Reverse Engineering 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 x 10^{28} cm, in any direction. It contains about 10^{90} elementary particles. The total mass is about 10^{50} tons.

Big Bang universe at the Planck time and density

In quantum gravity it is very convenient to use system of units where

$$c = \hbar = G = 1$$

In these units, the density of matter in the expanding universe was

$$\rho \sim \frac{1}{t^2}$$

At $t < 1$, density was > O(1), and quantum fluctuations were too strong. The time $t = 1$ (or 10^{-43} seconds, in more conventional units) is called the Planck time, and the density equal to 1 (or 10^{94} g/cm^3) is called the Planck density. At that time, each part of the universe of size O(1) (Planck length ~ 10^{-33} cm) contained O(1) particles, each of them with kinetic energy O(1).

One can talk about classical space - time only at $t > 1$ and at density smaller than the Planck density.

Hard Art of the Universe Creation

According to the standard hot Big Bang universe, the total number of particles during its expansion did not change much, so the universe at the Planck time was supposed to contain about 10^{90} particles. At the Planck time t =O(1), there was one particle per Planck length ct =O(1).

Thus, at the Planck time t = 1, the whole universe consisted of 10^{90} causally connected parts of size ct =O(1). Such parts did not know about each other. If someone wanted to create the universe at the Planck time, he/she could only make **a Very Small Bang** in his/her own tiny part of the universe of a Planck size ct = O(1). **Everything else was beyond causal control**.

Is it possible to make a miracle, start with less than a milligram of matter (Planck mass), in a tiny speck of space of Planck size O(1), and produce 10^{90} particles from it?

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

"If I've made myself too clear, you must have misunderstood me."

Alan Greenspan

If something looks too good to be true...

If the universe is empty, how can one tell that it expands?

The universe with a constant positive vacuum energy V_0 is de Sitter space. It looks expanding in one system of coordinates, collapsing in another system of coordinates, and static in yet another coordinates.

If there is no preferable coordinate system in the vacuum, then there is no preferable time when the vacuum state decays. Therefore vacuum decays chaotically, and the universe becomes grossly inhomogeneous. After a year of investigation, Alan Guth and Stephen Hawking concluded that this scenario cannot be improved.

Moreover, in the original scenario, it was assumed that the universe was large from the very beginning, started its evolution in the hot Big Bang, and inflation began only at $t > 10^5$. Does not fully address the problem.

Breaking the rules

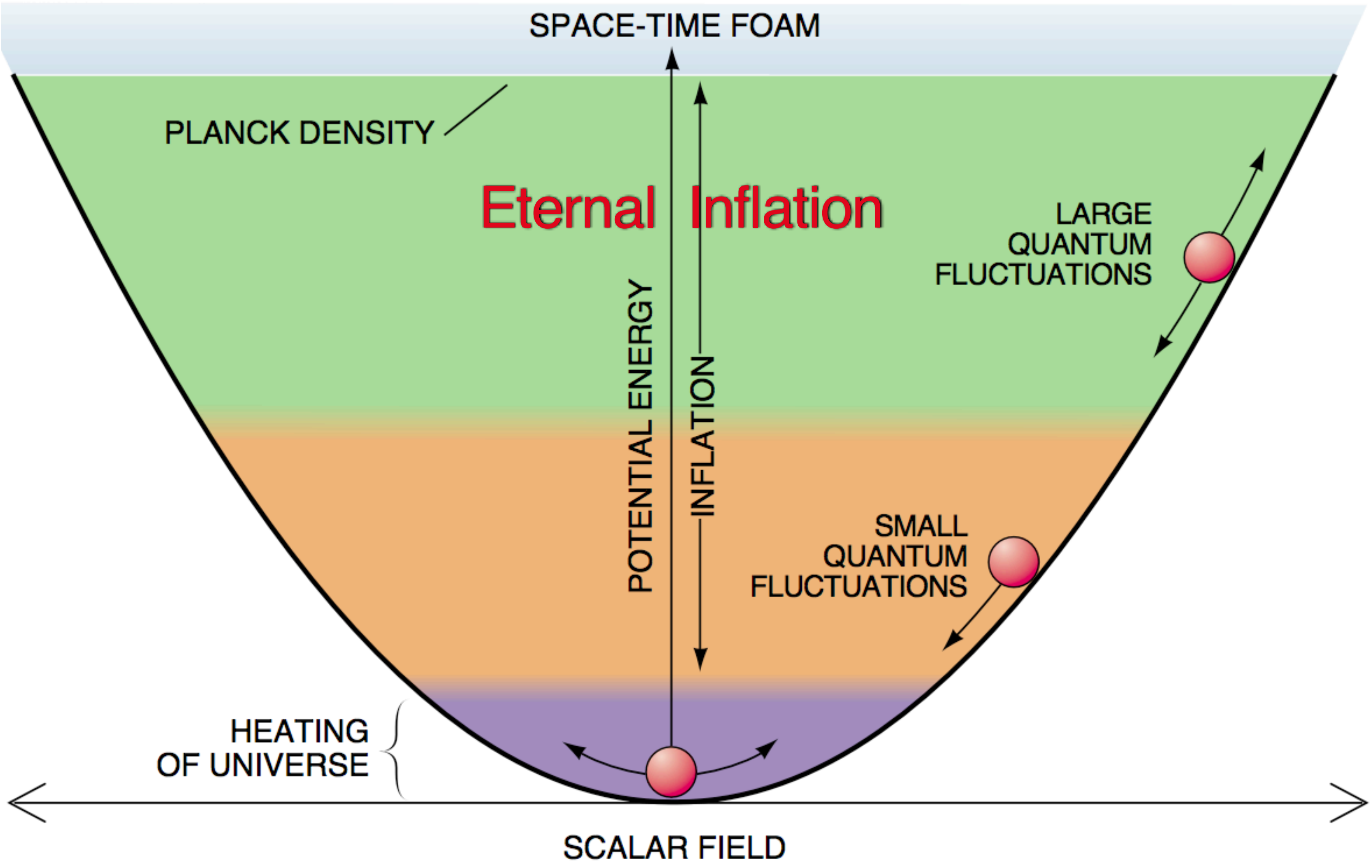
A solution was found in 1981-1983: Instead of a vacuum state with a constant vacuum energy V_0, one should consider a slowly changing scalar field with a sufficiently flat potential $V(\phi)$. If the potential is too steep – no inflation. If it is too flat – the universe becomes inhomogeneous.

And then it was realized that it is better to completely abandon the idea that the universe was born in the hot Big Bang.

The simplest inflationary model

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

AL 1983



Equations of motion:

- **Einstein equation:**

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

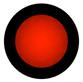
- **Klein-Gordon equation:**

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

Compare with equation for the harmonic oscillator with friction:

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

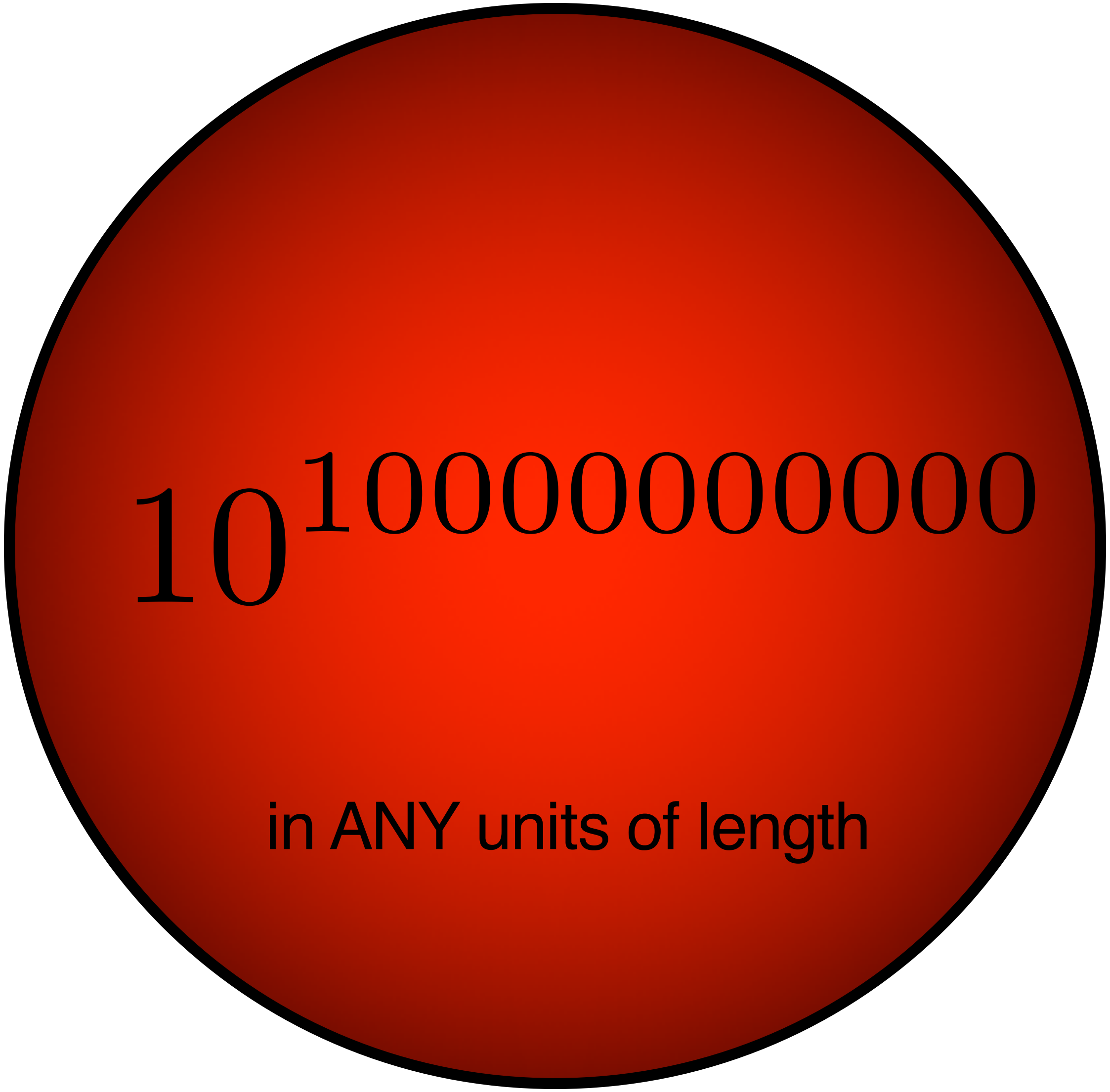
A newborn universe could be as small as 10^{-33} cm (Planck length) and as light as 10^{-5} g (Planck mass). If its energy density is dominated by V, inflation immediately begins



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

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

Inflationary universe 10^{-35} seconds old



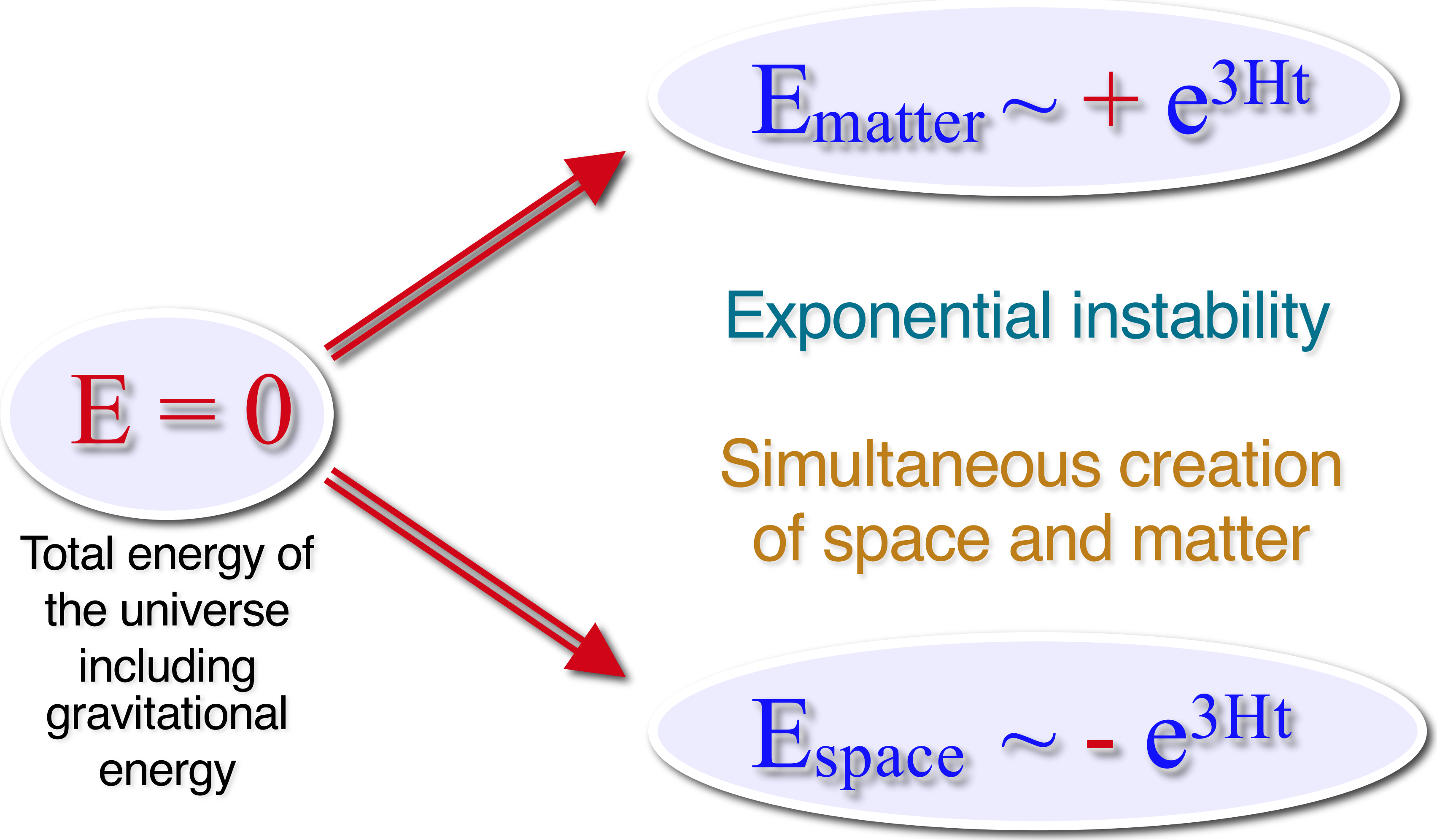
$$10^{10000000000}$$

in ANY units of length

How about energy conservation?

Energy of matter in the universe **IS NOT CONSERVED:** $dE = - p\, dV$. Volume V of an expanding universe grows, $dV > 0$, so its energy decreases if $p > 0$, and grows when $p < 0$.

For a slowly rolling scalar field one has $p < 0$, i.e. $dE > 0$.



$E = 0$

Total energy of the universe including gravitational energy

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

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 eternal inflation.

Origin of structure:

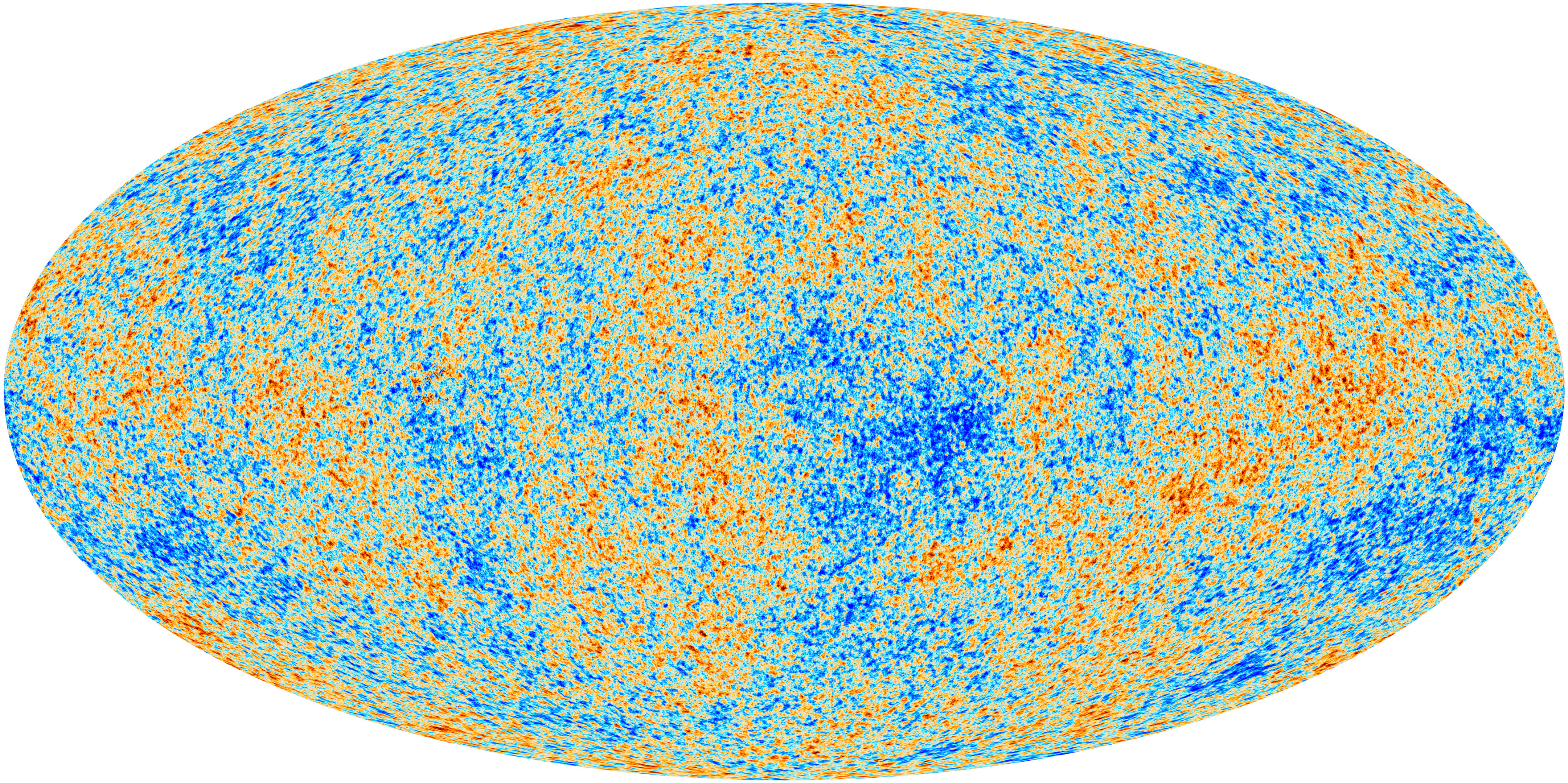
In this theory, original inhomogeneities are stretched away, but new ones are produced from **quantum fluctuations,** which are amplified and stretched exponentially during inflation.

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

Mukhanov and Chibisov 1981

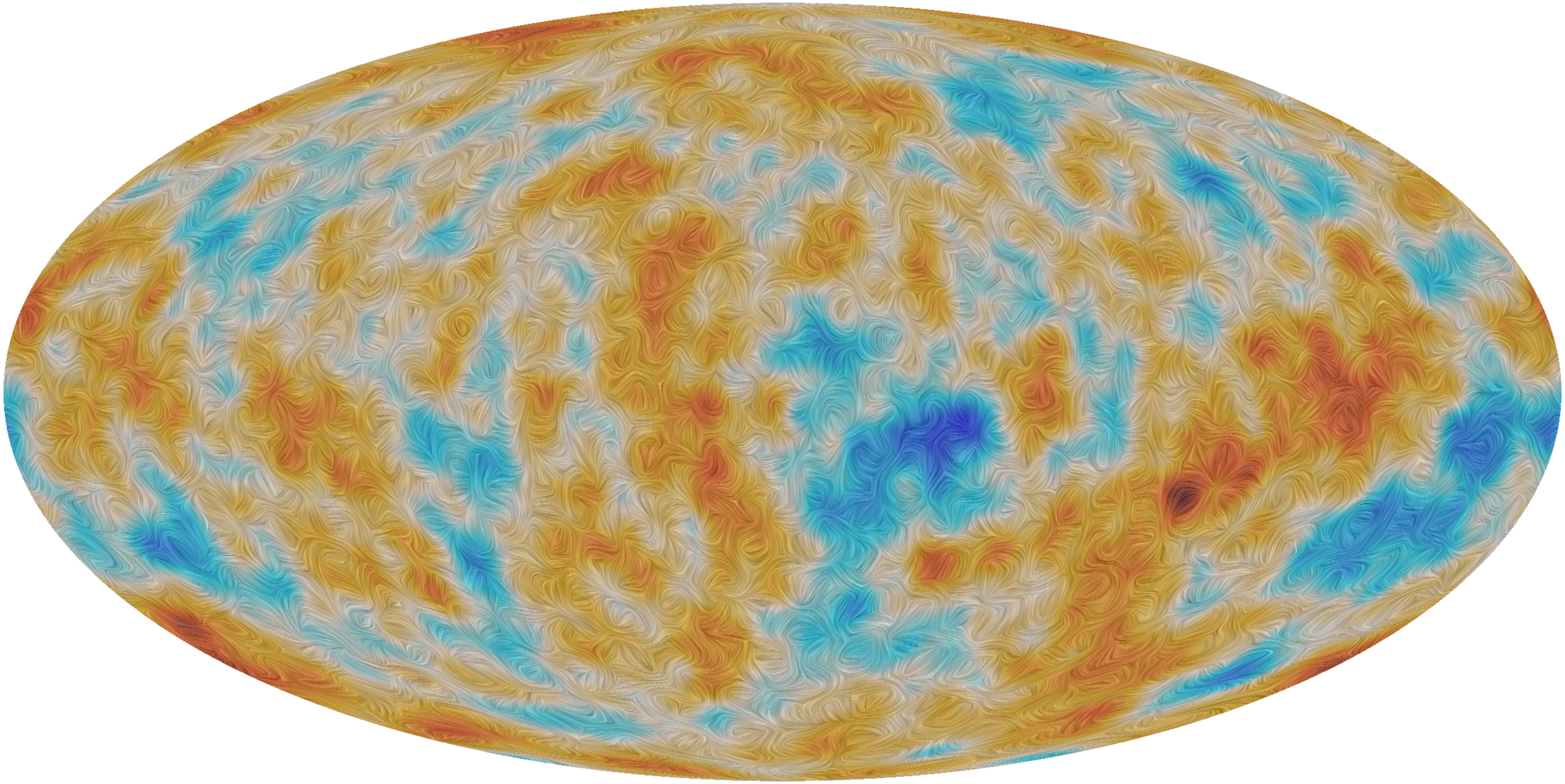
Planck 2013: Perturbations of temperature

This is an image of quantum fluctuations produced 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!!!

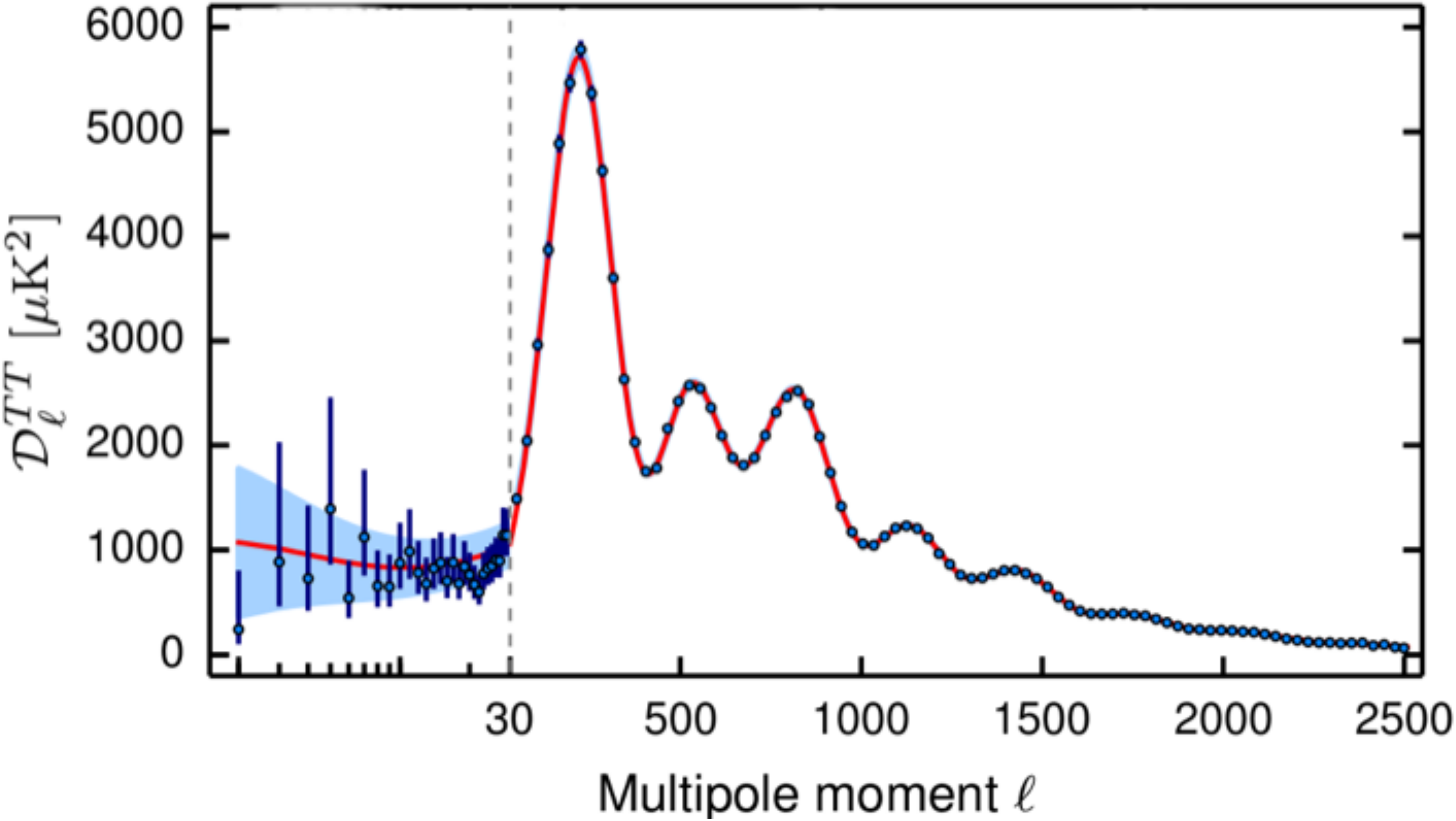


Planck 2015: Perturbations of polarization

E-modes



Planck 2015: TT spectrum (blue dots) and predictions of inflationary theory (red line)



Inflation and Planck2015

$$\Omega = 1 \pm 0.005$$

Universe is flat with accuracy 10^{-2}

$$n_s = 0.968 \pm 0.006$$

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

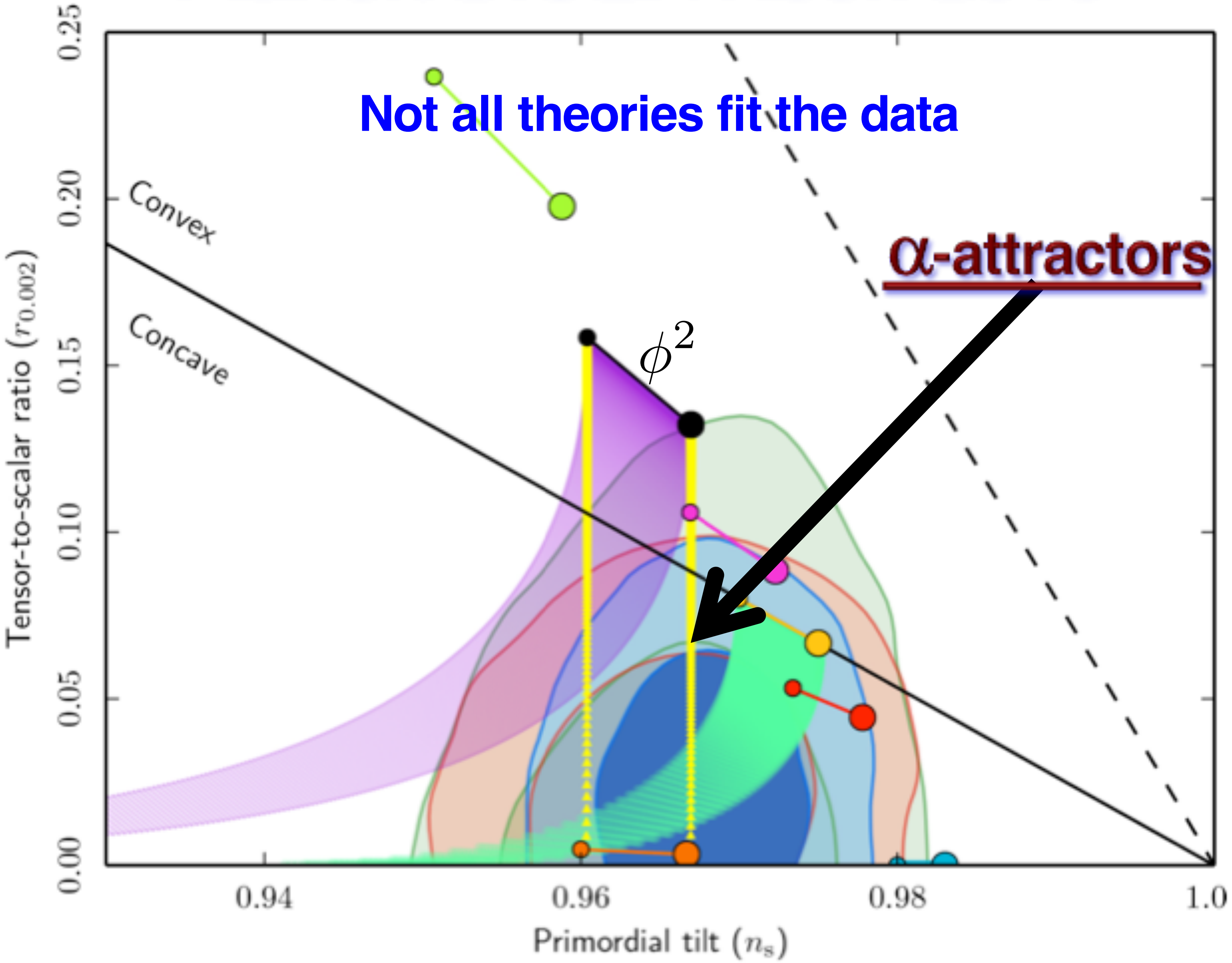
Can we test inflation even better ?

1) Yet another Planck data release is expected shortly.

2) **B-modes**: a special polarization pattern which can be produced by gravitational waves generated during inflation. A discovery of the gravitational waves of this type (BICEP/Keck and other experiments) could provide a strong **additional** evidence in favor of inflation.

A non-discovery is fine too: many inflationary models predict a very small amplitude of the gravitational waves.

Planck/BICEP/Keck 2015



What is the meaning of α-attractors?

Kallosh, AL, Roest 2014

Start with the simplest chaotic inflation model

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\partial\phi^2 - \frac{1}{2}m^2\phi^2$$

Modify its kinetic term (natural in SUGRA, talk by Kallosh)

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\underline{\frac{\phi^2}{6\alpha}})^2} - \frac{1}{2}m^2\phi^2$$

Switch to canonical variables $\phi = \sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}}$

The potential becomes

$$V = 3\alpha\, m^2 \tanh^2\frac{\varphi}{\sqrt{6\alpha}}$$

The essence of α-attractors

Galante, Kallosh, AL, Roest 1412.3797

$$\frac{1}{2}R - \frac{3}{4}\alpha\left(\frac{\partial t}{t}\right)^2 - V(t)$$

Suppose inflation takes place near the pole at t = 0, and V(0) > 0, V'(0) >0, and V has a minimum nearby. Then in canonical variables

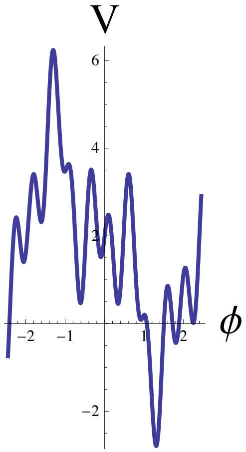
$$\frac{1}{2}R - \frac{1}{2}(\partial\varphi)^2 - V_0(1 - e^{-\sqrt{\frac{2}{3\alpha}}\varphi} + \ldots)$$

Then in the leading approximation in 1/N, for any non-singular V

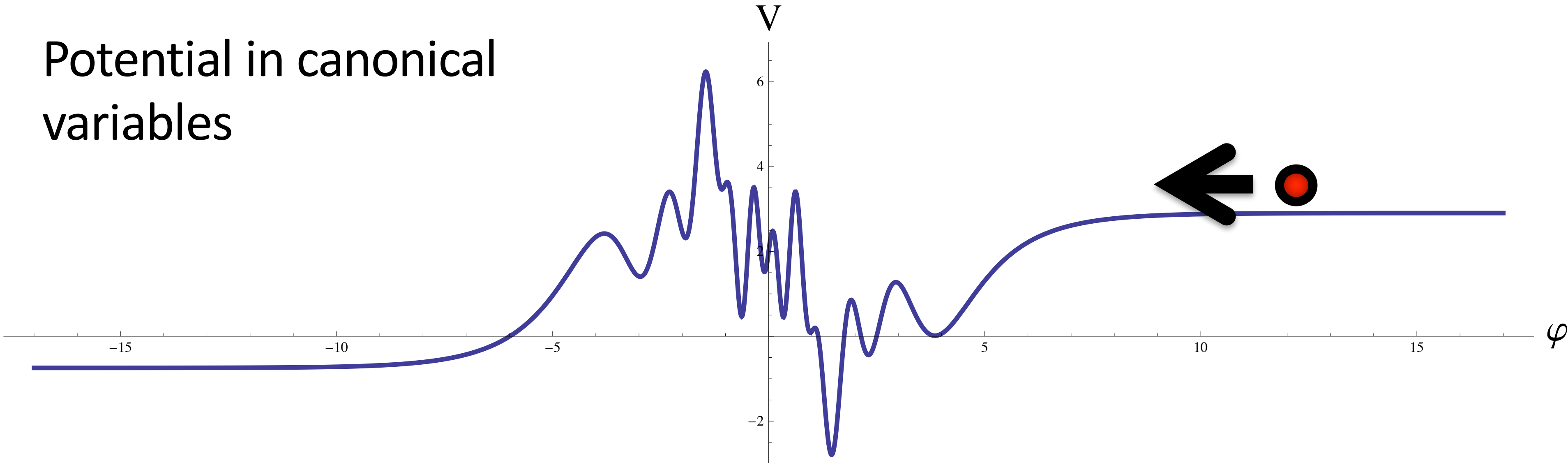
$$n_s = 1 - \frac{2}{N}, \qquad r = \alpha\frac{12}{N^2}$$

Stretching and flattening of the potential is similar to stretching of inhomogeneities during inflation

Potential in the original variables of the conformal theory



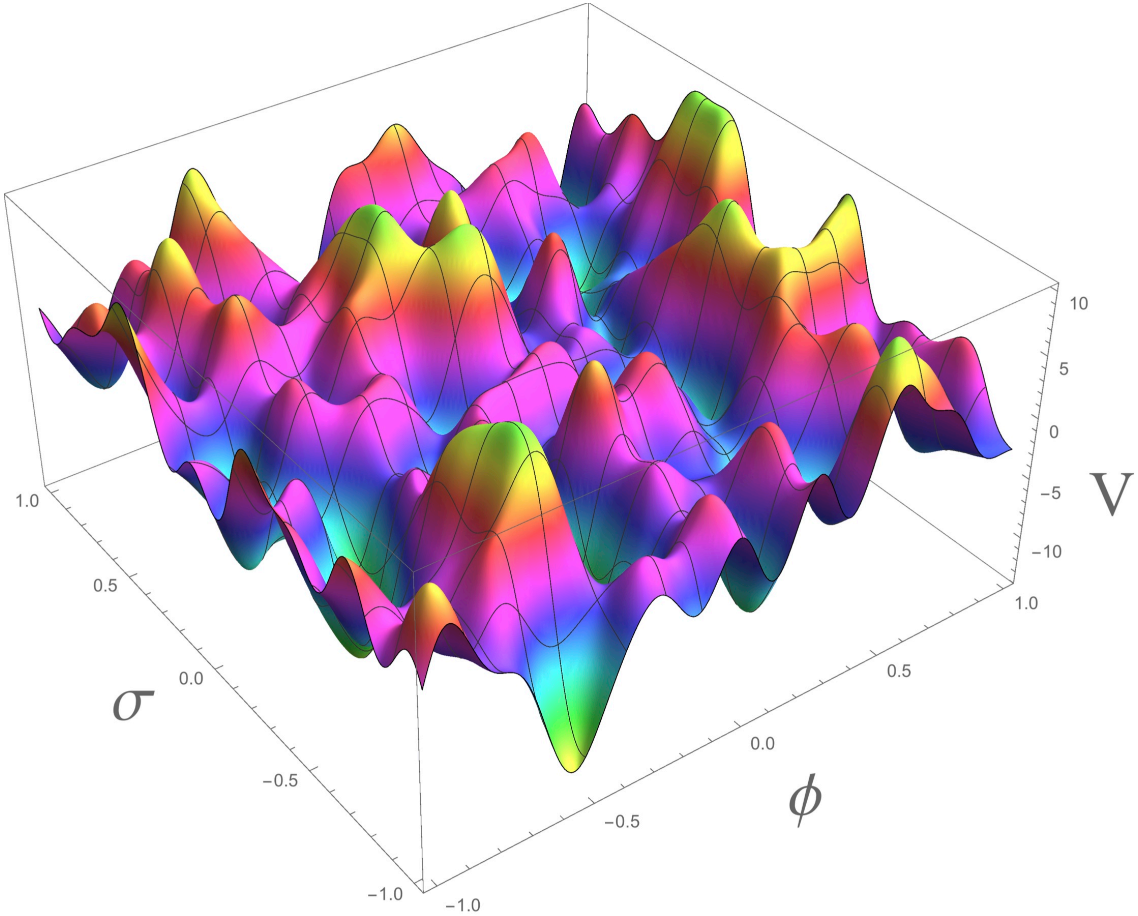
Potential in canonical variables



Inflation **in** the landscape is facilitated by inflation **of** the landscape

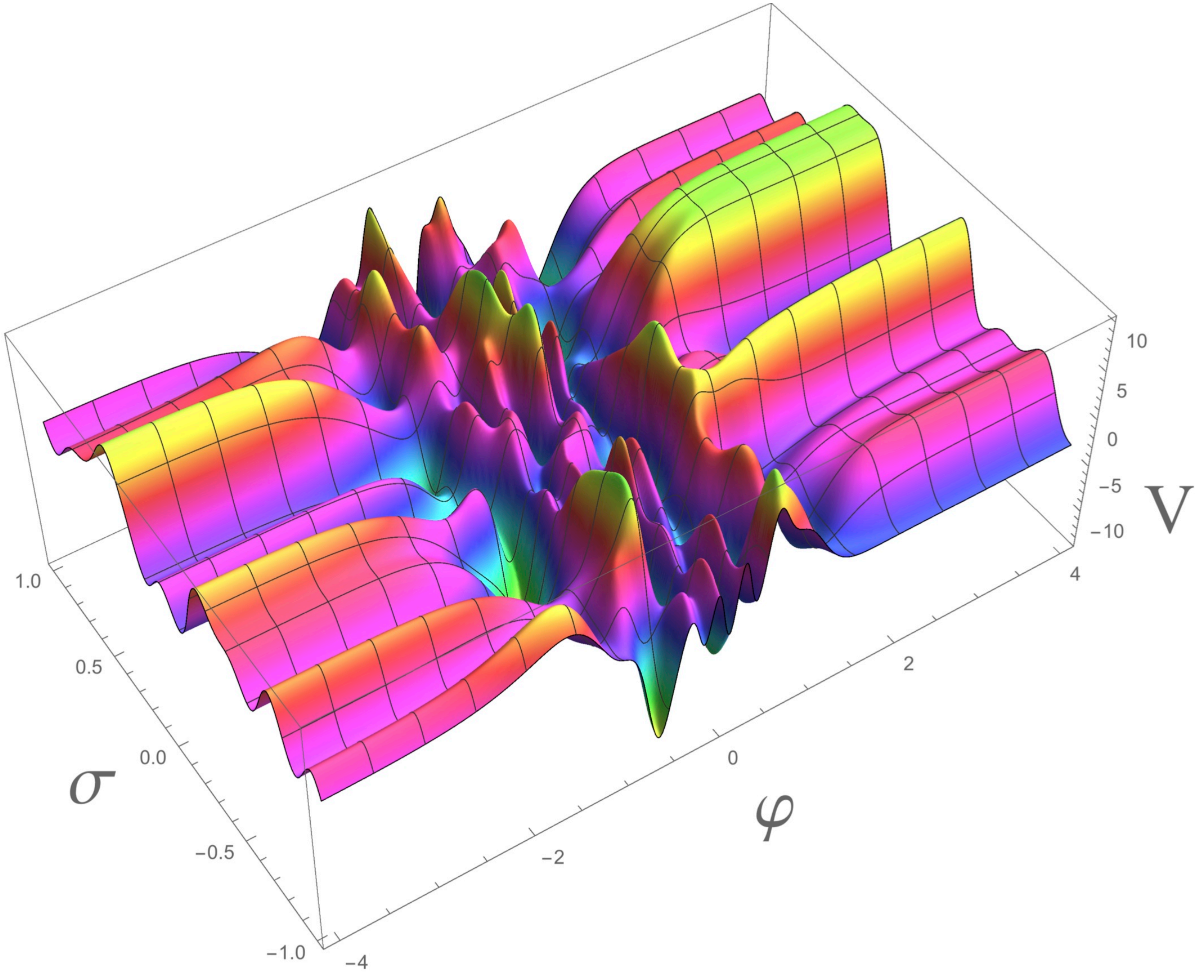
Inflation in Random Potentials and Cosmological Attractors

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{R}{2} - \frac{(\partial_\mu \phi)^2}{2(1-\frac{\phi^2}{6\alpha})^2} - \frac{(\partial_\mu \sigma)^2}{2} - V(\phi, \sigma)$$



In terms of canonical fields φ with the kinetic term $\frac{(\partial_\mu \varphi)^2}{2}$, the potential is

$$V(\varphi, \sigma) = V(\sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}}, \sigma)$$

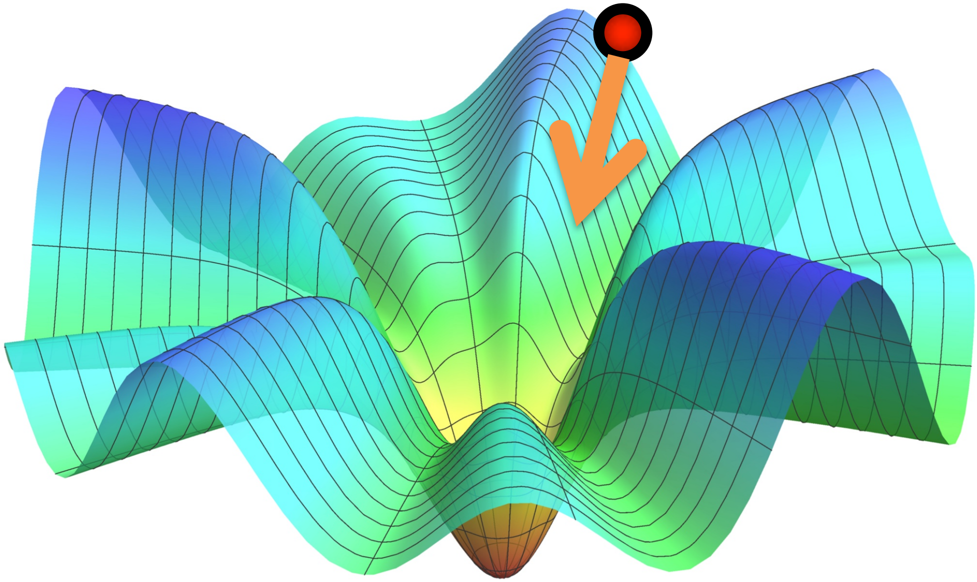


α-attractor mechanism makes the potentials flat, which makes inflation possible, which, in its turn, makes the universe flat

Multifield α-attractor

New model with axion shift symmetry in the geometry, broken by the potential

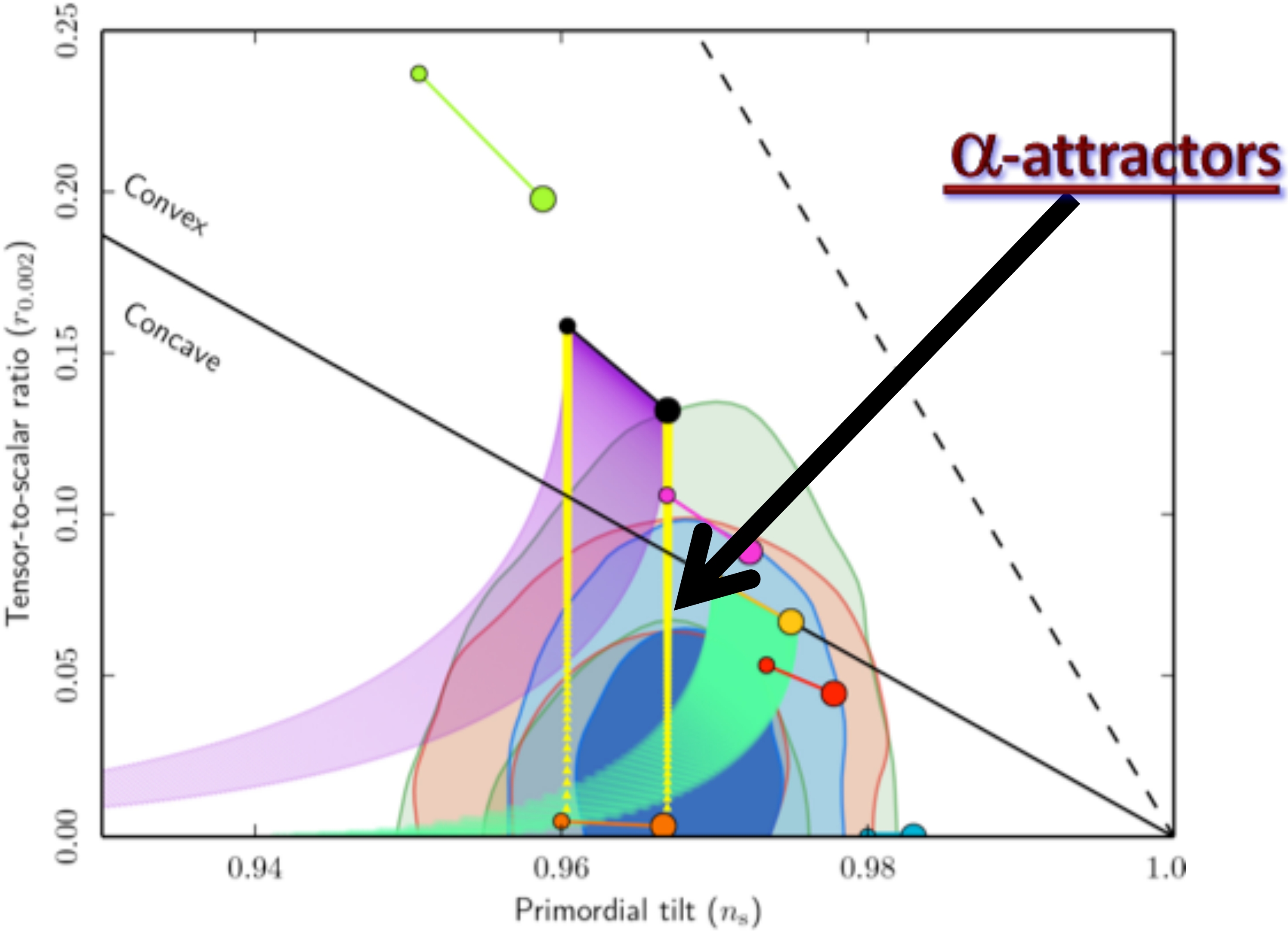
$$Z = e^{i\theta} \tanh \frac{\varphi}{\sqrt{2}} \qquad g^{-1}\mathcal{L} = \frac{1}{2}(\partial\varphi)^2 + \frac{1}{4}\underline{\sinh^2(\sqrt{2}\varphi)}(\partial\theta)^2 - V(\varphi,\theta)$$



Surprize! *rolling on the ridge* with almost constant θ

θ does not seem to move because physical distance in angular direction during inflation is exponentially large, proportional to $\sinh\sqrt{2}\varphi \sim e^{\sqrt{2}\varphi}$

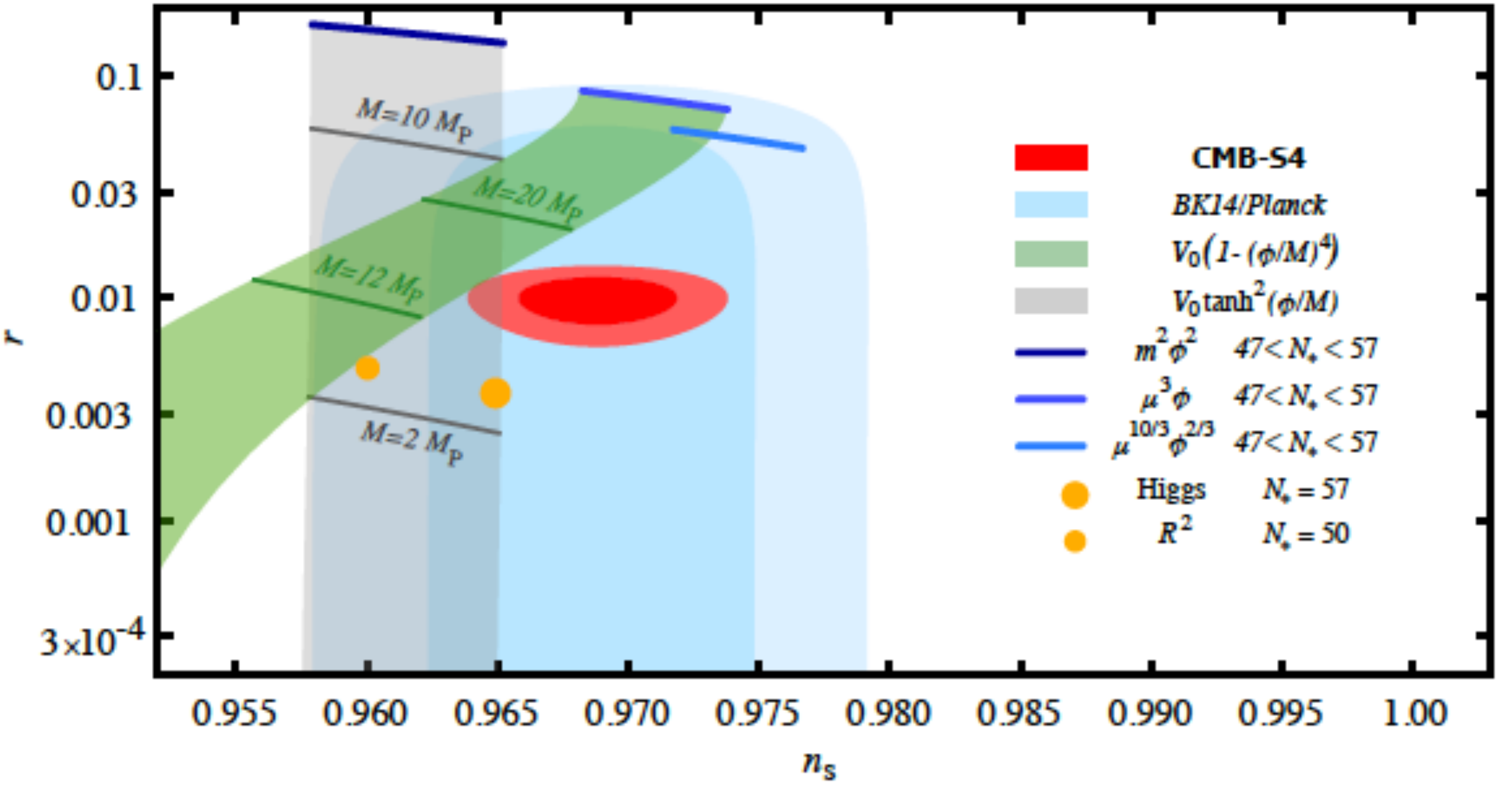
Predictions of α-attractors are very stable with respect to their modifications

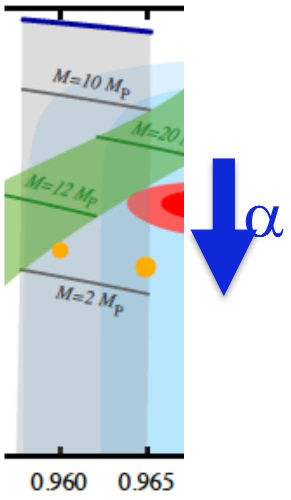


α-attractors and B-mode targets

to be discussed by Kallosh

CMB-S4





$$\boxed{n_s = 1 - \frac{2}{N}\,, \qquad r = \alpha\,\frac{12}{N^2}}$$

Can we see the moment of creation?

In the old Big Bang theory, by looking at the sky we were looking back in time, all the way to the Big Bang. Gravitational waves could come to us directly from the Big Bang – one could see the singularity.

In inflationary theory, we can study only the last stages of inflation, when the density of the universe was about 9 orders below the Planck density. Indeed, there is a relation between the tensor to scalar ratio

$$r \approx 3 \times 10^7\ V$$

According to BICEP – Keck data, r < 0.07 or so, which means that V < 10^{-9} at the edge of visibility. To see what happen at V = O(1) one would need to look beyond the horizon. These are bad news and good news simultaneously.

Too bad, we will never see the moment of creation. But this also means that **the absence of full knowledge of the processes near the cosmological singularity should not affect the basic features of inflation.**

The limits of classical cosmology

But there is something else. By observing our part of the universe and playing the movie back, we would see galaxies moving closer to each other, particles collide, but we would never see 10^{90} particles merge into nothing and disappear, we would never see their origin in a vacuum-like state containing no particles at all.

Indeed, **all particles were produced in the process of reheating after inflation**. This is an irreversible quantum mechanical process.

Remember the Schrodinger cat

Two consistent movies with one common element:

in the beginning, there was a cat

More about related issues - in talk by Nomura

The Universe is similar to the Schrodinger cat, but without the cat to start with…

By playing the "movie" back, we would expect to see 10^{90} elementary particles all the way back to the Big Bang. But in inflationary cosmology everything could be born from a tiny Planck-size domain with **no particles at all**. All particles and galaxies were born due to quantum effects during or after inflation.

Dreams of a Final Theory

I would like to state a theorem which at present can not be based upon anything more than a faith in the simplicity, i.e. intelligibility, of nature: There are no arbitrary constants… that is to say, nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory).

Albert Einstein
Autobiographical Notes, 1949

One of the main goals of inflationary cosmology was to explain why the universe is everywhere the same, and thus to realize at least some part of Einstein's dream.

And we were in for a surprise…

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.

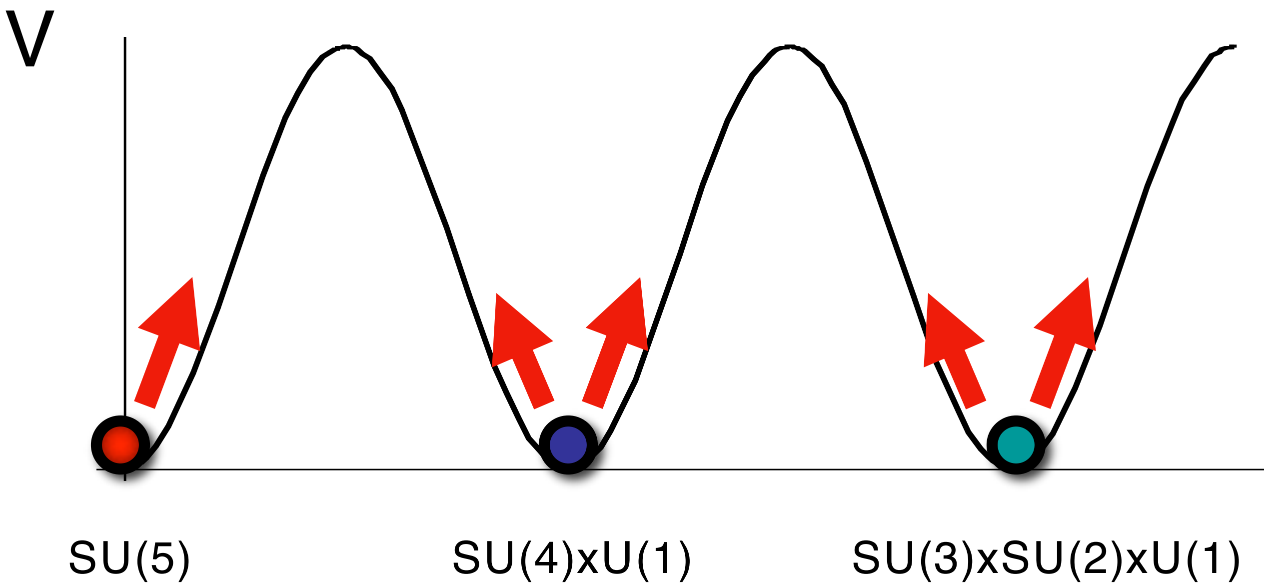
I'd rather be an optimist and a fool than a pessimist and right. Albert Einstein

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.

Example: SUSY landscape

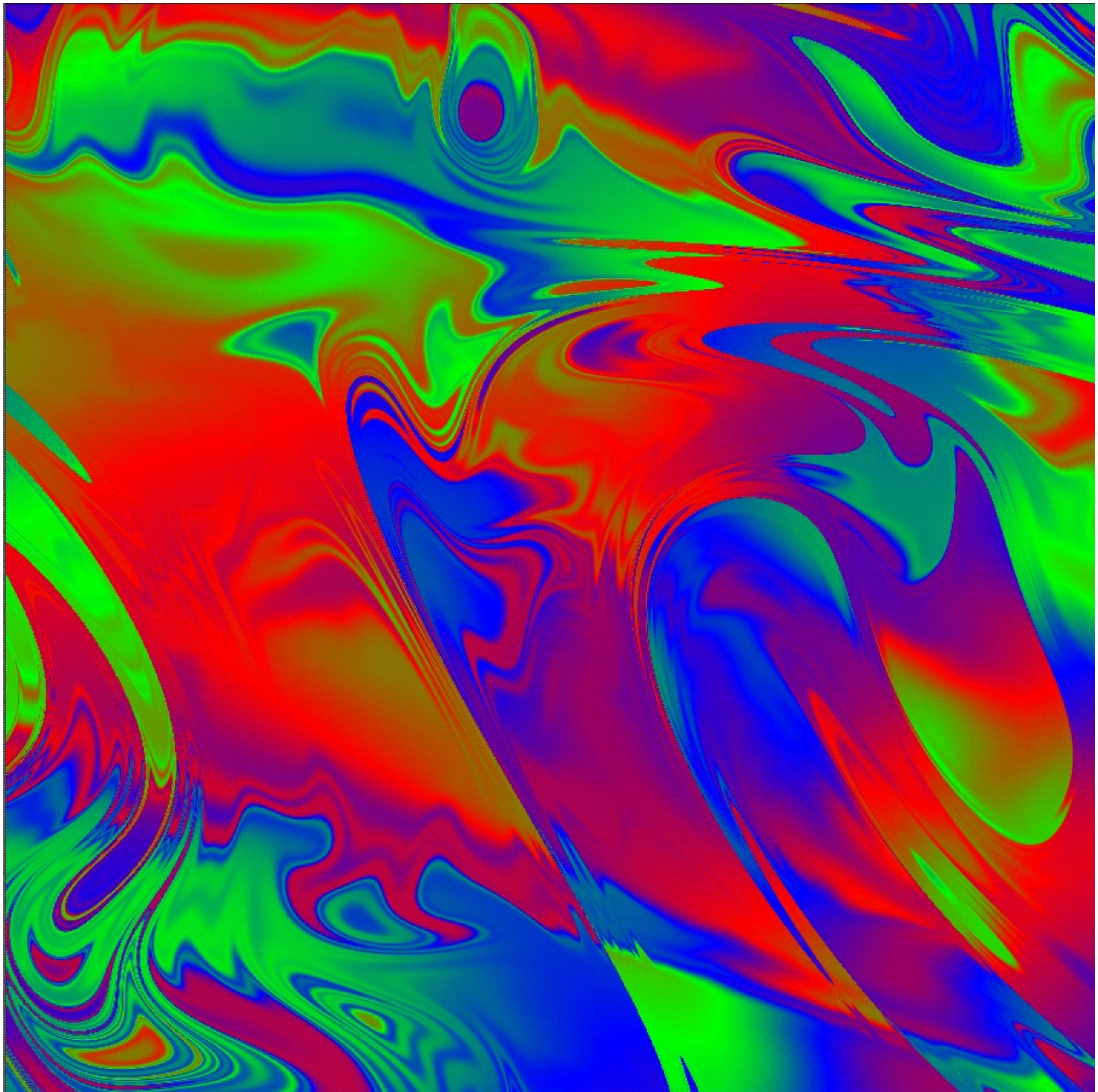
Supersymmetric SU(5)



Weinberg 1982: Supersymmetry forbids tunneling from SU(5) to SU(3)xSU(2)XU(1). This implied that we cannot break SU(5) symmetry.

A.L. 1983: Inflation solves this problem. Inflationary fluctuations bring us to each of the three minima. Inflation make each of the parts of the universe exponentially big. We can live only in the SU(3)xSU(2)xU(1) minimum.

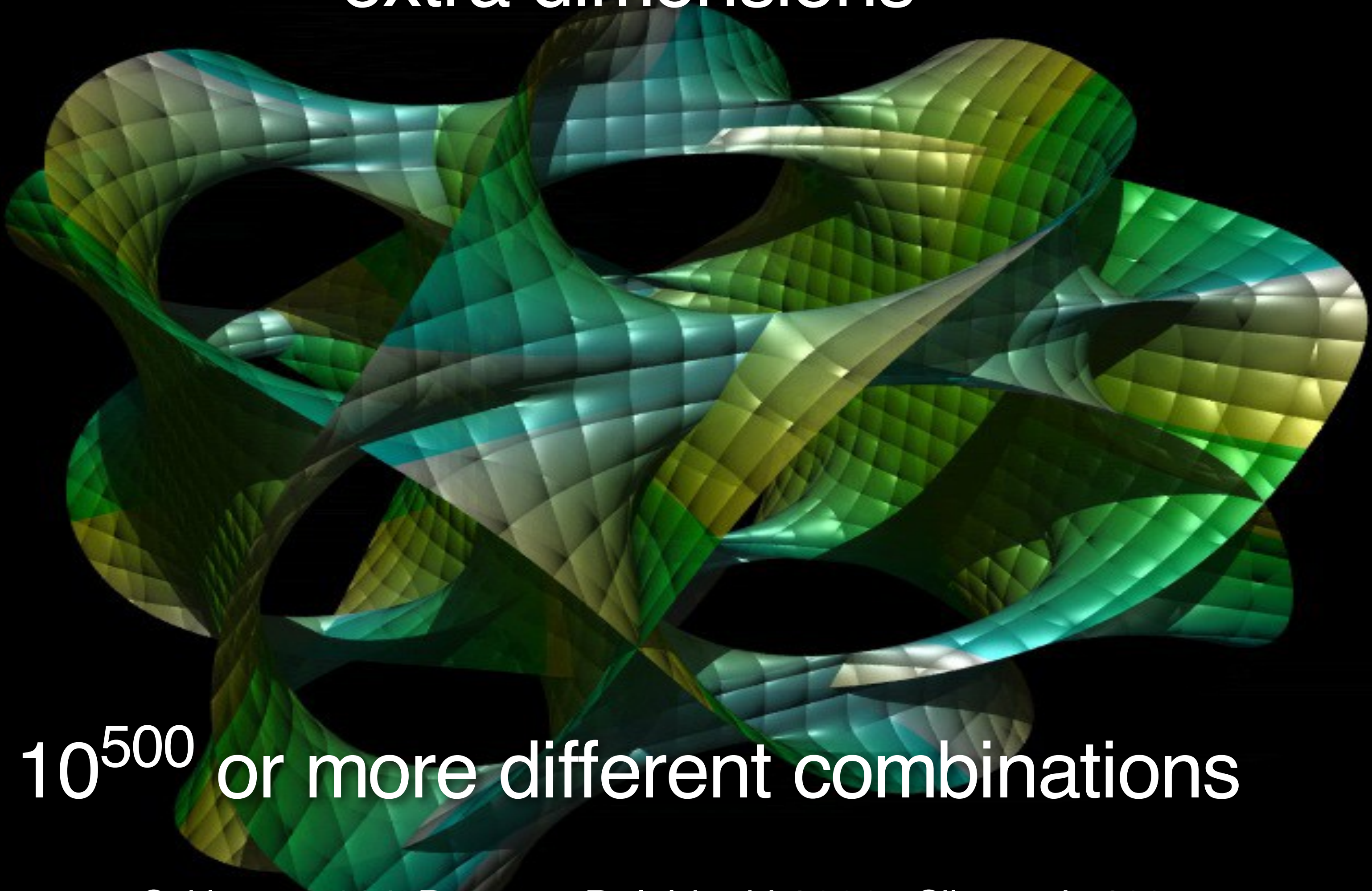
Kandinsky Universe



This allows us to justify the anthropic principle:

We live in those parts of the multiverse where we can live.

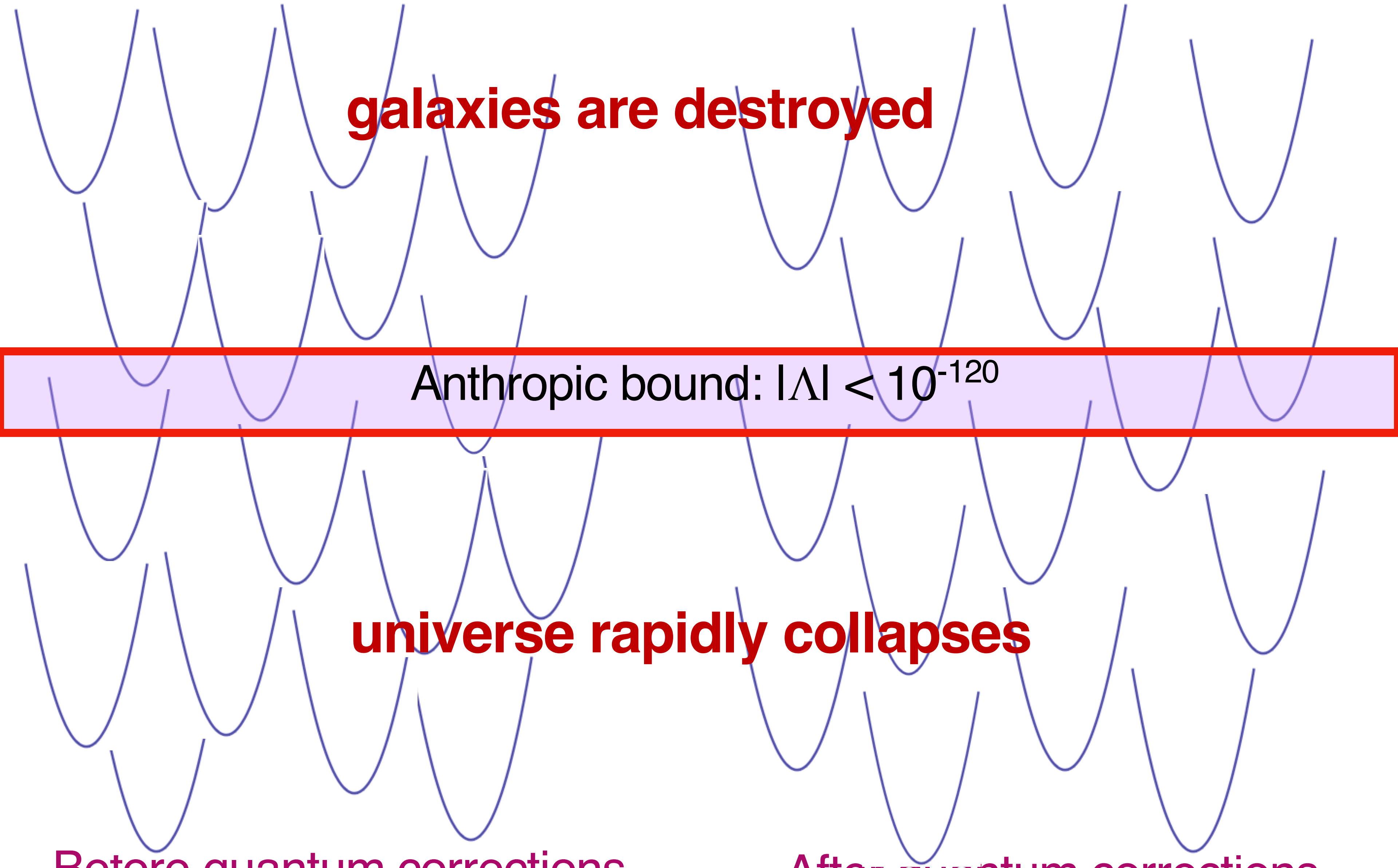
In string theory, genetic code of the universe is written in properties of compactification of extra dimensions



10^{500} or more different combinations

Sakharov 1984; Bousso, Polchinski 2000; Silverstein 2001;
Kachru, Kallosh, AL, Trivedi, 2003; Douglas 2003, Susskind 2003

Vacuum energy in string theory



galaxies are destroyed

Anthropic bound: $|\Lambda| < 10^{-120}$

universe rapidly collapses

Before quantum corrections

After quantum corrections

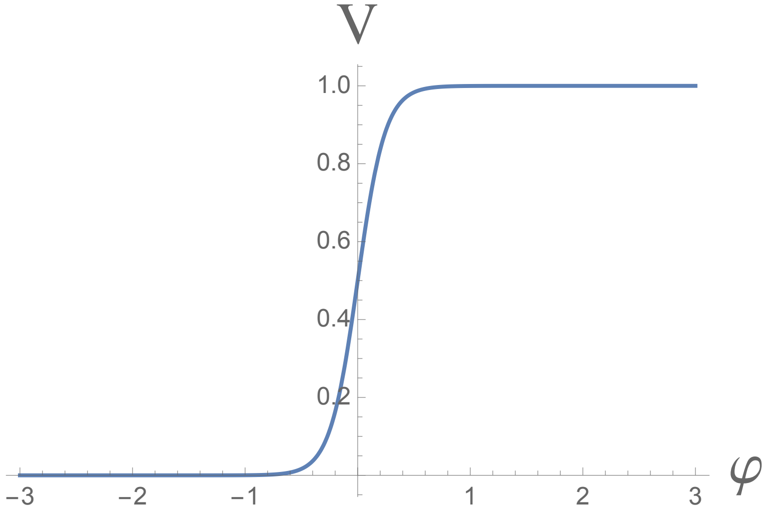
Quintessence in string landscape?

α-attractor version of the simplest linear dark energy potential

$$V(\phi) = \gamma\phi + \Lambda$$

In terms of the canonically normalized field φ, this potential is

$$V(\varphi) = \gamma\sqrt{6\alpha}(\tanh\frac{\varphi}{\sqrt{6\alpha}} + 1) + \Lambda$$



Can describe inflation and dark energy for α ~ 10^{-2}

Akrami, Kallosh, AL, Vardanyan 1712.09693

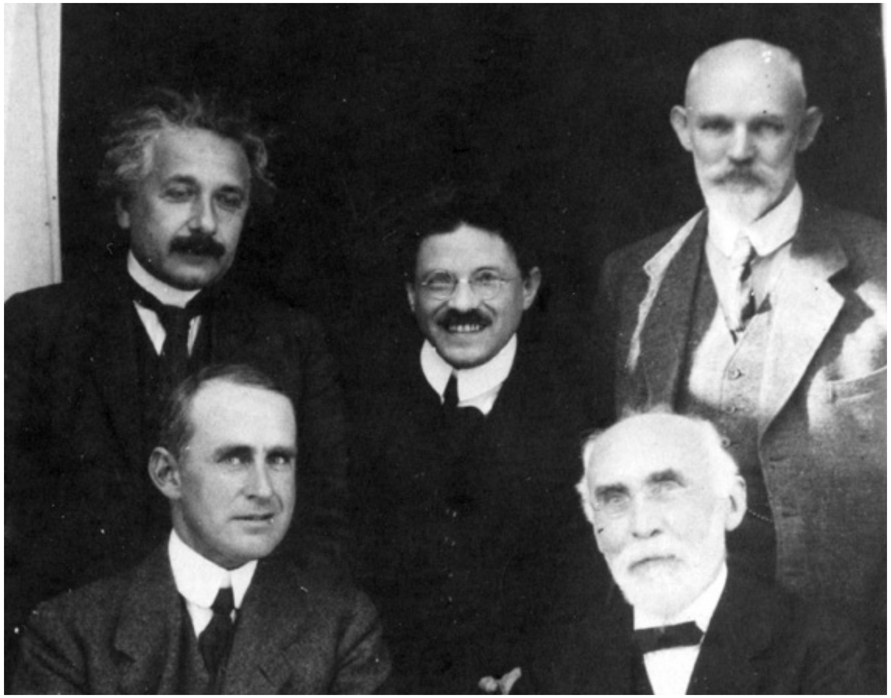
Why do we live in a 4-dimentional space-time?

P. Ehrenfest, Proc. Amsterdam Acad. 20, 200 (1917)

In space-time of dimension d > 4, planetary systems and atoms are unstable. For d < 4, in general theory of relativity there is no gravitational attraction between distant bodies, so planetary systems cannot exist. That is why can live only is space-time with d = 4.

Einstein

Eddington



de Sitter

Lorentz

Ehrenfest

Leiden Observatory, 1923

Why do we live in a 4-dimentional space-time?

P. Ehrenfest, Proc. Amsterdam Acad. 20, 200 (1917)

Back in 1917, this could seem just a mathematical curiosity: Our space has d=4; we simply do not have any other choice.

However, according to most popular versions of string theory, our world fundamentally is 10-dimensional, but some of these dimensions are tiny, compactified. In general, one could end with space-time of any dimension d, which would grow exponentially large due to inflation. We can live only in the parts of the world where the compactification produces space-time with d = 4.

Thus the observation made by Ehrenfest in 1917, in Leiden, in combination with string theory constructions developed in the beginning of this century, explains why we live in space-time with d = 4.

Can we test the multiverse theory ?

This theory provides **the only known explanation of numerous experimental results** (extremely small vacuum energy, the number of dimensions of space, 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

Can we still return to the old concept of a single universe?

In order to propose a true alternative to the theory of inflationary multiverse one should achieve several incredibly difficult goals:

One should propose an alternative to inflation and string theory.

One should explain why only one vacuum of string theory can actually exist and all other 10^{500} vacua are forbidden.

One should find an alternative solution of the cosmological constant problem and many other coincidence problems.

Any suggestions?

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

There is only one thing which is more unreasonable than the unreasonable effectiveness of mathematics in physics, and this is the unreasonable ineffectiveness of mathematics in biology.

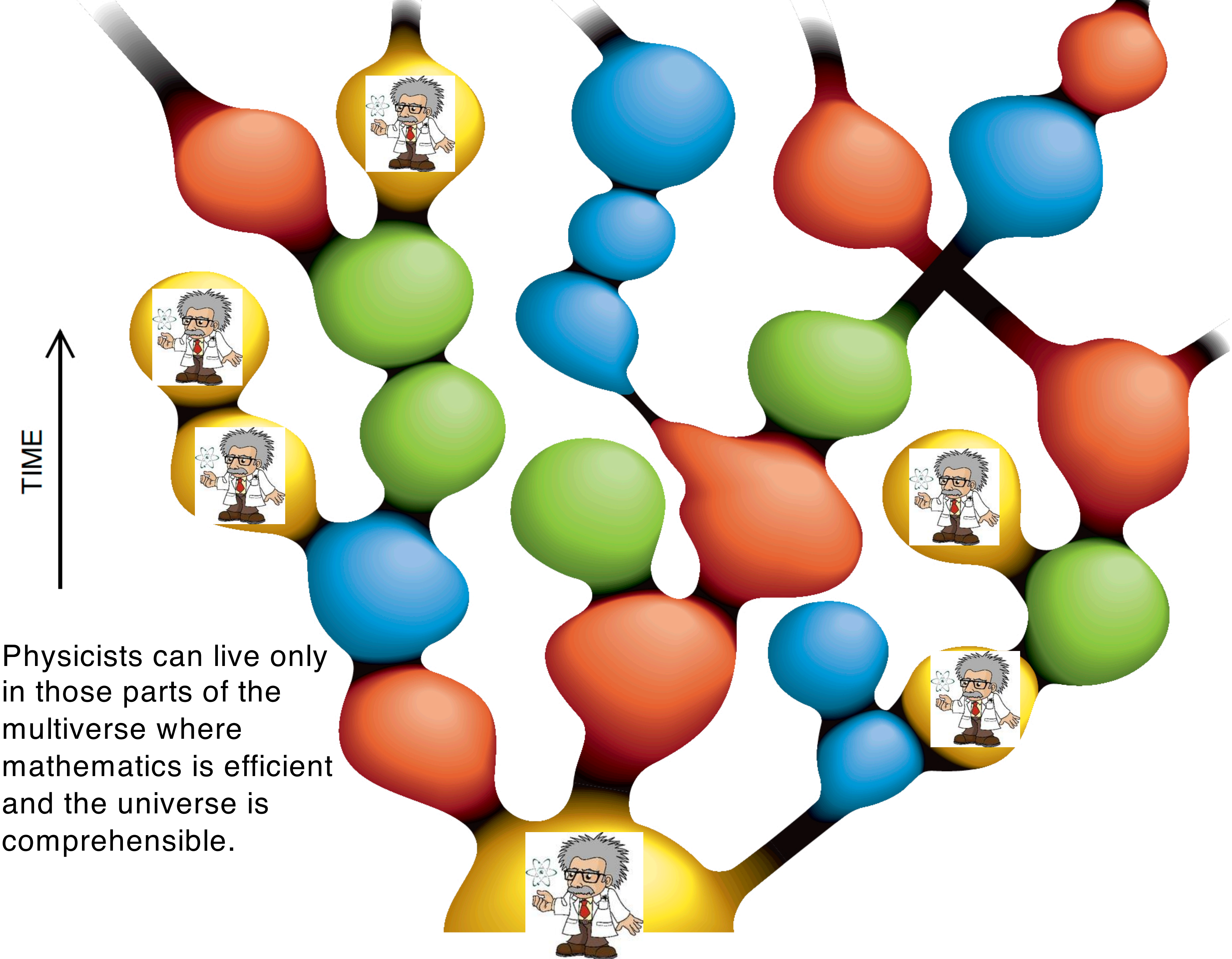
Israel Gelfand

The reason why Einstein was puzzled by the efficiency of physics and Wigner was puzzled by the efficiency of mathematic is very simple:

If the universe is everywhere the same (no choice), then the fact that it obeys so many different laws that we can discover, remember and use can be considered as an "undeserved gift of God" to physicists and mathematicians.

In the inflationary multiverse, this problem disappears. The laws of mathematics and physics are efficient only if they allow us to make reliable predictions. The possibility to make reliable predictions is necessary for our survival. There are some parts of the multiverse where information processing is inefficient; we cannot live there.

We can only live in those parts of the multiverse where the laws of mathematics and physics allow stable information processing and reliable predictions. That is why physics and mathematics are so efficient **in our part of the multiverse**.



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