SIGHTSEEING IN THE LANDSCAPE

CONTENTS

- Landscape remarks
- RCFT orientifolds
  (with Huiszoon,Fuchs, Schweigert,Walcher)
- 2004 results
  (with Dijkstra,Huiszoon)
- 2005 results
  (with Anastasopoulos,Dijkstra,Kiritsis)

The landscape (1986)

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1984-2006:
A SLOW REVOLUTION

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- 1986: Fermionic and Bosonic constructions

M.Dine
hep-th/0402101

Faced with this plethora of states, I, for a long time, comforted myself that not a single example of a (meta)stable ground state of this sort had been exhibited in a controlled approximation, and so perhaps there might be some unique or at least limited set of sensible states.

1984-2006:
A SLOW REVOLUTION

- 1984: Hopes for Unification and Uniqueness
- 1985: Calabi-Yau manifolds, Narain Lattices, Orbifolds
- 1986: Fermionic and Bosonic constructions
- 1987: Gepner models
- ....
- 1995: M-theory compactifications, F-theory, Orientifolds
- ....
- 2003: Non-uniqueness got a name: The Landscape

M. Kaku

(from Dutch TV,
VPRO, “Noorderlicht”, 1997)

MY POINT OF VIEW:

(physics/06041340)

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*... if string theory is correct...

Who cares,
just find the standard model....

VACUUM COUNTING

1998:

$$10^{30} \times 10^{-80} = 10^{-50}$$

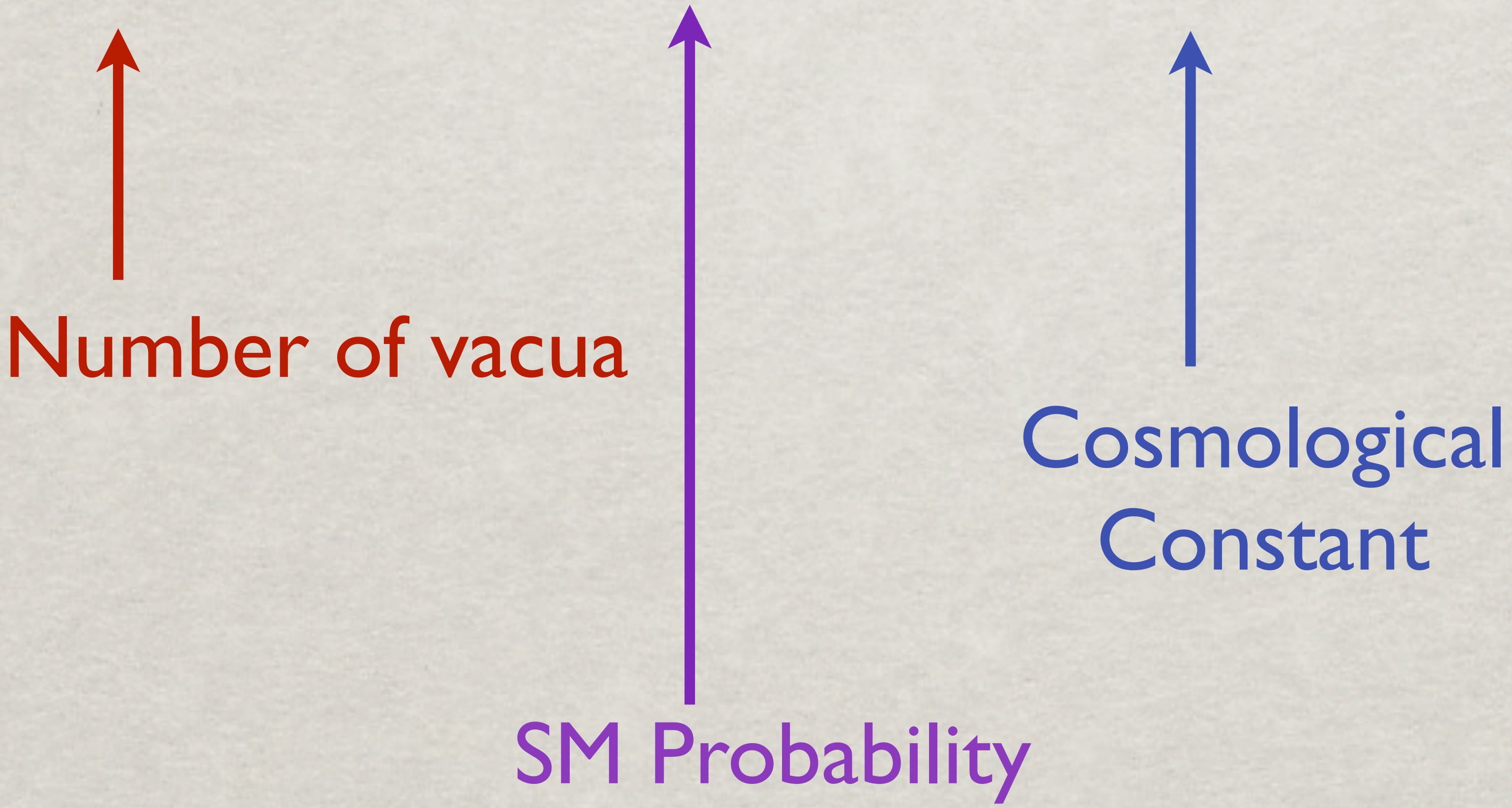
Number of vacua

SM Probability

Vacuum counting

2006:

$$10^{500} \times 10^{-80} \times 10^{-120} = 10^{300}$$



Number of vacua

SM Probability

Cosmological Constant

SO WHAT CAN WE STILL DO?

- Explore unknown regions of the landscape
- Establish the likelyhood of standard model features (gauge group, three families, ...)
- Convince ourselves that standard model is a plausible vacuum
- Understand vacuum statistics
- Understand cosmological likelyhood
- Understand “anthropicity”

ORIENTIFOLDS
OF
GEPNER MODELS

Earlier footprints

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].

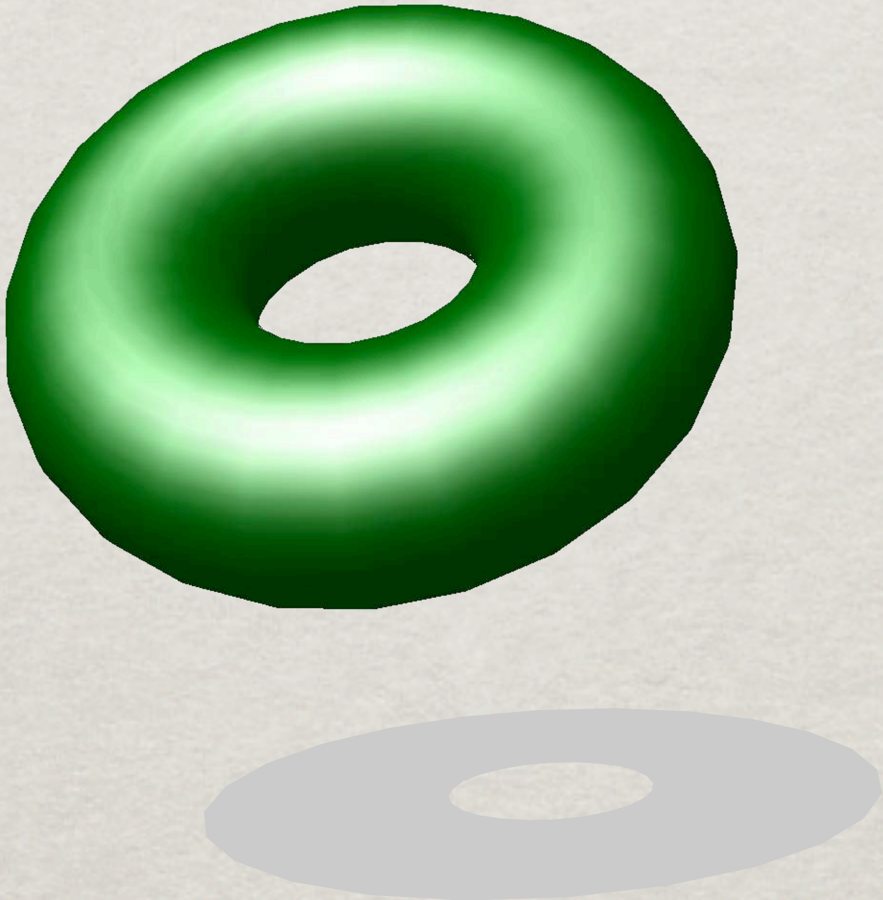
G. Aldazabal, E. C. Andres, M. Leston and C. Nunez, JHEP **0309**, 067 (2003) [arXiv:hep-th/0307183].

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].

CLOSED STRING PARTITION FUNCTION



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

ORIENTIFOLD PARTITION FUNCTIONS

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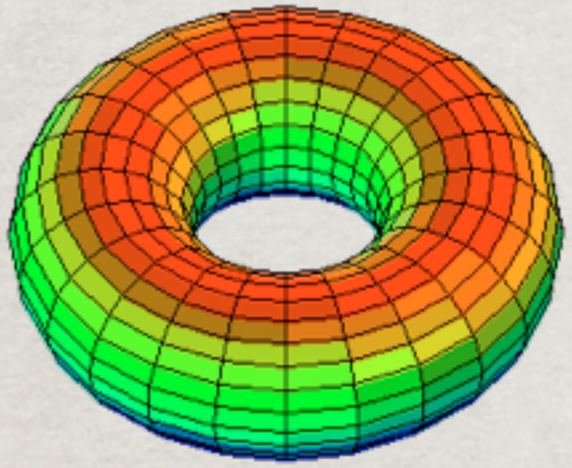
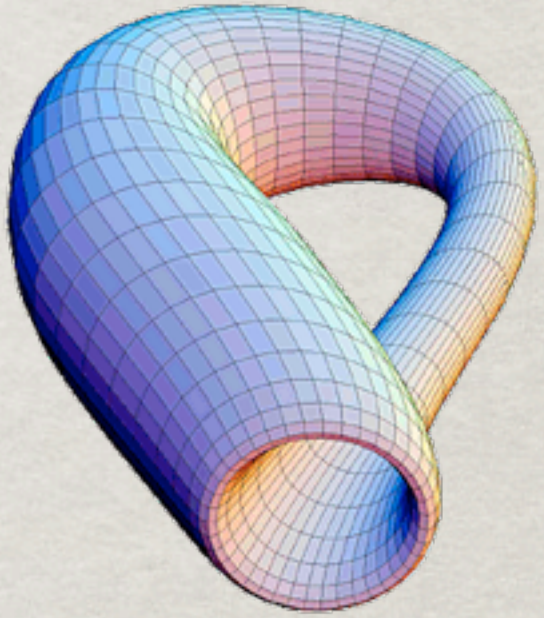
$\frac{1}{2}$ $\Big\{$  $+$  $\Big\}$

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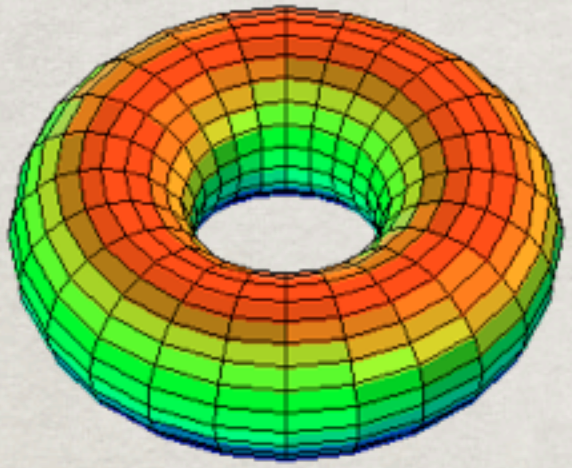
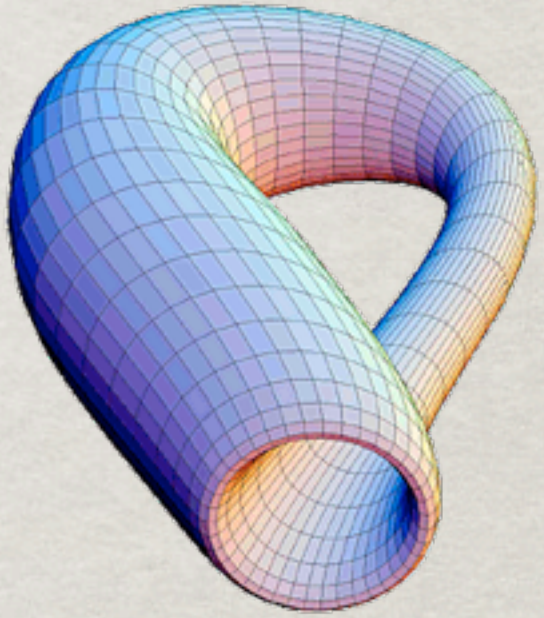
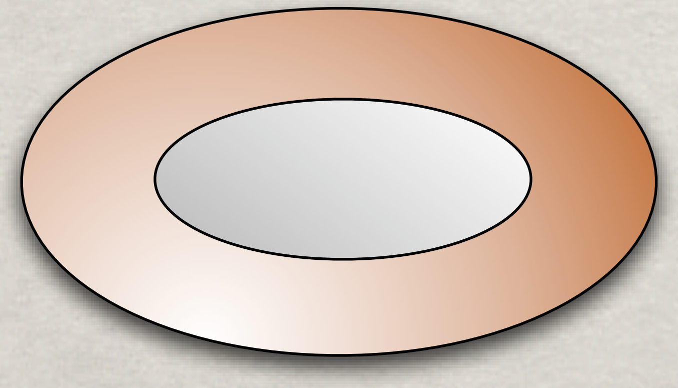
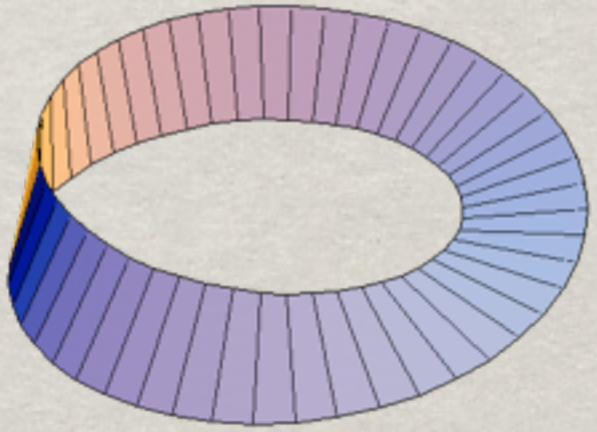
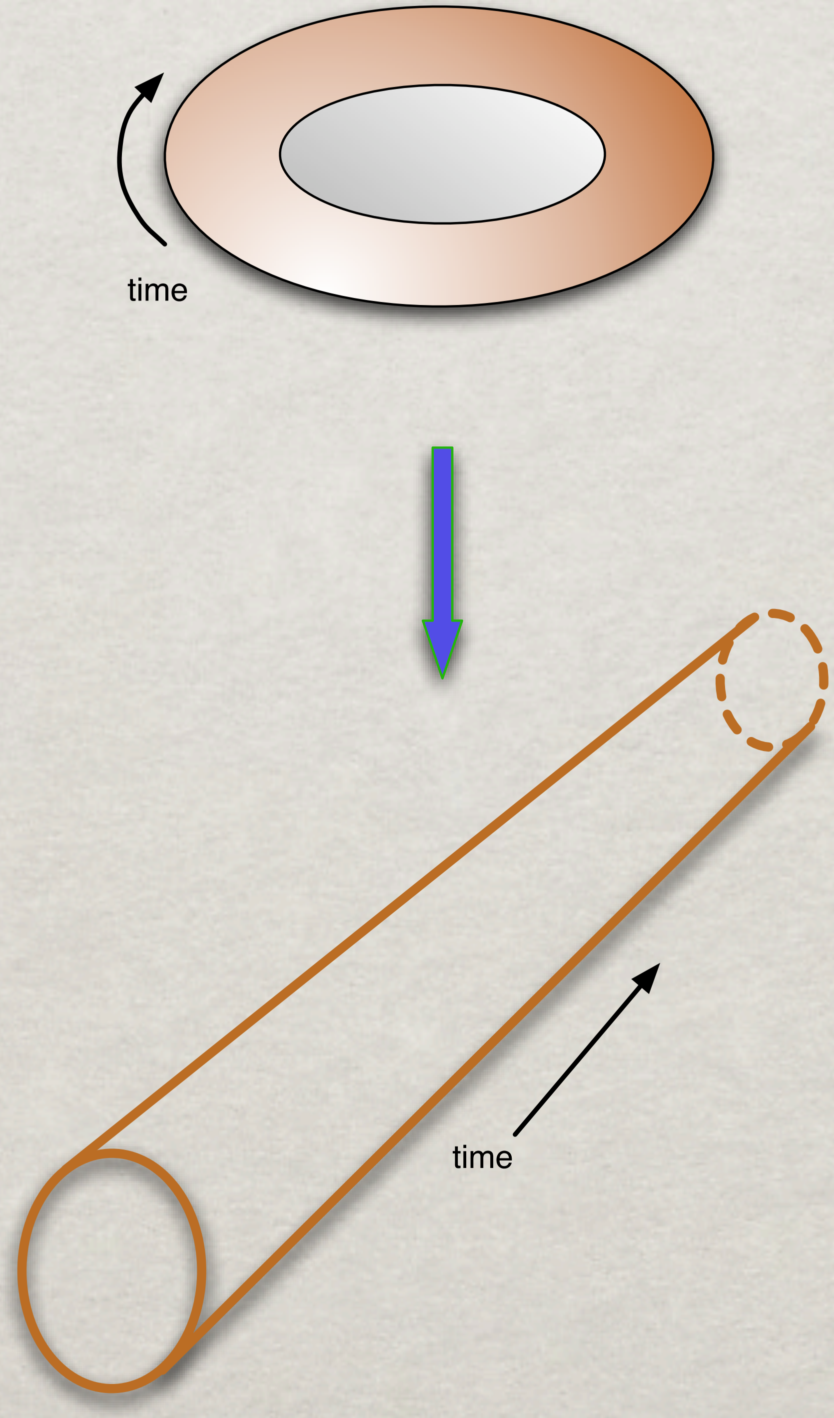
$\frac{1}{2}$ $\Big\{$  +  $\Big\}$

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

TRANSVERSE CHANNEL



boundary state

THE LONG ROAD TO THE CHIRAL SSM

- Angelantonj, Bianchi, Pradisi, Sagnotti, Stanev (1996)
  Chiral spectra from Orbifold-Orientifolds

- Aldazabal, Franco, Ibanez, Rabadan, Uranga (2000)
  Blumenhagen,Görlich,Körs,Lüst (2000)
  Ibanez, Marchesano, Rabadan (2001)
  Non-supersymmetric SM-Spectra with RR tadpole cancellation

- Cvetic, Shiu, Uranga (2001)
  Supersymmetric SM-Spectra with chiral exotics

- Blumenhagen, Görlich, Ott (2002)
  Honecker (2003)
  Supersymmetric Pati-Salam Spectra with brane recombination

- Dijkstra, Huiszoon, Schellekens (2004)
  Supersymmetric Standard Model (Gepner Orientifolds)

- Honecker, Ott (2004)
  Supersymmetric Standard Model (Z_6 orbifold/orientifold)

RCFT ORIENTIFOLDS*

Data needed:

- A rational CFT with N=2 and $c = 9$
- The exact spectrum
- The modular matrix S

For simple current MIPFs:

- The "fixed point resolution matrices" S^J

**Pioneering work by Cardy; Sagnotti, Pradisi, Stanev; ...*

FORMALISM CAN BE APPLIED TO:

- “Gepner Models”
  (minimal N=2 tensor products)
- Kazama-Suzuki models
  (requires exact spectrum computation)
- Permutation orbifolds
- …….

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

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

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)

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

$$U_{(m,J)} = \frac{1}{\sqrt{|\mathcal{H}|}}\sum_{L\in\mathcal{H}}\eta(K,L)P_{LK,m}\delta_{J,0}$$

S^J is the *fixed point resolution matrix*
$\mathcal{S}_a$ is the *Stabilizer* of a
$\mathcal{C}_a$ is the *Central Stabilizer* ($\mathcal{C}_a \subset \mathcal{S}_a \subset \mathcal{H}$)
ψ_a is a discrete group character of cC_a
$P = \sqrt{T}ST^2S\sqrt{T}$

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

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

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

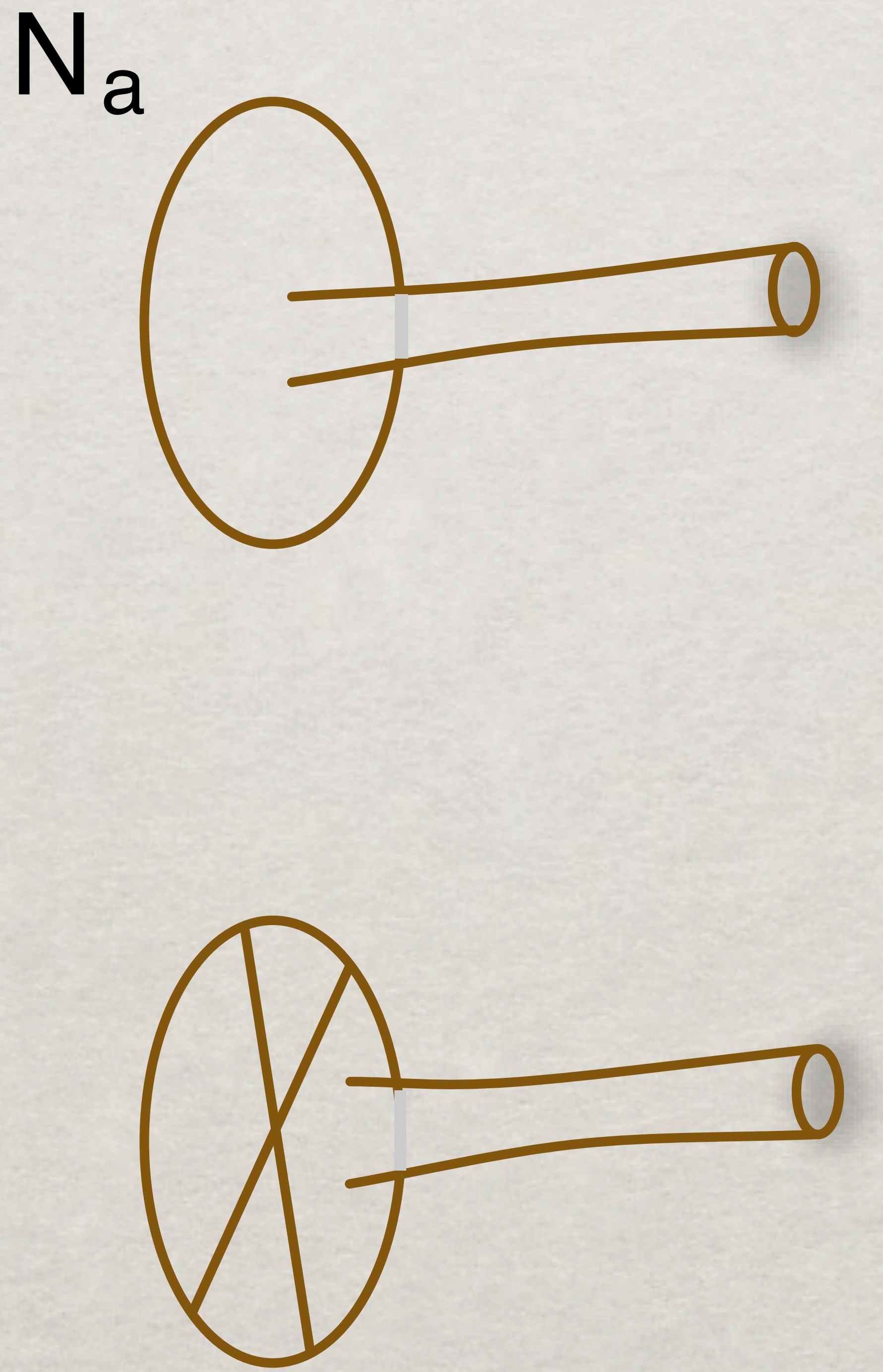
- Moebius

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

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

tadpoles & Anomalies

TADPOLES & ANOMALIES



tadpoles & Anomalies

TADPOLES & ANOMALIES

- Tadpole cancellation condition:

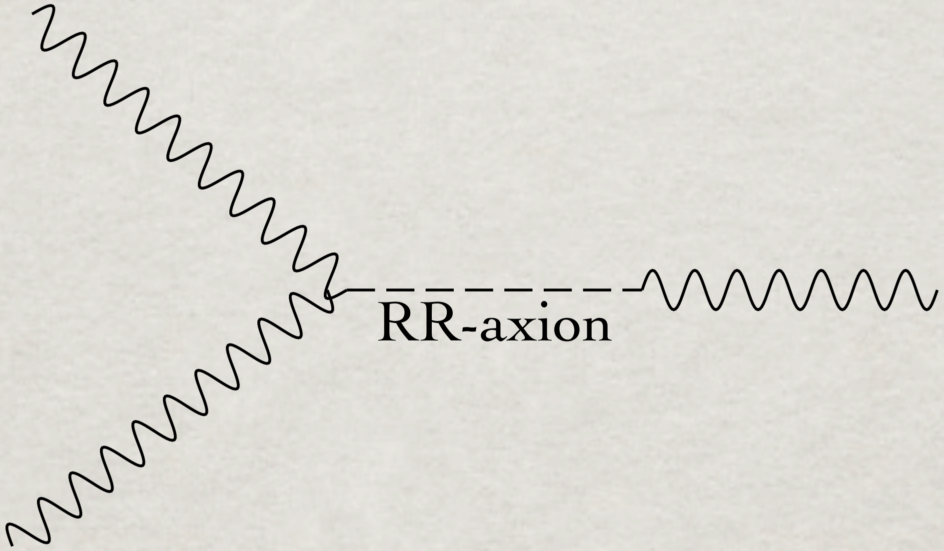
$$\sum_b N_b R_{b(m,J)} = 4\eta_m U_{(m,J)}$$

- Cubic $\mathrm{Tr} F^3$ anomalies cancel
- Remaining anomalies by Green-Schwarz mechanism
- In rare cases, additional conditions for global anomaly cancellation*

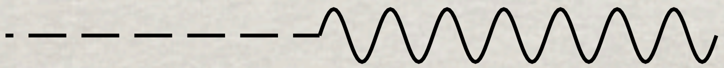
**Gato-Rivera, Schellekens (2005)*

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

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- 168 Gepner models

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- 168 Gepner models
- 5403 MIPFs

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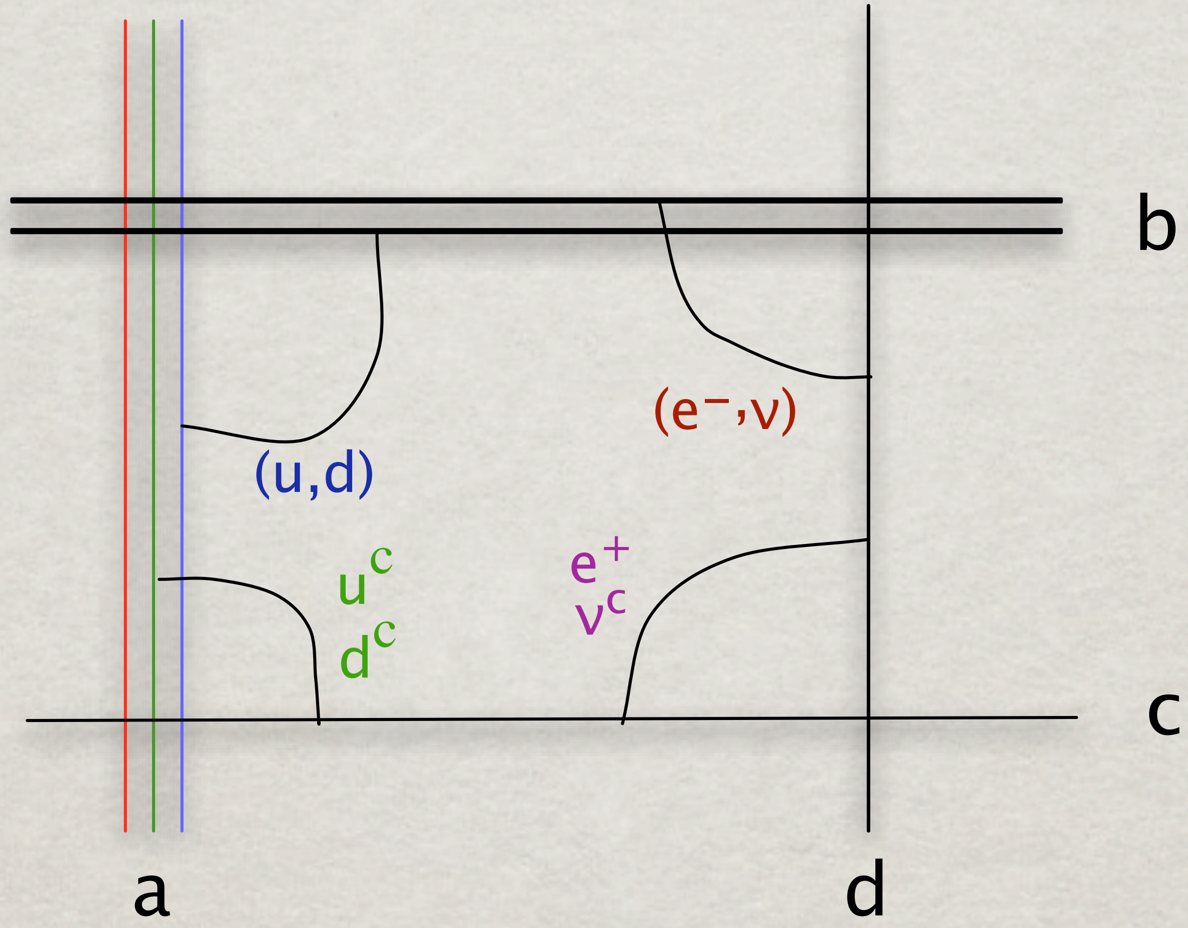
Essential to decide what to search for!

WHAT TO SEARCH FOR

The Madrid model



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

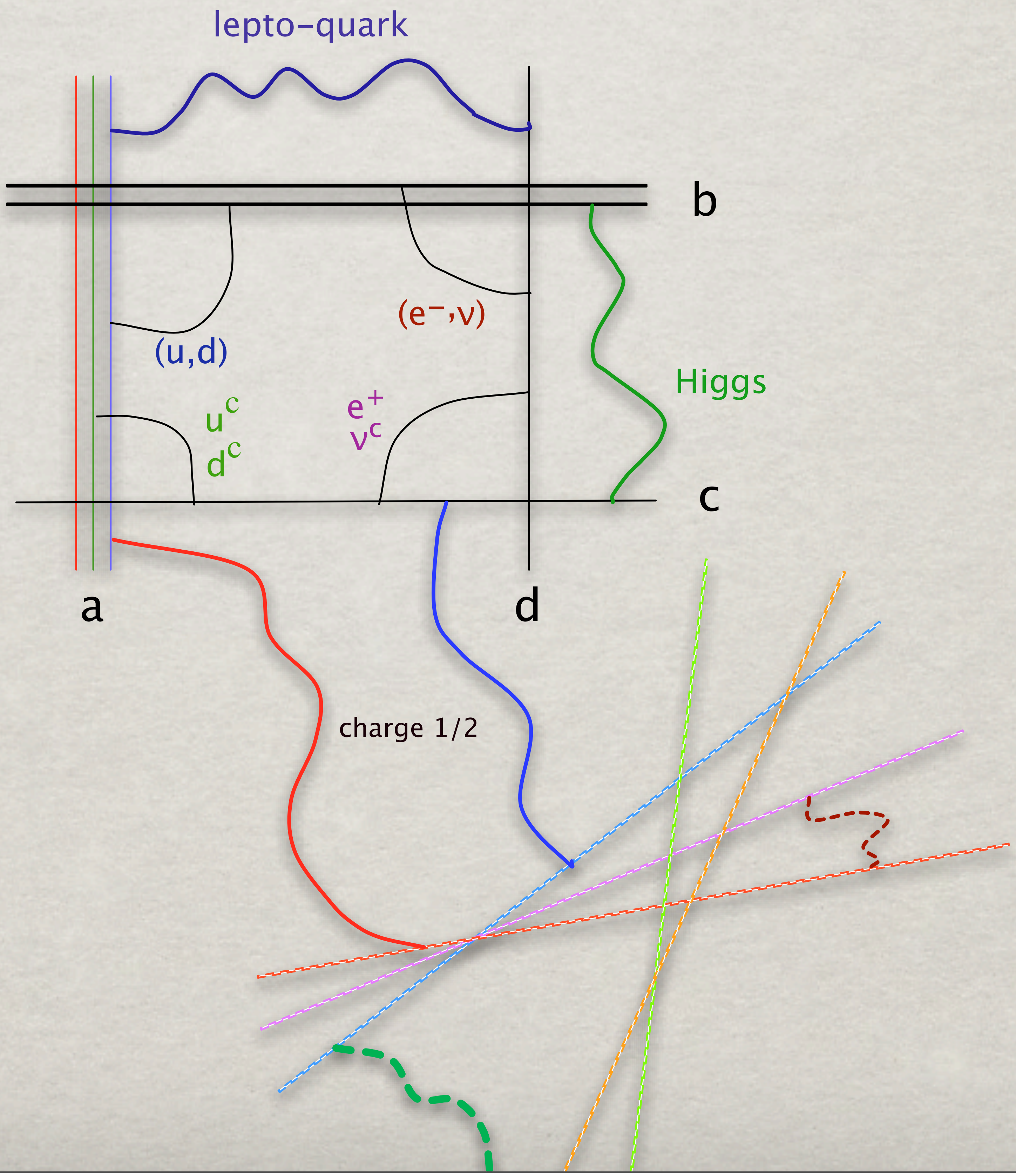
$$3(u,d)_L + 3u^c_L + 3d^c_L + 3(e^-,\nu)_L + 3e^+_L$$

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

N=1 Supersymmetry

No tadpoles, global anomalies

THE HIDDEN SECTOR



BRANE CONFIGURATIONS

Type	CP Group	B-L
0	U(3) x Sp(2) x U(1) x U(1)	massless
1	U(3) x U(2) x U(1) x U(1)	massless
2	U(3) x Sp(2) x O(2) x U(1)	massless
3	U(3) x U(2) x O(2) x U(1)	massless
4	U(3) x Sp(2) x Sp(2) x U(1)	massless
5	U(3) x U(2) x Sp(2) x U(1)	massless
6	U(3) x Sp(2) x U(1) x U(1)	massive
7	U(3) x U(2) x U(1) x U(1)	massive

RESULTS (2004)*

- First chiral SSM
- Solutions to Tadpole conditions for 44/168 Gepner models, 333/5403 MIPFs
- Total number of 4 stacks with SM spectrum: 45 x 10^{6} (out of 45 x10^{18})
- Total number of 4 stacks with tadpole solutions: 1.6 x 10^{6}
- Total number of distinct SM spectra: 1.8 x 10^{5} (counting non-chiral differences, but the not hidden sector)

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

STATISTICS

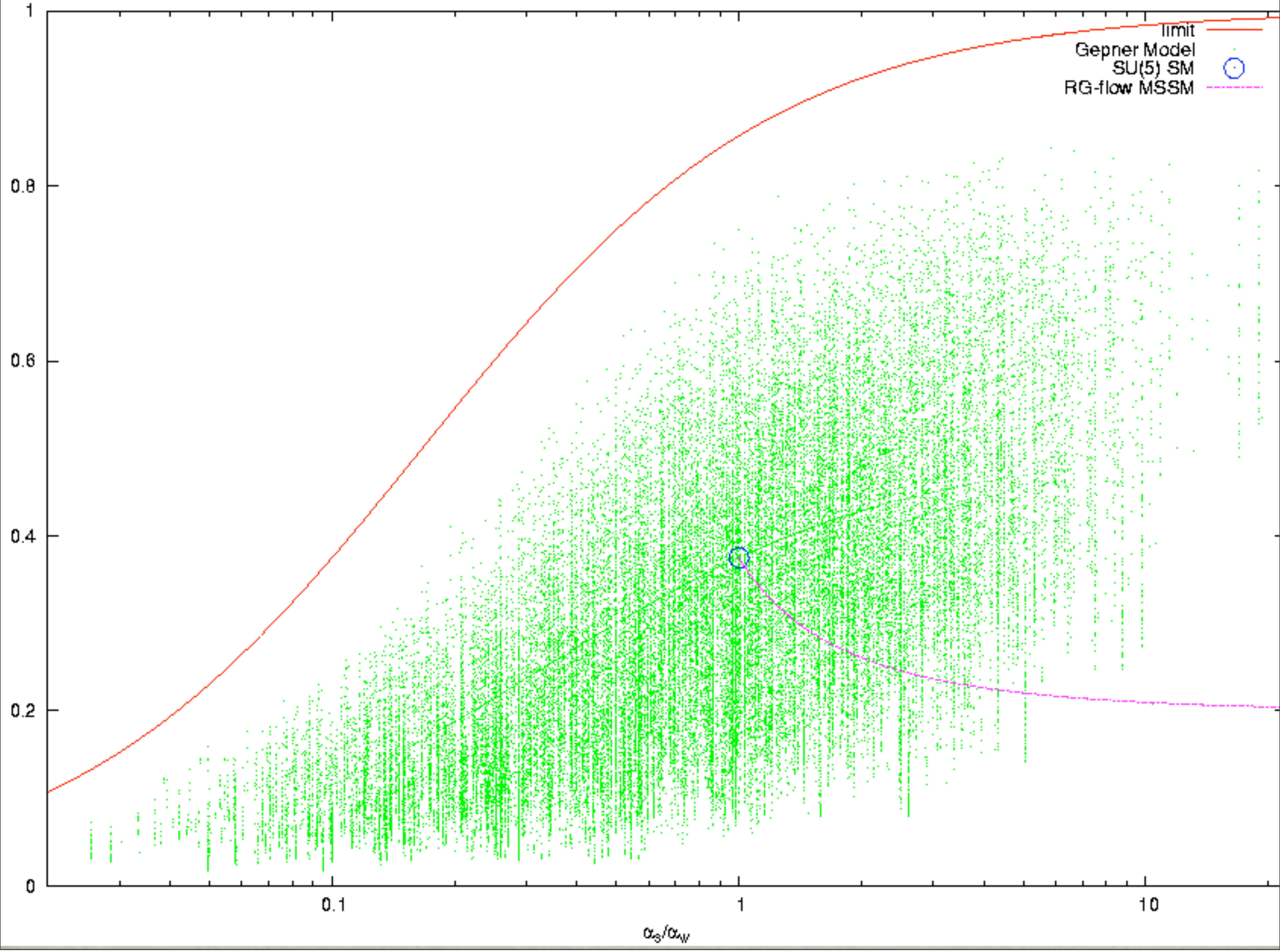
Total number of 4-stack configurations	45761187347637742772 (45.7×10^{18})
Total number scanned	4.37522E+19
Total number of SM configurations	45051902 fraction: 1.0×10^{-12}
Total number of tadpole solutions	1649642 fraction: 3.8×10^{-14} (*)
Total number of distinct solutions	211634

(*) cf. Gmeiner, Blumenhagen, Honecker, Lüst, Weigand: "One in a Billion"

TYPE DISTRIBUTION

Type	Quark*	Lepton*	Higgs*	Nr.
0	0	0	0	10564
1	-3	3	0	32
1	-9	3	6	1
1	-9	9	0	22
2	0	0	0	49661
3	-3	-1	4	141
3	-3	-3	6	24
3	-3	1	2	240
3	-3	3	0	740
3	-9	-3	12	24
3	-9	3	6	95
3	-9	5	4	1
3	-9	9	0	116
4	0	0	0	116304
5	-3	1	2	2
5	-3	3	0	1507
5	-9	9	0	46

Type 6 (Massive B-L, Type 0): 403
Type 7 (Massive B-L, Type 1): 0
No extra branes: 1270
Massive B-L, No extra branes: 22 (just SU(3)xSU(2)xU(1)!)



limit
Gepner Model
SU(5) SM
RG-flow MSSM
1
0.8
0.6
0.4
0.2
0
0.1
1
10
α_s/α_W

UNBIASED SEARCH*

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) but
- No fractionally charged mirror pairs
- Massless Y

P. Anastasopoulos, T. Dijkstra, E. Kiritsis, A.N.S, in (slow) progress

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

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

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

$$Y = (x - \frac{1}{3})Q_a + (x - \frac{1}{2})Q_b + \underbrace{xQ_C + (x-1)Q_D}_{\text{Distributed over c and d}}$$

Allowed values for x

1/2	Madrid model, Pati-Salam, Flipped SU(5)
0	(broken) SU(5)
1	
-1/2, 3/2	
any	Trinification ($x = 1/3$) (orientable)

THE BASIC ORIENTABLE MODEL

$$U(3) \times U(2) \times U(1) \times U(1)$$

$3 \times (V, V^*, 0, 0)$	(u,d)
$3 \times (V^*, 0, V, 0)$	d^c
$3 \times (V^*, 0, 0, V)$	u^c
$6 \times (0, V, V^*, 0)$	(e^-, ν) + H_1
$3 \times (0, V, 0, V^*)$	H_2
$3 \times (0, 0, V, V^*)$	e^+

“D-branes at singularities”

RESULTS

- Searched all MIPFs with < 1750 boundaries (4557 of 5403 MIPFs)
- 19345 chirally different SM embeddings found
- Tadpole conditions solved in 1900 cases (18 “old” ones)

STATISTICS

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

*Previous search: 45051902

BOTTOM-UP vs TOP-DOWN (1)

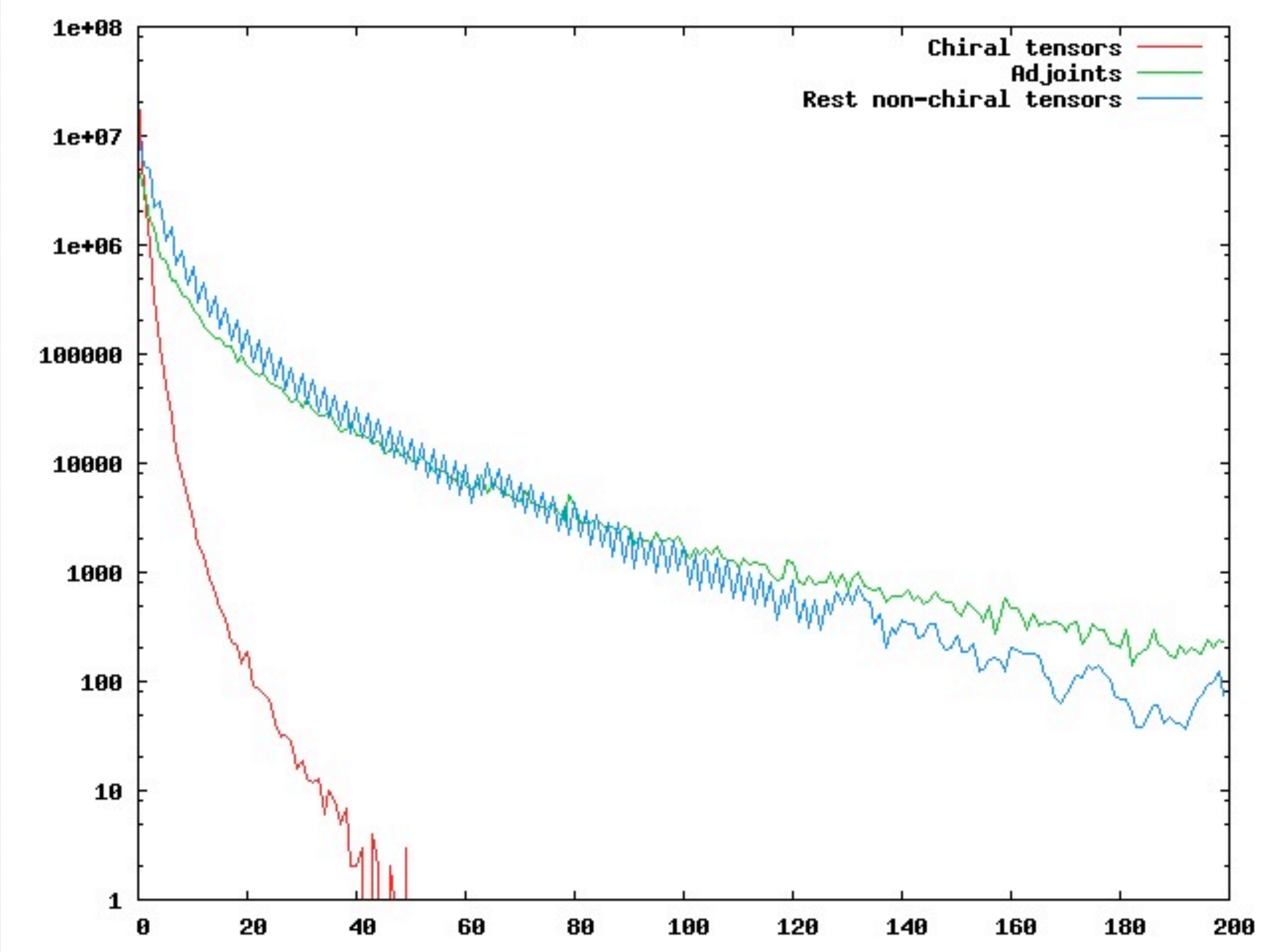
x	Config.	stack **c**	stack **d**	Bottom-up	Top-down	Occurrences	Solved
1/2	UUUU	C,D	C,D	27	9	5194	1
1/2	UUUU	C	C,D	103441	434	1311628	31
1/2	UUUU	C	C	10717308	156	758098	24
1/2	UUUU	C	F	351	0	0	0
1/2	UUU	C,D	-	4	1	24	0
1/2	UUU	C	-	215	5	26210	2
1/2	UUUR	C,D	C,D	34	5	3888	1
1/2	UUUR	C	C,D	185520	221	3121585	31
1/2	USUU	C,D	C,D	72	7	6473	2
1/2	USUU	C	C,D	153436	283	6268942	33
1/2	USUU	C	C	10441784	125	7310339	27
1/2	USUU	C	F	184	0	0	0
1/2	USU	C	-	104	2	222	0
1/2	USU	C,D	-	8	1	4881	1
1/2	USUR	C	C,D	54274	31	49859327	19

Continued on next page

Bottom-up vs Top-down (2)

x	Config.	stack **c**	stack **d**	Bottom-up	Top-down	Occurrences	Solved
1/2	USUR	C,D	C,D	36	2	858330	2
0	UUUU	C,D	C,D	5	5	4530	2
0	UUUU	C	C,D	8355	44	69956	2
0	UUUU	D	C,D	14	2	6480	0
0	UUUU	C	C	2890537	127	847924	9
0	UUUU	C	D	36304	16	6809	0
0	UUU	C	-	222	2	28340	1
0	UUUR	C,D	C	3702	39	171485	4
0	UUUR	C	C	5161452	289	5380920	32
0	UUUR	D	C	8564	22	50748	0
0	UUR	C	-	58	2	233071	2
0	UURR	C	C	24091	17	8452983	17
1	UUUU	C,D	C,D	4	1	1144	1
1	UUUU	C	C,D	16	5	25958	0
1	UUUU	D	C,D	42	3	5440	0
1	UUUU	C	D	870	0	0	0
1	UUUR	C,D	D	34	1	1024	0
1	UUUR	C	D	609	1	640	0
3/2	UUUU	C	D	9	0	0	0
3/2	UUUU	C,D	D	1	0	0	0
3/2	UUUU	C, D	C	10	0	0	0
3/2	UUUU	C,D	C,D	2	0	0	0
*	UUUU	C,D	C,D	2	2	5146	1
*	UUUU	C	C,D	10	7	521372	3
*	UUUU	D	C,D	1	1	116	0
*	UUUU	C	D	3	1	4	0

CHIRAL TENSOR SUPPRESSION



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

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

CURIOSITIES

nr.	Total occ.	MIPFs	Chan-Paton group	Spectrum	x	Solved
161	115466	335	$U(4) \times U(2) \times U(2)$	VVV	1/2	Y
256	71328	167	$U(3) \times U(3) \times U(3)$	VVV	$\frac{1}{3}$	
561	23954	26	$U(3) \times U(2) \times U(1)$	AAS	1/2	Y!
562	23954	26	$U(3) \times U(2) \times U(1)$	AAS	0	Y!
708	16845	296	$U(5) \times O(1)$	AV	0	Y
1296	6432	87	$U(3) \times U(3) \times U(3)$	VVV	*	Y
1522	4753	115	$U(6) \times Sp(2)$	AV	1/2	Y!
1523	4753	115	$U(6) \times Sp(2)$	AV	0	Y!
2157	2381	115	$U(6) \times Sp(2)$	AV	1/2	Y!
2348	2062	34	$U(5) \times U(1)$	AS	1/2	Y!
2349	2062	34	$U(5) \times U(1)$	AS	0	Y!
8118	114	3	$U(3) \times Sp(2) \times U(1)$	AVS	1/2	
8305	108	1	$U(3) \times Sp(2) \times U(1)$	VVT	1/2	
12973	24	1	$U(3) \times U(3) \times U(3)$	VVV	1/2	
17042	6	1	$U(3) \times U(2) \times U(1)$	AVT	1/2	Y!
19345	1	1	$U(5) \times U(2) \times O(3)$	ATV	0	

NOTATION

$5 \times (V, 0, 0, V)$ chirality -3

means

$4 \times (N^*,1,1,M^*) + (N,1,1,M)$

of a Chan-Paton group

$U(N) \times U(K) \times U(L) \times U(M)$

V=Vector
Adj = Adjoint

A = Anti-symmetric tensor
S = Symmetric tensor

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
```

PATI-SALAM (2)

161	115466	335	$U(4) \times U(2) \times U(2)$	VVV	1/2	Y

```
Type:       U  U  U  U  U  S  U  O  U  O
Dimension   4  2  2  6  2  2  2  2  2  2
      4 x ( V ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 2
      1 x ( V ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 1
      1 x ( V ,0 ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -1
      2 x ( V ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -2
      2 x ( 0 ,V ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -2
      2 x ( V ,0 ,0 ,0 ,V*,0 ,0 ,0 ,0 ,0 ) chirality 0
      4 x ( V ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ) chirality 0
      2 x ( 0 ,S ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
      2 x ( A ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
      1 x ( Ad,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
      2 x ( V ,0 ,0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ) chirality 0
      2 x ( 0 ,0 ,S ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
      4 x ( 0 ,V ,0 ,0 ,0 ,0 ,V*,0 ,0 ,0 ) chirality 0
      2 x ( 0 ,V ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ) chirality 0
      2 x ( 0 ,0 ,V ,0 ,0 ,0 ,V*,0 ,0 ,0 ) chirality 0
      1 x ( 0 ,Ad,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
      2 x ( V ,0 ,0 ,0 ,0 ,0 ,V*,0 ,0 ,0 ) chirality 0
      2 x ( V ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ,0 ) chirality 0
      1 x ( 0 ,0 ,Ad,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 0
      2 x ( 0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,V*,0 ) chirality 0
      2 x ( 0 ,0 ,V ,0 ,0 ,0 ,0 ,0 ,V ,0 ) chirality 0
```

PATI-SALAM (2)

161	115466	335	$U(4) \times U(2) \times U(2)$	VVV	1/2	Y

```
Type:            U   U   U   U   U   S   U   O   U   O
Dimension        4   2   2   6   2   2   2   2   2   2
          4 x (  V  ,V  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 2
          1 x (  V  ,V*,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 1
          1 x (  V  ,0  ,V*,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality -1
          2 x (  V  ,0  ,V  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality -2
          2 x (  0  ,V  ,V*,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality -2
          2 x (  V  ,0  ,0  ,0  ,V*,0  ,0  ,0  ,0  ,0  ) chirality 0
          4 x (  V  ,0  ,0  ,0  ,0  ,V  ,0  ,0  ,0  ,0  ) chirality 0
          2 x (  0  ,S  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
          2 x (  A  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
          1 x (  Ad,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
          2 x (  V  ,0  ,0  ,0  ,V  ,0  ,0  ,0  ,0  ,0  ) chirality 0
          2 x (  0  ,0  ,S  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
          4 x (  0  ,V  ,0  ,0  ,0  ,0  ,V*,0  ,0  ,0  ) chirality 0
          2 x (  0  ,V  ,0  ,0  ,0  ,0  ,V  ,0  ,0  ,0  ) chirality 0
          2 x (  0  ,0  ,V  ,0  ,0  ,0  ,V*,0  ,0  ,0  ) chirality 0
          1 x (  0  ,Ad,0  ,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
          2 x (  V  ,0  ,0  ,0  ,0  ,0  ,V*,0  ,0  ,0  ) chirality 0
          2 x (  V  ,0  ,0  ,0  ,0  ,0  ,V  ,0  ,0  ,0  ) chirality 0
          1 x (  0  ,0  ,Ad,0  ,0  ,0  ,0  ,0  ,0  ,0  ) chirality 0
          2 x (  0  ,V  ,0  ,0  ,0  ,0  ,0  ,0  ,V*,0  ) chirality 0
          2 x (  0  ,0  ,V  ,0  ,0  ,0  ,0  ,0  ,V  ,0  ) 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)!

FLIPPED SU(5)

2348	2062	34	$U(5) \times U(1)$	AS	1/2	Y!

```
Type:          U   U
Dimension      5   1
         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
```

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

FLIPPED SU(5)

2348	2062	34	$U(5) \times U(1)$	AS	1/2	Y!

```
Type:           U   U
Dimension       5   1
          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
```

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

Non-trivial U(1) anomaly cancellation!

SU(5) x U(1)

2349	2062	34	$U(5) \times U(1)$	AS	0	Y!

```
Type:           U   U
Dimension       5   1
          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
```

$$Y = -\frac{2}{3}Q_a + \frac{1}{2}Q_b$$

YUKAWA COUPLINGS

Standard SU(5) couplings

$$\mathcal{O}_1 \sim (\bar{\psi}^c)_\alpha \psi^{\alpha\beta} H_\beta \quad , \quad \mathcal{O}_2 \sim \epsilon_{\alpha\beta\gamma\delta\epsilon} (\bar{\psi}^c)^{\alpha\beta} \psi^{\gamma\delta} H^\epsilon$$

U(5) brane charges

1-2+1=0 -2-2-1=5

SU(5): no u,c,t couplings
flipped SU(5): no d,s,b coupings

Possible ways out:

- Higher dimension operators
- Composite condensate with charge 5
- Instantons

Requires additional and implausible dynamics

THE UNIFICATION DILEMMA

- Data suggest: Coupling unification*, no fractional charges
- Heterotic string: Wrong scale, fractional charges
- $x = \frac{1}{2}$ brane models: No unification, fractional charges
  No prediction for scale
- U(5) brane models: Unification, no fractional charges
  No prediction for scale
  No (u,c,t) Yukawa's

* assuming gauginos

TRINIFICATION

1296	6432	87	$U(3) \times U(3) \times U(3)$	VVV	*	Y

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

TRINIFICATION

1296	6432	87	$U(3) \times U(3) \times U(3)$	VVV	*	Y

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

Calabi-Yau dependence (1)

Tensor product	MIPF	h_{11}	h_{12}	Scalars	$x = 0$	$x = \frac{1}{2}$	$x = *$	Success rate
(1,1,1,1,7,16)	30	11	35	207	2352	715	0	3.08×10^{-3}
(1,1,1,1,7,16)	31	5	29	207	1341	1212	0	2.56×10^{-3}
(1,4,4,4,4)	53	20	20	150	2953179	347733	0	5.35×10^{-4}
(6,6,6,6)	37*	3	59	223	0	1589504	0	4.68×10^{-3}
(1,1,1,1,10,10)	50	12	24	183	2166	1100	36	4.23×10^{-3}
(1,4,4,4,4)	54	3	51	213	5400	5328	4248	3.92×10^{-3}
(1,1,1,1,10,10)	56	4	40	219	389	182	0	3.53×10^{-3}
(1,1,1,1,8.13)	5	20	20	140	465	47	0	2.78×10^{-3}
(1,1,1,1,7,16)	26	20	20	140	187	26	0	2.14×10^{-3}
(1,1,7,7,7)	9	7	55	276	7973	1254	0	1.83×10^{-3}
(1,1,1,1,7,16)	32*	23	23	217	152	28	0	1.81×10^{-3}
(1,4,4,4,4)	13	3	51	250	395712	315036	0	1.77×10^{-3}
(1,1,1,1,12,10)	21	20	20	142	3	2	0	1.67×10^{-3}

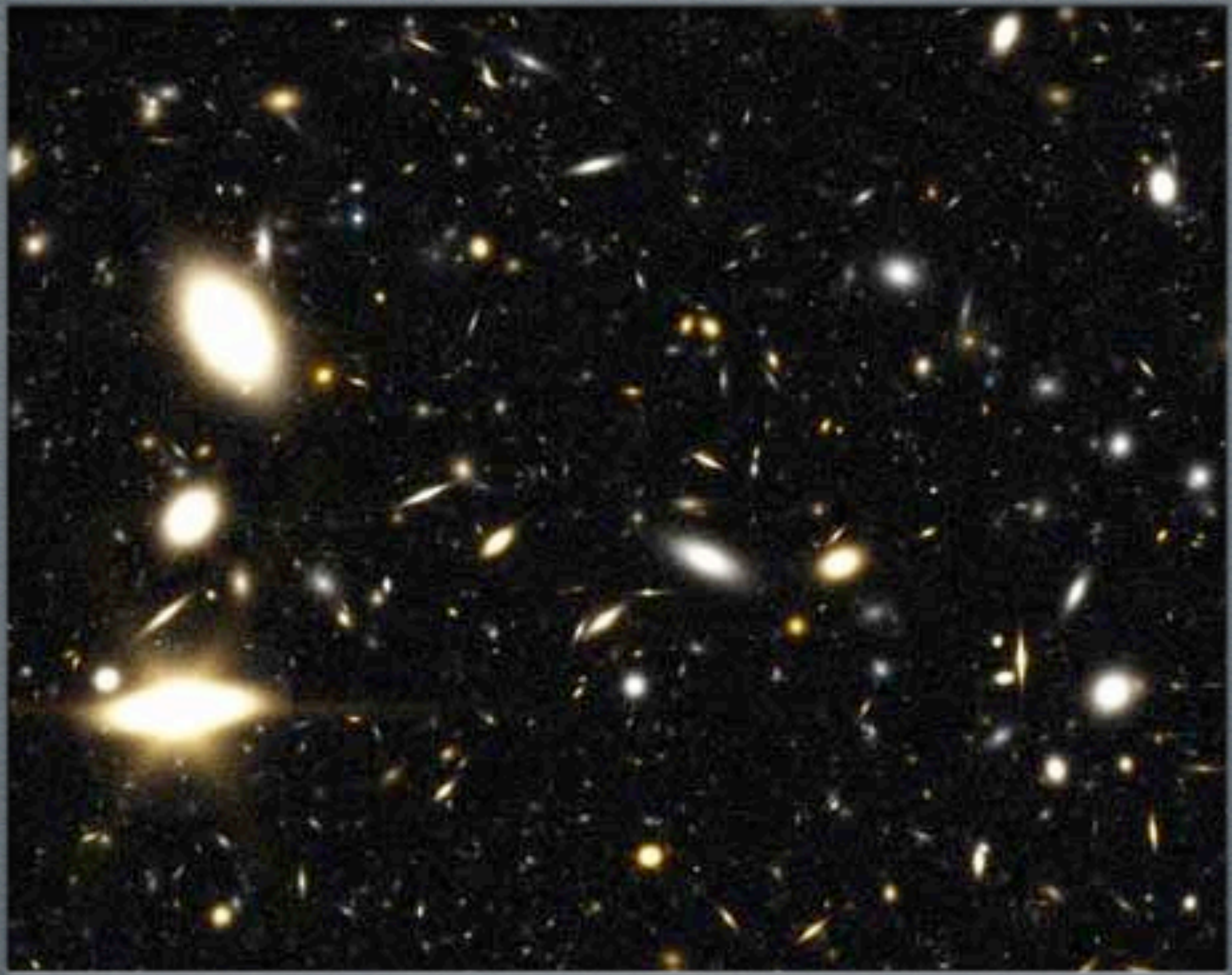
Continued on next page

CALABI-YAU DEPENDENCE (2)

Tensor product	MIPF	h_{11}	h_{12}	Scalars	$x = 0$	$x = \frac{1}{2}$	$x = *$	Success rate
(1,1,1,2,4,10)	44	12	24	225	952	496	0	1.54×10^{-3}
(1,4,4,4,4)	52	3	51	253	118796	16606	0	1.16×10^{-3}
(1,1,1,1,1,4,4)	124	0	0	78	729	0	0	9.8×10^{-5}
(1,1,1,1,5,40)	5	20	20	140	428	65	0	9.78×10^{-5}
(4,4,10,10)	79*	7	43	215	0	57924	0	9.39×10^{-5}
(4,4,10,10)	77*	5	53	232	0	1147070	0	8.9×10^{-5}
(1,4,4,4,4)	77	3	63	248	0	1024	0	8.12×10^{-5}
(4,4,10,10)	74*	9	57	249	0	1480812	0	8.06×10^{-5}
(1,1,1,1,12,10)	24	20	20	142	0	0	6	7.87×10^{-5}
…								…
(3,3,3,3,3)	6	21	17	234	0	192	0	6.54×10^{-6}
(3,3,3,3,3)	4	5	49	258	0	24	0	8.17×10^{-7}
(3,3,3,3,3)	2	49	5	258	6	27	6	1.65×10^{-9}

CONCLUSIONS

- Classification and construction of bottom-up models
- Huge number of bottom-up possibilities
- Huge number of top-down models
- Still, only small fraction of bottom-up realized
- Results dominated by x=1/2
- Anti-symmetric tensors heavily suppressed
- Very clean SU(5)'s....
- ....But are they good for anything?



It's just one small step:
874 Hodge numbers scanned
at least 30000 known (M. Kreuzer)