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Standard Model embeddings in orientifold string vacua

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Bibliography and credits

• Work done in collaboration with:

P. Anastasopoulos, T. Dijkstra and B. Schellekens **hep-th/0605226**

Related earlier work by:

• Antoniadis, Kiritsis, Rizos, Tomaras **hep-th/0210263** , **hep-ph/0004214**

• Dijkstra, Huiszoon, Schellekens **hep-th/0403196**, **hep-th/0411129**

Plan of the talk

- Introduction
- The name of the game: using Gepner models as building blocks
- Survey of the constructions
- Some dinstinguished vacua
- Outlook

Introduction/Motivations

Main goal: Find one or more string theory vacua that are compatible with the (supersymmetric) standard model.

- It is (by now) clear that string theory has a large number of stable vacua.

- It is also plausible that there are a large number of them that fit the Standard Model physics at low energy (although none is known to do it accurately)

♣Most people believe that these are the vacua of a unique theory.

♣It might be that they are distinct theories (like gauge theories are)

What is the right strategy?

• Explore unknown regions of the landscape of vacua

• Establish the likelihood of SM features (family number, gauge group, etc)

• Understand vacuum statistics

• Understand cosmological features.

• Understand the selectivity of anthropic arguments.

♠If string theory provides different models: is anything allowed?

What we will start to do here:

♠Explore the possibilities of embedding the SM in string theory

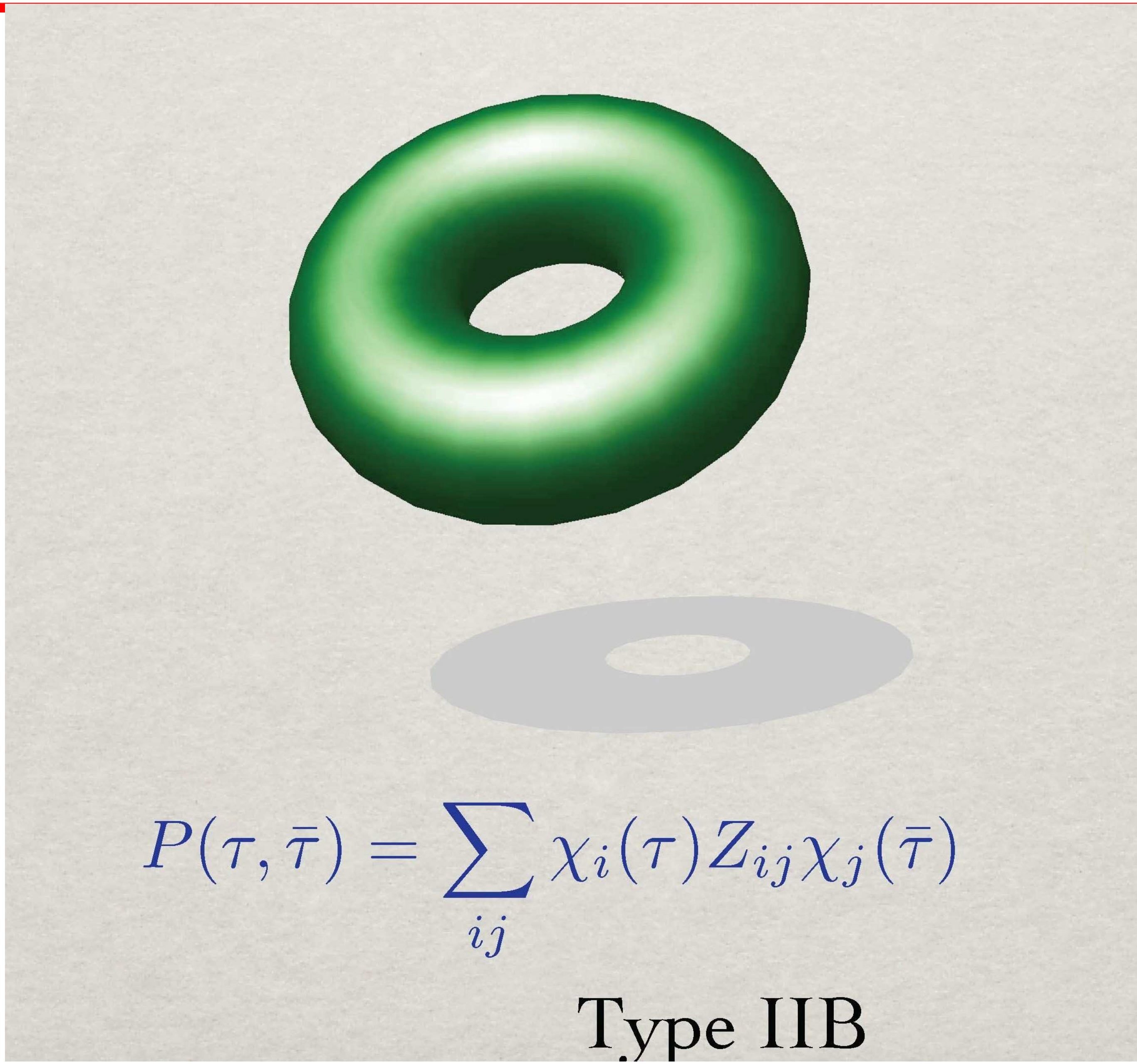
♠Decide eventually on promising vacua

• Embedding the SM in a theory that contains gravity is already a HIGHLY constrained business

♣We will profit from the fact that in a certain class of vacua, the algorithm of construction and the stringy constraints are explicit enough to be put in a computer.

♣We will use this to scan a large class of ground states for features that are reasonable close to the SM. In particular, we will be interested in how many distinct way the SM group can be embedded in the Chan-Paton (orientifold group).

The starting point: closed type II strings



Gepner models

Building Blocks:
Minimal N=2 CFT

$$c = \frac{3k}{k+2}, \quad k = 1, \ldots, \infty$$

168 ways of solving $\sum_i c_{k_i} = 9$

Spectrum:

$$h_{l,m} = \frac{l(l+2) - m^2}{4(k+2)} + \frac{s^2}{8}$$

$(l = 0, \ldots k; \quad q = -k, \ldots k+2; \quad s = -1, 0, 1, 2)$

(plus field identification)

$4(k+2)$ simple currents

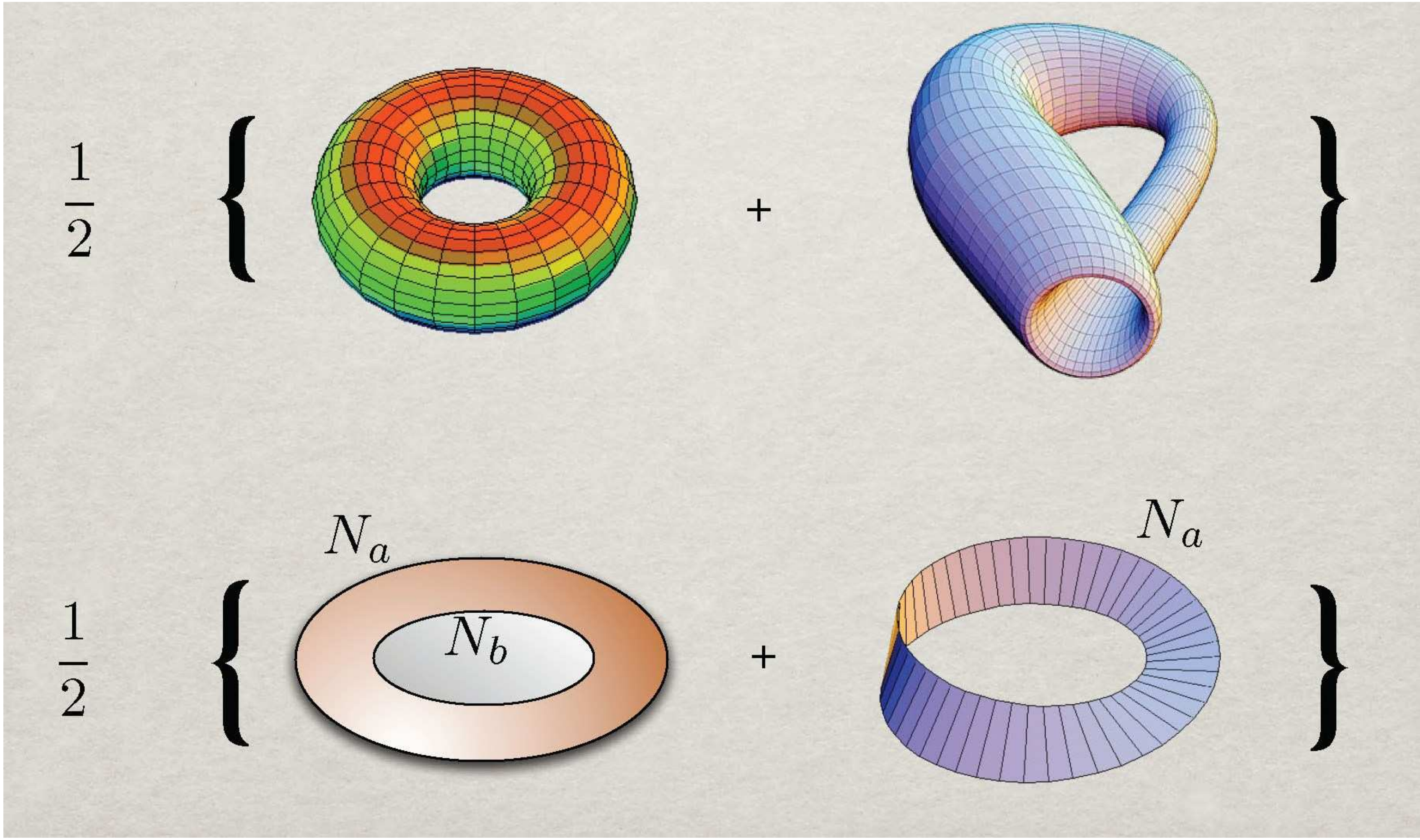
♠The tensoring must preserve world-sheet super-symmetry

♠The tensoring must preserve $\mathcal{N} = 1$ space-time supersymmetry

♠Use the discrete symmetries due to simple currents, to orbifold and construct all possible Modular Invariant Partition Functions (MIPFs)

♣The result is a stringy description of the type-II string on a CY manifold.

The (unoriented) open sector



Unoriented partition functions

Closed :
$$\frac{1}{2}\left[\sum_{ij} \chi_i(\tau)\ Z_{ij}\ \bar{\chi}_j(\bar{\tau}) + \sum_i\ K_i\ \chi_i(2\tau)\right]$$

Open :
$$\frac{1}{2}\left[\sum_{i,a,b}\ N^a\ N^b\ {A^i}_{ab}\ \chi_i\left(\frac{\tau}{2}\right) + \sum_{i,a}\ N^a\ {M^i}_a\ \chi_i\left(\frac{\tau+1}{2}\right)\right]$$

$N^a \quad \rightarrow \quad$ Chan-Paton multiplicity

More details

Scope of the search

There are:

- 168 Gepner model combinations

- 5403 MIPFS

- 49322 different orientifold projections.

- 45761187347637742772 ($\sim 5 \times 10^{19}$)combinations of four boundary labels (four-brane stacks).

♠It is therefore essential to decide what to look for

The (almost) unbiased search

Look for general SM embeddings satisfying:

• U(3) comes from a single brane

• SU(2) comes from a single brane

• Quarks, leptons and Y come from at most four-brane stacks. (Otherwise the sample to be searched is beyond our capabilities)

• $G_{CP} \subset SU(3) \times SU(2) \times U(1)_Y$

• Chiral G_{CP} particles reduces to chiral SM particles (3 families) plus non-chiral particles under SM gauge group but:

• There are no fractionally-charged mirror pairs.

• Y is massless.

Allowed features

- CP gauge group: $U(3)_a \times \left\{ \begin{matrix} U(2) \\ Sp(2) \end{matrix} \right\}_b \times G_c \times G_d$

- Antiquarks from antisymmetric tensors (of SU(3))

- Leptons from antisymmetric tensors of SU(2)

- Family symmetries (non-standard)

- Non-standard Y-charge embeddings.

- Unification (SU(5), Pati-Salam, trinification, etc) by allowing a,b,c,d labels to coincide

- Baryon and/or lepton number violation.

The hypercharge embedding

It has been realized early-on that the hypercharge embedding in orientifold models has several distinct posssibilities that affect crucially the physics.

Antoniadis+Kiritsis+Tomaras

$$U(3)_a \times \left\{ \begin{matrix} U(2) \\ Sp(2) \end{matrix} \right\}_b \times G_c \times G_d$$

$$Y = \alpha Q_a + \beta Q_b + \gamma Q_c + \delta Q_d + W_c + W_d$$

$Q_i \rightarrow$ brane charges (unitary branes)

$W_i \rightarrow$ traceless (non-abelian) generators.

Classification of hypercharge embeddings

$$Y = \left(x - \frac{1}{3}\right) Q_a + \left(x - \frac{1}{2}\right) Q_b + x Q_C + (x-1)\, Q_D$$

C,D are distributed on the c,d brane-stacks.

The following is exhaustive: (Allowed values for x)

- $x = \frac{1}{2}$: Madrid model, Pati-Salam, flipped-SU(5)+broken versions, model C of AD.
- $x = 0$: SU(5)+broken versions, AKT low-scale brane configurations, A,A'
- $x = 1$: AKT low-scale brane configurations, B,B'
- $x = -\frac{1}{2}$: None found
- $x = \frac{3}{2}$: None found
- $x =$arbitrary: Trinification (x=1/3). Some fixed by masslessnes of Y

Realizations: our terminology

BOTTOM-UP configurations: choosing the gauge group, postulating particles as open strings, imposing generalized cubic anomaly cancelation, and ignoring particles beyond the SM, as in the example

Antoniadis+Kiritsis+Tomaras

TOP-DOWN configurations: Configurations constructed in the Gepner model setup, satisfying all criteria but for tadpole cancellation: this will fix the hidden sector.

STRING VACUA: TOP-DOWN configurations with tadpoles solved.

The basic orientable model

Gauge Group: $U(3) \times U(2) \times U(1) \times U(1)$

multiplicity	U(3)	U(2)	U(1)	U(1)	particle
3	V	V*	0	0	(u,d)
3	V*	0	V	0	d^c
3	V*	0	0	V	u^c
6	0	V	V*	0	$(e,\nu)+H_1$
3	0	V	0	V*	H_2
3	0	0	V	V*	e^c

× is arbitrary! This simple model was VERY RARE: found only 4 times, with no tadpole solution.

The results

♠ Searched all MIPFs with less than 1750 boundaries. There are 4557 of the 5403 in total.

♠ We found 19345 different SM embeddings (Top-down constructions)

♠ Tadpoles were solved in 1900 cases (as usual there is a 1 % chance of solving the tadpoles)

Hypercharge statistics

x value	number of configurations	no SU(3) tensors
0	21303612 (2×10^7)	202108
$\frac{1}{2}$	124006839 (10^8)	115350426
1	12912 (10^4)	12912
$-\frac{1}{2}$	0	0
$\frac{3}{2}$	0	0
any	1250080 (10^6)	1250080

Bottom-Up versus Top-Down

Bottom-up versus Top-down results for spectra with at most three mirror pairs, at most three MSSM Higgs pairs, and at most six singlet neutrinos (otherwise there are an infinite numnber of options)

x	Config.	stack **c**	stack **d**	Bottom-up	Top-down	Occurrences	Solved
1/2	UUUU	C,D	C,D	27	9	5194	1
1/2	UUUU	C	C,D	103441	434	1056708	31
1/2	UUUU	C	C	10717308	156	428799	24
1/2	UUUU	C	F	351	0	0	0
1/2	UUU	C,D	-	4	1	24	0
1/2	UUU	C	-	215	5	13310	2
1/2	UUUR	C,D	C,D	34	5	3888	1
1/2	UUUR	C	C,D	185520	221	2560681	31
1/2	USUU	C,D	C,D	72	7	6473	2
1/2	USUU	C	C,D	153436	283	3420508	33
1/2	USUU	C	C	10441784	125	4464095	27

Table 1

x	Config.	stack **c**	stack **d**	Bottom-up	Top-down	Occurrences	Solved
1/2	USUU	C	F	184	0	0	0
1/2	USU	C	-	104	2	222	0
1/2	USU	C,D	-	8	1	4881	1
1/2	USUR	C	C,D	54274	31	49859327	19
1/2	USUR	C,D	C,D	36	2	858330	2
0	UUUU	C,D	C,D	5	5	4530	2
0	UUUU	C	C,D	8355	44	54102	2
0	UUUU	D	C,D	14	2	4368	0
0	UUUU	C	C	2890537	127	666631	9
0	UUUU	C	D	36304	16	6687	0
0	UUU	C	-	222	2	15440	1
0	UUUR	C,D	C	3702	39	171485	4
0	UUUR	C	C	5161452	289	4467147	32
0	UUUR	D	C	8564	22	50748	0
0	UUR	C	-	58	2	233071	2
0	UURR	C	C	24091	17	8452983	17

Table 1

x	Config.	stack **c**	stack **d**	Bottom-up	Top-down	Occurrences	Solved
1	UUUU	C,D	C,D	4	1	1144	1
1	UUUU	C	C,D	16	5	10714	0
1	UUUU	D	C,D	42	3	3328	0
1	UUUU	C	D	870	0	0	0
1	UUUR	C,D	D	34	1	1024	0
1	UUUR	C	D	609	1	640	0
3/2	UUUU	C	D	9	0	0	0
3/2	UUUU	C,D	D	1	0	0	0
3/2	UUUU	C, D	C	10	0	0	0
3/2	UUUU	C,D	C,D	2	0	0	0
$*$	UUUU	C,D	C,D	2	2	5146	1
$*$	UUUU	C	C,D	10	7	521372	3
$*$	UUUU	D	C,D	1	1	116	0
$*$	UUUU	C	D	3	1	4	0

A survey of the 19345 chirally-distinct configurations

nr	Total occ.	MIPFs	Chan-Paton Group	spectrum	x	Solved
1	9801844	648	$U(3) \times Sp(2) \times Sp(6) \times U(1)$	VVVV	1/2	Y!
2	8479808(16227372)	675	$U(3) \times Sp(2) \times Sp(2) \times U(1)$	VVVV	1/2	Y!
3	5775296	821	$U(4) \times Sp(2) \times Sp(6)$	VVV	1/2	Y!
4	4810698	868	$U(4) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!
5	4751603	554	$U(3) \times Sp(2) \times O(6) \times U(1)$	VVVV	1/2	Y!
6	4584392	751	$U(4) \times Sp(2) \times O(6)$	VVV	1/2	Y
7	4509752(9474494)	513	$U(3) \times Sp(2) \times O(2) \times U(1)$	VVVV	1/2	Y!
8	3744864	690	$U(4) \times Sp(2) \times O(2)$	VVV	1/2	Y!
9	3606292	467	$U(3) \times Sp(2) \times Sp(6) \times U(3)$	VVVV	1/2	Y
10	3093933	623	$U(6) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
11	2717632	461	$U(3) \times Sp(2) \times Sp(2) \times U(3)$	VVVV	1/2	Y!
12	2384626	560	$U(6) \times Sp(2) \times O(6)$	VVV	1/2	Y
13	2253928	669	$U(6) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!
14	1803909	519	$U(6) \times Sp(2) \times O(2)$	VVV	1/2	Y!
15	1676493	517	$U(8) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
16	1674416	384	$U(3) \times Sp(2) \times O(6) \times U(3)$	VVVV	1/2	Y
17	1654086	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
18	1654086	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
19	1642669	360	$U(3) \times Sp(2) \times Sp(6) \times U(5)$	VVVV	1/2	Y
20	1486664	346	$U(3) \times Sp(2) \times O(2) \times U(3)$	VVVV	1/2	Y!
21	1323363	476	$U(8) \times Sp(2) \times O(6)$	VVV	1/2	Y
22	1135702	350	$U(3) \times Sp(2) \times Sp(2) \times U(5)$	VVVV	1/2	Y!
23	1050764	532	$U(8) \times Sp(2) \times Sp(2)$	VVV	1/2	Y
24	956980	421	$U(8) \times Sp(2) \times O(2)$	VVV	1/2	Y

Table 2 –

nr	Total occ.	MIPFs	Chan-Paton Group	Spectrum	x	Solved
25	950003	449	$U(10) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
26	910132	51	$U(3) \times U(2) \times Sp(2) \times O(1)$	AAVV	0	Y
...	...	...	...	...	...	
411	31000	17	$U(3) \times U(2) \times U(1) \times U(1)$	AAVA	0	Y
417	30396	26	$U(3) \times U(2) \times U(1) \times U(1)$	AAVS	0	Y
495	23544	14	$U(3) \times U(2) \times U(1) \times U(1)$	AAVS	0	
509	22156	17	$U(3) \times U(2) \times U(1) \times U(1)$	AAVS	0	Y
519	21468	13	$U(3) \times U(2) \times U(1) \times U(1)$	AAVA	0	Y
543	20176(*)	38	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	1/2	Y
617	16845	296	$U(5) \times O(1)$	AV	0	Y
671	14744(*)	29	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	1/2	
761	12067	26	$U(3) \times U(2) \times U(1)$	AAS	1/2	Y!
762	12067	26	$U(3) \times U(2) \times U(1)$	AAS	0	Y!
1024	7466	7	$U(3) \times U(2) \times U(2) \times U(1)$	VAAV	1	
1125	6432	87	$U(3) \times U(3) \times U(3)$	VVV	*	Y
1201	5764(*)	20	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	1/2	
1356	5856(*)	10	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	1/2	Y
1725	2864	14	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	1/2	Y
1886	2381	115	$U(6) \times Sp(2)$	AV	1/2	Y!
1887	2381	115	$U(6) \times Sp(2)$	AV	0	Y!
1888	2381	115	$U(6) \times Sp(2)$	AV	1/2	Y!
...	...	...	...	...	...	
17055	4	1	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	*	
19345	1	1	$U(5) \times U(2) \times O(3)$	ATV	0	

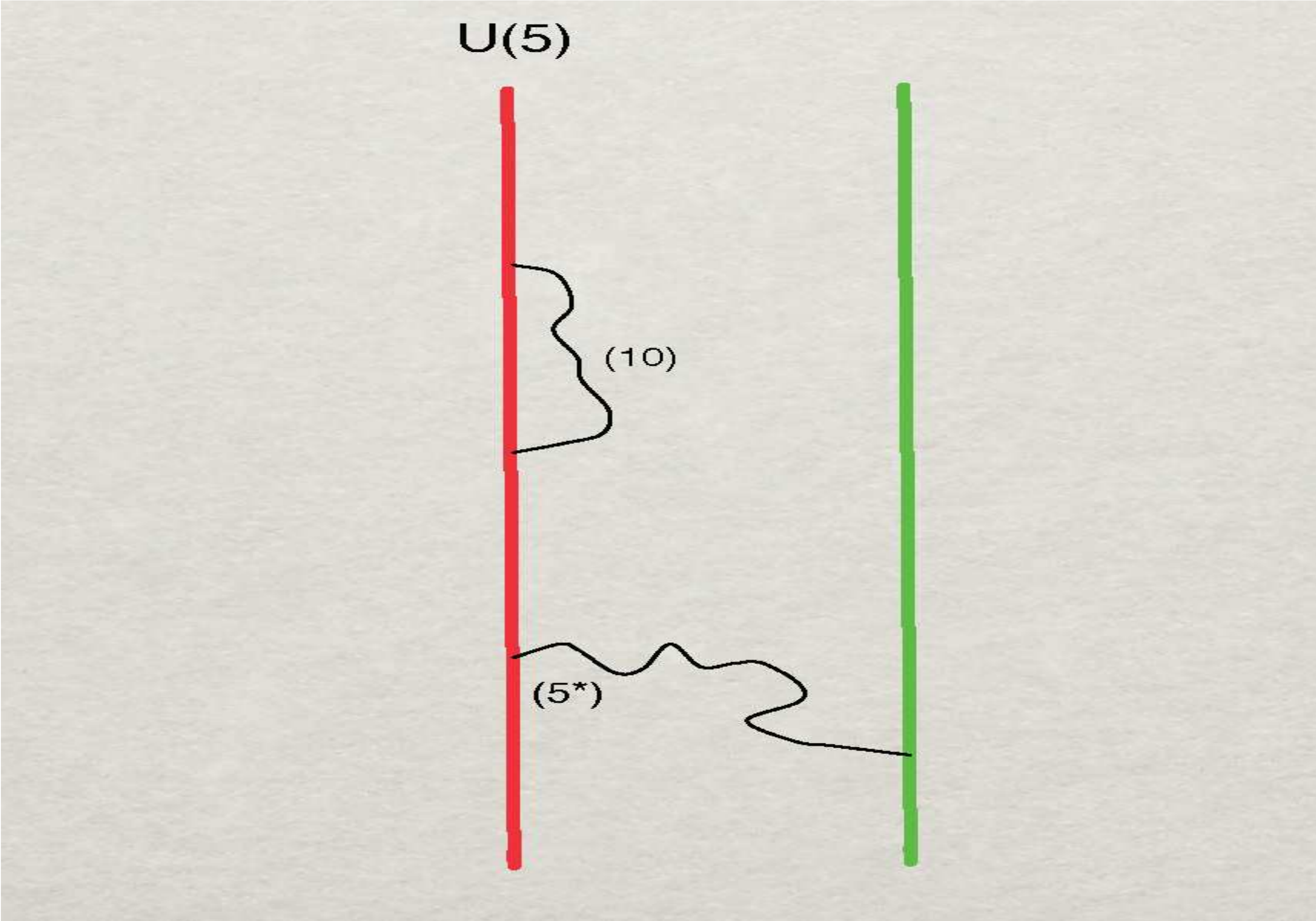
Pati-Salam: Version I

Type:	U	S	S	
Dimension	4	2	2	
5 x	(V	,0	,V)	chirality -3
3 x	(V	,V	,0)	chirality 3
2 x	(Ad	,0	,0)	chirality 0
2 x	(0	,A	,0)	chirality 0
7 x	(0	,0	,A)	chirality 0
4 x	(A	,0	,0)	chirality 0
2 x	(0	,S	,0)	chirality 0
5 x	(0	,0	,S)	chirality 0
7 x	(0	,V	,V)	chirality 0

Pati-Salam: Version II

Type:	U	U	U	U	U	S	U	O	U	O	
Dimension	4	2	2	6	2	2	2	2	2	2	
4 x	V	V	0	0	0	0	0	0	0	0	chirality 2
1 x	V	V*	0	0	0	0	0	0	0	0	chirality 1
1 x	V	0	V*	0	0	0	0	0	0	0	chirality -1
2 x	V	0	V	0	0	0	0	0	0	0	chirality -2
2 x	0	V	V*	0	0	0	0	0	0	0	chirality -2
2 x	V	0	0	0	V*	0	0	0	0	0	chirality 0
4 x	V	0	0	0	0	V	0	0	0	0	chirality 0
2 x	0	S	0	0	0	0	0	0	0	0	chirality 0
2 x	A	0	0	0	0	0	0	0	0	0	chirality 0
1 x	Ad	0	0	0	0	0	0	0	0	0	chirality 0
2 x	V	0	0	0	V	0	0	0	0	0	chirality 0
2 x	0	0	S	0	0	0	0	0	0	0	chirality 0
4 x	0	V	0	0	0	0	V*	0	0	0	chirality 0
2 x	0	V	0	0	0	0	V	0	0	0	chirality 0
2 x	0	0	V	0	0	0	V*	0	0	0	chirality 0
1 x	0	Ad	0	0	0	0	0	0	0	0	chirality 0
2 x	V	0	0	0	0	0	V*	0	0	0	chirality 0
2 x	V	0	0	0	0	0	V	0	0	0	chirality 0
1 x	0	0	Ad	0	0	0	0	0	0	0	chirality 0
2 x	0	V	0	0	0	0	0	0	V*	0	chirality 0
2 x	0	0	V	0	0	0	0	0	V	0	chirality 0

SU(5) spectrum from branes



SU(5)

Type:		U	O	O	
Dimension		5	1	1	
3	x	(A	,0	,0)	chirality 3
11	x	(V	,V	,0)	chirality -3
8	x	(S	,0	,0)	chirality 0
3	x	(Ad	,0	,0)	chirality 0
1	x	(0	,A	,0)	chirality 0
3	x	(0	,V	,V)	chirality 0
8	x	(V	,0	,V)	chirality 0
2	x	(0	,S	,0)	chirality 0
4	x	(0	,0	,S)	chirality 0
4	x	(0	,0	,A)	chirality 0

Note: the group is only SU(5)

- This is model No=617 .

- There is an O(1) “hidden sector”.

- There are 16845 configurations of this kind (same $SU(5) \times O(1)$ and chiral spectrum).

- The others differ by hidden sector, number of U(5) adjoints and mirrors.

Flipped SU(5)

```
Type:           U   U
Dimension       5   1
        11  x   (0 ,S ) chirality 3
         3  x   (A ,0 ) chirality 3
         5  x   (V ,V ) chirality -3
         8  x   (S ,0 ) chirality 0
         9  x   (Ad,0 ) chirality 0
         5  x   (0 ,Ad) chirality 0
         4  x   (0 ,A ) chirality 0
        12  x   (V ,V*) chirality 0
```

$$Y = \frac{1}{6}Q_a + \frac{1}{2}Q_c$$

- Non-trivial U(1) anomaly cancellation

- Model No=2880

- Model No 2881 is an SU(5) counterpart.

- All Higgses and others are already vectorlike, no extra symmetry breaking is needed.

BUT: All vacua with tensor antiquarks, have a VERY SERIOUS problem with quarkm masses being non-zero!

SU(5)×U(1)

```
Type:          U   U
Dimension      5   1

     11 x   (0 ,S ) chirality 3
      3 x   (A ,0 ) chirality 3
      5 x   (V ,V ) chirality -3
      8 x   (S ,0 ) chirality 0
      9 x   (Ad,0 ) chirality 0
      5 x   (0 ,Ad) chirality 0
      4 x   (0 ,A ) chirality 0
     12 x   (V ,V*) chirality 0
```

$$Y = -\frac{2}{3}Q_a + \frac{1}{2}Q_b$$

RETURN

Trinification

		U	U	U	O	O	U	U	O	U	O	
		3	3	3	4	2	6	12	12	12	4	
3	x	V	V	0	0	0	0	0	0	0	0	chirality 3
3	x	V	0	V	0	0	0	0	0	0	0	chirality -3
3	x	0	V	V*	0	0	0	0	0	0	0	chirality -3
1	x	0	0	0	V	0	V	0	0	0	0	chirality -1
1	x	0	0	0	0	0	S	0	0	0	0	chirality 1
5	x	0	0	0	0	0	0	0	V	V	0	chirality 1
3	x	0	0	0	0	0	0	0	0	S	0	chirality 1
1	x	0	0	0	0	0	A	0	0	0	0	chirality -1
2	x	0	0	0	0	0	0	0	0	A	0	chirality -2
1	x	0	0	0	V	0	0	0	0	V	0	chirality 1
1	x	0	0	0	0	V	0	0	0	V	0	chirality 1
1	x	0	0	0	0	0	V	0	V	0	0	chirality 1
1	x	0	0	0	0	0	V	0	0	V	0	chirality -1
1	x	0	0	0	0	0	0	V	V	0	0	chirality 1
1	x	0	0	0	0	0	0	V	0	V	0	chirality -1
1	x	0	0	0	0	0	V	0	0	0	V	chirality -1
1	x	0	0	0	V	V	0	0	0	0	0	chirality 0
1	x	0	0	0	0	S	0	0	0	0	0	chirality 0
1	x	0	0	0	0	0	Ad	0	0	0	0	chirality 0
1	x	0	0	0	0	0	0	Ad	0	0	0	chirality 0
3	x	0	0	0	0	0	0	0	S	0	0	chirality 0
3	x	0	0	0	0	0	0	0	0	Ad	0	chirality 0
1	x	0	0	0	0	0	0	0	0	0	S	chirality 0
2	x	0	0	0	0	V	V	0	0	0	0	chirality 0
1	x	0	0	0	0	V	0	0	V	0	0	chirality 0
2	x	0	0	0	0	0	V	0	0	V*	0	chirality 0
2	x	0	0	0	0	0	0	V	0	V*	0	chirality 0
1	x	0	0	0	0	V	0	0	0	0	V	chirality 0

Summary

♠We have investigated all possible embedding of the Standard Model in orientifold vacua build on Gepner-model related type-II groundstates

♠Many top-down configurations have been found, and associated tadpole solutions.

♠Most of the bottom up configurations do not occur (= they are extremely rare, or cannot occur)

♠Some popular configurations are VERY rare

♠It is timely to analyze in detail the phenomenology of the solutions found.

The BCFT data

Klein : $$K^i = \sum_{m,J,J'} \frac{S^i{}_m \; U_{(m,J)} \; g^{\Omega,m}_{J,J'} \; U_{(m,J')}}{S_{0m}}$$

Cylinder : $$A^i{}_{[a,\psi_a],[b,\psi_b]} = \sum_{m,J,J'} \frac{S^i{}_m \; R_{[a,\psi_a](m,J)} \; g^{\Omega,m}_{J,J'} \; R_{[b,\psi_b](m,J')}}{S_{0m}}$$

Moebius : $$M^i{}_{[a,\psi_a]} = \sum_{m,J,J'} \frac{P^i{}_m \; R_{[a,\psi_a](m,J)} \; g^{\Omega,m}_{J,J'} \; U_{(m,J')}}{S_{0m}}$$

with

$$g^{\Omega,m}_{J,J'} = \frac{S_{m0}}{S_{mK}} \; \beta_K(J) \; \delta_{J',J^c}$$

R,U are the boundary and crosscap coeeficients respectively.

• Tadpole cancellation conditions

$$\sum_b N^b \; R_{b,(m,J)} = 4\eta_m \; U_{m,J}$$

• Cubic anomalies cancel (including U(1) and U(2) anomalies)

• The rest is taken case by the Green-Schwarz-Sagnotti mechanism

• Rarely, absence of global anomalies must be imposed extra.

Gatto-Rivera+Schellekens

• Axion-U(1) gauge boson mixing can be calculated: it is crucial for giving U(1) bosons a mass. This is an important constraint for the hypercharge Y.

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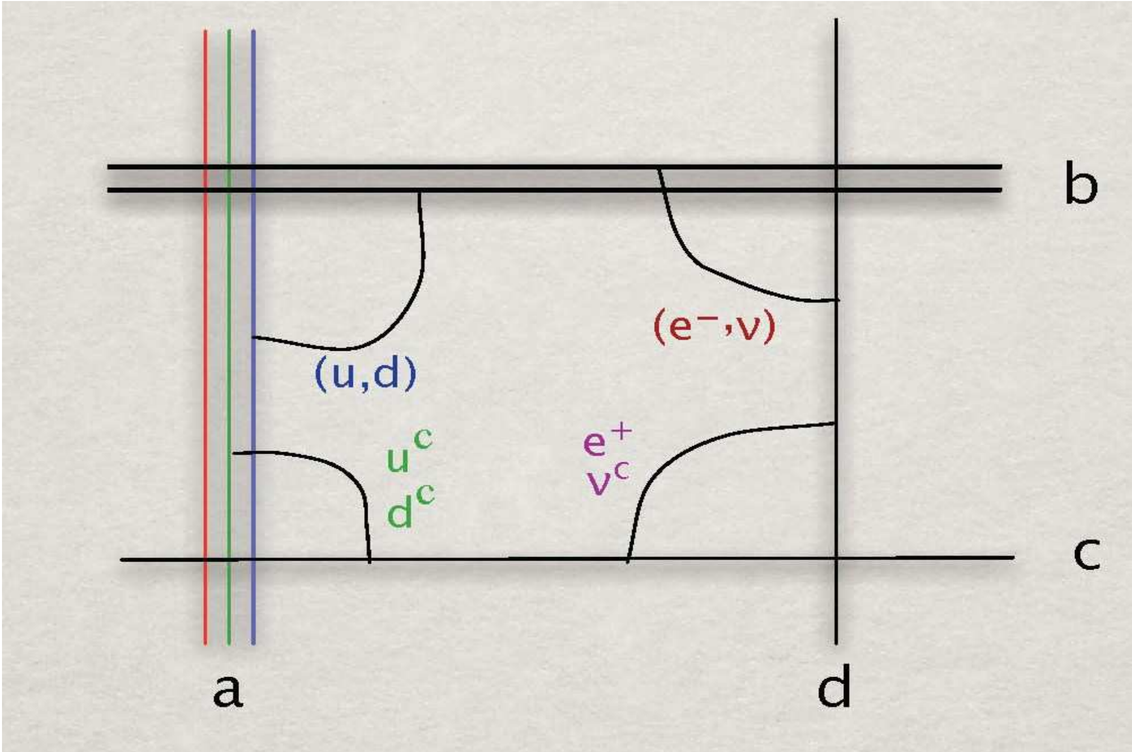
A fixed SM embedding

Fix the Madrid configuration: *Ibanez+Marchesano+Rabadan*



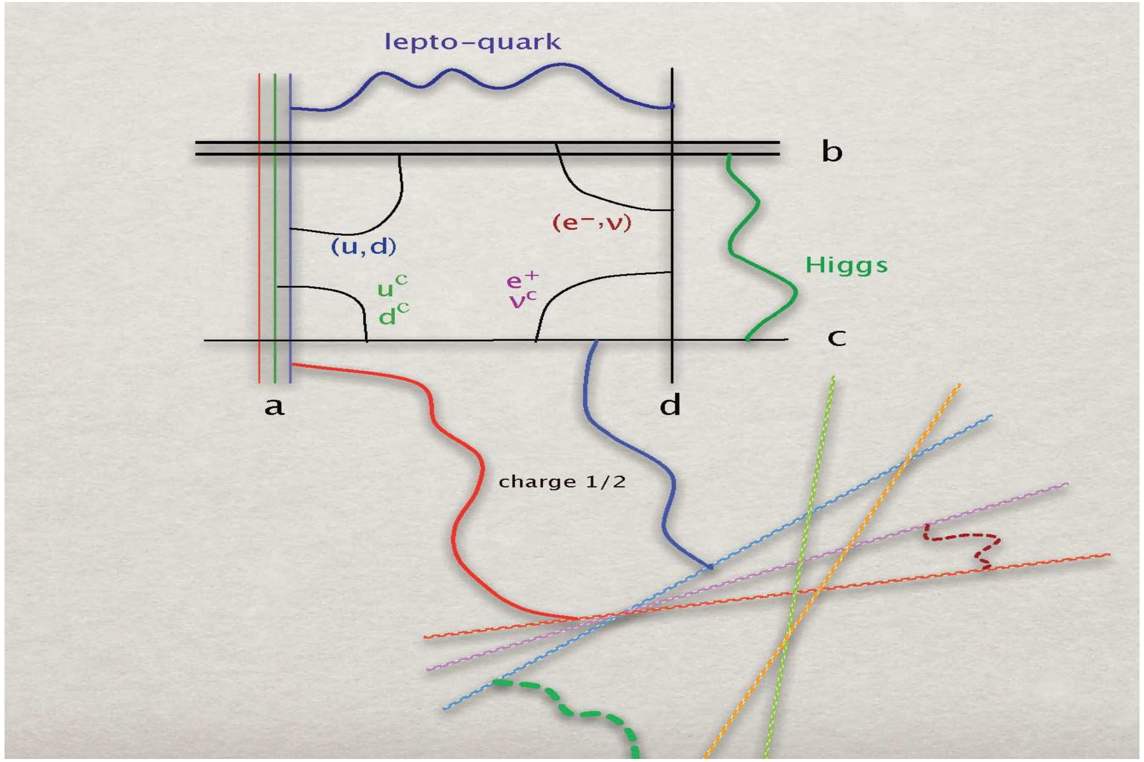
Search for: Chiral $SU(3) \times SU(2) \times U(1)$ spectrum: *Dijkstra+Huiszoon+Schellekens*

$$3(u,d)_L + 3u^c_L + 3d^c_L + 3(e^-,\nu)_L + 3e^+_L$$

$$\text{Massless} \quad Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Q_d$$

N=1 SUSY, no tadpoles, no global anomalies.

The hidden sector



- Non-chiral particles= no restrictions

- Chiral SM (families) = 3

- Non-chiral Sm/chiral CP: mirrors, Higgses, right-handed neutrinos, allowed.

The gauge groups

Dijkstra+Huiszoon+Schellekens

Type	CP Group	B-L
0	U(3) x Sp(2) x U(1) x U(1)	massless
1	U(3) x U(2) x U(1) x U(1)	massless
2	U(3) x Sp(2) x O(2) x U(1)	massless
3	U(3) x U(2) x O(2) x U(1)	massless
4	U(3) x Sp(2) x Sp(2) x U(1)	massless
5	U(3) x U(2) x Sp(2) x U(1)	massless
6	U(3) x Sp(2) x U(1) x U(1)	massive
7	U(3) x U(2) x U(1) x U(1)	massive

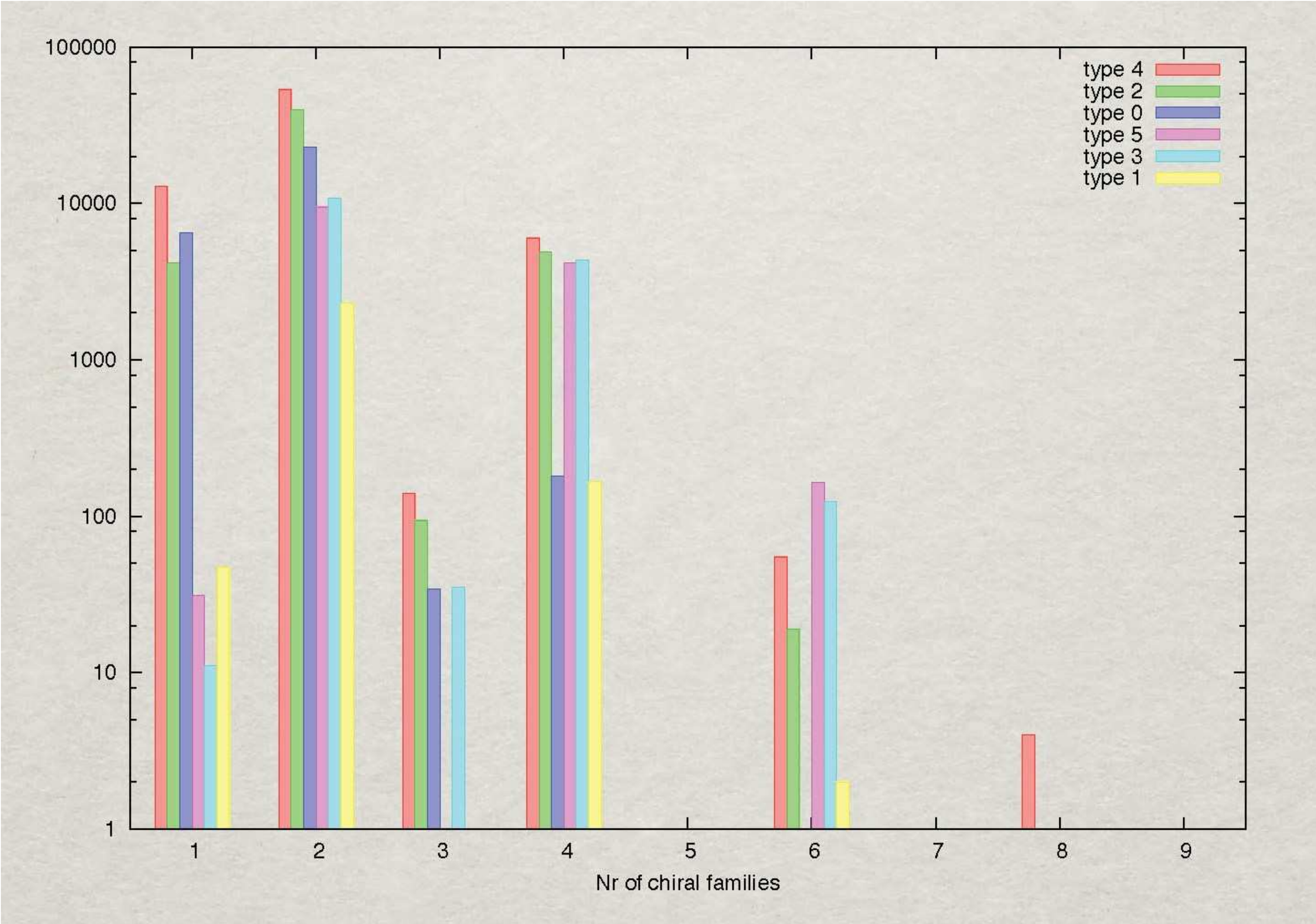
The statistics

Dijkstra+Huiszoon+Schellekens

Total number of 4-stack configurations	45761187347637742772 (45.7×10^{18})
Total number scanned	43752168618082181524
Total number of SM configurations	45051902 fraction: 1.0×10^{-12}
Total number of tadpole solutions	1649642 fraction: 3.8×10^{-14} (*)
Total number of distinct solutions	211634

The family statistics

Dijkstra+Huiszoon+Schellekens



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Generalized cubic anomaly cancelation

Cubic (four-dimensional) anomalies exist for groups with compex representations (SU(N), O(6) etc).

For SU(N), $A(\bar{R}) = -A(R)$

$$A(\square) = 1 \quad , \quad A\left(\begin{array}{c}\square\\[-4pt]\square\end{array}\right) = N-4 \quad , \quad A\left(\square\!\square\right) = N+4 \quad , \quad A(\text{adjoint}) = 0$$

Standard U(1) anomalies $Tr[Q] \neq 0$ and $Tr[Q^3] \neq 0$ are cancelled by the Green-Schwarz-Sagnotti mechanism.

But, the anomaly for U(N) applies also for N=2 and N=1!!!!

Example 1: U(1): $5\;\square_1$ and $\overline{\square\!\square}_{-2}$ is an anomaly free combination.

Example 2: U(1): $3\;\square_1$ and $\begin{array}{c}\square\\[-4pt]\square\end{array}_2$ is an anomaly free combination. Note that A is not massless!

Example 3: U(2): $2\;\square + \begin{array}{c}\square\\[-4pt]\square\end{array}$ is anomaly free. Note that the second is an SU(2) singlet.

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Brane configurations NOT searched

Type	Total	This work
UUU	1252013821335020	1443610298034
UUO, UOU	99914026743414	230651325566
UUS, USU	14370872887312	184105326662
USO	2646726101668	74616753980
USS	1583374270144	73745220170
UUUU	21386252936452225944	366388370537778
UUUO	2579862977891650682	105712361839642
UUUS	187691285670685684	8260457831286
UUOO	148371795794926076	19344849644848
UUOS	17800050631824928	2679835513461 2
UUSS	4487059769514536	1311715272980 6
USUU	93838457398899186	4121117625231 2
USUO	17800050631824928	2679835513461 2
USUS	8988490411916384	2641841078627 4

Review of the solutions

x	Config.	stack **c**	stack **d**	cases	Total occ.	Top MIPFs	Solved
1/2	UUUU	C,D	C,D	1732	1661111	8011	110(1,0)*
1/2	UUUU	C	C,D	2153	2087667	10394	145(43,5)*
1/2	UUUU	C	C	358	586940	1957	64(42,5)*
1/2	UUU	C,D	-	2	28	2	0
1/2	UUU	C	-	7	13310	74	3(3,2)*
1/2	UUUN	C,D	-	2	60	2	0
1/2	UUUN	C	-	11	845	28	0
1/2	UUUR	C,D	C,D	1361	3242251	12107	128(1,0)*
1/2	UUUR	C	C,D	914	3697145	12294	105(72,6)*
1/2	USUU	C,D	C,D	1760	4138505	14829	70(2,0)*
1/2	USUU	C	C,D	1763	8232083	17928	163(47,5)*
1/2	USUU	C	C	201	4491695	3155	48(39,7)*
1/2	USU	C,D	-	5	13515	384	5(2,0)
1/2	USU	C	-	2	222	4	0
1/2	USUN	C,D	-	29	46011	338	2(2,0)
1/2	USUN	C	-	1	32	1	0
1/2	USUR	C,D	C,D	944	45877435	34233	130(4,0)*
1/2	USUR	C	C,D	207	49917984	11722	70(54,10)*

Table 3

x	Config.	stack **c**	stack **d**	cases	Total occ.	Top MIPFs	Solved
0	UUUU	C,D	C,D	20	7950	110	2(2,0)
0	UUUU	C	C,D	164	50043	557	8(0,0)
0	UUUU	D	C,D	5	4512	40	0
0	UUUU	C	C	1459	999122	5621	119(40,3)*
0	UUUU	C	D	26	6830	54	0
0	UUU	C	-	11	17795	225	3(3,3)*
0	UUUN	C	-	31	5989	133	0
0	UUUR	C,D	C	90	195638	702	4(4,0)
0	UUUR	C	C	4411	7394459	24715	392(112,2)*
0	UUUR	D	C	24	50752	148	0
0	UUR	C	-	8	233071	1222	6(6,0)
0	UURN	C	-	37	260450	654	4(4,0)
0	UURR	C	C	1440	12077001	15029	218(44,0)
1	UUUU	C,D	C,D	5	212	8	0
1	UUUU	C	C,D	6	7708	21	0
1	UUUU	D	C,D	4	7708	11	0
1	UUUR	C,D	D	1	1024	2	0
1	UUUR	C	D	1	640	4	0
$*$	UUUU	C,D	C,D	109	571472	1842	19(1,0)*
$*$	UUUU	C	C,D	32	521372	1199	7(7,0)

Table 3

x	Config.	stack **c**	stack **d**	cases	Total occ.	Top MIPFs	Solved
*	UUUU	D	C,D	8	157232	464	0
*	UUUU	C	D	1	4	1	0

- 2. Branes: U=Unitary (complex), S=Symplectic, R=Real (Symplectic or Orthogonal) N: Neutral "Neutral" means that this brane does not participate to Y, and that there are no chiral bi-fundamentals ending on it. Such a brane can only give singlet neutrinos. We found a total of 111 such cases.

- 3,4. Composition of stack **c**, **d** in terms of branes of types C and D.

- 5. Total number of distinct spectra of the type specified in the first four columns.

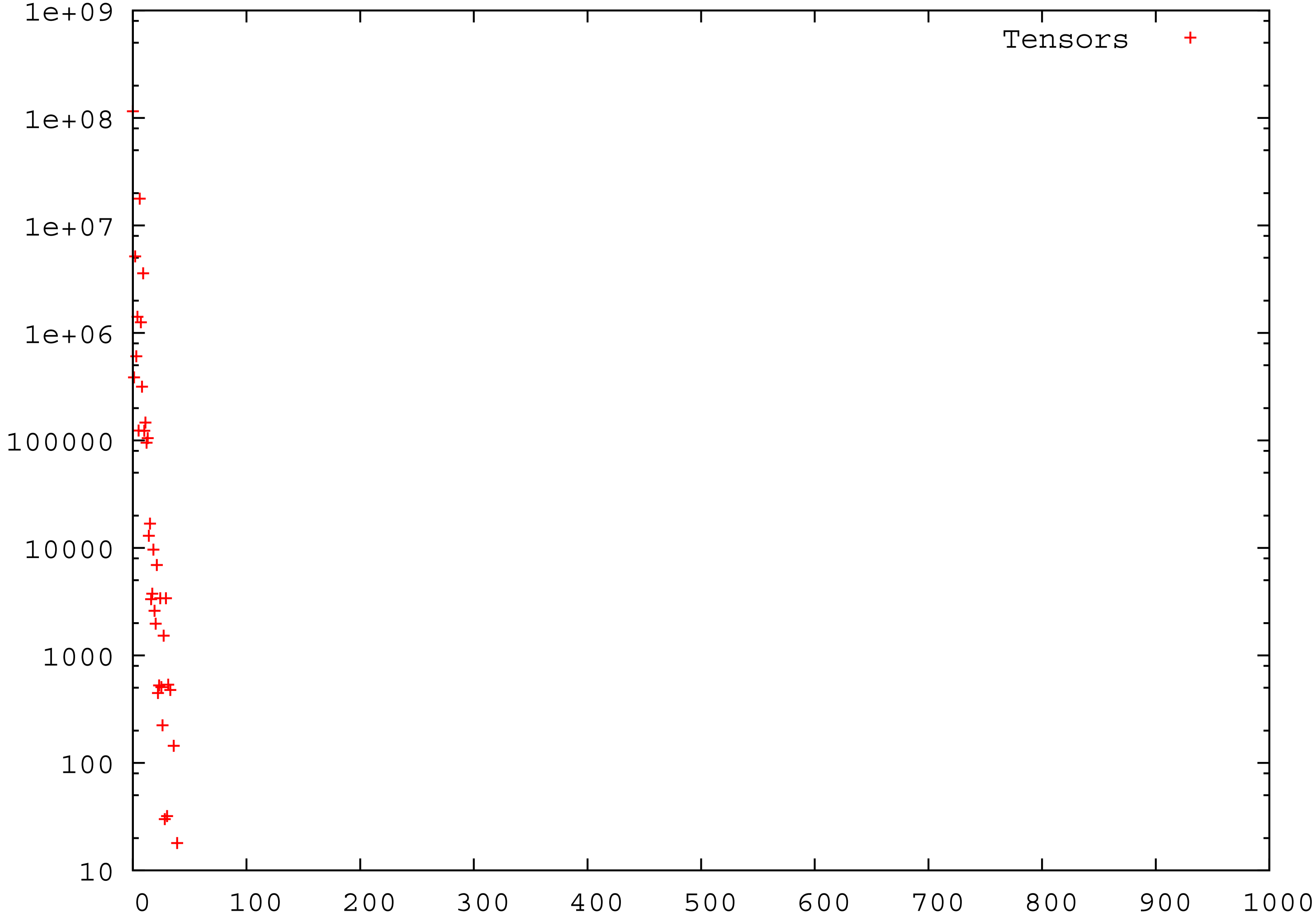
- 6. Total number of spectra of given type.

- 7. Total number of MIPFs for which spectra of given type were found.

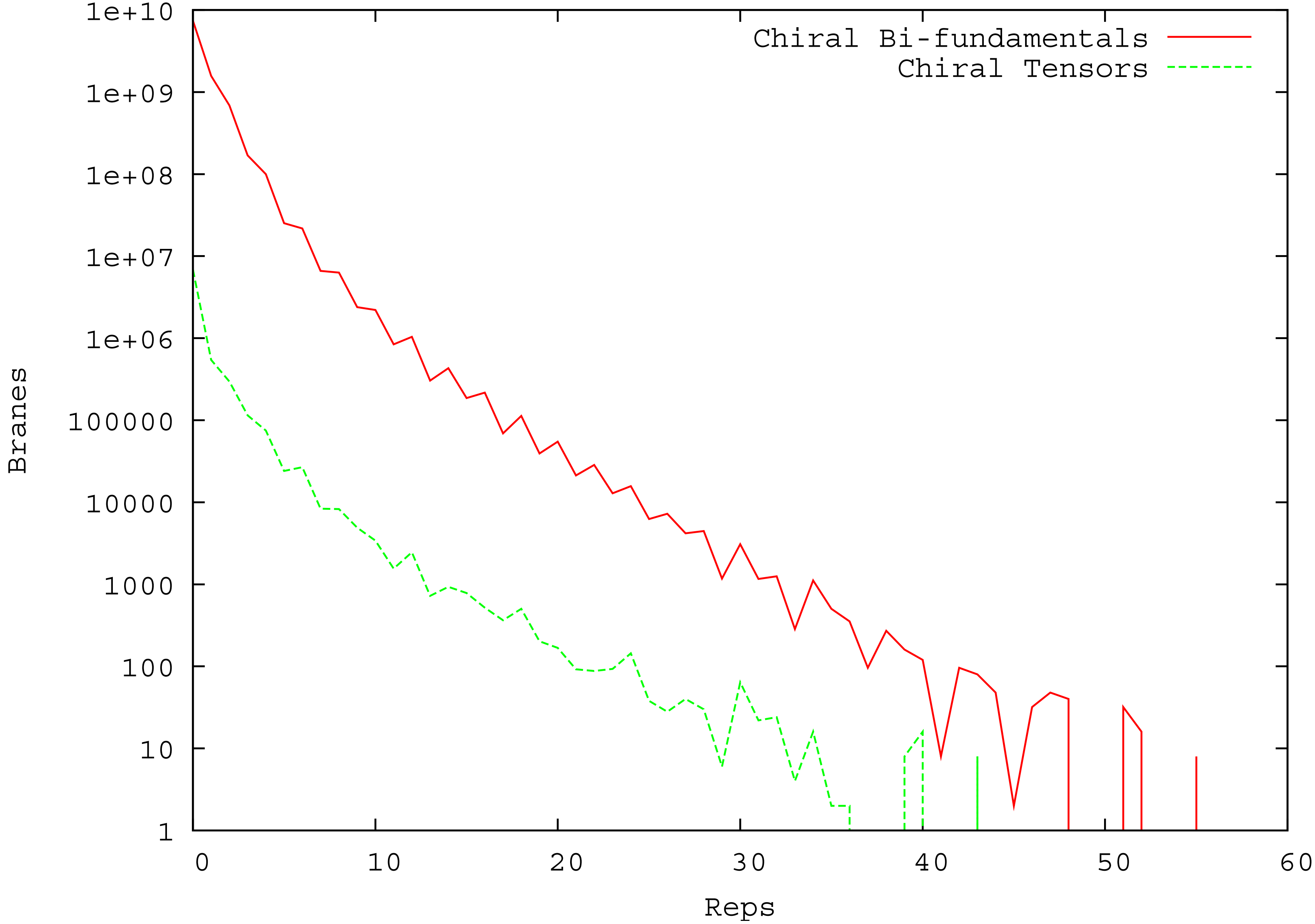
- 8. Number of distinct spectra for which tadpole solutions were found. Between parenthesis we specify how may of these solutions have at most three mirror pairs, three MSSM Higgs pairs and six singlet neutrinos, and how many have no mirror pairs, at most one Higgs pairs, and precisely three singlet neutrinos. An asterisk indicates that at least one solution was found without additional hidden branes.

The distribution of chiral A+S tensors

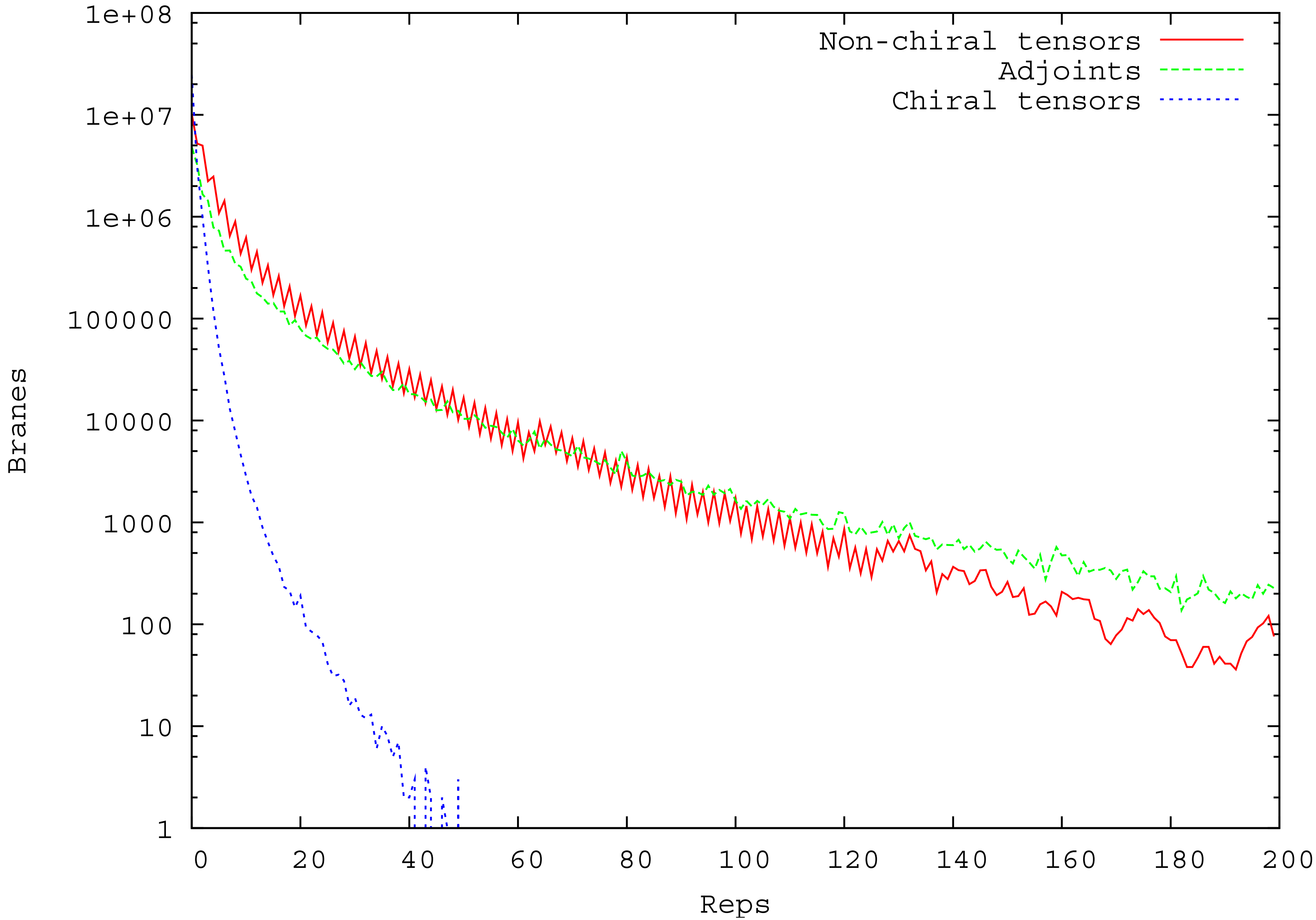
A key fact in order to explain the frequency of certain vacua is the that of chiral tensors, required in some case by (generalized) anomaly cancellation.



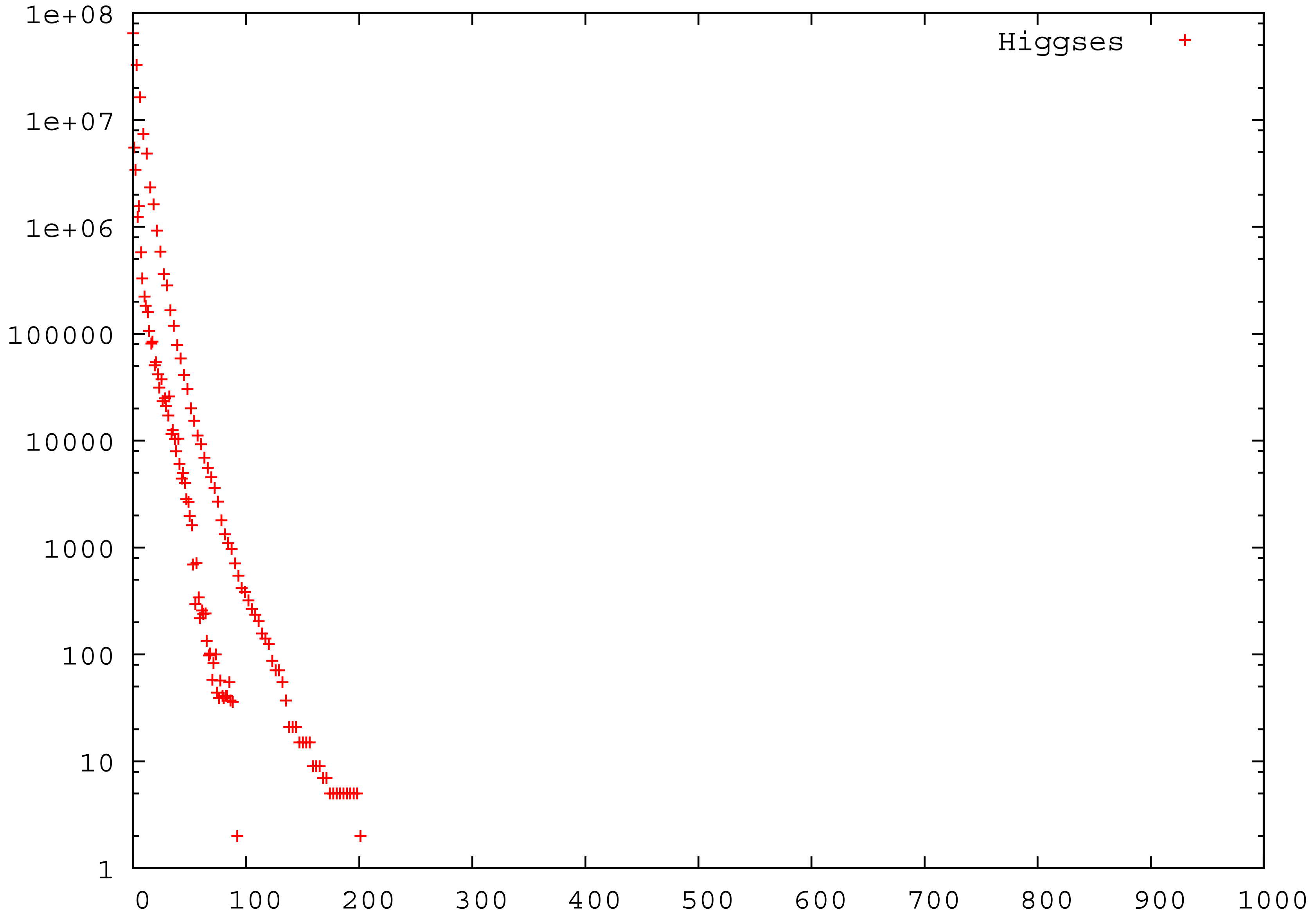
Tensors versus bifundamentals



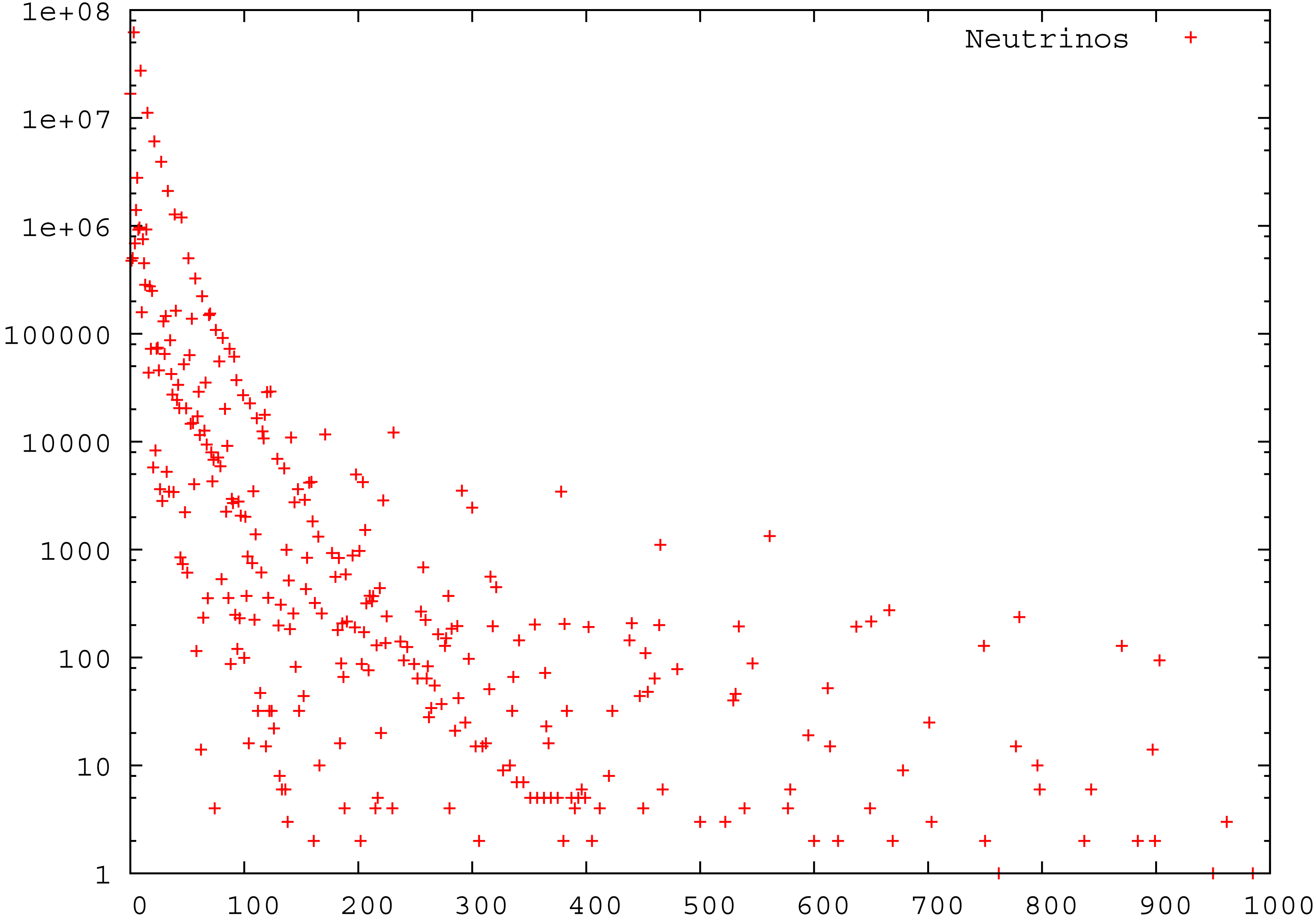
The distribution of tensor representations



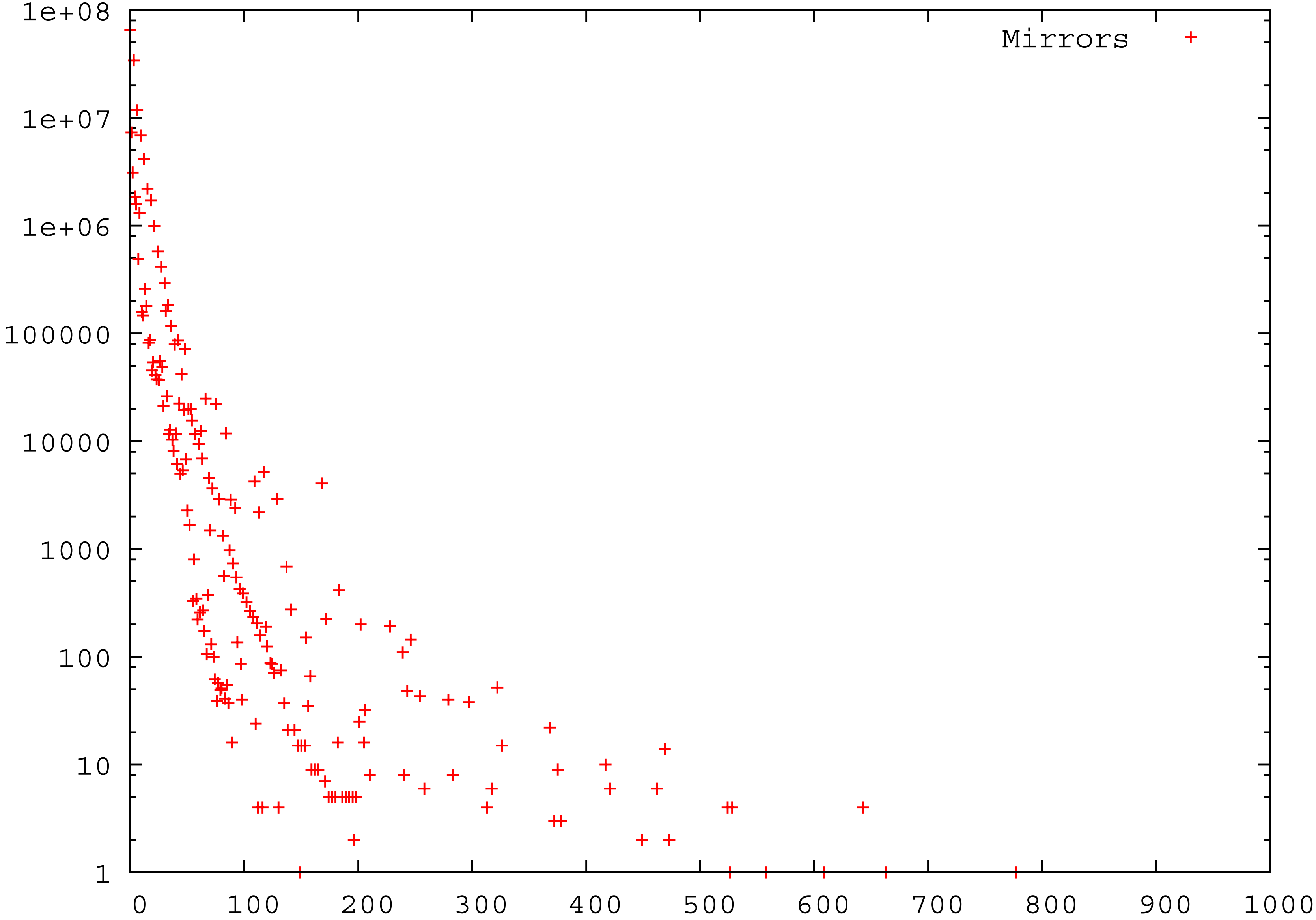
The distribution of Higgs pairs



The distribution of right-handed neutrino singlets



The distribution of mirrors



The basic orientable model

$$U(3)\times U(2)\times U(1)\times U(1)$$

$3\times(V,V^*,0,0)$	(u,d)
$3\times(V^*,0,V,0)$	d^c
$3\times(V^*,0,0,V)$	u^c
$6\times(0,V,V^*,0)$	(e^-,ν) + H_1
$3\times(0,V,0,V^*)$	H_2
$3\times(0,0,V,V^*)$	e^+

CY dependence

Tensor product	MIPF	h_{11}	h_{12}	Scalars	$x=0$	$x=\frac{1}{2}$	$x=*$	Success rate
(1,1,1,1,7,16)	30	11	35	207	1698	388	0	2.1×10^{-3}
(1,1,1,1,7,16)	31	5	29	207	890	451	0	1.35×10^{-3}
(1,4,4,4,4)	53	20	20	150	2386746	250776	0	4.27×10^{-4}
(1,4,4,4,4)	54	3	51	213	5400	5328	4248	3.92×10^{-4}
(6,6,6,6)	37	3	59	223	0	946432	0	2.79×10^{-4}
(1,1,1,1,10,10)	50	12	24	183	1504	508	36	2.63×10^{-4}
(1,1,1,1,10,10)	56	4	40	219	244	82	0	2.01×10^{-4}
(1,1,1,1,8,13)	5	20	20	140	328	27	0	1.93×10^{-4}
(1,1,1,1,7,16)	26	20	20	140	157	14	0	1.72×10^{-4}
(1,1,7,7,7)	9	7	55	276	7163	860	0	1.59×10^{-4}
(1,1,1,1,7,16)	32	23	23	217	135	20	0	1.56×10^{-4}
(1,4,4,4,4)	52	3	51	253	110493	8303	0	1.02×10^{-4}
(1,4,4,4,4)	13	3	51	250	238464	168156	0	1.01×10^{-4}
(1,1,1,2,4,10)	44	12	24	225	704	248	0	1.01×10^{-4}
(1,1,1,1,1,2,10)	21	20	20	142	2	1	0	1.00×10^{-4}
(1,1,1,1,1,4,4)	124	0	0	78	729	0	0	9.8×10^{-5}
(4,4,10,10)	79	7	43	215	0	57924	0	9.39×10^{-5}

Table 4 –

Tensor product	MIPF	h_{11}	h_{12}	Scalars	$x=0$	$x=\frac{1}{2}$	$x=*$	Success rate
(4,4,10,10)	77	5	53	232	0	1068926	0	8.29×10^{-5}
(1,4,4,4,4)	77	3	63	248	0	1024	0	8.12×10^{-5}
(4,4,10,10)	74	9	57	249	0	1480812	0	8.06×10^{-5}
(1,1,1,1,1,2,10)	24	20	20	142	0	0	6	7.87×10^{-5}
(1,2,4,4,10)	67	11	35	213	0	14088	1008	7×10^{-5}
(1,1,1,1,5,40)	5	20	20	140	303	36	0	6.73×10^{-5}
(2,8,8,18)	8	13	49	249	0	1506776	0	6.03×10^{-5}
(1,1,7,7,7)	7	22	34	256	2700	68	0	5.5×10^{-5}
(1,4,4,4,4)	78	15	15	186	20270	6792	0	5.39×10^{-5}
(2,8,8,18)	28	13	49	249	0	670276	0	5.25×10^{-5}
(1,2,4,4,10)	75	5	41	212	304	580	244	4.87×10^{-5}
(1,1,7,7,7)	17	10	46	220	1662	624	108	4.76×10^{-5}
(2,2,2,6,6)	106	3	51	235	0	201728	0	4.74×10^{-5}
(1,1,1,16,22)	7	20	20	140	244	19	0	4.67×10^{-5}
(1,2,4,4,10)	65	6	30	196	0	1386	0	4.41×10^{-5}
(4,4,10,10)	66	6	48	223	0	61568	0	4.33×10^{-5}
(1,4,4,4,4)	57	4	40	252	0	266328	58320	4.19×10^{-5}
(1,4,4,4,4)	80	7	37	200	0	1968	1408	4.15×10^{-5}
(6,6,6,6)	58	3	43	207	0	190464	0	3.93×10^{-5}
(1,1,1,1,10,10)	36	20	20	140	266	26	6	3.82×10^{-5}

Table 4 –

Tensor product	MIPF	h_{11}	h_{12}	Scalars	$x=0$	$x=\frac{1}{2}$	$x=*$	Success rate
(1,1,1,4,4,4)	125	12	24	214	351	0	0	3.62×10^{-5}
(4,4,10,10)	14	4	46	219	0	114702	0	3.3×10^{-5}
(1,1,1,1,10,10)	33	20	20	140	47	5	0	3.21×10^{-5}
...								...
(3,3,3,3,3)	6	21	17	234	0	192	0	6.54×10^{-6}
...								...
(3,3,3,3,3)	4	5	49	258	0	24	0	8.17×10^{-7}
...								...
(3,3,3,3,3)	2	49	5	258	6	27	6	1.65×10^{-9}
...								...

Masses for quarks

♠When antiquarks are the antisymmetric representation of SU(3), or a higher group (eg SU(5)) no mass terms can be generated in perturbation theory.

♠This is prohibited by $U(1)_3$ charge conservation.

♠If $U(1)_3$ is spontaneously broken, to avoid the problem, $SU(3)_c$ is also broken.

Two unlikely ways out:

♣Instanton effects

♣Implausible strong dynamics (charge 5 scalar vevs non-zero but no other ones)

Conclusion: SU(5) and related orientifold vacua are phenomenologically implausible.

RETURN

The search algorithm

♠Choose a MIPF and an orientifold projection

• Choose one complex brane (a) which contains no symmetric chiral tensors.

• Choose brane (b)so that: (1) it is not orthogonal (2) There are three chiral (3,2)+(3,2*), (3) There are no chiral symmetric tensors.

• Choose a braner (c) that: (1) is allowed by the tension constraint, (2) some antiquarks end on that brane.

• Choose brane d so that (1) one of b,c,d is complex. (2) at least one SM particles comes from brane (d)

• We must now cancel generalized cubic anomalies and determine N_c and N_d. This happens in most of the cases.

• We compute the Y linear combination. We impose the SM hypoercharges plus masslessness of Y. This is nost cases fixes the Y embedding.

• A final counting of quarks and leptons is done to check the spectrum.

• There are several degeneracies that are fixed at the end.

This provides a Top-Down configuration that is stored. Top-Down configurations are distinct of the SM part ois distinct (not mirrors or hidden gauge group) Then we solve tadpoles:

♣For every top down configuration we try to solve tadpoles, first without a hidden sector. If a solution is found, we stop.

♣Otherwise, we keep adding new branes untill there is a tadpole solution. For each top-down entry we stop after we find the first tadpole solution.

Detailed plan of the presentation

- The BCFT data
- A fixed SM embedding
- The hidden sector
- The gauge groups
- The statistics
- The family statistics
- Generalized cubic anomaly cancelation
- Brane configurations NOT searched
- Review of the solutions
- The distribution of chiral A+S tensors
- Tensors versus bifundamentals
- The distribution of tensor representations
- The distribution of Higgs pairs
- The distribution of right-handed neutrino singlets
- The distribution of mirrors
- The basic orientable model
- CY dependence
- Masses for quarks
- The search algorithm