

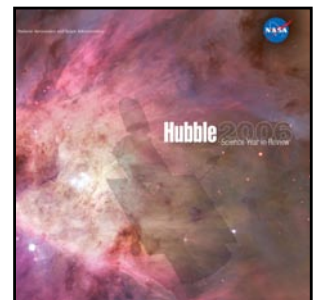
## Galaxies over the Latter Half of Cosmic Time

Marc Davis and Sandra M. Faber

Taken from: Hubble 2006 Science Year in Review

The full contents of this book include more Hubble science articles, an overview of the telescope, and more. The complete volume and its component sections are available for download online at:

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# Galaxies over the Latter Half of Cosmic Time

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*Marc Davis and Sandra M. Faber*

Galaxies are the basic systems of the universe. Like diamonds strewn across the sky, their tiny points of light mark the cosmic landscape. They reveal its organization into superclusters of thousands of galaxies, which border the vast voids of empty space. Galaxies make the universe interesting. Without them, the expansion of the universe would have diluted the cosmic soup into a thin broth of sterile and boringly diffuse gas. Instead, the excess gravity of tiny seeds of matter from the Big Bang slowed down cosmic expansion in regions that would become galaxies. The seeds drew in nearby gas, which eventually spawned the first generation of stars. Over billions of years, supernova explosions enriched the mix with oxygen, carbon, iron, and other elements that form only inside stars. These heavy elements are necessary to make planets such as Earth. The local gas consumed by star formation was replenished by fresh gas falling in from outside. By these cycles of stellar birth and death, galaxies became fertile, self-sustaining ecosystems and evolved to become more and more suited for planets, and for life.

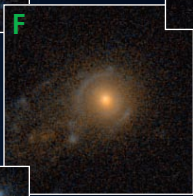
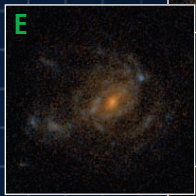
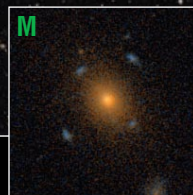
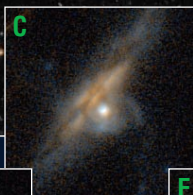
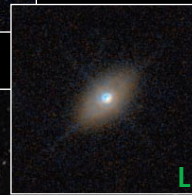
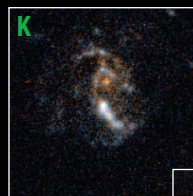
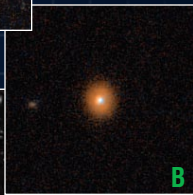
## **“Red-and-dead” galaxies**

While we think this picture describes the evolution of most galaxies, for many it apparently does not. In some galaxies, something intervenes to quench star formation by shutting off the supply of gas. This results in “red-and-dead” galaxies, which lack the characteristic blue tinge of freshly formed young stars. Such galaxies have given birth to all the stars and planetary systems they ever will, and for them the window of opportunity to create fresh habitats for life has closed.

The number of red-and-dead galaxies has increased dramatically over the latter half of cosmic time. What mysterious process is killing off star formation in the universe?

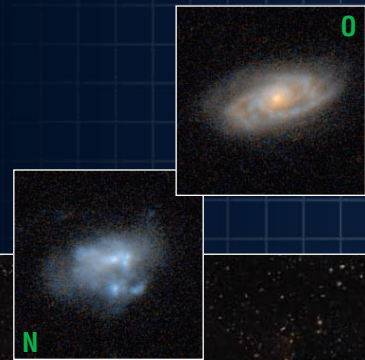
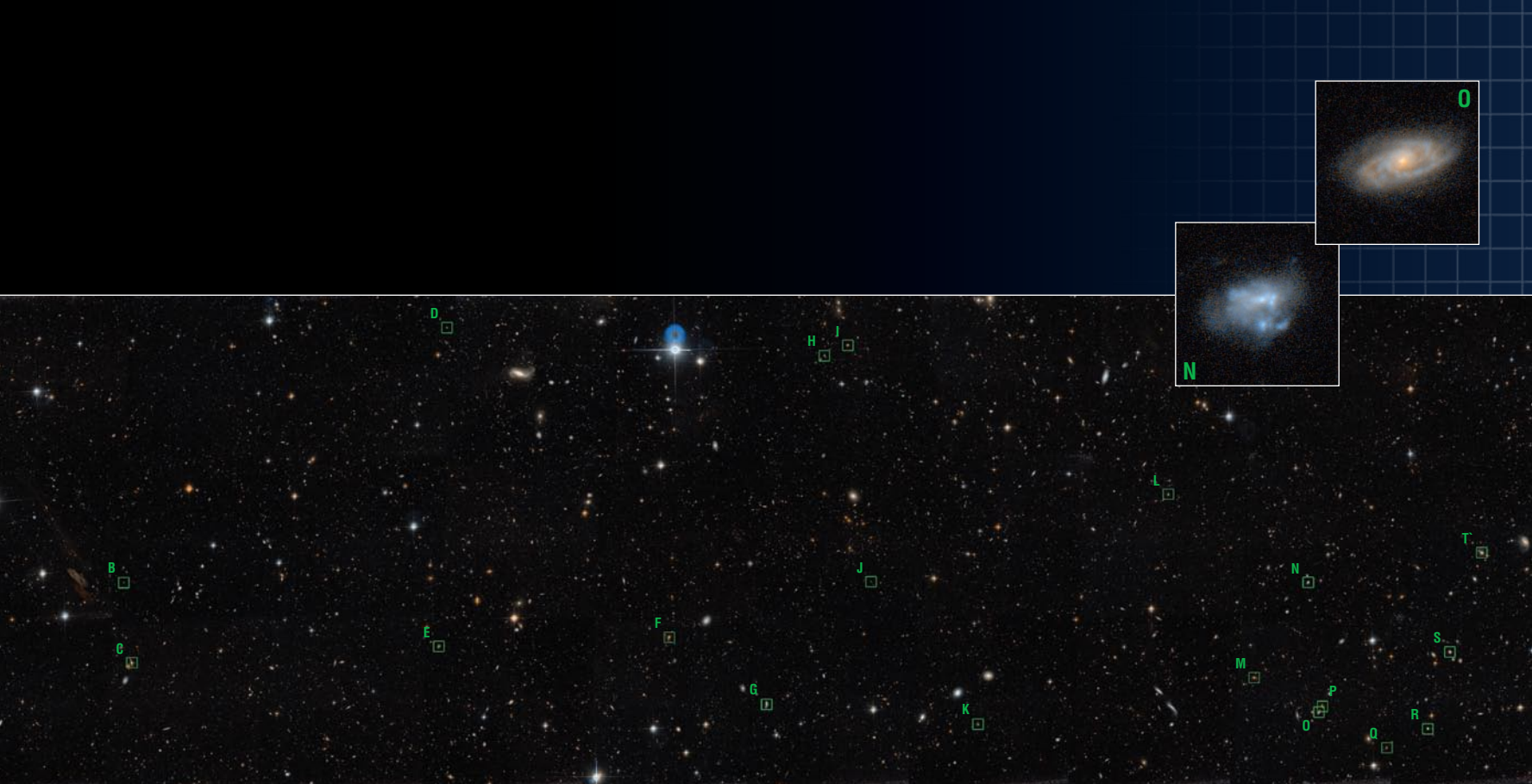


This new NASA *Hubble Space Telescope* image of the Antennae galaxies is the sharpest yet of this merging pair of galaxies. During the course of the collision, billions of stars will be formed. The brightest and most compact of these star-birth regions are called super star clusters, visible here as clumps of blue/white stars. As this essay explains, galaxy collisions producing massive bursts of stars might possibly lead over time to the formation of “red-and-dead” galaxies.

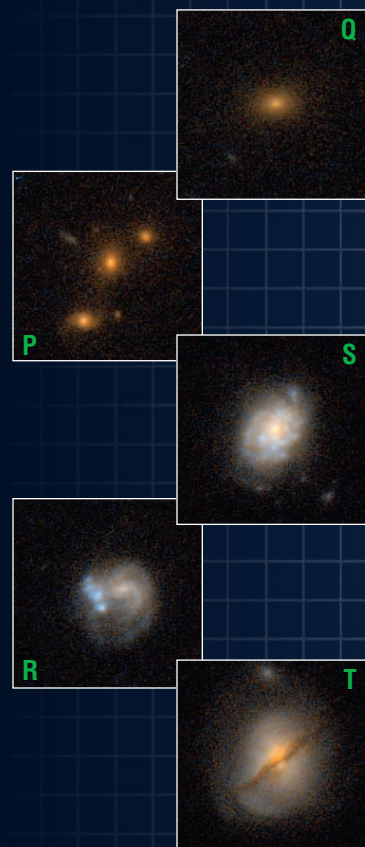


The AEGIS picture contains one billion picture elements—the equivalent of 500 high-definition TV screens. It includes images of over 25,000 galaxies maturing to adulthood over the last several billion years.

Currently, there are two different ideas to explain the origin of red-and-dead galaxies. The first is that some galaxies may fall into massive clusters, where intergalactic gas at millions of degrees is too hot to be collected. Starved of their gas supply, such galaxies would cease to form stars. An alternative idea is that occasional collisions of galaxies may trigger massive bursts of star formation, producing supernovae that sweep away the gas. Such collisions may also drive gas clouds toward the center of a galaxy, feeding a supermassive black hole and producing such intense emission from the active galactic nucleus that radiation pressure prevents other gas from falling into the galaxy.



*Hubble* is the perfect tool for testing such theories. Its images can tease out fine details in the structures of distant galaxies, showing which ones are forming stars normally, which are colliding, and which are red and dead. Active galactic nuclei (AGN)—the bright accretion disks feeding supermassive black holes—stand out as bright centers, which are visible to great distances and far back in time. In fact, each *Hubble* image is a “core drilling” through space-time, because successive strata disclose information from increasingly earlier epochs. Knowing the distance to a galaxy is the same as knowing its age when we see it, which allows us to reconstruct the galaxy populations of previous eras.

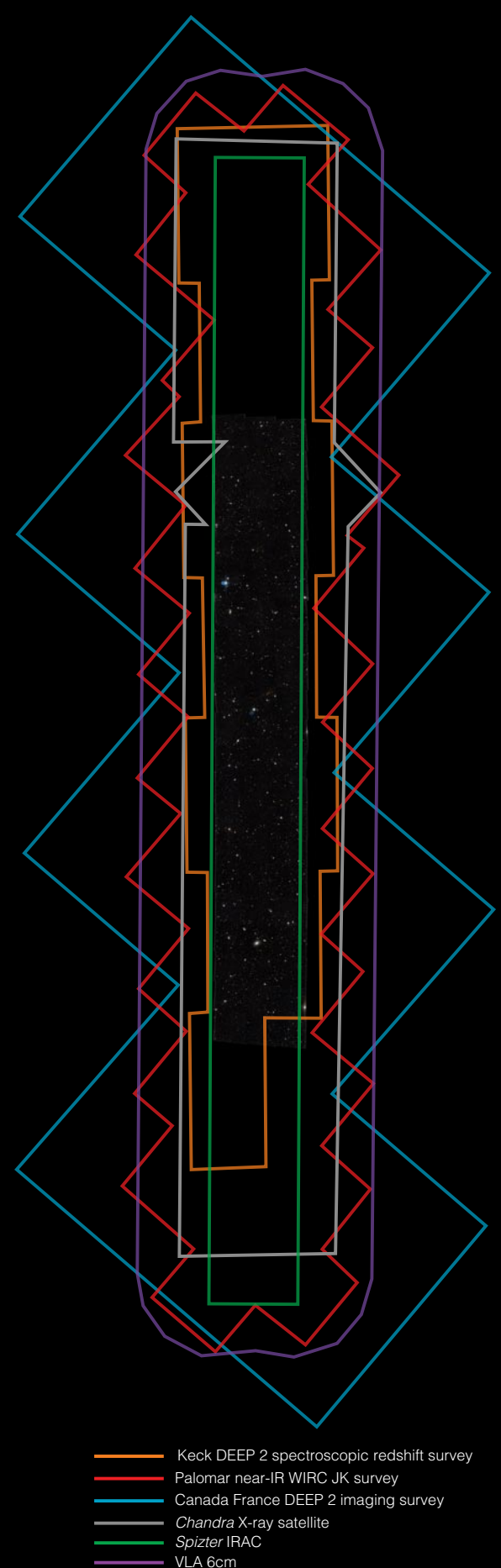


## The AEGIS survey

A new survey project called All-Wavelength Extended Groth Strip International Survey (AEGIS) has created one of the largest *Hubble* pictures to date. The image is  $1/6^\circ$  wide by  $1^\circ$  long, stretching twice the width of the full Moon. It is a mosaic of 63 tiles, each exposed through green and red filters, to produce diagnostic color images of some 25,000 galaxies bright enough for detailed study. The AEGIS team is counting the red-and-dead (quenched) galaxies and searching for circumstances—like collisions, AGN, and other factors—that may affect star formation on a galactic scale.

A special feature of AEGIS is a rich array of supporting data from other space- and ground-based observatories—nine besides *Hubble*. The *Chandra* x-ray satellite locates black holes buried in dust clouds and invisible to *Hubble*. Together, the *Galaxy Evolution Explorer* (ultraviolet) and *Spitzer* (infrared) satellites measure *all* new star formation, including any starbursts hidden by dust. The second phase of the Deep Extragalactic Evolutionary Probe (DEEP 2) redshift survey from the Keck Observatory provides optical spectra of thousands of galaxies, from which distances, galaxy masses, and chemical compositions can be determined. Each facility contributes key information to create a full portrait of every object.

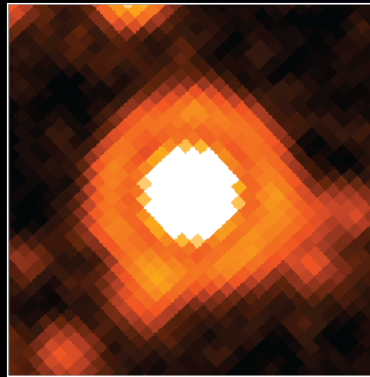
The AEGIS field, in the constellation Boötes, is one of the most intensively studied regions of the sky, with deep coverage at all wavelengths from radio waves to x-rays. Such panchromatic coverage provides individual portraits of over 25,000 galaxies, showing star formation and revealing factors that may affect it.



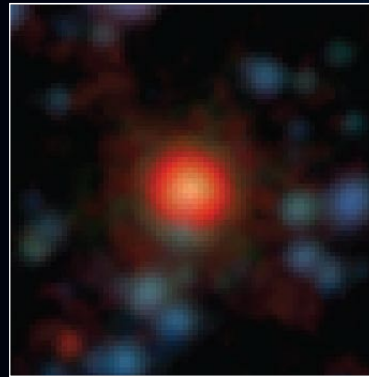
*Hubble*



*Spitzer*/Multiband Imaging Photometer



*Spitzer*/Infrared Array Camera



*Chandra*



The galaxy CXO–J141741.9 illustrates how telescopes at different wavelengths are needed to tell the whole story of an object. The spatial detail of the *Hubble* image is needed to identify the triggering collision. *Spitzer* images are needed to identify star formation heating the obscuring dust. *Chandra* x-rays are needed to identify the quasi-stellar object.

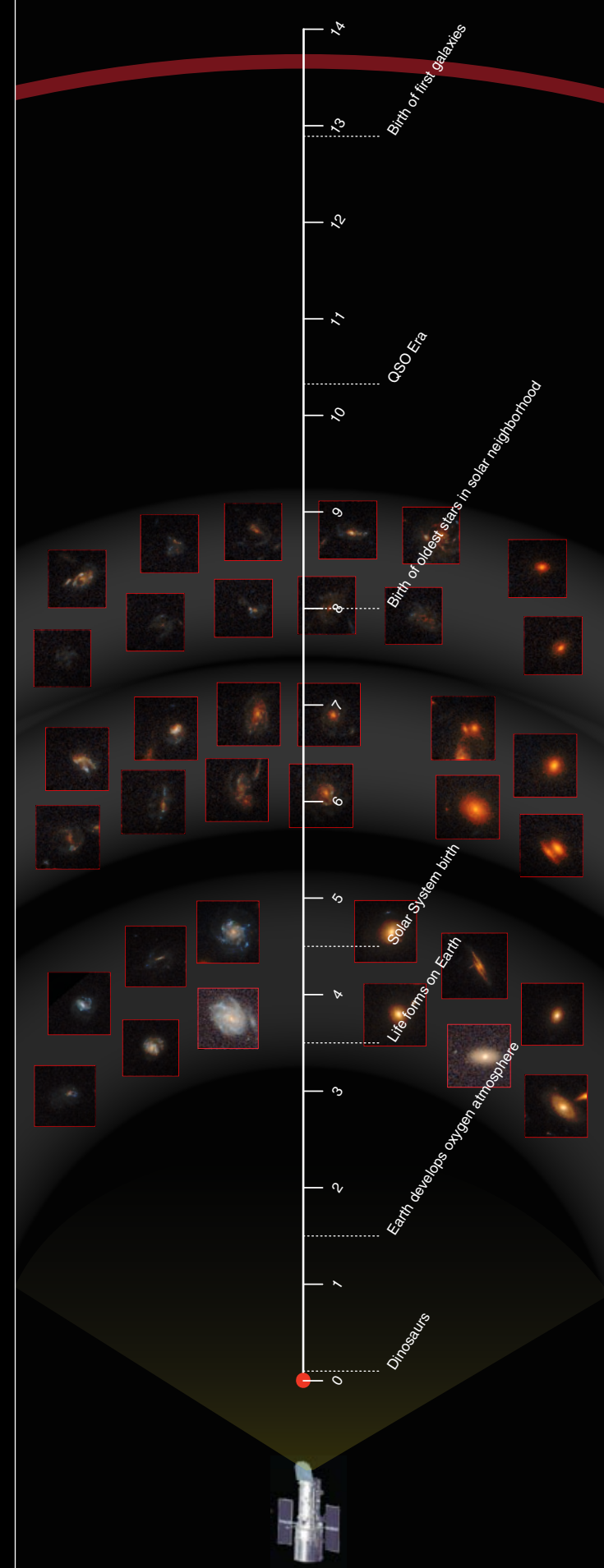
The galaxy CXO–J141741.9 is an example of how multispectral data fit together. The color *Hubble* image shows a highly disturbed object with clumps of newly formed stars. The brightest clump coincides with a bright x-ray source discovered by *Chandra*. This source is a quasi-stellar object (QSO) fueled by the clouds of gas being swallowed by a massive black hole. Ground-based data at millimeter wavelengths show an exceptionally bright starburst, emitting more energy at visible wavelengths than the entire galaxy does, but the starburst is completely hidden by dense, overlying dust clouds. The direct radiation of the starburst can be measured only at far-infrared and radio wavelengths. At mid-infrared wavelengths, the Multiband Imaging Photometer on *Spitzer* can see hot dust, both close to the QSO and surrounding the young stars. At shorter infrared wavelengths, *Spitzer's* Infrared Array Camera can also see the QSO.

CXO–J141741.9 is probably a pair of colliding galaxies in which perturbed gas clouds have burst into star formation and ignited a central black hole, producing the QSO. The intense releases of energy from both processes will probably sweep CXO–J141741.9 clean of gas after a few million years, which would mean that this galaxy is well on its way to becoming quenched, red, and dead.

### **A new tool for classifying galaxies**

To find more objects like CXO–J141741.9, the AEGIS team has created a new tool to classify galaxy images in an objective, automated manner. The tool processes the brightness information in all the pixels of a galaxy's image and decides what kind of galaxy it is. To classify galaxies as normal or disturbed, the tool measures the degree of clumpiness in the image and computes the center-to-edge brightness contrast ratio. It arranges the normal galaxies along a star-forming sequence. It identifies fully quenched, red-and-dead galaxies, as well as systems that are colliding.

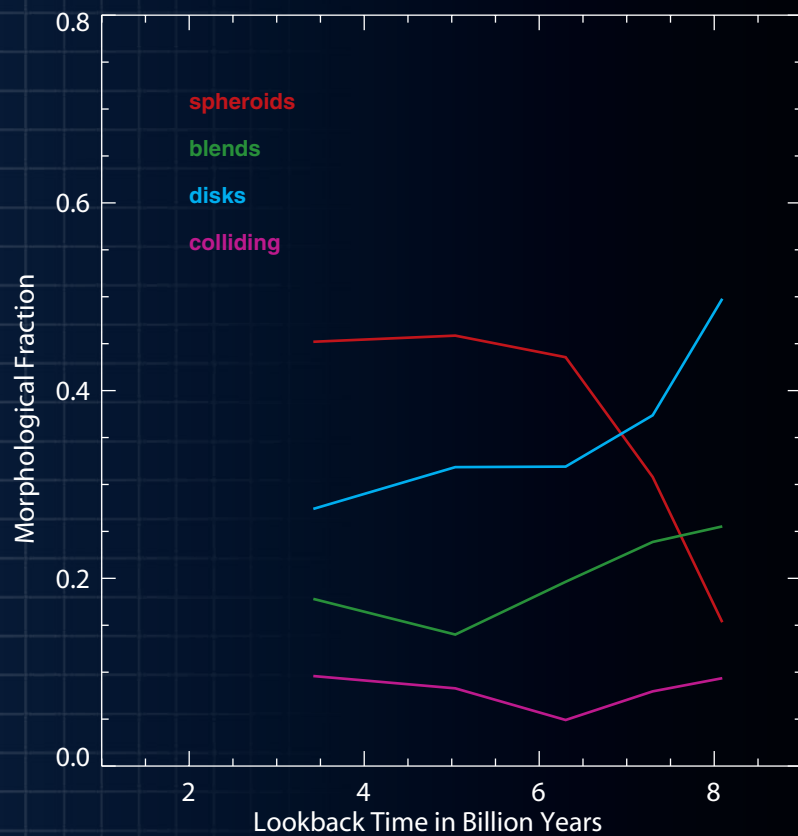
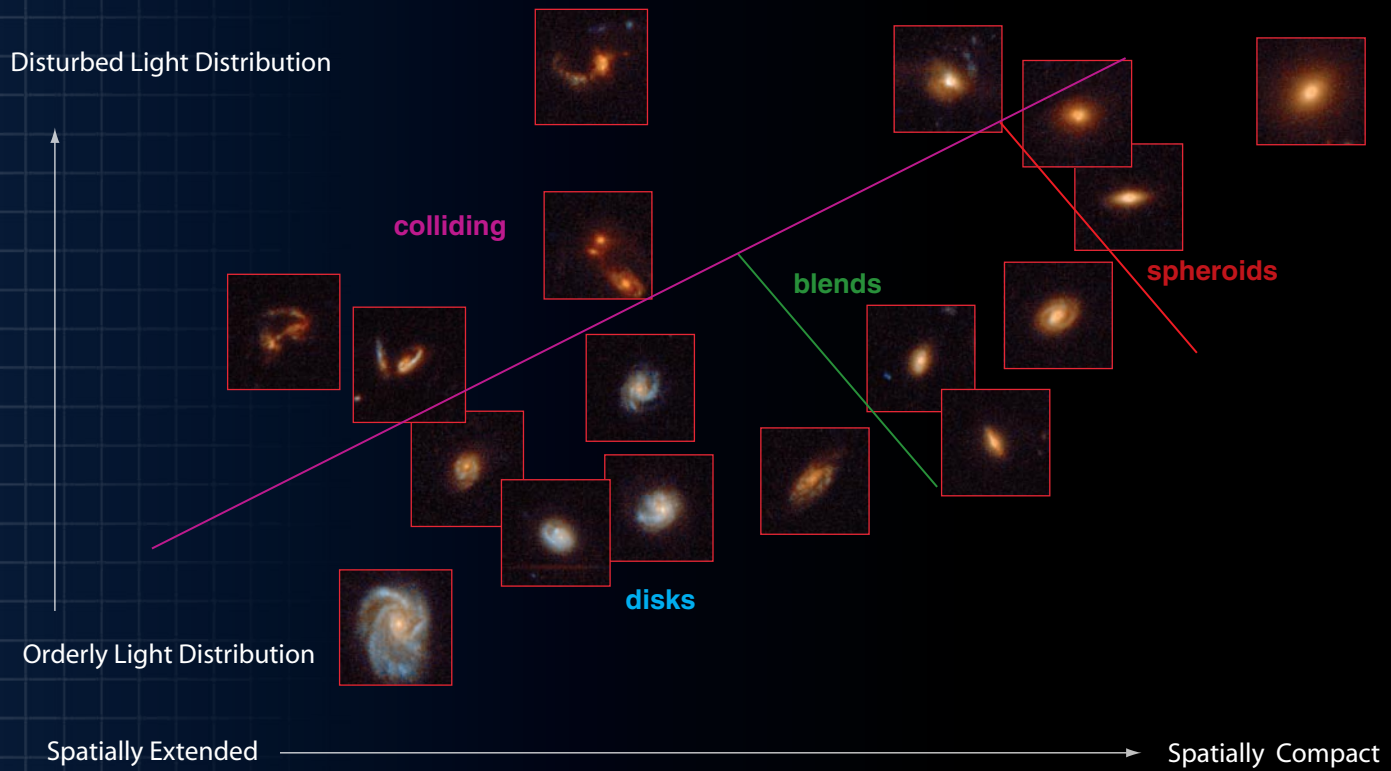
Preliminary results with this tool suggest that the collision rate has held steady over the last 9 billion years. If galaxy collisions are very efficient in producing red-and-dead galaxies, then the observed collision rate could fully account for the observed rate of growth of the population of quenched galaxies. However, if only a fraction of galaxy collisions result in new red-and-dead galaxies, as we have reason to believe, then starvation by hot intergalactic gas in galaxy clusters may also be important. We expect that continuing analyses of AEGIS observations will help us resolve the true causes of quenching.



## The Milky Way before the Sun and Earth formed

The AEGIS team is studying other properties of galaxy formation, too. From the new star-formation data, we find that each size of galaxy makes stars at a characteristic rate over cosmic time. From internal motions determined from Keck spectra, we find that only in the past few billion years have most disk galaxies (like our own Milky Way) stopped colliding with other galaxies and settled down to form ordered rotating disks. We are using the same spectra to measure how fast these galaxies synthesized heavy elements and enriched their interstellar gas to the level needed to make planetary systems. While we cannot look directly into the past to see our own galaxy forming and evolving, AEGIS data allow us to do the next-best thing—watch look-alikes of the Milky Way evolving billions of years ago, quite probably leading to the formation of suns and solar systems like our own.

*Hubble* looks out in space and back in time to observe star-formation rates in over 25,000 galaxies as they looked as long ago as half the age of the universe. Blue indicates regions where star formation is ongoing, red where it has been quenched. Typical galaxies are displayed in three time zones from the distant past to more recent times. The numbers along the central spine of the figure are “look-back” times in billions of years, i.e., the time light has traveled to reach us. In each zone—8–9, 6–7, and 3–5 billion years—a gap separates blue galaxies to the left and red-and-dead to the right. The number of red-and-dead galaxies increases with the passage of time, symbolized here by the increasing number of examples of red-and-dead galaxies—two, four, and six—in the three time zones. (The six red-and-dead galaxies at lowest redshift appear to be somewhat bluer than those at higher redshift. This is an artifact of data processing. They are still obviously redder than the six star-forming galaxies to the left.) The shapes of the blue star-forming galaxies become more regular as material settles into orderly, rotating disks.



The wide variety of galactic shapes and sizes is one of the most striking features of the deep, high-resolution AEGIS image. The automatic classification tool assigns to normal looking galaxies the labels "spheroid," "disk," or "blend," corresponding to normal nearby galaxies. The tool also measures the orderliness of the light distribution to identify colliding galaxies. Out to 9 billion years ago, more than 90% of galaxies have normal types and only 7% appear to be colliding. However, the number of spheroids more than doubles over the same time, probably due to collisions that result in mergers.



Sandra Faber is University Professor at the University of California, and Astronomer/Professor at the University of California Observatories, UC Santa Cruz. She has used the *Hubble Space Telescope* to discover black holes at the centers of galaxies and to study distant galaxy evolution. She is Co-Principal Investigator of the DEEP 2 redshift survey and PI of the DEIMOS spectrograph, which was used for the survey.



Marc Davis is Professor of Astronomy and Physics at UC Berkeley. He is a pioneer in redshift surveys and the analysis of galaxy clustering. He is the Principal Investigator of the DEEP 2 redshift survey, which is designed to study the evolution of galaxy properties and galaxy clustering as the universe evolved. Davis is a member of the National Academy of Sciences and the American Academy of Arts and Sciences.