Reverse Engineering of the Universe

Andrei Linde

Suppose we want to create the universe suitable for life, and we want to do it in the simplest possible way.

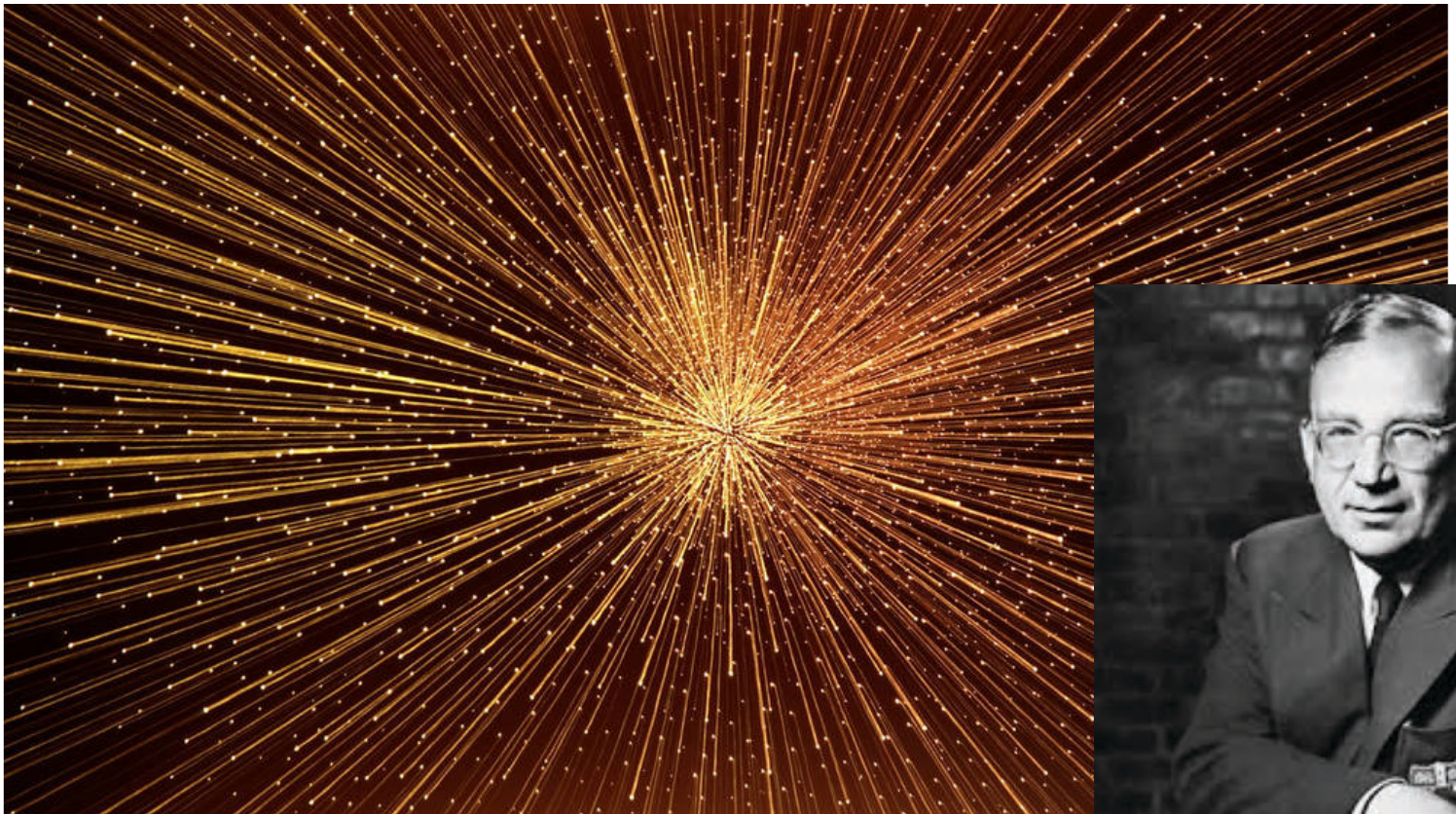
Is it possible to develop a fool-proof design?

Let us look at our own universe at present, and then “play the movie back in time”.

How big was the Big Bang?

The distance from Earth to the edge of the observable part of the universe is about 46.5 billion light years, or 4.4×10^{28} cm, in any direction. It contains about 10^{90} elementary particles. The total mass is about 10^{50} tons.

When the universe was born, its mass was greater, more than 10^{80} tons. Where did it come from? Can we play the movie back?



Problems of the Big Bang theory:

What was before the Big Bang?

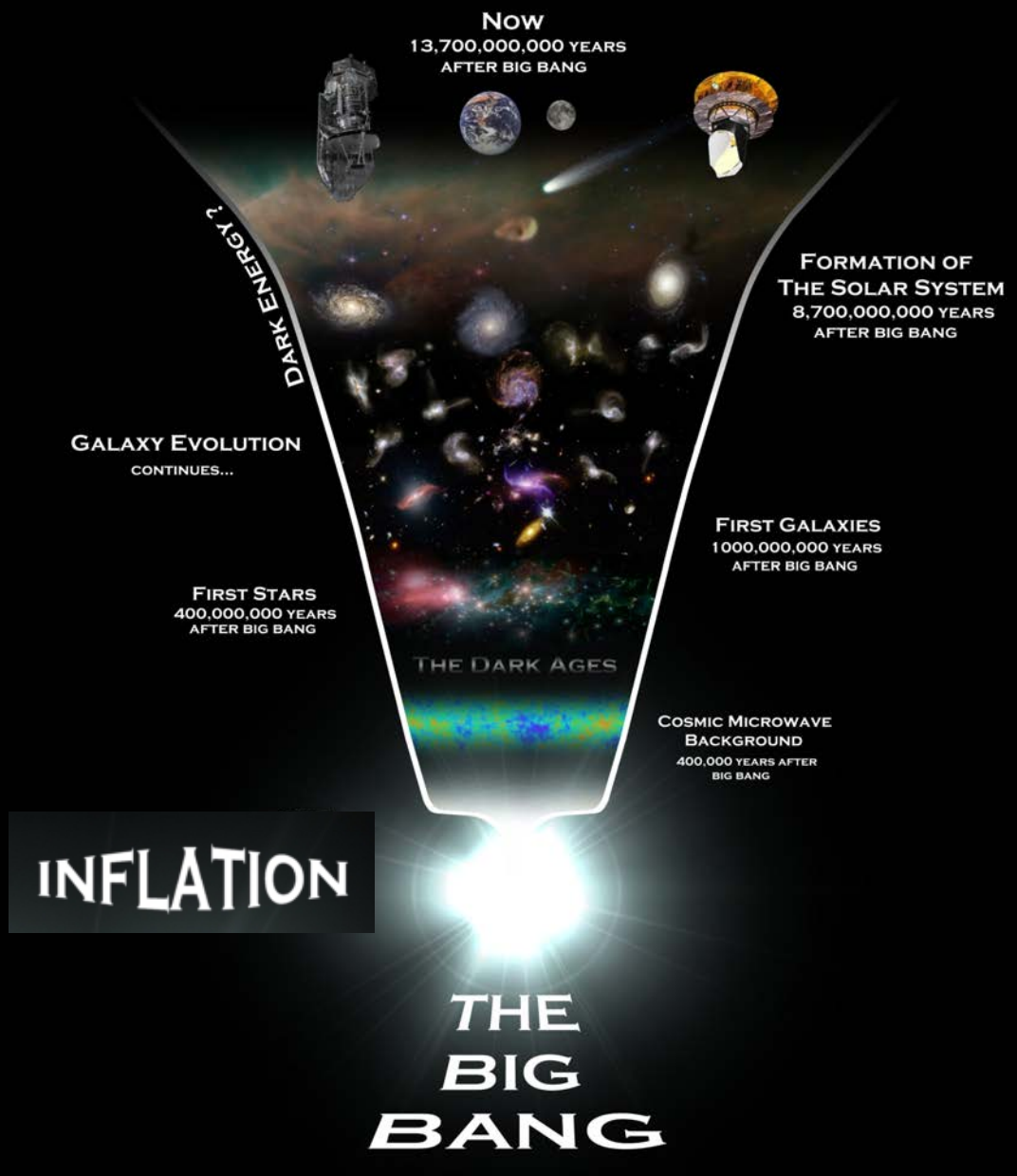
We still do not know, but have some ideas based on inflation and quantum cosmology

Why is our **universe** so **uniform**?
Why is it **not exactly** uniform?
Why is it **isotropic** (same in all directions)?
Why all of its parts started expanding simultaneously?
Why is it **flat ($\Omega = 1$)**?
Why is it so **large**?

Answered by inflation

In the Beginning there was… INFLATION

Alan Guth
Alexei Starobinsky
Andrei Linde
Vyatcheslav Mukhanov



Inflationary theory

solves many problems of the old Big Bang theory, and explains how the whole universe could be created from less than a milligram of matter

Basic idea:

One of the Einstein equations for the empty universe with vacuum energy density V_0 (cosmological constant) is

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{V_0^2}{3}$$

It has a solution describing an exponentially growing (inflating) universe:

$$a = a_0\, e^{Ht}$$

The total vacuum energy of such universe grows even faster, as volume

$$E = E_0\, e^{3Ht}$$

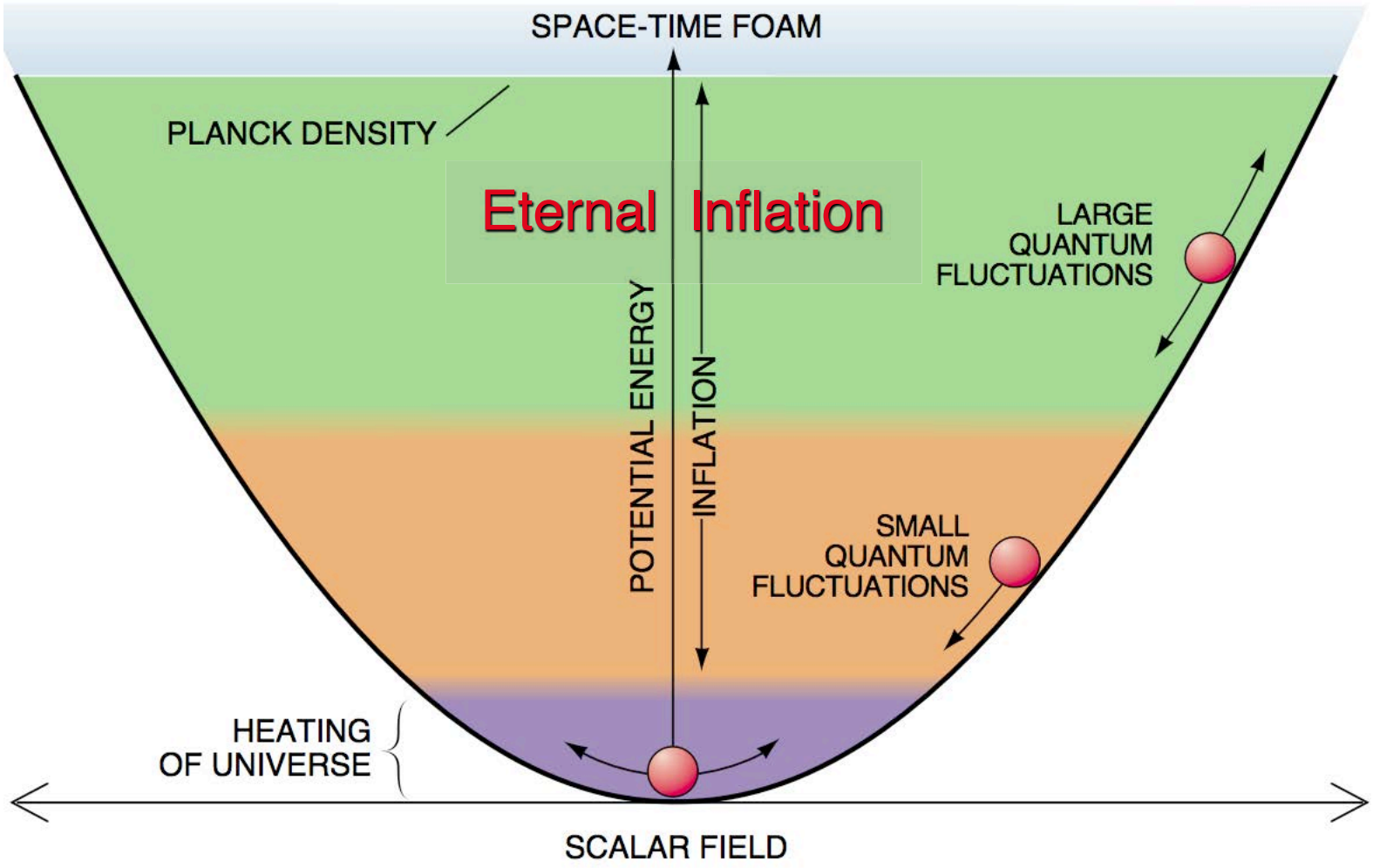
If eventually this vacuum state decays, it produces exponentially many elementary particles with exponentially large energy. Problem solved!

Alan Guth 1980

The simplest inflationary model

$$V(\phi) = \frac{m^2}{2}\phi^2$$

AL 1983

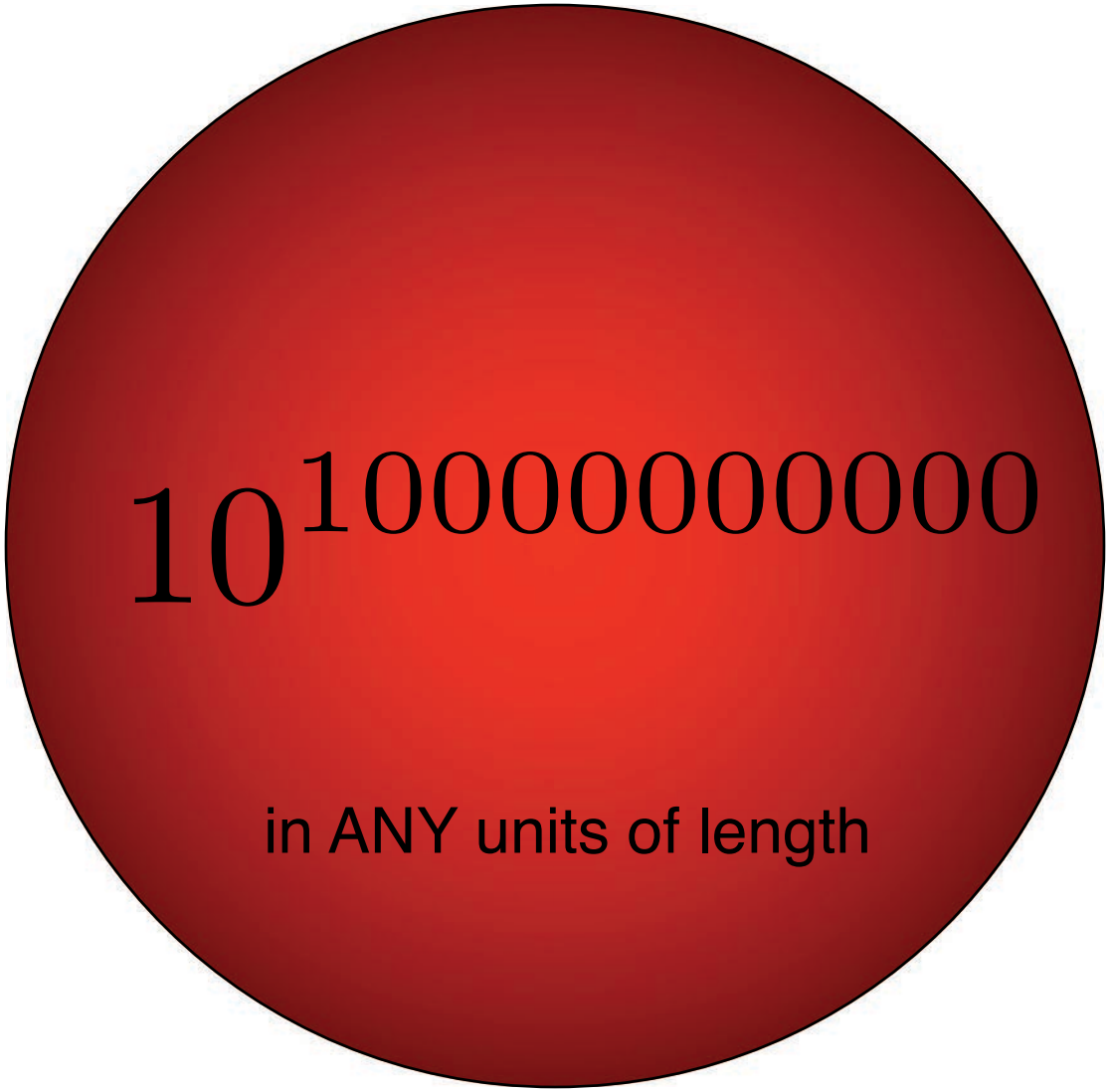


A newborn universe could be as small as 10^{-33} cm and as light as 10^{-5} g
(it could be born from nothing at all…)

$$l \sim 10^{-33} \text{ cm}$$

$$m \sim 10^{-5} \text{ g}$$

Inflationary universe 10^{-35} seconds old

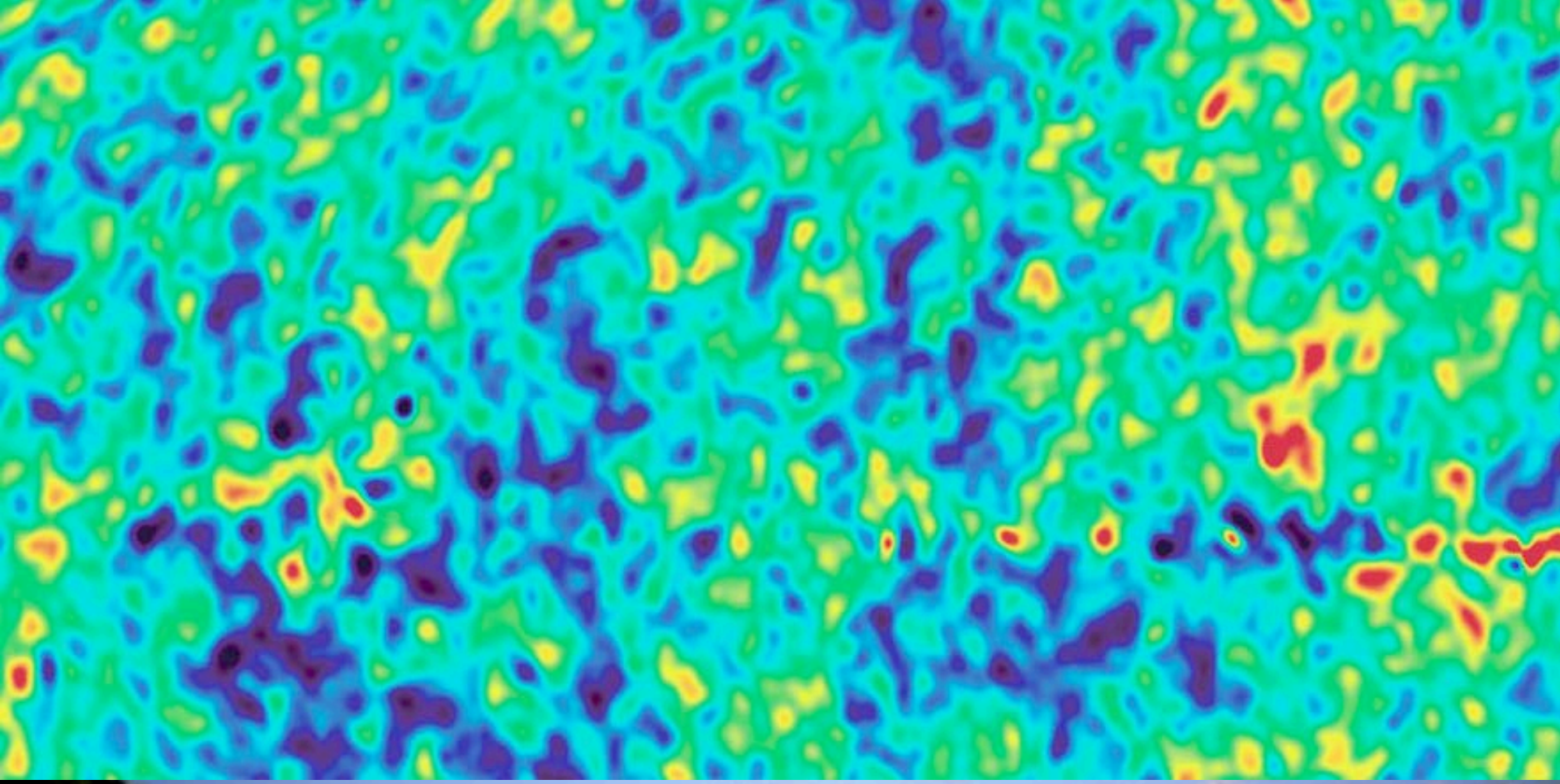


Origin of structure:

In this theory, original inhomogeneities are stretched away, but new ones are produced from **quantum fluctuations** amplified during the exponential growth of the universe.

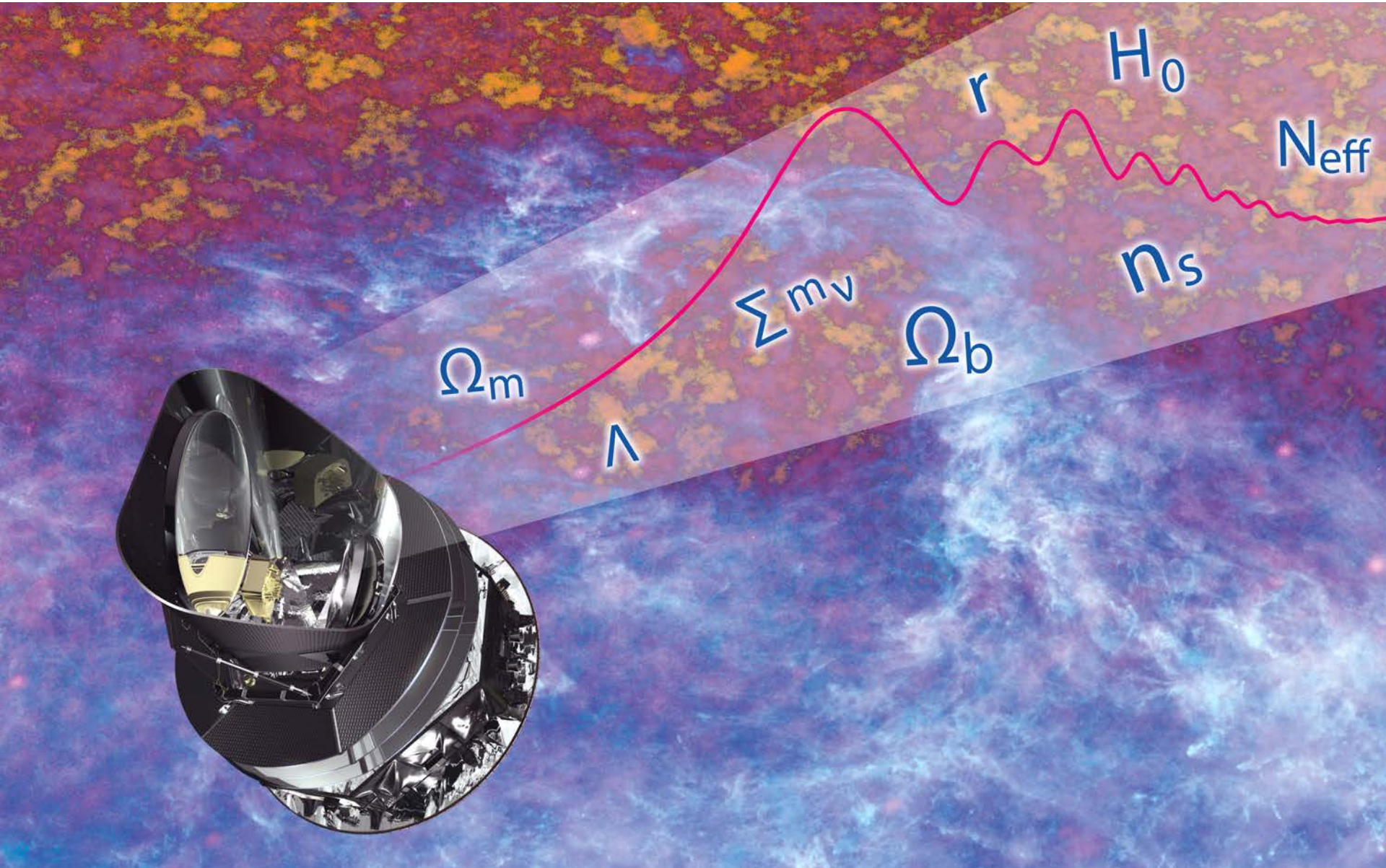
Galaxies are children of quantum fluctuations produced in the first 10^{-35} seconds after the birth of the universe.

Mukhanov 1981
Starobinsky 1980, 1982



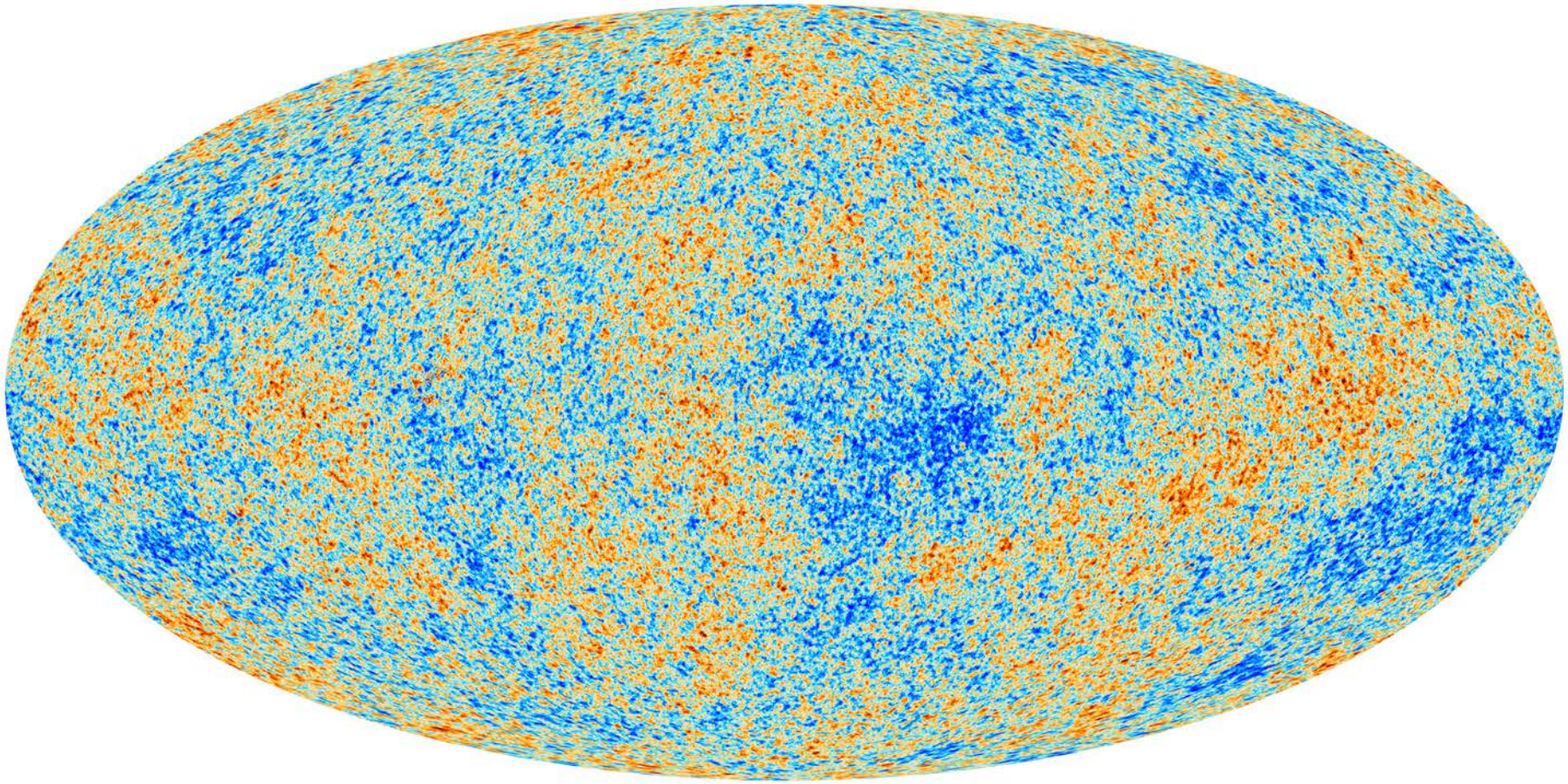
Observations

Planck satellite

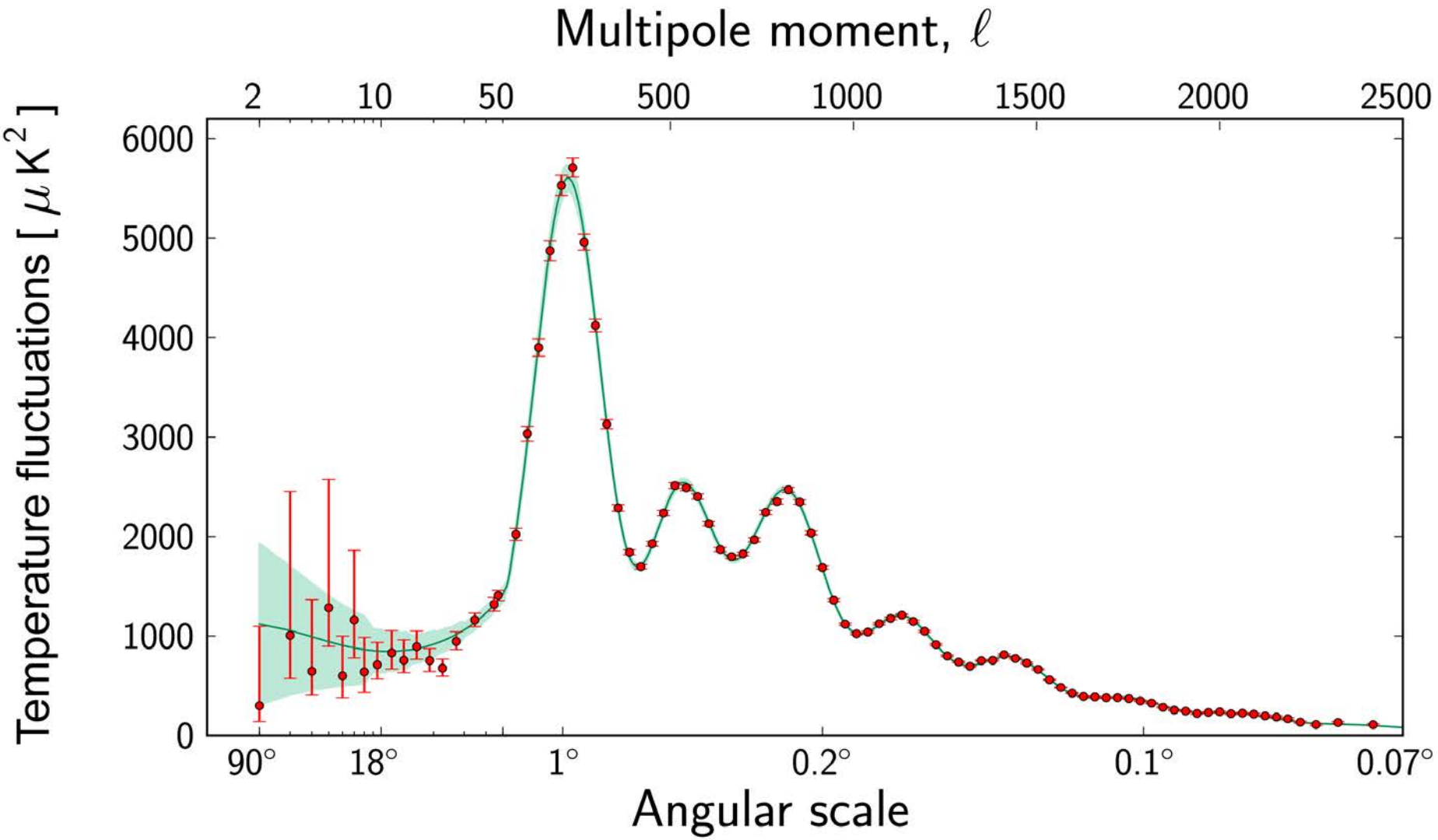


Planck satellite: Perturbations of temperature

This is an image of **quantum fluctuations produced by inflation 10^{-35} seconds after the Big Bang**. These tiny fluctuations were **stretched by inflation** to incredibly large size, and now we can observe them **using all sky as a giant photographic plate**



Planck satellite: Perturbations of temperature (red dots) and predictions of inflationary theory (green line)



Inflation and Planck 2018

$$\Omega = 1 \pm 0.005$$

Universe is flat with accuracy 10^{-2}

$$n_s = 0.965 \pm 0.004$$

Spectrum of perturbations is nearly flat

Non-inflationary HZ spectrum with $n_s = 1$ is ruled out at a better than 6σ level, just as predicted in 1981 by Mukhanov and Chibisov. (This is an important prediction of inflation, similar to asymptotic freedom in QCD.)

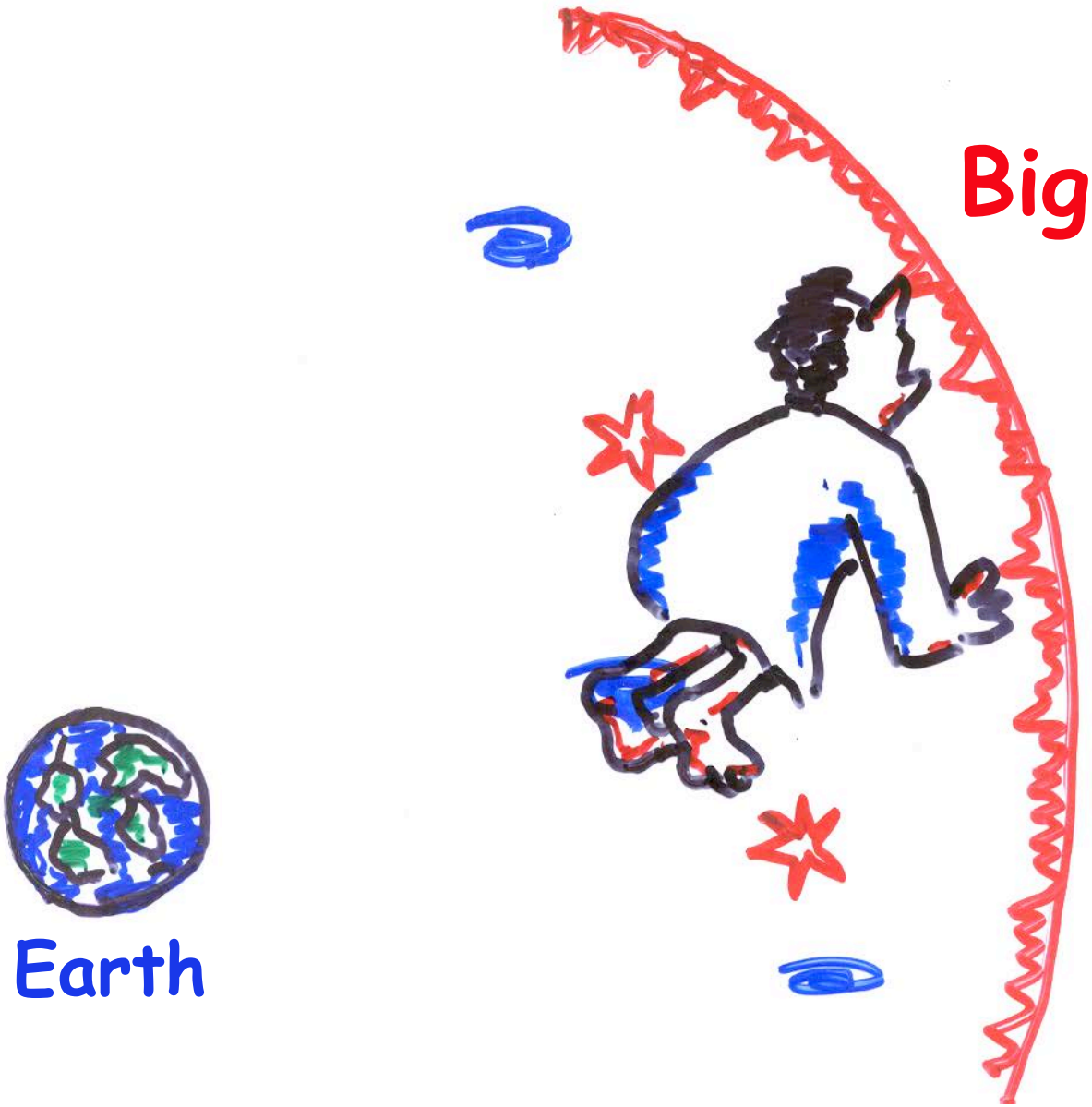
$$f_{\rm NL}^{\rm local} = 0.8 \pm 5$$

Agrees with predictions of the simplest inflationary models with accuracy $O(10^{-4})$.

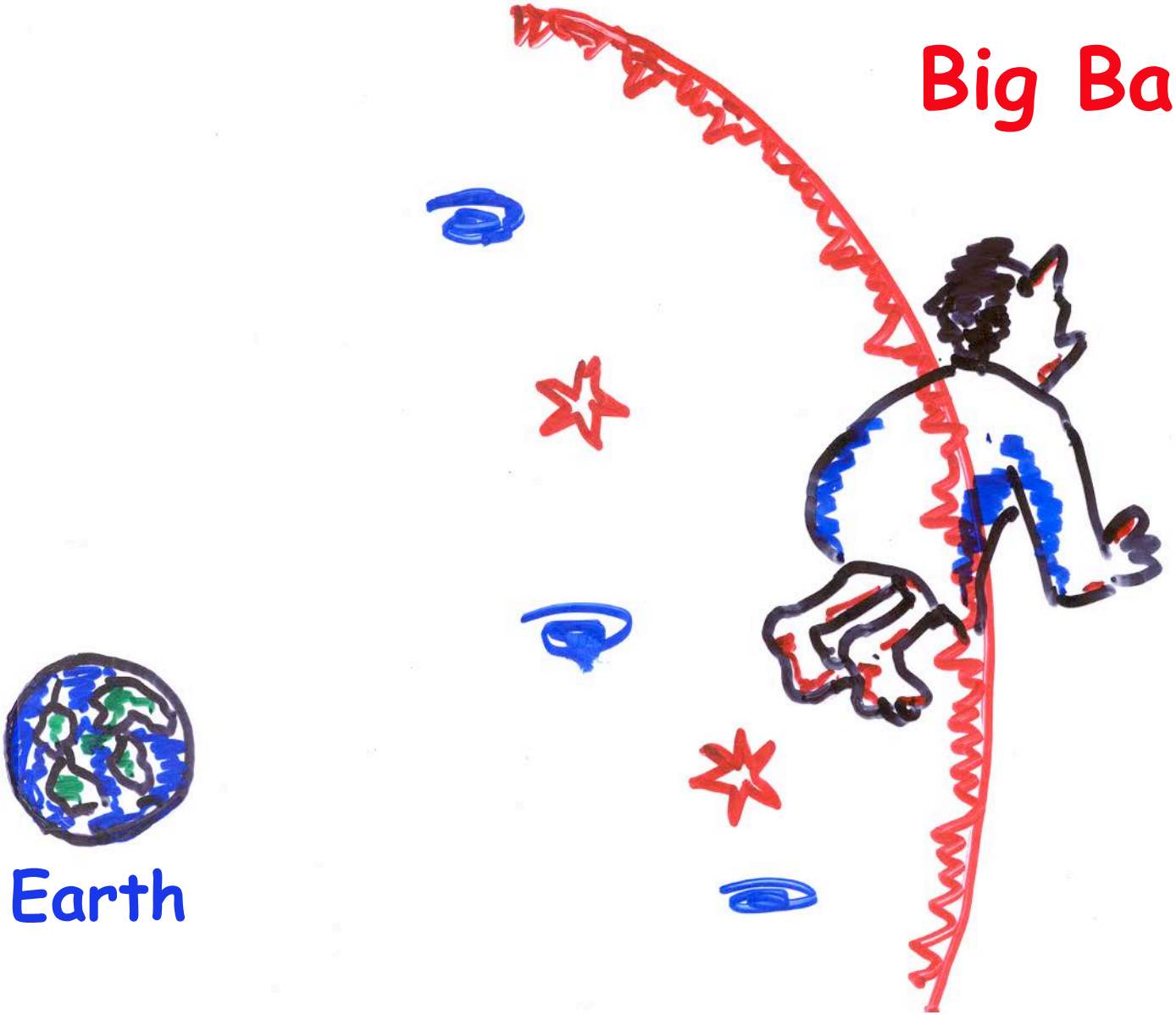
An impressive success of inflationary theory

Astronomers use our universe as a “time machine”. By looking at the stars close to us, we see them as they were several hundreds years ago.

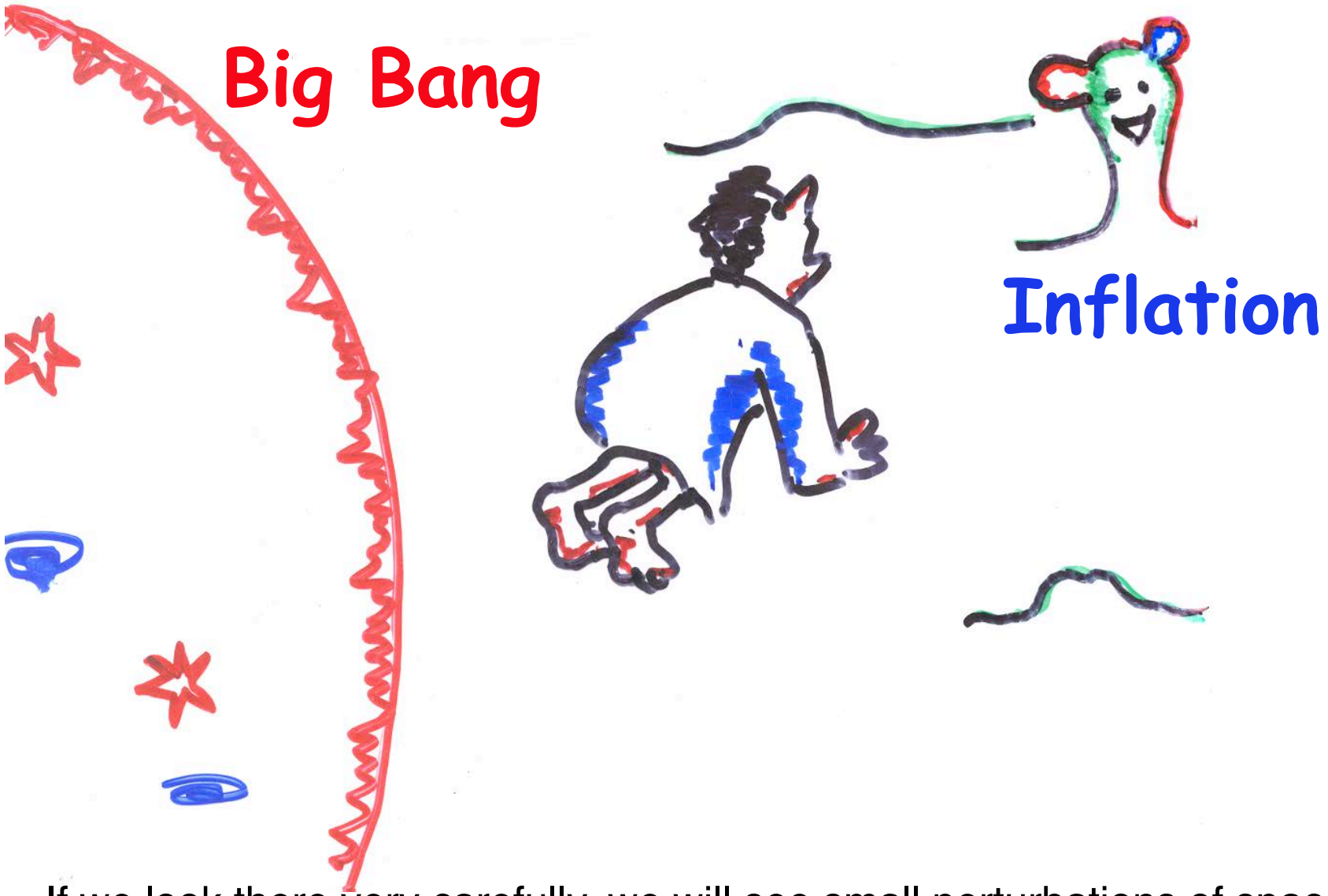
The light from distant galaxies travel to us for billions of years, so we see them in the form they had billions of years ago.



Looking even further, we can detect photons emitted 400000 years after the Big Bang. But 30 years ago everyone believed that there is nothing beyond the cosmic fire created in the Big Bang at the time t = 0.



Inflationary theory tells us that this cosmic fire was created not at the time t = 0, but after inflation. If we look beyond the circle of fire surrounding us, we will see enormously large empty space filled only by a scalar field.



If we look there very carefully, we will see small perturbations of space, which are responsible for galaxy formation. And if we look even further, we will see how new parts of inflationary universe are created by quantum fluctuations.

Uniformity of our **universe** is explained by **inflation**: Exponential stretching of the universe makes **our part** of the universe almost exactly uniform.

However, the same theory predicts that on a much greater scale, the universe is 100% non-uniform.

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

Here comes the 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:

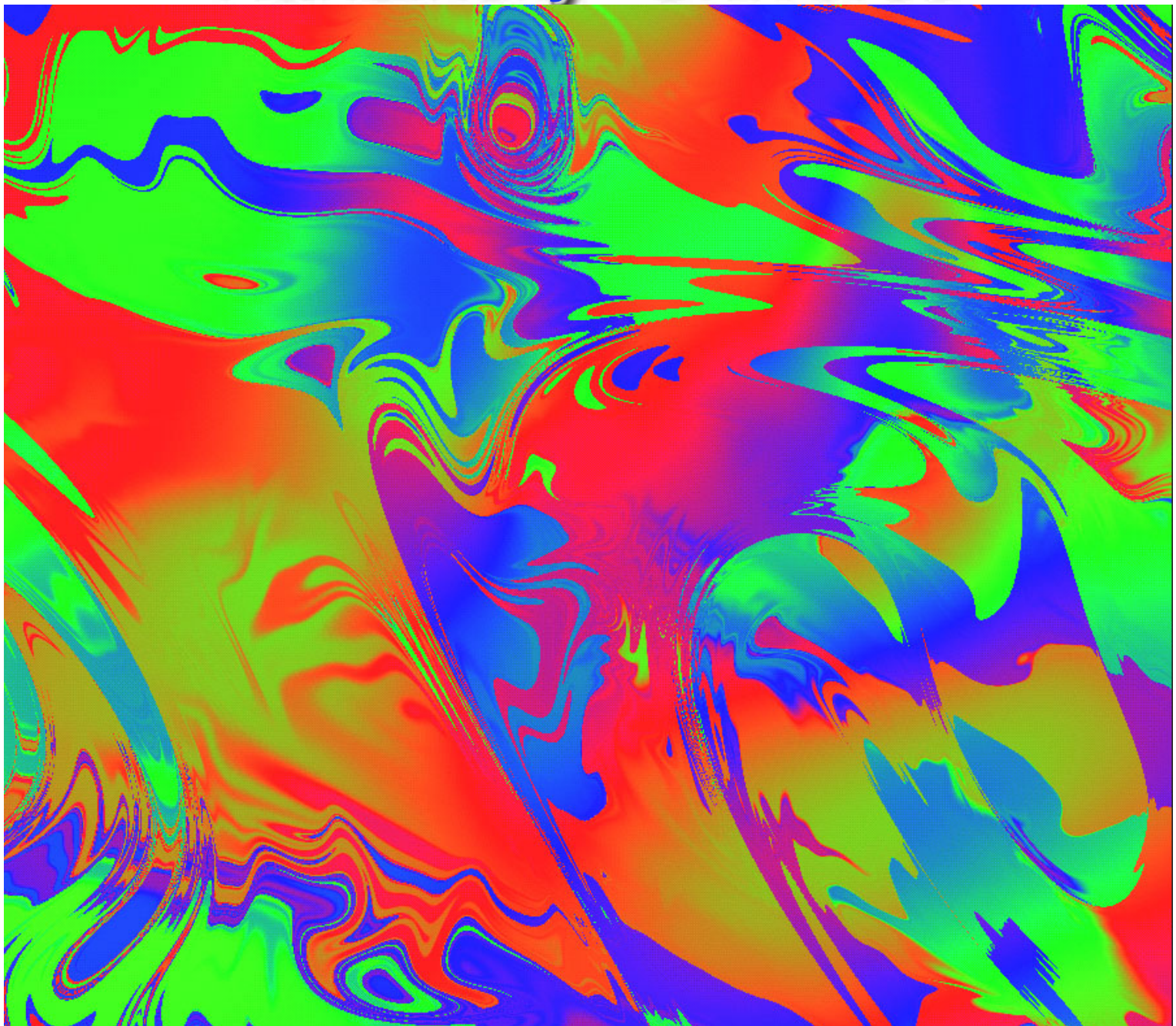
If each part of the multiverse is huge, we will never see other parts, so it is **impossible to disprove** that we live in the multiverse.

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

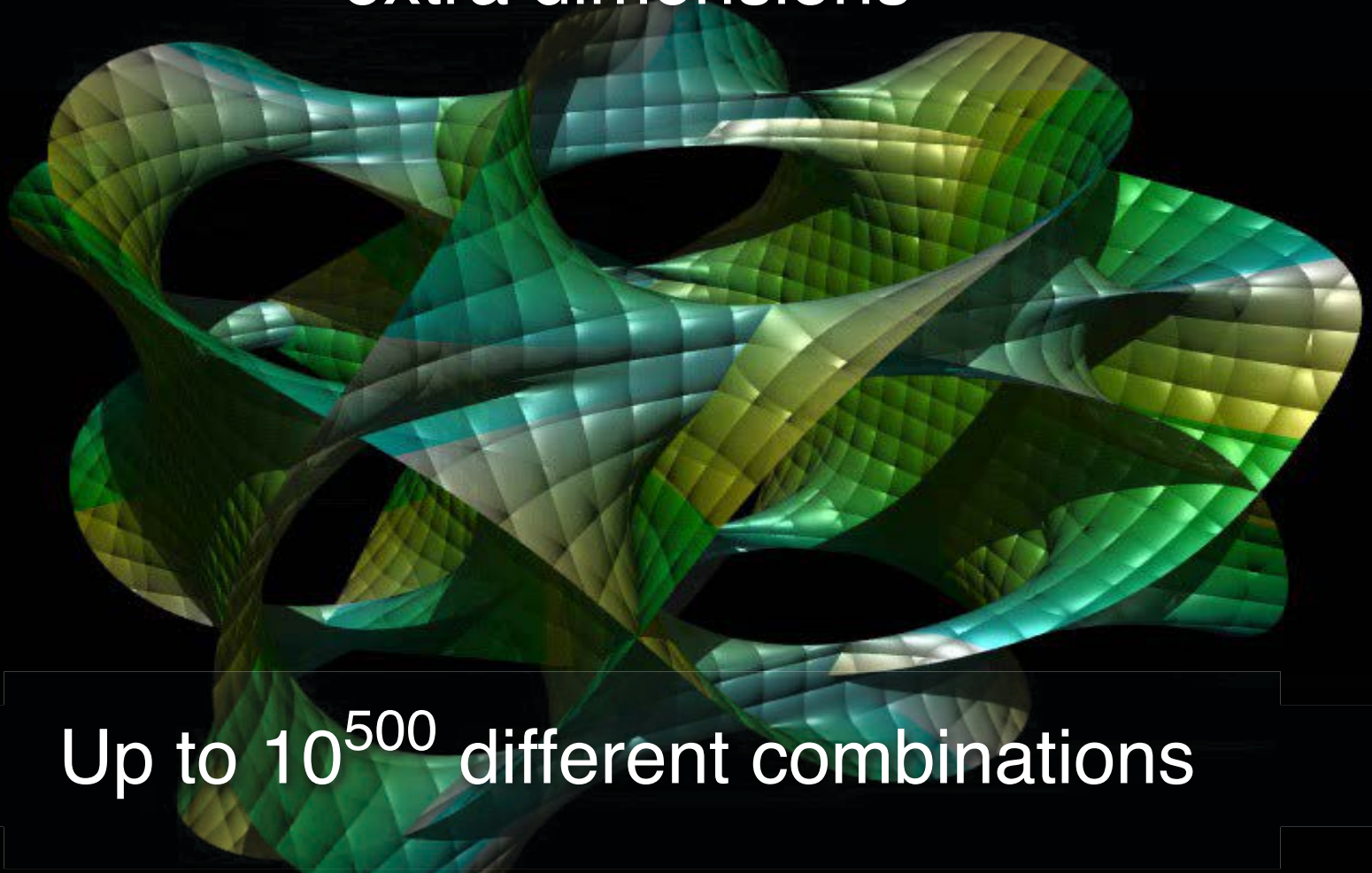
This scenario is **more general** (otherwise one would need to explain why all colors but one are forbidden). Therefore the theory of the **multi**verse, rather than the theory of the **uni**verse, is the basic theory.

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

Kandinsky Universe



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; Silverstein 2001; Kachru, Kallosh, AL, Trivedi, 2003; Douglas 2003; Susskind 2003

Can we test the multiverse theory ?

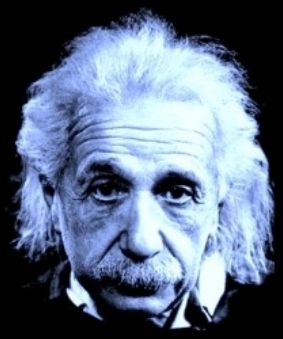
This theory provides the only known explanation of numerous experimental results (extremely small vacuum energy, strange masses of many elementary particles). **In this sense, it was already tested many times.**

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

Sherlock Holmes

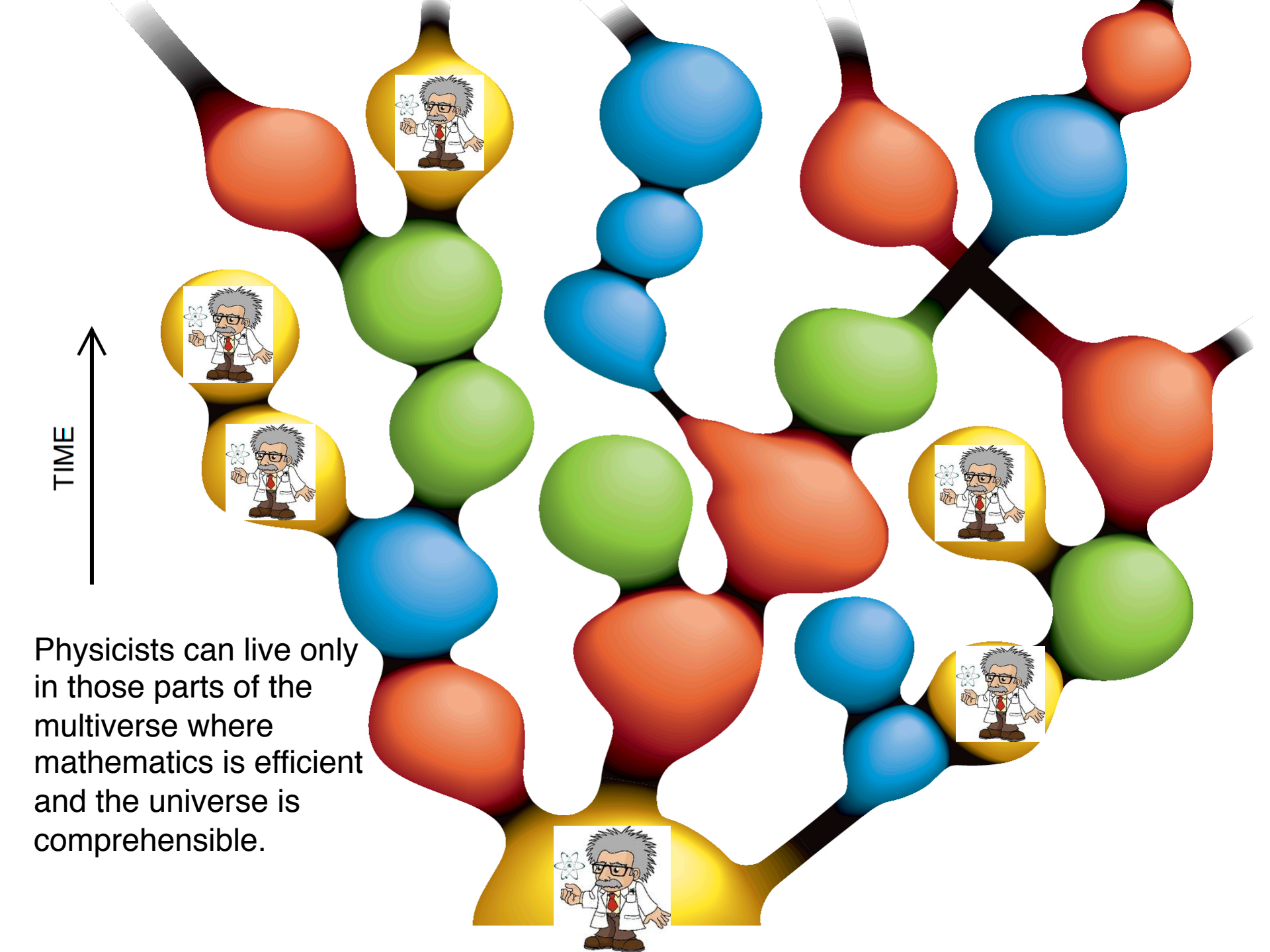
The most incomprehensible thing about the universe is that it is comprehensible

Albert Einstein



The unreasonable efficiency of mathematics in science is a gift we neither understand nor deserve

Eugene Wigner



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