THE STANDARD MODEL,

STRING THEORY

AND

THE ANTHROPIC PRINCIPLE

Based on:

The Emperor's Last Clothes?
Overlooking the String Theory Landscape.

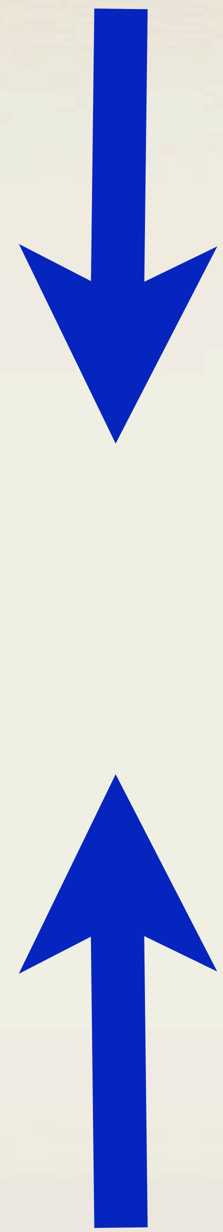
Rept. Prog. Phys. 71:072201,2008. **(20 pages)**

Extended version: **arXiv:0807.3249 (87 pages)**

String Theory

Standard Model

String Theory



Standard Model

"Theory of almost everything"

"Theory of ~~almost~~ everything"

String Theory

↓

↑

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↓

Anthropic Principle

↑

Standard Model

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“Theory of al~~m~~ost everything”

String Theory

↓

Anthropic Principle

David Gross (Strings 2008):
“We all know that it is wrong”

↑

Standard Model

“Theory of almost everything”

Anthropic Principle

What we observe is biased by
our own existence.

Criticisms

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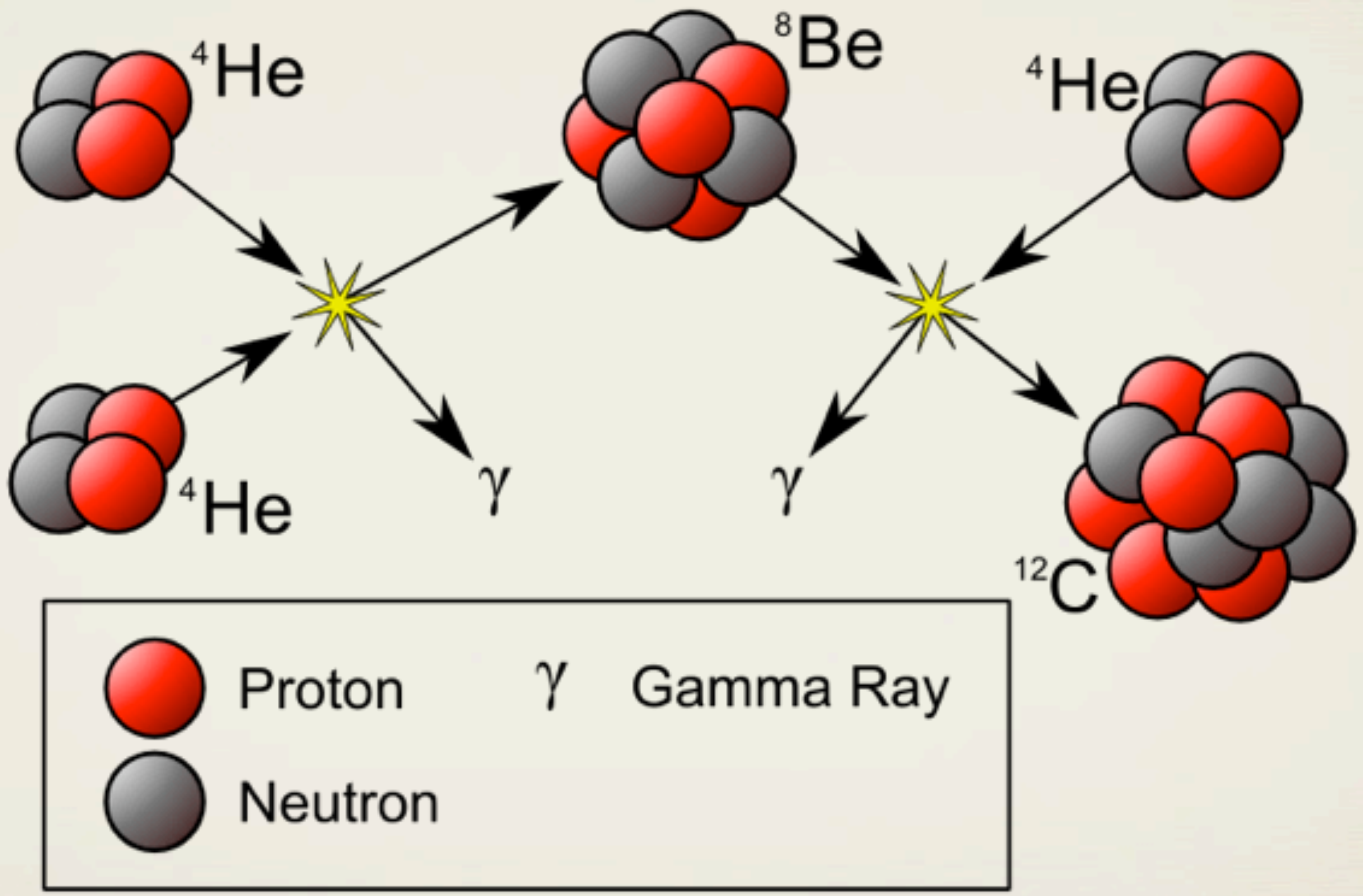
* What is intelligent life? (not just us)
* So what?

Example: The Beryllium Bottleneck



Hoyle: there should exist a carbon-12 resonance near 7.65 MeV.

This prediction was confirmed!

- One cannot vary a level of Carbon while keeping everything else fixed.
- Carbon is essential for our kind of life. But the relevant question is: is it essential for any kind of intelligent life?
  (In this case probably yes.
  But some anthropic arguments rely on special properties of water or DNA.)
- So what?
  Hoyle: "*A common sense interpretation of the facts suggests that a superintellect has monkeyed with physics, as well as with chemistry and biology*"

The Standard Model

Theory of quarks and leptons and their electromagnetic, strong and weak interactions interactions.

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Discrete choices:

Lie-algebra: $SU(3) \times SU(2) \times U(1)$

Quark and lepton Representation:

$$3 \times \left\{ (3, 2, \frac{1}{6}) + (\bar{3}, 1, -\frac{2}{3}) + (\bar{3}, 1, \frac{1}{3}) + (1, 2, -\frac{1}{2}) + (1, 1, 1) + (1, 1, 0) \right\}$$

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Continuous choices: 28 real parameters

(coupling constants, quark and lepton masses, mixing angles)

Feynman about α

There is a most profound and beautiful question associated with the observed coupling constant*, e the amplitude for a real electron to emit or absorb a real photon. It is a simple number that has been experimentally determined to be close to 1/137.03597. It has been a mystery ever since it was discovered more than fifty years ago, and all good theoretical physicists put this number up on their wall and worry about it.*

....

We know what kind of a dance to do experimentally to measure this number very accurately, but ***we don't know what kind of dance to do on the computer to make this number come out****, without putting it in secretly!*

Most variations in Nuclear Physics are invalid because by now we know what really can be varied: The QCD coupling constant and the quark masses.
You can't draw anthropic conclusions if you move "out of physics".

But how can a theory ever be immune to what we do not know yet?

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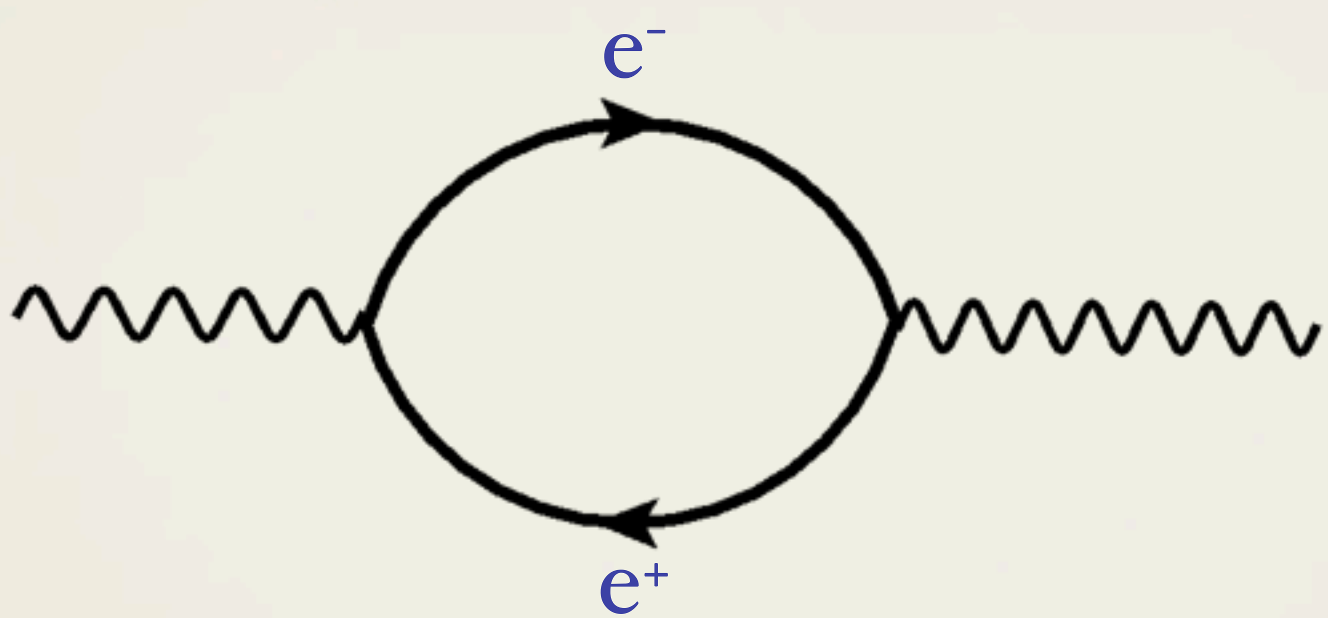

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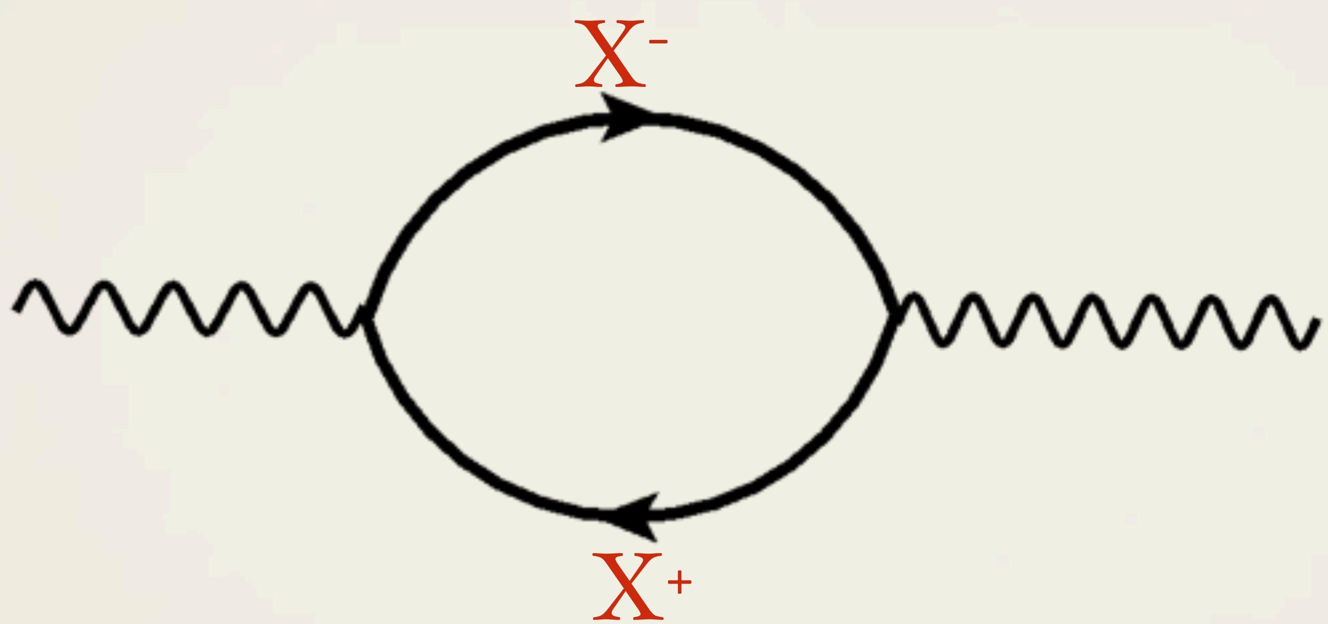

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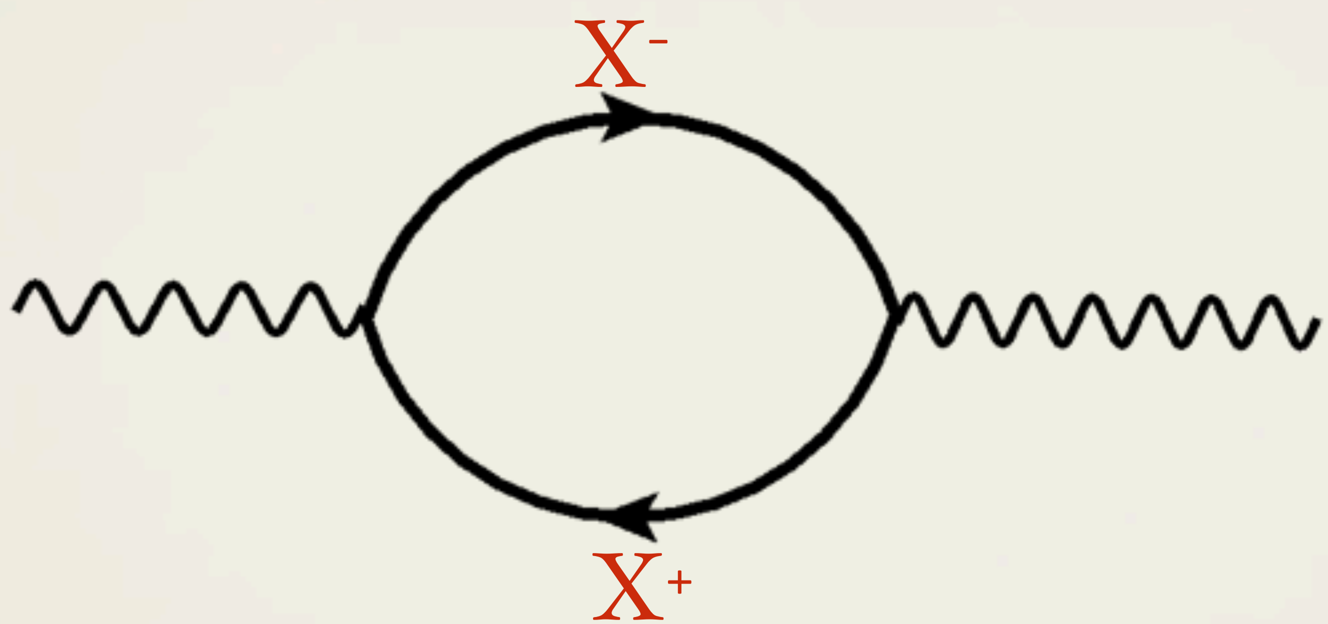


Physics at shorter distances (space-time structure, new particles) gives rise to an infinity of unknowns....

But:

In the Standard Model all these unknowns can be “packaged” together in a finite number of parameters (plus corrections of order E/M_{New}).

This makes the theory intrinsically insensistive to M_{New}

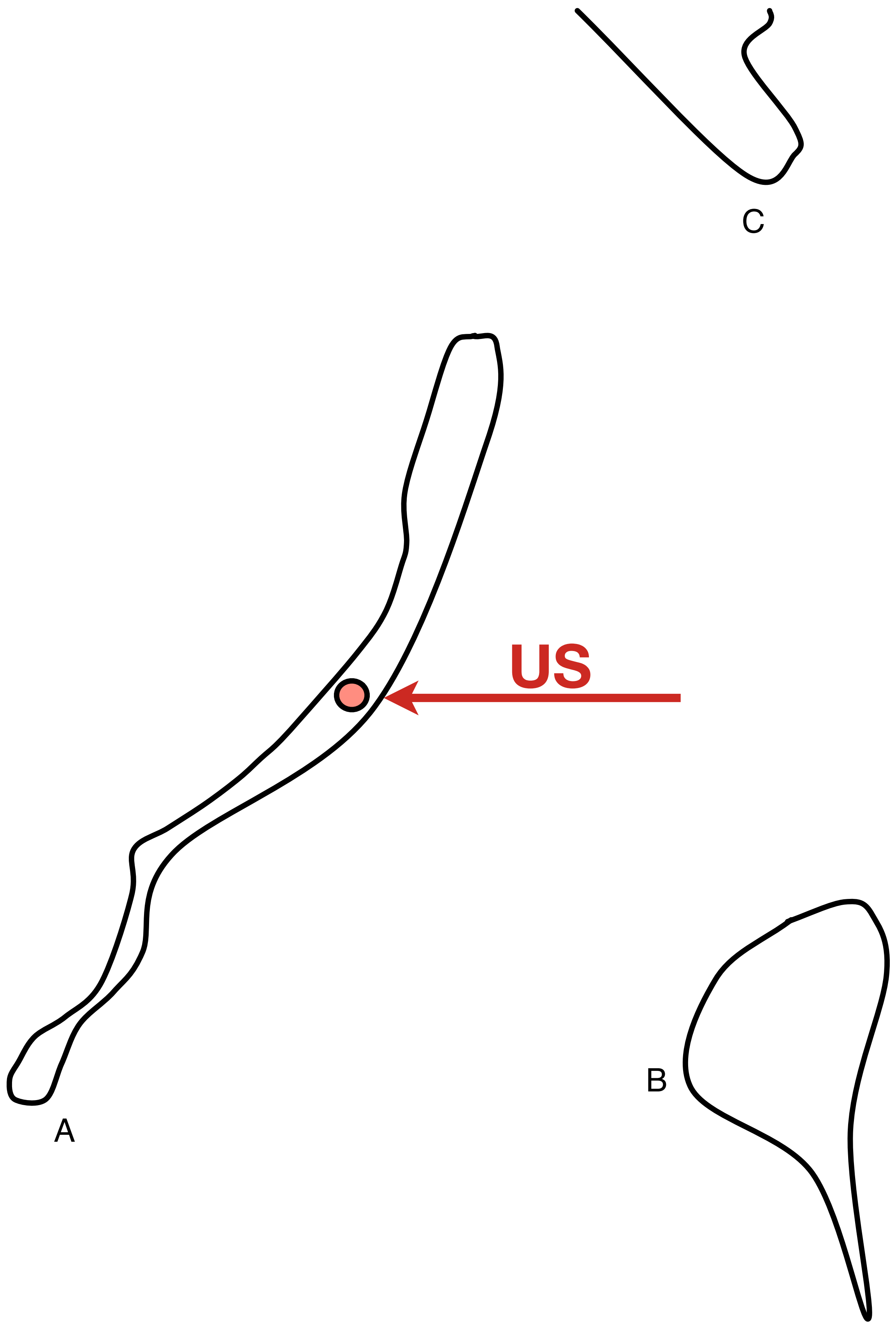
Experimentally M_{New} is at least about 1 TeV, well beyond the scale of Nuclear Physics.

Theoretically, the Standard Model can be extrapolated much further than that, perhaps until $M_{Planck}=10^{19}$ GeV.

Furthermore this is equally true for the relatives of the Standard Model: other gauge theories, with other groups, representations and parameters.

This allows us to do the following:

A “GEDANKEN” COMPUTATION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Anthropic Features
of the
Standard Model

- Structure:
  hard to analyse in general, but:
  - Odd SU(N) “color” group seems essential.
  - U(1) with massless photon seems essential.

- Scales:
  - Strong scale (Λ_{QCD}) determines proton mass.
  - Weak scale determines quark, lepton masses
  - Both must be much smaller than M_{plank} (10^{19} GeV) and not too different from each other.

- Parameters: m_u, m_d, m_e, α, α_{QCD} are clearly important.
  Less obvious: m_t, m_ν

Quark and lepton masses (GeV)

t,c,u (charge 2/3)	b,s,d (charge -1/3)	e,μ,τ (charge -1)
173	4.2	1.777
1.25	0.095	0.106
0.002	0.005	0.0005

Higgs mechanism: Mass = $\lambda \times$ (246 GeV)

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↓ 138	↓ 44	↓ 16
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↓ 625	↓ 19	↓ 206
0.002	0.005	0.0005

Higgs mechanism: Mass = $\lambda \times$ (246 GeV)

Some constraints

- Larger pion mass reduces the range of the strong force, destabilizing nuclei.

$$m_\pi \propto \sqrt{\Lambda_{\rm QCD}(m_u + m_d)}$$

- The proton (uud) should be stable against decay to a neutron (ddu)

$$p \rightarrow n + e^+ + \nu$$

Electromagnetic forces lower the neutron mass with respect to the proton mass. This is solved by the fact that the up-quark is extremely light.

- The neutron should be unstable, to prevent a neutron dominated universe. This limits the electron mass to $m_n - m_p = 1.29$ MeV

A second "gedanken" computation

Early String Theory Expectations: (≈ 1985)

"*The hope is that the constraints imposed on such theories solely by the need for mathematical consistency are so strong that they essentially determine a single possible theory uniquely, and that by working out the consequences of the theory in detail one might eventually be able to show that there must be particles with precisely the masses, interactions, and so on, of the known elementary particles: in other words, that the world we live in is the only possible one.*"

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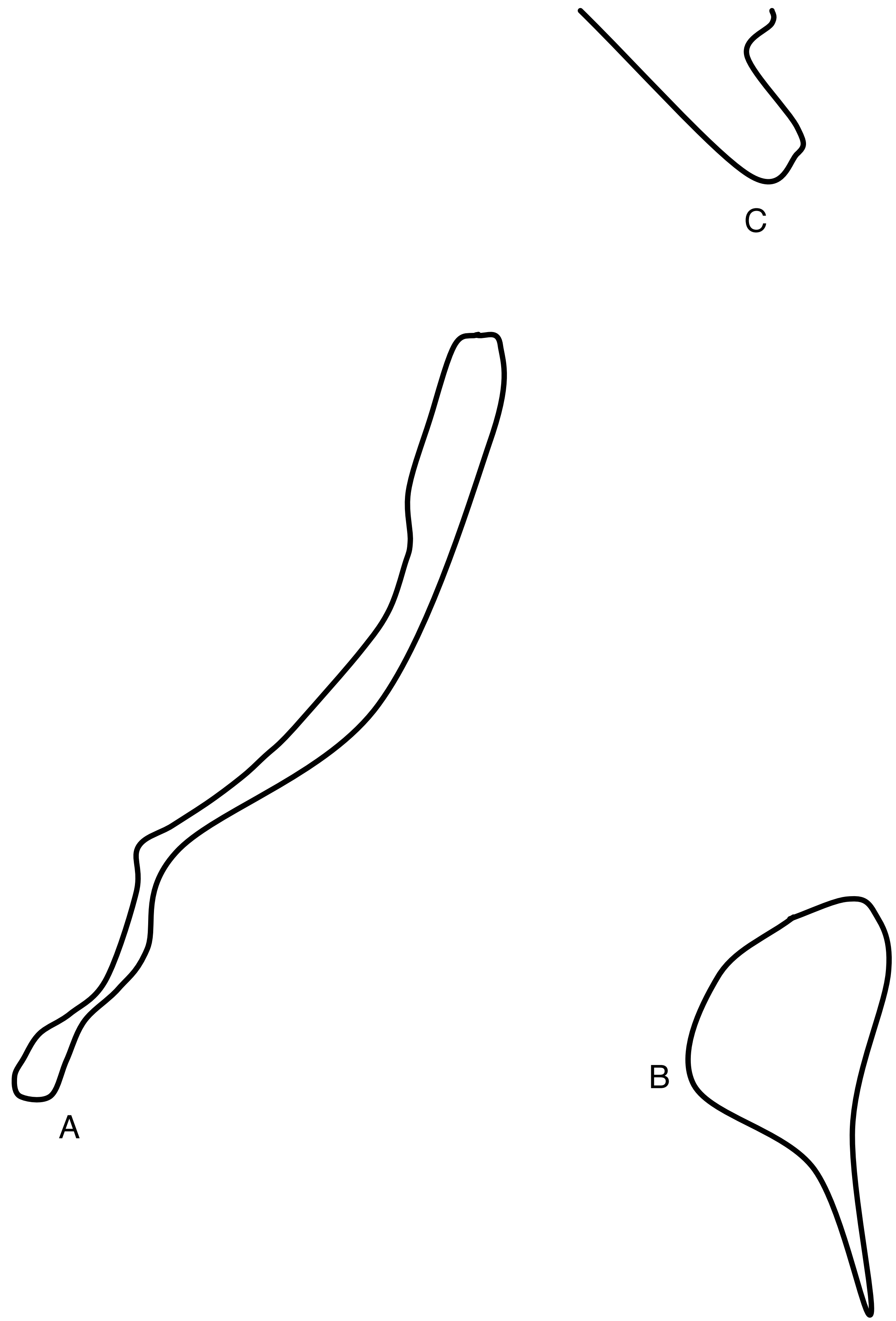
From "The Problems of Physics" by Antony Legget (1987)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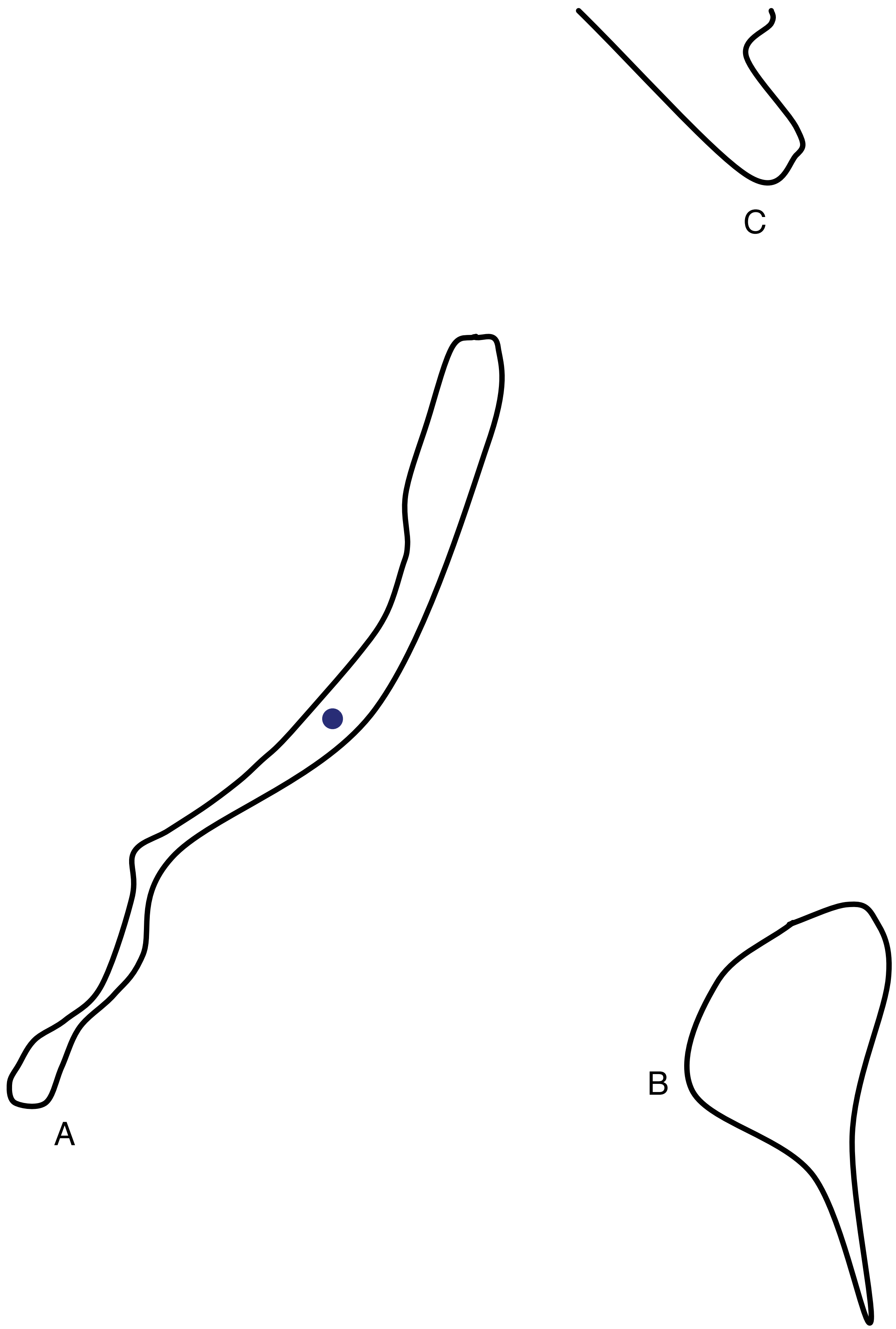
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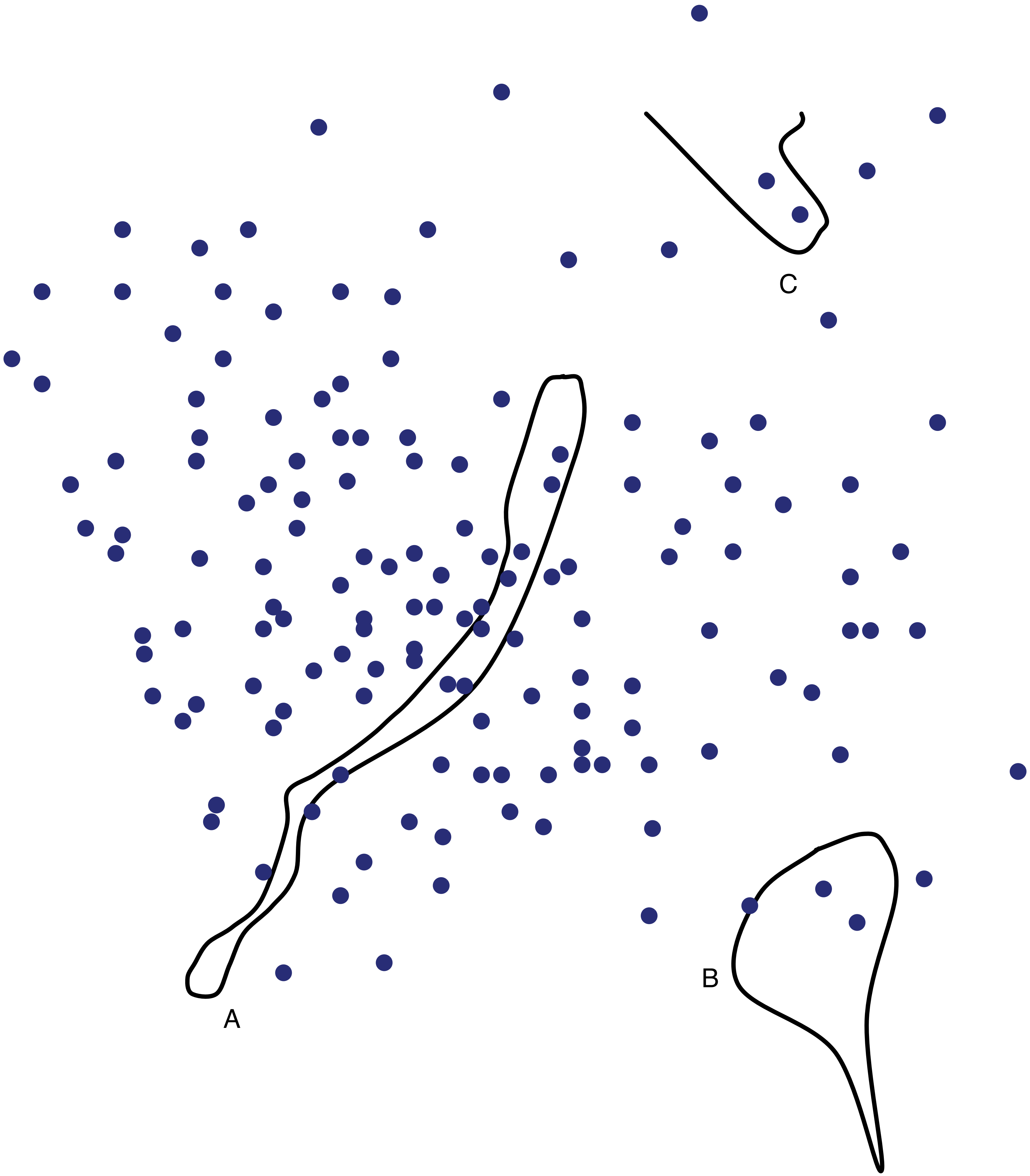
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How many?

From the knowledge of one point, one cannot decide that.

Assuming a distribution one could compute a required minimum number.

But let us have a look at the other side of the argument...

H. Georgi,
Fourth workshop on Grand Unification, Philadelphia,1983

Arguments in favor of uniqueness

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Grand Unification?

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

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$SU(5)$

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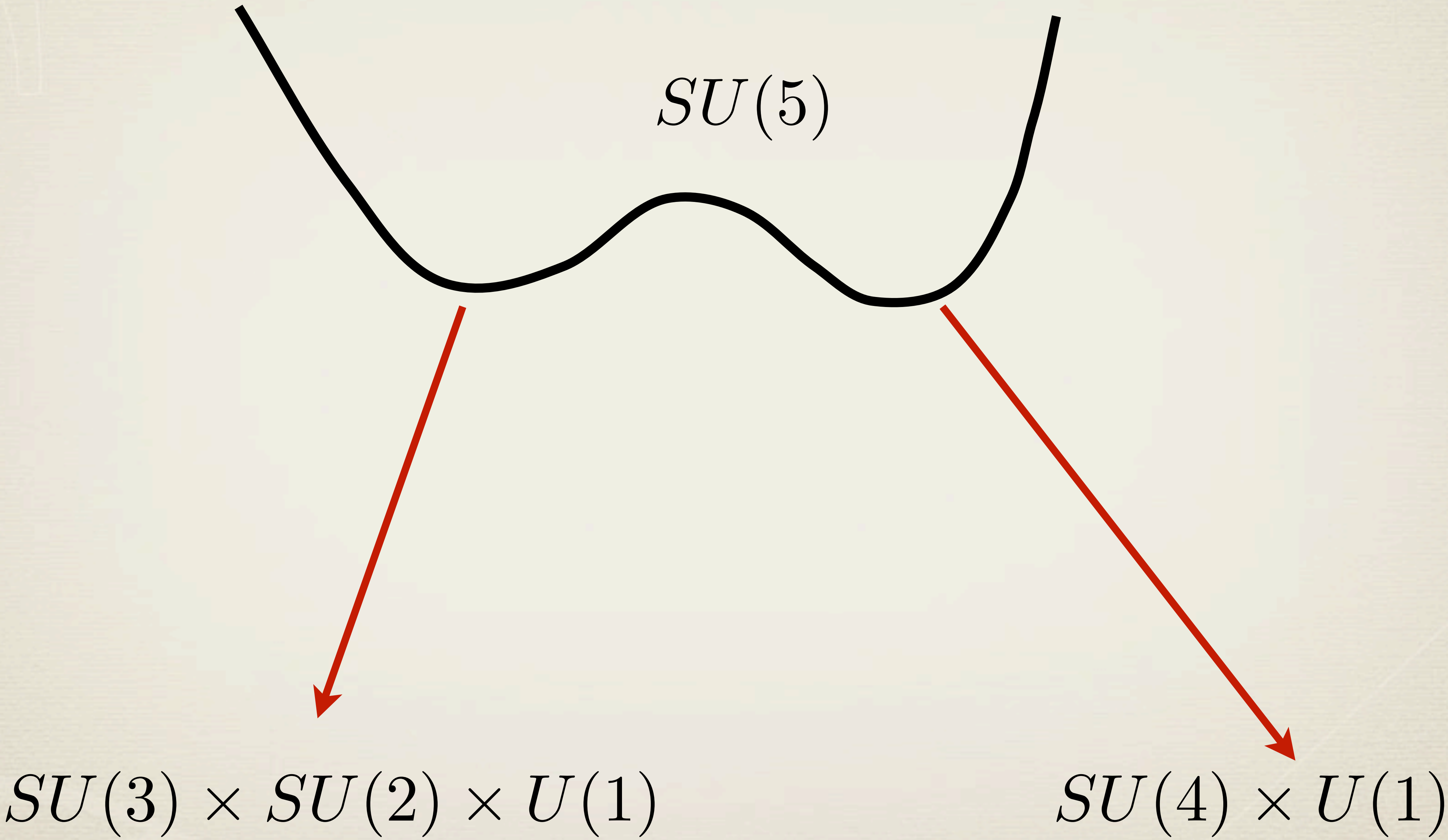

Uniqueness?

* The Standard model is just one point in a huge discrete and continuous set.
* We can observe only one point in this set anyway.
* There is no argument why the "fundamental equations" should have a unique "solution".
* The one we observe does not look mathematically unique.
* The one we observe seems tuned to allow us to exist: uniqueness would be a disaster!

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If not unique, then how many?

We have no principle to tell us how many solutions there should be.

Giving up?

To some people this sounds like:
"*The laws of physics are the way they are, because otherwise we would not exist. Therefore physics stops here.*"

If parameters like the light quark and lepton masses have a distribution of possible values, this is likely to be true for all standard model parameters.

But this does NOT imply that the Standard Model is nothing more than a bunch of random numbers. There is structure requiring an explanation, but we cannot expect to derive the entire set of choices.

All this does is define reasonable expectations for a "fundamental theory". I am not giving up on that.

In fact, I am aiming for something much better than uniqueness: a theory that contributes to the explanation of our existence, rather than converting that into an eternal mysterious coincidence.

SO WHAT?

The Ideal Theory

Example: 10^{30} discrete points
The Standard Model provides about 80 digits of data.

This leaves about 50 digits worth of *post*dictions
(plus an infinity of *pre*dictions).

This is more than enough to accept the correctness of such a theory, together with the existence of the 10^{30}-1 other "solutions".

It would be obvious that what we observe is biased by our existence (unless all 10^{30} points allow observers).

This anthropic principle would be equally unquestionable as the one for planets.

The difference is that for planetary properties we already have good theories and models, and we can observe alternatives. In such a situation an anthropic principle is only of secundary importance.

Requirements for an Ideal Theory

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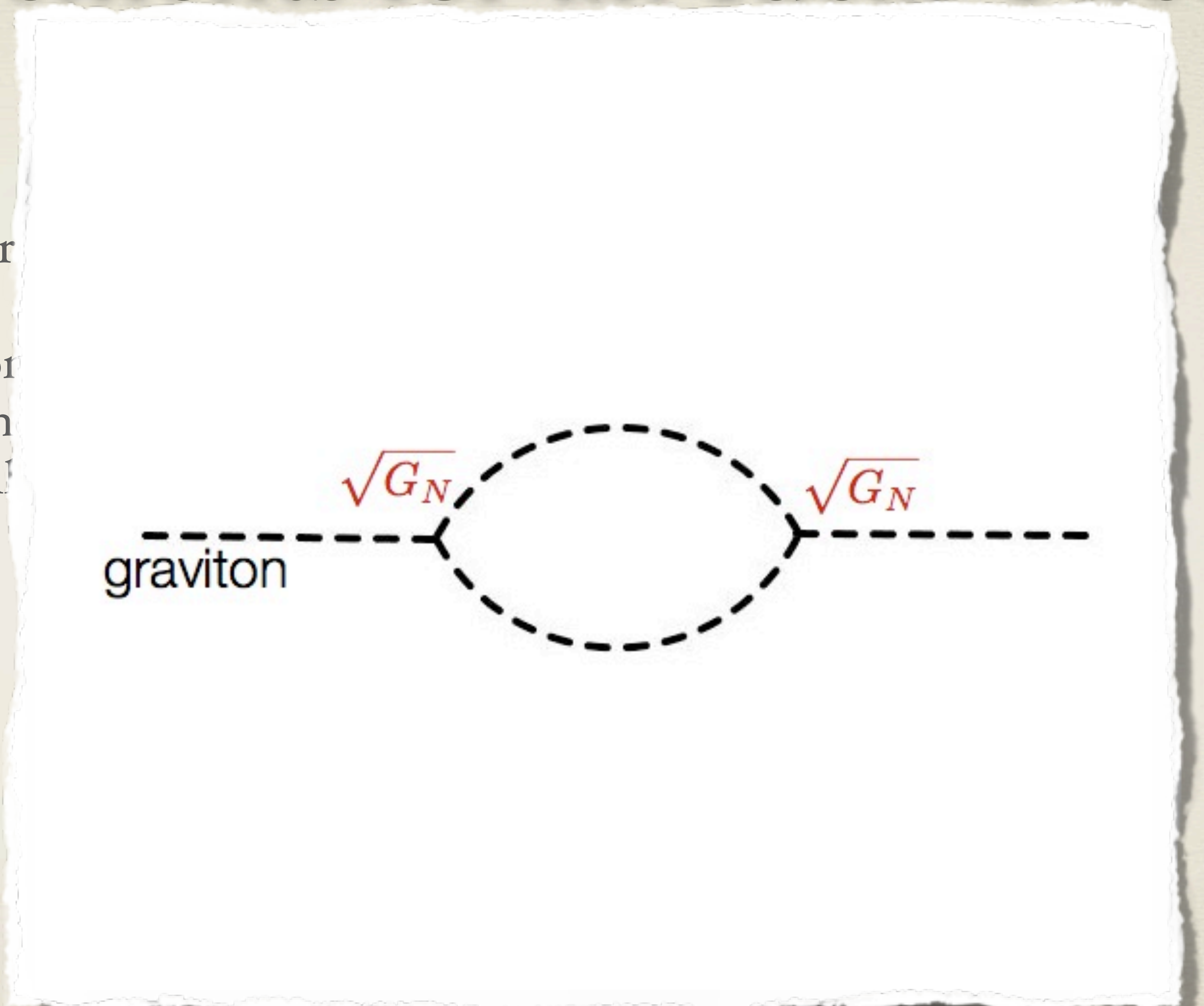
* All parameters should be fixed to some discrete set.

  - We must control all virtual processes ("infinities" of QFT)
  - Including those of quantum gravity.
  - Including all particles we have not observed yet, and all interactions

Requirements for an Ideal Theory

- All parameter

  - We must co
  - Including th
  - Including al



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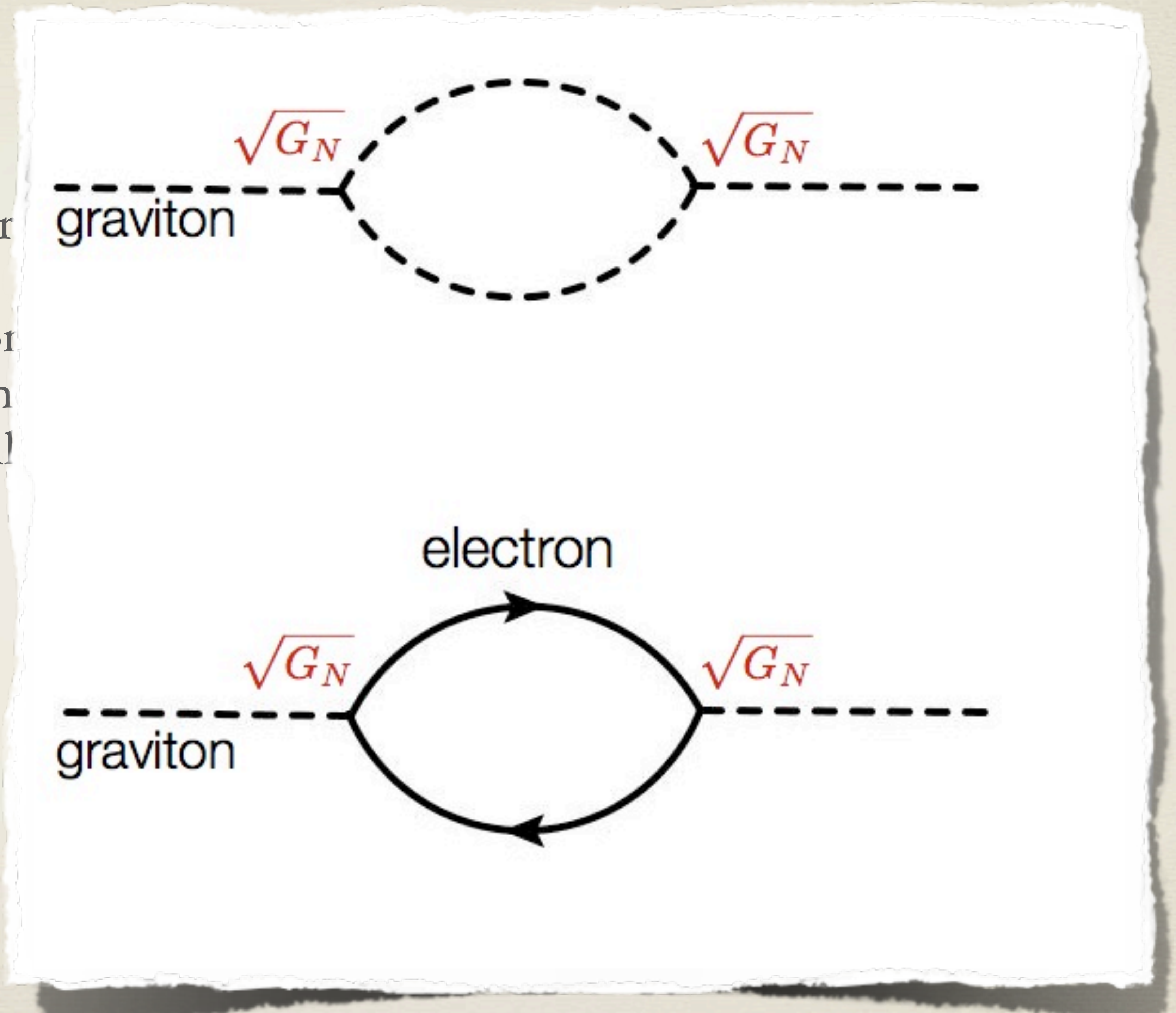

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- For each such discrete choice, there must be set of allowed parameter values.

- Distinct solutions must be connected: we must be able to get to the standard model.

Dynamical Parameters

If we ignore the problems of quantum gravity, perhaps 28 continuous parameters is all we need. This will certainly contain the Standard Model.

However, in QFT there is no relation between QED with $\alpha=1/137.039$ or $\alpha=1/140$.

Possible solution: make all parameters dynamical (functions of space-time satisfying equations of motion).

This forces us to think about vacuum energy: changes in parameters will create changes in the energy of the vacuum.

This is irrelevant in QFT, but also uncalculable (sum over the ground state energy of an inifinite number of oscillators). We may regulate it and subtract it for a given value of α, but this is not likely to be correct for a different value of α.

In the presence of gravity, it is no longer irrelevant. However, in the theory we are aiming at, it would be calculable.

Unfortunately, the answer is not likely to be correct.

The Cosmological Constant

Vacuum energy contributes to the infamous cosmological constant Λ

Gravity couples to it:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

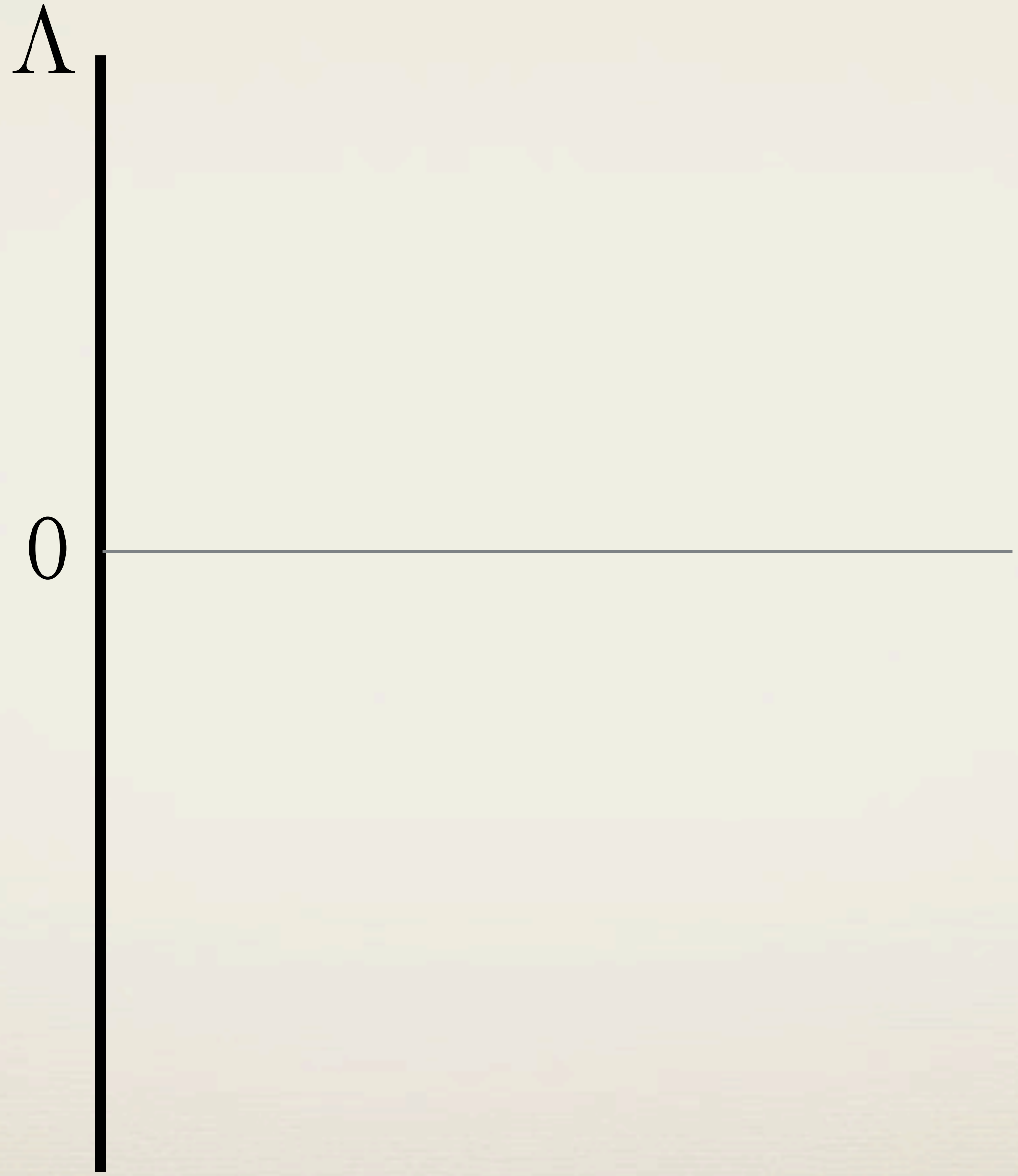
Its effect is to make the universe expand ($\Lambda > 0$) or collapse ($\Lambda < 0$)

Expected contribution from quantum gravity: $\approx (M_{planck})^4$

Expected contribution from known physics: $\approx 10^{-56}(M_{planck})^4$

Observed: $\approx .37 \times 10^{-121}(M_{planck})^4$

Anthropic Bounds



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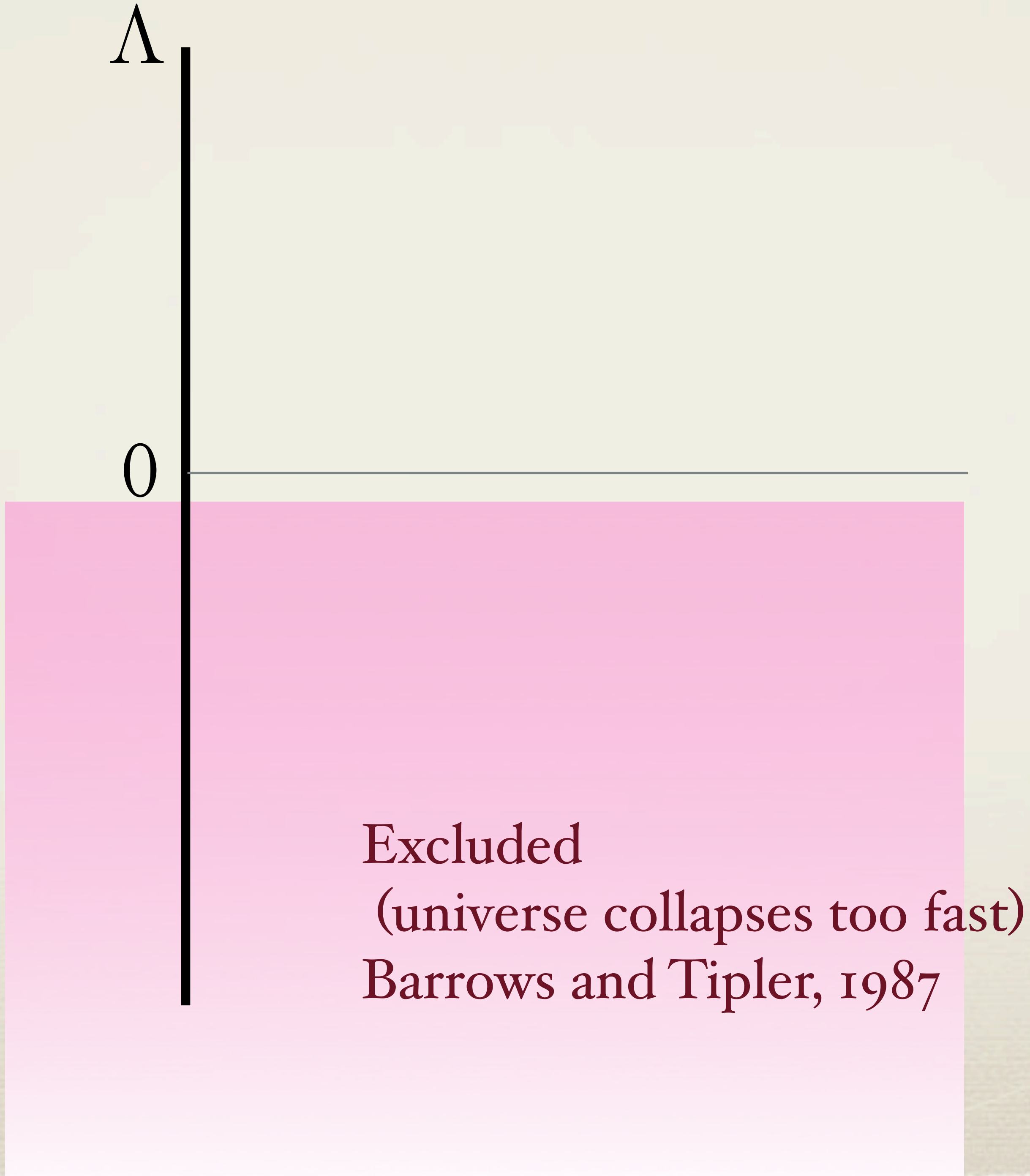

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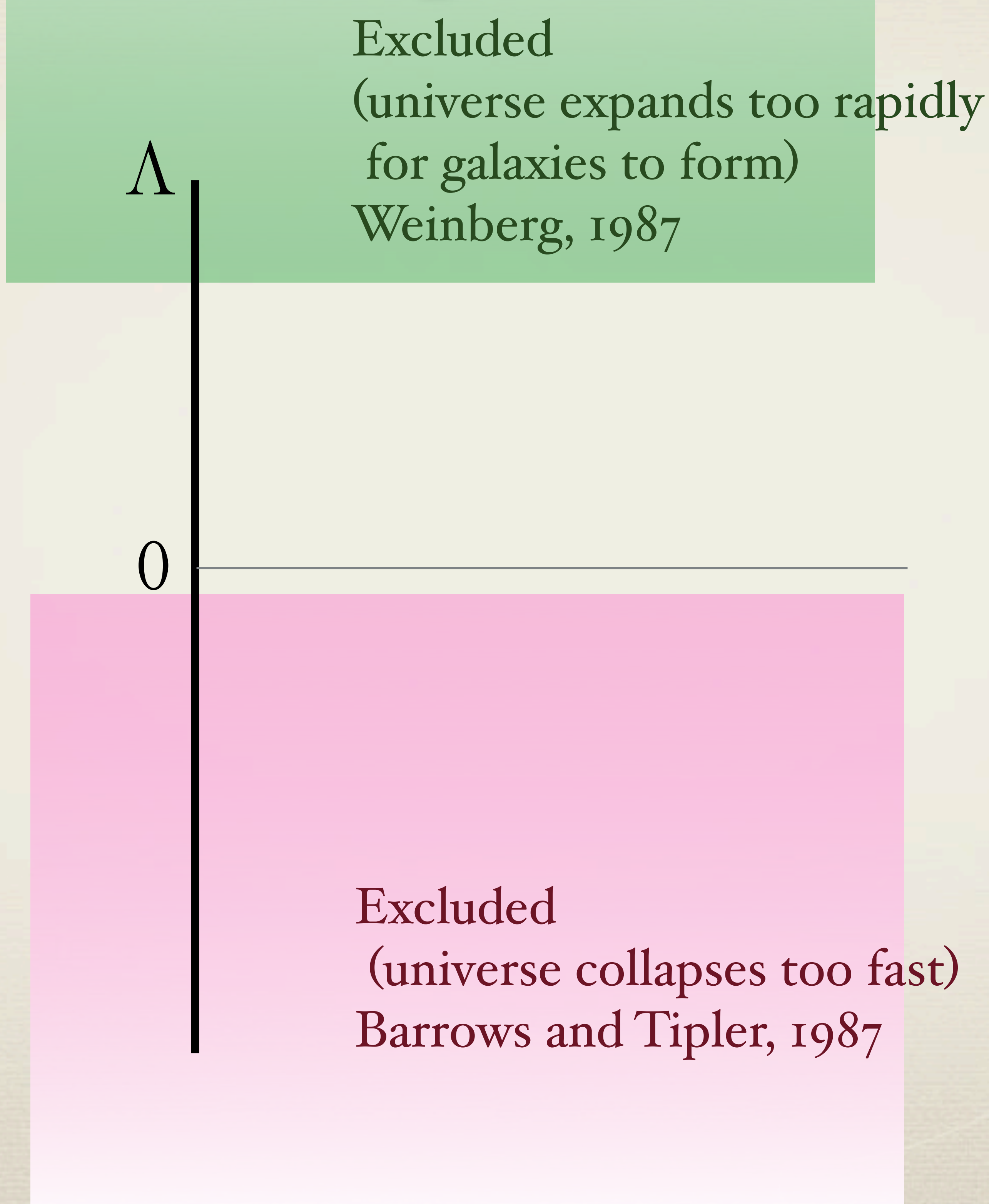

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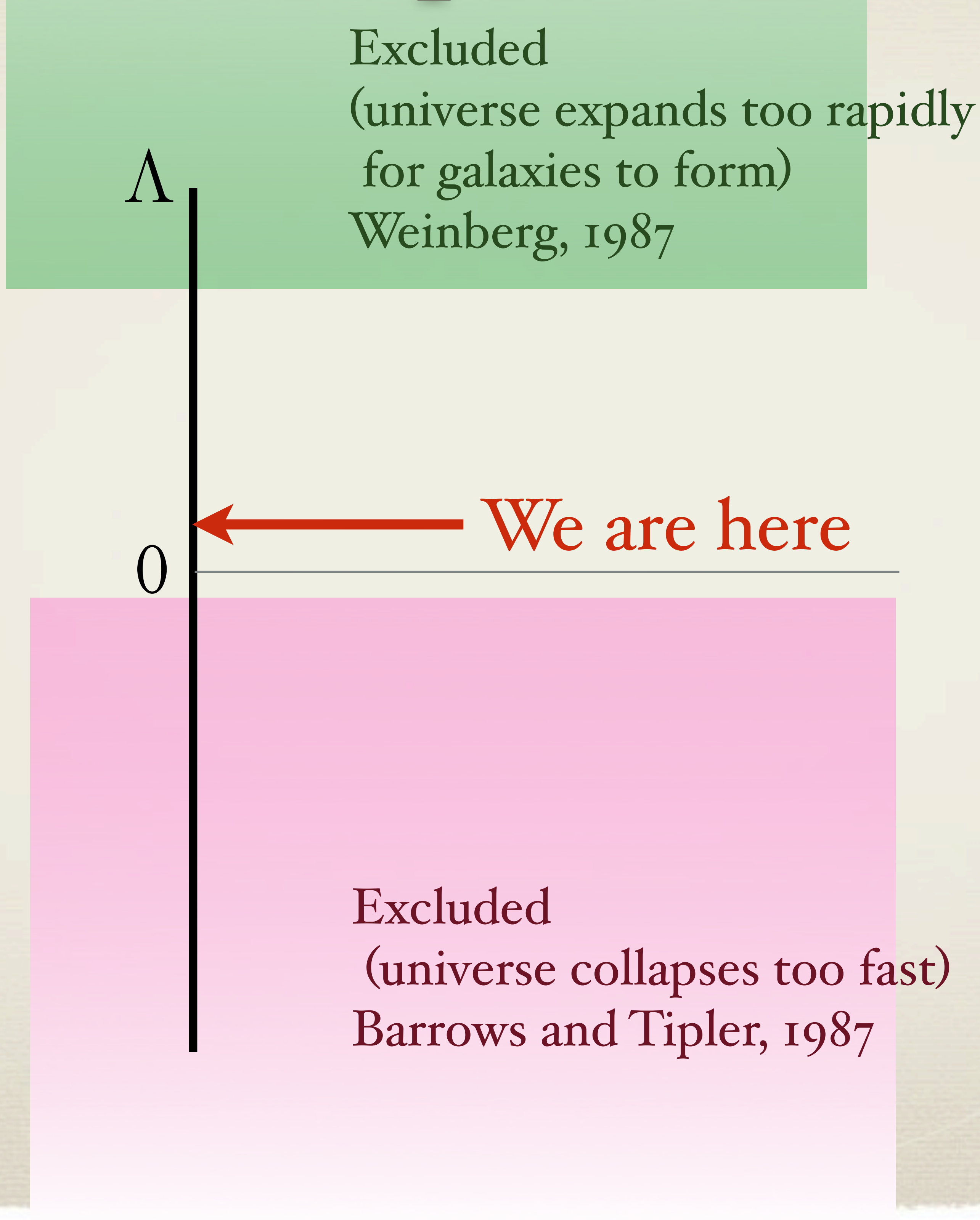


C.C. versus S.M.

An anthropic explanation requires more than 10^{120} points, assuming a flat distribution.

But:
Λ is less obviously a true variable of the laws of physics than the 28 standard model parameters.

The latter are clearly decoupled from what we do not know yet: gravity.

But Λ only makes sense in the presence of gravity.

So if in the true theory of gravity of our universe $\Lambda\equiv 0$ (or if gravity does not couple to vacuum energy), we are "out of physics" if we consider $\Lambda\neq 0$.

Of course, in that case we still have to find a way to explain the current observations.

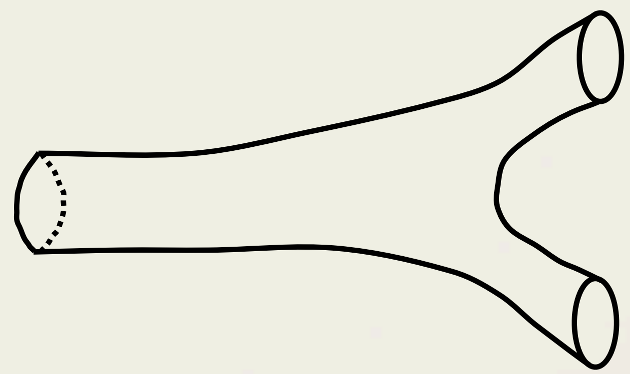
STRING THEORY

Disclaimer

String theory is “work in progress”.
It slowly being discovered using an amazing web of perturbative an non-perturbative methods.

Some of the perturbative methods involve splitting and joining of strings, hence the name.

H_0



εH_1

What follows is the picture that seems to be emerging.
There are plenty of things we do not know yet!

What is string theory?

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H_0

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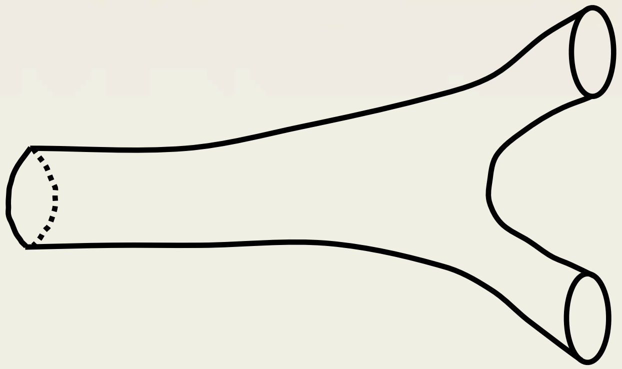

εH_1

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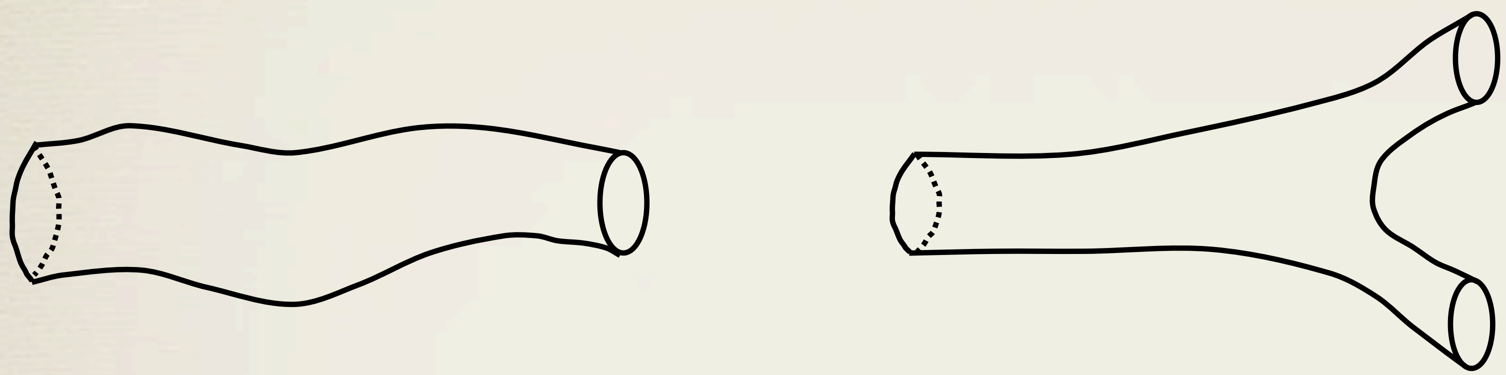

$$H_0 \quad + \quad \varepsilon H_1 \quad + \quad \cdots\cdots \quad \Rightarrow \quad ?$$

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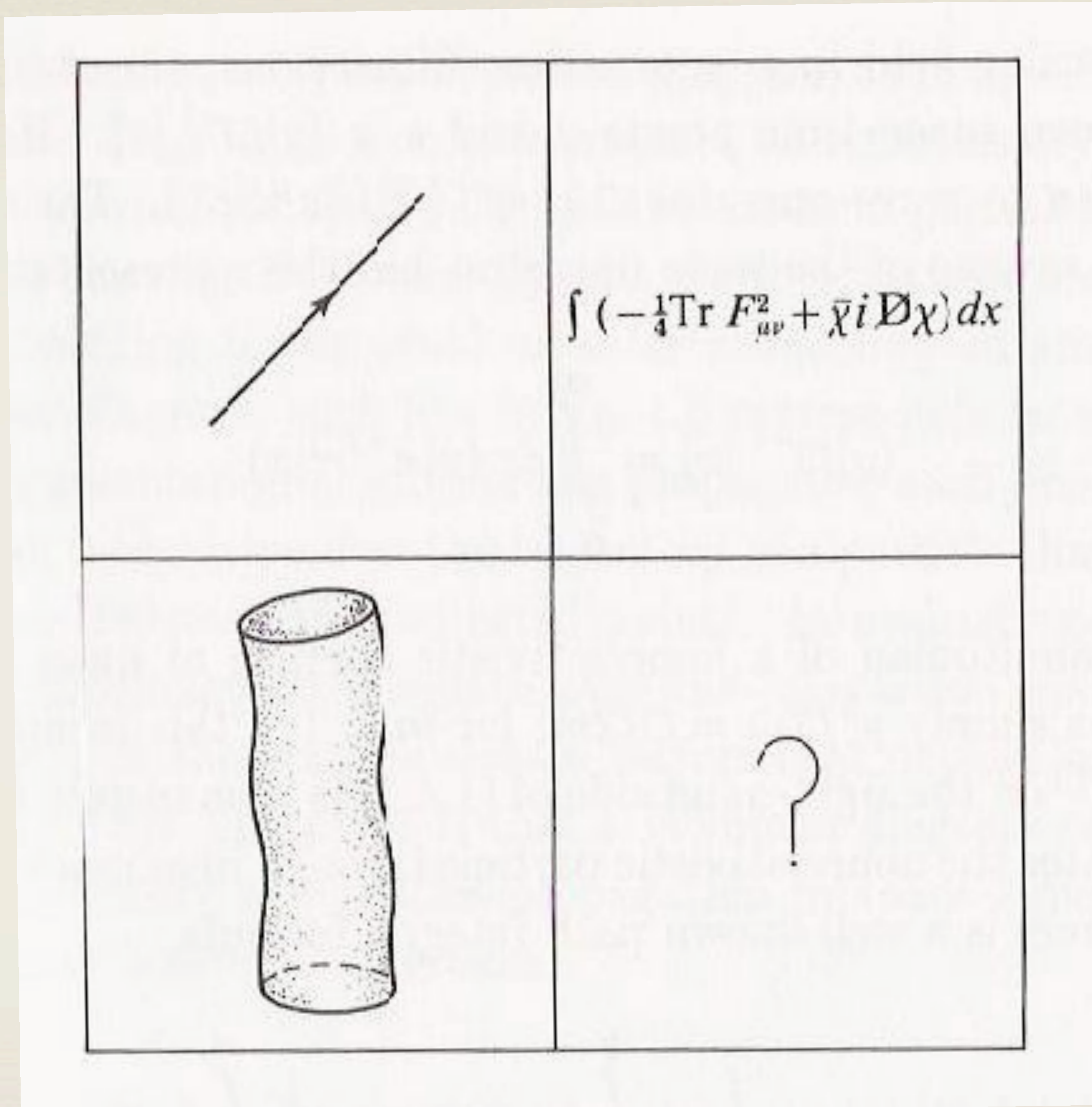
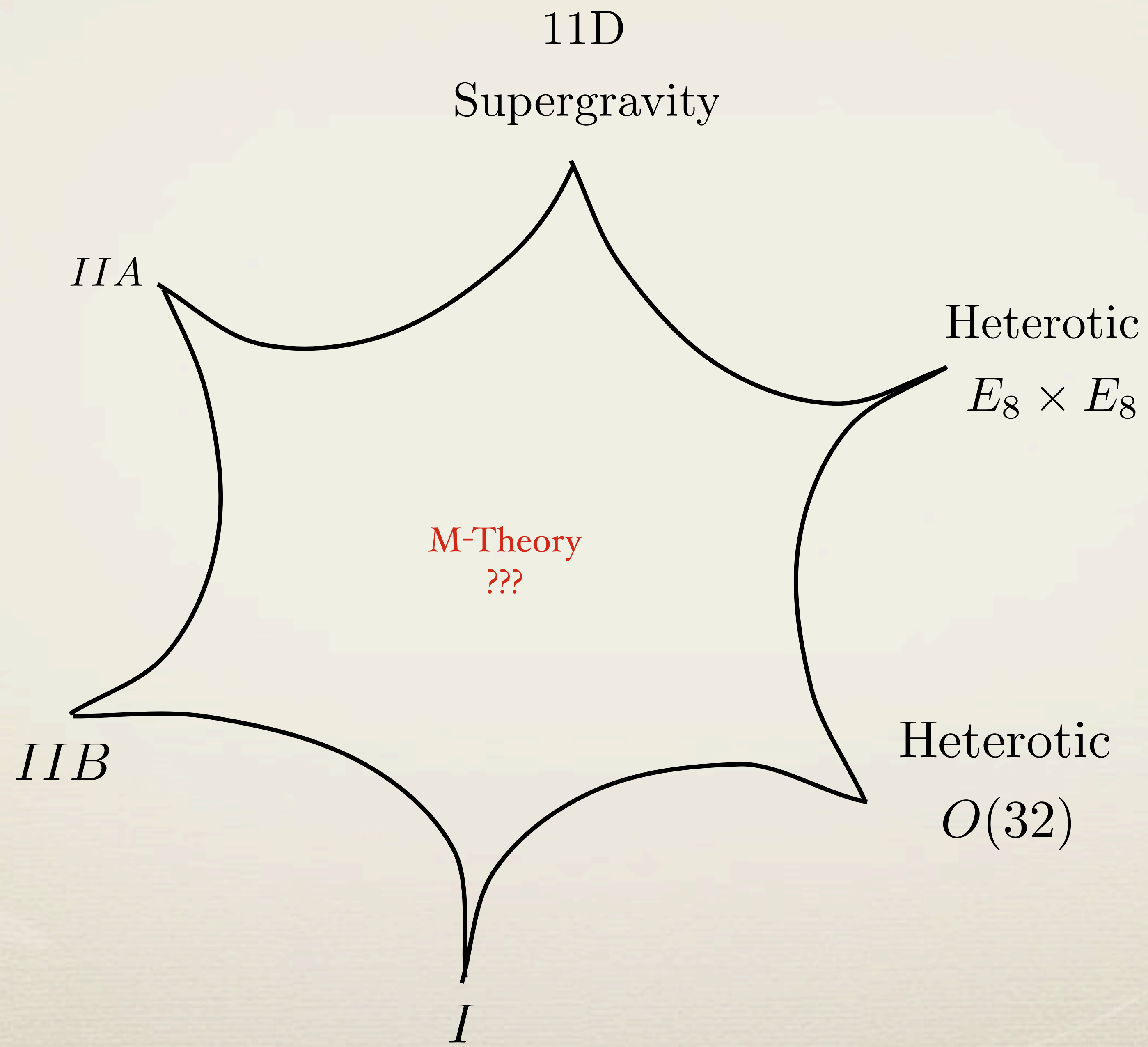


Green, Schwarz and Witten (1987)

What is string theory?

Several perturbative expansions in search of a theory.

(one of them does not even correspond to strings, and in all cases higher dimensional membranes are involved in addition to strings)



Fundamental Theory Wish List

* Discrete choices
* Finiteness and completeness
* Dynamical parameters
* Fixed at discrete values
* Small Cosmological Constant

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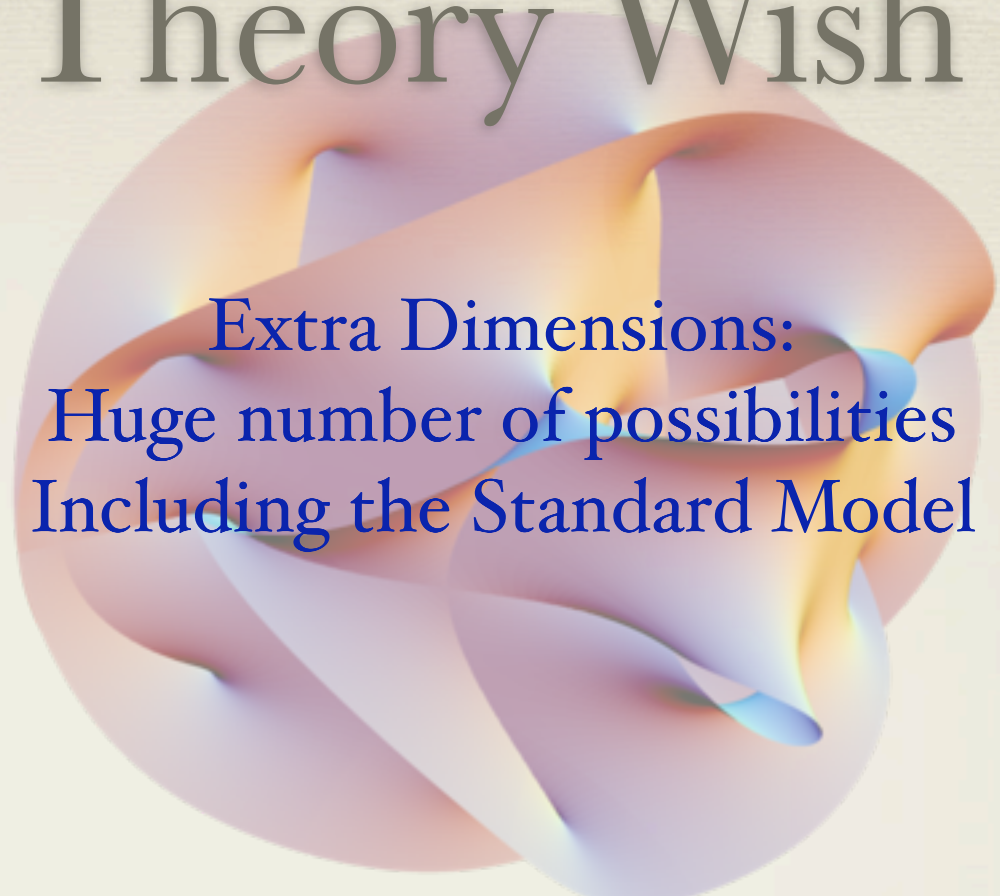

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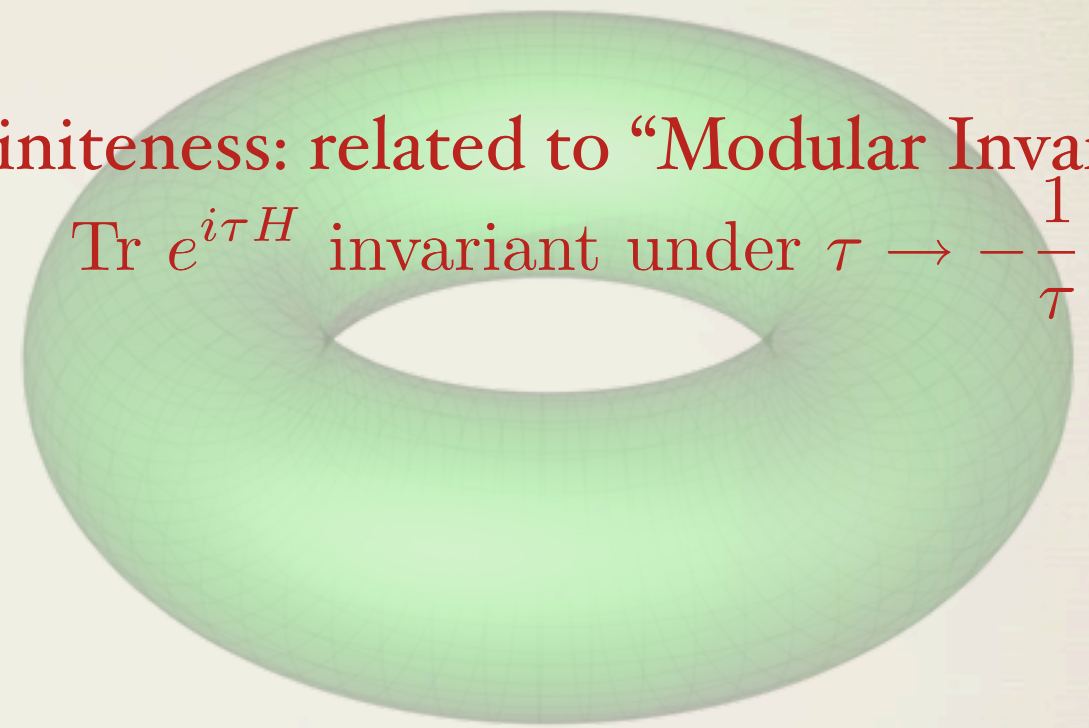

Finiteness: related to "Modular Invariance"

$\mathrm{Tr}\ e^{i\tau H}$ invariant under $\tau \to -\frac{1}{\tau}$

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Moduli:
hundreds or thousands

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Quantized tensor fields
winding around the handles ("fluxes")

(Bousso-Polchinski, 2000)

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Four-dimensional components of those fields

$$F^i_{\mu\nu\rho\sigma} = \partial_{[\sigma} A^i_{\mu\nu\rho]} = n_i y_i \epsilon_{\mu\nu\rho\sigma}$$

$$\Lambda = \Lambda_0 + \sum_i n_i^2 y_i^2$$

(Bousso-Polchinski, 2000)

Fundamental Theory Requirements

I: Discrete choices

String theory lives naturally in 10 (or 11) dimensions.

But there is a choice of space-time backgrounds.

This choice includes 4D Minkowski times a compact manifold.

There is a huge choice of compact backgrounds.

This apparent “embarrassment of choices” is precisely what is needed to get the required richness of choices for the 4D gauge theory.

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But so are many alternatives.

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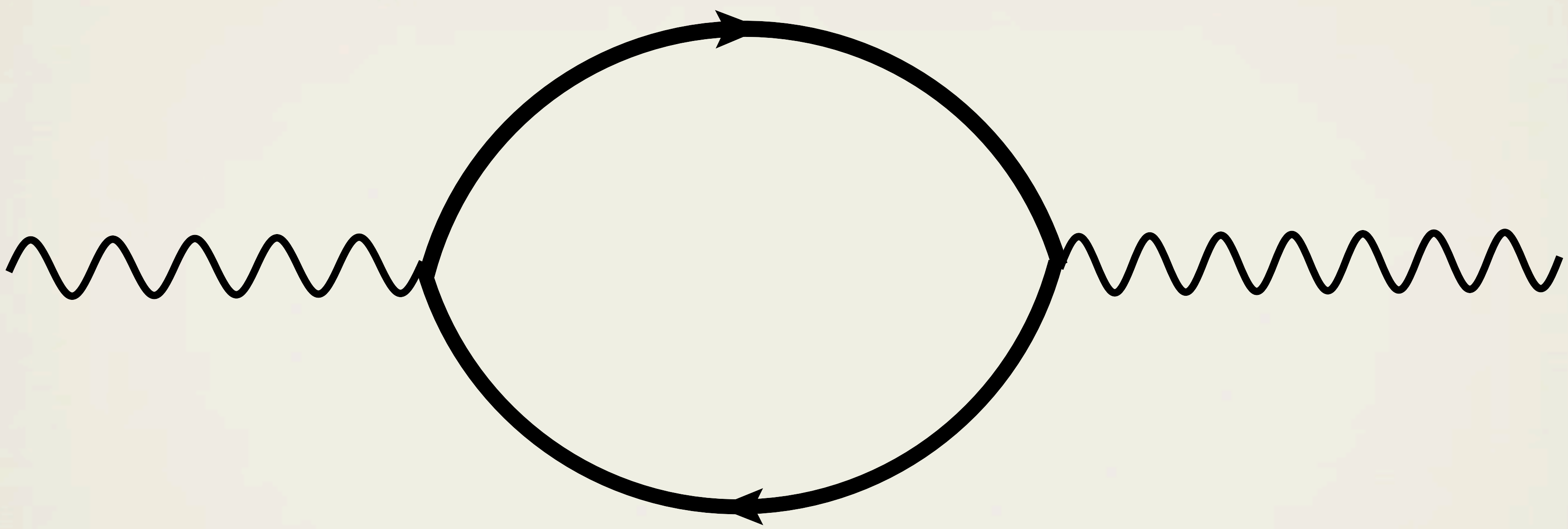
For the discrete choices the anthropic principle is already established in String theory

Fundamental Theory Requirements

II: Finiteness and Completeness



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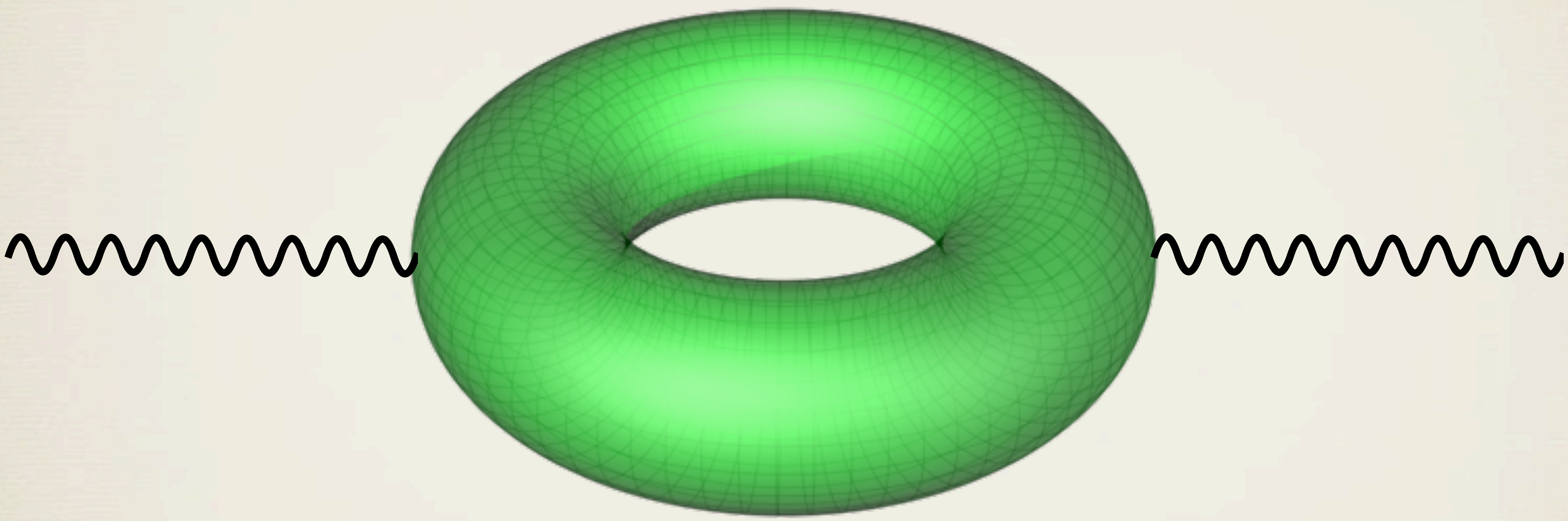

Fundamental Theory Requirements

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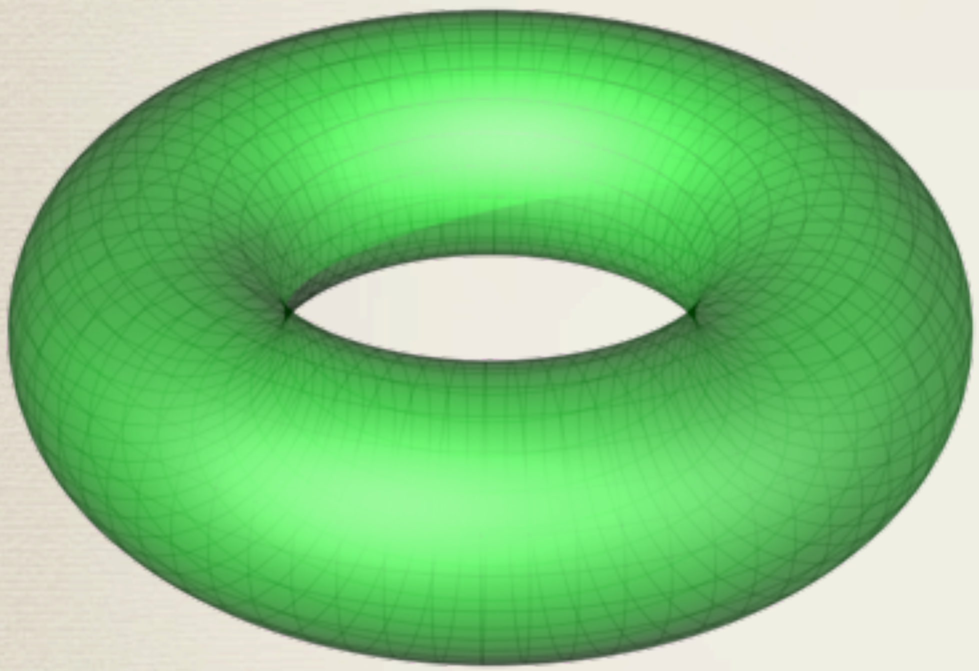

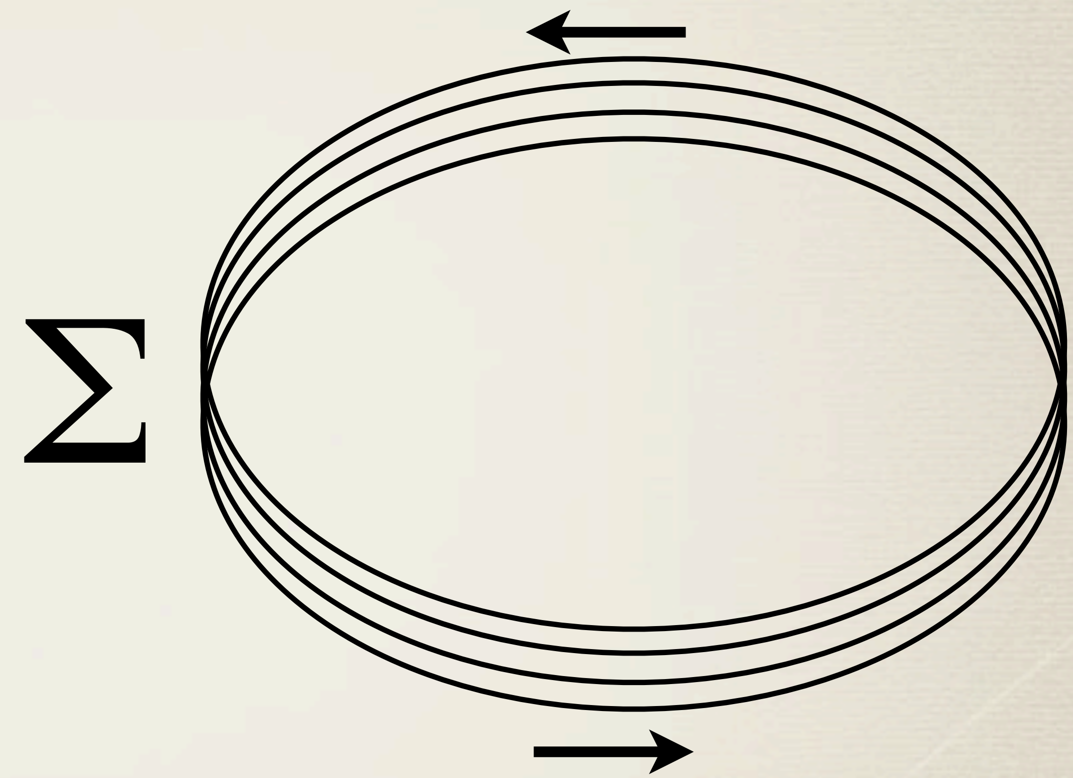

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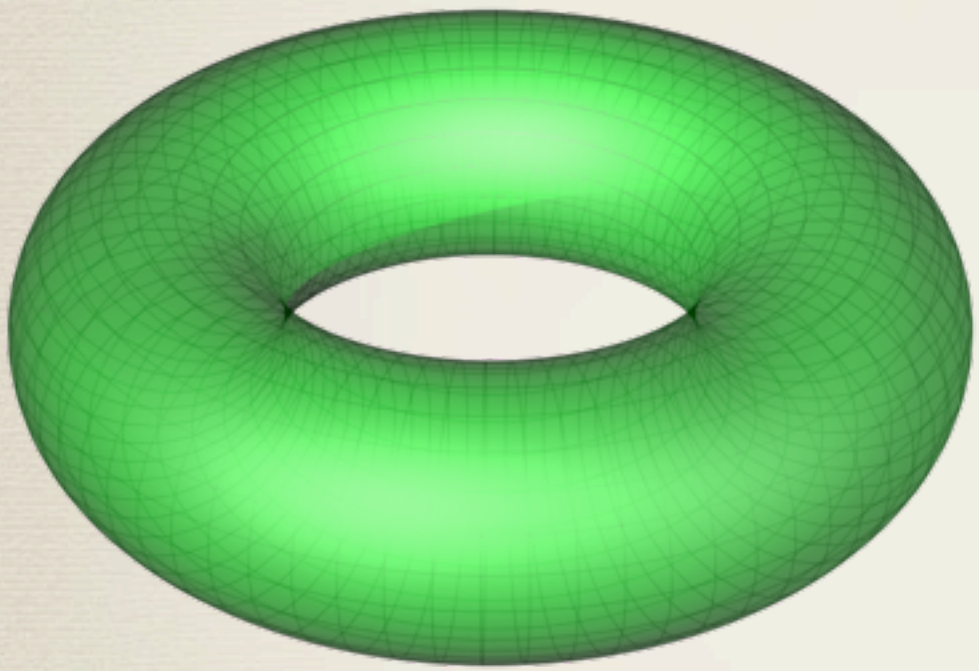
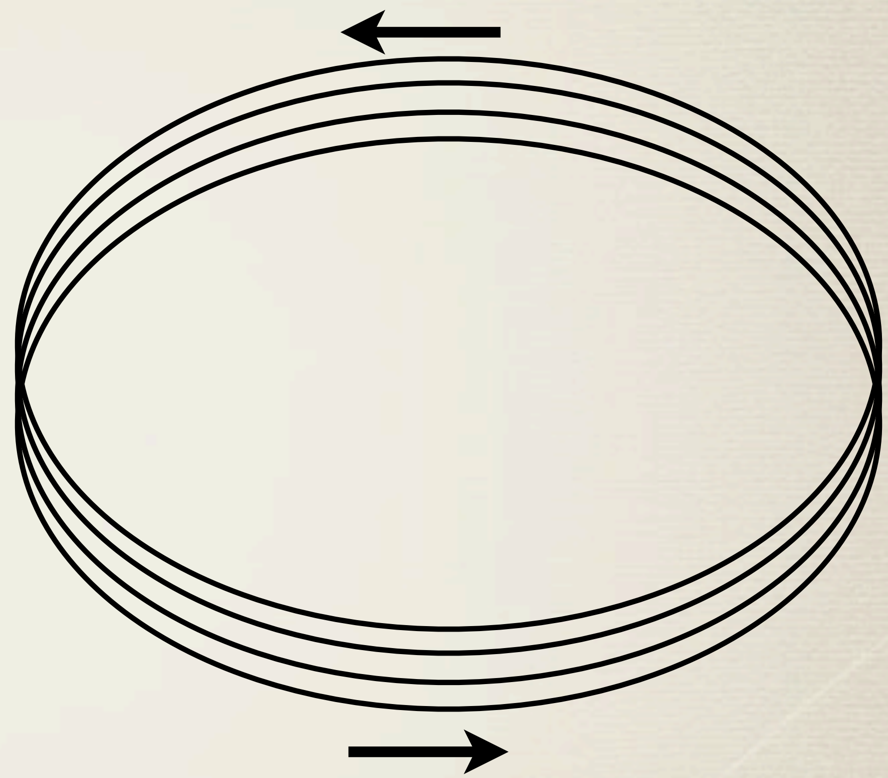
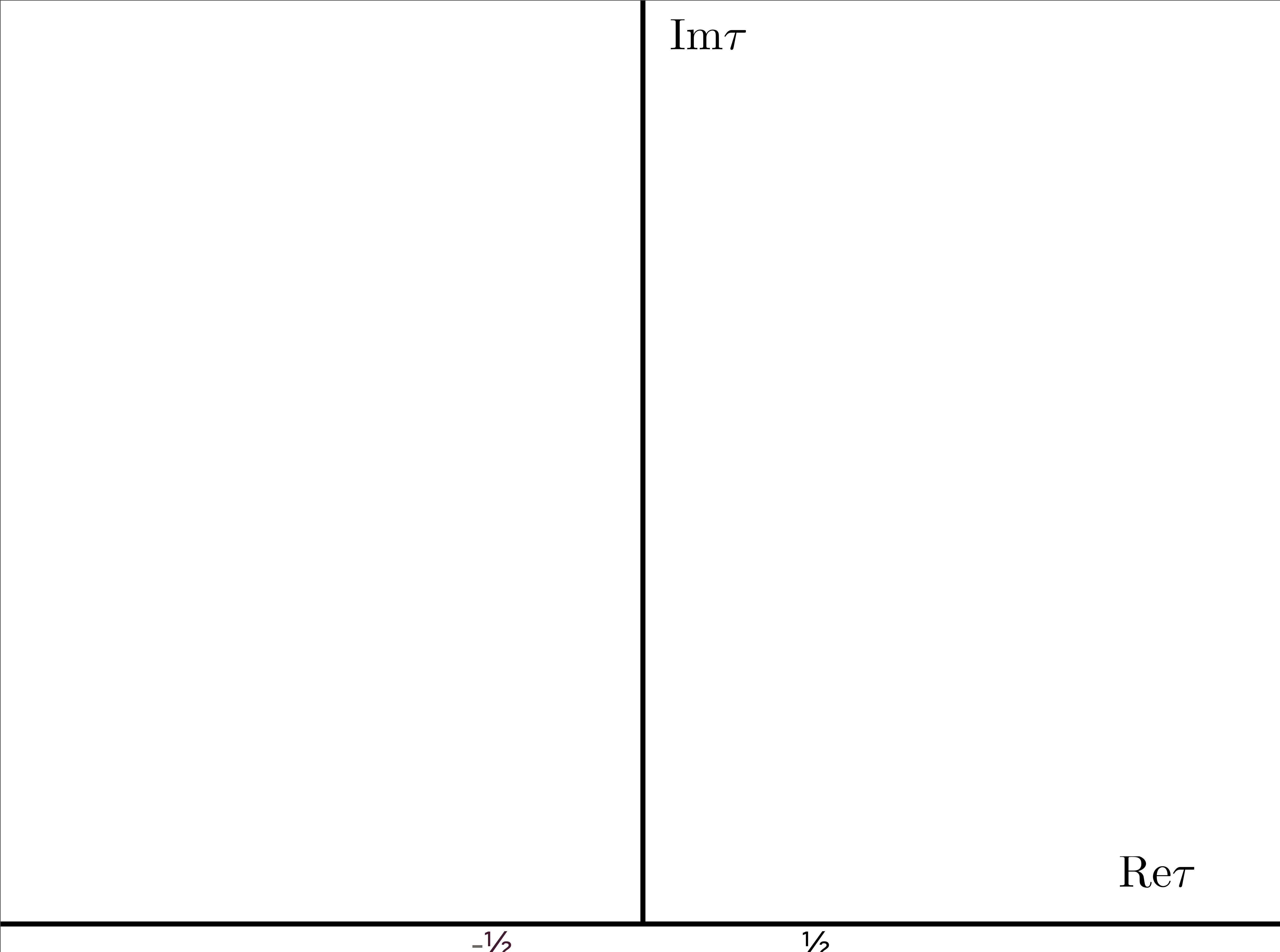
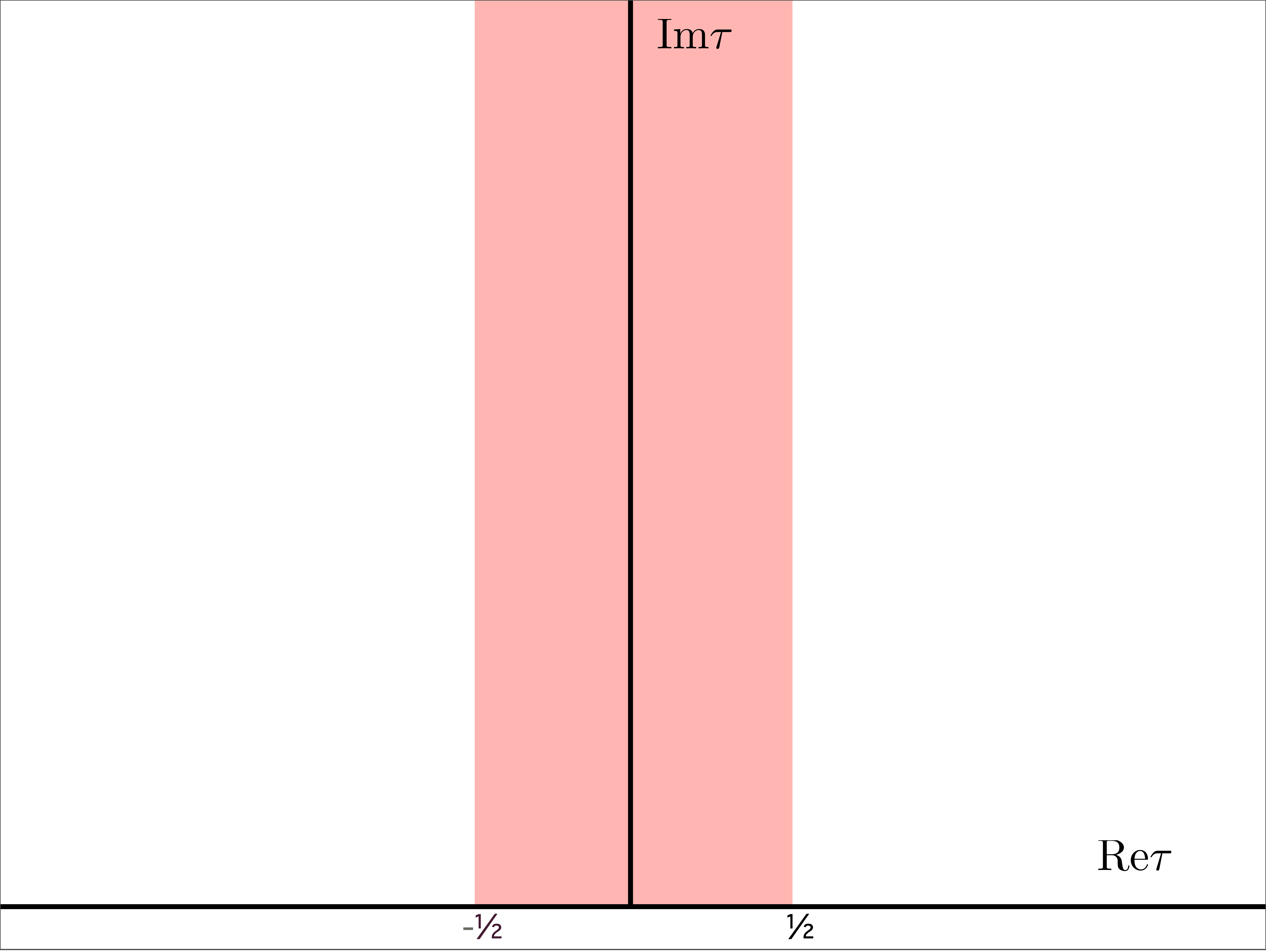


Σ



$$\int \frac{d^2\tau}{(\mathrm{Im}\tau)^{D/2+1}} \; \mathrm{Tr}\; e^{-\mathrm{Im}\tau H}$$


Imτ
Reτ
–½
½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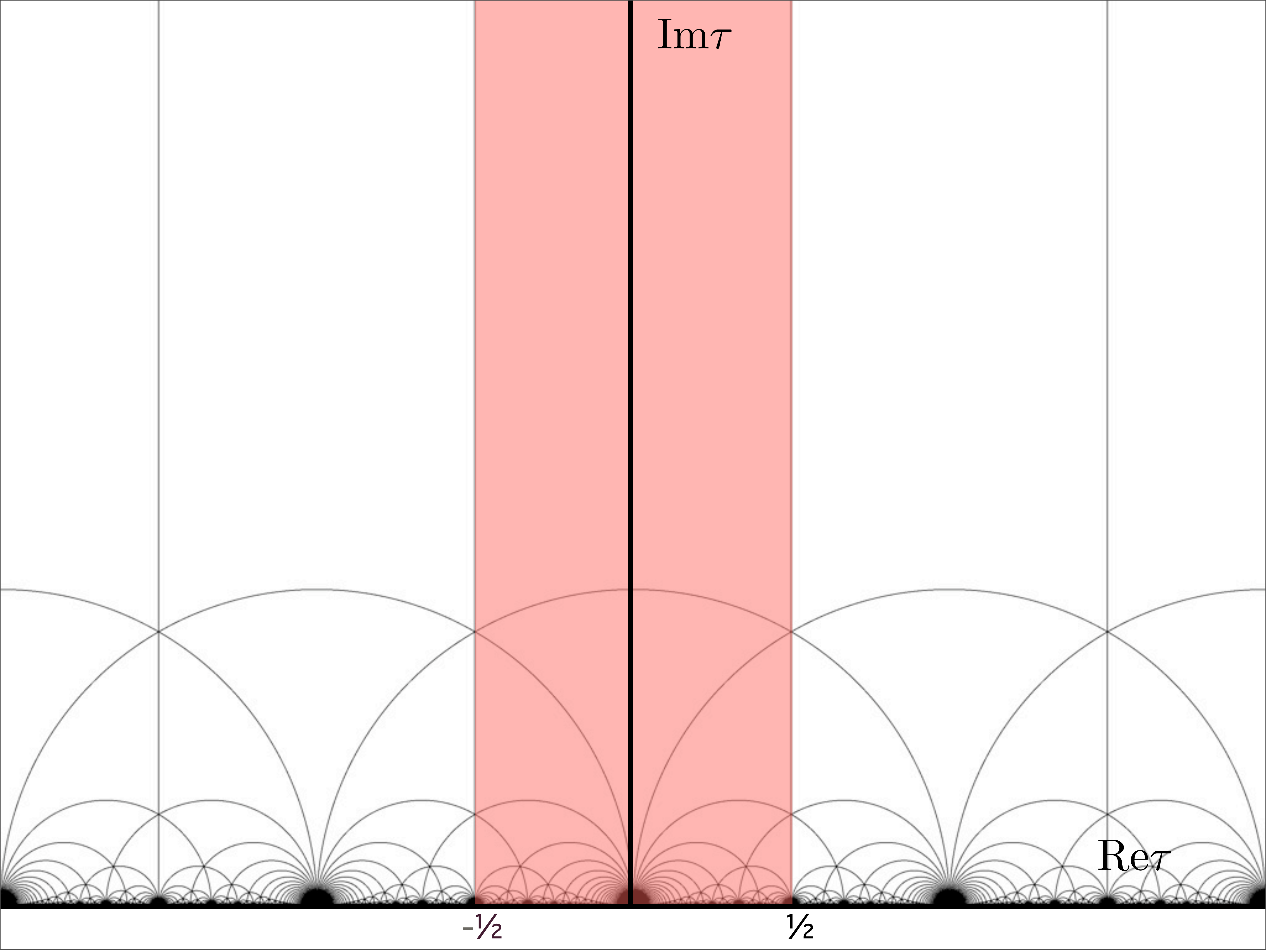
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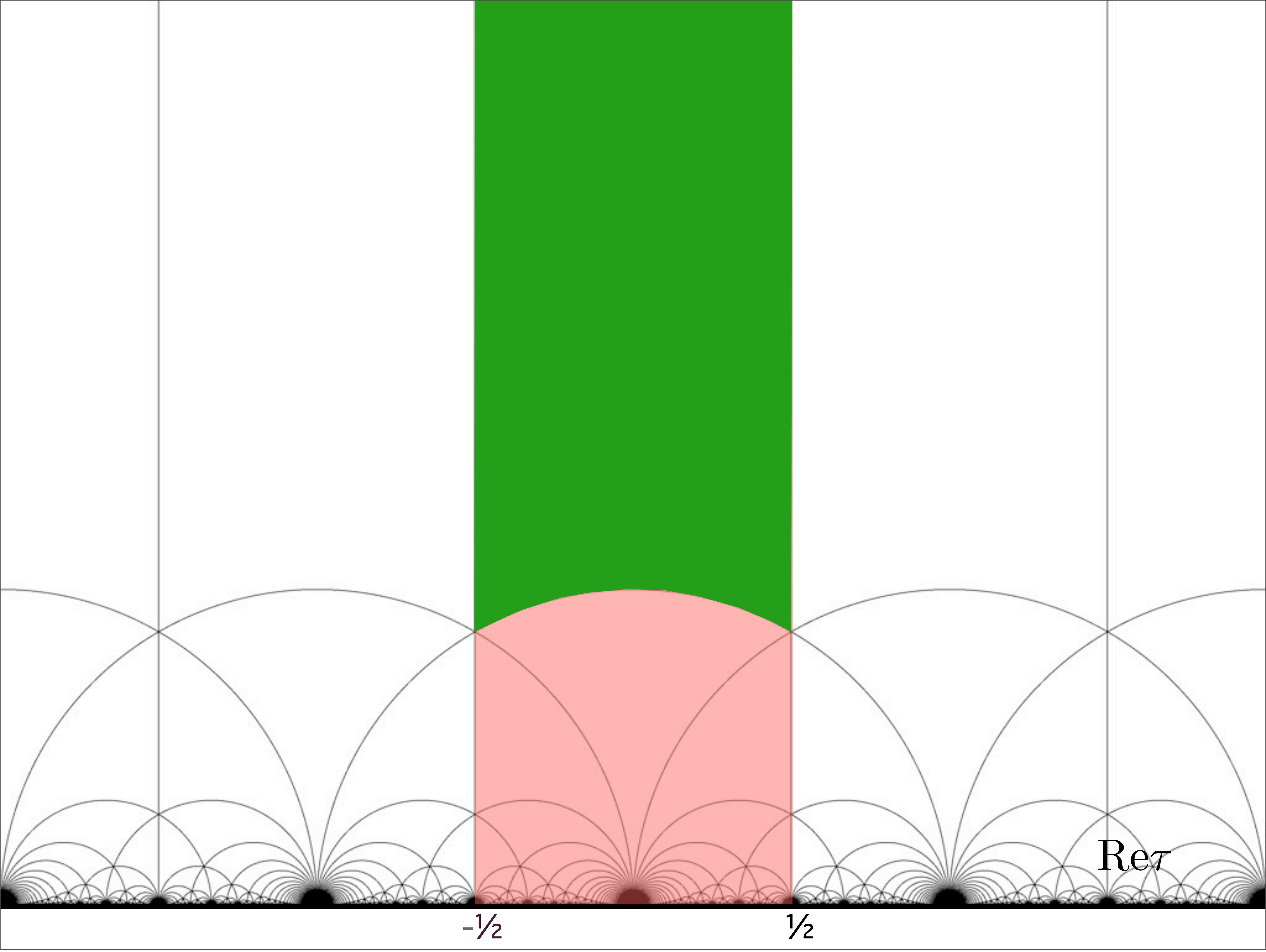
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Modular Invariance

Must be invariant under $SL_2(\mathbf{Z})/\mathbf{Z}_2$

$$\tau \to \frac{a\tau + b}{c\tau + d}, \qquad a, b, c, d \in \mathbf{Z}; \quad ad - bc = 1$$

Strong constraint on H!

These constraints imply that one cannot add particles or remove particles.
They are strongest in the maximal dimension of string theory.

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HOW MANY?

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

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

this number is of order 10^{1500} !

Even Self-dual lattices

Solutions to these constraints can be obtained from the partition functions of even self-dual lattices (all norms even, equal to its own dual (reciprocal) lattice).

$$\sum_{v \in L} e^{i\pi\tau v^2}$$

In 1986 we* showed how a class of 10 dimensional strings could be derived from the even self-dual lattices of dimension 24.

Later that year we** showed how a class of 4-dimensional strings could be derived from the even self-dual lattices of dimension 88.

(*)Ten-Dimensional Heterotic Strings From Niemeier Lattices, W. Lerche, D. Lüst and A.N. Schellekens (1986)

(**)Chiral Four-Dimensional Heterotic Strings from Selfdual Lattices, W. Lerche, D. Lüst and A.N. Schellekens, (1986)

$$N_{8k} > \sum_{\Lambda} \frac{1}{|\mathrm{Aut}(\Lambda)|} = \frac{|B_{4k}|}{8k} \prod_{j=1}^{4k-1} \frac{|B_{2j}|}{4j}$$

Dimension	Estimate	Total
8	2.8×10^{-9}	1
16	4.9×10^{-18}	2
24	15.8×10^{-15}	24
32	8.0×10^{7}	?
...		
88	$\approx 10^{1500}$	?

A. Strominger (1986)

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Contribution to the proceedings of the EPS conference, Uppsala, June 1987

The prevailing attitude seems to be that "non-perturbative string effects" will somehow select a unique vacuum. This is unreasonable and unnecessary wishful thinking. We do not know at present how to discuss such effects, and have no idea whether they impose any restrictions at all. One cannot reasonably expect that a mathematical condition will have a unique solution corresponding to the standard model with three generations and a bizarre mass matrix. It is important to realize that this quest for uniqueness is based on philosophy, not on physics. There is no logical reason why the "theory of everything" should have a unique vacuum.

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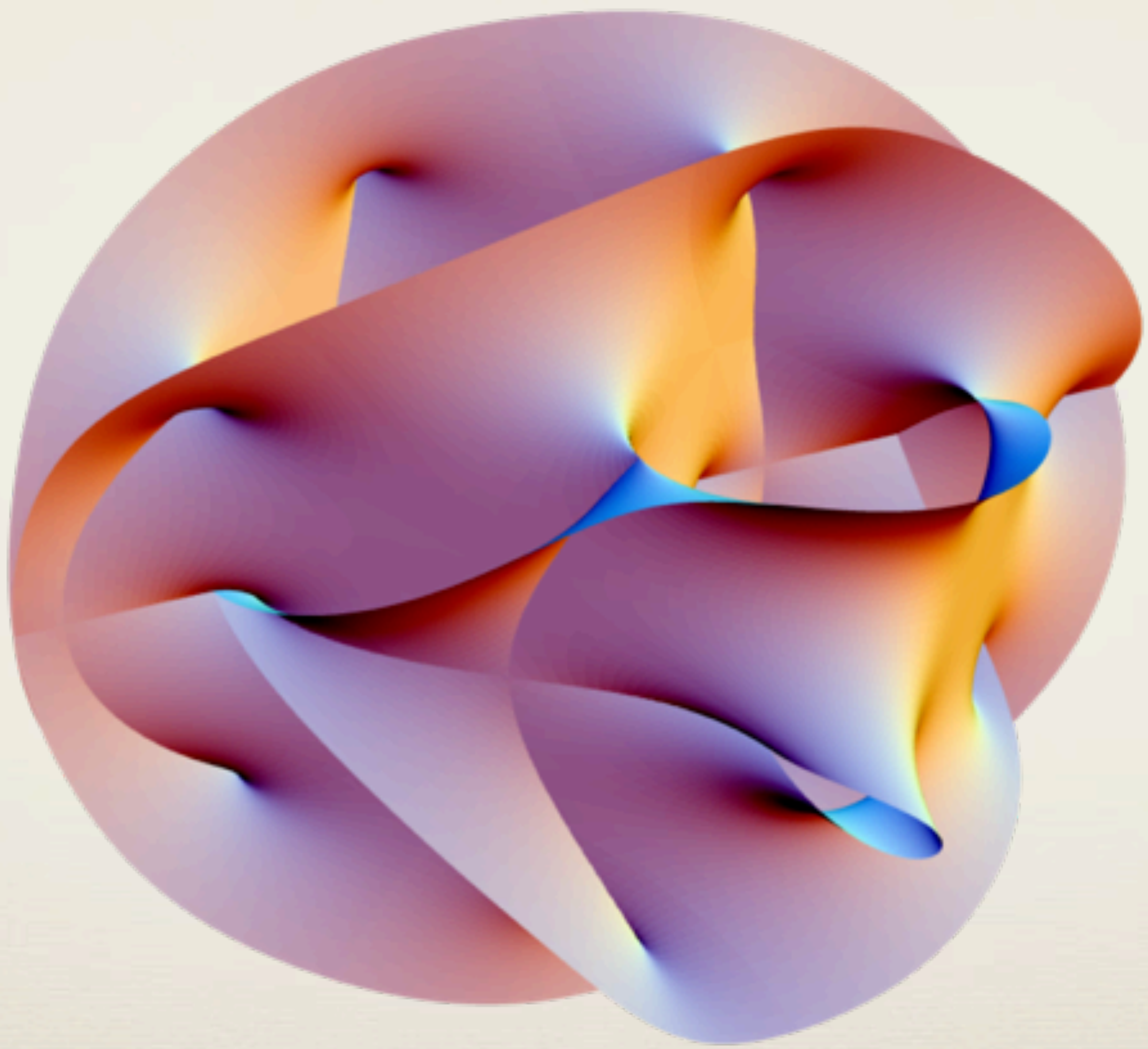
(Similar text including "anthropic principle": 1998, R.U. Nijmegen)

Fundamental Theory Requirements

III: Dynamical Parameters



Fundamental Theory Requirements
III: Dynamical Parameters

Shapes and size of the handles of internal manifolds give rise to dynamical parameters in the resulting four-dimensional gauge theory: moduli.
(“String theory has no parameters”)
Often there are hundreds or thousands of moduli.

To first approximation (supersymmetry) these have flat potentials.

It has been a long-standing problem to show that supersymmetry can be broken and that potentials with local minima can be generated (“moduli stabilization”)

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Fundamental Theory Requirements
IV: The Cosmological Constant

Bousso and Polchinski (2000)

Quantized generalizations of electric & magnetic fields ("fluxes") living in Minkowski and internal dimensions:

• May wind N times around closed cycles of the internal manifold to help stabilizing some moduli
• Have space-time components that contribute to the cosmological constant.

$$A_{\mu\nu\rho} \rightarrow F_{\mu\nu\rho\sigma} = \partial_{[\sigma} A_{\mu\nu\rho]}$$

Action with four-form contribution

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2\kappa^2}R - \Lambda_{\text{bare}} - \frac{Z}{48}F_4^2\right)$$

Solution to equations of motion

$$F^{\mu\nu\rho\sigma} = c\epsilon^{\mu\nu\rho\sigma}$$

Contribution to the cosmological constant

$$\Lambda = \Lambda_{\text{bare}} + \frac{1}{2}\frac{Zc^2}{2}$$

In String Theory:

- The constant c is quantized
- There are many such four-form fields

$$\Lambda = \Lambda_{\rm bare} + \frac{1}{2}\sum_i^{N_{\rm flux}} n_i^2 y_i^2$$

If the values of y_i are incommensurate and $N_{\rm flux}$ sufficiently large, Λ can be tuned to a very small value (starting with negative $\Lambda_{\rm bare}$ of natural size).

$N_{\rm vacua} \approx [N_{\rm values}]^{N_{\rm flux}}$ *Douglas, Denef:* 10^{500}

~ 2003

The basic estimate for numbers of flux vacua [4] is

$$\mathcal{N}_{vac} \sim \frac{(2\pi L)^{K/2}}{(K/2)!}[c_n]$$

where K is the number of distinct fluxes ($K = 2b_3$ for IIb on CY_3) and L is a "tadpole charge" ($L = \chi/24$ in terms of the related CY_4). The "geometric factor" $[c_n]$ does not change this much, while other multiplicities are probably subdominant to this one.

Typical $K \sim 100 - 400$ and $L \sim 500 - 5000$, leading to $\mathcal{N}_{vac} \sim 10^{500}$.

(M. Douglas)

The Anthropic Landscape of String Theory

L. Susskind

Department of Physics
Stanford University
Stanford, CA 94305-4060

A. Linde

Eternally Existing Selfreproducing Chaotic Inflationary Universe. **Phys.Lett.B175:395-400,1986**

If our universe would consist of one domain only (as it was believed several years ago), it would be necessary to understand why Nature has chosen just this one type of compactification, just this type of symmetry breaking, etc. At present it seems absolutely improbable that all domains contained in our exponentially large universe are *of the same type*. On the contrary, *all* types of mini-universes in which inflation is possible should be produced during the expansion of the universe, and it is unreasonable to expect that our domain is the only possible one or the best one. From this point of view, an enormously large number of possible types of compactification which exist e.g. in the theories of superstrings should be considered not as a difficulty but as a virtue of these theories, since it increases the probability of the existence of mini-universes in which life of our type may appear. The old question why our universe is the only possible one is now replaced by the question in which theories the existence of mini-universes of our type is possible. This question is still very difficult, but it is much easier than the previous one. In our opinion, the modification of the point of view on the global structure of the universe and on our place in the world is one of the most important consequences of the development of the inflationary-universe scenario.

Conclusions

Premature?

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Can we please discuss the "anthropic principle" without all the hysteria?