The Origin of the Universe

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Can you hear me.

Hubble’s discovery of the expansion of the universe, was one of the most important intellectual discoveries of the 20th century, or of any century. It transformed the debate about whether the universe had a beginning. If one traces the motion of the galaxies back in time, they would all have been on top of each other about 14 billion years ago. Georges Lemaitre was the first to propose a model in which the universe had such an infinitely dense beginning. So he, not George Gamow, is the father of the big bang.

Observational evidence, to confirm the idea that the universe was initially in a very dense state, came in October 1965, with the discovery of a faint background of microwaves throughout space. The only plausible explanation for the existence of this background of microwaves, is that it is radiation left over from an early time, when the universe was very hot and dense. As the universe expanded, the radiation cooled, until it is just the faint remnant we can detect today.

In order to understand the origin of the universe, we need to combine the general theory of relativity, with quantum theory. The best way of doing so, seems to be to use Feinman's idea of a sum over histories. Richard Feinman proposed that in quantum theory, a system gets from a state A, to a state B, by every possible path or history. In Feinman's picture, the probability for a state of the universe at the present time, is given by adding up the amplitudes for all the histories that end with that state. But how did the histories start.

It was at a conference in the Vatican, in 1981, that I first put forward the suggestion, that maybe time and space together, formed a surface that was finite in size, but did not have any boundary or edge. Together with James Hartle from the University of California, I worked out what physical conditions the early universe must have, if space time had no boundary in the past.

Our model became known as the no boundary proposal. It says that when we go back towards the beginning of our universe, space and time become fuzzy, and cap off, somewhat like the South Pole on the surface of the Earth. Asking what came before the Big Bang, is meaningless, according to the no boundary proposal, because there is no notion of time available to refer to. It would be like asking what lies South of the South Pole.

The no boundary proposal is a model of the physical conditions at the beginning. It describes how our familiar notions of space and time can come into being, thus realizing Georges Lemaitre’s vision. The same laws of nature hold at the South Pole, as in other places. This would remove the age-old objection to the universe having a beginning, that it would be a place where the normal laws broke down. The beginning of the universe would be governed by the laws of science.

The no boundary proposal cannot be deduced from some other principle. Like any other scientific theory, however, the real test is whether it makes predictions that agree with observations.

With my colleagues, James Hartle, and Thomas Hertog from the University of Leuven, we set out to calculate, what kind of universe would emerge from the Big Bang, according to the no boundary proposal. One of the most remarkable predictions of the no boundary proposal, we found, is that it predicts our universe came into existence with a burst of inflation. Inflation is a brief phase in the earliest moments of our universe's history, in which space expands at an ever increasing rate. In a fraction of a second, inflation takes the universe from a single point, to what we observe today.

Unlike inflation in prices, inflation in the early universe is a very good thing. It produces a very large and uniform universe, just as we observe. However, it would not be completely uniform. In the quantum sum over histories, histories that are very slightly irregular, will have almost as high probabilities, as the completely

uniform and regular history. The theory therefore predicts, that the early universe is likely to be slightly non-uniform. These irregularities would produce a characteristic pattern of small variations, in the intensity of the microwave background, from different directions.

As successive generations of space telescopes have measured the microwave background radiation, with increasing precision, this prediction has proved to be correct. There are indeed changes in the intensity of the radiation, at the level of about one part in one hundred thousand, and their precise pattern agrees with the specific predictions of inflation, combined with the no boundary proposal.

The irregularities in the early universe, mean that some regions will have slightly higher density than others. The gravitational attraction of the extra density, will slow the expansion of the region, and can eventually cause the region to collapse to form galaxies and stars. So look well at the map of the microwave sky. It is the blue print for all the structure in the universe. We are the product of quantum fluctuations in the very early universe.

However, there is one key prediction of the theory, which has yet to be verified. According to inflation, a small part of the fluctuations in the microwave radiation, can be traced to gravitational waves, generated during the phase of rapid expansion. This part shows up most clearly in the polarization of the radiation. We are only in the early stages of measuring this polarization, and there is real hope it will provide firm and convincing evidence for the theory.

These developments mean that in the last two decades, the theory of inflation and the no boundary proposal, has been transformed from speculation, into a cornerstone of modern cosmology. But not everyone likes its conclusions, since at the same time, it is thought that the theory gives rise to a vast number of different universes, known collectively as the multiverse, which exist in parallel, thereby limiting its predictive power.

The multiverse arises in inflation, from the same quantum mechanical effect, that leads to the irregularities in the early universe, seen in the microwave background. This is because if one traces the universe's history backwards in time, deep into the phase of inflation, one can encounter a regime of eternal inflation. In eternal inflation, the quantum fluctuations in the energy density of the matter, that drives the inflationary expansion, are large. This can keep inflation going forever in some regions of the universe. Our observable universe, would then become a local pocket universe, a region in which inflation has ended. Globally, the universe would have a highly complicated structure, and would consist of infinitely many such pocket universes, separated from each other by an eternally inflating ocean. The local laws of physics and chemistry can differ, from one pocket universe to another, which together form a multiverse. These different universes exist in parallel, in the no boundary proposal. If there is indeed an exceedingly wide variety of them, the theory will predict hardly any features, of our own observable pocket universe.

However, I want to argue the usual theory of inflation breaks down in eternal inflation.

In the usual account of eternal inflation, which I just gave, one assumes an inflating background universe, that evolves according to Einstein's classical theory of Relativity. The quantum evolution of the fluctuations around this background, is described using stochastic methods. Because the stochastic effects are large, it is argued eternal inflation produces an infinitely large universe, that is globally highly irregular, consisting of a mosaic of pocket universes, separated by inflationary domains. However this account is questionable, because the dynamics of eternal inflation, wipes out the separation into classical backgrounds and quantum fluctuations, that is assumed.

To make progress, Hertog and I, have recently studied eternal inflation, from a different viewpoint. Our approach is based on the concept of holography, in string theory. Holography says that Einstein's theory of gravity and space time, is equivalent, or dual, to a theory without gravity, that is defined on the boundary of space time. We have used holography, to excise the phase of eternal inflation in our past, and replace it by a dual theory, defined on the global exit surface from eternal inflation. This amounts to a refinement of the no boundary proposal, in which our universe does have a boundary in the past, that is at the threshold for eternal inflation.

The dual theory defined on this past boundary, provides an approximate description, of the transition from the quantum dynamics of eternal inflation, to a universe with classical notions of space and time.

One can use the dual theory, to calculate more reliably the probabilities of different shapes of the global exit surface, from eternal inflation. We find that the amplitude for highly irregular surfaces, is much lower than what the old theory of eternal inflation indicated. We take this as evidence, that the probability is low for universes with a highly complicated global structure. This raises doubts about the widely accepted idea, that eternal inflation gives rise to an infinitely large universe, that contains a broad variety of different pocket universes. Instead we conjecture, that the end of eternal inflation is reasonably smooth, leading to a much simpler universe, which is globally finite.

This would imply a significant reduction of the multiverse, to a much smaller set of universes. Not all universes in this multiverse will be habitable. Some pockets are not sufficiently long-lived, and others do not develop large-scale structures, such as galaxies, that can potentially harbour life. We may not live in the most probable of all universes. Rather we live in one, where the conditions are favourable for complexity, and the development of life. This basic fact signals a reversal from a Copernican world view, according to which our place in the universe is in no respect special. In a multiverse, we play a part in selecting the universe's history. Our observations today, give reality to what happened back then. In order to derive predictions for our observations from a theory of cosmology, one must take into account this perspective, that we are physical systems within the universe.

Thank you for listening.