Probing the String Landscape: Implications, Applications, and Altercations

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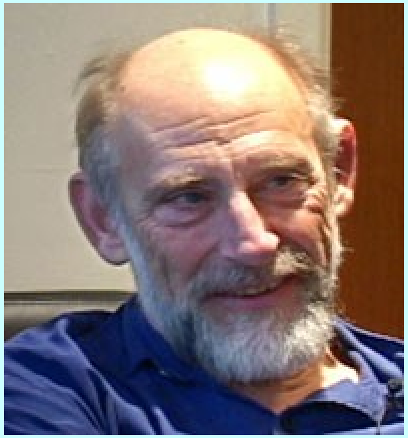
“What we've discovered in the last several years is that string theory has an incredible diversity—a tremendous number of solutions—and allows different kinds of environments. A lot of the practitioners of this kind of mathematical theory have been in a state of denial about it. They didn't want to recognize it. They want to believe the universe is an elegant universe—and it's not so elegant. It's different over here. It's that over here. It's a Rube Goldberg machine over here. And this has created a sort of sense of denial about the facts about the theory. The theory is going to win, and physicists who are trying to deny what's going on are going to lose.”



Leonard Susskind
Felix Bloch Professor of Theoretical Physics
Stanford University

Rules for Giving a Good Physics Colloquium

- Physicists are scientists. Show lots of data from expensive experiments using the latest cutting-edge technologies.
- Physicists are conservative. Stick to the facts, and avoid unnecessary speculation.
- Physicists are logical. Adhere to a straight logical line, with each result building on the previous one.
- Physicists are objectivists, dealing in universal truths and fundamental laws. There is no room for the personal opinions (much less biases) of the speaker.
- Physicists are smart

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- Physicists are only human. Like everyone else, they like a good conclusion, a firm punchline, a tidy final lesson to take away.

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- Can the ground state of a theory be completely irrelevant to that theory? Are we deluding ourselves by always focusing on the vacuum?
- What is the boundary between explanation and observation?
- How can we judge when a theory is “natural”? How can we judge whether one theory is more “natural” than another?
- What does it mean for a theory to be predictive? Falsifiable?
- What kinds of numbers should a fundamental theory of physics be capable of predicting?
    - The mass of the electron? The radius of the Earth's orbit around the Sun? The price of tea in China?
- What tools are we allowed to use in formulating a scientific theory?
    - Results of experiments? Theoretical expectations? *Ourselves?*
- Are we, once again, destined to be the center of the universe?
- To what extent can one talk meaningfully about alternative universes? Are all possible universes created equal?
- Is the number of possible universes finite or infinite? Is this even knowable? Does it matter?
- Is theoretical particle physics destined to become a branch of cosmology?

This doesn't sound like physics!

It sounds like...

Philosophy of physics

Sociology of physics

The first steps on the
slippery path to **Social science!**

The point is: We are currently in the throes of a potentially huge paradigm shift in physics.

My goal in this colloquium is to explain what this is, and where it came from.

No tidy outcome yet. Instead, I'll just try to convey the sense of excitement and frustration that many in the string community are currently facing.

Outline

- Some “standard” particle physics
- Some “Beyond-the-Standard” particle physics
- The Landscape

- Some sample explorations of the Landscape

- Cautionary tale: Counting is hard
- Cautionary tale: Not all vacua are vacua
- Natural versus unnatural
- Is string theory predictive? Should it be?
- The Multiverse and the A-word
- The Big Questions: brief overview followed by an audience free-for-all

The Standard Model: What we do believe is true today?

The goal of high-energy physics has always been to uncover the fundamental “elements” or building blocks of the natural world:

- The fundamental *particles* that make up the *matter*
- The fundamental *forces* that describe their *interactions*

In this way, we hope to expose the underlying laws of physics in their simplest forms…

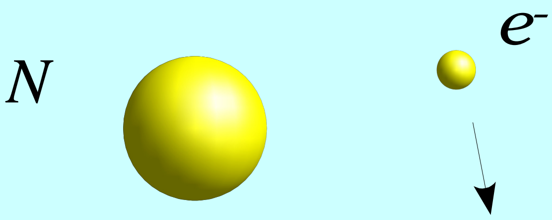
But what is “fundamental”?

- Biology: cell → nucleus → DNA
- Chemistry: compounds → molecules → atoms
- Physics: ??

What is fundamental to a physicist?

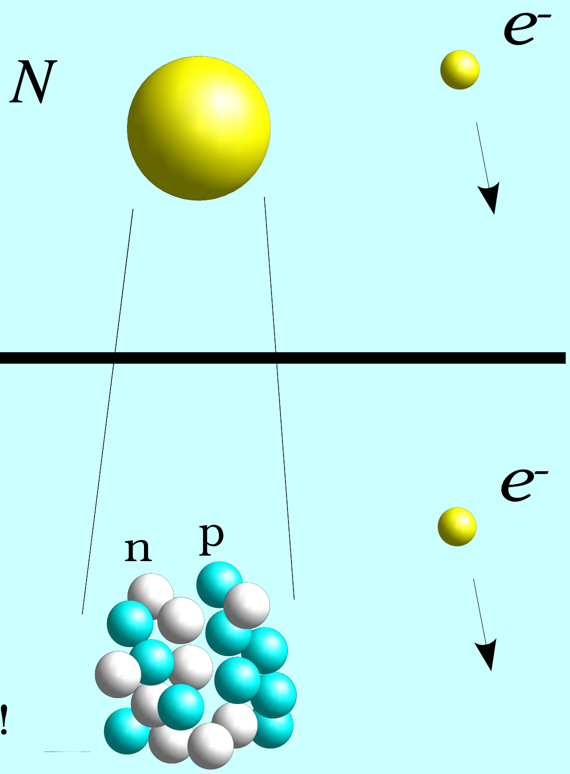
Answer: Depends on energy scale!
Recall: energy scale ↔ (length scale)$^{-1}$
Units: 1 eV = 1.6 x 10^{-19} Joules ↔ (2000 Angstroms)$^{-1}$

eV scale: atoms: *nuclei* plus electrons



But there are many different *types* of atoms/nuclei!

eV scale: atoms: *nuclei* plus electrons



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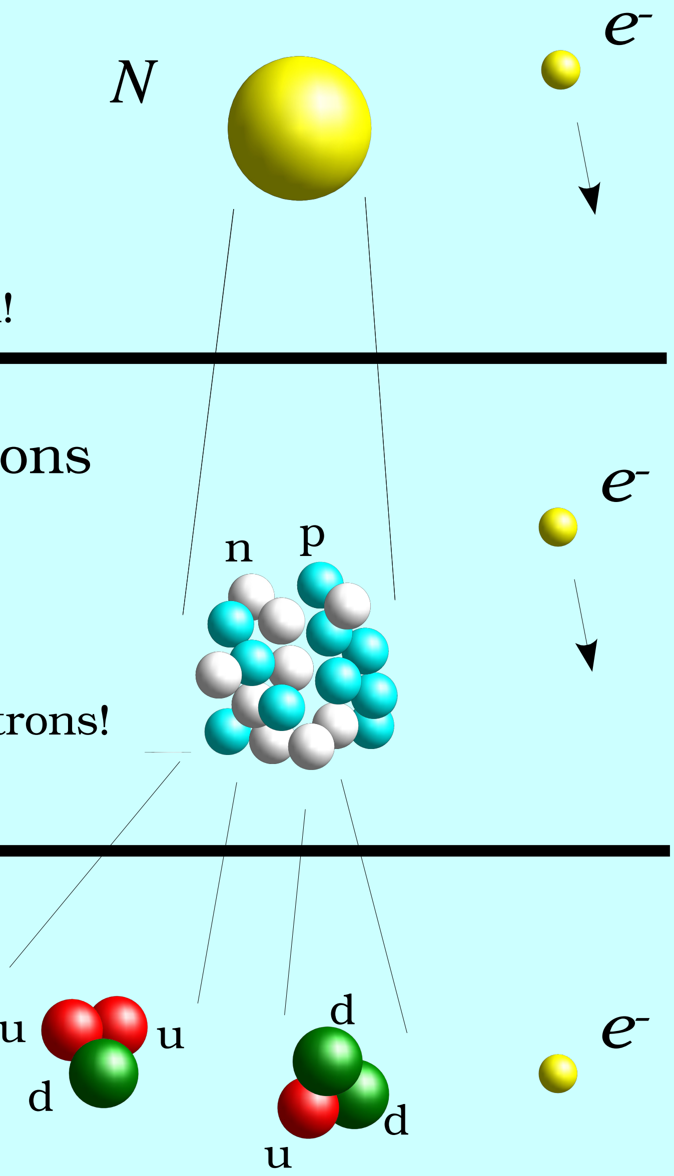
MeV scale: *protons and neutrons* plus electrons

But there are many different “types” of protons/neutrons!

- “hadrons”: p, n, π, K, ρ, Ω, ...

eV scale: atoms: *nuclei* plus electrons



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But there are many different “types” of protons/neutrons!

- “hadrons”: p, n, π, K, ρ, Ω, ...

GeV scale: *quarks* plus electrons!

(not directly visible, but well-confirmed experimentally)

But there are many different “types” of quarks and electrons!

- quarks: u, d, s, c, b, t
- “leptons”: e, μ, τ, ν_e, ν_μ, ν_τ

Beyond this?

This is as far as we've come!

The Standard Model

The particles

quarks: $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} s \\ c \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

The forces

- SU(3): The strong (color) force ($\alpha_3 = 1/8$)
    - Holds quarks together to form hadrons and nuclei
    - Felt only by quarks
- SU(2): The weak force ($\alpha_2 = 1/30$)
    - Responsible for β-decay, other “weak” decays
    - Felt by all (left-handed) particles
- U(1): The hypercharge force ($\alpha_1 = 1/59$)
    - Closely related to the weak force
    - Felt by all charged particles

(Ordinary EM is a combination of the SU(2) weak force and the U(1) hypercharge force:

Higgs: SU(2) x U(1) → EM)

Is that all there is?
Lots of reasons to believe in something deeper!

- Standard Model contains many arbitrary parameters
  - Masses of fundamental particles
  - Mixings of fundamental particles.

  Must be fit to data rather than explained.

- Many conceptual questions
  - Why are there three generations?
  - Why are there three kinds of forces?
  - Why do these forces have different strengths and ranges?

  A fundamental theory should explain these features.

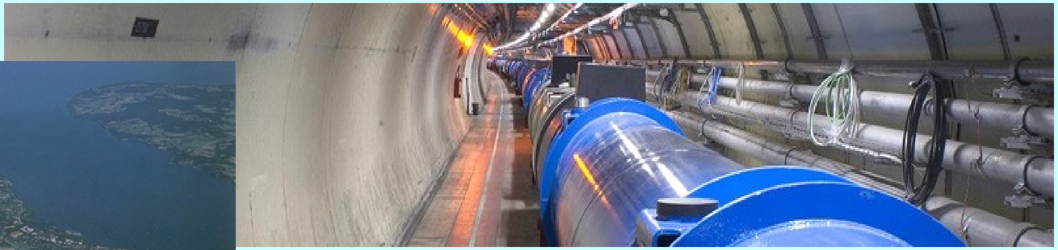
- What about gravity?
  - How to incorporate the gravitational force?
  - How to “quantize” gravity?

Just as in each previous case, there must still be a deeper underlying principle!

The Next Steps:

So what do we think will be true tomorrow?

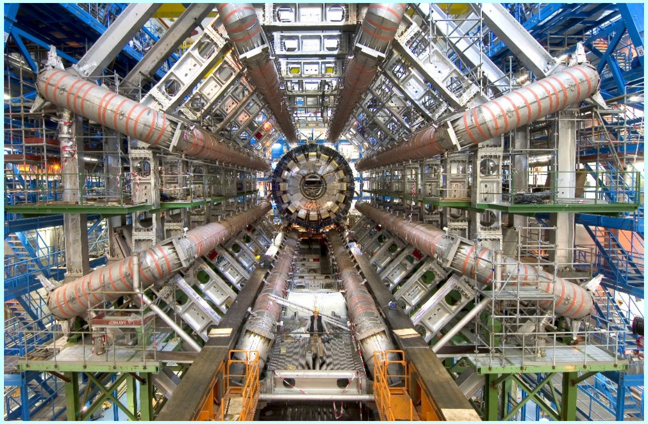
Very important question!
The next generation of accelerators and detectors
are coming online now!



27-kilometer beamline

CERN Large Hadron Collider
Geneva, Switzerland

ATLAS detector

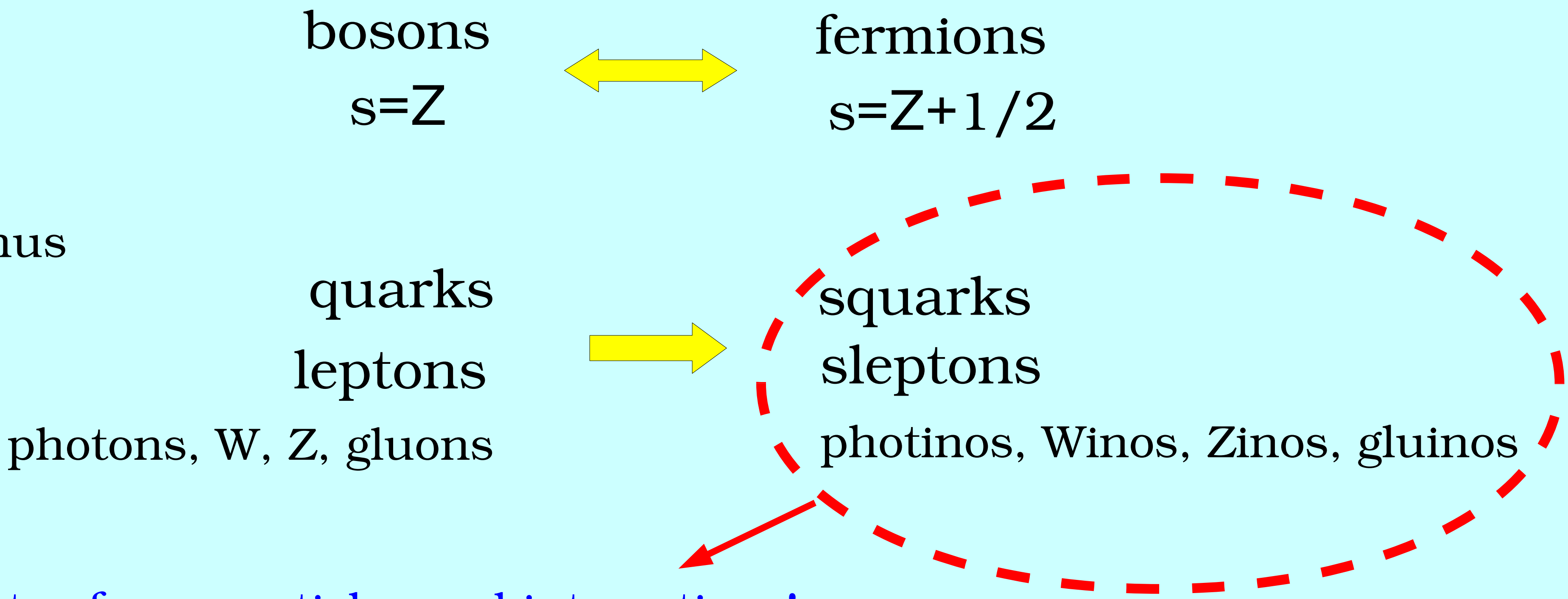


What do we expect to see?
What will high-energy physics be focusing on
over the next 10-20 years?

Two popular sets of ideas...

Supersymmetry (SUSY)

A new kind of symmetry in physics



bosons

$s=Z$

fermions

$s=Z+1/2$

Thus

quarks

leptons

photons, W, Z, gluons

squarks

sleptons

photinos, Winos, Zinos, gluinos

Lots of new particles and interactions!

Why go through all this trouble?

- explains relative strengths of forces
- can explain/trigger "electroweak symmetry breaking"
- has favorable cosmological implications
    - (e.g., may even explain dark matter)
- provides answer to a difficult theoretical puzzle in the Standard Model
    - "gauge hierarchy problem" --- why is the Higgs particle so light?

Supersymmetry is a beautiful theory,
but it is **not** observed in nature.

→ **Must be a *broken* symmetry!**

Problem ---

Supersymmetry is very robust!
Hard to find mechanism to “spontaneously” break SUSY!

Unsolved issue ---

How do we break SUSY?

We currently have to introduce SUSY-breaking by hand

→ Requires the introduction of many additional unknown parameters…

Grand Unified Theories (GUT's)

Try to realize different forces and particles as different "faces" of a single "GUT" force and a single "GUT" particle.

Analogy:

- *Electric force:* felt/caused by static charges
- *Magnetic force:* felt/caused by moving charges

Are these different forces?

No! --- shift from rest frame to moving frame...
then electric ⟺ magnetic!

So electric and magnetic forces are merely different aspects of one force, the "electromagnetic" force!

Is the same true for strong, electroweak, and hypercharge forces?
Is there a single "*strong-electroweak-hypercharge*" GUT force?

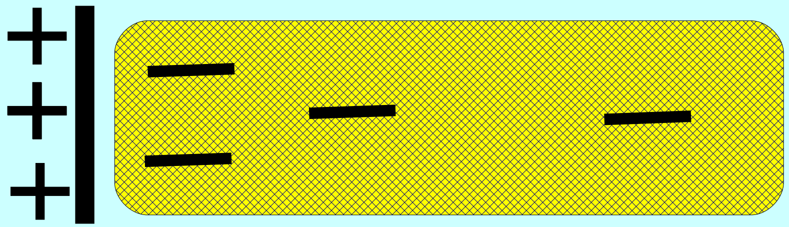
Doesn't seem possible --- forces have different strengths!

Recall: $\alpha_1 = 1/59$, $\alpha_2 = 1/30$, $\alpha_3 = 1/8$.

However, in quantum field theory, the strengths of the forces depend on the energy with which one does the measurement!

Why?

Analogy: Think of a charge next to a dielectric...

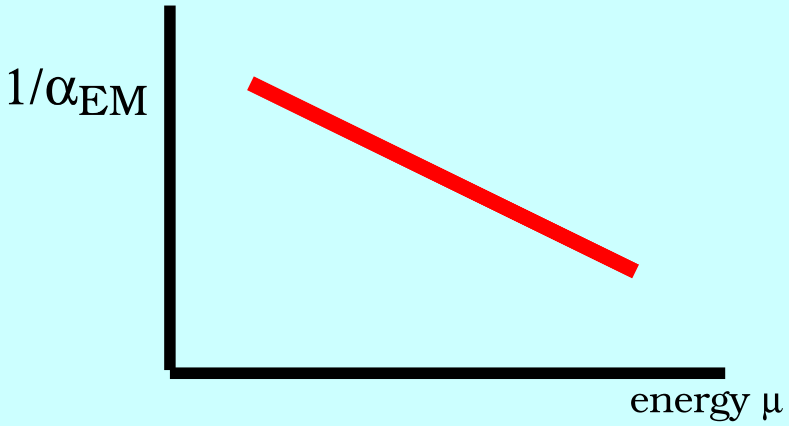


Dielectric medium partially screens charge!

Thus, effective strength of EM force varies with distance:

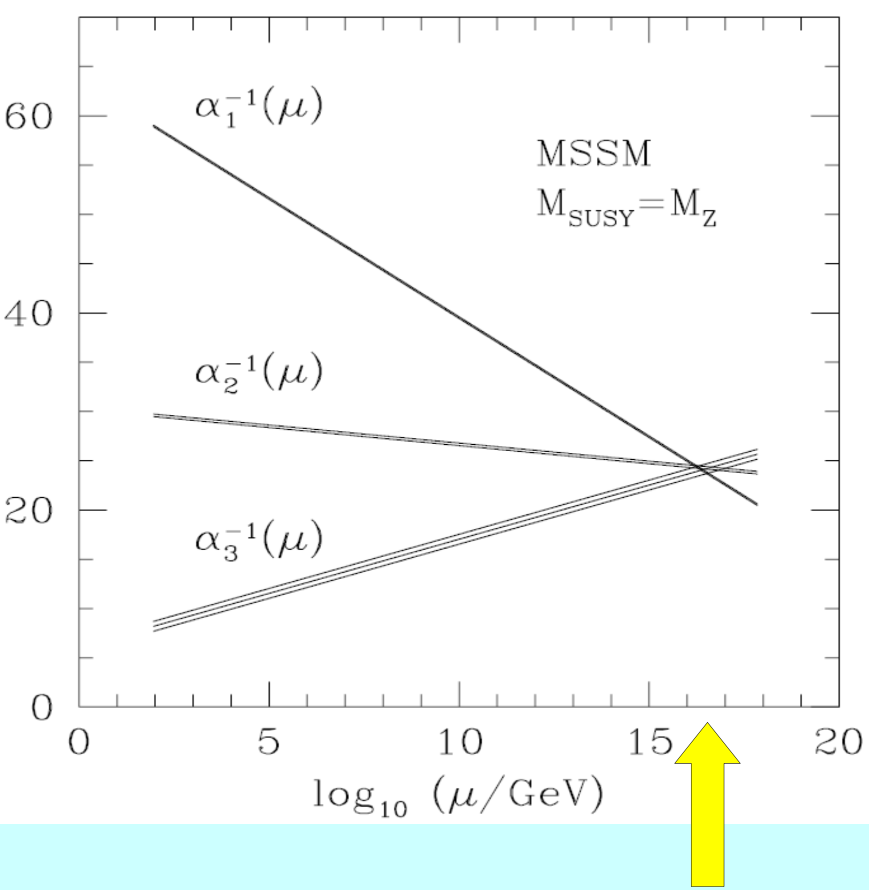
Higher energy → Shorter distance

→ Stronger force



In the SUSY SM, the “vacuum” is like a dielectric, except

- Hypercharge and weak forces: behave like dielectric
- Strong color force: behaves like *anti*-dielectric!



Forces can unify at 2×10^{16} GeV !

This would be the natural energy scale for grand unification!

GUTs would have important effects on particle physics:

- Would imply new interactions that mix the three forces
- Would permit rare decays of particles
  - e.g., proton decay lifetime = $10^{32\text{-}33}$ years
- Would explain charges and interactions of fundamental particles.

But there are many different kinds of GUT's:

- What is the larger symmetry group underlying the GUT force?
  - SU(5) ? SO(10) ? E6 ? Other groups?
- How do the different particles join together under these groups?
- What kinds of interactions are allowed while respecting these enlarged symmetries?

Many questions still remain!

Both the SUSY idea and the GUT idea are very compelling.
They and their low-energy effects will be the focus of experimental high-energy physics over the next 20 years.

But high-energy theorists have plenty of work to do!
Must be able to build theories in order to be able to interpret data!

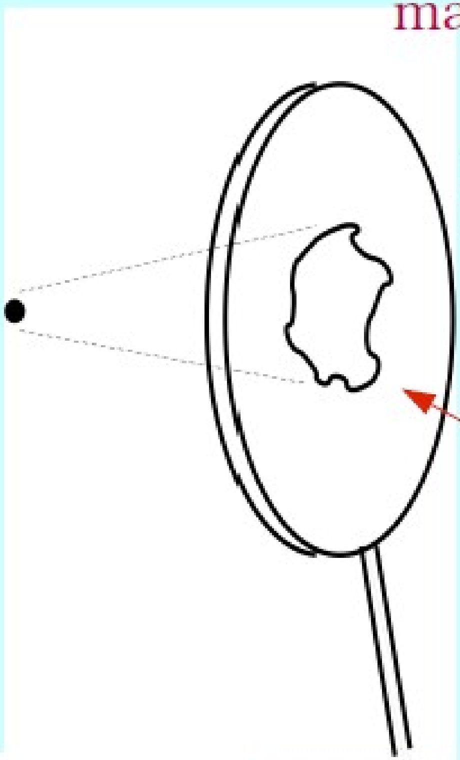
- How do we build realistic SUSY theories?
- How do we build realistic GUT theories?
- How can we make sense of alternate proposals for physics beyond the SM?
    - Alternative Higgs structures
    - Large extra spacetime dimensions
    - Strongly coupled (RS) scenarios
- How do we incorporate gravity?

The possibilities seem endless...
We still require guidance from some deeper principle...

String theory!

So what is string theory?

A deceptively simple premise…

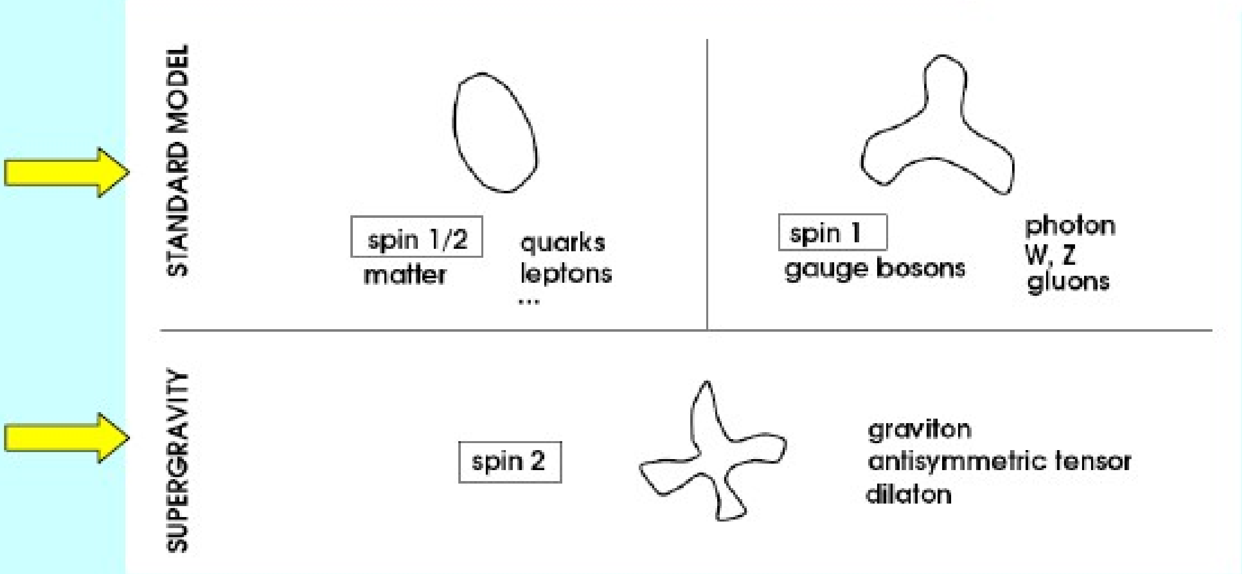


Planck-scale magnifying glass

Elementary particle (e.g., electron)

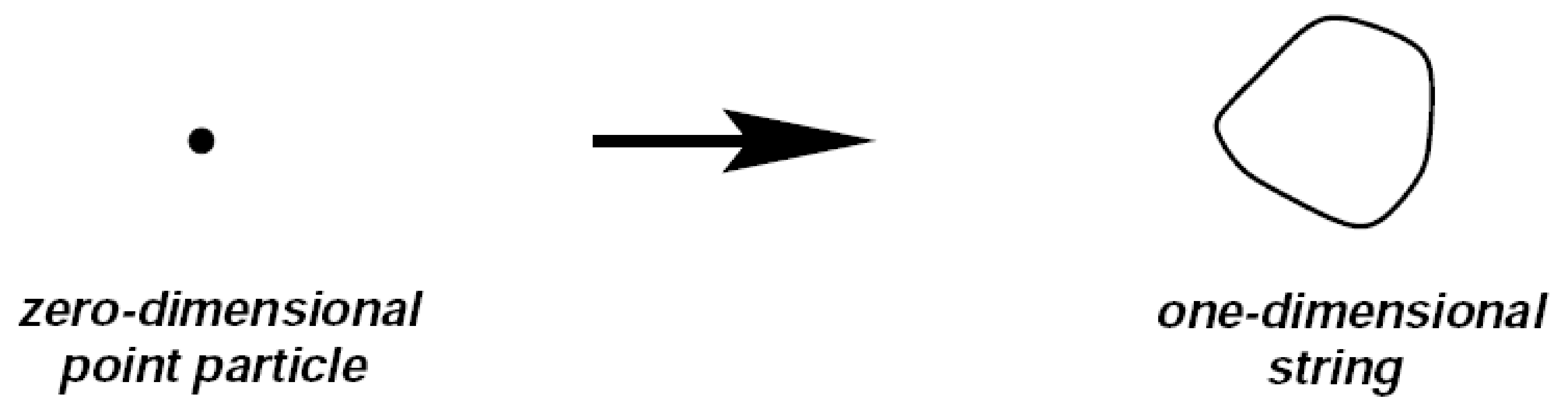
A vibrating string!

This idea has great power. Can unify all particles and forces in nature…

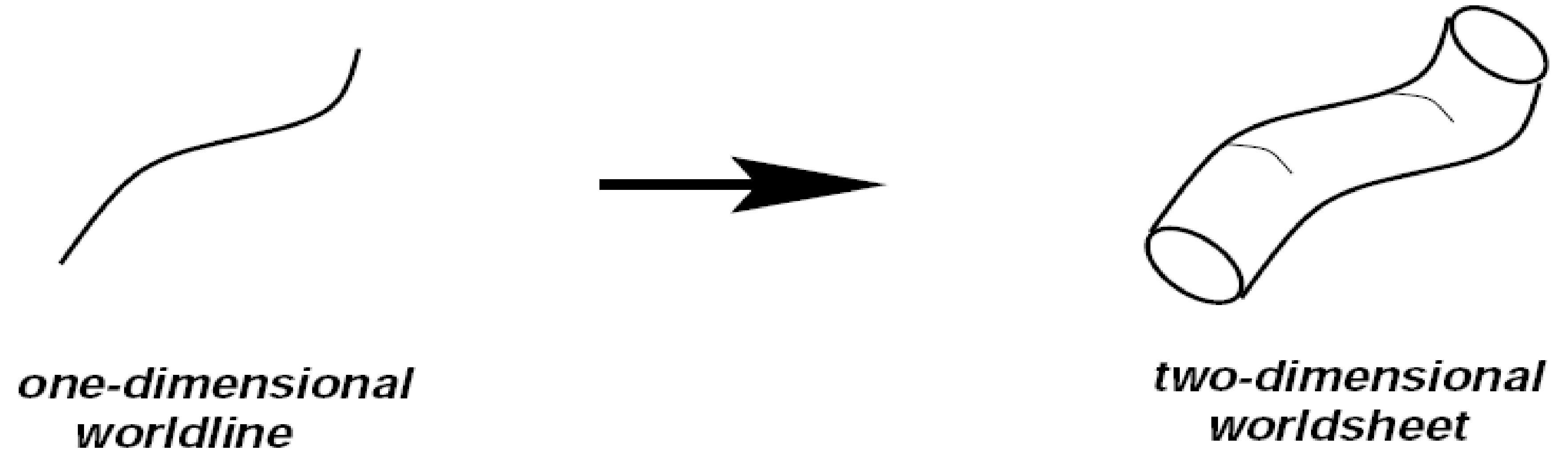


Gauge interactions, particles, and gravity are all unified as different excitations of one fundamental entity: *the string!*

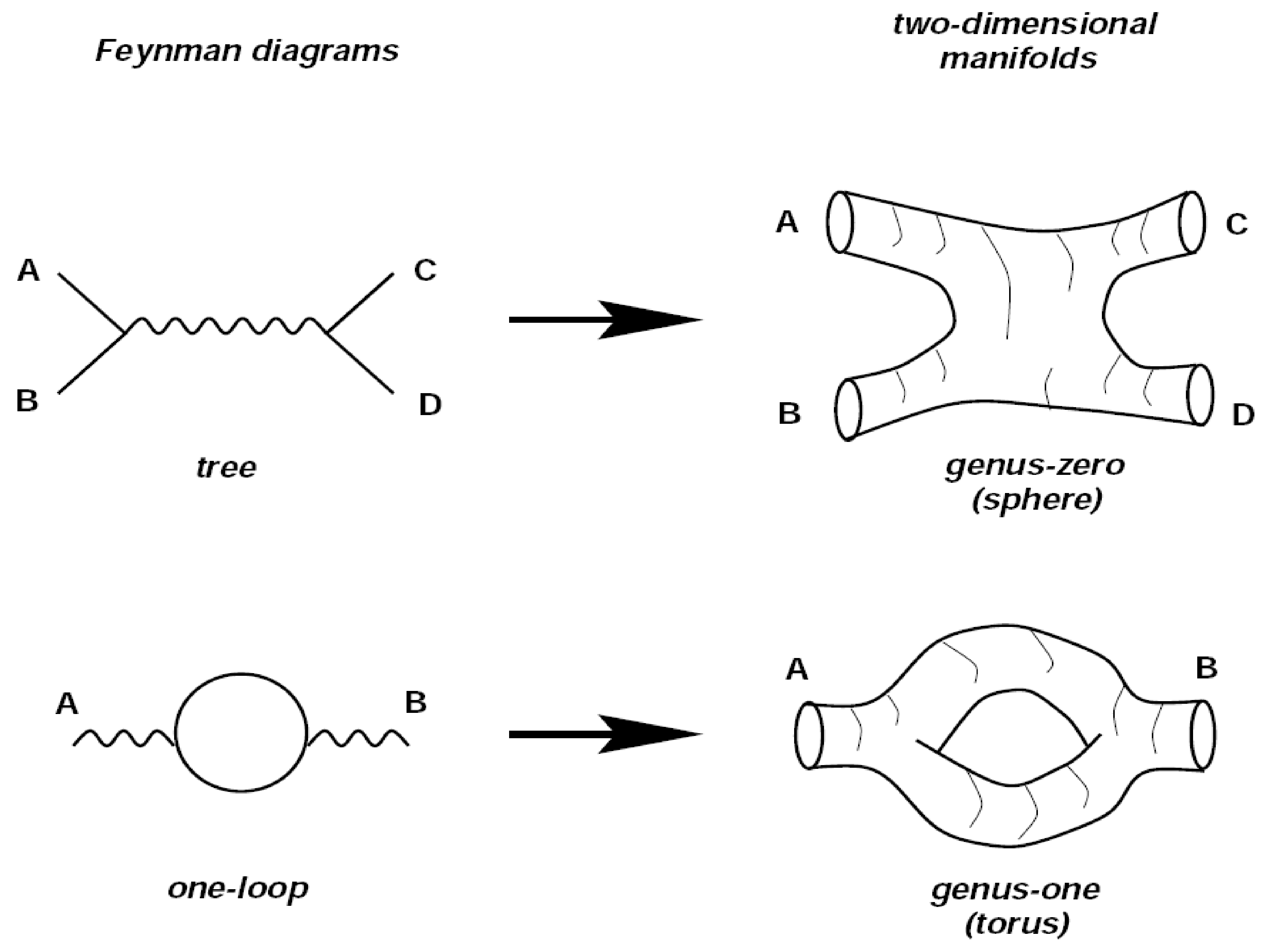
Thus, the physics of points becomes the physics of strings…



… and the physics of worldlines becomes the physics of worldsheets…



… and the physics of Feynman diagrams becomes the physics of manifolds…



Note: All of these pictures correspond to **closed** strings.

However, strings can also be **open**, with endpoints ending on membrane-like surfaces of various dimensionalities called **D-branes.** Moreover, these D-branes can intersect each other, and have strings stretching between them.

Likewise, both the strings and the D-branes can wrap around compactified spacetime dimensions, resulting in highly non-trivial geometric configurations.

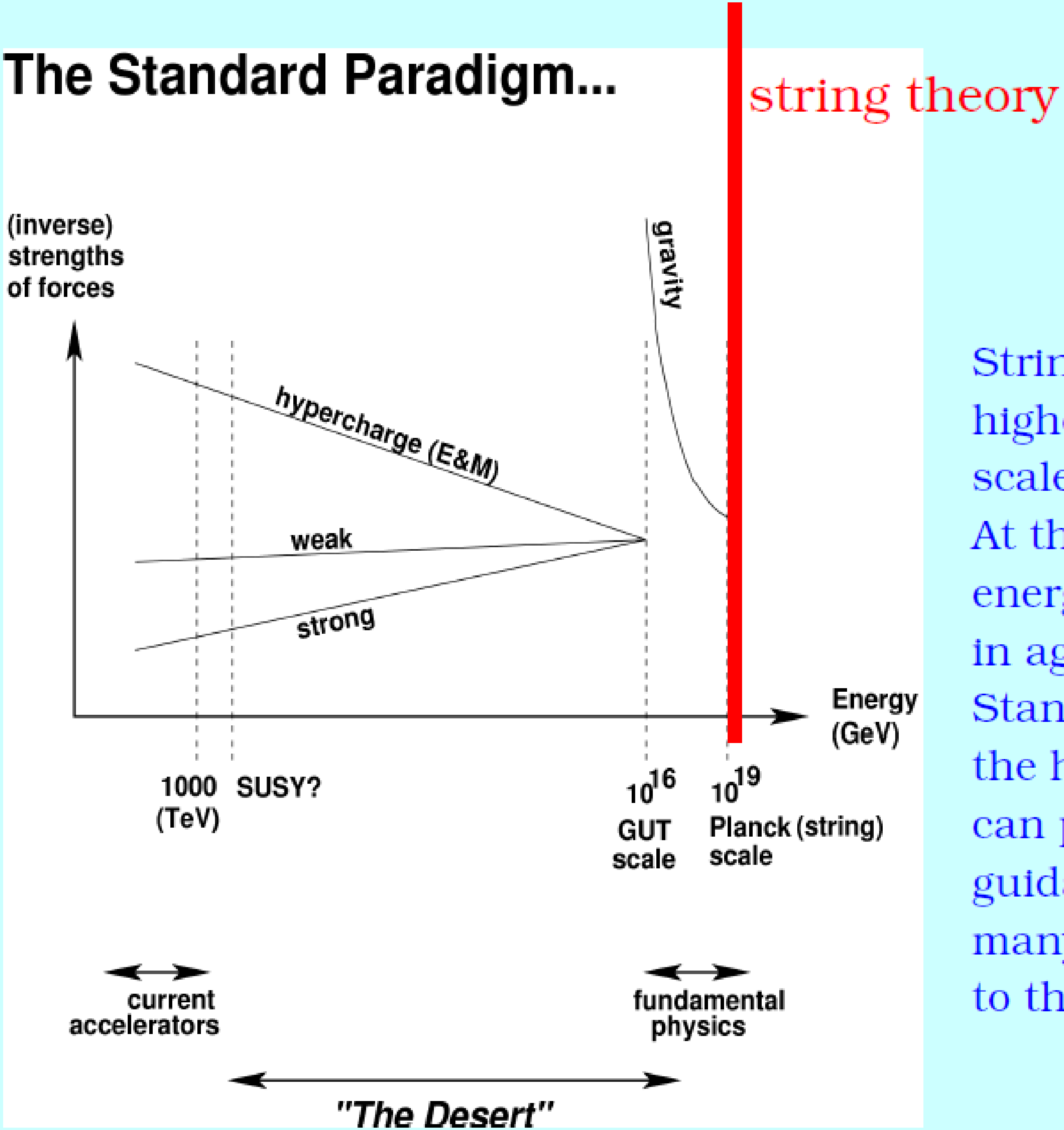
All of these features have profound implications for the allowed excitations of the fundamental strings and branes in the theory, and for the resulting low-energy spectrum of particles which they predict.

This is clearly a whole new geometric “language” for doing physics!

However, because string theory also includes *gravity* (which is very *weak* compared with the other forces), its fundamental energy scale is very high!

$$M_{\mathrm{Planck}} \equiv \sqrt{\frac{\hbar c}{G_N}} \approx 10^{19}\ \mathrm{GeV} \approx (10^{-33}\ \mathrm{cm.})^{-1}$$

Thus, string theory is ultimately a theory of *Planck-scale* physics!



String theory sits at the highest possible energy scale that we can consider. At the very least, its low-energy predictions must be in agreement with the Standard Model, and it is the hope that string theory can provide theoretical guidance concerning the many possible extensions to the Standard Model.

Over the past 25 years, string theory has come to occupy a central place in high-energy physics.

It has had a profound impact in many branches of theoretical physics and mathematics, and has led to many new ideas and insights concerning the structure of field theory, gauge theory, supersymmetry, and their relations to gravity.

Indeed, it has even been called “a piece of 21st century physics that fell by chance into the 20th century”...

Edward Witten
IAS, Princeton
Fields Medalist, 1990

But how many string theories are there??

Is the theory unique??

And therein lies the rub...

String theory gives rise to a multitude of self-consistent vacua.

Each one is called a different “**string vacuum**”, or a different “**string model**”. It is like having a big master equation with many possible solutions, each with different properties.

Roughly speaking, each of these different string vacua corresponds to a different way of compactifying the theory from ten dimensions down to four dimensions. The different vacua correspond to different choices of compactification manifolds, different Wilson lines, different vacuum expectation values for unfixed moduli fields, different choices of fluxes, and so forth.

That there are so many self-consistent ways of compactifying the theory has been known since the mid-1980's.

However, by and large, string theorists didn't worry about this.

- These string models usually had flat directions --- there were no dynamical ways of fixing many of the continuous parameters that could be freely adjusted. Flat directions are in direct conflict with experiment, since they correspond to extra (unobserved) massless particles and unseen forces.
- These models were usually supersymmetric, yet the real world is non-supersymmetric.
- These models were usually formulated in flat space or anti- de Sitter space (negative cosmological constant) .... also not realistic.

It was therefore assumed that some sort of vacuum selection mechanism would be found (probably relying on *non-perturbative* aspects of string theory), and that this stabilization mechanism would lead to a unique vacuum that would solve the other problems (break SUSY and introduce de Sitter space).

So what changed?

Starting over the past decade, and most recently since 2003, there has been an increasing realization that this is *not* what is going to occur.

- In the mid-1990's, we gained considerable insight into the non-perturbative behavior of these theories, and discovered that they continue to be self-consistent with these parameters left unfixed, even at strong coupling.
- In 2003, various proposals suggested the existence of controlled methods of stabilizing vacua, breaking SUSY, and realizing de Sitter space in string theory.

KKLT 2003

None of these ideas led to a vacuum selection principle. In fact, they showed that a plethora of self-consistent string compactifications is likely to continue to exist, even after vacuum stabilization and other problems are solved.

What resulted, then, is the realization that string theory *really does contain* an entire multitude of solutions, i.e., a multitude of stable ground states, without a dynamical or symmetry argument to select amongst them.

Such ground states --- such vacua --- can be viewed as local minima in a complex theoretical terrain of hills and valleys....

... the string-theory landscape.

The *real* string landscape...

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Tucson, Arizona

10^{500} = Pretty darn big

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Does it matter?

Yes!

The low-energy phenomenology that emerges from the string depends critically on the particular choice of vacuum state.

Detailed quantities such as

- choice of gauge group
- number of chiral generations
- SUSY-breaking scale
- cosmological constant, etc.

...all depend on the particular vacuum state selected.

How then can we make progress in the absence of a vacuum selection principle?

Recent proposal: Examine the landscape *statistically*, look for correlations between low-energy phenomenological properties that would otherwise be unrelated in field theory.

Douglas,...

This then provides a new method for extracting phenomenological predictions from string theory.

This idea has triggered a surge of activity examining the statistical properties of the landscape...

- SUSY-breaking scale
- Cosmological constant
- Ranks of gauge groups
- Prevalence of SM gauge group
- Numbers of chiral generations, etc.

Douglas, Dine, Gorbatov, Thomas, Denef, Giryavets, de Wolfe, Kachru, Tripathy, Conlon, Quevedo, Kumar, Wells, Taylor, Acharya, Gorbatov, Blumenhagen, Gmeiner, Honecker, Lust, Weigand, Dijkstra, Huiszoon, Schellekens, Nilles, Raby, Ratz, Wingerter, Faraggi,...

This line of attack has also led to various paradigm shifts...

- Alternative notions of naturalness
- New cosmo/inflationary scenarios
- Anthropic arguments
- Field-theory analogues
- Landsape versus swampland
- Land-skepticism

Douglas, Dine, Gorbatov, Thomas, Weinberg, Susskind, Bousso, Polchinski, Feng, March-Russell, Sethi, Wilczek, Firouzjahi, Sarangi, Tye, Kane, Perry, Zytkow, KRD, Dudas, Gherghetta, Arkani-Hamed, Dimopoulos, Kachru, Freivogel, Vafa, Banks,...

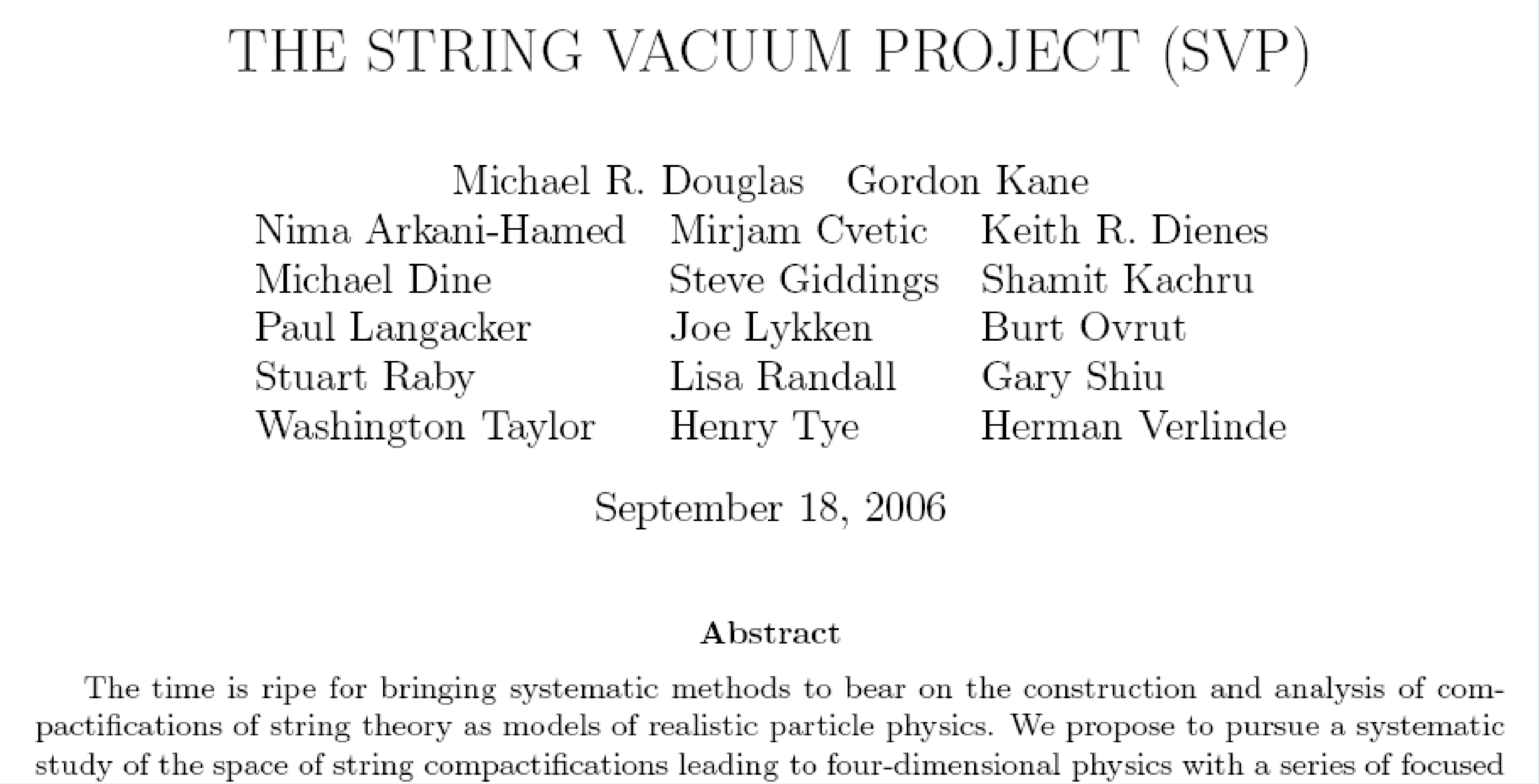
The String Vacuum Project (SVP)

A large, multi-year, multi-institution, interdisciplinary collaboration to explore the space of string vacua, compactifications, and their low-energy implications through

- enumeration and classification of string vacua
- detailed analysis of those vacua with realistic low-energy phenomenologies
- statistical studies across the landscape as a whole.

Will involve intensive research at the intersection of

- *Particle physics:* string theory and string phenomenology
- *Mathematics:* algebraic geometry, classification theory
- *Computer science:* algorithmic studies, parallel computations, database management.



THE STRING VACUUM PROJECT (SVP)

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September 18, 2006

Abstract

The time is ripe for bringing systematic methods to bear on the construction and analysis of compactifications of string theory as models of realistic particle physics. We propose to pursue a systematic study of the space of string compactifications leading to four-dimensional physics with a series of focused

- **Wiki at:** `http://strings0.rutgers.edu:8000`
- **European SVP website at:**

`http://www.ippp.dur.ac.uk/~dgrell/svp`

Unfortunately, although there have been many abstract theoretical discussions of string vacua and their statistical properties, there have been very few direct statistical examinations of actual string vacua.

In spite of recent progress, this is because the construction and analysis of actual string vacua remains a fairly complicated affair.

Much of the effort over the past few years has focused on the landscape of **open** (so-called Type I) strings.

One of my main efforts over the past few years has been to perform the first-ever statistical studies of the heterotic (**closed**-string) landscape.

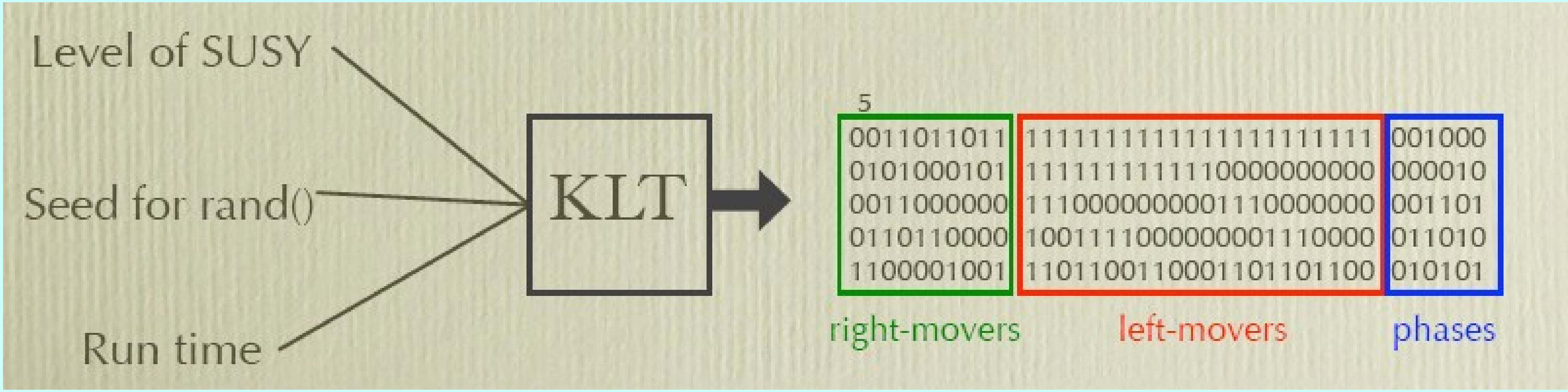
This is important because heterotic models are fundamentally different from Type I models...

- tighter constraints (central charges, modular invariance, ...)
- gauge groups generated differently, maximal ranks
- different phenomenologies (e.g., gauge coupling unification)

Expect potentially different statistical properties/correlations.
(May even provide useful guides for heterotic model-builders.)

How we do it:

Step #1: Generating models



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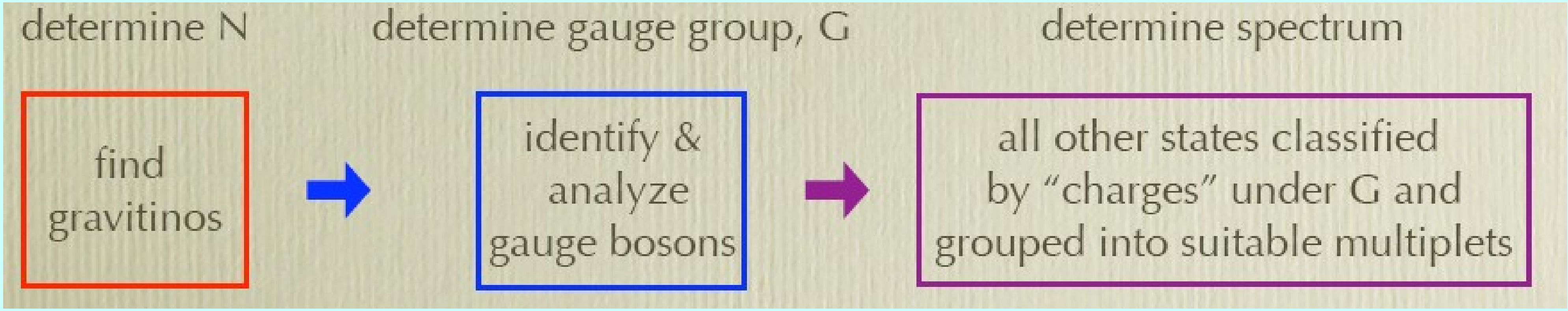
0101000101 1111111111110000000000 000010
0011000000 1110000000001110000000 001101
0110110000 1001111000000001110000 011010
1100001001 1101100110001101101100 010101
```

Can generate millions/billions of self-consistent configurations of twists/phases very easily!

D. Senechal

Step #2: Analyze candidate model

- For each spin-structure, enumerate all states in Fock space satisfying level-matching and GSO constraints
- Organize these states into meaningful representations
    - first gravitinos, then appropriate gauge multiplets, finally rest of spectrum



determine N

find gravitinos

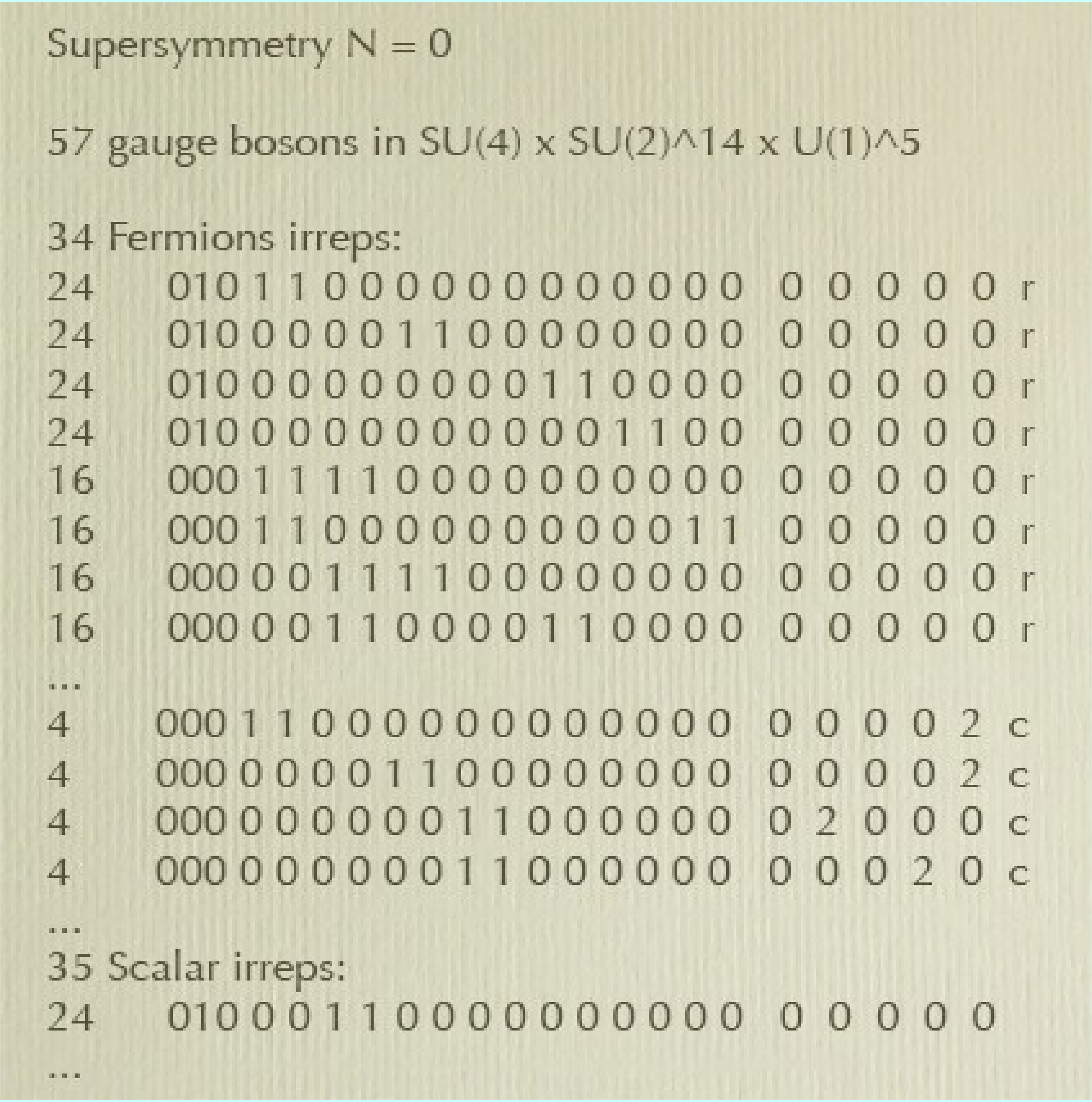
determine gauge group, G

identify & analyze gauge bosons

determine spectrum

all other states classified by “charges” under G and grouped into suitable multiplets

Resulting spectrum is then quoted in terms of Dynkin labels and U(1) charges, labelled as real or complex, chiral or non-chiral, etc.



```
Supersymmetry N = 0

57 gauge bosons in SU(4) x SU(2)^14 x U(1)^5

34 Fermions irreps:
24     010 1 1 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 r
24     010 0 0 0 0 1 1 0 0 0 0 0 0 0 0   0 0 0 0 0 r
24     010 0 0 0 0 0 0 0 0 1 1 0 0 0 0   0 0 0 0 0 r
24     010 0 0 0 0 0 0 0 0 0 0 1 1 0 0   0 0 0 0 0 r
16     000 1 1 1 1 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0 r
16     000 1 1 0 0 0 0 0 0 0 0 0 0 1 1   0 0 0 0 0 r
16     000 0 0 1 1 1 1 0 0 0 0 0 0 0 0   0 0 0 0 0 r
16     000 0 0 1 1 0 0 0 0 1 1 0 0 0 0   0 0 0 0 0 r
...
4     000 1 1 0 0 0 0 0 0 0 0 0 0 0 0   0 0 0 0 2 c
4     000 0 0 0 0 1 1 0 0 0 0 0 0 0 0   0 0 0 0 2 c
4     000 0 0 0 0 0 0 1 1 0 0 0 0 0 0   0 2 0 0 0 c
4     000 0 0 0 0 0 0 1 1 0 0 0 0 0 0   0 0 0 2 0 c
...
35 Scalar irreps:
24     010 0 0 1 1 0 0 0 0 0 0 0 0 0 0   0 0 0 0 0
...
```

D. Senechal

So what do we find?

Here, I'll show a few random results, just to give examples of the kinds of analyses people are doing...

- KRD, hep-th/0602286
- KRD & M. Lennek, hep-th/0610319
- KRD, M. Lennek, D. Senechal, V. Wasnik, 0704.1320
- KRD, M. Lennek, D. Senechal, V. Wasnik, 0804.4718
- KRD & M. Lennek, 0809.0036

Across all string models in our sample,

- 10.65% contain SU(3) factors. Among these models, the average number of such factors is 1.88.
- 95.06% contain SU(2) factors; average number 6.85.
- 90.80% contain U(1) factors; average number 4.40.

By contrast, across all distinct *gauge groups*,

- 23.98% contain SU(3) factors; average number 2.05.
- 73.87% contain SU(2) factors; average number 5.66.
- 91.47% contain U(1) factors; average number 5.10.

Thus, e.g., although SU(3) factors appear in 24% of gauge groups, those groups emerge from actual string models in our sample only half as frequently as we would have expected.

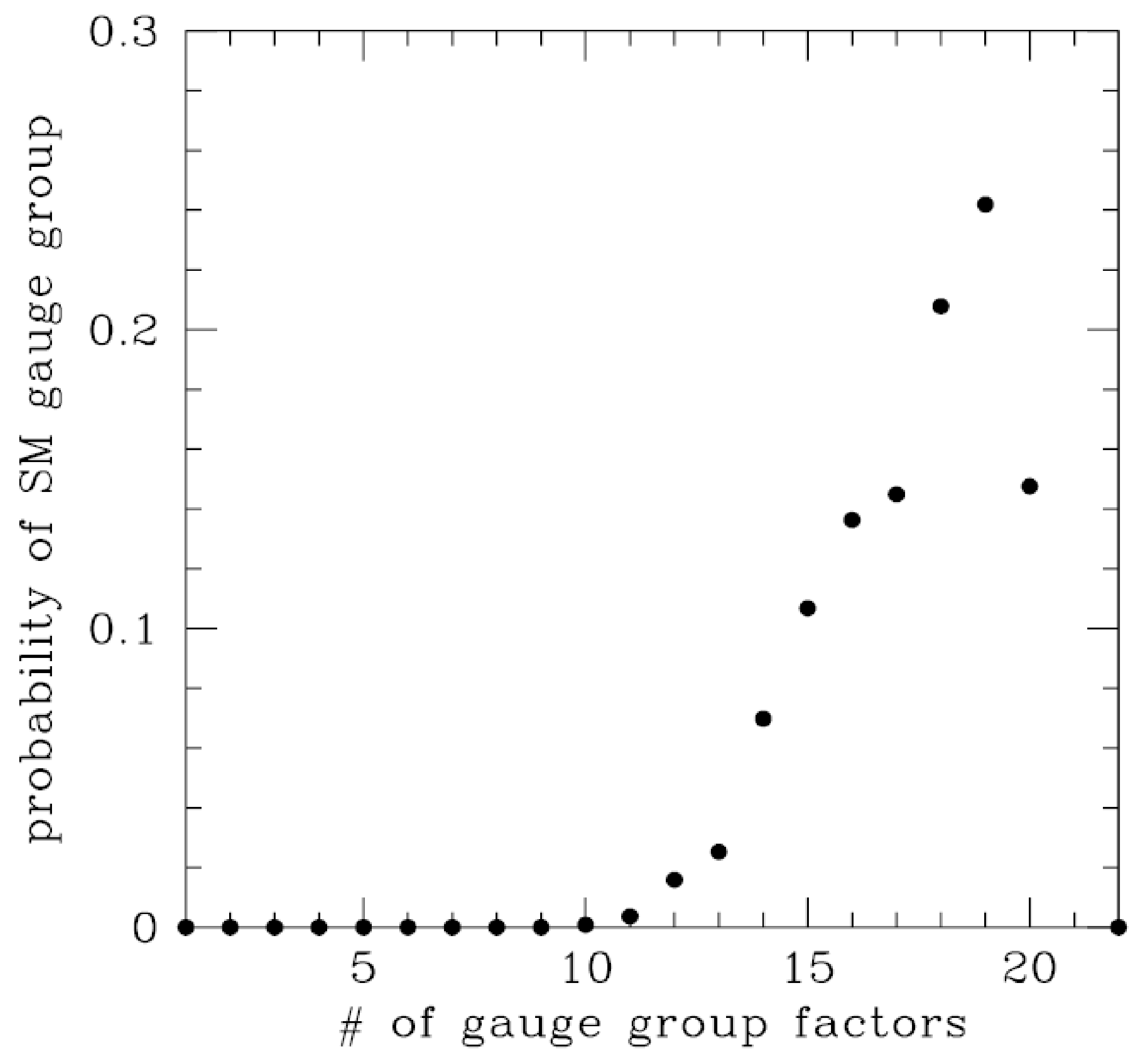
In fact, 99.81% of all heterotic string models in our sample which contain *one or more* SU(n) factors also exhibit an *equal or greater number* of U(1) factors.

True for SU(3) and all SU(n), n≥5.

By contrast, this is true of only 75% of models with SO(2n≥6) factors and only 61% of models with 'E' factors... i.e., no such correlation for these groups!

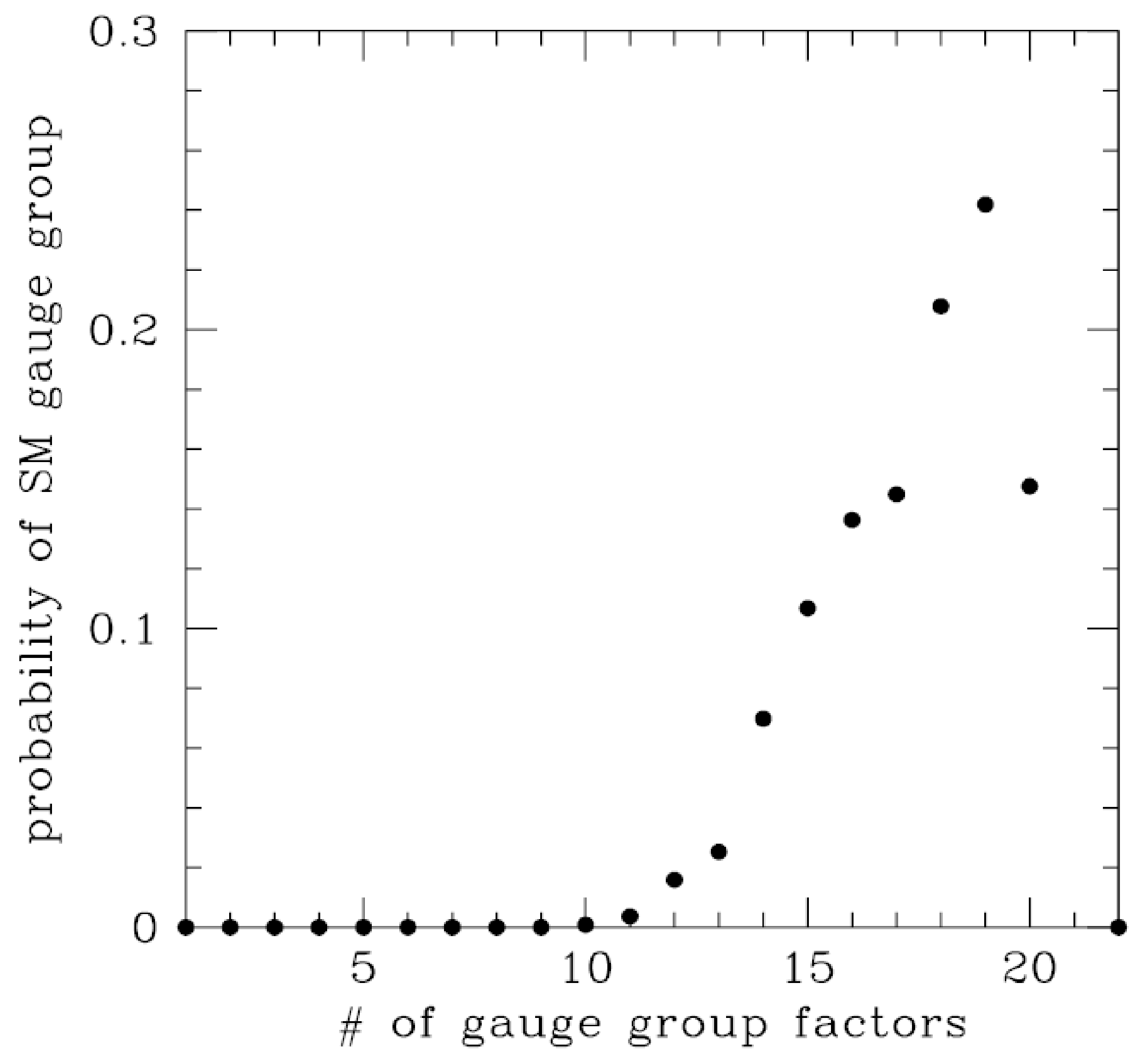
The origin of this SU(n)/U(1) correlation involves the possible embeddings of the charge/momentum lattice on integer/half-integers lattice sites.

How likely are SU(3), SU(2), and U(1) to appear *simultaneously* in a given string model in our sample?



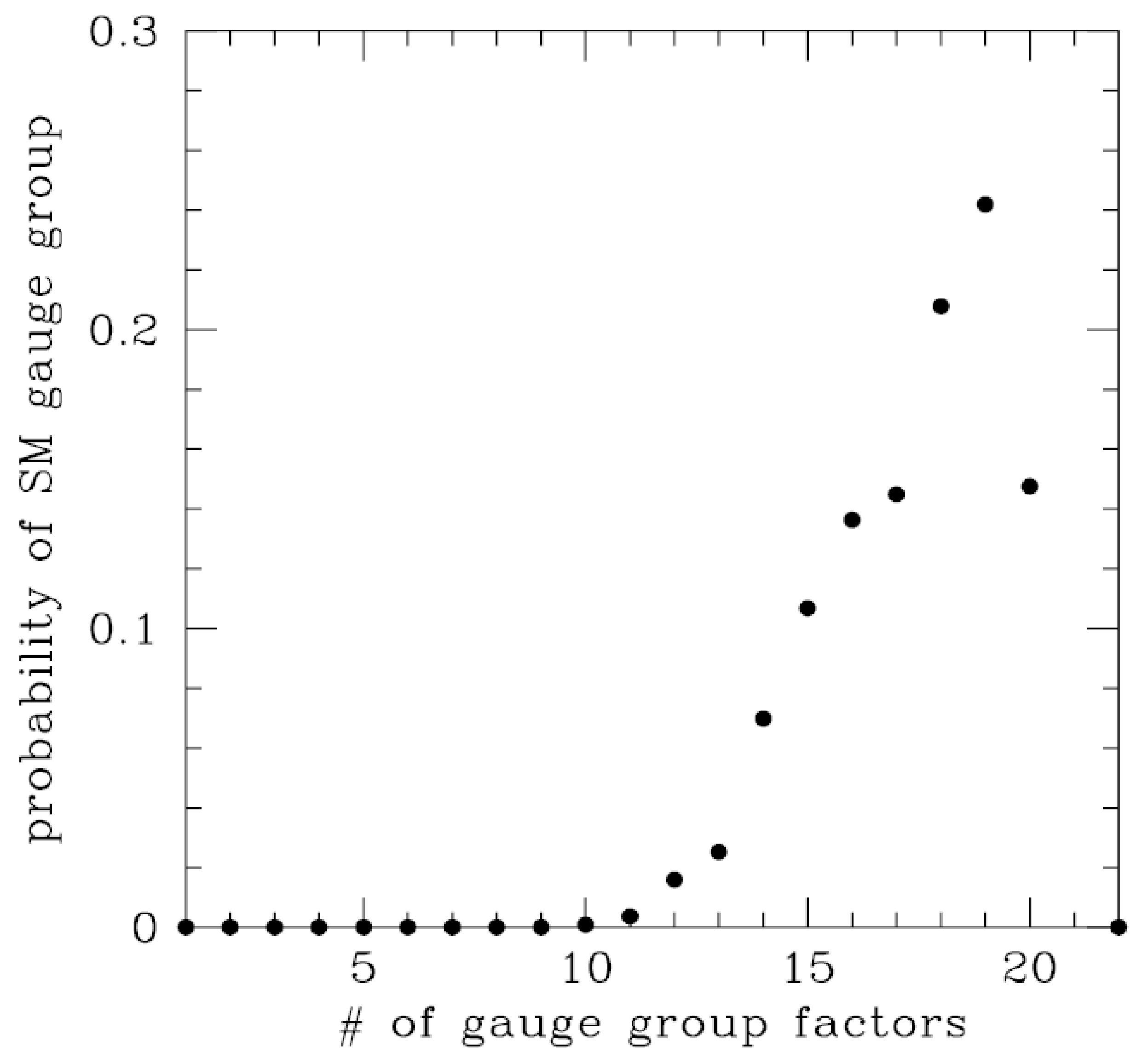
- SM gauge group is most likely to emerge in situations in which the total gauge group of the string model is highly broken.

How likely are SU(3), SU(2), and U(1) to appear *simultaneously* in a given string model in our sample?



- These conclusions agree with all known such semi-realistic string models in literature.
- Provides limits on possible hidden-sector gauge groups for such models.
- Useful guide for future string model-building.

How likely are SU(3), SU(2), and U(1) to appear *simultaneously* in a given string model in our sample?



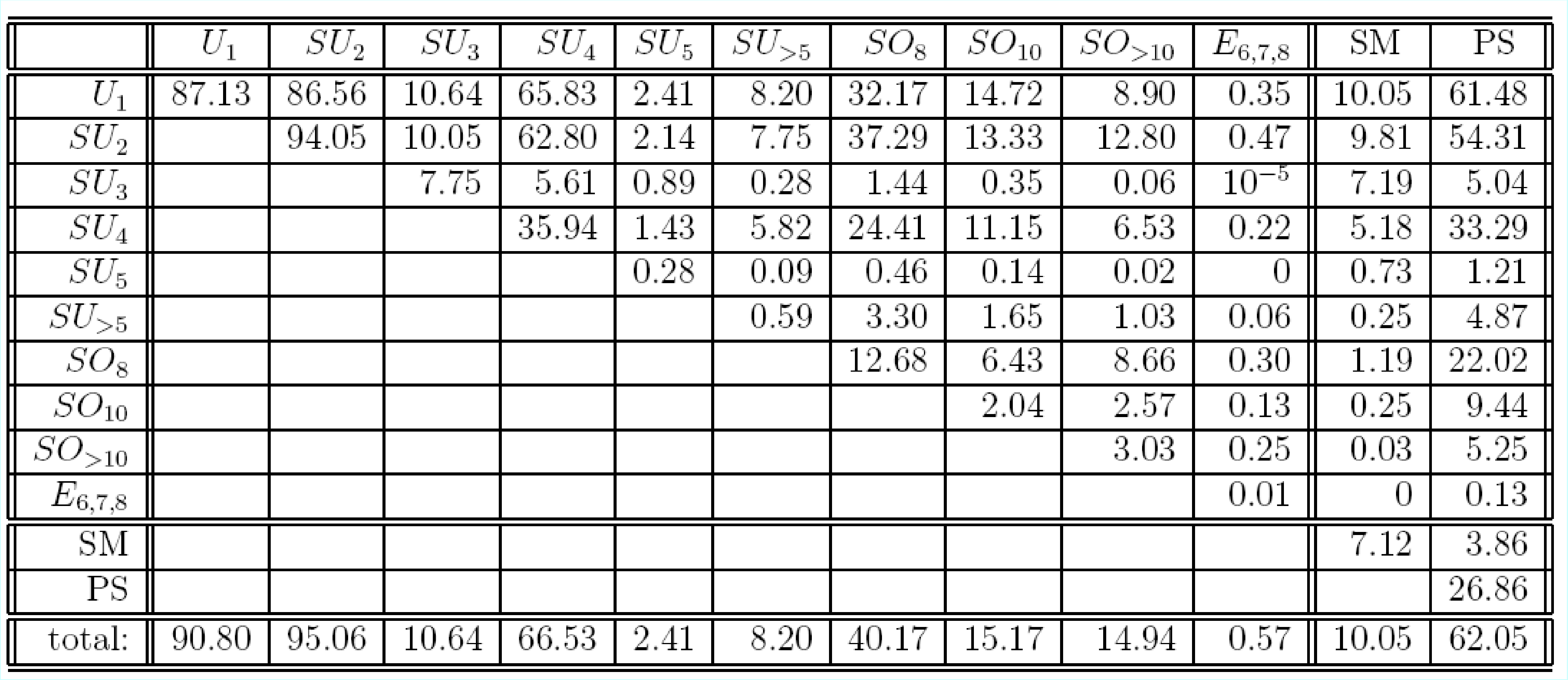
Indeed, averaged across all degrees of shatter, the total probability of obtaining the SM gauge group in this sample of models is only 10.05% --- similar to what is found for Type I strings.

How about cross-correlations between *all* possible gauge groups of interest?

What are the joint probabilities that two different gauge group factors will appear within the same string model simultaneously?

This is especially useful to know if one factor is "observable", the other "hidden"...

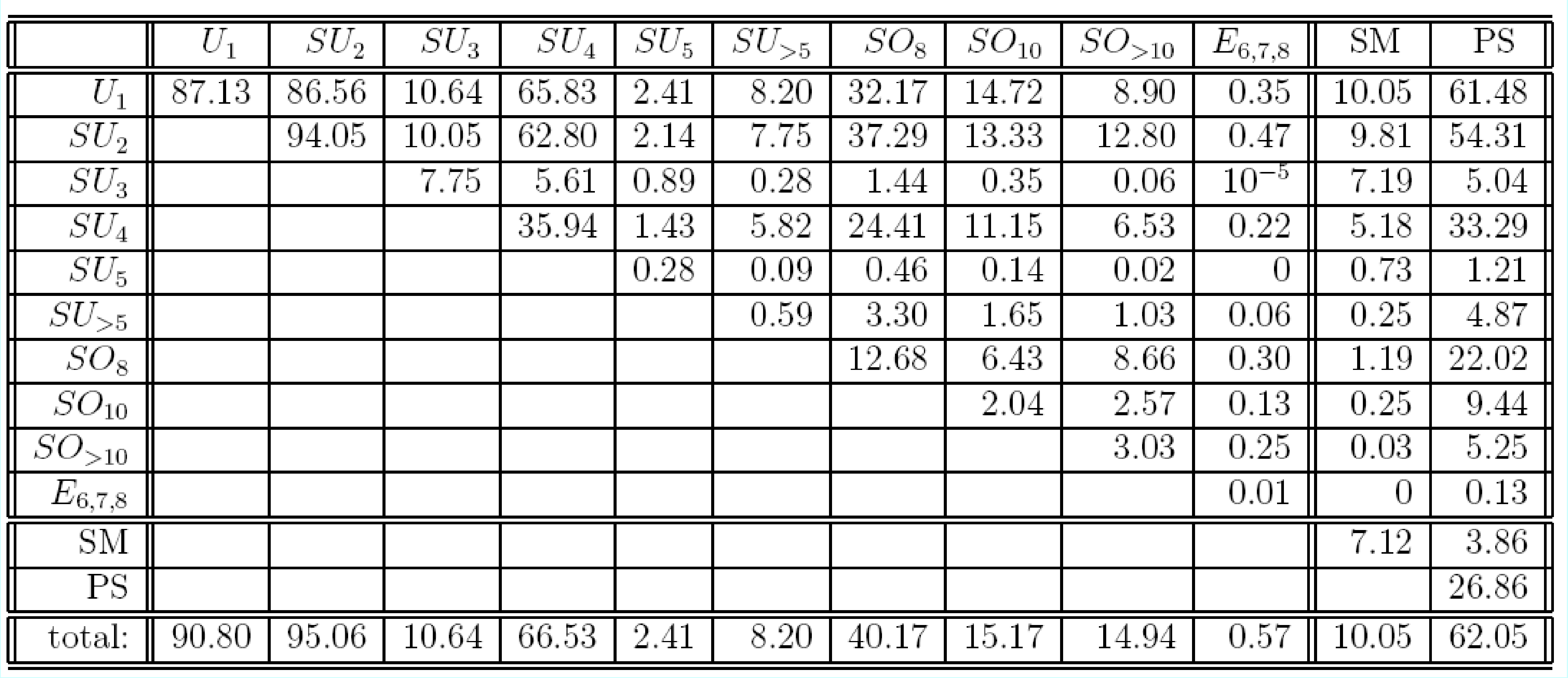
Correlation probability table (quoted in % of models)...



	U_1	SU_2	SU_3	SU_4	SU_5	$SU_{>5}$	SO_8	SO_{10}	$SO_{>10}$	$E_{6,7,8}$	SM	PS
U_1	87.13	86.56	10.64	65.83	2.41	8.20	32.17	14.72	8.90	0.35	10.05	61.48
SU_2		94.05	10.05	62.80	2.14	7.75	37.29	13.33	12.80	0.47	9.81	54.31
SU_3			7.75	5.61	0.89	0.28	1.44	0.35	0.06	10^{-5}	7.19	5.04
SU_4				35.94	1.43	5.82	24.41	11.15	6.53	0.22	5.18	33.29
SU_5					0.28	0.09	0.46	0.14	0.02	0	0.73	1.21
$SU_{>5}$						0.59	3.30	1.65	1.03	0.06	0.25	4.87
SO_8							12.68	6.43	8.66	0.30	1.19	22.02
SO_{10}								2.04	2.57	0.13	0.25	9.44
$SO_{>10}$									3.03	0.25	0.03	5.25
$E_{6,7,8}$										0.01	0	0.13
SM											7.12	3.86
PS												26.86
total:	90.80	95.06	10.64	66.53	2.41	8.20	40.17	15.17	14.94	0.57	10.05	62.05

- SM = Standard Model;   PS = Pati Salam SO(4) x SO(6)
- Off-diagonal entries show pairwise percentages;
  diagonal entries show percentages for factor appearing *twice*.
- "Total" is *uncorrelated* probability for single group factor.

Correlation probability table (quoted in % of models)…



	U_1	SU_2	SU_3	SU_4	SU_5	$SU_{>5}$	SO_8	SO_{10}	$SO_{>10}$	$E_{6,7,8}$	SM	PS
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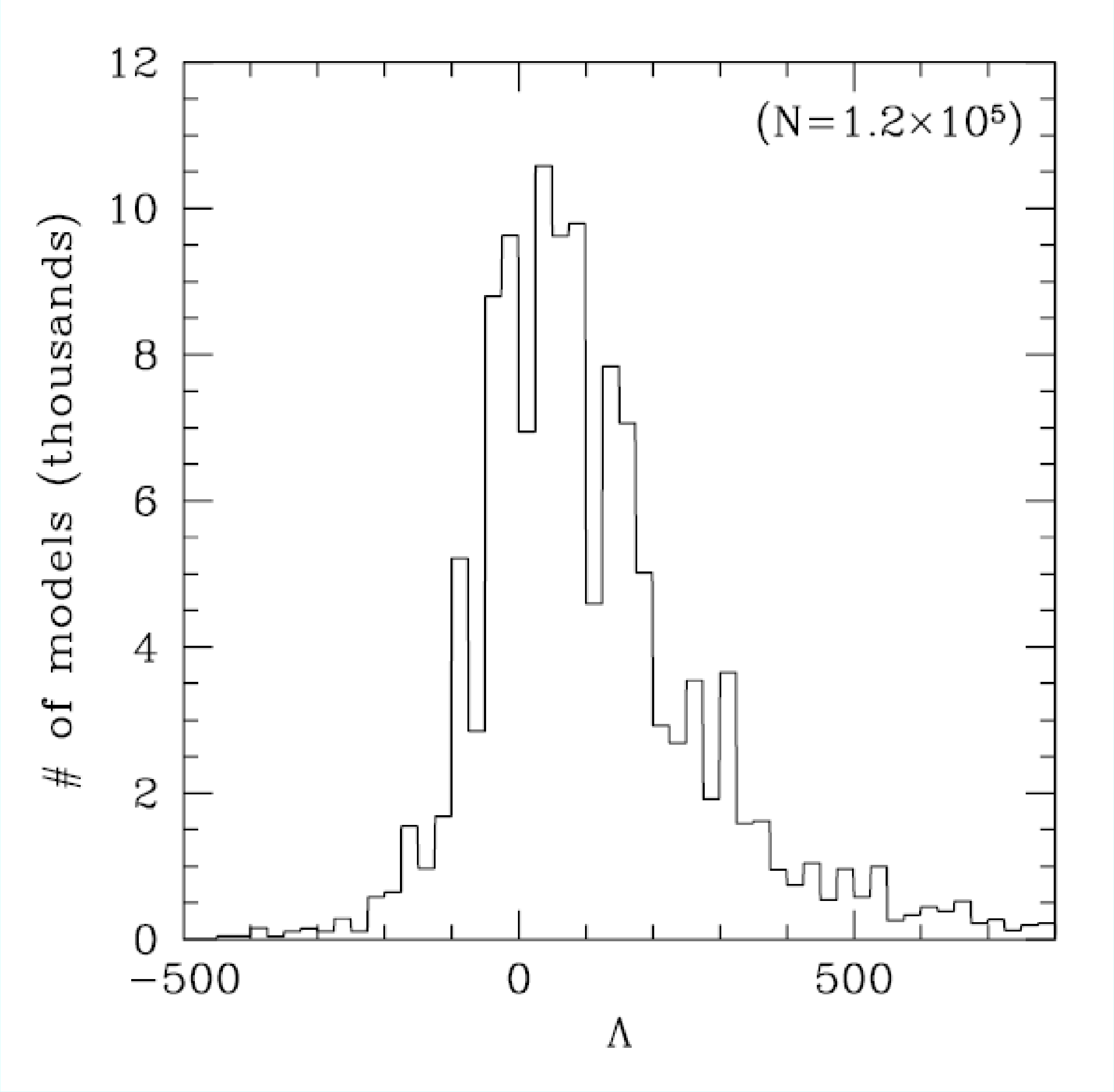
PS												26.86
total:	90.80	95.06	10.64	66.53	2.41	8.20	40.17	15.17	14.94	0.57	10.05	62.05

- Almost all SU(3), SU(n≥5) factors come with U(1), as already noted.
- No models with SU(5) x (any E-group); no models with SM x (E-group); only one with SU(3) x (E-group).
- Overall, Pati-Salam is *much more prevalent* than SM, while SO(10) is *somewhat more prevalent* and SU(5) is *slightly less prevalent* than SM.

Another important quantity which string theory is in a unique position to predict/evaluate is the cosmological constant Λ .

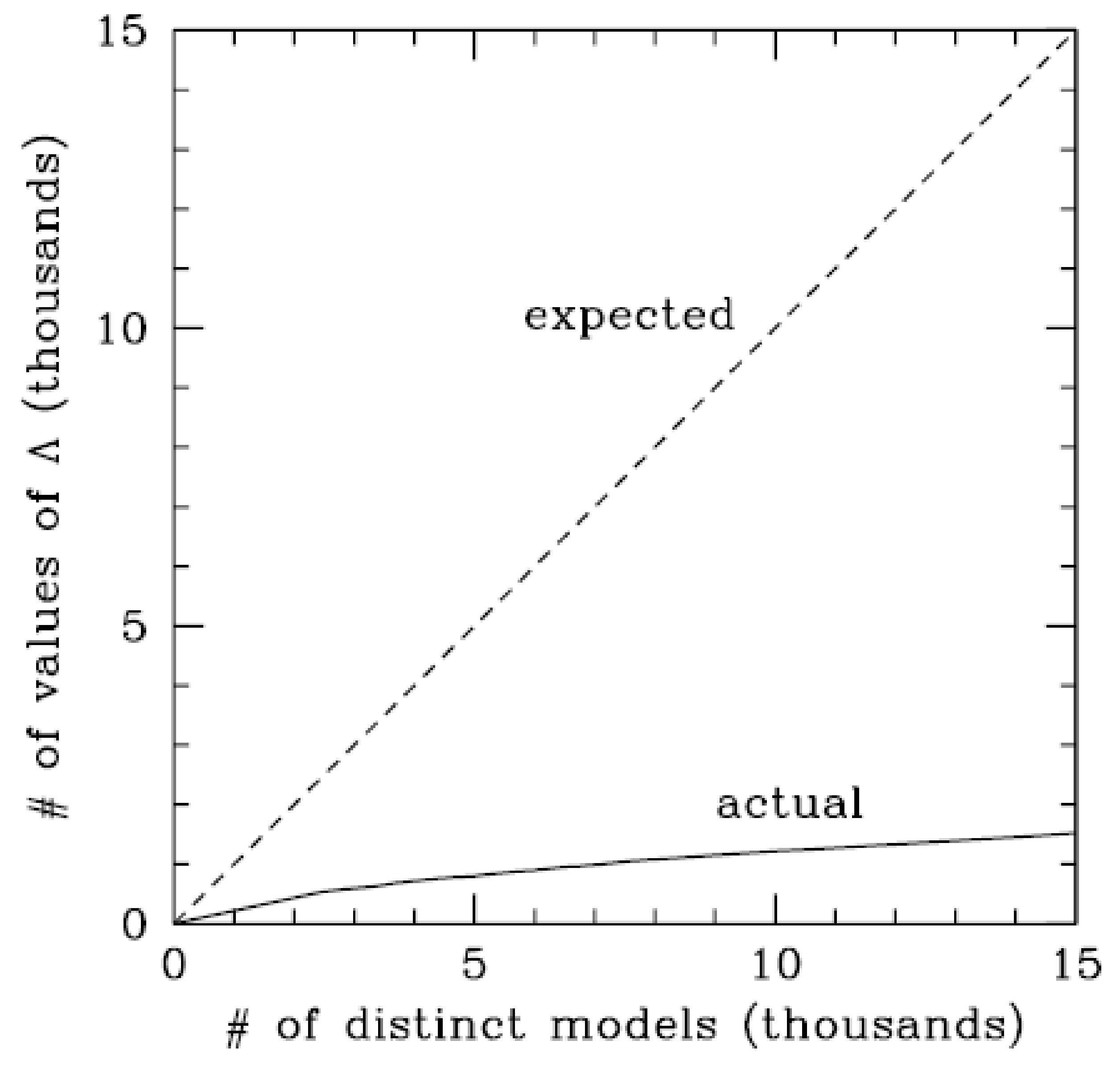
So what values of Λ do we find for our sample?



- Both positive and negative values emerge, with over 73% *positive* (i.e., *negative* λ --> AdS).
- Over 10^5 models, but smallest value of $|\Lambda|$ found is 0.0187.

Why none smaller?

There's a great redundancy in values of Λ !



- The number of values of Λ found is significantly less than the number of models examined!
- Unrelated models with completely different gauge groups and particle content can nevertheless have *identical* values of Λ !

In fact, it appears that the number of cosmological constant values may actually *saturate*...

If so, fit curve to exponential form

$$\Sigma(t) = N_0 \left(1 - e^{-t/t_0}\right)$$

maximum value

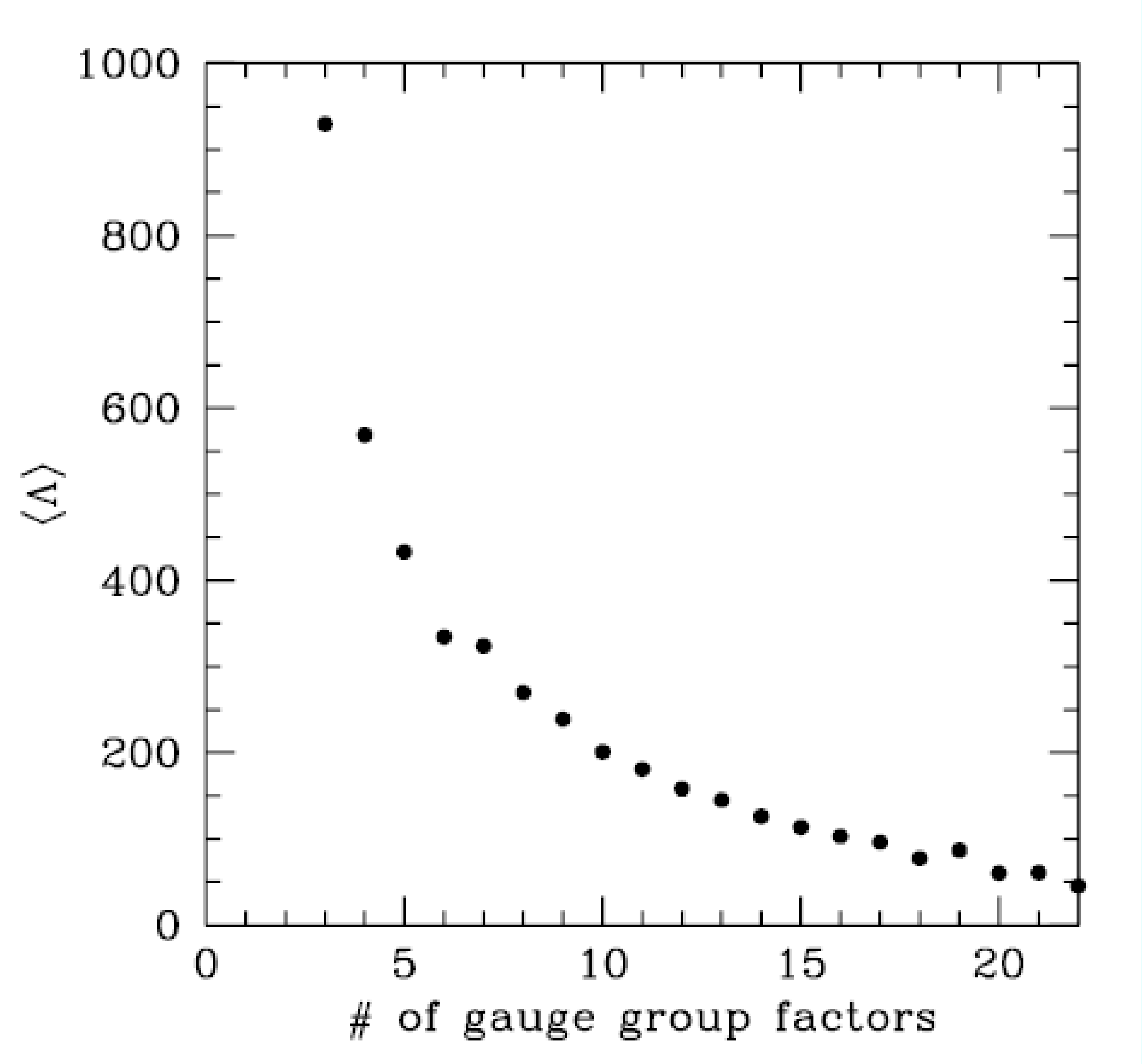
“time constant”

find $N_0 \sim 5500$, $t_0 \sim 70{,}000$.

Of course, haven't really examined enough models to observe saturation reliably...

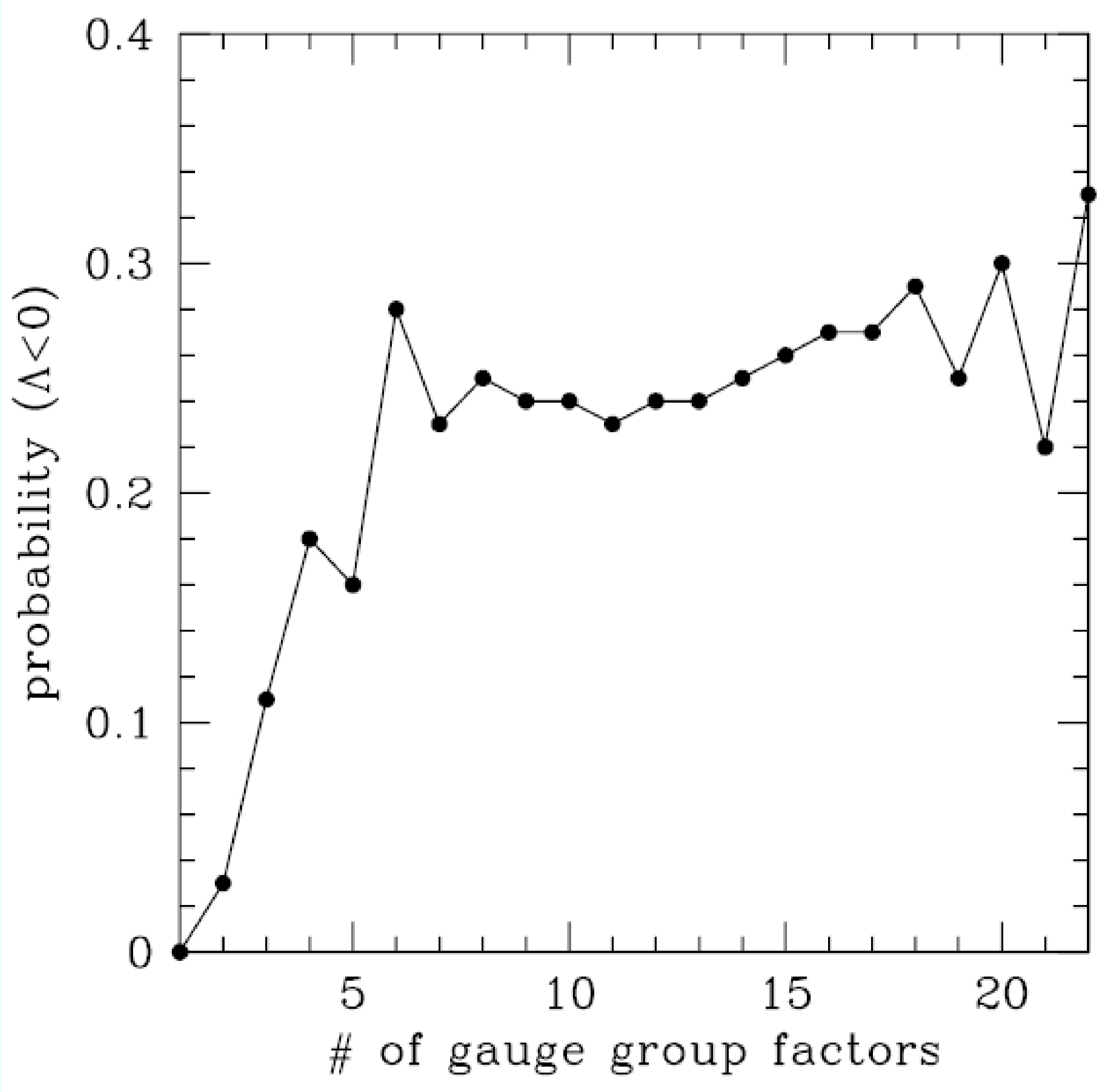
Are there significant correlations between gauge groups and Λ?

Yes! Look at Λ versus degree of shatter:



- These are *statistical averages* across all models with same degree of shatter.
- **More twists (i.e., smaller gauge-group factors) tends to lead to smaller one-loop cosmological constants.**

What is the probability that a randomly chosen heterotic string model has a negative Λ (i.e., positive λ)?



- No significant probability until shatter reaches 4-5.
- Probability then remains constant as further shattering occurs.
- Overall probability averages to 27%.

On the one hand, it is incredible that string theory allows such calculations to be done!

> After all, these are literally *statistical calculations regarding probabilities that one set of laws and fundamental constants for the universe are favored over another!*

On the other hand, there are numerous subtleties that emerge when trying to perform analyses of this type, and new methods need to be developed in order to extract phenomenological predictions in a meaningful way...

The problem of floating correlations

This problem was not discussed previously in the literature, but turns out to play a huge role in obtaining meaningful statistical results from a data set to which one has only limited computational access.

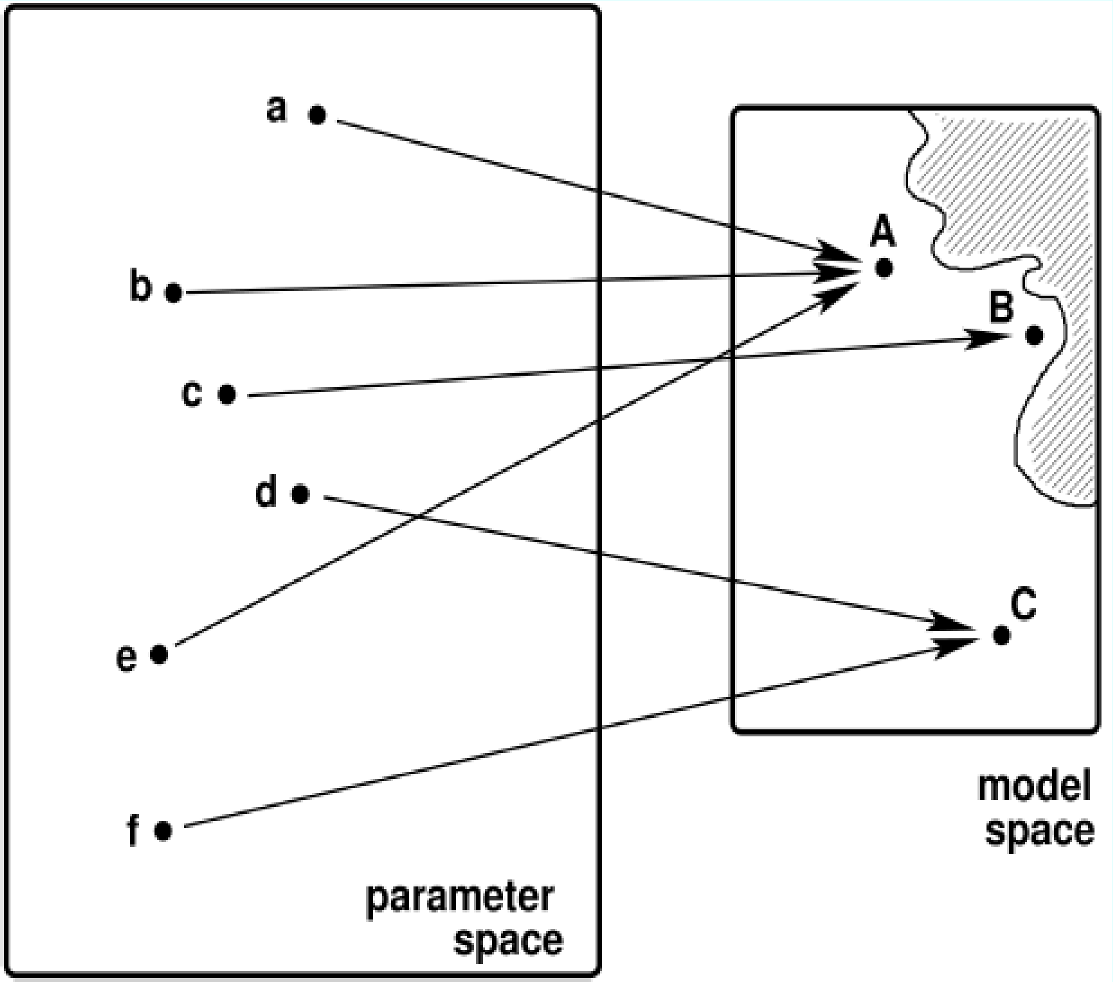
- KRD and M. Lennek, hep-th/0610319 (PRD)

The problem of floating correlations is the observation that some statistical correlations are *unstable* --- they “*float*” (or evolve) as the sample size increases.

Why does this happen?

Essentially, as we continue to randomly generate models, it gets harder and harder to find new (i.e., distinct) models. Thus, physical characteristics which were originally “rare” are often forced to become less “rare” as the sample size increases and we probe more deeply into the space of models.

In particular,
consider the process of randomly generating string models...



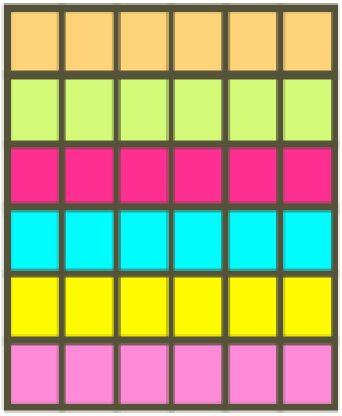
- One must generically employ a model-construction technique which specifies models according to some set of internal parameters (e.g., fluxes, orbifold twists, boundary conditions or phases, Wilson lines, etc.)

- Each set of parameters maps to a single model, but the mapping is rarely unique!

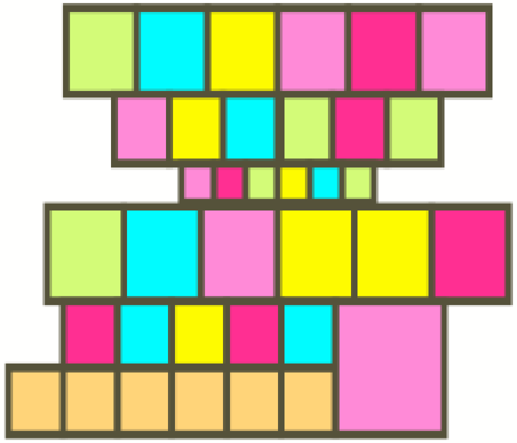
Thus some models are much more likely to be generated than others! This feature is essentially *unavoidable*.

Thus, we don't see the model space directly:

We see a deformed version of it, a "probability space":



Ω_{model}

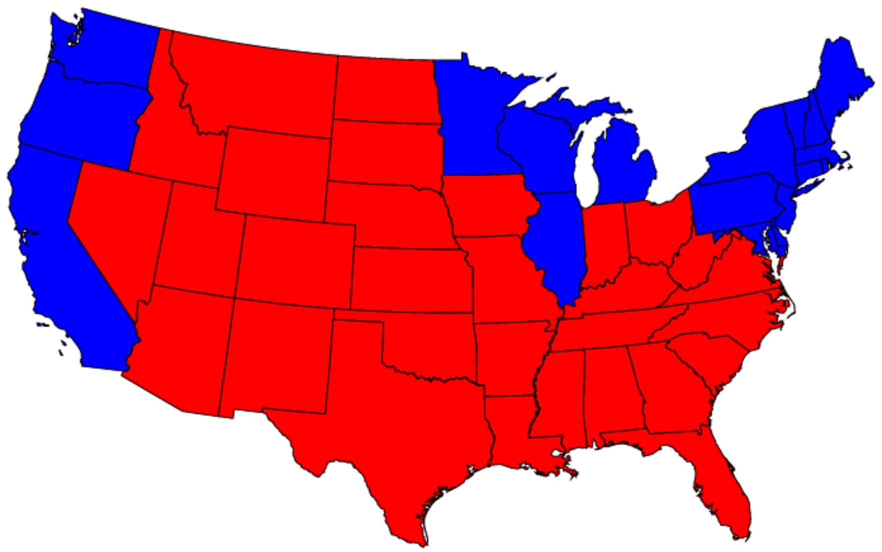


Ω_{prob}

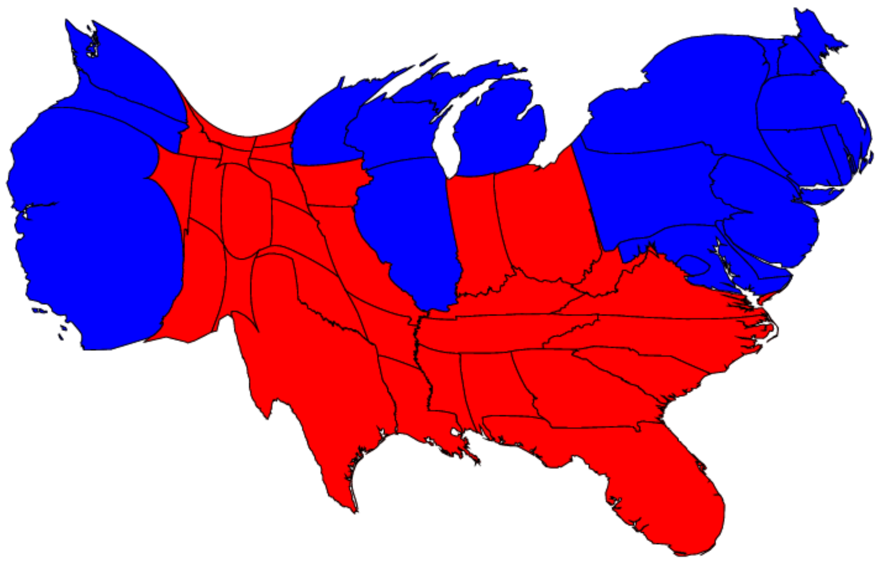
Does this difference matter for our statistical correlations between physical observables?

Yes, if the physical properties are somehow correlated with these probability deformations.

To use a real-world example, it's the difference between this:

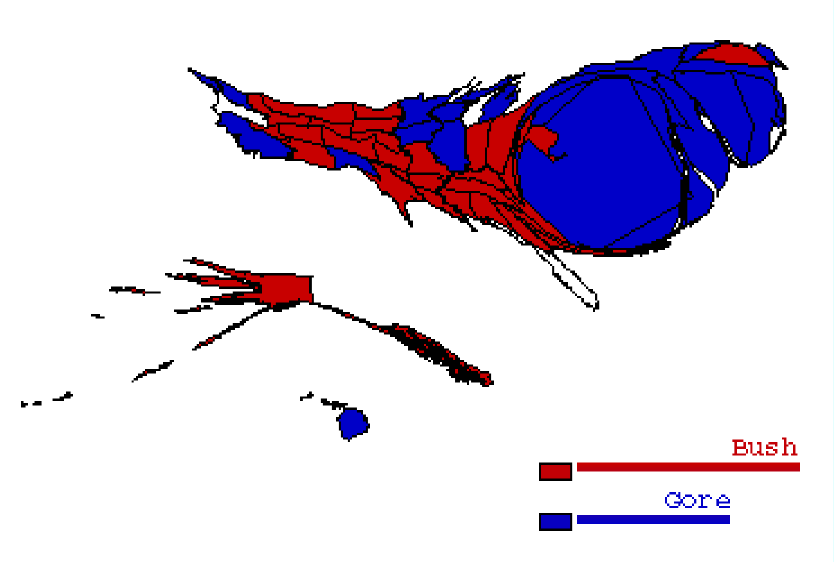


and this:



Cartogram based on population.

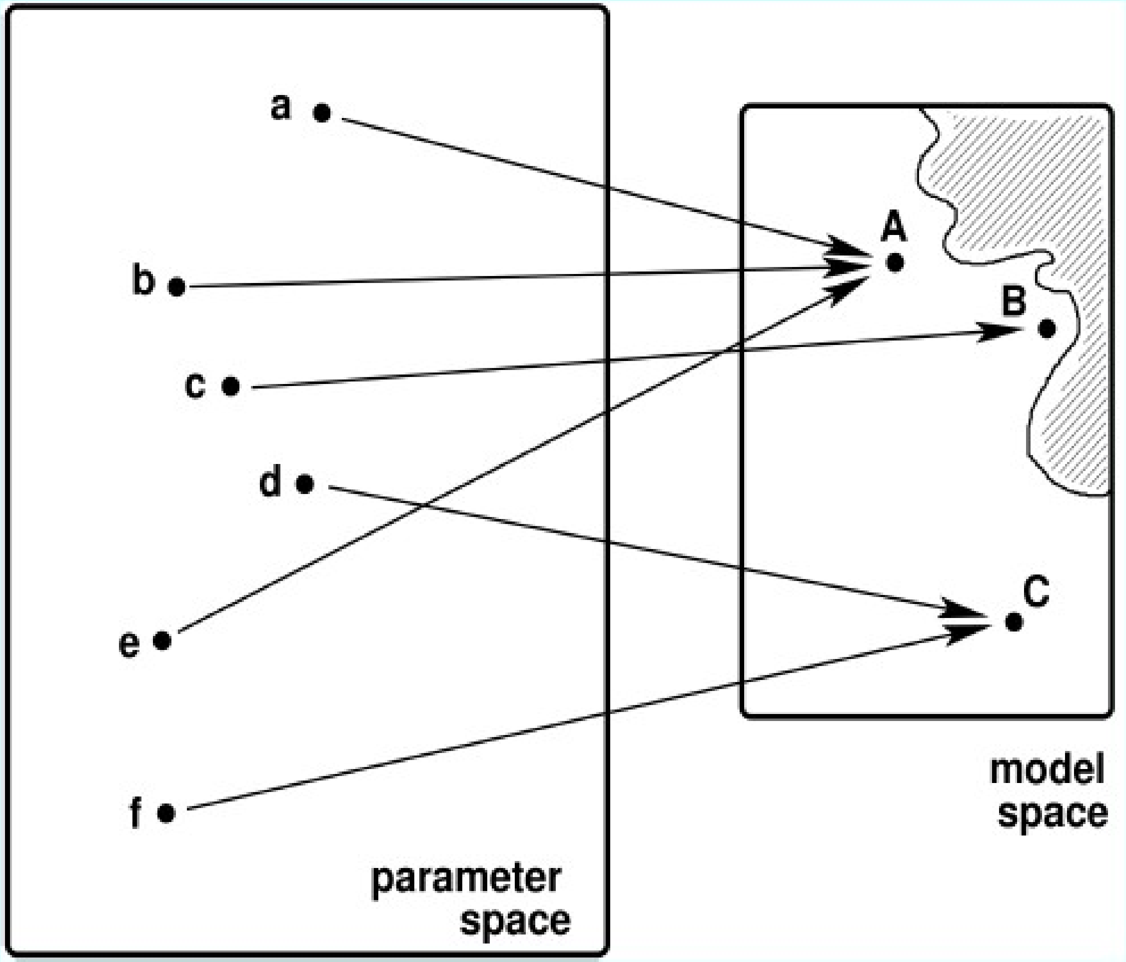
…or even this:



Cartogram based on population density.

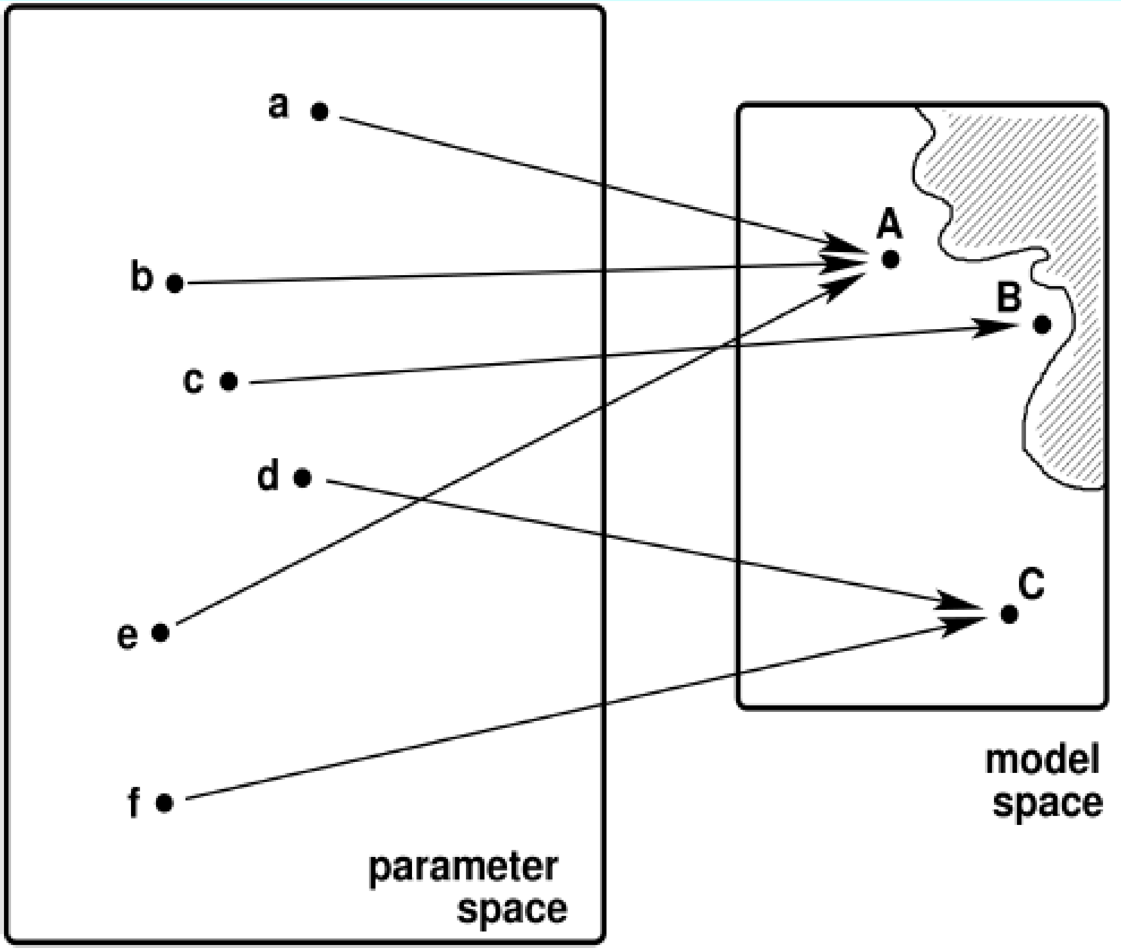
Sadly, these things *do* matter and can affect outcomes.

How can we get around this problem?



- Partial solution: don't count the “new” model if it's already in the data set. Consider it a “failed attempt”, disregard this case, and try again.

How can we get around this problem?



- But we are still not finding the very “rare” models (such as Model B), close to the “unreachable” region. It will take a considerably larger data set before we will stumble across such rare models, and we have *no information* about where they are, how common they are, or whether they even exist!

This is the whole problem: we do not have computational access to the entire landscape! Thus, our statistical data “floats” as we keep digging for new nuggets (which, since they are still “new”, are necessarily “rare”).

What we need is a way of extracting information (even if only limited information) about the full landscape on the basis of only partial information.

Analogous to lattice gauge theory: need to extract information about the continuum limit on the basis of calculations done at finite lattice spacing.

Solution:

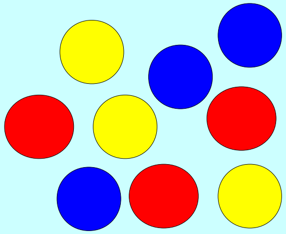
- Restrict attention to relative *ratios* of probabilities of models with different characteristics.
- But calculate these ratios only when the spaces of models with these characteristics *are equally explored.*

Of course, we need a measure for "equally explored".
How can we judge how deeply we have penetrated into a particular model space?

> *Solution:* Look at *number of attempts to generate a model with a specified characteristic.*
> If it is easy to generate new models of a given type, then the corresponding space of models of that type is relatively unexplored. As we progress, it gets much harder to find new models of that type and the number of failed attempts per new model increases.

Thus, by measuring numbers of models found against numbers of *attempts* to generate new models, and comparing this ratio for two different groups of models, we can extract information about the relative volumes of their corresponding full model spaces and thereby deduce their true relative probabilities.

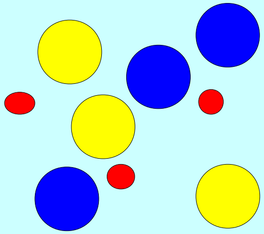
Example: Plucking balls from an urn.



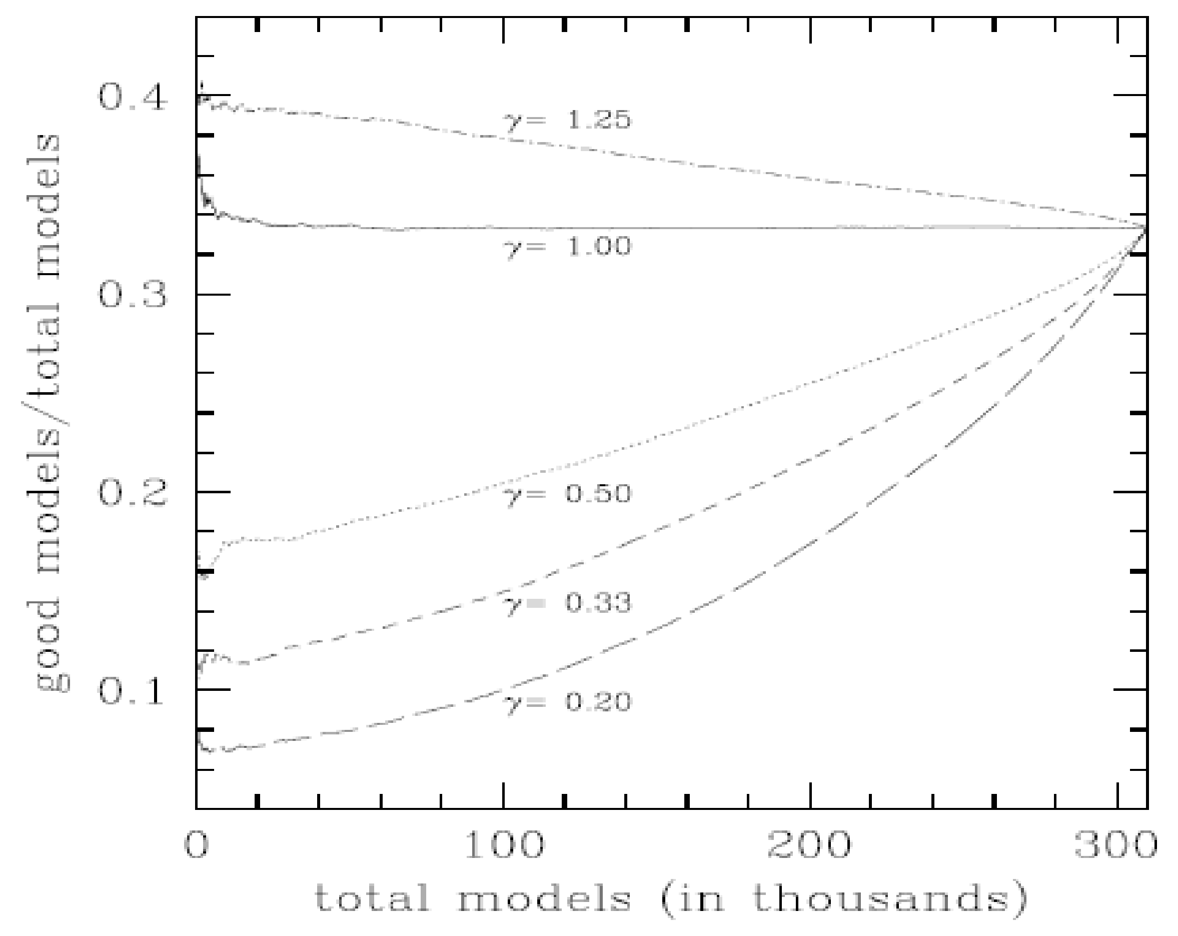
An urn contains 300,000 balls of different colors. One third of the balls are red. We seek to know what fraction of balls in the urn are red, and we try to determine this by choosing a ball randomly from the urn, noting its color, marking it for future identification, replacing the ball in the urn, mixing, and then repeating over and over.

If all balls are treated equally (no bias), approximately one third of all balls selected will be red. This will not vary significantly with sample size.

However, suppose the red balls have a different size than the others, so that the probability of picking a red ball from the urn on a given try is γ times the probability of picking a ball of any other color.



What fraction of selected balls will be red?
Clearly this “floats” with the sample size:



True fraction emerges only upon full exploration of the urn.

But suppose we don't have enough time/ability to wait that long and we don't know γ. What can we do?

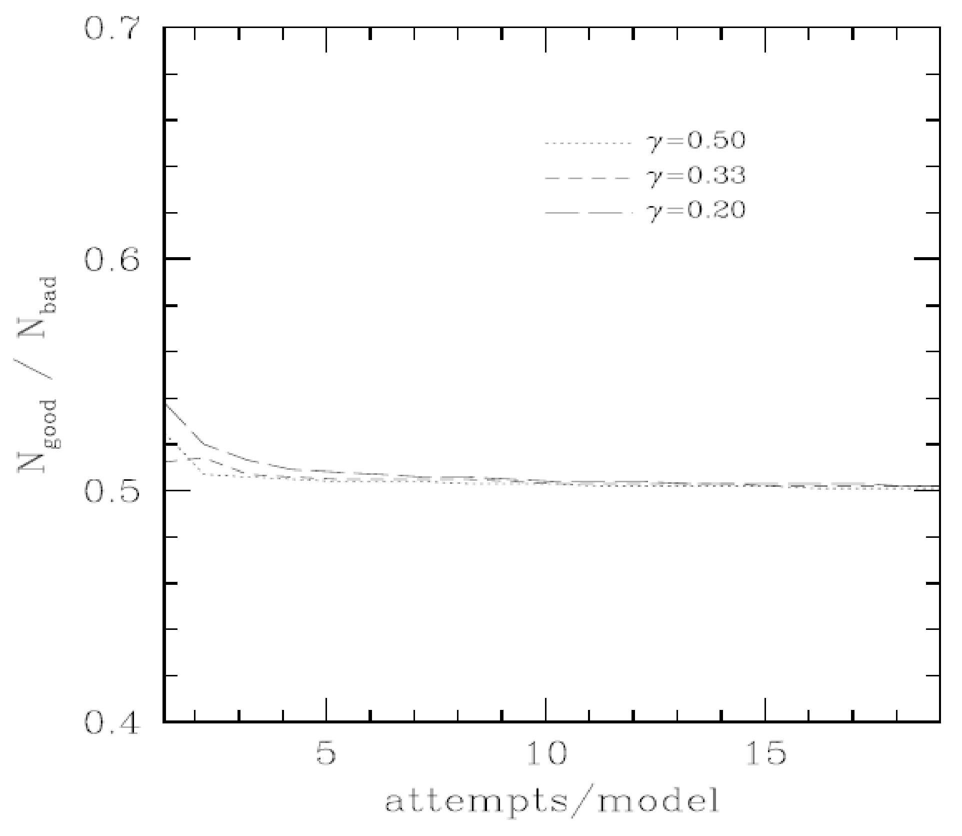
Keep a running record of

- X_{red} = number of failed “red” attempts to find the last new red ball
- X_{other} = number of failed “other” attempts to find a new ball of any other color.

Then

$$\frac{\text{Number of red balls in urn}}{\text{Number of other balls in urn}} = \frac{\text{\# red balls that have been found}}{\text{\# other balls that have been found}}$$

evaluated at values for which $X_{red} = X_{other}$!!



“Continuum” limit reached quite quickly regardless of chosen X!

In fact, the true computational situation we face for the landscape is even more complicated ---

- There can be a whole *spectrum of different sizes* (intrinsic probabilities) for the different balls (string models).
- There is no guarantee that the *sizes* (intrinsic probabilities) of the balls (models) are in any way correlated with their *colors* (physical characteristics).

➡ In general, there can be a huge “CKM matrix” between colors and sizes, all of whose entries are essentially unknown!

Need methods of extracting meaningful statistical information, even for such general situations.

- KRD and Lennek, hep-th/0610319 (PRD)

There is also another possible complication.

All of the previous discussions assume that the low-energy limit of a given string model has a relatively simple field-theory structure:

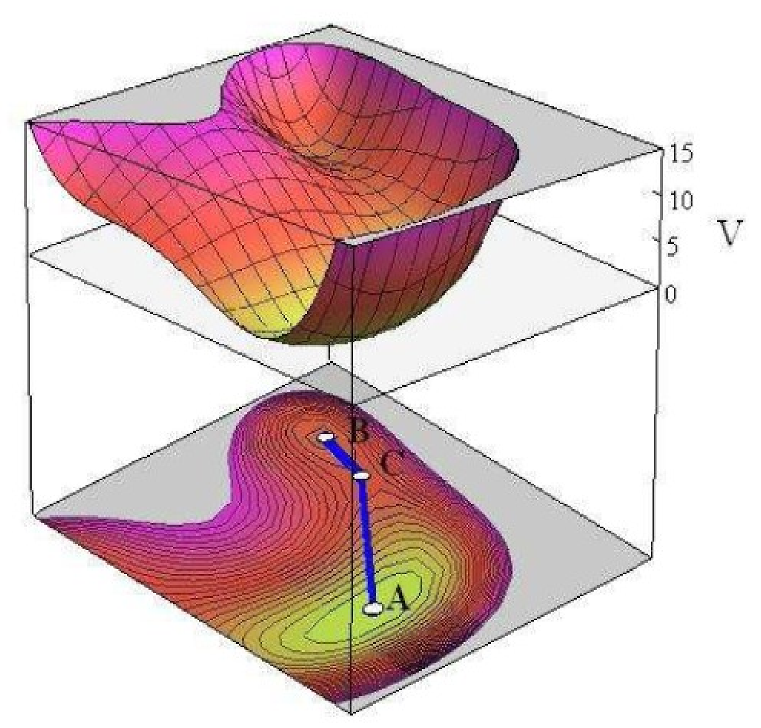
- A single vacuum (the ground state)
- A tower of excited states built on that vacuum.

As such, the resulting phenomenology associated with each string model is uniquely determined, and each string model corresponds to a unique possible ground state for the universe.

One string model ⟺ One vacuum

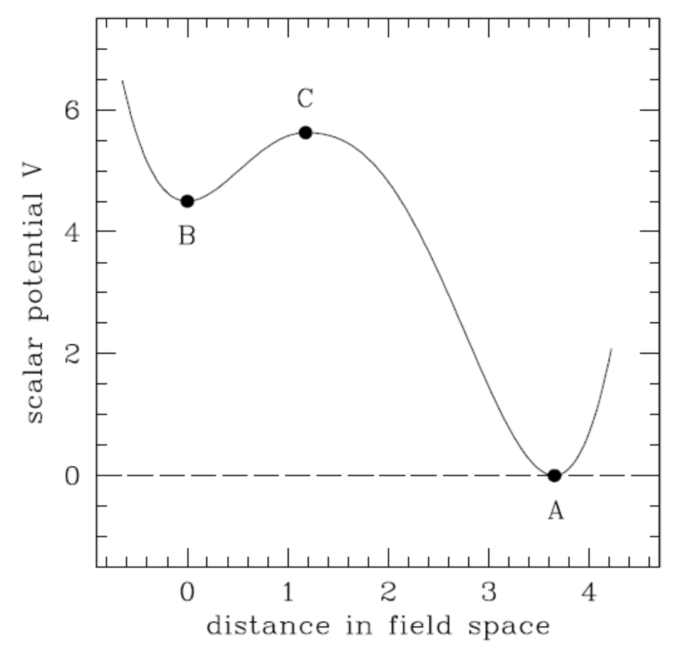
Counting models ⟺ Counting vacua

In recent years, however, there has been increasing recognition that many models also contain additional ***metastable vacua*** whose lifetimes can easily exceed cosmological timescales.



Dine, Nelson, Nir, Shirman, Dimopoulos, Dvali, Rattazzi, Giudice, Luty, Terning, Banks, Intriligator, Seiberg, Shih, Abel, Khoze, Aharony, Forste, Feng, Silverstein, Dienes, Thomas, ...

Moreover, the phenomenological properties of the metastable vacuum can be completely different than those of the true ground state! (e.g., SUSY and R-symmetries preserved vs. broken, different gauge groups, etc.)



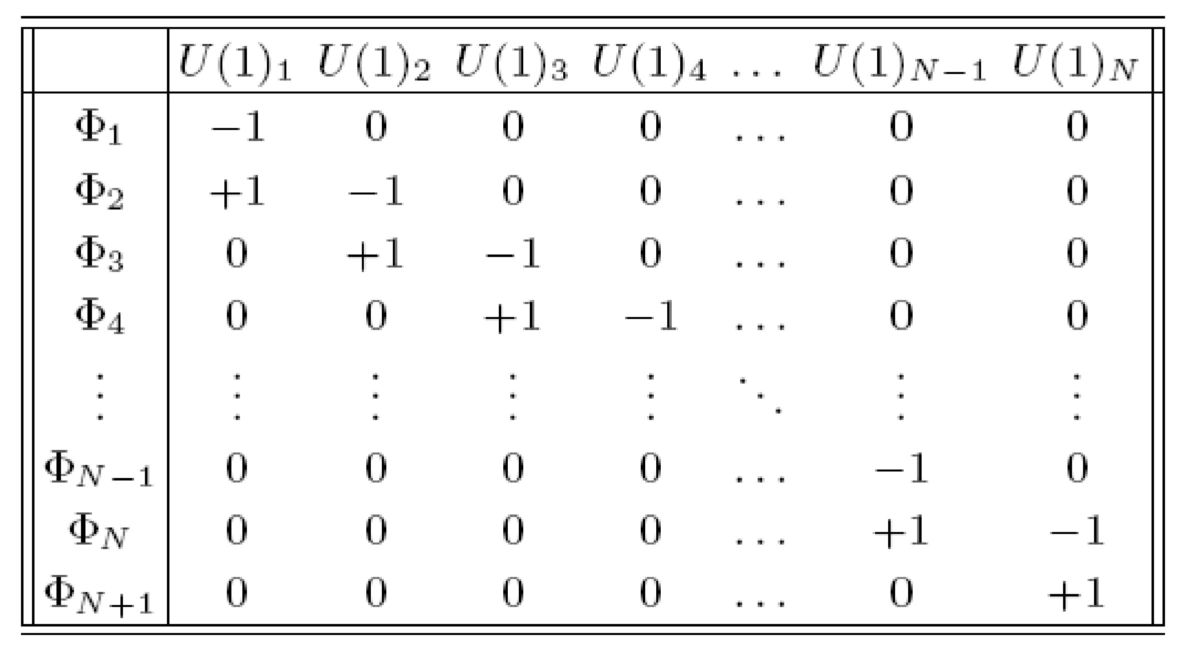
KRD & B. Thomas, 0806:3364

As a result, the one-to-one connection between models and vacua need not apply!

The full landscape of string theory can be even richer than previously imagined, since all long-lived metastable vacua must be included in the analysis.

In fact, this effect can be extremely dramatic and can completely alter our perspective on the sorts of physics which might dominate the landscape.

This is because many string vacua take the form of so-called “flux compactifications”, and these theories have “deconstructed” low-energy versions which correspond to supersymmetric abelian gauge theories with very specific particle content:

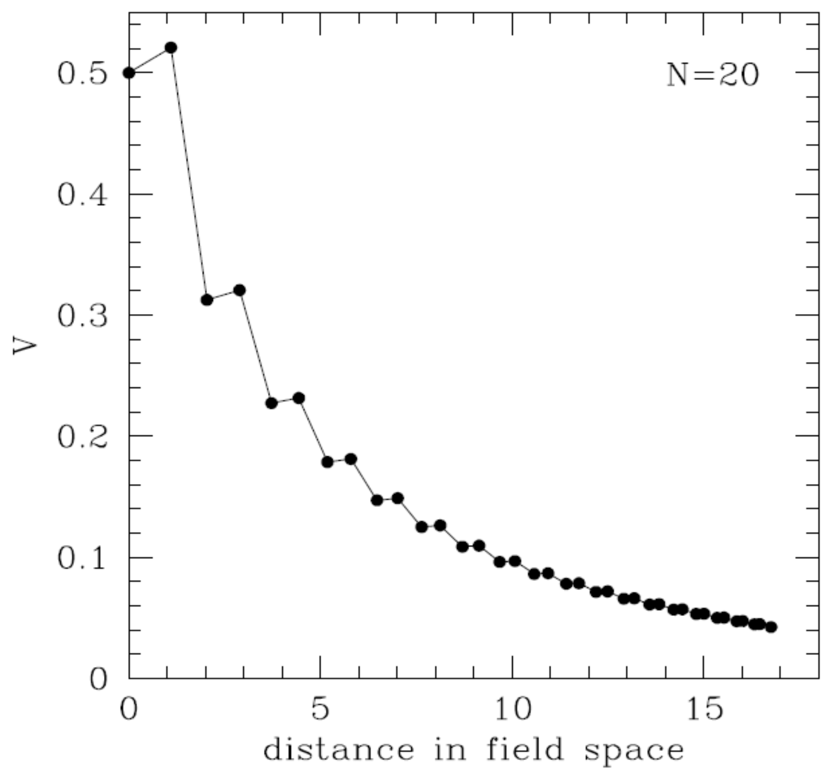


	$U(1)_1$	$U(1)_2$	$U(1)_3$	$U(1)_4$	$\ldots$	$U(1)_{N-1}$	$U(1)_N$
Φ_1	-1	0	0	0	$\ldots$	0	0
Φ_2	$+1$	-1	0	0	$\ldots$	0	0
Φ_3	0	$+1$	-1	0	$\ldots$	0	0
Φ_4	0	0	$+1$	-1	$\ldots$	0	0
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
Φ_{N-1}	0	0	0	0	$\ldots$	-1	0
Φ_N	0	0	0	0	$\ldots$	$+1$	-1
Φ_{N+1}	0	0	0	0	$\ldots$	0	$+1$

In the presence of kinetic mixing, however, it has recently been shown that these theories give rise to ***infinite towers of metastable vacua with higher and higher energies!***

As the number of vacua grows towards infinity, the energy of the highest vacuum remains fixed while the energy of the true ground state tends towards zero.

KRD & B. Thomas, 0811:3335



Thus, even if such models are relatively rare across the landscape, the fact that they give rise to infinitely many vacua means that they could completely dominate the properties of the landscape as a whole!

The existence of the landscape allows us to reformulate many of our usual theoretical notions in hitherto-unimaginable ways.

For example, let us ask a simple question:

Is SUSY natural?

This is an important question.

Most theoretical frameworks for physics beyond the SM involve the introduction of SUSY ---

- solves technical gauge hierarchy problem
- can trigger electroweak symmetry breaking
- improves gauge coupling unification
- provides dark matter candidate

➡ SUSY is truly ubiquitous ---

- in our theories
- on the arXiv
- in our colloquium presentations

--- indeed, everywhere except the data.

However, lots of competing theories have recently appeared --

- Large extra dimensions
- Small extra dimensions
- Strongly coupled theories, etc.

And the theories have grown more and more complex…

- We are made of open strings
- and we live on a brane
- and the brane lives in extra dimensions
- and the brane is wrapped and intersects other branes
- and the extra dimensions are warped
- and the warping is severe and forms a throat
- and the brane is falling into the throat
- and…, and …, and…

This is cutting-edge model-building, but to some, it may sound like a lot to swallow (pardon the pun)!

All of this may sound highly unnatural.

But is SUSY itself truly natural?

What does it mean to be “natural”, anyway?

Lots of different notions of “naturalness”…

- **EFT (Dirac) naturalness:** an EFT is “natural” if the dimensionless coefficients of all operators are of order 1 --- no unnaturally small numbers
  - e.g., gauge hierarchy is unnatural (biggest motivation for SUSY)

- **'t Hooft naturalness:** even if a number is small, it can be “natural” if protected by a symmetry

But neither of these addresses the question as to whether a theory, even if “natural” in the above sense, is *likely* to be right.

How *likely* is SUSY to be the correct theory?

“Likely”…??!

Even though we constantly judge theories in this way, we don't say it aloud because the question seems more philosophical than scientific.

- How likely relative to *what*?
- All other theories that one can imagine?
- Who is doing the imagining?

(me? Ed Witten? Arnold Schwarzenegger? ... Sarah Palin?!
--- might get very different answers!)

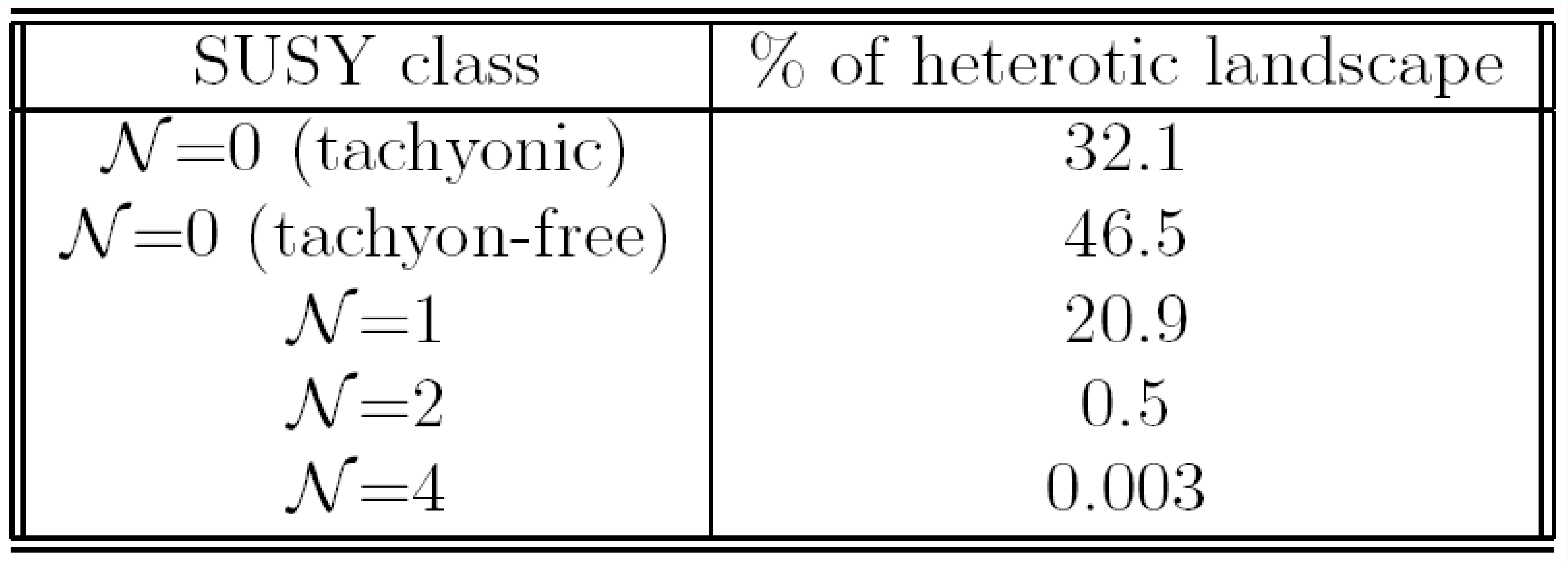
How can one compare the likelihood of one theory against another?

String theory provides a framework in which this question can be addressed in a meaningful way.

Thanks to the landscape, we can reformulate this question as follows:

In the landscape of possible string solutions,
how many of these solutions are supersymmetric?
Is SUSY "natural" on this landscape, or relatively rare?

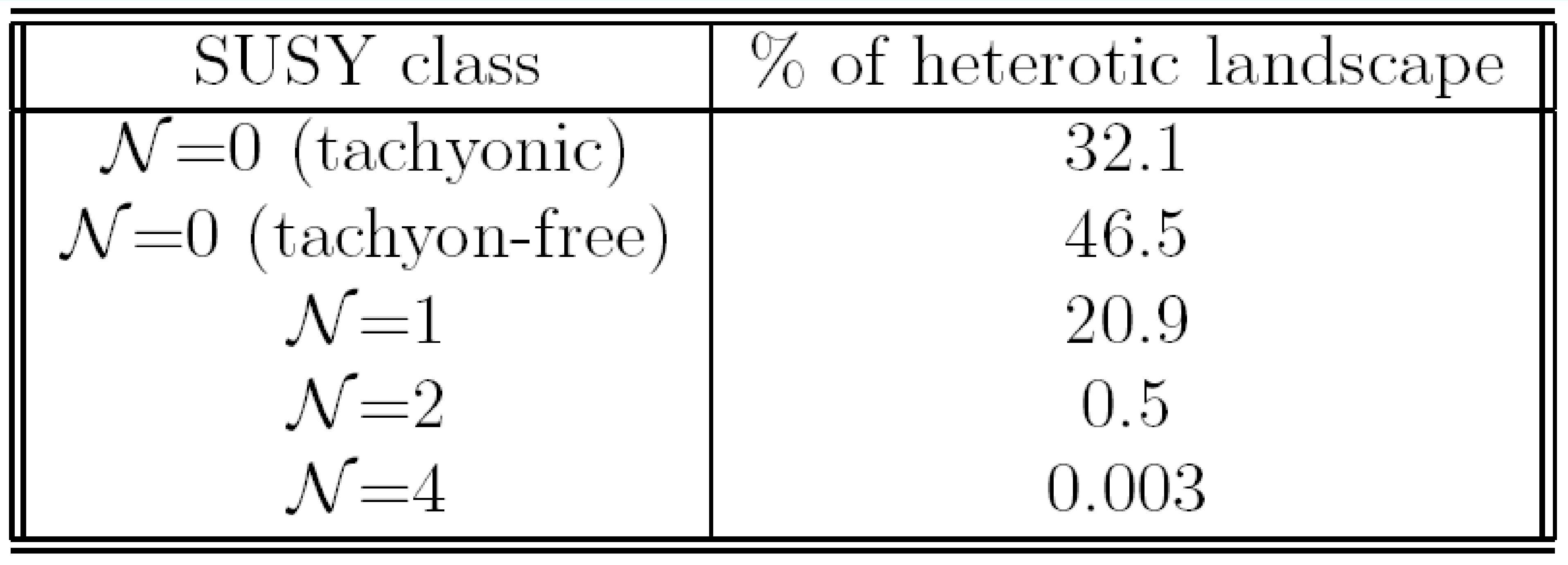
Using the new statistical techniques we developed, we ultimately find the results:



SUSY class	% of heterotic landscape
$\mathcal{N}$=0 (tachyonic)	32.1
$\mathcal{N}$=0 (tachyon-free)	46.5
$\mathcal{N}$=1	20.9
$\mathcal{N}$=2	0.5
$\mathcal{N}$=4	0.003

- Nearly half of the heterotic landscape is non-SUSY but tachyon-free!
- The SUSY portion of the heterotic landscape represents less than ¼ of the full landscape, even at the string scale!
- Models exhibiting extended (N>1) SUSY are exceedingly rare, representing less than 1% of the full landscape.

Using the new statistical techniques we developed, we ultimately find the results:



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$\mathcal{N}=2$	0.5
$\mathcal{N}=4$	0.003

In fact, SUSY fraction of full landscape may be even smaller ---

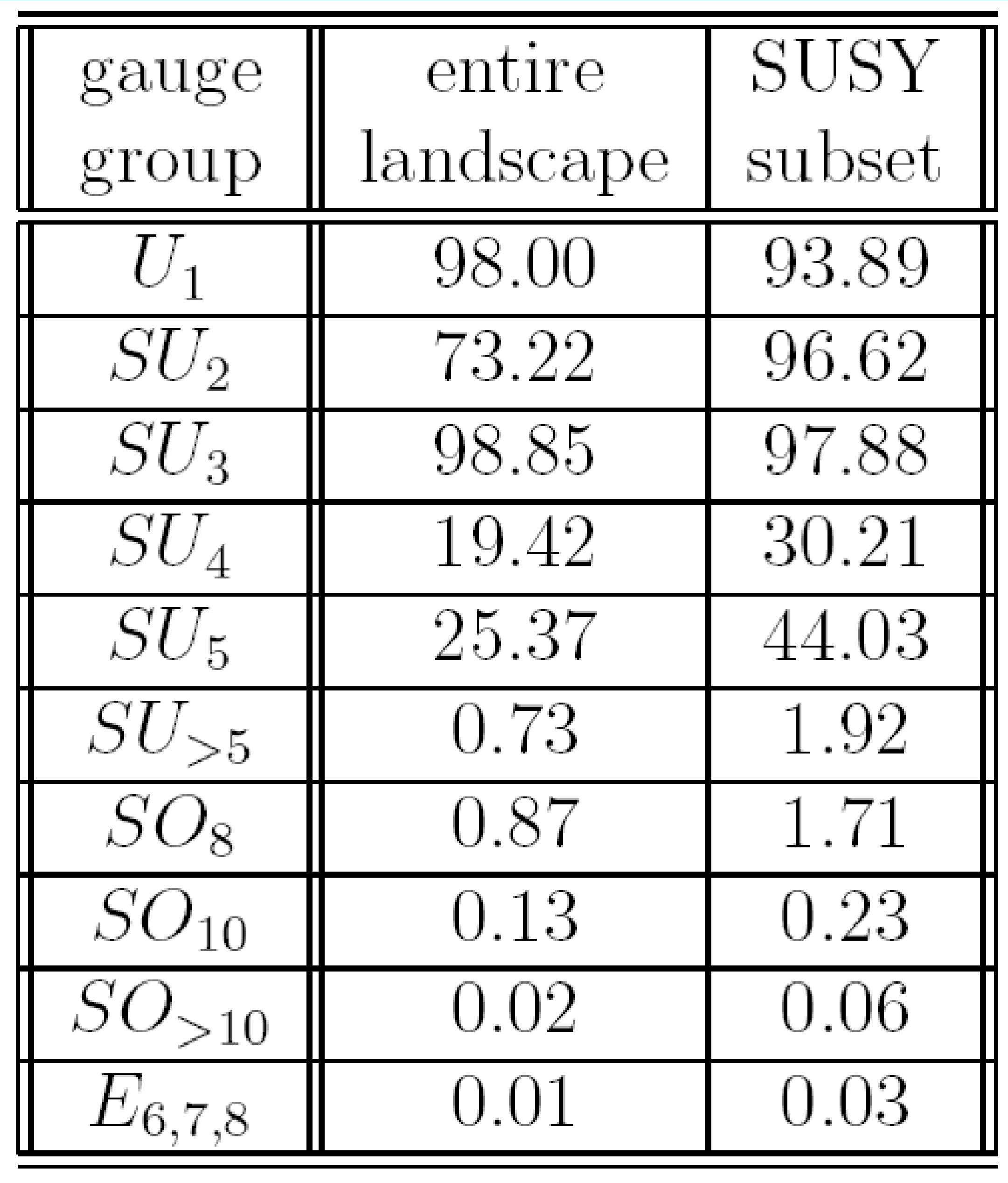
- Free-field constructions probably tend to *favor* models with unbroken SUSY and large gauge groups.
- Even when stabilized models exhibit SUSY at string scale, it's statistically unlikely that SUSY will survive down to weak scale...

Thus, weak-scale SUSY is rather *unnatural* from a string landscape perspective.

A problem?
Not at all --- could even be considered good news ---

Implies that we will actually learn something about string theory and its preferred compactifications if/when weak-scale SUSY is discovered in upcoming collider experiments.

We can also statistically determine whether supersymmetry favors some gauge groups over others.

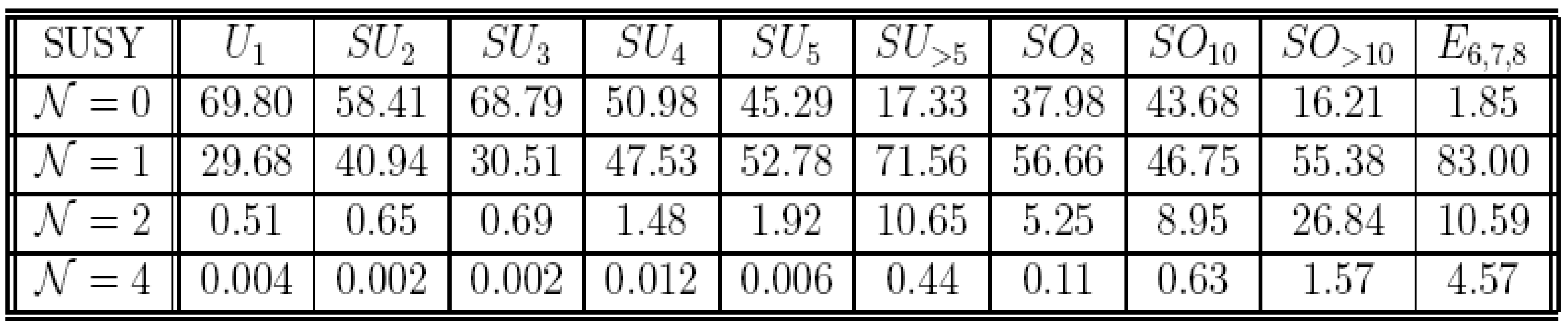


gauge group	entire landscape	SUSY subset
U_1	98.00	93.89
SU_2	73.22	96.62
SU_3	98.85	97.88
SU_4	19.42	30.21
SU_5	25.37	44.03
$SU_{>5}$	0.73	1.92
SO_8	0.87	1.71
SO_{10}	0.13	0.23
$SO_{>10}$	0.02	0.06
$E_{6,7,8}$	0.01	0.03

- Gauge groups with larger ranks are favored more strongly with SUSY than without SUSY.
- Thus, small factors such as U(1) and SU(3) are slightly *less* prevalent with SUSY… they are "sacrificed" in order to make room for larger-rank gauge groups.

Of course, the interesting phenomenological question is the "inverse" question:

> If we *know* the gauge group, how likely are the different degrees of SUSY?



SUSY	U_1	SU_2	SU_3	SU_4	SU_5	$SU_{>5}$	SO_8	SO_{10}	$SO_{>10}$	$E_{6,7,8}$
$\mathcal{N}=0$	69.80	58.41	68.79	50.98	45.29	17.33	37.98	43.68	16.21	1.85
$\mathcal{N}=1$	29.68	40.94	30.51	47.53	52.78	71.56	56.66	46.75	55.38	83.00
$\mathcal{N}=2$	0.51	0.65	0.69	1.48	1.92	10.65	5.25	8.95	26.84	10.59
$\mathcal{N}=4$	0.004	0.002	0.002	0.012	0.006	0.44	0.11	0.63	1.57	4.57

- The Standard Model prefers to remain non-supersymmetric.
- GUTs have greater preference for SUSY than does the SM alone.
- Exceptional groups (E6, E7, E8) almost *require* SUSY!
- Thus, strings favor either the non-SUSY SM or SUSY GUTs, but not the MSSM!

And the list goes on…

- Chirality
- Numbers of fermion generations
- Hypercharge normalizations
- Gauge coupling unification
- Yukawa couplings
- String threshold corrections
- Intermediate-scale physics (SUSY-breaking, new gauge structures, …)
- etc.

Such work is ongoing.

"Now Umpire Rodino is dusting off the plate. Incidentally, fans, this is the eighth time Rodino has dusted off the plate in this game, raising his total for the season to sixteen hundred and twenty-two!"

Needless to say, the existence of the landscape also prompts a number of questions of a more philosophical nature…

Given the existence of the landscape, to what extent is string theory predictive?

Goes to the heart of what it means to be doing science!

As such, there can be no more critical question for string theory than this!

But predictivity is not an absolute necessity for all aspects of science — indeed, good science often begins with observation and classification.

True, but while observers and experimentalists need not be primarily concerned with making predictions, theorists must be. Theories of science must incorporate the ability not only to explain, but also to predict.

But the most direct experimental consequences of string theory lie at inaccessible energy scales! Is it fair, then, to hold string theory to normal standards of predictivity?

Even though many of the direct consequences of string theory lie at presently inaccessible energy scales, not all will be.

And even if all of the firm experimental consequences of string theory were somehow proven to lie at scales exceeding those reachable by current accelerator technology, this would not free string theory from its obligations to make predictions which are testable at those higher energy scales — i.e., *testable in principle, if not in practice.*

But “string theory” is not a *model* like the Standard Model --- it's a **language** (like QFT) within which the subsequent act of model-building takes place! QFT does not make predictions on its own --- why hold string theory to such a standard?

This misses a critical point. While quantum field theory tolerates many free parameters, string theory does not: generally all free parameters in string theory (such as gauge couplings, Yukawa couplings, etc.) are determined by the vacuum expectation values of scalar fields and thus are expected to have dynamical origins within the theory itself. String theory should determine its own parameters!

- Given the existence of the landscape, it is certainly too much to demand that string theory give rise to predictions for such individual quantities as the number of particle generations.

- However, as we've seen, it is perhaps not too much to ask that string theory manifest its predictive power through the existence of *correlations between physical observables that would otherwise be uncorrelated in quantum field theory*.

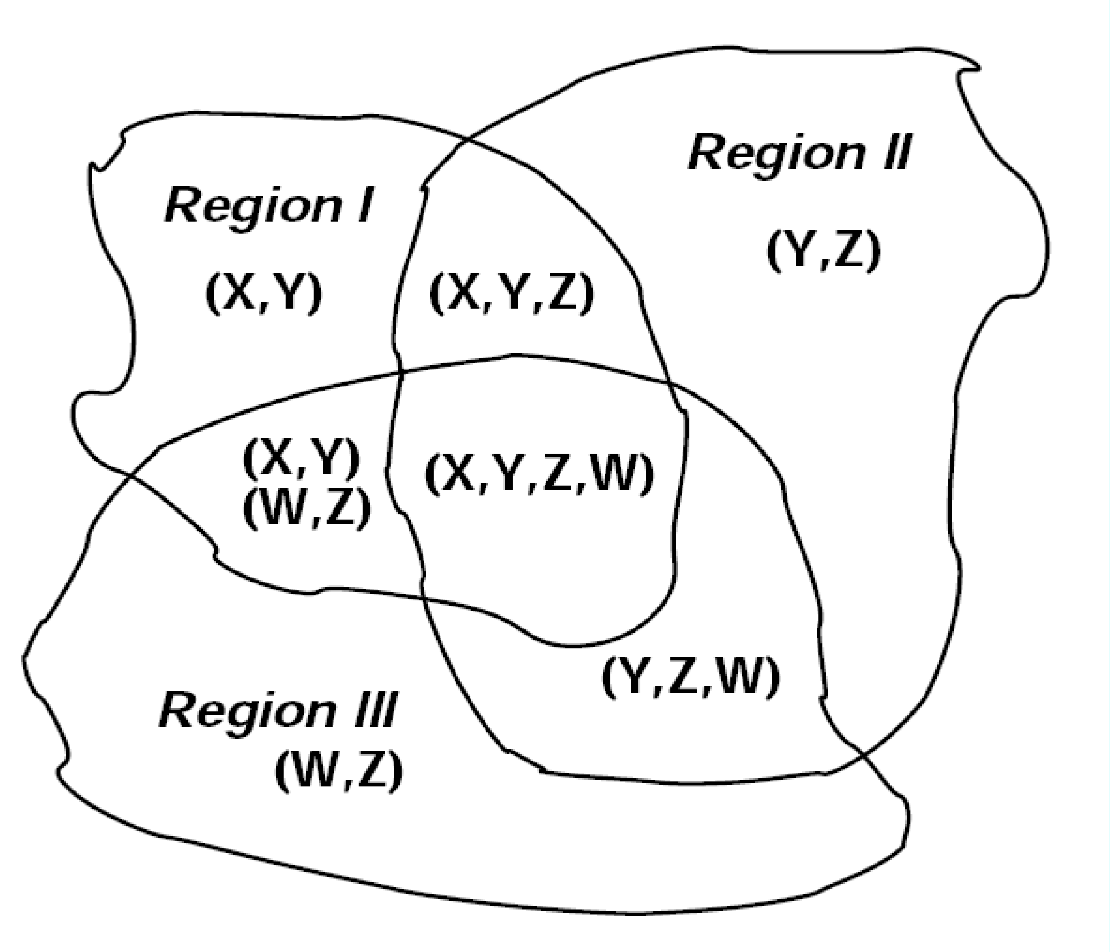
- Such correlations would be the spacetime phenomenological manifestations of the deeper underlying geometric structure that ultimately defines string theory and distinguishes it from a theory whose fundamental degrees of freedom are based on point particles.

Thus, our question concerning the predictivity of string theory boils down to a single critical question:

To what extent are there correlations between different physical observables across the string-theory landscape as a whole?

- *Existence* of correlations: predictive
- *Absence* of correlations: non-predictive

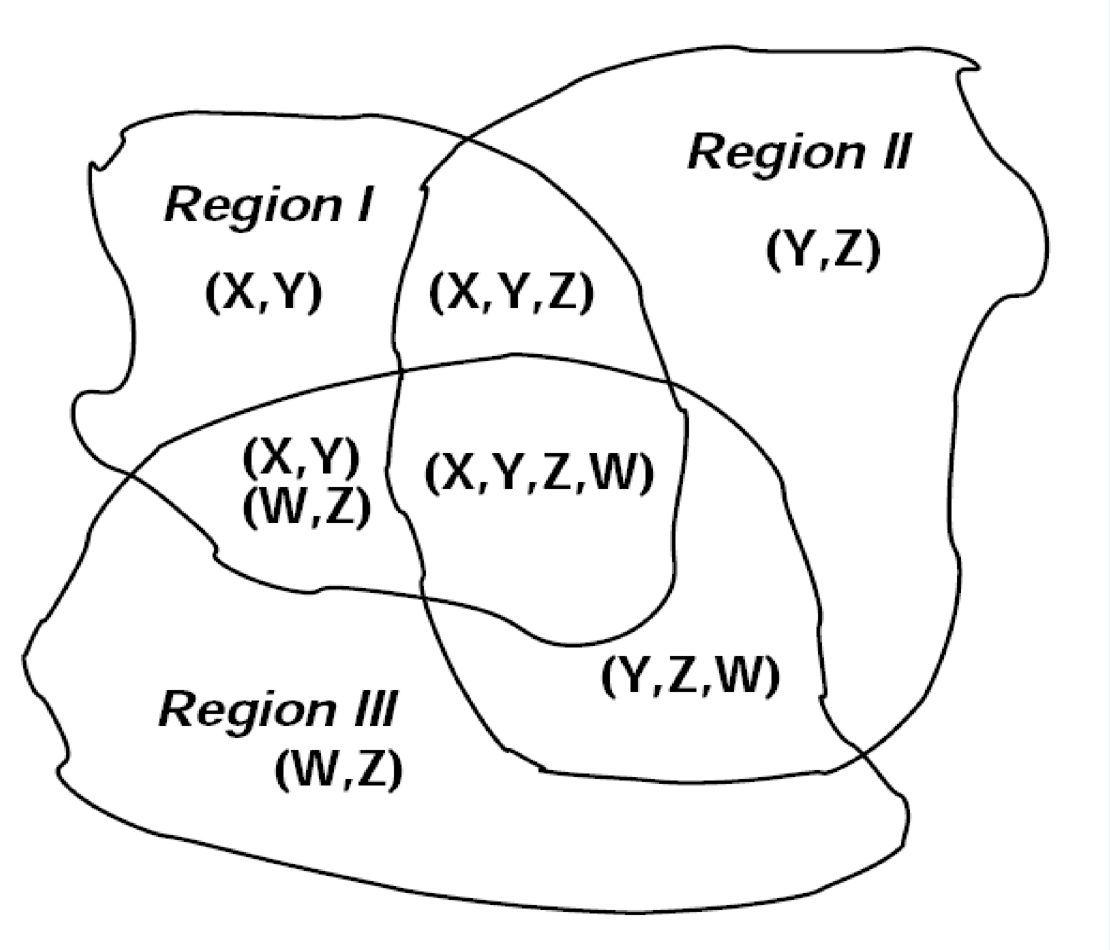
Unfortunately, the true picture is likely to be much more complicated, lying somewhere between these two extremes…



Different regions of the landscape exhibit different correlations. Such regions may have **different sizes**, and moreover are likely to exhibit **non-trivial overlaps**.

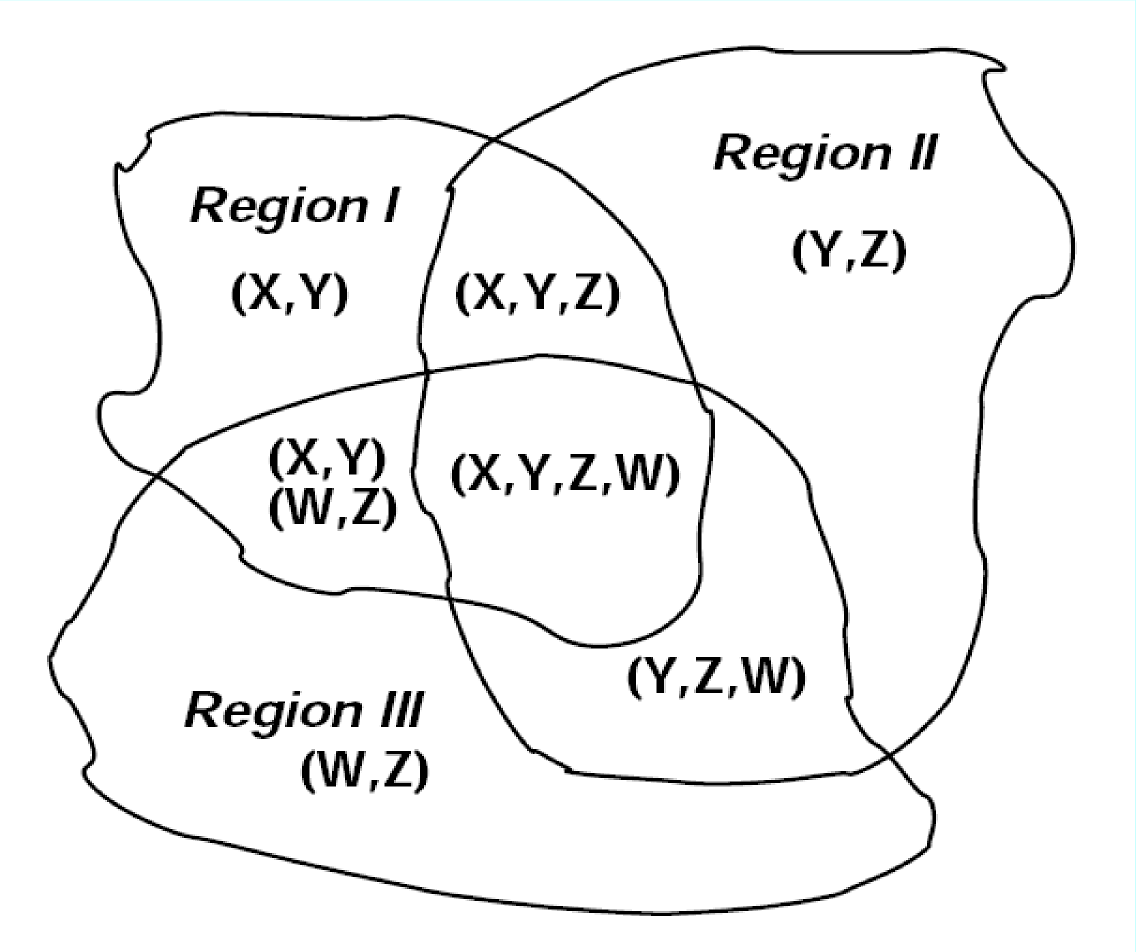
This leads to a highly non-trivial pattern of correlations.

Suppose each region exhibits a correlation between only two physical observables:



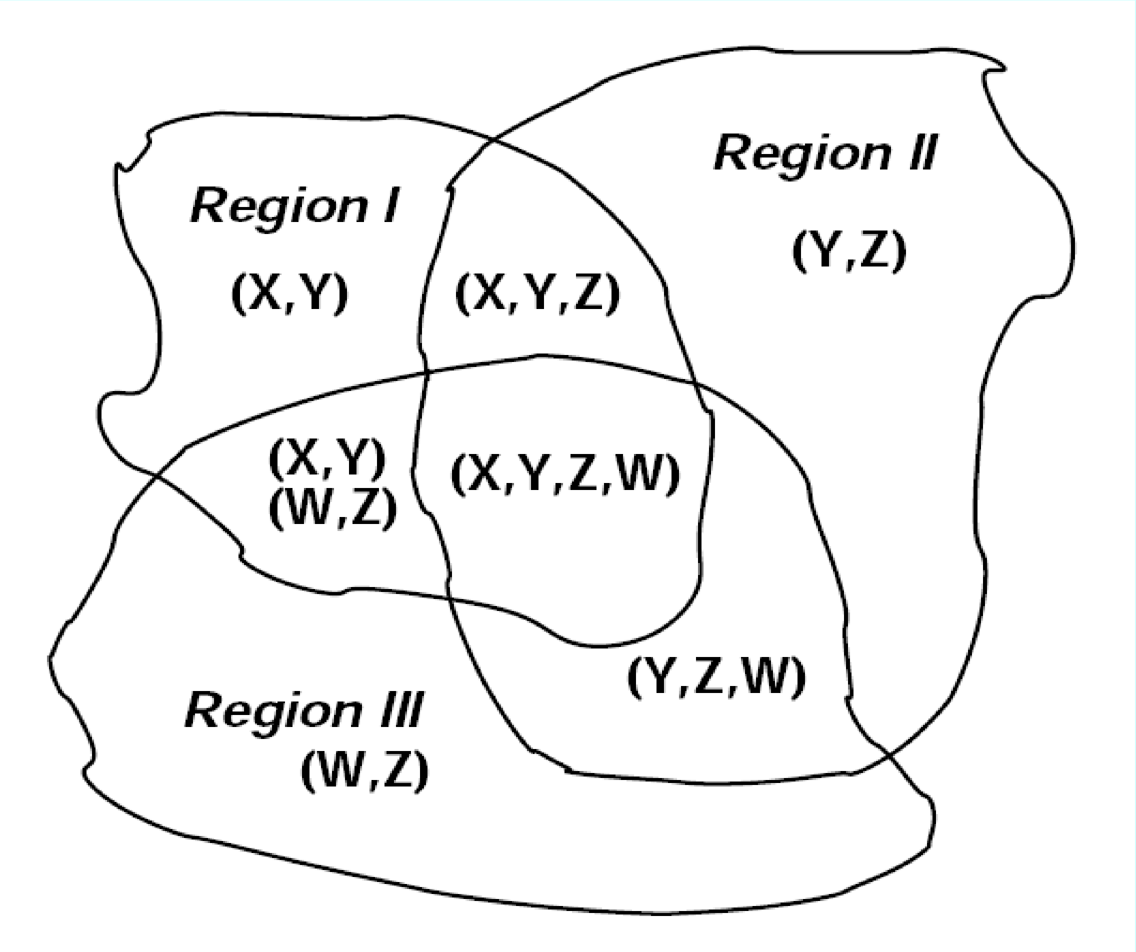
- Region I: Correlation between X and Y
- Region II: Correlation between Y and Z
- Region III: Correlation between W and Z

This then leads to a highly non-trivial pattern of correlations in the different overlap regions!



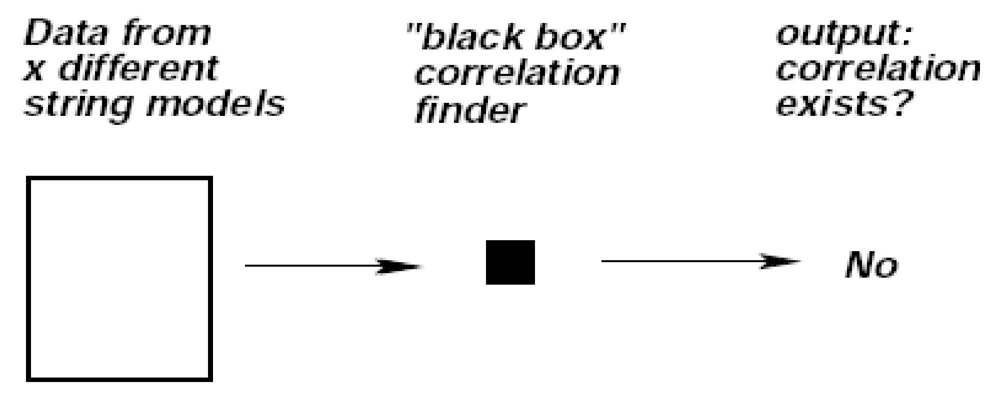
- Regions I & II: Single 3-quantity correlation (X,Y,Z)
- Regions II & III: Single 3-quantity correlation (Y,Z,W)
- Regions I & III: Two 2-quantity correlations (X,Y) and (W,Z)
- Regions I, II, & III: Single 4-quantity correlation (X,Y,Z,W)

Very complex structure!
How then to proceed?

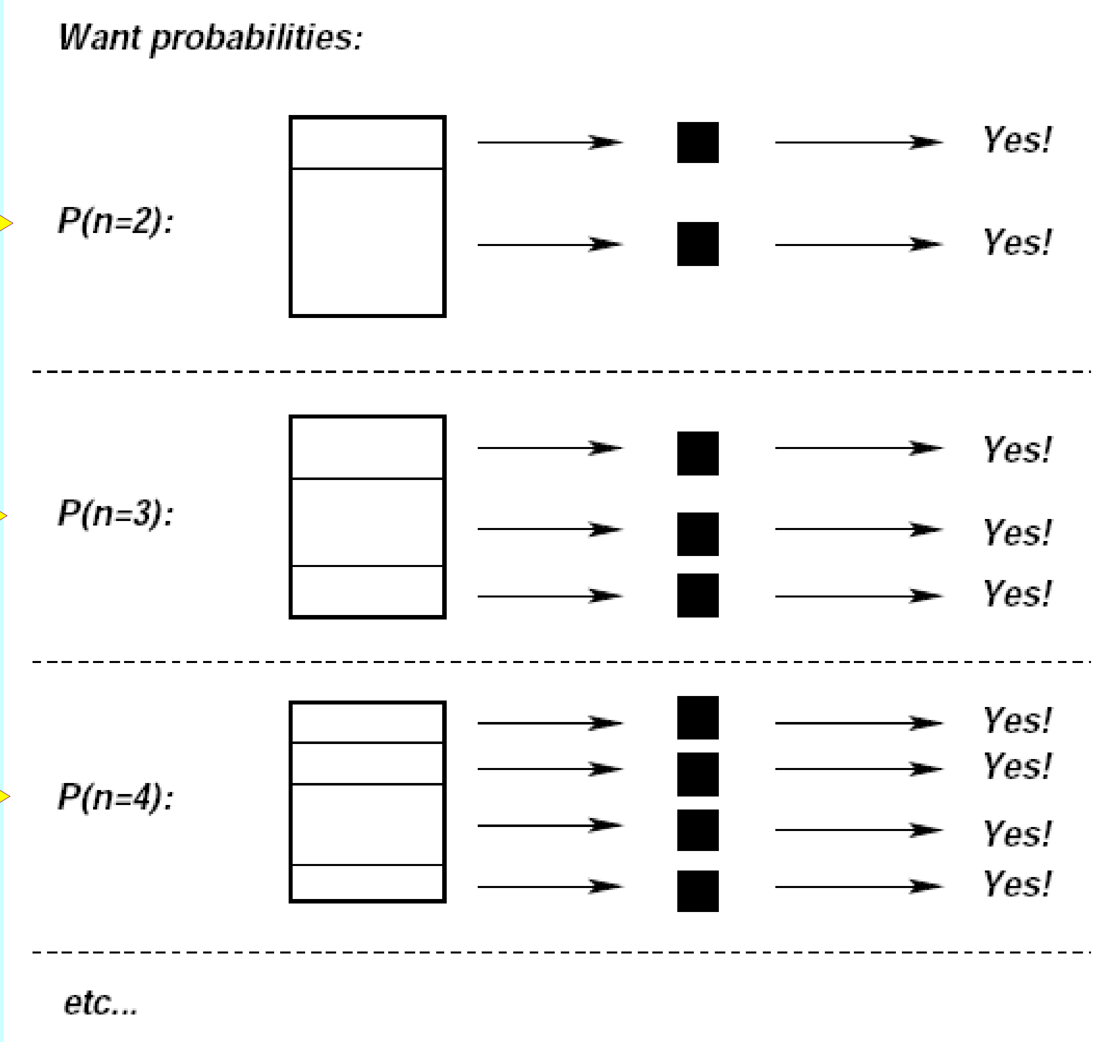


- Need to develop **practical statistical methods** of probing such a non-trivial correlation structure “experimentally” through the random generation and analysis of string models drawn across the landscape as a whole!
- In this way, hope to **develop and quantify a practical notion of “predictivity”** for such a system.

Ultimately, our tools are the probabilities that a set of x different, randomly-selected models are all in the same correlation class. Suppose…



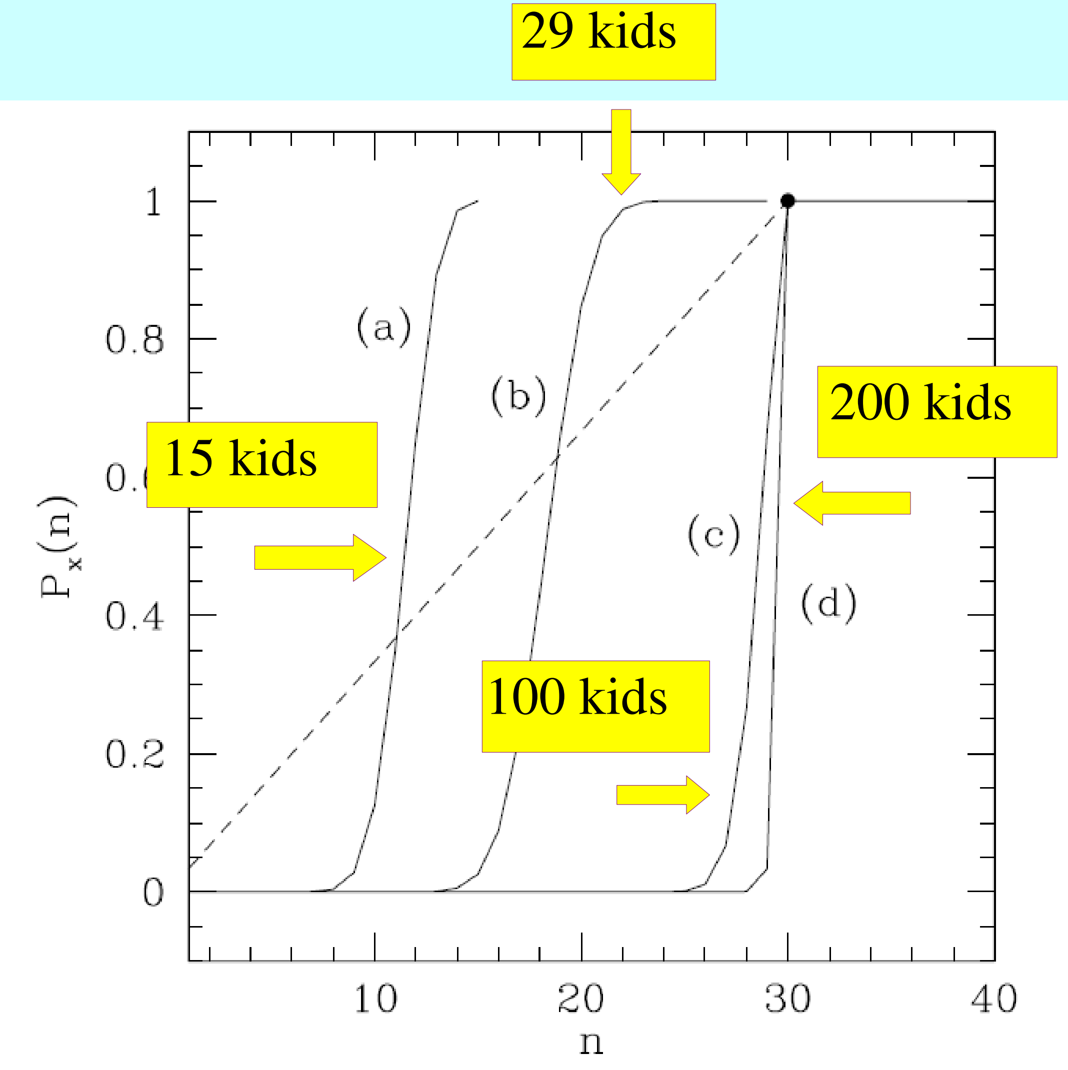
The probabilities $P_x(n)$ are our "experimental" method of probing the correlation-class structure of the landscape and quantifying its degree of predictivity.



Easy to calculate probabilities when all regions are equally sized and disjoint…

In this case, reduces to birthdate problem:
What is the likelihood that a classroom of x kids will have n different birthdates (1 through 30)?

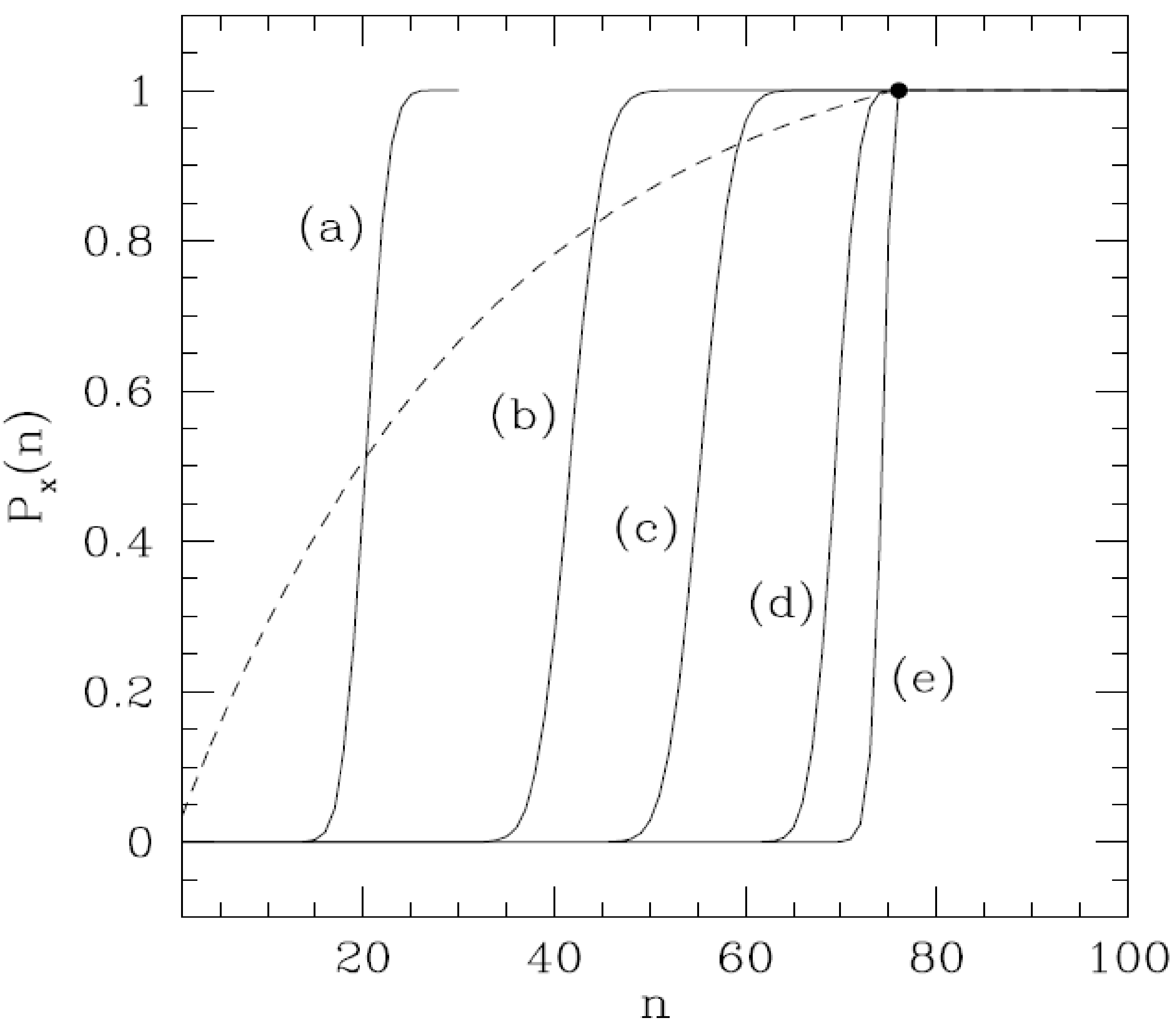
As the number of kids increases, the probability approaches a sharp step-function at n=30.



Gives an “experimental” way of determining the number of correlation classes (birthdates) in classroom landscape. Less than 30 would have suggested a non-random (i.e., predictive) underlying set of kids.

Similar situation occurs even when there are highly non-trivial overlaps between correlation-class regions…

Thus, **the evolution of probability function as more and more models are examined** gives an “experimental” way of determining the total number of correlation classes on the landscape as well as relative sizes of overlaps, thereby quantifying the degree of predictivity of the landscape as a whole.



Thus far, we have treated the landscape in a rather simplistic manner: *There are many possible states, and the universe chooses one.*

But of course, from a quantum cosmological standpoint, it is more likely that **all possibilities are realized, and that our universe is only one "bubble" in a such a larger multiverse (or megaverse). In accordance with the string landscape, each universe in the multiverse would have its own physical laws and its own constants of nature.**

Welcome to the Multiverse!

If so, then our own universe is not special at all, and there would be many other "parallel" universes whose properties need not resemble those of our own universe in any way!

Indeed, one can further imagine that these different universes are continually being spawned in a process dubbed ***eternal inflation,*** first proposed in a more general context more than 25 years ago.

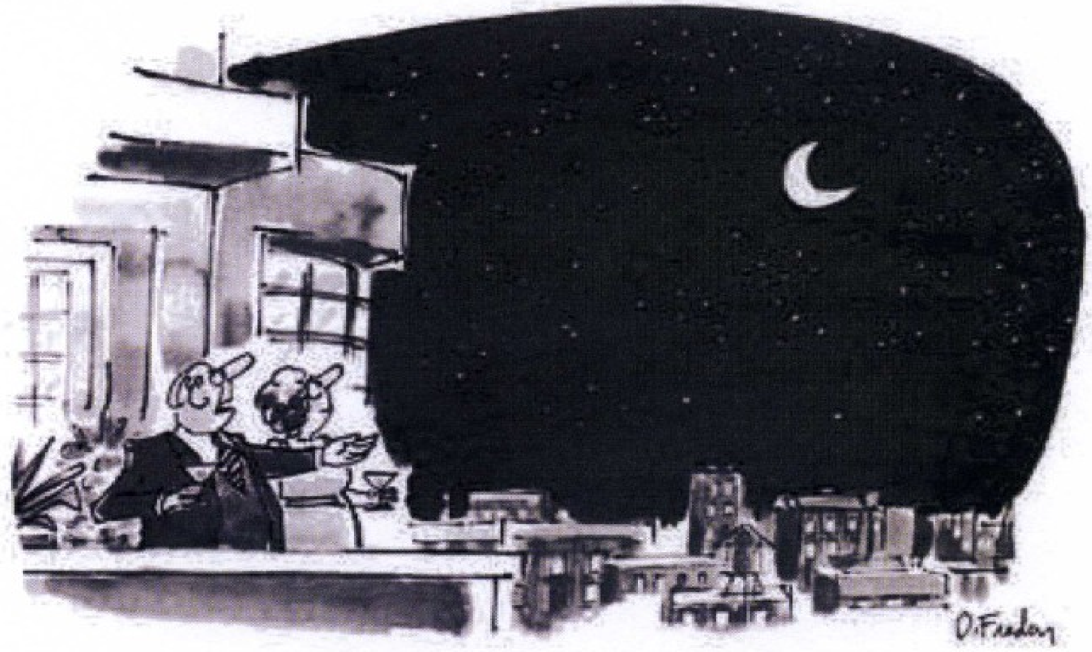
Andrei Linde
Stanford University
Dirac Medal, 2002

If these ideas are correct, then entirely new sets of questions are spawned as well…

- Is the number of possible universes finite or infinite? Is this even knowable? Does it matter?
- How are these universes generated? Through vacuum decay/tunneling? In the interiors of black holes?
- Are all possible universes created equal?
- How did we land in *this* universe? Are the fundamental laws of physics (as we know them) destined to become nothing more than environmental accidents of initial conditions?
- Are quantities such as the electron/proton mass ratio now going to be viewed as having no deep theoretical underpinnings, but instead like the planetary orbital radii, valid just “by accident” in this universe?
- *Is theoretical particle physics destined to become a branch cosmology?*

And the biggest question of them all:

Why are we ***HERE*** ?
Is there anything special about our own universe whatsoever, any tool that remains by which we can hope to develop insight into our universe and make predictions?



"Do you know why the universe works so well? God runs it like a business, that's why."

The Anthropic Principle

The universe takes the form that it does so as to allow observers to observe it.

My verdict: SILLY.
The universe doesn't care about me or you, and it doesn't exhibit narcissistic or exhibitionist tendencies that make it want to be observed.

(This is not only anthropic, but anthropomorphic!)

Maybe not so silly:
The “Star Trek” version

A pop quiz:

The Enterprise enters an uncharted solar system with 10^{500} planets. In order to survey the planets quickly, Kirk sends a landing party down to each planet simultaneously. After an hour, he puts out a general call for survey reports to be sent back to the ship.

- *Question:* What percentage of surveys will report an M-type planet (capable of supporting life)?

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- *Question:* What percentage of surveys will report an M-type planet (capable of supporting life)?
- *Answer:* **100%.** All other teams will be dead, and won't be able to file any reports.

Certain outcomes about the universe are guaranteed, because otherwise we couldn't have even asked the question.

This form of the anthropic principle has had some successes, *most notably the prediction of a non-zero cosmological constant of approximately the right size ---* a full decade before it was observed!

Weinberg (1987): Λ cannot be too big, or else the universe would have expanded too rapidly to allow the formation of structure (galaxies, stars, ...) as needed to generate life. This gives an upper value for Λ.

This alone is not the anthropic principle. This is just an upper bound on Λ. In particular, $\Lambda=0$ is still allowed.

The anthropic principle which Weinberg then used is to say that since there is no other argument concerning the size of Λ, there is nothing else to suppress Λ further. Consequently the value of Λ should be at or near this critical value (and hence not zero).

If the multiverse is real, the only hope we may have for understanding the properties of our own universe is through these sorts of applications of the anthropic principle.

But there is also fierce opposition to this idea.

- This is not the way science should be done.
- The anthropic principle represents a surrendering of the idea that the fundamental laws of physics are unique and not tuned for particular outcomes --- especially not an outcome such as life.
- "The anthropic principle is not an *explanation*; it's an *observation*."

Burt Richter
Nobel Prize, 1976
Former Director of SLAC

In science, we normally accept various “priors” (inputs, assumptions, axioms) and seek to use those inputs in order to derive new results.

- Is it fair to use our own existence as such an input?
- How we decide which input “data” are acceptable, and which “data” isn't?
- And what is the data: intelligent civilizations? Life in general? What kinds of life can we imagine?
- Are universes which are capable of supporting life somehow preferred (in a Darwinian sense) over those that don't?

“And to all you people on those other planets out there, a Happy New Year!”

Obviously, no easy answers to these questions.... just a raging debate.

However, it *is* possible to give an *existence proof* that intelligent and sophisticated civilizations can exist --- even *thrive* --- under the most inhospitable external “environmental” circumstances.

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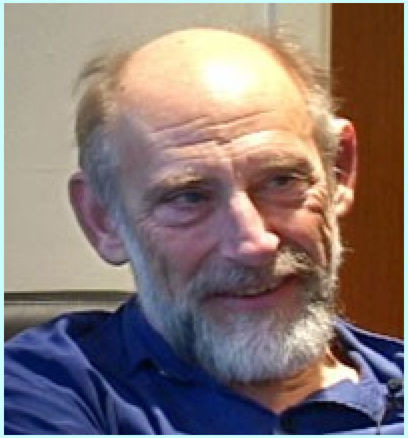
However, it *is* possible to give an *existence proof* that intelligent and sophisticated civilizations can exist --- even *thrive* --- under the most inhospitable external “environmental” circumstances.

… however, even such advanced civilizations apparently cannot resist obvious pandering from the colloquium speaker.

Another critical question:

How can we test these ideas?
Are they even falsifiable??

“Throughout my long experience as a scientist, I have heard unfalsifiability hurled at so many important ideas that I am inclined to think that no idea can have great merit unless it has drawn this criticism. I'll give some examples…



- In the early days of the quark theory, its many opponents dismissed it as unfalsifiable. Quarks are permanently bound together into protons, neutrons and mesons. They can never be separated and examined individually. They are, so to speak, hidden behind a veil. But by now, although no single quark has ever been seen in isolation, there is no one who seriously questions the correctness of the quark theory. It is part of the bedrock foundation of modern physics.

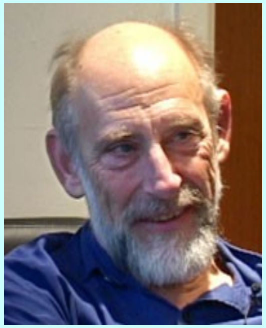
- Another example is Allan Guth's inflationary theory. In 1980 it seemed impossible to look back to the inflationary era and see direct evidence for the phenomenon. Another impenetrable veil called the "surface of last scattering" prevented any observation of the inflationary process.

- I can imagine the partisans of Lamark criticizing Darwin, "Your theory is un-falsifiable, Charles. You can't go backward in time, through the millions of years over which natural selection acted. All you will ever have is circumstantial evidence and an un-falsifiable hypothesis. By contrast, our Lamarkian theory is scientific because it is falsifiable. All we have to do is create a population that lifts weights in the gym every day for a few hours. After a few generations, their children's muscles will bulge at birth."

Good scientific methodology is not an abstract set of rules dictated by philosophers. It is conditioned by, and determined by, the science itself and the scientists who create the science. What may have constituted scientific proof for a particle physicist of the 1960's—namely the detection of an isolated particle—is inappropriate for a modern quark physicist who can never hope to remove and isolate a quark. Let's not put the cart before the horse. Science is the horse that pulls the cart of philosophy.

In each case that I described—quarks, inflation, Darwinian evolution—the accusers were making the mistake of underestimating human ingenuity. It only took a few years to indirectly test the quark theory with great precision. It took 20 years to do the experiments that confirmed inflation. And it took 100 years or more to decisively test Darwin. What people usually mean when they make the accusation of unfalsifiability is that they, themselves, don't have the imagination to figure out how to test the idea.

Will it be possible to test eternal inflation and the Landscape? I certainly think so, although it may be, as in the case of quarks, that the tests will be less direct, and involve more theory than some would like."



Indeed, several ideas along these lines have already been proposed.

Some are possible only in principle...

- in the long-distance future, if/when our horizon expands sufficiently
- if/when our universe tunnels into another vacuum state
- signatures of physics at or near a domain wall

... while others are potentially more realistic

- traces of stringy physics and/or inflationary history imprinted on the Cosmic Microwave Background (CMB)
- evidence for strings through deviations from general relativity
- direct observation of string theory at the LHC: possible if M_{string} in TeV range
- observation of spatial variation of the fundamental constants.

But the issues are far from settled…

I am very glad that Susskind has been able to give these issues much more visibility. But it would be very unfortunate if string theorists finally accept there is an issue with predictability, only to fall for the easy temptation of adopting a strategy towards it that cannot yield falsifiable theories. The problem with non-falsifiable theories is nothing other than that they cannot be proven wrong. If a large body of our colleagues feels comfortable believing a theory that cannot be proved wrong, then the progress of science could get stuck, leading to a situation in which false but unfalsifiable theories dominate the attention of our field.

Lee Smolin
Perimeter Institute
Waterloo, Canada

Finally, why go through all this worry?
Even if the multiverse exists, why not just focus on our own universe (the so-called *fertile patch*)?

- Why climb Mount Everest? Because it's there.
- If there are really 10^{500} vacua, it is very unlikely that we will be able to know which one is our universe, exactly. Many will satisfy current experimental constraints. So our need to make predictions still requires that we understand something of the more global structure.
- We still want to answer the “why” questions of the Standard Model: why three generations? why three types of non-gravitational forces? *If the Standard Model is part of a huge ensemble, then the only way to answer such questions is to understand the distribution of that ensemble.* We *have* to care about more than just our own universe, and it is inevitable that anthropic arguments will play a role in addressing such questions.

-- A.N. Schellekens

Conclusions, Prospects, and Warnings

Clearly, a statistical analysis of the string landscape has lots of potential to address questions of relevance to phenomenology --- *even without a vacuum-selection principle.*

Much more work remains to be done...

- Other phenomenological features need to be examined: particle content, etc., as already discussed.
- Develop algorithmic/statistical tools to handle analyses of this type.
- Extend analysis to broader classes of string theories (more general constructions, also non-perturbative formulations).
- Develop methods to generate large classes of *stable* vacua --- comparison of results will then indicate phenomenological role played by vacuum stability.
- Comparison with Type I results may even permit *statistical* confirmation of duality conjectures.

Indeed, the SVP will be tackling many of these questions.

But one must be aware of certain dangers…

- The “lamppost” effect --- the danger of restricting one's attention to those portions of the landscape where one has control over calculational techniques.
- The “Godel” effect --- landscape is so large that it is possible that no matter how many input “priors” one demands, there will always be another observable which cannot be uniquely predicted.
- The “bull's-eye” effect --- don't always know what the target is, since we are not certain how our low-energy world embeds into the fundamental theory (SUSY? GUTs? technicolor? something else?).

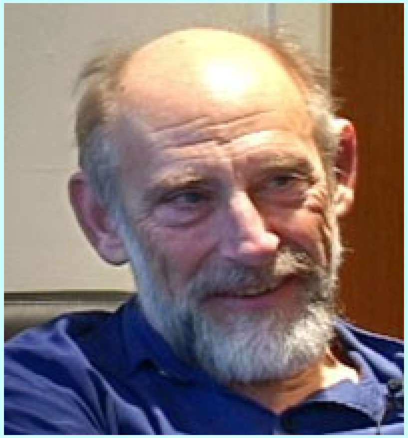
Nevertheless, despite these dangers,

- Direct examination of actual string models uncovers features and behaviors that might not otherwise be expected.
- Through direct enumeration, we gain valuable experience in the construction and analysis of phenomenologically viable string vacua.
- As string theorists, we must ultimately come to terms with the landscape. Just as in astrophysics, botany, and zoology, the first step in the analysis of a large data set is enumeration and classification.
- In cases where statistical correlations can be interpreted directly in terms of underlying physical symmetries, we have indeed extracted true predictions from the landscape.

Thus, properly interpreted, statistical landscape studies can be useful and relevant in this overall endeavor.

So where does this leave us?

“What we've discovered in the last several years is that string theory has an incredible diversity—a tremendous number of solutions—and allows different kinds of environments. A lot of the practitioners of this kind of mathematical theory have been in a state of denial about it. They didn't want to recognize it. They want to believe the universe is an elegant universe—and it's not so elegant. It's different over here. It's that over here. It's a Rube Goldberg machine over here. And this has created a sort of sense of denial about the facts about the theory. The theory is going to win, and physicists who are trying to deny what's going on are going to lose.”



Leonard Susskind
Felix Bloch Professor of Theoretical Physics
Stanford University

I love Lenny, but I hate this recent landscape idea and I am hopeful it will go away.

Paul Steinhardt
Albert Einstein Professor of Science
Princeton University

I want to thank Paul Steinhardt for his concise summary of the views of the other side in this debate.

Lenny

When I hear Lenny say that “this theory is going to win, and physicists who are trying to deny what is going on are going to lose", then to my opinion he is going too far… This is not the way physics has worked for us in the past, and it is not too late to hope that we will be able to find better arguments in the future.

Gerardus 't Hooft
University of Utrecht, the Netherlands
Nobel Prize in Physics, 1999

That's hard to argue with. I consider myself to be a cautious, rather conservative physicist. I really don't like new ideas. But I also find wisdom in a quote from Sherlock Holmes: "When you have eliminated all that is impossible, whatever remains must be the truth, no matter how improbable it is."

Lenny

I feel the views of some, that such a picture is unscientific, or a cop-out, are extreme. In particular, understanding the laws that give rise to the megaverse is a very scientific question, and one that I think is well worth studying further.

Steve Giddings
University of California, Santa Barbara

Finally, after 15 years, the debate has started that should have started around the mid-80's, but was stifled by irrational opposition against the notion that our observation of the Standard Model could be biased by our own existence. To me, at least one thing seems absolutely obvious: the idea that the Standard Model is (even approximately) unique will eventually find its place in history next to Kepler's attempt to compute the orbits in the solar system: understandable at its time, but terribly anthropocentric.

A.N. Schellekens
NIKHEF, Amsterdam, the Netherlands

We now believe we live on an ordinary planet, one of many, circling an ordinary star, one of many, in an ordinary galaxy, one of many. Perhaps we need to take the next step, admittedly a revolutionary one, of saying we live in an ordinary universe, a very small part of an enormous megaverse.

Gino Segre
University of Pennsylvania