# A GOLDEN AGE OF COSMOLOGY

*A Conversation With*

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Even though cosmology doesn't have that much to do with information, it certainly has a lot to do with revolution and phase transitions. In fact, it is connected to phase transitions in both the literal and the figurative sense of the phrase.

It's often said — and I believe this saying was started by the late David Schramm — that today we are in a golden age of cosmology. That's really true. Cosmology at this present time is undergoing a transition from being a bunch of speculations to being a genuine branch of hard science, where theories can be developed and tested against precise observations. One of the most interesting areas of this is the prediction of the fluctuations, the non-uniformities, in the cosmic background radiation, an area that I've been heavily involved in. We think of this radiation as being the afterglow of the heat of the Big Bang. One of the remarkable features of the radiation is that it's uniform in all directions, to an accuracy of about one part in a hundred thousand, after you subtract the term that's related to the motion of the earth through the background radiation.

I've been heavily involved in a theory called the inflationary universe, which seems to be our best explanation for this uniformity. The uniformity is hard to understand. You might think initially that maybe the uniformity could be explained by the same principles of physics that cause a hot slice of pizza to get cold when you take it out of the oven; things tend to come to a uniform temperature. But once the equations of cosmology were worked out, so that one could calculate how fast the universe was expanding at any given time, then physicists were able to calculate how much time there was for this uniformity to set in.

They found that, in order for the universe to have become uniform fast enough to account for the uniformity that we see in the cosmic background radiation, information would have to have been transferred at approximately a hundred times the speed of light. But according to all our theories of physics, nothing can travel faster than light, so there's no way that this could have happened. So the classical version of the Big Bang theory had to simply start out by assuming that the universe was homogeneous — completely uniform — from the very beginning.

The inflationary universe theory is an add-on to the standard Big Bang theory, and basically what it adds on is a description of what drove the universe into expansion in the first place. In the classic version of the Big Bang theory, that expansion was put in as part of the initial assumptions, so there's no explanation for it whatever. The classical Big Bang theory was never really a theory of a bang; it was really a theory about the aftermath of a bang. Inflation provides a possible answer to the question of what made the universe bang, and now it looks like it's almost certainly the right answer.

Inflationary theory takes advantage of results from modern particle physics, which predicts that at very high energies there should exist peculiar kinds of substances which actually turn gravity on its head and produce repulsive gravitational forces. The inflationary explanation is the idea that the early universe contains at least a patch of this peculiar substance. It turns out that all you need is a patch; it can actually be more than a billion times smaller than a proton. But once such a patch exists, its own gravitational repulsion causes it to grow, rapidly becoming large enough to encompass the entire observed universe.

The inflationary theory gives a simple explanation for the uniformity of the observed universe, because in the inflationary model the universe starts out incredibly tiny. There was plenty of time for such a tiny region to reach a uniform temperature and uniform density, by the same mechanisms through which the air in a room reaches a uniform density throughout the room. And if you isolated a room and let it sit long enough, it will reach a uniform temperature as well. For the tiny universe with which the inflationary model begins, there is enough time in the early history of the universe for these mechanisms to work, causing the universe to become almost perfectly uniform. Then inflation takes over and magnifies this tiny region to become large enough to encompass the entire universe, maintaining this uniformity as the expansion takes place.

For a while, when the theory was first developed, we were very worried that we would get too much uniformity. One of the amazing features of the universe is how uniform it is, but it's still by no means completely uniform. We have galaxies, and stars and clusters and all kinds of complicated structure in the universe that needs to be explained. If the universe started out completely uniform, it would just remain completely uniform, as there would be nothing to cause matter to collect here or there or any particular place.

I believe Stephen Hawking was the first person to suggest what we now think is the answer to this riddle. He pointed out — although his first calculations were inaccurate — that quantum effects could come to our rescue. The real world is not described by classical physics, and even though this was very "high-brow" physics, we were in fact describing things completely classically, with deterministic equations. The real world, according to what we understand about physics, is described quantum-mechanically, which means, deep down, that everything has to be described in terms of probabilities.

The "classical" world that we perceive, in which every object has a definite position and moves in a deterministic way, is really just the average of the different possibilities that the full quantum theory would predict. If you apply that notion here, it is at least qualitatively clear from the beginning that it gets us in the direction that we want to go. It means that the uniform density, which our classical equations were predicting, would really be just the average of the quantum mechanical densities, which would have a range of values which could differ from one place to another. The quantum mechanical uncertainly would make the density of the early universe a little bit higher in some places, and in other places it would be a little bit lower.

So, at the end of inflation, we expect to have ripples on top of an almost uniform density of matter. It's possible to actually calculate these ripples. I should confess that we don't yet know enough about the particle physics to actually predict the amplitude of these ripples, the intensity of the ripples, but what we can calculate is the way in which the intensity depends on the wavelength of the ripples. That is, there are ripples of all sizes, and you can measure the intensity of ripples of different sizes. And you can discuss what we call the spectrum — we use that word exactly the way it's used to describe sound waves. When we talk about the spectrum of a sound wave, we're talking about how the intensity varies with the different wavelengths that make up that sound wave.

We do exactly the same thing in the early universe, and talk about how the intensity of these ripples in the mass density of the early universe varied with the wavelengths of the different ripples that we're looking at. Today we can see those ripples in the cosmic background radiation. The fact that we can see them at all is an absolutely fantastic success of modern technology. When we were first making these predictions back in 1982, at that time astronomers had just barely been able to see the effect of the earth's motion through the cosmic background radiation, which is an effect of about one part in a thousand. The ripples that I'm talking about are only one part in a hundred thousand — just one percent of the intensity of the most subtle effect that it had been possible to observe at the time we were first doing these calculations.

I never believed that we would ever actually see these ripples. It just seemed too far fetched that astronomers would get to be a hundred times better at measuring these things than they were at the time. But, to my astonishment and delight, in 1992 these ripples were first detected by a satellite called COBE, the Cosmic Background Explorer, and now we have far better measurements than COBE, which had an angular resolution of about 7 degrees. This meant that you could only see the longest wavelength ripples. Now we have measurements that go down to a fraction of a degree, and we're getting very precise measurements now of how the intensity varies with wavelength, with marvelous success.

About a year and a half ago, there was a spectacular set of announcements from experiments called BOOMERANG and MAXIMA, both balloon-based experiments, which gave very strong evidence that the universe is geometrically flat, which is just what inflation predicts. (By flat I don't mean two-dimensional; I just mean that the three-dimensional space of the universe in not curved, as it could have been, according to general relativity.) You can actually see the curvature of space in the way that the pattern of ripples has been affected by the evolution of the universe. A year and a half ago, however, there was an important discrepancy that people worried about; and no one was sure how big a deal to make out of it. The spectrum they were measuring was a graph that had, in principle, several peaks. These peaks had to do with successive oscillations of the density waves in the early universe, and a phenomenon called resonance that makes some wavelengths more intense than others. The measurements showed the first peak beautifully, exactly where we expected it to be, with just the shape that was expected. But we couldn't actually see the second peak.

In order to fit the data with the theories, people had to assume that there were about ten times as many protons in the universe as we actually thought, because the extra protons would lead to a friction effect that could make the second peak disappear. Of course every experiment has some uncertainty — if an experiment is performed many times, the results will not be exactly the same each time. So we could imagine that the second peak was not seen purely because of bad luck. However, the probability that the peak could be so invisible, if the universe contained the density of protons that is indicated by other measurements, was down to about the one percent level. So, it was a very serious-looking discrepancy between what was observed and what was expected. All this changed dramatically for the better about 3 or 4 months ago, with the next set of announcements with more precise measurements. Now the second peak is not only visible, but it has exactly the height that was expected, and everything about the data now fits beautifully with the theoretical predictions. Too good, really. I'm sure it will get worse before it continues to get better, given the difficulties in making these kinds of measurements. But we have a beautiful picture now which seems to be confirming the inflationary theory of the early universe.

Our current picture of the universe has a new twist, however, which was discovered two or three years ago. To make things fit, to match the observations, which are now getting very clear, we have to assume that there's a new component of energy in the universe that we didn't know existed before. This new component is usually referred to as "dark energy." As the name clearly suggests, we still don't know exactly what this new component is. It's a component of energy which in fact is very much like the repulsive gravity matter I talked about earlier — the material that drives the inflation in the early universe. It appears that, in fact, today the universe is filled with a similar kind of matter. The antigravity effect is much weaker than the effect that I was talking about in the early universe, but the universe today appears very definitely to be starting to accelerate again under the influence of this so-called dark energy.

Although I'm trying to advertise that we've understood a lot, and we have, there are still many uncertainties. In particular, we still don't know what most of the universe is made out of. There's the dark energy, which seems to comprise in fact about 60% of the total mass/energy of the universe. We don't know what it is. It could in fact be the energy of the vacuum itself, but we don't know that for a fact. In addition, there's what we call dark matter, which is another 30%, or maybe almost 40%, of the total matter in the universe; we don't know what that is, either. The difference between the two is that the dark energy causes repulsive gravity and is smoothly distributed; the dark matter behaves like ordinary matter in terms of its gravitational properties — it's attractive and it clusters; but we don't know what it's made of. The stuff we do know about — protons, neutrons, ordinary atoms and molecules — appear to comprise only about 5% of the mass of the universe.

The moral of the story is we have a great deal to learn. At the same time, the theories that we have developed so far seem to be working almost shockingly well.