What Energy Drives the Universe?

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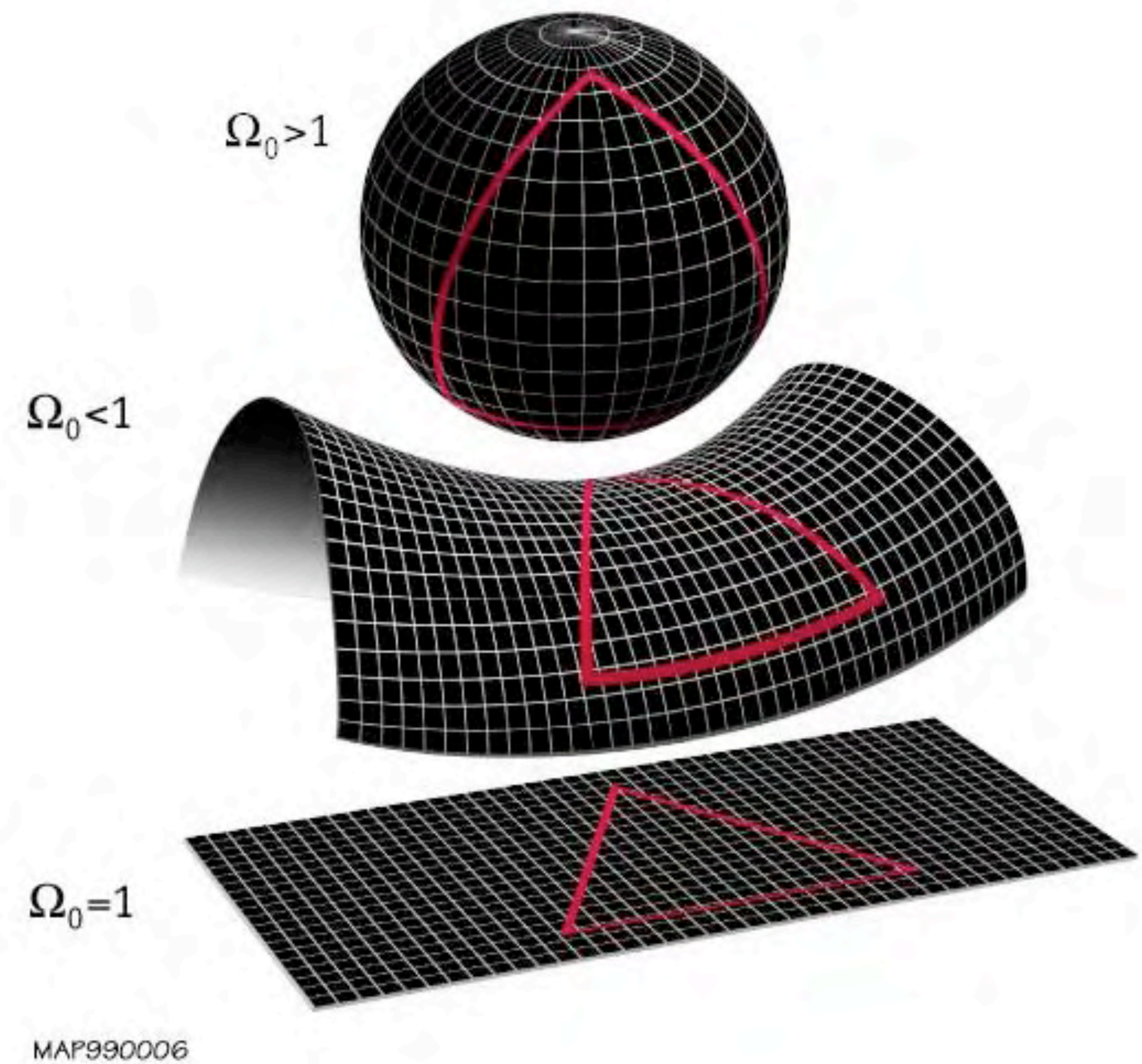
Two major cosmological discoveries:

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

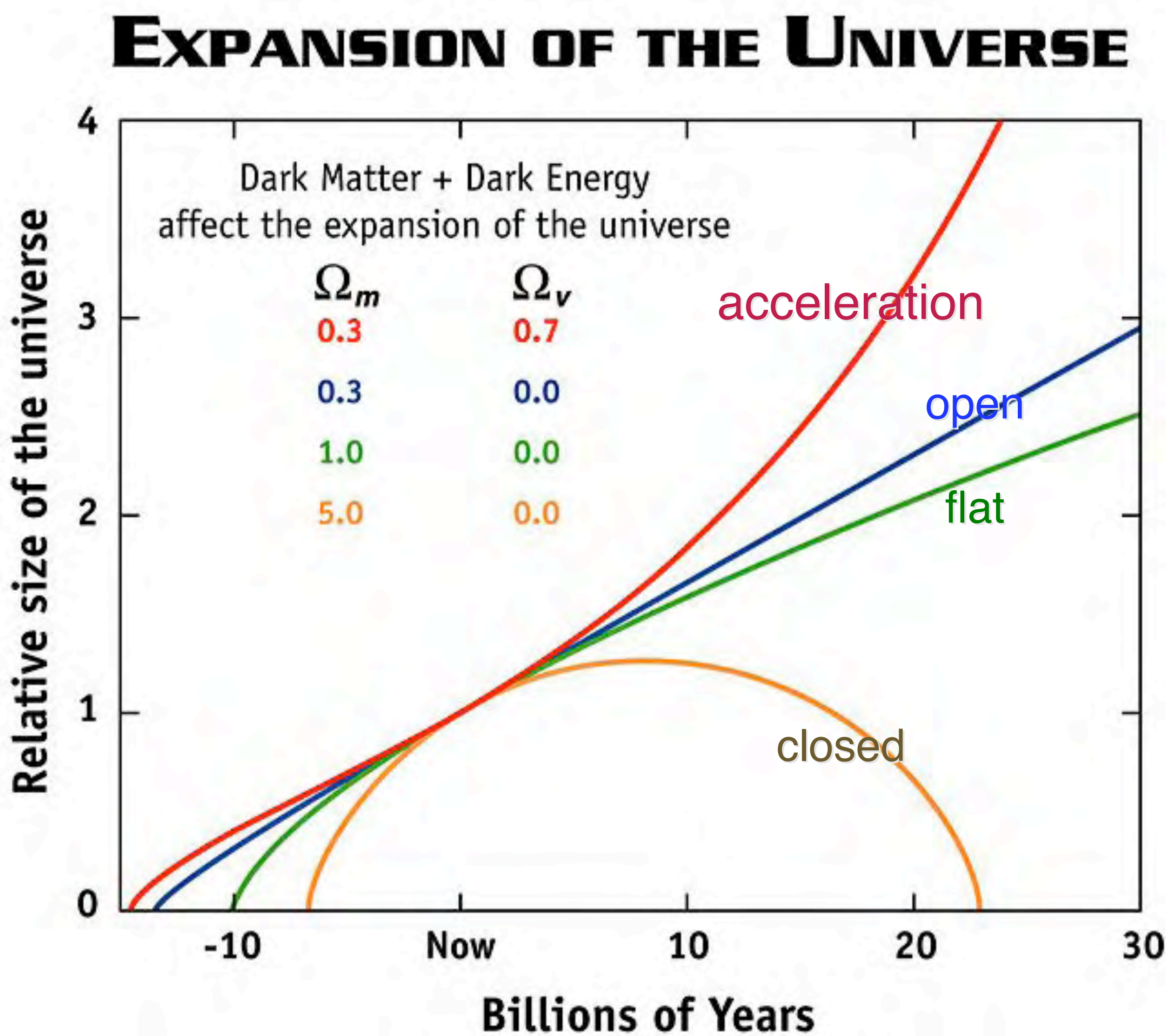
- A new (slow) stage of acceleration started 5 billion years ago (dark energy)

What is the mechanism of this acceleration?
What is the source of energy of matter in the universe?

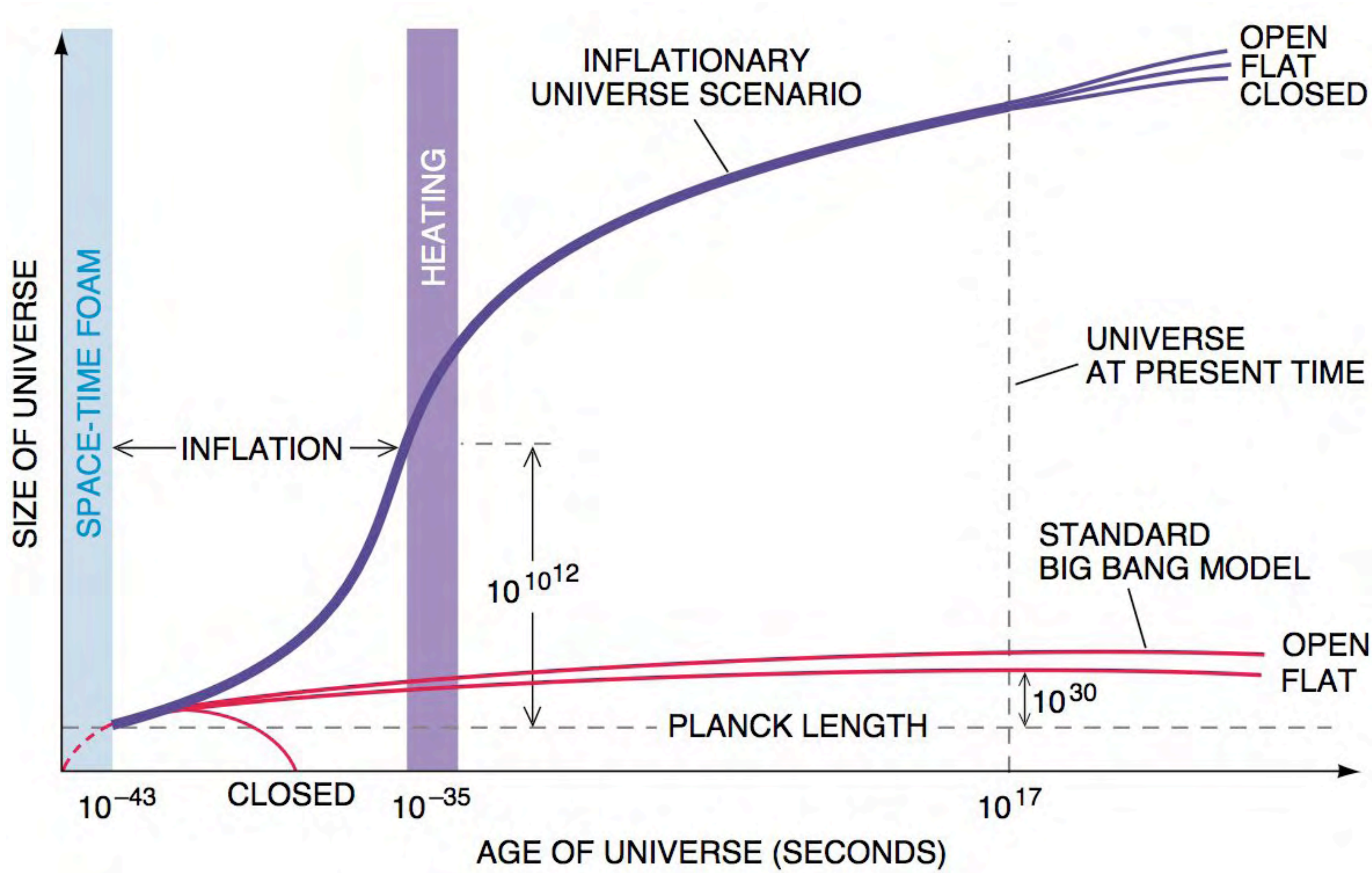
Closed, open or flat universe



Big Bang Theory



Inflationary Universe



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 photons in the Big Bang theory

The total energy of radiation in the universe now is greater than **10^{53} g**. According to the Big Bang theory, the total number of photons in the universe practically did not change during its evolution, but the energy of each photon decreased as the temperature of the universe T. The standard classical description of the universe becomes possible at the Planck time, when the temperature of the universe was 10^{32} times greater than now. At that time, the energy of radiation was greater than $10^{53} \times 10^{32} = \mathbf{10^{85}\ g}$

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

Where did it come from?

Extending this investigation back to the cosmological singularity, where T was infinite, one finds that in order to create the universe in the Big Bang singularity one should have

INFINITE AMOUNT OF ENERGY

Other problems of the Big Bang theory:

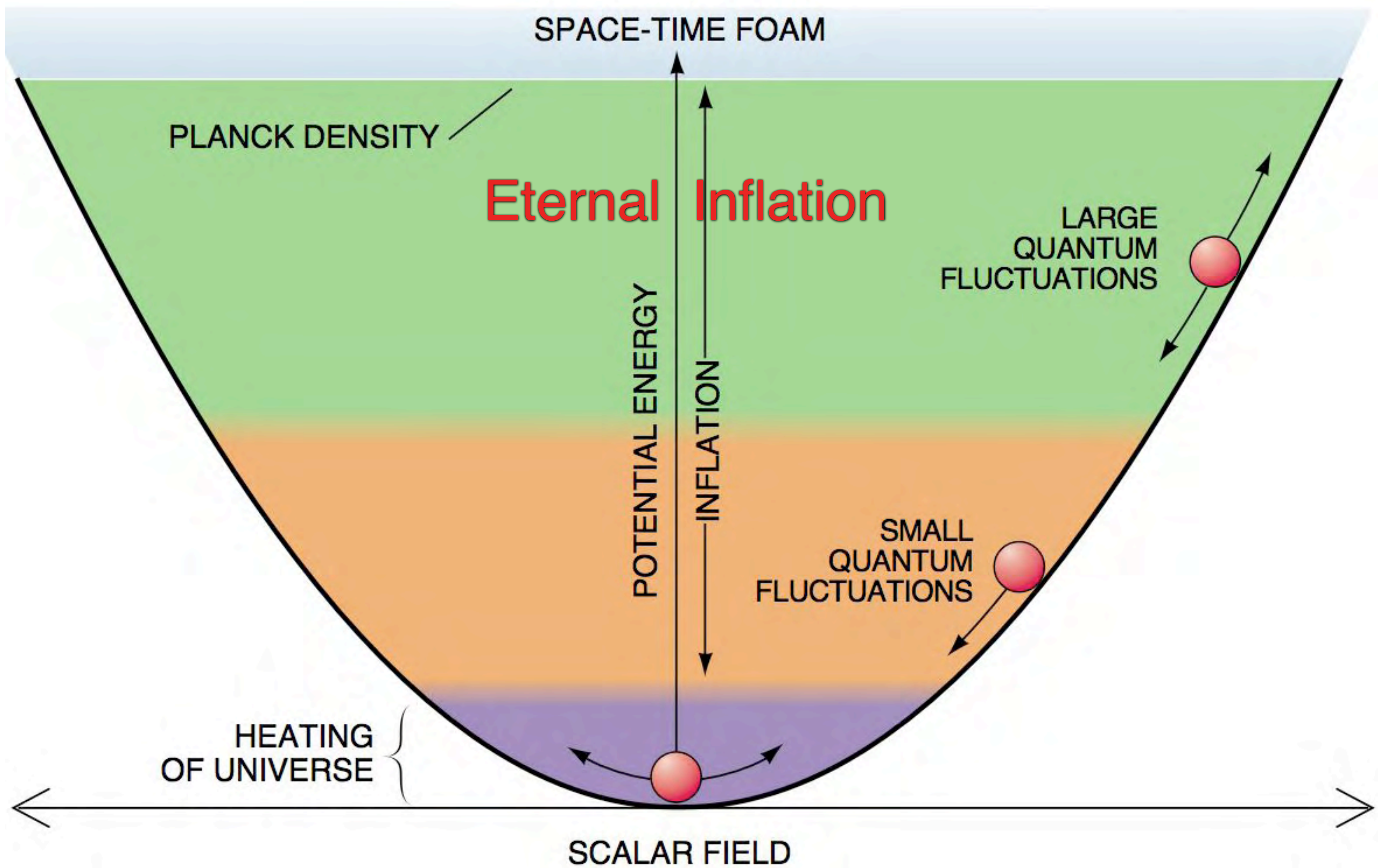
- What was before the Big Bang?
- Why is our universe so **homogeneous** (better than 1 part in 10000)?
- Why is it **isotropic** (the same in all directions)?
- Why all of its parts started expanding simultaneously?
- Why is it **flat**? Why parallel lines do not intersect? Why is the universe so large?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

Inflationary theory

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

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 $\longrightarrow$ large H $\longrightarrow$ large friction

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

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

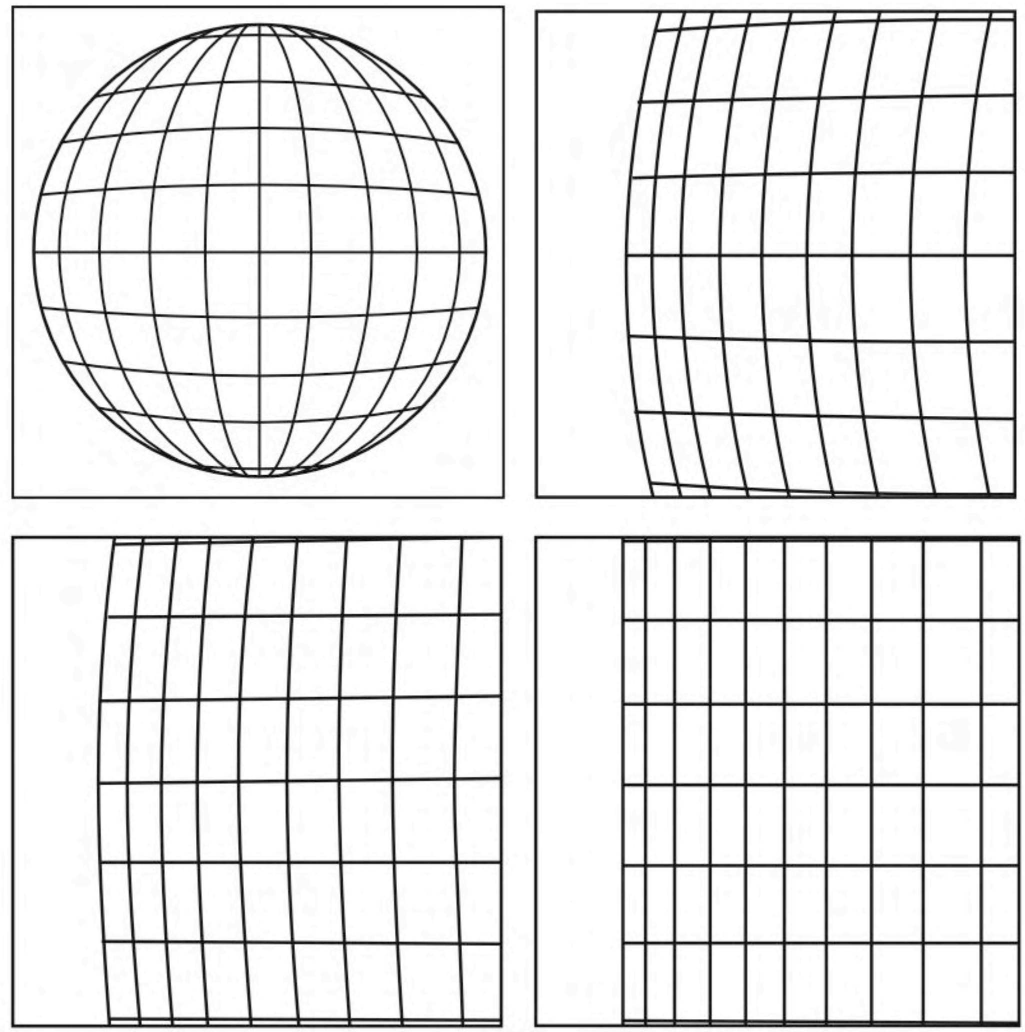
$$\Downarrow$$

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

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.

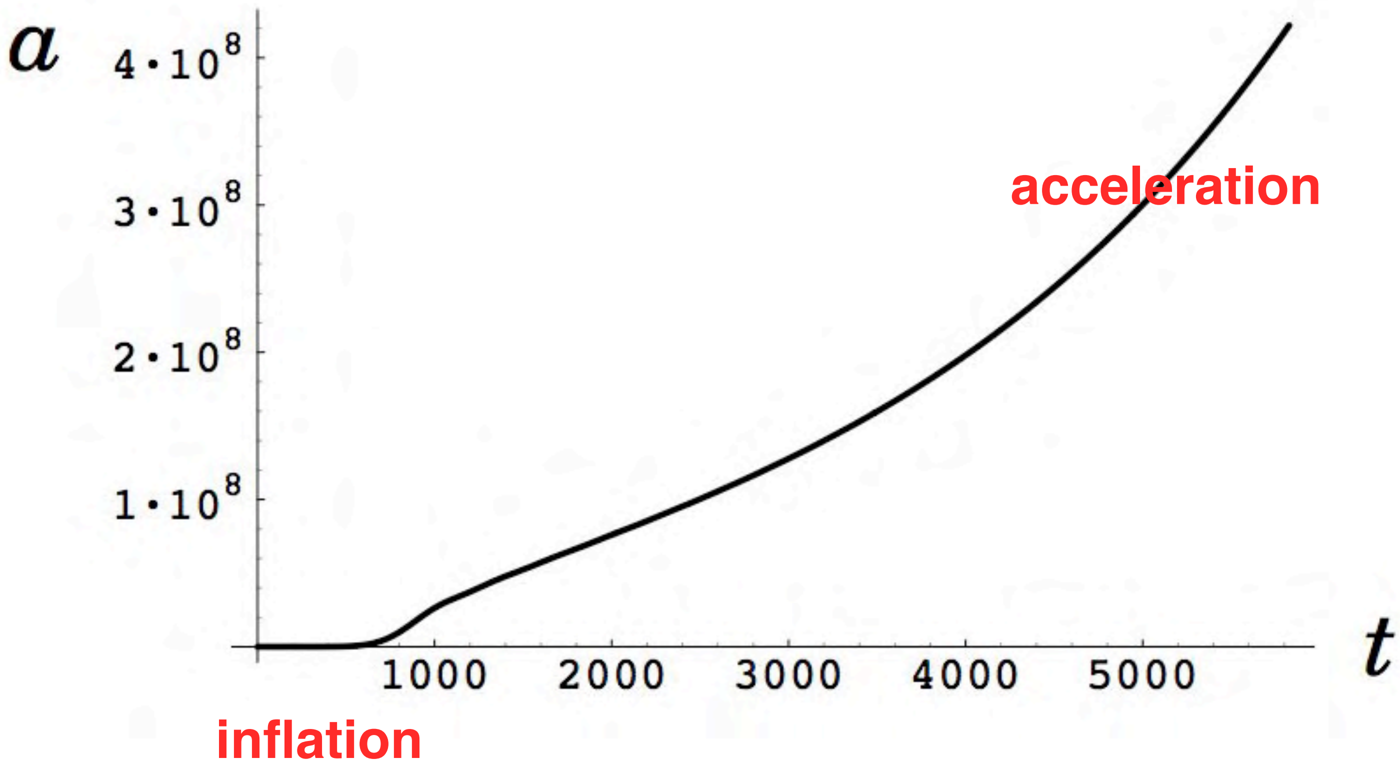


Add a constant to the inflationary potential

- obtain inflation and acceleration

$$V = \frac{m^2}{2}\phi^2 + \Lambda$$

The simplest model of inflation AND dark energy



Note that the energy density of the scalar field during inflation remains nearly constant, because at that stage the field practically does not change.

Meanwhile, the total volume of the universe during inflation grows exponentially, as $a^3(t) \sim e^{3Ht}$.

Therefore the total energy of the scalar field also grows exponentially, as $E \sim e^{3Ht}$.

After inflation, scalar field decays, and all of its energy is transformed into the exponentially large energy/mass of particles populating our universe.

We can start with a tiny domain of the smallest possible size (Planck length $l_P = M_P^{-1} \sim 10^{-33}$ cm) at the largest possible density (Planck density $M_P^4 \sim 10^{94}$ g/cm^3). The total energy of matter inside such a domain is $l_P^3 M_P^4 \sim M_P \sim 10^{-5}$ g. Then inflation makes this domain much larger than the part of the universe we see now.

What is the source of this energy?

Energy density and pressure for the scalar field:

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

If the scalar field moves slowly, its pressure is negative,

$$p = w\rho, \qquad w \approx -1$$

Therefore energy of matter grows, $dE = -p\,dV > 0$

Existence of matter with $\mathrm{p} < 0$ allows the total energy of matter to grow at the expense of the gravitational energy, which becomes equally large but negative.

$$E_{matter} \sim + e^{3Ht}$$

$$E = 0$$

Total energy of
the universe

Exponential instability

Simultaneous creation
of space and matter

$$E_{space} \sim - e^{3Ht}$$

If such instability is possible, it appears over and over again. This leads to <u>eternal inflation,</u> which we will discuss later.

So inflation may start in the universe of the Planck mass (energy) $E \sim M_P \sim 10^{-5}$ g, at the Planck time $t_P \sim M_P^{-1} \sim 10^{-43}$ s.

But where did these initial 10^{-5} g of matter come from?

Uncertainty relation (in units $c = \hbar = 1$):

$$\Delta E \cdot \Delta t = M_P \cdot M_p^{-1} = 1$$

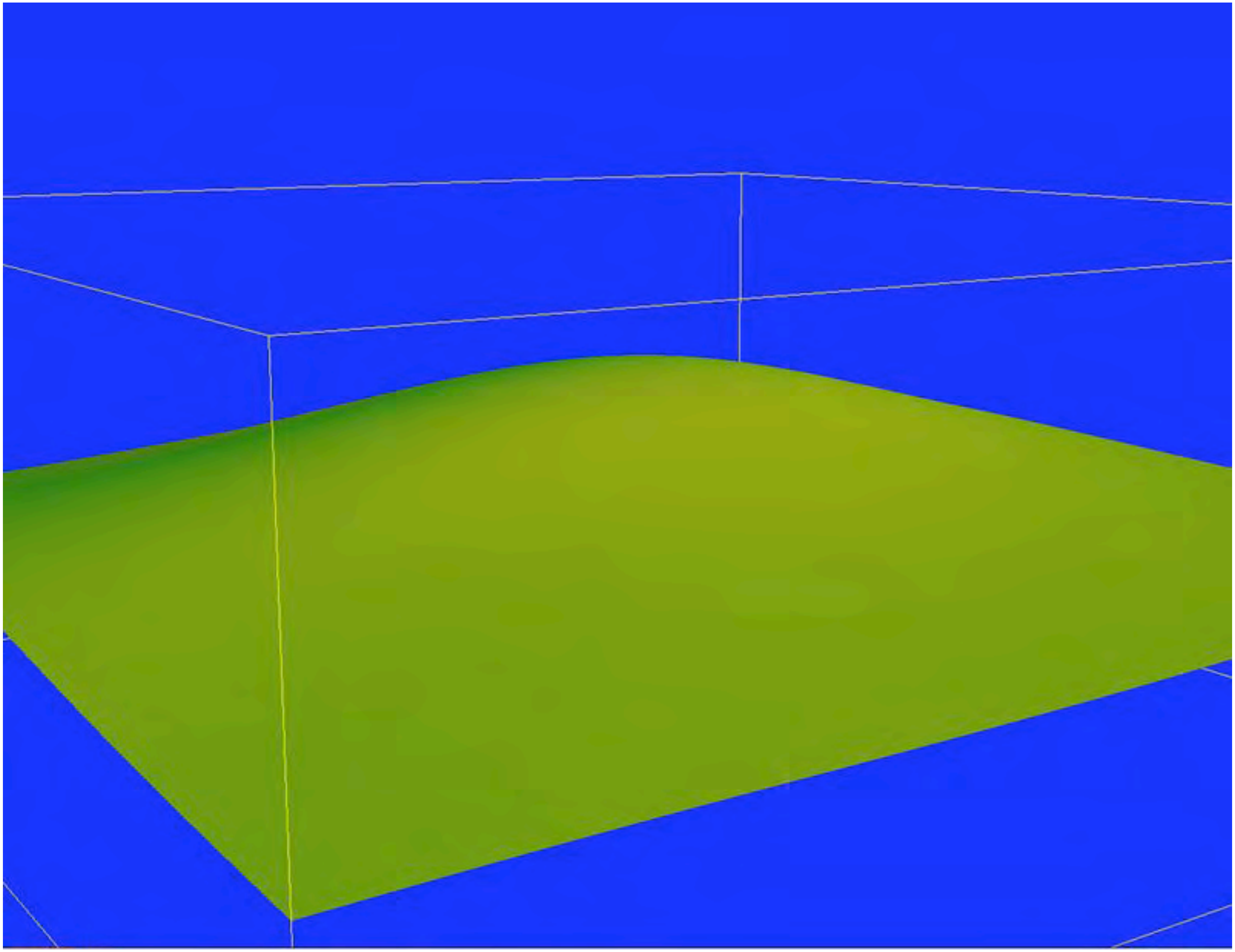
Thus the emergence of the initial 10^{-5} g of matter is a simple consequence of the quantum mechanical uncertainty principle. And once we have 10^{-5} g of matter in the form of a scalar field, inflation begins, and energy becomes exponentially large.

If one can create the whole universe from 1 milligram of matter, what else is possible?

1) Inflation can create galaxies from quantum fluctuations.

2) Inflationary fluctuations can create new exponentially large parts of the universe (eternal inflation).

Generation of Quantum Fluctuations

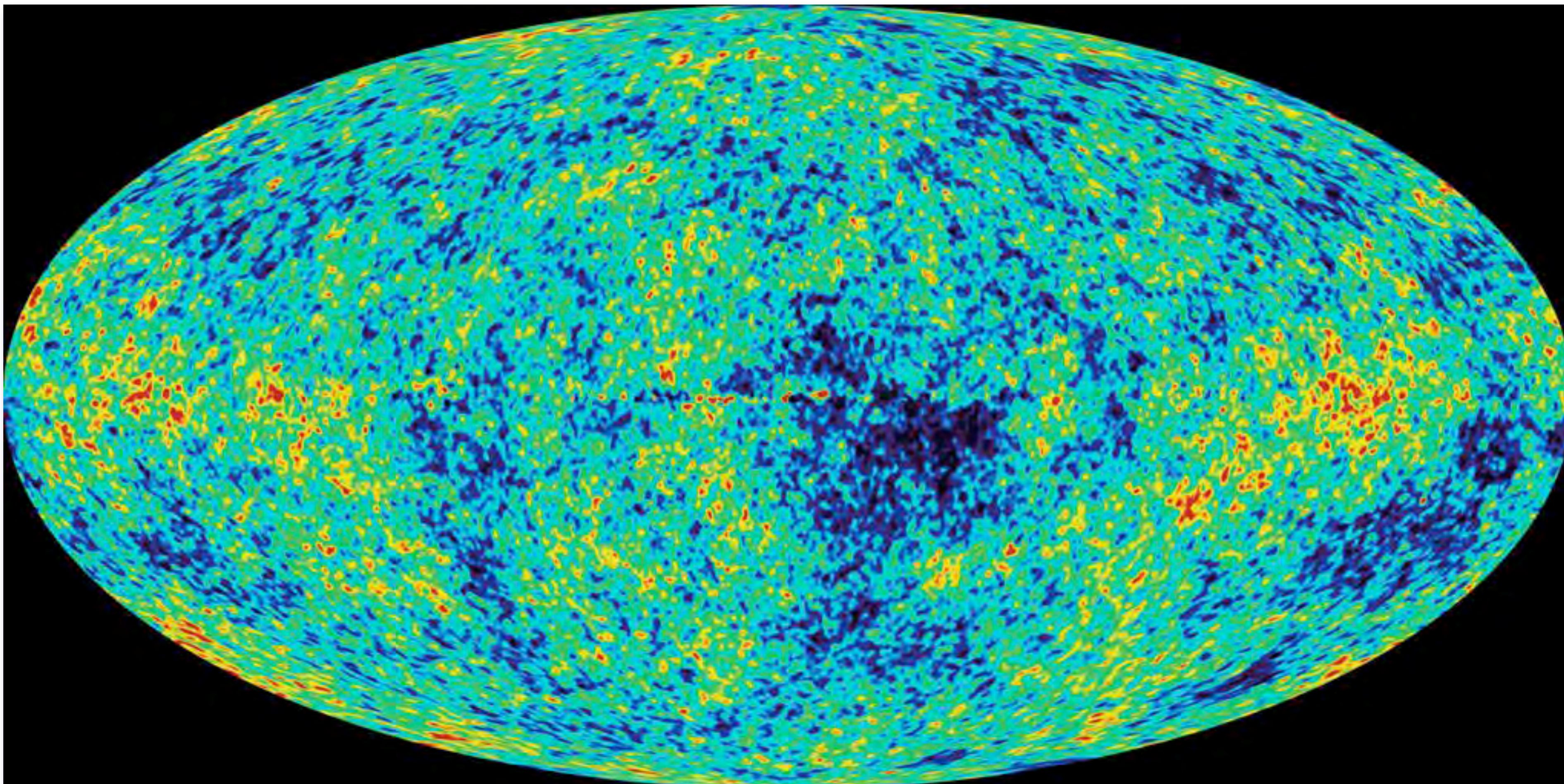


Is it science or science fiction?

1) During the last 25 years no alternative solution of many problems of the Big Bang theory have been found

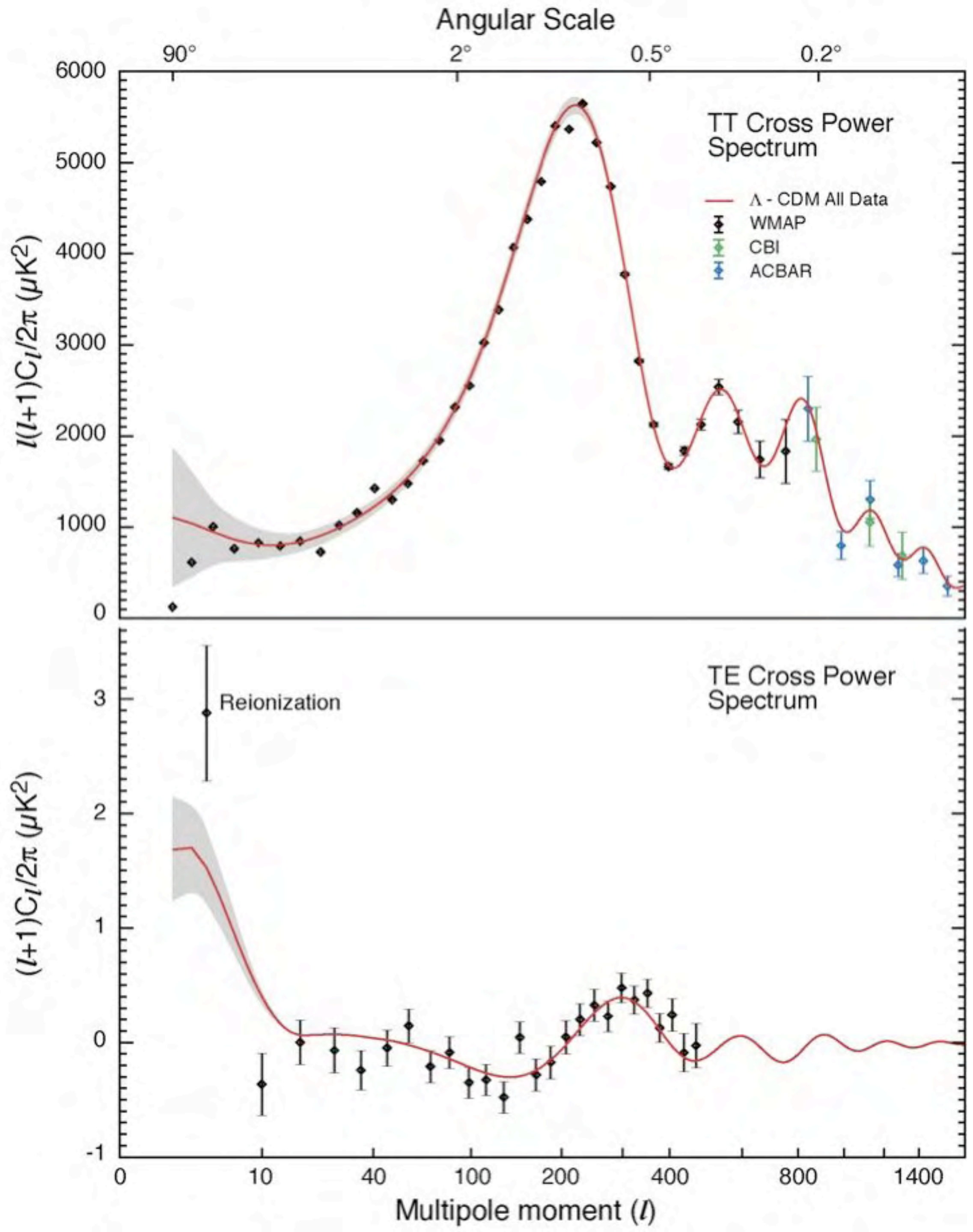
2) Many predictions of this theory have been confirmed

WMAP and the temperature of the sky



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, $n_s = 1 + O(10^{-2})$

From the Universe to the Multiverse

In realistic theories of elementary particles there are <u>many scalar fields</u>, and their potential energy has <u>many different minima</u>. 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.

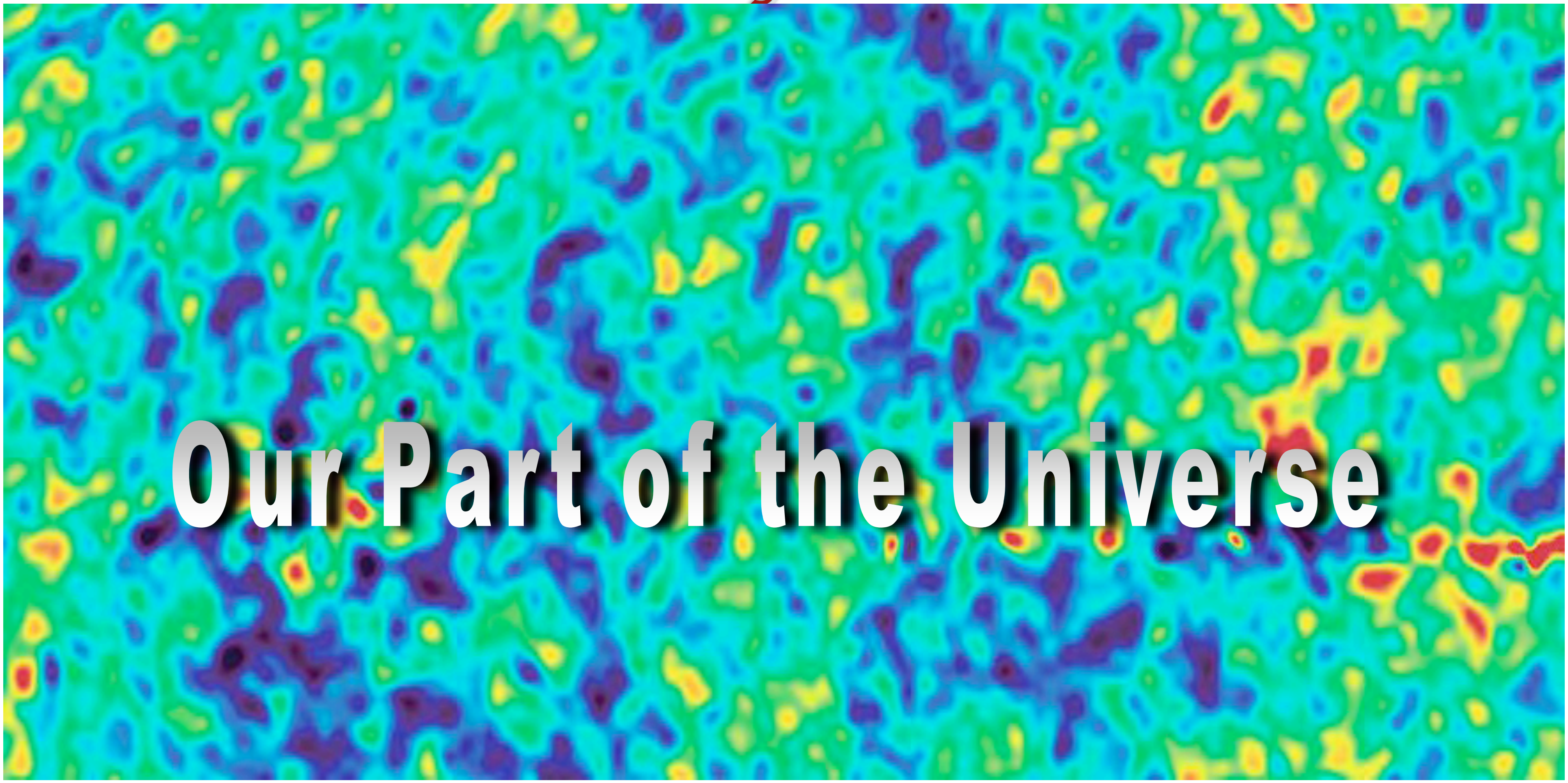
Genetic code of the Universe

There may be just **<u>one</u>** 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, **<u>altering its genetic code</u>**. Once it happens in a small part of the universe, inflation makes this part exponentially big.

This is a cosmological **<u>mutation</u>** mechanism

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



Kandinsky Universe

String Theory Landscape

Different parts of the universe may collapse and disappear, but because of eternal inflation, <u>the total energy of matter in the universe will continue to grow exponentially</u>

The universe as a whole is immortal