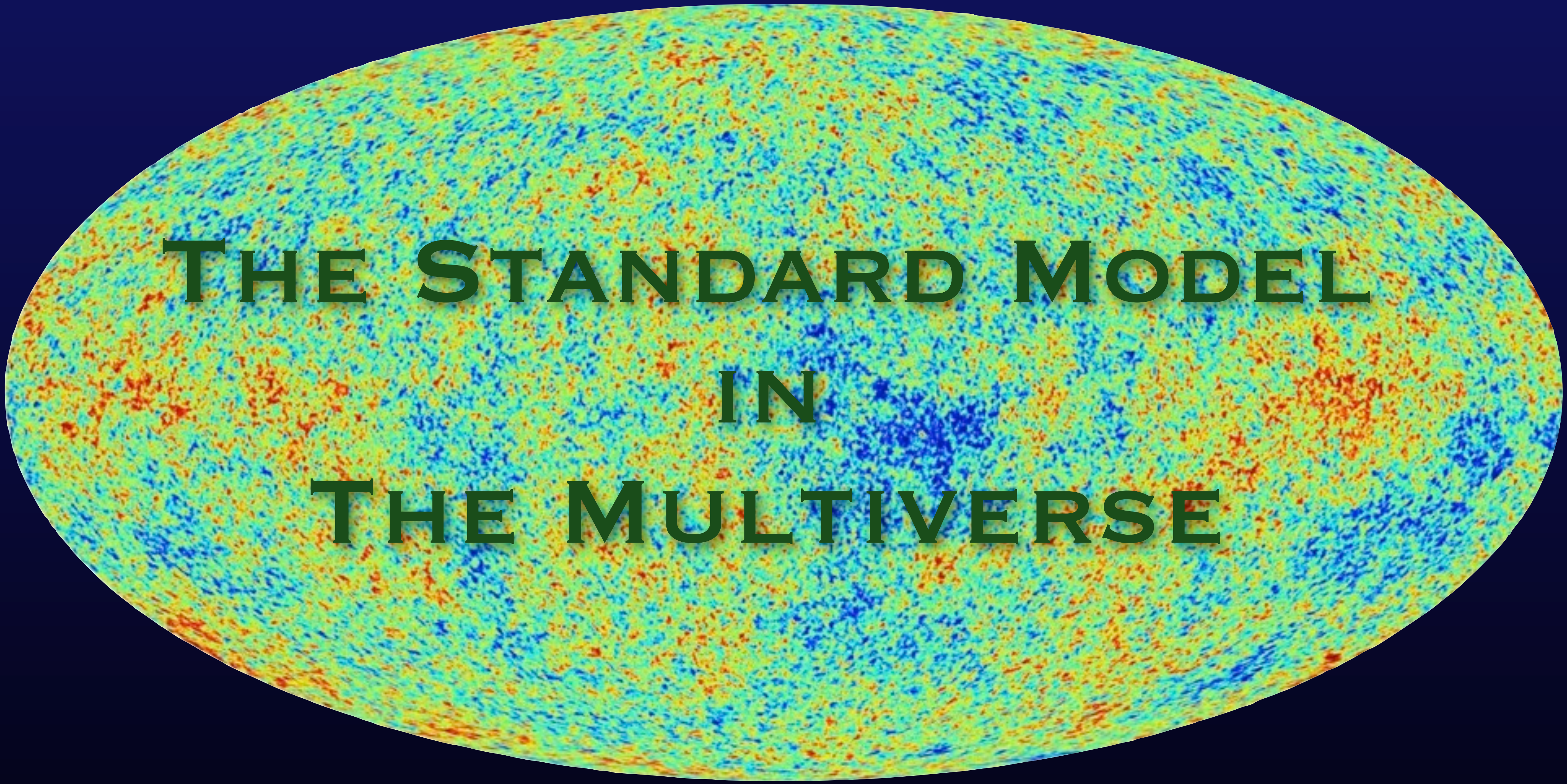
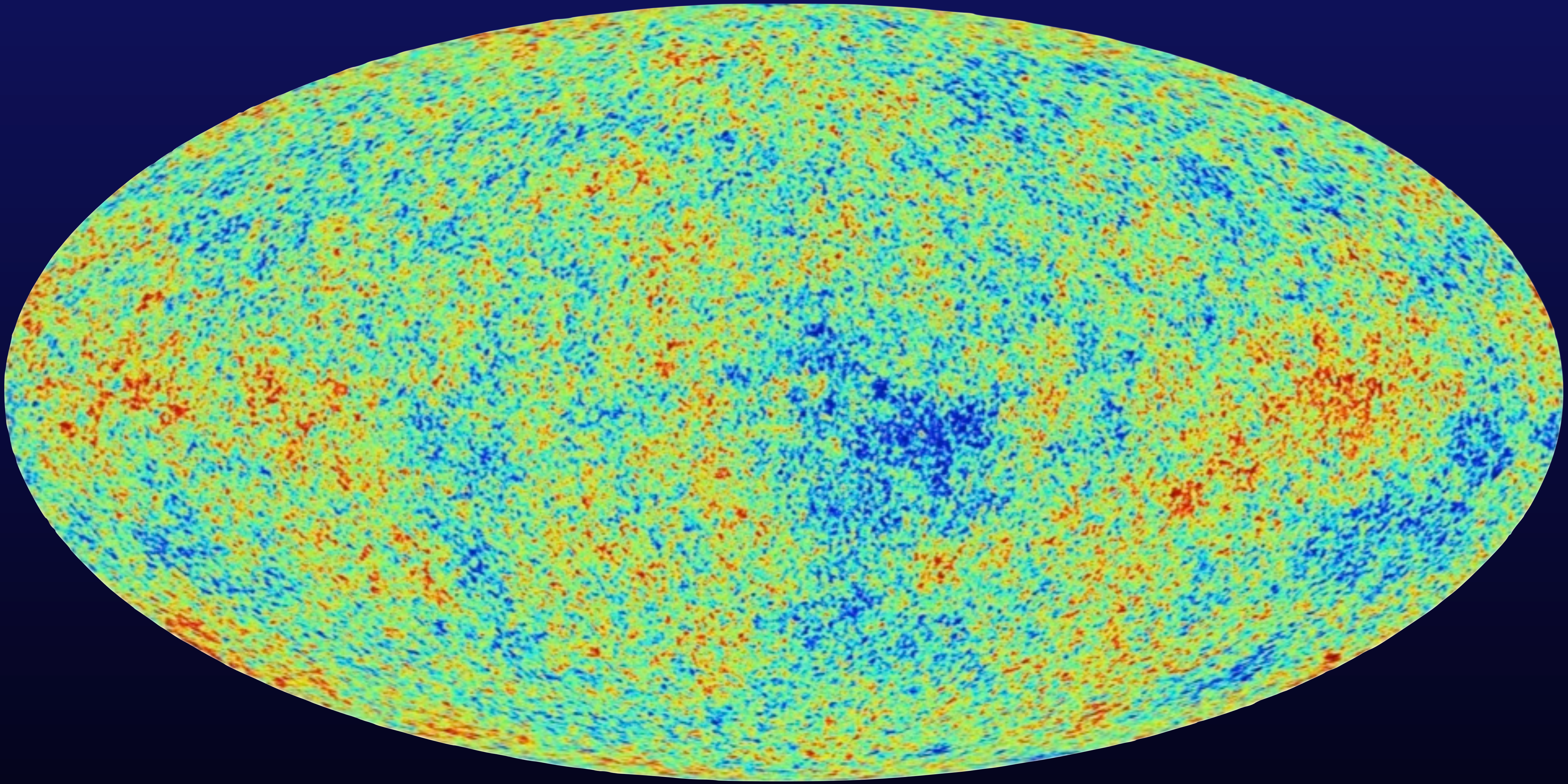
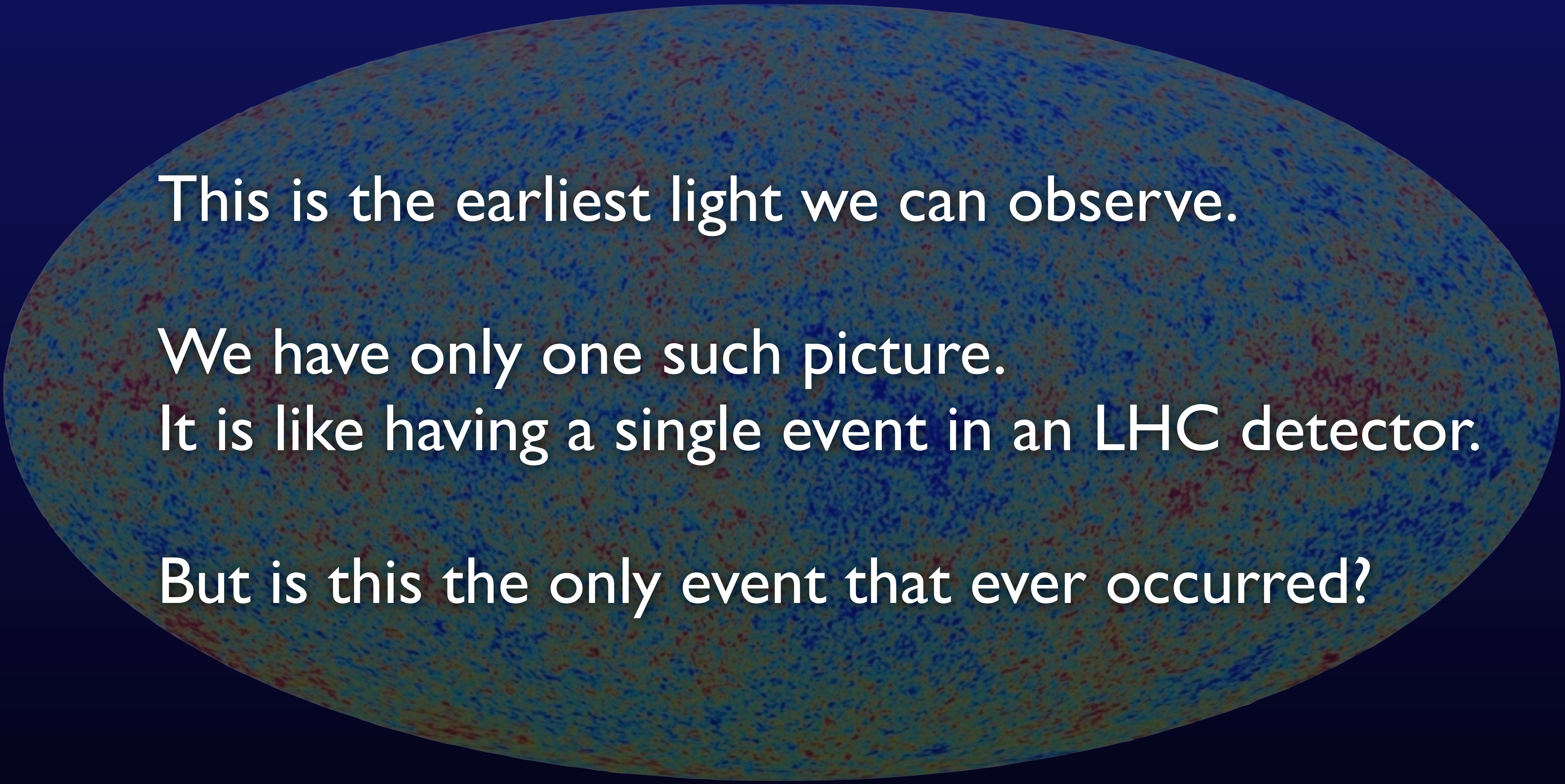


THE STANDARD MODEL
IN
THE MULTIVERSE

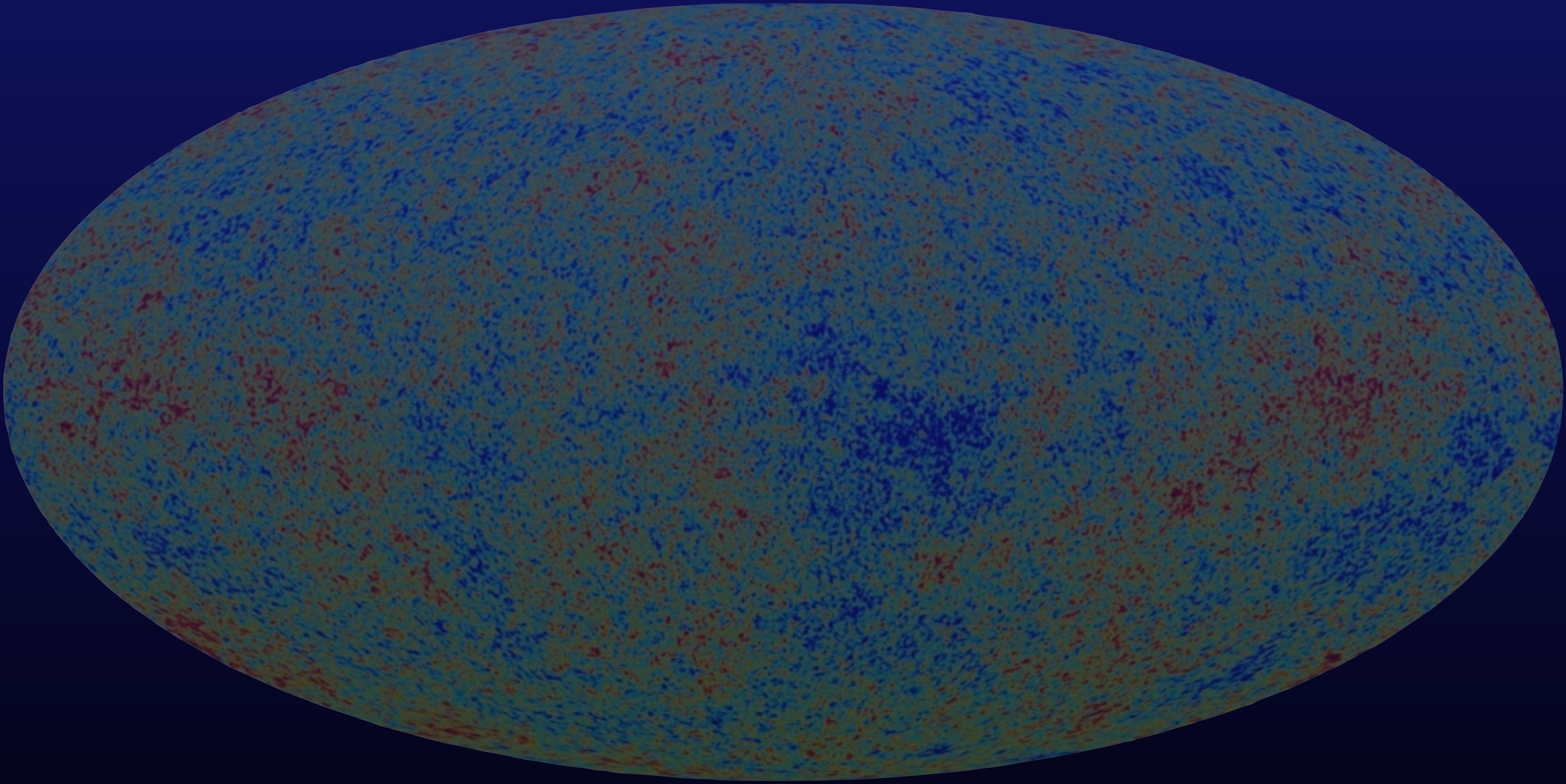




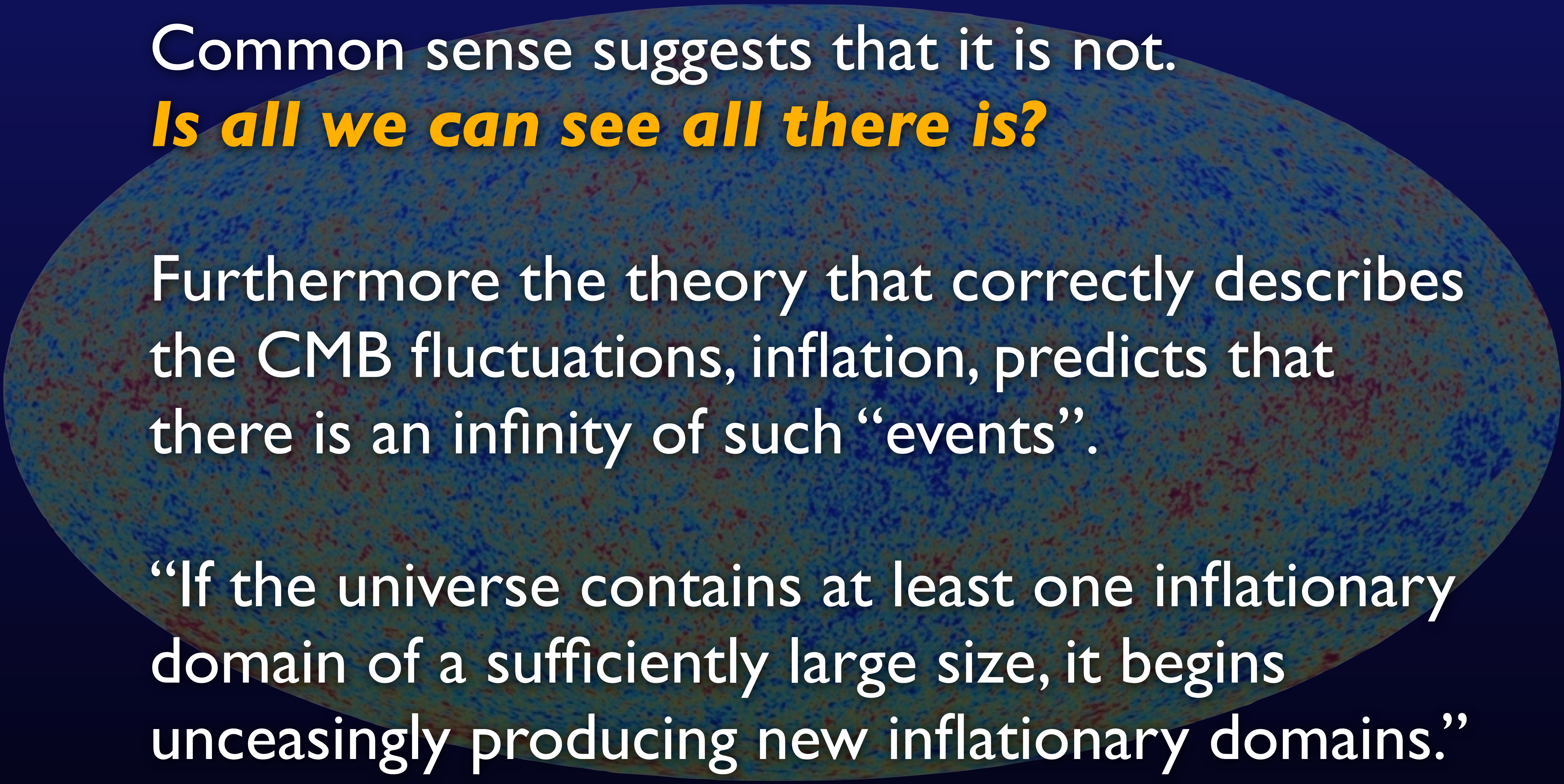
This is the earliest light we can observe.

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?



Andrei Linde (1994)

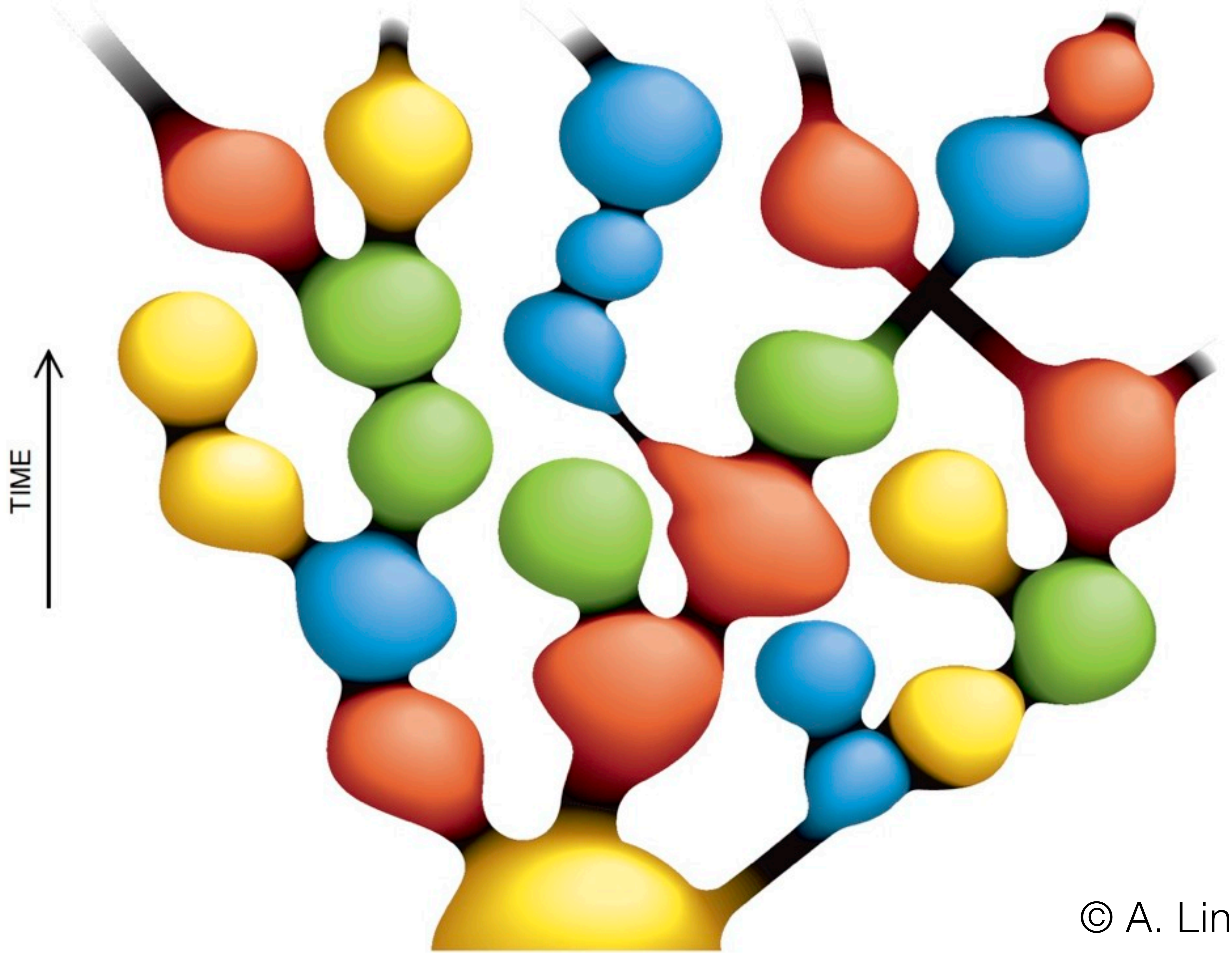


Common sense suggests that it is not.
Is all we can see all there is?

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

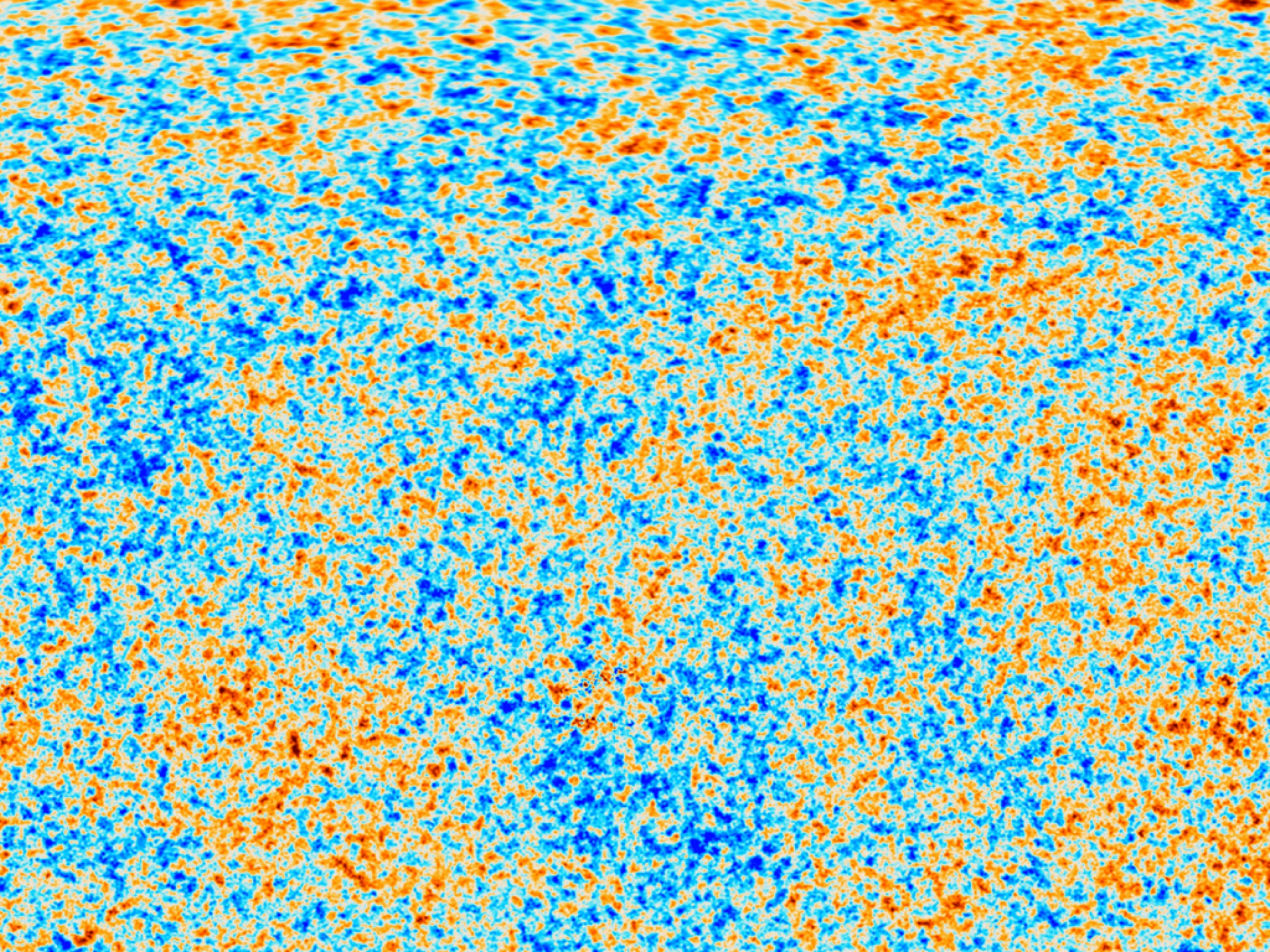
“If the universe contains at least one inflationary domain of a sufficiently large size, it begins unceasingly producing new inflationary domains.”

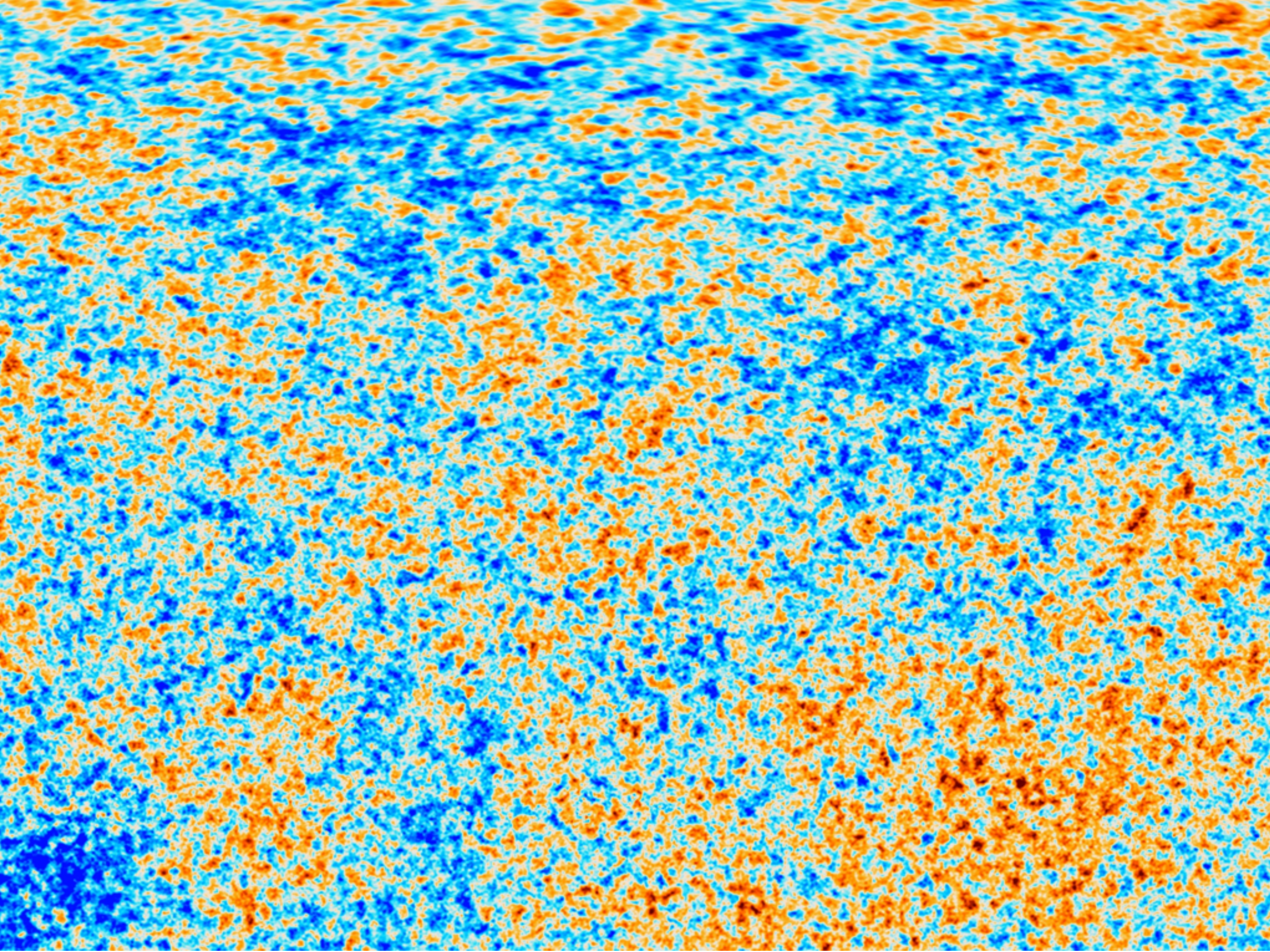
Andrei Linde (1994)


TIME

So what would these other universe 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?

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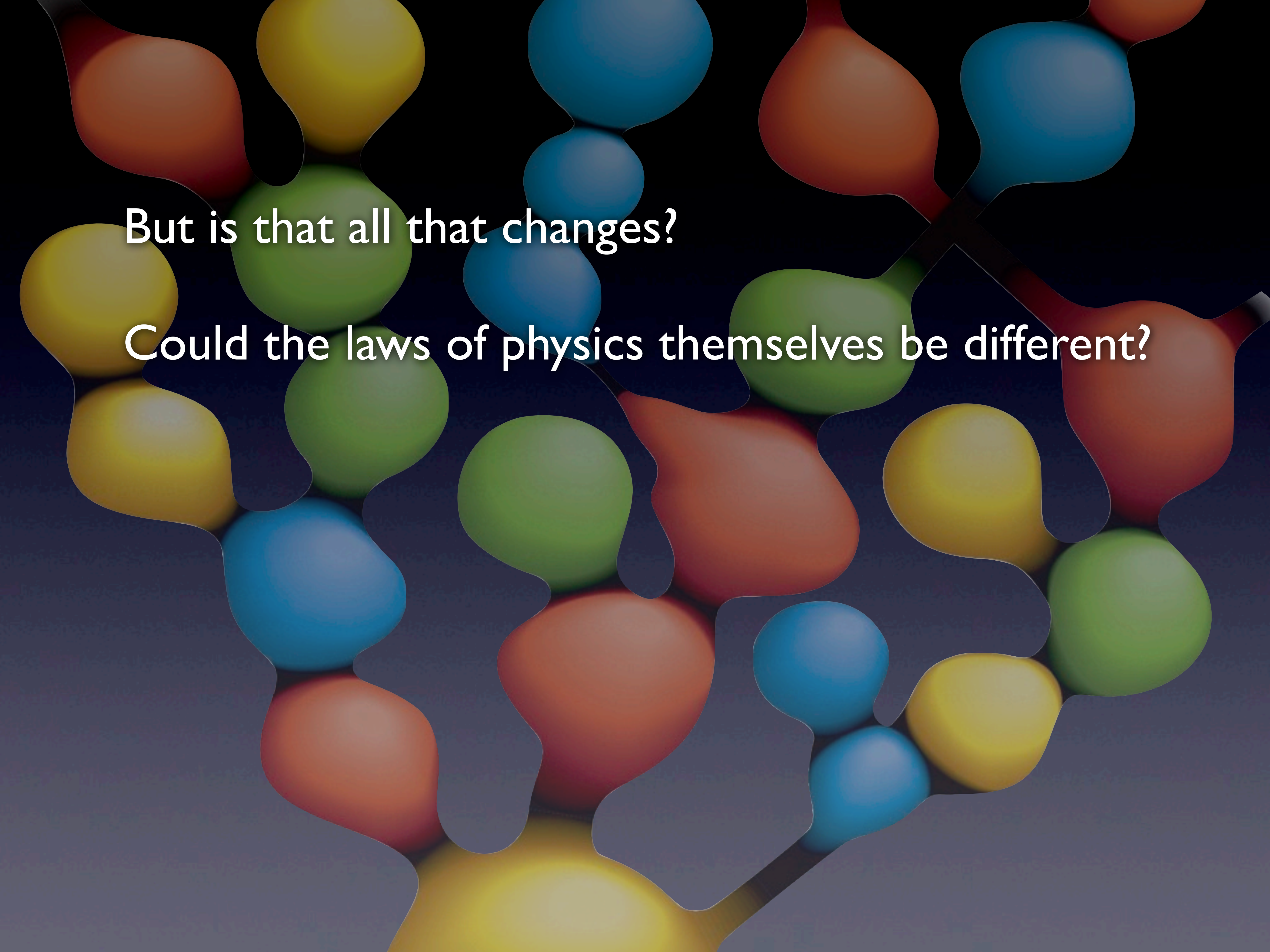
Could the laws of physics themselves be different?



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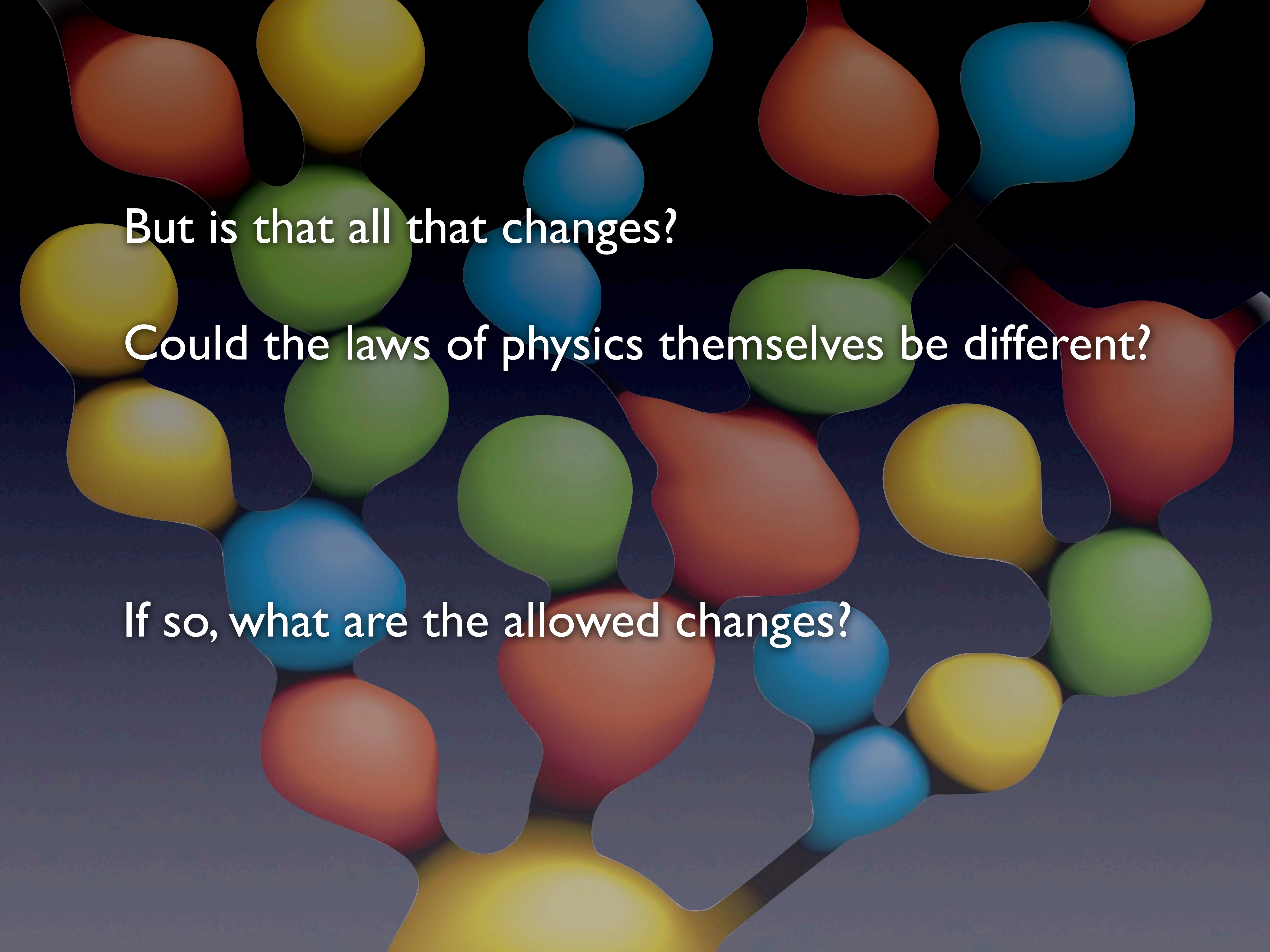

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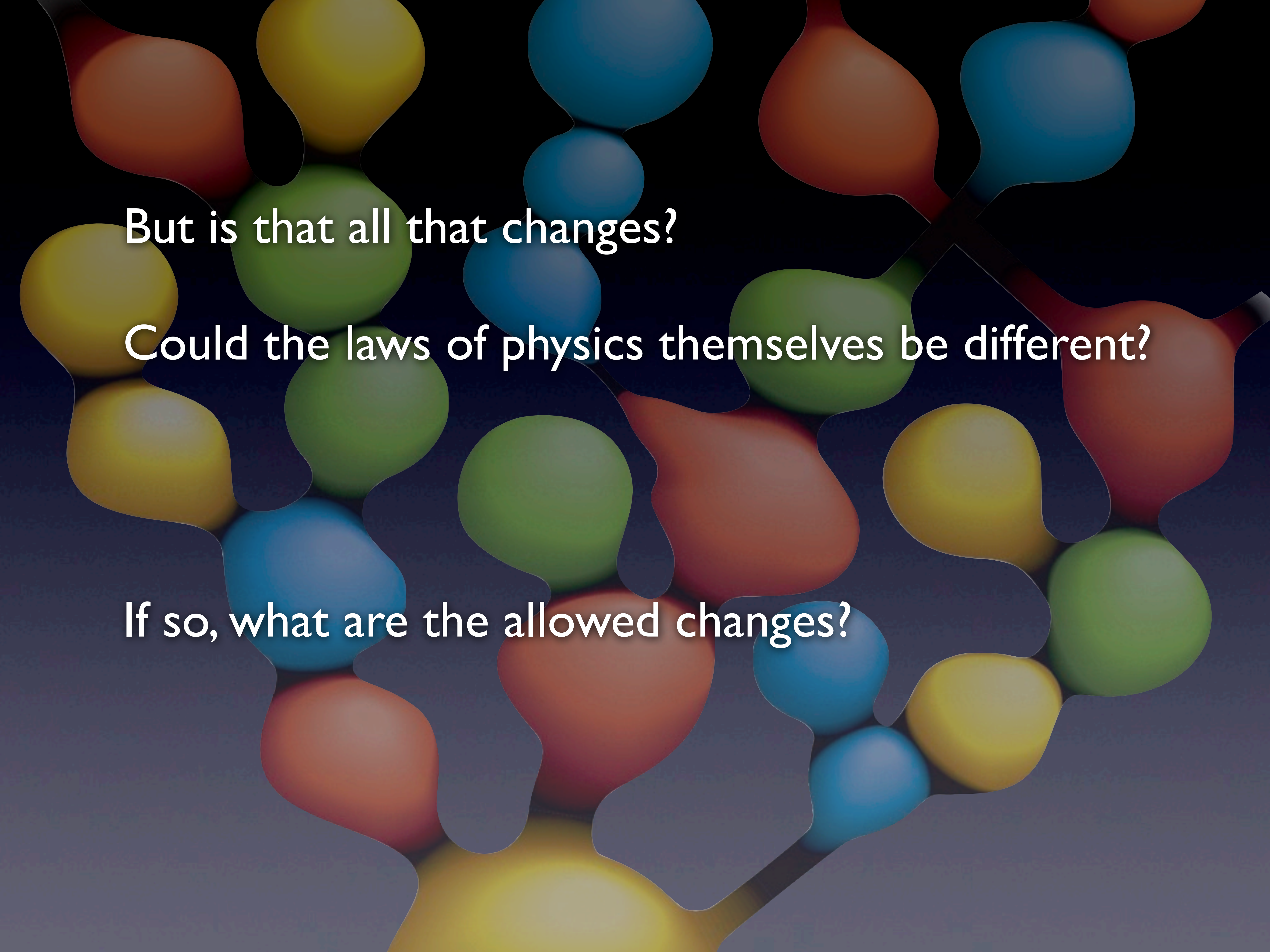

But is that all that changes?

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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.

But who cares?

But who cares?

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.

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Why $SU(3) x SU(2) x U(1)$, 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 (with everything else the same)

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.

(

In this case there is no known anthropic argument.

A guess might be:
1. Three families are needed for CP-violation in the CKM matrix,
2. CP-violation is needed for baryogenesis
3. A net number of baryons is crucial for life.

But:

- This argument would also allow four families.
- The CP-phase in the CKM matrix is not sufficient.
- There are probably other CP violating phases in the couplings of Majorana neutrinos.
  They can lead to baryogenesis via leptogenesis.
  This requires only two families.

)

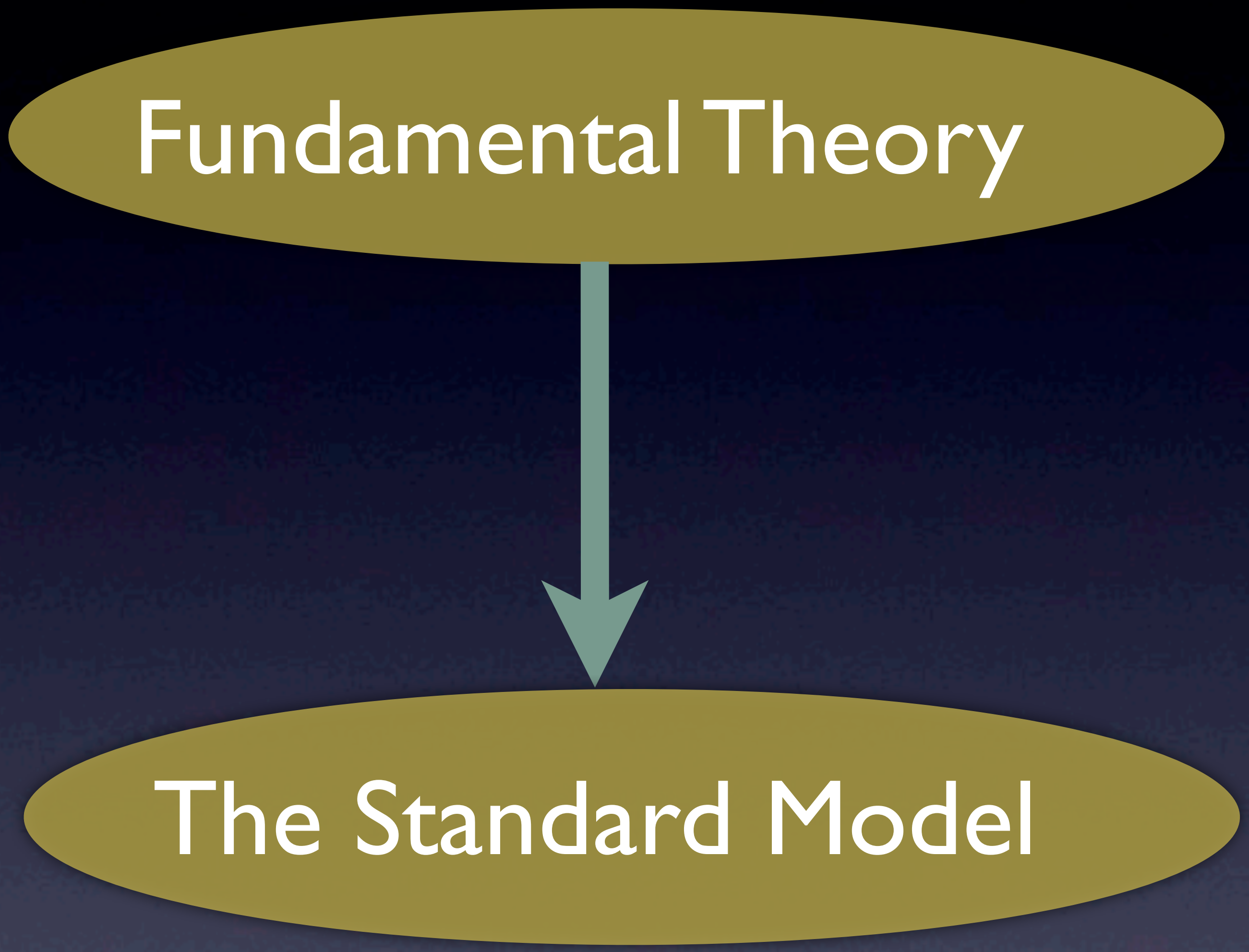
The philosophical objection

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, or because it can be derived from a plausible principle of nature.

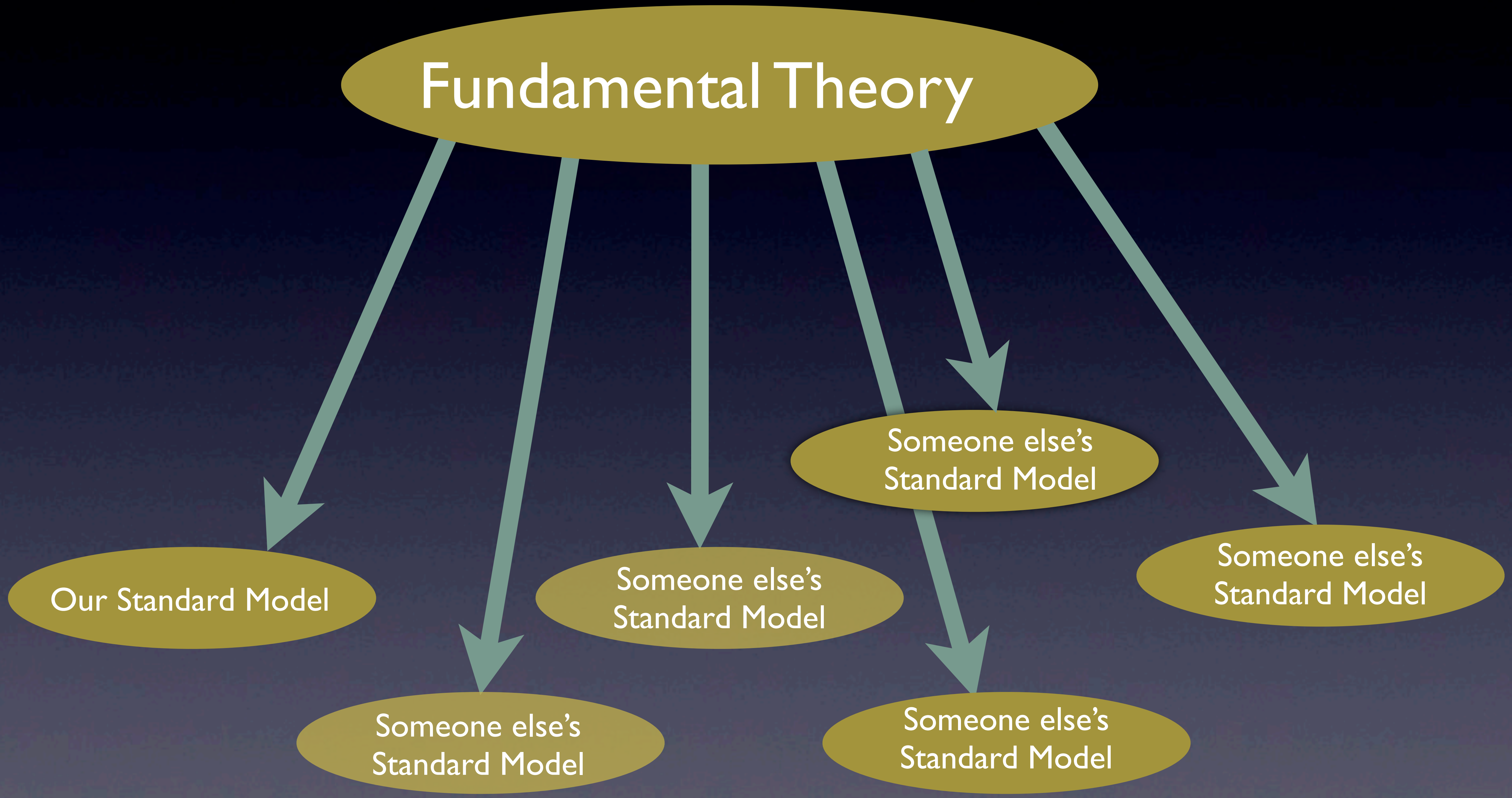
Instead of:



Fundamental Theory

The Standard Model

We would have:



Fundamental Theory

Our Standard Model

Someone else's Standard Model

Someone else's Standard Model

Someone else's Standard Model

Someone else's Standard Model

Someone else's Standard Model

The second picture is suggested by:

- Common sense

  Why would the only gauge theory we can observe be the only one that can exist mathematically?

  Is all we can see all there is?

- Anthropic arguments

  The Standard Model appears to be fine-tuned for the existence of (intelligent) life. So how could it be mathematically unique?

- String theory

  Despite initial hopes of uniques, by 1986 it started becoming clear that there exists a huge number of four-dimensional "vacua" corresponding to different gauge theories.

  If it contains the Standard Model, then surely it contains many others on equal footing with the Standard Model.

- Scalars

The first scalar particle, the Higgs boson, has just been found.
It is a Lorentz singlet, but not a gauge singlet.

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?

String theory has hundreds of them ("moduli").
Even if we don't assume string theory, it is logically possible that many scalar singlets exist.

Polynomials of these scalars would multiply all terms in the Langrangian.

For example, in QED

$$\frac{1}{\alpha}F_{\mu\nu}F^{\mu\nu} \rightarrow P(\tfrac{\phi_i}{M})F_{\mu\nu}F^{\mu\nu}$$

(M is the Planck Mass)

Then the value of the fine structure constant α is determined by the v.e.v. of the fields ϕ_i.

Then all Standard Model parameter are "environmental".

In string theory, these functions are believed to have a huge number of minima ("the String Theory Landscape"), of order 10^{hundreds}

This would imply a devastatingly negative answer to Einstein’s famous question:

“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.”

Perhaps the Standard Model is just a random sample out of a huge ensemble of possibilities, restricted by anthropic constraints.

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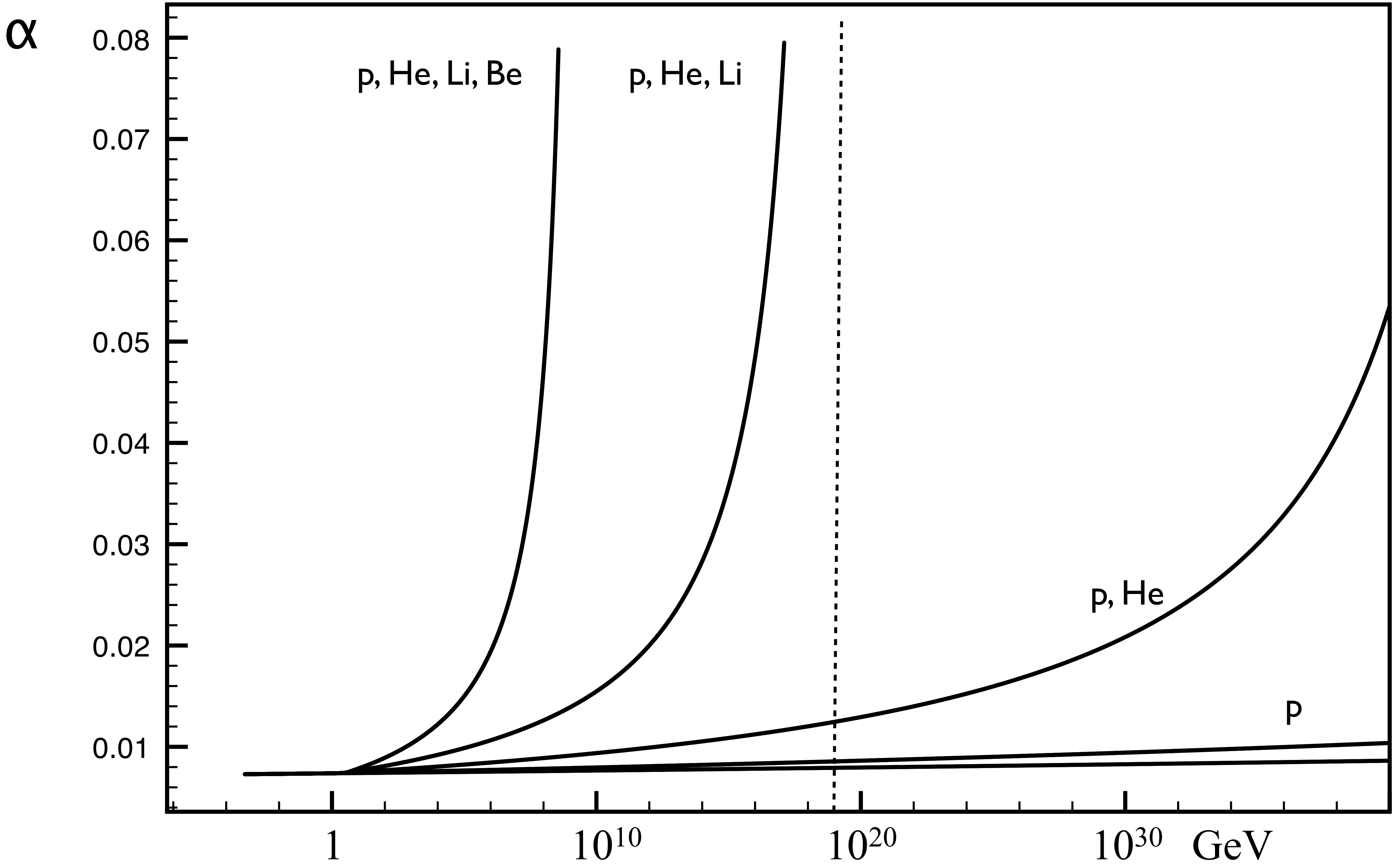
This is a historic moment:
Atomic, nuclear and hadronic physics do not qualify.


α
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
p, He, Li, Be
p, He, Li
p, He
p
1
10^{10}
10^{20}
10^{30}
GeV

SYMMETRY OR ANARCHY?

So….

So....

Game Over

?

No!

There are still plenty of unsolved problems. Dark matter*, dark energy, baryogenesis, inflation, ...

Some or all of these may require physics beyond the Standard Model.

But none of these require structural changes. All this new physics could be in the singlet sector.

***Is all we can see all there is?**

IS THE STANDARD MODEL REALLY A RANDOM* CHOICE OUT OF SOME ENSEMBLE?

(*) up to anthropic constraints

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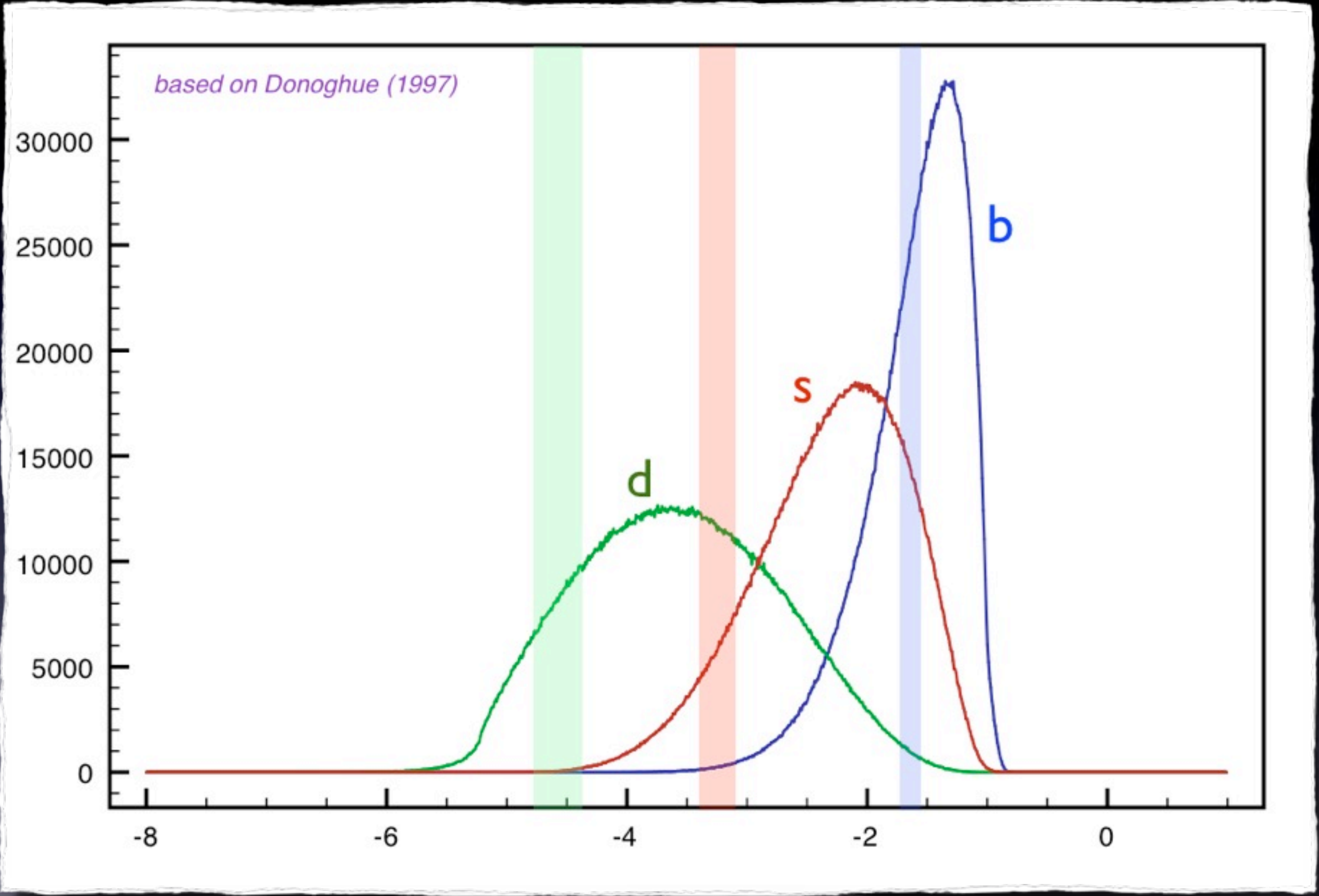

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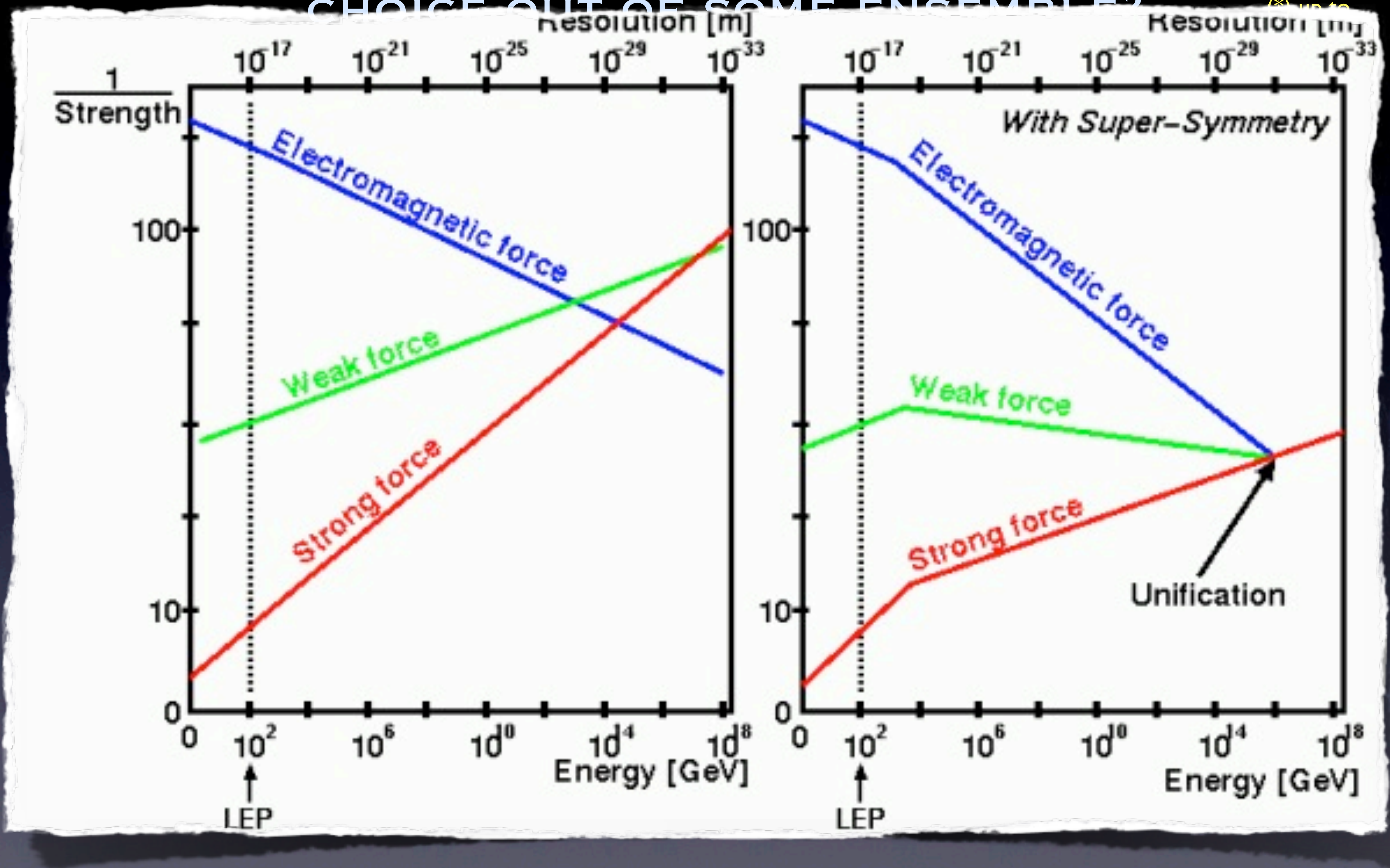

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- Neutrino masses: seesaw mechanism!

  Not random, but requires a minor extension of the Standard Model (Majorana mass)
- The strong CP problem: PQ mechanism!

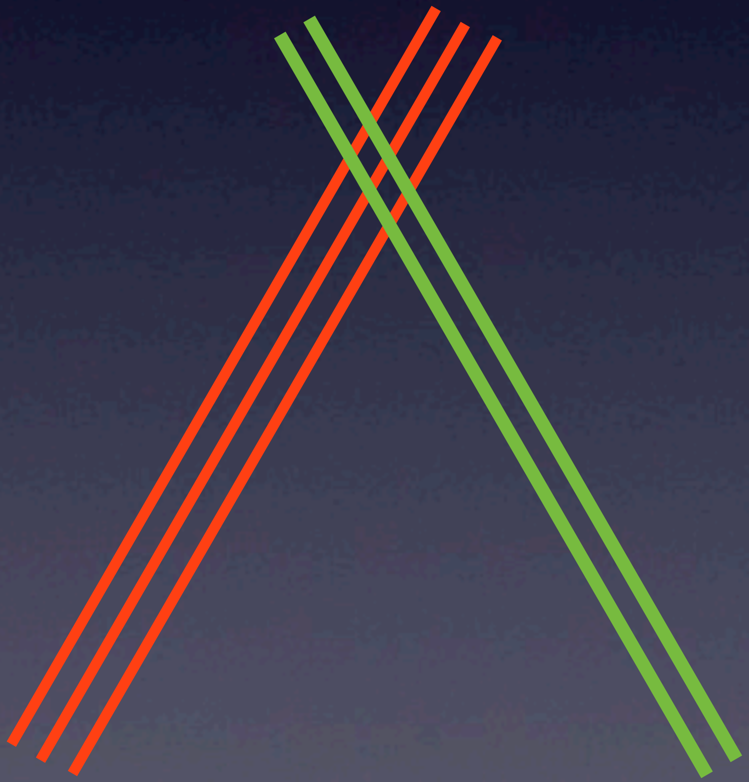
$$\theta < 10^{-10}, \quad \theta \in [0, 2\pi)$$

Not random, but requires a minor extension of the Standard Model (axions).

There are additional anthropic considerations in all four cases

IS THE STANDARD MODEL REALLY A RANDOM CHOICE OUT OF SOME ENSEMBLE?

- Family structure and charge quantization:
  Can be derived uniquely from a simple intersecting membrane model plus mild anthropic constraints (massless photon and no massless charged leptons)



Input: *SU(3) x SU(2) x U(1)*
NO GUT!

Output: quark and lepton representations and Higgs rep.

(work in progress with B. Gato-Rivera)

The Hierarchy Problem

$$\mu^2\phi^\dagger\phi$$

(The Higgs mass term)

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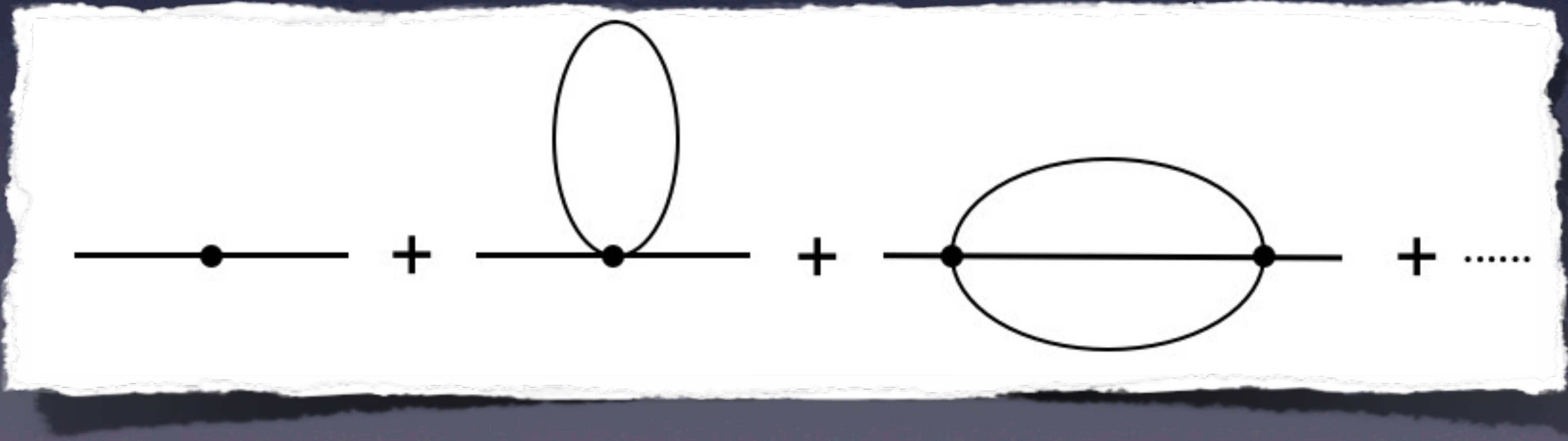

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Worse yet, quantum loop corrections to μ^2 are proportional to the squares of these higher scales.

So it seems *strange* that μ^2 is more than 30 orders of magnitude smaller than its “natural” size. But is it a *problem*?

In a finite theory, the full expression for μ^2 is

$$\mu^2_{\text{phys}} = \mu^2_{\text{bare}} + \sum_i a_i \Lambda^2 + \text{logs}$$

But note that only the μ_{phys} is measurable.
Even if it is much smaller than each term in the sum, this has no physical consequences.

There is no hierarchy problem, just a strange hierarchy.

The Standard Model is perfectly fine as it is.
There is no problem that ***requires*** a solution.

Misconceptions

"quantum corrections destabilize the hierarchy".
This is wrong and confusing. There is no physical instability.

Furthermore it invites confusion with the metastability of the Higgs potential, which is genuine* (for $m_H < 129$ GeV).

Some people believe that μ_{phys} runs quadratically with energy. This is incorrect. It only runs logarithmically, just as any other SM parameter.

(*) But don't worry, it won't happen soon.

μ in the multiverse

Pure chance? $$\mu_{\text{phys}}^2 = \mu_{\text{bare}}^2 + \sum_i a_i \Lambda^2 + \text{logs}$$

Is this problems solved by simply assuming a sufficiently large ensemble of theories?

You would have a chance of 1 in 10^{34} to get a small enough value for $\boldsymbol{\mu}$.

Accepting this essentially implies the end of physics.

Anthropic?

- 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^{24} protons not to be a black hole, we need $m_{\text{p}} < 10^{-8}\, m_{\text{Planck}}$

- Stars would not ignite if $m_{\text{p}}/m_{\text{Planck}}$ is increased by a factor 10
  (F. Adams, 2008)

- All nuclei decay if μ is a factor 2-5 larger (Yukawas kept fixed)
  (Agrawal et. al., 1998)

- Triple-α process produces too little Carbon or Oxygen if μ is about 10% larger than it is.
  (Hoyle, 1954; many others)

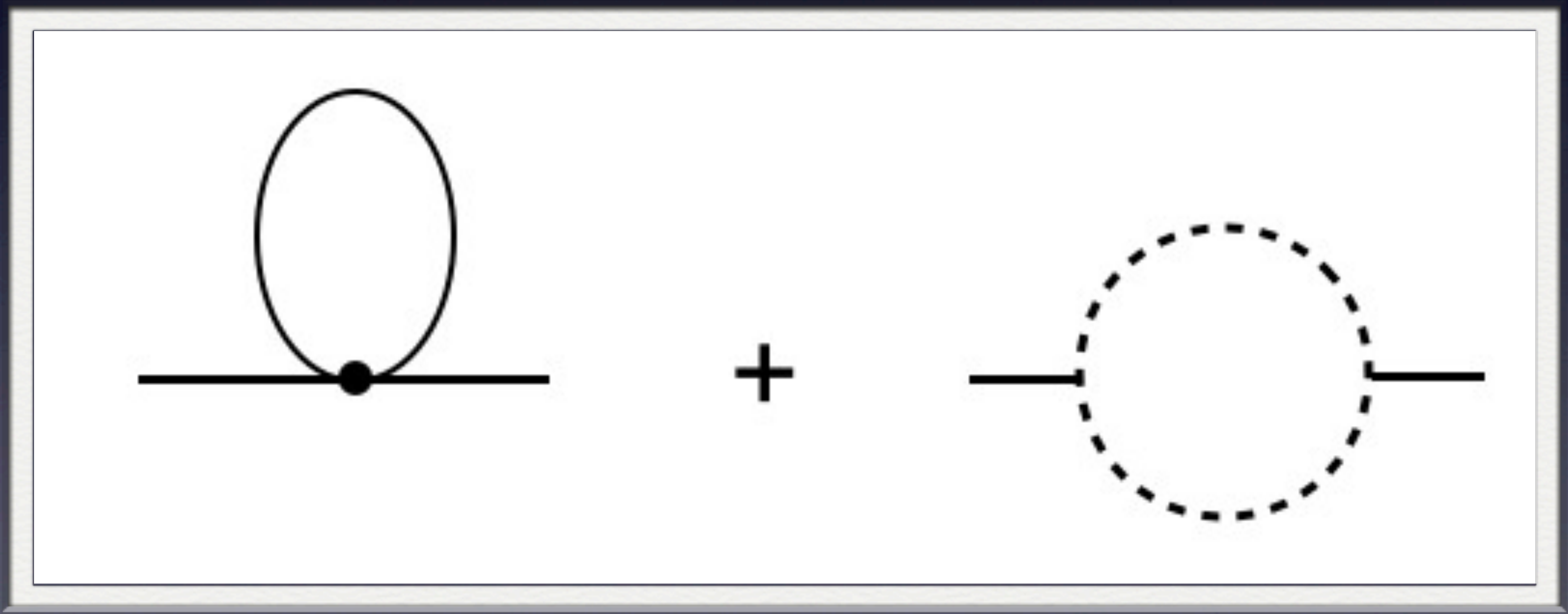
Anthropic or New Physics?

S. Weinberg (2005)

“If the electroweak symmetry breaking scale is anthropically fixed, then we can give up the decades long search for a natural solution of the hierarchy problem.”

Supersymmetry

Kills the quadratic divergences order by order by cancelling bosonic and fermionic loops.



Technical naturalness

Theories like the supersymmetric SM are called “technically natural”.

This means that they do not (necessarily) explain the hierarchy, but at least radiative corrections do not destroy the hierarchy.

This looks good intuitively, but how can we make that precise?

Without supersymmetry, getting the right hierarchy seems unlikely, by a factor 10^{-34}. But how do we define “unlikely”?

This only makes sense by considering ensembles of theories:
a landscape.

The cost of supersymmetry

Non-susy theories have a statistical price tag of 10^{-34}.
In supersymmetric theories this will be less.
How much less depends on details
(μ-problem, mechanism of susy breaking).

But what is the cost of other anthropic bounds (proton stability!)
And what is the statistical cost of low energy susy?

The cost of supersymmetry

In a *technically non-natural* theory we know the distribution of theories, because it is generated by quantum corrections.

In a *technically natural* theory we do not know the distribution, so we may hope it is better. But this can only be established in the context of a landscape.

In a region of the string theory landscape, Douglas (2004) and Susskind (2004) concluded that the distributions are like this:

$$\left(\frac{\mu^2}{M^2_{\text{susy}}}\right)\left(\frac{M^2_{\text{susy}}}{M^2_{\text{Planck}}}\right)^N$$

μ : Weak Scale
M_{susy} : Supersymmetry breaking scale
N : Number of susy breaking terms

But later work found additional suppression factors.
No prediction for Low/High susy yet.

Conclusions

- In discussion of the hierarchy problem, anthropic arguments and landscape distributions have been stubbornly ignored.

  Is this the reason why "naturalness" has been such a poor guiding principle?

- The same may well apply to all remaining Standard Model problems.

- We probably live in a multiverse.
  We have to learn to live with that!