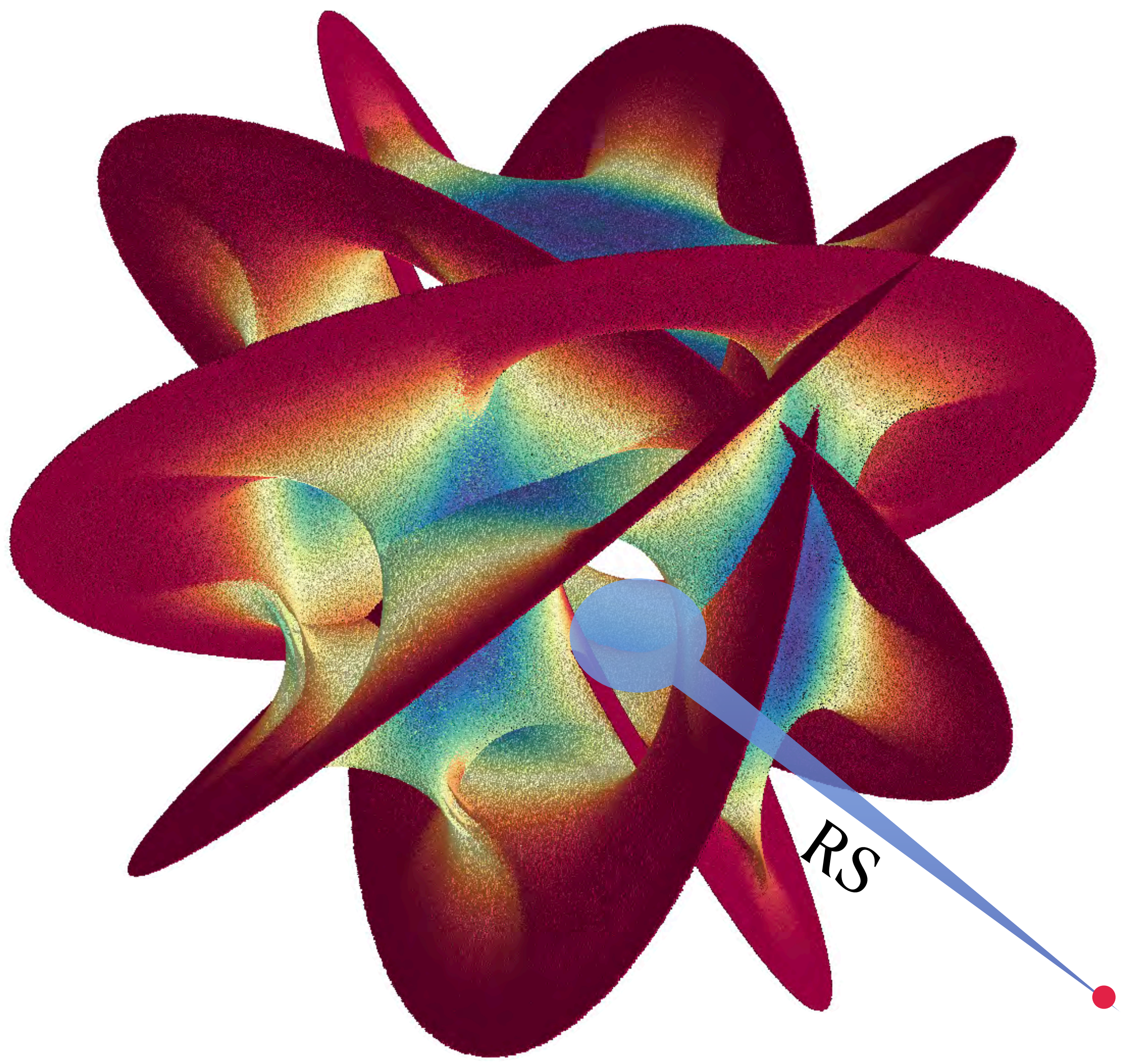
Candidate De Sitter Vacua



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)

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

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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

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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,

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

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

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

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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.

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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.

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Grimm, Louis '04

$h^{1,1}_+$	Kähler moduli	T_i
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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:

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

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

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(steps 4. and 5.)

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

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Witten '96

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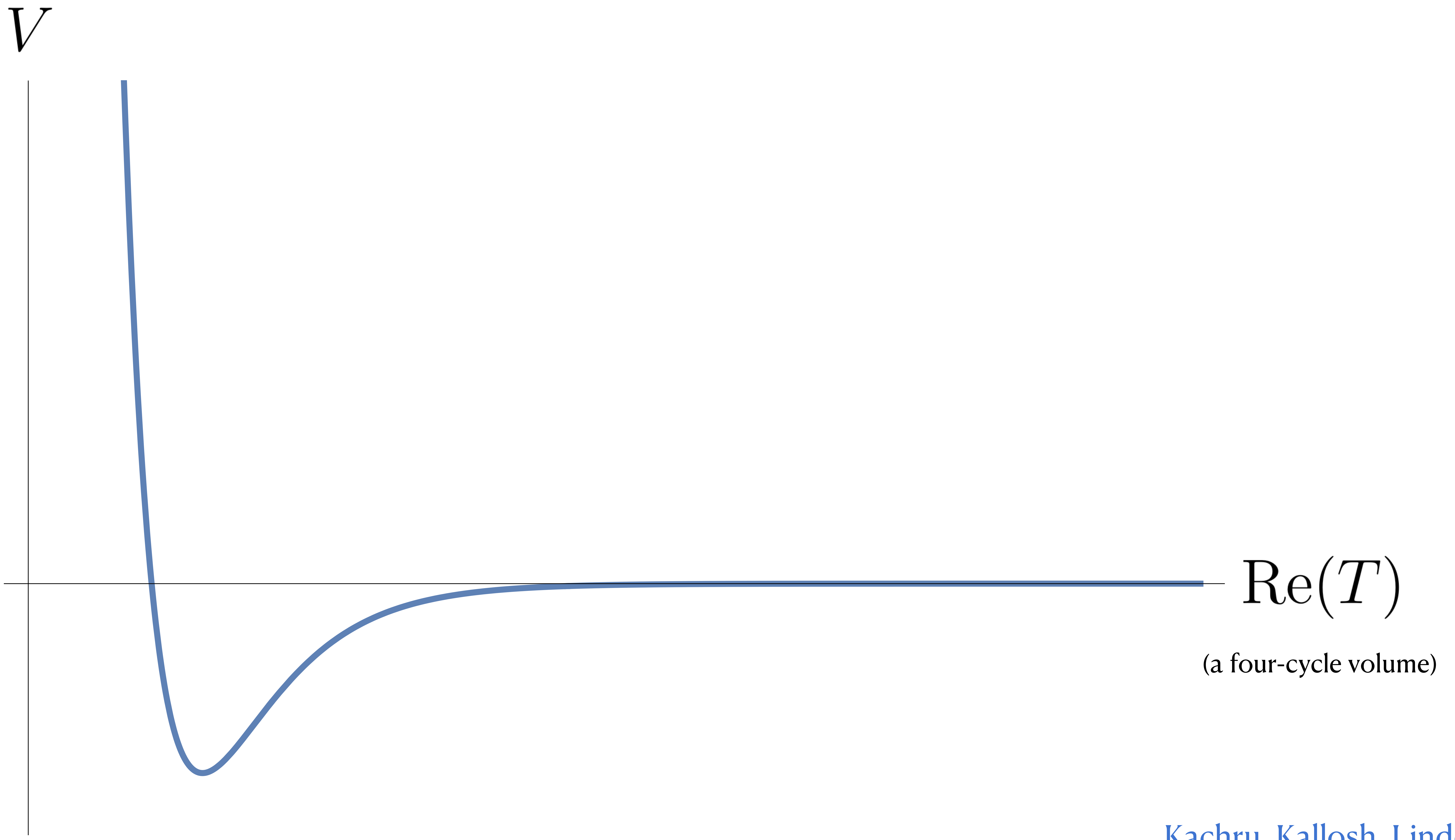
Given at least $h^{1,1}$ such corrections, one expects Kähler moduli to be stabilized at

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

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

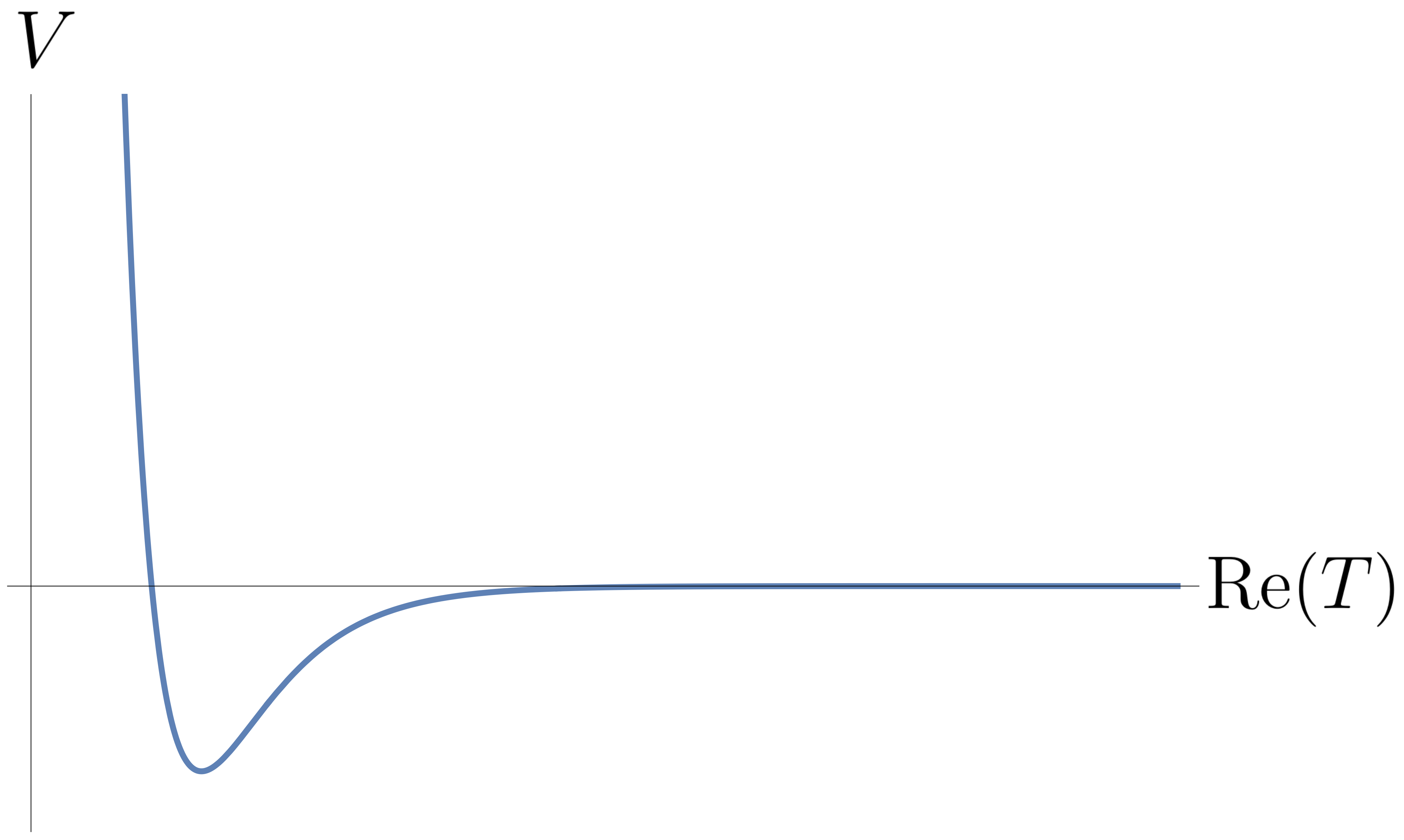
Anti-D3 brane uplift

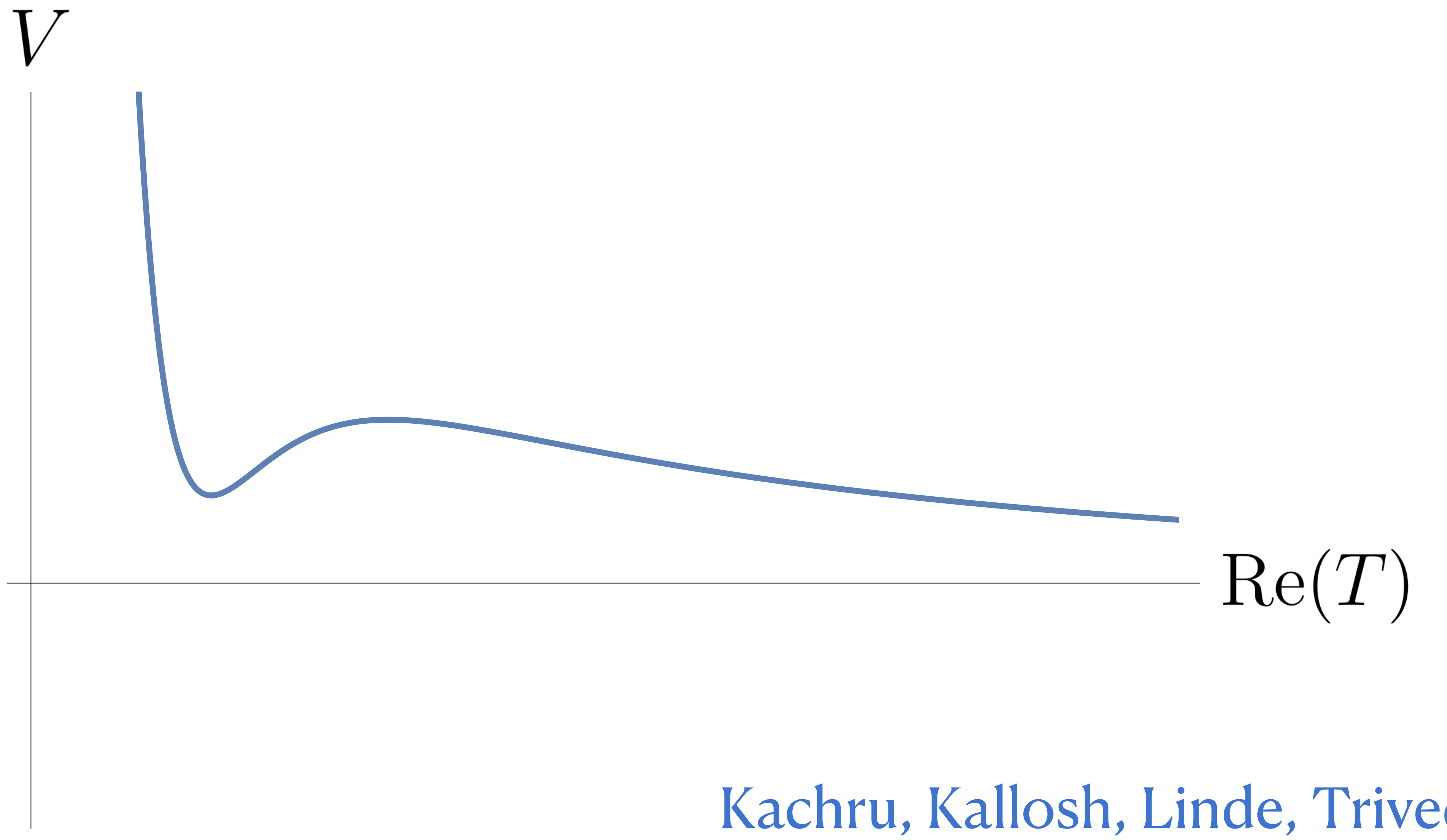
(step 6.)

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

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

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...

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... but now let's do it for real!

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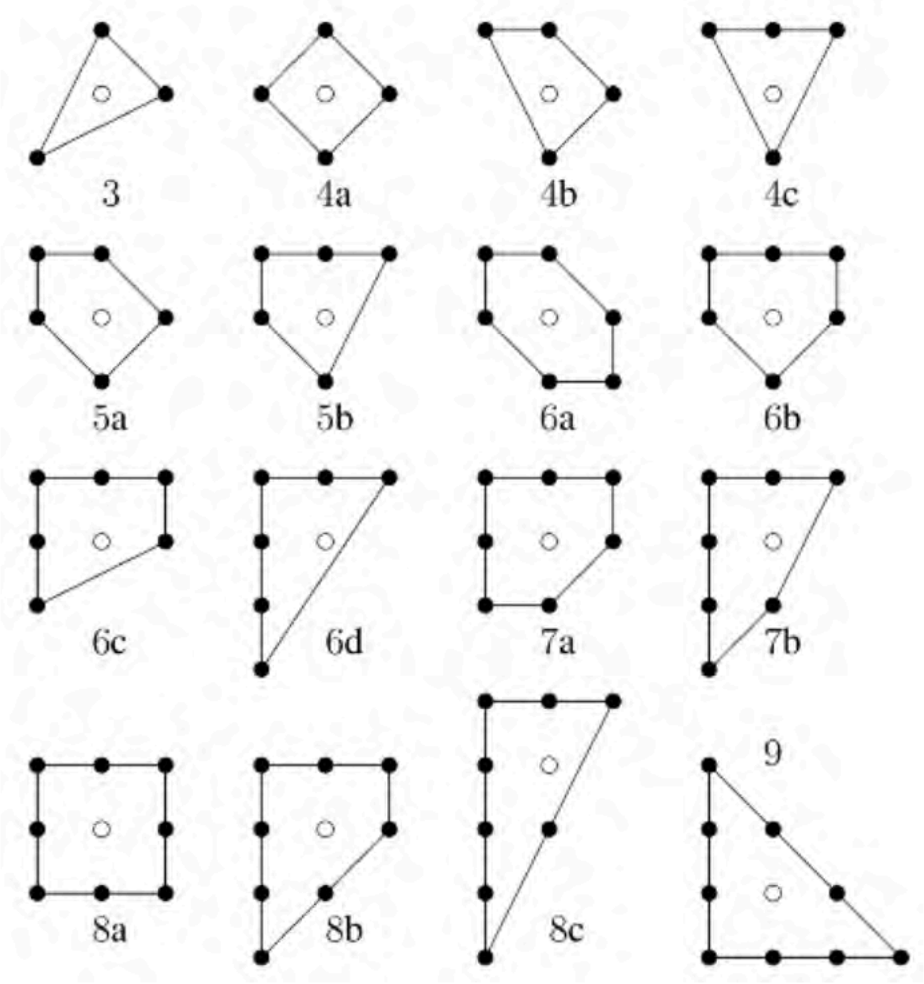
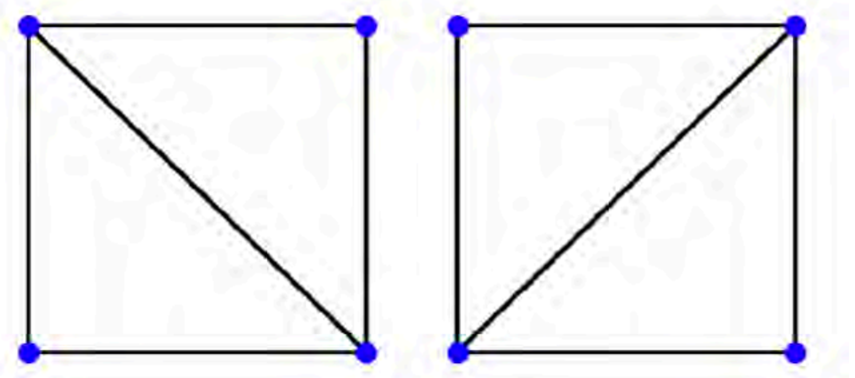
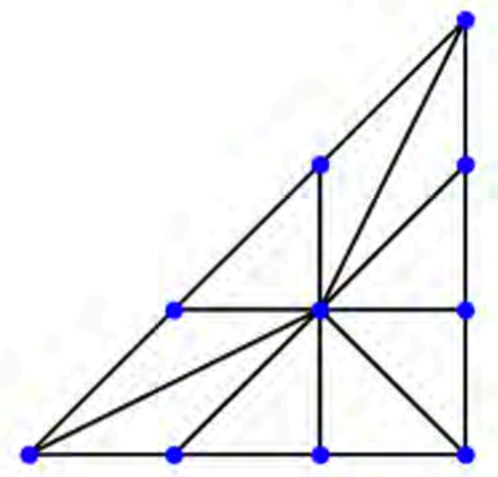


In practice, we work with the Kreuzer-Skarke dataset of reflexive polytopes in four dimensions, from which Calabi-Yau threefold hypersurfaces are constructed in combinatorial terms

Batyrev '93 Kreuzer, Skarke '00





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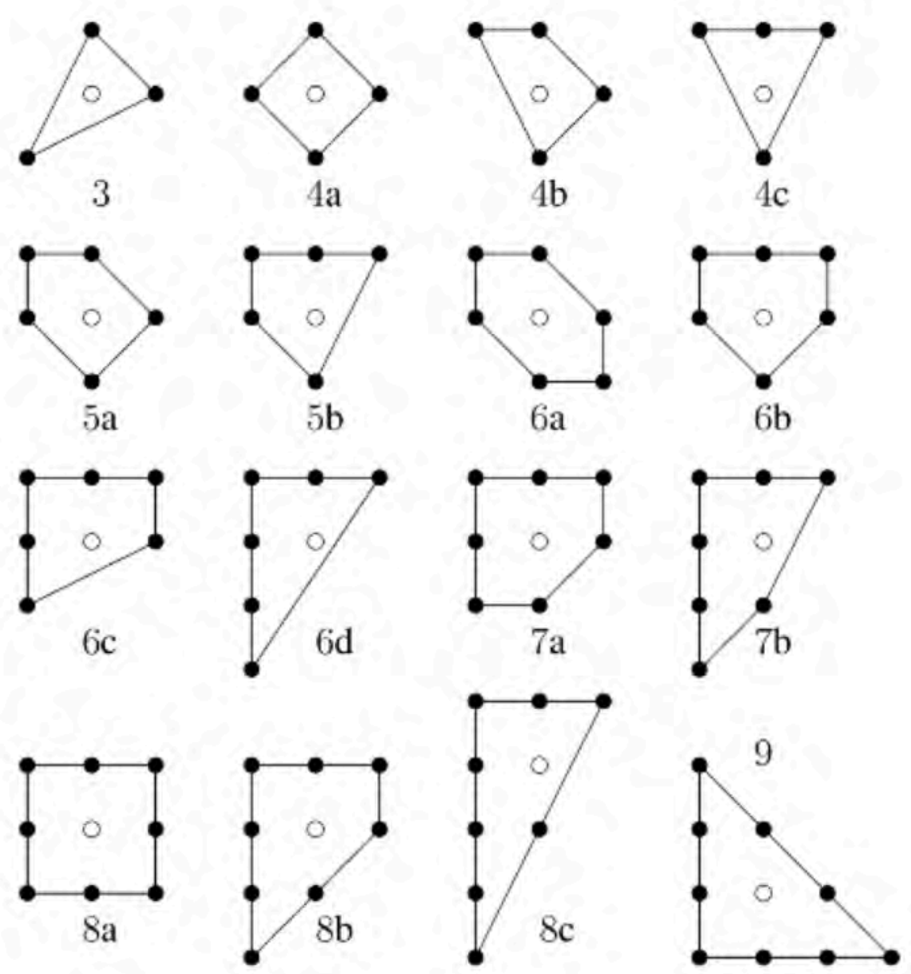

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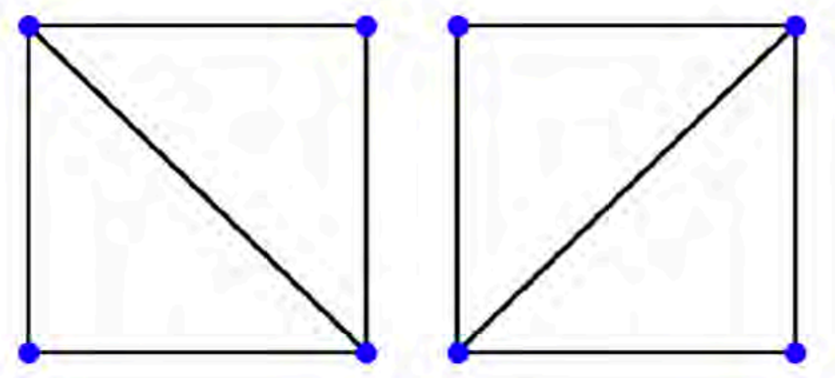
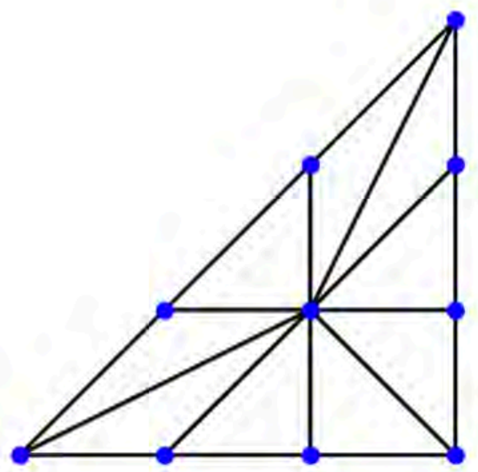
Given any such polytope, we then enumerate O3/O7 orientifold projections and compute all relevant data of fixed loci JM ‘23





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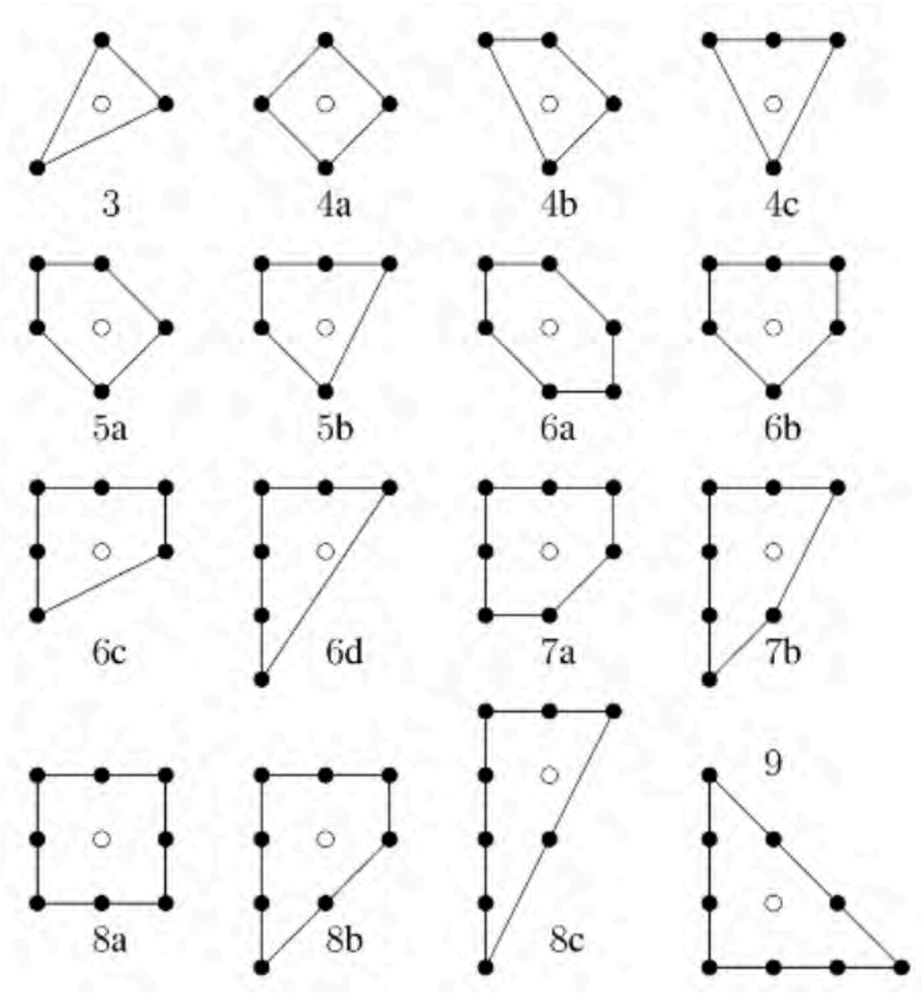

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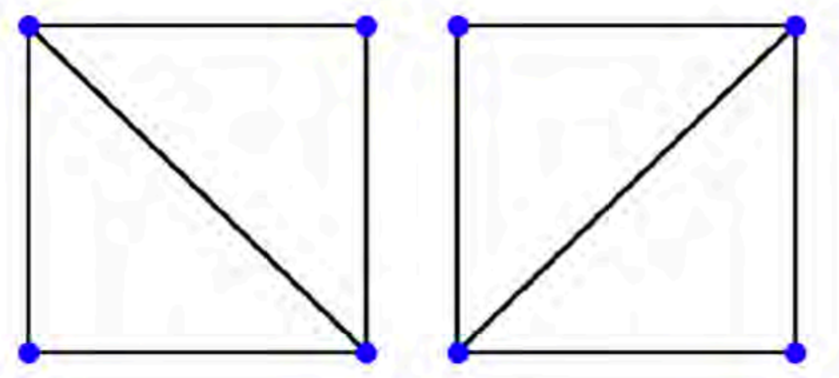

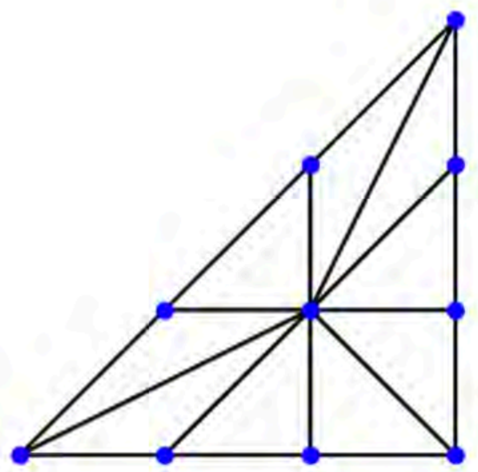

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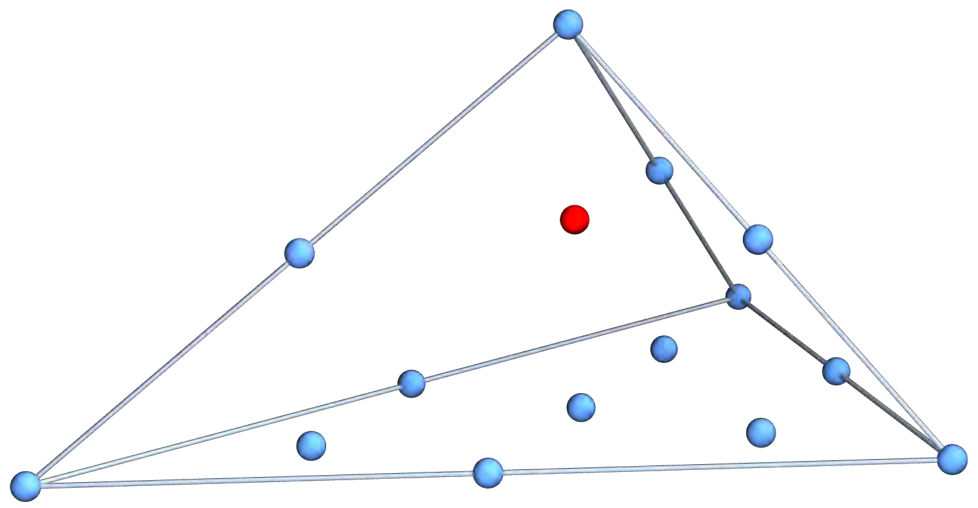
A simple class of orientifolds with $h^{1,1}_{-} = h^{2,1}_{+} = 0$ arises from special polytopes



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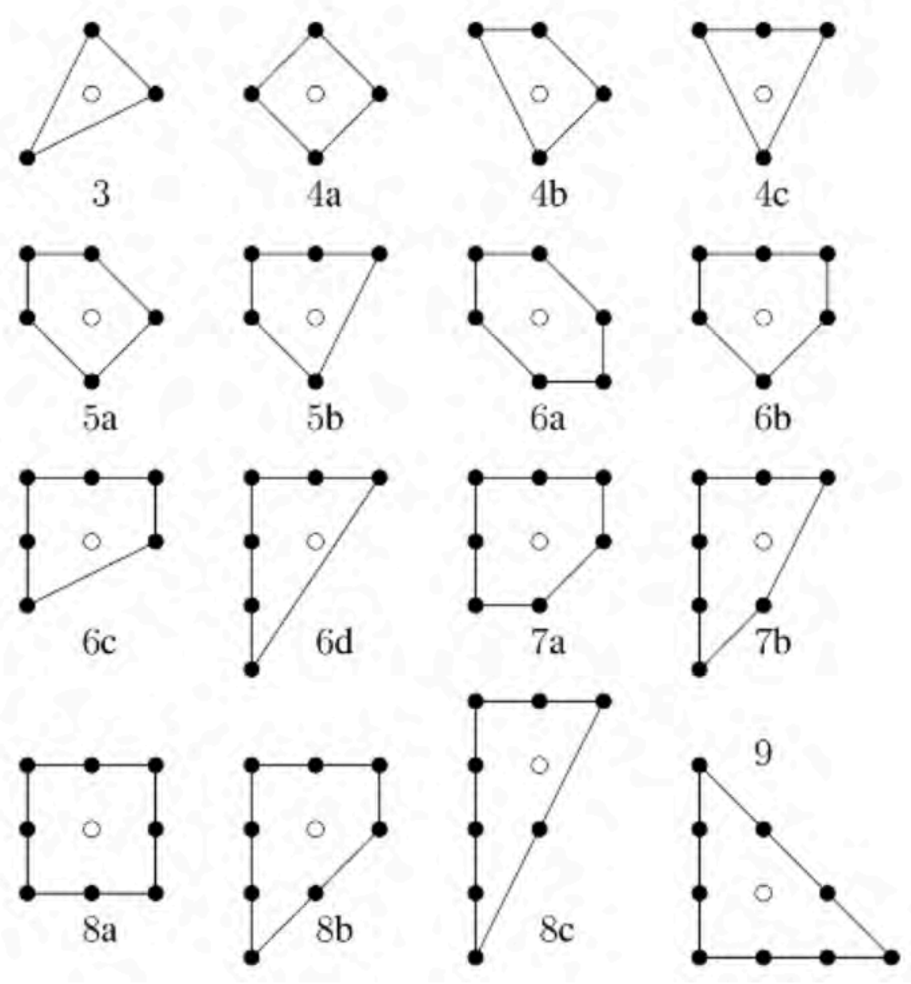

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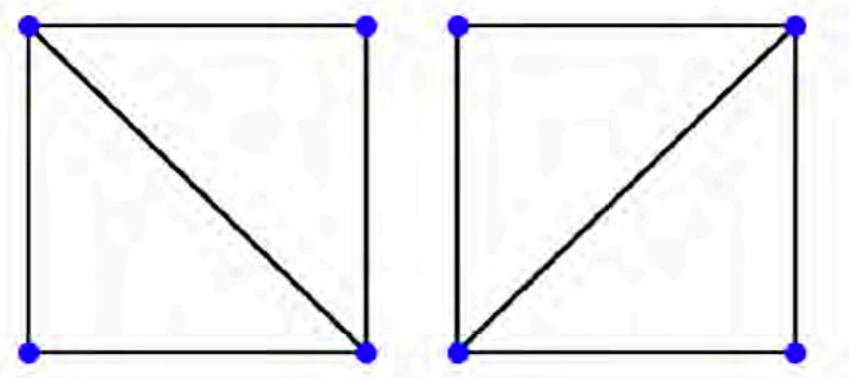

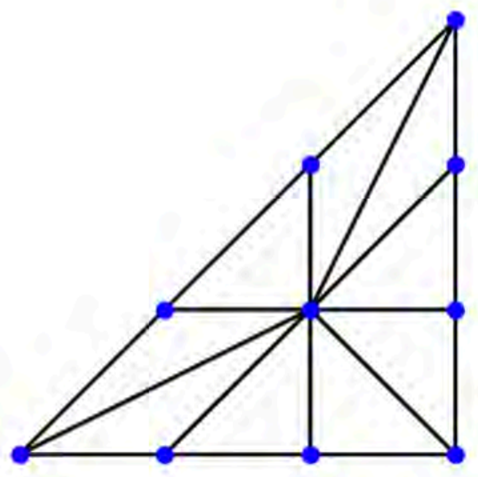

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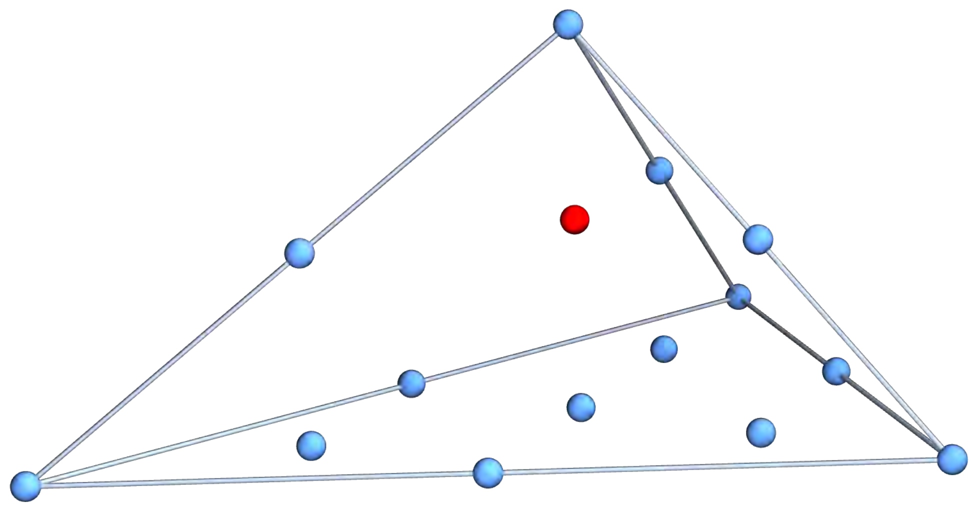

For these the vanishing of overall D3 charge requires $\frac{1}{2}\int_X H_3 \wedge F_3 \leq Q_{D3} := \frac{1}{2}(h^{1,1} + h^{2,1}) + 1$

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

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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

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

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

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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!

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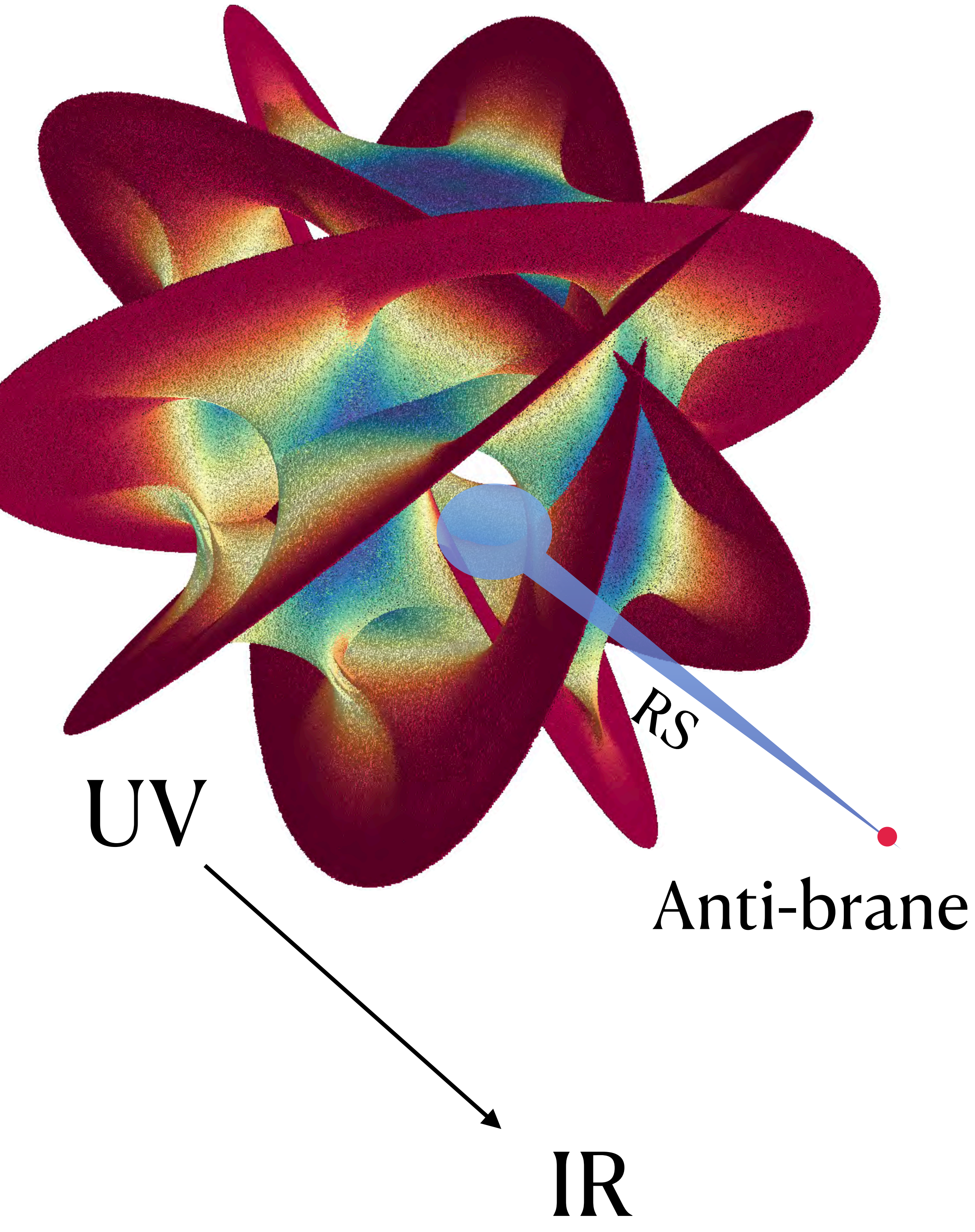
First, instead of stabilizing at large complex structure, we need to stabilize them near a conifold singularity in moduli space.

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

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



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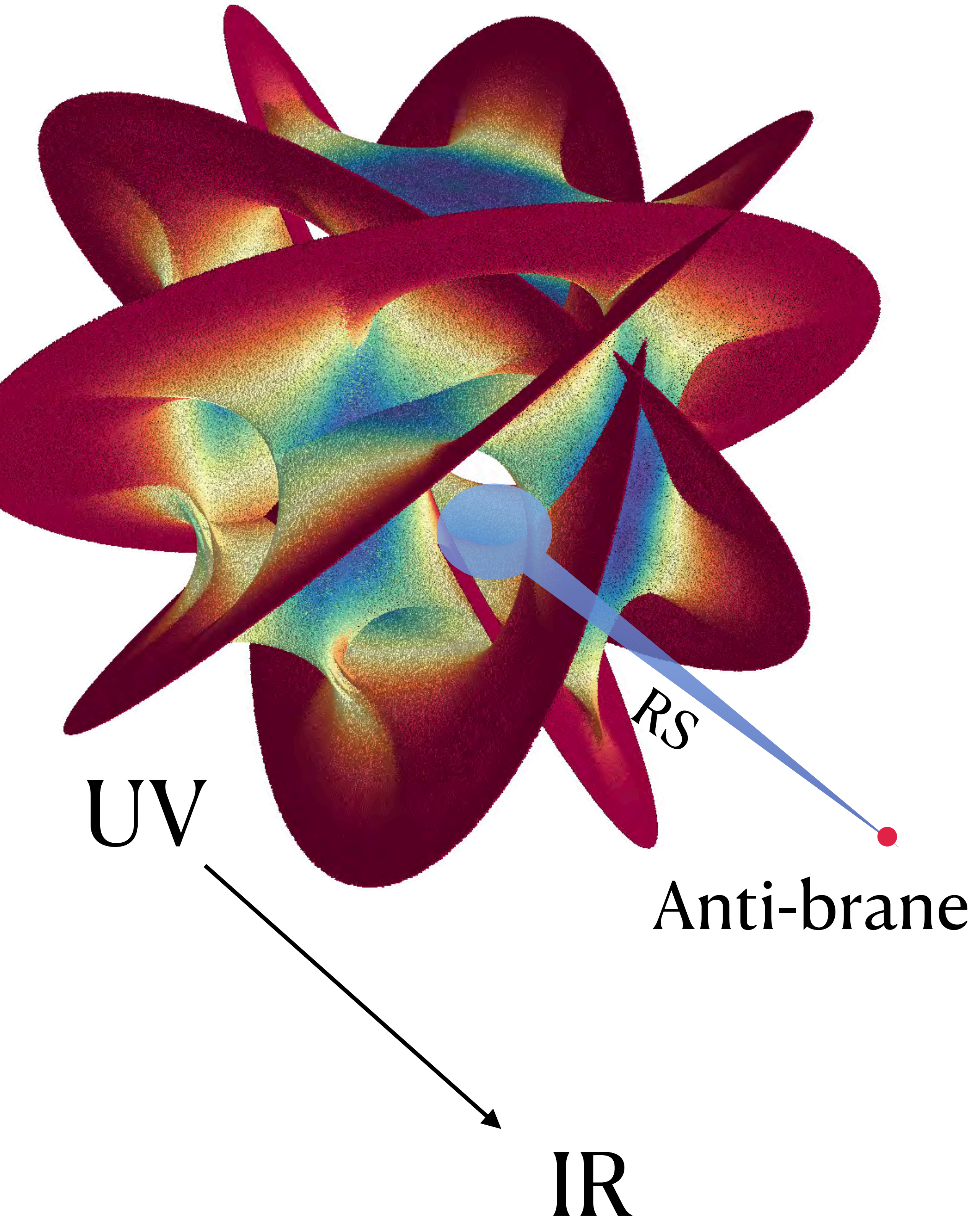

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distance from conifold locus in moduli space

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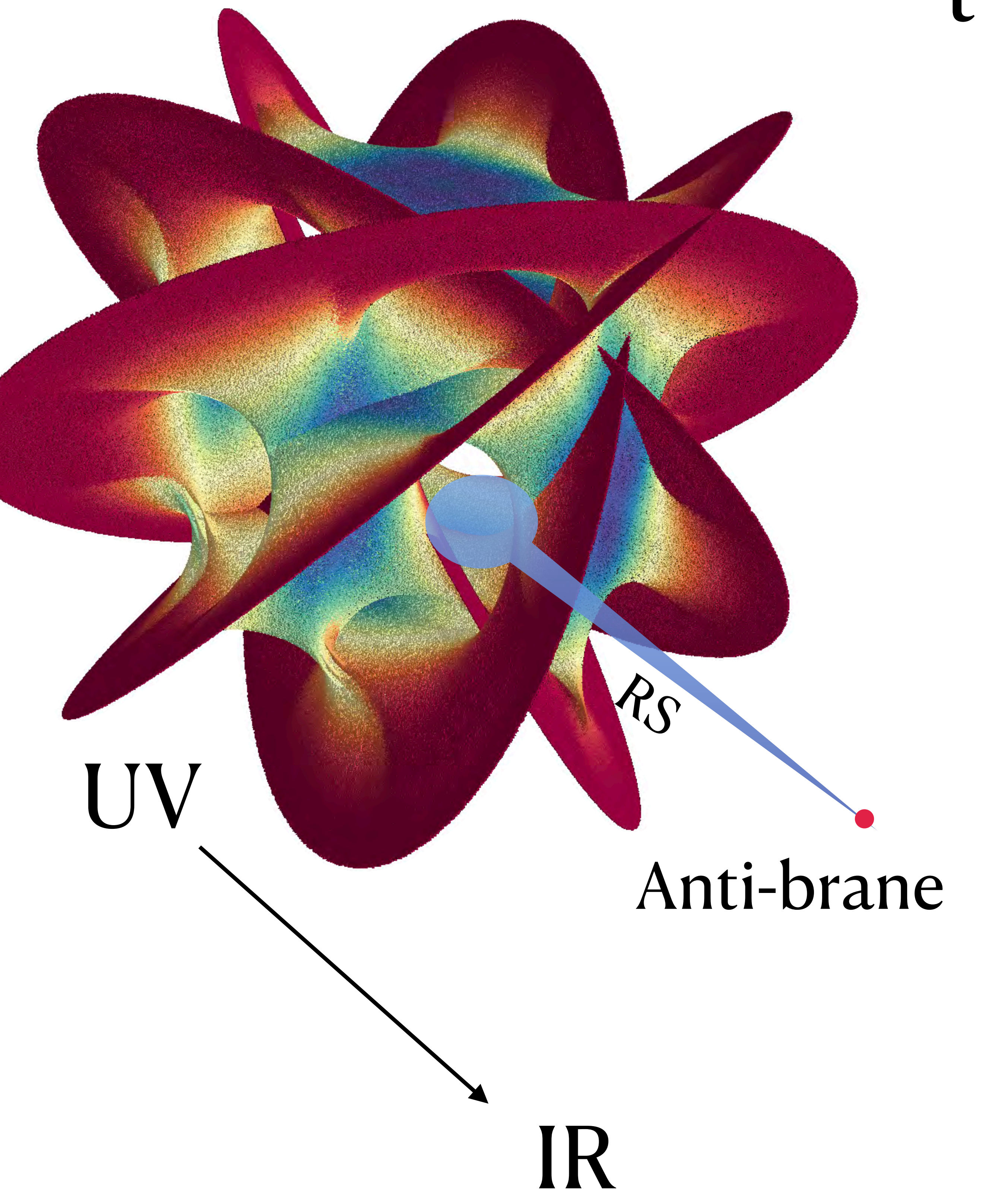

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distance from conifold locus in moduli space

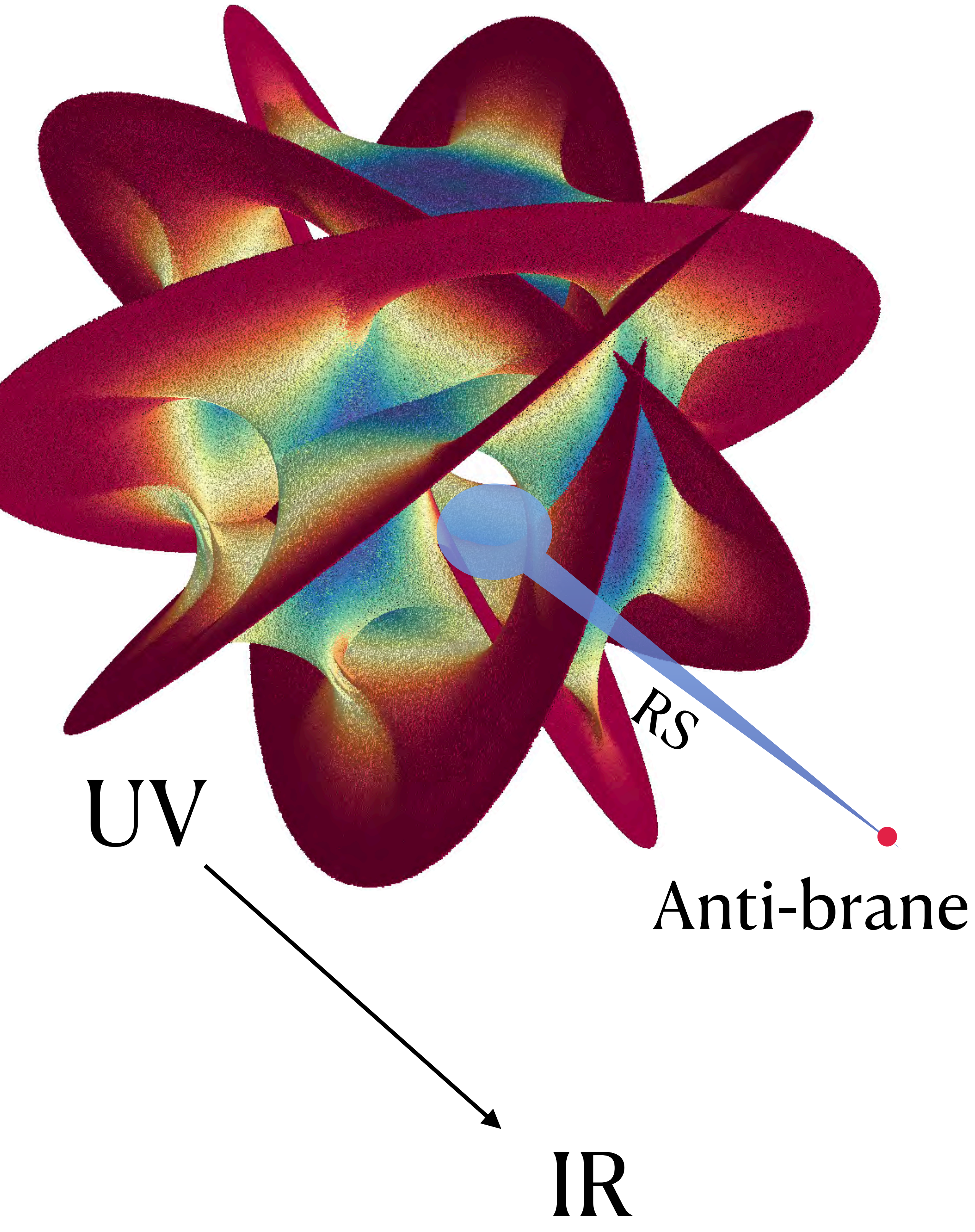
For a single Anti-D3 brane to raise the vacuum energy to positive values, without causing a decompactification instability, we need

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

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

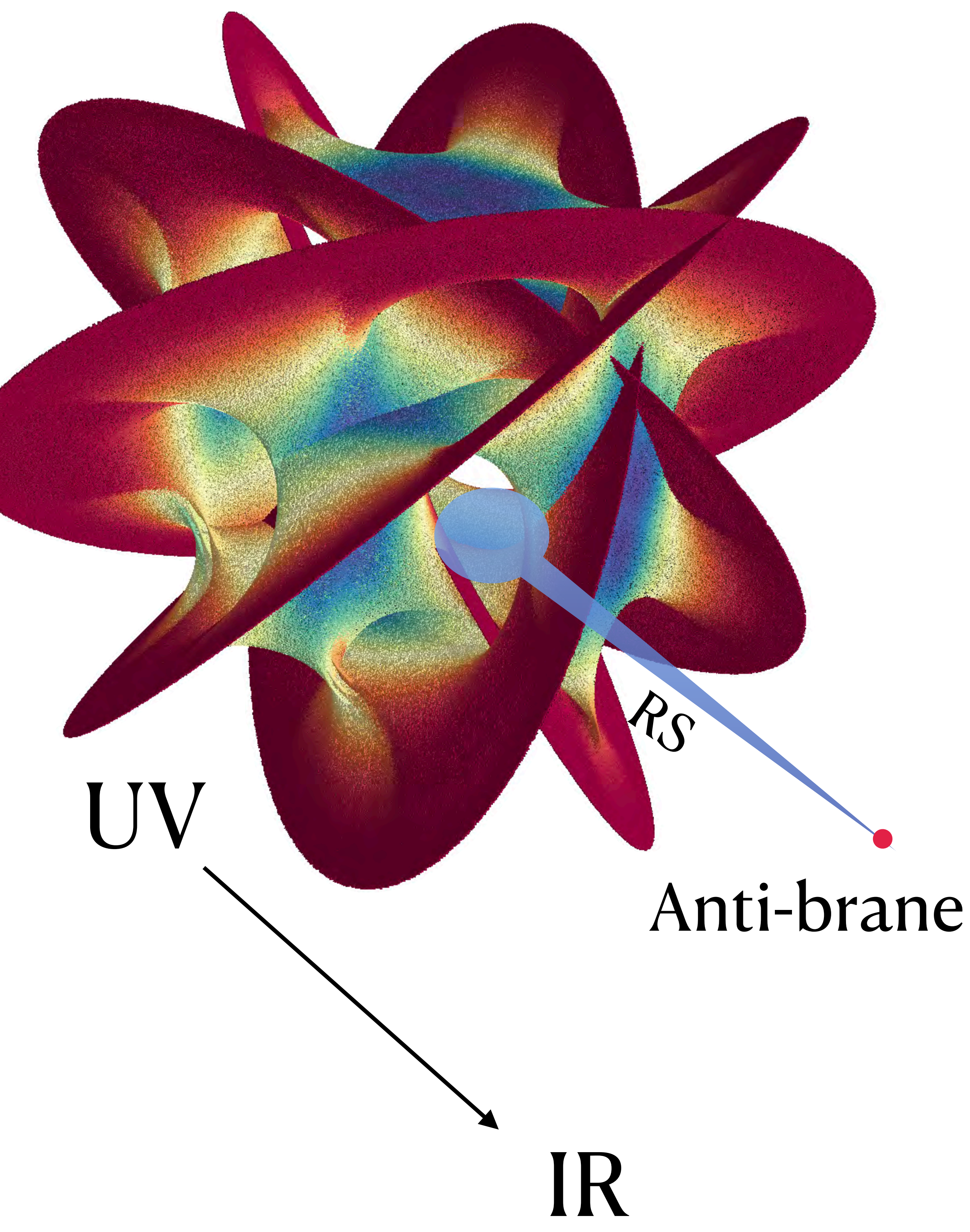
$$\frac{|z|^{\frac{4}{3}}}{(g_s M)^2} \approx \underbrace{5.5 \times 10^{-3}}_{\text{from KS solution}} \times \frac{|W_0|^2}{\mathcal{V}_E^{\frac{2}{3}}\tilde{\mathcal{V}}_s^{\frac{1}{3}}} \ll 1 \qquad M := \int_{\text{Conifold } S^3} F_3$$

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



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

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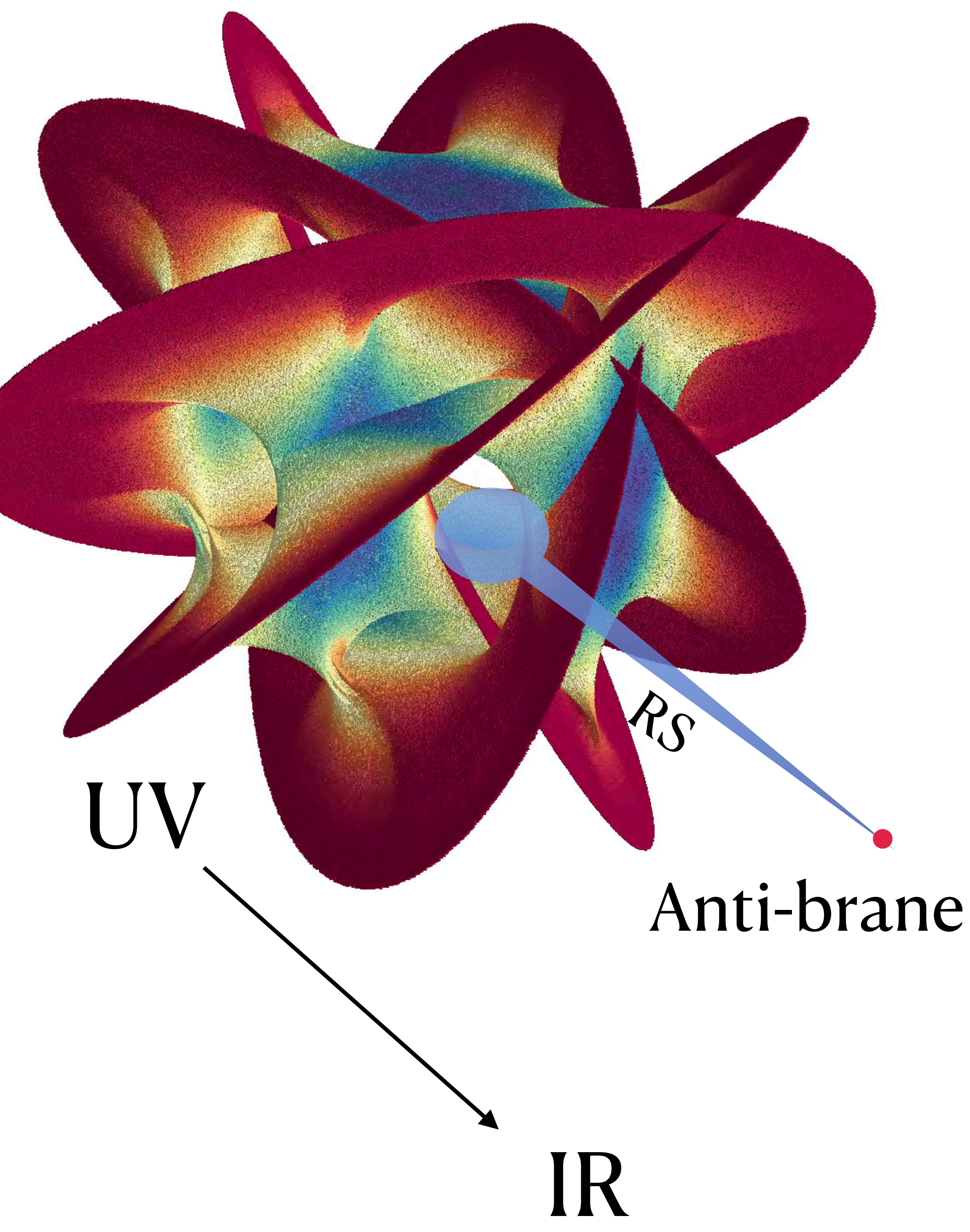

The conifold F-term is solved for

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

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

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.

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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.

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- 24,510 vacua with $Q_{D3}^{\text{flux}} = Q_{D3} + 1$ and $M > 12$

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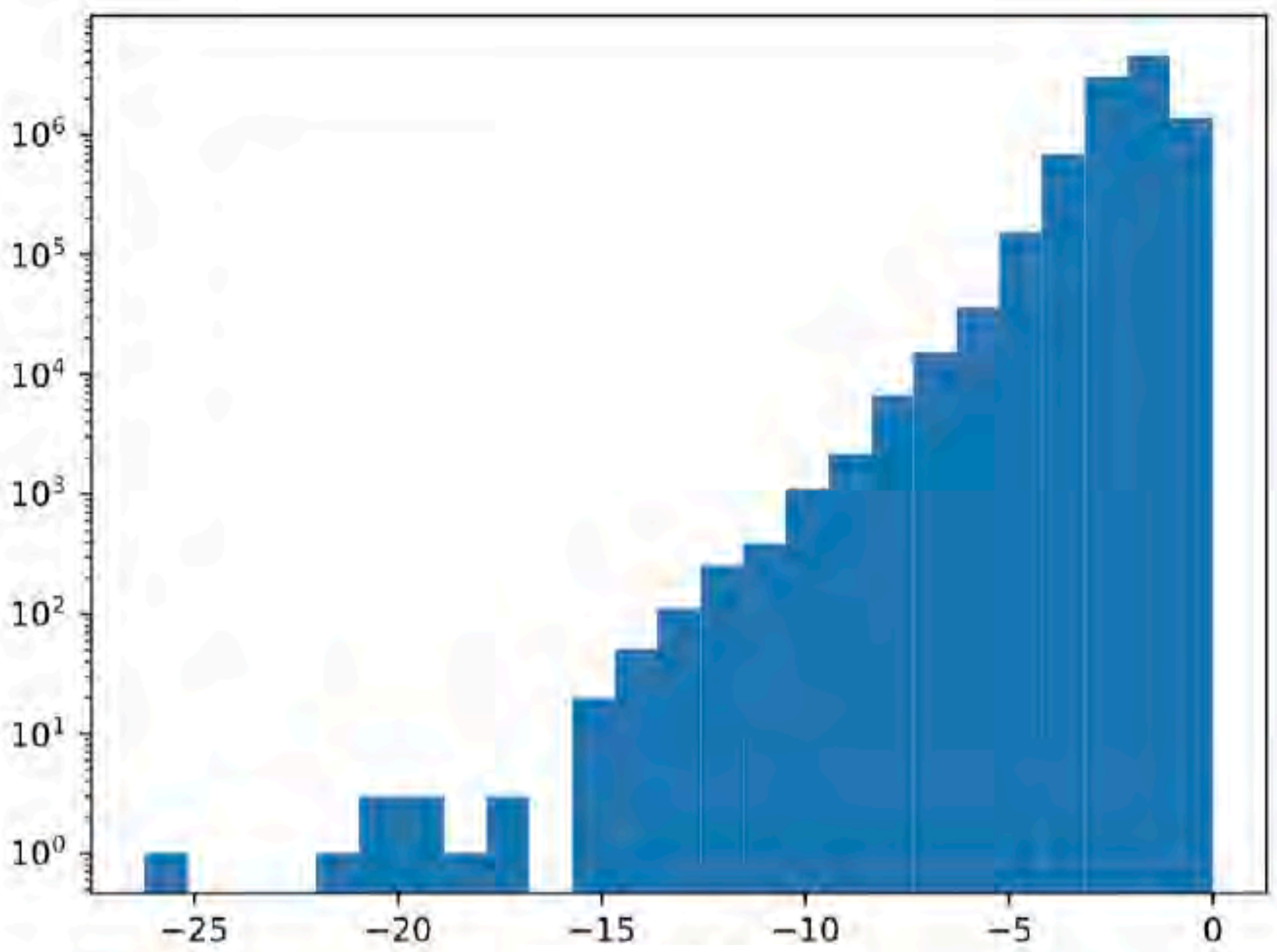

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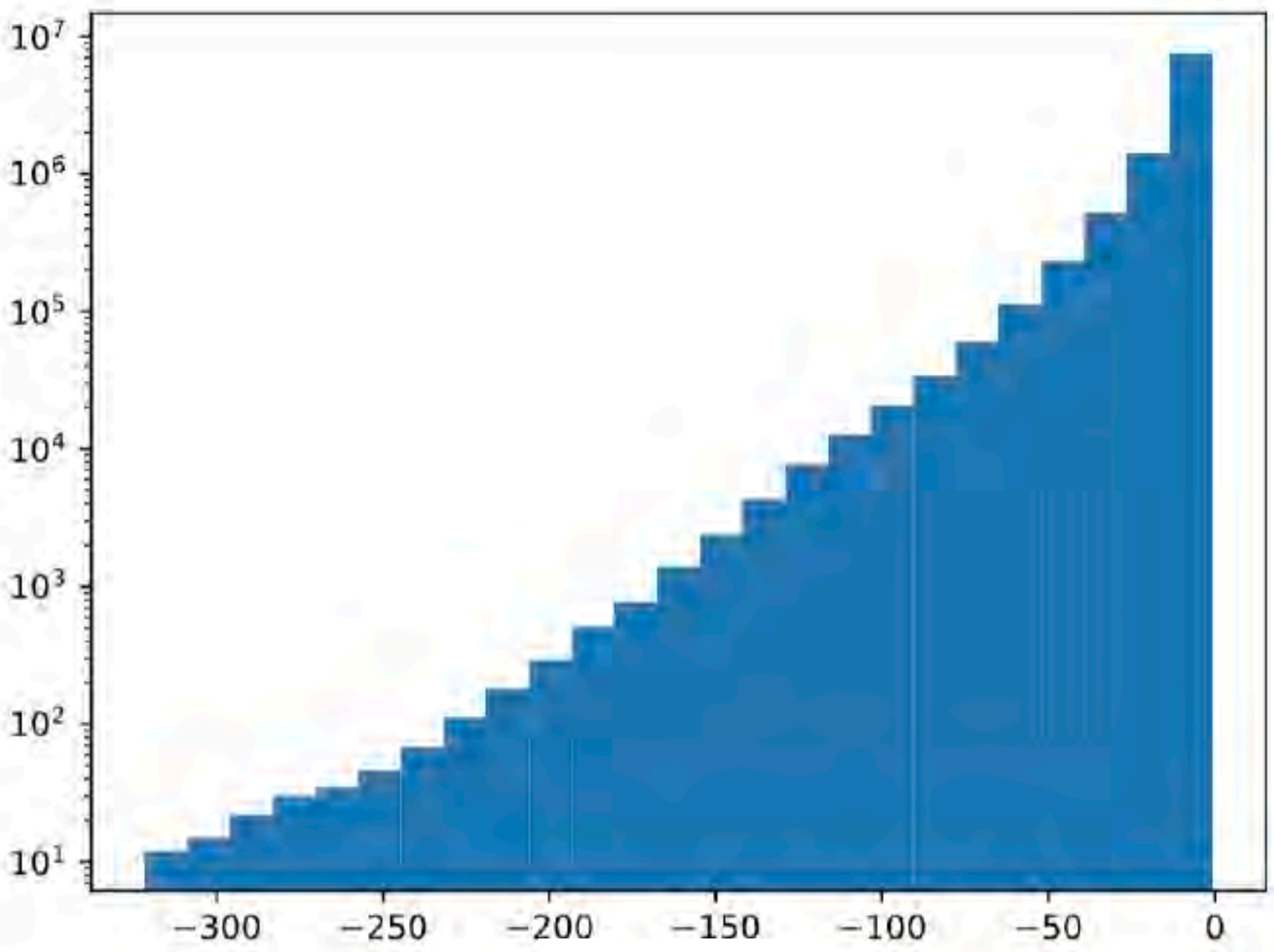

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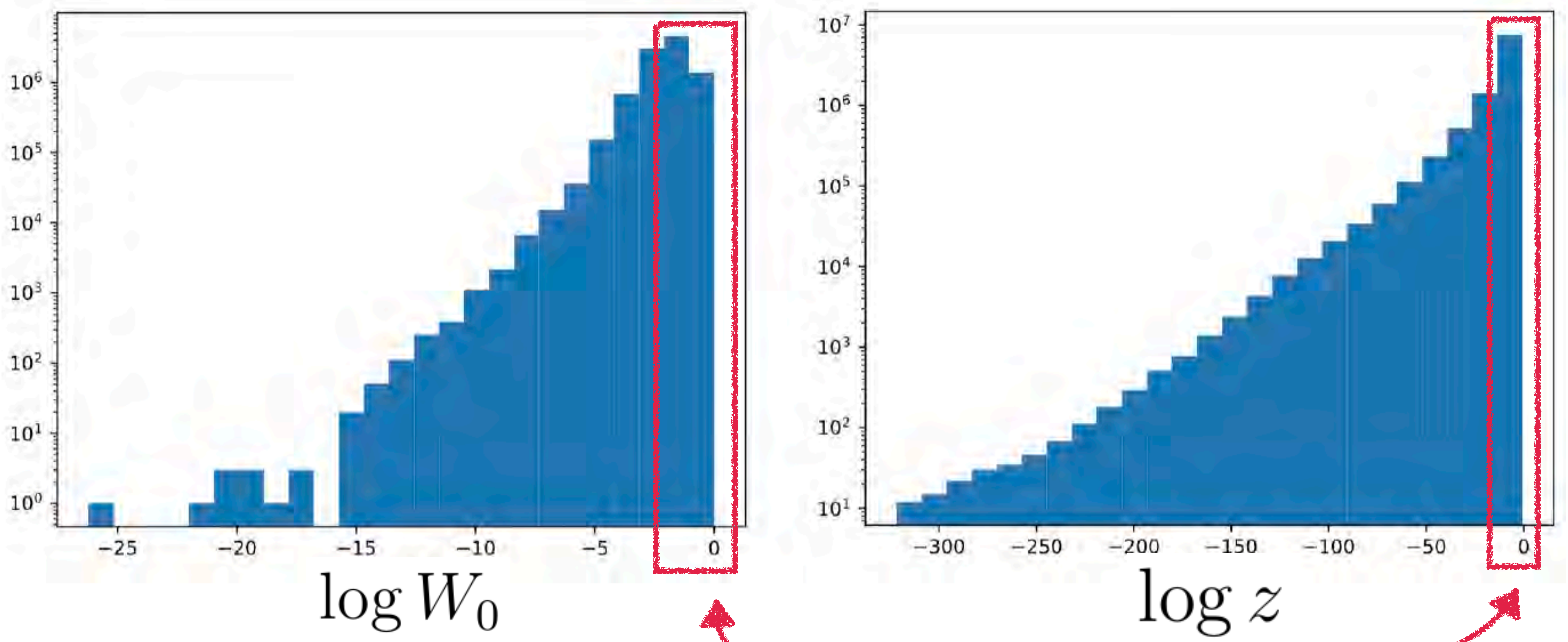

The regime where weakly curved throats are possible

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

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

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

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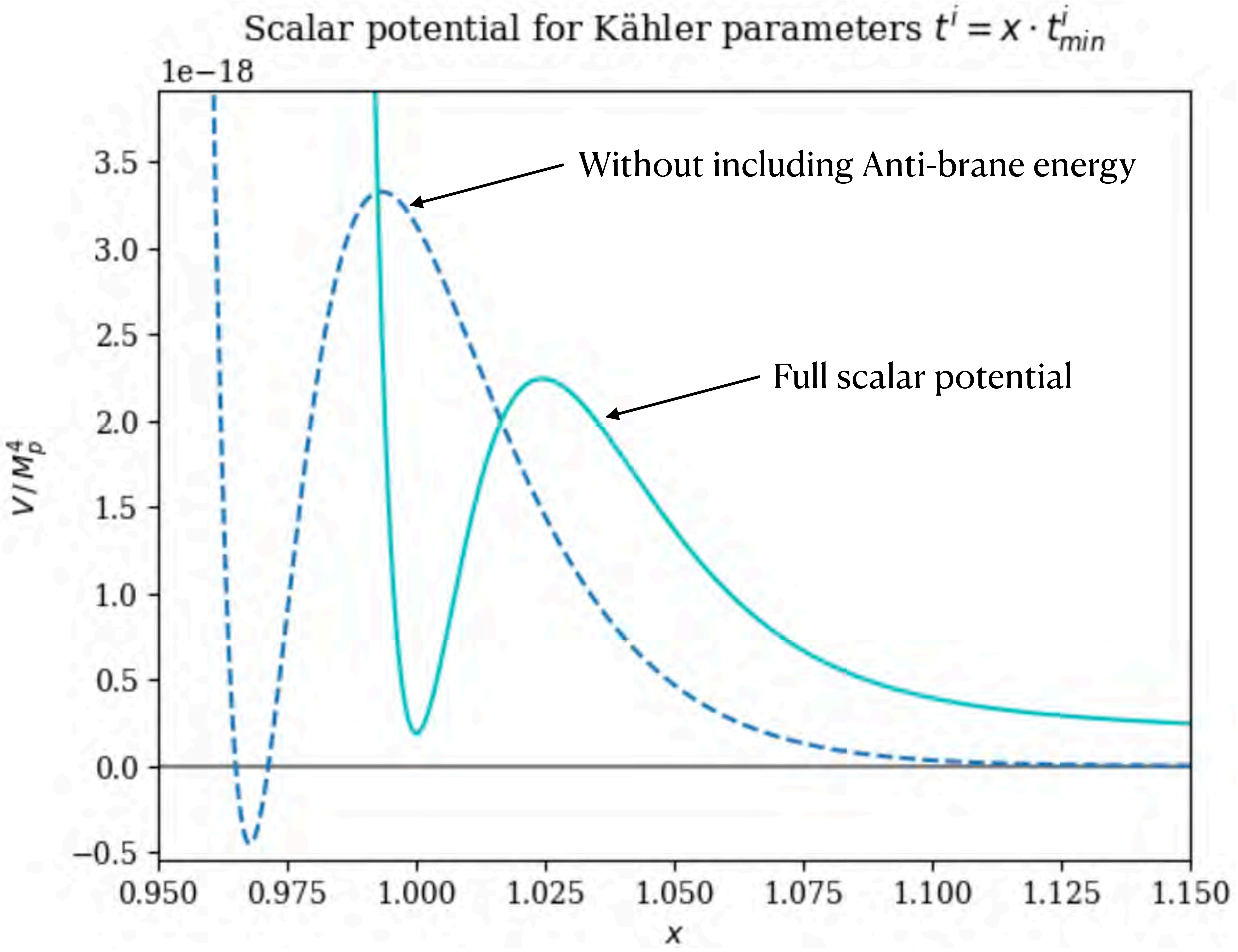

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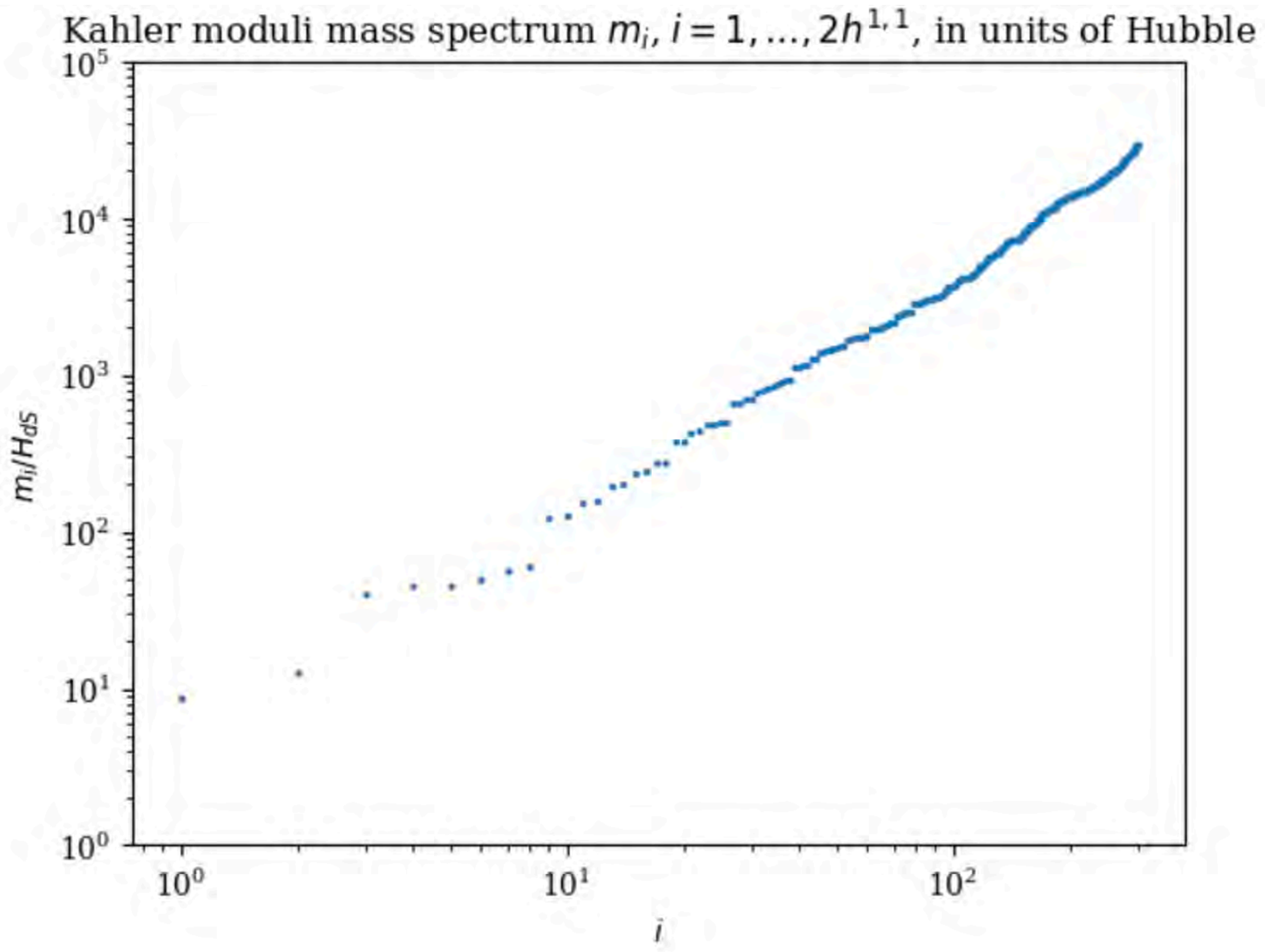

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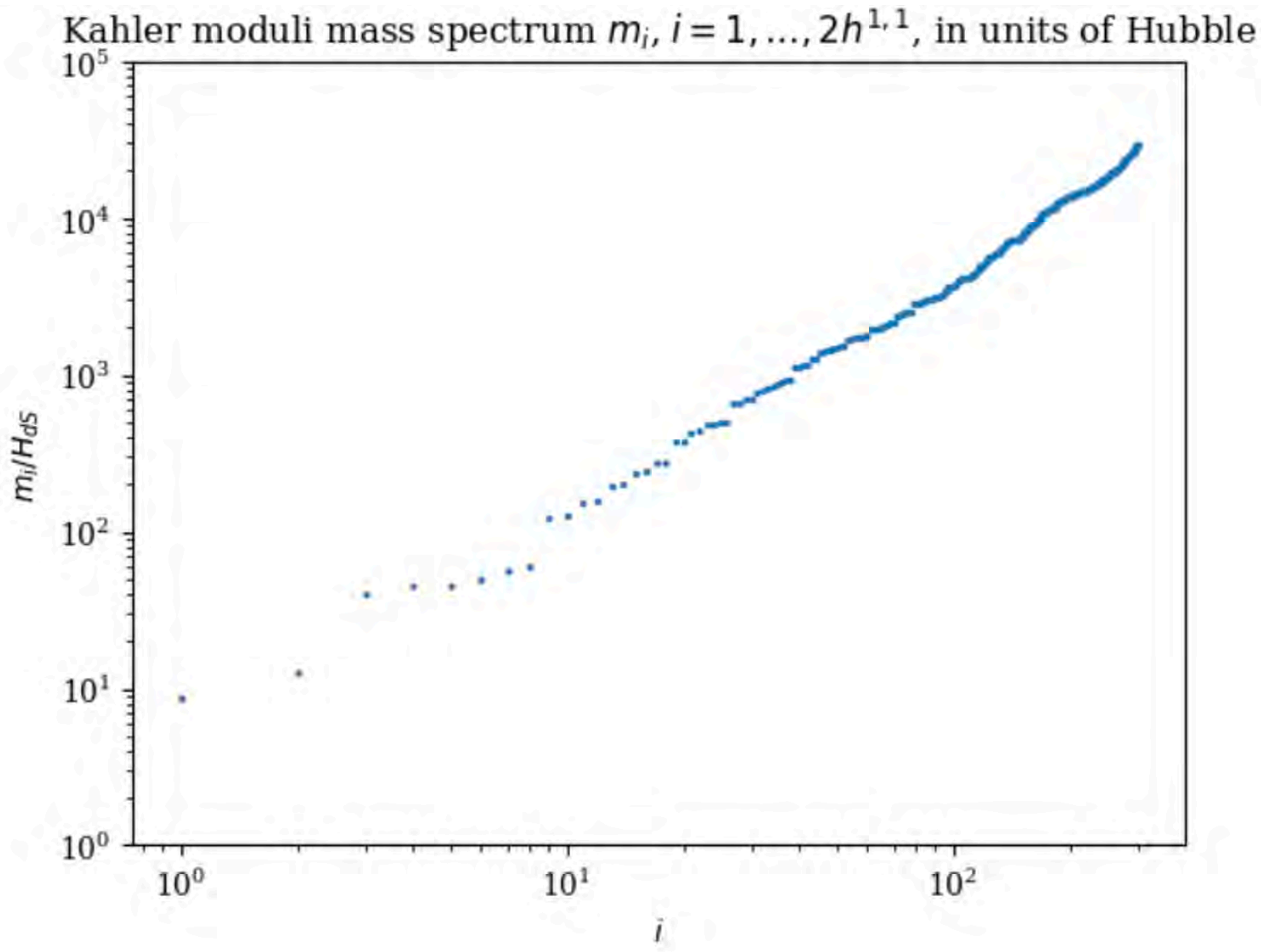

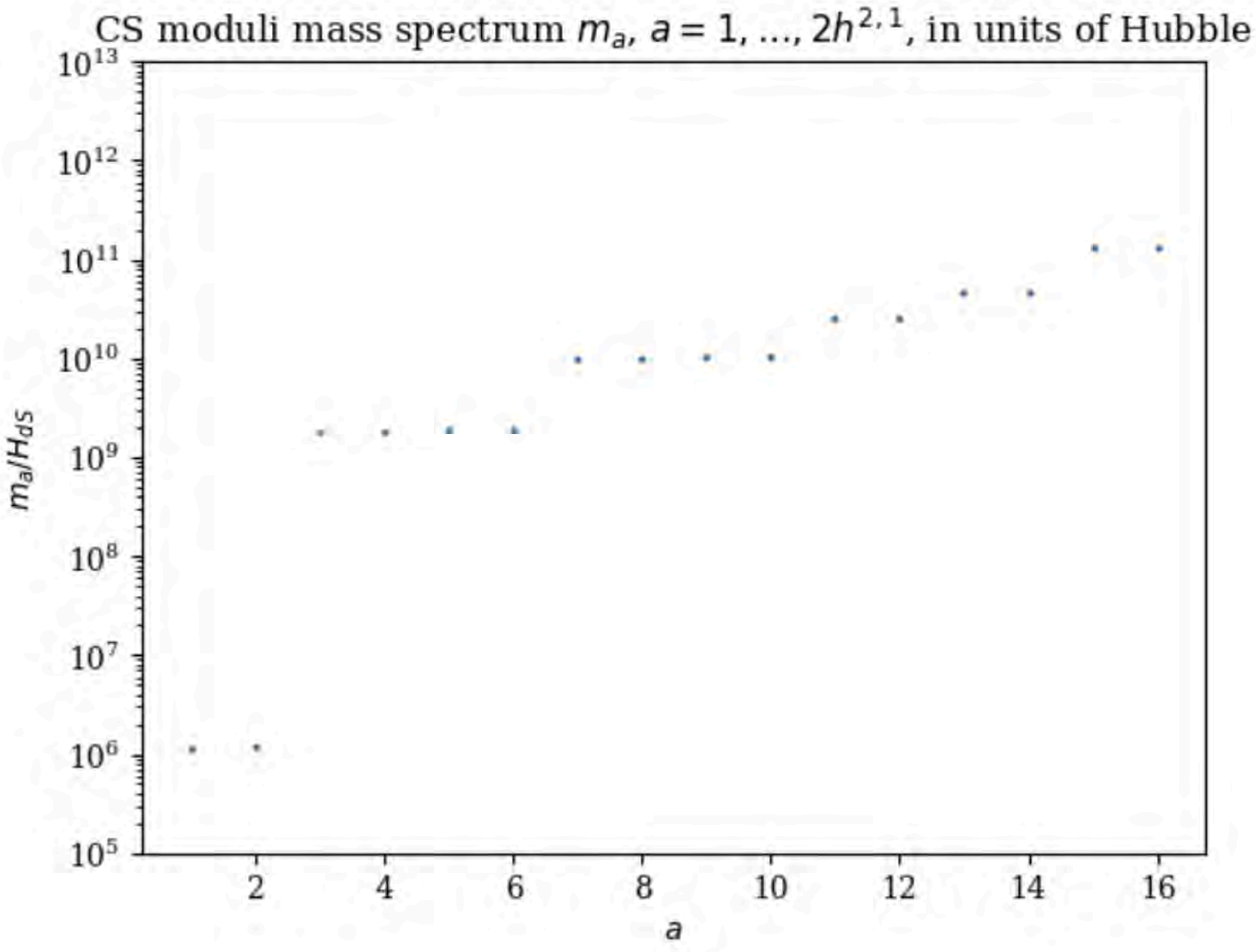

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Becker, Becker, Haack, Louis ‘02
Robles-Llana, Rocek, Saueressig, Theis, Vandoren ‘06
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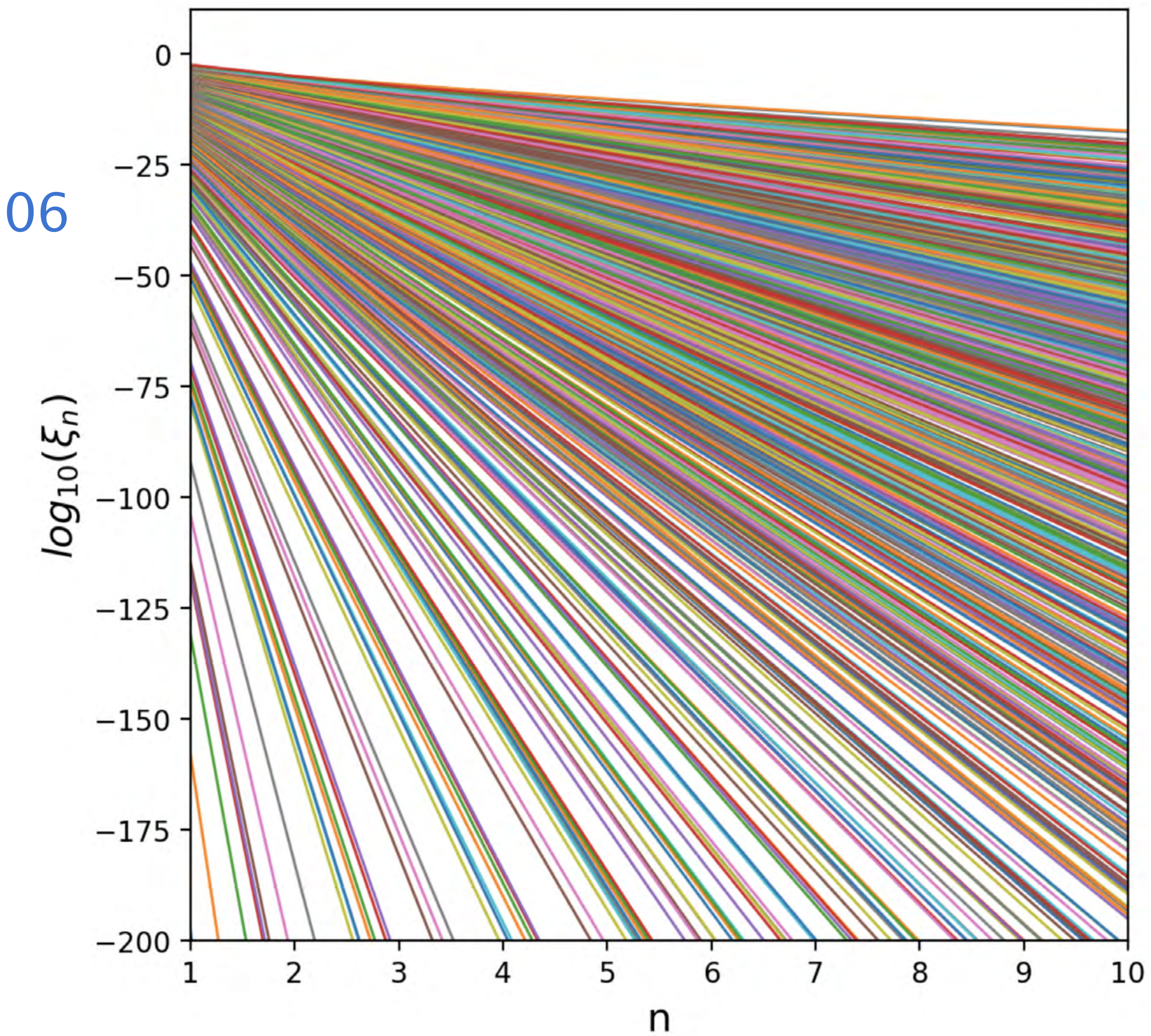

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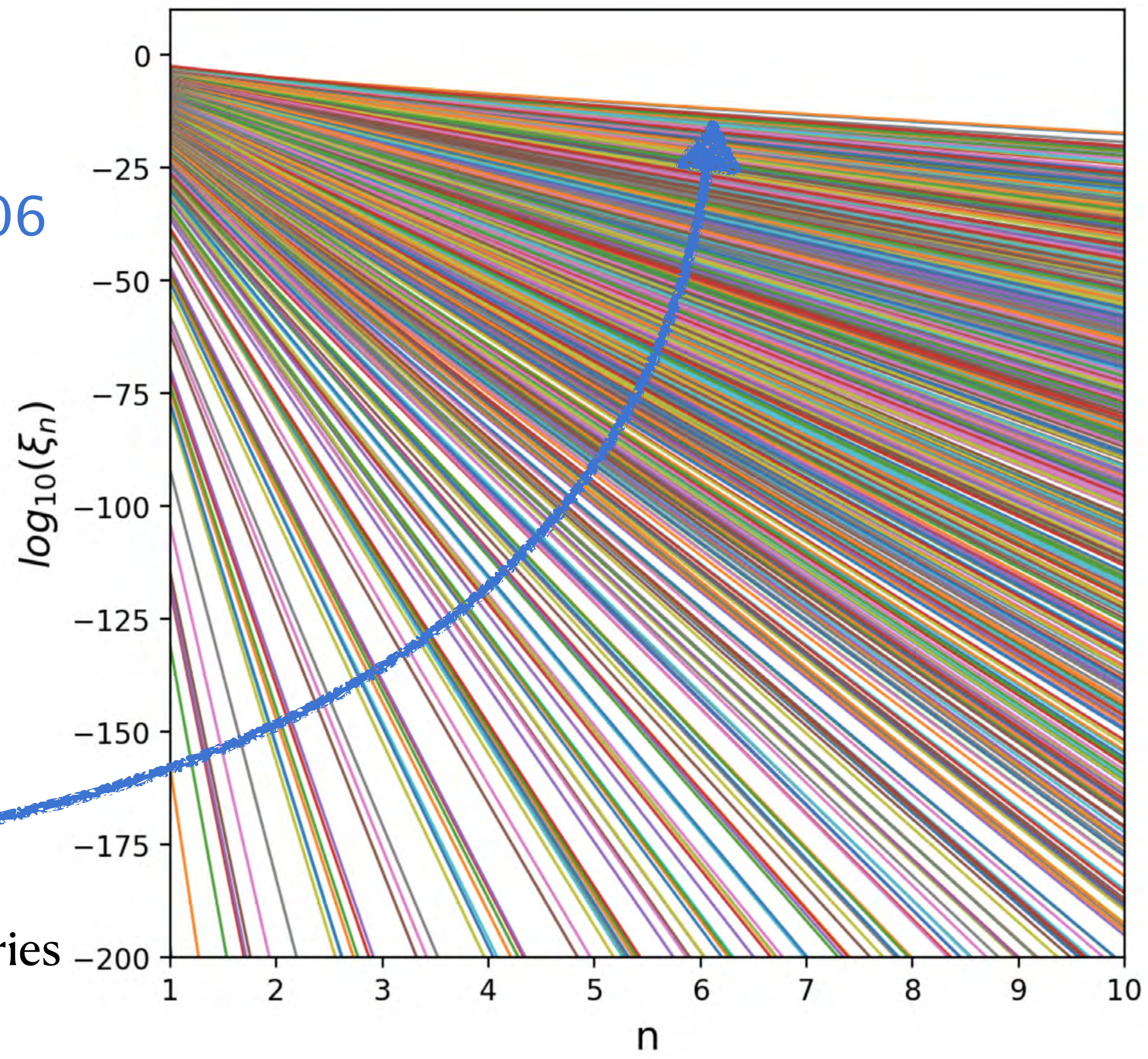
Negative slopes
$\updownarrow$
Converging worldsheet instanton series



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

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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.

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This is not the last word on this subject...

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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
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Gao, Hebecker, Schreyer, Venken ‘22
3x Kim ‘23
Cho, Kim ‘23
Schreyer ‘24 …

Thank You!

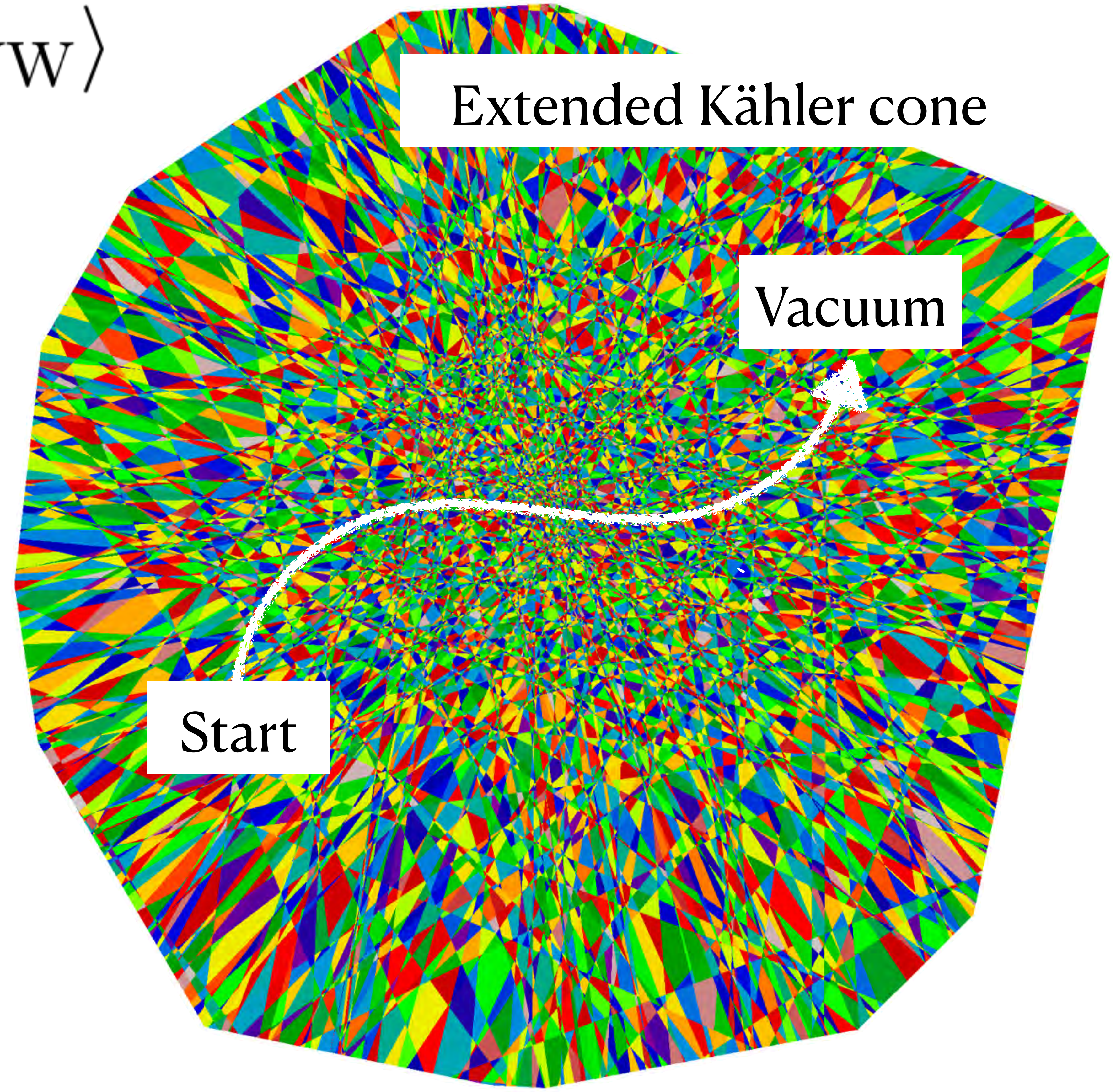
Kähler moduli stabilization

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

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

And leads to a vacuum with

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

After stabilizing Kähler moduli:

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