Optimisation in the String Axiverse

Andreas Schachner

WISPs in String Cosmology
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Navigating the String Landscape

Numerical minimisation:

How do we find critical points of potentials from string theory?

Dubey, Krippendorf, **AS**: *2306.06160*, Krippendorf, **AS**: *2308.15525*

Numerical optimisation:

How do we select EFTs from string theory?

MacFadden, **AS**, Sheridan: 2405.08871

Applications:

- *Distributions in the string landscape:* Ebelt, Krippendorf, **AS**: *2307.15749*
- *dS vacua in string theory:* McAllister, Moritz, Nally, **AS**: 2406.13751
- *Fuzzy DM in the String Axiverse:* Carta, Righi, **AS** et al.: 2411.XXXX (see talk by F. Carta)

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Outline

1 INTRODUCTION

2 NAVIGATING THE STRING LANDSCAPE

3 OPTIMISATION IN THE STRING AXIVERSE

4 CONCLUSIONS

Outline

Introduction and Motivation

The String Axiverse

Typical string compactifications contain $\mathcal{O}(100)$ axion-like particles ϕ^a with a rich phenomenology [Arvanitaki et al. 0905.4720] → **String Axiverse**

The general Lagrangian in string compactifications

$$\mathcal{L} = -\frac{1}{2} K_{ab}(\partial_\mu \phi^a)(\partial^\mu \phi^b) - V(\phi) - g_{a\gamma\gamma}\, \phi^a \frac{\alpha}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} + \dots$$

naturally contains axionic couplings to

- moduli parametrising the compact geometry,
- SM degrees of freedom like photons or gluons, and
- other hidden sectors.

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^α, $\alpha = 1,\ldots,h^{2,1}_-$, Kähler moduli $T^a = \tau^a + \mathrm{i}\,\phi^a$, $a = 1,\ldots,h^{1,1}_+$, axio-dilaton $\tau = c + \mathrm{i}\,s$

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

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

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

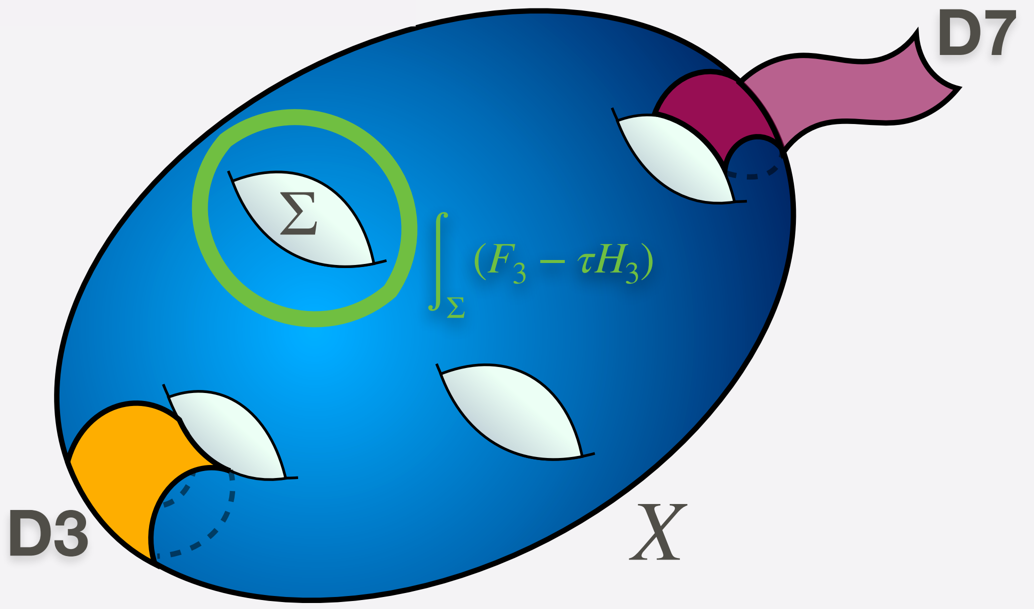
The superpotential receives contributions from two sources

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

From this, we compute the **masses** m_a **and decay constants** f_a **for** C_4**-axions as**

$$f_a \sim \frac{1}{\tau^a}\ ,\qquad m_a^2 \sim m_{3/2}\,\tau^a\,\frac{\mathrm{e}^{-2\pi\tau^a}}{f_a^2}\,.$$

Exponential suppression of m_a^2 naturally leads to **ultra-light ALP** in the regime $\tau^a \gg 1$.



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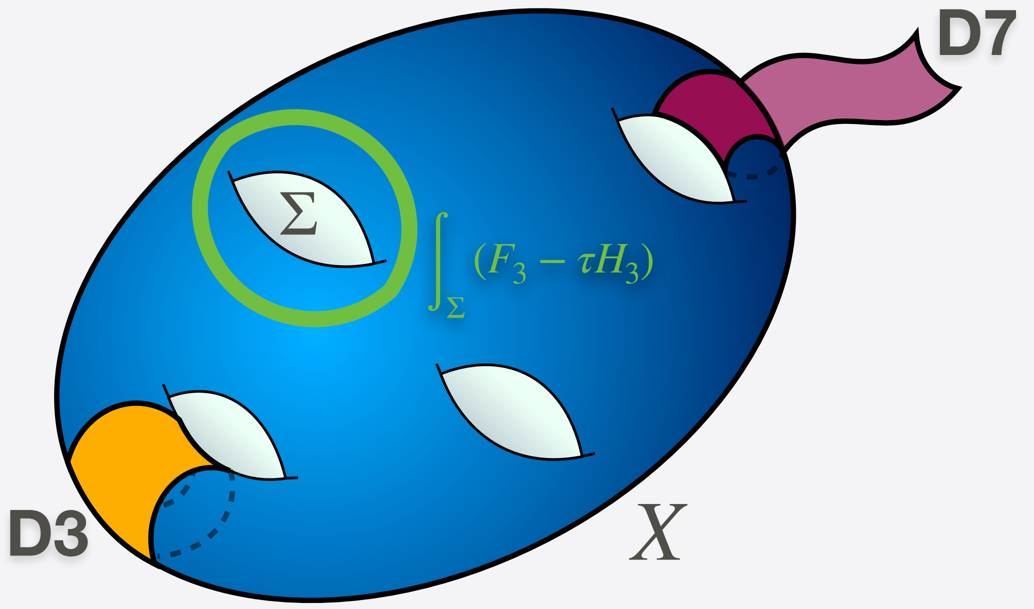

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2 **NAVIGATING THE STRING LANDSCAPE**

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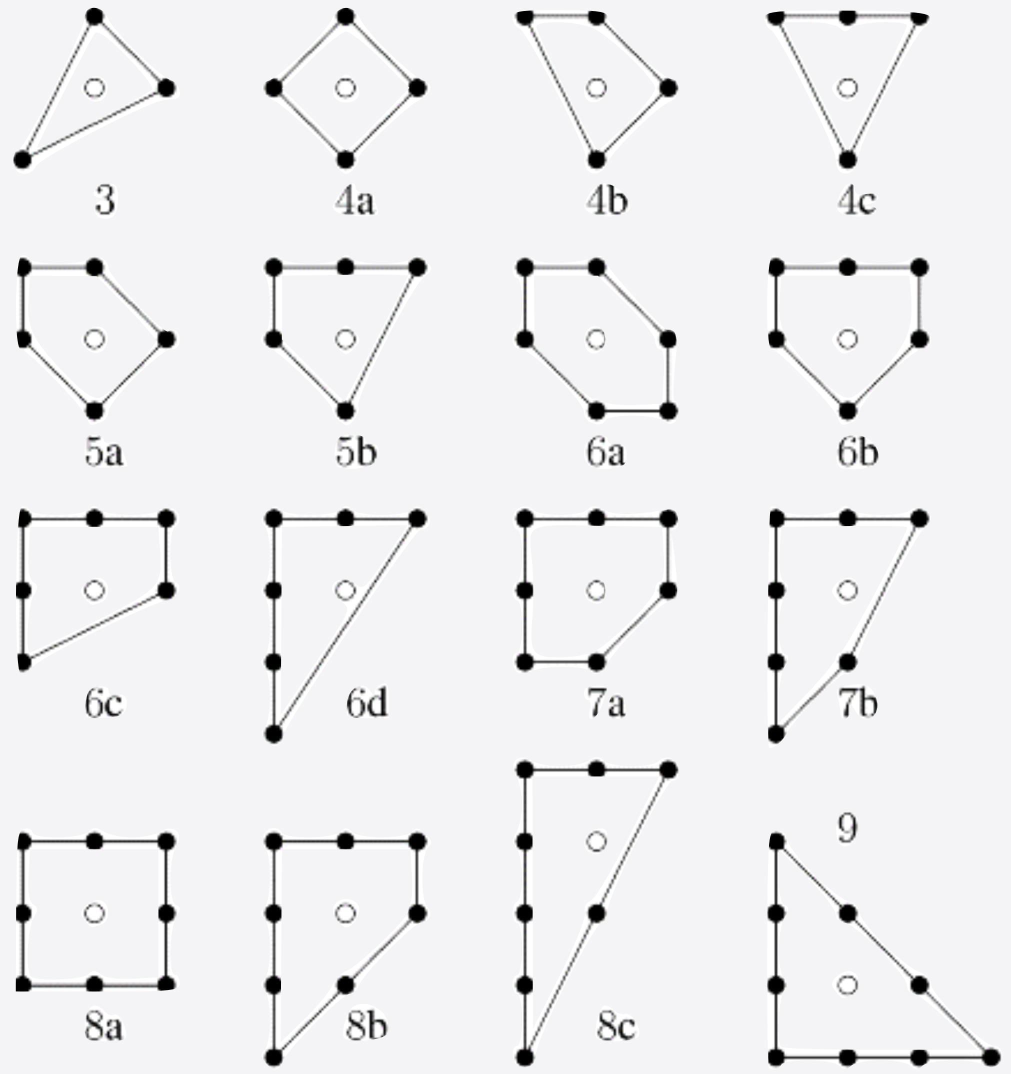
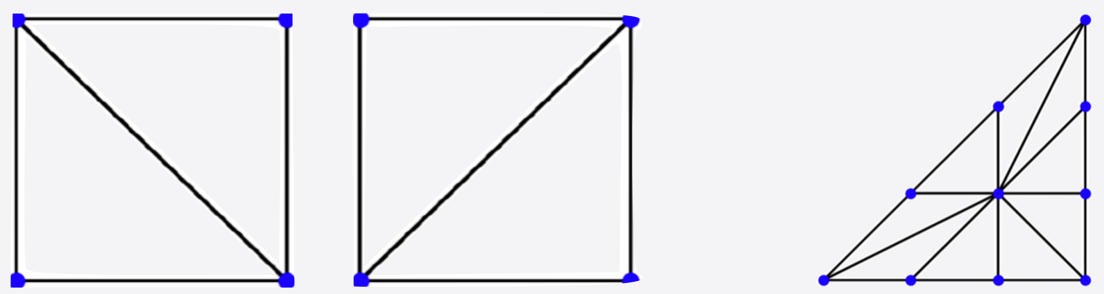
Navigating the String Landscape

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 X. [Batyrev alg-geom/9310003]



Demirtas, Rios-Tascon, McAllister 2211.03823

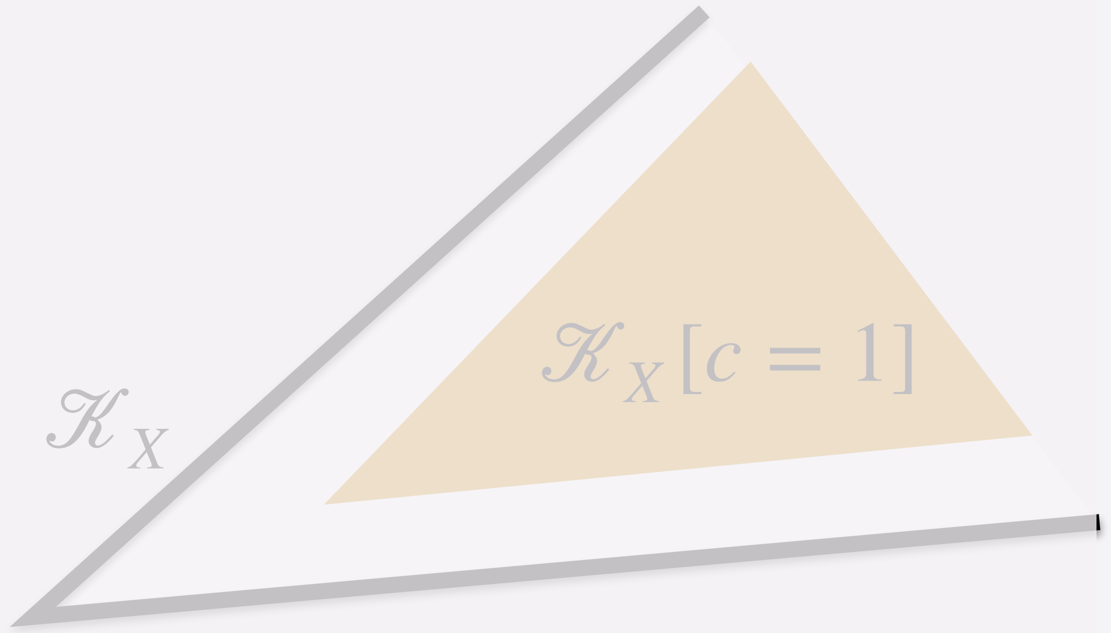
A large dataset of CY compactifications from **toric methods** allowing us to compute GV invariants, Mori cones $\mathcal{M}_X$, Kähler cones $\mathcal{K}_X$ etc.

An important object is the **stretched Kähler cone**:

$$\mathcal{K}_X[c] = \{J \in H^{1,1}(X, \mathbb{R}) : \ \mathrm{Vol}_J(Y) \geq c \ \ \forall \text{ sub-varieties } Y \in X\}$$

Here the sub-varieties include in particular curves and divisors.

For computational control over quantum corrections requires $c \gtrsim 1$.



Genus-zero GV invariants [Gopakumar, Vafa hep-th/9809187] can be computed using publicly availble code [Demirtas et al. 2303.00757]: https://github.com/ariostas/cygv

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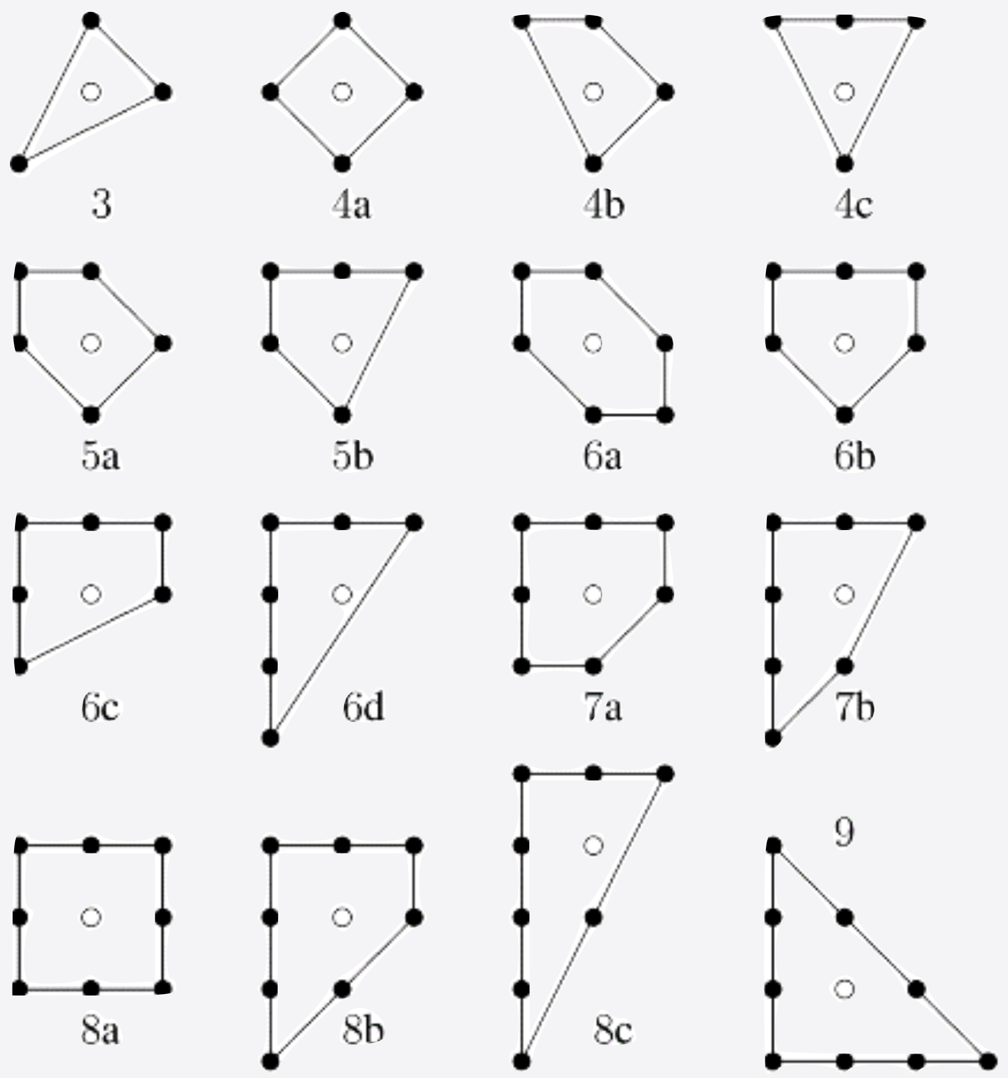

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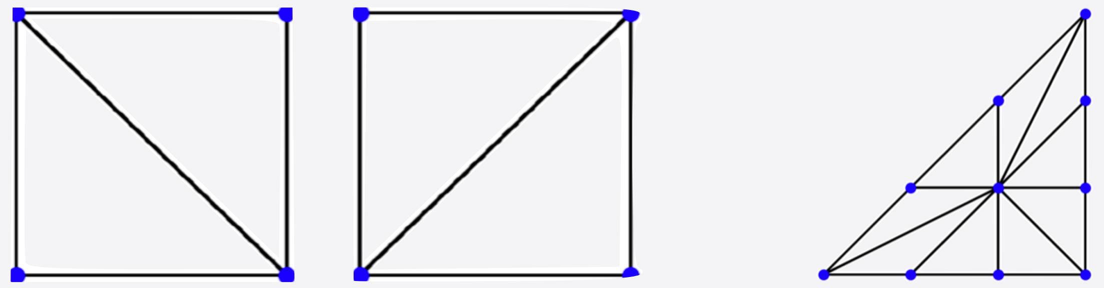

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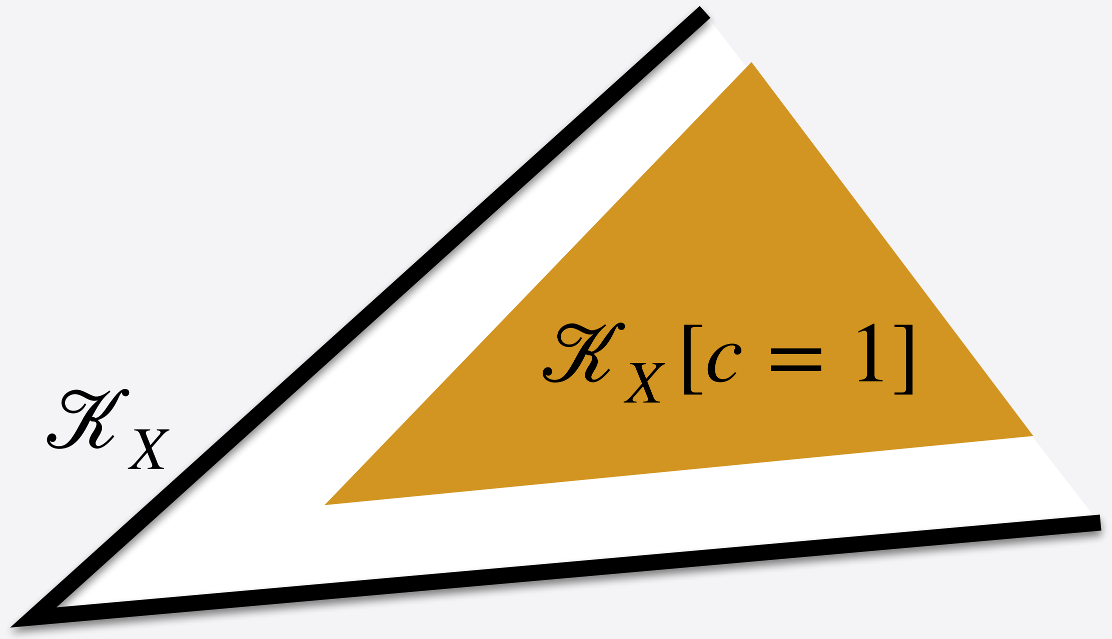

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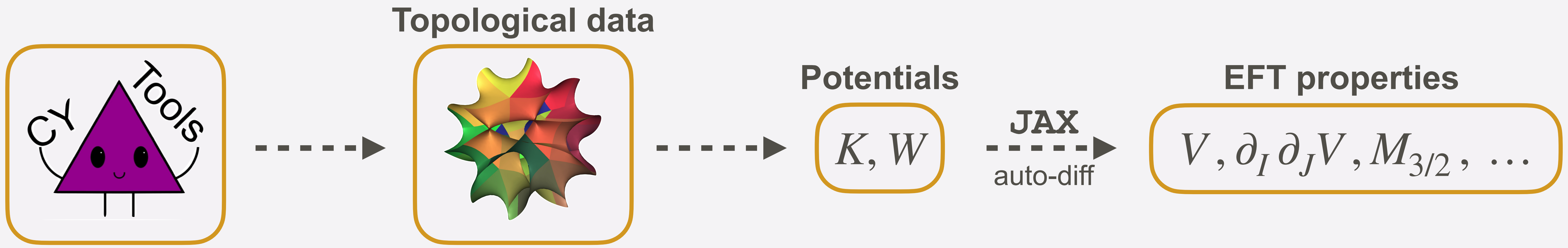
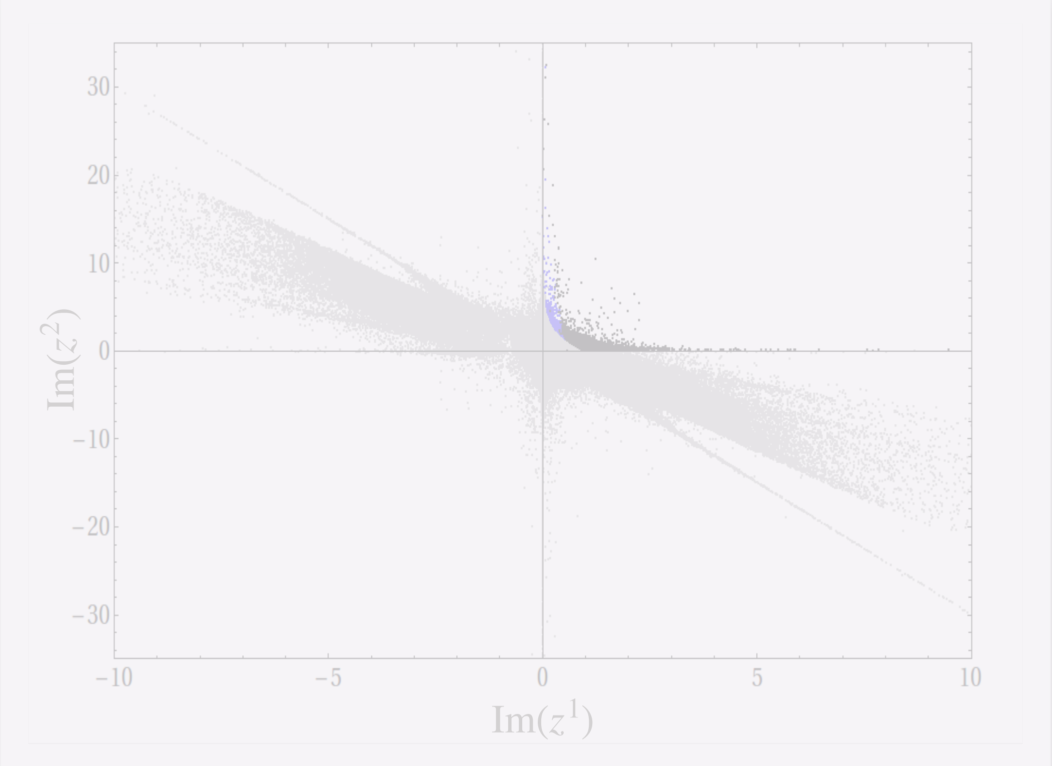
JAXVacua — A framework for constructing EFTs from string theory

[Dubey, Krippendorf, **AS**: 2306.06160]



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



24,882 solutions in **75,000 hrs** using `homotopy continuation`

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[**AS** work in progress]

Distribution of W_0

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Non-SUSY vacua constructed in [Krippendorf, **AS**: 2308.15525]

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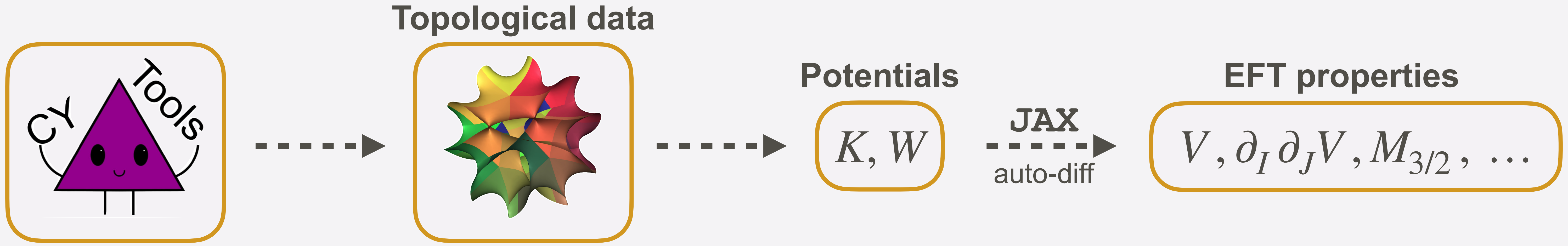

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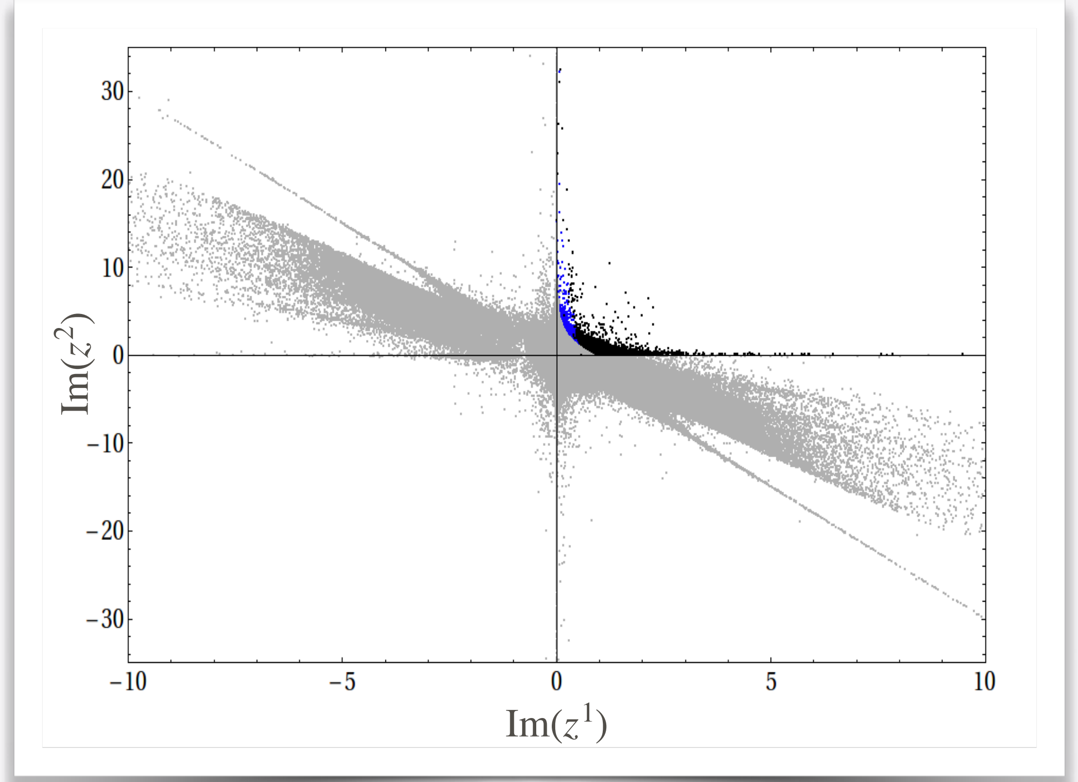

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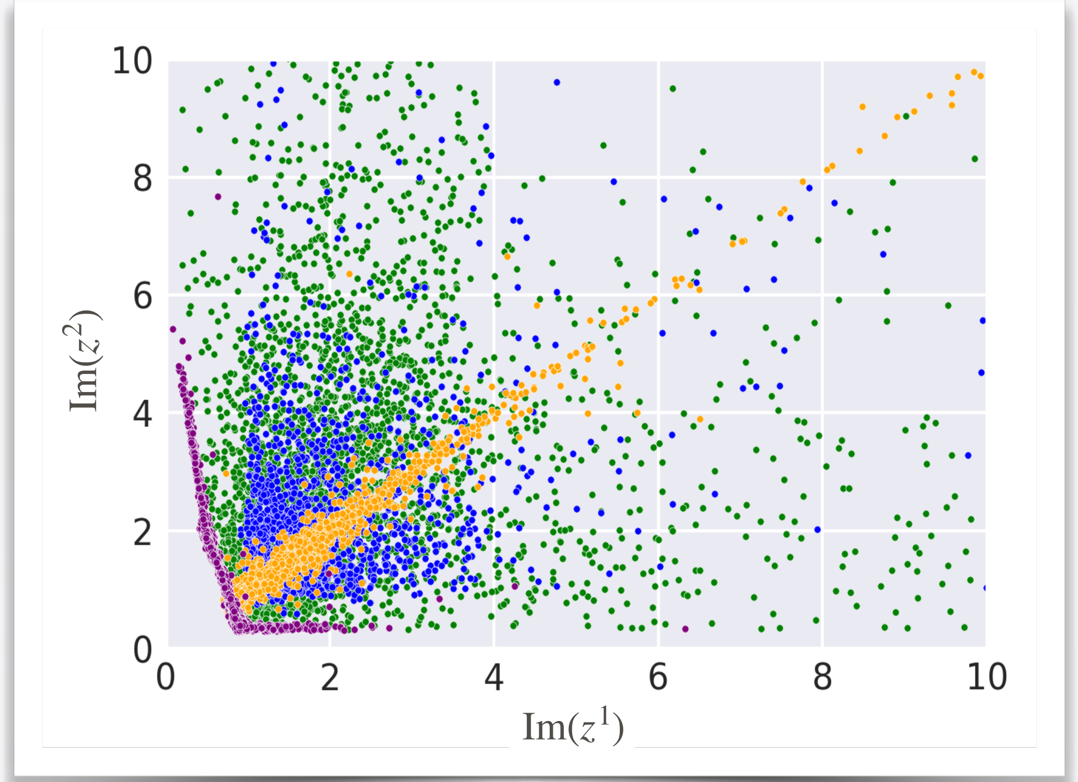

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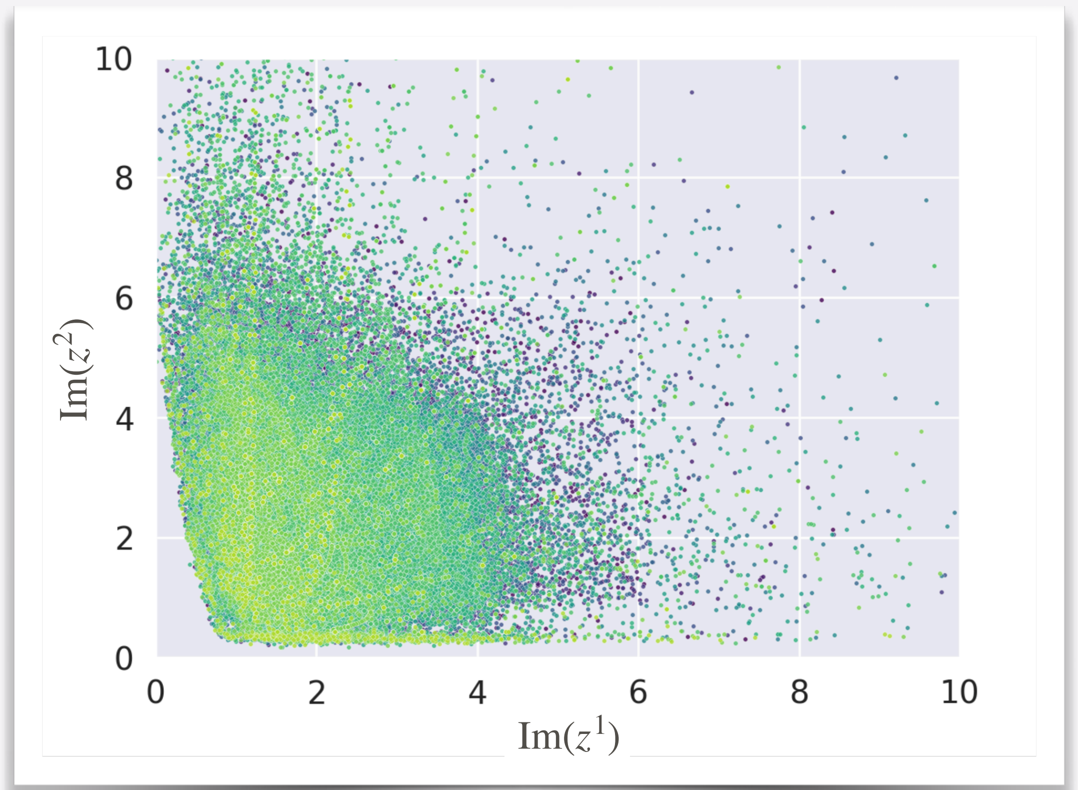

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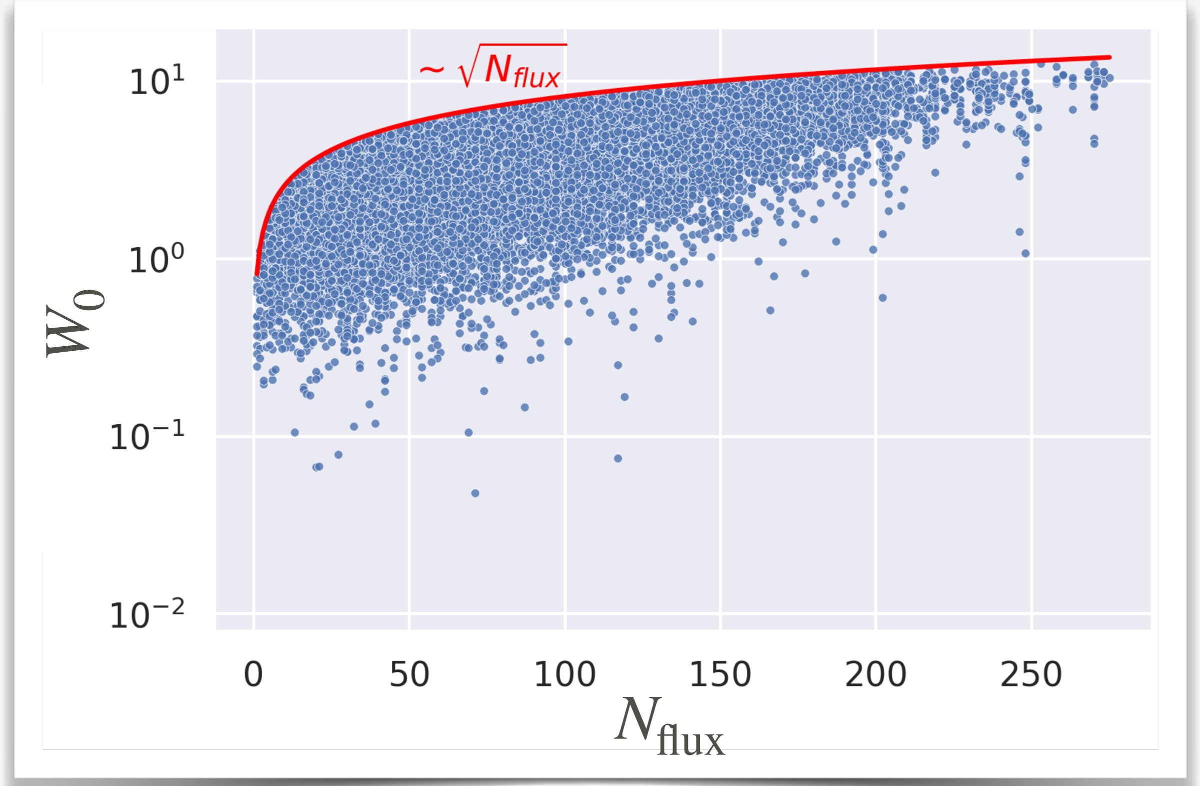

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Navigating the String Landscape

See also talk by Simon Schreyer

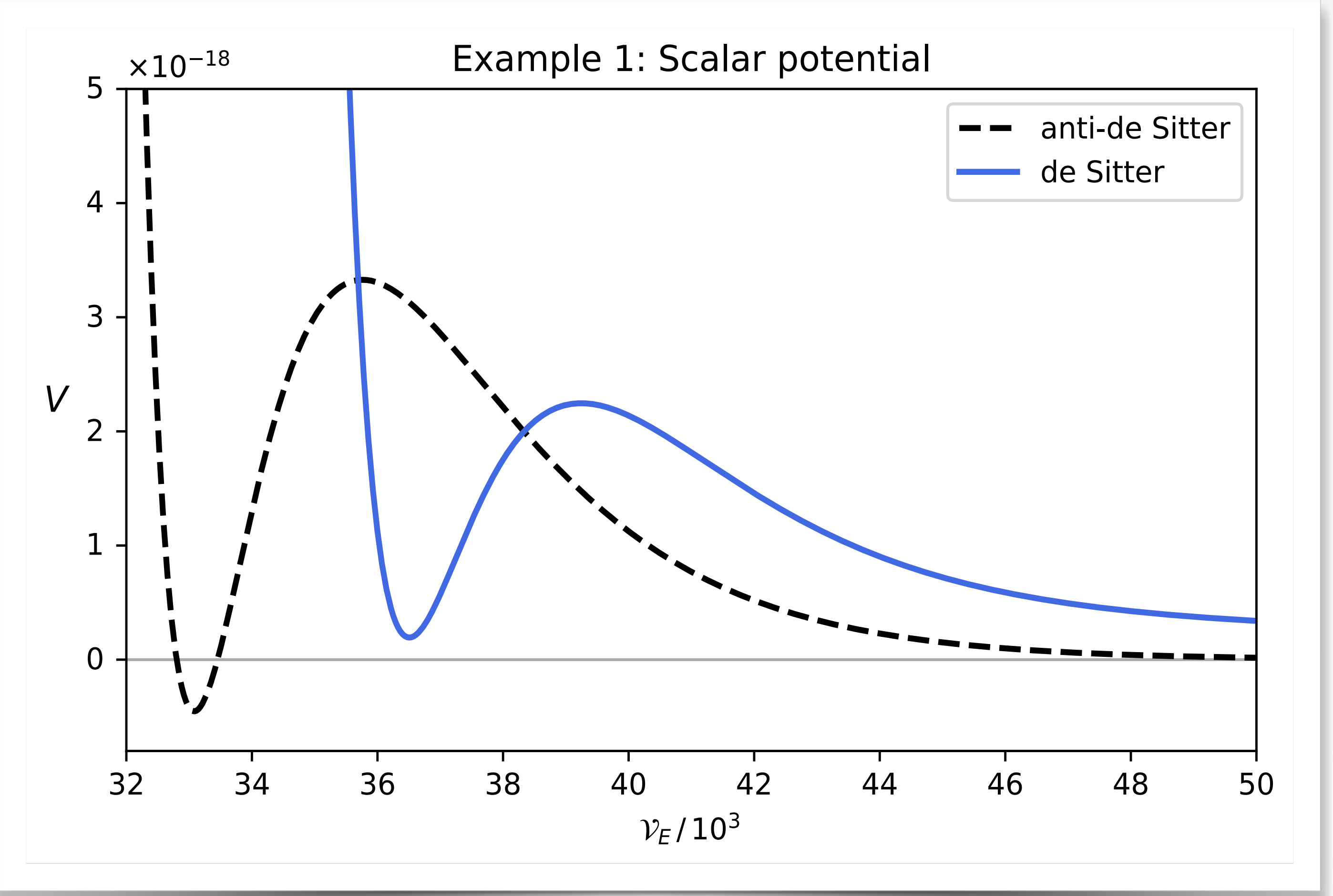
Towards fully stabilised de Sitter vacua in string theory

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

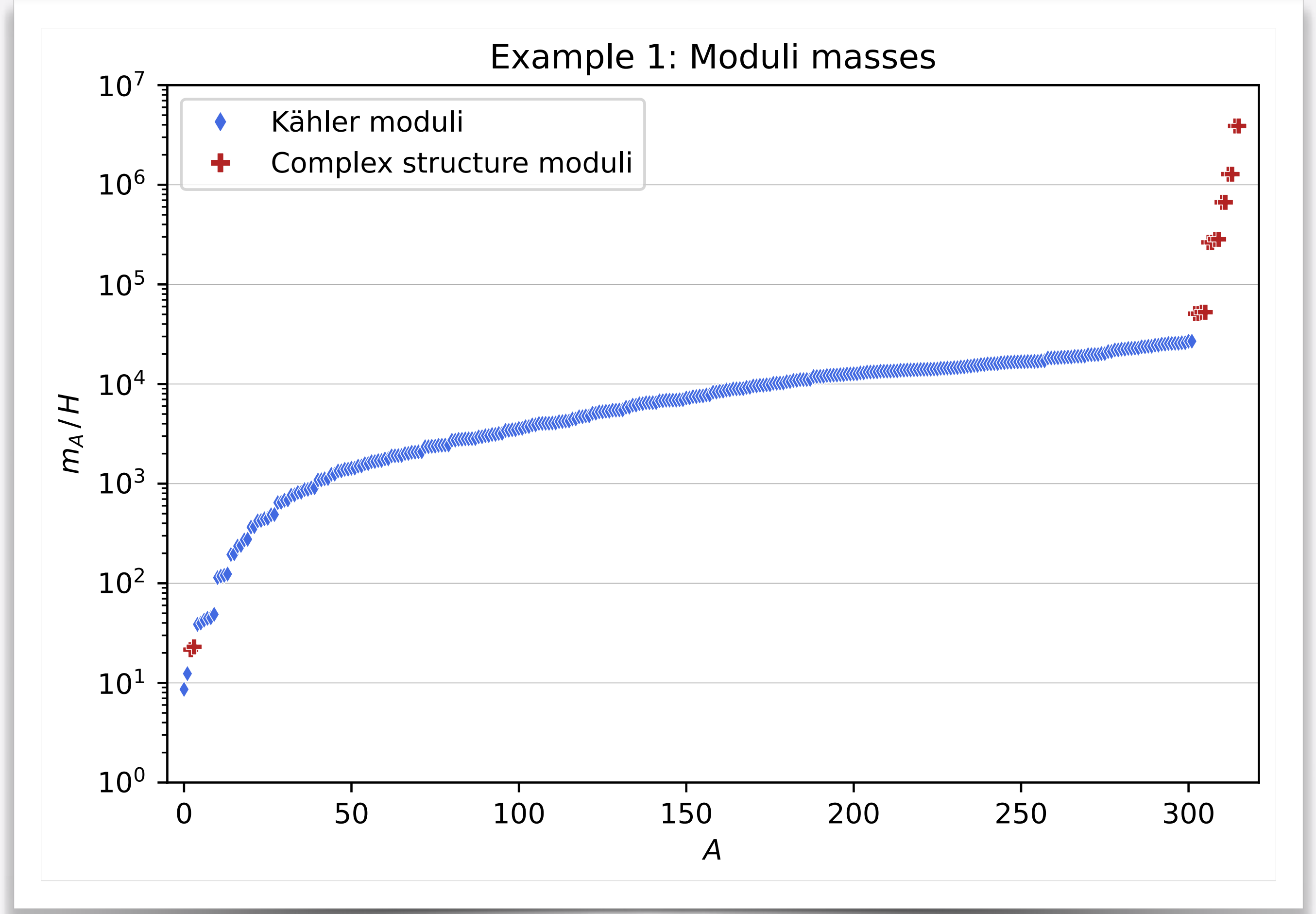
We found first **explicit candidates** for de Sitter vacua as envisioned by KKLT [KKLT hep-th/0301240].

These examples have **strongly warped throats** at $h^{1,1} \gtrsim \mathcal{O}(100)$, and $W_0 \lesssim 10^{-2}$.

Potential before and after uplift:



The vacuum is free of tachyons!



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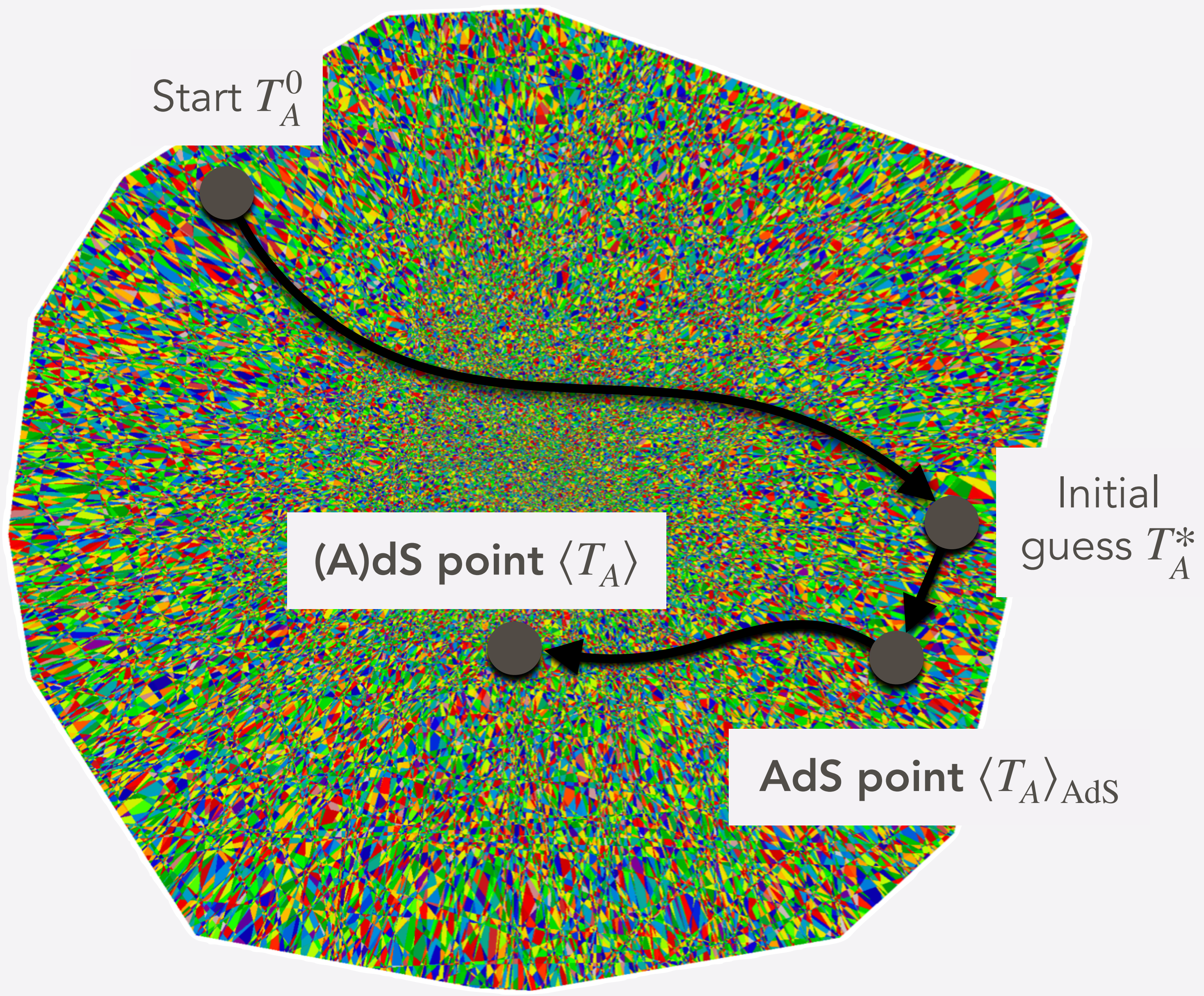

Data is **publicly** available at: https://github.com/AndreasSchachner/kklt_de_sitter_vacua

Summary

In recent years, we have made significant progress in **numerically constructing string vacua**.

However, these models are phenomenologically quite boring…

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However, these models are phenomenologically quite boring…

<u>Question:</u>

How can we find more "promising" compactifications?

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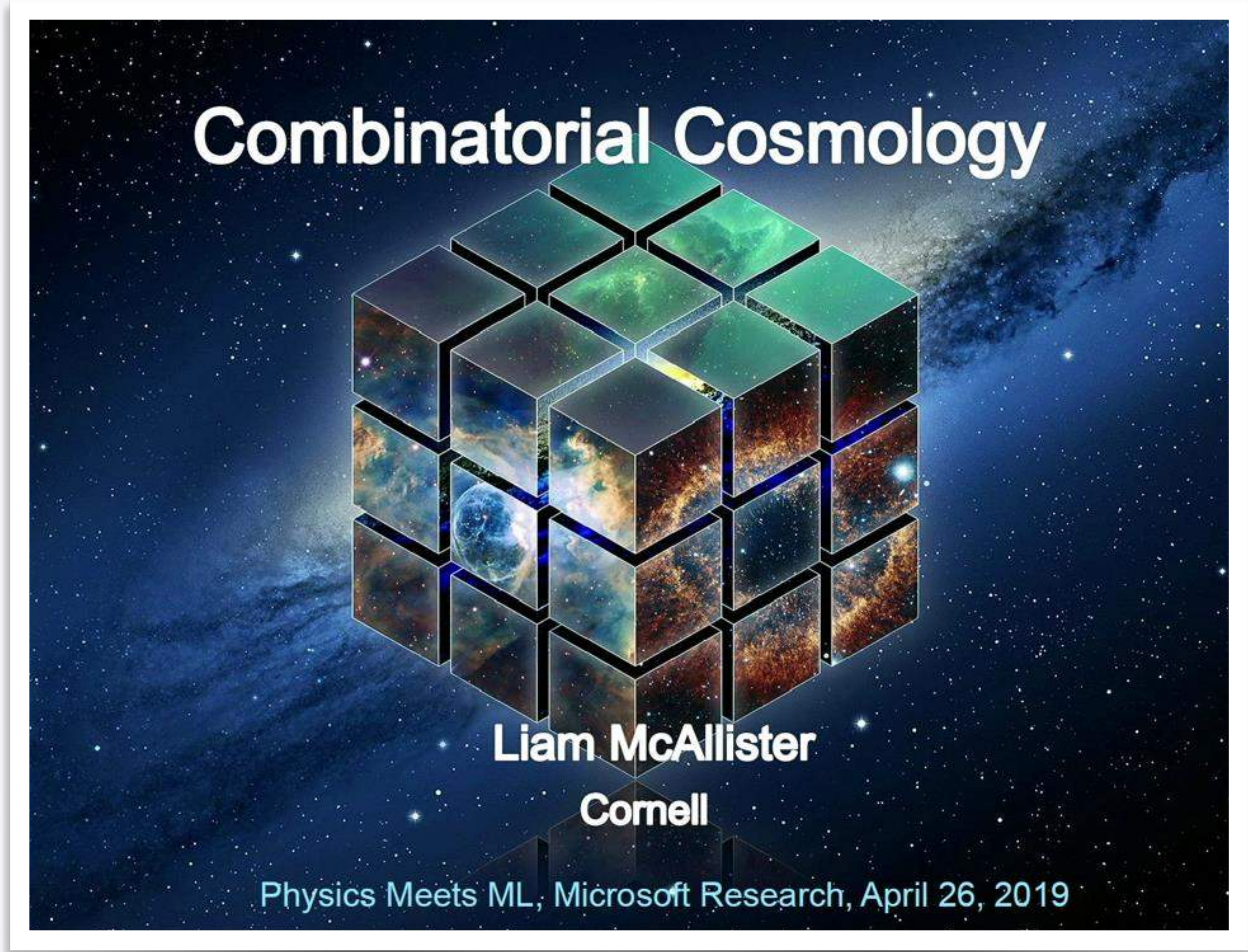
The DNA of toric Calabi-Yau threefolds

A Genetic Algorithm (GA) for polytope triangulations

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

meets



The DNA of toric Calabi-Yau threefolds

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CAN STOCHASTIC OPTIMISATION 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
- …

Redundancies in the KS database

Diffeomorphism classes of CY threefold hypersurfaces

[Gendler, MacFadden, McAllister, Moritz, Nally, **AS**, Stillman: 2310.06820]

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

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

GENERAL FACT: HOMOTOPY TYPE OF CY HYPERSURFACES IS DETERMINED BY INDUCED TRIANGULATIONS OF ***TWO-FACES*** Θ_i°.

Wall's theorem [Wall 1966]

For given $h^{1,1}$, we reflexive polytope Δ°

- **NTFE FRSTs**: all FRSTs with distinct restriction on two-faces Θ_i°
- **FRST classes**: all NTFE FRSTs modded out by polytope automorphisms
- **CY classes**: diffeomorphism classes of CY threefolds

We have proven the exact number of CY classes for $h^{1,1} \leq 5$ in KS and bounds for $h^{1,1} = 6,7$.

See also [Carta, Mininno, Righi, Westphal: 2101.07272] for CICYs and [Chandra et al. 2310.05909] for KS

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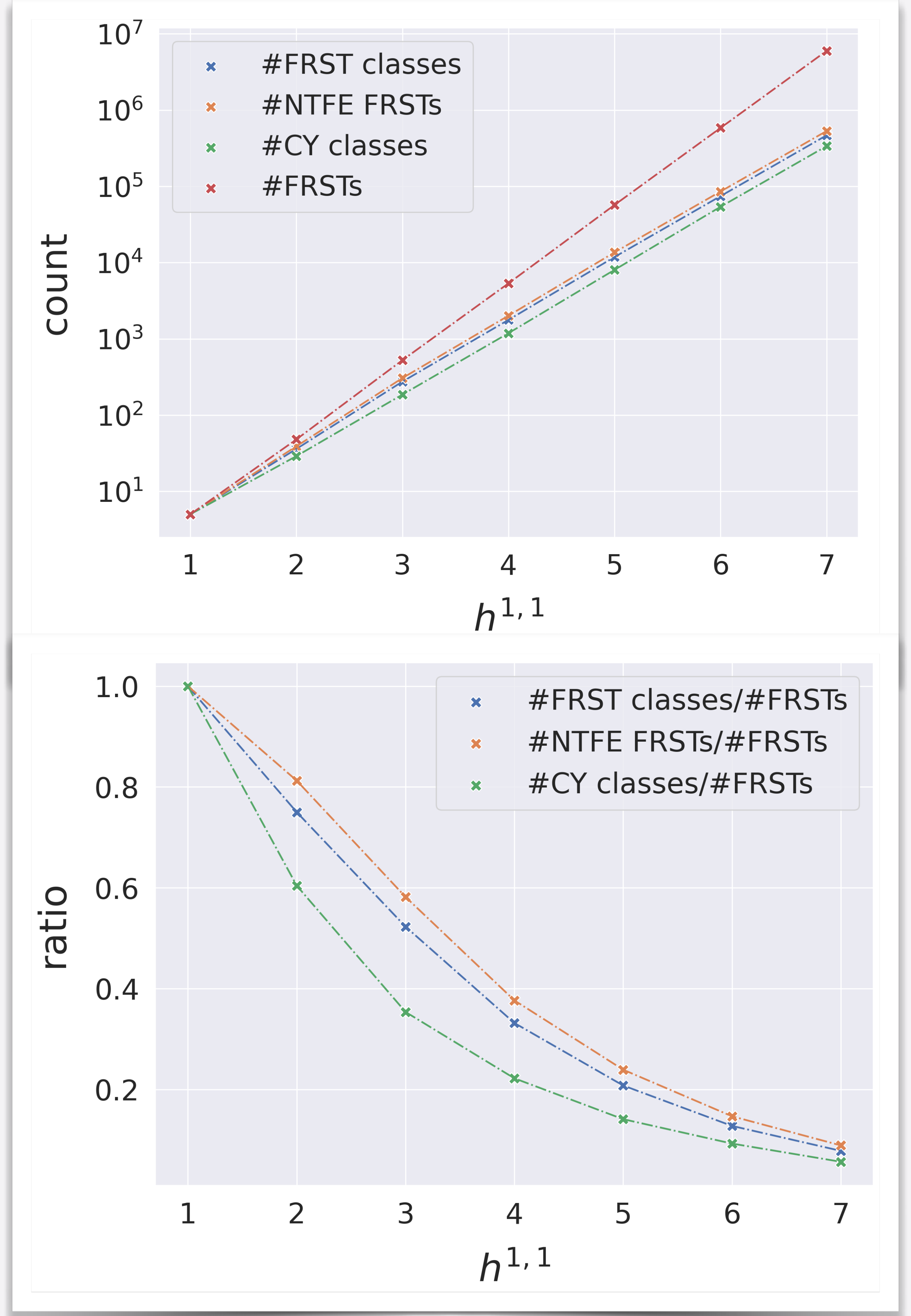

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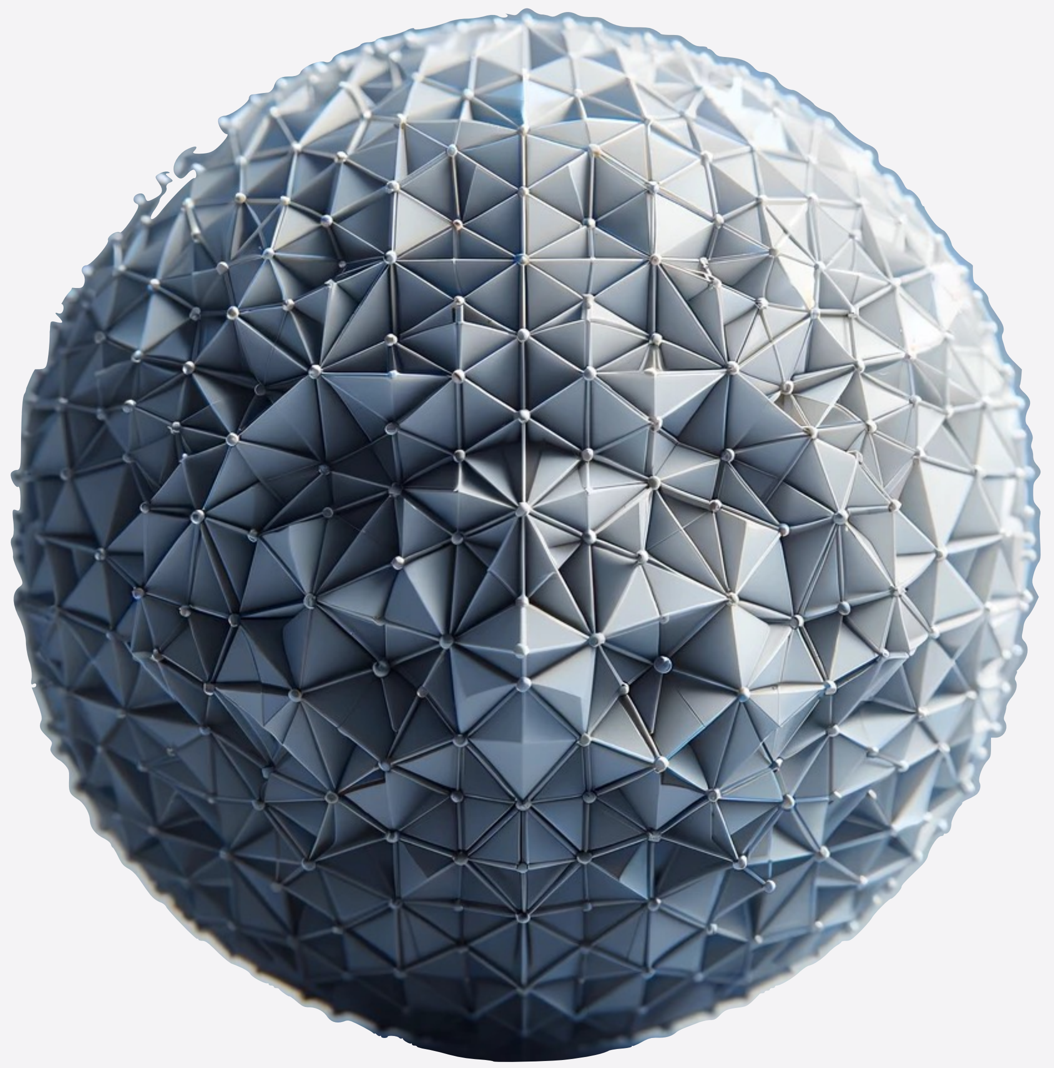
Generating 2-face inequivalent Triangulations

Defining a suitable Encoding for FRSTs

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



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 labels 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.

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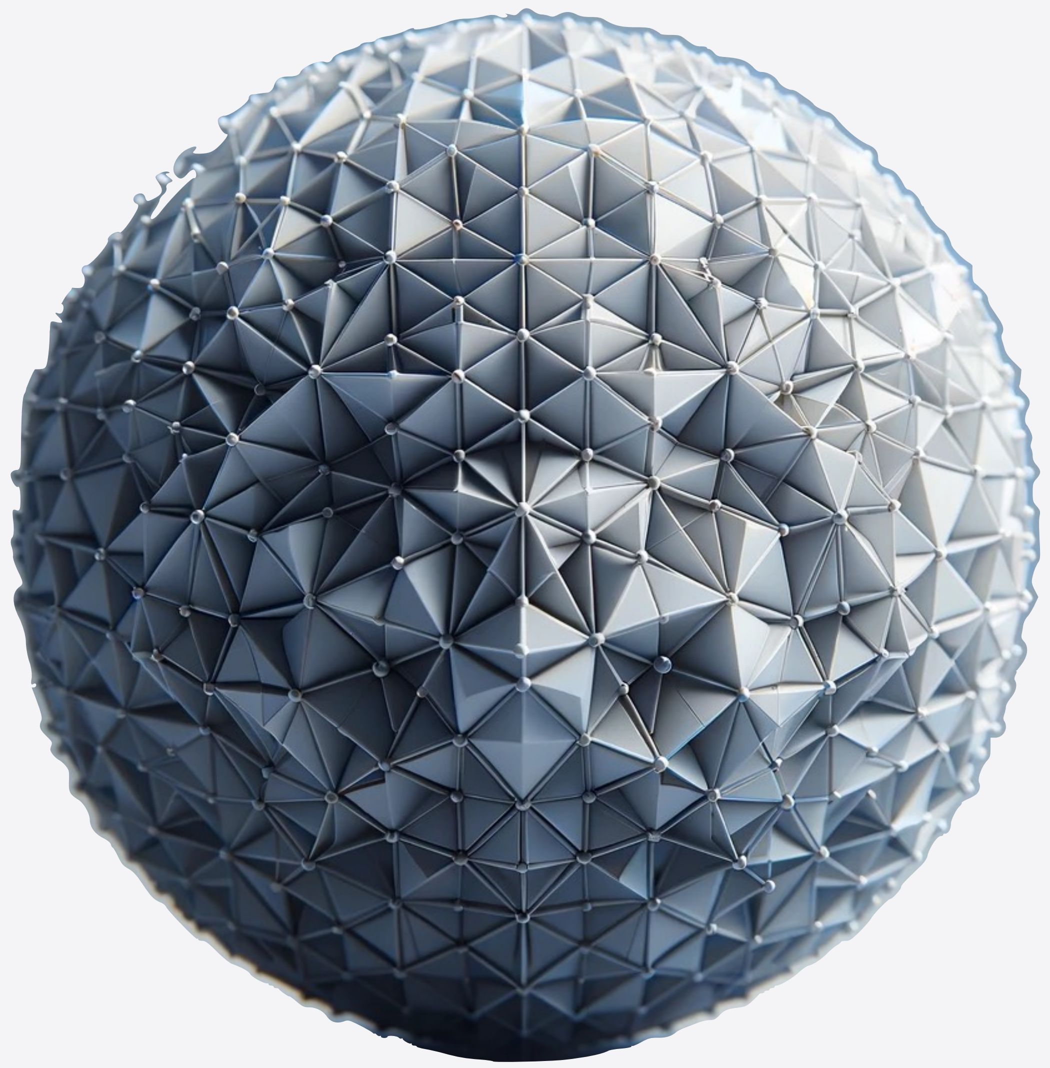

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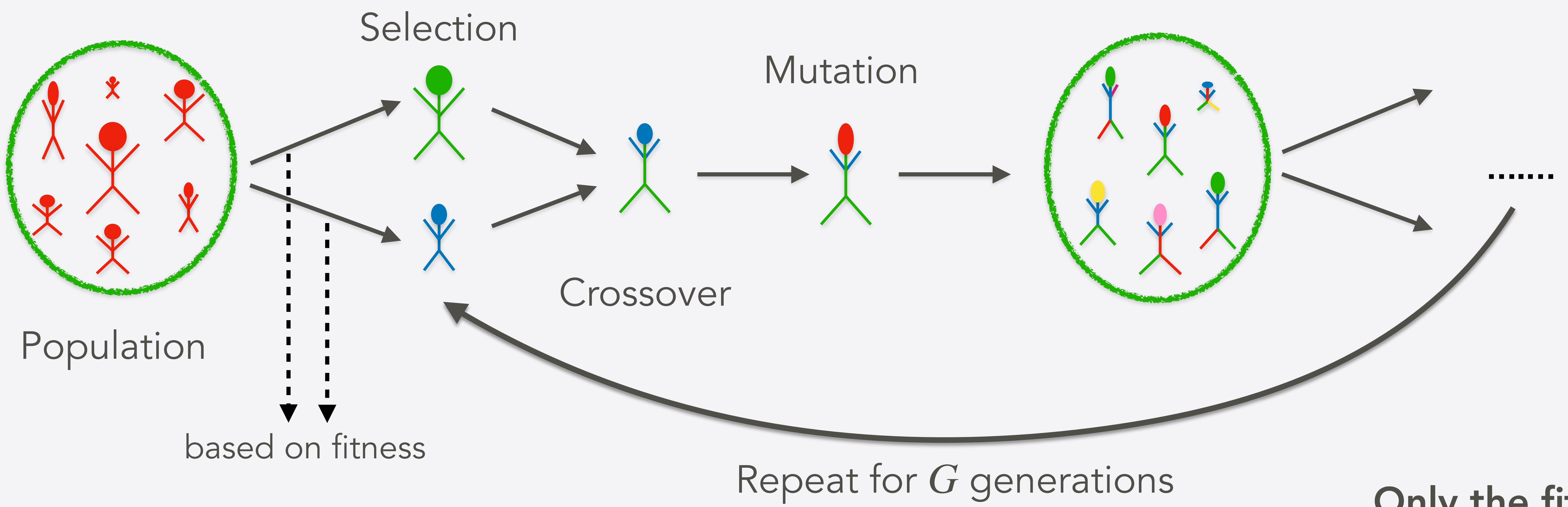
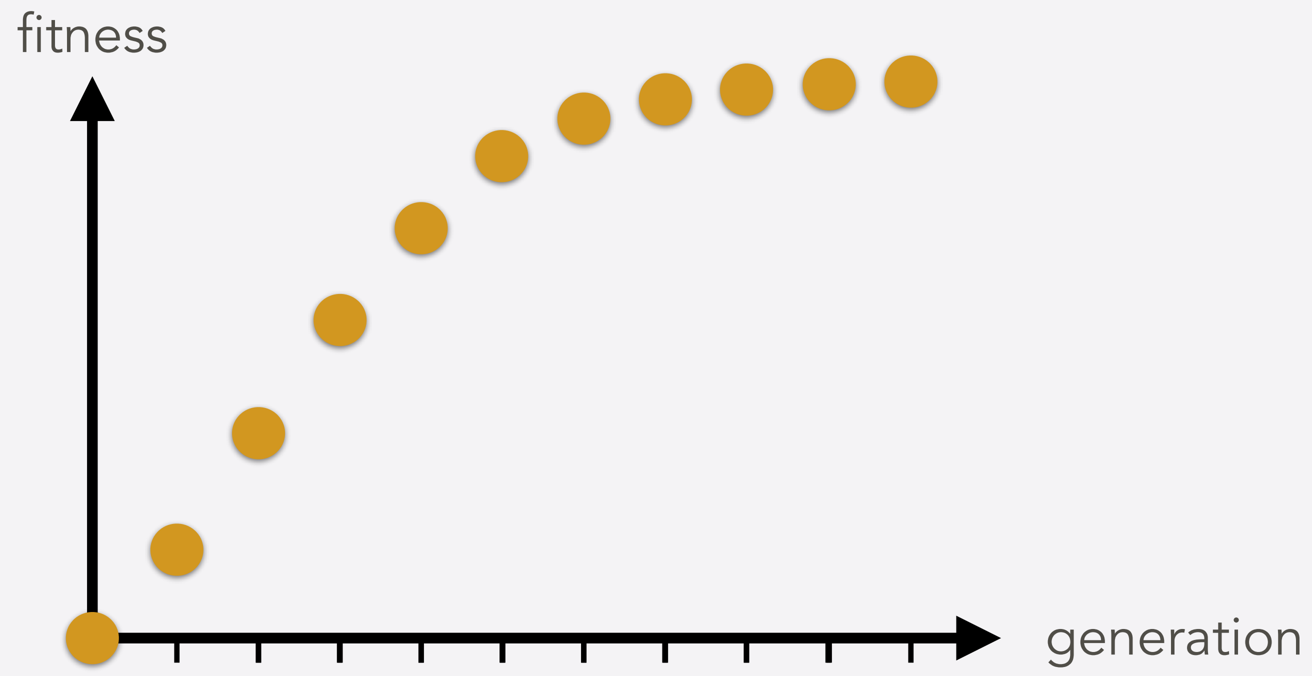
Genetic Algorithms (GAs)

Optimisation algorithms from natural evolution

Stochastic search method based on natural selection processes:



Only the fittest CYs survive!



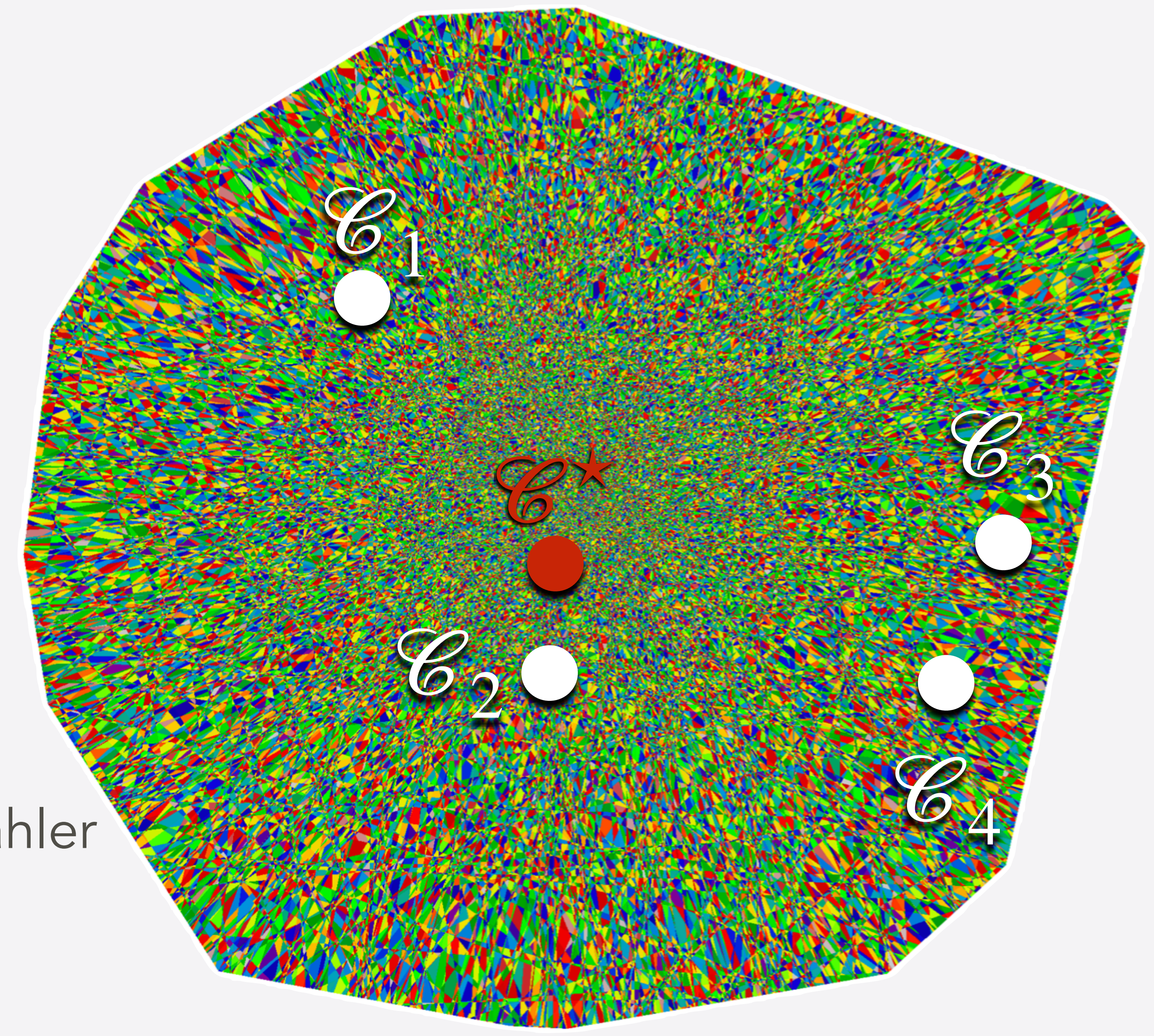
Implementation for polytope triangulations:

- **Search space**: NTFE FRSTs for **fixed** polytope Δ°
- **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

Genetic Algorithms (GAs)

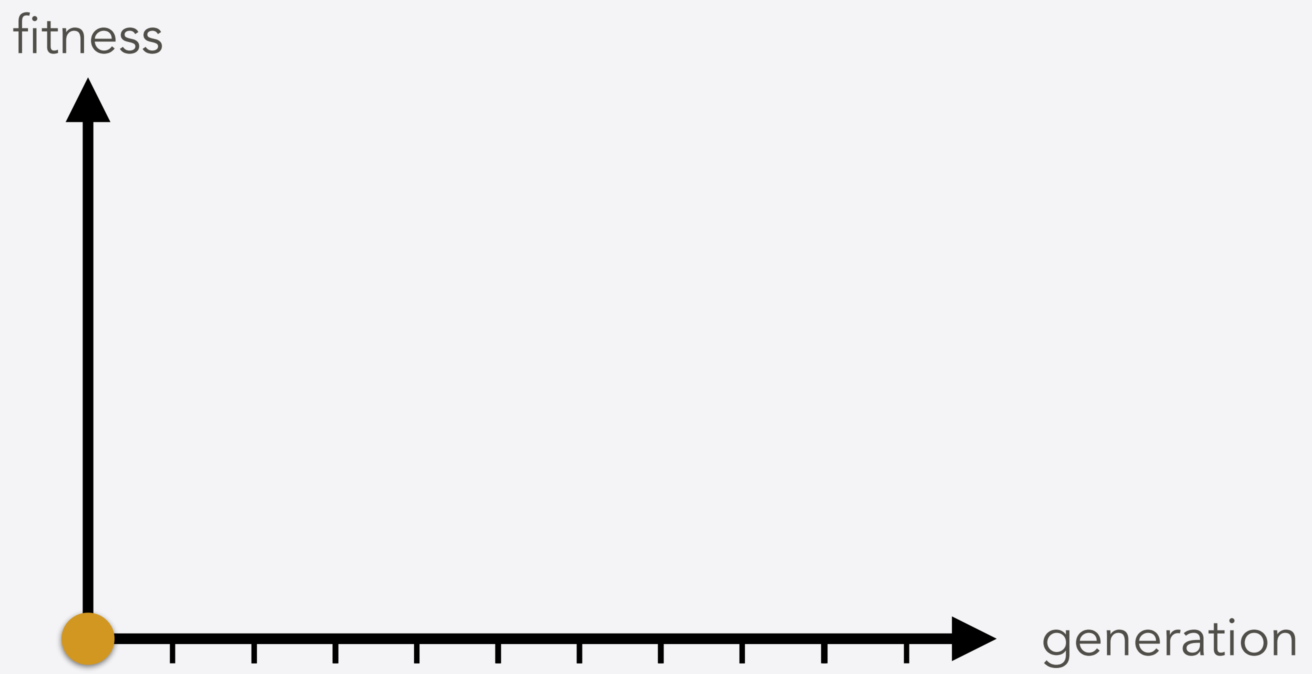
Illustrative example

Example with $P = 4$



Extended Kähler cone $\mathscr{K}$

Initial population = “generation 0”



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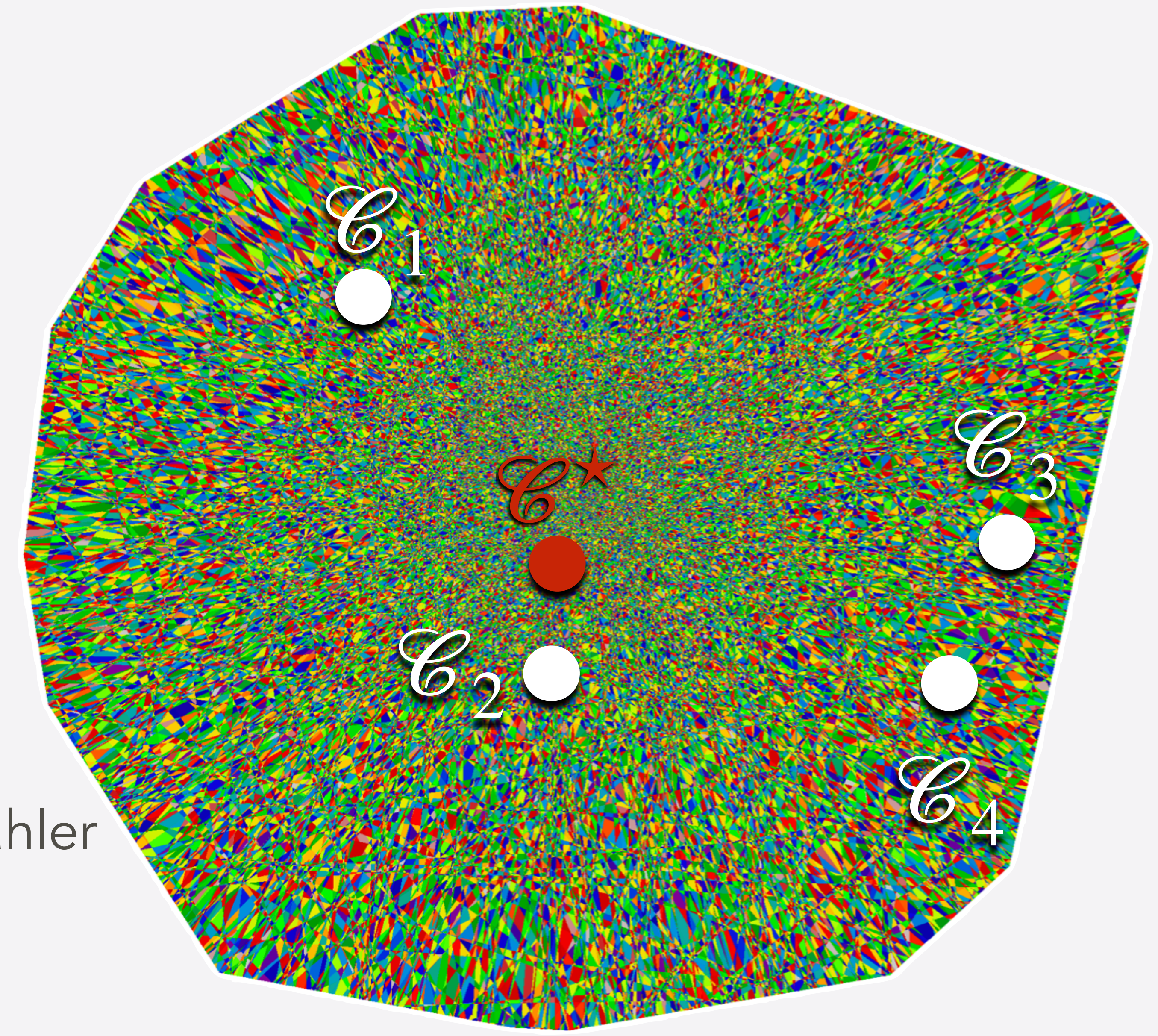

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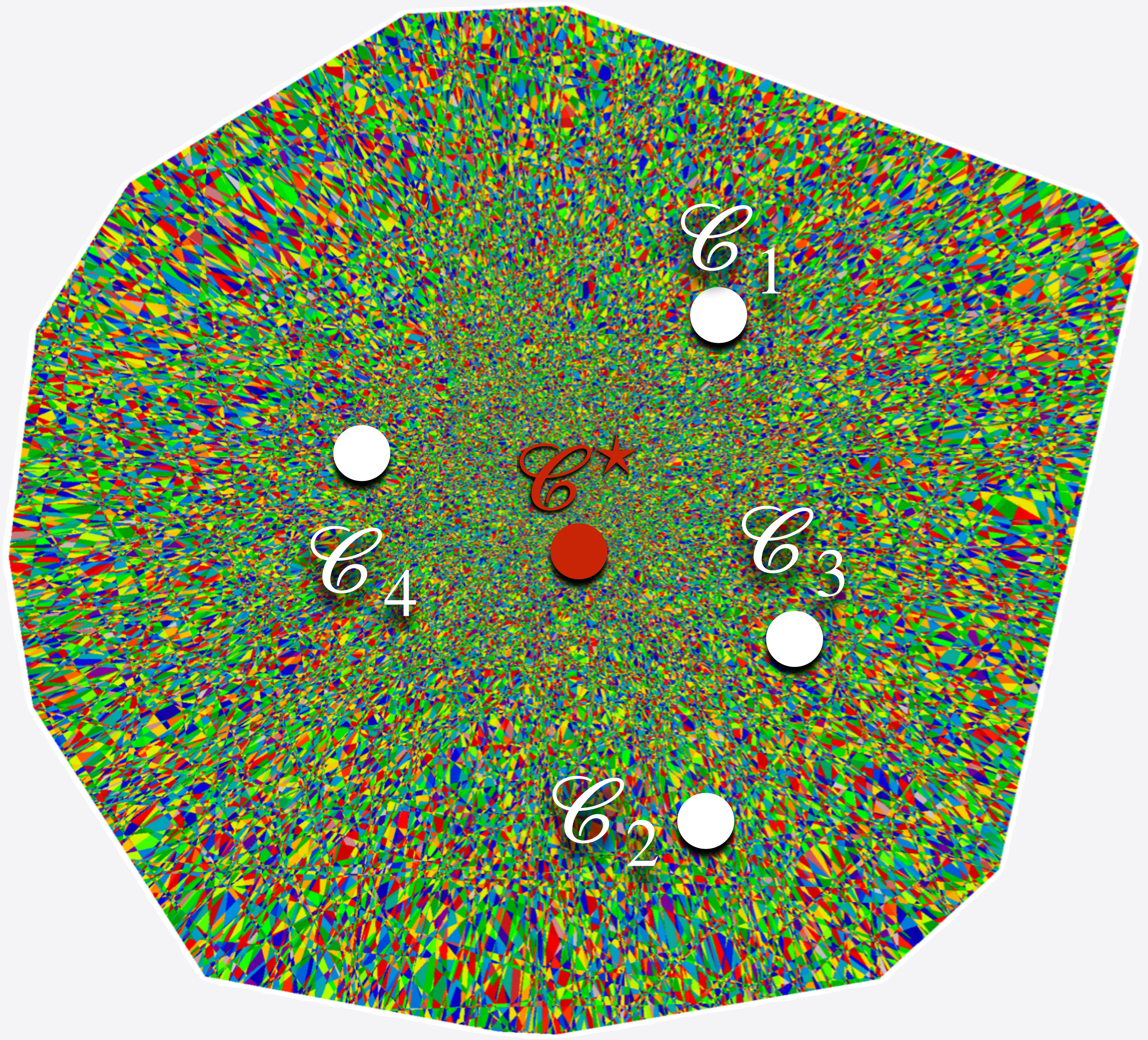
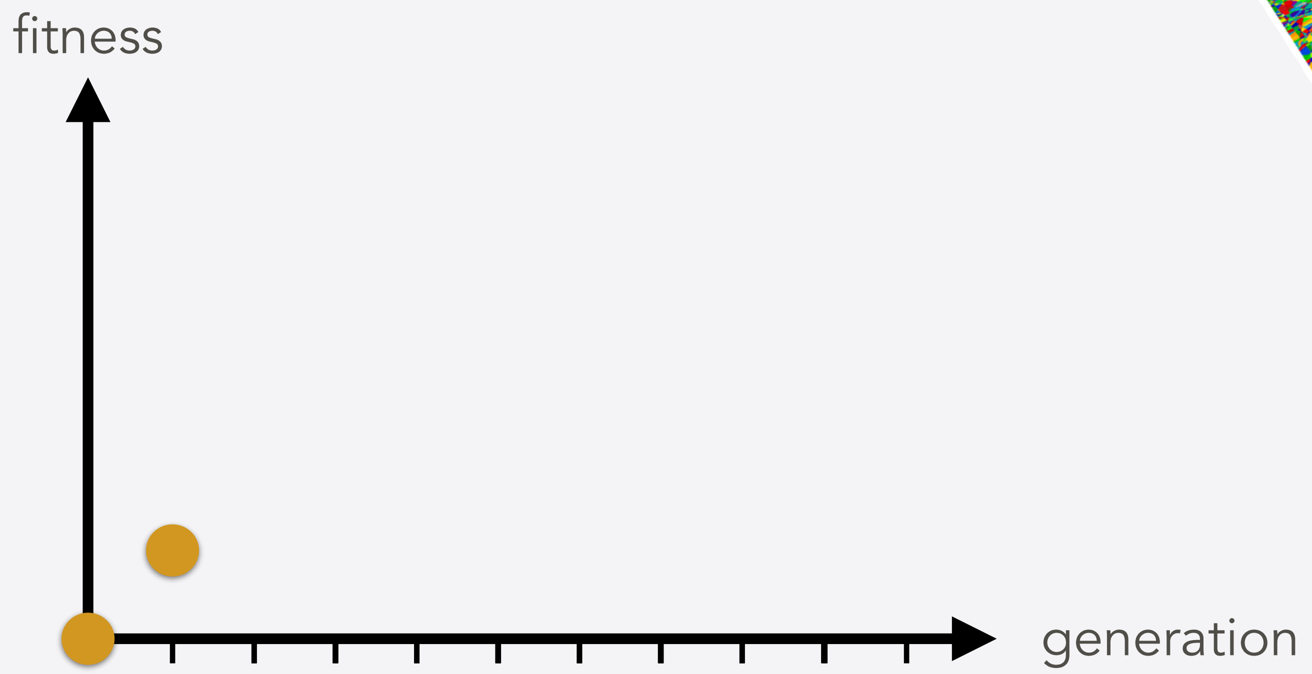


generation 1



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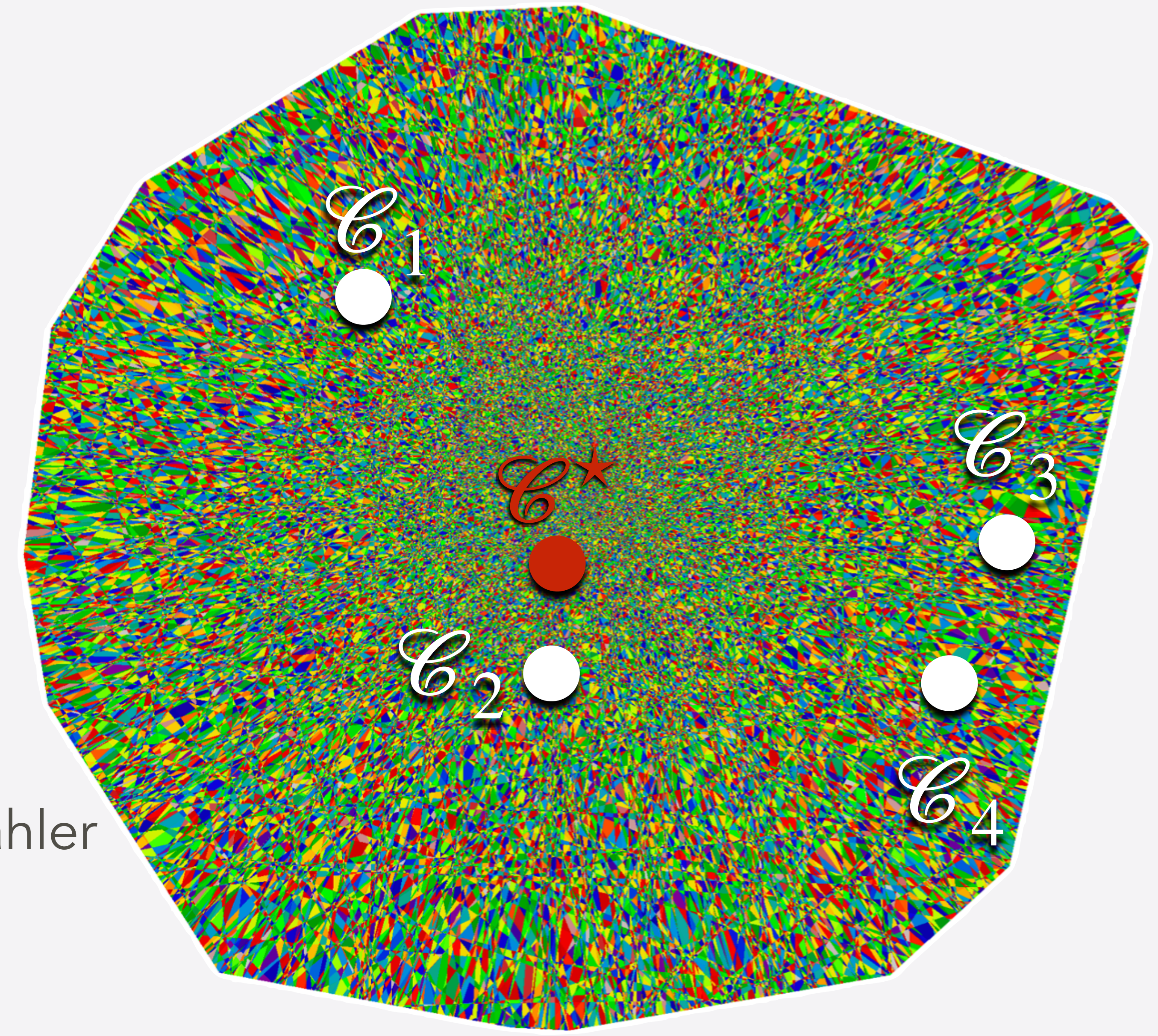
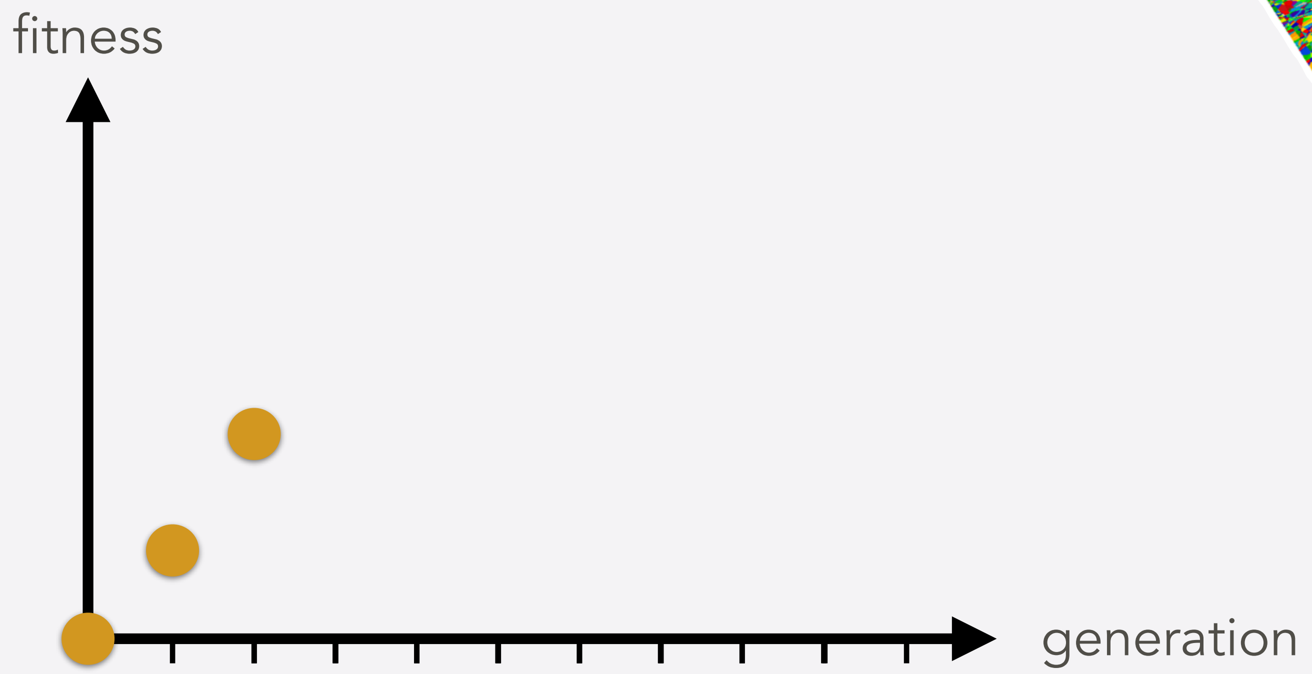
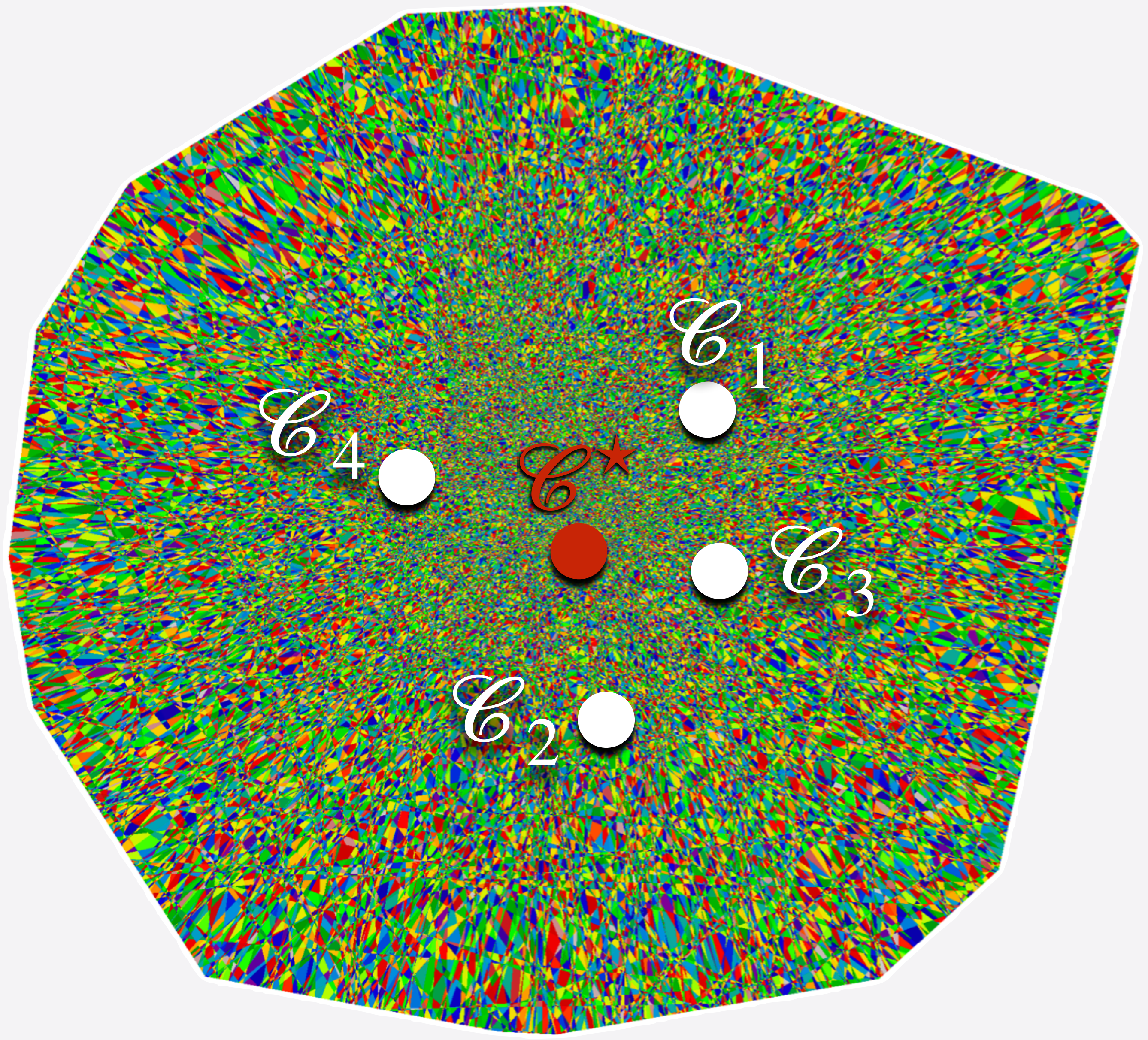


Initial population = "generation 0"

GA evolution



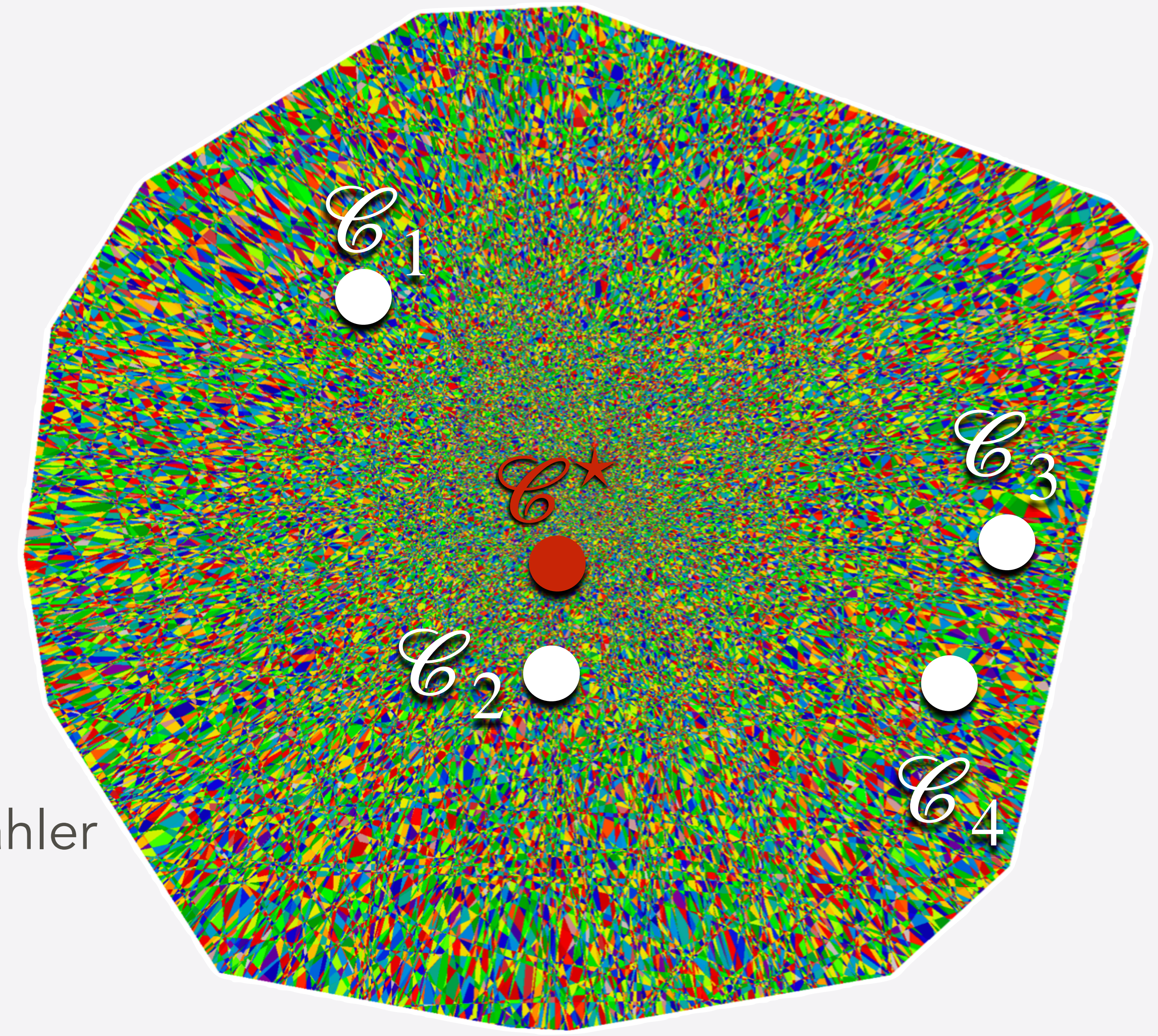


generation 2

Genetic Algorithms (GAs)

Illustrative example

Example with $P = 4$



Extended Kähler cone $\mathscr{K}$

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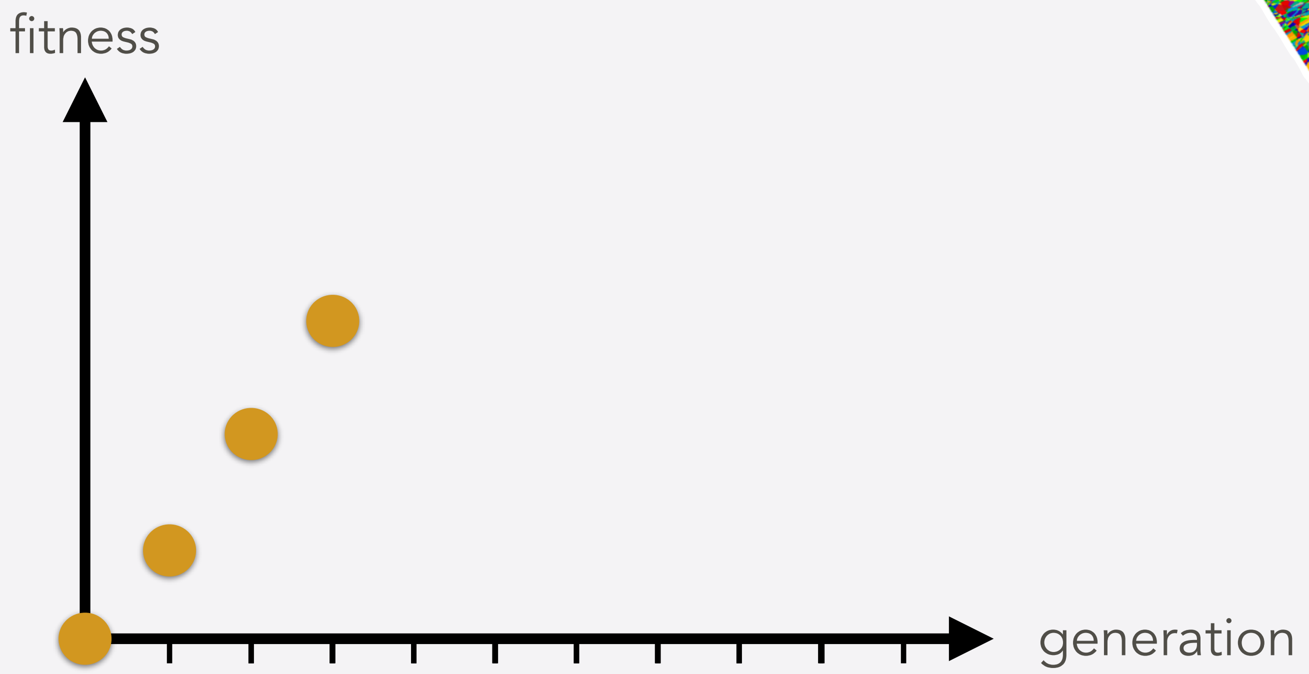
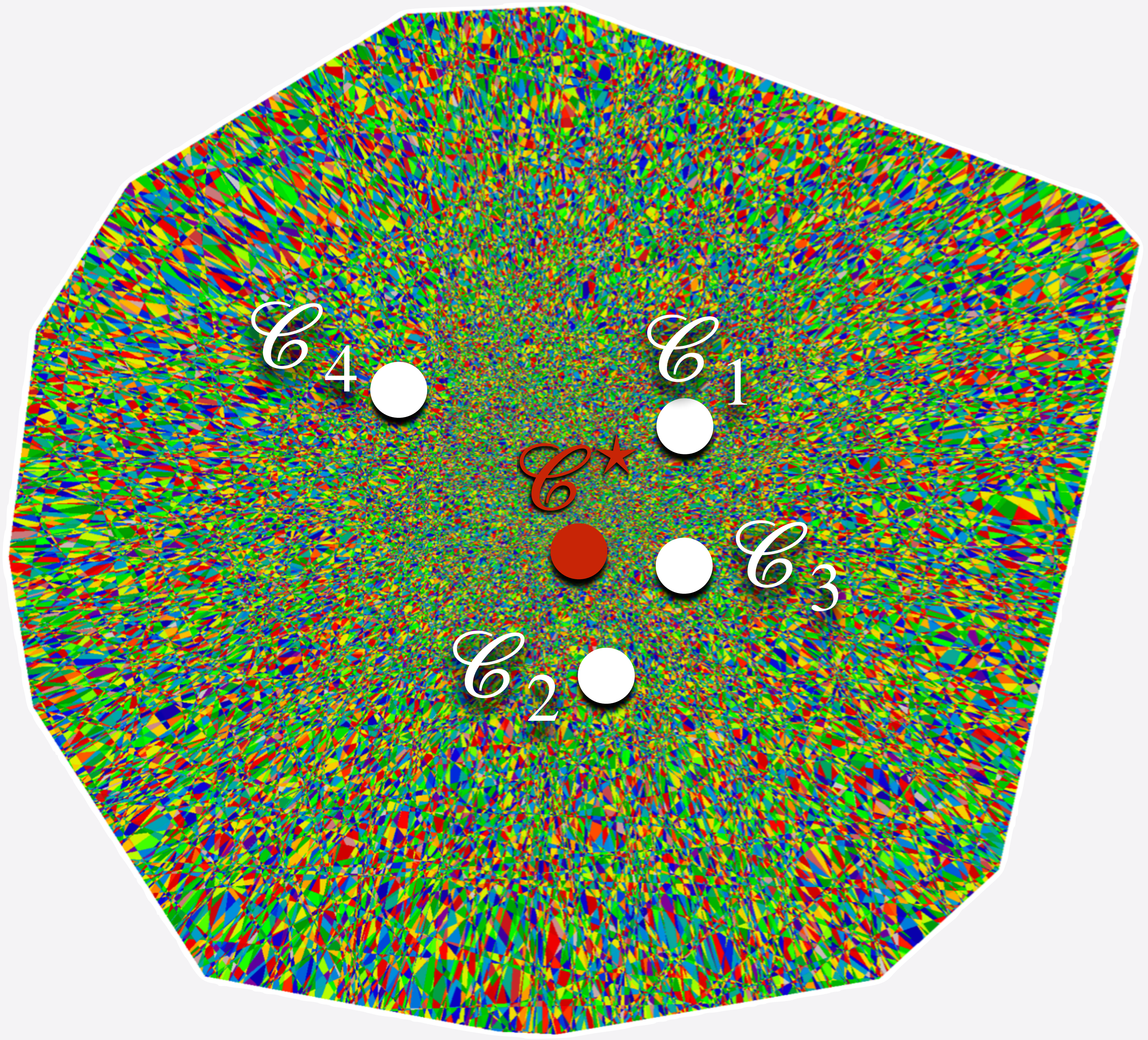


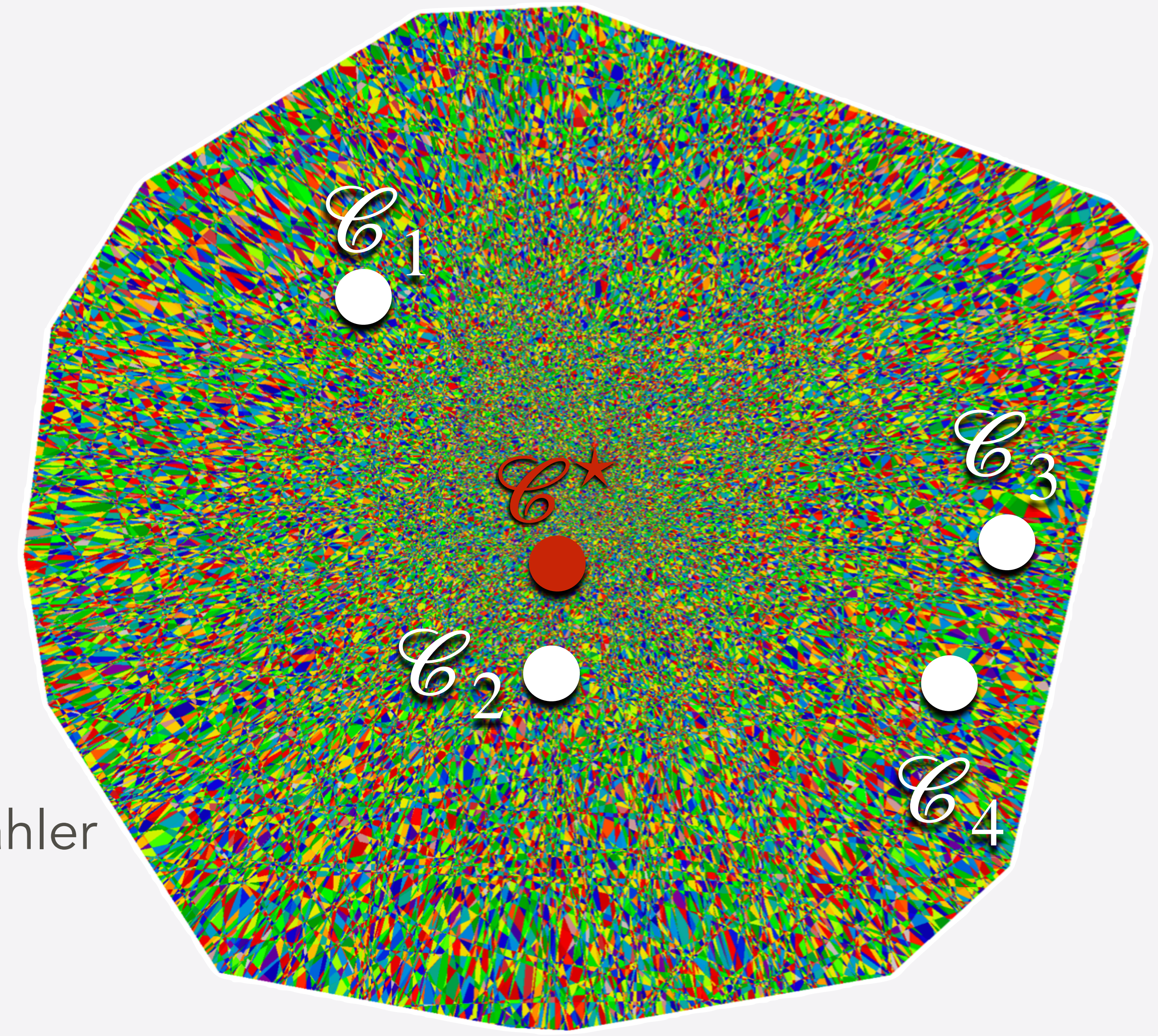


generation 3

Genetic Algorithms (GAs)

Illustrative example

Example with $P = 4$



Extended Kähler cone $\mathscr{K}$

Initial population = "generation 0"

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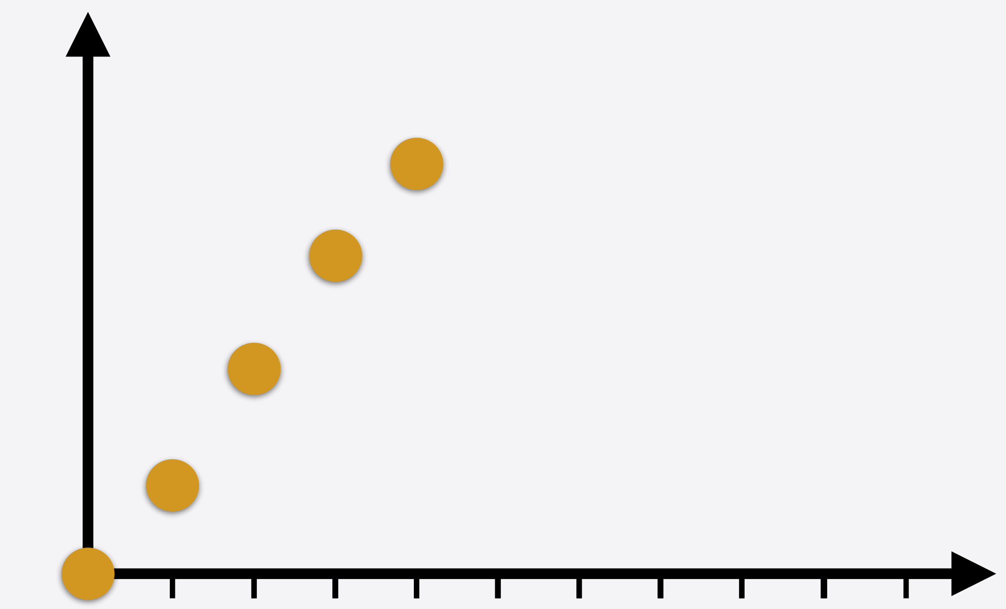
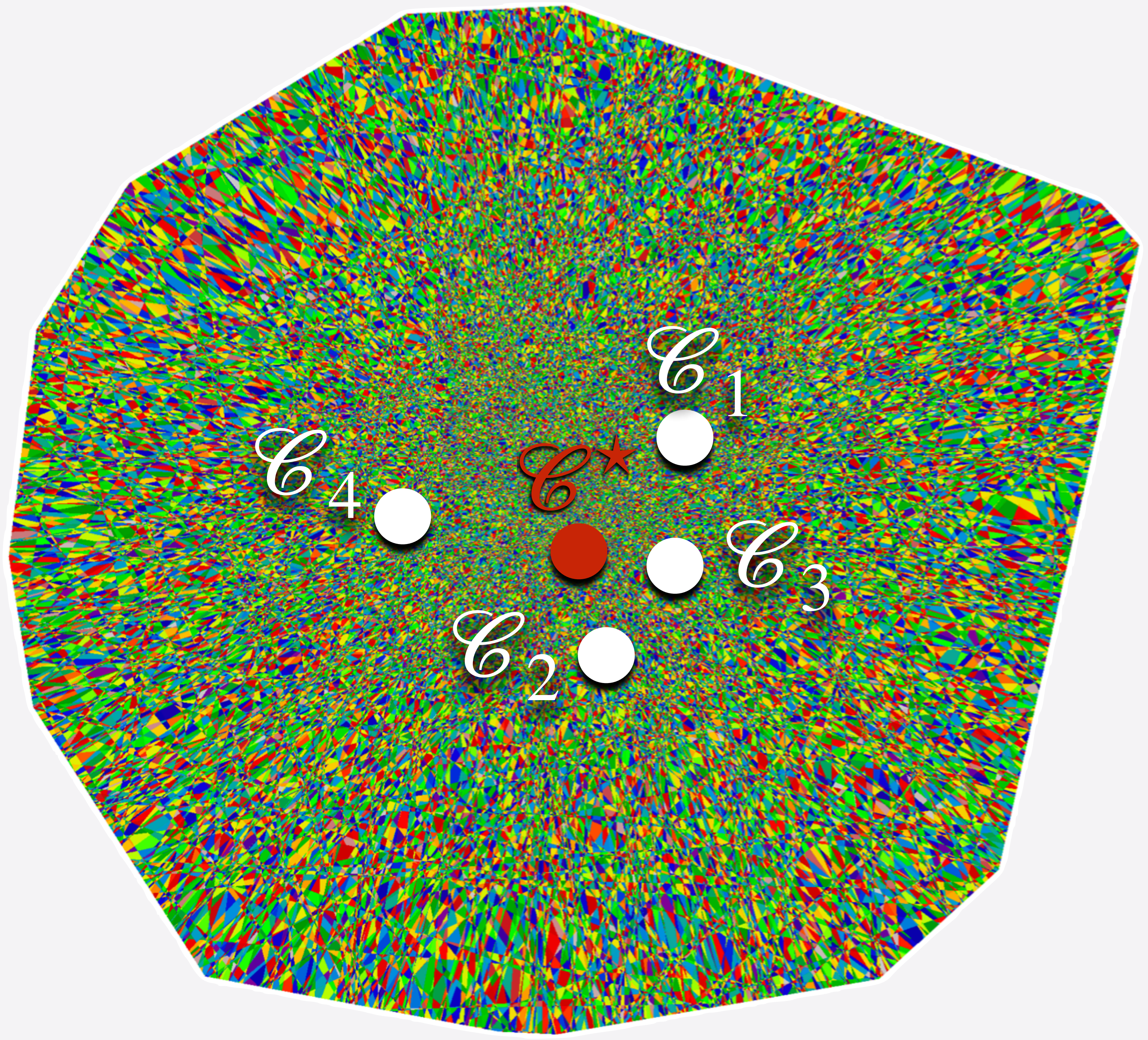


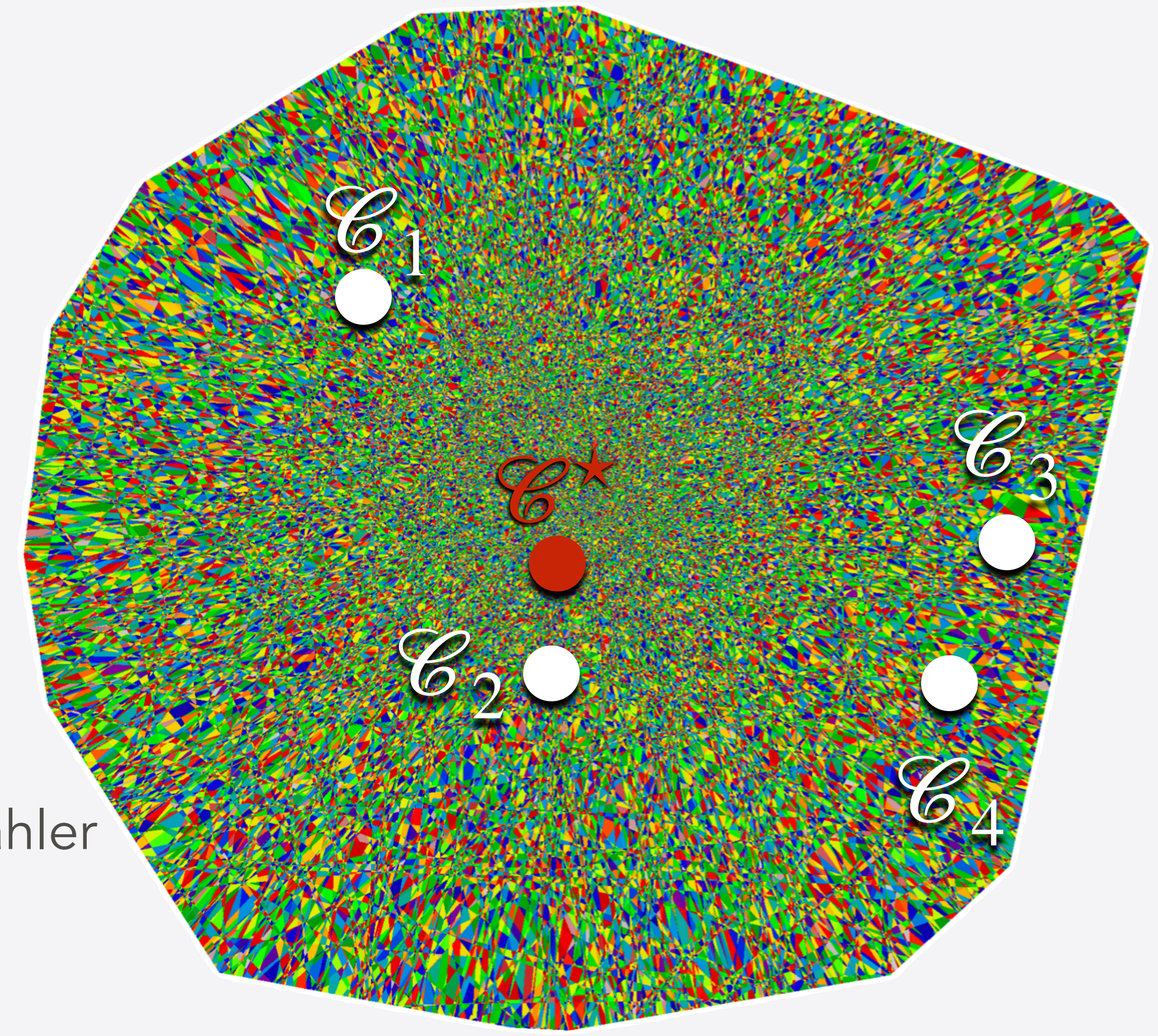


generation 4

Genetic Algorithms (GAs)

Illustrative example

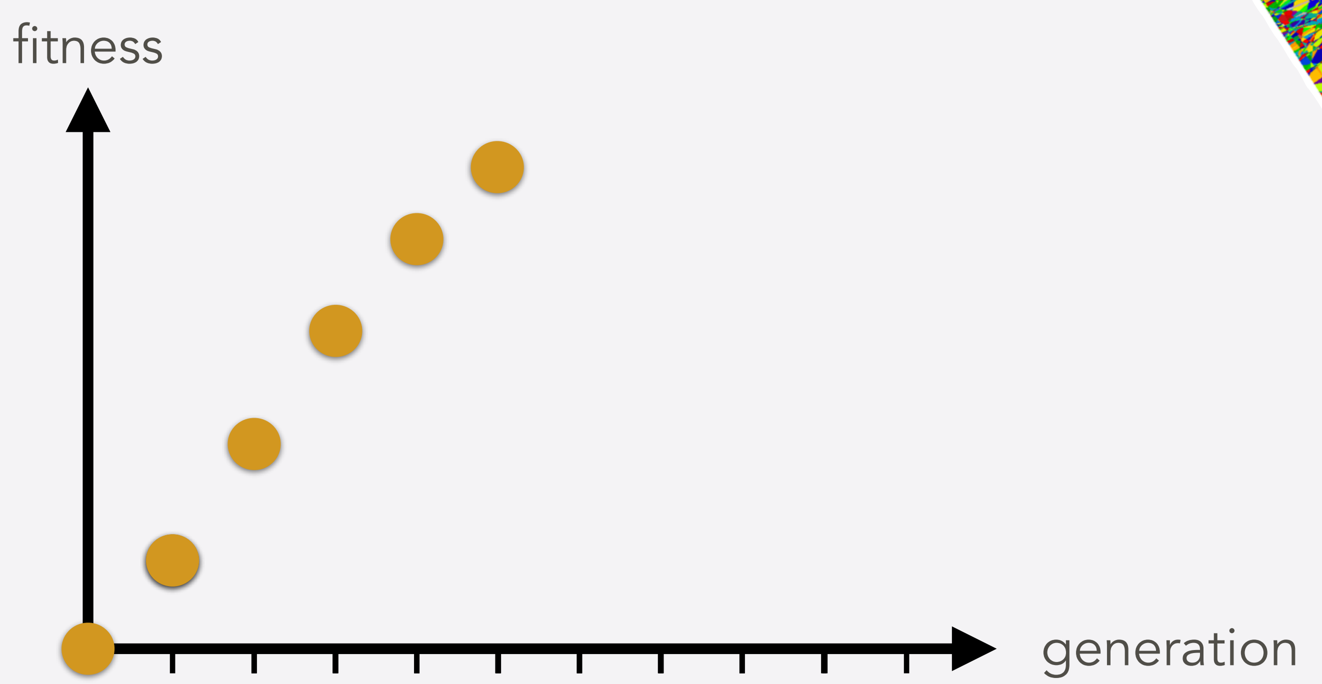
Example with $P = 4$

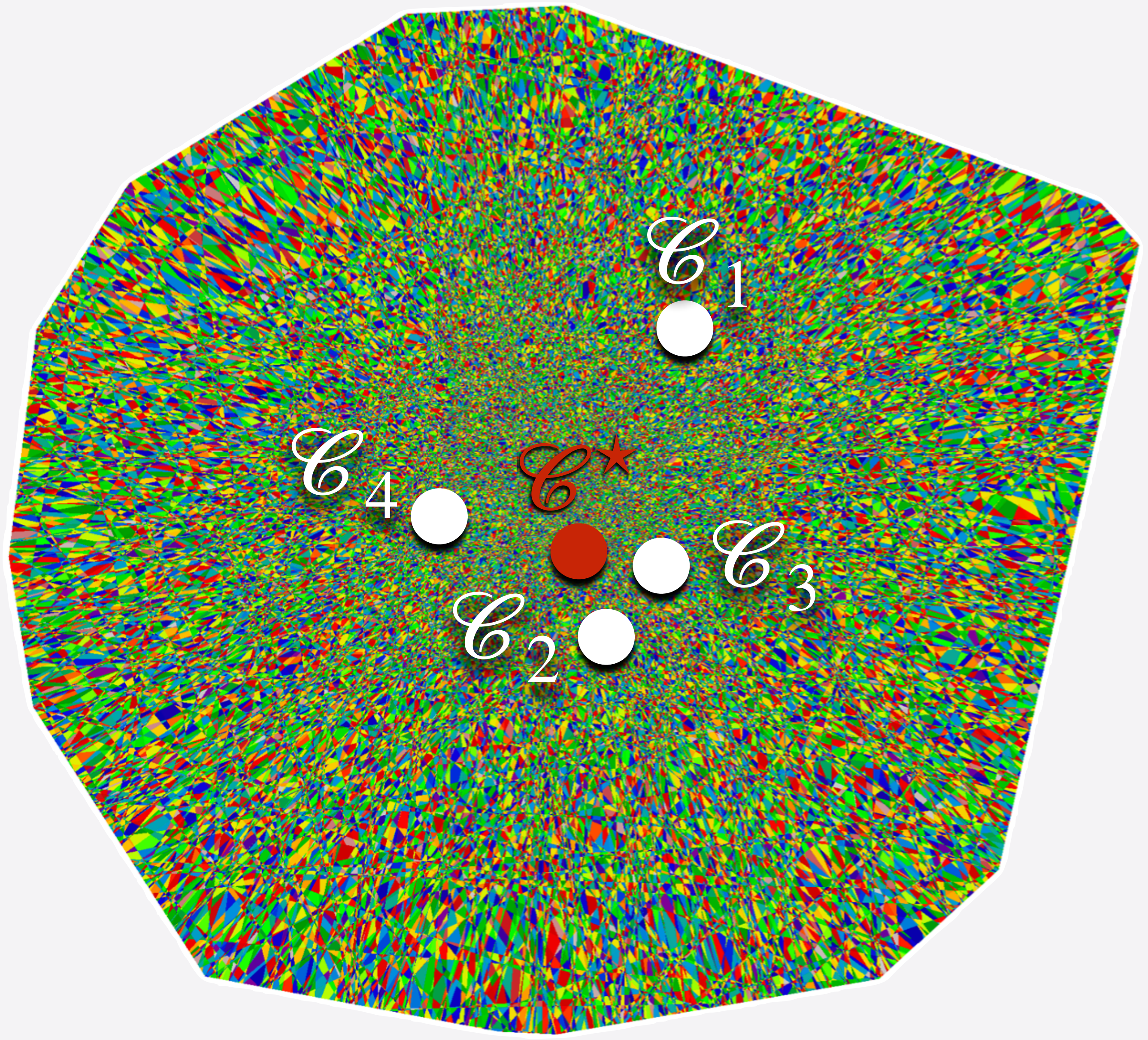


Extended Kähler cone $\mathscr{K}$

Initial population = "generation 0"

GA evolution



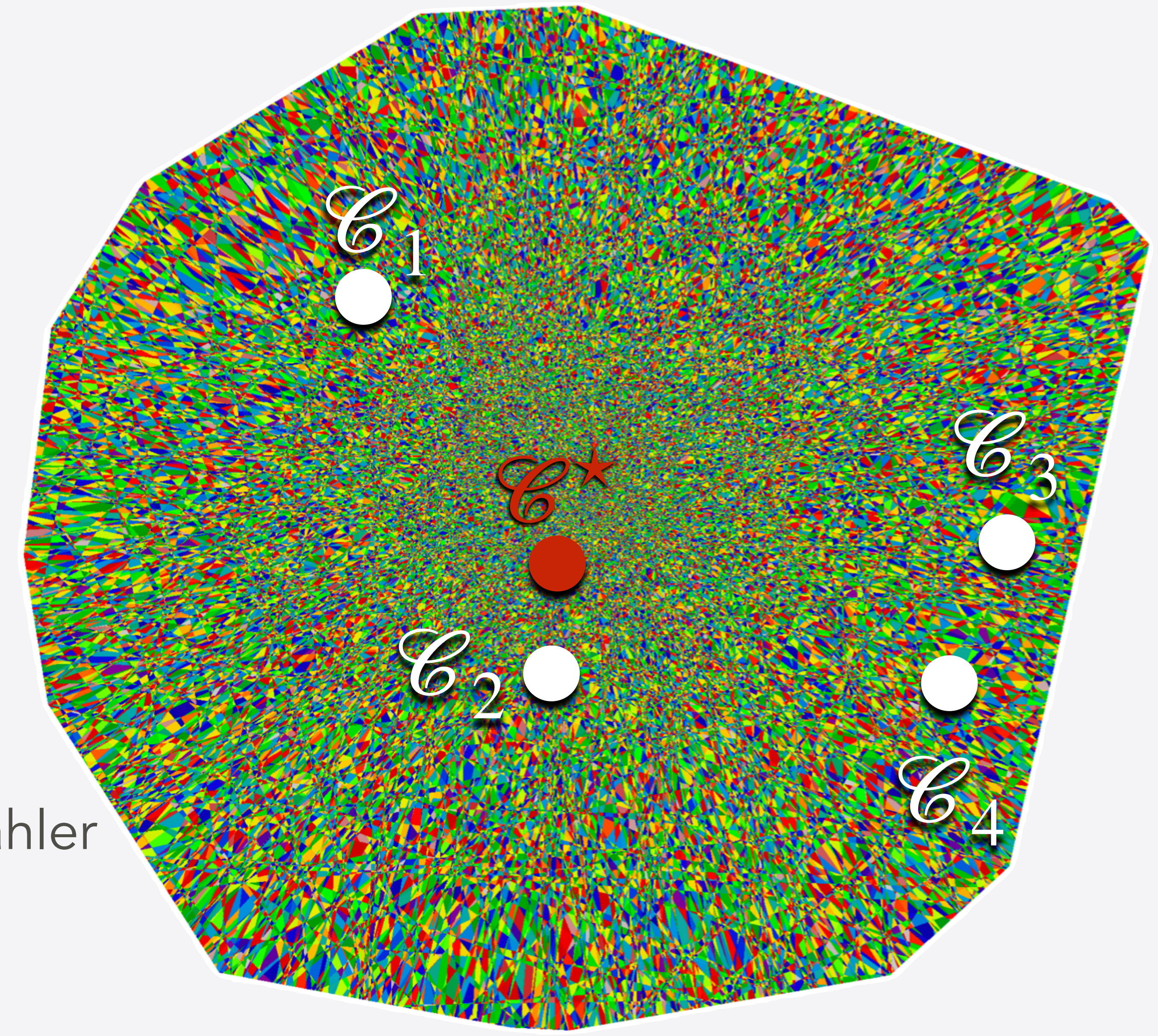


generation 5

Genetic Algorithms (GAs)

Illustrative example

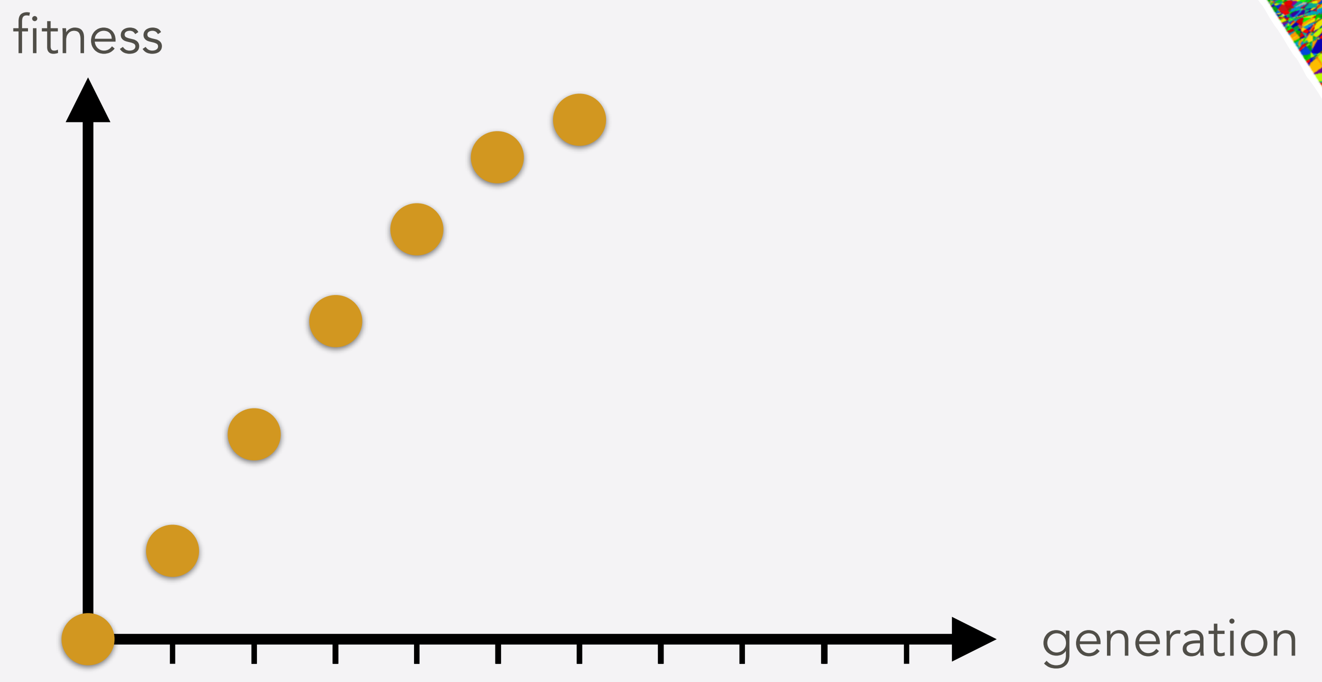
Example with $P = 4$

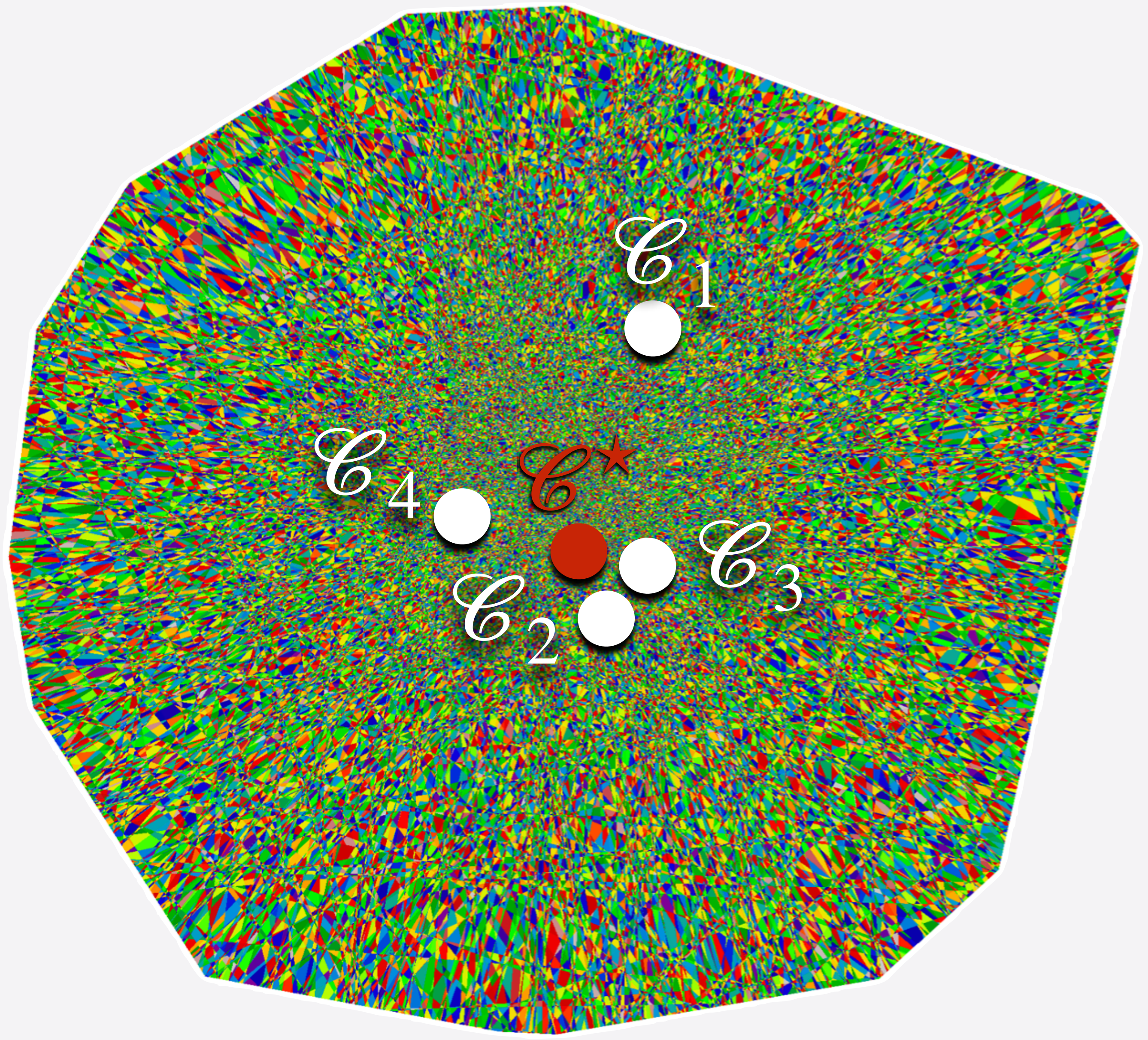


Extended Kähler cone $\mathscr{K}$

Initial population = "generation 0"

GA evolution



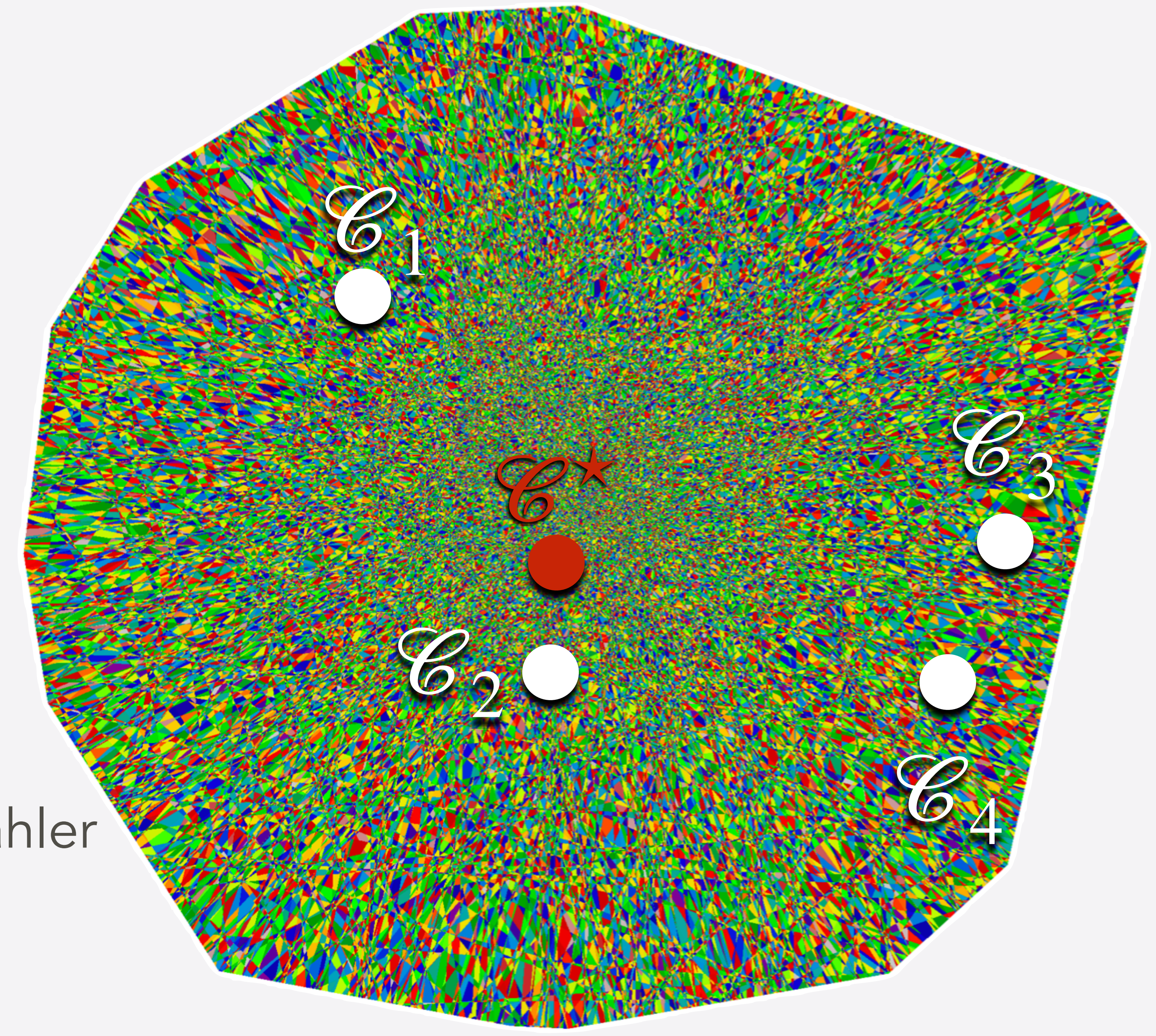


generation 6

Genetic Algorithms (GAs)

Illustrative example

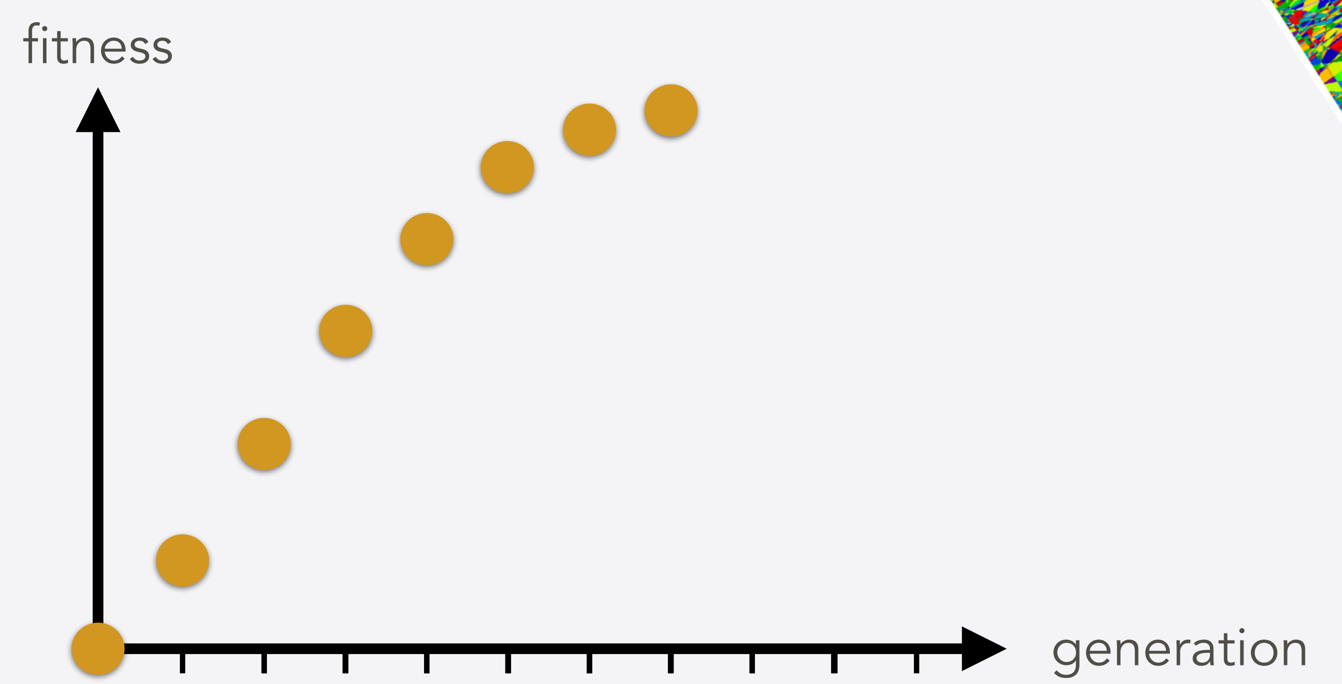
Example with $P = 4$

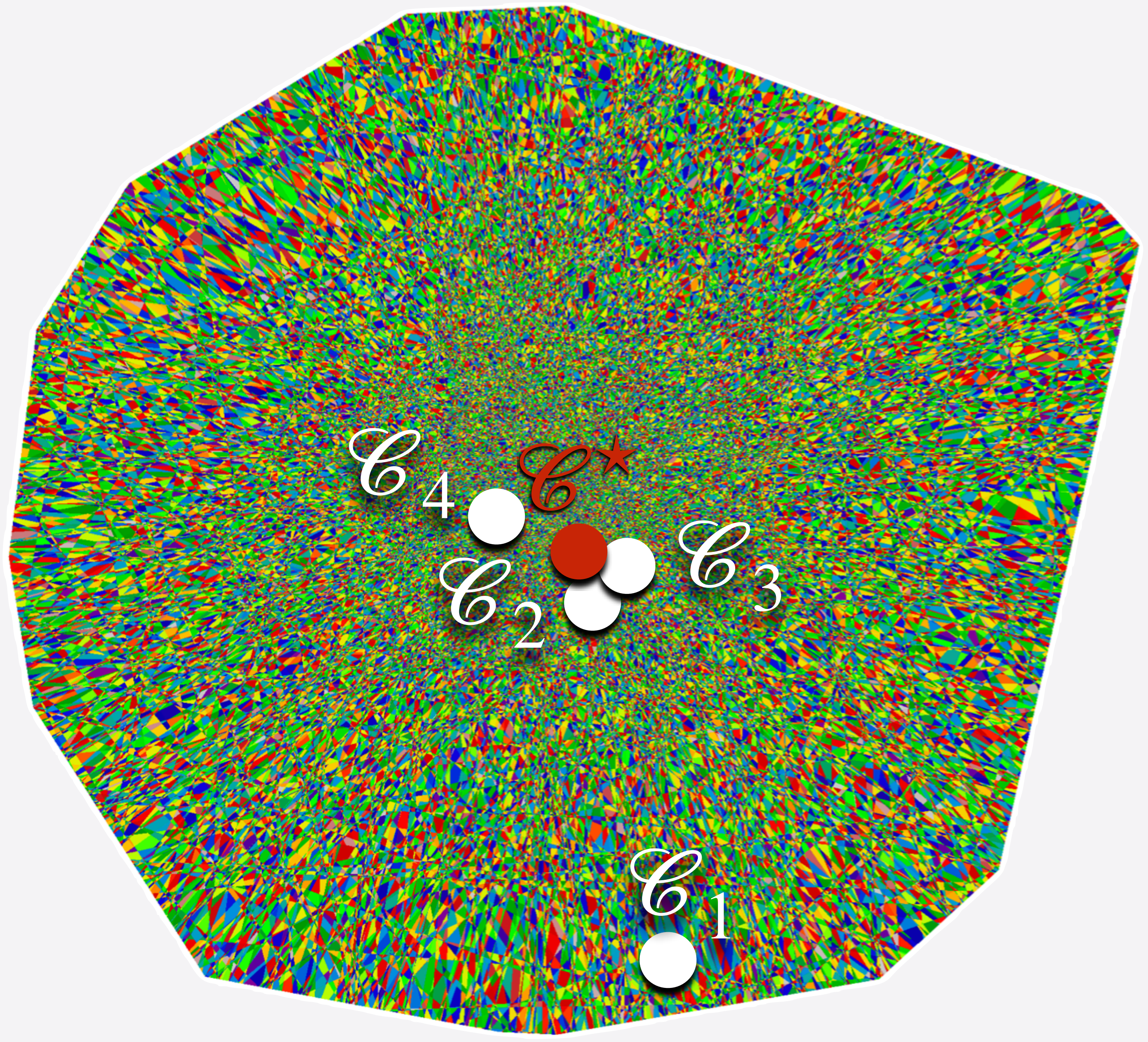


Extended Kähler cone $\mathscr{K}$

Initial population = "generation 0"

GA evolution



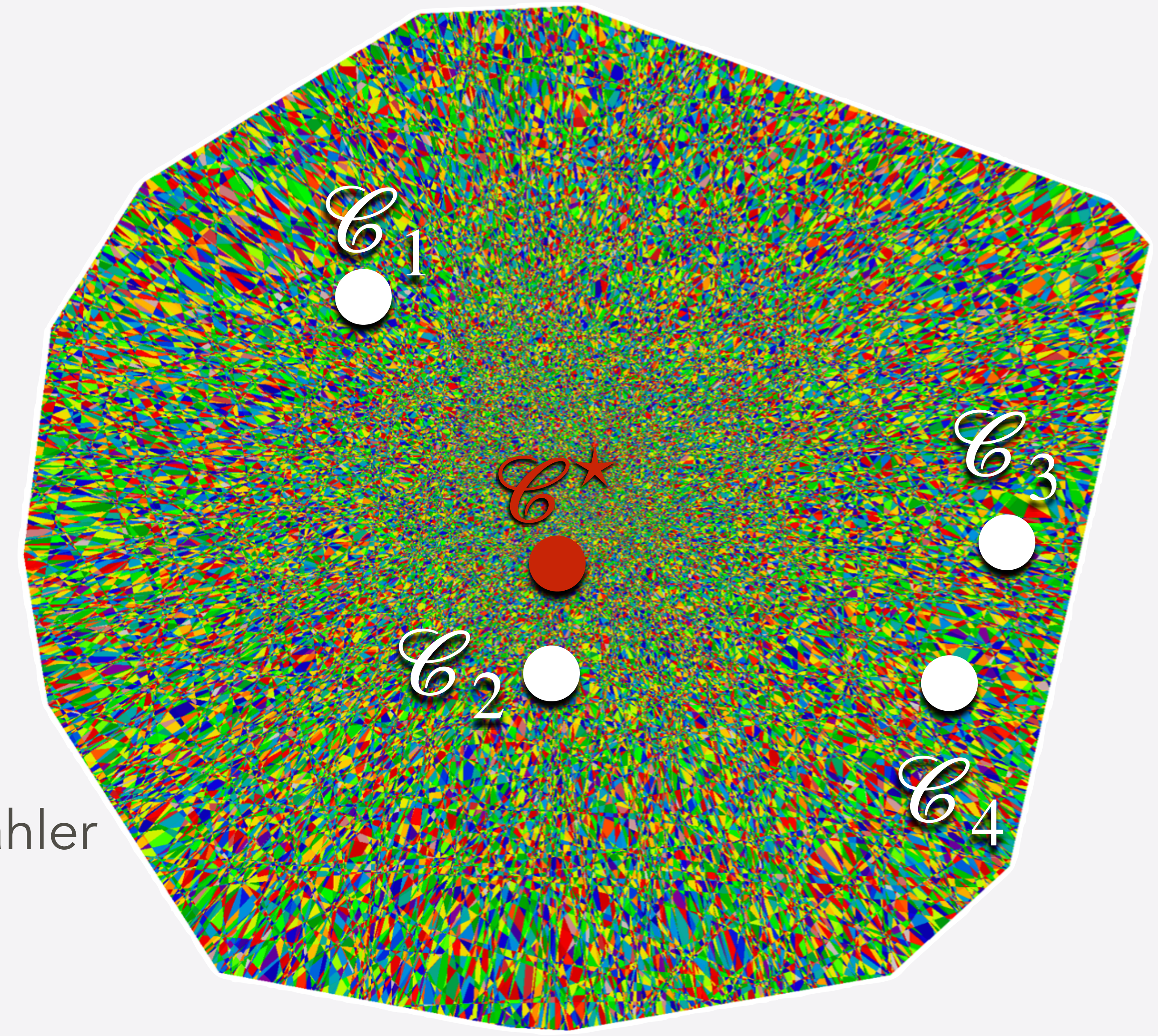


generation 7

Genetic Algorithms (GAs)

Illustrative example

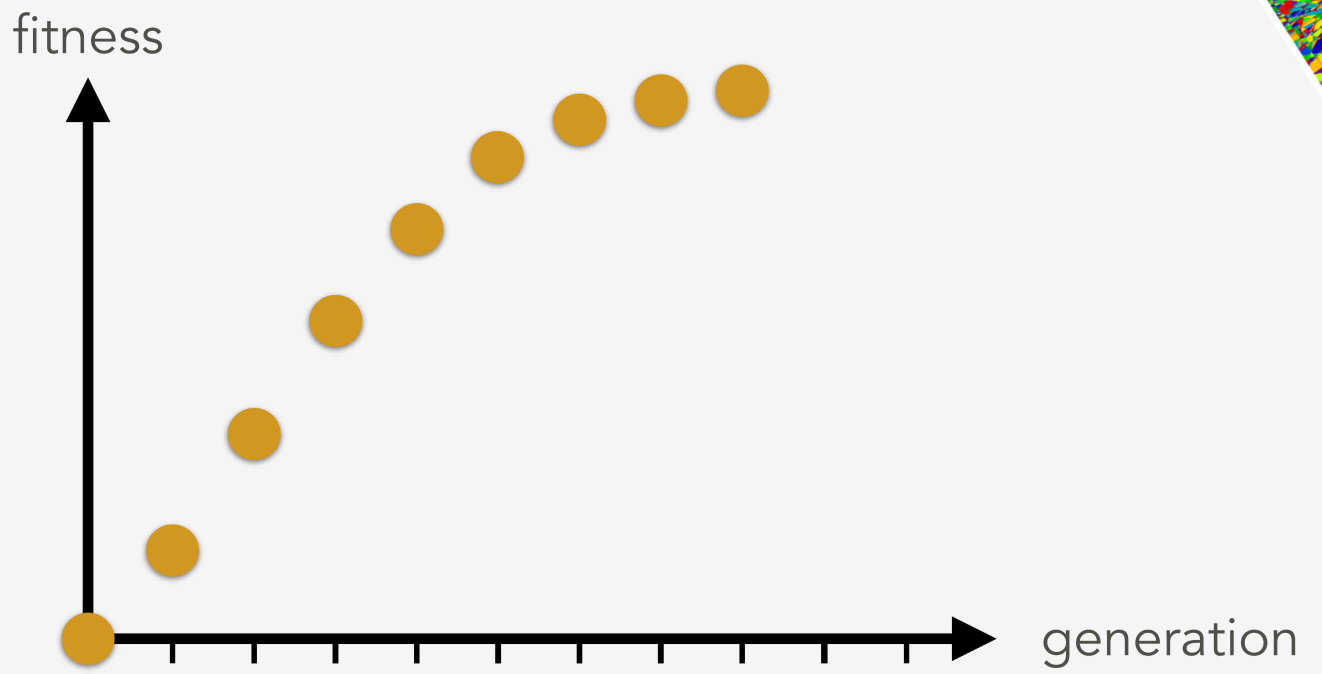
Example with $P = 4$

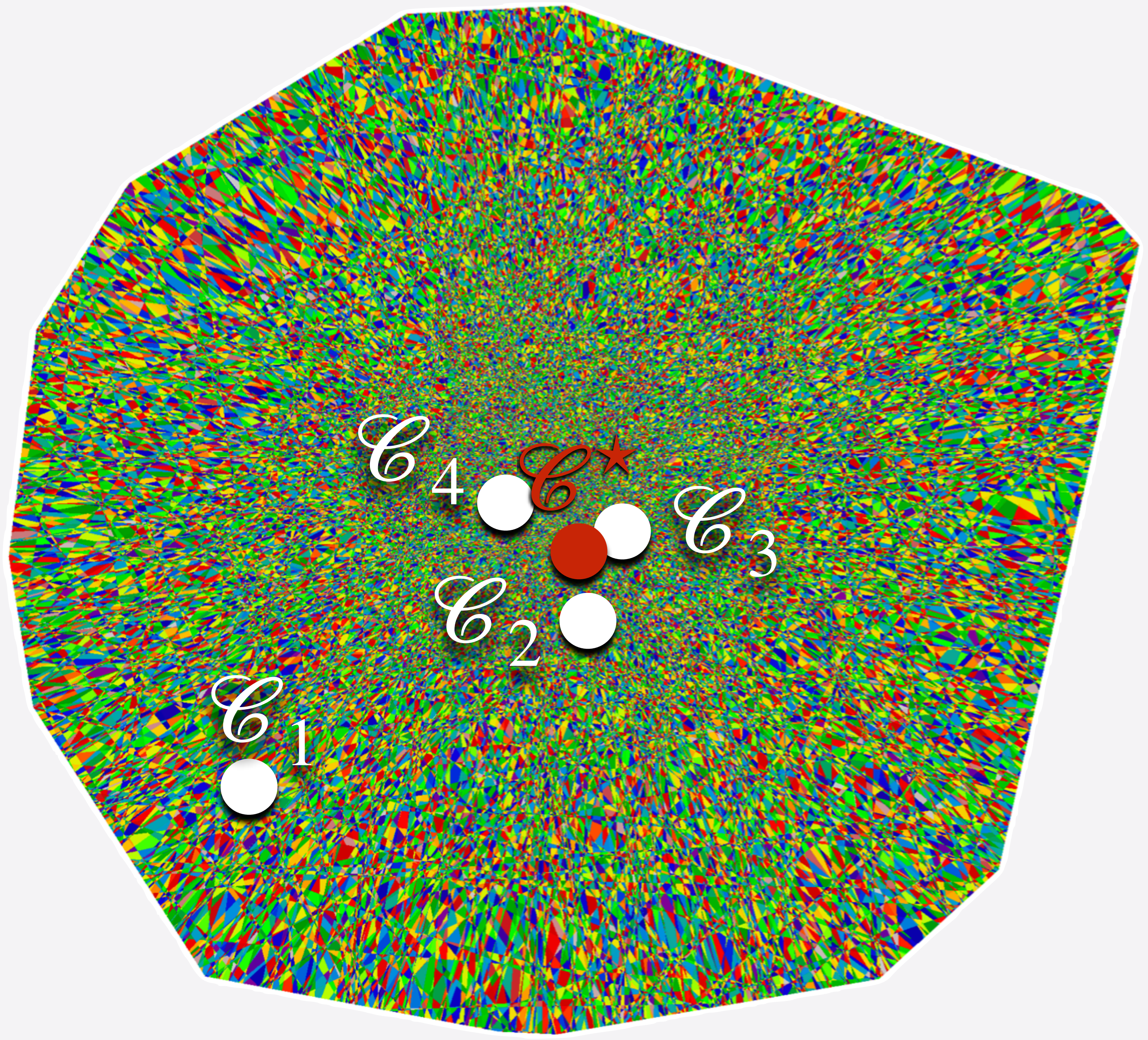


Extended Kähler cone $\mathscr{K}$

Initial population = "generation 0"

GA evolution



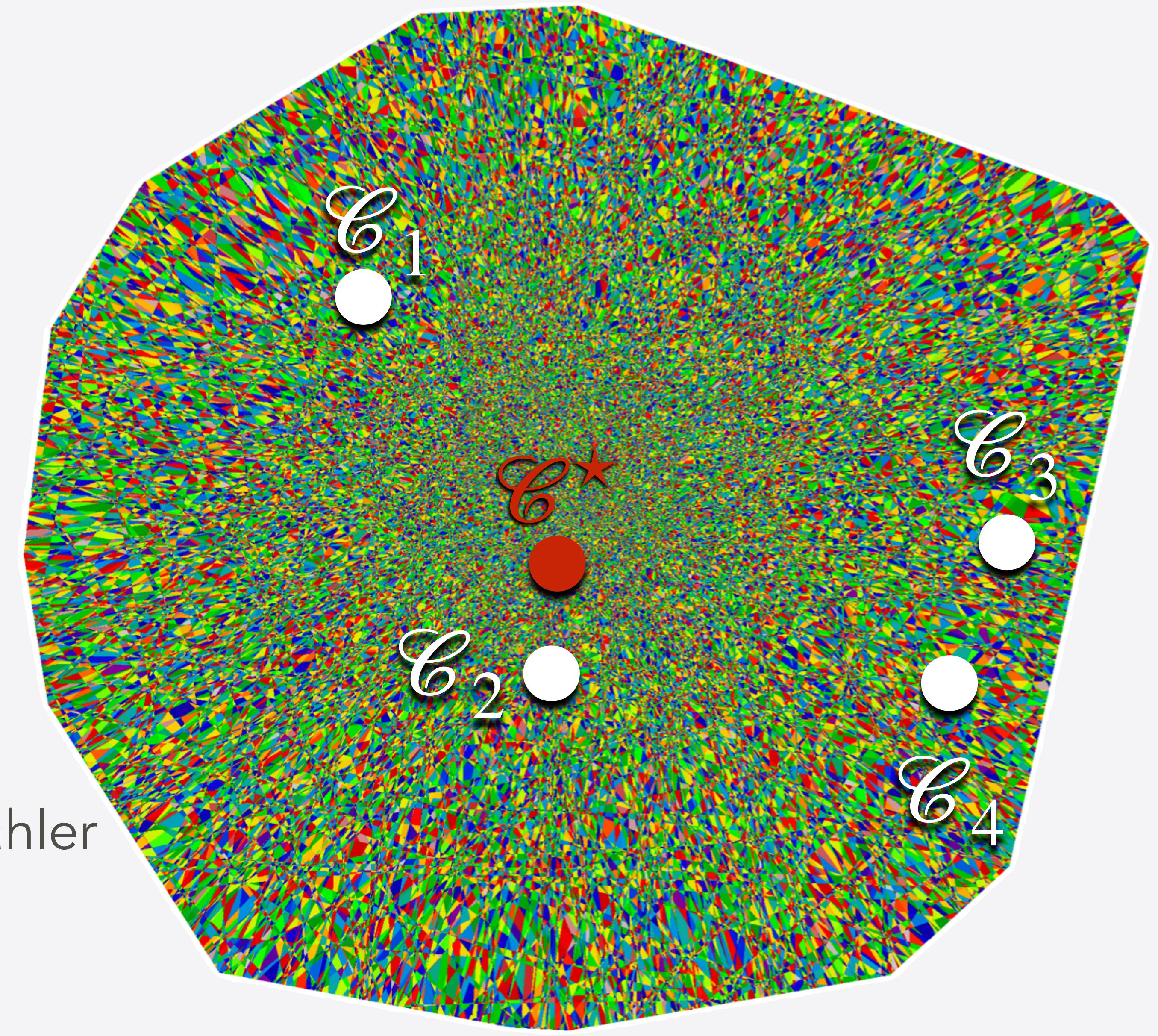


generation 8

Genetic Algorithms (GAs)

Illustrative example

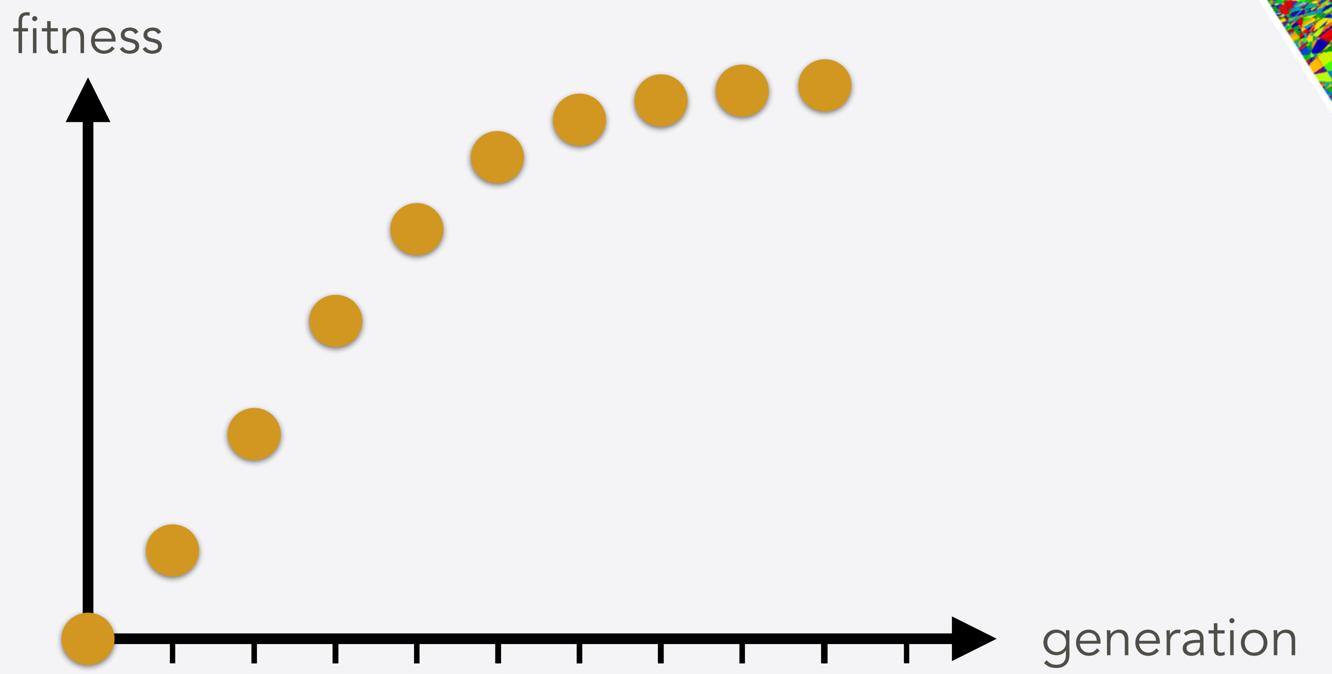
Example with $P = 4$

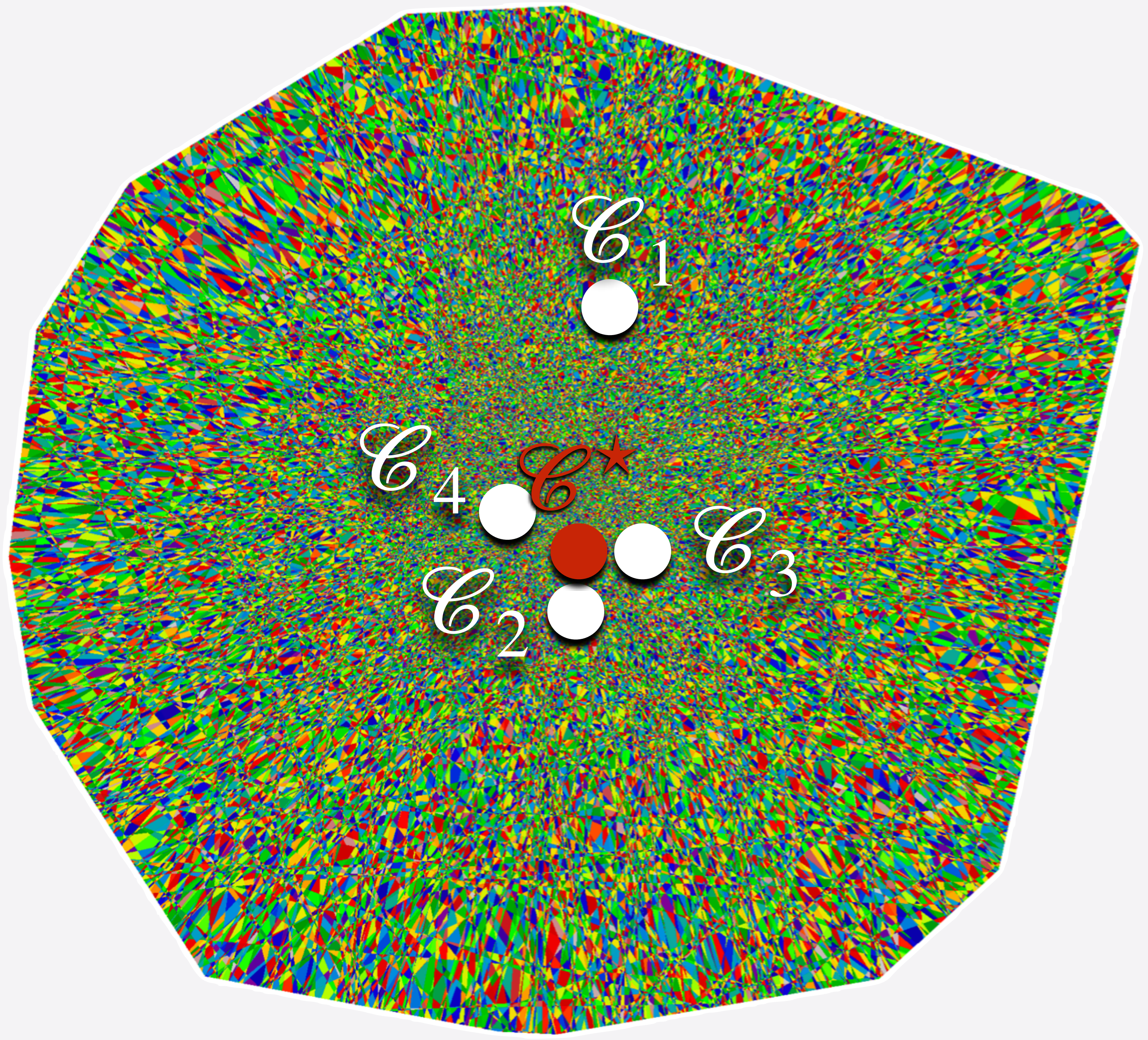


Extended Kähler cone $\mathscr{K}$

Initial population = "generation 0"

GA evolution





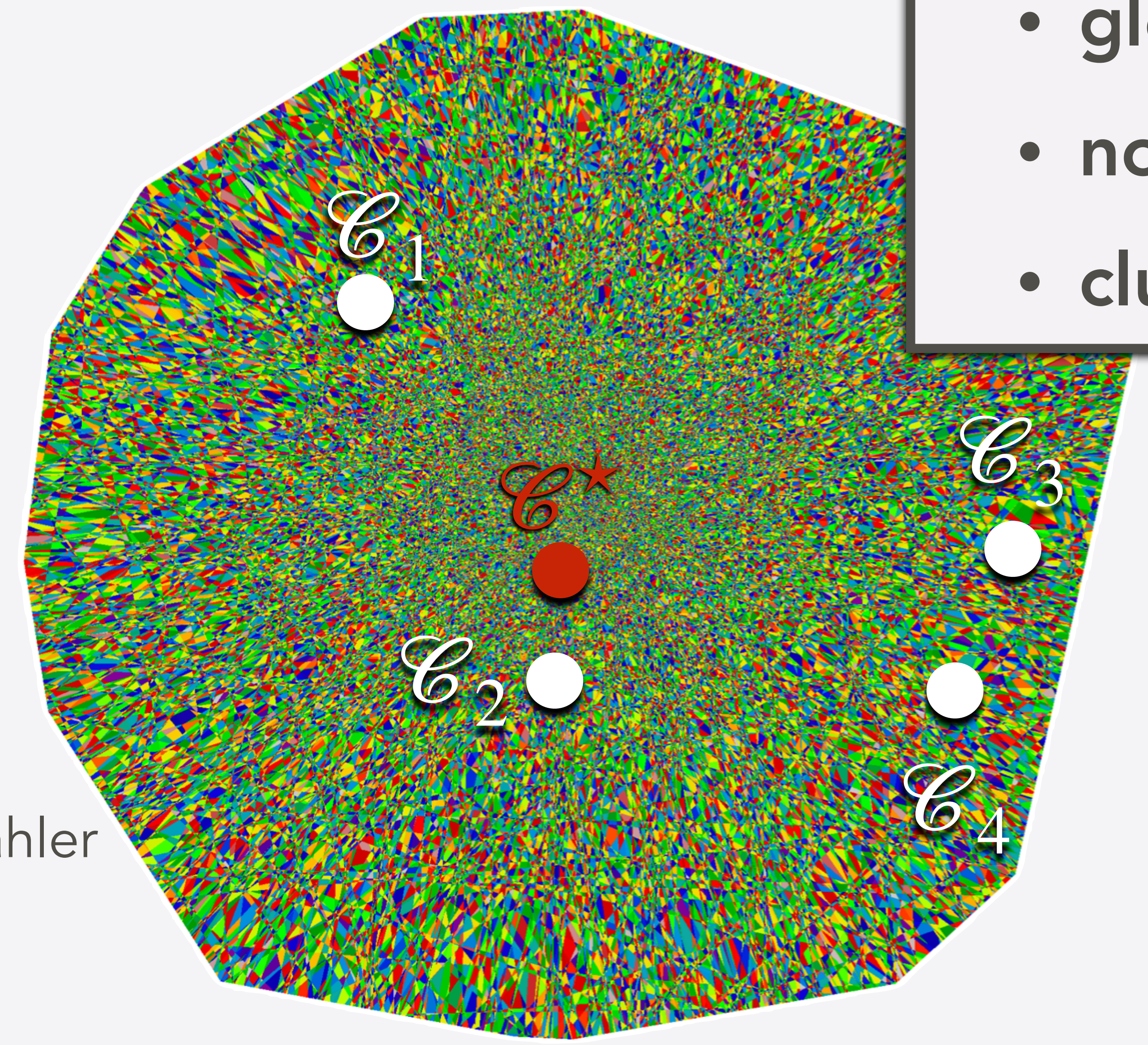
generation 9

Genetic Algorithms (GAs)

Illustrative example

Observe that evolution is

- **global:** have access to all of $\mathscr{K}$
- **non-local**: can jump across phases of $\mathscr{K}$
- **clustering**: (almost) all CYs get close to $\mathscr{C}^\star$



Extended Kähler cone $\mathscr{K}$

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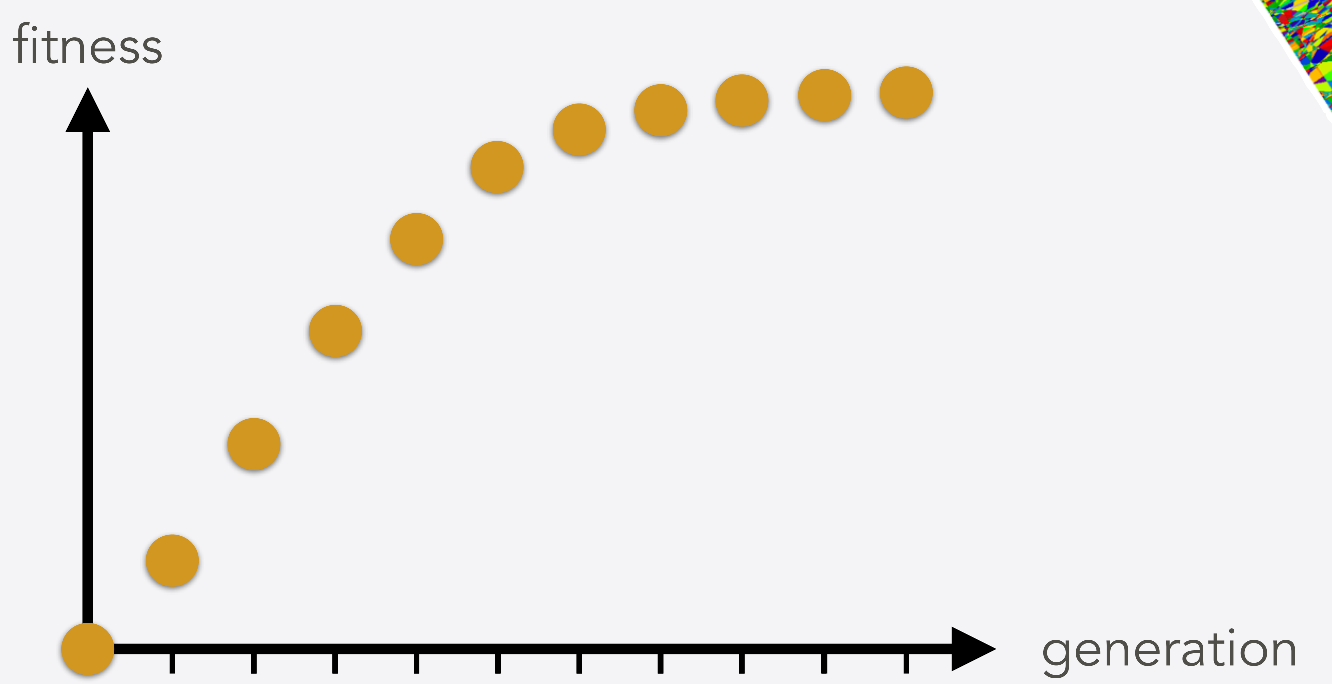
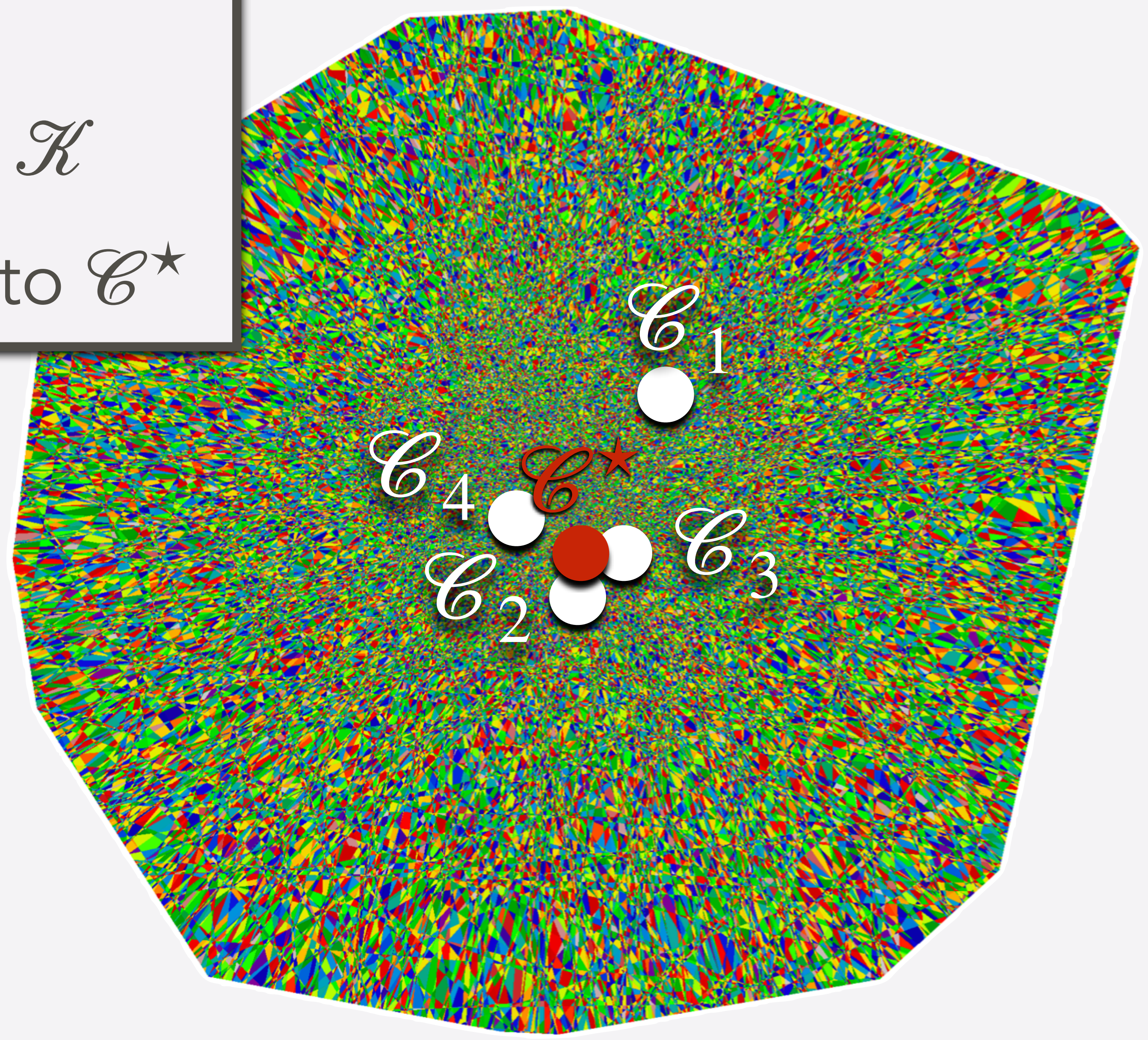
GA evolution



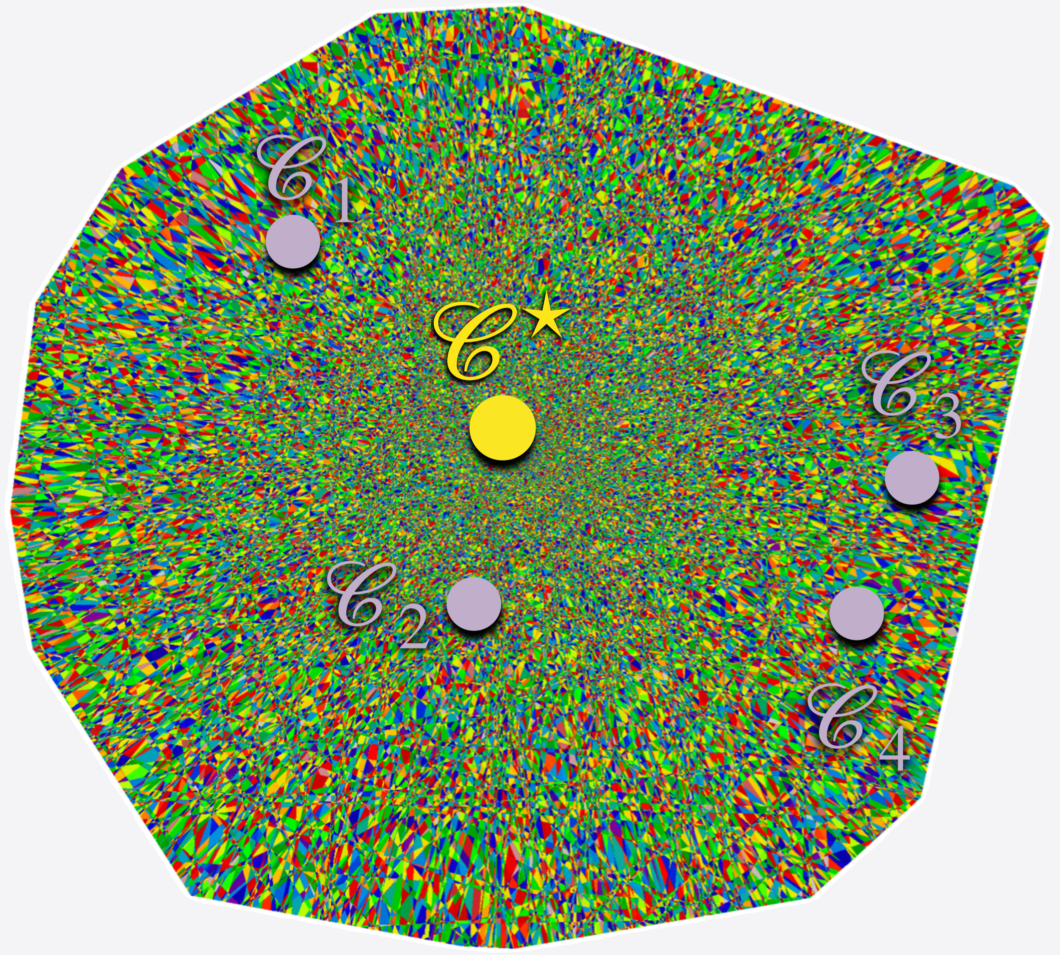


generation 10

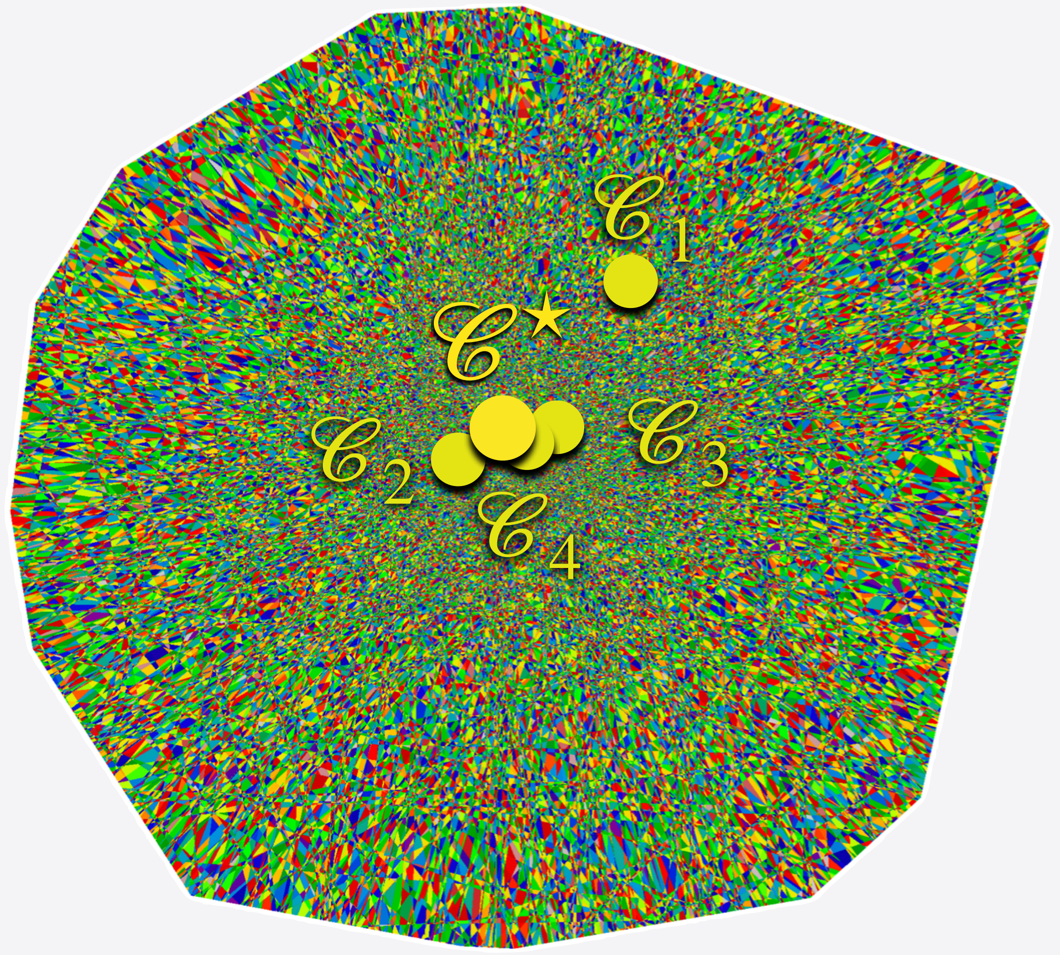
GA results — $h^{1,1} = 23$

Benchmarking the GA

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



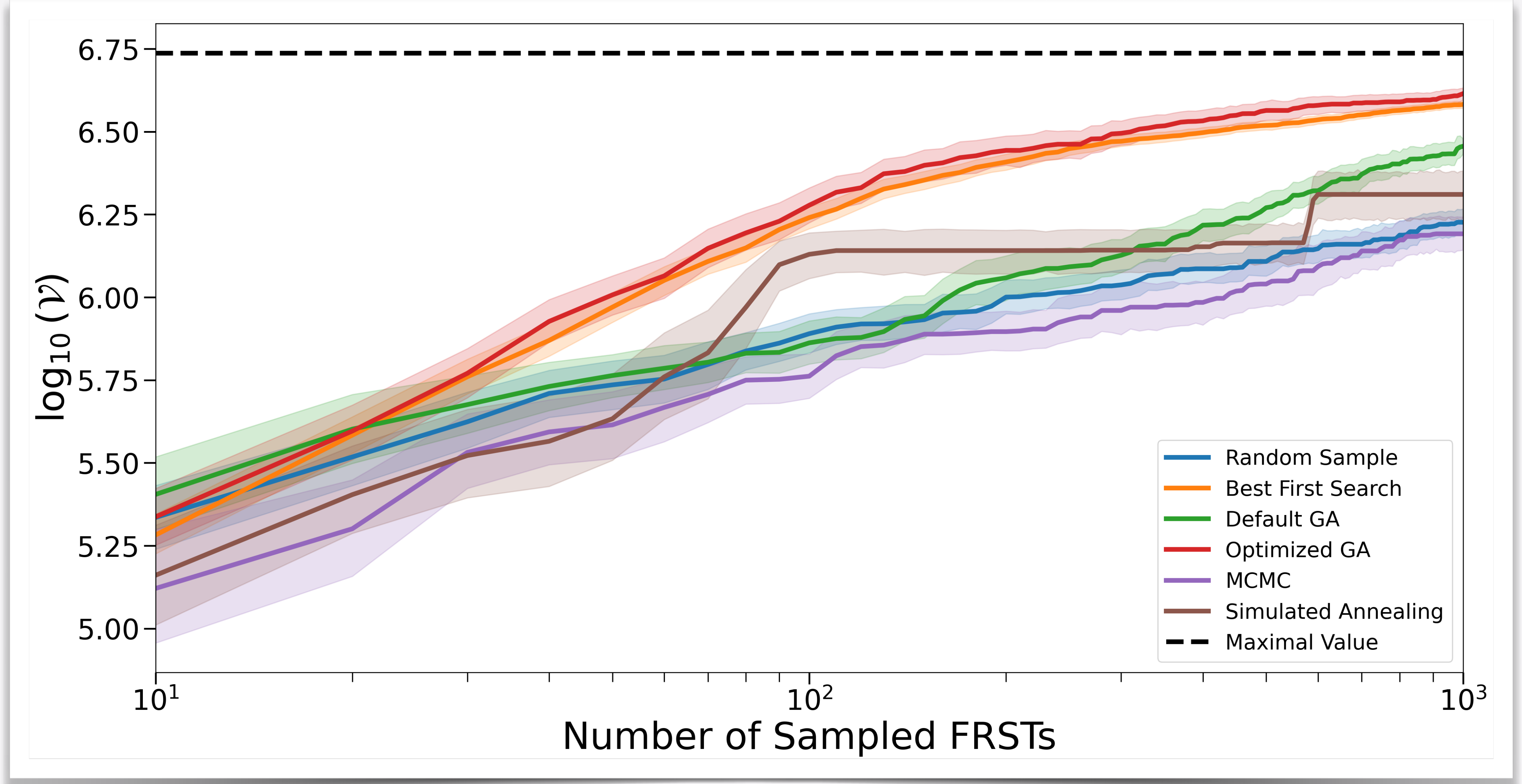
generation 0



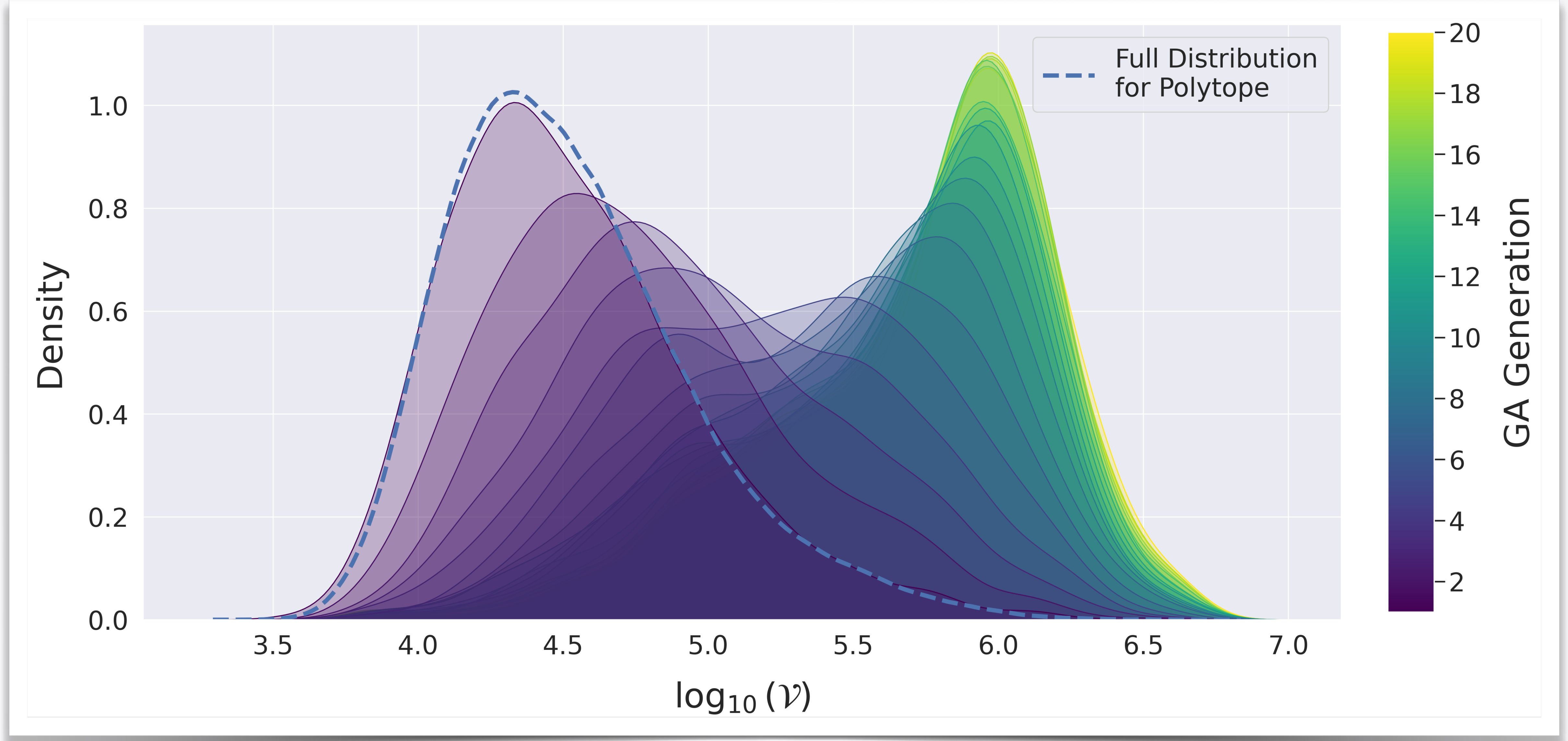
generation 20

We **maximised the CY volume** at the tip of the stretched Kähler cone for a polytope at $h^{1,1} = 23$ with 331,192 NTFE FRSTs.

Comparison with other algorithms



Evolution of volume distributions



Axion EFTs from Type IIB String Theory

From Polytopes to Axions — Summary

See also talk by Federico Carta

We will focus on the **Kreuzer-Skarke (KS) Axiverse** [Demirtas et al. 1808.01282] for C_4-axions which is part of the **Type IIB Axiverse** [Cicoli et al. 1206.0819].

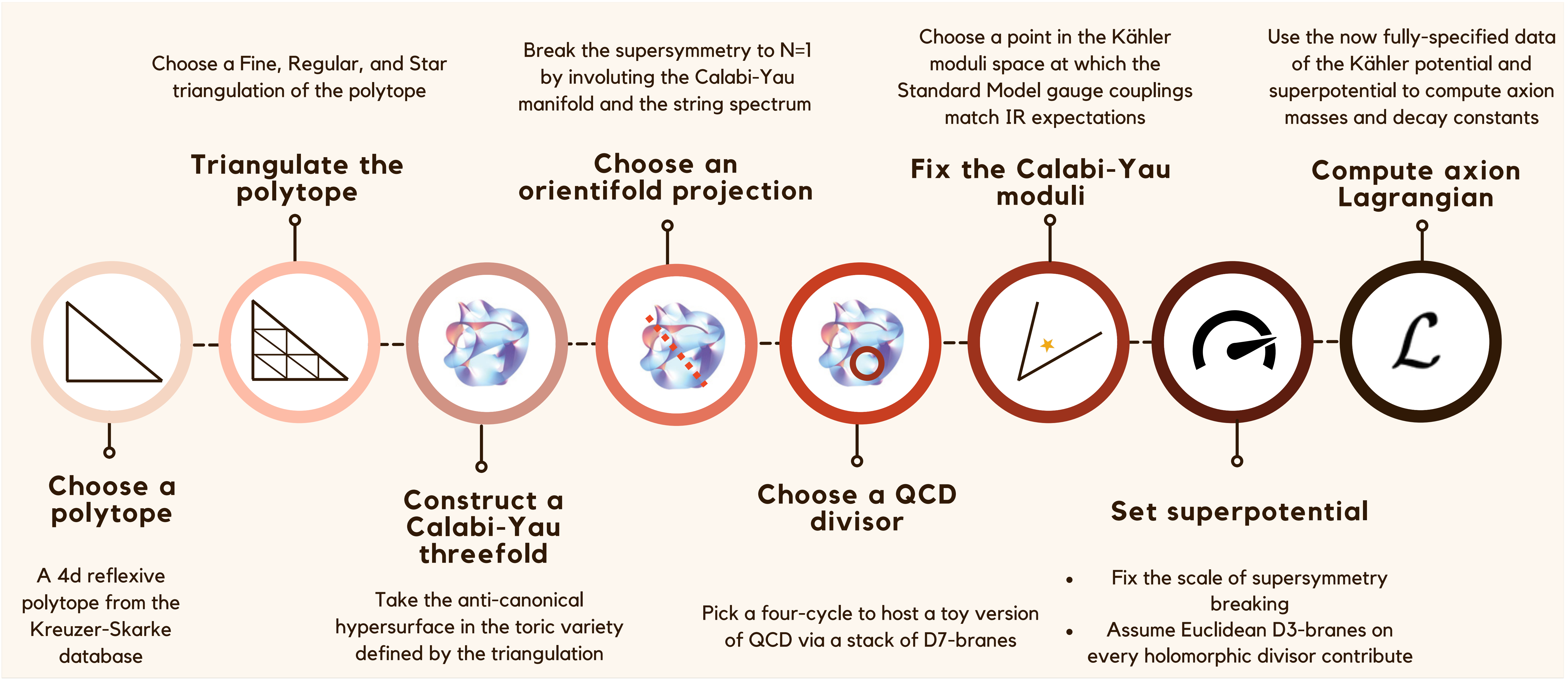


Figure credit: N. Gendler

In the KS axiverse, previous works studied e.g.

- BH superradiance [Mehta et al. 2011.08693, 2103.06812]
- PQ quality problem [Demirtas et al. 2112.04503]
- Axion-photon couplings [Gendler et al. 2309.13145]

GA results — $h^{1,1} = 60$

Axion decay constants in string theory — Part 1

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

Fact: In string cosmology, models typically need axion decay constants of e.g. the **lightest axion** to be in a certain range.

As proof of concept, we want to find CY threefolds X with

$$f_* = 10^{14}\text{GeV}$$

at the tip of the stretched Kähler cone $\mathscr{K}_X[c=1]$. We pick Δ° with

$$(h^{1,1}, h^{1,2}) = (60,4) \quad \Rightarrow \quad \text{\#2-face ineq. FRSTs} \lesssim 3.3 \times 10^{36}$$

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

Evolution of the distribution of decay constants f

GA results — $h^{1,1} = 60$

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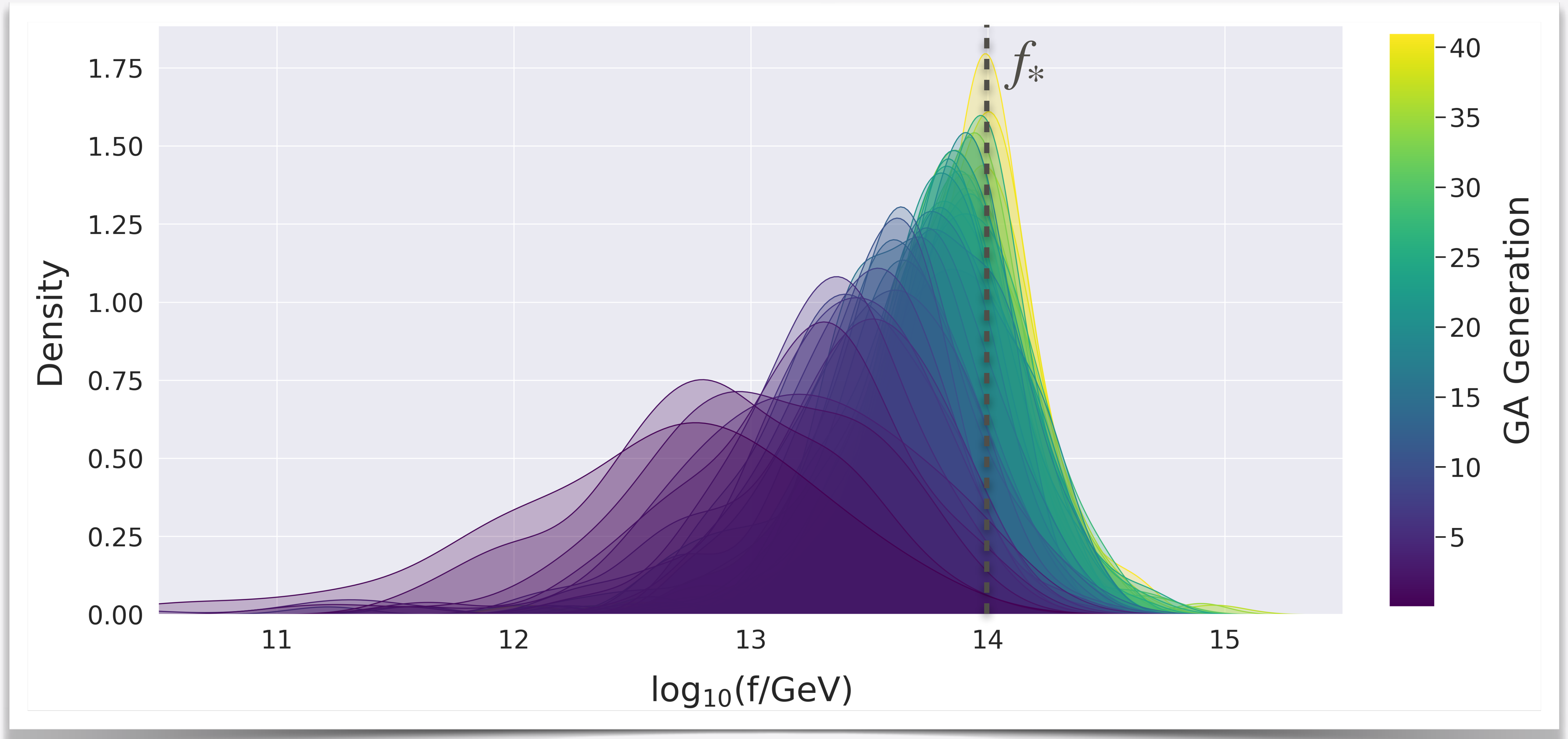

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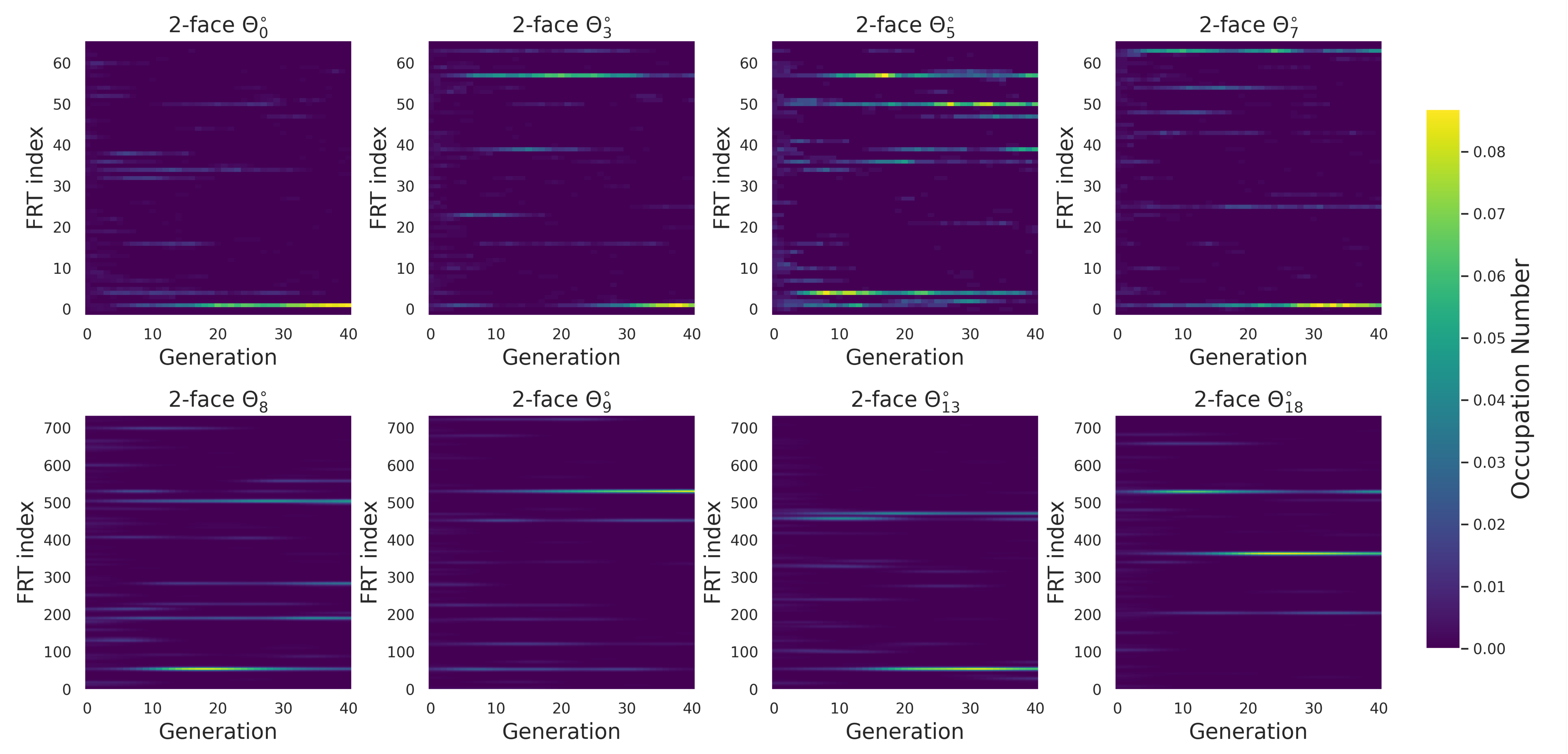
Axion decay constants in string theory — Part 2

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

Structure in the distributions of two-face FRTs



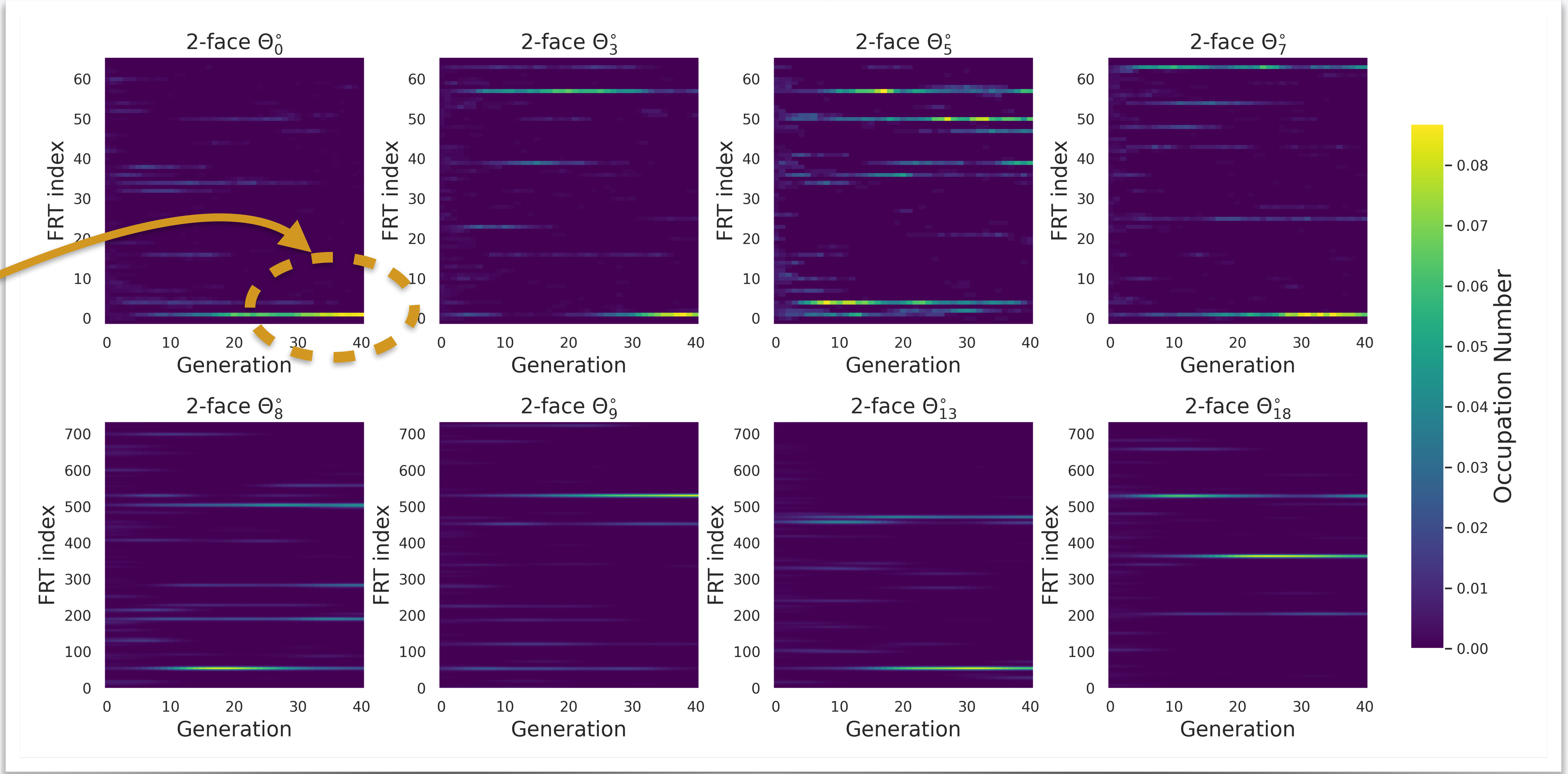
GA results — $h^{1,1} = 60$

Axion decay constants in string theory — Part 2

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

Structure in the distributions of two-face FRTs

A **single** two-face triangulation dominates!



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Axion decay constants in string theory — Part 2

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

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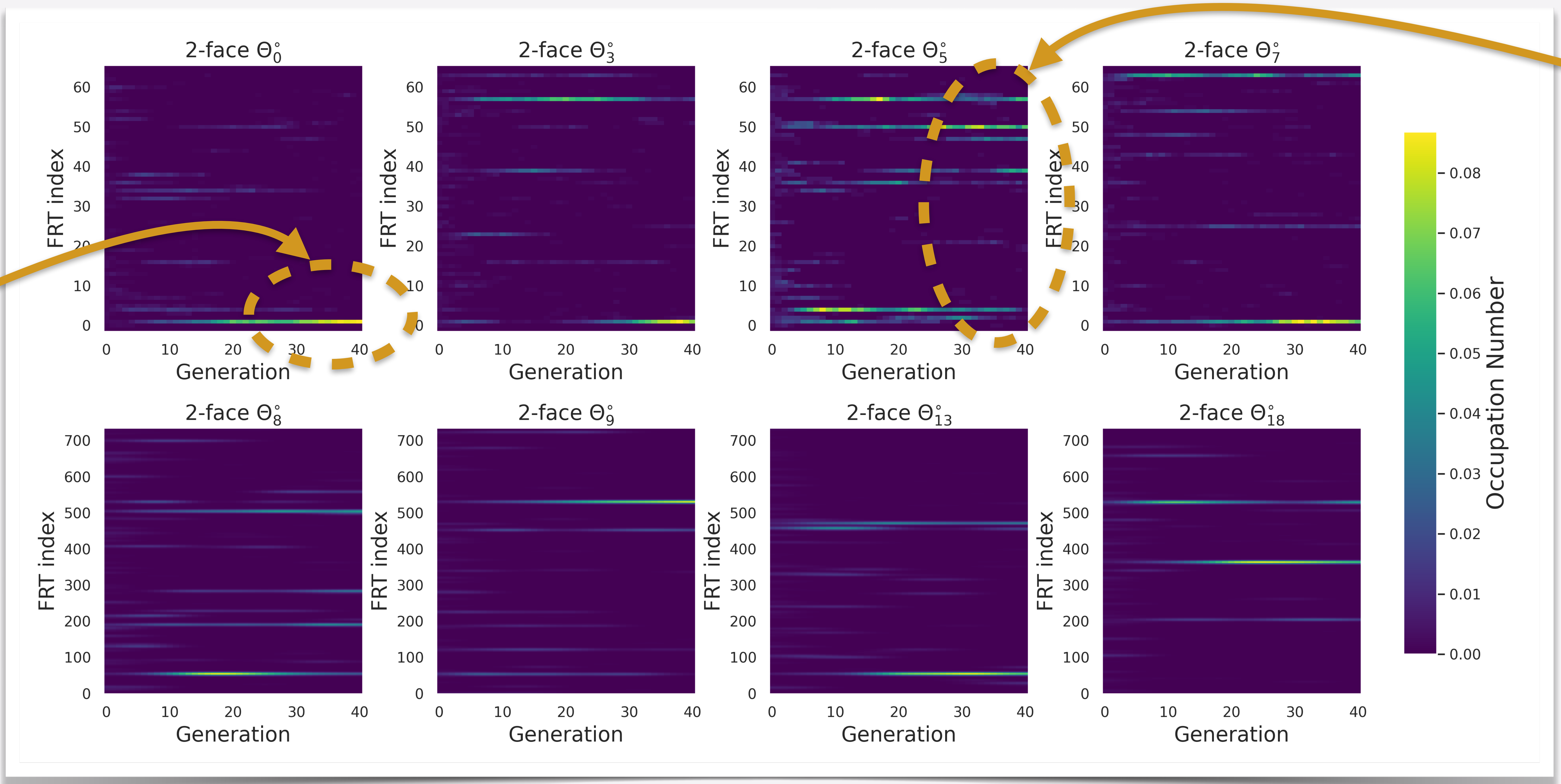


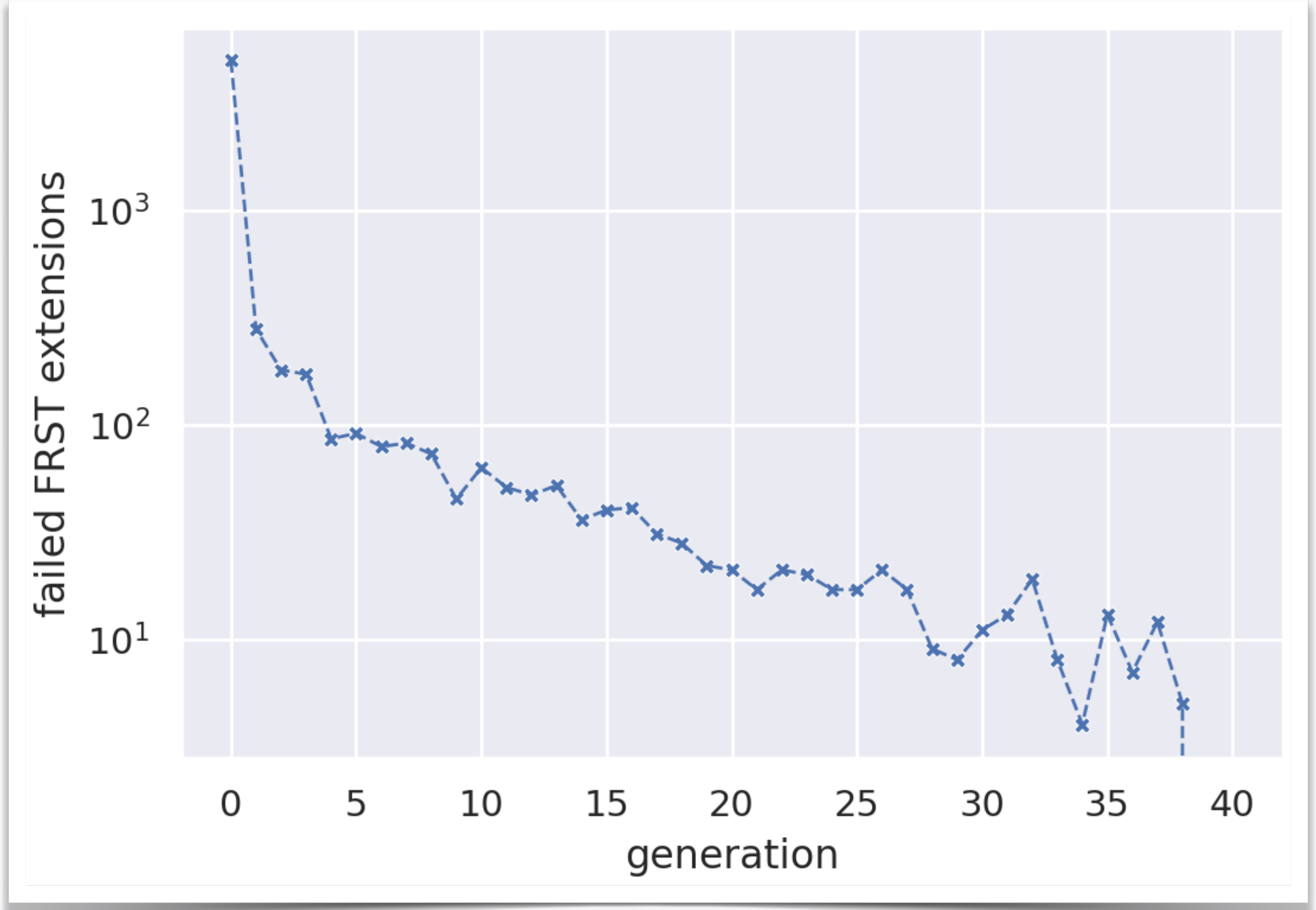
Many different triangulations remain in the final population!

GA results — $h^{1,1} = 60$

Axion decay constants in string theory — Part 3

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

Learning progress of the GA



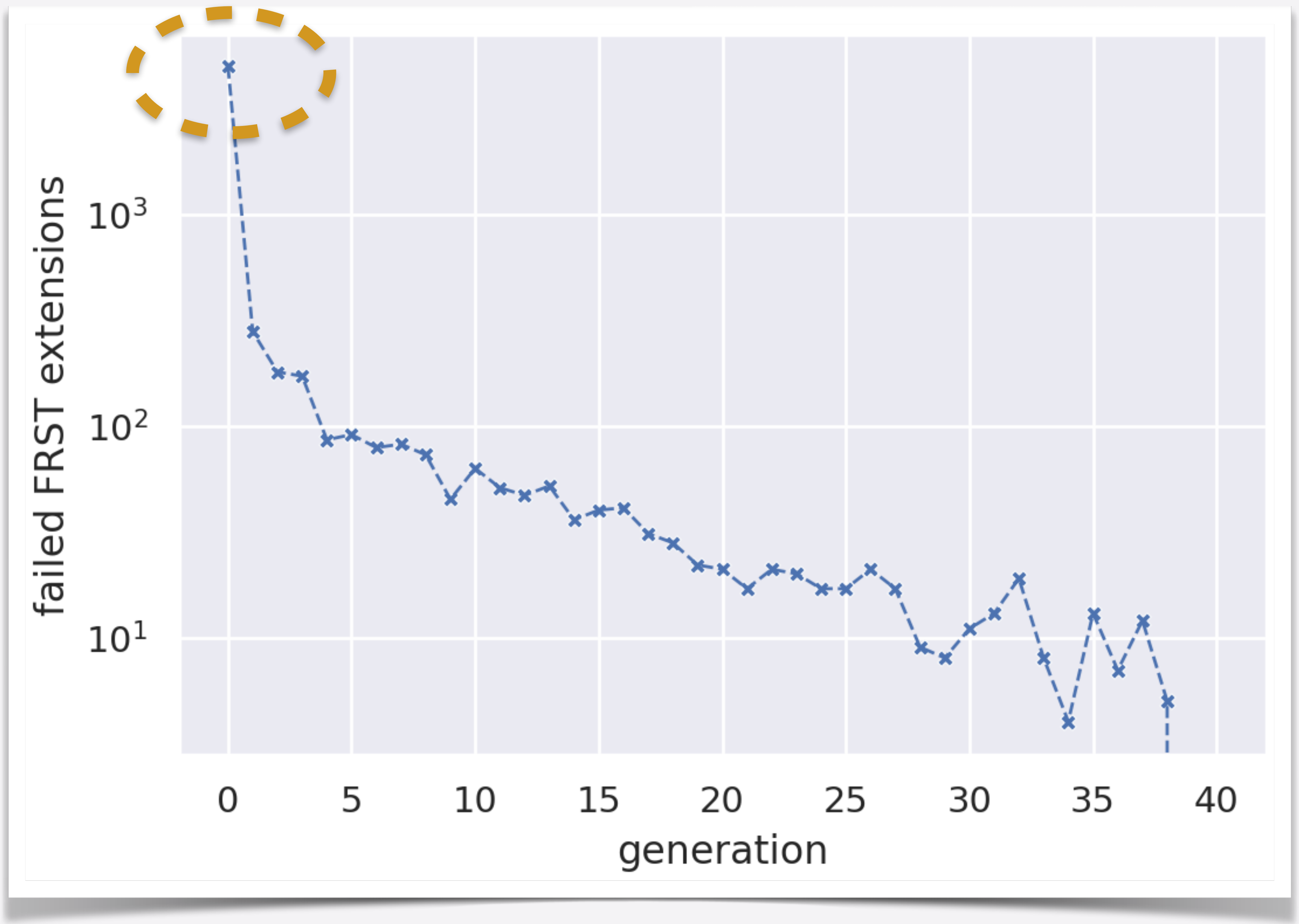
GA results — $h^{1,1} = 60$

Axion decay constants in string theory — Part 3

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

Picking random two-face FRTs is **very inefficient** to construct FRSTs!

Learning progress of the GA



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Axion decay constants in string theory — Part 3

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

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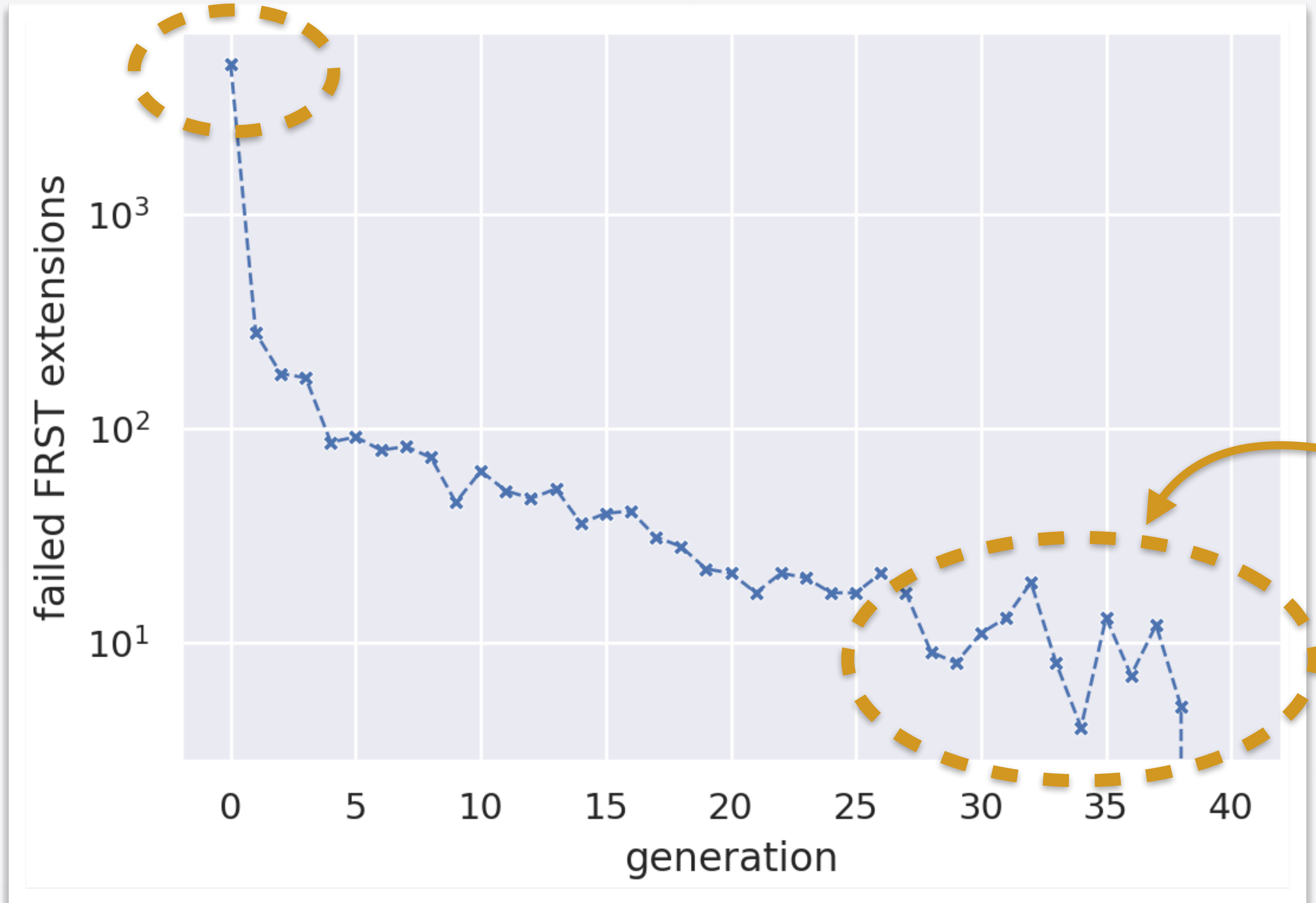


Basically all configurations of two-face FRTs generated by the GA lift to FRSTs!

GA results — $h^{1,1} = 491$

Maximising axion-photon couplings

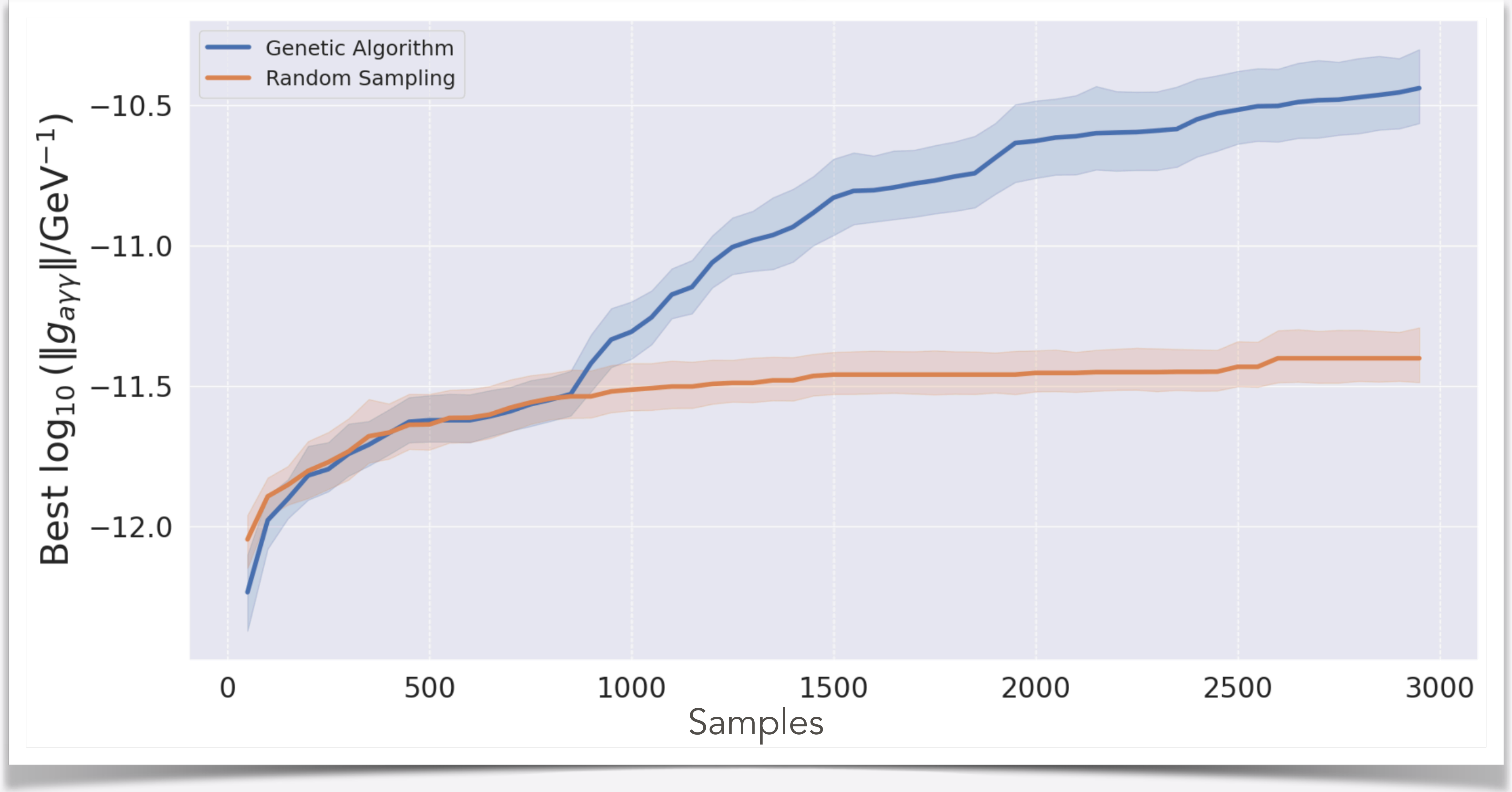
[MacFadden, **AS**, Sheridan: 2405.08871]

Axion-photon couplings $\sim g_{a\gamma\gamma}\,\phi^a\,F_{\mu\nu}\,F^{\mu\nu}$ most vulnerable to phenomenological constraints at large $h^{1,1}$ [Halverson et al. 1909.05257]

We use methods developed in [Gendler et al. 2309.13145] to compute $g_{a\gamma\gamma}$ in our compactifications.

Averaging over 17 runs, we find

$$\log_{10}(g_{a\gamma\gamma})_{\max} = \begin{cases} -10.57 \pm 0.15 & \text{Genetic Algorithm} \\ -11.62 \pm 0.09 & \text{Random Sampling}\,. \end{cases}$$



GAs easily beat brute-force searching even for the polytope with the most computationally intricate search space.

Fuzzy Dark Matter in the String Axiverse

based on upcoming work with F. Carta, N. Gendler, M. Jain, D. Marsh, L. McAllister, N. Righi, K. Rogers and E. Sheridan

See next talk by Federico Carta

For GA searches, we chose a **fixed** point in Kähler moduli space.

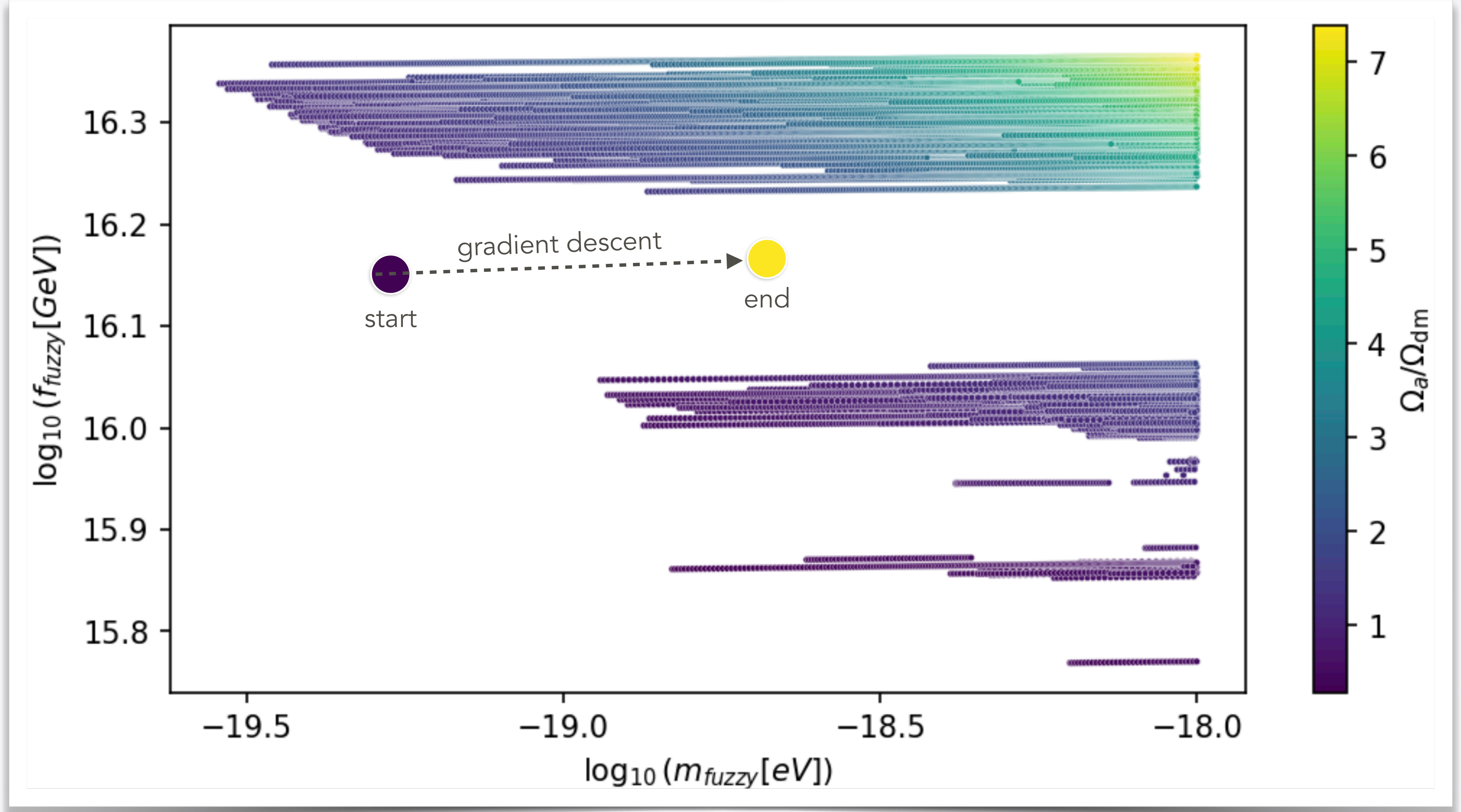
Interesting physics might however happen at other places…

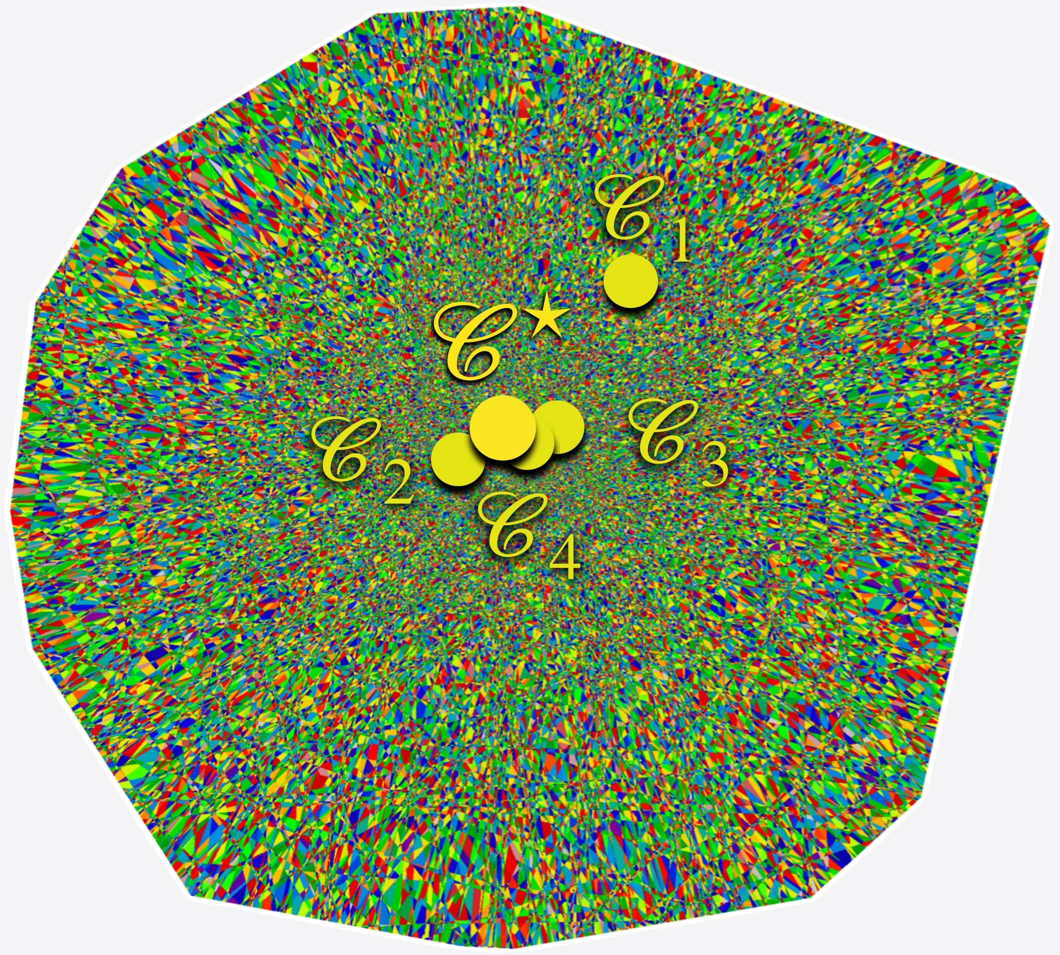
Can we find models of **fuzzy dark matter** in these setups?

Among others, we used **optimisation methods** from `scipy.optimize`, `jax`, `optax` to obtain models with e.g. **large fuzzy DM abundance**.

In the future, develop pipeline to sample models more efficiently and combine with moduli stabilisation. [Cicoli et al. 2110.02964]

Pipeline for sampling stringy axion models





Conclusions

Main takeaway:

We developed the first algorithms to perform optimisation **across different compact geometries**.

These can be used to **explore the string axiverse more globally**!

Open issues and future directions:

1. Combine with moduli stabilisation in explicit setups (see [Cicoli et al. 2110.02964] for initial attempts)
2. Make construction of SM sector more explicit (F-theory, Branes at singularities [Cicoli, **AS** et al. 2106.11964], …)
3. Study different axionic sectors (C_2/B_2-axions [Cicoli, Shukla, **AS**: 2109.14624], open-string axions, …)


Thank you!

Backup slides

Axion EFTs from Type IIB String Theory

The Type IIB Axiverse [Cicoli et al. 1206.0819]

In the 4D EFT, the **(F-term) scalar potential** for the Kähler moduli $T^a = \tau^a + \mathrm{i}\,\phi^a$, $a = 1,\ldots,h^{1,1}$, is of the form

$$V(\tau^a,\phi^a) = V(\tau^a) + \sum_I \Lambda_I^4(\tau^a)\cos\left(-2\pi\mathcal{Q}_b^I\phi^b + \delta^I\right) + \ldots\,, \quad \Lambda_I^4 \sim m_{3/2}\,\mathcal{Q}_b^I\,\tau^b\,\exp\left(-2\pi\mathcal{Q}_b^I\tau^b\right)\,, \quad m_{3/2} \sim \frac{W_0}{\mathcal{V}^2}\,.$$

The masses m_a and decay constants f_a for axions **depend on values of moduli** τ^a

$$f_a \sim \frac{1}{\tau^a}\,, \quad m_a^2 \sim m_{3/2}\,\tau^a\,\frac{\mathrm{e}^{-2\pi\tau^a}}{f_a^2}\,.$$

Exponential suppression of m_a^2 naturally leads to **ultra-light ALP** in the regime $\tau^a \gg 1$.

The SM sector can e.g. be realised on wrapped branes with $T^{QCD} = \tau^{QCD} + \mathrm{i}\,\phi^{QCD}$ where

- ϕ^{QCD} is the **QCD axion**, and
- τ^{QCD} sets the **QCD gauge coupling** in the UV (see talk by J. Leedom)

$$g_{QCD}^2 \sim \frac{1}{\tau^{QCD}} \quad \Rightarrow \quad \tau^{QCD} \approx 40 \;\text{ s.t. }\; \alpha_s(M_Z^2) \approx 0.118\,.$$