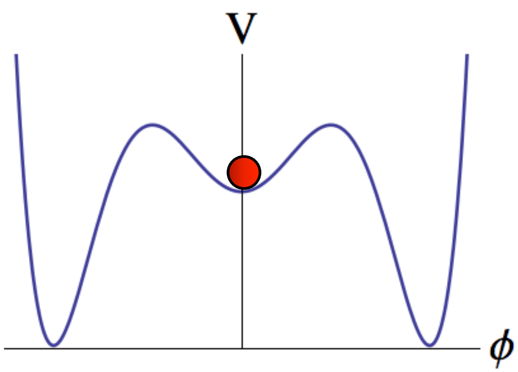
Inflation 30

Andrei Linde

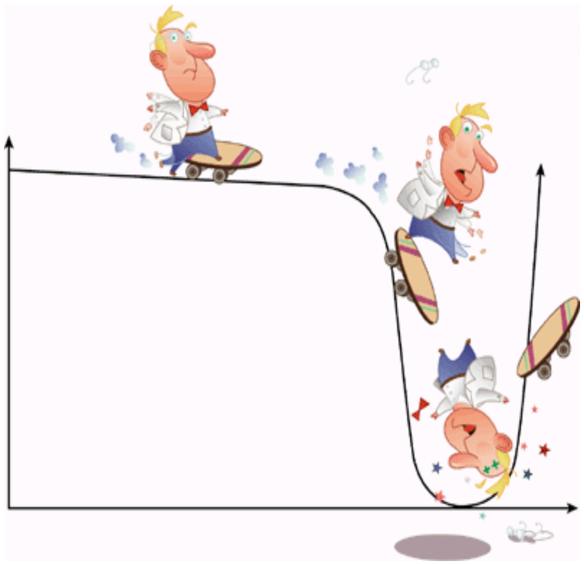
Inflation

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

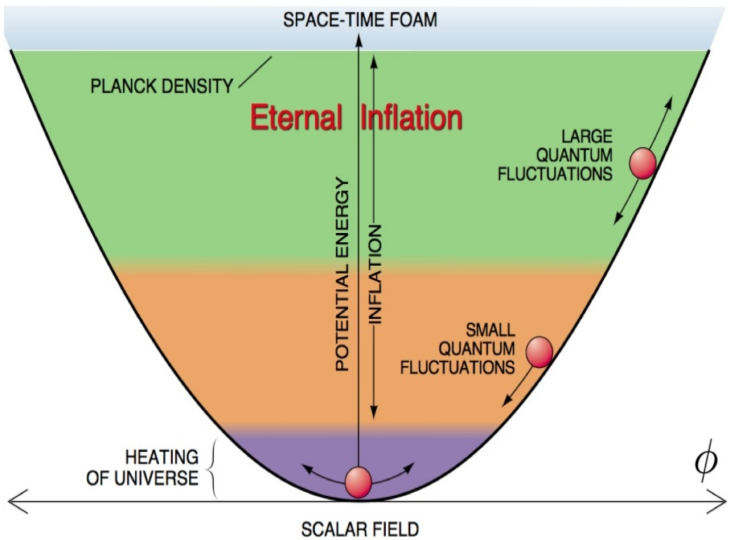
Guth, 1981 - old inflation. Great idea, but did not work, and did not predict inflationary perturbations



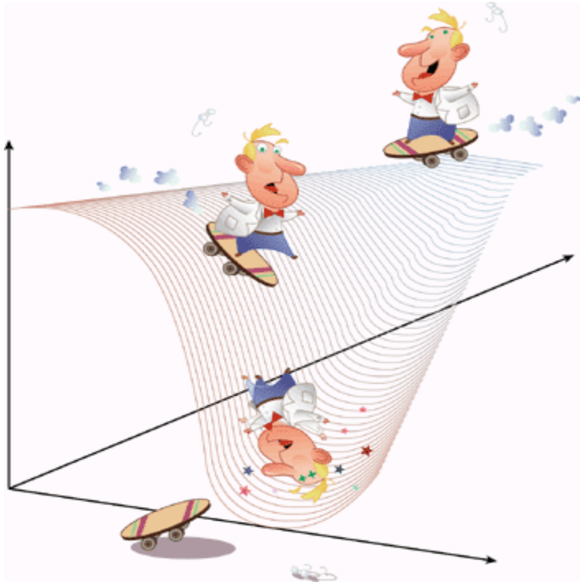
$$V(\phi) = \frac{m^2}{2}\phi^2$$



A.L., 1982 - new inflation (also Albrecht, Steinhardt)



1983 - chaotic inflation



1991 - hybrid inflation

Inflation was invented 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? Why it contains so many particles?

Energy in the Big Bang theory

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

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?...

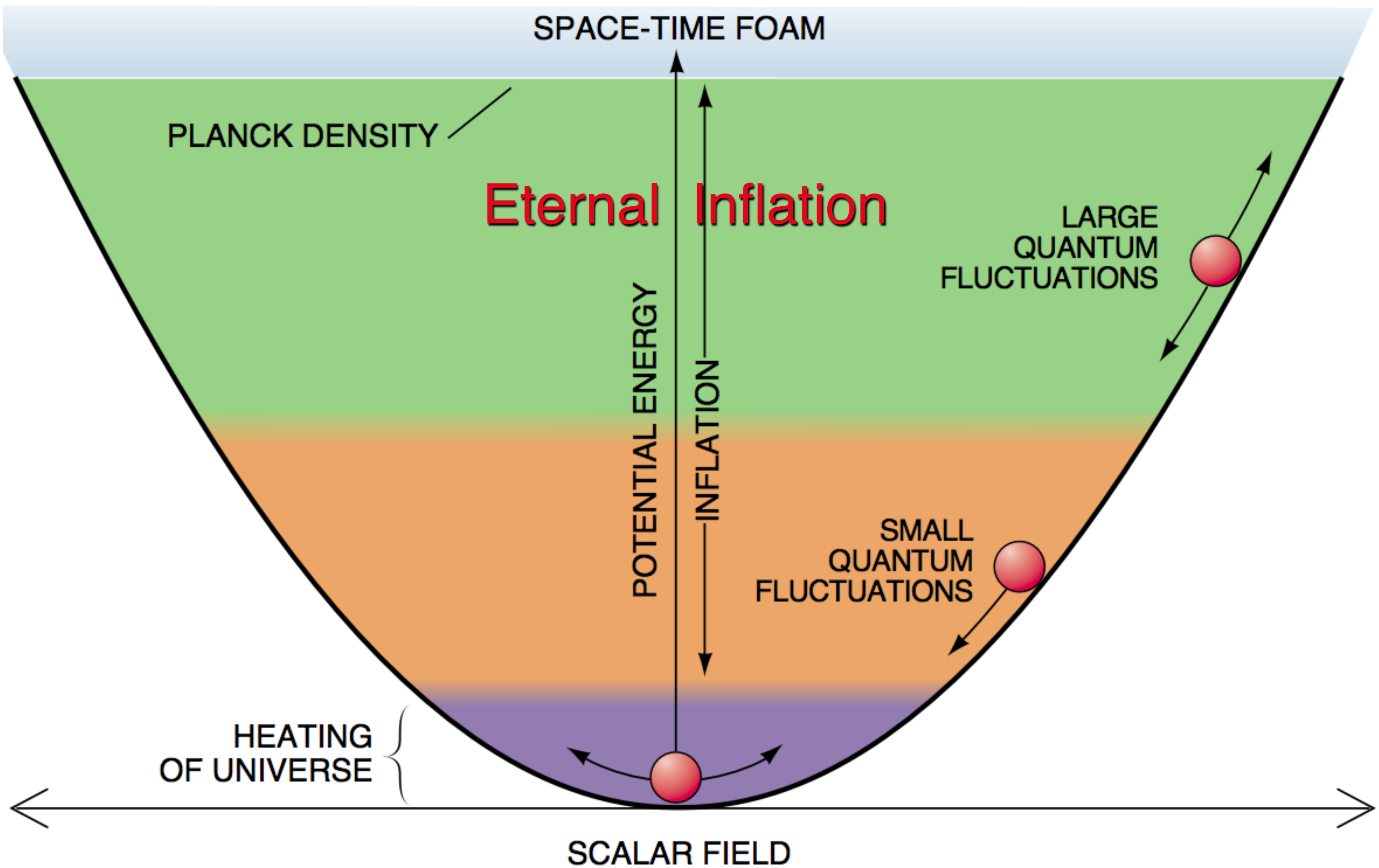
Who could do it ?

Inflationary theory

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

Chaotic Inflation

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



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

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

↓

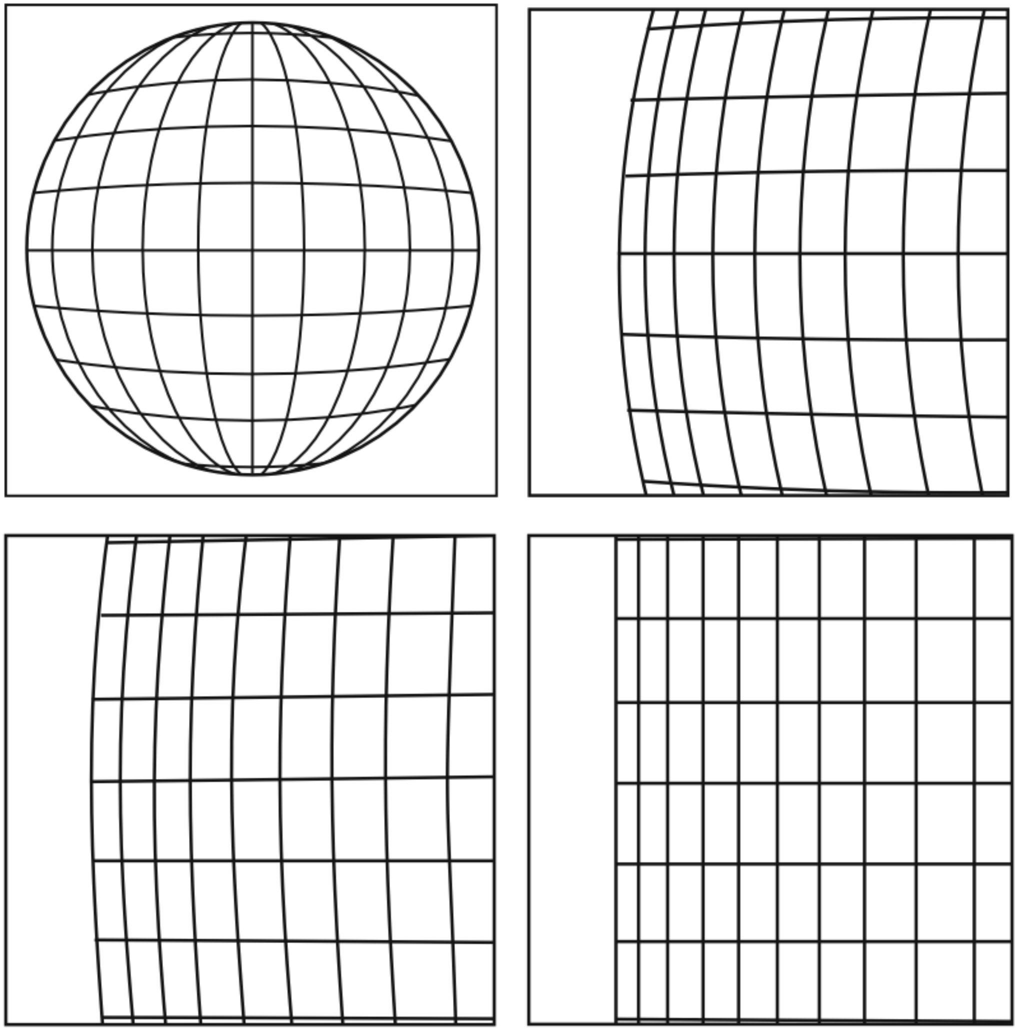
$$a \sim e^{Ht}$$

This is the stage of inflation

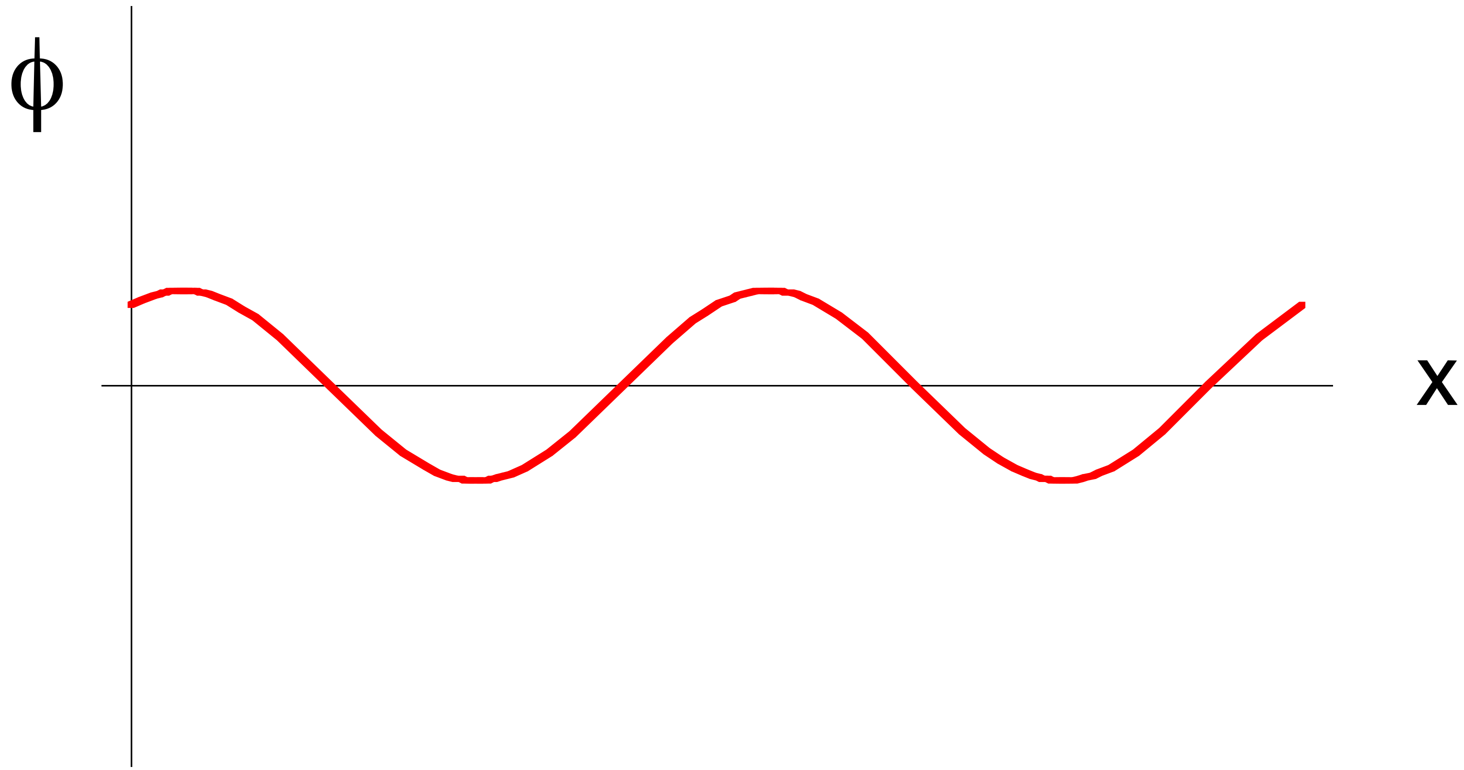
Inflation makes the universe flat, homogeneous and isotropic

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

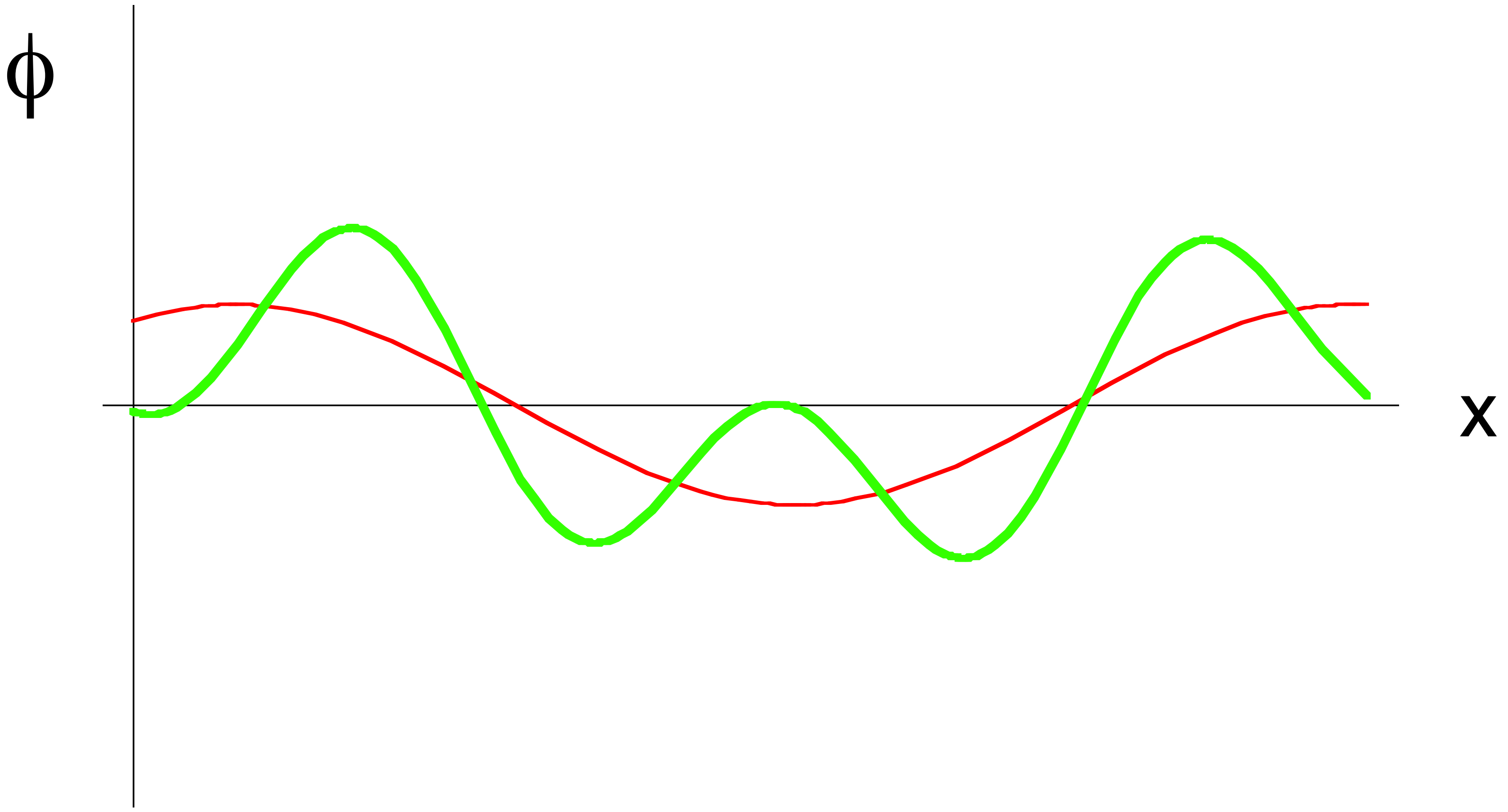
Now we can see just a tiny part of the universe of size $ct = 10^{10}$ light yrs. That is why the universe looks homogeneous, isotropic, and flat.



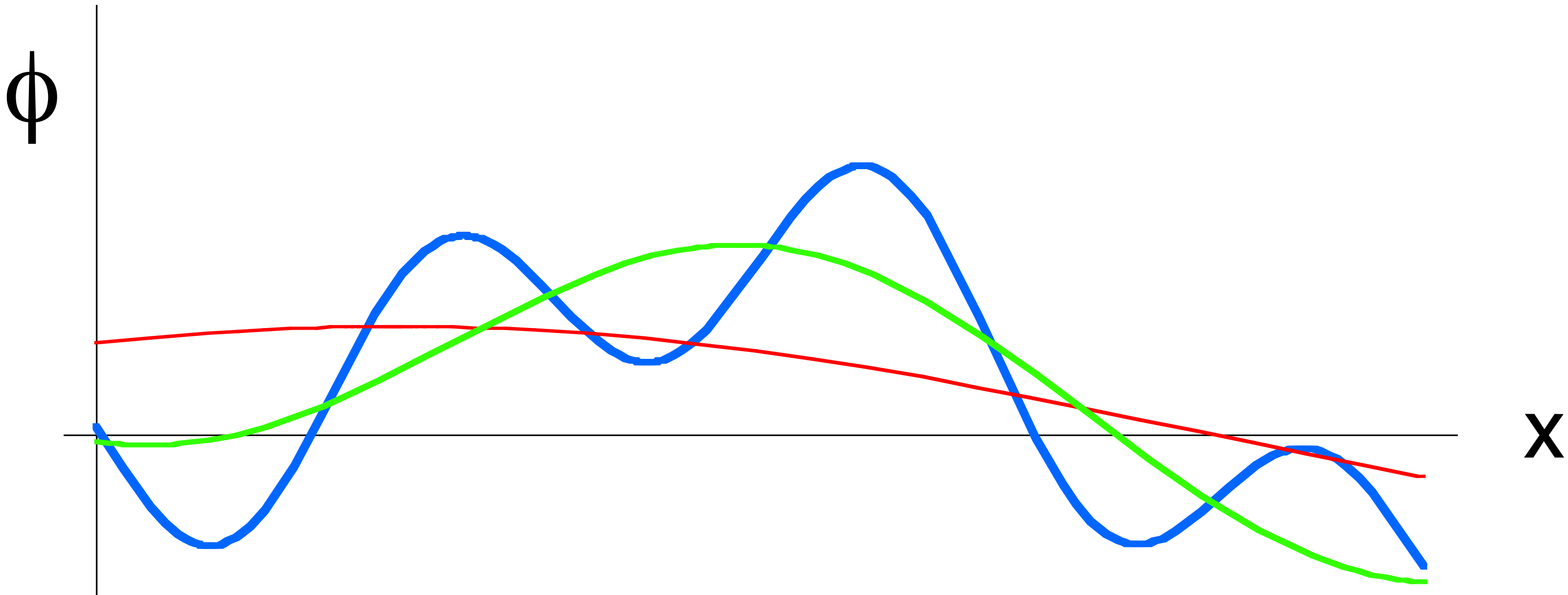
Quantum fluctuations produced during inflation



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.



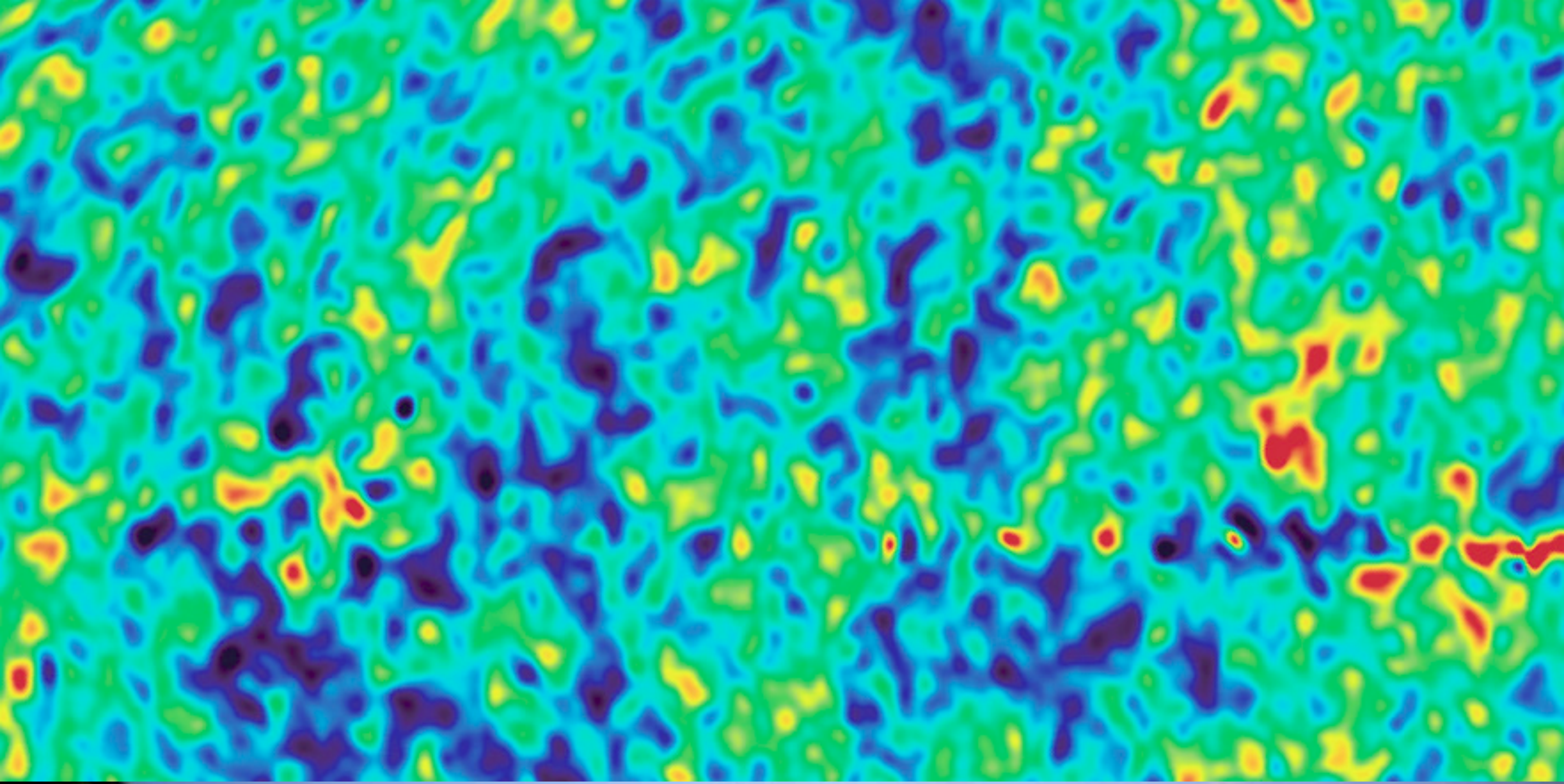
When expansion of the universe continues, new quantum fluctuations become stretched, stop oscillating, and freeze on top of the previously frozen fluctuations.



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.

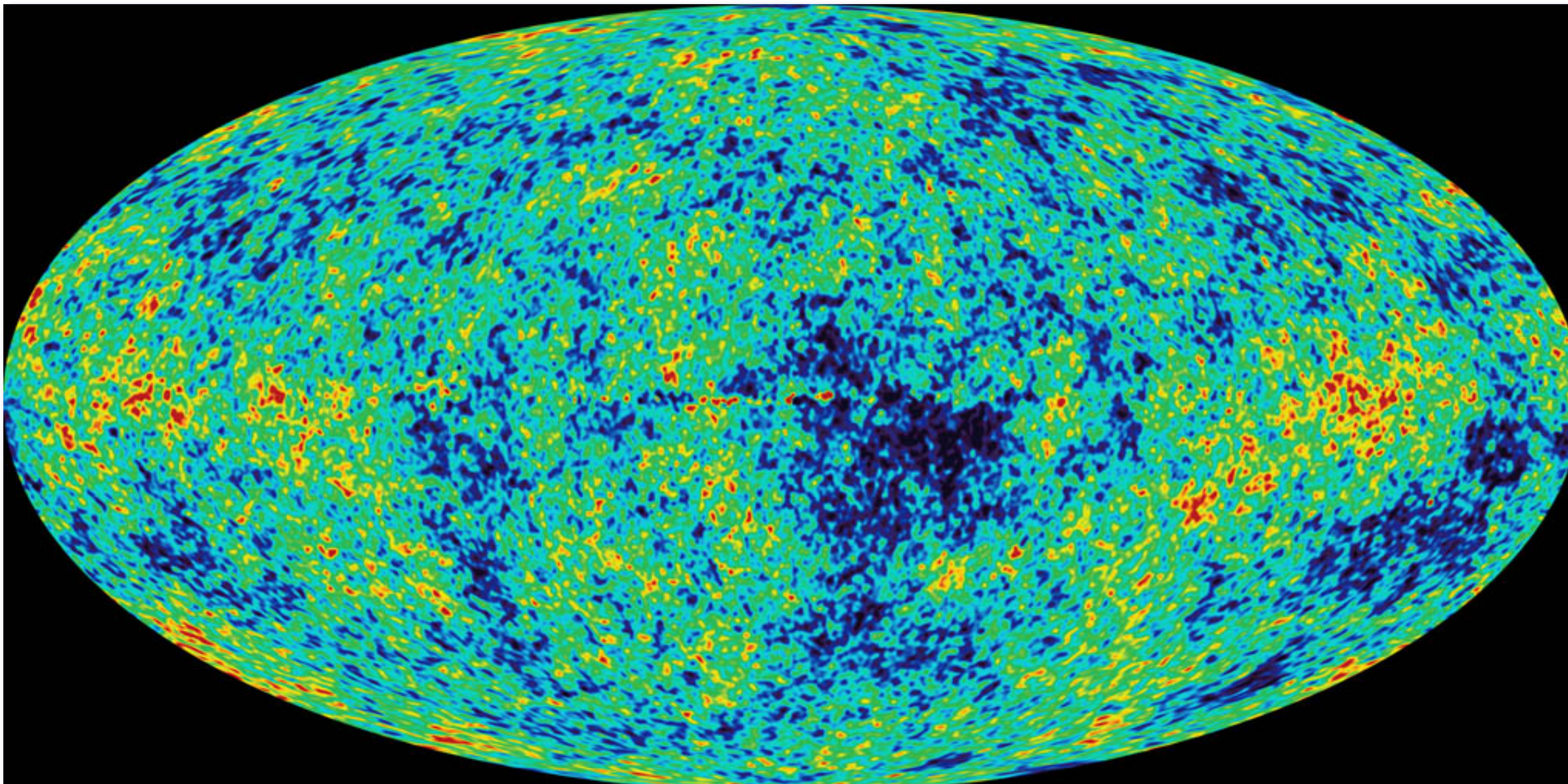
Sometimes these fluctuations are so large that they can increase the value of the scalar field in some parts of the universe. Then inflation in these parts of the universe occurs again and again. In other words, the process of inflation becomes eternal.

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

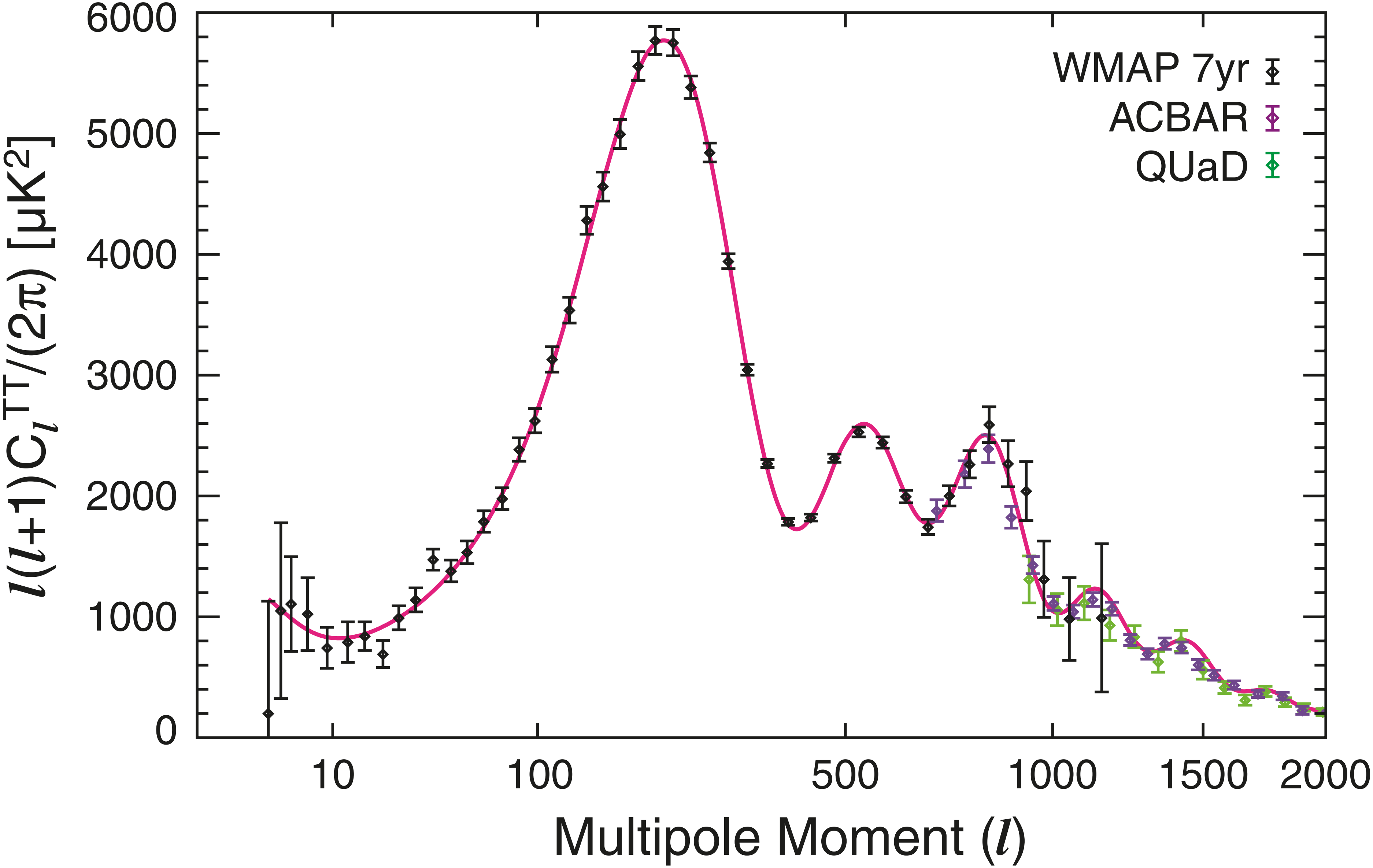



Observations

WMAP and the temperature of the sky



WMAP7 + Acbar + QUaD



Predictions of Inflation:

The universe should be homogeneous, isotropic and flat,

$\Omega = 1 + O(10^{-4})$

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

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

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

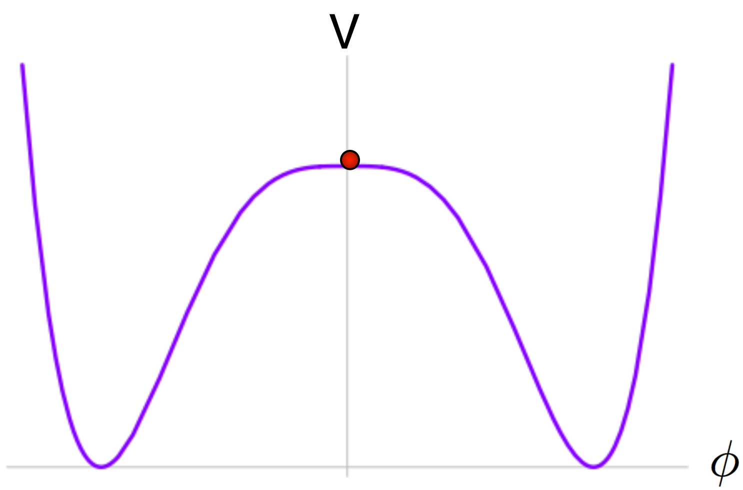
But if they are even slightly non-gaussian, at the level of 0.1% (to be explored by Planck), it may rule out all single-field inflationary models!

This will force us to develop a class of more complicated models involving many scalar fields – but it will be still much less complicated than MSSM

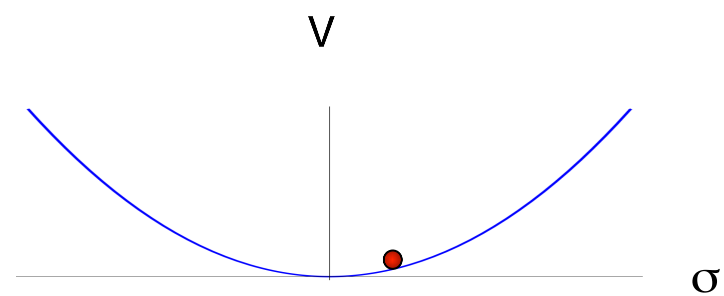
Can we have large non-gaussianity ?

A.L., Mukhanov, 1996,

Lyth, Wands, Ungarelli, 2002



Inflaton



Curvaton

Decay of perturbed field σ → adiabatic perturbations

$$\delta_H \sim \frac{\delta\sigma}{\sigma}$$

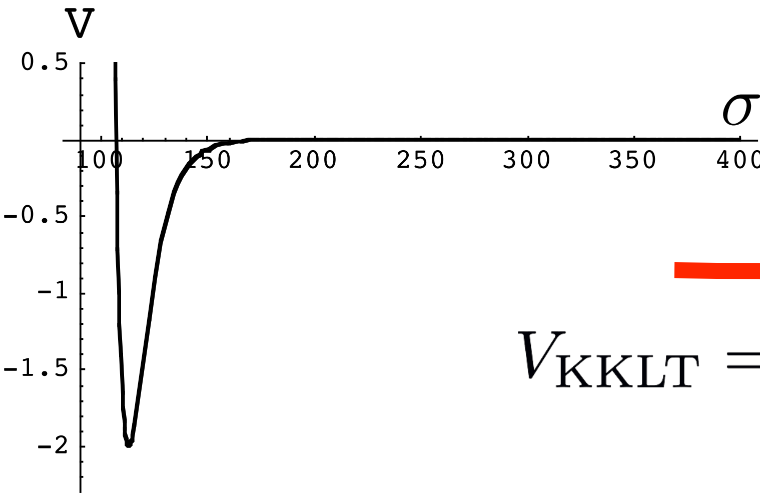
σ is determined by quantum fluctuations, so δ_H is different in different places. Curvaton perturbations can be strongly non-gaussian

Inflation and SUSY breaking in string theory

Kachru, Kallosh, A.L., Trivedi 2003

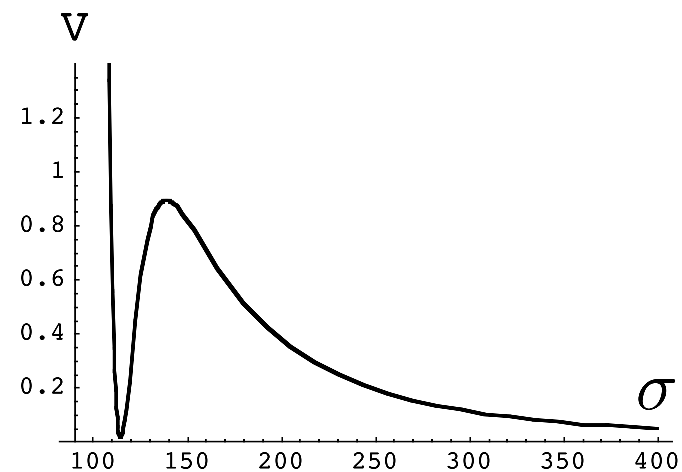
$$W = W_0 + Ae^{-a\rho} \qquad \mathcal{K} = -3\ln[(\rho+\bar\rho)]$$

$$\rho = \sigma + i\alpha$$



Stabilization in a supersymmetric AdS minimum

$$V_{\rm KKLT} = V_{\rm AdS} + \frac{D}{\sigma^2}$$



Uplifting to dS breaks SUSY

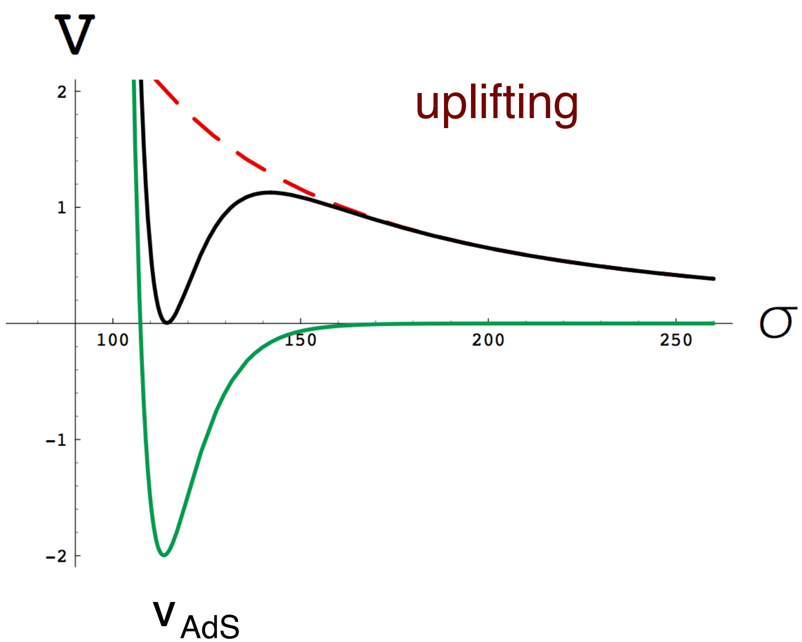
$$m_{3/2}^2 = |V_{\rm AdS}/3|$$

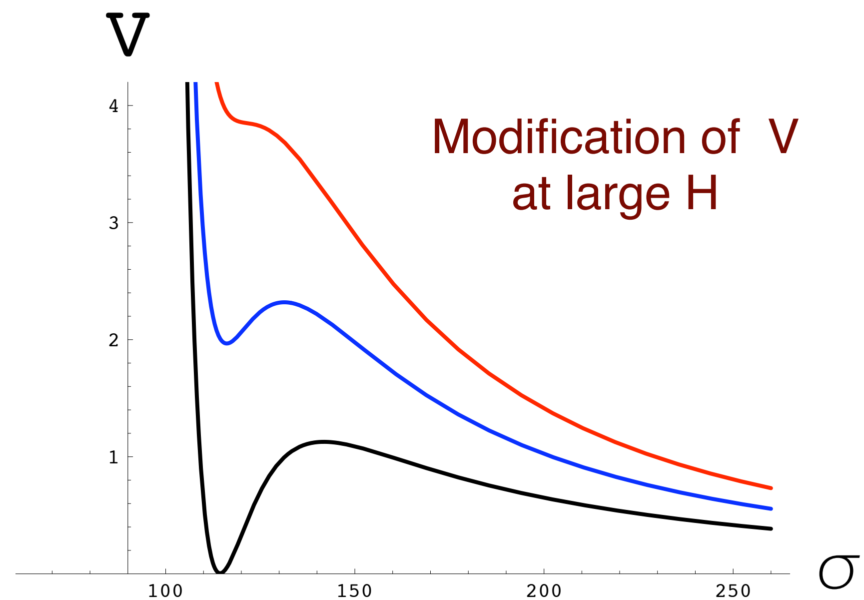

Future Beach

String Cosmology and the Gravitino Mass

Kallosh, A.L. 2004

The height of the KKLT barrier is smaller than $|V_{AdS}| = 3m^2_{3/2}$. The inflationary potential V_{infl} cannot be much higher than the height of the barrier. Inflationary Hubble constant is $H^2 = V_{infl}/3 < |V_{AdS}/3| \sim m^2_{3/2}$.





Constraint on the Hubble constant in this class of models:

$$H < m_{3/2}$$

Tensor modes in CMB and gravitino

$$r \sim 10^8 H^2$$

$$H \leq M_{3/2}$$

$$r \leq 10^8 \; M_{3/2}^2$$

Kallosh, A.L. 2007

$$r \sim 10^{-2} \longrightarrow M_{3/2} \sim 10^{13} GeV$$

superheavy gravitino

$$M_{3/2} \sim 1 TeV \longrightarrow r \sim 10^{-24}$$

unobservable

A discovery or non-discovery of tensor modes would be a crucial test for string theory and SUSY phenomenology

Modern versions of string theory

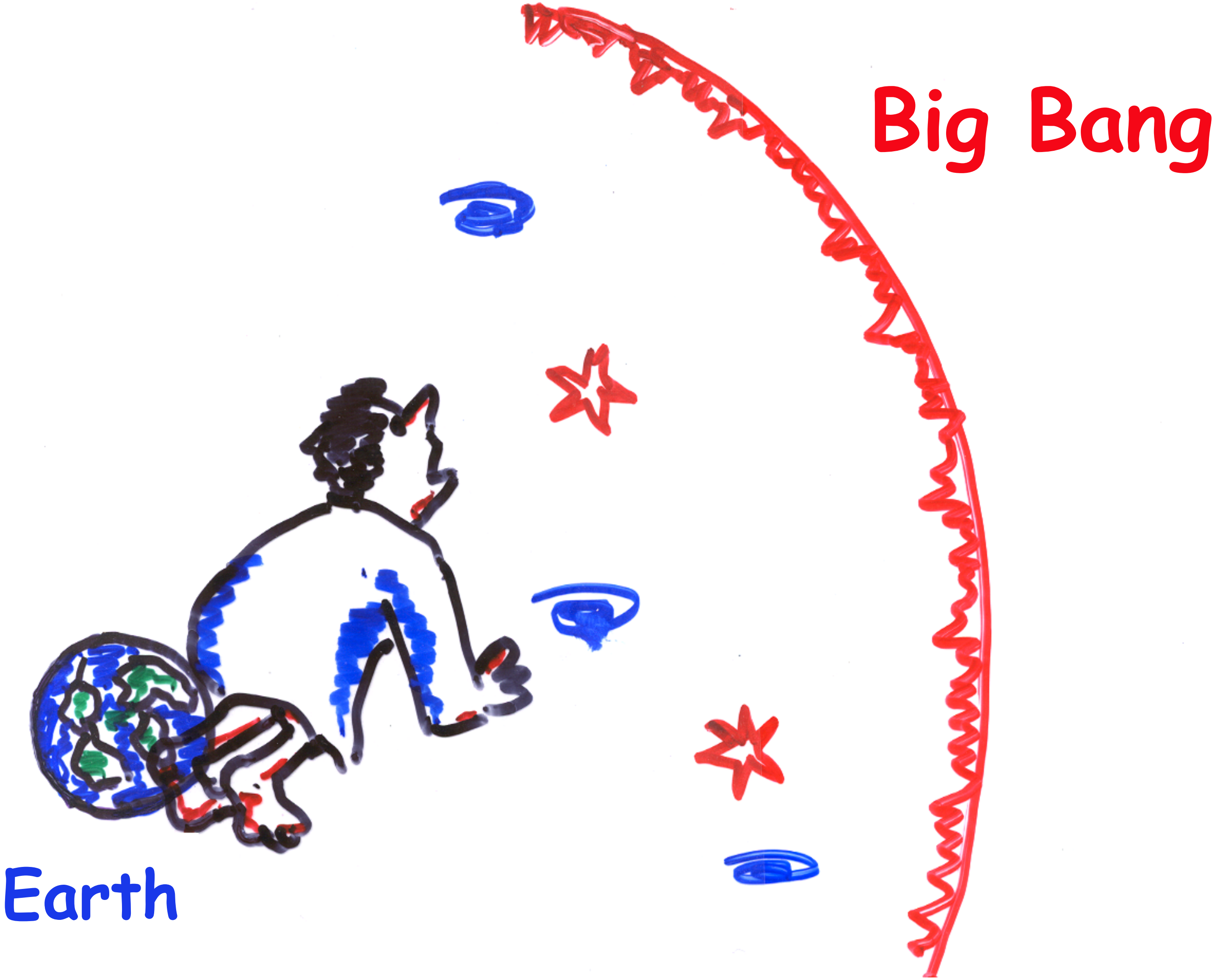
Discovery of SUSY particles at LHC

Discovery of gravity waves

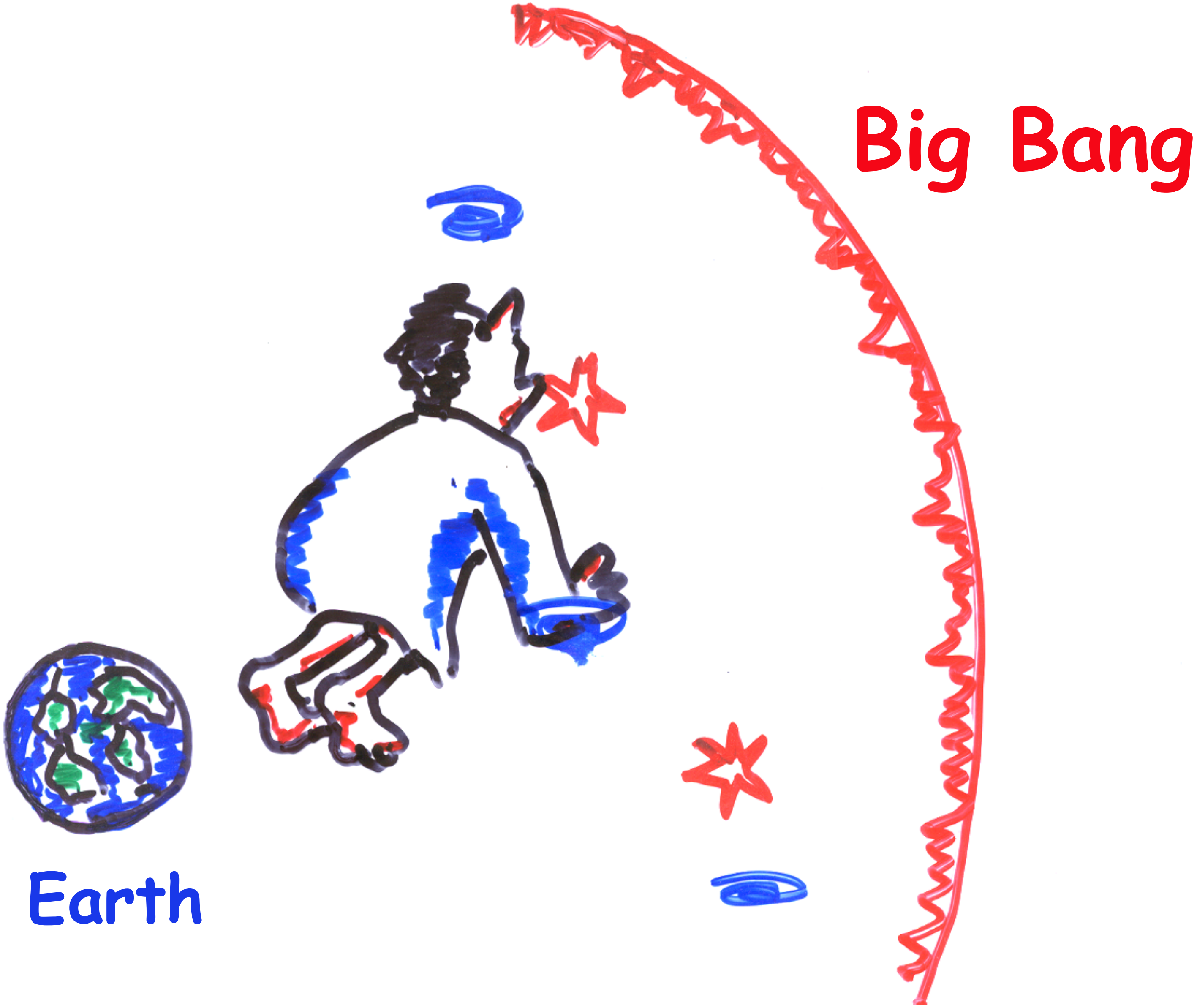
Any 2 of these 3 items are compatible with each other. Can all 3 of them live in peace?

There are several ways to address this issue: Kallosh, A.L. 2004; Badziak and M. Olechowski 2008, 2010; Conlon, Kallosh, A.L. and Quevedo 2008; He, Kachru and Westphal 2010; Kallosh, A.L., Olive, Rube

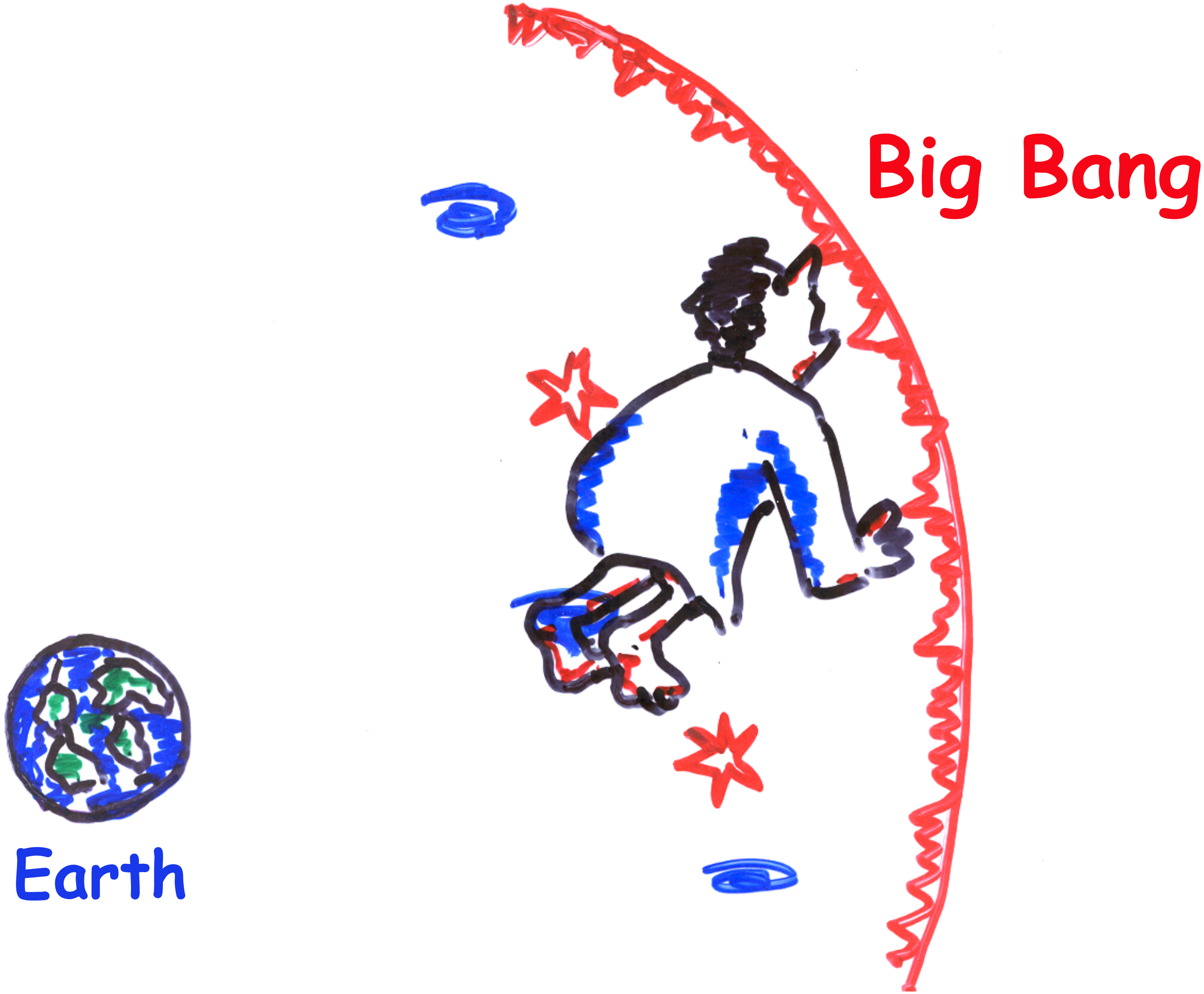
One should remember, however, that there is a certain price to pay for the desire to have low scale SUSY breaking. Split supersymmetry?



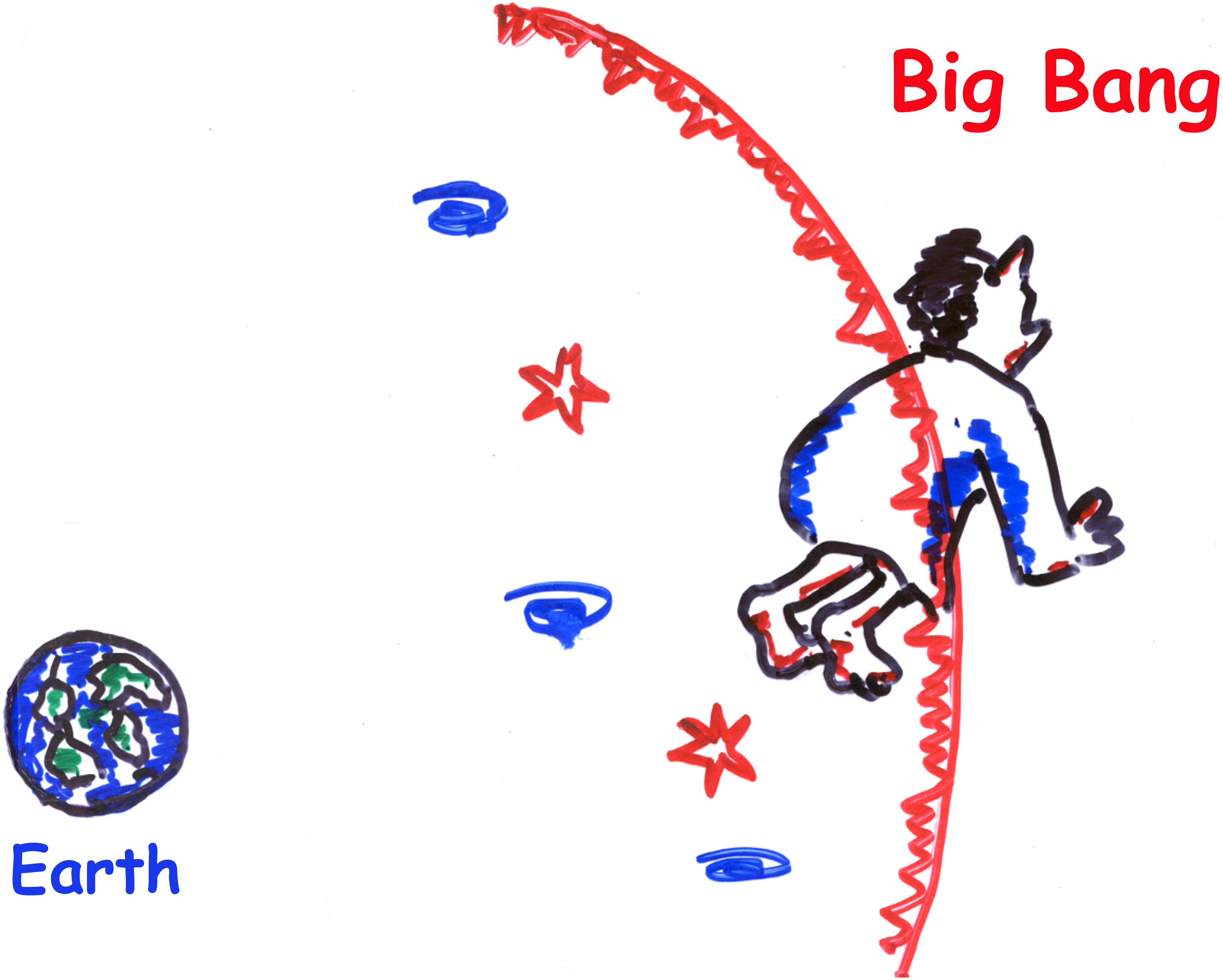
Astronomers use our universe as a “time machine”. By looking at the stars ose to us, we see them as they were several hundreds years ago.



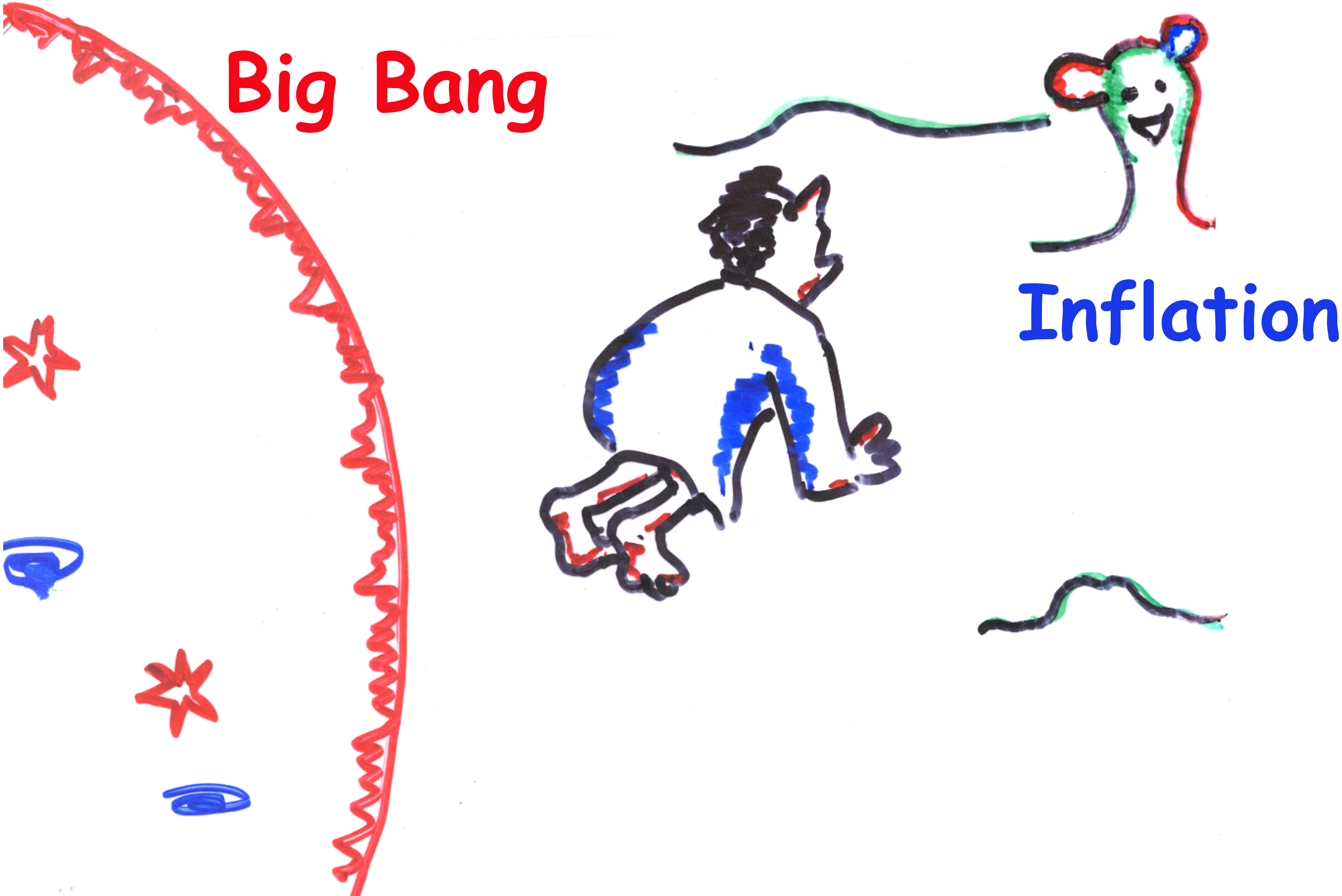
The light from distant galaxies travel to us for billions of years, so we see them in the form they had billions of years ago.



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.

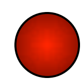


Inflationary theory tells us that this cosmic fire was created not at the time t = 0, but after inflation. If we look beyond the circle of fire surrounding us, we will see enormously large empty space filled only by a scalar field.

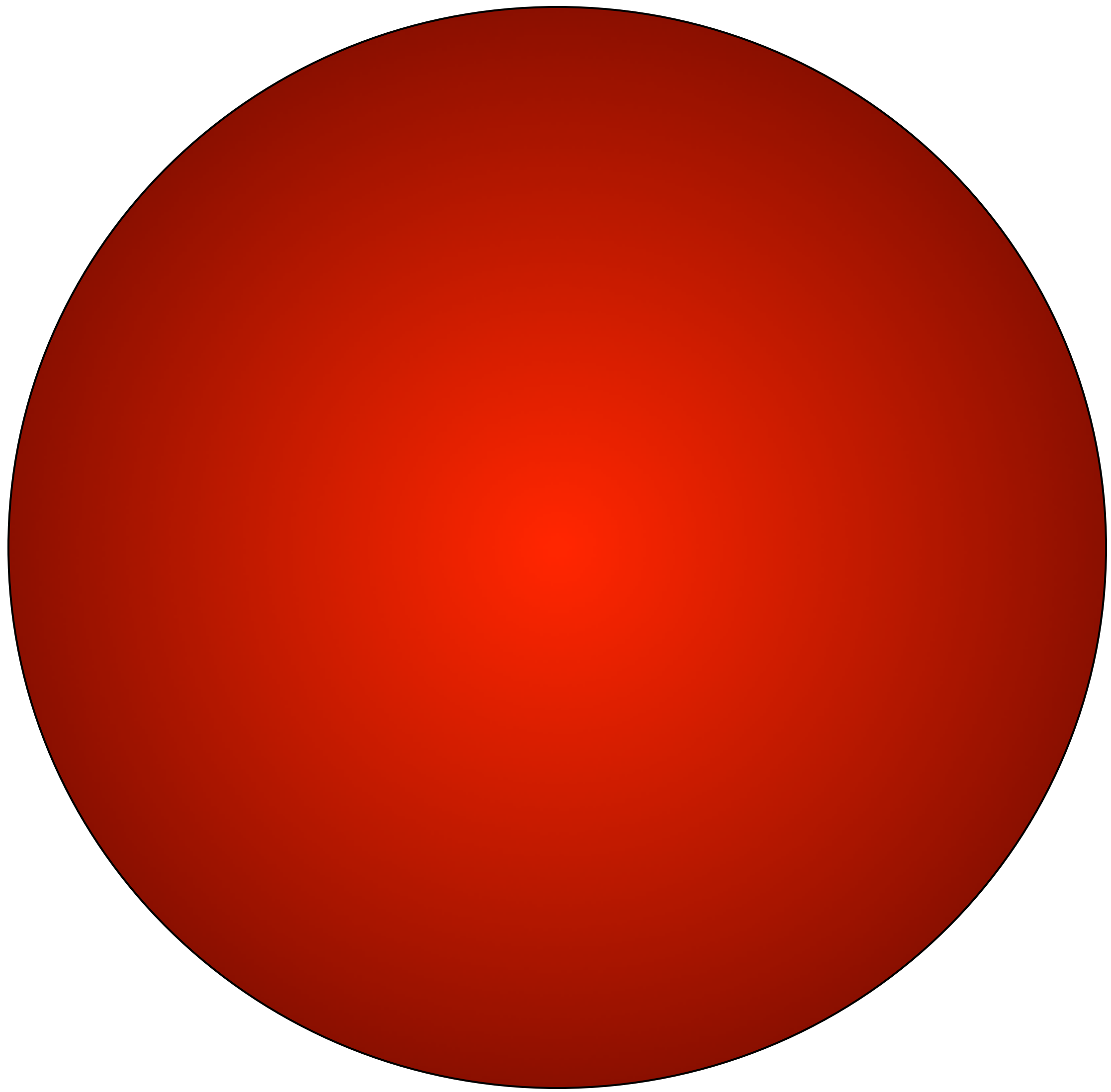


If we look there very carefully, we will see small perturbations of space, which are responsible for galaxy formation. And if we look even further, we will see how new parts of inflationary universe are created by quantum fluctuations.

Inflationary universe



Inflationary universe



Thus, **uniformity** of our world 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

A.L. 1982

Genetic code of the Universe

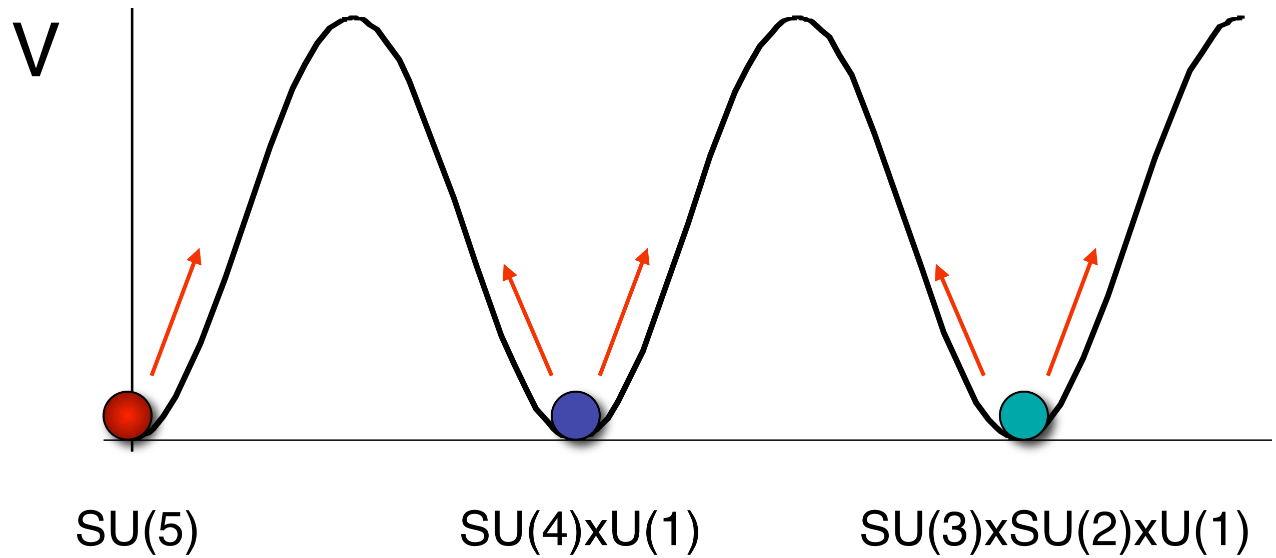
There may be **one** fundamental law of physics, like a single genetic code for the whole Universe. However, this law may have different realizations. For example, water can be liquid, solid or gas. In elementary particle physics, the effective laws of physics depend on the values of the scalar fields.

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

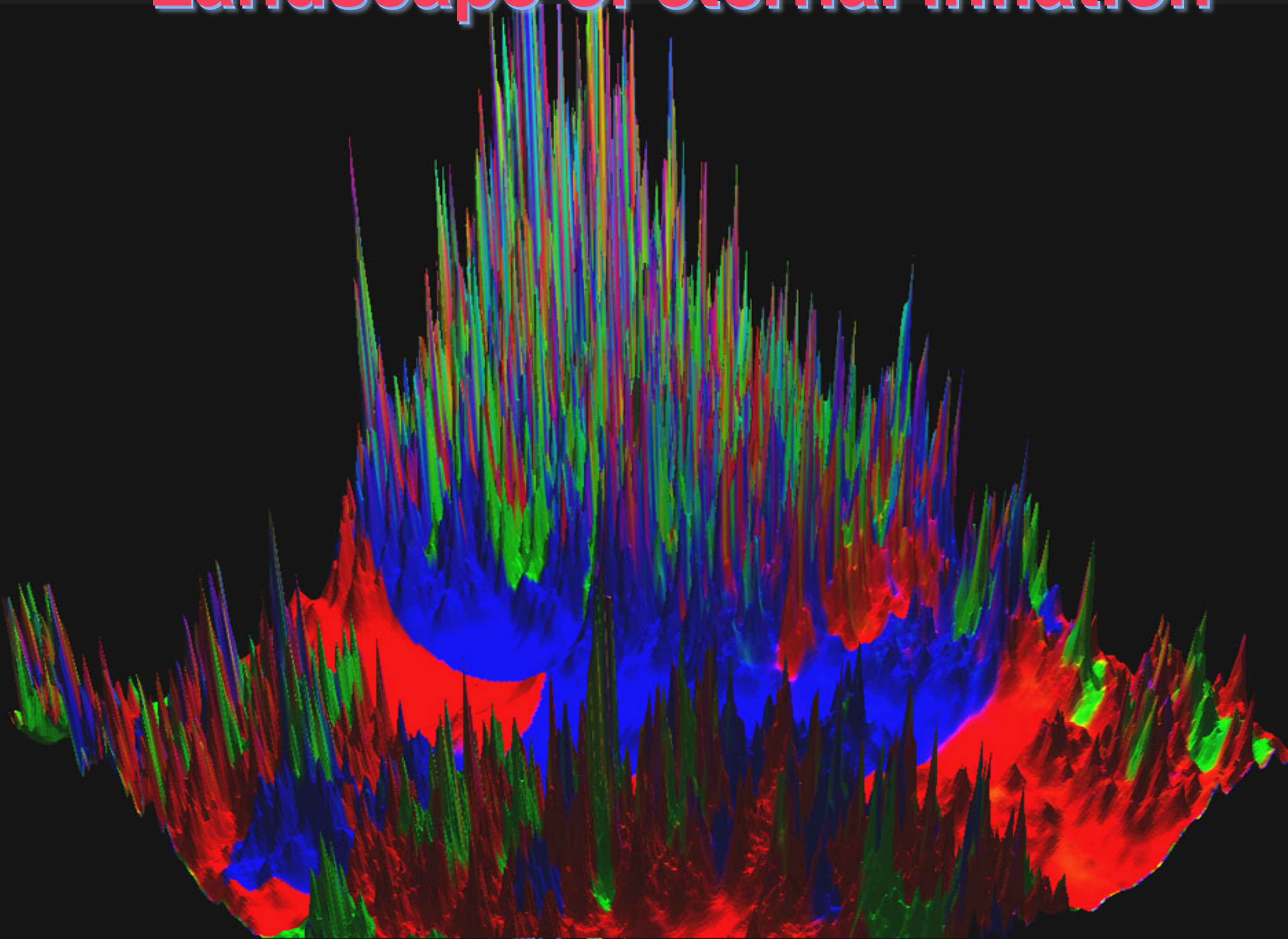
From the Universe to the Multiverse

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.

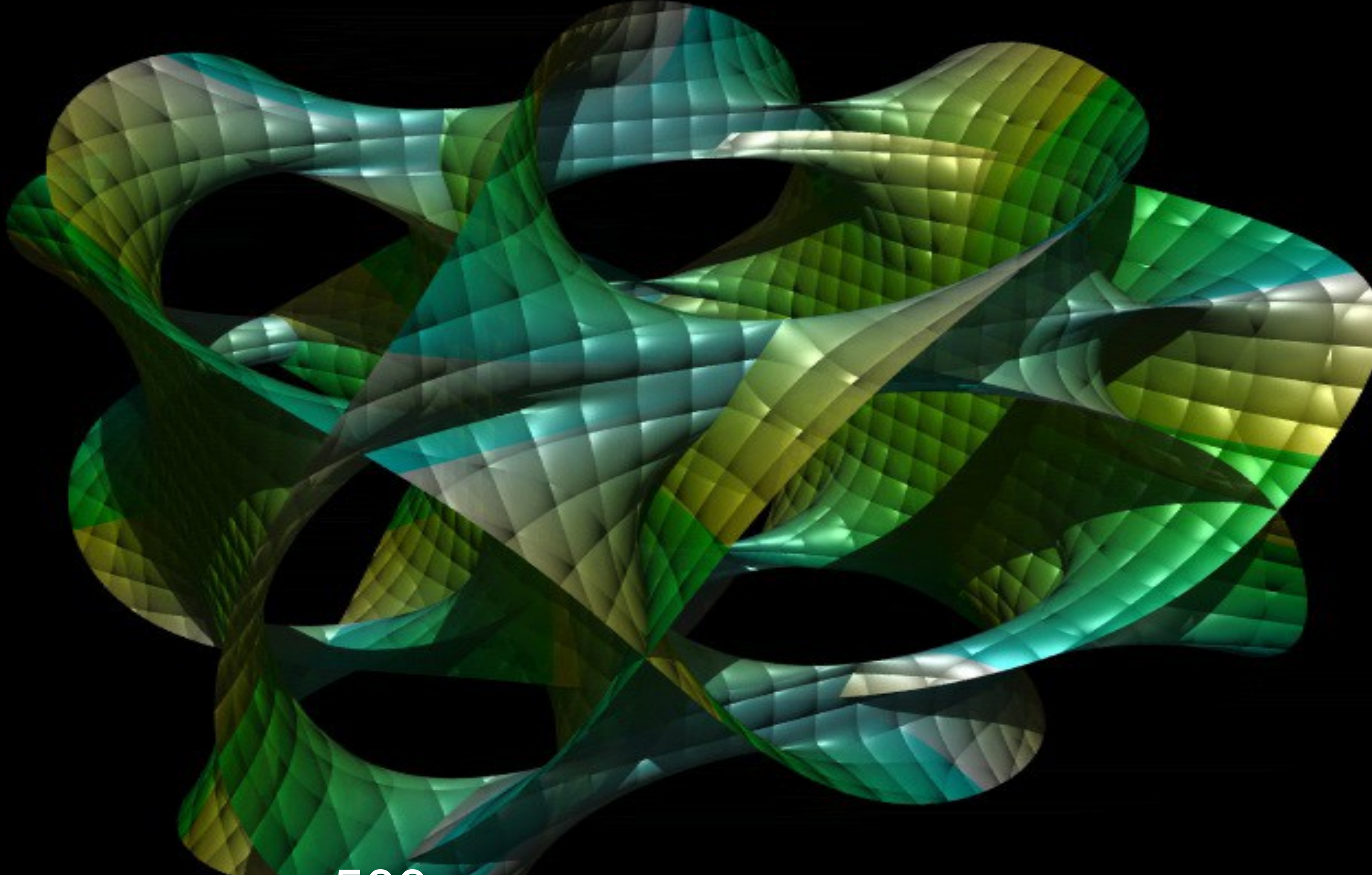


Quantum fluctuations during eternal inflation can bring the scalar fields to different minima in different parts of the universe. The universe becomes divided into many exponentially large parts with **different laws of physics** operating in each of them.

Landscape of eternal inflation

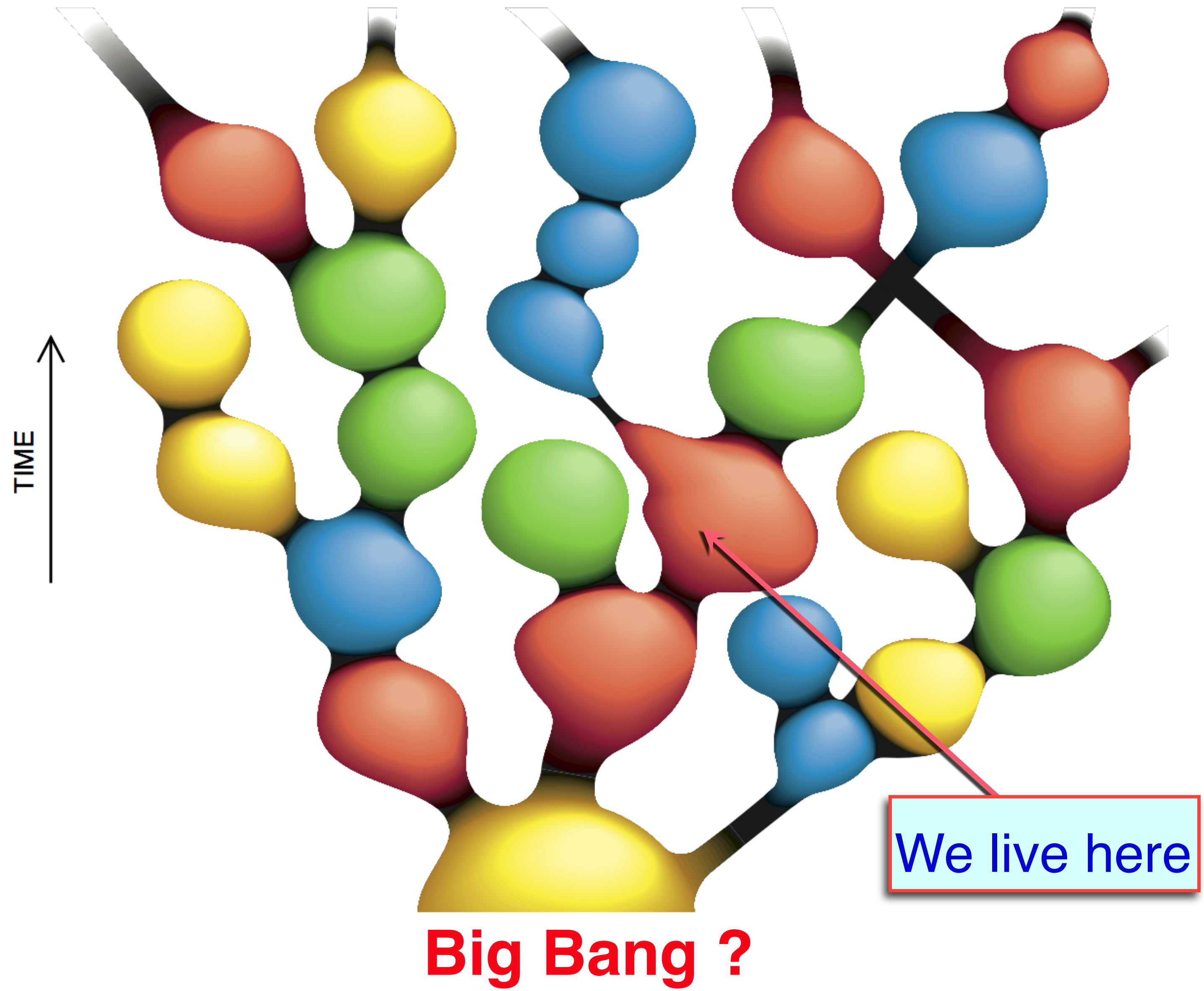


In string theory, genetic code is written in properties of compactification of extra dimensions



Up to 10^{500} different combinations

Self-reproducing Inflationary Universe



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

Alan Guth 1981

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.

A.L. 1983

All vacuum states in string theory are **UNSTABLE**.
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

Is it physics or metaphysics?

Can it be experimentally tested?

Can we test the multiverse theory ?

This theory provides the only known explanation of numerous anthropic coincidences (extremely small vacuum energy, strange masses of elementary particles, etc.) In this sense, it was already tested.

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

Sherlock Holmes