Reunion du groupe Dimensions supplementaires du GDR-SUSY

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Searching for the Standard Model in orientifold 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**

• A review of the D-brane approach to particle physics and cosmology:

Elias Kiritsis **Phys. Rept. 421 (2005) 105-190**

Plan of the talk

- Introduction and scope.

- The assumptions

- Survey of the constructions

- Some distinguished vacua

- Outlook

Introduction

- String theory is under scrutiny because it unifies quantum gravity and gauge interactions

- The quantum theory is finite in perturbation theory

The downside:

- The theory seems to have an enormous number of stable vacua.

- It is notoriously difficult to do "model building"

Why is string "Model Building" difficult?

♠In gauge theories, model building is VERY modular. Most important features are decided quickly by picking the gauge group, spectrum (quantum numbers)and global symmetries.

♣In string theory the construction of vacua is quasi-geometrical (In general worse: relying on CFT)

- No direct way of choosing the gauge group or the spectrum.

- No direct way of choosing the effective potential.

- The analysis of a single ground state is a major project computationally

How do we do physics with such a theory?

- Original approach: TOP-DOWN Driven by hopes of uniqueness.

Such hopes seem very dim, these days.

- Alternative approach: BOTTOM-UP

Antoniadis+Kiritsis+Tomaras

Aldazabal+Ibanez+Quevedo+Uranga

- Can be implemented in orientifolds (vacua with D-branes)

- Is closer to traditional model building

- The downside: it is not always embedable in string theory

What we will start to do here:

♠Explore the possibilities of embedding the SM in string theory

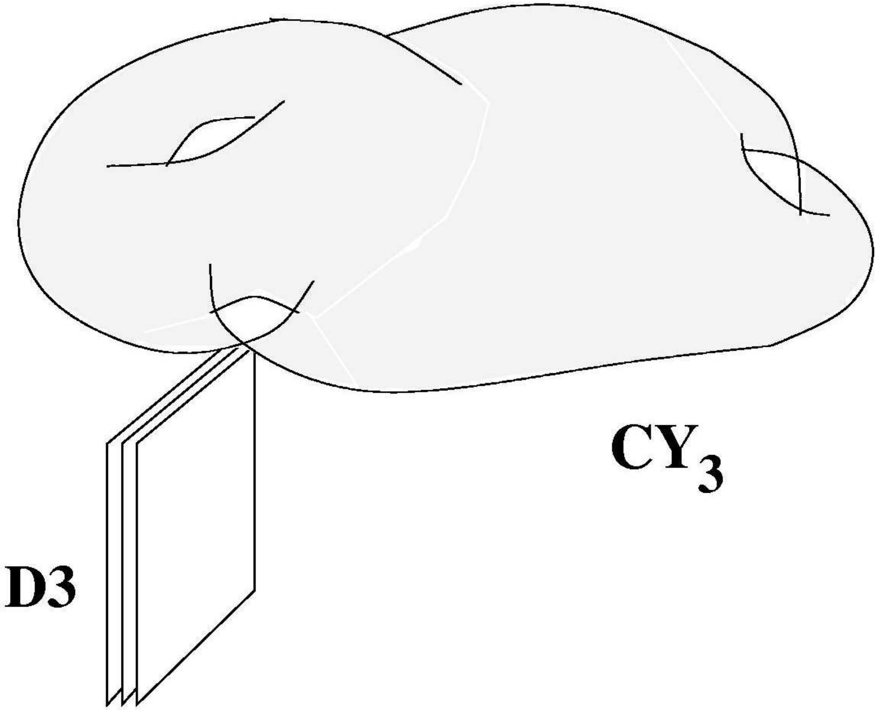
♠Decide eventually on promising vacua

♣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 ways the SM group can be embedded in the Chan-Paton (orientifold group).

Orientifolds



• This is a new class of vacua of string theory, which on top of a partly compactified space-time, contain also D-branes that stretch along the four Minkowski directions and may or may not wrap some internal dimensions.

• Since D-branes carry gauge bosons as well as matter fermions they contribute to the gauge group and matter content of the particular ground-state.

♣The construction proceeds with the following steps:

(a) Construct the compact manifold (closed CFT)

(b) Construct the D-brane "slots" (boundary/open CFT)

(c) Fill-in the branes+gauge groups (tadpole cancellation)

Technicalities

• The closed string vacua are constructed from CFT building blocks known as Gepner models Each such construction corresponds to a compactification of the closed string theory on a CY manifold of stringy size

• The open string data for such building blocks are known. They correspond to "slots" on the CY where D-branes can be inserted so that they are stable.

• The construction then proceeds by putting the SM branes in various ways in such slots while checking the spectrum of massless modes of the associated open strings.

• Finally "tadpole cancellation" is imposed: it corresponds to cancellation of UV divergences and anomalies.

Scope of the search

There are:

- 168 Gepner model combinations

- 5403 MIPFs

- 49322 different orientifold projections.

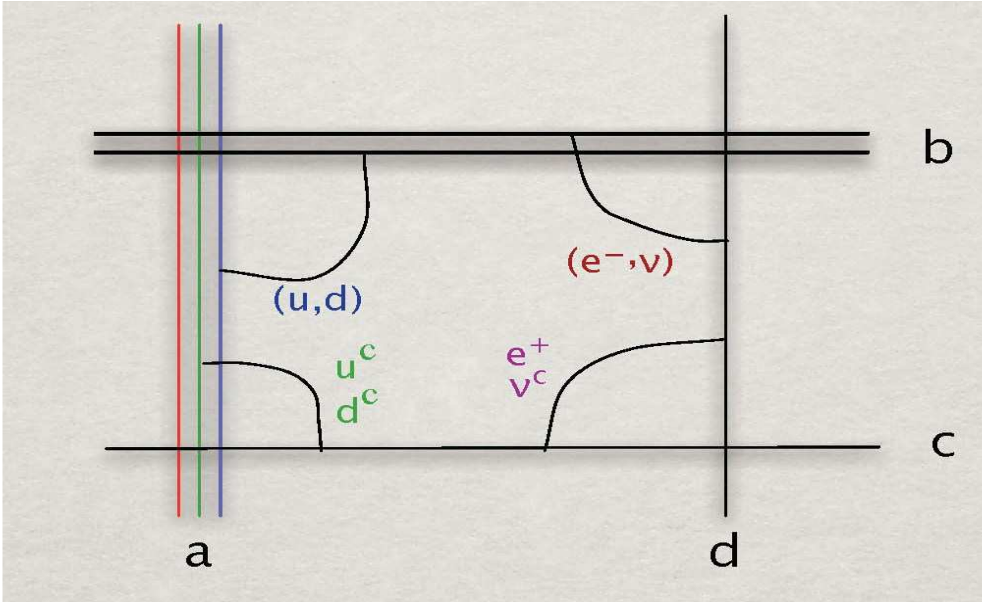
- 45761187347637742772 ($\sim 5 \times 10^{19}$)combinations of four boundary labels (four brane-stacks).

♠It is therefore essential to decide what to look for

The first effort: look for a "nice" configuration

Fix the Madrid configuration: U(3)× U(2)× U(1)× U(1)'

Ibanez+Marchesano+Rabadan



Search for: Chiral $SU(3) \times SU(2) \times U(1)$ spectrum:

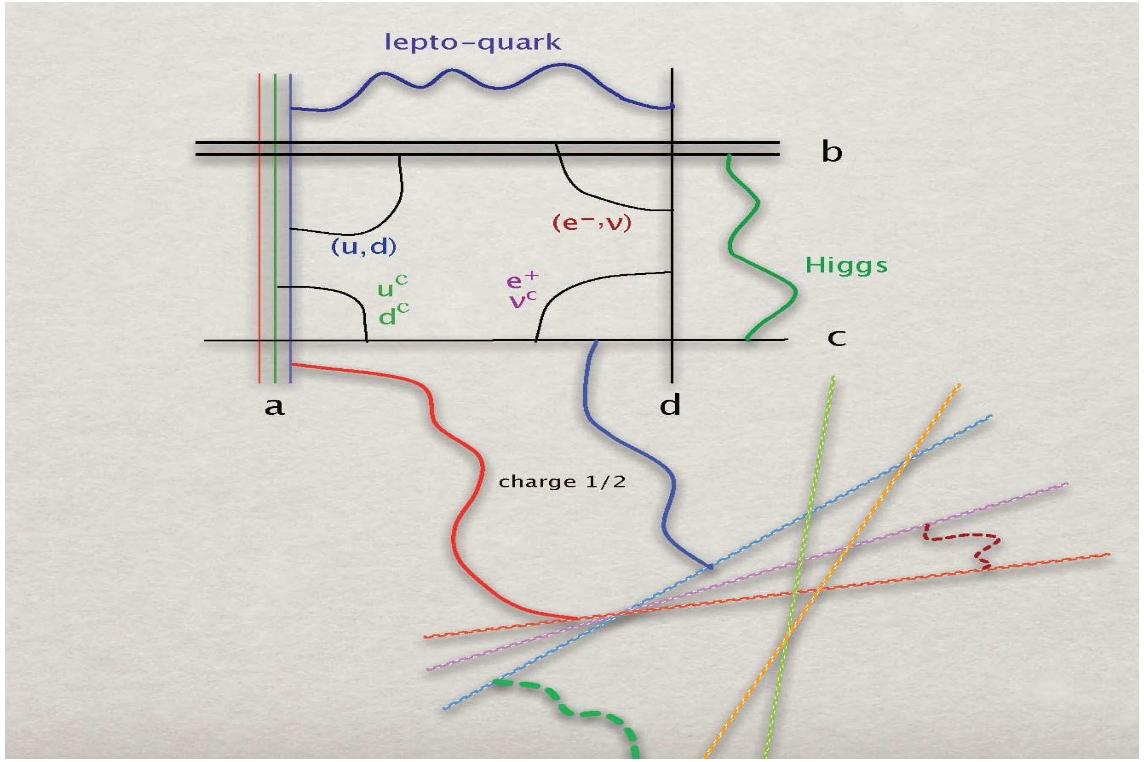
Dijkstra+Huiszoon+Schellekens

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

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

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 statistics

Dijkstra+Huiszoon+Schellekens

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

The (almost) unbiased search

Anastasopoulos+Dijkstra+Kiritsis+Schellekens

Look for general SM embeddings satisfying:

• U(3) comes from a single brane-stack (No $SU(3) \times SU(3) \to SU(3)$)

• SU(2) comes from a single brane-stack

• 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 (mixed-anomaly-free).

• No constraint on potential right-handed neutrinos, and Higgs pairs.

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 BCFT criteria but for tadpole cancellation.

STRING VACUA: TOP-DOWN configurations with tadpoles solved. This is achieved by varying the hidden sector.

The results

♠ We have set up a formalism to describe the classification of different hypercharge embeddings.

♠ We 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)

♠ One hypercharge embedding dominates by far all other ones.

♠ Chiral antisymmetric/symmetric tensors are highly suppressed. As they are needed for anomaly cancellation in some embeddings, they make them unlikely. For some no examples have been found.

♠We produce the first examples of SU(5) and flipped SU(5) orientifold vacua with the correct chiral spectrum (no hidden gauge group and no chiral exotics).

♠We find minimal Pati-Salam and trinification vacua.

♠We have examples of TOP-DOWN constructions (but no vacua yet) with N=4 or N=8 susy in the bulk and N=1 on the branes.

♠We have found SM spectra on orbifolds on the quintic CY.

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

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

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

$Q_i \rightarrow$ 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

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

The rarity of the $x = 1$ family is due to the need of chiral tensors

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 number 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

- V→ vector, A→antisymetric, S→ symmetric, T=A+S
- First 26 models are relatives of the Madrid configuration
- No=543 is the most frequent purely bi-fundamental model.

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

Table 2 –

nr	Total occ.	MIPFs	Chan-Paton Group	Spectrum	x	Solved
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
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
...	...	...	...	...	...	
34	869428(1096682)	246	$U(3) \times Sp(2) \times U(1) \times U(1)$	VVVV	1/2	Y!
153	115466	335	$U(4) \times U(2) \times U(2)$	VVV	1/2	Y
225	71328	167	$U(3) \times U(3) \times U(3)$	VVV	1/3	
303	47664	18	$U(3) \times U(2) \times U(1) \times U(1)$	AAVA	1/2	Y
304	47664	18	$U(3) \times U(2) \times U(1) \times U(1)$	AAVA	0	Y
343	40922(49794)	63	$U(3) \times Sp(2) \times U(1) \times U(1)$	VVVV	1/2	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

Table 2 –

nr	Total occ.	MIPFs	Chan-Paton Group	Spectrum	x	Solved
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	

“Popular” hypercharge embeddings

Four-stack low-scale models: $U(3) \times U(2) \times U(1) \times U(1)$

- Models A,A' (x=0) $Y = -\frac{1}{3}Q_a + \frac{1}{2}Q_b + Q_c$.

Antoniadis+Kiritsis+Tomaras

More complicated versions found

- Models B,B' (x=1) $Y = \frac{2}{3}Q_a - \frac{1}{2}Q_b + Q_c$.

Antoniadis+Kiritsis+Tomaras

A $U(3) \times U(2) \times U(2) \times U(1)$ variant was found. This is VERY rare

- Madrid embedding: $\left(\mathrm{x} = \frac{1}{2}\right)$: $Y = \frac{1}{6}Q_a + \frac{1}{2}Q_c + \frac{1}{2}Q_d$ *Ibanez+Marchesano+Rabadan*

Three-stack bottom-up models $U(3) \times U(2) \times U(1)$

- Model A: (x=0) $Y = -\frac{1}{3}Q_a + \frac{1}{2}Q_b$. SU(5) spectrum (many found)

Antoniadis+Dimopoulos

- Models B,C:(x=1) $Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c$: B$\rightarrow$ flipped SU(5) (many found)

Antoniadis+Dimopoulos

A variant of C : $U(3) \times Sp(2) \times U(1)$ was found, as a top-down construction.

Minimal exotics

Bottom-up versus Top-down results for spectra without mirror pairs, at most one MSSM Higgs pair, and precisely three singlet neutrinos.

x	Config.	stack **c**	stack **d**	Bottom-up	Top-down	Occurrences	Solved
1/2	UUU	C	-	8	2	13242	1
1/2	UUUU	C	C	10670	16	81985	4
1/2	UUUU	C	C,D	148	8	378418	3
1/2	UUUR	C	C,D	495	13	641485	3
1/2	USUU	C	C,D	314	6	2757164	3
1/2	USUU	C	C	10816	6	4037872	4
1/2	USUR	C	C,D	434	3	47689675	3
0	UUUU	C	C,D	23	1	6	0
0	UUUU	C	C	1996	5	17301	2
0	UUUU	C	D	91	4	4227	0
0	UUU	C	-	9	1	15282	1
0	UUUR	C	C	5136	15	63051	1

Unification

- $a = b$:$\rightarrow$ SU(5) and flipped SU(5) variants.

- $a = c$:$\rightarrow$ Simplest is Pati-Salam $U(4) \times U(2) \times U(2)$

- $b = c$: $\rightarrow$ Trinification $U(3) \times U(3) \times U(3)$

- $a = b = d$: $\rightarrow$ An $U(6) \times Sp(2)$ curiosity

Pati-Salam: Version I

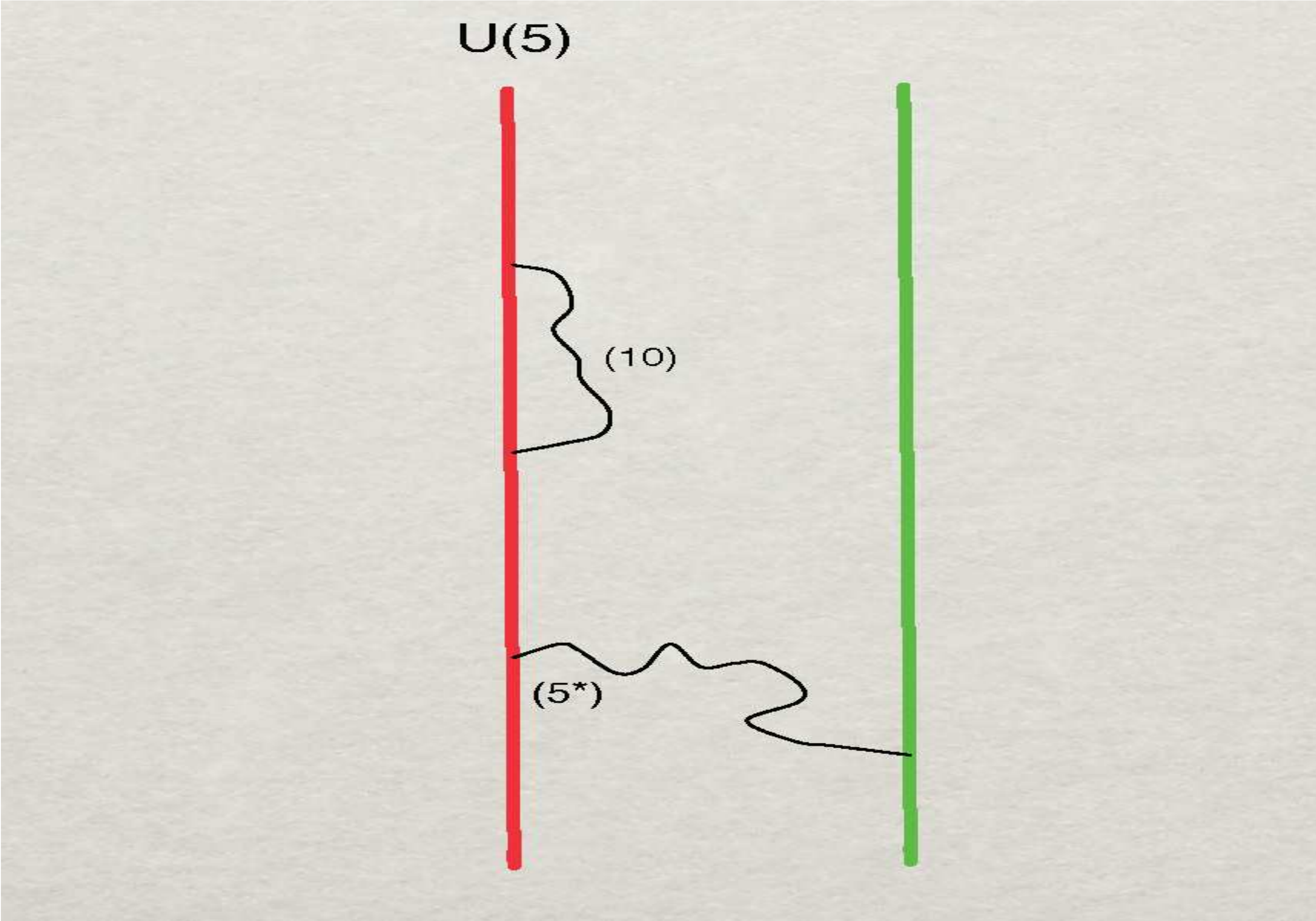
```
Type:           U   S   S
Dimension       4   2   2
      5 x ( V  ,0  ,V  ) chirality -3
      3 x ( V  ,V  ,0  ) chirality 3
      2 x ( Ad,0  ,0  ) chirality 0
      2 x ( 0  ,A  ,0  ) chirality 0
      7 x ( 0  ,0  ,A  ) chirality 0
      4 x ( A  ,0  ,0  ) chirality 0
      2 x ( 0  ,S  ,0 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

- Model No=4

- $a = d\,:\; U(3)\times U(1)\rightarrow U(4)$

- $Y = \frac{1}{6}Q_a - \frac{1}{2}Q_d + W_c$ with $W_c = \frac{1}{2}\sigma^3$

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”.

- The branes are on a (h_{21},h_{11})=(7,31) CY manifold

- 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 quark masses being non-zero!

Outlook

♠We have investigated all possible embeddings of the Standard Model in orientifold vacua build on type-II groundstates, with at most four brane-stacks.

♠Many top-down configurations have been found, and associated tadpole solutions including mimimal gauge groups like $U(3) \times U(2) \times U(1)$ or various unified groups.

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

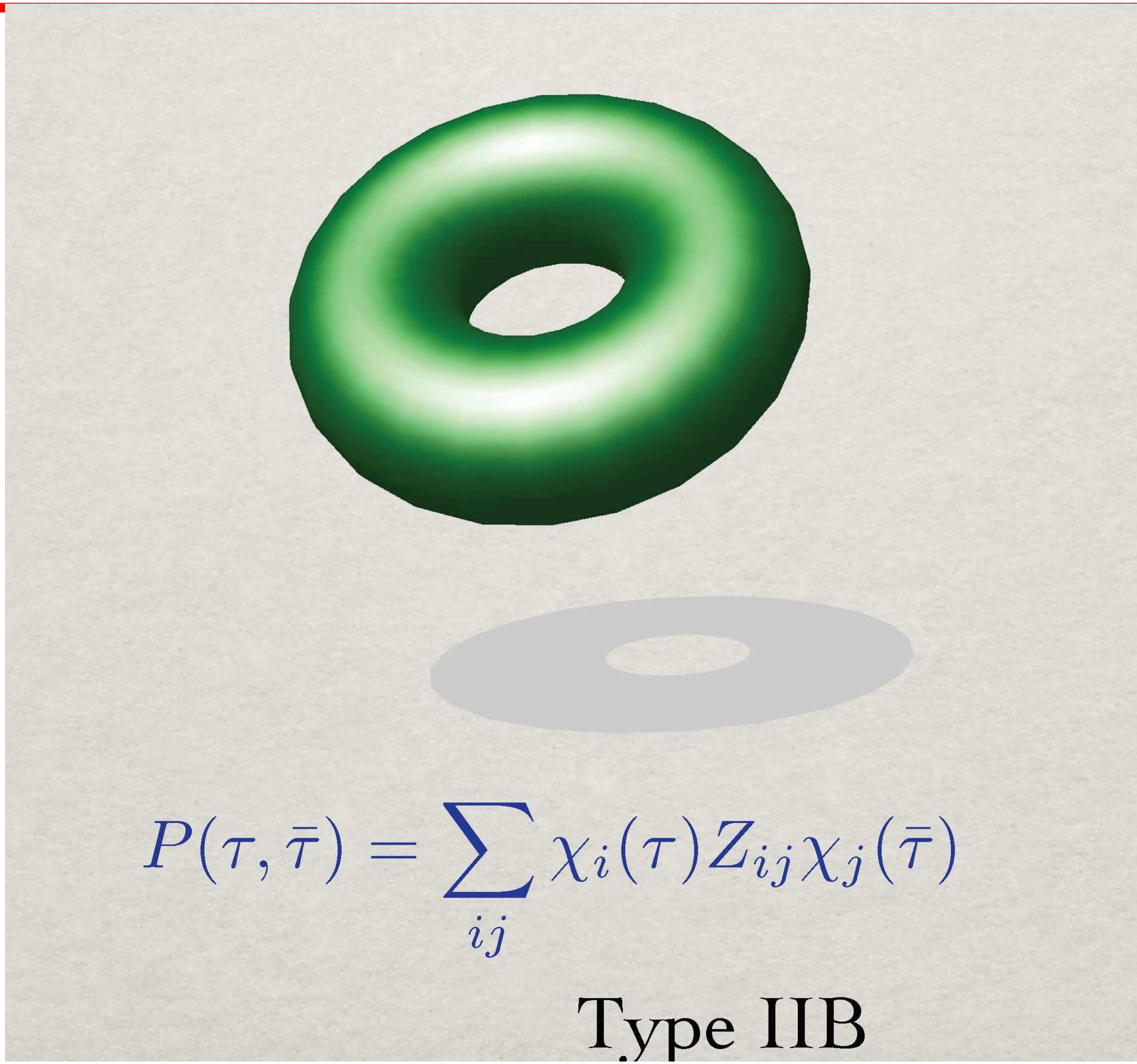
♠So far it is only spectra that are matched. The precise phenomenology of some promising models needs to be analyzed.

♠There are no general formulae for couplings: (a) choose specific examples and calculate (b) do an analysis of patterns of symmetry breaking based on symmetries (which are many)

♠Implement SUSY breaking via gaugino condensation

♠Implement moduli stabilisation

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

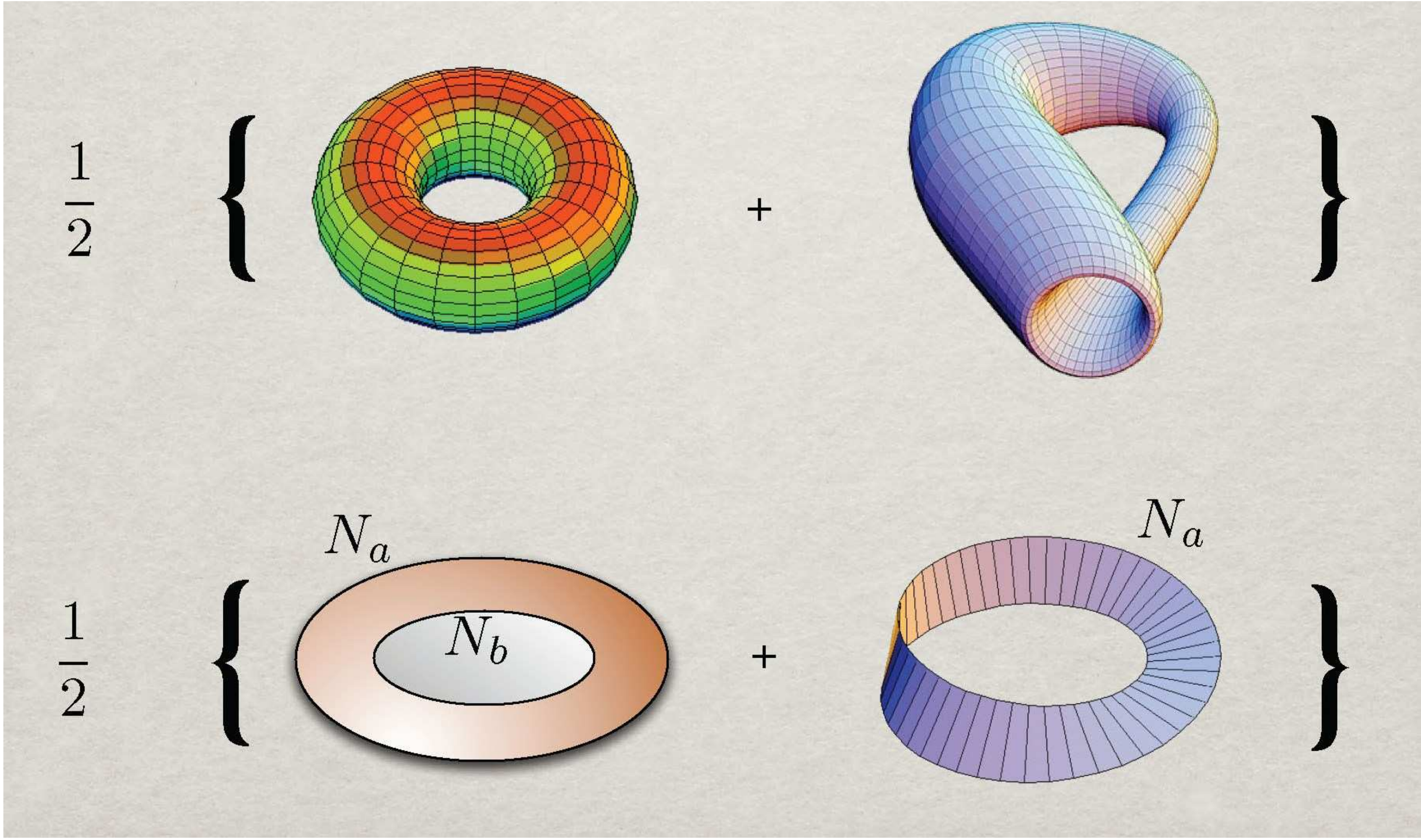
♠The tensoring must preserve world-sheet super-symmetry

♠The tensoring must preserve $\mathcal{N} = 2$ space-time supersymmetry in (4d)

♠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 (string-sized) 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 :

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

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

More details

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 coeficients 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.

RETURN

Allowed features

- CP gauge group: $U(3)_a \times \left\{ \begin{matrix} U(2) \\ Sp(2) \end{matrix} \right\}_b \times G_c \times G_d$ All known SM particles originate from strings among these stacks.

- G_c, G_d are (non-standard) family symmetries.

- Anti-quarks from antisymmetric tensors (of SU(3))

- Leptons from antisymmetric tensors of SU(2)

- 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 conservation/violation.

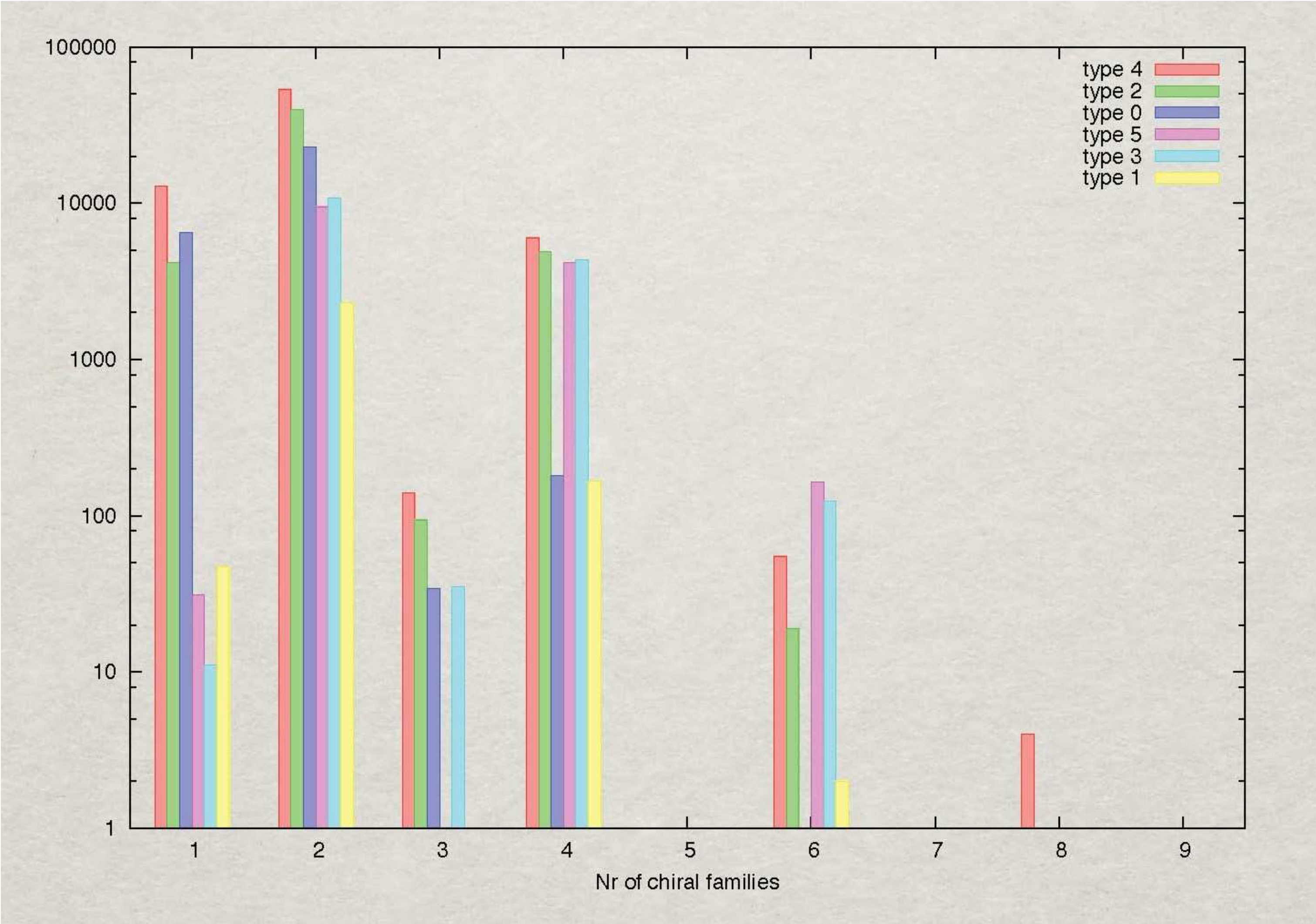
The gauge groups

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 family statistics

Dijkstra+Huiszoon+Schellekens



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Arbitrary x

When upon matching charges, x is not fixed, this implies the presence of another non-anomalous U(1) gauge boson A_μ, beyong Y_μ so that all SM particles are not charged under it.

• If masslessness fixes x, then there is a Stuckelberg mass term of the type

$$S \sim M^2(\partial_\mu a + A_\mu + Y_\mu)^2$$

The orthogonal combination is hypercharge. The phenomenology of such models has been analyzed by Nath, Kors et al.

• If masslessness does not fix x, then there is a massless photon that can communicate with SM either via massive particles BSM, or via string modes.

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	82606457831286
UUOO	148371795794926076	19344849644848
UUOS	17800050631824928	26798355134612
UUSS	4487059769514536	13117152729806
USUU	93838457398899186	41211176252312
USUO	17800050631824928	26798355134612
USUS	8988490411916384	26418410786274

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 4

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 4

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.

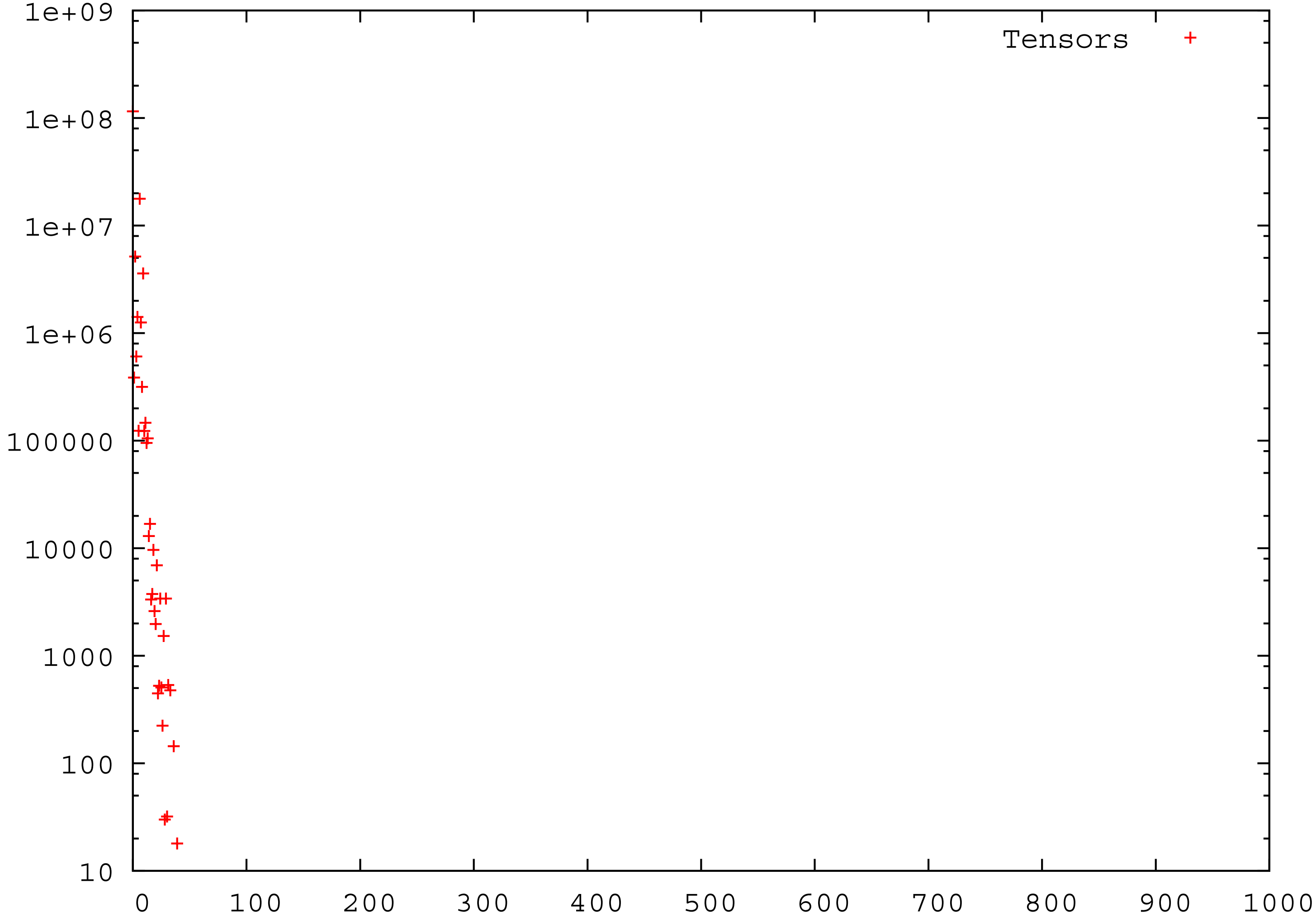
- 6. Total number of spectra of given type.

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

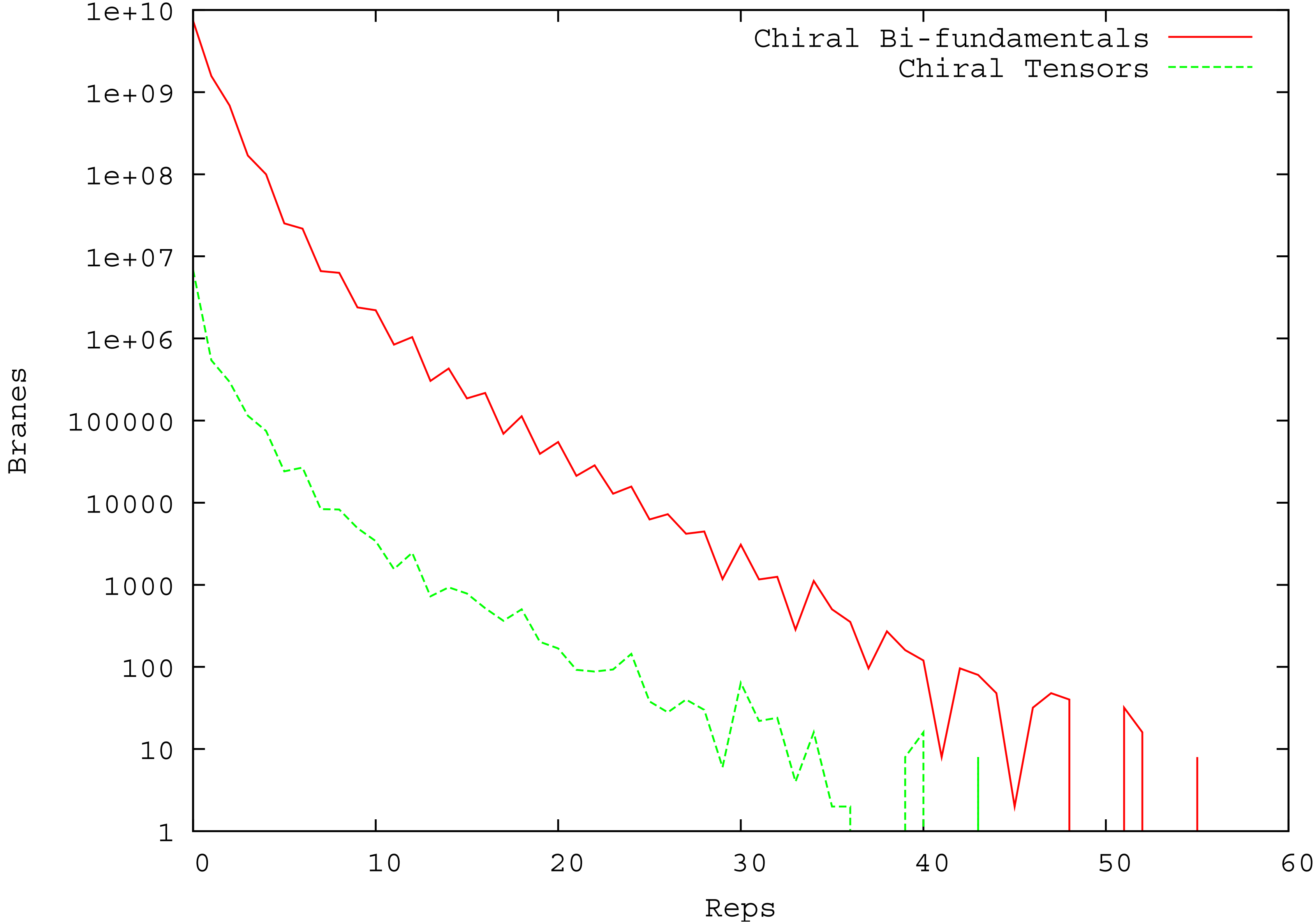
- 8. Number of distinct spectra for which tadpole solutions were found. Between parenthesis we specify how may of these solutions have at most three mirror pairs, three MSSM Higgs pairs and six singlet neutrinos, and how many have no mirror pairs, at most one Higgs pairs, and precisely three singlet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

The distribution of chiral A+S tensors

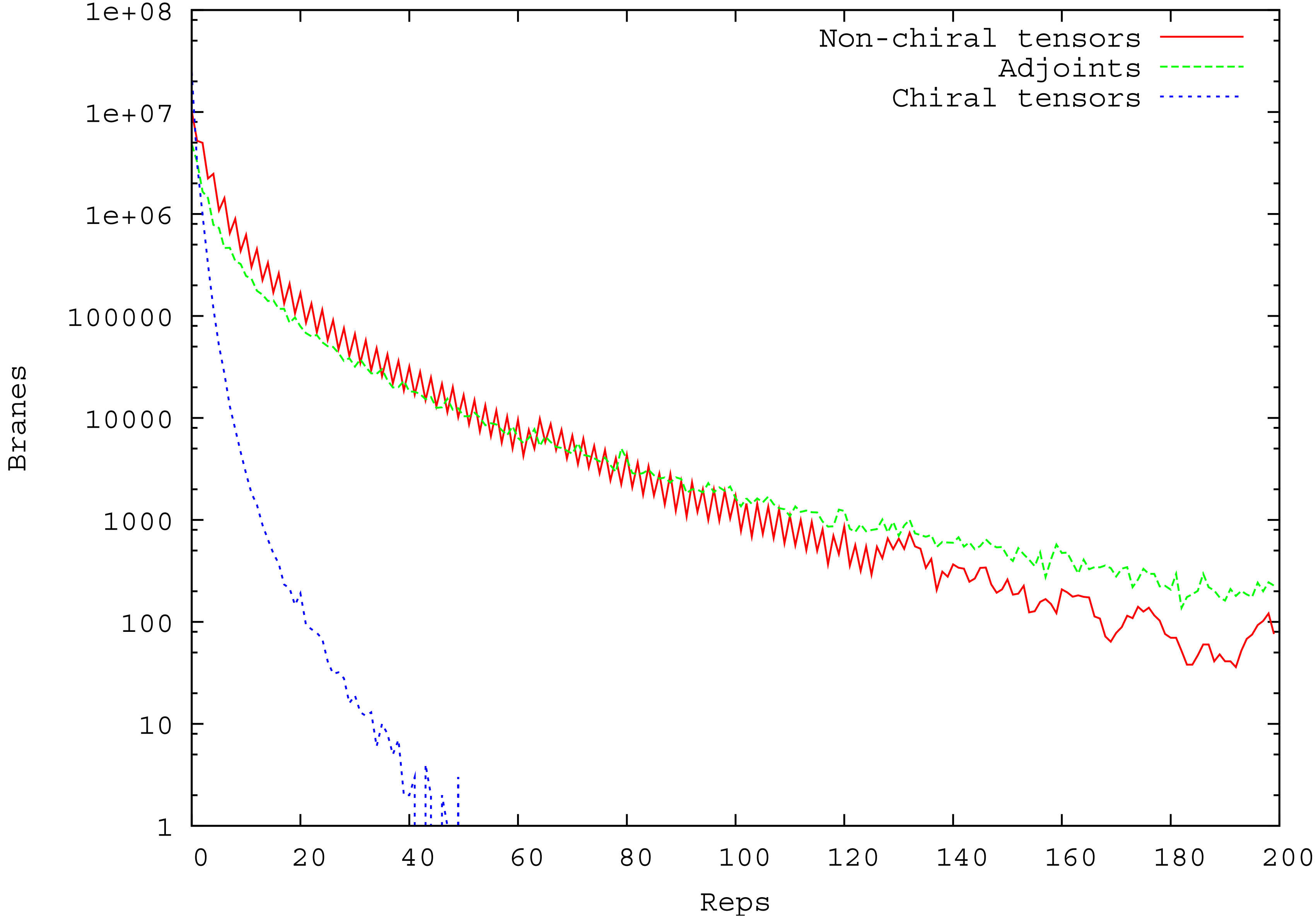
A key fact in order to explain the frequency of certain vacua is the that of chiral tensors, required in some case by (generalized) anomaly cancellation.



Tensors versus bifundamentals



The distribution of tensor representations



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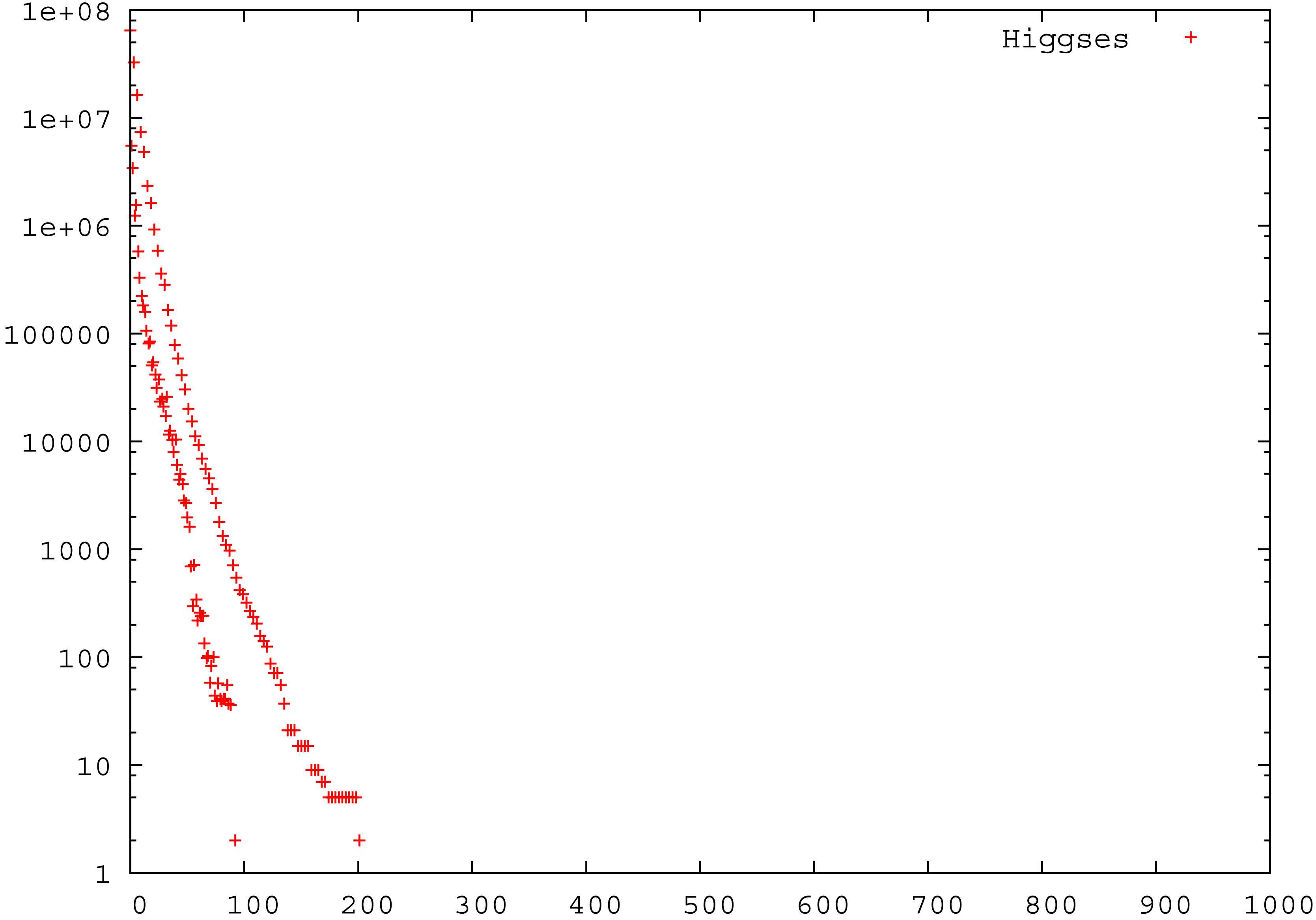
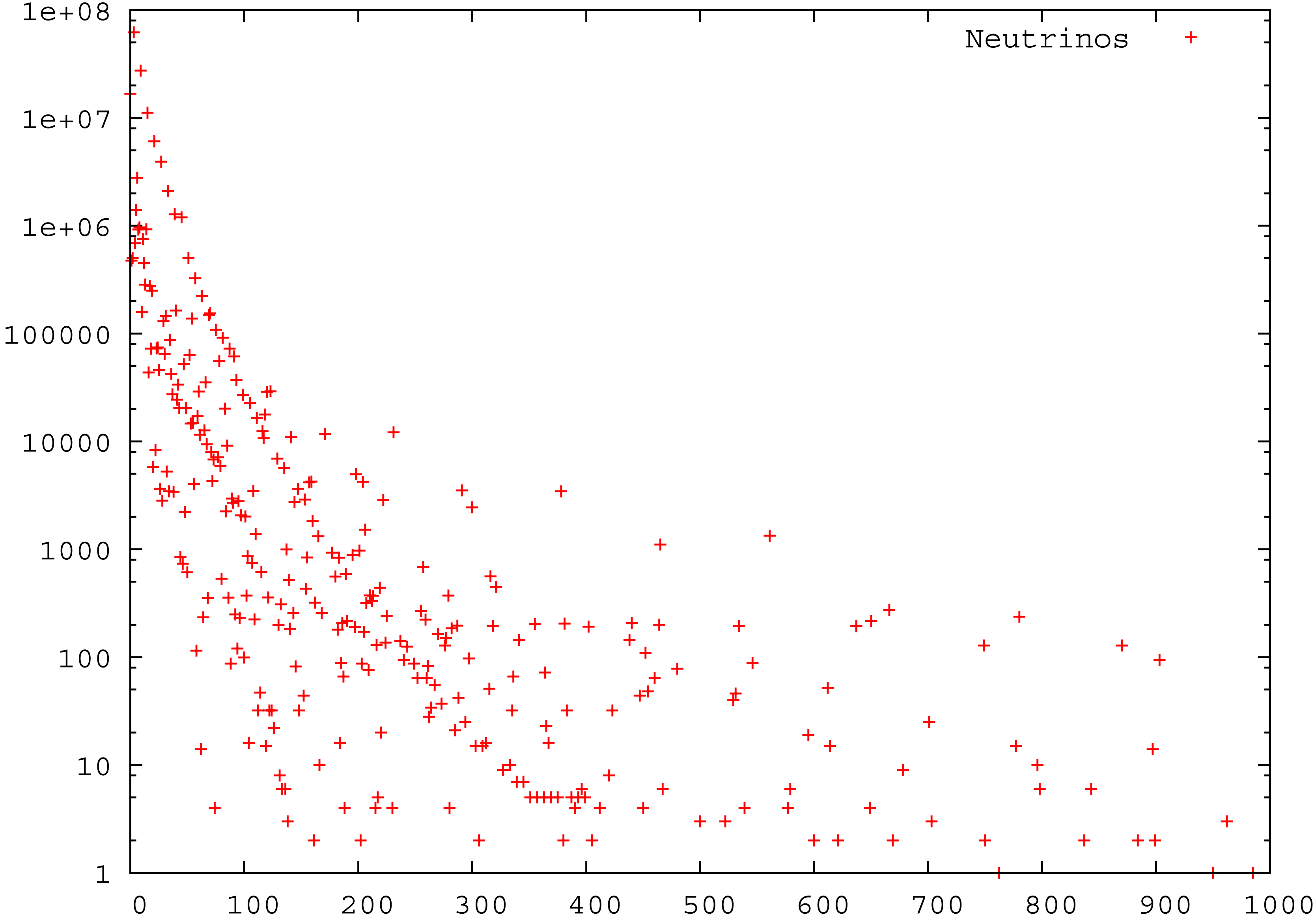
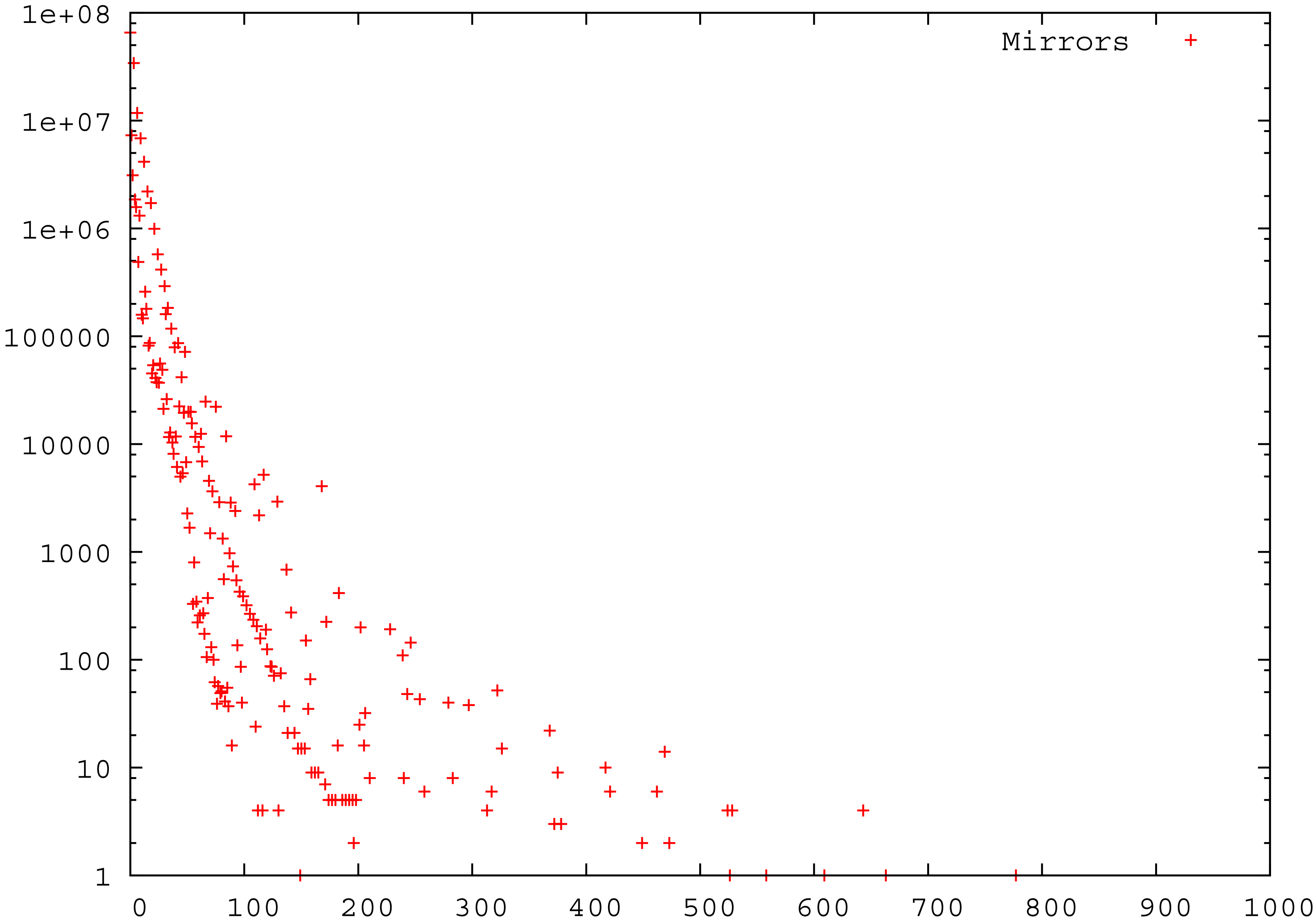
The distribution of potential Higgs pairs



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
$6 \times$	$(0, V, V^*, 0)$	$(e^-, \nu) + H_1$
$3 \times$	$(0, V, 0, V^*)$	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 5 –

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 5 –

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 ways out:

♣Instanton effects (Difficult)

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

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

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 hypercharges 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 if the SM part is 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.

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

U(6)×Sp(2)

$$9 \times (A,0)_3$$

$$9 \times (V,V)_{-3}$$

$$8 \times (Ad,0)$$

$$1 \times (0,A)$$

$$7 \times (0,S)$$

- SM: U(6)×Sp(2)→ $U(3)_a \times U(2)_b \times Sp(2)_c \times U(1)_d$ $Y=\frac{1}{6}Q_a - \frac{1}{2}Q_d + W_c$
- U(6)→U(5)×U(1) → $U(3)_a \times U(2)_b \times U(1)_d$ via flipped SU(5).
- U(6)→U(4)×U(2) → $U(3)_a \times U(2)_b \times U(1)_d$ via Pati-Salam.
- Also: SM: U(6)×Sp(2)→ $U(3)_a \times U(2)_b \times Sp(2)_c \times U(1)_d$ $Y=-\frac{1}{3}Q_a + \frac{1}{2}Q_b$=Standard SU(5)
- 3 candidate Higgs pairs, 3 mirror $\bar{D}$, 6 R-handed neutrino candidates (U(6)-chiral)
- Models 1886, 1887,1888.

RETURN

Generalized cubic anomaly cancelation

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

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

$$A(\square) = 1 \quad , \quad A\left(\begin{smallmatrix}\square\\ \square\end{smallmatrix}\right) = N-4 \quad , \quad A\left(\square\square\right) = N+4 \quad , \quad A(\text{adjoint}) = 0$$

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 $\begin{smallmatrix}\square\\ \square\end{smallmatrix}_{\,2}$ is an anomaly free combination. Note that A is not massless!

Example 3: U(2): $2\ \square + \begin{smallmatrix}\square\\ \square\end{smallmatrix}_{\,2}$ is anomaly free. Note that the second is an SU(2) singlet.

RETURN

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 is VERY RARE: found only 4 times, with no tadpole solution.

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
```

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

Detailed plan of the presentation

- Title page 1 minutes
- Bibliography 2 minutes
- Plan 3 minutes
- Introduction 4 minutes
- Why is string “Model Building” difficult? 6 minutes
- How do we do physics with such a theory? 9 minutes
- Orientifolds 11 minutes
- Technicalities 12 minutes
- Scope of the search 14 minutes
- The first effort: look for a nice configuration 16 minutes
- The hidden sector 18 minutes
- The statistics 20 minutes
- The (almost) unbiased search 25 minutes

- The starting point: closed type II strings 61 minutes
- Gepner models 61 minutes
- The (unoriented) open sector 61 minutes
- Unoriented partition functions 61 minutes
- The BCFT data
- Allowed features
- The gauge groups
- The family statistics
- Arbitrary x
- 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

- SU(5)×U(1)
- $U(6) \times Sp(2)$
- Generalized cubic anomaly cancelation
- The basic orientable model
- Pati-Salam: Version II
- Trinification