A BALLOON PRODUCING BALLOONS, PRODUCING BALLOONS:A BIG FRACTAL

A Conversation with

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I should probably start by explaining what happened during the last 30 years in cosmology. This story will begin with very old news: the creation of inflationary theory. Then we will talk about the relatively recent developments, when inflation became a part of the theory of the inflationary multiverse and string theory landscape. Then—what we expect in the future.

Let me start by saying that many, many years ago, and I mean like almost a century ago, Einstein came up with something called the "cosmological principle," which says that our universe must be homogenous and uniform. And for many years, people used this principle. In fact, it was formulated even much earlier, by Newton. The universe is still represented this way in current books on astrophysics, where you can find different versions of the cosmological principle.

For a while this was the only way of answering the question, why the universe is everywhere the same. In fact, why it is the universe. So we did not think about the multiverse, we just wanted to explain why the world is so homogenous around us, why it is so big, why there are so many people, why parallel lines do not intercept. Which is, in fact, part of the same question: if the universe was tiny, like a small globe, and you draw parallel lines perpendicular to the equator of the globe, they would intersect at the south and the north poles. Why has nobody ever seen parallel lines intersecting?

These kinds of questions, for many years, could seem a bit silly. For example, one may wonder what happened before the universe even emerged. The textbook of general relativity, which we used in Russia, said that it was meaningless to ask this question because the solutions of the Einstein equations cannot be continued through the singularity, so why bother. And yet people bothered. They are still trying to answer these kinds of questions. But for many people such questions looked metaphysical, not to be taken seriously.

When inflationary theory was invented, people started taking these questions seriously. Alan Guth asked these questions and proposed the theory of cosmic inflation, a framework in which a consistent answer to these questions could be found. The problem was that, as Guth immediately recognized, his own answer to these questions was incomplete. And then, after more than a year of work, I proposed a new version of inflationary theory, which helped to find a way to answer many of these questions.

At first it sounded like science fiction, but once we found possible answers to the questions, which previously were considered metaphysical, we couldn't just forget about it. This was the first reason for us to believe the idea of cosmic inflation. So let me explain this idea.

Standard Big Bang theory says that everything begins with a big bang, a huge explosion.

Terrorists started the universe. But when you calculate how much high tech explosives these guys would have to have at their disposal to start the universe formation, they would need 10^{80} tons of high tech explosives, compressed to a ball smaller than 1 centimeter, and ignite all of its parts exactly at the same time with precision better than 1 in 10,000.

Another problem was that in the standard Big Bang scenario, the universe could only expand slower as the time went on. But then why did the universe started to expand? Who gave it the first push? It looks totally incredible, like a miracle. However, people sometimes believe that the greater the miracle, the better: Obviously, God could create 10^{80} tons of explosive from nothing, then ignite it, and make it grow, all for our benefit. Can we make an attempt to come with an alternative explanation?

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According to inflationary theory, one may avoid many of these problems if the universe began in some special state, almost like a vacuum-like state. The simplest version of such a state involves something called "scalar field." Remember electric and magnetic fields? Well, scalar field is even simpler, it does not point to any direction. If it is uniform and does not change in time, it is invisible like vacuum, but it may have lots of energy packed in it. When the universe expands, scalar field remains almost constant, and its energy density remains almost constant.

This is the key point, so let us talk about it. Think about the universe as a big box containing many atoms. When the universe expands two times, its volume grows eight times, and therefore the density of atoms decreases eight times. However, when the universe is filled with a constant scalar field, its energy density remains constant when the universe expands. Therefore when the size of the universe grows two times, the total energy of matter in the universe grows eight times. If the universe continues to grow, its total energy (and its total mass) rapidly becomes enormously large, so one could easily get all of these 10^{80} tons of mater starting from almost nothing. That was the basic idea of inflation. At the first glance, it could seem totally wrong, because of energy conservation. One cannot get energy from nothing. We always have the same energy with which we started.

Once I was invited to give an opening talk at the Nobel Symposium in Sweden on the concept of energy. And I wondered, why did they invite me there, what am I going to tell these people who study solar energy, oil, wind? What can I tell them? And then I told them: "If you want to get lots of energy, you can start from practically nothing, and you can get all the energy in the universe."

Not everyone knows that when the universe expands, the total energy of matter does change. The total energy of matter plus gravity *does not* change, and it amounts to exactly zero. So the energy conservation for the universe is always satisfied, but it is trivial: zero equals zero. But we are not interested in the energy of the universe as a whole; we are interested in the energy of matter.

If we can have a regime where we have some kind of instability where the initial zero energy can split into a very big positive energy of matter, and a very big negative energy of gravity, the total sum remains zero. But the total energy of matter can become as large as we want. This is one of the main ideas of inflation.

We have found how to start this instability, and how to stop it, because if it doesn't stop, then it goes forever, and then it's not the universe where we can we live. Alan Guth's idea was how to start inflation, but he did not know how to stop it in a graceful way. My idea was how to start it, continue it, and eventually stop it without damaging the universe. And when we learned how to do it, we understood that yes, we can start from practically nothing, or even literally nothing, as suggested by Alex Vilenkin, and account for everything that we see now. At that time it was quite a revolutionary development: We finally could understand many properties of our universe. We no longer needed to postulate the cosmological principle; we finally knew the real physical reason why the world that we see around us is uniform.

But then, soon after inventing new inflation, I realized something else. If you take a universe which initially was tiny, tiny, but still contained different parts with different properties, then our part of the universe might have exploded exponentially, and we no longer see other parts of the universe, which become far away from us because the distance between different parts of the universe increased exponentially during inflation. And those who live in other parts of the universe will be unable see us, because we will be far away. We look around, we do not see other parts of the universe with different properties, and so we think: "This is our universe, it is everywhere the same, other parts do not exist." And those who live in other parts of the universe will also think: "All the universe is the way we see it."

For example, I could start in a red part of the universe, like in the Soviet Union, and you can start in a blue universe, and then, after inflation, after each part becomes exponentially large, each of us would look around and say, just like Einstein and Newton did: "This is the universe, this is the whole thing, it is single-colored." And then some of us will try to explain why the universe must be red, and others will try to explain why the universe must be blue, all over the world. But now we know that from the point of view of inflation, it's quite possible that our universe is divided into many regions with different properties. Instead of the cosmological principle that asserted that the whole world is the same everywhere and all of us must live in the parts of the universe with similar properties, we are coming to a more cosmopolitan perspective: We live in a huge inflationary multiverse. Some of us can live in its red parts, some can live in blue parts, and there is nothing wrong about this picture as long as each of its parts is enormously large because of inflation.

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postulate the cosmological principle; we finally knew the real physical reason why the world that we see around us is uniform.

Thus inflationary theory explained why our part of the universe looks so uniform: everything that surrounds us was created by the exponential expansion of a tiny part of the universe. But we cannot see what happens at a distance much greater than the speed of light multiplied by the age of the universe. Inflationary theory tells that our part of the universe, the part that we can see, is much, much smaller than the whole universe. Inflation of other parts of the universe may produce enormous regions with different properties. This was the first realization, which paved the way towards the theory of inflationary multiverse. And the second realization was that even if we start with the same universe everywhere, like red universe, quantum fluctuations produced during inflation could make it multicolored.

I am talking about different colors here only to help us to visualize what happens during inflation and after it. Let me explain what I actually mean by that. Think about water. It can be liquid water, solid, or vapor. The chemical composition is the same, H_2O. But fish can live only in liquid water. Liquid, solid or vapor are called different phases of water. The same may happen with different realizations of the laws of physics in the universe. We usually assume, for simplicity, that all parts of the universe should obey the same fundamental laws of physics. Nevertheless, different parts of the universe may dramatically differ from each other, just as icebergs differ from water surrounding them. But instead of saying that water can be in different phases, in application to physical laws we say that different parts of the universe may be in different vacuum states, and in each of them the same fundamental law of physics may be realized differently. For example, in some parts of the universe we have weak, strong and electromagnetic interactions, and in some other parts, these interactions do not differ from each other.

If we started in a red part of the universe, it does not stay red forever. Inflation is capable of producing and amplifying quantum fluctuations, and these quantum fluctuations let us jump from one vacuum state to another, and then to another. The universe becomes multicolored. The basic mechanism was understood as soon as the inflationary theory was invented. But its most interesting consequences appear in string theory.

Long time ago, string theorists realized that this theory allows many different vacua, so just by saying that we deal with a given version of string theory one cannot actually predict the properties of our world, which depend on the choice of the vacuum state. Many people thought that this multiplicity of possible outcomes is a real problem of string theory. But in the context of the theory of inflationary multiverse this is no longer a problem. In one of my papers written in 1986, I said that it is actually a virtue of string theory. It allows creation of universes of many different types, with different laws of low-energy physics operating in each of them.

This simplifies the difficult task of explaining why laws of physics in our part of the universe so nicely match the conditions required for our existence. Instead of the cosmological principle, asserting that all parts of the world look alike, we found a justification of the cosmological anthropic principle. It says that different exponentially large parts of the universe may be very different from each other, and we live only in those parts where life as we know it is possible. 30 years ago, ideas of this type were extremely unpopular, but two decades later, when we learned more about properties of string theory vacua, the situation changed dramatically. The picture outlined above became a part of what Lenny Susskind called "the string theory landscape."

The way from the invention of inflationary theory to the string theory landscape has taken a very long time. In the beginning, it was pretty hard to work in this direction. Nobody wanted it, nobody expected that inflationary theory, which was invented for explaining the observed uniformity of the universe, will end up predicting that on a much greater scale that we can see now, the universe is 100% non-uniform. It was just too much. Even the simplest versions of inflationary theory seemed a little bit too revolutionary, providing a possibility to create everything from practically nothing. It seemed like science fiction; it was too bold, too exotic.

For example, I found that in the first model of new inflation, which I invented back in 1981, the universe could expand 10^{800} times during the inflationary stag. It was surreal; we have never seen numbers like that in physics. When I was giving my first talks on new inflation at Lebedev Physical Institute, where I invented this theory, I had to apologize all the time, saying that 10^{800} was way too much. Probably later, I said, we'll come to something more realistic, the numbers will decrease and everything will become smaller. But then I invented a better inflationary theory, the theory of chaotic inflation, and the number became $10^{1000000000000}$. And then I found that inflation in this theory may continue eternally.

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Inflationary theory explained many properties of our world, which we could not understand without it, and it also predicted many things that were confirmed experimentally. For example, quantum fluctuations produced during inflation, if the theory is right, explain formation of galaxies of the same type as our galaxy.

Secondly, there is a cosmic microwave radiation (CMB), which reaches our earth from all parts of the sky. It has very interesting properties. When this radiation was discovered, almost 50 years ago, its temperature was measured, 2.7 Kelvin: very, very small. It comes to us from all parts of the universe in a uniform way. Then people looked at it more carefully, and they found that its temperature is 2.7 Kelvin plus 10^{-3} Kelvin to the right of you, and 2.7 minus 10^{-3} Kelvin to the left of you, a strange thing. But then an interpretation came. We are moving with respect to the universe, and there is a red shift. One part of the sky, in the direction of our motion, seems a little bit warmer, and another part of the sky seems a little bit cooler, because of the redshift, and that is OK.

Then people measured the temperature of the cosmic microwave radiation with accuracy of about 10^{-5} Kelvin. That's what COBE satellite did, and that is what WMAP satellite is doing right now, and many other experiments. And they have found many tiny spots in the sky, some—a little bit warmer, some—a little bit colder. They classified these spots, studied their distribution, and found that the distribution of spots was in a total agreement with the predictions of the simplest versions of inflationary theory. That was quite an unexpected confirmation.

Theoretically, we knew that it should be there. What was incredible is that people who make observations could achieve this absolutely astonishing accuracy. It's just amazing.

Nobel Prizes are awarded for definitely established facts. Observers found fluctuations in CMB, but one may wonder whether they were produced by inflation or by some other mechanism. So far, from my point of view, there are no other fully developed theories that would explain these observations. Who knows, maybe ten years later somebody will come up with something as smart as inflation. However, many people already tried to do it during the last 30 years, but no other theory comparable to inflation was invented yet.

Let me tell you a little bit about how inflation was invented, from my perspective. Because things look very, very different when you look at it from a Russian perspective, or from an American perspective, simply because at the time inflation theory was developed, Russia and America were not closely connected; every letter from Russia would come to the United States with an interval of about 1.5 or 2 months. You know, in the '30s there was the record flight from Russia landing in the United States, and it took almost a day, and then 50 years later the letter from Russia to the United States would take maybe 40 to 60 days, so that was the progress achieved. Whatever.

I was educated at Moscow State University. I graduated, and then became a post-doc at Lebedev Physical Institute, where I worked with David Kirzhnits, an expert in condensed matter physics, in astrophysics, in quantum field theory, and non-local theories, and everything else. He was a really amazing person. He discovered the theory of cosmological phase transitions, and I further developed it. So one of the things that became a basis for many inflationary models was that in the early universe, physics could be completely different, and there may have been no difference between the weak, strong and electromagnetic interactions.

Then for a while we thought that maybe this was just an exotic idea. I mean, not exotic. We knew that it was true, but we were afraid that it was untestable, like a platonic idea, of which we would never know any consequences. But we were overly pessimistic. Some consequences of what we studied included creation of strange objects in the early universe, which were called "primordial monopoles." If the theory we developed was right and if unified theories of weak, strong and electromagnetic interactions proposed in the '70s were right—and at that time everybody thought they were right—then in the process of the cosmological phase transitions in very early universe, when the whole world cooled down from its original hot state—which is what everybody believed it was—the theory predicted creation of some strange objects, which look like separate south and north magnetic poles.

If you cut a magnet into two pieces, each of its parts will always have both a south pole and a north pole; you cannot have a south pole or a north pole separately. But according to these unified theories, there would also be objects in the universe called "monopoles," each of them having either a south pole, or a north pole. And each of them would be a million billion times heavier than the proton. People then calculated how many there should be, and the answer was that the total number of monopoles right now should be approximately the same as the number of protons, which would make our universe a million billion times heavier than it is now. Such universe would be closed, and it would have collapsed already, in the first seconds of its evolution. Since we're still around, there's something wrong with this theory. So this was the primordial monopole problem. It was a consequence of the theory of cosmological phase transitions, which we developed.

Many people were trying to resolve this problem, and they could not. Somehow consistent solutions would not appear. Then, in parallel with these studies, we learned about a new cosmological theory proposed by Alexei Starobinsky in Russia, in '79 and '80. It was a rather exotic model where quantum corrections in quantum gravity produced the state of exponential expansion of the universe. This was a very interesting scenario, very similar to the inflation. But nobody called it inflationary theory because it was proposed a year before Alan Guth proposed his “old inflation.” It was called the "Starobinsky model." It was the number one subject of all discussions and debates at all cosmology conferences in Russia. But it did not propagate to the United States, and one of the reasons why it didn't was that the goal of Starobinsky was to solve the singularity problem, and the model did not quite solve it, and he did not attempt to solve other problems, which were addressed by inflationary cosmology.

In fact, he assumed that the universe was homogeneous from the very beginning. He did not try to explain why it was homogenous. Nevertheless, when we look back at the history of inflationary models, formally, this model had all the features of successful inflationary models, except for the problem with the beginning of an inflationary stage. And the motivation for this model was rather obscure. But it worked, or almost worked.

Then Alan Guth formulated his model. But I didn't know about it. I attended a seminar at the Institute of Nuclear Research in Moscow, sometime in '80. At that seminar, Valery Rubakov, one of the famous Russian scientists who still lives and works there, discussed the possibility of solving the flatness and homogeneity problems by exponential expansion of the universe due to cosmological phase transitions in the so-called Coleman-Weinberg model. They were discussing all of these things without knowing anything about the paper by Alan Guth. They explained the problems, and they also explained why their model didn't solve these problems. Then they sent the paper for publication, but it was not accepted, because by that time the paper by Alan Guth had already come out.

Thus I learned about the idea how one could solve many different cosmological problems during exponential expansion in the false vacuum, but I learned it not from Alan's paper, it happened quite a while before Alan's paper appeared in the Soviet Union, and the delay was just this mail delay. Moreover, I knew that one can have exponential expansion in the false vacuum since 1978, when we worked on it with Gennady Chibisov, but we found that this model does not work, and so we did not continue studying it; we did not know that it may be useful for solving many cosmological problems until Rubakov and his collaborators told us about it.

When Alan’s preprint arrived to Russia, Lev Okun, one of the famous Russian scientists, called me and asked: "You know, I heard something about the paper by Alan Guth who is trying to solve the flatness problem by exponential expansion of the universe. Have you heard about it, anything?" And I told him, "No, I have not heard anything about it, but let me tell you how it works, and let me tell you why it doesn't work, in fact." So for half an hour I explained to him Alan Guth's paper although I did not see it at that time, and explained to him why it didn't work. And then after a while I received Alan Guth's paper. We had been in correspondence with Alan some time before that, to discuss the cosmological phase transitions, the expansion of the universe, and bubbles. But we did not discuss the possibility to use it for solving cosmological problems.

So that was it. If I would want to write a paper about that, I could do it immediately after Okun called me, but it would be completely dishonest, so I did not even think about it, but of course I knew the basic ideas and I knew why they wouldn't work. So I didn't do anything. In fact, I was in a pretty depressed state because the idea, obviously, was very beautiful, and the idea that I'd learned from Rubakov was very, very beautiful. And it was a real pain that one could not make it work. The problems were extremely difficult.

A year later, Alan Guth, together with Eric Weinberg, wrote a 78-pages long paper proving that it was impossible to improve Alan’s model. Fortunately I received it already after I improved it. Again, many thanks to the slow mail from the United States to Russia. While they were working on the paper, I was working on a solution. I found the solution somewhere in the summer of '81. In order to check whether this solution was obvious or not, I called Rubakov to check with him, because he had first introduced me to this set of ideas. In fact, my solution was so obvious, so when it occurs to you, it's seems simple. You cannot understand why you did not think of it before.

I called him late in the evening. Because at that time my wife and kids were sleeping, I took the phone to our bathroom, and I was sitting on the floor there dialing him, checking with him, and he told me, "No, I haven't heard about it." So at that time I woke up my wife and I said, "You know, I think that I know how the universe was created." So I woke her up, anyway. And then I wrote—this was the summer of '81—I wrote a paper about it. But it took about 3 months to get permission for its publication.

At that time in Russia, if you wanted to send a paper in for publication abroad, first of all you had to do a lot of bureaucratic work in your institute: you typed it in Russian and got lots of signatures, then you sent it to the Academy of Sciences of the USSR, and they would send it to some other place that checked whether it was possible to publish it, or it contained some important secrets which should remain that way. Then you received it back, typed it once in English, for a preprint, and typed it the second time, the same thing, no Xeroxes. And only then you could send it for publication. But the whole procedure usually took two months, sometimes three months. I got permission only in October. But in October there was a conference in Moscow, on quantum cosmology. And the best people came. Stephen Hawking came, many other good people came, and I gave a talk on this. And people were kind of excited, really excited about this, and they immediately offered their help to smuggle it from Russia as a preprint, and they would send it for publication, permitted or not. You know, friends. Okay? Good friends can do it for you. But then there was an unexpected complication.

The next morning after I gave a talk at this conference, I found myself at the talk… oh, my God, this is going to be a funny story... I found myself at the talk by Stephen Hawking at Sternberg Institute of Astronomy in Moscow University. I came there by chance because I have heard from somebody that Hawking was giving a talk there. And they asked me to translate. I was surprised. Okay, I will do it. Usually at that time Stephen would give his talk well prepared, which means his student would deliver the talk, and Stephen from time to time would say something, and then the student would stop, and change his presentation and do something else. So Stephen Hawking would correct and guide the student. But in this case they were completely unprepared; the talk was about inflation. The talk was about the impossibility to improve Alan Guth's inflationary theory.

So they were unprepared, they just finished their own paper on it. As a result, Stephen would say one word, his student would say one word, and then they waited until Stephen would say another word, and I would translate this word. And all of these people in the auditorium, the best scientists in Russia, were waiting, and asking what is going on, what it is all about? So I decided let's just do it, because I knew what it's all about. So Stephen would say one word, the student would say one word, and then after that I would talk for five minutes, explaining what they were trying to say.

For about a half an hour we were talking this way and explained to everyone why it was impossible to improve Alan Guth's inflationary model, what are the problems with it. And then Stephen said something, and his students said: "Andrei Linde recently proposed a way to overcome this difficulty." I didn't expect it, and I happily translated it into Russian. And then Stephen said: "But this suggestion is wrong." And I translated it… For half an hour I was translating what Stephen said, explaining in great detail why what I'm doing is totally wrong. And it was all happening in front of the best physicists in Moscow, and my future in physics depended on them. I've never been in a more embarrassing situation in my life.

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Then the talk was over, and I said: “I translated, but I disagree," and I explained why. And then I told Stephen: "Would you like me to explain it to you in greater detail?" and he said, "Yeah." And then he rode out from this place, and we found some room, and for about two or three hours all the people in Sternberg Institute were in panic because the famous British scientist just disappeared, nobody knew where to.

During that time, I was near the blackboard, explaining what was going on there. From time to time, Stephen would say something, and his student would translate: “But you did not say that before.” Then I would continue, and Stephen would again say something, and his student would say again the same words: “But you did not say that before.” And after we finished, I jumped into his car and they brought me to their hotel. We continued the discussion, which ended by him showing me photographs of his family, and we became friends. He later invited me to a conference in Cambridge, in England, which was specifically dedicated to inflationary theory. So that's how it all started. It was pretty dramatic.

Because Stephen had made some objections to what I said, I polished the end of the paper to respond to some of his objections. I didn't give it to my friends to smuggle from Russia. So I sent it for publication in October. It arrived eventually to *Physics Letters*, but because it was delayed, it was published in '82 instead of '81. And I also sent lots of preprints to the United States, and one of them reached Paul Steinhardt and Andy Albrecht, who both worked on similar ideas. Three months after I sent my paper for publication, they sent for publication their own paper, with the same idea described in it, and with a reference to my work.

It was a miracle that the government allowed me to go to Cambridge. I had visited Italy previously, but then for a while, for some reasons, which were not explained to me, they were unwilling to let me go anywhere outside Soviet Union. But that time it had worked, and it was the most wonderful conference in my life. It was the first conference on inflationary cosmology attended by the best people in this area. Things really *happened* at this conference. It was magnificent. Three weeks of intense discussion and work together...

The conference was in summer 1982. The whole conference was about new inflation. I gave this name to the scenario that I developed. But this theory, just like the old scenario proposed by Guth, did not live long. Because of this symposium, new inflation in its original form essentially died in '82. The theory predicted too large perturbations of density. The model required modifications, and these modifications were such that there could be no thermal equilibrium in the universe, no cosmological phase transitions, so no way to realize a scenario like Alan Guth and I envisioned. Interestingly, most of the books on astronomy still describe inflation as exponential expansion during the cosmological phase transitions; this theory was so popular that nobody even noticed that it died back in `82. But a year later, in '83, I invented a different scenario, which was actually much simpler. It was chaotic inflation, and it did not require the universe to be hot to start with.

In the chaotic inflation scenario, one could have inflationary regime without assuming that the universe initially was hot. I abandoned the idea of the cosmological phase transitions, metastability, false vacua—most of the things that formed the basis for the old inflation model proposed by Guth and for my own new inflationary scenario. After all of these modifications, the inflationary regime became much simpler, more general, and it could exist in a much broader class of theories. In '86 I found that if we have inflation in the simplest chaotic inflation models, then, because of quantum fluctuations, inflation would go forever in some parts of the universe. Alex Vilenkin found a similar effect for the new inflation scenario. The effect that I have found was very generic, I called it "eternal inflation."

What Vilenkin studied was the theory of new inflation, and in new inflation you may start at the top of the potential energy, and the field does not know whether to roll down to the right, or to roll down to the left, so while you stay at the top, you're thinking you'll fall down, but you may think for a long time, and during this time expansion of the universe produces lots of volume. In chaotic inflation, where the potential energy has the simplest parabolic form, no specifically flat pieces of potential are required, you just take a model like that, and if the field is sufficiently high, there are quantum fluctuations, and the scalar field wants to go down, but quantum fluctuations sometimes throw it higher. The probability of jumping high is very small, but if you jump, you are exponentially rewarded by the creation of huge amounts of new volume of the universe. You start with a tiny part of the universe, and then it just spreads and spreads. It's like a chain reaction. It is called "branching diffusion process."

This is the basic idea of eternal inflation. In the paper of '86 where I discovered eternal chaotic inflation, I also noted that if you have eternal inflation in string theory, then the universe will be divided into enormous number of different exponentially large parts with different properties corresponding to large number of different stringy vacua, and that's an advantage. That was what later became string theory landscape.

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in the simplest chaotic inflation models, then, because of quantum fluctuations, inflation would go forever in some parts of the universe. Alex Vilenkin found a similar effect for the new inflation scenario. The effect that I have found was very generic, I called it "eternal inflation."

I should say that one of the most important predictions of inflation was the theory of quantum fluctuations, which give rise to galaxies eventually. Just think about it. If inflation were not to produce inhomogeneities, then when it blows up the universe and the universe becomes almost exactly homogenous, that would be the end of the game: No galaxies, no life. We would be unable to live in an exactly uniform universe, because it would be empty.

Fortunately, there was a way around it. Before I even introduced new inflation, I knew about an interesting work of two men from Lebedev Physical Institute, Gennady Chibisov and Slava Mukhanov. Mukhanov was younger, but he was the ideological leader in this group. By studying the Starobinsky model, which, as we now know, is a version of inflationary theory, they found that during inflation in Starobinsky model quantum fluctuations grow, and they may eventually give rise to galaxies. And we looked at them and said, "Oh, come on, guys. You cannot be right. It's impossible because galaxies are big classical objects. And you are starting with nothing. You start with quantum fluctuations.”

What they managed to explain to us, and this was an important ingredient that influenced everything we did later, was that these quantum fluctuations become essentially classical when the universe becomes large. They give rise to galaxy formation. Their paper of 1981 was the first paper on that subject.

After that, in '82, similar ideas were rediscovered by a group of people who were all at the Cambridge symposium. This group included Hawking, Starobinsky, Guth, Bardeen, Steinhardt and Turner. Their ideas were developed in application to new inflation, but it all started by Chibisov and Mukhanov in '81. And then Mukhanov continued studying it more and more, and he developed a general theory of these quantum fluctuations. From my perspective, this is one of the most important parts of inflationary theory. This is most important not only for the theory of galaxy formation. Chaotic eternal inflation would be impossible if not for these quantum fluctuations.

Some of the most interesting recent developments of inflationary cosmology are related to string theory. My understanding of this theory is based in part on my collaboration with my wife, Renata Kallosh. She is also a Professor of Physics at Stanford; she studies supergravity and string theory. So let me tell you about these theories just a little.

During the last years of his life, Einstein dreamed about final theory, which would unify symmetries of space with symmetries of elementary particles. And he failed. I was told that during the last years of his life he continued writing on the blackboard, filling it with equations of the new theory, and although he could not successfully finish it, he was still happy. Then people learned there is a no-go theorem. One just cannot do it, period. It is impossible to realize Einstein's dream of a unified theory of everything.

Then other people found that there was a loophole in the no-go theorem. If the theory has a special symmetry, supersymmetry, relating to each other bosons (scalar fields, photons) and fermions (quarks and leptons), then these no-go theorems go away.

Thus it all began with supersymmetry, and then it became a more advanced theory, supergravity. One could unify the theory of gravity with the theory of elementary particles. It was fantastic. The theory flourished in the middle of the '70s up to the '80s. It resolved some problems of quantum gravity. Some infinite expressions, which appeared in calculations in quantum theory of gravity, disappeared in supergravity. Everybody was ecstatic until the moment they found that these infinities might still appear in supergravity in the third approximation, or maybe in the eighth approximation. Something was not quite working. Although some of the very recent results suggest that maybe people were too pessimistic at that time, and maybe some versions of the theory of supergravity are quite good.

But at that time, they looked at it and said: "Okay, it doesn't work, there are some problems with the theory, can we do something about it?" The next step was the theory of superstrings. The development of science was not like, "Oh, come on, we can go to the right, we can go to the left, we can go anywhere, let's go straight." No, it was not like that. We wanted to achieve unity of all forces, and because of the no-go theorem, there was no way to do it except using supersymmetry. Then it becomes supergravity. You just must have it if you want to describe curved space in supersymmetric theories. Now you have supergravity, but sorry, it does not quite work, you need to somehow generalize it, and then string theory was developed.

This was like a valley in the mountains. It is not about going to the right, or to the left. Your valley shows you the best way, maybe even the only way. That's how people came to string theory, and then they became very optimistic. This was '85. They were thinking they would do everything pretty quickly. I must say that not everybody was so optimistic at that time. In particular, John Schwartz, one of the fathers of string theory, said, "Oh, well. It may actually take more than 20 years for string theory to come to fruition as a phenomenological theory of everything." He made a warning. Well, enthusiasm was, nevertheless, overwhelming, which was good and bad. It was good because so many talented young people entered into the field. It was bad because the supergravity tradition was partially forgotten. In Europe, the supergravity tradition is still alive, very much so. In the United States, it's not that much.

String theory is based on the idea that our universe fundamentally has more dimensions, not just four. This idea was also part of some versions of supergravity. It was also a part of Kaluza-Klein theory long time ago. The standard attitude was that string theory required an assumption that our space is 10-dimensional, and six dimensions should be compactified. After that, we have three large dimensions of space, and one time. The other six dimensions would be very small. Superstring people often use Calabi-Yau space to describe compactification of six extra dimensions. This space may have a very complicated topology.

The question, though, was how do we know that this is true? For a long time nobody could construct a working mechanism that would allow Calabi-Yau space to be really small. Why do we need it to be small? Because we cannot move in these six dimensions, we are too big for that. We can go to the right, to the left, and upward, but we cannot go in six other directions. At least nobody told me that they tried, had been there.

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Six dimensions. We need to explain why they are small. There was a property, an unfortunate property of string theory that, if treated naively, without any special effort, then these six dimensions actually want to decompactify, want to spread out, become large. There could be many ways of compactifying space, which is the origin of many different vacua in string theory. But nevertheless, the problem was how to keep these extra dimensions small.

The attitude was, oh, well, we will do something. We will do something. But this "we will do something" continued for almost 20 years. Nobody took this problem too seriously because there were lots of other problems in string theory, and they thought: let's just go forward. But we needed to study these string vacua. "Vacuum" means the state that looks empty from our 4-dimensional point of view, but its properties depend on the properties of the compactified Calabi-Yau space, the compactified six dimensional space. Vacuum does not contain particles. If we add the particles, then we can have our universe. This vacuum, this place without particles, galaxies, us—what properties does this vacuum have? As I said, in order to study it consistently, we need to have stable compactification of extra 6 dimensions of space. There are also other fields in this theory, which need to be stabilized. People did not know how to do it, but for a while it was not such an urgent problem.

But then in the end of the '90s, cosmologists discovered exponential, accelerating expansion of our universe, which happens because of what people call dark energy, or cosmological constant. This discovery made a very strong impact on the development of string theory.

The rumor was that at a conference in India, Ed Witten, who is the leading authority in string theory, said that he didn't actually know how to explain acceleration of the universe in the context of string theory, and when Ed Witten doesn't know something, people start taking it seriously, and panicking a bit. So at that moment they started really paying attention to the properties of vacuum in string theory. They wanted to explain this exponential expansion of the universe, which apparently started about five billion years ago, and it goes on very slowly. So people started trying to explain it, and it didn't work. Then they started thinking even more attentively about this problem, what actually defines this vacuum state, what stabilizes it.

In 2003, I was part of a group at Stanford (Kallosh, Kachru, Linde and Trivedi) that proposed a possible solution of this problem. There were some earlier works, I must say, which came very close to a solution. And now there are some other ways of doing it. But this was kind of like a point of crystallization, where people have realized that we can actually solve the problem and stabilize the vacuum in string theory.

When we found a way to do it, it was immediately realized that there are exponentially many ways to do it. People who estimated the total number of different ways to stabilize the vacuum in string theory came up with astonishing numbers, like 10^{500}. Michael Douglas and his collaborators made this estimate. And this fact has profound cosmological implications. If you marry string theory with the theory of eternal inflation, then one can have one type of vacuum in one part of the universe, another vacuum in another part of the universe, and it is possible to jump from one vacuum to another due to quantum effects. Lenny Susskind gave this scenario a very catchy name, string theory landscape.

What I mean is that when we're talking about this vacuum state, vacuum state means homogenous state describing our three dimensions, three dimensions plus one. But the remaining six dimensions, they may squeeze like this, or they may squeeze like that. There are lots of different topologies in it. In addition to different topologies, there are different fields, which may exist in this six-dimensional space, so-called fluxes.

There are other objects which may exist there, and which may determine properties of our space. In our space we do not see them, they are in this tiny six-dimensional compactified space. But they determine properties of our vacuum, in particular vacuum energy density. The level of this vacuum energy depends on what is going on there, in the compactified space. Properties of elementary particle physics depend on what happens there. If you have many different ways of compactification, you have the same string theory fundamentally, but your world, three-dimensional space and one time, will have completely different properties. That is what is called string theory landscape, you have the same string theory, but you have many different realizations of that. That is exactly what I envisioned in my paper on eternal chaotic inflation in '86: We have lots of possibilities, and this is good.

But in ’86 we did not know a single example of a stable string theory vacuum; we just expected that there should be exponentially many such vacua. In 2003 we learned how to find such vacua, and then it was realized that indeed there a lots and lots of them. So that is the present view.

Let me say a few words about what I'm studying right now. 10^{500} is an abnormally large number, it tells you how many choices of vacua do you have. You have this huge amount of possibilities. And by the way, there is a question, which many people ask: “How do you know?” How do we know that we have this multitude, that these other parts of the universe are somewhere inside our universe?

This is the picture: the universe is very, very big, and it is divided into parts. Here is one realization of the string of vacua. There, in the same universe, but far away from us, it's a different vacuum. The guys here and there do not know about each other because they're exponentially far apart. That's important to understand in order to have a vision of the universe. It's important that you have a choice. But if you do not see these parts, how do you know that they actually exist, and why do you care?

Usually I answer in the following way: If we do not have this picture, then we cannot explain many strange coincidences, which occur around us. Like why vacuum energy is so immensely small, incredibly small. Well, that is because we have many different vacua, and in those vacua where vacuum energy is too large, galaxies cannot form. In those vacua, where energy density is negative, the universe rapidly collapses, and in our vacuum the energy density is just right, and that is why we live here. That's the anthropic principle. But you cannot use anthropic principle if you do not have many possibilities to choose from. That's why multiverse is so desirable, and that's what I consider experimental evidence in favor of multiverse.

I introduced anthropic principle in the context of inflationary multiverse back in '82. The idea of new inflation was proposed in '81, and then in '82 I had written two papers where I emphasized anthropic principle in the context of inflationary cosmology. I said that the universe may consist of many different exponentially large parts. I did not use the word “multiverse”, I just said that the universe may consist of many, many mini-universes with different properties, and I've studied this possibility since that time for many, many years.

But what is important is that when we studied inflationary theory, we started asking questions which seemed to be metaphysical, like why parallel lines do not intersect, why the universe is so big. And if we had said, "Oh, my God, these are metaphysical questions, we should not venture into it," then we would never have discovered the solutions. Now we're asking metaphysical questions about anthropic principle, about stuff like that, and many, many people tell us, "Don't do it, this is bad, this is the "a" word (anthropic). You should avoid it."

We shouldn't avoid anything. We should try to do our best to use the simplest explanations possible, or what proves simplest, and if something falls into your hands as an explanation of why cosmological constant vacuum energy is so small, and you decide not to accept it for ideological reasons, this is very much what we had in Russia long ago. That ideology told me which type of physics was right and which type of physics was wrong. We should not proceed this way. Once you have multiple possibilities, then you can have scientific premises for anthropic considerations, not just philosophically talking about “other worlds”. Now we have a consistent picture of the multiverse, so now we can tell: "this is physics, this is something serious." That was about multiverse and different versions of it.

When you look at our own part of the universe, you have a galaxy to the right of you, you have a set of galaxies to the left of you. Could it be that our universe was formed differently? Is there a chance that me, my copy, might live somewhere far away from me? How far away from me? Why my exact copy? Well, because quantum fluctuations produce different universes over and over again. Alex Vilenkin has this description of "many worlds in one." He had written a book about it. The question is, how many of these different types of the universes you can produce. And “different types of universes” does not just mean vacuum states, but different distributions of matter. The distribution of matter in our part of the universe, the distribution of galaxies, is determined by quantum fluctuations, which were produced during inflation.

For example, you may have a scalar field that rolls down slowly, which is how inflation ends, but then quantum fluctuations push it locally up just a little. Then in these places, energy of the universe will locally increase. Then it becomes very, very big, and at this part you'll see a galaxy in the place where you live. If the jump will be down, then in this place you will see no galaxies. When this happens during inflation over and over again at different scales, then you check, how many different jumps, or kinds of configurations of jumps, have there been?

These jumps produce what later looks like different classical universes, galaxy here, void there. How many possibilities are there? And the answer, and this is purely a combinatorial answer, is that if n is the number of times the size of the universe doubled during inflation, and you take 2^{3n}, this will show you the volume of the universe after inflation. Where the volume grows by 2^{3n}, the total number of possible configurations, which may occur there because of these quantum jumps, will be also proportional to 2^{3n}. This will give you the total number of possible configurations of matter that you can produce during inflation, and this number typically is much, much greater than 10^{500}.

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Of course, during eternal inflation, inflation goes forever, so one could even expect that this number is infinite. However, during eternal inflation each jump can be repeated; it can repeat itself. Scalar field jumps again to the state where it jumps again, to a state where it jumps again, and eventually it start producing identical configurations of matter.

Think about it this way: previously we thought that our universe was like a spherical balloon. In the new picture, it's like a balloon producing balloons, producing balloons. This is a big fractal. The Greeks were thinking about our universe as an ideal sphere, because this was the best image they had at their disposal. The 20th century idea is a fractal, the beauty of a fractal. Now, you have these fractals. We ask, how many different types of these elements of fractals are there, which are irreducible to each other? And the number will be exponentially large, and in the simplest models it is about 10 to the degree 10, to the degree 10, to the degree 7. It actually may be much more than that, even though nobody can see all of these universes at once.

Soon after Alan Guth proposed his version of the inflationary theory, he famously exclaimed that the universe is an ultimate free lunch. Indeed, in inflationary theory the whole universe emerges from almost nothing. A year later, in the proceedings of the first conference on inflation in Cambridge, I expanded his statement by saying that the universe is not just a free lunch; it is an eternal feast where all possible dishes are served. But at that time I could not even imagine that the menu of all possible universes could be so incredibly large.