Understanding Dark Energy: Symposium Summary

2005 AAAS Annual Meeting, Washington, DC
1:45-4:45 p.m., Friday, 18 February, 2005
`http://pancake.uchicago.edu/~carroll/aaas05/`

Speakers: Sean Carroll, University of Chicago (Organizer); Adam Riess, Space Telescope Science Institute; Leonard Susskind, Stanford University; Licia Verde, University of Pennsylvania; Georgi Dvali, New York University; John Carlstrom, University of Chicago.

Abstract: A variety of observations have led cosmologists to conclude that our universe is dominated by a mysterious form of "dark energy" (in addition to the well-established "dark matter," which now seems prosaic by comparison). We have a complete inventory of the universe: five percent is ordinary matter, twenty-five percent is dark matter, and seventy percent is dark energy. The dark energy component is the most surprising and hardest to understand, and consequently poses the greatest challenges and opportunities to physics and cosmology. Indeed, dark energy may hold the key to the long-sought unification of quantum mechanics and gravity.

Given the high stakes, experimenters and theorists are devoting major resources to the quest to understand dark energy. This symposium will present an overview of the most exciting directions these efforts are taking, from the most profound ideas to the most ambitious experiments.

Summary of Presentations

The idea of dark energy is simple, if unusual: a tiny amount of energy that exists in every region of space, even regions that are completely devoid of matter and radiation. The characteristic feature of dark energy is that it is (close to) the same everywhere throughout space and time; it doesn't accumulate noticeably into overly dense regions, nor does it evolve appreciably as the universe expands. Fortunately, Einstein tell us that all forms of energy affect the curvature of spacetime. Hence, cosmologists are able to detect the influence of dark energy, and learn something about its properties, by observing its effects on the overall curvature and expansion rate of the universe.

Over the last few years, the evidence in favor of dark energy (or something much like it) has become overwhelming. Nevertheless, our understanding of it remains paltry – we don't know why the amount of dark energy takes on its particular value, whether the dark energy can gradually evolve or is truly constant, whether it can interact with ordinary matter, or even whether we are being tricked into believing in dark energy by a breakdown in our understanding of gravity.

With these issues in mind, this symposium will focus on the future: what ideas are being proposed to help understand the nature of dark energy, and what observations and experiments are being undertaken to put these ideas to the test. The topics will range from upcoming observations of supernovae, galaxy clusters, large-scale structure, and the cosmic microwave background, to theoretical proposals involving quintessence, string theory, multiple universes, and extra dimensions of spacetime.

Sean Carroll (University of Chicago; `carroll@theory.uchicago.edu`), organizer of the symposium, will provide a survey of the experimental reasons why we believe in dark energy and the different ideas physicists are pursuing to explain it. The original evidence for dark energy – the fact that the expansion of the universe is accelerated, as seen in observations of distant supernova explosions – was impressively confirmed by measurements of the total energy of the universe as deduced from temperature fluctuations in the cosmic microwave background.

Further observations of galaxy clusters and large-scale structure have again verified the "concordance model" of cosmology, in dark energy makes up about seventy percent of the energy in the universe, dark matter about twenty-five percent, and ordinary matter only about five percent. Thus far, observations are consistent with a very simple idea of dark energy: a cosmological constant, or vacuum energy, that is strictly constant throughout space and time. If the dark energy is really vacuum energy, we are faced with the difficult problem of explaining its magnitude: simple estimates of the vacuum energy give a value 10^{120} times larger than the observed density. Alternatively, the dark energy may be dynamical and evolving, simply at a rate too slow to have been detected as yet. This possibility can be tested by upcoming cosmological observations of the type described by the other speakers. In addition, dynamical dark energy can interact directly with ordinary particles, potentially opening a completely new window to understanding this mysterious substance.

Adam Riess (Space Telescope Science Institute; `ariess@stsci.edu`) is a member of the High-Redshift Supernova Search Team, one of the two original teams that used supernova observations to determine that the universe is accelerating. Acceleration is the most direct effect of dark energy: because the density of dark energy remains approximately constant as the universe expands, it provides a persistent impulse to the universe, leading to a gradual increase in the apparent recession velocity of distant galaxies. Certain supernovae, known as Type Ia, are very bright but rare events, which fortunately serve as "standardizable candles" – knowledge of how the luminosity of the supernova rises to maximum and then falls off can be used to infer the absolute brightness of the explosion, and thus the distance to the galaxy in which the supernova is located.

A number of observational programs are currently under way to use supernovae to learn more about dark energy. These efforts have a well-defined goal: to determine whether or not the dark energy density is strictly constant (as it would be for vacuum energy), or gradually changing with time (definitive evidence for dark-energy dynamics, and something other than a cosmological constant). Cosmologists describe the variation of dark energy in terms of the "equation-of-state parameter" w, which is equal to -1 if the dark energy density is constant, greater than -1 if it is gradually diminishing, and below -1 in the dramatic case where the dark energy density is actually growing as the universe expands. This distinction is of crucial importance to theorists, as a discovery that $w \neq -1$ would necessitate a complete overhaul in our understanding of the nature of dark energy. Riess will discuss current efforts to observe supernovae with telescopes on the ground and in space, as well as talking about the shape of future programs to measure this crucial quantity.

Leonard Susskind (Stanford University; `susskind@stanford.edu`) is one of the originators of string theory, the most promising candidate for a theory that can reconcile quantum mechanics with Einstein's general relativity. String theory has been the dominant framework in theoretical high-energy physics for the past two decades; with the discovery by cosmologists of the accelerating universe, the direction of research in string theory is being dramatically shaped by experimental data for the first time.

String theory naturally lives in eleven dimensions of spacetime; to be compatible with our observed four dimensions, seven dimensions of space must be "compactified" to an invisibly small size. It turns out that there is an extremely large number of ways to perform this compactification, giving rise to a Landscape of more than 10^{100} different possible "vacuum states" of the theory (each corresponding to a possible state for the universe). The various states of this Landscape each has a different value of the vacuum energy, distributed across a tremendous range of values. Among all of these possible states of the universe, it is perhaps not surprising that we find ourselves in one with a relatively small value of the vacuum energy; if the energy were much larger, there wouldn't be enough time for galaxies to form, much less for living beings to evolve. Susskind's talk will present the evidence for this new paradigm for fundamental physics, and discuss its consequences for the question of dark energy.

Licia Verde (University of Pennsylvania; `lverde@physics.upenn.edu`) is a member of the Wilkinson Microwave Anisotropy Probe (WMAP) collaboration, as well as an expert in the analysis of surveys of large-scale structure in the universe. These two phenomena – the small temperature fluctuations in the cosmic microwave background (CMB) and the current distribution of galaxies – are closely related to each other, despite being separated by billions of years. The CMB, leftover radiation from the Big Bang, reflects a time when the universe was almost perfectly smooth, containing small perturbations in density of only one part in one hundred thousand. But through the relentless pull of gravity, these perturbations gradually grew into the galaxies and clusters we observe today.

By measuring fluctuations in the temperature of the CMB, we can determine the state of the universe when it was only 370,000 years old. By measuring the distribution of galaxies in the nearby universe, we can deduce how the universe has evolved between then and now, when the universe is 13.7 billion years old. This evolution depends sensitively on various cosmological parameters, including the abundance and properties of the dark energy. Currently, separate observations of both the CMB and large-scale structure provide important constraints on the behavior of dark energy. Observations planned for the near future will allow us to combine independent datasets into powerful new tools for probing the equation-of-state parameter w as well as other crucial cosmological parameters.

Georgi Dvali (New York University; `dvali@physics.nyu.edu`) was one of the first theorists to propose the possibility that extra dimensions of space could be macroscopically large, an idea whose consequences are still being actively explored. In these scenarios, particles of ordinary matter are confined to a three-dimensional "brane" embedded in a larger universe, into which only gravity can reach. An intriguing possibility is that there is an extra dimension that is *infinitely large*, but whose influence can only be felt on the very large scales relevant to cosmology.

Models of this type would show up in our observable world as slight modifications to Einstein's general relativity. As a dramatic consequence, it would be possible to explain the observed acceleration of the universe without invoking dark energy at all – merely appealing to the new behavior of gravity on large scales. As speculative as it may be, this idea comes along with very clear experimental consequences, including a signature that could be observed by high-precision lunar ranging observations. Dvali will discuss the possibility that dark energy could be replaced by modified gravity, focusing on the consequences of this idea for future theories and experiments.

John Carlstrom (University of Chicago; `jc@oddjob.uchicago.edu`) was a lead investigator of the Degree-Scale Angular Interferometer (DASI), a telescope located at the South Pole that first discovered the polarization of the cosmic microwave background. He is currently leading two new ambitious projects aimed at using clusters of galaxies as cosmological probes: the Sunyaev-Zel'dovich Array (SZA) in California, and the South Pole Telescope (SPT) in Antarctica. Both observatories will measure the Sunyaev-Zel'dovich (SZ) effect, the scattering of CMB photons by hot gas in clusters of galaxies.

The crucial feature of the SZ effect is that it is a "shadow" on the CMB, rather than an emission of radiation. That means that the SZ effect does not diminish as a function of distance to the galaxy cluster; it can be detected regardless of how far away the cluster is. Therefore, a survey of galaxies using the SZ effect can allow us to track the number of clusters as a function of redshift. This quantity is extremely sensitive to the underlying dynamics of the universe, especially to the properties of dark energy. Carlstrom will discuss how the SZA, SPT, and related experiments will open a dramatic new window onto the expansion history of the universe.