Topics in RCFT Orientifolds

Orientifold Partition Functions

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

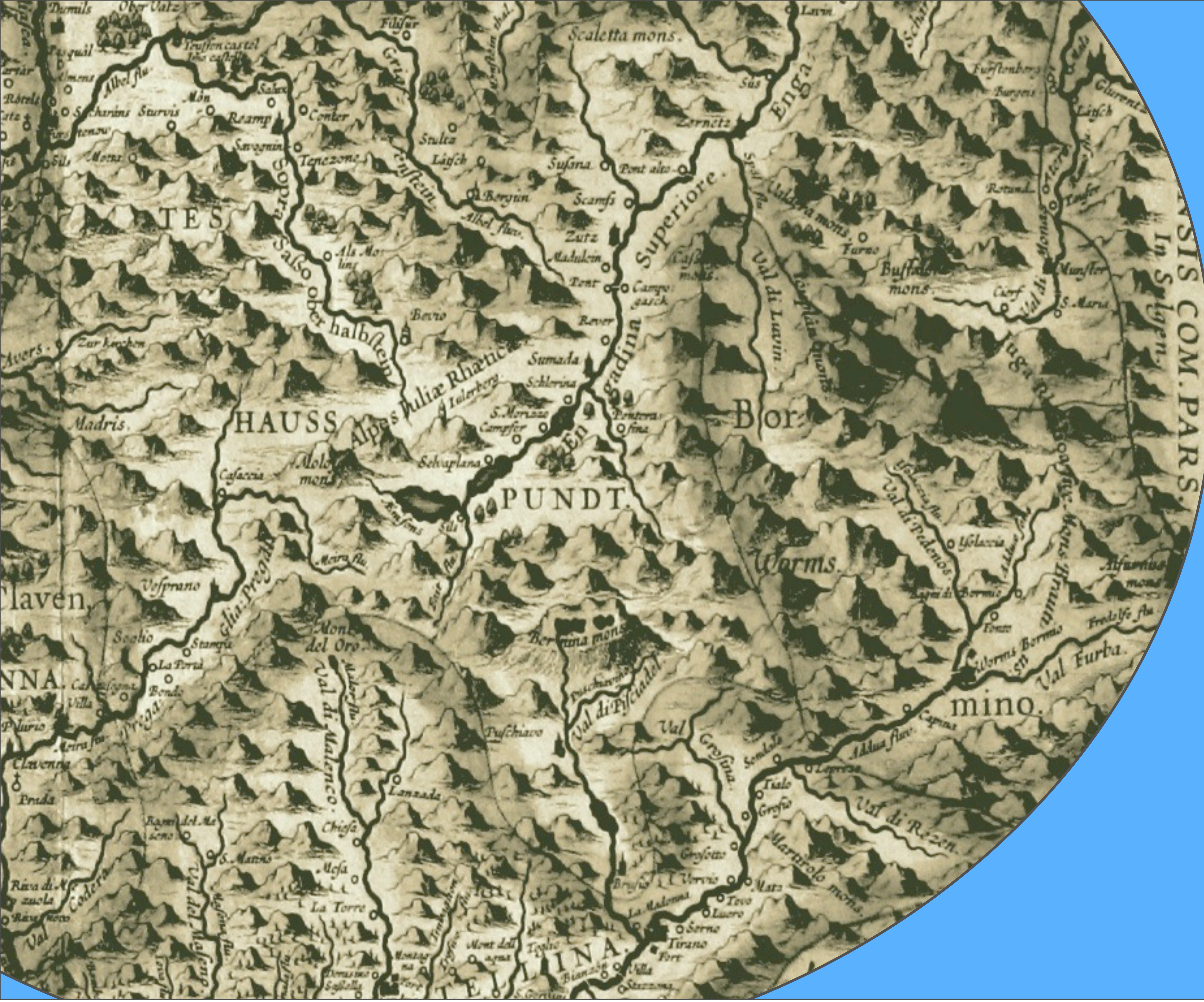
- Open $$\frac{1}{2}\left[\sum_{i,a,n}N_aN_bA^i{}_{ab}\chi_i(\frac{\tau}{2})+\sum_{i,a}N_aM^i{}_a\hat{\chi}_i(\frac{\tau}{2}+\frac{1}{2})\right]$$

i : Primary field label (finite range)

a : Boundary label (finite range)

χ_i : Character

N_a : Chan-Paton (CP) Multiplicity


Scaletta mons.
Zernetz
Enga
Superiore.
Pont alto
Scamfs
Zutz
Madulein
Pont
Campo gasch
Bever
Sumada
Schlerina
S. Morizze
Campfer
Schoaplana
Sils
gadina
En
PUNDT.
HAUSS
TES
Alpes Iuliæ Rhæticæ
ober halbstein
Sopra
Salso
Bevio
Tenezone
Conter
Reamp
Savognin
Stulz
Lätsch
Bergün
Albel flu.
Susana
Madris.
Casaccia
Vesprano
Claven
Soglio
Stampa
La Porta
Bondo
Bor
Worms.
mino.
Val Furba.
Val di Luvin
Val di Pedenos
Iuga Rha
Furstenborg
Burgeis
Lätsch
Rotund
Taufer
Munster
S. Maria
Buffalora mons.
Furno
Bernina mons
Val di Piscadel
Poschiavo
Val Grosina
Val di Malenco
Chiesa
Lanzada
Mont del Oro
La Torre
Val di Rezen.
Mortirolo mons.
Sondalo
Tiolo
Grosio
Grosotto
Mazo
Tovo
Lovero
Serno
Tirano
Villa
Stazzona
Bianzone
Addua flu.
Val del Masino
Val
Codera
Clavenna
Pruda
S. Martino
Mesa
Puschiavo
Val di Pedenos.
Ysolaccia
Fonte
Worms Bormio
Val di Ri
IN Selgen.
VSIS COM. PARS.
TE
INA.


Scaletta mons.
Superiore.
Engadina
HAUSS
Alpes Iuliæ Rhæticæ
PUNDT.
Bor
Worms.
mino.
Val Furba.
Claven
Madris.
Bernina mons
Val di Malenco.
Free Fields


RCFT
Free Fields

Hic Sunt Leones

What we can compute

- Exact perturbative string spectra
- Gauge couplings in rational points

What we can't do (yet)

- Compute Yukawa couplings
- Compute couplings to moduli
- Perturbations around rational points
- Moduli stabilization
- ...

Algebraic choices

- Basic CFT (N=2 tensor[(1)], free fermions[(2)]...)
- Chiral algebra extension

  May imply space-time symmetry (e.g. Susy: GSO projection).

  But this is optional!

  Reduces number of characters.
- Modular Invariant Partition Function (MIPF)

  May imply bulk symmetry (e.g Susy), not respected by all boundaries.

  Defines the set of boundary states

  (Sagnotti-Pradisi-Stanev completeness condition)
- Orientifold choice

(1) Dijkstra, Huiszoon, Schellekens (2005);
Anastasopoulos, Dijkstra, Kiritsis, Schellekens (2006)

(2) Kiritsis, Lennek, Schellekens, to appear.

Consistency conditions

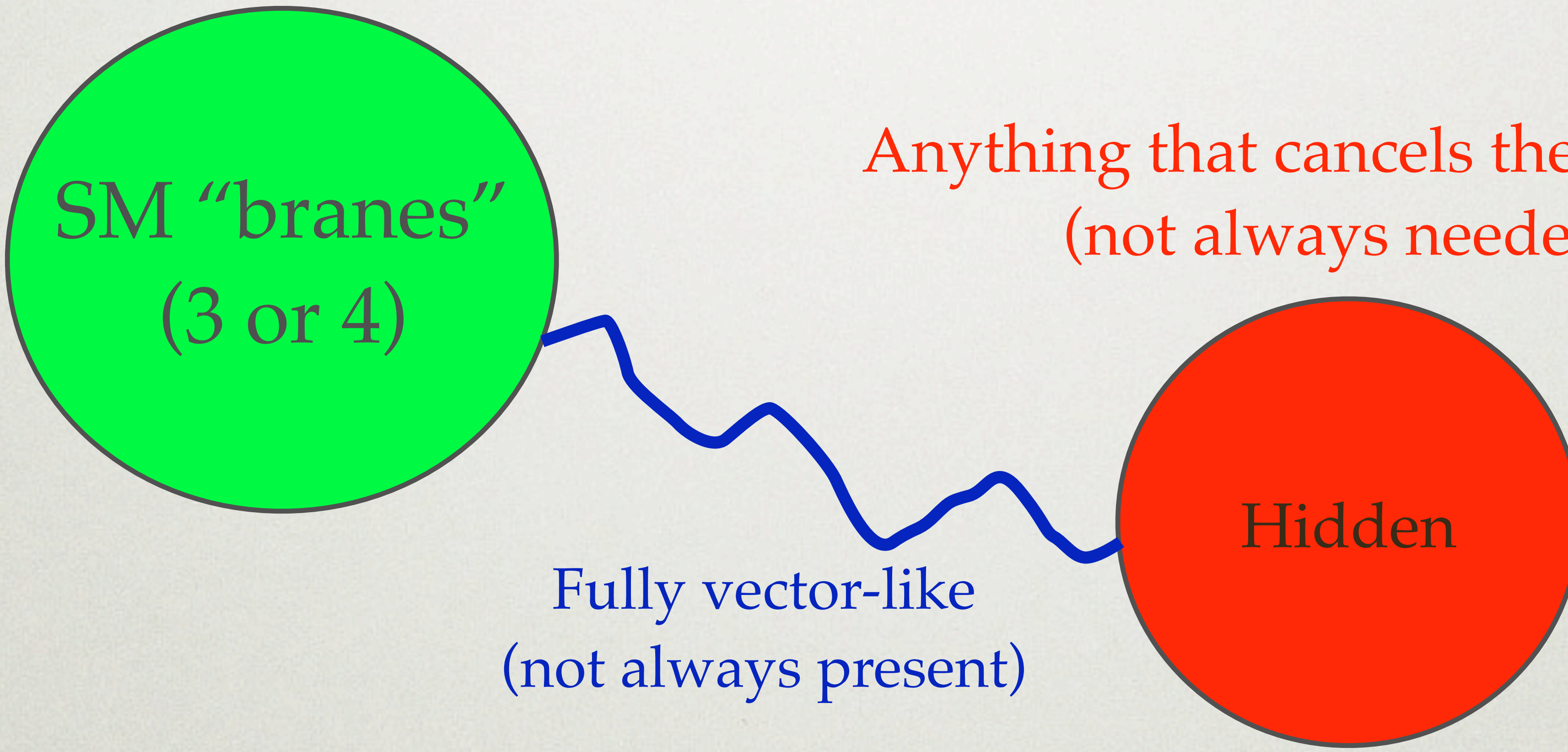
- Tadpole cancellation
- Absence of axion mixing for Y
- Global anomalies*

Same as for all other orientifold models

(*) "probe branes" (Uranga)
B. Gato-Rivera and A.N Schellekens, Phys.Lett.B632:728-732,2006

SM realization

3 families
+ anything vector-like



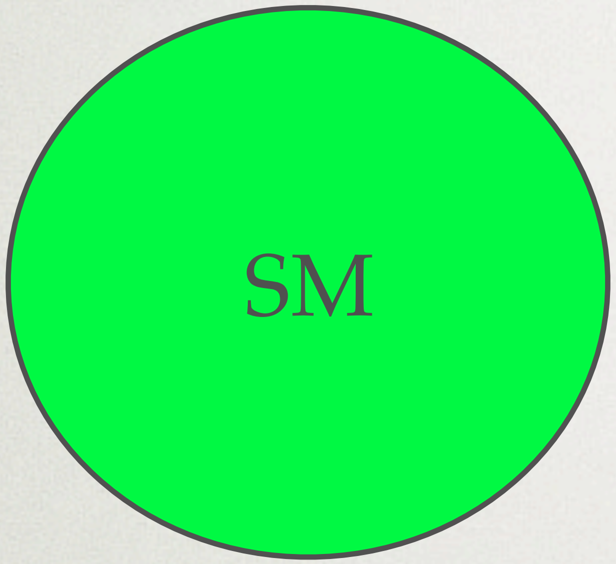
Anything that cancels the tadpoles
(not always needed)

Fully vector-like
(not always present)

Vector-like: mass allowed by SU(3) × SU(2) × U(1)
Fully vector-like: mass allowed by all gauge symmetries

DHS RESULTS
(2004-2005)

Huiszoon, Dijkstra, Schellekens



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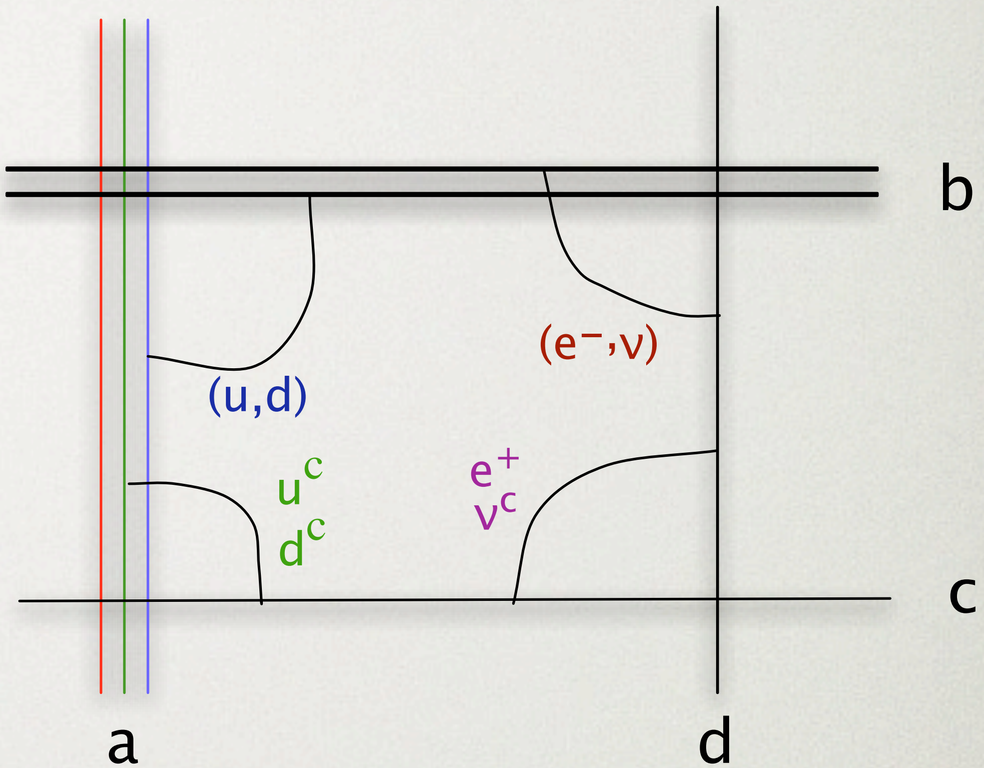


210000 distinct tadpole-free spectra found

Best imaginable result:

The exact MSSM spectrum

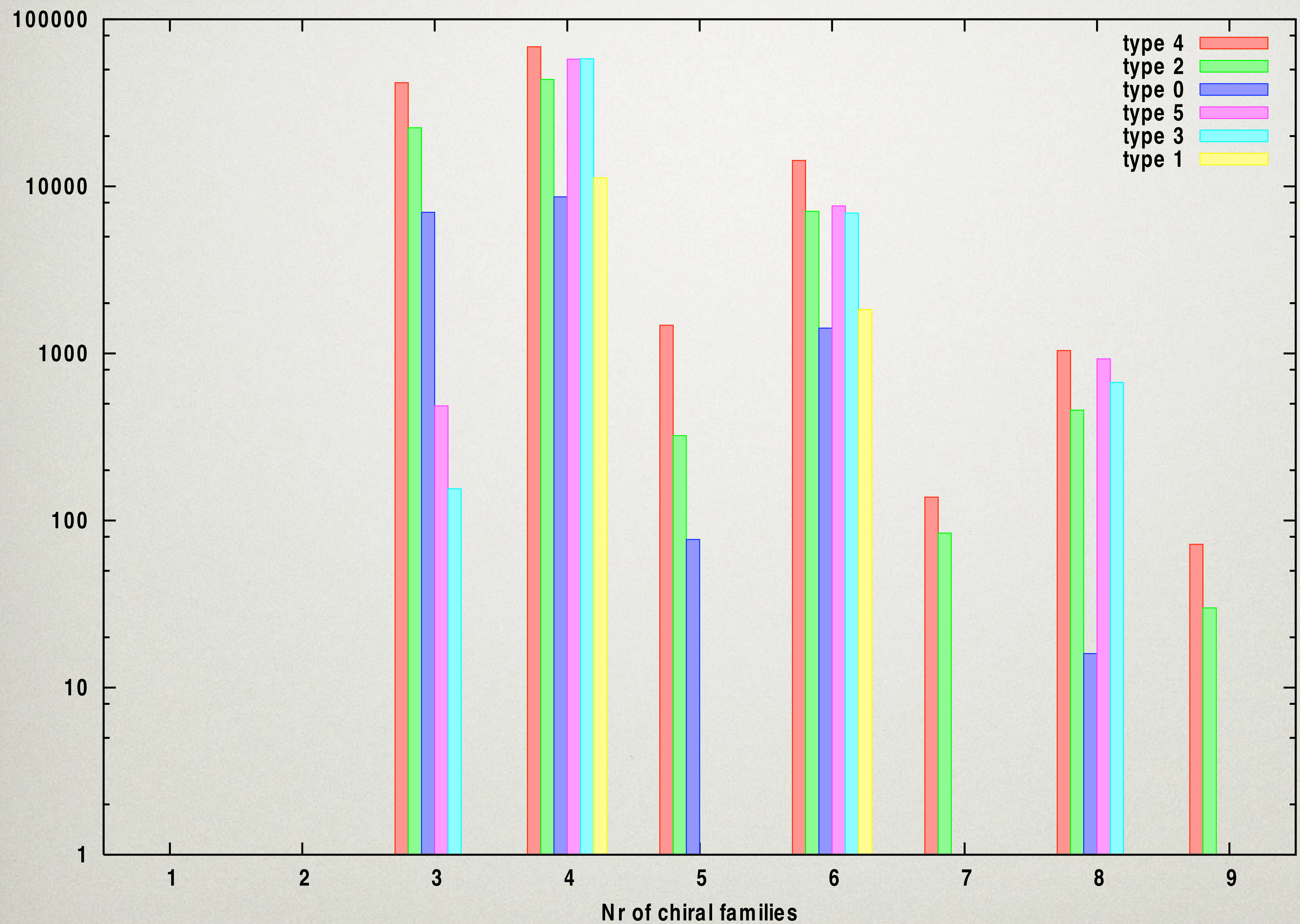
```
Gauge group: U(3) x Sp(2) x U(1) x U(1)

  7 x (V ,V ,0 ,0 ) chirality 3
  3 x (V ,0 ,V ,0 ) chirality -3
  3 x (V ,0 ,V*,0 ) chirality -3
  9 x (0 ,V ,0 ,V ) chirality 3
  5 x (0 ,0 ,V ,V ) chirality -3
  3 x (0 ,0 ,V ,V*) chirality 3
  6 x (V ,0 ,0 ,V )
 10 x (0 ,V ,V ,0 )
  2 x (Ad,0 ,0 ,0 )
  2 x (A ,0 ,0 ,0 )
  6 x (S ,0 ,0 ,0 )
 14 x (0 ,A ,0 ,0 )
 10 x (0 ,S ,0 ,0 )
  9 x (0 ,0 ,Ad,0 )
  6 x (0 ,0 ,A ,0 )
 14 x (0 ,0 ,S ,0 )
  3 x (0 ,0 ,0 ,Ad)
  4 x (0 ,0 ,0 ,A )
  6 x (0 ,0 ,0 ,S )
```

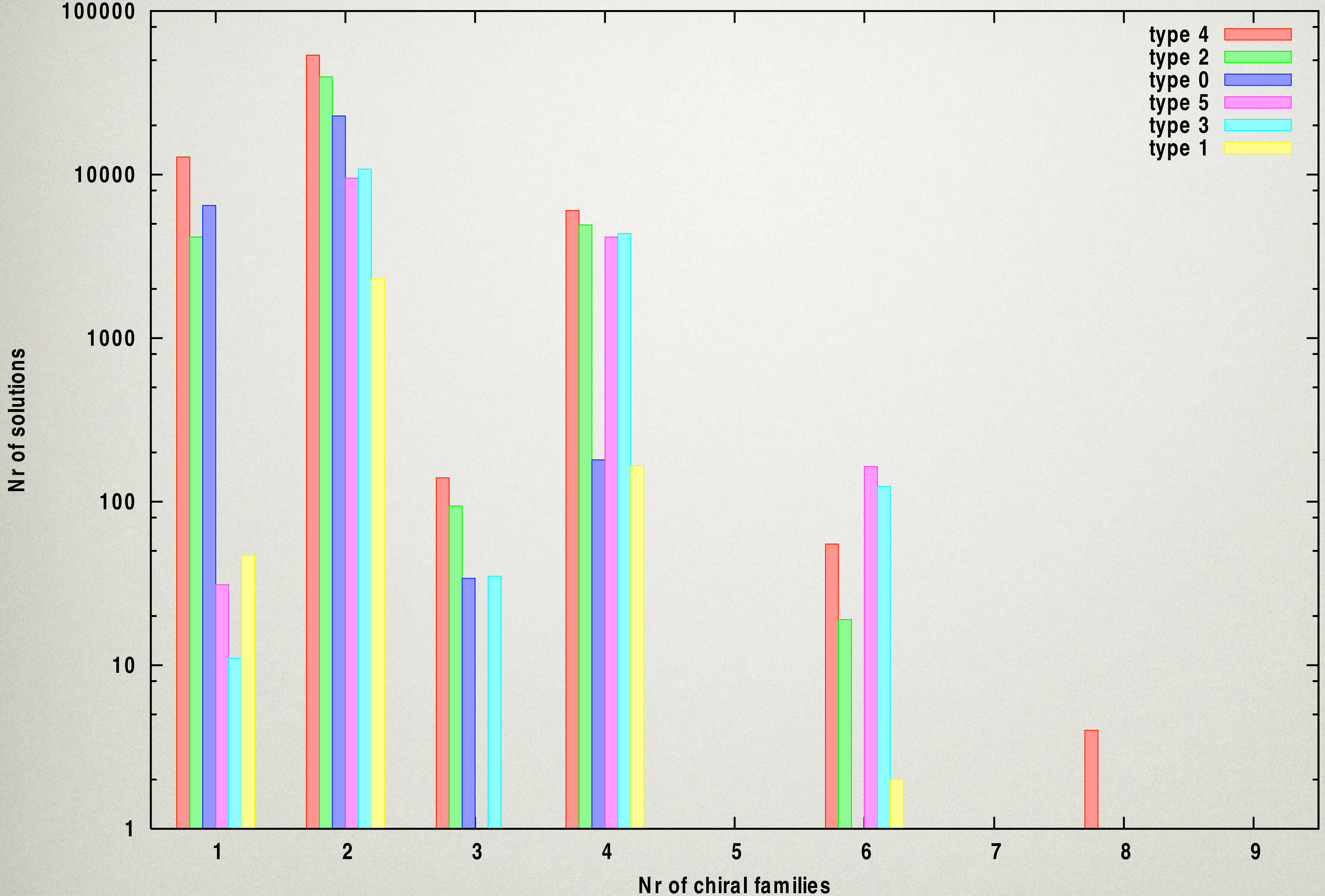
No hidden sector

B-L Massive (axion mixing)

Gauge group:

Exactly SU(3)× SU(2)×U(1)


100000
10000
1000
100
10
1
type 4
type 2
type 0
type 5
type 3
type 1
1
2
3
4
5
6
7
8
9
Nr of chiral families



cf. Gmeiner et. al.

ADKS RESULTS (2005-2006)

Anastasopoulos, Dijkstra, Kiritsis, Schellekens

Search Criteria

Require only:

- U(3) from a single brane
- U(2) from a single brane
- Quarks and leptons, Y from at most four branes
- $G_{CP} \supset SU(3) \times SU(2) \times U(1)$
- Chiral G_{CP} fermions reduce to quarks, leptons (plus non-chiral particles)
- Massless Y

Chan-Paton group

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

Embedding of Y:

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

Q: Brane charges (for unitary branes)

W: Traceless generators

Classification

$$Y = (x - \frac{1}{3})Q_a + (x - \frac{1}{2})Q_b + \underbrace{xQ_C + (x-1)Q_D}$$

Distributed over c and d

Allowed values for x

1/2	Madrid model, Pati-Salam, Flipped SU(5)
0	(broken) SU(5)
1	Antoniadis, Kiritsis, Tomaras model
-1/2, 3/2	
any	Trinification ($x = 1/3$) (orientable)

Results

- 19345 chirally distinct spectra
  (19 of Madrid type)

- 1900 distinct ones with tadpole solutions
  (≈ 1900 distinct hep-th papers)

Statistics

Value of x	Total
0	24483441
1/2	138837612
1	30580
-1/2, 3/2	0
any	1250080

A curiosity

Gauge group $SU(3)\times SU(2) \times U(1) \times [\, U(2)_{Hidden})]$

	U3	S2	U1	U1	U2		
3 x	(V	,V	,0	,0	,0)	chirality 3	Q
3 x	(0	,0	,V	,V	,0)	chirality -3	E*
1 x	(V	,0	,0	,V*	,0)	chirality -1	U*
2 x	(V	,0	,V	,0	,0)	chirality -2	D*
2 x	(0	,V	,0	,V	,0)	chirality 2	L
3 x	(V	,0	,0	,V	,0)	chirality -1	D*+(D+D*)
3 x	(0	,V	,V	,0	,0)	chirality 1	$L+H_1+H_2$
2 x	(V	,0	,V*	,0	,0)	chirality -2	U*
1 x	(0	,0	,V	,V*	,0)	chirality 1	N*
4 x	(A	,0	,0	,0	,0)		U+U*
2 x	(0	,0	,0	,S	,0)		E+E*

A curiosity

Gauge group $SU(3)\times SU(2)\times U(1)\times [\,U(2)_{Hidden})]$

	U3	S2	U1	U1	U2		
3 x	(V	,V	,0	,0	,0)	chirality 3	Q
3 x	(0	,0	,V	,V	,0)	chirality -3	E*
1 x	(V	,0	,0	,V*	,0)	chirality -1	U*
2 x	(V	,0	,V	,0	,0)	chirality -2	D*
2 x	(0	,V	,0	,V	,0)	chirality 2	L
3 x	(V	,0	,0	,V	,0)	chirality -1	D*+(D+D*)
3 x	(0	,V	,V	,0	,0)	chirality 1	$L+H_1+H_2$
2 x	(V	,0	,V*	,0	,0)	chirality -2	U*
1 x	(0	,0	,V	,V*	,0)	chirality 1	N*
4 x	(A	,0	,0	,0	,0)		U+U*
2 x	(0	,0	,0	,S	,0)		E+E*

↑

Truly hidden
hidden sector

A curiosity

Gauge group $SU(3)\times SU(2) \times U(1) \times [\, U(2)_{\text{Hidden}})]$

	U3	S2	U1	U1	U2		
3 x	(V	,V	,0	,0	,0)	chirality 3	Q
3 x	(0	,0	,V	,V	,0)	chirality -3	E*
1 x	(V	,0	,0	,V*	,0)	chirality -1	U*
2 x	(V	,0	,V	,0	,0)	chirality -2	D*
2 x	(0	,V	,0	,V	,0)	chirality 2	L
3 x	(V	,0	,0	,V	,0)	chirality -1	D*+(D+D*)
3 x	(0	,V	,V	,0	,0)	chirality 1	$L+H_1+H_2$
2 x	(V	,0	,V*	,0	,0)	chirality -2	U*
1 x	(0	,0	,V	,V*	,0)	chirality 1	N*
4 x	(A	,0	,0	,0	,0)		U+U*
2 x	(0	,0	,0	,S	,0)		E+E*

Free-field realization with $(2)^6$ Gepner model

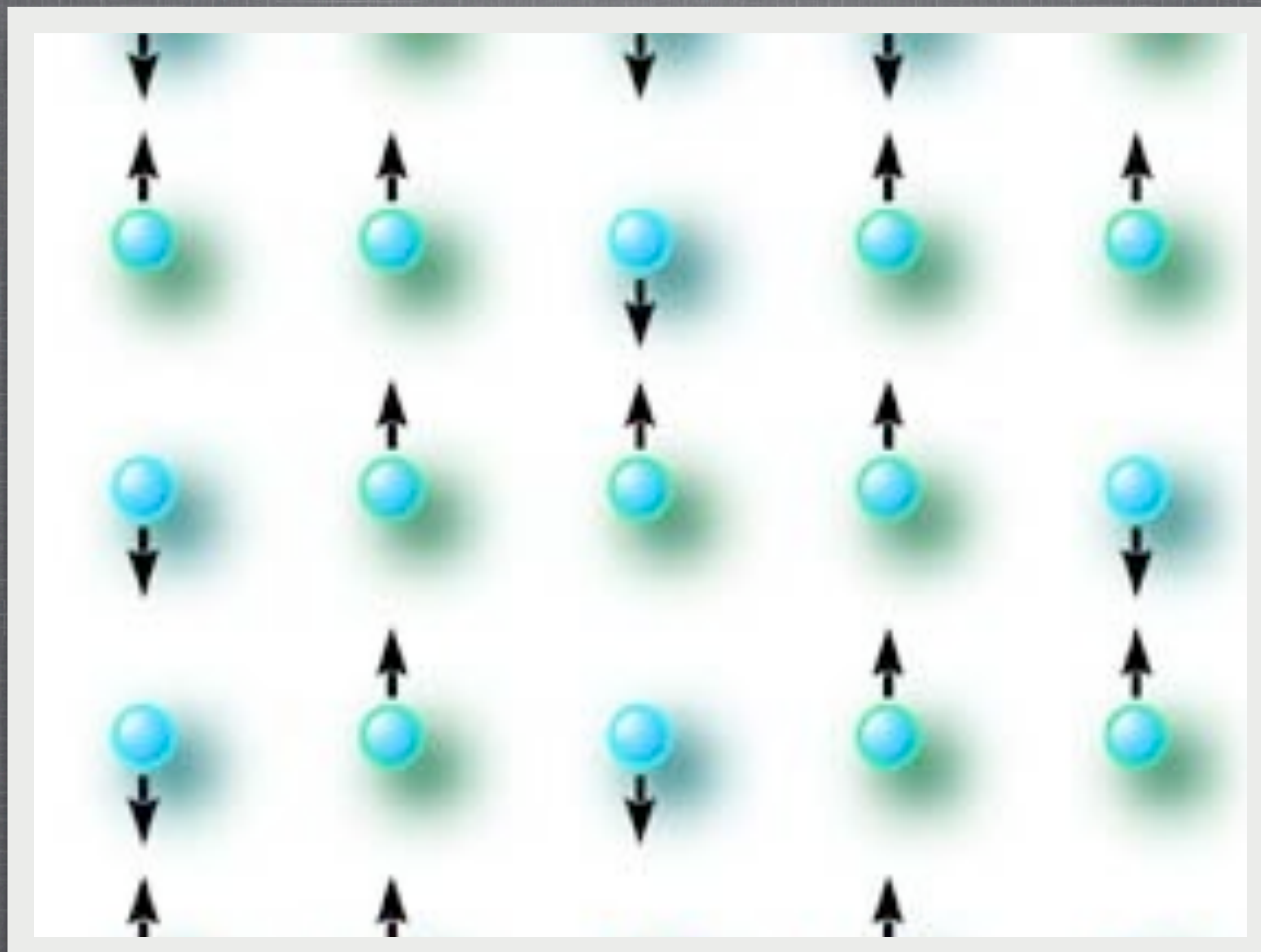
(Kiritsis, Schellekens, Tsulaia, to appear)

FREE THEORIES

Motivation:

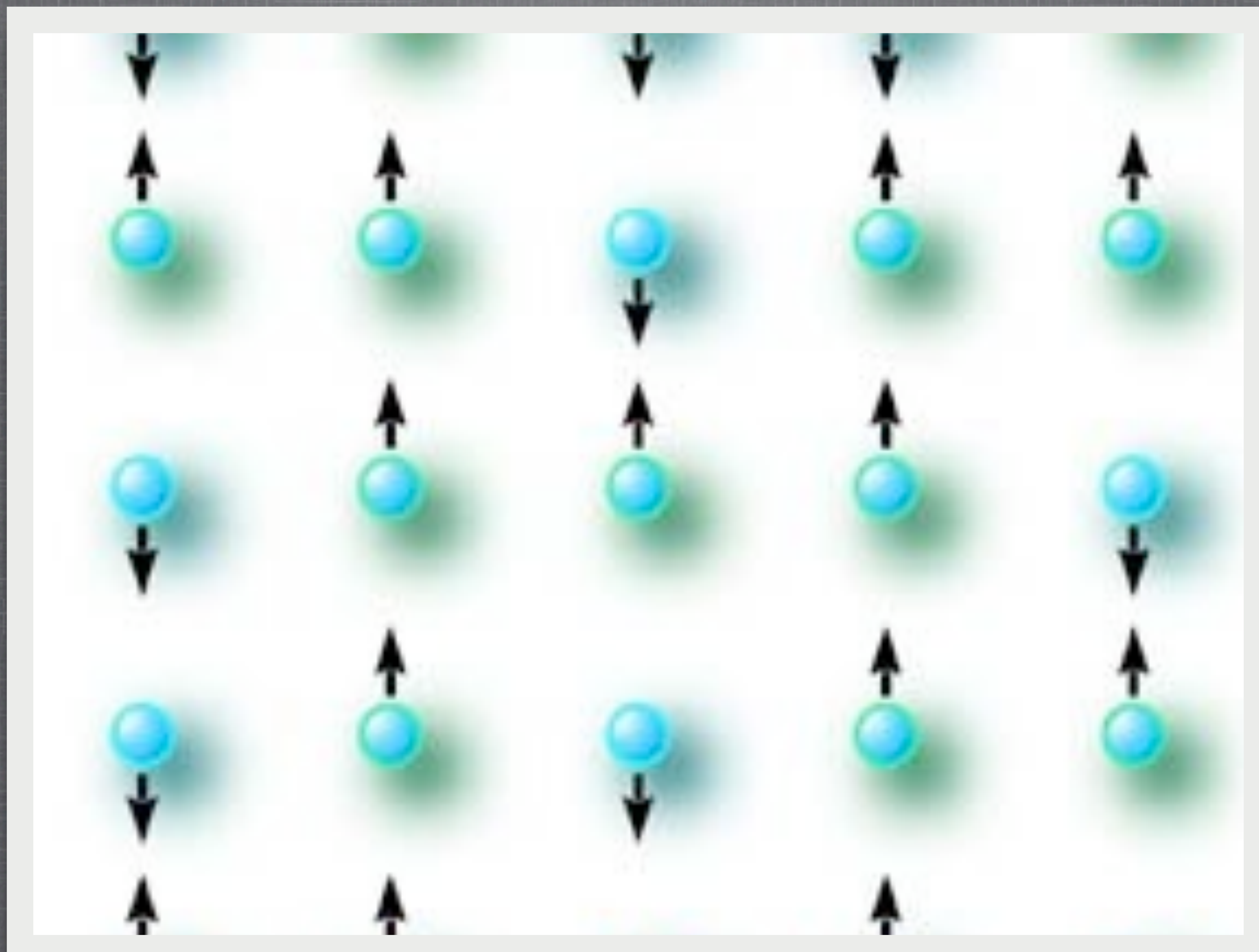
- Compare with other approaches
- Allow computation of more quantities

FREE FERMIONS



FREE FERMIONS

M. Lennek, E. Kiritsis, A.N. Schellekens



NUMBER OF MIPFS

Tensor product of 18 real free fermions or “Ising Models”.
World-sheet susy via KLT-ABK “triplet constraint”.

Complex fermions: $(\text{Ising})^2 \rightarrow D_1$ (within triplets).

$(\text{NSR})\ (D_1)^9$	685 MIPFs
$(\text{NSR})\ (D_1)^7\ (\text{Ising})^4$	7466 MIPFs
$(\text{NSR})\ (D_1)^5\ (\text{Ising})^8$	75427 MIPFs
$(\text{NSR})\ (D_1)^3\ (\text{Ising})^{12}$	534700 MIPFs

Far more MIPFs than for Gepner Models (≈ 5000)

Hodge numbers

359	(51,3,4)
359	(3,51,4)
2962	(31,7,4)
2962	(7,31,4)
4066	(27,3,4)
4066	(3,27,4)
6	(25,1,4)
6	(1,25,4)
1720	(21,9,4)
1720	(9,21,4)
16866	(19,7,4)
16866	(7,19,4)
29118	(17,5,4)
29118	(5,17,4)
11132	(15,3,4)
11132	(3,15,4)
65072	(12,6,4)
65072	(6,12,4)

917	(21,21,8)	(K3 × T2)
2214	(19,19,4)	
13225	(15,15,4)	
6152	(13,13,8)	
12	(13,13,4)	
92684	(11,11,4)	
1187	(9,9,16)	(Tori)
3550	(9,9,8)	
100838	(9,9,4)	
103414	(7,7,4)	
4252	(5,5,8)	
15018	(5,5,4)	
12209	(3,3,4)	
4	(1,1,8)	

cf. Donagi and Faraggi, 2004
($Z_2 \times Z_2$ orbifolds)

SEARCH RESULTS

(NSR) $(D_1)^9$	SM configuration, no tadpole cancellation
(NSR) $(D_1)^7$ $(\text{Ising})^4$	Nothing
(NSR) $(D_1)^5$ $(\text{Ising})^8$	Nothing
(NSR) $(D_1)^3$ $(\text{Ising})^{12}$	Nothing (using random MIPF selection)

SM CONFIGURATION
(FREE BOSONS)

U(4)	U(2)	U(2)	mult.
0	V*	V	2
V*	0	V	1
V	V	0	2
V*	0	V*	2
V	V*	0	1

Exact! No non-chiral states!

Also a U(3)×U(1) version

NON-SUPERSYMMETRIC SPECTRA

B. Gato-Rivera and A.N. Schellekens, Phys.Lett.B656:127-131,2007
and to appear.

Arguments in favor of Susy

- Stabilizes weak hierarchy
- Coupling convergence
- LSP and Dark Matter

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Not needed for C.C.

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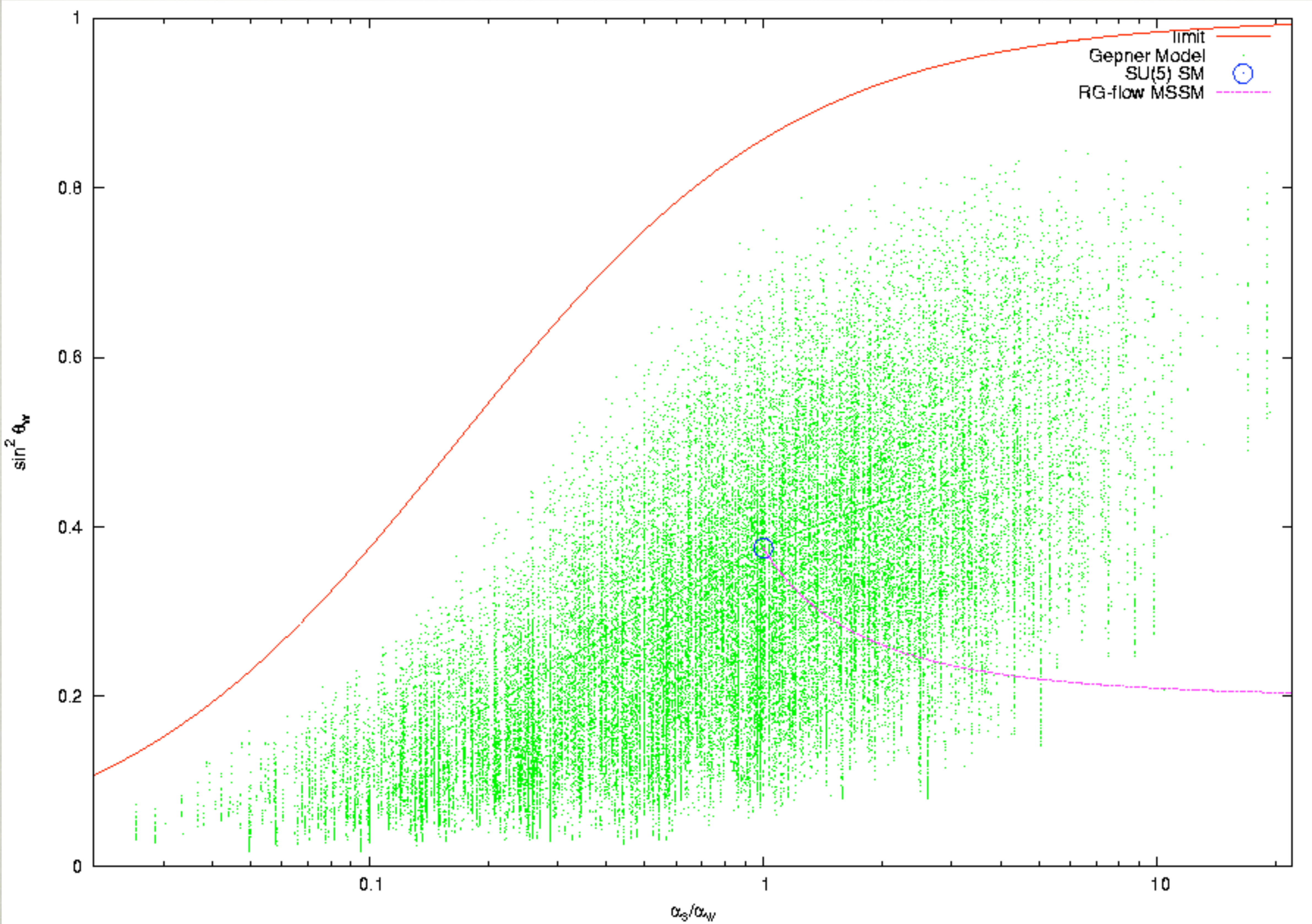

Dijkstra, Huiszoon, Schellekens, **Nucl.Phys.B710:3-57,2005**

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Not needed for C.C.

- ~~Stabilizes weak hierarchy~~
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- ~~Stabilizes weak hierarchy~~ Not needed for C.C.
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For the record: I am NOT making an LHC prediction here!

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- ~~Stabilizes weak hierarchy~~ Not needed for C.C.
- ~~Coupling convergence~~ Coincidence in orientifolds
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For the record: I am NOT making an LHC prediction here!

But: does string theory predict low energy supersymmetry or GUT unification at 10^{16} GeV?

Non-supersymmetric strings

Additional complications:

- Tachyons: Closed sector, Open sector
- Tadpoles: Separate equations for NS and R.

Best imaginable outcome:

- Exactly the standard model (open sector)

But even then, there will be plenty of further problems: tadpoles at genus 1, how to compute anything of interest without the help of supersymmetry, etc.

cf. Ibañez, Marchesano, Rabadan

Closed sector

Four ways of removing closed string tachyons:

- Chiral algebra extension (non-susy)
  All characters non-supersymmetric, but tachyon-free.
- Automorphism MIPF
  No tachyons in left-right pairing of characters.
- Susy MIPF
  Non-supersymmetric CFT, but supersymmetric bulk.
  Allows boundaries that break supersymmetry.
- Klein Bottle
  This introduces crosscap tadpoles. Requires boundaries with non-zero CP multiplicity.

Closed sector

Do these possibilities occur?

- Chiral algebra extension (non-susy)
- Automorphism MIPF
- Susy MIPF
- Klein Bottle

Closed sector

Do these possibilities occur?

- Chiral algebra extension (non-susy) ✖
- Automorphism MIPF ✔ (44054 MIPFs)
- Susy MIPF ✔ (40261 MIPFs)
- Klein Bottle ✔ (186951 Orientifolds)

EXAMPLES OF TADPOLE AND TACHYON-FREE SPECTRA

Orientifolds of tachyon-free non-supersymmetric oriented closed strings (automorphism MIPFs)

CFT 11111111, Extension 176, MIPF 35, orientifold 0

Gauge group Sp(4)
Bosons: 2 × (S) (Symmetric Tensor)
Fermions: None

CFT 11111111, Extension 70, MIPF 56, orientifold 0

Gauge group Sp(4)
Bosons: None (Symmetric Tensor)
Fermions: 2 x (S)

CFT 11111111, Extension 176, MIPF 21, orientifold 0

Gauge group Sp(4)
Bosons: None
Fermions: None

CFT 1112410, Extension 157, MIPF 63, orientifold 0

Gauge group O(4) × U(1) × U(2)

Fermions

2 x (V ,0 ,V) chirality -2
2 x (0 ,V ,V) chirality 2
2 x (0 ,V ,V*) chirality -2
6 x (0 ,0 ,A) chirality -2
4 x (V ,V ,0)
2 x (S ,0 ,0)
6 x (0 ,Ad,0)
4 x (0 ,S ,0)
2 x (0 ,0 ,Ad)

Bosons

2 x (V ,0 ,V)
2 x (A ,0 ,0)
3 x (V ,V ,0)
6 x (0 ,Ad,0)
3 x (0 ,A ,0)
4 x (0 ,S ,0)
3 x (0 ,0 ,Ad)
4 x (0 ,0 ,S)

Chiral!

CFT 11111111, Extension 67, MIPF 508, orientifold 0

Gauge group Sp(2) × U(1)

Fermions

8 x (V ,V)
6 x (S ,0)
6 x (0 ,Ad)
8 x (0 ,S)

Bosons

8 x (V ,V)
5 x (S ,0)
5 x (0 ,Ad)
8 x (0 ,S)

FINDING THE SM

Search for non-susy SM Configurations

Total number of tachyon-free boundary state combinations satisfying our criteria:

3456601

Subdivided as follows

Bulk Susy	3389835	98.1%
Tachyon-free automorphism	66378	1.9%
Tachyon-free Klein bottle projection	388	0.01%

An example

CFT 44716, Extension 124, MIPF 27, Orientifold 0

N=1 Susy Bulk symmetry

Spectrum type 20088 (Not on ADKS list)

Gauge Group $U(3) \times U(2) \times Sp(4) \times U(1)$

(broken by axion couplings to $SU(3) \times SU(2) \times Sp(4) \times U(1)$)

3 x (A ,0 ,0 ,0) chirality 3	3 x (S ,0 ,0 ,0)
3 x (0 ,A ,0 ,0) chirality 3	3 x (0 ,S ,0 ,0)
4 x (0 ,0 ,0 ,A) chirality -2	4 x (0 ,0 ,0 ,A)
5 x (0 ,0 ,0 ,S) chirality -3	5 x (0 ,0 ,0 ,S)
3 x (V ,0 ,V ,0) chirality -1	3 x (V ,0 ,V ,0)
1 x (V ,0 ,0 ,V) chirality 1	2 x (V ,0 ,0 ,V)
1 x (0 ,V ,0 ,V) chirality 1	2 x (0 ,V ,0 ,V)
1 x (0 ,0 ,V ,V) chirality 1	3 x (0 ,0 ,V ,V)
5 x (V ,V ,0 ,0) chirality 3	5 x (V ,V ,0 ,0)
1 x (0 ,V ,V ,0) chirality -1	1 x (0 ,V ,V ,0)
3 x (Ad,0 ,0 ,0)	2 x (Ad,0 ,0 ,0)
3 x (0 ,Ad,0 ,0)	2 x (0 ,Ad,0 ,0)
4 x (0 ,0 ,0 ,Ad)	3 x (0 ,0 ,0 ,Ad)
2 x (0 ,0 ,A ,0)	1 x (0 ,0 ,S ,0)
4 x (S ,0 ,0 ,0)	4 x (A ,0 ,0 ,0)
4 x (0 ,S ,0 ,0)	4 x (0 ,A ,0 ,0)
2 x (V ,0 ,0 ,V*)	
2 x (0 ,V ,0 ,V*)	
2 x (V ,V*,0 ,0)	2 x (V ,V*,0 ,0)

3 x (A ,0 ,0 ,0) chirality 3	3 x (S ,0 ,0 ,0)
3 x (0 ,A ,0 ,0) chirality 3	3 x (0 ,S ,0 ,0)
4 x (0 ,0 ,0 ,A) chirality -2	4 x (0 ,0 ,0 ,A)
5 x (0 ,0 ,0 ,S) chirality -3	5 x (0 ,0 ,0 ,S)
3 x (V ,0 ,V ,0) chirality -1	3 x (V ,0 ,V ,0)
1 x (V ,0 ,0 ,V) chirality 1	2 x (V ,0 ,0 ,V)
1 x (0 ,V ,0 ,V) chirality 1	2 x (0 ,V ,0 ,V)
1 x (0 ,0 ,V ,V) chirality 1	3 x (0 ,0 ,V ,V)
5 x (V ,V ,0 ,0) chirality 3	5 x (V ,V ,0 ,0)
1 x (0 ,V ,V ,0) chirality -1	1 x (0 ,V ,V ,0)
3 x (Ad,0 ,0 ,0)	2 x (Ad,0 ,0 ,0)
3 x (0 ,Ad,0 ,0)	2 x (0 ,Ad,0 ,0)
4 x (0 ,0 ,0 ,Ad)	3 x (0 ,0 ,0 ,Ad)
2 x (0 ,0 ,A ,0)	1 x (0 ,0 ,S ,0)
4 x (S ,0 ,0 ,0)	4 x (A ,0 ,0 ,0)
4 x (0 ,S ,0 ,0)	4 x (0 ,A ,0 ,0)
2 x (V ,0 ,0 ,V*)	
2 x (0 ,V ,0 ,V*)	
2 x (V ,V*,0 ,0)	2 x (V ,V*,0 ,0)

3 x (A ,0 ,0 ,0) chirality 3	3 x (S ,0 ,0 ,0)
3 x (0 ,A ,0 ,0) chirality 3	3 x (0 ,S ,0 ,0)
4 x (0 ,0 ,0 ,A) chirality -2	4 x (0 ,0 ,0 ,A)
5 x (0 ,0 ,0 ,S) chirality -3	5 x (0 ,0 ,0 ,S)
3 x (V ,0 ,V ,0) chirality -1	3 x (V ,0 ,V ,0)
1 x (V ,0 ,0 ,V) chirality 1	2 x (V ,0 ,0 ,V)
1 x (0 ,V ,0 ,V) chirality 1	2 x (0 ,V ,0 ,V)
1 x (0 ,0 ,V ,V) chirality 1	3 x (0 ,0 ,V ,V)
5 x (V ,V ,0 ,0) chirality 3	5 x (V ,V ,0 ,0)
1 x (0 ,V ,V ,0) chirality -1	1 x (0 ,V ,V ,0)
3 x (Ad,0 ,0 ,0)	2 x (Ad,0 ,0 ,0)
3 x (0 ,Ad,0 ,0)	2 x (0 ,Ad,0 ,0)
4 x (0 ,0 ,0 ,Ad)	3 x (0 ,0 ,0 ,Ad)
2 x (0 ,0 ,A ,0)	1 x (0 ,0 ,S ,0)
4 x (S ,0 ,0 ,0)	4 x (A ,0 ,0 ,0)
4 x (0 ,S ,0 ,0)	4 x (0 ,A ,0 ,0)
2 x (V ,0 ,0 ,V*)	
2 x (0 ,V ,0 ,V*)	
2 x (V ,V*,0 ,0)	2 x (V ,V*,0 ,0)

FINDING HIDDEN SECTORS

A tachyon-free, tadpole-free hidden sector could be found for 896 of the 3456601 SM configurations.

All of these have bulk susy.

“Statistically” 16 would be expected for the tachyon-free automorphism, 0 for tachyon-free Klein bottles.

All 896 have a supersymmetric spectrum (exact boson fermion matching). They are probably identical to supersymmetric models from earlier searches.

Conclusions

- Non-supersymmetric, tadpole and tachyon-free standard models must exist, but are still hidden in the noise.
- Better chance with 1, 2 or 4 families.
- Supersymmetry is very persistent.