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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- Then some experimental problems arise:
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  - 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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- But there is another revolution most people preferred to overlook: The string vacuum 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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We would like to thank B. Nilsson for discussions.

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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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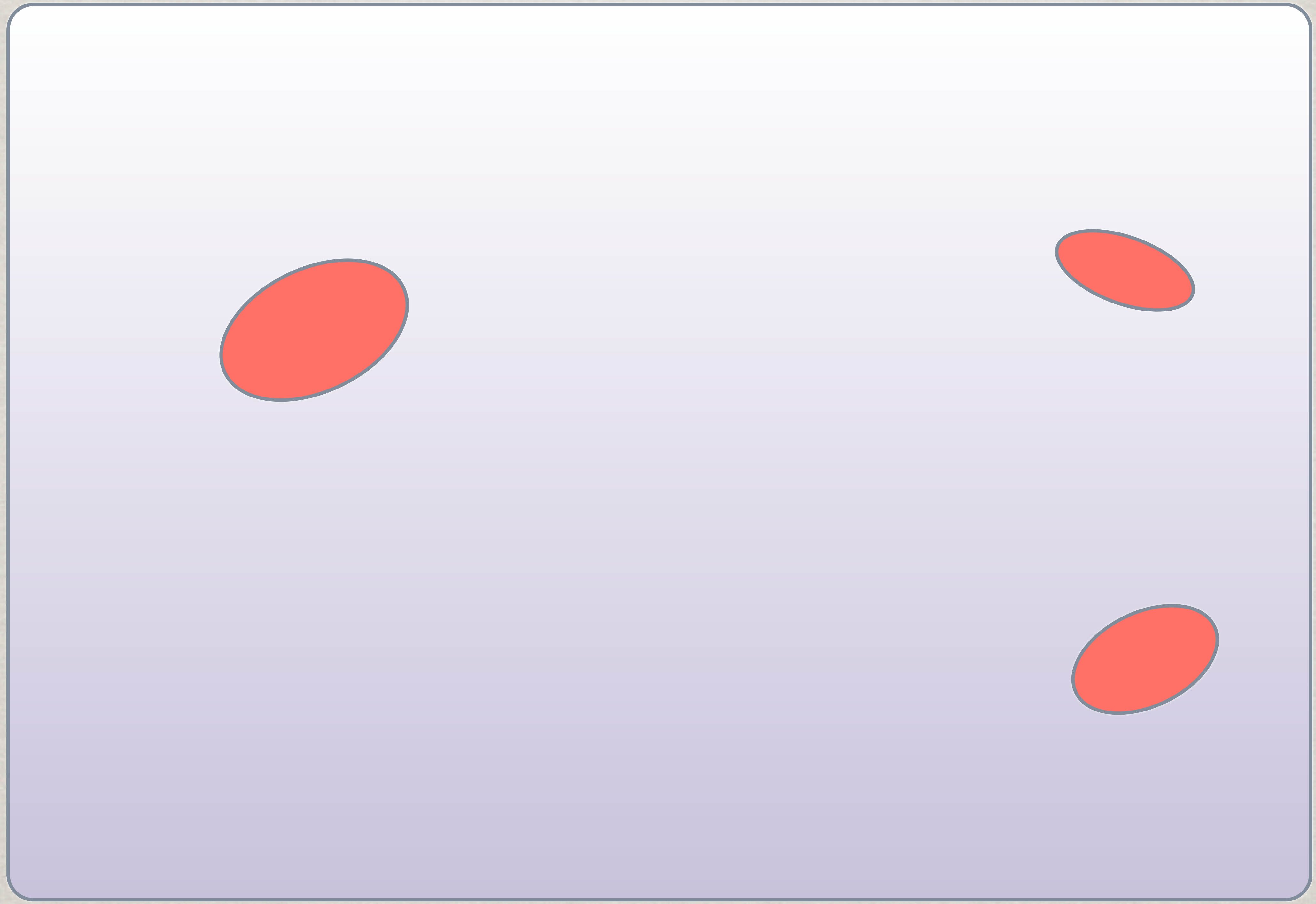

Complexity

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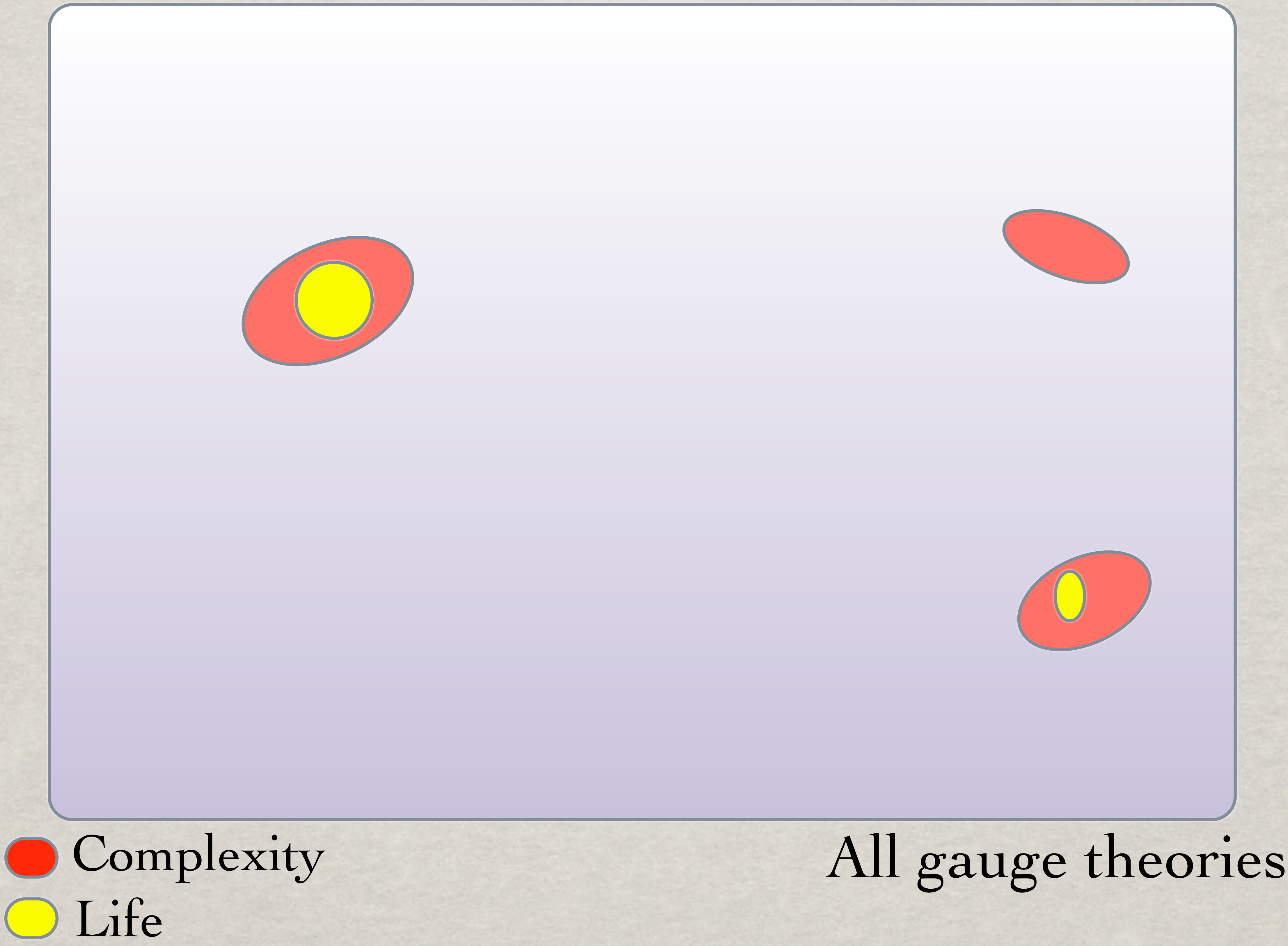

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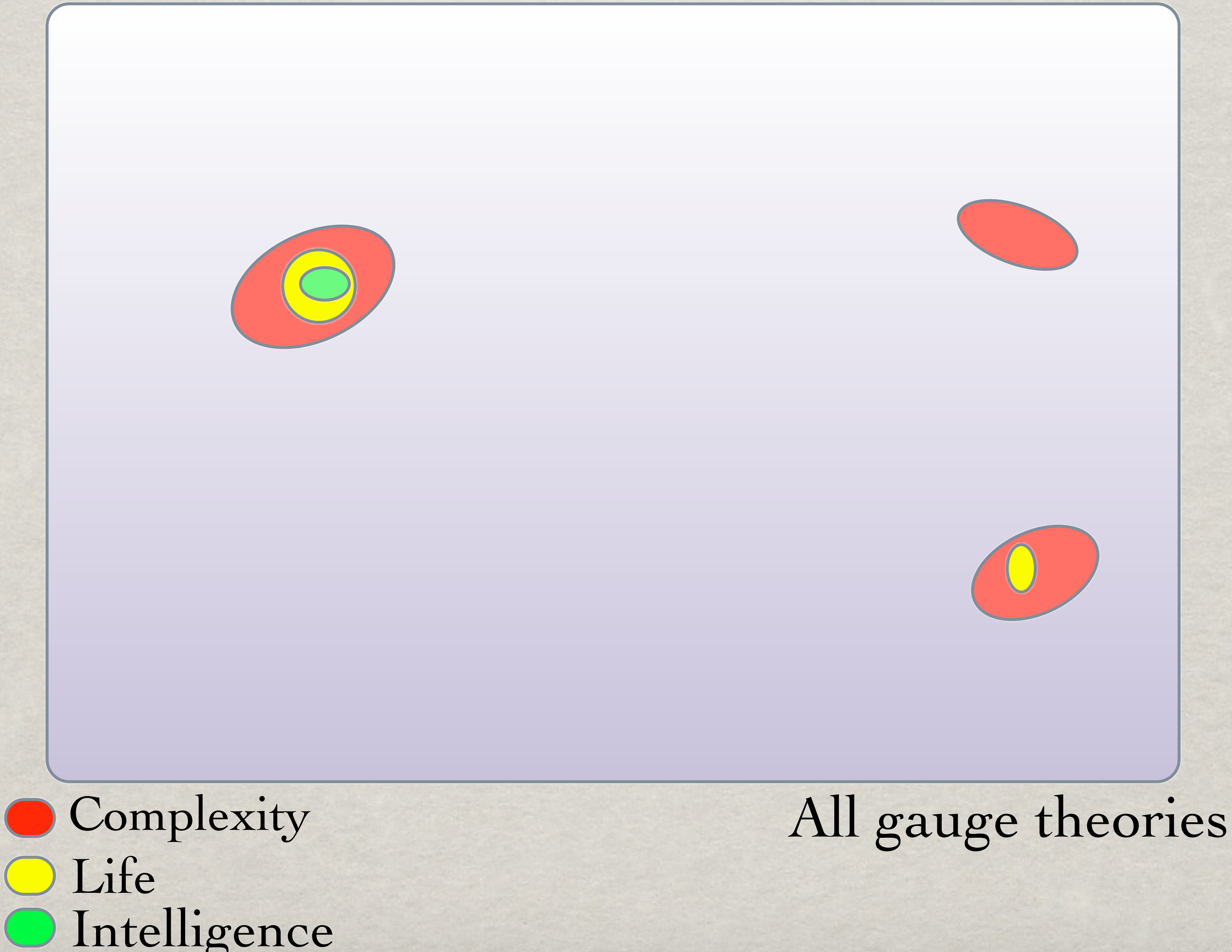

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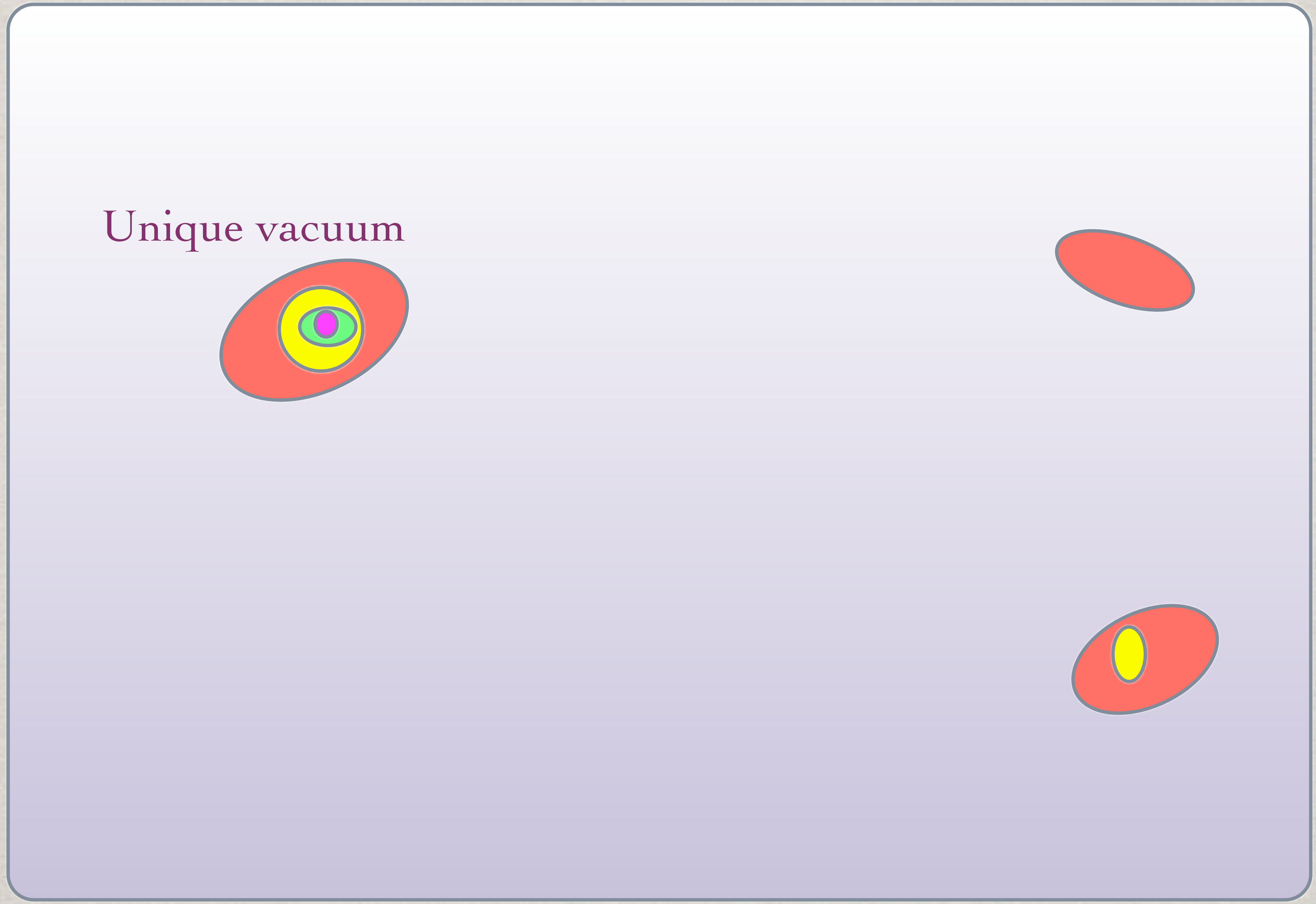

Complexity

Life

Intelligence

All gauge theories

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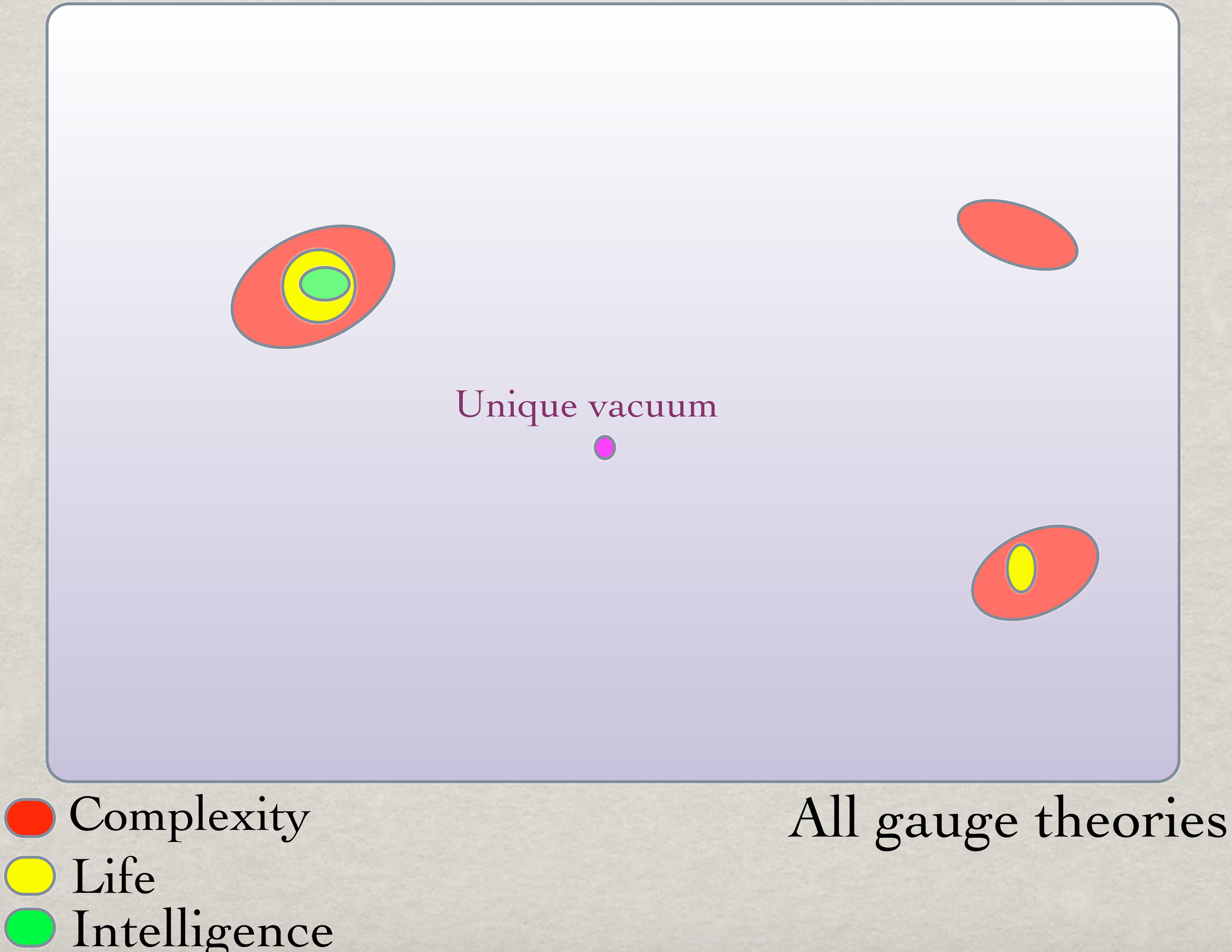

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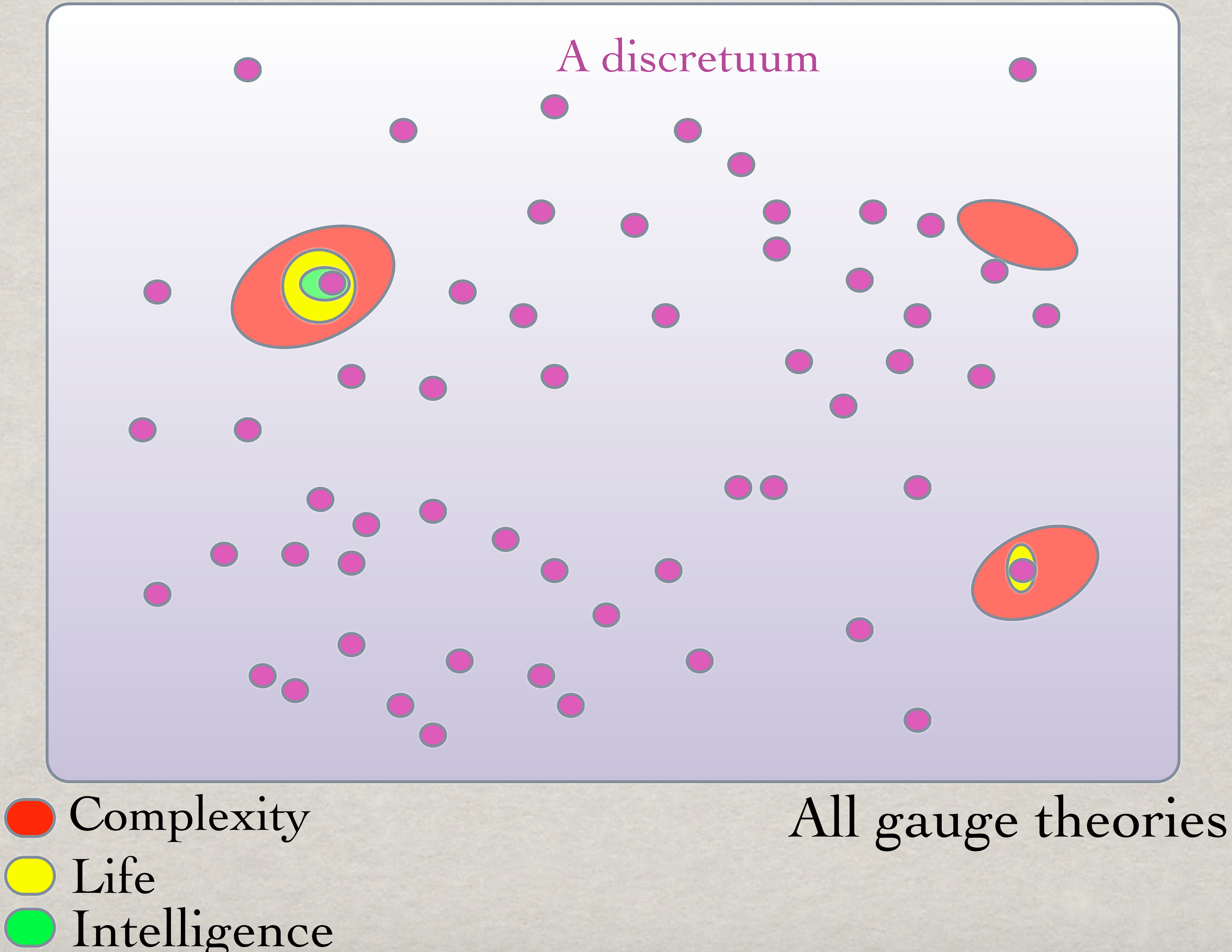


Naar een waardig slot
Bert Schellekens

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

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The Anthropic Principle

- Most formulations are nonsense. (including statements by Brandon Carter, Barrows & Tippler).
- Does not make sense without String Theory (or better) or Eternal Inflation (or equivalent).
- Is an inevitable consequence of String Theory.
- Incredibly, the papers relating String Theory and the Anthropic principle during last century can be counted on the fingers of one hand.
- 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.

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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  - Chiral Fermions (without anomalies)
  - The Standard Model gauge group
  - Three Families
  - Couplings of reasonable size
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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)
- 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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- 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

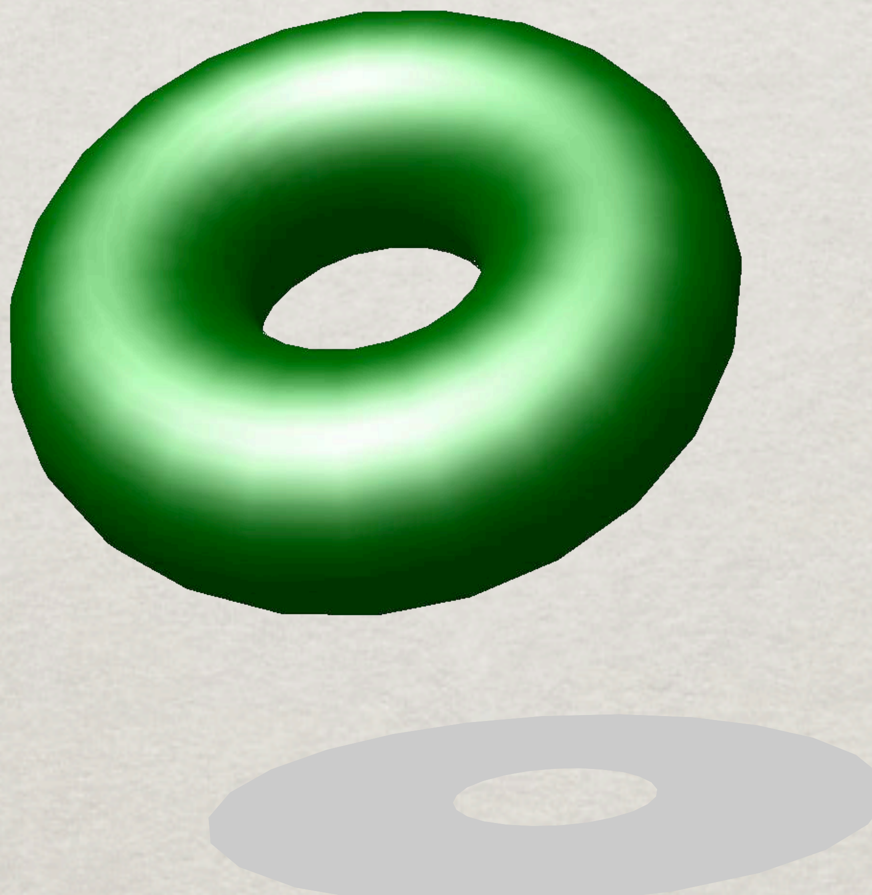
- Cvetic, Shiu, Uranga (2001)
  Supersymmetric SM-Spectra with chiral exotics

- 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

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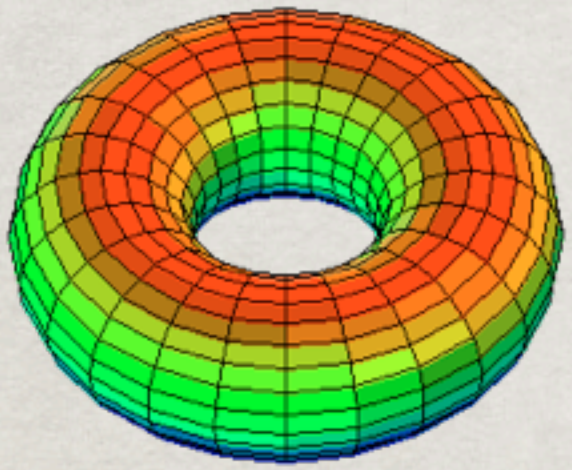
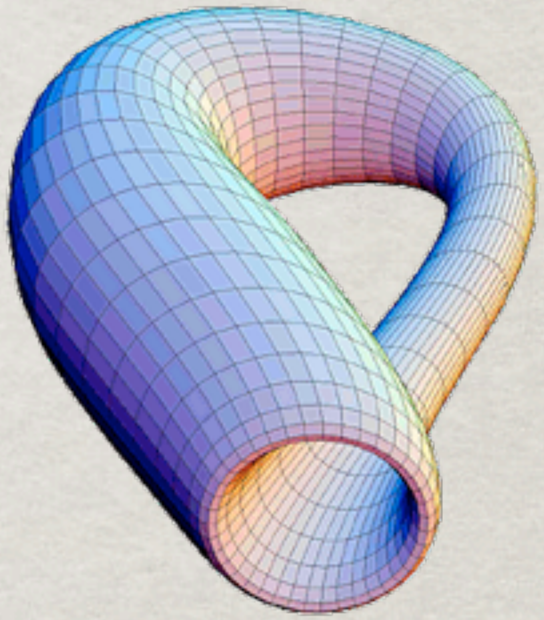
$\frac{1}{2}\Big\{$  $+$  $\Big\}$

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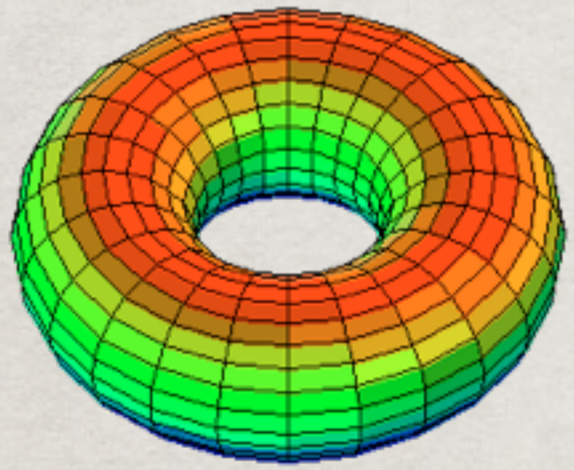
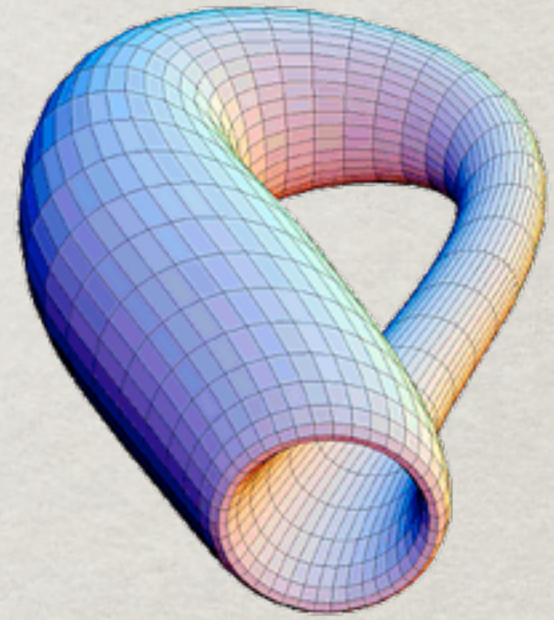
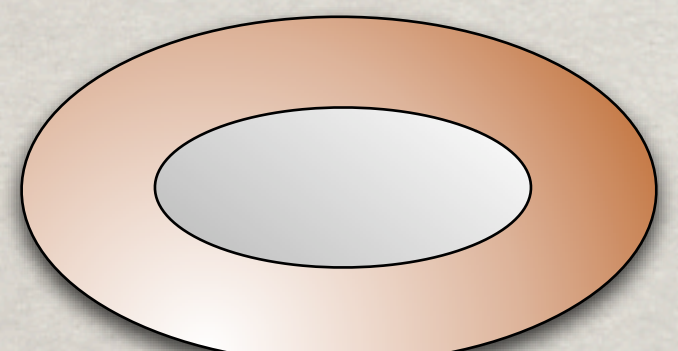
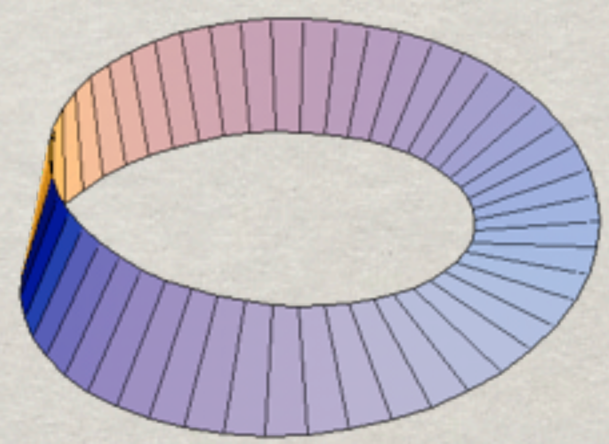
$\frac{1}{2}\Big\{$  $+$  $\Big\}$

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

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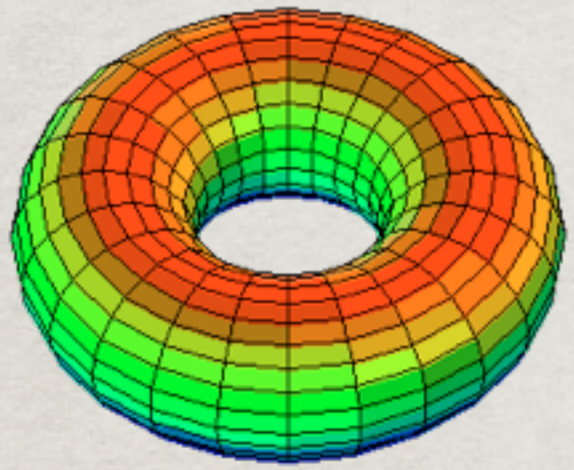

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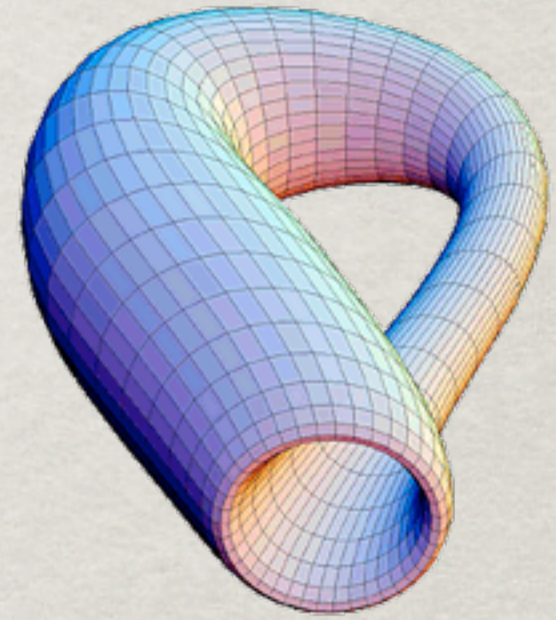

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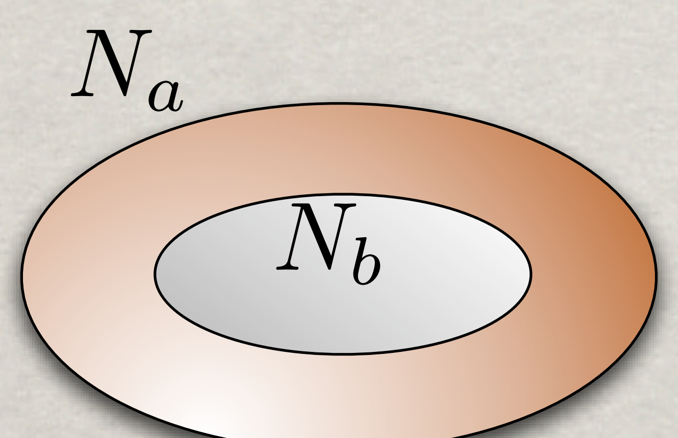

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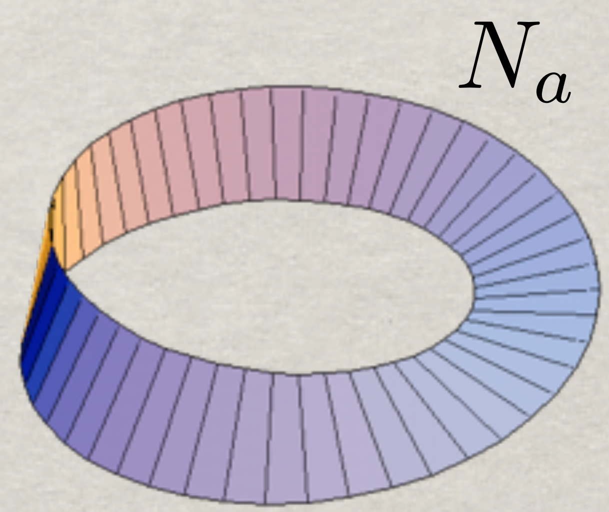

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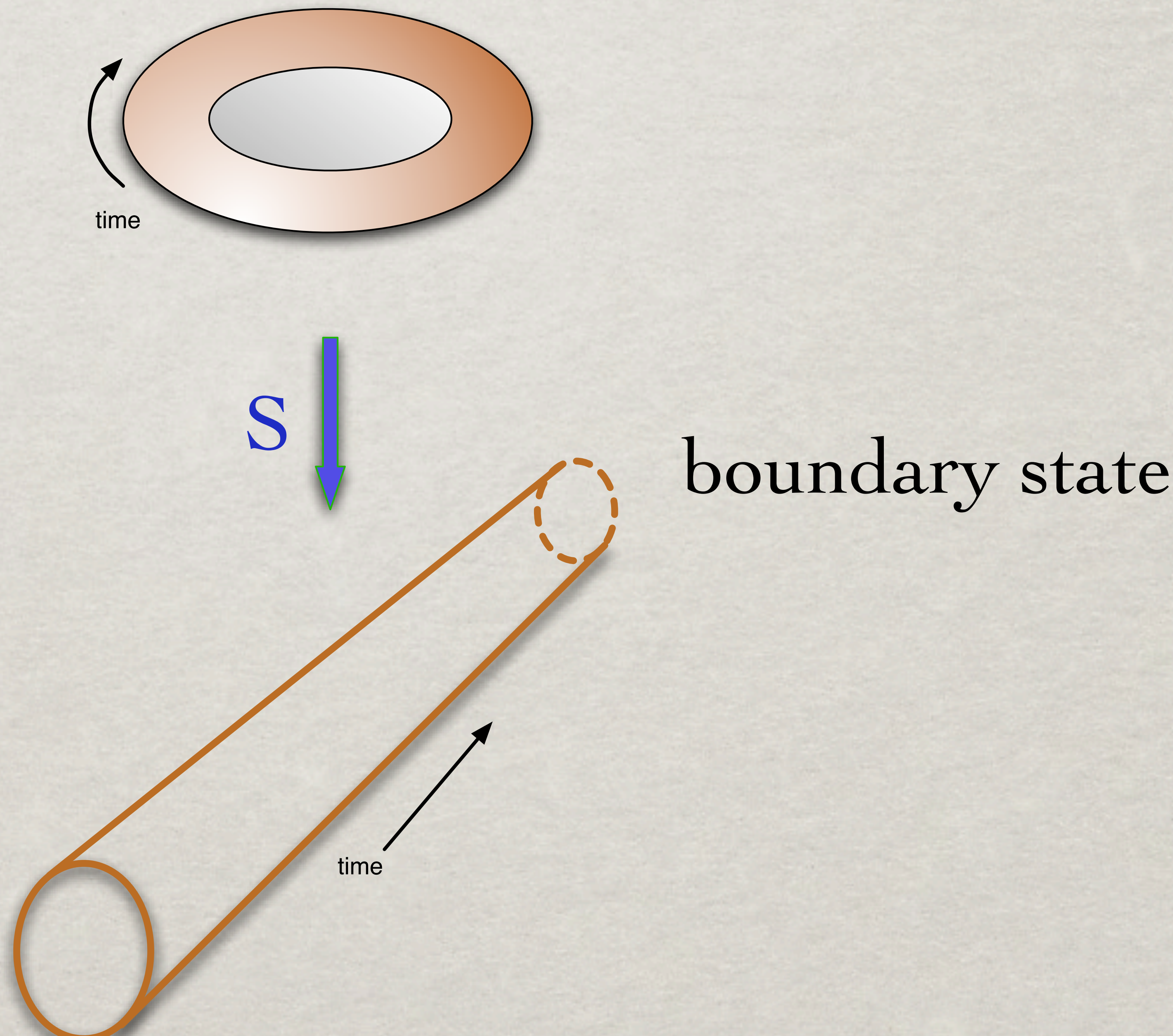
Transverse Channel



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:

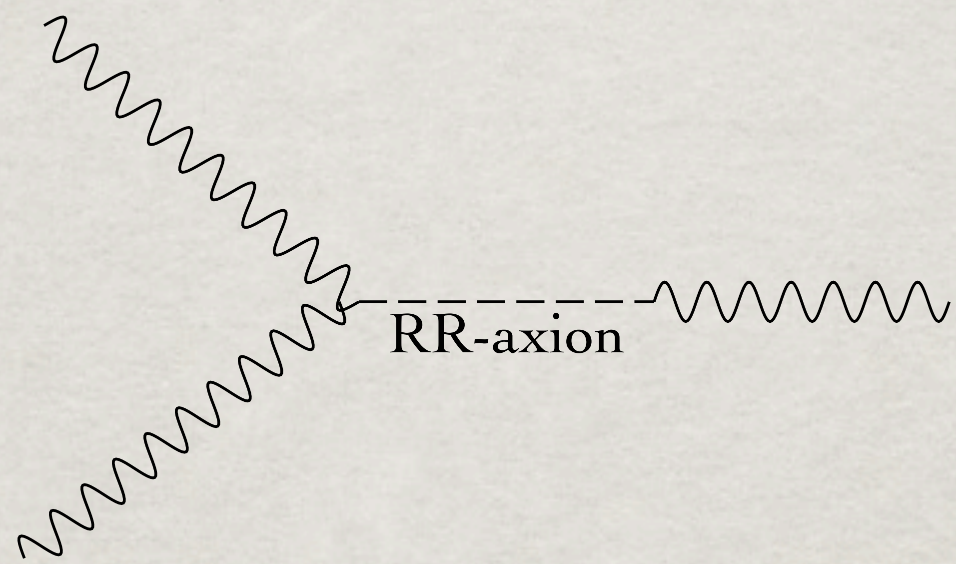
$$\sum_b N_b R_{b(m,J)} = 4\eta_m U_{(m,J)}$$

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

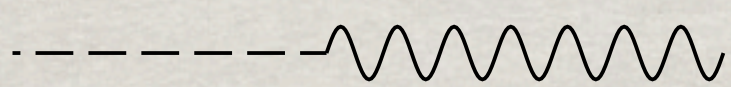
**Gato-Rivera, Schellekens (2005)*

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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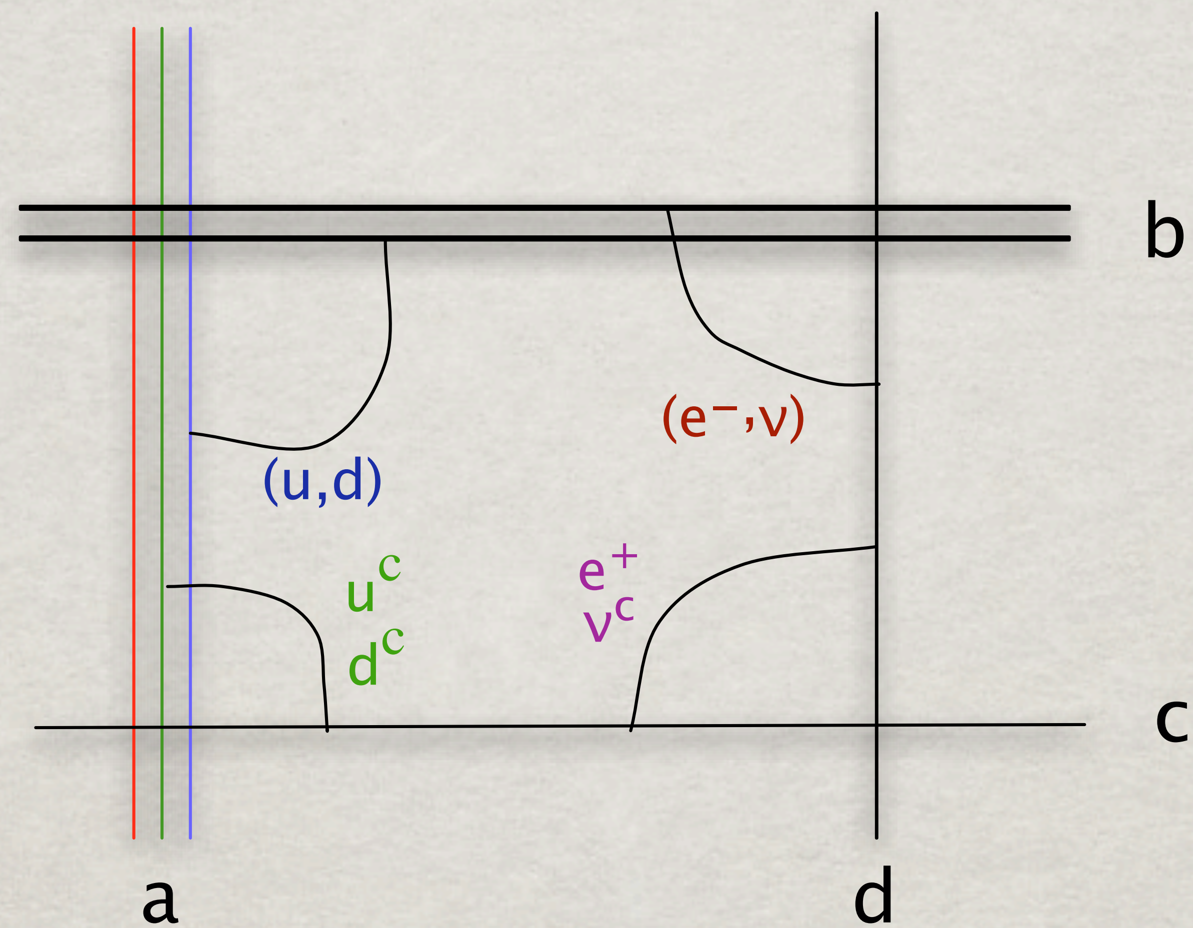
Essential to decide what to search for!

What to search for

The Madrid model



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

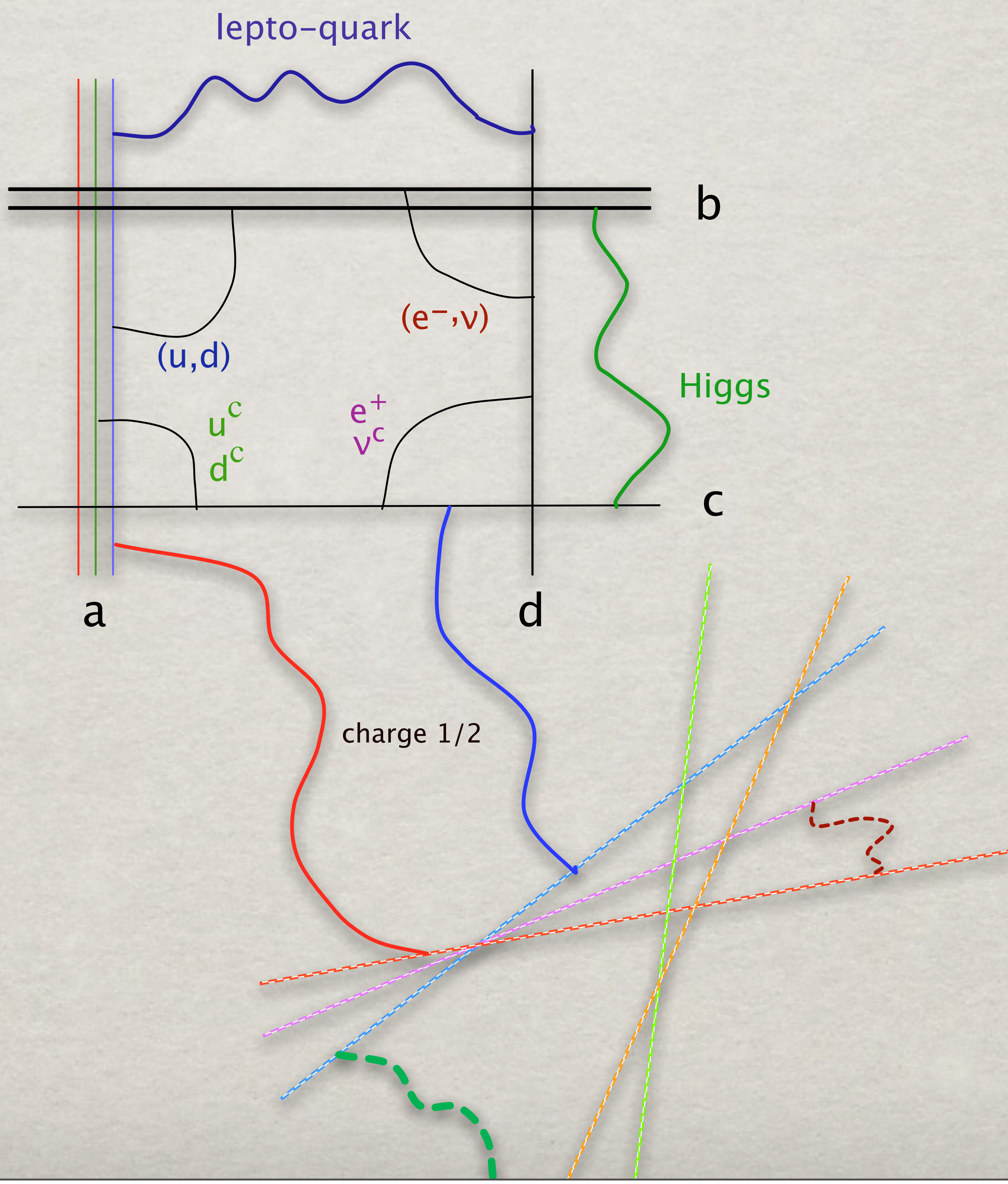
$$3(u,d)_L + 3u^c_L + 3d^c_L + 3(e^-,\nu)_L + 3e^+_L$$

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

+ 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"

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

Summary for each model | Filter

```
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)
```

$\sin^2(\theta_w) = .3610368$

$$\frac{\alpha_3}{\alpha_2} = .8660246$$

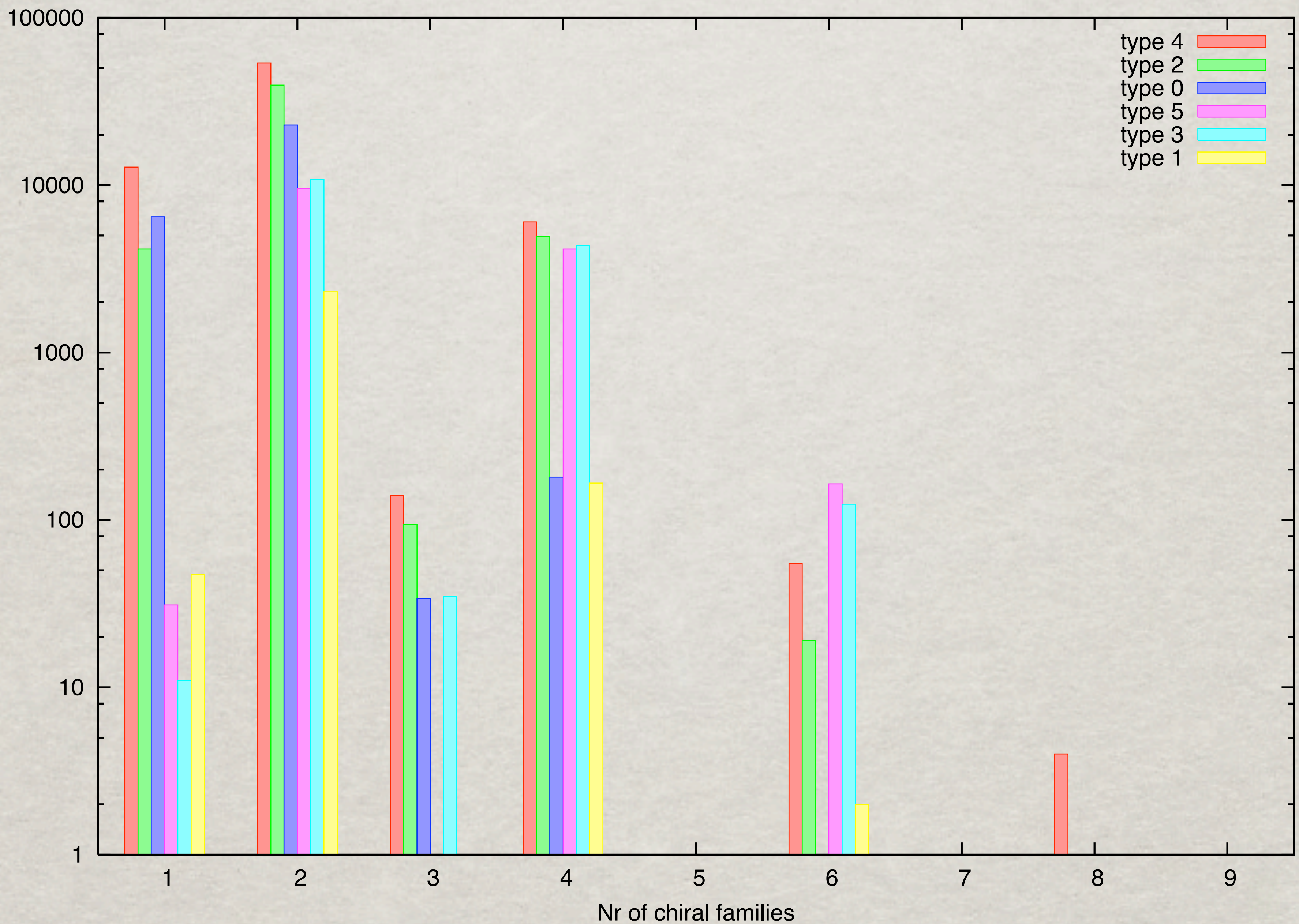
```
Standard model type: 6
Number of factors in hidden gauge group: 0
Gauge group: U(3) x Sp(2) x U(1) x U(1)

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 -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 )
```

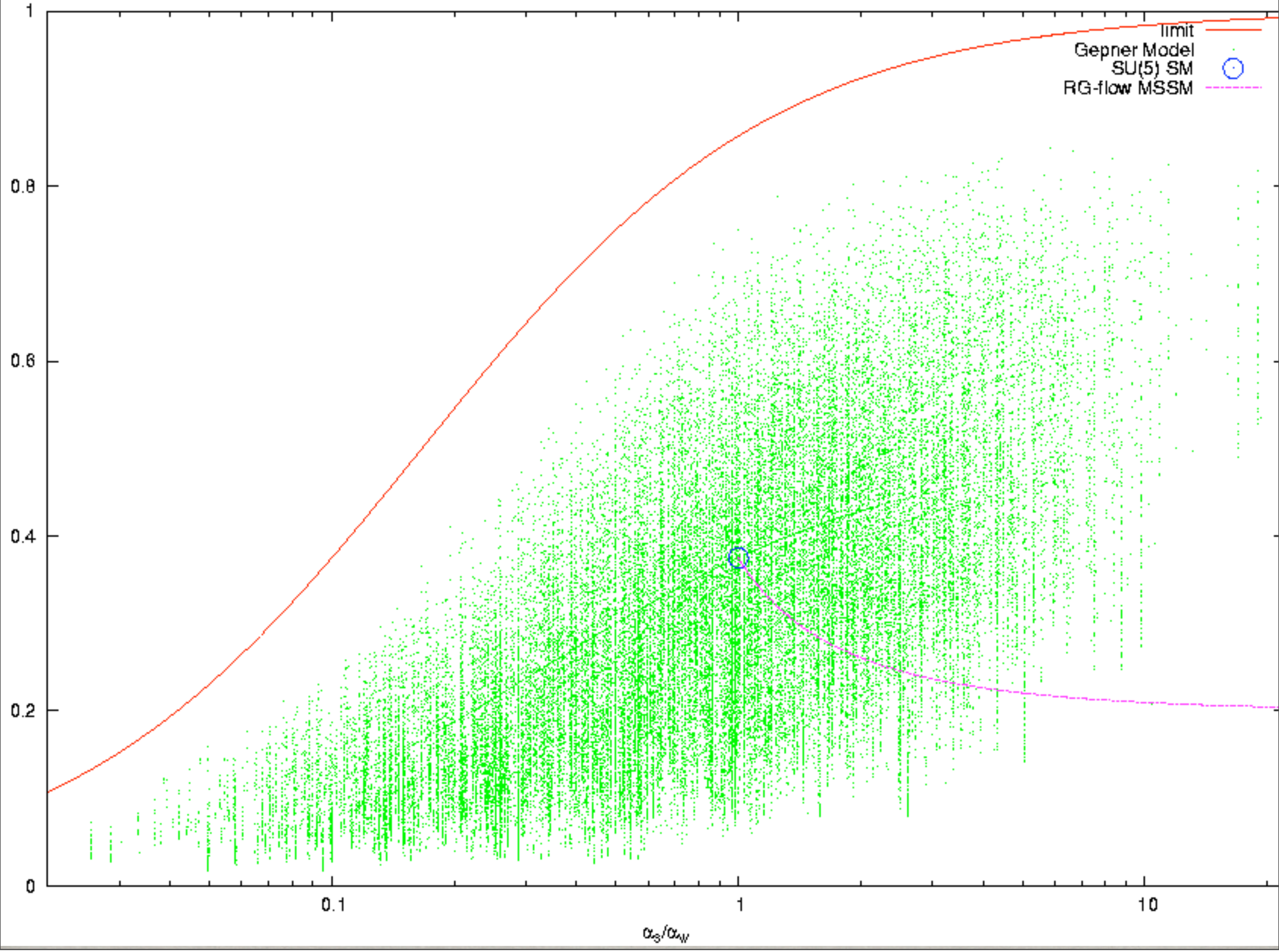
....

```
    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)
```

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

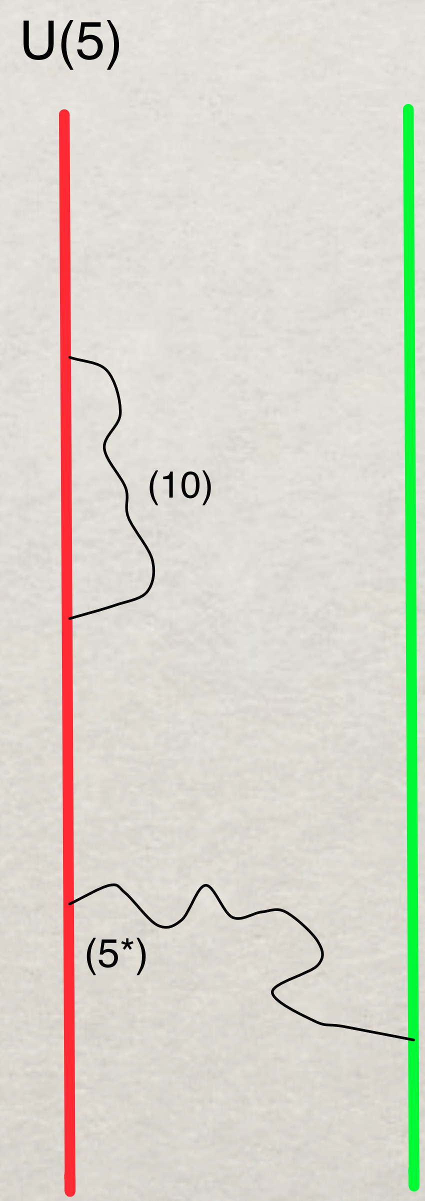
$$\frac{\alpha_3}{\alpha_2} = 3.2320501$$


100000
10000
1000
100
10
1
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
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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Examples exist of chiral orientifold SSM spectra exist

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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)