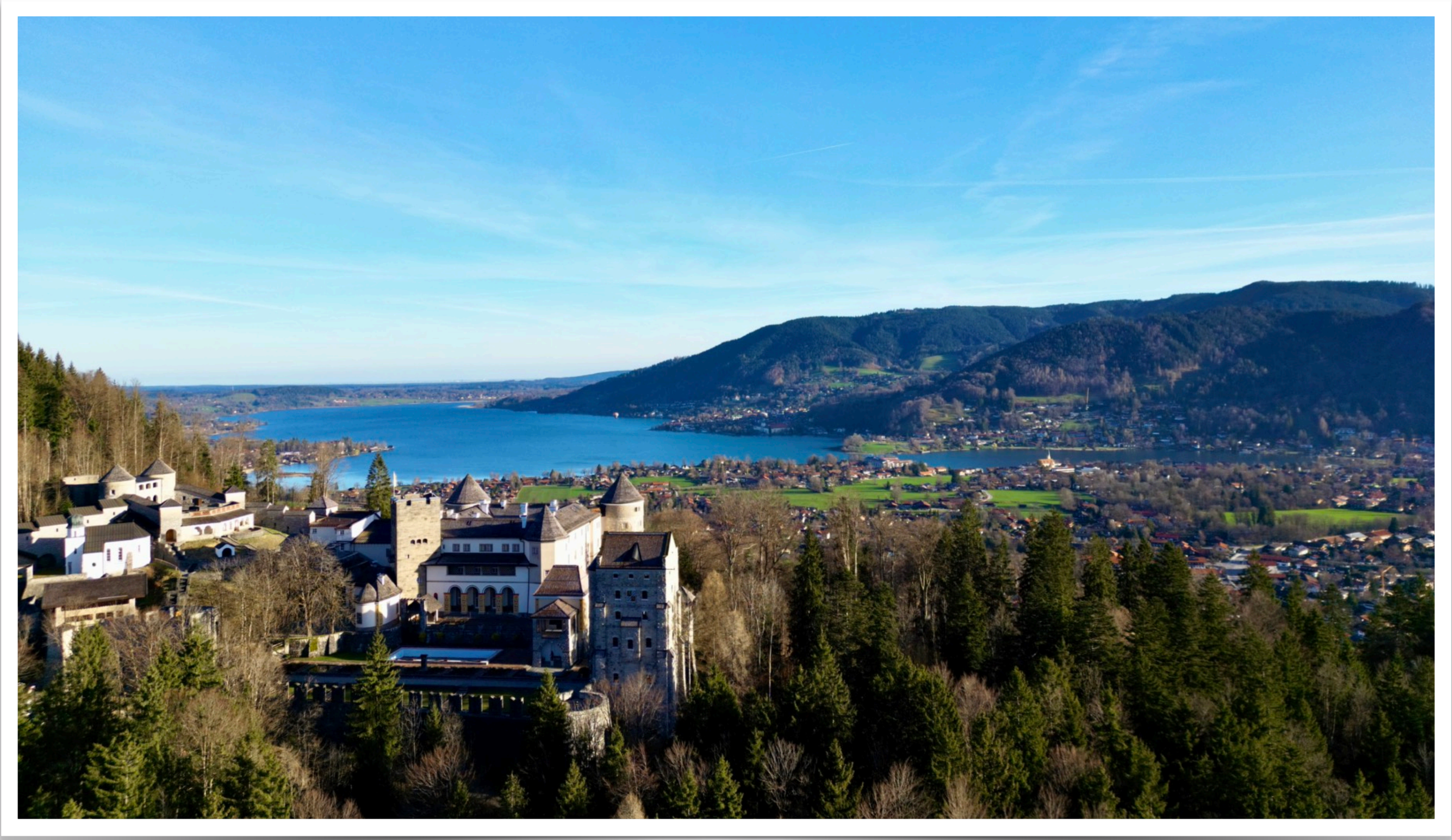


Exploring new corners of the string landscape

Andreas Schachner

Geometry, Strings and the Swampland Program

Ringberg Castle, Tegernsee

March 22, 2024

Upshot

Numerical minimisation:

How do we find critical points in string theory?

based on work with

- Dubey, Krippendorf: *2306.06160*
- Ebelt, Krippendorf: *2307.15749*
- Krippendorf: *2308.15525*

CONJECTURE

There must be more out there than just KKLT, LVS, DGKT, …

One way forward is to make vacua construction more systematic using numerical methods.

Numerical optimisation:

How do we select EFTs from string theory?

based on work with

- MacFadden, Sheridan: 2403.XXXX

Type IIB orientifold flux compactifications

Notation and convention

Consider Type IIB superstring theory on a CY orientifold X with O3/O7-planes and scalar fields:

complex structure moduli z^a, $a = 1,\ldots,h^{2,1}_-$, Kähler moduli T_α, $\alpha = 1,\ldots,h^{1,1}_+$, axio-dilaton $\tau = c + \mathrm{i}\, s$

In the 4D EFT, the **F-term scalar potential** for these fields is defined by

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

in terms of a Kähler potential K and the superpotential W.

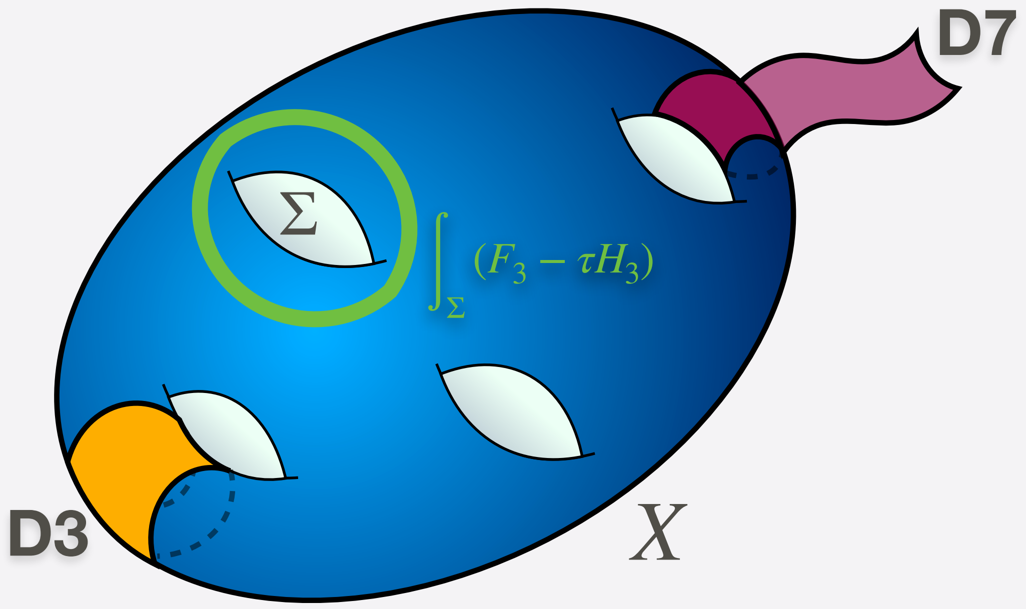
The superpotential receives contributions from two sources

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

Fluxes have to satisfy D3-tadpole cancellation condition

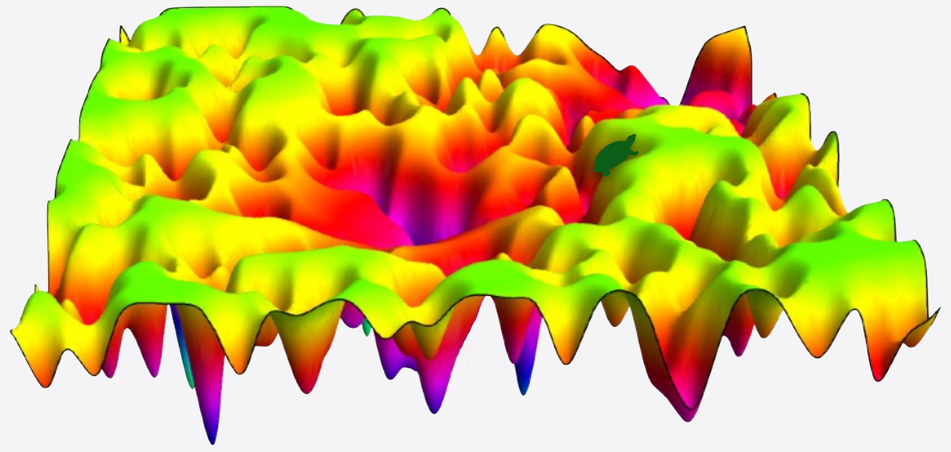
$$N_{\text{flux}} + N_{D3} - \overline{N}_{D3} = Q_{D3}\ ,\qquad N_{\text{flux}} = \int_X H_3\wedge F_3$$

with Q_{D3} depending on localised sources like D7-branes and O3/O7-planes.



The string theory landscape

Numerical minimisation in string compactifications

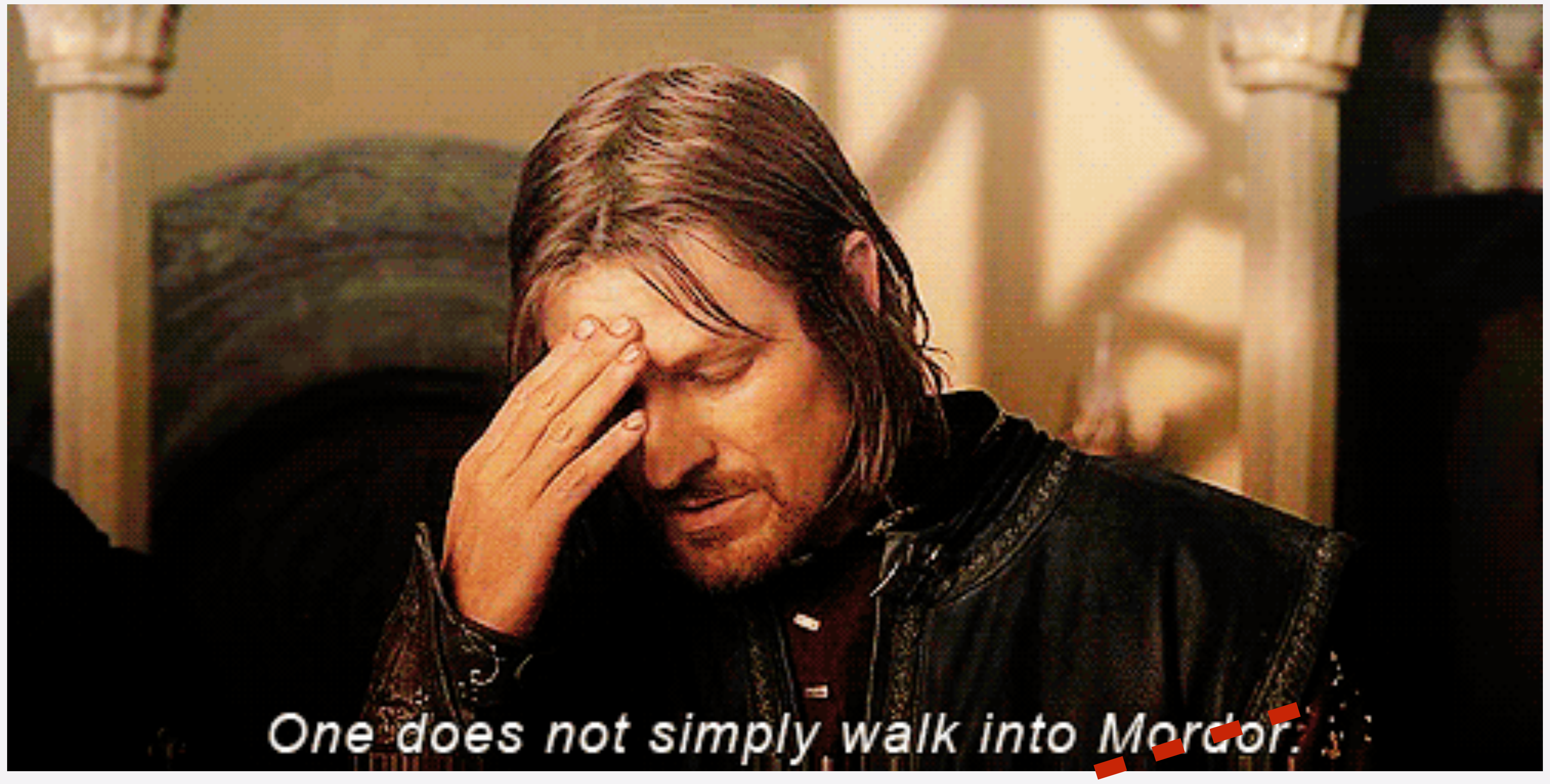


Bousso et al.: hep-th/0004134
Susskind: hep-th/0302219

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 $\Rightarrow$ **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 in a controlled way. **How?**

JAXVacua

Model construction
CY data from CYTools
as input

EFT module
Auto-differentiation to
compute EFT from K, W

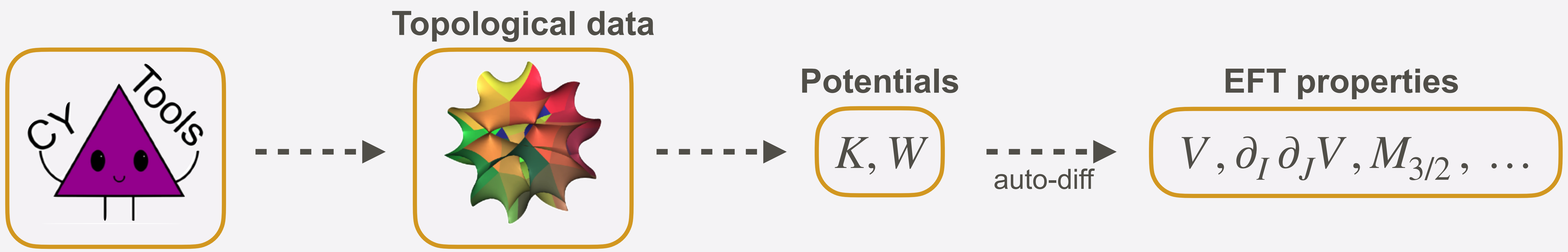
Sampling module
Choice of initial guesses
for fields and parameters

Optimisation module
Find minima by solving $\partial_I V = 0$
using numerical optimiser

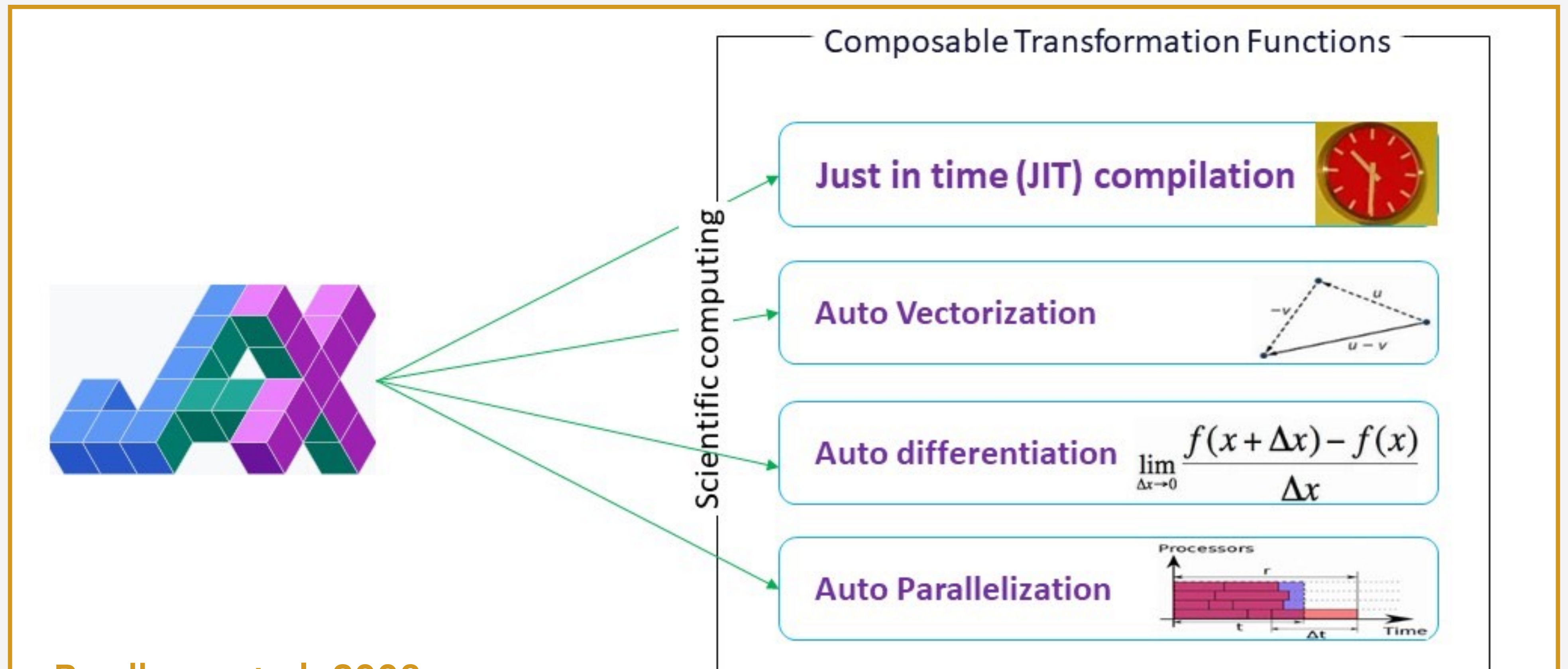
Filter module
Consistency of truncation
and absence flat directions

A framework for constructing EFTs from string theory

[Dubey, Krippendorf, AS: 2306.06160]

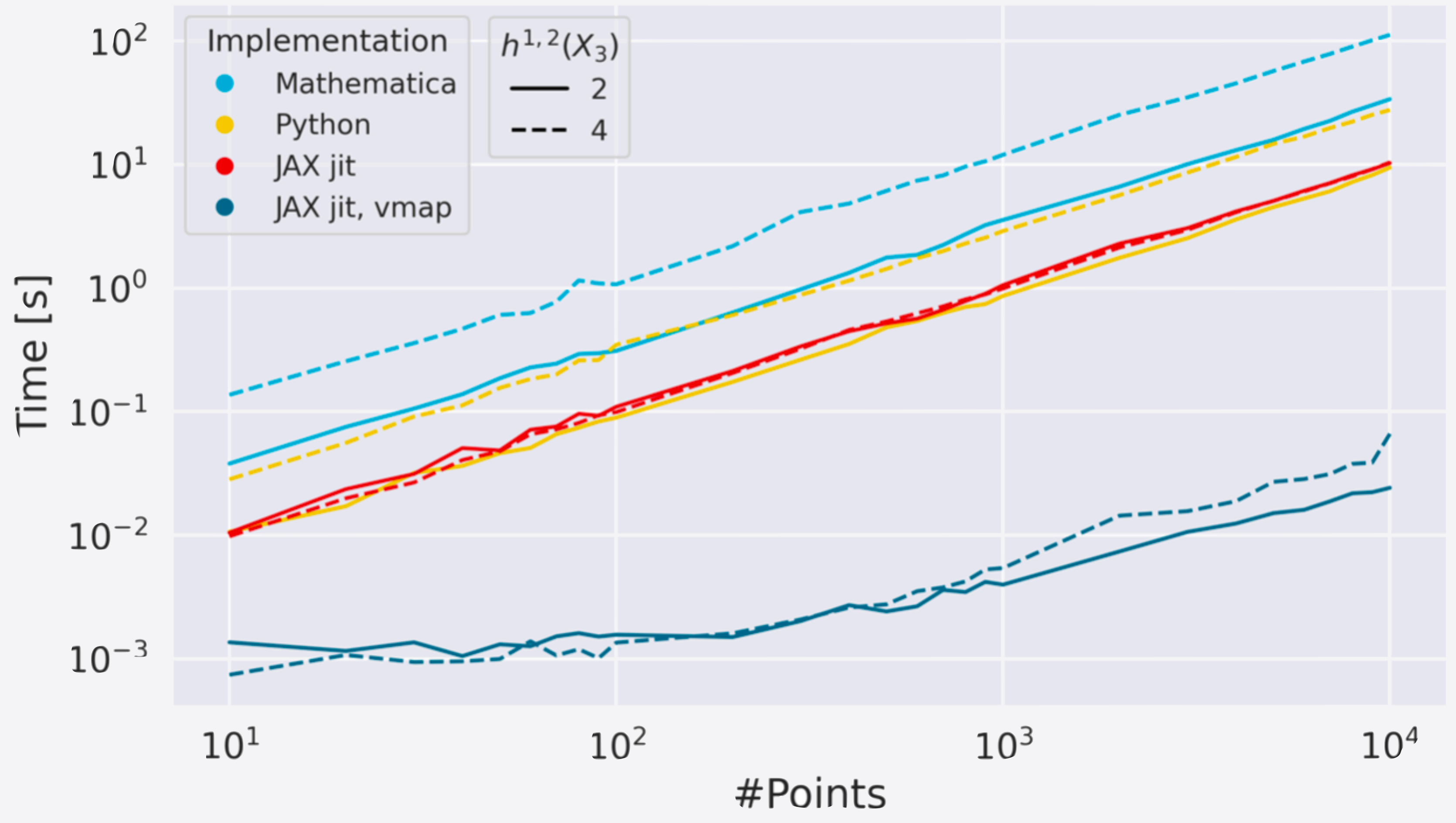


Demirtas et al. 2211.03823



Bradbury et al. 2008

Timing for evaluating ∂W



Orders of magnitude speed improvements!

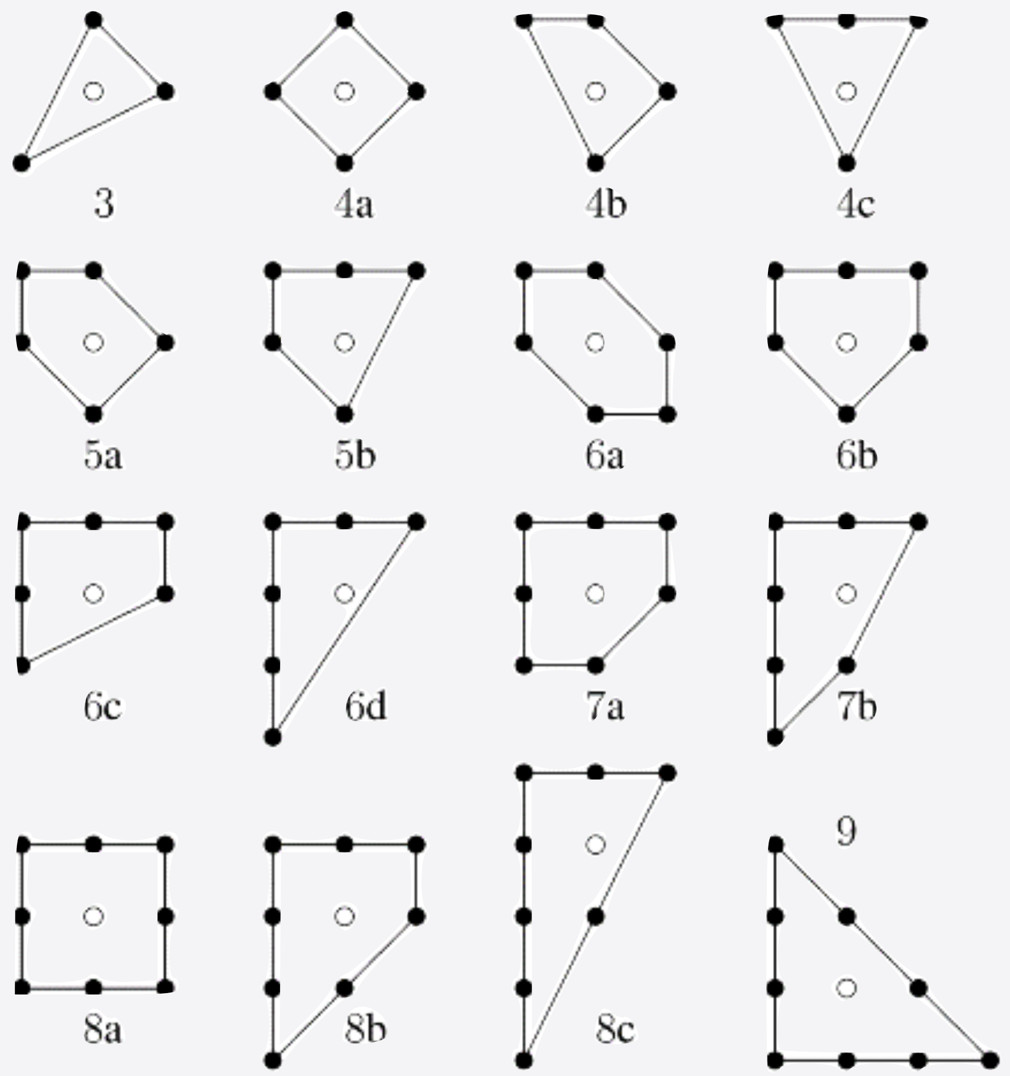
I will present one particular use case: **flux vacua at Large Complex Structure (LCS).**

But our framework is able to

- add Kähler moduli (work in progress)
- find vacua for all CICYs (work in progress with Cicoli, Krippendorf, Piantadosi)
- work with general periods away from LCS (please help…)
- F-theory compactifications
- …

Model construction

Scan for Geometries and Orientifolds

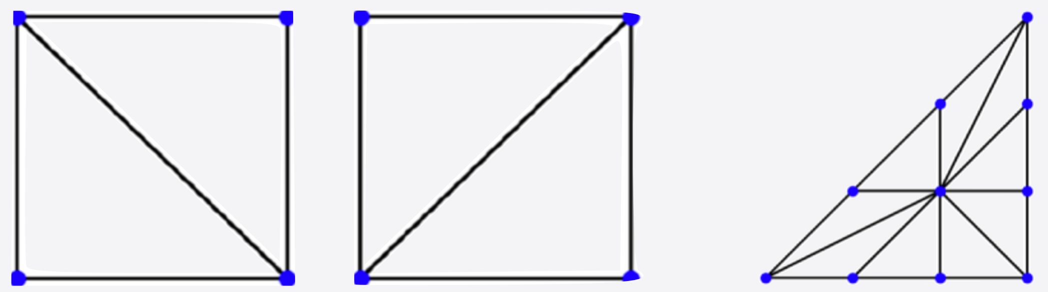


473,800,776 reflexive polytopes in 4D Kreuzer, Skarke (KS) [hep-th/0002240]

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

In our constructions:

* holomorphic orientifold projections following [Moritz 2305.06363].
* only $\mathbb{Z}_2$-involutions $x \to -x$ with O3/O7-planes such that $h^{1,1}_- = h^{1,2}_+ = 0$.
* the D3-tadpole is simply $Q_{D3} = h^{1,1} + h^{2,1} + 2$.

Model construction

Flux vacua at Large Complex Structure (LCS)

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

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

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

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

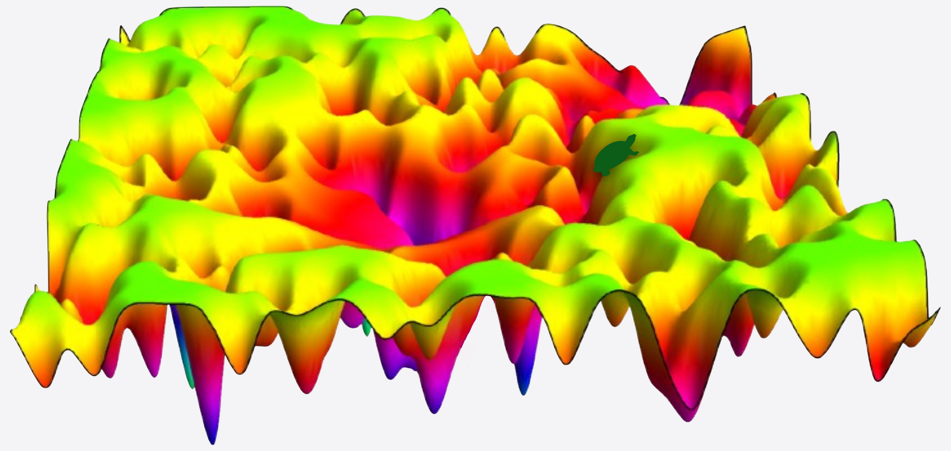
in terms of (see [Demirtas et al. 2303.00757] for recent computational advances)

$$\tilde{c}_a = \int_{\widetilde{X}} c_2(\widetilde{X}) \wedge \tilde{\beta}_a \ , \qquad \tilde{a}_{ab} \equiv \frac{1}{2} \begin{cases} \widetilde{\kappa}_{aab} & a \geq b \\ \widetilde{\kappa}_{abb} & a < b \end{cases} \ , \qquad \chi(\widetilde{X}) = \int_{\widetilde{X}} c_3(\widetilde{X}) \ , \qquad \mathscr{N}_{\tilde{\mathbf{q}}} = \text{genus zero GV invariants}$$

[Gopakumar, Vafa hep-th/9809187]

The string theory landscape

Flux vacua revisited



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

Focussing on the complex structure sector, the F-flatness conditions imply

$$D_\tau W = D_{z^a} W = 0 \qquad \Rightarrow \qquad \langle V_{\mathrm{Flux}} \rangle = 0 \qquad \Rightarrow \qquad \text{Minkowski vacua}$$

This implies that the flux G_3 is **imaginary self-dual (ISD)** [GKP hep-th/0105097]

$$\star_6 G_3 = i G_3 \quad \leftrightarrow \quad f_I = \left(\mathscr{M}(z^i, \bar{z}^i)\, \Sigma\, s + c \right)_{IJ} h^J \quad , \qquad \Sigma = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

in terms of ISD matrix $\mathscr{M}(z^i, \bar{z}^i)$ (see also talk by Erik).

HOW CAN WE EFFICIENTLY GENERATE SUCH VACUA NUMERICALLY?

Some earlier searches:

Numerical analysis (so far mainly at low $h^{1,2}$):

- $h^{1,2} = 1$: [Plauschinn et al. 2310.06040]
- $h^{1,2} = 2$: [Martinez-Pedrera et al. 1212.4530]
- $h^{1,2} = 3$: [Cicoli et al. 1312.0014]
- …

Analytic approximations for special flux choices:

- PFVs [Demirtas et al. 1912.10047]
- Type IIB1/2 [Coudarchet et al. 2212.02533, 2304.04789]
- …

Sampling Module

Random vs. ISD Sampling

For alternative sampling techniques, see [Denef et al. hep-th/0404257, Louis et al. 1208.3208]

HOW DO WE EFFICIENTLY FIND CRITICAL POINTS OF THE FLUX POTENTIAL?

We have to sample flux quanta and initial guesses:

- **Random sampling:** Sample fluxes $\vec{F} = (f_a, h^b) \in \mathbb{Z}^N$ uniformly and solve $D_{z^a}W = 0$ for the moduli z^a
- **ISD sampling:** Sample **half of the fluxes** n^J plus initial points z_0^i, τ_0 and fix other fluxes $\tilde{m}_I$ by the ISD condition

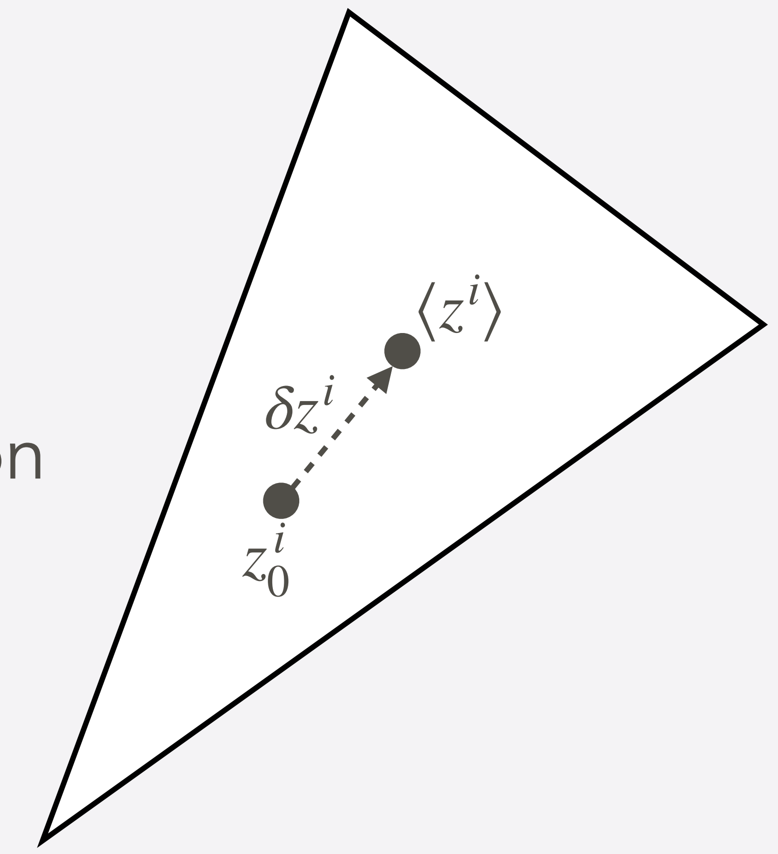
$$\tilde{m}_I = \Lambda^{(0)}_{IJ}\, n^J\,, \quad \Lambda^{(0)}_{IJ} = \Lambda_{IJ}(z_0^i, \bar{z}_0^i, \tau_0)$$

see also [Tsagkaris, Plauschinn 2207.13721]

In general, rounding becomes necessary

$$\tilde{m}_I \in \mathbb{R} \xrightarrow{\textit{rounding}} m_I = \tilde{m}_I + \delta m_I \in \mathbb{Z} \xrightarrow{\textit{shift}} \langle z^i \rangle = z_0^i + \delta z^i\,, \quad \langle \tau \rangle = \tau_0 + \delta\tau$$

shifting the true moduli VEVs $\langle z^i \rangle, \langle \tau \rangle$ away from the initial guess.



We solve the ISD conditions for given choices of fluxes and starting points using the python package `scipy.optimize`!

Example: We can choose n^J to be the NSNS 3-form fluxes h^J, then

$$\tilde{f}_I = \Lambda^{(0)}_{IJ}\, h^J\,, \quad \Lambda^{(0)}_{IJ} = \mathscr{M}(z_0^i, \bar{z}_0^i)\,\Sigma\,\mathrm{Im}(\tau_0) + \mathrm{Re}(\tau_0)$$

where $\tilde{f}_I$ are (continuous) RR 3-form fluxes.

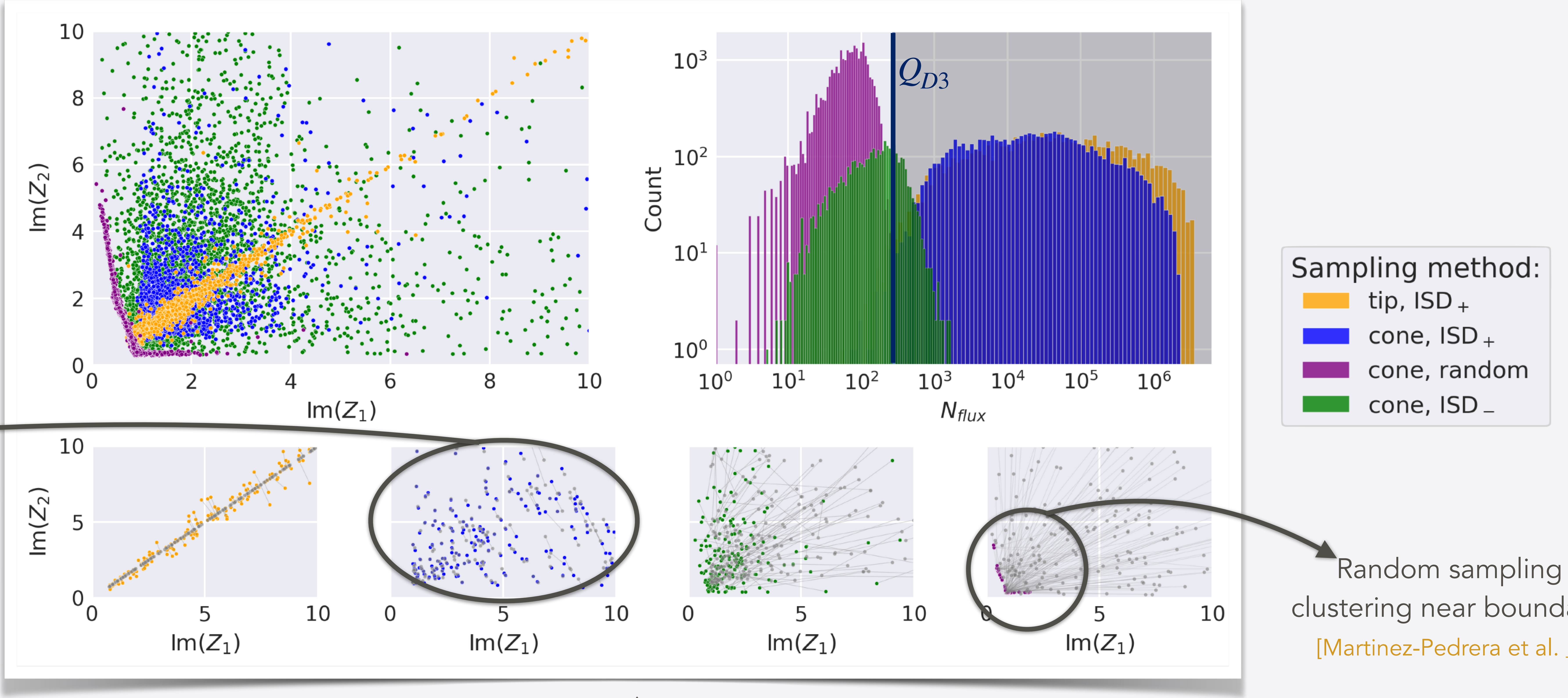
JAXVacua

Sampling bias at $h^{1,2} = 2$

[Dubey, Krippendorf, AS: 2306.06160]

Study degree 18 hypersurface in $\mathbb{P}[1,1,1,6,9]$ which admits an orientifold with $h^{1,1}_- = h^{1,2}_+ = 0$ and $Q_{D3} = 276$

see e.g. [Crinò, Quevedo, AS, Valandro: 2204.13115]



Shifts δz^i small

$\langle z^i \rangle = z_0^i + \delta z^i$

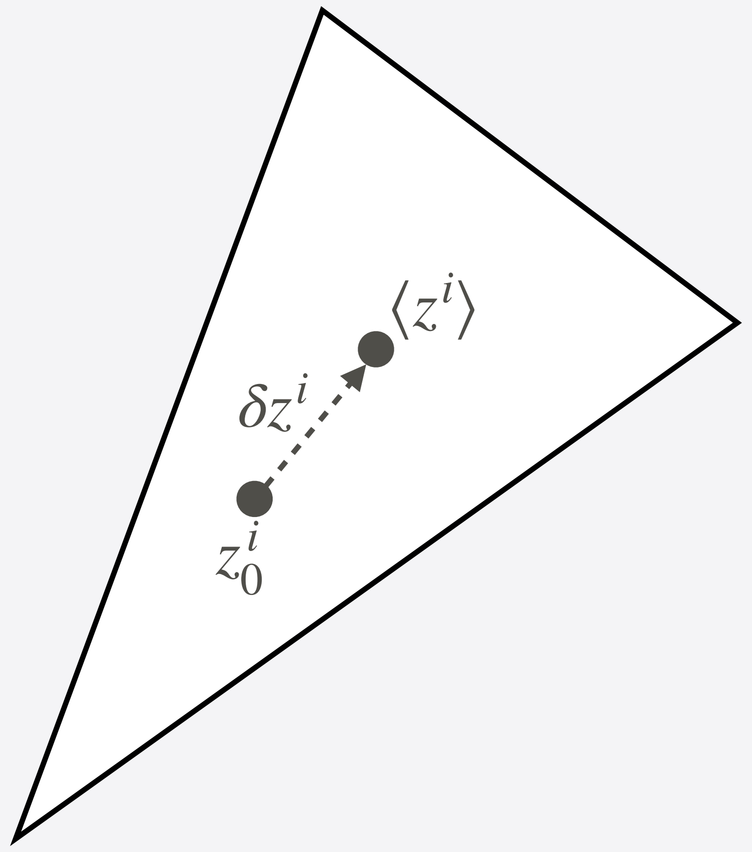
MORE EFFICIENT SAMPLING STRATEGY

Random sampling leads to clustering near boundary, see e.g. [Martinez-Pedrera et al. 1212.4530]!

Including GVs up to degree 10.

Optimisation module

ISD optimiser — Part 1



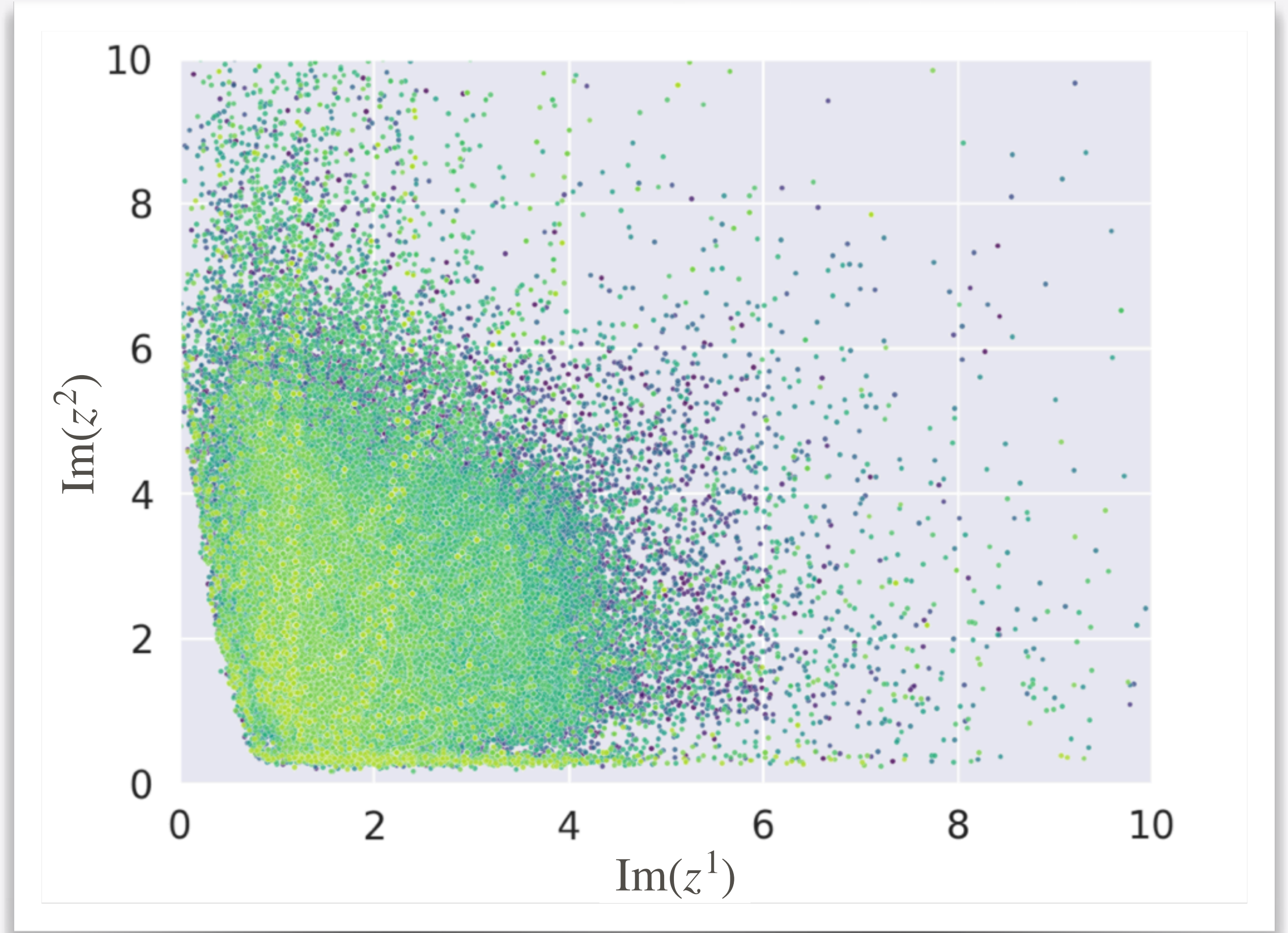
CAN WE SOLVE ISD CONDITIONS MORE EFFICIENTLY?

From ISD sampling, we obtain

$$\tilde{m}_I = \Lambda^{(0)}_{IJ}\, n^J \in \mathbb{R} \quad \xrightarrow{\textit{rounding}} \quad m_I = \tilde{m}_I + \delta m_I \in \mathbb{Z} \quad \xrightarrow{\textit{shift}} \quad \langle z^i \rangle = z_0^i + \delta z^i \,, \quad \langle \tau \rangle = \tau_0 + \delta\tau$$

We can estimate the shifts $\delta z^i, \delta\tau$ in the moduli by solving the **linearised ISD equation**:

$$m_I = \Lambda_{IJ}(\langle z^i \rangle, \langle \bar{z}^i \rangle, \langle \tau \rangle)\, n^J \quad \Rightarrow \quad \delta m_I = \left(\delta z^k \partial_{z^k} \Lambda_{IJ} + \delta \bar{z}^k \partial_{\bar{z}^k} \Lambda_{IJ} + \delta\tau \partial_\tau \Lambda_{IJ} \right)\Big|_{z_0^i, \tau_0} n^J + \ldots$$



This idea can be used to **iteratively solve ISD condition** which is advantageous because

- constraints like **tadpole cancellation** or **Kähler cone hyperplanes** can be easily included
- `JAX`-compatible (in particular **differentiable** and **parallelisable**)
- works for **general** choices of fluxes

Optimisation module

ISD optimiser — Part 2

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`

[Martinez-Pedrera et al. 1212.4530]

vs.

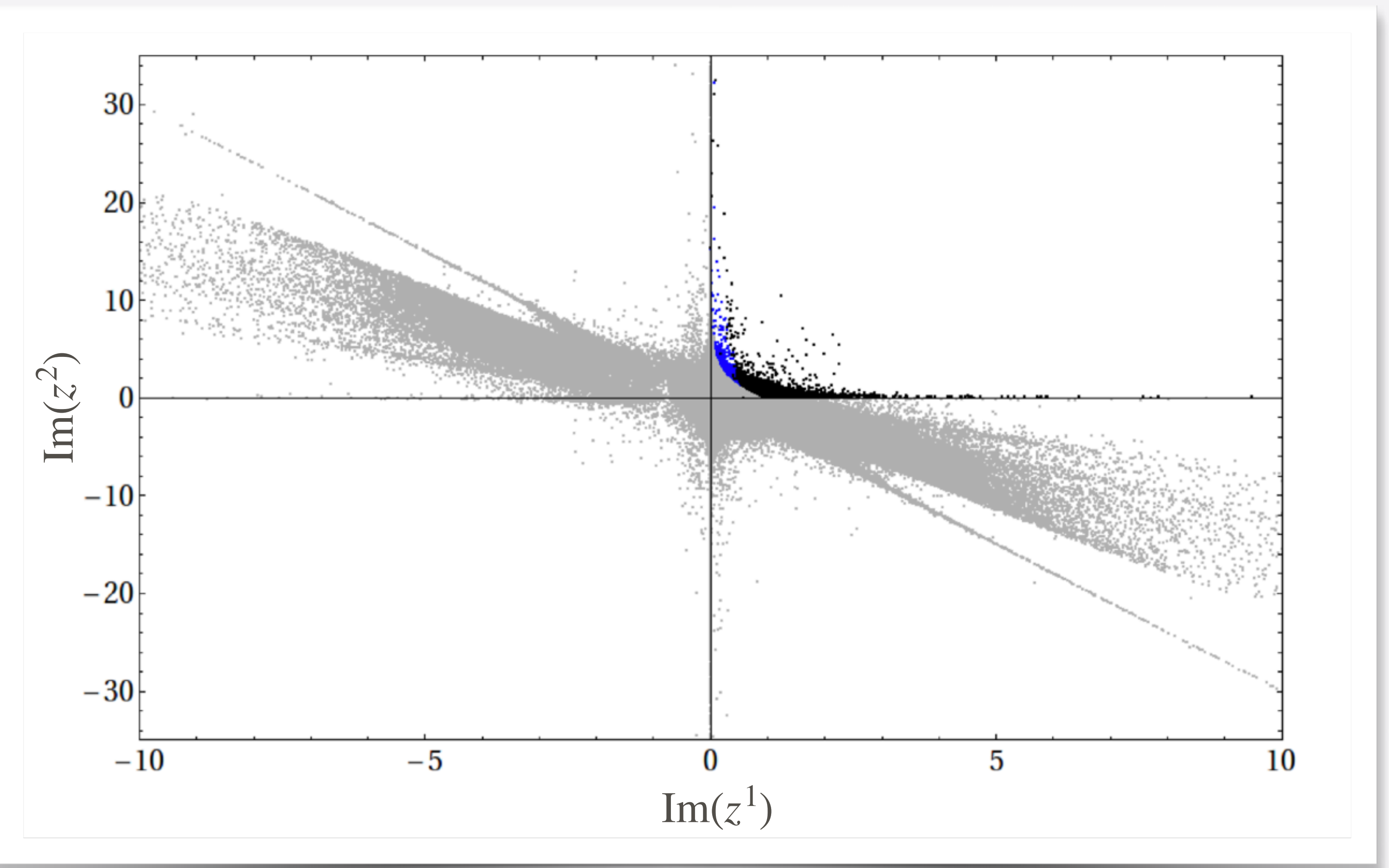
4 cores with 5GB of memory **33,019 solutions** in **45 minutes** using `scipy.optimize`

[Dubey, Krippendorf, AS 2306.06160]

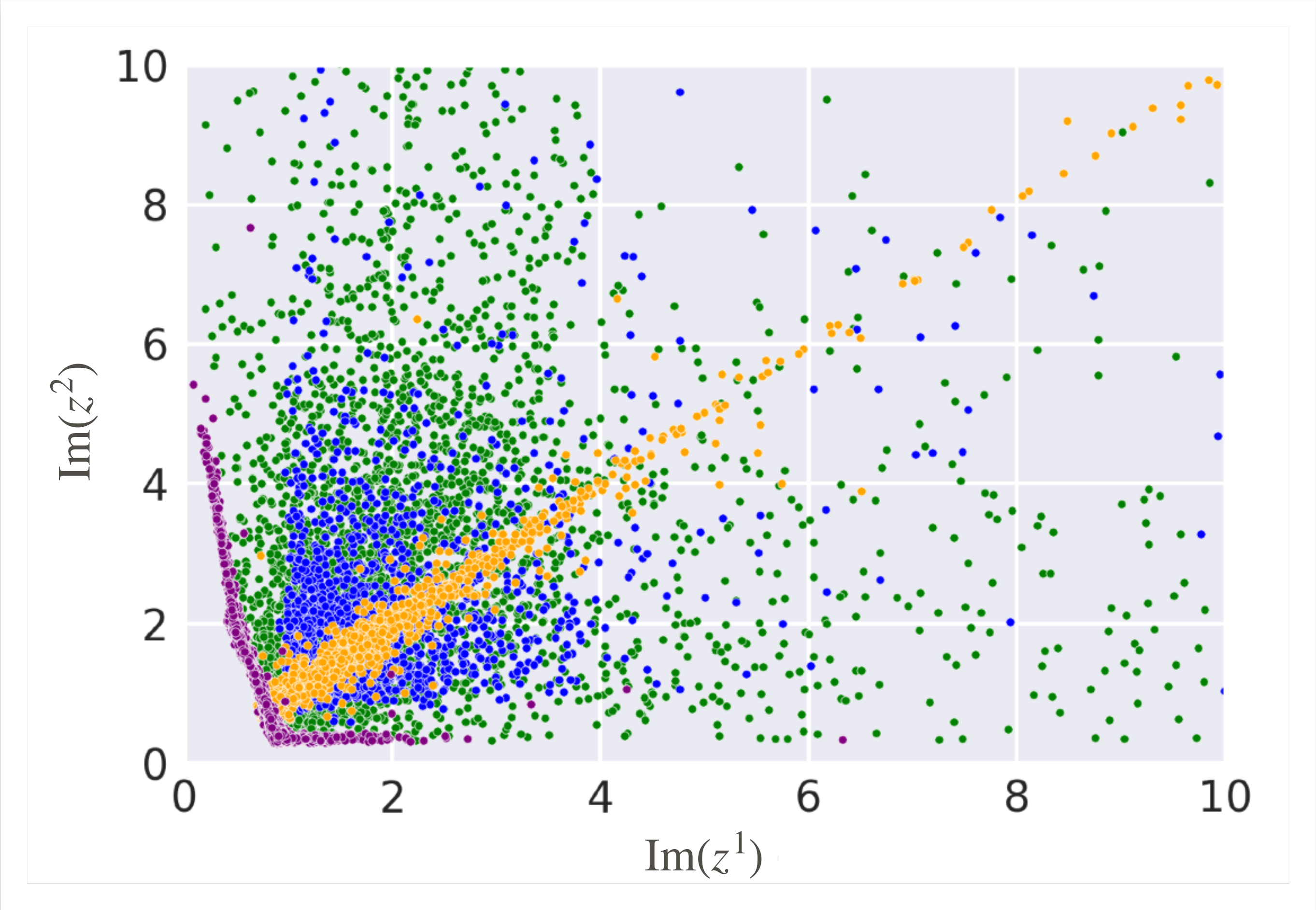
vs.

2 cores with 200MB of memory **94,157 solutions** in **<1 minute** using `ISD optimiser`

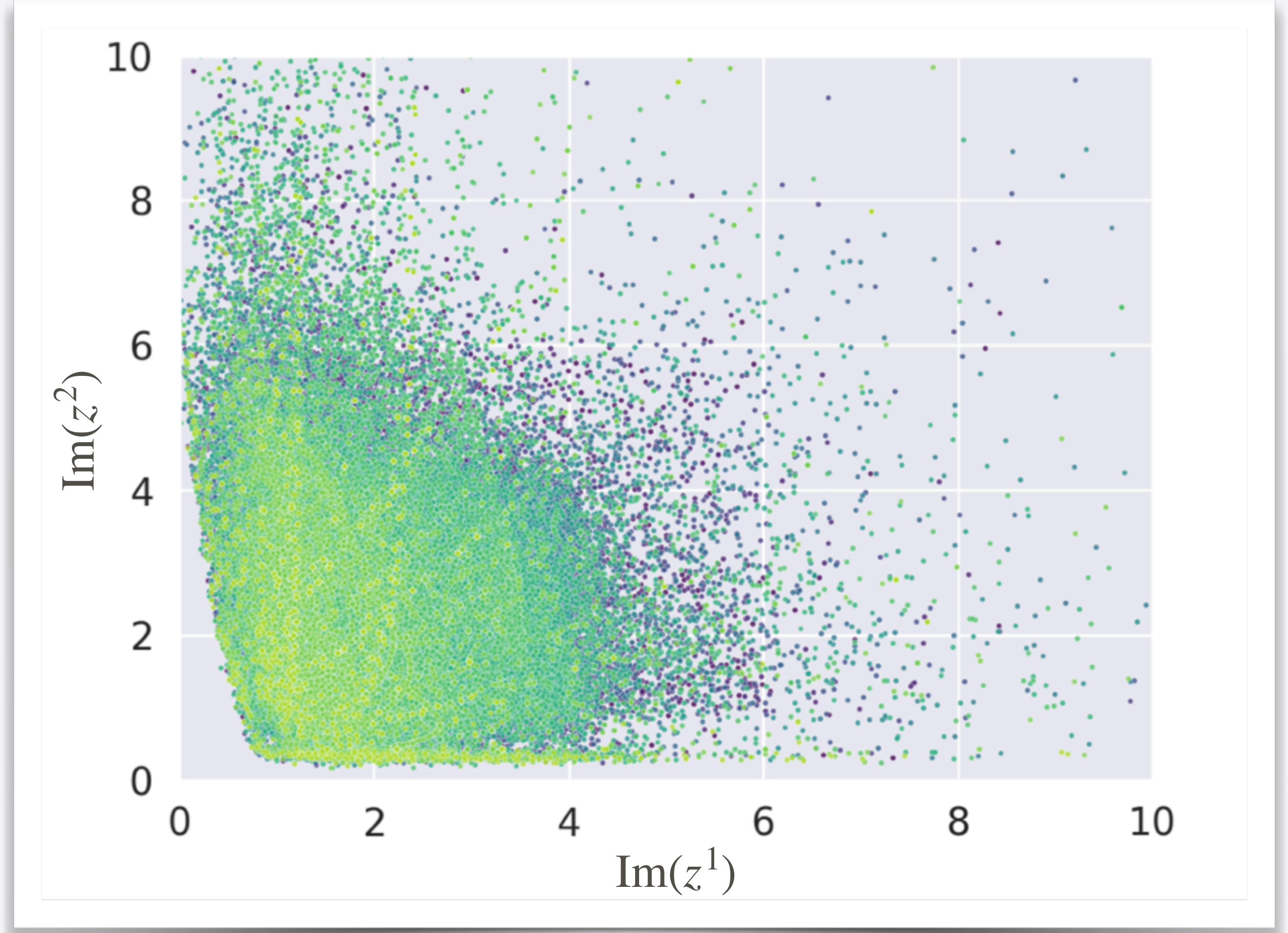
[work in progress]



"Classical" and dimensionally reduced.



Including GVs up to degree 10.



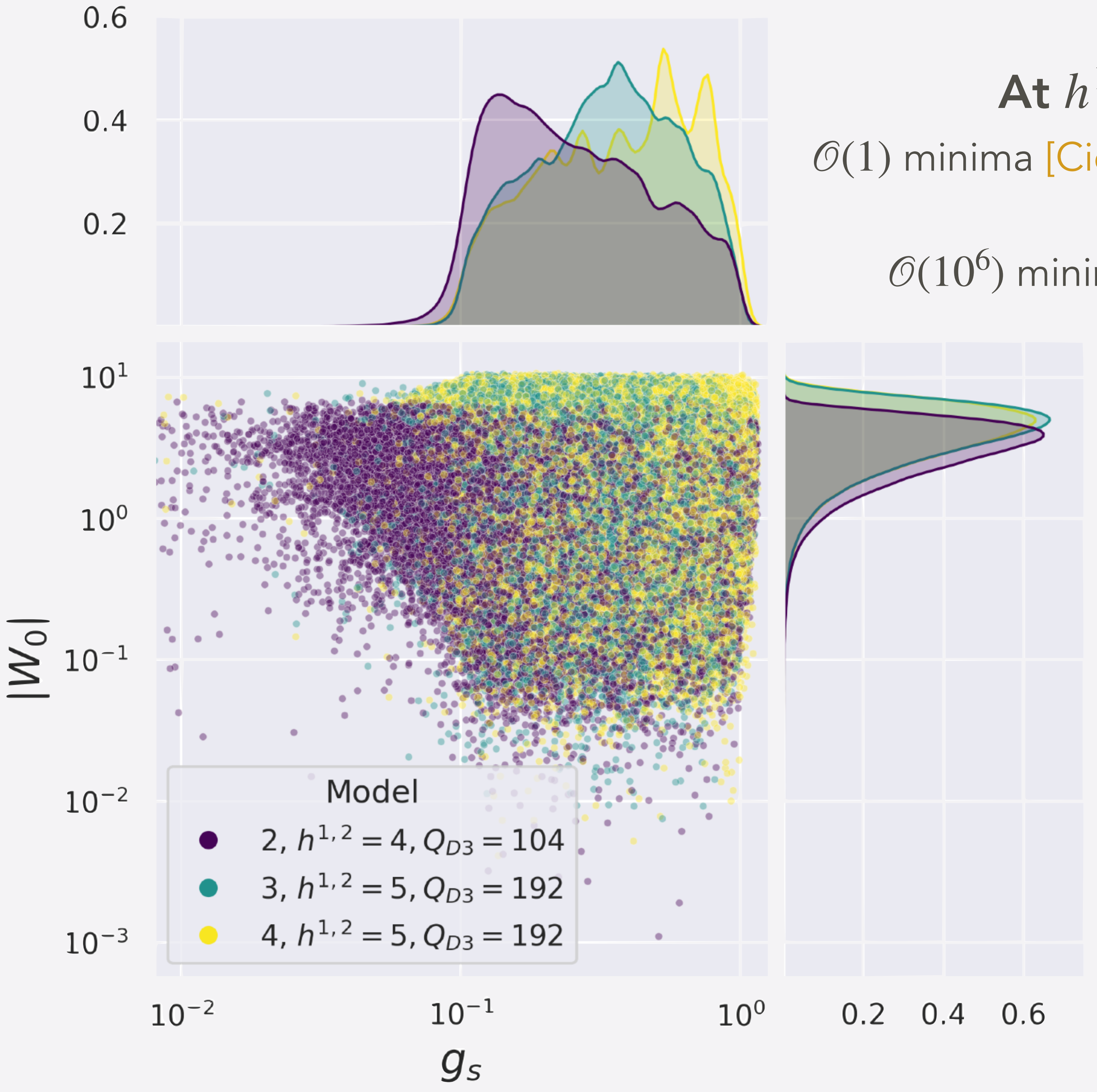
Including GVs up to degree 10.

JAXVacua

Numerical results — $h^{1,2} \geq 4$

[Dubey, Krippendorf, AS: 2306.06160]

GENERATE LARGE DATABASES OF STRING VACUA IN NEW REGIMES



At $h^{1,2} = 4{,}5$:

$\mathcal{O}(1)$ minima [Cicoli et al. 1312.0014]

vs.

$\mathcal{O}(10^6)$ minima [2306.06160]

Scaling behaviour at larger $h^{1,2}$

$h^{1,1}$	$h^{1,2}$	Q_{D3}	success rate	♯vacua
213	5	220	50%	1,370,842
244	10	256	16%	498,545
399	15	416	7%	168,291
350	20	372	$< 1\%$	36
245	25	272	$< 1\%$	1

Success rate decreases rapidly because

- high dimensionality means slower evaluation time
- harder to perform numerical optimisation
- field space $\mathscr{M}$ becomes narrower [Demirtas et al. 1808.01282]

In the future, we should be able to test the **tadpole conjecture** [Bena et al. 2010.10519]...

JAXVacua

Landscape distributions

[Ebelt, Krippendorf, AS: 2307.15749]

GOAL: PROBE DISTRIBUTIONS IN THE STRING LANDSCAPE

Motivation: Understanding such distributions is important to narrow down regimes with desirable features.

As a first test, we study the distribution of

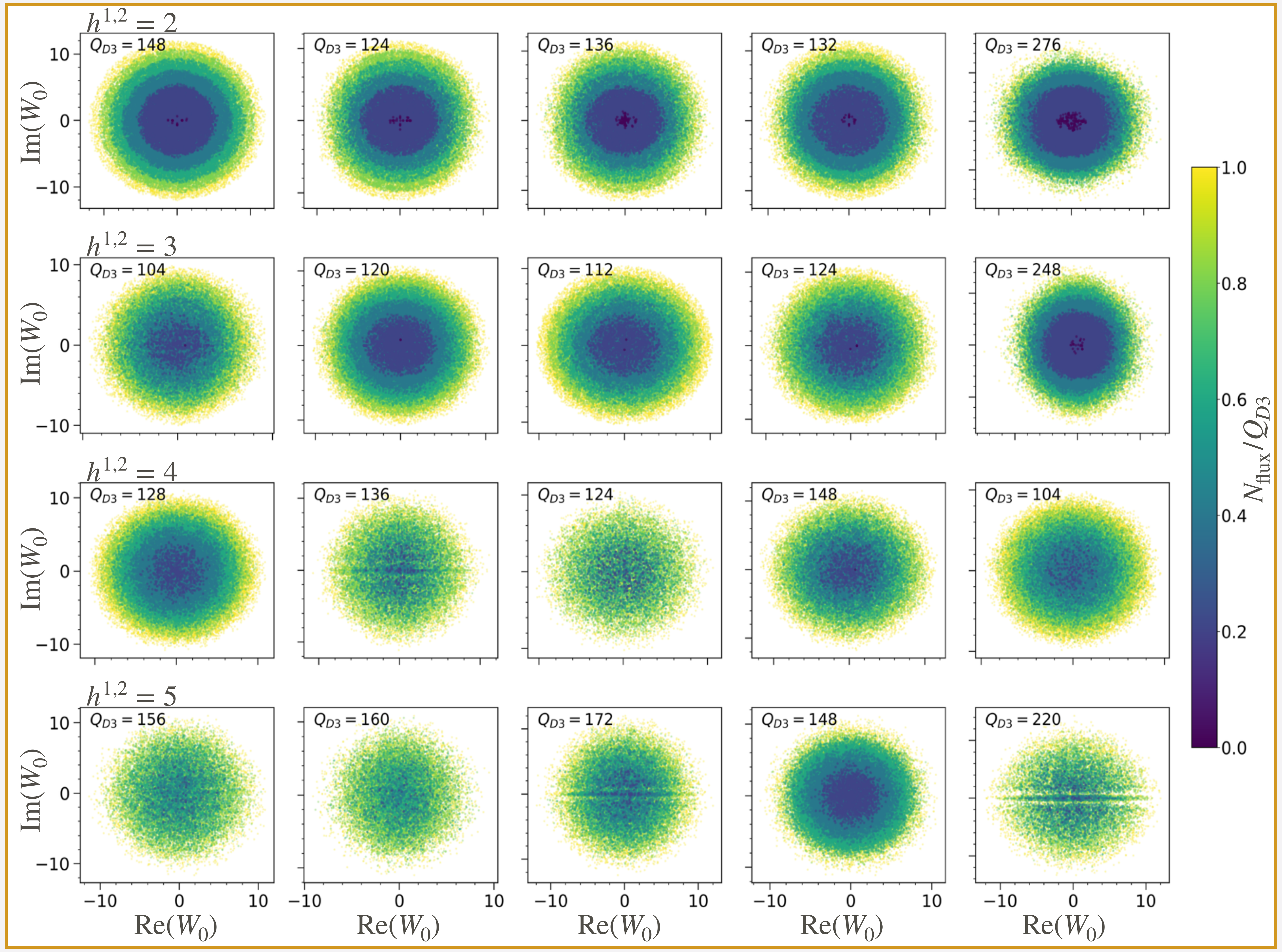
$$W_0 = \langle e^{K/2}\, W \rangle$$

which sets e.g. the gravitino mass.

Observations:

- A normal distribution is a good fit for W_0 in our datasets
- Color coding by N_{flux}/Q_{D3} reveals non-trivial scaling of the width with N_{flux}
- In agreement with expectation of [Denef, Douglas hep-th/0404116]
- However seems to be in disagreement with [Plauschinn et al. 2310.06040]

20 geometries with $h^{1,2} = 2,3,4,5$ and $\mathcal{O}(10^5)$ solutions each



JAXVacua

Supersymmetry Breaking and de Sitter uplifts — Part 1

[Krippendorf, AS: 2308.15525]

QUESTION: HOW CAN WE FIND SOLUTIONS WITH $\rho_{\rm vac} > 0$?

Recall the expression for the full potential:

$$V_F(z,\tau,T) = \frac{V_{\rm Flux}(z,\tau)}{\mathscr{V}^2} + V_{\rm rest}(z,\tau,T) \qquad V_{\rm Flux} = e^{K_{cs}} K^{a\bar{b}} D_a W D_{\bar{b}} \overline{W}$$

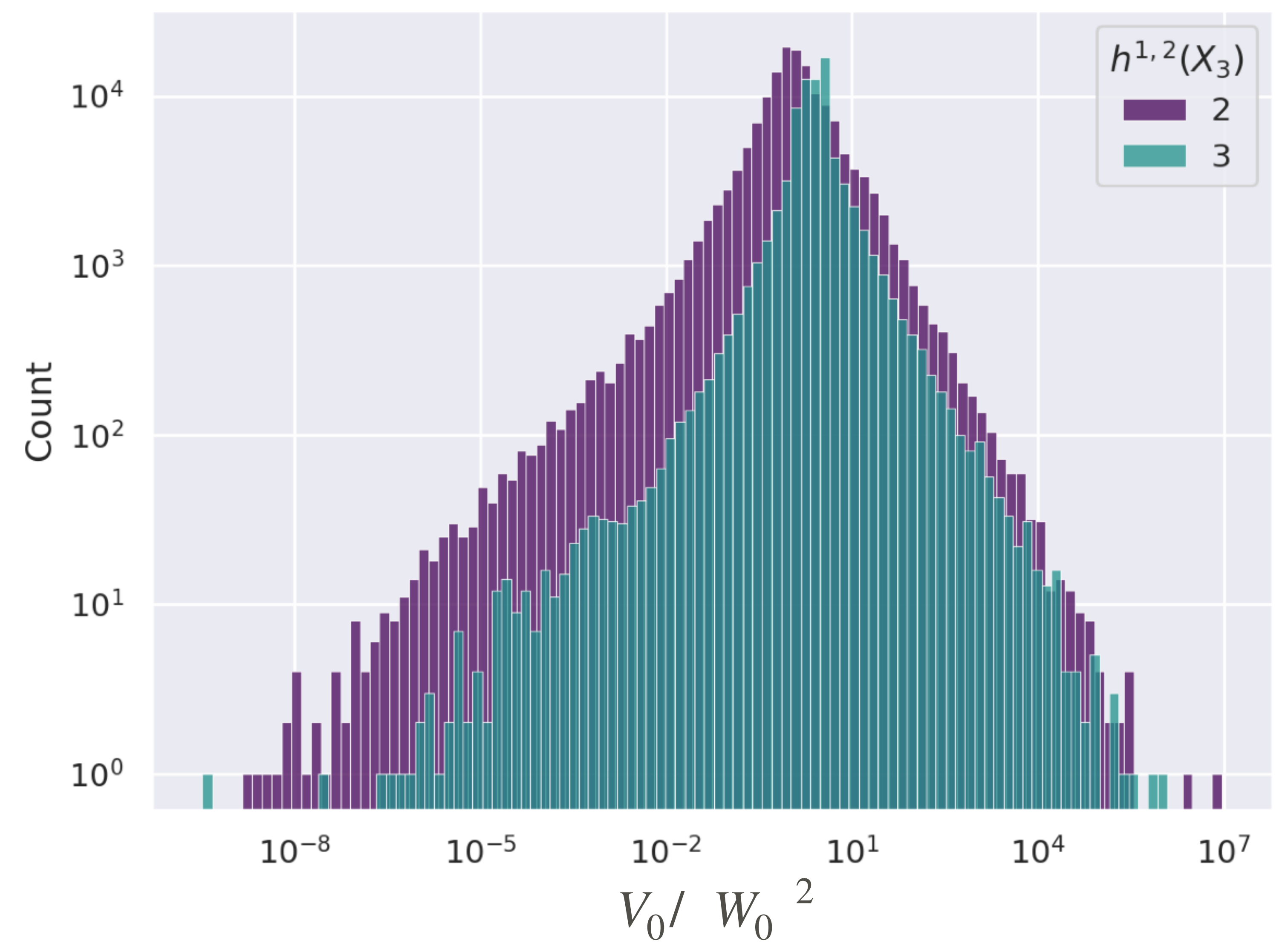
Idea: If we find solutions with $V_0 = \langle V_{\rm Flux}(z,\tau)\rangle > 0$, we might be able to find minima with positive cosmological constant $\langle V(z,\tau,T)\rangle > 0$.

[Saltman, Silverstein hep-th/0402135]

Comments:

- These solutions break supersymmetry since $D_{z^a} W \neq 0$ for some z^a
- Provided that SUSY breaking effects from $V_{\rm Flux}(z)$ are suitably small, the full potential can have a metastable minimum $\rho_{\rm vac} > 0$ [Marsh et al. 1411.6625, 1707.01095, Hebecker et al. 2012.00010]
- We know almost nothing about solution space, see however [Douglas et al. hep-th/0411183]

Can search for such solutions easily in our framework by using $\partial_{z^a} V_{\rm Flux} = 0$ for the optimisation target



JAXVacua

Supersymmetry Breaking and de Sitter uplifts — Part 2

[Krippendorf, AS: 2308.15525]

Question: Do the distributions for SUSY and non-SUSY solutions show different characteristics?

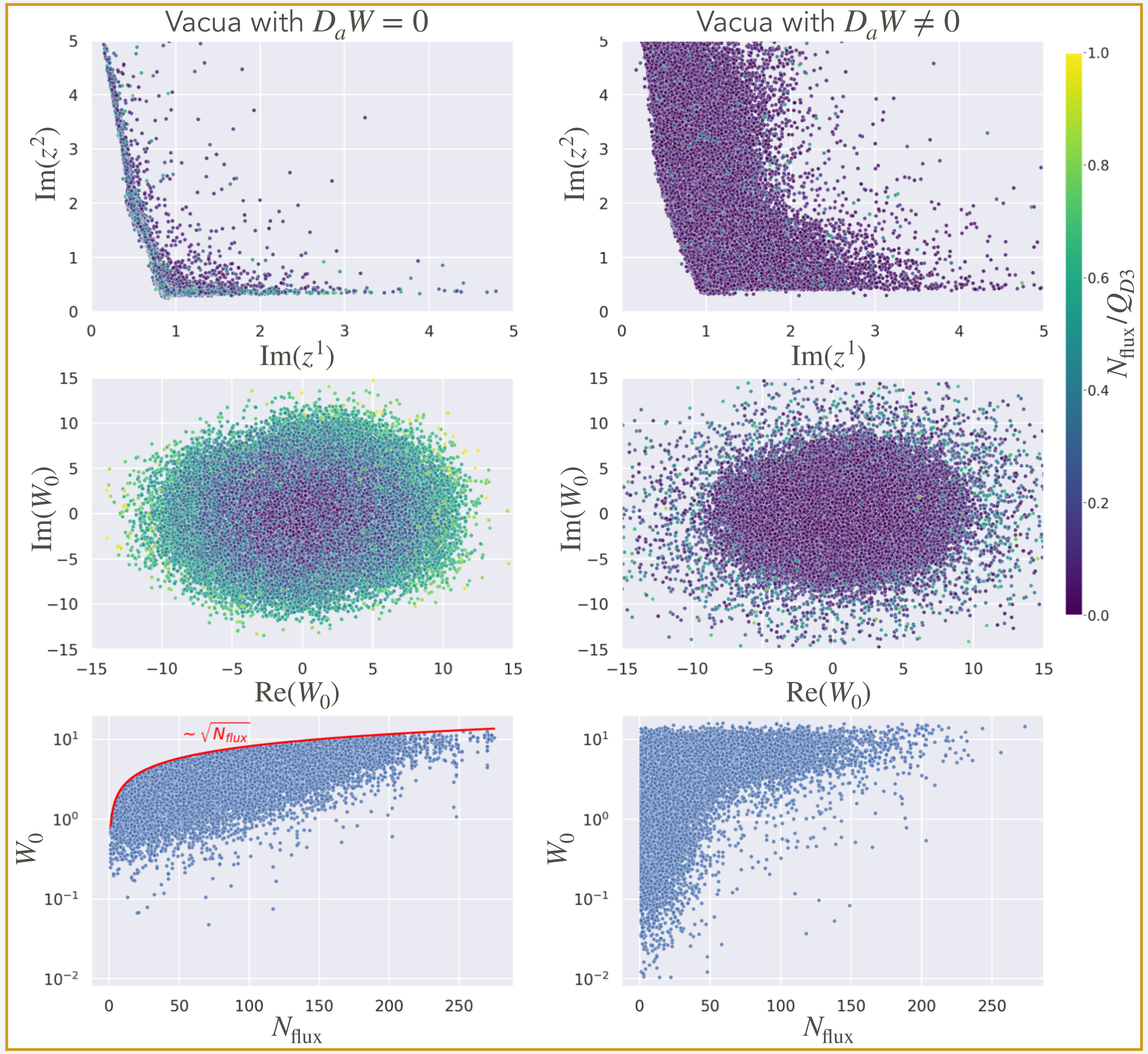
Distributions show differences:

- SUSY condition forces moduli VEVs closer to the boundary of moduli space, while non-SUSY solutions probe the far interior
- W_0 distribution for non-SUSY solutions shows no strong correlations with $N_{\rm flux}$
- SUSY solutions are strongly bounded in the W_0 direction

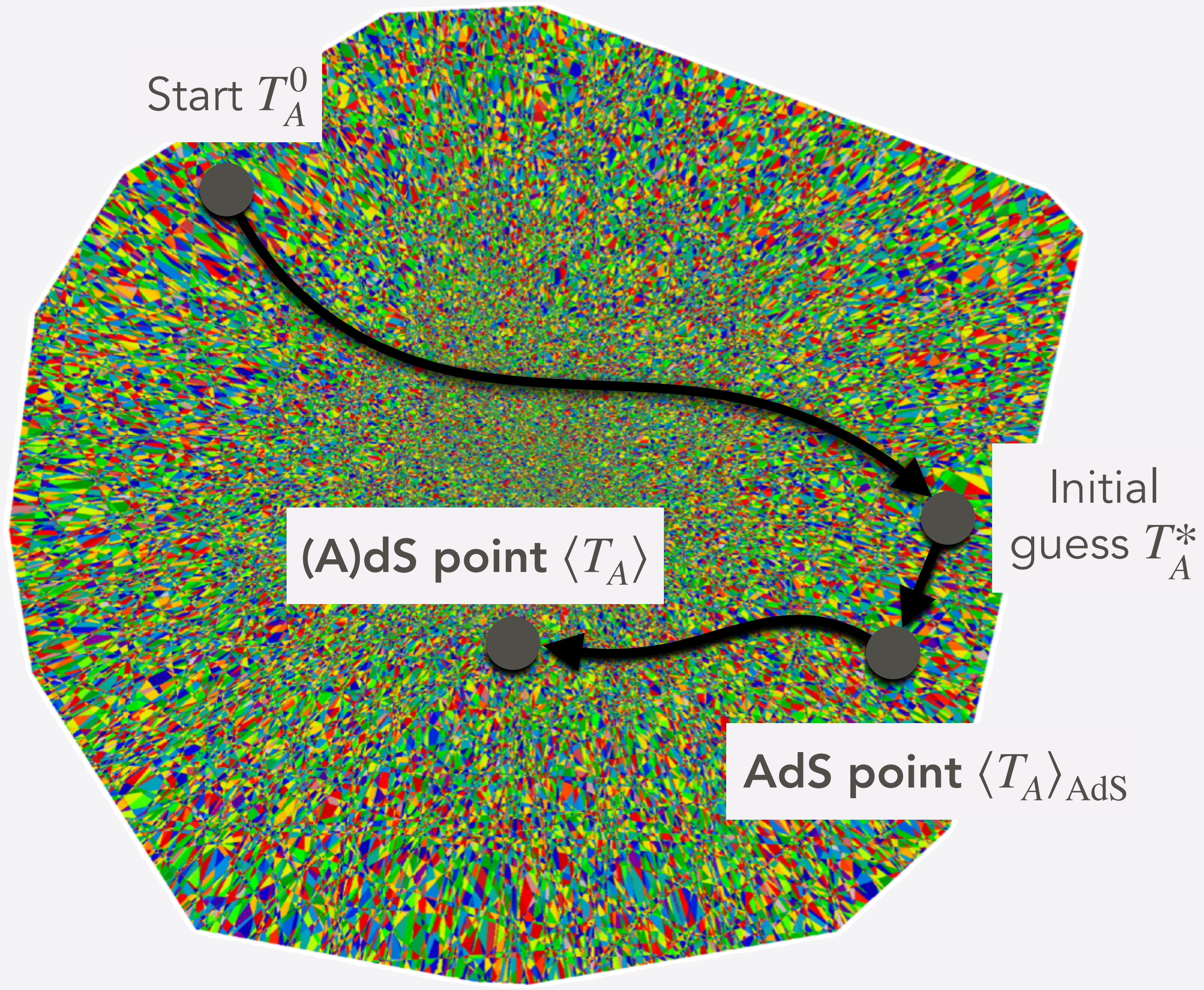
Future directions:

How are the underlying flux quanta distributed in their corresponding charge lattice?

[Krippendorf, AS, Shiu, Yip: work in progress]



Beyond flux vacua



Leading order EFT for Kähler moduli

work in progress

We work with scalar potentials of the form

$$V_F = \mathrm{e}^K \left(K^{I\bar{J}} D_I W D_{\bar{J}} \overline{W} - 3 |W|^2 \right) , \qquad W(z, \tau, T) = W_{\mathrm{flux}}(z, \tau) + \sum_D A_D(z, \tau)\, \mathrm{e}^{-\frac{2\pi}{c_D} T_D}$$

At leading order, we include $(\alpha')^3$ [Becker et al. hep-th/0204254] and worldsheet instanton (WSI) [Robles-Llana et al. hep-th/0612027] corrections

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

$$T_A^{\mathrm{l.o.}} = \frac{1}{2} \kappa_{ABC}\, t^B t^C - \frac{\chi(D_A)}{24} + \frac{1}{(2\pi)^2} \sum_{\mathbf{q} \in \mathscr{M}(X)} q_i \mathscr{N}_{\mathbf{q}}\, \mathrm{Li}_2\left((-1)^{\gamma\cdot\mathbf{q}} e^{-2\pi \mathbf{q}\cdot\mathbf{t}} \right) + i \int_X C_4 \wedge \omega_A$$

Using a pipeline similar to [Dubey, Krippendorf, AS: 2306.06160], we reproduced the (LVS, KKLT, or hybrid) minima of [AbdusSalam et al. 2005.11329] at $h^{1,1} = 2, 3$.

WE CAN EASILY INCLUDE MIXING BETWEEN ALL MODULI OR PARAMETRISE UNKNOWN $\mathscr{N} = 1$ CORRECTIONS.

The DNA of toric Calabi-Yau threefolds

A Genetic Algorithm (GA) for polytope triangulations

[MacFadden, AS, Sheridan: 2403.XXXX]

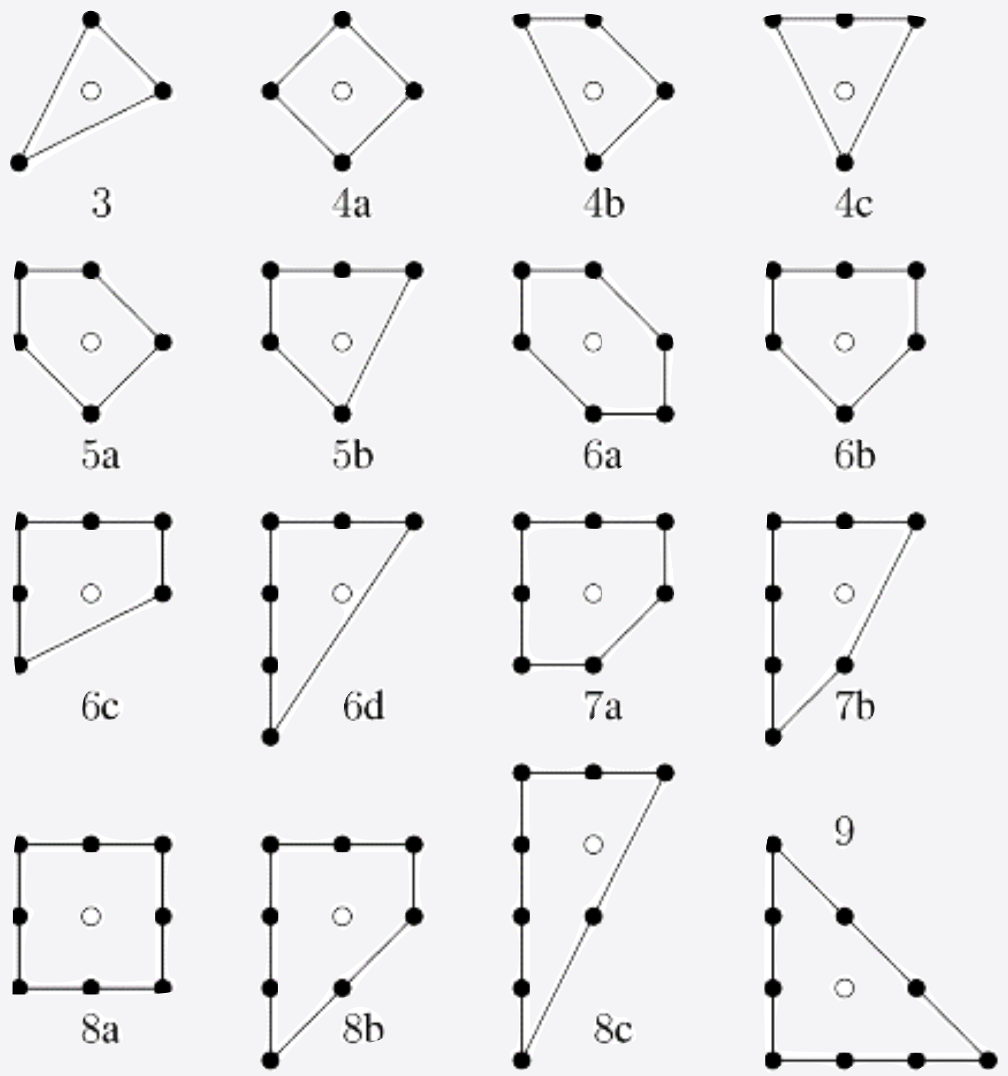
MOTIVATION: CAN STOCHASTIC OPTIMIZATION BE USED TO SEARCH FOR DESIRABLE CY GEOMETRIES?

Earlier work on applications of GAs in string phenomenology

- **Flux vacua**: Cole, (Krippendorf), AS, Shiu 1907.10072, 2111.11466
- **Intersecting branes**: Loges, Shiu 2112.08391
- **Reflexive Polytopes**: Berglund et al. 2306.06159
- …

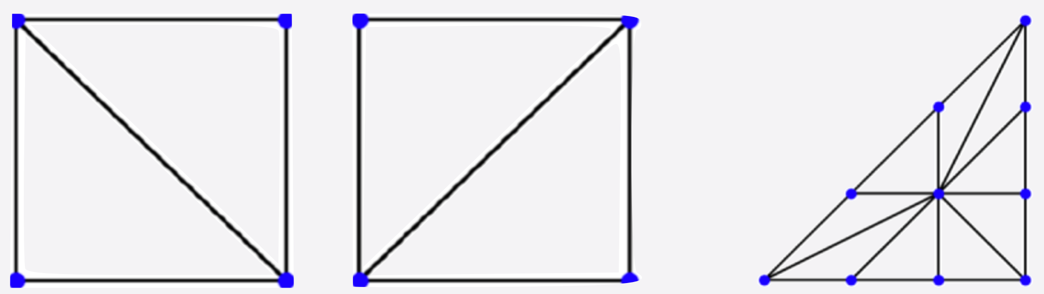
Calabi-Yau threefolds from polytope triangulations

Batyrev's construction



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

Any **fine, regular, star** triangulations (FRSTs) of a 4D reflexive polytope Δ° defines a Calabi-Yau hypersurface. [Batyrev alg-geom/9310003]



The number of FRSTs is expected to be huge [Demirtas et al. 2008.01730]

$$\#\text{FRSTs} \lesssim 10^{928}$$

WHICH FRSTS ARE PREFERRED FOR STRING MODEL BUILDING?

CY Tools

Demirtas, Rios-Tascon, McAllister 2211.03823

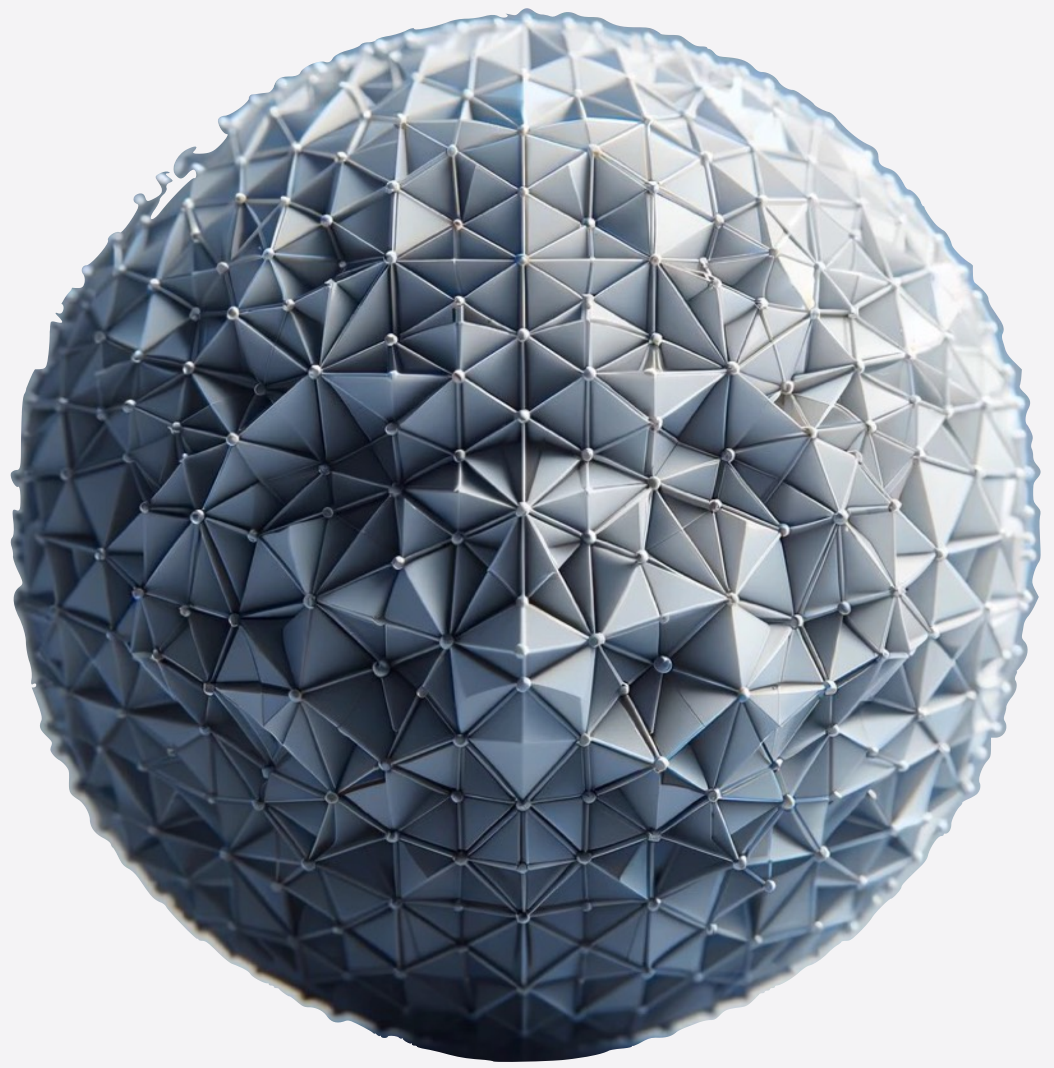
Generating homotopy inequivalent CY threefolds

Two-face inequivalent triangulations

Recent studies of diffeomorphism classes of CY threefolds [with Gendler et al. 2310.06820, Chandra et al. 2310.05909]

GENERAL FACT: CALABI-YAU HYPERSURFACES ARE DETERMINED BY INDUCED TRIANGULATIONS OF TWO-FACES.

Wall's theorem [Wall 1966]



We enumerate all **fine, regular triangulations (FRTs)** of two-faces Θ_i°, $i = 1, \ldots, n$, of a given reflexive polytope Δ°.

By assigning random IDs c_i to each FRTs, we define the **DNA** or **chromosome** $\mathscr{C}$ of a CY as

$$\mathscr{C} = (c_1, \ldots, c_n) \in \mathbb{N}^n$$

We **lift** a choice of two-face triangulations $\mathscr{C}$ to a **full triangulation** $\mathscr{T}$ of Δ° following [MacFadden 2309.10855].

Comments:

- relevant enumeration is that of FRTs of two-faces
- $\mathscr{T}$ is not always an FRST (regularity is problem)
- efficient construction which removes redundancies

The number of **two-face inequivalent** FRSTs is bounded by [Demirtas et al. 2008.01730]

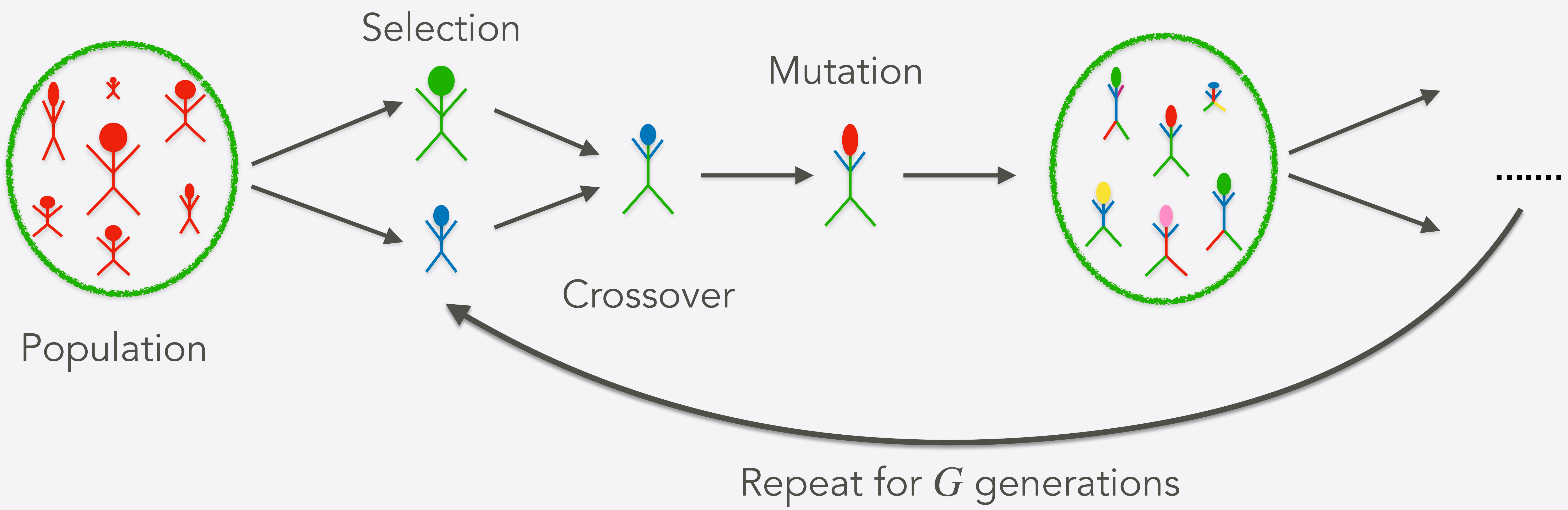
$$\#\text{FRSTs} \lesssim 10^{928} \quad \rightarrow \quad \#\text{2-face inequivalent FRSTs} \lesssim 10^{428}$$

Our encoding avoids these trivial redundancies when relating FRSTs to CY threefolds.

Genetic Algorithms (GAs)

Algorithms from natural evolution

Stochastic search method based on natural selection processes:



For polytope triangulations:

- Population of CYs $\{\mathscr{C}_1, \mathscr{C}_2, \ldots, \mathscr{C}_P\}$ encoded by DNAs $\mathscr{C}_i = (c_1, \ldots, c_n) \in \mathbb{N}^n$
- Crossover: exchange two-face FRTs
- Mutation: randomly alter two-face FRTs

GA results

Axion decay constants in string theory — Part 1

The Lagrangian for the C_4 axions ϕ^a reads

$$\mathscr{L} = -\frac{K_{ab}}{2}(\partial_\mu \phi^a)(\partial^\mu \phi^b) - \sum_I \Lambda_I^4 \Big(1 - \cos\left(2\pi \mathscr{Q}_{Ia}\phi^a\right)\Big)$$

Let us focus on the decay constant f of the **lightest axion**.

For string model building, we typically want f to be in a certain range.

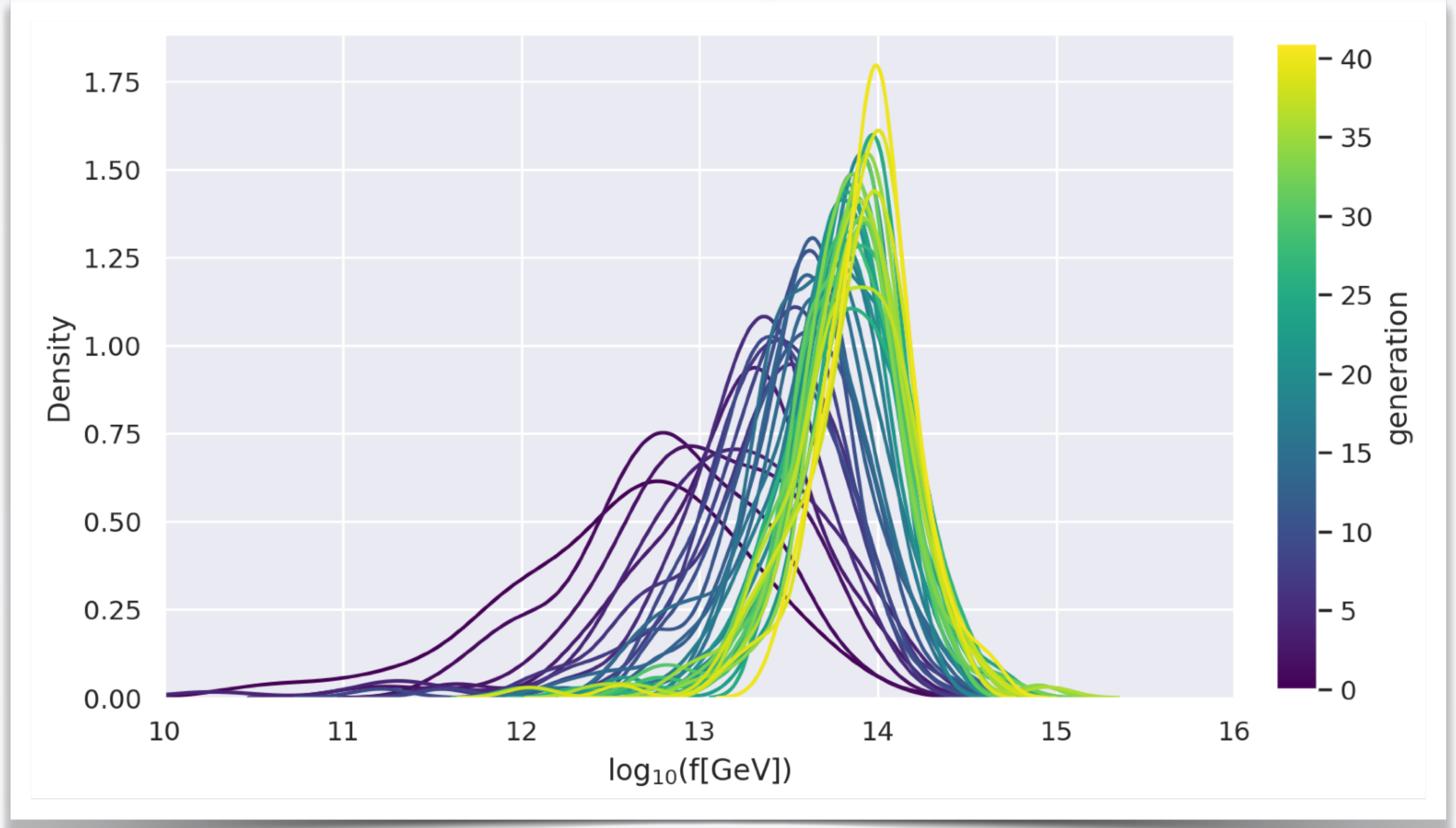
Here, we want to find CY threefolds leading to $f_* = 10^{14}$GeV at a particular point in moduli space.

We choose a polytope Δ° with $(h^{1,1}, h^{1,2}) = (60,4)$ whose **search space is bounded by**

#2-face ineq. FRSTs $\lesssim 3.3 \times 10^{36}$

We run the GA with a population of size $P = 100$ for $G = 40$ generations.

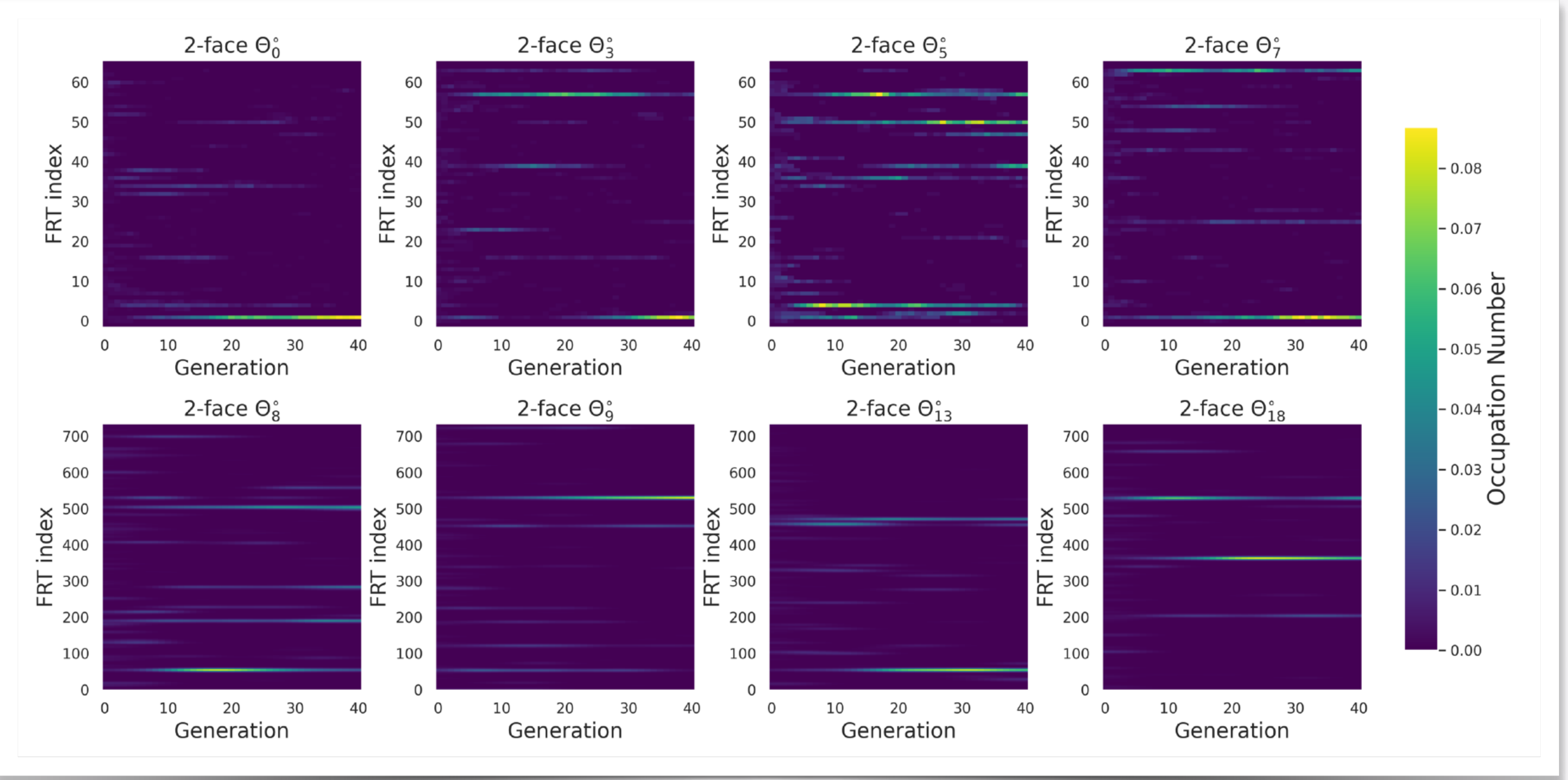
Distributions of axion decay constants



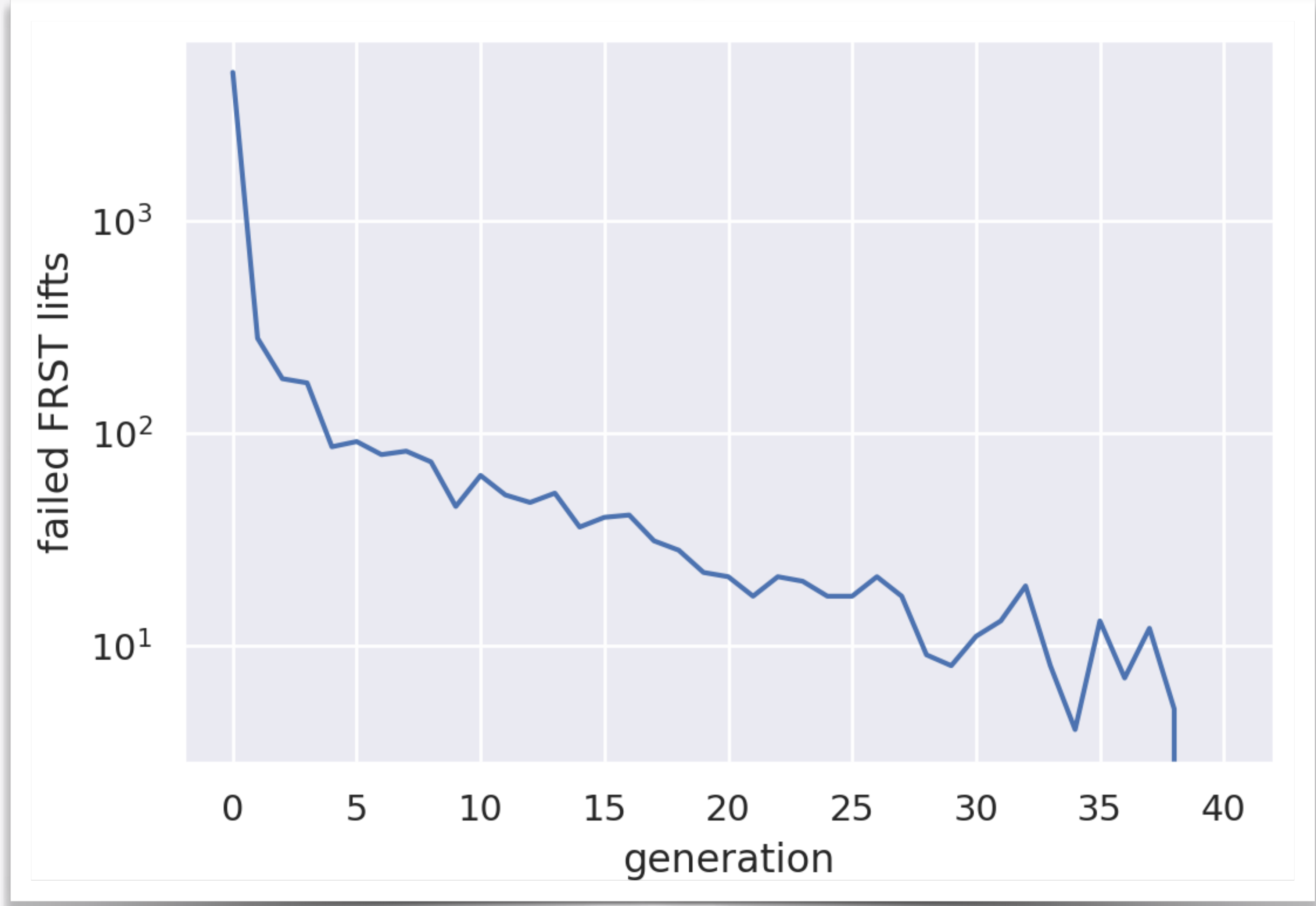
GA results

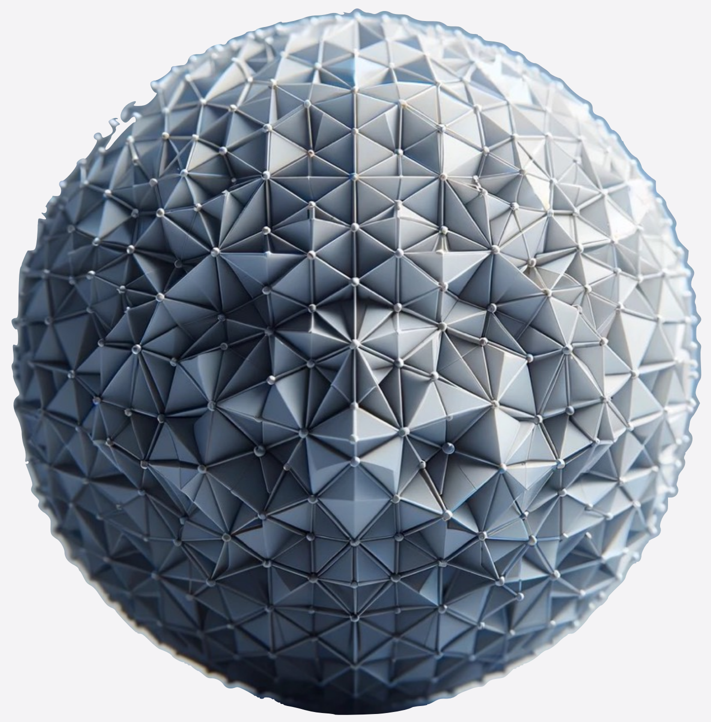
Axion decay constants in string theory — Part 2

Structure in the distributions of two-face FRTs

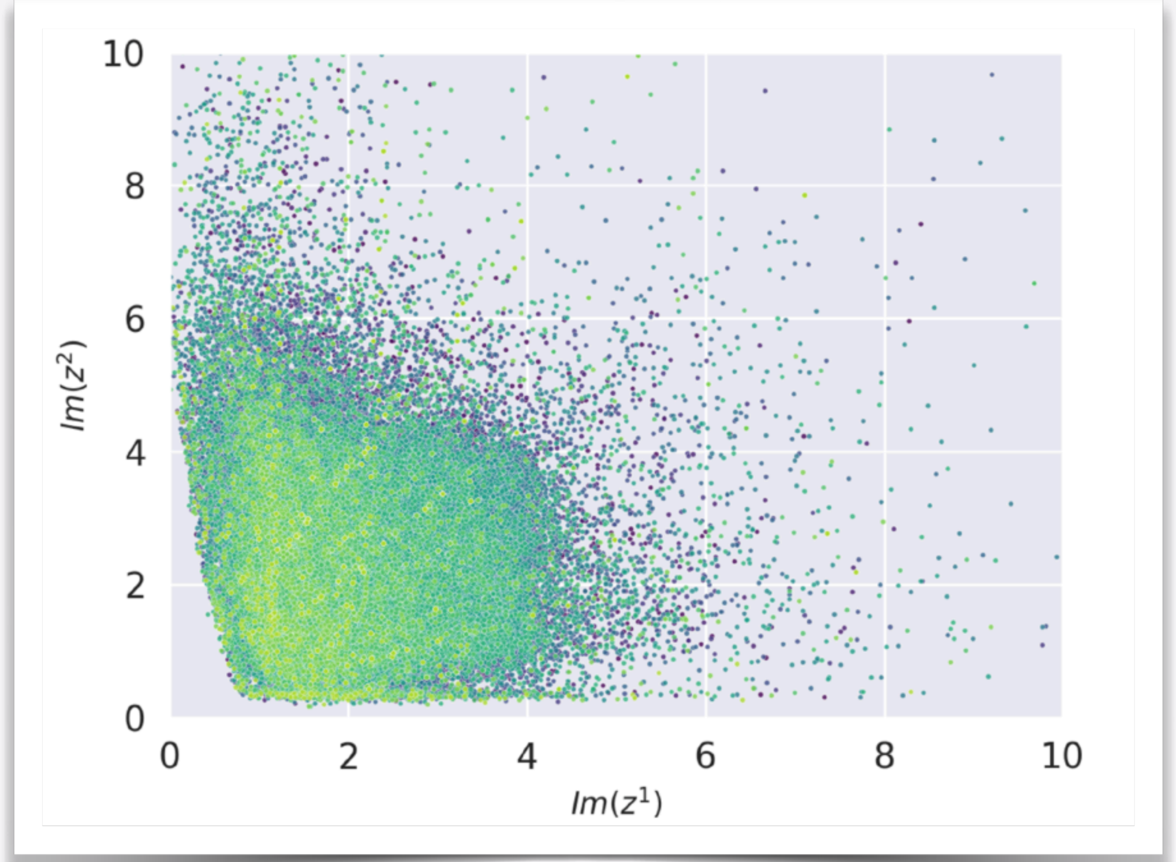


Learning progress of the GA





Conclusions



Main takeaways:

1. Generation of critical points is completely automated even at $h^{p,q} > 1$
2. Distributions of EFT quantities and sampling biases can be studied
3. SUSY-breaking flux vacua can be efficiently constructed → useful for uplifts? [Saltman, Silverstein hep-th/0402135]
4. GA can help us finding and selecting Calabi-Yau manifolds based on physics constraints

Future directions:

1. Include general corrections to understand the **vacuum structure**,
2. Compare with **exact methods** (see talk by Thomas G.) and **exhaustive searches** (see talk by Erik), and
3. Study **models of particle physics/cosmology** in these setups.


Thank you!