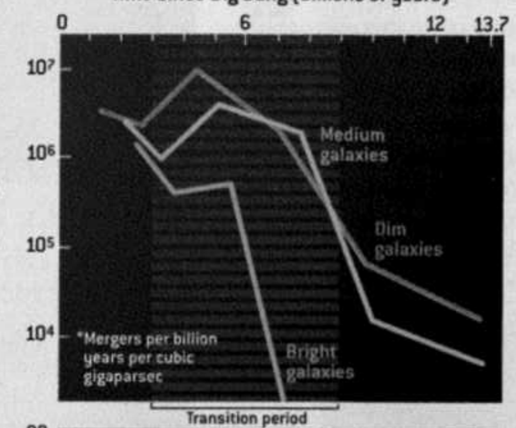
# Dark Energy Takes Charge

**Despite getting a quick start after the big bang, the construction of the universe soon petered out. Initially galaxies merged together, changed shape and formed stars at a brisk pace, but this activity began to wane during the period when dark energy became comparable in strength to matter (*brown area in graphs*). Coincidence?**

### GALAXIES STOPPED MERGING

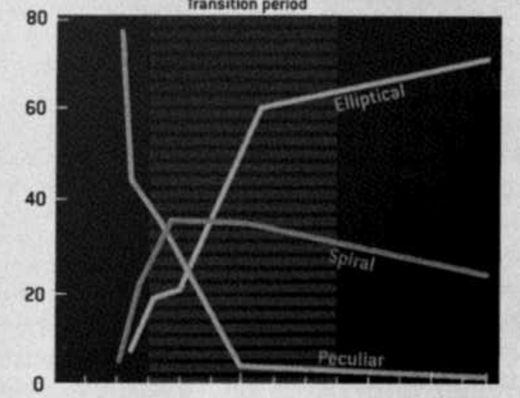
The brightest galaxies stopped colliding and amalgamating at a cosmic age of about six billion years. Less luminous galaxies can still merge but have become much less likely to do so.




Merging galaxies NGC 4676

### GALAXIES SETTLED INTO REGULAR SHAPES

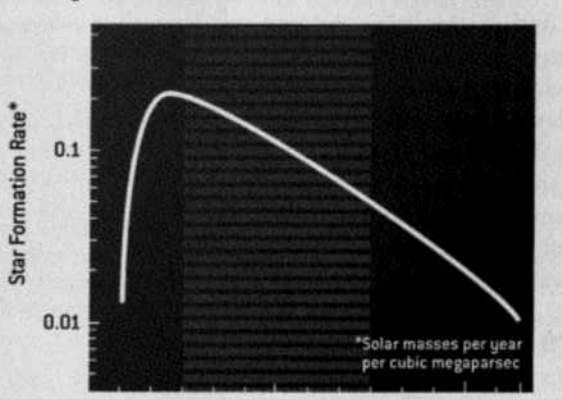
Early on, most galaxies looked peculiar—a sign they were merging with one another. As mergers became less frequent, spiral and elliptical shapes become prevalent.




Hickson Compact Galaxy Group 87

### STAR FORMATION WANED

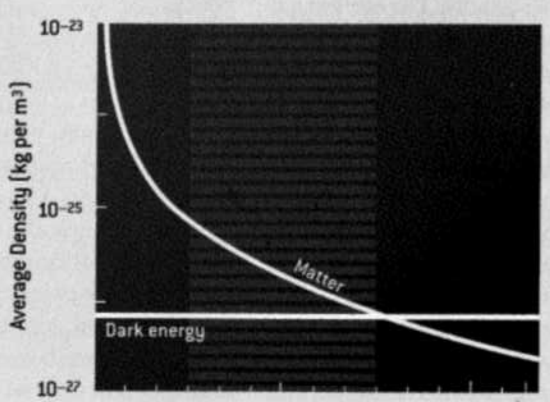
The early universe was a cauldron of star formation, but the formation rate soon peaked and began to drop. It is now lower than it has ever been.

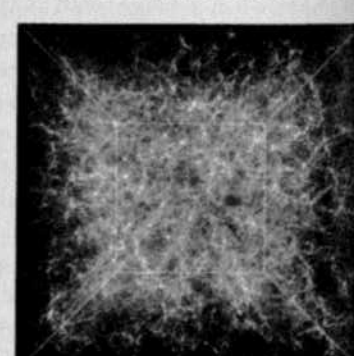



New Stars in Trapezium Cluster

### DARK ENERGY BECAME A PLAYER

All these observed trends can be related to one simple fact: as the universe expanded, matter was spread thinner, and as its density approached that of dark energy (whose density is constant in the simplest model), the rate of expansion began to switch from decelerating to accelerating. Galaxies were pulled apart faster and became less likely to bump into one another or sweep up gas to fuel star formation.



Simulation of Matter Distribution



ones led by Simon J. Lilly, then at the University of Toronto, Piero Madau, then at the Space Telescope Science Institute, and Charles C. Steidel of the California Institute of Technology. More recently, researchers have learned how this trend occurred. It turns out that star formation in massive galaxies shut down early. Since the universe was half its current age, only lightweight systems have continued to create stars at a significant rate. This shift in the venue of star formation is called galaxy downsizing [see "The Midlife Crisis of the Cosmos," by Amy J. Barger; SCIENTIFIC AMERICAN, January 2005]. It seems paradoxical. Galaxy formation theory predicts that small galaxies take shape first and, as they amalgamate, massive ones arise. Yet the history of star formation shows the reverse: massive galaxies are initially the main stellar birthing grounds, then smaller ones take over.

merged. New stars formed as gas clouds within galaxies collided, and black holes grew when gas was driven toward the centers of these systems. As time progressed and space expanded, matter thinned out and its gravity weakened, whereas the strength of dark energy remained constant (or nearly so). The inexorable shift in the balance between the two eventually caused the expansion rate to switch from deceleration to acceleration. The structures in which galaxies reside were then pulled apart, with a gradual decrease in the galaxy merger rate as a result. Likewise, intergalactic gas was less able to fall into galaxies. Deprived of fuel, black holes became more quiescent.

This sequence could perhaps account for the downsizing of the galaxy population. The most massive dark matter halos, as well as their embedded galaxies, are also the most clustered; they reside in close proximity to other massive halos. Thus,

**The universe has run out of steam since it was half its current age. Mergers have ceased, and black holes are quiescent.**

Another oddity is that the buildup of supermassive black holes, found at the centers of galaxies, seems to have slowed down considerably. Such holes power quasars and other types of active galaxies, which are rare in the modern universe; the black holes in our galaxy and others are quiescent. Are any of these trends in galaxy evolution related? Is it really possible that dark energy is the root cause?

## The Steady Grip of Dark Energy

SOME ASTRONOMERS HAVE PROPOSED that internal processes in galaxies, such as energy released by black holes and supernovae, turned off galaxy and star formation. But dark energy has emerged as possibly a more fundamental culprit, the one that can link everything together. The central piece of evidence is the rough coincidence in timing between the end of most galaxy and cluster formation and the onset of the domination of dark energy. Both happened when the universe was about half its present age.

The idea is that up to that point in cosmic history, the density of matter was so high that gravitational forces among galaxies dominated over the effects of dark energy. Galaxies rubbed shoulders, interacted with one another, and frequently

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they are likely to knock into their neighbors earlier than are lower-mass systems. When they do, they experience a burst of star formation. The newly formed stars light up and then blow up, heating the gas and preventing it from collapsing into new stars. In this way, star formation chokes itself off: stars heat the gas from which they emerged, preventing new ones from forming. The black hole at the center of such a galaxy acts as another damper on star formation. A galaxy merger feeds gas into the black hole, causing it to fire out jets that heat up gas in the system and prevent it from cooling to form new stars.

Apparently, once star formation in massive galaxies shuts down, it does not start up again—most likely because the gas in these systems becomes depleted or becomes so hot that it cannot cool down quickly enough. These massive galaxies can still merge with one another, but few new stars emerge for want of cold gas. As the massive galaxies stagnate, smaller galaxies continue to merge and form stars. The result is that massive galaxies take shape before smaller ones, as is observed. Dark energy perhaps modulated this process by determining the degree of galaxy clustering and the rate of merging.

Dark energy would also explain the evolution of galaxy clusters. Ancient clusters, found when the universe was less than half its present age, were already as massive as today's clusters. That is, galaxy clusters have not grown by a significant amount in the past six billion to eight billion years. This lack of growth is an indication that the infall of galaxies into clusters has been curtailed since the universe was about half its current age—a direct sign that dark energy is influencing the way galaxies are interacting on large scales. Astronomers knew as early as the mid-1990s that galaxy clusters had not grown much in the past eight billion years, and they attributed