Inflation and String Cosmology

Andrei Linde

Contents:

- From the Big Bang theory to Inflationary Cosmology
- Eternal inflation and string theory landscape

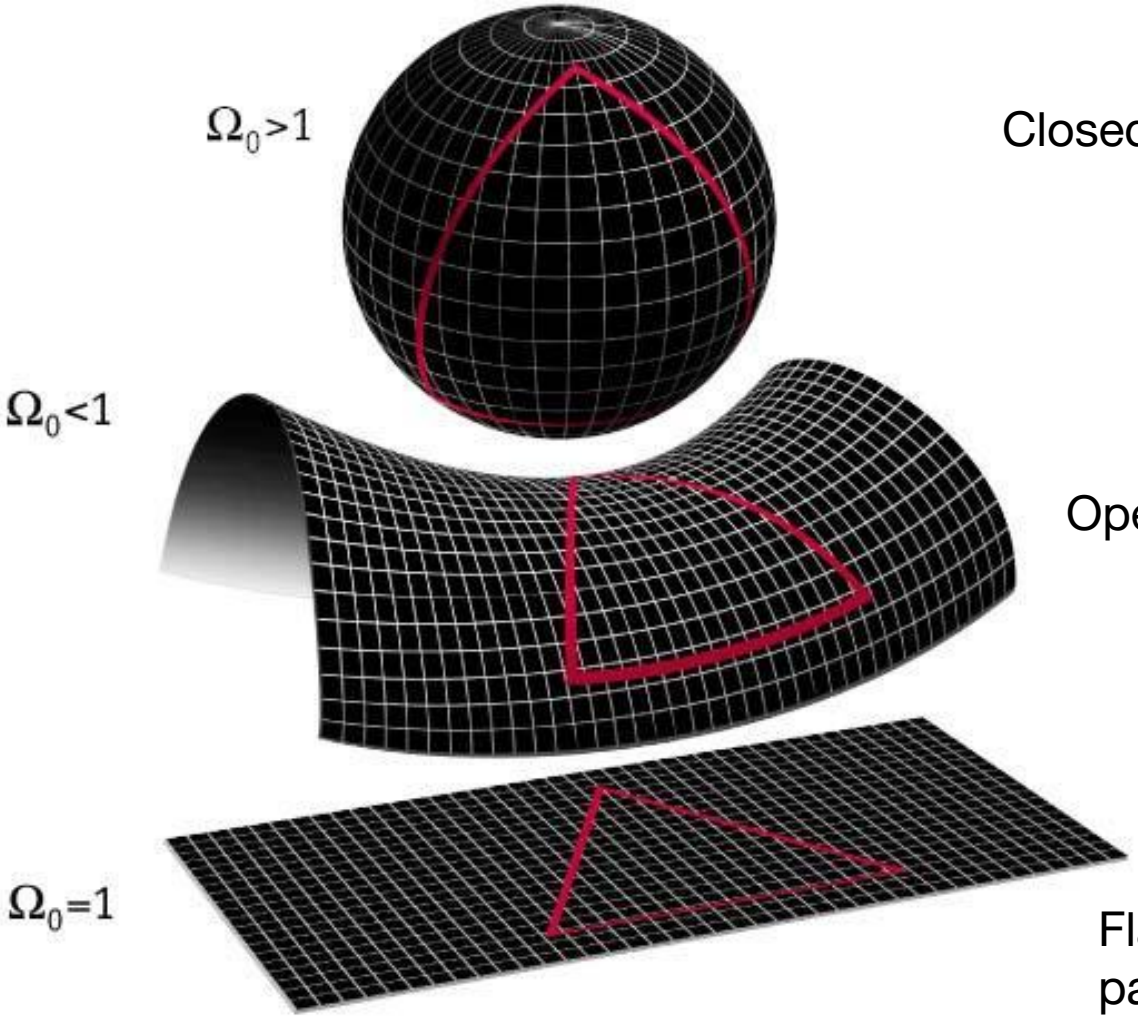
Two major cosmological discoveries:

- The new-born universe experienced rapid acceleration (inflation)

- A new (slow) stage of acceleration started 5 billion years ago (dark energy)

How did it start, and how it is going to end?

Closed, open or flat universe

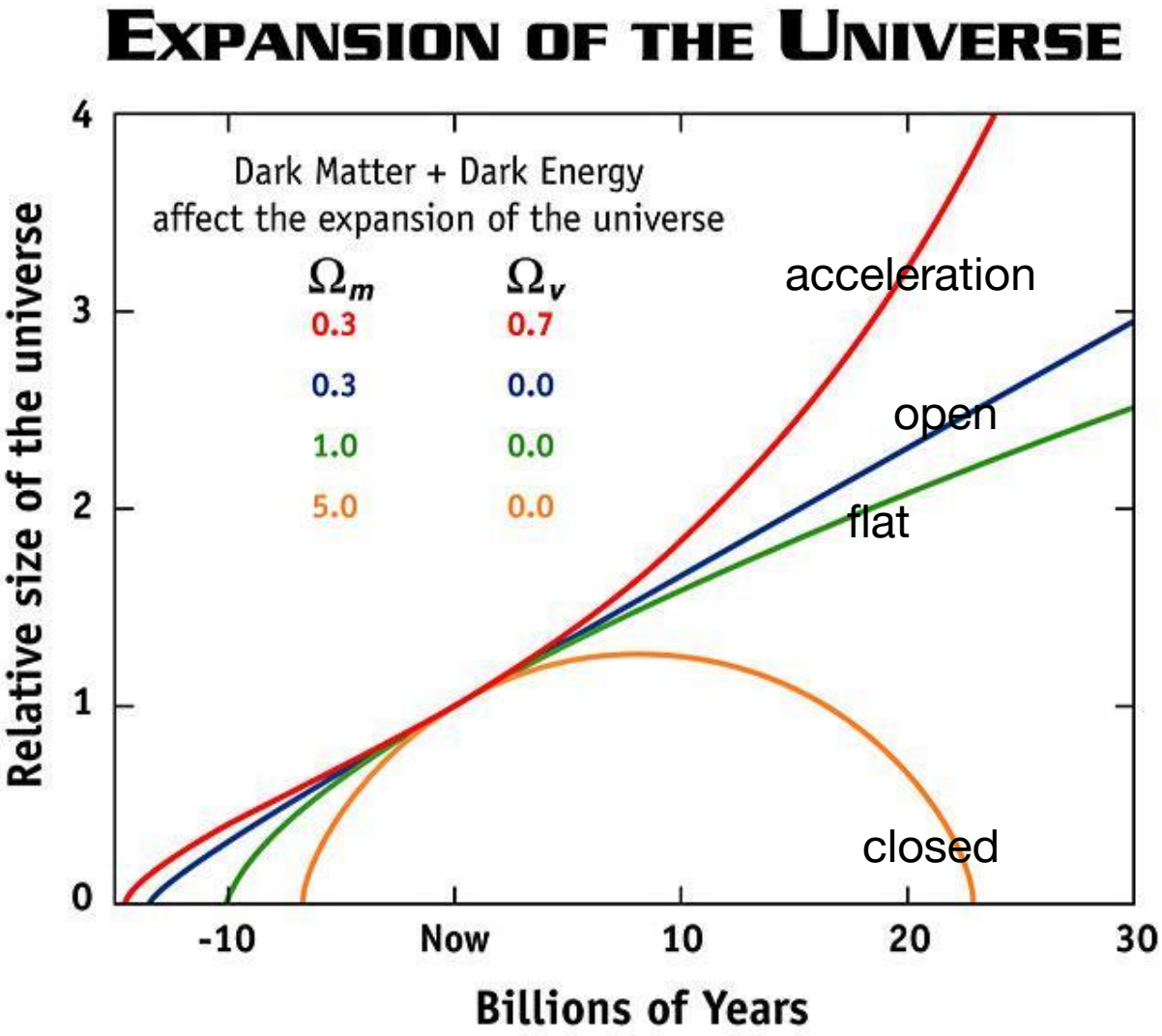


Closed universe. Parallel lines intersect

Open universe. Parallel lines diverge

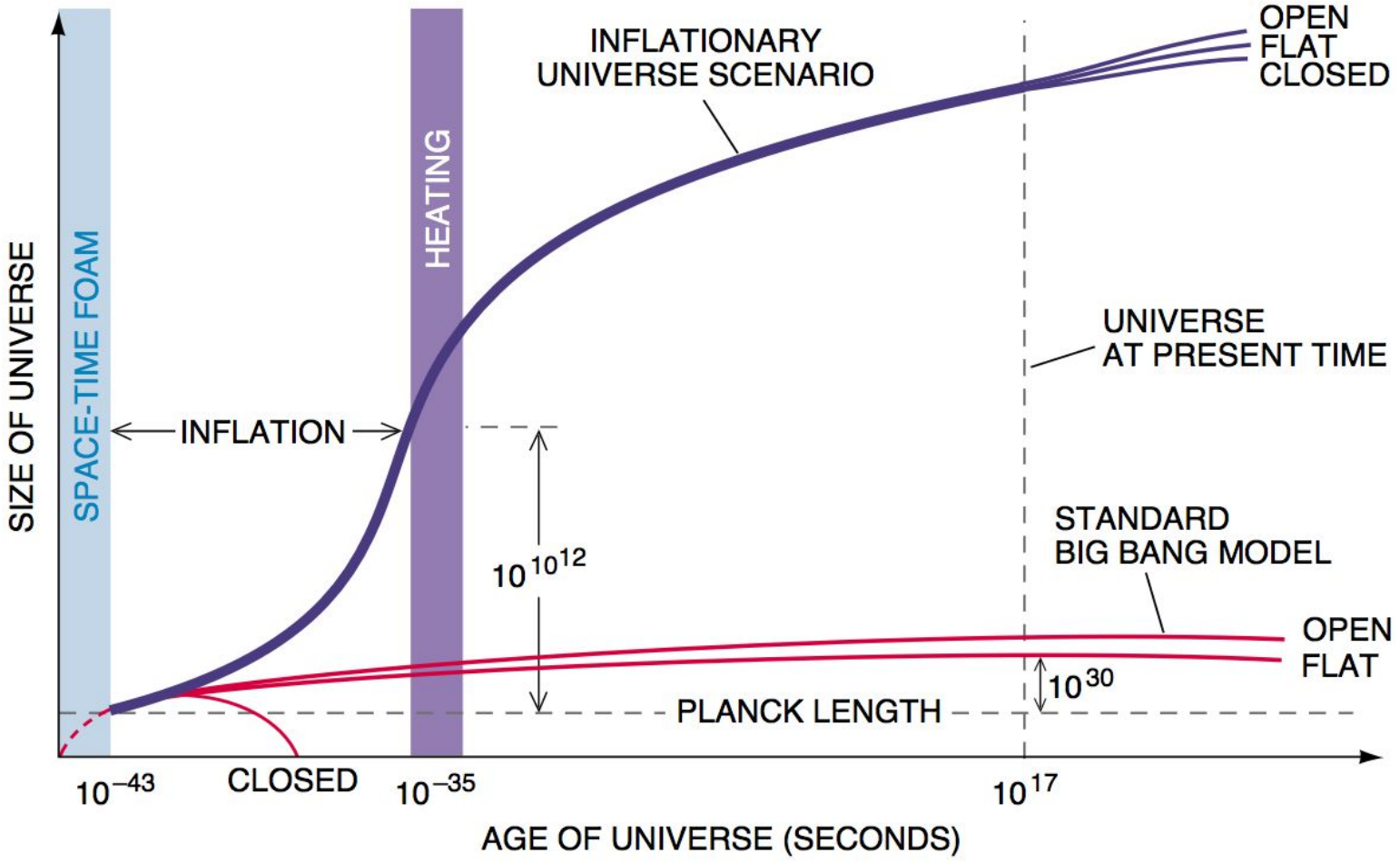
Flat universe. Parallel lines remain parallel, but the distance between them grow with time

Big Bang Theory



If vacuum has positive energy density (dark energy), the universe may accelerate, as it is shown on the upper curve. Such universe may not collapse even if it is closed.

Inflationary Universe

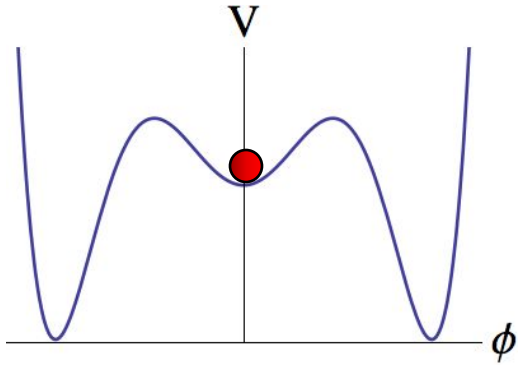


Inflation is an extremely rapid acceleration in the universe soon after its creation.

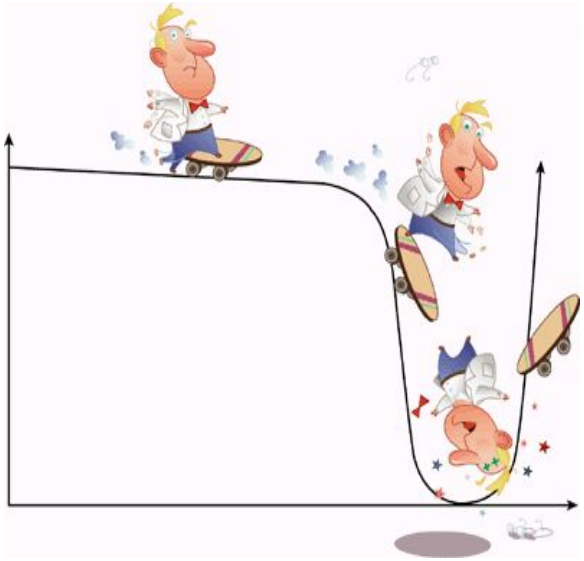
Inflation

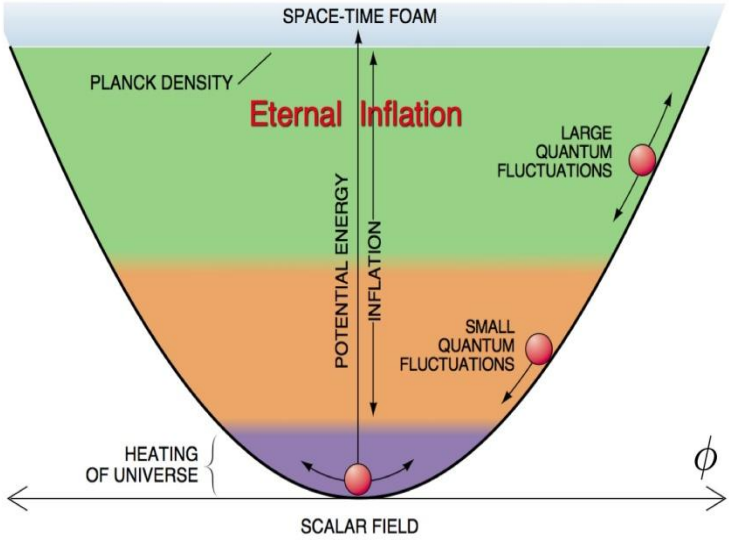
Starobinsky, 1980 – modified gravity, $R + R^2$
a complicated but almost working model

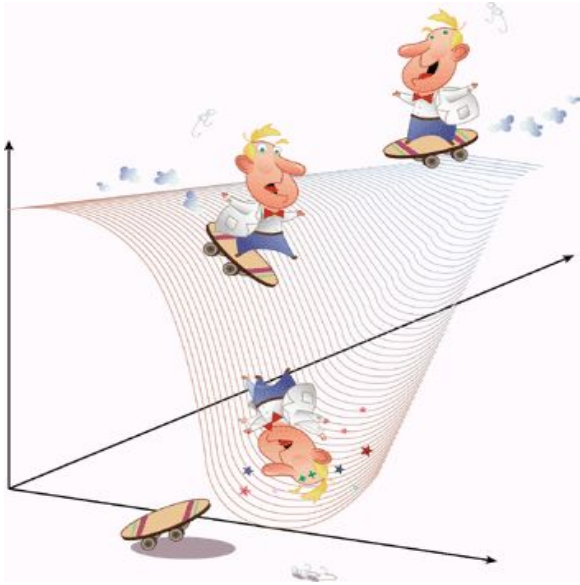
Guth, 1981 - old inflation (inflation in a false vacuum)



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







A.L., 1982 - new inflation

1983 - chaotic inflation

1991 - hybrid

Inflation was invented in an attempt to answer almost metaphysical questions:

- What was before the Big Bang?
- Why is our universe so **homogeneous** (better than 1 part in 10000) ?
- Why is it **isotropic** (the same in all directions)?
- Why all of its parts started expanding simultaneously?
- Why is it **flat**? Why parallel lines do not intersect?

Where did the energy come from?

Some basic facts:

1) Energy of matter in the universe **IS NOT CONSERVED:**

$$dE = -p\,dV$$

Volume V of an expanding universe grows, so its energy decreases if pressure p is positive.

2) **Total** energy of matter and of gravity (related to the shape and the volume of the universe) is conserved, but this conservation is somewhat unusual:

The sum of the energy of matter and of the gravitational energy is equal to

zero

Energy of matter in the Big Bang theory

According to the Big Bang theory, the total mass of matter soon after the Big Bang was greater than **10^{80} ton**

Mass = Energy: $E = mc^2$

Before the Big Bang there was NOTHING, and then suddenly we got A HUGE AMOUNT OF ENERGY

Where did it come from?

To create our universe we would need more than **10^{80} tons** of high tech explosive compressed to a size of 1cm, and exploded simultaneously, with accuracy 10^{-43} s.

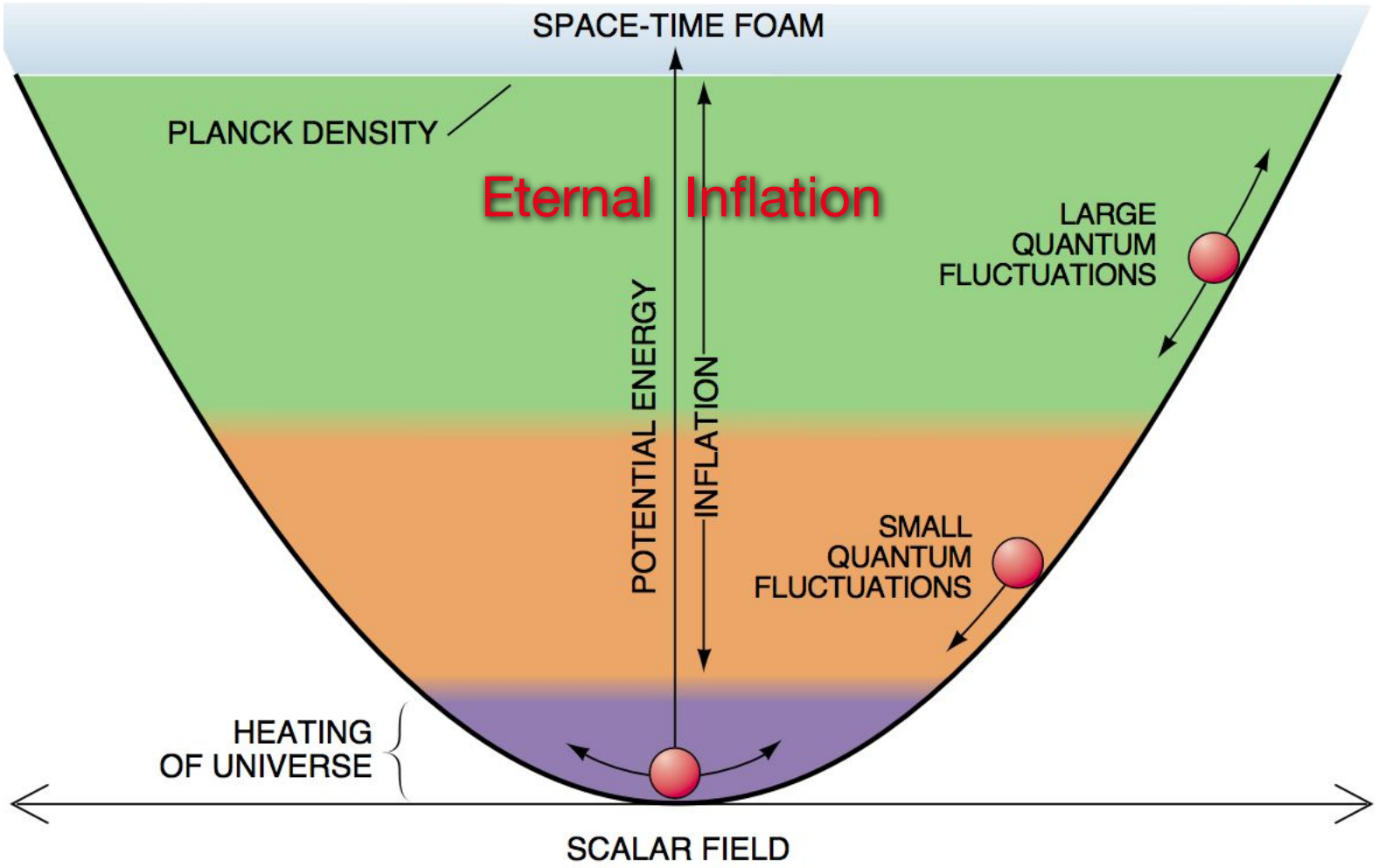
Who could do it?…

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

oscillator

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



Equations of motion:

- **Einstein equation:**

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{m^2}{6}\phi^2$$

- **Klein-Gordon equation:**

$$\ddot{\phi} + 3H\dot{\phi} = -m^2\phi$$

Compare with equation for the harmonic oscillator with friction:

$$\ddot{x} + \alpha\dot{x} = -kx$$

Logic of Inflation:

Large φ → large H → large friction

field φ moves very slowly, so that its potential energy for a long time remains nearly constant

$$H = \frac{\dot{a}}{a} = \frac{m\phi}{\sqrt{6}} \approx \text{const}$$

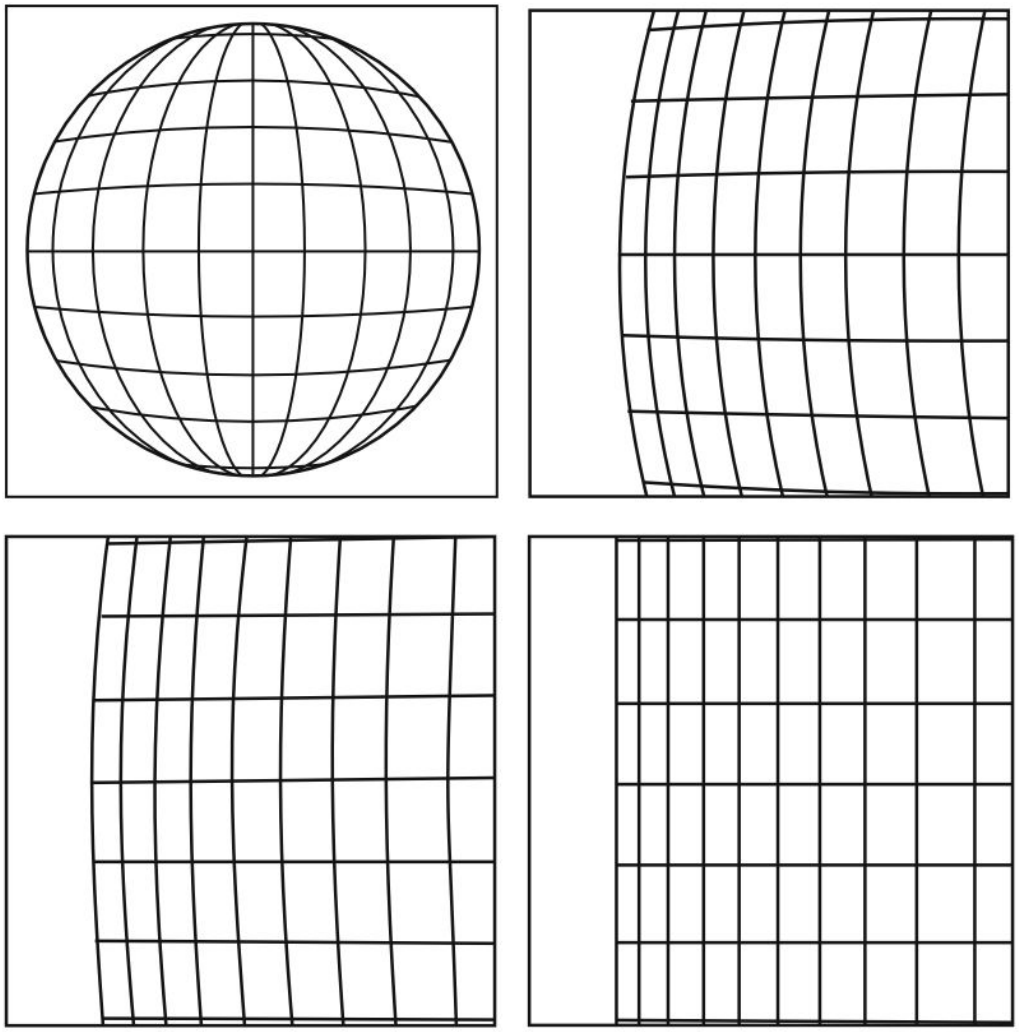
$$a \sim e^{Ht}$$

This is the stage of inflation

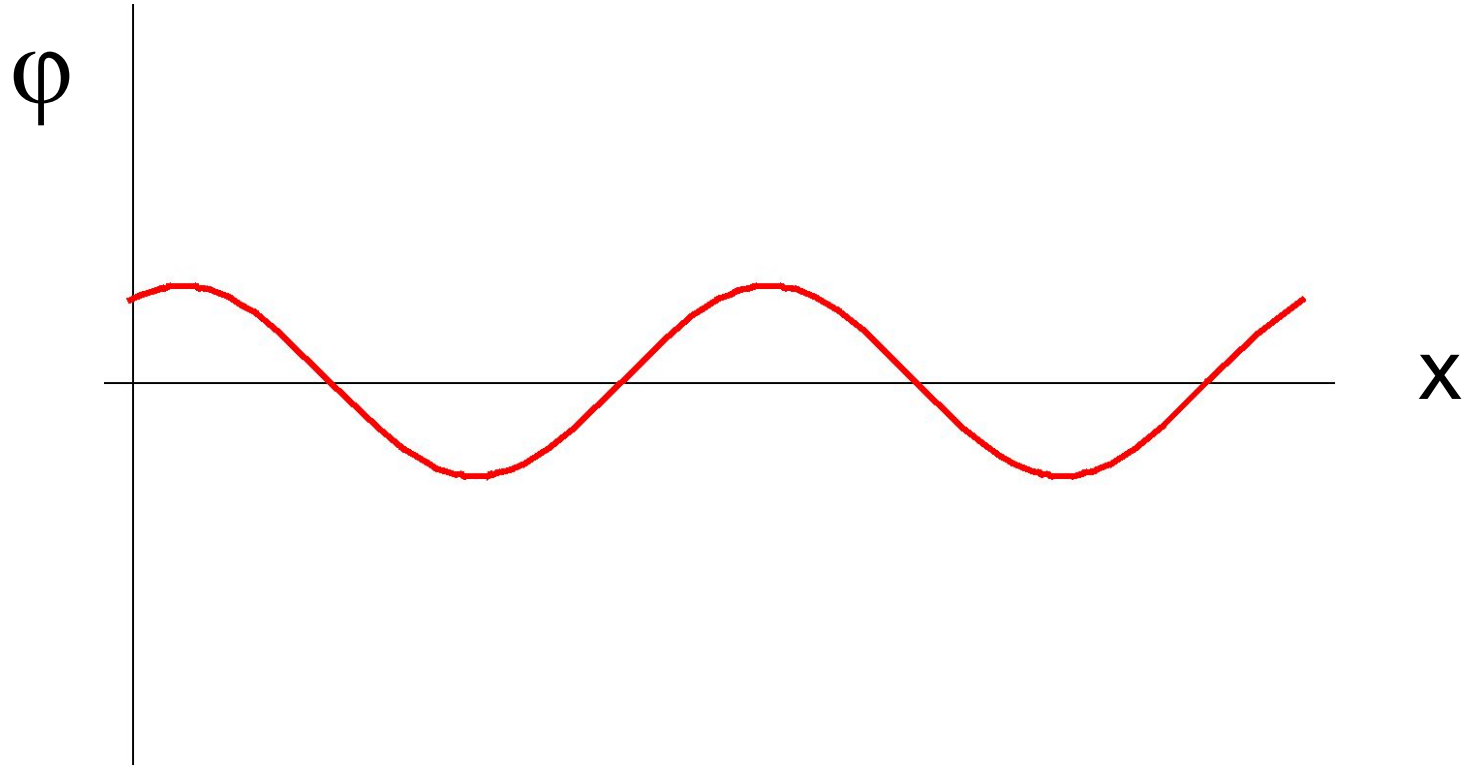
Inflation makes the universe flat, homogeneous and isotropic

In this simple model the universe typically grows $10^{1000000000000}$ times during inflation.

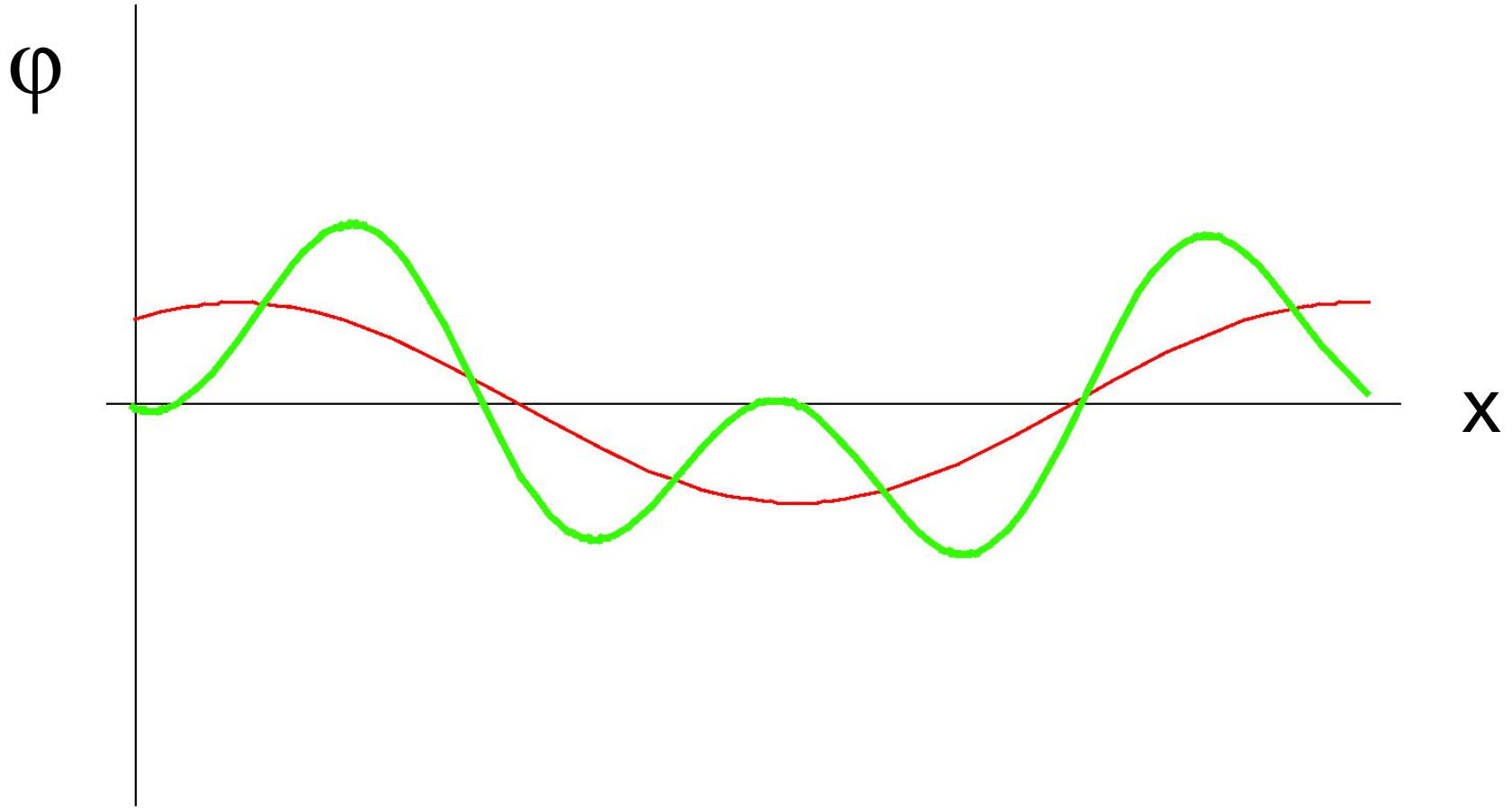
Now we can see just a tiny part of the universe of size ct = 10^{10} light yrs. That is why the universe looks homogeneous, isotropic, and flat.



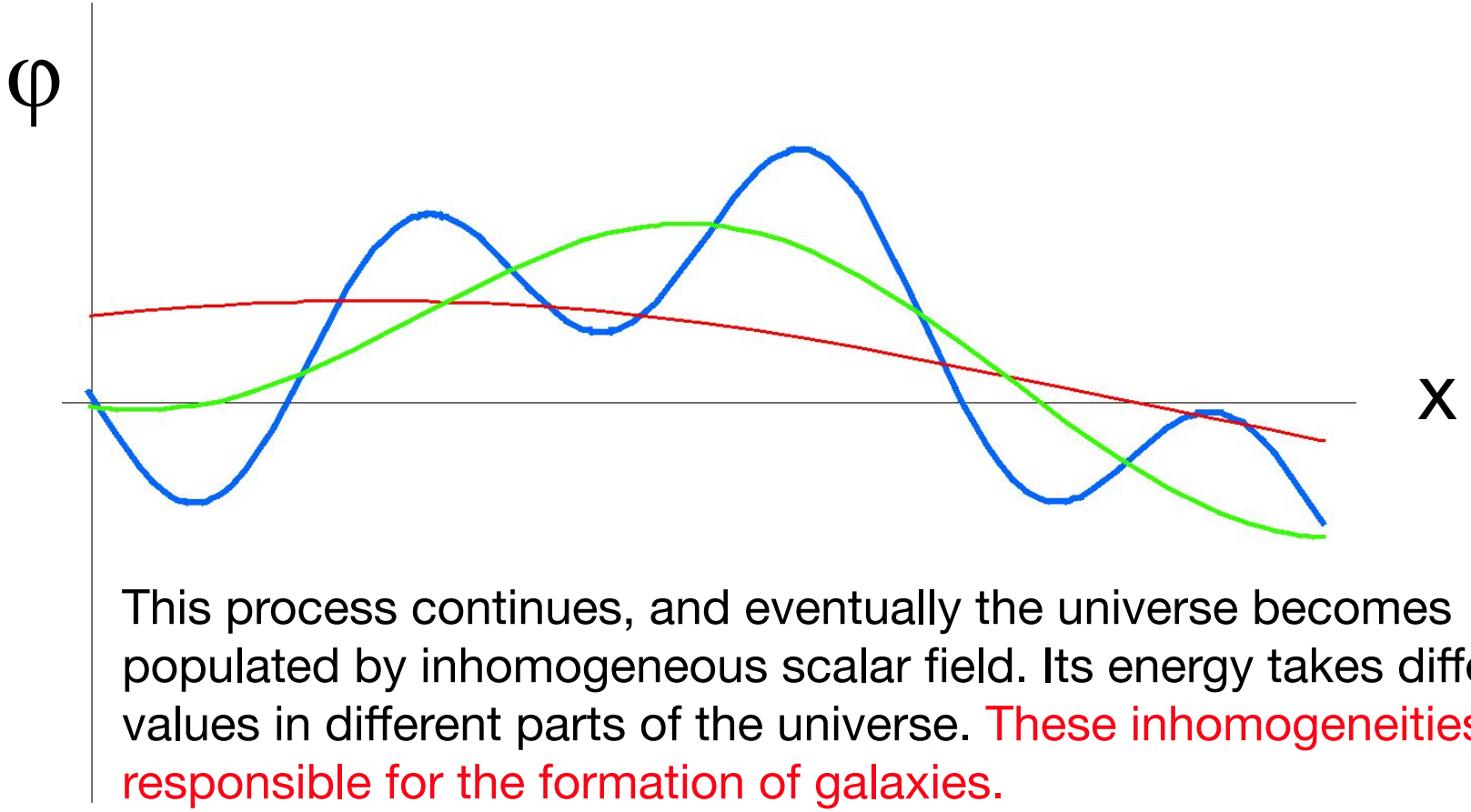
Quantum fluctuations produced during inflation



Small quantum fluctuations of all physical fields exist everywhere. They are similar to waves, which appear and then rapidly oscillate, move and disappear. Inflation stretched them, together with stretching the universe. When the wavelength of the fluctuations becomes sufficiently large, they stop moving and oscillating, and do not disappear. They look like frozen waves.



When expansion of the universe continues, new quantum fluctuations become stretched, stop oscillating, and freeze on top of the previously frozen fluctuations.

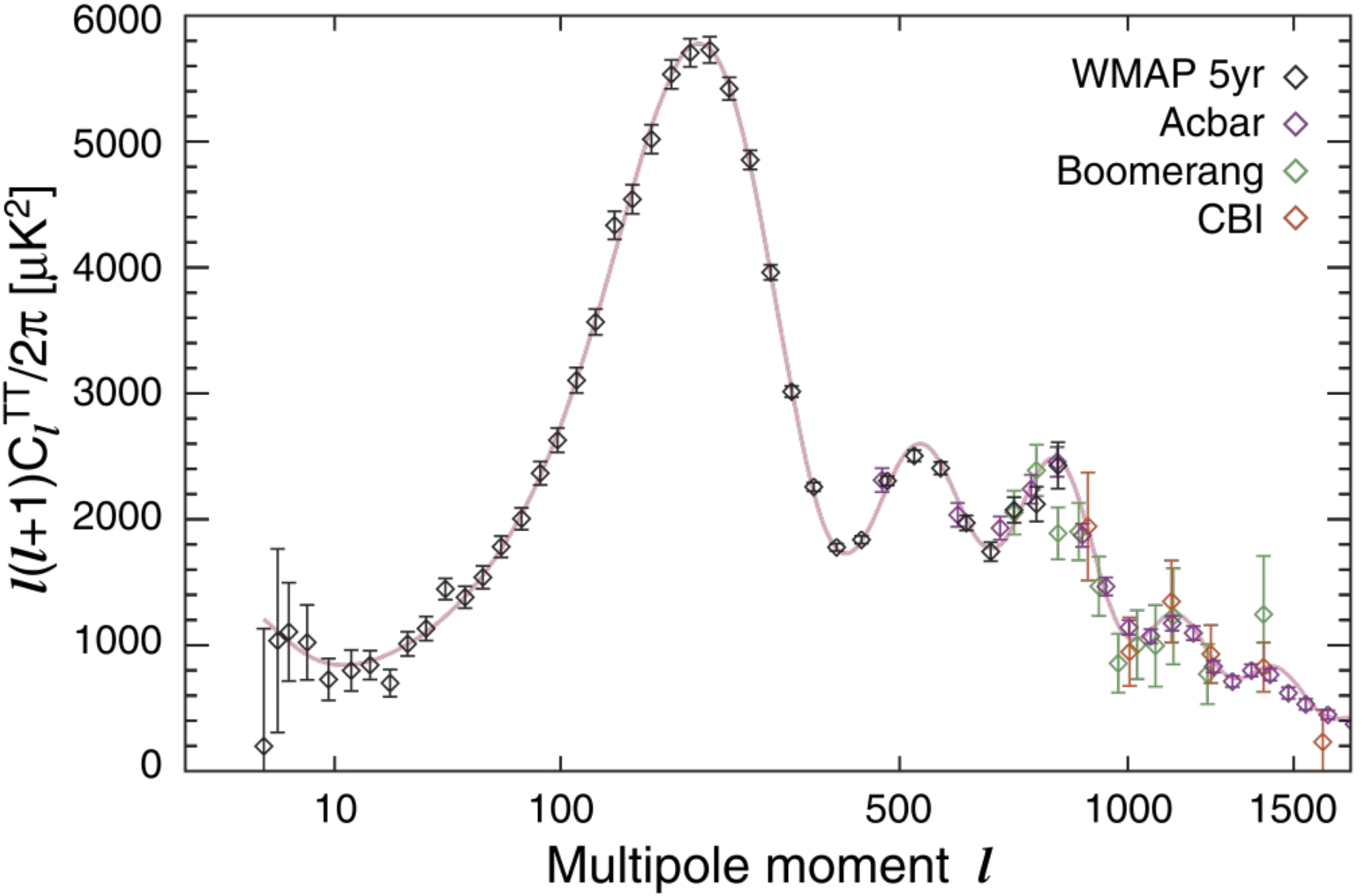


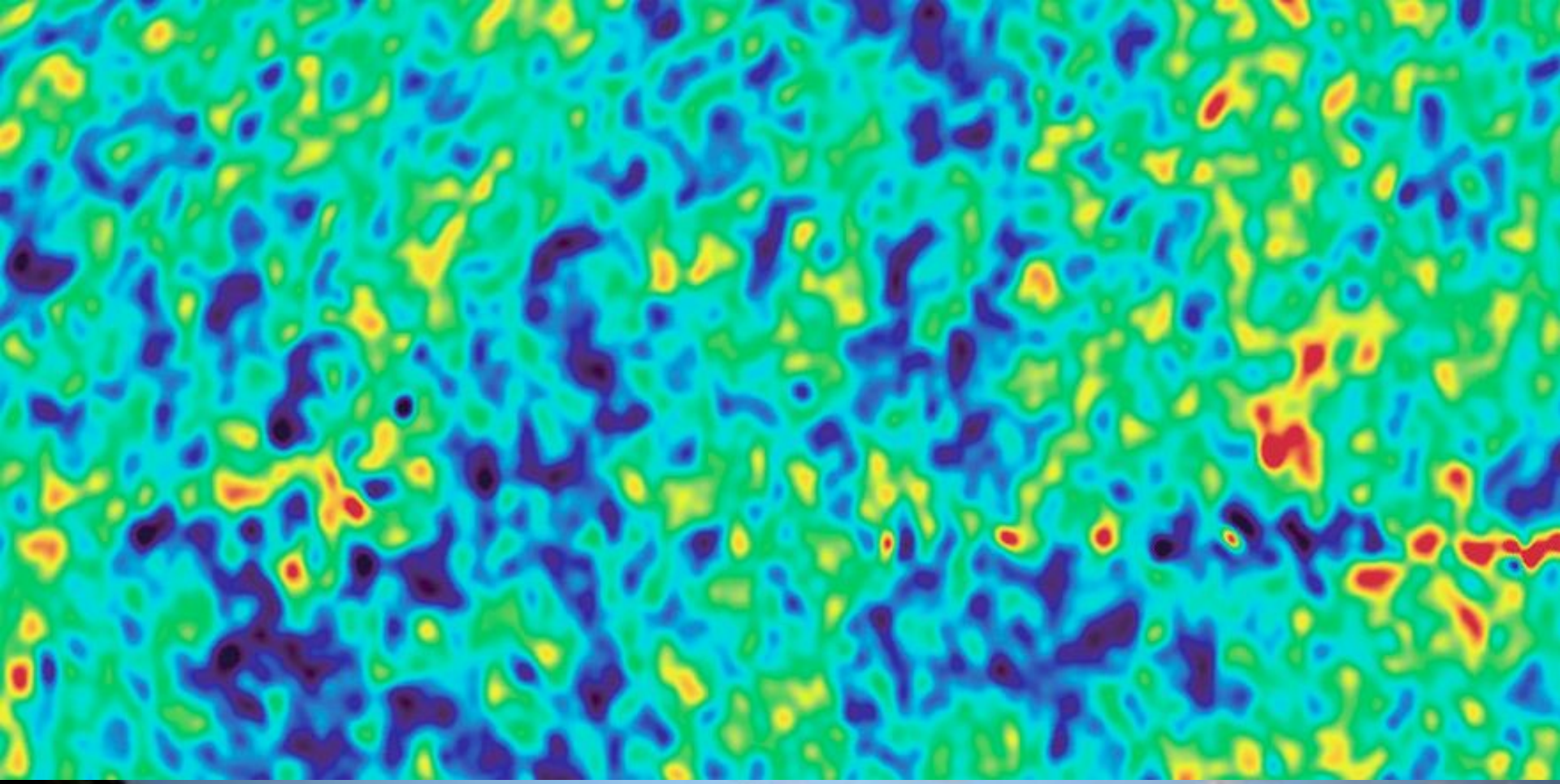
This process continues, and eventually the universe becomes populated by inhomogeneous scalar field. Its energy takes different values in different parts of the universe. These inhomogeneities are responsible for the formation of galaxies.

Sometimes these fluctuations are so large that they can increase the value of the scalar field in some parts of the universe. Then inflation in these parts of the universe occurs again and again. In other words, the process of inflation becomes eternal.

We will illustrate it now by computer simulation of this process.

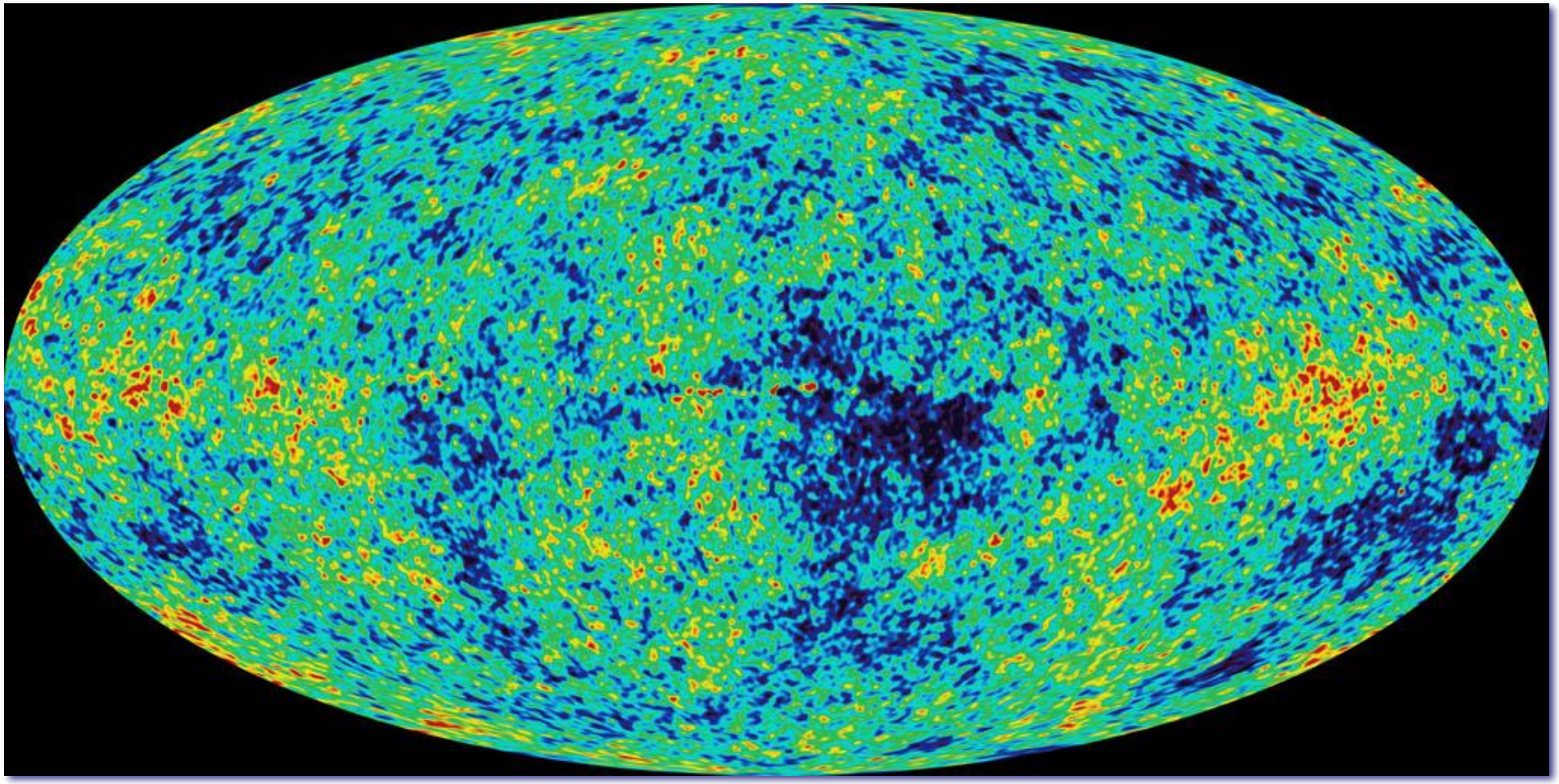
WMAP5 + Acbar + Boomerang + CBI



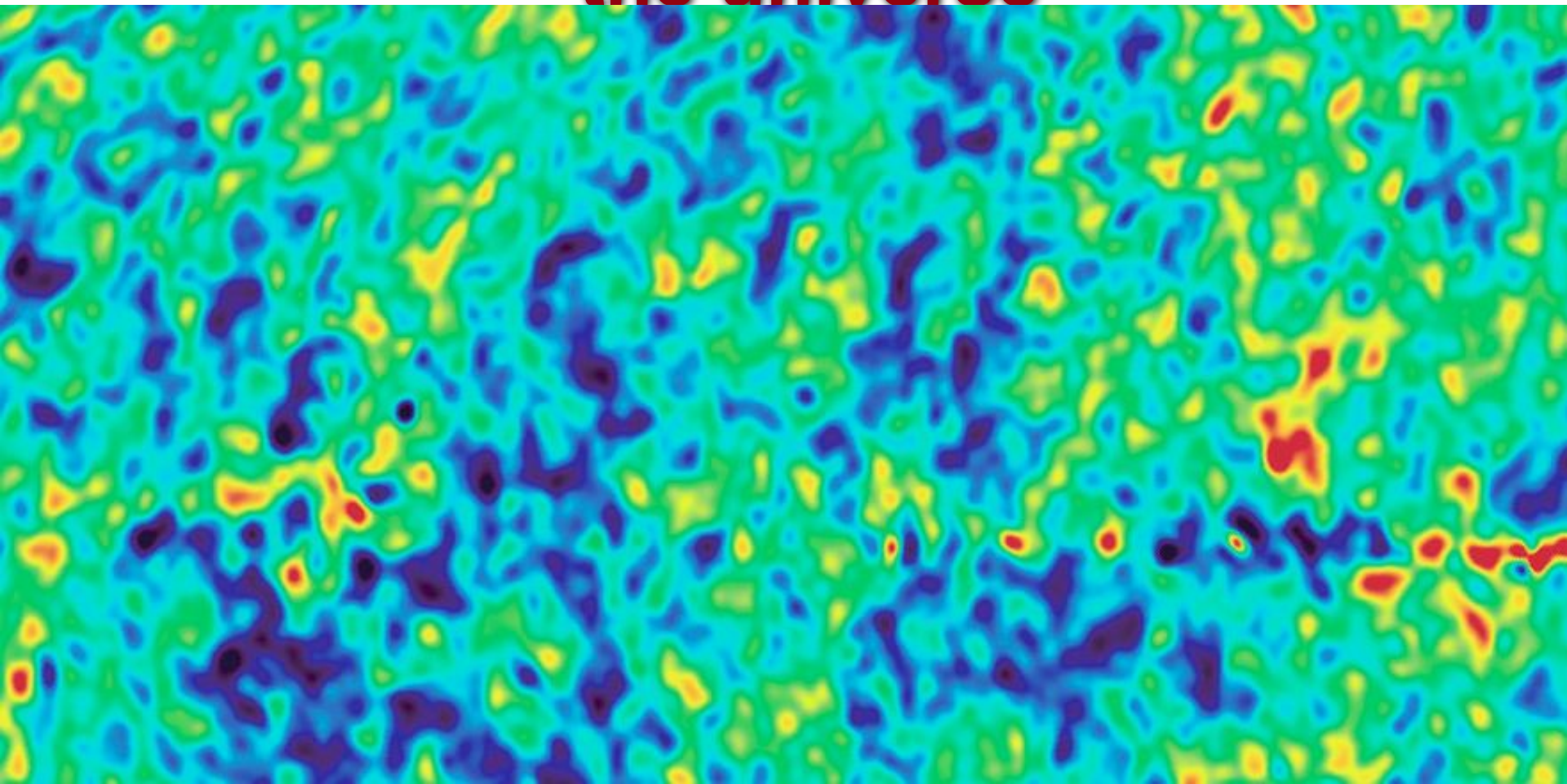


Observations

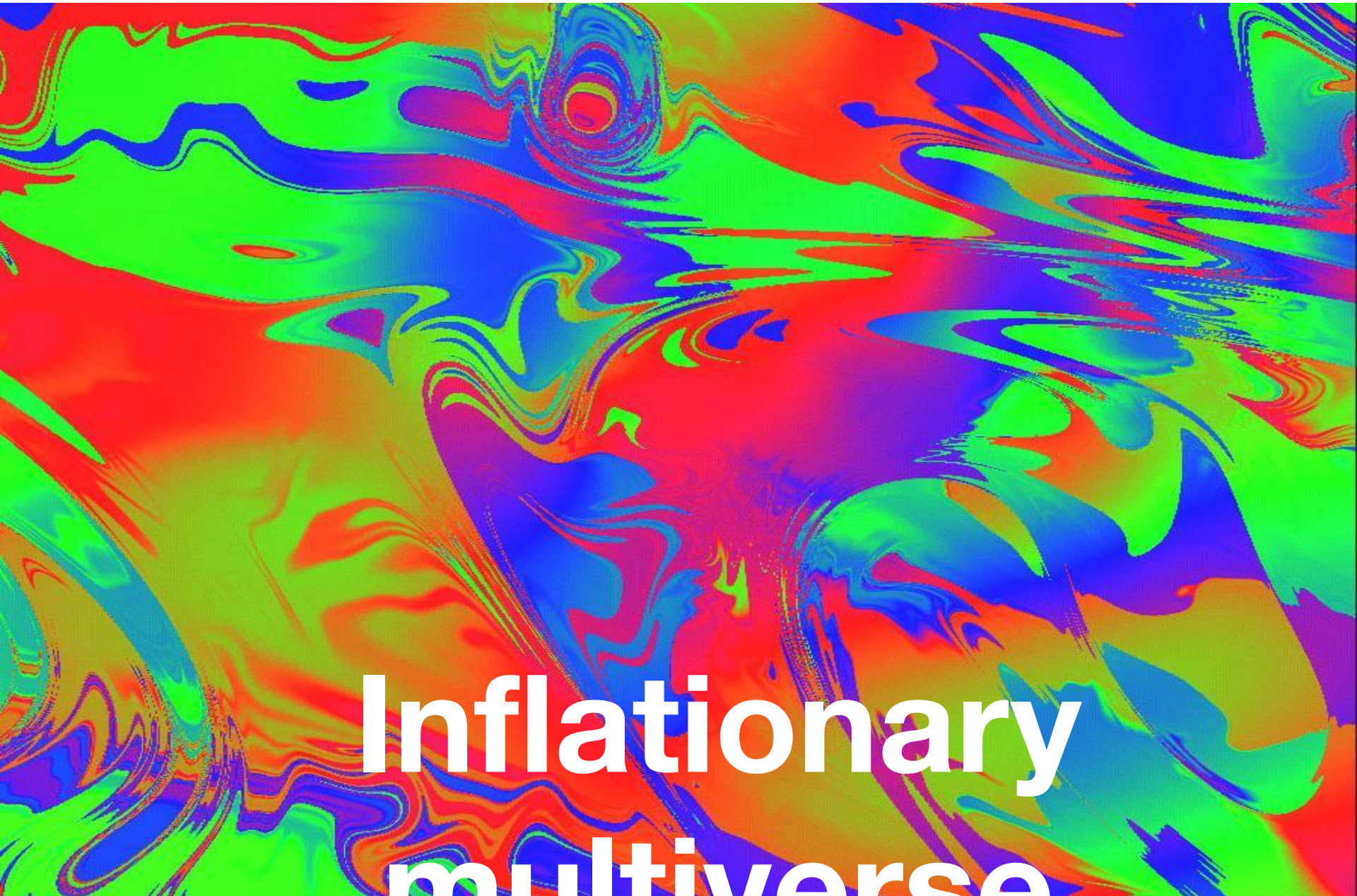
WMAP and the temperature of the sky



This is a photographic image of quantum fluctuations blown up to the size of the universe



On a much, much larger scale…



Predictions of Inflation:

1) The universe should be homogeneous, isotropic and flat, $\Omega = 1 + O(10^{-4})$ $[\Omega=\rho/\rho_0]$

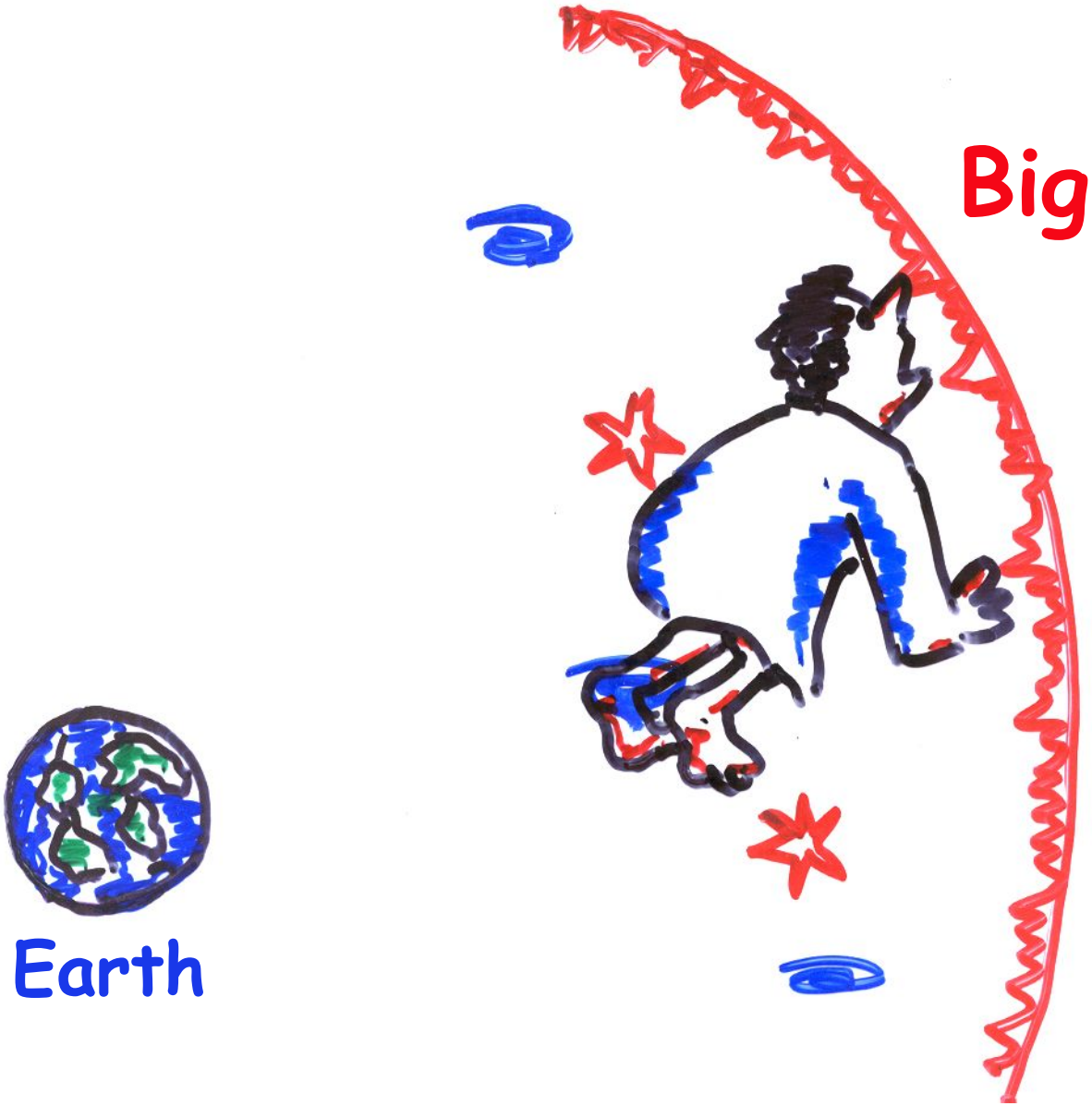
Observations: the universe is homogeneous, isotropic and flat, $\Omega = 1 + O(10^{-2})$

- Inflationary perturbations should be gaussian and adiabatic, with flat spectrum, $n_s = 1+ O(10^{-1})$

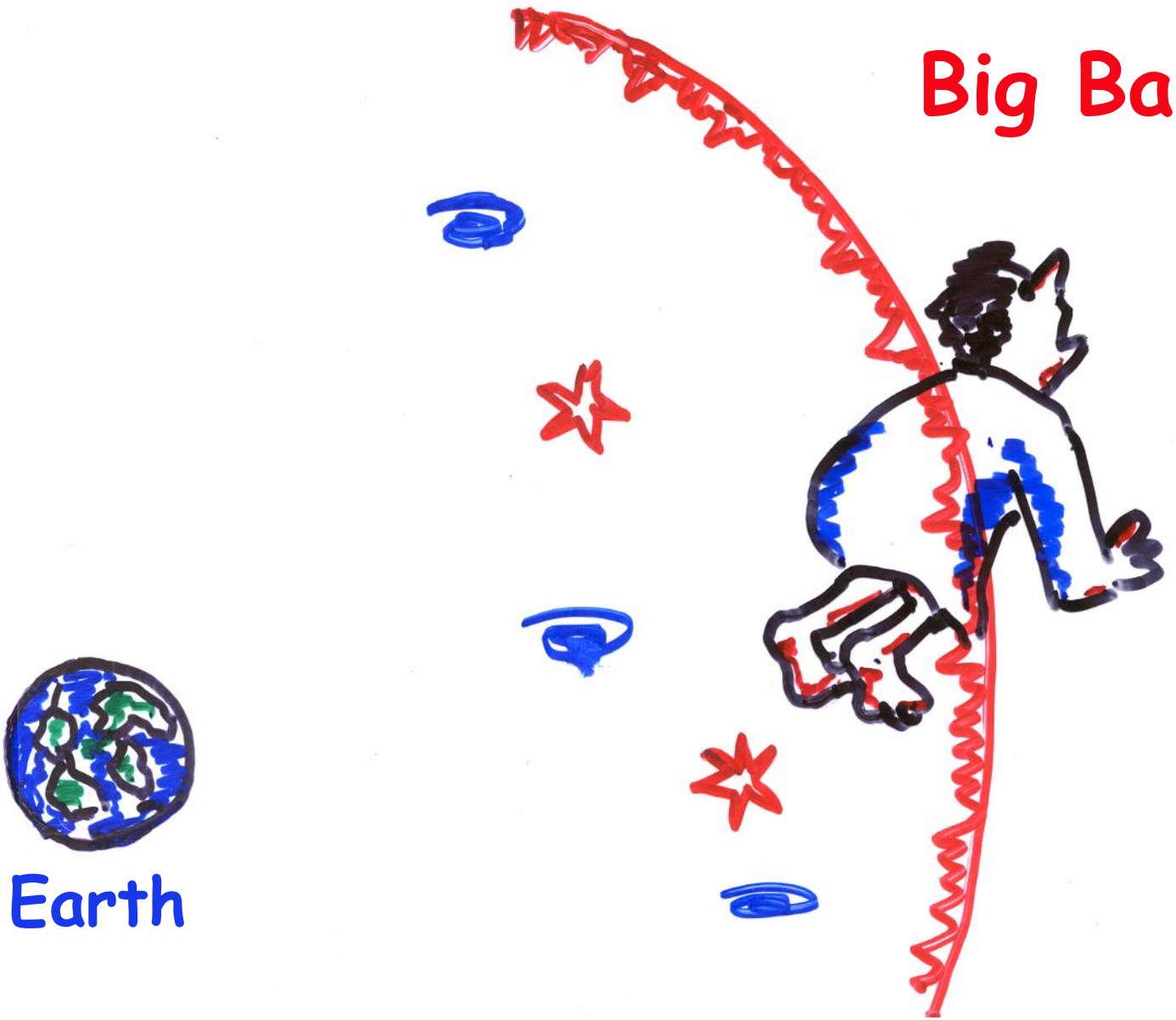
Observations: perturbations are gaussian and adiabatic, with flat spectrum, $n_s = 1 + O(10^{-2})$

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.

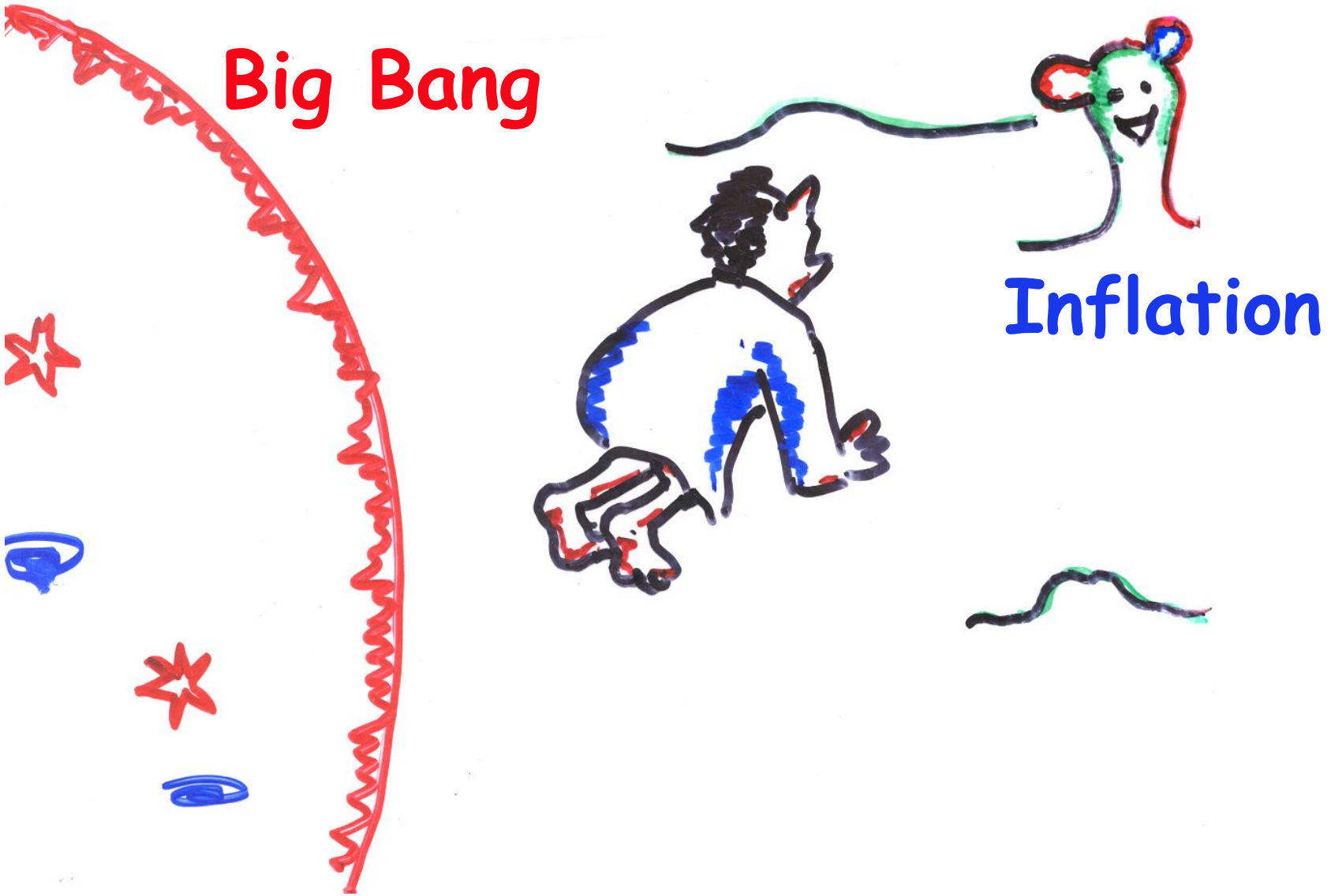
The light from distant galaxies travel to us for billions of years, so we see them in the form they had billions of years ago.



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.



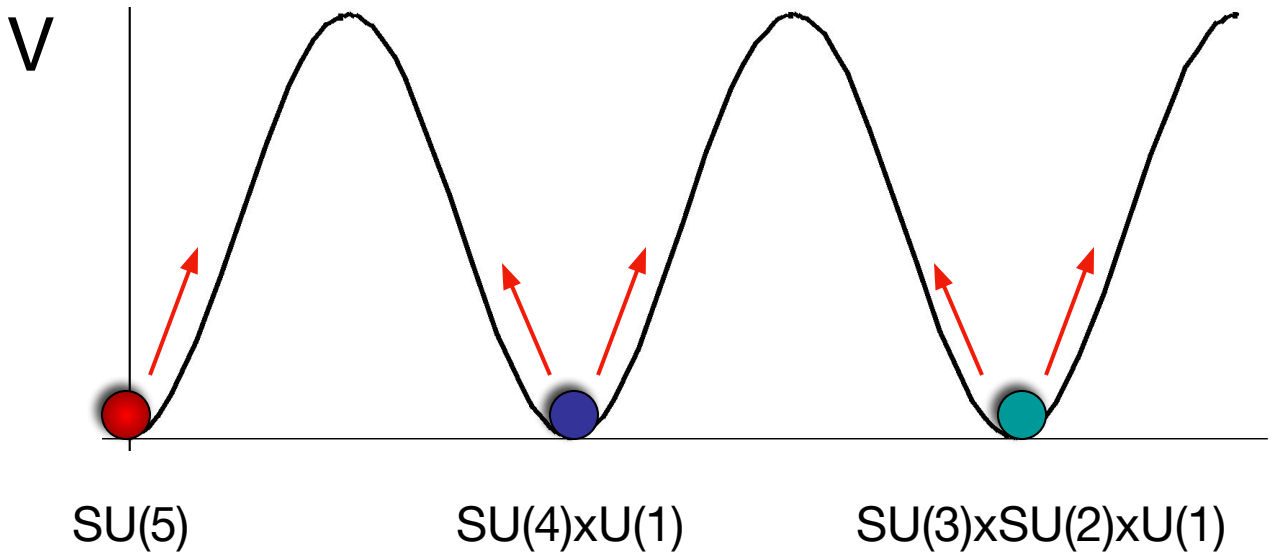
Inflationary theory tells us that this cosmic fire was created not at the time t = 0, but after inflation. If we look beyond the circle of fire surrounding us, we will see enormously large empty space filled only by a scalar field.



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.

From the Universe to the Multiverse

In realistic theories of elementary particles there are **many scalar fields**, and their potential energy has **many different minima**. Each minimum corresponds to different masses of particles and different laws of their interactions.



Quantum fluctuations during eternal inflation can bring the scalar fields to different minima in different exponentially large parts of the universe. The universe becomes divided into many exponentially large parts with **different laws of physics** operating in each of them. (In our computer simulations we will show them by using different colors.)

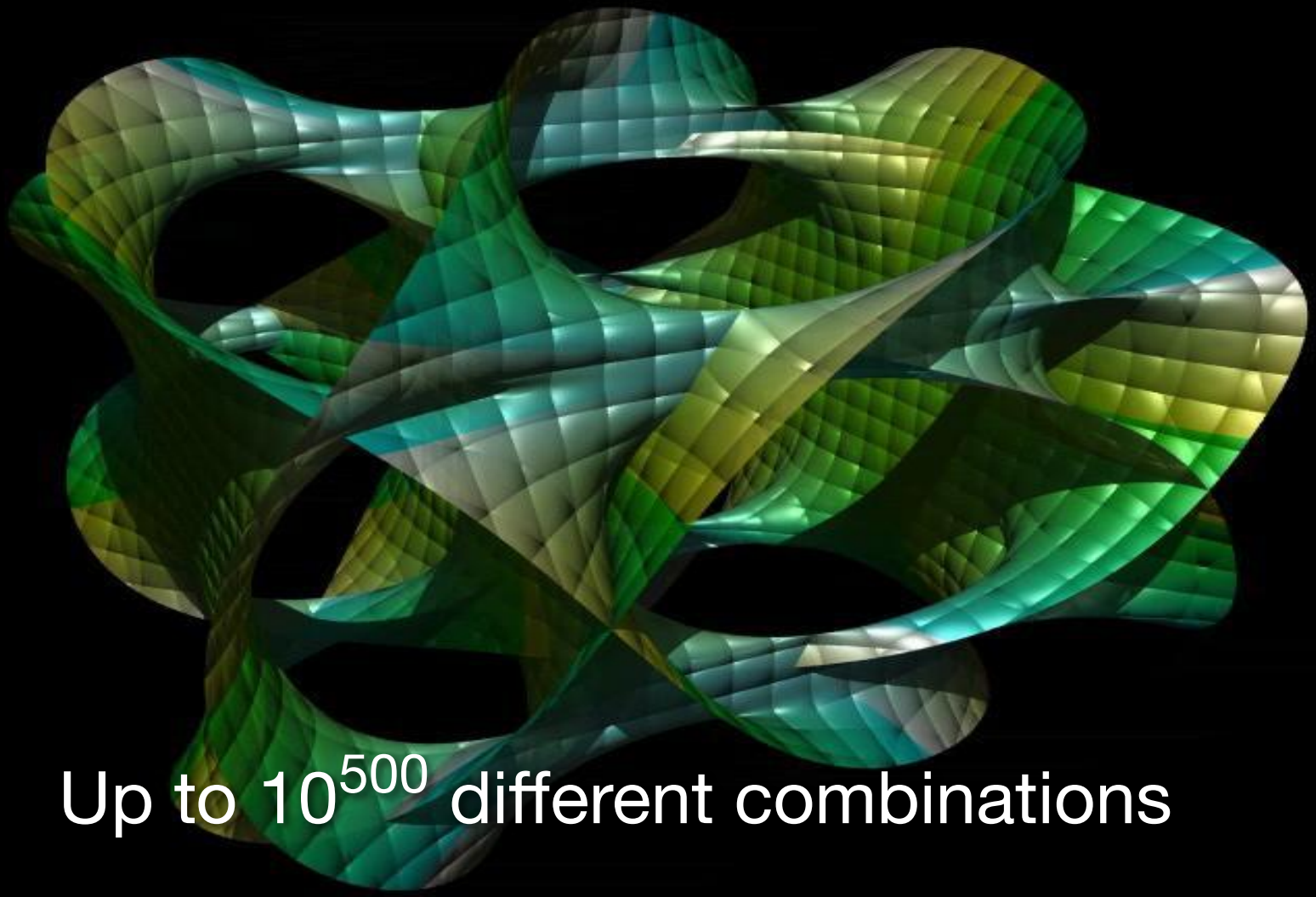
Genetic code of the Universe

There may be **one** fundamental law of physics, like a single genetic code for the whole Universe. However, this law may have different realizations. For example, water can be liquid, solid or gas. In elementary particle physics, the effective laws of physics depend on the values of the scalar fields.

Quantum fluctuations during inflation can take the scalar fields from one minimum of their potential energy to another, altering its genetic code. Once it happens in a small part of the universe, inflation makes this part exponentially big.

This is the cosmological mutation mechanism

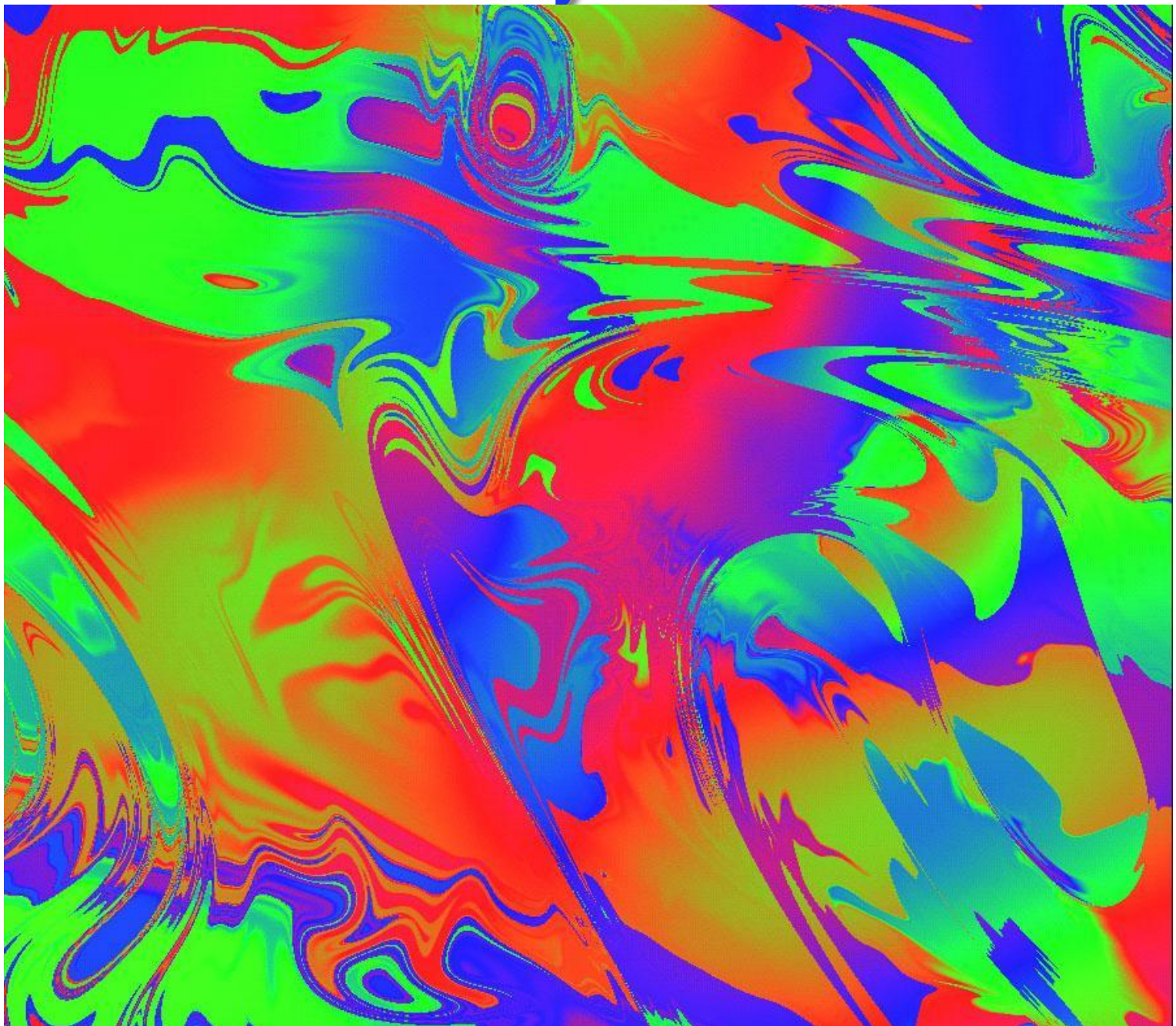
In string theory, genetic code is written in the properties of compactification of extra dimensions



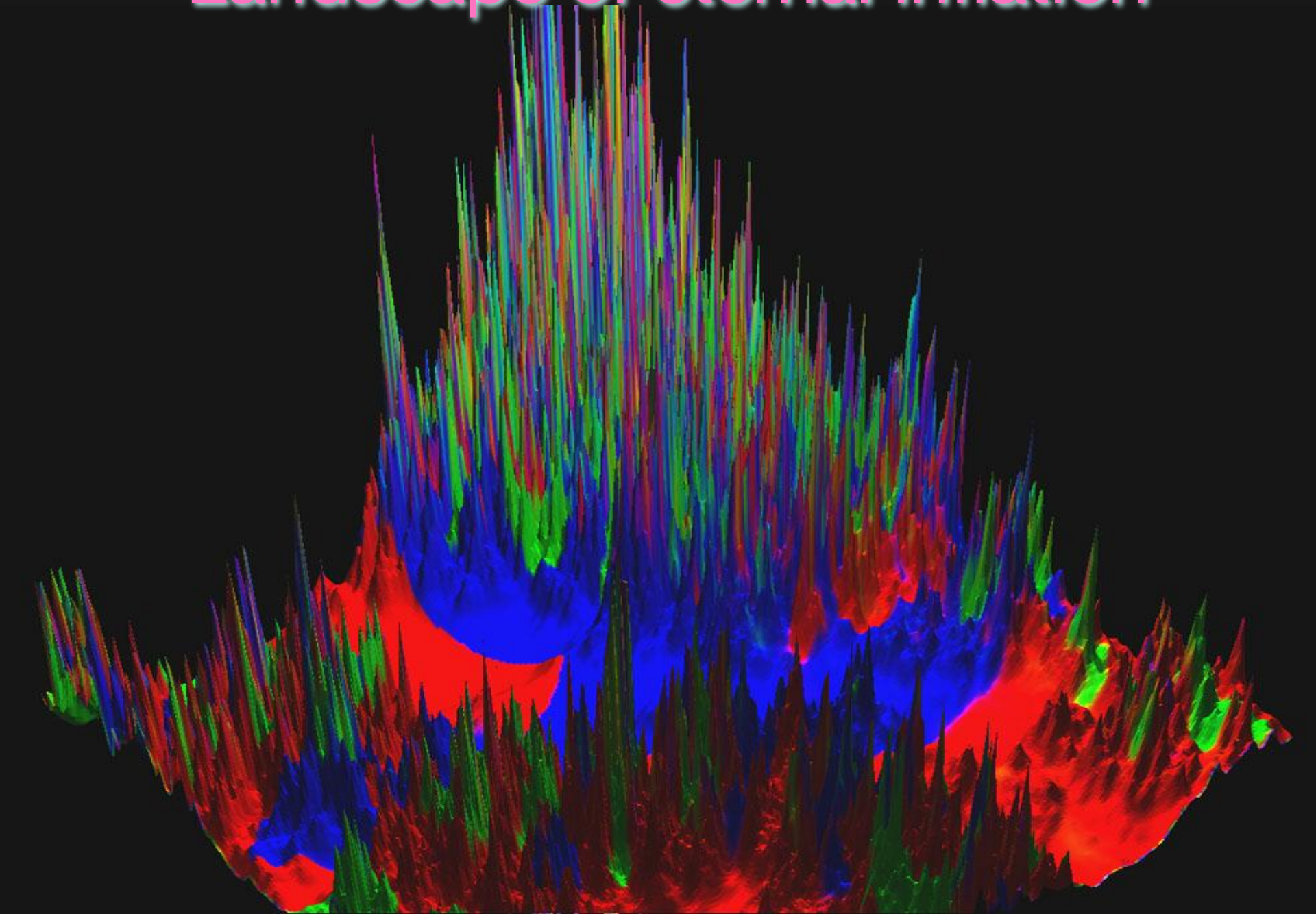
Up to 10^{500} different combinations

String Theory Landscape

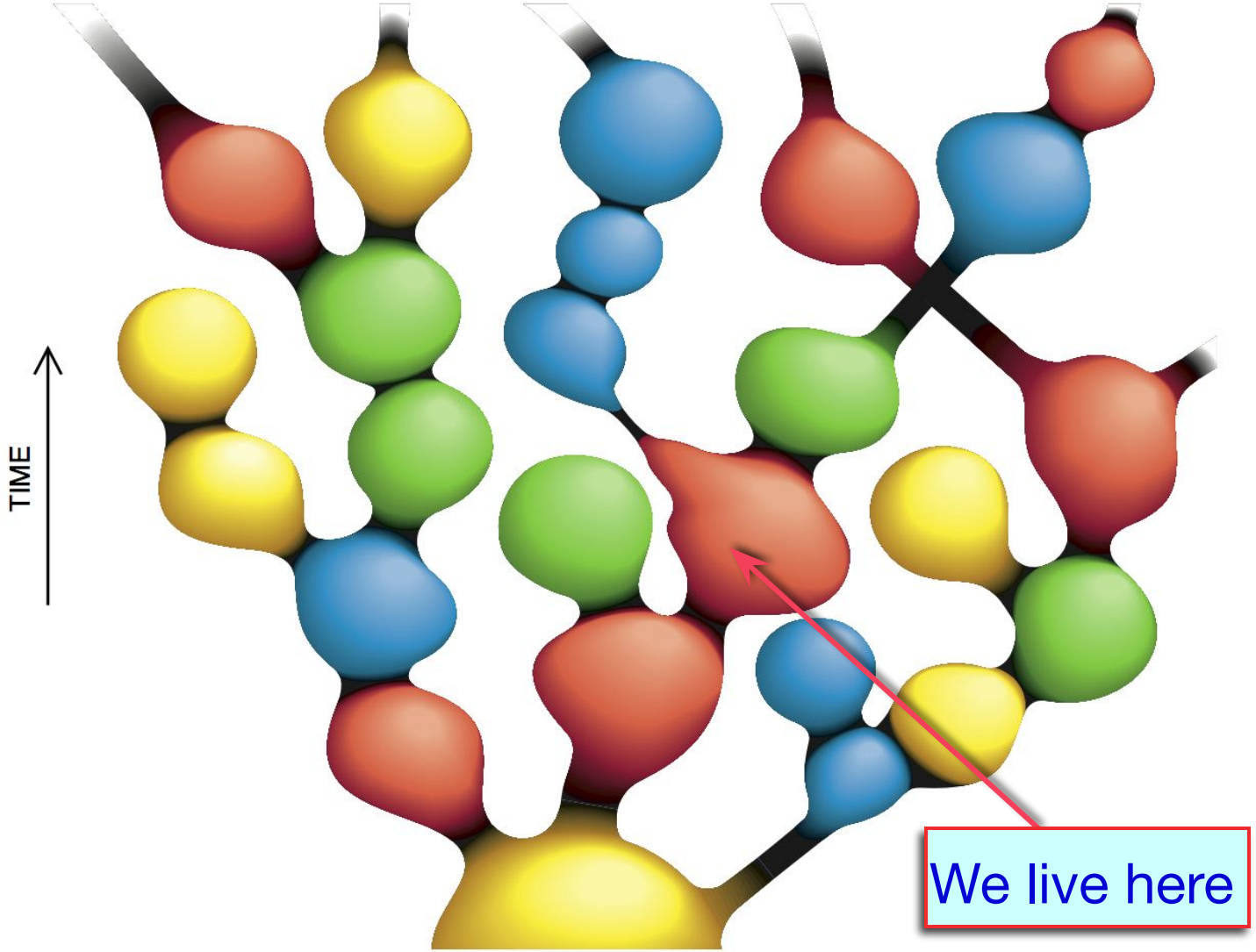
Kandinsky Universe



Landscape of eternal inflation



Self-reproducing Inflationary Universe



Big Bang ?

"It is said that there is no such thing as a free lunch. But the universe is the ultimate free lunch".

Alan Guth

Now we know that the universe is not just a free lunch: It is an eternal feast were ALL possible types of dishes are served.

All vacuum states in string theory are METASTABLE. After a very long time, vacuum will decay. At that time, our part of the universe will become ten-dimensional, or it will collapse and disappear.

But because of eternal inflation, **the universe as a whole is immortal**