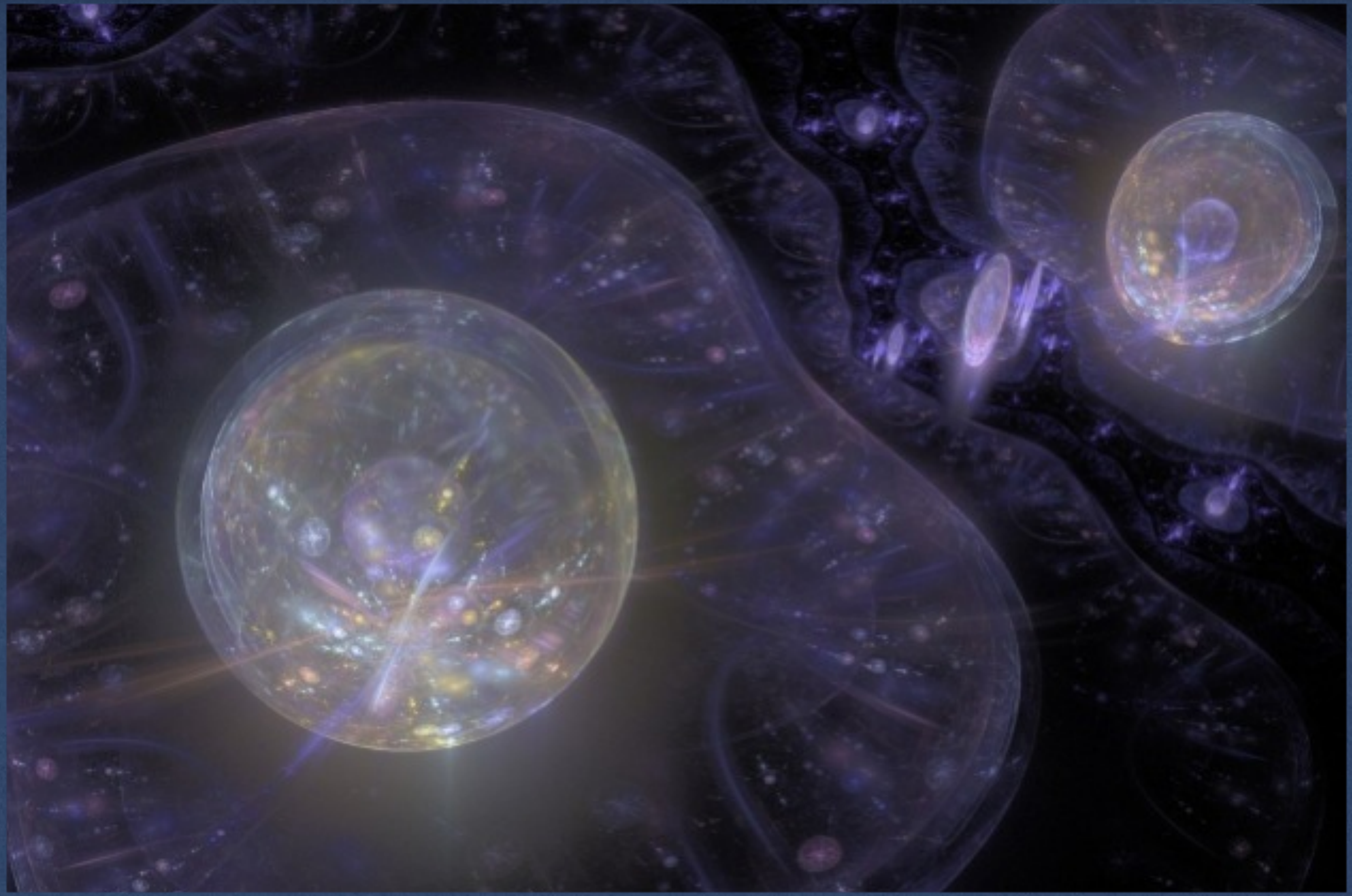

Particle Physics in the Multiverse

Liverpool, 31-10-2014

"What I'm really interested in is whether God could have made the world in a different way; that is, whether the necessity of logical simplicity leaves any freedom at all."

A. Einstein

"What I'm really interested in is whether God could have made the world in a different way; that is, whether the necessity of logical simplicity leaves any freedom at all."

A. Einstein

I would like to state a theorem which at present can not be based upon anything more than a faith in the simplicity, i.e. intelligibility, of nature: There are no arbitrary constants that is to say, nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory)

Quoted by Andre Linde in arXiv:1402.0526

There is a most profound and beautiful question associated with the observed coupling constant… 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.

R. Feynman

Some formulas for α

$$\alpha = 2^{-4}3^{-3}\pi$$

W. Heisenberg

$$\alpha = \frac{9}{16\pi^3}\sqrt[4]{\frac{\pi}{5!}}$$

A. Wyler

$$\alpha = \frac{\cos(\pi/137)}{137}\frac{\tan(\pi/(137\times 29))}{\pi/(137\times 29)}$$

F. Gilson

$$\frac{1}{\alpha} = \pi^{\pi e/2} + \sqrt{e^3 - 1}$$

???

Expectations for String Theory

"*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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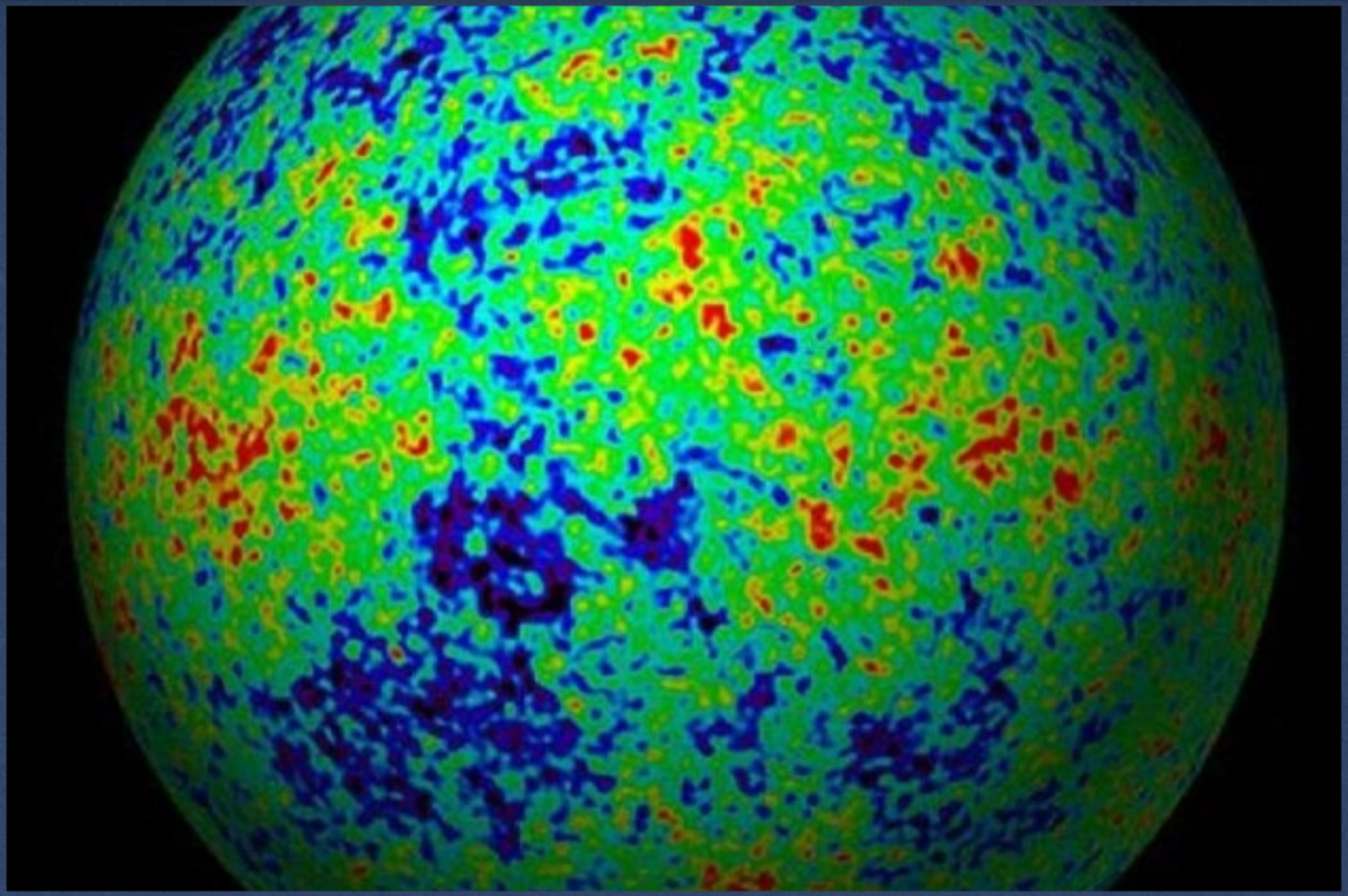
From "The Problems of Physics" by Antony Leggett (1987)

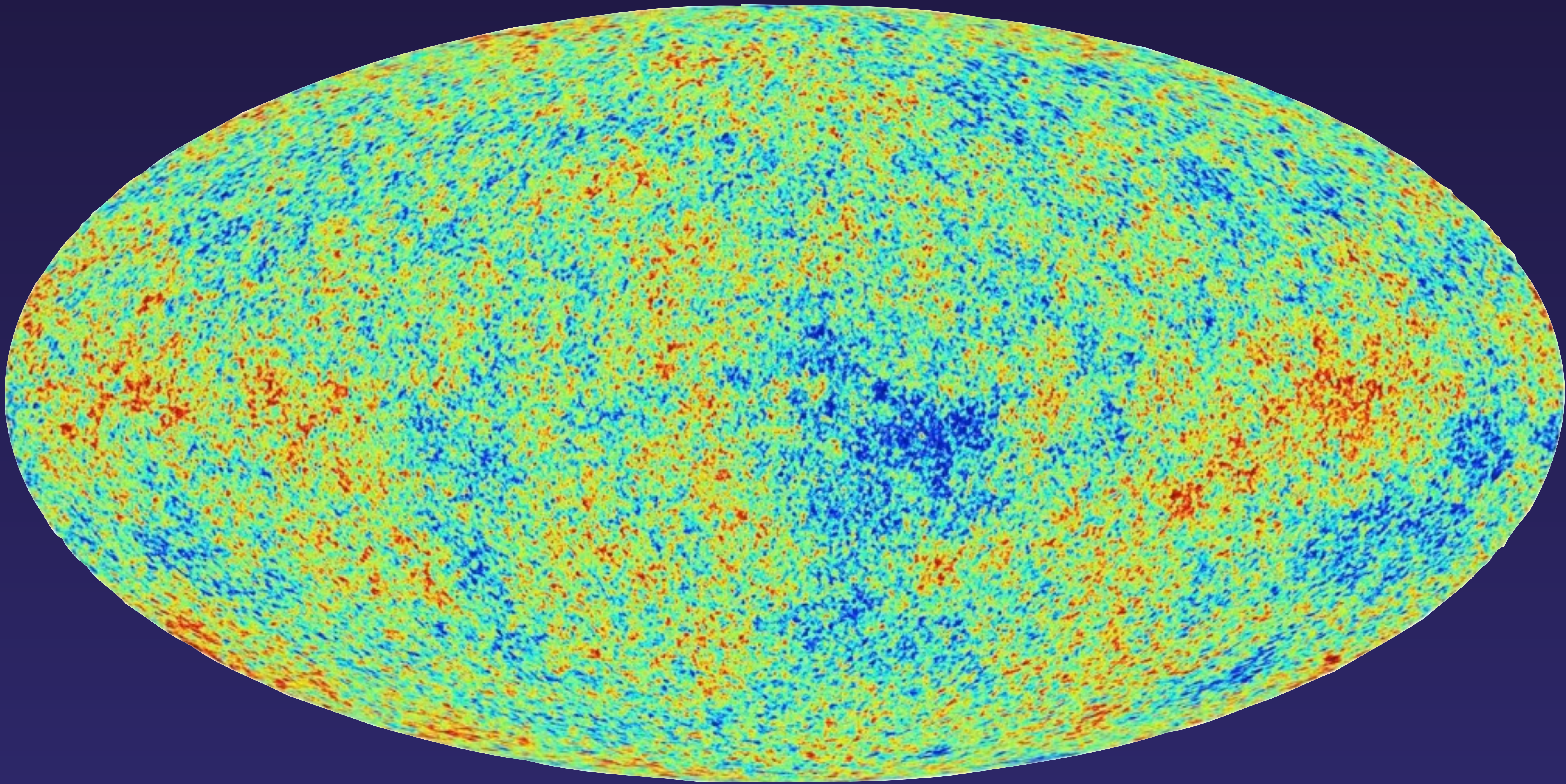
Paul Steinhardt
Albert Einstein Professor in Science, Departments of Physics and Astrophysical Sciences, Princeton University

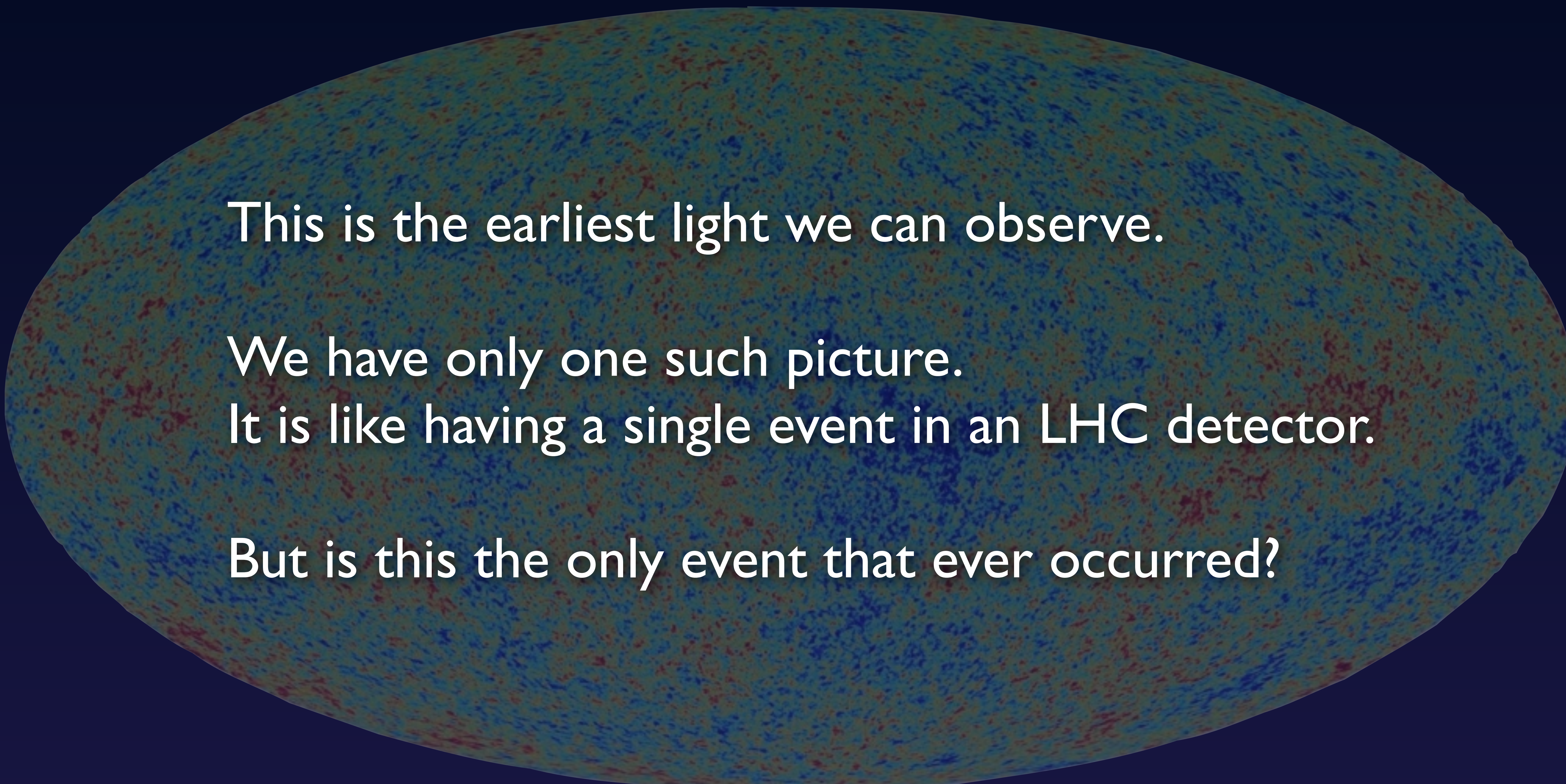
"String theory was supposed to explain why elementary particles could only have the precise masses and forces that they do. After more than 30 years investment in each of these ideas, theorists have found that they are not able to achieve these ambitious goals"

2014



I. The Multiverse





This is the earliest light we can observe.

We have only one such picture.
It is like having a single event in an LHC detector.

But is this the only event that ever occurred?

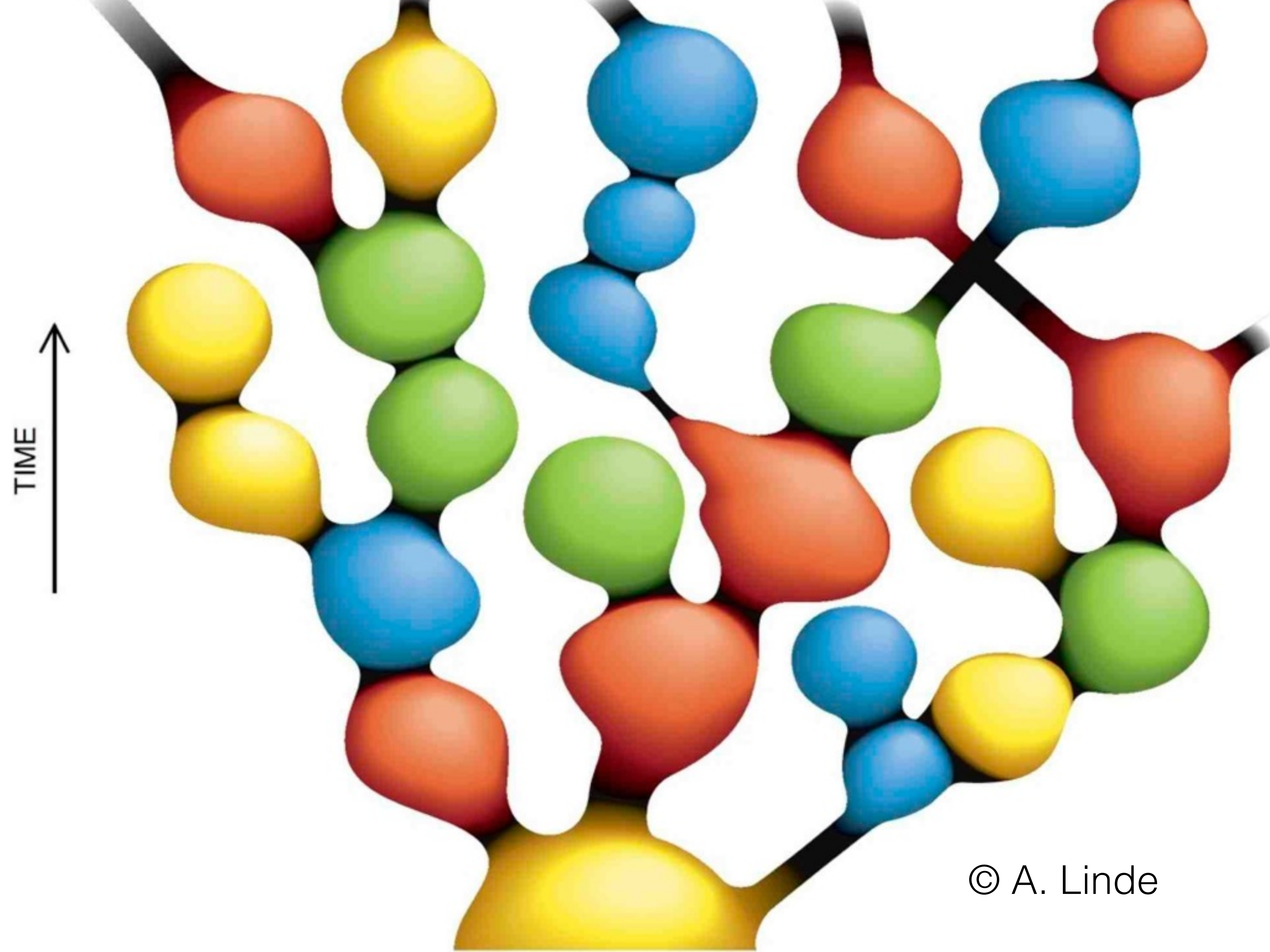
Common sense suggests that it is not.

Is all we can see all there is?

Furthermore the theory that correctly describes the CMB fluctuations, inflation, predicts that there is an infinity of such "events".

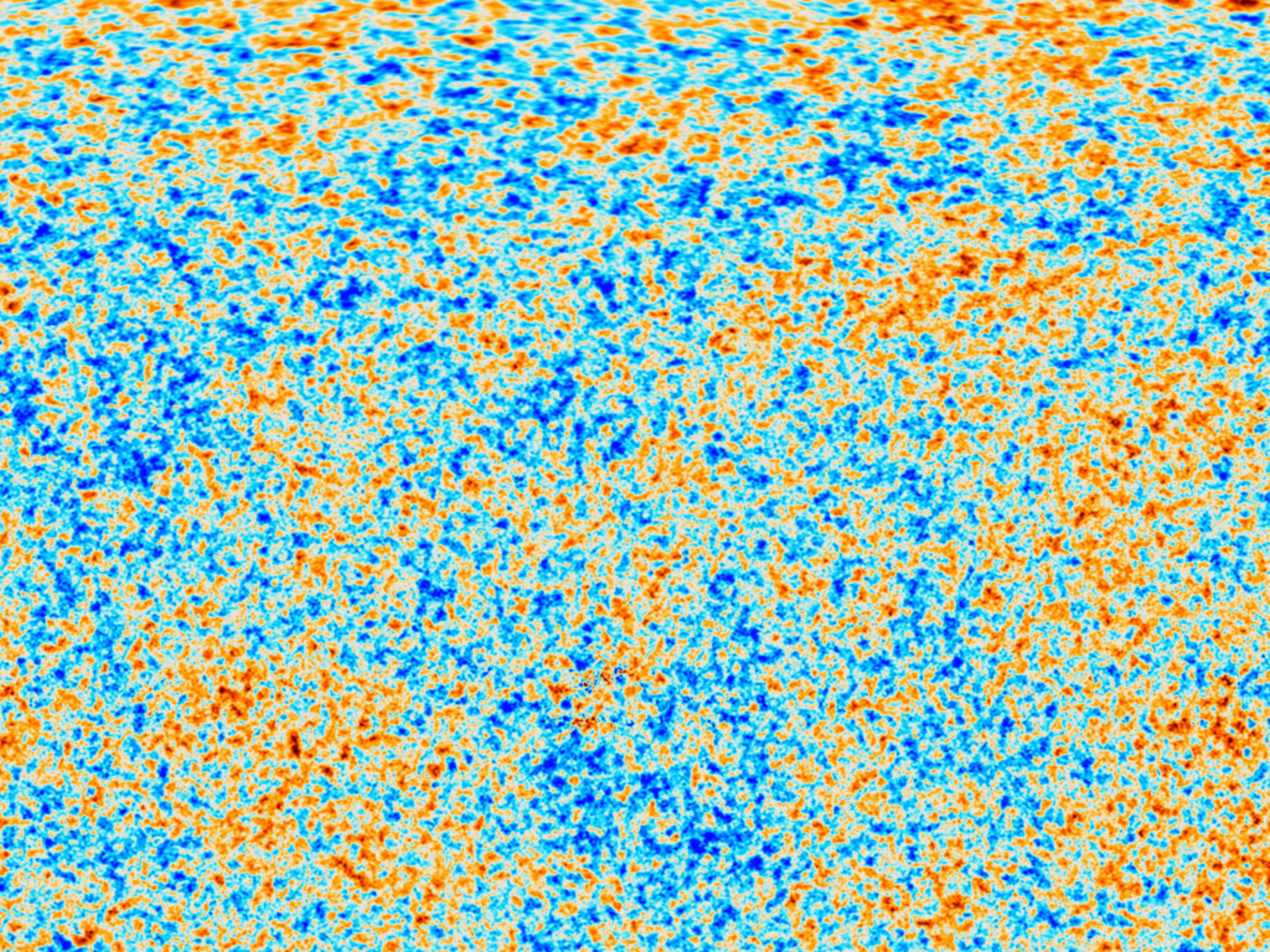
"If the universe contains at least one inflationary domain of a sufficiently large size, it begins unceasingly producing new inflationary domains."

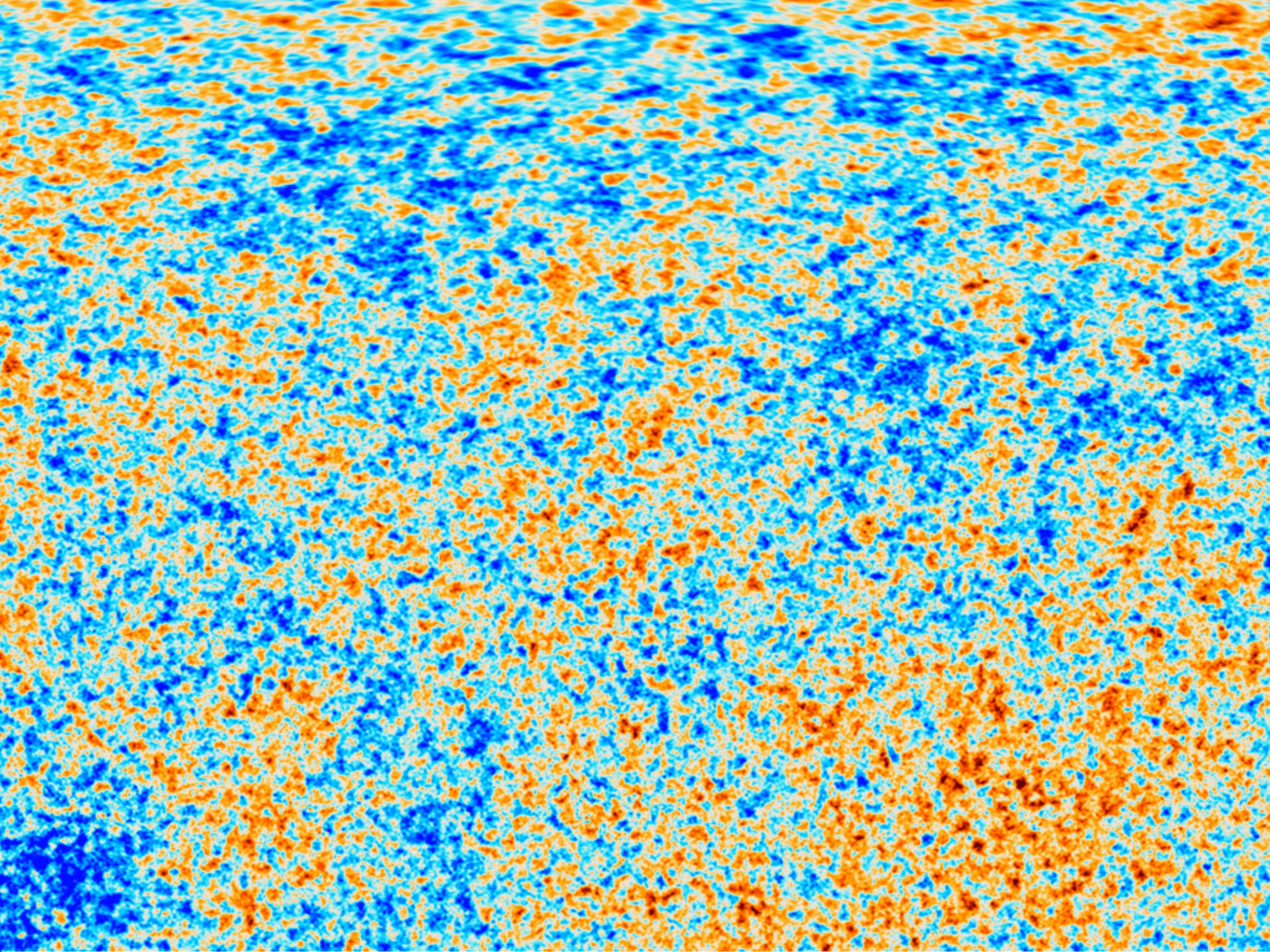
Andrei Linde (1994)


TIME

So what would these other universes look like?
(and is there anyone to look at them?)

At the very least the CMB fluctuations would be different.





But is that all that changes?

Could the laws of physics themselves be different?

If so, what are the allowed changes?

Consider the pillars of modern physics:

Quantum Mechanics:

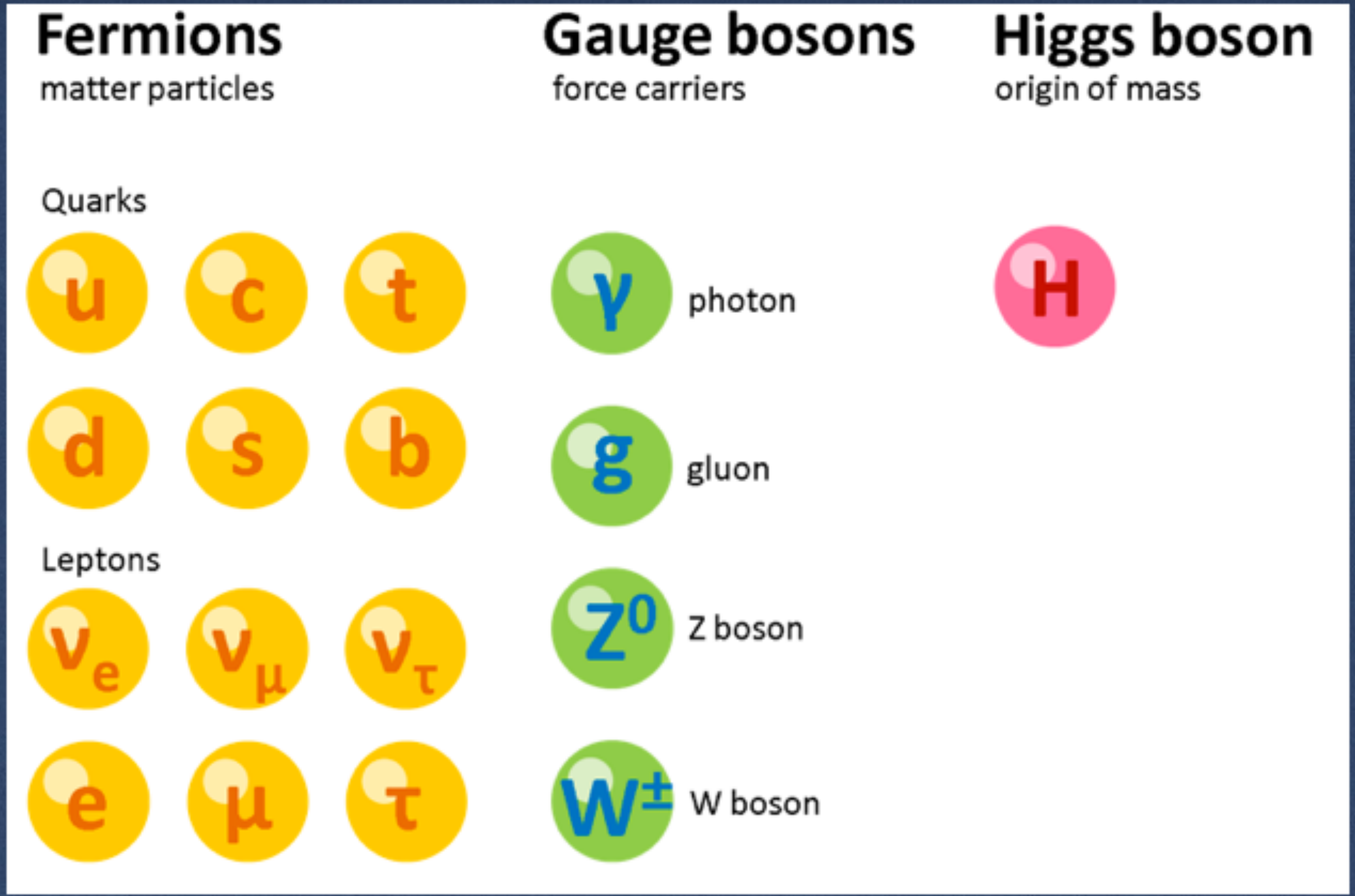
Cannot be modified in any way we know

General Relativity:

Can change space-time dimension, cosmological constant ("vacuum energy"), curvature.

The Standard Model:

Many options for change: the gauge group, the particle representations (charges), and all continuous parameters.



The Standard Model

The Standard Model

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

Quarks and leptons

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

Higgs $(1,2,-\frac{1}{2})$ Gives masses to all quark and leptons

Most general interactions respecting all the symmetries: 28 parameters
These can only be measured, not computed.
Some of them have strange value (small dimensionless ratios, like 10^{-6})

This gives a theory that correctly describes all known interactions except gravity.
But we can easily write down a multitude of theoretical alternatives

But who cares about alternatives?

Phenomenological objection:
Shouldn't we be satisfied in understanding just our own universe?

Philosophical objection:
We (probably) cannot see these other universes.
(perhaps as signals of "bubble collisions" in the CMB, a few billion years from now.
Or perhaps as information encoded in the CMB radiation, but only in principle)

So this is not science...

The answer to the phenomenological objection is that most of Standard Model phenomenology is aimed at the "why" questions.

Why $SU(3) \times SU(2) \times U(1)$, why quarks and leptons, why three families, why these strange masses, why such large hierarchies?

Surely, if these could be different in other universes, this is relevant to the answer.

Suppose the number of families could be different.
Then clearly we can never derive this number.

Then just the following options are left:

- In our universe, the number 3 came out purely by chance.

- In the full ensemble of universes, 3 is statistically favored.
  Very tricky: all multiplicities are infinite, so it is not immediately obvious how to compare them.
  This is know as the "multiverse measure problem".
  Despite a lot of work and some progress, there is no generally accepted solution yet.

- Any number other than 3 cannot be observed, because life cannot exist unless there are 3 families.
  This is (a form of) the anthropic principle.
  (Probably not true in this case)

The philosophical objection

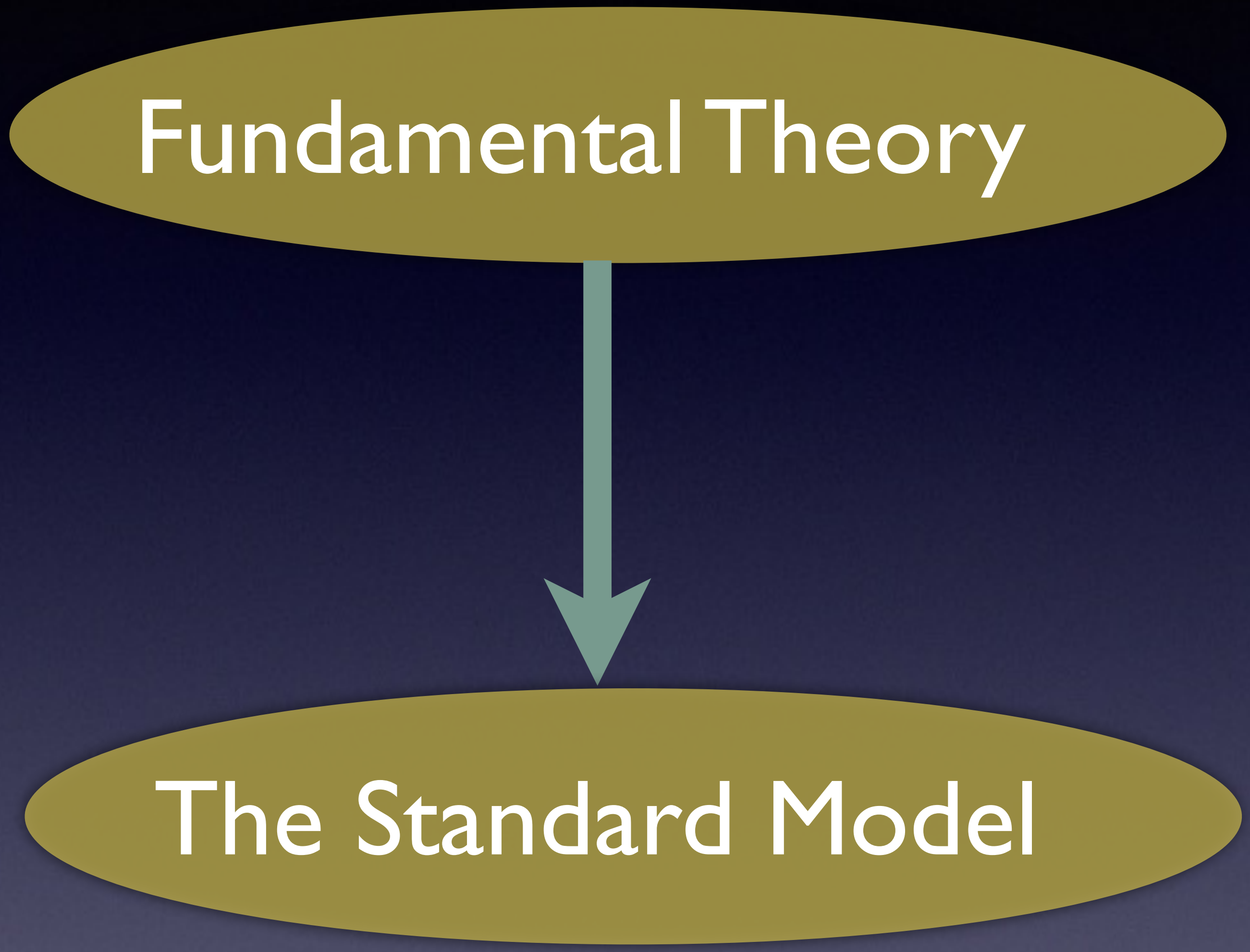
Let us assume the worst-case scenario:
Other universes are unobservable in principle.

Then it is still possible that we will find a theory that *demonstrably* contains our Standard Model, and contains many other gauge theories as well.

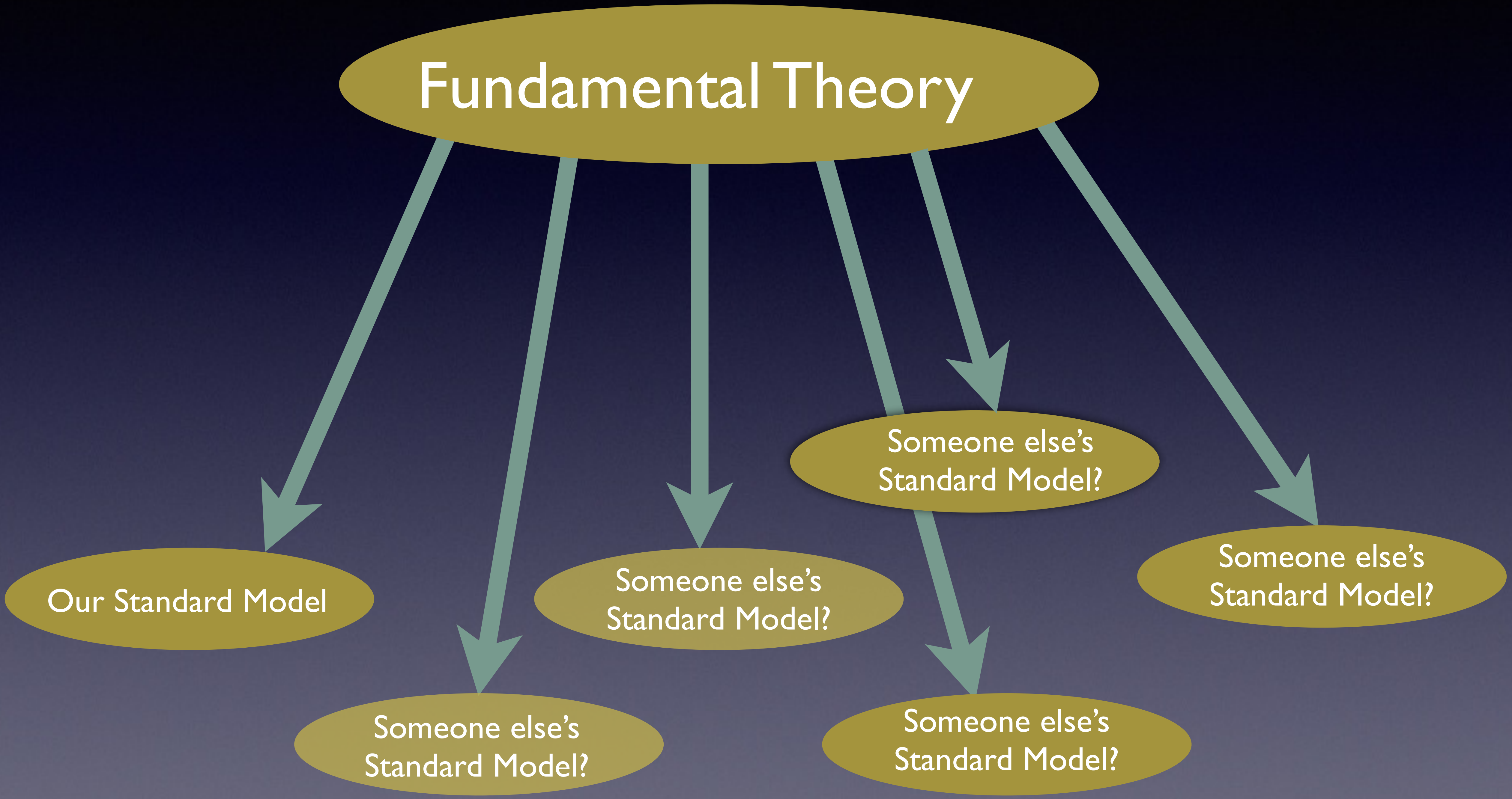
We could confirm that theory either

- By correct predictions in our own Universe
- By deriving it from a principle of Nature

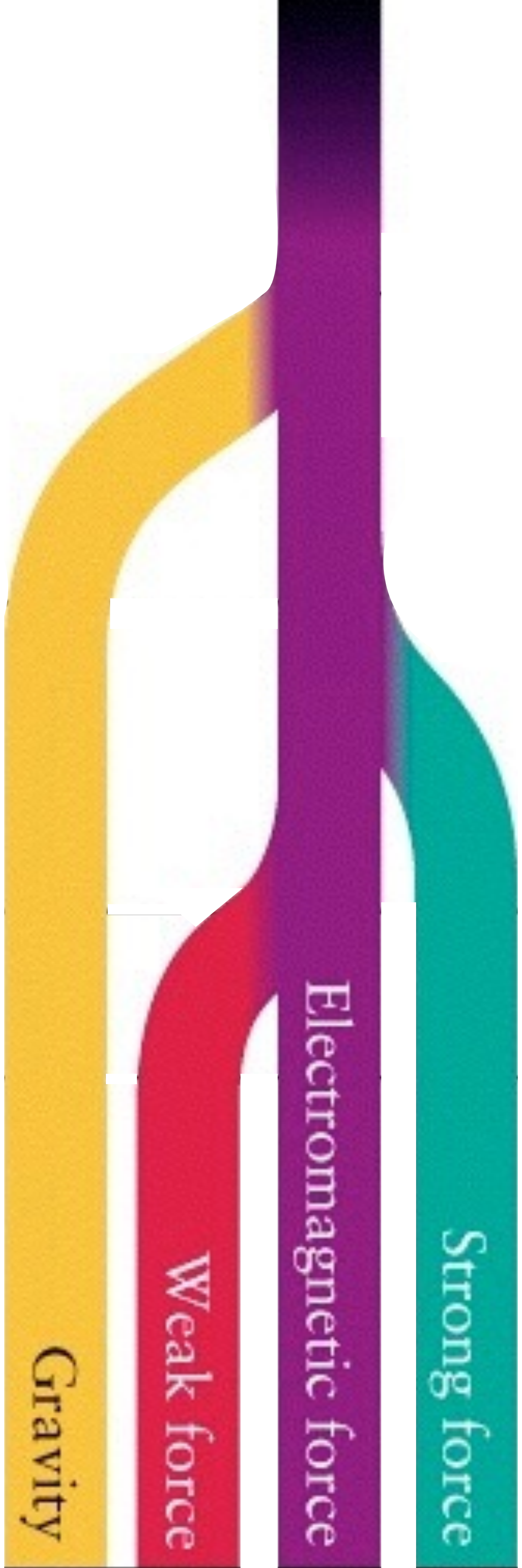
Instead of:



We would have:



II. Unification



String Theory?

GUT?

Electro-weak

Grand Unification

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

One family: $(3, 2, \frac{1}{6}) + (3^*, 1, \frac{1}{3}) + (3^*, 1, -\frac{2}{3}) + (1, 2, -\frac{1}{2}) + (1, 1, 1) \; +(1, 0, 0)$

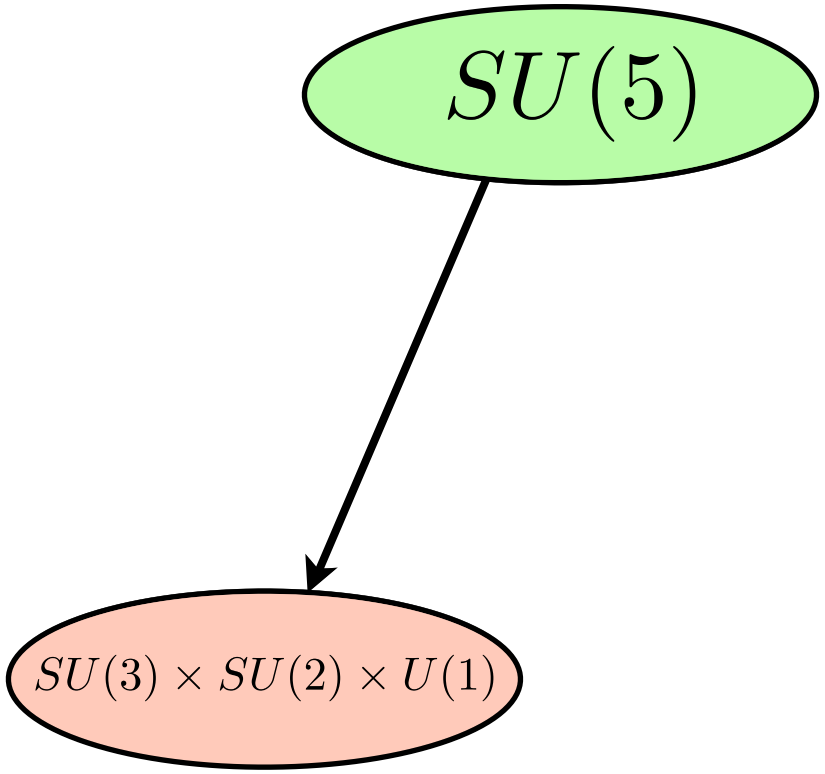
Higgs $+(1, 2, -\frac{1}{2})$

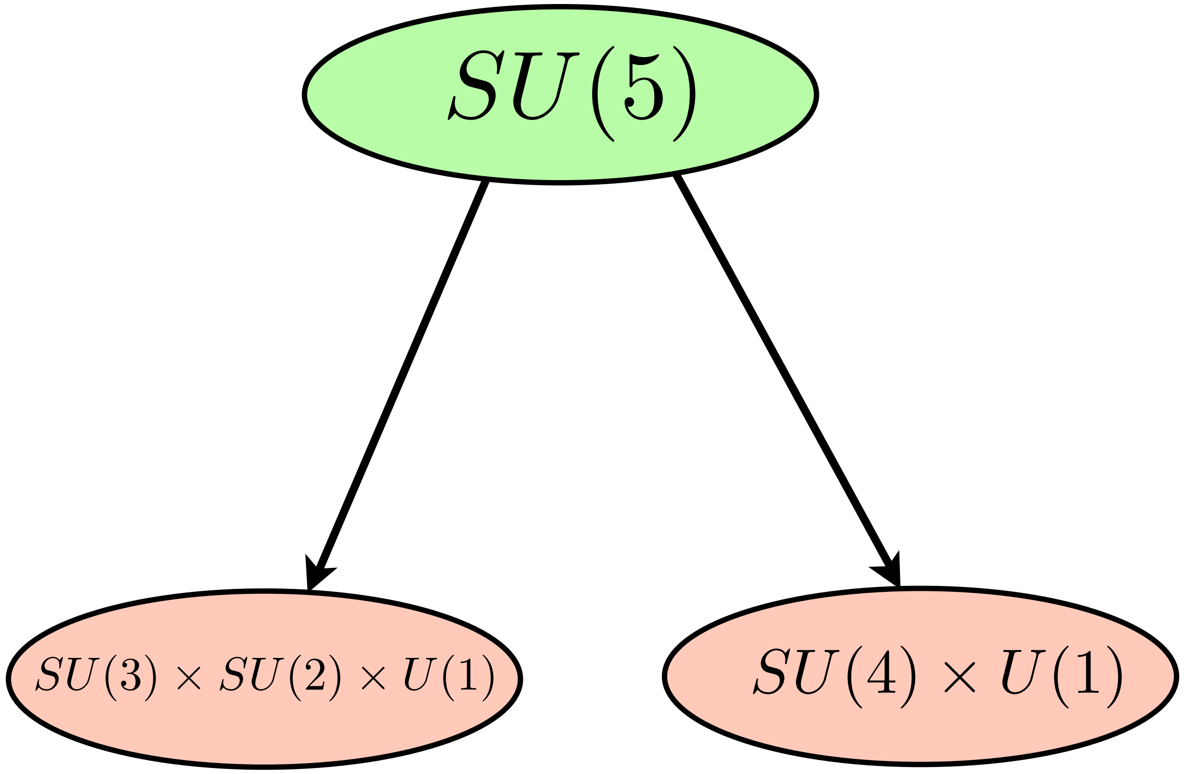
Structure looks arbitrary.

The most popular explanation is Grand Unified Theories

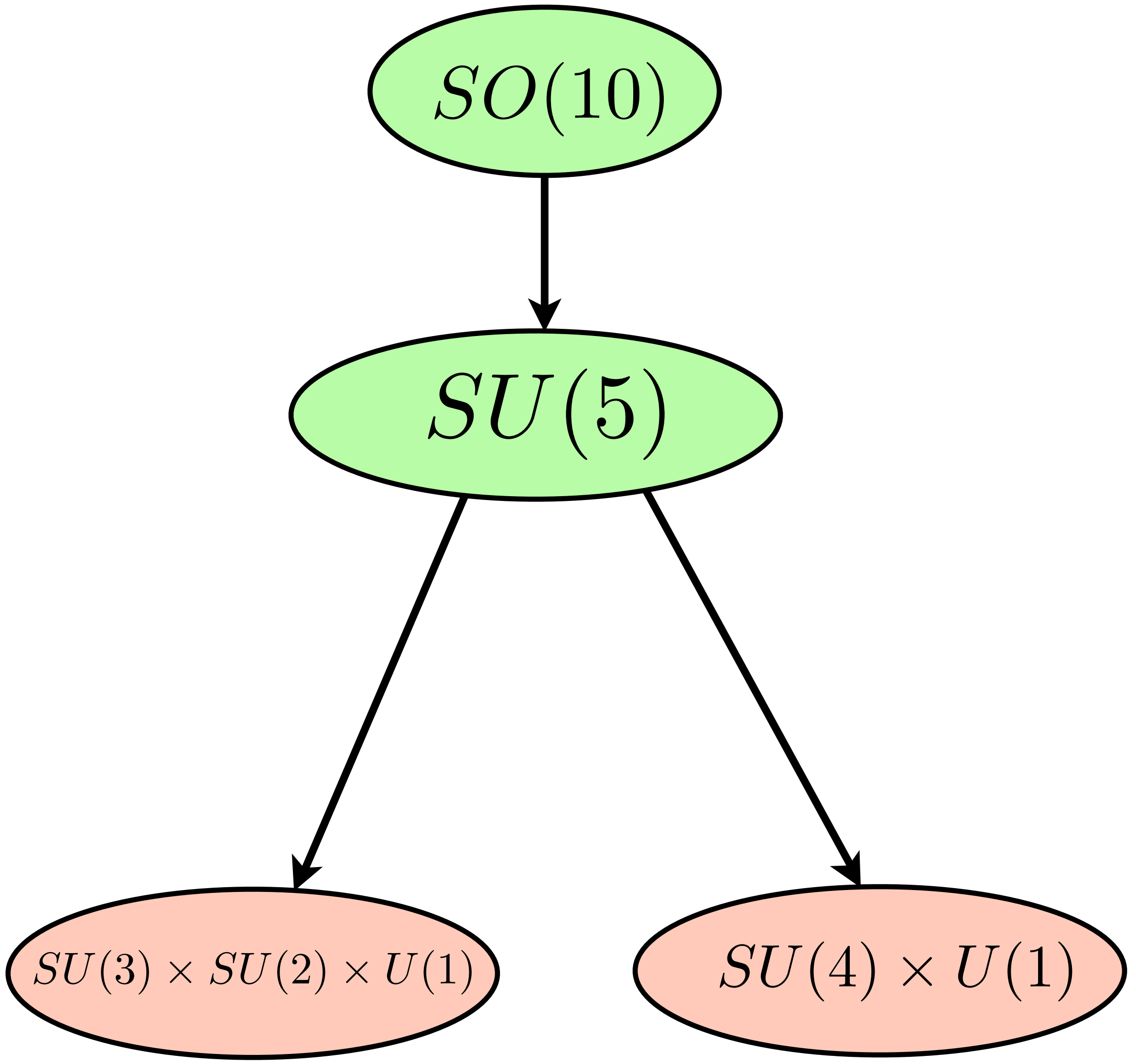
One family: $(5^*) + (10) + (1)$ of $SU(5)$

(16) of $SO(10)$

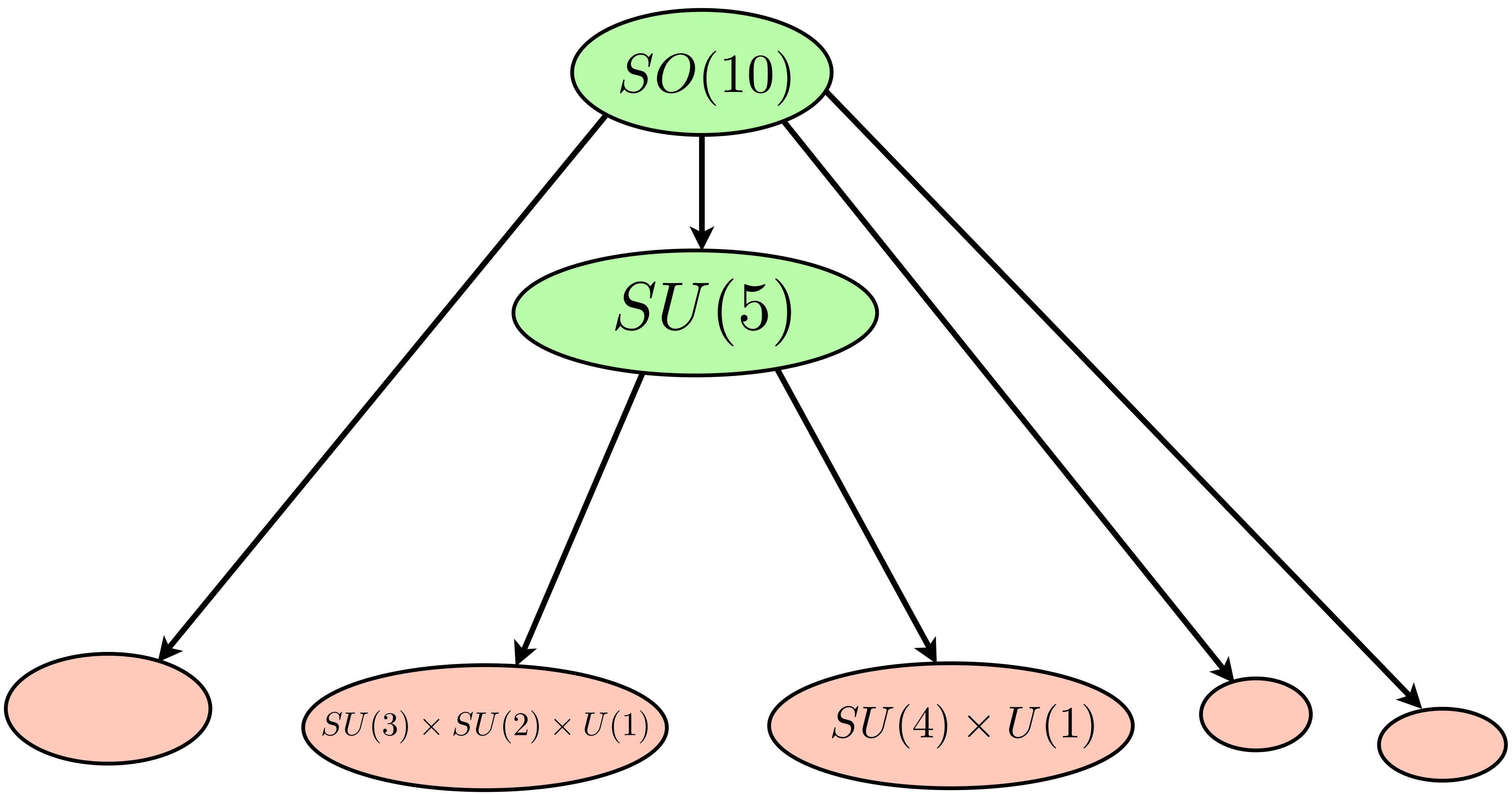

$SU(5)$
$SU(3) \times SU(2) \times U(1)$



$SU(5)$
$SU(3) \times SU(2) \times U(1)$
$SU(4) \times U(1)$



$SO(10)$
$SU(5)$
$SU(3) \times SU(2) \times U(1)$
$SU(4) \times U(1)$



$SO(10)$
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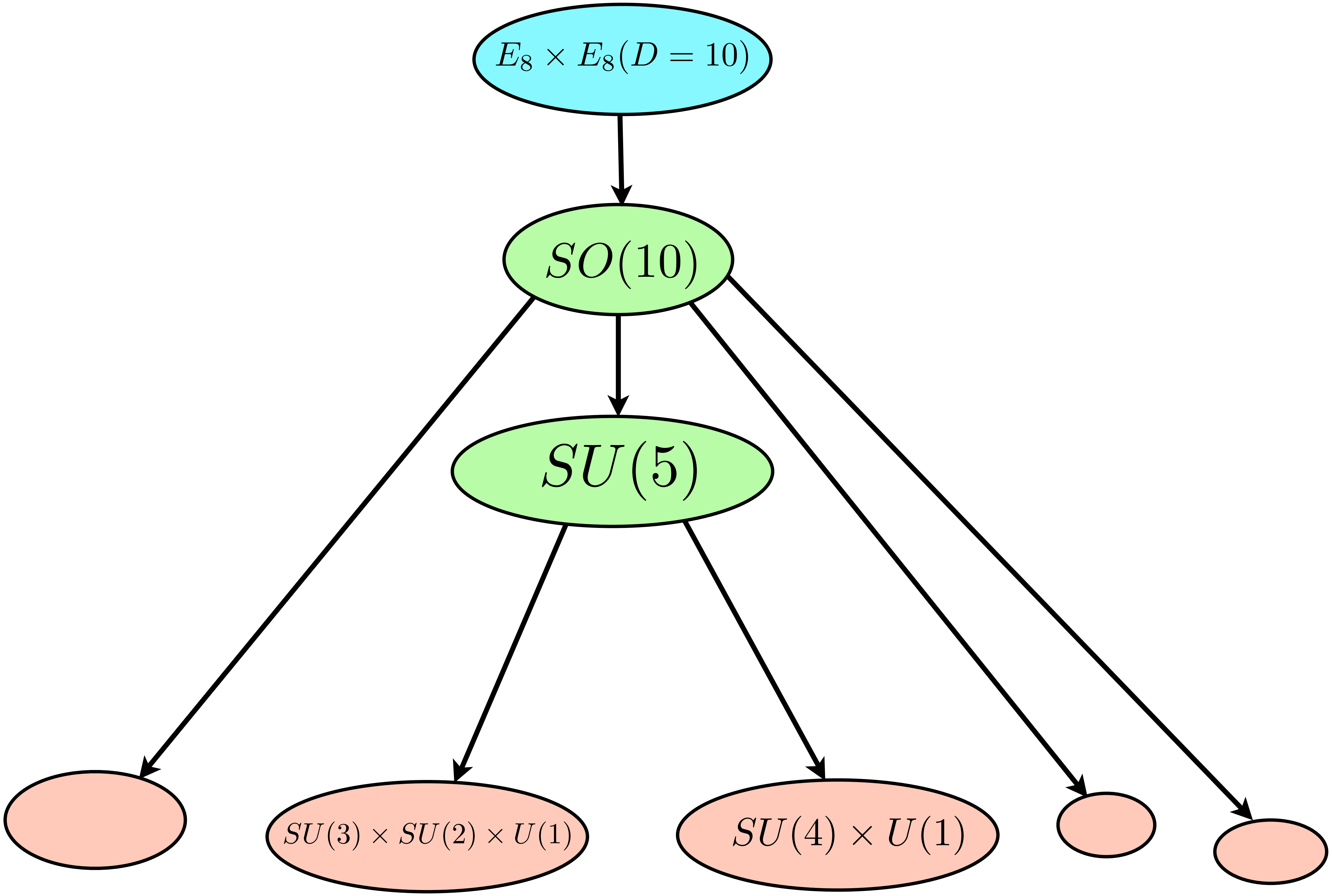
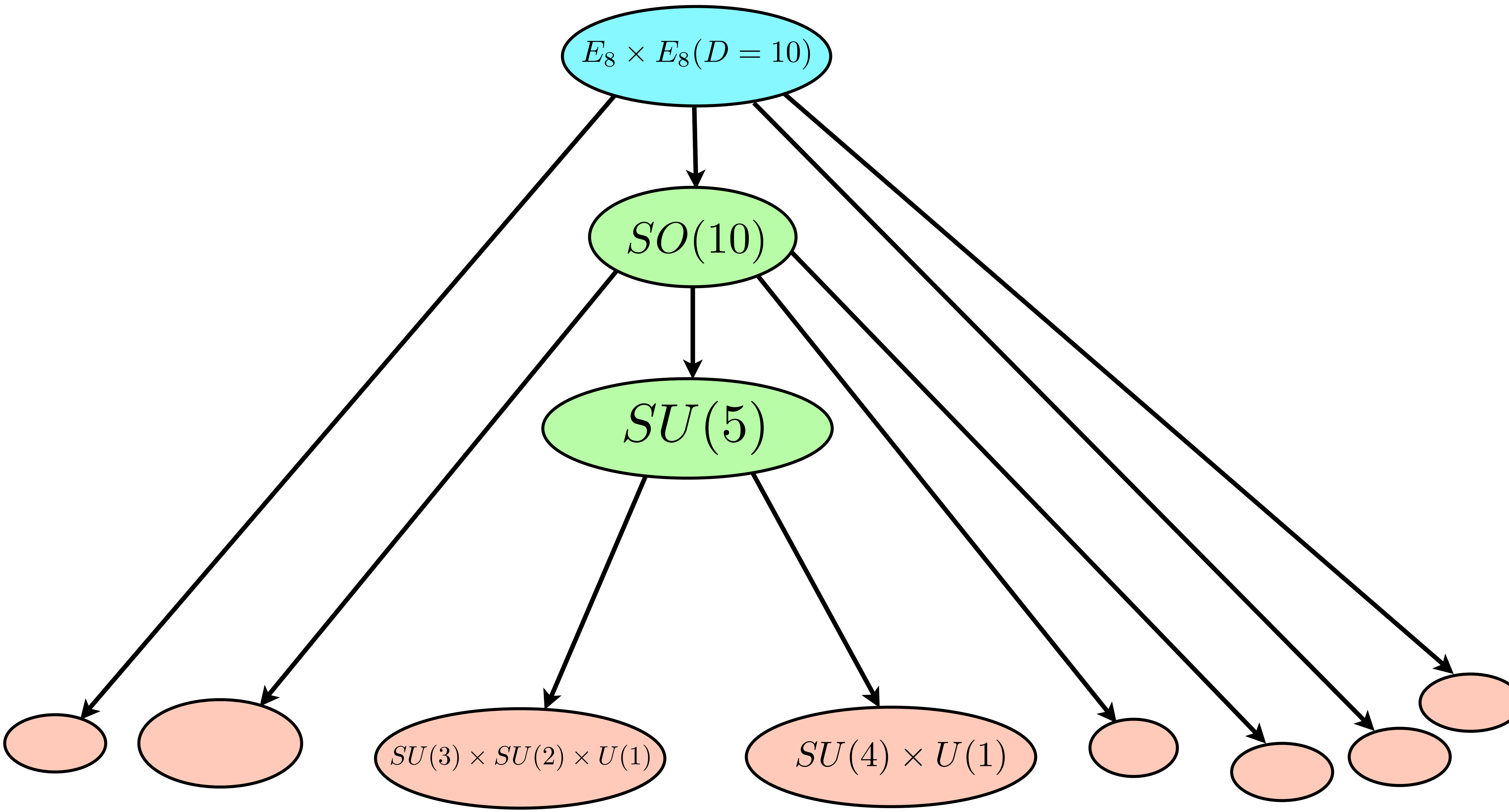


$E_8 \times E_8 (D = 10)$
$SO(10)$
$SU(5)$
$SU(3) \times SU(2) \times U(1)$
$SU(4) \times U(1)$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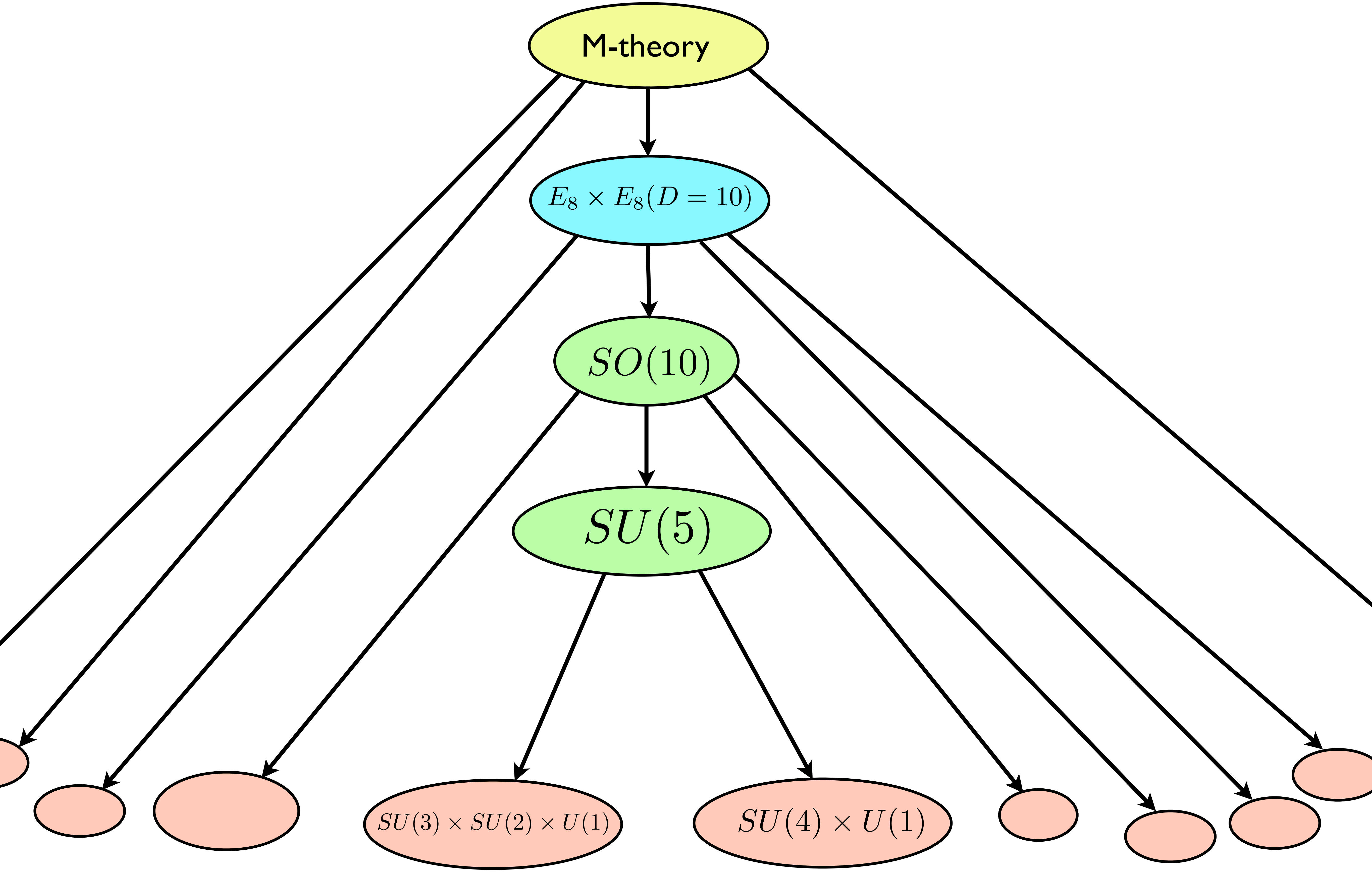

M-theory
$E_8 \times E_8 (D = 10)$
$SO(10)$
$SU(5)$
$SU(3) \times SU(2) \times U(1)$
$SU(4) \times U(1)$

The 1986 String Revolution

An explosion of papers and vacua:

Candelas,Horowitz, Strominger, Witten
Dixon, Vafa, Harvey, Witten
....
Strominger
Kawai, Tye, Lewellen
Lerche, Lüst, Schellekens
Antoniadis, Bachas, Kounnas
Ibanez, Nilles, Quevedo
Narain, Sarmadi, Vafa
....

A. Strominger
"Superstrings with Torsion", 1986

All predictive power seems to have been lost.

All of this points to the overwhelming need to find a dynamical principle for determining the ground state, which now appears more imperative than ever.

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

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

this number is of order 10^{1500} !

It seems that not much is left of the once celebrated uniqueness of string theory.

These large numbers are due to "compactification" of extra dimensions

But what did this mean?

III. Anthropic Arguments

Anthropic Features of the Standard Model

- **Structure:**
  - $U(1)$ with massless photon seems essential.
  - Strong interactions (nuclear physics, sun)
  - Weak interactions to protect chiral fermions?

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

- **Parameters:**

  $m_u,\ m_d,\ m_e,\ \alpha,\ \alpha_{\rm QCD}$ are clearly important.

  (Other masses in order of decreasing relevance:
  $m_H,\ m_t,\ m_\nu$; ……. $m_s,\ m_\mu$; ……. $m_c,\ m_b,\ m_\tau$)

Some constraints

- 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

$$m_e < m_n - m_p = 1.29\text{MeV}$$

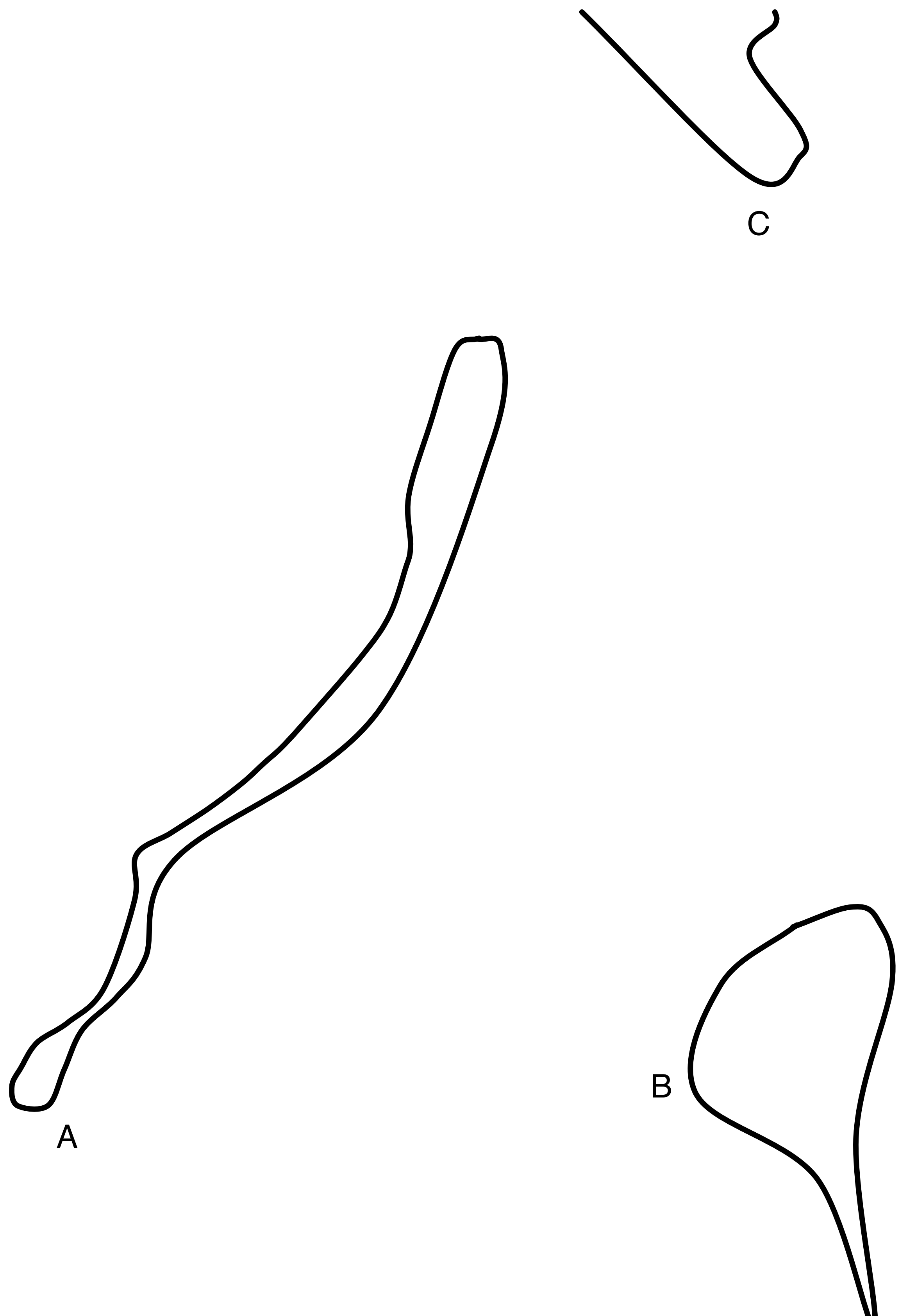
The gauge hierarchy

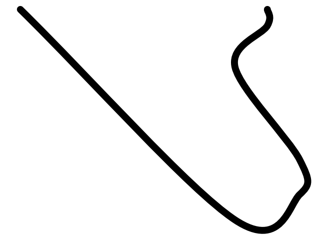
- Weakness of gravity: brains would collapse into black holes.

  Maximal number of constituents: $$\left(\frac{m_{\text{Planck}}}{m_p}\right)^3$$

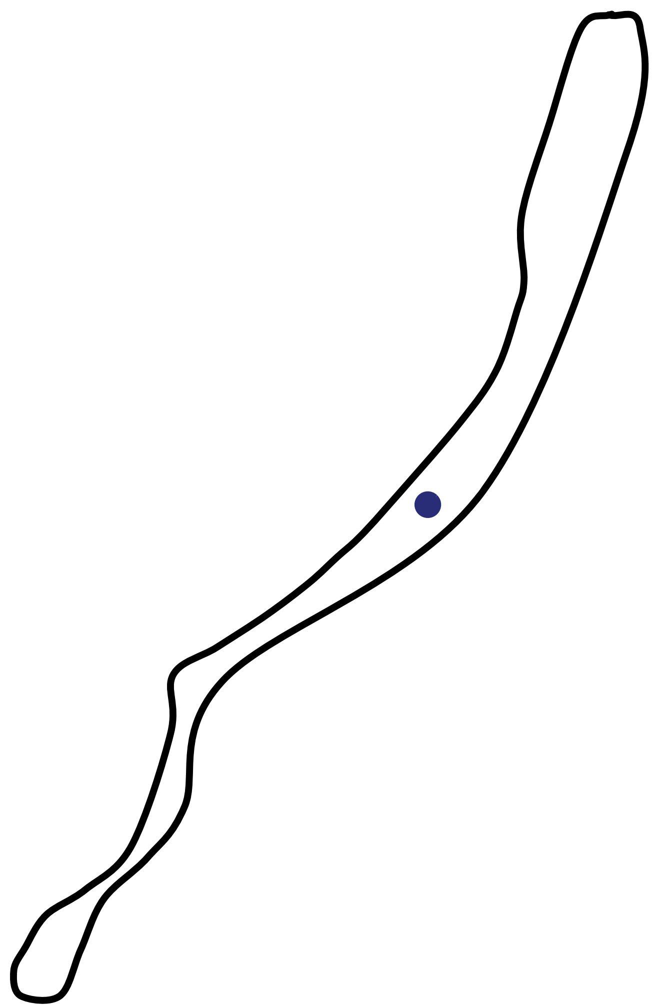
  For a "brain" with 10^{27} protons not to be a black hole,
  we need $m_{\text{p}} < 10^{-9}\, m_{\text{Planck}}$

- For more arguments see my review:
  Rev. Mod. Phys. 85 (2013) pp. 1491-1540


C
A
B

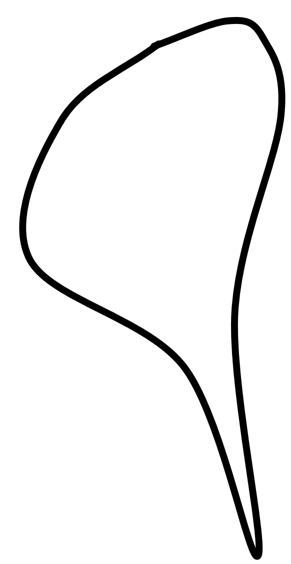


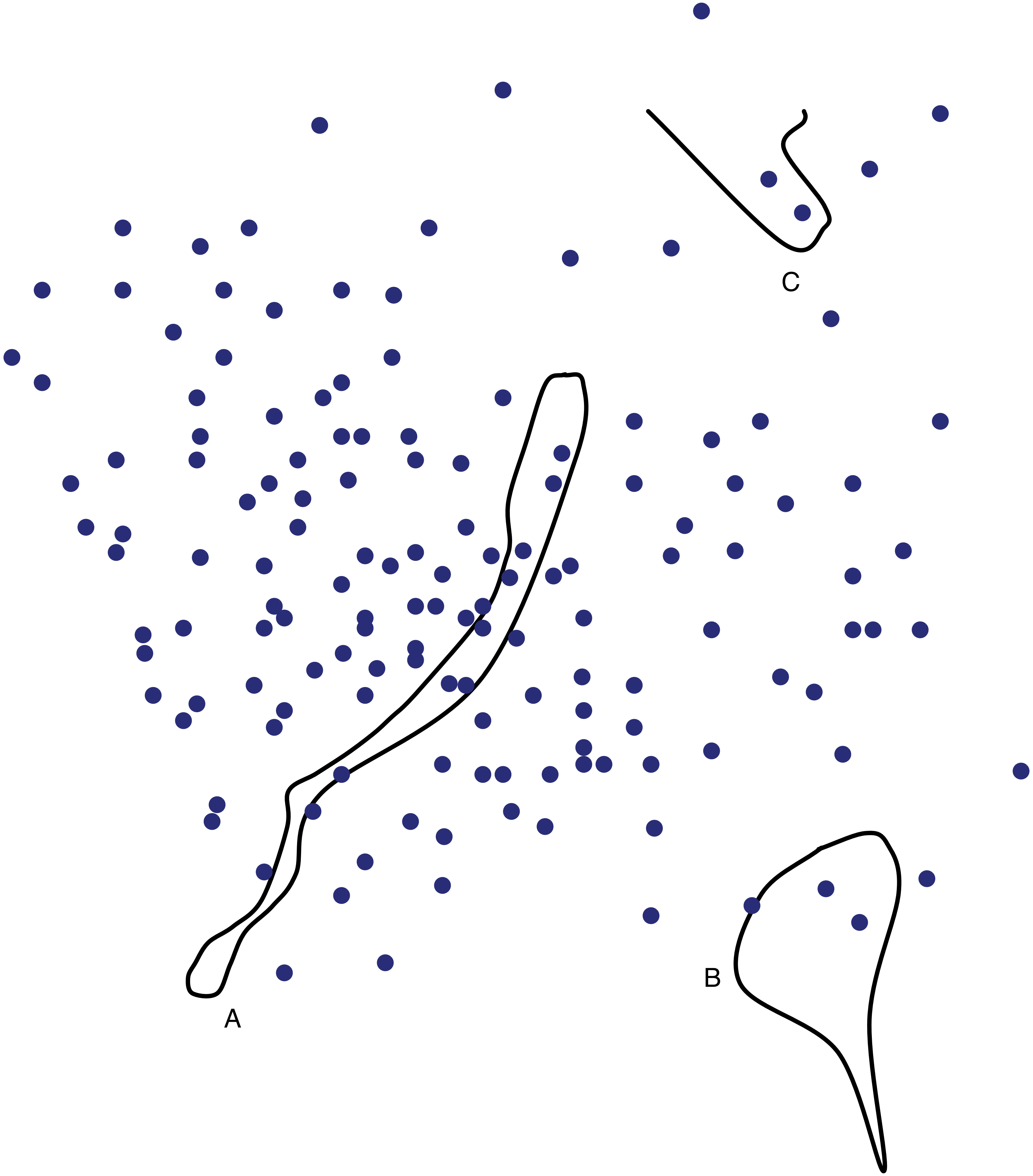
C



A

B




C
B
A

Why Now?

Atomic Physics

Nuclei as fundamental particles, plus an electron:

- Masses not fine-tuned.
- Fine-structure constant α not fine-tuned.
- Charges belong to the set of integers; changing them does not reduce complexity.

Nuclear Physics

Not a theory, nothing can be varied.
Not even the proton mass.

If the multiverse picture is true, one would expect to find some not especially nice gauge theory, with a not especially nice choice of matter and not especially nice parameter values, which can be consistently extrapolated to the Planck scale, because that is where it came from.

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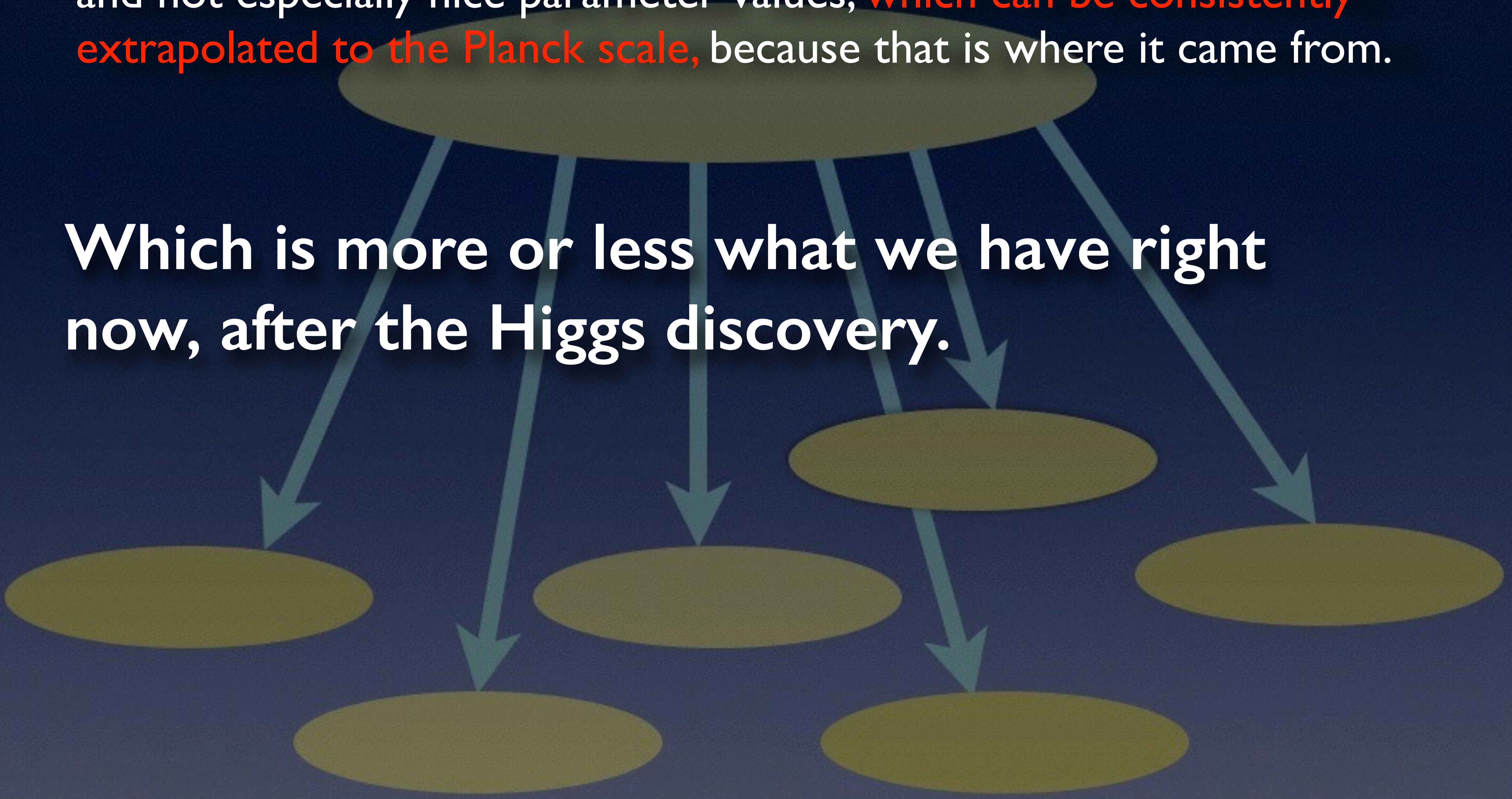
Which is more or less what we have right now, after the Higgs discovery.



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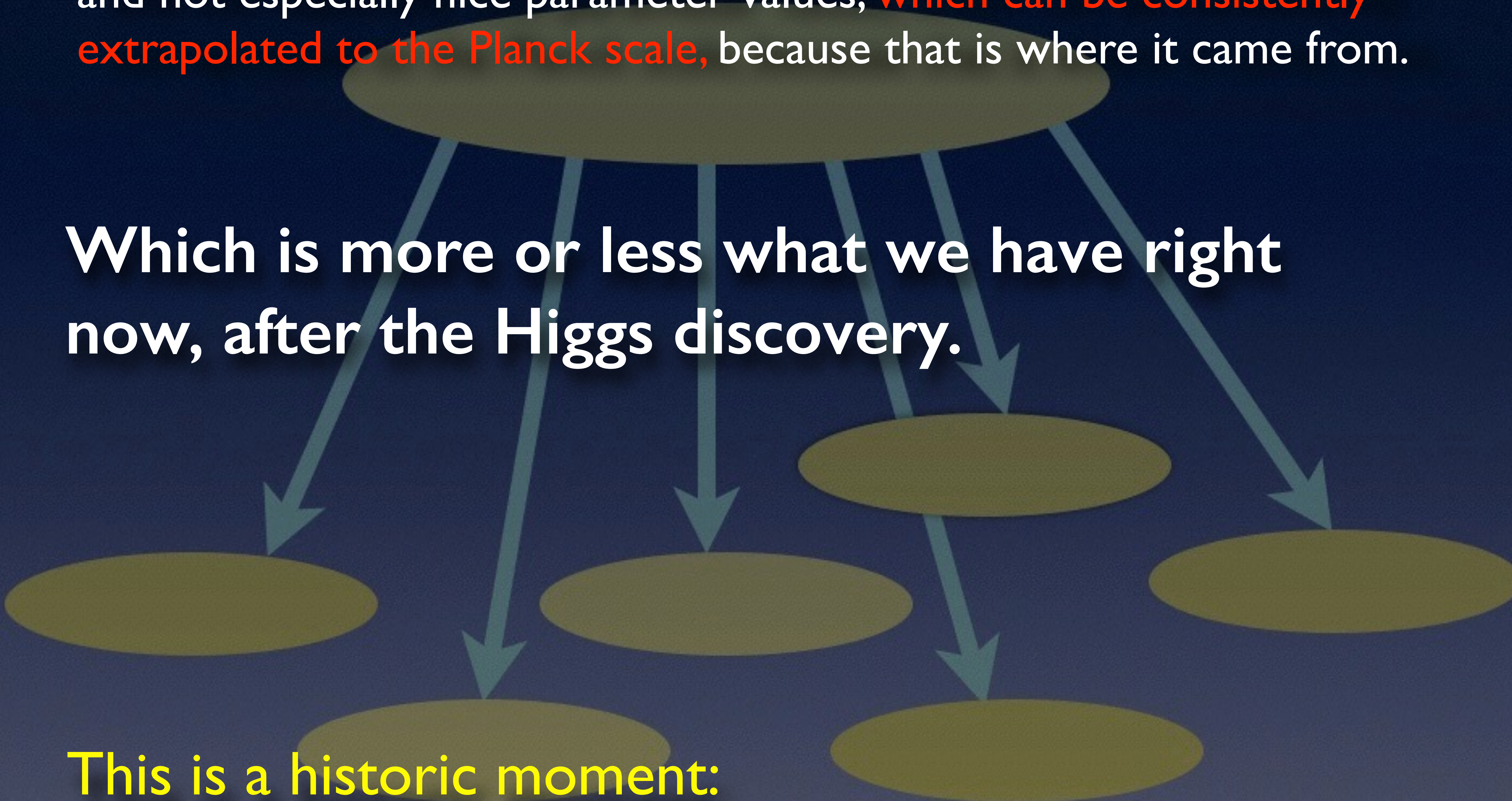


Which is more or less what we have right now, after the Higgs discovery.

This is a historic moment:
Atomic, nuclear and hadronic physics do not qualify.

Problems and Worries

Problems:

(Clearly requiring something beyond the Standard Model)

- Gravity
- Dark matter
- Baryogenesis
- Inflation.

Worries:

(Problems that may exist only in our minds)

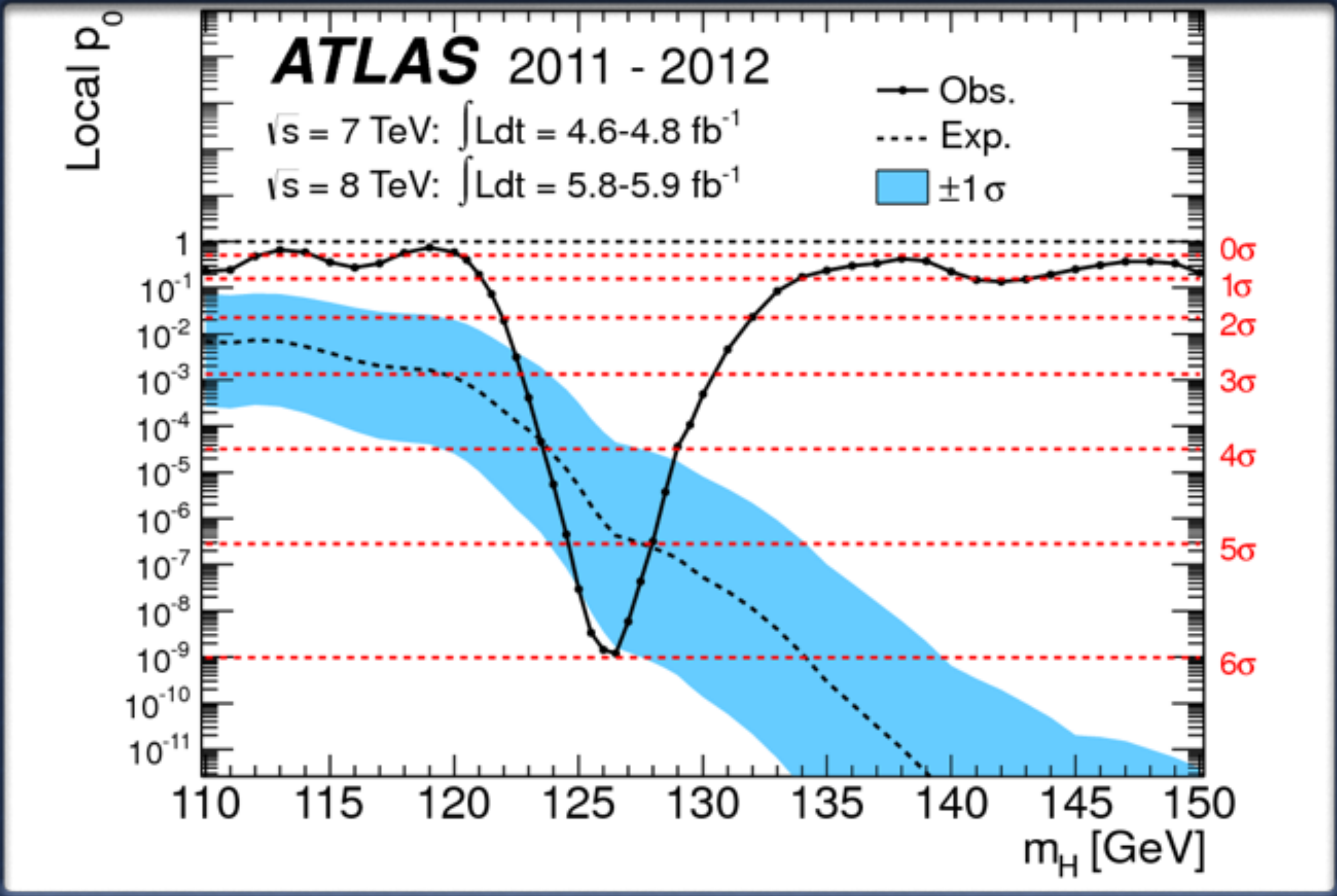
- Choice of gauge group and representations
- Why three families?
- Charge quantization
- Quark and lepton mass hierarchies, CKM matrix.
- Small neutrino masses.
- Strong CP problem.
- Gauge hierarchy problem
- Dark Energy (non-zero, but very small)

The Singlet Era?

All problems and several worries can be solved by singlets:

- Dark matter
  (axions or singlet neutrinos)
- Baryogenesis
  (Leptogenesis using Majorana phases of neutrinos)
- Inflation
  (axions? Perhaps even just the Higgs can do it)
- Strong CP problem
  (axions)
- Small neutrino masses
  (see-saw mechanism using singlet neutrinos)

Radical new physics (supersymmetry, Grand Unification, ...) is only needed to deal with some of the worries



Local p_0
ATLAS 2011 - 2012
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8-5.9 fb^{-1}
Obs.
Exp.
±1 σ
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0σ
1σ
2σ
3σ
4σ
5σ
6σ
110
115
120
125
130
135
140
145
150
m_H [GeV]

IV. Scalars

The first scalar particle, the Higgs boson, has just been found. It is a Lorentz singlet, but it couples to quarks and leptons.

It was hard enough to find, but gauge singlet scalars are even harder to find, especially if they are very massive.

Is all we can see all there is?

If fundamental scalars exist, polynomials of these scalars would multiply all terms in the Langrangian.

For example, in QED

$$\frac{1}{\alpha} F_{\mu\nu} F^{\mu\nu} \to P\left(\frac{\phi_i}{M}\right) F_{\mu\nu} F^{\mu\nu}$$

(M is the Planck Mass)

The value of α is determined by the v.e.v. of the fields φ_i.

Then all Standard Model parameter are "environmental".

In string theory, hundreds of such scalars exist ("moduli").
Their potentials are believed to have a huge number of minima ("the String Theory Landscape"), of order $10^{\textit{hundreds}}$

Bousso, Polchinski (2000)
Kallosh, Linde, Kachru, Trivedi (2003)
Douglas (2003)
"The Anthropic Landscape of String Theory"
L. Susskind (2003)

Changing shapes and sizes of the "balloons" corresponds in four dimensions to changing vacuum expectations of scalar field.

Changes in energy generate a potential for those fields.

We have to find local minima that are stable in all directions.

Furthermore the energy of the ground state is important.

Vacuum Energy

Vacuum energy in Quantum Field Theory

$$T_{\mu\nu} = -\rho_{\mathrm{vac}} g_{\mu\nu}$$

Irrelevant (in the absence of gravity).

Einstein equation, including the cosmological constant

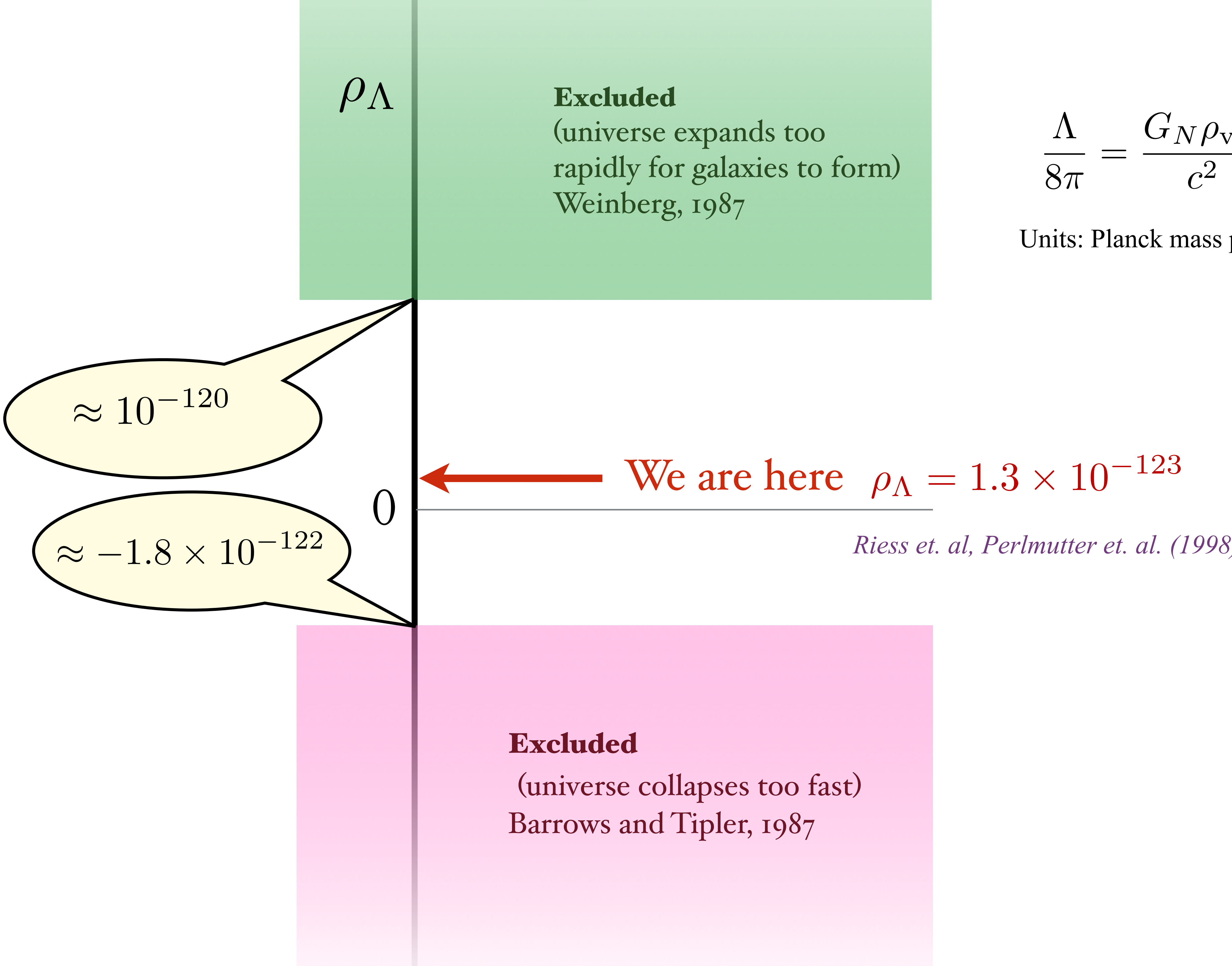
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Gravity sees vacuum energy as a contribution to Λ.

Anthropic Bounds

$$\frac{\Lambda}{8\pi} = \frac{G_N \rho_{\text{vac}}}{c^2} := \rho_\Lambda$$

Units: Planck mass per Planck volume



To “neutralize” the cosmological constant we need a “discretuum” of at least 10^{120} ground states.

The hope is to get such large numbers using “fluxes”.

(R. Bousso, J. Polchinski, 2000)

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, 2003)

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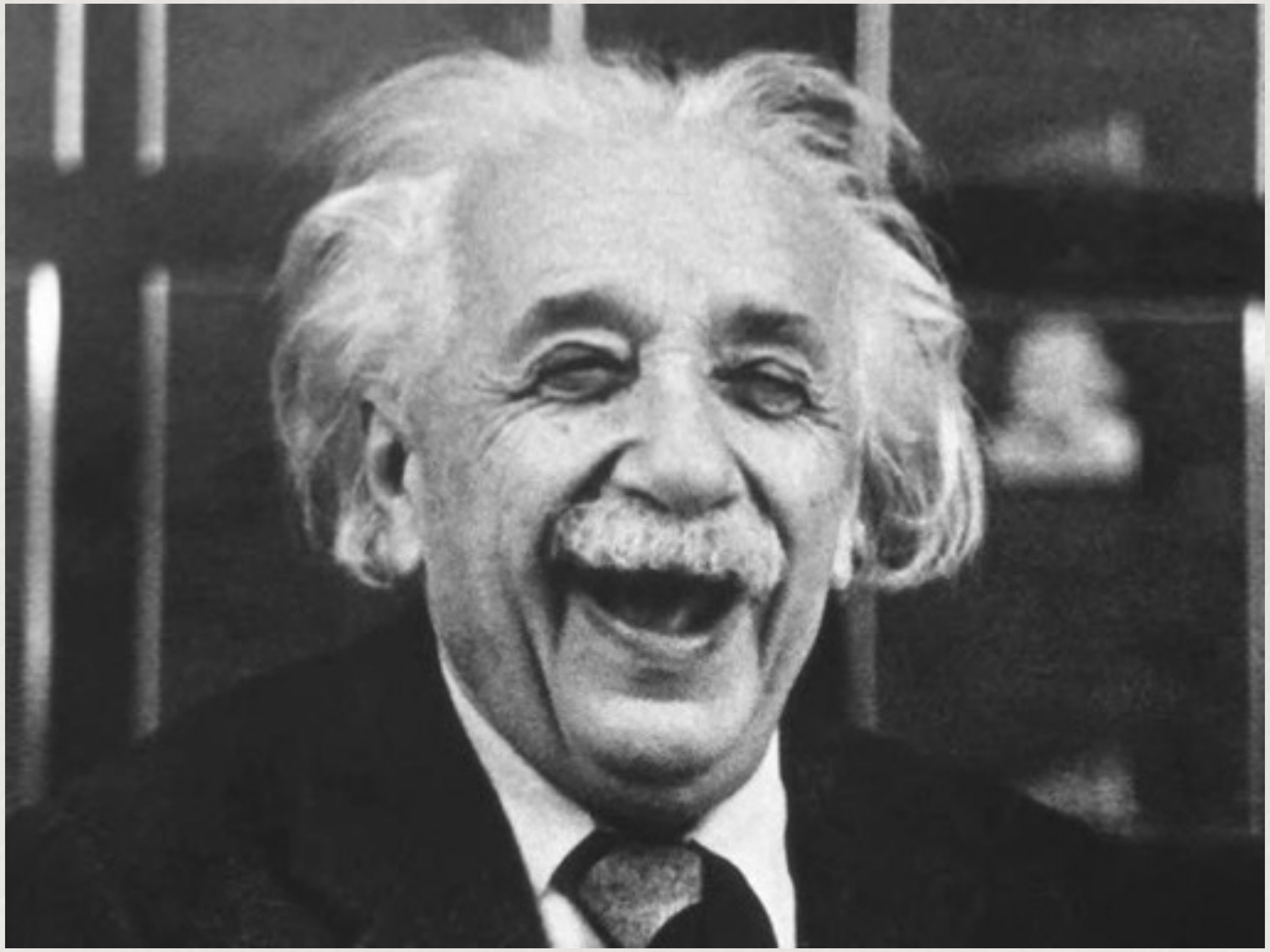
(M. Douglas, 2003)

$(N_{max})^{Loops}$

deSitter Vacua?

- *Large numbers of meta-stable "vacua" are likely to exist*
- *But this is under good computational control only for negative Λ (using supersymmetry)*
- *Existence of a landscape of deSitter vacua (positive Λ) remains to be demonstrated convincingly*

What would Einstein say?



What would Einstein say?

- The masses and coupling constants cannot be computed from first principles, but given enough digits, one can compute the rest exactly.
- If Einstein's dream is wrong, a finite discrete set is the next best thing.
- Furthermore, a finite set demystifies anthropic coincidences.
  So this is better than Einstein's dream.
- To achieve this, one needs a theory that controls all quantum corrections including those of gravity, and yields physical transitions between the vacua.
- String theory is the only candidate we know:
  A unified theory, though not exactly what Einstein was dreaming of.

Conclusions

- We may very well live in a multiverse.
- This is not irrelevant. It has a huge impact on our outlook on problems in particle physics and gravity.
- Plenty of possibilities (from theory, experiment and observations) for discovering this is wrong, but no gold-plated method for proving it is correct.
- Extraordinary claims require extraordinary evidence.
  But the extraordinary claim is the uniqueness of the laws of physics, given the enormous number of alternatives in QFT.

Variations in Constants of Nature

Spatial variation in the fine-structure constant – new results from VLT/UVES

Julian A. King, John K. Webb, Michael T. Murphy, Victor V. Flambaum, Robert F. Carswell[3] Matthew B. Bainbridge, Michael R. Wilczynska and F. Elliot Koch. **Mon.Not.Roy.Astron.Soc. 422 (2012) 3370-3413** **(arXiv:1202.4758)**

"We derive values of $\Delta\alpha/\alpha \equiv (\alpha_z - \alpha_0)/\alpha_0$ from 154 absorbers, and combine these values with 141 values from previous observations at the Keck Observatory in Hawaii. In the VLT sample, we find evidence that α increases with increasing cosmological distance from Earth. However, as previously shown, the Keck sample provided evidence for a smaller α in the distant absorption clouds. Upon combining the samples an apparent variation of α across the sky emerges which is well represented by an angular dipole model."

$\Delta\alpha/\alpha \approx .5 \times 10^{-5}$

A Stringent Limit on a Drifting Proton-to-Electron Mass Ratio from Alcohol in the Early Universe **Science 339 (6115), 46 (2012)**

Julija Bagdonaite, Paul Jansen, Christian Henkel, Hendrick L. Bethlem, Karl M. Menten, Wim Ubachs

"we deduced a constraint of $\Delta\mu/\mu = (0.0 \pm 1.0) \times 10^{-7}$ at redshift z=0.89"

If confirmed this has huge consequences

- Evidence against derivability of the Standard Model and its parameters
In particular, against fine structure constant numerology.

- Evidence against the string theory landscape
(in particular the tuning of vacuum energy)

$$\Lambda = \ldots + \frac{1}{\alpha} F_{\mu\nu} F^{\mu\nu} + \ldots = 10^{-120} \times (M_{\text{Planck}})^4$$

Dine, Banks, Douglas (2002)

Grand Unification

One family: $(3, 2, \frac{1}{6}) + (3^*, 1, \frac{1}{3}) + (3^*, 1, -\frac{2}{3}) + (1, 2, -\frac{1}{2}) + (1, 1, 1) + (1, 0, 0)$

Higgs $+(1, 2, -\frac{1}{2})$

Structure looks arbitrary
Charge quantization not explained by *SU(3)* x *SU(2)* x *U(1)*

The most popular explanation is Grand Unified Theories

One family: $(5^*) + (10) + (1)$ of $SU(5)$

(16) of $SO(10)$

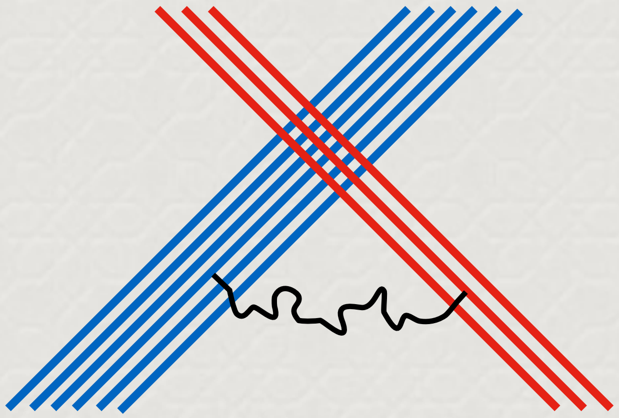
Grand Unification?

- Higgs does not fit in a GUT rep.
- Breaking to *SU(3)* x *SU(2)* x *U(1)* is not explained
  (There are alternatives, like *SU(4)* x *U(1)*.)
- Choice of representations is not explained

We can solve all of these problems by replacing symmetry by an anthropic argument

B. Gato-Rivera and A. N. Schellekens, arXiv:1401.1782

An Anthropic Alternative



Stacks of *M* and *N* intersecting branes.

This produces matter coupling to a gauge group $SU(M) \times SU(N) \times U(1)$

Anthropic requirements:

- Massless photon
- No massless charged leptons
- $>$ 3 distinct stable atoms

Standard Model group and families are the only solution.
The Higgs choice is determined!

Charge quantization without GUTs
In the absence of susy, GUTs only offer disadvantages