Non-supersymmetric Gepner Orientifolds

A.N. Schellekens

NIKHEF

String Phenomenology 2008

Based on

- B. Gato-Rivera and A.N. Schellekens,

  Phys.Lett.B656:127-131,2007

  and to appear.

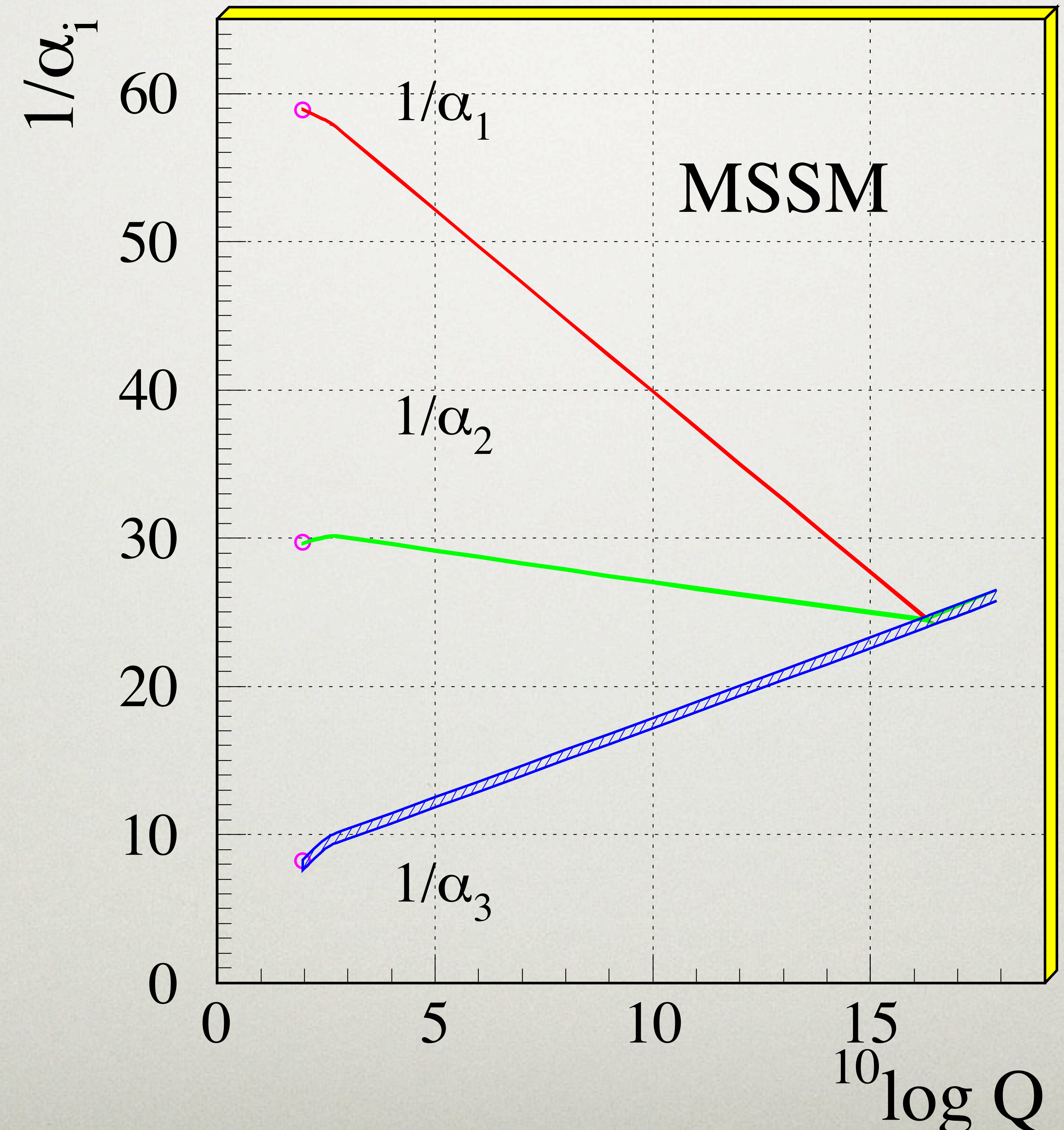
- Also:
  Dijkstra, Huiszoon, Schellekens,

  Phys.Lett.B609:408-417,2005, Nucl.Phys.B710:3-57,2005,

  Anastasopoulos, Dijkstra, Kiritsis, Schellekens.

  Nucl.Phys.B759:83-146,2006

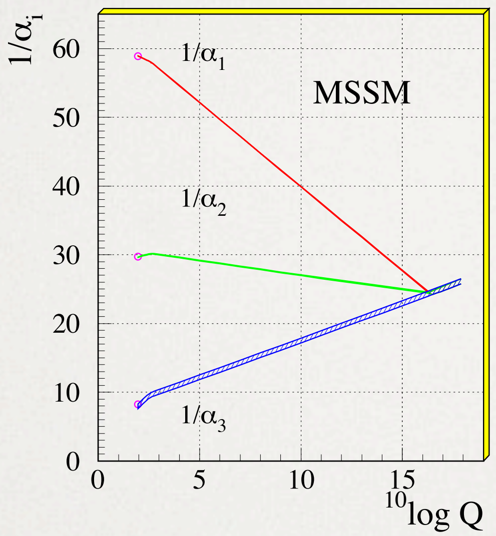
LHC may provide evidence in favor of this picture:

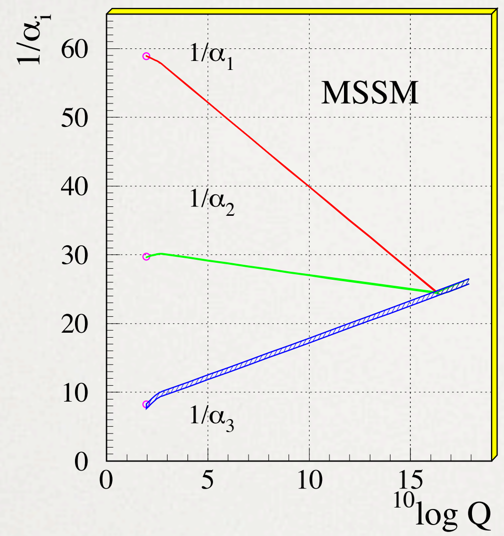


Finding supersymmetry plus better evidence for GUT unification would be an exciting event in “Beyond the Standard Model” phenomenology.

It would point to a new fundamental theory with more symmetries.

But we are *string* phenomenologists, so we already have some idea what that new fundamental theory should be.

But might this  be just a coincidence?

But might this  be just a coincidence?

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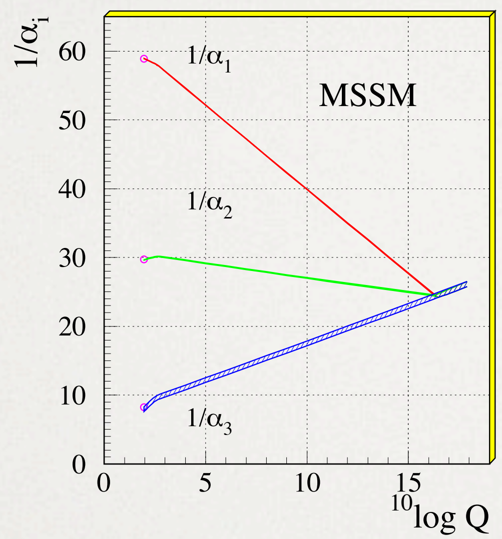
But might this  be just a coincidence?

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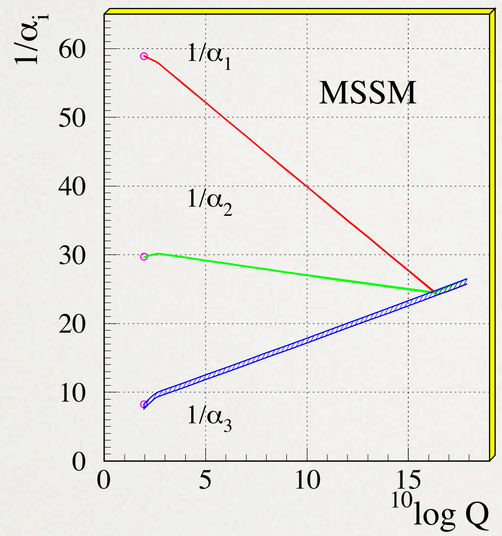
Ibanez, Marchesano, Rabadan, Cveltic, Shiu, Uranga, Lüst, Blumenhagen, Gorlich, Ott, Honecker, Quevedo, Cremades, Conlon, Verlinde, Wijnholt, Weigand, Gmeiner, Aldazabal, Andres, Font, Juknevich, Li, Liu, Körs, Stieberger, Cascales, Camara, Antoniadis, Kiritsis, Anastasopoulos, Kokorelis, Rizos, Tomaras, Bailin, Love, Nanopoulos, ...

But might this  be just a coincidence?

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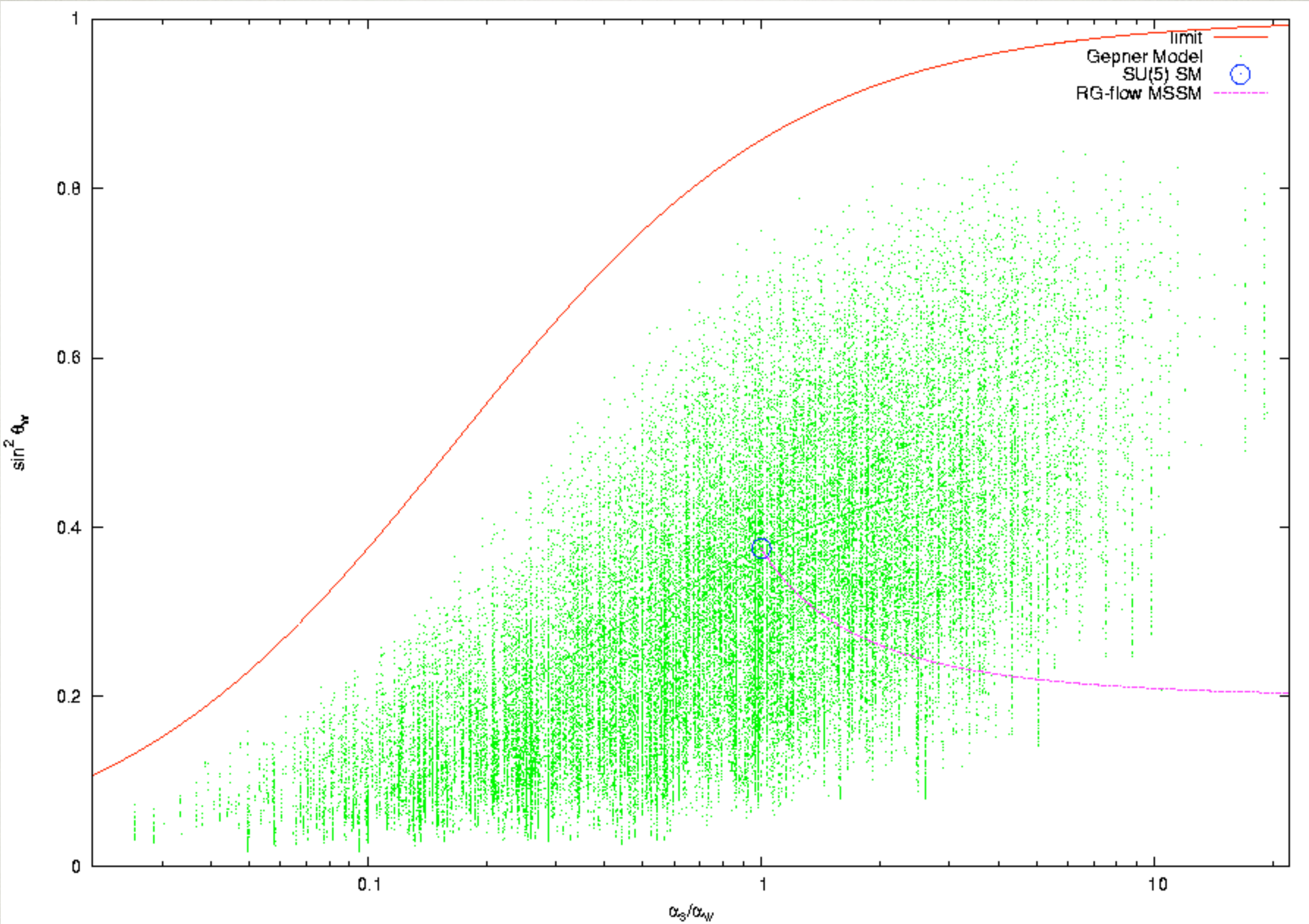
So we are in excellent company...

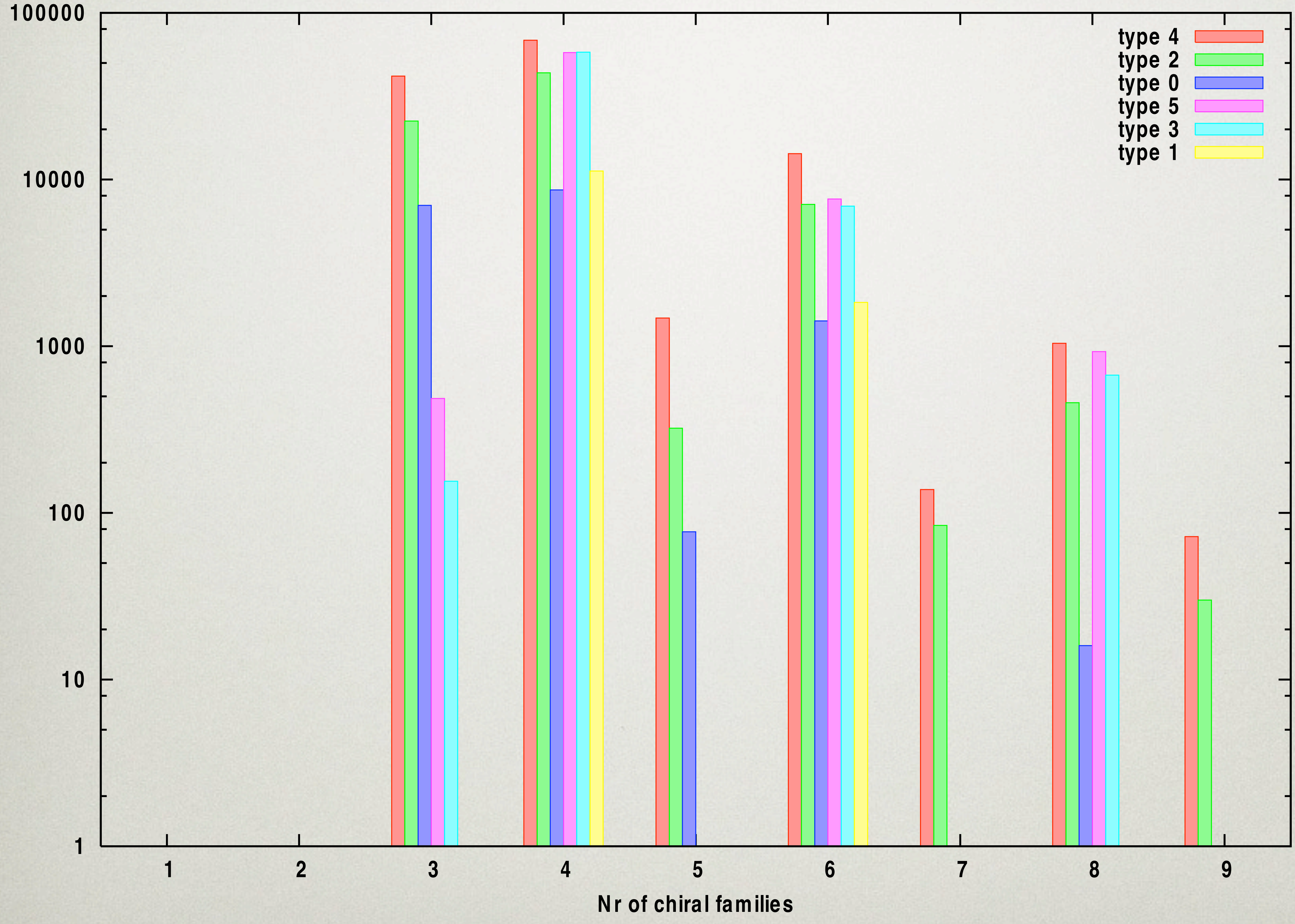


Dijkstra, Huiszoon, Schellekens, **Nucl.Phys.B710:3-57,2005**

Motivation

Motivation

- If coupling constant convergence is just a coincidence, who needs susy?
- Even if not, this part of the landscape must be explored anyway, in order to know why we *don't* live there.
- Can we really eradicate susy from the spectrum?
- The supersymmetric results suggest that Gepner models are more "generic" that free-field theory based approaches (free fermions, orbifolds)
- It can be done.



100000
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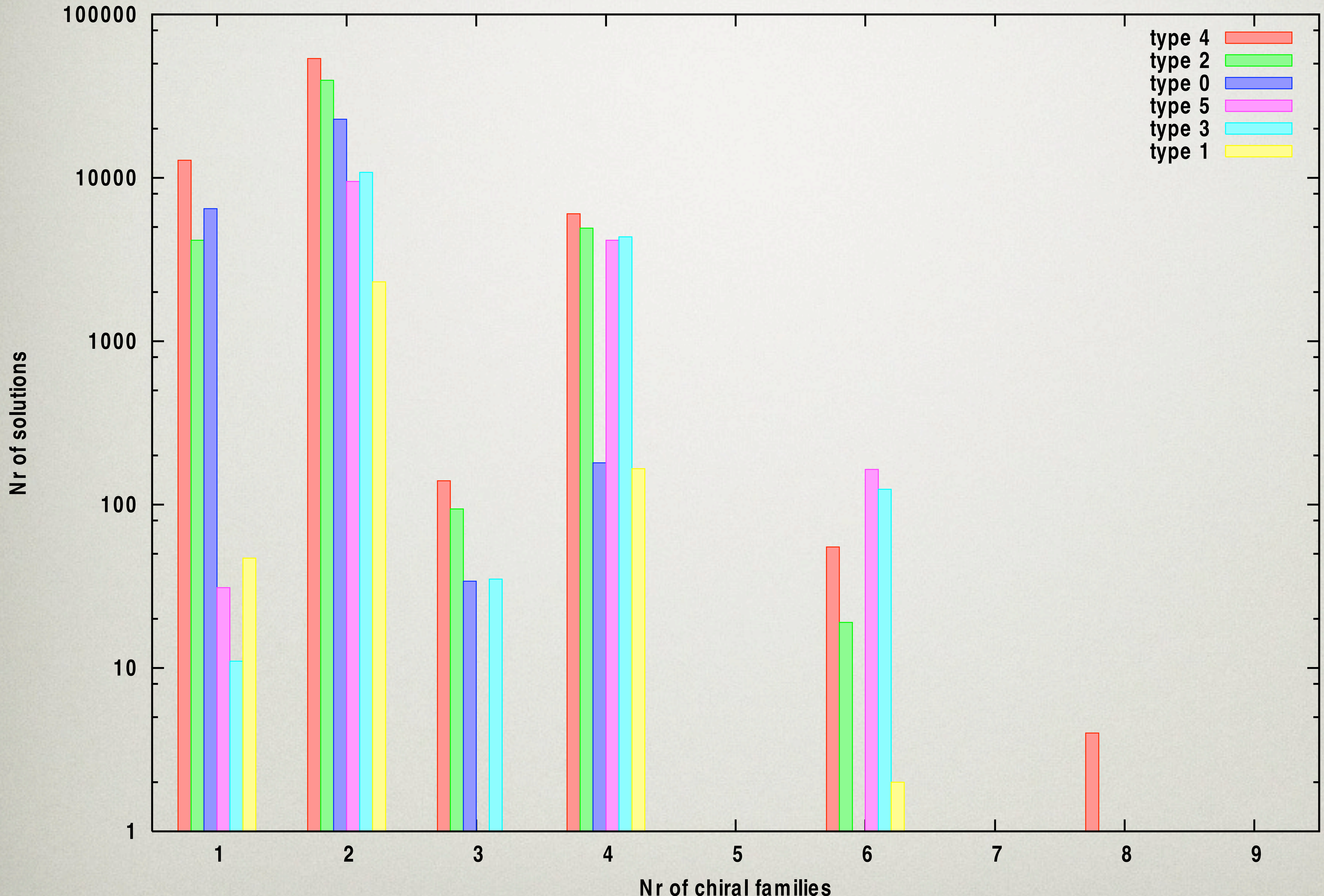
Nr of chiral families
type 4
type 2
type 0
type 5
type 3
type 1



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

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)

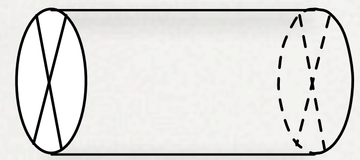
a : Boundary label (finite range)

χ_i : Character

N_a : Chan-Paton (CP) Multiplicity

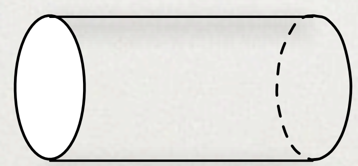
Coefficients

- Klein bottle



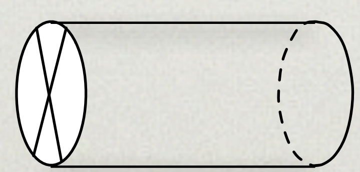
$$K^i = \sum_{m,J,J'} \frac{{S^i}_m U_{(m,J)} g^{\Omega,m}_{J,J'} U_{(m,J')}}{S_{0m}}$$

- Annulus



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

- Moebius



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

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

Boundaries and Crosscaps

- Boundary coefficients

$$R_{[a,\psi_a](m,J)} = \sqrt{\frac{|\mathcal{H}|}{|\mathcal{C}_a||\mathcal{S}_a|}}\psi_a^*(J)S^J_{am}$$

- Crosscap coefficients

$$U_{(m,J)} = \frac{1}{\sqrt{|\mathcal{H}|}}\sum_{L\in\mathcal{H}} e^{\pi i(h_K - h_{KL})}\beta_K(L)P_{LK,m}\delta_{J,0}$$

Cardy (1989)
Sagnotti, Pradisi, Stanev (~1995)
Huiszoon, Fuchs, Schellekens, Schweigert, Walcher (2000)

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

Non-supersymmetric string theories

A surprisingly common misconception:

``Absence of tachyons requires supersymmetry."

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Counter example: O(16) x O(16) Heterotic string.

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Many examples in four dimensions, e.g.

Kawai, Tye, Lewellen, Lerche, Lüst, A.N.S, Kachru, Silverstein, Kumar, Shiu, Dienes, Blum, Angelantonj, Sagnotti, Blumenhagen, Font, ...

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Once again we are in excellent company.

Non-supersymmetric strings

Additional complications:

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

Non-supersymmetric strings

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.

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)

Tachyon-free closed strings

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	63	26	816	0,0,0,0	4,0,0,0
	333	130	33804	72,48,0,0	635,40,0,0
	12	3	14	0,0,0,0	1,0,0,0
	36	10	162	0,12,0,0	0,0,0,0
	123	61	1160	15,16,0,0	0,0,0,0
	36	12	186	0,6,0,0	0,0,0,0
)	78	29	1208	16,24,0,0	1,1,0,0
	108	35	892	0,8,0,0	0,0,0,0
	228	106	8888	16,24,0,0	39,3,0,0
	88	43	3652	0,0,0,0	0,16,0,0
	197	113	8534	430,95,0,0	395,78,0,0
	216	100	16972	408,148,0,0	676,0,0,0
	265	164	49008	160,120,0,0	396,172,0,0
	546	403	388155	2912,1583,0,387	4180,1564,0,0
	754	617	2112682	17680,12560,0,1942	105653,43836,6818,4202
)	56	31	2984	28,52,0,0	0,0,0,0
	120	80	8668	270,200,26,0	97,86,0,0
	126	82	12832	0,84,32,0	27,50,4,0
	120	91	38228	0,448,0,186	0,416,0,0
4)	60	41	4426	218,190,95,0	9,11,8,0
2)	35	24	2838	0,18,24,0	0,0,0,0
1,1)	289	202	161774	52058,17568,5359,0	41168,10292,3993,478

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EXAMPLES OF TADPOLE AND TACHYON-FREE SPECTRA

I. Orientifolds of tachyon-free closed strings

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 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)

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)

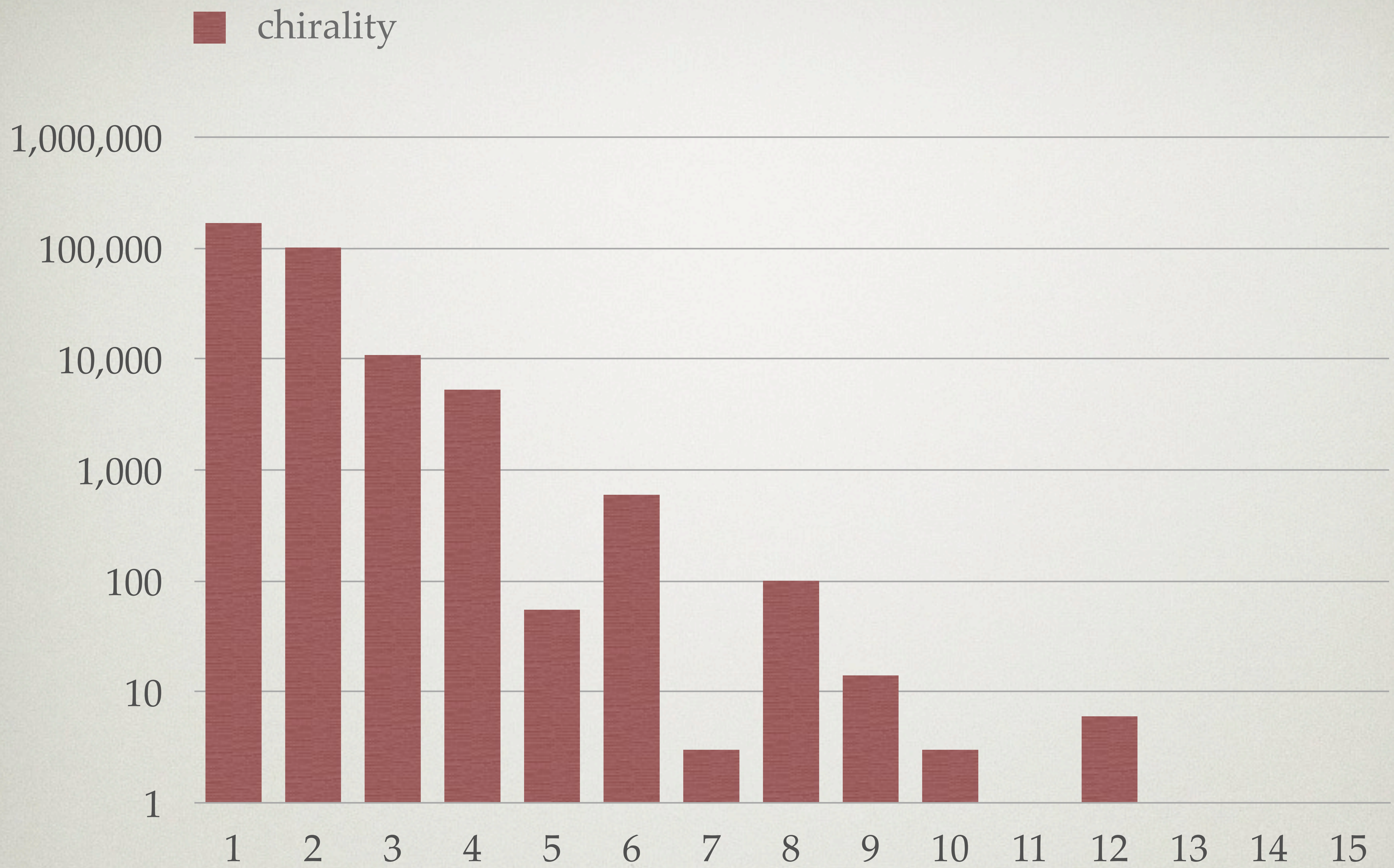
EXAMPLES OF TADPOLE AND TACHYON-FREE SPECTRA

II. Orientifolds of tachyonic closed strings,
with tachyons projected out by the Klein bottle

CFT 22266, Extension 710, MIPF 635, orientifold 6

Gauge group U(1) × U(1) × U(4) × U(2)

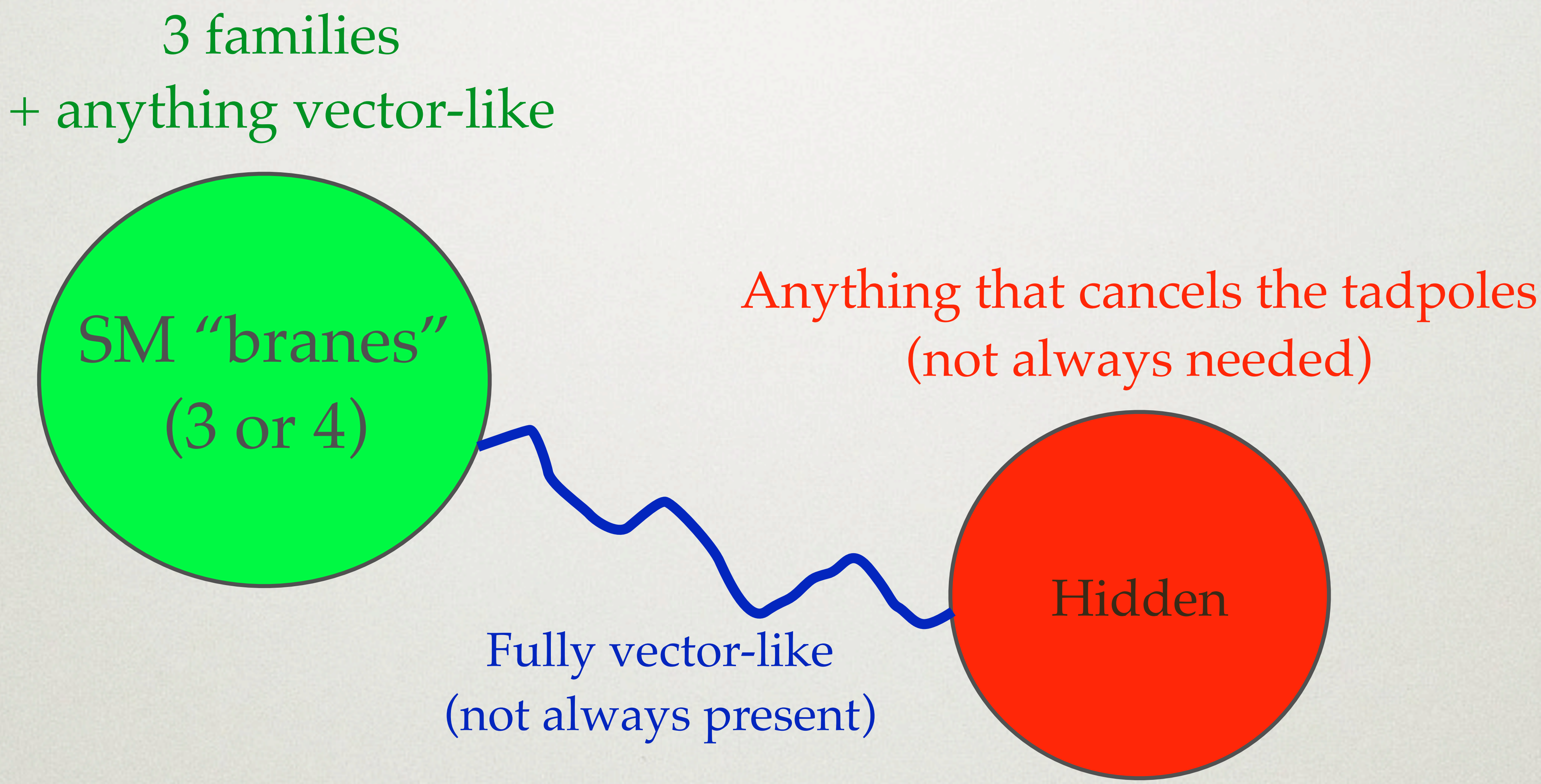
3 x (V ,0 ,0 ,V) chirality 3	3 x (V ,0 ,0 ,V)
3 x (V ,0 ,0 ,V*) chirality -3	3 x (V ,0 ,0 ,V*)
3 x (0 ,V ,0 ,V) chirality -3	3 x (0 ,V ,0 ,V)
3 x (0 ,V ,0 ,V*) chirality 3	3 x (0 ,V ,0 ,V*)
1 x (V ,0 ,V ,0) chirality 1	1 x (V ,0 ,V ,0)
1 x (V ,0 ,V*,0) chirality -1	1 x (V ,0 ,V*,0)
1 x (0 ,V ,V ,0) chirality -1	1 x (0 ,V ,V ,0)
1 x (0 ,V ,V*,0) chirality 1	1 x (0 ,V ,V*,0)
6 x (V ,V ,0 ,0)	6 x (V ,V ,0 ,0)
6 x (V ,V*,0 ,0)	6 x (V ,V*,0 ,0)
2 x (0 ,0 ,V ,V)	2 x (0 ,0 ,V ,V)
1 x (0 ,0 ,Ad,0)	2 x (0 ,0 ,0 ,Ad)
3 x (0 ,0 ,0 ,Ad)	3 x (Ad,0 ,0 ,0)
4 x (0 ,0 ,V ,V*)	2 x (A ,0 ,0 ,0)
2 x (Ad,0 ,0 ,0)	2 x (S ,0 ,0 ,0)
4 x (A ,0 ,0 ,0)	3 x (0 ,Ad,0 ,0)
4 x (S ,0 ,0 ,0)	2 x (0 ,A ,0 ,0)
2 x (0 ,Ad,0 ,0)	2 x (0 ,S ,0 ,0)
4 x (0 ,A ,0 ,0)	2 x (0 ,0 ,A ,0)
4 x (0 ,S ,0 ,0)	2 x (0 ,0 ,S ,0)
4 x (0 ,0 ,0 ,S)	6 x (0 ,0 ,0 ,A)
	2 x (0 ,0 ,0 ,S)



Based on a sample of 72912 tadpole and tachyon-free spectra

FINDING THE SM

Models



Vector-like: mass allowed by SU(3) × SU(2) × U(1)
(Higgs, right-handed neutrino, gauginos, sparticles....)

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

(*) Anastasopoulos et. al. (2006)

Supersymmetric Gepner models

- 168 tensor combinations(Susy extension)
- 5403 MIPFs (880 Hodge number pairs)
- 49322 Orientifolds

Two scans:

with Dijkstra, Huiszoon (2004/2005)

- 19 Chiral types ("Madrid models")
- 18 with tadpole cancellation
- 211000 non-chirally distinct spectra

with Anastasopoulos, Dijkstra, Kiritsis (2005/2006)

- 19345 Chiral types
- 1900 with tadpole cancellation

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)
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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.

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Preliminary

Conclusions

- Non-supersymmetric, tadpole and tachyon-free standard models must exist, but are still hidden in the noise.
- Supersymmetry is very persistent.