The RCFT orientifold "Landschap"

Exploring the landscape

1986 (with Lerche, Lüst): many "vacua"

A few people: string theory must be wrong, or "just a framework".
Most people: wait and see...
Some people: probably true, but who cares?
My conclusion: "anthropic landscape"

Present motivation

Landscape remains to a large extent unexplored.
Very few "standard model spectra" known.
Are there any generic features?
How many fit current data?

Exploring the landscape

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Landscape remains to a large extent unexplored.
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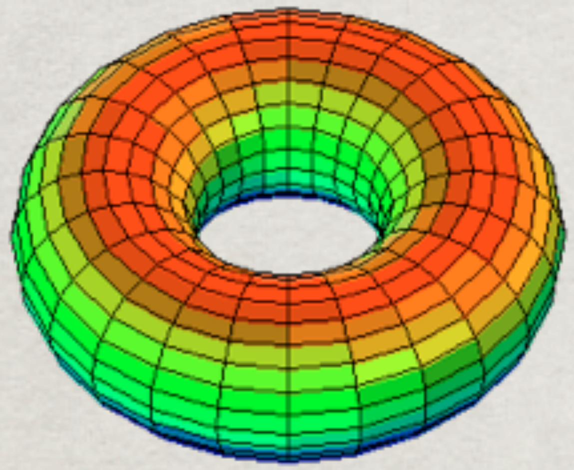
Are there any generic features?
How many fit current data?

"Is the standard model a plausible solution to the landscape and anthropic constraints?"

Orientifold Partition Functions

$\frac{1}{2}$ {



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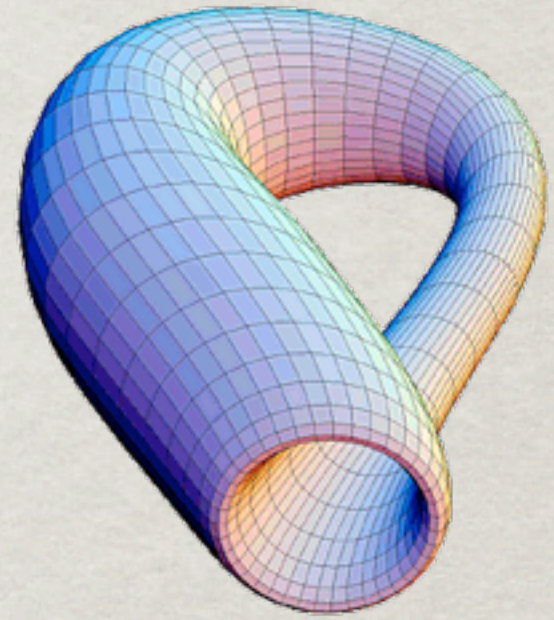

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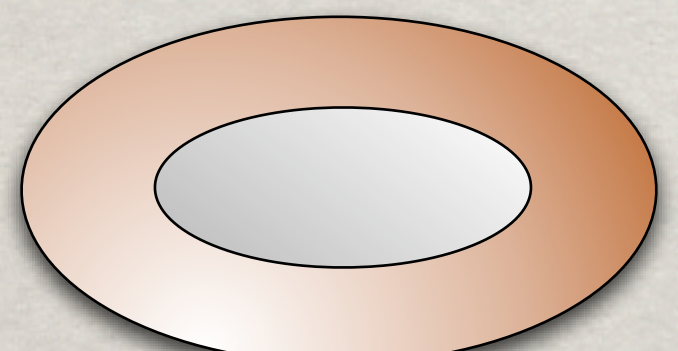
$\frac{1}{2}$ {



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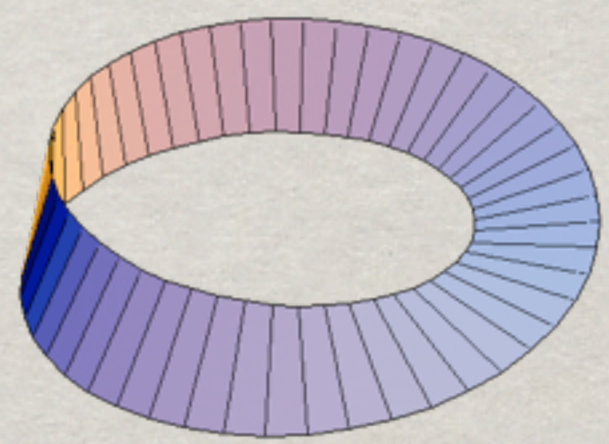

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Orientifold Partition Functions

- 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)

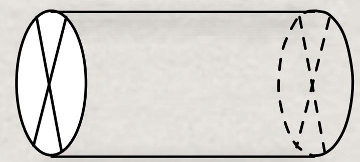
a : Boundary label (finite range)

χ_i : Character

N_a : Chan-Paton (CP) Multiplicity

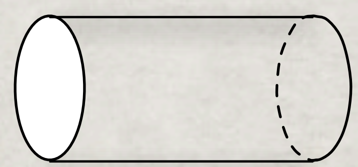
Coefficients

- Klein bottle



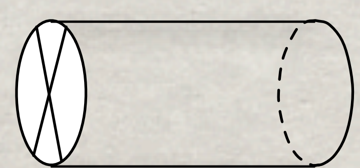
$$K^i = \sum_{m,J,J'} \frac{{S^i}_m U_{(m,J)} g^{\Omega,m}_{J,J'} U_{(m,J')}}{S_{0m}}$$

- 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

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

- 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)

Algebraic choices

- Basic CFT (N=2 tensor, free fermions...)
  (Type IIB closed string theory)

- Chiral algebra extension(*)
  May imply space-time symmetry (e.g. Susy: GSO projection).
  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)

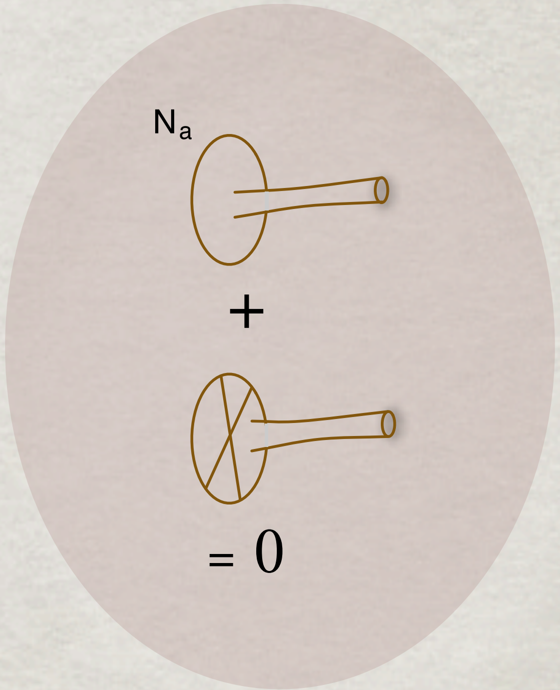
- Orientifold choice(*)

(*) all these choices are simple current related

TADPOLES & ANOMALIES

- Tadpole cancellation condition:

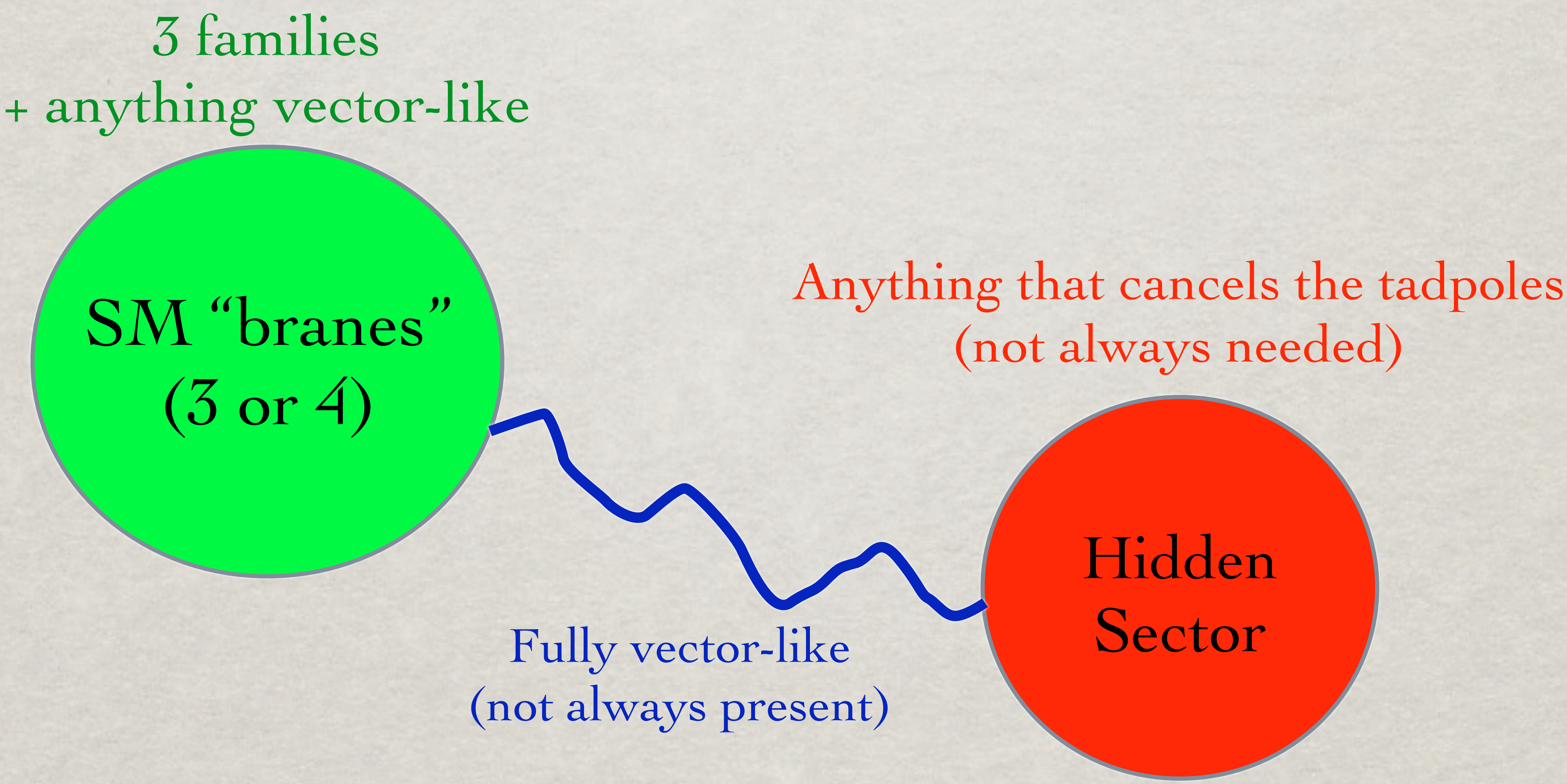
$$\sum_b N_b R_{b(m,J)} = 4\eta_m U_{(m,J)}$$



- Cubic anomalies cancel
- Remaining anomalies by Green-Schwarz mechanism
- In rare cases, additional conditions for global anomaly cancellation*

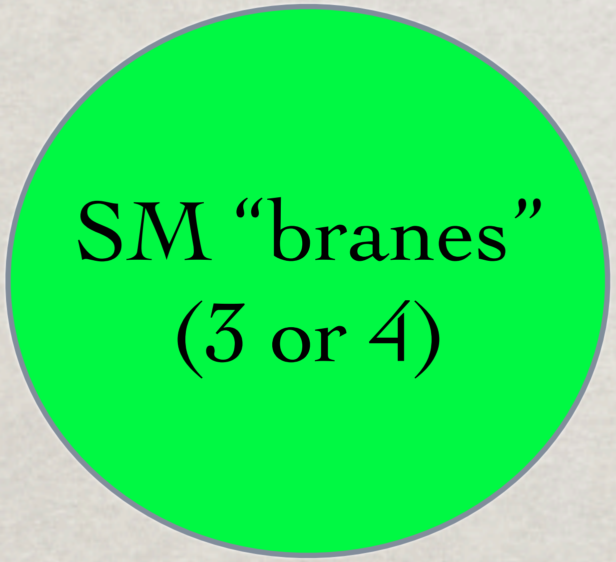
Gato-Rivera, Schellekens (2005)

Models



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

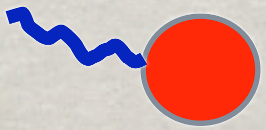
Models



$G_{CP} \supset SU(3) \times SU(2) \times U(1)$

Chiral fermions $\rightarrow$ 3 families

Criteria for distinguishing spectra

1. Chiral G_{CP} spectrum ("chiral type"), e.g SU(5), Pati-Salam, ...
2. Massless G_{CP} spectrum
3. Massless G_{CP} spectrum + 

Free Fermion Models*

The following real and complex free fermion models are accessible

(NSR) $(D_1)^9$	685 MIPFs	❶
(NSR) $(D_1)^7$ $(\mathrm{Ising})^4$	3858 MIPFs	❷
(NSR) $(D_1)^5$ $(\mathrm{Ising})^8$	111604 MIPFs	❸
(NSR) $(D_1)^3$ $(\mathrm{Ising})^{12}$	$> 2^{28}$ MIPFs	

❶ One SM config, no tadpole solutions
❷ Nothing!
❸ > 40000 MIPFs done, > 30 days, Nothing yet!

(*) with E. Kiritsis

Gepner models*

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

Two scans:

with Dijkstra, Huiszoon (2004/2005)

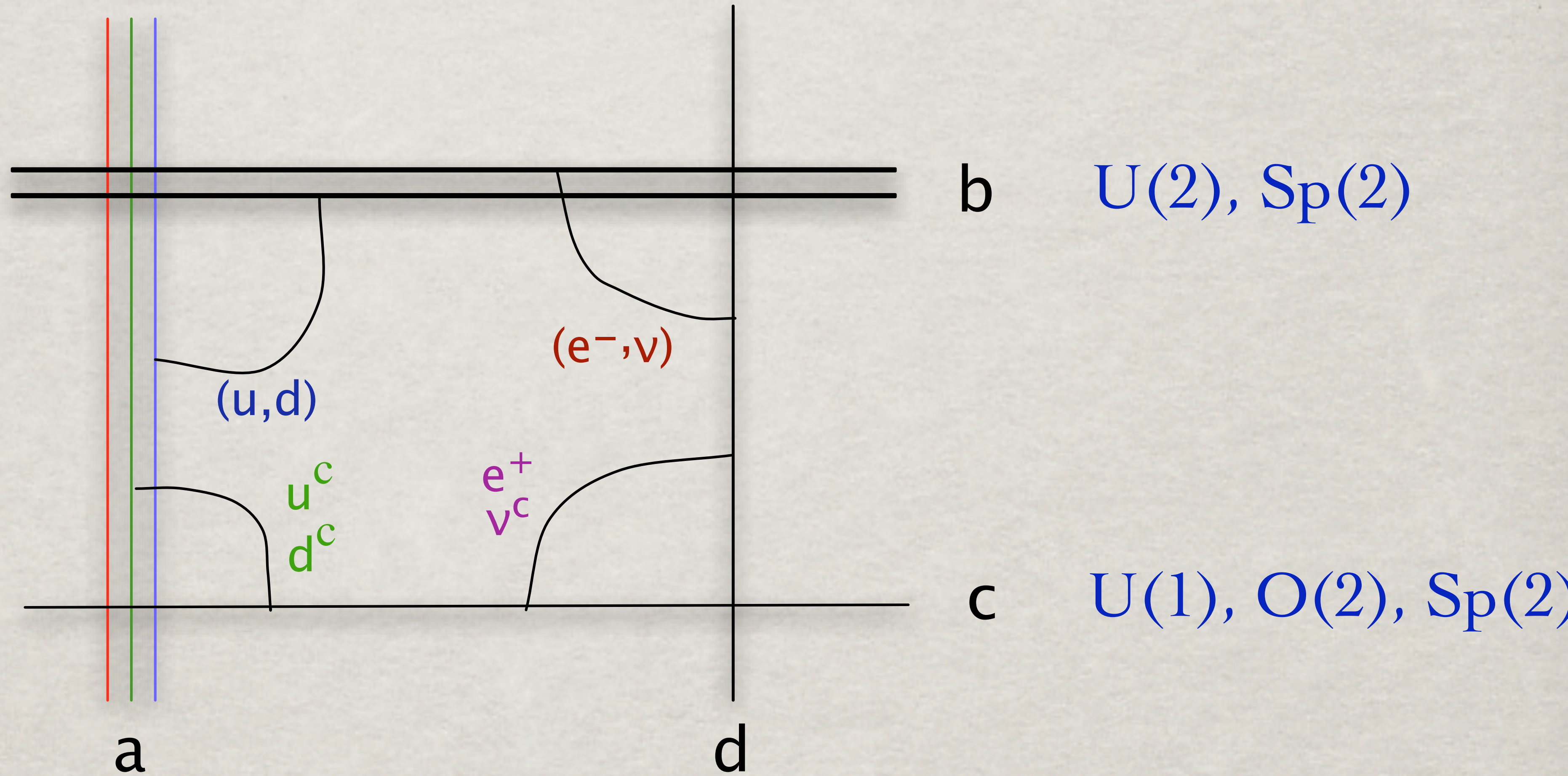
- 19 Chiral types ("Madrid models")
- 18 with tadpole cancellation
- 211000 non-chirally distinct spectra (criterium 2)

with Anastasopulos, Dijkstra, Kiritsis (2005/2006)

- 19345 Chiral types
- 1900 with tadpole cancellation
- 1900 non-chirally distinct spectra (criterium 1)

(*)Also: Angelantonj et. al, Blumenhagen et. al., Aldazabal et. al, Brunner et al.....

The Madrid Model*

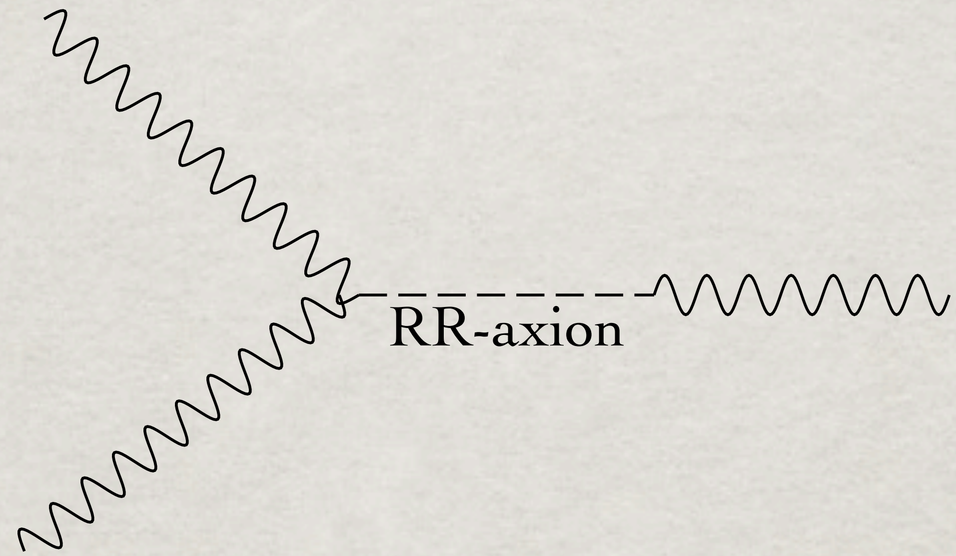


$$Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Qd$$

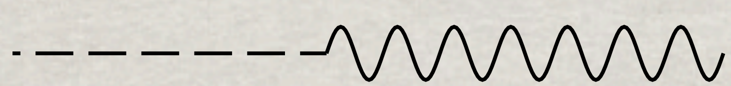
(*) Ibanez, Marchesano, Rabadan

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

$(Y, B - L)$

A "madrid" Model

Gauge group: Exactly SU(3) × SU(2) × U(1)!

[U(3)×Sp(2)×U(1)×U(1), Massive B-L, No hidden sector]

3 x	(V	,V	,0	,0)	chirality 3	Q
3 x	(V	,0	,V	,0)	chirality -3	U*
3 x	(V	,0	,V*	,0)	chirality -3	D*
3 x	(0	,V	,0	,V)	chirality 3	L
5 x	(0	,0	,V	,V)	chirality -3	E*+(E+E*)
3 x	(0	,0	,V	,V*)	chirality 3	N*
18 x	(0	,V	,V	,0)		Higgs
2 x	(V	,0	,0	,V)		
2 x	(Ad	,0	,0	,0)		
2 x	(A	,0	,0	,0)		
6 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)		

A "MADRID" MODEL

Gauge group: Exactly SU(3) × SU(2) × U(1)!

[U(3)×Sp(2)×U(1)×U(1), Massive B-L, No hidden sector]

3 x	(V	,V	,0	,0)	chirality 3	Q
3 x	(V	,0	,V	,0)	chirality -3	U*
3 x	(V	,0	,V*	,0)	chirality -3	D*
3 x	(0	,V	,0	,V)	chirality 3	L
5 x	(0	,0	,V	,V)	chirality -3	E*+(E+E*)
3 x	(0	,0	,V	,V*)	chirality 3	N*
18 x	(0	,V	,V	,0)		Higgs
2 x	(V	,0	,0	,V)		
2 x	(Ad	,0	,0	,0)		
2 x	(A	,0	,0	,0)		
6 x	(S	,0	,0	,0)		
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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)		

Vector-like matter

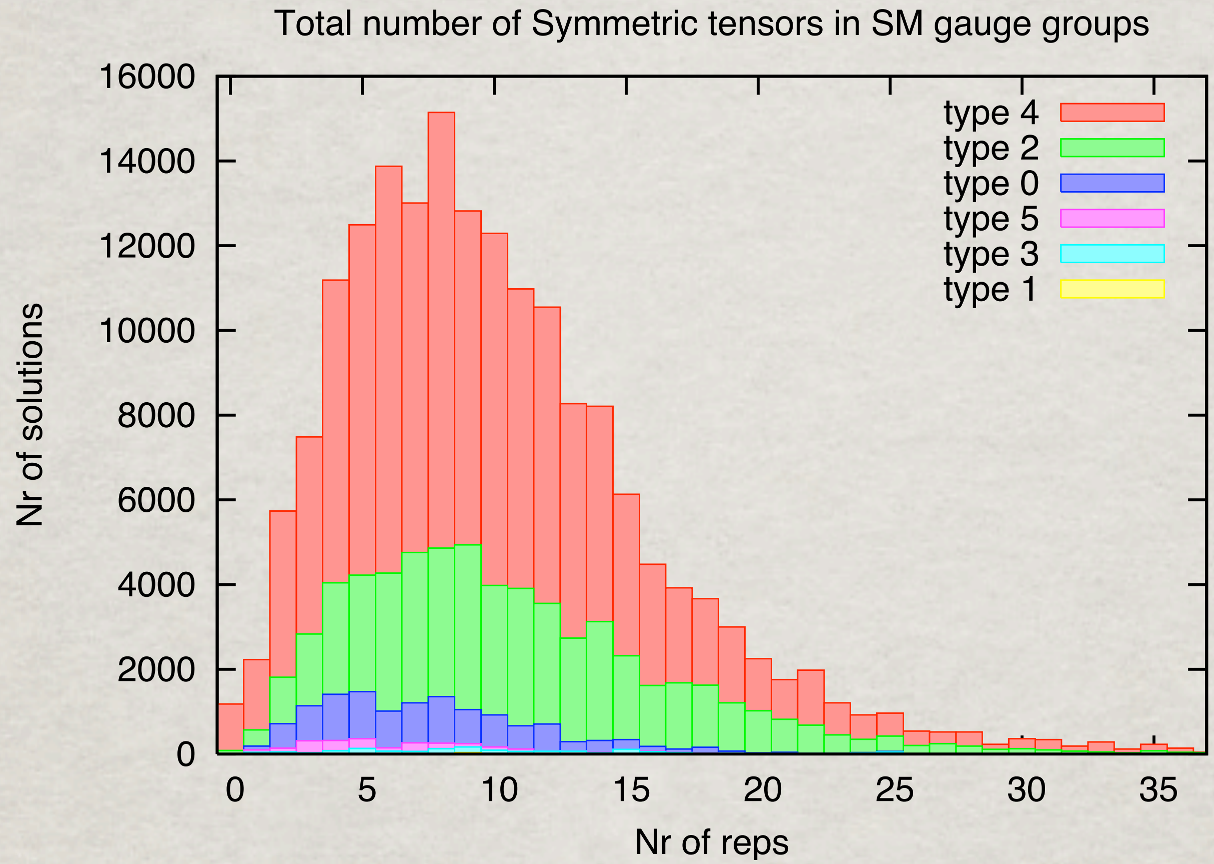
V=vector

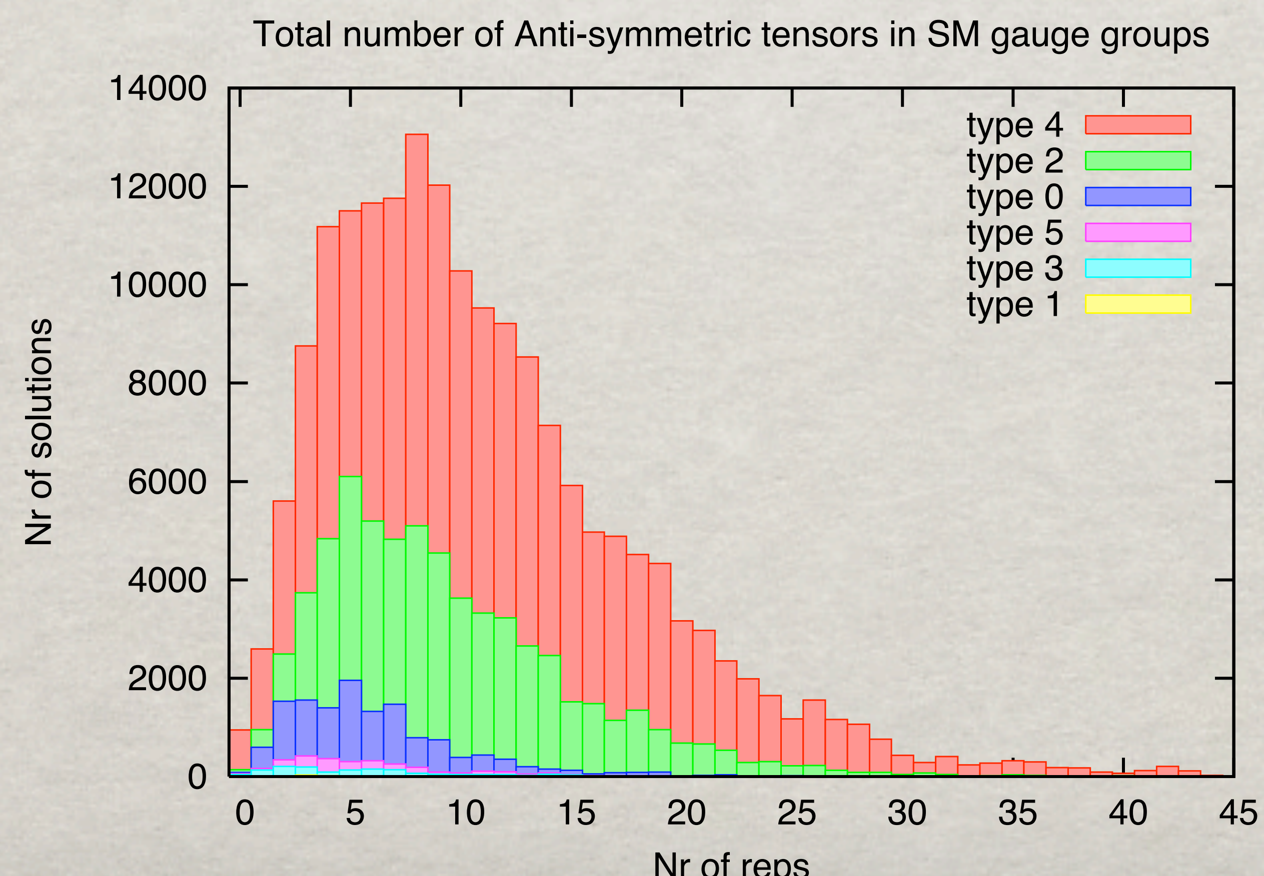
A=Anti-symm. tensor

S=Symmetric tensor

Ad=Adjoint

Rank-2 tensors





No mirrors, no rank-2 tensors

(Left-right symmetric model)

	U3	S2	S2	U1	S6	S4	S2		
3 x	(V	,V	,0	,0	,0	,0	,0)	chirality 3	Q
3 x	(V	,0	,V	,0	,0	,0	,0)	chirality -3	U*,D*
3 x	(0	,V	,0	,V	,0	,0	,0)	chirality 3	L
3 x	(0	,0	,V	,V	,0	,0	,0)	chirality -3	E*,N*
2 x	(V	,0	,0	,V	,0	,0	,0)		Leptoquark pair
2 x	(0	,V	,V	,0	,0	,0	,0)		2 Higgs pairs
2 x	(V	,0	,0	,0	,V	,0	,0)		
2 x	(V	,0	,0	,0	,0	,V	,0)		
2 x	(V	,0	,0	,0	,0	,0	,V)		
1 x	(0	,V	,0	,0	,V	,0	,0)		
1 x	(0	,0	,V	,0	,V	,0	,0)		
2 x	(0	,0	,0	,V	,0	,V	,0)		
1 x	(0	,0	,0	,0	,V	,0	,V)		
2 x	(0	,0	,0	,0	,0	,V	,V)		
2 x	(0	,0	,0	,0	,A	,0	,0)		
1 x	(0	,0	,0	,0	,S	,0	,0)		
5 x	(0	,0	,0	,0	,0	,A	,0)		
5 x	(0	,0	,0	,0	,0	,S	,0)		
1 x	(0	,0	,0	,0	,0	,0	,S)		

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

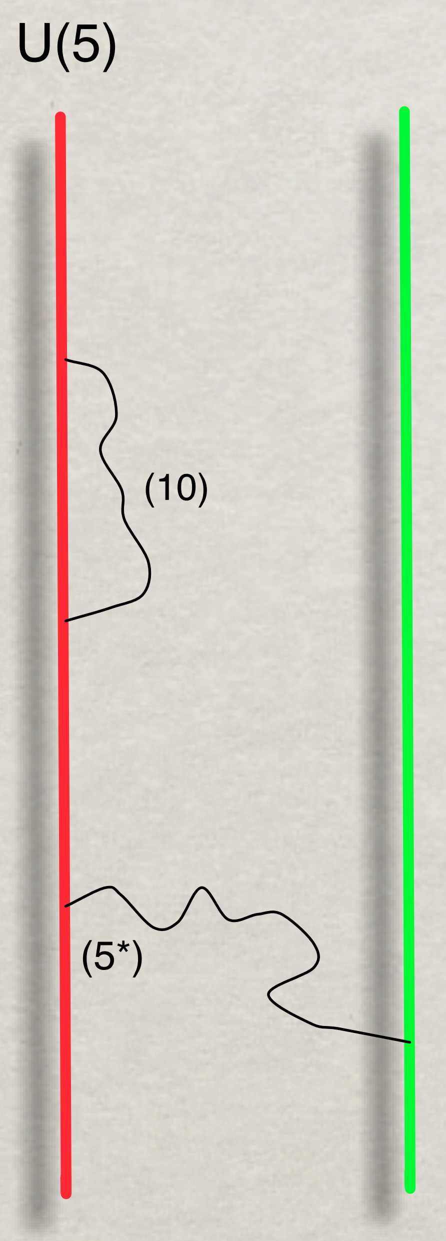
Gauge group SU(3)× SU(2) × U(1) × [U(2)$_{\text{Hidden}}$)]

	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

An SU(5) model

Gauge group is just SU(5)!



U5 O1 O1

3	x	(A	,0	,0	)	chirality 3
11	x	(V	,V	,0	)	chirality -3
8	x	(S	,0	,0	)	
3	x	(Ad	,0	,0	)	
1	x	(0	,A	,0	)	
3	x	(0	,V	,V	)	
8	x	(V	,0	,V	)	
2	x	(0	,S	,0	)	
4	x	(0	,0	,S	)	
4	x	(0	,0	,A	)	

Top quark Yukawa's?

One in how many?

$$\frac{\text{Madrid configurations}}{\text{All 4-brane configurations}} = 10^{-12}$$

$$\frac{\text{With tadpole solution}}{\text{All 4-brane configurations}} = 3.8 \times 10^{-14}$$

} *Dijkstra et. al. (2005)*

$$\frac{\text{Madrid configurations}}{\text{All SM configurations}} = 1/6$$

Anastasopoulos et. al. (2006)

Gmeiner, Blumenhagen, Honecker, Lüst, Weigand (2005)
Douglas, Taylor (2006)

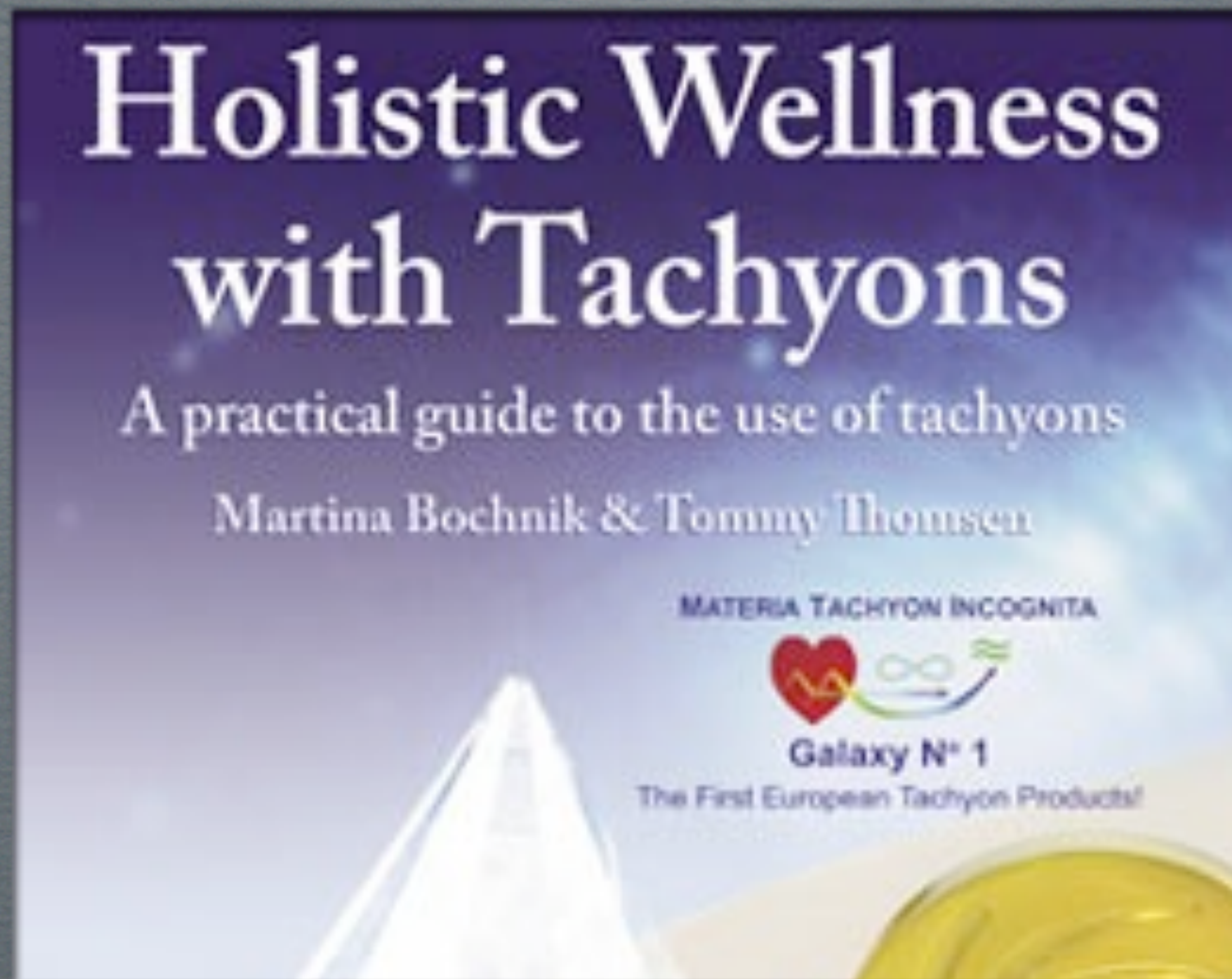
$T^6/Z_2 \times Z_2$ orientifolds

$$\frac{\text{Madrid configurations with tadpole solution}}{\text{All tadpole solutions}} \sim 1 \times 10^{-9}$$

T^6/Z_6 orientifolds

Gmeiner, Lüst, Stein (2007)

$$\frac{\text{Madrid configurations with tadpole solution}}{\text{All tadpole solutions}} \sim 1 \times 10^{-22}$$



Non-supersymmetric models

Non-supersymmetric models*

Four ways of removing closed string tachyons

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

(*) with Beatriz Gato-Rivera

Non-supersymmetric models*

Four ways of removing closed string tachyons

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

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Non-supersymmetric models*

Four ways of removing closed string tachyons

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

Huge number of possibilities!

(*) with Beatriz Gato-Rivera

Neutrino masses

NEUTRINO MASSES*

- In field theory: easy; several solutions.
  Most popular:
  add three right-handed neutrinos
  add "natural" Dirac & Majorana masses (see-saw)

$$m_\nu = \frac{(M_D)^2}{M_M}; \quad M_D \approx 100 \text{ MeV}, \qquad M_M \approx 10^{11} \dots 10^{13} \text{ GeV}$$

- In string theory: non-trivial.
  (String theory is much more falsifiable!).

- Potentially anthropic.

(*) *Ibañez, Schellekens, Uranga,* **arXiv:0704.1079, JHEP (to appear)**
Blumenhagen, Cvetic, Weigand, hep-th/0609191
Ibañez, Uranga, hep-th/0609213

Other ideas: see e.g. Conlon, Cremades; Giedt, Kane, Langacker, Nelson; Buchmuller, Hamaguchi, Lebedev, Ratz, ...

Neutrino masses in Madrid models

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 10000 models with $SU(3)\times Sp(2)\times U(1)\times U(1)$
(out of 211000 in total)

B-L Violation by instantons

B-L still survives as a perturbative symmetry.
It may be broken to a discrete subgroup by instantons.

RCFT instanton boundary state M:
"Matter" boundary state m, change space-time boundary conditions from Neumann to Dirichlet.

Condition for B-L violation: $I_{M\mathbf{a}} - I_{M\mathbf{a}'} - I_{M\mathbf{d}} + I_{M\mathbf{d}'} \neq 0$

Non-gauge (stringy, exotic) instanton:
CP multiplicity of the assocated matter brane = 0

- Does not introduce new anomalies/tadpoles
- Suppression factor not related to gauge coupling strengths

$$M_M \propto M_s e^{-\frac{1}{g_M^2}}$$

ZERO-MODES

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

$$I_{Mc} = 2; \quad I_{Md} = -2$$

or

$$I_{Md'} = 2; \quad I_{Mc'} = -2$$

Furthermore there must be precisely two susy zero-modes to generate an F-term contribution.

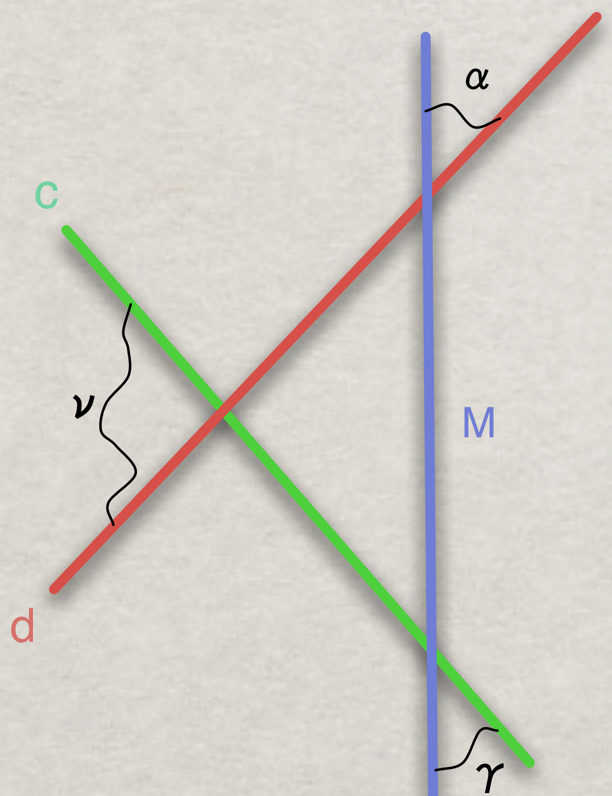
And nothing else!

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

a' = boundary conjugate of a

Zero-mode integral

Zero-mode/neutrino coupling



$$L_{\text{disk}} \propto d_a^{ij}(\alpha_i \nu^a \gamma_j)$$

$$a = 1, 2, 3; \quad i, j = 1, 2$$

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

INSTANTON TYPES

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

Matter/Instanton
zero modes: 0, ±2

Possible for:

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

Instanton-Instanton
susy zero modes: 2

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

Only solution: O(1)

Instanton scan

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

- About 30.000 "instanton branes" ($I_{M\mathbf{a}} - I_{M\mathbf{a}'} - I_{M\mathbf{d}} + I_{M\mathbf{d}'} \neq 0$)
- Quantized in units of 1,2 or 4

  (1 may give R-parity violation, 4 means no Majorana mass)
- Some models have no RCFT instantons
- 1315 instantons with correct ***chiral*** intersections
- None of these models has R-parity violating instantons.
- Most instantons are symplectic in this sample.
- There are examples with exactly the right number, ***non-chirally***, except for the spurious extra susy zero-modes (Sp(2) instantons).

...almost

An Sp(2) instanton model

	U3	S2	U1	U1	O	
3 x	V	V	0	0	0	chirality 3
3 x	V	0	V	0	0	chirality -3
3 x	V	0	V*	0	0	chirality -3
3 x	0	V	0	V	0	chirality 3
5 x	0	0	V	V	0	chirality -3
3 x	0	0	V	V*	0	chirality 3
1 x	0	0	V	0	V	chirality -1
1 x	0	0	0	V	V	chirality 1
18 x	0	V	V	0	0	
2 x	V	0	0	V	0	
2 x	Ad	0	0	0	0	
2 x	A	0	0	0	0	
6 x	S	0	0	0	0	
14 x	0	A	0	0	0	
6 x	0	S	0	0	0	
9 x	0	0	Ad	0	0	
6 x	0	0	A	0	0	
14 x	0	0	S	0	0	
3 x	0	0	0	Ad	0	
4 x	0	0	0	A	0	
6 x	0	0	0	S	0	

An Sp(2) instanton model

	U3	S2	U1	U1	O	
3 x	V	V	0	0	0	chirality 3
3 x	V	0	V	0	0	chirality -3
3 x	V	0	V*	0	0	chirality -3
3 x	0	V	0	V	0	chirality 3
5 x	0	0	V	V	0	chirality -3
3 x	0	0	V	V*	0	chirality 3
1 x	0	0	V	0	V	chirality -1
1 x	0	0	0	V	V	chirality 1
18 x	0	V	V	0	0	
2 x	V	0	0	V	0	
2 x	Ad	0	0	0	0	
2 x	A	0	0	0	0	
6 x	S	0	0	0	0	
14 x	0	A	0	0	0	
6 x	0	S	0	0	0	
9 x	0	0	Ad	0	0	
6 x	0	0	A	0	0	
14 x	0	0	S	0	0	
3 x	0	0	0	Ad	0	
4 x	0	0	0	A	0	
6 x	0	0	0	S	0	

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

Conclusions

- Many desirable SM features can be realized in the RCFT orientifold landscape...
  - 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

  ....but not all at the same time.
  Seems just a matter of statistics.

- Neutrino masses from instantons: probably possible, but very rare in RCFT.