# From Strings to the Universe

## Bridging Geometry and Cosmology

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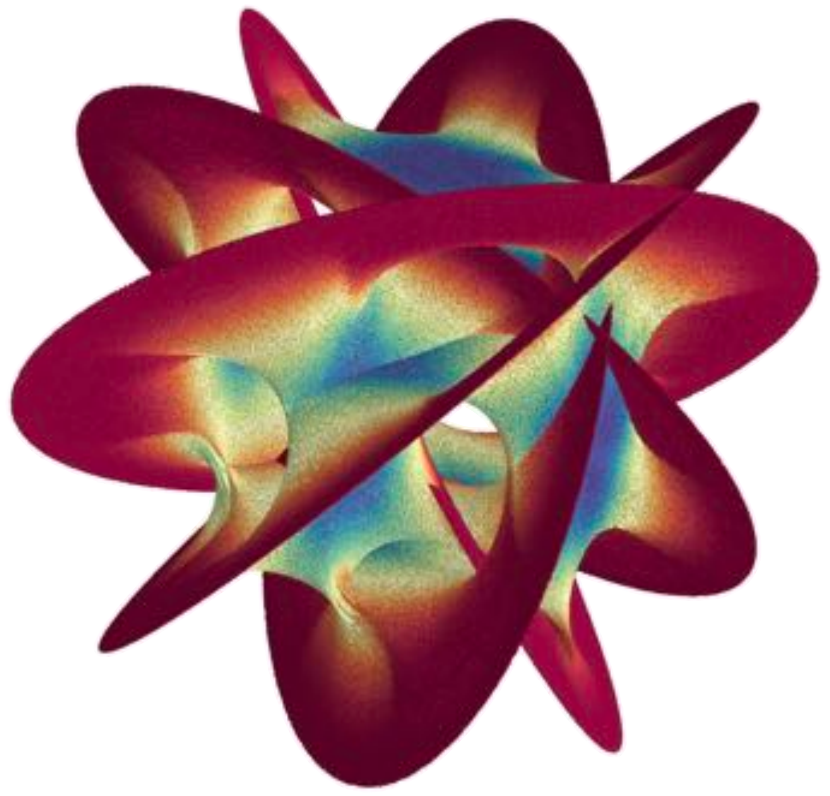
*HEP seminar, Toronto University*

March 30, 2026



based on:

- *2406.13751* with L. McAllister, J. Moritz, R. Nally
- *upcoming work* with N. MacFadden, L. McAllister, J. Moritz, R. Nally
- *upcoming work* with F. Compagnin, N. MacFadden, L. McAllister, J. Moritz, R. Nally


Federico Compagnin
*Cornell*


Nate MacFadden
*Cornell*


Liam McAllister
*Cornell*

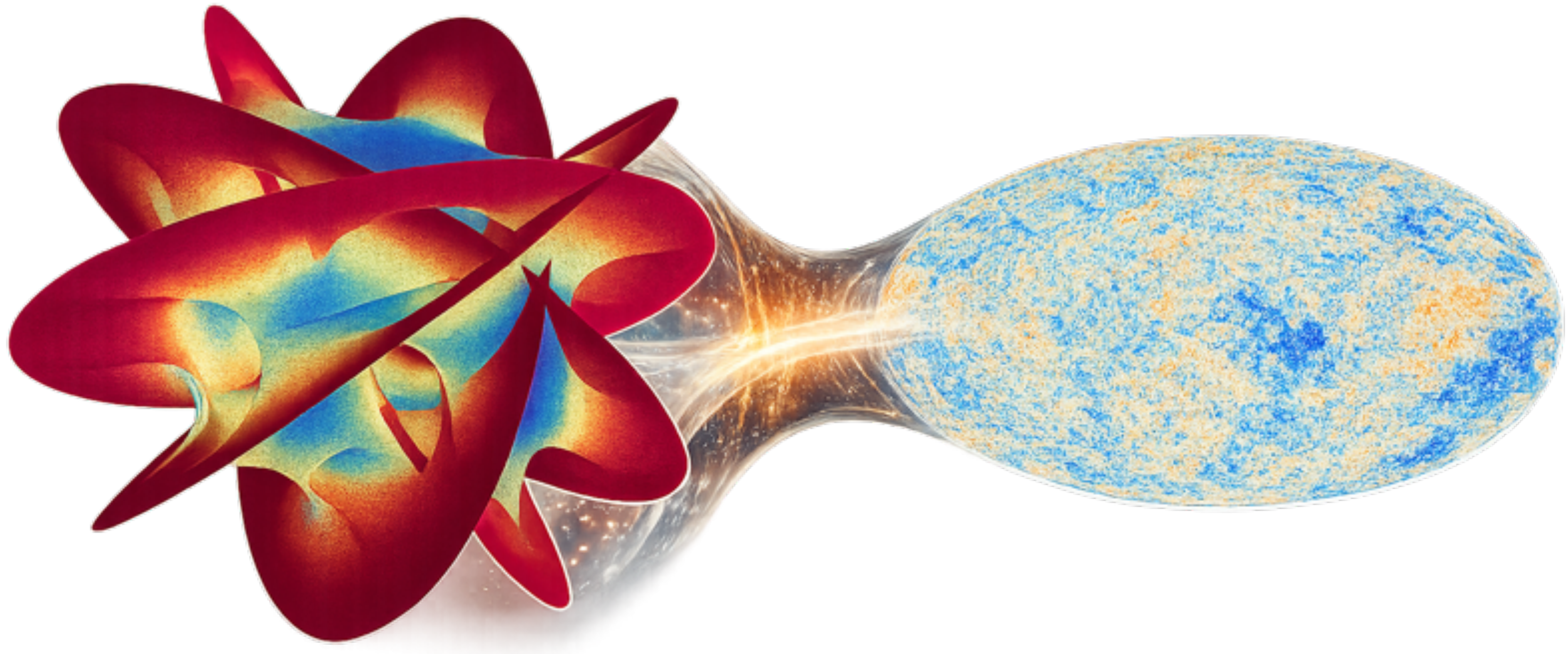

Jakob Moritz
*UW Madison*


Richard Nally
*MIT*

Also relevant: recent work with Abhishek Dubey, Mudit Jain, Sven Krippendorf, Doddy Marsh, Fernando Quevedo, Keir Rogers, Elijah Sheridan, ...

# Outline

1. Introduction: *Strings, the Universe, and all that*
2. The Vacuum Problem: *The Challenge of Stabilising Extra Dimensions*
3. Towards de Sitter solutions: *Ingredients for Candidate de Sitter Vacua*
4. Explicit Vacuum Constructions: *Computable Corners of the Landscape*
5. Outlook: *Limits, Lessons, and Next Steps*



# 1. Introduction: *Strings, the Universe, and all that*

Based on reviews:

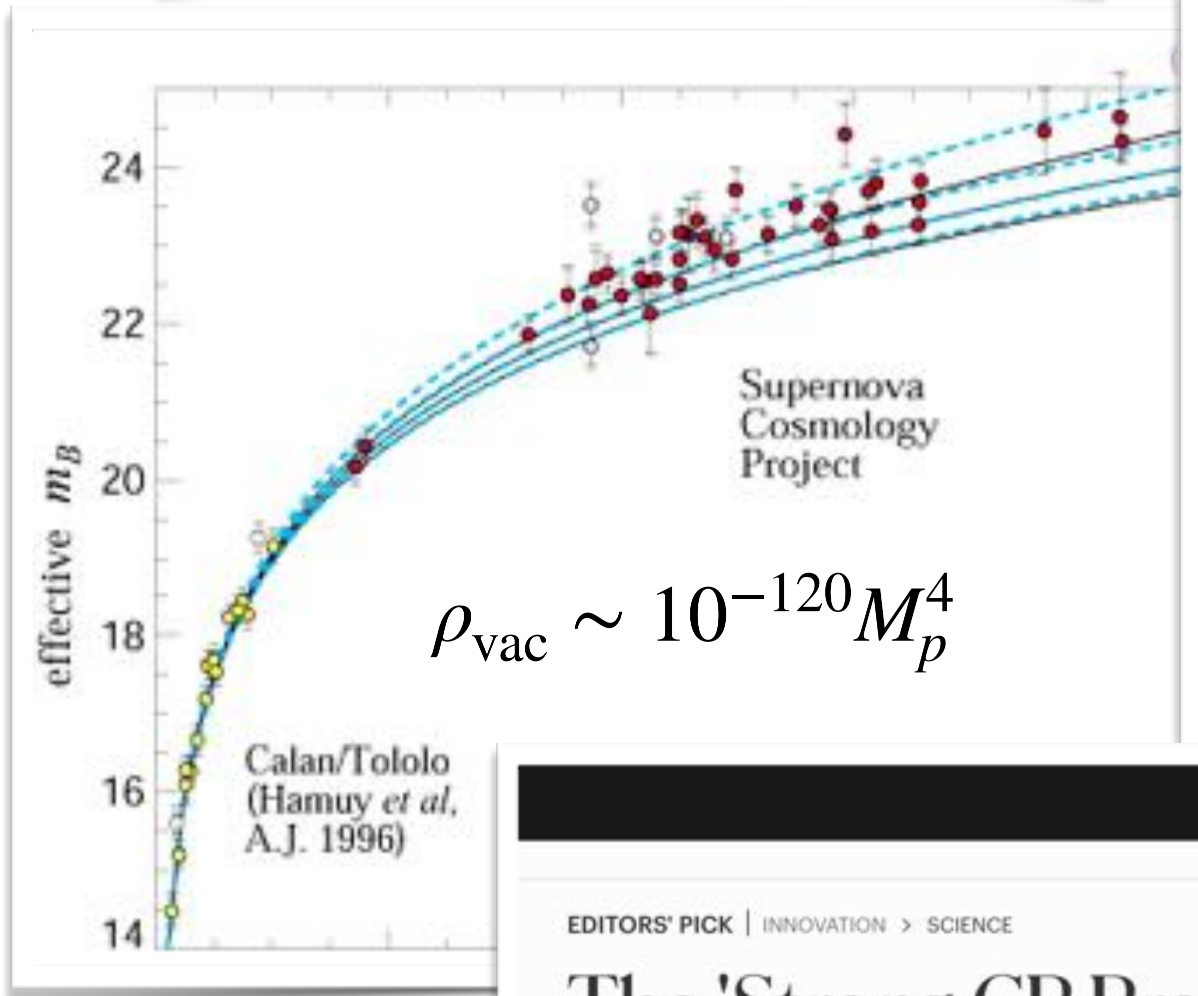
"*Flux Compactifications*" (hep-th/0610102) by M. Douglas, and S. Kachru

"*Inflation and String Theory*" (1404.2601) by D. Baumann, and L. McAllister

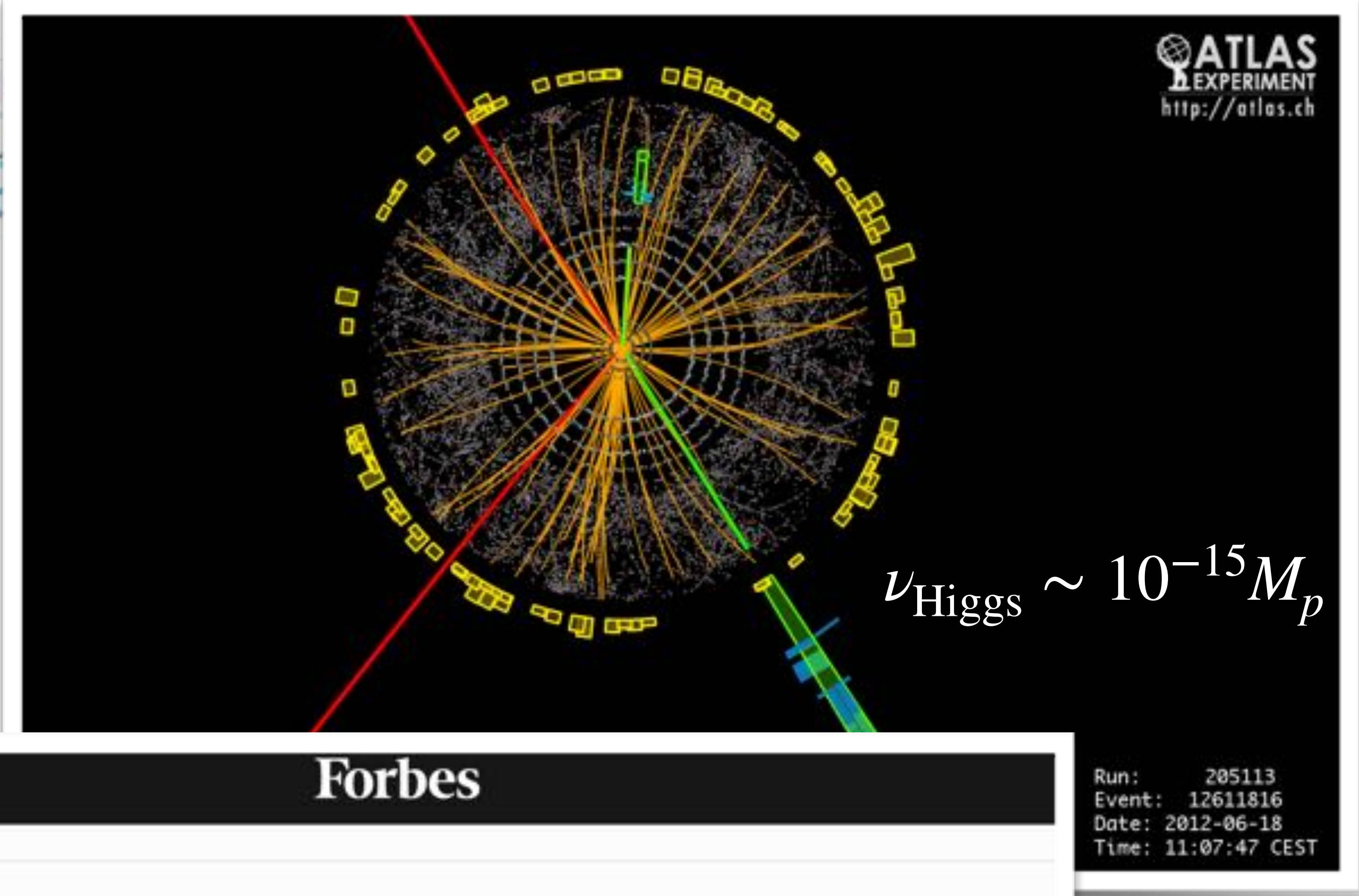
"*TASI 2025 Lectures on de Sitter vacua*" (2512.17095) by L. McAllister, and A. Schachner

# The Big Open Problems

## Hierarchy problems




$\rho_{\text{vac}} \sim 10^{-120} M_p^4$




$\nu_{\text{Higgs}} \sim 10^{-15} M_p$

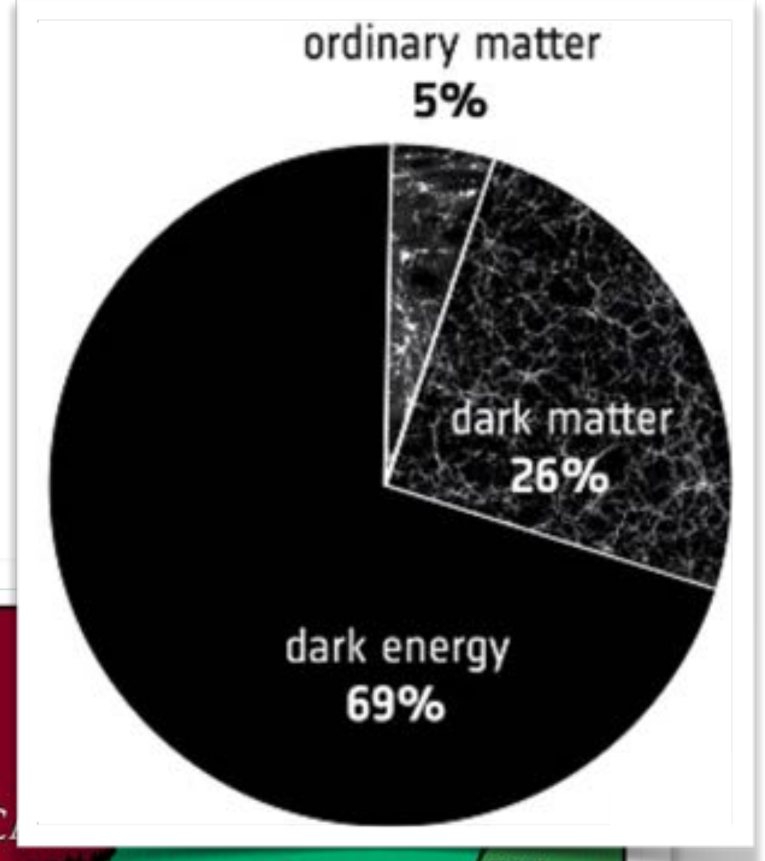

Forbes

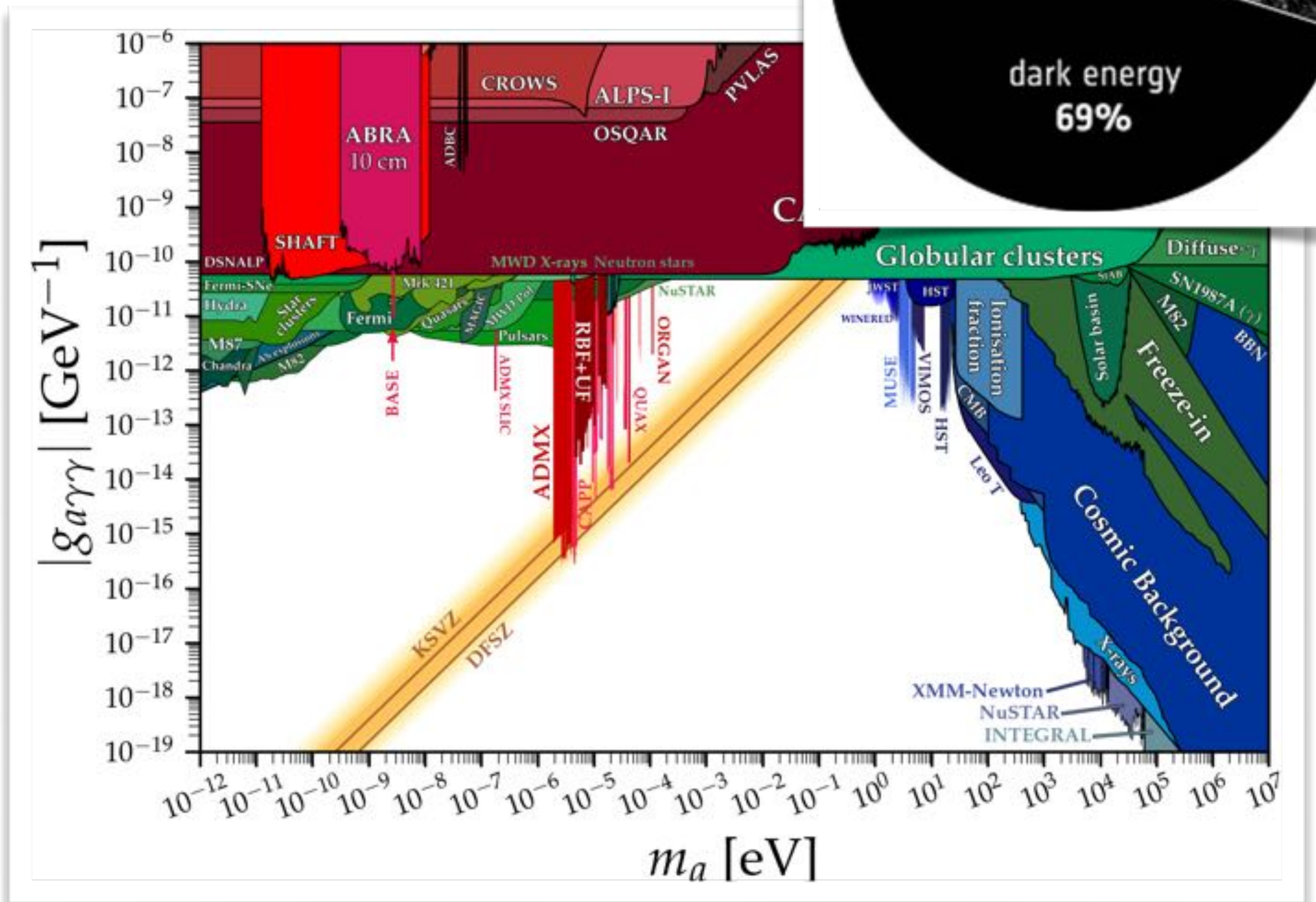
EDITORS' PICK | INNOVATION > SCIENCE

The 'Strong CP Problem' Is The Most Underrated Puzzle In All Of Physics

$\Theta_{\text{QCD}} \lesssim 10^{-10}$

## Nature of Dark Matter




https://github.com/cajohare/AxionLimits

Not obvious where to go from here from the "**bottom-up**":

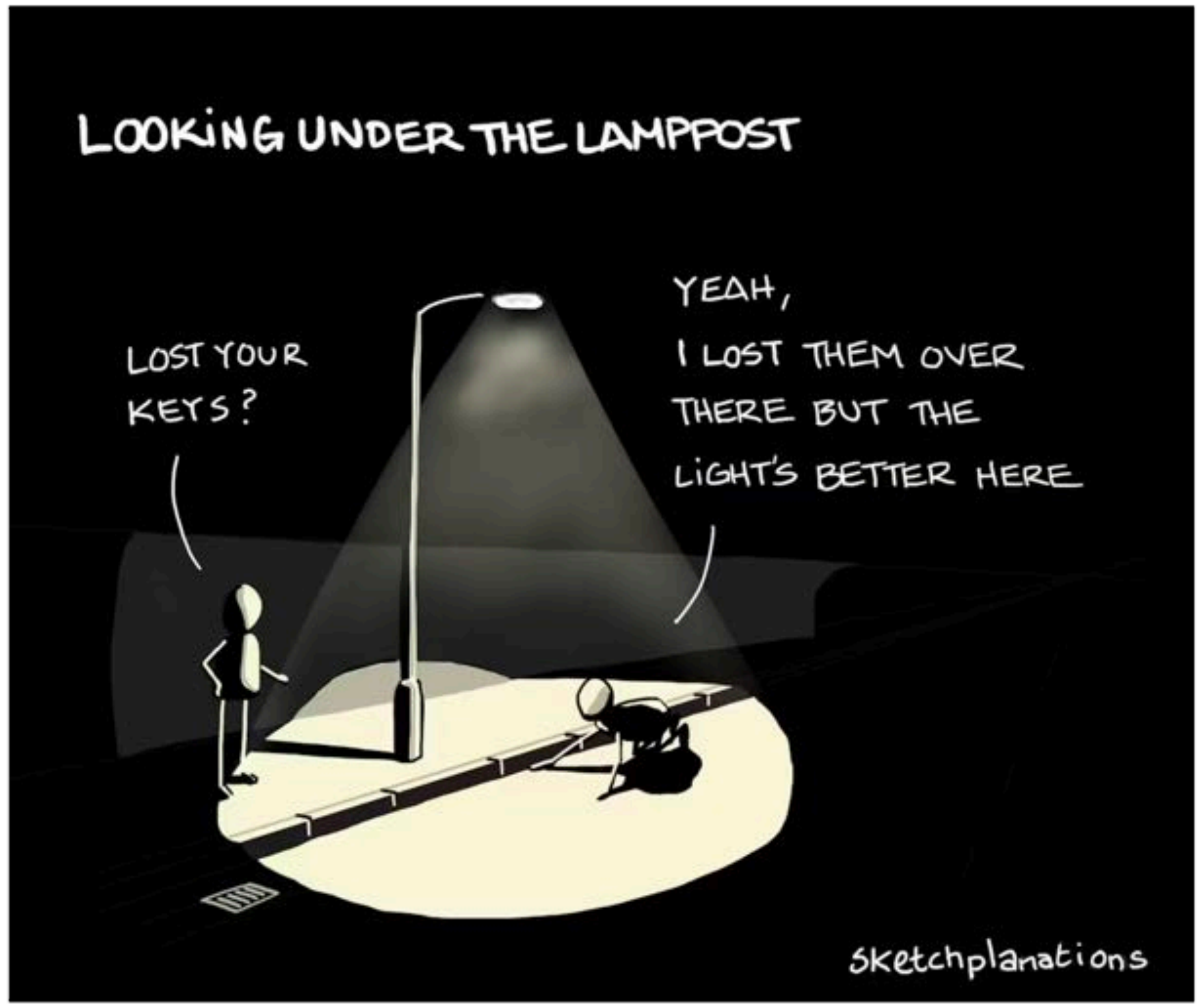
- SM is "**complete**": internally consistent up to very high energies
- Dark matter mass almost completely **unconstrained**
- Fine tuning issues in SM and ΛCDM (by definition) **UV-sensitive**

+ small Yukawas, neutrino masses, ...

Compelling (in principle-)alternative route:

- Start with **UV-complete quantum gravity** (like string theory)
- Work out its **predictions** (with statistical error bars)
- Compare with **experiment**!

Nobody knows how to do this presently!

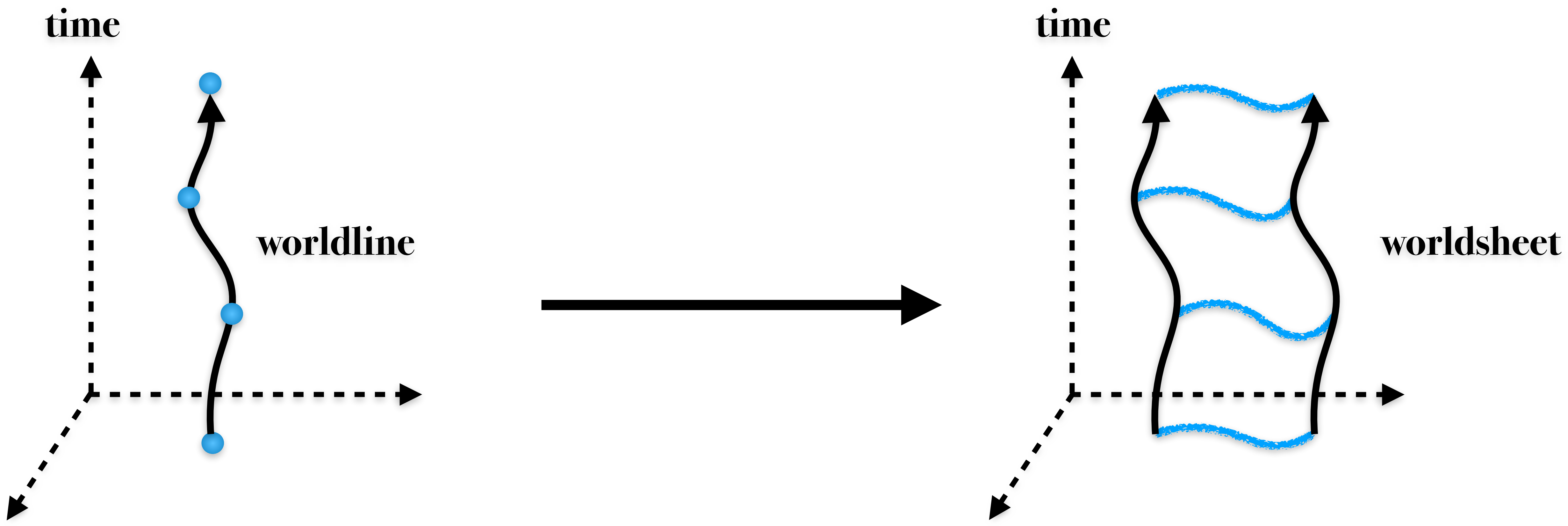



## The String Phenomenology Paradigm

Though our understanding of string theory is incomplete, we can **approximate** the "**quantum gravity prior**" for low energy observables by studying **weakly coupled corners** of string theory.

# String Theory in a Nutshell

**Basic idea:** replace particles by 1d strings…




**Three major consequences:**

i) string vibrations are particle species

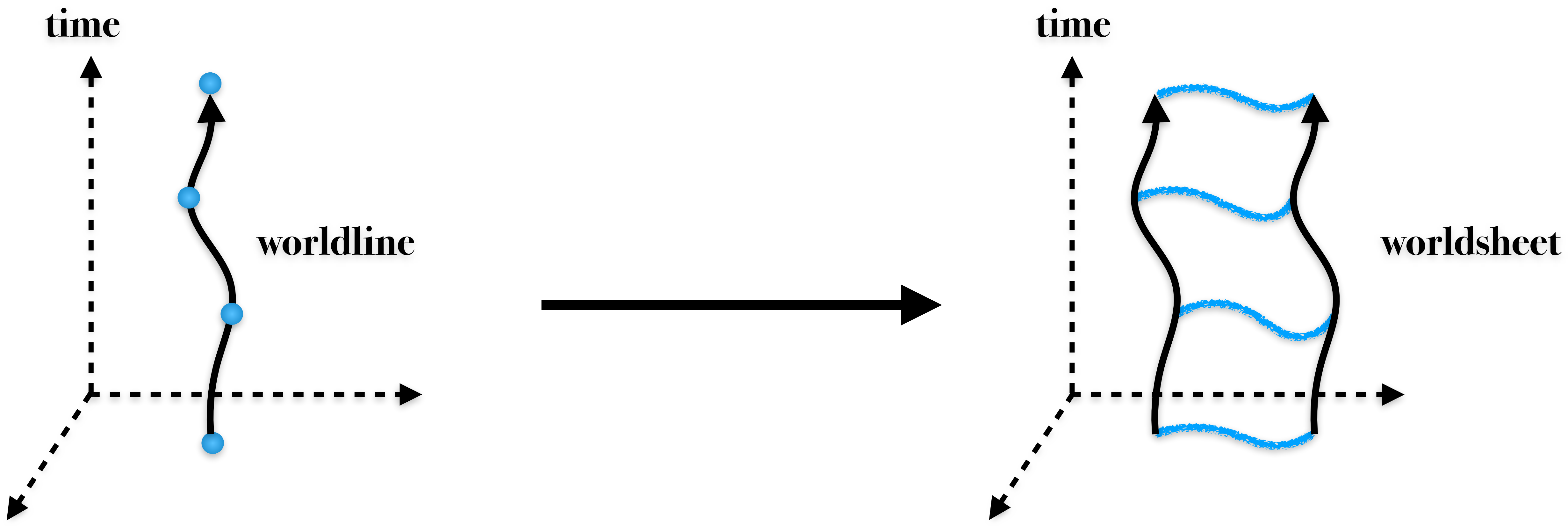
ii) interactions are non-local and universal

iii) no anomalies requires extra dimensions

3d space → 9d space

# String Theory in a Nutshell

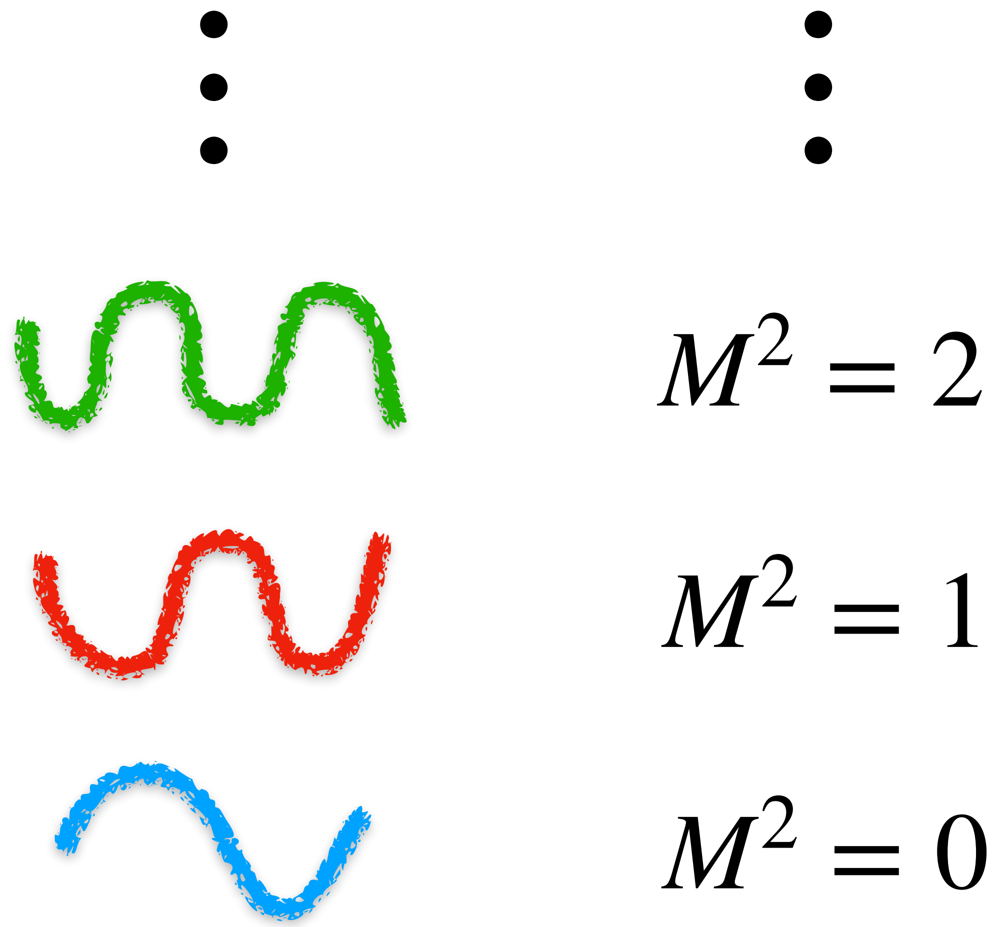
**Basic idea:** replace particles by 1d strings...



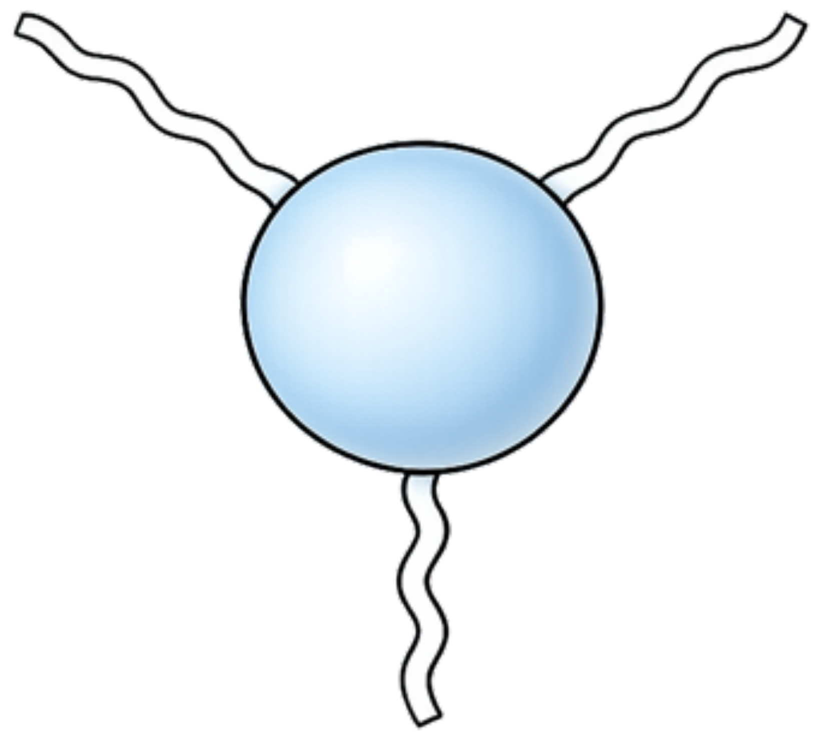

**Excitations** of string → **infinite tower of states** with increasing $M^2$

**At low energies** → restrict to **massless states**

metric : $g_{MN}$ scalar : $\phi$ $p$-forms : $C_p$ fermions



# String Theory at low energies



**Three-point string scattering** → leading-order 10D action for massless d.o.f.

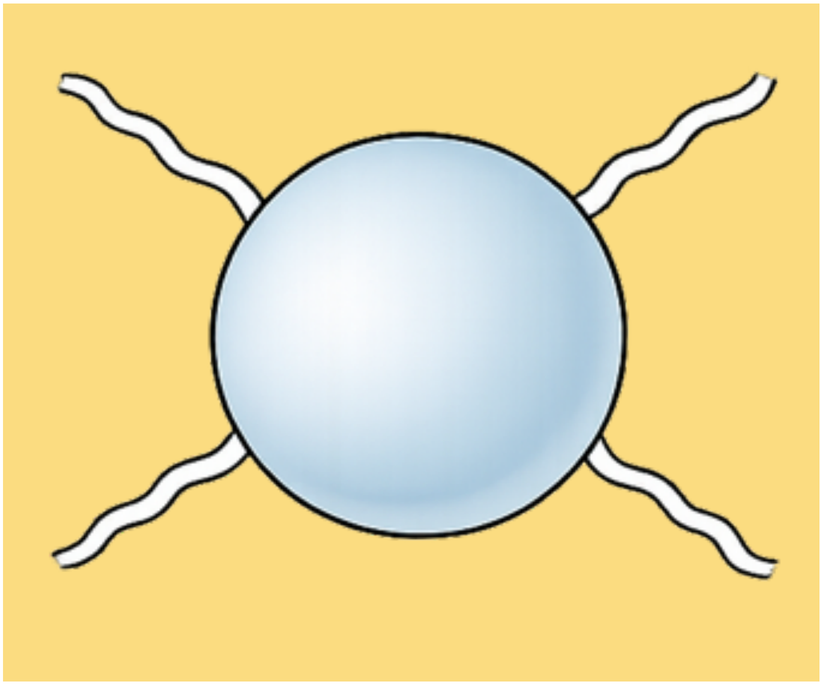
$$S^{(0)} = M_{10}^2 \int \left\{ e^{-2\phi}\left(R + 4(\partial\phi)^2\right) + \sum_p a_p \,|F_{p+1}|^2 + \dots \right\} \sqrt{|g|}\, d^{10}x$$

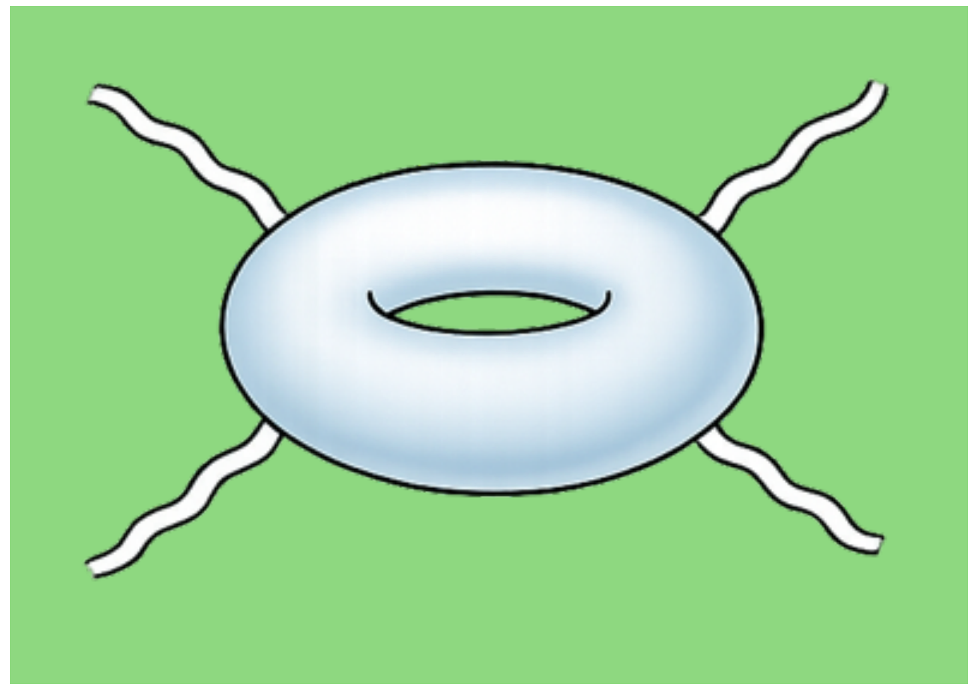
Higher-point scattering leads to further corrections to this action …

**Double** perturbative expansion:

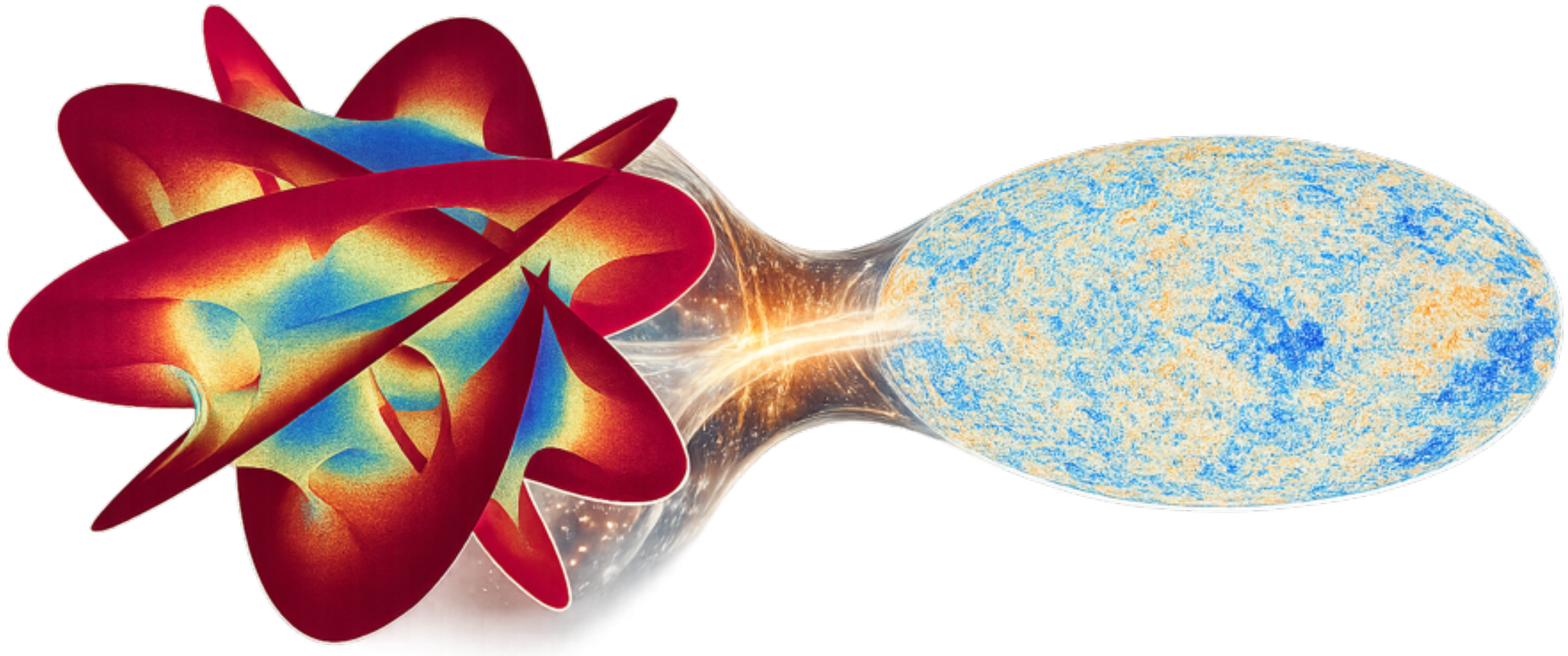
- **loop corrections** → string coupling $g_s = e^{\phi}$
- $\alpha'$ **corrections** → higher-derivative terms like $R^4$

Gross, Witten 1986; Gross, Sloan 1987; … ;
Green, Gutperle, Vanhove 1997; … ;
Liu, Minasian, Savelli, **AS** 2022, 2025;
Kim, **AS** *work in progress*





$$S^{(3)} = M_{10}^2 (\alpha')^3 \int \left\{ e^{-2\phi}\left([1 + e^{2\phi}]R^4 + \dots \right\} \sqrt{|g|}\, d^{10}x$$



To obtain **four-dimensional Universe** from string theory

→ **compactify** ten-dimensional theory on **6D compact space**

This is achieved through so-called **Kaluza-Klein reductions**

Kaluza 1921
Klein 1926

→ let us begin with simple toy example

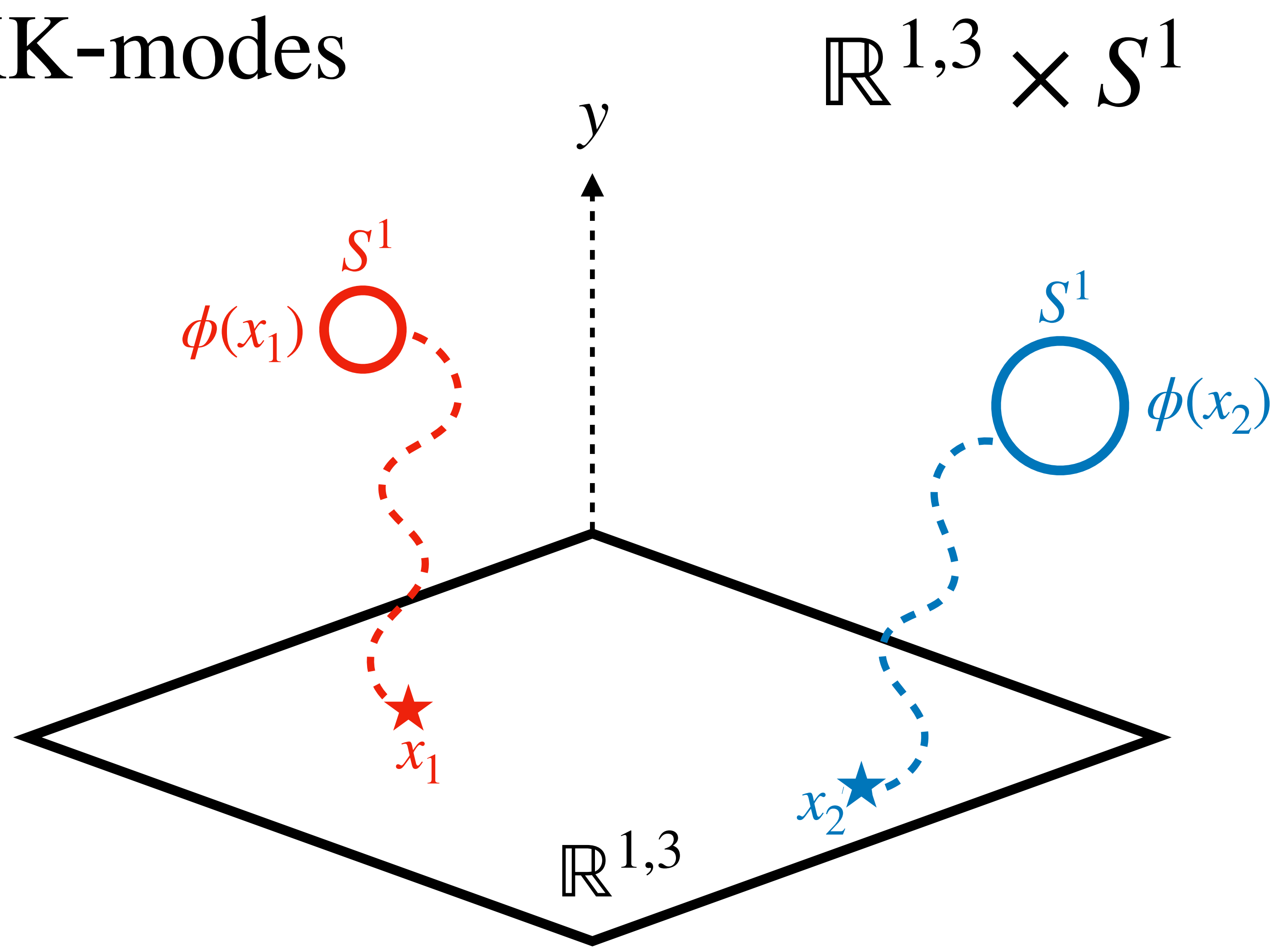
# Kaluza-Klein reductions

Toy model: **5-dimensional** gravity+U(1) gauge theory compactified **on a circle $S^1$**

$$S = \int \left(R^{(5)} - \frac{1}{2g^2} F_{MN}F^{MN}\right) \sqrt{-G}\, \mathrm{d}^5 x$$

Expand fields in **Fourier eigenmodes** $\sim \mathrm{e}^{2\pi \mathrm{i}\, ky}$ on $S^1$

$$G_{55}(x,y) = \phi(x) + \sum_{k>0} \varphi_k(x)\, \mathrm{e}^{2\pi \mathrm{i}\, ky} \qquad A_5(x,y) = a(x)\, \mathrm{d}\lambda(y) + \text{higher KK-modes}$$




**Higher Kaluza-Klein (KK) modes** like $\varphi_k$ are massive

$$(\Delta_4 + \partial_y^2 G_{55}) = 0 \quad \Longrightarrow \quad \Delta_4 \varphi_k = (2\pi k)^2\, \varphi_k \qquad \Delta_4 \phi(x) = 0$$

→ at low energies, only keep the **massless modes**

- $\phi(x)$ (called **modulus**) parametrises the size of **extra dimension** $\mathrm{Vol}(S^1) \sim \sqrt{\phi(x)}$
- **axion-like particle** $a(x)$ with **shift symmetry** $a(x) \to a(x) + c$ from 5d gauge symmetry $A \to A + \mathrm{d}\Lambda$

# Kaluza-Klein reductions

Reducing the action on $S^1$ to 4D leads to

$$\int R^{(5)}\sqrt{-G}\,\mathrm{d}^5x \quad \Longrightarrow \quad \int \left[R^{(4)} + \frac{(\partial\phi)^2}{6\phi^2}\right]\sqrt{-g}\,\mathrm{d}^4x + \ldots$$

Higher-dimensional gravity contains **deformation modes** of extra dimensions

$$\int F_{MN}F^{MN}\sqrt{-G}\,\mathrm{d}^5x \quad \Longrightarrow \quad \int \left(\phi F_{\mu\nu}F^{\mu\nu} + \frac{1}{\phi^2}(\partial a)^2\right)\sqrt{-g}\,\mathrm{d}^4x + \ldots$$

To all orders in perturbation theory: **massless axion with** $f \simeq 1/\phi$

Couplings in 4D are determined by field values of $\phi$

→ **"no free"** parameters

→ need **mechanism** to fix value of modulus $\phi$ (size of $S^1$)

**Moduli stabilisation:** generate potential for $\phi$ "fixing" modulus at a minimum.

**Aside**: potential from **non-perturbative instantons**

$$V(a,\phi) \simeq \sum_{k=1}^{\infty} c_k\,\mathrm{e}^{-k\phi}\,(1 - \cos(ka))$$

Naturally light at weak coupling $\phi \gg 1$

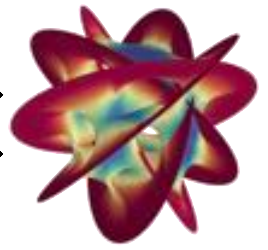
→ **excellent candidate for dark matter!**

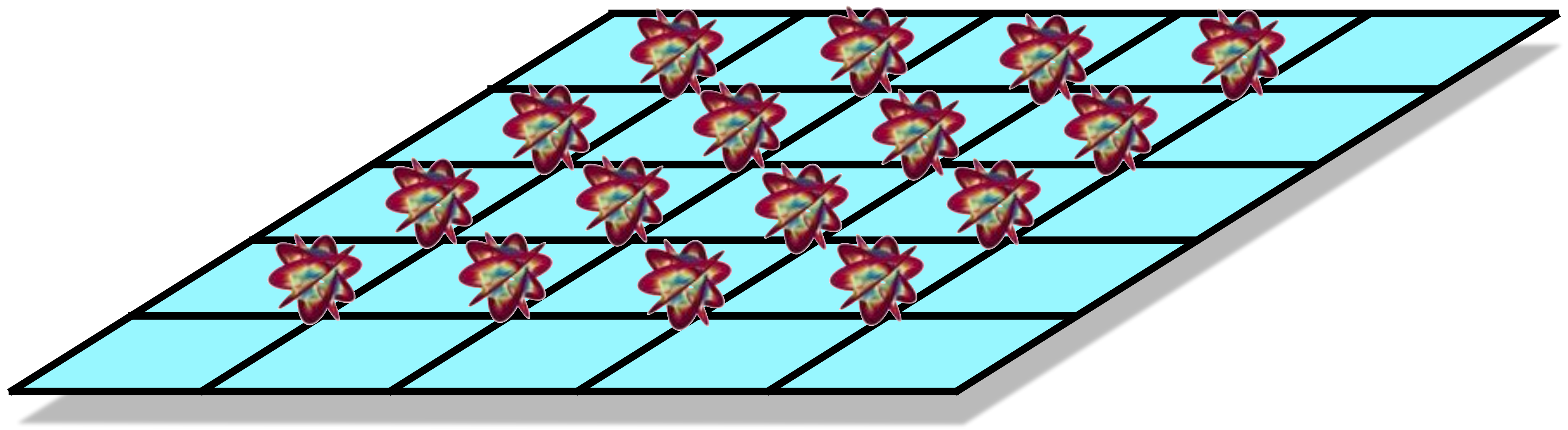
e.g. Svrcek, Witten '06

# String compactifications to four dimensions

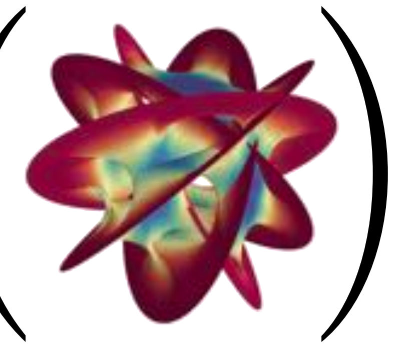
Choice of 6D compact manifold → **Calabi-Yau** (CY) manifolds $X$

Candelas, Horowitz, Strominger, Witten 1985

$$M_{1,9} = (\mathrm{AdS}_4, \mathbb{R}^{1,3}, \mathrm{dS}_4) \times$$ 



There exists **Ricci-flat metric** on $X$

$$R_{\alpha\bar{\beta}}\Big($$  $$\Big) = 0$$

Calabi 1954, Yau 1978

**Alternatives:** break SUSY at

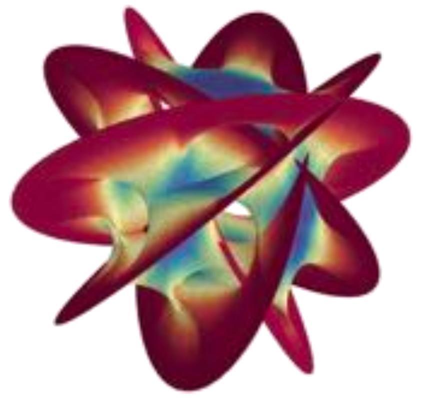
A. the compactification scale e.g. de Luca, Silverstein, Torroba '21

B. the string scale: e.g. Dixon, Harvey '86, Ginsparg, Vafa '87, … , Raucci, Tomasiello '25

# Deformations of CY metrics

Given a CY metric $g$, what are the deformations $\delta g$ that preserve $R_{\alpha\bar{\beta}}(g + \delta g) = 0$?

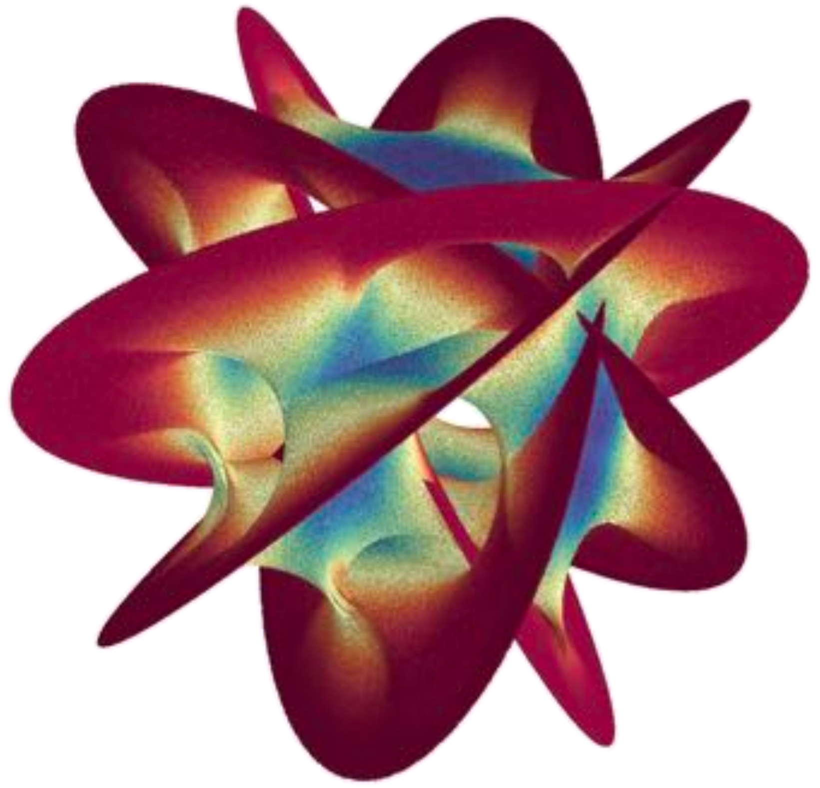
Two* types of deformations



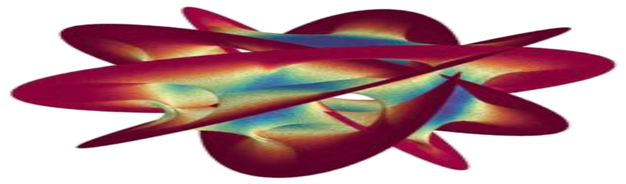
$\delta g$ changes **size**

$\delta g$ changes **shape**

* There are usually many representatives for each type, see later!



Kähler modulus $T$



complex structure modulus $z$

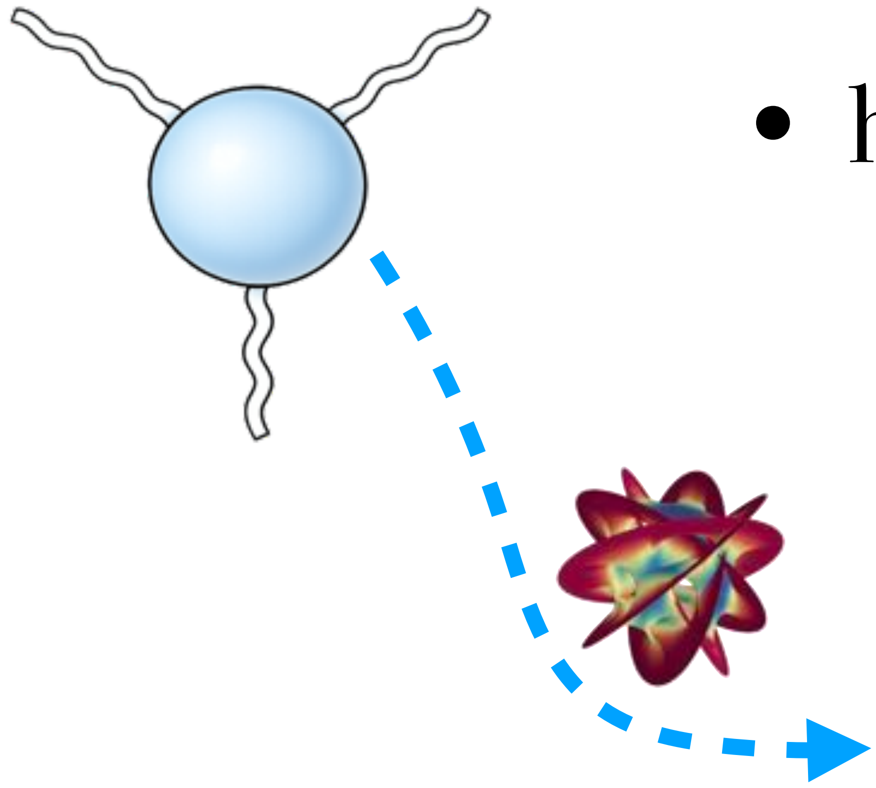
Moduli of a CY are **4D fields**!

# The 4D EFT

The resulting 4D EFT corresponds to $\mathcal{N}=1$ * supergravity in terms of

- complex scalars $\Phi^I \in \{T, z, \ldots\}$
- real Kähler potential $K(\Phi^I, \overline{\Phi}^{\bar{I}})$
- holomorphic superpotential $W(\Phi^I)$

* strictly speaking, reduction on CY leads to $\mathcal{N}=2$, but we will break it to $\mathcal{N}=1$ later



For the purposes of this talk, the relevant terms in the action are

$$S = M_4^2 \int \mathrm{d}^4x \sqrt{-g}\left(\frac{1}{2}R^{(4)} - K_{I\bar{J}}(\partial_\mu \Phi^I)(\partial^\mu \overline{\Phi}^{\bar{J}}) - M_4^2\, V_F(\Phi^I, \overline{\Phi}^{\bar{I}}) + \ldots\right)$$

| F-term scalar potential | F-terms | Kähler metric |
|---|---|---|
| $V_F = \mathrm{e}^K\left(K^{I\bar{J}} D_I W D_{\bar{J}} \overline{W} - 3\,|W|^2\right)$ , | $D_I W = \partial_I W + (\partial_I K) W$ , | $K_{I\bar{J}} = \partial_{\Phi^I} \partial_{\bar{\Phi}^{\bar{J}}} K$ |

# 2. The Vacuum Problem:

## *The Challenge of Stabilising Extra Dimensions*

The 4D EFT contains additional light fields – the **moduli** of $X$ – which

- are massless at leading order,
- affect cosmological evolution, and
- can mediate fifth forces, which are tightly constrained experimentally.

# Vacua in String Theory

A **tachyon-free, isolated, 4d string vacuum** is a solution of the equations of motion such that

- $m^2 > 0$ for all spin-less fields
- 3 spatial dimensions are large

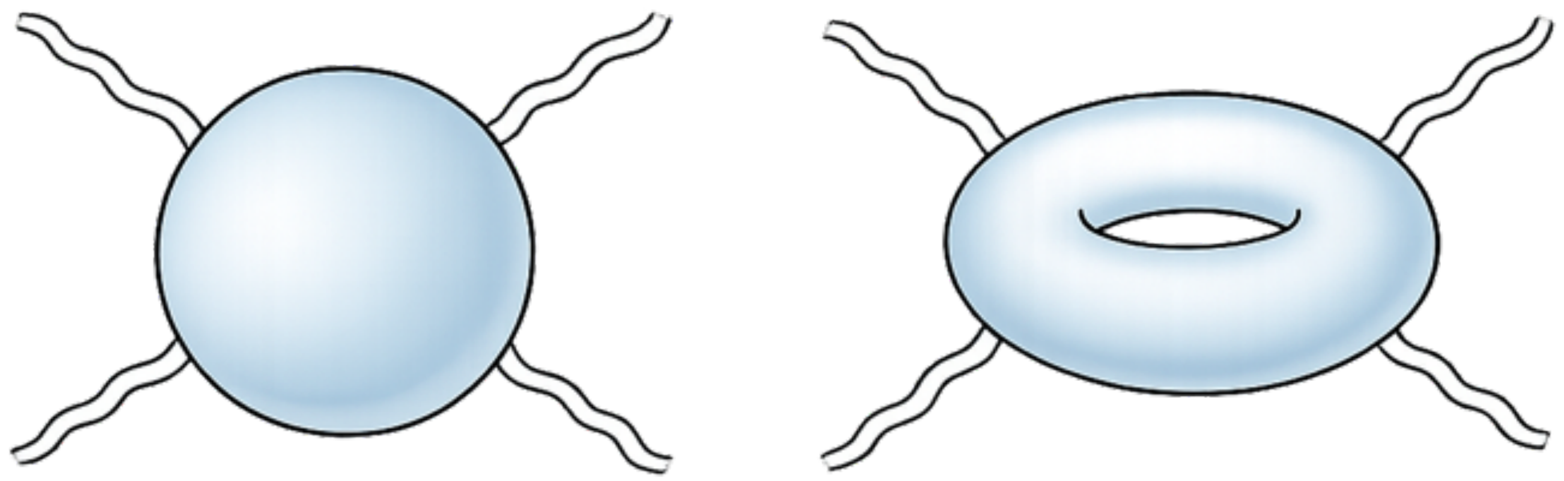
Not to be confused with vacuum solutions $R_{\mu\nu} = 0$ to Einstein's equations!

A string vacuum generally includes **sources of stress-energy** $R_{\mu\nu} \neq 0$, see later!

Usually no worldsheet description* for such solutions, so instead

→ Compute 10D EFT order by order in the **$\alpha'$ and $g_s$ expansion**

→ Seek solution to EOM at **weak coupling** (weakly-curved $X$ at $g_s \ll 1$)



* recent progress in finding worldsheet descriptions of string vacua from string field theory: Cho, Kim 2311.04959

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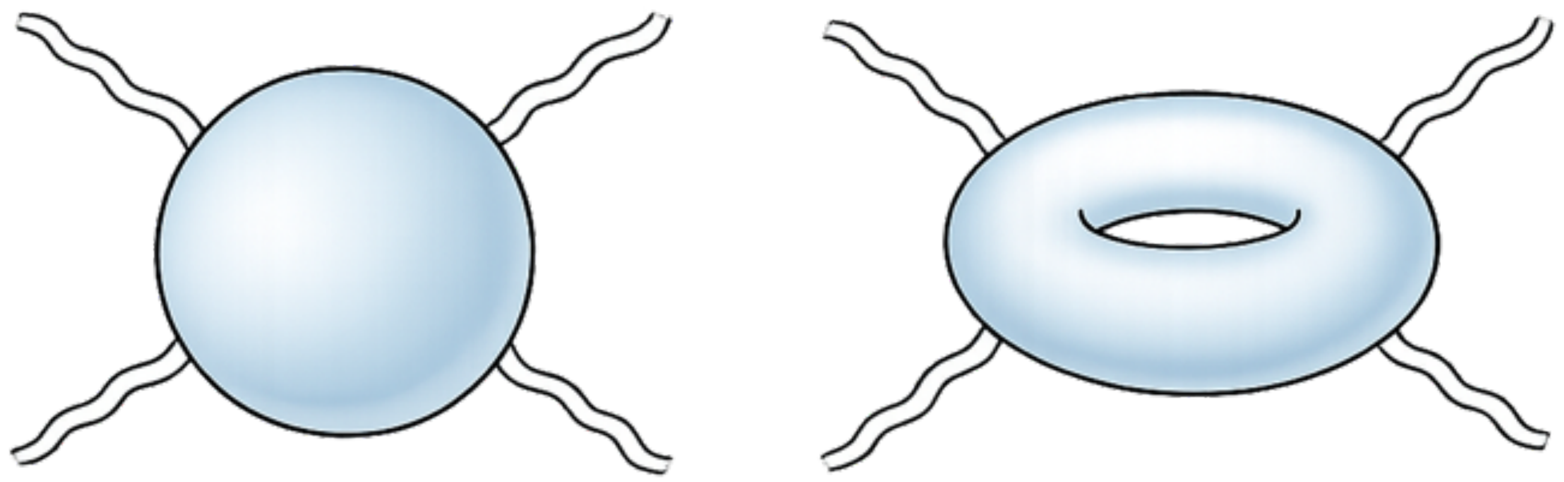


The **solutions to the 10D EOMs** correspond to **critical points of a scalar potential** in the 4D EFT!

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

# Systematics of string corrections

2512.17095 McAllister, **AS**

The supersymmetric 4D EFT receives corrections in $g_s$ and $\alpha'$

$$W(\Phi^A) = \sum_{m,n} g_s^m (\alpha')^n W_{m,n}(\Phi^A) \qquad K(\Phi^A, \bar{\Phi}^{\bar{A}}) = \sum_{m,n} g_s^m (\alpha')^n K_{m,n}(\Phi^A, \bar{\Phi}^{\bar{A}})$$

$W$ protected by **non-renormalisation theorem:**

$$W_{m,n}(\Phi^A) = 0 \quad m, n > 0$$

e.g. Burgess, Escoda, Quevedo hep-th/0510213

$K$ receives corrections at **all orders** in perturbation theory

$$K = K_{\text{tree}} + \delta K^{\mathcal{N}=2}_{\text{sphere}} + \delta K^{\mathcal{N}=2}_{(g_s)} + \delta K^{\mathcal{N}=1}_{\text{sphere}} + \delta K^{\mathcal{N}=1}_{(g_s)}$$

We compute $K$ at "leading-order" incorporating all "known" effects

$$K_{\text{l.o.}} = -2 \log \left[ \frac{1}{6} \kappa_{ijk} t^i t^j t^k - \frac{\zeta(3)\chi(X)}{4(2\pi)^3} + \frac{1}{2(2\pi)^3} \sum_{\mathbf{q} \in \mathcal{M}(X)} \mathcal{N}_{\mathbf{q}} \left( \mathrm{Li}_3\left( (-1)^{\gamma \cdot \mathbf{q}} e^{-2\pi \mathbf{q} \cdot \mathbf{t}} \right) + \ldots \right) \right]$$

[Becker et al. hep-th/0204254, Robles-Llana et al. hep-th/0612027, 0707.0838, Grimm 0705.3253]

$$\int R^4 \, \mathrm{d}^{10}x \supset \int \chi(X) \, R \, \mathrm{d}^4 x$$

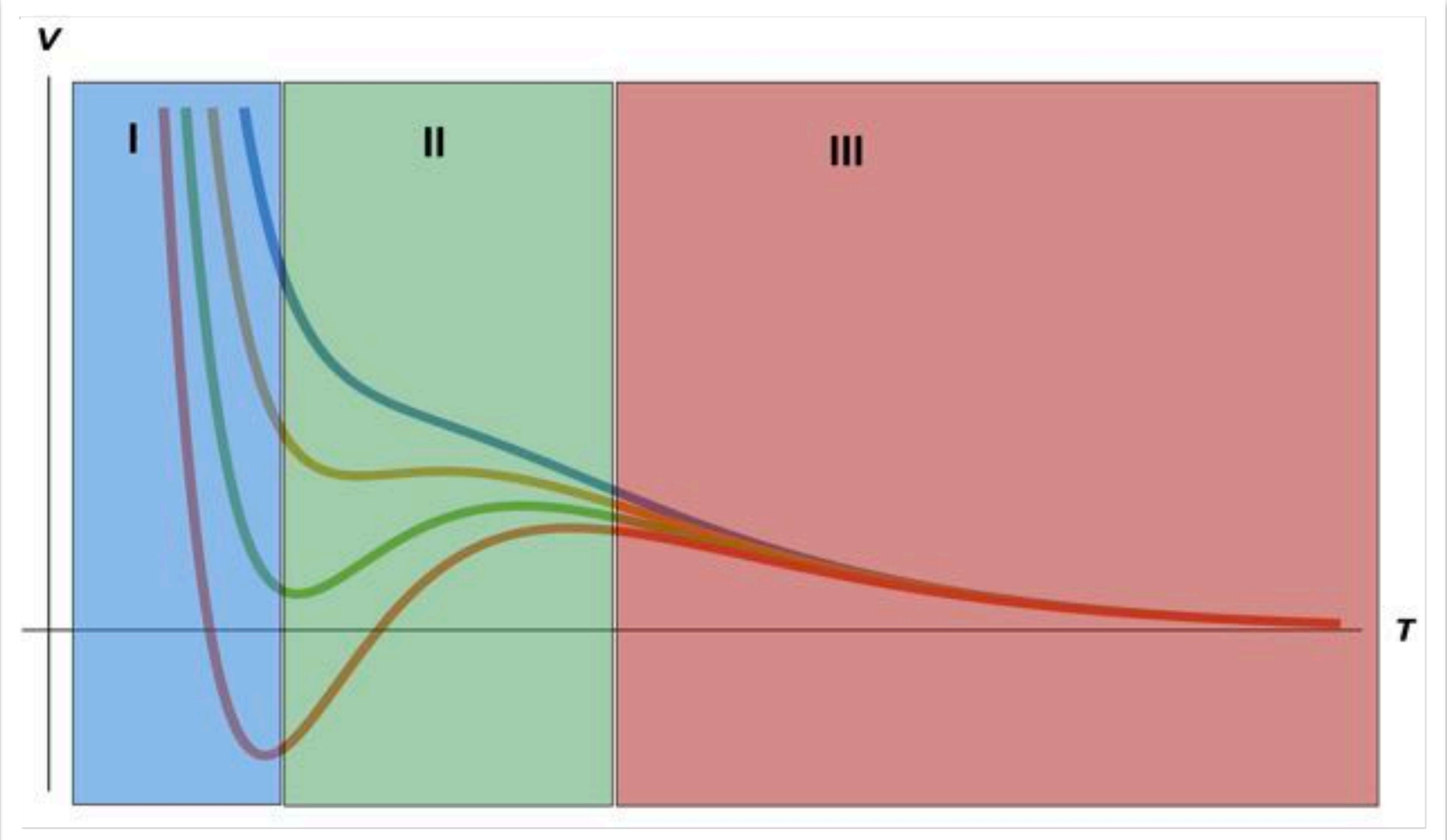
Gopakumar-Vafa invariants $\mathcal{N}_{\mathbf{q}}$ [Gopakumar, Vafa hep-th/9809187]

# Dine-Seiberg vs. Dirac

**Dine-Seiberg problem:**

No non-trivial solutions to EOMs at weak coupling!

Dine, Seiberg: 1985




I. quantum effects ~ classical ⇒ strong coupling

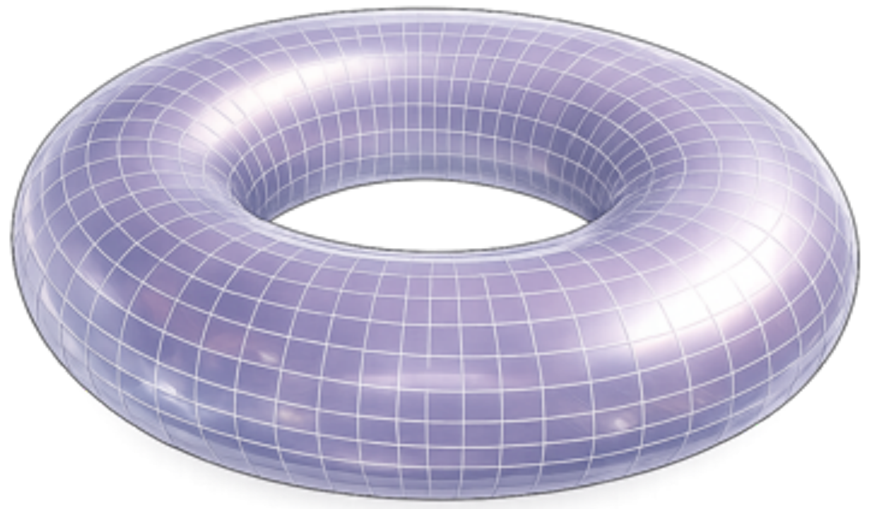
II. intermediate regime ⇒ needs extra sources

III. large volume ⇒ arbitrarily weak coupling

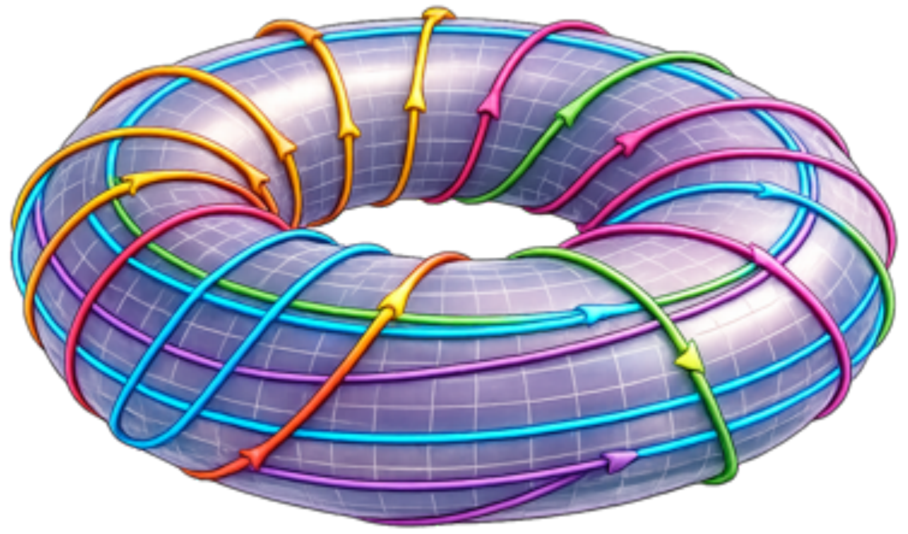
see e.g. McAllister, Quevedo 2310.20559

Avoided by introducing **fluxes** $\vec{F}$ as generalised electromagnetic charges!

Giddings, Kachru, Polchinski (GKP) hep-th/0105097



$\vec{F} = 0$



$\vec{F} \neq 0$

→ are **quantised** $\vec{F} \in \mathbb{Z}^k$

→ constrained by **Gauß law** $|| \vec{F} || \leq Q$

→ induce **stress-energy** $R_{\mu\nu} \sim (F^2)_{\mu\nu} + \ldots$

Components of $\vec{F}$:

$$\int_{3d} F_3 \,, \quad \int_{3d} H_3$$

**Let us compute the 4D scalar potential in terms of $\vec{F}$ …**

# Types of vacua and the superpotential

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

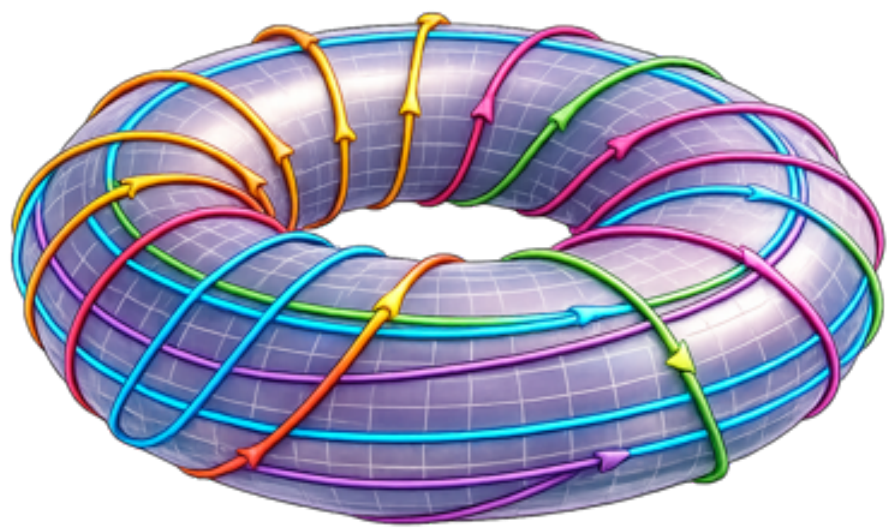
**SUSY vacua: $D_I W = 0$**

$\Longrightarrow$ AdS with $\langle V_F \rangle = -3\langle \mathrm{e}^K |\,W\,|^2 \rangle$

**non-SUSY vacua: $D_I W \neq 0$ for some $\Phi^I$**

$\Longrightarrow$ dS with $\langle V_F \rangle > 0$ possible!

$\vec{F} \neq 0$



$\rightarrow$ need to compute* the **superpotential $W$**

$$W(z, T) = W_{\text{flux}}(z) + W_{\text{np}}(z, T)$$

* focus on a single complex structure and Kähler modulus $z, T$, usually many more, see later!

$$W_{\text{flux}}(z) = a_3 z^3 + a_2 z^2 + a_1 z + a_0 + \sum_q N_q\, \mathrm{e}^{2\pi \mathrm{i}\, qz}$$

$a_i, N_q \in \mathbb{Q}$ determined by **topology** and **fluxes** $\vec{F} \in \mathbb{Z}^k$

# Types of vacua and the superpotential

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**non-SUSY vacua: $D_I W \neq 0$ for some $\Phi^I$**

$\Longrightarrow$ dS with $\langle V_F \rangle > 0$ possible!

$\rightarrow$ need to compute* the **superpotential $W$**

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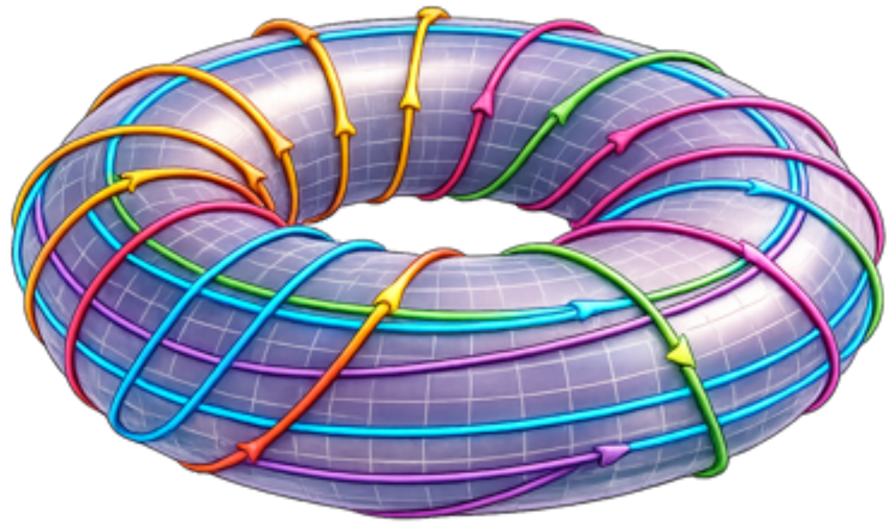
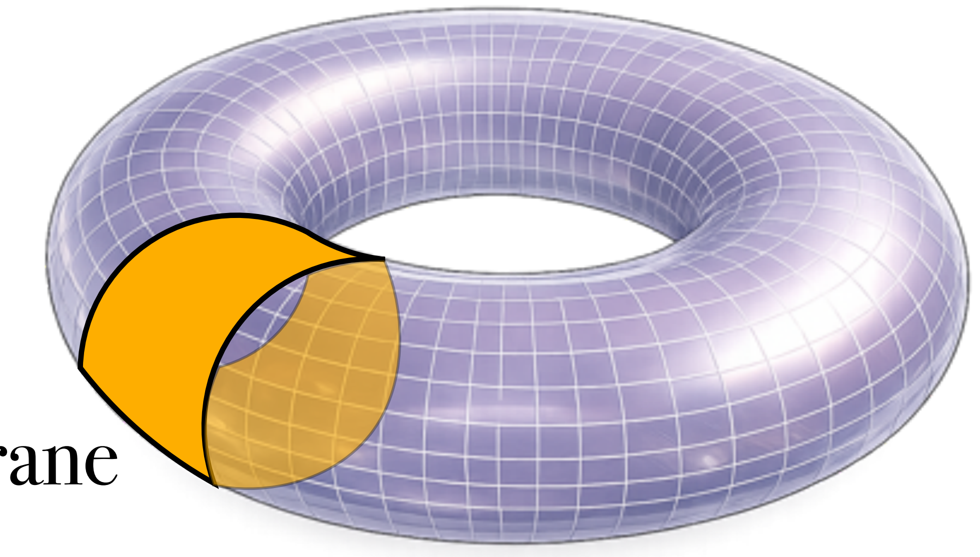
$\vec{F} \neq 0$





Dp-brane

$$W_{\text{flux}}(z) = a_3 z^3 + a_2 z^2 + a_1 z + a_0 + \sum_q N_q\, \mathrm{e}^{2\pi \mathrm{i}\, qz}$$

$a_i, N_q \in \mathbb{Q}$ determined by **topology** and **fluxes** $\vec{F} \in \mathbb{Z}^k$

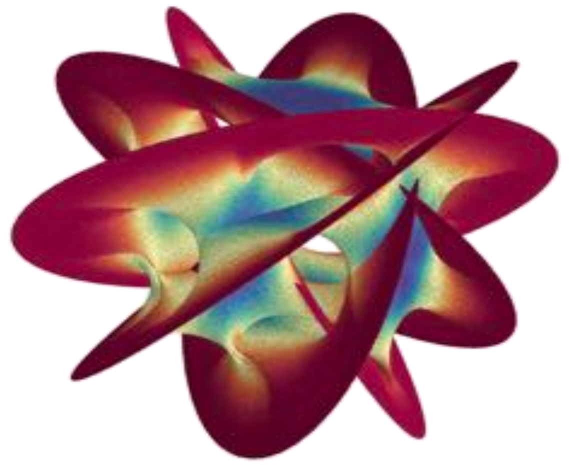
$$W_{\text{np}}(z,T) = \sum_{m=1}^{\infty} A_m(z)\mathrm{e}^{-2\pi m T}$$

**Non-perturbative** effects from D-branes wrapping cycles

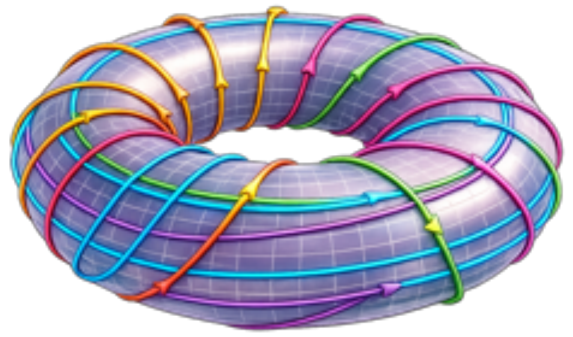
# 3. Towards de Sitter solutions:

## *Ingredients for Candidate de Sitter Vacua*

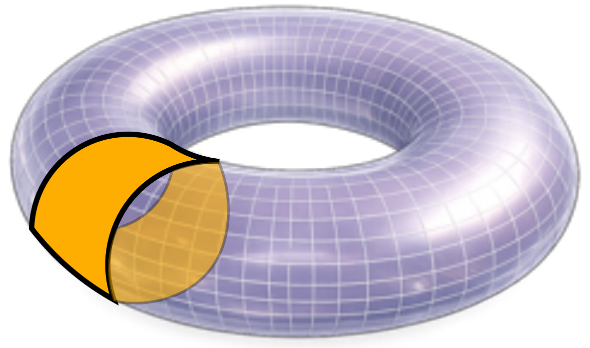
**Goal:** assemble tools for constructing explicit string vacua!



choices of $X$

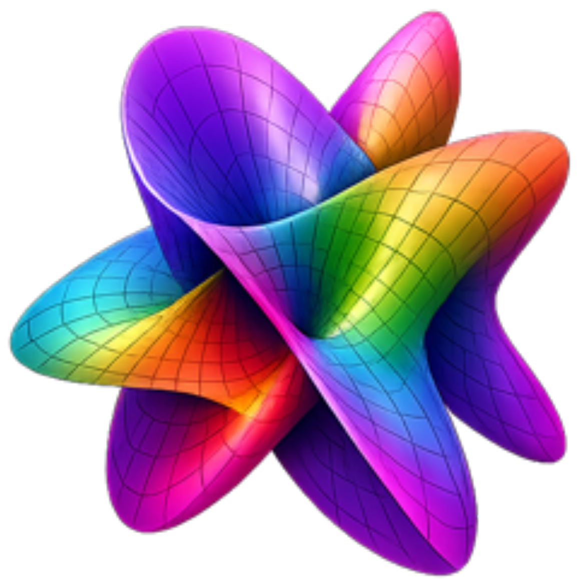


choices of $\vec{F}$



branes

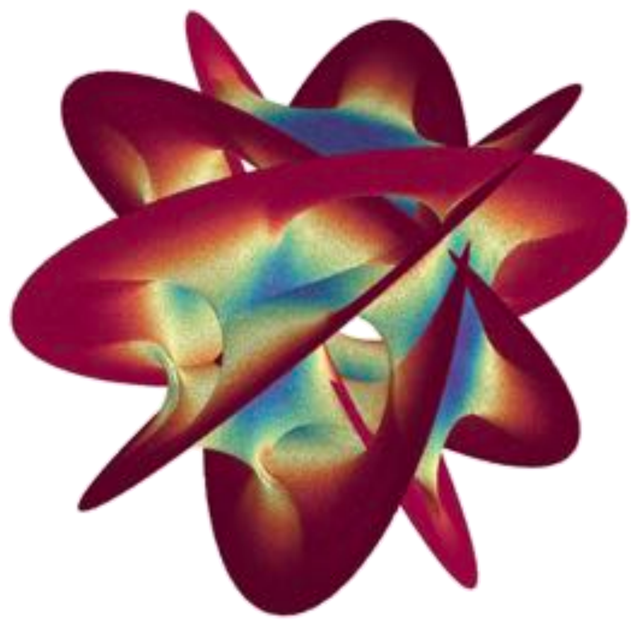
# The Geometric Toolkit



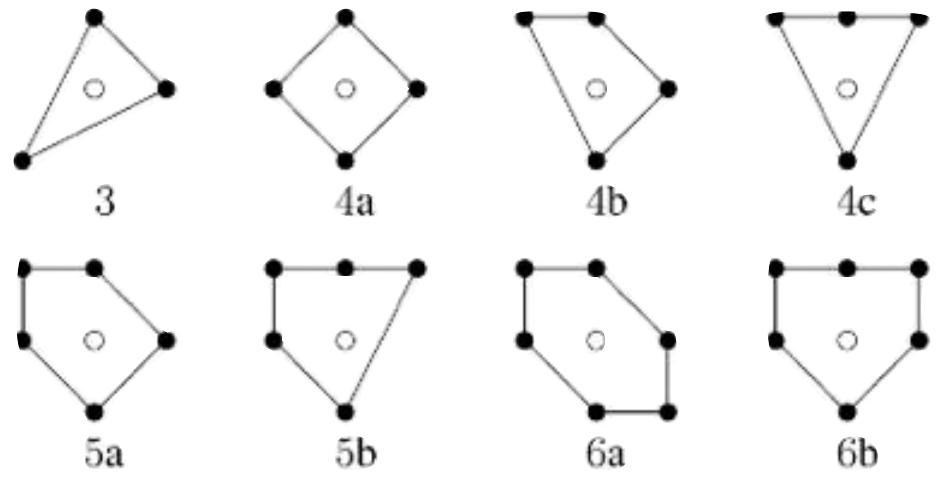
$y^2 = x^3 + fx + g$

How do we **construct** and compute (topological) CY data in practice?

→ largest class of known CYs realised as **hypersurfaces in toric varieties**

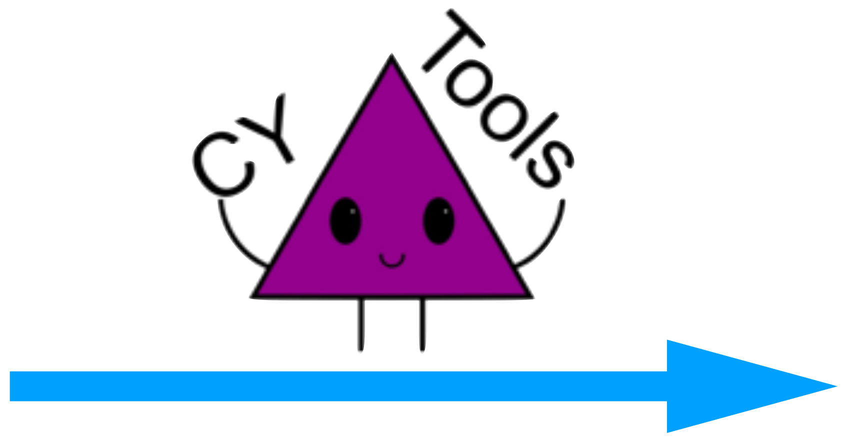


$$\sum_{i=1}^{5} x_i^5 = 0$$




473,800,776 reflexive polytopes in four dimensions

Kreuzer, Skarke hep-th/0002240

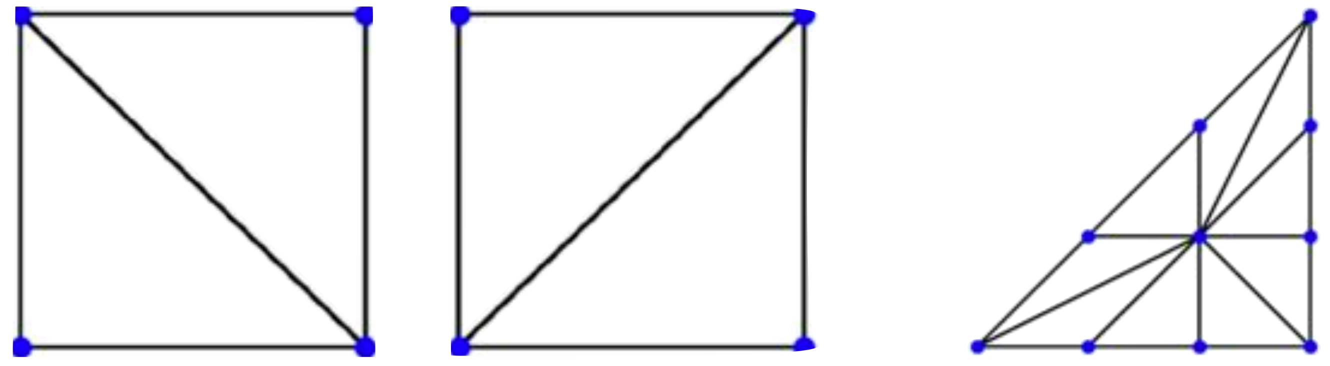



polytope triangulations

Demirtas, Rios-Tascon, McAllister 2211.03823

Construct **toric varieties** from combinatorial data

Batyrev alg-geom/9310003



# CY selection and the lamppost effect

Every growing **database** of Calabi-Yau geometries from which we can **efficiently sample**!

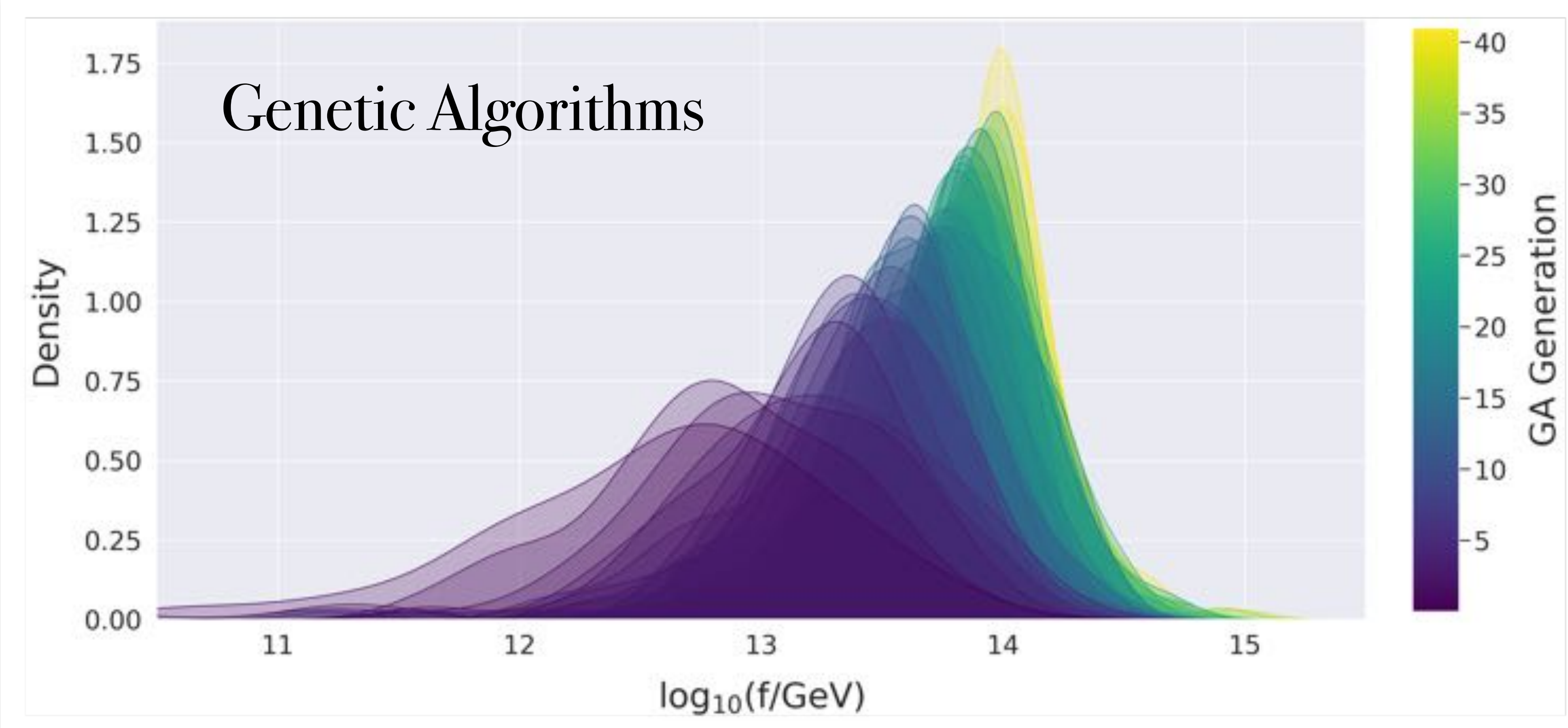
$\lesssim 10^{296}$ Calabi-Yau threefolds

Demirtas, Rios-Tascon, McAllister 2008.01730

MacFadden, Orevkov, Stepniczka 2602.16909

This is a lamppost, but already huge search space!


Optimisation in geometric landscape




MacFadden, **AS**, Sheridan: 2405.08871]

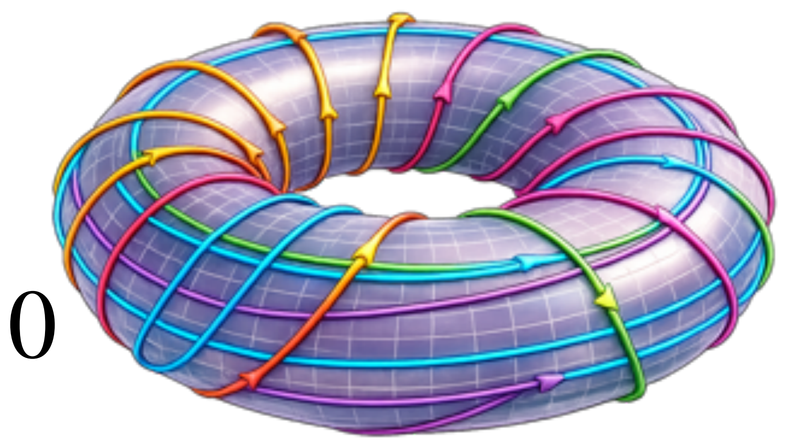
# Back to the Vacuum Problem

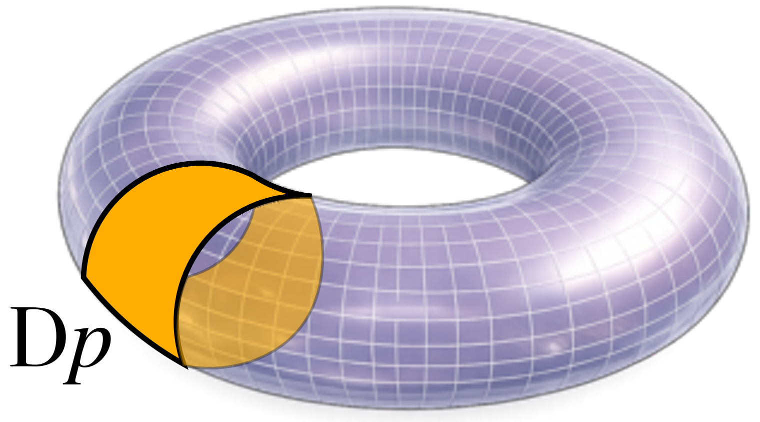
For given CY $X$, how can we construct solutions with $\rho_{\text{vac}} > 0$?

$$V_F = \mathrm{e}^K \left( K^{I\bar{J}} D_I W D_{\bar{J}} \overline{W} - 3|W|^2 \right)$$

**Plan:** find SUSY minimum $D_z W = D_T W = 0$ and **break SUSY** afterwards!

$\vec{F} \neq 0$





Dp

$$W_{\text{flux}}(z) = a_3 z^3 + a_2 z^2 + a_1 z + a_0 + \sum_q N_q \mathrm{e}^{2\pi \mathrm{i}\, qz}$$

$$W_{\text{np}}(z, T) = \sum_{m=1}^{\infty} A_m(z) \mathrm{e}^{-2\pi m T}$$

# SUSY Vacua – concretely

For experts, this is KKLT
Kachru, Kallosh, Linde, Trivedi hep-th/0301240

If we can find $\vec{F} \in \mathbb{Z}^k$ such that $a_i = 0$ (**Diophantine problem**!), then we can fix $z$

$$W_{\text{flux}}(z) = a_3 z^3 + a_2 z^2 + a_1 z + a_0 + \sum_q N_q \, \mathrm{e}^{2\pi \mathrm{i}\, qz} \quad \to D_z W = 0 \text{ so that } |W_0| \ll 1 \text{ with } W_0 = \langle W_{\text{flux}} \rangle$$

The remaining **Kähler modulus $T$** is fixed at leading order as

$$W_{\text{np}}(z,T) = \sum_{m=1}^{\infty} A_m(z) \mathrm{e}^{-2\pi m T} \quad \to D_T W = 0 \text{ for } T \approx \frac{1}{2\pi} \log\left(|W_0|^{-1}\right)$$

**Self-consistent:**
Perturbative control $T \gg 1$
achieved for $|W_0| \ll 1$!

At the end of the day, one obtains …

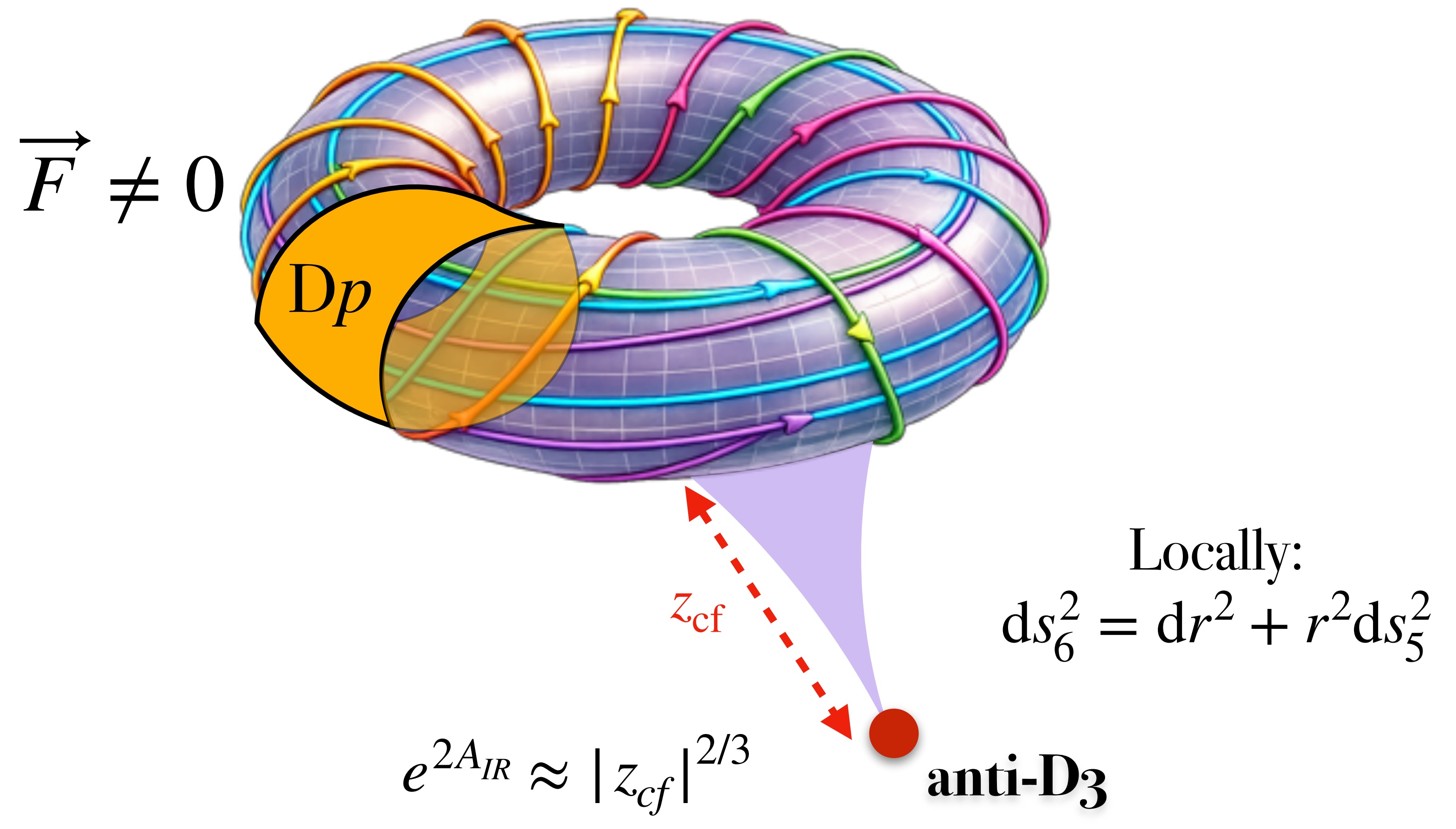
$\Rightarrow$ **SUSY AdS minimum** with $\rho_{\text{vac}} = -3\langle \mathrm{e}^K |W|^2 \rangle$

**SUSY CC problem:** Solutions with
$\rho_{\text{vac}} \sim -10^{-122} M_p^4$ have been found, but **see later**!

Demirtas, Kim, McAllister, Moritz: 2107.09064
*wip* MacFadden, McAllister, Moritz, Nally, **AS**

# SUSY breaking and uplift

For experts, this is KKLT
Kachru, Kallosh, Linde, Trivedi hep-th/0301240

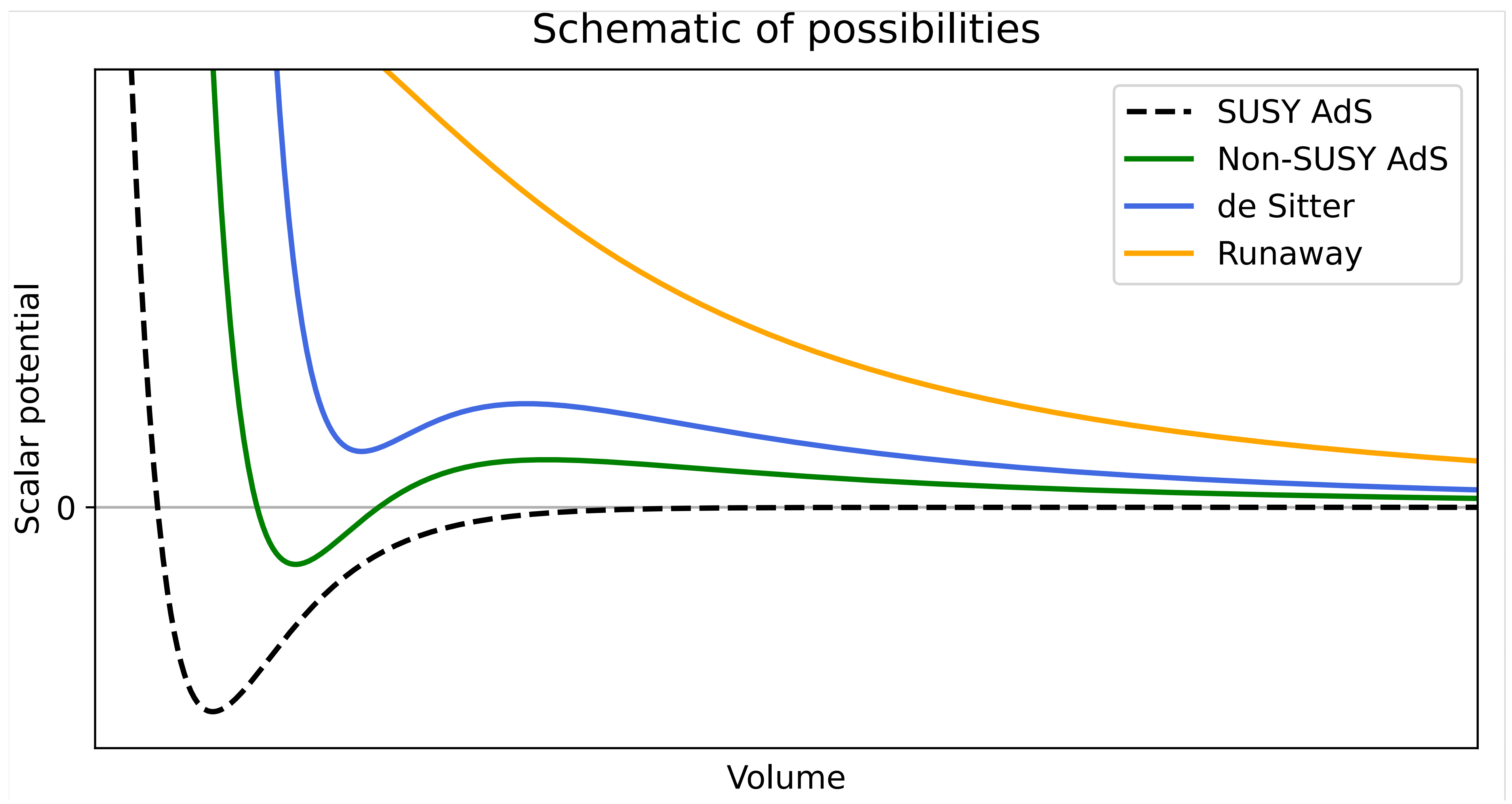



To get $\rho_{vac} > 0$, we need to **break SUSY** * and change our setup in some regards!

A **redshifted anti-D3 brane** in a warped throat breaks SUSY and can **uplift** an AdS vacuum to a candidate dS vacuum.

[Klebanov, Strassler hep-th/0007191]
[GKP hep-th/0105097]
[Kachru, Pearson, Verlinde (KPV) hep-th/0112197]

$$V = V_F + V_{up} \quad \text{so that } \langle V \rangle > 0 \text{ at } \partial V = 0$$




* Alternative approach e.g. **F-term uplifting** from $\vec{F}$
[Saltman, Silverstein hep-th/0402135]
[Hebecker, Lüst, **AS**, Schreyer 2512.17995]

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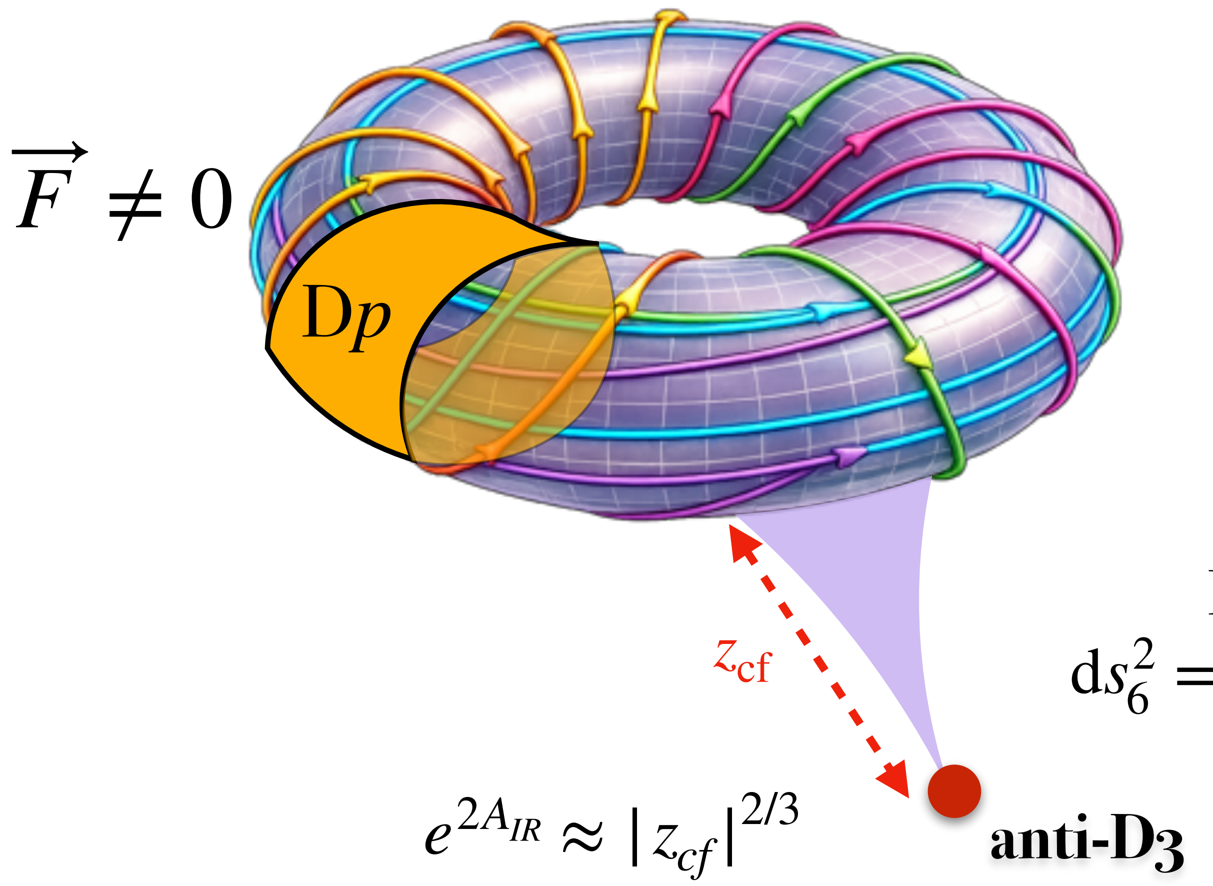


Locally:
$\mathrm{d}s_6^2 = \mathrm{d}r^2 + r^2 \mathrm{d}s_5^2$

The main difficulty is achieving $|V_F| \sim V_{\text{up}}$ in a **discrete, finite landscape** of EFTs!

A **redshifted anti-D3 brane** … **uplift** an AdS vacuum to a candidate dS vacuum.

[Klebanov, Strassler hep-th/0007191]
[GKP hep-th/0105097]
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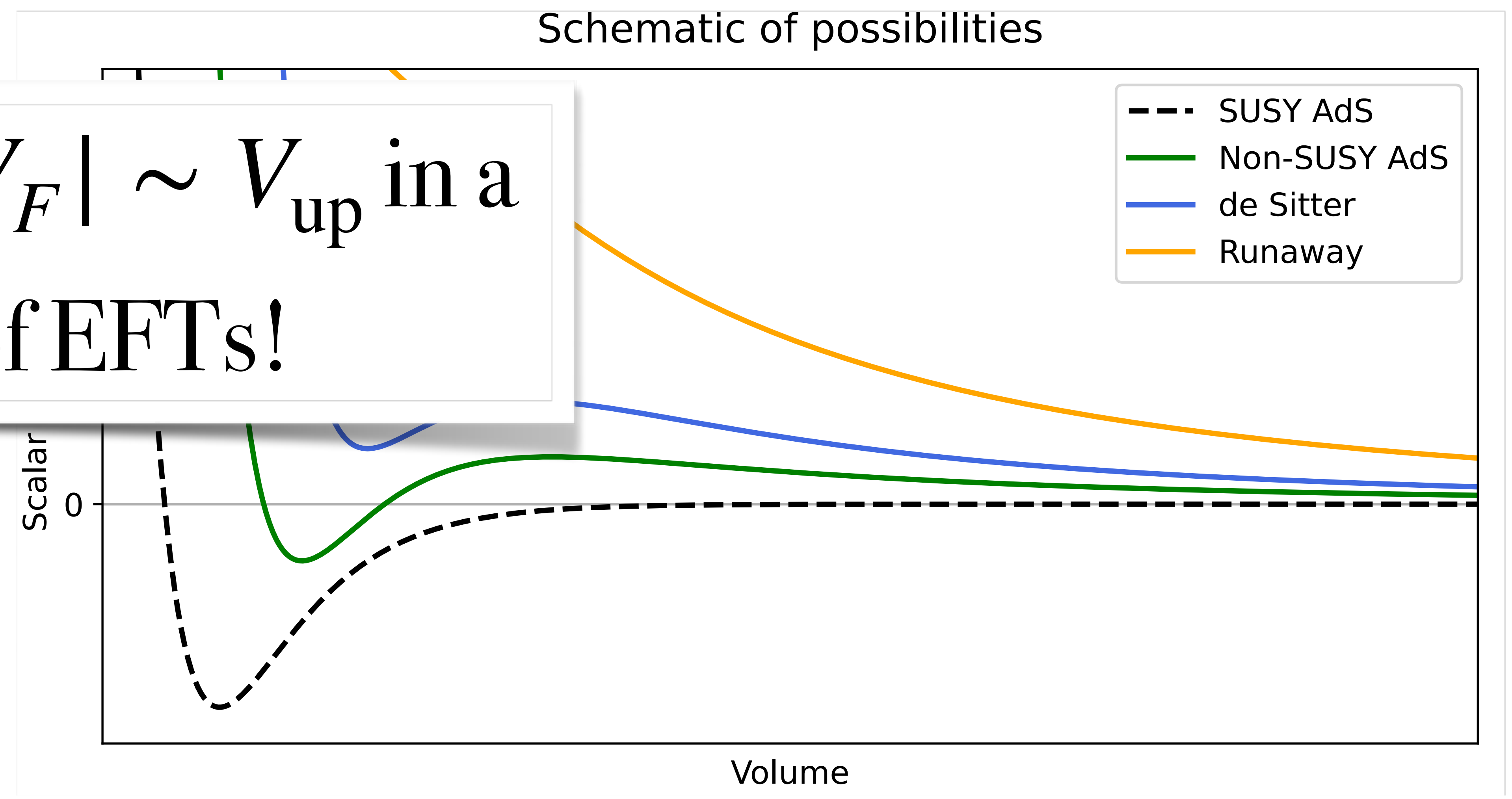


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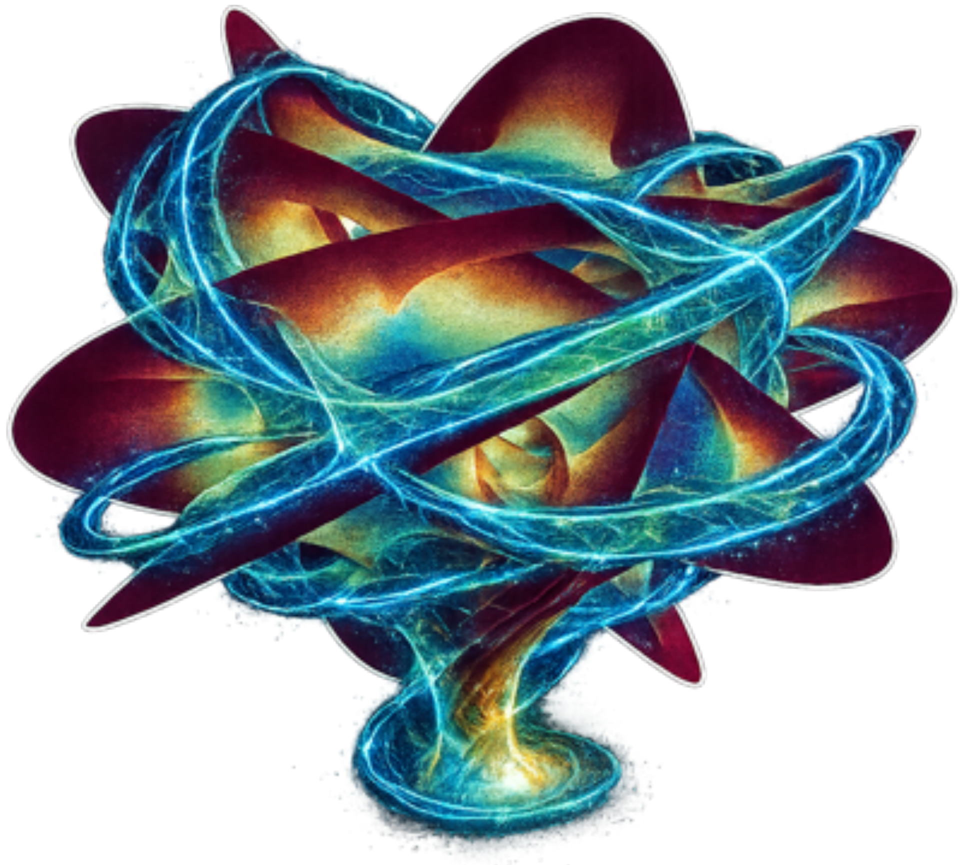


# 4. Explicit Vacuum Constructions:

## *Computable Corners of the Landscape*

Based on

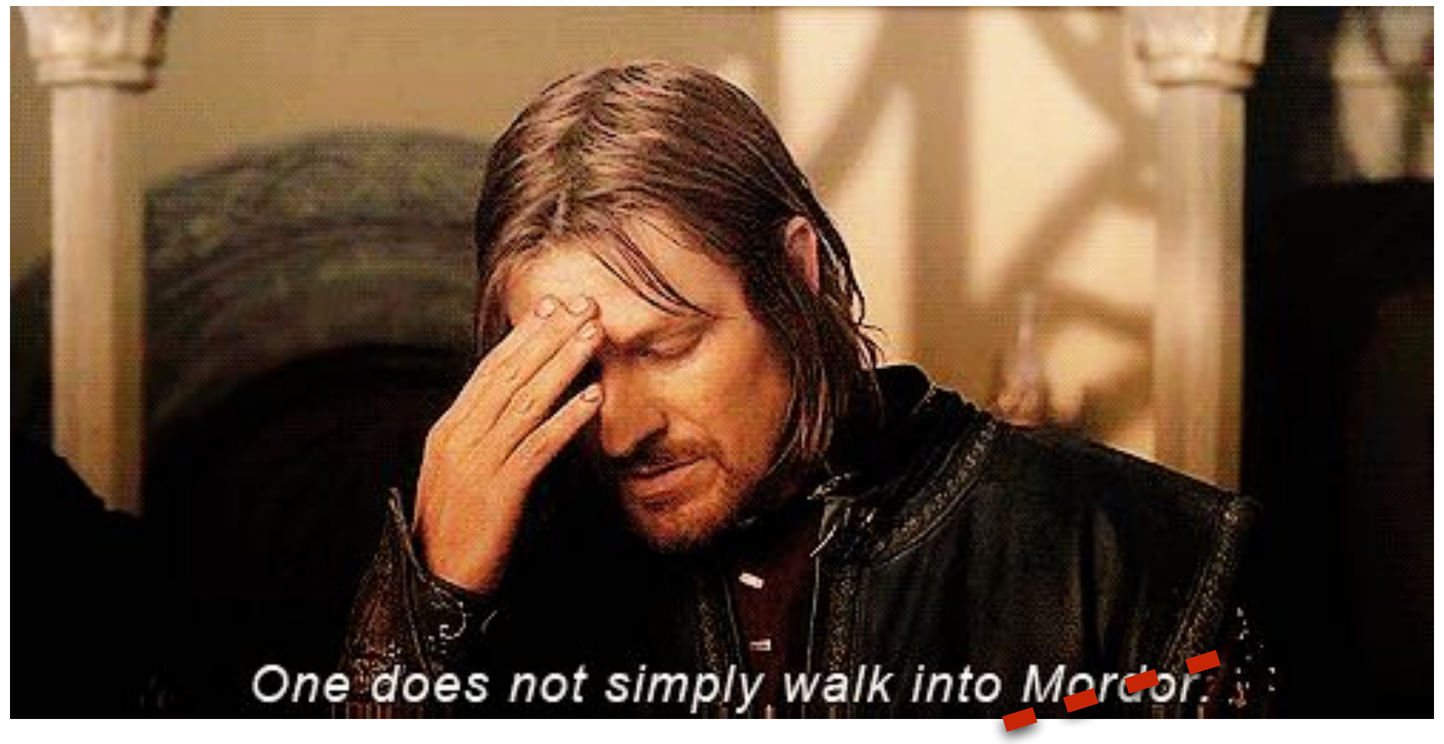
*2406.13751* (*Phys.Rev.D* 111 (2025) 8, 086015) with L. McAllister, J. Moritz, R. Nally

*work in progress* with N. MacFadden, L. McAllister, J. Moritz, R. Nally

*work in progress* with F. Compagnin, N. MacFadden, L. McAllister, J. Moritz, R. Nally

# Challenges in the search for fully explicit models

Let us try to implement this mechanism in a fully explicit example …




the landscape.

**… but this is hard!**

A. Need to choose **suitable** $X$ ⇒ not any "works" (right now)

B. $h^{p,q}(X) \sim \mathcal{O}(100)$ * ⇒ $\partial V = 0$ high-dimensional optimisation problem

C. computational **control** ⇒ strong constraints on the solution

* Number of moduli fields are counted by **topological (Hodge) numbers** $h^{p,q}(X)$

This requires dedicated **computational software development** …

# Automation in String Compactifications

Given a CY $X$, how do we **numerically solve** optimisation problems?

We developed dedicated software tools to automate

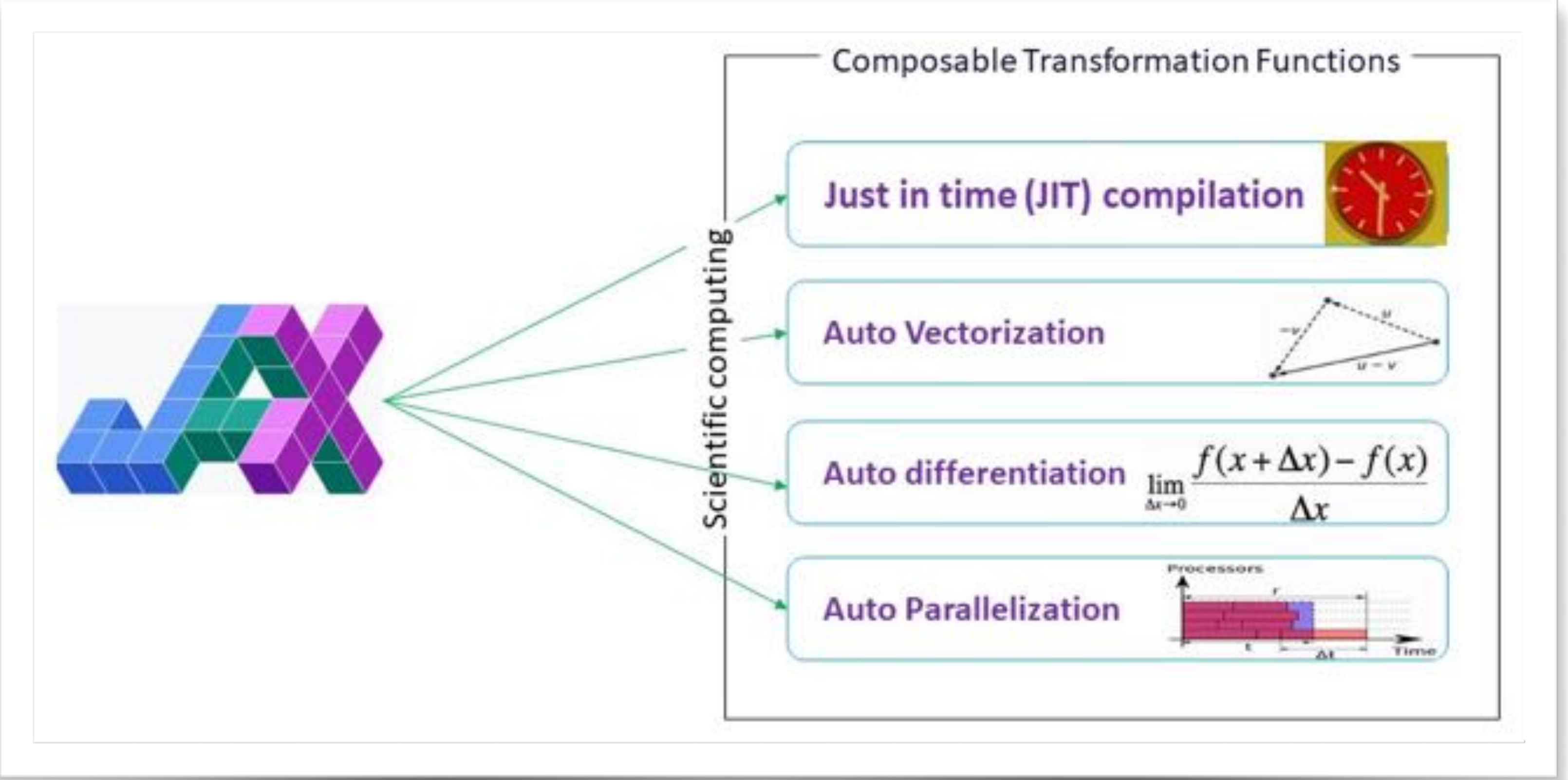
A. the computation of **objective functions** (i.e. $K$, $W$),

B. **minimisation routines** for general EFT inputs, and

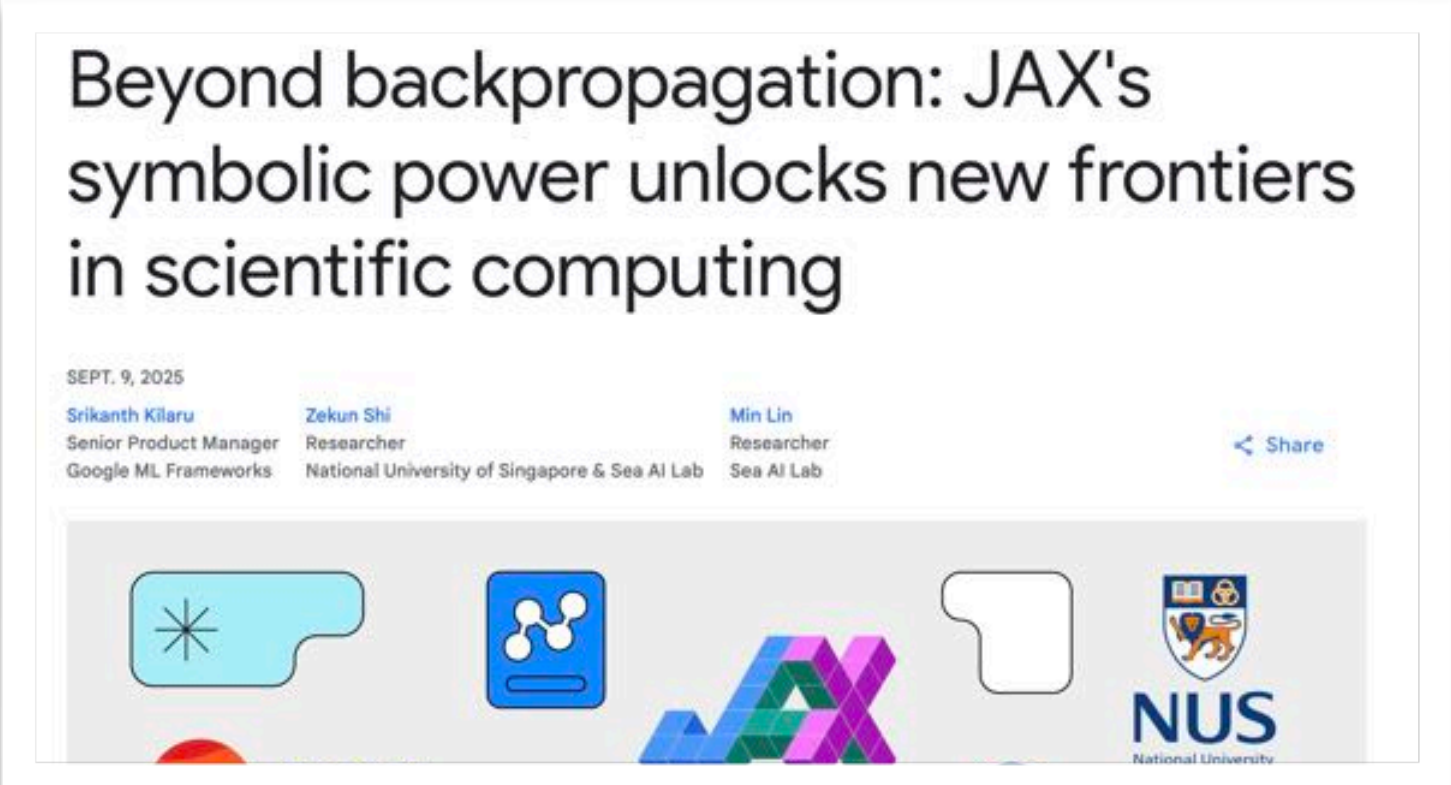
C. the **control analysis** of solutions under varying constraints.

JAXVacua
STRING VACUA WITH JAX

**AS** work in progress

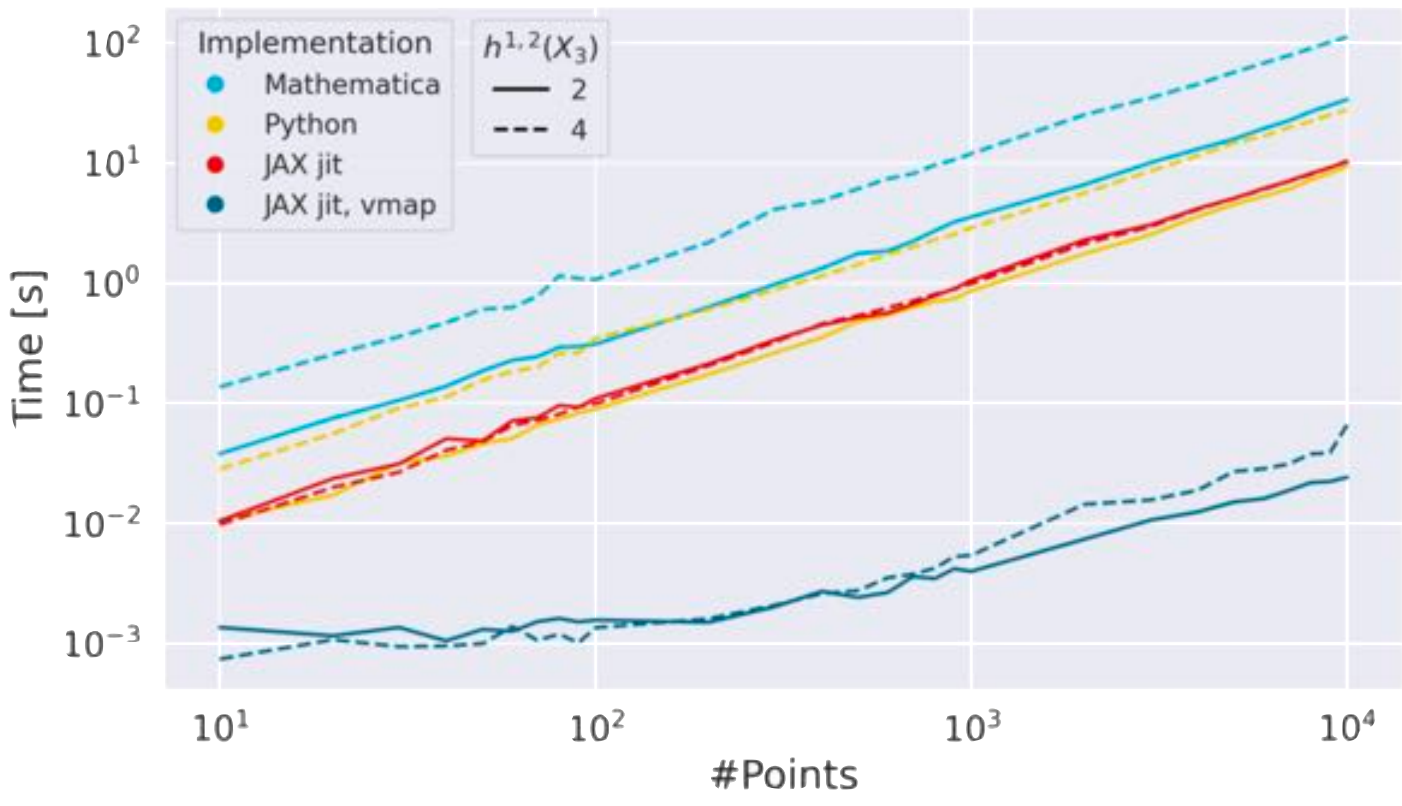



Bradbury et al. (2008)




Developers googleblog

Timing for evaluating $V$




Dubey, Krippendorf, **AS** 2306.06160

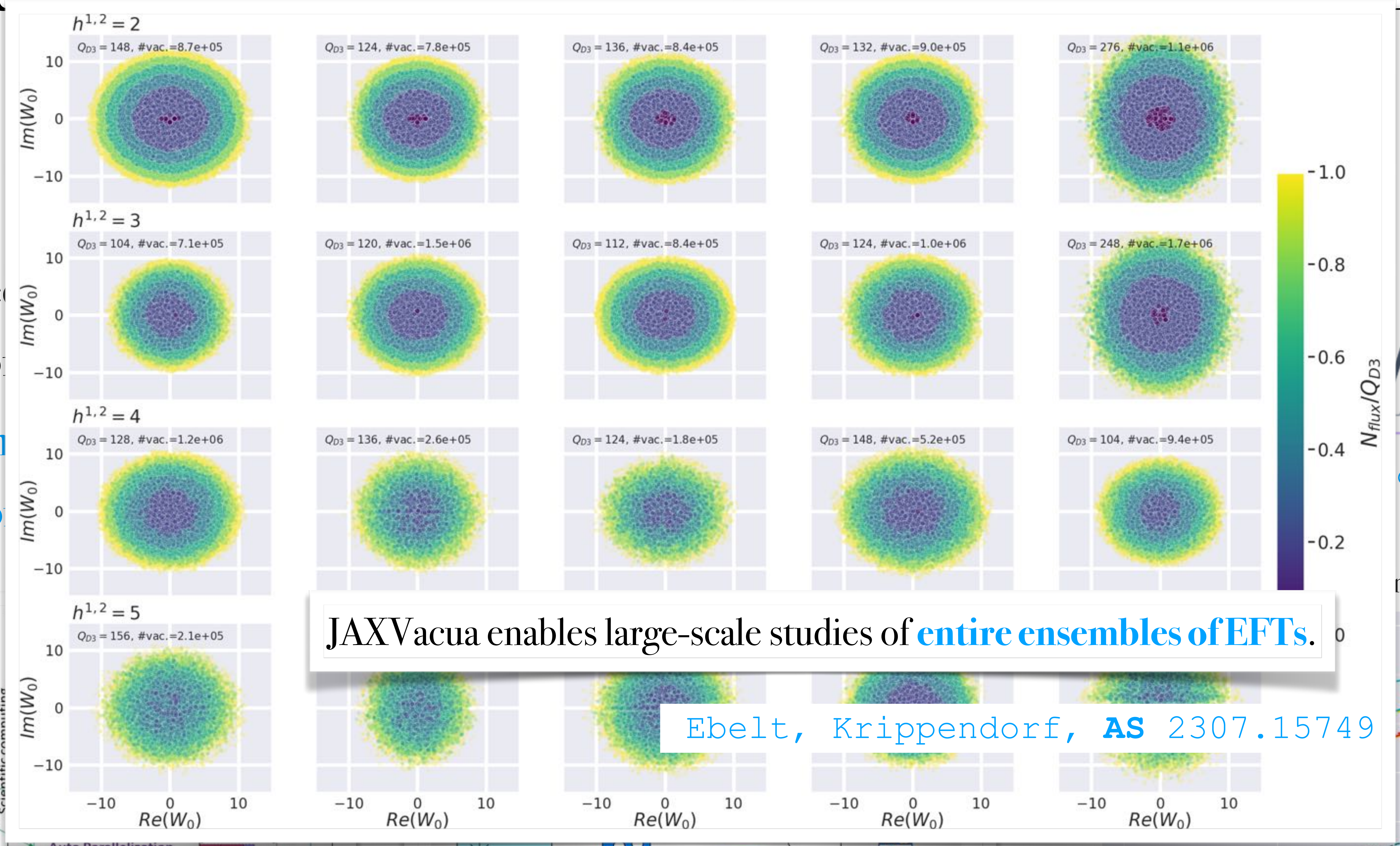
# Automation in String Compactifications

We develope[d]…

A. the co…

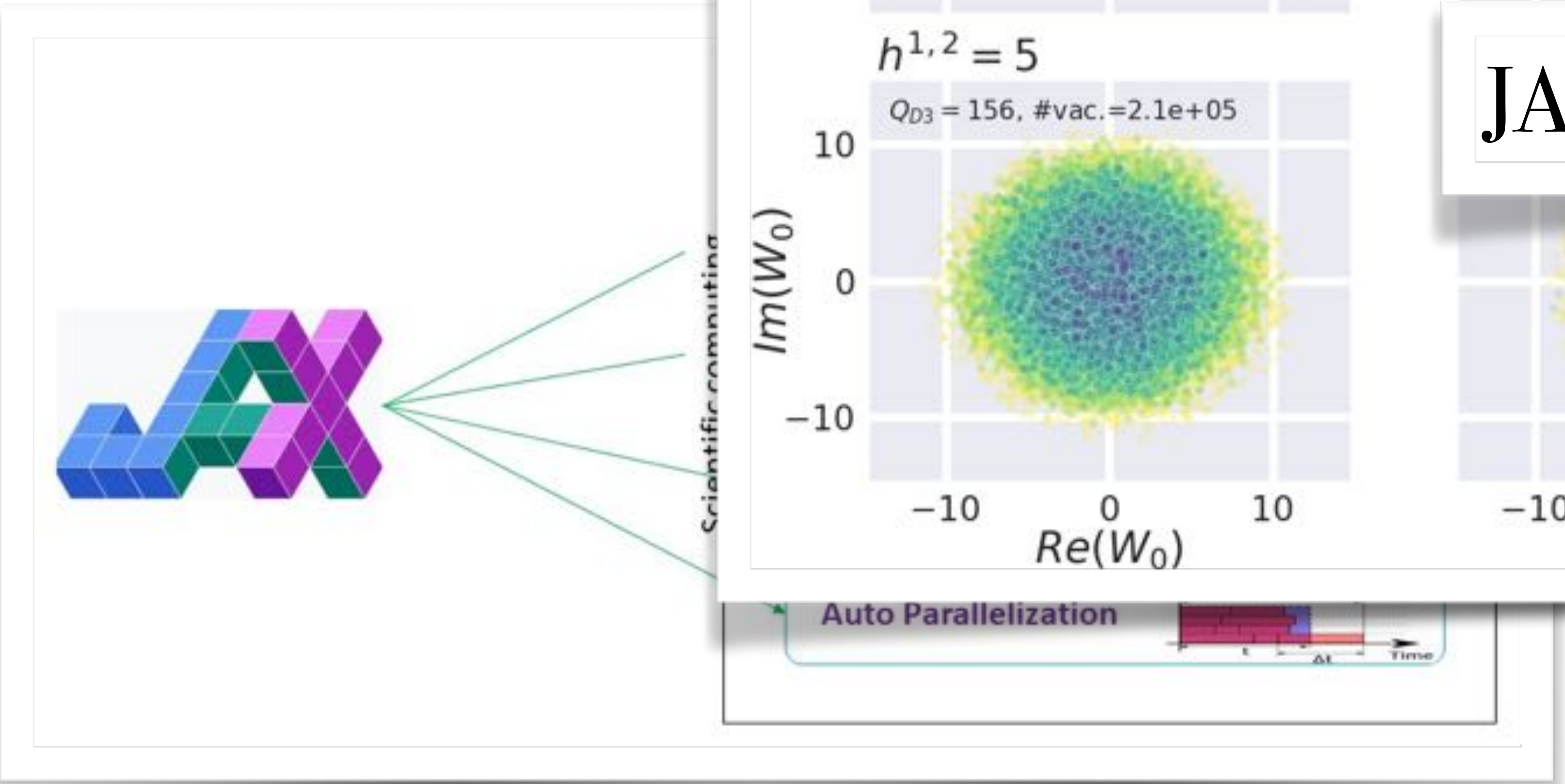
B. **minin**…

C. the **co**…




JAXVacua enables large-scale studies of **entire ensembles of EFTs**.

Ebelt, Krippendorf, **AS** 2307.15749




Bradbury et al. (2008)


[Developers googleblog]

…acua

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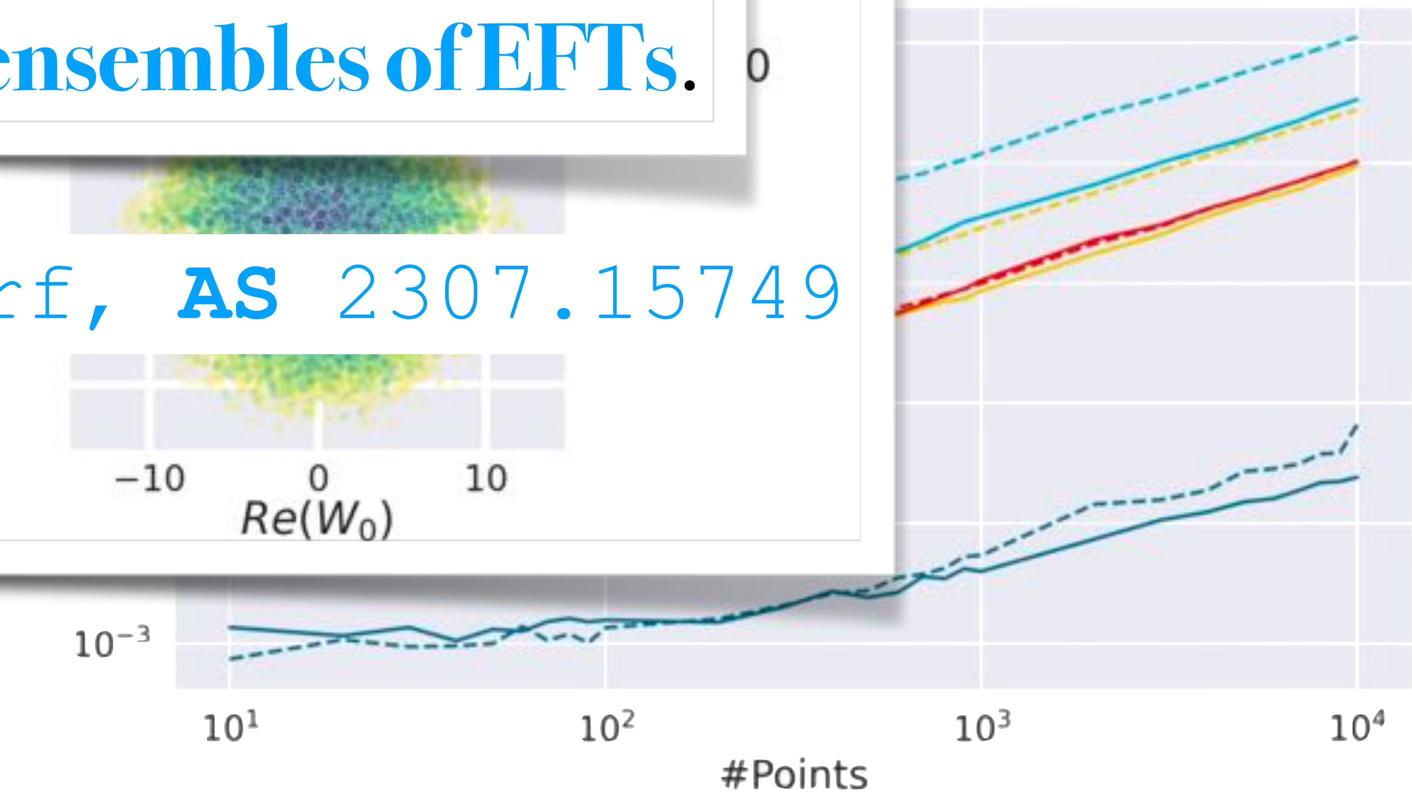


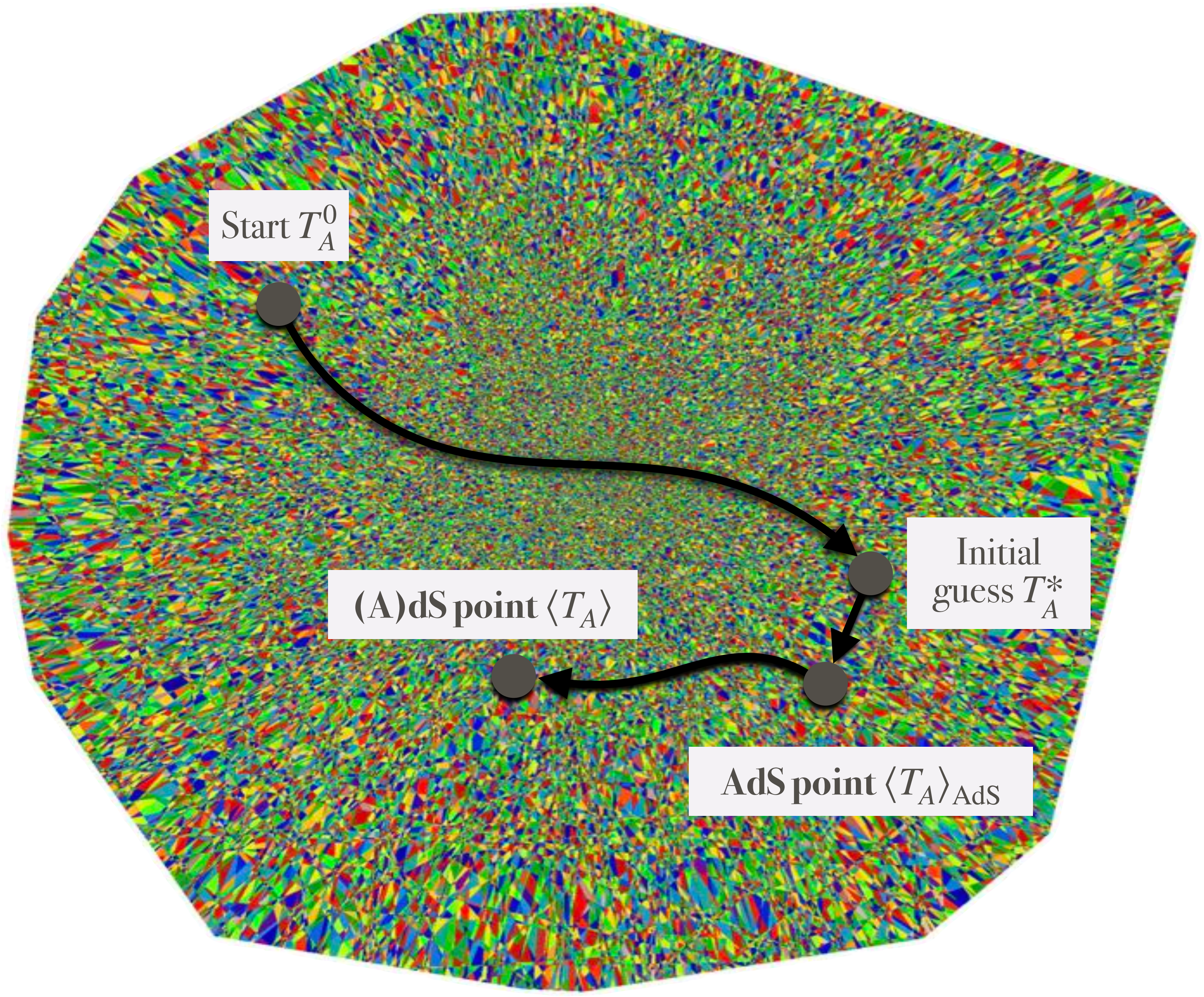

Dubey, Krippendorf, **AS** 2306.06160

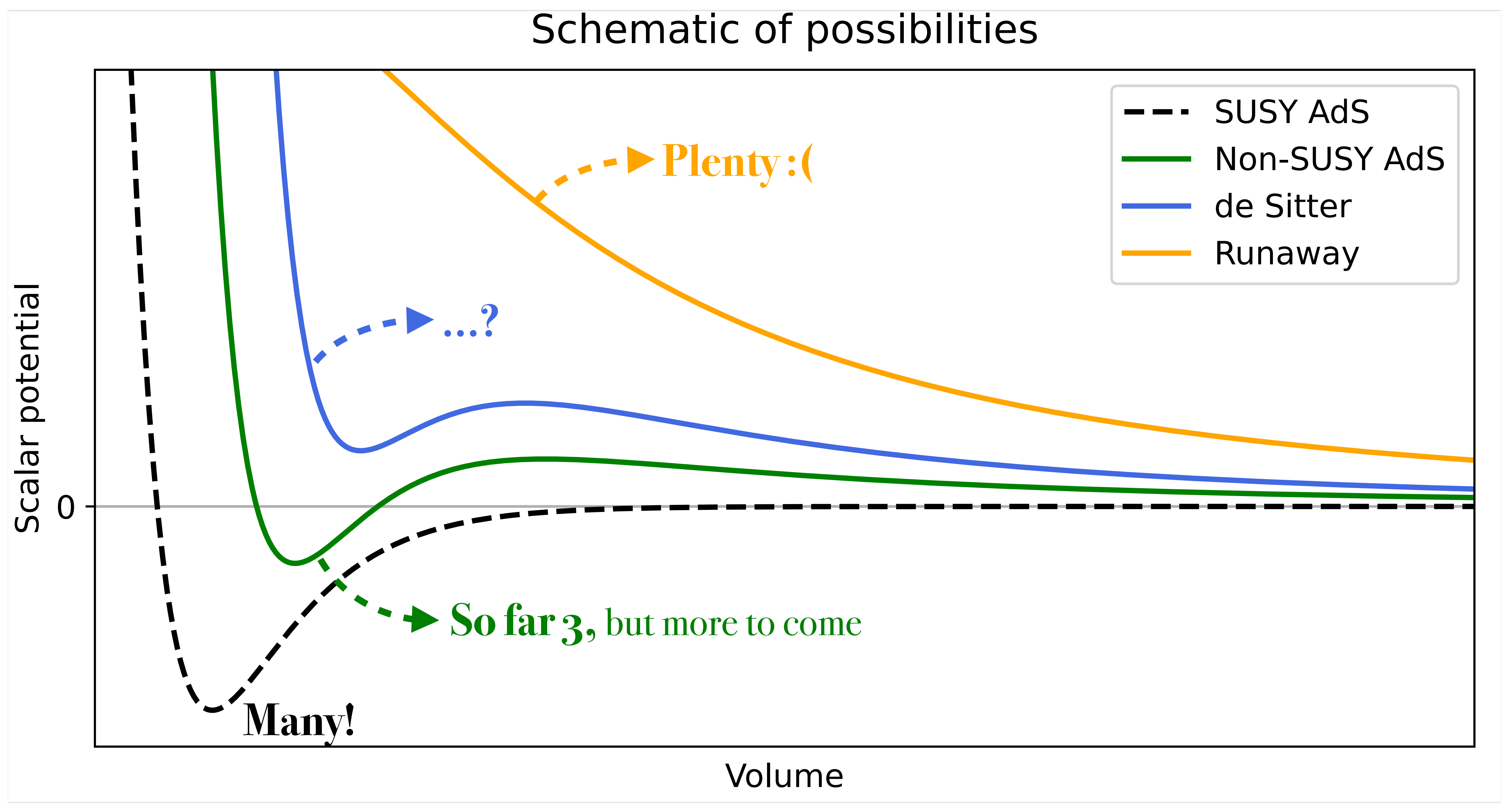
# The search for dS vacua

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

**Target:** Find first concrete examples of de Sitter vacua in string theory as envisioned by KKLT 20 years ago.

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




Our data is publicly available on GitHub:

https://github.com/AndreasSchachner/kklt_de_sitter_vacua

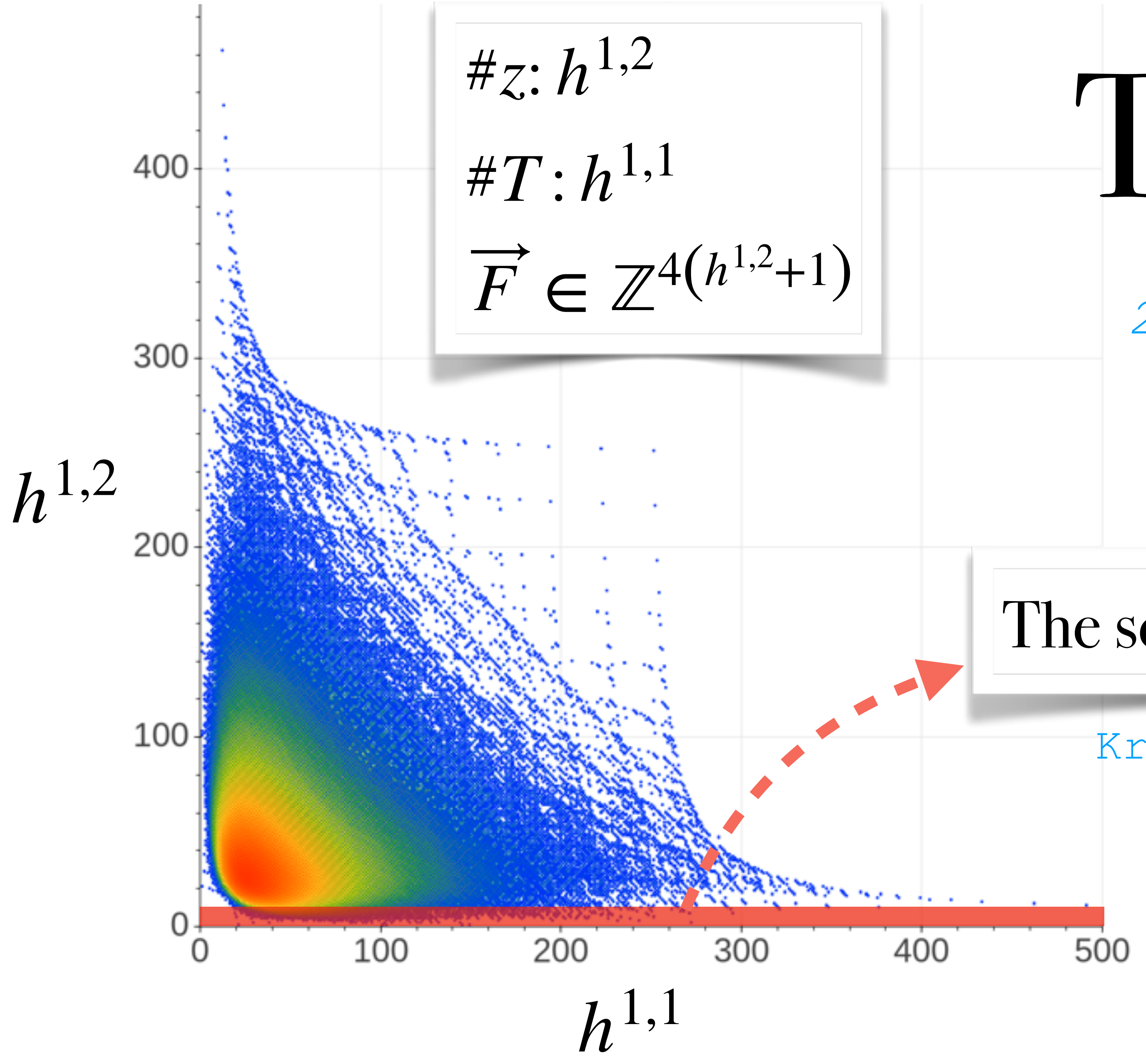
# The search for vacua

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

#z: $h^{1,2}$

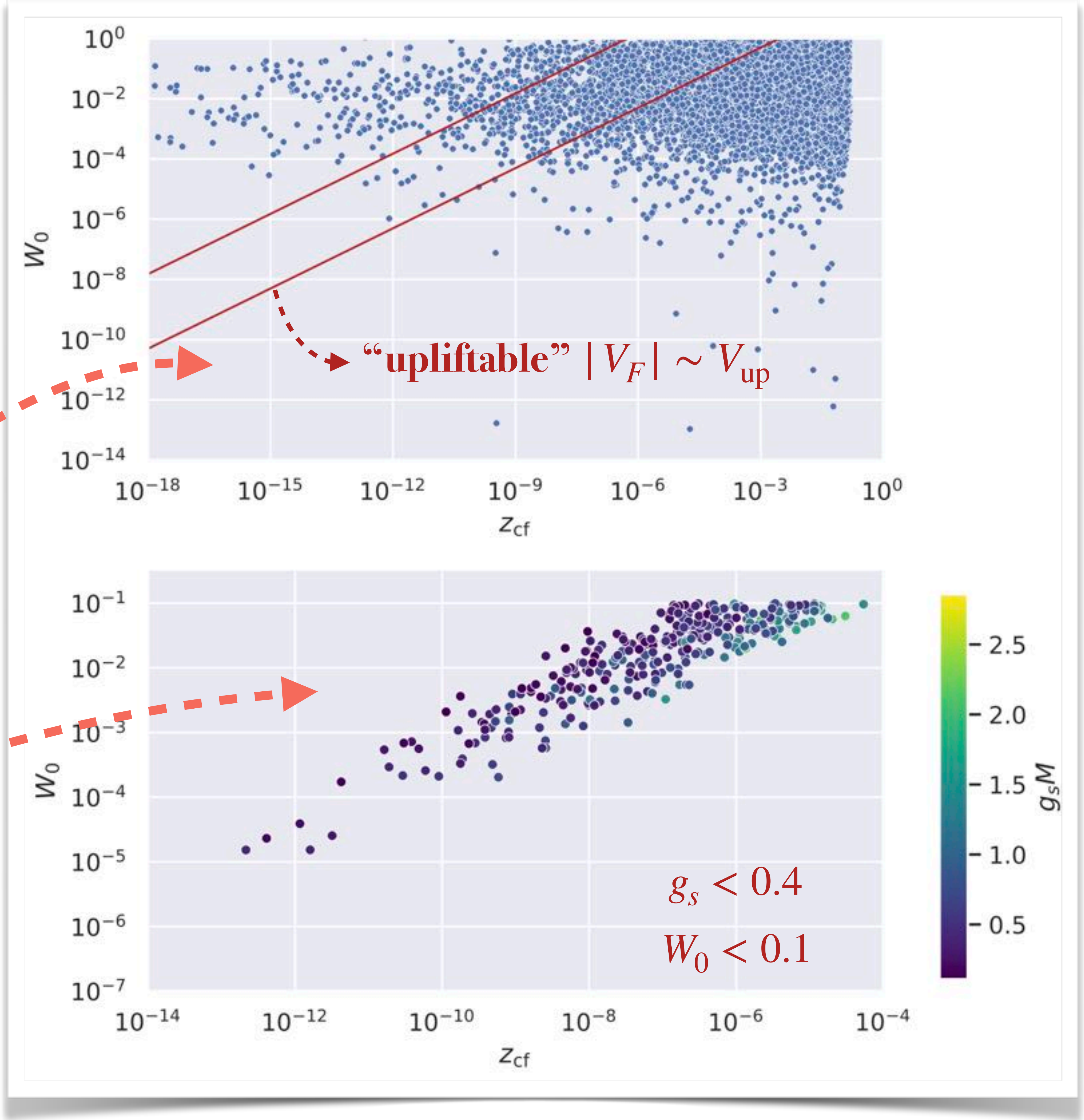
#T : $h^{1,1}$

$\vec{F} \in \mathbb{Z}^{4(h^{1,2}+1)}$




The scan * over 4D reflexive polytopes!

Kreuzer, Skarke hep-th/0002240



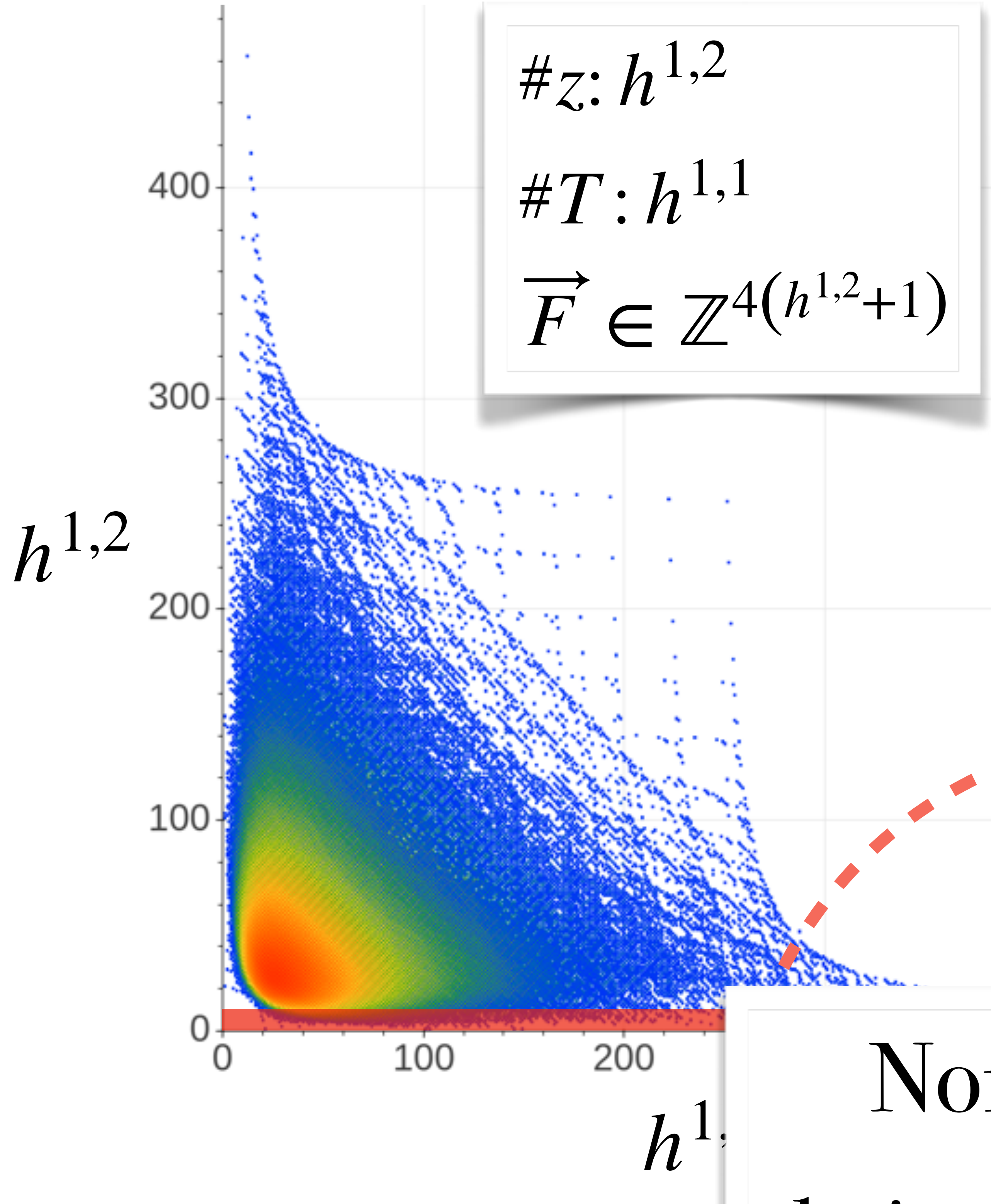

The scan leads to the following

- #CYs with conifolds: 416
- #consistent $\vec{F}$ with SUSY AdS: 90,457,494
- #upliftable solutions: 24,510

* we only looked at 202,703 out of 473,800,776 4D reflexive polytopes

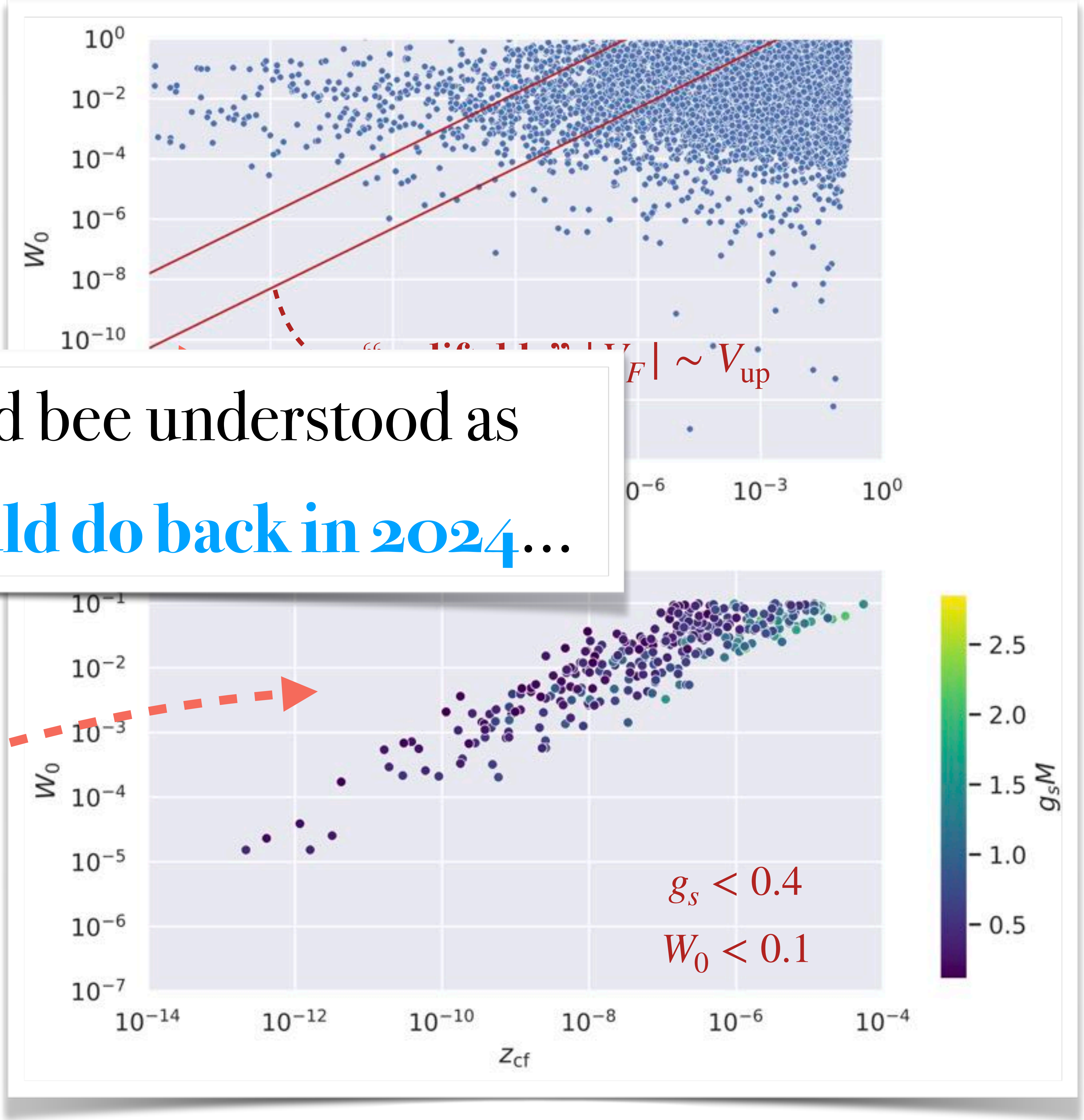
# The search for vacua

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




The scan* over 4D reflexive polytopes!

Kreuzer, Skarke hep-th/0002240




None of the numbers stated here should bee understood as being exhaustive! This is **the best we could do back in 2024**...

The scan leads to the following

- #CYs with conifolds: 416
- #consistent $\vec{F}$ with SUSY AdS: 90,457,494
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# A Candidate de Sitter vacuum

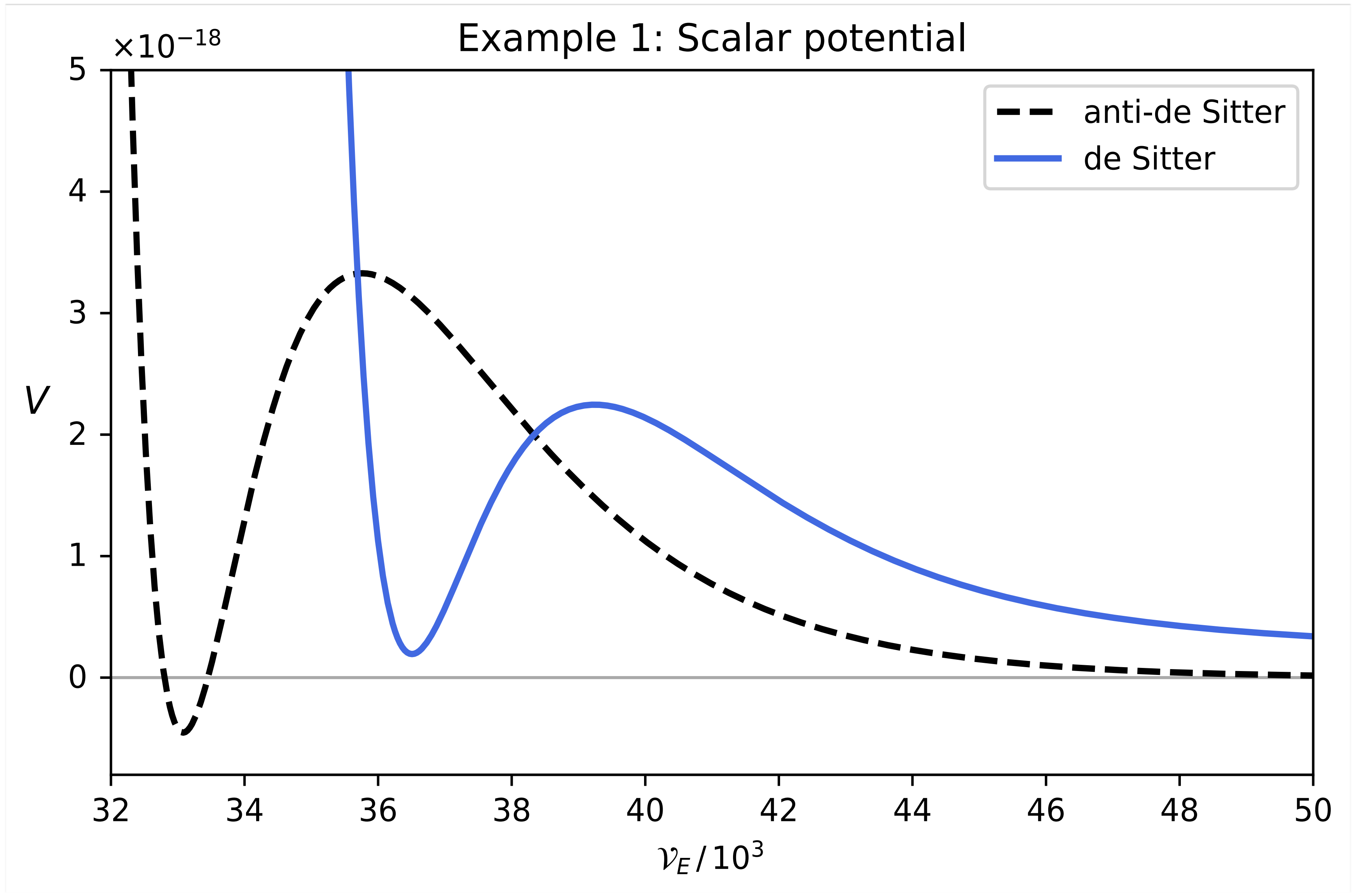
2406.13751 McAllister, Moritz, Nally, **AS**

*$158 \times 2 = 316$-dimensional optimisation problem!

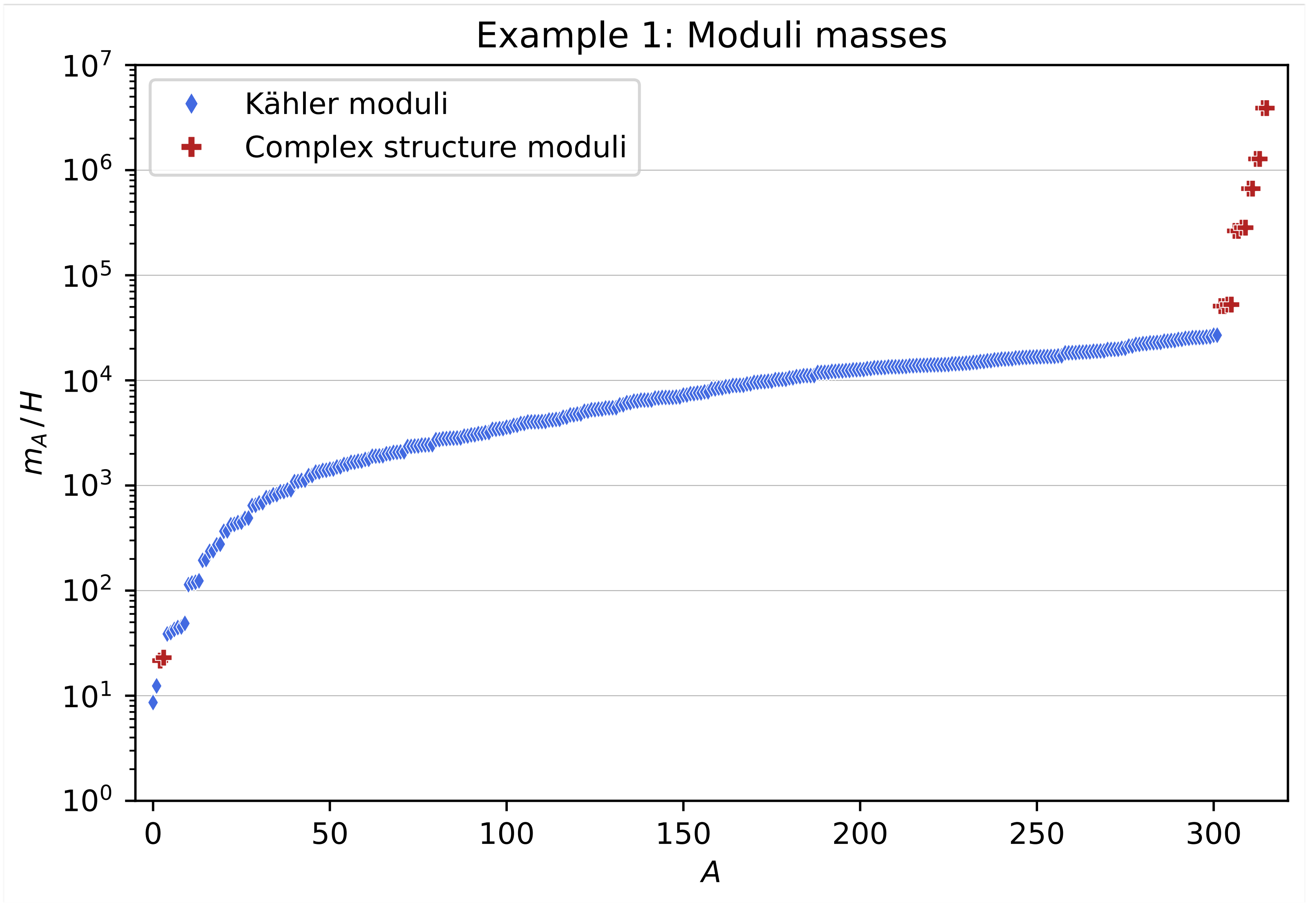
Here is an explicit example of a de Sitter candidate vacuum with* $h^{1,1} = 150, h^{2,1} = 8$ and

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

Potential before and after uplift:

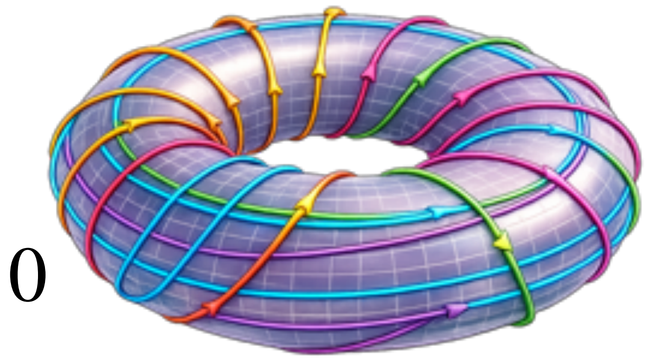



The vacuum is **free of tachyons**!



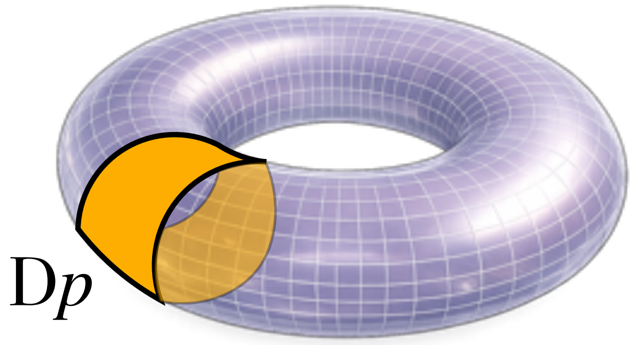
# Control analysis and convergence tests

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



$\vec{F} \neq 0$

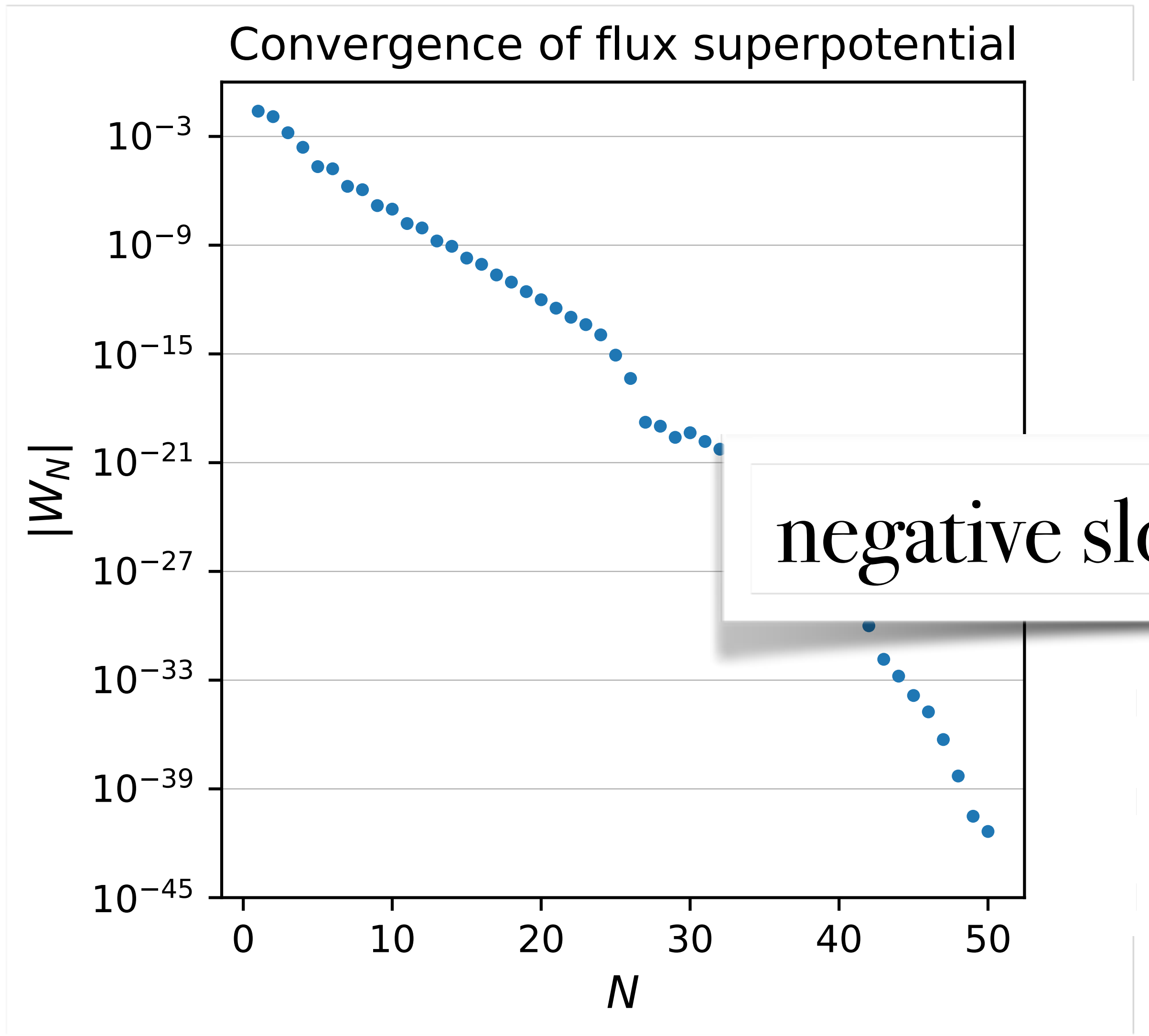
We need to ensure that we incorporate **all relevant corrections** in the EFT...

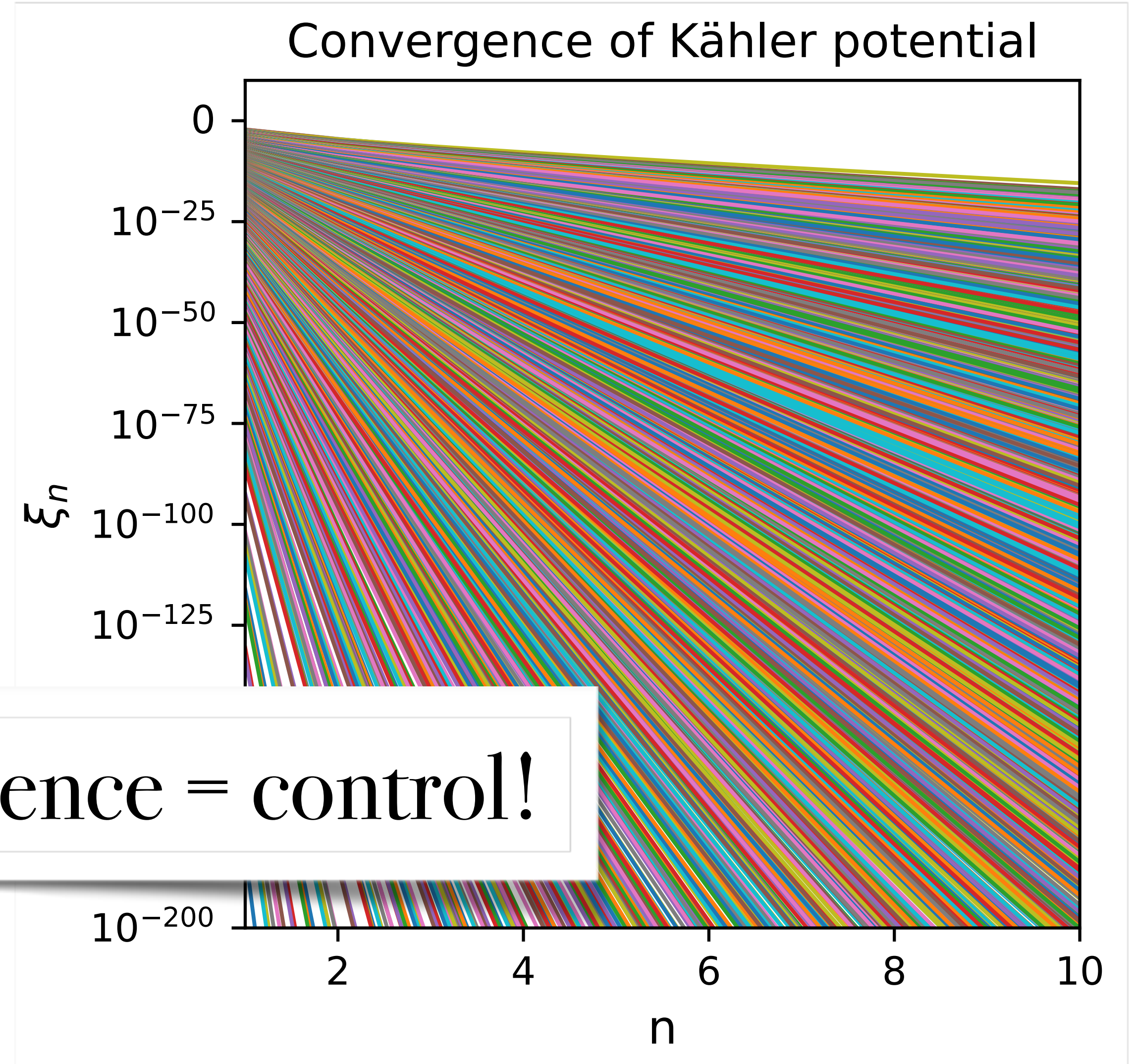


Dp

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

$$W_N \sim \sum_{\mathbf{q}\cdot p = N} \mathcal{N}_{\mathbf{q}}\,(\vec{F}\cdot\mathbf{q})\,\mathrm{Li}_2\!\left(\mathrm{e}^{2\pi i N z}\right)$$




negative slope = convergence = control!

**Flux potential**

Contributions from **worldsheet instantons**

$$K \supset \sum_{\mathbf{q}\in\mathcal{M}(X)} \mathcal{N}_{\mathbf{q}} \left(\mathrm{Li}_3\!\left(e^{-2\pi\mathbf{q}\cdot\mathbf{t}}\right) + \ldots\right)$$

Pfaffian prefactors*

$$W_{\mathrm{np}}(T) = \sum_D A_D \mathrm{e}^{-2\pi T_D} \qquad A_D = \sqrt{\frac{2}{\pi}}\,\frac{1}{(4\pi)^2} \times n_D$$

We set $n_D = 1$, but checked that solutions survive for

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

* Computing $A_D$ or $n_D$ in actual examples has so far remained out of reach, see however

[Kim 2107.09779, 2301.03602]
[Jefferson, Kim 2211.00210]
[Alexandrov et al. 2204.02981]

# The leading order EFT

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

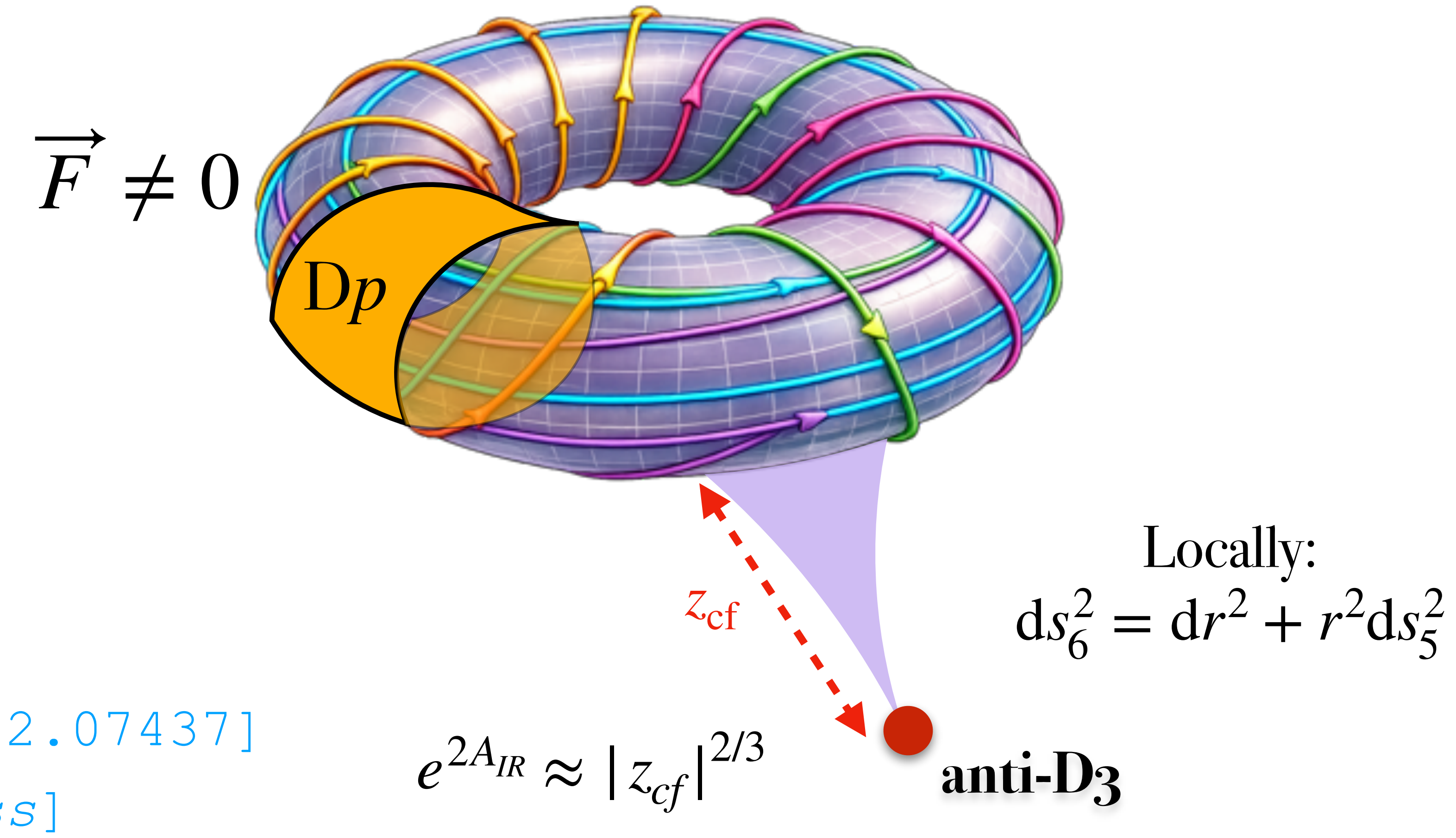
Our vacua "live" at **leading order in string perturbation theory** (including **all known** corrections), but are potentially vulnerable to unknown corrections.

$$K_{\text{l.o.}} \approx K_{\text{tree}} + K_{(\alpha')^3} + K_{\text{WSI}} \quad , \qquad T_i^{\text{l.o.}} \approx T_i^{\text{tree}} + \delta T_i^{(\alpha')^2} + \delta T_i^{\text{WSI}}$$

For the moment, we ignore

- **string loop corrections**, especially $\mathcal{N} = 1$ corrections
- **$\alpha'$ corrections to the KPV potential** for the anti-D3 brane
- …

[Junghans 2201.03572]
[(Hebecker), Schreyer, Venken 2208.02826, 2212.07437]
[Compagnin, Kim, **AS**, Schreyer *work in progress*]



# The leading order EFT

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

Our vacua "live" at **leading order in string perturbation theory** (including **all known** corrections), but are potentially vulnerable to unknown corrections.

We are laying the **groundwork** for future investigations in which all corrections can be consistently accounted for. Even if the current solutions cease to exist, there are new solutions to be found!

For the m

- **string loop corrections**, especially $\mathcal{N} = 1$ corrections
- $\alpha'$ **corrections to the KPV potential** for the anti-D3 brane
- …

[Junghans 2201.03572]
[(Hebecker), Schreyer, Venken 2208.02826, 2212.07437]
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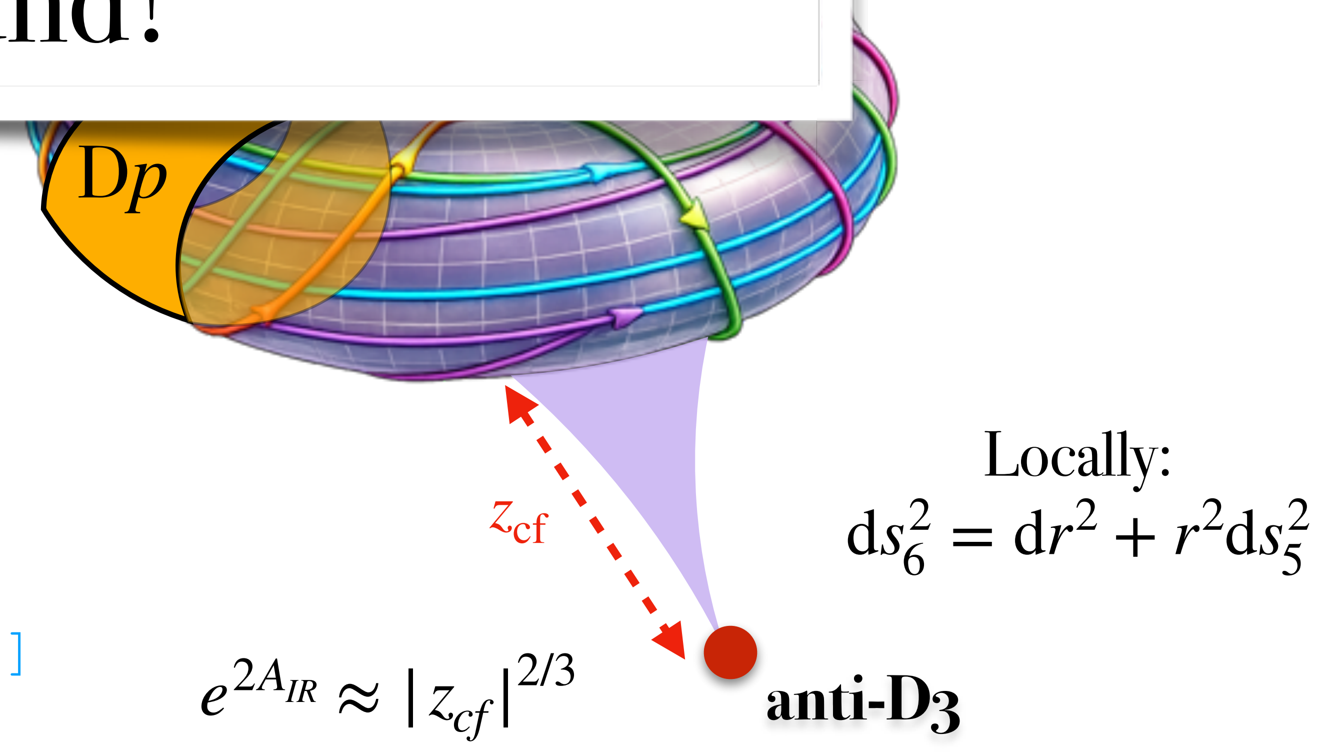
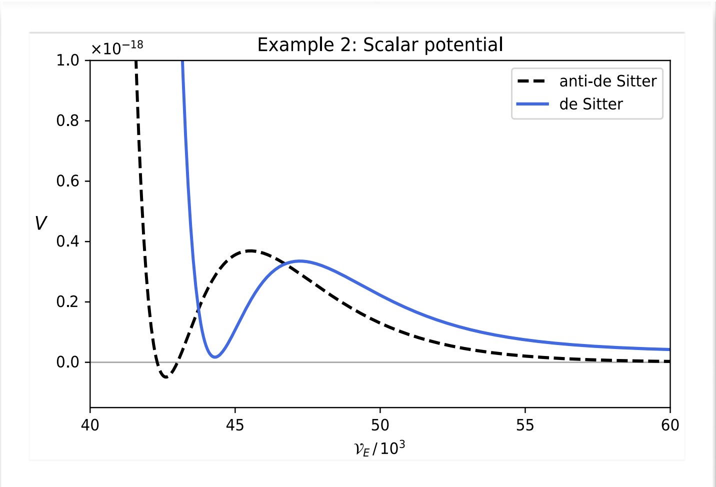
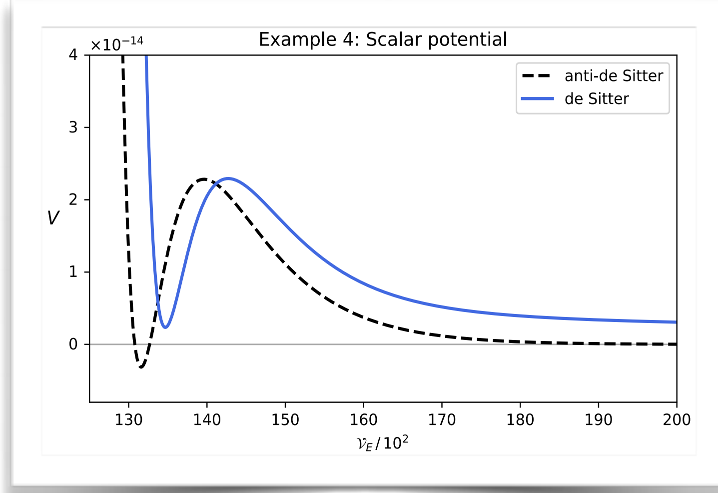


# 30 de Sitter vacua

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




# Even smaller CCs with SUSY

wip MacFadden, McAllister, Moritz, R. Nally, **AS**

Previously $\rho_{\rm vac} \sim -10^{-122} M_p^4$

Demirtas et al 2107.09064

Recall: choose $\vec{F} \in \mathbb{Z}^k$ such that $a_i = 0$, then

$$W_{\rm flux}(z) = a_3 z^3 + a_2 z^2 + a_1 z + a_0 + \sum_q N_q e^{2\pi i\, qz}$$

Improving upon search algorithms for suitable $\vec{F}$

$$|\rho_{\rm vac}| \lesssim 10^{-1230} M_p^4$$

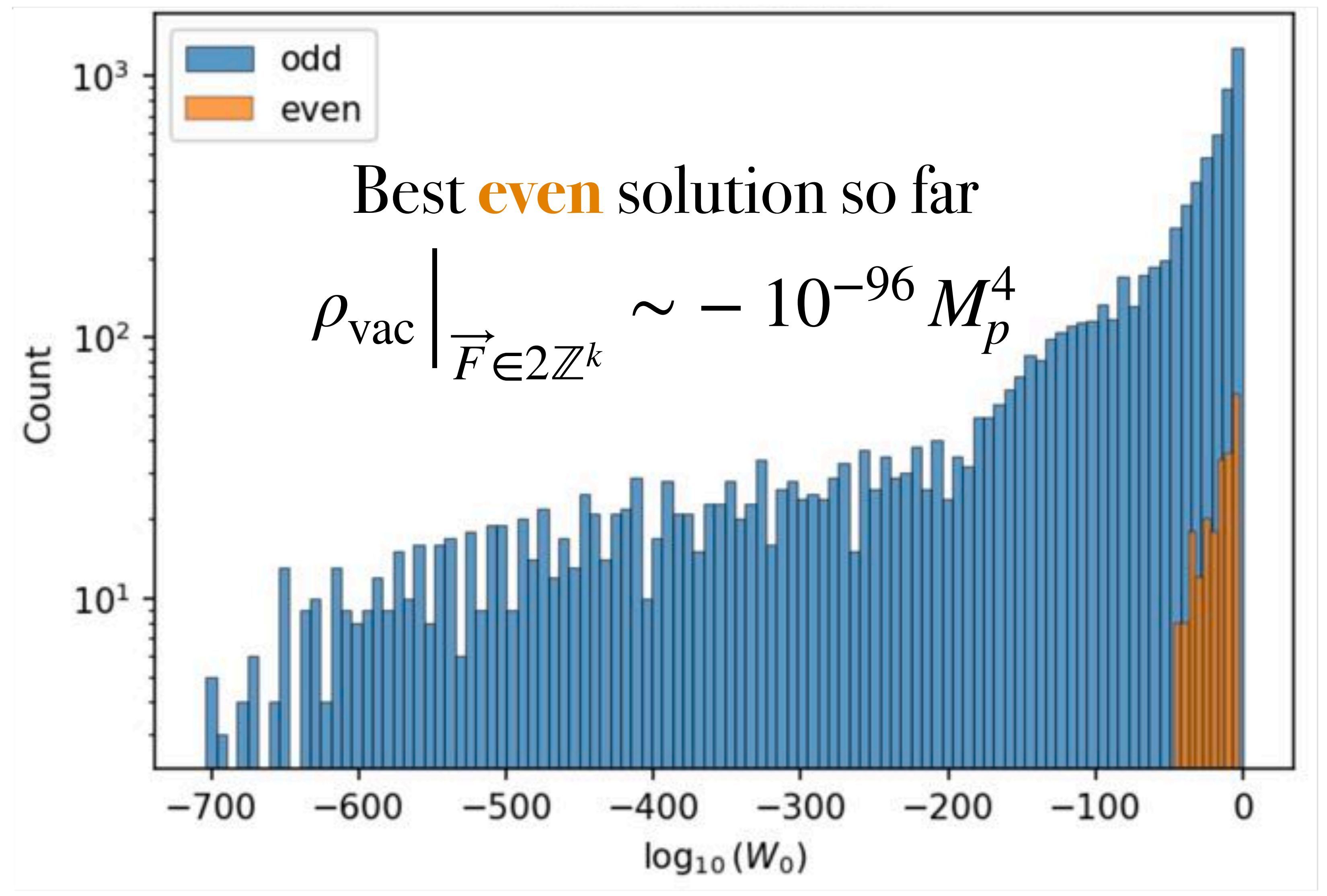
Even smaller plays **double role** here:

Uncertainty over precise flux quantisation conditions could imply that $\vec{F} \in 2\mathbb{Z}^k$ needs to be even.

[Frey, Polchinski hep-th/0201029]

For SUSY vacua, $D_{\Phi^I} W = 0$ we simply have

$$\langle V \rangle \approx -3e^K |W_0|^2 \qquad W_0 = \langle W_{\rm flux} \rangle$$



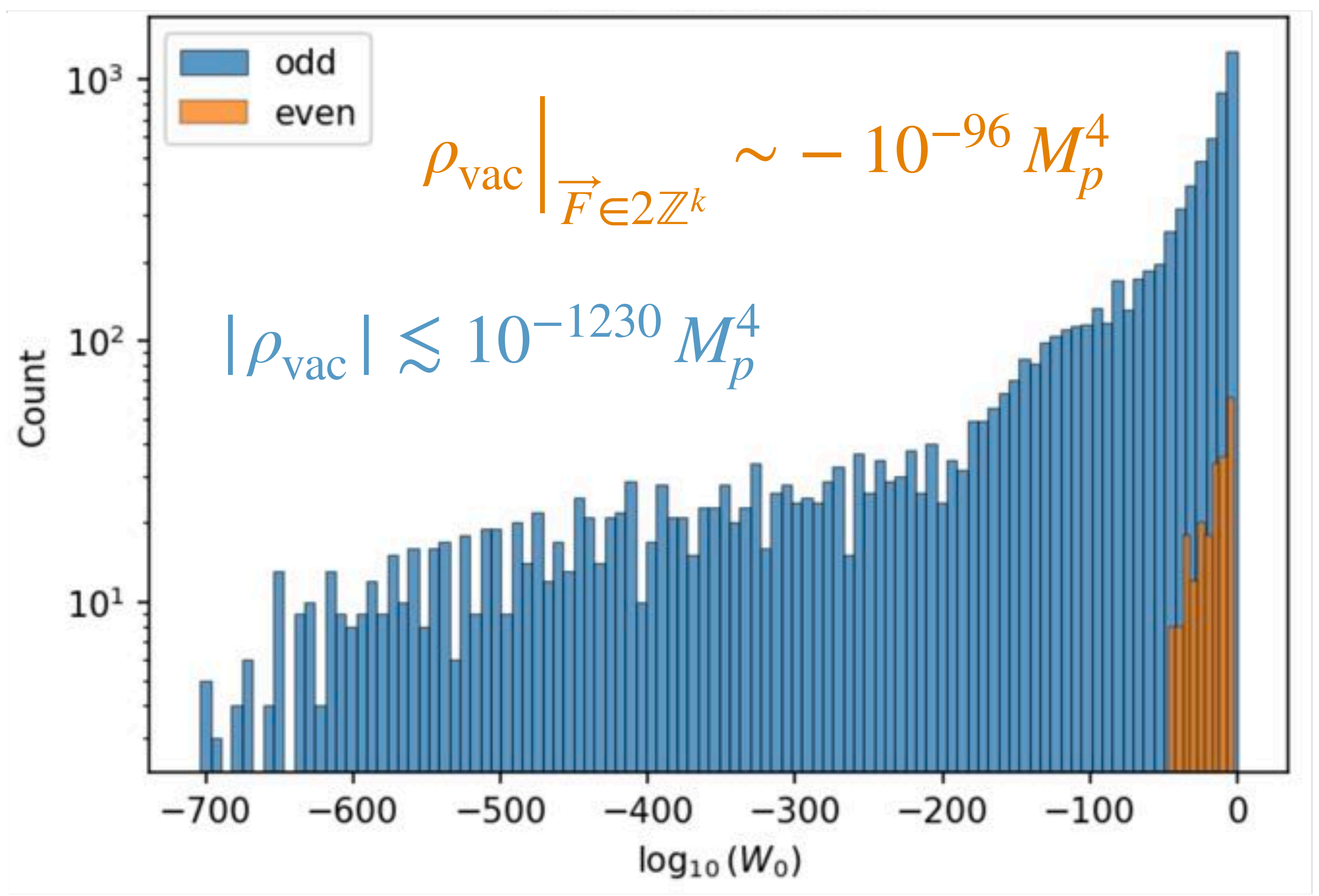
# Even smaller CCs with SUSY

*wip* MacFadden, McAllister, Moritz, R. Nally, **AS**

These solutions are safe against **perturbative corrections**

$$K \to K + g_s \Delta K \implies \langle V \rangle \approx -3e^K |W_0|^2 (1 + \mathcal{O}(g_s))$$

e.g. 2512.17095 McAllister, **AS**




These solution

- solve the **SUSY CC problem**
- explain how a **large (4D SUSY) Universe** can arise in a theory with a small fundamental length scale
- exhibit **scale separation** $R_{\rm cosmo.} \sim M_p^2/\sqrt{|\rho_{\rm vac}|} \gg \sqrt{\alpha'}$

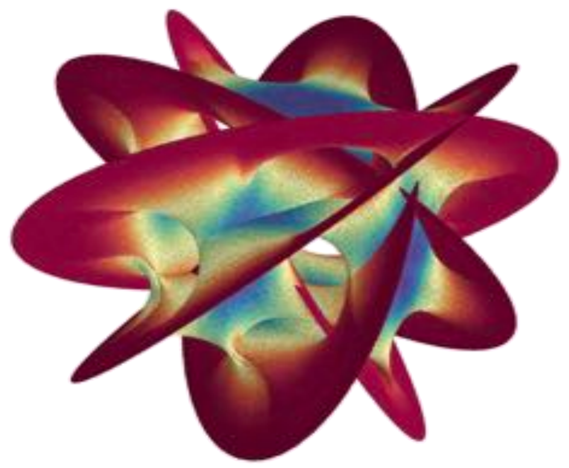
SUSY Universes much bigger than strings, but mostly "**empty**" ...

Could open new approaches to the **actual CC problem**!

# Fine tuning in QG?

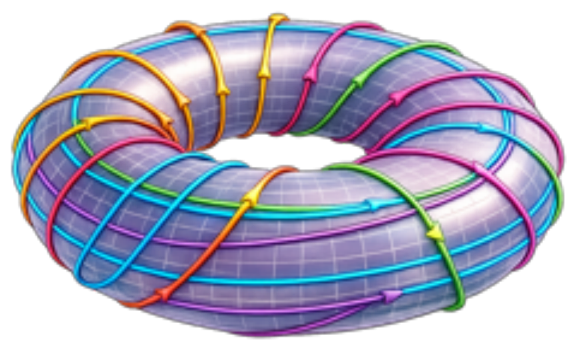
$$W_{\text{flux}}(z) = a_3 z^3 + a_2 z^2 + a_1 z + a_0 + \sum_q N_q \, e^{2\pi i\, qz}$$

**Mechanism is intrinsically tied to quantum gravity!**



Exact cancellation of polynomial terms due to

- **flux quantisation** (thanks Dirac), and
- **compactness** of internal manifold!

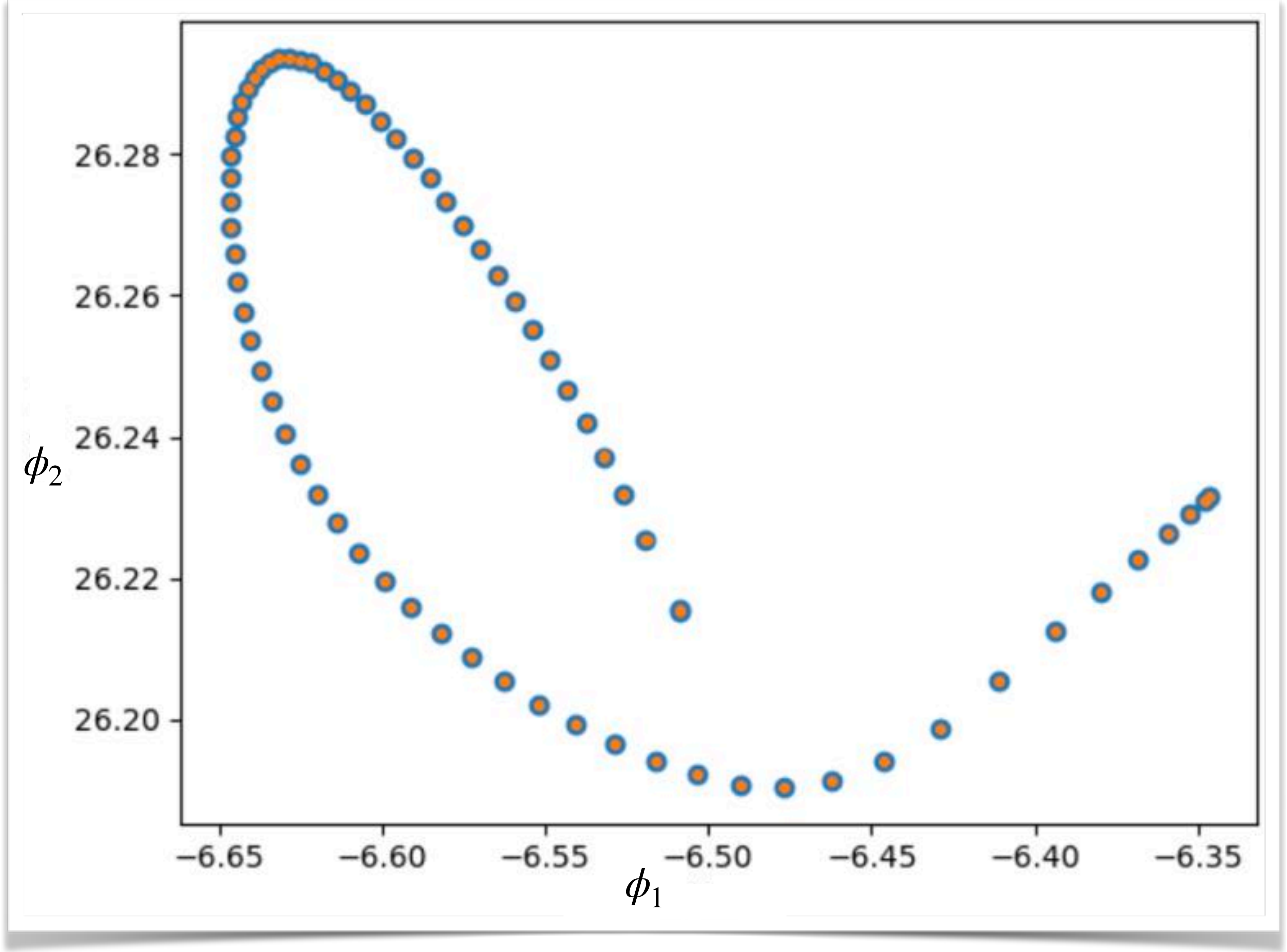


**Philosophical question:** Is this how nature works – with polynomial contributions canceling, leaving exponentials to dominate?

# Chains of AdS vacua

*wip* Compagnin, MacFadden, McAllister, Moritz, R. Nally, **AS**

In the **classical** theory → **chains** of AdS vacua

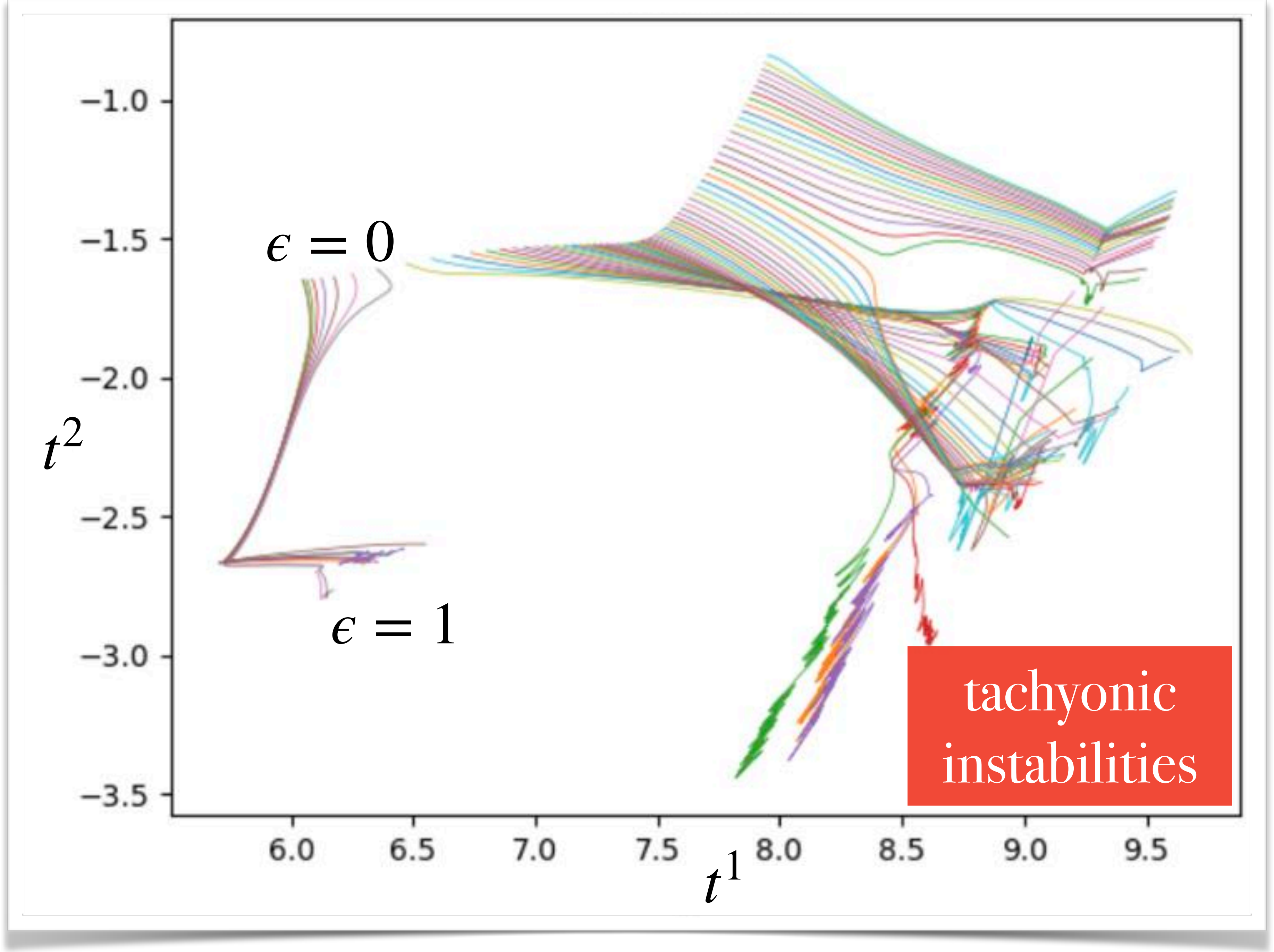



**Homotopy type analysis**

Add quantum corrections

$K \to K + \epsilon\delta K$

In the **quantum** theory → **intricate landscape**

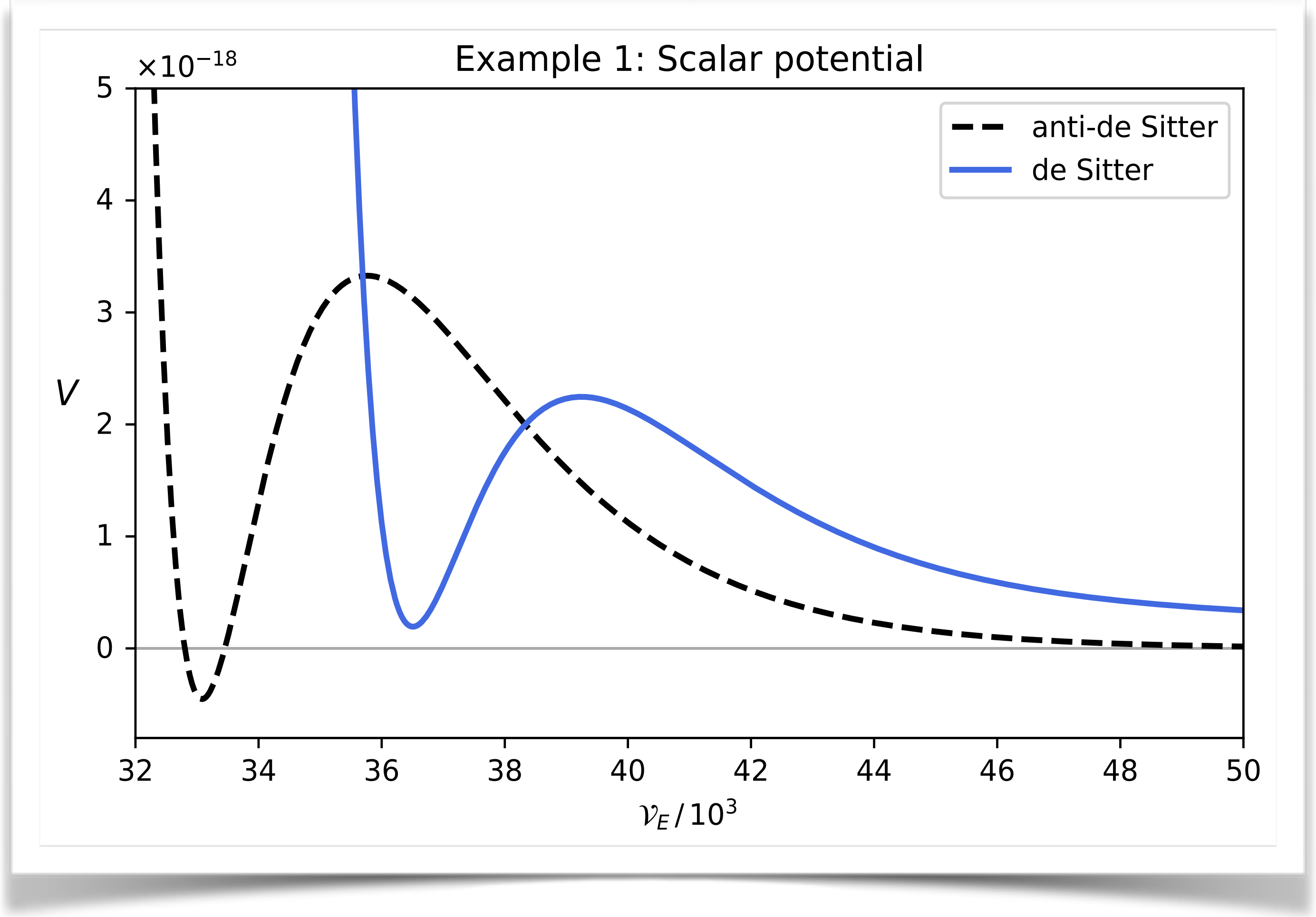



Highly interesting vacuum structures!

$\Longrightarrow$ **tunnelling** and **vacuum selection** in explicit setups?

*Coleman, De Luccia 1980;*
*… ; Johnson, Larfors 2008*

# Summary

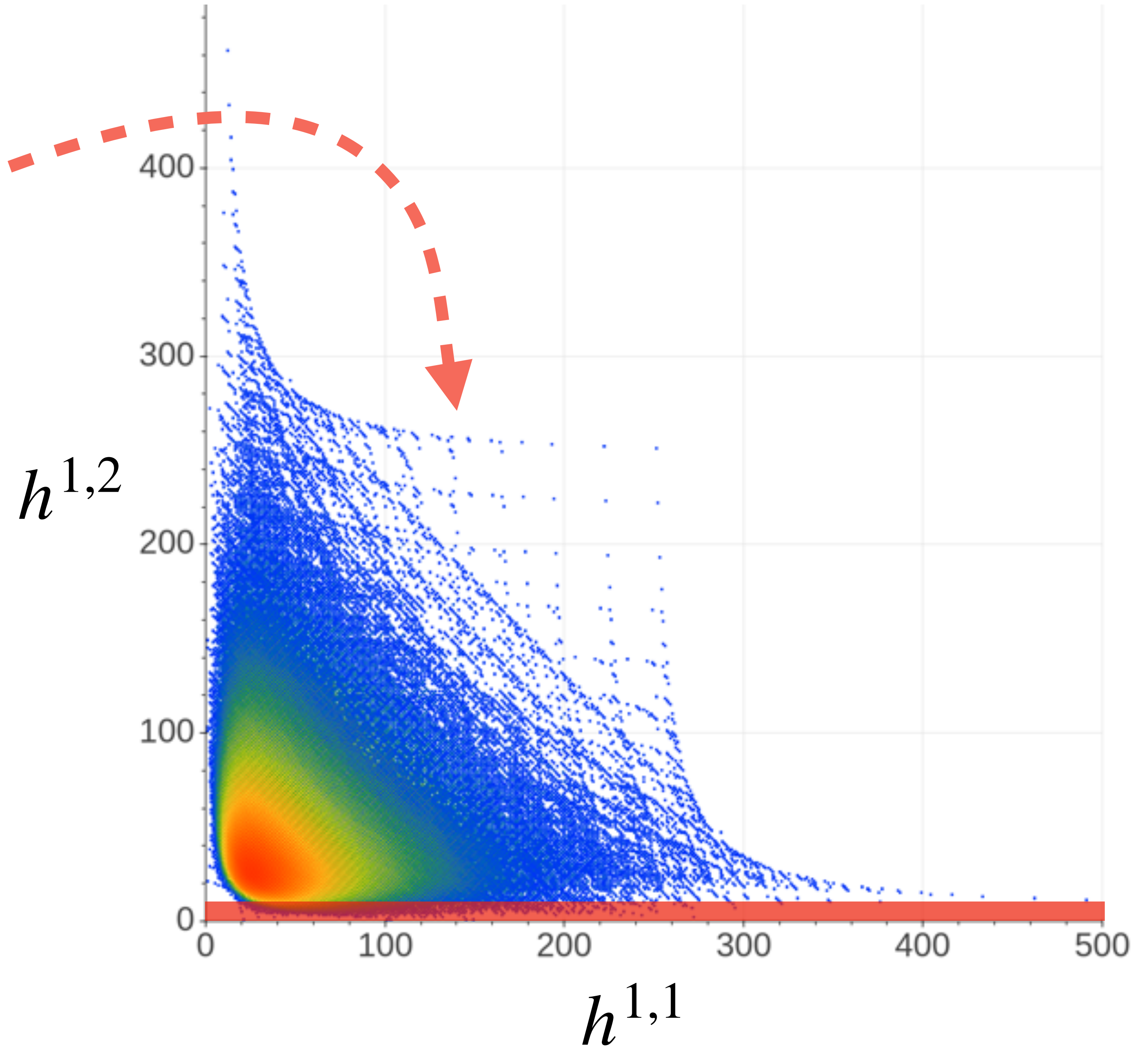



1. **We have come a long way since the early days of the string landscape:** ideas that once felt like fantasy, such as KKLT compactifications, are now moving to our fingertips.

2. **What once looked out of reach is now computable:** explicit candidate de Sitter constructions in string theory are no longer just a dream scenario.

3. **Even under this lamppost, the story is far from complete:** the computable corner explored here likely contains many more candidate vacua still waiting to be found.

4. **The next frontier is computational control:** the geometries are increasingly explicit, but the decisive quantum corrections are still the bottleneck.



# Thank you!

# Summary of Candidate de Sitter vacua

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

| 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 | $2.822\times10^{-8}$ | $+1.937\times10^{-19}$ |
| 2 | 8 | 150 | 16 | $\frac{93}{19}$ | 0.0571 | 0.00490 | 0.913 | $7.934\times10^{-9}$ | $+1.692\times10^{-20}$ |
| 3 | 8 | 150 | 18 | $\frac{40}{11}$ | 0.0442 | 0.0222 | 0.796 | $8.730\times10^{-8}$ | $+4.983\times10^{-19}$ |
| 4 | 5 | 93 | 20 | $\frac{17}{5}$ | 0.0404 | 0.0539 | 0.808 | $1.965\times10^{-6}$ | $+2.341\times10^{-15}$ |
| 5 | 5 | 93 | 16 | $\frac{29}{10}$ | 0.0466 | 0.0304 | 0.746 | $8.703\times10^{-7}$ | $+2.113\times10^{-15}$ |

# The leading order EFT

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

The leading order potential is defined by

$$V = V_F + V_{\rm up} \ , \qquad V_F = e^K\left(K^{I\bar{J}}\, D_I W \, D_{\bar{J}} \overline{W} - 3\,|W|^2\right) \ , \qquad V_{\rm up} = V_{\rm KPV}^{\overline{\rm D3}} \ , \qquad W(z,\tau,T) = W_{\rm flux}(z,\tau) + W_{\rm np}(z,\tau,T)$$

We work in the leading-order EFT where the Kähler potential and Kähler coordinates are given by

$$K_{\rm l.o.} \approx K_{\rm tree} + K_{(\alpha')^3} + K_{\rm WSI} \ , \qquad T_i^{\rm l.o.} \approx T_i^{\rm tree} + \delta T_i^{(\alpha')^2} + \delta T_i^{\rm WSI}$$

Genus-zero Gopakumar-Vafa invariants $\mathcal{N}_{\mathbf{q}}$ can be computed using `CYTools`.
[Gopakumar, Vafa hep-th/9809187]

Here the tree level $\alpha'$ and worldsheet instanton (WSI) corrections amount to

$$K_{\rm l.o.} = -2\log\left[\frac{1}{6}\kappa_{ijk}\, t^i t^j t^k - \frac{\zeta(3)\chi(X)}{4(2\pi)^3} + \frac{1}{2(2\pi)^3}\sum_{\mathbf{q}\in\mathcal{M}(X)} \mathcal{N}_{\mathbf{q}}\left(\mathrm{Li}_3\left((-1)^{\gamma\cdot\mathbf{q}} e^{-2\pi\mathbf{q}\cdot\mathbf{t}}\right) + 2\pi\mathbf{q}\cdot\mathbf{t}\ \mathrm{Li}_2\left((-1)^{\gamma\cdot\mathbf{q}} e^{-2\pi\mathbf{q}\cdot\mathbf{t}}\right)\right)\right],$$

$$T_i^{\rm l.o.} = \frac{1}{2}\kappa_{ijk}\, t^j t^k - \frac{\chi(D_i)}{24} + \frac{1}{(2\pi)^2}\sum_{\mathbf{q}\in\mathcal{M}(X)} q_i\, \mathcal{N}_{\mathbf{q}}\, \mathrm{Li}_2\left((-1)^{\gamma\cdot\mathbf{q}} e^{-2\pi\mathbf{q}\cdot\mathbf{t}}\right) + i\int_X C_4\wedge\omega_i \,.$$

See in particular:
[Becker et al. hep-th/0204254]
[Robles-Llana et al. hep-th/0612027, 0707.0838]
[Grimm 0705.3253]

For the moment, we ignore

- string loop corrections, especially $\mathcal{N}=1$ corrections
- $\alpha'$ corrections to the KPV potential for the anti-D3 brane as derived in
- …

[Junghans 2201.03572, (Hebecker), Schreyer, Venken 2208.02826, 2212.07437]