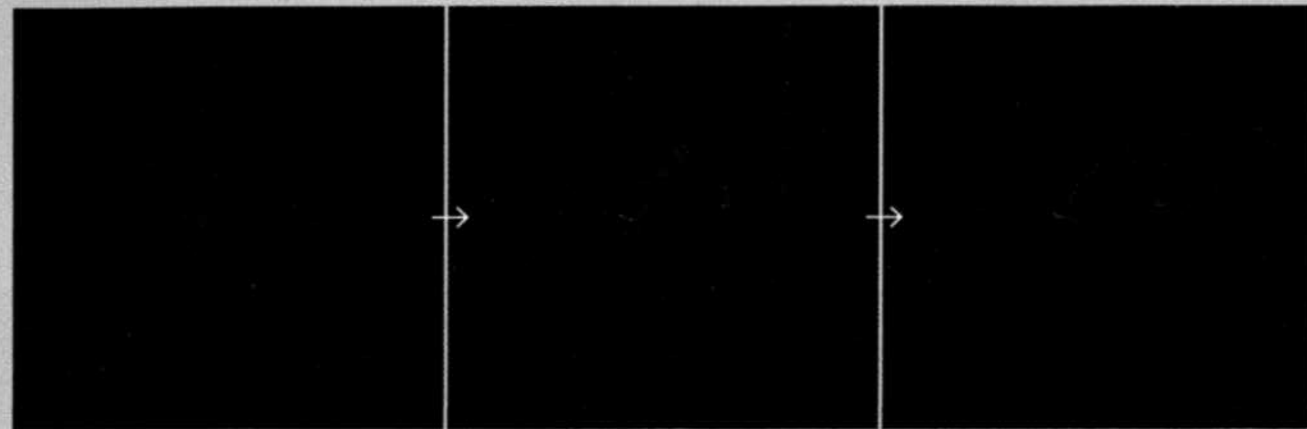


What-If Scenarios

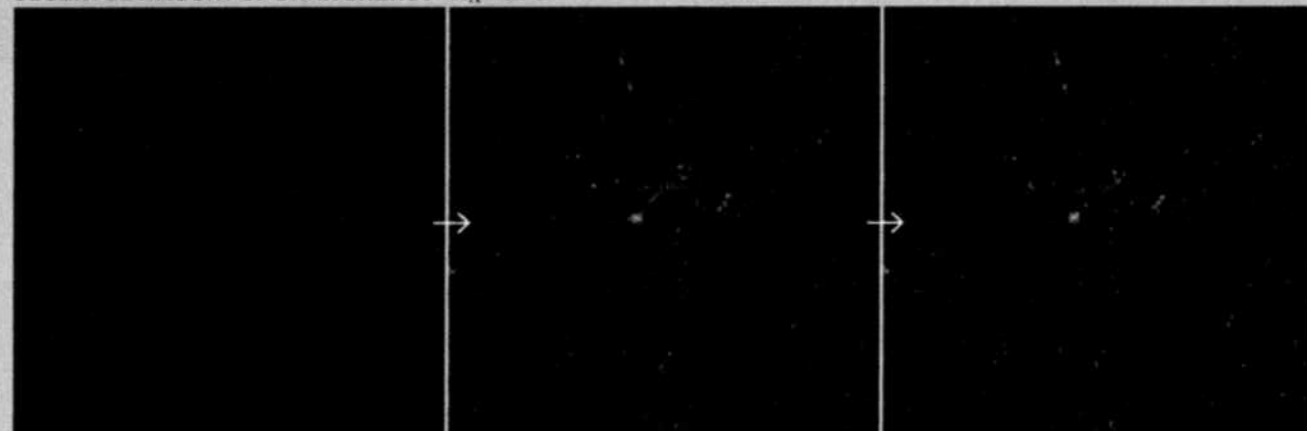
If the universe had more dark energy in it, it would look radically different. Cosmic acceleration would have started sooner, pulled material apart faster and nipped the formation of large structures in the bud. The converse would happen if the universe had less dark energy. Each box below shows a region

that is now one billion light-years across and contains 27 million particles, each representing a galaxy. These simulations assume that the dark energy density is constant in space and time. The quantity Ω_Λ is the governing cosmological parameter; it represents the density of dark energy today.

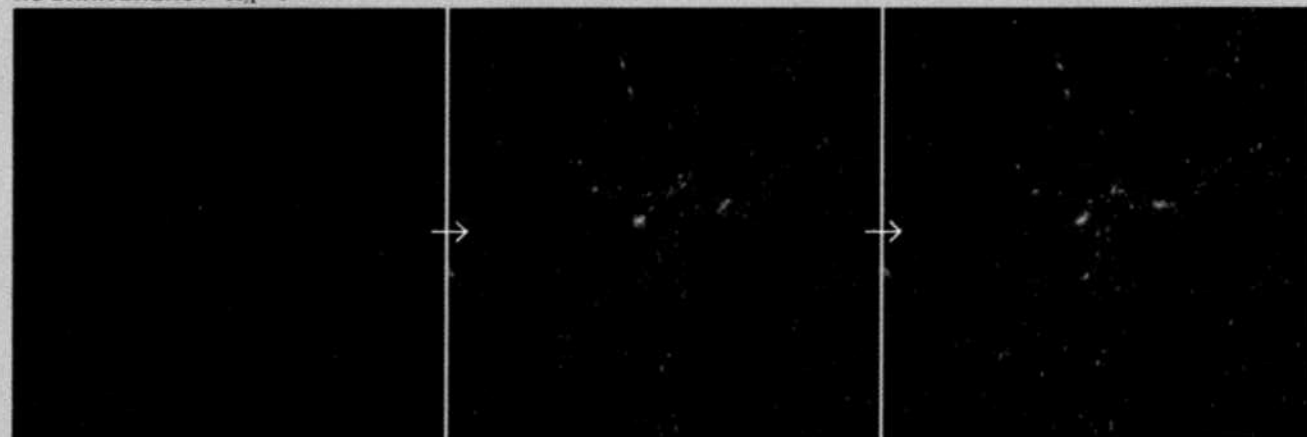
MORE DARK ENERGY $\Omega_\Lambda = 0.99$



OBSERVED AMOUNT OF DARK ENERGY $\Omega_\Lambda = 0.75$



NO DARK ENERGY $\Omega_\Lambda = 0$



EARLY UNIVERSE: When the universe is a sixth of its current size, matter is evenly distributed in all three scenarios. Dark energy has not yet exerted its influence.

TRANSITION PERIOD: When the universe is 75 percent of its current size, the effects of dark energy are stark. In the high dark energy scenario (top), the universe looks amorphous. In the other two scenarios, structure formation still continues, producing a cobweb pattern.

TODAY: In a universe with the observed amount of dark energy (middle), large-scale structure formation has ended, leaving the cobweb frozen in place. In a zero dark energy scenario (bottom), the cobweb continues to develop.

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this to a lower matter density than theoretical arguments had predicted. The discovery of dark energy resolved the tension between observation and theory.

An example of how dark energy alters the history of galaxy clusters is the fate of the galaxies in our immediate vicinity, known as the Local Group. Just a few years ago astronomers thought that the Milky Way and Andromeda, its closest large neighbor, along with their retinue of satellites, would fall into the nearby Virgo cluster. But it now appears that we shall escape that fate and never become part of a large cluster of galaxies. Dark energy will cause the distance between us and Virgo to expand faster than the Local Group can cross it.

By throttling cluster development, dark energy also controls the makeup of galaxies within clusters. The cluster envi-

sive galaxies and galaxy clusters. Spiral and low-mass dwarf irregular galaxies would be more common, because fewer galaxy mergers would have occurred throughout time, and galaxy clusters would be much less massive or perhaps not exist at all. It is also likely that fewer stars would have formed, and a higher fraction of our universe's baryonic mass would still be in a gaseous state.

Although these processes may seem distant, the way galaxies form has an influence on our own existence. Stars are needed to produce elements heavier than lithium, which are used to build terrestrial planets and life. If lower star formation rates meant that these elements did not form in great abundance, the universe would not have many planets, and life itself might never have arisen. In this way, dark energy could

Space is emptying out, leaving our Milky Way galaxy and its neighbors an increasingly isolated island.

ronment facilitates the formation of a zoo of galaxies such as the so-called lenticulars, giant ellipticals and dwarf ellipticals. By regulating the ability of galaxies to join clusters, dark energy dictates the relative abundance of these galaxy types.

This is a good story, but is it true? Galaxy mergers, black hole activity and star formation all decline with time, and very likely they are related in some way. But astronomers have yet to follow the full sequence of events. Ongoing surveys with the Hubble Space Telescope, the Chandra X-ray Observatory and sensitive ground-based imaging and spectroscopy will scrutinize these links in coming years. One way to do this is to obtain a good census of distant active galaxies and to determine the time when those galaxies last underwent a merger. The analysis will require the development of new theoretical tools but should be within our grasp in the next few years.

Striking a Balance

AN ACCELERATING UNIVERSE dominated by dark energy is a natural way to produce all the observed changes in the galaxy population—namely, the cessation of mergers and its many corollaries, such as loss of vigorous star formation and the end of galactic metamorphosis. If dark energy did not exist, galaxy mergers would probably have continued for longer than they did, and today the universe would contain many more massive galaxies with old stellar populations. Likewise, it would have fewer lower-mass systems, and spiral galaxies such as our Milky Way would be rare (given that spirals cannot survive the merger process). Large-scale structures of galaxies would have been more tightly bound, and more mergers of structures and accretion would have occurred.

Conversely, if dark energy were even stronger than it is, the universe would have had fewer mergers and thus fewer mas-

have had a profound effect on many different and seemingly unrelated aspects of the universe, and perhaps even on the detailed history of our own planet.

Dark energy is by no means finished with its work. It may appear to benefit life: the acceleration will prevent the eventual collapse that was a worry of astronomers not so long ago. But dark energy brings other risks. At the very least, it pulls apart distant galaxies, making them recede so fast that we lose sight of them for good. Space is emptying out, leaving our galaxy and its immediate neighbors an increasingly isolated island. Galaxy clusters, galaxies and even stars drifting through intergalactic space will eventually have a limited sphere of gravitational influence not much larger than their own individual sizes.

Worse, dark energy might be evolving. Some models predict that if dark energy becomes ever more dominant over time, it will rip apart gravitationally bound objects, such as galaxy clusters and galaxies. Ultimately, planet Earth will be stripped from the sun and shredded, along with all objects on it. Even atoms will be destroyed. Dark energy, once cast in the shadows of matter, will have exacted its final revenge.

MORE TO EXPLORE

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