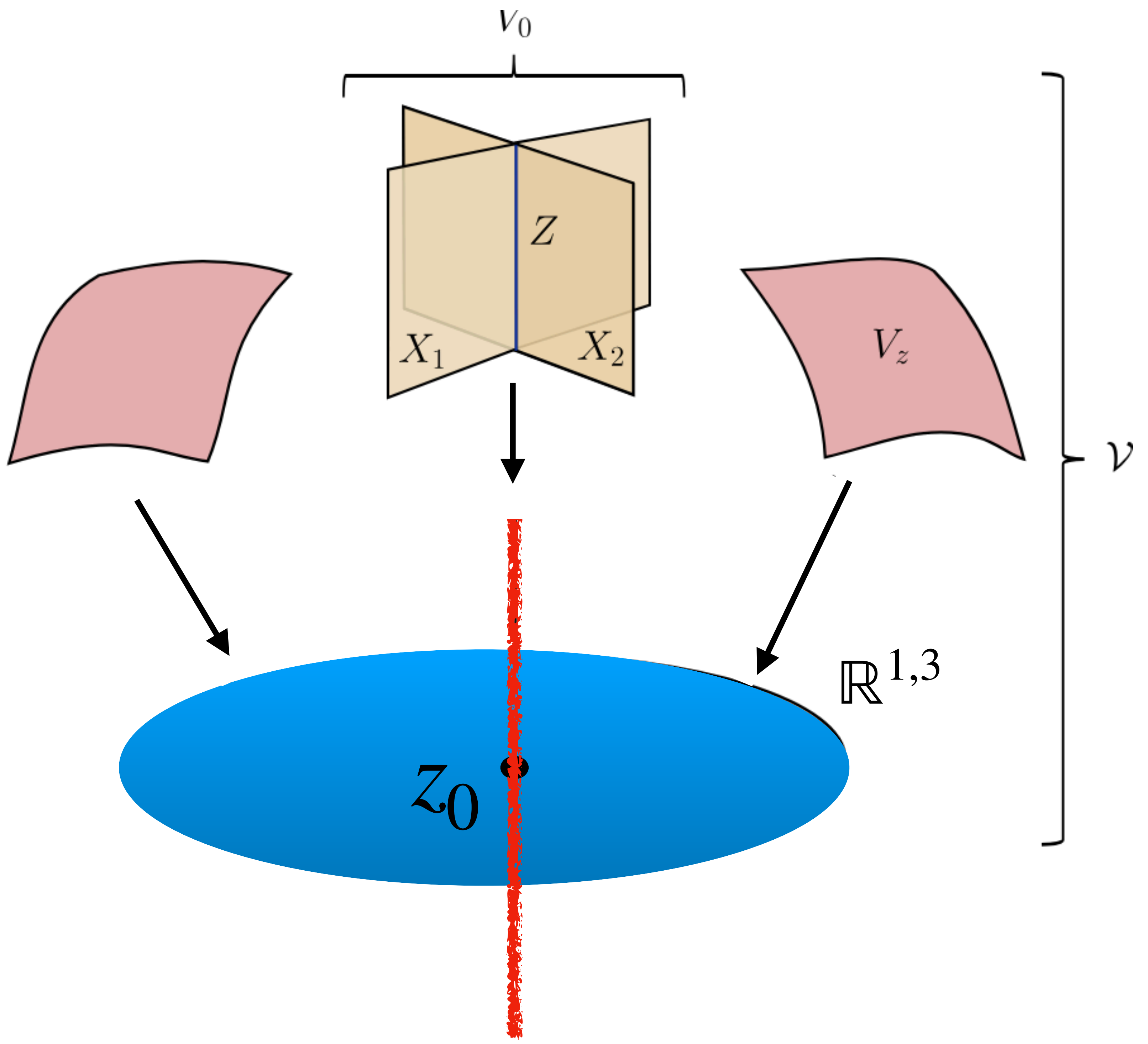
Type II as emergent string limit

By identifying tensionless SUGRA BPS string (EFT string) as a heterotic or critical string

Key: V_{12} is K3 or T^4

D3 branes on $\Gamma^{(a)}$: Dual winding states of that string

Details: **[Friedrich,Monnee,Wiesner,TW'25]**



Interpretation of enhancement chains

1) EFT string limits: $s^{k_1} \sim s^{k_2} \sim \lambda \to \infty$

Physics determined by type of *enhanced* singularity

II → III: 6d decomp.

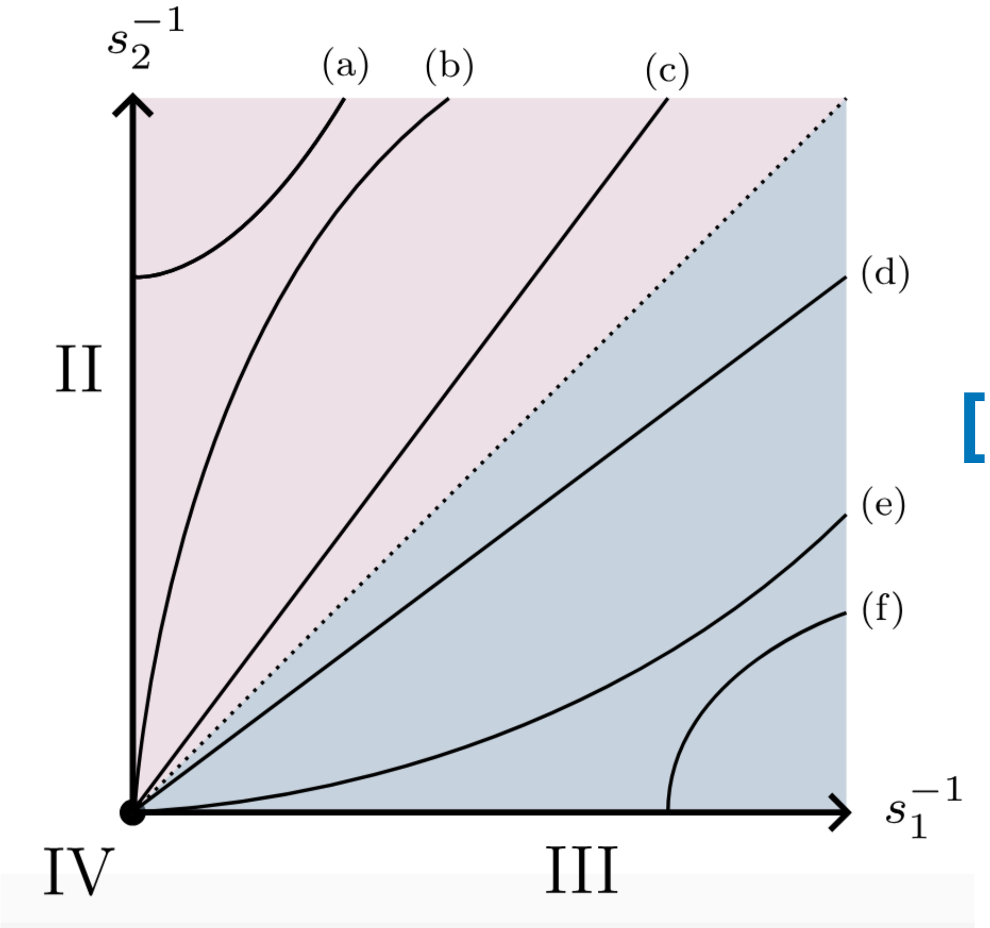
II → IV: 5d decomp.

III → IV: 5d decomp.

cf.
[Lanza,Marchesano, Martucci,Valezuela'20/21]
[Catellano,Ibanez,Herraez'22]
[Castellano,Ruiz,Valenzuela'23]
....

2) Non-EFT string limits: $s^{k_1} \sim \lambda, \quad s^{k_2} \sim \lambda^{\alpha_{k_2}} \quad \alpha_{k_2} < 1\,, \ldots$

Gravitational frame determined by type of *first* singularity with subsequent limits taken therein



[Monnee,TW,Wiesner'25]

II → III: emergent string, decompactified to 6d

II → IV: emergent string, decompactified to 5d

III → IV: anisotropic 6d decompactification

II → III → IV: emergent string, decompactified to anisotropic 6d

Part 2:

Testing perturbative heterotic string theory with ALP coupling-to-mass ratios

[Agrawal,Nee,Reig'22, '24] [Reig,TW'25]

Axions in the heterotic string

i) model independent axion: $a = \int_X B_6$

ii) model independent axions: $b_i = \int_{C_i} B_2$

iii) non-perturbative axions: $\tilde{b}_r = \int_{\Gamma_r} \tilde{B}_2$

from NS5-branes along curve Γ_r

Couplings $\int_{\mathbb{R}^{1,3}} (\text{axion})\, F \wedge F$ from Green-Schwarz terms :

➡ $S_{\text{GS}} = -\frac{1}{768\pi^3} \int_{\mathbb{R}^{1,3}\times X} B_2 \wedge X_8$

$$X_8 = -(\mathrm{tr}_1\mathscr{F}^2 + \mathrm{tr}_2\mathscr{F}^2)\mathrm{tr}\mathscr{R}^2 + 2\left[(\mathrm{tr}_1\mathscr{F}^2)^2 + (\mathrm{tr}_2\mathscr{F}^2)^2 - \mathrm{tr}_1\mathscr{F}^2\mathrm{tr}_2\mathscr{F}^2\right] + \mathrm{tr}\mathscr{R}^4 + \frac{1}{4}(\mathrm{tr}\mathscr{R}^2)^2$$

➡ 5-brane dependent counter-terms

$$S_{GS}^{\text{new, 2}} = \frac{1}{64\pi^3}\sum_r N_r \int_{\Gamma_r} \tilde{B}_2^{(r)} \wedge \left(\mathrm{tr}_1\mathscr{F}^2 - \mathrm{tr}_2\mathscr{F}^2\right)\ .$$

Axion couplings in the heterotic string

Result:

$$\mathcal{L} = \frac{\theta_1}{8\pi}\mathrm{tr}_1 F^2 + \frac{\theta_2}{8\pi}\mathrm{tr}_2 F^2$$

$E_8^{(1)}$ $E_8^{(2)}$

$a = \int_X B_6$ $b_i = \int_{C_i} B_2$ **field theory axions** $\tilde{b}_r = \int_{\Gamma_r} \tilde{B}_2$

$$\theta_1 = a + \sum_i n_i^{(1)} b_i + \sum_j m_j^{(1)} c_j + \sum_r N_r \tilde{b}_r \,,$$

$$\theta_2 = a + \sum_i n_i^{(2)} b_i + \sum_j m_j^{(2)} c_j - \sum_r N_r \tilde{b}_r \,.$$

$$n_i^{1,2} = \int_X \frac{1}{16\pi^2}\beta_i \wedge \left(\mathrm{tr}_{1,2}F^2 - \frac{1}{2}\mathrm{tr}R^2 + \frac{1}{3}\sum_r N_r \bar{\gamma}_r\right)$$

$$\mathrm{tr}_1 \bar{F}^2 + \mathrm{tr}_2 \bar{F}^2 - \mathrm{tr}\bar{R}^2 = \sum_r N_r [\Gamma_r]$$

ALP coupling-to-mass ratios

$$\mathcal{L} = \frac{\theta_1}{8\pi}\mathrm{tr}_1 F^2 + \frac{\theta_2}{8\pi}\mathrm{tr}_2 F^2$$

- If $SU(3) \times SU(2) \times U(1)_Y \subset E_8^{(1)}$: Every axion coupling directly to $U(1)_{e.m.}$ also couples to QCD!
- Any other axion coupling to $U(1)_{e.m.}$ can do so only through kinetic or mass mixing with QCD axion e.g. for light axions mass mixing suppressed by $m_a^2/m_{\mathrm{a,QCD}}^2$

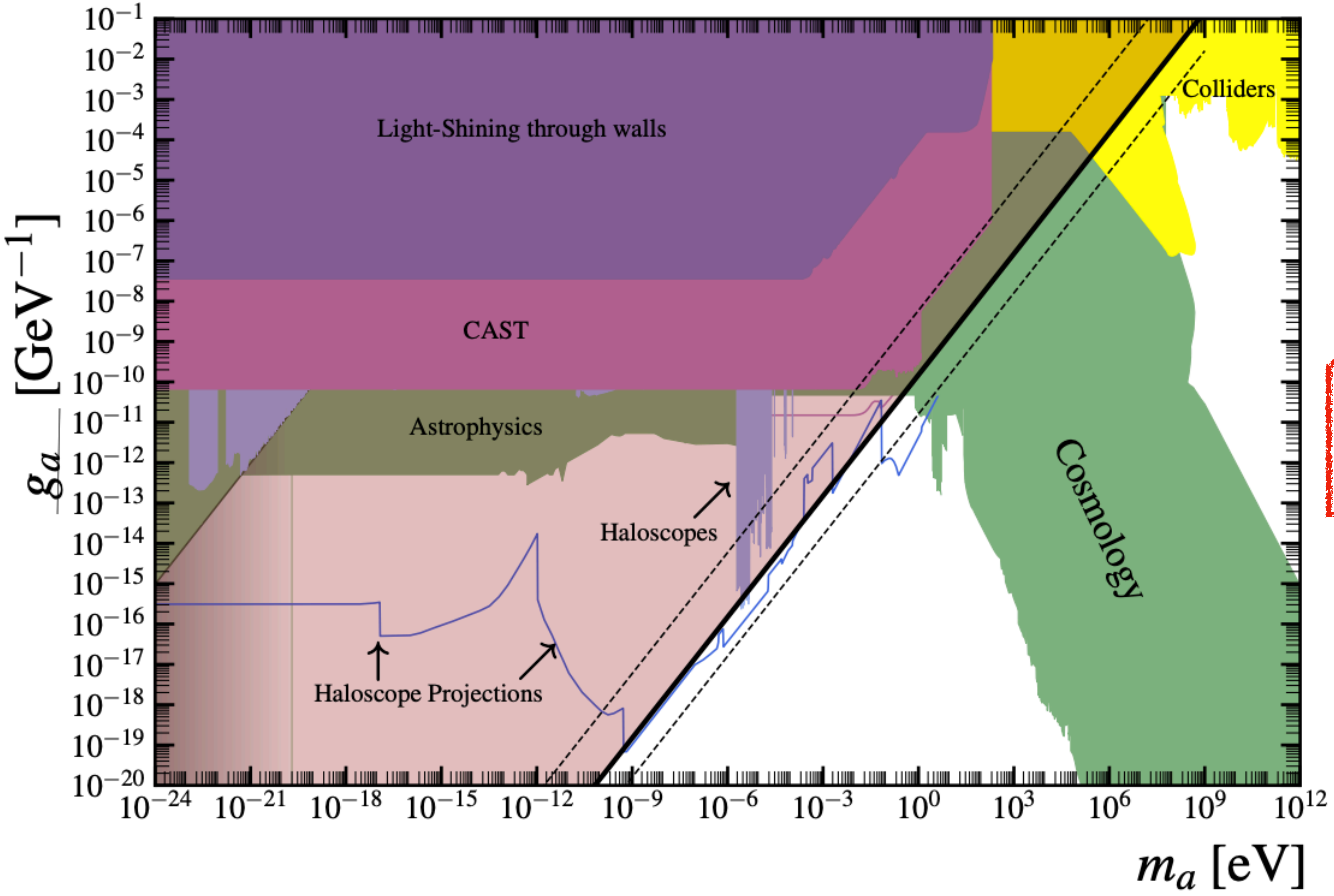
Key consequence:

$$\boxed{\frac{g_{ALP,\gamma}}{m_{\mathrm{ALP}}} \leq \frac{g_{a_{\mathrm{QCD}},\gamma}}{m_{a_{\mathrm{QCD}}}}}$$

[Agrawal, Nee, Reig '22]
[Agrawal, Nee, Reig '24]

holds for any general GUT!

ALPs and heterotic GUTs



[Agrawal, Nee, Reig ’22 + ’24]

Finding an ALP above black line would rule out any GUT, including heterotic string with SM inside one E_8

Non-standard embeddings

Loophole: Non-standard embedding of SM into both $E_8^{(1)}$ and $E_8^{(2)}$

Most interesting case: **Hypercharge** embedded into **both** $E_8^{(i)}$

[Blumenhagen,Moster,TW'06]
[Blumenhagen,Honecker,TW'05]

Can be achieved by embedding gauge backgrounds with **non-trivial first Chern class (U(1) flux)**

$$\begin{tikzcd}
E_8^{(1)}\times E_8^{(2)} \arrow[r] & (G_1\times\prod_{m_1}U(1)_{m_1}) \arrow[d, dotted] & \times & (G_2\times\prod_{m_2}U(1)_{m_2}) \arrow[d, dotted] \\
& SU(3)\times SU(2)\times U(1)_0 \arrow[dr, dotted] & & U(1)_1\times(\text{rest}) \arrow[dl, dotted] \\
& & U(1)_Y = aU(1)_0 + bU(1)_1 &
\end{tikzcd}$$

Stückelberg massless combination

✓

Examples with
exactly 3 generations of
SM matter
and no chiral exotics
on simply connected
CY 3-folds

Gauge coupling unification

Non-standard hypercharge embedding

$$\frac{1}{\alpha_Y} = \frac{5/3}{\alpha_{\mathrm{GUT}}} + \frac{k_1^{(2)}}{\alpha_{\mathrm{GUT}}} + \Delta_Y$$

[Blumenhagen,Moster,TW'06]

$k_1^{(2)}$: level of embedding of $U(1)_Y$ into $E_8^{(2)}$

e.g. for 2 U(1): $k_1^{(2)} = \frac{5}{3}\left(\frac{\kappa_{0,0}\ell_0}{\kappa_{1,1}\ell_1}\right)^2 \frac{\eta_{1,1}}{\eta_{0,0}}$

$\kappa_{i,i} : \; tr_{\mathrm{E}_8} F^2 = \kappa_{i,i} f_i^2 + \ldots$ $\qquad$ $\eta_{i,i} : trF\bar{F} = \eta_{i,i} f_i \bar{f}_i + \ldots$

$c_1(L_i) = \ell_i v \in H^2(X)$

Δ_Y: 1-loop threshold corrections

Required: $$0 \overset{!}{=} \frac{k_1^{(2)}}{\alpha_{\mathrm{GUT}}} + \Delta_Y + \Delta$$

←········ from intermediate mass states

Axions in the heterotic string

New: **Two ALPs** coupling to electro-magnetism due to U(1) fluxes

$$\mathcal{L} = \frac{\theta_1}{8\pi}\left[k_3^{(1)}\alpha_3 \mathrm{tr} G\tilde{G} + \left(\frac{(k_1^{(1)})^2}{k_1^{(1)}+k_1^{(2)}} + k_2^{(1)}\right)\alpha_{\mathrm{em}}F_{\mathrm{em}}\tilde{F}_{\mathrm{em}}\right] + \frac{\theta_2}{8\pi}\left(\frac{(k_1^{(2)})^2}{k_1^{(1)}+k_1^{(2)}}\right)\alpha_{\mathrm{em}}F_{\mathrm{em}}\tilde{F}_{\mathrm{em}} + \frac{\varphi}{8\pi}\frac{(\kappa_{0,0}\ell_0)^2}{\eta_{0,0}}k_1^{(1)}\alpha_{\mathrm{em}}F_{\mathrm{em}}\tilde{F}_{\mathrm{em}}\,.$$

[Reig,TW'25]

Origin of φ:

$$S_{\mathrm{GS}} \supset \frac{1}{768\pi^3}\int B\wedge \mathrm{tr}_i(F\bar{F})^2 - \frac{1}{768\pi^3}\int B\wedge \mathrm{tr}_1(F\bar{F})\mathrm{tr}_2(F\bar{F})$$

$$\theta_1 = a + \sum_i n_i^{(1)}b_i + \sum_j m_j^{(1)}c_j + \sum_r N_r\tilde{b}_r\,,$$

$$\theta_2 = a + \sum_i n_i^{(2)}b_i + \sum_j m_j^{(2)}c_j - \sum_r N_r\tilde{b}_r\,.$$

Does this evade the previous bounds?

$$\varphi = \sum_j b_j \int \beta_j \wedge c_1^2(L) = \sum_j \tilde{n}_j b_j$$

Axions in the heterotic string

Key observation:

θ_2, φ receive a potential from small $E_8^{(2)}$ instantons due to Euclidean NS5-branes

Ignoring effect of gauge threshold corrections for now:

$$\boxed{V(\theta_2,\varphi) = \frac{16\pi}{\alpha_{\rm GUT}}\left(\frac{M_{\rm UV}}{m_f}\right)^{n_f} m_{\rm susy}M_{\rm UV}^3\, e^{-\frac{2\pi}{\alpha_{\rm GUT}}}\cos(\theta_2) + (\theta_2 \leftrightarrow \varphi)}$$

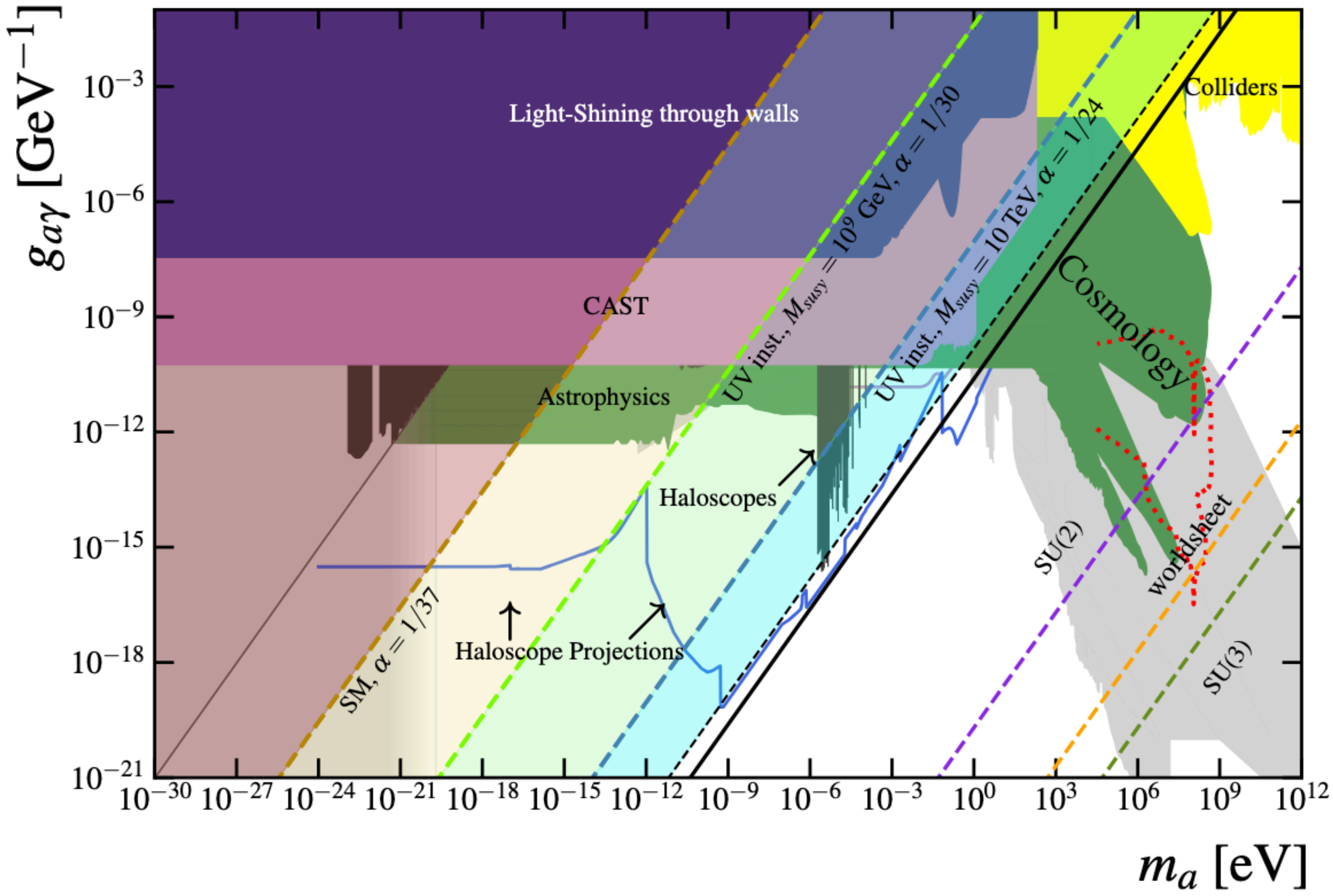
[Reig,TW'25]

Chiral suppression factor

from n_f intermediate superfields:
increases mass due to
running of gauge coupling!

at tree-level: $\alpha_{E_8^{(2)}} = \alpha_{\rm GUT}$

precise value key for suppression!



[Reig,TW'25]

conservative bounds
ignoring thresholds

Compatibility with gauge couplings

$$\frac{1}{\alpha_Y} = \frac{5/3}{\alpha_{\rm GUT}} + \frac{k_1^{(2)}}{\alpha_{\rm GUT}} + \Delta_Y \qquad \text{requires} \qquad 0 = \frac{k_1^{(2)}}{\alpha_{\rm GUT}} + \Delta_Y + (\Delta \text{ from intermediate states})$$

All three effects decrease $g_{a\gamma}/m_a$ for heterotic ALPs!

previous tree-level plot
is (very!) conservative

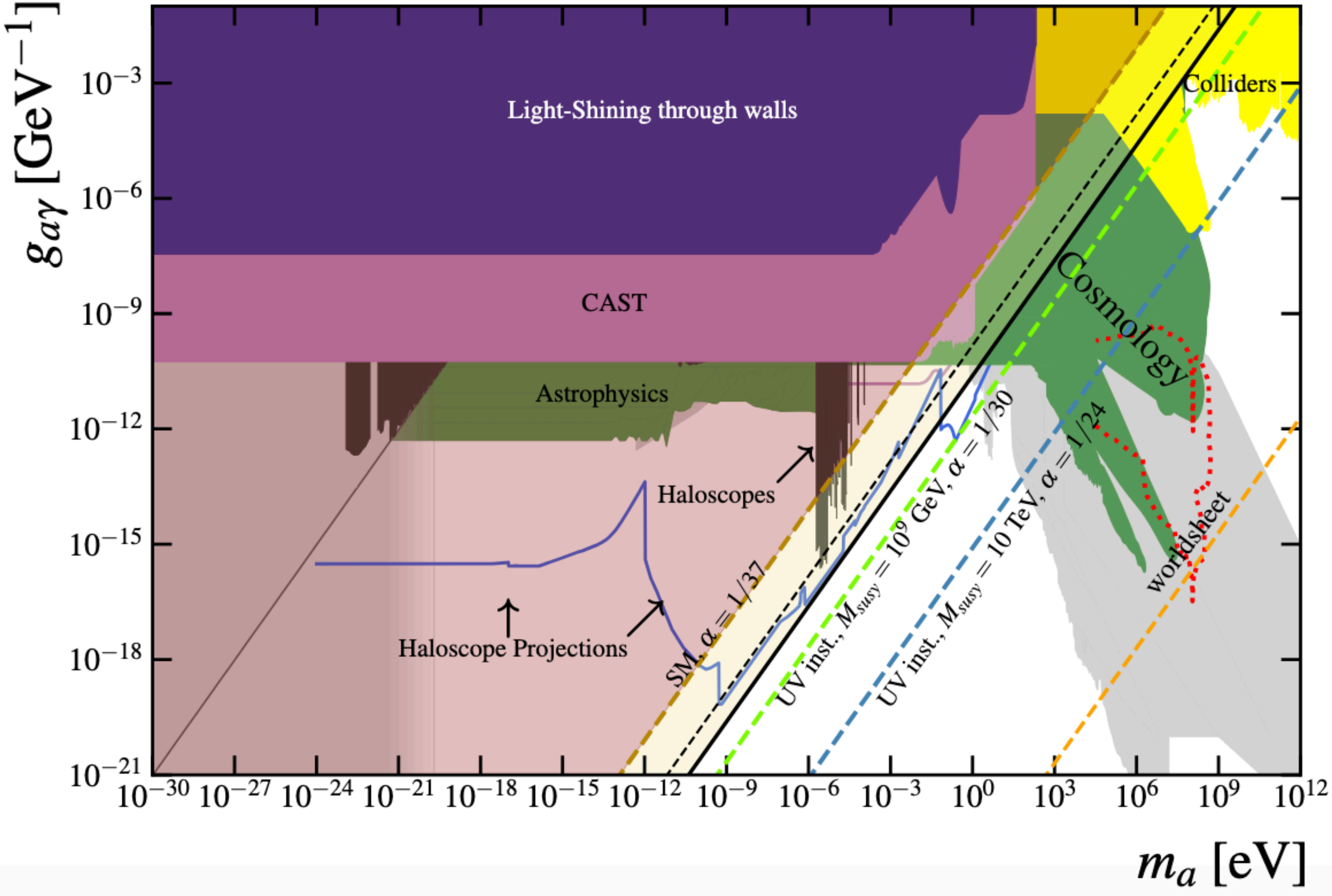
1) **Engineering $k_1^{(2)} \ll 1$:** decreases coupling to photons by $(k_1^{(2)})^2$

2) **Intermediate matter:** increases $\alpha_{\rm GUT}$ $\implies$ increases masses

e.g. $\alpha_{\rm GUT} \geq \frac{1}{22} \implies$ QCD bound obeyed!

3) **Invoking threshold corrections:**

- more complicated analysis, but unless perturbative control is lost, $g_{a\gamma}/m_a$ **decreases**



[Reig,TW'25]

for thresholds
75% of tree-level
(borderline perturbative)

Example:
cosmic birefringence
axion

$$m_a = 10^{-30}\mathrm{eV}$$
$$g_{a\gamma} = 10^{-18}\mathrm{GeV}^{-1}$$

would rule out
perturbative
heterotic string!

Summary

Part 1) Testing ESC via stable degenerations:

$\mathrm{vol}(\Gamma) \sim s^{-1}$	type II	$S^1 \hookrightarrow \Gamma^a \to C_2^a$	**Emergent string limits**
$\mathrm{vol}(\Gamma) \sim s^{-2}$	type III	$T^2 \hookrightarrow \Gamma^{(A,B)} \to S_1^{(A,B)}$	**Decompactification 4d → 6d**
$\mathrm{vol}(\Gamma) \sim s^{-3}$	type IV	$\Gamma = T^3$	**Decompactification 4d → 5d**

Part 2) Testing the perturbative heterotic string via ALP coupling-to-mass ratios:

Finding an ALP far above QCD line would rule out perturbative heterotic string
- and comparable GUT(-like) models