RCFT Orientifolds:

SU(5) GUTs

Bert Schellekens
GGI, April 6 2009

NIKHEF

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

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)

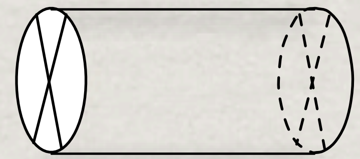
$a:$ Boundary label (finite range)

$\chi_i:$ Character

$N_a:$ Chan-Paton (CP) Multiplicity

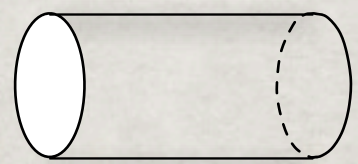
Coefficients

- Klein bottle



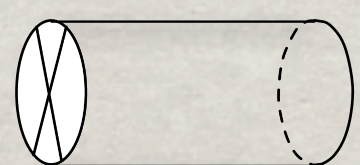
$$K^i = \sum_{m,J,J'} \frac{S^i{}_m U_{(m,J)} g^{\Omega,m}_{J,J'} U_{(m,J')}}{S_{0m}}$$

- 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 "Gepner Models"(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

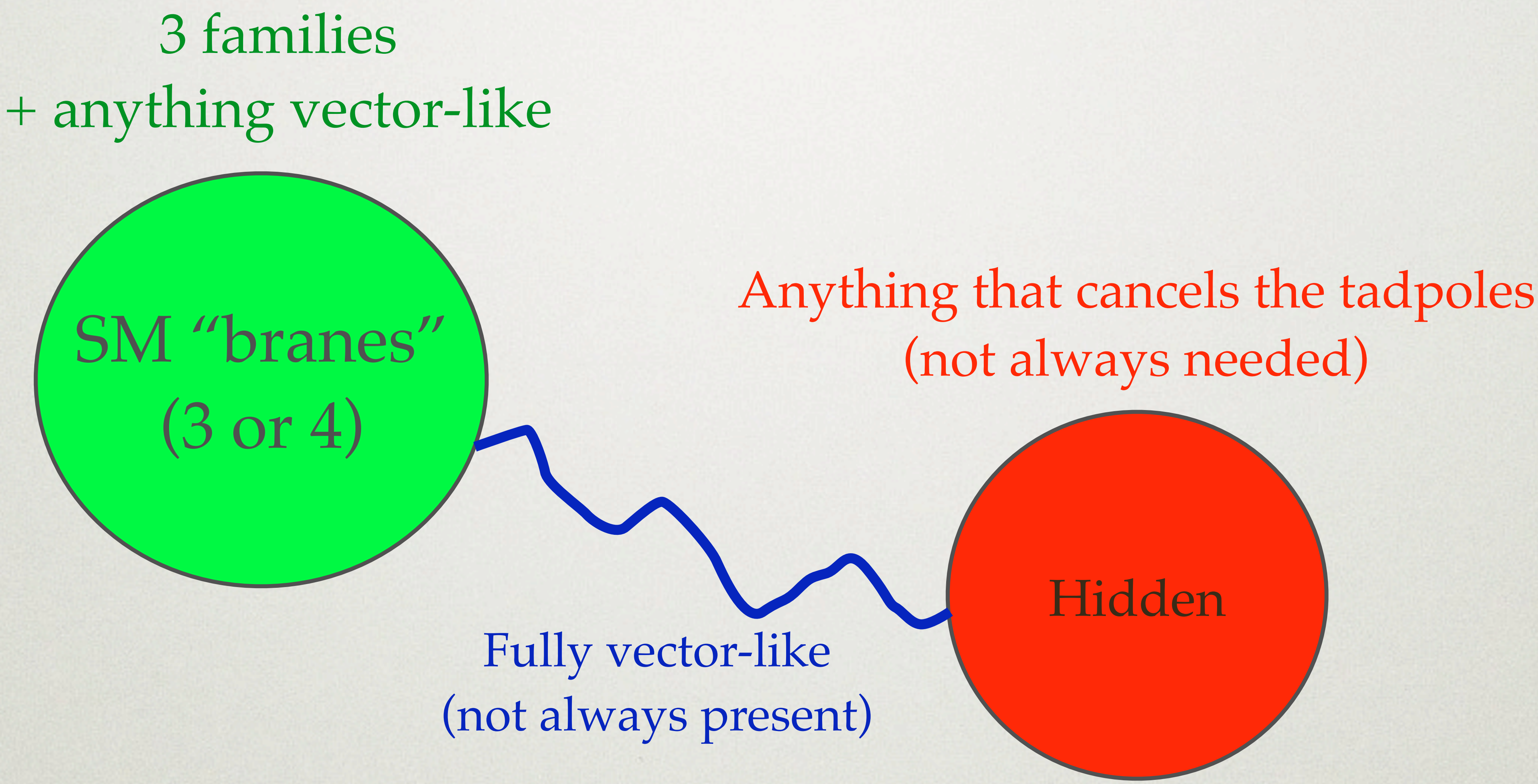
Pioneering work:

(1) Angelantonj, Bianchi, Pradisi, Sagnotti, Stanev, Phys. Lett. B 387 (1996) 743
Blumenhagen, Wisskirchen, Phys. Lett. B 438, 52 (1998), ...
(2) Bianchi, Sagnotti (1989-1991)

Standard Model Searches:

(1) Dijkstra, Huiszoon, Schellekens, Nucl.Phys.B710:3-57,2005
Anastasopoulos, Dijkstra, Kiritsis, Schellekens, Nucl.Phys.B759:83-146,2006
(2) Kiritsis, Lennek, Schellekens, JHEP 0902:030,2009.

SM realization



Vector-like: mass allowed by SU(3) × SU(2) × U(1)

Fully vector-like: mass allowed by all gauge symmetries

Consistency conditions

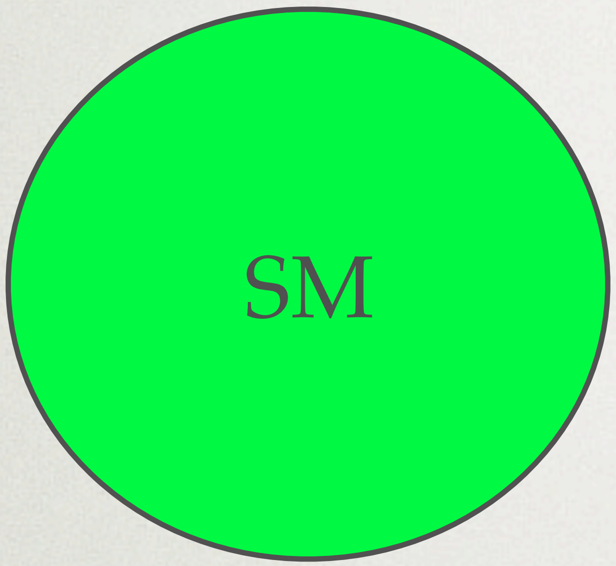
- Tadpole cancellation
- Absence of axion mixing for Y
- Global anomalies*

(Same as for all other orientifold models)

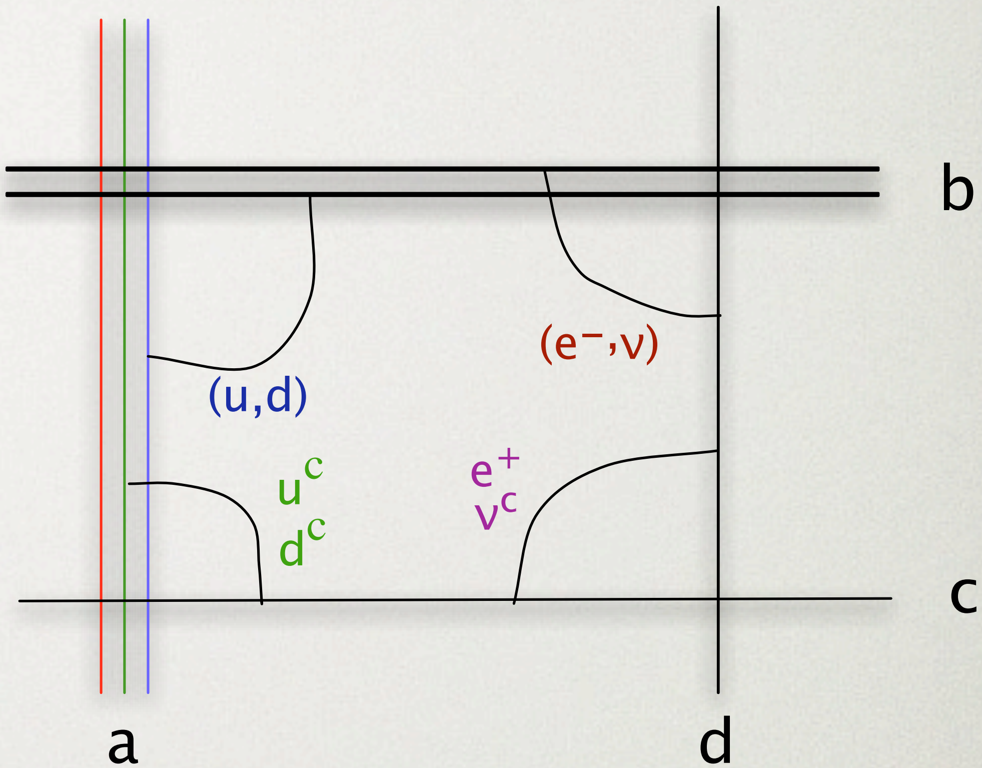
(*) "Probe Branes" A.M. Uranga Nucl. Phys. B598, 225 (2001)
B. Gato-Rivera and A.N Schellekens Phys. Lett. B632, 728 (2006)

DHS RESULTS (2004-2005)

Dijkstra, Huiszoon, 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)

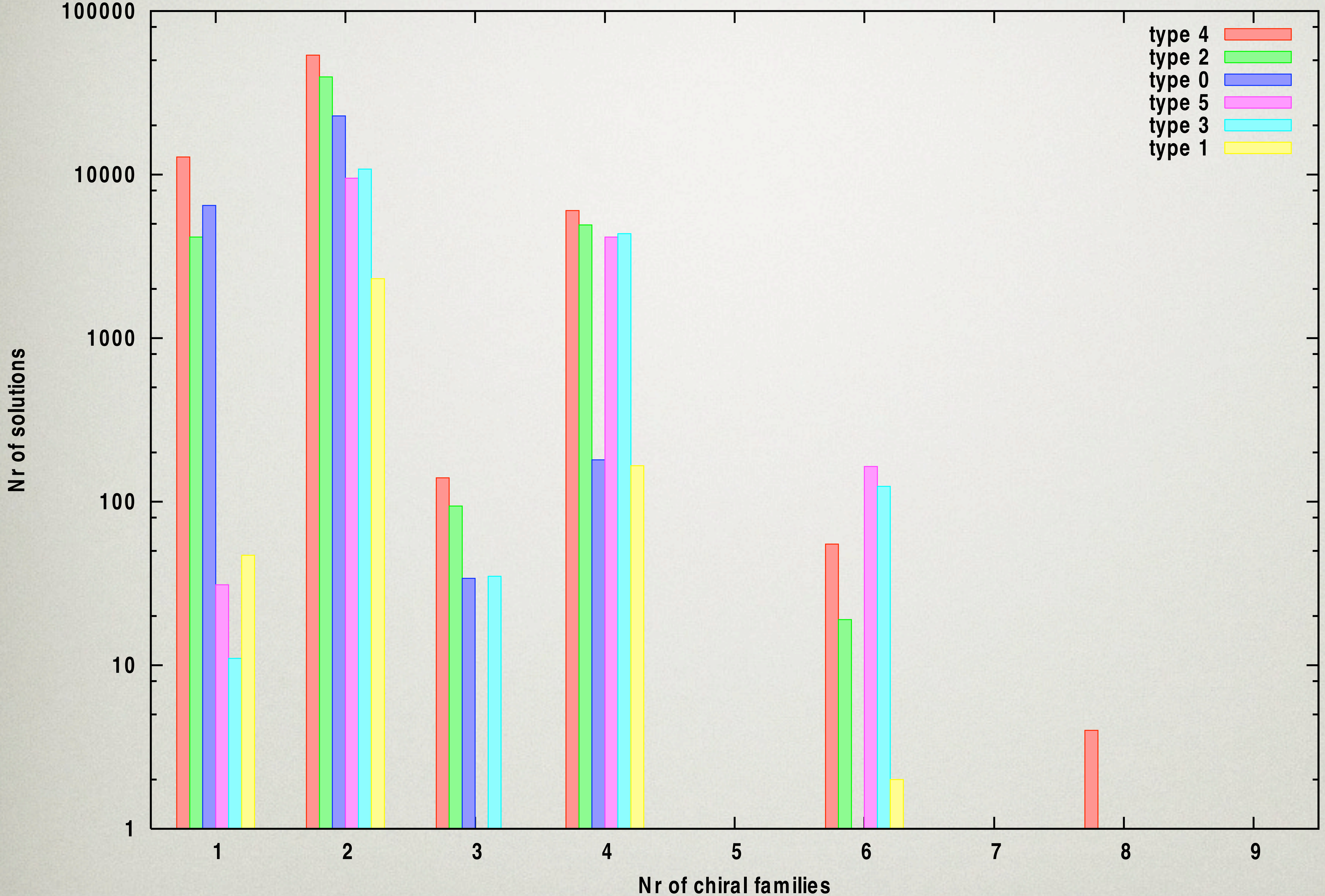
Q	7 x (V ,V ,0 ,0)	chirality 3
U	3 x (V ,0 ,V ,0)	chirality -3
D	3 x (V ,0 ,V*,0)	chirality -3
L	9 x (0 ,V ,0 ,V)	chirality 3
E	5 x (0 ,0 ,V ,V)	chirality -3
	3 x (0 ,0 ,V ,V*)	chirality 3
	6 x (V ,0 ,0 ,V)	
H	10 x (0 ,V ,V ,0)	
	2 x (Ad,0 ,0 ,0)	
	2 x (A ,0 ,0 ,0)	
	6 x (S ,0 ,0 ,0)	
	14 x (0 ,A ,0 ,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

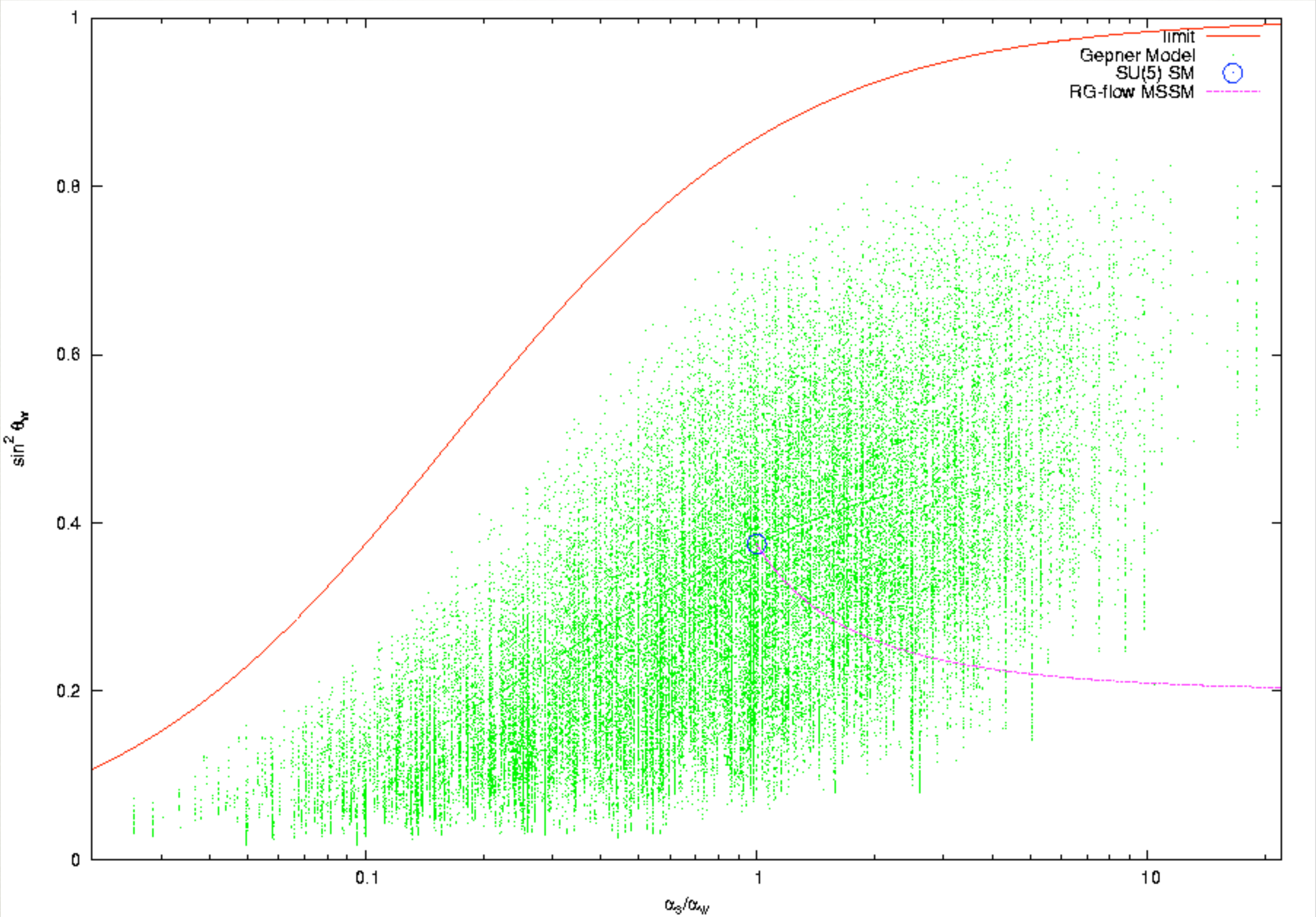
B-L Massive (axion mixing)

Gauge group:

Exactly SU(3)×SU(2)×U(1)



cf. Gmeiner et. al.



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

ADKS RESULTS
(2005-2006)

Anastasopoulos, Dijkstra, Kiritsis, Schellekens

Search Criteria

Require only:

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

Chan-Paton group

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

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

	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*

Truly hidden
hidden sector

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*

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

(Kiritsis, Schellekens, Tsulaia, arXiv:0809.0083)

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	3093933	623	$U(6) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
11	2717632	461	$U(3) \times Sp(2) \times Sp(2) \times U(3)$	VVVV	1/2	Y!
12	2384626	560	$U(6) \times Sp(2) \times O(6)$	VVV	1/2	Y
13	2253928	669	$U(6) \times Sp(2) \times Sp(2)$	VVV	1/2	Y!
14	1803909	519	$U(6) \times Sp(2) \times O(2)$	VVV	1/2	Y!
15	1676493	517	$U(8) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
16	1674416	384	$U(3) \times Sp(2) \times O(6) \times U(3)$	VVVV	1/2	Y
17	1654086	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
18	1654086	340	$U(3) \times Sp(2) \times U(3) \times U(1)$	VVVV	1/2	Y
19	1642669	360	$U(3) \times Sp(2) \times Sp(6) \times U(5)$	VVVV	1/2	Y
20	1486664	346	$U(3) \times Sp(2) \times O(2) \times U(3)$	VVVV	1/2	Y!
21	1323363	476	$U(8) \times Sp(2) \times O(6)$	VVV	1/2	Y
22	1135702	350	$U(3) \times Sp(2) \times Sp(2) \times U(5)$	VVVV	1/2	Y!
23	1050764	532	$U(8) \times Sp(2) \times Sp(2)$	VVV	1/2	Y
24	956980	421	$U(8) \times Sp(2) \times O(2)$	VVV	1/2	Y
25	950003	449	$U(10) \times Sp(2) \times Sp(6)$	VVV	1/2	Y
26	910132	51	$U(3) \times U(2) \times Sp(2) \times O(1)$	AAVV	0	Y
...						

Curiosities

nr	Total occ.	MIPFs	Chan-Paton Group	Spectrum	x	Solved
617	16845	296	$U(5) \times O(1)$	AV	0	Y
671	14744(*)	29	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	1/2	
761	12067	26	$U(3) \times U(2) \times U(1)$	AAS	1/2	Y!
762	12067	26	$U(3) \times U(2) \times U(1)$	AAS	0	Y!
1024	7466	7	$U(3) \times U(2) \times U(2) \times U(1)$	VAAV	1	
1125	6432	87	$U(3) \times U(3) \times U(3)$	VVV	*	Y
1201	5764(*)	20	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	1/2	
1356	5856(*)	10	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	1/2	Y
1725	2864	14	$U(3) \times U(2) \times U(1) \times U(1)$	VVVV	1/2	Y
1886	2381	115	$U(6) \times Sp(2)$	AV	1/2	Y!
1887	2381	115	$U(6) \times Sp(2)$	AV	0	Y!
1888	2381	115	$U(6) \times Sp(2)$	AV	1/2	Y!
2624	1248	3	$U(3) \times U(2) \times U(2) \times U(3)$	VAAV	1	
2753	1136	74	$U(5) \times U(1)$	AS	0	Y
2880	1049	34	$U(5) \times U(1)$	AS	1/2	Y!
2881	1049	34	$U(5) \times U(1)$	AS	0	Y!
6580	146	18	$U(5) \times U(1)$	AS	0	
14861	12	2	$U(5) \times U(1)$	AS	0	

GUTS

(with M. Lennek, E. Kiritsis)

GUTs vs. Strings

- Heterotic (affine level 1)

  + Naturally (16)'s of SO(10) or 27's of E6
  − No adjoints
  − Wrong scale
  − Fractional charges

- Heterotic (higher level)

  + Adjoint breaking, no fractional charges
  − Statistically challenged
  − Higher representations allowed

- Orientifolds (x=1/2)

  + Scale adjustable
  − No coupling unification
  − No SU(5), SO(10)
  − Higher representations allowed
  − Half-integer charges often present

- Orientifolds (x=0)

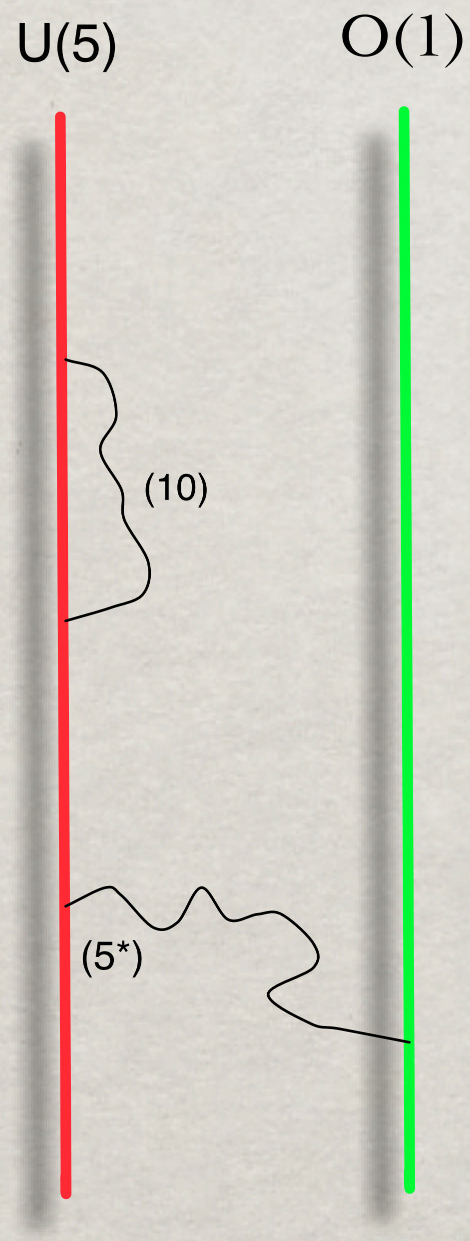
  + Standard SU(5) GUT possible
  (adjoint breaking, no fractional charges)
  − Statistically challenged
  − Higher reps allowed (15)
  − No top Yukawa's perturbatively

- F-theory?

- ....

MODEL NR. 617

Gauge group is just SU(5)!

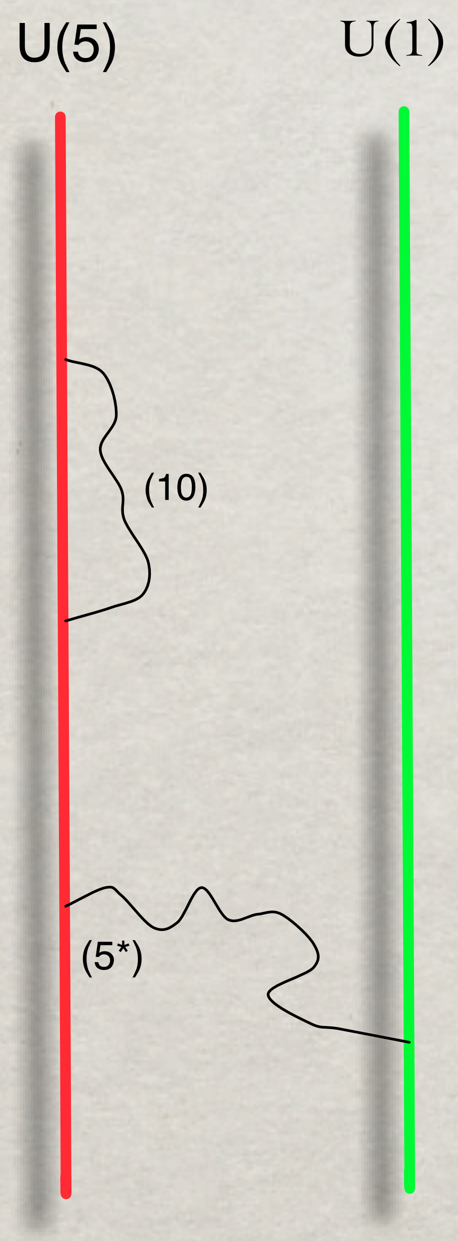


	U5	O1	O1	
3 x	(A	,0	,0)	chirality 3
11 x	(V	,V	,0)	chirality -3
8 x	(S	,0	,0)	
3 x	(Ad	,0	,0)	
1 x	(0	,A	,0)	
3 x	(0	,V	,V)	
8 x	(V	,0	,V)	
2 x	(0	,S	,0)	
4 x	(0	,0	,S)	
4 x	(0	,0	,A)	

Hidden sector

MODEL NR. 2880

Gauge group is SU(5) × U(1)



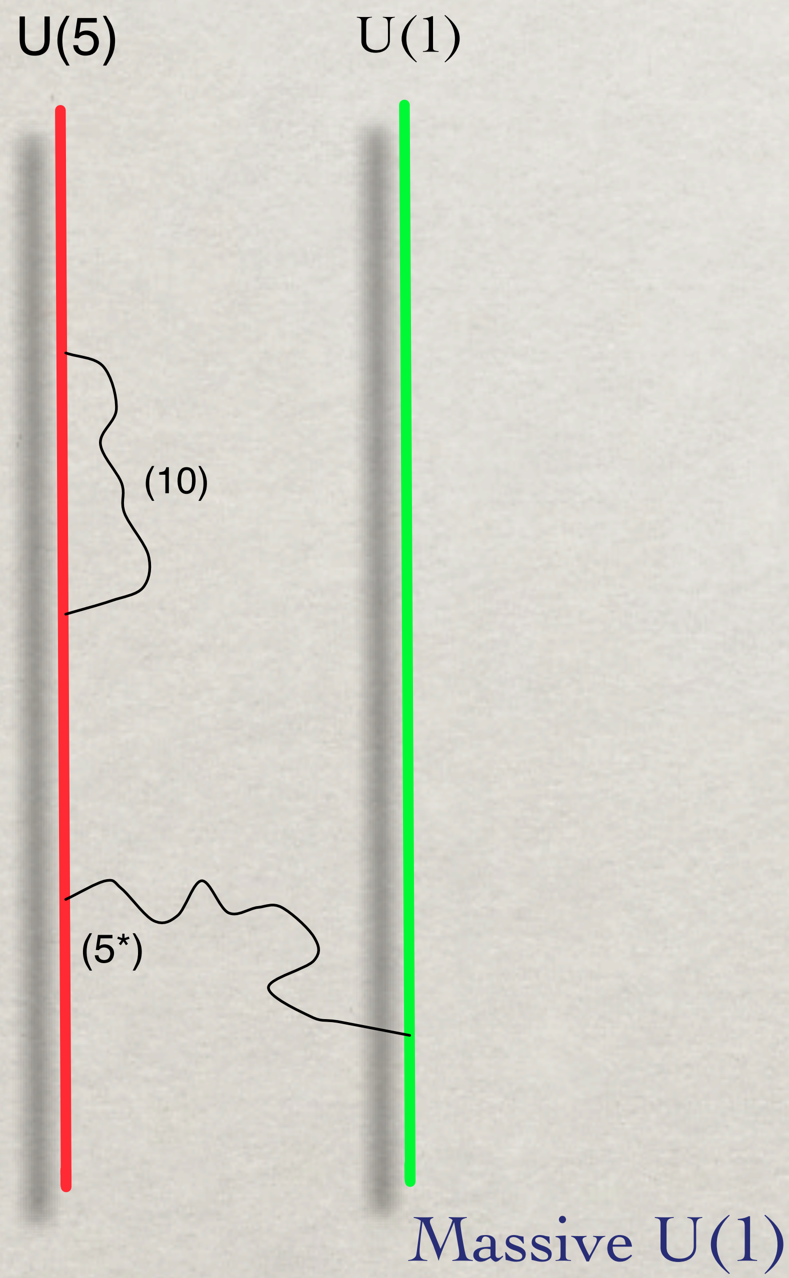
Massless U(1)
Allows flipped SU(5)

U5 U1

11	x	(0 ,S)	chirality 3
3	x	(A ,0)	chirality 3
5	x	(V ,V)	chirality -3
8	x	(S ,0)	chirality 0
9	x	(Ad,0)	chirality 0
5	x	(0 ,Ad)	chirality 0
4	x	(0 ,A)	chirality 0
12	x	(V ,V*)	chirality 0

No hidden sector!

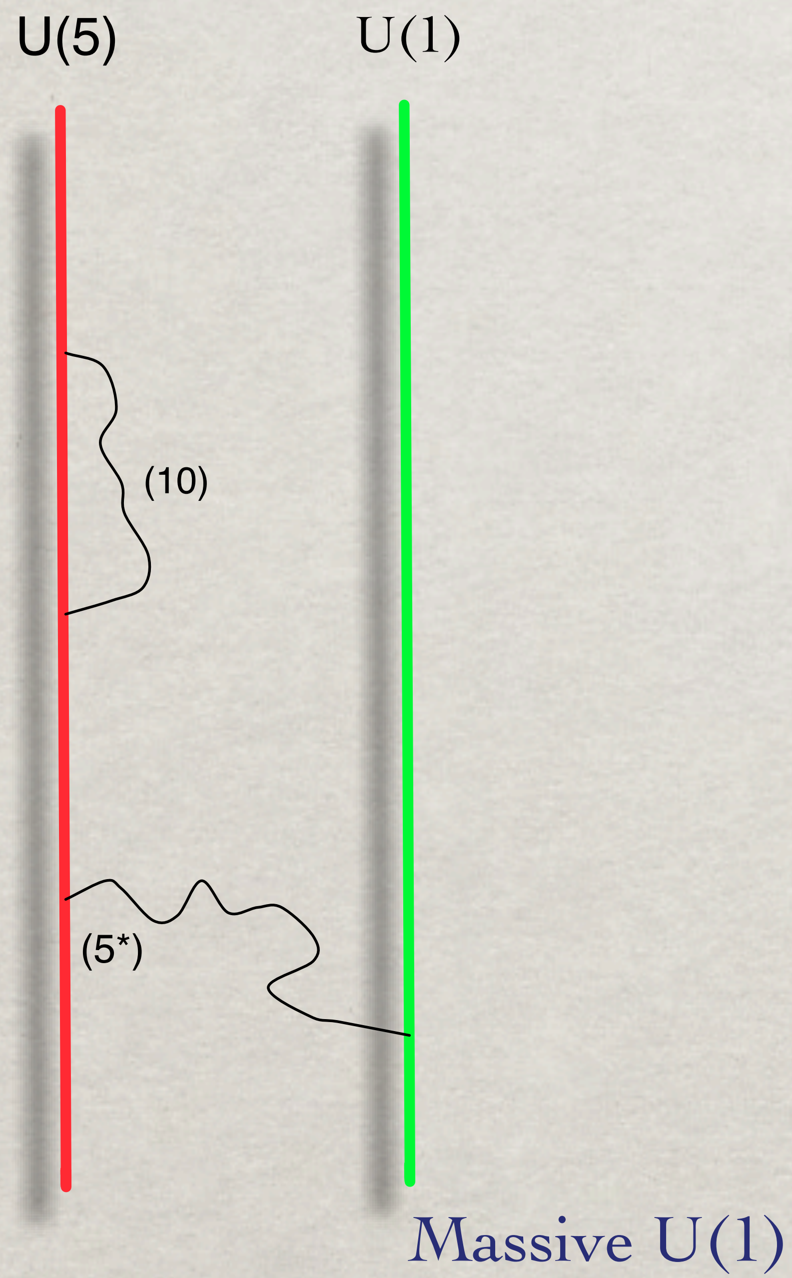
MODEL NR. 2753



	U5	U1	O2	U2	O2	U5	S4	U1	U1	
7 x	0	S	0	0	0	0	0	0	0	chirality 3
3 x	A	0	0	0	0	0	0	0	0	chirality 3
3 x	V	V	0	0	0	0	0	0	0	chirality -3
2 x	S	0	0	0	0	0	0	0	0	chirality 0
2 x	0	A	0	0	0	0	0	0	0	chirality 0
3 x	Ad	0	0	0	0	0	0	0	0	chirality 0
2 x	0	Ad	0	0	0	0	0	0	0	chirality 0
4 x	0	V	0	0	V	0	0	0	0	chirality 0
2 x	V	0	0	0	0	0	0	0	V*	chirality 0
4 x	V	0	0	0	0	0	0	0	V	chirality 0
2 x	V	0	0	0	0	V	0	0	0	chirality 0
2 x	V	0	0	0	0	0	V	0	0	chirality 0
2 x	V	0	0	0	0	0	0	V*	0	chirality 0
2 x	V	V*	0	0	0	0	0	0	0	chirality 0
2 x	0	V	0	0	0	0	0	0	V*	chirality 0
3 x	0	0	0	0	0	0	0	0	A	chirality -1
1 x	0	0	0	0	0	0	0	S	0	chirality 1
1 x	0	0	0	V	V	0	0	0	0	chirality 1
3 x	0	0	0	0	0	0	V	0	V	chirality 1
2 x	0	0	0	0	0	0	0	0	S	chirality -2
1 x	0	0	V	0	0	V	0	0	0	chirality 1
1 x	0	0	0	V	0	V	0	0	0	chirality -1
1 x	0	0	0	0	0	A	0	0	0	chirality -1
5 x	0	0	0	0	0	0	0	A	0	chirality -1
1 x	0	0	0	0	V	V	0	0	0	chirality -1
3 x	0	0	0	0	0	0	0	V	V	chirality 1
2 x	0	0	0	0	0	0	0	V	V*	chirality 2
2 x	0	0	0	0	V	0	0	0	V	chirality 2
1 x	0	0	V	0	0	0	0	V	0	chirality 1
1 x	0	0	0	V	0	0	V	0	0	chirality 1
1 x	0	0	0	V	0	0	0	V	0	chirality -1
1 x	0	0	0	0	0	V	V	0	0	chirality 1
1 x	0	0	0	0	0	V	0	V	0	chirality -1
3 x	0	0	0	0	V	0	0	V	0	chirality -3
6 x	0	0	0	0	0	0	V	V	0	chirality 0
1 x	0	0	0	0	S	0	0	0	0	chirality 0
1 x	0	0	0	0	0	0	A	0	0	chirality 0
2 x	0	0	0	0	0	0	0	Ad	0	chirality 0
2 x	0	0	0	0	0	0	0	0	Ad	chirality 0
1 x	0	0	0	0	0	0	S	0	0	chirality 0

Hidden sector

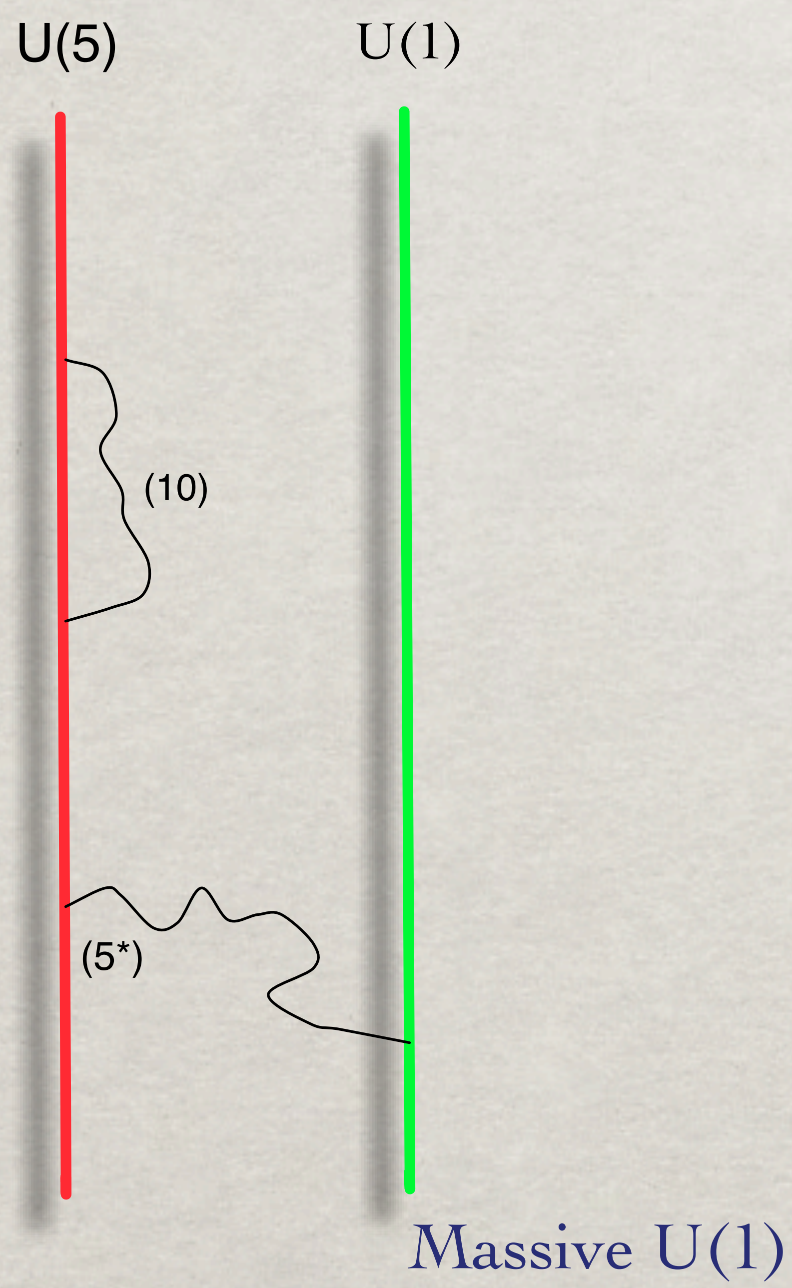
MODEL NR. 6580



Spectrum
(without tadpole cancellation)

```
          U   U
          5   1
2 x ( V  ,V ) chirality -2
1 x ( 0  ,S ) chirality 1
3 x ( A  ,0 ) chirality 3
1 x ( V  ,V*) chirality -1
```

MODEL NR. 6580

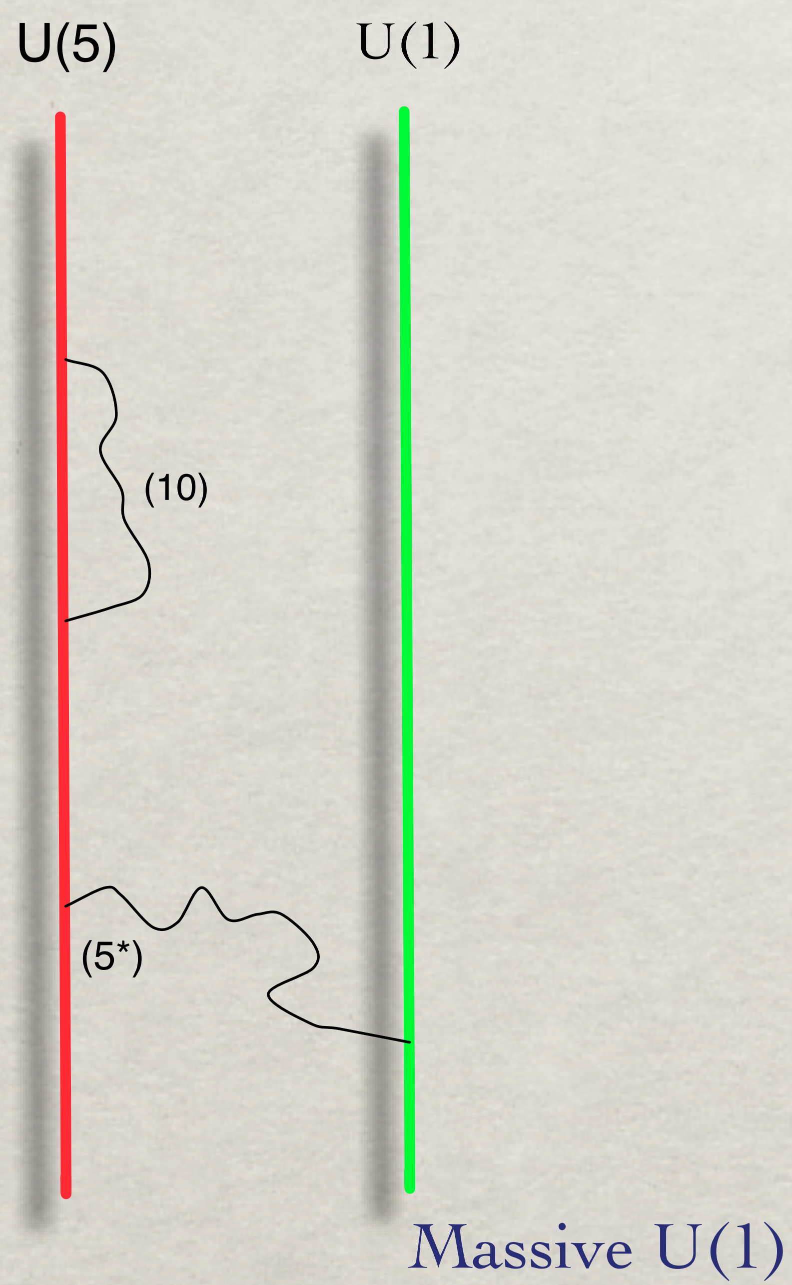


Spectrum
(without tadpole cancellation)

```
          U   U
          5   1
2 x ( V ,V ) chirality -2
1 x ( 0 ,S ) chirality 1
3 x ( A ,0 ) chirality 3
1 x ( V ,V*) chirality -1
```

+ NOTHING!
(no adjoints, mirrors,
non-chiral matter)

MODEL NR. 6580



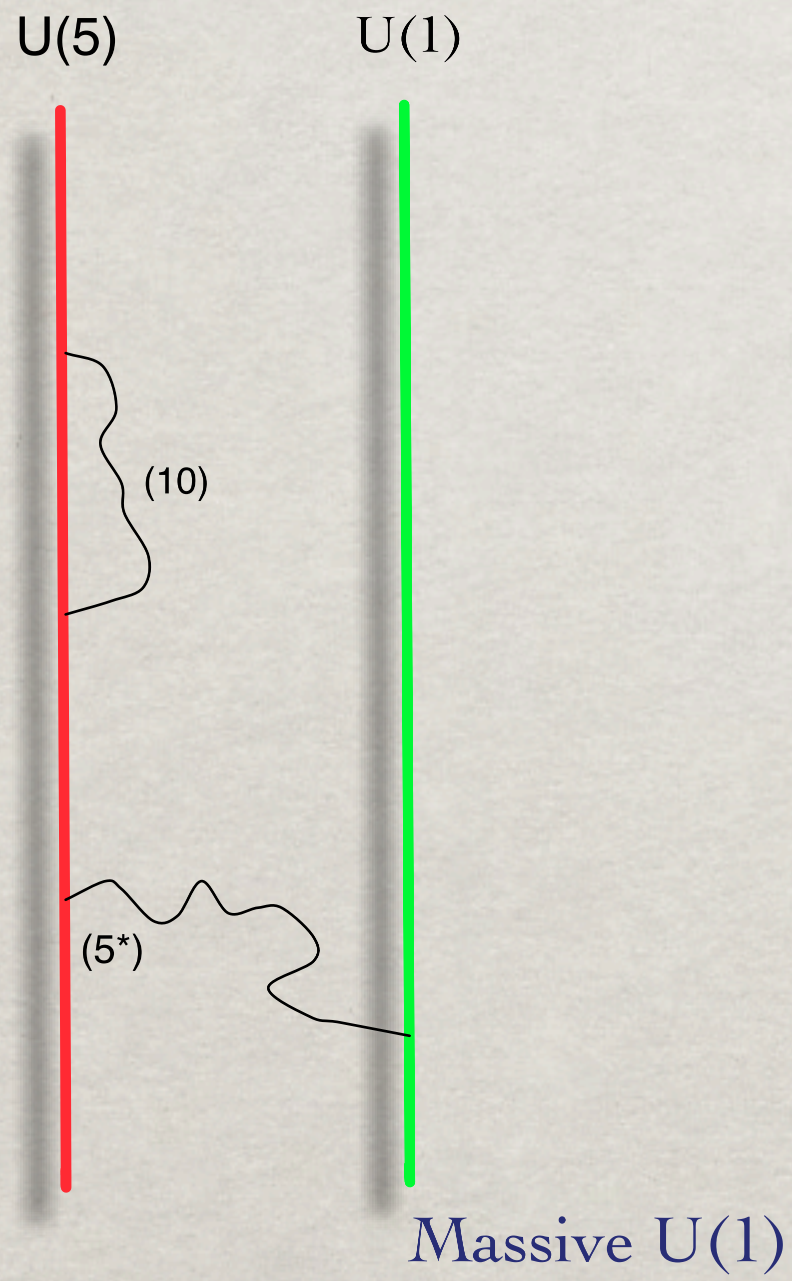
Spectrum
(without tadpole cancellation)

```
            U   U
            5   1
2 x ( V ,V ) chirality -2
1 x ( 0 ,S ) chirality 1
3 x ( A ,0 ) chirality 3
1 x ( V ,V*) chirality -1
```

+ NOTHING!
(no adjoints, mirrors, non-chiral matter)

(but also no Higgs)

MODEL NR. 14861



Spectrum
(without tadpole cancellation)

		U 5	U 1		
3	x	A	0	chirality	3
15	x	0	S	chirality	9
6	x	V	V	chirality	-6
5	x	V	V*	chirality	3
1	x	Ad	0	chirality	0
4	x	0	Ad	chirality	0

All tadpole solutions for the U(5) × O(1) models

Candidates (configurations prior to tadpole cancellation): 16845

→ **Allowing chiral OH matter**
- 15499 ✗
- 641 ✓
- 705 ?

→ **Allowing only non-chiral OH matter(*)**
- 521 ✗
- 109 ✓
- 11 ?

↘
- 508 ✗
- 64 ✓
- 133 ?

(*) as in all previous work with Dijkstra et. al., Anastasopoulos et. al

Yukawa couplings

Top quark Yukawa coupling is forbidden by U(5) brane charge conservation.

$(\mathbf{10})(\bar{\mathbf{5}})(\bar{\mathbf{5}}_{\mathrm{H}})$ bottom quark masses: charge preserved*

$(\mathbf{10})(\mathbf{10})(\mathbf{5}_{\mathrm{H}})$ top quark mass: charges violated

May be generated by stringy/exotic instantons

(Blumenhagen, Cvetic, Lüst, Richter, Weigand)

(More recent work on instantons: See Richter and Ibañez, ref. [18-65])

(*) forbidden by O(1) charge in the U(5) × O(1) models

[18] R. Blumenhagen, M. Cvetič, and T. Weigand, "Spacetime instanton corrections in 4D string vacua - the seesaw mechanism for D-brane models," *Nucl. Phys.* **B771** (2007) 113–142, hep-th/0609191.

[19] M. Haack, D. Krefl, D. Lüst, A. Van Proeyen, and M. Zagermann, "Gaugino condensates and D-terms from D7-branes," *JHEP* **01** (2007) 078, hep-th/0609211.

[20] L. E. Ibáñez and A. M. Uranga, "Neutrino Majorana masses from string theory instanton effects," *JHEP* **03** (2007) 052, hep-th/0609213.

[21] B. Florea, S. Kachru, J. McGreevy, and N. Saulina, "Stringy instantons and quiver gauge theories," *JHEP* **05** (2007) 024, hep-th/0610003.

[22] S. A. Abel and M. D. Goodsell, "Realistic Yukawa couplings through instantons in intersecting brane worlds," *JHEP* **10** (2007) 034, hep-th/0612110.

[23] N. Akerblom, R. Blumenhagen, D. Lüst, E. Plauschinn, and M. Schmidt-Sommerfeld, "Non-perturbative SQCD Superpotentials from String Instantons," *JHEP* **04** (2007) 076, hep-th/0612132.

[24] M. Bianchi and E. Kiritsis, "Non-perturbative and Flux superpotentials for Type I strings on the Z3 orbifold," *Nucl. Phys.* **B782** (2007) 26–50, hep-th/0702015.

[25] M. Cvetič, R. Richter, and T. Weigand, "Computation of D-brane instanton induced superpotential couplings - Majorana masses from string theory," *Phys. Rev.* **D76** (2007) 086002, hep-th/0703028.

[26] R. Argurio, M. Bertolini, S. Franco, and S. Kachru, "Metastable vacua and D-branes at the conifold," *JHEP* **06** (2007) 017, hep-th/0703236.

[27] R. Argurio, M. Bertolini, G. Ferretti, A. Lerda, and C. Petersson, "Stringy Instantons at Orbifold Singularities," *JHEP* **06** (2007) 067, arXiv:0704.0262 [hep-th].

[28] M. Bianchi, F. Fucito, and J. F. Morales, "D-brane Instantons on the T6/Z3 orientifold," *JHEP* **07** (2007) 038, arXiv:0704.0784 [hep-th].

[29] L. E. Ibáñez, A. N. Schellekens, and A. M. Uranga, "Instanton Induced Neutrino Majorana Masses in CFT Orientifolds with MSSM-like spectra," *JHEP* **06** (2007) 011, arXiv:0704.1079 [hep-th].

[30] N. Akerblom, R. Blumenhagen, D. Lüst, and M. Schmidt-Sommerfeld, "Instantons and Holomorphic Couplings in Intersecting D- brane Models," *JHEP* **08** (2007) 044, arXiv:0705.2366 [hep-th].

[31] S. Antusch, L. E. Ibáñez, and T. Macri, "Neutrino Masses and Mixings from String Theory Instantons," *JHEP* **09** (2007) 087, arXiv:0706.2132 [hep-ph].

[32] R. Blumenhagen, M. Cvetič, D. Lüst, R. Richter, and T. Weigand, "Non-perturbative Yukawa Couplings from String Instantons," *Phys. Rev. Lett.* **100** (2008) 061602, 0707.1871.

[33] O. Aharony and S. Kachru, "Stringy Instantons and Cascading Quivers," *JHEP* **09** (2007) 060, arXiv:0707.3126 [hep-th].

[34] O. Aharony, S. Kachru, and E. Silverstein, "Simple Stringy Dynamical SUSY Breaking," *Phys. Rev.* **D76** (2007) 126009, arXiv:0708.0493 [hep-th].

[35] R. Blumenhagen, M. Cvetič, R. Richter, and T. Weigand, "Lifting D-Instanton Zero Modes by Recombination and Background Fluxes," *JHEP* **10** (2007) 098, arXiv:0708.0403 [hep-th].

[36] M. Billó *et al.*, "Instantons in N=2 magnetized D-brane worlds," *JHEP* **10** (2007) 091, arXiv:0708.3806 [hep-th].

[37] M. Billó *et al.*, "Instanton effects in N=1 brane models and the Kahler metric of twisted matter," *JHEP* **12** (2007) 051, arXiv:0709.0245 [hep-th].

[38] M. Aganagic, C. Beem, and S. Kachru, "Geometric Transitions and Dynamical SUSY Breaking," *Nucl. Phys.* **B796** (2008) 1–24, arXiv:0709.4277 [hep-th].

[39] P. G. Camara, E. Dudas, T. Maillard, and G. Pradisi, "String instantons, fluxes and moduli stabilization," *Nucl. Phys.* **B795** (2008) 453–489, arXiv:0710.3080 [hep-th].

[40] M. Cvetič and T. Weigand, "Hierarchies from D-brane instantons in globally defined Calabi-Yau Orientifolds," arXiv:0711.0209 [hep-th].

[41] L. E. Ibáñez and A. M. Uranga, "Instanton Induced Open String Superpotentials and Branes at Singularities," *JHEP* **02** (2008) 103, arXiv:0711.1316 [hep-th].

[42] I. García-Etxebarria and A. M. Uranga, "Non-perturbative superpotentials across lines of marginal stability," *JHEP* **01** (2008) 033, arXiv:0711.1430 [hep-th].

[43] C. Petersson, "Superpotentials From Stringy Instantons Without Orientifolds," arXiv:0711.1837 [hep-th].

[44] R. Blumenhagen, S. Moster, and E. Plauschinn, "Moduli Stabilisation versus Chirality for MSSM like Type IIB Orientifolds," *JHEP* **01** (2008) 058, arXiv:0711.3389 [hep-th].

[45] M. Bianchi and J. F. Morales, "Unoriented D-brane Instantons vs Heterotic worldsheet Instantons," *JHEP* **02** (2008) 073, arXiv:0712.1895 [hep-th].

[46] R. Blumenhagen and M. Schmidt-Sommerfeld, "Power Towers of String Instantons for N=1 Vacua," *JHEP* **07** (2008) 027, 0803.1562.

[47] Y. Matsuo, J. Park, C. Ryou, and M. Yamamoto, "D-instanton derivation of multi-fermion F-terms in supersymmetric QCD," *JHEP* **06** (2008) 051, 0803.0798.

[48] R. Argurio, G. Ferretti, and C. Petersson, "Instantons and Toric Quiver Gauge Theories," *JHEP* **07** (2008) 123, 0803.2041.

[49] M. Cvetič, R. Richter, and T. Weigand, "(Non-)BPS bound states and D-brane instantons," *JHEP* **07** (2008) 012, 0803.2513.

[50] M. Cvetič and P. Langacker, "D-Instanton Generated Dirac Neutrino Masses," 0803.2876.

[51] I. García-Etxebarria, F. Marchesano, and A. M. Uranga, "Non-perturbative F-terms across lines of BPS stability," *JHEP* **07** (2008) 028, 0805.0713.

[52] M. Buican and S. Franco, "SUSY breaking mediation by D-brane instantons," 0806.1964.

[53] D. Forcella, I. García-Etxebarria, and A. Uranga, "E3-brane instantons and baryonic operators for D3-branes on toric singularities," 0806.2291.

[54] R. Blumenhagen, S. Moster, and E. Plauschinn, "String GUT Scenarios with Stabilised Moduli," 0806.2667.

[55] P. G. Camara and E. Dudas, "Multi-instanton and string loop corrections in toroidal orbifold models," *JHEP* **08** (2008) 069, 0806.3102.

[56] M. Billó *et al.*, "Flux interactions on D-branes and instantons," 0807.1666.

[57] M. Cvetič and T. Weigand, "A string theoretic model of gauge mediated supersymmetry breaking," 0807.3953.

[58] M. Billó *et al.*, "Non-perturbative effective interactions from fluxes," 0807.4098.

[59] J. Kumar, "A Toy Model for Gauge-Mediation in Intersecting Brane Models," 0808.1264.

[60] J. Marsano, N. Saulina, and S. Schäfer-Nameki, "Gauge Mediation in F-Theory GUT Models," 0808.1571.

[61] J. Marsano, N. Saulina, and S. Schäfer-Nameki, "An Instanton Toolbox for F-Theory Model Building," 0808.2450.

[62] A. M. Uranga, "D-brane instantons and the effective field theory of flux compactifications," 0808.2918.

[63] J. J. Heckman and C. Vafa, "F-theory, GUTs, and the Weak Scale," 0809.1098.

[64] I. García-Etxebarria, "D-brane instantons and matrix models," 0810.1482.

[65] T. Jeliński and J. Pawelczyk, "Multi-Instanton Corrections to Superpotentials in Type II Compactifications," 0810.4369.

[66] N. Akerblom, R. Blumenhagen, D. Lüst, and M. Schmidt-Sommerfeld, "D-brane Instantons in 4D Supersymmetric String Vacua," *Fortsch. Phys.* **56** (2008) 313–323, 0712.1793.

[67] M. Cvetič, R. Richter, and T. Weigand, "D-brane instanton effects in Type II orientifolds: local and global issues," 0712.2845.

(FOR COMPARISON: NEUTRINO MASSES

Sunday, 2 May 2010

Neutrino mass generation by instantons*

Possible in "Madrid" models with massive B-L
(391 out of the set of 200.000)

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

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

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

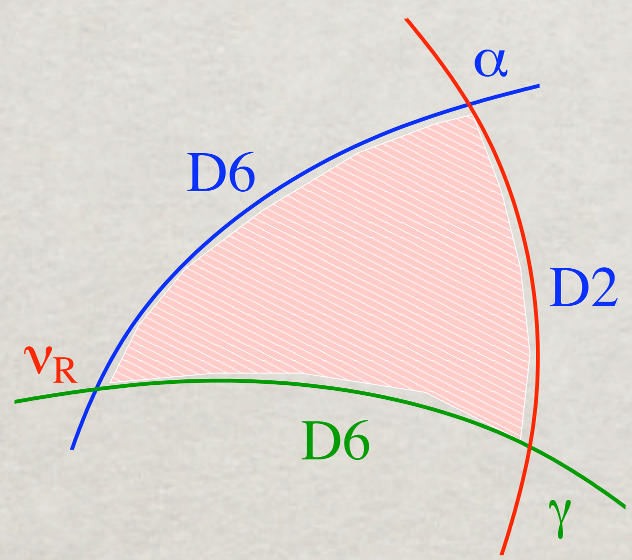
(*) Blumenhagen, Cvetic, Weigand, Nucl.Phys.B771:113-142,2007
Ibañez, Uranga, JHEP 0703:052,2007

Studied for Gepner orientifolds in

Ibañez, Schellekens, Uranga, JHEP 0706:011,2007

Neutrino-zero mode coupling

The following world-sheet disk is allowed by all symmetries



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

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 nullify the 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.

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

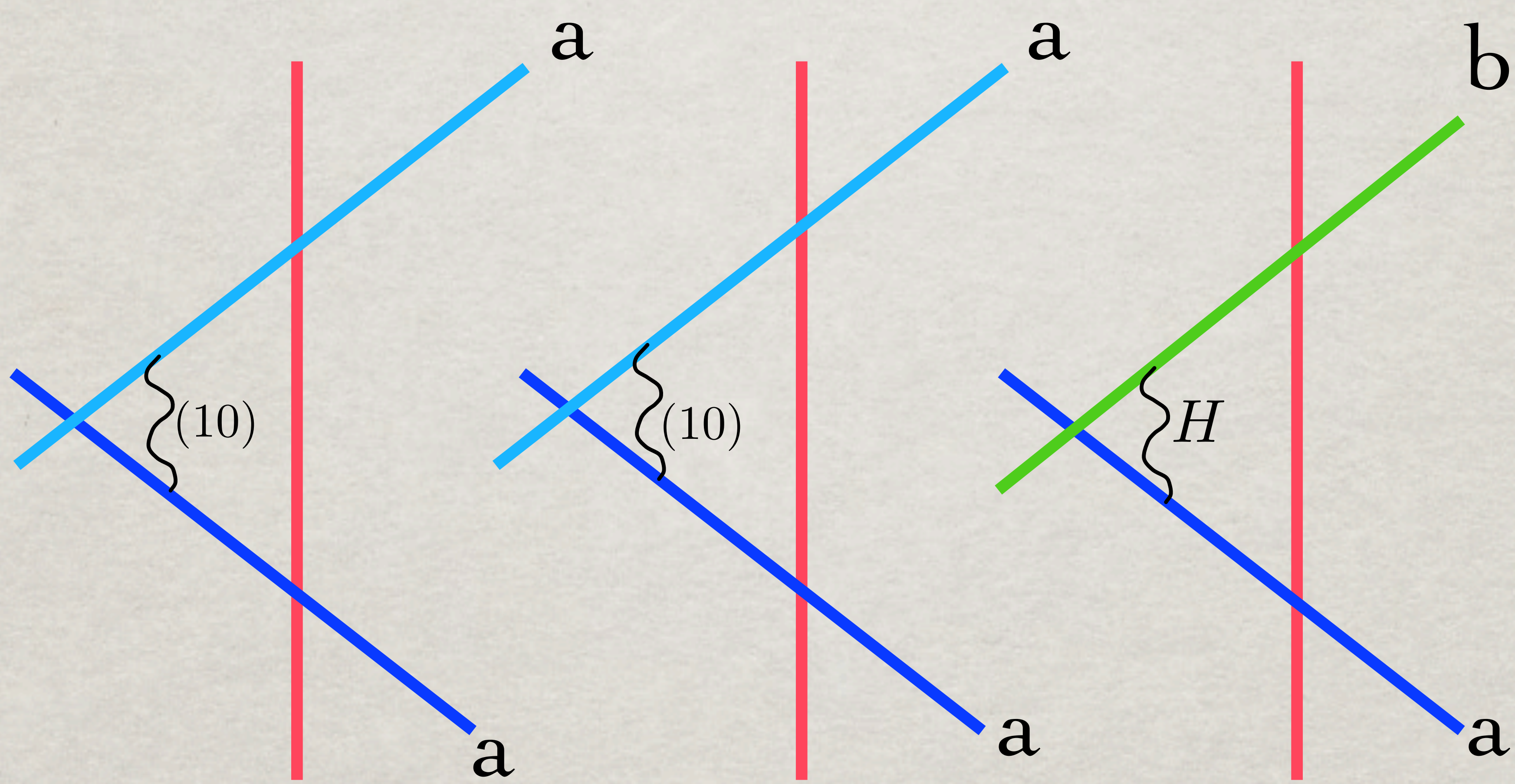
The O1 instanton

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	

)

Back to Yukawa couplings...

Find a brane (boundary state) with the right zero mode structure, so that in combination with the following perturbatively allowed disk amplitudes ...



... the instanton associated with that brane can generate the missing couplings.

Instantons

Nr.	Models	U1	S2	O1	Zeromodes OK	Solutions
617	16845	3.5×10^6	1.1×10^6	6.1×10^5	12889	0
2753	1136	4.9×10^5	1.5×10^5	4.8×10^4	84	6
2881	1049	2.1×10^5	5.5×10^4	4.5×10^4	30	0
6580	146	7.0×10^4	9680	8092	73	0
14861	12	1190	504	0	0	0

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

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

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

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

Quarks, Leptons

	U 5	U 1	O 1	U 1	O 3	U 1	O 2	O 4	O 2	O 2	O 1	S --		
5 x	0	S	0	0	0	0	0	0	0	0	0	0	chirality 3	Quarks, Leptons
5 x	A	0	0	0	0	0	0	0	0	0	0	0	chirality 3	Quarks, Leptons
3 x	V	V	0	0	0	0	0	0	0	0	0	0	chirality -3	Quarks, Leptons
1 x	0	V	0	0	0	0	0	0	0	0	0	V	chirality 1	
1 x	V	0	0	0	0	0	0	0	0	0	0	V	chirality -1	
2 x	V	V*	0	0	0	0	0	0	0	0	0	0	chirality 0	Higgs
1 x	V	0	0	0	0	0	0	V	0	0	0	0	chirality 1	
1 x	V	0	0	0	0	0	0	0	0	V	0	0	chirality 1	
2 x	V	0	0	0	0	0	V	0	0	0	0	0	chirality -2	
3 x	0	V	0	0	0	0	0	0	0	V	0	0	chirality -1	
1 x	0	V	0	0	0	0	V	0	0	0	0	0	chirality 1	
2 x	V	0	0	0	0	0	0	0	0	0	V	0	chirality -2	
2 x	S	0	0	0	0	0	0	0	0	0	0	0	chirality 0	
4 x	0	A	0	0	0	0	0	0	0	0	0	0	chirality 0	
6 x	Ad	0	0	0	0	0	0	0	0	0	0	0	chirality 0	
4 x	0	V	0	0	0	0	0	0	0	0	V	0	chirality 0	
2 x	0	Ad	0	0	0	0	0	0	0	0	0	0	chirality 0	
2 x	0	V	0	0	0	0	0	V	0	0	0	0	chirality 0	
4 x	0	V	0	0	0	V	0	0	0	0	0	0	chirality 0	
2 x	0	V	0	0	0	0	0	0	V	0	0	0	chirality 0	
1 x	0	0	0	0	0	S	0	0	0	0	0	0	chirality -1	
1 x	0	0	0	0	0	A	0	0	0	0	0	0	chirality 1	
1 x	0	0	0	0	0	V	V	0	0	0	0	0	chirality 1	
1 x	0	0	0	0	0	V	0	V	0	0	0	0	chirality 1	

	U 5	U 1	O 1	U 1	O 3	U 1	O 2	O 4	O 2	O 2	O 1	S --		
5 x	0	S	0	0	0	0	0	0	0	0	0	0	chirality 3	Quarks, Leptons
5 x	A	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	chirality -3	
1 x	0	V	0	0	0	0	0	0	0	0	0	V	chirality 1	Instanton
1 x	V	0	0	0	0	0	0	0	0	0	0	V	chirality -1	
2 x	V	V*	0	0	0	0	0	0	0	0	0	0	chirality 0	Higgs
1 x	V	0	0	0	0	0	0	V	0	0	0	0	chirality 1	
1 x	V	0	0	0	0	0	0	0	0	V	0	0	chirality 1	
2 x	V	0	0	0	0	0	V	0	0	0	0	0	chirality -2	
3 x	0	V	0	0	0	0	0	0	0	V	0	0	chirality -1	
1 x	0	V	0	0	0	0	V	0	0	0	0	0	chirality 1	
2 x	V	0	0	0	0	0	0	0	0	0	V	0	chirality -2	
2 x	S	0	0	0	0	0	0	0	0	0	0	0	chirality 0	
4 x	0	A	0	0	0	0	0	0	0	0	0	0	chirality 0	
6 x	Ad	0	0	0	0	0	0	0	0	0	0	0	chirality 0	
4 x	0	V	0	0	0	0	0	0	0	0	V	0	chirality 0	
2 x	0	Ad	0	0	0	0	0	0	0	0	0	0	chirality 0	
2 x	0	V	0	0	0	0	0	V	0	0	0	0	chirality 0	
4 x	0	V	0	0	0	V	0	0	0	0	0	0	chirality 0	
2 x	0	V	0	0	0	0	0	0	V	0	0	0	chirality 0	
1 x	0	0	0	0	0	S	0	0	0	0	0	0	chirality -1	
1 x	0	0	0	0	0	A	0	0	0	0	0	0	chirality 1	
1 x	0	0	0	0	0	V	V	0	0	0	0	0	chirality 1	
1 x	0	0	0	0	0	V	0	V	0	0	0	0	chirality 1	

The bottom of the barrel

- 2004: 200.000 SM spectra, 18 chiral types. *(with Dijkstra, Huiszoon)*
- 2006: 19000 chiral types. *(with Anastasopoulos,Dijkstra, Kiritsis)*
- Neutrino masses: No perfect solution found. *(with Ibañez, Uranga)*
- Free Fermion Orientifolds: No solution. *(with Kiritsis, Lennek)*
- Tachyon-free non-susy strings: No SM. *(with Gato-Rivera)*
- Yukawa couplings from instantons: solution, but with chiral exotics. *(with Kiritsis, Lennek)*

Conclusions

- RCFT orientifolds have proved to be a powerful probe of the orientifold landscape.
- In general "richer" than free field theory based methods.
- We are reaching the end of statistics with RCFT.
- A lesson: don't focus too much on 3 families?