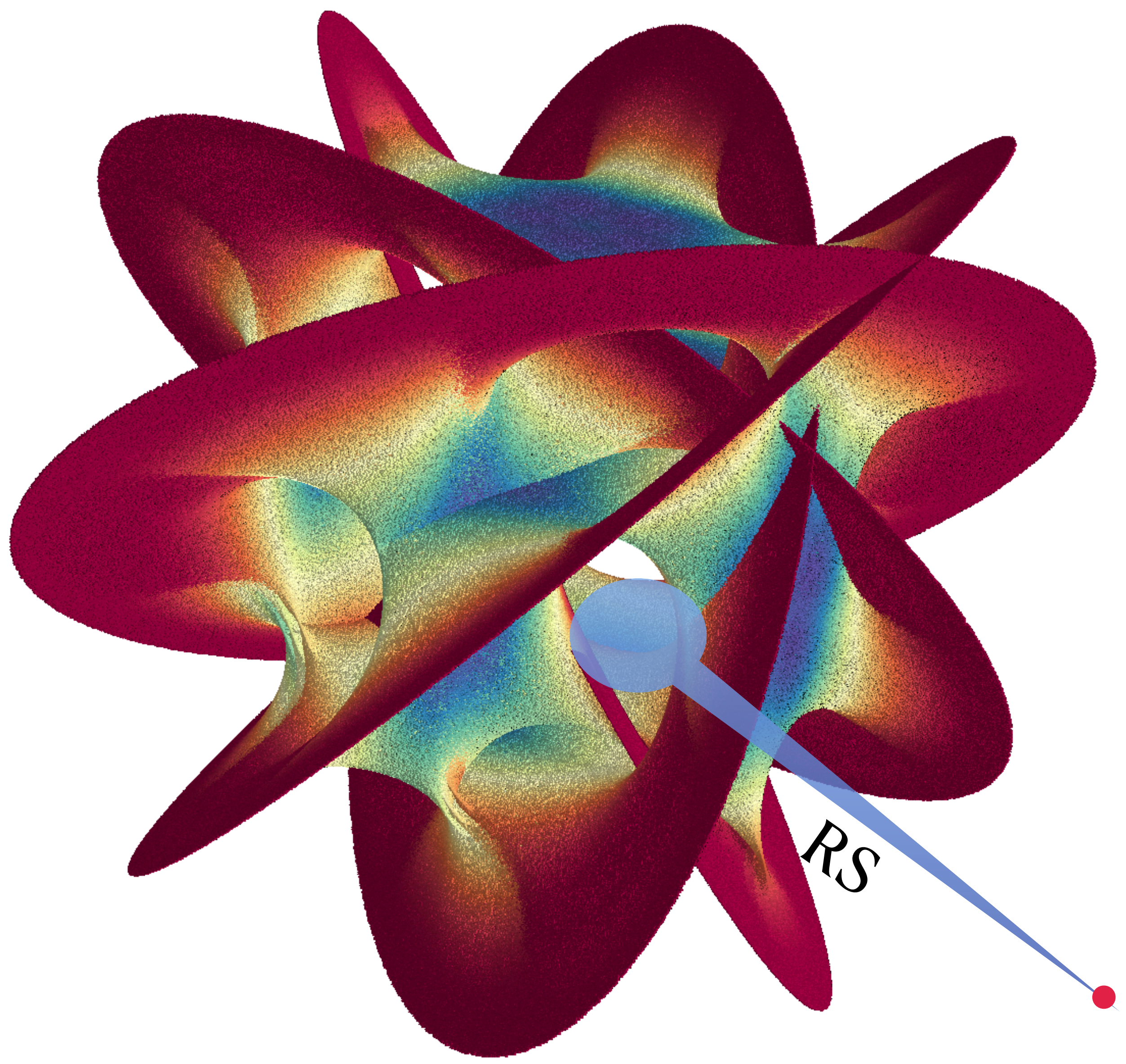
Candidate De Sitter Vacua



based on upcoming work with Liam McAllister, Richard Nally and Andreas Schachner

and previous works with Mehmet Demirtas, Manki Kim and Andres Rios-Tascon

Jakob Moritz

CERN

06/05/2024 at Strings 2024

upshot of this talk:

First concrete candidates for de Sitter vacua
as envisioned by Kachru, Kallosh, Linde and Trivedi (KKLT)

upshot of this talk:

First concrete candidates for de Sitter vacua
as envisioned by Kachru, Kallosh, Linde and Trivedi (KKLT)

with an important caveat: our candidates come with finite control parameters, such as the string coupling, and are potentially vulnerable to unknown corrections.

Plan:

1. Some Motivation
2. The KKLT scenario
3. Vacua with small superpotential
4. Warped throats and “Uplift” to de Sitter: an example
5. Control over corrections
6. Conclusions

Plan:

1. Some Motivation
2. The KKLT scenario
3. Vacua with small superpotential
4. Warped throats and “Uplift” to de Sitter: an example
5. Control over corrections
6. Conclusions

An important goal for many string theorists is to understand the imprint of Quantum Gravity on observable scales

An important goal for many string theorists is to understand the imprint of Quantum Gravity on observable scales

One possible avenue to this end, is to construct and study semi-realistic cosmologies and models of particle physics in string theory.

An important goal for many string theorists is to understand the imprint of Quantum Gravity on observable scales

One possible avenue to this end, is to construct and study semi-realistic cosmologies and models of particle physics in string theory.

By constructing solutions realizing exponential hierarchies, one might begin to understand the UV origin of the hierarchies that dominate our universe, e.g., the cosmological constant problem,

$$\rho_{cc} \approx 10^{-120} M_{\rm pl}^4$$

(and perhaps one might gain insight into the microscopic meaning of the de Sitter entropy?)

But unfortunately, constructing such solutions with realistic scales,

$$M_{SUSY} \gtrsim \mathrm{TeV}$$

does not currently appear feasible...

But unfortunately, constructing such solutions with realistic scales,

$$M_{SUSY} \gtrsim \text{TeV}$$

does not currently appear feasible...

But, one can study a supersymmetric version of the cosmological constant problem by finding vacua of stringy F-term potentials:

$$V_F = e^K (g^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2)$$

But unfortunately, constructing such solutions with realistic scales,

$$M_{SUSY} \gtrsim \text{TeV}$$

does not currently appear feasible...

But, one can study a supersymmetric version of the cosmological constant problem by finding vacua of stringy F-term potentials:

$$V_F = e^K (g^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2)$$

with small superpotential: $\langle W \rangle \ll 1$

but without any fine tuning: $g^{a\bar{b}} D_a W \overline{D_b W} \sim |W|^2$

But unfortunately, constructing such solutions with realistic scales,

$$M_{SUSY} \gtrsim \text{TeV}$$

does not currently appear feasible...

But, one can study a supersymmetric version of the cosmological constant problem by finding vacua of stringy F-term potentials:

$$V_F = e^K (g^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2)$$

with small superpotential: $\langle W \rangle \ll 1$

but without any fine tuning: $g^{a\bar{b}} D_a W \overline{D_b W} \sim |W|^2$

In this way one can hope to construct controlled (A)dS vacua in string theory!

Plan:

1. Some Motivation
2. The KKLT scenario
3. Vacua with small superpotential
4. Warped throats and “Uplift” to de Sitter: an example
5. Control over corrections
6. Conclusions

In 2003 Kachru, Kallosh, Linde and Trivedi proposed an avenue to constructing de Sitter vacua in string theory. A great many aspects of string compactifications were assumed to be realizable, at least in principle:

In 2003 Kachru, Kallosh, Linde and Trivedi proposed an avenue to constructing de Sitter vacua in string theory. A great many aspects of string compactifications were assumed to be realizable, at least in principle:

1. a Calabi-Yau threefold X
2. a holomorphic O3/O7 orientifold projection $(-1)^{F_L} \circ \Omega \circ (z^\alpha \mapsto f^\alpha(z))$
3. a choice of threeform fluxes yielding a very small flux superpotential:

$$W_0 \ll 1$$

4. sufficiently generic non-perturbative corrections to the superpotential.
5. an F-term vacuum for Kähler moduli.
6. a warped throat region with redshift of scales of order $|W_0|$, hosting a supersymmetry breaking anti-D3 brane state.

In 2003 Kachru, Kallosh, Linde and Trivedi proposed an avenue to constructing de Sitter vacua in string theory. A great many aspects of string compactifications were assumed to be realizable, at least in principle:

1. a Calabi-Yau threefold X
2. a holomorphic O3/O7 orientifold projection $(-1)^{F_L} \circ \Omega \circ (z^\alpha \mapsto f^\alpha(z))$
3. a choice of threeform fluxes yielding a very small flux superpotential:

$$W_0 \ll 1$$

4. sufficiently generic non-perturbative corrections to the superpotential.
5. an F-term vacuum for Kähler moduli.
6. a warped throat region with redshift of scales of order $|W_0|$, hosting a supersymmetry breaking anti-D3 brane state.

The point of this talk is to show you how to actually do all this!

Calabi-Yau Orientifolds

(steps 1. and 2.)

Type IIB string theory compactified on a Calabi-Yau threefold X gives an effective four dimensional supergravity theory with 8 supercharges.

Calabi-Yau Orientifolds

(steps 1. and 2.)

Type IIB string theory compactified on a Calabi-Yau threefold X gives an effective four dimensional supergravity theory with 8 supercharges.

Dividing string spectrum by an orientifold involution of O3/O7 type,

$$(-1)^{F_L} \circ \Omega \circ (z^\alpha \mapsto f^\alpha(z))$$

Calabi-Yau Orientifolds

(steps 1. and 2.)

Type IIB string theory compactified on a Calabi-Yau threefold X gives an effective four dimensional supergravity theory with 8 supercharges.

Dividing string spectrum by an orientifold involution of O3/O7 type,

$$(-1)^{F_L} \circ \Omega \circ (z^\alpha \mapsto f^\alpha(z))$$

Left-moving spacetime fermion number

Calabi-Yau Orientifolds

(steps 1. and 2.)

Type IIB string theory compactified on a Calabi-Yau threefold X gives an effective four dimensional supergravity theory with 8 supercharges.

Dividing string spectrum by an orientifold involution of O3/O7 type,

$$(-1)^{F_L} \circ \Omega \circ (z^\alpha \mapsto f^\alpha(z))$$

Left-moving spacetime fermion number

Worldsheet parity

Calabi-Yau Orientifolds

(steps 1. and 2.)

Type IIB string theory compactified on a Calabi-Yau threefold X gives an effective four dimensional supergravity theory with 8 supercharges.

Dividing string spectrum by an orientifold involution of O3/O7 type,

$$(-1)^{F_L} \circ \Omega \circ (z^\alpha \mapsto f^\alpha(z))$$

Left-moving spacetime fermion number

Worldsheet parity

Any holomorphic involution on X with smooth fixed locus, and fixed points at dimension 0 and 4

Calabi-Yau Orientifolds

(steps 1. and 2.)

Type IIB string theory compactified on a Calabi-Yau threefold X gives an effective four dimensional supergravity theory with 8 supercharges.

Dividing string spectrum by an orientifold involution of O3/O7 type,

$$(-1)^{F_L} \circ \Omega \circ (z^\alpha \mapsto f^\alpha(z))$$

Left-moving spacetime fermion number

Worldsheet parity

Any holomorphic involution on X with smooth fixed locus, and fixed points at dimension 0 and 4

yields a four dimensional effective theory with 4 supercharges.

Calabi-Yau Orientifolds

(steps 1. and 2.)

Type IIB string theory compactified on a Calabi-Yau threefold X gives an effective four dimensional supergravity theory with 8 supercharges.

Dividing string spectrum by an orientifold involution of O3/O7 type,

$$(-1)^{F_L} \circ \Omega \circ (z^\alpha \mapsto f^\alpha(z))$$

Left-moving spacetime fermion number

Worldsheet parity

Any holomorphic involution on X with smooth fixed locus, and fixed points at dimension 0 and 4

yields a four dimensional effective theory with 4 supercharges.

The light chiral multiplets are:

Grimm, Louis '04

$h^{1,1}_+$	Kähler moduli T_i
$h^{2,1}_-$	Complex structure moduli z^a
	+the axio-dilaton τ

Calabi-Yau Orientifolds

(steps 1. and 2.)

Type IIB string theory compactified on a Calabi-Yau threefold X gives an effective four dimensional supergravity theory with 8 supercharges.

Dividing string spectrum by an orientifold involution of O3/O7 type,

$$(-1)^{F_L} \circ \Omega \circ (z^\alpha \mapsto f^\alpha(z))$$

Left-moving spacetime fermion number

Worldsheet parity

Any holomorphic involution on X with smooth fixed locus, and fixed points at dimension 0 and 4

yields a four dimensional effective theory with 4 supercharges.

The light chiral multiplets are:

Grimm, Louis '04

$h^{1,1}_+$	Kähler moduli T_i
$h^{2,1}_-$	Complex structure moduli z^a
	+the axio-dilaton τ

We will consider

$$h^{1,1}_- = h^{2,1}_+ = 0$$

Flux Vacua

(step 3.)

In a non-trivial background of threeform fluxes $(F_3, H_3) \neq 0$ a superpotential is generated:

$$W_{\mathrm{GVW}}(z^a, \tau) = \int_X (F_3 - \tau H_3) \wedge \Omega(z^a)$$

Gukov, Vafa, Witten '99

Flux Vacua

(step 3.)

In a non-trivial background of threeform fluxes $(F_3, H_3) \neq 0$ a superpotential is generated:

$$W_{\mathrm{GVW}}(z^a, \tau) = \int_X (F_3 - \tau H_3) \wedge \Omega(z^a)$$

Gukov, Vafa, Witten '99

Assuming there are vev's $\langle z^a, \tau \rangle$ that solve the F-terms,

$$\langle D_{z^a,\tau} W_{\mathrm{GVW}} \rangle = 0$$

Flux Vacua

(step 3.)

In a non-trivial background of threeform fluxes $(F_3, H_3) \neq 0$ a superpotential is generated:

$$W_{\rm GVW}(z^a,\tau) = \int_X (F_3 - \tau H_3) \wedge \Omega(z^a)$$

Gukov, Vafa, Witten '99

Assuming there are vev's $\langle z^a, \tau \rangle$ that solve the F-terms,

$$\langle D_{z^a,\tau} W_{\rm GVW} \rangle = 0$$

one can then go on to attempt solving the Kähler moduli F-terms...

D-instanton corrections and the stabilization of Kähler moduli

(steps 4. and 5.)

D-instanton corrections and the stabilization of Kähler moduli

(steps 4. and 5.)

D3-instantons wrapped on rigid, orientifold invariant, and holomorphic four-cycles contribute to the superpotential,

$$W \supset \mathcal{A}_i(z, \tau)e^{-2\pi T_i}$$

Witten '96

and condensing gauge groups on seven-branes contribute in a similar manner.

D-instanton corrections and the stabilization of Kähler moduli

(steps 4. and 5.)

D3-instantons wrapped on rigid, orientifold invariant, and holomorphic four-cycles contribute to the superpotential,

$$W \supset \mathcal{A}_i(z,\tau)e^{-2\pi T_i}$$

Witten '96

and condensing gauge groups on seven-branes contribute in a similar manner.

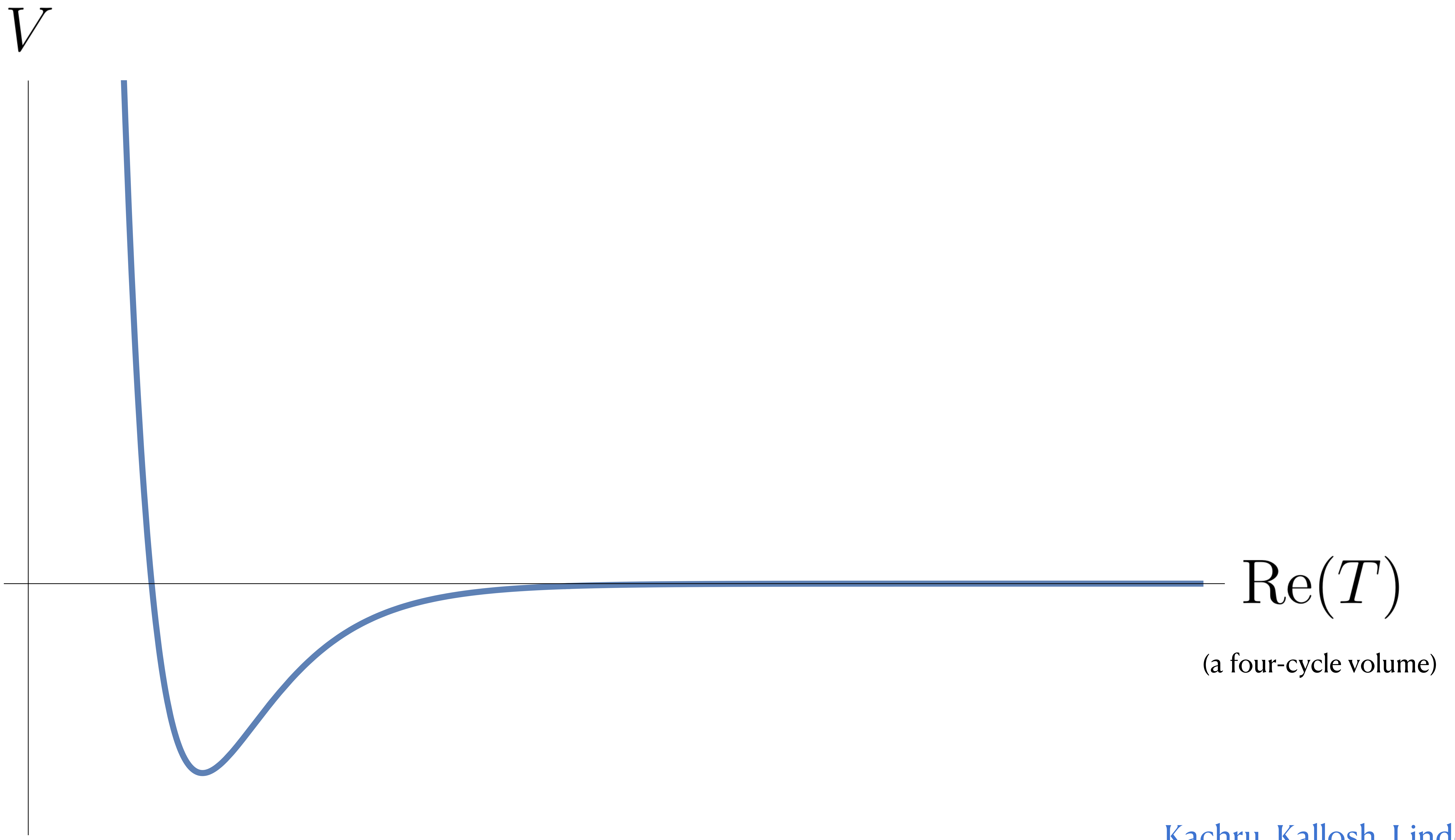
Given at least $h^{1,1}$ such corrections, one expects Kähler moduli to be stabilized at

$$\langle \mathrm{Re}(T_i) \rangle \sim \frac{\log(|W_0|^{-1})}{2\pi} \quad \text{with} \quad W_0 := \langle W_{\mathrm{GVW}} \rangle$$

Kachru, Kallosh, Linde, Trivedi '03

Control over large volume expansion thus requires a small flux superpotential.

This is how the F-term potential looks like in a toy model with a single Kähler modulus:



Kachru, Kallosh, Linde, Trivedi '03

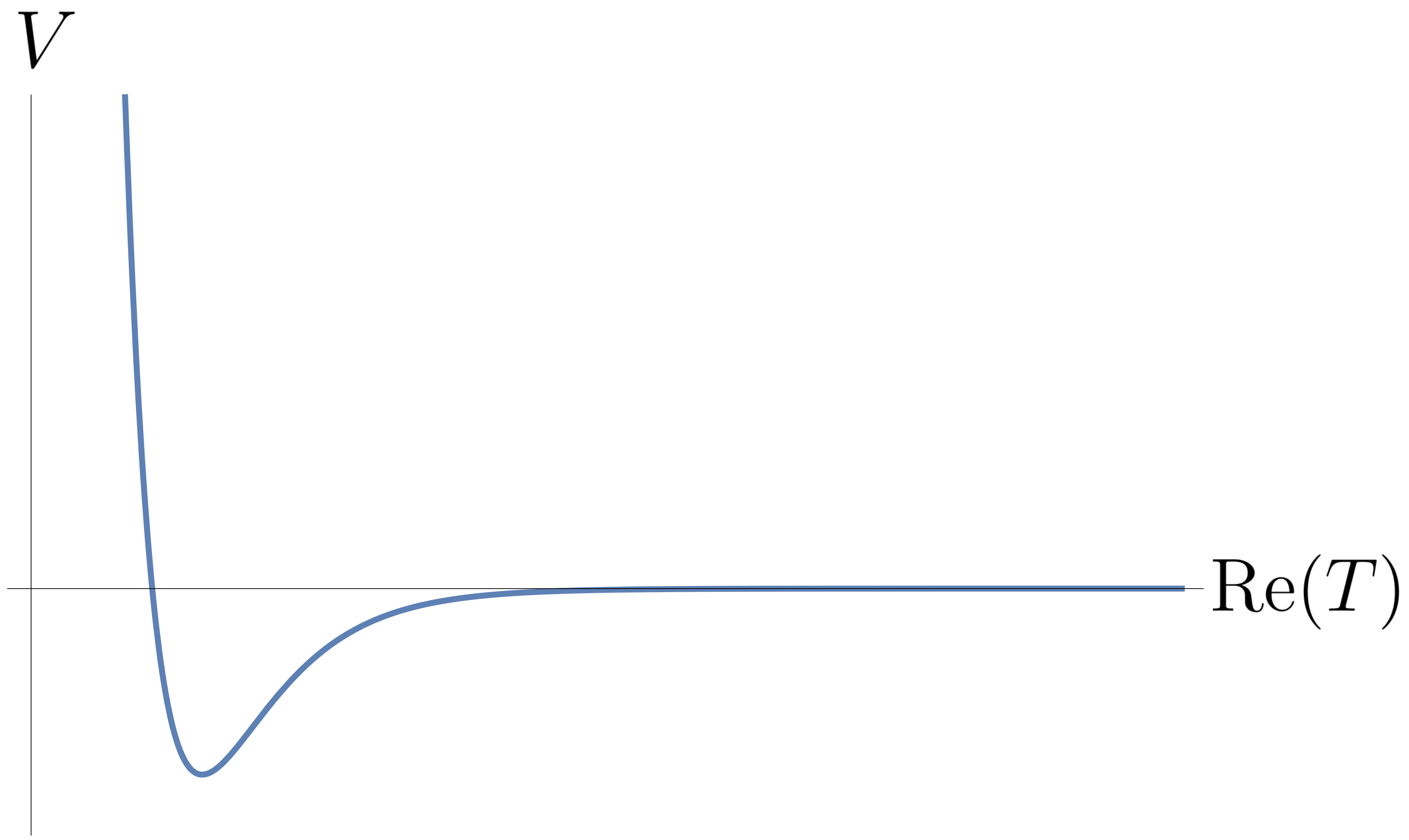
Anti-D3 brane uplift

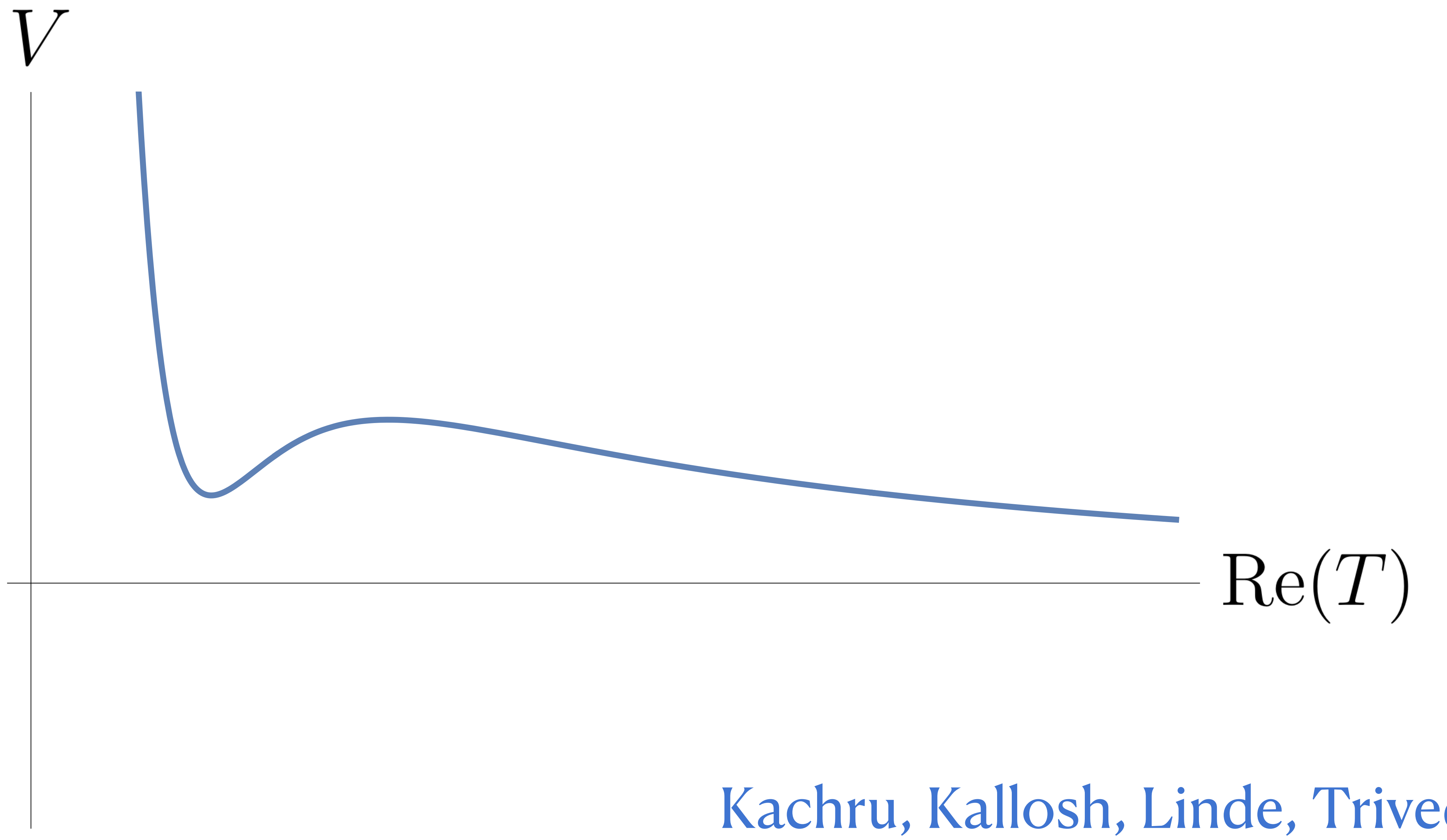
(step 6.)

Further, given a warped Randall-Sundrum throat with tuned hierarchy of scales

$$e^{4\mathcal{A}_{\mathrm{IR}}} \sim |W_0|^2$$

the SUSY breaking potential of a warped meta-stable Anti-D3 brane can uplift the solution to a four-dimensional de Sitter vacuum





Kachru, Kallosh, Linde, Trivedi '03

so far the fantasy...

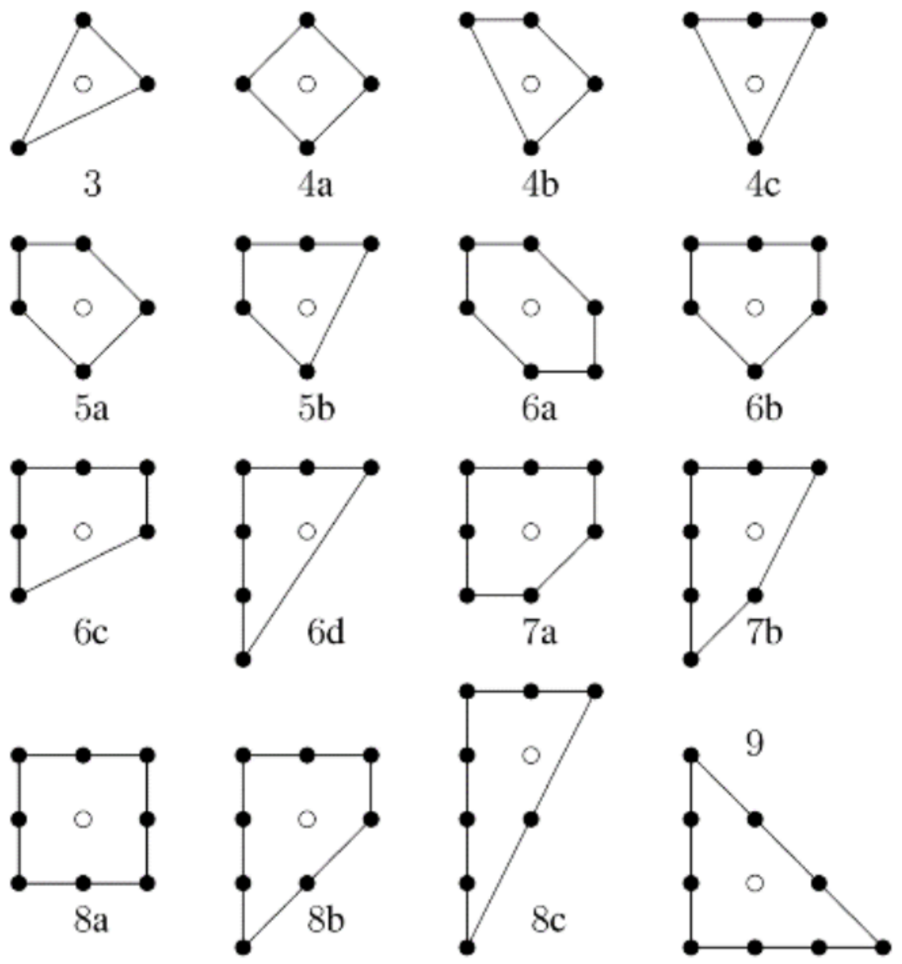
so far the fantasy…

… but now let’s do it for real!

Plan:

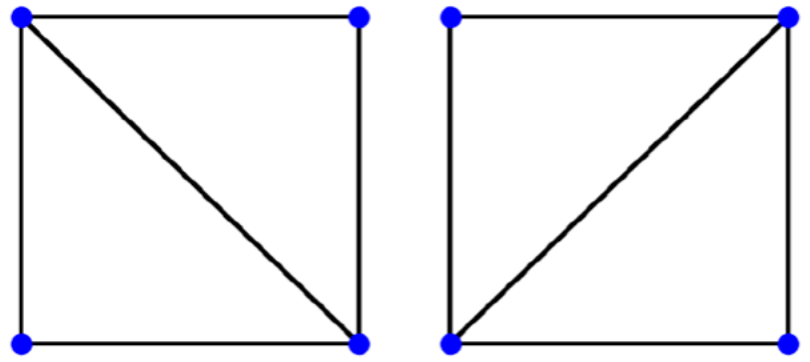
1. Some Motivation
2. The KKLT scenario
3. Vacua with small superpotential
4. Warped throats and “Uplift” to de Sitter: an example
5. Control over corrections
6. Conclusions

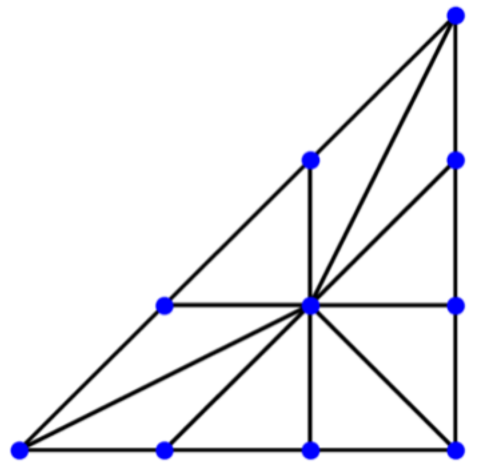
Calabi-Yau Orientifolds



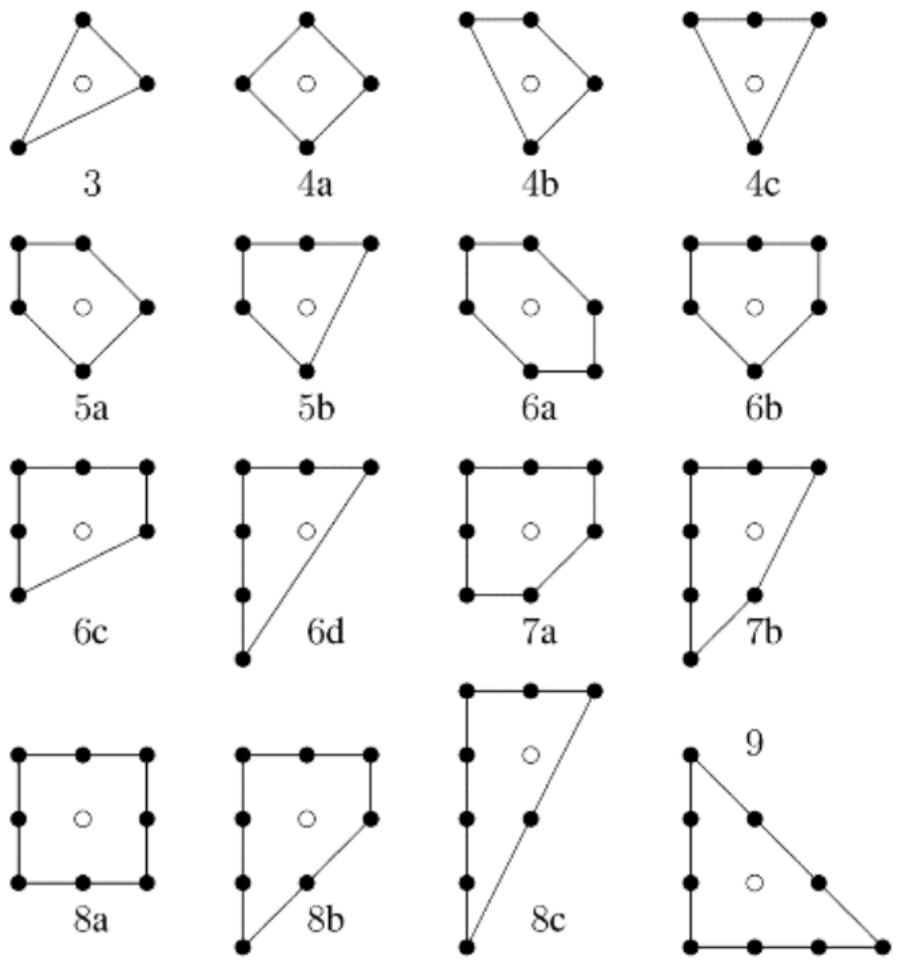
In practice, we work with the Kreuzer-Skarke dataset of reflexive polytopes in four dimensions, from which Calabi-Yau threefold hypersurfaces are constructed in combinatorial terms

Batyrev '93 Kreuzer, Skarke '00





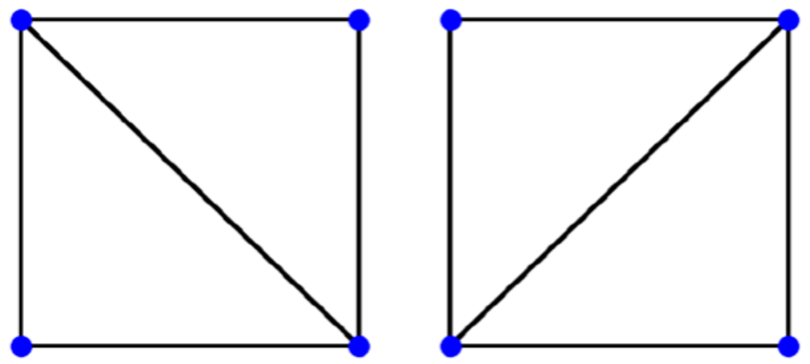
Calabi-Yau Orientifolds

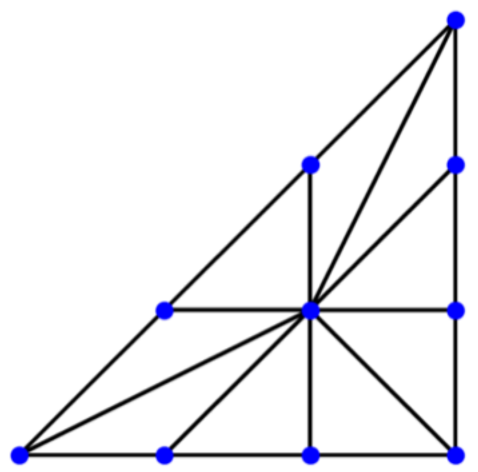


In practice, we work with the Kreuzer-Skarke dataset of reflexive polytopes in four dimensions, from which Calabi-Yau threefold hypersurfaces are constructed in combinatorial terms

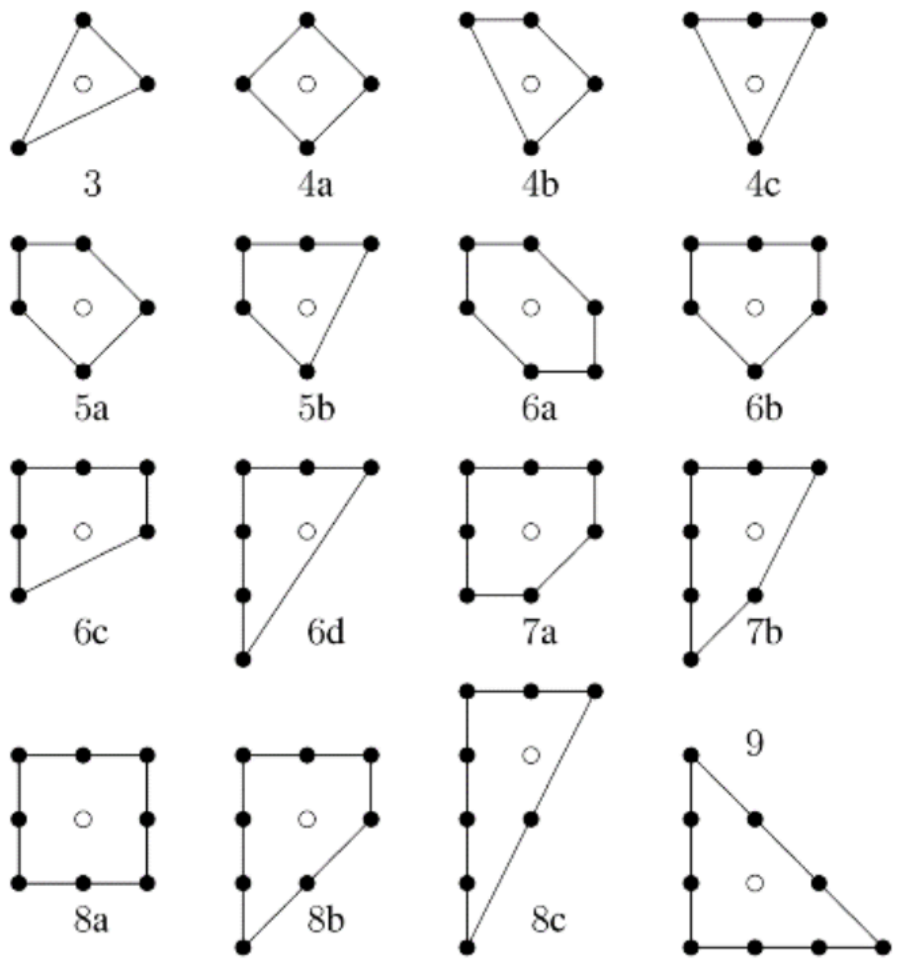
Batyrev '93   Kreuzer, Skarke '00

Given any such polytope, we then enumerate O3/O7 orientifold projections and compute all relevant data of fixed loci   JM '23

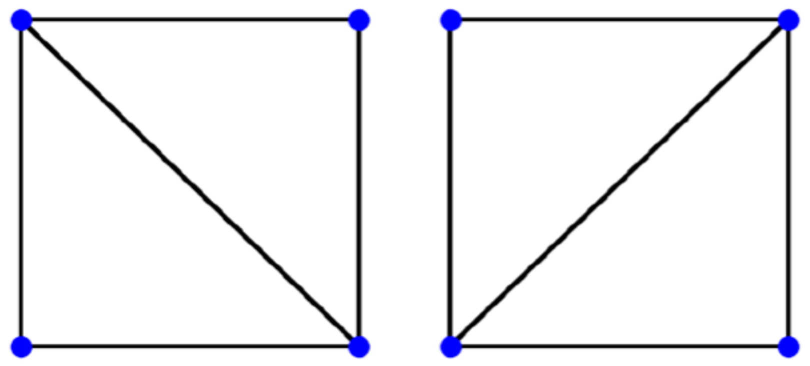


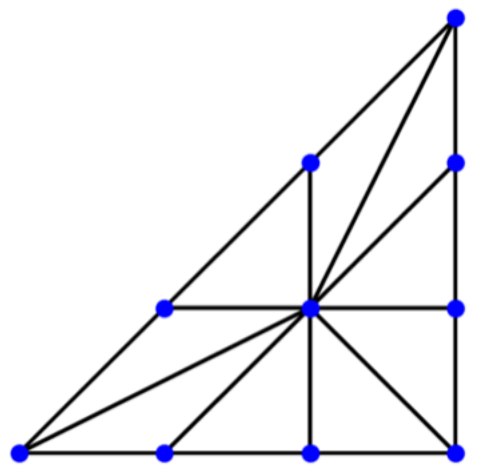


Calabi-Yau Orientifolds



In practice, we work with the Kreuzer-Skarke dataset of reflexive polytopes in four dimensions, from which Calabi-Yau threefold hypersurfaces are constructed in combinatorial terms

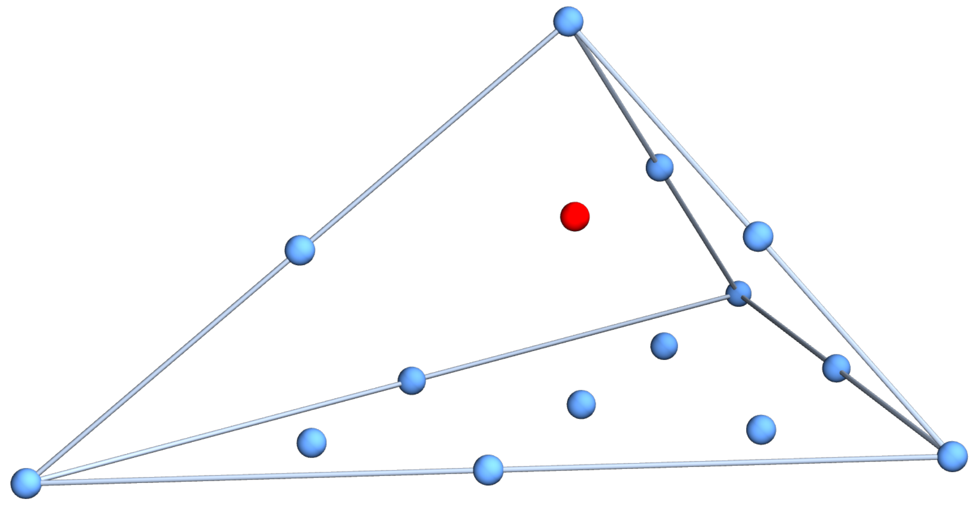




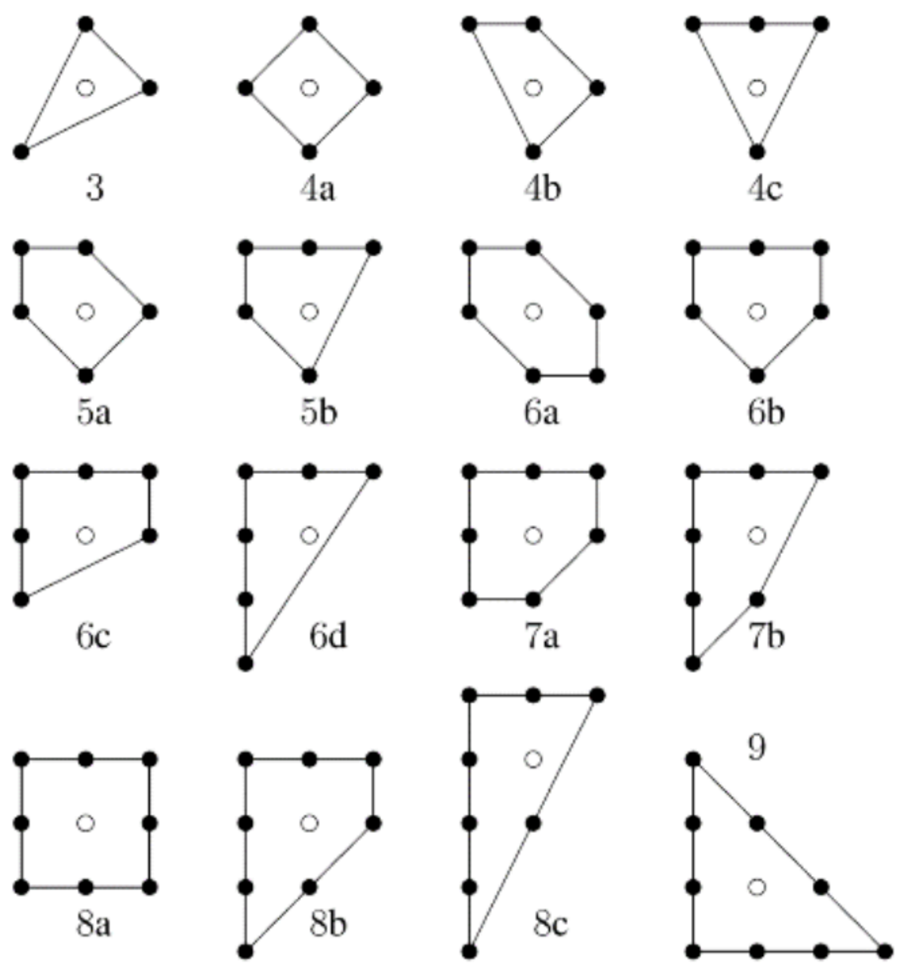
Batyrev '93 Kreuzer, Skarke '00

Given any such polytope, we then enumerate O3/O7 orientifold projections and compute all relevant data of fixed loci JM '23

A simple class of orientifolds with $h^{1,1}_{-} = h^{2,1}_{+} = 0$ arises from special polytopes

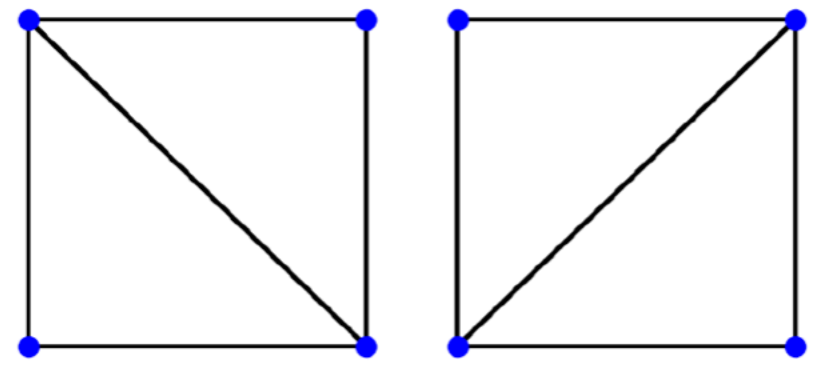


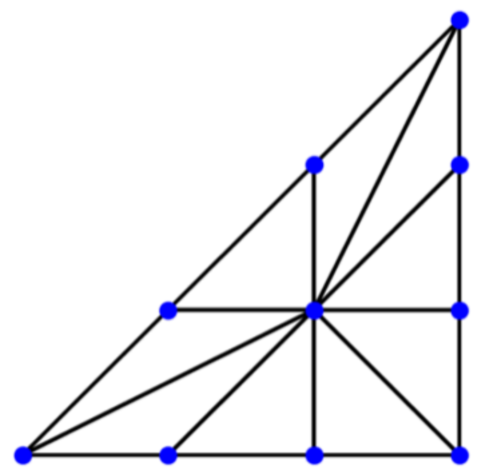
Calabi-Yau Orientifolds



In practice, we work with the Kreuzer-Skarke dataset of reflexive polytopes in four dimensions, from which Calabi-Yau threefold hypersurfaces are constructed in combinatorial terms

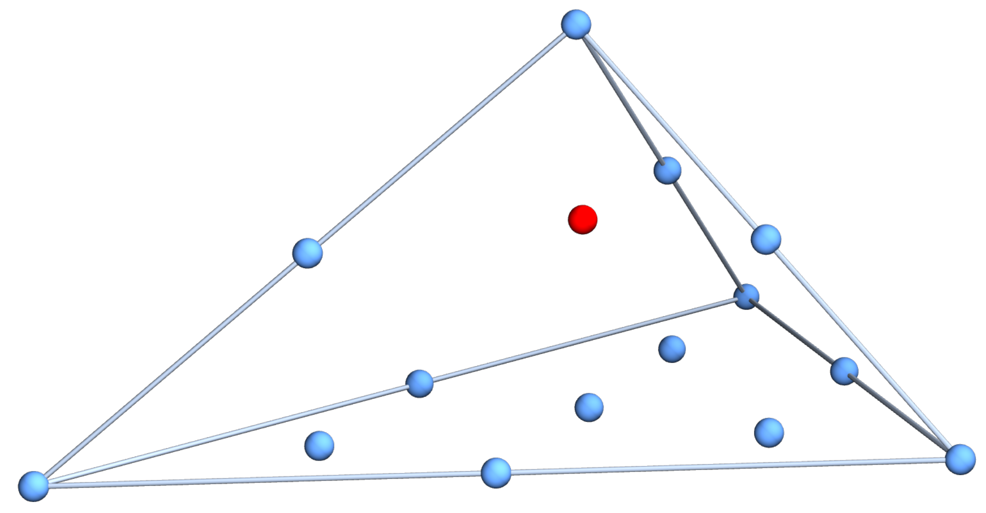
Batyrev '93 Kreuzer, Skarke '00





Given any such polytope, we then enumerate O3/O7 orientifold projections and compute all relevant data of fixed loci JM '23

A simple class of orientifolds with $h^{1,1}_{-} = h^{2,1}_{+} = 0$ arises from special polytopes



For these the vanishing of overall D3 charge requires $\frac{1}{2}\int_X H_3 \wedge F_3 \leq Q_{D3} := \frac{1}{2}(h^{1,1} + h^{2,1}) + 1$

Perturbatively Flat Vacua

For a special ansatz in quantized fluxes, around large complex structure the superpotential enjoys an expansion

$$W_{\mathrm{GVW}} = \frac{1}{2}\mathbb{N}_{ab} z^a z^b - \tau \mathbb{K}_a z^a + \mathcal{O}(e^{2\pi i z}) \qquad \mathbb{N}_{ab} := \kappa_{abc}\mathbb{M}^c$$

Demirtas, Kim, McAllister, JM '19

Perturbatively Flat Vacua

For a special ansatz in quantized fluxes, around large complex structure the superpotential enjoys an expansion

$$W_{\text{GVW}} = \frac{1}{2}\mathbb{N}_{ab}z^a z^b - \tau\mathbb{K}_a z^a + \mathcal{O}(e^{2\pi i z}) \qquad \mathbb{N}_{ab} := \kappa_{abc}\mathbb{M}^c$$

If the fluxes $\vec{\mathbb{M}}$ and $\vec{\mathbb{K}}$ satisfy, in addition, the Diophantine equation,

$$p^a\mathbb{K}_a = 0 \quad p^a := (\mathbb{N}^{-1})^{ab}\mathbb{K}_b$$

Demirtas, Kim, McAllister, JM '19

Perturbatively Flat Vacua

For a special ansatz in quantized fluxes, around large complex structure the superpotential enjoys an expansion

$$W_{\mathrm{GVW}} = \frac{1}{2}\mathbb{N}_{ab} z^a z^b - \tau \mathbb{K}_a z^a + \mathcal{O}(e^{2\pi i z}) \qquad \mathbb{N}_{ab} := \kappa_{abc}\mathbb{M}^c$$

If the fluxes $\vec{\mathbb{M}}$ and $\vec{\mathbb{K}}$ satisfy, in addition, the Diophantine equation,

$$p^a \mathbb{K}_a = 0 \quad p^a := (\mathbb{N}^{-1})^{ab}\mathbb{K}_b$$

the polynomial part, and its F-terms, vanish along the one-dimensional locus

$$z^a = p^a \tau$$

Demirtas, Kim, McAllister, JM '19

Vacua with small superpotential

The remaining superpotential is then naturally exponentially small, and computable in terms of Gopakumar-Vafa invariants.

Demirtas, Kim, McAllister, JM, Rios-Tascon ‘21

Vacua with small superpotential

The remaining superpotential is then naturally exponentially small, and computable in terms of Gopakumar-Vafa invariants.

For a concrete example with Hodge numbers $h^{2,1} = 5$ and $h^{1,1} = 113$ we find an effective flux superpotential

$$W_{\text{eff}}(\tau) \propto -2e^{2\pi i \frac{7}{29}\tau} + 252e^{2\pi i \frac{7}{28}\tau} + \ldots$$

Demirtas, Kim, McAllister, JM, Rios-Tascon '21

Vacua with small superpotential

The remaining superpotential is then naturally exponentially small, and computable in terms of Gopakumar-Vafa invariants.

For a concrete example with Hodge numbers $h^{2,1} = 5$ and $h^{1,1} = 113$ we find an effective flux superpotential

$$W_{\text{eff}}(\tau) \propto -2e^{2\pi i \frac{7}{29}\tau} + 252e^{2\pi i \frac{7}{28}\tau} + \ldots$$

which features an isolated F-term minimum at

$$W_0 \propto \left(\frac{2}{252}\right)^{29} \approx 1.23 \times 10^{-61}$$

Demirtas, Kim, McAllister, JM, Rios-Tascon ‘21

Vacua with small superpotential

The remaining superpotential is then naturally exponentially small, and computable in terms of Gopakumar-Vafa invariants.

For a concrete example with Hodge numbers $h^{2,1} = 5$ and $h^{1,1} = 113$ we find an effective flux superpotential

$$W_{\text{eff}}(\tau) \propto -2e^{2\pi i \frac{7}{29}\tau} + 252 e^{2\pi i \frac{7}{28}\tau} + \ldots$$

which features an isolated F-term minimum at

$$W_0 \propto \left(\frac{2}{252}\right)^{29} \approx 1.23 \times 10^{-61}$$

Demirtas, Kim, McAllister, JM, Rios-Tascon ‘21

Kähler moduli are stabilized in this example, yielding a SUSY Anti de Sitter vacuum with very small Cosmological Constant!

PLAN:

1. Some Motivation
2. The KKLT scenario
3. Vacua with small superpotential
4. Warped throats and "Uplift" to de Sitter: an example
5. Control over corrections
6. Conclusions

Engineering Warped Throats

For an “Uplift” to de Sitter we have to change our setup in some regards.

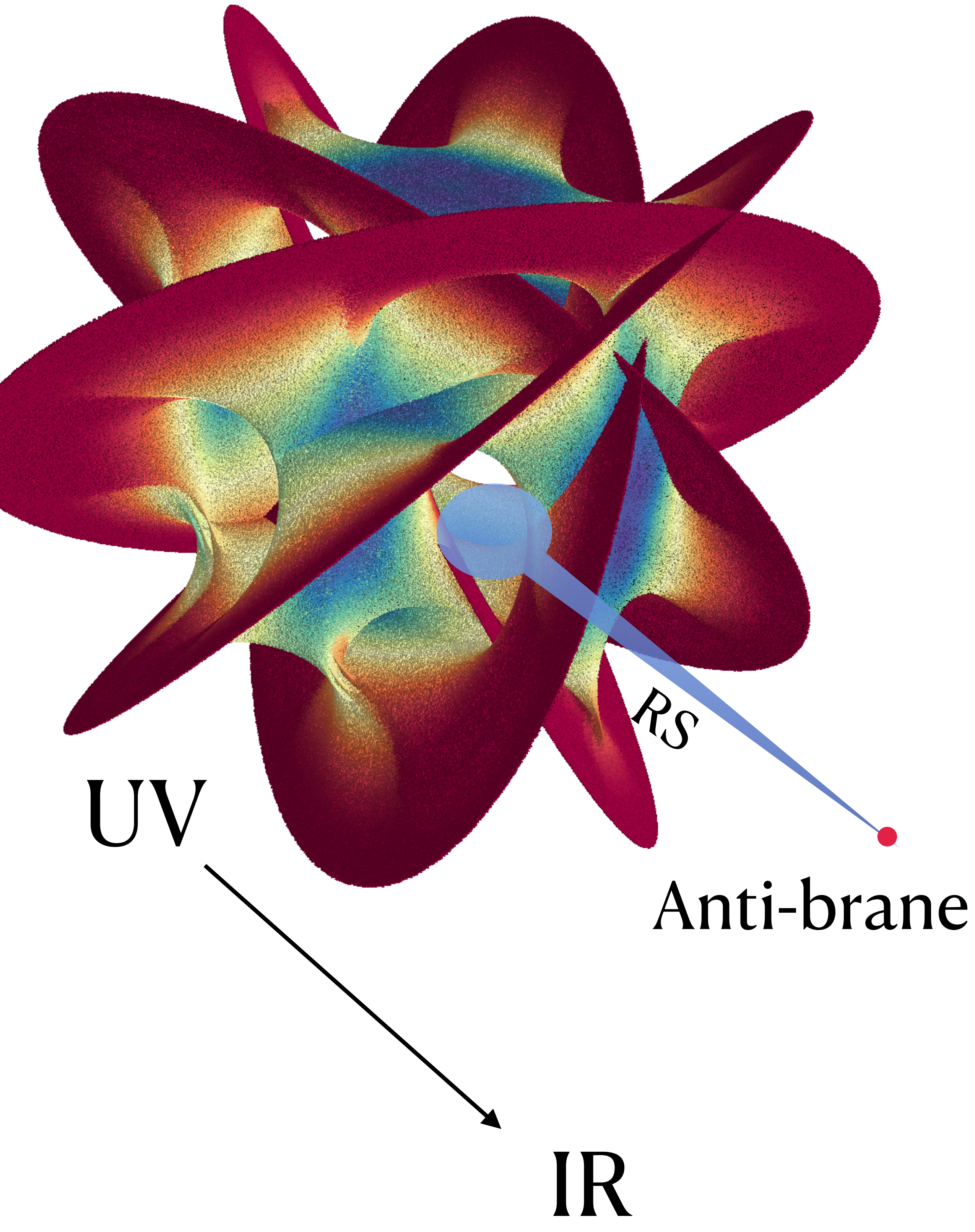
Engineering Warped Throats

For an "Uplift" to de Sitter we have to change our setup in some regards.

First, instead of stabilizing at large complex structure, we need to stabilize them near a conifold singularity in moduli space.

$$ds^2 = e^{2\mathcal{A}(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2\mathcal{A}(y)}g_{mn}dy^m dy^n$$

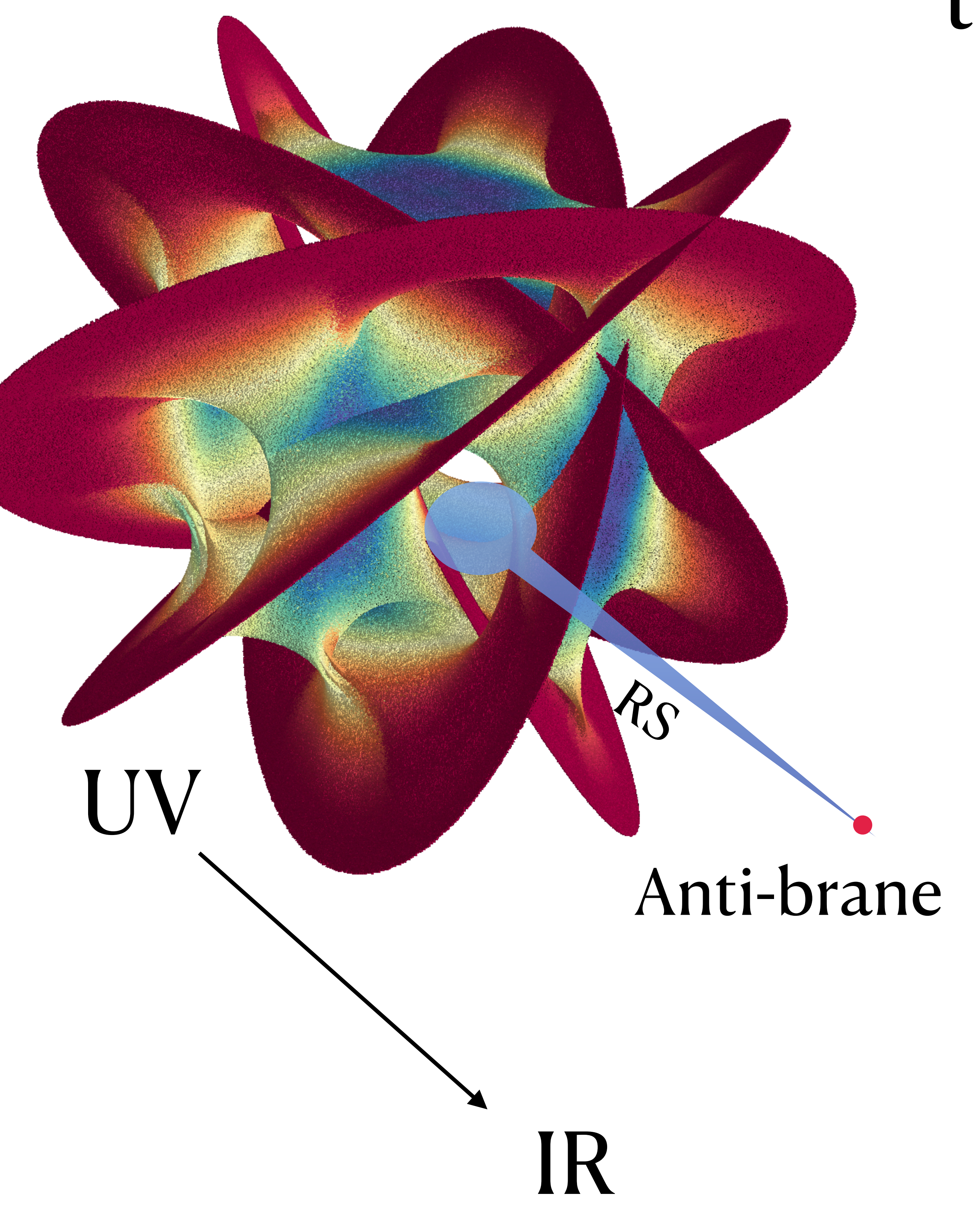
Klebanov, Strassler '00
Giddings, Kachru, Polchinski '01



Engineering Warped Throats

For an "Uplift" to de Sitter we have to change our setup in some regards.

First, instead of stabilizing at large complex structure, we need to stabilize them near a conifold singularity in moduli space.



$$ds^2 = e^{2\mathcal{A}(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2\mathcal{A}(y)}g_{mn}dy^m dy^n$$

$$e^{2\mathcal{A}_{IR}} \sim |z|^{\frac{2}{3}}$$

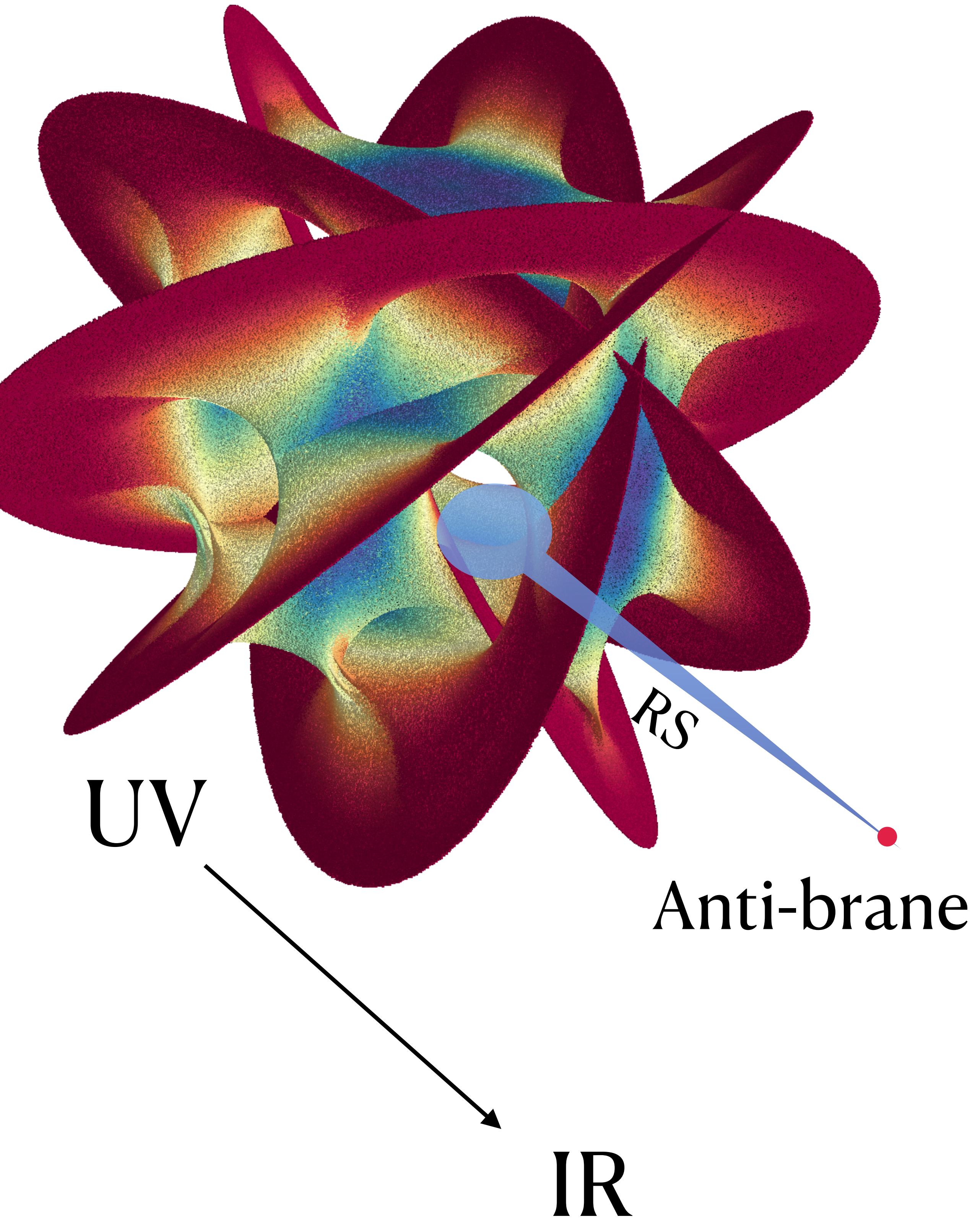
Klebanov, Strassler '00
Giddings, Kachru, Polchinski '01

distance from conifold locus in moduli space

Engineering Warped Throats

For an "Uplift" to de Sitter we have to change our setup in some regards.

First, instead of stabilizing at large complex structure, we need to stabilize them near a conifold singularity in moduli space.



$$ds^2 = e^{2\mathcal{A}(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2\mathcal{A}(y)}g_{mn}dy^m dy^n$$

$$e^{2\mathcal{A}_{IR}} \sim |z|^{\frac{2}{3}}$$

Klebanov, Strassler '00
Giddings, Kachru, Polchinski '01

distance from conifold locus in moduli space

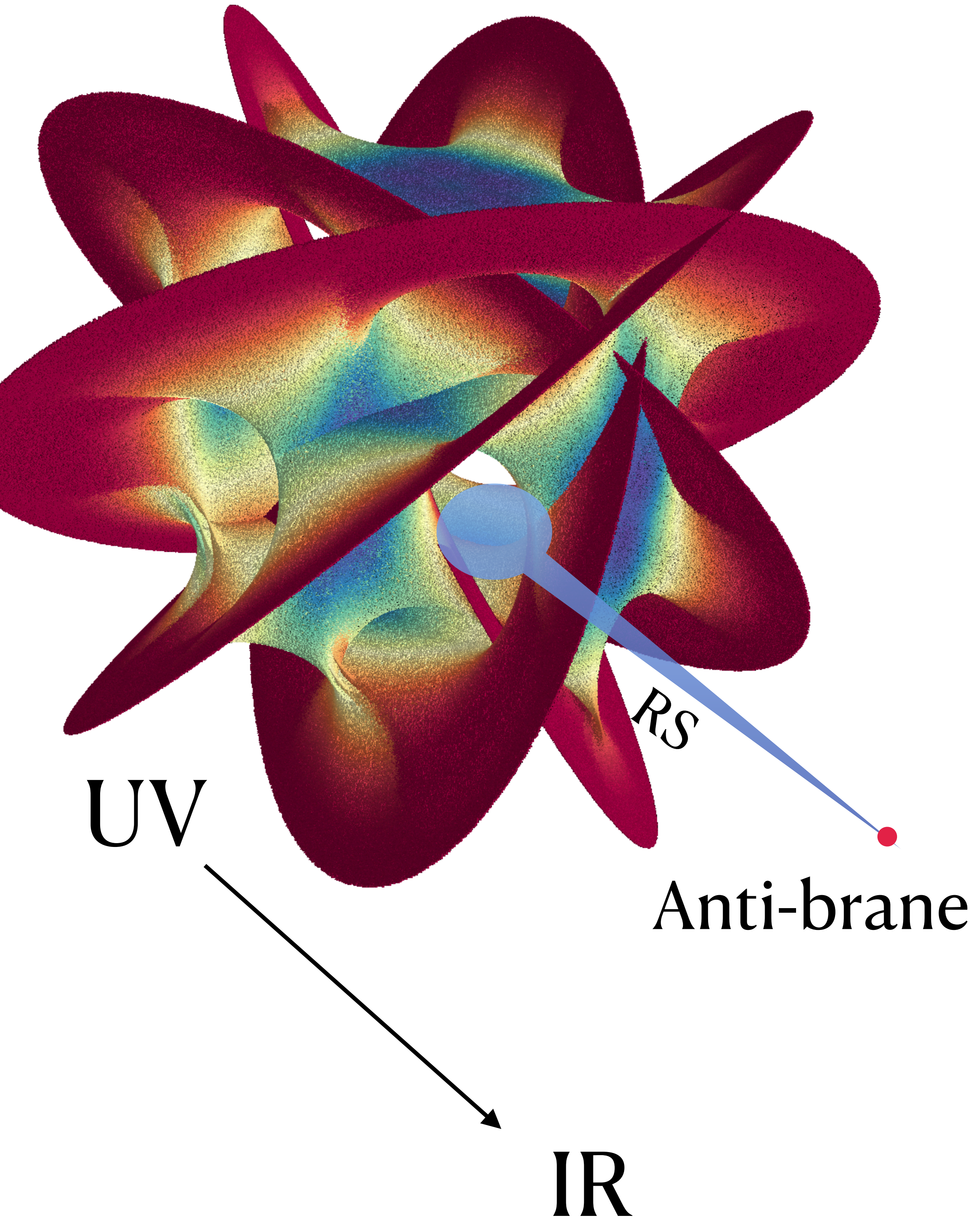
For a single Anti-D3 brane to raise the vacuum energy to positive values, without causing a decompactification instability, we need

$$\frac{|z|^{\frac{4}{3}}}{(g_s M)^2} \approx \underbrace{5.5 \times 10^{-3}}_{\text{from KS solution}} \times \frac{|W_0|^2}{\mathcal{V}_E^{\frac{2}{3}}\tilde{\mathcal{V}}_s^{\frac{1}{3}}} \ll 1 \qquad M := \int_{\text{Conifold } S^3} F_3$$

Engineering Warped Throats

For an "Uplift" to de Sitter we have to change our setup in some regards.

First, instead of stabilizing at large complex structure, we need to stabilize them near a conifold singularity in moduli space.



$$ds^2 = e^{2\mathcal{A}(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2\mathcal{A}(y)}g_{mn}dy^m dy^n$$

$$e^{2\mathcal{A}_{IR}} \sim |z|^{\frac{2}{3}}$$

Klebanov, Strassler '00
Giddings, Kachru, Polchinski '01

distance from conifold locus in moduli space

For a single Anti-D3 brane to raise the vacuum energy to positive values, without causing a decompactification instability, we need

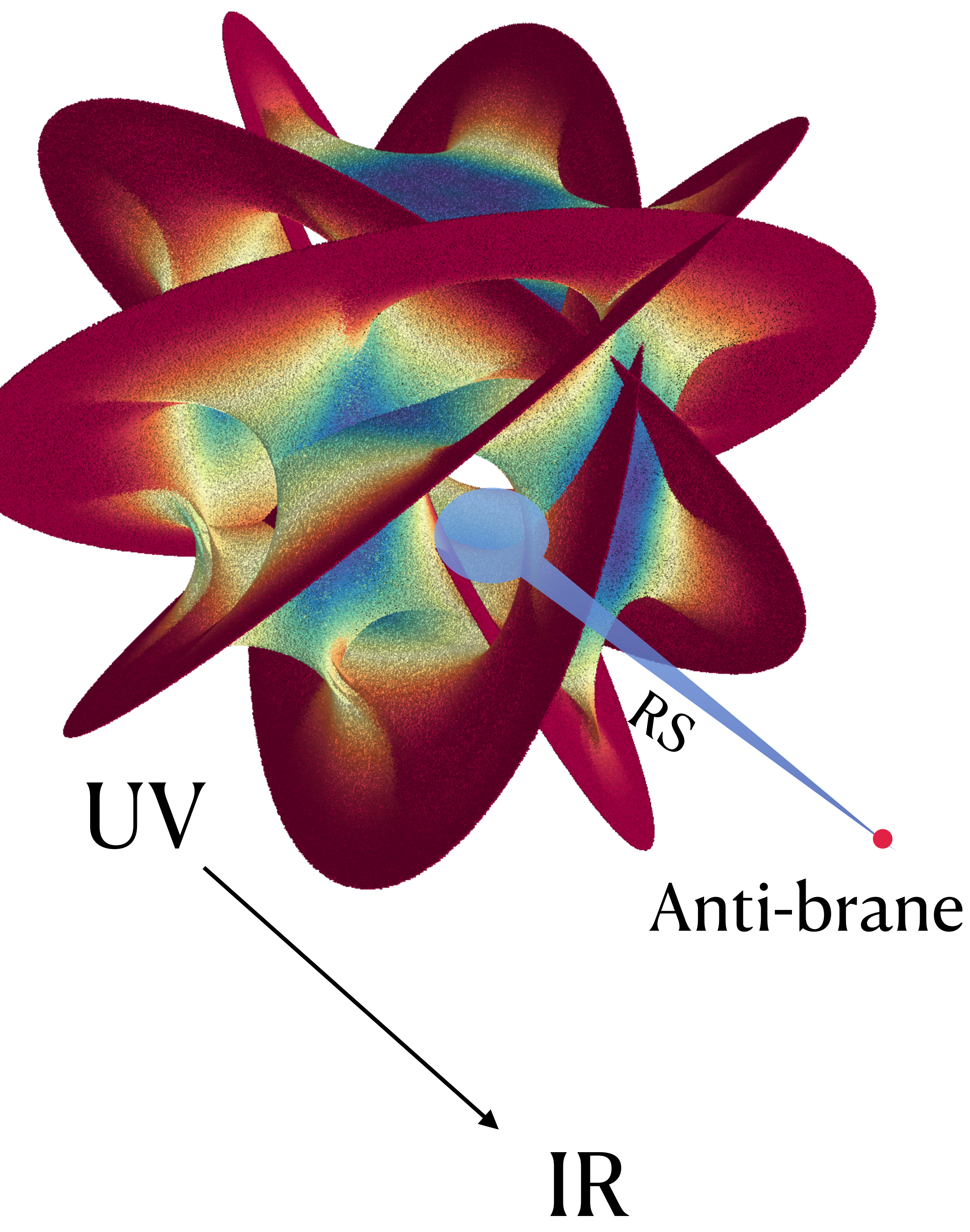
$$\frac{|z|^{\frac{4}{3}}}{(g_s M)^2} \approx \underbrace{5.5 \times 10^{-3}}_{\text{from KS solution}} \times \frac{|W_0|^2}{\mathcal{V}_E^{\frac{2}{3}}\tilde{\mathcal{V}}_s^{\frac{1}{3}}} \ll 1 \qquad M := \int_{\text{Conifold } S^3} F_3$$

Therefore we need to stabilize moduli such that both z and W_0 are small!

Engineering Warped Throats (actually doing it)

One can compute the superpotential systematically, order by order in z :

Álvarez-García, Blumenhagen, Brinkmann, Schlechter'20
Demirtas, Kim, McAllister, JM '20

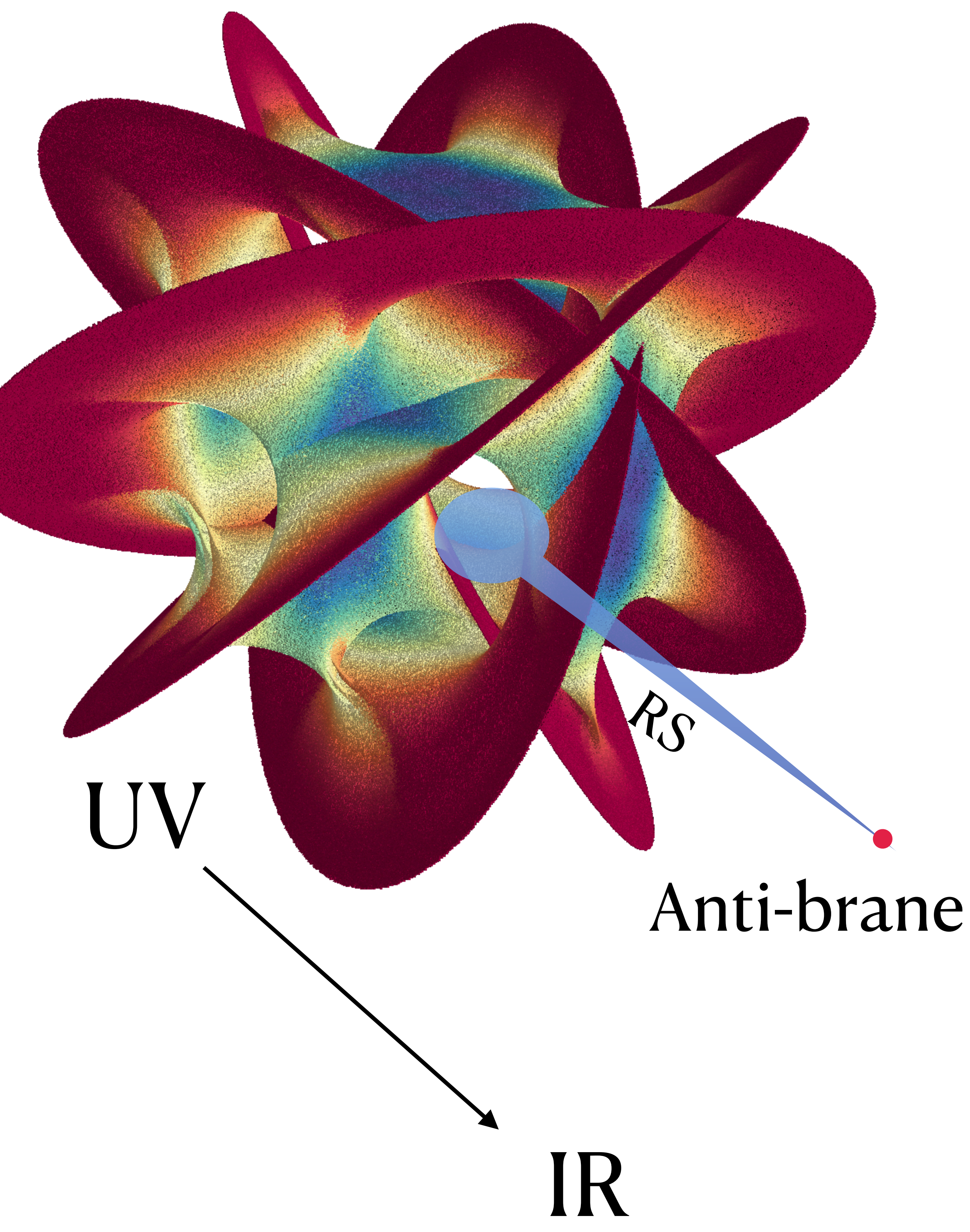


$$W_{GVW}(z, z^\alpha, \tau) = W_{\text{bulk}}(z^\alpha, \tau) + z\, W^{(1)}(z, z^\alpha, \tau) + \mathcal{O}(z^2)$$

Engineering Warped Throats (actually doing it)

One can compute the superpotential systematically, order by order in z :

Álvarez-García, Blumenhagen, Brinkmann, Schlechter'20
Demirtas, Kim, McAllister, JM '20



$$W_{GVW}(z, z^\alpha, \tau) = W_{\text{bulk}}(z^\alpha, \tau) + z\, W^{(1)}(z, z^\alpha, \tau) + \mathcal{O}(z^2)$$

The conifold F-term is solved for

$$\langle |z| \rangle = \frac{1}{2\pi} \exp\left(-\frac{2\pi}{g_s M^2} Q_{D3}^{\text{throat}} \right)$$

$$Q_{D3}^{\text{throat}} := -\frac{1}{2} \vec{\mathbb{M}} \cdot \vec{\mathbb{K}} - \langle \vec{\mathbb{M}}, \vec{\mathbb{M}} \rangle$$

Meta-stable Anti-D3 brane

In addition to constructing a strongly warped throat, one needs to ensure meta-stability of an Anti-D3 brane uplift.

At leading order in α' this requires $M > 12$, Kachru, Pearson, Verlinde '01

Meta-stable Anti-D3 brane

In addition to constructing a strongly warped throat, one needs to ensure meta-stability of an Anti-D3 brane uplift.

At leading order in α' this requires $M > 12$, Kachru, Pearson, Verlinde '01

and controlling α'-corrections to KS requires $g_s M \stackrel{!}{\gtrsim} 1$

Meta-stable Anti-D3 brane

In addition to constructing a strongly warped throat, one needs to ensure meta-stability of an Anti-D3 brane uplift.

At leading order in α' this requires $M > 12$, Kachru, Pearson, Verlinde '01

and controlling α'-corrections to KS requires $g_s M \overset{!}{\gtrsim} 1$

Requiring an uplift to de Sitter then severely limits our computational control:

$$\frac{|z|^{\frac{4}{3}}}{(g_s M)^2} \approx \underbrace{5.5 \times 10^{-3}}_{\text{from KS solution}} \times \frac{|W_0|^2}{\mathcal{V}_E^{\frac{2}{3}} \tilde{\mathcal{V}}_s^{\frac{1}{3}}} \ll 1$$

Meta-stable Anti-D3 brane

In addition to constructing a strongly warped throat, one needs to ensure meta-stability of an Anti-D3 brane uplift.

At leading order in α' this requires $M > 12$, Kachru, Pearson, Verlinde '01

and controlling α'-corrections to KS requires $g_s M \overset{!}{\gtrsim} 1$

Requiring an uplift to de Sitter then severely limits our computational control:

$$\frac{1}{(2\pi)^{4/3}(g_s M)^2}\exp\left(-\frac{8\pi}{3 g_s M^2} Q_{D3}\right) < \frac{|z|^{\frac{4}{3}}}{(g_s M)^2} \approx \underbrace{5.5 \times 10^{-3}}_{\text{from KS solution}} \times \frac{|W_0|^2}{\mathcal{V}_E^{\frac{2}{3}} \tilde{\mathcal{V}}_s^{\frac{1}{3}}} \ll 1$$

Meta-stable Anti-D3 brane

In addition to constructing a strongly warped throat, one needs to ensure meta-stability of an Anti-D3 brane uplift.

At leading order in α' this requires $M > 12$, Kachru, Pearson, Verlinde '01

and controlling α'-corrections to KS requires $g_s M \overset{!}{\gtrsim} 1$

Requiring an uplift to de Sitter then severely limits our computational control:

$$\frac{1}{(2\pi)^{4/3}(g_s M)^2}\exp\left(-\frac{8\pi}{3 g_s M^2} Q_{D3}\right) < \frac{|z|^{\frac{4}{3}}}{(g_s M)^2} \approx \underbrace{5.5\times 10^{-3}}_{\text{from KS solution}} \times \frac{|W_0|^2}{\mathcal{V}_E^{\frac{2}{3}}\tilde{\mathcal{V}}_s^{\frac{1}{3}}} \ll 1$$

E.g., for the largest D3-charge possible in known Calabi-Yau threefolds, $Q_{D3} = 252$ and control parameters $1/(g_s M) = g_s = 0.2$, typical values for volumes, this bound is saturated for $W_0 = 10^{-2}$ ...

McAllister, JM, Nally, Schachner (upcoming)

Everything, Everywhere, All at Once

Kwan, Scheinert'22

So far, we have understood all components of the KKLT proposal separately.

But, finding fully concrete solutions that feature them all, has required sifting through a substantial set of candidates:

McAllister, JM, Nally, Schachner (upcoming)

Everything, Everywhere, All at Once

Kwan, Scheinert'22

So far, we have understood all components of the KKLT proposal separately.

But, finding fully concrete solutions that feature them all, has required sifting through a substantial set of candidates:

- 202,703 polytopes in Kreuzer-Skarke in range $3 \leq h^{2,1} \leq 8$

McAllister, JM, Nally, Schachner (upcoming)

Everything, Everywhere, All at Once

Kwan, Scheinert'22

So far, we have understood all components of the KKLT proposal separately.

But, finding fully concrete solutions that feature them all, has required sifting through a substantial set of candidates:

- 202,703 polytopes in Kreuzer-Skarke in range $3 \leq h^{2,1} \leq 8$
- 3,187 favorable polytopes admitting an orientifold with $h^{1,1}_{-} = h^{2,1}_{+} = 0$

McAllister, JM, Nally, Schachner (upcoming)

Everything, Everywhere, All at Once

Kwan, Scheinert'22

So far, we have understood all components of the KKLT proposal separately.

But, finding fully concrete solutions that feature them all, has required sifting through a substantial set of candidates:

- 202,703 polytopes in Kreuzer-Skarke in range $3 \leq h^{2,1} \leq 8$
- 3,187 favorable polytopes admitting an orientifold with $h^{1,1}_{-} = h^{2,1}_{+} = 0$
- 322 polytopes yielding large D3-charges $Q_{D3} \geq 100$, and hosting enough rigid divisors.

McAllister, JM, Nally, Schachner (upcoming)

Everything, Everywhere, All at Once

Kwan, Scheinert'22

So far, we have understood all components of the KKLT proposal separately.

But, finding fully concrete solutions that feature them all, has required sifting through a substantial set of candidates:

- 202,703 polytopes in Kreuzer-Skarke in range $3 \leq h^{2,1} \leq 8$
- 3,187 favorable polytopes admitting an orientifold with $h^{1,1}_{-} = h^{2,1}_{+} = 0$
- 322 polytopes yielding large D3-charges $Q_{D3} \geq 100$, and hosting enough rigid divisors.
- 416 Calabi-Yau orientifolds with suitable conifold limits (i.e., that arise away from O-planes).

McAllister, JM, Nally, Schachner (upcoming)

Everything, Everywhere, All at Once

Kwan, Scheinert'22

So far, we have understood all components of the KKLT proposal separately.

But, finding fully concrete solutions that feature them all, has required sifting through a substantial set of candidates:

- 202,703 polytopes in Kreuzer-Skarke in range $3 \leq h^{2,1} \leq 8$
- 3,187 favorable polytopes admitting an orientifold with $h^{1,1}_{-} = h^{2,1}_{+} = 0$
- 322 polytopes yielding large D3-charges $Q_{D3} \geq 100$, and hosting enough rigid divisors.
- 416 Calabi-Yau orientifolds with suitable conifold limits (i.e., that arise away from O-planes).
- 90,457,494 vacua with conifolds.

McAllister, JM, Nally, Schachner (upcoming)

Everything, Everywhere, All at Once

Kwan, Scheinert'22

So far, we have understood all components of the KKLT proposal separately.

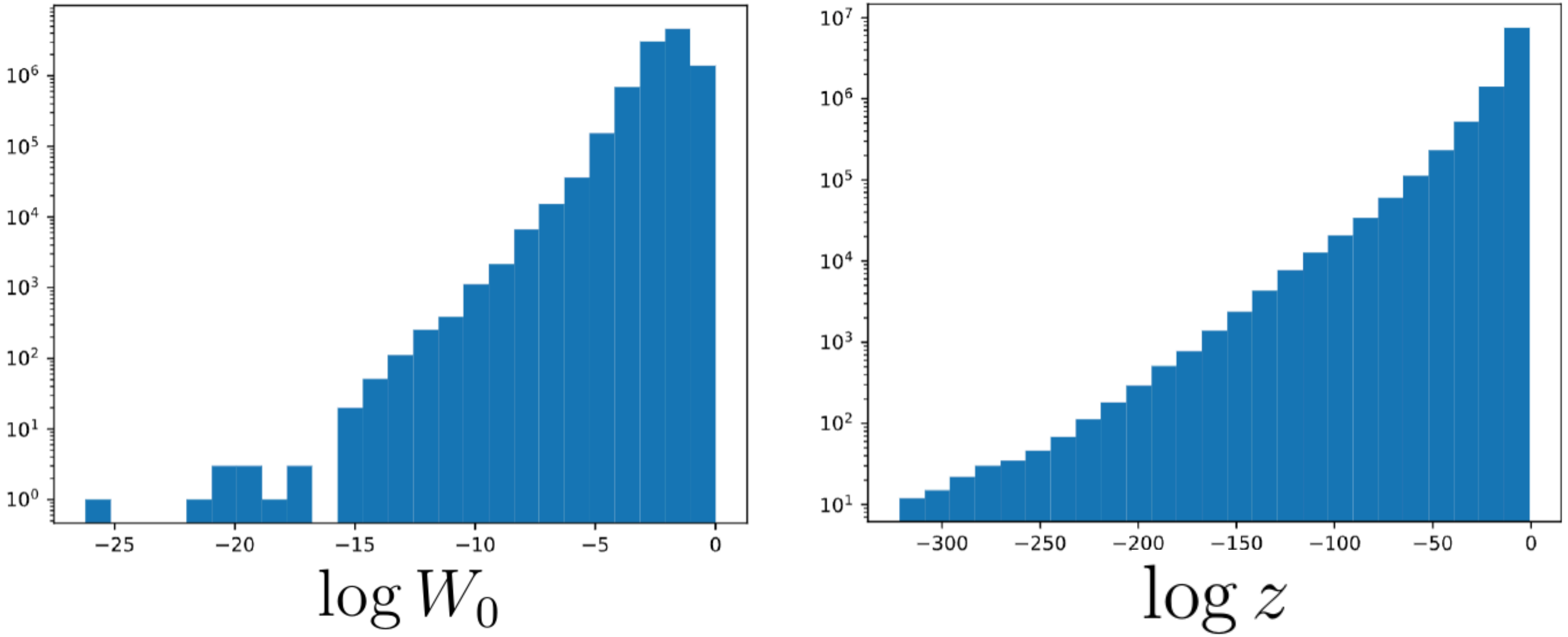
But, finding fully concrete solutions that feature them all, has required sifting through a substantial set of candidates:

- 202,703 polytopes in Kreuzer-Skarke in range $3 \leq h^{2,1} \leq 8$
- 3,187 favorable polytopes admitting an orientifold with $h^{1,1}_{-} = h^{2,1}_{+} = 0$
- 322 polytopes yielding large D3-charges $Q_{D3} \geq 100$, and hosting enough rigid divisors.
- 416 Calabi-Yau orientifolds with suitable conifold limits (i.e., that arise away from O-planes).
- 90,457,494 vacua with conifolds.
- 24,510 vacua with $Q_{D3}^{\text{flux}} = Q_{D3} + 1$ and $M > 12$

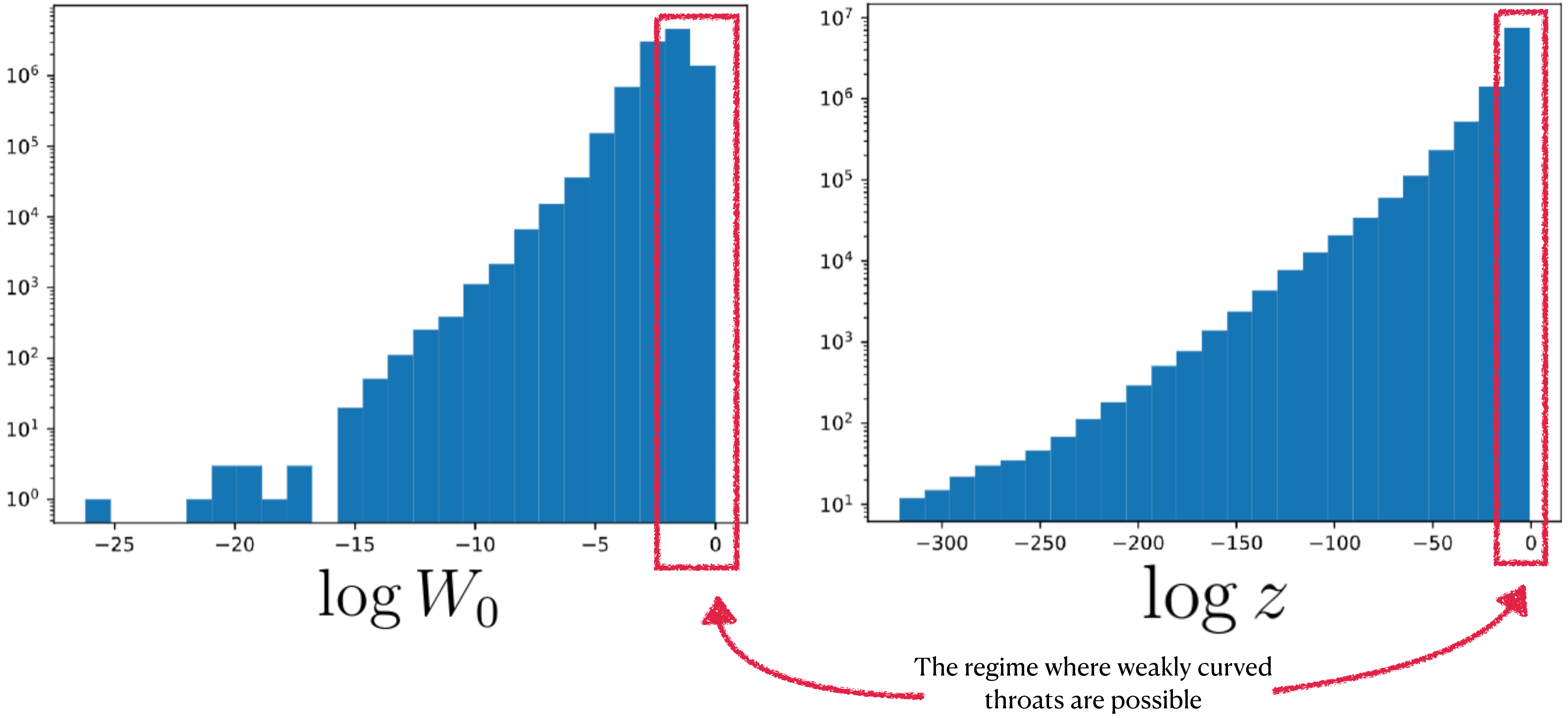
McAllister, JM, Nally, Schachner (upcoming)

In the remaining set of “only” 24,510 vacua one still has to select those in which the generically unrelated scales of the warped throat, and the bulk superpotential, match:

In the remaining set of "only" 24,510 vacua one still has to select those in which the generically unrelated scales of the warped throat, and the bulk superpotential, match:



In the remaining set of "only" 24,510 vacua one still has to select those in which the generically unrelated scales of the warped throat, and the bulk superpotential, match:



Even so, some good examples make it through to the end, and here is one of them:

Even so, some good examples make it through to the end, and here is one of them:

$h^{1,1} = 150$ $h^{2,1} = 8$

McAllister, JM, Nally, Schachner (upcoming)

Even so, some good examples make it through to the end, and here is one of them:

$$h^{1,1} = 150 \qquad h^{2,1} = 8$$

$$\mathbb{M} = \begin{pmatrix} 16 & 10 & -26 & 8 & 32 & 30 & 18 & 28 \end{pmatrix}$$

$$\mathbb{K} = \begin{pmatrix} -6 & -1 & 0 & 1 & -3 & 2 & 0 & -1 \end{pmatrix}$$

McAllister, JM, Nally, Schachner (upcoming)

Even so, some good examples make it through to the end, and here is one of them:

$$g_s \approx 0.066 \qquad \mathcal{V}_E \approx 3.6 \times 10^5 \, \ell_s^6$$

$$h^{1,1} = 150 \qquad h^{2,1} = 8$$

$$\mathbb{M} = \begin{pmatrix} 16 & 10 & -26 & 8 & 32 & 30 & 18 & 28 \end{pmatrix}$$

$$\mathbb{K} = \begin{pmatrix} -6 & -1 & 0 & 1 & -3 & 2 & 0 & -1 \end{pmatrix}$$

McAllister, JM, Nally, Schachner (upcoming)

Even so, some good examples make it through to the end, and here is one of them:

$$g_s \approx 0.066 \qquad \mathcal{V}_E \approx 3.6 \times 10^5\, \ell_s^6$$

$$W_0 \approx 0.012$$

$$|z| \approx 2.82 \times 10^{-8}$$

$$h^{1,1} = 150 \qquad h^{2,1} = 8$$

$$\mathbb{M} = \begin{pmatrix} 16 & 10 & -26 & 8 & 32 & 30 & 18 & 28 \end{pmatrix}$$

$$\mathbb{K} = \begin{pmatrix} -6 & -1 & 0 & 1 & -3 & 2 & 0 & -1 \end{pmatrix}$$

McAllister, JM, Nally, Schachner (upcoming)

Even so, some good examples make it through to the end, and here is one of them:

$$g_s \approx 0.066 \qquad \mathcal{V}_E \approx 3.6 \times 10^5\, \ell_s^6$$

$$W_0 \approx 0.012$$

$$|z| \approx 2.82 \times 10^{-8} \qquad g_s M \approx 1.05$$

$$h^{1,1} = 150 \qquad h^{2,1} = 8$$

$$\mathbb{M} = \begin{pmatrix} 16 & 10 & -26 & 8 & 32 & 30 & 18 & 28 \end{pmatrix}$$

$$\mathbb{K} = \begin{pmatrix} -6 & -1 & 0 & 1 & -3 & 2 & 0 & -1 \end{pmatrix}$$

McAllister, JM, Nally, Schachner (upcoming)

Even so, some good examples make it through to the end, and here is one of them:

$$g_s \approx 0.066 \qquad \mathcal{V}_E \approx 3.6 \times 10^5\, \ell_s^6$$

$$W_0 \approx 0.012$$

$$|z| \approx 2.82 \times 10^{-8} \qquad g_s M \approx 1.05$$

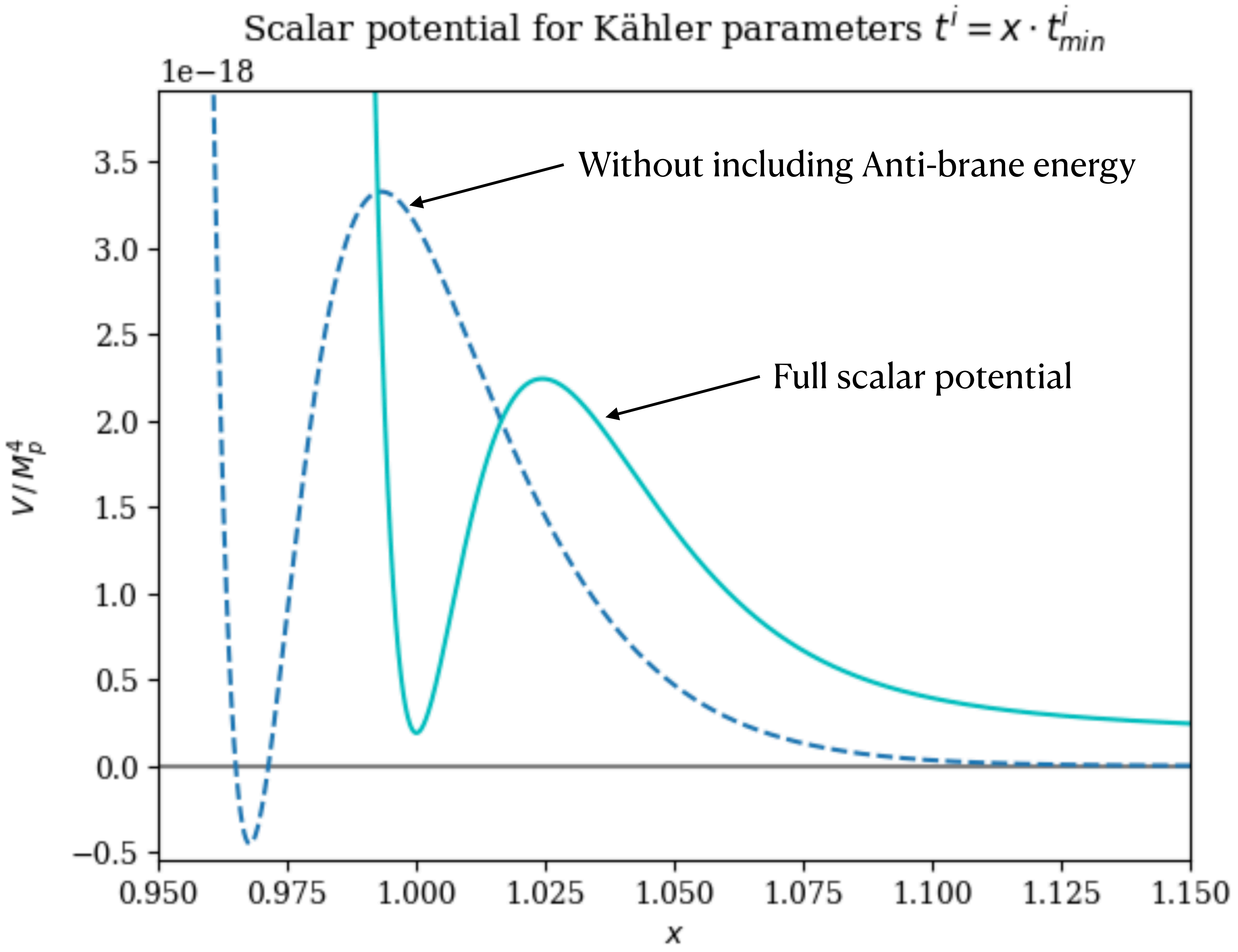
Including the contribution of the anti-D3 brane, the vacuum energy is positive:

$$\rho_{\text{vacuum}} \approx 1.9 \times 10^{-19} M_{\text{pl}}^4$$

$$h^{1,1} = 150 \qquad h^{2,1} = 8$$

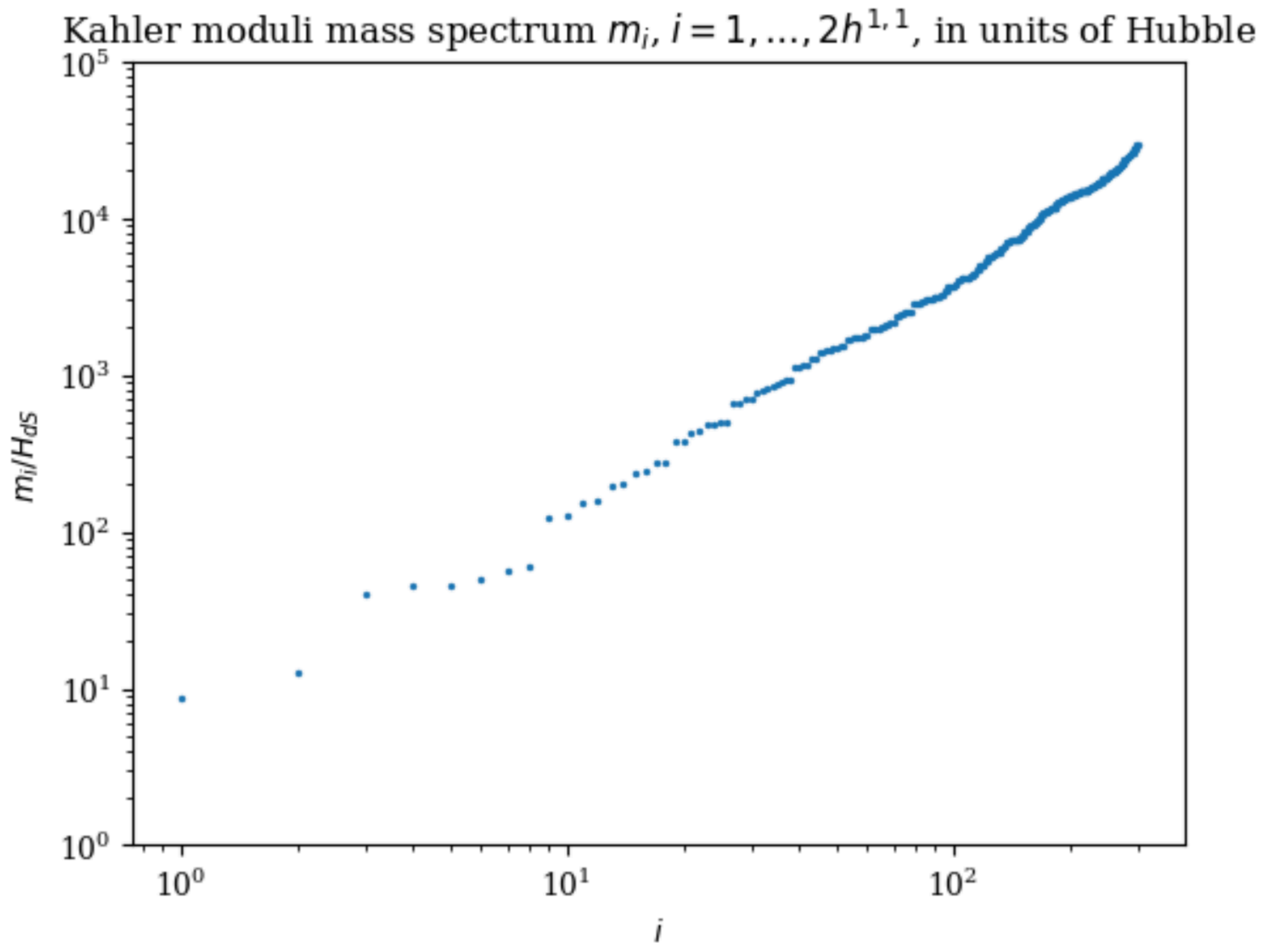
$$\mathbb{M} = \begin{pmatrix} 16 & 10 & -26 & 8 & 32 & 30 & 18 & 28 \end{pmatrix}$$

$$\mathbb{K} = \begin{pmatrix} -6 & -1 & 0 & 1 & -3 & 2 & 0 & -1 \end{pmatrix}$$



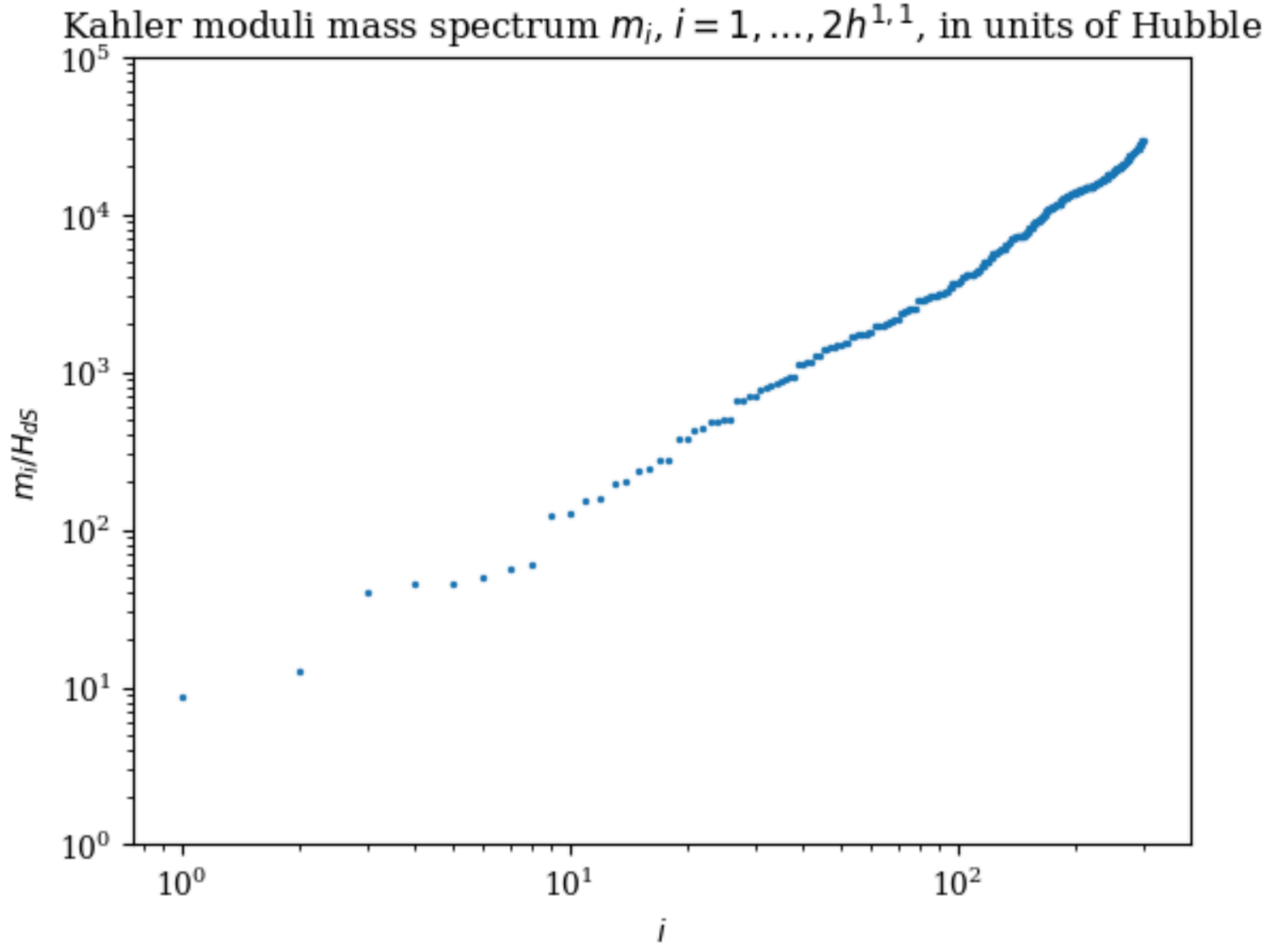
McAllister, JM, Nally, Schachner (upcoming)

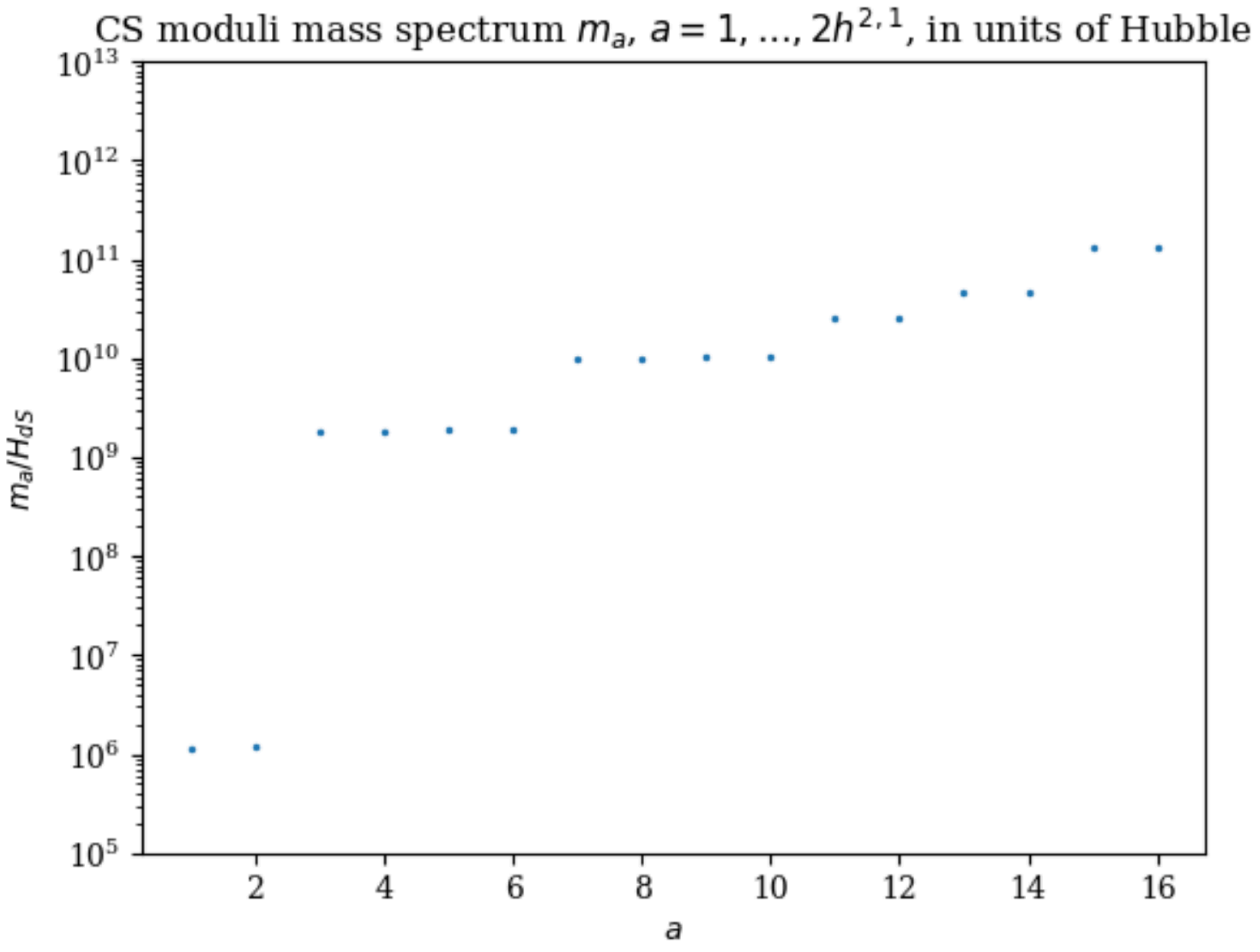
… and the vacuum is free of tachyons:



McAllister, JM, Nally, Schachner (upcoming)

… and the vacuum is free of tachyons:





Plan:

1. Some Motivation
2. The KKLT scenario
3. Vacua with small superpotential
4. Warped throats and “Uplift” to de Sitter: an example
5. Control over corrections
6. Conclusions

At first sight, the perhaps most serious issue with our solutions is that there is no parametric control over α' corrections, whatsoever!

For small superpotential, Einstein-frame volumes become large, but simultaneously the string coupling becomes small…

At first sight, the perhaps most serious issue with our solutions is that there is no parametric control over α' corrections, whatsoever!

For small superpotential, Einstein-frame volumes become large, but simultaneously the string coupling becomes small...

Fortunately, to leading order in the string coupling, all α' corrections to the Kähler potential are inherited from the N=2 parent compactification, and are thus computable using mirror symmetry:

Becker, Becker, Haack, Louis ‘02
Robles-Llana, Rocek, Saueressig, Theis, Vandoren ‘06
Demirtas, Kim, McAllister, JM, Rios-Tascon ‘21

$$\delta K|_{\mathcal{O}(1/g_s^2)} = \delta K_{\alpha'^3} + \delta K_{\text{worldsheet instantons}}$$

At first sight, the perhaps most serious issue with our solutions is that there is no parametric control over α' corrections, whatsoever!

For small superpotential, Einstein-frame volumes become large, but simultaneously the string coupling becomes small...

Fortunately, to leading order in the string coupling, all α' corrections to the Kähler potential are inherited from the N=2 parent compactification, and are thus computable using mirror symmetry:

Becker, Becker, Haack, Louis ‘02
Robles-Llana, Rocek, Saueressig, Theis, Vandoren ‘06
Demirtas, Kim, McAllister, JM, Rios-Tascon ‘21

$$\delta K|_{\mathcal{O}(1/g_s^2)} = \delta K_{\alpha'^3} + \delta K_{\text{worldsheet instantons}}$$

Actually computing them was a serious undertaking, but we were able to this, and consistently incorporate them in evaluating the F-term potential.

At first sight, the perhaps most serious issue with our solutions is that there is no parametric control over α' corrections, whatsoever!

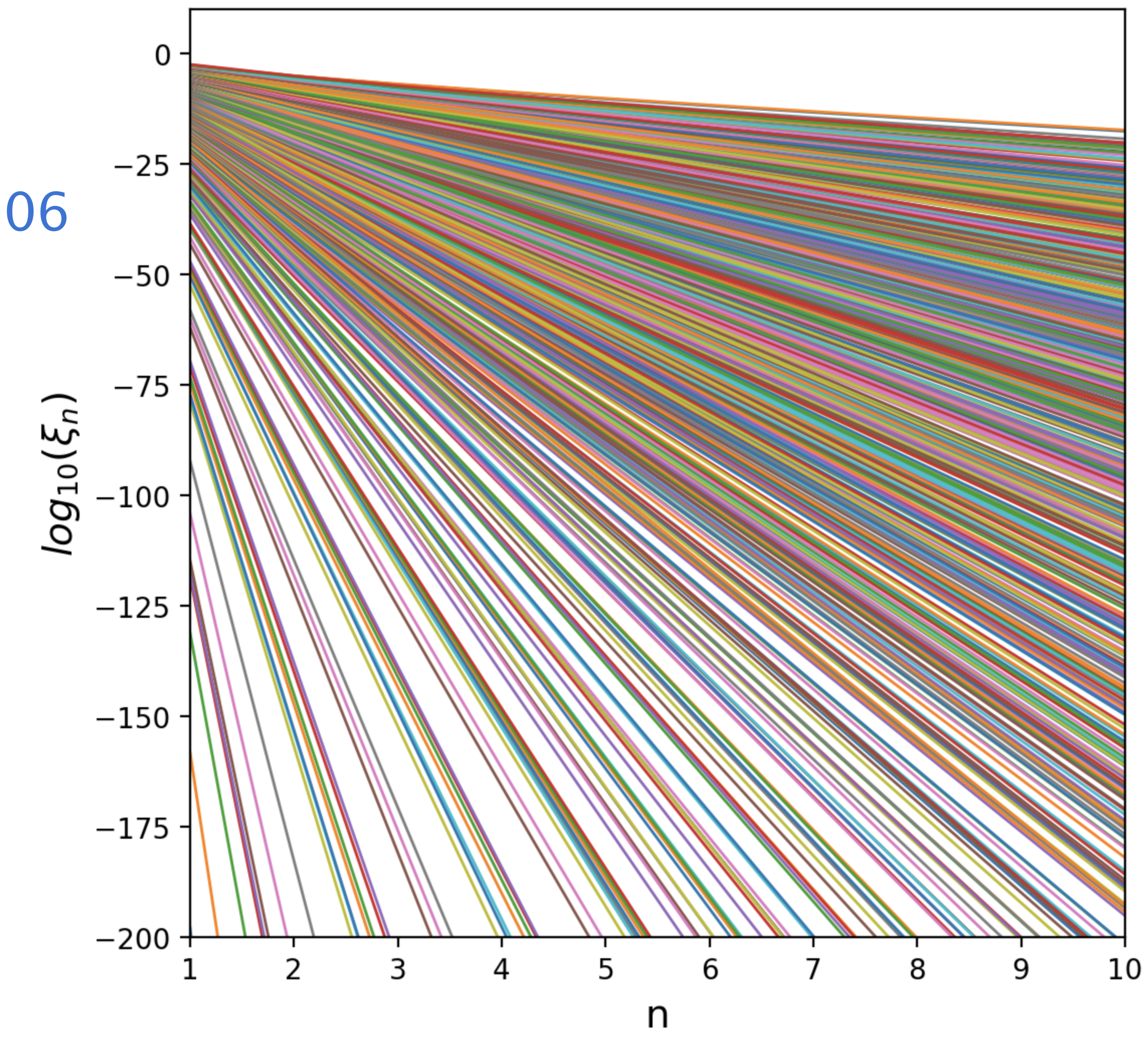
For small superpotential, Einstein-frame volumes become large, but simultaneously the string coupling becomes small…

Fortunately, to leading order in the string coupling, all α' corrections to the Kähler potential are inherited from the N=2 parent compactification, and are thus computable using mirror symmetry:

Becker, Becker, Haack, Louis ‘02
Robles-Llana, Rocek, Saueressig, Theis, Vandoren ‘06
Demirtas, Kim, McAllister, JM, Rios-Tascon ‘21

$$\delta K|_{\mathcal{O}(1/g_s^2)} = \delta K_{\alpha'^3} + \delta K_{\text{worldsheet instantons}}$$

Actually computing them was a serious undertaking, but we were able to this, and consistently incorporate them in evaluating the F-term potential.



At first sight, the perhaps most serious issue with our solutions is that there is no parametric control over α' corrections, whatsoever!

For small superpotential, Einstein-frame volumes become large, but simultaneously the string coupling becomes small…

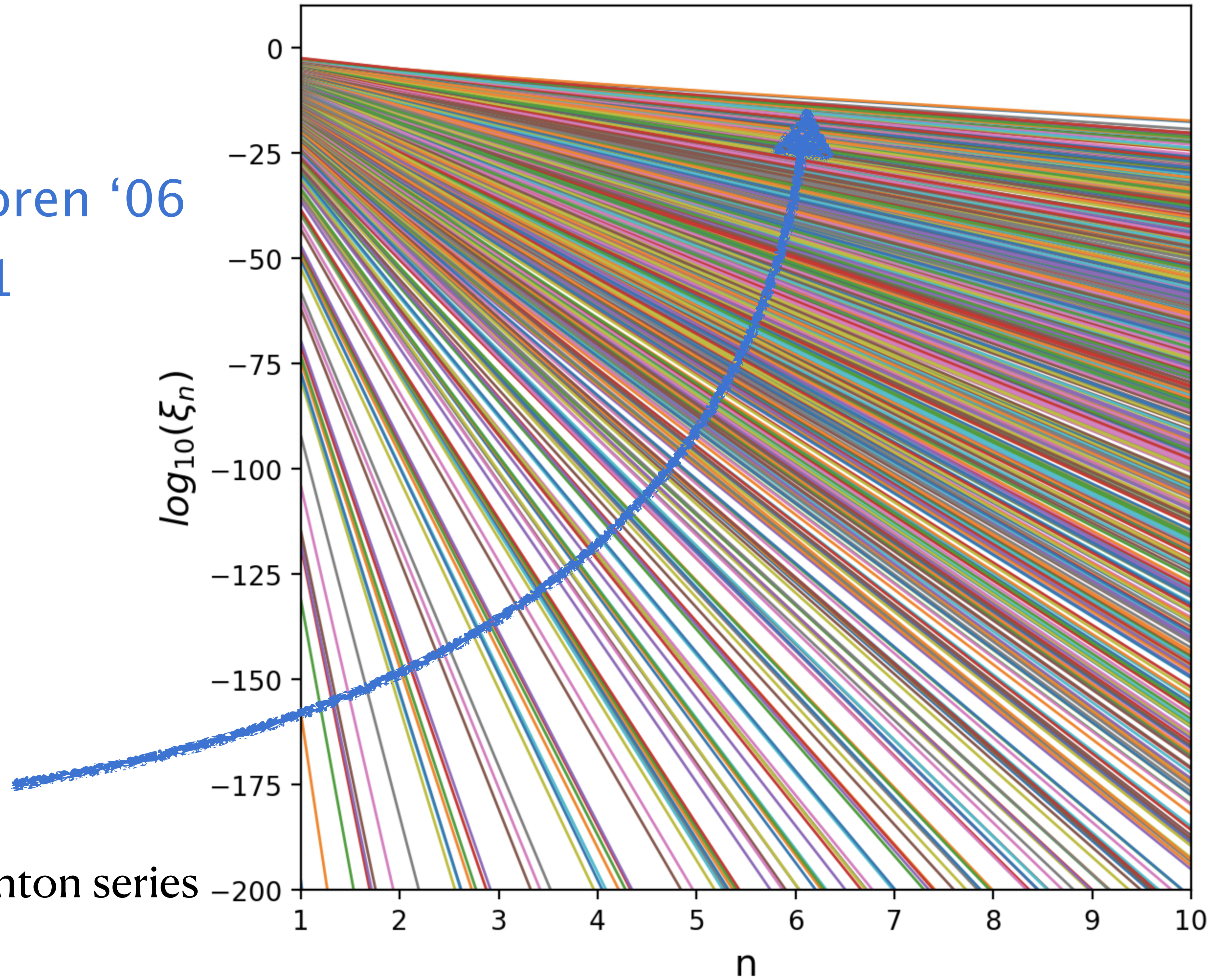
Fortunately, to leading order in the string coupling, all α' corrections to the Kähler potential are inherited from the N=2 parent compactification, and are thus computable using mirror symmetry:

Becker, Becker, Haack, Louis ‘02
Robles-Llana, Rocek, Saueressig, Theis, Vandoren ‘06
Demirtas, Kim, McAllister, JM, Rios-Tascon ‘21

$$\delta K|_{\mathcal{O}(1/g_s^2)} = \delta K_{\alpha'^3} + \delta K_{\text{worldsheet instantons}}$$

Actually computing them was a serious undertaking, but we were able to this, and consistently incorporate them in evaluating the F-term potential.

Negative slopes
↕
Converging worldsheet instanton series



More generally, the control parameters in these solutions are the best we could do in 2024, but can conceivably be improved.

More generally, the control parameters in these solutions are the best we could do in 2024, but can conceivably be improved.

The perhaps most vulnerable aspect of these constructions is the question of meta-stability of the warped anti-D3 state. At tree level in α' we satisfy all constraints …

More generally, the control parameters in these solutions are the best we could do in 2024, but can conceivably be improved.

The perhaps most vulnerable aspect of these constructions is the question of meta-stability of the warped anti-D3 state. At tree level in α' we satisfy all constraints ...

... but recent computations of α' corrections to the anti-D3 brane imply that our throat radii are not large enough to safely ignore them.

Hebecker, Schreyer, Venken ‘22
Schreyer, Venken ‘22
Gao, Hebecker, Schreyer, Venken ‘22
Schreyer ‘24

More generally, the control parameters in these solutions are the best we could do in 2024, but can conceivably be improved.

The perhaps most vulnerable aspect of these constructions is the question of meta-stability of the warped anti-D3 state. At tree level in α' we satisfy all constraints ...

... but recent computations of α' corrections to the anti-D3 brane imply that our throat radii are not large enough to safely ignore them.

Hebecker, Schreyer, Venken ‘22

Schreyer, Venken ‘22

Gao, Hebecker, Schreyer, Venken ‘22

Schreyer ‘24

The question of meta-stability of the uplift in the regime $g_s M \sim 1$ remains an important open problem!

Similarly, the string coupling is not extremely small, and Einstein-frame cycle volumes are not impressively large. Simple models of loop and warping corrections to the Kähler potential suggest $\mathcal{O}(20-30\%)$ corrections.

Similarly, the string coupling is not extremely small, and Einstein-frame cycle volumes are not impressively large. Simple models of loop and warping corrections to the Kähler potential suggest $\mathcal{O}(20-30\%)$ corrections.

Further, while relevant perturbations to the KS-throat are parametrically negligible when $|z|^{2/3} \sim |W_0| \to 0$, one needs to check numerically how it turns out in our example(s). This requires knowing the CY-metric…

Similarly, the string coupling is not extremely small, and Einstein-frame cycle volumes are not impressively large. Simple models of loop and warping corrections to the Kähler potential suggest $\mathcal{O}(20-30\%)$ corrections.

Further, while relevant perturbations to the KS-throat are parametrically negligible when $|z|^{2/3} \sim |W_0| \to 0$, one needs to check numerically how it turns out in our example(s). This requires knowing the CY-metric...

Finally, in orientifolds of tori, odd integer quantized fluxes lead to exotic O3 planes, related to the existence of "twisted cycles" ~ $T^3/\mathbb{Z}_2$ Frey, Polchinski '02

Similarly, the string coupling is not extremely small, and Einstein-frame cycle volumes are not impressively large. Simple models of loop and warping corrections to the Kähler potential suggest $\mathcal{O}(20-30\%)$ corrections.

Further, while relevant perturbations to the KS-throat are parametrically negligible when $|z|^{2/3} \sim |W_0| \to 0$, one needs to check numerically how it turns out in our example(s). This requires knowing the CY-metric…

Finally, in orientifolds of tori, odd integer quantized fluxes lead to exotic O3 planes, related to the existence of "twisted cycles" ~ $T^3/\mathbb{Z}_2$ Frey, Polchinski '02

Whether odd fluxes are allowed in our Calabi-Yau orientifolds, or if one has to adapt the search to find all even fluxes remains to be understood.

Plan:

1. Some Motivation
2. The KKLT scenario
3. Vacua with small superpotential
4. Warped throats and “Uplift” to de Sitter: an example
5. Control over corrections
6. Conclusions

Main takeaway: we have constructed the first explicit de Sitter solutions in type IIB string theory along the lines anticipated by Kachru, Kallosh, Linde and Trivedi in '03, by

Main takeaway: we have constructed the first explicit de Sitter solutions in type IIB string theory along the lines anticipated by Kachru, Kallosh, Linde and Trivedi in '03, by

1. computing superpotentials from fluxes and D3-instantons using toric geometry, and enumerative invariants,

Main takeaway: we have constructed the first explicit de Sitter solutions in type IIB string theory along the lines anticipated by Kachru, Kallosh, Linde and Trivedi in '03, by

1. computing superpotentials from fluxes and D3-instantons using toric geometry, and enumerative invariants,
2. finding vacua by solving Diophantine equations in flux quanta, and identifying F-term solutions in low energy effective theory featuring explicit racetrack superpotential,

Main takeaway: we have constructed the first explicit de Sitter solutions in type IIB string theory along the lines anticipated by Kachru, Kallosh, Linde and Trivedi in ’03, by

1. computing superpotentials from fluxes and D3-instantons using toric geometry, and enumerative invariants,
2. finding vacua by solving Diophantine equations in flux quanta, and identifying F-term solutions in low energy effective theory featuring explicit racetrack superpotential,
3. explicitly constructing warped throat regions suitable for anti-D3 uplift to de Sitter,

Main takeaway: we have constructed the first explicit de Sitter solutions in type IIB string theory along the lines anticipated by Kachru, Kallosh, Linde and Trivedi in '03, by

1. computing superpotentials from fluxes and D3-instantons using toric geometry, and enumerative invariants,
2. finding vacua by solving Diophantine equations in flux quanta, and identifying F-term solutions in low energy effective theory featuring explicit racetrack superpotential,
3. explicitly constructing warped throat regions suitable for anti-D3 uplift to de Sitter,
4. identifying the F-term minima in Kähler moduli (via following a discretized BPS attractor flow in the extended Kähler cone).

Main takeaway: we have constructed the first explicit de Sitter solutions in type IIB string theory along the lines anticipated by Kachru, Kallosh, Linde and Trivedi in '03, by

1. computing superpotentials from fluxes and D3-instantons using toric geometry, and enumerative invariants,
2. finding vacua by solving Diophantine equations in flux quanta, and identifying F-term solutions in low energy effective theory featuring explicit racetrack superpotential,
3. explicitly constructing warped throat regions suitable for anti-D3 uplift to de Sitter,
4. identifying the F-term minima in Kähler moduli (via following a discretized BPS attractor flow in the extended Kähler cone).

This is not the last word on this subject…

… within constraints set by D3-tadpole, one should be able to find better values for the control parameters.

… within constraints set by D3-tadpole, one should be able to find better values for the control parameters.

Furthermore, one can improve control by better understanding the structure of corrections along lines of recent work

Alexandrov, Firat, Kim, Sen, Stefanski ‘22
Gendler, Kim, McAllister, JM, Stillman ‘22
Liu, Minasian, Savelli, Schachner ‘22
Hebecker, Schreyer, Venken ‘22
Schreyer, Venken ‘22
Gao, Hebecker, Schreyer, Venken ‘22
3x Kim ‘23
Cho, Kim ‘23
Schreyer ‘24 …

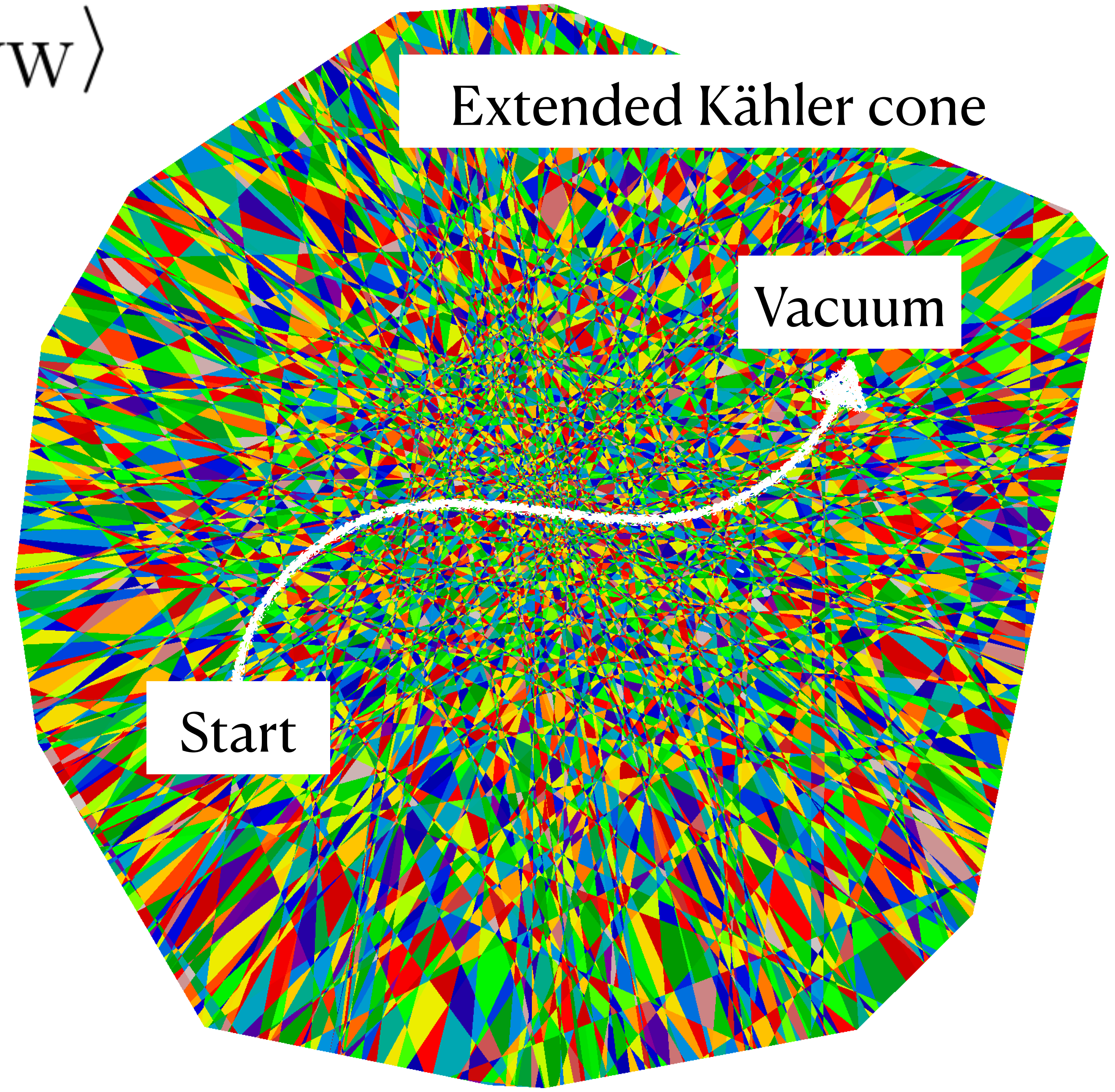
Thank You!

Kähler moduli stabilization

Given non-perturbative contributions to superpotential (of full rank) one expects Kähler moduli to be stabilized near

$$\langle \mathrm{Re}(T_i) \rangle \sim \frac{\log(|W_0|^{-1})}{2\pi} \quad \text{with} \quad W_0 := \langle W_{\mathrm{GVW}} \rangle$$

It is useful to first find this point, by following a BPS attractor flow of sorts, starting from any point in Kähler moduli space.



Once one arrives at this point, one typically is close enough to the minimum, such that straightforward methods such Newton's method can be successfully implemented to find the vacuum solution numerically.

An Anti de Sitter vacuum with even fluxes

Here is an example of a supersymmetric flux vacuum in which all fluxes are even:

A Calabi-Yau hypersurface with Hodge numbers $h^{1,1} = 85$ and $h^{2,1} = 5$

leads to a "PFV" with $\vec{z} = \frac{1}{22}\begin{pmatrix} 21 & 1 & 44 & 50 & 32 \end{pmatrix} \tau$

For flux choice: $\mathbb{M} = 2\begin{pmatrix} 10 & -11 & 1 & -4 & 0 \end{pmatrix}$ $\mathbb{K} = 2\begin{pmatrix} 7 & 9 & -2 & -2 & 1 \end{pmatrix}$

The resulting effective superpotential reads

$$W_{\text{eff}}(\tau) = \xi \cdot \left(-2e^{2\pi i \frac{21}{22}\tau} - 200e^{2\pi i\tau} - 20e^{2\pi i \frac{23}{22}\tau} + \ldots\right) \,, \quad \xi = \frac{\sqrt{2/\pi}}{(2\pi)^2}$$

And leads to a vacuum with

$g_s \approx 0.06 \qquad W_0 \approx 7 \times 10^{-46}$

After stabilizing Kähler moduli:

$\rho_{\text{vacuum}} \approx -1.34 \times 10^{-108} M_{\text{pl}}^4 \qquad \mathcal{V}_E \approx 1.2 \times 10^6\, \ell_s^6$