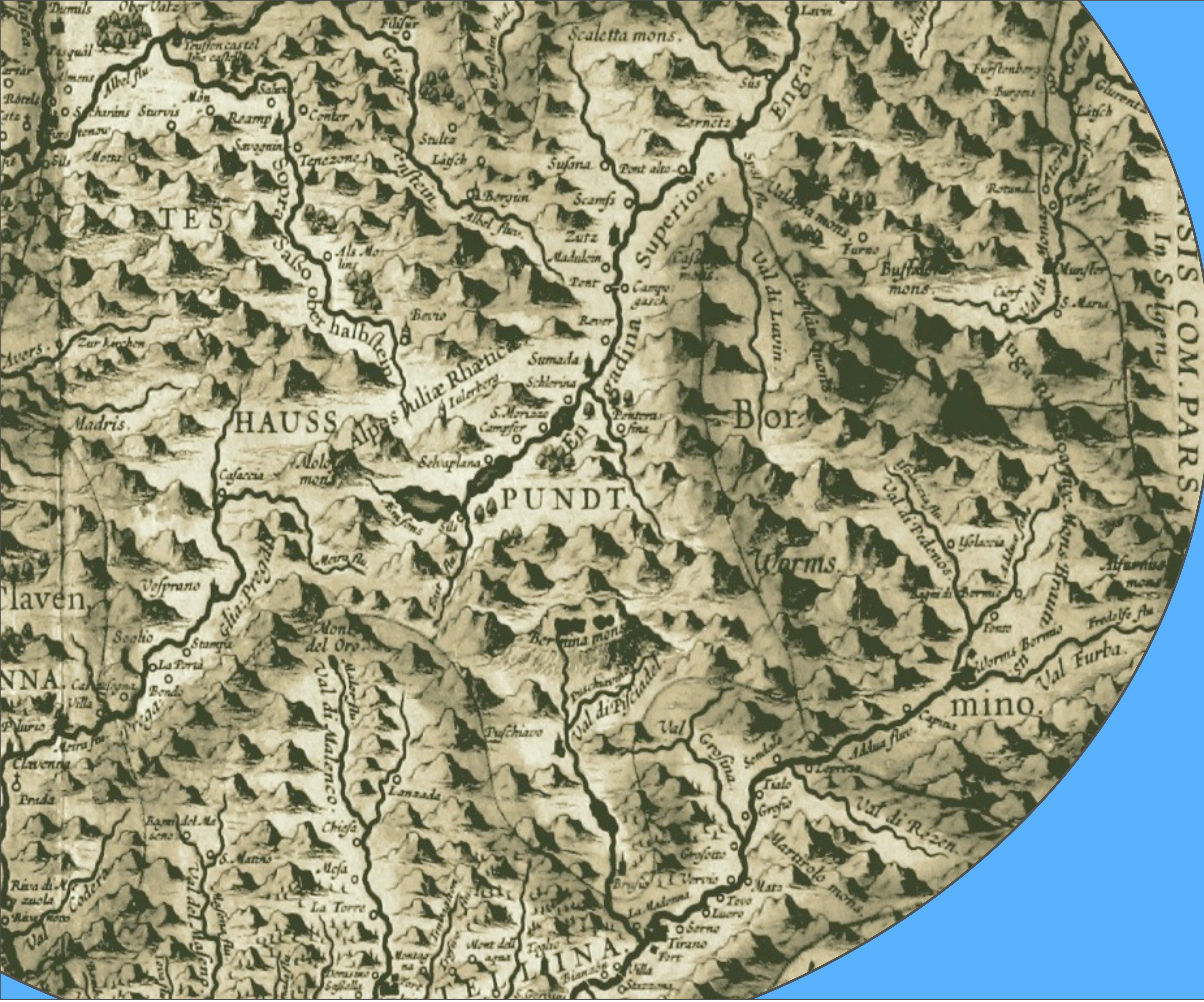
RCFT Orientifolds

Bert Schellekens

Paris, September 3 2008

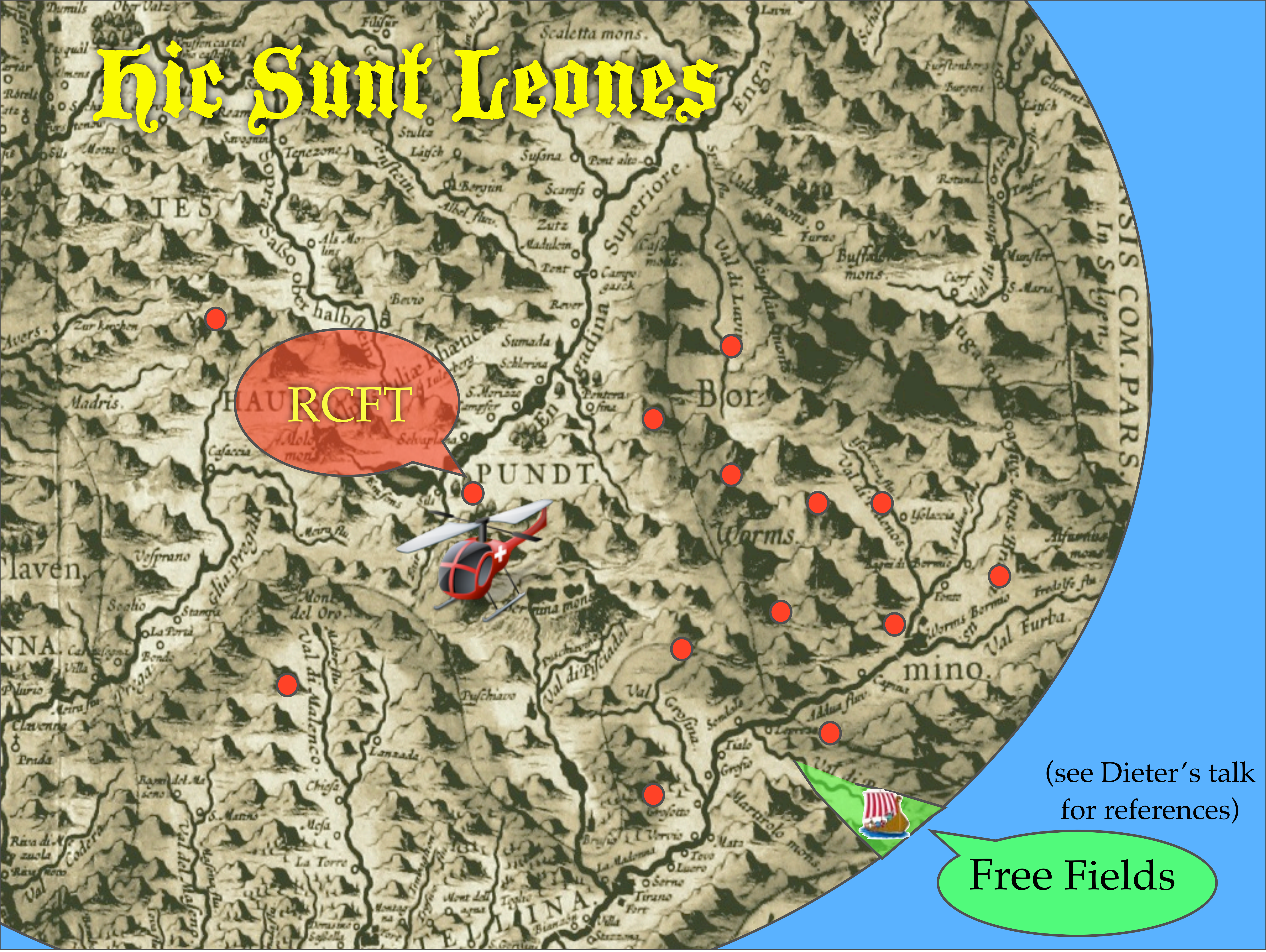
Sunday, 2 May 2010


Scaletta mons.
Lavin
Sus
Zernetz
Enga
Superiore.
Engadina
En
Pont alto
Susana
Scamfs
Zutz
Madulein
Pont
Campogasch
Bever
Sumada
Schlerina
S. Morizze
Campfer
Schoaplana
Sils
PUNDT.
HAUSS
TES
Alpes Iuliæ Rhæticæ
ober halbstein
Bevio
Savognin
Tenezone
Conter
Stulz
Latsch
Bergun
Filisur
Reamp
Albel flu.
Avers.
Zur kirchen
Madris.
Casaccia
Claven
Soglio
Stampa
La Porta
Mont del Oro
Val di Malenco.
Lanzada
Chiesa
Mesa
La Torre
Bernina mons
Val di Pisciadel
Puschiavo
Val Grosina.
Grosotto
Vervio
Mazo
Tovo
Lovero
Sernio
Tirano
Villa
Sondalo
Tiolo
Grosio
Martirolo mons.
Val di Rezen.
mino.
Val Furba.
Fonte
Worms.
Bor
Val di Luvin
Val di Pedenos.
Ysolaccia
Furno
Buffalora mons.
Munster
S. Maria
In Solgen.
NSIS COM. PARS.

(see Dieter's talk for references)

Free Fields


RCFT
Free Fields
(see Dieter's talk
for references)

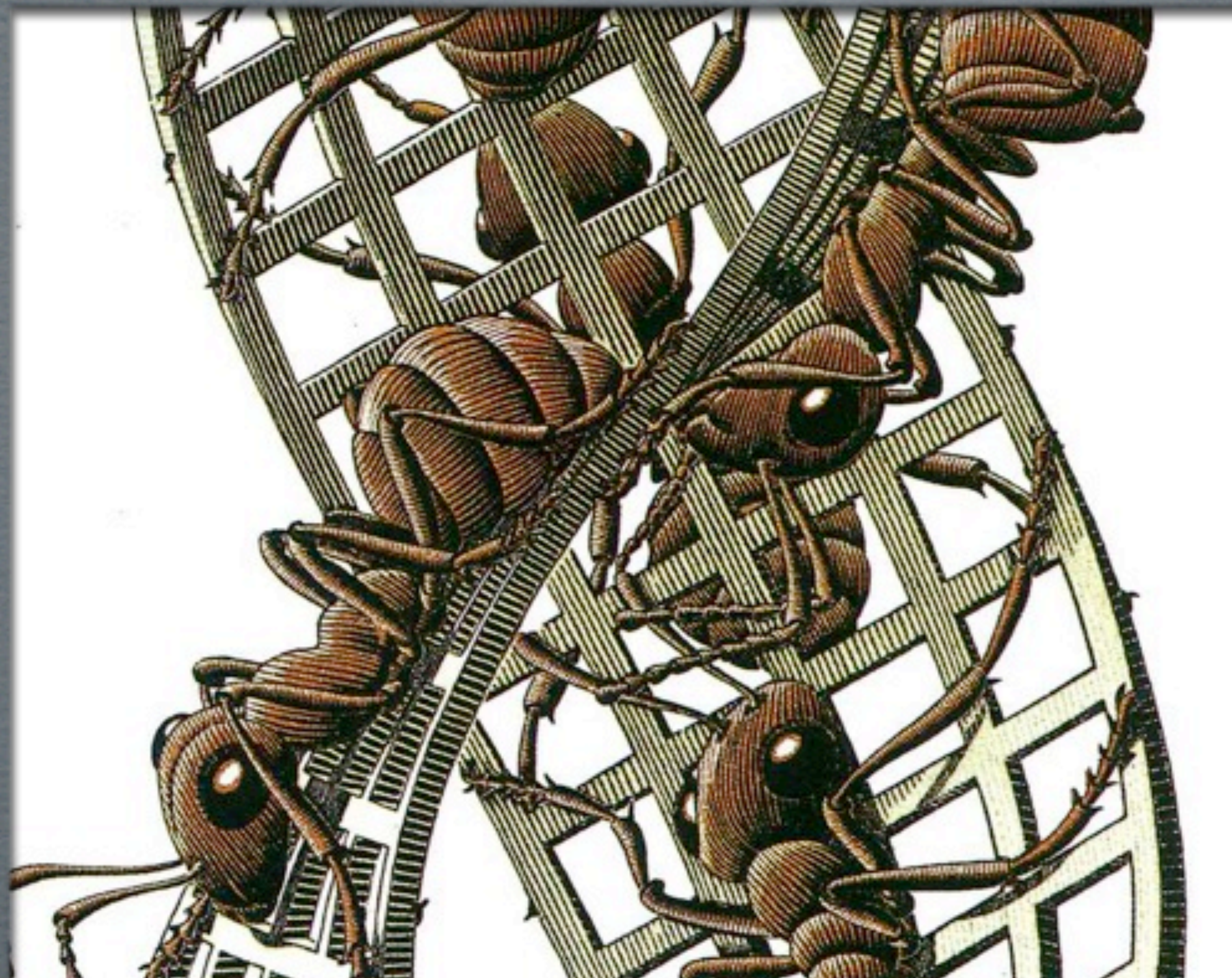

Hic Sunt Leones
RCFT
Free Fields
(see Dieter's talk
for references)

What we can compute

- Exact perturbative string spectra
- Gauge couplings in rational points
- RCFT instanton corrections

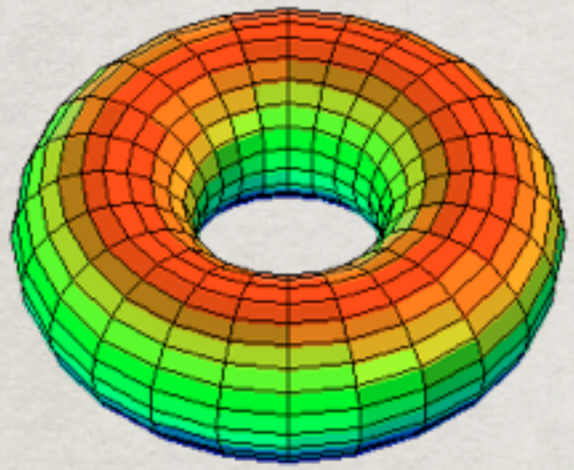
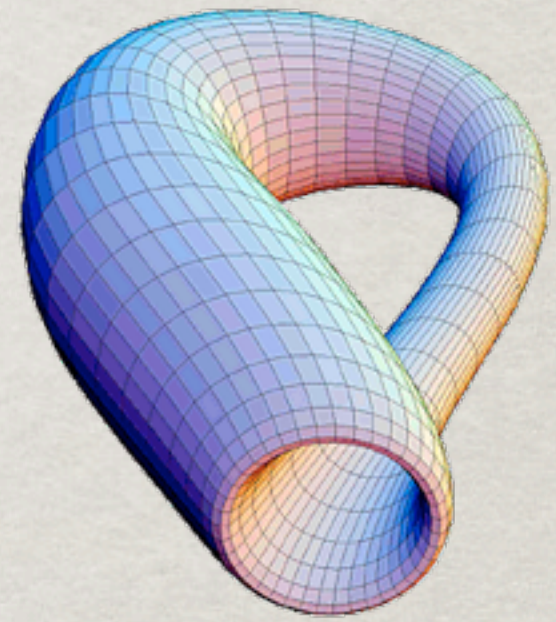
What we can't do (yet)

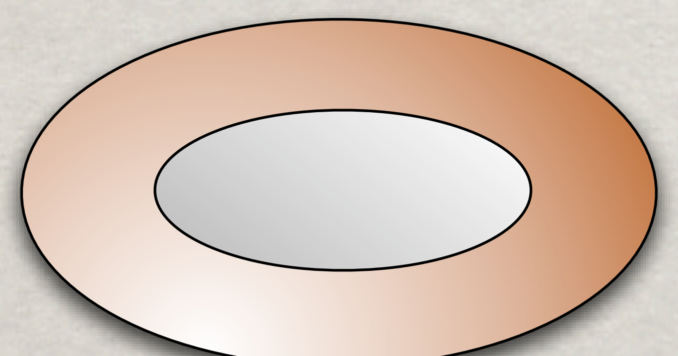
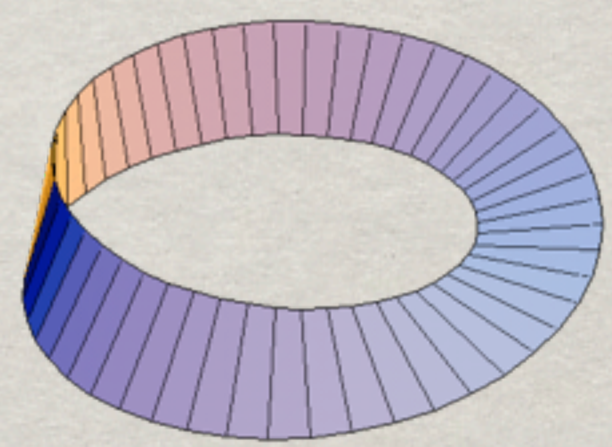
- Compute Yukawa couplings
- Compute couplings to moduli
- Perturbations around rational points
- Moduli stabilization
- ...



Orientifolds

Orientifold Partition Functions

$\frac{1}{2}\Bigg\{$  $+$  $\Bigg\}$

$\frac{1}{2}\Bigg\{$  $+$  $\Bigg\}$

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)

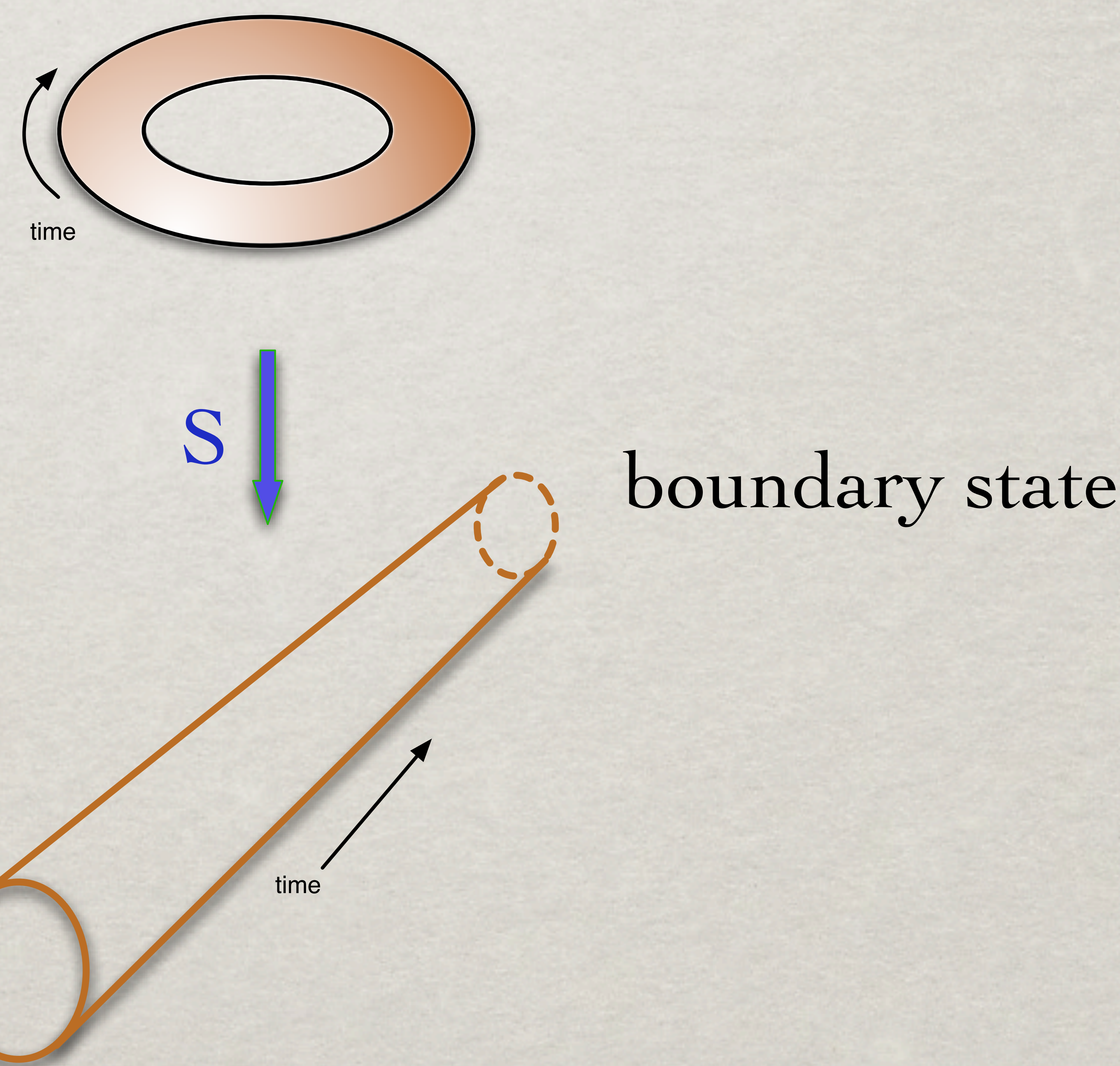
a : Boundary label (finite range)

χ_i : Character

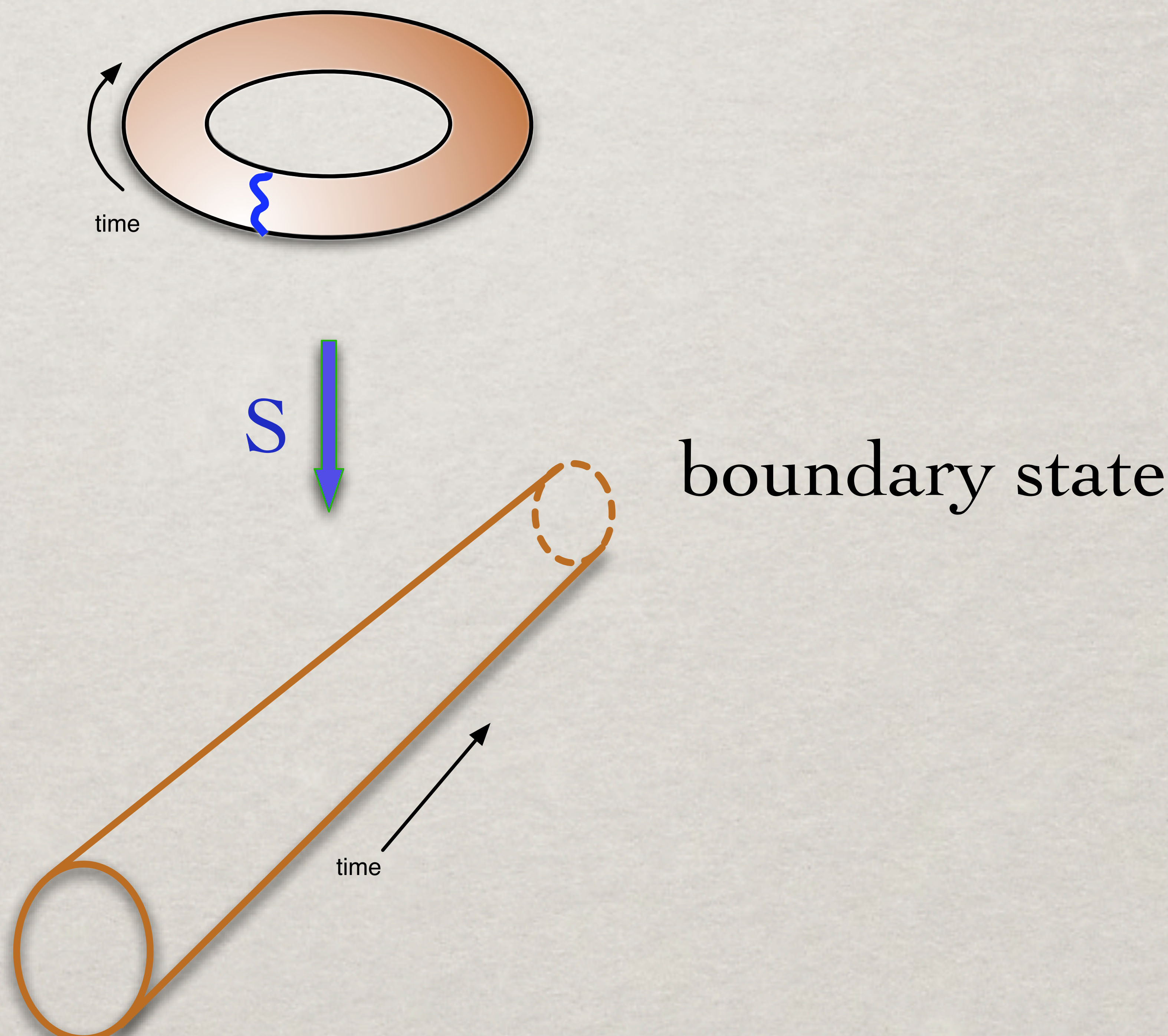
N_a : Chan-Paton (CP) Multiplicity

RCFT Tools

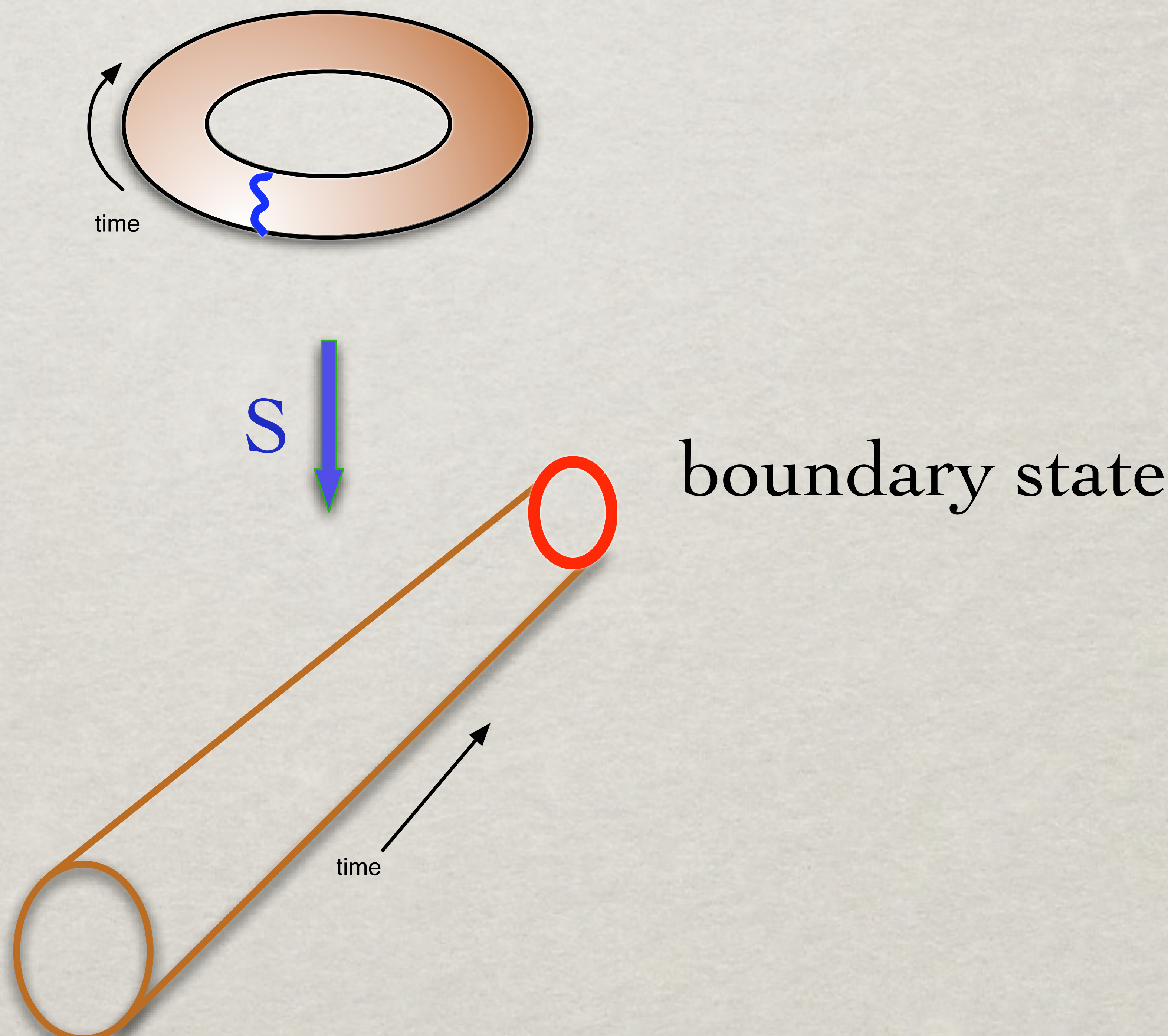
Transverse Channel



Transverse Channel

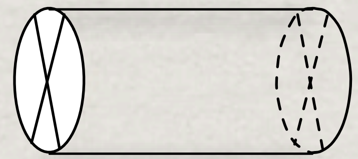


Transverse Channel



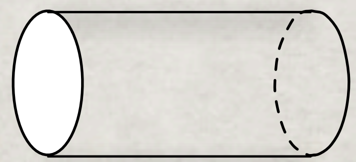
Coefficients

- Klein bottle



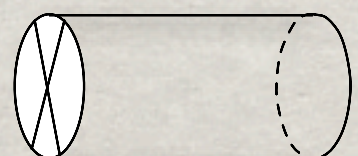
$$K^i = \sum_{m,J,J'} \frac{S^i{}_m U_{(m,J)} g^{\Omega,m}_{J,J'} U_{(m,J')}}{S_{0m}}$$

- 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



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

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

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.

(*) Simple Current related

Boundaries and Crosscaps

- Boundary coefficients

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

- 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)

A MIPF

$$\sum_{ij} \chi_i(\tau) Z_{ij} \bar{\chi}_j(\bar{\tau})$$

A MIPF

(0+2)^2 + (1+3)^2 + (4+6)*(13+15) + (5+7)*(12+14)
+ (8+10)^2 + (9+11)^2 + (12+14)*(5+7) + (13+15)*(4+6)
+ (16+18)*(25+27) + (17+19)*(24+26) + (20+22)^2 + (21+23)^2
+ (24+26)*(17+19) + (25+27)*(16+18) + (28+30)^2 + (29+31)^2
+ (32+34)^2 + (33+35)^2 + (36+38)*(45+47) + (37+39)*(44+46)
+ (40+42)^2 + (41+43)^2 + (44+46)*(37+39) + (45+47)*(36+38)
+ (48+50)*(57+59) + (49+51)*(56+58) + (52+54)^2 + (53+55)^2
+ (56+58)*(49+51) + (57+59)*(48+50) + (60+62)^2 + (61+63)^2
....

+ 2*(2913)*(2915) + 2*(2914)*(2912) + 2*(2915)*(2913)
+ 2*(2916)^2 + 2*(2917)^2 + 2*(2918)^2 + 2*(2919)^2
+ 2*(2920)^2 + 2*(2921)^2 + 2*(2922)^2 + 2*(2923)^2
+ 2*(2924)*(2926) + 2*(2925)*(2927) + 2*(2926)*(2924)
+ 2*(2927)*(2925) + 2*(2928)^2 + 2*(2929)^2 + 2*(2930)^2
+ 2*(2931)^2 + 2*(2932)*(2934) + 2*(2933)*(2935)
+ 2*(2934)*(2932) + 2*(2935)*(2933) + 2*(2936)*(2938)
+ 2*(2937)*(2939) + 2*(2938)*(2936) + 2*(2939)*(2937)
+ 2*(2940)^2 + 2*(2941)^2 + 2*(2942)^2 + 2*(2943)^2

Ishibashi States

(0+2)^2 + (1+3)^2 + (4+6)*(13+15) + (5+7)*(12+14)
+ (8+10)^2 + (9+11)^2 + (12+14)*(5+7) + (13+15)*(4+6)

.....

+ 2*(2937)*(2939) + 2*(2938)*(2936) + 2*(2939)*(2937)
+ 2*(2940)^2 + 2*(2941)^2 + 2*(2942)^2 + 2*(2943)^2

Ishibashi States

(0+2)^2 + (1+3)^2 + (4+6)*(13+15) + (5+7)*(12+14)
+ (8+10)^2 + (9+11)^2 + (12+14)*(5+7) + (13+15)*(4+6)

.....

+ 2*(2937)*(2939) + 2*(2938)*(2936) + 2*(2939)*(2937)
+ 2*(2940)^2 + 2*(2941)^2 + 2*(2942)^2 + 2*(2943)^2

Ishibashi States

(0+2)^2 + (1+3)^2 + (4+6)*(13+15) + (5+7)*(12+14)
+ (8+10)^2 + (9+11)^2 + (12+14)*(5+7) + (13+15)*(4+6)

.....

+ 2*(2937)*(2939) + 2*(2938)*(2936) + 2*(2939)*(2937)
+ 2*(2940)^2 + 2*(2941)^2 + 2*(2942)^2 + 2*(2943)^2

$(m, J): \quad J \in \mathcal{S}_m$

with $Q_L(m) + X(L, J) = 0 \bmod 1$ for all $L \in \mathcal{H}$

$\mathcal{S}_m : J \in \mathcal{H}$ with $J \cdot m = m$

(Stabilizer of m)

Boundary States

(0+2)^2 + (1+3)^2 + (4+6)*(13+15) + (5+7)*(12+14)
+ (8+10)^2 + (9+11)^2 + (12+14)*(5+7) + (13+15)*(4+6)

.....

+ 2*(2937)*(2939) + 2*(2938)*(2936) + 2*(2939)*(2937)
+ 2*(2940)^2 + 2*(2941)^2 + 2*(2942)^2 + 2*(2943)^2

Boundary States

(0+2)^2 + (1+3)^2 + (4+6)*(13+15) + (5+7)*(12+14)
+ (8+10)^2 + (9+11)^2 + (12+14)*(5+7) + (13+15)*(4+6)

.....

+ 2*(2937)*(2939) + 2*(2938)*(2936) + 2*(2939)*(2937)
+ 2*(2940)^2 + 2*(2941)^2 + 2*(2942)^2 + 2*(2943)^2

Boundary States

(0+2)^2 + (1+3)^2 + (4+6)*(13+15) + (5+7)*(12+14)
+ (8+10)^2 + (9+11)^2 + (12+14)*(5+7) + (13+15)*(4+6)

.....

+ 2*(2937)*(2939) + 2*(2938)*(2936) + 2*(2939)*(2937)
+ 2*(2940)^2 + 2*(2941)^2 + 2*(2942)^2 + 2*(2943)^2

$[a, \psi_a]$, ψ_a is a character of the group $\mathcal{C}_a$

$\mathcal{C}_a$ is the Central Stabilizer of a

$$\mathcal{C}_i := \{J \in \mathcal{S}_i \,|\, F_i^X(K,J) = 1 \text{ for all } K \in \mathcal{S}_i\}$$

$$F_i^X(K,J) := \mathrm{e}^{2\pi \mathrm{i} X(K,J)}\, F_i(K,J)^*$$

$$S^J_{Ki,j} = F_i(K,J)\, \mathrm{e}^{2\pi \mathrm{i} Q_K(j)}\, S^J_{i,j}\,.$$

Boundaries and Crosscaps

- Boundary coefficients

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

- Crosscap coefficients

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

The Fixed point resolution matrices

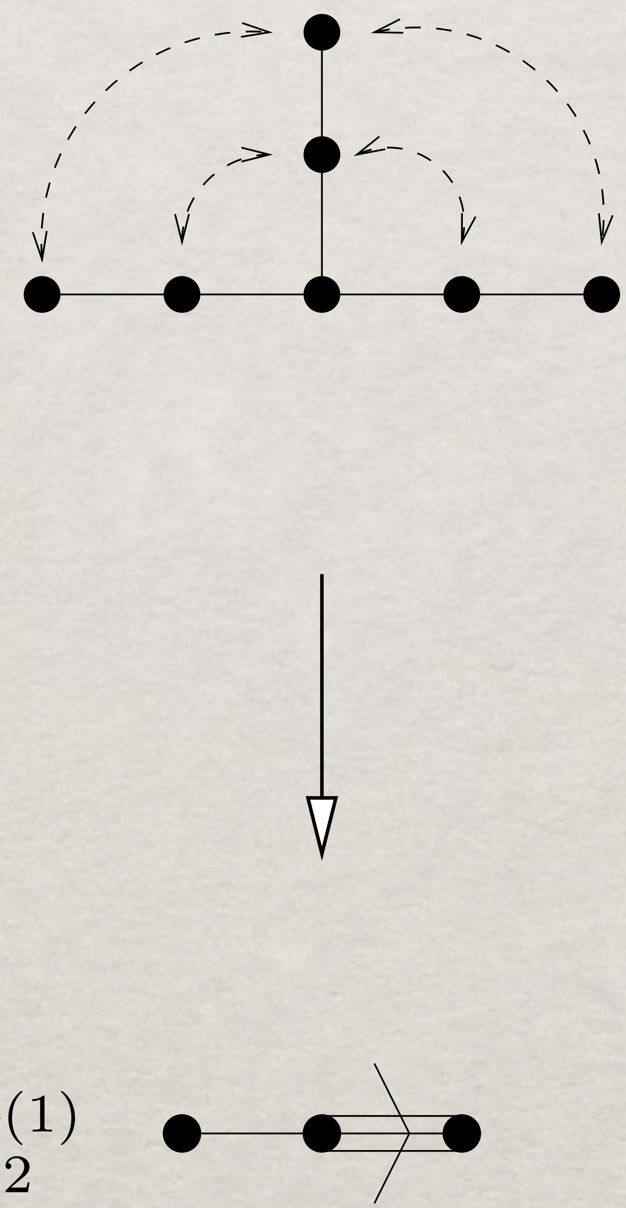
S^J_{am} (of a WZW model W)

Modular transformation matrices of the WZW model W^J defined by folding the extended Dynkin diagram of W by the symmetry defined by J

Schellekens, Yankielowicz (1989)
Fuchs,Schellekens,Schweigert (1995)

Orbit Lie algebras

$\mathrm{g} = E_6^{(1)}$



$\breve{\mathrm{g}} = G_2^{(1)}$

Fuchs, Schellekens, Schweigert (1995)

Model Building

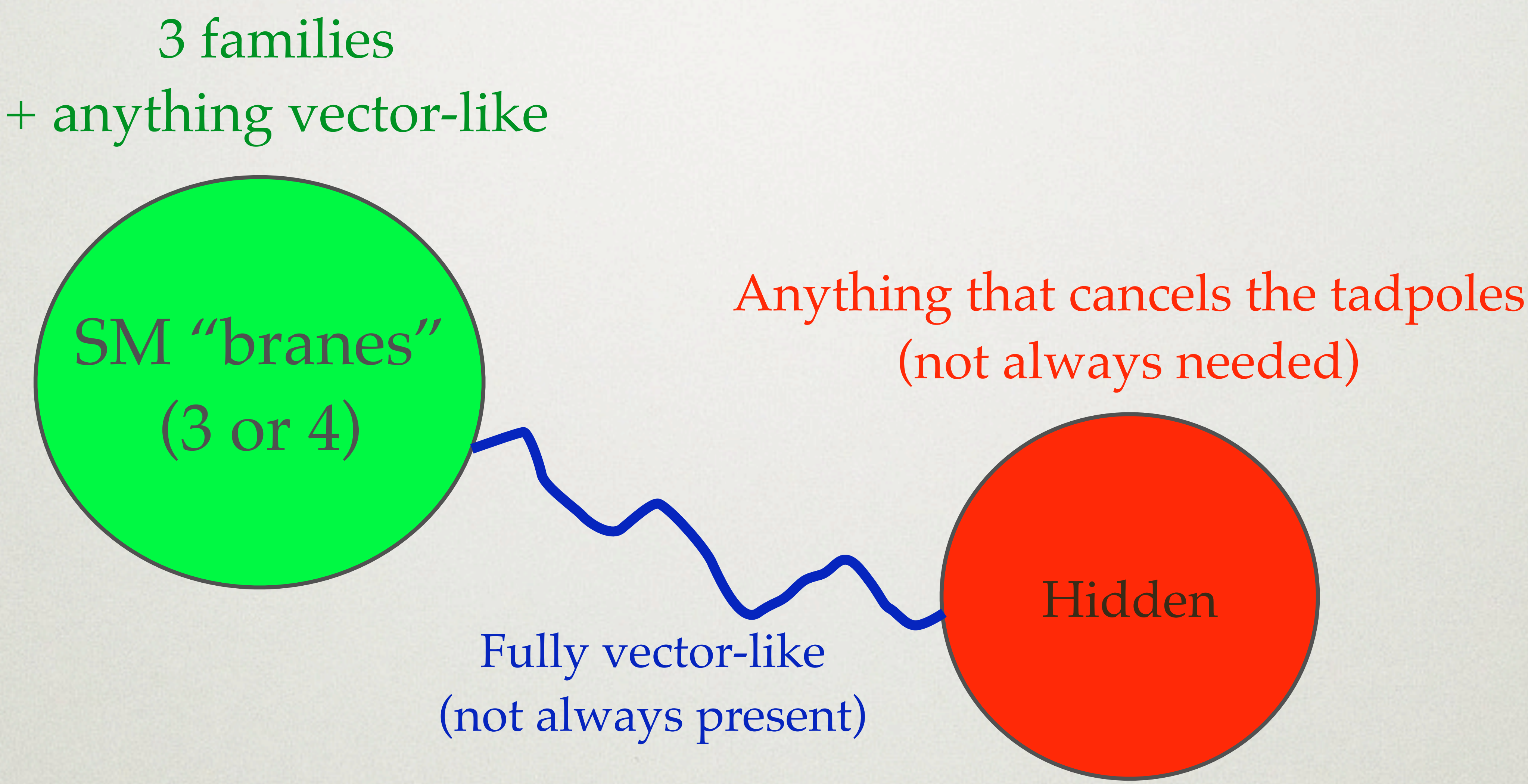
Consistency conditions

- 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

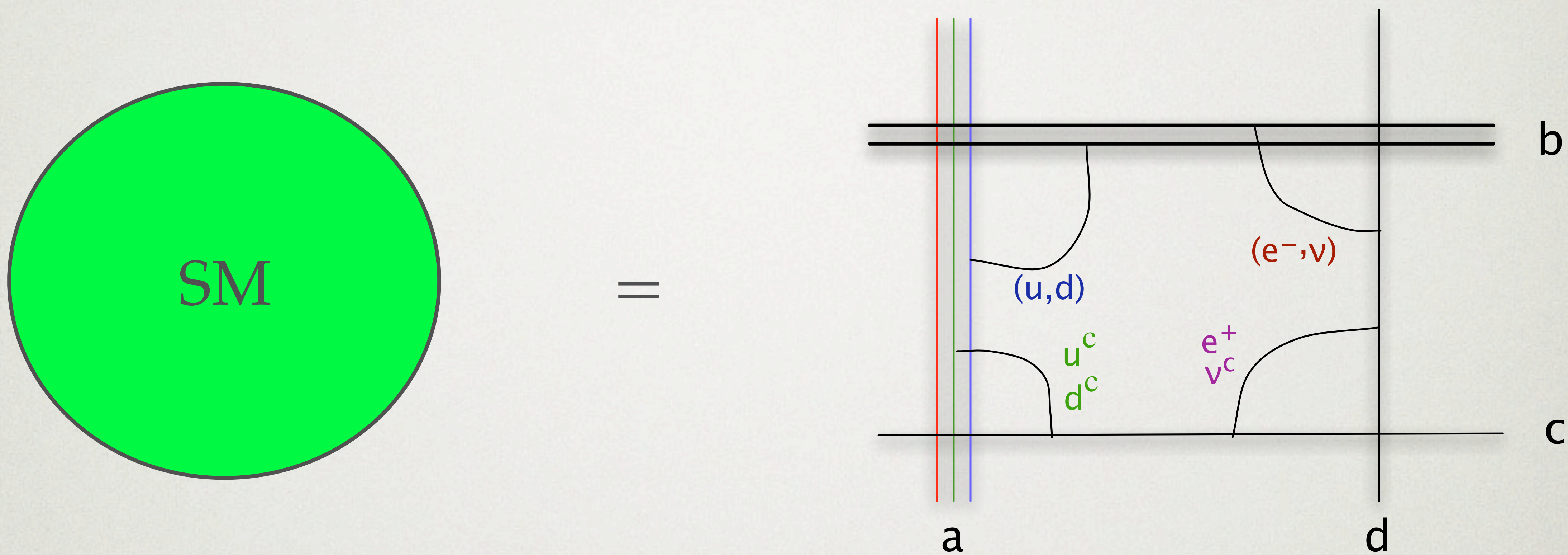
SM realization



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



210000 distinct tadpole-free spectra found

(without chiral exotics, but distinguished by non-chiral exotics)

Best imaginable result:

The exact MSSM spectrum

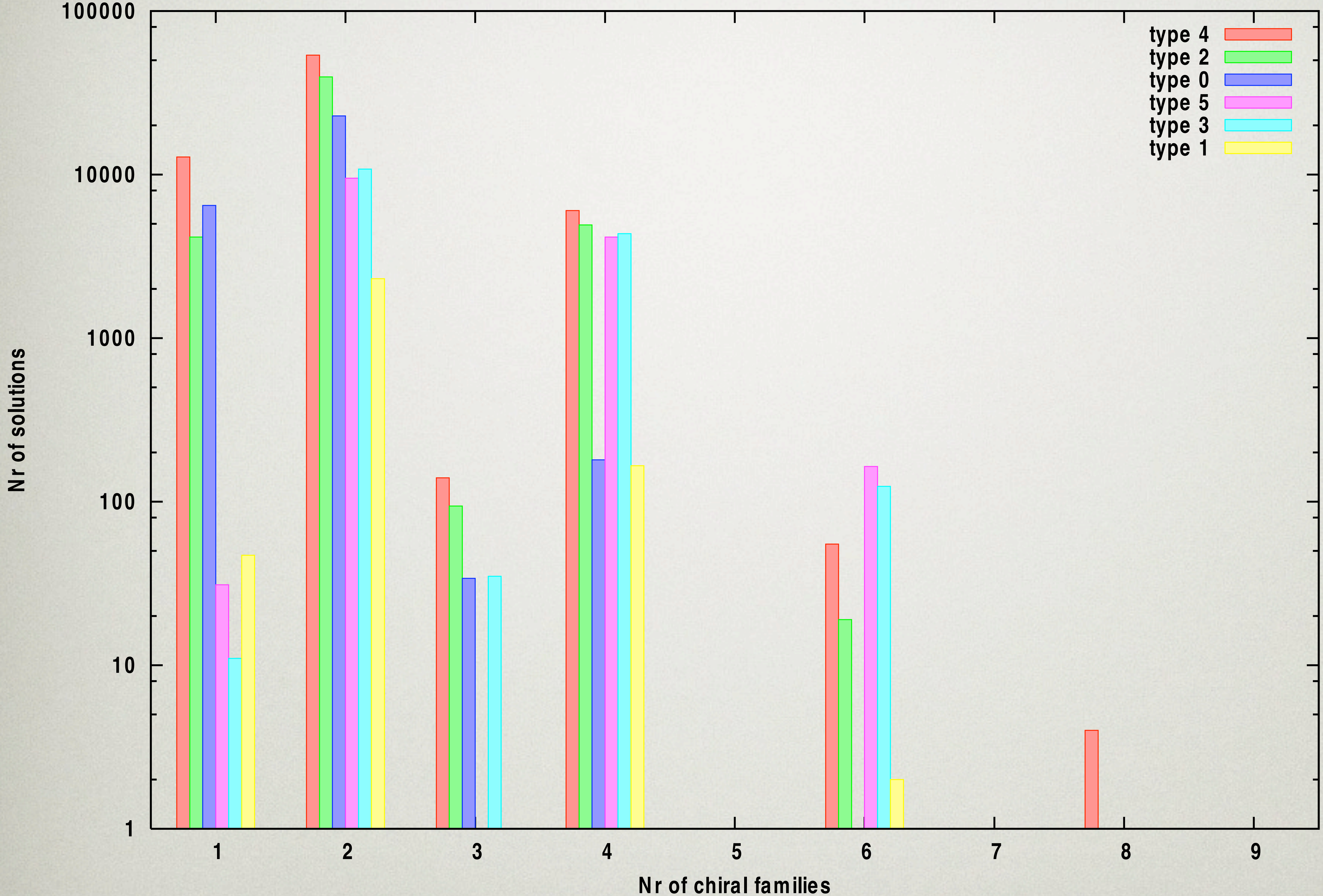
```
Gauge group: U(3) x Sp(2) x U(1) x U(1)

  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)



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) × SU(2) × 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

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

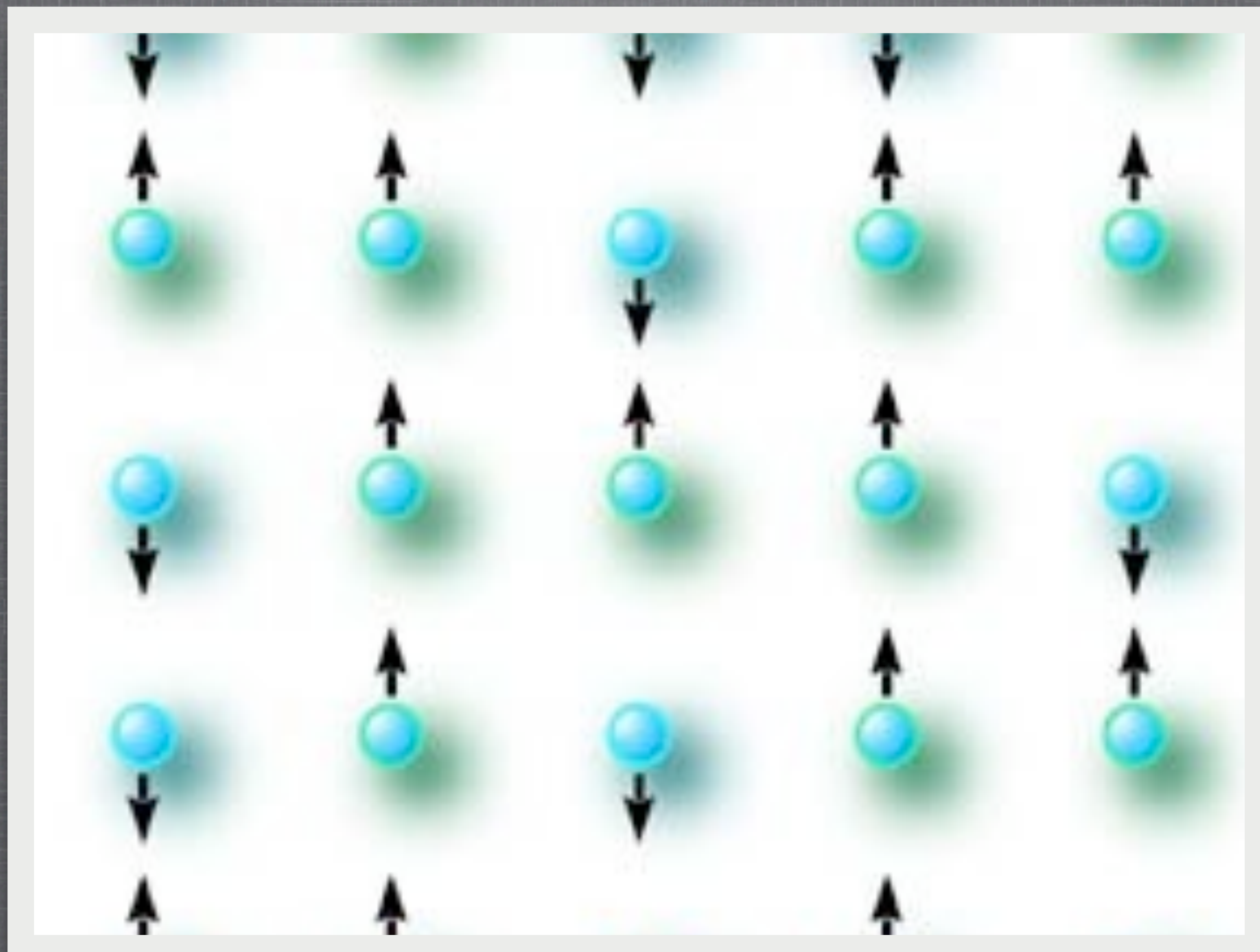
	U3	S2	U1	U1	U2		
3 x	V	V	0	0	0	chirality 3	Q
3 x	0	0	V	V	0	chirality -3	E*
1 x	V	0	0	V*	0	chirality -1	U*
2 x	V	0	V	0	0	chirality -2	D*
2 x	0	V	0	V	0	chirality 2	L
3 x	V	0	0	V	0	chirality -1	D*+(D+D*)
3 x	0	V	V	0	0	chirality 1	$L+H_1+H_2$
2 x	V	0	V*	0	0	chirality -2	U*
1 x	0	0	V	V*	0	chirality 1	N*
4 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, arXiv:0809.0083)

FREE FERMIONS

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



Motivation:

- Compare with other approaches
- Allow computation of more quantities

ISING MODEL

RCFT with just three primary fields

$$
\begin{aligned}
0 :& \qquad h = 0 \\
\psi :& \qquad h = \frac{1}{2} \\
\sigma :& \qquad h = \frac{1}{16}
\end{aligned}
$$

Fusion rules:

$$[\psi] \times [\psi] = [0]$$

Simple current

$$[\sigma] \times [\sigma] = [0] + [\psi]$$

TENSORING

Central charge: $c = 1/2$

To get c=9 we tensor 18 copies.
But: the Ising model has no supersymmetry.

This can be overcome by imposing it on the tensor product by means of a chiral algebra extension:

KLT/ABK Triplet constraint (1986)

Current $\psi^\mu \partial X_\mu \psi_i \psi_j \psi_k$

This is a simple current, so the FHSSW formalism applies

SPACE-TIME SUSY

This requires another chiral algebra extension

Current $\quad S_\alpha \sigma_1 \sigma_4 \sigma_7 \sigma_{10} \sigma_{13} \sigma_{16}$

SPACE-TIME SUSY

This requires another chiral algebra extension

Current $S_\alpha \sigma_1 \sigma_4 \sigma_7 \sigma_{10} \sigma_{13} \sigma_{16}$

But this is *not* a simple current;
we do not have a boundary state
formalism for such an extension.

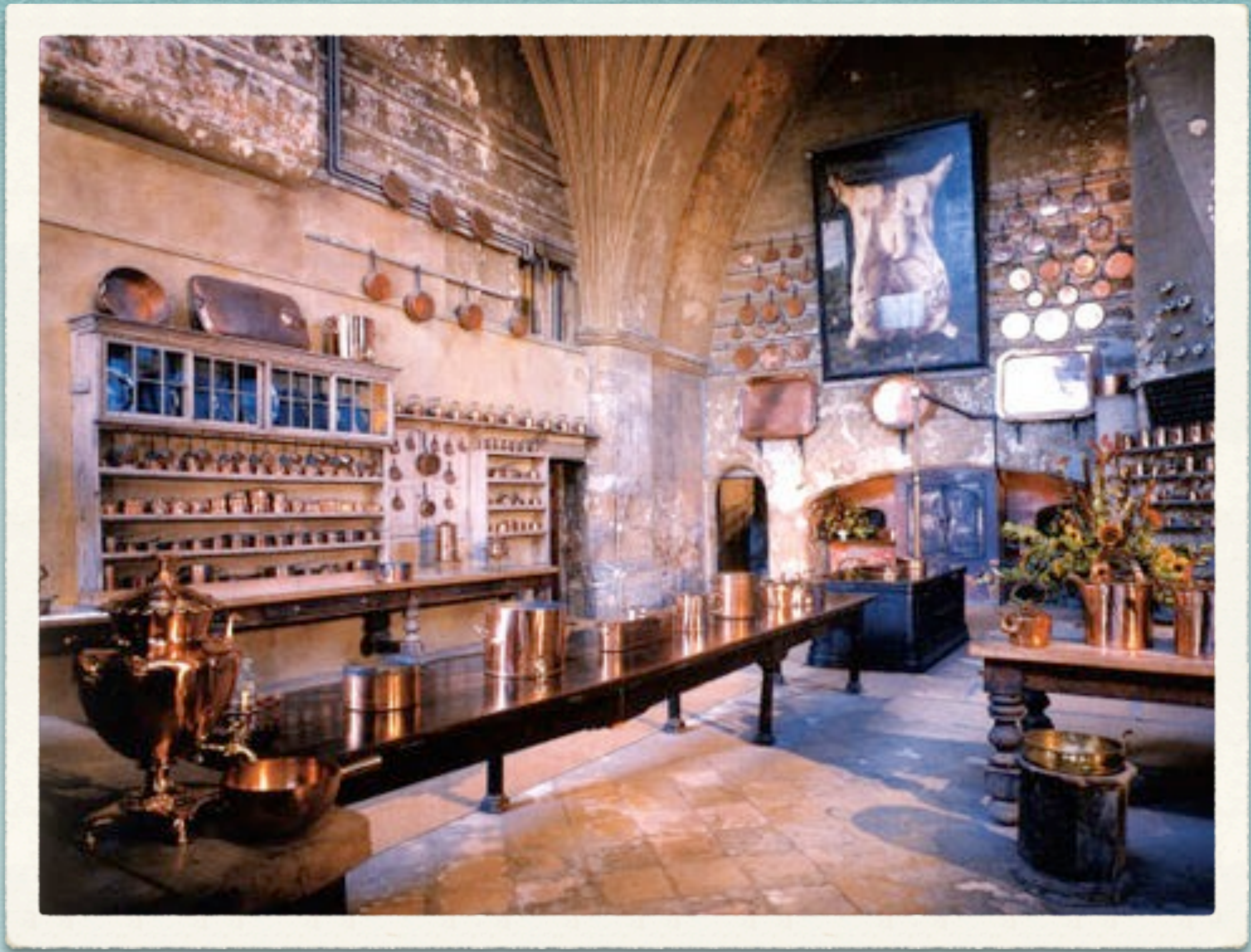
Solution: pair two Ising models into a real boson.

$$|\chi_0\chi_0 + \chi_\psi\chi_\psi|^2 + |\chi_0\chi_\psi + \chi_\psi\chi_0|^2 + 2|\chi_\sigma|^2$$

0 $\qquad$ ψ $\qquad$ σ_1 $\quad$ σ_2

Simple Currents

This yields the D_1 free boson CFT



A look into the kitchen

The Quintic [Gepner (3,3,3,3,3)]

```
g D 5 1
g min 2 3
g min 2 3
g min 2 3
g min 2 3
g min 2 3
current 2 10 0 0 0 0
current 2 0 10 0 0 0
current 2 0 0 10 0 0
current 2 0 0 0 10 0
current 2 0 0 0 0 10
current 1 1 1 1 1 1
compute spectrum
```

The Quintic [Gepner (3,3,3,3,3)]

```
g D 5 1
g min 2 3
g min 2 3
g min 2 3
g min 2 3
g min 2 3
current 2 10 0 0 0 0
current 2 0 10 0 0 0
current 2 0 0 10 0 0
current 2 0 0 0 10 0
current 2 0 0 0 0 10
current 1 1 1 1 1 1
compute spectrum
```

NSR

Lerche, Lüst, Schellekens, **Nucl.Phys.B287:477,1987**

The Quintic [Gepner (3,3,3,3,3)]

```
g D 5 1
g min 2 3
g min 2 3
g min 2 3
g min 2 3
g min 2 3
current 2 10 0 0 0 0
current 2 0 10 0 0 0
current 2 0 0 10 0 0
current 2 0 0 0 10 0
current 2 0 0 0 0 10
current 1 1 1 1 1 1
compute spectrum
```

NSR

Minimal Models

Lerche, Lüst, Schellekens, **Nucl.Phys.B287:477,1987**

D. Gepner, **Nucl.Phys.B296:757,1988**

The Quintic [Gepner (3,3,3,3,3)]

```
g D 5 1
g min 2 3
g min 2 3
g min 2 3
g min 2 3
g min 2 3
current 2 10 0 0 0 0
current 2 0 10 0 0 0
current 2 0 0 10 0 0
current 2 0 0 0 10 0
current 2 0 0 0 0 10
current 1 1 1 1 1 1
compute spectrum
```

NSR

Minimal Models

W.S. Susy

Lerche, Lüst, Schellekens, **Nucl.Phys.B287:477,1987**

D. Gepner, **Nucl.Phys.B296:757,1988**

The Quintic [Gepner (3,3,3,3,3)]

```
g D 5 1
g min 2 3
g min 2 3
g min 2 3
g min 2 3
g min 2 3
current 2 10 0 0 0 0
current 2 0 10 0 0 0
current 2 0 0 10 0 0
current 2 0 0 0 10 0
current 2 0 0 0 0 10
current 1 1 1 1 1 1
compute spectrum
```

NSR

Minimal Models

W.S. Susy

S.T. Susy

Lerche, Lüst, Schellekens, **Nucl.Phys.B287:477,1987**

D. Gepner, **Nucl.Phys.B296:757,1988**

```
G D 5 1
G U 4
G U 4
G U 4
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
current 2 2 0 0 1 1 0 0 0 0 0 0 0 0 0 0
current 2 2 0 0 0 0 1 1 0 0 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 1 1 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 0 0 1 1 0 0 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 1 1 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 0 0 1 1
current 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0
compute spectrum
```

```
G D 5 1
G U 4
G U 4
G U 4
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
current 2 2 0 0 1 1 0 0 0 0 0 0 0 0 0 0
current 2 2 0 0 0 0 1 1 0 0 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 1 1 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 0 0 1 1 0 0 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 1 1 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 0 0 1 1
current 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0
compute spectrum
```

NSR

```
G D 5 1
G U 4
G U 4
G U 4
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
current 2 2 0 0 1 1 0 0 0 0 0 0 0 0 0 0
current 2 2 0 0 0 0 1 1 0 0 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 1 1 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 0 0 1 1 0 0 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 1 1 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 0 0 1 1
current 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0
compute spectrum
```

NSR

Free Bosons

```
G D 5 1
G U 4
G U 4
G U 4
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
current 2 2 0 0 1 1 0 0 0 0 0 0 0 0 0 0
current 2 2 0 0 0 0 1 1 0 0 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 1 1 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 0 0 1 1 0 0 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 1 1 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 0 0 1 1
current 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0
compute spectrum
```

NSR

Free Bosons

Free Fermions
(Ising Models)

```
G D 5 1
G U 4
G U 4
G U 4
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
current 2 2 0 0 1 1 0 0 0 0 0 0 0 0 0 0
current 2 2 0 0 0 0 1 1 0 0 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 1 1 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 0 0 1 1 0 0 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 1 1 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 0 0 1 1
current 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0
compute spectrum
```

NSR

Free Bosons

Free Fermions
(Ising Models)

W.S. Susy

Kawai, Lewellen, Tye, Phys.Rev.Lett.57:1832,1986

Antoniadis, Bachas, Kounnas, Nucl.Phys.B289:87,1987

```
G D 5 1
G U 4
G U 4
G U 4
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
G min 0 1
current 2 2 0 0 1 1 0 0 0 0 0 0 0 0 0 0
current 2 2 0 0 0 0 1 1 0 0 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 1 1 0 0 0 0 0 0
current 2 0 2 0 0 0 0 0 0 0 1 1 0 0 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 1 1 0 0
current 2 0 0 2 0 0 0 0 0 0 0 0 0 0 1 1
current 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0
compute spectrum
```

NSR

Free Bosons

Free Fermions
(Ising Models)

W.S. Susy

S.T. Susy

Kawai, Lewellen, Tye, **Phys.Rev.Lett.57:1832,1986**

Antoniadis, Bachas, Kounnas, **Nucl.Phys.B289:87,1987**

ACCESSIBLE MIPFS

6 of the 18 fermions *must* be paired into bosons to get a susy simple current.

The other fermions *may* be paired into bosons in a definite way.

Such a pairing produces a new class of models because the spinor currents are now available as simple currents.

There are 62 possible pairing choices

DEGENERACIES

The number of simple current MIPFs is extremely large ($> 10^{28}$ for (NSR) $(D_1)^3$ (Ising)^{12}).

But there are many degeneracies

- Permutations of identical factors.
  [occurs also in Gepner models with identical factors]
- Ising degeneracy $[\psi] \times [\sigma] = \sigma$
  (some generically distinct MIPFs are identical)
  [occurs also in Gepner models with k=2 factors]
- Non-trivial free field theory relations.
  [occurs also in Gepner models with k=1 factors]

NUMBER OF MIPFS

Pairings within triplets:

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

Pairings across triplets:

58 additional possibilities, still being analysed

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
Donagi and Wendland (to appear)
($Z_2 \times Z_2$ 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.

The Quintic [Gepner (3,3,3,3,3)]

```
g D 5 1
g min 2 3
g min 2 3
g min 2 3
g min 2 3
g min 2 3
current 2 10 0 0 0 0
current 2 0 10 0 0 0
current 2 0 0 10 0 0
current 2 0 0 0 10 0
current 2 0 0 0 0 10
current 1 1 1 1 1 1
compute spectrum
```

NSR

Minimal Models

W.S. Susy

S.T. Susy

The Quintic [Gepner (3,3,3,3,3)]

`g D 5 1`	NSR
`g min 2 3` `g min 2 3` `g min 2 3` `g min 2 3` `g min 2 3`	Minimal Models

`current 2 10 0 0 0 0`
`current 2 0 10 0 0 0`
`current 2 0 0 10 0 0`
`current 2 0 0 0 10 0`
`current 2 0 0 0 0 10`
	W.S. Susy

~~`current 1 1 1 1 1 1`~~	~~S.T. Susy~~
`compute spectrum`	

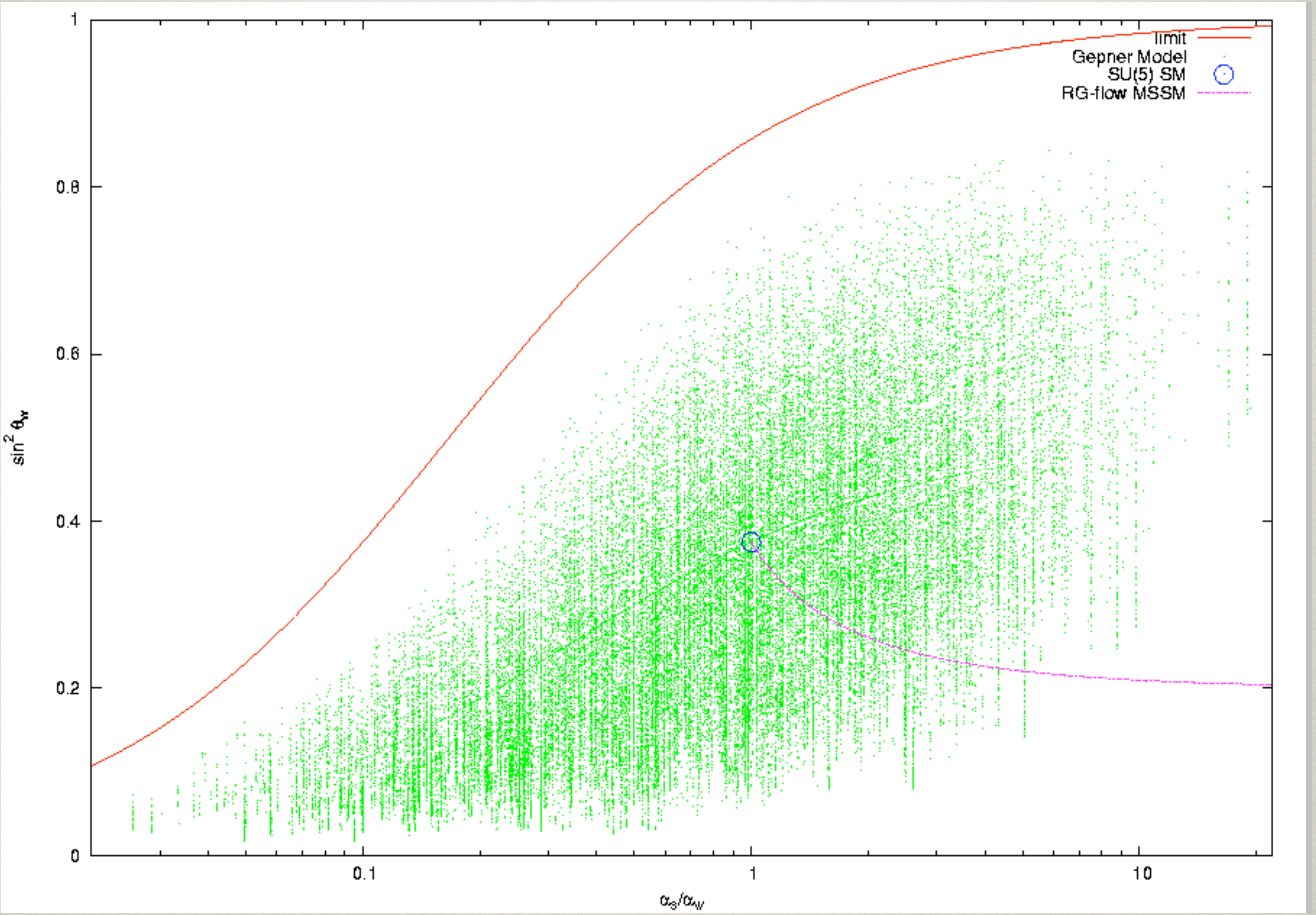
Arguments in favor of Low Energy Susy

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

Arguments in favor of Low Energy Susy

Not needed for C.C.

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



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

Arguments in favor of Susy

Not needed for C.C.

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

Arguments in favor of Susy

- ~~Stabilizes weak hierarchy~~ Not needed for C.C.
- ~~Coupling convergence~~ Coincidence in orientifolds
- LSP and Dark Matter

Arguments in favor of Susy

- ~~Stabilizes weak hierarchy~~ Not needed for C.C.
- ~~Coupling convergence~~ Coincidence in orientifolds
- LSP and Dark Matter

For the record: I am NOT making an LHC prediction here!

Arguments in favor of Susy

- ~~Stabilizes weak hierarchy~~ Not needed for C.C.
- ~~Coupling convergence~~ Coincidence in orientifolds
- LSP and Dark Matter

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 string theories

A surprisingly common misconception:

``Absence of tachyons requires supersymmetry."

Non-supersymmetric string theories

A surprisingly common misconception:

``Absence of tachyons requires supersymmetry."

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

Non-supersymmetric string theories

A surprisingly common misconception:
``Absence of tachyons requires supersymmetry."

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

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, ...

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

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

Closed sector

Do these possibilities occur?

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

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

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)

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

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

- Interacting CFT's are "richer" than free CFT's.
- 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.
- Perhaps try N=1 tensor products?