Title: Probing the String Landscape: Implications, Applications, and Altercations

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Abstract: We are currently in the throes of a potentially huge paradigm shift in physics. Motivated by recent developments in string theory and the discovery of the so-called \'string landscape\', physicists are beginning to question the uniqueness of fundamental theories of physics and the methods by which such theories might be understsood and investigated. In this colloquium, I will give a non-technical introduction to the nature of this paradigm shift and how it developed. I will also discuss some of the questions to which it has led, and the nature of the controversies it has spawned.

Probing the String Landscape: Implications, Applications, and Altercations

Keith R. Dienes
University of Arizona

Perimeter Institute
December 10, 2008

"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

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- Is theoretical particle physics destined to become a branch of cosmology?

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Philosophy of physics

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

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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.

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- 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?

eV scale: atoms: *nuclei* plus electrons

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

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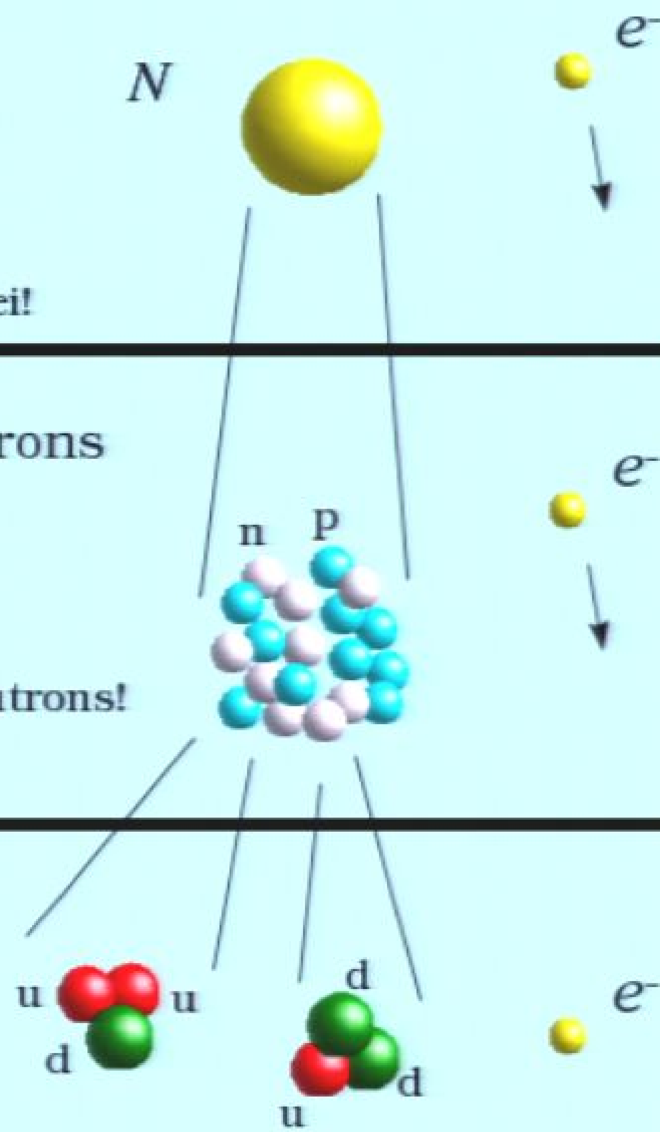
MeV scale: *protons and neutrons* plus electrons

But there are many different "types" of protons/neutrons!

- "hadrons": p, n, π, K, ρ, Ω, ...

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!

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The particles

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

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

Higgs: SU(2) x U(1) ⟶ EM)

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

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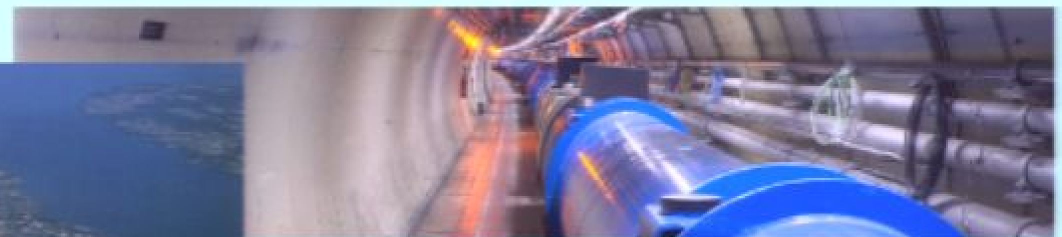

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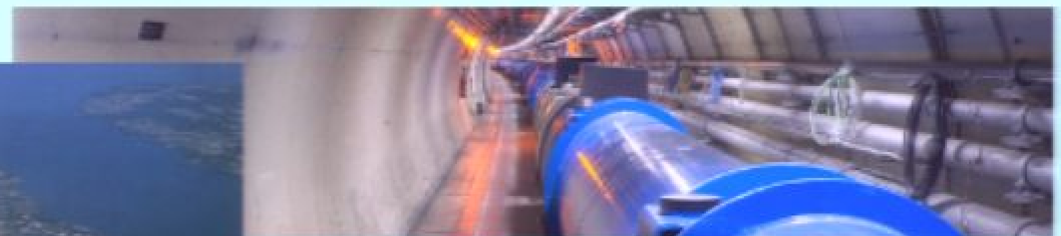

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What do we expect to see?
What will high-energy physics be focusing on
over the next 10-20 years?

Two popular sets of ideas...

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A new kind of symmetry in physics

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Lots of new particles and interactions!
Why go through all this trouble?

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- 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?

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Unsolved issue ---

How do we break SUSY?

We currently have to introduce SUSY-breaking by hand

⇒ Requires the introduction of many additional unknown parameters...

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

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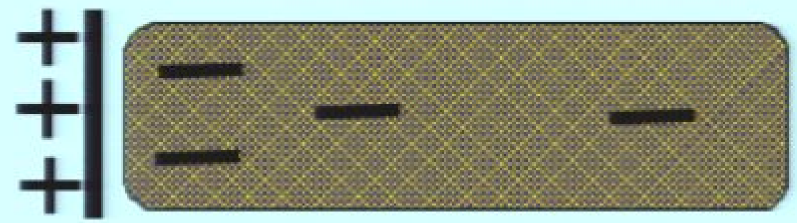

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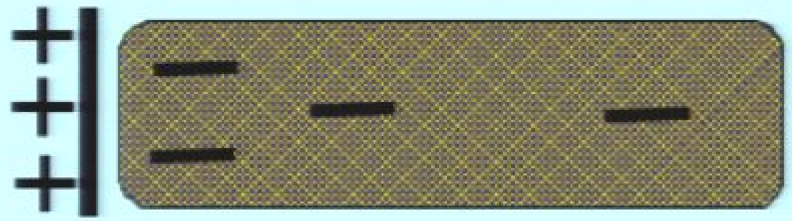

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Thus, effective strength of EM force varies with distance:

Higher energy ⇒ Shorter distance

⇒ Stronger force

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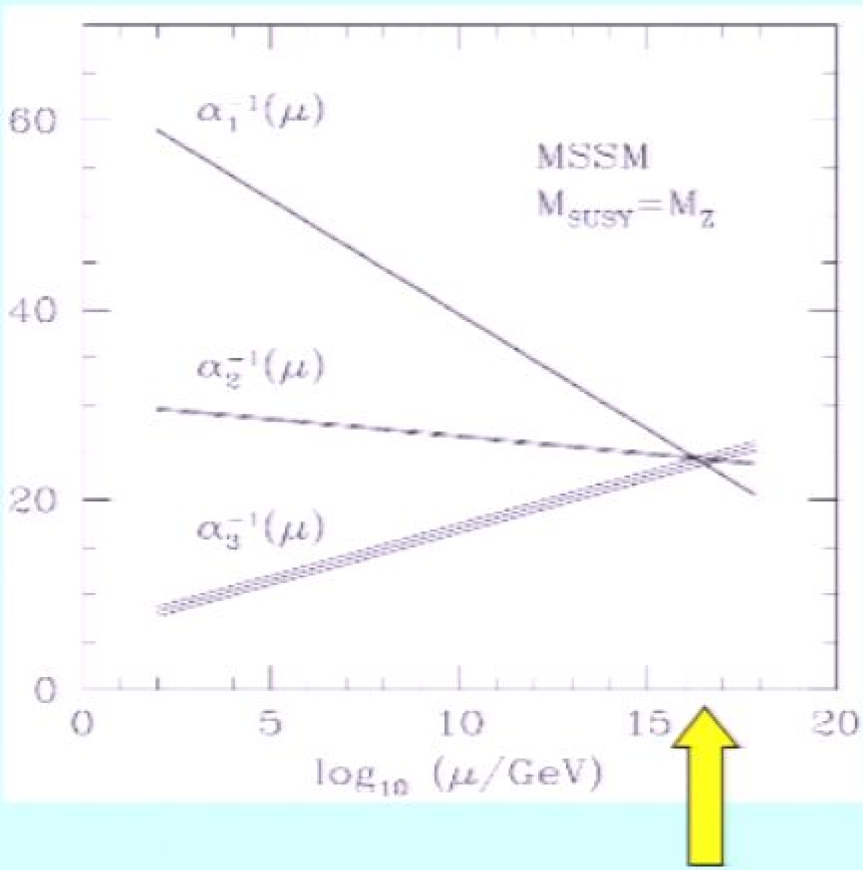

Forces can unify at 2×10^{16} GeV !

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
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    - e.g., proton decay lifetime = 10^{32-33} years
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But there are many different kinds of GUT's:

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    - SU(5) ? SO(10) ? E6 ? Other groups?
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- How do we build realistic SUSY theories?
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- 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?

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- How do we incorporate gravity?

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

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...

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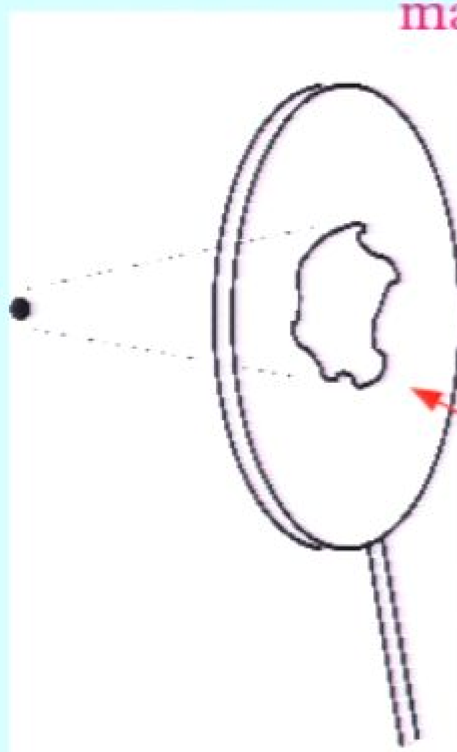

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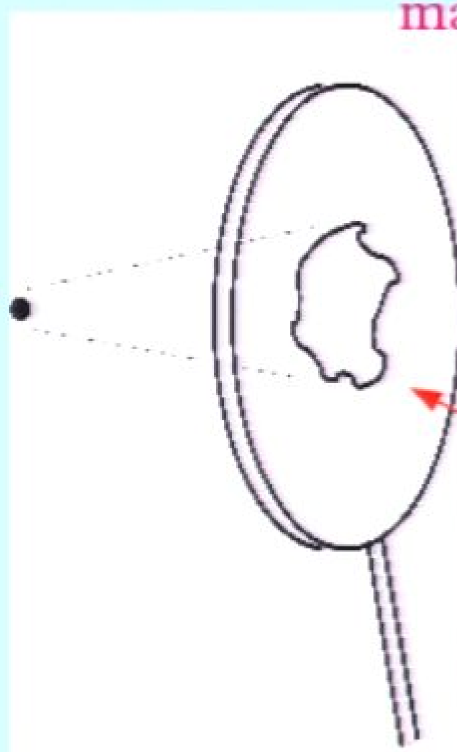


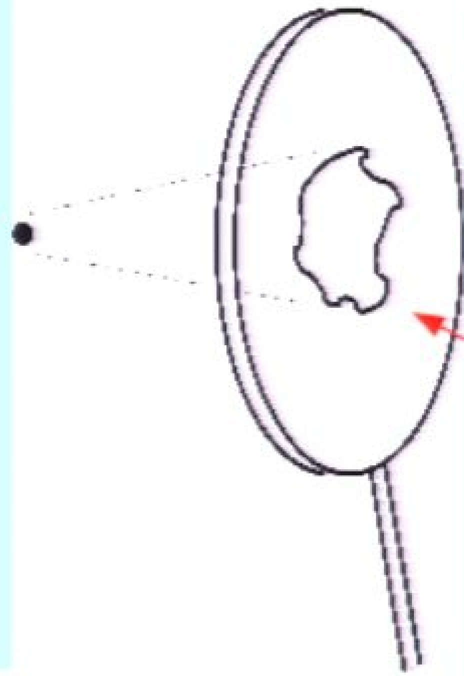
This idea has great power.
Can unify all particles and
forces in nature...

So what is string theory?

A deceptively simple premise...

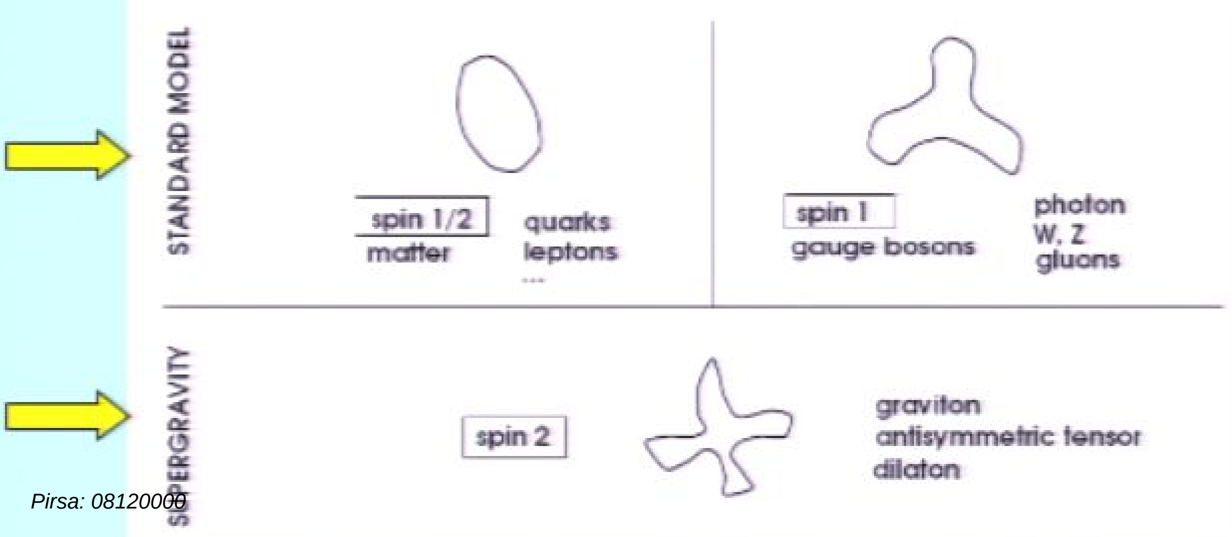
Planck-scale magnifying glass

Elementary particle (e.g., electron)



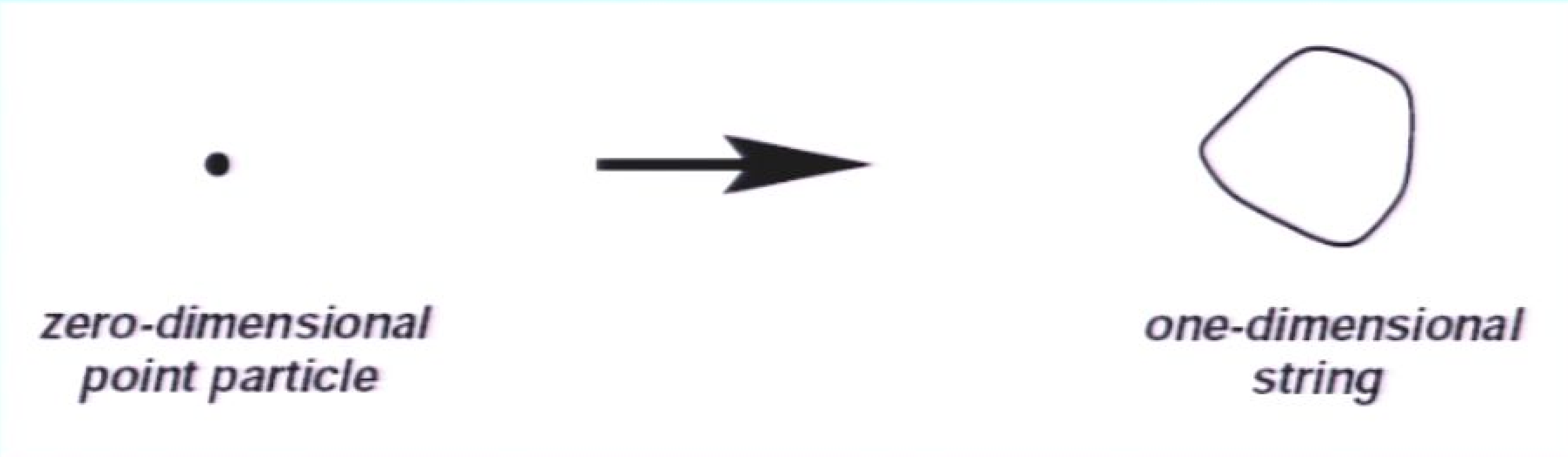
A vibrating string!

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...



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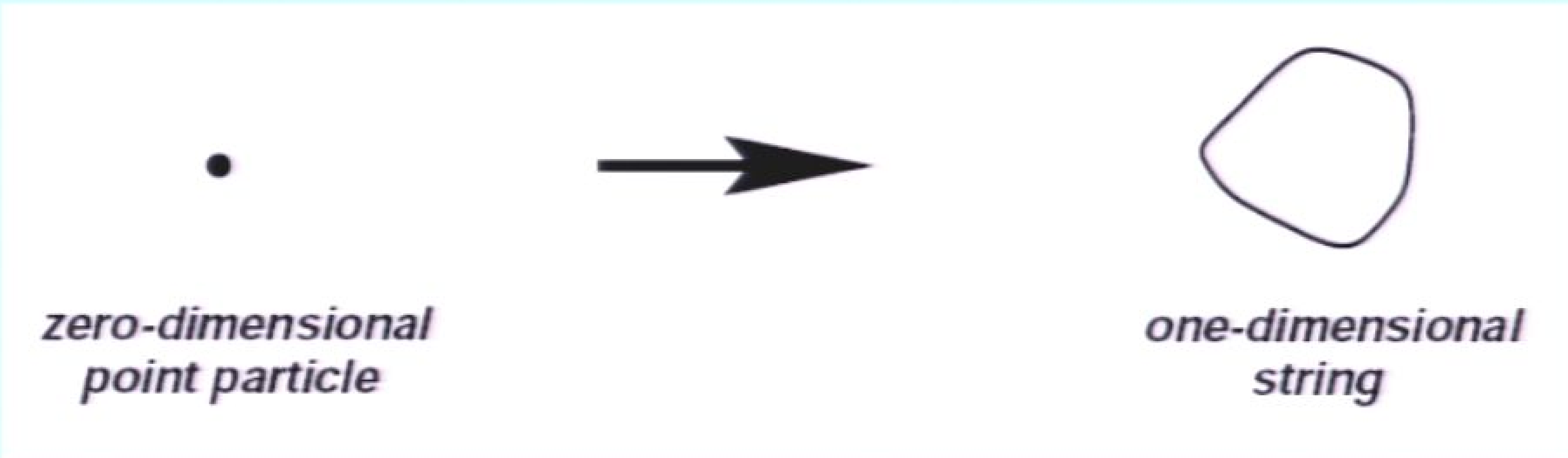
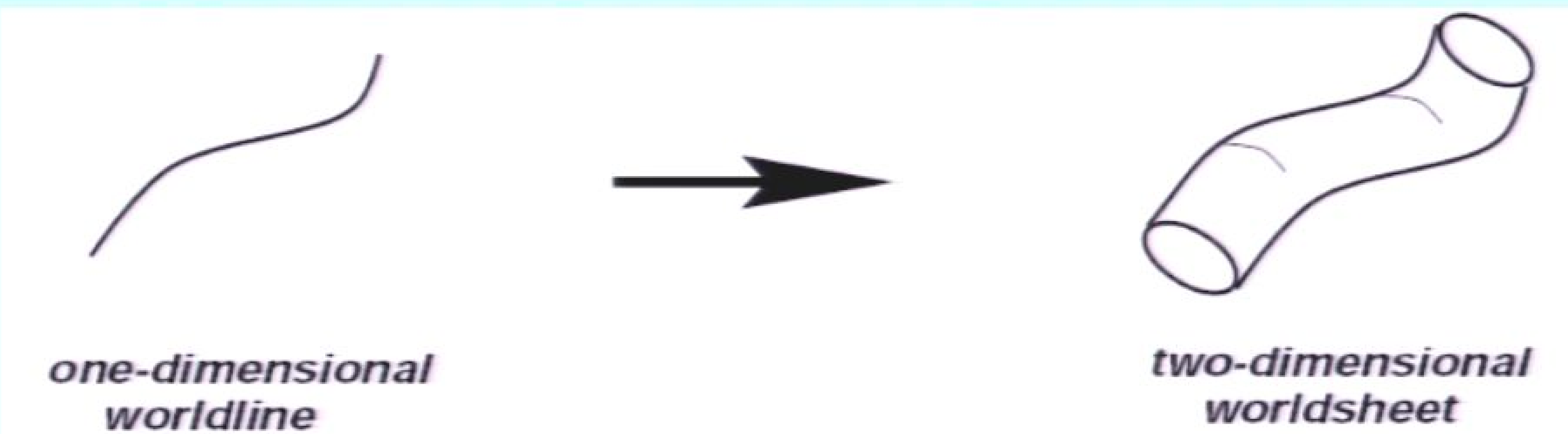
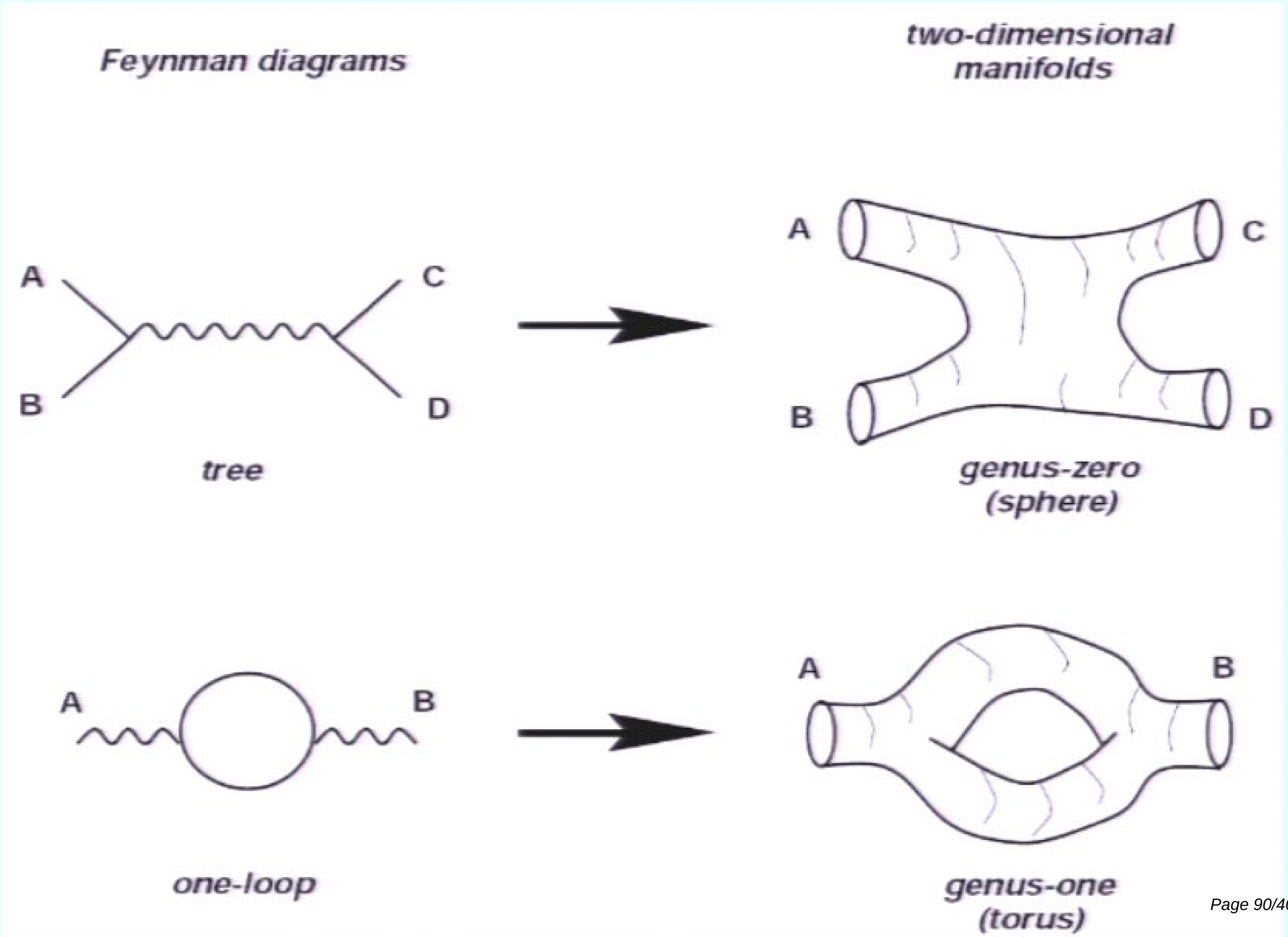


... and the physics of worldlines becomes the physics of worldsheets...



... 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.

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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.

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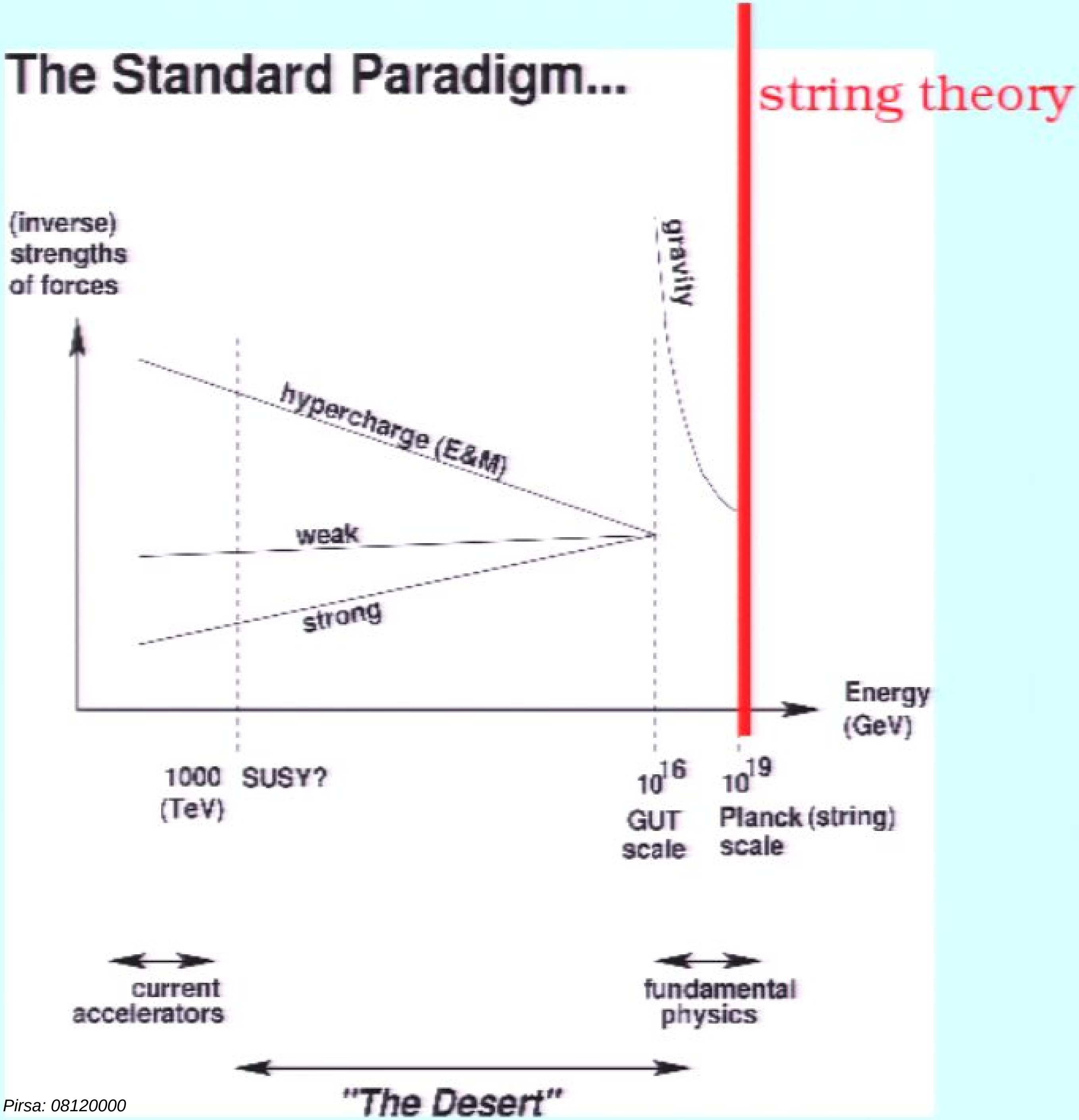
$$M_{\mathrm{Planck}} \equiv \sqrt{\frac{\hbar c}{G_N}} \approx 10^{19}\ \mathrm{GeV} \approx (10^{-33}\ \mathrm{cm.})^{-1}$$

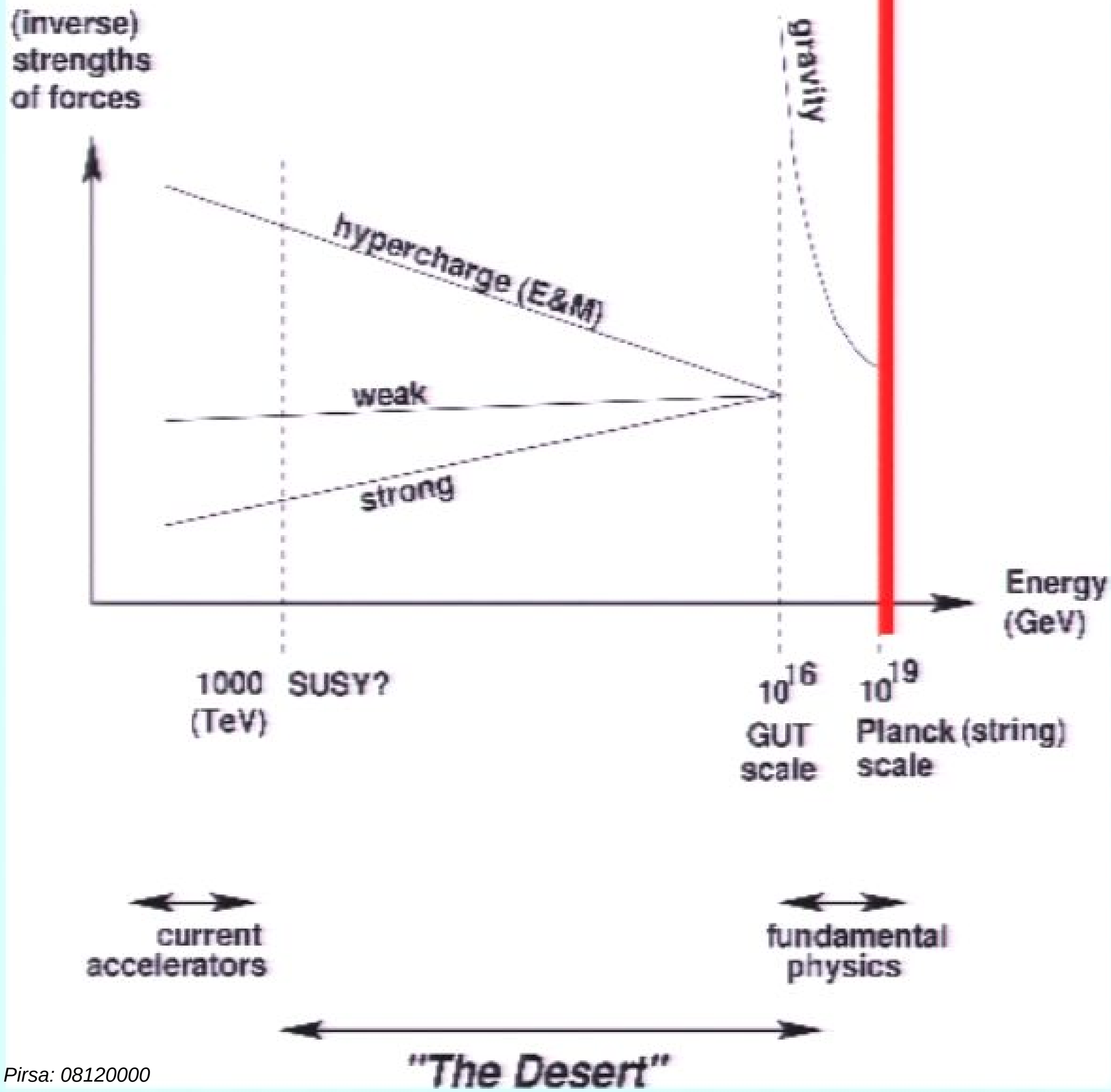
Thus, string theory is ultimately a theory of *Planck-scale* physics!

The Standard Paradigm...



The Standard Paradigm...

string theory



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.

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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 21^{st} century physics that fell by chance into the 20^{th} century"...

Edward Witten
IAS, Princeton
Fields Medalist, 1990

But how many string theories are there??

Is the theory unique??

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And therein lies the rub...

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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.

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- 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).

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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.

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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

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Does it matter?

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Yes!

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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?

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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...

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- SUSY-breaking scale
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- Ranks of gauge groups
- Prevalence of SM gauge group
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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,...

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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)

Michael R. Douglas Gordon Kane

Nima Arkani-Hamed Mirjam Cvetic Keith R. Dienes
Michael Dine Steve Giddings Shamit Kachru
Paul Langacker Joe Lykken Burt Ovrut
Stuart Raby Lisa Randall Gary Shiu
Washington Taylor Henry Tye Herman Verlinde

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

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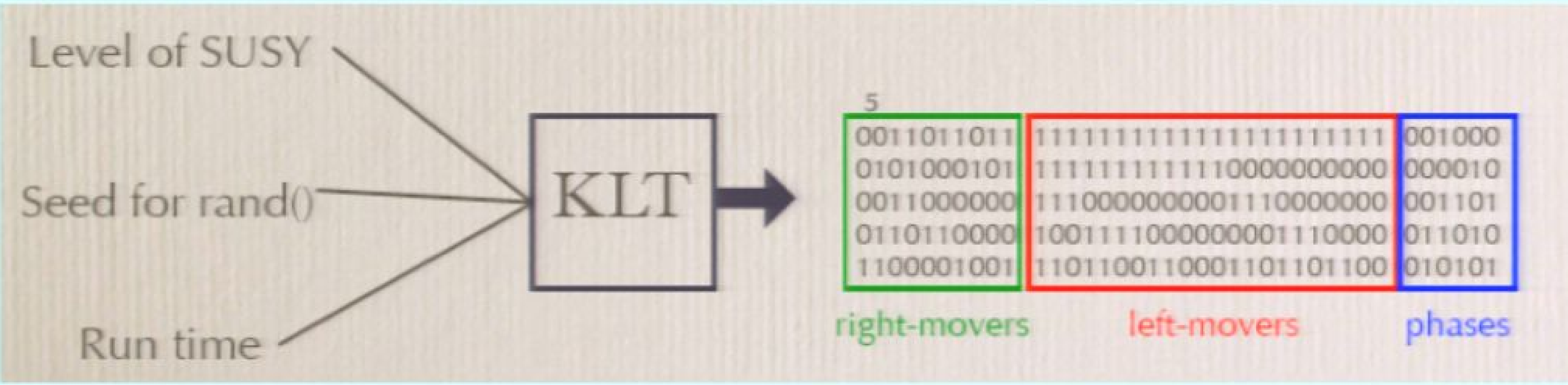
- tighter constraints (central charges, modular invariance, ...)
- gauge groups generated differently, maximal ranks
- different phenomenologies (e.g., gauge coupling unification)

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

How we do it:

Step #1: Generating models

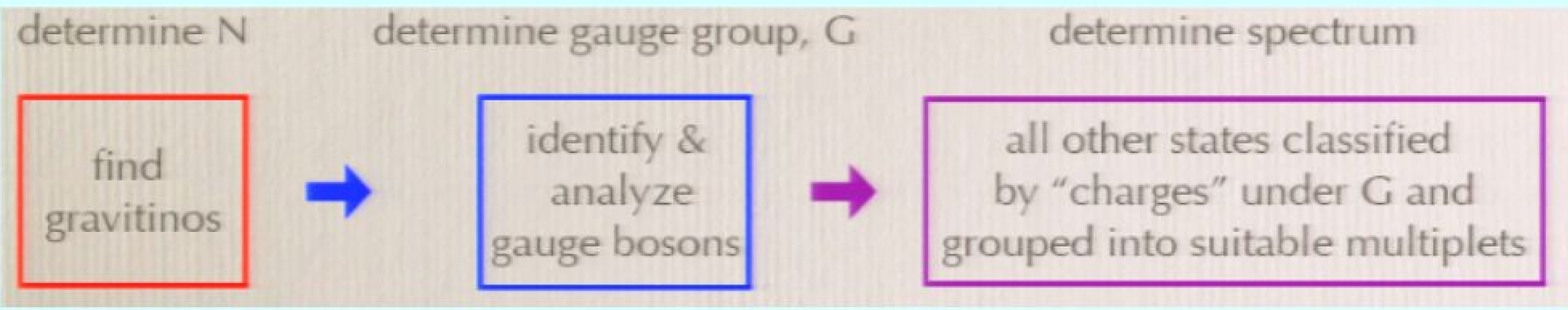


Can generate millions/billions of self-consistent configurations of twists/phases very easily!

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



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
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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,

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- 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.
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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.

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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?

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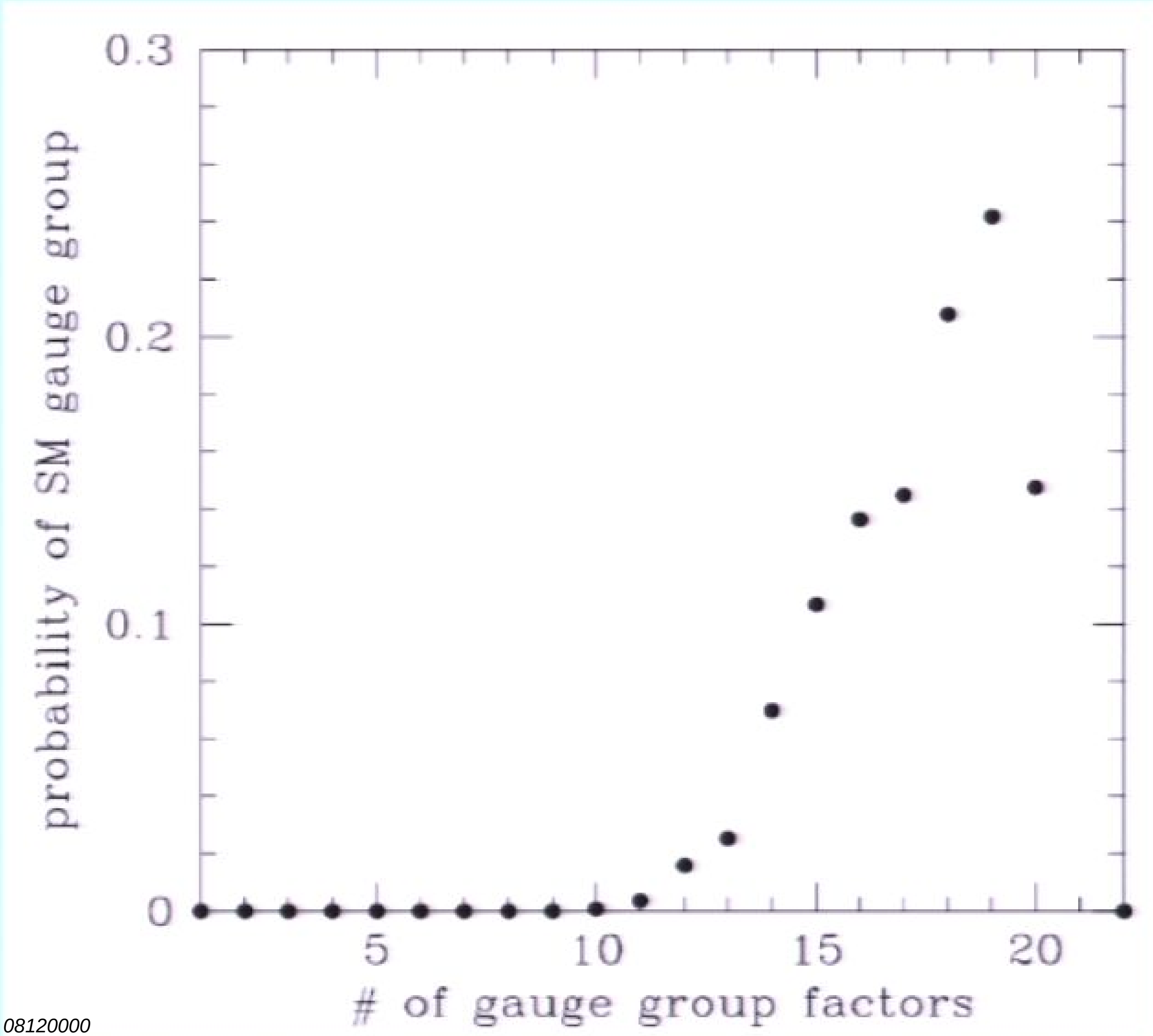

- SM gauge group is most likely to emerge in situations in which the total gauge group of the string model is highly broken.

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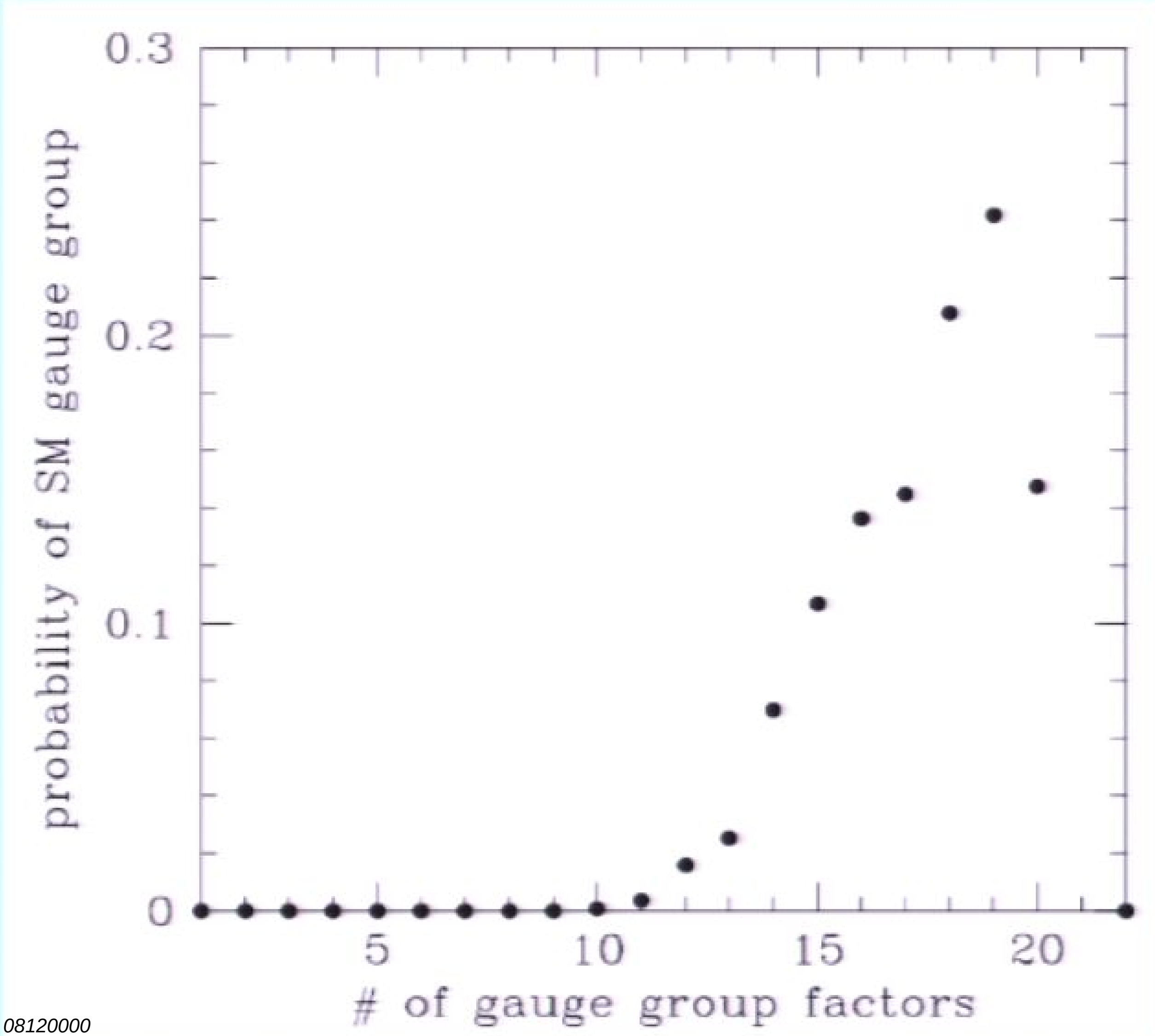

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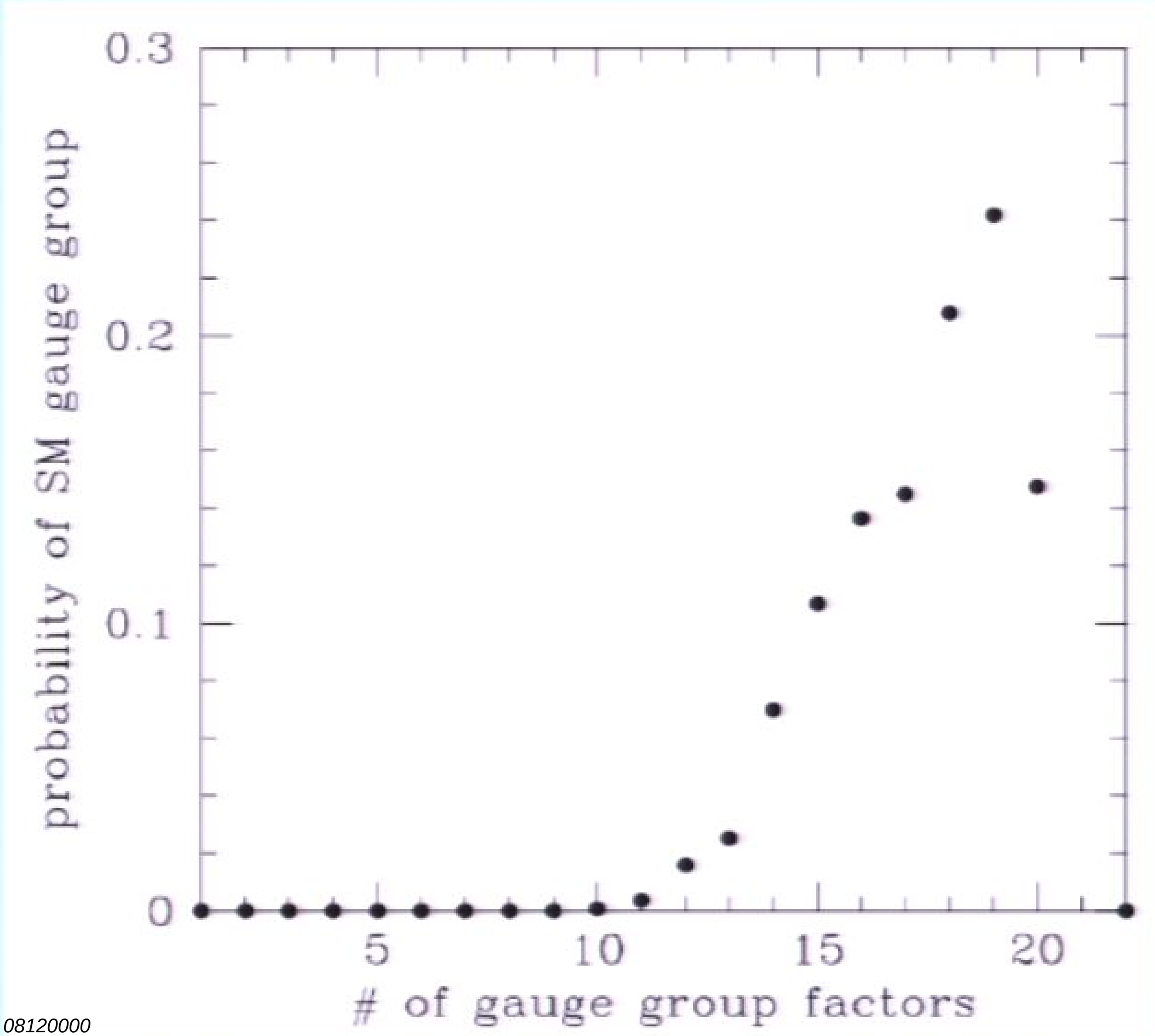

- These conclusions agree with all known such semi-realistic string models in literature.
- Provides limits on possible hidden-sector gauge groups for such models.

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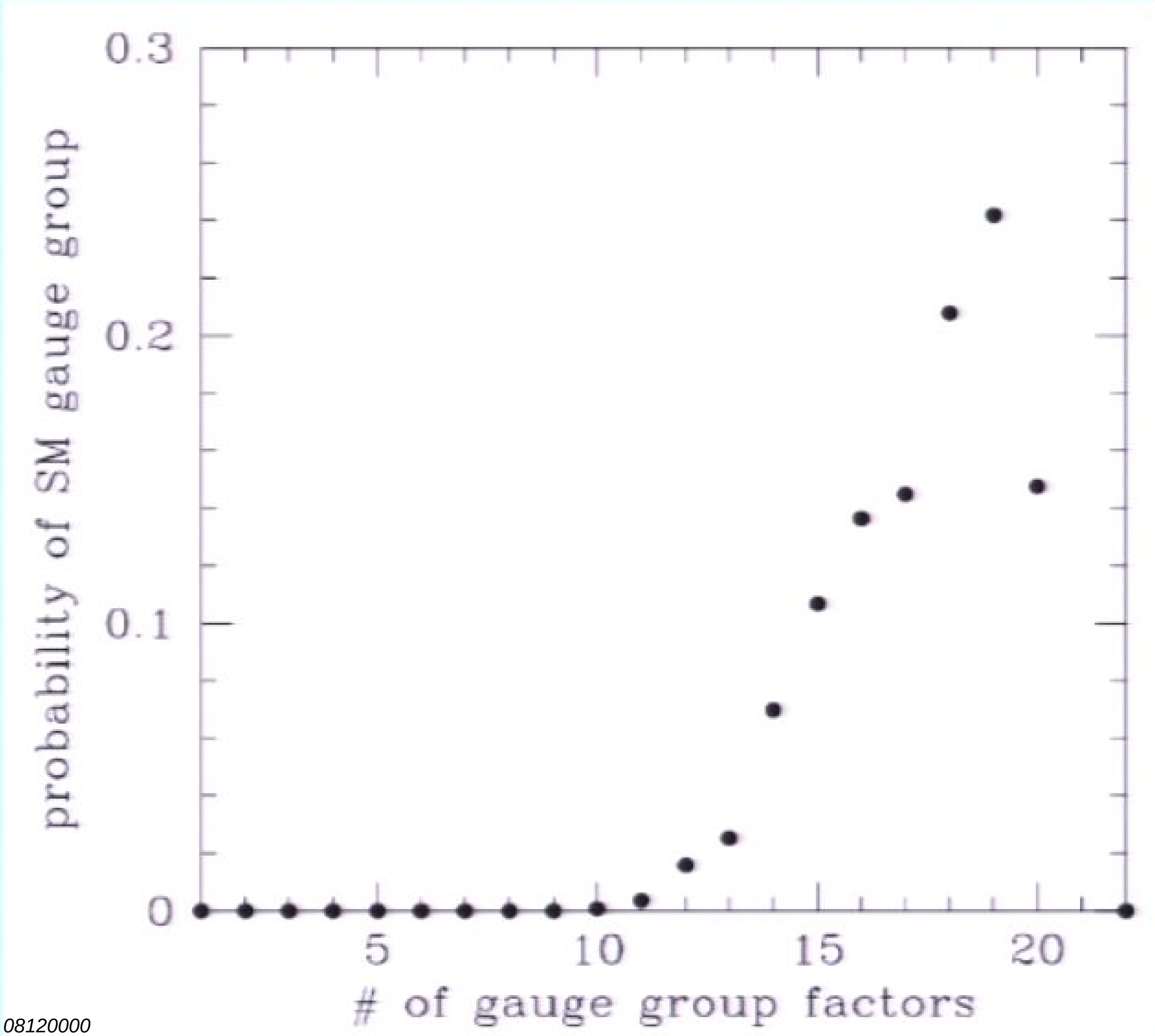

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- Provides limits on possible hidden-sector gauge groups for such models.
- Useful guide for future string model-building.

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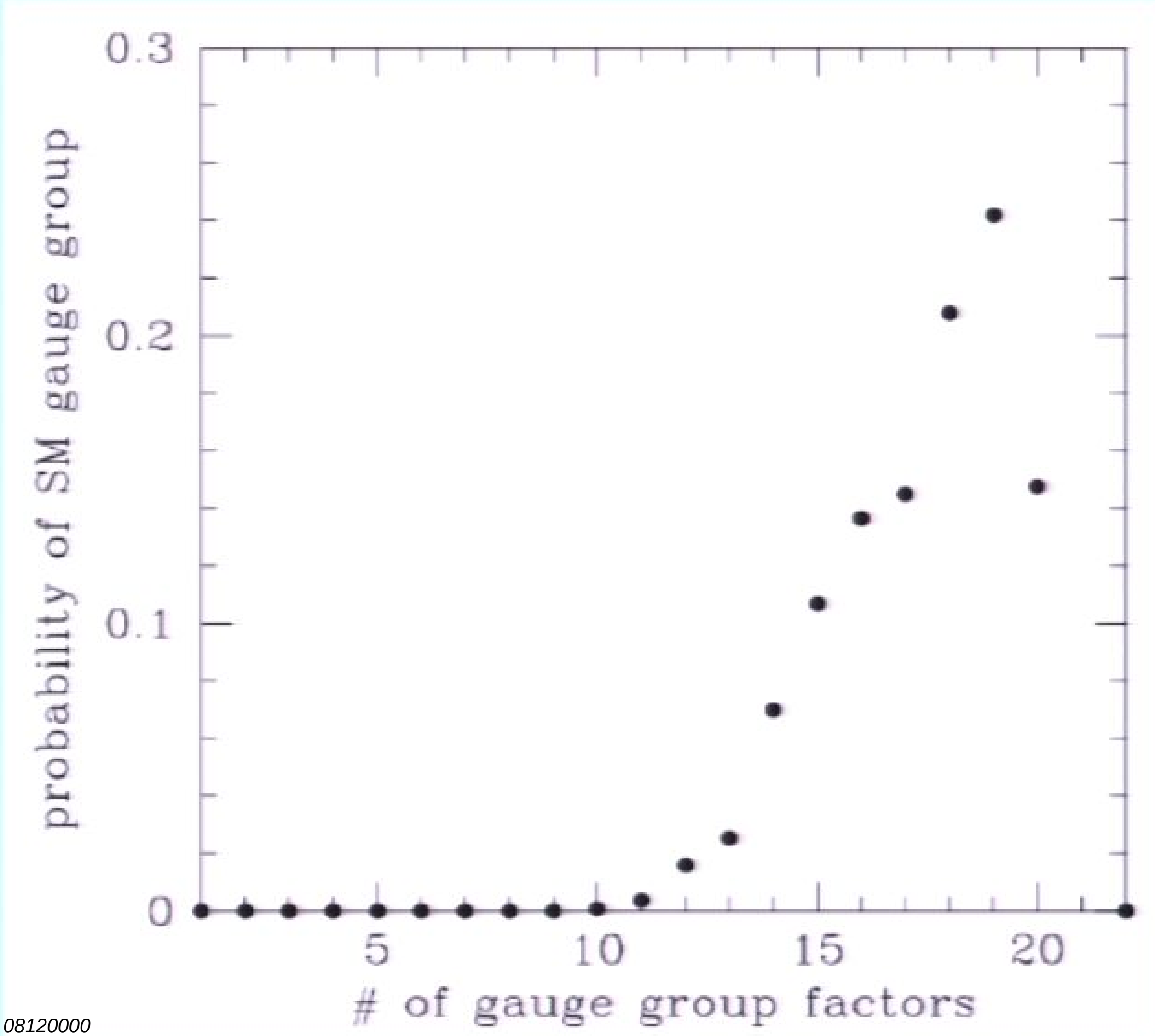

Indeed, averaged across all degrees of shatter, the total probability of obtaining the SM gauge group in this sample of models is only 10.05% --- similar to what is found for Type I strings.

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)...

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	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.

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- 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?

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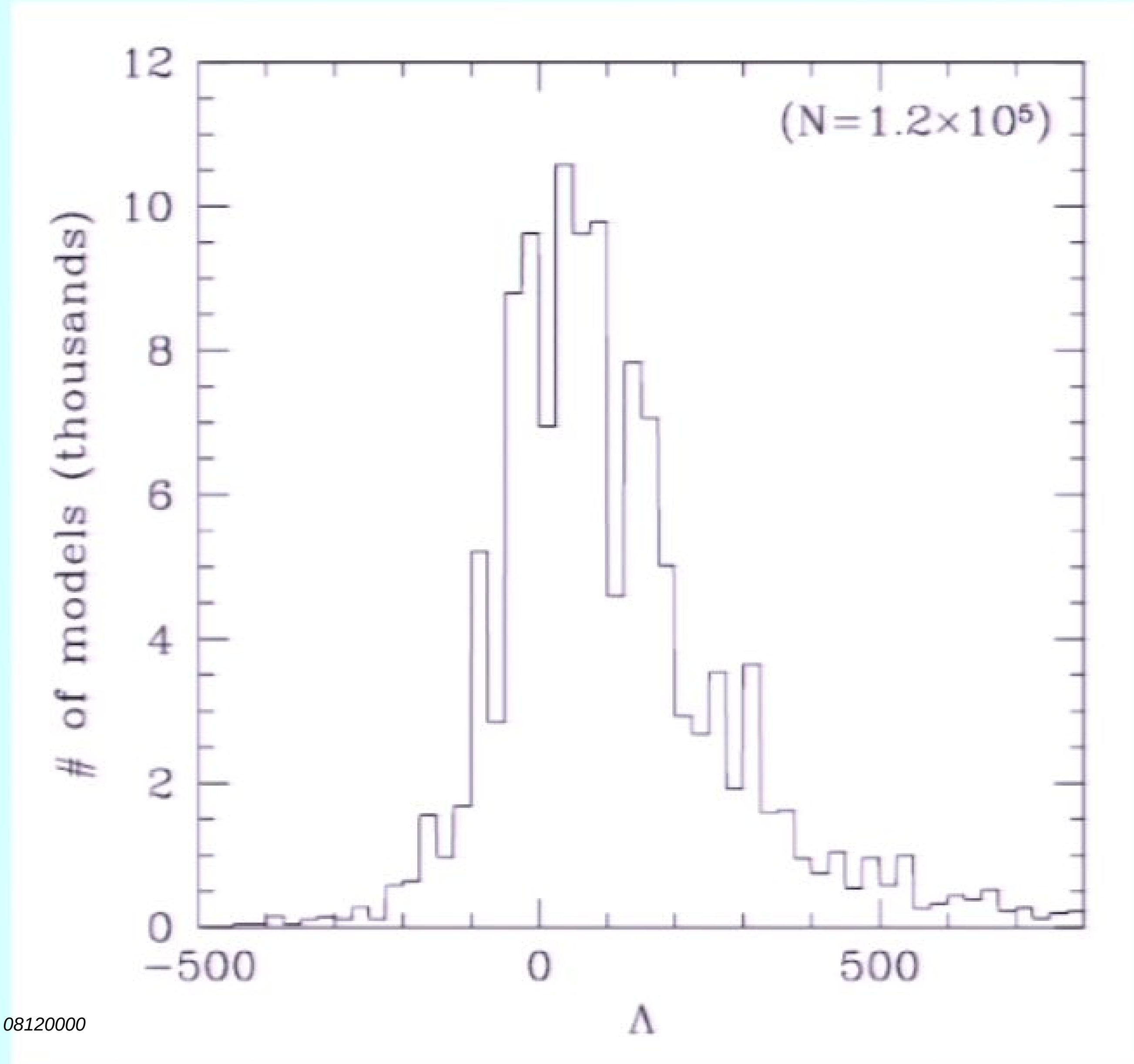

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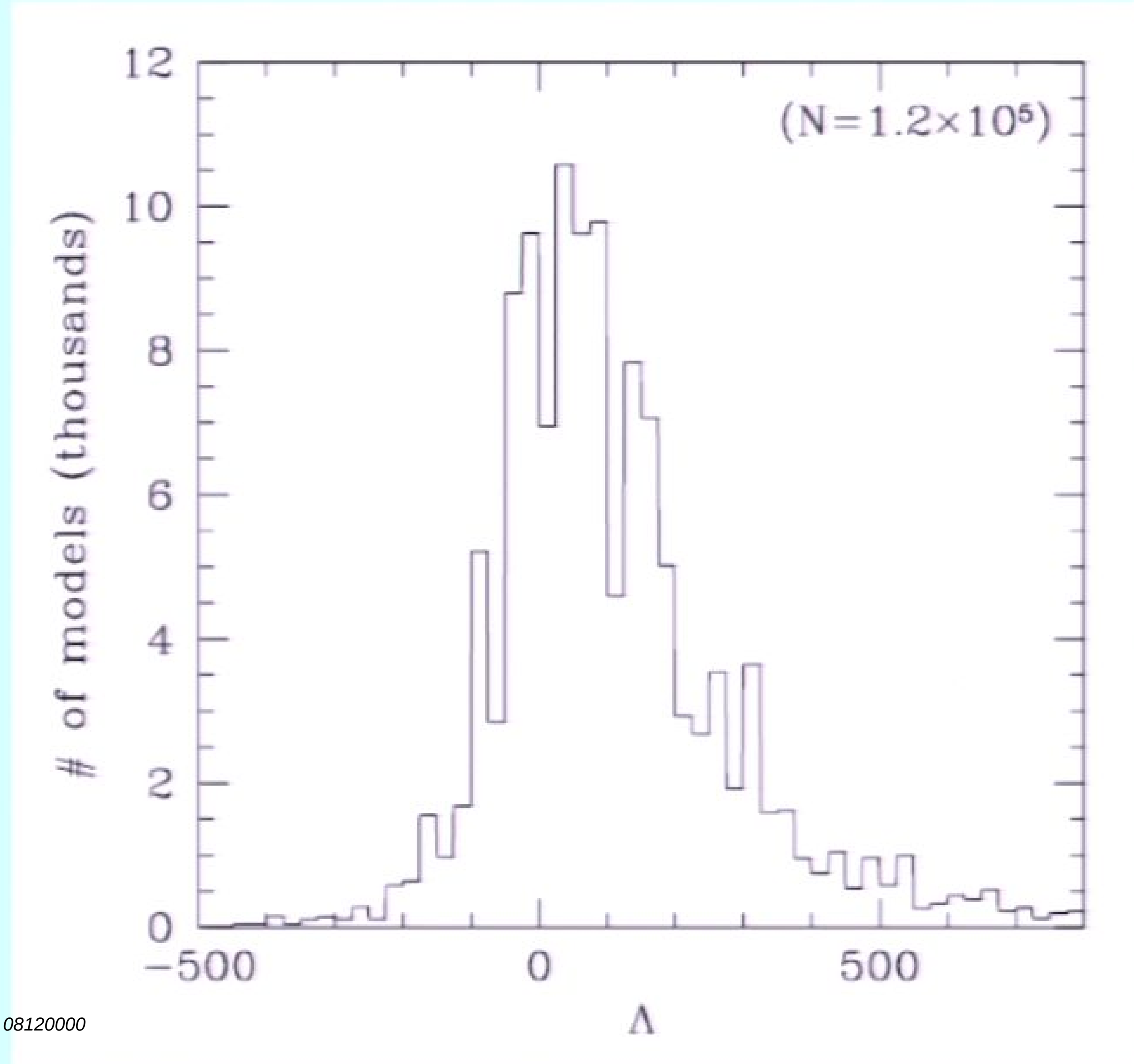

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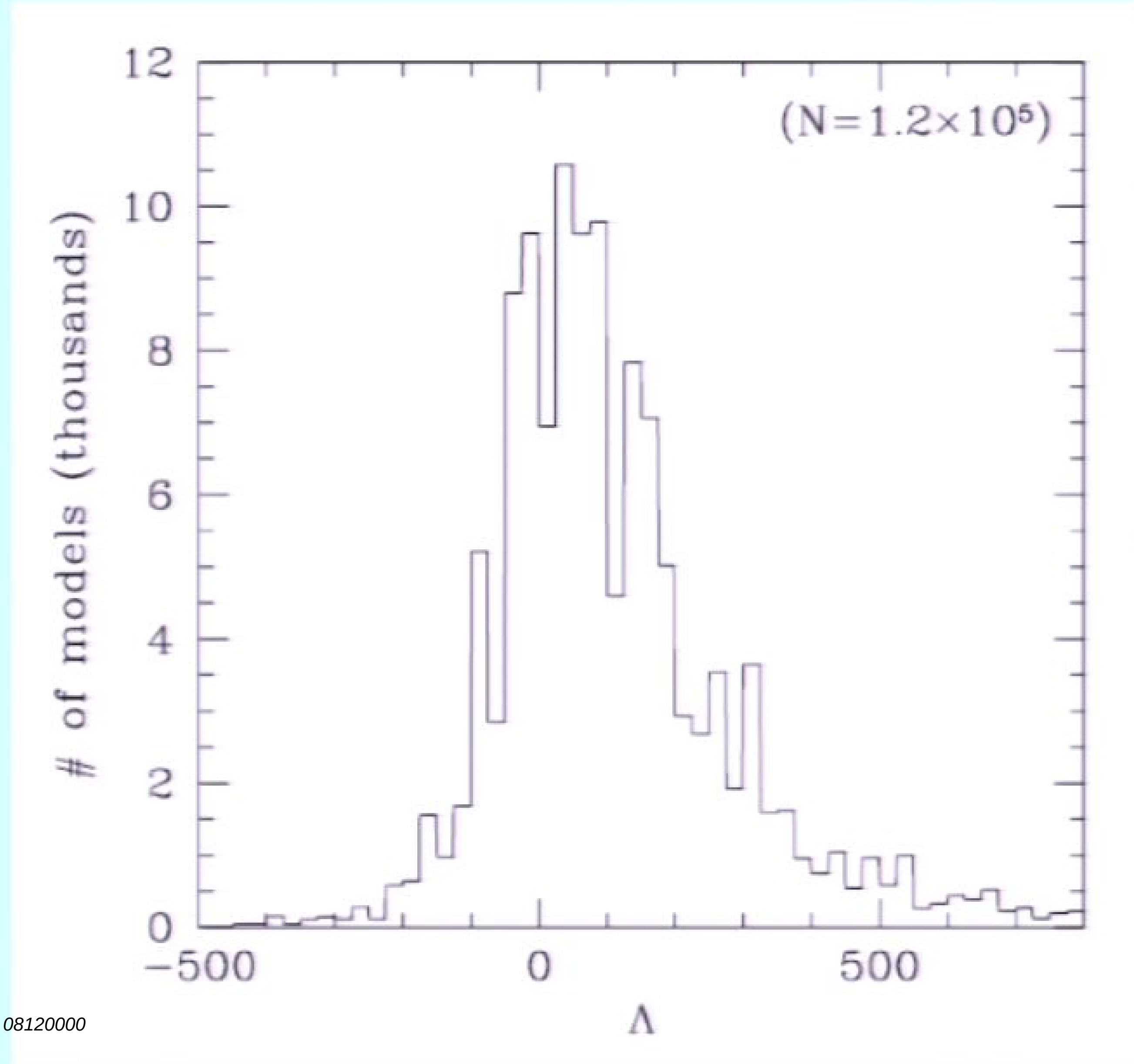

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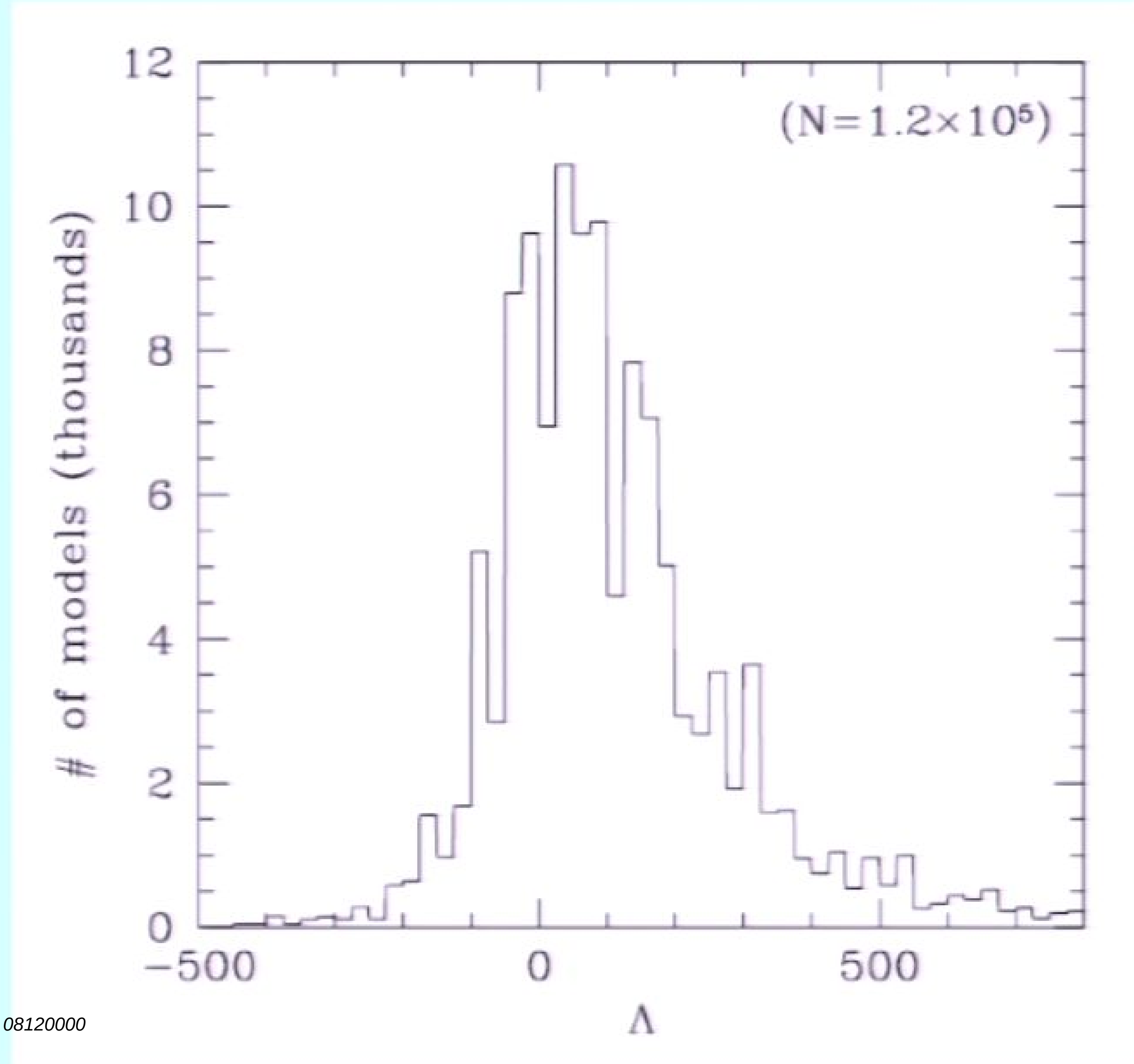

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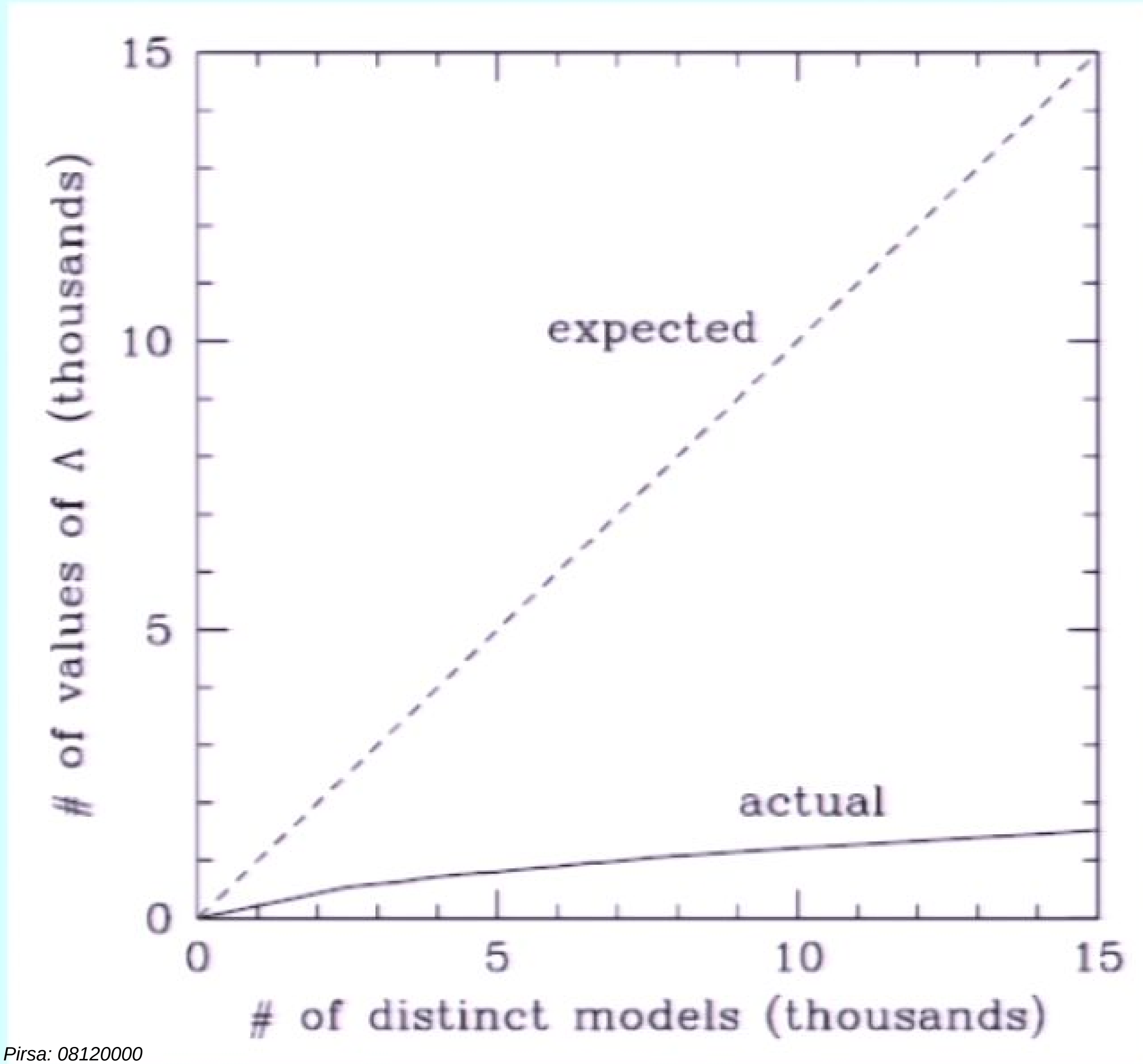

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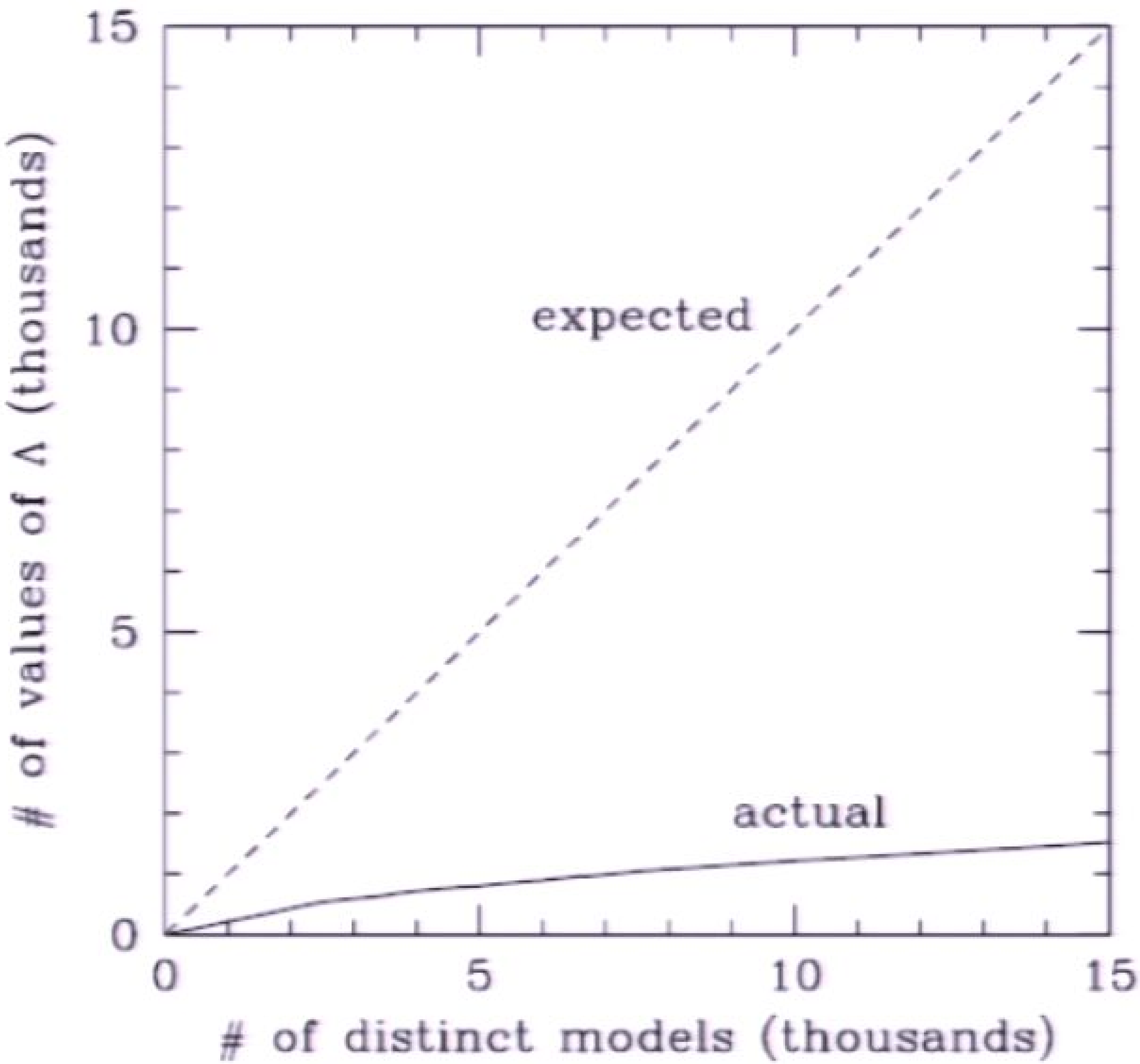

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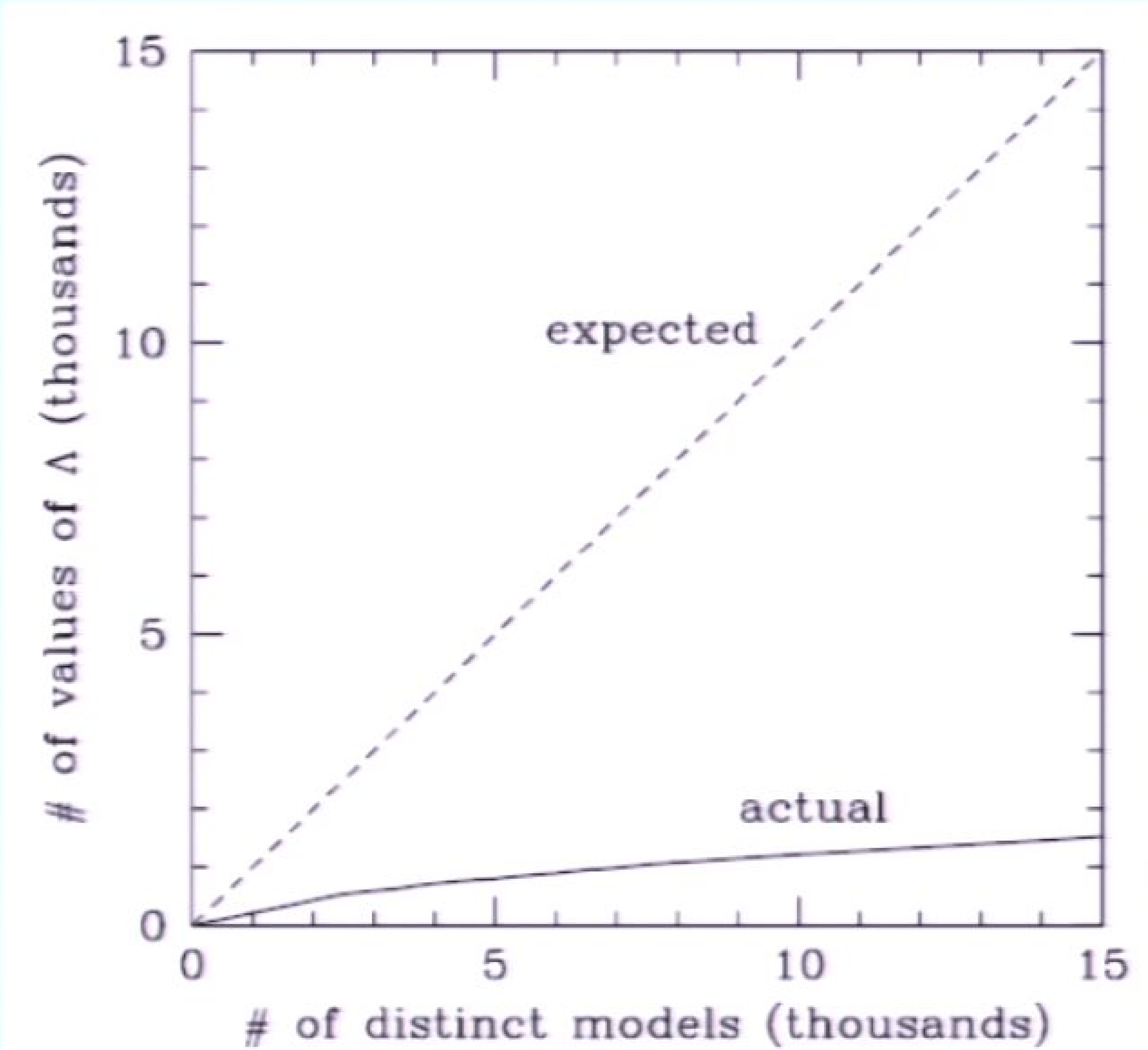

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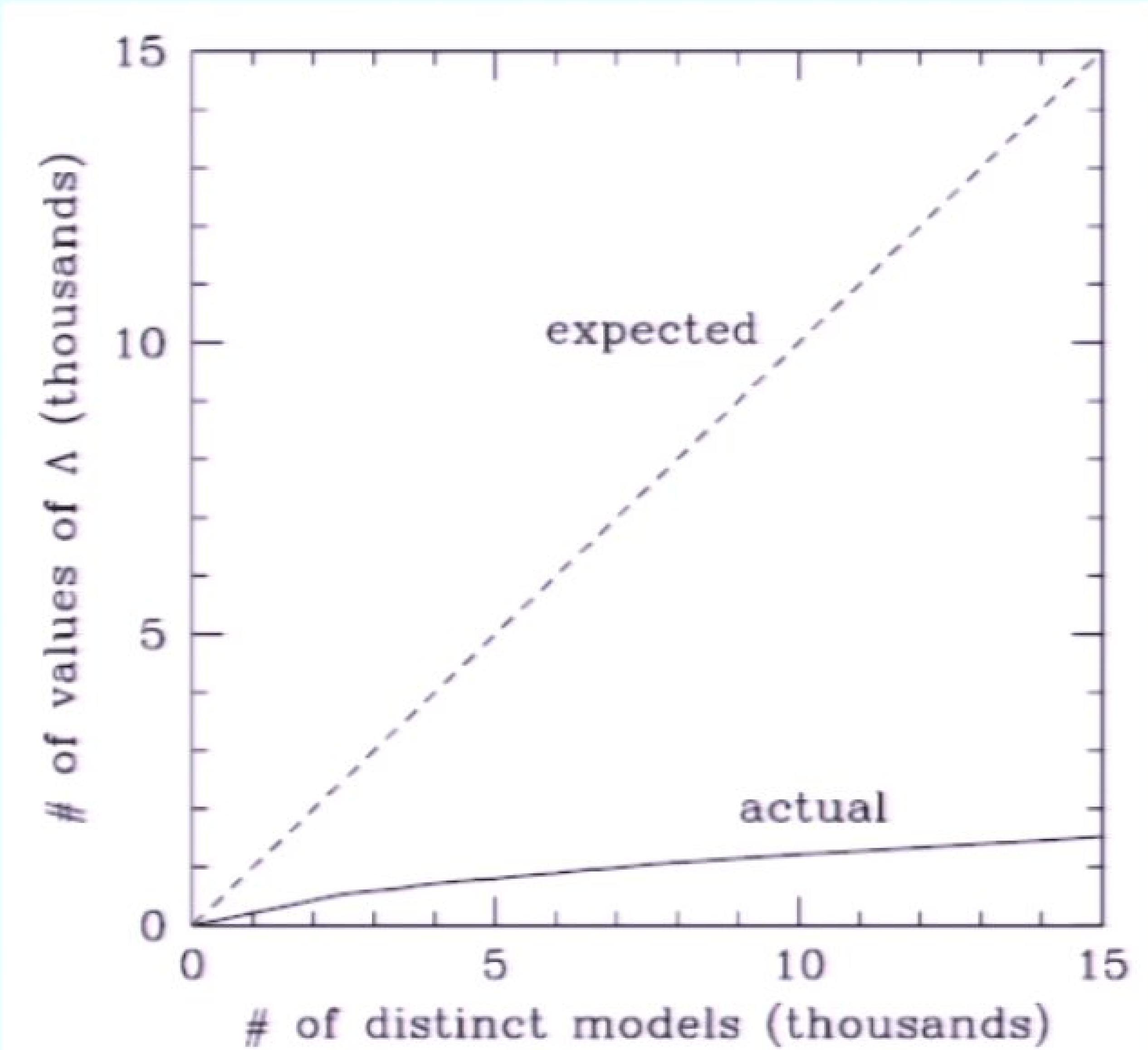

- The number of values of Λ found is significantly less than the number of models examined!
- Unrelated models with completely different gauge groups and particle content can nevertheless have *identical* values of Λ !

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

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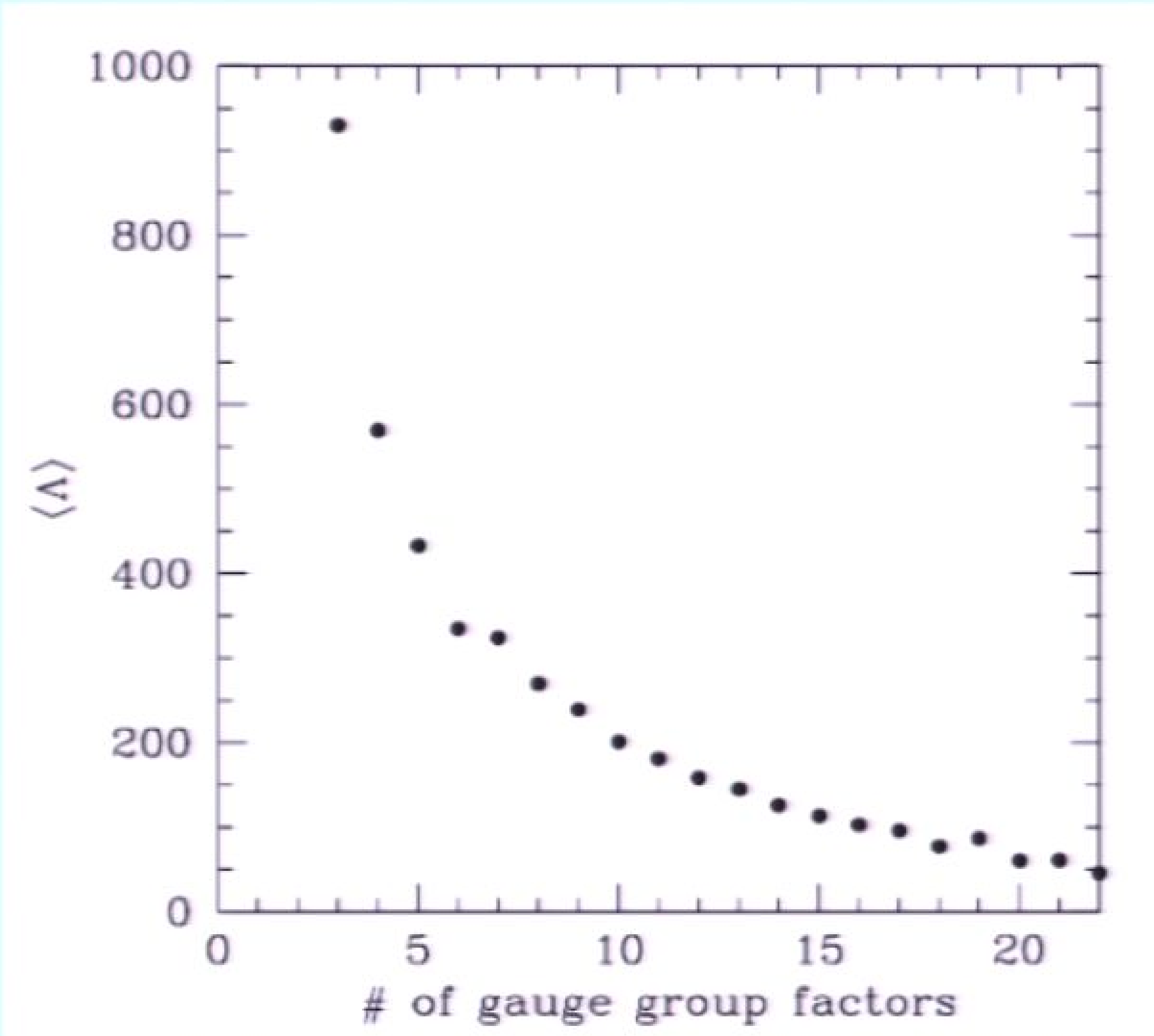

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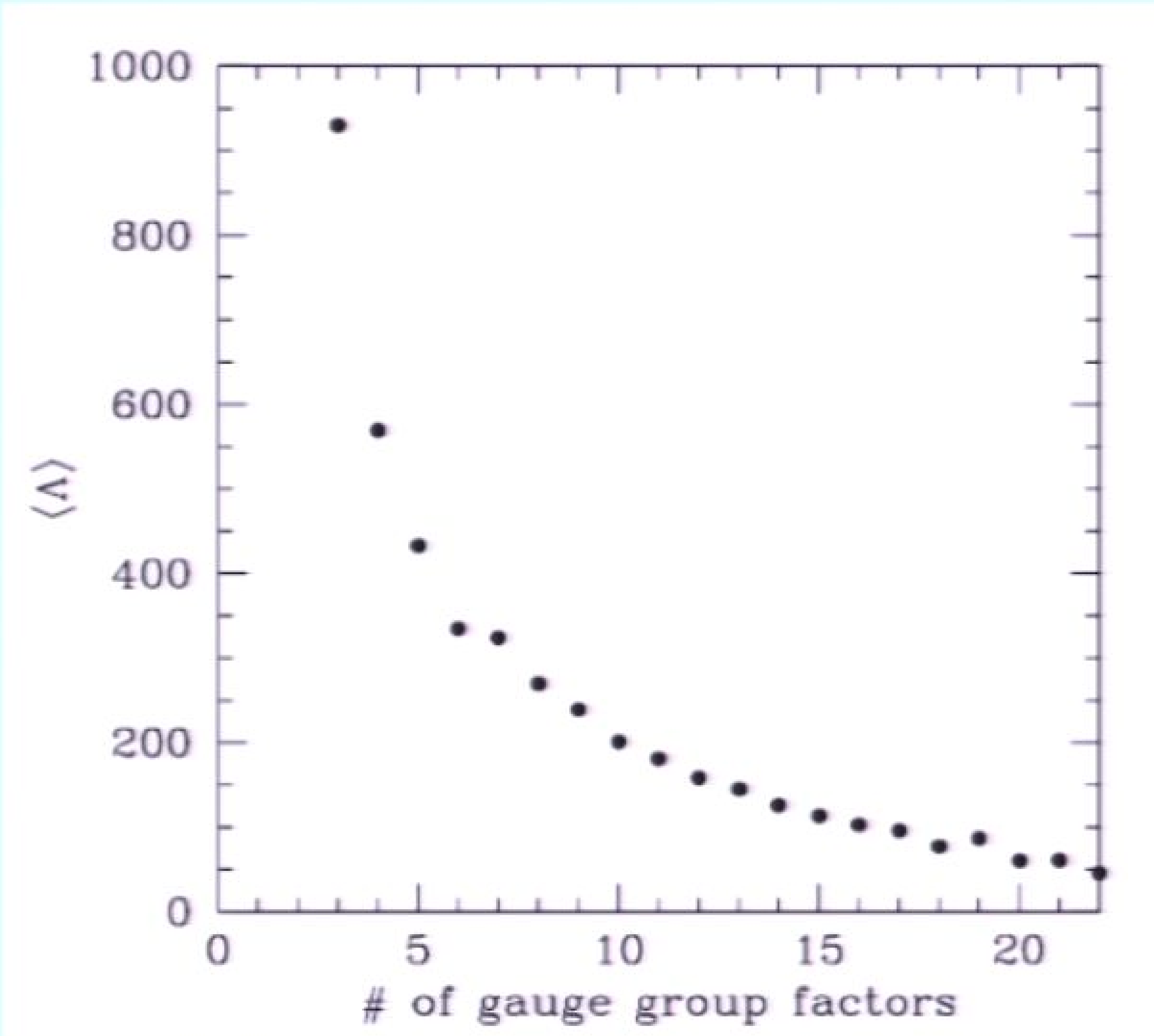

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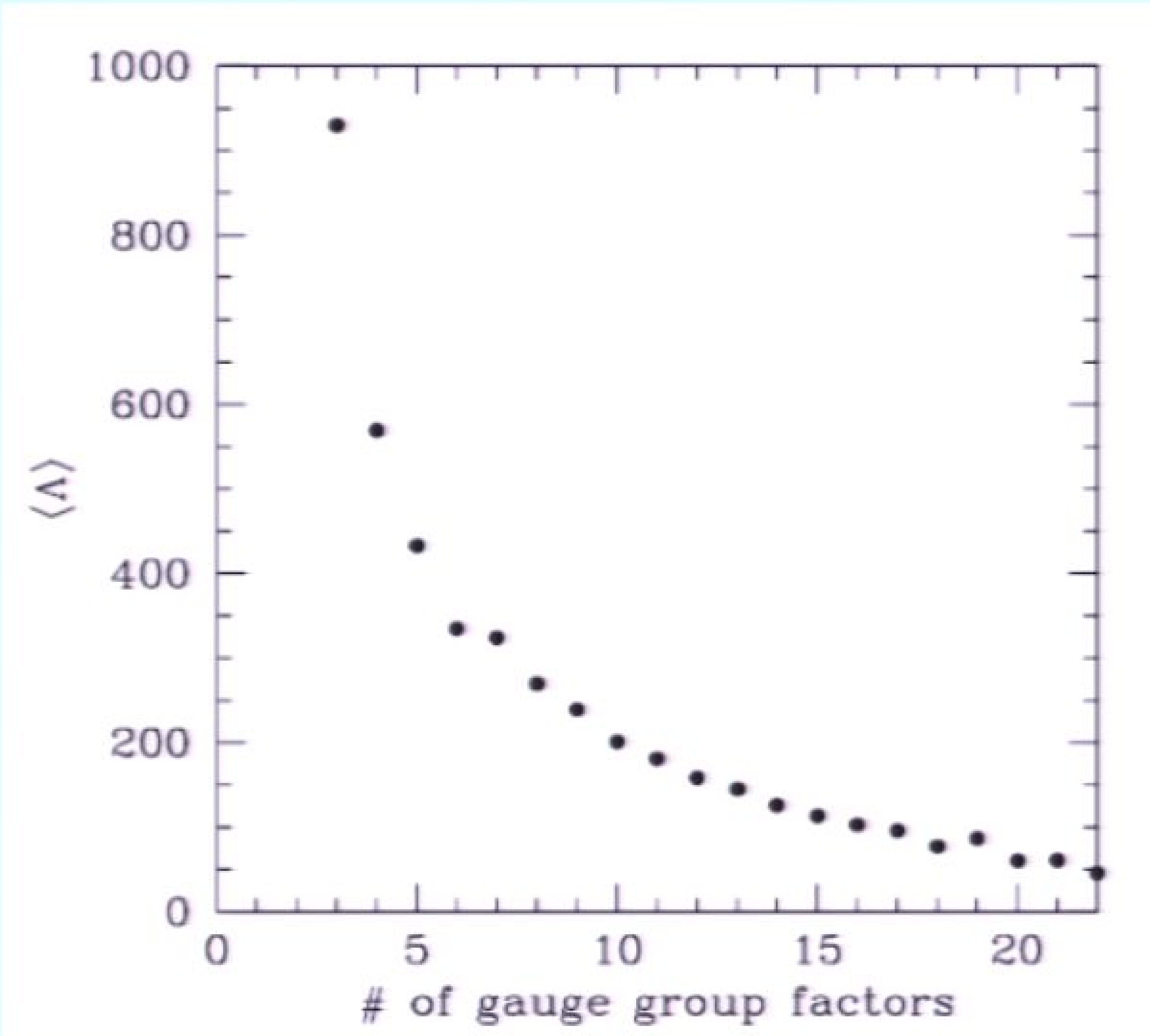

- These are *statistical averages* across all models with same degree of shatter.
- **More twists (i.e., smaller gauge-group factors) tends to lead to smaller one-loop cosmological constants.**

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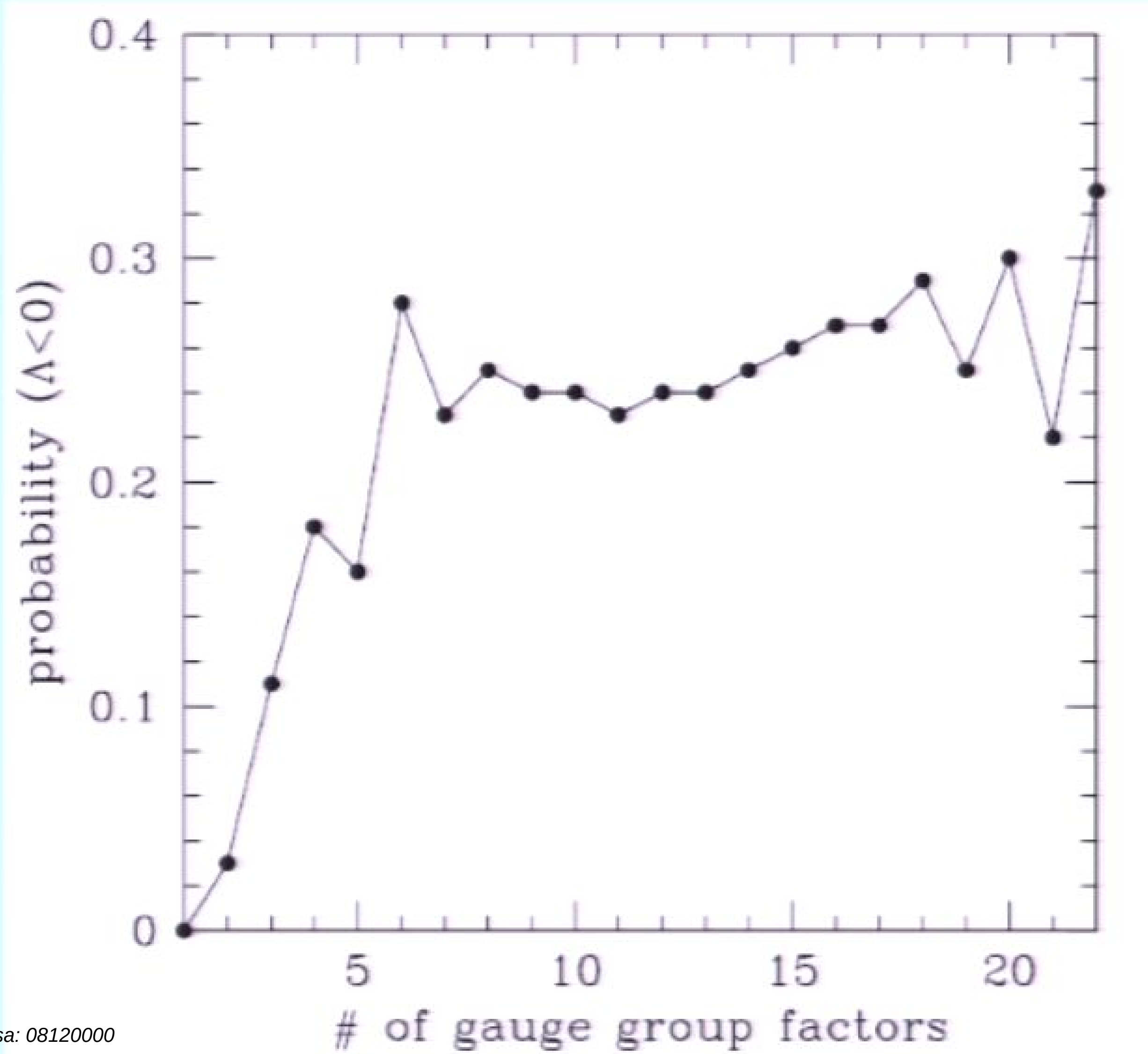

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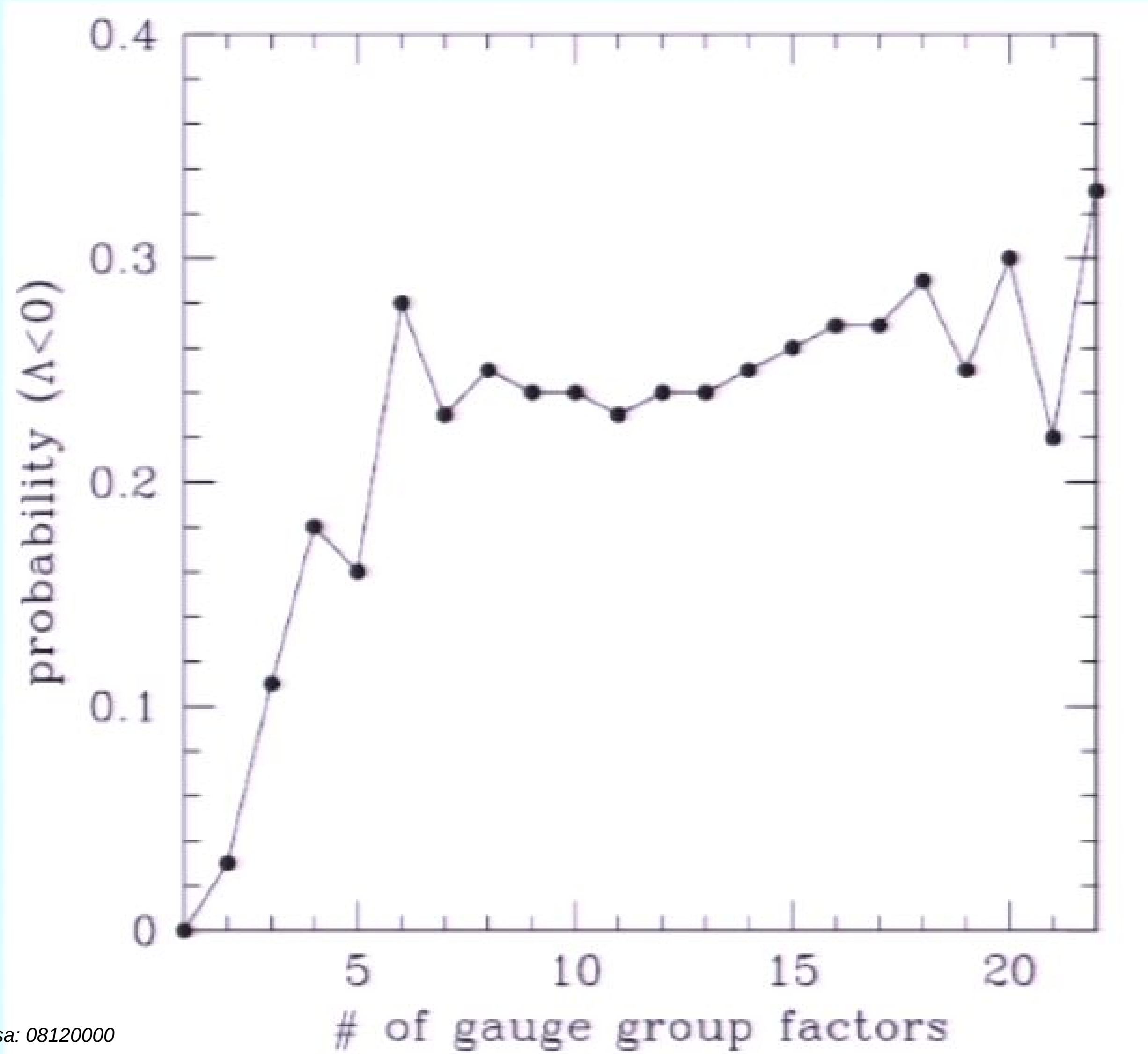

- No significant probability until shatter reaches 4-5.
- Probability then remains constant as further shattering occurs.

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)

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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.

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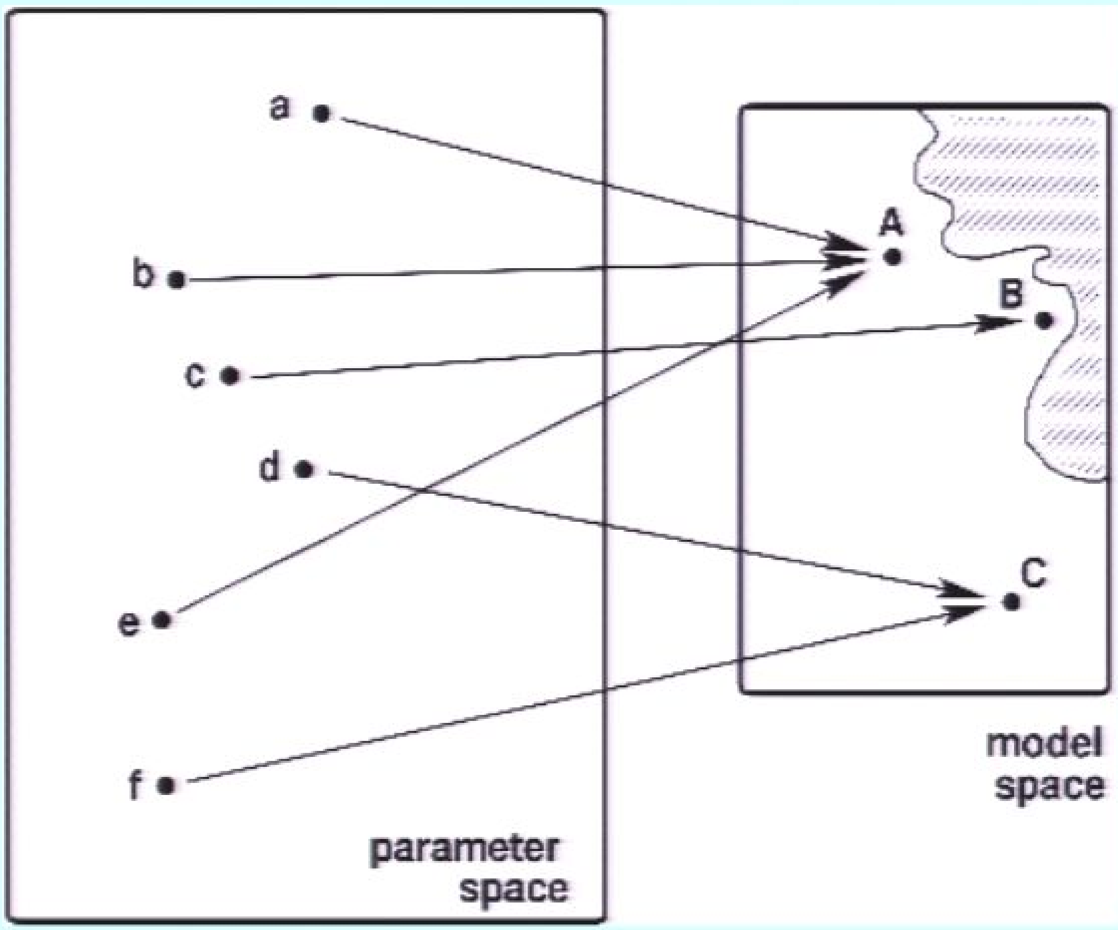

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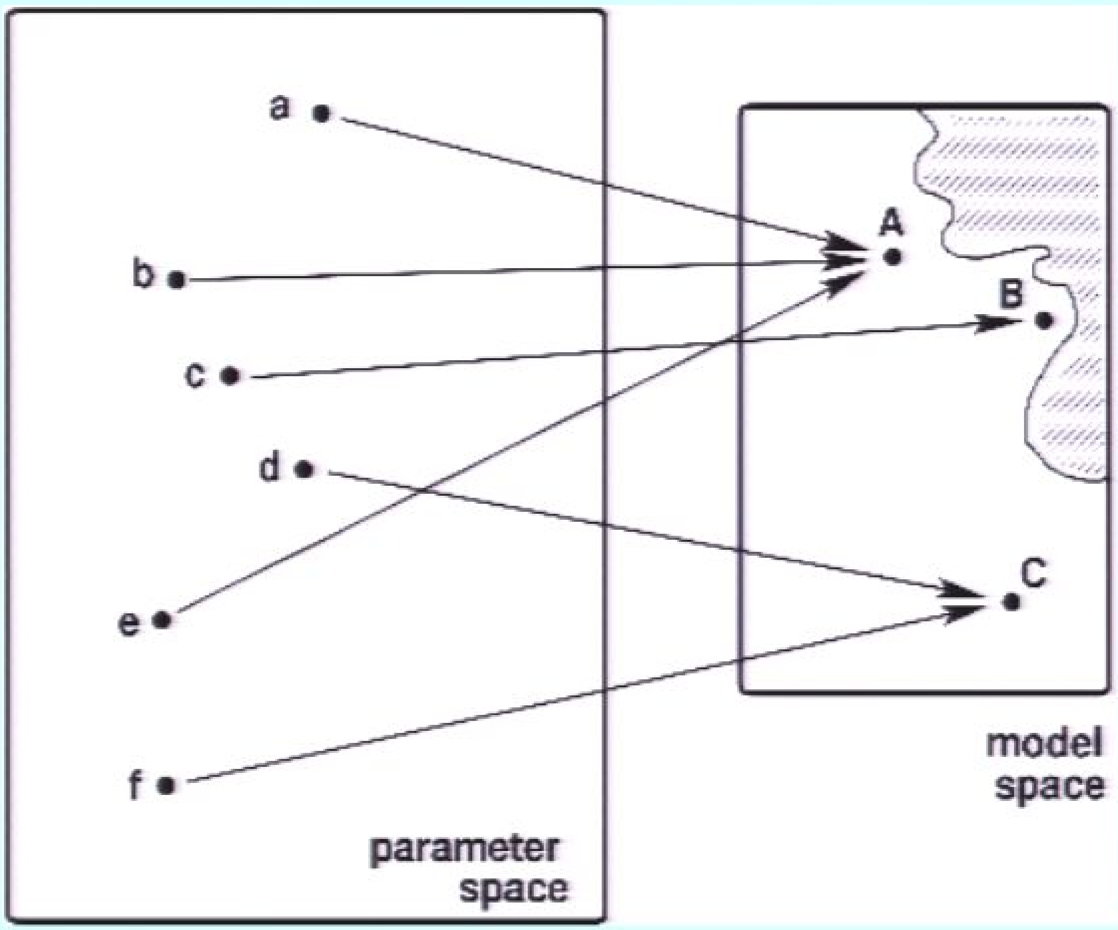

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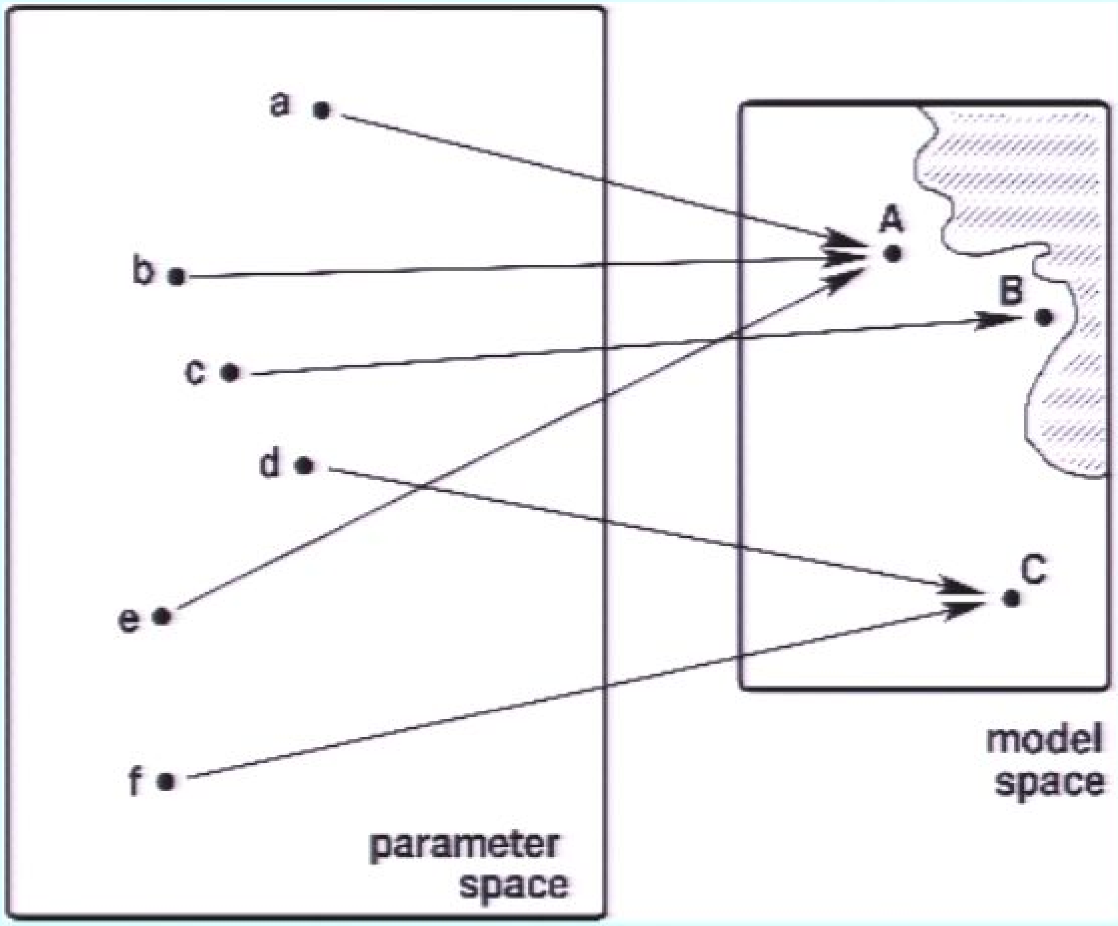

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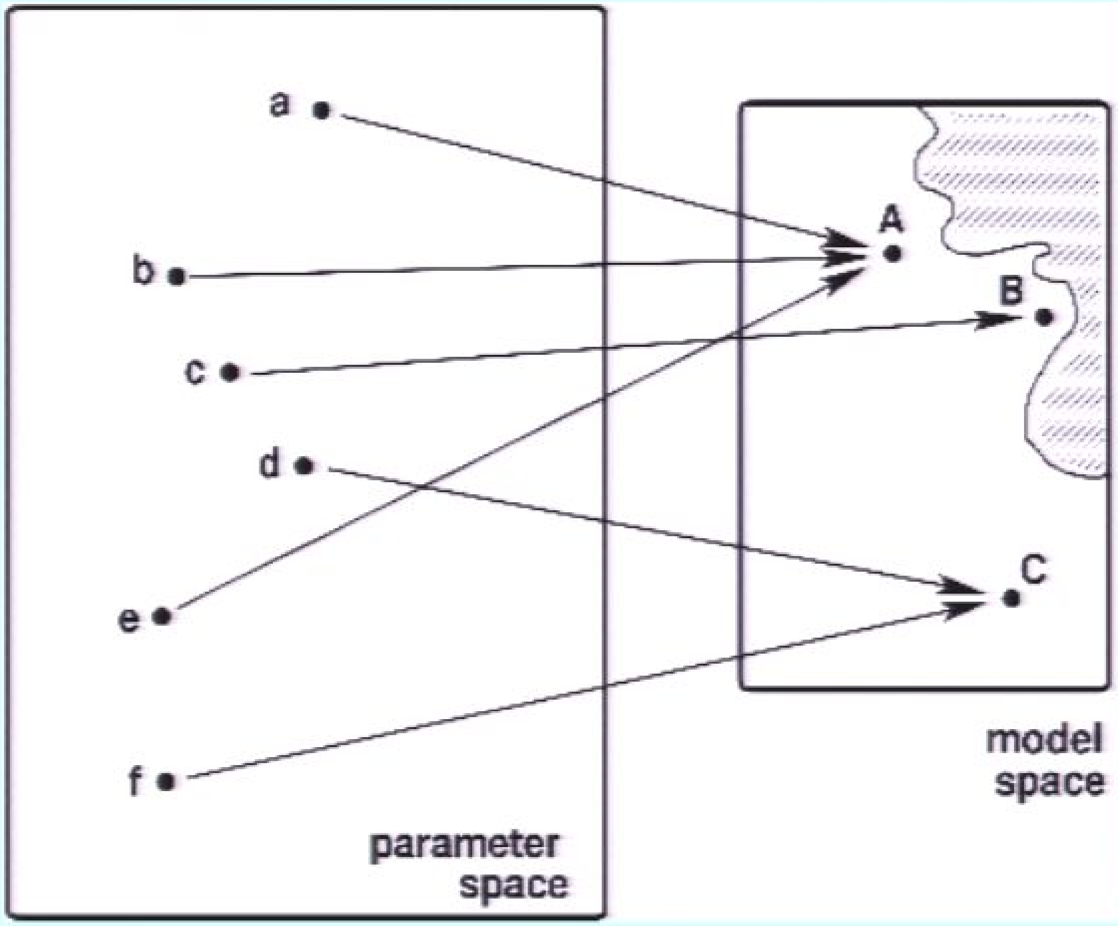

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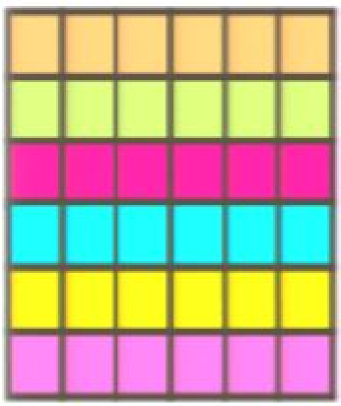
- Each set of parameters maps to a single model, but the mapping is rarely unique!

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:



Ω_{model}

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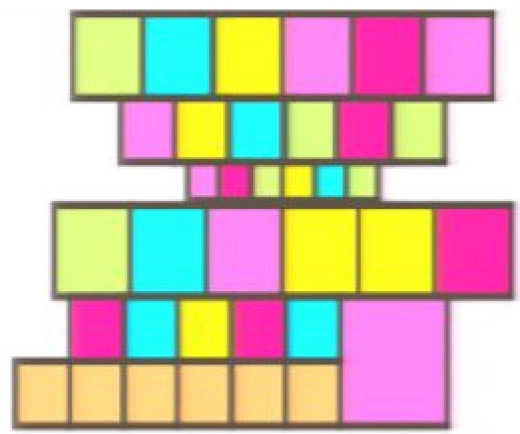

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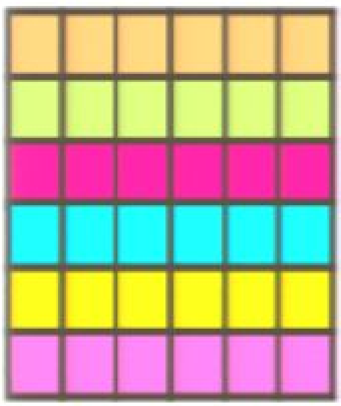

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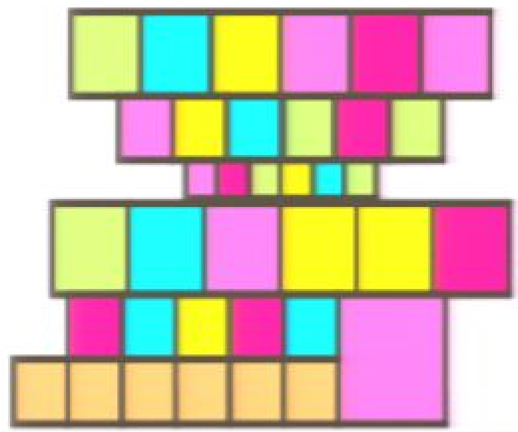

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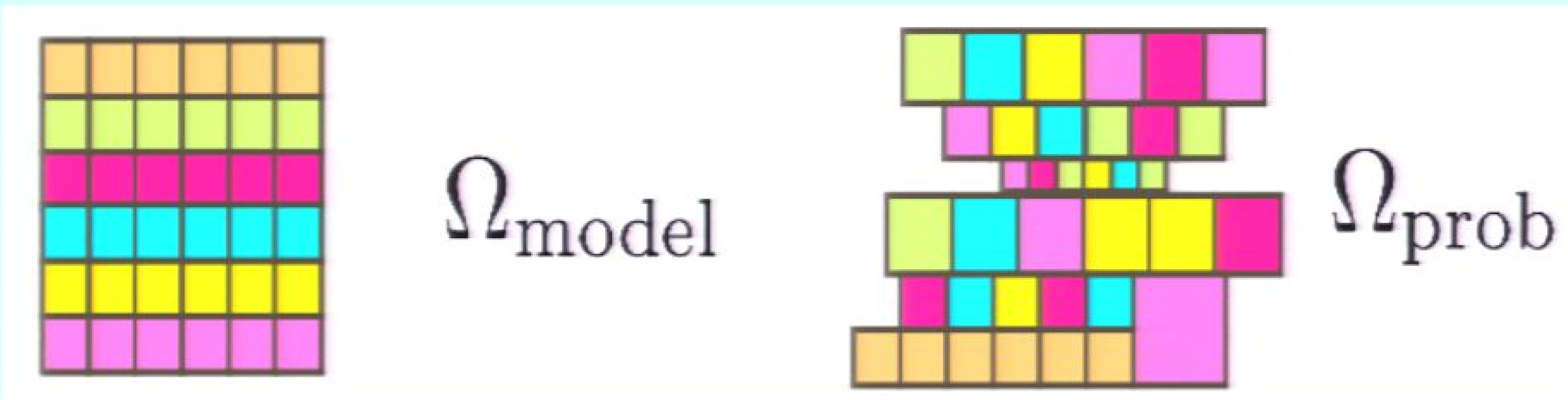

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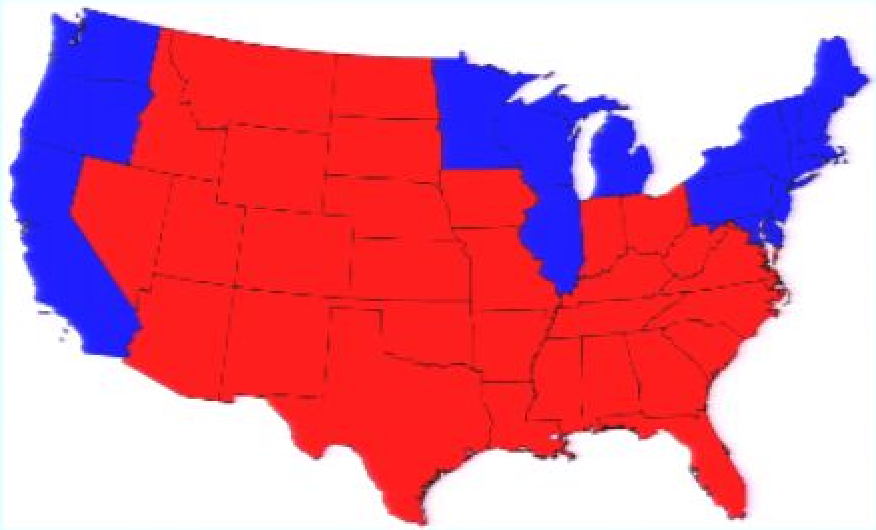

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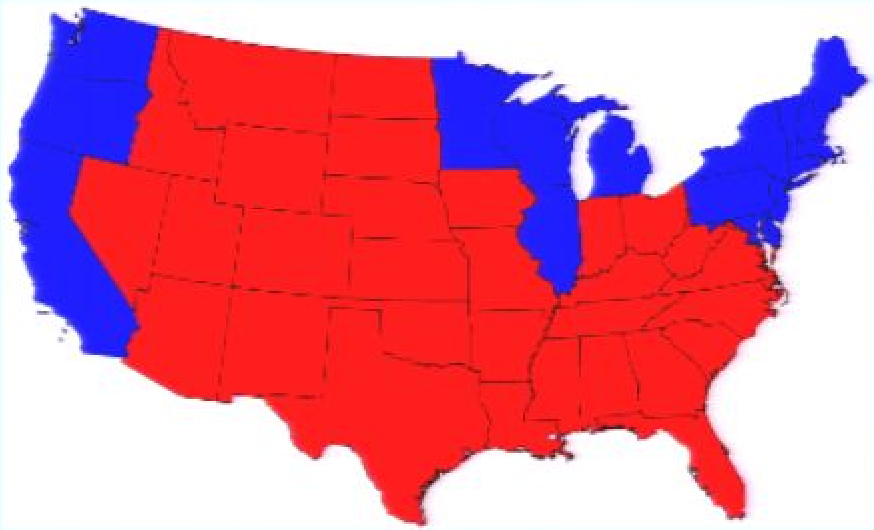

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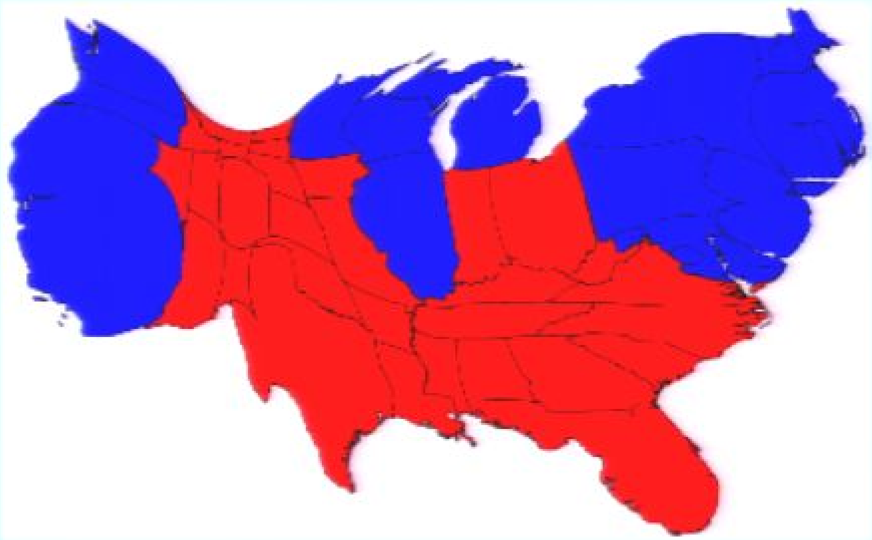

Cartogram based on population.

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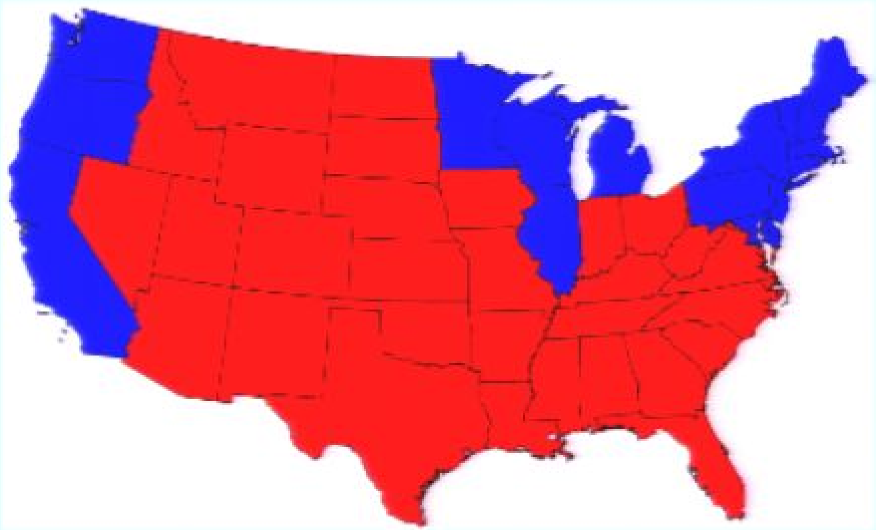

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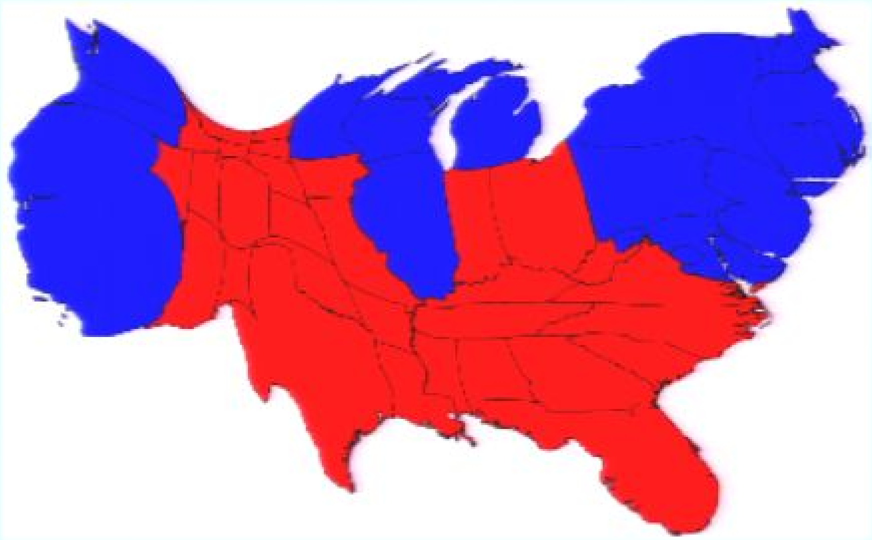

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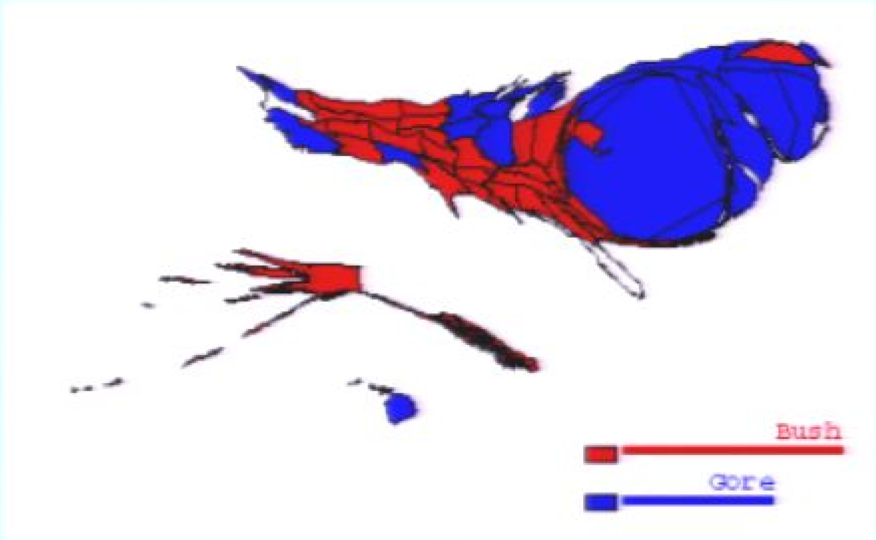

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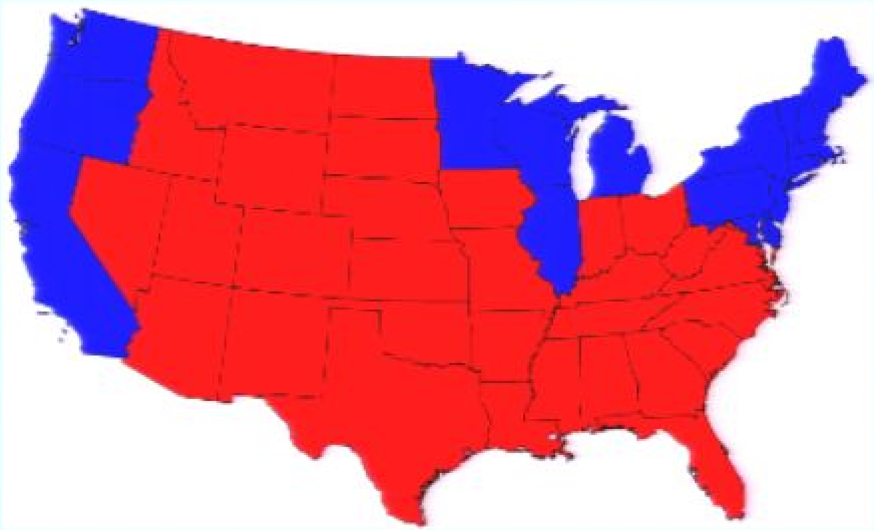

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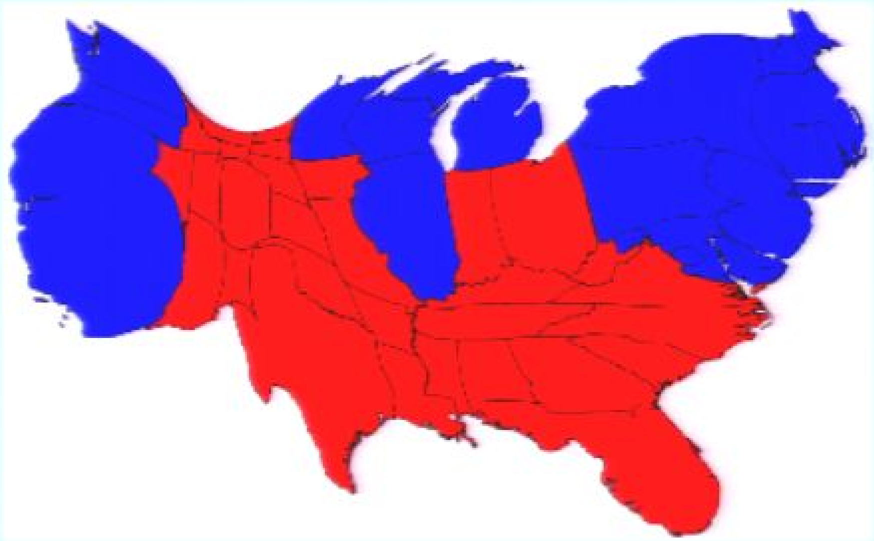

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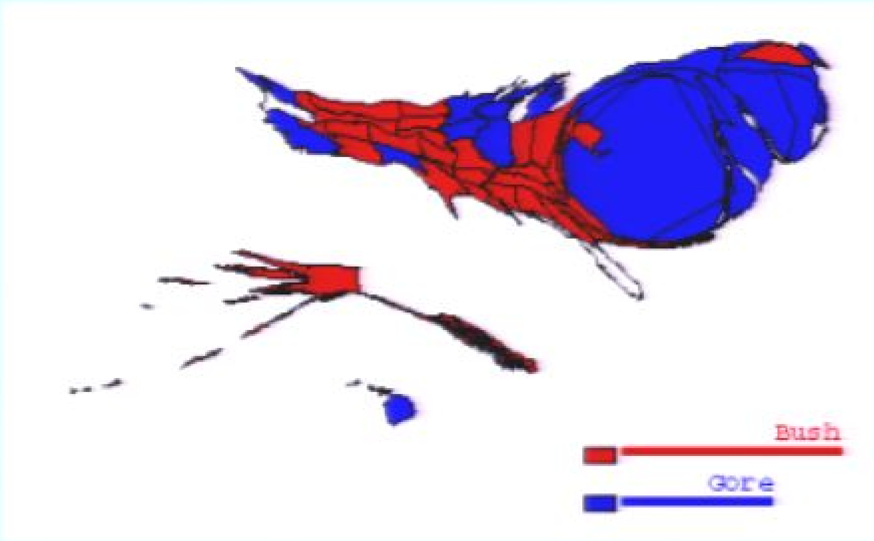
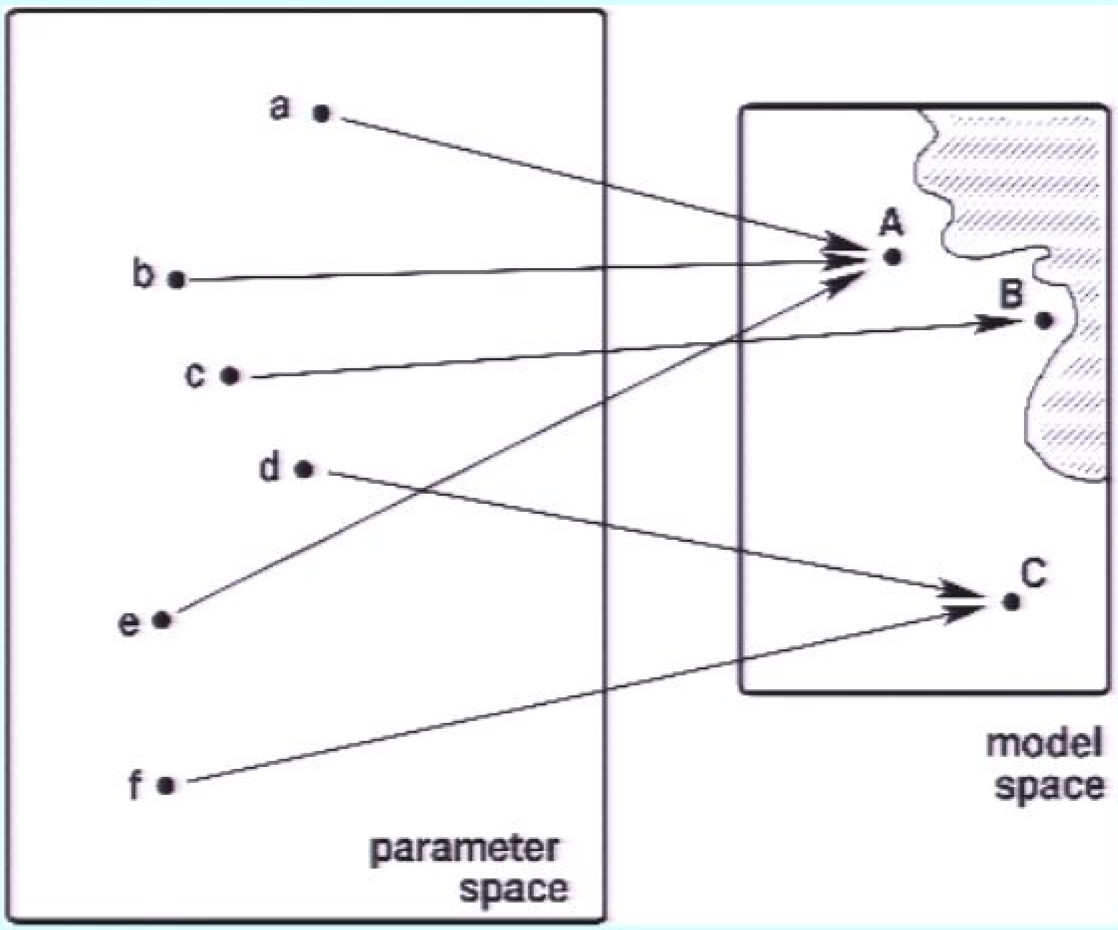


Cartogram based on population density.

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

How can we get around this problem?



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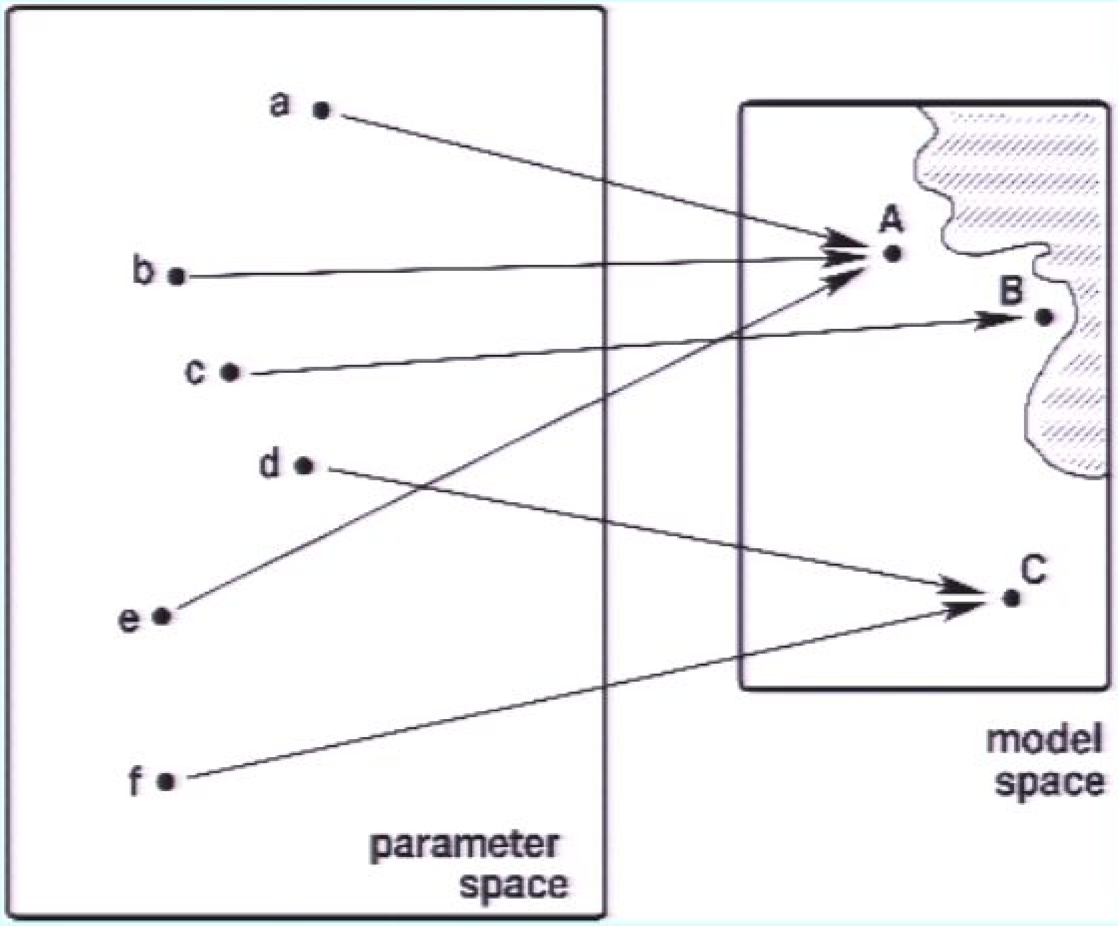

- Partial solution: don't count the "new" model if it's already in the data set. Consider it a "failed attempt", disregard this case, and try again.

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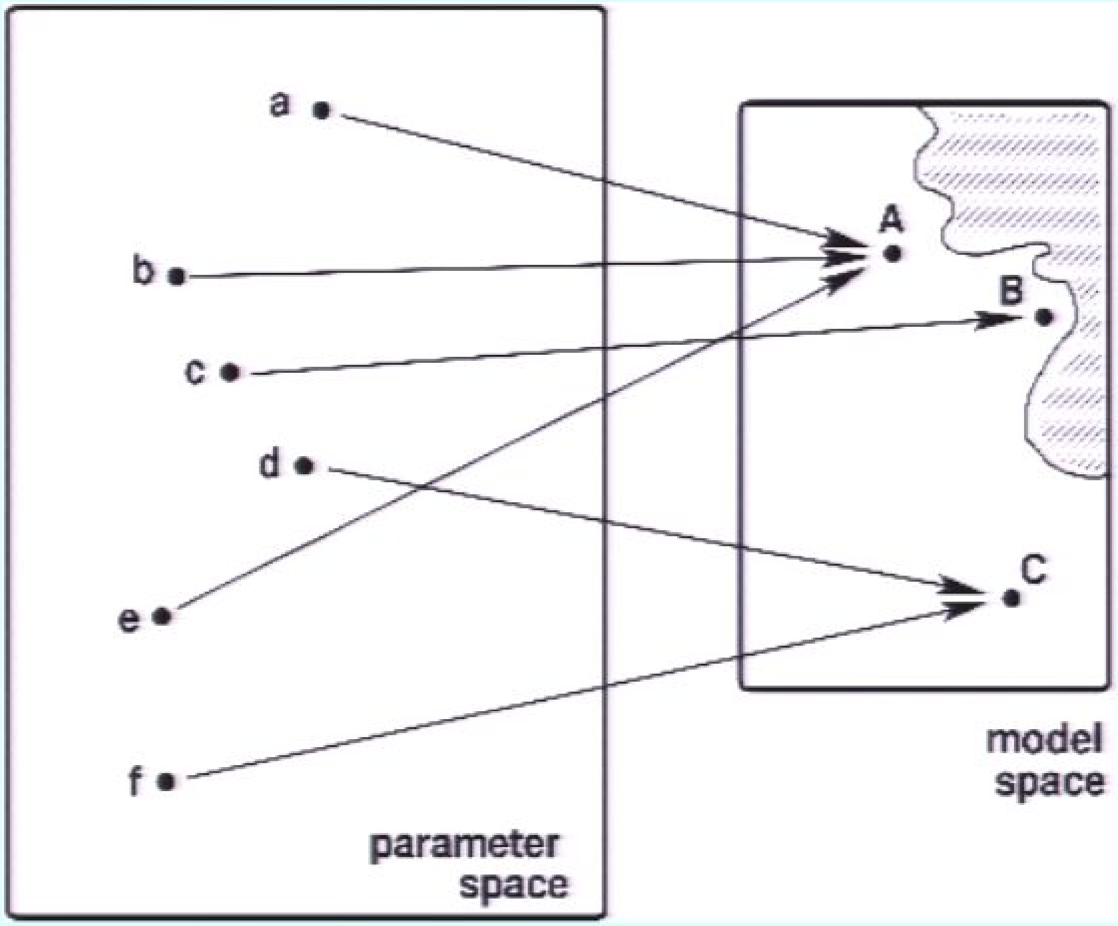
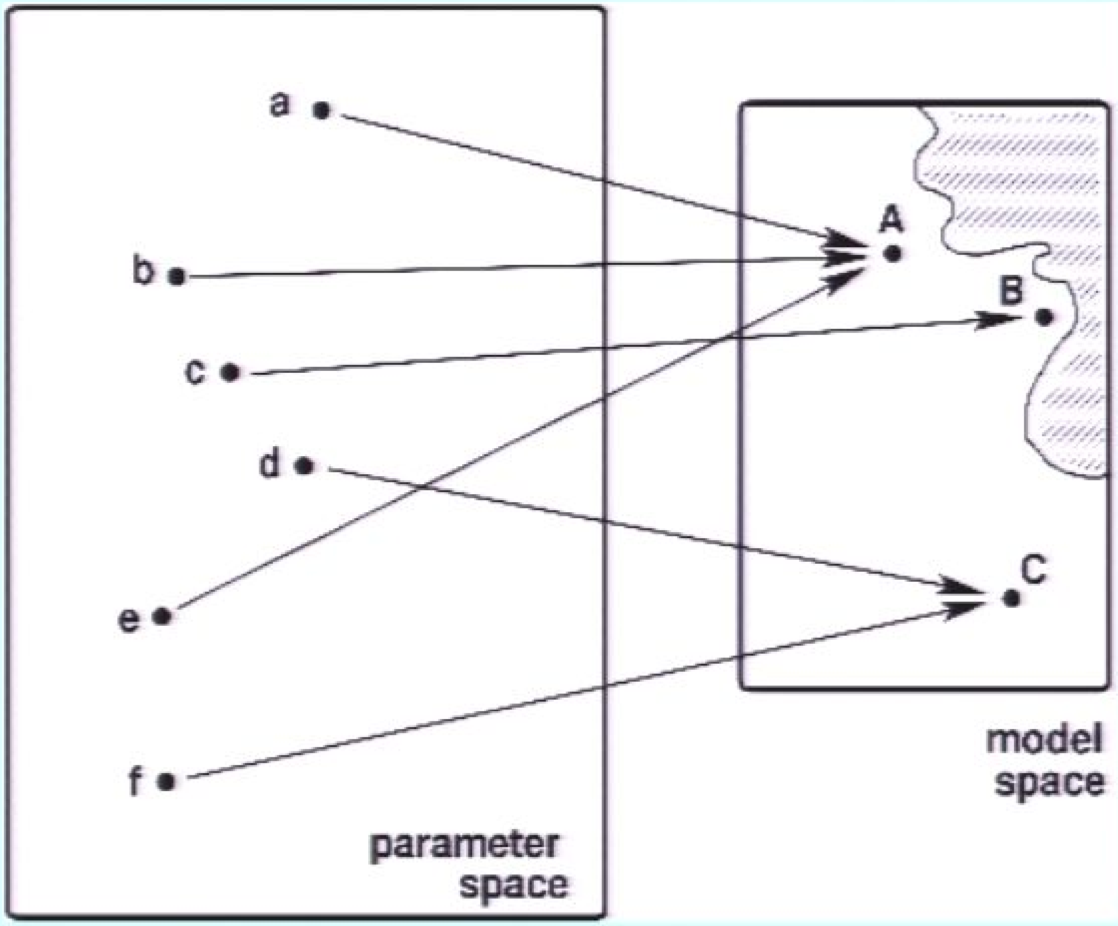


- But we are still not finding the very "rare" models (such as Model B), close to the "unreachable" region. It will take a considerably larger data set before we will stumble across such rare models, and we have *no information* about where they are, how common they are, or whether they even exist!

How can we get around this problem?



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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.

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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.*

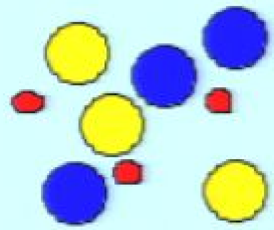
Of course, we need a measure for "equally explored". How can we judge how deeply we have penetrated into a particular model space?

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.

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:



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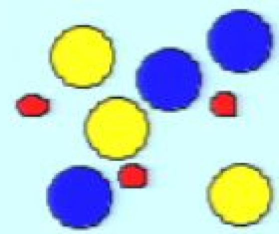

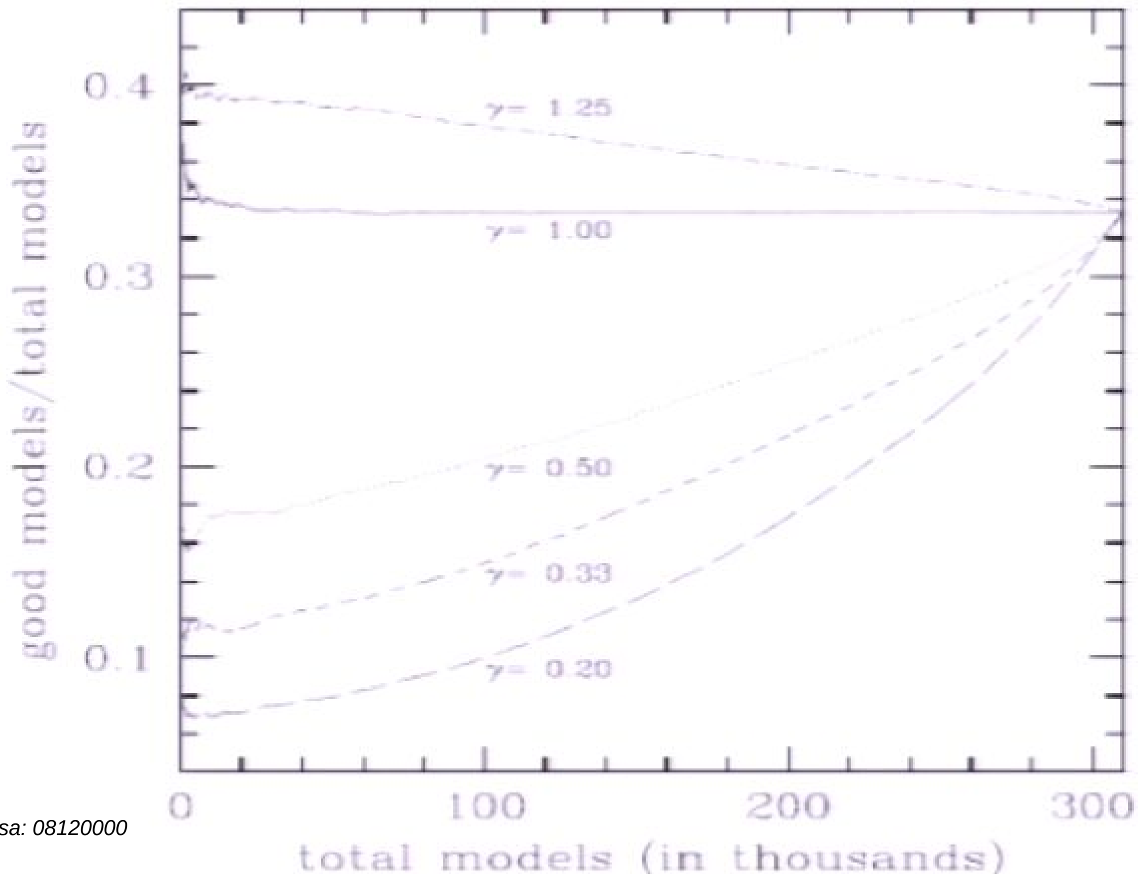

True fraction emerges only upon full exploration of the urn.

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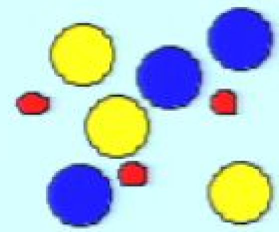

What fraction of selected balls will be red?
Clearly this "floats" with the sample size:

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 $X_{red} = X_{other}$!!

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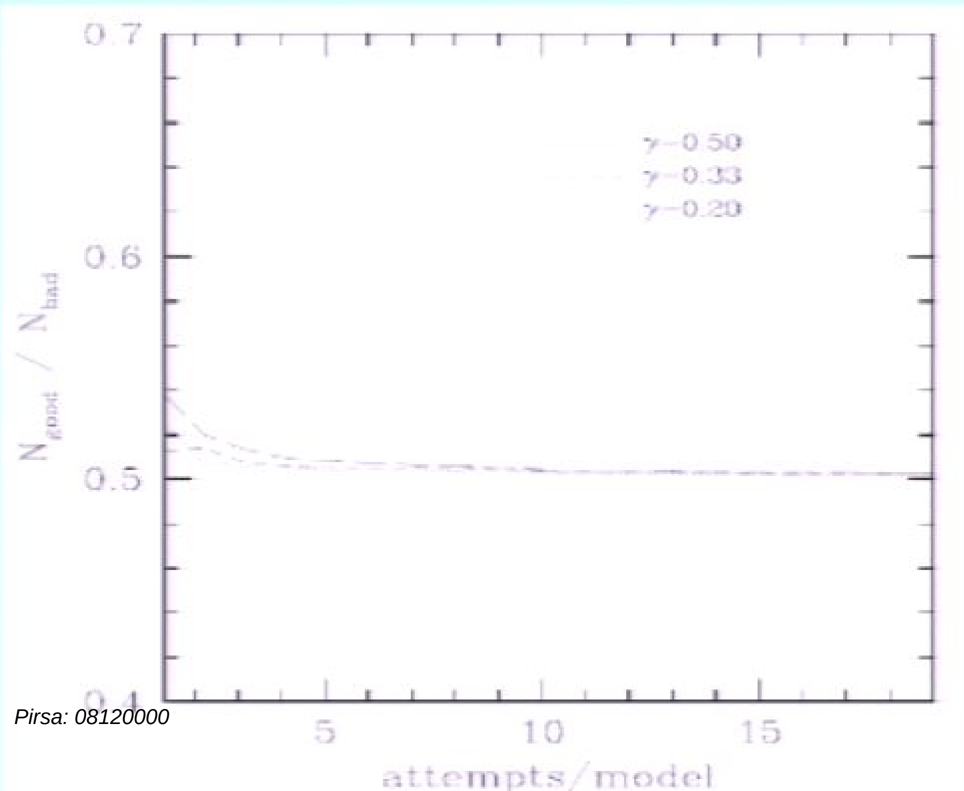

"Continuum" limit reached quite quickly regardless of chosen X!

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).

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⇒ 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)

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One string model ⟺ One vacuum

Counting models ⟺ Counting vacua

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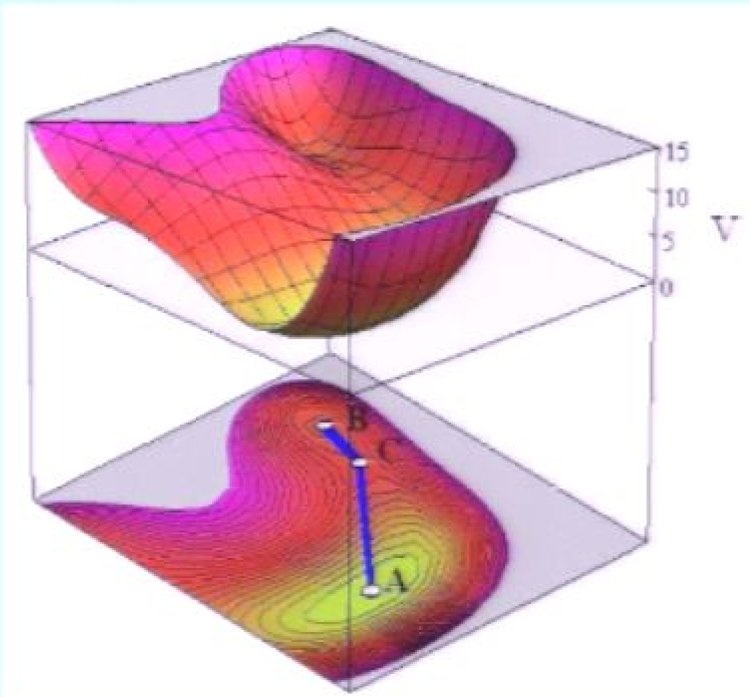
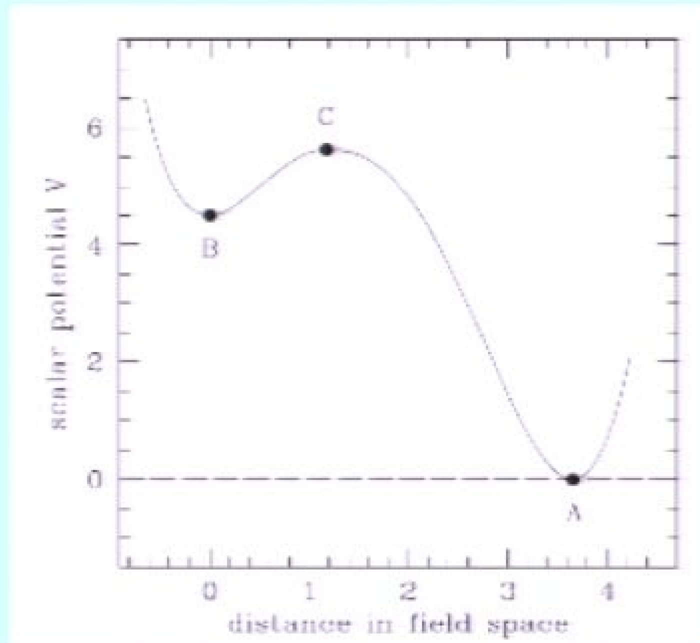


Dine, Nelson, Nir, Shirman, Dimopoulos, Dvali, Rattazzi, Giudice, Luty, Terning, Banks, Intriligator, Seiberg, Shih, Abel, Khoze, Aharony, Forste, Feng, Silverstein, Dienes, Thomas, ...



KRD & B. Thomas, 0806:3364

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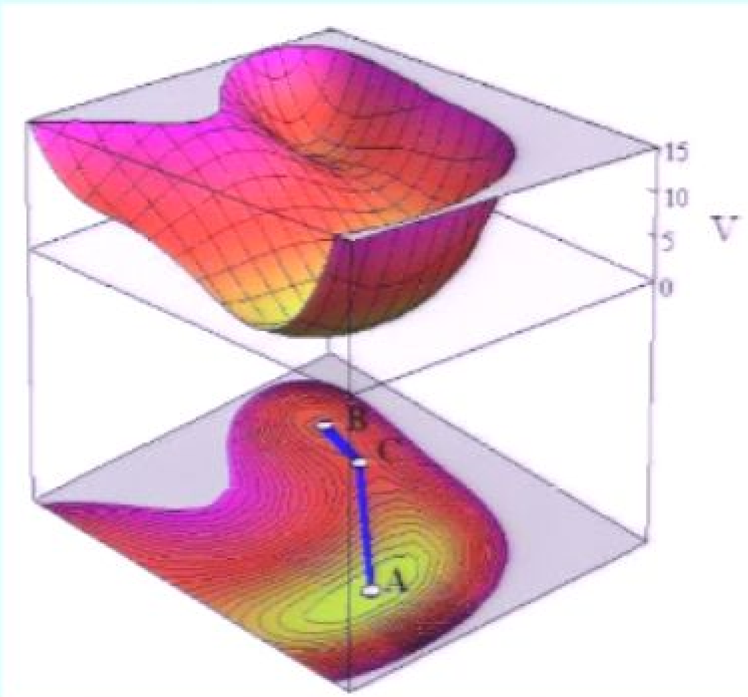

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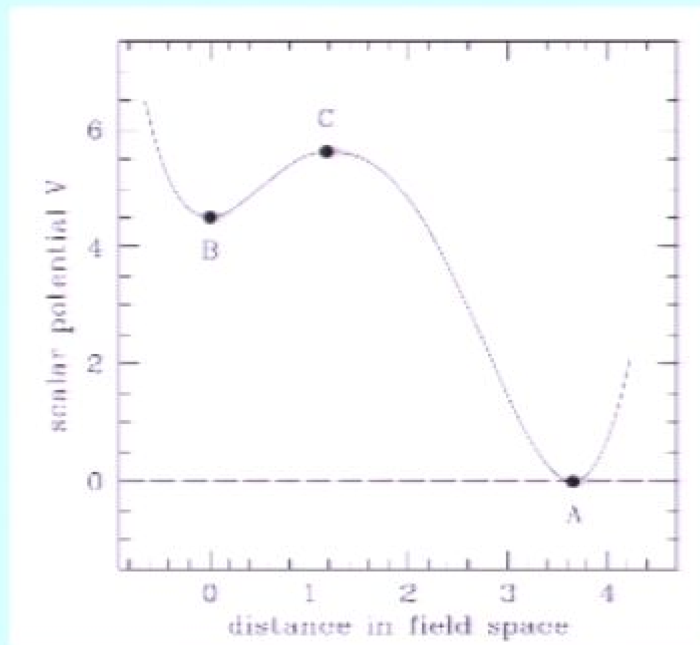

KRD & B. Thomas, 0806:3364

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.)

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

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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.

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	$U(1)_1$	$U(1)_2$	$U(1)_3$	$U(1)_4$	$\ldots$	$U(1)_{N-1}$	$U(1)_N$
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	$+1$

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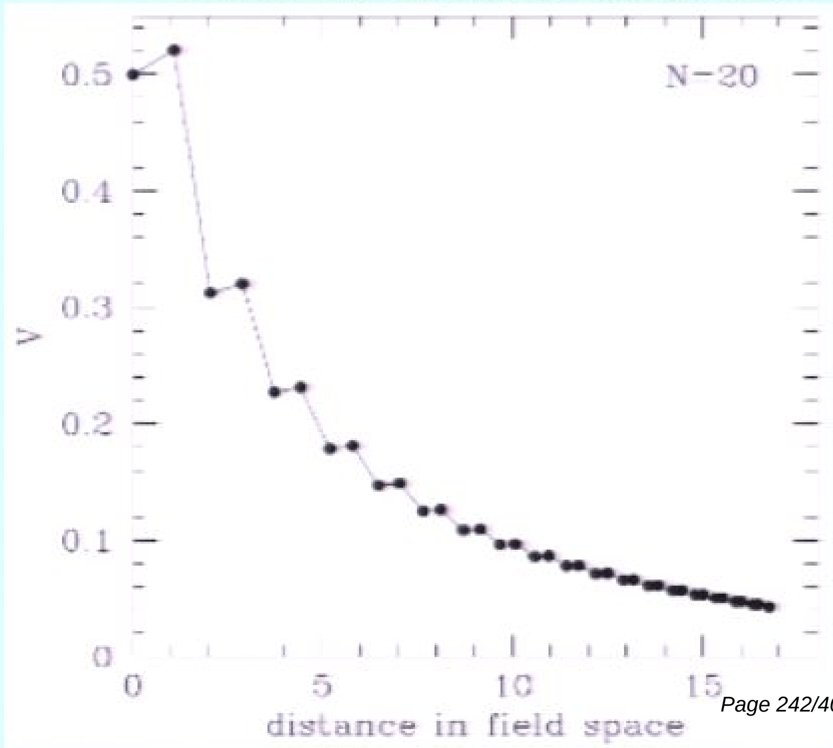
KRD & B. Thomas, 0811:3335



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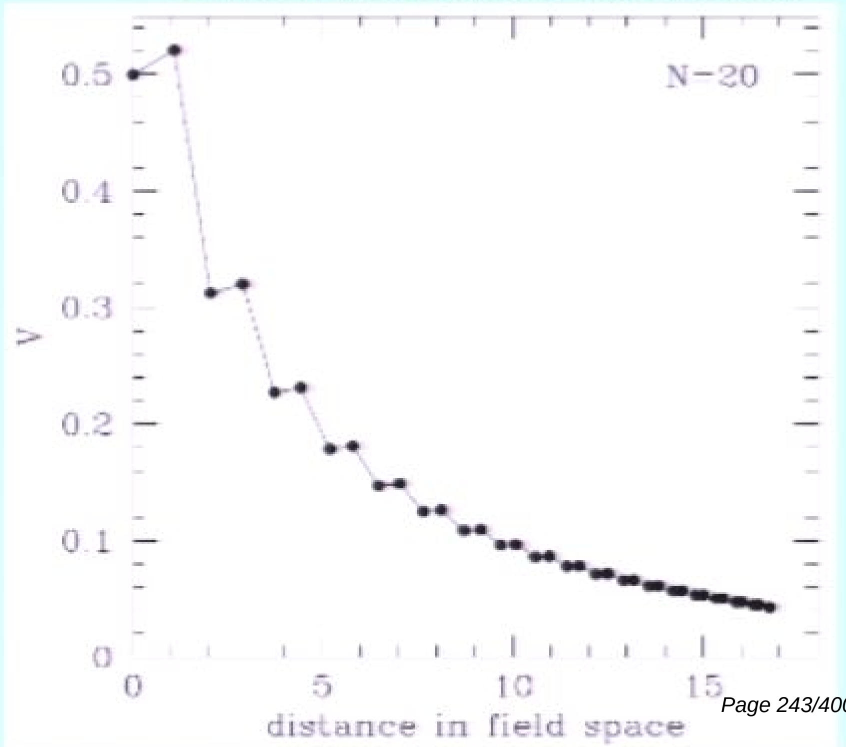
Thus, even if such models are relatively rare across the landscape, the fact that they give rise to infinitely many vacua means that they could completely dominate the properties of the landscape as a whole!



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Is SUSY natural?

This is an important question.

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--- indeed, everywhere except the data.

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- and..., and ..., and...

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

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But is SUSY itself truly natural?

What does it mean to be "natural", anyway?

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

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

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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 heteroric 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

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- 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.

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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...

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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

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$SU_{>5}$	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.

Of course, the interesting phenomenological question is the “inverse” question:

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

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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

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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, ...)
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"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!"

Such work is ongoing.

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

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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.

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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.*

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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!

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- 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.

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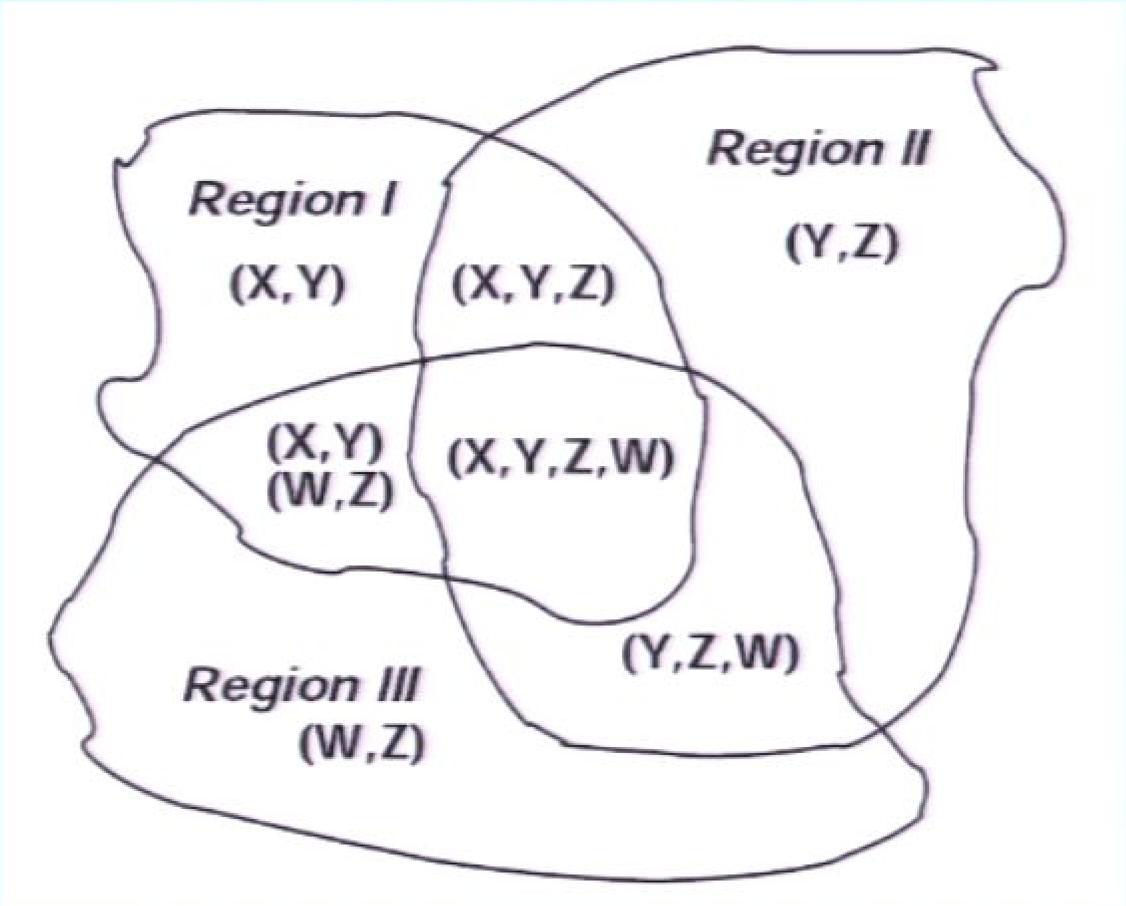
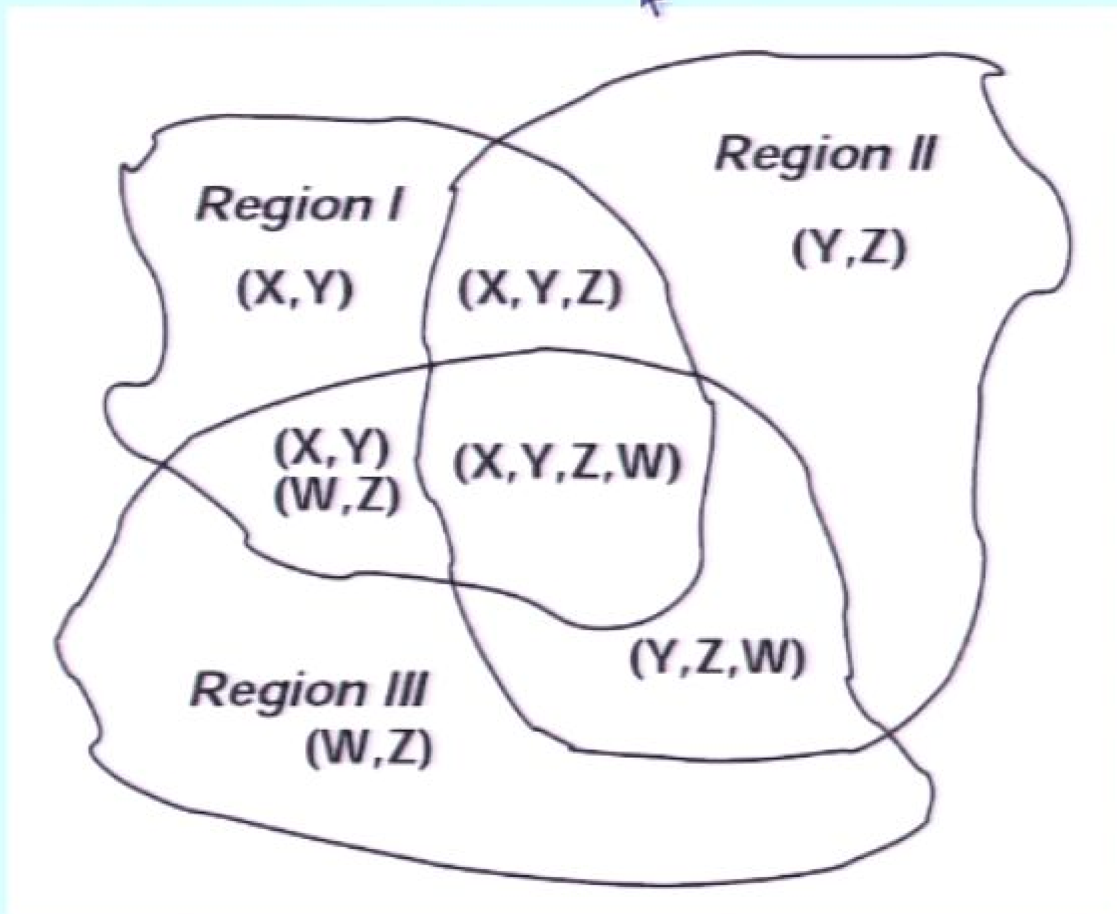
- *Existence* of correlations: predictive
- *Absence* of correlations: non-predictive

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.



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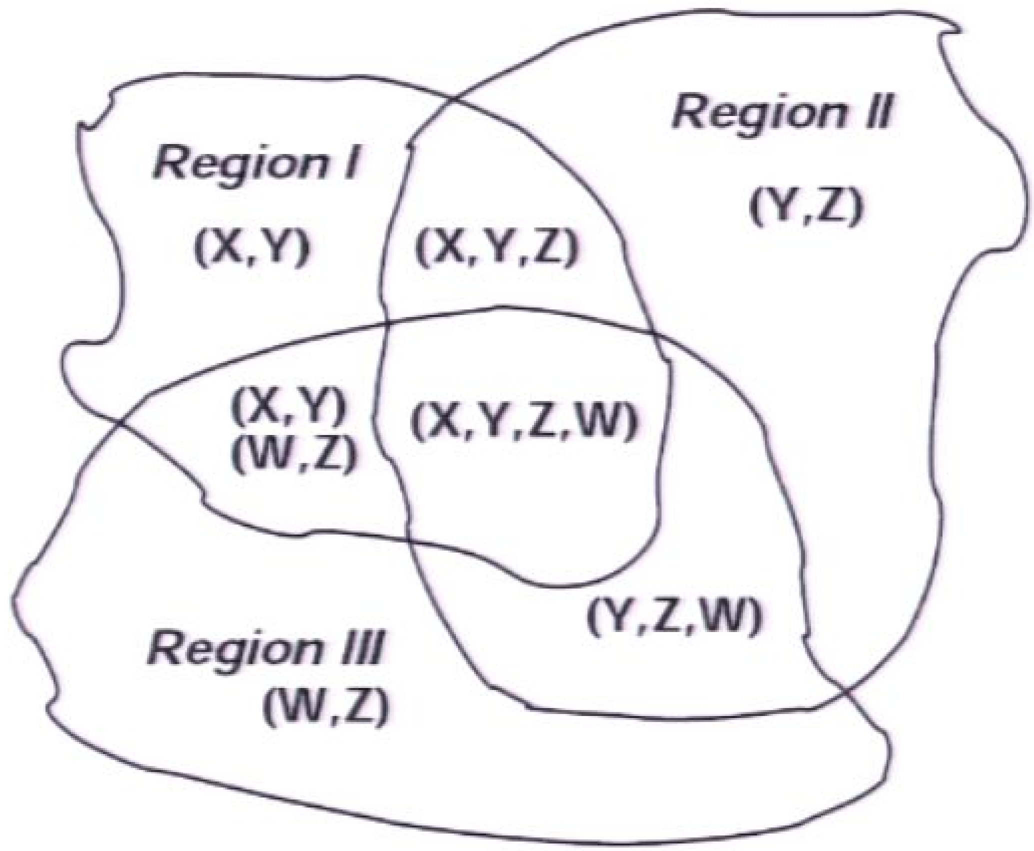
Suppose each region exhibits a correlation between only two physical observables:



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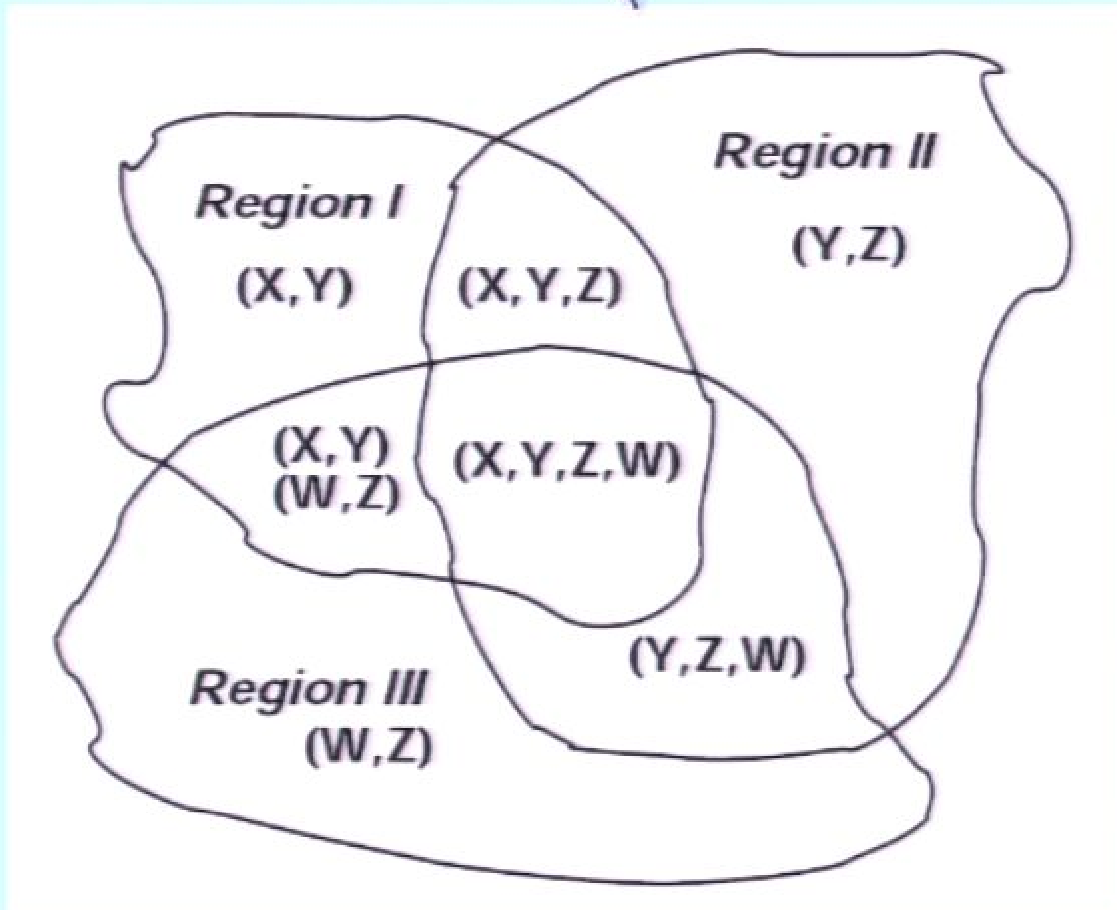
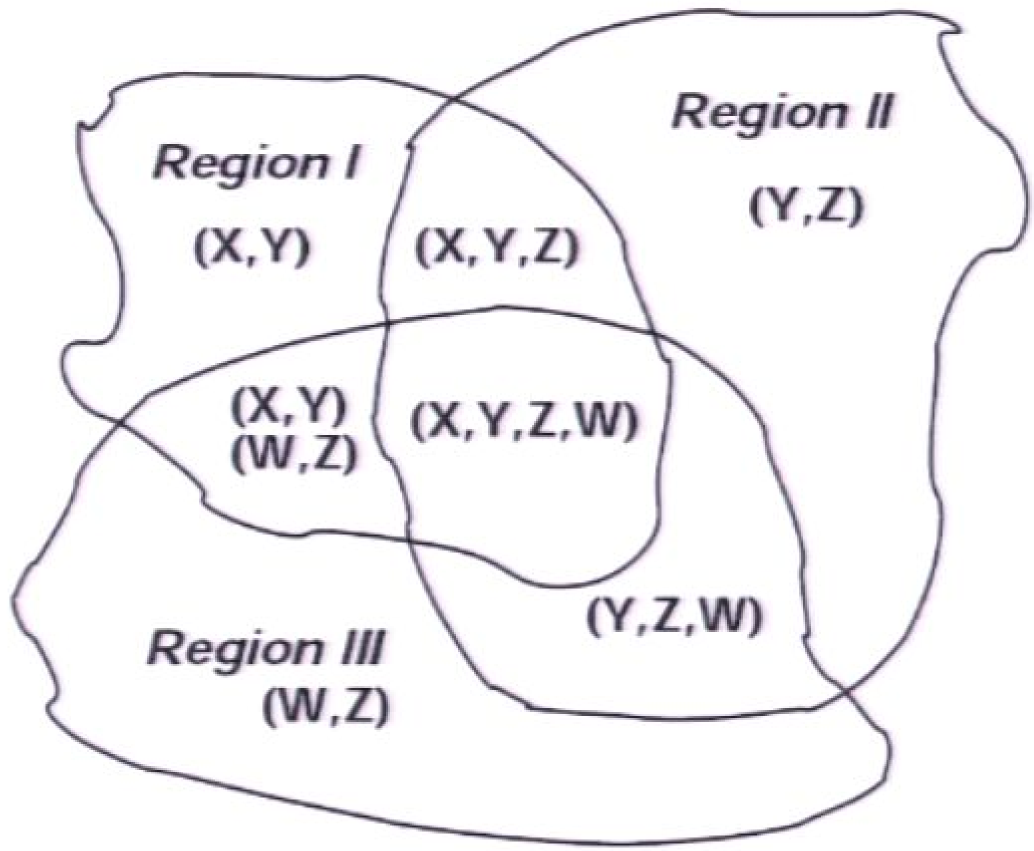


- Region I: Correlation between X and Y
- Region II: Correlation between Y and Z
- Region III: Correlation between W and Z

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



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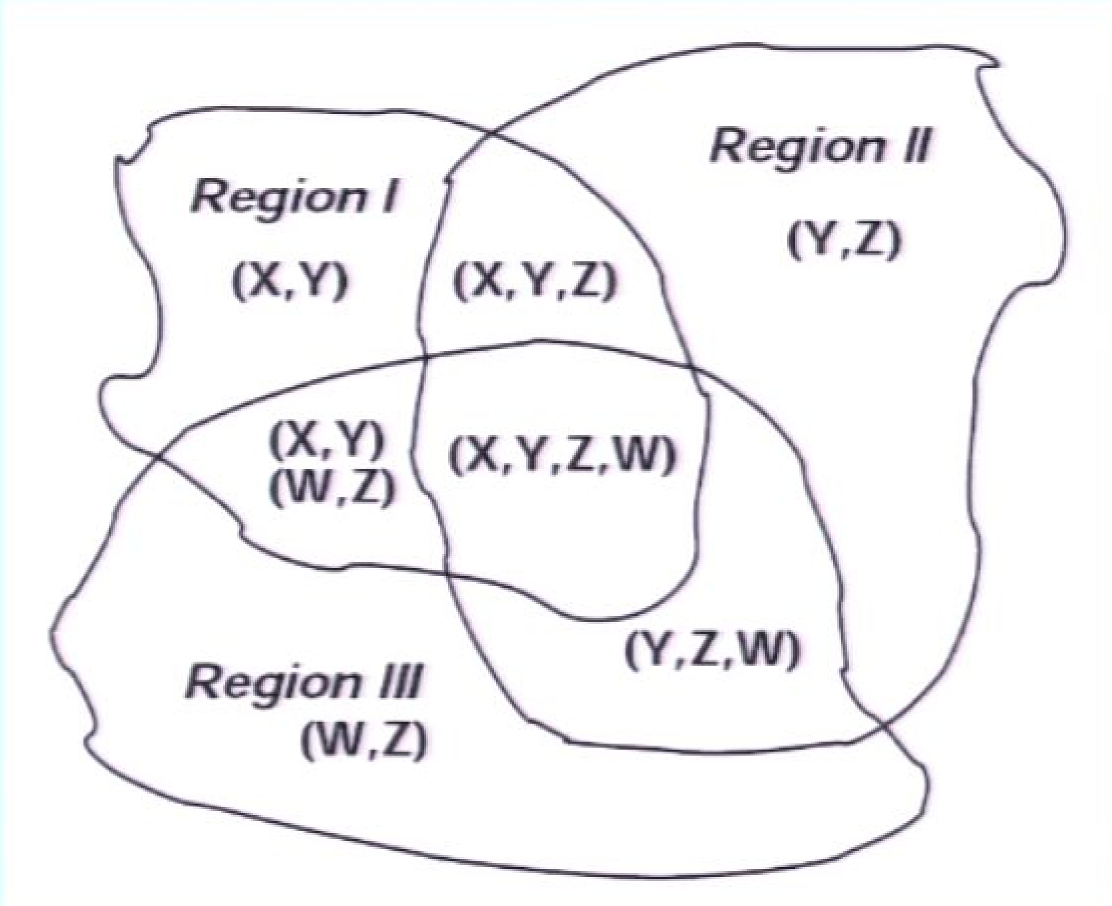
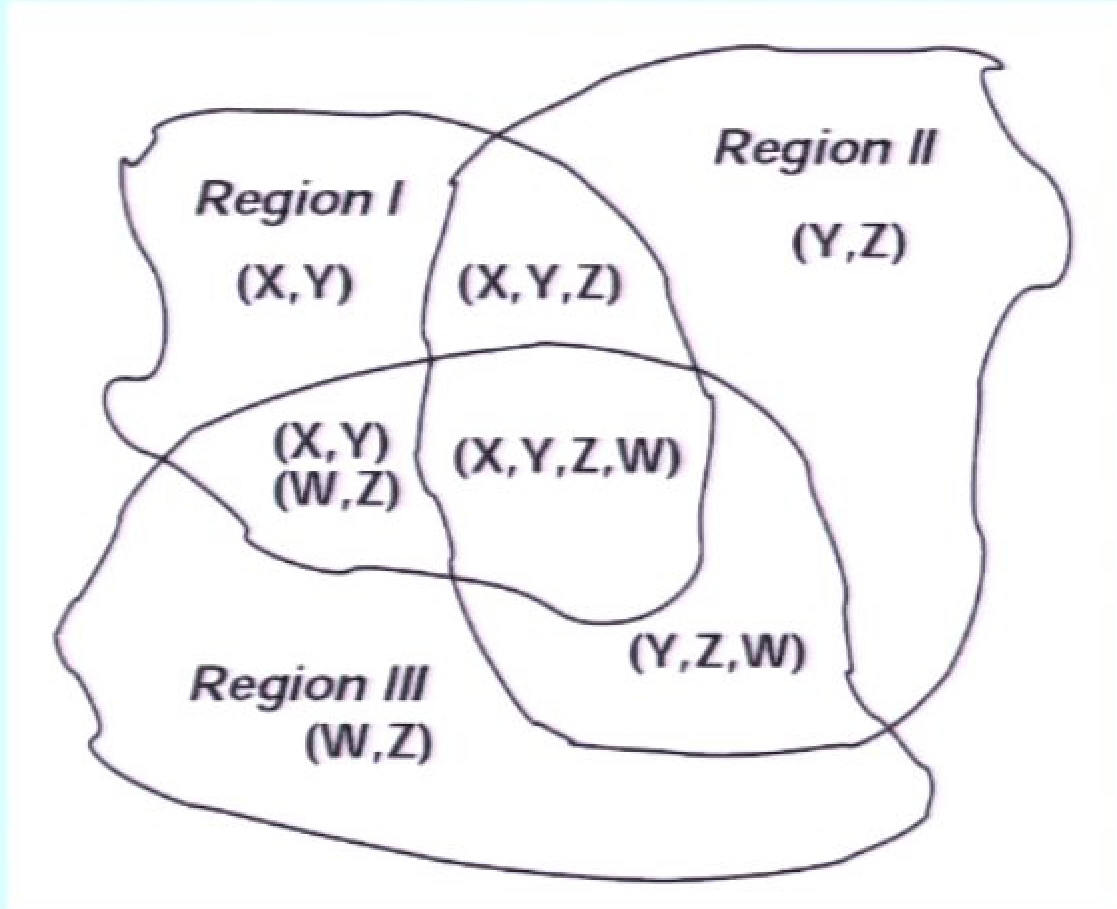


- Regions I & II: Single 3-quantity correlation (X,Y,Z)
- Regions II & III: Single 3-quantity correlation (Y,Z,W)
- Regions I & III: Two 2-quantity correlations (X,Y) and (W,Z)
- Regions I, II, & III: Single 4-quantity correlation (X,Y,Z,W)

Very complex structure!
How then to proceed?



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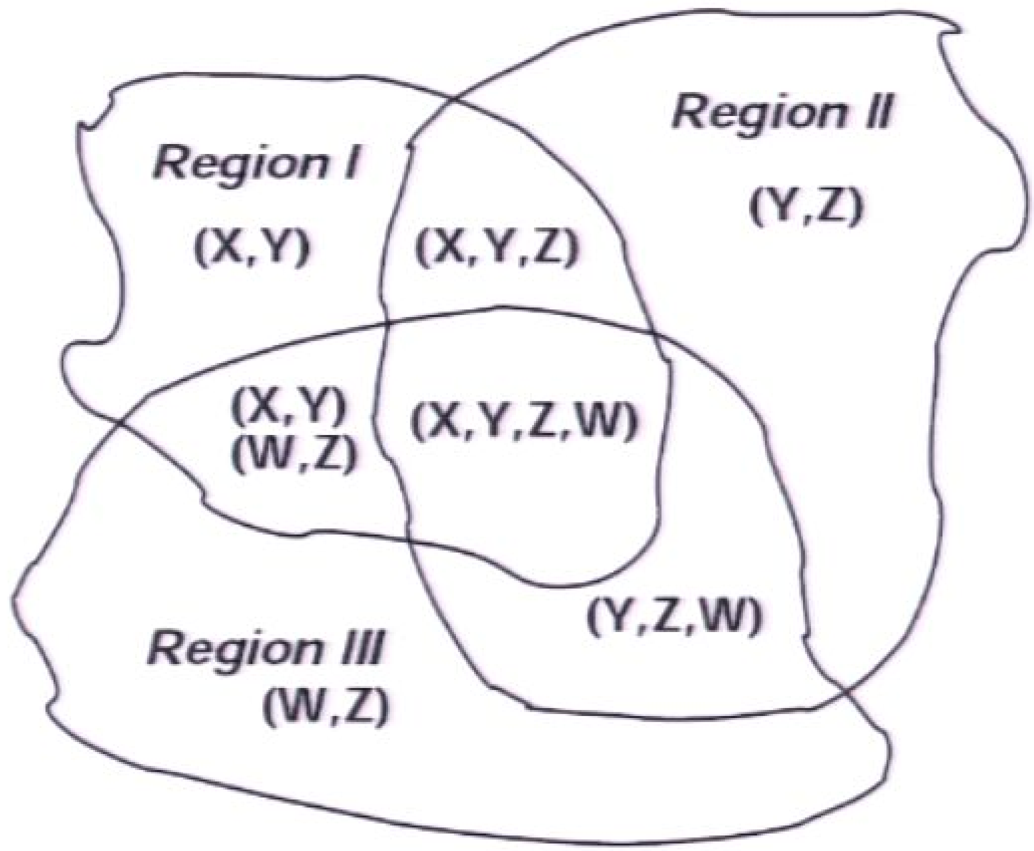

- Need to develop **practical statistical methods** of probing such a non-trivial correlation structure "experimentally" through the random generation and analysis of string models drawn across the landscape as a whole!
- In this way, hope to **develop and quantify a practical notion of "predictivity"**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

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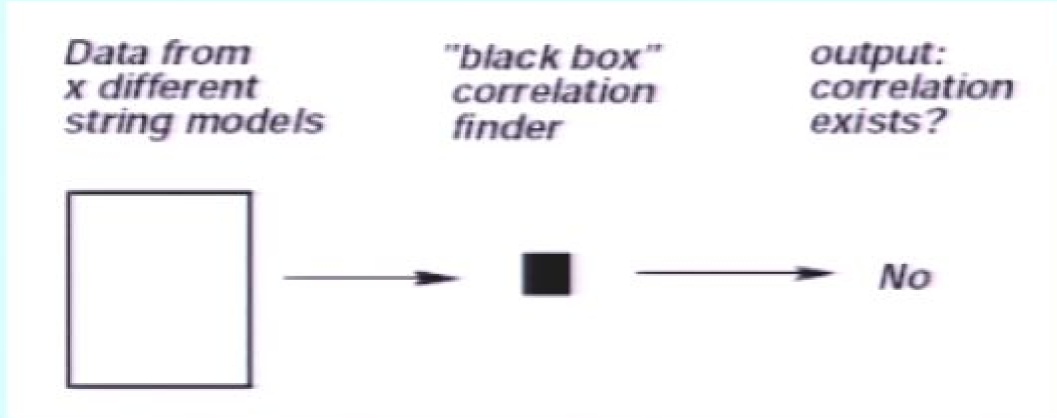

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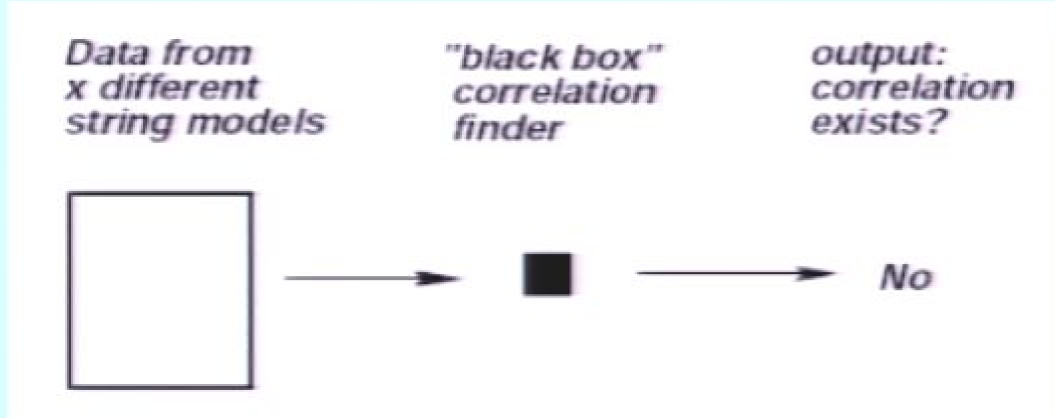
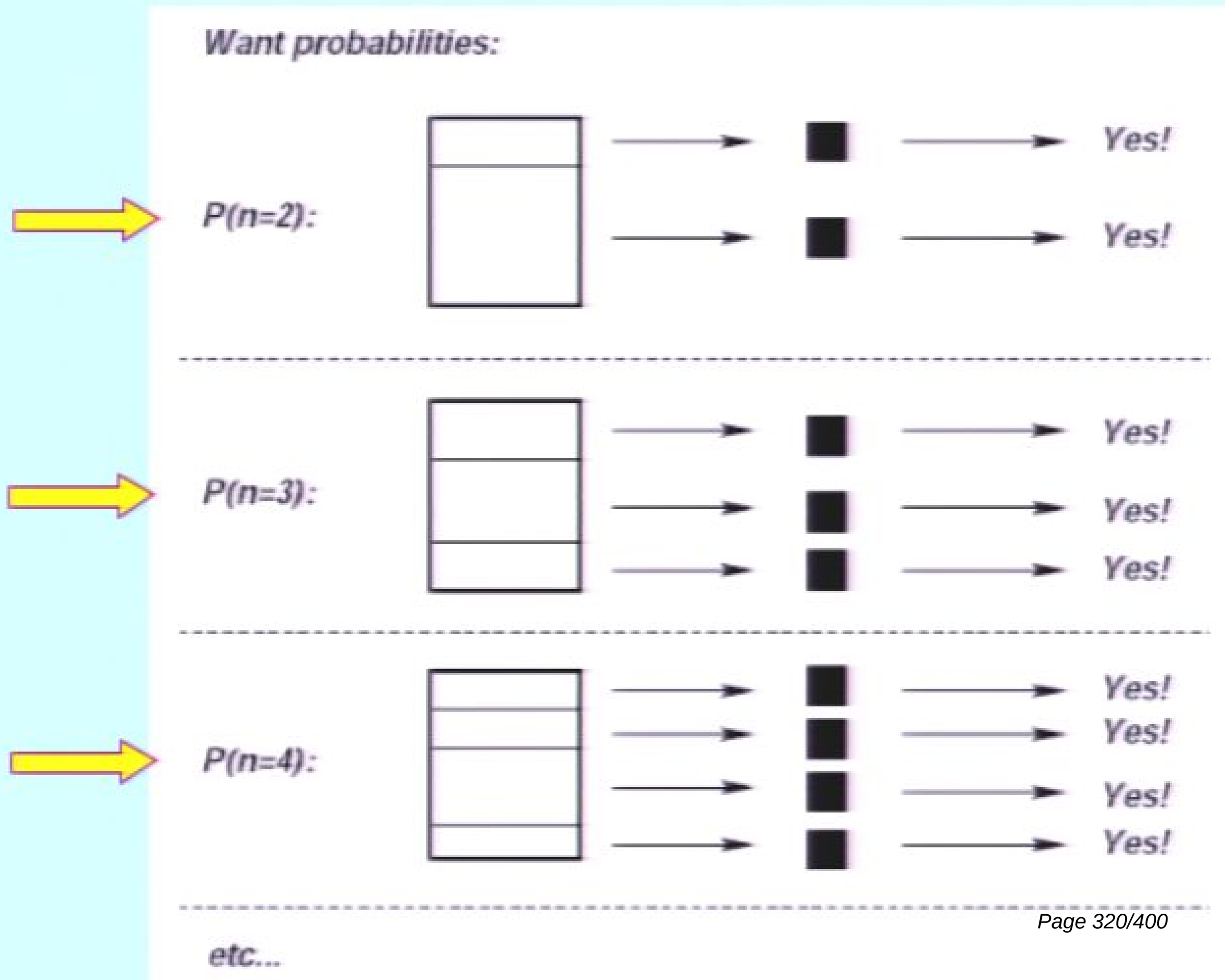


The probabilities $P_x(n)$ are our "experimental" method of probing the correlation-class structure of the landscape and quantifying its degree of predictivity.



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What is the likelihood that a classroom of x kids will have n different birthdates (1 through 30)?

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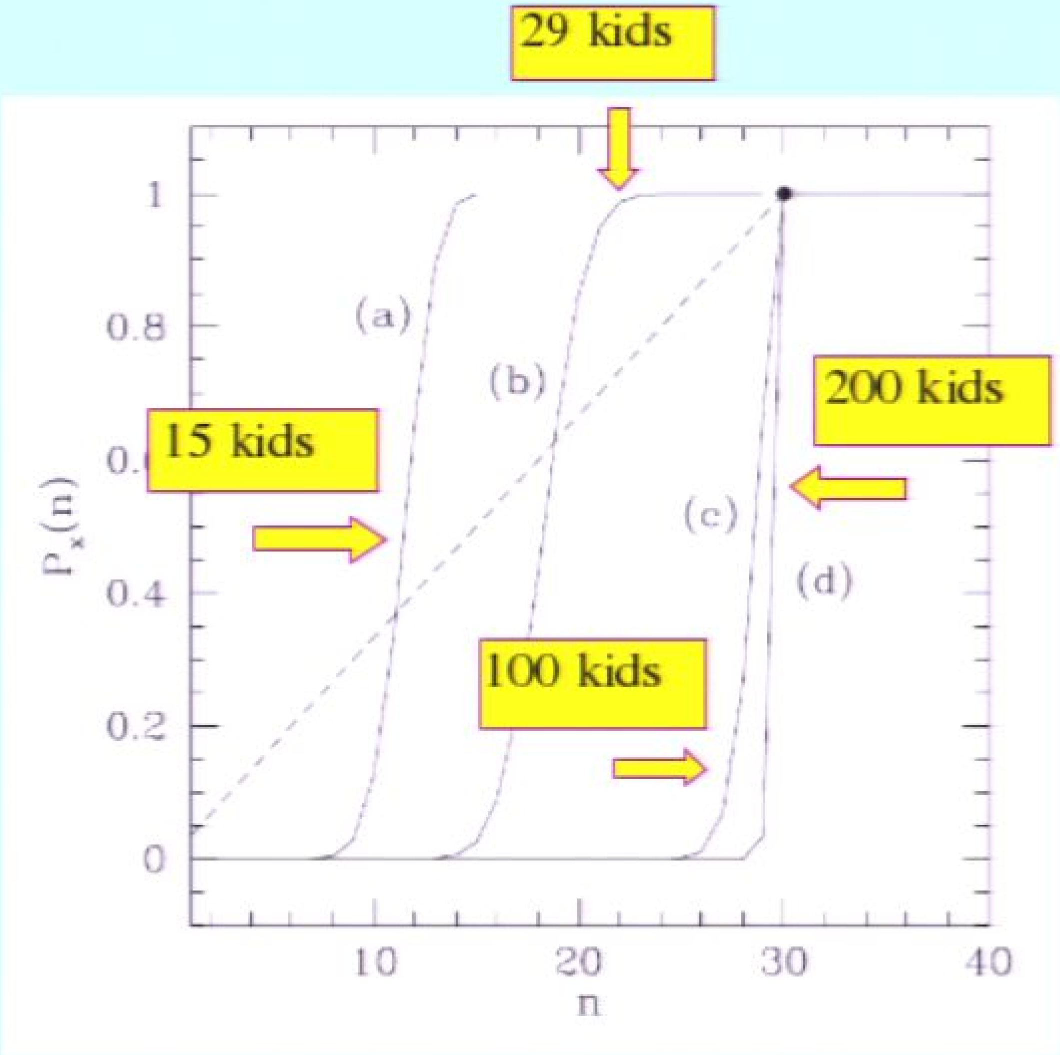
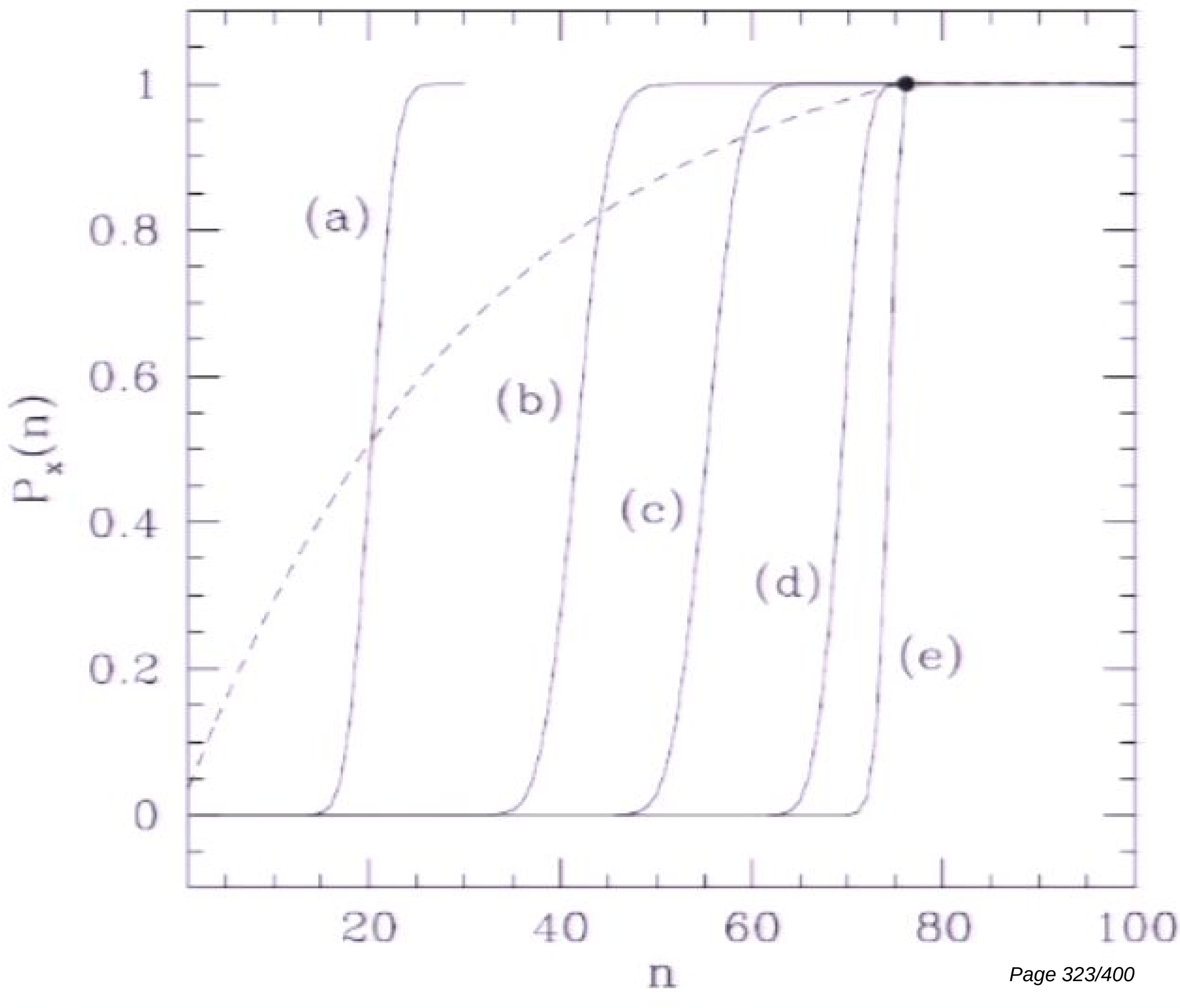
As the number of kids increases, the probability approaches a sharp step-function at n=30.



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.



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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.**

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Welcome to the Multiverse!

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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

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- *Is theoretical particle physics destined to become a branch cosmology?*

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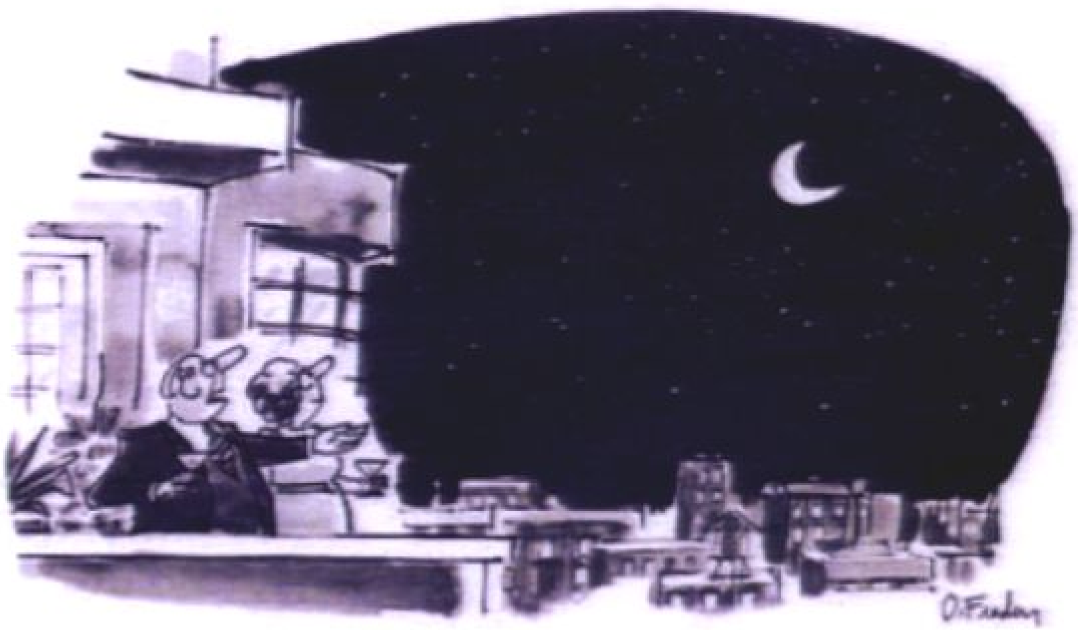

"Do you know why the universe works so well? God runs it like a business, that's why."

The

The Anthropic Principle

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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!)

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The "Star Trek" version

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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.

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

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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).

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- "The anthropic principle is not an *explanation*; it's an *observation*."

Burt Richter
Nobel Prize, 1976
Former Director of SLAC

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"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.

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...

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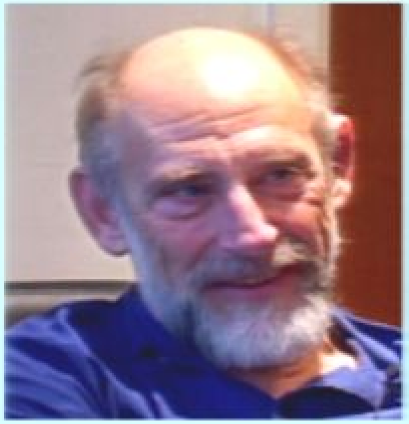

- In the early days of the quark theory, its many opponents dismissed it as unfalsifiable. Quarks are permanently bound together into protons, neutrons and mesons. They can never be separated and examined individually. They are, so to speak, hidden behind a veil. But by now, although no single quark 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.

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- 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.

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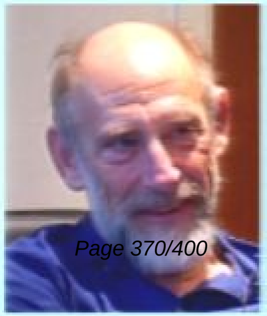
Will it be possible to test eternal inflation and the Landscape? I certainly think so, although it may be, as in the case of quarks, that the tests will be less direct, and involve more theory than some would like."



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... 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?
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- 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

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

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- 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

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

"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

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Albert Einstein Professor of Science
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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

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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.

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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

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