The Origin and the Fate of the Universe

Andrei Linde

Contents:

- From the Big Bang theory to Inflationary Cosmology
- Inflation as a theory of a harmonic oscillator
- Eternal inflation and string theory landscape

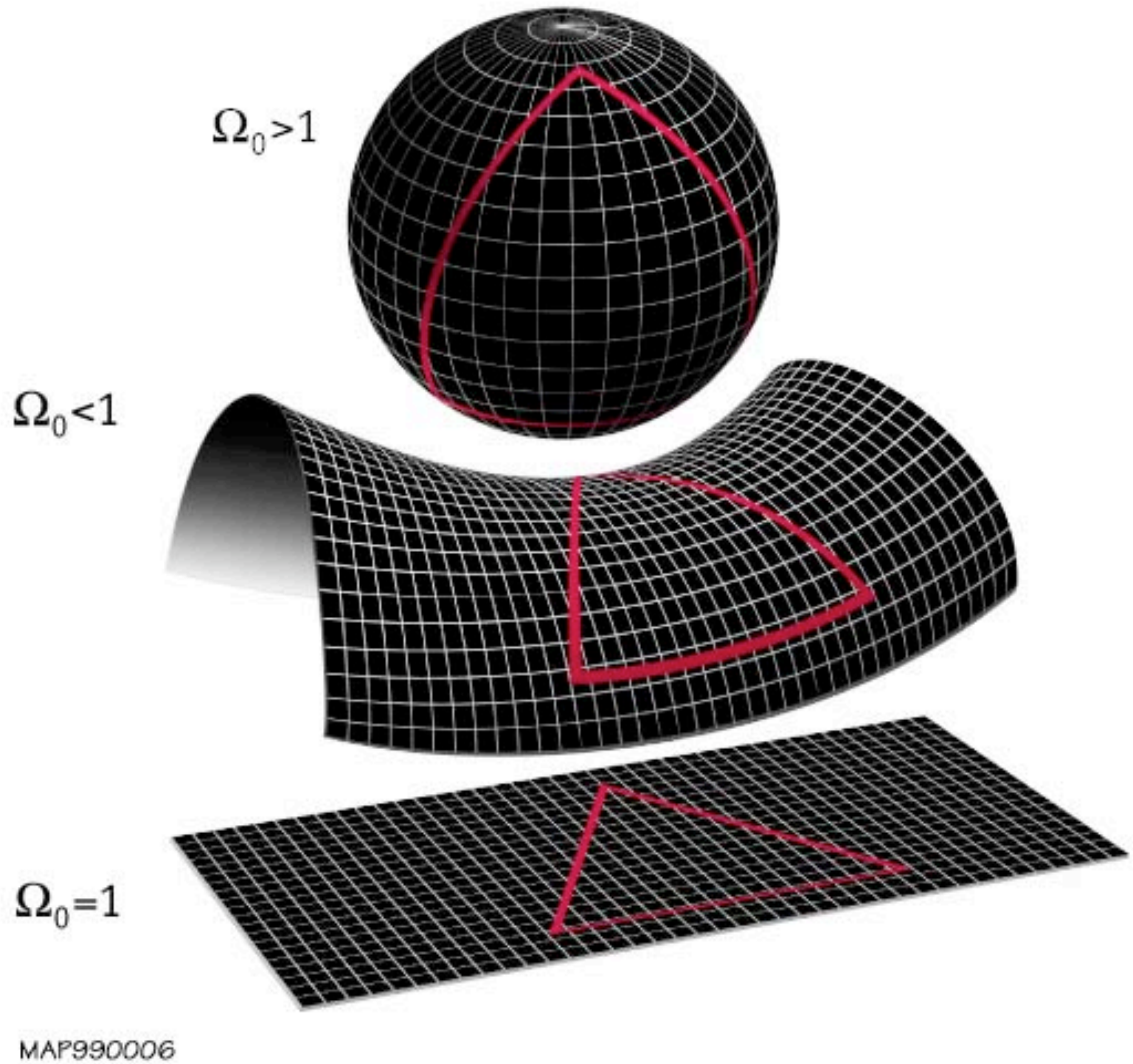
Two major cosmological discoveries:

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

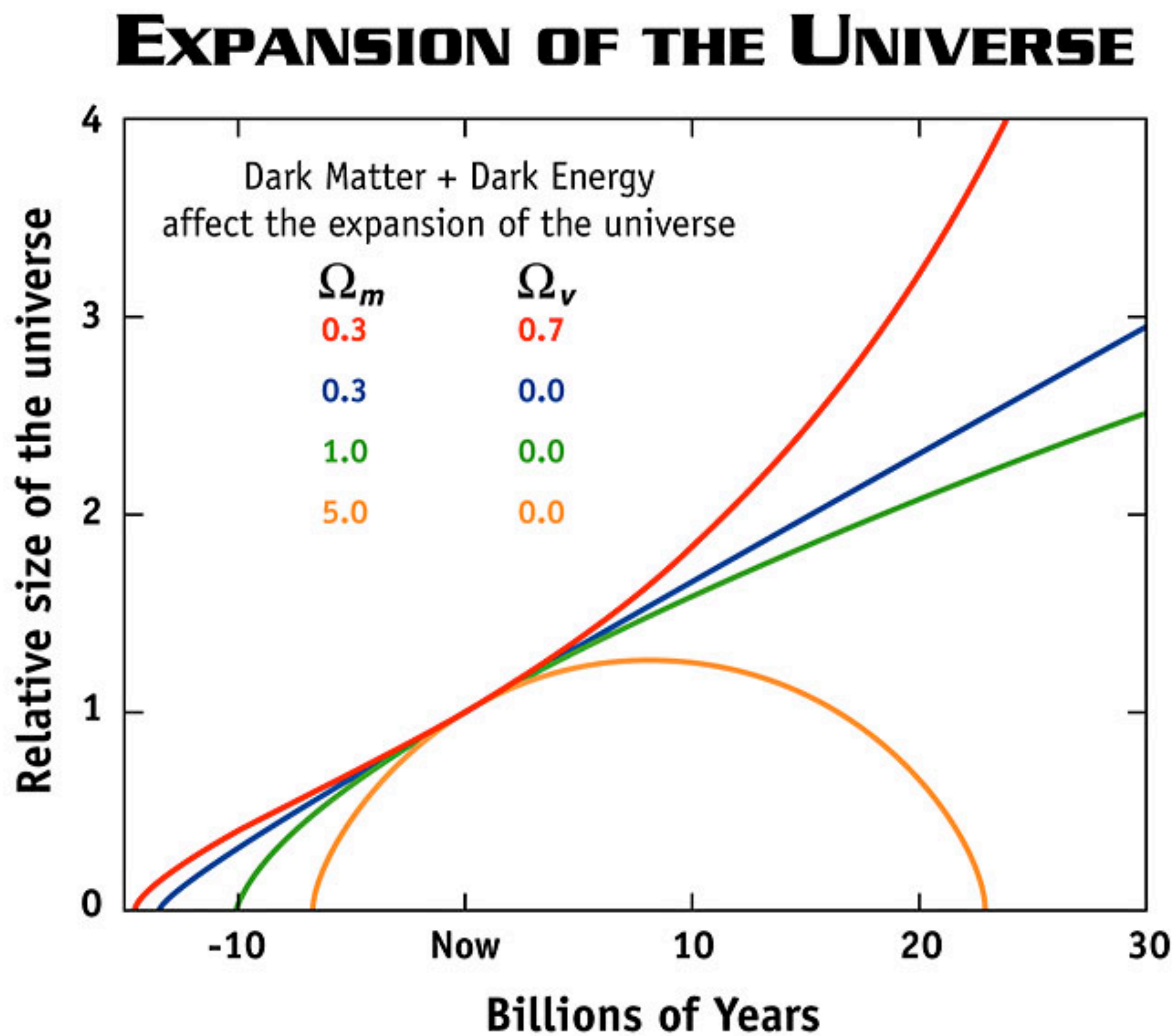
- A new (slow) stage of acceleration started 5 billion years ago (dark energy)

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

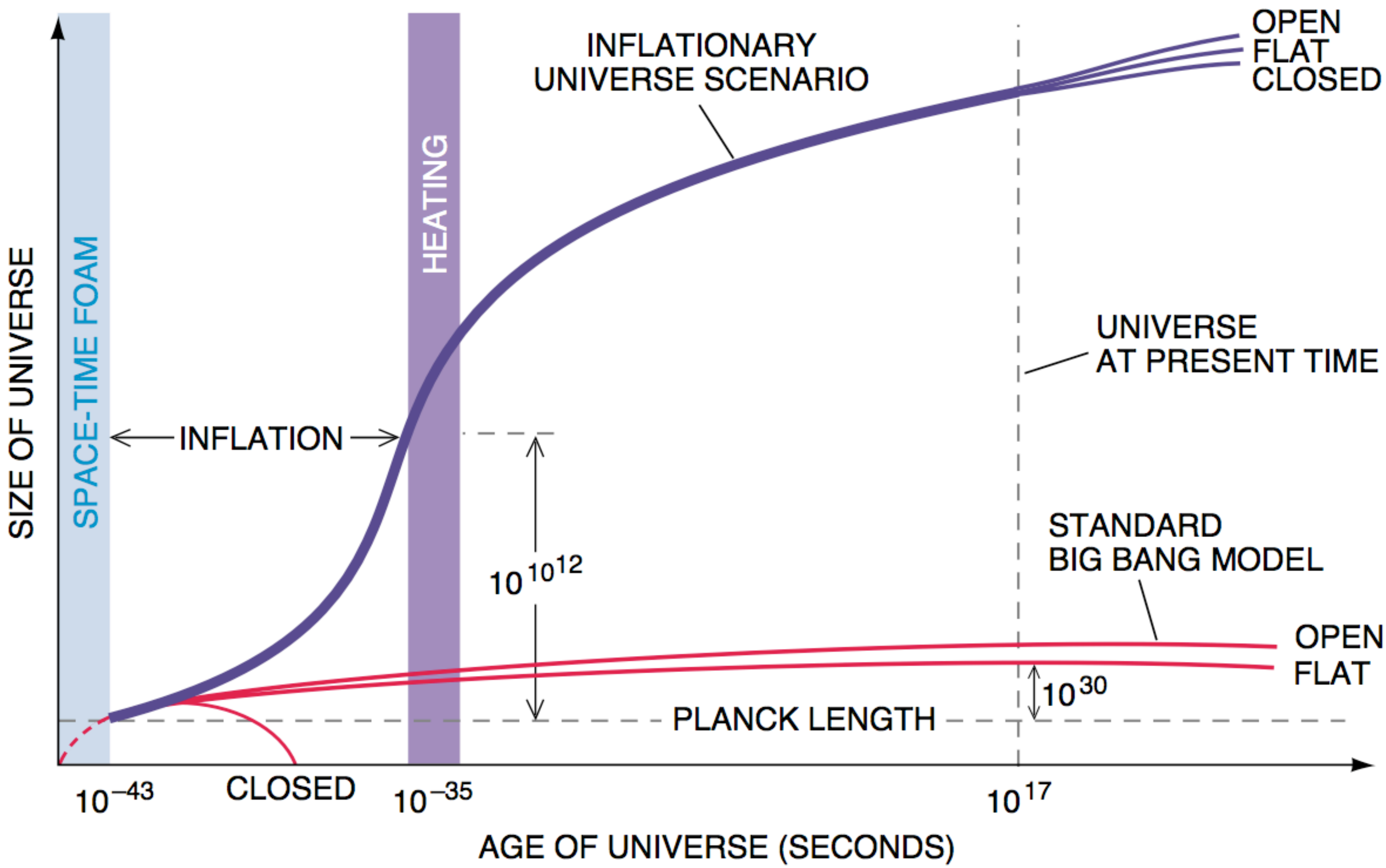
Closed, open or flat universe



Big Bang Theory



Inflationary Universe



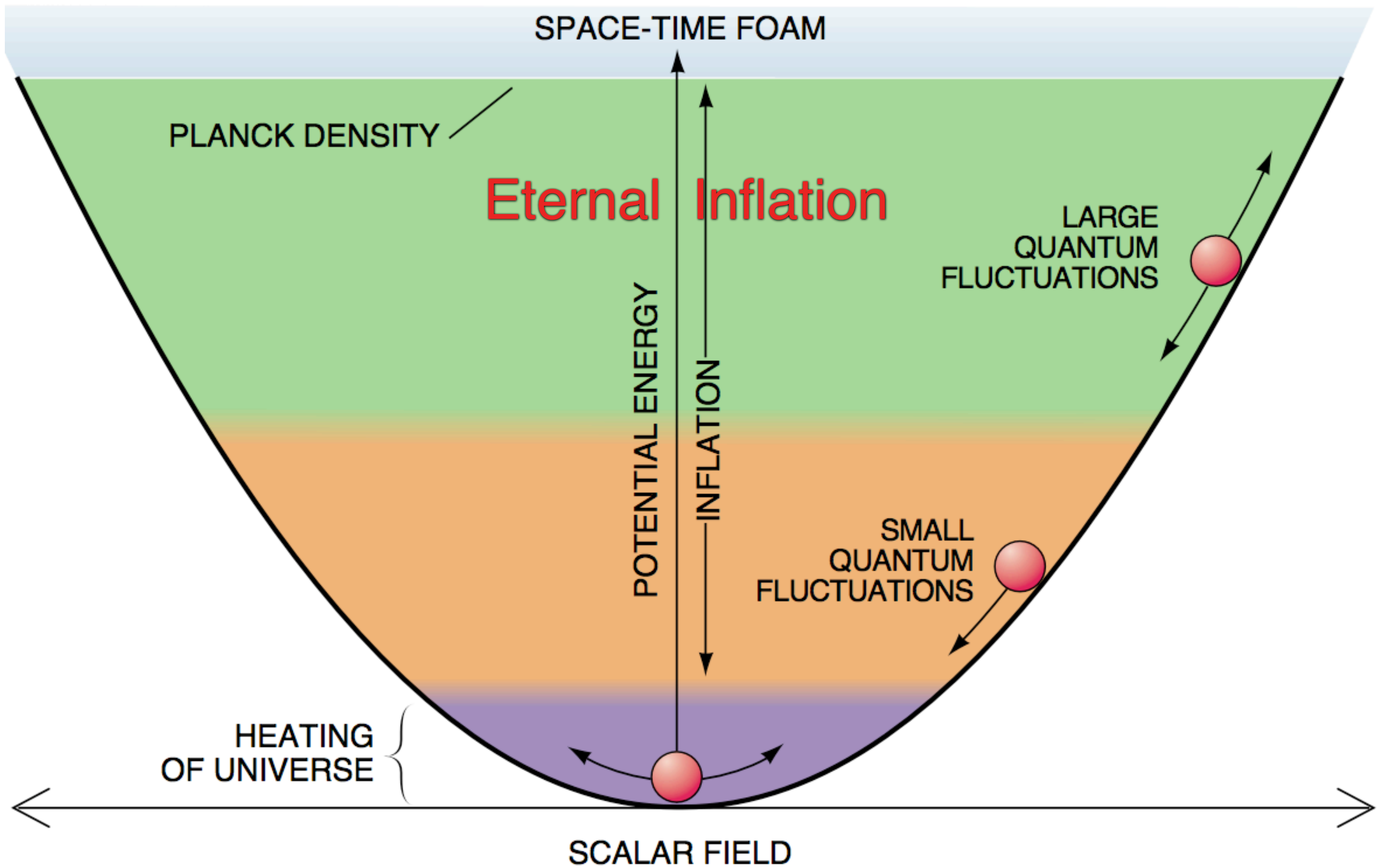
Why do we need inflation?

Problems of the standard Big Bang theory:

- 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? Why it contains so many particles? Why there are so many people in this auditorium?

Inflation as a theory of a harmonic oscillator

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



Equations of motion:

- **Einstein:**

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

- **Klein-Gordon:**

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

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

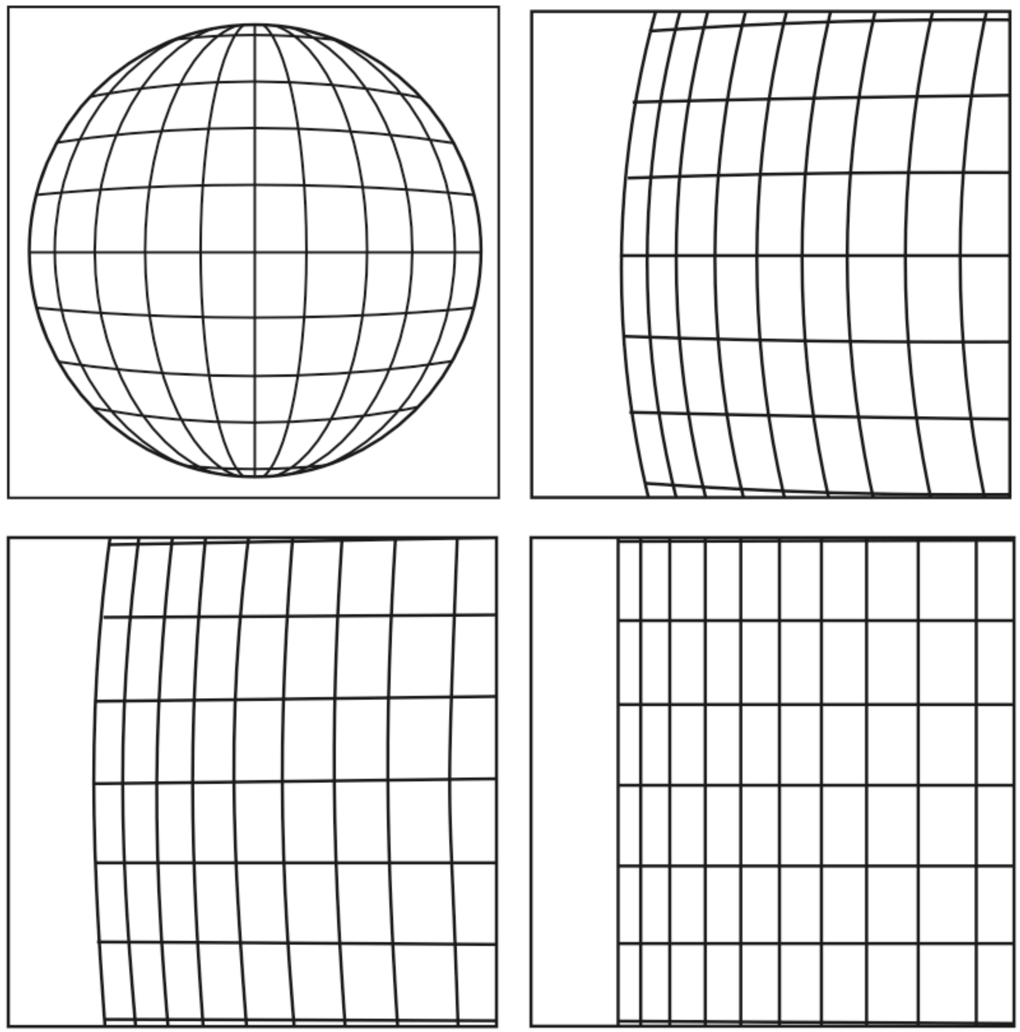
$$H = \frac{\dot{a}}{a} = \frac{m\phi}{\sqrt{6}} \approx \text{const}$$

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

No need for false vacuum, supercooling, phase transitions, etc.

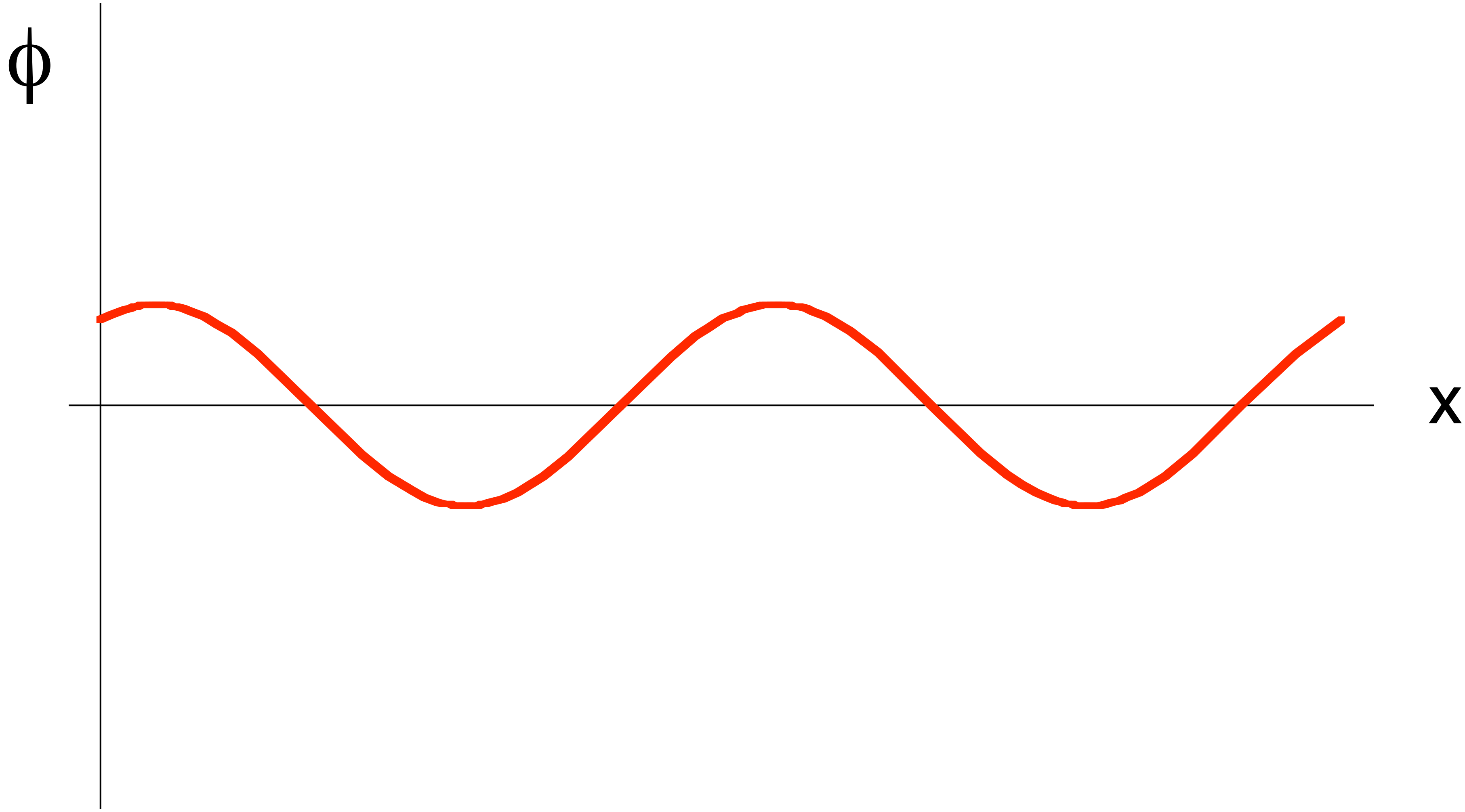
Inflation makes the universe flat, homogeneous and isotropic

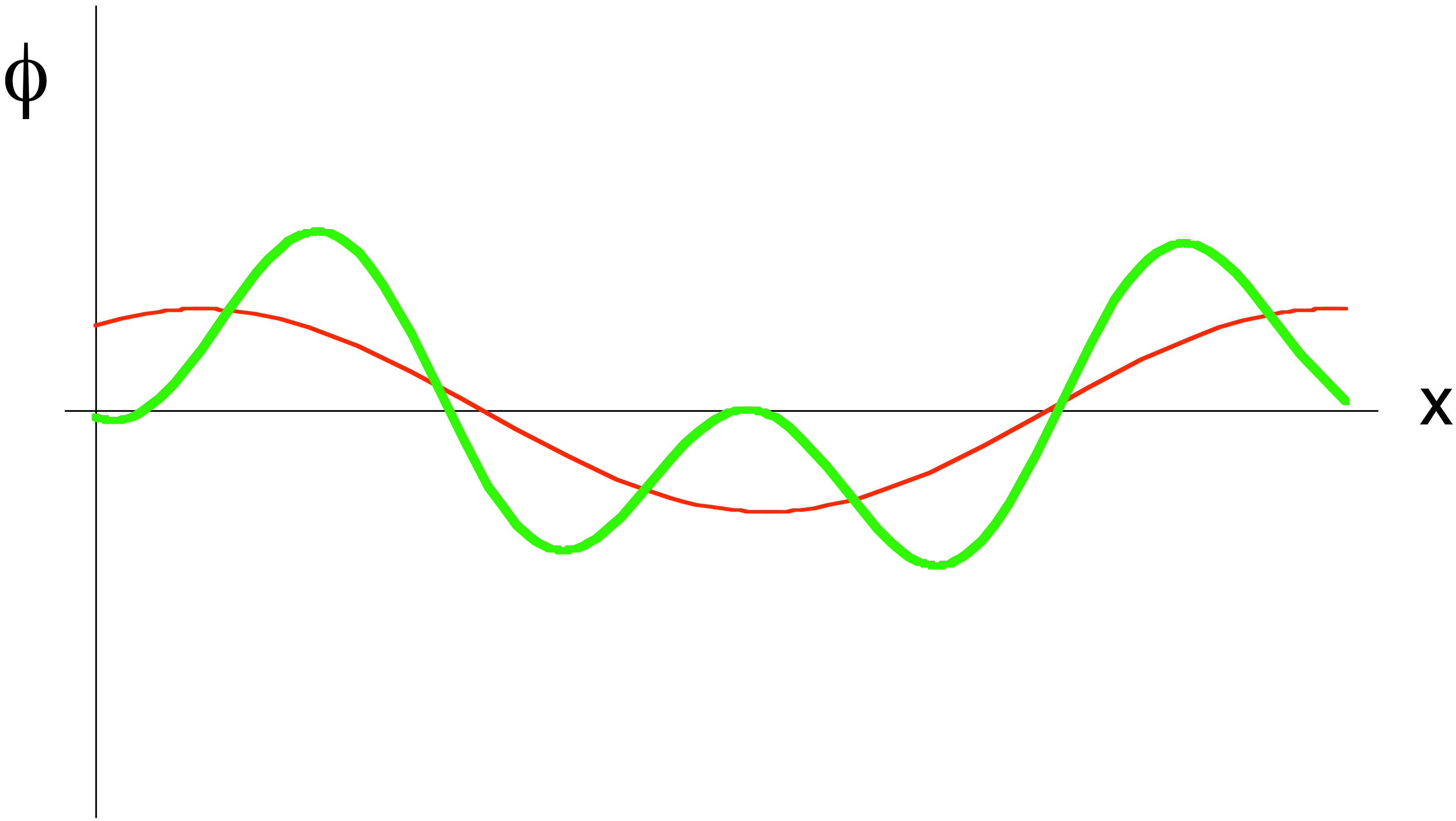
In this simple model the universe typically grows $10^{1000000000000}$ times during inflation.



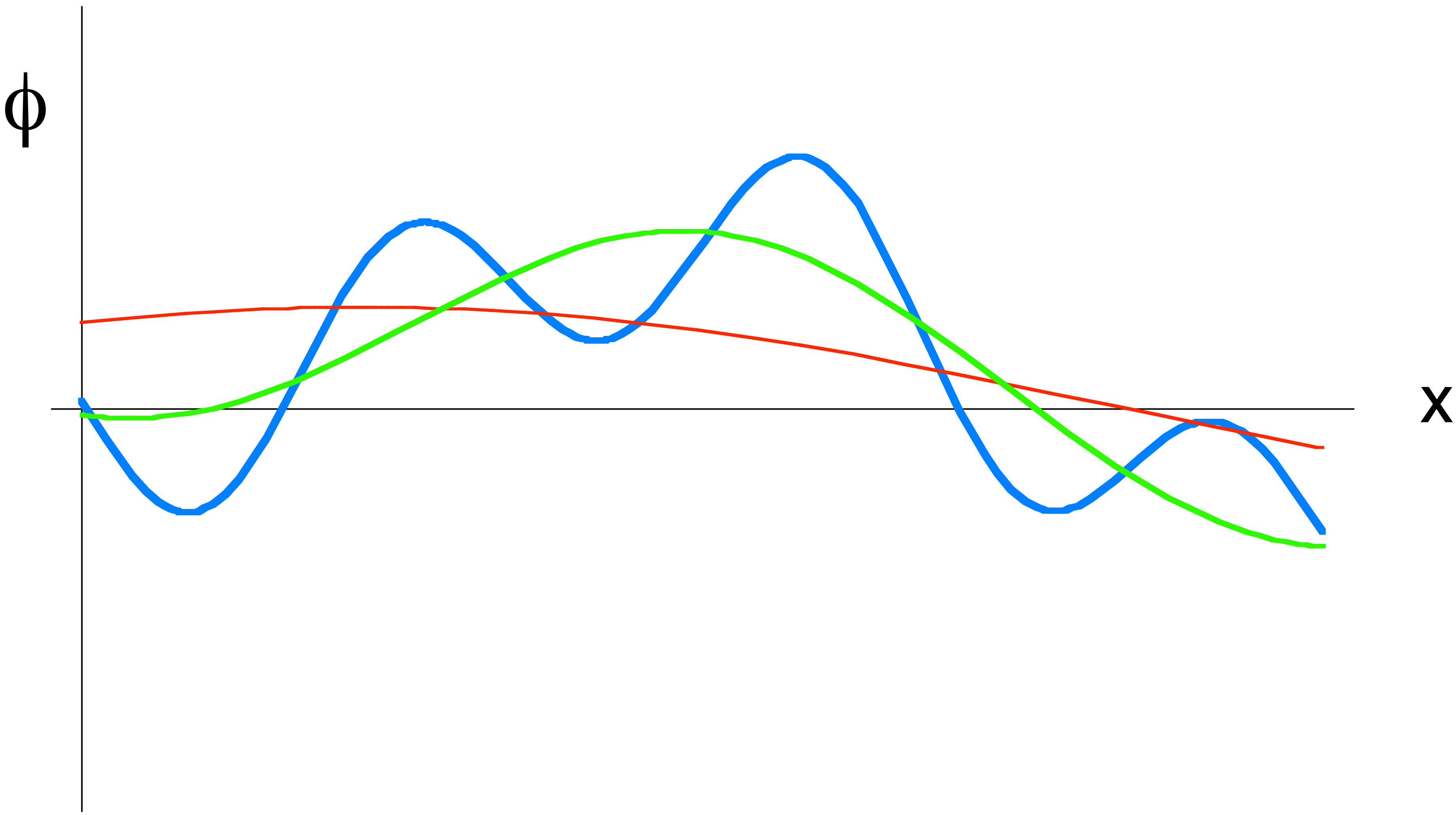
Now we can see just a tiny part of the universe of size ct = 10^{10} light yrs. That is why the universe looks homogeneous, isotropic, and flat.

Quantum fluctuations produced during inflation

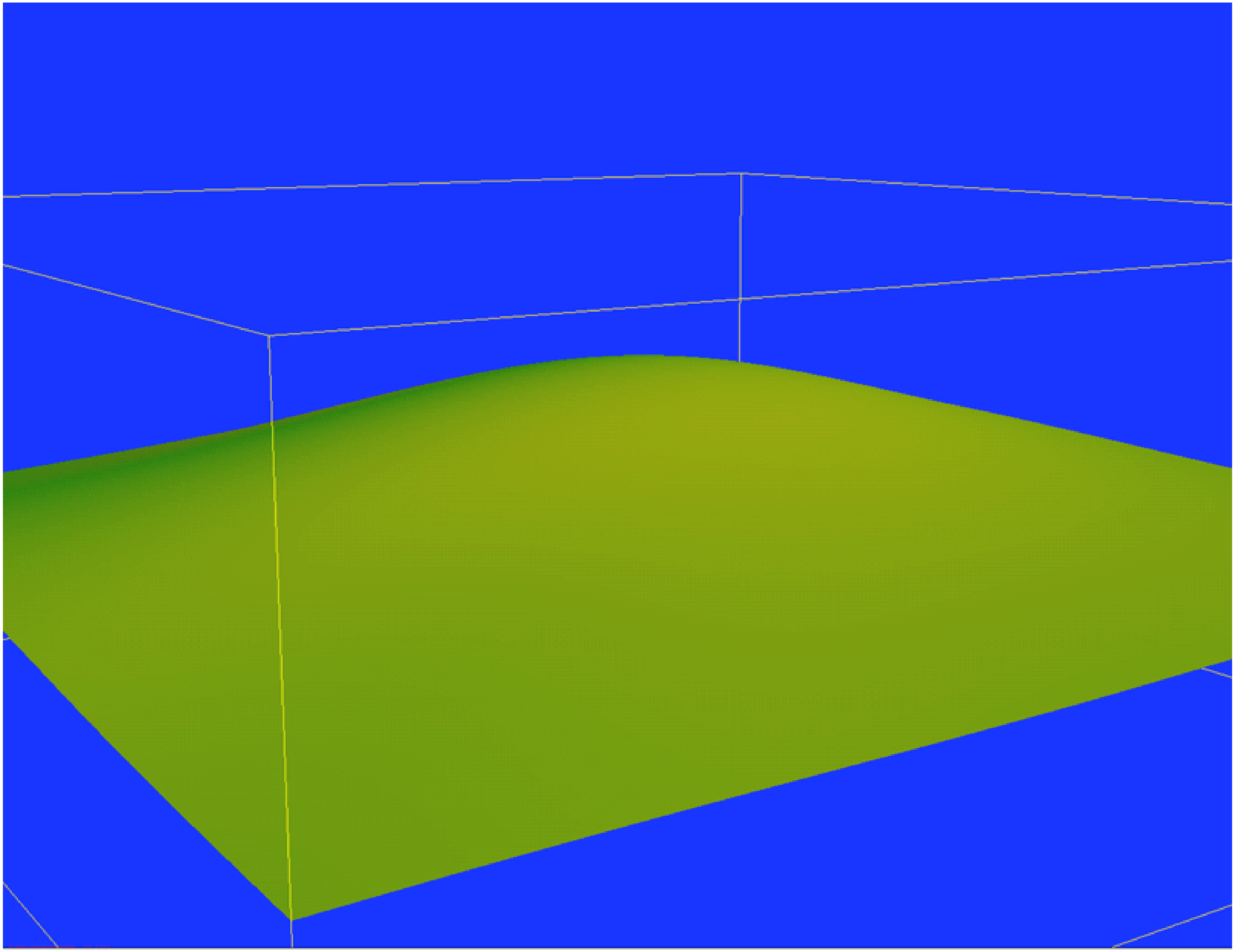




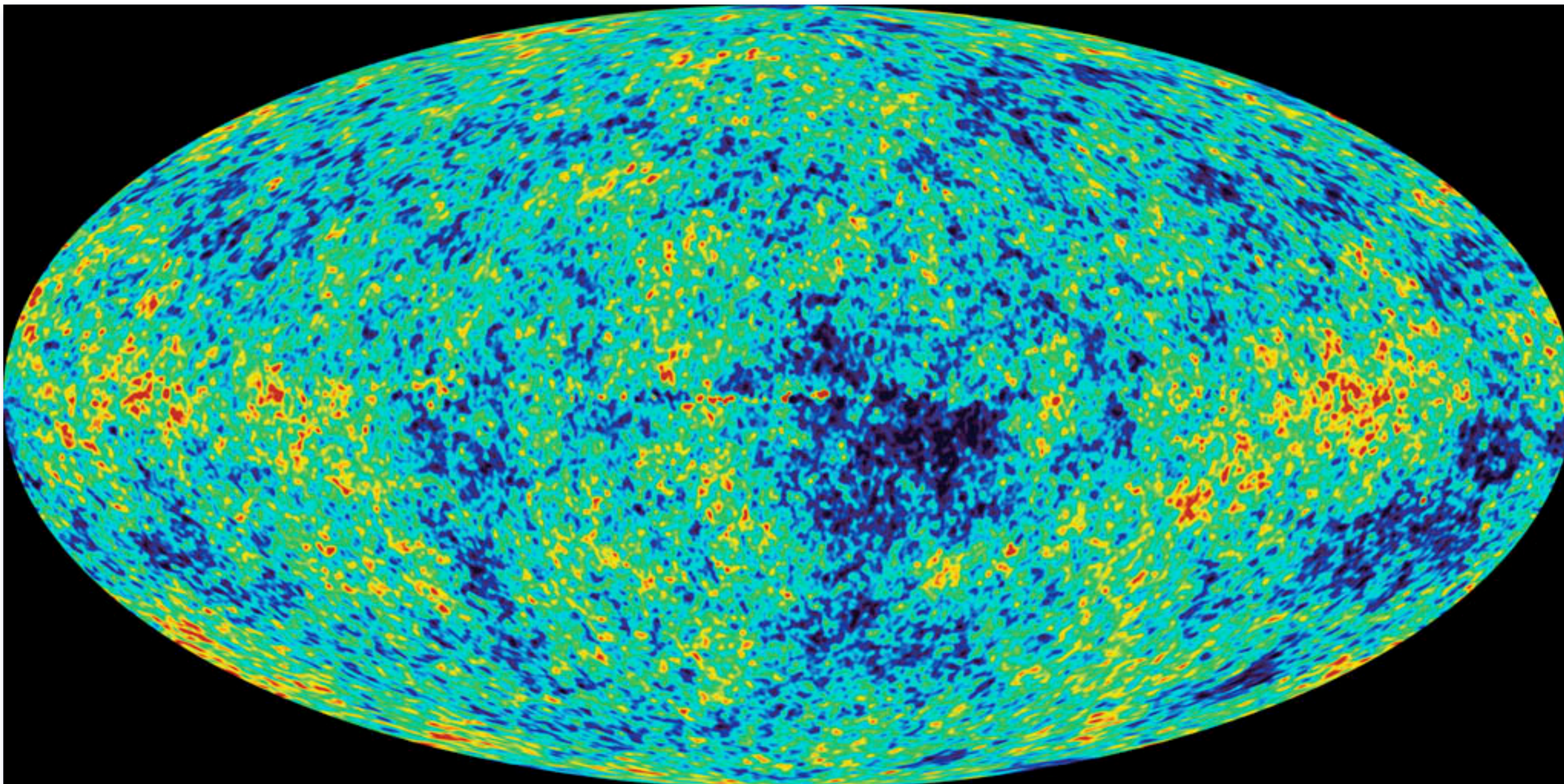
φ
x


ϕ
x

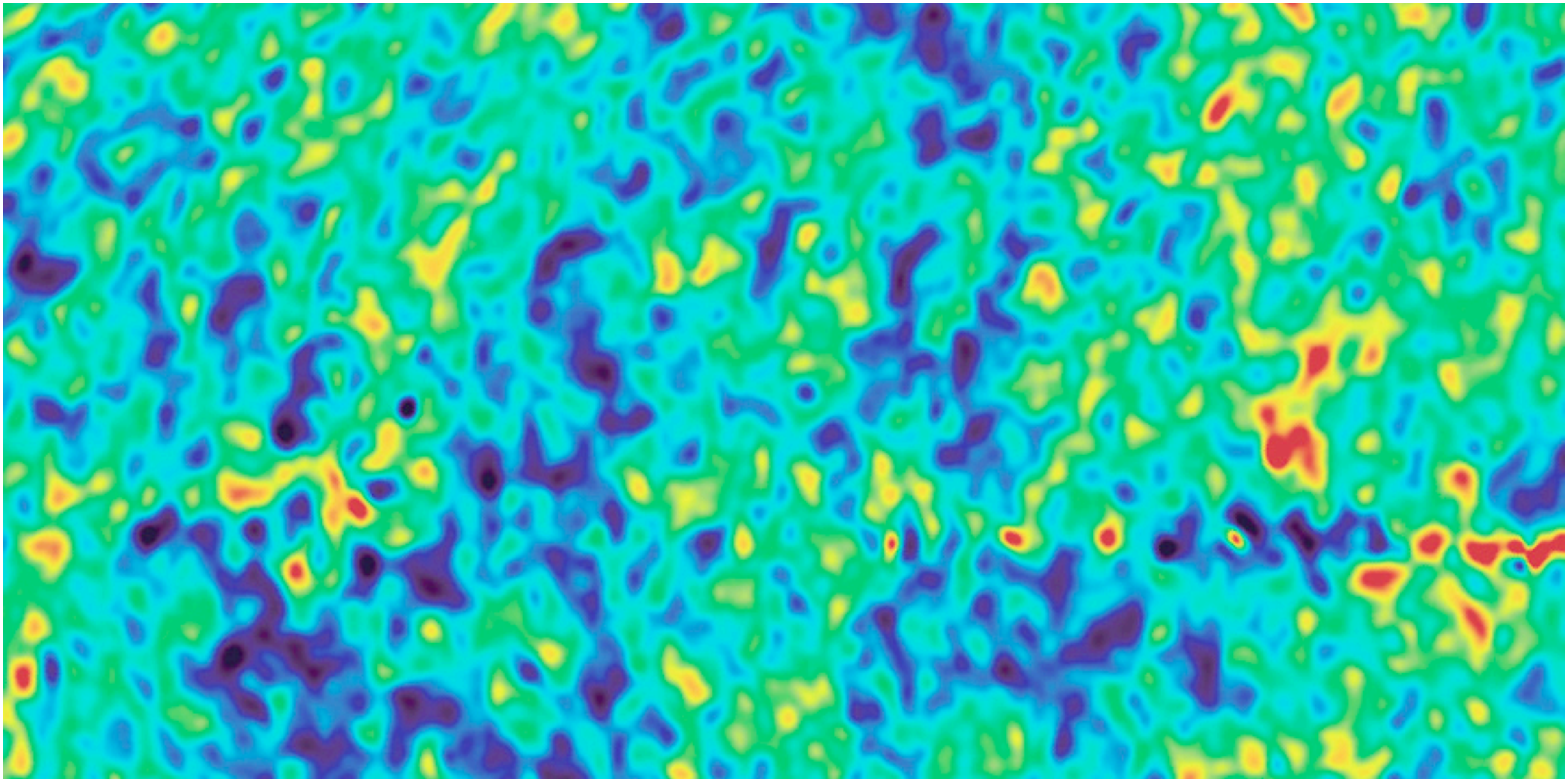
Generation of Quantum Fluctuations



WMAP and the temperature of the sky

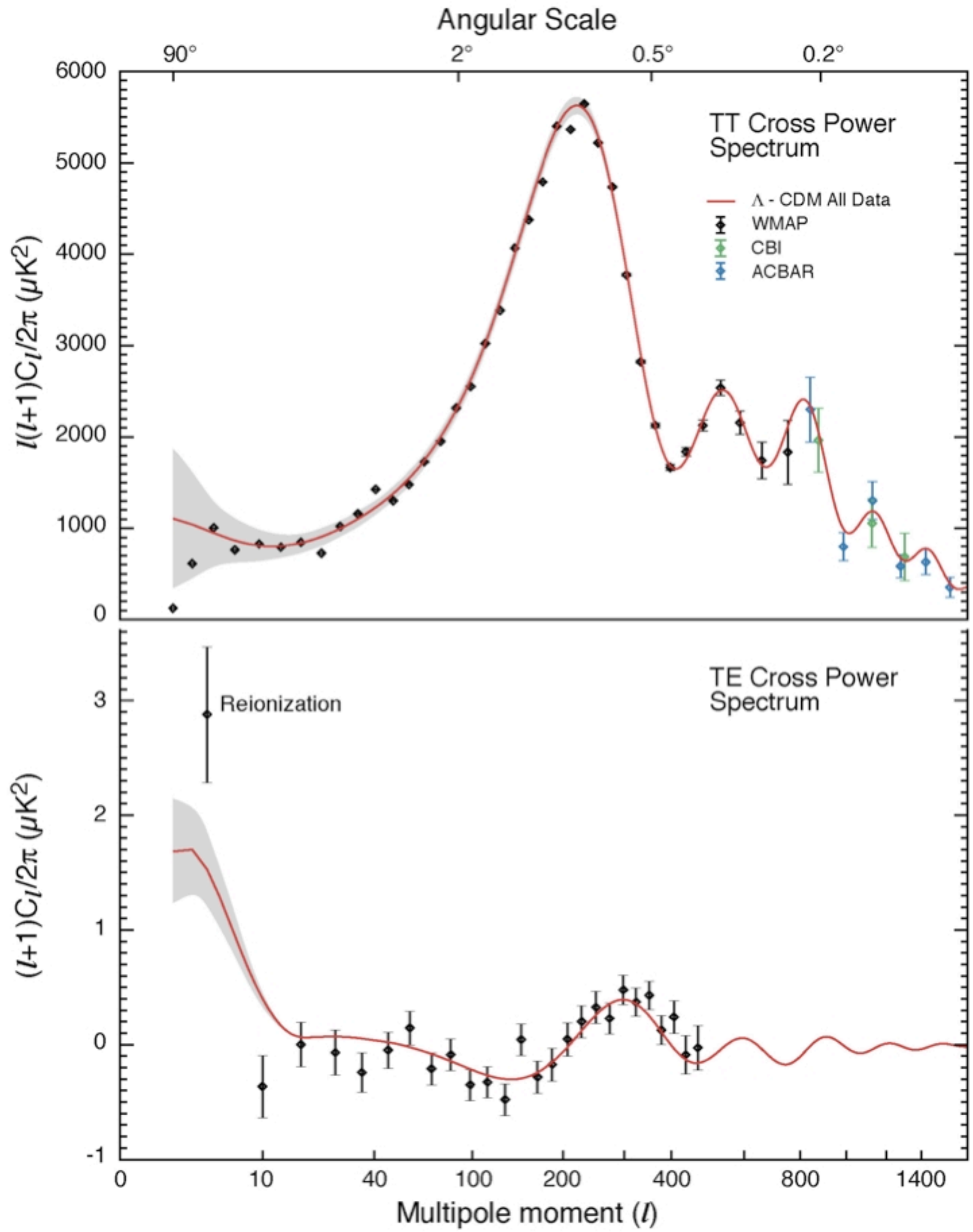


A photographic image of quantum fluctuations blown up to the size of the universe



WMAP

and spectrum of the cosmic microwave background anisotropy



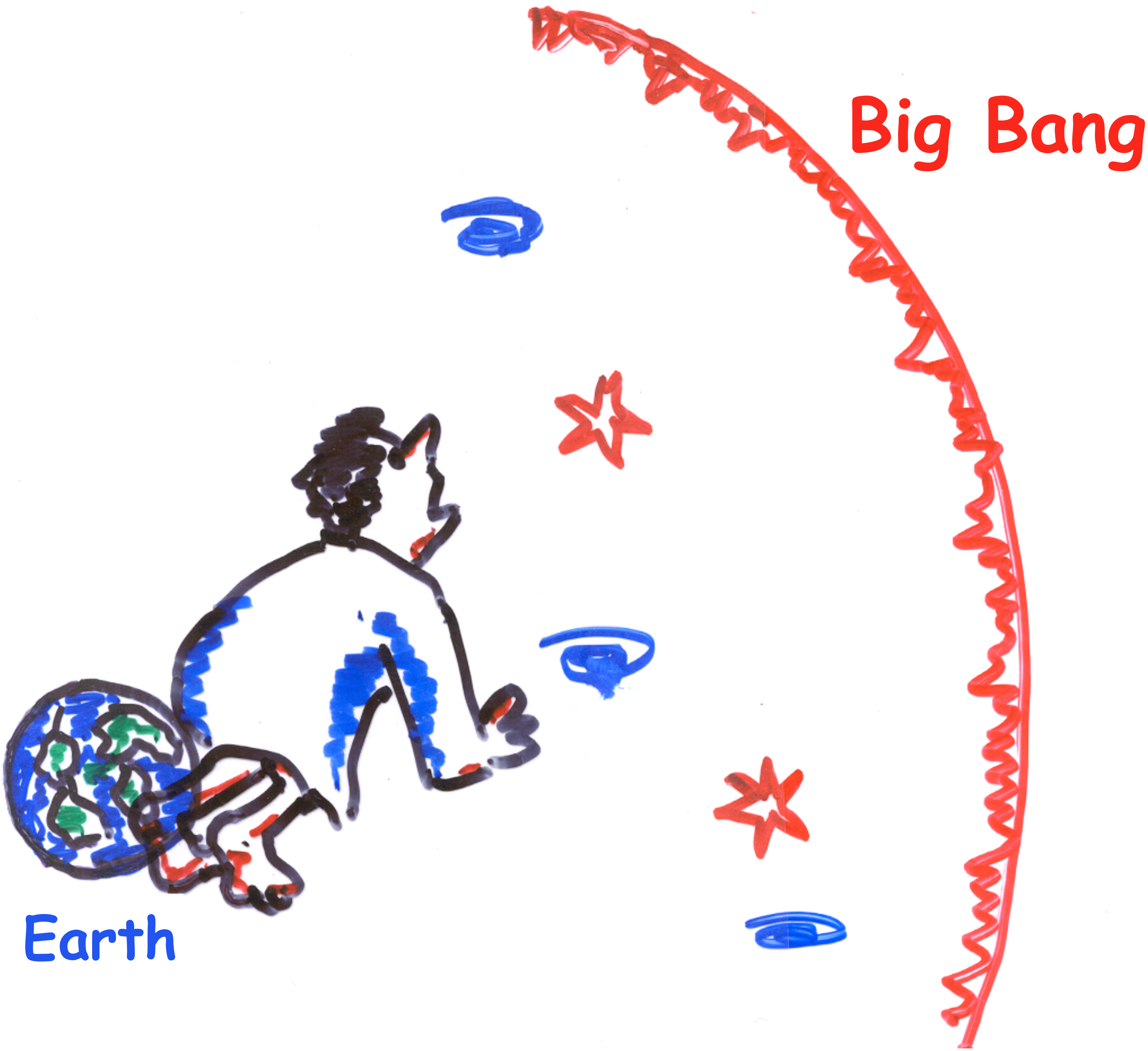
Predictions of Inflation:

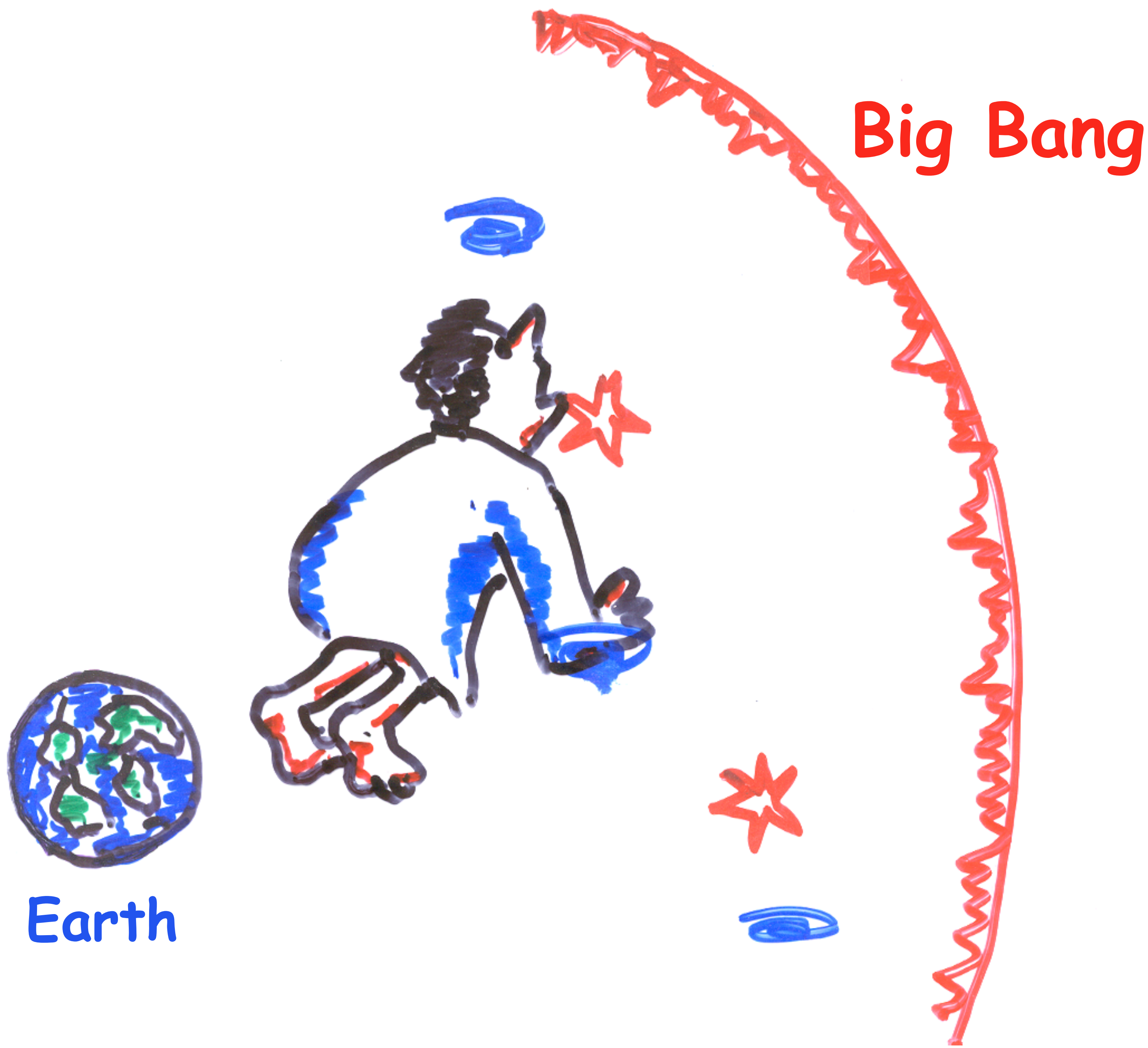
1) The universe should be homogeneous, isotropic and flat, $\Omega = 1 + O(10^{-4})$ $[\Omega=\rho/\rho_0]$

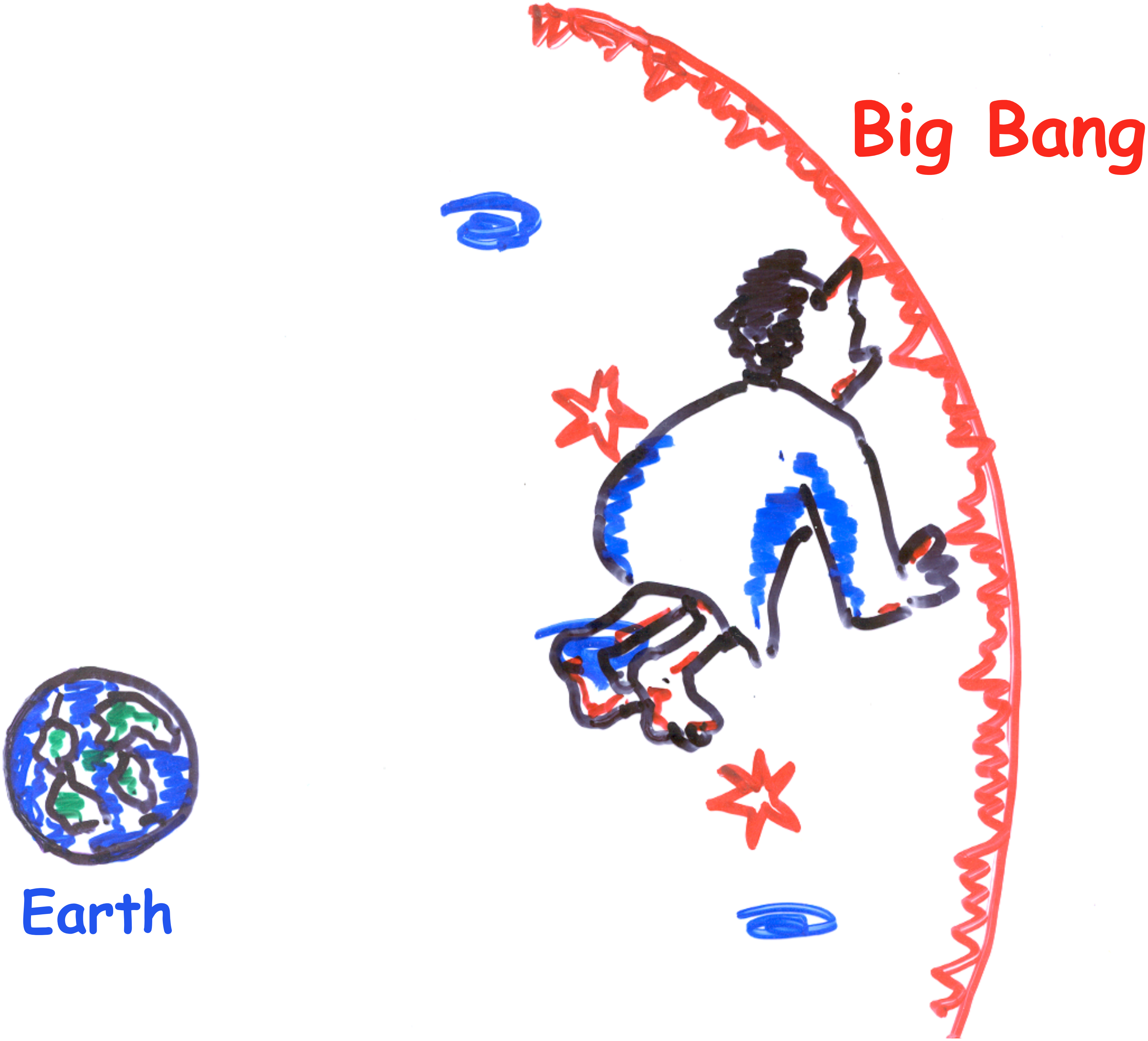
Observations: the universe is homogeneous, isotropic and flat, $\Omega = 1 + O(10^{-2})$

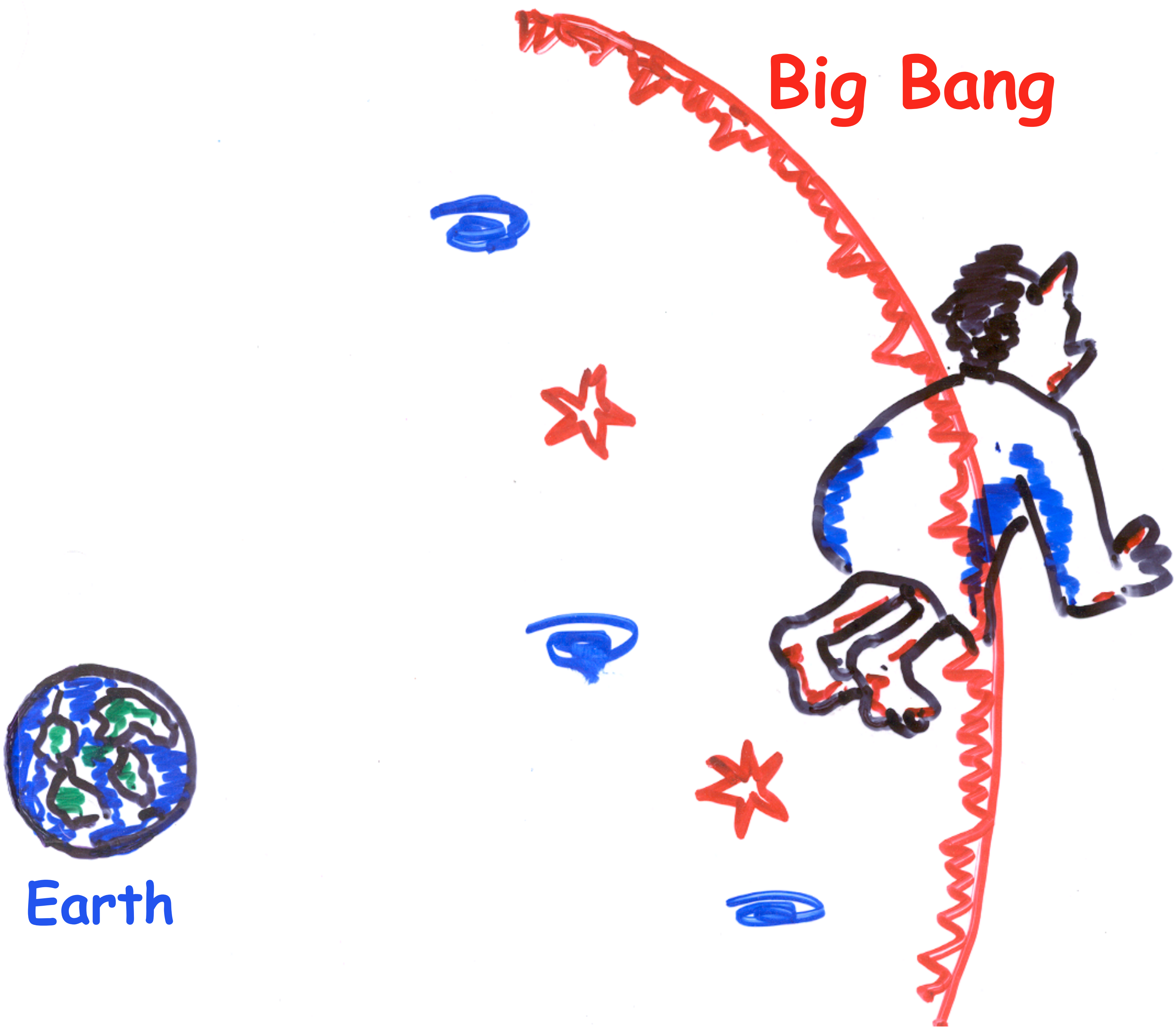
2) Inflationary perturbations should be gaussian and adiabatic, with flat spectrum, $n_s = 1+ O(10^{-1})$

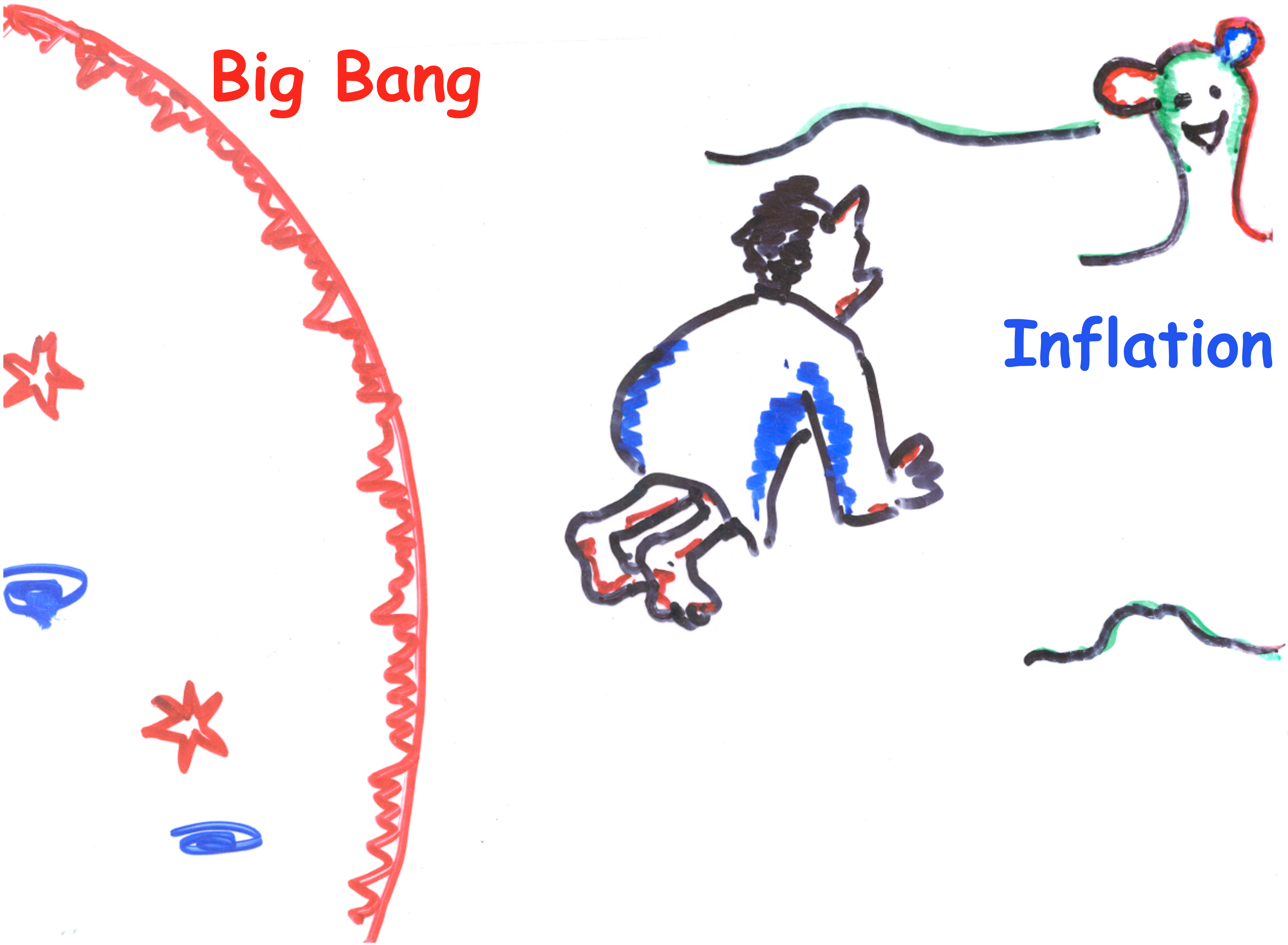
Observations: perturbations are gaussian and adiabatic, with flat spectrum, $n_s = 1 + O(10^{-2})$


Big Bang
Earth


Big Bang
Earth


Big Bang
Earth


Big Bang
Earth


Big Bang
Inflation

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.

Genetic code of the Universe

To be more accurate, one may have **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.

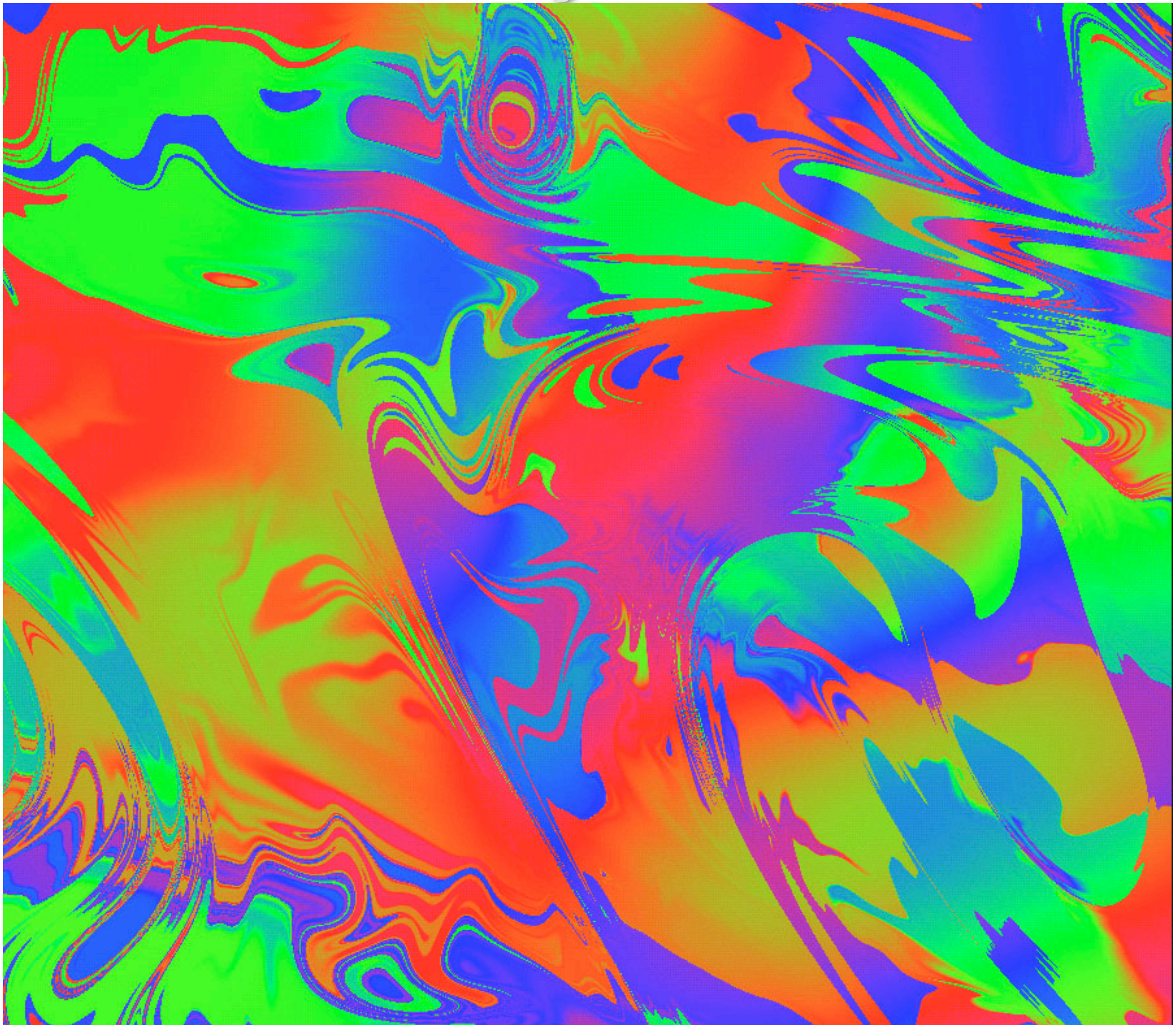
Quantum fluctuations during inflation can take the scalar fields from one minimum of their potential energy to another, altering its genetic code. Once it happens in a small part of the universe, inflation makes this part exponentially big.

This is the cosmological

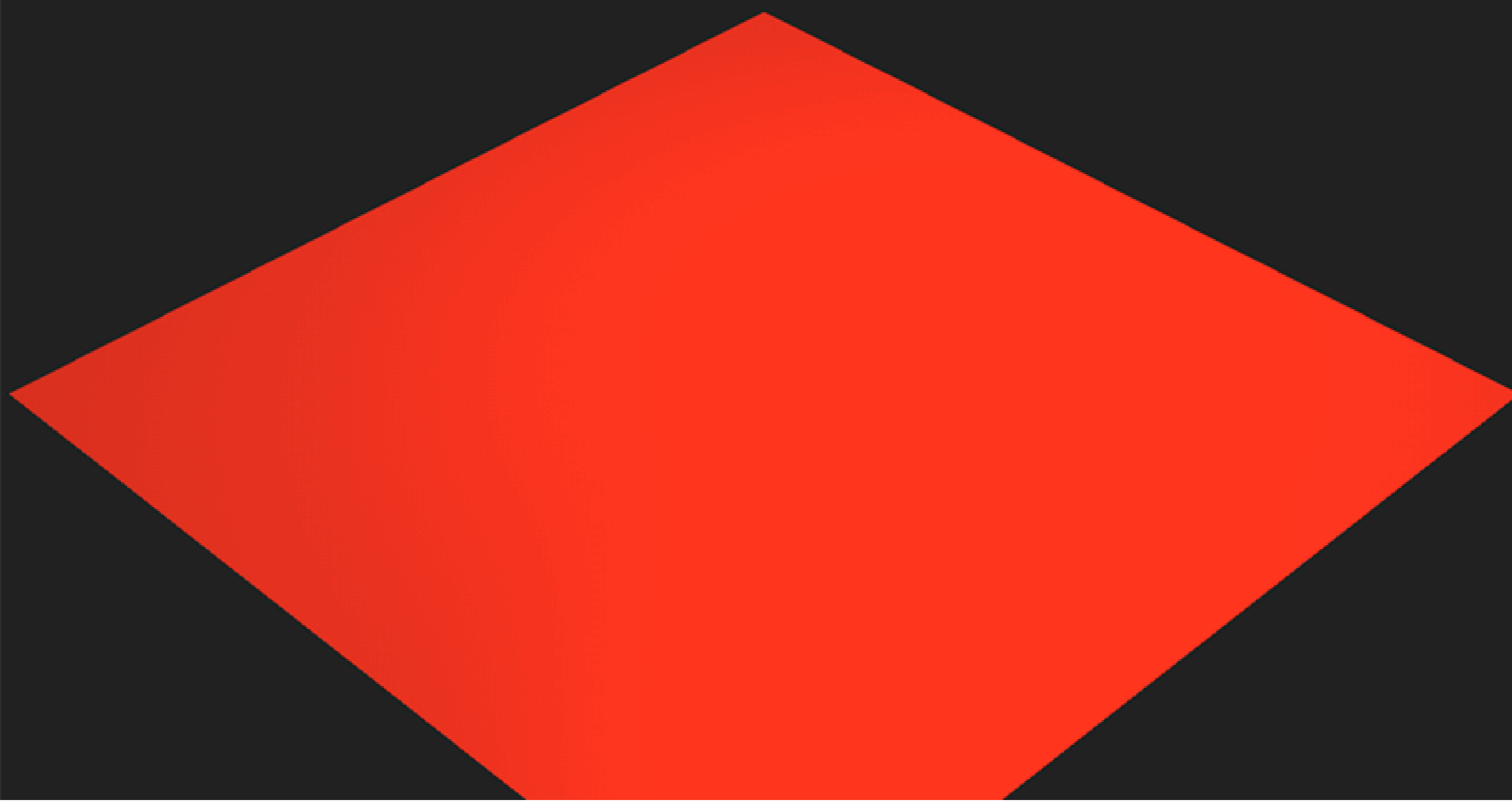
mutation mechanism

String Theory Landscape

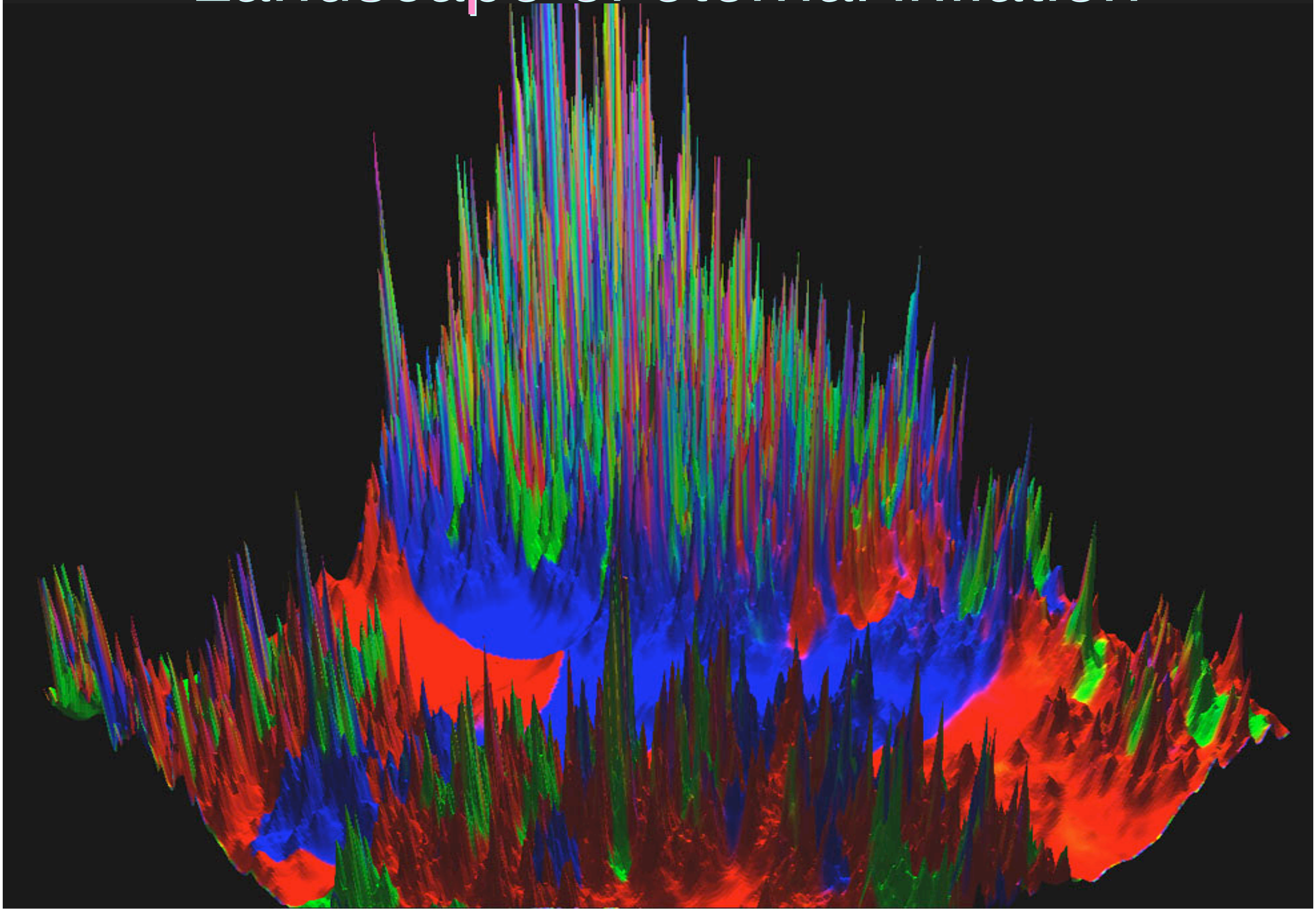
Kandinsky Universe



Populating the Landscape



Landscape of eternal inflation



All vacuum states in string theory are METASTABLE, they eventually decay. The decay may either make our universe ten-dimensional, or lead to its local collapse.

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

Self-reproducing Inflationary Universe