Croucher Foundation
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Fermion Masses and Mixings from String-inspired Models

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based on arXiV:2410.17704

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Motivation

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- explain Yukawa couplings & fermion mass hierarchies
- **Froggatt and Nielsen** [1979] proposed using horizontal symmetries $U(1)_H$ to explain flavour structures

$$\hat{\Lambda}_{ij} = a_{ij} \langle \phi \rangle^{n_{ij}}$$

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

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$$\hat{\Lambda}_{ij} = a_{ij} \langle \phi \rangle^{n_{ij}}$$

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

from [Leurer et al. ('93)]

$$\begin{array}{ccccccccc} Q_1 & Q_2 & Q_3 & \bar{d}_1 & \bar{d}_2 & \bar{d}_3 & \bar{u}_1 & \bar{u}_2 & \bar{u}_3 \\ (3) & (2) & (0) & (3) & (2) & (2) & (3) & (1) & (0) \end{array}$$

with $\phi \quad (-1), \quad \langle \phi \rangle \sim \lambda$

$$M^d \sim \langle \phi_d \rangle \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^5 & \lambda^4 & \lambda^4 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}, \quad M^u \sim \langle \phi_u \rangle \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix}.$$

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Q_1	Q_2	Q_3	$\bar{d}_1$	$\bar{d}_2$	$\bar{d}_3$	$\bar{u}_1$	$\bar{u}_2$	$\bar{u}_3$
(3)	(2)	(0)	(3)	(2)	(2)	(3)	(1)	(0)

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- **top-down** 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, also Butbaia et al. 2401.15078]**
- salient feature of these models: **flavour symmetries** $\mathcal{G}$ **[Anderson et al. 1202.1757]**

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

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

Overview

- Heterotic standard models with split bundles - bottom-up
- Strategy of search + simple example
- Genetic algorithms
- Implementation
- Results
- Conclusion

4d $\mathcal{N}=1$ SUSY Standard Models [Anderson et al. 1202.1757]

- These **bottom-up** models are inspired by heterotic SMs with split bundles.
- Gauge symmetry - $G_{\text{SM}} \times \mathcal{G}$, $\dfrac{\mathcal{G}}{\mathbf{n}\mathbb{Z}} \cong U(1)^{f-1}$
- For field F: $\quad \boldsymbol{Q}_{\mathcal{G}}(F) \sim \boldsymbol{Q}_{\mathcal{G}}(F) + \mathbf{n}$

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

Specifies Split Bundle Structure Group

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

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

field	SM rep	name	SU(5)	$\mathcal{G}$ charge pattern	SU(5)$\times\mathcal{G}$
Q	$(\mathbf{3},\mathbf{2})_1$	LH quark	$\mathbf{10}$	$\mathbf{e}_a$	$\mathbf{10}_a$
u	$(\bar{\mathbf{3}},\mathbf{1})_{-4}$	RH u-quark			
e	$(\mathbf{1},\mathbf{1})_6$	RH electron			
d	$(\bar{\mathbf{3}},\mathbf{1})_2$	RH d-quark	$\bar{\mathbf{5}}$	$\mathbf{e}_a+\mathbf{e}_b$	$\bar{\mathbf{5}}_{a,b}$
L	$(\mathbf{1},\mathbf{2})_{-3}$	LH lepton			
H^d	$(\mathbf{1},\mathbf{2})_{-3}$	down-Higgs	$\bar{\mathbf{5}}^{H^d}$	$\mathbf{e}_a+\mathbf{e}_b$	$\bar{\mathbf{5}}^{H^d}_{a,b}$
H^u	$(\mathbf{1},\mathbf{2})_3$	up-Higgs	$\mathbf{5}^{H^u}$	$-\mathbf{e}_a-\mathbf{e}_b$	$\mathbf{5}^{H^u}_{a,b}$
ϕ	$(\mathbf{1},\mathbf{1})_0$	pert. FN scalar	$\mathbf{1}$	$\mathbf{e}_a-\mathbf{e}_b$	$\mathbf{1}_{a,b}$
Φ	$(\mathbf{1},\mathbf{1})_0$	non-pert. FN scalar	$\mathbf{1}$	$\mathbf{k}=(k_1,\ldots,k_f)$	$\mathbf{1}$

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Φ	$(\mathbf{1},\mathbf{1})_0$	non-pert. FN scalar	$\mathbf{1}$	$\mathbf{k} = (k_1, \ldots, k_f)$	$\mathbf{1}$

Different to traditional FN:

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

Strategy of search for bottom-up string-inspired models

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Phenomenological Considerations

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

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(1) ↓

Charge + VEV powers

Yukawa Textures

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(2) ↓

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

Strategy of search for bottom-up string-inspired models

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↓ 1

Charge + VEV powers

Yukawa Textures

↓ 2

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

7 charge choices to be searched

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

Strategy of search for bottom-up string-inspired models

Example in $\boldsymbol{n} = (1,1,1,1,1)$ with $H^{d}_{4,5}$

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Example in $\boldsymbol{n} = (1,1,1,1,1)$ with $H^d_{4,5}$

Spectrum

$\mathbf{10}_1,\ \mathbf{10}_2,\ \mathbf{10}_5;\ 3\bar{\mathbf{5}}_{1,2};\ H^u_{4,5},\ H^d_{4,5}$

$\phi_{5,1},\ \phi_{3,5},\ \phi_{1,2},\ \phi_{4,1},\ \phi_{4,5}$

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→

$$\begin{aligned} \text{up sector:} &\quad \text{(singlet insertions)} \times\ H^u_{-\mathbf{e}_a-\mathbf{e}_b}\mathbf{10}^i_{\mathbf{e}_c}\mathbf{10}^j_{\mathbf{e}_d} \\ \text{down sector:} &\quad \text{(singlet insertions)} \times\ H^d_{\mathbf{e}_a+\mathbf{e}_b}\bar{\mathbf{5}}^i_{\mathbf{e}_c+\mathbf{e}_d}\mathbf{10}^j_{\mathbf{e}_e}\ , \end{aligned}$$

Strategy of search for bottom-up string-inspired models

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$$\text{up sector:} \quad (\text{singlet insertions}) \times \ H^u_{-\mathbf{e}_a-\mathbf{e}_b}\mathbf{10}^i_{\mathbf{e}_c}\mathbf{10}^j_{\mathbf{e}_d}$$

$$\text{down sector:} \quad (\text{singlet insertions}) \times \ H^d_{\mathbf{e}_a+\mathbf{e}_b}\bar{\mathbf{5}}^i_{\mathbf{e}_c+\mathbf{e}_d}\mathbf{10}^j_{\mathbf{e}_e}\ ,$$

Yukawa Textures

$$\text{up sector:} \quad \begin{pmatrix} \phi_{5,1}\phi_{4,1} & \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{4,1} \\ \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{5,1}\phi_{1,2}^2\phi_{4,1} & \phi_{1,2}\phi_{4,1} \\ \phi_{4,1} & \phi_{1,2}\phi_{4,1} & \phi_{4,5} \end{pmatrix}$$

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Example in $n = (1,1,1,1,1)$ with $H^d_{4,5}$

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$\sim O(10^{11})$ **choices**

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Example in $\boldsymbol{n} = (1,1,1,1,1)$ with $H^d_{4,5}$

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Choice of VEV-powers

$$\langle\phi_{5,1}\rangle \sim \epsilon^3, \langle\phi_{3,5}\rangle \sim \epsilon^4, \langle\phi_{4,5}\rangle \sim \epsilon, \langle\phi_{1,2}\rangle \sim \epsilon^5, \langle\phi_{4,1}\rangle \sim \epsilon^4$$

Strategy of search for bottom-up string-inspired models

Example in $n = (1,1,1,1,1)$ with $H^d_{4,5}$

Yukawa Textures

up sector: $\begin{pmatrix} \phi_{5,1}\phi_{4,1} & \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{4,1} \\ \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{5,1}\phi_{1,2}^2\phi_{4,1} & \phi_{1,2}\phi_{4,1} \\ \phi_{4,1} & \phi_{1,2}\phi_{4,1} & \phi_{4,5} \end{pmatrix}$

down sector: $\begin{pmatrix} \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} \\ \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} \\ \phi_{3,5} & \phi_{3,5} & \phi_{3,5} \end{pmatrix}$

Choice of VEV-powers

typical $\epsilon \sim 0.4$

$$\langle\phi_{5,1}\rangle \sim \epsilon^3, \langle\phi_{3,5}\rangle \sim \epsilon^4, \langle\phi_{4,5}\rangle \sim \epsilon, \langle\phi_{1,2}\rangle \sim \epsilon^5, \langle\phi_{4,1}\rangle \sim \epsilon^4$$

Strategy of search for bottom-up string-inspired models

Example in $n = (1,1,1,1,1)$ with $H^d_{4,5}$

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Yukawa Matrices

$$\text{up sector} \sim \begin{pmatrix} \epsilon^7 & \epsilon^{12} & \epsilon^4 \\ \epsilon^{12} & \epsilon^{17} & \epsilon^9 \\ \epsilon^4 & \epsilon^9 & \epsilon \end{pmatrix}$$

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typical $\epsilon \sim 0.4$

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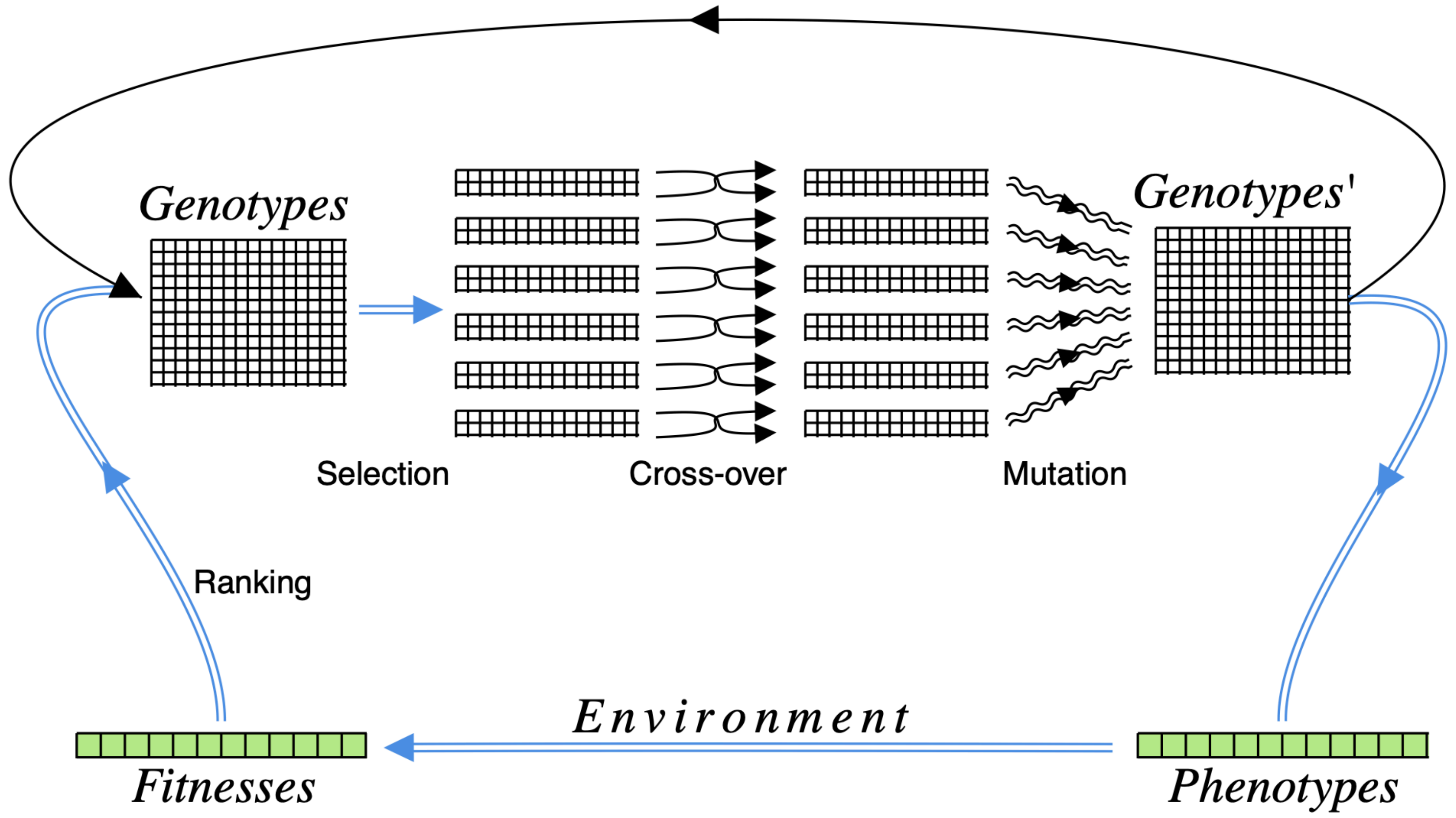
typical $\epsilon \sim 0.4$

$\sim O(10^{16})$ **choices**

Genetic Algorithms

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



from [Abel et al. ('23)]

Bitlist → **Fitness**

ENVIRONMENT

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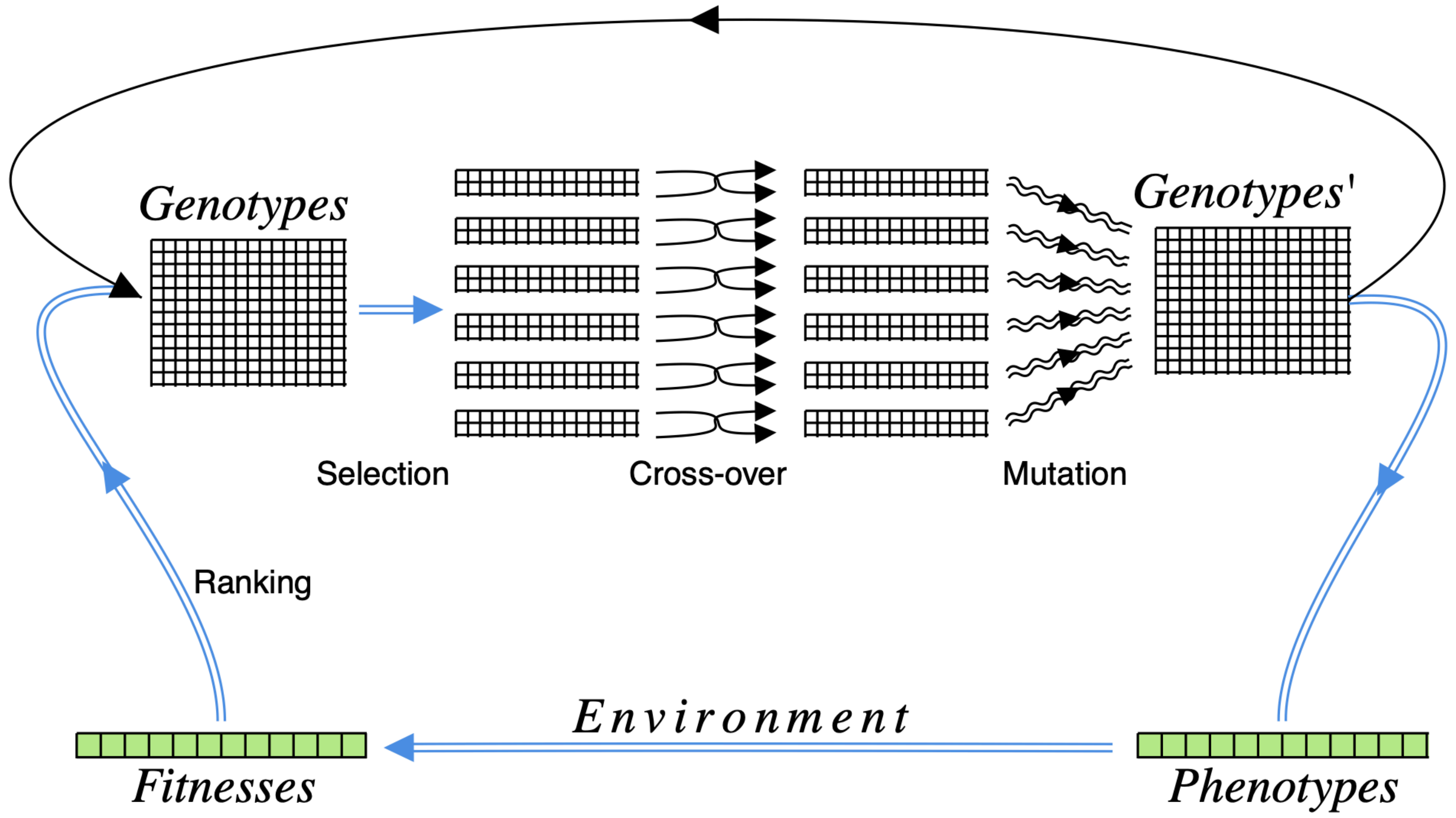

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ENVIRONMENT

Charge Patterns + VEVs

$10_a, 10_b, 10_c, \bar{5}_{a,b}, \bar{5}_{c,d}, \bar{5}_{e,f}, H_{a,b}, 1_{a,b} \ldots$

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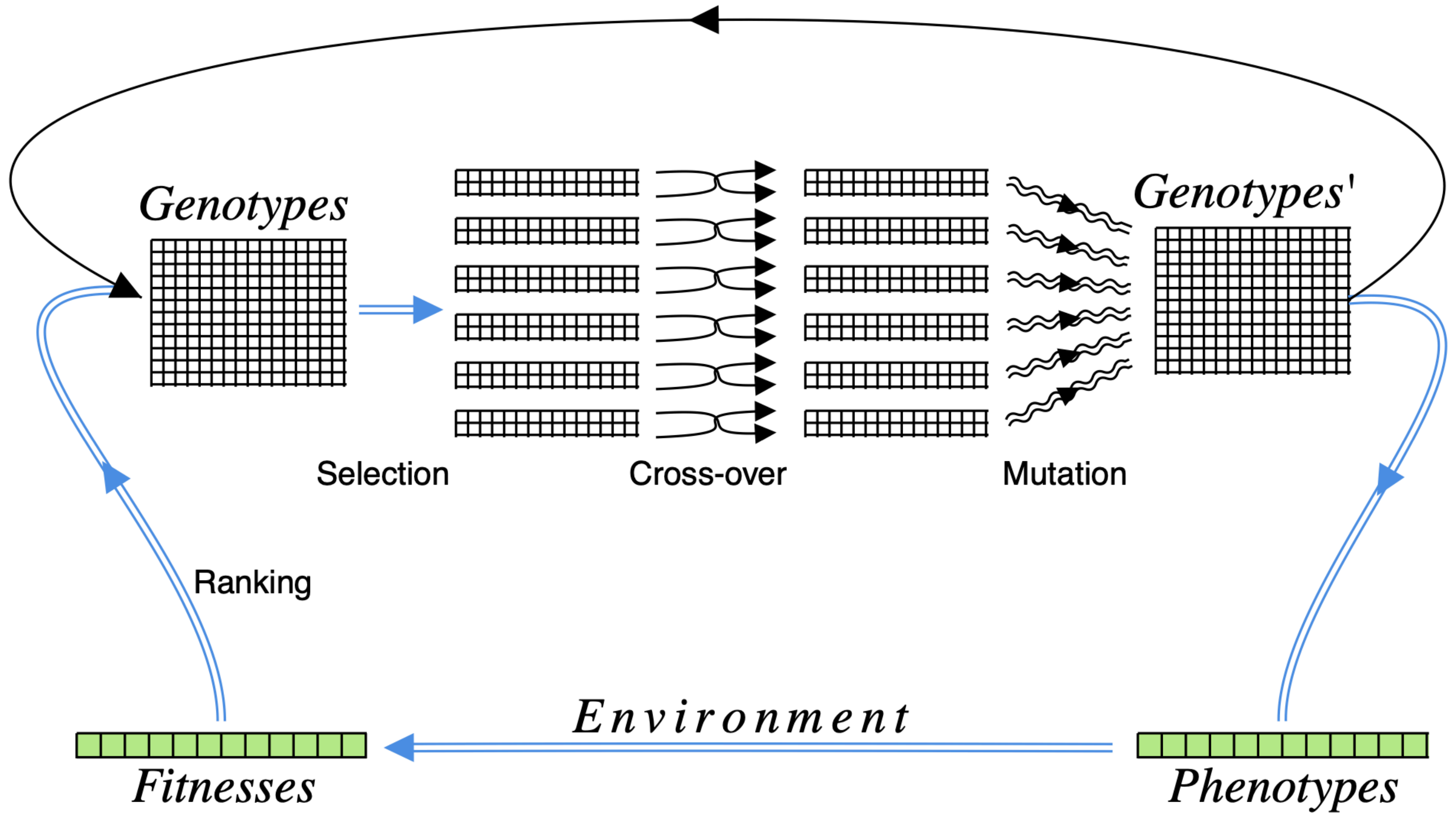

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Superpotential Operators

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

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

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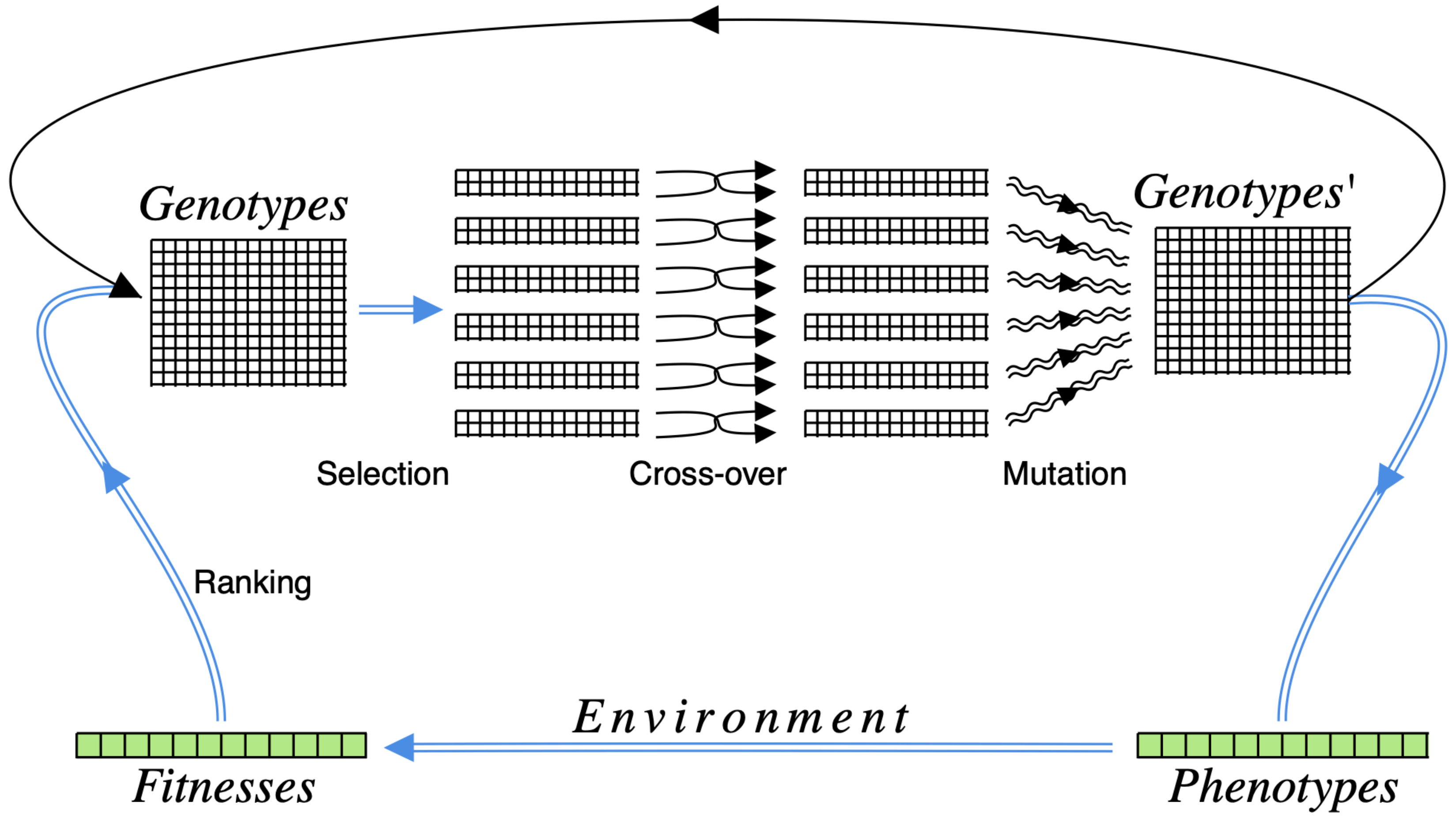

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Superpotential Operators

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

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

Physical Observables

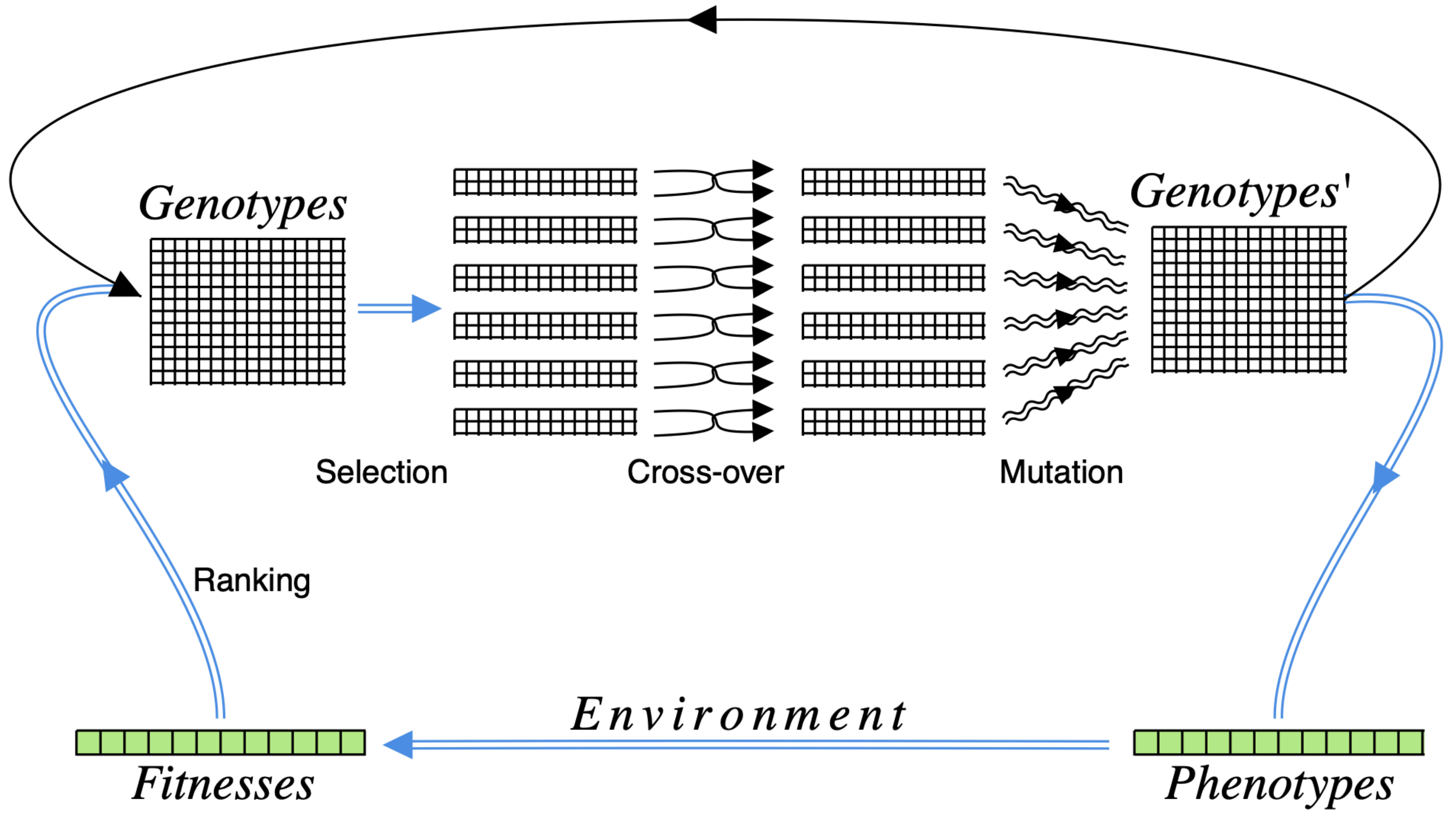
$$v = \langle H \rangle,$$

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

$$V_{CKM}$$

Genetic Algorithms

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



from [Abel et al. ('23)]

Bitlist → **Fitness**

ENVIRONMENT

Charge Patterns + VEVs

$10_a, 10_b, 10_c, \bar{5}_{a,b}, \bar{5}_{c,d}, \bar{5}_{e,f}, H_{a,b}, 1_{a,b} \dots$

Superpotential Operators

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

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

Physical Observables

$$v = \langle H \rangle,$$

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

$$V_{CKM}$$

Fitness Functions

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

Results - Scans (Perturbative Only)

Results - Scans (Perturbative Only)

n	Fixed charges	N_ϕ	Env Size	States visited	Full scan	Models	Inequiv. spectra
$(1,1,1,1,1)$	$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_5, \bar{\mathbf{5}}^H_{4,5}$	2	10^9		Yes	0	0
		3	10^{11}	10^8		0	0
		4	10^{13}	10^8		301	4
		5	10^{16}	10^9		29213	289
$(1,1,1,2)$	$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_4, \bar{\mathbf{5}}^H_{4,4}$	2	10^8		Yes	0	0
		3	10^{10}		Yes	98	1
		4	10^{12}	10^8		18825	55
		5	10^{14}	10^8		320557	449
$(1,1,1,2)$	$\mathbf{10}_2, \mathbf{10}_3, \mathbf{10}_4, \bar{\mathbf{5}}^H_{1,4}$	2	10^8		Yes	0	0
		3	10^{10}		Yes	56	1
		4	10^{12}	10^8		11538	128
		5	10^{14}	10^8		259175	1128
$(1,1,1,2)$	$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_3, \bar{\mathbf{5}}^H_{1,4}$	2	10^8		Yes	0	0
		3	10^{10}		Yes	70	3
		4	10^{12}	10^8		8110	63
		5	10^{14}	10^8		204148	500
$(1,1,1,2)$	$\mathbf{10}_1, \mathbf{10}_3, \mathbf{10}_4, \bar{\mathbf{5}}^H_{1,2}$	2	10^8		Yes	0	0
		3	10^{10}		Yes	0	0
		4	10^{12}	10^8		0	0
		5	10^{14}	10^8		0	0
$(1,1,3)$	$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_3, \bar{\mathbf{5}}^H_{3,3}$	2	10^6		Yes	8	1
		3	10^8		Yes	1218	18
		4	10^{10}		Yes	22734	81
		5	10^{12}	10^8		154532	234
$(1,2,2)$	$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_3, \bar{\mathbf{5}}^H_{3,3}$	2	10^6		Yes	0	0
		3	10^8		Yes	0	0
		4	10^{10}		Yes	0	0
		5	10^{12}	10^8		0	0

Results - Scans (Perturbative Only)

n	Fixed charges	N_ϕ	Env Size	States visited	Full scan	Models	Inequiv. spectra
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		3	10^{11}	10^8		0	0
		4	10^{13}	10^8		301	4
		5	10^{16}	10^9		29213	289
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		3	10^{10}		Yes	98	1
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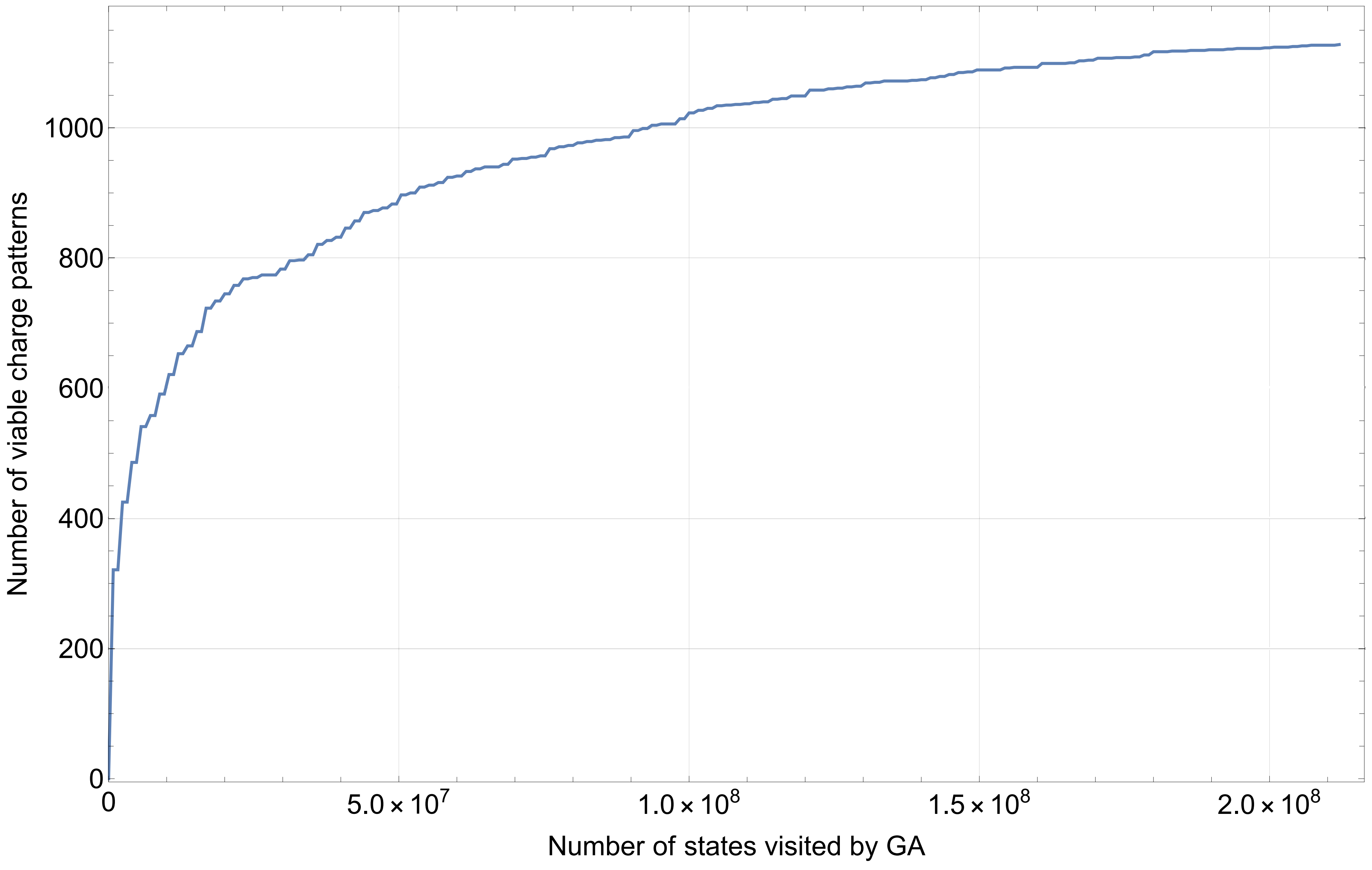
		4	10^{10}		Yes	0	0
		5	10^{12}	10^8		0	0

Total number of inequiv. spectra obtained against states visited



Results - Scans (Perturbative Only)

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$(1,1,1,1,1)$	$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_5, \bar{\mathbf{5}}^H_{4,5}$	2	10^9		Yes	0	0
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		4	10^{13}	10^8		301	4
		5	10^{16}	10^9		29213	289
$(1,1,1,2)$	$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_4, \bar{\mathbf{5}}^H_{4,4}$	2	10^8		Yes	0	0
		3	10^{10}		Yes	98	1
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		3	10^{10}		Yes	0	0
		4	10^{12}	10^8		0	0
		5	10^{14}	10^8		0	0
$(1,1,3)$	$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_3, \bar{\mathbf{5}}^H_{3,3}$	2	10^6		Yes	8	1
		3	10^8		Yes	1218	18
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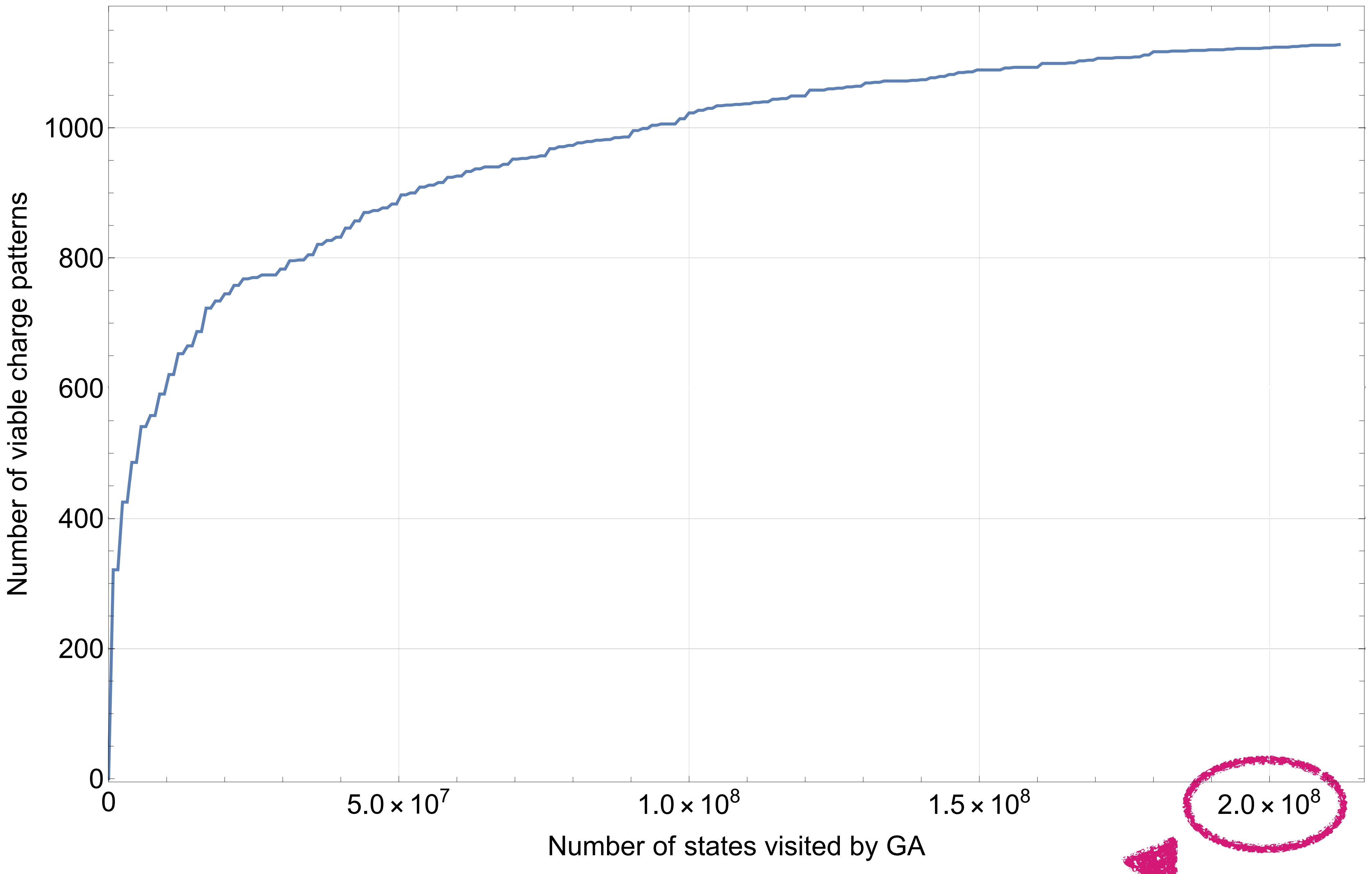
$(1,2,2)$	$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_3, \bar{\mathbf{5}}^H_{3,3}$	2	10^6		Yes	0	0
		3	10^8		Yes	0	0
		4	10^{10}		Yes	0	0
		5	10^{12}	10^8		0	0

Total number of inequiv. spectra obtained against states visited



Environment size
$\sim \mathcal{O}(10^{14})$

Results - Model Example

Results - Model Example

Spectrum

$\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_5;\ 3\bar{\mathbf{5}}_{1,2};\ H^u_{4,5}, H^d_{4,5}$

$\phi_{5,1}, \phi_{3,5}, \phi_{1,2}, \phi_{4,1}, \phi_{4,5}$

Results - Model Example

Spectrum

$\mathbf{10}_1,\ \mathbf{10}_2,\ \mathbf{10}_5;\ 3\bar{\mathbf{5}}_{1,2};\ H^u_{4,5},\ H^d_{4,5}$

$\phi_{5,1},\ \phi_{3,5},\ \phi_{1,2},\ \phi_{4,1},\ \phi_{4,5}$

Yukawa Textures

$$\text{up sector:}\quad \begin{pmatrix} \phi_{5,1}\phi_{4,1} & \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{4,1} \\ \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{5,1}\phi_{1,2}^2\phi_{4,1} & \phi_{1,2}\phi_{4,1} \\ \phi_{4,1} & \phi_{1,2}\phi_{4,1} & \phi_{4,5} \end{pmatrix}$$

$$\text{down sector:}\quad \begin{pmatrix} \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} \\ \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} \\ \phi_{3,5} & \phi_{3,5} & \phi_{3,5} \end{pmatrix}$$

Results - Model Example

Yukawa Textures

$$\text{up sector:} \quad \begin{pmatrix} \phi_{5,1}\phi_{4,1} & \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{4,1} \\ \phi_{5,1}\phi_{1,2}\phi_{4,1} & \phi_{5,1}\phi_{1,2}^2\phi_{4,1} & \phi_{1,2}\phi_{4,1} \\ \phi_{4,1} & \phi_{1,2}\phi_{4,1} & \phi_{4,5} \end{pmatrix}$$

$$\text{down sector:} \quad \begin{pmatrix} \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} \\ \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} \\ \phi_{3,5} & \phi_{3,5} & \phi_{3,5} \end{pmatrix}$$

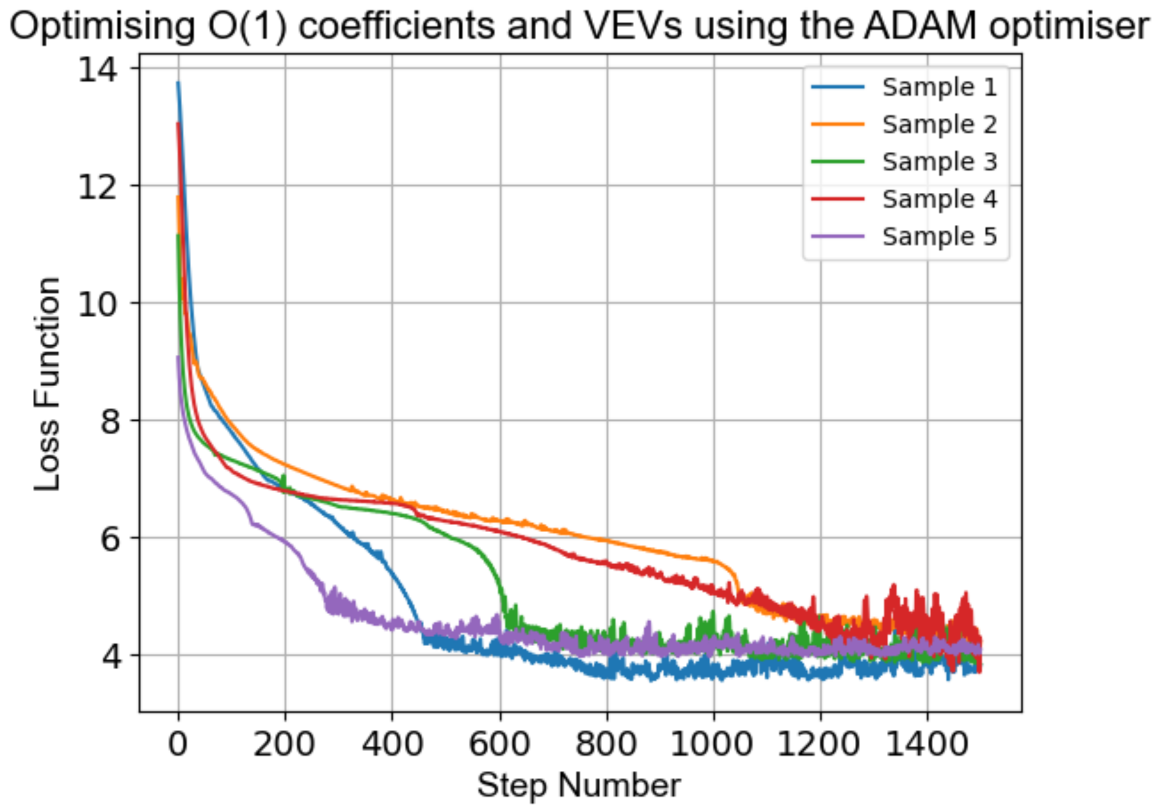
Spectrum

$$\mathbf{10}_1,\ \mathbf{10}_2,\ \mathbf{10}_5;\ 3\bar{\mathbf{5}}_{1,2};\ H^u_{4,5},\ H^d_{4,5}$$

$$\phi_{5,1},\ \phi_{3,5},\ \phi_{1,2},\ \phi_{4,1},\ \phi_{4,5}$$

Optimise coefficients - $\epsilon = 0.554$ and

$$\underset{\text{up-quark sector}}{\begin{pmatrix} 1.090 & 2.282 & 1.896 \\ 0.961 & 2.027 & 1.979 \\ 1.966 & 2.978 & 2.648 \end{pmatrix}} \quad \underset{\text{down-quark sector}}{\begin{pmatrix} 1.379 & 1.843 & 0.947 \\ 2.708 & 1.726 & 2.063 \\ 1.530 & 2.526 & 0.680 \end{pmatrix}} \quad \underset{\text{lepton sector}}{\begin{pmatrix} 1.064 & 2.051 & 1.707 \\ 1.183 & 2.628 & 2.262 \\ 0.514 & 1.623 & 0.706 \end{pmatrix}}$$



Results - Model Example

Spectrum

$$\mathbf{10}_1,\ \mathbf{10}_2,\ \mathbf{10}_5;\ \ 3\bar{\mathbf{5}}_{1,2};\ \ H^u_{4,5},\ H^d_{4,5}$$

$$\phi_{5,1},\ \phi_{3,5},\ \phi_{1,2},\ \phi_{4,1},\ \phi_{4,5}$$

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$$\text{down sector:}\quad \begin{pmatrix} \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} & \phi_{5,1}\phi_{3,5} \\ \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} & \phi_{5,1}\phi_{3,5}\phi_{1,2} \\ \phi_{3,5} & \phi_{3,5} & \phi_{3,5} \end{pmatrix}$$

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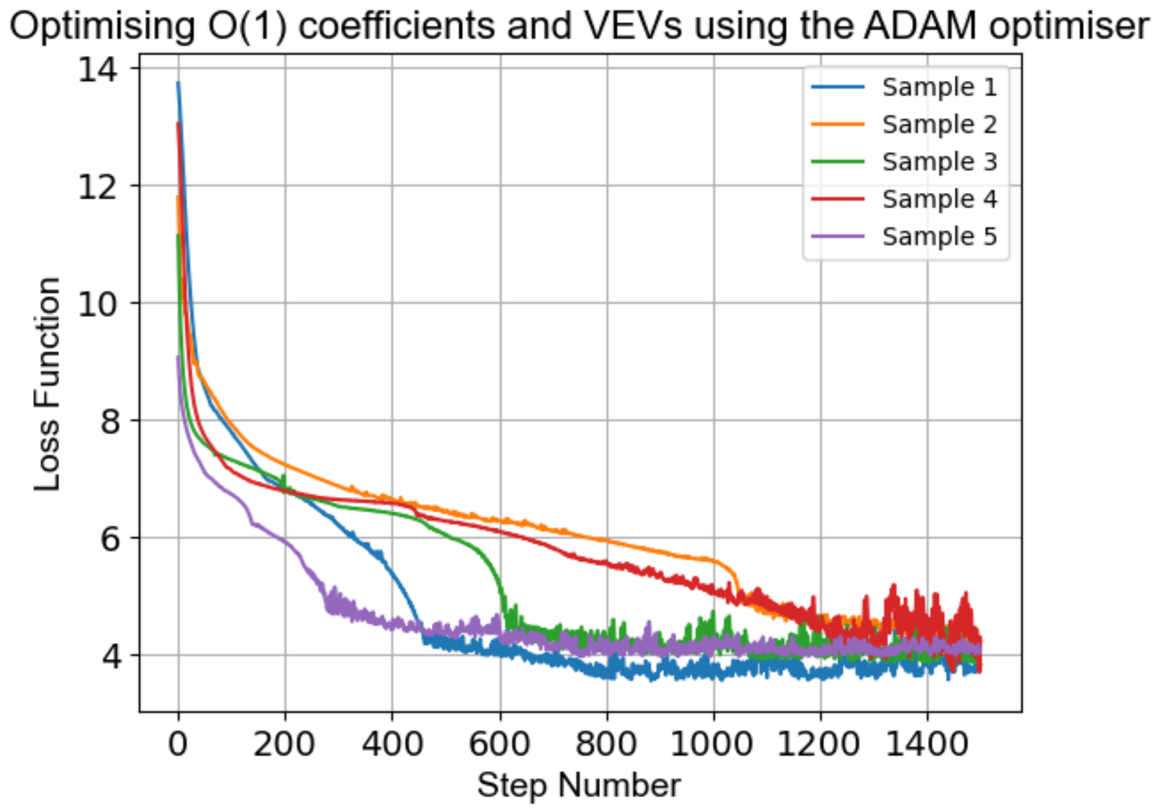
up-quark sector, down-quark sector, lepton sector



Compute Quantities

Higgs VEV	$\langle H \rangle = 174$ GeV		
Quark	m_u (MeV)	m_c (GeV)	m_t (GeV)
Mass	2.16	1.27	173
Quark	m_d (MeV)	m_s (MeV)	m_b (GeV)
Mass	4.70	93.9	4.18
Lepton	m_e (MeV)	m_μ (MeV)	m_τ (GeV)
Mass	0.511	106	1.78

$$|V_{\text{CKM}}| \simeq \begin{pmatrix} 0.970 & 0.242 & 0.00359 \\ 0.242 & 0.969 & 0.0447 \\ 0.00733 & 0.0443 & 0.999 \end{pmatrix}$$

Results - Scans

Results - Scans

Non-perturbative sector scan

e.g. $\mathbf{n} = (1,1,1,1,1)$

N_ϕ	N_Φ	Env. Size	States Visited	Full Scan	Models	Inequiv. q-patterns
0	1	10^9		Yes	0	0
0	2	10^{13}	10^8		0	0
0	3	10^{18}	10^8		0	0
0	4	10^{22}	10^8		22	2
1	1	10^{11}	10^8		0	0
1	2	10^{16}	10^8		0	0
1	3	10^{20}	10^8		648	107
1	4	10^{25}	10^8		7377	2154
2	1	10^{14}	10^8		0	0
2	2	10^{18}	10^8		328	23
2	3	10^{23}	10^8		6073	1490
2	4	10^{27}	10^8		7354	1708
3	1	10^{16}	10^8		76	5
3	2	10^{20}	10^8		720	159
3	3	10^{25}	10^8		892	149
4	1	10^{18}	10^8		263	9
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An Example:

$$\mathbf{10}_1,\ \mathbf{10}_2,\ \mathbf{10}_5,\ \bar{\mathbf{5}}_{3,4},\ \bar{\mathbf{5}}_{3,4},\ \bar{\mathbf{5}}_{3,4},\ H^u_{4,5},\ H^d_{4,5},\ \phi_{4,5},\ \phi_{5,1},\ \Phi^{(1)},\ \Phi^{(2)}$$

$$(k^i_a) = \begin{pmatrix} 1 & -1 & 0 & -1 & 1 \\ 1 & 1 & 0 & -1 & -1 \end{pmatrix} \quad \begin{matrix} \Phi^{(1)} \\ \Phi^{(2)} \end{matrix}$$

up sector: $\begin{pmatrix} \phi_{4,5}\phi_{5,1}^2 & \phi_{4,5}^2\phi_{5,1}^2\Phi_1 & \phi_{4,5}\phi_{5,1} \\ \phi_{4,5}^2\phi_{5,1}^2\Phi_1 & \phi_{4,5}^3\phi_{5,1}^2\Phi_1^2 & \phi_{4,5}^2\phi_{5,1}\Phi_1 \\ \phi_{4,5}\phi_{5,1} & \phi_{4,5}^2\phi_{5,1}\Phi_1 & \phi_{4,5} \end{pmatrix}$,

down sector: $\begin{pmatrix} \phi_{5,1}\Phi_2 & \phi_{5,1}\Phi_2 & \phi_{5,1}\Phi_2 \\ \phi_{4,5}\phi_{5,1}\Phi_1\Phi_2 & \phi_{4,5}\phi_{5,1}\Phi_1\Phi_2 & \phi_{4,5}\phi_{5,1}\Phi_1\Phi_2 \\ \Phi_2 & \Phi_2 & \Phi_2 \end{pmatrix}$

Results - Scans

Non-perturbative sector scan

e.g. $\mathbf{n} = (1,1,1,1,1)$

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$$\text{down sector:} \quad \begin{pmatrix} \phi_{5,1}\Phi_2 & \phi_{5,1}\Phi_2 & \phi_{5,1}\Phi_2 \\ \phi_{4,5}\phi_{5,1}\Phi_1\Phi_2 & \phi_{4,5}\phi_{5,1}\Phi_1\Phi_2 & \phi_{4,5}\phi_{5,1}\Phi_1\Phi_2 \\ \Phi_2 & \Phi_2 & \Phi_2 \end{pmatrix}$$

$\epsilon = 0.77$

$$\underset{\text{up-quark sector}}{\begin{pmatrix} 1.403 & 1.701 & 2.414 \\ 2.465 & 2.805 & 1.150 \\ 2.999 & 2.999 & 2.914 \end{pmatrix}} \quad \underset{\text{down-quark sector}}{\begin{pmatrix} 1.389 & 1.737 & 1.554 \\ 0.564 & 0.500 & 2.995 \\ 2.997 & 2.962 & 0.500 \end{pmatrix}} \quad \underset{\text{lepton sector}}{\begin{pmatrix} 0.608 & 0.708 & 2.567 \\ 0.658 & 0.675 & 2.658 \\ 1.354 & 0.577 & 0.500 \end{pmatrix}}$$

Results - Scans

Non-perturbative sector scan

e.g. $\mathbf{n} = (1,1,1,1,1)$

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An Example:

$$\mathbf{10}_1,\ \mathbf{10}_2,\ \mathbf{10}_5,\ \bar{\mathbf{5}}_{3,4},\ \bar{\mathbf{5}}_{3,4},\ \bar{\mathbf{5}}_{3,4},\ H^u_{4,5},\ H^d_{4,5},\ \phi_{4,5},\ \phi_{5,1},\ \Phi^{(1)},\ \Phi^{(2)}$$

$$(k^i_a) = \begin{pmatrix} 1 & -1 & 0 & -1 & 1 \\ 1 & 1 & 0 & -1 & -1 \end{pmatrix} \quad \begin{matrix} \Phi^{(1)} \\ \Phi^{(2)} \end{matrix}$$

up sector: $\begin{pmatrix} \phi_{4,5}\phi_{5,1}^2 & \phi_{4,5}^2\phi_{5,1}^2\Phi_1 & \phi_{4,5}\phi_{5,1} \\ \phi_{4,5}^2\phi_{5,1}^2\Phi_1 & \phi_{4,5}^3\phi_{5,1}^2\Phi_1^2 & \phi_{4,5}^2\phi_{5,1}\Phi_1 \\ \phi_{4,5}\phi_{5,1} & \phi_{4,5}^2\phi_{5,1}\Phi_1 & \phi_{4,5} \end{pmatrix}$,

down sector: $\begin{pmatrix} \phi_{5,1}\Phi_2 & \phi_{5,1}\Phi_2 & \phi_{5,1}\Phi_2 \\ \phi_{4,5}\phi_{5,1}\Phi_1\Phi_2 & \phi_{4,5}\phi_{5,1}\Phi_1\Phi_2 & \phi_{4,5}\phi_{5,1}\Phi_1\Phi_2 \\ \Phi_2 & \Phi_2 & \Phi_2 \end{pmatrix}$

$\epsilon = 0.77$

$$\begin{pmatrix} 1.403 & 1.701 & 2.414 \\ 2.465 & 2.805 & 1.150 \\ 2.999 & 2.999 & 2.914 \end{pmatrix} \quad \begin{pmatrix} 1.389 & 1.737 & 1.554 \\ 0.564 & 0.500 & 2.995 \\ 2.997 & 2.962 & 0.500 \end{pmatrix} \quad \begin{pmatrix} 0.608 & 0.708 & 2.567 \\ 0.658 & 0.675 & 2.658 \\ 1.354 & 0.577 & 0.500 \end{pmatrix}$$

up-quark sector, down-quark sector, lepton sector

Higgs VEV	$\langle H \rangle = 175$ GeV		
Quark	m_u (MeV)	m_c (GeV)	m_t (GeV)
Mass	2.17	1.27	173
Quark	m_d (MeV)	m_s (MeV)	m_b (GeV)
Mass	4.75	93.8	4.18
Lepton	m_e (MeV)	m_μ (MeV)	m_τ (GeV)
Mass	0.533	106	1.79

$$|V_{\rm CKM}| \simeq \begin{pmatrix} 0.970 & 0.242 & 0.00362 \\ 0.242 & 0.969 & 0.0449 \\ 0.00739 & 0.0445 & 0.999 \end{pmatrix}$$

Conclusions

- 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 + found examples of viable models with non-perturbative insertions.
- **Guidance to top-down model building!**

Outlook

- **Extension to the neutrino sector.** R-parity violating terms, the μ-term and Weinberg operator. Neutrino mass generation?
- Possible to use RL?
- **Consistent heterotic line bundle Standard Models?**
- **String perspective** - guidance on systematic computation with non-perturbative corrections?

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- **Extension to the neutrino sector.** R-parity violating terms, the μ-term and Weinberg operator. Neutrino mass generation?
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String model landscape (part of)?