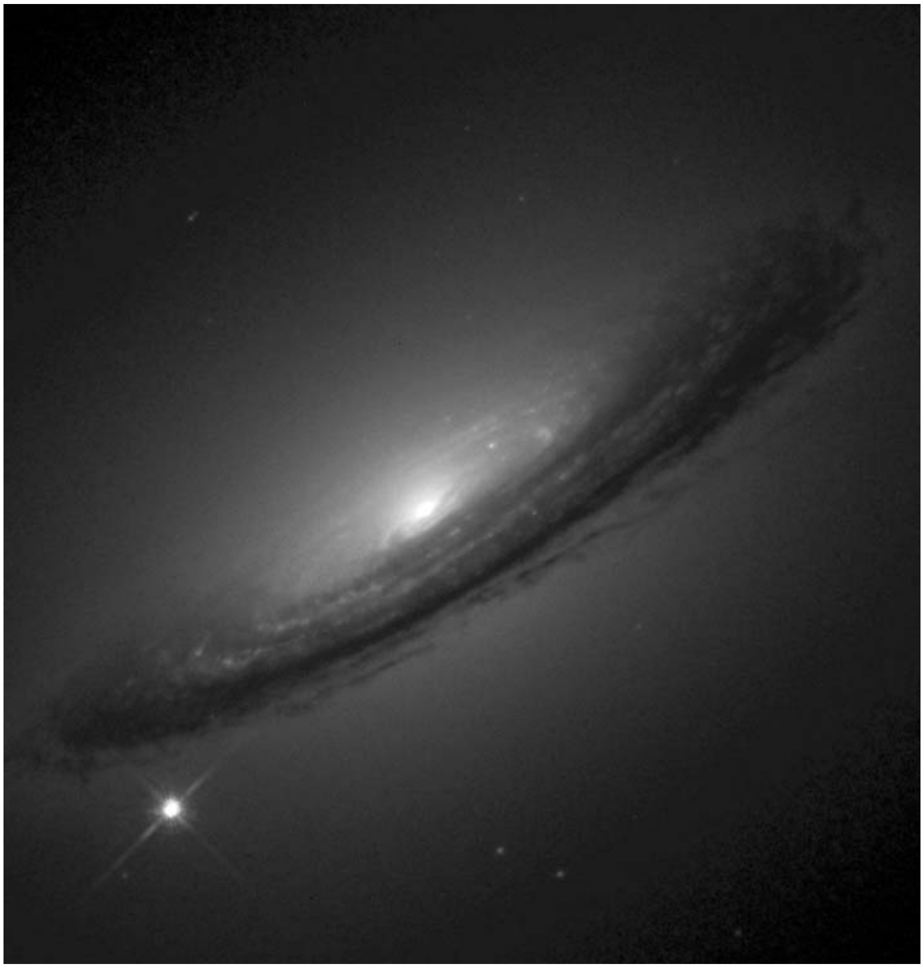

NASA: HST image of SN1994D. Figure courtesy of NASA.

Are There Limits To Our Cosmic Arrogance?

Michael S. Turner

This essay is based on Michael Turner's presentation that was given at the Academy's Midwest Center's Stated Meeting, held at the Adler Planetarium in Chicago on November 1, 2003.

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From Quark Soup to the Expanding Universe

Cosmologists are arrogant. They believe they can determine how the universe began and how it has evolved thus far. They also aspire to understand its ultimate destiny. As a cosmologist, I must defend this arrogance. Without it, we would have never undertaken the seemingly impossible task of trying to figure out the universe – fourteen billion years of history (thus far) stretched across a trillion trillion kilometers of observable space. And, as if that were not enough, we have to do this sitting on a tiny rock, which orbits a very ordinary star within a slightly above average galaxy.

The past century's cosmologists have much to fuel their arrogance. The hot big bang theory charts the evolution of the universe from the hot, formless, quark soup that existed earlier than 0.00001 seconds, to the universe we see fourteen billion years later, one comprised of hundreds of billions of galaxies. The grand adventure began in the 1920s when Edwin Powell Hubble established that galaxies are the building blocks of the universe and discovered that all the galaxies visible in the sky (in Hubble's time, only a few hundred) are moving away from our own Milky Way. Einstein's theory of gravity provided the theoretical foundation: space and time are flexible, and Hubble's observations are a manifestation of an expansion of space that moves galaxies away from one another.

Since then, cosmologists have imaged hundreds of millions of galaxies and mapped the large-scale features of the universe, including great clusters of galaxies, superclusters of clusters, giant voids (great regions of space populated with very few galaxies), and great walls (sheets comprised of tens of thousands of galaxies). The Hubble Space Telescope has revealed the birth of galaxies (figure 1); the Chandra X-ray Observatory has glimpsed billion-solar-mass black holes that formed less than a billion years after the beginning; and microwave telescopes have imaged the universe as it was when it was only four hundred thousand years old and atoms were forming (figure 2).

Still, cosmologists are not satisfied. We aspire to trace our cosmic origins back to before the quark soup – to the subatomic quantum fluctuations that we think seeded the galaxies, clusters of galaxies, and even larger structures. We want to understand the nature of the mysterious dark matter that holds the universe together, and of the dark energy that is causing its expansion to speed up. With ideas as bold as was Einstein's relativity theory ninety years ago, and new, more powerful instruments made possible by great technological advances, the flyboys of today's science speak of a golden age in cosmology – and it is hard to argue with us!

Inner Space/Outer Space Connections

The key idea powering the current cosmological revolution is the deep connection that exists between the inner space of the elementary particles and the outer space of the cosmos. These connections go well beyond the fact that the infant universe was a soup of elementary particles, and they are well illustrated by the guiding paradigm of cosmology today, "Inflation + Cold Dark Matter." This theory holds that "our universe" was created in a burst of expansion (called cosmic inflation) powered by "false-vacuum" energy. Because of that explosive growth spurt, all that we can and will ever be able to see originated from the tiniest bit of the pre-inflationary landscape. This explains why the universe we observe is so uniform (on the large scale, it looks the same everywhere and in all directions), and predicts space is uncurved, or is "flat" (Einstein's theory allows for space to be curved; the inflationary burst flattens any spatial curvature).

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This burst of expansion was our big bang event, and the demise of the false-vacuum energy that caused it was the origin of the heat of the big bang (seen today in the cosmic microwaves that fill space) and ultimately all forms of matter and energy within it. If inflation occurred once, there is every reason to believe that it has occurred an infinite number of times in the past and will continue with this frequency in the future. Inflation sidesteps the issue of "The Beginning," changes "The Big Bang" into countless "big bangs," and leads to a universe that is actually a multiverse comprised of countless bubble universes.

The Cold Dark Matter part of the theory purports that the matter holding our universe together is not the star stuff that we are made of, but rather slowly moving elementary particles (called Cold Dark Matter) left over from the earliest fiery moments (see figure 3). Owing to quantum fluctuations on subatomic scales blown up to astronomical size during inflation, the Cold Dark Matter is not uniformly distributed; it is a little lumpy (with variations in the density of around 1 part in 100,000). Gravity acting over the past fourteen billion years has turned this lumpiness into all the cosmic structure that we see today. The gravity of the Cold Dark Matter particles provides the cosmic infrastructure that holds together galaxies including our own Milky Way, the great clusters of galaxies and superclusters. The atomic matter within galaxies further condenses and forms the stars that light up these objects.

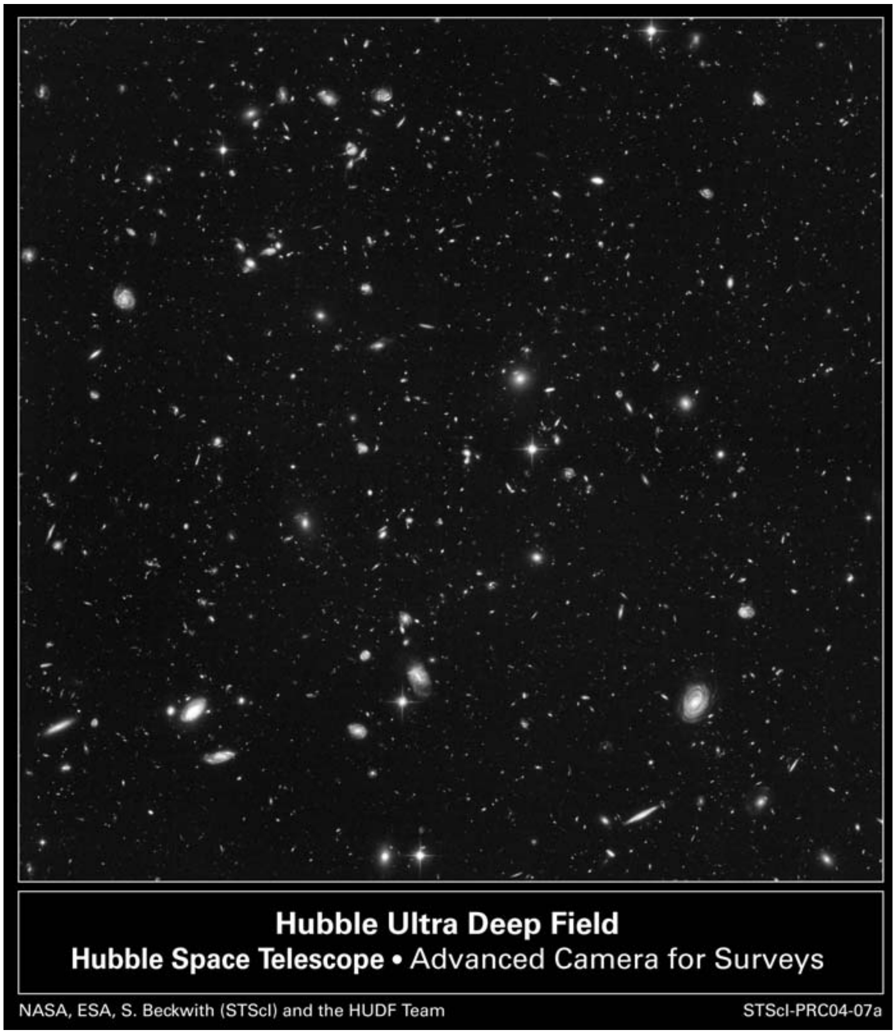

Figure 1: The HST Ultra Deep Field. In this small patch of the sky (one ten millionth of the entire sky), imaged by the Hubble Space Telescope for almost two weeks, there are ten thousand galaxies. The light from most of the galaxies originated when the universe was a few billion years old or less. This is as far as one can see because one is looking back to the time when galaxies were just forming. Figure courtesy of NASA.

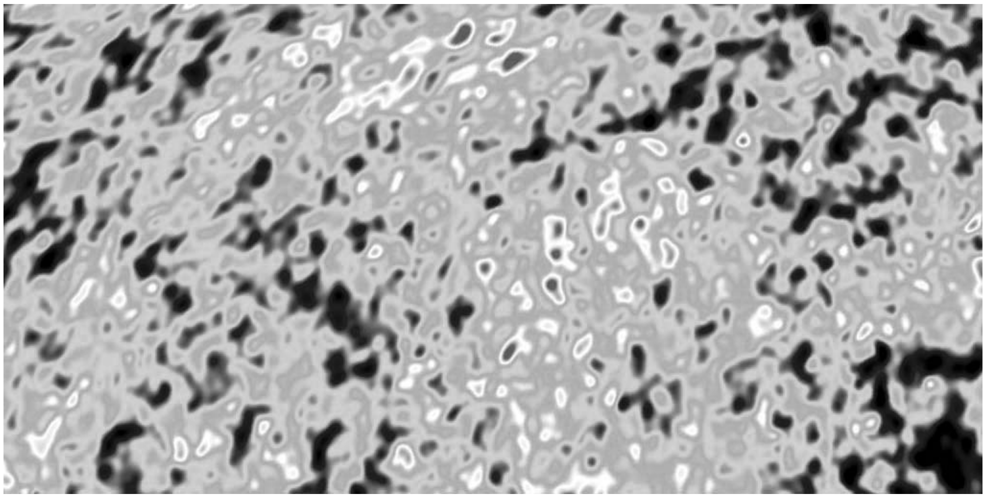

Figure 2: A several hundred square-degree patch of the microwave sky imaged by the Wilkinson Microwave Anisotropy Probe (WMAP). The tiny variations in microwave intensity (parts in 100,000) are displayed as color variations and indicate the slightly lumpy distribution of Cold Dark Matter four hundred thousand years after the beginning. According to inflation theory, these variations arose from quantum fluctuations during inflation, and thus, this WMAP image is a picture of subatomic quantum fuzziness blown up and projected across the sky by enormous expansion during inflation. Figure courtesy of WMAP and NASA.

Evidence for an Inflationary Beginning

The first solid evidence supporting this remarkable picture came in 1998. Measurements of the tiny variations in the intensity of the cosmic microwave background radiation across the sky indicated that the universe is flat, as predicted by inflation. The detailed pattern of these tiny

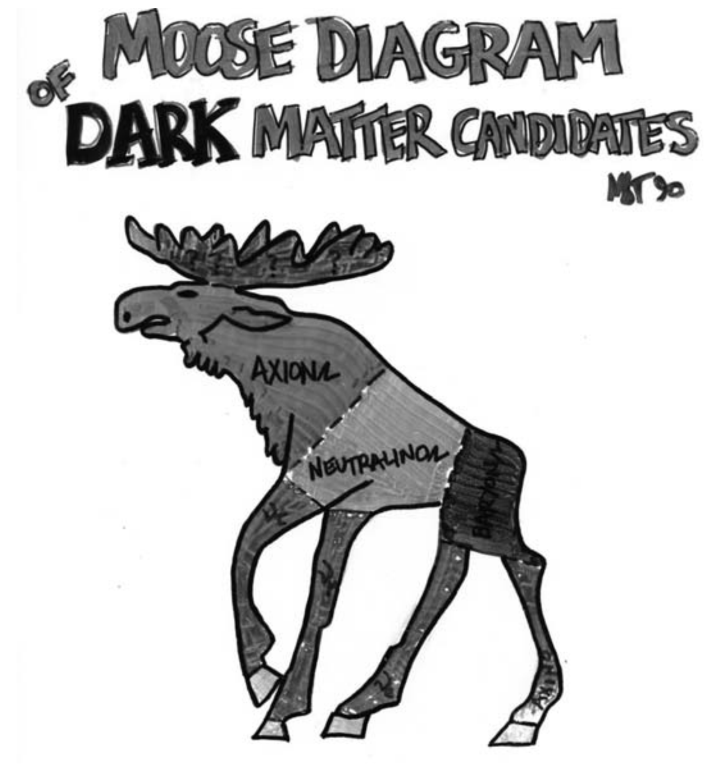

Figure 3: List of particle candidates for the dark matter. Some of the dark matter (1 percent of the critical density or less) is now known to be made of neutrinos; the bulk is believed to be made of an as of yet undiscovered elementary particle, with the axion and the neutralino being the leading candidates.

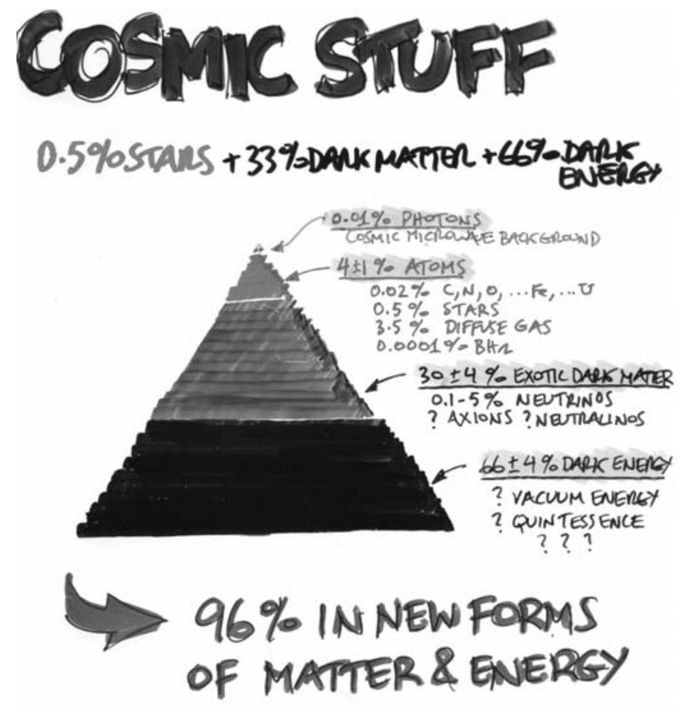

Figure 4: The composition of our critical density, flat universe. Less than 1 percent exists in the form of stars, 4 percent in atoms, 30 percent in Cold Dark Matter, and 66 percent in weird dark energy. The bulk of matter and energy are in as of yet unidentified forms of matter and energy. While the photons in the CMB (Cosmic Microwave Background) contribute much less than 1 percent of the total, they are an invaluable relic today, and at an early time provided the bulk of the mass/energy density.

variations was consistent with a quantum origin of the lumpiness. Further, the "missing energy" needed to bring the total mass/energy density to the critical value was found: a flat universe must have the critical density, and matter only accounts for 30 percent. Evidence for the other 70 percent came in the unexpected discovery of "cosmic speed up."

For seventy years cosmologists tried to measure the gravitational slowing of the expansion; when they finally succeeded they found that the universe is actually speeding up. This odd twist was good news for inflation, because the speed up implies the existence of a weird form of dark energy that contributes 70 percent of the critical density and whose gravity is repulsive. When added to the 30 percent known to exist in matter, this totals 100 percent (see figure 4). Now we just have to figure out exactly what the dark energy is – but, of course, we are confident that we will.

A host of evidence since – from the Wilkinson Microwave Anisotropy Probe's (WMAP) recent measurements of the cosmic microwave background to the mapping of structure in the universe by the Sloan Digital Sky Survey – has further strengthened the case for Inflation + Cold Dark Matter. But this is just the tip of the cosmic iceberg. A veritable avalanche of cosmological data will definitively test this paradigm: a higher resolution map of the cosmic microwave background from experiments at the South Pole to the new Planck satellite; and measurements of the expansion rate by a variety of techniques to get at the dark energy. In the laboratory, some will attempt to directly detect the Cold Dark Matter particles that hold our own galaxy together, and others will try to create them with powerful particle accelerators at Fermilab and CERN. The James Webb Space Telescope, successor to HST, will take us deeper into space and further back in time to view the first stars.

The End of Cosmology?

There is much work to be done, and many questions still to be answered. But will proving that Inflation + Cold Dark Matter is correct finally satisfy cosmologists and lead to the end of cosmology? Arrogance is pretty powerful stuff, so probably not. But are there limits to how much we can learn about the universe? There are the obvious worries – money and public interest in spending for an activity with no practical application, for instance. I doubt these factors will set the limit, however. Curiosity about the beginning has been and always will be unlimited.

A more serious worry is that cosmology is an archaeological science. Since experiments as grand as creating a universe cannot be carried out, we must rely upon relics, such as the cosmic microwave echo, the lightest elements in the periodic table that were cooked in the big bang, and both forms of matter, atoms and dark matter. I cannot resist mentioning that the father of inflation theory, MIT's Alan Guth, undertook a serious study of how to create a universe in the laboratory and concluded that it is possible. Need I say more about arrogance? Maybe our bubble universe is a freshman physics lab experiment in another universe gone awry. It is certainly possible that we will run out of relics before our curiosity is satisfied, but I am too optimistic to believe that this will be our demise.

The most interesting obstacles are more fundamental. A key feature of inflation – that it makes the present state of the universe insensitive to how it began – throws up a kind of screen that blocks knowledge of earlier times. Further, inflation multiplies the possibilities and exponentially increases the territory to be explored. With an infinite number of inflationary bubbles that will never communicate with one another, even complete knowledge of our universe amounts to infinitesimal knowledge of the whole. If the Copernican principle, the guiding principle in cosmology for the past four hundred years, is correct, then this is not an obstacle in practice. (The Copernican princi-

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ple, sometimes known as the principle of cosmic mediocrity, holds that we occupy a typical place in the cosmos.)

However, in a universe of infinite possibilities, even the extremely improbable happens. It could be that our bubble universe is very atypical. For example, it may be that the typical bubble never evolves living creatures. If this is the case, then our view of the universe depends critically upon our existence. While a handful of cosmologists have long advocated the anti-Copernican or anthropic principle – namely, that the laws of physics and the universe itself are the way they are so life could evolve and become aware of them – few took this view seriously. I am not a fan of the anthropic principle (which I like to call the narcissistic principle), because it strikes me as giving up on a hard problem by looking in the back of the book for the answer. Inflation, however, makes us take a more serious and more scientific look.

According to string theory (the most promising attempt to unify all the forces and particles of nature), while there are universal laws of physics, there can be different realizations of these laws (local bylaws) within individual bubbles. The variations can be quite profound and include the number of spatial dimensions, whether or not matter is stable, and other factors that determine whether or not life will develop. Further, even within identical bubbles, historical accidents could make the difference between a barren universe and one teeming with life. It might be that an extremely improbable event shortly after inflation led to a future that is conducive to life. If anthropocentric considerations and not simply the laws of physics have determined the character of the bubble in which we find ourselves, there may truly be a fundamental limit to what we can infer about the universe as a whole.

Fundamental limits or not, I am bullish on cosmology. During the next two decades there will be exciting developments, new surprises, and great advances in our understanding of the universe. Still, the question remains, are the limits to our understanding of the universe set by our own creativity and boldness? Or are there fundamental limits to our understanding? ■

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