RCFT Orientifolds and Standard Model Realizations

The Anthropic Landscape of Quantum Gravity:

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- Unthinkable 25 years ago

The Anthropic Landscape of Quantum Gravity:

- Unthinkable 25 years ago
- Will be generally accepted 25 years from now

Reasonable goals

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- Explore unknown regions of the landscape

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Reasonable goals

- Explore unknown regions of the landscape
- Establish the likelyhood of standard model features (gauge group, three families, ...)
- Convince ourselves that the standard model is a plausible vacuum
- Determine if we are the “Chinese” or the “Andorrans” of the landscape
- ... and maybe we get lucky

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].

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

Selecting MIPFs and Orientifolds

Each tensor product has a discrete group $\mathcal{G}$
of simple currents: $J \cdot a = b$

Choose:

- A subgroup $\mathcal{H}$ of $\mathcal{G}$
- A rational matrix $X_{\alpha\beta}$ defined on $\mathcal{H}$
- An element K of $\mathcal{G}$
- A set of signs $\beta_K(J)$ defined on $\mathcal{H}$

Conditions

[definition: $Q_J(a) \equiv h(a) + h(J) - h(Ja)$]

$\mathcal{H}$

$$N_J h_J \in \mathbf{Z}, \text{ for all } J \in \mathcal{H}$$

$X_{\alpha\beta}$

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

K

$$Q_I(K) = 0 \text{ mod } 1 \text{ for all } I \in \mathcal{H}, I^2 = 0.$$

$\beta_K(J)$

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

A MIPF

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

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

Boundaries and Crosscaps*

- Boundary coefficients

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

- Crosscap coefficients

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

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

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

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

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

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

Accessible configurations

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- 168 Gepner models

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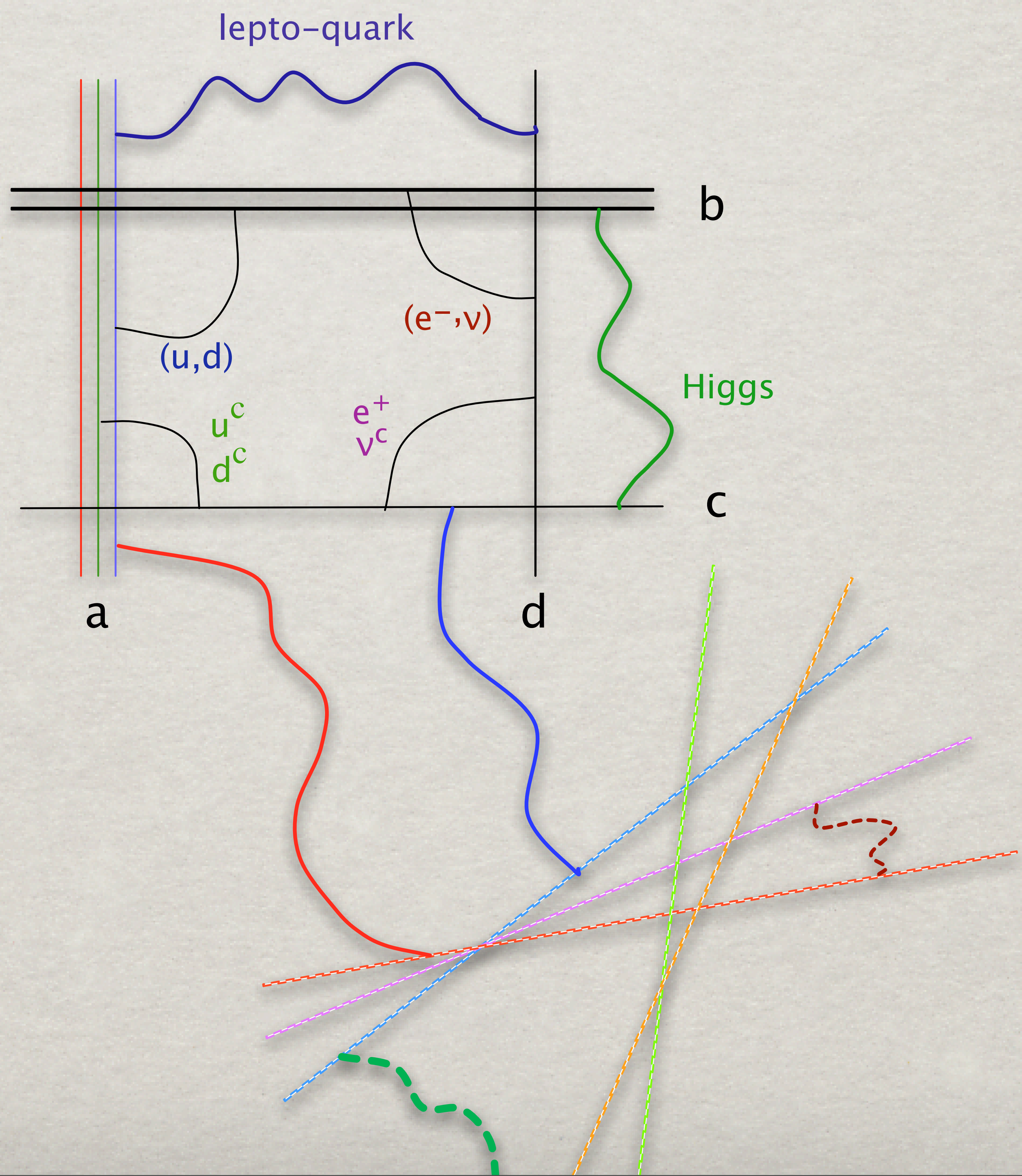
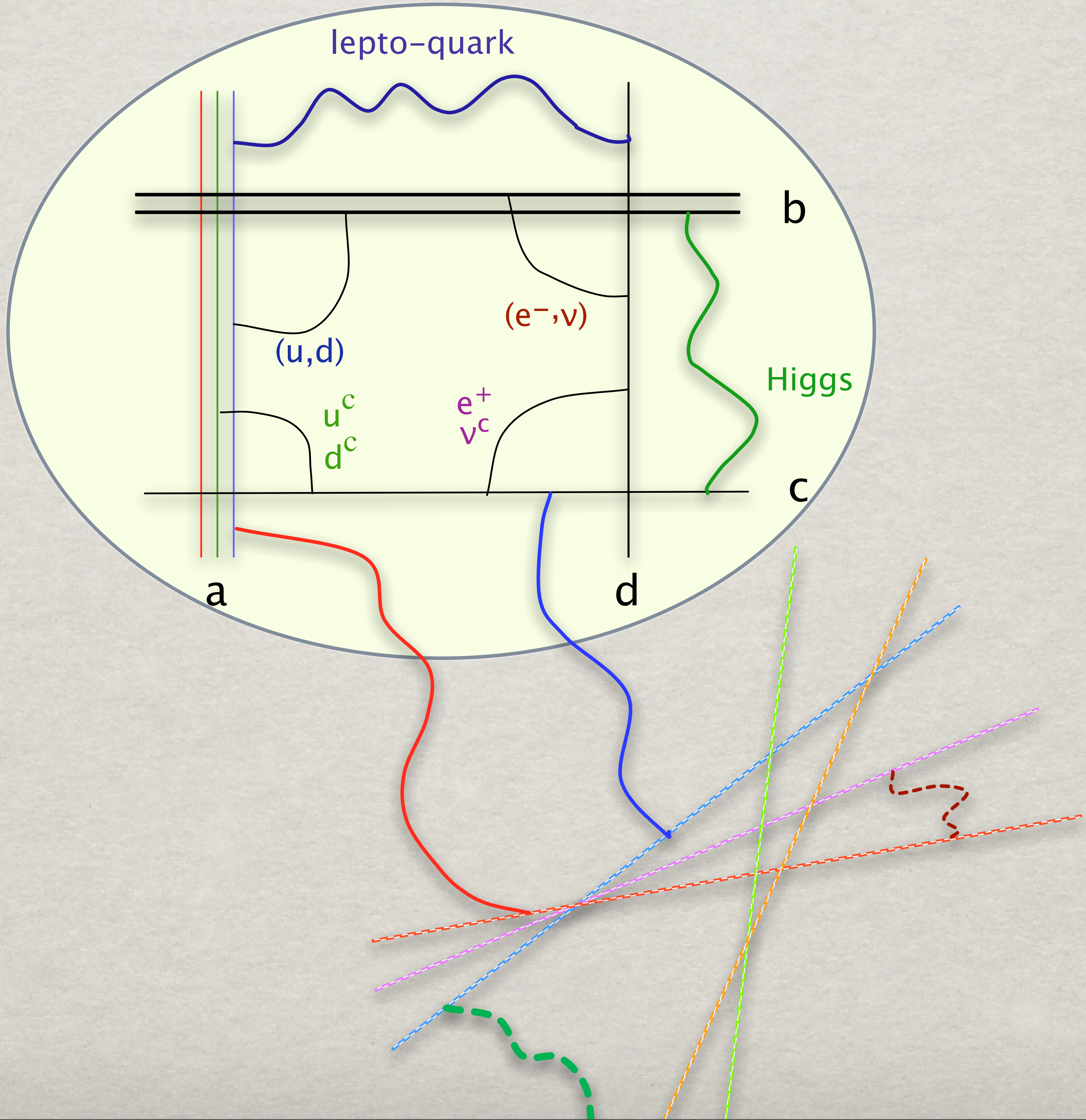
Essential to decide what to search for!

Standard Model realization

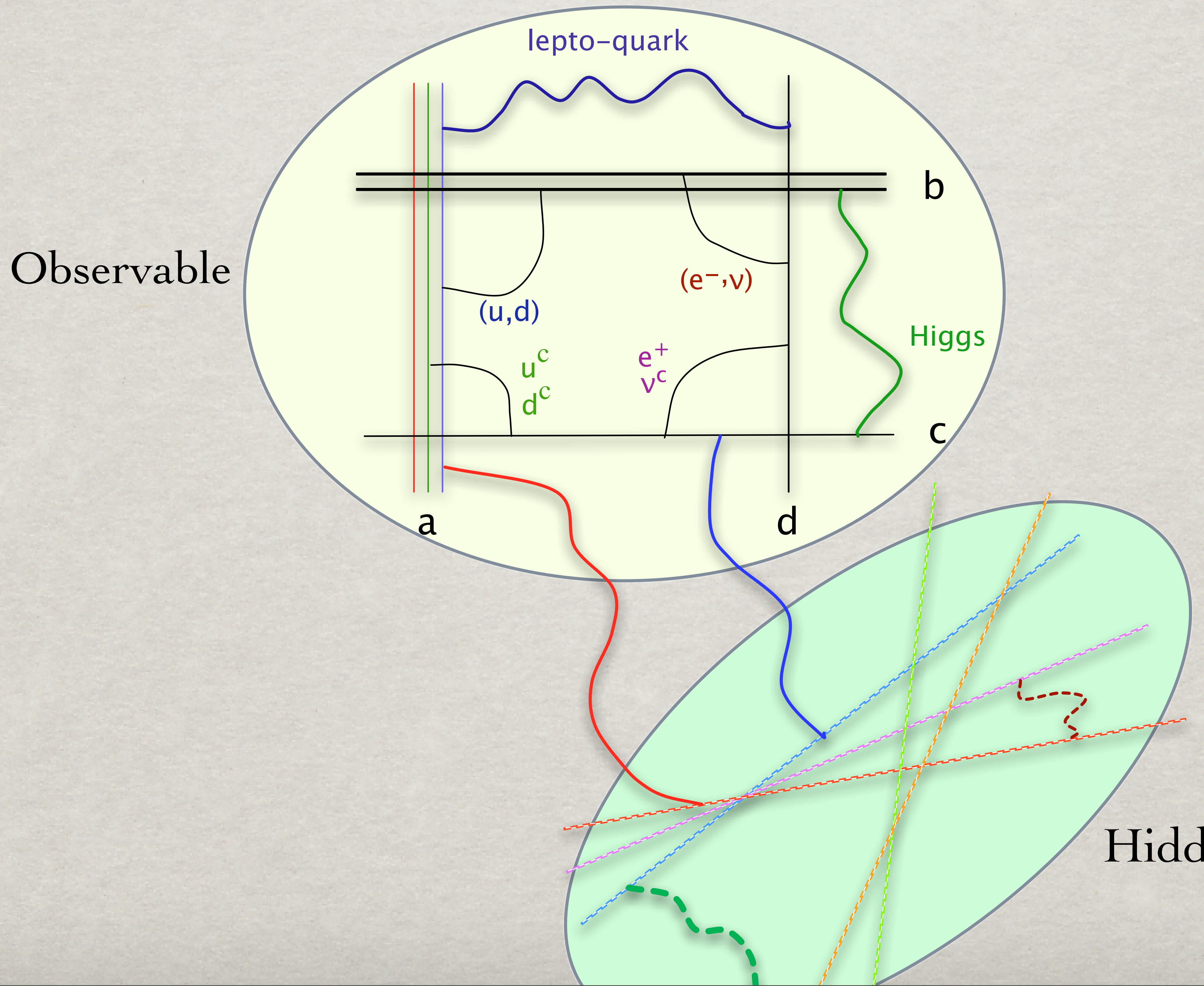


Standard Model realization

Observable



Standard Model realization



Basic assumptions

- CP group contains SU(3) x SU(2) x U(1)
- Massless Y
- Spectrum: 3 families + SM-non-chiral
- Supersymmetry
- Complete tadpole cancellation
- Global anomaly cancellation
  (using Uranga's probe brane method)

Additional Assumption

2004-2005 results:

(with T. Dijkstra and L. Huiszoon)

2005-2006 results:

(with P. Anastasopoulos, T. Dijkstra and E. Kiritsis)

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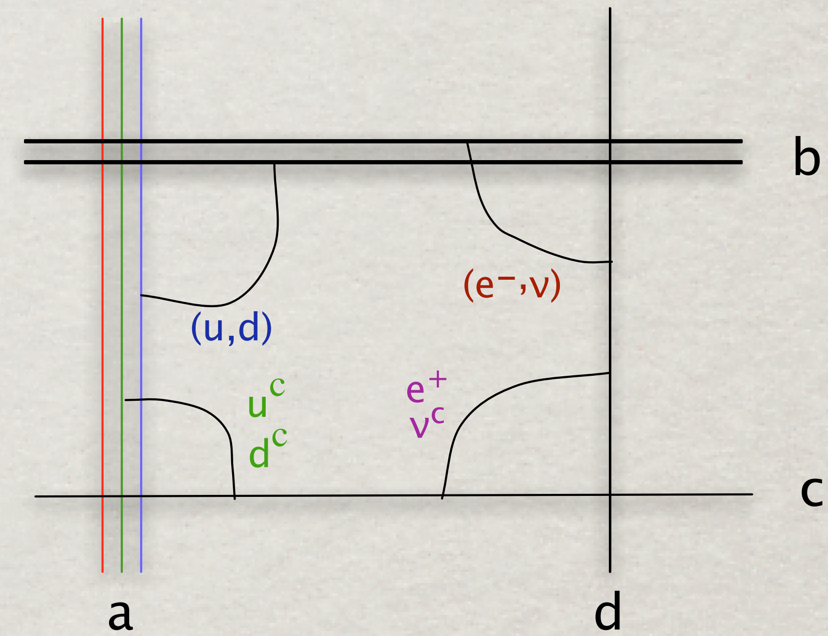

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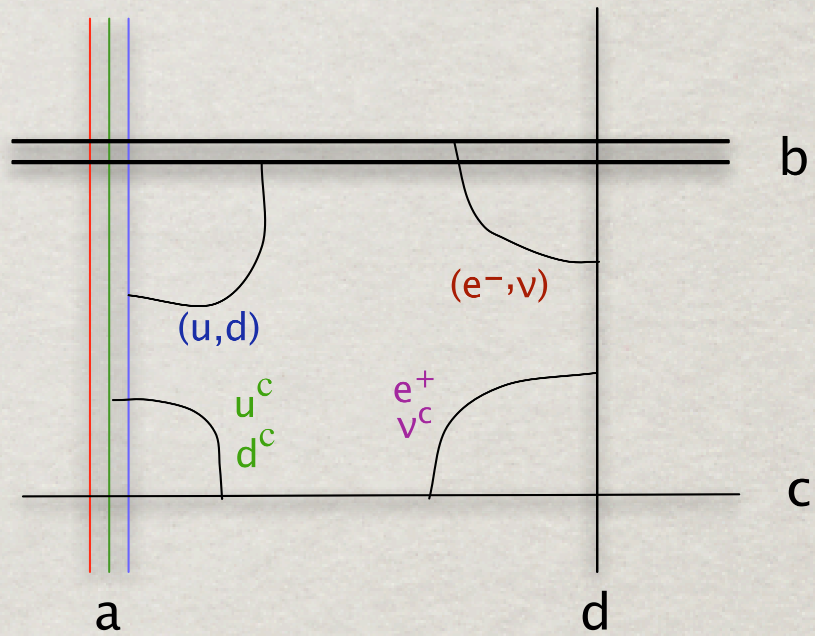

- U(3) from a single brane

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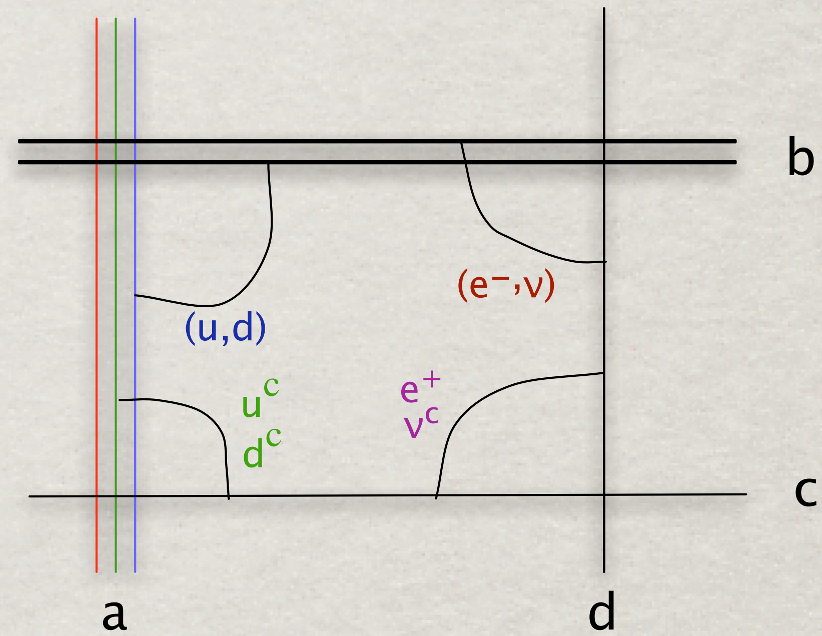
Additional Assumption



2004-2005 results:

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2005-2006 results:

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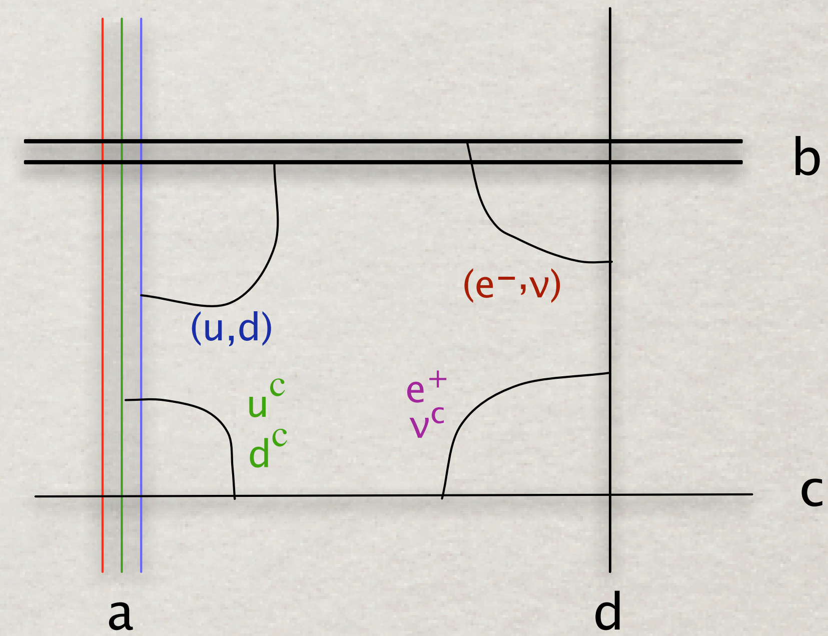
- U(3) from a single brane
- U(2) from a single brane

Additional Assumption

2004-2005 results:

(with T. Dijkstra and L. Huiszoon)



2005-2006 results:

(with P. Anastasopoulos, T. Dijkstra and E. Kiritsis)

- U(3) from a single brane
- U(2) from a single brane
- At most four branes

Additional Assumption

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2005-2006 results:

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Additional Assumption

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About 20
chirally distinct
SM configurations(*)

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About 19000
chirally distinct
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Additional Assumption

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2005-2006 results:

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About 19000
chirally distinct
SM configurations(*)

(*) before attempting tadpole cancellation

Additional Assumption

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Additional Assumption

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Modulo
Hidden Sector

2005-2006 results:

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Additional Assumption

2004-2005 results:
(with T. Dijkstra and L. Huiszoon)

Modulo
Hidden Sector

2005-2006 results:
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Modulo
CP-Non-chiral states

Additional Assumption

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2005-2006 results:

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Additional Assumption

2004-2005 results:

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211634 distinct

String Vacua

2005-2006 results:

(with P. Anastasopoulos, T. Dijkstra and E. Kiritsis)

Additional Assumption

2004-2005 results:
(with T. Dijkstra and L. Huiszoon)

211634 distinct

String Vacua

2005-2006 results:
(with P. Anastasopoulos, T. Dijkstra and E. Kiritsis)

1900 distinct
String Vacua
(MIPFs with < 1750 boundaries)

Brane Configurations (2004-2005)

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

$U(2)_{weak}$ allows additional chiral sub-types

STATISTICS

Total number of 4-stack configurations	45761187347637742772 (45.7×10^{18})
Total number scanned	43752168618082181524
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"

```
Gauge group: U(3) x Sp(2) x O(2) x U(1) x U(2) x Sp(6) x Sp(4) x Sp(2) x Sp(2) x Sp(2)

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

                              Summary:
           Higgs: (2,1/2)+(2*,1/2)              3
Non-chiral SM matter (Q,U,D,L,E,N):  0  0  0  0  0  0
   Adjoints:                            0  0  0  0
   Symmetric Tensors:                   0  0  0  0
   Anti-Symmetric Tensors:              0  0  0  0
      Lepto-quarks: (3,-1/3),(3,2/3)       1  2
   Non-SM (a,b,c,d)                    12 12  4  4
 Hidden (Total dimension)            58 (chirality 0)

        alpha_3/alpha_2 =       1.2071071
         sin^2(theta_w) =       0.3918058
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Gauge group: U(3) x Sp(2) x O(2) x U(1) x U(2) x Sp(6) x Sp(4) x Sp(2) x Sp(2) x Sp(2)

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

                         Summary:
          Higgs: (2,1/2)+(2*,1/2)              3
Non-chiral SM matter (Q,U,D,L,E,N):   0   0   0   0   0   0
   Adjoints:                              0   0   0   0
   Symmetric Tensors:                     0   0   0   0
   Anti-Symmetric Tensors:                0   0   0   0
      Lepto-quarks: (3,-1/3),(3,2/3)          1   2
   Non-SM (a,b,c,d)                      12  12   4   4
 Hidden (Total dimension)             58 (chirality 0)

         alpha_3/alpha_2 =       1.2071071
          sin^2(theta_w) =       0.3918058
```

```
Gauge group: U(3) x Sp(2) x O(2) x U(1) x U(2) x Sp(6) x Sp(4) x Sp(2) x Sp(2) x Sp(2)

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

                 Summary:
     Higgs: (2,1/2)+(2*,1/2)              3
Non-chiral SM matter (Q,U,D,L,E,N):  0  0  0  0  0  0
   Adjoints:                            0  0  0  0
   Symmetric Tensors:                   0  0  0  0
   Anti-Symmetric Tensors:              0  0  0  0
      Lepto-quarks: (3,-1/3),(3,2/3)       1  2
   Non-SM (a,b,c,d)                    12 12  4  4
 Hidden (Total dimension)          58 (chirality 0)

     alpha_3/alpha_2 =       1.2071071
      sin^2(theta_w) =       0.3918058
```

```
Gauge group: U(3) x Sp(2) x O(2) x U(1) x U(2) x Sp(6) x Sp(4) x Sp(2) x Sp(2) x Sp(2)

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

                    Summary:
         Higgs: (2,1/2)+(2*,1/2)               3
Non-chiral SM matter (Q,U,D,L,E,N):  0  0  0  0  0  0
   Adjoints:                                0  0  0  0
   Symmetric Tensors:                       0  0  0  0
   Anti-Symmetric Tensors:                  0  0  0  0
      Lepto-quarks: (3,-1/3),(3,2/3)           1  2
   Non-SM (a,b,c,d)                        12 12  4  4
 Hidden (Total dimension)              58 (chirality 0)

        alpha_3/alpha_2 =        1.2071071
         sin^2(theta_w) =       0.3918058
```

Complete Hidden Sector
(assuming CP-non-chiral Observable-Hidden states)

```
U(3) [fixed]
Sp(2) [fixed]
SO(2) [fixed]
U(1) [fixed]
Sp(2N_128+4N_130+2N_131+2N_132+2N_133+2N_135+2N_136+2N_137+2N_139)
SO(6-N_12-2N_134-2N_135-2N_136-4N_137-6N_138-2N_139)
Sp(2N_134+2N_135+2N_136+2N_137+2N_138+2N_139)
SO(2-N_128-2N_130-2N_133-2N_135-2N_136-N_137-N_139)
Sp(2N_133)
Sp(2N_132)
SO(2N_135)
SO(N_128)
SO(N_12)
SO(1-N_134-N_137-N_138-N_139)
SO(2+2N_131-2N_133-2N_135-2N_136-N_137-2N_138-N_139)
SO(5-N_128-2N_130-2N_131-2N_132-2N_133-N_134-2N_135-2N_136-2N_137-N_138-2N_139)
SO(2N_134+N_137+N_139)
Sp(2N_131)
SO(1-N_134-N_138)
U(-N_12+N_139)
U(N_137+2N_138)
Sp(2N_136)
Sp(2N_130+2N_133+2N_135+2N_136+2N_137+2N_138+2N_139)
U(1-N_134-N_137-N_138-N_139)
Sp(2N_138)
```

if we also allow CP-chiral
(but SM non-chiral) exotics...

```
U(3) [fixed]
Sp(2) [fixed]
SO(2) [fixed]
U(1) [fixed]
Sp(2N_272+4N_281+2N_282+2N_289+2N_290+2N_291+2N_292+2N_293+2N_295+2N_296)
SO(6-N_24-N_279-2N_280-N_281-2N_283-2N_284+N_285-4N_293-2N_294-N_296-2N_297)
Sp(2N_297)
SO(1-N_80-N_272+N_279+N_280-N_281+N_282+N_283+N_284+N_285+N_286-N_287-N_288-N_289-N_290-N_291-N_292-N_293-N_296+N_297)
Sp(2N_296)
Sp(2N_295)
U(-N_13+N_287+N_288+2N_289+2N_290+2N_291+2N_292+2N_293+2N_294)
SO(1-N_279-N_280-N_281-N_282-N_283-N_284-N_285-N_286+N_287-N_288-N_289-N_290-N_291-N_292-N_293-N_294-N_296-N_297)
SO(N_272)
SO(N_24)
SO(-N_80+N_286)
U(2-N_282-N_283-N_284-2N_286-2N_289-2N_290-2N_291-2N_292-2N_293-2N_294-2N_297)
SO(2+N_279+2N_280+N_281+2N_282+2N_283+2N_284+N_285-N_287-N_288-2N_291+2N_292-2N_293-N_294-N_296)
SO(5-N_272-N_280-2N_281-N_282-N_283-N_284-N_289-N_290-N_291-N_292-N_293-2N_295-2N_296-N_297)
SO(1-N_279-N_280-N_281-N_282-N_283-N_284-N_285-N_286-N_289-N_290-N_291-N_292-N_293-N_294-N_296-N_297)
SO(2N_289+N_294+2N_297)
SO(-N_28+N_279+N_281+N_285+N_296)
SO(N_286+N_294)
SO(N_28)
U(-N_13+2N_282)
U(-N_24+N_285)
U(N_284)
U(N_282+N_283)
U(N_279+N_280+N_281+N_282+N_283+N_284+2N_293+N_294+N_296)
U(N_80)
U(N_13)
Sp(2N_288)
Sp(2N_281+2N_293+2N_296)
Sp(2N_290+2N_292)
Sp(2N_292)
Sp(2N_291)
Sp(2N_290+2N_291)
U(N_280+2N_283)
U(N_280+2N_284)
U(1-N_28-N_289-N_290-N_291-N_292-N_293-N_294-N_297)
Sp(2N_293)
```

17 equations, 397 variables

(obvious splittings $U(n+m) \longrightarrow U(m) \times U(n)$ not counted)

Just the SM gauge group

```
          Standard model type: 6
Number of factors in hidden gauge group: 0
 Gauge group: U(3) x Sp(2) x U(1) x U(1)

      Number of representations: 19

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

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

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

Summary

Examples exist:

- Without mirrors
- Without adjoints
- Without (anti)-symmetric tensors
- Without Observable-Hidden matter
- Without hidden sector

Summary

Examples exist:

- Without mirrors
- Without adjoints
- Without (anti)-symmetric tensors
- Without Observable-Hidden matter
- Without hidden sector

....but to get all this simultaneously requires more statistics

But why do we require “clean” spectra?

Presently known standard model string spectra:
3 chiral families + non-chiral mess

We seem to have the following options:

But why do we require "clean" spectra?

Presently known standard model string spectra:
3 chiral families + non-chiral mess

We seem to have the following options:

- Generically non-chiral states are absent
  and our current set of examples is too special.

But why do we require "clean" spectra?

Presently known standard model string spectra:
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- Generically non-chiral states are present
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- Generically non-chiral states are present
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- Generically non-chiral states are present,
  but they remain light and are ruled out anthropically.

But why do we require "clean" spectra?

Presently known standard model string spectra:
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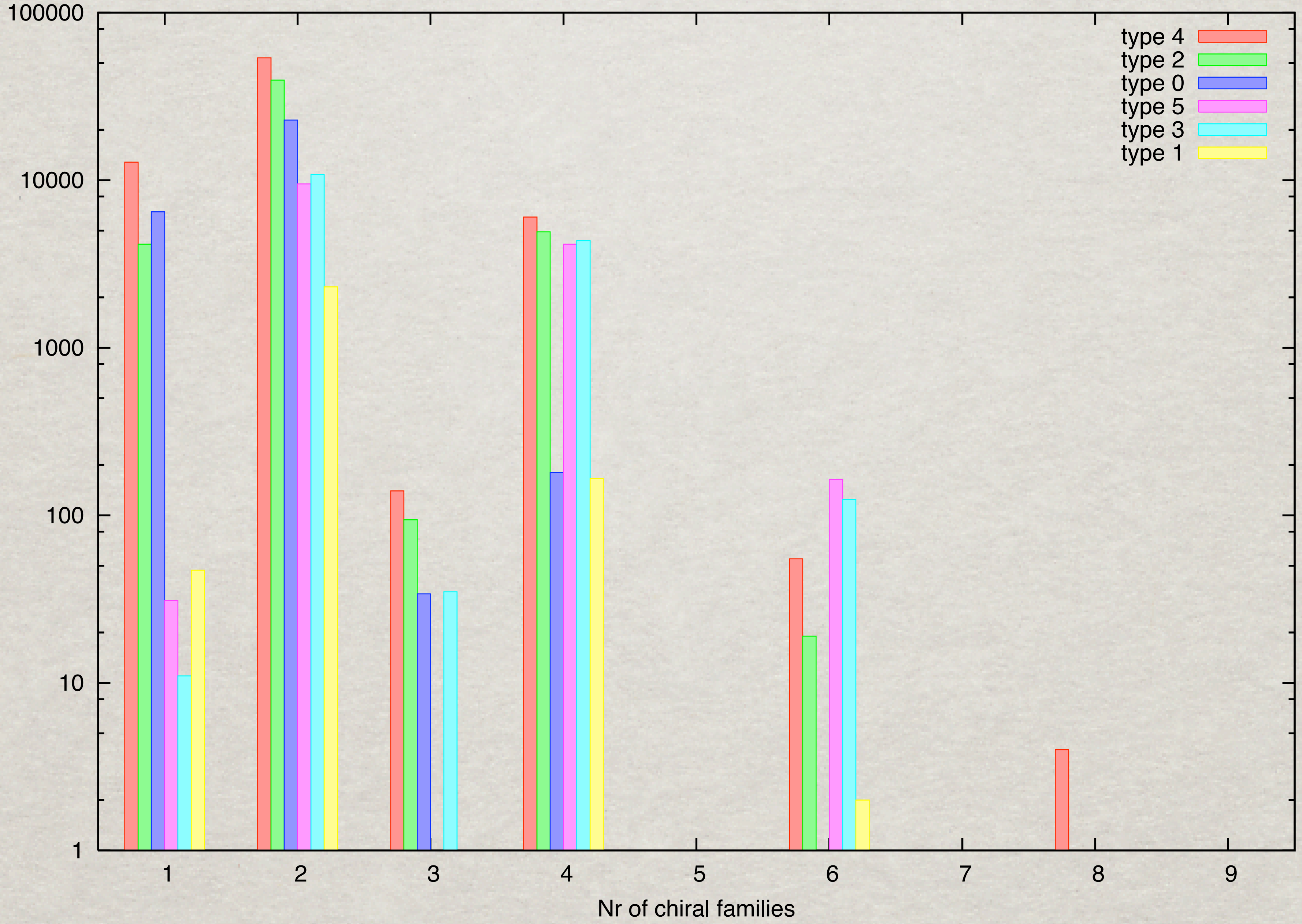
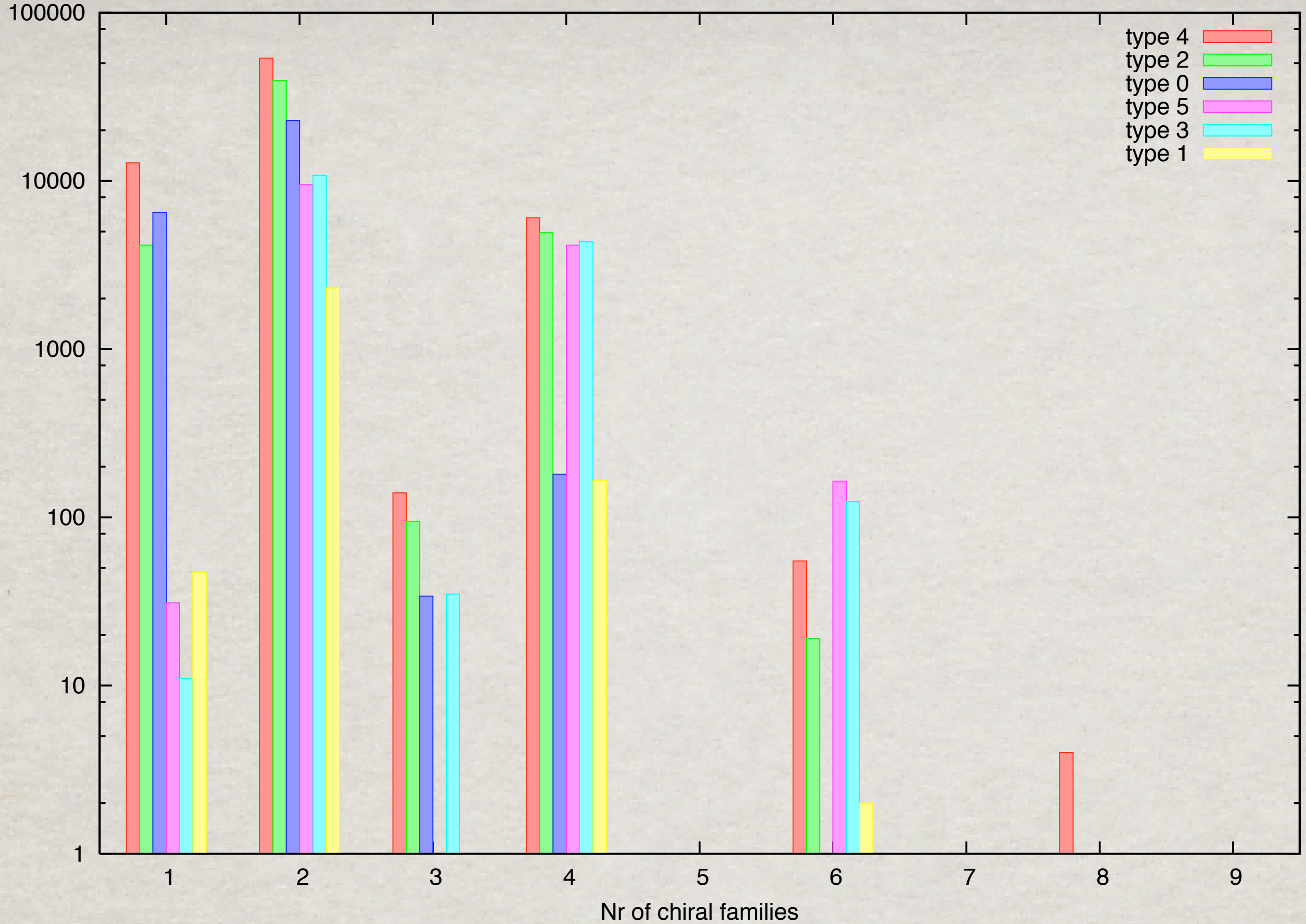
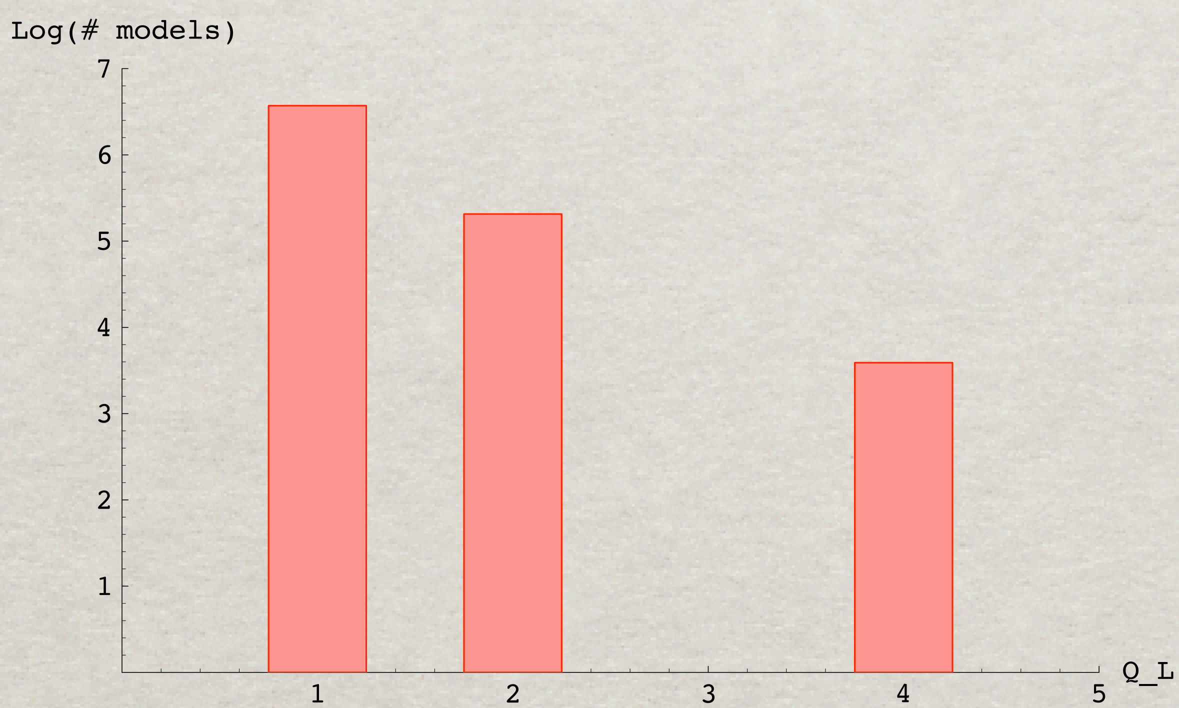
- Generically non-chiral states are absent and our current set of examples is too special.
- Generically non-chiral states are present and will be seen at LHC (or beyond).
- Generically non-chiral states are present, but they remain light and are ruled out anthropically.
- We are Andorrans.



100000
10000
1000
100
10
1
1
2
3
4
5
6
7
8
9
Nr of chiral families
type 4
type 2
type 0
type 5
type 3
type 1



Dijkstra et. al.
hep-th/0411129



(a) MSSM models

Gmeiner et. al.
hep-th/0510170

SM-realizations (2005-2006)

Chan-Paton gauge group

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

Embedding of Y:

$$Y = \alpha Q_a + \beta Q_b + \gamma Q_c + \delta Q_d + W_c + W_d$$

Q: Brane charges (for unitary branes)

W: Traceless generators

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

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	Antoniadis, Kiritsis, Tomaras
-1/2, 3/2	
any	Trinification ($x = 1/3$) (orientable)

Statistics

Value of x	Total
0	21303612
1/2	124006839*
1	12912
-1/2, 3/2	0
any	1250080

*Previous search: 45051902

Terminology

- **Bottom-Up configuration:**
  Any hypothetical brane configuration that yields 3 chiral standard model families
- **Top-Down configuration:**
  Any such configuration realized with boundary states of Gepner models
- **String Vacuum:**
  Top-down configuration with tadpole cancellation (with or without hidden sector)

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	1056708	31
1/2	UUUU	C	C	10717308	156	428799	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	13310	2
1/2	UUUR	C,D	C,D	34	5	3888	1
1/2	UUUR	C	C,D	185520	221	2560681	31
1/2	USUU	C,D	C,D	72	7	6473	2
1/2	USUU	C	C,D	153436	283	3420508	33
1/2	USUU	C	C	10441784	125	4464095	27
1/2	USUU	C	F	184	0	0	0

Continued on next page

≤ 3 CP-chiral mirror pairs

≤ 3 CP-chiral Susy Higgs pairs

≤ 6 CP-chiral singlets (right-handed neutrinos)

x	Config.	stack **c**	stack **d**	Bottom-up	Top-down	Occurrences	Solved
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
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	54102	2
0	UUUU	D	C,D	14	2	4368	0
0	UUUU	C	C	2890537	127	666631	9
0	UUUU	C	D	36304	16	6687	0
0	UUU	C	-	222	2	15440	1
0	UUUR	C,D	C	3702	39	171485	4
0	UUUR	C	C	5161452	289	4467147	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	10714	0
1	UUUU	D	C,D	42	3	3328	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

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
...						
34	869428(1096682)	246	$U(3) \times Sp(2) \times U(1) \times U(1)$	VVVV	1/2	Y!
153	115466	335	$U(4) \times U(2) \times U(2)$	VVV	1/2	Y
225	71328	167	$U(3) \times U(3) \times U(3)$	VVV	1/3	

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
...						
34	869428(1096682)	246	$U(3) \times Sp(2) \times U(1) \times U(1)$	VVVV	1/2	Y!
153	115466	335	$U(4) \times U(2) \times U(2)$	VVV	1/2	Y
225	71328	167	$U(3) \times U(3) \times U(3)$	VVV	1/3	

SU(5)

```
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)!

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