Candidate de Sitter Vacua

based on ArXiv:2406.13751 with Liam McAllister, Jakob Moritz, and Richard Nally

Andreas Schachner

Quantum Gravity, Strings and the Swampland
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Upshot

First concrete candidates of de Sitter vacua as envisioned by Kachru, Kallosh, Linde and Trivedi (KKLT) 20 years ago.

IMPORTANT CAVEAT:

These vacua are solutions in a particular leading-order EFT that I will define.
Whether these solutions lift to full string theory remains open.

The setup

Type IIB orientifold compactifications

See also talk by G. Leontaris

Setup: Type IIB on CY orientifolds $X/\mathcal{I}$ for a holomorphic and isometric involution $\mathcal{I}: X \to X$.

Notation: complex structure moduli z^a, $a = 1, \ldots, h^{2,1}_-(X)$, Kähler moduli T_A, $A = 1, \ldots, h^{1,1}_+(X)$ and axiodilaton τ

We will mainly be interested in the **F-term scalar potential** for these fields

$$V_F = e^K \left(K^{I\bar{J}} D_I W D_{\bar{J}} \overline{W} - 3 |W|^2 \right) , \qquad D_I W = \partial_I W + (\partial_I K) W , \qquad K_{I\bar{J}} = \partial_I \partial_{\bar{J}} K$$

The superpotential W is given by [GVW hep-th/9906070, Witten hep-th/9604030]

$$W(z, \tau, T) = W_{\text{flux}}(z, \tau) + W_{\text{np}}(z, \tau, T) , \qquad W_{\text{flux}}(z, \tau) = \sqrt{\frac{2}{\pi}} \int_X (F_3 - \tau H_3) \wedge \Omega(z) , \qquad W_{\text{np}}(z, \tau, T) = \sum_D A_D(z, \tau) \, e^{-\frac{2\pi}{c_D} T_D}$$

The 3-form fluxes have to obey the **D3-tadpole cancellation condition**

$$Q_{\text{flux}} + 2(N_{D3} - N_{\overline{D3}}) = Q_O , \qquad Q_{\text{flux}} = \int_X H_3 \wedge F_3$$

where Q_O receives contributions from localised sources like O3/O7-planes or D7-branes.

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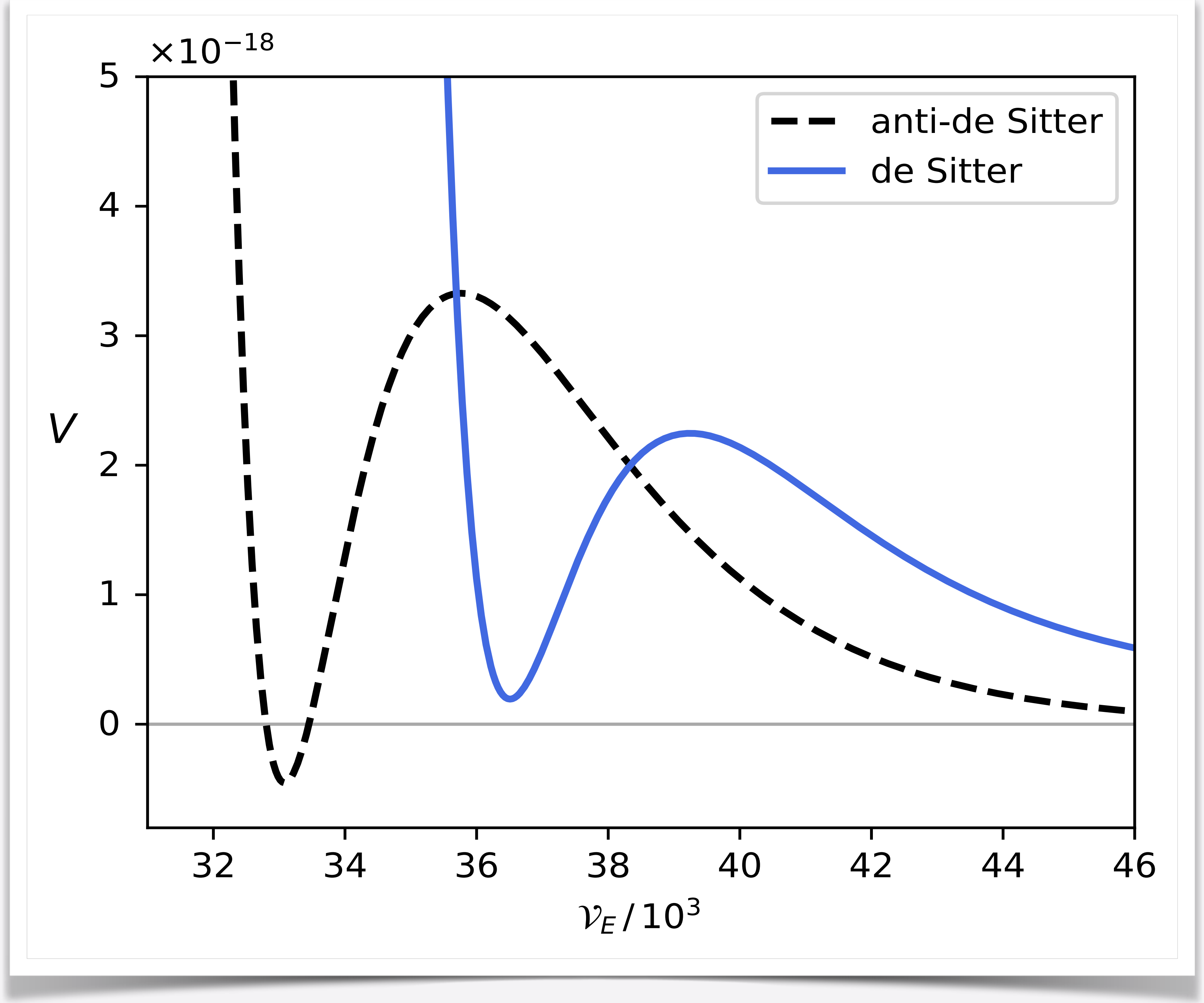
Recipe for KKLT vacua

The KKLT scenario

[Kachru, Kallosh, Linde, Trivedi hep-th/0301240]

The KKLT scenario is a proposal to construct de Sitter vacua in string theory.



CLAIM 1.

Well-controlled SUSY AdS_4 exist in Type IIB flux compatifications with

1. $\langle W_{flux} \rangle \ll 1$, and
2. non-perturbative D-brane instantons.

Explicit examples in [Demirtas et al. 2107.09064]

CLAIM 2.

For such a SUSY AdS_4, provided one finds

3. warped deformed conifold [Klebanov, Strassler hep-th/0007191]
4. containing some anti-D3 branes [Kachru, Pearson, Verlinde hep-th/0112197]
5. in a suitable parameter regime

there are metastable dS_4 vacua.

We provide the first examples fulfilling conditions 1., 2., 3., 4., and 5.

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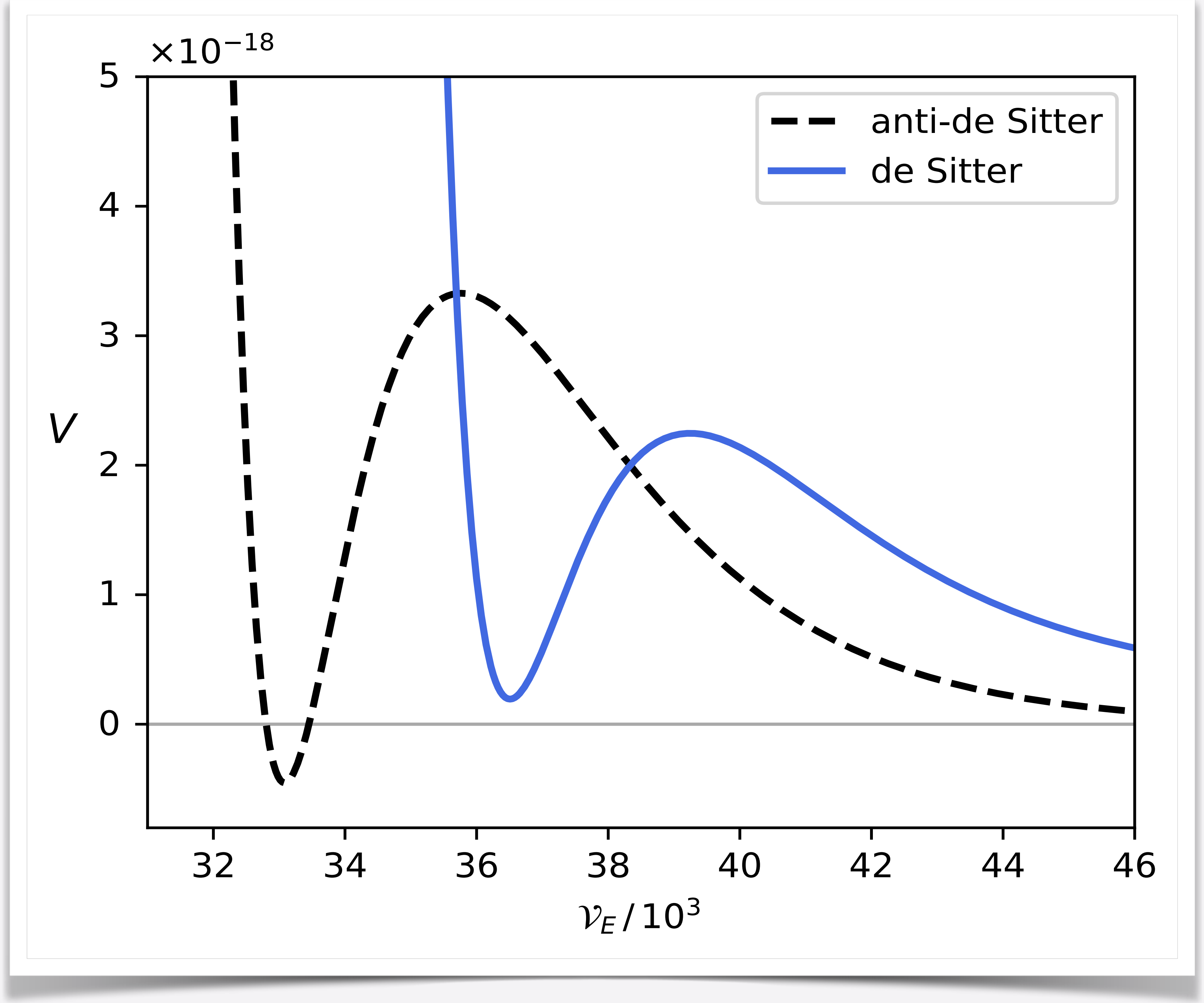

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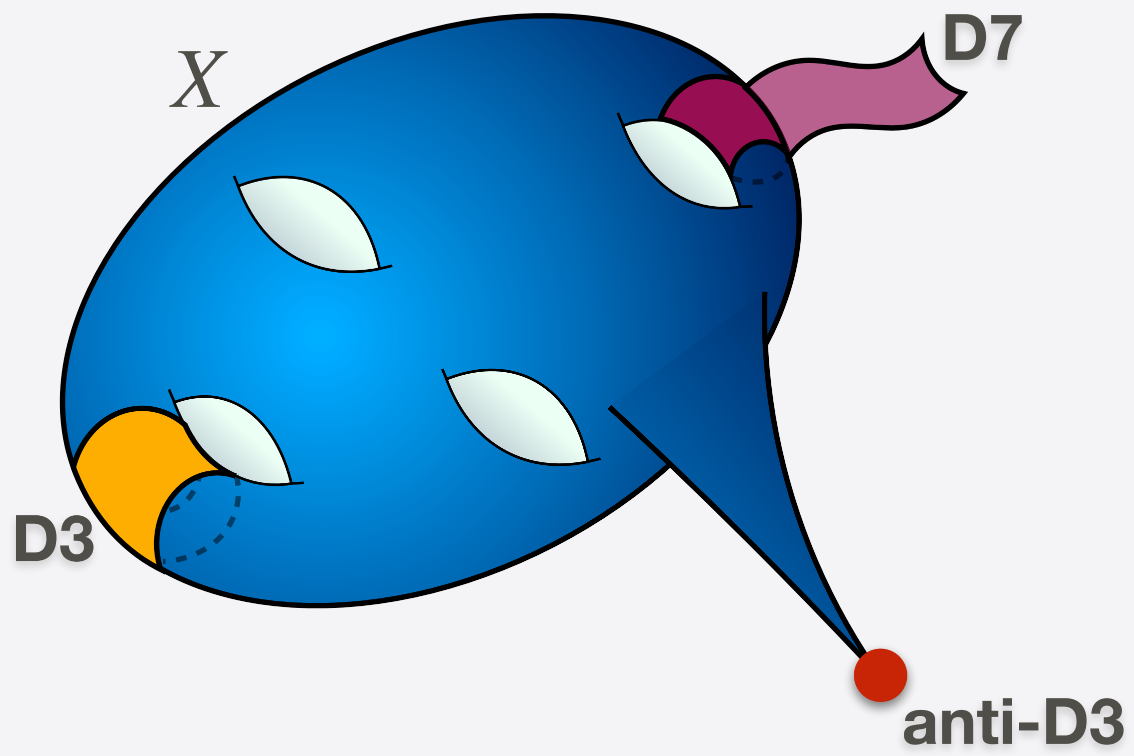


Uplift to de Sitter vacua

[Kachru, Kallosh, Linde, Trivedi hep-th/0301240]

Klebanov-Strassler throats arise in CY compactifications through conifold singularities threaded by 3-form fluxes

$$e^{4A_{IR}} \approx e^{-8\pi K/3n_{cf}g_sM} \sim z_{cf}^{\frac{4}{3}}$$

[Klebanov, Strassler hep-th/0007191]
[Giddings, Kachru, Polchinski hep-th/0105097]

where M, K are the fluxes threading the S^3 of the deformed conifold.

Control over the α' expansion at the tip of the throat, i.e., small curvature at the bottom of the throat requires $g_sM \gtrsim 1$.

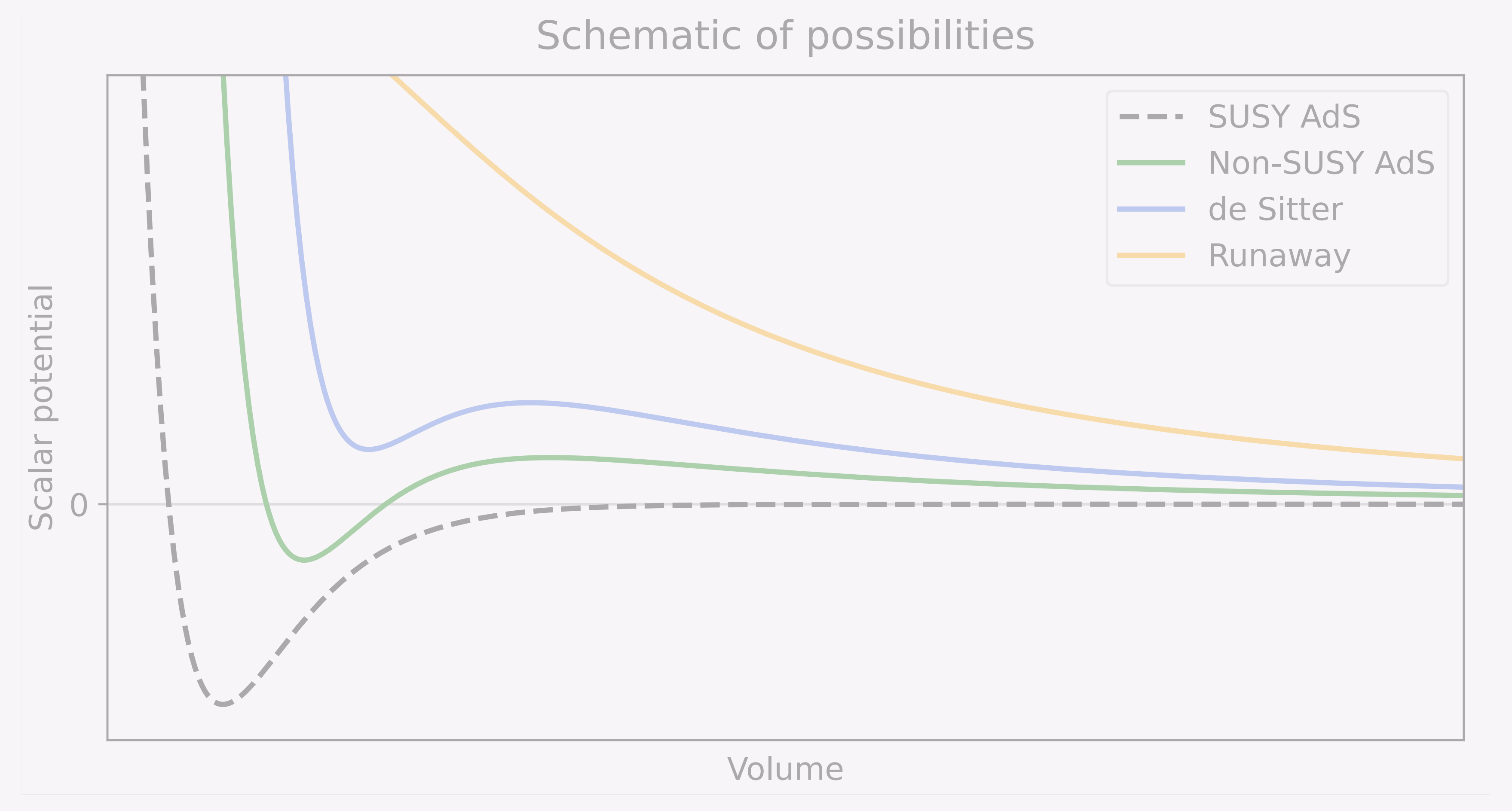
To achieve **CLAIM 2**, an anti-D3 brane at the tip of the throat provides a positive source of energy which potentially uplifts the AdS minimum to a dS minimum provided

$$V_{\text{KPV}}^{\overline{D3}} = \frac{c}{\mathcal{V}_E^{4/3}}, \quad \Xi = \frac{V_{\text{KPV}}^{\overline{D3}}}{V_F} = \frac{\zeta\, e^{K_{cs}/3}}{(g_sM)^2}\mathcal{V}_E^{2/3}\frac{z_{cf}^{\;4/3}}{W_0^{\;2}} \sim 1 \;, \quad \zeta \approx 114.037$$

We call vacua satisfying $\Xi \sim 1$ **well-aligned** which are the main targets of this talk!

The anti-D3-brane state at the bottom of the Klebanov-Strassler throat is metastable provided $M > 12$.

[Kachru, Pearson, Verlinde hep-th/0112197]



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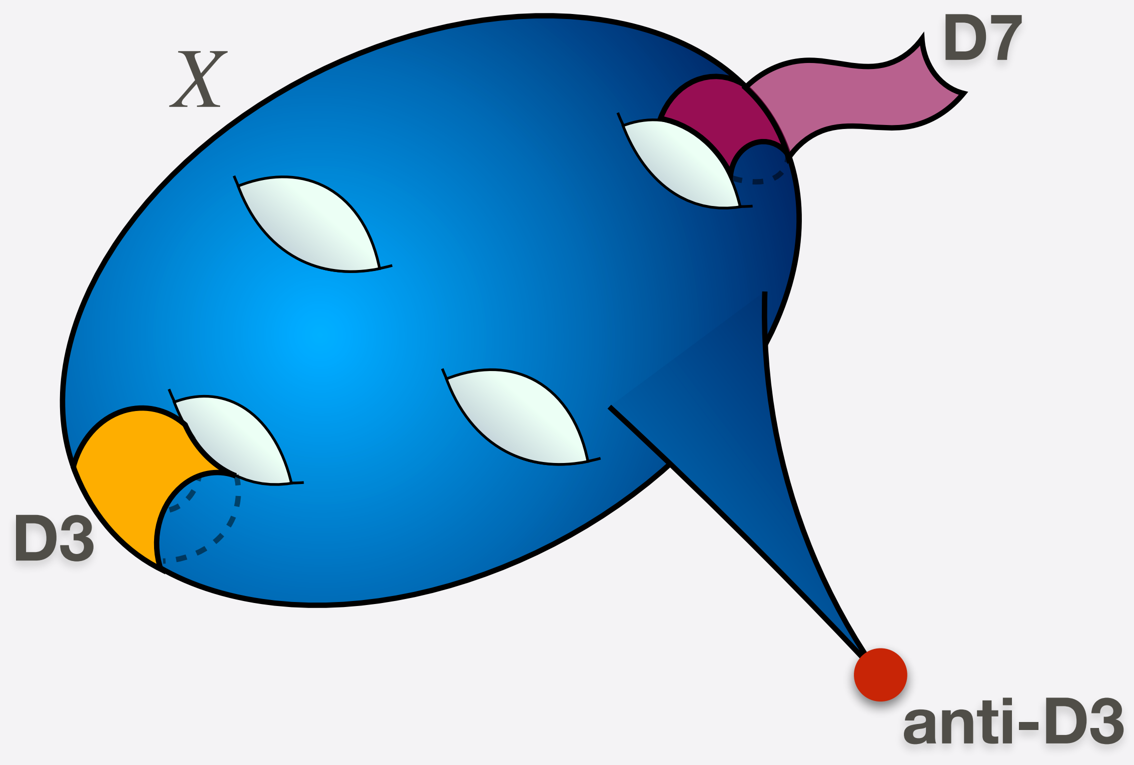

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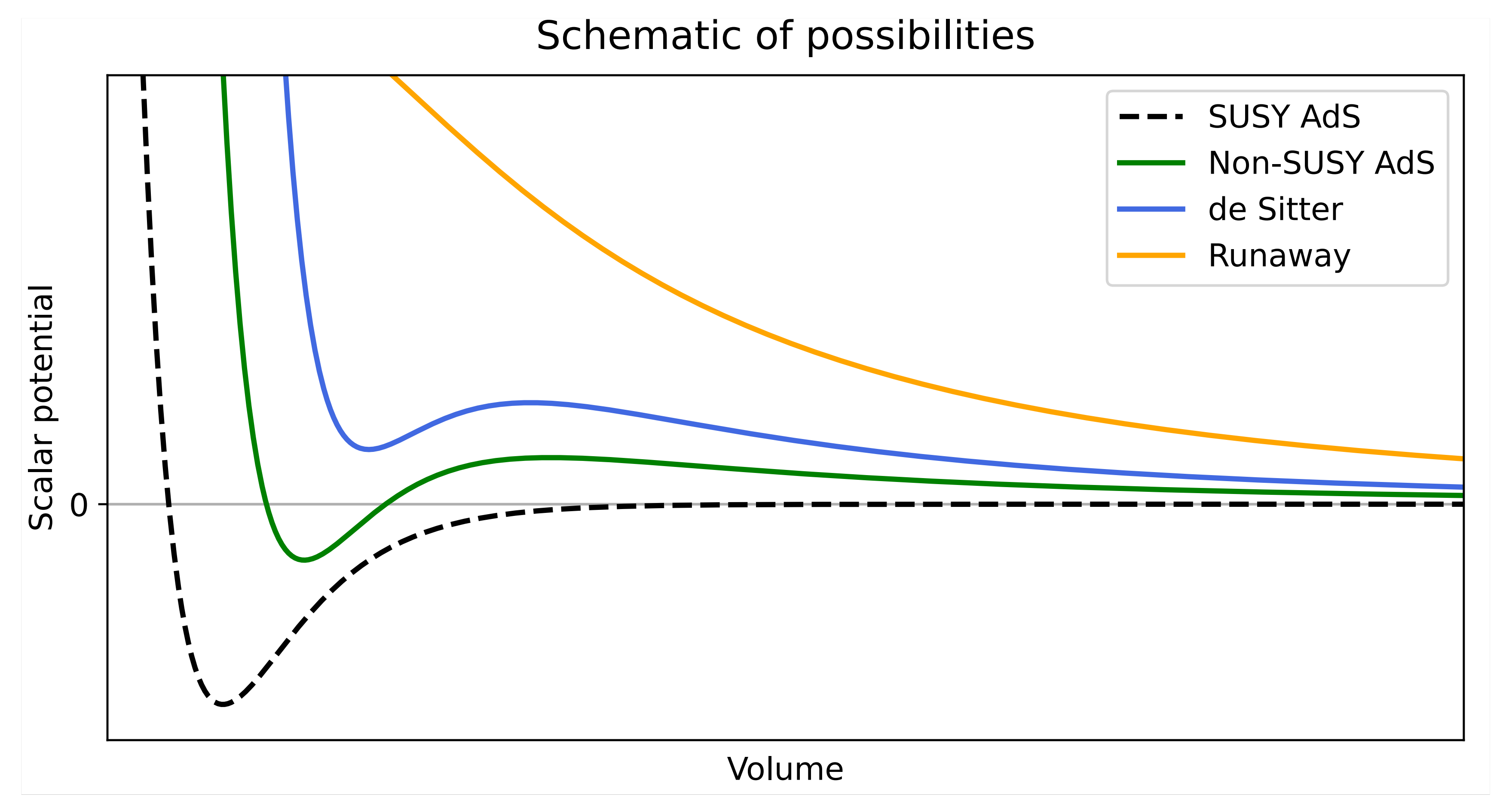


Recipe for KKLT vacua

Checklist for KKLT vacua

1 **FLUX CHOICES**

- ✓ small g_s
- ✓ small W_0
- ✓ stabilisation near conifold
- ✓ ….

2 **ANTI-DE SITTER SOLUTION**

- ✓ sufficiently many D-instanton effects
- ✓ stabilisation of all moduli
- ✓ control over corrections
- ✓ …

3 **DE SITTER VACUUM**

- ✓ well-aligned vacuum
- ✓ large M
- ✓ tachyon-free
- ✓ …

The point of this talk is to show you how to actually accomplish all this in explicit setups!

The working plan

1 CY GEOMETRIES

CY3 from 4D reflexive polytopes with $3 \leq h^{2,1} \leq 8$ [Kreuzer, Skarke hep-th/0002240]

2 ORIENTIFOLDS

orientifolds with $h^{1,2}_{+} = 0$ from $\mathbb{Z}_2$-involutions $x \to -x$ [Moritz 2305.06363]

3 CONIFOLDS

conifold points from shrinking toric flop curves [Demirtas et al. 2009.03312]

4 FLUX SOLUTIONS

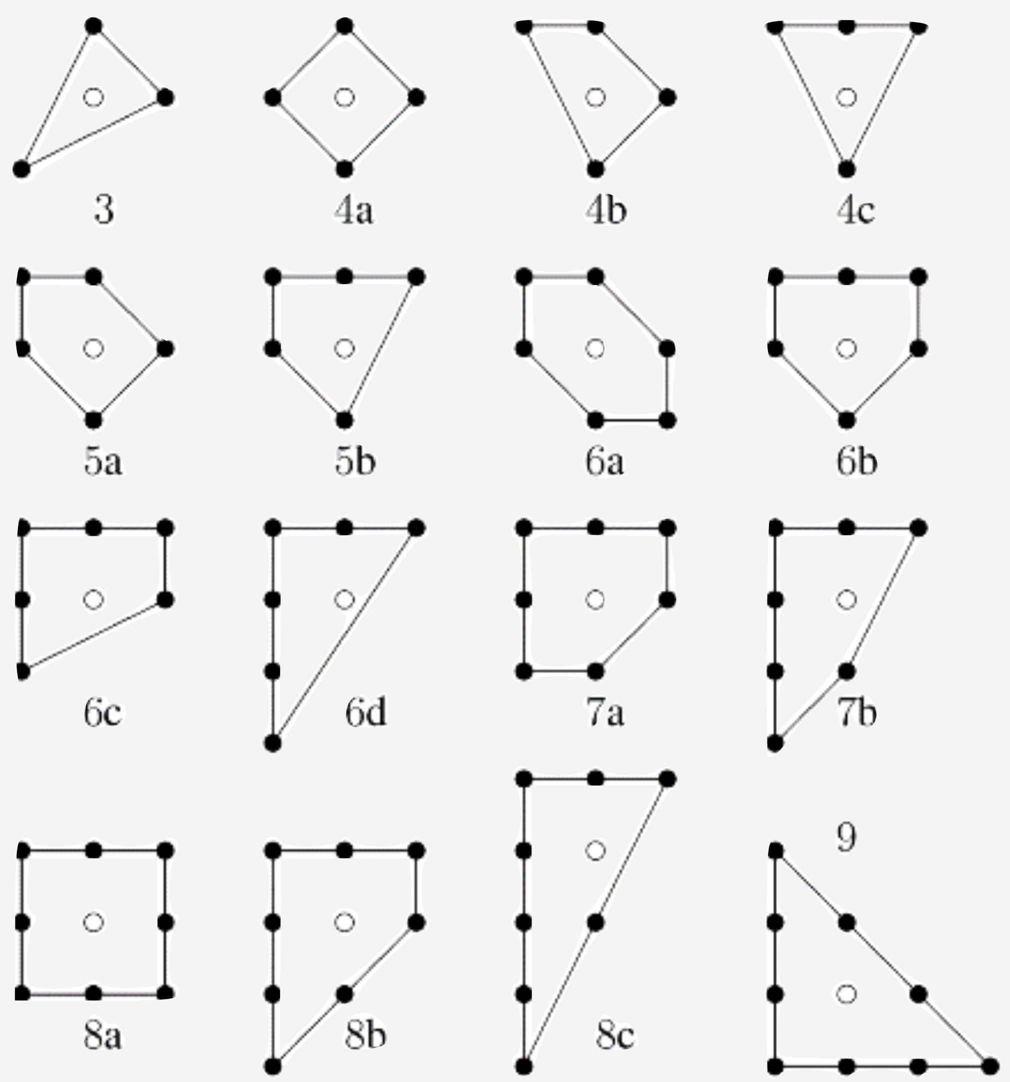
Fluxes with $W_0 \ll 1$ [Demirtas et al. 1912.10047, 2009.03312]

5 (NON-)SUSY $(\mathrm{A})\mathrm{dS}$ VACUA

Kähler moduli stabilisation [Demirtas et al. 2107.09064]]

Constructing the leading order EFT

Scan for Geometries and Orientifolds

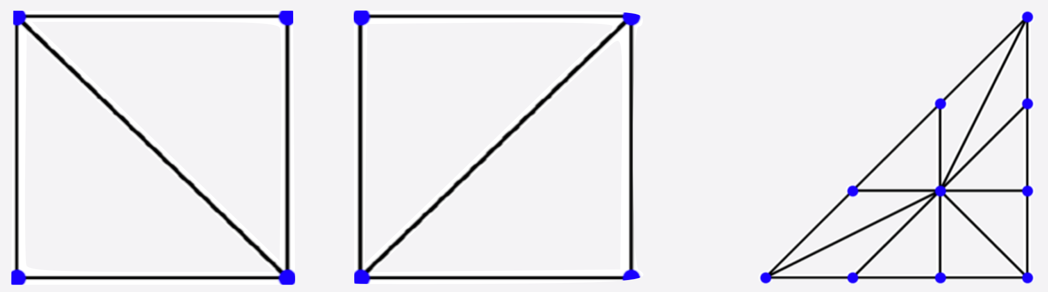


473,800,776 reflexive polytopes in 4D Kreuzer, Skarke (KS) [hep-th/0002240]

We will work with mirror pairs of CY_3 hypersurfaces $X, \widetilde{X}$

in toric varieties $V, \widetilde{V}$

obtained from triangulations of 4D polytopes Δ°, Δ



Demirtas, Rios-Tascon, McAllister 2211.03823

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We cancel the D7-tadpole locally giving rise to $\mathfrak{so}(8)$ $\mathcal{N} = 1$ super Yang-Mills theory hosted on four-cycles with O7-planes.

In these setups, the D3-tadpole is $Q_O = h^{1,1} + h^{2,1} + 2$.

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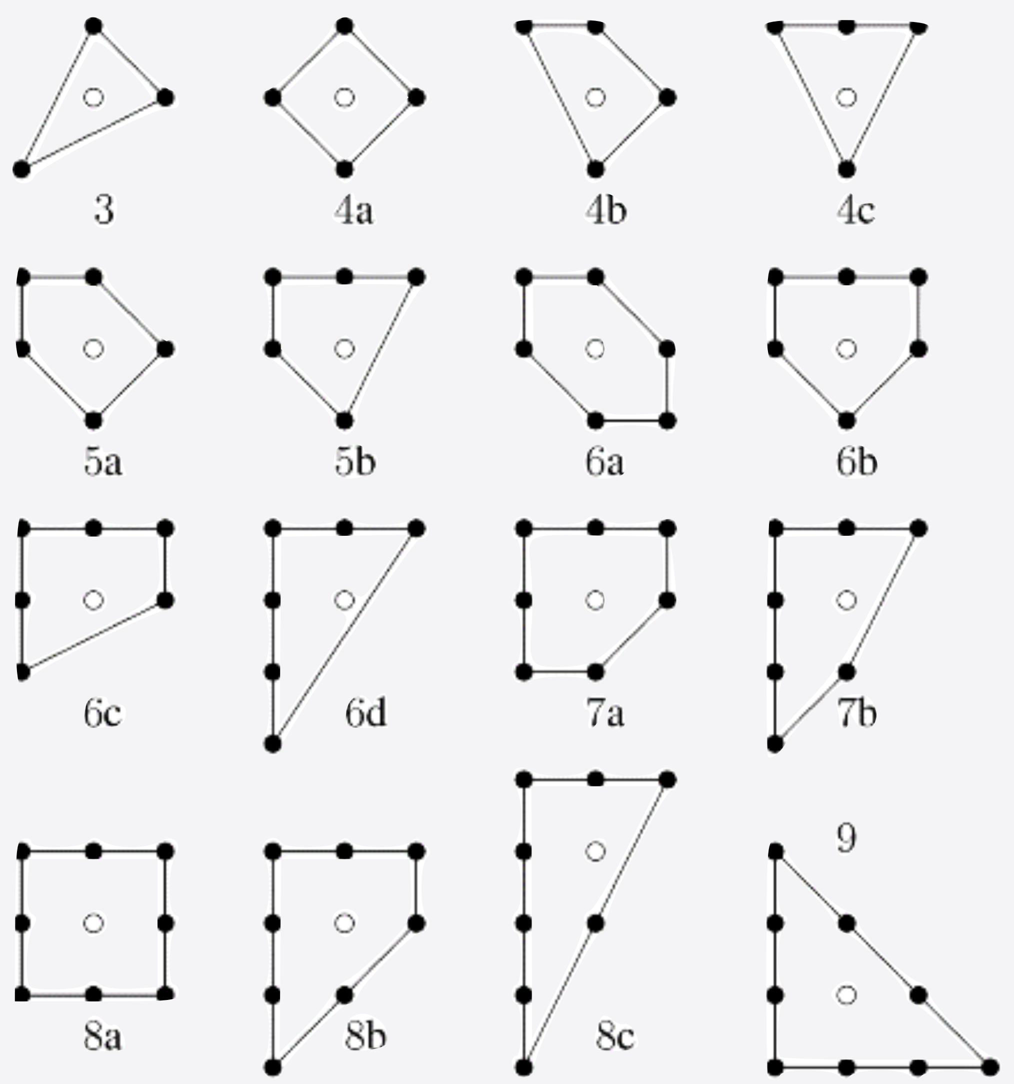

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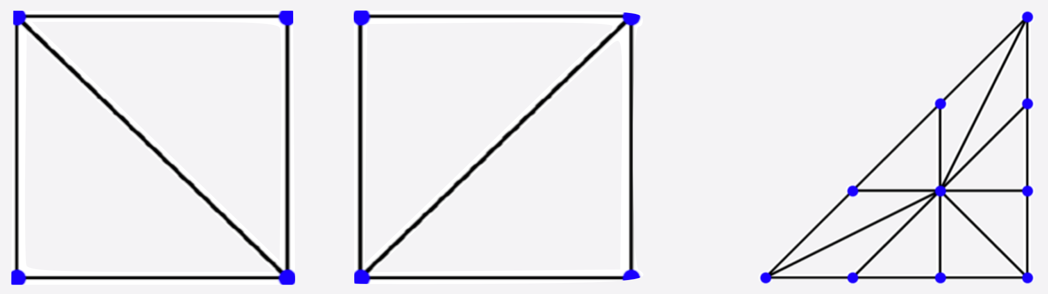

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The Kähler moduli sector

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Here the tree level α' and worldsheet instanton (WSI) corrections amount to

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See in particular:

[Becker et al. hep-th/0204254]

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Genus-zero Gopakumar-Vafa invariants $\mathcal{N}_{\mathbf{q}}$ [Gopakumar, Vafa hep-th/9809187] can be computed using publicly availble code: https://github.com/ariostas/cygv

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For the moment, we ignore

- string loop corrections, especially $\mathcal{N}=1$ corrections
- α' corrections to the KPV potential for the anti-D3 brane as derived in [Junghans 2201.03572] [Hebecker, 3xSchreyer, 2xVenken 2208.02826, 2212.07437, 2402.13311]
- …

Constructing the leading order EFT

The flux superpotential

The flux superpotential is given in terms of the **period vector** $\vec{\Pi}$ and the **pre-potential** $F = F(z)$ as

$$W_{\rm flux}(\tau, z^a) = \sqrt{\frac{2}{\pi}} \int_X (F_3 - \tau H_3) \wedge \Omega(z) = \sqrt{\frac{2}{\pi}}\, \vec{\Pi}^\top \cdot \Sigma \cdot (\vec{f} - \tau \vec{h}) \ , \qquad \vec{\Pi} = \left(2F - z^a F_a, F_a, 1, z^a\right) \ , \quad F_a = \partial_a F$$

We compute $F(z)$ explicitly at **Large Complex Structure (LCS)** using mirror symmetry following [Hosono et al. hep-th/9406055]

$$F_{\rm poly}(z) = -\frac{1}{3!}\widetilde{\kappa}_{abc} z^a z^b z^c + \frac{1}{2}\tilde{a}_{ab} z^a z^b + \frac{1}{24}\tilde{c}_a z^a + \frac{\zeta(3)\chi(\widetilde{X})}{2(2\pi i)^3}\,, \quad F_{\rm inst}(z) = -\frac{1}{(2\pi i)^3} \sum_{\tilde{\mathbf{q}} \in \mathcal{M}(\widetilde{X})} \mathcal{N}_{\tilde{\mathbf{q}}}\, \mathrm{Li}_3\!\left(e^{2\pi i\, \tilde{\mathbf{q}} \cdot \mathbf{z}}\right)$$

in terms of quantities $\widetilde{\kappa}_{abc}\,, \tilde{a}_{ab}, \tilde{c}_a$ defined on the mirror CY $\widetilde{X}$, see e.g. [Demirtas et al. 2303.00757].

It is known how to construct conifolds by shrinking a set of curves in $\widetilde{X}$ to zero volume [Demirtas et al. 2009.03312] [Álvarez-García et al. 2009.03325].

We write $z^a = (z_{\rm cf}, z^\alpha)$, $\alpha = h^{2,1}(X) - 1$, and expand the periods order by order in the conifold modulus $z_{\rm cf}$

$$W_{\rm flux}(z^a, \tau) = W_{\rm poly}(z^\alpha, \tau) + W_{\rm inst}(z^\alpha, \tau) + z_{\rm cf}\, W^{(1)}(z^\alpha, z_{\rm cf}, \tau) + \mathcal{O}(z_{\rm zf}^2)\,.$$

Constructing the leading order EFT

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Constructing the leading order EFT

The non-perturbative superpotential

The non-perturbative superpotential from D-branes wrapping rigid divisors D reads [Witten hep-th/9610234]

$$W_{\rm np}(z,\tau,T) = \sum_D A_D(z,\tau)\, \mathrm{e}^{-\frac{2\pi}{c_D} T_D}\,, \qquad c_D = \begin{cases} 1 & \text{Euclidean D3-branes}\,, \\ 6 & \text{gaugino condensation on 7-branes}\,. \end{cases}$$

We check that the **only** contributing divisors are **pure rigid** implying [Witten hep-th/9610234, Demirtas et al. 2107.09064]

$$A_D(z,\tau) = A_D = \text{const}$$

For the normalisation of the A_D we choose

$$A_D = \sqrt{\frac{2}{\pi}}\,\frac{n_D}{(4\pi)^2}\,.$$

The constant n_D is

- related to an integral over worldsheet modes [Alexandrov et al. 2204.02981], and
- expected to be an order-one number [Kim 2301.03602].

Computing n_D has so far been out of reach.

In our vacua, we take $n_D = 1$ and then check a posteriori that our vacua persist for $10^{-3} \leq n_D \leq 10^4$.

See also
[Kim 2107.09779, 2301.03602]
[Jefferson, Kim 2211.00210]

Constructing the leading order EFT

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See also
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The working plan

CY GEOMETRIES

CY3 from 4D reflexive polytopes with $3 \leq h^{2,1} \leq 8$ [Kreuzer, Skarke hep-th/0002240]

ORIENTIFOLDS

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CONIFOLDS

conifold points from shrinking toric flop curves [Demirtas et al. 2009.03312]

4 **FLUX SOLUTIONS**

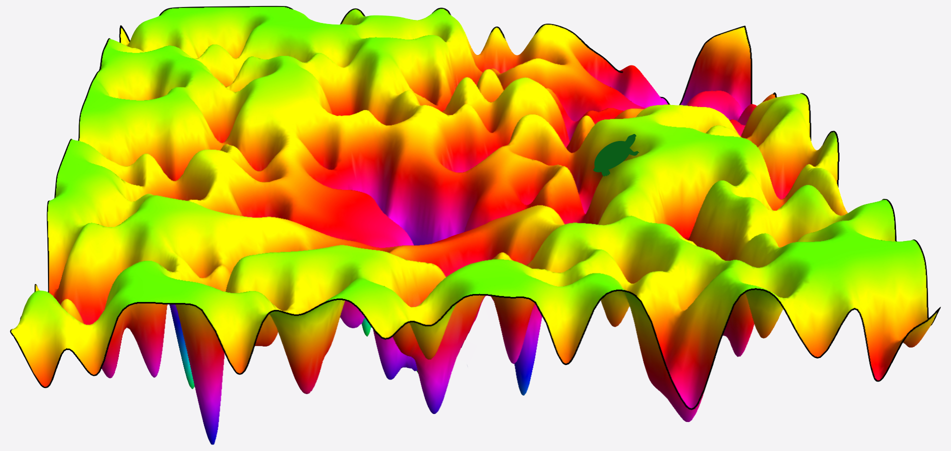
Fluxes with $W_0 \ll 1$ [Demirtas et al. 1912.10047, 2009.03312]

5 **(NON-)SUSY (A)dS VACUA**

Kähler moduli stabilisation [Demirtas et al. 2107.09064]

Finding KKLT vacua in KS

Numerical minimisation in string compactifications

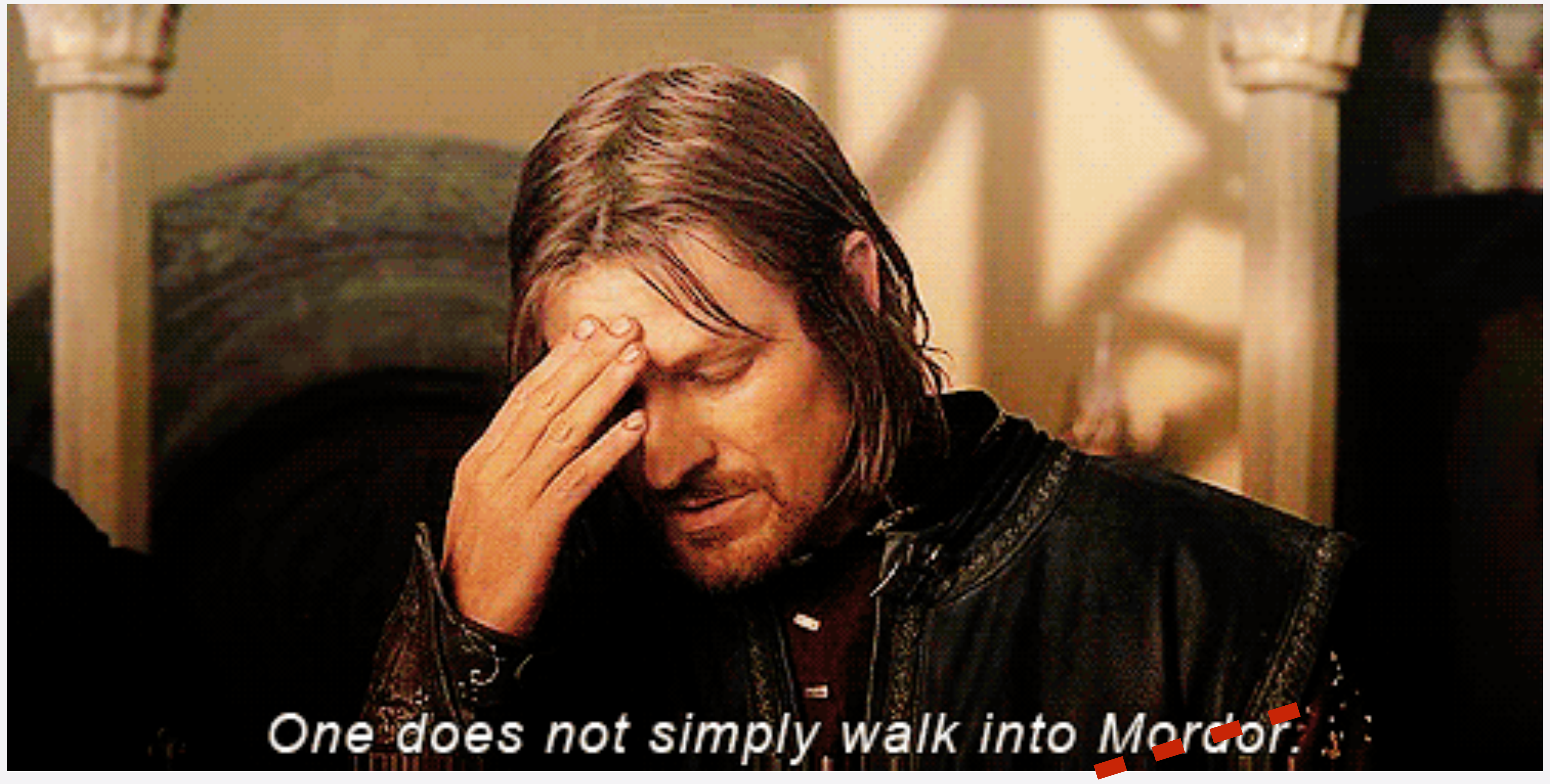


Bousso et al.: hep-th/0004134
Susskind: hep-th/0302219

We want to find critical points of the potential

$$V_F(z, \tau, T) = \frac{V_{\text{Flux}}(z, \tau)}{\mathcal{V}^2} + V_{\text{rest}}(z, \tau, T)$$

but this is hard…



the landscape.

Challenges

A. Need to solve coupled system of equations in $\mathcal{O}(100)$ **scalar fields**

$$z^a\,, a = 1, \ldots, h^{1,2}_- \quad , \qquad T_\alpha\,, \alpha = 1, \ldots, h^{1,1}_+$$

B. Not any solution suffices ⇒ **constrained optimisation problem:**

1. $z^a, T_\alpha \in \mathcal{M}$ take values in **field** or **moduli space** $\mathcal{M}$
2. **truncation** on spectrum and contributions justified?
3. **perturbative control** guaranteed? E.g. couplings small?

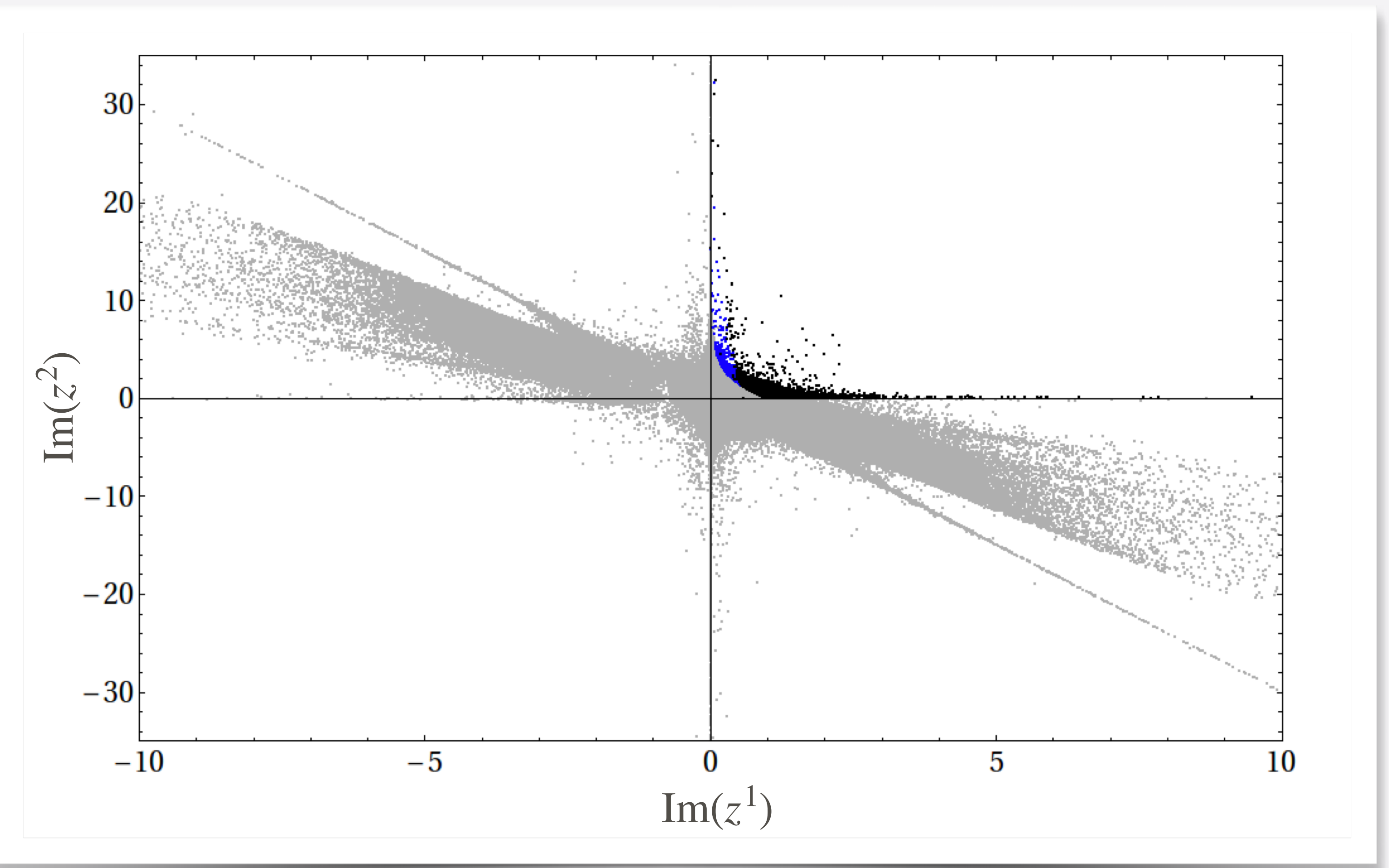
C. $\rho_{\text{vac}} > 0$ requires SUSY breaking by adding anti-D3 brane. **Control?**

Finding KKLT vacua in KS

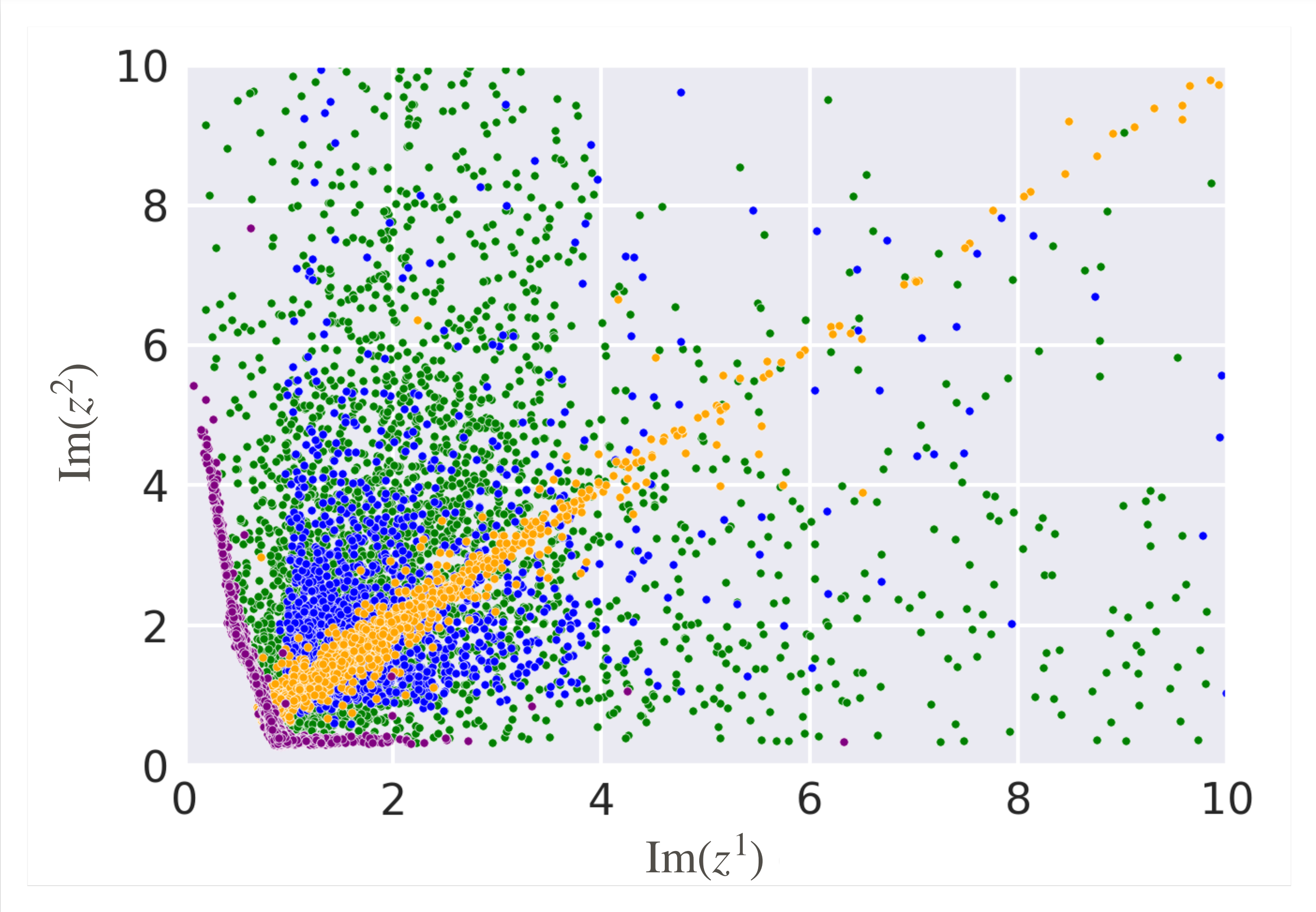
Recent progress in finding flux vacua

Performance comparison for $h^{2,1} = 2$:

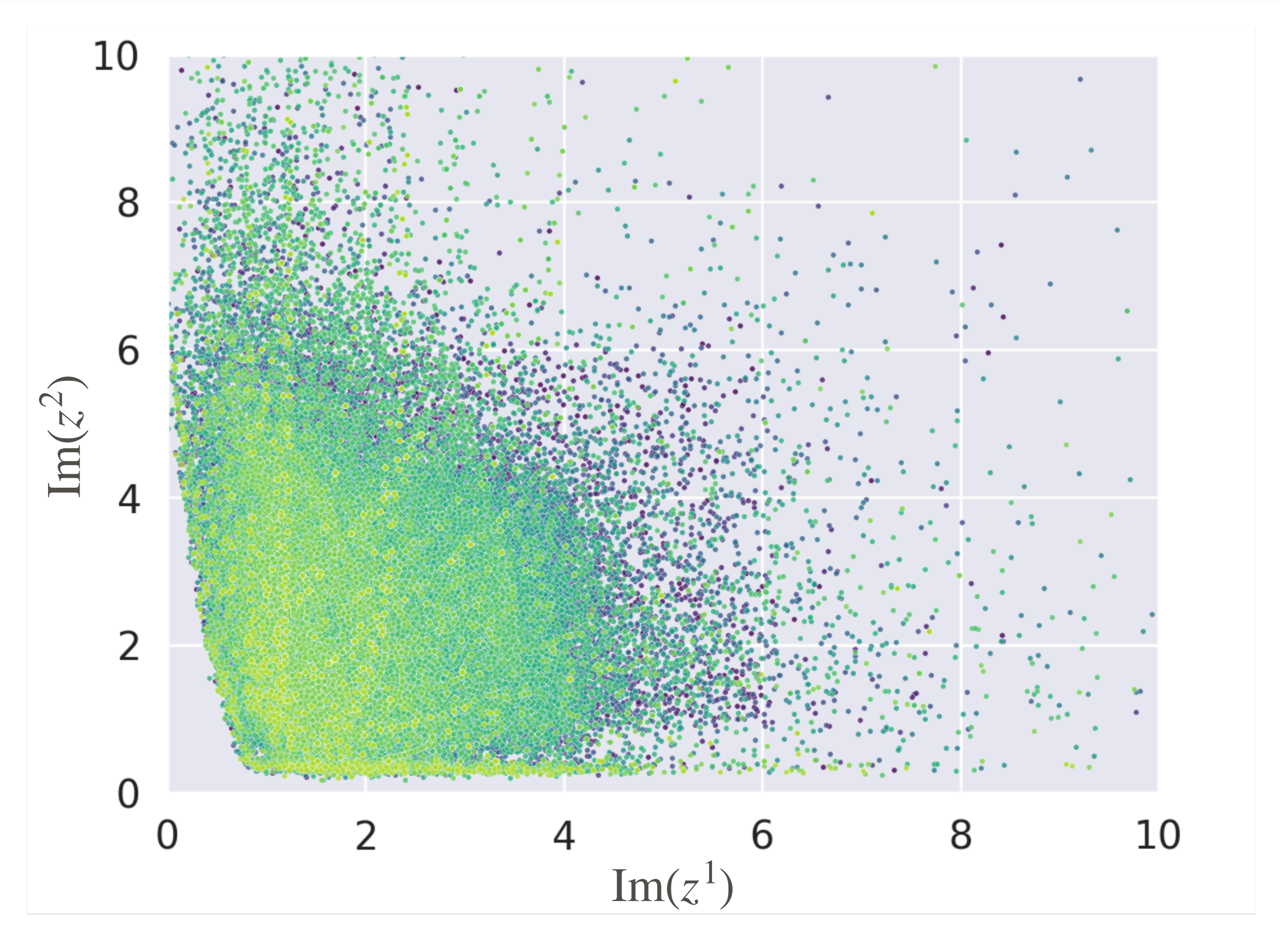
100 nodes each with 32 cores to find **24,882 solutions** in **75,000 hours** using `homotopy continuation`	vs.	4 cores with 5GB of memory **33,019 solutions** in **45 minutes** using `scipy.optimize`	vs.	2 cores with 200MB of memory **94,157 solutions** in **<1 minute** using `ISD optimiser`
[Martinez-Pedrera et al. 1212.4530]		[Dubey, Krippendorf, **AS**: 2306.06160]		[**AS**: work in progress]



"Classical" and dimensionally reduced.



Including GVs up to degree 10.



Including GVs up to degree 10.

Finding KKLT vacua in KS

In the presence of conifolds
[Demirtas et al. 2009.03312]
[Álvarez-García et al. 2009.03325]

Perturbatively Flat Vacua (PFVs)

Demirtas, Kim, McAllister, Moritz: 1912.10047

For special flux choices $\vec{M}, \vec{K} \in \mathbb{Z}^{h^{2,1}}$, the polynomial flux superpotential $W_{\rm poly}$ and the F-terms vanish along $z^a = p^a \tau$ where

$$p^a = (N^{-1})^{ab} K_b\,, \quad N_{ab} = \widetilde{\kappa}_{abc} M^c$$

The remaining superpotential terms are computable in terms of GV invariants on $\widetilde{X}$

$$W_{\rm inst} = \frac{-1}{(2\pi)^2} \sum_{\tilde{\mathbf{q}} \in \mathcal{M}(\widetilde{X})} \mathcal{N}_{\tilde{\mathbf{q}}}\, (M^a \tilde{\mathbf{q}}_a)\, \mathrm{Li}_2\!\left(e^{2\pi i\, \tilde{\mathbf{q}}_\alpha p^\alpha \tau}\right)$$

A minimum for the light degree of freedom τ arises frequently through the **racetrack mechanism** so that

$$W_0 = \langle W_{\rm flux} \rangle = \langle W_{\rm inst} \rangle \ll 1$$

In practice, we obtain the **true minimum** by numerically solving F-term conditions.

For related work, see also
[Honma, Otsuka 2103.03003]
[Marchesano et al. 2105.09326]
[Broeckel et al. 2108.04266]
[Basitian et al. 2108.11962]
[Carta et al. 2112.13863]
[Blumenhagen et al. 2206.08400]
[Cicoli et al. 2209.02720]

Finding KKLT vacua in KS

Kähler moduli stabilisation in explicit setups

Demirtas, Kim, McAllister, Moritz, Rios-Tascon: 2107.09064

To solve the F-terms for the Kähler moduli,

$$D_A W = \partial_A W + K_A W = 0\,,$$

we use an algorithm described in [Demirtas et al. 2107.09064]

1. Pick arbitrary triangulation of Δ° and choose arbitrary point t_0^A in the Kähler cone
2. Find **initial guess** as classical F-term minimum

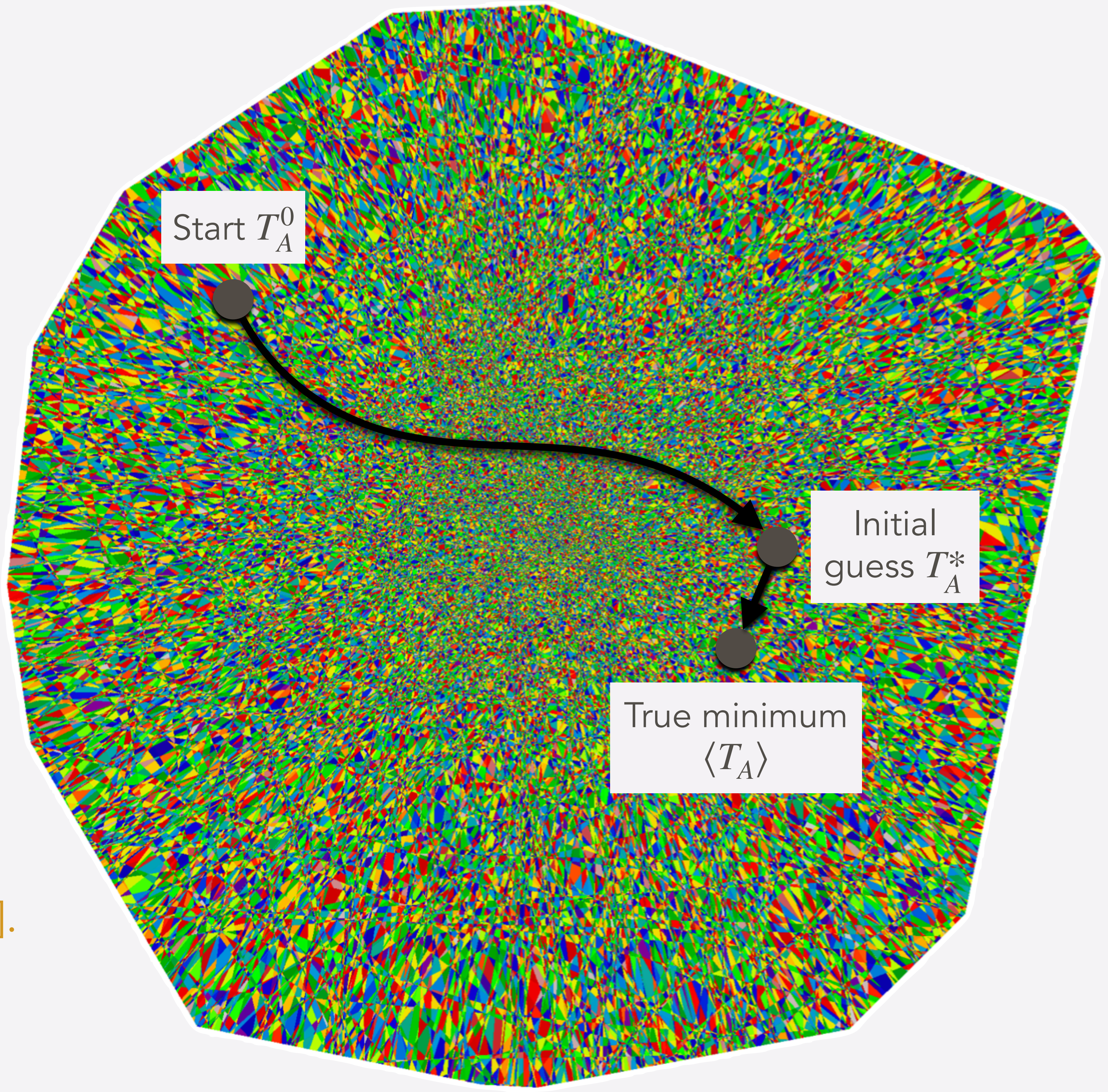
$$T_A^0 = \frac{1}{2}\kappa_{ABC}\, t_0^B\, t_0^C \quad \rightarrow \quad T_A^* \approx \frac{c_A}{2\pi}\log\left(W_0^{\ -1}\right)$$

2. Obtain **true F-term minimum including corrections** by using e.g. Newton's method

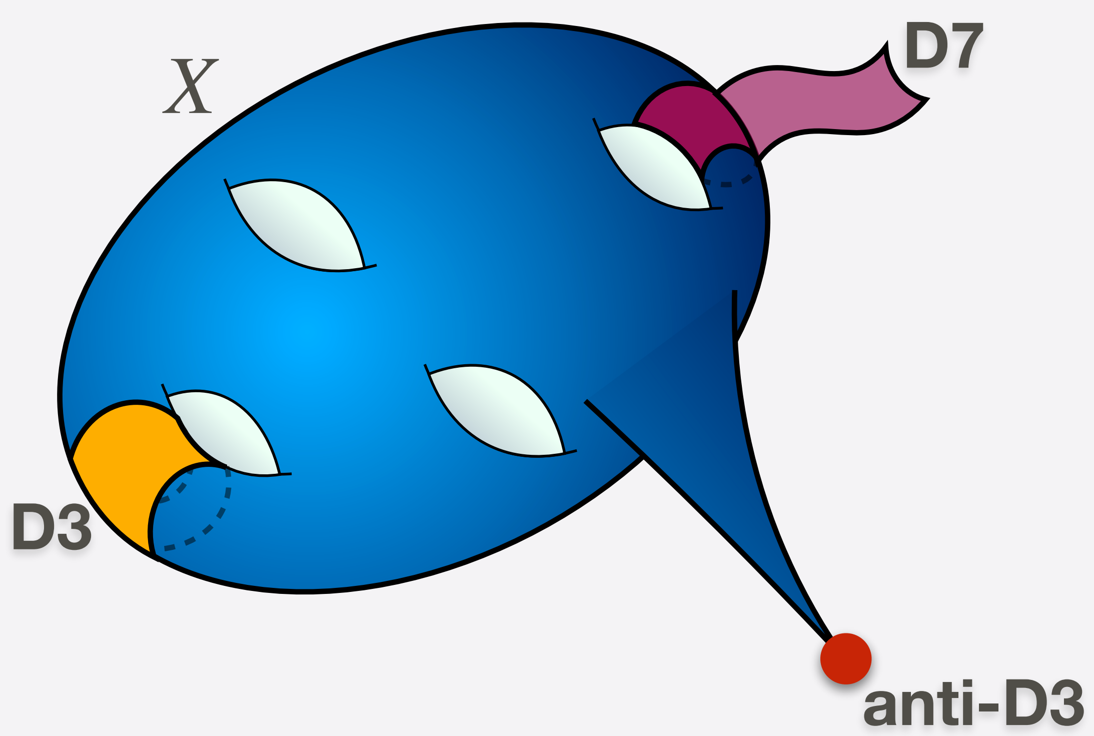
$$T_A^* \quad \rightarrow \quad \langle T_A \rangle$$

In the absence of conifolds, this was achieved explicitly in [Demirtas et al. 2107.09064, 2107.09065].

We have new solutions with KS throats and only even fluxes [McAllister, Moritz, Nally, AS: 2406.13751].



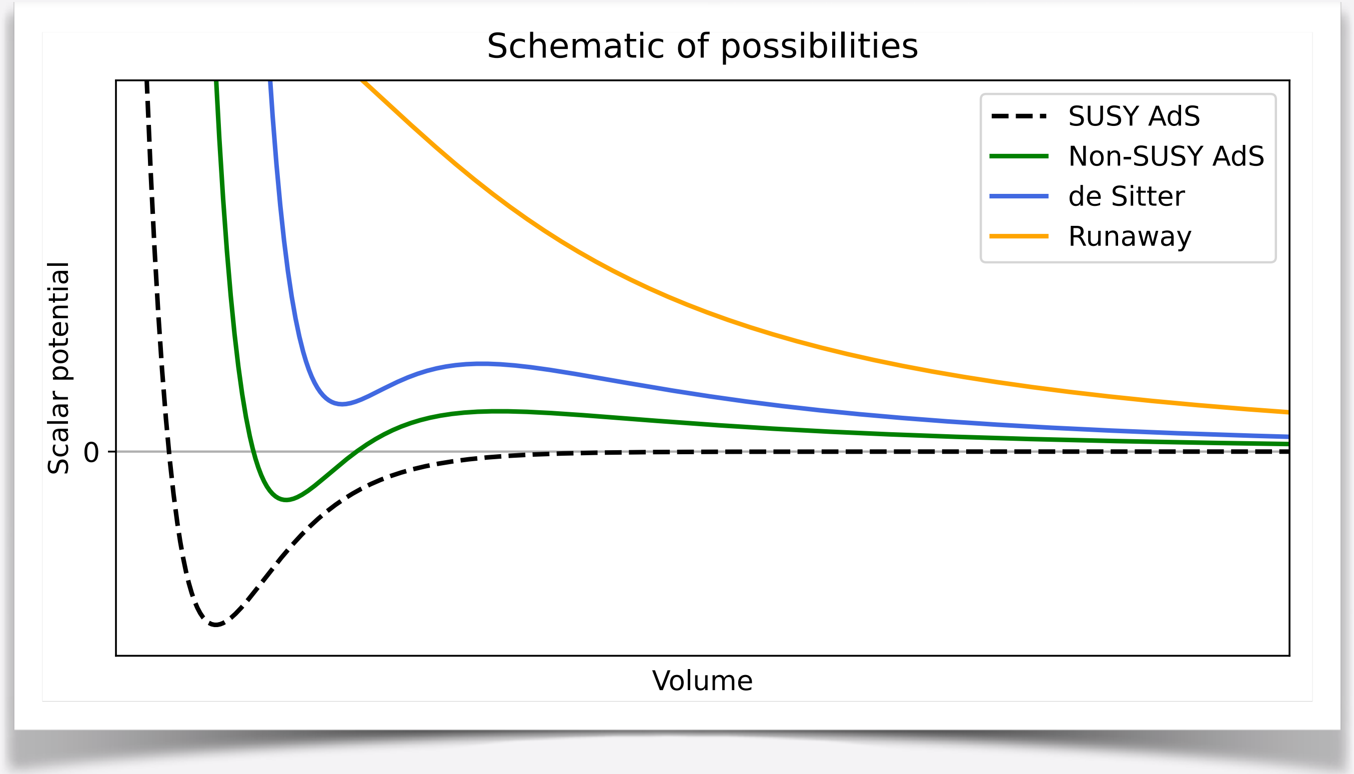
Extended Kähler cone



Finding KKLT vacua in KS

De Sitter vacuum containing anti-D3 branes

McAllister, Moritz, Nally, **AS**: 2406.13751



We restrict to configurations with $Q_{\text{flux}} = Q_0 + 2$ for which the tadpole is cancelled exactly by adding **a single anti-D3 brane** at the tip of the throat.

This makes the previous AdS geometry an **unphysical AdS precursor**!

Practically, it is however important because it makes it easier to locate the true uplifted minimum!

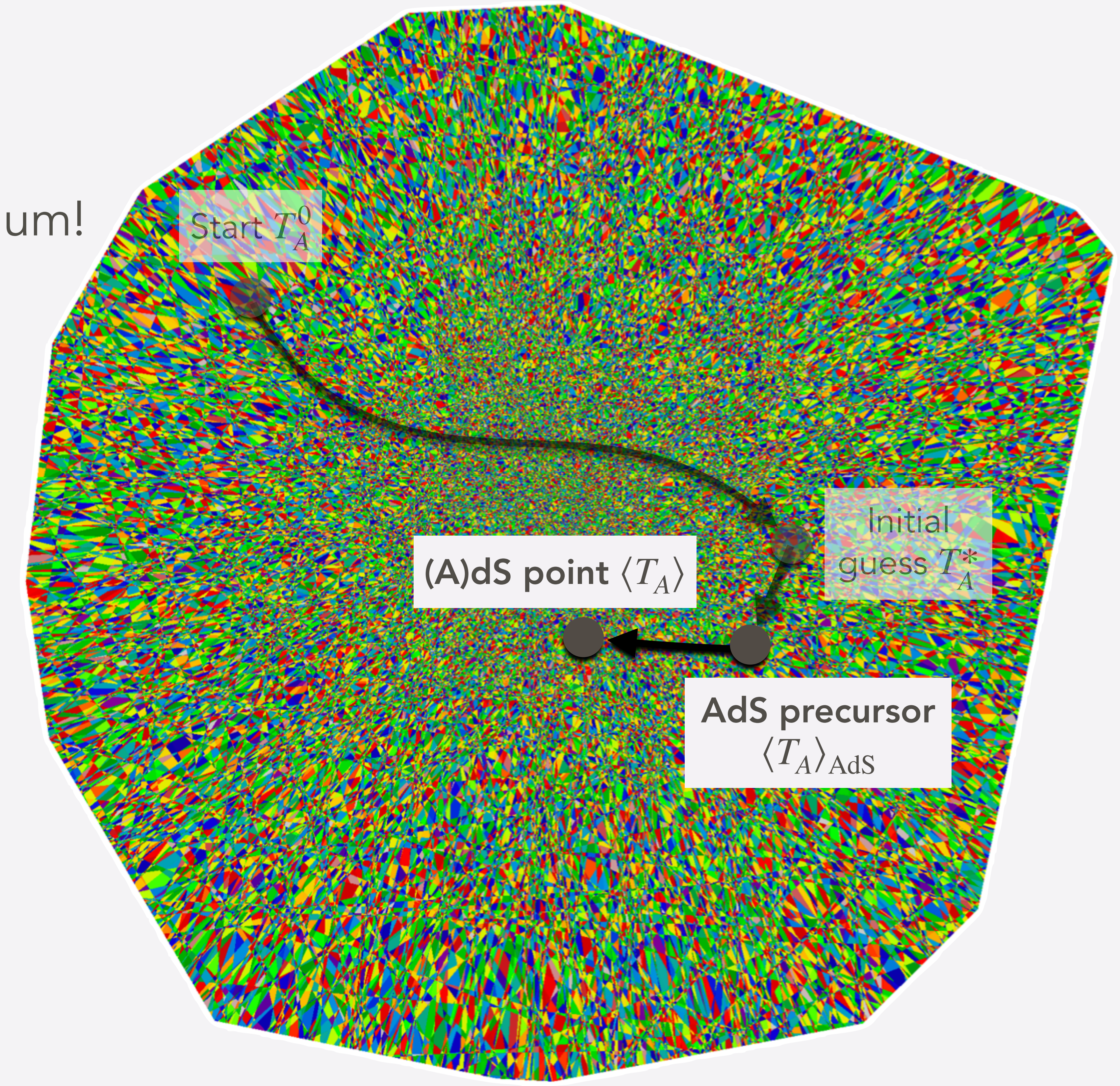
The vacuum is obtained by solving

$$\partial_A V = \partial_A (V_F + V_{\text{up}}) = 0 \ , \qquad V_{\text{up}} \sim \frac{e^{-8\pi K/3n_{cf}g_sM}}{\mathscr{V}^{4/3}}$$

for the Kähler moduli **and** complex structure moduli. We follow the same strategy as before:

1. Use triangulation and Kähler parameters for the AdS precursor as initial guess
2. Obtain **uplifted non-SUSY (A)dS vacuum** (if it exists) by using Newton's method

$$\langle T_A \rangle_{\text{AdS}} \ \rightarrow \ \langle T_A \rangle$$



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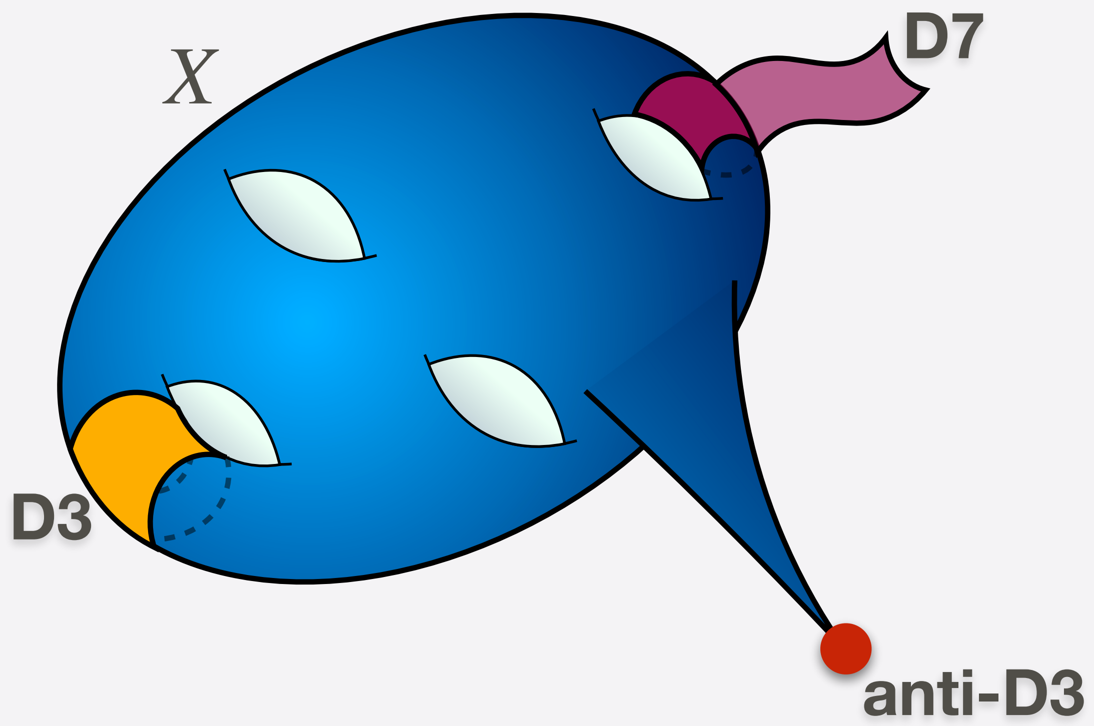

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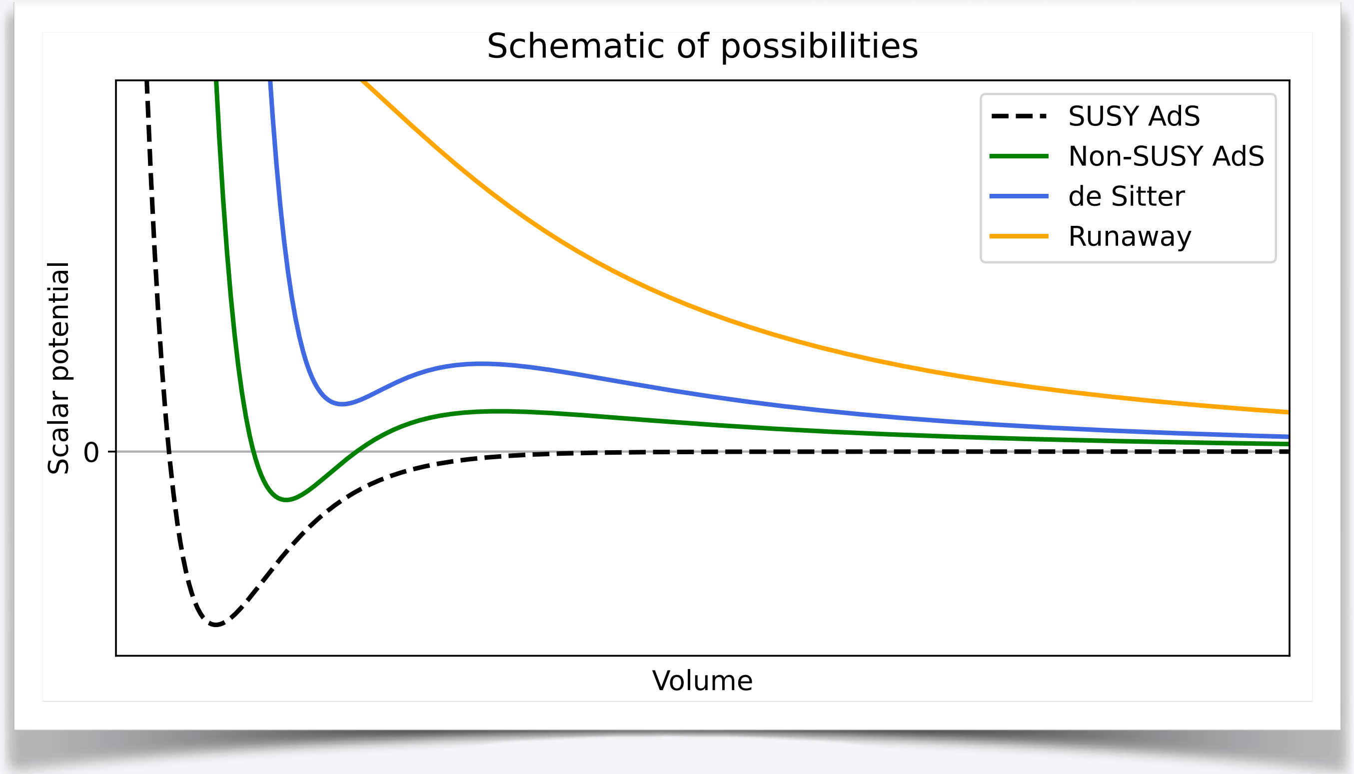

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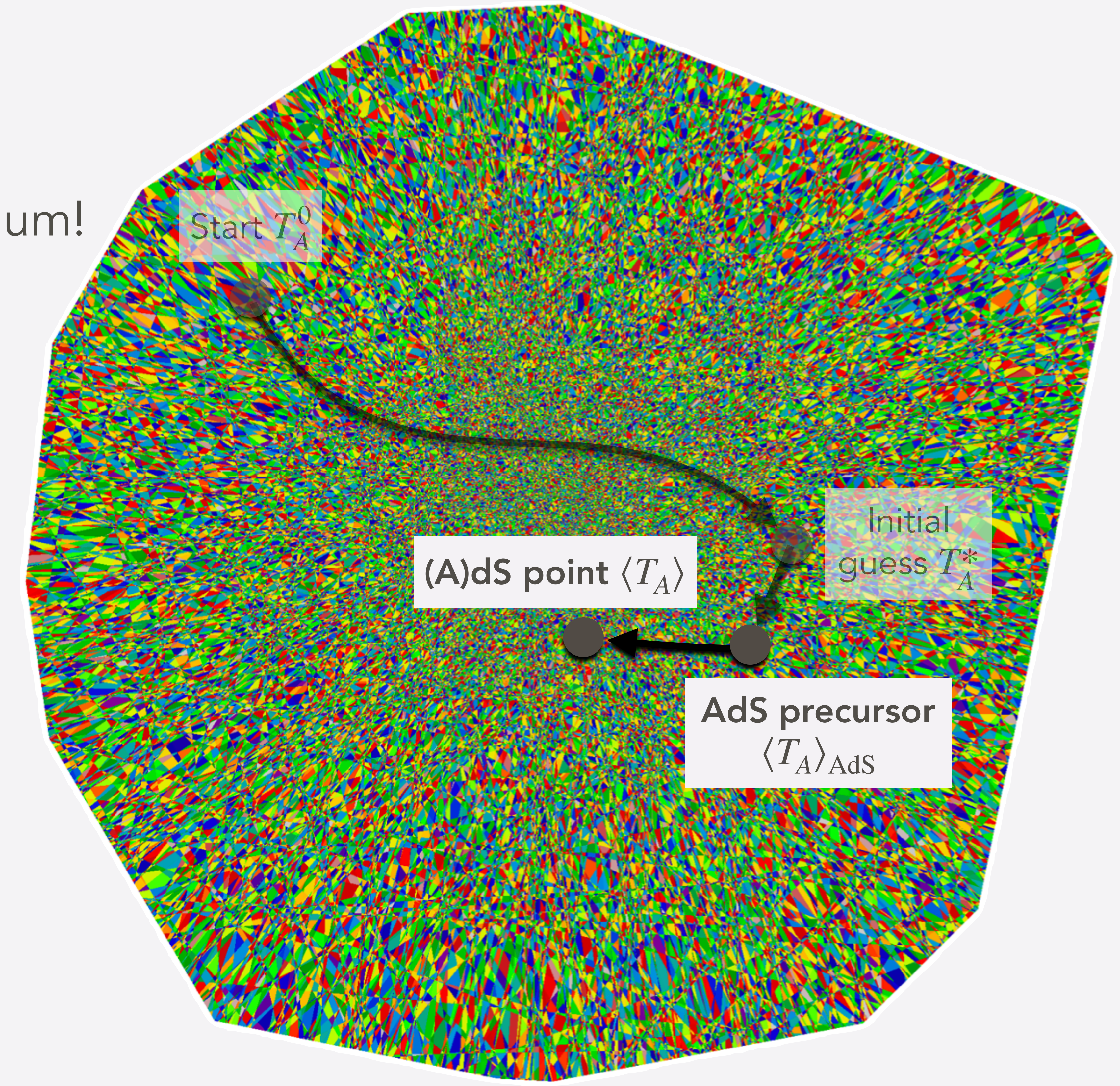

Extended Kähler cone

The working plan

CY GEOMETRIES

CY3 from 4D reflexive polytopes with $3 \leq h^{2,1} \leq 8$ [Kreuzer, Skarke hep-th/0002240]

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(NON-)SUSY (A)dS VACUA

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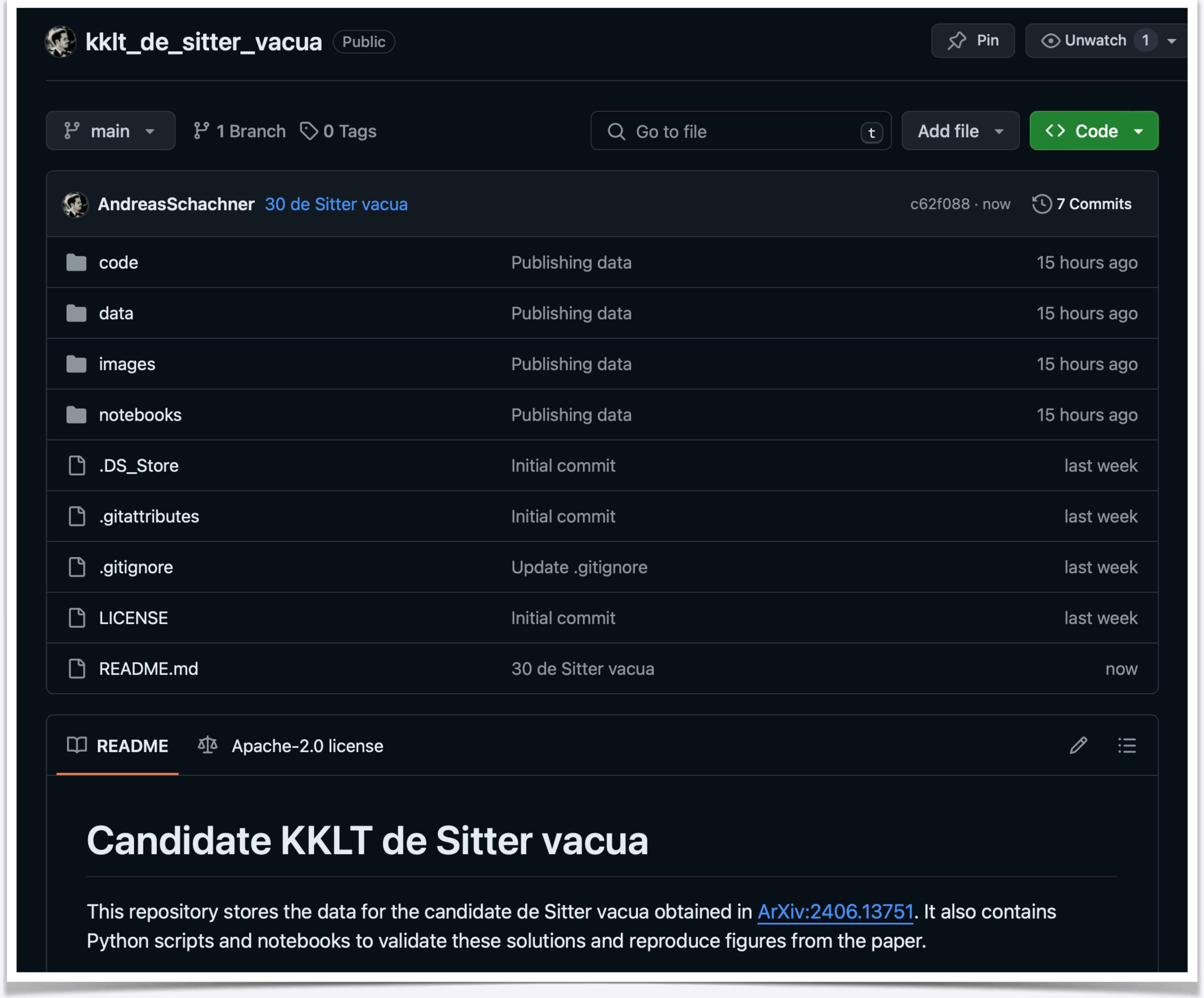
Let us put everything together …

Open access



https://github.com/AndreasSchachner/kklt_de_sitter_vacua

Our entire data is publicly available on GitHub!

On top of that, we provide

- **independent python code** to compute e.g. the vacuum energy or corrected volumes
- jupyter notebooks to **validate our solutions** in the approximations explained below
- a **tutorial notebook** to work with the data and to start new calculations by e.g. using **CYTools**
- plotting tools to reproduce some figures from our paper

Everyone can explore our solutions for themselves by using our repository!

Explicit examples of KKLT vacua

The scan for suitable candidates

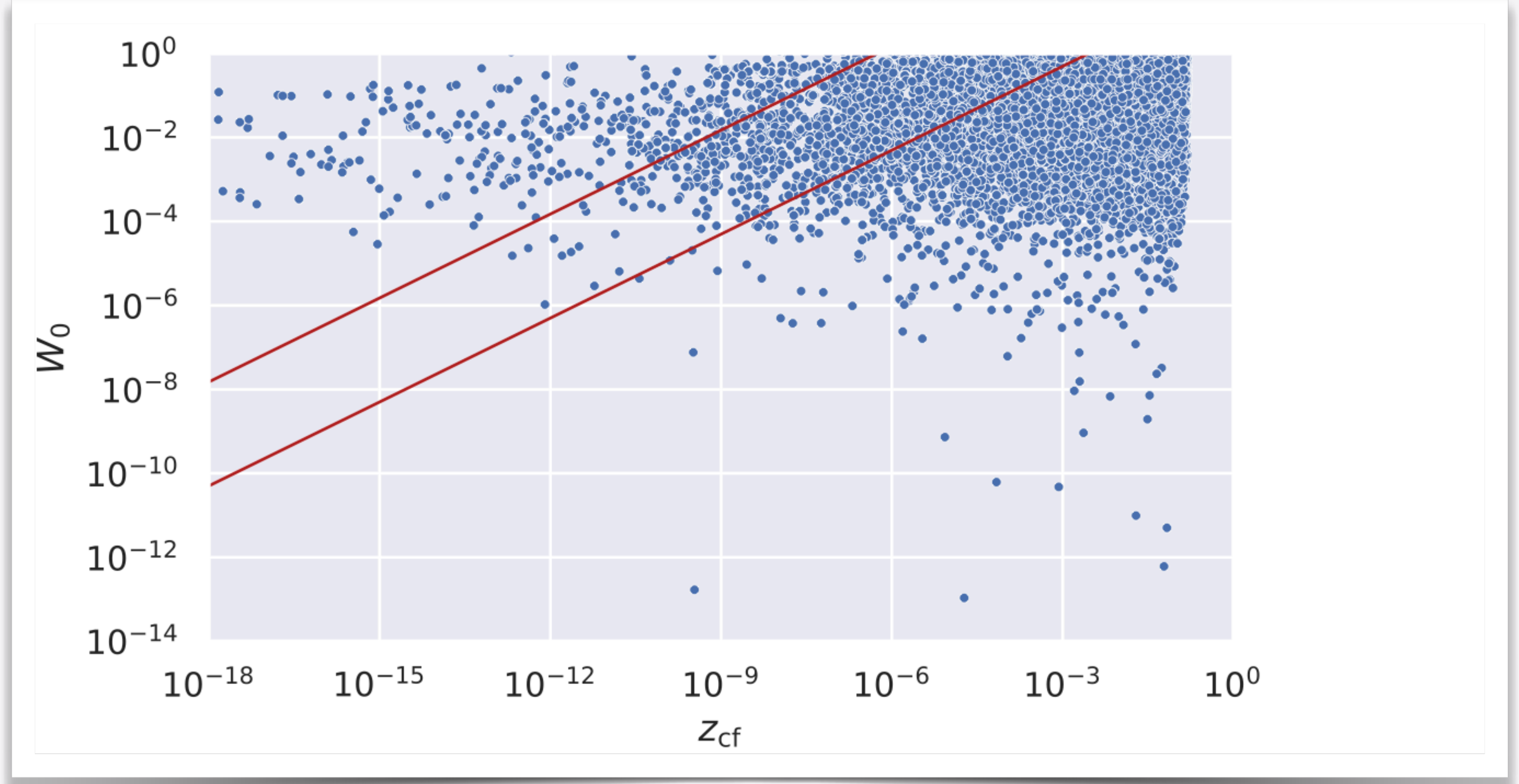
McAllister, Moritz, Nally, **AS**: 2406.13751

Condition	**Number of configurations**
$3 \leq h^{2,1} \leq 8$	202,073 polytopes
trilayer, Δ and Δ° favorable	3187 polytopes
Hodge number cuts	322 polytopes
$\geq h^{1,1}$ rigid divisors	322 polytopes
conifold disjoint from O-planes	2669 conifolds
conifold consistent with KKLT point	416 conifolds
fluxes giving conifold PFV	240,480,253 conifold PFVs
two-term racetrack	141,594,222 racetrack PFVs
$M > 12$; one anti-D3-brane	33,371 anti-D3-brane PFVs

Explicit examples of KKLT vacua

Racetrack minima with anti-D3 branes

McAllister, Moritz, Nally, **AS**: 2406.13751



We obtained **33,371 anti-D3 PFVs** with $Q_{\rm flux} = Q_O + 2$ of which 396 satisfy

$$0.1 \leq \Xi \leq 10\,, \quad g_s < 0.4\,, \quad W_0 < 0.1\,.$$

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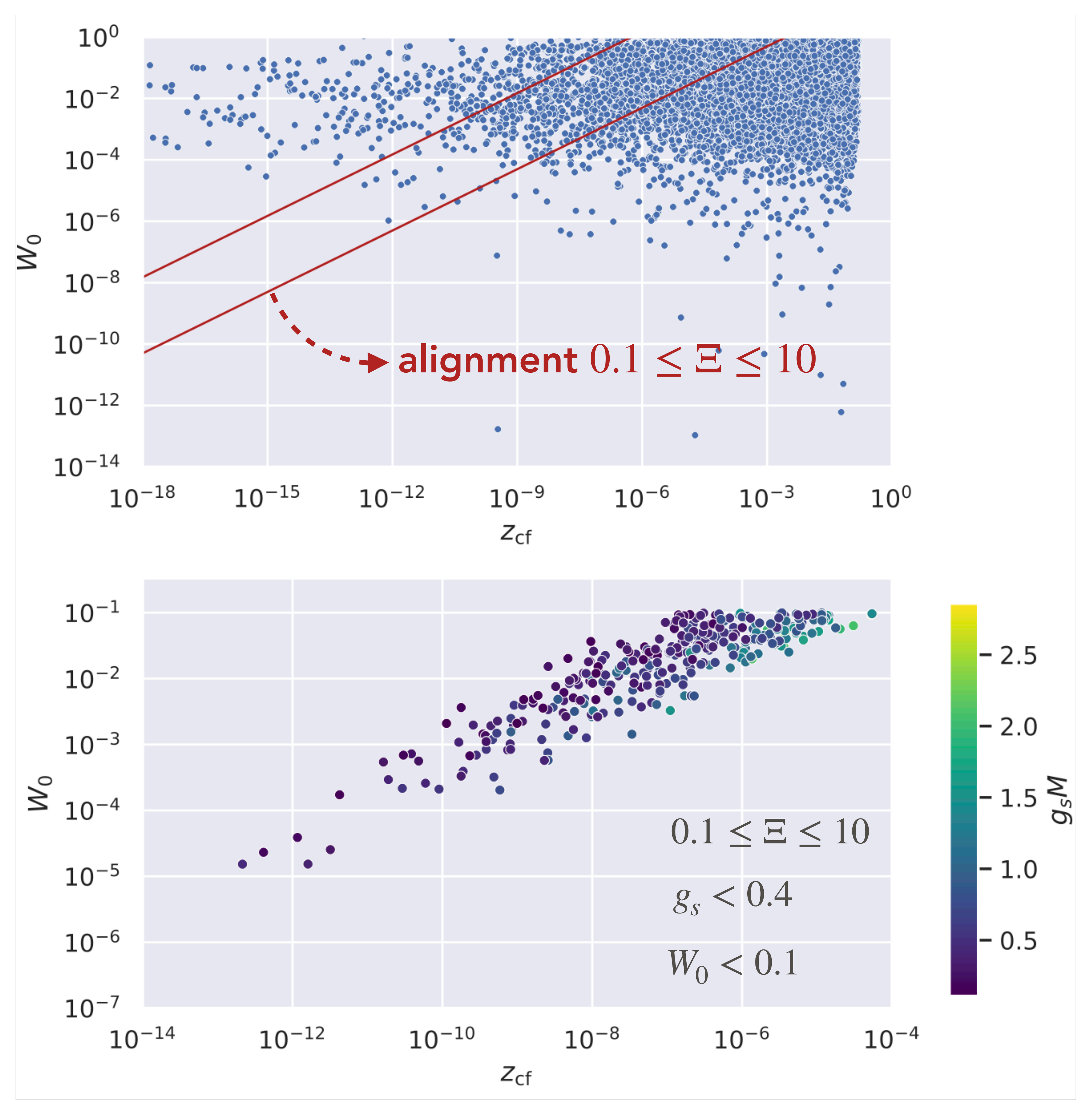

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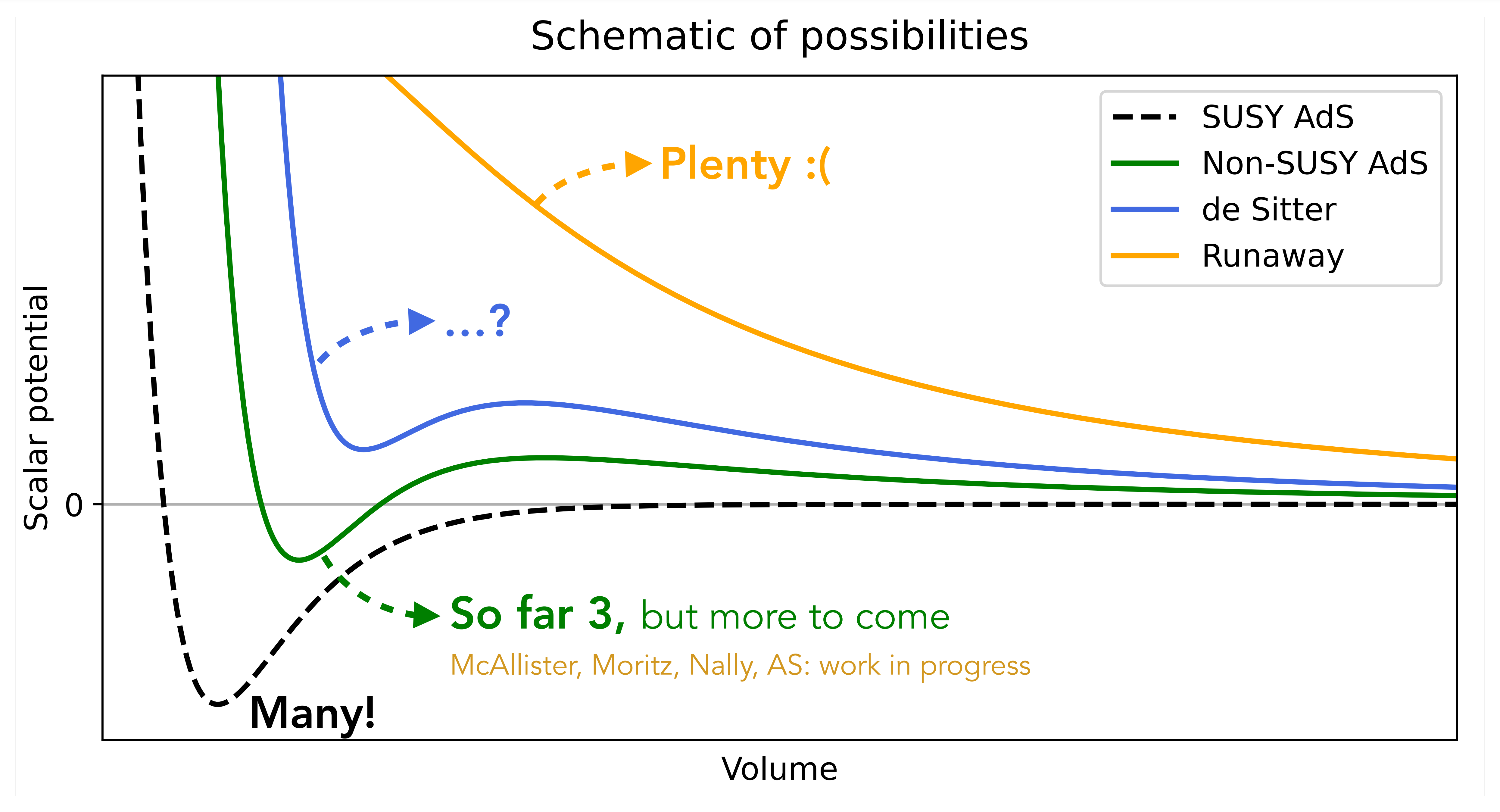


Explicit candidates of KKLT vacua

One de Sitter to rule them all

McAllister, Moritz, Nally, **AS**: 2406.13751

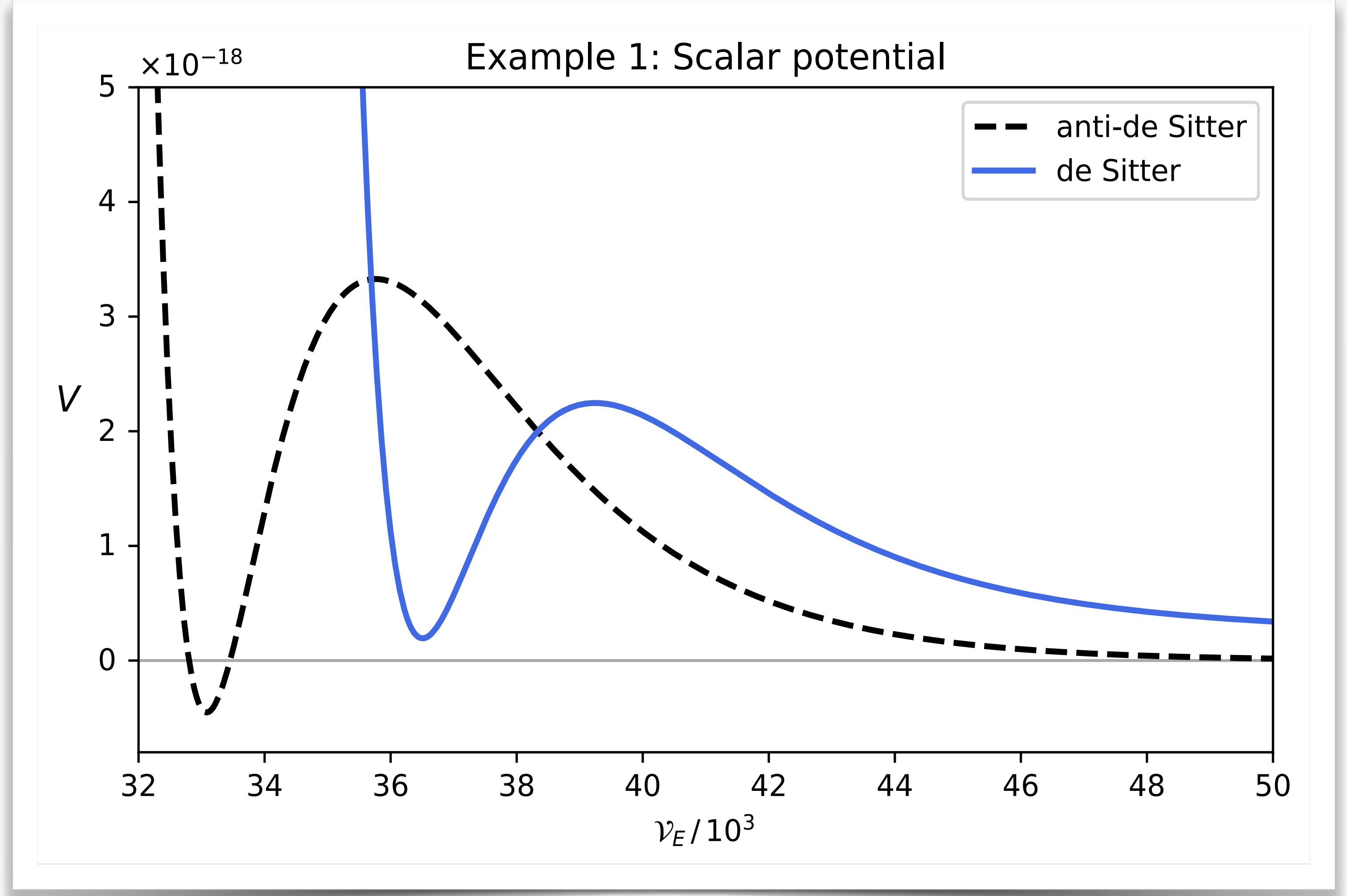
Here is an explicit example of a de Sitter candidate vacuum at $h^{1,1} = 150$ and $h^{2,1} = 8$

$$\vec{M} = (16\,,10\,,\,-26\,,8\,,32\,,30\,,18\,,28)^{\top}\quad,\qquad \vec{K} = (-6\,,\,-1\,,0\,,1\,,\,-3\,,2\,,0\,,\,-1)^{\top}\quad,\qquad \vec{p} = \frac{1}{40}(0\,,\,-8\,,0\,,\,-2\,,4\,,5\,,5\,,4)^{\top}$$

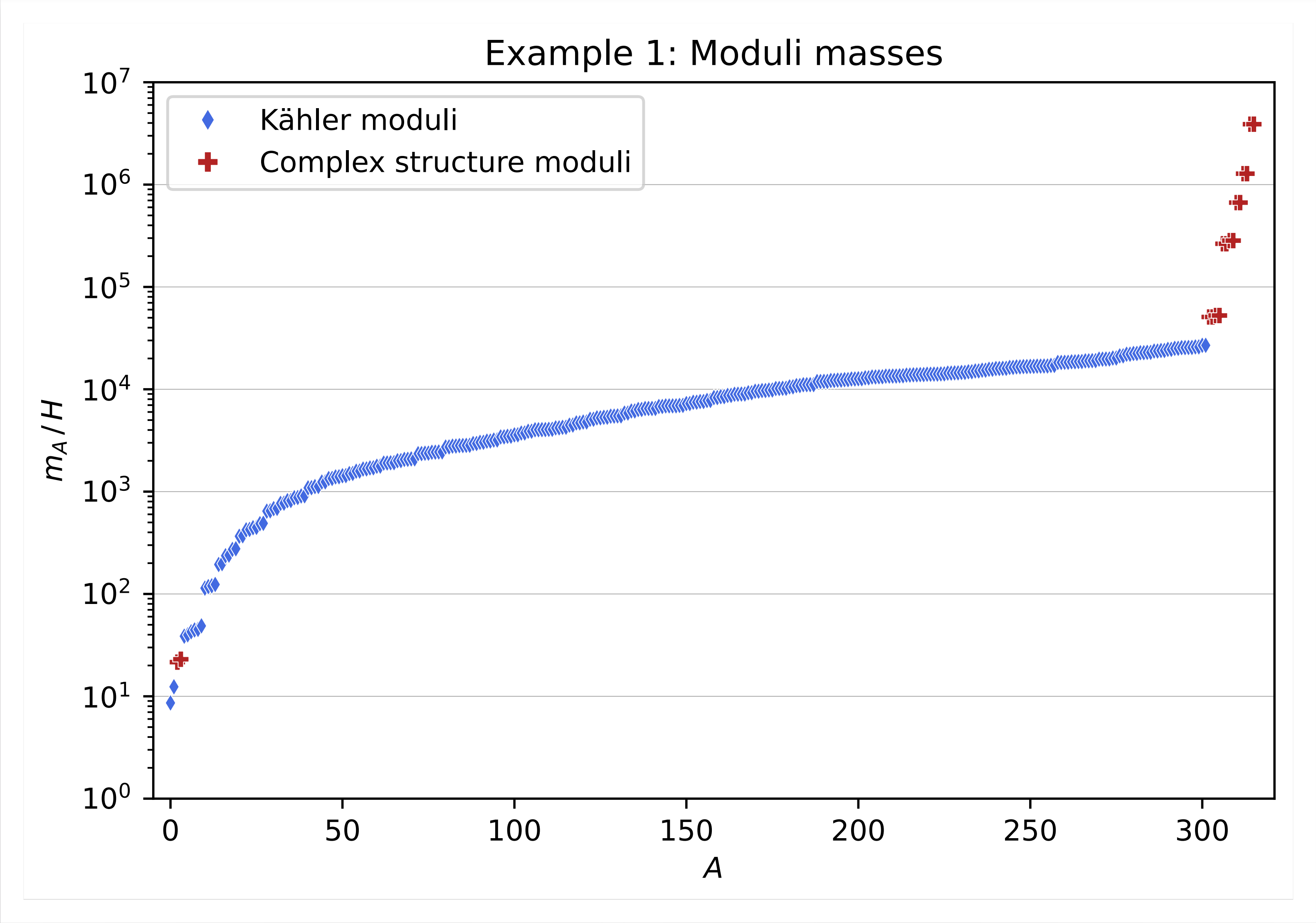
giving rise to

$$g_s = 0.0657 \qquad W_0 = 0.0115 \qquad g_s M = 1.051 \qquad z_{\text{cf}} = 2.882\times 10^{-8} \qquad V_{\text{dS}} = +\,1.937\times 10^{-19}\,M_{pl}^4$$

Potential before and after uplift:



The vacuum is free of tachyons!

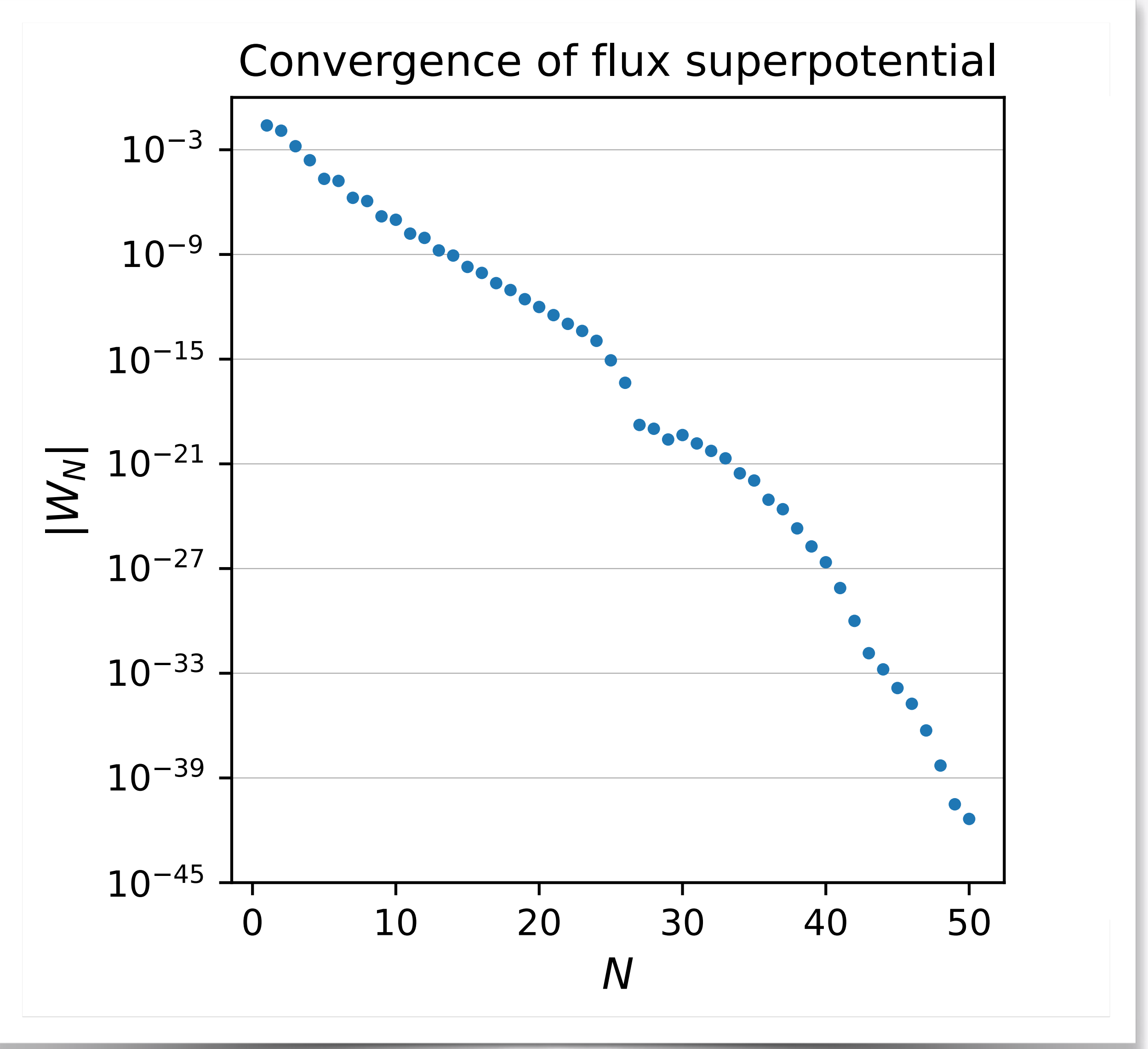


Explicit candidates of KKLT vacua

One de Sitter to rule them all

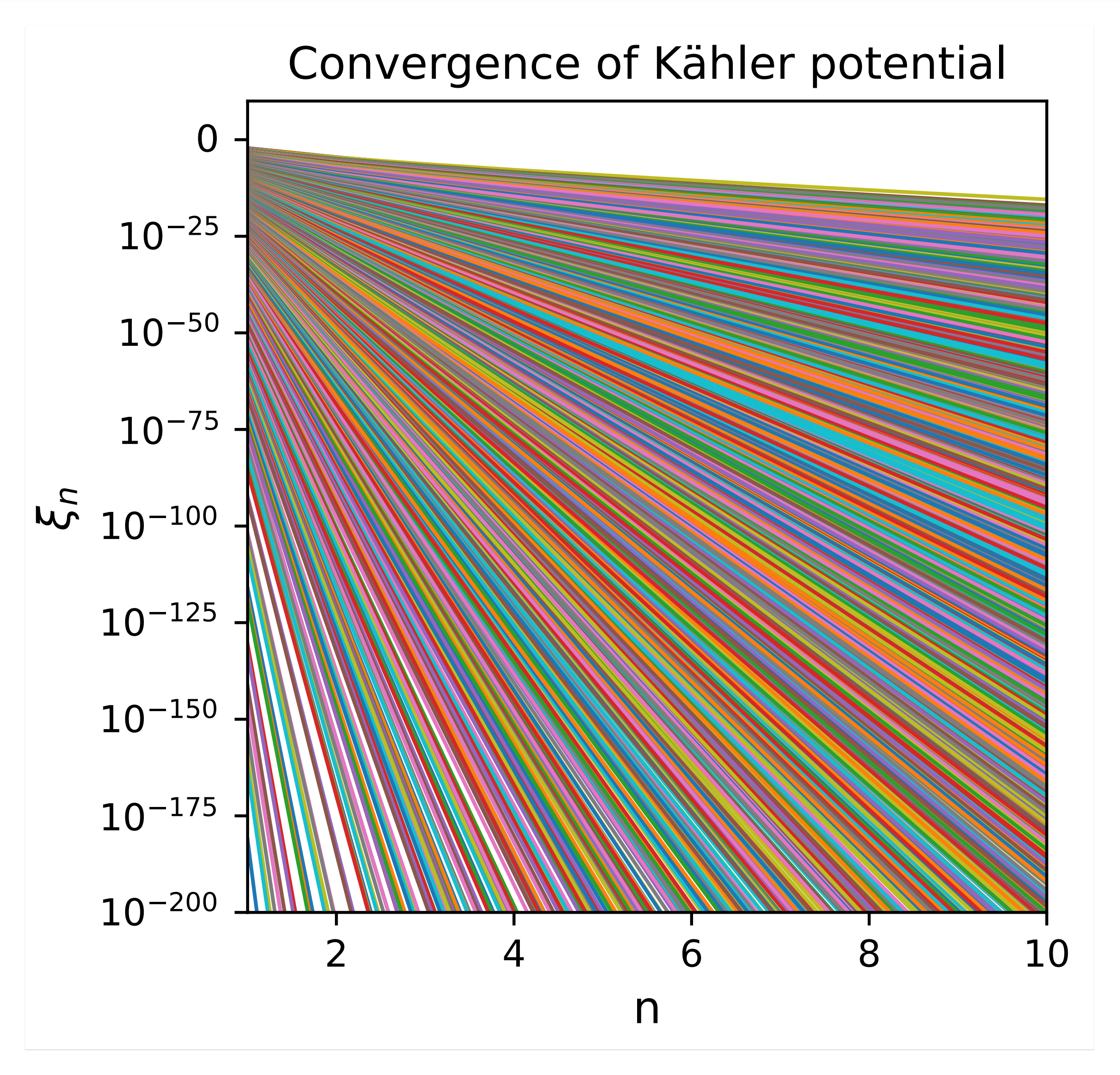
McAllister, Moritz, Nally, **AS**: 2406.13751

$$W_N \sim \sum_{\tilde{\mathbf{q}}\cdot p = N} \mathcal{N}_{\tilde{\mathbf{q}}}\,(M^a \tilde{\mathbf{q}}_a)\,\mathrm{Li}_2\!\left(\mathrm{e}^{2\pi i N\tau}\right)$$



Racetrack potential

$$\xi_n = \mathcal{N}_{n\mathbf{q}}\,\mathrm{e}^{-2\pi n\,\mathbf{q}\cdot\mathbf{t}}$$



Contributions from potent curves

Pfaffian prefactors:

Recall the for our results, we set $n_D = 1$ in

$$A_D = \sqrt{\frac{2}{\pi}}\,\frac{1}{(4\pi)^2} \times n_D$$

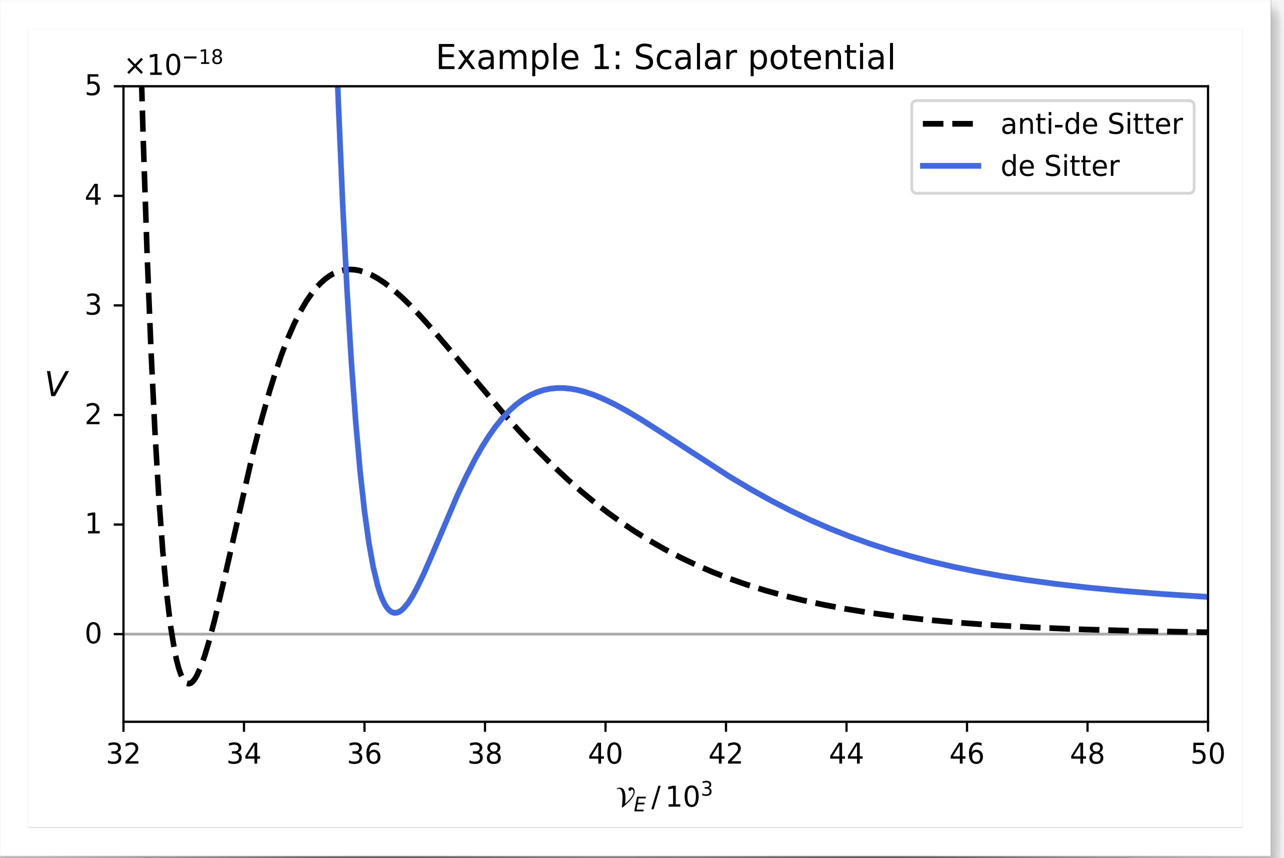
We checked that our vacua survive for

$$10^{-3} \leq n_D \leq 10^4$$

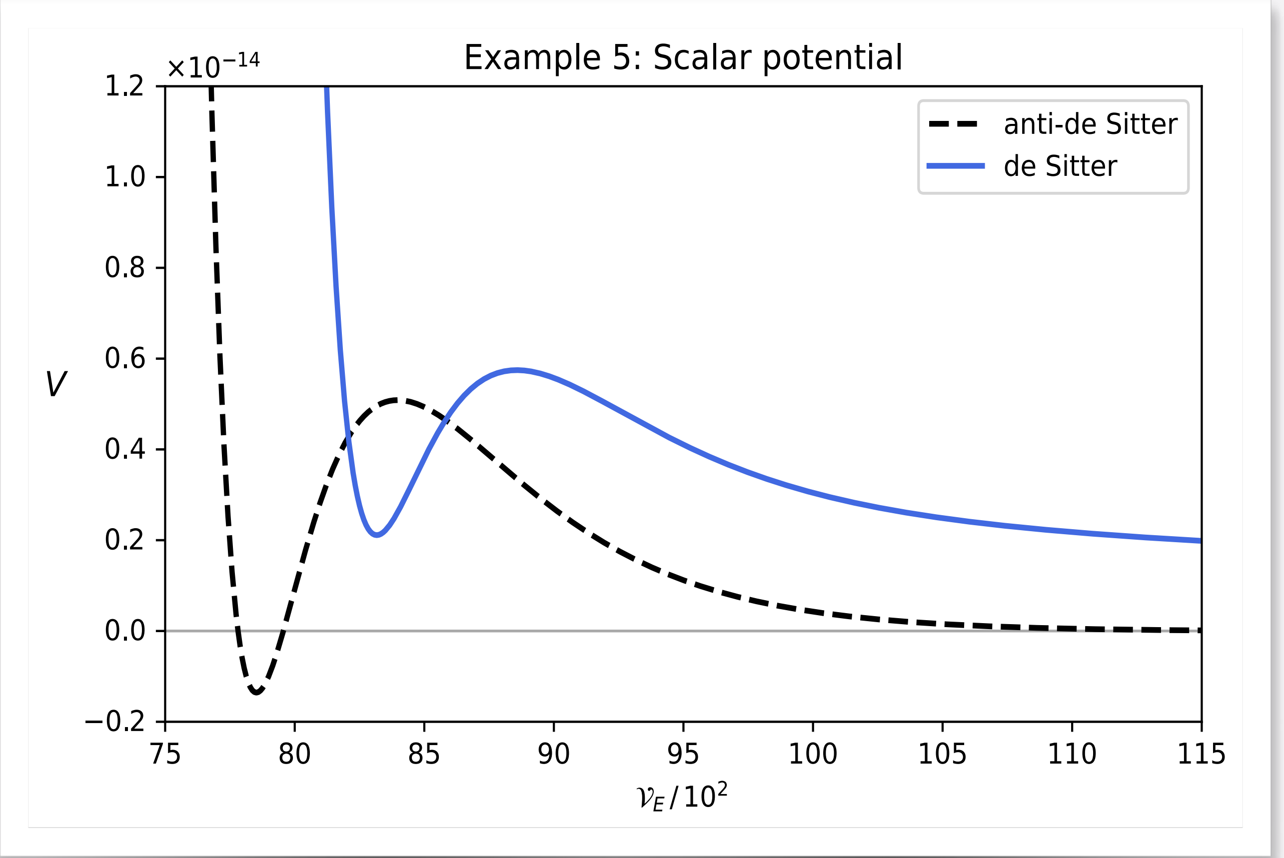
Explicit candidates of KKLT vacua

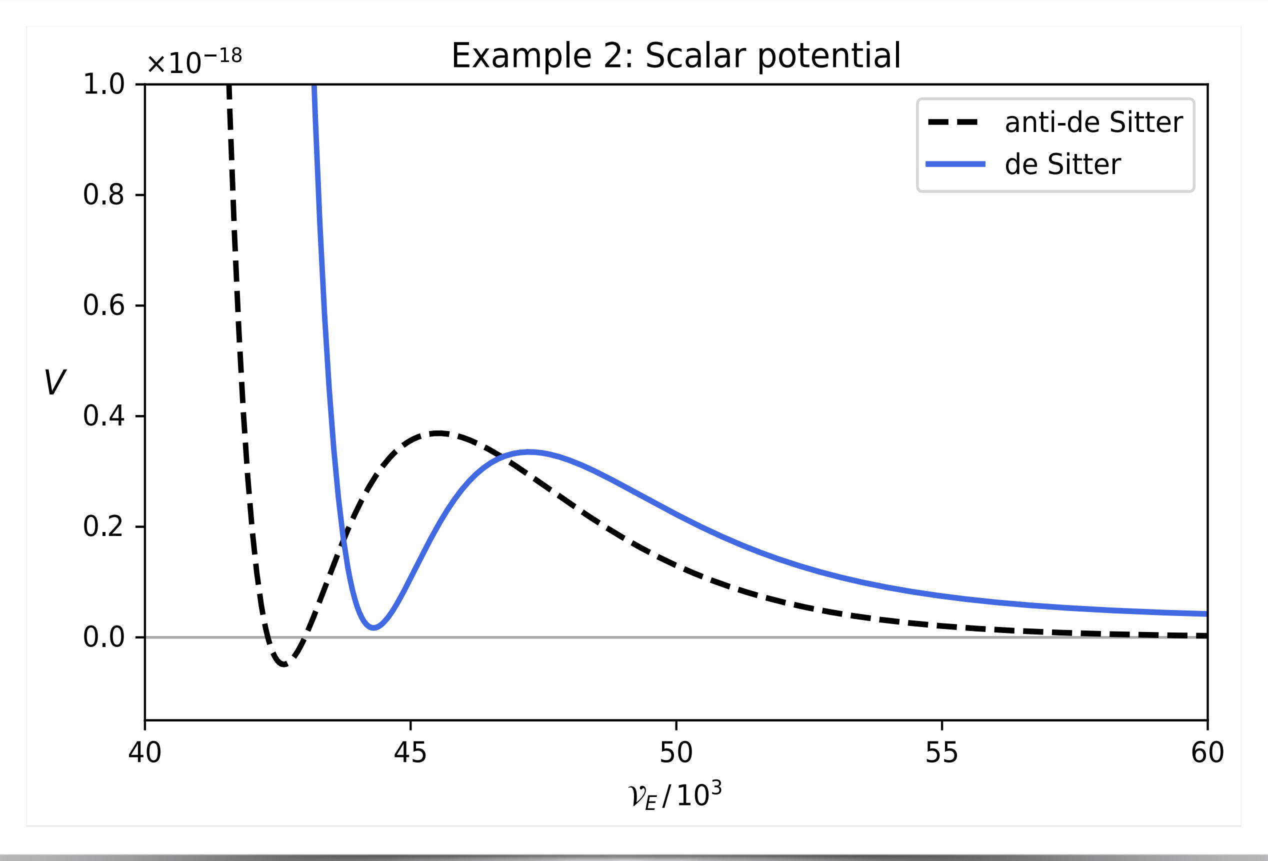
~~One~~ **five de Sitters** to rule them all

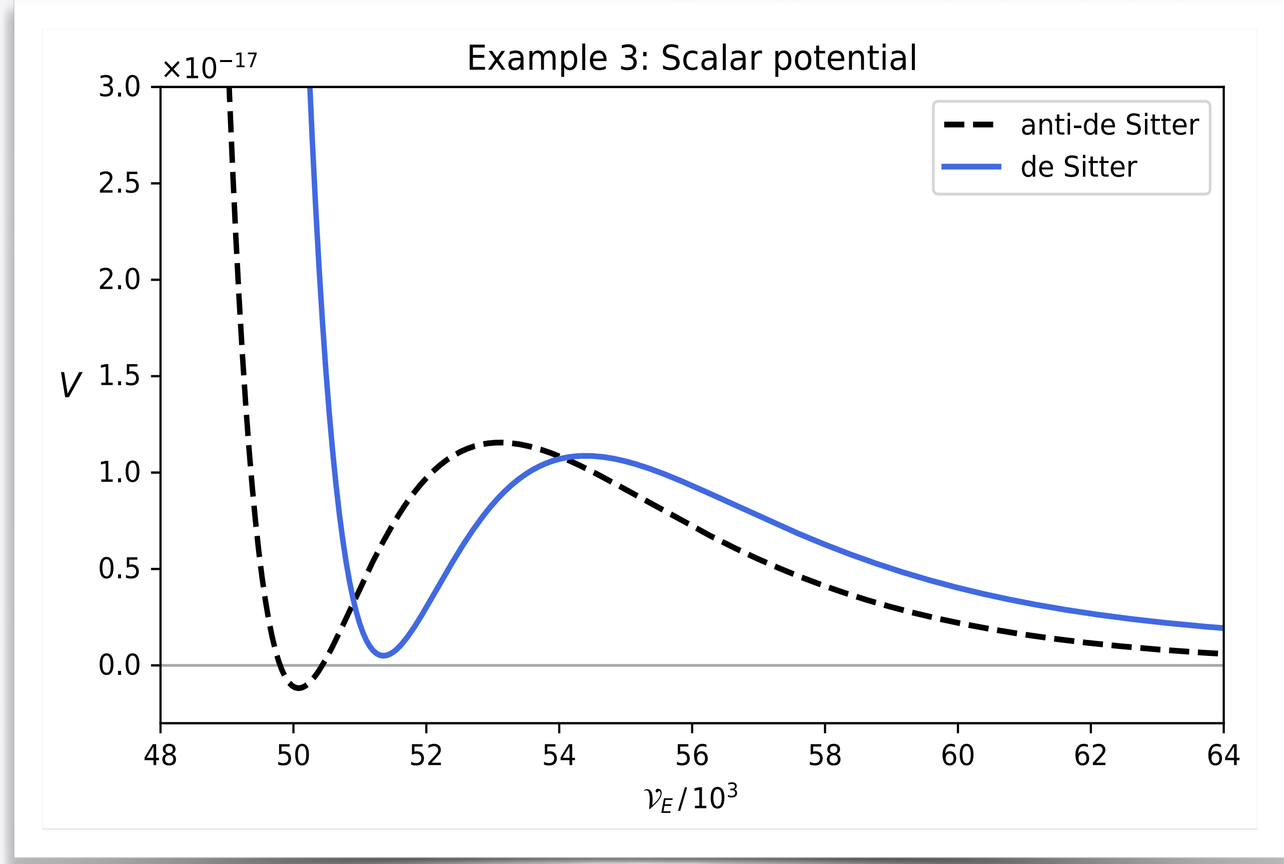
McAllister, Moritz, Nally, **AS**: 2406.13751

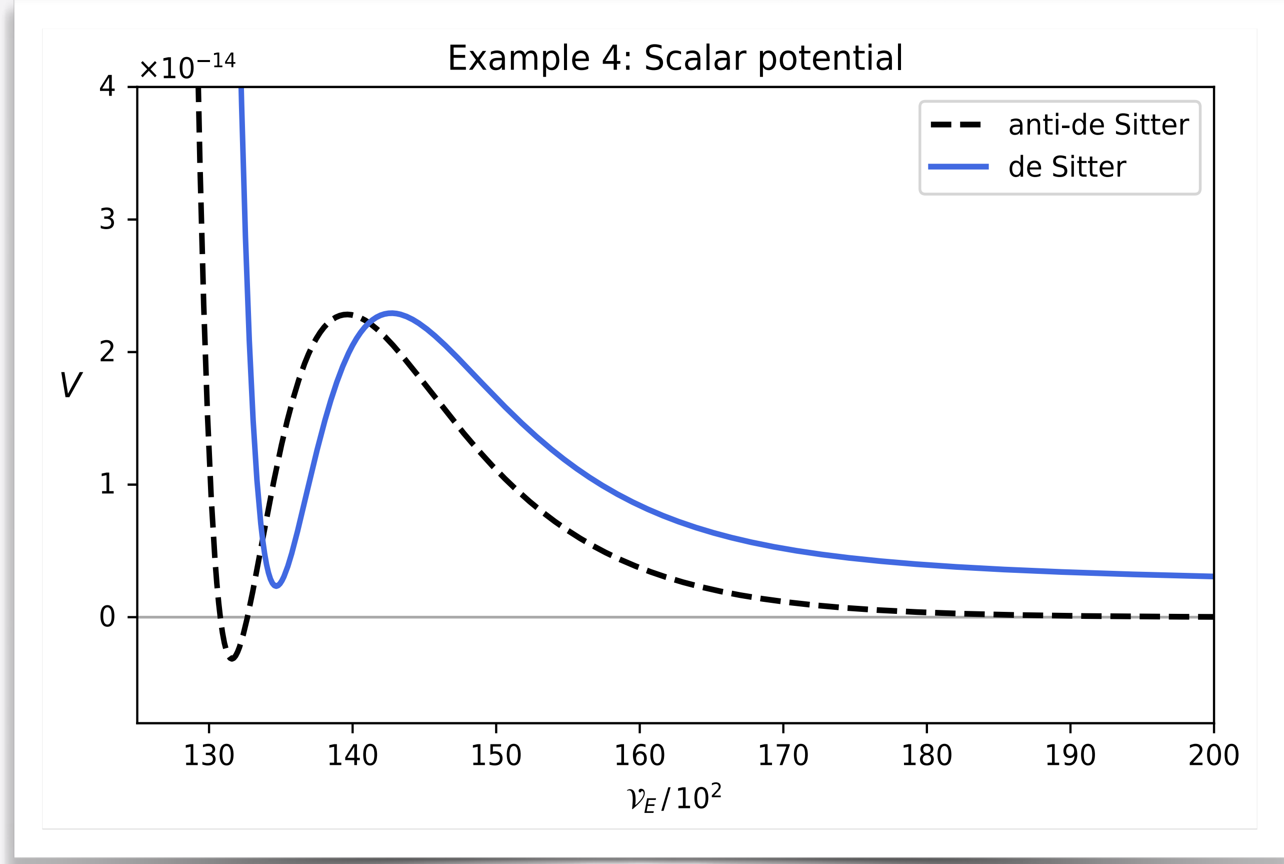


ID	$h^{2,1}$	$h^{1,1}$	M	K'	g_s	W_0	$g_s M$	$\lvert z_{\rm cf}\rvert$	V_0
1	8	150	16	$\frac{26}{5}$	0.0657	0.0115	1.051	2.822×10^{-8}	$+1.937\times10^{-19}$
2	8	150	16	$\frac{93}{19}$	0.0571	0.00490	0.913	7.934×10^{-9}	$+1.692\times10^{-20}$
3	8	150	18	$\frac{40}{11}$	0.0442	0.0222	0.796	8.730×10^{-8}	$+4.983\times10^{-19}$
4	5	93	20	$\frac{17}{5}$	0.0404	0.0539	0.808	1.965×10^{-6}	$+2.341\times10^{-15}$
5	5	93	16	$\frac{29}{10}$	0.0466	0.0304	0.746	8.703×10^{-7}	$+2.113\times10^{-15}$





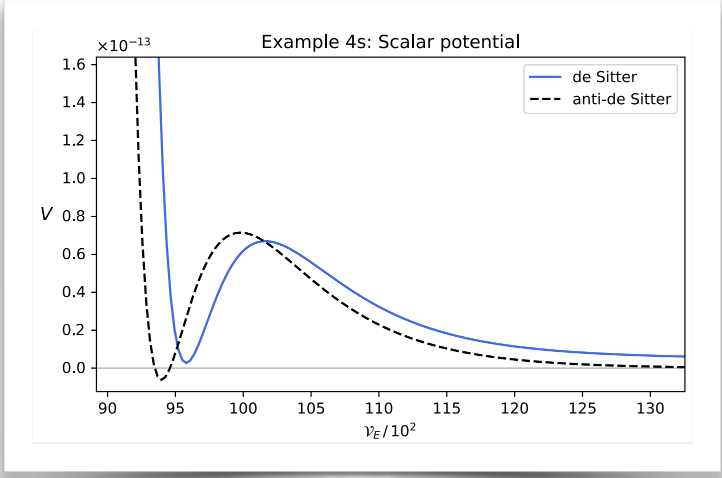


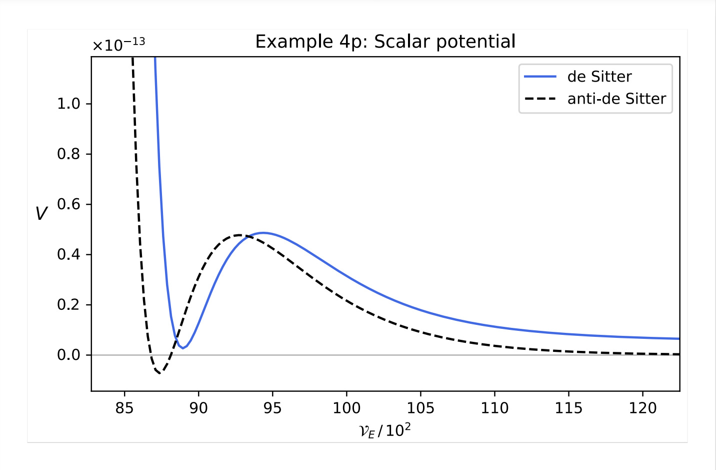


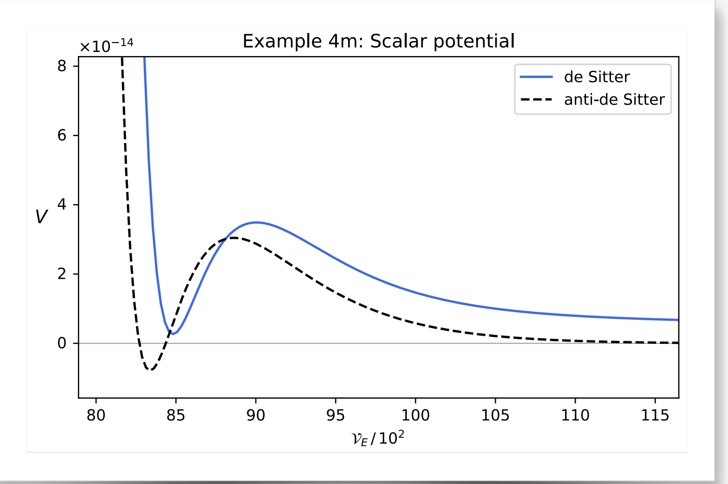
Explicit candidates of KKLT vacua

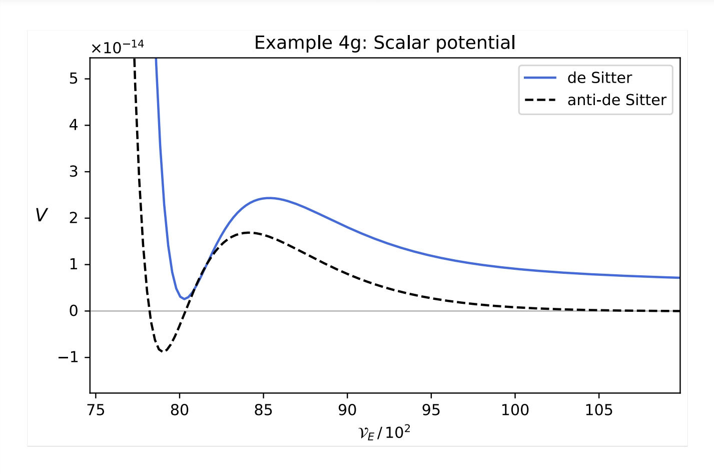
~~One~~ ~~five~~ **30 de Sitters** to rule them all

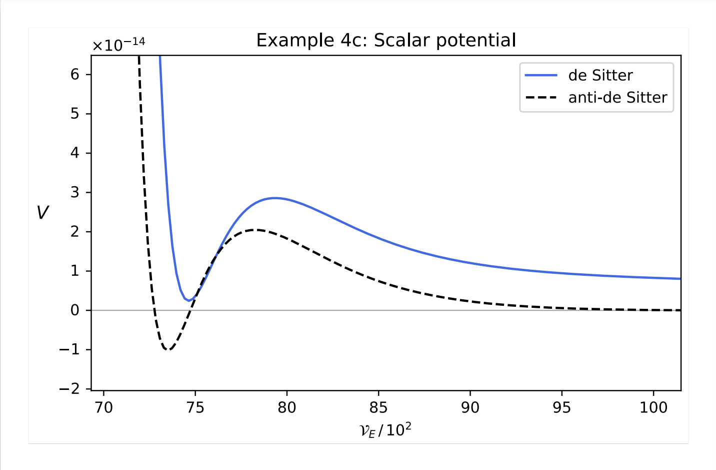
McAllister, Moritz, Nally, **AS**: 2406.13751











Explicit candidates of KKLT vacua

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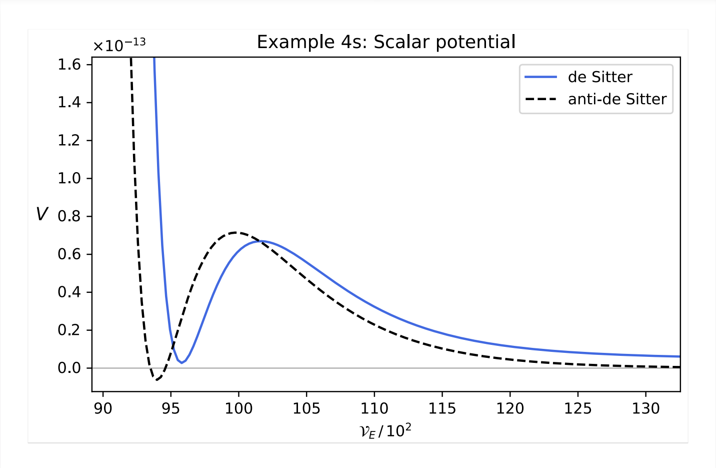
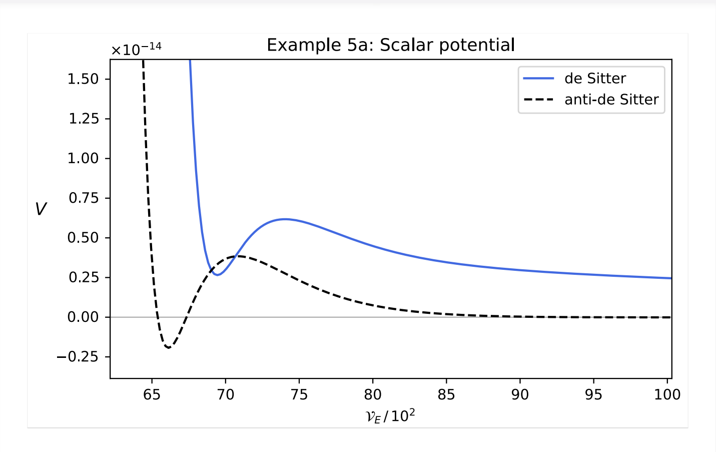
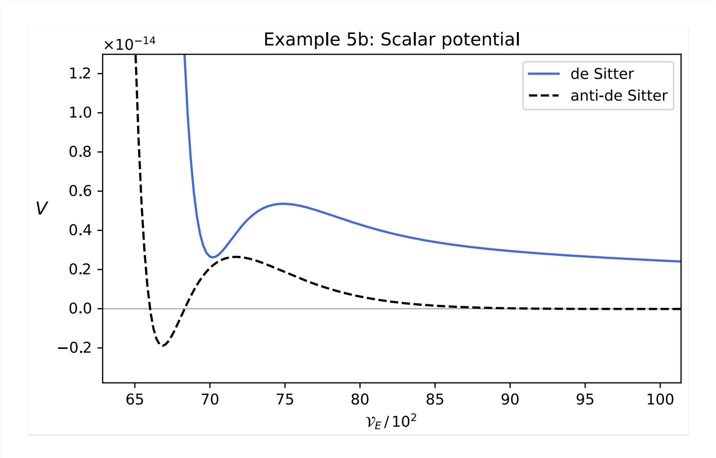
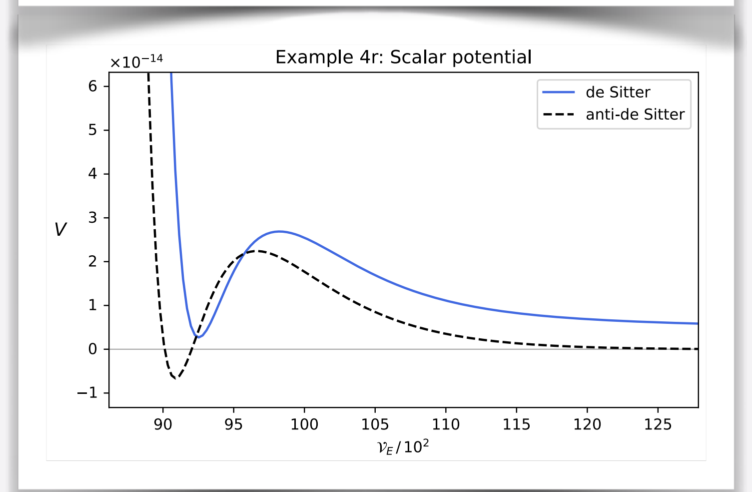
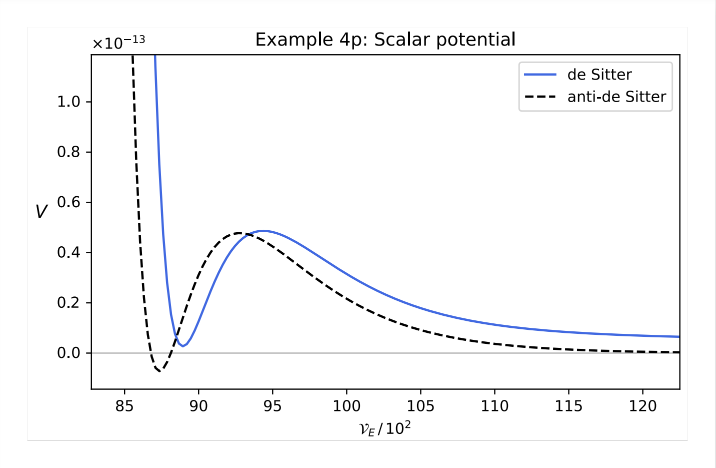
McAllister, Moritz, Nally, **AS**: [2406.13751]

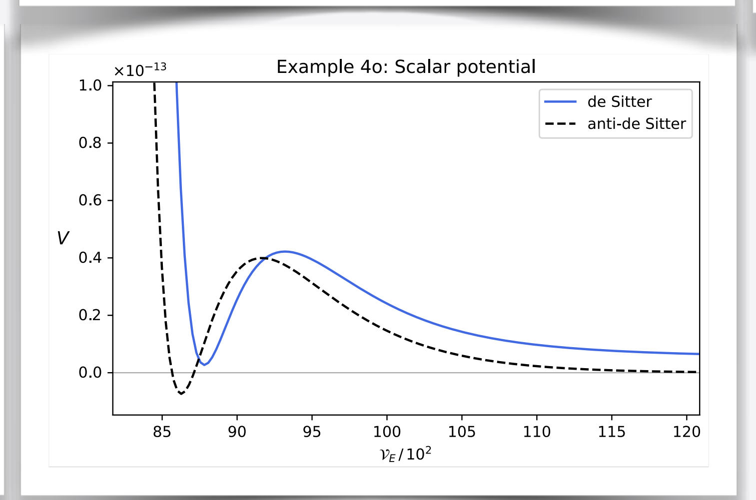


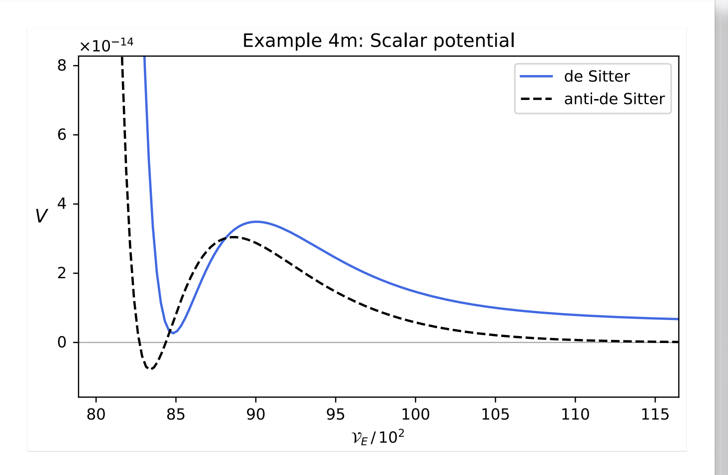


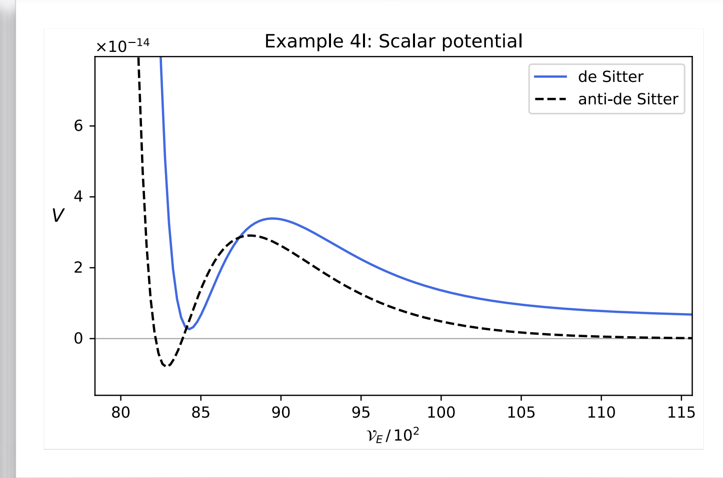


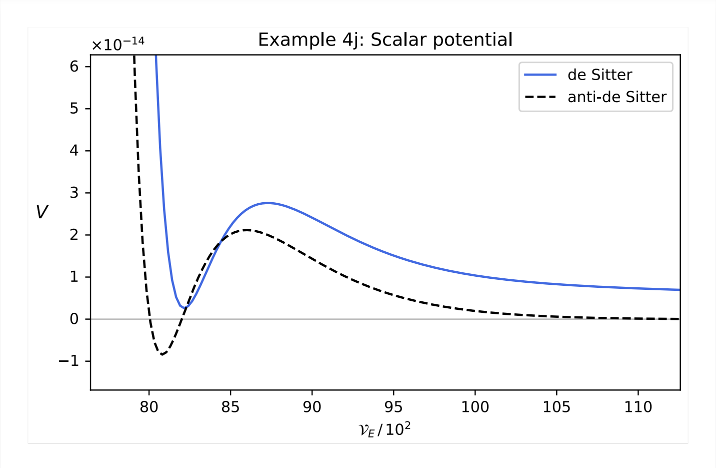


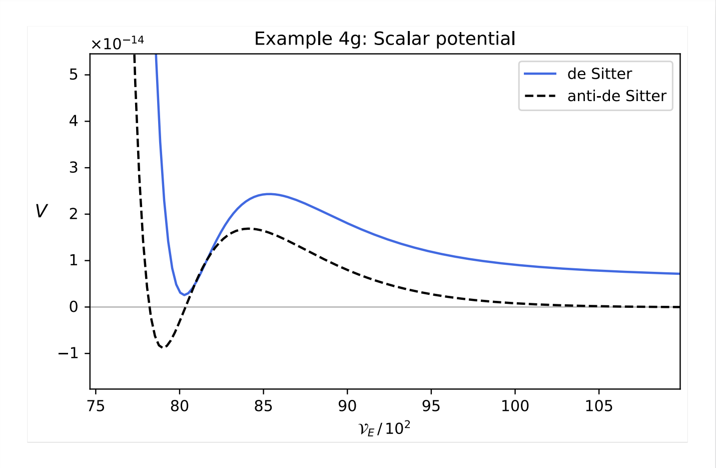


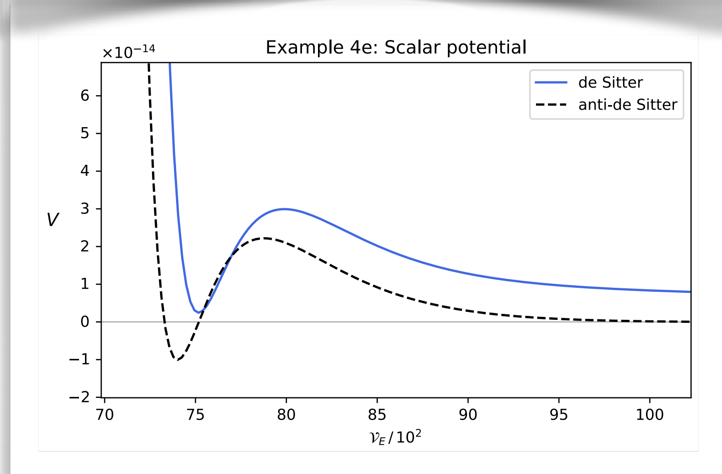


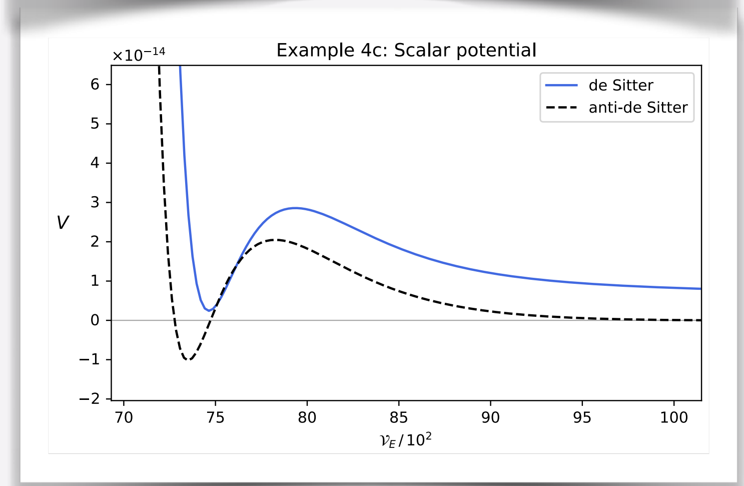


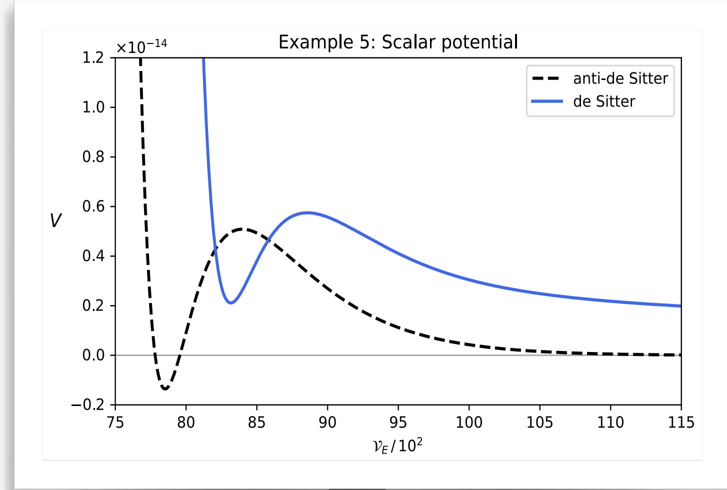








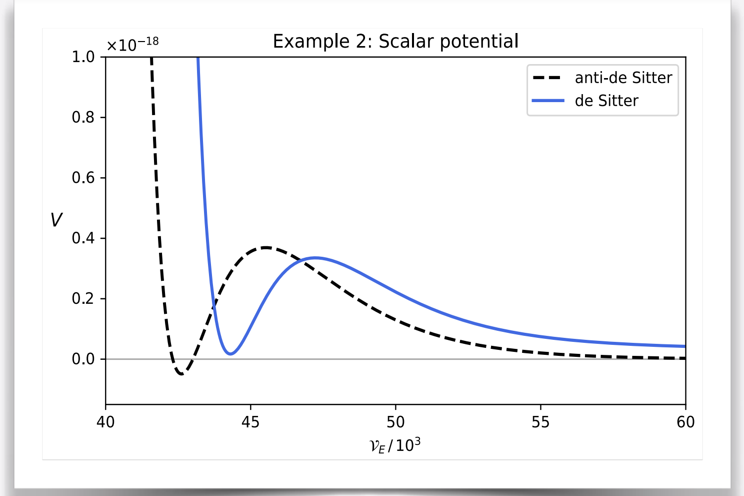


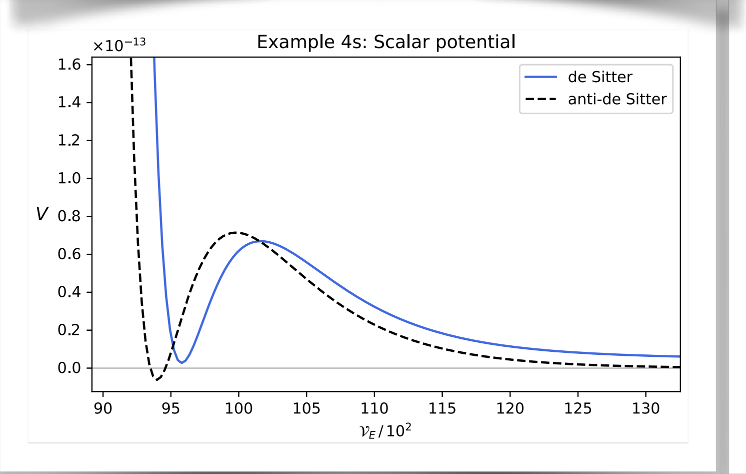


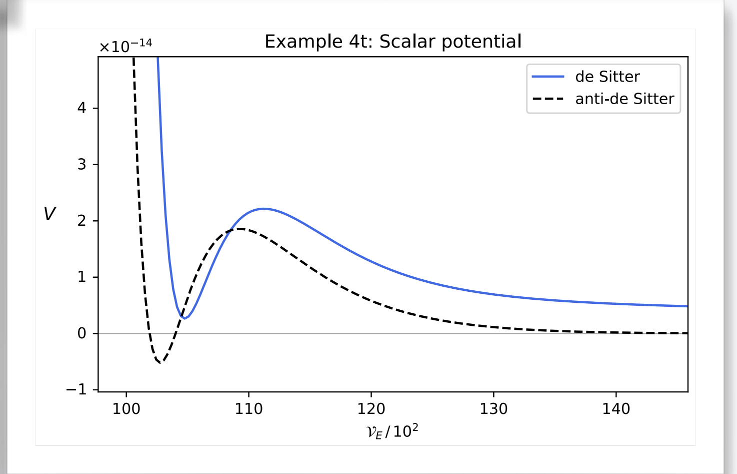
Explicit candidates of KKLT vacua

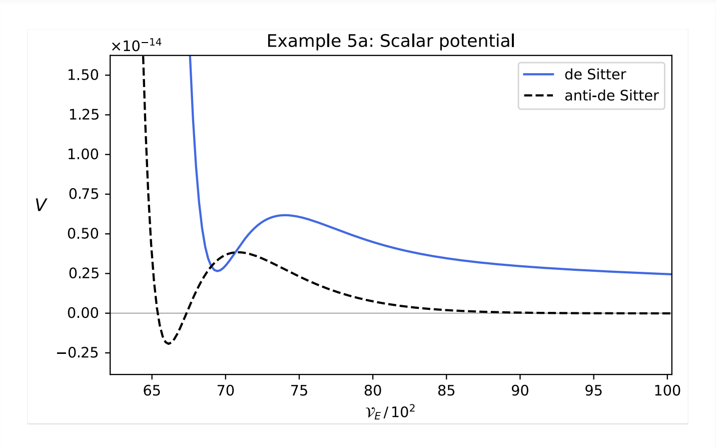
~~One~~ ~~five~~ **30 de Sitters** to rule them all

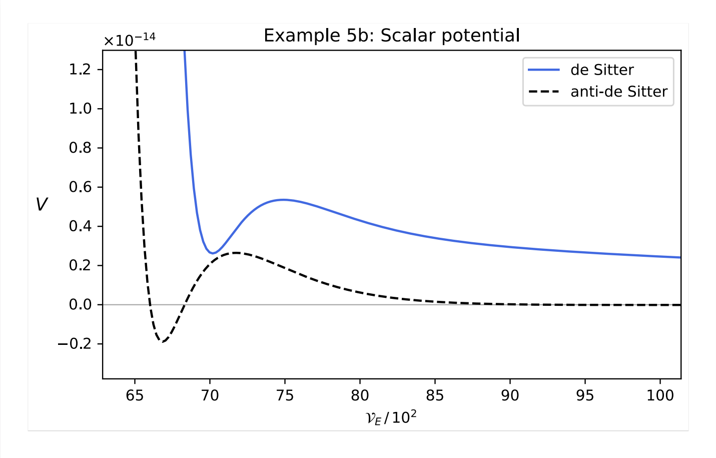
McAllister, Moritz, Nally, **AS**: 2406.13751

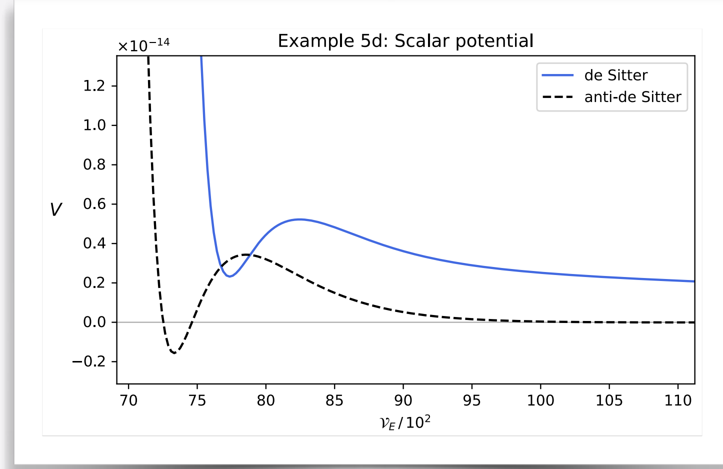


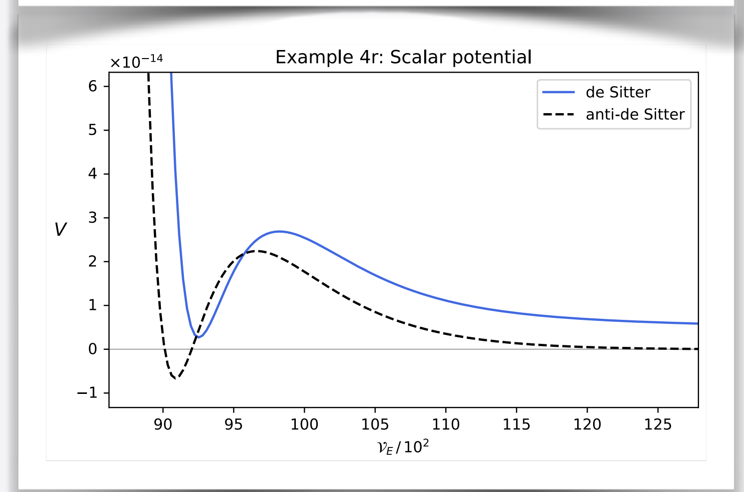


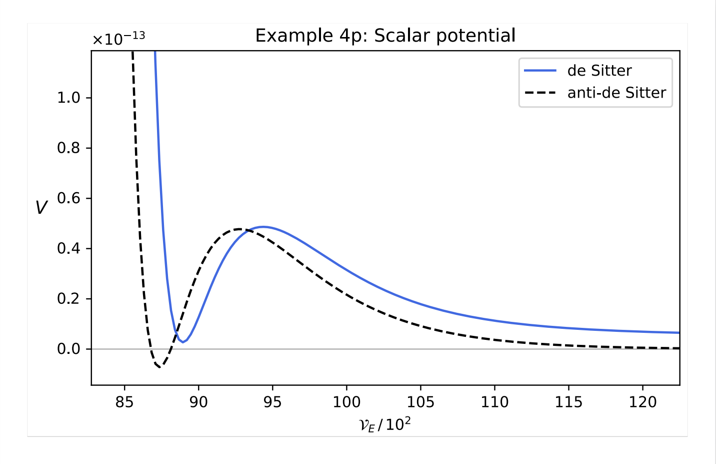


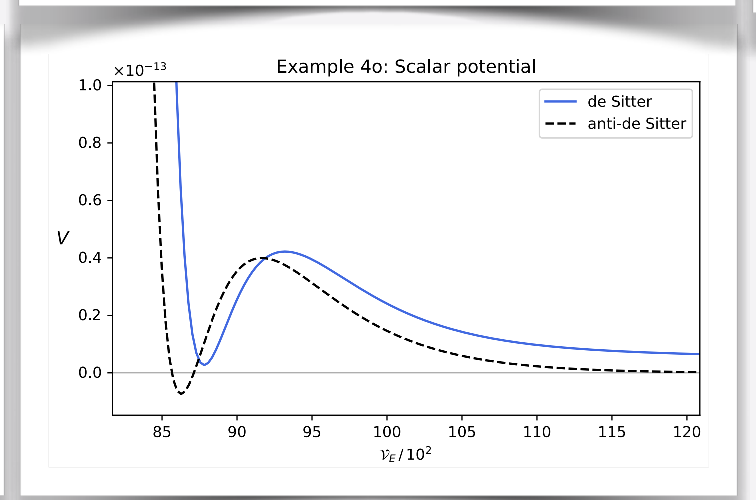


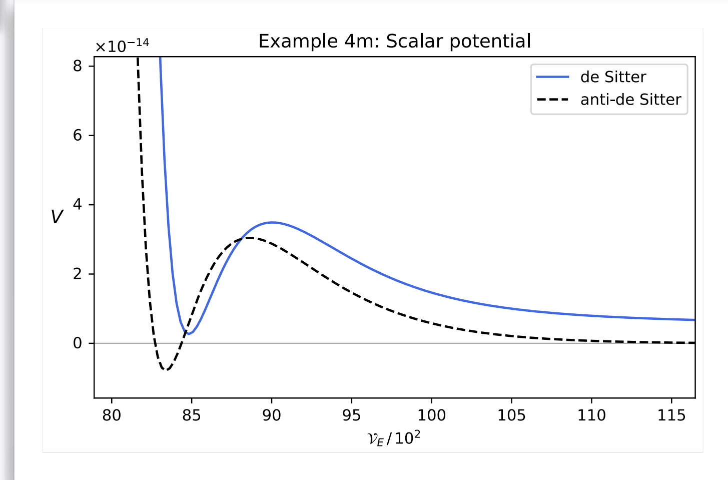


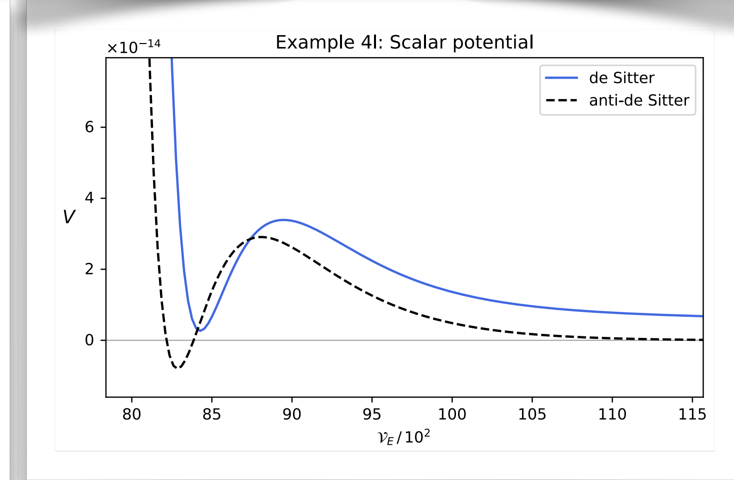


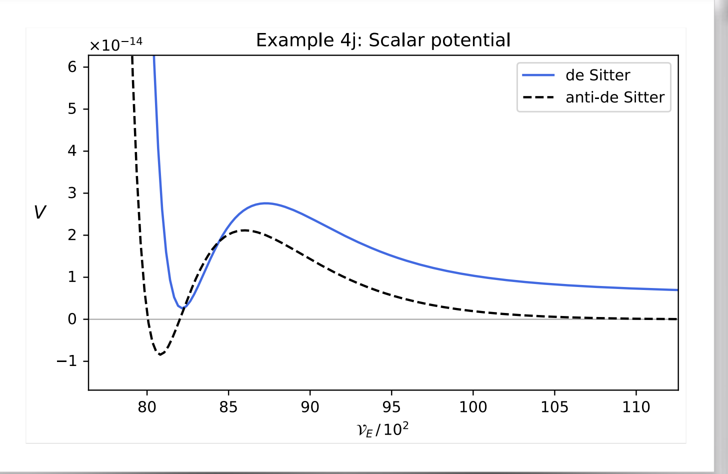


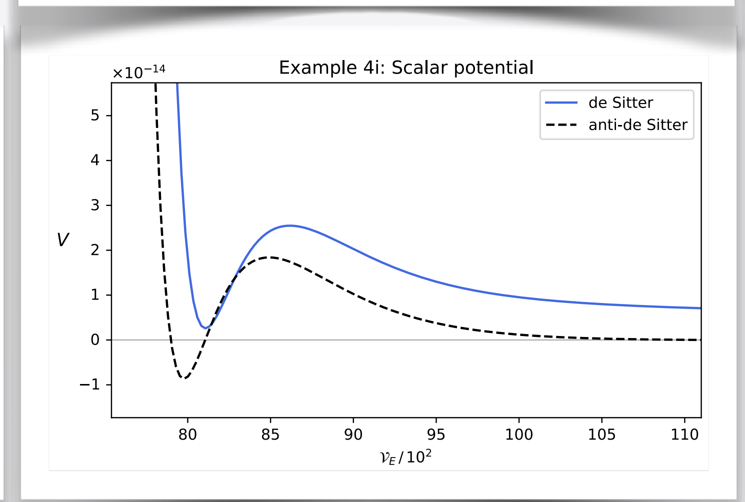


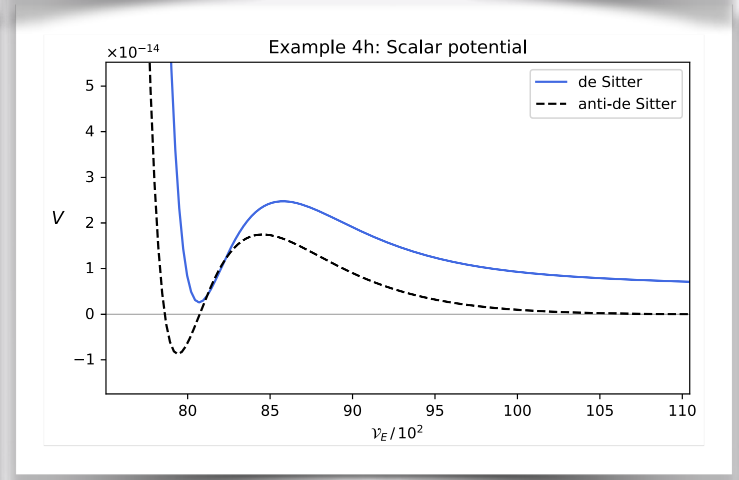


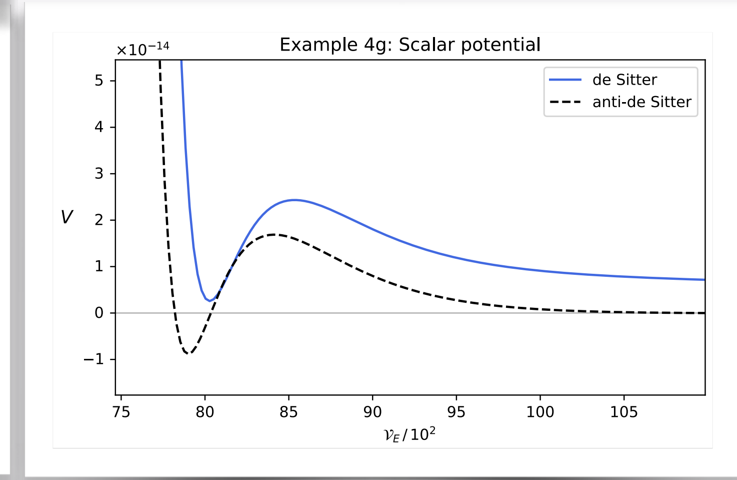


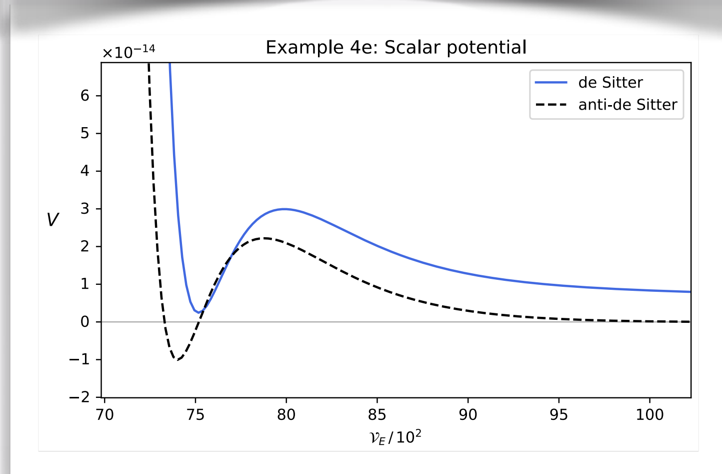


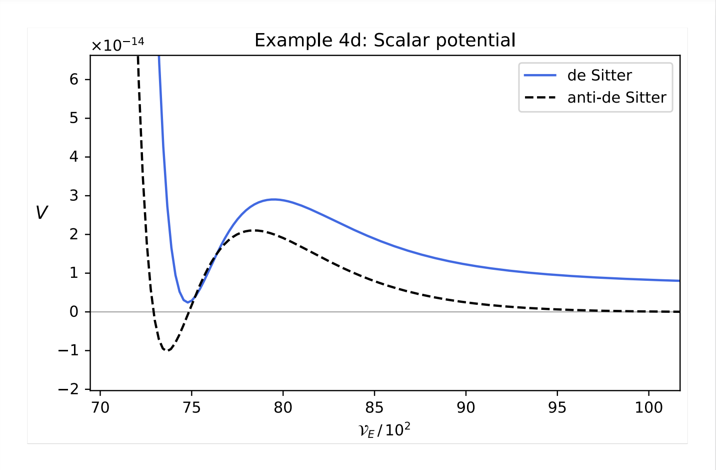


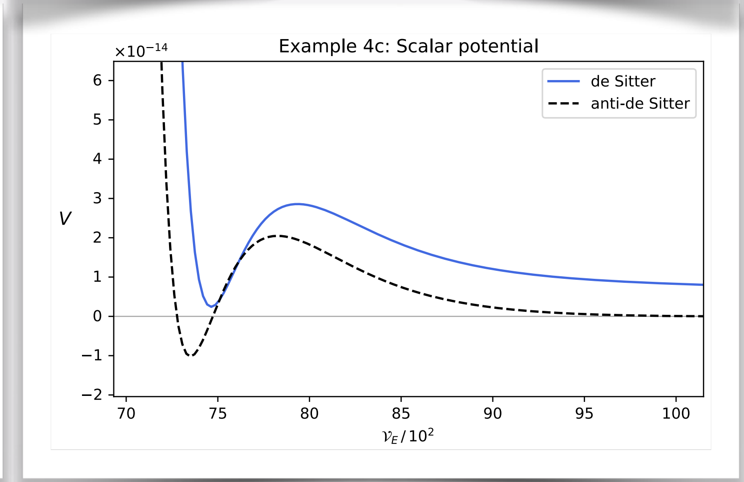


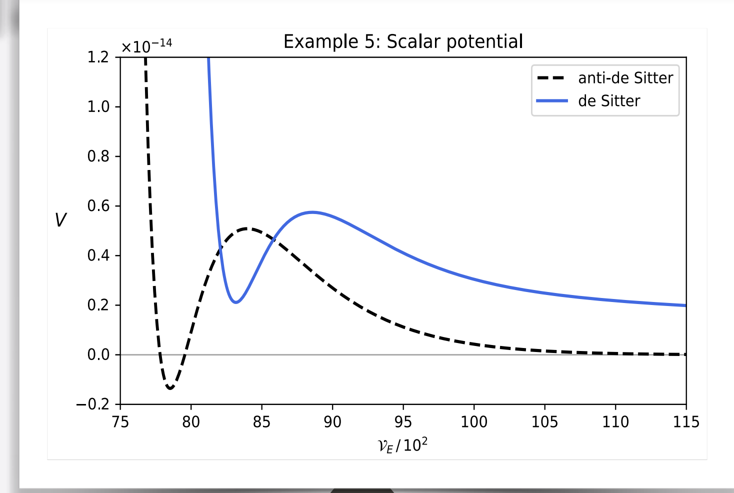


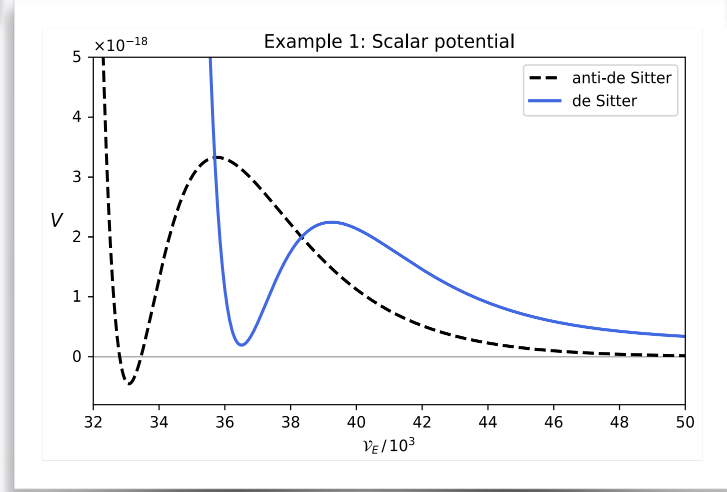




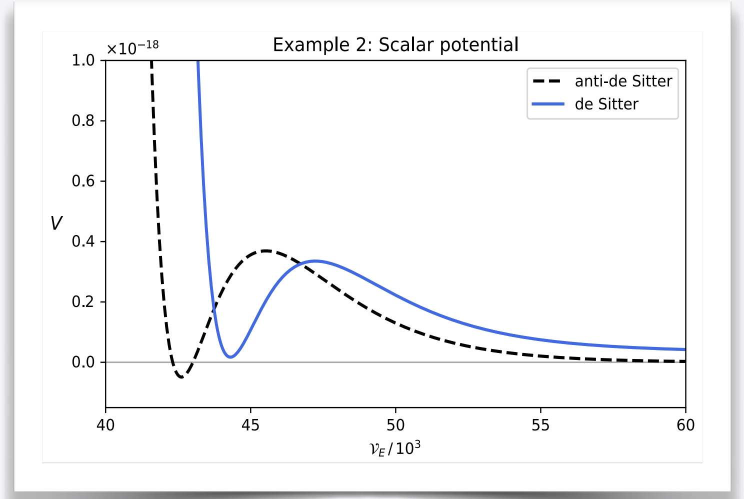






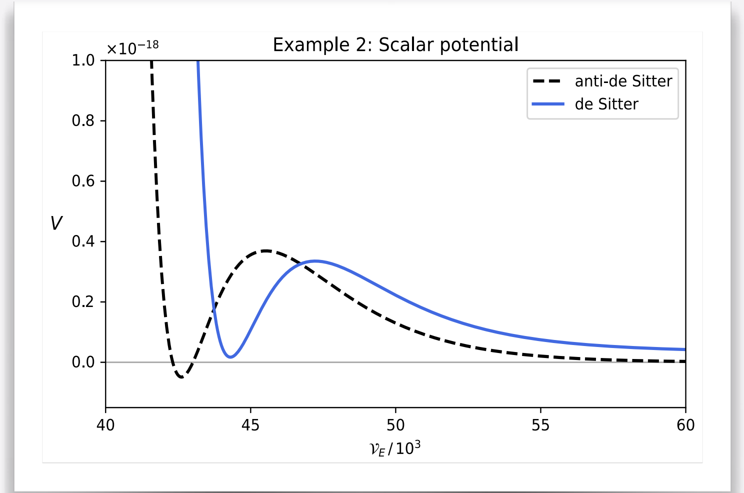


Explicit candidates of KKLT vacua



~~One~~ ~~five~~ **30 de Sitters** to rule them all

McAllister, Moritz, Nally, **AS**: 2406.13751



Explicit candidates of KKLT vacua

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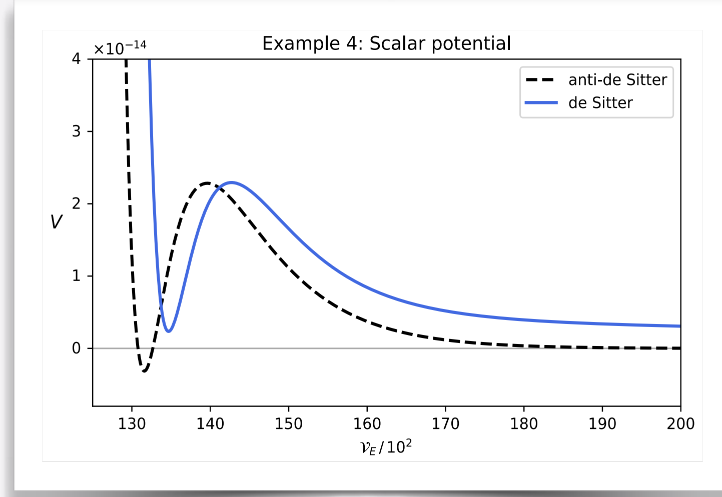
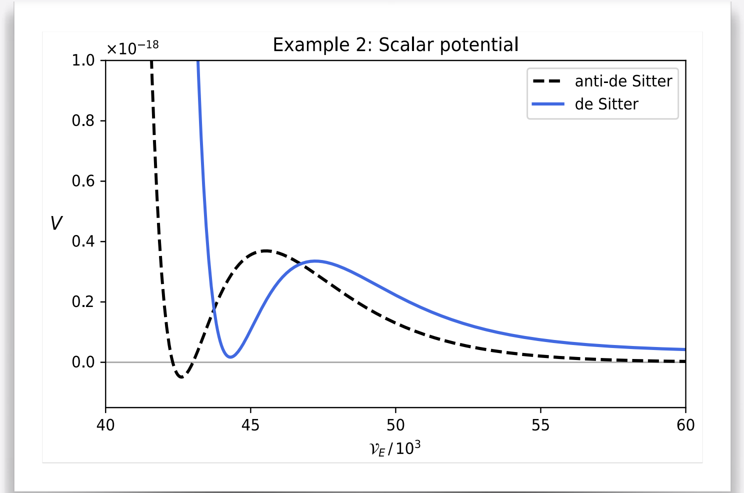
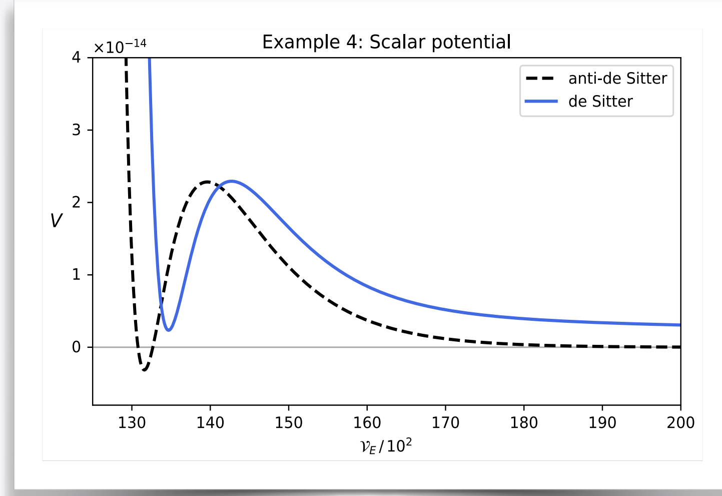


Explicit candidates of KKLT vacua





~~One~~ ~~five~~ **30 de Sitters** to rule them all

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Conclusions

Main takeaway:

First explicit candidate de Sitter solutions along the lines anticipated by Kachru, Kallosh, Linde and Trivedi in '03.

The control parameters in our solutions are currently the best we could do in 2024, but we barely scratched the surface of available compactifications in the KS database.

Open issues and future directions:

- dS vacua are probably most vulnerable to corrections to the anti-D3 brane,
- meta-stability of the uplift in the regime $g_s M \sim 1$ remains an important open problem!
- better understanding the structure of corrections (like string loop or warping corrections),
- perturbations of the throat (would require computing the CY-metric), and
- flux quantisation conditions for CY orientifolds (for toroidal orientifolds, some fluxes have to be even)

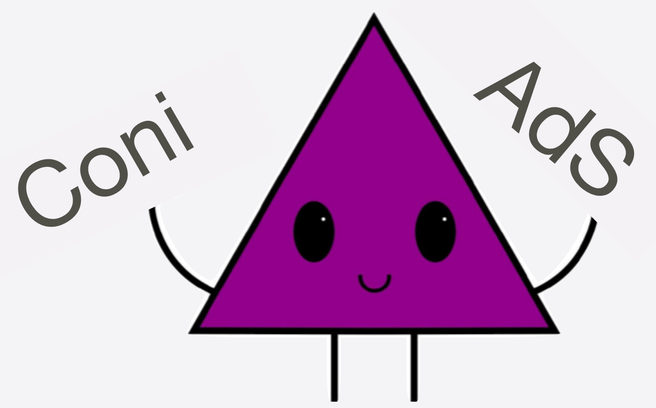
[Junghans 2201.03572]
[Hebecker, Schreyer, Venken 2208.02826]
[Schreyer, Venken 2212.07437]
[Schreyer 2402.13311]

[Frey, Polchinski hep-th/0201029]

In the future, some candidate vacua may survive as genuine de Sitter vacua of string theory.


Thank you!

Finding KKLT vacua in KS



A landscape of supersymmetric AdS vacua

McAllister, Moritz, Nally, AS: 2406.13751, *work in progress*

We found new supersymmetric AdS vacua with **Klebanov-Strassler throats**…

ID	$(h^{2,1}, h^{1,1})$	M	K'	N_{D3}	g_s	W_0	$g_s M$	$\lvert z_{cf}\rvert$	$-V_F$	Ξ
a	$(6, 160)$	8	$\frac{1}{15}$	2	$3 \cdot 10^{-3}$	$1.0 \cdot 10^{-35}$	0.021	$6.0 \cdot 10^{-6}$	$2.5 \cdot 10^{-90}$	10^{70}
b	$(7, 155)$	8	2	0	0.18	$7.4 \cdot 10^{-18}$	1.46	$2.1 \cdot 10^{-3}$	$5.1 \cdot 10^{-50}$	10^{34}
c	$(6, 160)$	2	10	0	0.015	$1.6 \cdot 10^{-27}$	0.30	$2.4 \cdot 10^{-47}$	$5.8 \cdot 10^{-72}$	0.06
d	$(6, 160)$	2	$\frac{33}{2}$	11	0.27	$3.2 \cdot 10^{-25}$	0.55	$1.3 \cdot 10^{-42}$	$2.3 \cdot 10^{-66}$	0.65
e	$(8, 150)$	14	4	0	0.075	0.032	1.05	$9.1 \cdot 10^{-7}$	$1.8 \cdot 10^{-17}$	3.38

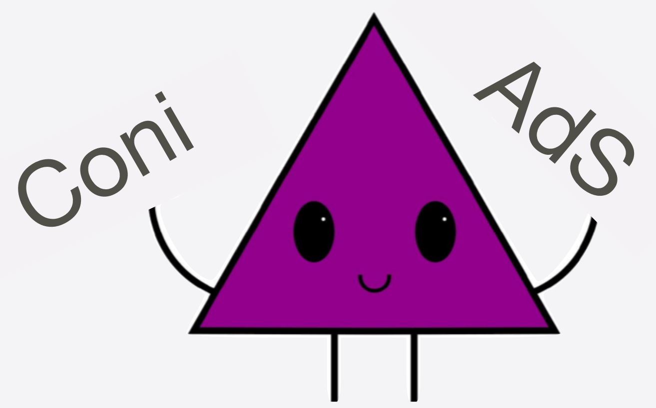
Can add brane-antibrane pair and achieve uplift to positive energy.

Interesting candidate for an explicit setting for the inflationary scenario of [KKLMMT: hep-th/0308055]

Finding KKLT vacua in KS

A landscape of supersymmetric AdS vacua

McAllister, Moritz, Nally, AS: 2406.13751, *work in progress*



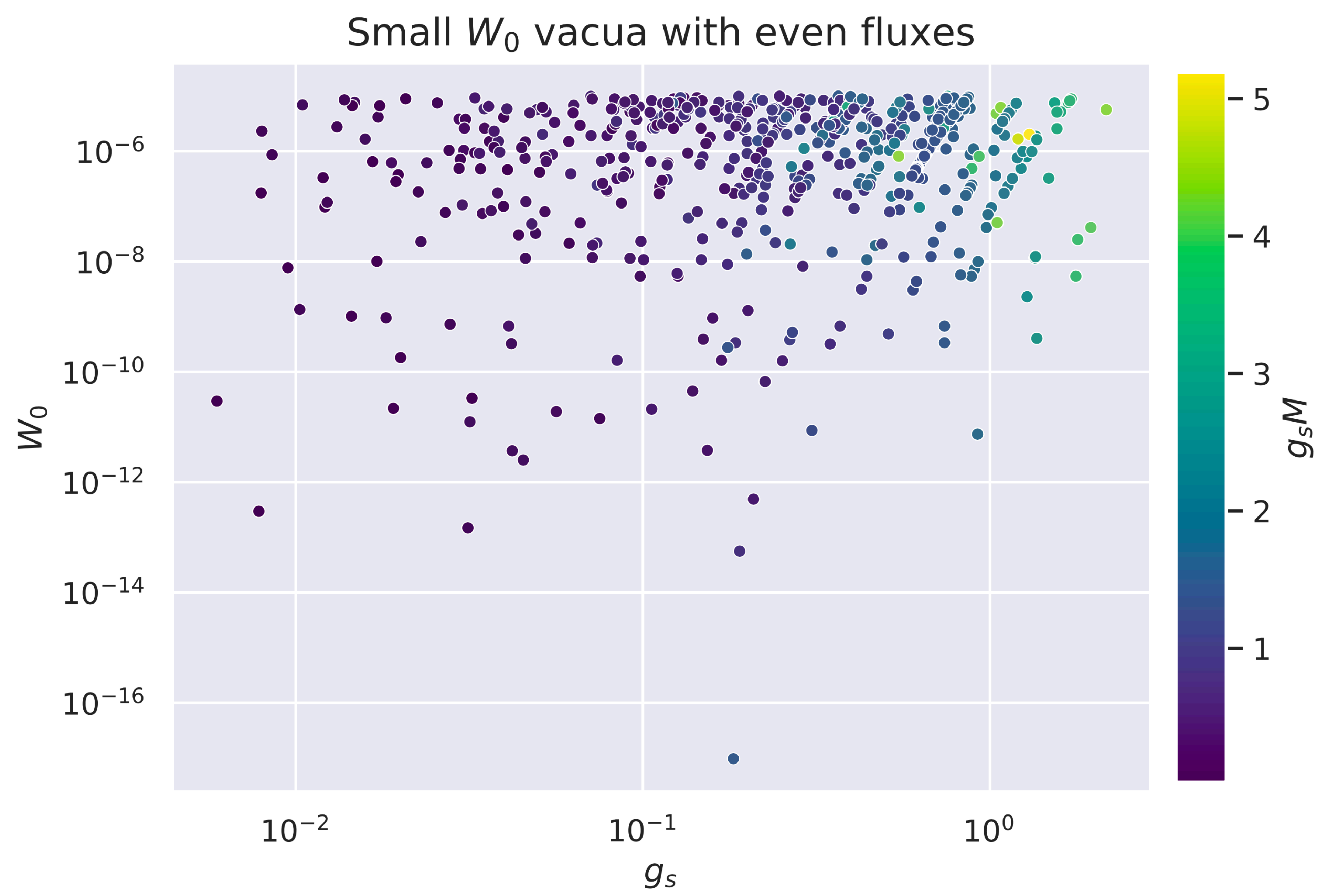
We found new supersymmetric AdS vacua with **Klebanov-Strassler throats**…

ID	$(h^{2,1}, h^{1,1})$	M	K'	N_{D3}	g_s	W_0	$g_s M$	$\|z_{cf}\|$	$-V_F$	Ξ
a	$(6, 160)$	8	$\frac{1}{15}$	2	$3 \cdot 10^{-3}$	$1.0 \cdot 10^{-35}$	0.021	$6.0 \cdot 10^{-6}$	$2.5 \cdot 10^{-90}$	10^{70}
b	$(7, 155)$	8	2	0	0.18	$7.4 \cdot 10^{-18}$	1.46	$2.1 \cdot 10^{-3}$	$5.1 \cdot 10^{-50}$	10^{34}
c	$(6, 160)$	2	10	0	0.015	$1.6 \cdot 10^{-27}$	0.30	$2.4 \cdot 10^{-47}$	$5.8 \cdot 10^{-72}$	0.06
d	$(6, 160)$	2	$\frac{33}{2}$	11	0.27	$3.2 \cdot 10^{-25}$	0.55	$1.3 \cdot 10^{-42}$	$2.3 \cdot 10^{-66}$	0.65
e	$(8, 150)$	14	4	0	0.075	0.032	1.05	$9.1 \cdot 10^{-7}$	$1.8 \cdot 10^{-17}$	3.38

… and in addition with **only even fluxes**.

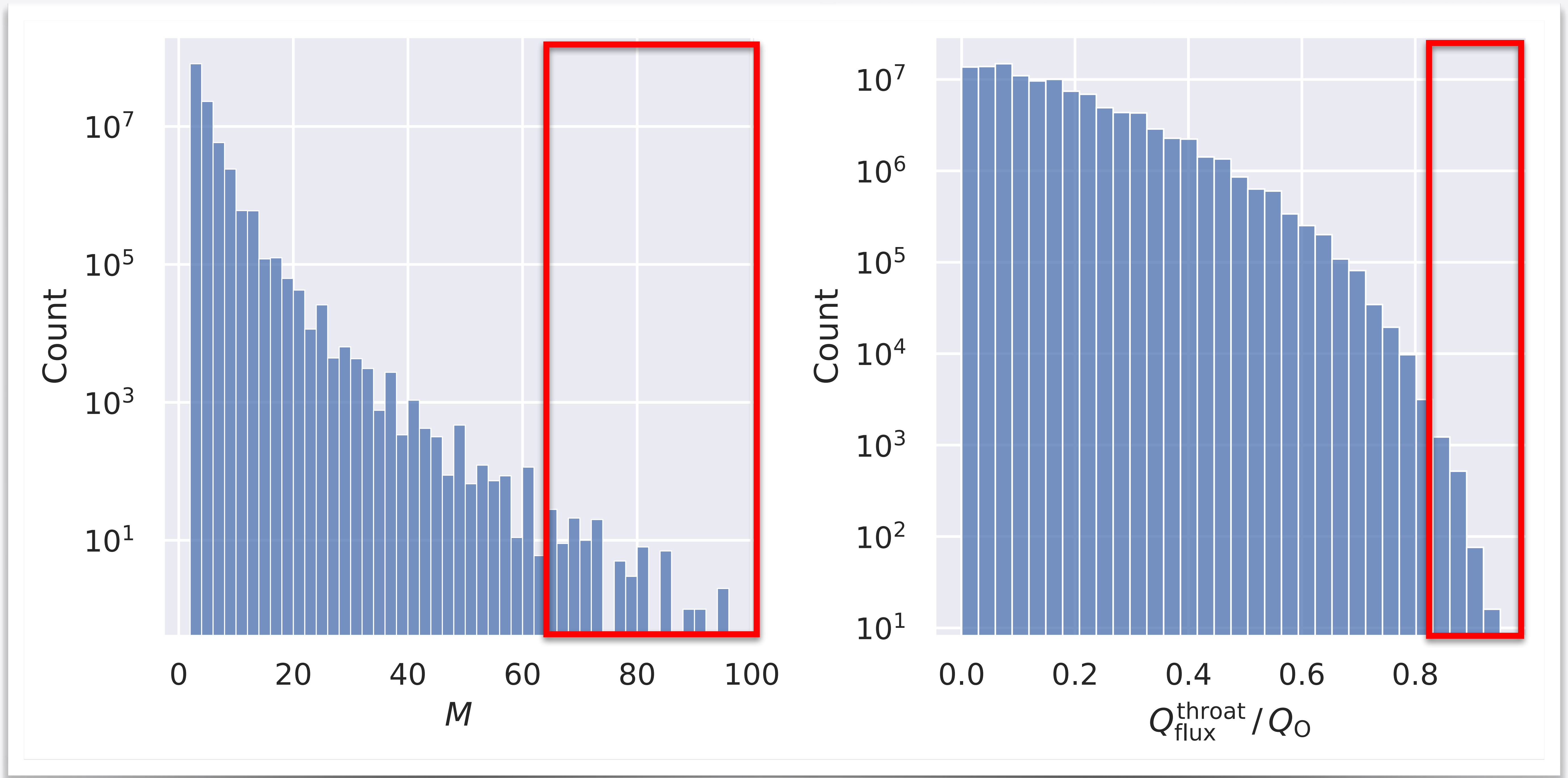
ID	$(h^{2,1}, h^{1,1})$	M	K'	N_{D3}	g_s	W_0	$g_s M$	$\|z_{cf}\|$	V_F	Ξ
f	$(7, 155)$	8	2	0	0.18	$9.7 \cdot 10^{-18}$	1.46	$2.1 \cdot 10^{-3}$	$-8.3 \cdot 10^{-50}$	10^{35}
g	$(8, 150)$	8	$\frac{54}{7}$	0	0.23	$2.3 \cdot 10^{-2}$	1.86	$3.1 \cdot 10^{-7}$	$-1.6 \cdot 10^{-16}$	0.28
h	$(6, 160)$	4	$\frac{7}{2}$	-2	0.056	$1.9 \cdot 10^{-11}$	0.23	$1.0 \cdot 10^{-22}$	$-2.2 \cdot 10^{-38}$	0.22

Requires two anti-D3 branes



Racetrack PFVs

McAllister, Moritz, Nally, AS: 2406.13751



We see that both $M \gg 1$ and KS throats containing almost the entire D3-brane charge of the compactification occur in our ensemble, but **both are exponentially rare**.

Finding KKLT vacua in KS

Engineering conifolds

[Demirtas, Kim, McAllister, Moritz: 2009.03312]

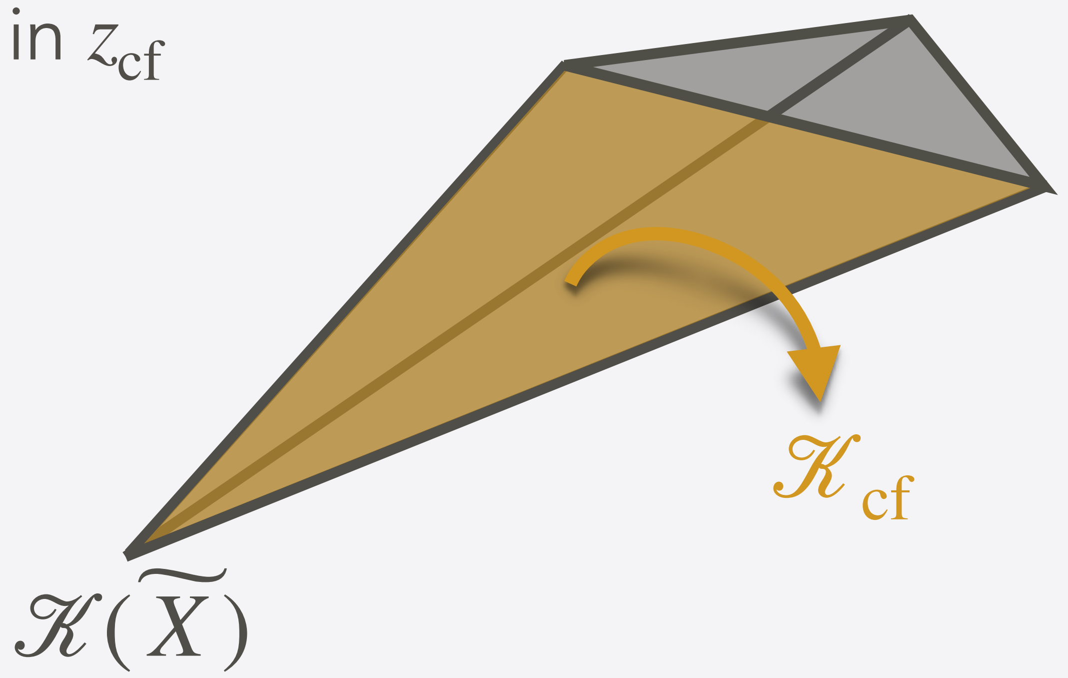
See also [Álvarez-García, Blumenhagen, Brinkmann, Schlechter: 2009.03325]

Conifold singularities in X arise when a set of n_{cf} three-cycles shrinks to zero volume.

In an LCS patch, they correspond to facets $\mathscr{K}_{\text{cf}}$ of the (complexified) Kähler cone $\mathscr{K}(\widetilde{X})$ where set of curves $\mathscr{C}_{\text{cf}}$ shrinks.

We write $z^a = (z_{\text{cf}}, z^\alpha)$, $\alpha = h^{2,1}(X) - 1$, and compute the superpotential systematically order by order in z_{cf}

$$W_{\text{flux}}(z^a, \tau) = W_{\text{poly}}(z^\alpha, \tau) + W_{\text{inst}}(z^\alpha, \tau) + z_{\text{cf}}\, W^{(1)}(z^\alpha, z_{\text{cf}}, \tau) + \mathscr{O}(z_{\text{zf}}^2)\,.$$



A warped Euclidean D3-brane

In our constructions, there **always** exists a toric divisor $D_{\text{cf}} = \{x_{\text{cf}} = 0\}$ that intersects the conifold.

An Euclidean D3-brane on D_{cf} will pass through a highly warped region of the KS throat exponentially suppressing the contribution to W_{np}, see e.g. [Baumann et al. hep-th/0607050].

Below, we therefore remove D_{cf} from the list of contributing divisors to W_{np}.