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Flavour Physics from Heterotic Standard Models with Split Bundles

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based on arXiV:2407.XXXXX
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Motivation

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- explaining Yukawa couplings: VEVs of moduli fields
- **Froggatt and Nielsen** [1979] proposed using horizontal symmetries $\mathrm{U}(1)_H$ to explain flavour structures

$\mathcal{O}(1)$-coefficients

$$Y_{ij} = a_{ij} \langle \phi \rangle^{n_{ij}}$$

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- computation of Yukawa couplings in heterotic line bundle standard models can be achieved - but it is **HARD** + done on a case-by-case basis **[Constantin et al. 2402.01615]**
- salient feature of these models: **flavour symmetries** $\mathcal{J}$ **[Anderson et al. 1202.1757]**

$$\mathcal{J}/\mathbb{Z}\boldsymbol{n} \cong U(1)^n \quad \text{i.e. } \boldsymbol{q}_{\mathcal{J}} \sim \boldsymbol{q}_{\mathcal{J}} + \boldsymbol{n}$$

- correct spectrum using **GA** $\sim \mathcal{O}(10^5)$ models **[Anderson et al. 1307.4787]**
- **Goal: additional constraints from flavour symmetries from an EFT approach**

Overview

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4d $\mathcal{N} = 1$ SUSY Standard Models [Anderson et al. (2012)]

- These 4d $\mathcal{N} = 1$ SUSY Standard Models are inspired by heterotic SMs with split bundles
- Gauge symmetry - $G_{\text{SM}} \times \mathcal{J}$, $\dfrac{\mathcal{J}}{\mathbb{Z}\boldsymbol{n}} \cong U(1)^{f-1}$
- For field F: $\boldsymbol{Q}_{\mathcal{J}}(F) \sim \boldsymbol{Q}_{\mathcal{J}}(F) + \boldsymbol{n}$

$\boldsymbol{n} = (n_1, n_2, \ldots, n_f)$ $|\boldsymbol{n}| = 5$

Specifies Split Bundle Structure Group

$H = S(U(n_1) \times \ldots \times U(n_f))$

- Charge pattern of matter and moduli fields in $\mathcal{J}$:

Symbol	SM rep	SU(5) rep	Charge Pattern in $\mathcal{J}$	Notation	Description
Q_I	$(\mathbf{3},\mathbf{2})_1$	$\mathbf{10}^I$	$q = e_a$	$\mathbf{10}_a$	LH quarks
u_I	$(\bar{\mathbf{3}},\mathbf{1})_{-4}$	$\mathbf{10}^I$	$q = e_a$	$\mathbf{10}_a$	RH u quarks
e_I	$(\mathbf{3},\mathbf{2})_1$	$\mathbf{10}^I$	$q = e_a$	$\mathbf{10}_a$	RH electrons
d_I	$(\bar{\mathbf{3}},\mathbf{1})_2$	$\bar{\mathbf{5}}^I$	$q = e_a + e_b$	$\bar{\mathbf{5}}_{a,b}$	RH d quarks
L_I	$(\mathbf{1},\mathbf{2})_{-3}$	$\bar{\mathbf{5}}^I$	$q = e_a + e_b$	$\bar{\mathbf{5}}_{a,b}$	LH leptons
H_d	$(\mathbf{1},\mathbf{2})_{-3}$	$\bar{\mathbf{5}}_H$	$q = e_a + e_b$	$\bar{\mathbf{5}}^H_{a,b}$	Down-Higgs
H_u	$(\mathbf{1},\mathbf{2})_3$	$\mathbf{5}_H$	$q = -e_a - e_b$	$\mathbf{5}^H_{a,b}$	Up-Higgs
ν_I	$(\mathbf{1},\mathbf{1})_1$	$\mathbf{1}^I$	$q = e_a - e_b$	$\mathbf{1}_{a,b}$	RH neutrinos
ϕ_i	$(\mathbf{1},\mathbf{1})_1$	$\mathbf{1}$	$q = e_a - e_b$	$\phi_{a,b}$	Bundle moduli

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Different to traditional FN:

- **discrete quotients**
- **small SM charges**
- **non-perturbative contributions**

Flavour Physics of Heterotic Standard Models with Split Bundles

Phenomenological Considerations

- Mass and Mixing Hierarchies
- Match Electroweak-breaking Scale $\langle H \rangle$
- Avoid Fine-Tuning with $\mathcal{O}(1)$-coefficients

↓

Yukawa Textures

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Optimise $\mathcal{O}(1)$-coefficients and VEVs

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Optimise $\mathcal{O}(1)$-coefficients and VEVs

Only 7 sectors to be searched

$\boldsymbol{n}$	Charges			
$(1,1,1,1,1)$	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_5$	$\bar{\mathbf{5}}^H_{4,5}$
$(1,1,1,2)$	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_4$	$\bar{\mathbf{5}}^H_{4,4}$
	$\mathbf{10}_2$	$\mathbf{10}_3$	$\mathbf{10}_4$	$\bar{\mathbf{5}}^H_{1,4}$
	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\bar{\mathbf{5}}^H_{1,4}$
	$\mathbf{10}_1$	$\mathbf{10}_3$	$\mathbf{10}_4$	$\bar{\mathbf{5}}^H_{1,2}$
$(1,1,3)$	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\bar{\mathbf{5}}^H_{3,3}$
$(1,2,2)$	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\bar{\mathbf{5}}^H_{3,3}$
$(1,4)$	-			
$(2,3)$	-			
(5)	unsplit			

Flavour Physics of Heterotic Standard Models with Split Bundles

Example in $n = (1,1,1,2)$ with $\bar{5}^H_{4,4}$

$$Y^u \sim \begin{array}{c} \\ \mathbf{10}_2 \\ \mathbf{10}_3 \\ \mathbf{10}_4 \end{array} \begin{array}{c} \begin{array}{ccc} \mathbf{10}_2 & \mathbf{10}_3 & \mathbf{10}_4 \end{array} \\ \begin{pmatrix} \phi_{1,4}\phi_{4,2}^2\phi_{3,2}^2 & \phi_{1,4}\phi_{4,3}^2\phi_{3,2} & \phi_{1,4}\phi_{4,3}\phi_{3,2} \\ \phi_{1,4}\phi_{4,3}^2\phi_{3,2} & \phi_{1,4}\phi_{4,3}^2 & \phi_{1,4}\phi_{4,3} \\ \phi_{1,4}\phi_{4,3}\phi_{3,2} & \phi_{1,4}\phi_{4,3} & \phi_{1,4} \end{pmatrix} \end{array}$$

$$Y^d \sim \begin{array}{c} \\ \mathbf{10}_2 \\ \mathbf{10}_3 \\ \mathbf{10}_4 \end{array} \begin{array}{c} \begin{array}{ccc} \bar{\mathbf{5}}_{1,2} & \bar{\mathbf{5}}_{1,4} & \bar{\mathbf{5}}_{2,3} \end{array} \\ \begin{pmatrix} \phi_{3,2}^2\phi_{2,1}\phi_{4,3} & \phi_{3,2}\phi_{2,1} & \phi_{3,2}\phi_{2,1}\phi_{1,4} \\ \phi_{4,3}\phi_{3,2}\phi_{2,1} & \phi_{2,1} & \phi_{2,1}\phi_{1,4} \\ \phi_{3,2}\phi_{2,1} & \phi_{2,1}^2\phi_{1,4}\phi_{3,2} & \phi_{2,1}^2\phi_{1,4}^2\phi_{3,2} \end{pmatrix} \end{array}$$

$$\langle \phi_{4,2} \rangle \sim \epsilon^2 \,, \langle \phi_{2,1} \rangle \sim \epsilon \,, \langle \phi_{1,3} \rangle \sim \epsilon^2 \,, \langle \phi_{3,4} \rangle \sim \epsilon^2$$

$$Y_u = \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \,, \; Y_d = \begin{pmatrix} \epsilon^7 & \epsilon^7 & \epsilon^5 \\ \epsilon^6 & \epsilon^6 & \epsilon^4 \\ 0 & 0 & \epsilon^2 \end{pmatrix}$$

Yukawa Textures ⟶ **with choice of VEV powers**

Flavour Physics of Heterotic Standard Models with Split Bundles

Example in $n = (1,1,1,2)$ with $\bar{5}^H_{4,4}$

typical $\epsilon \sim 0.4$

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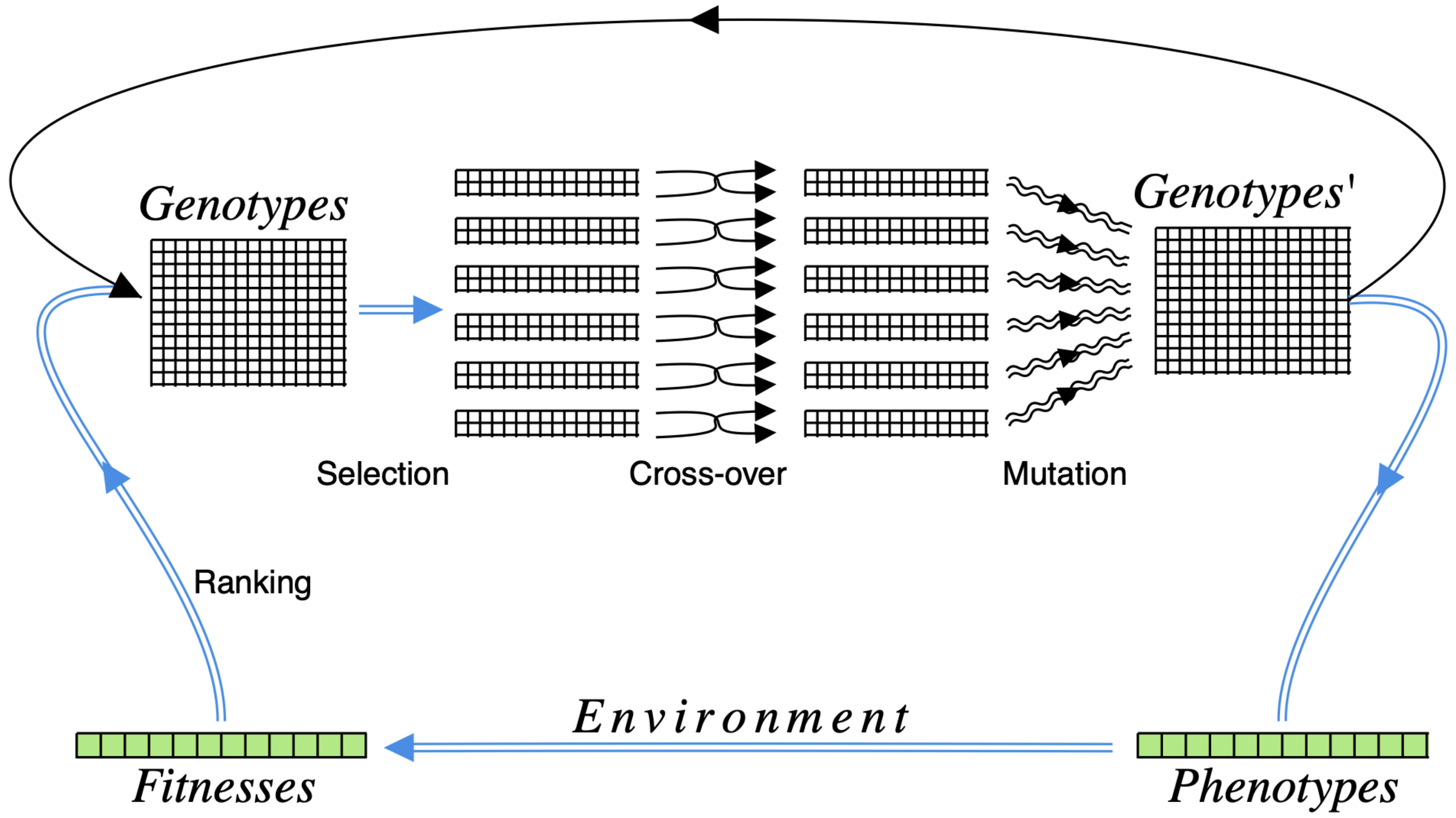
Yukawa Textures ⟶ **with choice of VEV powers**

$\sim O(10^9)$ choices

Genetic Algorithms

- A family of optimisation-search algorithms.
- Two parts: **Environment** + **Evolution**



from [Abel et al. ('23)]

Bitlist → **Fitness**

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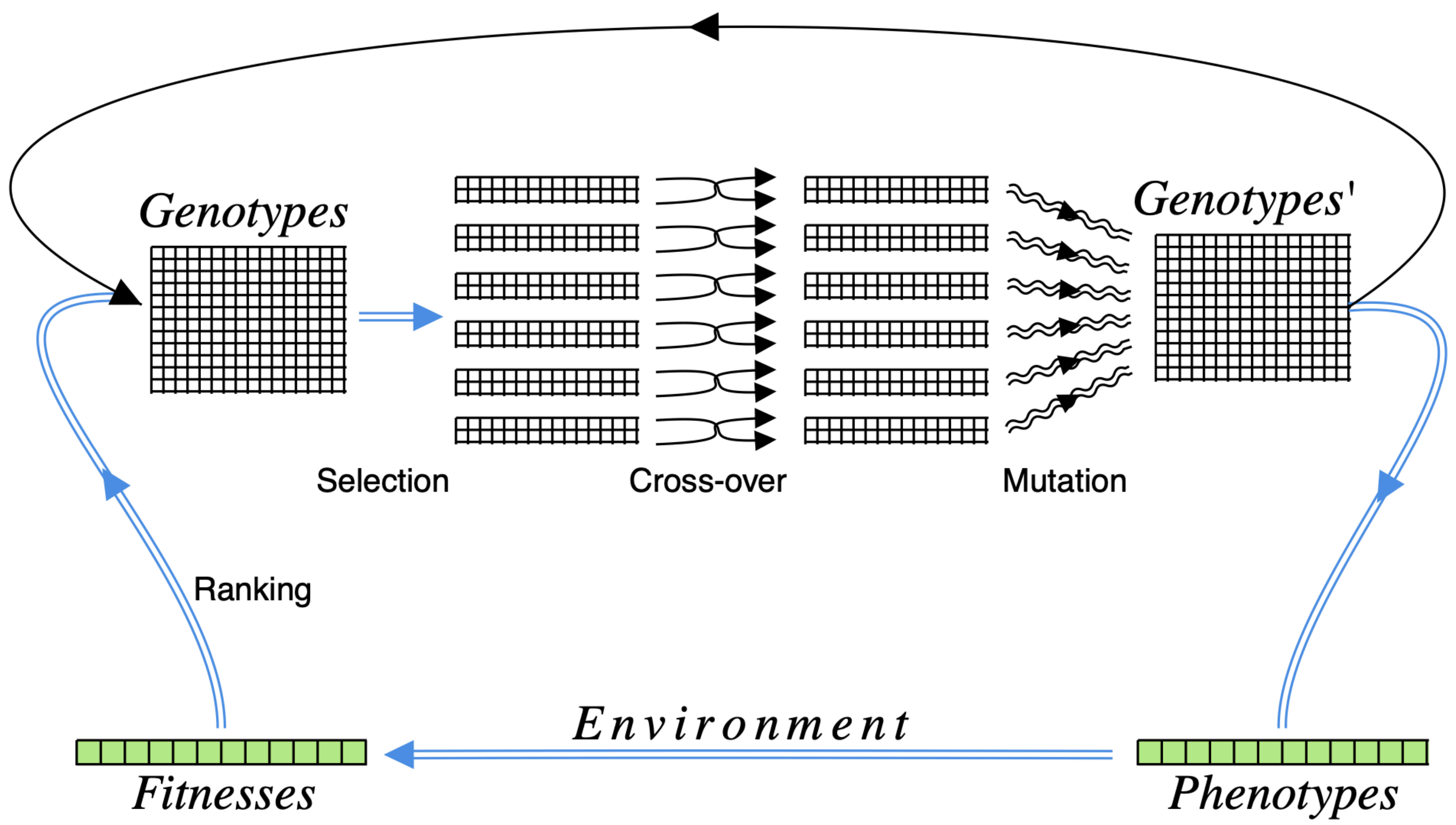

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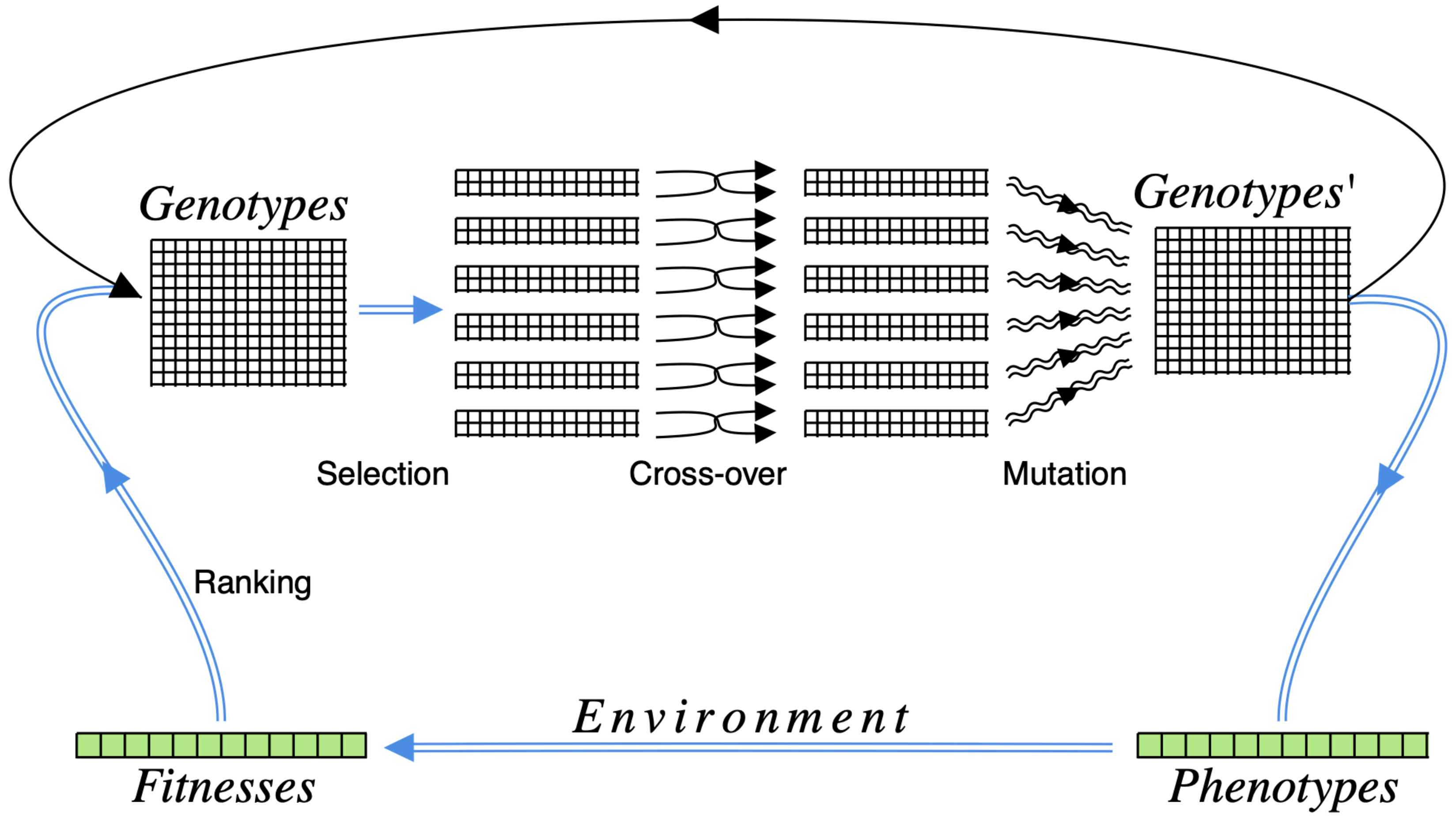

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Superpotential Operators

$$\mathcal{O}_{Y_u} \sim Y_u^{(IJ)} 10_{(I)} 5^H 10_{(J)}$$

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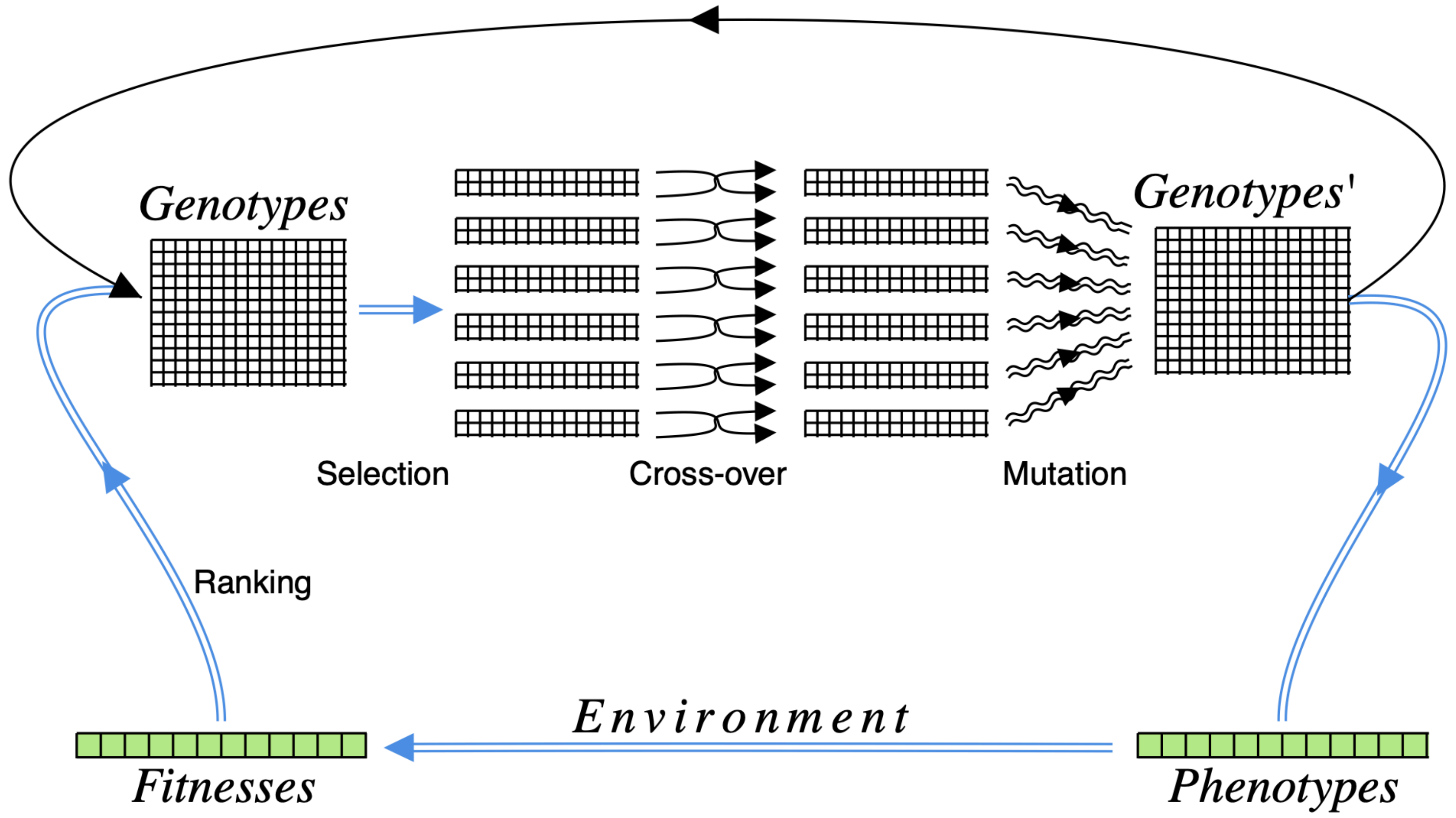

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Physical Observables

$$\langle H \rangle, \ \tan\beta$$

$$m_u, m_c, m_t, m_d, m_s, m_b$$

$$V_{CKM}$$

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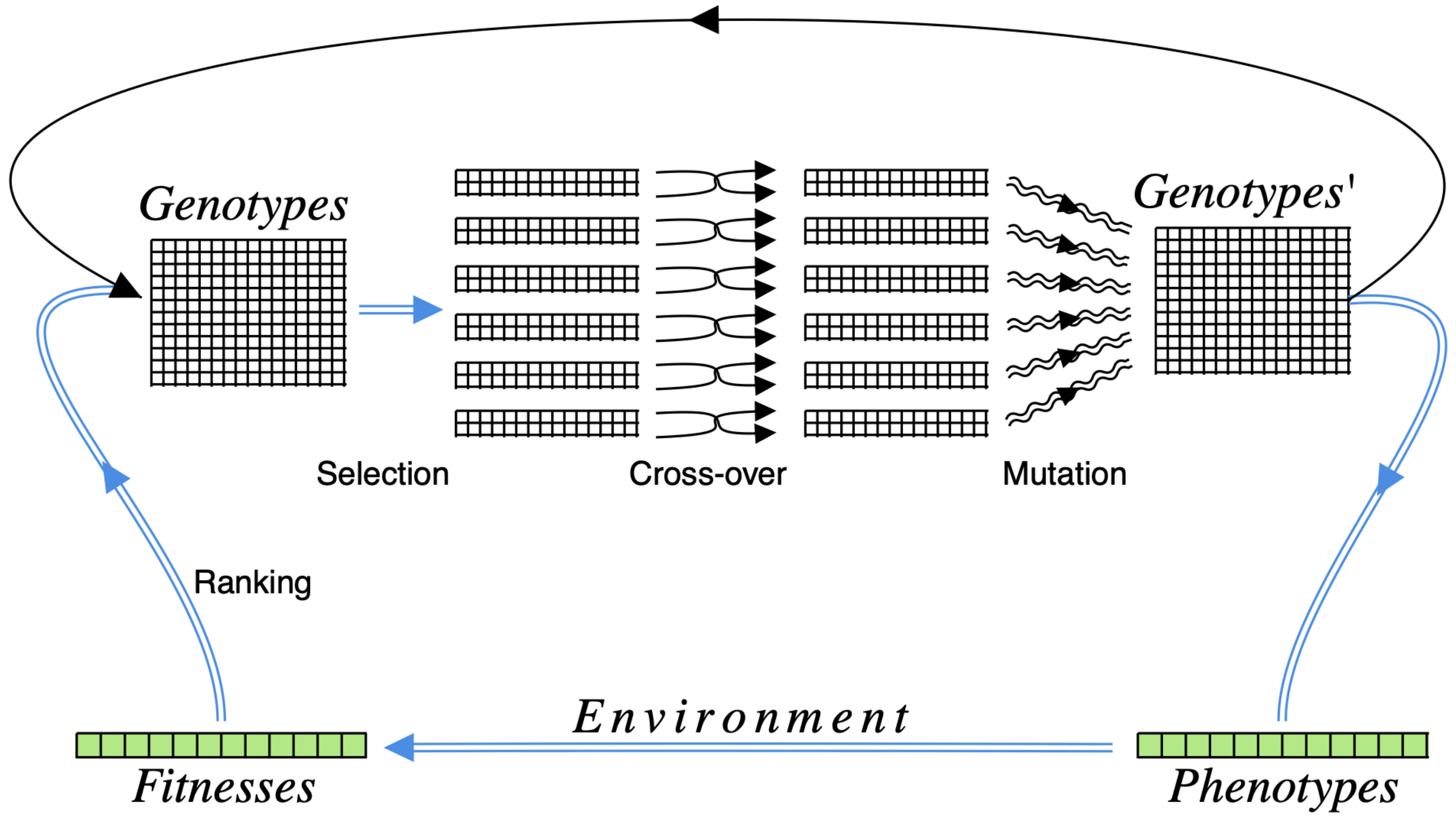

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Fitness Functions

- texture contributions
- log-deviations of physical observables to measured SM values
- $\mathcal{O}(1)$-coefficient fine-tuning

Results - Scans

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Perturbative (Bundle Moduli) Scan

$\boldsymbol{n}$	Charges of $\mathbf{10}$ and $\bar{\mathbf{5}}^H$				$n_\phi \leq 3$	$n_\phi = 4$	$n_\phi = 5$
$(1,1,1,1,1)$	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_5$	$\bar{\mathbf{5}}^{\boldsymbol{H}}_{4,5}$	$-$	≥ 10	≥ 550
$(1,1,1,2)$	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_4$	$\bar{\mathbf{5}}^{\boldsymbol{H}}_{4,4}$	$-$	≥ 10	≥ 1200
	$\mathbf{10}_2$	$\mathbf{10}_3$	$\mathbf{10}_4$	$\bar{\mathbf{5}}^{\boldsymbol{H}}_{1,4}$	$-$	≥ 100	≥ 350
	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\bar{\mathbf{5}}^{\boldsymbol{H}}_{1,4}$	$-$	$-$	$-$
	$\mathbf{10}_1$	$\mathbf{10}_3$	$\mathbf{10}_4$	$\bar{\mathbf{5}}^{\boldsymbol{H}}_{1,2}$	$-$	$-$	$-$
(1,1,3)	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\bar{\mathbf{5}}^{\boldsymbol{H}}_{3,3}$	$-$	$-$	$-$
(1,2,2)	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\bar{\mathbf{5}}^{\boldsymbol{H}}_{3,3}$	$-$	$-$	$-$

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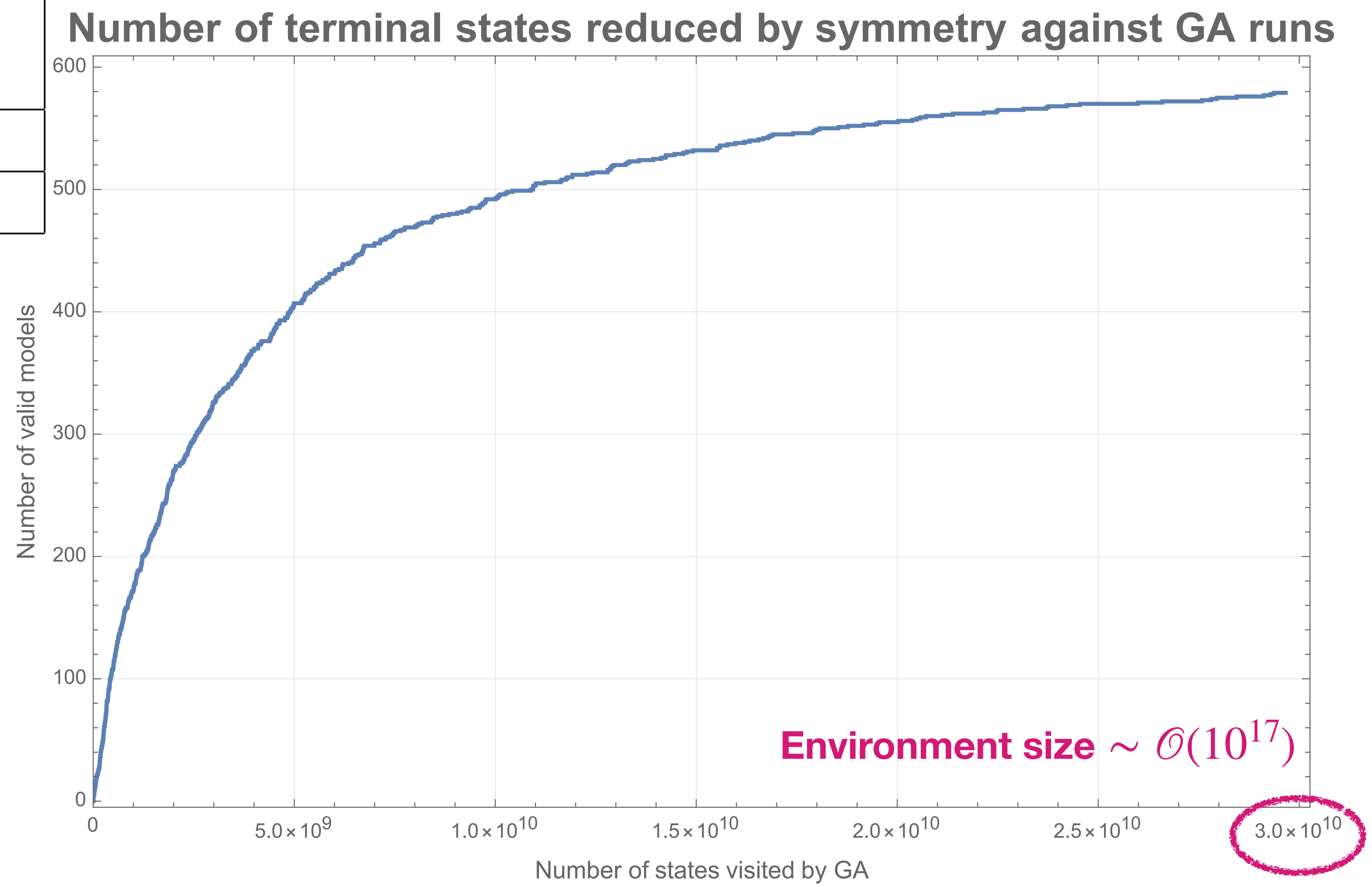
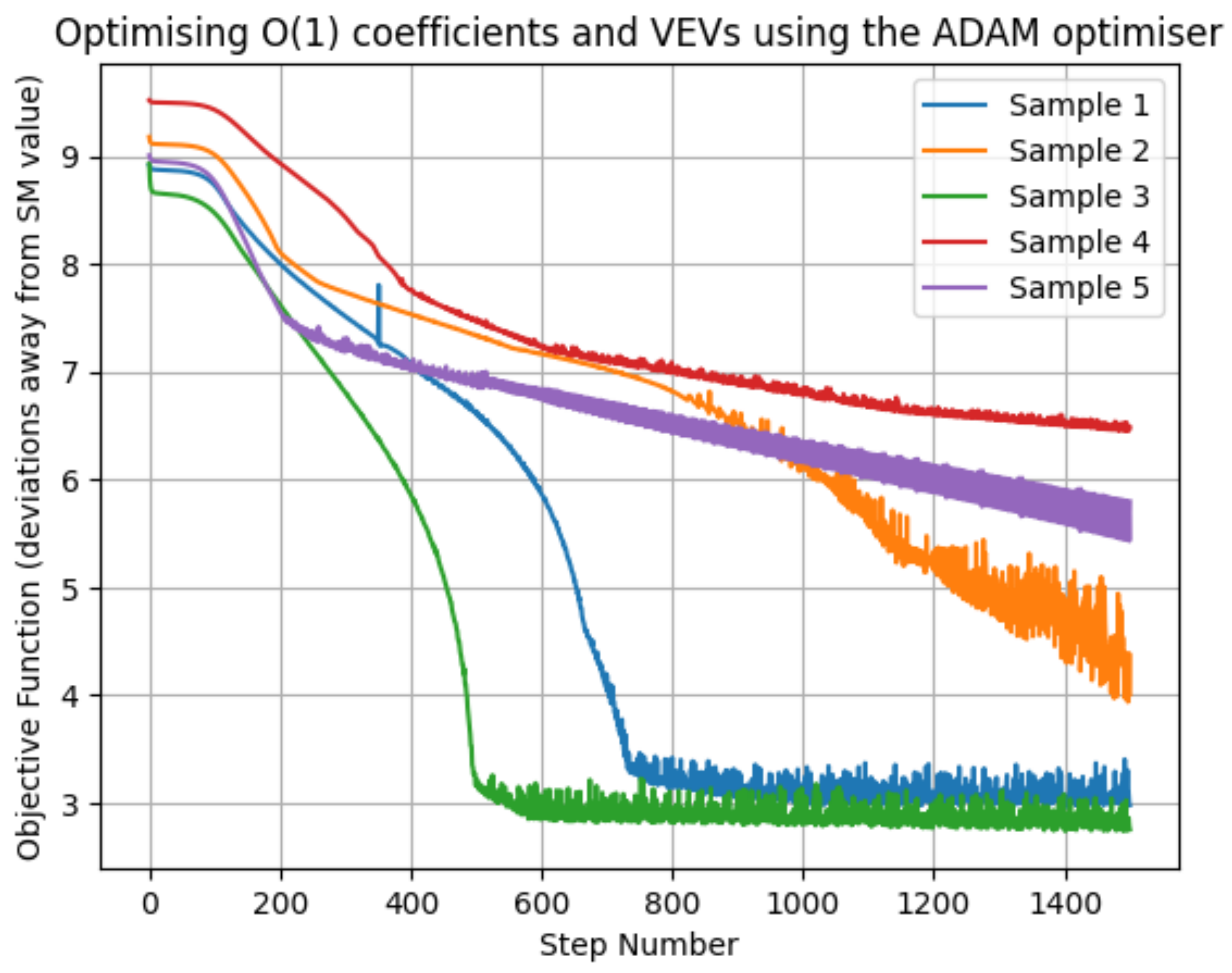


Results - Model Example



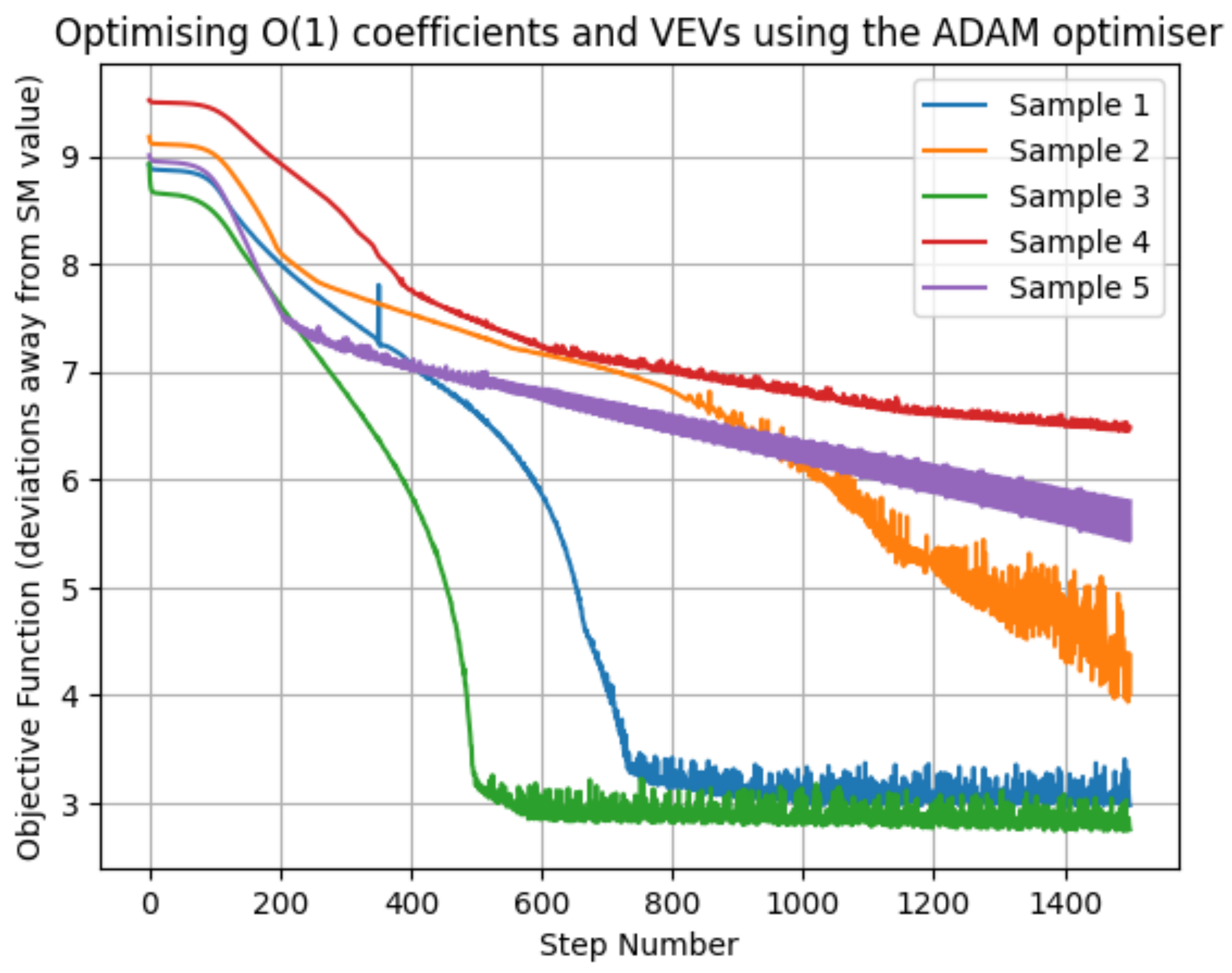
Results - Model Example

Spectrum

$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_5$		
$\bar{\mathbf{5}}_{1,2}$	$\bar{\mathbf{5}}_{1,2}$	$\bar{\mathbf{5}}_{1,2}$		
$\bar{\mathbf{5}}^{\boldsymbol{H}}_{4,5}$				
$\phi_{5,1}$	$\phi_{3,5}$	$\phi_{4,5}$	$\phi_{1,2}$	$\phi_{4,1}$

VEVs

Moduli VEV	Value $(/M_{pl})$
$\langle\phi_{5,1}\rangle$	0.05117908
$\langle\phi_{3,5}\rangle$	0.49406093
$\langle\phi_{4,5}\rangle$	0.36864188
$\langle\phi_{1,2}\rangle$	0.1319671
$\langle\phi_{4,1}\rangle$	0.10001969



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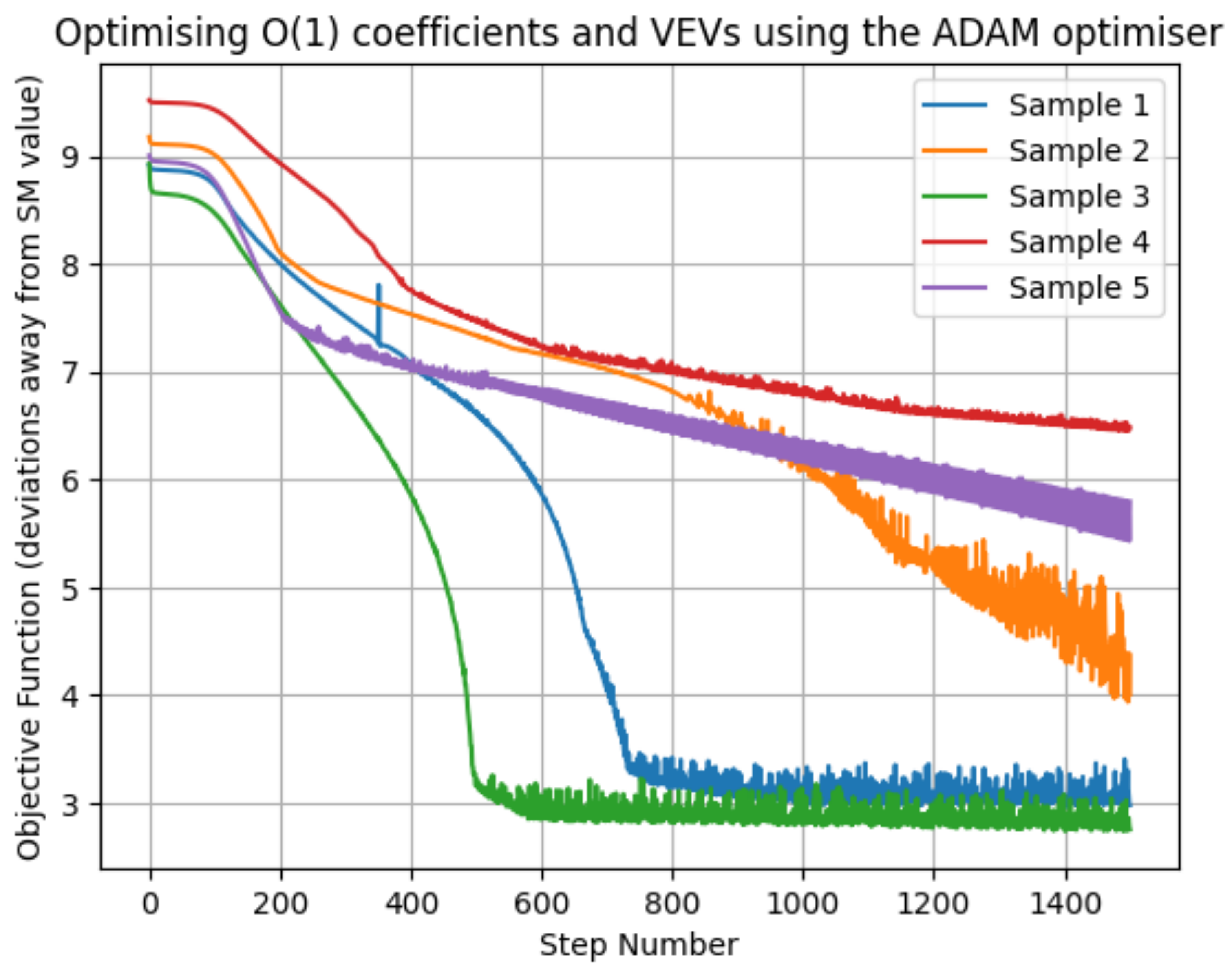


Spectrum

$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_5$		
$\bar{\mathbf{5}}_{1,2}$	$\bar{\mathbf{5}}_{1,2}$	$\bar{\mathbf{5}}_{1,2}$		
$\bar{\mathbf{5}}^{\boldsymbol{H}}_{4,5}$				
$\phi_{5,1}$	$\phi_{3,5}$	$\phi_{4,5}$	$\phi_{1,2}$	$\phi_{4,1}$

VEVs

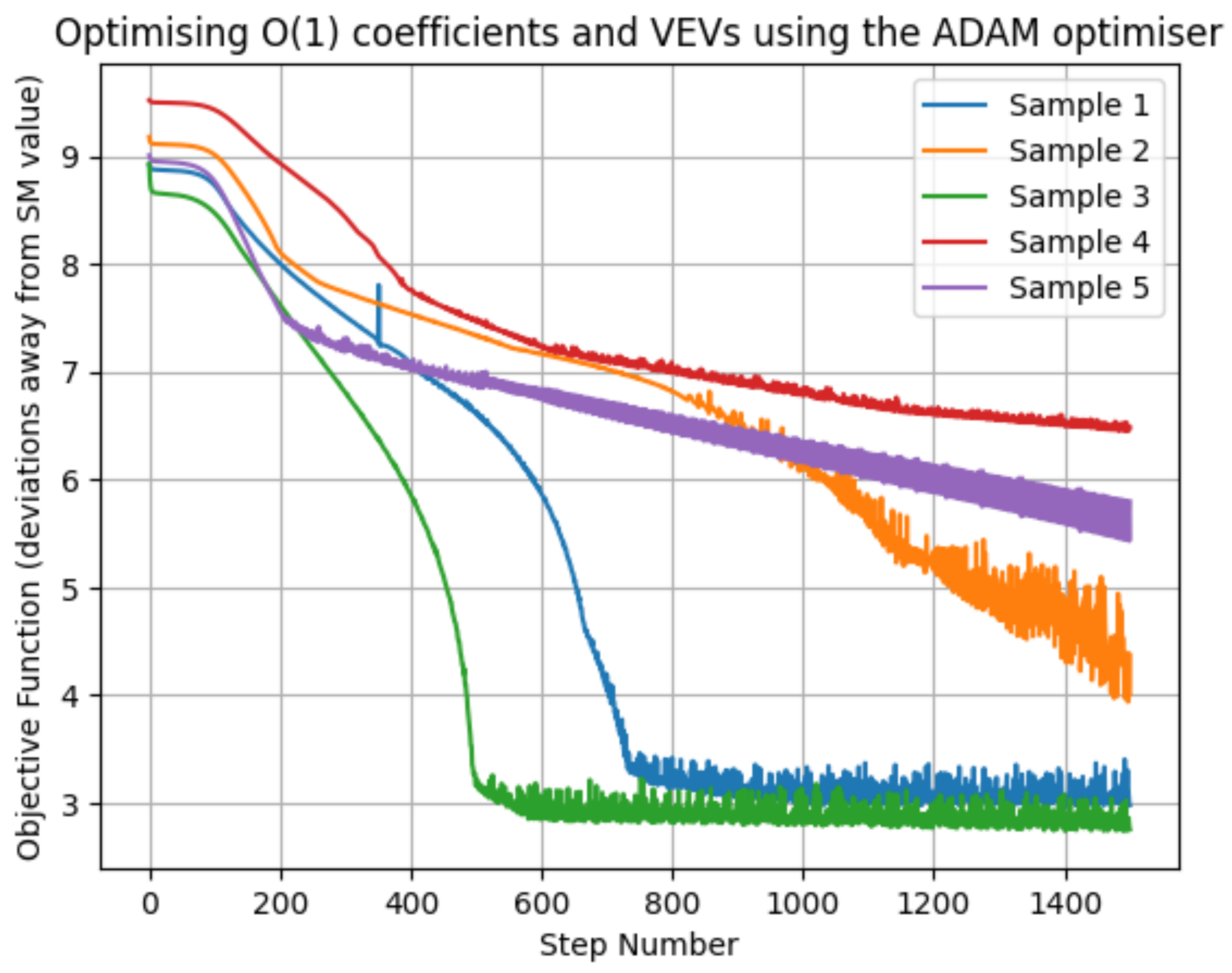
Moduli VEV	Value $(/M_{pl})$
$\langle\phi_{5,1}\rangle$	0.05117908
$\langle\phi_{3,5}\rangle$	0.49406093
$\langle\phi_{4,5}\rangle$	0.36864188
$\langle\phi_{1,2}\rangle$	0.1319671
$\langle\phi_{4,1}\rangle$	0.10001969

Yukawa Textures

$$Y_u \sim \begin{pmatrix} \phi_{5,1}\phi_{4,1} & \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{4,1} \\ \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{5,1}\phi_{1,2}^2\phi_{4,1} & \phi_{1,2}\phi_{4,1} \\ \phi_{4,1} & \phi_{1,2}\phi_{4,1} & \phi_{4,5} \end{pmatrix}$$

$$Y_d \sim \begin{pmatrix} \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} \\ \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} \\ \phi_{3,5} & \phi_{3,5} & \phi_{3,5} \end{pmatrix}$$

Results - Model Example



Spectrum

$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_5$		
$\bar{\mathbf{5}}_{1,2}$	$\bar{\mathbf{5}}_{1,2}$	$\bar{\mathbf{5}}_{1,2}$		
$\bar{\mathbf{5}}^{\boldsymbol{H}}_{4,5}$				
$\phi_{5,1}$	$\phi_{3,5}$	$\phi_{4,5}$	$\phi_{1,2}$	$\phi_{4,1}$

VEVs

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Yukawa Textures

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$$Y_d \sim \begin{pmatrix} \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} \\ \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} \\ \phi_{3,5} & \phi_{3,5} & \phi_{3,5} \end{pmatrix}$$

Computed Physical Quantities

$$\langle H\rangle = 174.064GeV$$

$$m_u = (2.18MeV \quad 1.27GeV \quad 172.69GeV)$$

$$m_d = (4.94MeV \quad 100.25MeV \quad 4.18GeV)$$

$$V_{CKM} = \begin{pmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.043 \\ 0.006 & 0.042 & 0.999 \end{pmatrix}$$

Conclusions & Outlook

- We have constructed a **GA environment** that allows us to search for heterotic standard models with split bundles using flavour symmetries.
- We have performed **searches** on the perturbative sector of the system and found a list of viable models.
- **Guidance to top-down model building!**

- **Extension with non-perturbative** contributions.
- **Extension to the lepton sector.** R-parity violating terms, the μ-term and Weinberg operator. Neutrino mass generation?
- **String perspective** - similar flavour constraints in F-theory local models?