UNIVERSITY OF LIVERPOOL

Uplifted Non-Supersymmetric Heterotic String and Asymmetric Orbifolds

Work in collaboration with Alonzo R. Diaz Avalos, Alon Faraggi and Viktor Matyas. Based on: arxiv:2306.16878 and 2202.04507

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Overview

- Plan for talk:
  - Motivation
  - The Non-SUSY heterotic string landscape
  - Symmetric Z_2 Z_2 model building
  - Fayet-Iliopoulos (FI) D-term from $U(1)_A$
  - Uplifted potential examples
  - Towards asymmetric uplifted models
  - Conclusions

Motivation: Non-SUSY Uplifting

? Swampland program- dS vacua from string theory?

? Idea: extra positive corrections to AdS, e.g. anti-D3 branes of KKLT [Kachru+ '03] or D-term uplifts [Burgess+ '03]

? No signal of SUSY motivates $\mathbf{N} = 0$ model building- opens "Pandora's box" [Rizos, Corfu 2017]:

? Instabilities: tachyons, dilaton backreaction, computational control...

? Gauge coupling unification, CC problem, hierarchy problem...

Motivation: Asymmetric Orbifolds

- Non-geometric spaces (asymmetric orbifolds)- stringy geometry

  [Narain+ ’87,Antoniadis+ ’87,Kawai+ ’86,Plauschinn ’19,Groot Nibbelink+ ’17,Dabholkar+ ’09,Graña+ ’08]

- Fix Geometric Moduli + Pheno. features [Faraggi ’05,’94,’93,’92]:
  - Early realistic free fermionic models asymmetric [Faraggi+’90,’92]
  - Doublet-Triplet Splitting
  - Untwisted Top quark mass coupling
  - Hierarchical Top-bottom quark mass splitting
  - Type II Models with vanishing one-loop CC [Kumar+ ’99; Angelantonj+ ’04; Harvey+ ’99; Shiu,Tye ’99; Sugawara+ ’21;]

Non-SUSY Heterotic Landscape I

? Known since 80s [Dixon,Harvey '86; Kawai+ '86]

1. 2 SUSY even self-dual lattices: E_8 E_8 and $SO(32)$
2. 1 Non-SUSY tachyon-free: $SO(16)$ $SO(16)$.
3. 6 Non-SUSY tachyonic: $SO(32)$, $O(16)$ E_8, $SO(8)$ $SO(24)$, $(E_7$ $SU(2))^2$, $U(16)$, E_8 (level-2)

? Modern formulation verifies [Smith, Lin, Tachikawa, Zheng '23]

? String web much larger than standard SUSY duality web

? Tachyons \$ expanding theory around wrong vacuum!

Non-SUSY Heterotic Landscape II

? Non-SUSY in $D < 10$ can interpolate to SUSY [Itoyama, Taylor '87; ... Faraggi, Tsulaia '10; Abel, Dienes, Mavroudi '16; Koga '22; Nakajima '23]

? Tachyons can be projected in lower dimensional non-SUSY models [Kawai, Tye, Lewellen, Lerche, Lüst, A.N.S, Kachru, Silverstein, Kumar, Shiu, Faraggi, Dienes, Blumenhagen, Angelantonj, Sagnotti, Blumenhagen, Font, ...]

? Tachyon condensation [Kaidi '20; Hellerman, Swanson '06]

? Non-SUSY heterotic branes in SUSY theories also provide relations between non-SUSY heterotic vacua

1. NS5 branes CY/K3 $SO(16) \quad SO(16)$ compactifications [Blaszczyk+ '15]
2. New heterotic branes [Kaidi+ '23; Tachikawa talk Peking University '23]

Free Fermion Construction I

- Worldsheet CFT construction of heterotic string defined at enhanced symmetry point in moduli space [Antoniadis + '87; Kawai+ '86]
- $D = 10 \implies$ Free fermions on worldsheet

$$\{\underbrace{\psi^{\mu=1,2}, \chi^{i=1,\dots,6}}_{\substack{\text{S'partners of } X^{\mu} \\ (\chi\text{'s compact in 4D})}} \,\Big|\, \underbrace{\overline{\psi}^{1,2,3,4,5}, \overline{\eta}^{1,2,3}}_{\substack{\text{rank 8} \\ \text{Observable G. G.}}}, \underbrace{\overline{\phi}^{1,2,3,4,5,6,7,8}}_{\substack{\text{rank 8} \\ \text{Hidden G. G.}}}\} \tag{1}$$

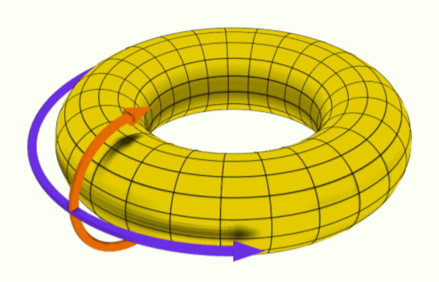
- Reduction to $D = 4 \implies$

$$\{y^i, w^i \,||\, \overline{y}^i, \overline{w}^i\}, \quad i = 1, \dots, 6 \tag{2}$$

  $\Rightarrow$ T^6 fermionised coordinates: $i\partial X^i_L = y^i w^i$.

- Freedom to bosonise on antiholomorphic side gives many bosonic interpretations [Faraggi, Groot Nibbelink, Percival '23]

Free Fermion Construction II



- PF: $Z_f = \sum_{\alpha,\beta} C\binom{\alpha}{\beta} Z\binom{\alpha}{\beta}$
- Model defined by:
  - Basis vectors $\mathbf{B} \ni v_i = \{\alpha(f_1), \alpha(f_2), \ldots, \alpha(f_n)\}$
  - GGSO phases: $C\binom{v_i}{v_j}$.

Symmetric Z_2 Z_2 Orbifolds

? Some of most phenomenologically viable string models

? Z_2 Z_2 orbifolds underlie ‘realistic’ models in free fermionic

[Faraggi+ ’93]

? Z_2 Z_2 twist vectors achieve:

  ? $\mathbf{N} = 4$! 1

  ? 3 Fixed planes **$** 3 generations

  ? Break to $SO(10)$ GUT

? Typical realisation associated to $(h_{11}, h_{21}) = (27, 3)$ Calabi-Yaus

[Berglund+ ’98]

The NAHE Set

[Faraggi, Nanopoulos '92]

? To ensure there's an R and NS sector for M.I.

$$\mathbb{1} = \{\text{all Ramond}\} \tag{3}$$

? SUSY generator ($\mathcal{N} = 4$)

$$S = \{\psi^{\mu}, \chi^{1,\ldots,6}\} \tag{4}$$

? $\mathbb{Z}_2 \quad \mathbb{Z}_2$ twists s.t. $\mathcal{N} = 4 \; ! \; 1$

$$\begin{aligned} b_1 &= \{\psi^{\mu}, \chi^{12}, y^{34}, y^{56} \;\mathbf{j}\; \bar{y}^{34}, \bar{y}^{56}, \bar{\psi}^{1,\ldots,5}, \bar{\eta}^{1}\}, \\ b_2 &= \{\psi^{\mu}, \chi^{34}, y^{12}, w^{56} \;\mathbf{j}\; \bar{y}^{12}, \bar{w}^{56}, \bar{\psi}^{1,\ldots,5}, \bar{\eta}^{2}\}, \\ b_3 &= \{\psi^{\mu}, \chi^{56}, w^{12}, w^{34} \;\mathbf{j}\; \bar{w}^{12}, \bar{w}^{34}, \bar{\psi}^{1,\ldots,5}, \bar{\eta}^{3}\}. \end{aligned} \tag{5}$$

? Untwisted G.G. $SO(10) \quad SO(6)^3 \quad SO(16)$

NAHE Moduli

? Symmetric $Z_2 \times Z_2$ NAHE Set moduli space

$$\left(\frac{SO(2,2)}{SO(2)\times SO(2)}\right)^3 \tag{6}$$

$$(T^1, U^1),\ (T^2, U^2),\ (T^3, U^3)$$

? Marginal operators generating Abelian Thirring Interactions [Chang, Kumar '88]

$$J_L^i(z)\bar{J}_R^j(\bar{z}) =: y^i w^i :: \bar{y}^j \bar{w}^j := \begin{cases} (i,j = 1,2) \\ (i,j = 3,4) \\ (i,j = 5,6) \end{cases} \tag{7}$$

Symmetric Z_2 Z_2 Classification

- $\mathbf{N} = 1$ Symmetric classification [Faraggi,Rizos,Kounnas,...,Percival '02-present] essentially adds vectors to NAHE that:

  1. Break hidden group $\$ \;\; \overline{\phi}^{1,\ldots,8}$
  2. Break $SO(10)$ to intermediate GUT $\$ \;\; \overline{\psi}^{1,\ldots,5}$
  3. Allow symmetric shifts of internal directions:
     $e_{i=1,\ldots,6} = \{y^i, w^i \,\mathbf{jj}\, \overline{y}^i, \overline{w}^i\}$

- Concrete statements about phenomenology of classes of string vacua

- Recently extended $\mathbf{N} = 0$ derived from $SO(16)$ $SO(16)$ or tachyonic 10D starting point

Symmetric $\mathbf{N} = 0$ Z_2 Z_2 Classification Highlights

$SO(16)$ $SO(16)$-Derived: [Dixon, Harvey; Seiberg, Witten; Alvarez-Gaumé +]

- Gravitino projected by GGSO phase [Ashfaque+ '15, Abel+ '16; Faraggi+ '20]
- Scherk-Schwarz can be implemented

Tachyonic-Derived: [Faraggi, Matyas, Percival]

- Tachyon-free in 4D and always explicit SUSY breaking
- No intermediate GUT Higgs except $SU(3)$ $SU(2)$ $U(1)^2$

General Features

- SAT/SMT Solvers aid in classification [Faraggi,Percival+ '21]
- CC Distributions, misaligned SUSY [Dienes; Angelantonj+; Cribiori+;...] and 'super no-scale' models [Itoyama+ '87; Antoniadis '91; Kounnas,Partouche;...]

D-term Uplifting in $SO(10)$ Symmetric Models

? NAHE-derived basis of 12 vectors give symmetric $Z_2 \times Z_2$ orbifolds [Faraggi,Kounnas,Nooij,Rizos, '04;...;Diaz Avalos,Faraggi,Matyas,Percival '23]

? Gauge group

$$SO(10) \times \underbrace{U(1)_1 \times U(1)_2 \times U(1)_3}_{\text{Anomalous combination } U(1)_A} \times SO(8)^2 \tag{8}$$

? $U(1)_A$ generic in heterotic string model building

? ! Generates a FI D-term contributing to the vacuum energy!

[Dine, Seiberg, Witten '87; Atick, Sen '88]

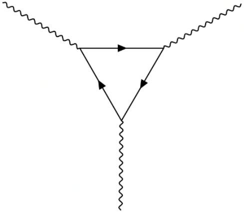
Green-Schwarz Mechanism

- Gauge anomaly under A_μ ! $A_\mu + \partial\Lambda$ such that

$$\delta \mathbf{L} = \xi \Lambda F^2 \tag{9}$$

with ξ $\mathrm{Tr}[U(1)_A]$ (Model-dependent part!)

- $\mathbf{N} = 1$ Green-Schwarz mechanism- compensate anomaly via variation of axion field a ! a $\xi\Lambda$.



D-term Uplift

[Burgess, Kallosh, Quevedo '03]

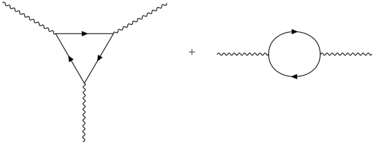
? FI D-term induces dilaton tadpole at 2-loop. Get positive potential contribution

$$V_D = \frac{1}{2} g_s^2 \xi^2. \tag{10}$$

Will remain when **N** = 1 ! 0

? Dilaton of course not fixed! Requires non-perturbative mechanism. We fix to **O (**1**)** to get numerical results...

? Add to one-loop potential



SUSY-Breaking

- Gravitino projected by GGSO phase(s)- can be spontaneous or explicit breaking
- Can realise Scherk-Schwarz in first torus via $(-1)^F \delta_1$
- Super No-Scale models: exponentially suppressed CC [Itoyama, Taylor '87; Antoniadis '91; Kounnas,Partouche...] (necessary but not sufficient [Florakis, Rizos '22])

$$\Lambda \sim (N_b^0 - N_f^0)\frac{1}{\mathrm{Im}(T^1)^2} + \mathcal{O}(e^{-c\sqrt{\mathrm{Im}(T^1)}}), \qquad (11)$$

- There's a CC problem either way so we do both breaking types

Partition function $SO(10)$ symmetric models

- PF takes schematic form

$$Z_f = \sum_{\text{spin structs.}} (-1)^{\Phi(\dots)} \left[\prod_{f = \psi^\mu, \chi^{12}, \chi^{34}, \chi^{56}} \theta_f \right] \left[\prod_{\bar{f} = \bar{\psi}^{1,\dots,5}, \bar{\eta}^{123}, \bar{\phi}^{1,\dots,8}} \bar{\theta}_{\bar{f}} \right] \underbrace{\Gamma_{2,2}^{3}}_{Z_{y^i, w^i, \bar{y}^i, \bar{w}^i}} \qquad (12)$$

- For generic point in moduli space via lattice resummation
$\Gamma^i_{2,2} \to \Gamma_{2,2}(T^{(i)}, U^{(i)})$

Explicit form of partition function

- Here's the non-schematic form of the PF for completeness...

$$
\begin{aligned}
Z = \frac{1}{\eta^{10}\bar{\eta}^{22}} \frac{1}{2^2} \square_{\substack{a,k\\ b,l}} \frac{1}{2^6} \square_{\substack{H_i\\ G_i}} \frac{1}{2^4} \square_{\substack{h_1,h_2,P_i\\ g_1,g_2,Q_i}} (\square 1)^{a+b+P_1Q_1+P_2Q_2+\square\left\square\begin{smallmatrix} a & k & H_i & h_1 & h_2 & P_i \\ b & l & G_i & g_1 & g_2 & Q_i \end{smallmatrix}\right\square} \\
\vartheta\left[\begin{smallmatrix} a \\ b \end{smallmatrix}\right]_{\psi^\mu} \vartheta\left\square\begin{smallmatrix} a+h_1 \\ b+g_1 \end{smallmatrix}\right\square_{\chi^{12}} \vartheta\left\square\begin{smallmatrix} a+h_2 \\ b+g_2 \end{smallmatrix}\right\square_{\chi^{34}} \vartheta\left\square\begin{smallmatrix} a & h_1 & h_2 \\ b & g_1 & g_2 \end{smallmatrix}\right\square_{\chi^{56}} \\
\square^{(1)}_{2,2}\left\square\begin{smallmatrix} H_1 & H_2 \\ G_1 & G_2 \end{smallmatrix}\right\square\begin{smallmatrix} h_1 \\ g_1 \end{smallmatrix}\right\square \left(T^{(1)}, U^{(1)}\right) \\
\square^{(2)}_{2,2}\left\square\begin{smallmatrix} H_3 & H_4 \\ G_3 & G_4 \end{smallmatrix}\right\square\begin{smallmatrix} h_2 \\ g_2 \end{smallmatrix}\right\square \left(T^{(2)}, U^{(2)}\right) \\
\square^{(3)}_{2,2}\left\square\begin{smallmatrix} H_5 & H_6 \\ G_5 & G_6 \end{smallmatrix}\right\square\begin{smallmatrix} h_1+h_2 \\ g_1+g_2 \end{smallmatrix}\right\square \left(T^{(3)}, U^{(3)}\right) \\
\bar{\vartheta}\left\square\begin{smallmatrix} k \\ l \end{smallmatrix}\right\square^5_{\bar{\psi}^1\ 5} \bar{\vartheta}\left\square\begin{smallmatrix} k+h_1 \\ l+g_1 \end{smallmatrix}\right\square_{\bar{\eta}^1} \bar{\vartheta}\left\square\begin{smallmatrix} k+h_2 \\ l+g_2 \end{smallmatrix}\right\square_{\bar{\eta}^2} \bar{\vartheta}\left\square\begin{smallmatrix} k & h_1 & h_2 \\ l & g_1 & g_2 \end{smallmatrix}\right\square_{\bar{\eta}^3} \bar{\vartheta}\left\square\begin{smallmatrix} k+P_1 \\ l+Q_1 \end{smallmatrix}\right\square^4_{\bar{\phi}^1\ 4} \bar{\vartheta}\left\square\begin{smallmatrix} k+P_2 \\ l+Q_2 \end{smallmatrix}\right\square^4_{\bar{\phi}^5\ 8} .
\end{aligned}
\tag{13}
$$

One-loop potential: $SO(10)$ symmetric models

- One-loop potential

$$V_{1\ loop}(T^i, U^i) \qquad \int \frac{d^2\tau}{\tau_2^3} Z(\tau, \bar{\tau}, T^i, U^i) \tag{14}$$

$\Rightarrow$ 6 complex moduli

- We fix all at FF point in moduli except $\mathrm{Im}(T^1)$ that we vary and plot potential via modular integral numerics

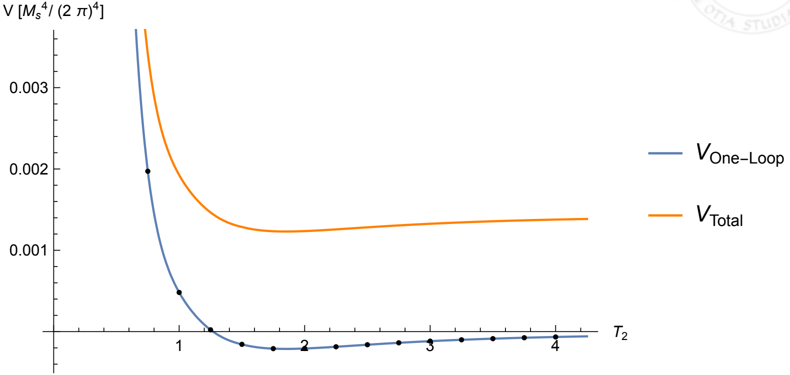
Scherk-Schwarz uplifted model

The GGSO phase configuration

$$C\begin{bmatrix} v_i \\ v_j \end{bmatrix} = \begin{array}{c|cccccccccccc} & \mathbf{1} & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & b_1 & b_2 & z_1 & z_2 \\ \hline \mathbf{1} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ S & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ e_1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ e_2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ e_3 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ e_4 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ e_5 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ e_6 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ b_1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ b_2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ z_1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ z_2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{array} \tag{15}$$

(Intricate) Scherk-Schwarz relation holds and calculating Tr $U(1)_A$ we find D-term enough to uplift potential!

Scherk-Schwarz uplifted model



Explicitly broken uplifted model

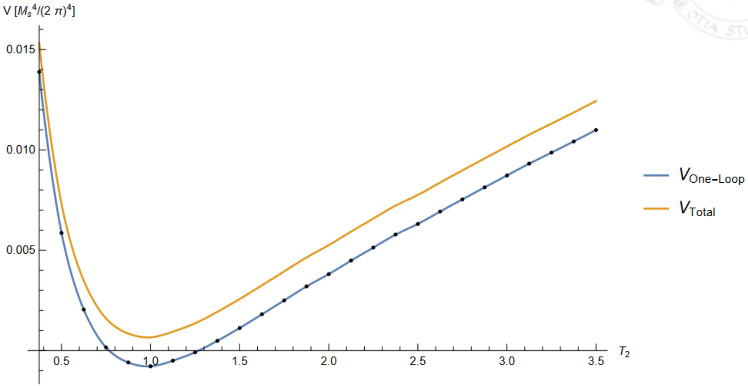
- GGSO phase configuration for example explicitly broken model

$$C\binom{v_i}{v_j} =$$

	$\mathbf{1}$	S	e_1	e_2	e_3	e_4	e_5	e_6	b_1	b_2	z_1	z_2
$\mathbf{1}$	1	1	1	1	1	1	1	1	1	1	1	1
S	1	1	1	1	1	1	1	1	1	1	1	1
e_1	1	1	1	1	1	1	1	1	1	1	1	1
e_2	1	1	1	1	1	1	1	1	1	1	1	1
e_3	1	1	1	1	1	1	1	1	1	1	1	1
e_4	1	1	1	1	1	1	1	1	1	1	1	1
e_5	1	1	1	1	1	1	1	1	1	1	1	1
e_6	1	1	1	1	1	1	1	1	1	1	1	1
b_1	1	1	1	1	1	1	1	1	1	1	1	1
b_2	1	1	1	1	1	1	1	1	1	1	1	1
z_1	1	1	1	1	1	1	1	1	1	1	1	1
z_2	1	1	1	1	1	1	1	1	1	1	1	1

(16)

Explicitly broken uplifted model



Some more example SSS potentials

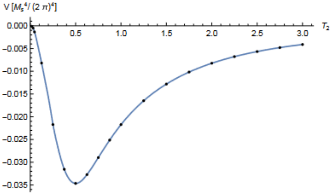


Figure 3: *One-loop Scherk-Schwarz Potential with local minimum and unbroken T-duality*

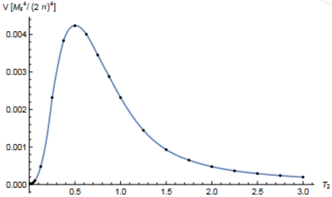


Figure 4: *One-loop Scherk-Schwarz Potential with local maximum and unbroken T-duality*

Some more example SSS potentials

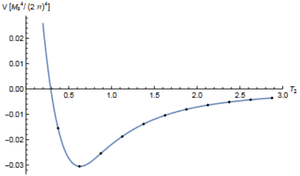


Figure 5: *One-loop Scherk-Schwarz Potential with local minimum and broken T-duality*

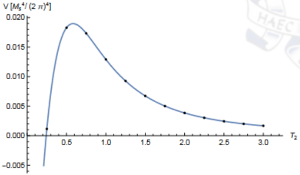


Figure 6: *One-loop Scherk-Schwarz Potential with local maximum and broken T-duality*

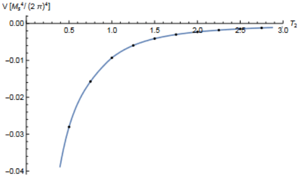


Figure 7: *One-loop Scherk-Schwarz Potential without any extreme point and broken T-duality*

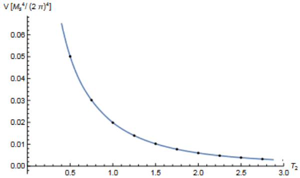


Figure 8: *One-loop Scherk-Schwarz Potential without any extreme point and broken T-duality*

Some more explicitly broken potentials

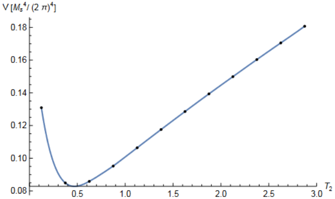


Figure 10: *One-loop Potential with explicitly broken SUSY and local minimum*

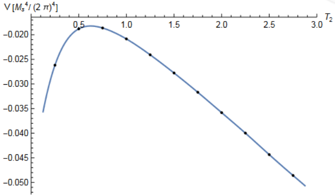


Figure 11: *One-loop Potential with explicitly broken SUSY and local maximum*

Some more explicitly broken potentials

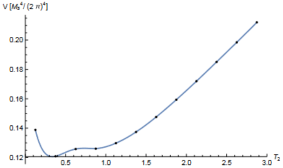


Figure 12: *One-loop Potential with explicitly broken SUSY and local minima and maximum*

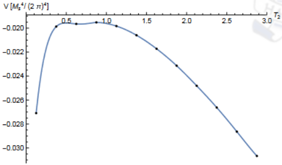


Figure 13: *One-loop Potential with explicitly broken SUSY and local minimum and maxima*

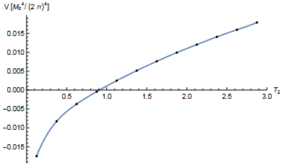


Figure 14: *One-loop Potential with explicitly broken SUSY without any extreme point*

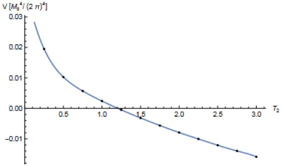


Figure 15: *One-loop Potential with explicitly broken SUSY without any extreme point*

Towards Asymmetric Classification

- ? Vectors with asymmetric BCs of $\{y^i, w^i \,\mathbf{jj}\, \bar{y}^i, \bar{w}^i\}$ can project Thirring interactions (7), *i.e.* freeze moduli! [Faraggi '05]
- ? Symmetric shifts $e_{i=1,\ldots,6}$ incompatible [Faraggi,Matyas,Percival '22]
- ? Can fix all geometric moduli (just dilaton left)

  [...,Faraggi,Matyas,Percival '20, Groot Nibbelink,Vaudrevange '17]
- ? Moduli fixing impacts other aspects of phenomenology

Asymmetric Classification: Flipped $SU(5)$ Models

[Faraggi,Matyas,Percival '22]

Untwisted Moduli in each Torus	Odd Number Generations Possible	Frequency
(2, 2, 0)	No	992
(2, 0, 2)	No	992
(0, 2, 2)	No	992
(4, 2, 2)	No	824
(2, 4, 2)	No	824
(2, 2, 4)	No	824
(0, 0, 0)	No	256
(4, 0, 0)	No	244
(0, 4, 0)	No	244
(0, 0, 4)	No	244
(4, 4, 0)	No	200
(4, 2, 2)	Yes	200
(4, 0, 4)	No	200
(2, 4, 2)	Yes	200
(2, 2, 4)	Yes	200
(0, 4, 4)	No	200
(4, 4, 4)	No	146
(4, 4, 4)	Yes	94
(4, 4, 0)	Yes	56
(4, 0, 4)	Yes	56
(0, 4, 4)	Yes	56
(2, 2, 0)	Yes	32
(2, 0, 2)	Yes	32
(0, 2, 2)	Yes	32
(4, 0, 0)	Yes	12
(0, 4, 0)	Yes	12
(0, 0, 4)	Yes	12

Example Contradiction of 3 Generation Models

Retaining only (T^1, U^1) contradicts 3 $SU(5)$ $U(1)$ generations

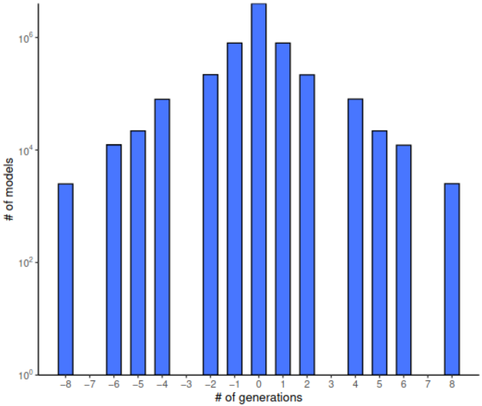


Figure: Distribution of generation number for sample of 10^7 Case 3 vacua

Example Asymmetric $SU(5) \quad U(1)$ Results

	Total models in sample: 10^9				
	SUSY or Non-SUSY:	$\mathcal{N}=1$	Probability	$\mathcal{N}=0$	Probability
	Total	15624051	1.56×10^{-2}	984375949	0.984
(1)	+ Tachyon-Free			30779240	3.08×10^{-2}
(2)	+ No Observable Enhancements	15135704	1.51×10^{-2}	28581301	2.86×10^{-2}
(3)	+ Complete Generations	15135704	1.51×10^{-2}	28581301	2.86×10^{-2}
(4)	+ Three Generations	89930	8.99×10^{-5}	195716	1.96×10^{-4}
(5)	+ Heavy Higgs	89820	8.98×10^{-5}	129233	1.29×10^{-4}
(7)	+ TQMC	89820	8.98×10^{-5}	129233	1.29×10^{-4}
(8)	+ $a_{00} = N_b^0 - N_f^0 = 0$			388	3.88×10^{-7}

Figure: Results from scan of 10^9 GGSO configurations for phenomenological characteristics allowing for both $\mathbf{N} = 1$ and $\mathbf{N} = 0$ vacua

Results Case 2: CC Distribution

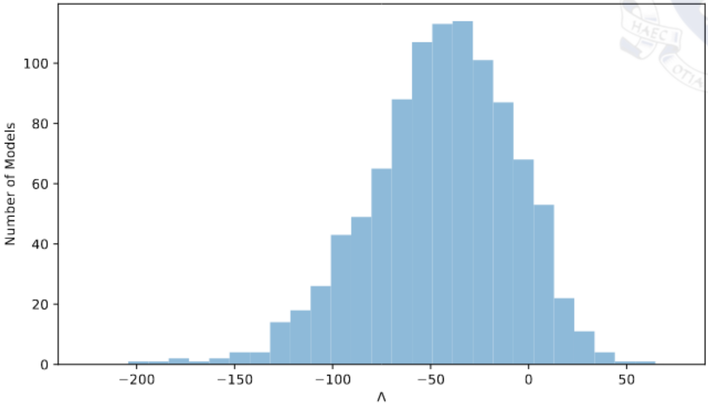


Figure: Distribution of one-loop CC (at FF point) for sample of 10^3 satisfying constraints (1)-(7)

Towards asymmetric $SO(10)$ uplifts

? Taking the NAHE set and adding:

$$b_4 = \{\psi^\mu, \chi^{12}, y^{34}, y^{56} \;\mathbf{j}\; \bar{\eta}^{23}, \bar{\phi}^{12}\} \tag{17}$$

leaves $SO(10)$ and moduli space

$$\square \; \frac{SO(2,2)}{SO(2) \quad SO(2)} \; \square \tag{18}$$

? *i.e.* fixes internal moduli except 1st torus (T^1, U^1)

? Now repeat classification of potentials analysis without worrying about other internal moduli... work in progress!

Conclusions

? Analysis of one-loop potential and FI D-term find example uplifted models!

? Asymmetric orbifold classification method outlined- moduli fixing!

? Extension to asymmetric case of free moduli only in 1 torus currently under exploration

? Many open issues. Need to be brave/reckless to do Non-SUSY strings!

[The Irregularites of Discernment - Manalo]