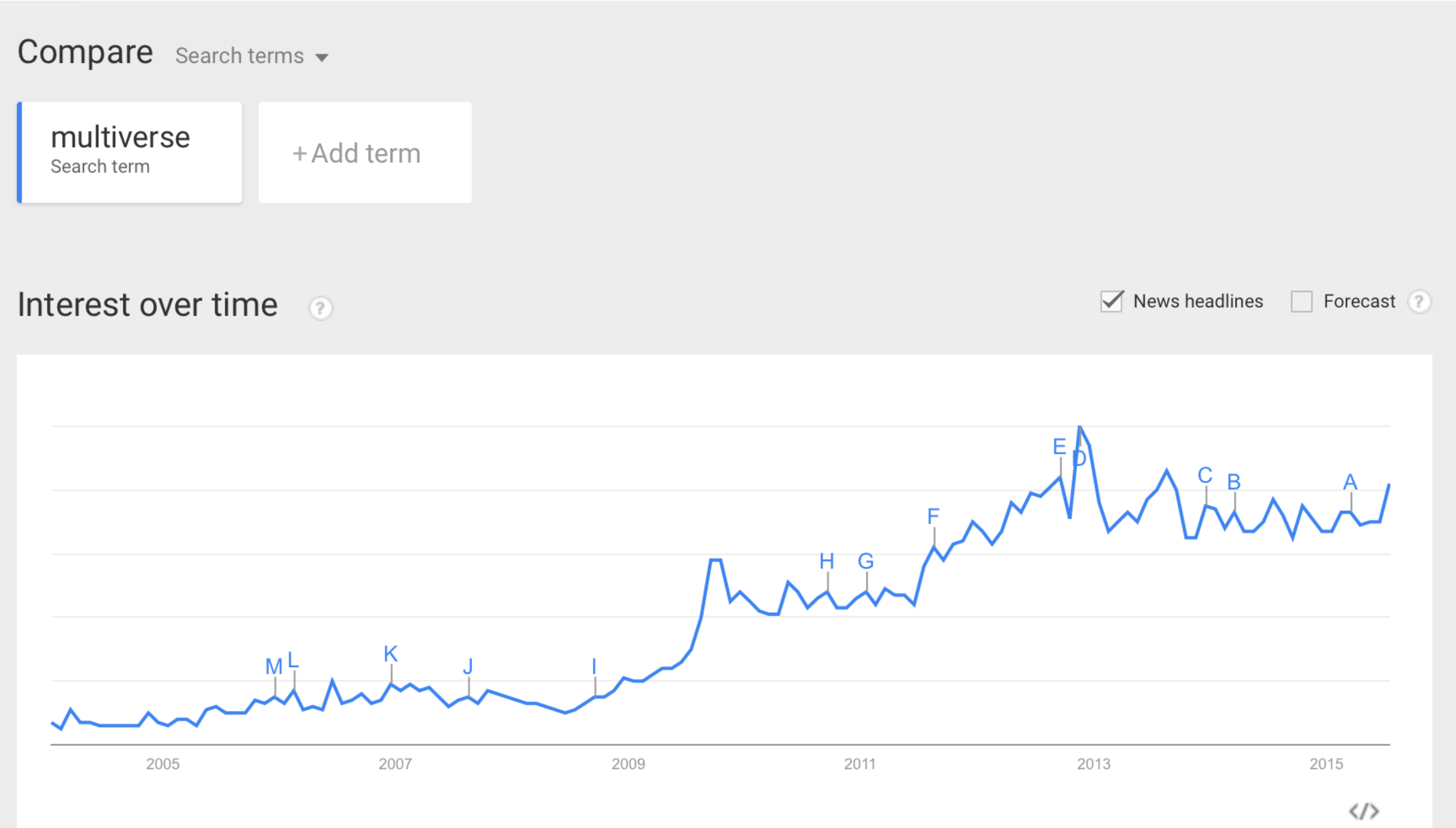
Universe or Multiverse?

Andrei Linde

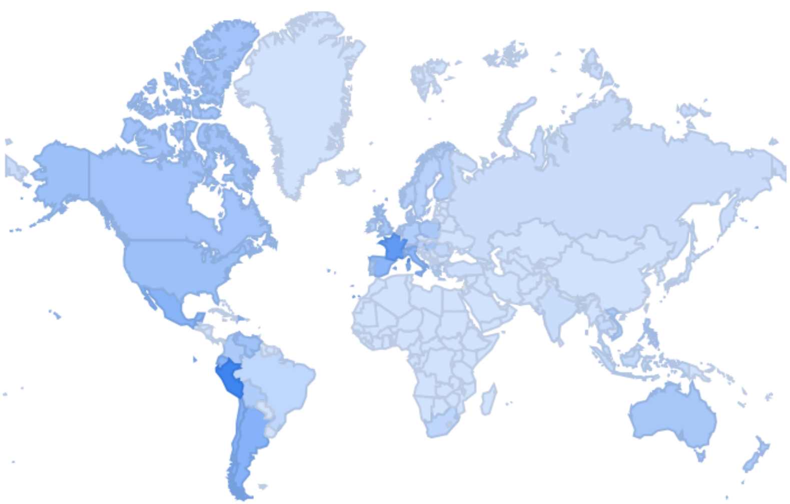
Multiverse according to *Google Trends*



Multiverse according to *Google Trends*

Regional interest ?

Region | City



Peru	100
France	77
Chile	53
Argentina	52
Ecuador	51
Mexico	50
Spain	47

▸ View change over time ? </>

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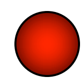
Multiverse according to *Google Trends*

Related searches

Topics	Top / Rising
Multiverse	100
Dragon Ball - Manga series	40
Family Guy: Back to the Multiver…	5

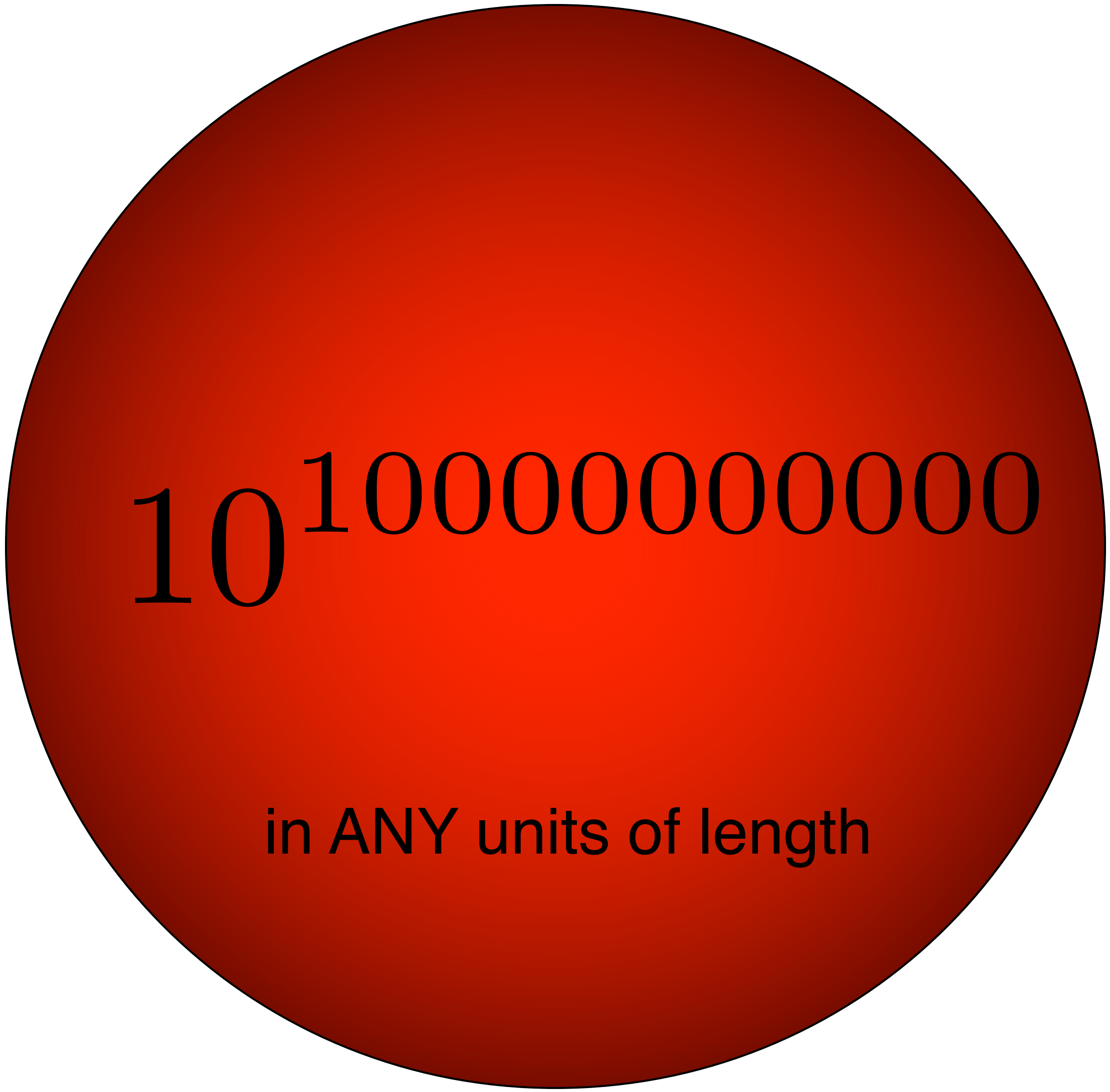
Queries	Top / Rising
dragon multiverse	100
dragon ball multiverse	100
the multiverse	45
family guy multiverse	20
dbz multiverse	20
db multiverse	20
multiverse dragonball	20

A newborn universe could be as small as 10^{-33} cm (Planck length) and as light as 10^{-5} g (Planck mass). If its energy density is dominated by V, inflation immediately begins



$$l \sim 10^{-33}\ \mathrm{cm}$$
$$m \sim 10^{-5}\ \mathrm{g}$$

Inflationary universe 10^{-35} seconds old



Any customer can have a car painted any color that he wants so long as it is black

Henry Ford

Here comes the multiverse

Uniformity of our **universe** is explained by **inflation**:   Exponential stretching of the universe makes **our part** of the universe almost exactly uniform. But classical stretching of the universe does NOT imply its global uniformity.

At the quantum level, the same theory often predicts that on a much greater scale, the universe is 100% non-uniform.

Inflationary **universe** becomes a **multiverse**

Pessimist:

If each part of the multiverse is huge, we will never see other parts, so it is **impossible to prove** that we live in the multiverse.

Optimist:

If each part of the multiverse is huge, we will never see other parts, so it is **impossible to disprove** that we live in the multiverse.

I'd rather be an optimist and a fool than a pessimist and right. Albert Einstein

This scenario is **more general** (otherwise one would need to explain why all colors but one are forbidden). Therefore the theory of the **multi**verse, rather than the theory of the **uni**verse, is the basic theory.

Moreover, even if one begins with a single-colored universe, quantum fluctuations make it multi-colored.

Origin of structure:

In inflationary theory, original inhomogeneities are stretched away, but new ones are produced from **quantum fluctuations,** which are amplified and stretched exponentially during inflation.

Galaxies are children of quantum fluctuations produced in the first 10^{-35} seconds after the birth of the universe.

The limits of classical cosmology

By observing our part of the universe and playing the movie back, we would see galaxies moving closer to each other, particles collide, but we would never see 10^{90} particles merge into nothing and disappear, we would never see their origin in a vacuum-like state containing no galaxies and no particles at all.

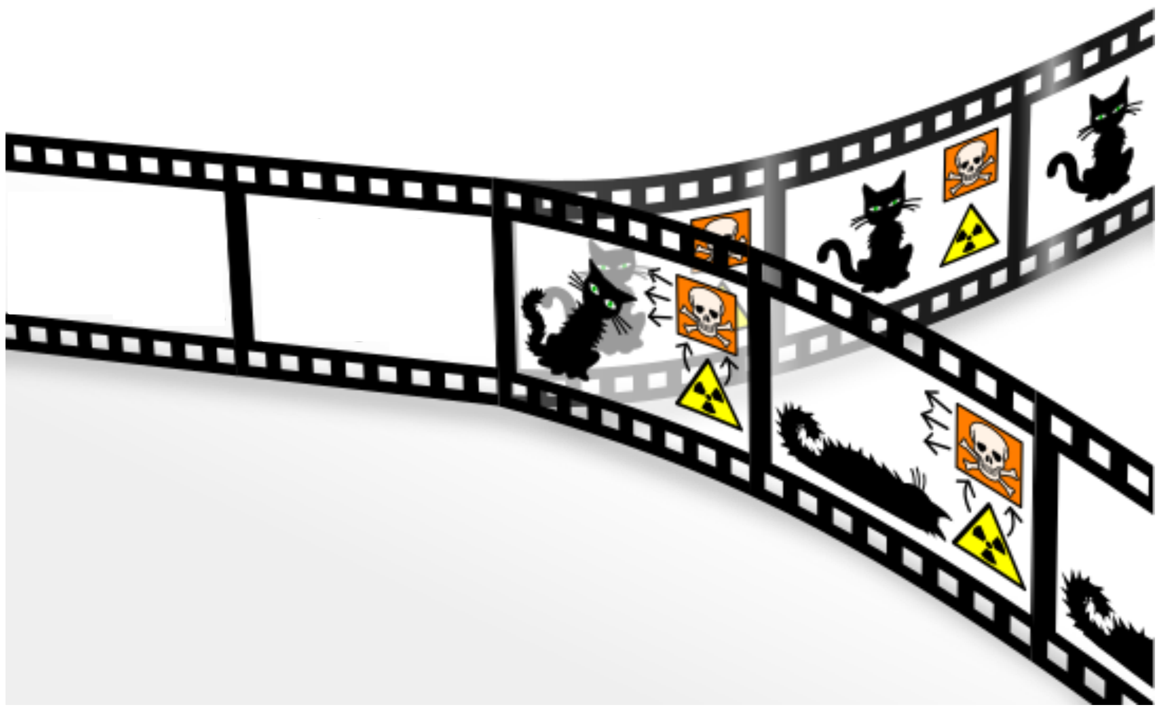
Indeed, all particles were produced in the process of reheating after inflation. This is an irreversible quantum mechanical process.

Remember the Schrodinger cat

Two consistent movies with one common element:
in the beginning, there was a cat

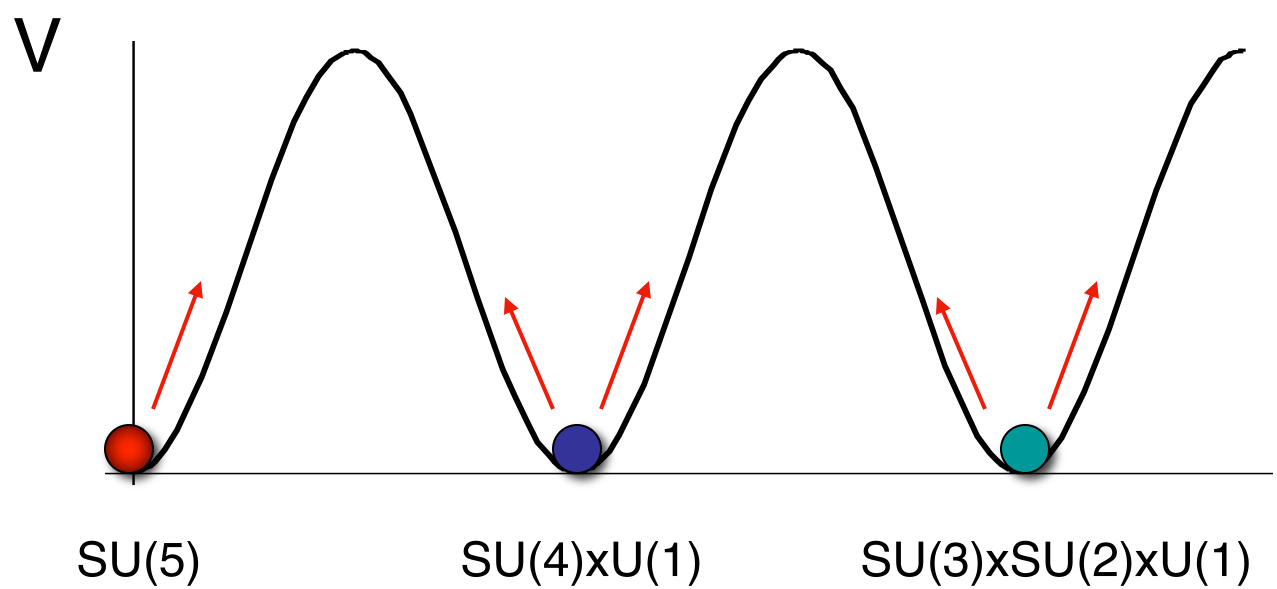
The Universe is similar to the Schrodinger cat, but without the cat to start with…

By playing the "movie" back, we would expect to see 10^{90} elementary particles all the way back to the Big Bang. But in inflationary cosmology everything could be born from a tiny Planck-size domain with **no particles at all**. All particles and galaxies were born due to quantum effects during or after inflation.



Example: SUSY landscape

Supersymmetric SU(5)

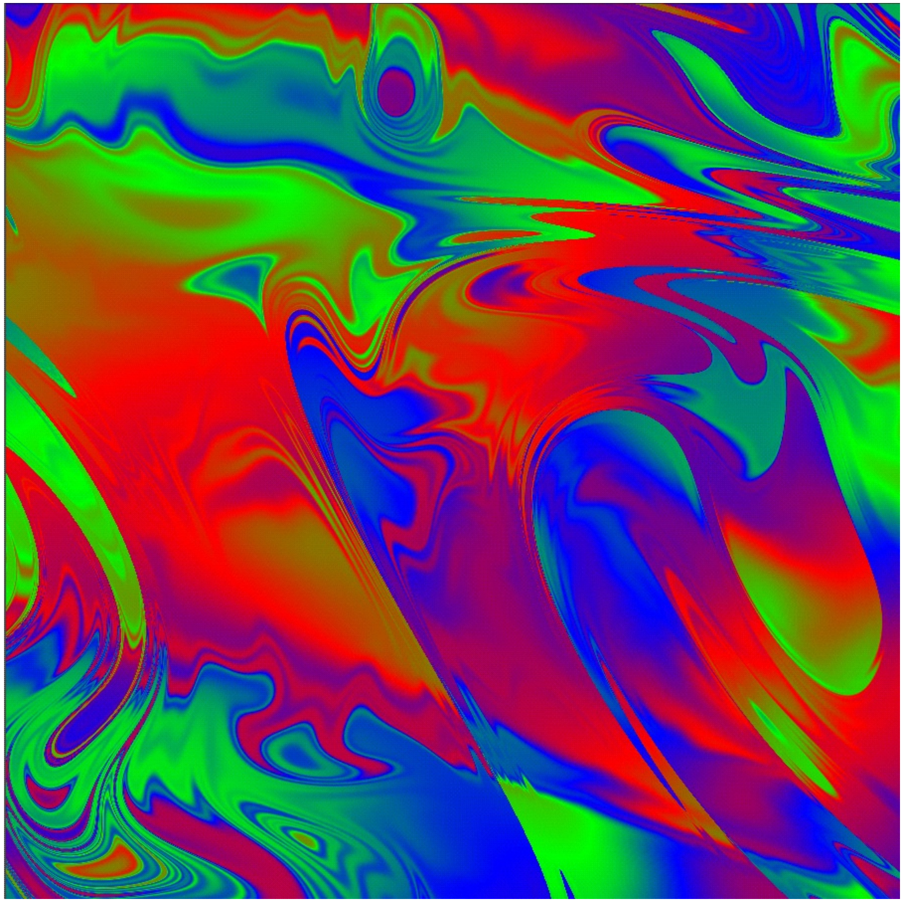


Weinberg 1982: Supersymmetry forbids tunneling from SU(5) to SU(3)xSU(2)XU(1). This implied that we cannot break SU(5) symmetry.

A.L. 1983: Inflation solves this problem. Inflationary fluctuations bring us to each of the three minima. Inflation make each of the parts of the universe exponentially big. We can live only in the SU(3)xSU(2)xU(1) minimum.

Kandinsky Universe

This process can be illustrated by computer simulations. We start with a small single-colored inflationary universe, and we end up in a universe consisting of many exponentially large parts with different laws of low-energy physics: SU(5), SU(4) x U(1), or SU(3) x SU(2) x U(1), as in the part where we live now.

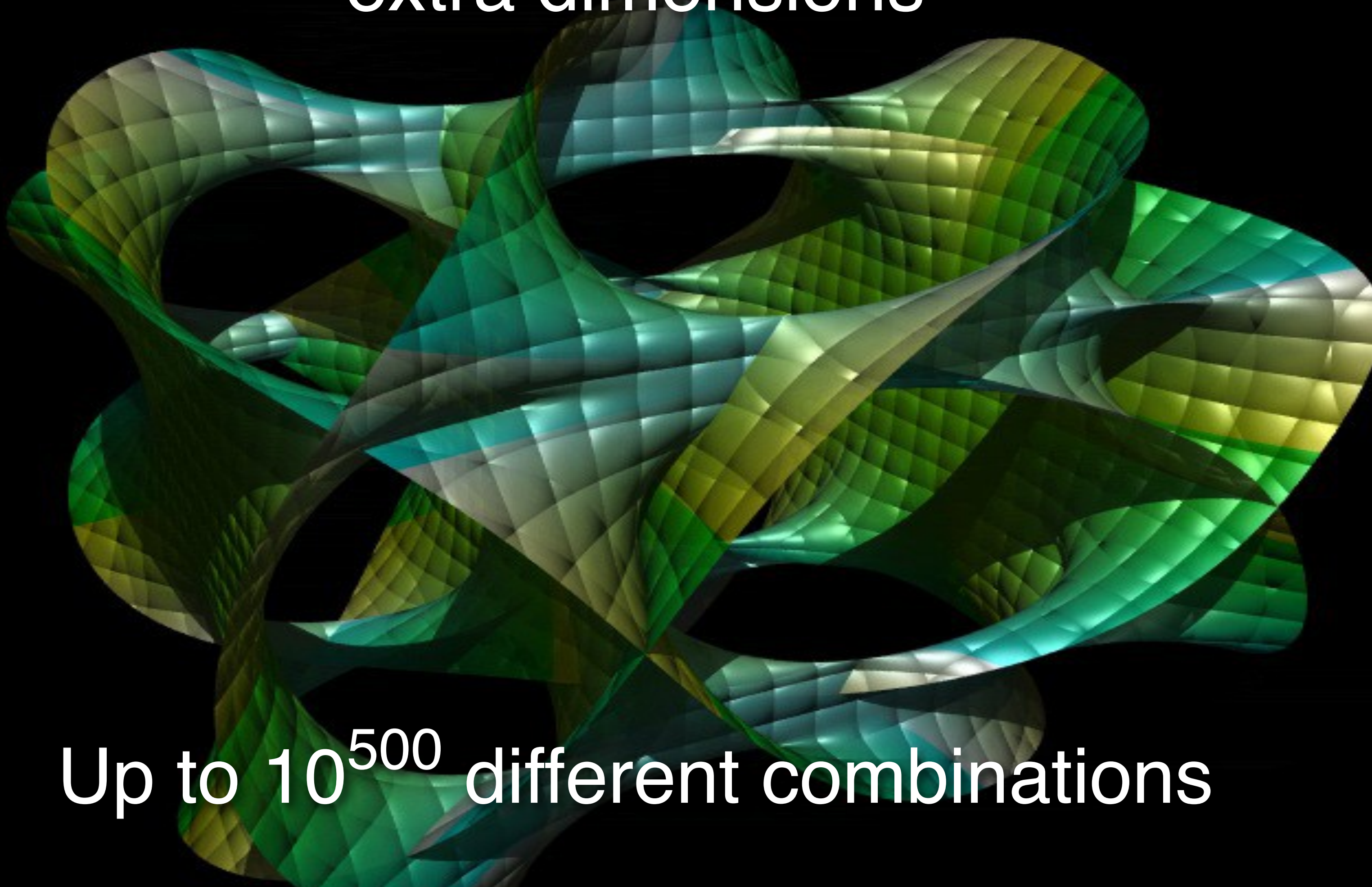


These are consequences of a simple particle physics theory, and philosophical considerations cannot change these results.

Now we may be at a new turning point, a radical change in what we accept as a legitimate foundation for a physical theory.

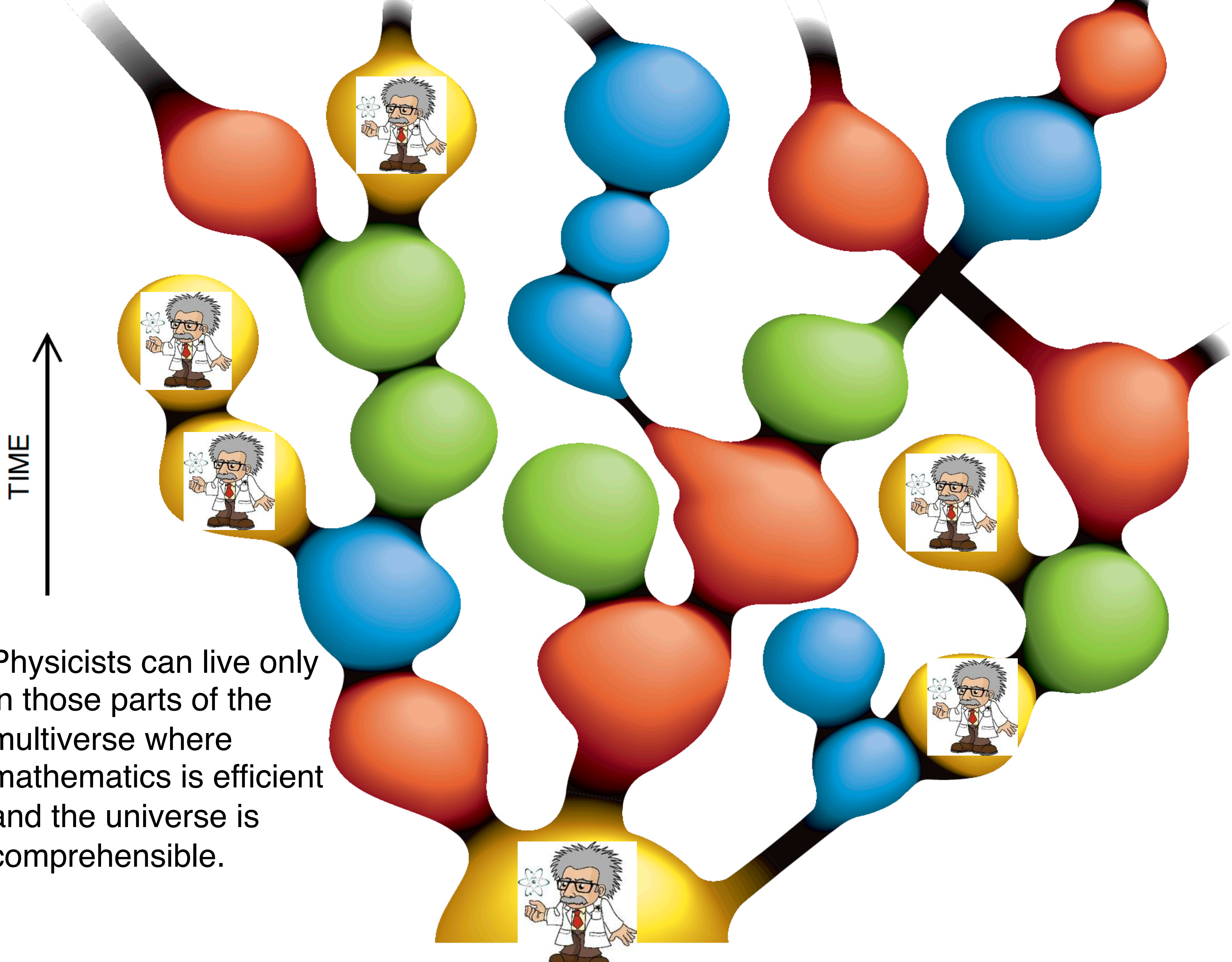
Steven Weinberg
“Living in the Multiverse”

In string theory, genetic code of the universe is written in properties of compactification of extra dimensions



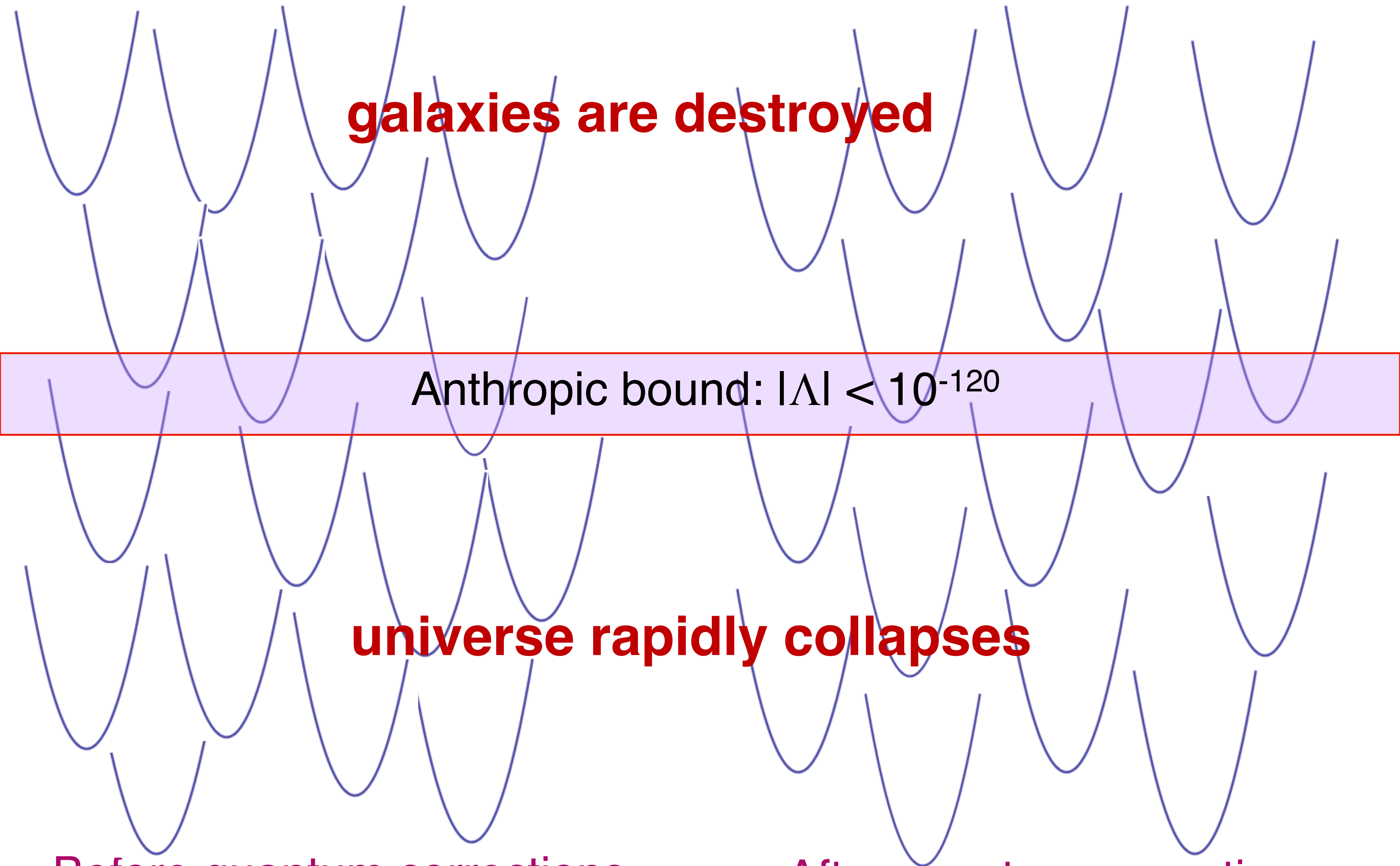
Up to 10^{500} different combinations

Sakharov 1984; Bousso, Polchinski 2000; Kachru, Kallosh, AL, Trivedi, 2003; Douglas 2003, Susskind 2003



Physicists can live only in those parts of the multiverse where mathematics is efficient and the universe is comprehensible.

Example: Vacuum energy in string theory:



Before quantum corrections

After quantum corrections

Is the string theory quintessence in the swampland?

Consider exponential potential $e^{\lambda\phi}$ with λ =0.7 (all higher values are ruled out with 95% confidence). How large should be the excursion of the field to span the distance between the Planck density V =O(1) and the present value of dark energy V =O(10^{-120}) = e^{-276}

$$\Delta\phi \sim 400$$

This would strongly contradict the weak gravity conjecture.

If only the Planck excursions O(1) are allowed, then the quintessence potential $e^{\lambda\phi}$ describing our universe can be valid only for V =O(10^{-120}). How can we use such a theory in cosmology?

Many string theory based models of quintessence were proposed by the authors of the swampland hypothesis in 1806.08362 and 1810.05506.

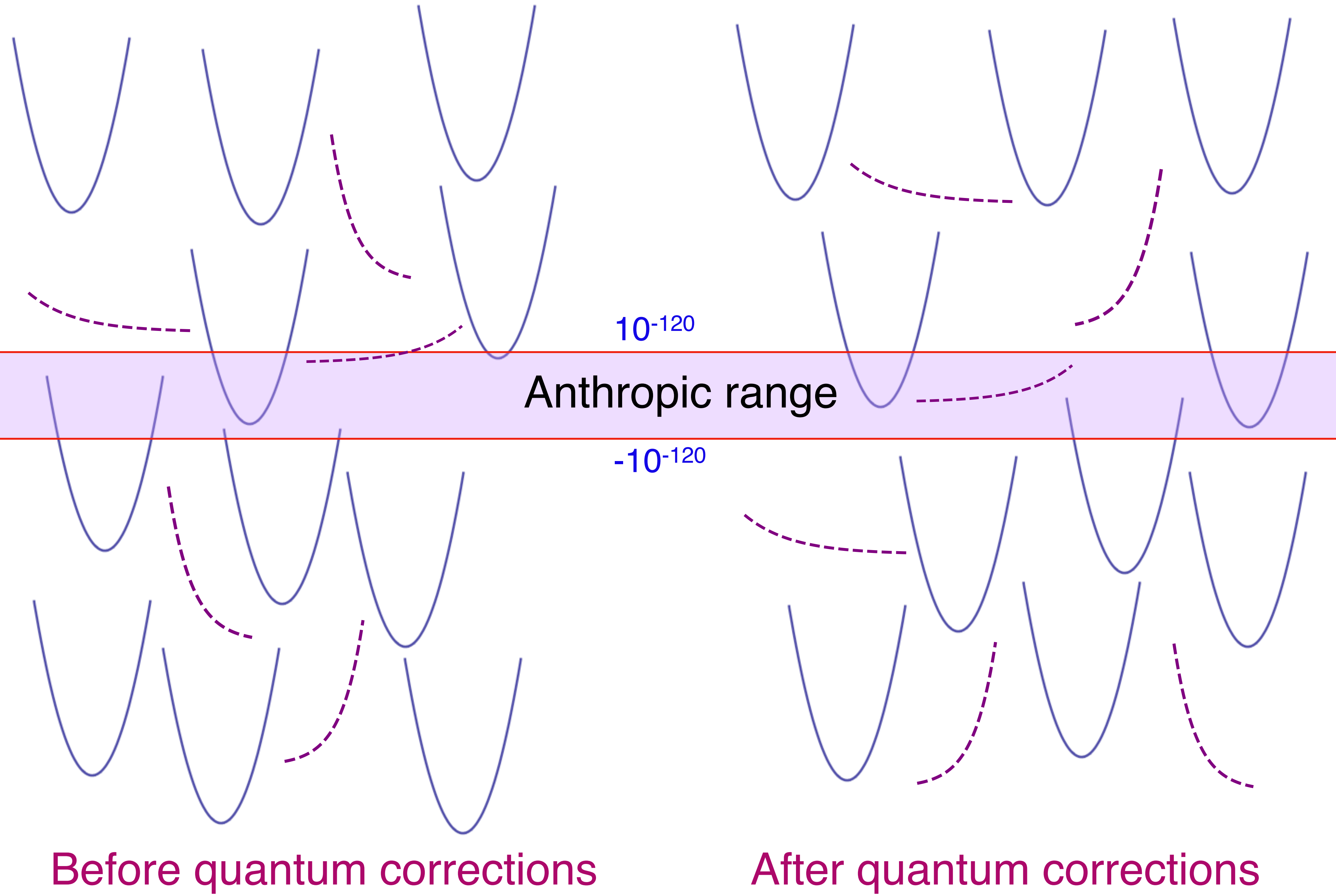
All of these models are ruled out by cosmological observations at better than 3σ level

Akrami, Kallosh, A L, Vardanyan 1808.09440

Recently there was a significant progress in confirmation of the KKLT scenario in type IIB string theory (Kachru, Kim, McAllister, Zimet 1908.04788) and in dS vacua construction in type IIA string theory (Cribiori, Kallosh, Roupec, Wrase 1909.08629, and Kallosh and AL)

Therefore even if consistent string theory models of quintessence eventually will be found, it is quite likely that they will become a part of the string theory landscape, as shown in the next slide

Anthropic approach to Λ in string theory



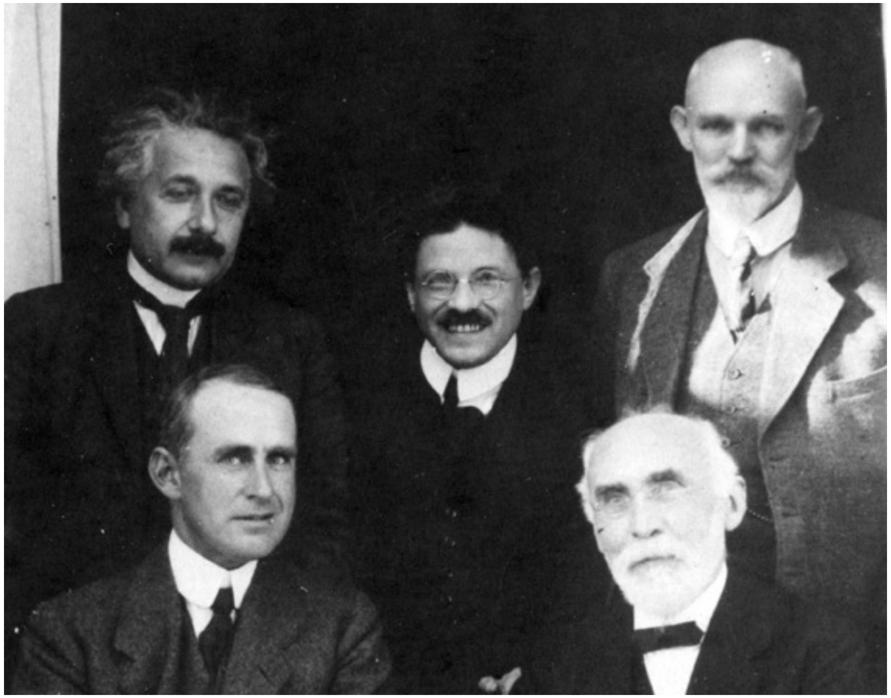
Why do we live in a 4-dimentional space-time?

P. Ehrenfest, Proc. Amsterdam Acad. 20, 200 (1917)

In space-time of dimension d > 4, planetary systems and atoms are unstable. For d < 4, in general theory of relativity there is no gravitational attraction between distant bodies, so planetary systems cannot exist. That is why can live only is space-time with d = 4.

Einstein

de Sitter



Eddington

Lorentz

Ehrenfest

Leiden Observatory, 1923

Why do we live in a 4-dimentional space-time?

P. Ehrenfest, Proc. Amsterdam Acad. 20, 200 (1917)

Back in 1917, this could seem just a mathematical curiosity: Our space has d=4; we simply do not have any other choice.

However, according to string theory, our world fundamentally is 10-dimensional, but some of these dimensions are tiny, compactified. In general, one could end with space-time of any dimension d, which would grow exponentially large due to inflation. We can live only in the parts of the world where the compactification produces space-time with d = 4.

Thus the observation made by Ehrenfest in 1917, in Leiden, in combination with string theory constructions developed in the beginning of this century, explains why we live in space-time with d = 4.

Can we test the multiverse theory ?

This theory provides the only known explanation of numerous experimental results (extremely small vacuum energy, strange masses of many elementary particles). **In this sense, it was already tested many times.**

"When you have eliminated the impossible, whatever remains, however improbable, must be the truth."

Sherlock Holmes