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)

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A brief history

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

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- The Duality Revolution of 1995:
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- But there is another revolution most people preferred to overlook: The string vacuum revolution.

1984-2006:
A Slow Revolution

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A Cern Cafetaria Napkin (~ 1988)

All gauge theories

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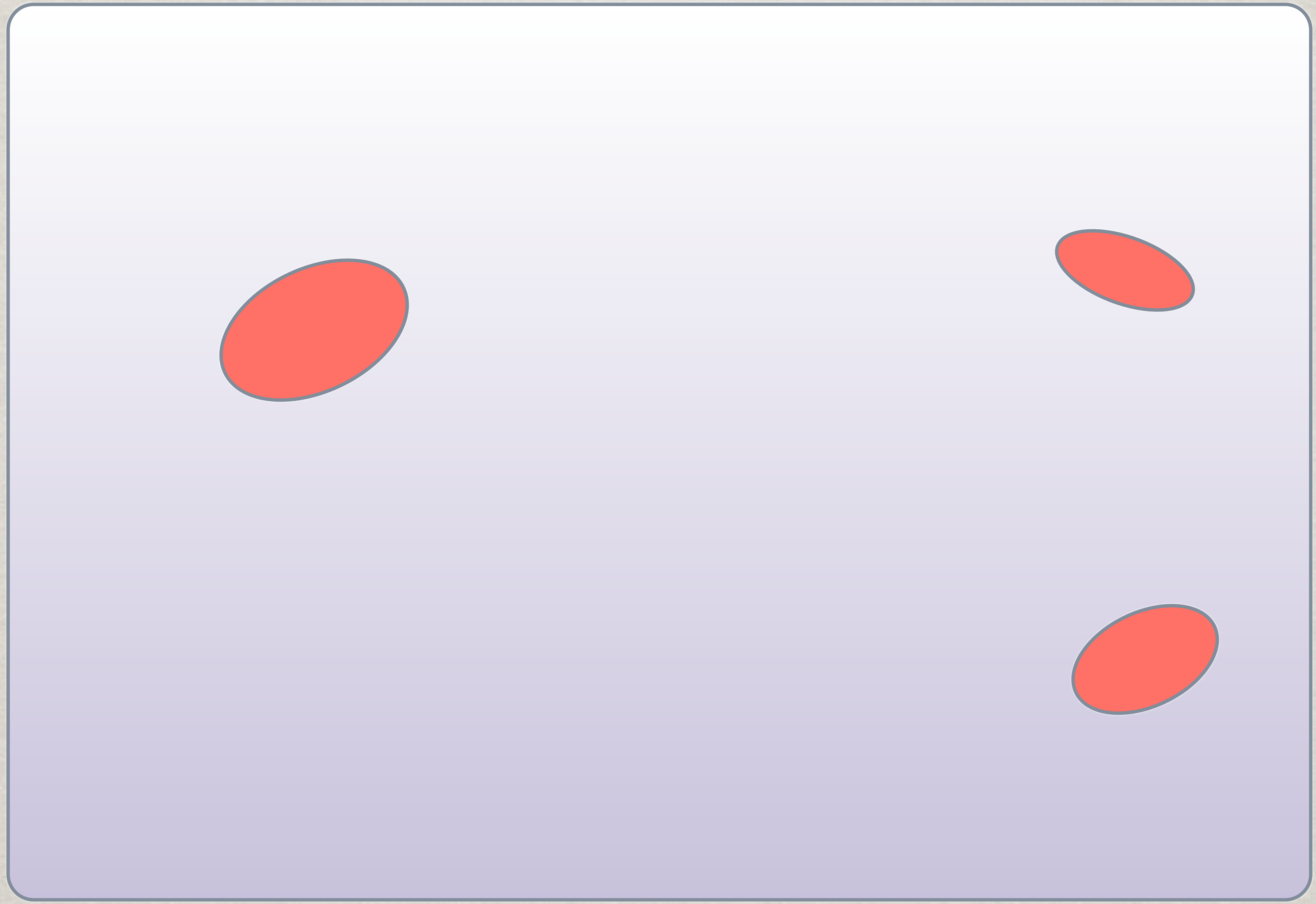

Complexity

All gauge theories

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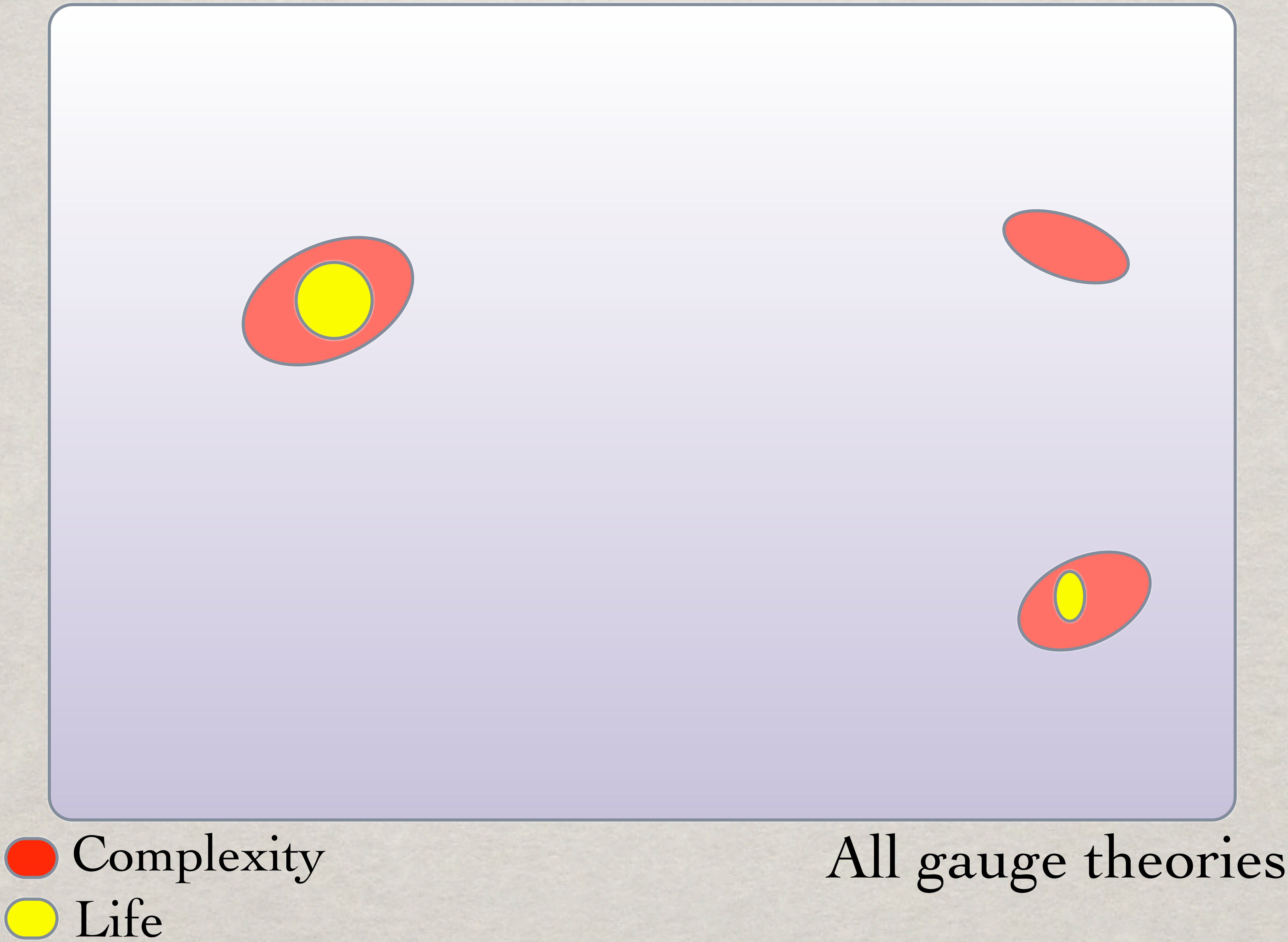

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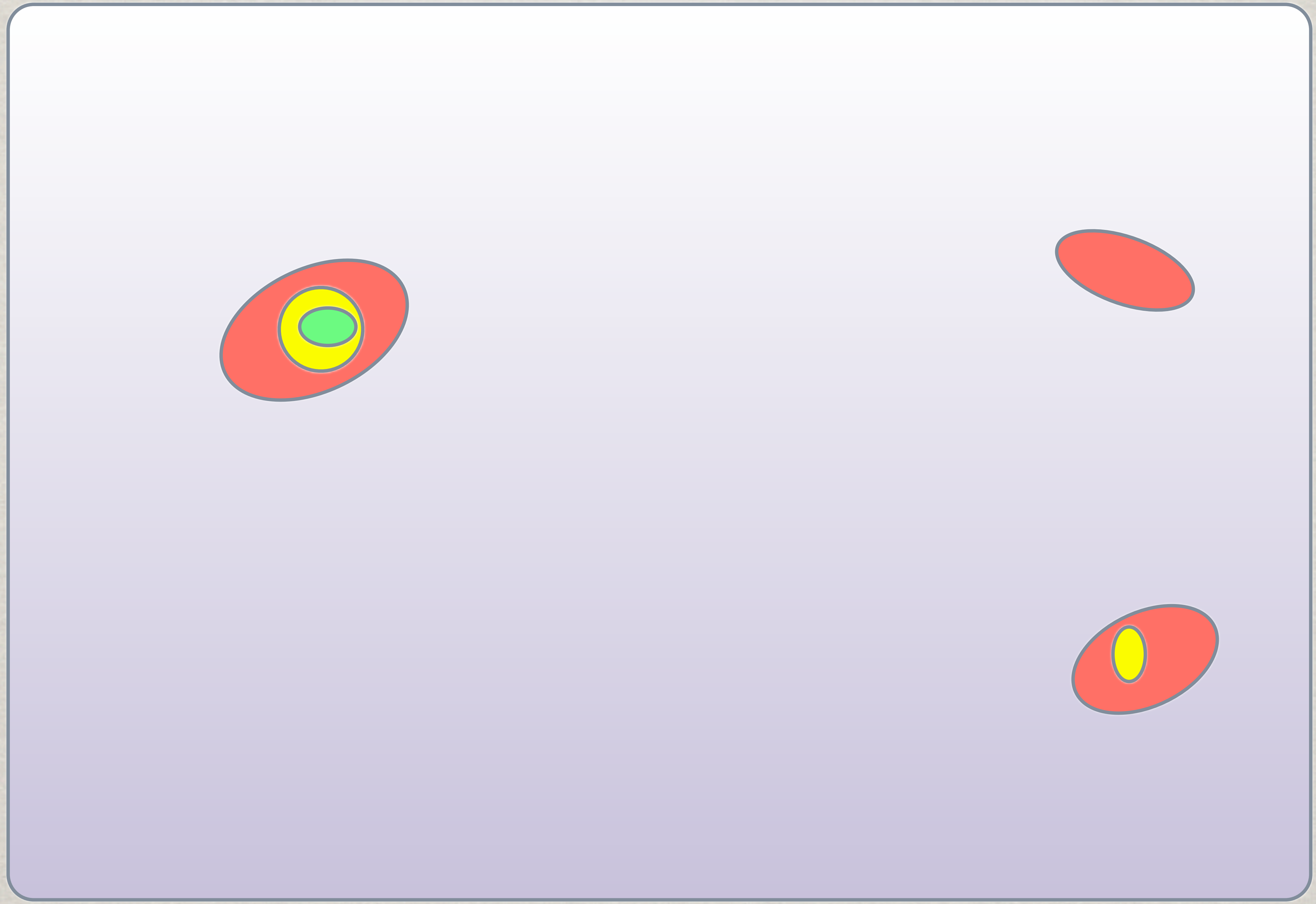

Complexity
Life
Intelligence

All gauge theories

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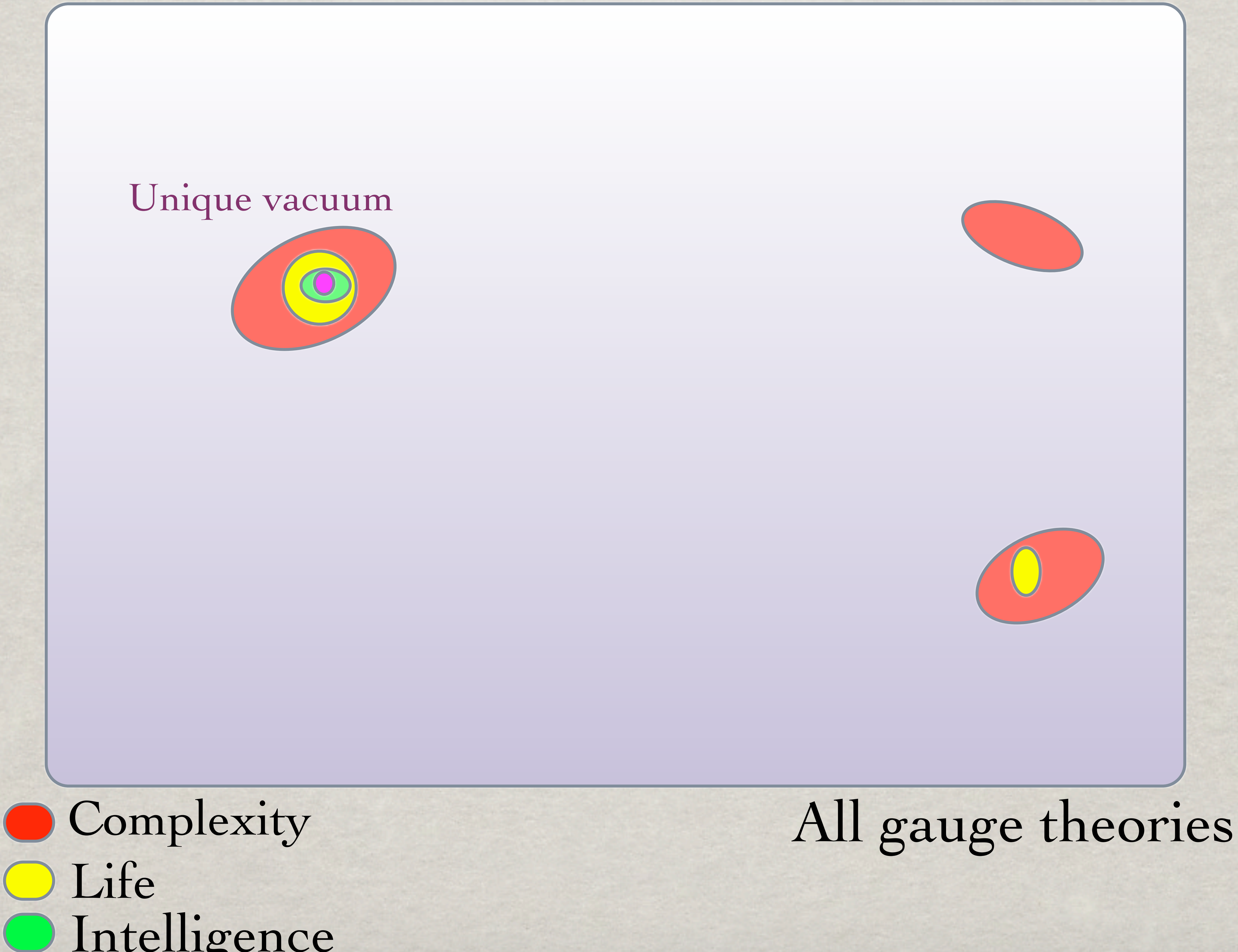

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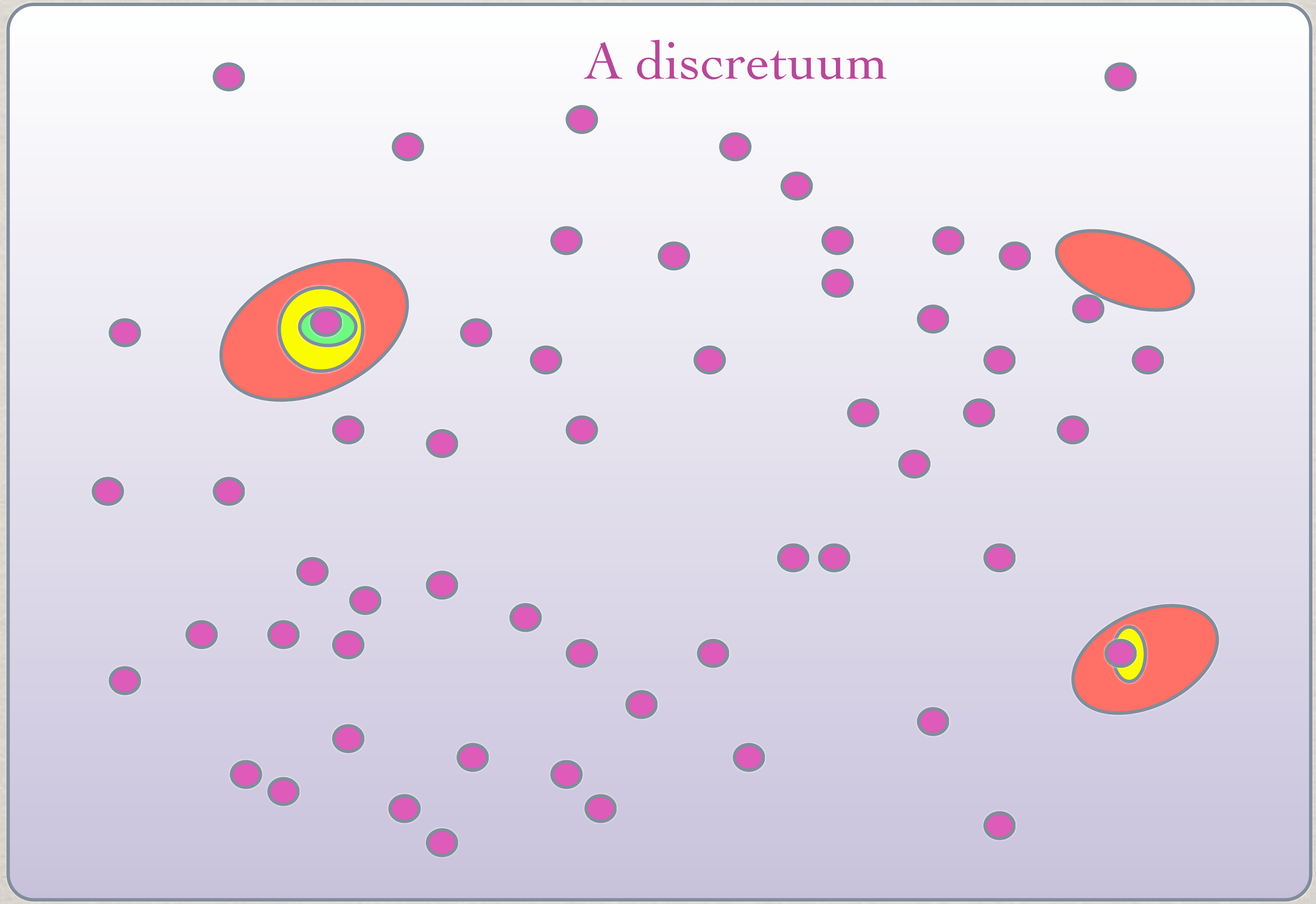

Complexity
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All gauge theories


Naar een waardig slot
Bert Schellekens

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

The Anthropic Principle

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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.

Anthropic Principles

- The SM gauge theory is not the only solution.
- Many others do not allow "life".
- There should be enough to understand why ours exist.
- Within anthropic regions, we can determine parameters using probabilities.

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,...

Summary:

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- A landscape of vacua is the only sensible outcome for a "Theory of Everything"

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- 4-D Quantum gravity implies that the SM is part of a huge landscape: an amazing conclusion! (if correct).

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)

- String Theory has never looked better...

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- ... but it has never looked harder.

Reasonable goals

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- 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

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

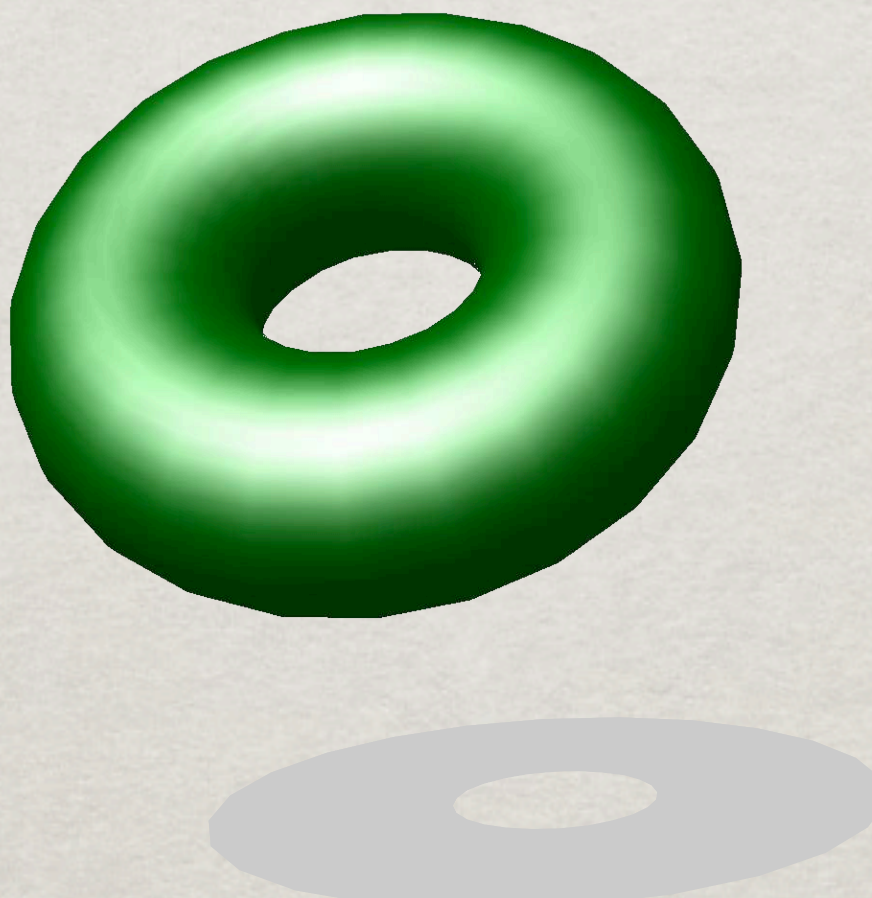
- Cvetic, Shiu, Uranga (2001)
  Supersymmetric SM-Spectra with chiral exotics

- 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



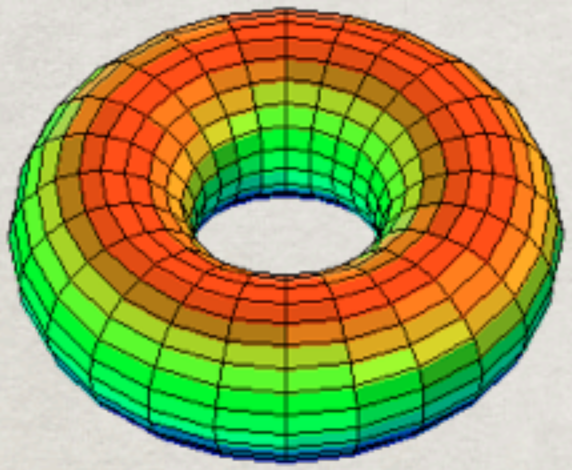
$$P(\tau, \bar{\tau}) = \sum_{ij} \chi_i(\tau) Z_{ij} \chi_j(\bar{\tau})$$

Type IIB

Orientifold Partition Functions

Orientifold Partition Functions

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



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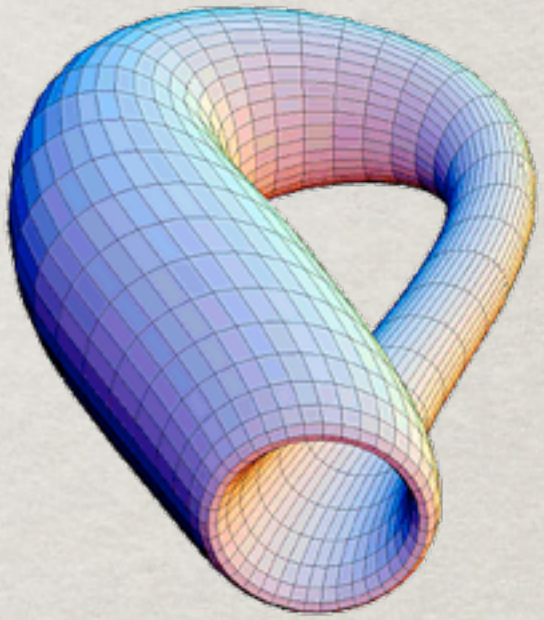

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Orientifold Partition Functions

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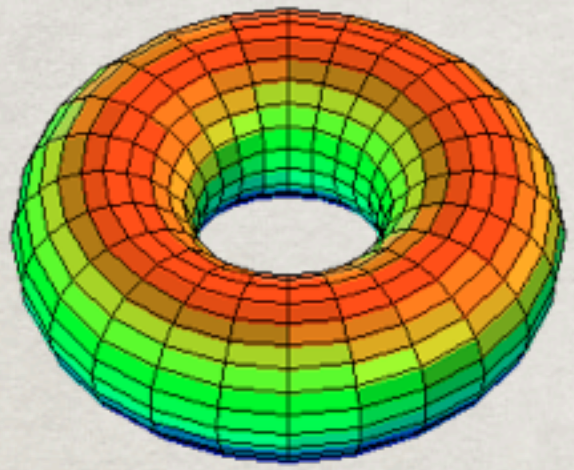

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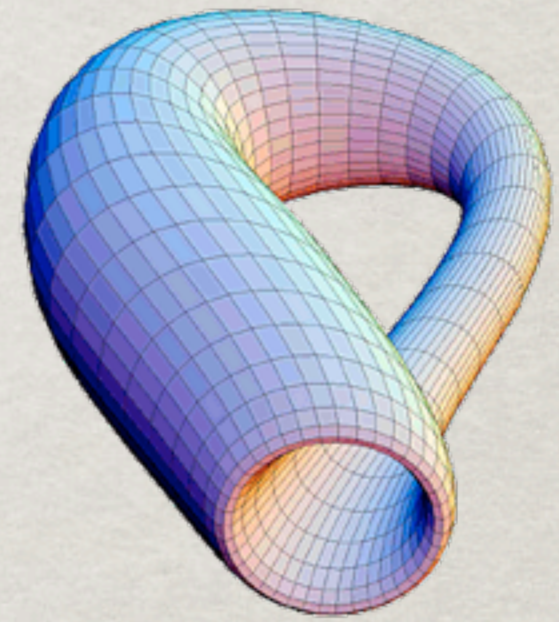

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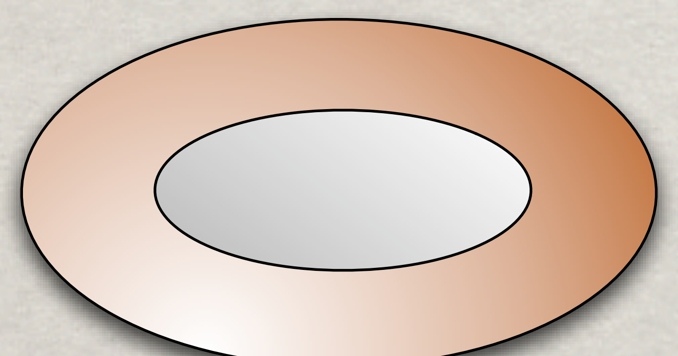

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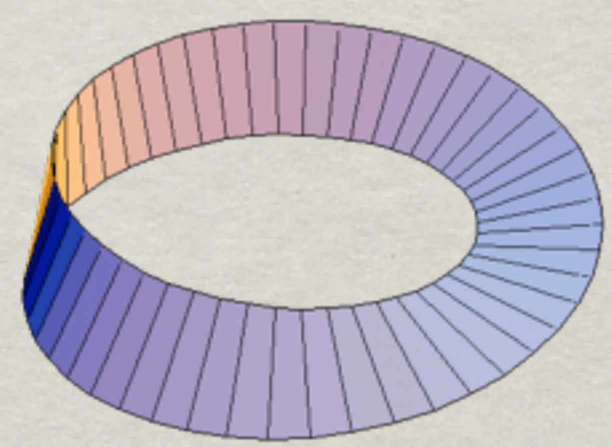

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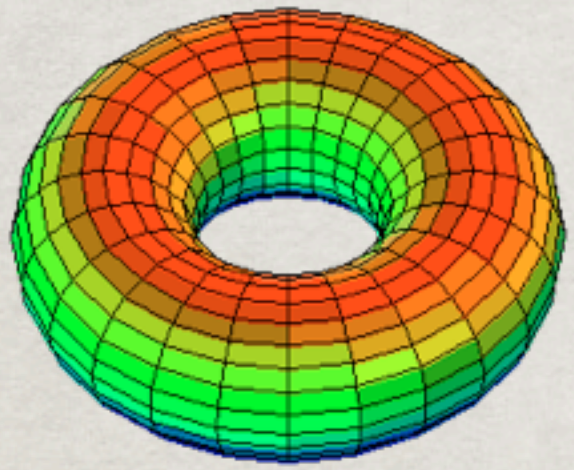

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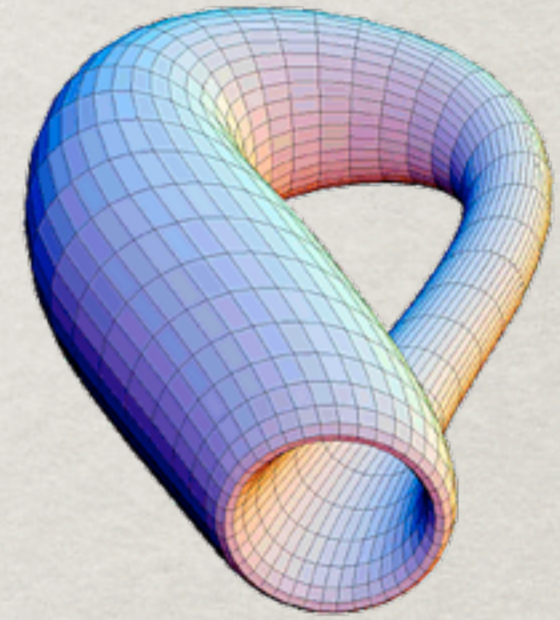

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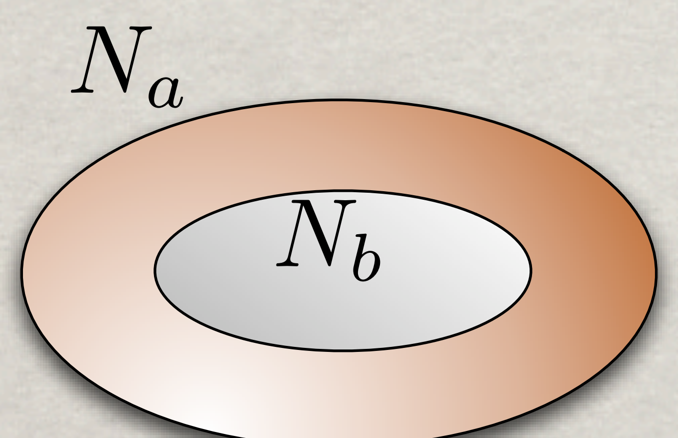

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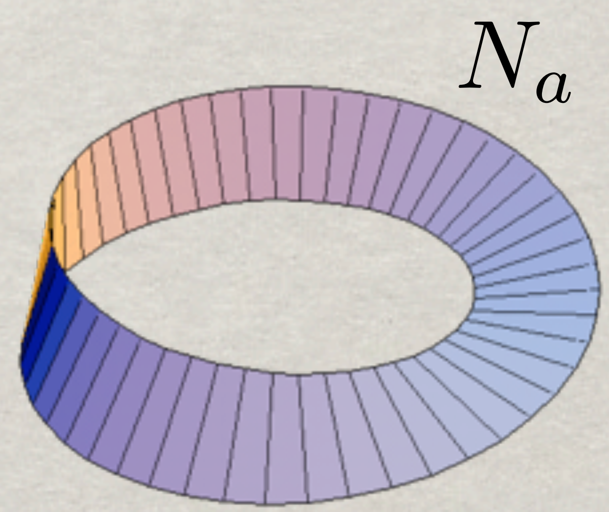

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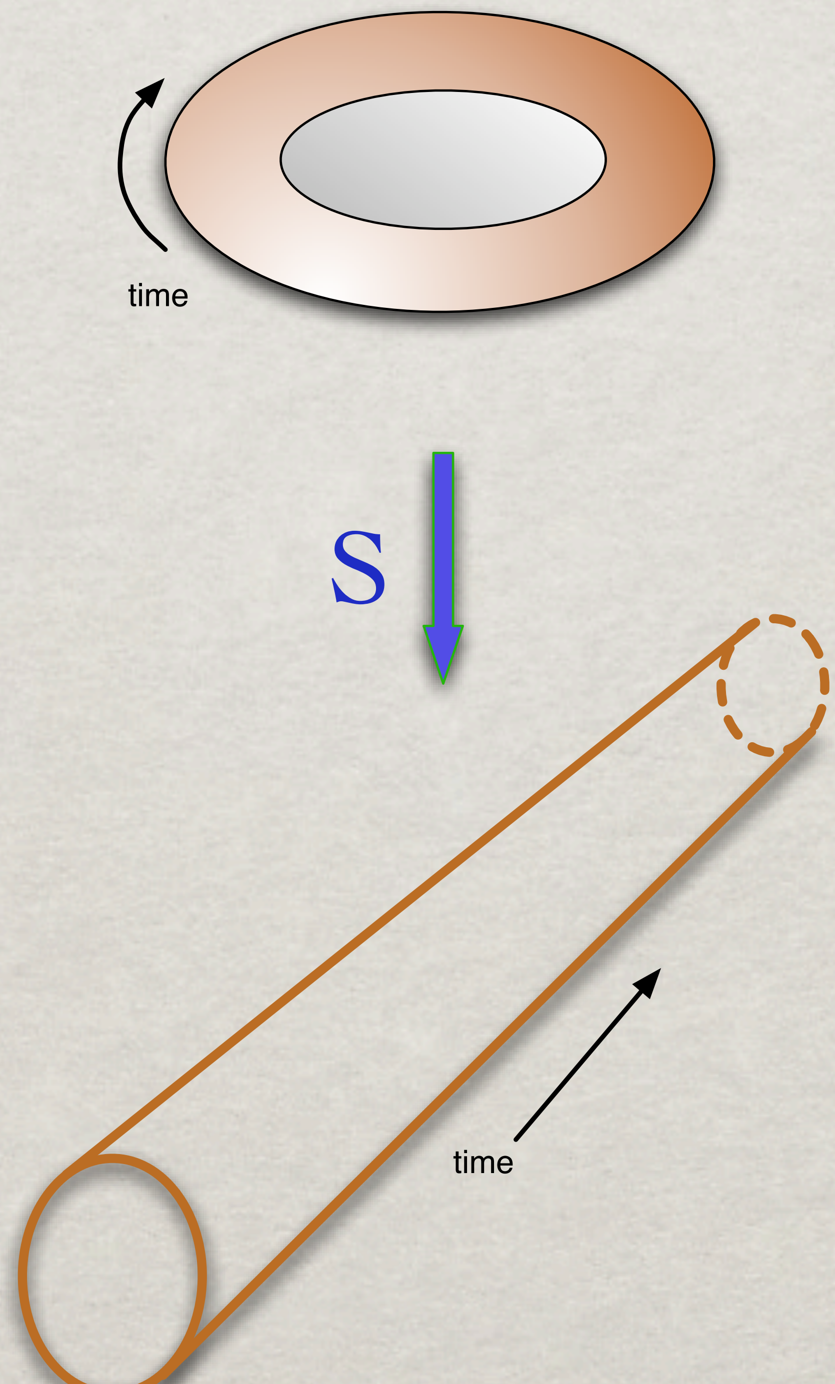
Transverse Channel



boundary state

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)
+ 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

TADPOLES & ANOMALIES

- Tadpole cancellation condition:

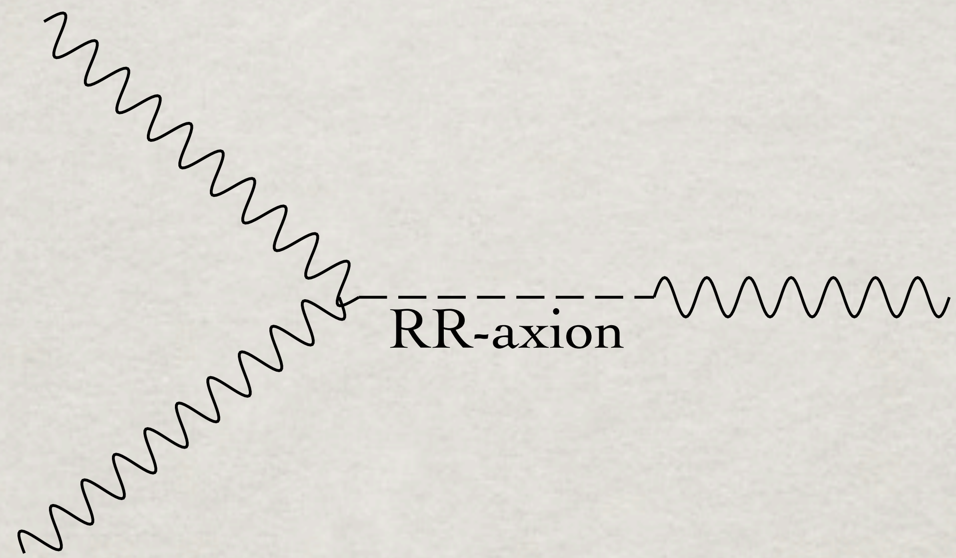
$$\sum_b N_b R_{b(m,J)} = 4\eta_m U_{(m,J)}$$

- 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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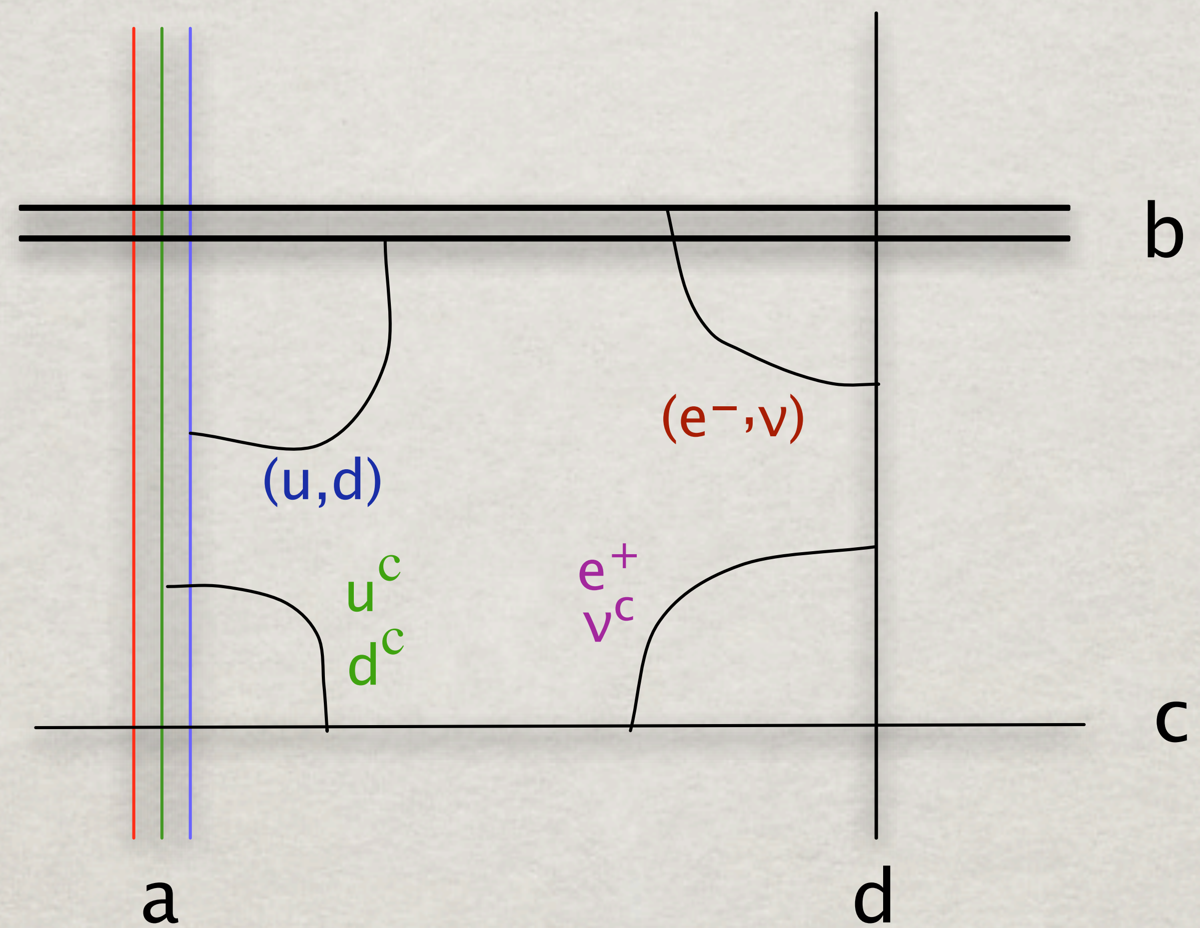
Essential to decide what to search for!

What to search for

The Madrid model



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

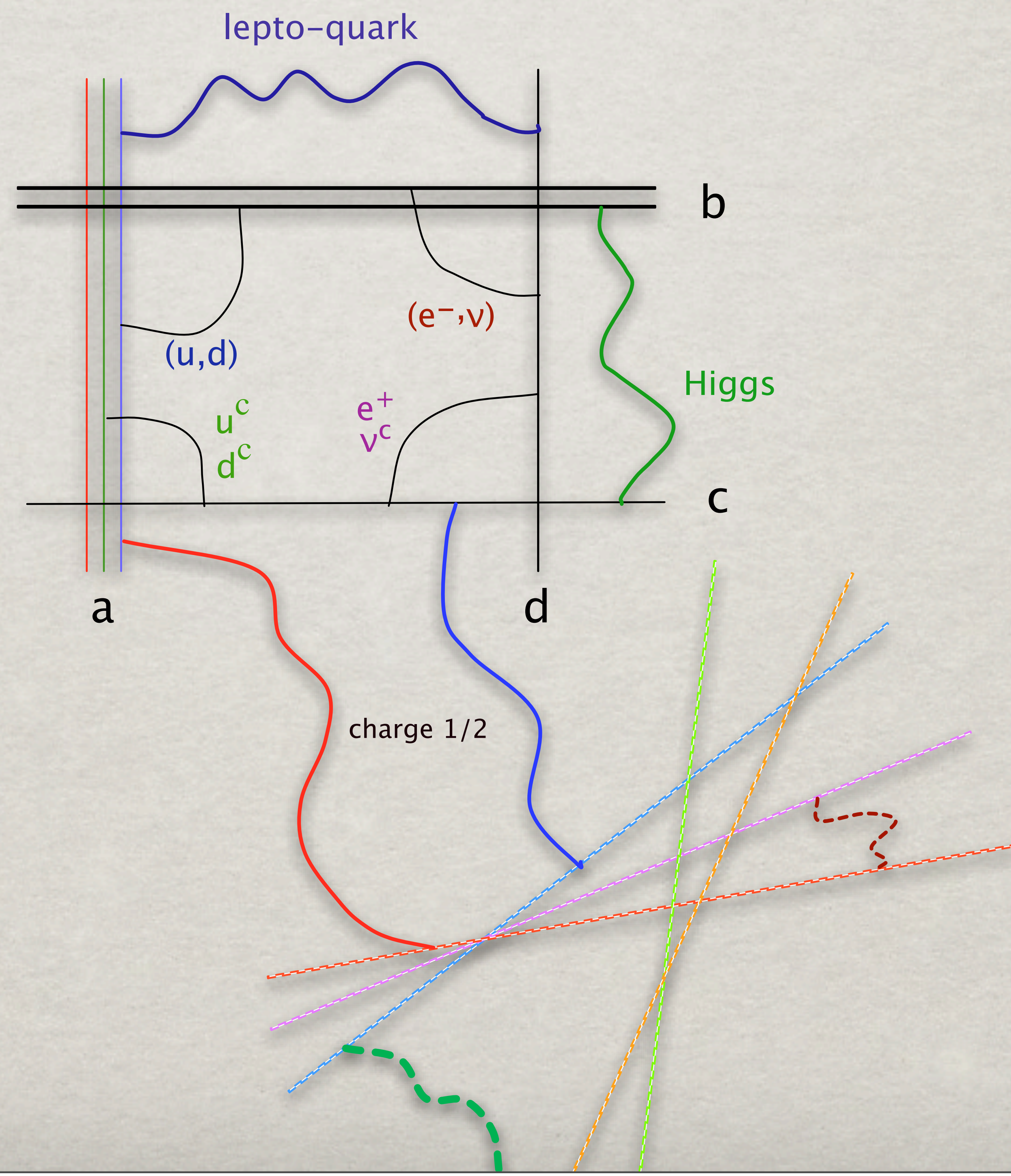
$$3(u,d)_L + 3u_L^c + 3d_L^c + 3(e^-,\nu)_L + 3e_L^+$$

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

+ 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"

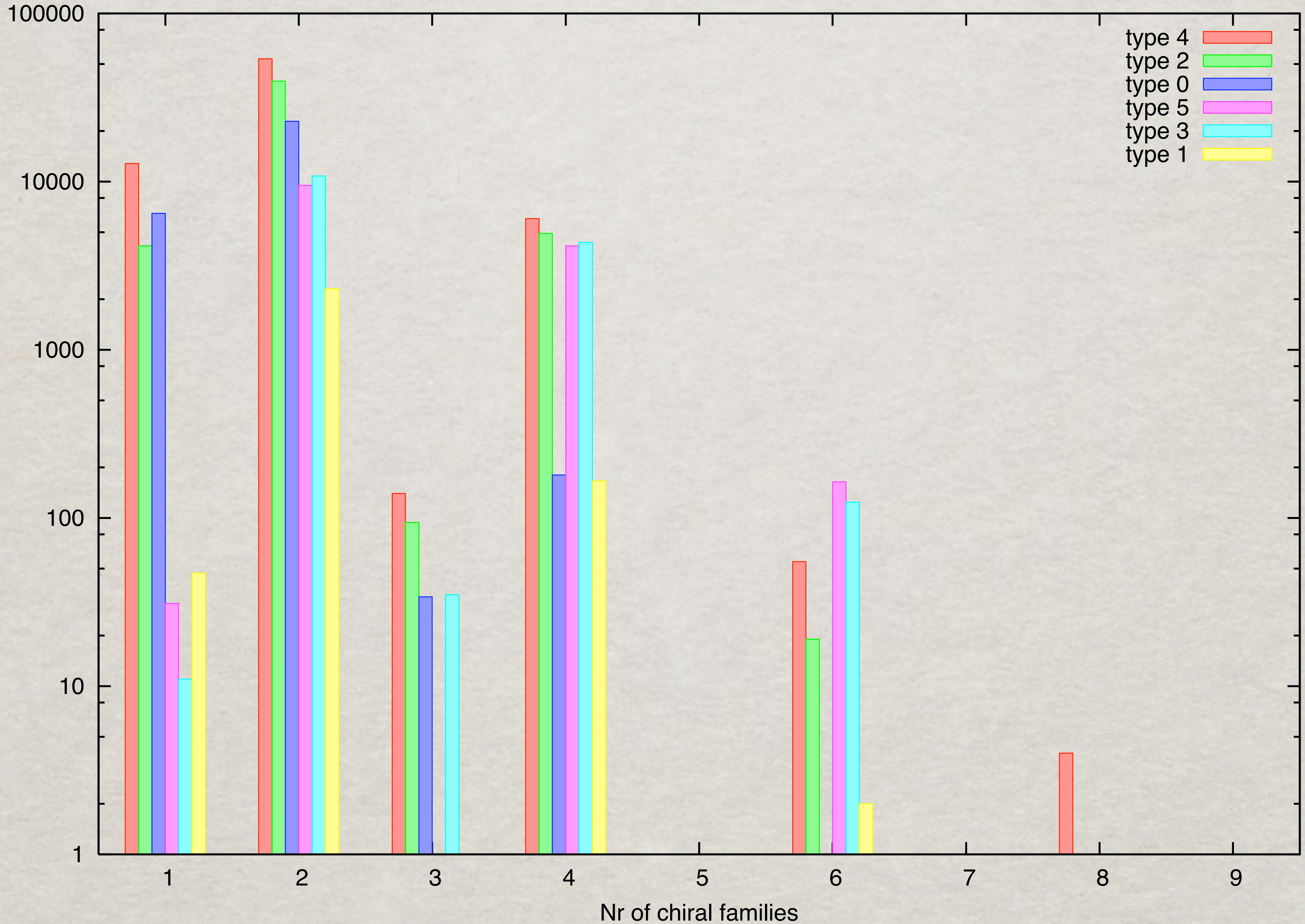
```
Standard model type: 6
Number of factors in hidden gauge group: 0
Gauge group: U(3) x Sp(2) x U(1) x U(1)

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
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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

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. Schellekens

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

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

Embedding of Y:

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

Q: Brane charges (for unitary branes)

W: Traceless generators

Classification

$$Y = (x - \frac{1}{3})Q_a + (x - \frac{1}{2})Q_b + \underbrace{xQ_C + (x-1)Q_D}$$

Distributed over c and d

Allowed values for x

1/2	Madrid model, Pati-Salam, Flipped SU(5)
0	(broken) SU(5)
1	Antoniadis, Kiritsis, Tomaras
-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

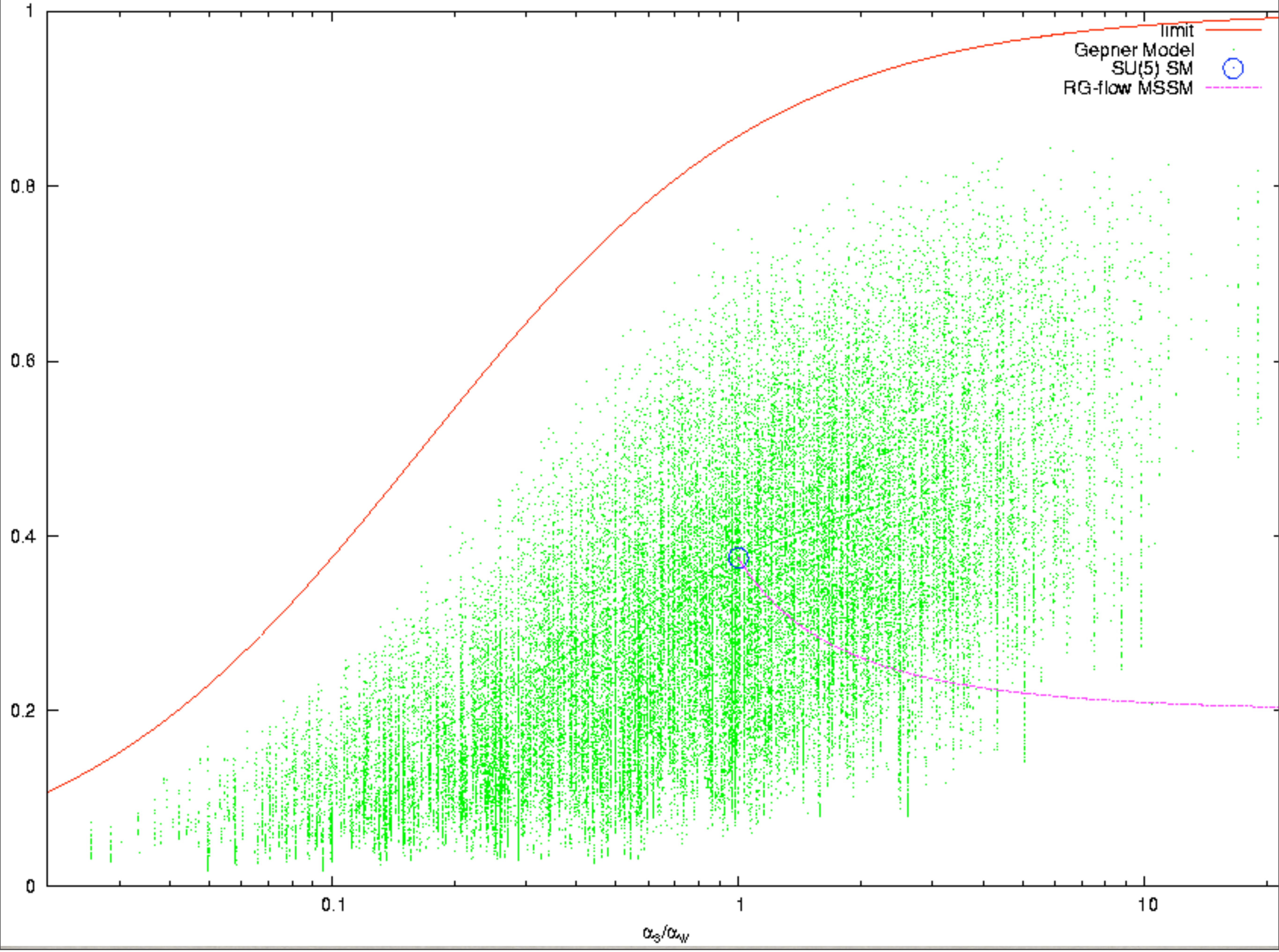
- Searched all MIPFs with $<$ 1750 boundaries (4557 of 5403 MIPFs)
- 19345 chirally different SM embeddings found
- Tadpole conditions solved in 1900 cases (18 "old" ones)

Statistics

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

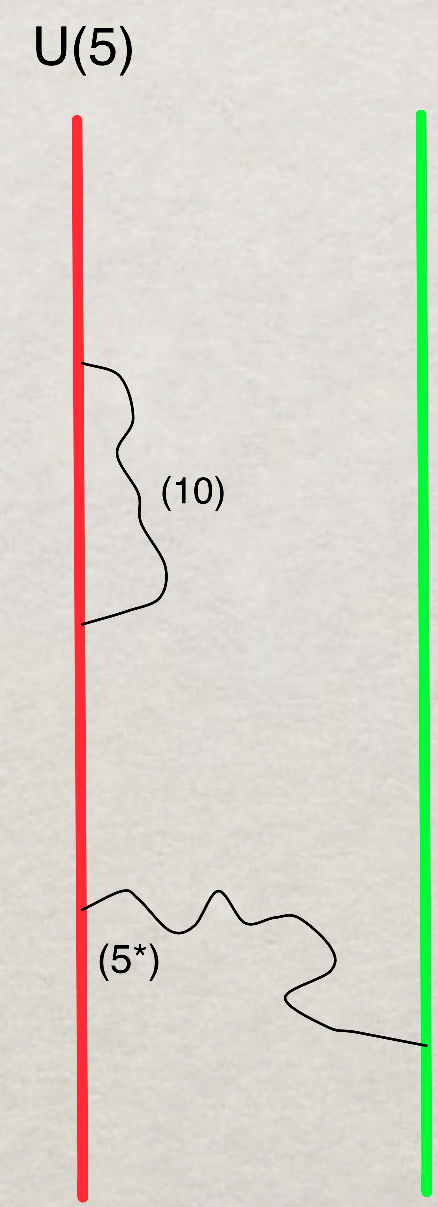
*Previous search: 45051902

Unification



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)