Sightseeing in the Landscape

Contents

- Landscape remarks
  (physics/06041340, Dutch version 1998)
- RCFT orientifolds
  (with Huiszoon,Fuchs, Schweigert,Walcher)
- 2003-2004 results
  (with Dijkstra,Huiszoon)
- 2005-2006 results
  (with Anastasopoulos,Dijkstra,Kiritsis, hep-th/0605226)

Unification / Uniqueness
A brief history

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  - Muon (quark/lepton families)
  - Parameters (masses, coupings)

- Then some theoretical problems arise:
  Yang-Mills theory: QED is not unique.
  Many other gauge theories are possible.

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  Once again suggests an underlying unified theory.
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- But there is another revolution most people preferred to overlook: The string vacuum revolution.

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A Slow Revolution

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A. Strominger,
"Calabi-Yau manifolds with Torsion", 1986

All predictive power seems to have been lost.

All of this points to the overwhelming need to find a dynamical principle for determining the ground state, which now appears more imperative than ever.

Lerche, Lüst, Schellekens
"Chiral, Four-dimensional Heterotic Strings From Self-Dual Lattices", 1986

$(\Gamma_{22}\times D_3\times(D_7)^9)_L$, a Euclidean lattice of dimension 88. A lower limit on the total number of such lattices is provided by the Siegel mass formula [21] [22]

this number is of order 10^{1500} !

It seems that not much is left of the once celebrated uniqueness of string theory.

Even if all that string theory could achieve would be a completely finite theory of all interactions including gravity, but with no further restrictions on the gauge groups and the representations, it would be a considerable success. But the situation

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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.

A Cern Cafetaria Napkin (~ 1988)

All gauge theories

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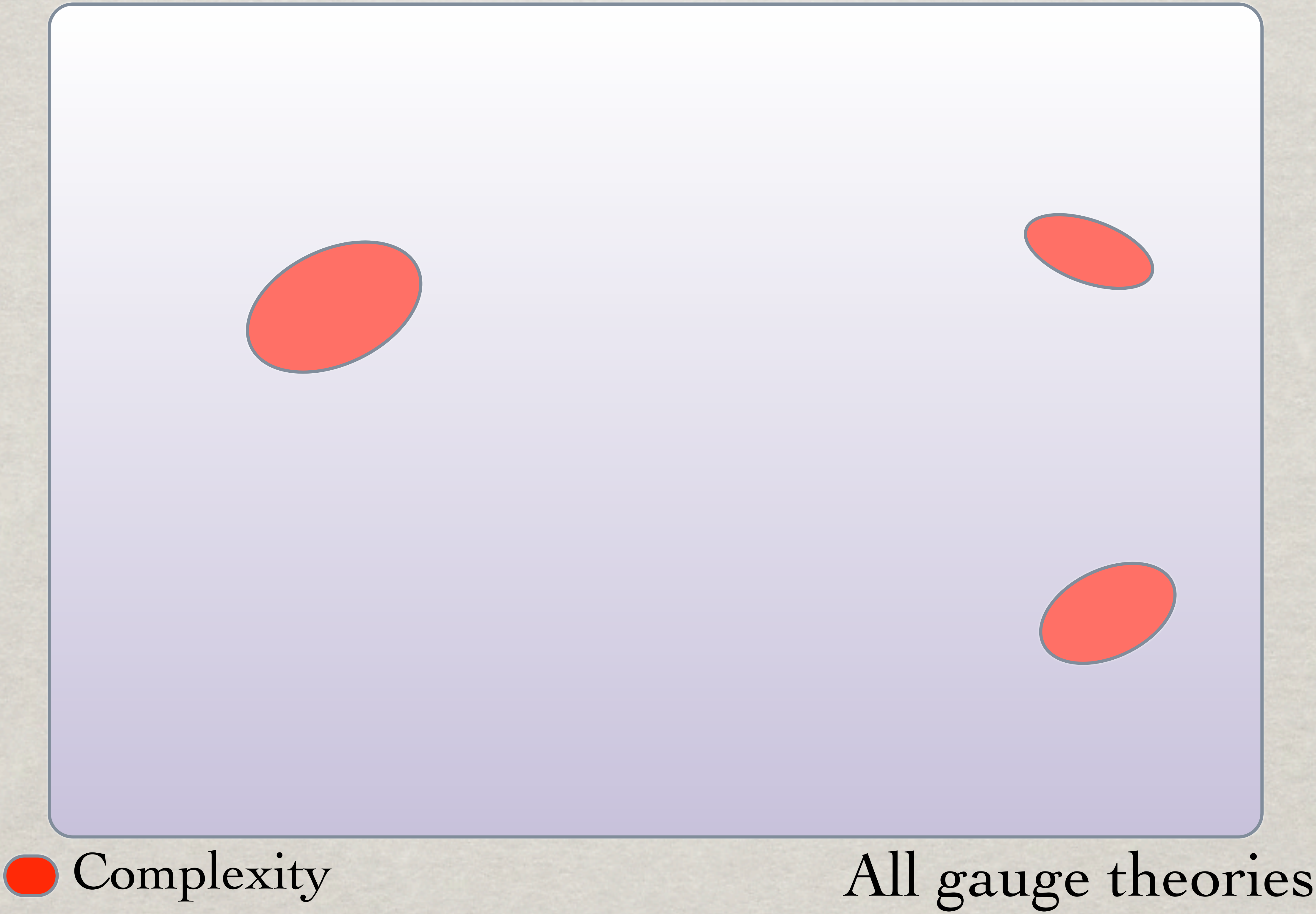

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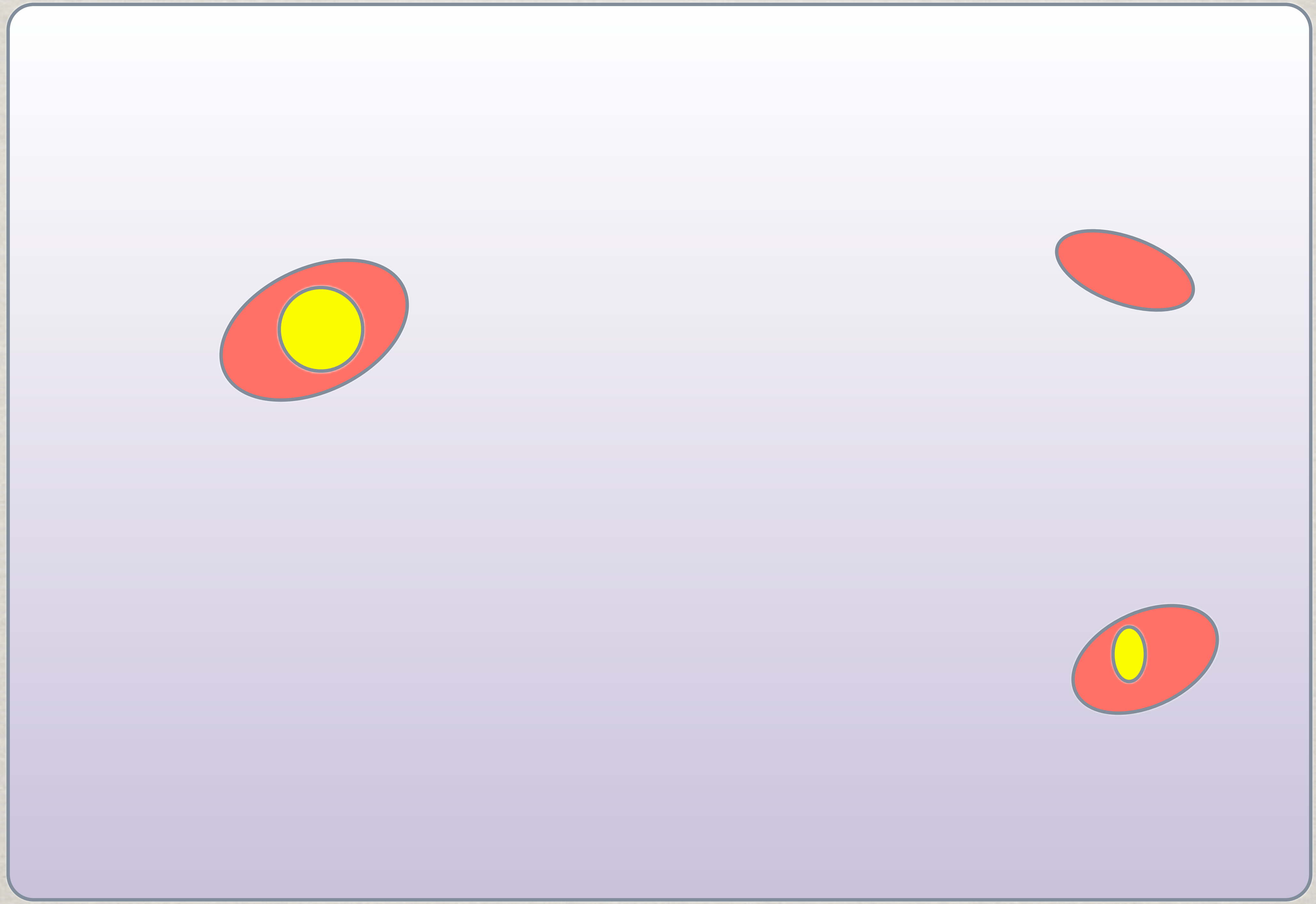

Complexity

Life

All gauge theories

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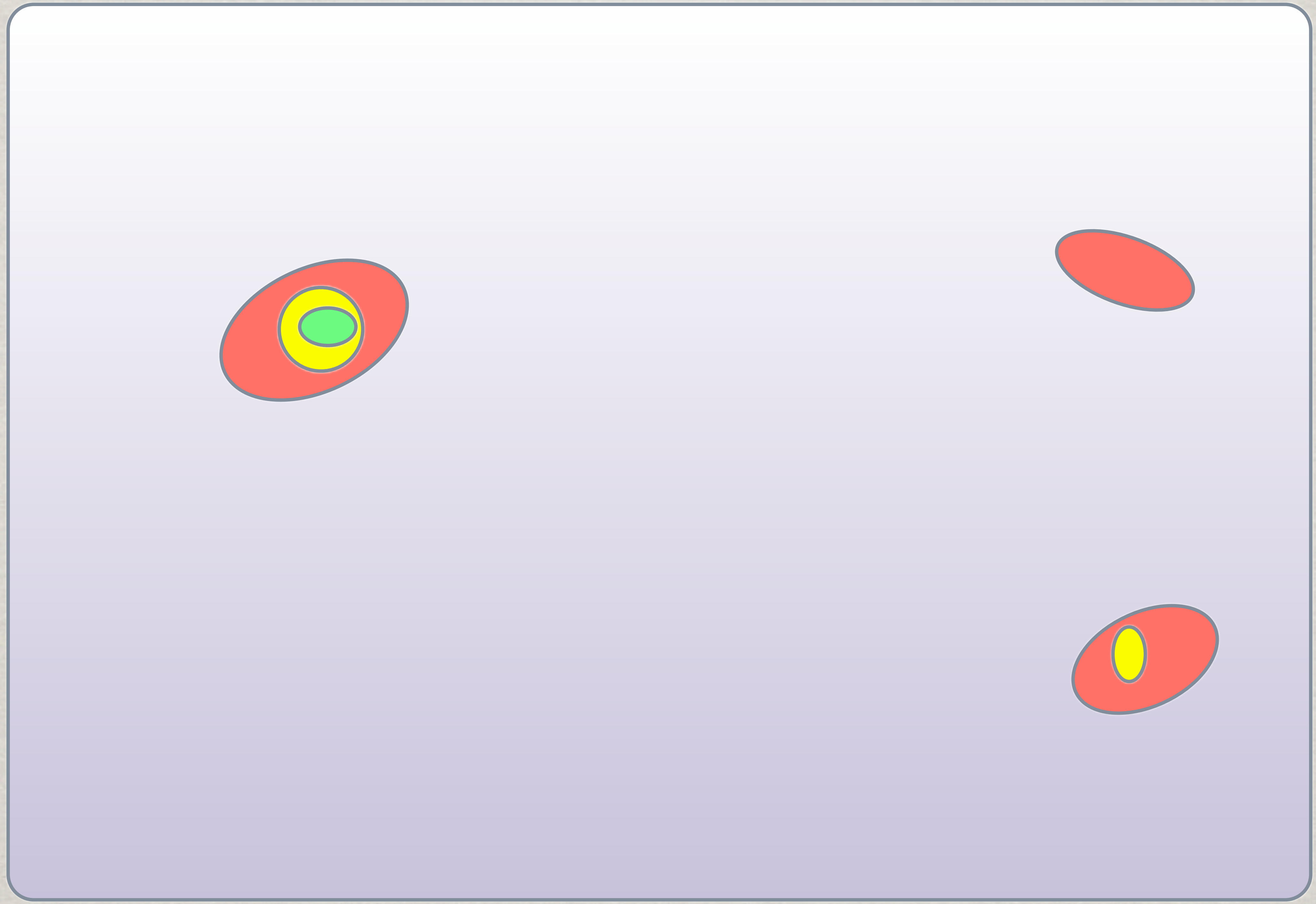

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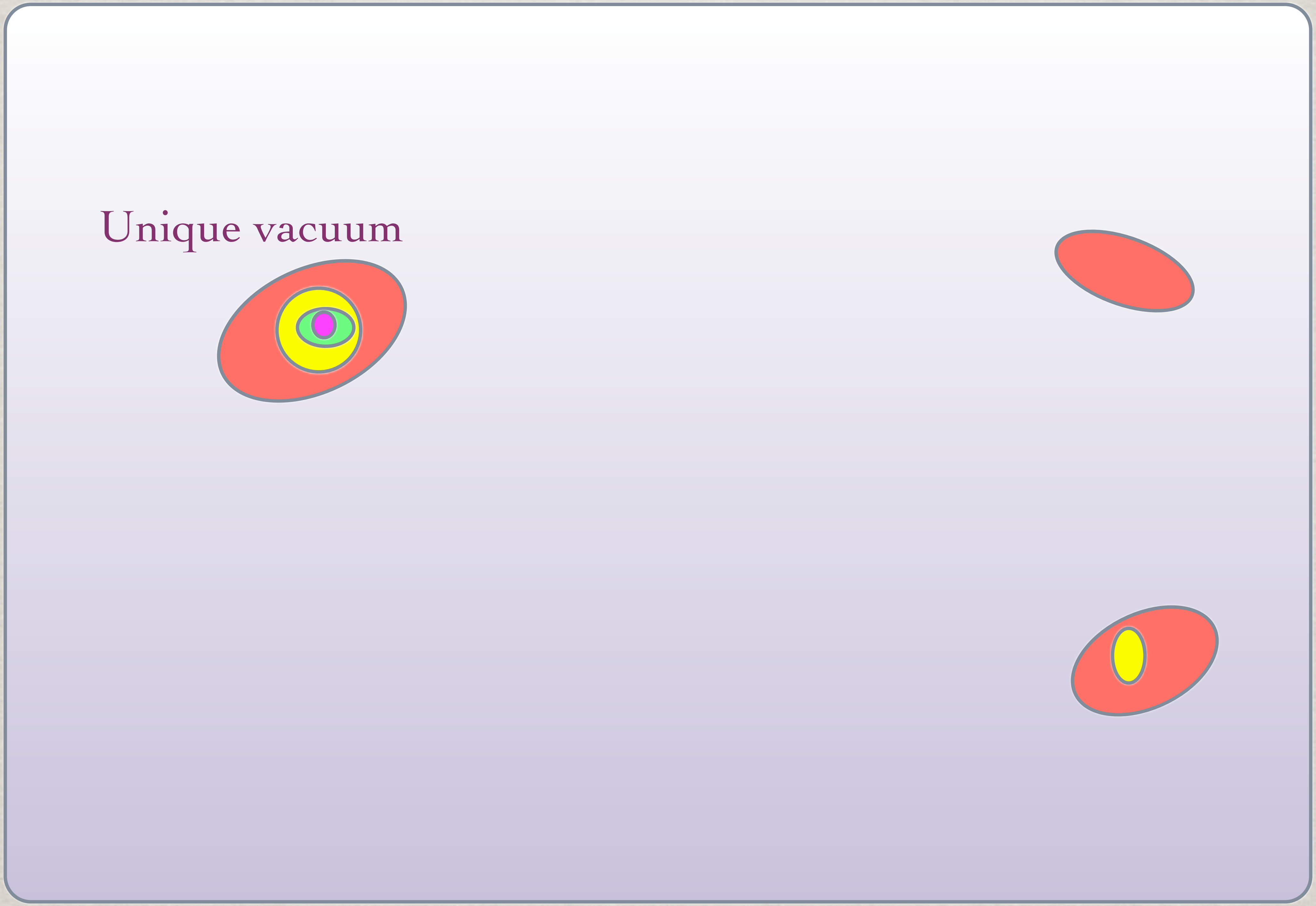

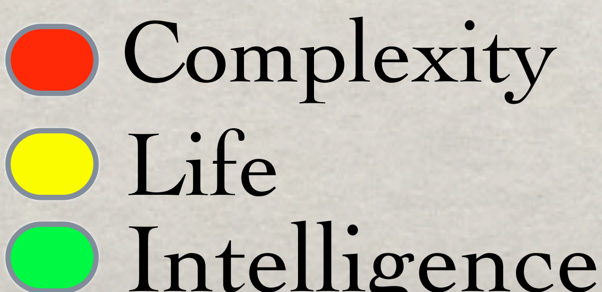

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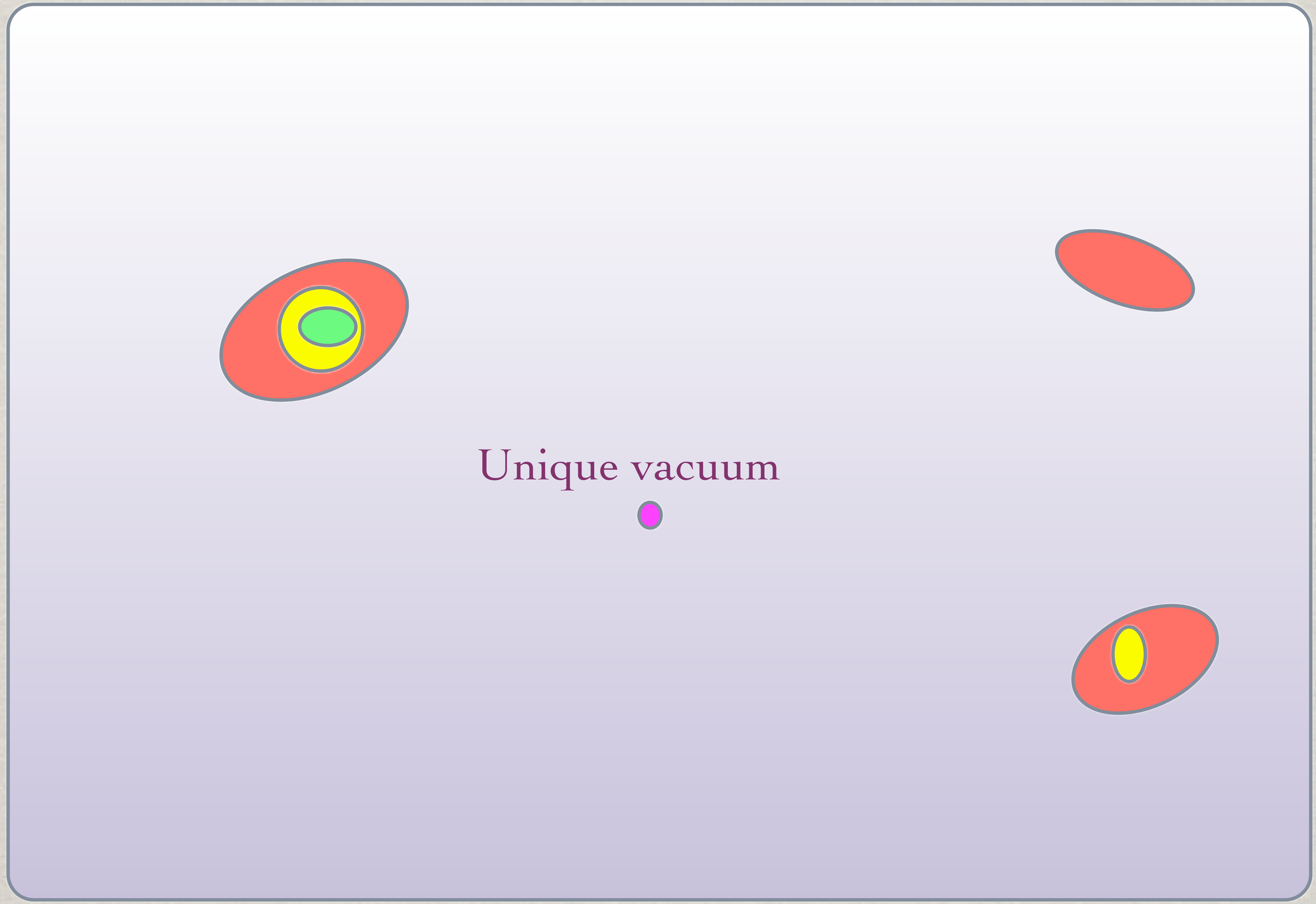

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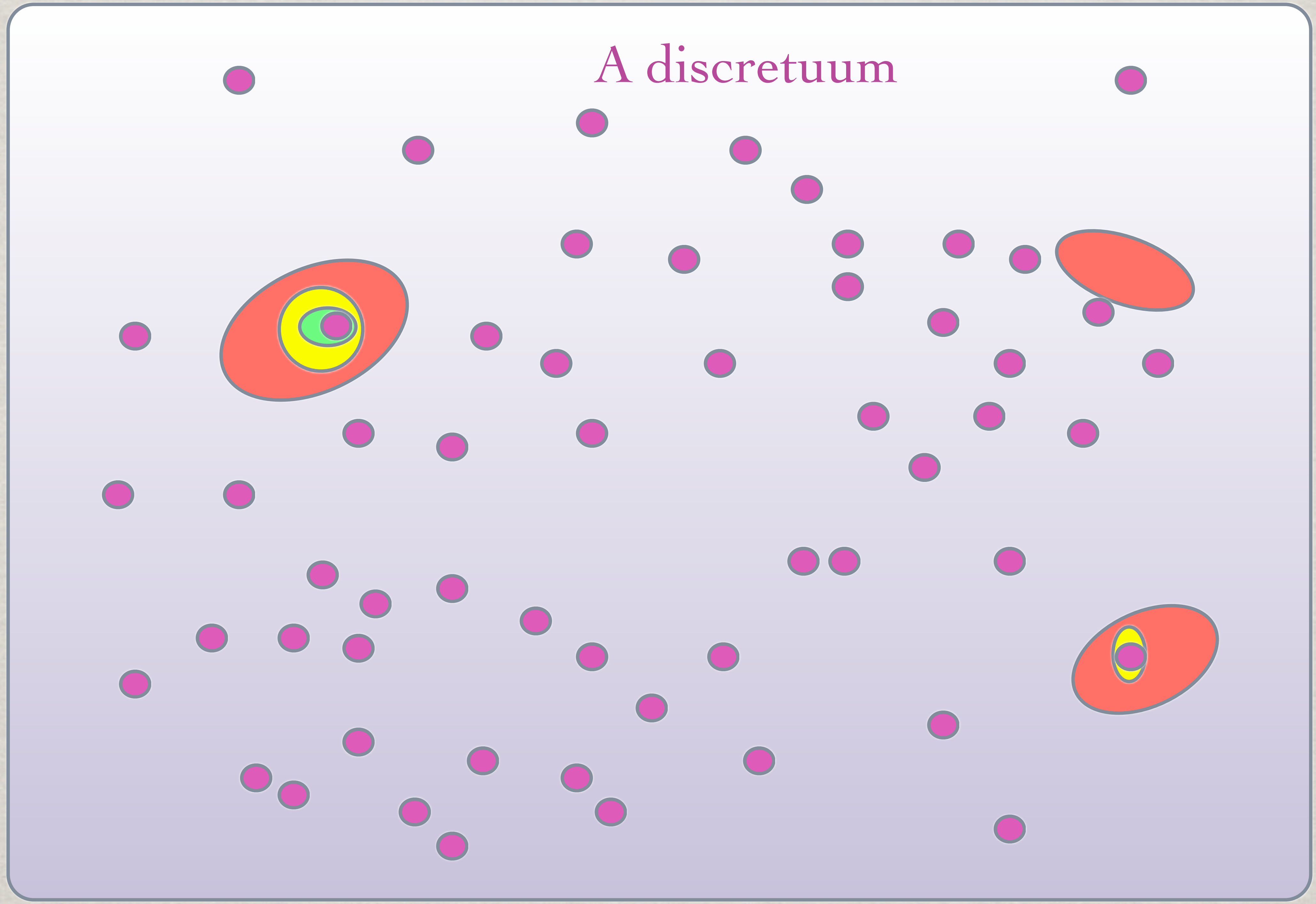

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Naar een waardig slot
Bert Schellekens

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- 2003: "The Anthropic Landscape of String Theory" (L. Susskind)

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- Does not make sense without String Theory (or better) or Eternal Inflation (or equivalent).
- Is an inevitable consequence of String Theory.
- Until 2000, almost no papers relate String Theory and the Anthropic principle.
- Without anti-anthropic prejudices, we might have predicted the "Anthropic Landscape of Quantum Gravity".

Hindsight...

Soon after starting graduate school, I went to see Howard Georgi. “What are you thinking about?” he asked me. I rattled off several things that seemed interesting to me, ending with, “... and quantum gravity.” **“Don’t waste your time!”** he barked, “There’s no decoupling limit in which it’s sensible to consider quantum gravity effects, while neglecting other interactions. Unless you know particle physics all the way up to the Planck scale, you can never hope to say anything predictive about quantum gravity.” Howard was, of course, completely correct.

Jacques Distler, “Musings”

How many "vacua" are needed?

- Requires understanding of "anthropic" considerations for different gauge theories.
- Requires some definition of a measure and boundaries.

Wild guess: about 10^{20} for SM fine-tunings

The same problems exist in principle for the cosmological constant, but seem less serious there: about 10^{120} would be needed.

Recent estimates: String Theory has plenty of ground states to understand all fine-tunings.

(Bousso-Polchinski, Douglas Denef,...

Vacuum counting (1998)

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

Number of vacua

SM Probability
(experimental)

Vacuum counting (2006)

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

Number of vacua

SM Probability

Cosmological Constant

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  - Three Families
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  - Black hole entropy
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- Non-anthropic nature of other vacua is (theoretically) falsifiable.

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Summary:

- A landscape of vacua is the only sensible outcome for a "Theory of Everything"
- Therefore: A Success for String Theory
- 4-D Quantum gravity implies that the SM is part of a huge landscape: an amazing conclusion! (if correct).
- Fits nicely with some of the great discoveries in the history of science (heliocentric model, theory of Evolution...)

Demystification by huge numbers:

- Planets (Giordano Bruno)
- Mutations (Evolution)
- Universes (Eternal Inflation)
- Alternative "Standard Models" (The Landcape)

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A repetion of an old mistake:

There is nothing "special" about us.

This line of thought fits in very well with a series of insights that pointed out our modest place in the cosmos. Our planet is not the center of the solar system, our sun is just one of many stars and not even a very special one, and the same is true for our galaxy. It seems natural to assume that also our universe, including the quarks, leptons and interactions we observe is just one out of many possibilities.

(From physics/06041340)

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- ... but it has never looked harder.

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- 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

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].

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

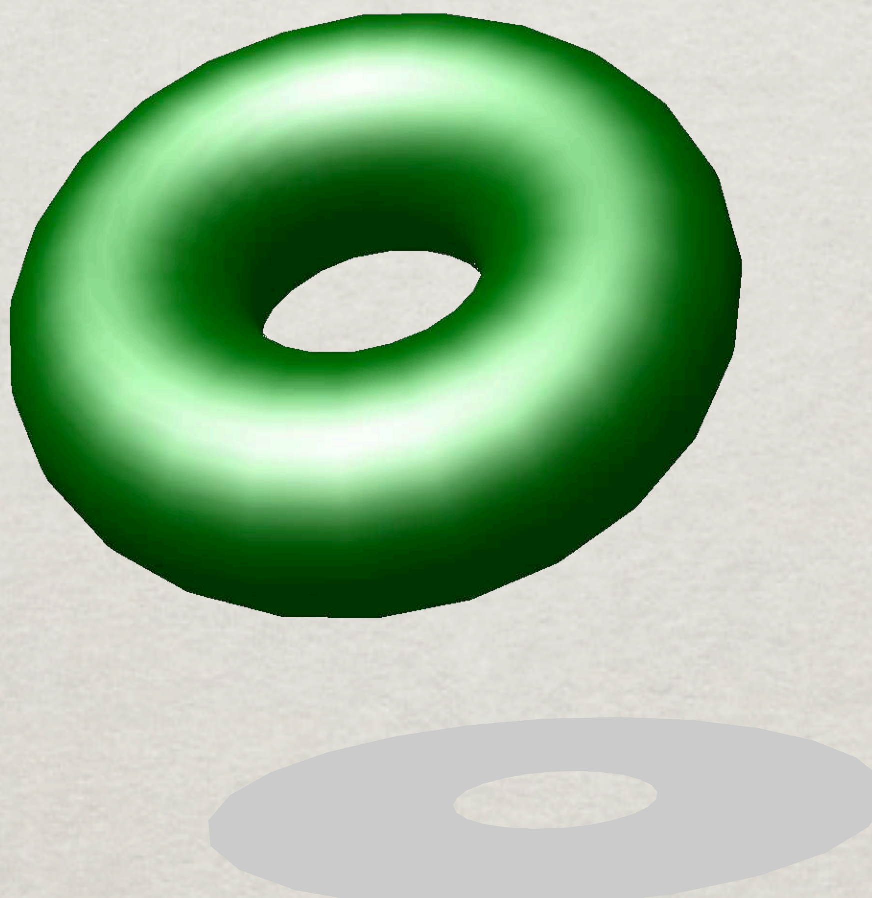
- Cvetic, Shiu, Uranga (2001)
  Supersymmetric SM-Spectra with chiral exotics

- 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)

Closed String Partition Function



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

Type IIB

Orientifold Partition Functions

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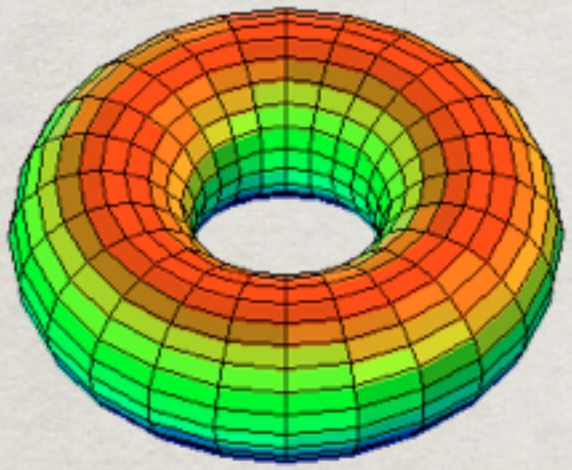
$\frac{1}{2}\Big\{$



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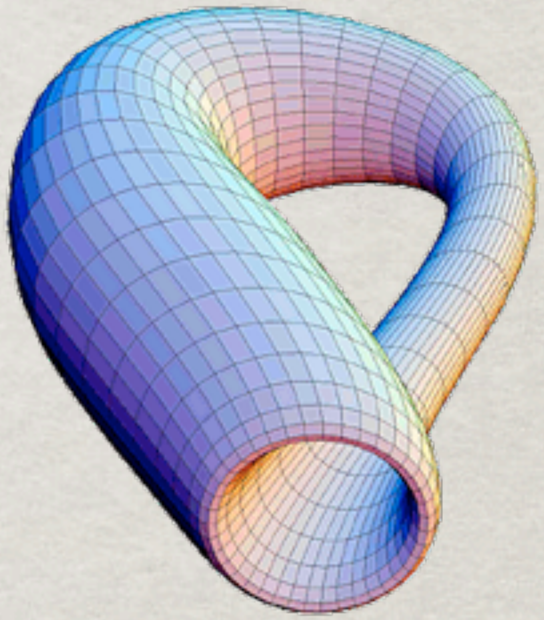

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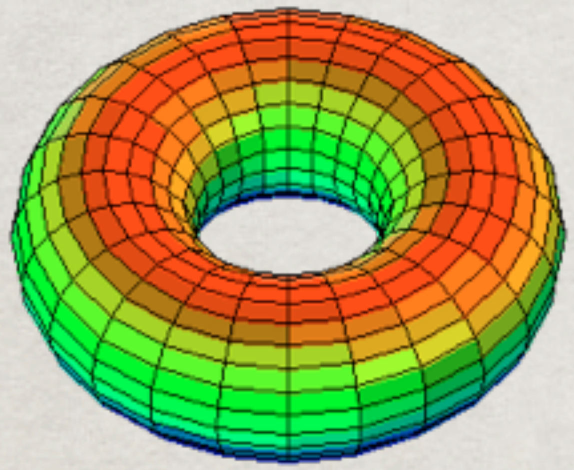
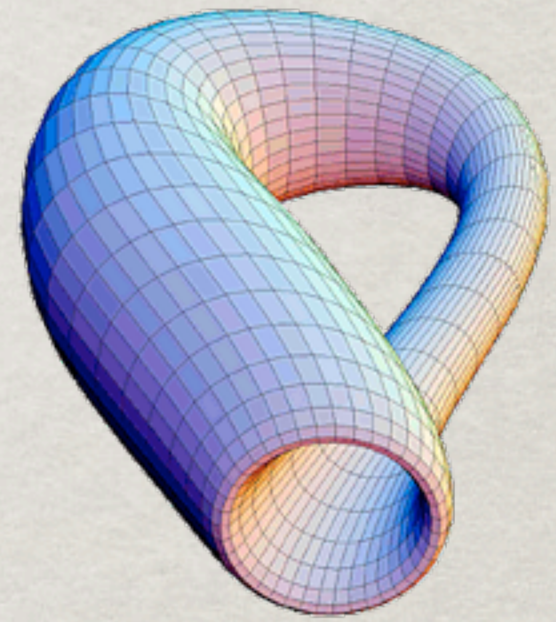
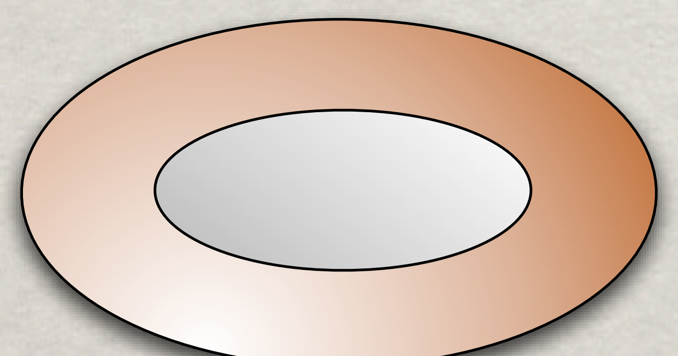
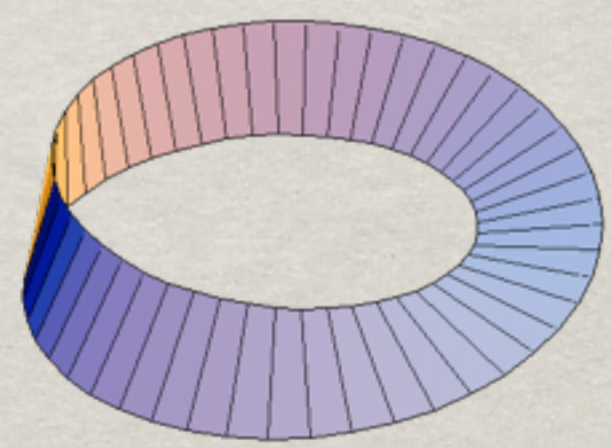
Orientifold Partition Functions

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

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

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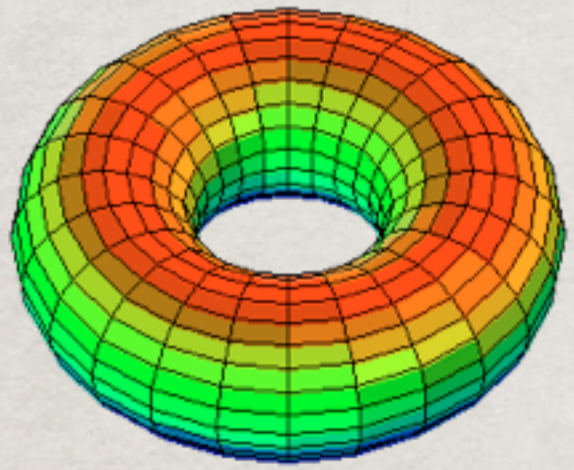
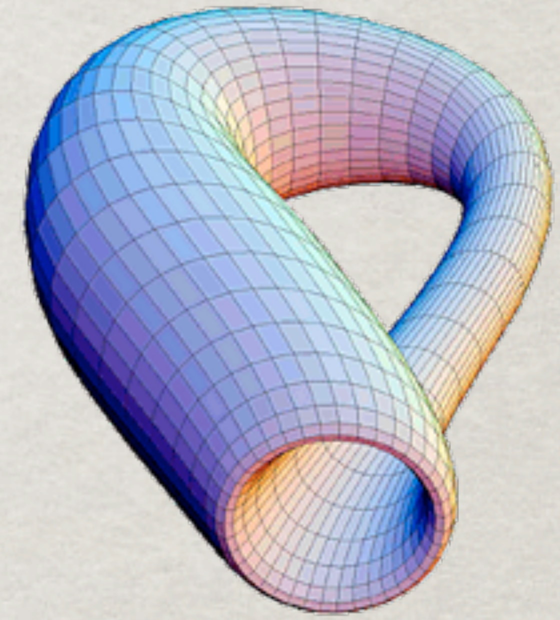
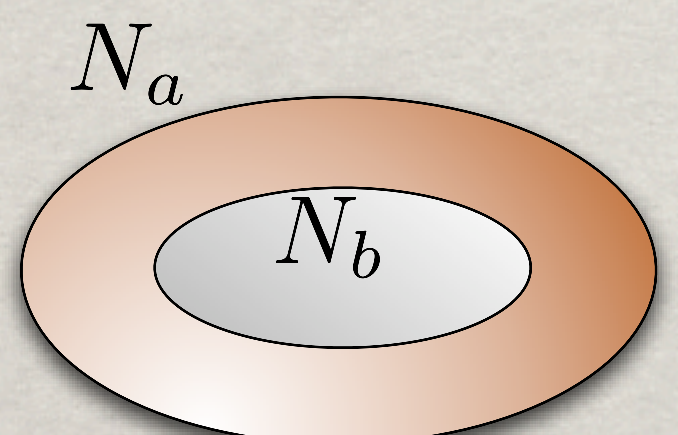
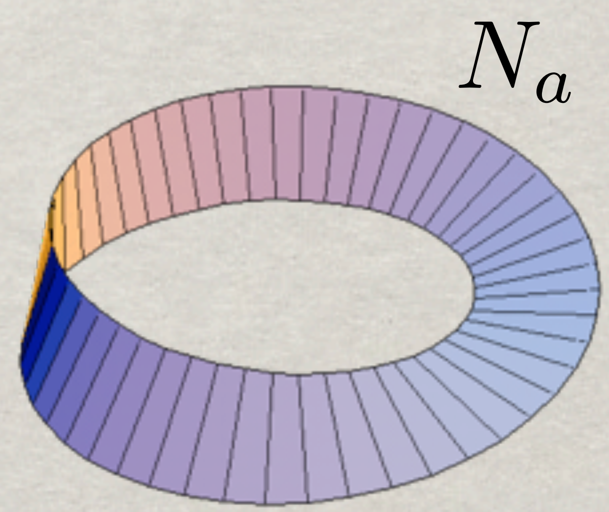
$\frac{1}{2} \Bigg\{$  $+$  $\Bigg\}$

$\frac{1}{2} \Bigg\{$ 

$+$ 

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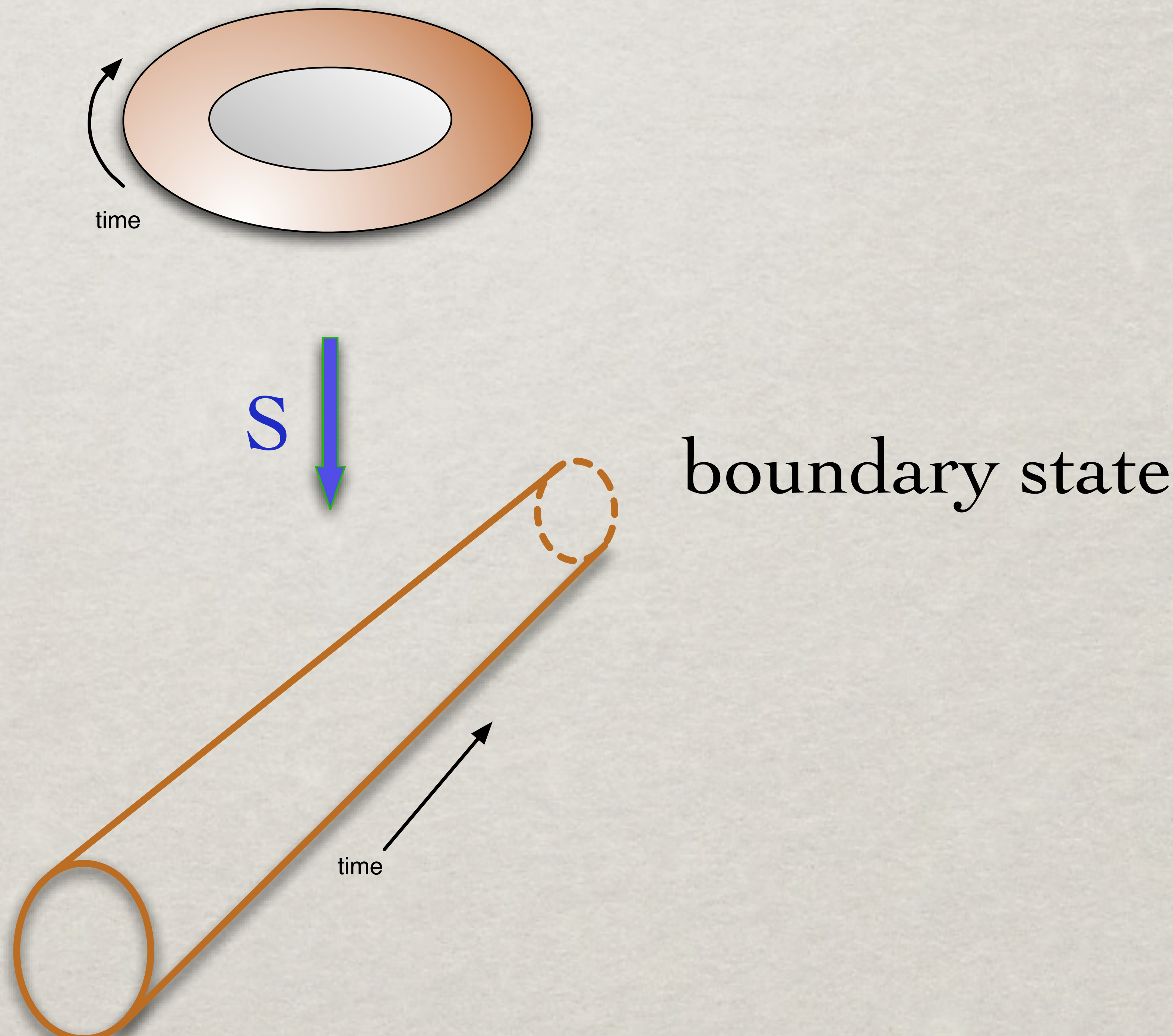
Transverse Channel



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 $\mathcal{H}$

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)
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+ 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

TADPOLES & ANOMALIES

- Tadpole cancellation condition:

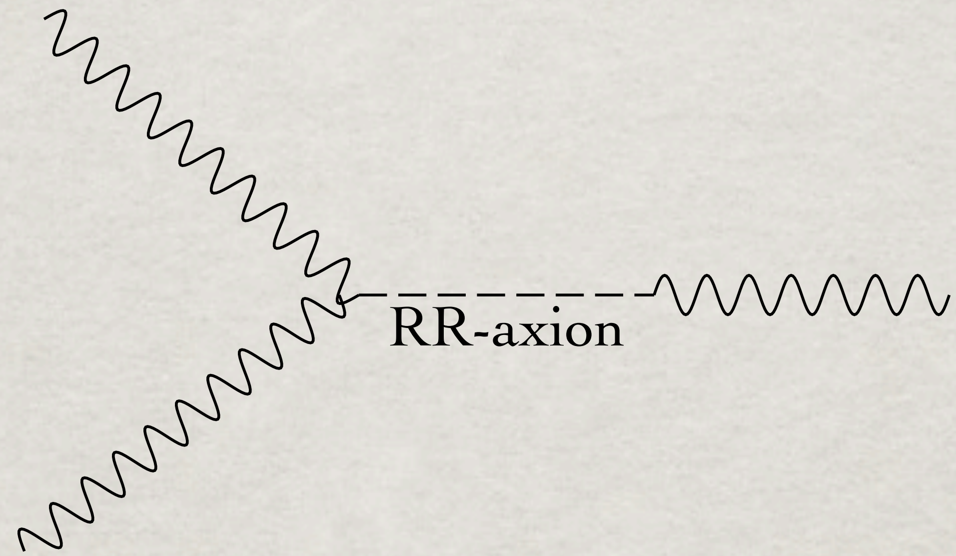
$$\sum_b N_b R_{b(m,J)} = 4\eta_m U_{(m,J)}$$

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

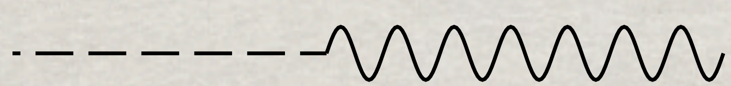
**Gato-Rivera, Schellekens (2005)*

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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- 5403 MIPFs

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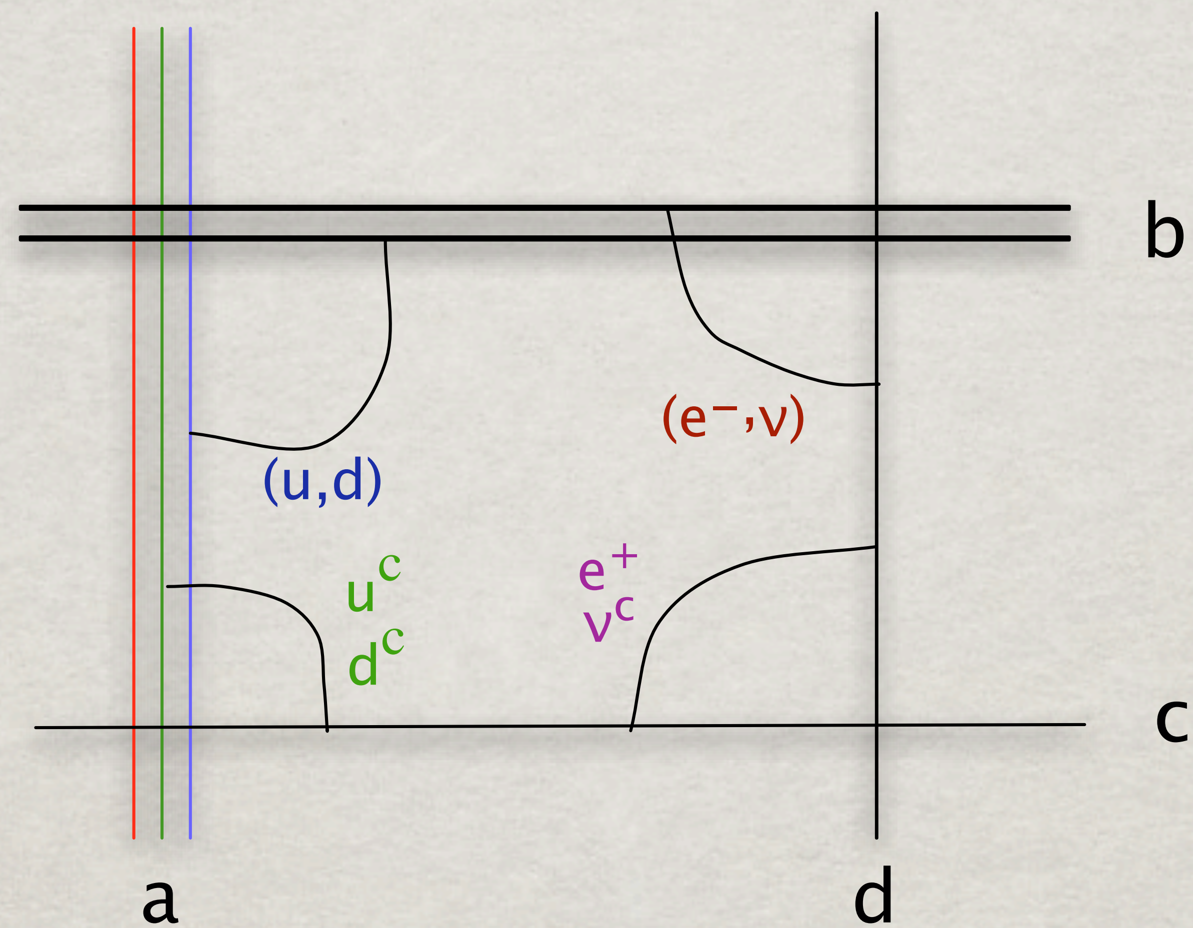
Essential to decide what to search for!

What to search for

The Madrid model



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

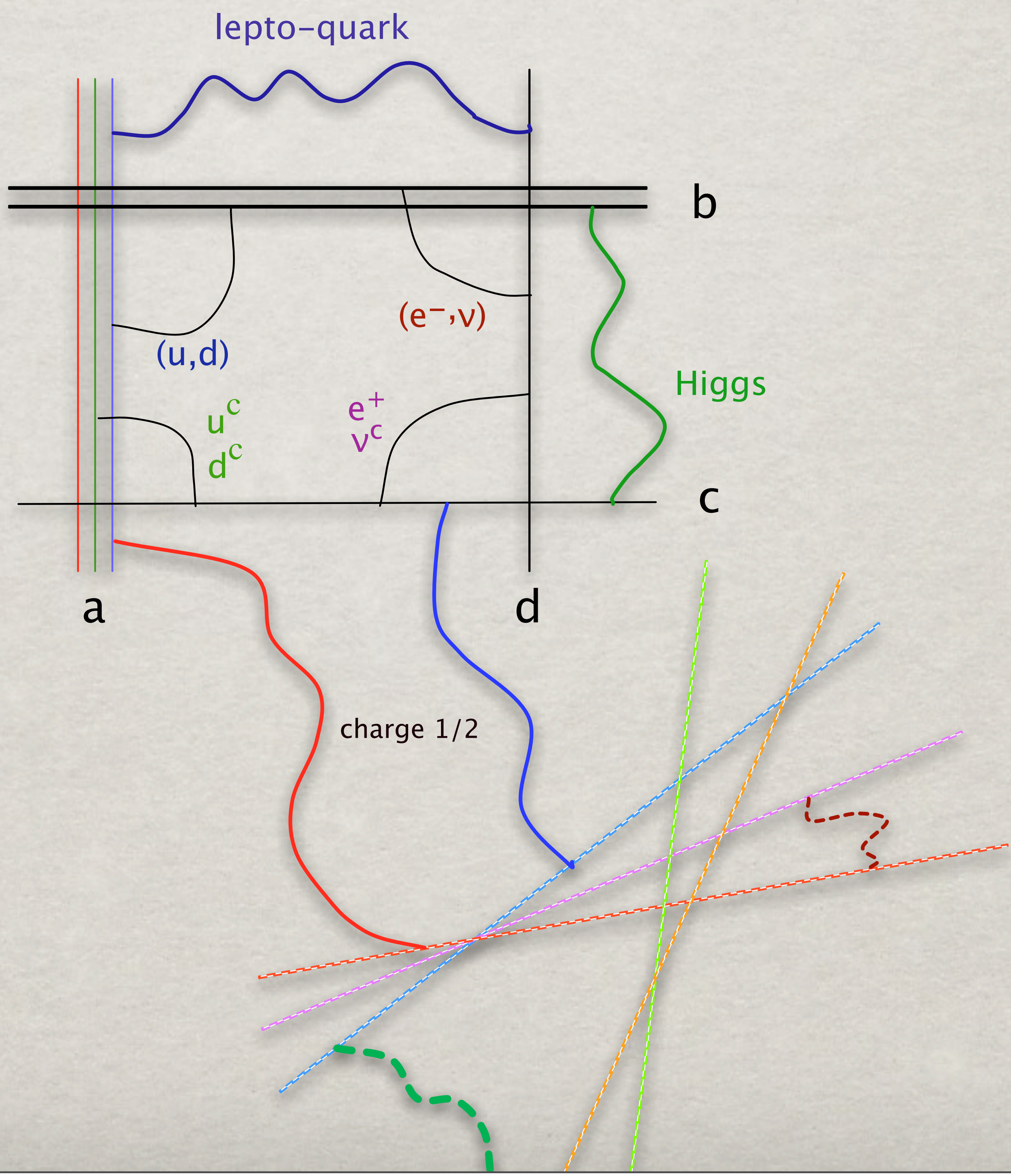
$$3(u,d)_L + 3u^c_L + 3d^c_L + 3(e^-,\nu)_L + 3e^+_L$$

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



Required Spectrum

3 families of SU(3) × SU(2) × U(1)

+ non-chiral matter

STATISTICS

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

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

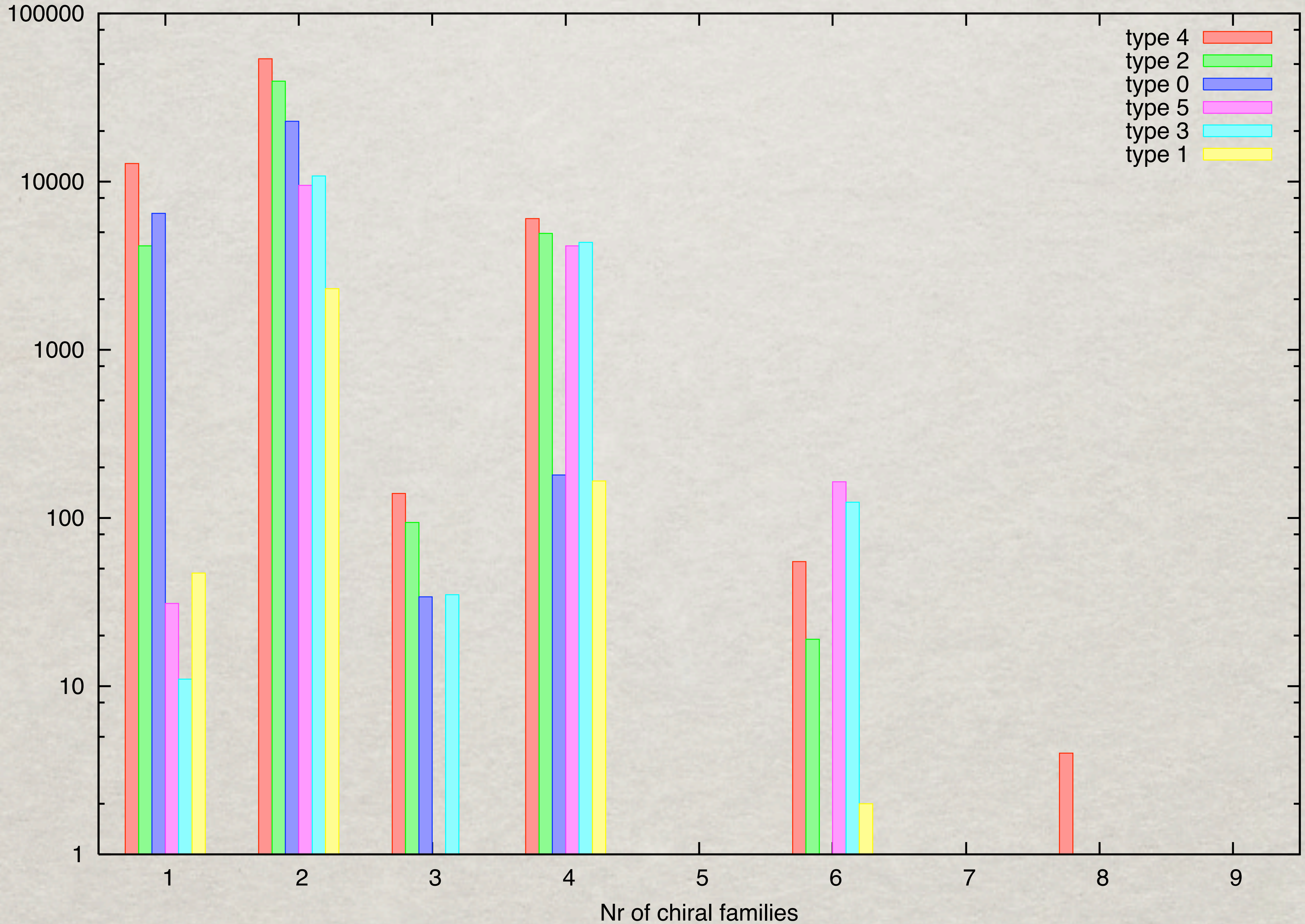
```
Standard model type: 6
Number of factors in hidden gauge group: 0
Gauge group: U(3) x Sp(2) x U(1) x U(1)

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 -3
 2 x  (V ,0 ,0 ,V )
10 x  (0 ,V ,V ,0 )
 2 x  (Ad,0 ,0 ,0 )
 2 x  (A ,0 ,0 ,0 )
```

•••••••

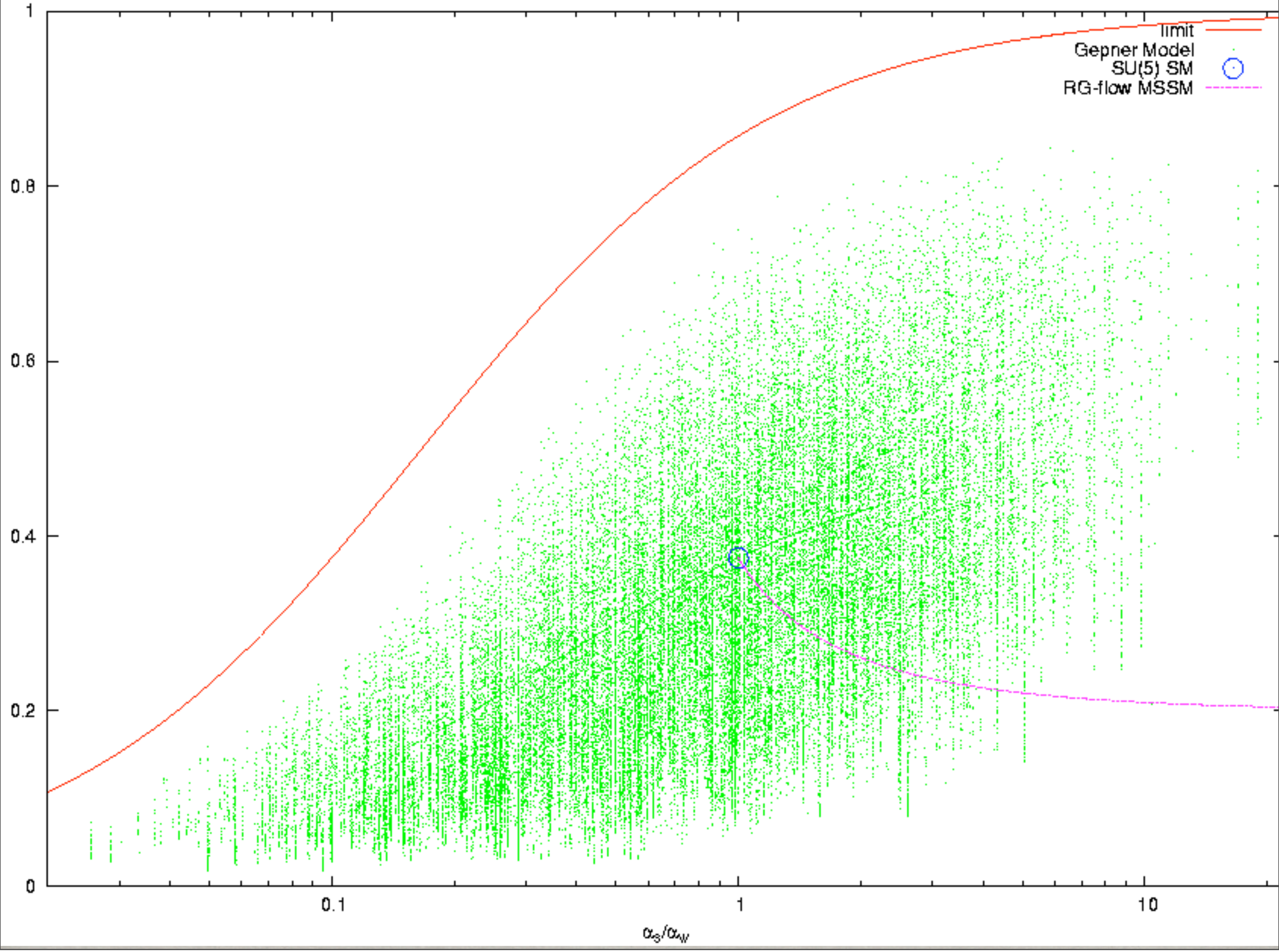
```
    Higgs:    (2,1/2)+  2*,1/2)              5
Non-chiral SM matter   (Q,U,D,L,E,N):  0  0  0  3  1  0
  Adjoints:                            2  0  9  3
  Symmetric Tensors:                   1 10  7  3
  Anti-Symmetric Tensors:              1 14  3  2
    Lepto-quarks:   3,-1/3),   3,2/3)     1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

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

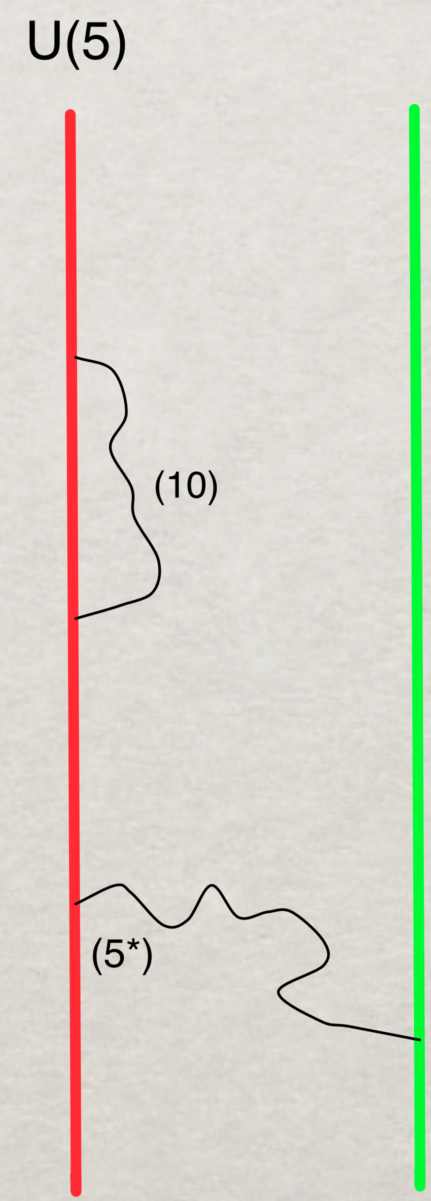
$$\frac{\alpha_3}{\alpha_2} = 3.2320501$$



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


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

SU(5) MODELS



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)!

Summary

Examples exist of chiral orientifold SSM spectra exist

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

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

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