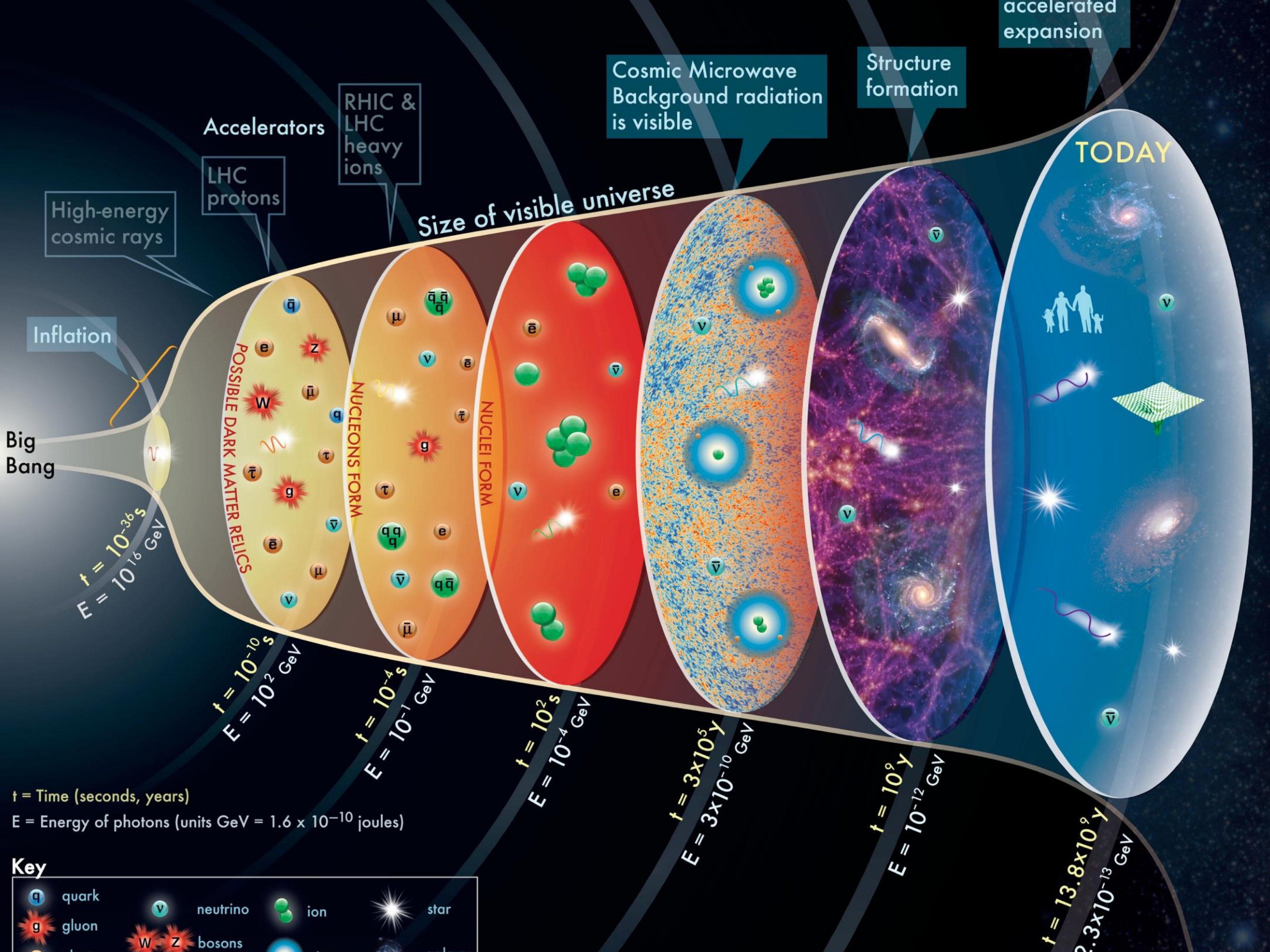
Reverse Engineering of the Universe

Andrei Linde



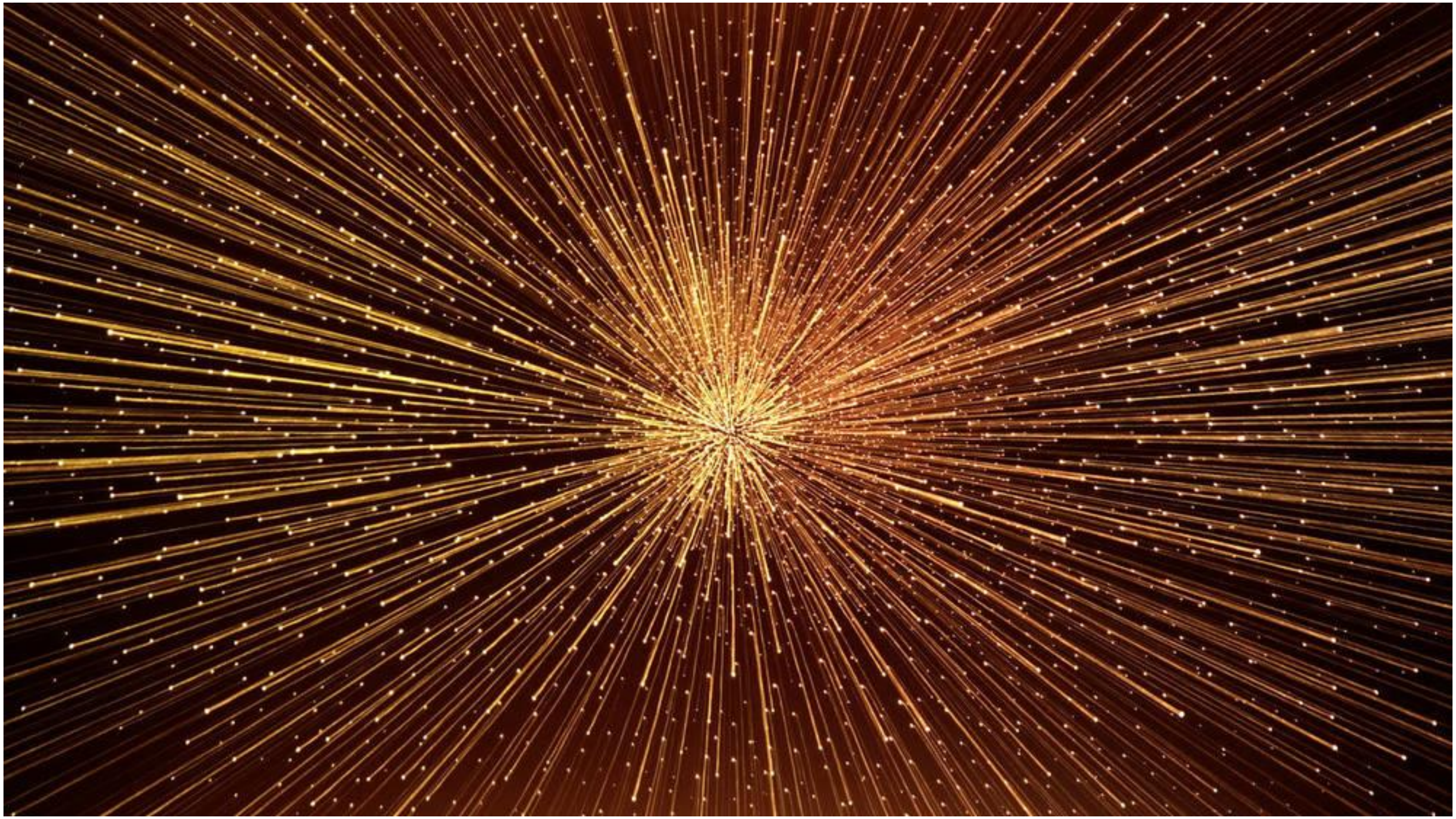
t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6×10^{-10} joules)

Why do we need inflation?

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 greater than 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

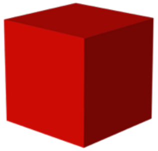
According to the standard hot Big Bang universe, the total number of particles during its expansion did not change much, so the universe at the Planck time was supposed to contain about 10^{90} particles. At the Planck time t =O(1), there was one particle per Planck length ct =O(1).

Thus, at the Planck time t = 1, the whole universe consisted of 10^{90} parts of size ct =O(1). These parts did not know about each othe because the distance between them was greater than ct =O(1). 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 the Planck size ct = O(1). **Everything else was beyond causal control.**

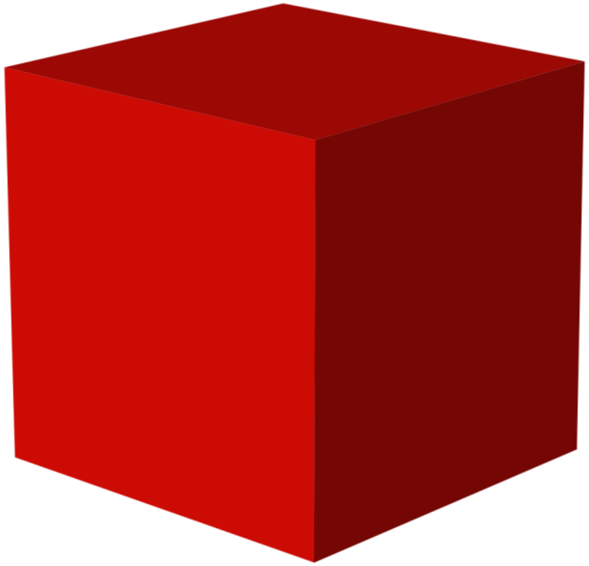
Is it possible to make a miracle, start with less than a milligram of matter (Planck mass), in a tiny speck of space of Planck size O(1), and produce 10^{90} particles from it?

Standard Big Bang cosmology:

Take a box with 1000 protons



In an expanding universe this box grows in size



After expansion it still contains 1000 protons, far away from each other

Problems of the Big Bang theory:

What was before the Big Bang?

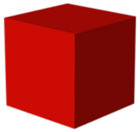
We still do not know, but have some ideas
based on inflation and quantum cosmology

Why is our **universe** so **uniform**?
Why is it **not exactly** uniform?
Why is it **isotropic** (same in all directions)?
Why all of its parts started expanding simultaneously?
Why is it **flat** ($\Omega = 1$)?
Why is it so **large**?

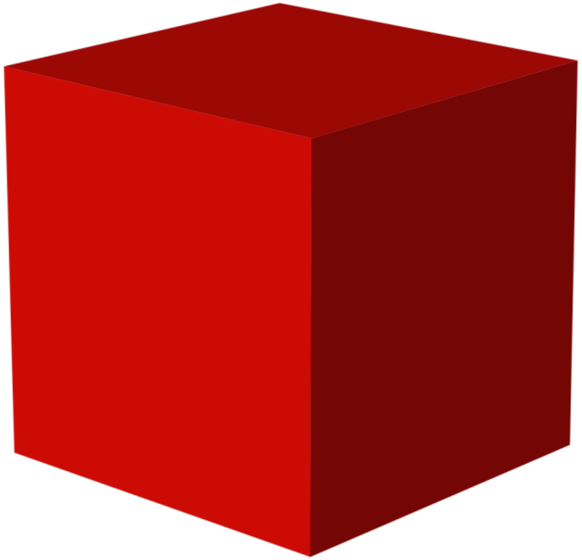
Answered by inflation

Basic idea of inflation:

Take a box with heavy vacuum



In an expanding universe this box grows in size. It has the same vacuum inside, with the same ENERGY DENSITY. The total energy inside GROWS



And then vacuum decays and produces enormous number of protons, proportional to the volume of the box.

Basic idea of inflation:

One of the Einstein equations for the flat empty universe with vacuum energy density V_0 (cosmological constant) is

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{V_0}{3}$$

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.

Alan Guth 1980

If something looks too good to be true…

If the universe is empty, how can anyone know that it expands?

The universe with a constant positive vacuum energy V_0 is **de Sitter space**, which 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, there is **no preferable time** when the vacuum state decays. Therefore, vacuum decays chaotically, and the universe becomes grossly inhomogeneous, unsuitable for life. After a year of investigation, Guth and Hawking concluded that this scenario cannot be improved.

Breaking the rules

A solution was found a year later ("new inflation"): Instead of a vacuum state with a constant vacuum energy V_0, one should consider a slowly changing scalar field with a not very steep potential $V(\phi)$. If the potential is too steep, no inflation. If it is too flat – the universe becomes grossly inhomogeneous.

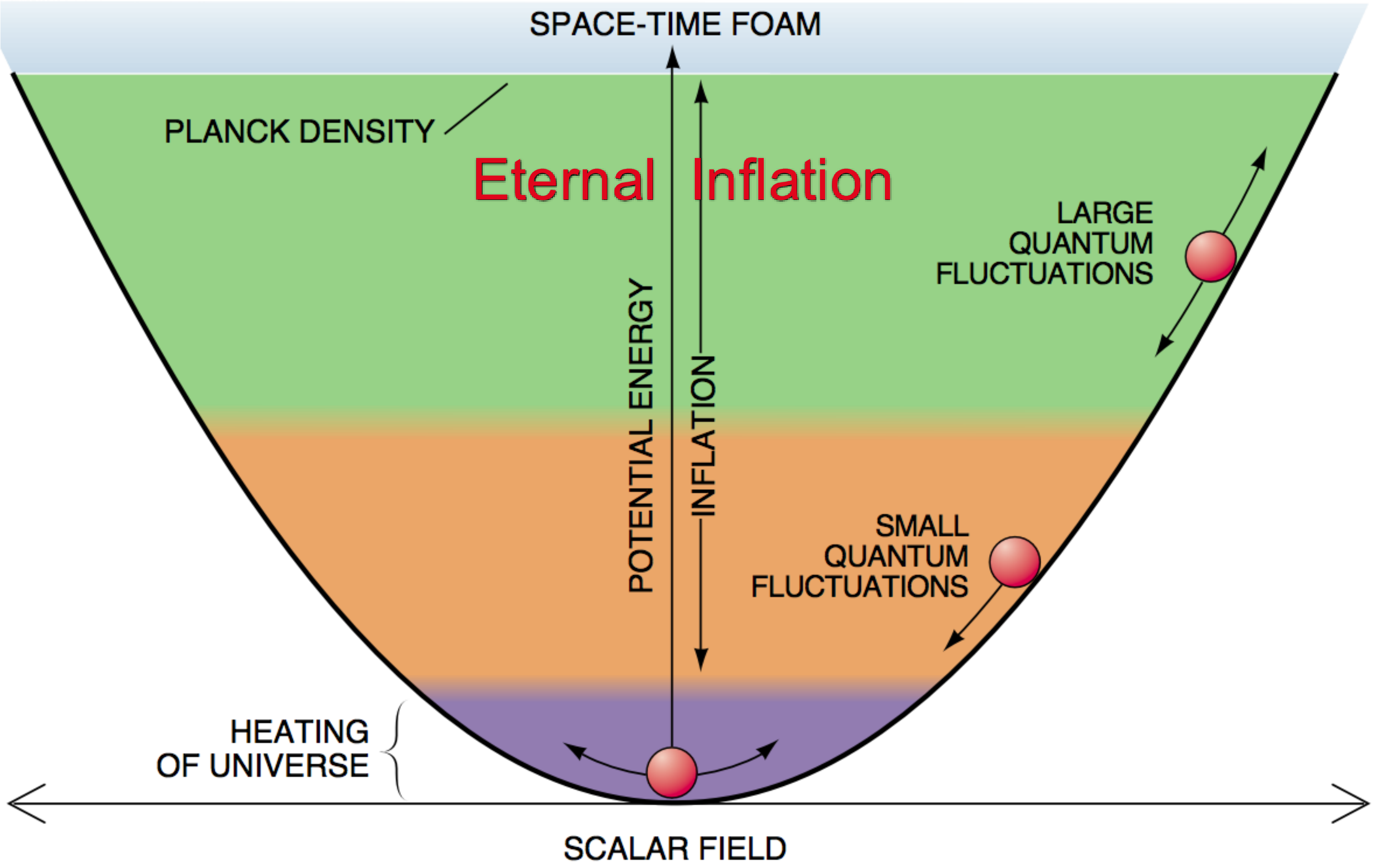
And then, a year later, it was realized ("chaotic inflation") that it is better not to rely on the idea that the universe was born in the hot Big Bang.

The simplest inflationary model

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

AL 1983, 1986

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



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

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

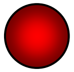
↓

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

This is the stage of inflation

A newborn universe could be as small as 10^{-33} cm and as light as 10^{-5} g

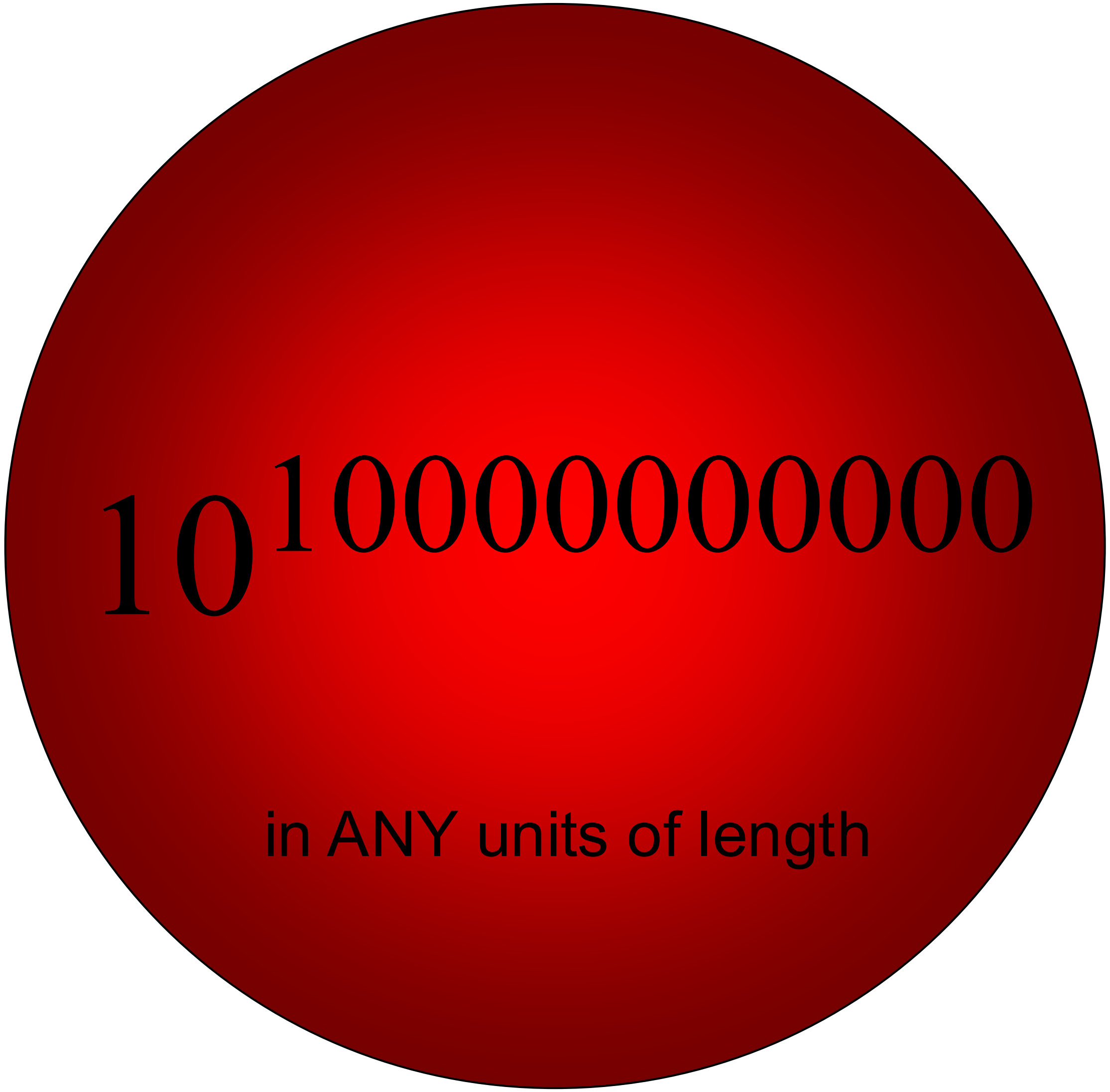
(it could be born from nothing at all…)



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

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

Inflationary universe 10^{-35} seconds old

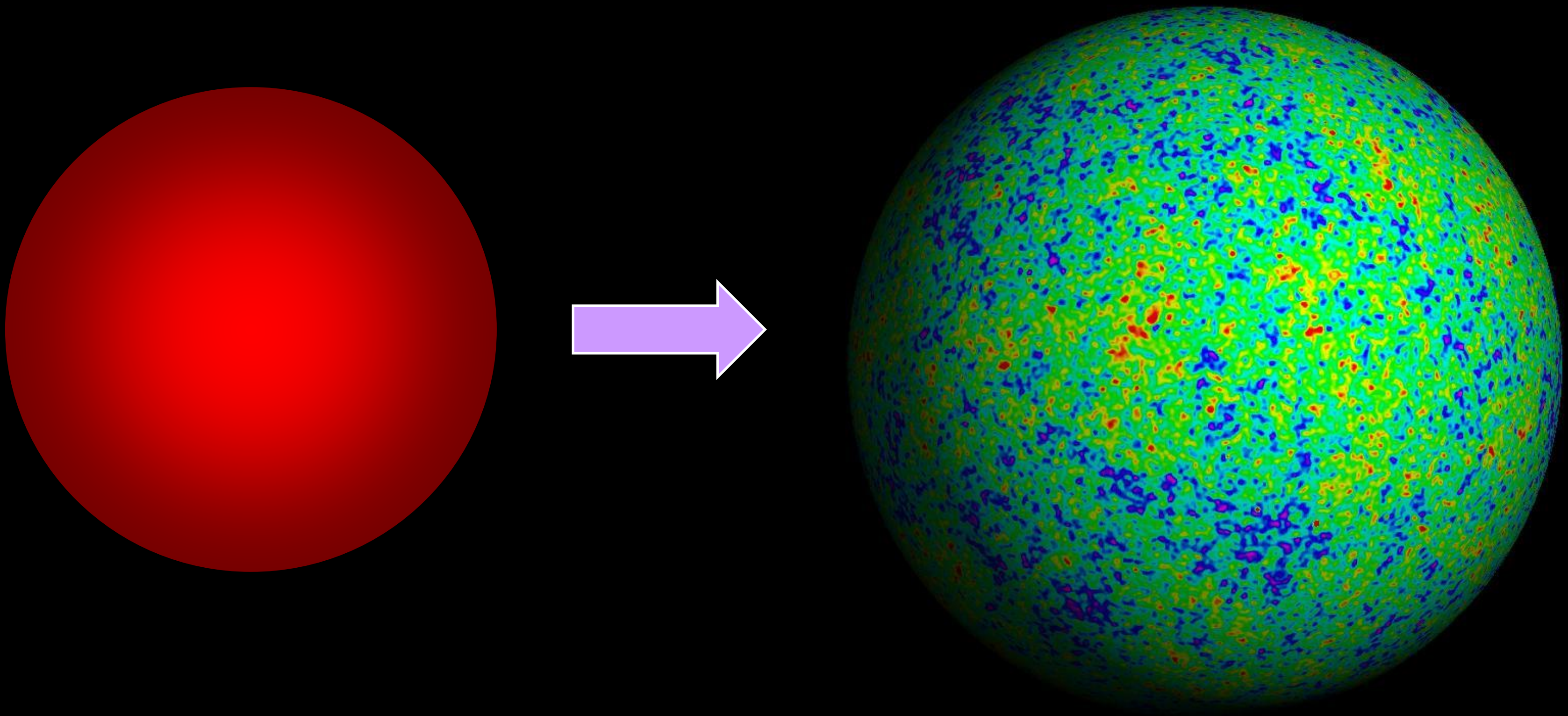


$$10^{10000000000}$$

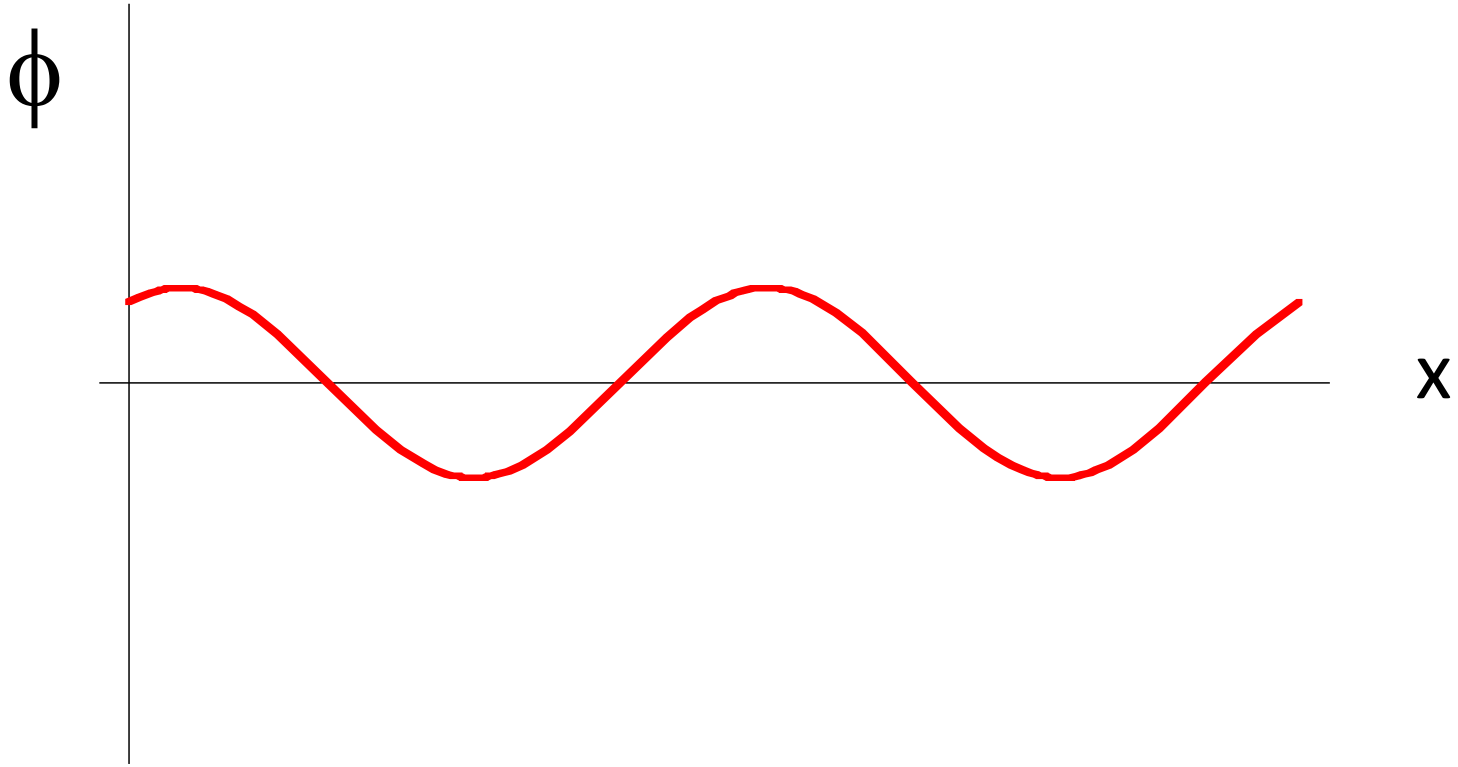
in ANY units of length

All matter in the universe was born after the decay of the scalar field driving inflation

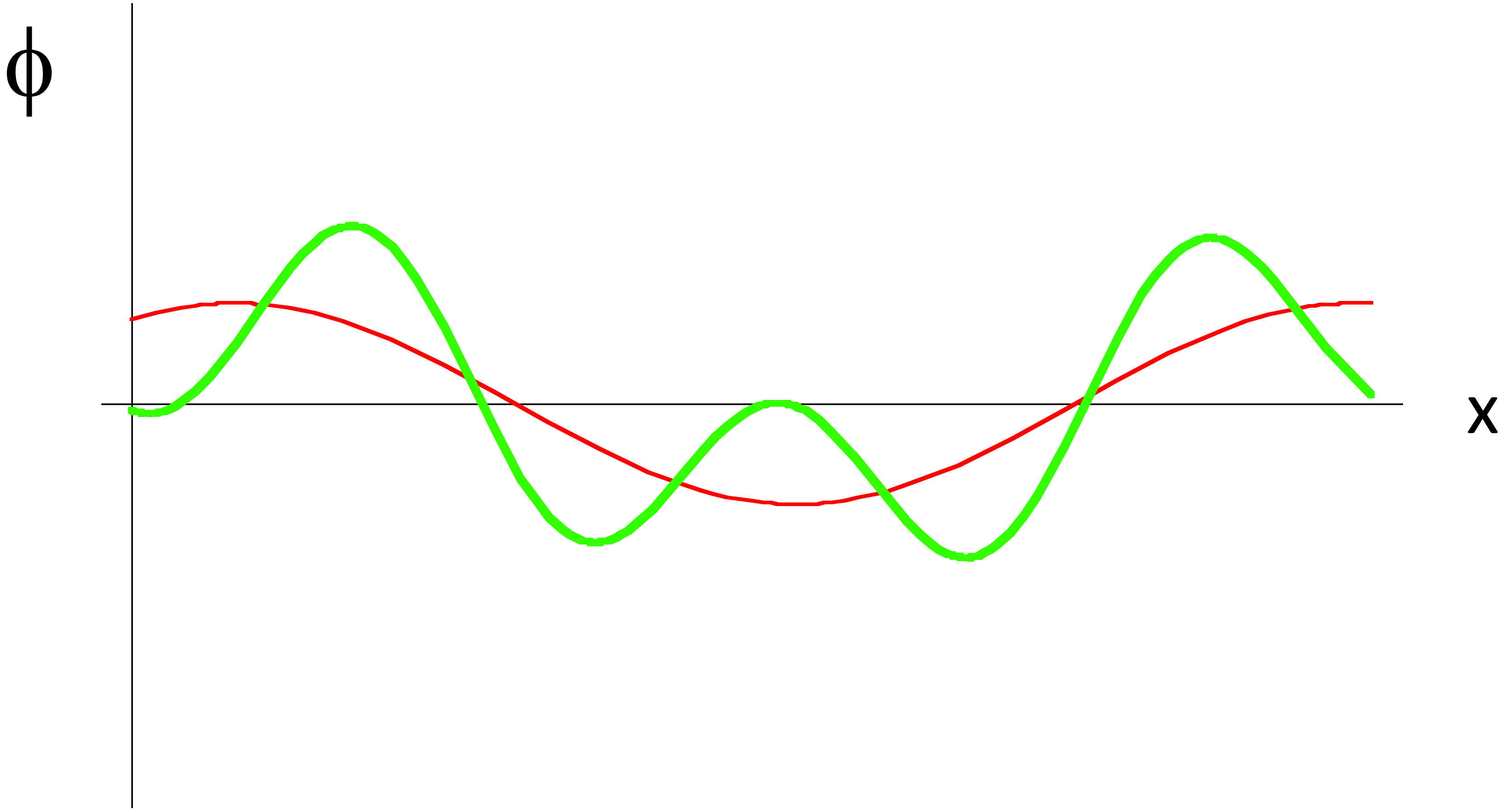
The universe after inflation becomes almost absolutely uniform, but quantum fluctuations make it slightly non-uniform, which later produces galaxies and tiny perturbations of the temperature of the universe



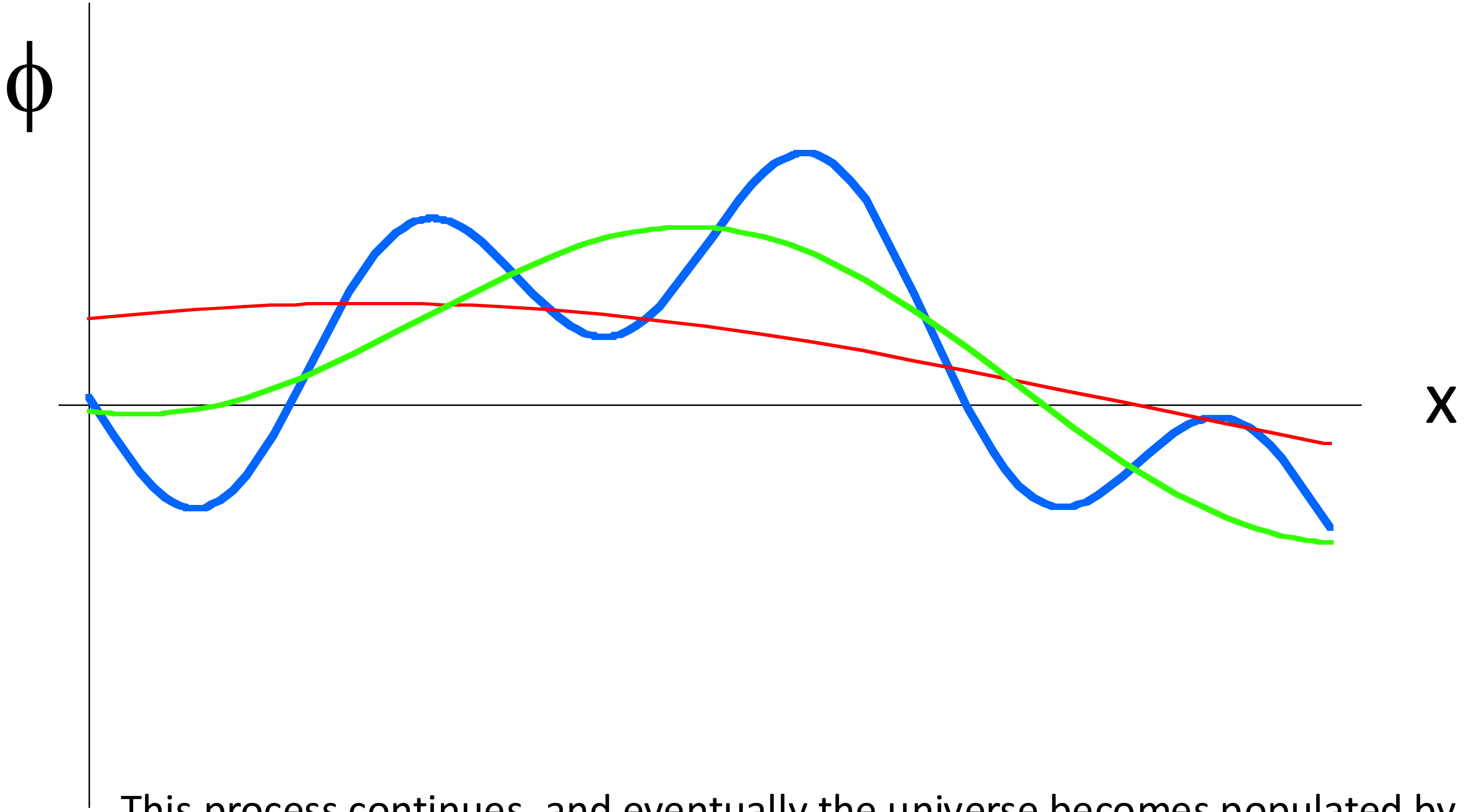
Quantum fluctuations produced during inflation



Small quantum fluctuations of all physical fields exist everywhere. They are similar to waves in the vacuum, which appear and then rapidly oscillate, move and disappear. Inflation stretched them, together with stretching the universe. When the wavelength of the fluctuations became 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 oscillation and freeze on top of the previously frozen fluctuations.



This process continues, and eventually the universe becomes populated by an inhomogeneous scalar field. Its energy takes different values in different parts of the universe. These inhomogeneities are responsible for the formation of galaxies and for temperature fluctuations in the cosmic microwave background radiation (CMB).

Origin of structure:

In this theory, original inhomogeneities are stretched away, but new ones are produced from **quantum fluctuations** amplified during the exponential growth of the universe.

Mukhanov and Chibisov 1981

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

Testing predictions of inflation

1) **The universe is flat, $\Omega = 1$**. (In the mid-90's, the consensus was that $\Omega = 0.3$, until the discovery of dark energy confirming inflation.)

2) The observable part of the universe is **uniform** (homogeneous).

3) It is **isotropic**. In particular, it does not rotate. (Back in the 80's we did not know that it is uniform and isotropic at such an incredible level.)

4) Perturbations produced by inflation are adiabatic

5) Unlike perturbations produced by cosmic strings, inflationary perturbations lead to many **peaks in the spectrum**

6) The large angle TE anti-correlation (WMAP, Planck) is a distinctive signature of **superhorizon fluctuations** (Spergel, Zaldarriaga 1997), ruling out many alternative possibilities

7) Inflationary perturbations should have a **nearly flat (but not exactly flat) spectrum**. A small deviation from flatness is one of the distinguishing features of inflation. It is as significant for inflationary theory as the asymptotic freedom for the theory of strong interactions

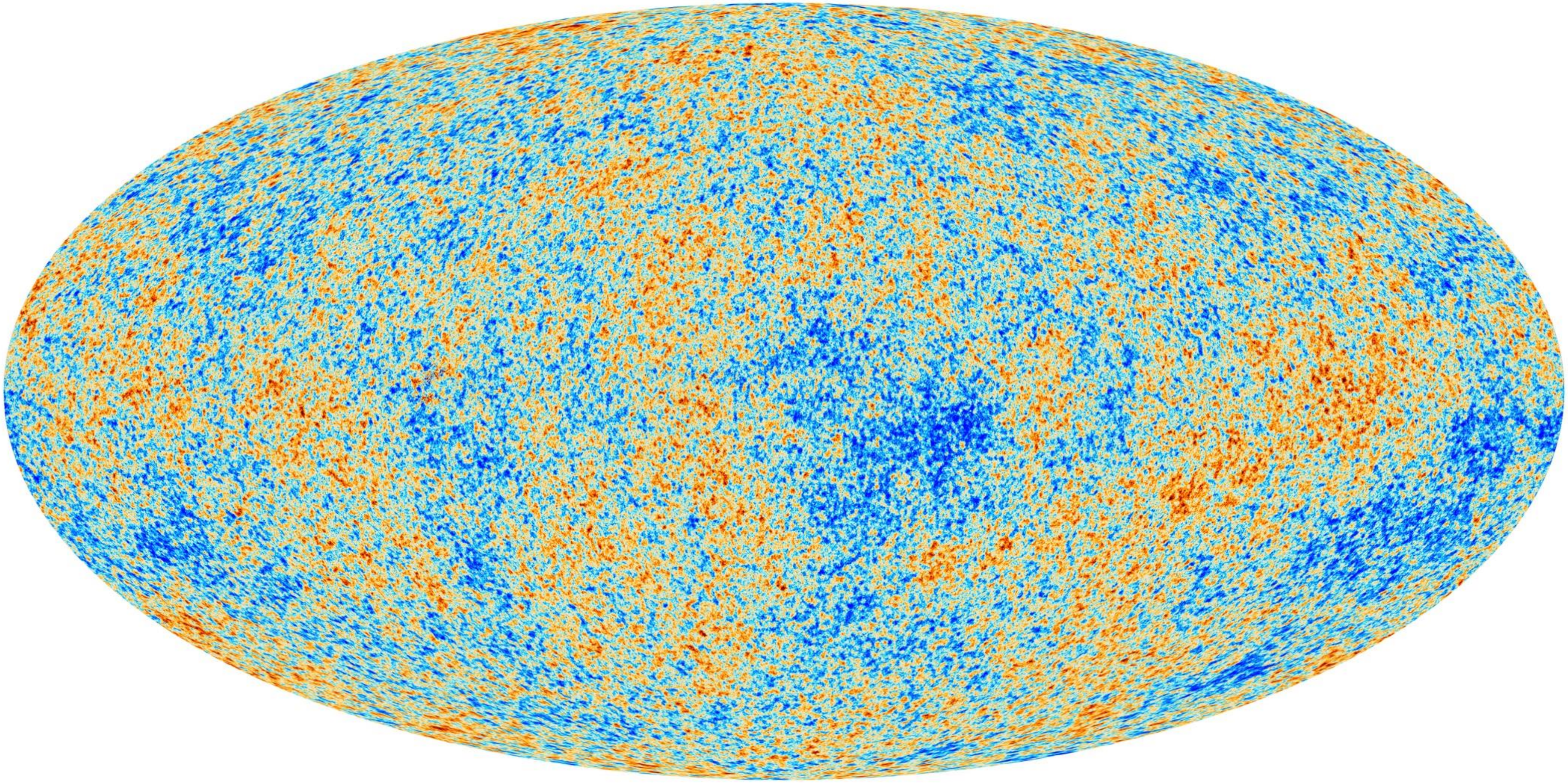
8) **Inflation produces scalar perturbations** and **tensor perturbations** with nearly flat spectrum, and it **does not produce vector perturbations**. There are certain relations between the properties of scalar and tensor perturbations

9) In the early 80's it seemed that inflation is ruled out because scalar perturbations are not observed at the expected level 10^{-3} required for galaxy formation. Thanks to dark matter, smaller perturbations are sufficient, and they were **found by COBE**.

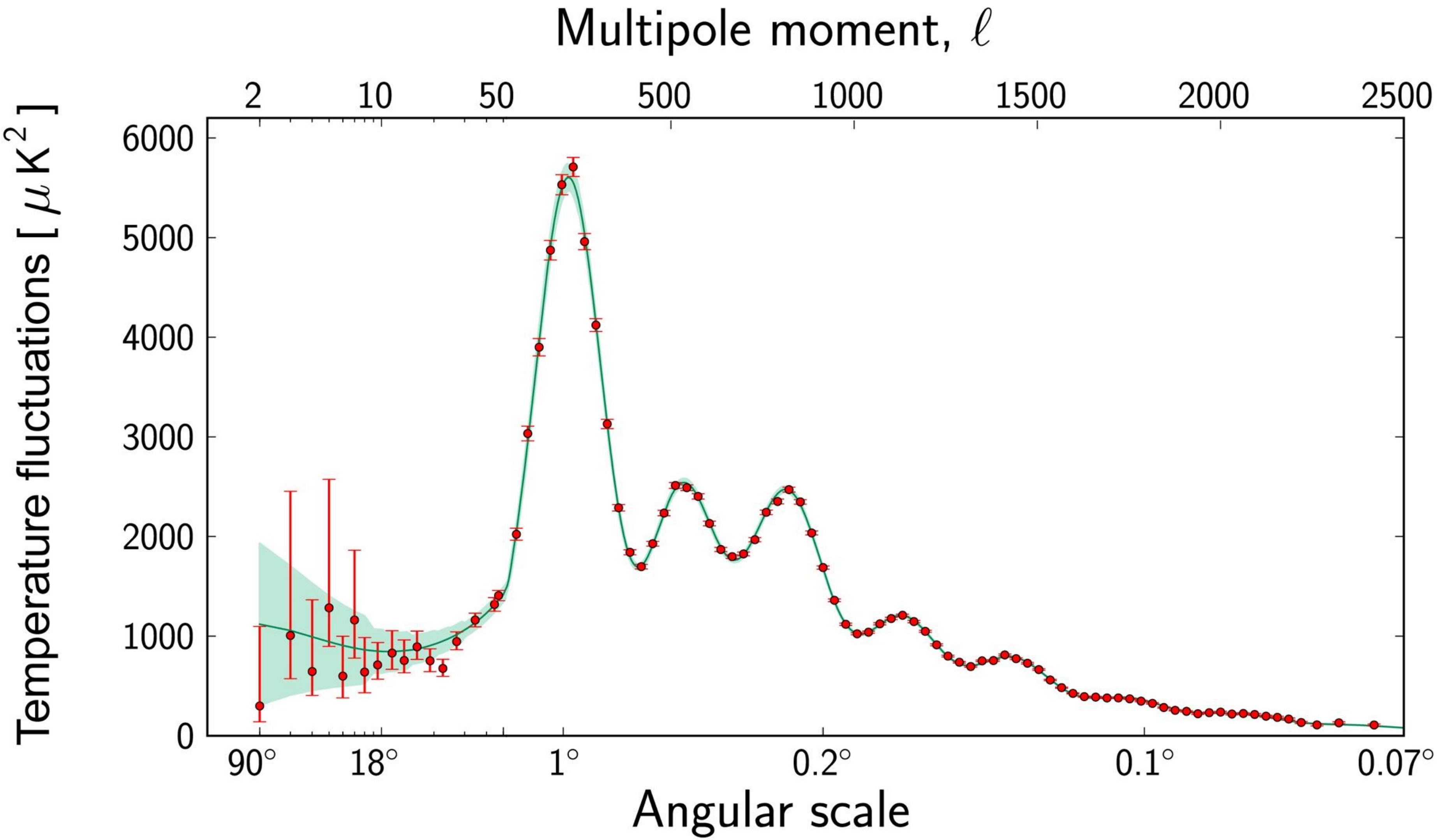
10) Scalar perturbations are **Gaussian**. In non-inflationary models, the parameter f_{NL}^{local} describing the level of local non-Gaussianity can be as large as 10^4, but it is predicted to be O(1) in all single-field inflationary models. **Confirmed by Planck.** Prior to the Planck2013 data release, there were rumors that $f_{NL}^{local} \gg O(1)$, which would rule out **all** single field inflationary models

Planck satellite: Perturbations of temperature

This is an image of **quantum fluctuations produced by inflation 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 satellite: Perturbations of temperature (red dots) and predictions of inflationary theory (green line)



Planck, ACT and SPT

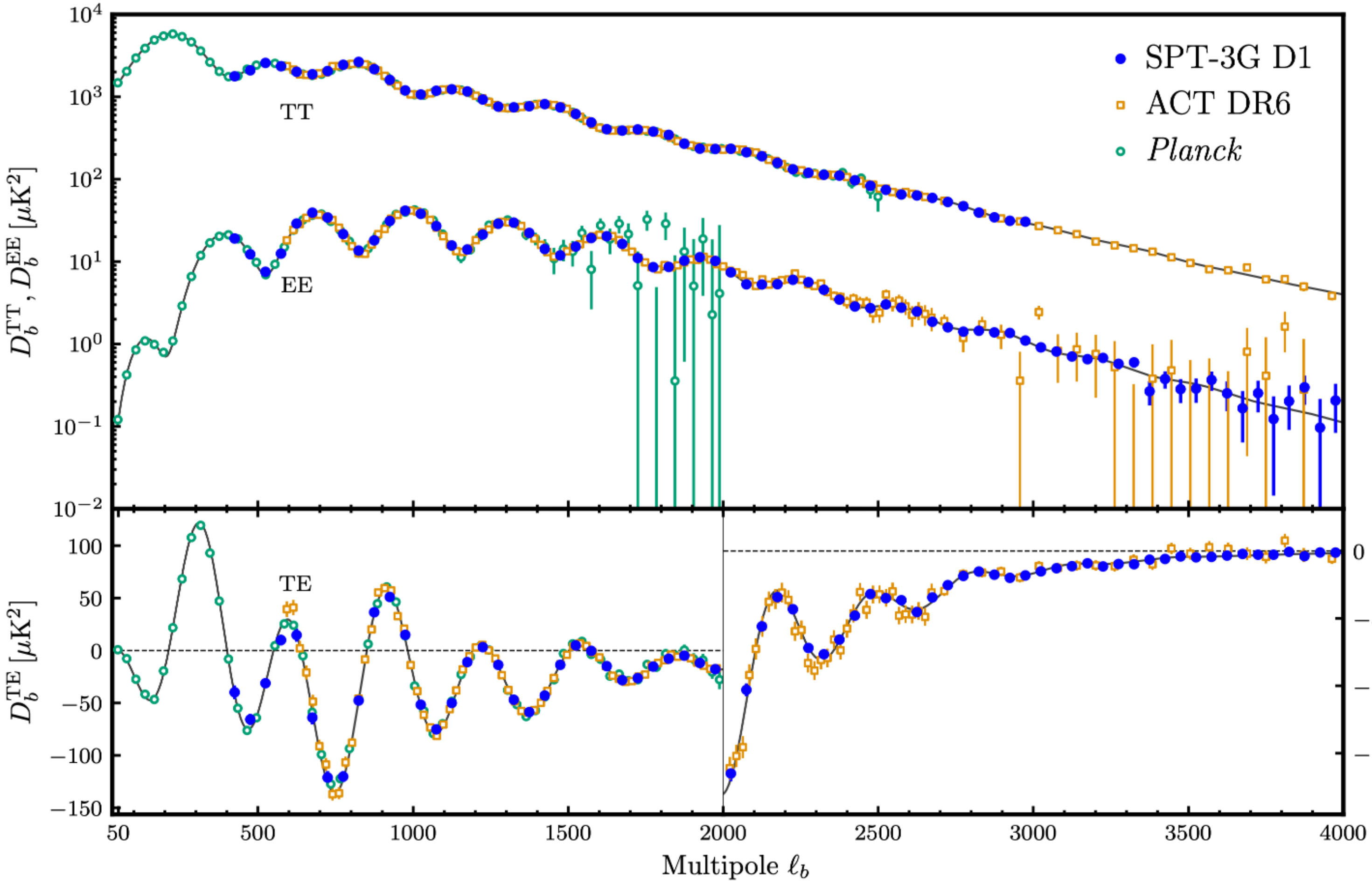


FIG. 1. TT, TE, and EE band powers from SPT-3G D1 (blue dots), ACT DR6 (orange empty squares) and *Planck* PR3 (green empty dots). Band powers from each experiment are foreground- and nuisance-parameter cleaned combinations of all auto- and cross-frequency spectra. We also show the best-fit ΛCDM model to SPT-3G D1 T&E (solid line). *Top*: TT and EE band powers on a logarithmic scale. SPT TT band powers are estimated in the multipole range $\ell = 400$ to 3000, while the range for TE and EE band powers is $\ell = 400$ to 4000, see §IV D for details. *Bottom*: TE band powers in linear scale, with a zoomed-in view of the $\ell > 2000$ region where ground-based experiments dominate the measurement. These data sets demonstrate excellent agreement with each other, and the SPT-3G D1 T&E data provide the tightest measurement of the lensed EE and TE band powers at $\ell =$ 1800-4000 and $\ell =$ 2200-4000, respectively.

Can we test inflation even better ?

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 could provide a strong additional evidence in favor of inflation.

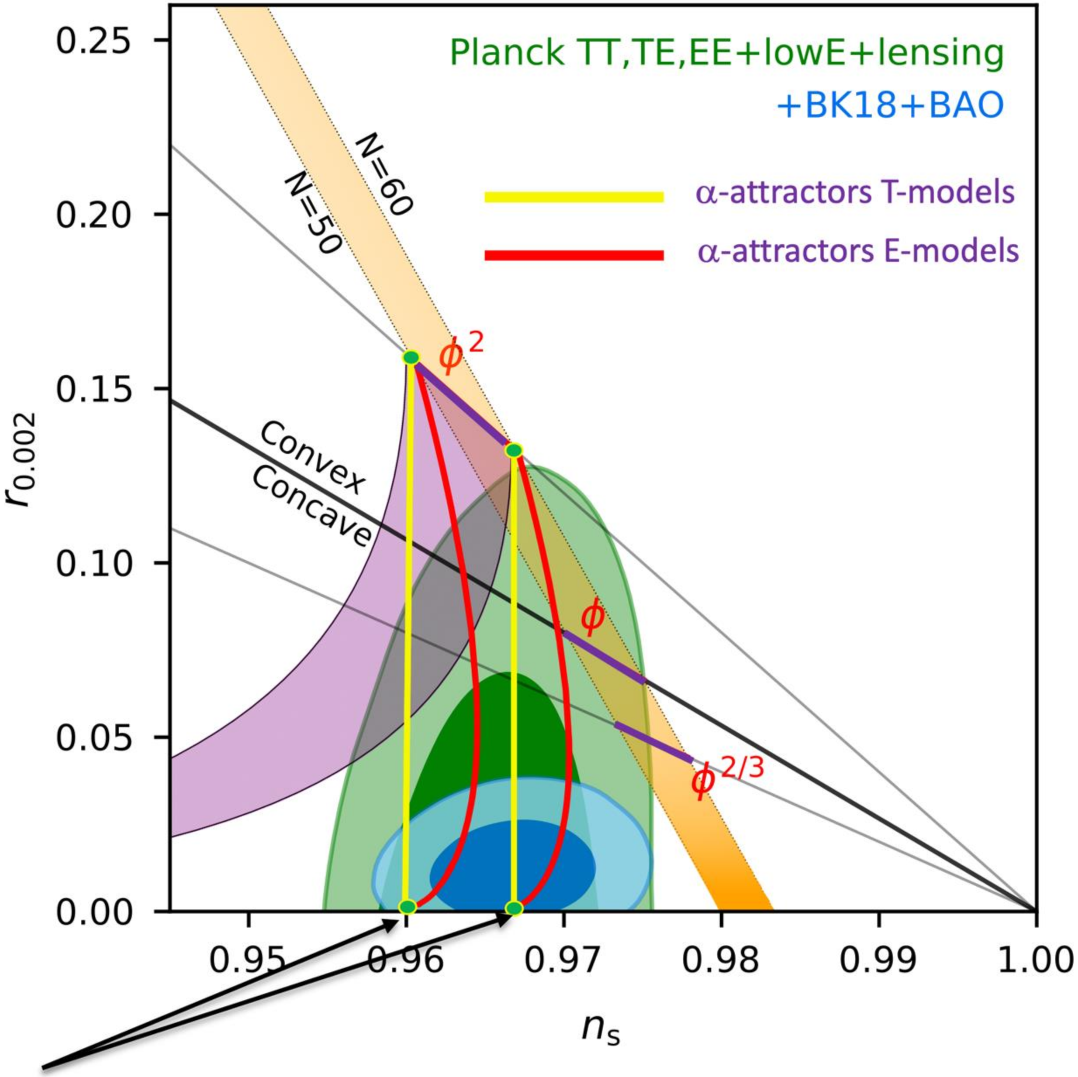
A.A. Starobinsky, Pis'ma Zh. Eksp. Teor. Fiz. 30 (1979) 719
V.A. Rubakov, M.V. Sazhin, A.V. Veryaskin, Phys.Lett.B 115 (1982)

BICEP/Keck, LiteBIRD and other experiments

A non-discovery of B-modes is fine too: many models predict gravitational waves with a tiny amplitude.

A discovery of inflationary gravitational waves is **NOT** required for proving inflation, but it would be **a great gift indeed**, and not only for inflation, but for investigation of quantum gravity and processes at energies many orders above LHC.

Planck2018 – BICEP/Keck2021 constraints



Starobinsky model and **Higgs inflation**

α-attractors

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

In canonical variables

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{R}{2} - \frac{(\partial_\mu \varphi)^2}{2} - V\big(\sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}}\big)$$

Asymptotically at large values of the inflaton

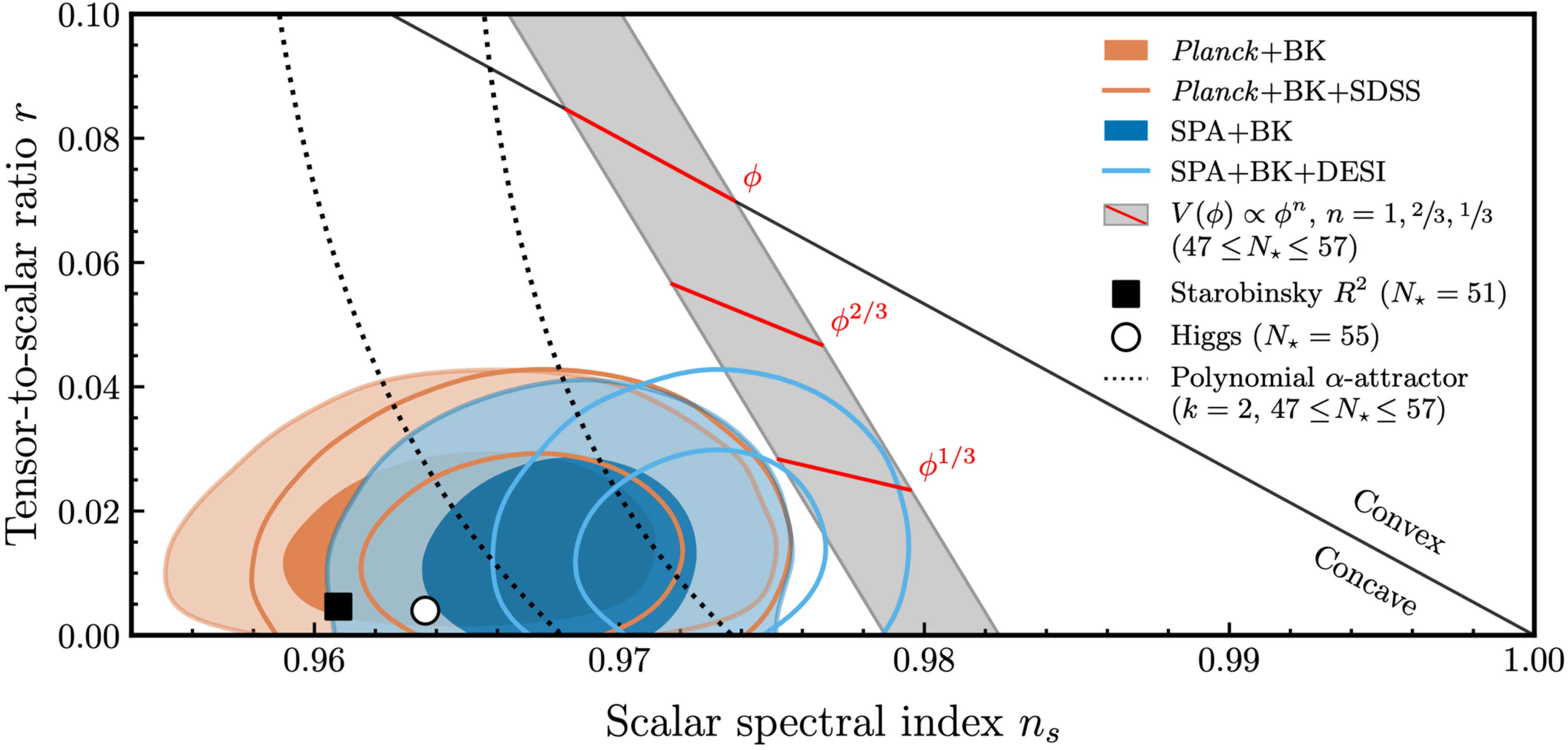
$$V(\varphi) = V_0 - 2\sqrt{6\alpha}\,V_0'\,e^{-\sqrt{\frac{2}{3\alpha}}\varphi}$$

Here $V_0' = \partial_\phi V|_{\phi=\sqrt{6\alpha}}$ This factor can be absorbed in the redefinition (shift) of the field. **Therefore, at small α, values of n_s and r depend only on V_0 and α**, not on the shape of $V(\phi)$.

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

Planck-ACT-SPT combined with DESI suggest some increase in n_s

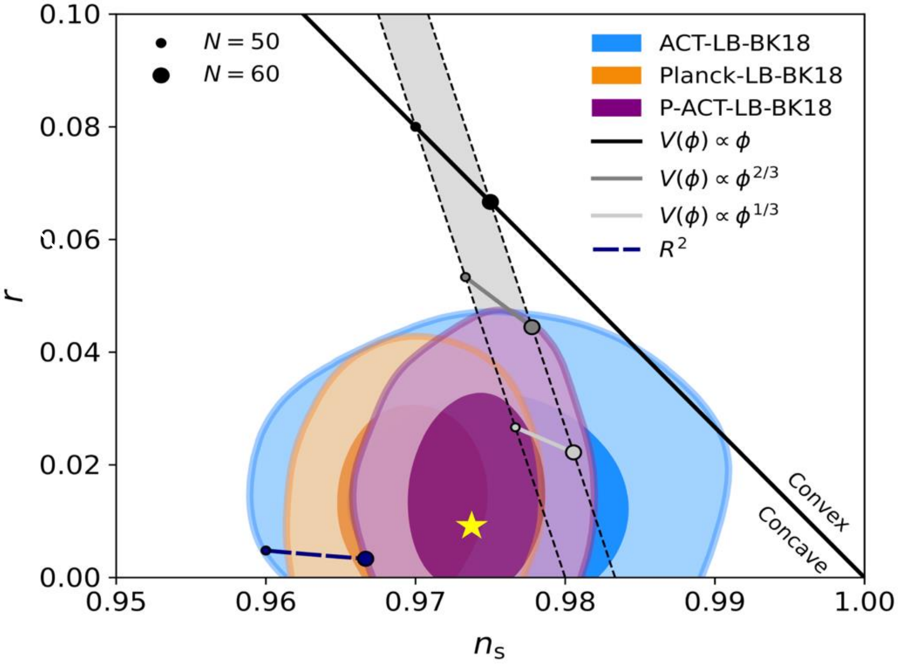
Inflation at the End of 2025: Constraints on r and n_s Using the Latest CMB and BAO Data



A non-minimal version of chaotic inflation

$$\frac{1}{2}(1+\underline{\phi})R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2$$

Kallosh, AL, Roest
2503.21030

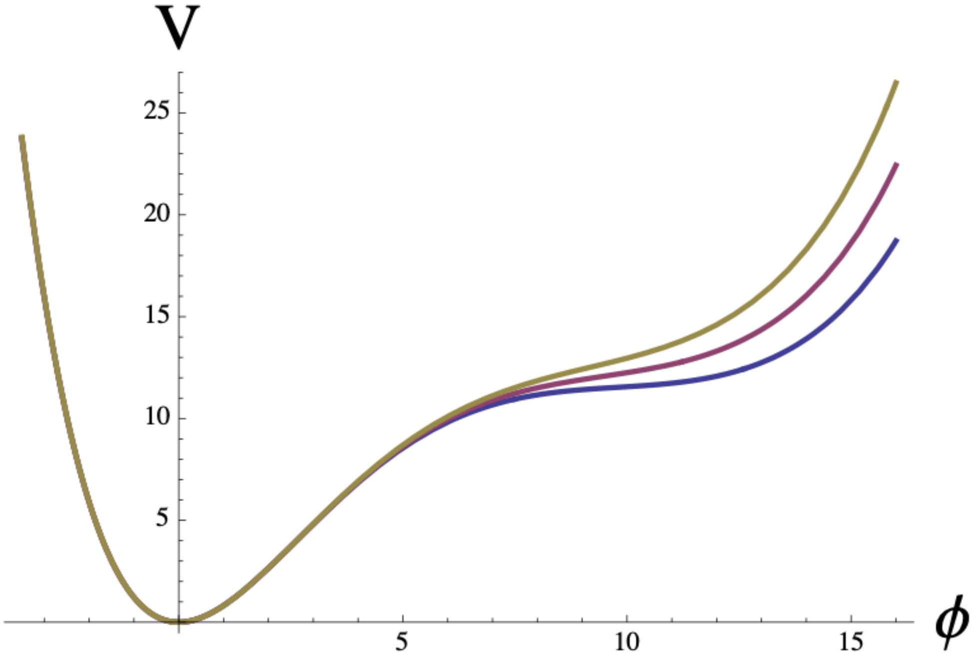


This simple version of chaotic inflation is fully compatible with Planck+ACT+SPT+DESI

A simple polynomial potential with 3 parameters can describe the full range of all possible values of A_s, n_s and r, all the way to $r = 0$ and $n_s = 1$

$$V = \frac{m^2\phi^2}{2}(1 - a\phi + b(a\phi)^2)^2$$

Destri, de Vega, Sanchez, 2007
Nakayama, Takahashi and Yanagida, 2013
Kallosh, AL, Westphal 2014



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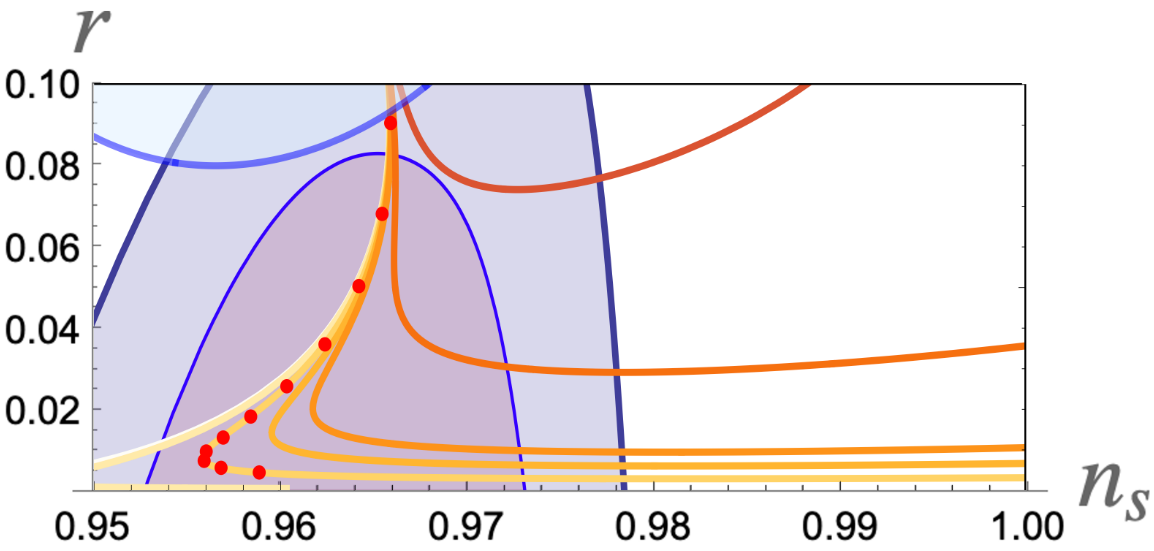


Example: For **b** = 0.34, we have **r** = 0.01. By increasing **a** from 0.13 to 0.17, we move from **n_s** = 0.967 (Planck) to 0.974 (ACT), and all the way to **n_s** = 1.

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.

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.

We almost did it, but then 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 can be (and probably should be) 100% non-uniform due to quantum fluctuations.

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.

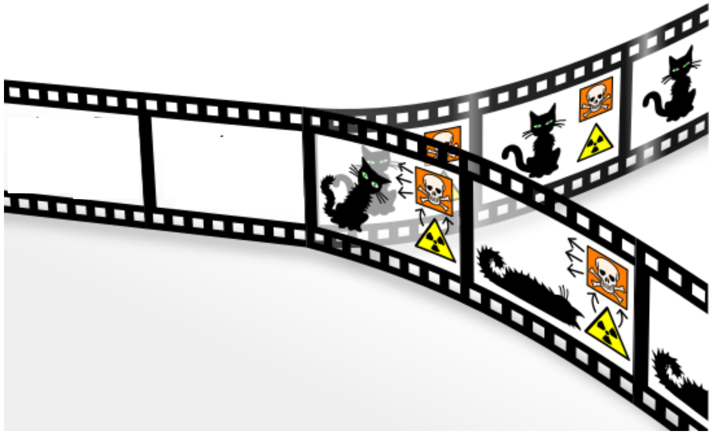
Numerous attempts to propose a **non-quantum** mechanism of formation of the large-scale structure of the universe during the last 40 years have failed.

Thus, it is time to take very seriously the assumption that **the large-scale structure of the universe was formed due to quantum fluctuations**.

This is the Cosmological Schrodinger Cat story.

A warm-up: Remember the Schrodinger cat

The Universe is similar to it, but more weird, since **initially there was <u>no cat</u>**, so the movie that we see now shows something that **did not exist** before inflation

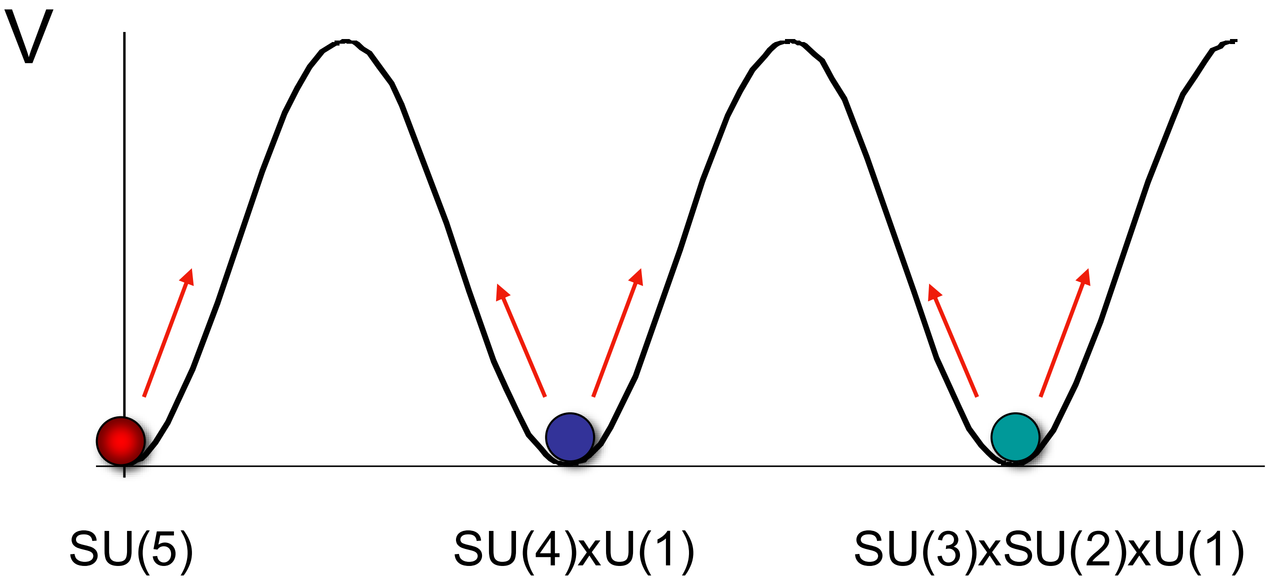


The difference between this picture and the old one is that in quantum field theory (unlike quantum mechanics) the number of particles is not conserved.

In inflationary cosmology, this effect is pushed to its limits. We may start with the universe weighting less than a milligram, without any particles at all, and we may end up with a humongous multiverse consisting of exponentially large parts where all possible outcomes consistent with the underlying physical theory are realized.

Example: SUSY landscape

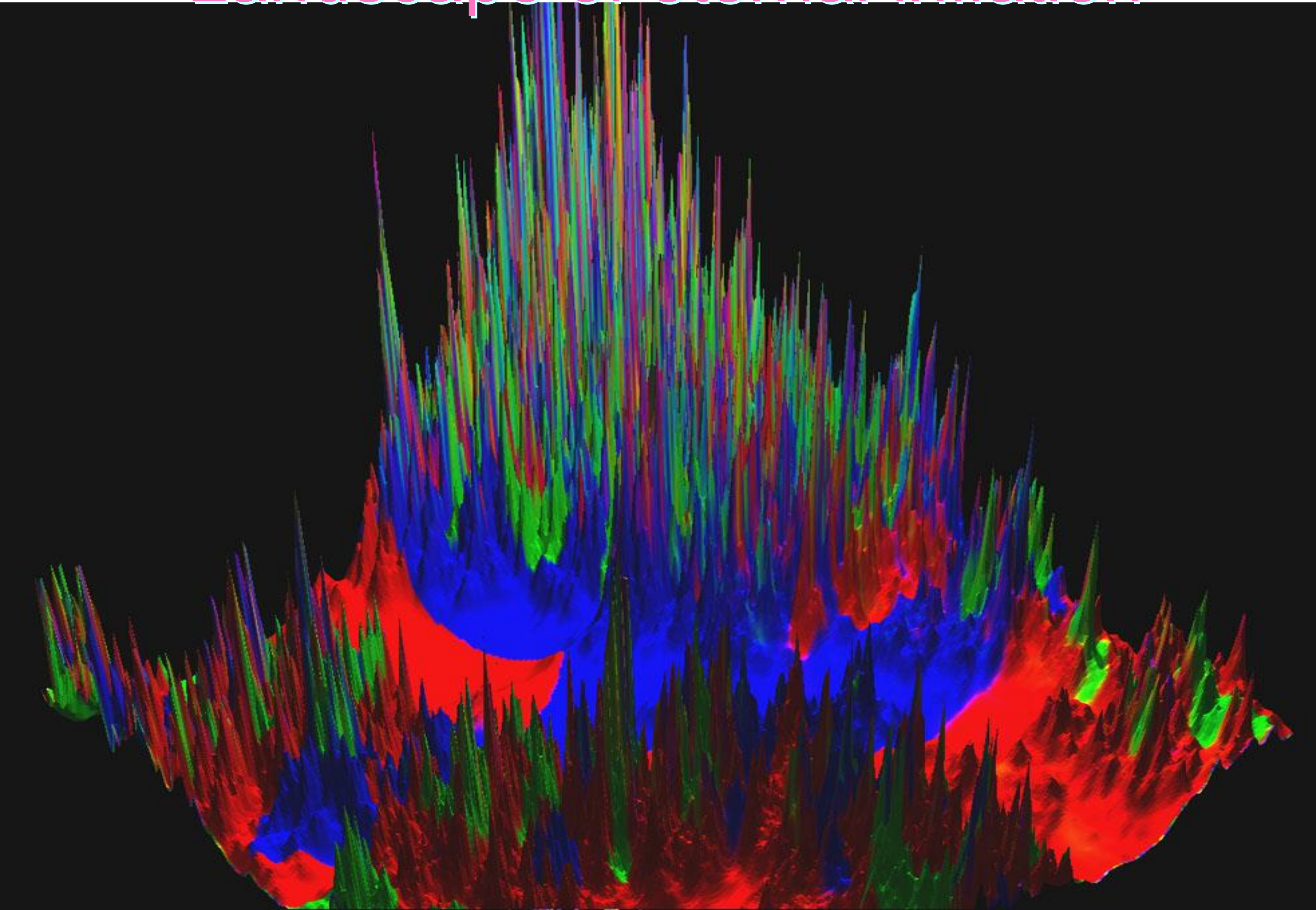
Supersymmetric SU(5)



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 makes each of the parts of the universe exponentially large. We can live only in the SU(3)xSU(2)xU(1) minimum.

Landscape of eternal inflation



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

Alan Guth 1981

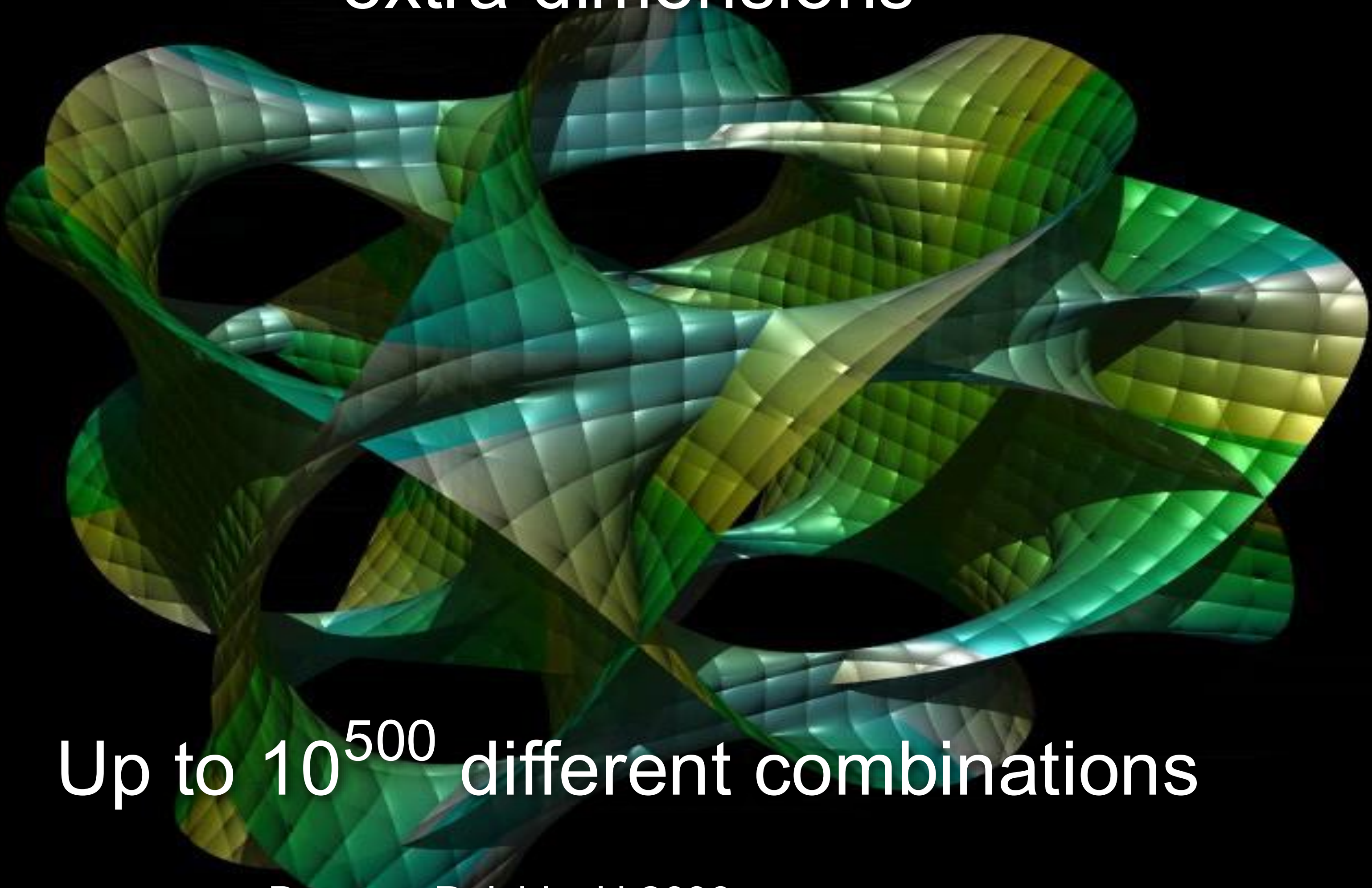
Now we know that the universe is not just a free lunch: It is an eternal feast where ALL possible types of dishes are served.

A.L. 1983

This allows us to justify the anthropic principle:

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

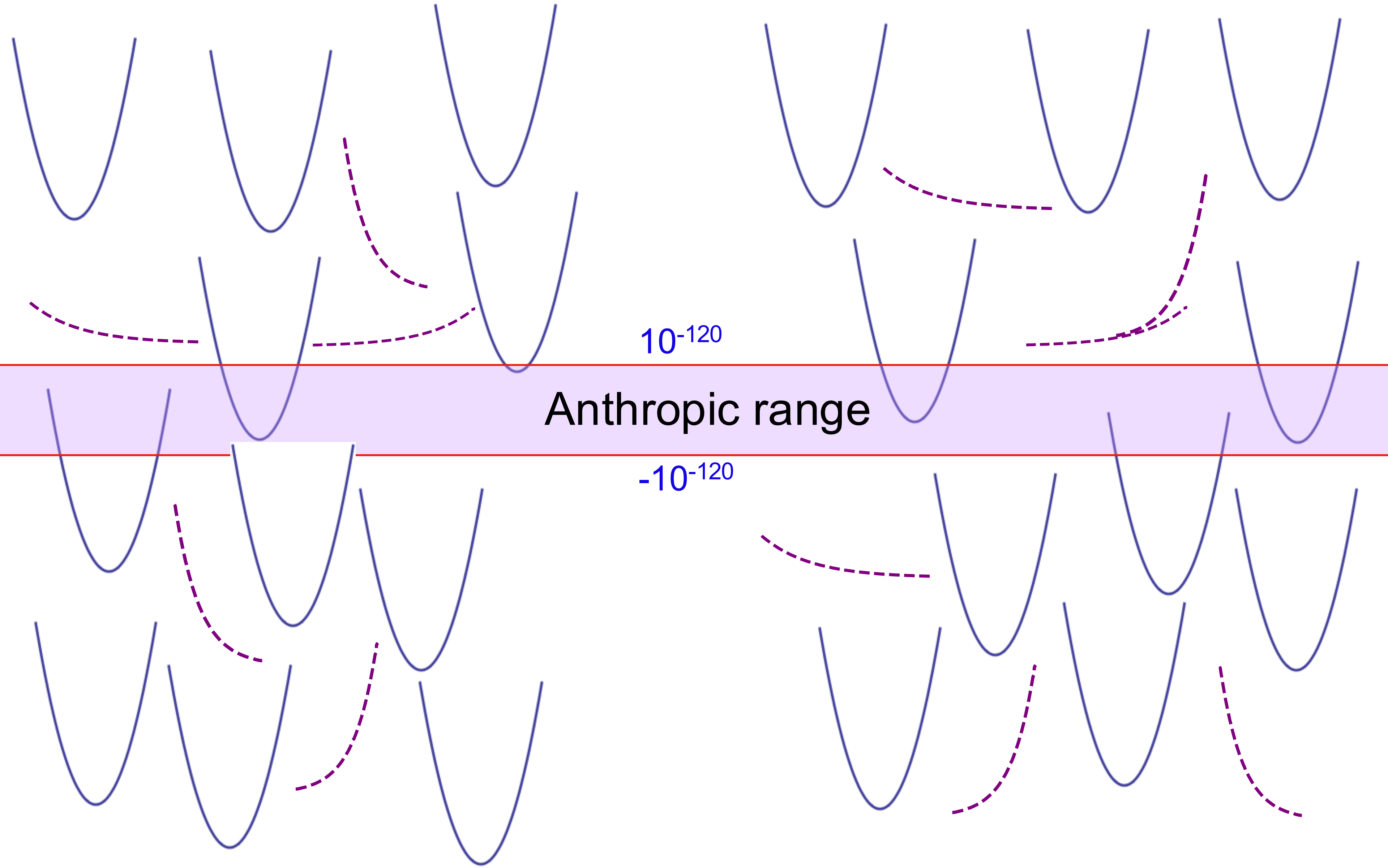
In string theory, genetic code of the universe is written in properties of compactification of extra dimensions



Up to 10^{500} different combinations

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

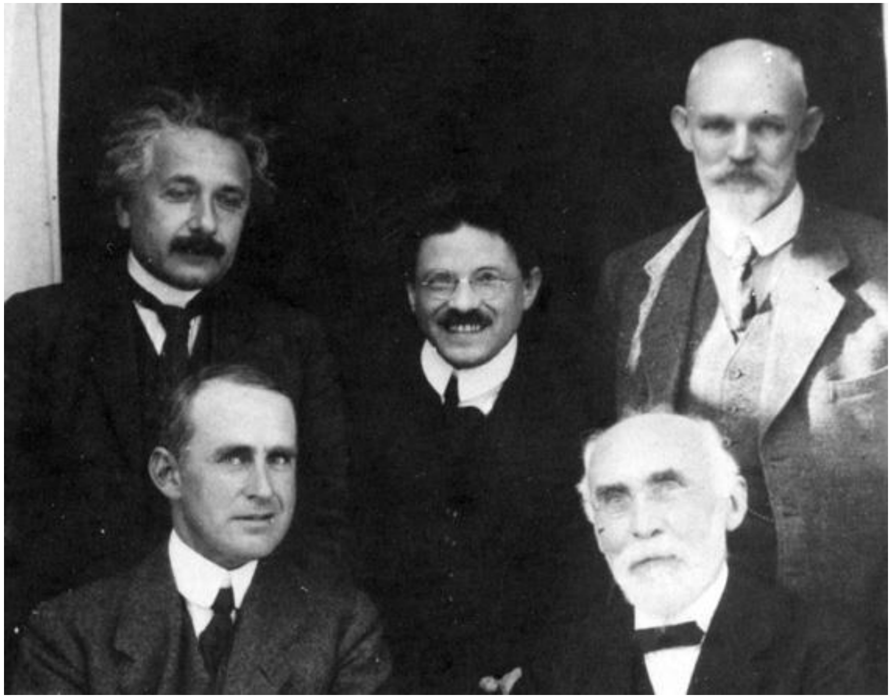
Anthropic approach to Λ in string theory



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

de Sitter

Eddington

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 popular versions of string theory, our world is 10 dimensional, but some of these dimensions are tiny, compactified. In general, one could end with space-time of any dimension d <10, which would grow exponentially large due to inflation. But 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 2003, 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, 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

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.

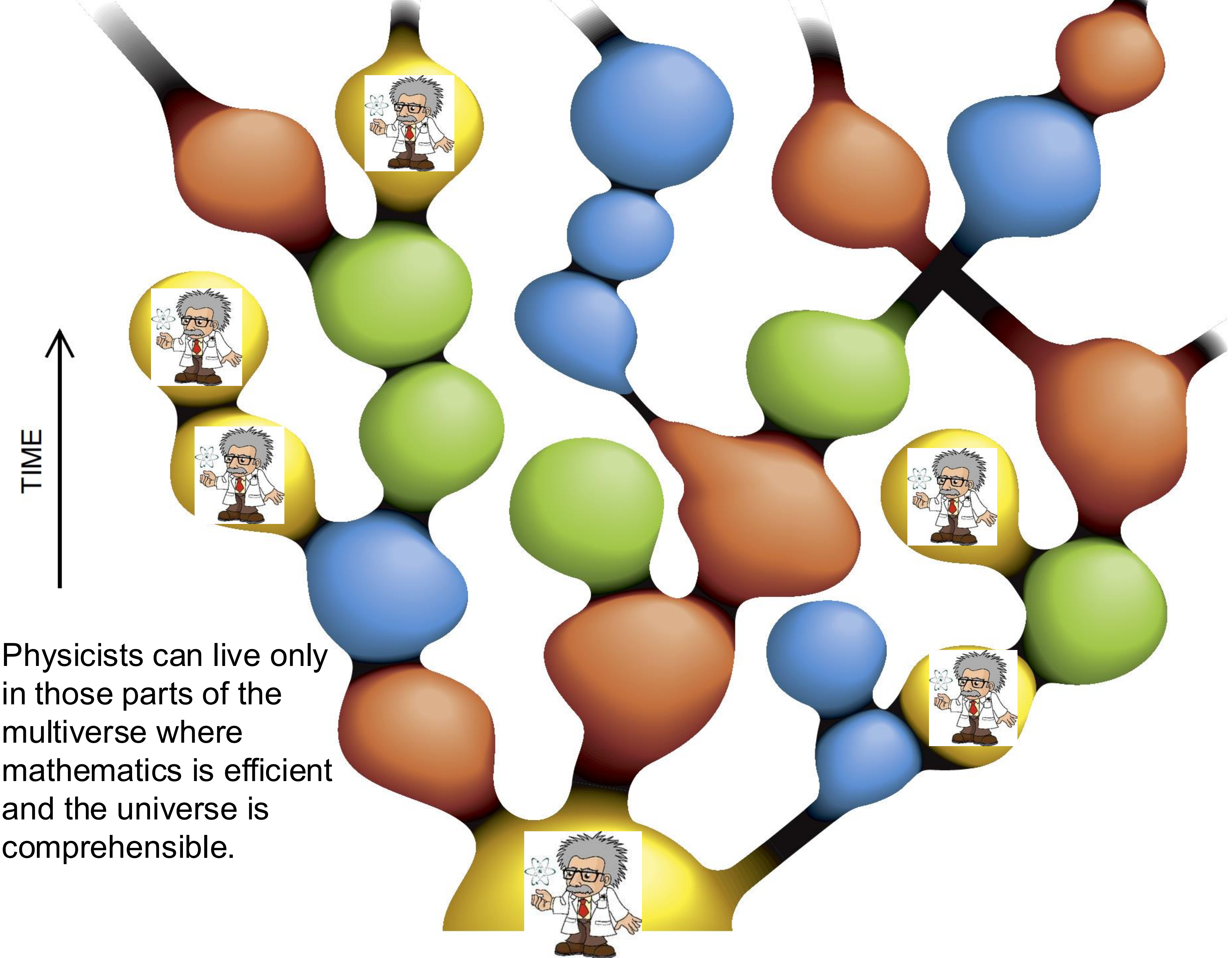
Israel Gelfand

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.