Model Building With RCFT Orientifolds

Sunday, 2 May 2010

Based on work with:

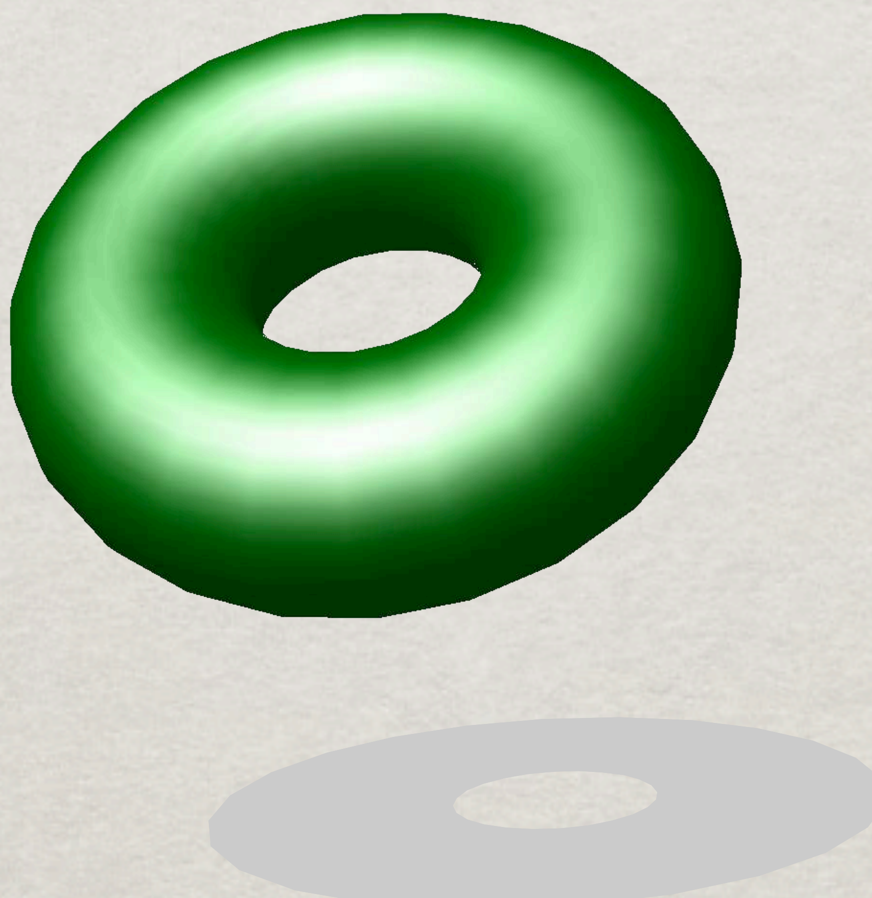
- Huiszoon, Fuchs, Schweigert and Walcher [Formalism]
  Phys.Lett.B495:427-434,2000
- Huiszoon, Dijkstra [SM Search]
  Phys.Lett.B609:408-417,2005, Nucl.Phys.B710:3-57,2005
- Anastasopoulos, Dijkstra, Kiritsis [SM Search]
  Nucl.Phys.B759:83-146,2006
- Ibañez, Uranga [Majorana masses from instantons]
  (hep-th/07yyzzz)
- Gato-Rivera [Tachyon-free non-susy strings]
  (hep-th/07yyzzz)
- Gato-Rivera, Gmeiner, Kiritsis [Free CFT models]
  (hep-th/xxyyzzz)

Objectives

- Explore unknown regions of the landscape.
- Establish realization of standard model features (gauge group, three families, neutrino masses ...).
  [not necessarily all in the same model]
- Convince ourselves that the standard model is indeed a "ground state".
- Discover relations between parameters.
- Find A Standard Model ?
- Find THE Standard Model ????

Orientifolds

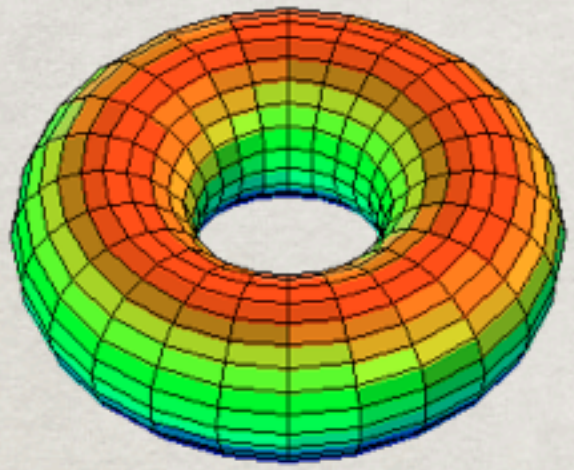
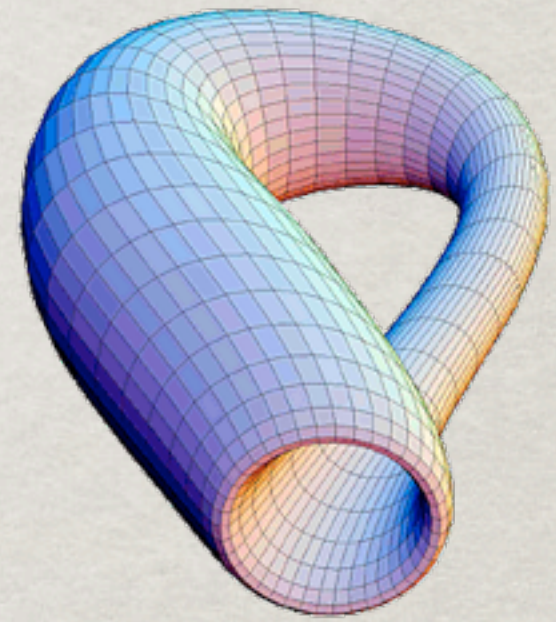
Closed String Partition Function



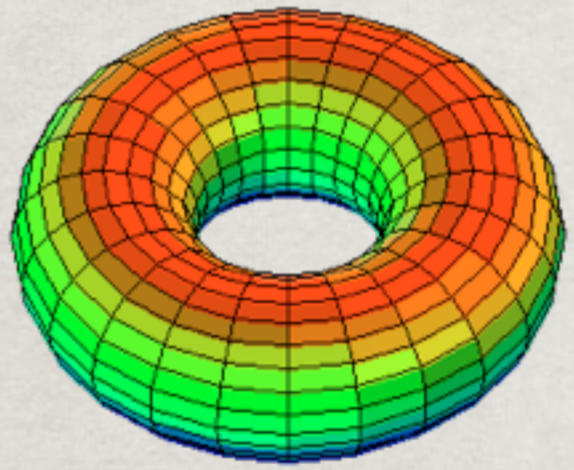
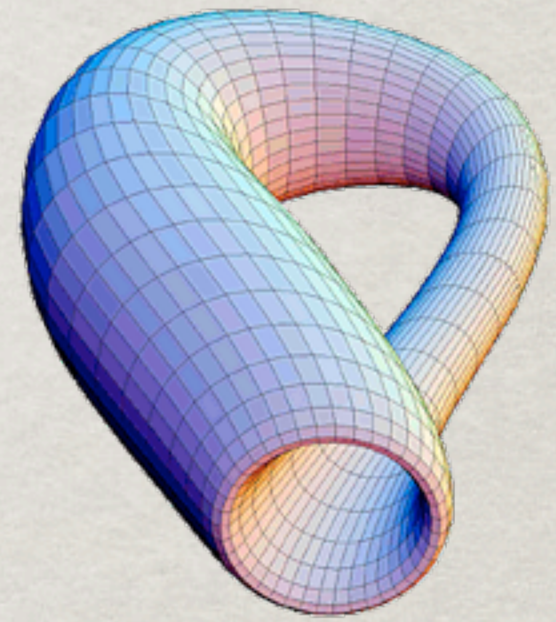
$$P(\tau,\bar{\tau}) = \sum_{ij} \chi_i(\tau) Z_{ij} \chi_j(\bar{\tau})$$

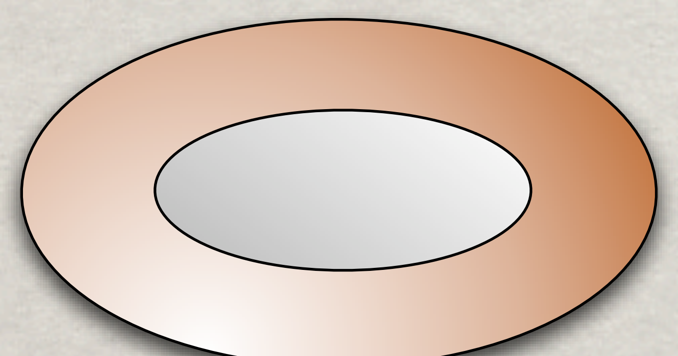
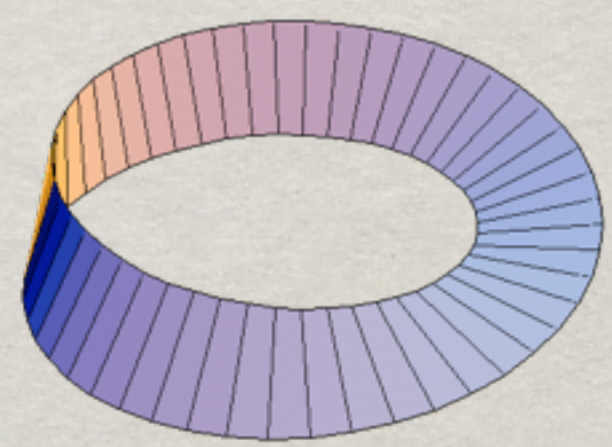
Orientifold Partition Functions

Orientifold Partition Functions

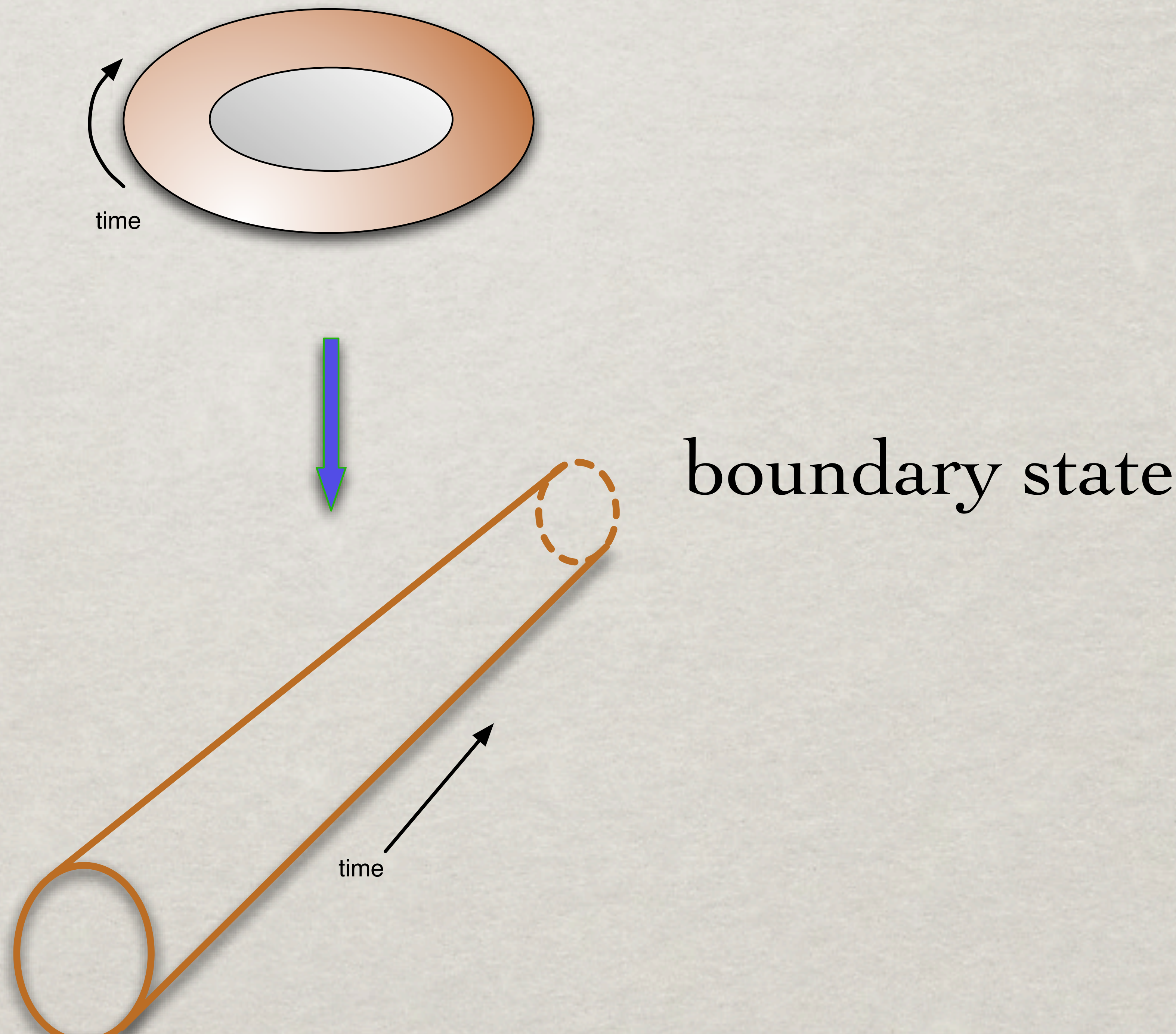
$\frac{1}{2} \Big\{$  $+$  $\Big\}$

Orientifold Partition Functions

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

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

Transverse Channel



Torus CFT: Type-IIB 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

Gepner Orientifolds

C. Angelantonj, M. Bianchi, G. Pradisi, A. Sagnotti and Y. S. Stanev, Phys. Lett. B **387** (1996) 743 [arXiv:hep-th/9607229].

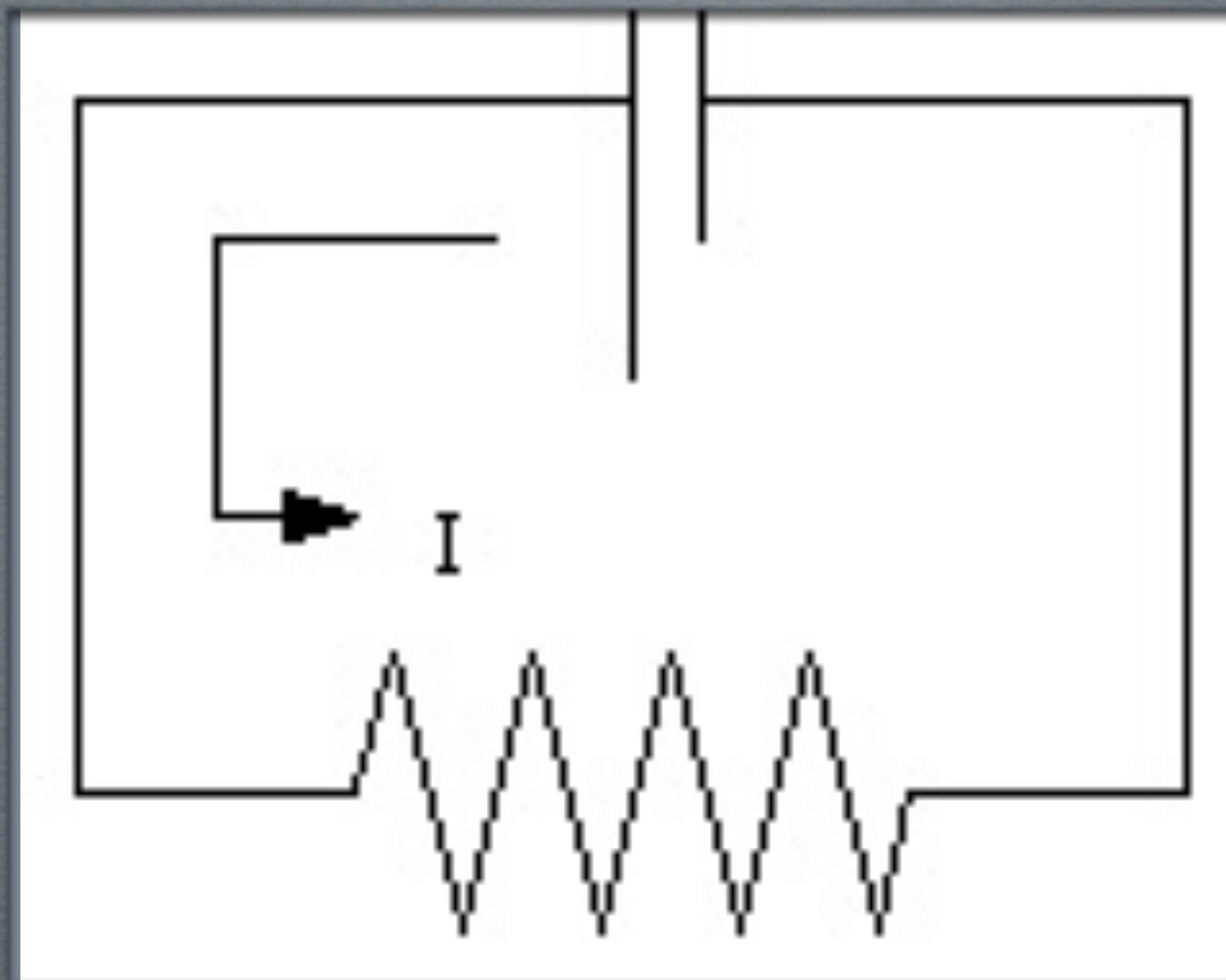
R. Blumenhagen and A. Wisskirchen, Phys. Lett. B **438**, 52 (1998) [arXiv:hep-th/9806131].

G. Aldazabal, E. C. Andres, M. Leston and C. Nunez, JHEP **0309**, 067 (2003) [arXiv:hep-th/0307183].

I. Brunner, K. Hori, K. Hosomichi and J. Walcher, arXiv:hep-th/0401137.

R. Blumenhagen and T. Weigand, JHEP **0402** (2004) 041 [arXiv:hep-th/0401148].

G. Aldazabal, E. C. Andres and J. E. Juknevich, JHEP **0405**, 054 (2004) [arXiv:hep-th/0403262].



Simple Currents

Tensoring

- Preserve world-sheet susy
- Preserve space-time susy (GSO)
- Use surviving simple currents to build MIPFs
- This yields one point in the moduli space of a Calabi-Yau manifold

Quintic

```
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
```

Quintic

```
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

Quintic

```
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

Quintic

```
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

Quintic

```
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

MIPFs*

- CFT has a discrete "simple current" group $\mathcal{G}$
  Choose a subgroup $\mathcal{H}$ of $\mathcal{G}$

- Choose a rational matrix $X_{\alpha\beta}$ obeying

$$
\begin{aligned}
2X_{\alpha\beta} &= Q_{J_\alpha}(J_\beta) \text{ mod } 1, \alpha \neq \beta \\
X_{\alpha\alpha} &= -h_{J_\alpha} \\
N_\alpha X_{\alpha\beta} &\in \mathbb{Z} \text{ for all } \alpha, \beta
\end{aligned}
$$

$$Q_J(a) = h(a) + h(J) - h(Ja)$$

- This defines the torus partition function as

Z_{ij} is the number of currents $L \in \mathcal{H}$ such that

$$
\begin{aligned}
j &= Li \\
Q_M(i) + X(M, L) &= 0 \text{ mod } 1 \qquad \text{for all } M \in \mathcal{H}.
\end{aligned}
$$

Gato-Rivera, Kreuzer, Schellekens (1991-1993)

ORIENTIFOLD CHOICES*

- "Klein bottle current" K (element of $\mathcal{H}$)
- "Crosscap signs" (signs defined on a subgroup of $\mathcal{H}$), satisfying

$$\beta_K(J)\beta_K(J') = \beta_K(JJ')e^{2\pi i X(J,J')} \quad , J, J' \in \mathcal{H}$$

**Huiszoon, Sousa, Schellekens (1999-2000)*

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

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

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

**Huiszoon, Fuchs, Schellekens, Schweigert, Walcher (2000)*

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Ishibashi States

(0+2)^2 + (1+3)^2 + (4+6)*(13+15) + (5+7)*(12+14)
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.....

+ 2*(2937)*(2939) + 2*(2938)*(2936) + 2*(2939)*(2937)
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$(m, J): \quad J \in \mathcal{S}_m$

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)

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

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

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

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

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

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The Fixed point resolution matrices

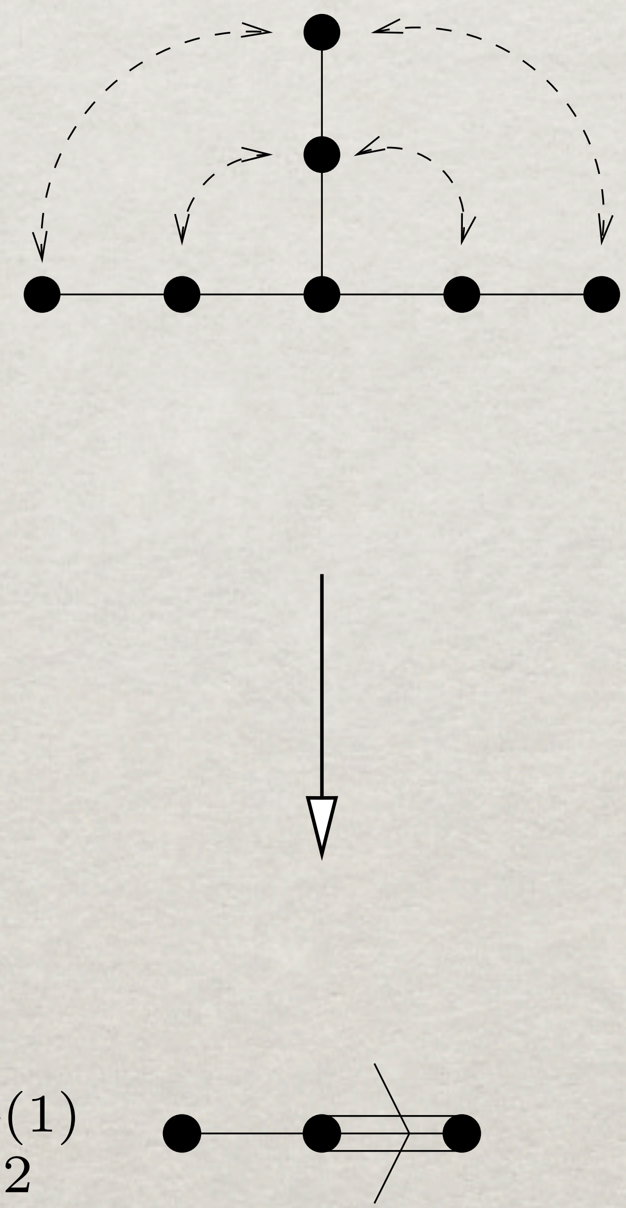
S^J_{am} (of a WZW model W)

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

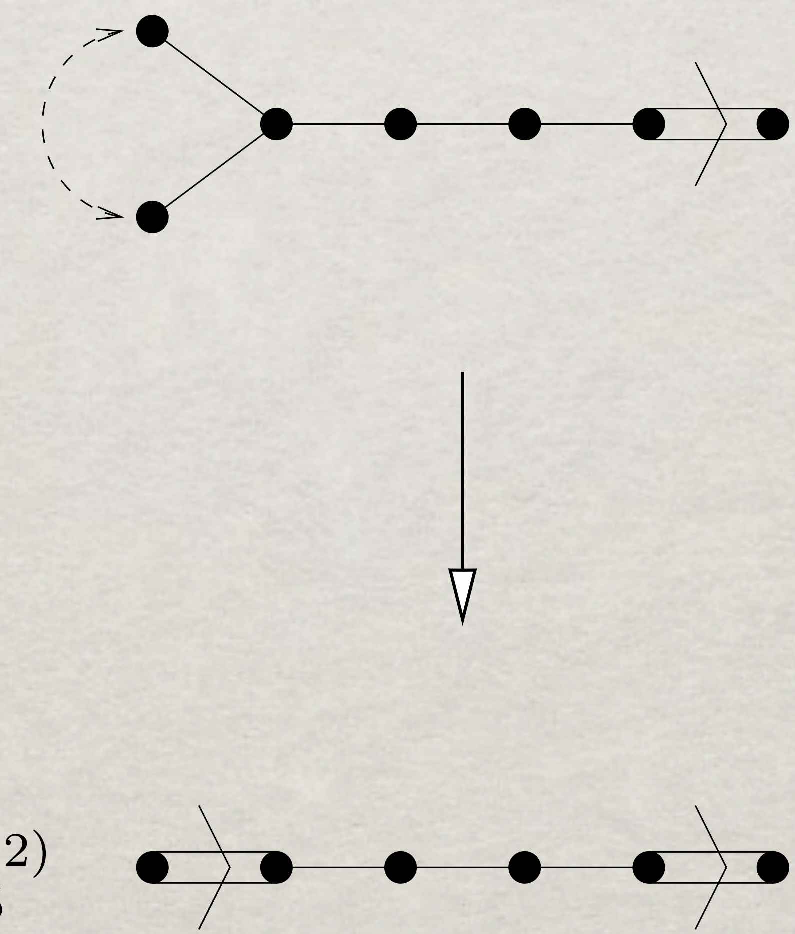
$\mathrm{g} = E_6^{(1)}$



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

Orbit Lie algebras

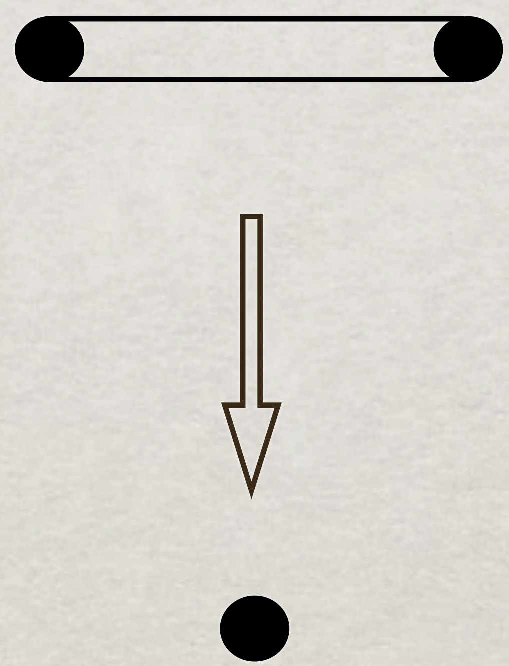
$\mathrm{g} = B_6^{(1)}$



$\breve{\mathrm{g}} = \tilde{B}_5^{(2)}$

Orbit Lie algebras

needed for Gepner Models



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**Huiszoon, Fuchs, Schellekens, Schweigert, Walcher (2000)*

The P-matrix*

$$P = \sqrt{T} S T^2 S \sqrt{T}$$

$$T \quad : \quad \tau \to \tau + 1$$

$$S \quad : \quad \tau \to -\frac{1}{\tau}$$

*Sagnotti, Pradisi, Stanev

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

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

N_a: Chan-Paton 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

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

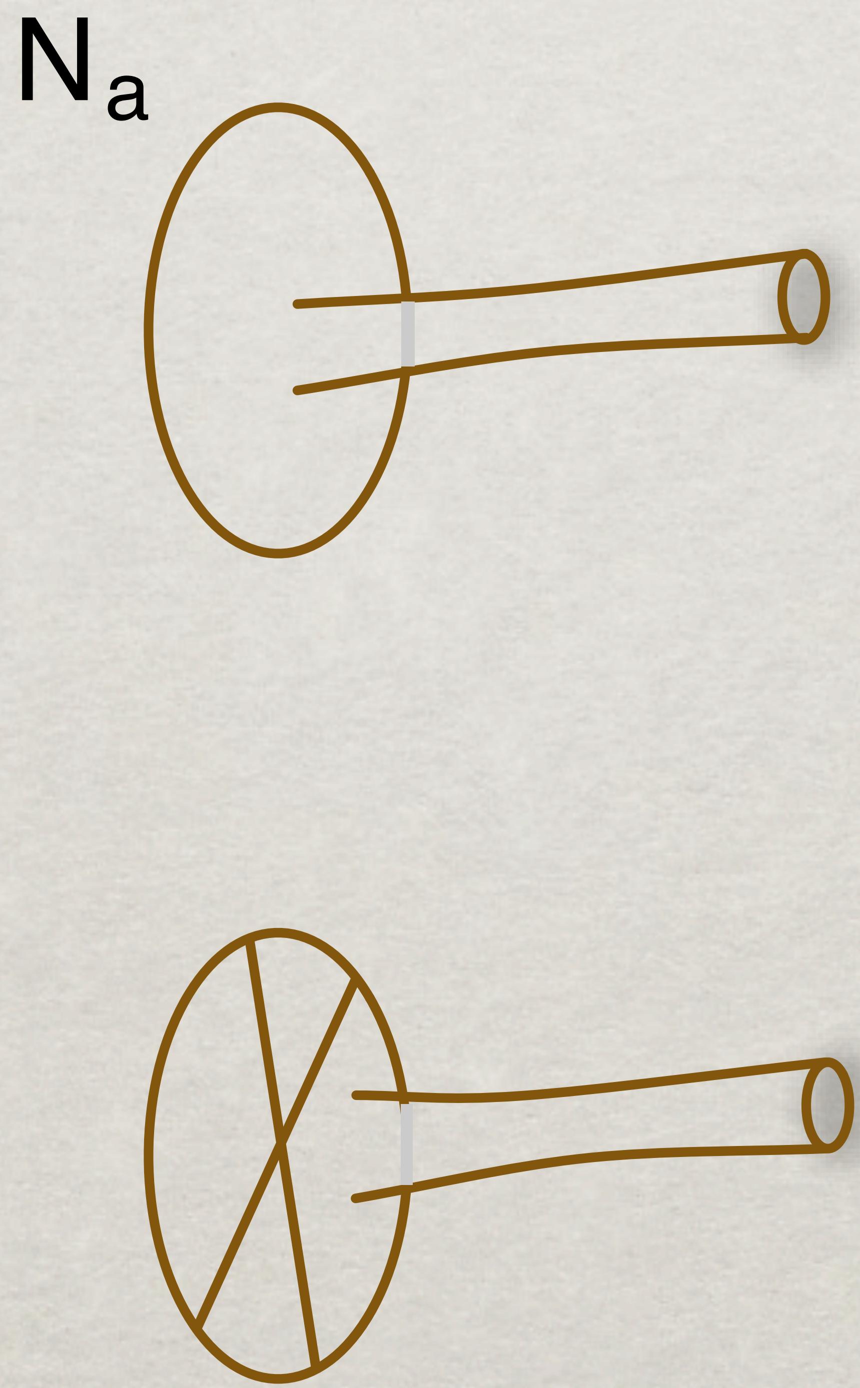
- Moebius

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

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

tadpoles & Anomalies

tadpoles & Anomalies



tadpoles & Anomalies

TADPOLES & ANOMALIES

- Tadpole cancellation condition:

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

- Cubic $\mathrm{Tr}F^3$ anomalies cancel

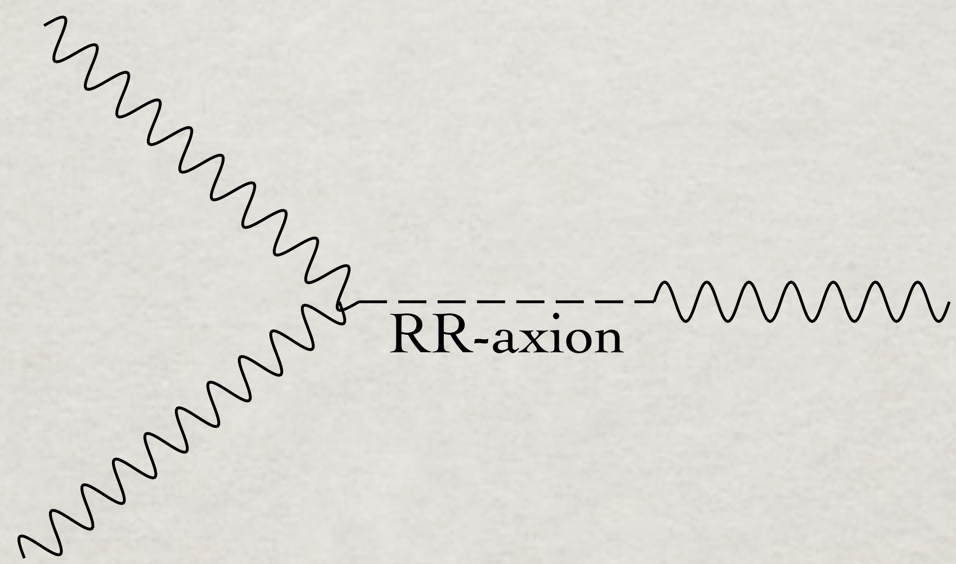
- Remaining anomalies by Green-Schwarz mechanism

- In rare cases, additional conditions for global anomaly cancellation*

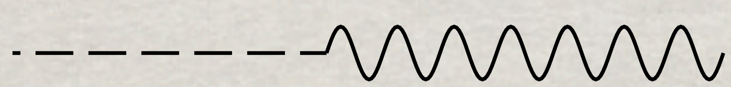
**Gato-Rivera, Schellekens (2005)*

Abelian Masses

Green-Schwarz mechanism



Axion-Vector boson vertex



Generates mass vector bosons of anomalous symmetries

$(e.g.\ B + L)$

But may also generate mass for non-anomalous ones

$(Y, B-L)$

Scope of the Search

Scope of the Search

- 168 Gepner models

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- 168 Gepner models
- 5403 MIPFs

Scope of the Search

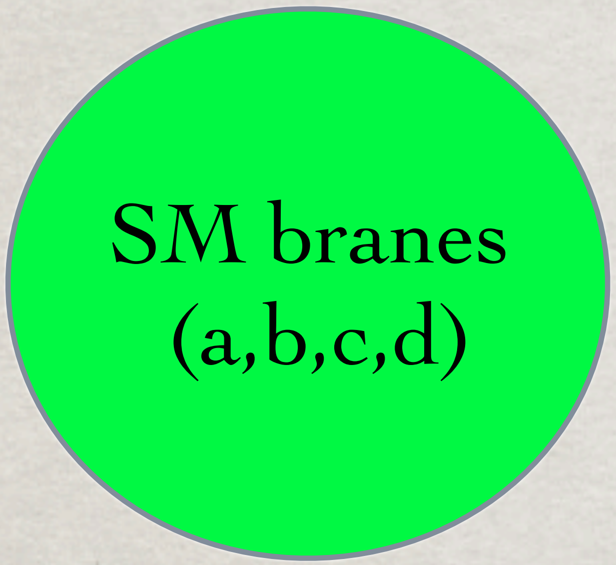
- 168 Gepner models
- 5403 MIPFs
- 49322 Orientifolds

Scope of the Search

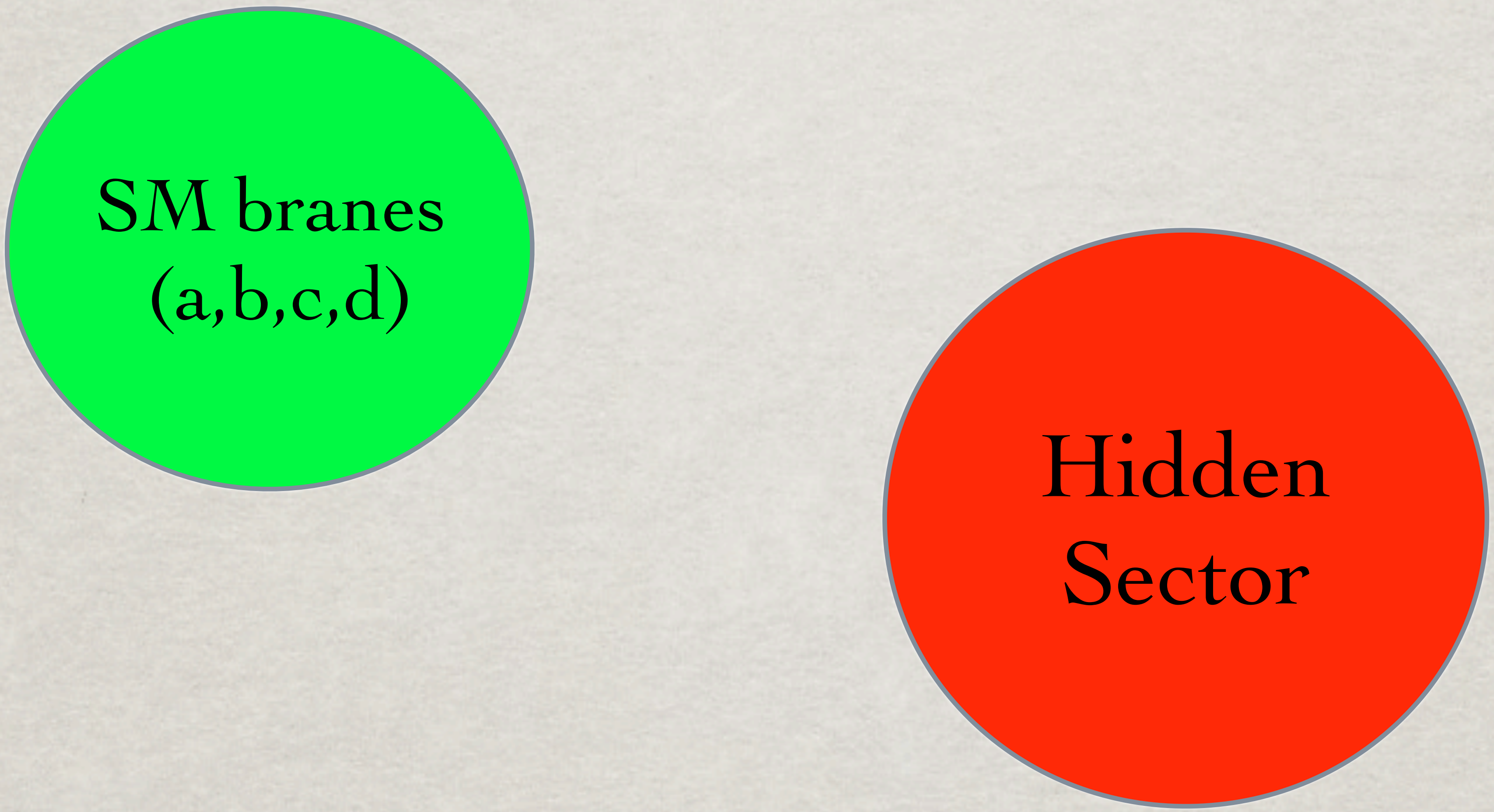
- 168 Gepner models
- 5403 MIPFs
- 49322 Orientifolds
- 4576118734763742772 combinations of four boundary labels (brane stacks)

STRATEGY

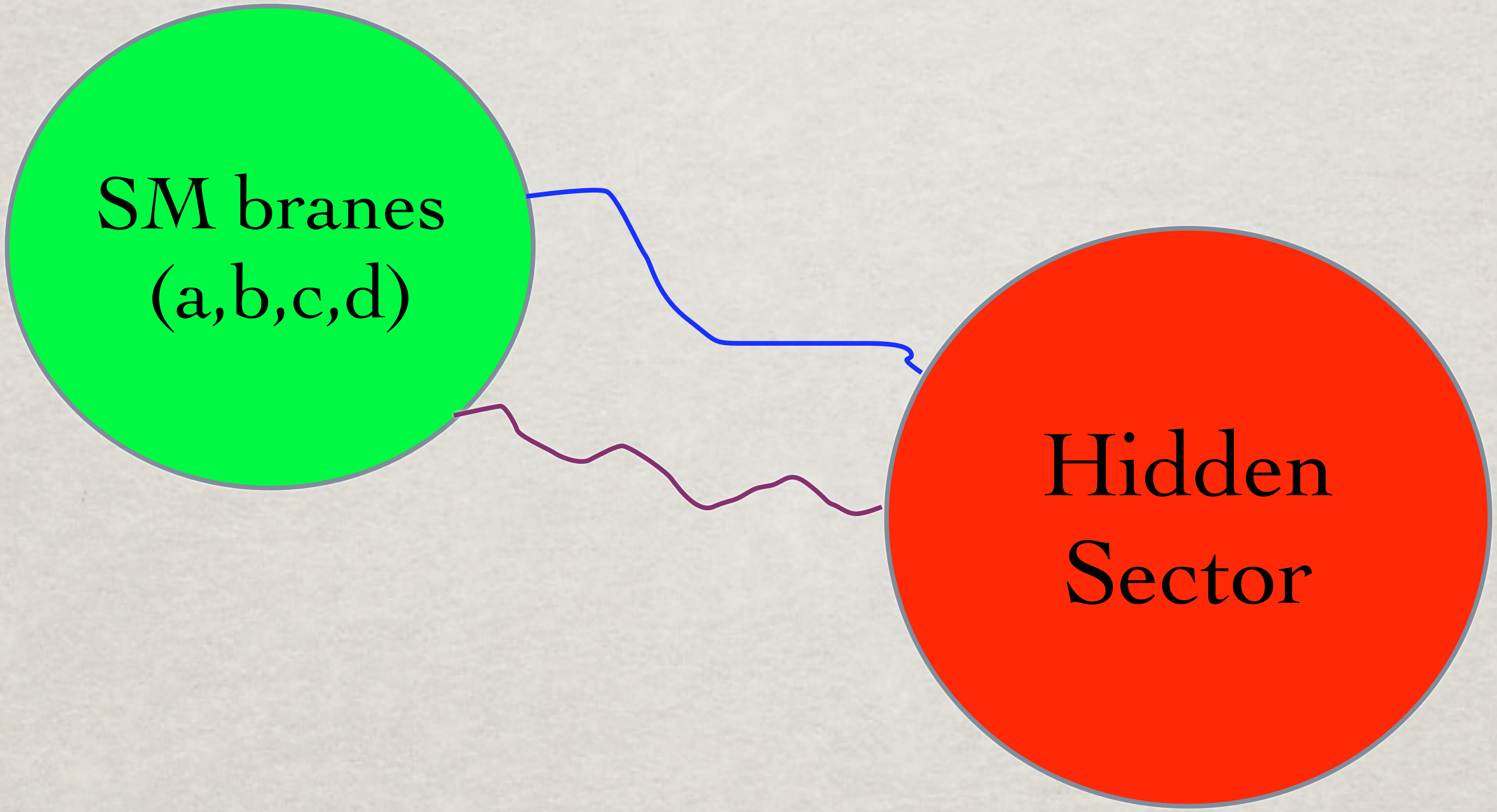
STRATEGY



STRATEGY



STRATEGY



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)
- No fractionally charged mirror pairs
- Massless Y

ALLOWED SPECTRA

w.r.t. $SU(3) \times SU(2) \times U(1)$

3 families + vector-like matter

w.r.t. $G_{CP} \supset SU(3) \times SU(2) \times U(1)$

Anything

Allowed Features

- (Anti)-quarks from anti-symmetric tensors
- leptons from anti-symmetric tensors
- family symmetries
- non-standard Y-charge assignments
- Unification (Pati-Salam, (flipped) SU(5), trinification)*
- Baryon and/or lepton number violation
- ....

*a,b,c,d may be identical

Chan-Paton gauge group

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

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

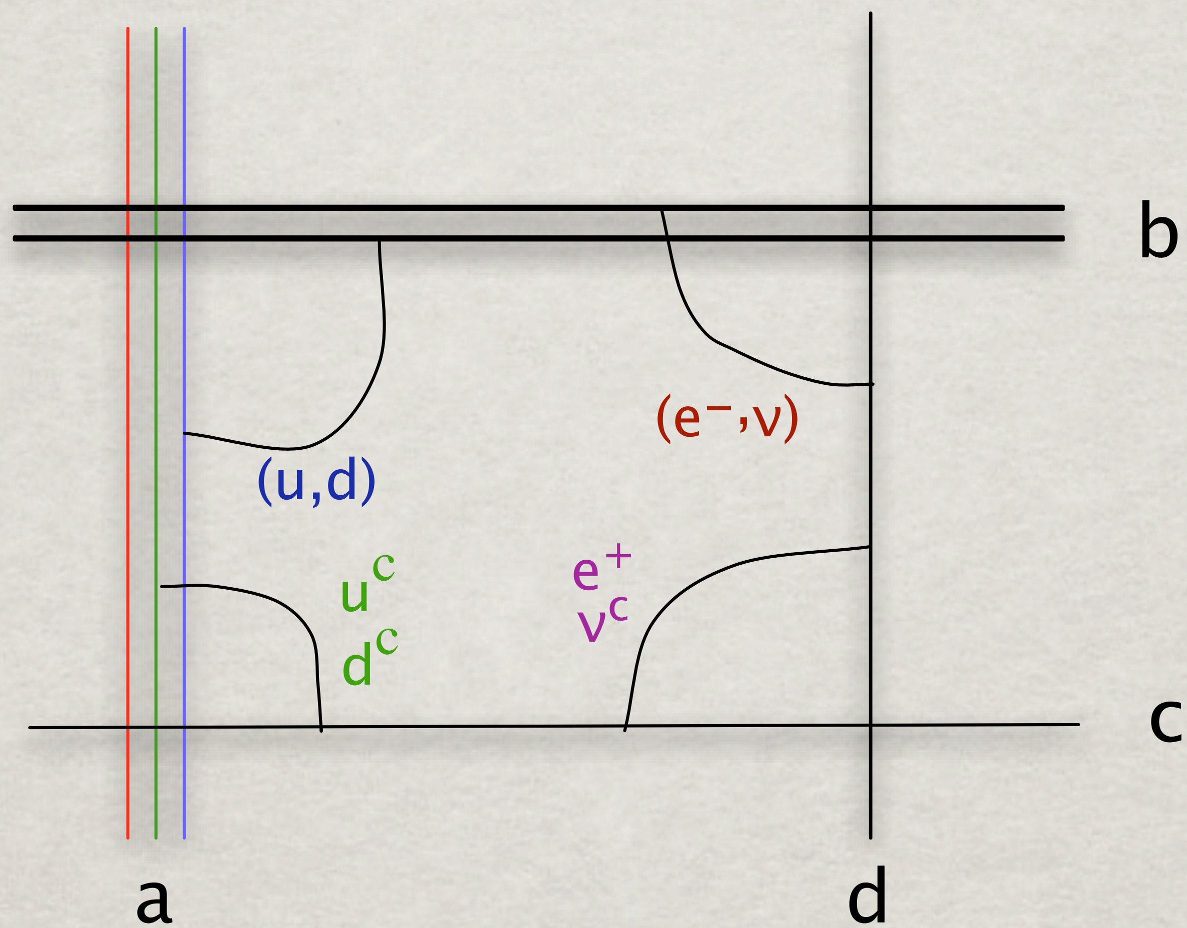
$$Y = (x - \frac{1}{3})Q_a + (x - \frac{1}{2})Q_b + \underbrace{xQ_C + (x-1)Q_D}$$

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)

The Madrid Model



Chiral SU(3) x SU(2) x U(1) spectrum:

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

Y massless $\qquad Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Qd$

Results

- Searched all MIPFs with < 1750 boundaries (4557 of 5403 MIPFs)
- 19345 *chirally* distinct SM embeddings found (out of infinitely many possible ones)
- Tadpole conditions solved in 1900 chirally distinct cases
- About 213000 *non-chirally* distinct models in database

Statistics

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

*Previous search: 45051902

Most frequent models

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	3308076	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
11	3308076	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
12	3093933	623	$U(6) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
13	2717632	461	$U(3) \times Sp(2) \times Sp(2) \times U(3)$	VVVV	1/2	Y!
14	2384626	560	$U(6) \times Sp(2) \times O(6)$	VVV	1/2	Y
15	2253928	669	$U(6) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!
16	1803909	519	$U(6) \times Sp(2) \times O(2)$	VVV	1/2	Y!
17	1787210	486	$U(4) \times Sp(2) \times U(3)$	VVV	1/2	Y
18	1787210	486	$U(4) \times Sp(2) \times U(3)$	VVV	1/2	Y
19	1676493	517	$U(8) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
20	1674416	384	$U(3) \times Sp(2) \times O(6) \times U(3)$	VVVV	1/2	Y
21	1642669	360	$U(3) \times Sp(2) \times Sp(6) \times U(5)$	VVVV	1/2	Y
22	1486664	346	$U(3) \times Sp(2) \times O(2) \times U(3)$	VVVV	1/2	Y!
23	1323363	476	$U(8) \times Sp(2) \times O(6)$	VVV	1/2	Y
24	1135702	350	$U(3) \times Sp(2) \times Sp(2) \times U(5)$	VVVV	1/2	Y!
25	1106616	209	$U(3) \times Sp(2) \times U(3) \times U(3)$	VVVV	1/2	Y
26	1106616	209	$U(3) \times Sp(2) \times U(3) \times U(3)$	VVVV	1/2	Y
27	1050764	532	$U(8) \times Sp(2) \times Sp(2)$	VVV	1/2	Y
28	956980	421	$U(8) \times Sp(2) \times O(2)$	VVV	1/2	Y
29	950003	449	$U(10) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
30	935034	351	$U(6) \times Sp(2) \times U(3)$	VVV	1/2	Y
31	935034	351	$U(6) \times Sp(2) \times U(3)$	VVV	1/2	Y

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26	1106616	209	$U(3) \times Sp(2) \times U(3) \times U(3)$	VVVV	1/2	Y
27	1050764	532	$U(8) \times Sp(2) \times Sp(2)$	VVV	1/2	Y
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30	935034	351	$U(6) \times Sp(2) \times U(3)$	VVV	1/2	Y
31	935034	351	$U(6) \times Sp(2) \times U(3)$	VVV	1/2	Y

Pati-Salam

4	4801518	867	$U(4) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!

```
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
```

SU(5)

708	16845	296	$U(5) \times O(1)$	AV	0	Y

```
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: gauge group is just SU(5)!

A free field theory model

```
Type:         U  S  U  U  O
Dimension     3  2  1  1  2
      3 x ( V ,V ,0 ,0 ,0 ) chirality 3
      3 x ( 0 ,0 ,V ,V ,0 ) chirality -3
      2 x ( V ,0 ,V ,0 ,0 ) chirality -2
      2 x ( V ,0 ,V*,0 ,0 ) chirality -2
      2 x ( 0 ,V ,0 ,V ,0 ) chirality 2
      3 x ( V ,0 ,0 ,V ,0 ) chirality -1
      1 x ( V ,0 ,0 ,V*,0 ) chirality -1
      3 x ( 0 ,V ,V ,0 ,0 ) chirality 1
      1 x ( 0 ,0 ,V ,V*,0 ) chirality 1
      4 x ( 0 ,0 ,V ,0 ,V ) chirality 0
      2 x ( A ,0 ,0 ,0 ,0 ) chirality 0
      2 x ( S ,0 ,0 ,0 ,0 ) chirality 0
      2 x ( 0 ,0 ,0 ,A ,0 ) chirality 0
      1 x ( 0 ,0 ,0 ,0 ,A ) chirality 0
      2 x ( 0 ,0 ,0 ,0 ,S ) chirality 0
```

Gepner model (2,2,2,2,2,2)

(2)=(Ising)×(Free boson)

This model was not discovered before because it as "masked" by this one from (2,2,2,6,6)

	U	S	U	U	U		
Dimension	3	2	1	1	2		
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	chirality 0	U+U*
2 x	0	0	0	S	0	chirality 0	E+E*

Truly hidden hidden sector

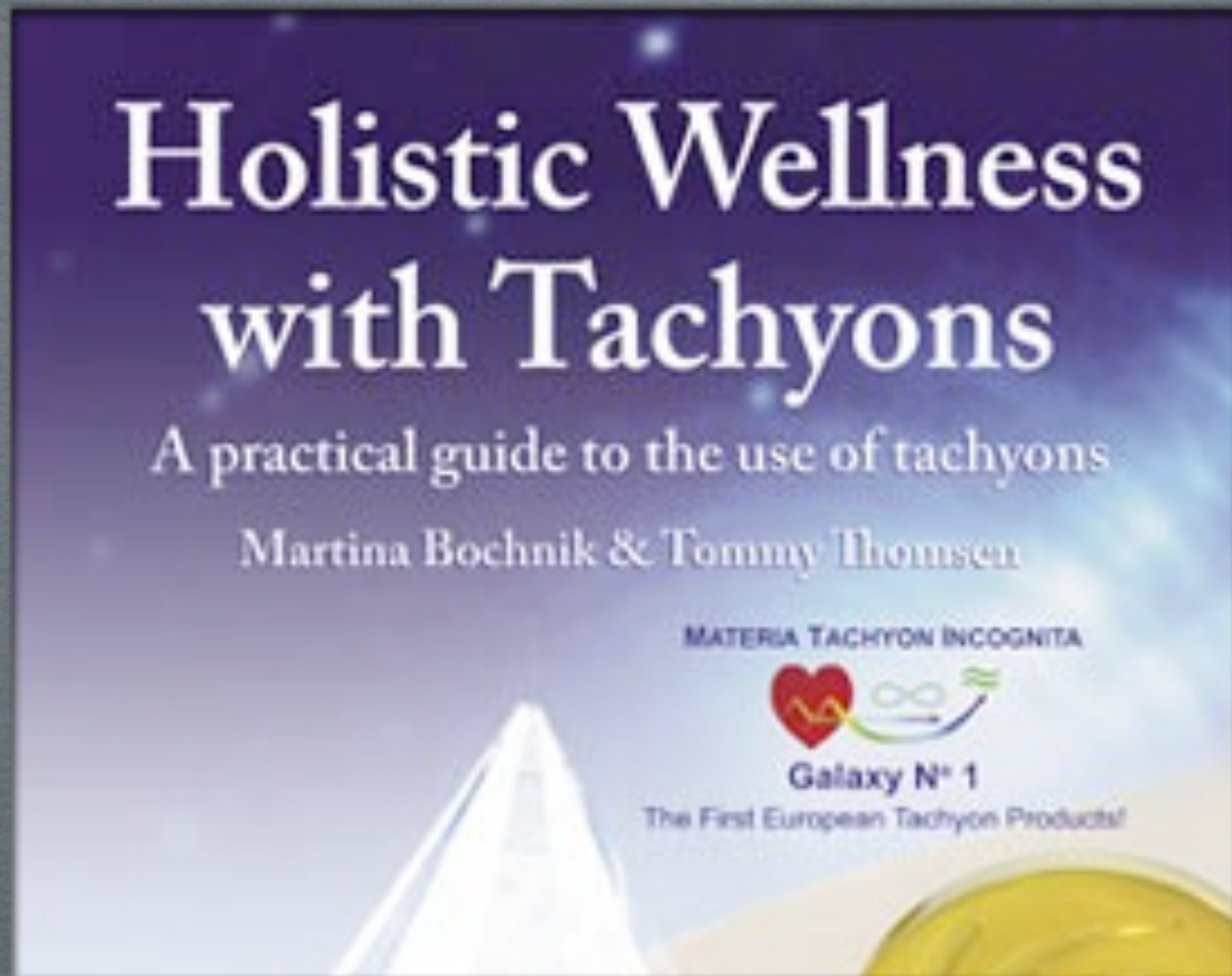
Free Fermion Models

The following real and complex free fermion models are accessible

(NSR) $(D_1)^9$	685 MIPFs*
(NSR) $(D_1)^7$ $(\text{Ising})^4$	3858 MIPFs*
(NSR) $(D_1)^5$ $(\text{Ising})^8$	111604 MIPFs
(NSR) $(D_1)^3$ $(\text{Ising})^{12}$	??? MIPFs

Plus combinations with Gepner models

(*) analyzed, yield essentially nothing of interest



Tachyon-free non-susy models

Non-supersymmetric Models

```
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

Non-supersymmetric Models

```
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
```

NSR

Minimal Models

W.S. Susy

[redacted]

```
compute spectrum
```

Non-supersymmetric models

Result:

- Far more possibilities
- Tachyons!

Four ways of removing closed string tachyons

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

Non-supersymmetric models

Result:

- Far more possibilities
- Tachyons!

Four ways of removing closed string tachyons

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

Non-supersymmetric models

Result:
- Far more possibilities
- Tachyons!

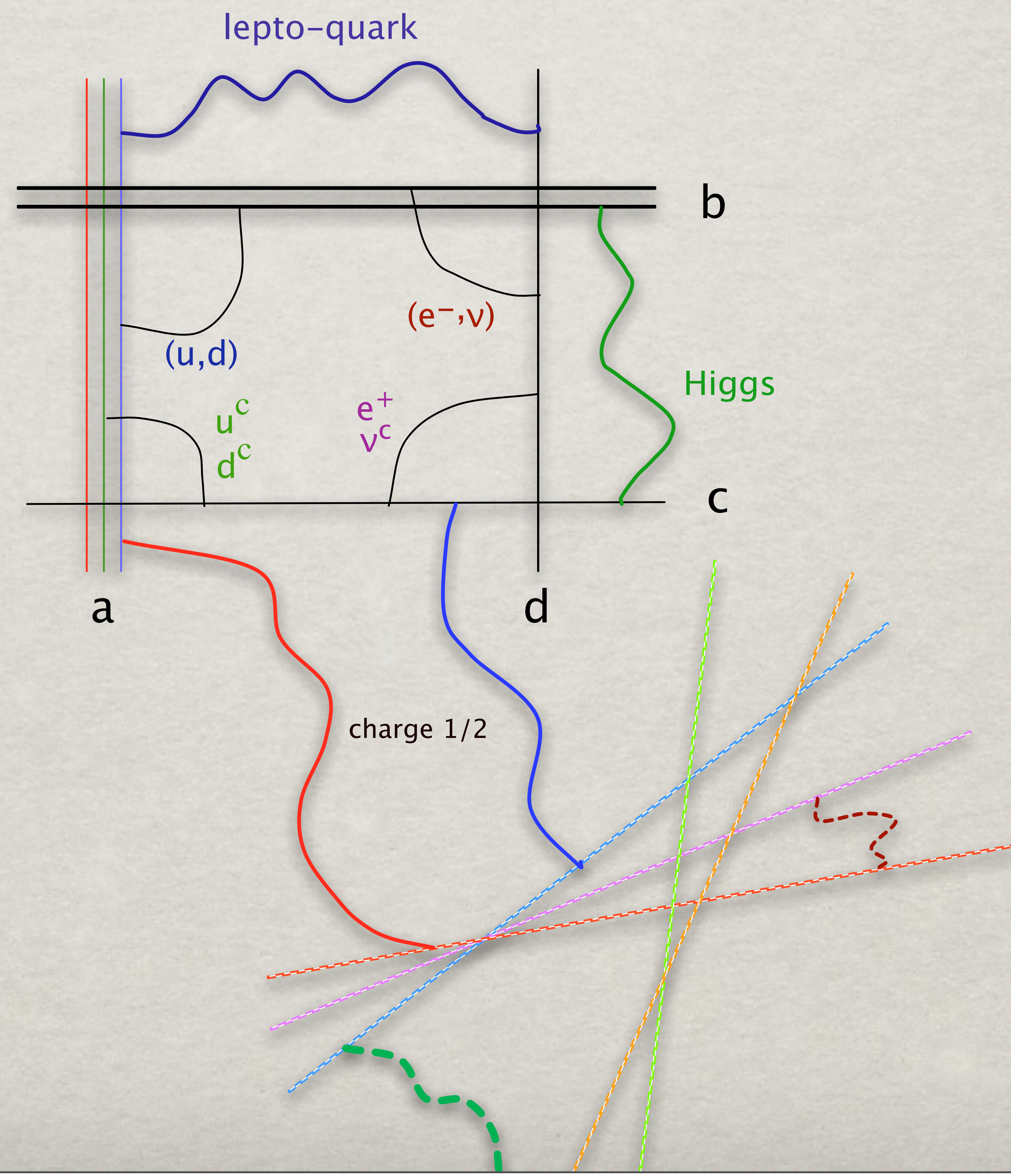
Four ways of removing closed string tachyons

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

Huge number of possibilities

Neutrino masses

Madrid model (with hidden sector)



Neutrinos

All these models have three right-handed neutrinos (required for cubic anomaly cancellation)

In most of these models:
B-L survives as an exact gauge symmetry

Neutrino's can get Dirac masses, but not Majorana masses (both needed for see-saw mechanism).

In a very small* subset, B-L acquires a mass due to axion couplings.

(*) 391 out of 213000, all with $SU(3)\times Sp(2)\times U(1)\times U(1)$

B-L Violation

But even then, B-L still survives as a perturbative symmetry.

It may be broken to a discrete subgroup by instantons.

This possibility can be explored if the instanton is described by a RCFT brane M.
B-L violation manifests itself as:

$$I_{M\mathbf{a}} - I_{M\mathbf{a}'} - I_{M\mathbf{d}} + I_{M\mathbf{d}'} \neq 0$$

I_{Ma} = chiral [# (V,V*) - # (V*,V)]   between branes M and a

a' = boundary conjugate of a

B-L anomalies

$$I_{M\mathbf{a}} - I_{M\mathbf{a}'} - I_{M\mathbf{d}} + I_{M\mathbf{d}'} \neq 0$$

Implies a cubic B-L anomaly if M is a "matter" brane (Chan-Paton multiplicity ≠ 0).

$\Rightarrow$ *M cannot be a matter brane: non-gauge-theory instanton*

Implies a (B-L)$(G_M)^2$ anomaly even if we cancel the cubic anomaly

$\Rightarrow$ *B-L must be massive*

(The converse is not true: there are massive B-L models without such instanton branes)

Required zero-modes

Neutrino mass generation by non-gauge theory instantons*

The desired neutrino mass term $\nu^c\nu^c$ violates c and d brane charge by two units. To compensate this, we must have

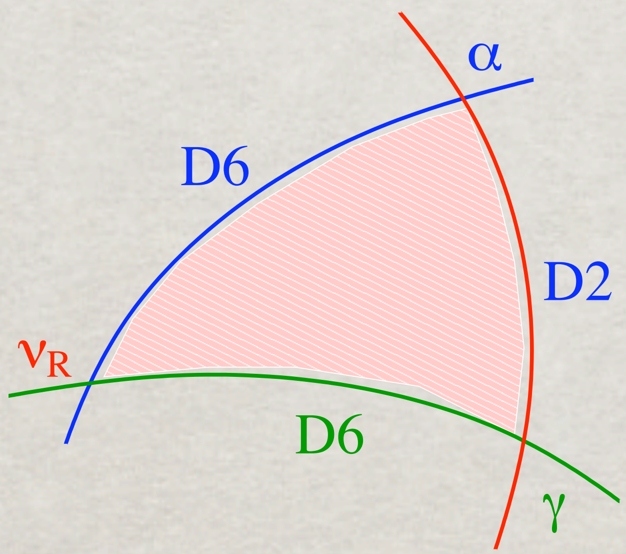
$$I_{M\mathbf{c}} = 2\ ;\ I_{M\mathbf{d}} = -2 \quad or \quad I_{M\mathbf{d}'} = 2\ ;\ I_{M\mathbf{c}'} = -2$$

and all other intersections 0.
(d' is the boundary conjugate of d)

(*) Blumenhagen, Cvetic, Weigand, hep-th/0609191
Ibañez, Uranga, hep-th/0609213

Neutrino-zero mode coupling

The following world-sheet disk is allowed by all symmetries



$$L_{cubic} \propto d_a^{ij} \, (\alpha_i \, \nu^a \gamma_j) \quad , a = 1, 2, 3$$

Zero-mode integrals

$$\int d^2\alpha\, d^2\gamma\; e^{-d_a^{ij}\;(\alpha_i \nu^a \gamma_j)} \;=\; \nu_a \nu_b \left(\, \epsilon_{ij}\epsilon_{kl} d_a^{ik} d_b^{jl}\,\right)$$

Additional zero modes yield additional fermionic integrals and hence no contribution

Therefore $I_{Ma}=I_{Mb}=I_{Mx}=0$ (x = Hidden sector), and there should be no vector-like zero modes.

There should also be no instanton-instanton zero-modes except 2 required by susy.

INSTANTON TYPES

In orientifold models we can have complex and real branes

Matter brane M	Instanton brane M
U(N)	U(k)
O(N)	Sp(2k)
Sp(2N)	O(k)

$$I_{M\mathbf{c}} = 2 \; ; \; I_{M\mathbf{d}} = -2 \quad or \quad I_{M\mathbf{d}'} = 2 \; ; \; I_{M\mathbf{c}'} = -2$$

Possible for:

- U, k=1 or 2
- Sp, k=1
- O, k=1,2

Universal instanton-instanton zero-modes

- U(k): 4 Adj
- Sp(2k): 2 A + 2 S
- O(k): 2 A + 2 S

Only O(1) has the required 2 zero modes

Instanton scan

Can we find such branes M in the 391 models with massive B-L?

Tensor	MIPF	Orientifold	Instanton	Solution
(2,4,18,28)	17	0		
(2,4,22,22)	13	3	$S2^+!$, $S2^-!$	Yes!
(2,4,22,22)	13	2	$S2^+!$, $S2^-!$	Yes
(2,4,22,22)	13	1	$S2^+$, $S2^-$	No
(2,4,22,22)	13	0	$S2^+$, $S2^-$	Yes
(2,4,22,22)	31	1	$U1^+, U1^-$	No
(2,4,22,22)	20	0		
(2,4,22,22)	46	0		
(2,4,22,22)	49	1	$O2^+, O2^-, O1^+, O1^-$	Yes
(2,6,14,14)	1	1	$U1^+$	No
(2,6,14,14)	22	2		
(2,6,14,14)	60	2		
(2,6,14,14)	64	0		
(2,6,14,14)	65	0		
(2,6,10,22)	22	2		
(2,6,8,38)	16	0		
(2,8,8,18)	14	2	$S2^+!$, $S2^-!$	Yes
(2,8,8,18)	14	0	$S2^+!$, $S2^-!$	No
(2,10,10,10)	52	0	$U1^+, U1^-$	No
(4,6,6,10)	41	0		
(4,4,6,22)	43	0		
(6,6,6,6)	18	0		

A model with S2 instantons

```
 5 x (V ,V ,0 ,0 ) chirality 3
 3 x (V ,0 ,V ,0 ) chirality -3
 3 x (V ,0 ,V*,0 ) chirality -3
 3 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 )
18 x (0 ,V ,V ,0 )
 2 x (Ad,0 ,0 ,0 )
 2 x (A ,0 ,0 ,0 )
 2 x (S ,0 ,0 ,0 )
14 x (0 ,A ,0 ,0 )
 6 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 )
```

Gauge group: SU(3) × SU(2) × U(1) × Nothing.
Exactly the correct number of instanton zero modes
(except for 2 universal symmetric tensors)

A model with S2 instantons

```
 5 x (V ,V ,0 ,0 ) chirality 3
 3 x (V ,0 ,V ,0 ) chirality -3
 3 x (V ,0 ,V*,0 ) chirality -3
 3 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 )
18 x (0 ,V ,V ,0 )
 2 x (Ad,0 ,0 ,0 )
 2 x (A ,0 ,0 ,0 )
 2 x (S ,0 ,0 ,0 )
14 x (0 ,A ,0 ,0 )
 6 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 )
```

Gauge group: SU(3) × SU(2) × U(1) × Nothing.
Exactly the correct number of instanton zero modes
(except for 2 universal symmetric tensors)

$$\sin^2(\theta_w) = .5271853$$

$$\frac{\alpha_3}{\alpha_2} = 3.2320501$$

The O1 instanton

```
Type:           U  S  U  U   U  O  O  U  O  O  O  U  S  S  O   S
Dimension       3  2  1  1   1  2  2  3  1  2  3  1  2  2  2   --
       2 x ( 0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ) chirality 2
       5 x ( V ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -3
       5 x ( 0 ,0 ,V ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 3
      12 x ( 0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ) chirality -2
       3 x ( V ,0 ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -3
       3 x ( 0 ,0 ,V ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -3
       3 x ( V ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 3
       3 x ( 0 ,V ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 3
      25 x ( 0 ,0 ,Ad,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( A ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       4 x ( V ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( 0 ,0 ,0 ,A ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
      34 x ( 0 ,0 ,A ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
      14 x ( 0 ,0 ,S ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ) chirality 0
       2 x ( 0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ) chirality 0
       1 x ( Ad,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( 0 ,S ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       1 x ( 0 ,0 ,0 ,Ad,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       6 x ( 0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ) chirality 0
       2 x ( S ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( 0 ,0 ,0 ,S ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( 0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ) chirality 0
       1 x ( 0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       1 x ( 0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       1 x ( 0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( V ,0 ,0 ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( V ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( 0 ,0 ,0 ,V ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( 0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ) chirality 0
       6 x ( 0 ,V ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       6 x ( 0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ) chirality 0
       2 x ( V ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       2 x ( 0 ,0 ,0 ,V ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
       3 x ( 0 ,0 ,0 ,0 ,S ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -1
       3 x ( 0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ) chirality 1
       1 x ( 0 ,0 ,0 ,0 ,A ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -1
       2 x ( 0 ,0 ,0 ,0 ,V ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 2
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Conclusions

- A huge number of tadpole and tachyon free models can be built with RCFT orientifolds.
- Many desirable SM features can be realized
    - Chiral SM spectrum
    - No mirrors
    - No adjoints, rank-2 tensors
    - No hidden sector
    - No hidden-observable massless matter
    - Matter free hidden sector
    - Exact $SU(3)\times SU(2)\times U(1)$
    - O1 instantons
    - S2 instantons with correct zero-modes
    - .....

but not all at the same time