Sight-seeing in the Landscape

Bert Schellekens
NIKHEF

Topics

- Landscape remarks
- RCFT orientifolds
- Summary of 2004 results*
- Preliminary results from the 2005 run**

*With L. Huiszoon and T. Dijkstra

**With P. Anastasopoulos, T. Dijkstra, E Kiritsis, to appear

1984-2005: a slow revolution

1984-2005: a slow revolution

1984: Hope for deriving Standard Model from string theory

1984-2005: a slow revolution

1984: Hope for deriving Standard Model from string theory

.

.

.

1984-2005: a slow revolution

1984: Hope for deriving Standard Model from string theory

.

.

.

2005: Evidence for a huge “discretuum” or “landscape”

1984-2005: a slow revolution

1984: Hope for deriving Standard Model from string theory

.

.

.

2005: Evidence for a huge "discretuum" or "landscape"

A unique theory with a very large number of ground states:
The ideal setting for the anthropic principle

Landscape Advertisement

Landscape Advertisement

- A success for String Theory

Landscape Advertisement

- A success for String Theory
- Evidence for its correctness

Landscape Advertisement

- A success for String Theory
- Evidence for its correctness
- An answer to Einstein's question
  "Did the creator of our Universe have any choice?"

Landscape Advertisement

- A success for String Theory
- Evidence for its correctness
- An answer to Einstein's question
  "Did the creator of our Universe have any choice?"
- The big paradigm shift in physics

Landscape Advertisement

- A success for String Theory
- Evidence for its correctness
- An answer to Einstein's question
  "Did the creator of our Universe have any choice?"
- The big paradigm shift in physics
- Fits nicely with other controversial discoveries
  (Heliocentric model, Evolution, ...)

Landscape Advertisement

- A success for String Theory
- Evidence for its correctness
- An answer to Einstein's question
  "Did the creator of our Universe have any choice?"
- The big paradigm shift in physics
- Fits nicely with other controversial discoveries
  (Heliocentric model, Evolution, ...)

... if string theory is correct...

The Landscape "Drake" equation

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

Number of vacua

SM Probability

Cosmological Constant

The Landscape “Drake” equation

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

Number of vacua

SM Probability

Cosmological
Constant

Not likely to yield 1!

The Landscape “Drake” equation

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

Number of vacua

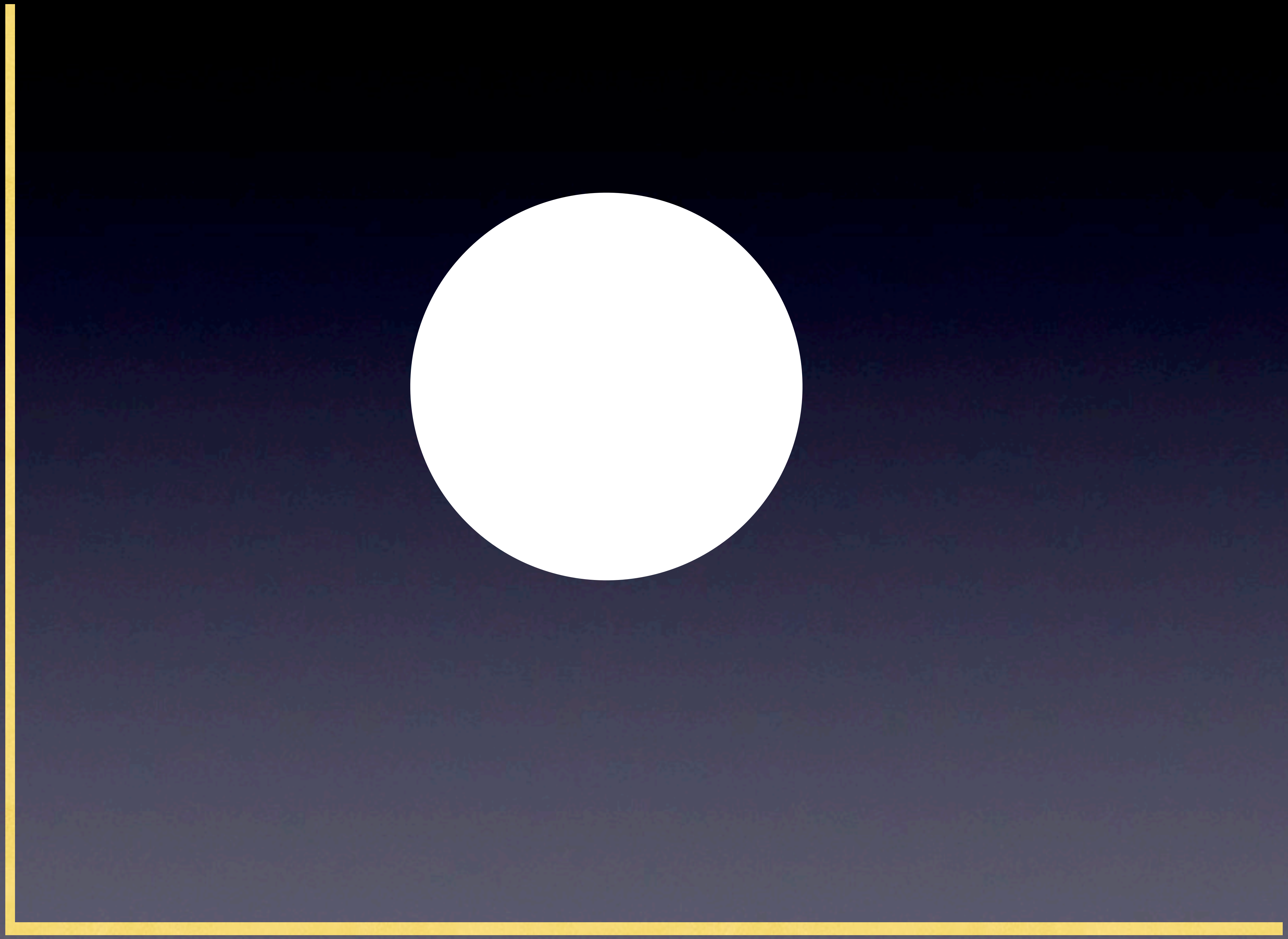
SM Probability

Cosmological Constant

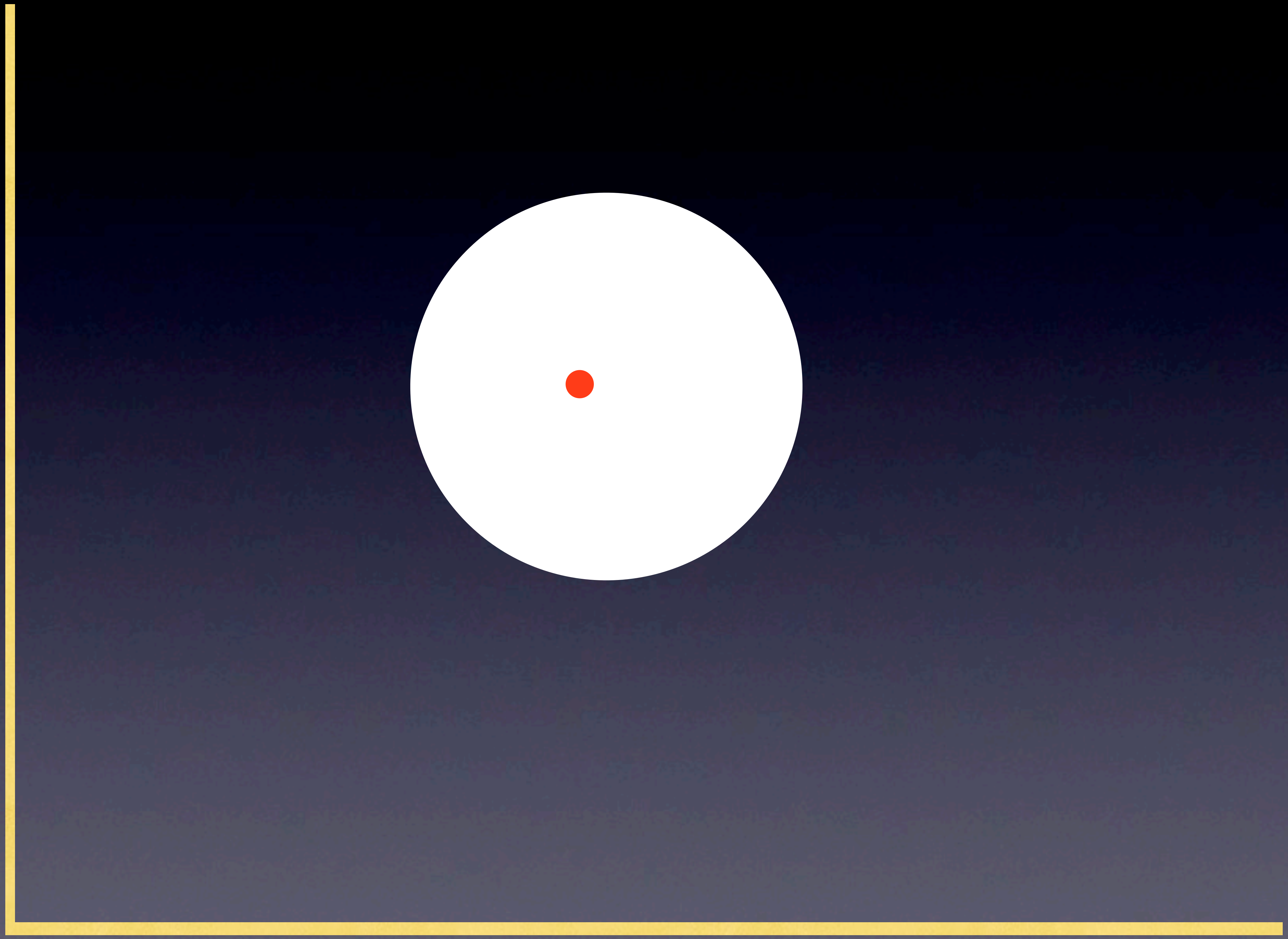
Not likely to yield 1!

Not likely to yield 0, either?

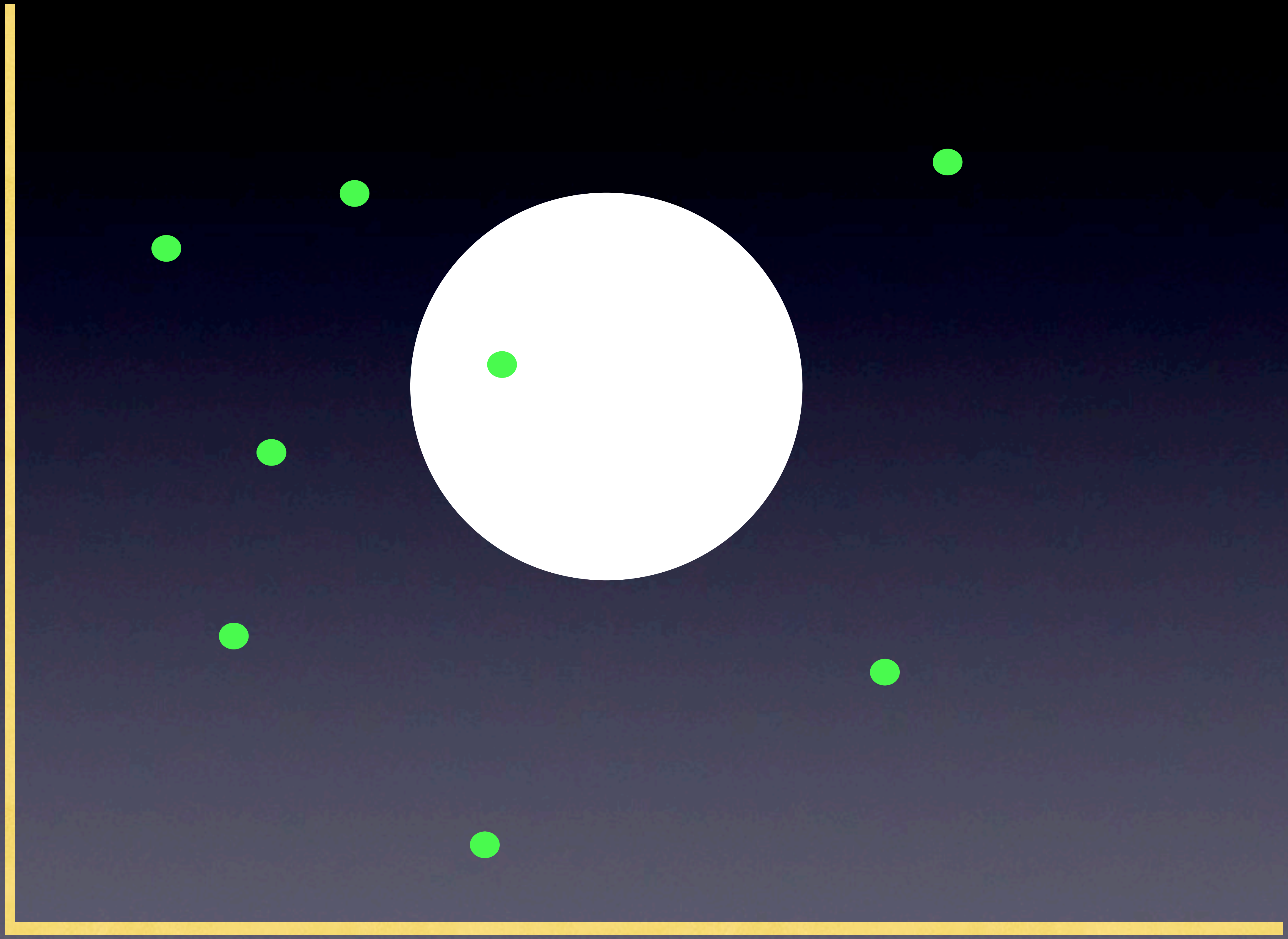
Shifting goals



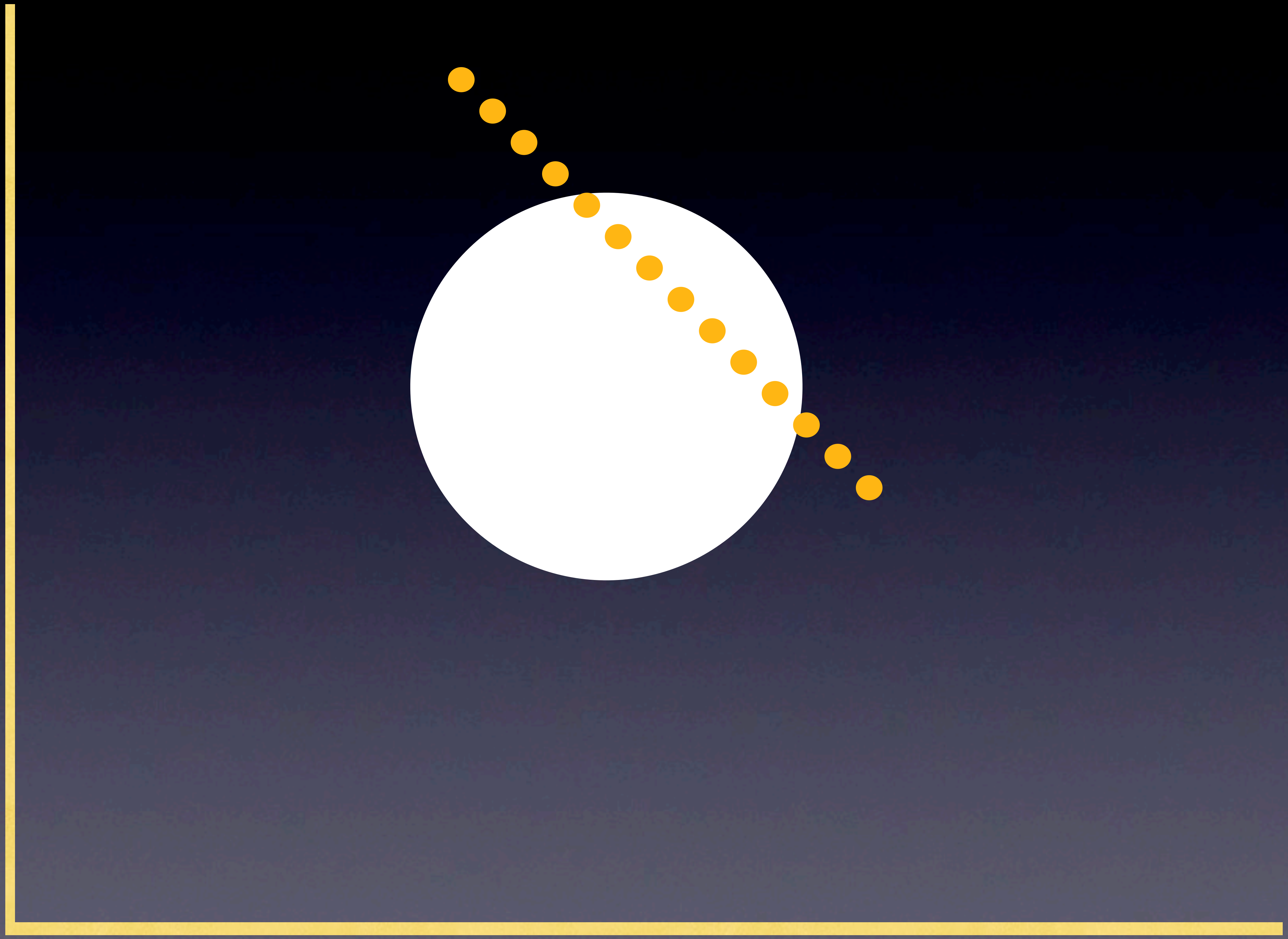
Shifting goals Find THE vacuum of string theory



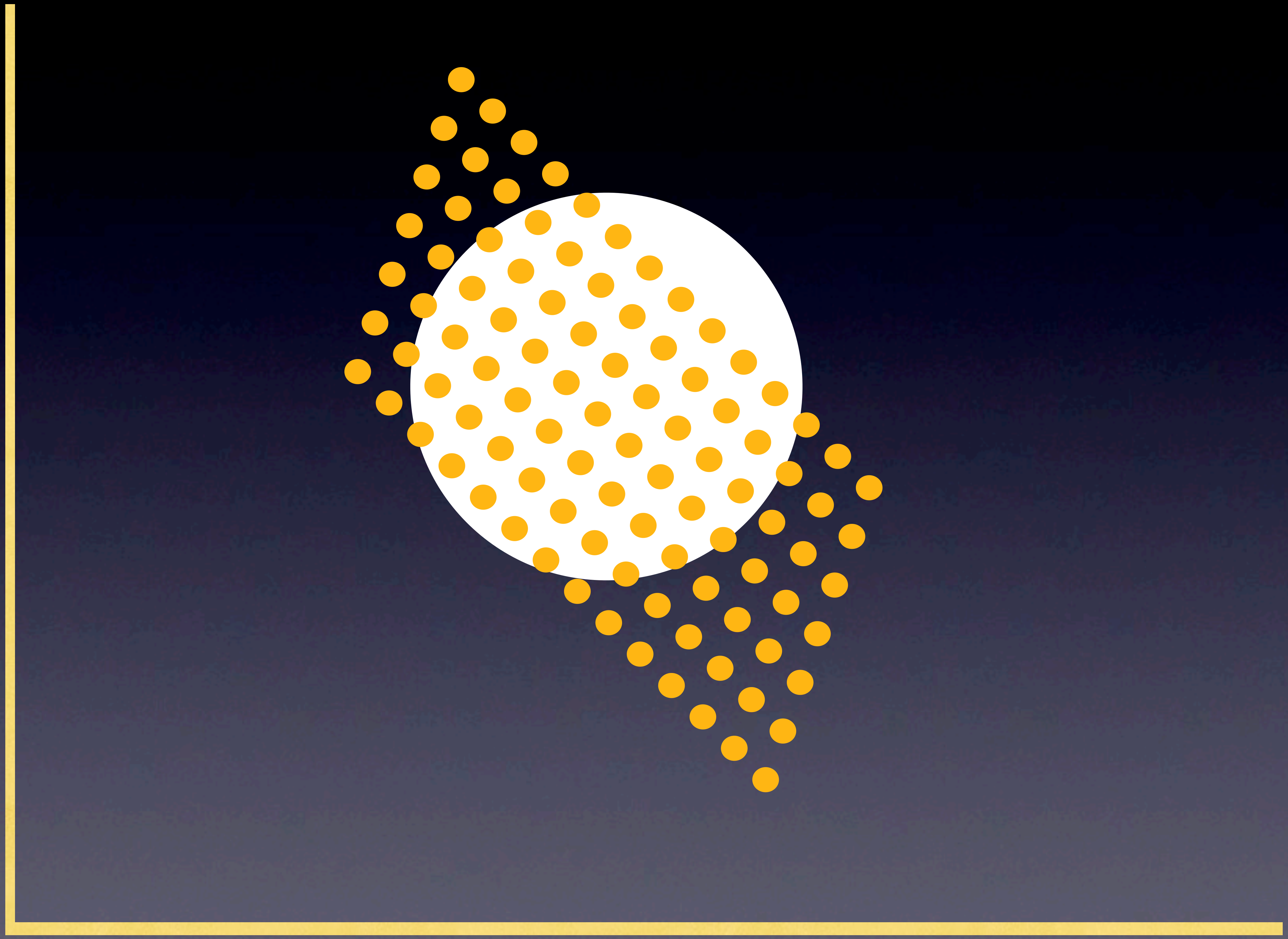
Shifting goals Find THE SM vacuum of string theory



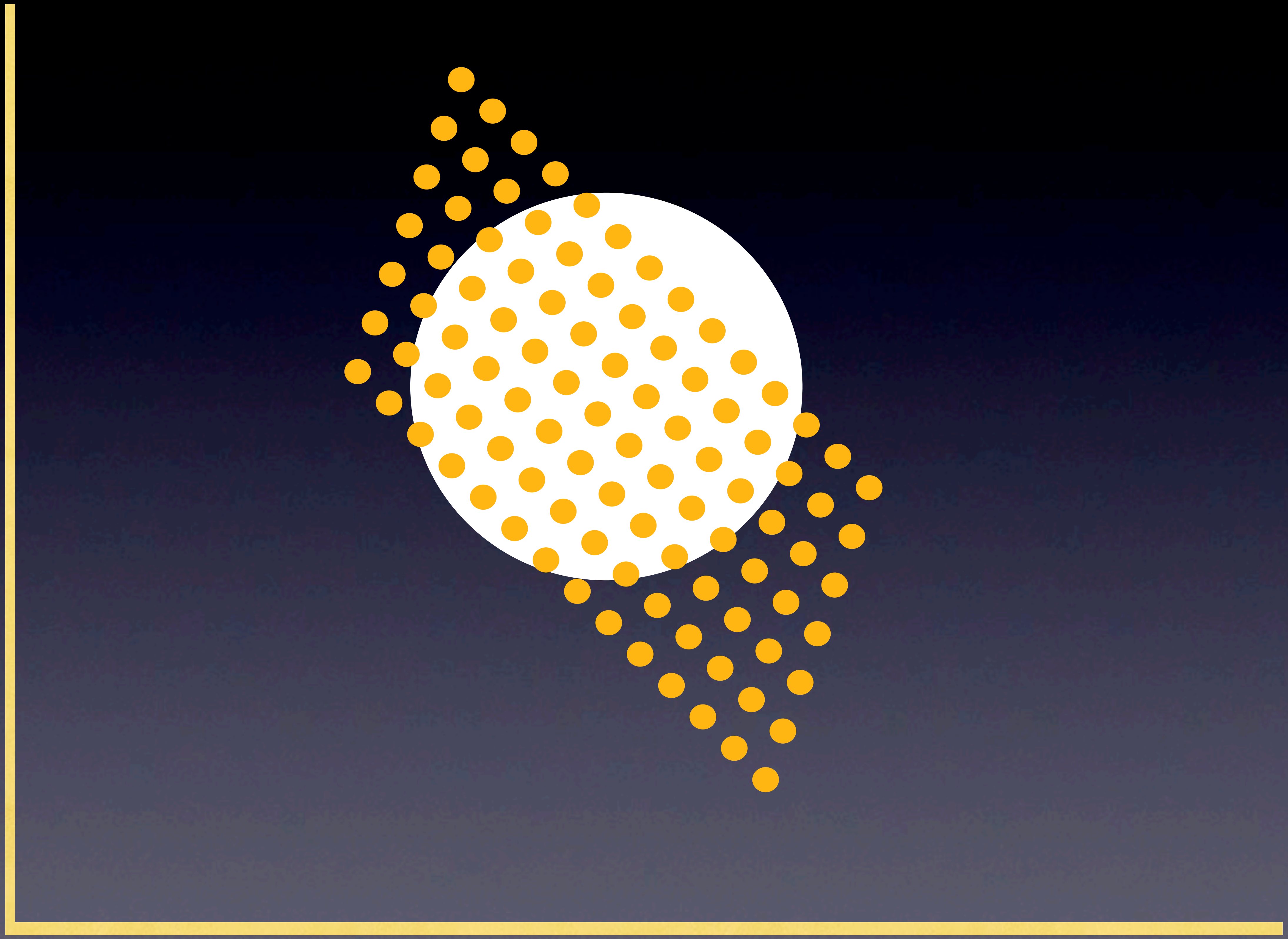
Shifting goals



Shifting goals



Shifting goals Find A SM vacuum of string theory



RCFT Orientifolds

Data:

- 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

Closed strings:

CY compactification (Heterotic, type-II)

With boundary and crosscap states:

CY orientifold with wrapped D-branes

Formalism can be applied to:

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

Strong points:

- Scan parts of the landscape that are otherwise unaccessible
- Conceptually very simple

Weak points:

- More data needed for couplings (not yet available)
- Fixed point in moduli space
- Moduli stabilization?

→ ***Especially useful as a scanning tool***

Gepner Models

$$c = \frac{3k}{k+2}, \quad k = 1, \ldots, \infty$$

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 worldsheet Susy

Simple current extension with “alignment currents”

- Impose space-time Susy

Simple current extension with gravitino vertex operator
(can be relaxed to allow broken susy)

- Surviving simple currents used to build MIPFs and define orientifold projection

For symmetric MIPFs: Type IIB

- Use complete set of boundaries that respect all bulk symmetries

Simple current MIPFs are specified by

- A group $\mathcal{H}$ that consists of simple currents[3]
  $\mathcal{H} = \prod_\alpha \mathbb{Z}_{N_\alpha}$.
  The generator of the $\mathbb{Z}_{N_\alpha}$ will be denoted as J_α;
  Then $J = \prod_\alpha J_\alpha^{n_\alpha}$
- A symmetric matrix $X_{\alpha\beta}$ that obeys

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

  Here $Q_J(a) = h(a) + h(J) - h(Ja)$, h is the conformal weight.

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

$$\begin{aligned} j &= Li \\ Q_M(i) + X(M, L) &= 0 \text{ mod } 1 \end{aligned}$$

for all $M \in \mathcal{H}$. ($X(J, J') = \prod_{\alpha,\beta} n_\alpha m_\beta X_{\alpha\beta}$)

---

[3] Satisfying Order x Weight = Integer

Orientifold specification

- A *Klein bottle current* K. This can be any simple current that obeys

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

- A set of phases $\beta_K(J)$ for all $J \in \mathcal{H}$ that satisfy

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

  with $\beta_K(L) = e^{i\pi(h_{KL}-h_K)}\eta(K,L)$, $\eta(K,L) = \pm 1$.
  if $\mathcal{H}$ has N even factors, there are 2^N free signs in the solution of this equation.
  These are called the $crosscap\ signs$

— This includes all know RCFT orientifold choices.
— Not all choices are inequivalent.

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

Cardy; Sagnotti, Pradisi, Stanev, ...; Fuchs, Schweigert;
Fuchs, Huiszoon, Schellekens, Schweigert, Walcher (2000)

Partition functions

— Klein bottle:

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

— Unoriented 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:

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

Here $g^{\Omega,m}$ is the *Ishibashi metric*

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

Closed string partition function

$$\frac{1}{2}\left[\sum_{ij}\chi_i(\tau)Z_{ij}\chi_i(\bar{\tau})+\sum_i K_i\chi_i(2\tau)\right]$$

Open string partition function

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

Subject to tadpole cancellation

$$\sum_b N_bR_{b(m,J)}=4\eta_mU_{(m,J)}\ ,$$

Model Building

- Find set of labels a,b,c,d,... that match the required spectrum
  (done systematically)

- If needed, search for "hidden branes" to solve tadpoles
  (systematic search impossible)

In both steps, we allow NON-chiral "exotic" matter

Exotic: anything except quarks, leptons, Higgs

Orientifold model building

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

Blumenhagen, Wisskirchen (1998)
Gepner Orientifolds

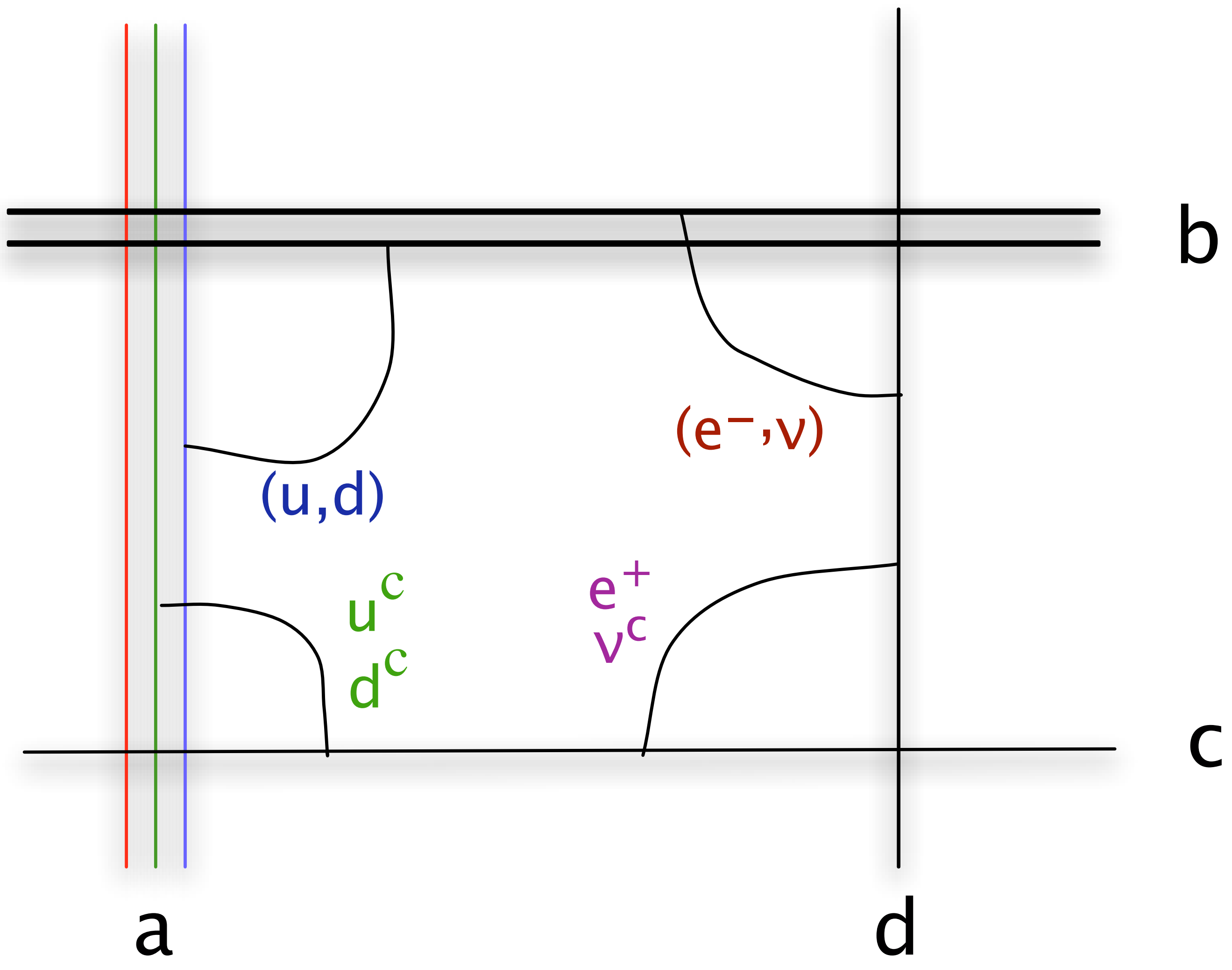
Aldazabal, Franco, Ibanez, Rabadan, Uranga (2000)
Blumenhagen, Görlich,Körs,Lüst (2000)
Ibanez, Marchesano, Rabadan (2001)
Non-supersymmetric SM-Spectra with RR tadpole cancellation

Cvetic, Shiu, Uranga (2001)
Cvetic, Papadimitriou (2003)
Supersymmetric SM-Spectra with chiral exotics

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

Brunner, Hori, Hosomichi, Walcher (2004)
Chiral spectrum from Gepner Orientifolds

“The Spanish Quiver”



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

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)*

- 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 ~ 10^{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, but the not hidden sector)
- No solutions for C-invariant
- No solutions for orbifolds
- No solutions for quintic
- More solutions for more "rational" combinations

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

Global Anomalies[*]

[*]B. Gato-Rivera and A.N. Schellekens, hep-th/0510074

Global anomalies in the CP group

Odd number of vectors in a symplectic factor
(including doublets of SU(2)):

Occurs in 1015 out of 270058 spectra
and in 2075 out of 845513 symplectic factors

Global Anomalies on Probe Branes

Local anomaly cancellation from tadpole cancellation:

$$\sum_{i,a} N_a[(\chi_i)_{0,L} - (\chi_i)_{0,R}](A^i_{ab} + 4M^i_b) = 0$$

for any label b.

Global anomaly cancellation for symplectic boundaries b

$$\sum_{i,a} N_a A^i_{ab}(\chi_i)_{0,L} = 0 \bmod 2 \ ,$$

Requires re-generation of old models

Seems to lead to a huge number of restrictions

Example:

Tensor (1,6,46,46), MIPF 10

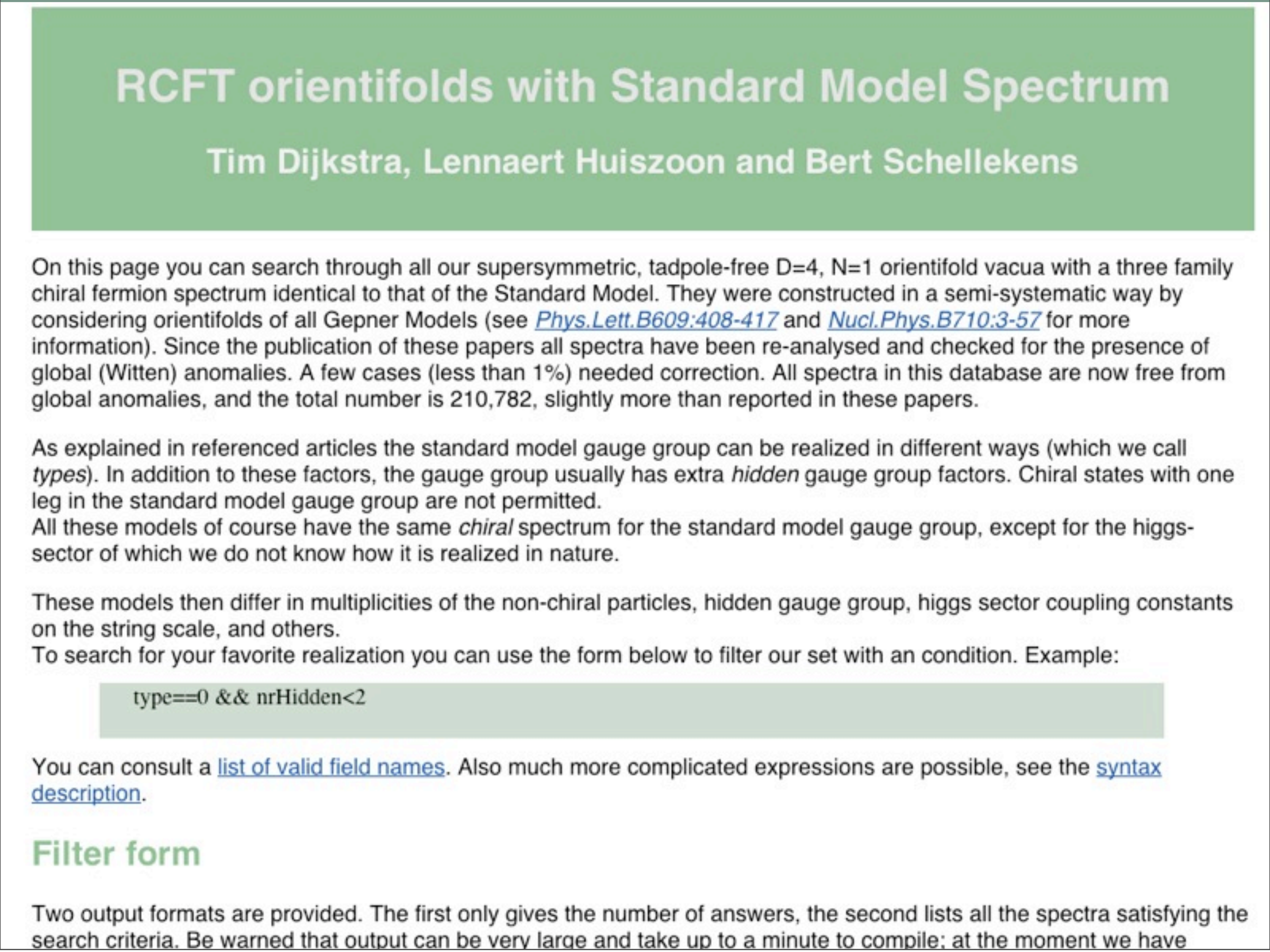
Tadpole conditions: 24
Independent: 10
Local anomalies mod 2: 2
All tadpole conditions mod 2: 10
From symplectic probe branes: 155
Combined: 157 conditions, 10 already satisfied

Result:

Previously: 19644 solutions
Probe brane constraint violations: 59 (-8)

Conclusions on Global Anomalies

- Very important in principle
- Almost irrelevant in practice (only occur in 25 out of 333 MIPFs with solutions)
- Relation with K-theory charges to be understood
- Are probe branes sufficient?



RCFT orientifolds with Standard Model Spectrum

Tim Dijkstra, Lennaert Huiszoon and Bert Schellekens

On this page you can search through all our supersymmetric, tadpole-free D=4, N=1 orientifold vacua with a three family chiral fermion spectrum identical to that of the Standard Model. They were constructed in a semi-systematic way by considering orientifolds of all Gepner Models (see *Phys.Lett.B609:408-417* and *Nucl.Phys.B710:3-57* for more information). Since the publication of these papers all spectra have been re-analysed and checked for the presence of global (Witten) anomalies. A few cases (less than 1%) needed correction. All spectra in this database are now free from global anomalies, and the total number is 210,782, slightly more than reported in these papers.

As explained in referenced articles the standard model gauge group can be realized in different ways (which we call *types*). In addition to these factors, the gauge group usually has extra *hidden* gauge group factors. Chiral states with one leg in the standard model gauge group are not permitted.
All these models of course have the same *chiral* spectrum for the standard model gauge group, except for the higgs-sector of which we do not know how it is realized in nature.

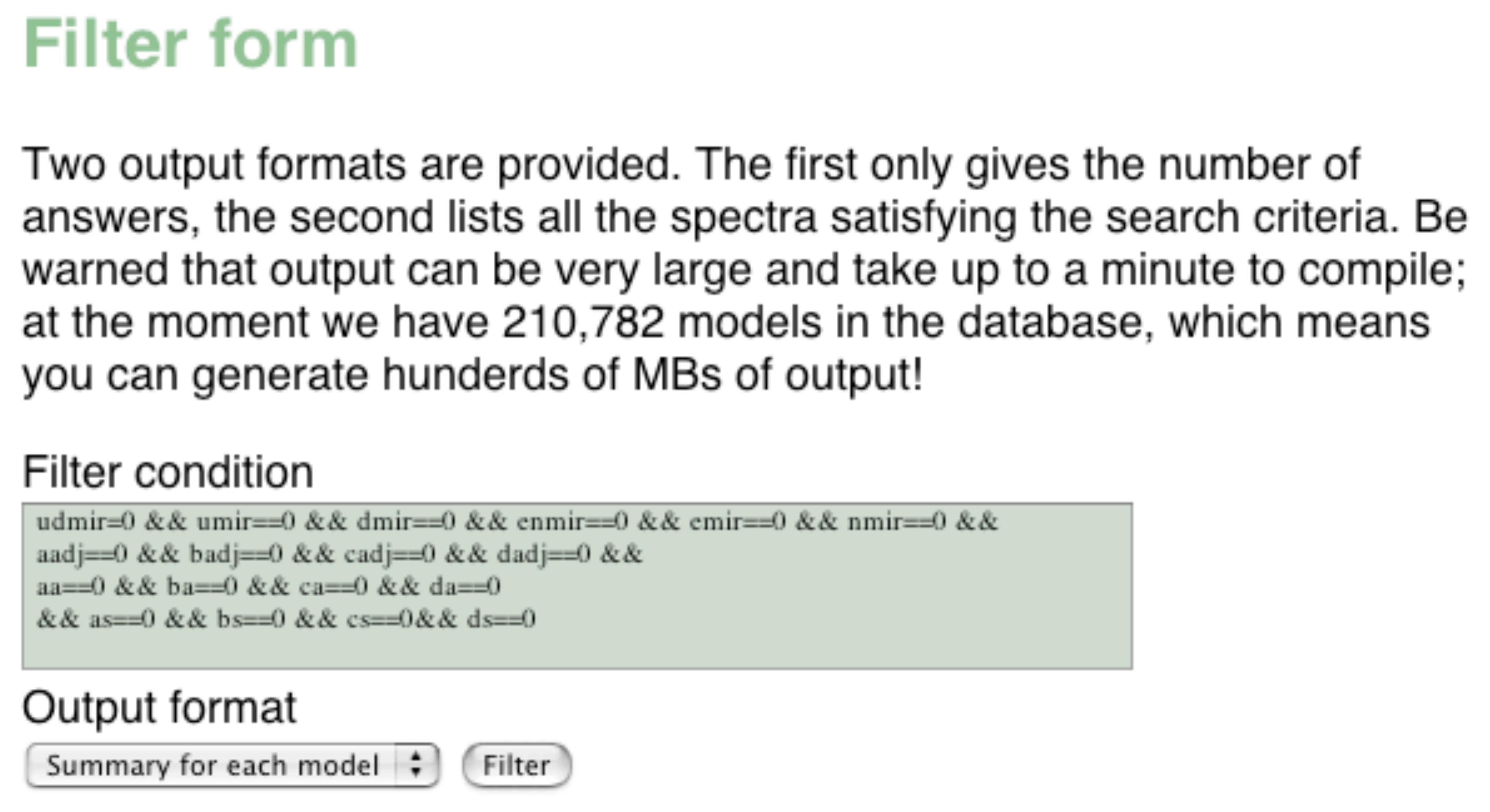
These models then differ in multiplicities of the non-chiral particles, hidden gauge group, higgs sector coupling constants on the string scale, and others.
To search for your favorite realization you can use the form below to filter our set with an condition. Example:

```
type==0 && nrHidden<2
```

You can consult a list of valid field names. Also much more complicated expressions are possible, see the syntax description.

Filter form

Two output formats are provided. The first only gives the number of answers, the second lists all the spectra satisfying the search criteria. Be warned that output can be very large and take up to a minute to compile; at the moment we have



Filter form

Two output formats are provided. The first only gives the number of answers, the second lists all the spectra satisfying the search criteria. Be warned that output can be very large and take up to a minute to compile; at the moment we have 210,782 models in the database, which means you can generate hunderds of MBs of output!

Filter condition

```
udmir=0 && umir==0 && dmir==0 && enmir==0 && emir==0 && nmir==0 &&
aadj==0 && badj==0 && cadj==0 && dadj==0 &&
aa==0 && ba==0 && ca==0 && da==0
&& as==0 && bs==0 && cs==0&& ds==0
```

Output format

```
               Tensor 44622, MIPF 8, Orientifold 0
       Klein bottle current: 12  Crosscap signs:   (-1,-1)
             Standard model boundaries: (89,44,45,2)
           Dilaton couplings to SM branes and O-plane:
   0.0070459    0.0122039    0.0122039    0.0070459    0.1073896
                alpha_3/alpha_2 =       0.8660246
                sin^2(theta_w) =       0.3610368
                    Total number of branes: 9
 CP multiplicities: 89:3 91:3 44:2 45:2 2:1 3:1 400:6 38:4 349:2
                     Standard model type: 4
           Number of factors in hidden gauge group: 3
Gauge group: U(3) x Sp(2) x Sp(2) x U(1) x Sp(6) x Sp(4) x Sp(2)

                  Number of representations: 19

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

                            Summary:
             Higgs: (2,1/2)+(2*,1/2)              2
      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  0
         Non-SM (a,b,c,d)                    12  6  6  4
      Hidden (Total dimension)            162 (chirality 0)

                          Closed sector
                             h11-=2
                            h11+=31
                             h21=9
                      Vector multiplets: 2
                     Chiral multiplets: 40
```

```
                Number of representations: 19

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

                         Summary:
         Higgs: (2,1/2)+(2*,1/2)                2
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  0
   Non-SM (a,b,c,d)                    12  6  6  4
Hidden (Total dimension)             162 (chirality 0)
```

$\sin^2(\theta_w) = .3610368$ $\frac{\alpha_3}{\alpha_2} = .8660246$

```
         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

          3 x  (V ,V ,0 ,0 ) chirality 3
          3 x  (V ,0 ,V ,0 ) chirality -3
          3 x  (V ,0 ,V*,0 ) chirality -3
          9 x  (0 ,V ,0 ,V ) chirality 3
          5 x  (0 ,0 ,V ,V ) chirality -3
          3 x  (0 ,0 ,V ,V*) chirality
          2 x  (V ,0 ,0 ,V )
         10 x  (0 ,V ,V ,0 )
          2 x  (Ad,0 ,0 ,0 )
          2 x  (A ,0 ,0 ,0 )
```

•••••••

```
               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

             3 x  (V ,V ,0 ,0 ) chirality 3
             3 x  (V ,0 ,V ,0 ) chirality -3
             3 x  (V ,0 ,V*,0 ) chirality -3
             9 x  (0 ,V ,0 ,V ) chirality 3
             5 x  (0 ,0 ,V ,V ) chirality -3
             3 x  (0 ,0 ,V ,V*) chirality
             2 x  (V ,0 ,0 ,V )
            10 x  (0 ,V ,V ,0 )
             2 x  (Ad,0 ,0 ,0 )
             2 x  (A ,0 ,0 ,0 )
```

•••••••

```
     Higgs:   (2,1/2)+  2*,1/2)              5
Non-chiral SM matter   (Q,U,D,L,E,N):  0  0  0  3  1  0
  Adjoints:                            2  0  9  3
  Symmetric Tensors:                   1 10  7  3
  Anti-Symmetric Tensors:              1 14  3  2
    Lepto-quarks:   3,-1/3),  3,2/3)      1  0
 Non-SM   a,b,c,d)                      0  0  0  0
 Hidden   Total dimension)              0   (chirality 0)
```

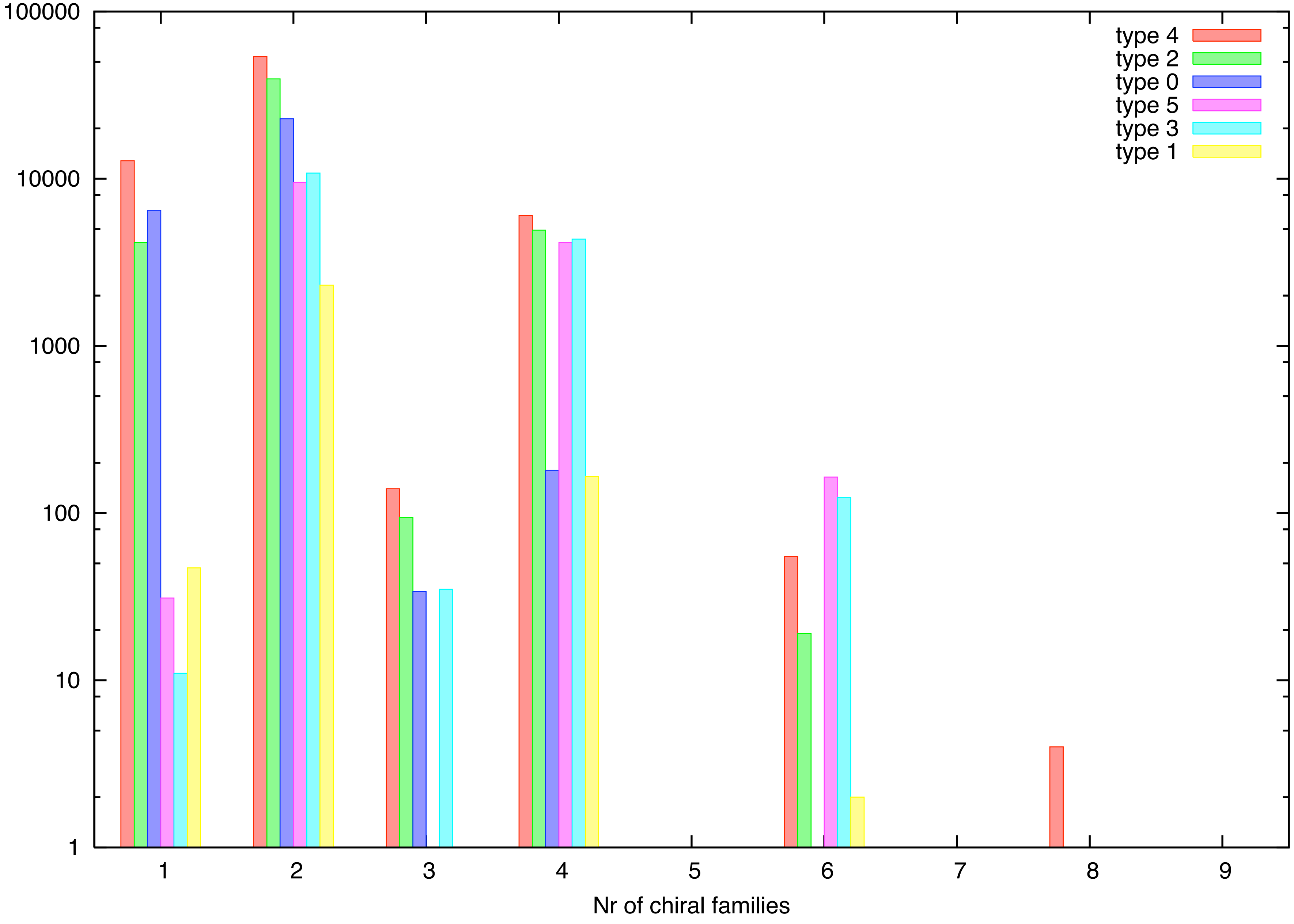
```
          Standard model type: 6
Number of factors in hidden gauge group: 0
   Gauge group: U(3) x Sp(2) x U(1) x U(1)

        Number of representations: 19

               3 x  (V ,V ,0 ,0 ) chirality 3
               3 x  (V ,0 ,V ,0 ) chirality -3
               3 x  (V ,0 ,V*,0 ) chirality -3
               9 x  (0 ,V ,0 ,V ) chirality 3
               5 x  (0 ,0 ,V ,V ) chirality -3
               3 x  (0 ,0 ,V ,V*) chirality
               2 x  (V ,0 ,0 ,V )
              10 x  (0 ,V ,V ,0 )
               2 x  (Ad,0 ,0 ,0 )
               2 x  (A ,0 ,0 ,0 )
```

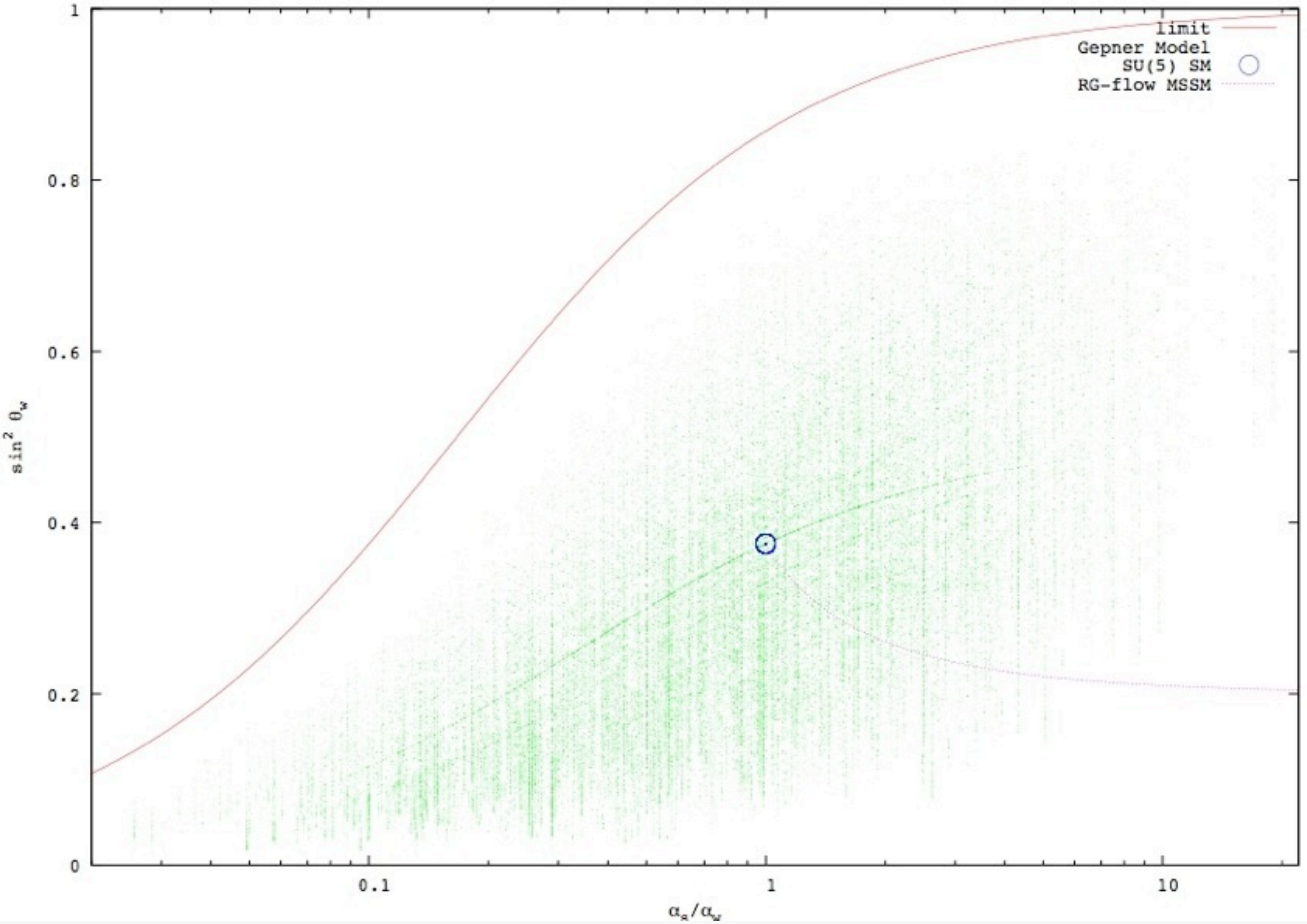
••••••••

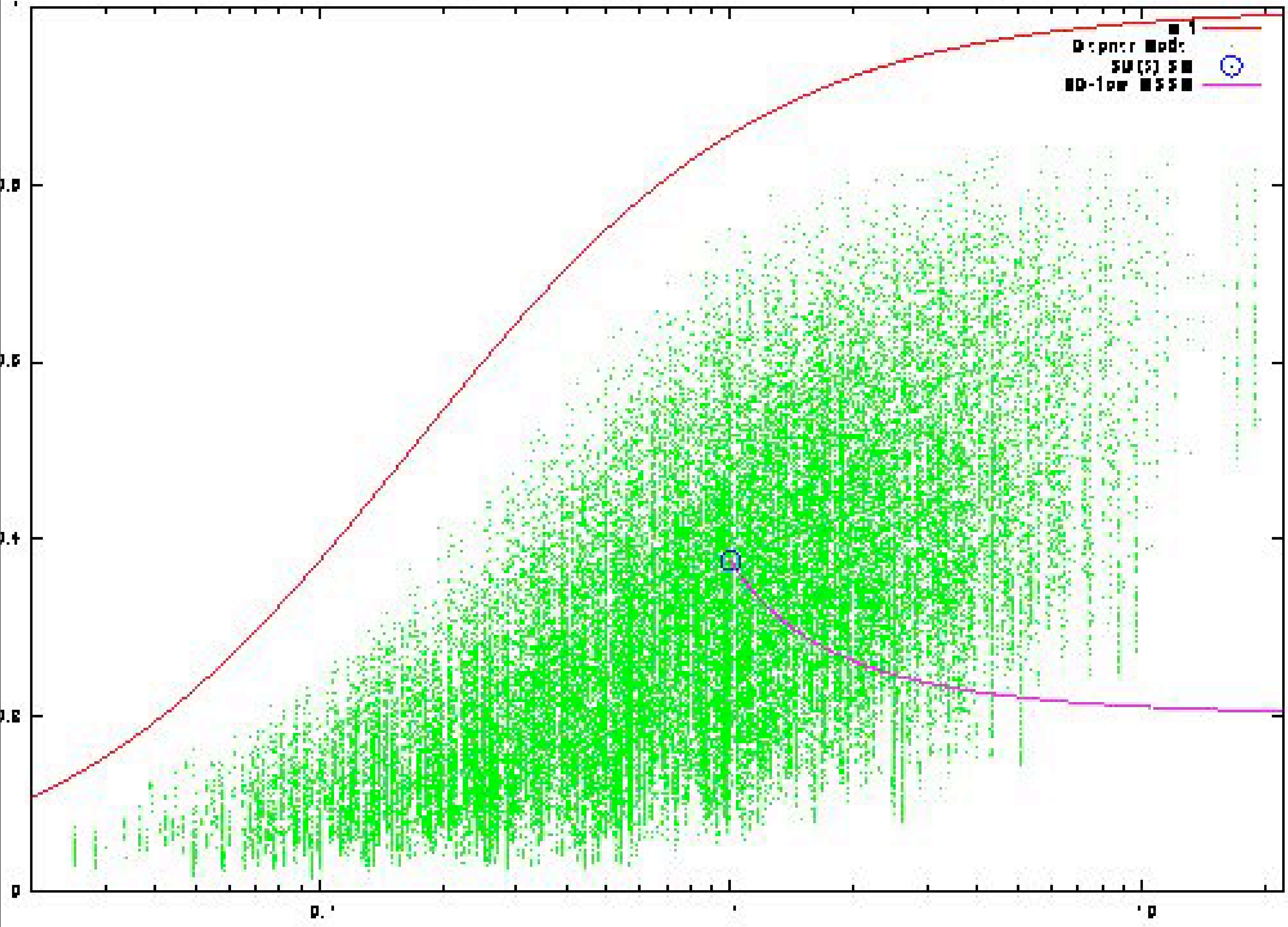
```
     Higgs:   (2,1/2)+  2*,1/2)              5
Non-chiral SM matter   (Q,U,D,L,E,N):  0  0  0  3  1  0
  Adjoints:                            2  0  9  3
  Symmetric Tensors:                   1 10  7  3
  Anti-Symmetric Tensors:              1 14  3  2
    Lepto-quarks:   3,-1/3),  3,2/3)       1  0
 Non-SM   a,b,c,d)                      0  0  0  0
 Hidden   Total dimension)              0   (chirality 0)
```

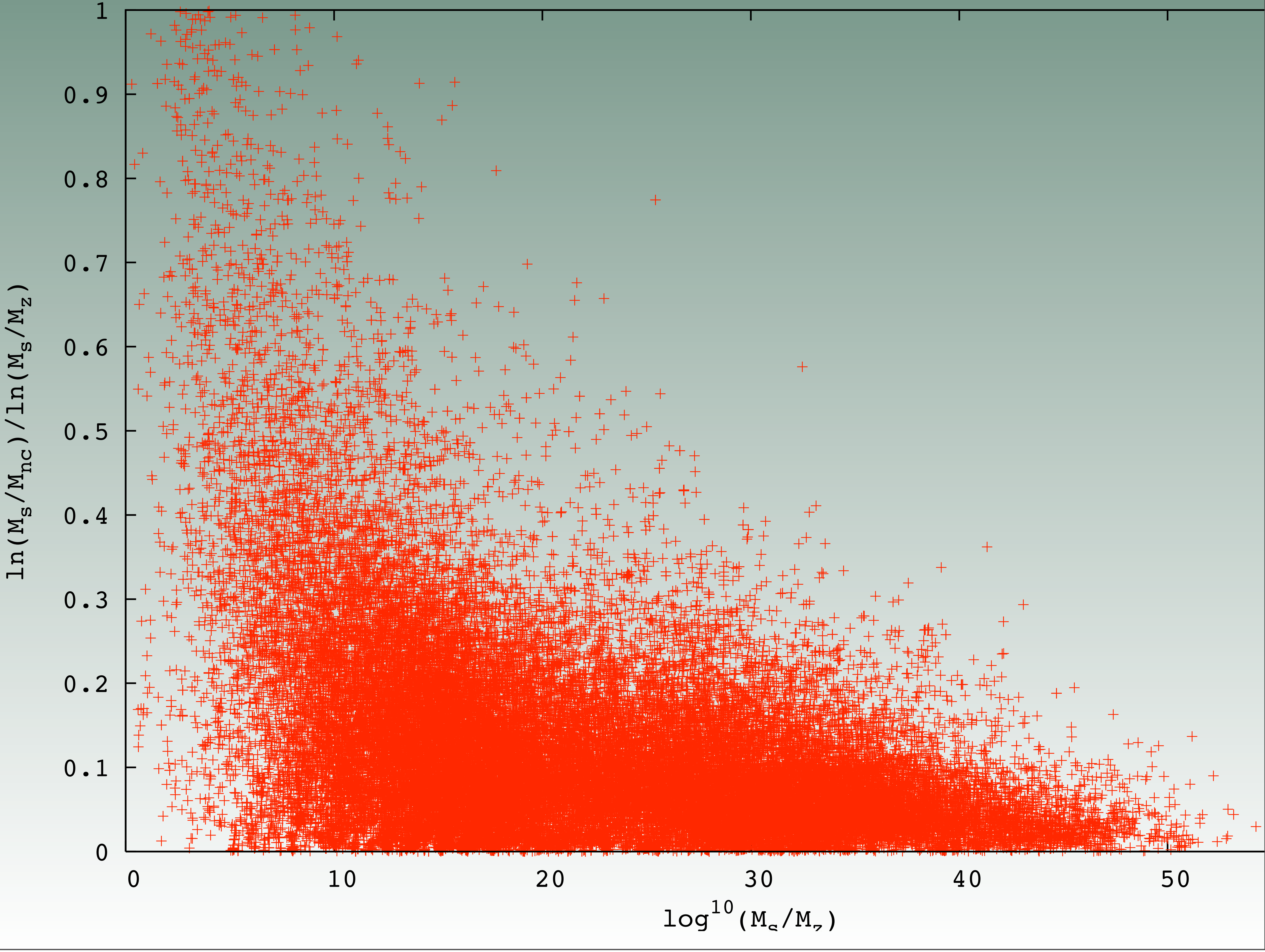
$$\sin^2(\theta_w) = .5271853$$

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


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


limit
Gepner Model
SU(5) SM
RG-flow MSSM
1
0.8
0.6
0.4
0.2
0
$\sin^2\theta_w$
0.1
1
10
α_s/α_w


1
0.8
0.6
0.4
0.2
0
0.1
1
10


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$\ln(M_s/M_{nc})/\ln(M_s/M_z)$
0
10
20
30
40
50
$\log^{10}(M_s/M_z)$

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

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

This allows in particular:

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

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

$$Y = \alpha Q_a + \beta Q_b + T_c + T_d$$

*a,b,c,d may be identical

Results

- Searched all MIPFs with < 1750 boundaries
- 19845 *chirally* different SM embeddings found
- Tadpole conditions solved in 1894 cases

  (18 “old” ones)

0	1512	9785532	647	U3S2S6U1	VVVV	✔	!	
1	838	8459664	674	U3S2S2U1	VVVV	✔	!	(Type 4)
2	722	5769030	820	U4S2S6	VVV	✔	!	
3	559	4801518	867	U4S2S2	VVV	✔	!	
4	1514	4751603	554	U3S2O6U1	VVVV	✔	!	
5	546	4584392	751	U4S2O6	VVV	✔		
6	837	4509752	513	U3S2O2U1	VVVV	✔	!	(Type 2)
7	564	3744864	690	U4S2O2	VVV	✔	!	
8	1513	3603236	466	U3S2S6U3	VVVV	✔		
9	2755	3308076	340	U3S2U3U1	VVVV	✔		
10	2756	3308076	340	U3S2U3U1	VVVV	✔		
11	1206	3091021	622	U6S2S6	VVV	✔		
12	1164	2713960	460	U3S2S2U3	VVVV	✔	!	
13	1424	2384626	560	U6S2O6	VVV	✔		
14	560	2250118	668	U6S2S2	VVV	✔	!	
15	835	1803909	519	U6S2O2	VVV	✔	!	
16	718	1787210	486	U4S2U3	VVV	✔		
17	719	1787210	486	U4S2U3	VVV	✔		
18	1421	1674989	516	U8S2S6	VVV	✔		
19	1707	1674416	384	U3S2O6U3	VVVV	✔		
20	1577	1641845	359	U3S2S6U5	VVVV	✔		
21	1163	1486664	346	U3S2O2U3	VVVV	✔	!	
22	1425	1323363	476	U8S2O6	VVV	✔		
23	1515	1135044	349	U3S2S2U5	VVVV	✔	!	
24	2757	1106616	209	U3S2U3U3	VVVV	✔		
25	2758	1106616	209	U3S2U3U3	VVVV	✔		
26	834	1049176	531	U8S2S2	VVV	✔		
27	836	956980	421	U8S2O2	VVV	✔		

28	1422	949189	448	U10S2S6	VVV	✔		
29	720	935034	351	U6S2U3	VVV	✔		
30	721	935034	351	U6S2U3	VVV	✔		
31	774	910132	51	U3U2S2O1	AAVV	✔		
32	1578	884695	292	U3S2S6U7	VVVV	✔		
33	2751	869428	246	U3S2U1U1	VVVV	✔	!	(Type 0)
34	554	853080	36	U3S2S2U3	VVVV	✔		
35	1708	762244	297	U3S2O6U5	VVVV	✔		
36	1426	760721	409	U10S2O6	VVV	✔		
37	1579	667189	262	U3S2O2U5	VVVV	✔	!	
38	775	641312	43	U3U2S4O1	AAVV			
39	7166	572804	301	U8S2U3	VVV	✔		
40	7167	572804	301	U8S2U3	VVV	✔		
41	6323	567930	276	U3S2S2U7	VVVV	✔		
42	555	558996	31	U3S2S2U5	VVVV	✔	!	
43	1423	555346	398	U12S2S6	VVV	✔		
44	511	553200	237	U5O2O1	AVV	✔		
45	532	552009	163	U5S2O1	AVV	✔		
46	1420	550774	445	U10S2S2	VVV	✔		
47	7170	536512	158	U3S2U3U5	VVVV	✔		
48	7171	536512	158	U3S2U3U5	VVVV	✔		
49	2740	526202	354	U10S2O2	VVV	✔		
50	770	491928	83	U3U2O2O1	AAVV	✔		
51	388	491026	451	U6U2O6	VVV	✔		
52	1188	485396	366	U4S2U1	VVV	✔	!	

Pati-Salam

```
 3    559    4801518    867 U4S2S2 VVV        ✔  !
```

```
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)

```
160     101      115466    335 U4U2U2  VVV            ✔


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
      2 x ( V ,0 ,0 ,0 ,0 ,0 ,0 ,V ,0 ,0 ) chirality 0
      3 x ( 0 ,0 ,0 ,0 ,0 ,0 ,0 ,V ,V ,0 ) chirality 3
```

....

SU(5)

```
709        7        16845    296 U5O1_AV              ✔
```

```
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)!

broken SU(5)

```
394     169       39642     107 U3U2O1_AAV         ✔
```

```
Type:      ( U ,U ,O ,O ,U ,O )
Dimension  ( 3 ,2 ,1 ,1 ,1 ,1 )
```

```
 3 x ( A ,0 ,0 ,0 ,0 ,0 ) chirality 3
11 x ( V ,0 ,V ,0 ,0 ,0 ) chirality -3
 3 x ( 0 ,A ,0 ,0 ,0 ,0 ) chirality 3
 5 x ( V ,V ,0 ,0 ,0 ,0 ) chirality 3
 5 x ( 0 ,V ,V ,0 ,0 ,0 ) chirality -3
 4 x ( Ad,0 ,0 ,0 ,0 ,0 ) chirality 0
 1 x ( 0 ,Ad,0 ,0 ,0 ,0 ) chirality 0
 1 x ( 0 ,0 ,A ,0 ,0 ,0 ) chirality 0
 8 x ( S ,0 ,0 ,0 ,0 ,0 ) chirality 0
 8 x ( V ,0 ,0 ,V ,0 ,0 ) chirality 0
 8 x ( V ,0 ,0 ,0 ,V ,0 ) chirality 0
 8 x ( 0 ,0 ,V ,0 ,V ,0 ) chirality 0
 6 x ( V ,0 ,0 ,0 ,V*,0 ) chirality 0
 3 x ( 0 ,0 ,S ,0 ,0 ,0 ) chirality 0
 3 x ( 0 ,0 ,V ,V ,0 ,0 ) chirality 0
 8 x ( V ,0 ,0 ,0 ,0 ,V ) chirality 0
 8 x ( 0 ,V ,0 ,0 ,0 ,V ) chirality 0
 3 x ( 0 ,0 ,V ,0 ,0 ,V ) chirality 0
 8 x ( 0 ,0 ,0 ,V ,V ,0 ) chirality -6
 3 x ( 0 ,0 ,0 ,0 ,A ,0 ) chirality 3
 5 x ( 0 ,0 ,0 ,0 ,S ,0 ) chirality 3
 1 x ( 0 ,0 ,0 ,A ,0 ,0 ) chirality 0
 1 x ( 0 ,0 ,0 ,0 ,Ad,0 ) chirality 0
 4 x ( 0 ,0 ,0 ,0 ,0 ,A ) chirality 0
 8 x ( 0 ,0 ,0 ,0 ,V ,V ) chirality 0
 3 x ( 0 ,0 ,0 ,V ,0 ,V ) chirality 0
 5 x ( 0 ,0 ,0 ,0 ,0 ,S ) chirality 0
```

SU(5) × U(1)

```
2372    218        2062    34 U5U1 AS              !
```

```
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
```

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

✓ Gauge coupling unification

✗ No up-quark Higgs couplings

Flipped SU(5)

```
2371    217       2062     34 U5U1 AS              !
```

```
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
```

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

✘ No gauge coupling unification

✔ Up-quark Higgs couplings

Trinification

1303 552 6432 87 U3U3U3 VVV ✔

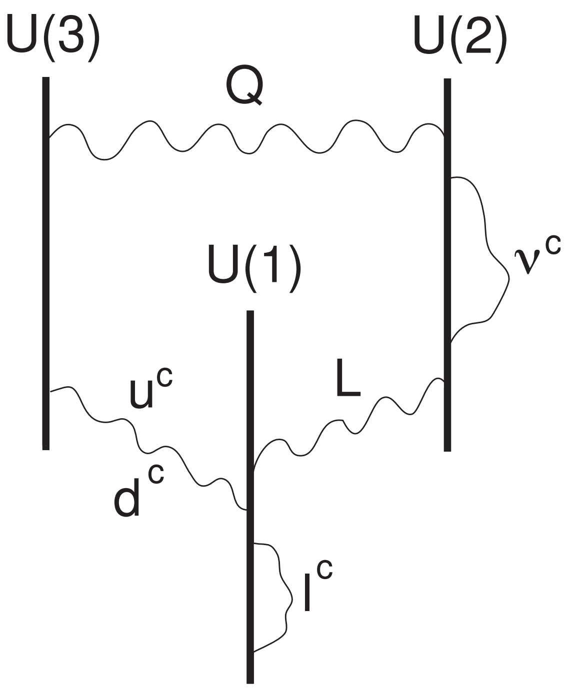
```
                U  U  U  O  O  U  U  U  U  O
                3  3  3  4  2  6 12 12 12  4
      3 x  (V ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality 3
      3 x  (V ,0 ,V ,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -3
      3 x  (0 ,V ,V*,0 ,0 ,0 ,0 ,0 ,0 ,0 ) chirality -3
      1 x  (0 ,0 ,0 ,V ,0 ,V ,0 ,0 ,0 ,0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

1303 552 6432 87 U3U3U3 VVV ✔

```
          U   U   U   O   O   U   U   U   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
```

What we don’t get:



Antoniadis & Dimopoulos, hep-th/0411032, (“type C”)

The same model with Sp(2) instead of U(2)
does occur, but without tadpole solution

```
8459   18825          108       1 U3S2U1_VVT
```

Final question

Which percentage of the landscape have we visited so far?

Our results: 873 Hodge number pairs
Kreuzer’s list: 30000 Hodge number pairs