by ANDREW PHILLIPS & NICOLE VOGT

PROBING THE EVOLVING UNIVERSE

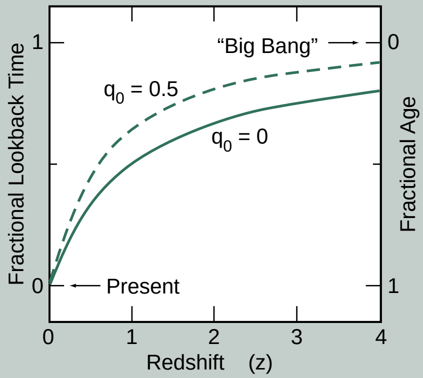
The evolution of the Universe can be
compared to a display of fireworks that
has just ended. Some few wisps, ashes and
smoke. Standing on a well-chilled cinder, we
see the slow fading of the suns and try to
recall the vanished brilliance
of the origin of the worlds.
—George Lemaitre (1930)

FAR ABOVE TROPICAL blue seas, in the rarefied air atop Hawaii's Mauna Kea volcano, astronomers are seeking clues to understanding the evolution of galaxies in the Universe. When did galaxies form? What physical processes dominated? Why do galaxies have different morphologies? What is the distribution of matter in the Universe, and how did it change with time?

Astronomers working on the evolution of the Universe have a unique opportunity: because of finite light-travel time, the more distant a galaxy is, the further back in time we are seeing it. The "look back" time to a galaxy is directly proportional to its distance, but galaxy distance is not directly measurable. However, in an expanding universe, the distance to a galaxy can be derived from its redshift—how much its light has been shifted to longer, or redder, wavelengths (see sidebar on the next page).

The Expanding Universe

IN 1929, Edwin Hubble discovered the expansion of the Universe, noting that most galaxies have Doppler shifts in their spectra indicating motion away from us, with the most distant receding the fastest. This so-called redshift is now generally interpreted as due to the stretching of the fabric of space-time in the expanding Universe. It is parametrized as $z = (\lambda_{obs} - \lambda_0)/\lambda_0$, the fractional ratio of observed to emitted wavelengths of light. Redshift is related to the distance of the object—astronomers often use redshift and distance interchangeably—and is key to converting observed quantities like a galaxy's apparent size and brightness into actual size and luminosity. Due to the finite speed of light, as we look to greater distance we are looking back in time, meaning we observe distant galaxies not as they are today but as they were some time in the past. The most distant galaxies known have redshifts of $z \sim 3$–4, corresponding to look back times of 80–90 percent of the age of the Universe.



Two major problems impede the comparison of past and present galaxies. At different redshifts, we observe different regions of the spectrum. For example, what we observe as the optical spectrum of a $z \sim 3$ galaxy was emitted in the ultraviolet near Lyman α (1216 Å), a spectral region which is little studied for local galaxies because it is accessible only to space-based instruments. At the same redshift, the familiar optical region of the spectrum has been shifted into the infrared to wavelengths of ~2–3 μm, a region of poor sensitivity from the ground and for which space-based instruments have not yet been built.

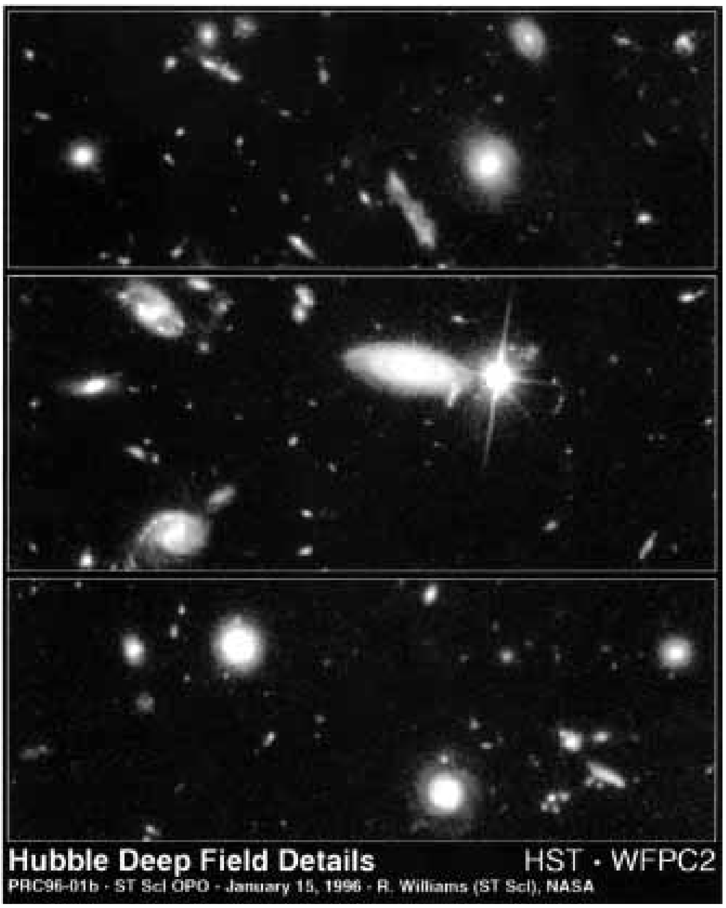
The second problem involves the conversion of observed parameters such as size and brightness into intrinsic properties, for which we also need to know the geometry of the Universe—that is, the rate of expansion and the curvature of space-time, which depends on its overall density. These two quantities are described by the "Hubble constant," H_0, and the deceleration parameter, q_0. Astronomers now agree on the value of H_0, which describes the rate of expansion, to within ±30 percent. The effects of q_0 only become strongly apparent at redshifts $z \sim 1$ and greater, however, and its value is controversial. Galaxy counts and apparent size distributions favor a low value ($q_0 < 0.1$), indicating a Universe of such low density that gravity does little to slow the expansion. Cosmologists, however, favor a value of $q_0 = 0.5$, a critical value required by popular models and for which the Universe contains just enough matter to stop the expansion after an infinite amount of time. These two models for the Universe are sometimes referred to as "open" and "critically closed" universes.

The most widely accepted model of the Big Bang theory has structure forming very early in the expanding, cooling Universe, as small fluctuations in matter density grow under the influence of gravity. Smaller clumps of matter form first; these later merge to form larger and larger structures. Initially, mass concentrations are in the form of gas and mysterious dark matter, but at some point the gas collapses to form stars. The exact point at which galaxies form is not yet known, nor is the sequence clear—do they form as units of gas with masses similar to galaxies today, or as small units of stars and gas that then merge into more massive galaxies? Some clues are found in the morphologies of present-day galaxies. Certain galaxies, called ellipticals, have light profiles and kinematics consistent with the merging of already-formed stellar systems. Disk galaxies, including the well-known spirals, have flattened, rotating components of stars formed from a pre-existing gas disk. Most spirals also contain a "bulge" component similar in many respects to a small elliptical. The ages of stars in these galaxies are consistent with ellipticals and bulges forming early in the history of the Universe, within the first few billion years, and disks forming much later.

While the details of galaxy formation are still vague, certain expectations for the early Universe are clear. The basic mass units should be smaller than in the present-day Universe, because at very early times the massive galaxies of today should have been in pieces. Star formation should have been much more vigorous than it is today, in order to explain the currently-seen stellar populations of galaxies.

Until quite recently, studies of distant galaxies were limited to counting the number of faint galaxies per square degree in each brightness interval, in different colors. Such number counts were then compared to models of how the local population of galaxies would appear if projected back in time, making various assumptions about the star formation rate, how stellar populations in galaxies age, the rate at which galaxies merge, and the geometry of the Universe. More detailed studies were hampered by two main problems. First, distant galaxies have very small angular sizes, and the blurring caused by the Earth's atmosphere prevented astronomers from determining the structure, or even the size, of such galaxies. Second, distant galaxies are exceedingly faint, and existing telescopes were unable to gather enough photons for even low-resolution spectroscopy—crucial to determining the redshift, and hence distance, age, and the means to convert observed properties into intrinsic sizes and luminosities.

With the launch of the Hubble Space Telescope (HST), and particularly following the refurbishment mission in 1992 to correct its flawed optics, astronomers were finally able to analyze the shapes and angular sizes of truly distant galaxies, those seen back in time at a significant fraction of the age of the Universe. While the Hubble Space Telescope is not large by ground-based standards, from its vantage point above the atmosphere it is able to detect galaxies much fainter than is possible from the ground. However, the superb HST images are impossible to interpret without knowing the redshifts of the galaxies, which are essential to converting apparent size and brightness to intrinsic values. Thus, the second key advance was the building of a next generation of large ground-based telescopes, beginning with the 10-meter Keck telescope in 1994, providing photon-gathering advantages of four to six times over existing instruments. These new telescopes would have the spectroscopic capabilities needed to provide redshifts for the galaxies imaged by HST.



Hubble Space Telescope

Hubble Deep Field Details

HST · WFPC2

PRC96-01b · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

Hubble Space Telscope images of galaxies have superb resolution unattainable from ground-based observatories, but without distance information there is little we can tell about each galaxy. (Courtesy AURA/STScI)

IN 1991, in view of these pending developments, Garth Illingworth, David Koo, and Sandra Faber, three galaxy experts at the University of California at Santa Cruz (UCSC), decided to team up with other experts across the country to orchestrate a systematic study of distant galaxies that had to date been impossible. This project, called the Deep Extragalactic Evolutionary Probe, or DEEP, makes use of the unique facilities of HST and the Keck telescope to push faint galaxy observations to look back times within one or two billion years of the Big Bang.

The study of evolution in galaxies is easy in principle: one simply takes an inventory of galaxies in a nearby volume of space and a similar inventory at greater distances (and hence look back times) and compares them. In practice, the situation is much more complicated. The local Universe is surprisingly difficult to inventory—since galaxies come in a wide range of morphologies, sizes, and brightness, the inclusion or exclusion of galaxies is affected severely by selection criteria. In addition, covering a sufficiently large volume to get a representative sample means covering large areas on the sky, which has not been feasible to date. Fortunately, the Sloan Digital Sky Survey (see article on page 22), will clarify immensely our understanding of the local galaxy population.

Now consider more distant galaxies. The redshift of each galaxy must be known in order to place it in the correct volume, and to determine its intrinsic luminosity and size. Clearly, the inventories will only be complete down to a particular observed brightness—only the most luminous galaxies will be observed in each volume, and this selection bias worsens with distance. Since we expect the luminosities of galaxies to evolve, this makes a comparison with local samples much more complicated to interpret. Furthermore, any interpretation must include the effects of galaxy merging. Finally, with increasing redshift, the optical observing window corresponds to increasingly shorter wavelengths in the galaxy's spectrum. By a look back time of half the age of the Universe, the visible spectrum of a galaxy corresponds to light emitted in the ultraviolet, a spectral regime dominated by hot, luminous young stars, rather than the older stellar population that accounts for most of the luminous matter in a galaxy.

In order to disentangle evolutionary changes from selection biases, especially given the wide range in galaxy properties, large samples of galaxies with well-defined selection criteria are needed. Furthermore, these samples need to be acquired in several different directions on the sky, both to study the clumpiness in the matter distribution, and to smooth over its effects for evolution studies. Obtaining and interpreting these samples is the primary goal of the DEEP project.

DEEP IS ENVISIONED as a two-phase program. The initial phase seeks to characterize the basic properties of distant galaxies: masses, luminosities, sizes, the abundance of elements other than hydrogen and helium, and dust content. For these purposes, spectra of approximately 1000 distant galaxies must be acquired. The initial phase also permits exploration of various observing strategies for the second phase, a large-scale survey of about 15,000 targets. This second phase depends on the completion of a new spectrograph, DEIMOS (see sidebar on the left).

The initial phase of DEEP has been underway for about two years, and has already generated important discoveries. Most of these—but not all—support the standard view of galaxy evolution.

A few years ago, astronomers realized that young, star-forming galaxies at very high redshift ($z > 3$) would exhibit a unique spectral signature that permits their identification merely from images taken in different colors. Shortward of $\lambda = 912$ Å, photons emitted by

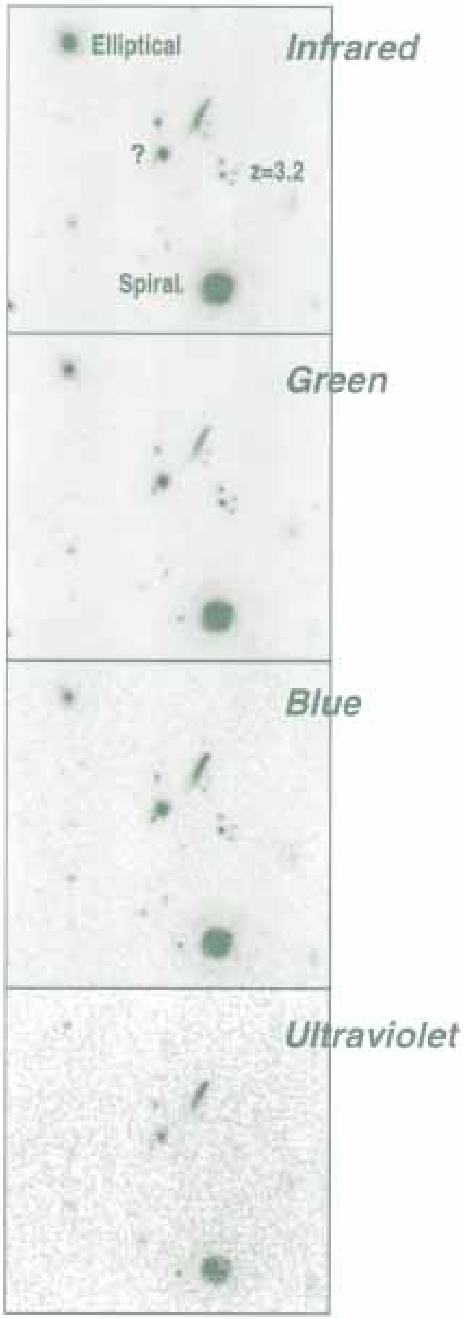
DEIMOS

DEIMOS, the Deep Imaging Multi-Object Spectrograph, is central to the large survey aspect of the DEEP project. In spectroscopic mode, DEIMOS will acquire spectra of roughly 150 faint galaxies simultaneously. For normal survey operations, spectra from 0.4–0.9 μm, at a spectral resolution of ~2000, will be acquired in a single exposure.

DEIMOS consists of two separate optical paths or "beams," each imaging a region roughly 5×16 arcminutes on the sky. For spectroscopy, a thin metal sheet with precisely positioned "slitlets" milled into it is placed in the lightpath; each slitlet covers not only a targeted object but also the adjacent blank sky, as night sky emission lines can be two orders of magnitude stronger than the galaxy signal and must be carefully removed during analysis. The spectrograph camera design, by Harland Epps of the University of California, Santa Cruz is the most ambitious ever attempted in astronomy. The camera consists of seven elements (three of CaF_2), and includes three highly aspheric surfaces. The detector is a mosaic of eight low-noise, high quantum efficiency CCDs arranged in an overall format of 8192×8192 pixels. This configuration is mirrored in the second beam.

As designed, DEIMOS should be roughly 14 times more efficient for faint galaxy spectroscopy than existing instruments. This advantage comes from the large area covered on the sky and the very large detector format which permits observing a wide spectral range at fairly high resolution. In addition, there will be an active optical control to remove any effects of mechanical flexure as the instrument changes position to track the sky, allowing highly precise instrumental calibration.

Currently, DEIMOS is under construction with one of the two proposed beams and is scheduled to be placed on the Keck-II telescope in mid-1998. The second beam is awaiting funding from a private source.



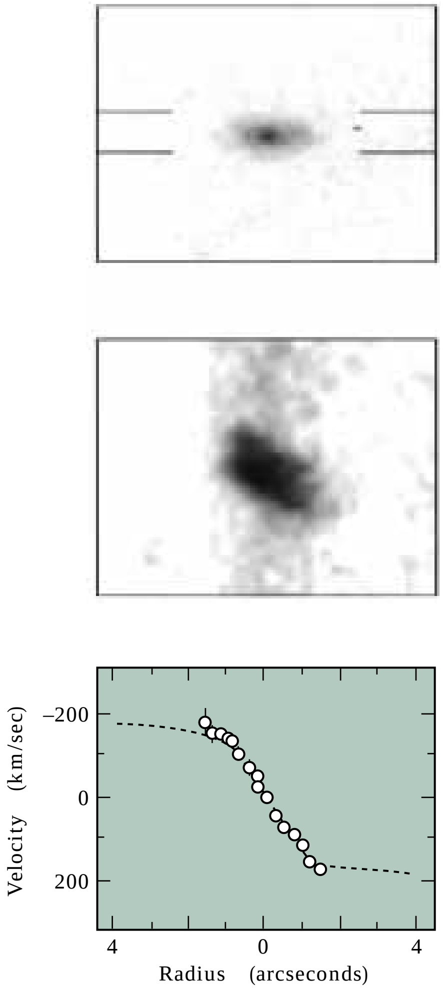
HST images in different colors give limited spectral information. Going from near-infrared through ultraviolet, the intrinsically red elliptical becomes fainter. The spiral remains bright, although its morphology changes as star-forming regions progressively dominate toward the UV. The cluster of four objects at redshift $z = 3.2$ is intrinsically blue, and stays bright until the UV, when it disappears or "drops out." The object labeled "?" shows similar behavior, although it does not completely disappear in the UV, suggesting a high redshift but with $z < 3$.

galaxies have sufficient energy to ionize hydrogen in intervening clouds; in effect, the transparency of space falls dramatically and suppresses the light escaping from the galaxy. These changes in the spectrum are so strong that they are easily detected in broad passband images—the high-redshift objects appear relatively blue, but virtually disappear in ultraviolet images (see figure on the right). The technique of selecting such high-z objects was pioneered by Charles Steidel at Caltech (see Virginia Trimble's article in the last issue of the *Beam Line*, Vol. 27, No. 2, p. 31) and has opened up an opportunity to study galaxies at a mere 10 to 20 percent of the age of the Universe.

Last year, DEEP researchers led by James Lowenthal obtained spectra for a dozen such "UV dropout" galaxies, confirming redshifts of $z \sim 3$. These distant objects are luminous yet surprisingly small and display a wide range in morphologies and spectral characteristics. While some astronomers believe these are the progenitors of the bulge components of present-day massive galaxies, caught near the moment of formation, Lowenthal and his coworkers find their numbers to be too great for this—the number of these distant objects matches or exceeds that of luminous galaxies of all types seen today. This, along with the small sizes, suggests that we are seeing "pieces" of galaxies that will later merge into the larger systems seen today.

DEEP researchers Andrew Phillips and Rafael Guzmán headed a study that determined the nature of small, bright galaxies seen in deep images from the HST—galaxies of such small apparent size that even their HST images tell us little. The spectra of these galaxies reveal a redshift distribution roughly similar to that of other galaxies of comparable apparent brightness, showing them to be intrinsically small and luminous. The majority have strong emission lines, revealing vigorous on-going star formation. Also, the width of the emission lines implies low internal velocities, meaning these objects have small masses. These tiny galaxies are very similar to local "H II galaxies," low-mass dwarf galaxies which are forming stars at an extremely high rate. It appears that a significant fraction of the total star formation in the Universe at redshift $z = 0.4$–1.0 took place in such dwarf galaxies, whereas in the present-day Universe a much smaller fraction does so. The fate of these galaxies has yet to be determined—do they fade into faint systems of aging stars, difficult to detect in local surveys, or are they accreted by larger galaxies?

DEEP researchers led by Nicole Vogt have, for the first time, measured the rotational velocity of spiral galaxy disks out to redshifts of $z \sim 1$, or roughly half the age of the Universe. Since the rotational velocity is directly proportional to a galaxy's mass, this enables us to probe galaxy masses at these earlier epochs. In the local Universe, there is a well known linear relation (the "Tully-Fisher Relation") between rotational velocity and luminosity. Surprisingly, the more distant galaxies follow nearly this same relationship, meaning that galaxies very similar to local galaxies existed at significantly earlier ages—even near the expected epoch of disk formation, when we might expect disks to be



Rotation in a distant disk galaxy seen by HST (top) is reflected in the tilted emission lines due to ionized oxygen (middle). The receding and approaching sides of the galaxy disk produce Doppler shifts to the red and blue of the average redshift, z = 0.50. The lower panel shows the measured velocity shifts.

unusually bright due to the vigorous production of new, luminous stars. The exact interpretation of this result is uncertain, but it clearly constrains the amount of evolution in the luminosity of large disk galaxies. The mere existence of well-formed, massive disks so early is problematic for some theories of galaxy formation.

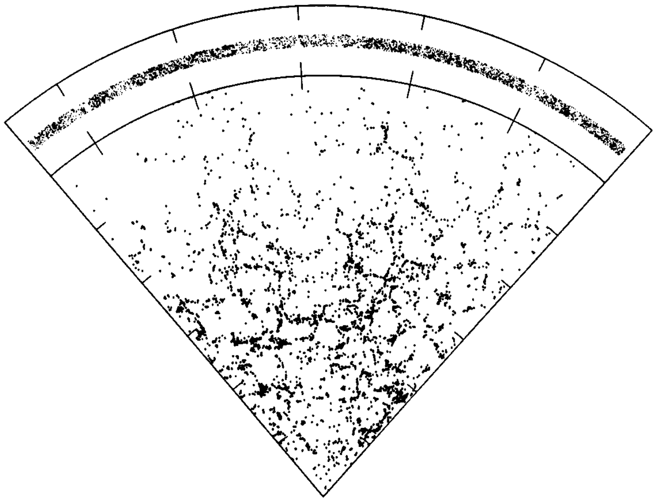
Finally, DEEP and other groups have found sharp "spikes'' in the overall distribution of galaxy redshifts at least out to $z \sim 1$. We know that in the local Universe, galaxies are concentrated in "walls" that outline great bubbles or "voids" (see figure on the next page). These giant structures show up as clumps in the redshifts along any given line of sight. Distant redshift spikes confirm that galaxies at earlier epochs were already organized in similar large structures, as expected from cosmological models. In depth study of the sizes, shapes and velocity dispersion of these distant structures should provide estimates of values of cosmological parameters and insight into the nature of the mysterious dark matter in the Universe. At present the number of galaxies observed is too small to draw significant

Forefront Instruments in Optical Astronomy

STUDIES of distant galaxies such as DEEP have been made possible through the advent of two unique instruments. The Hubble Space Telescope, despite its relatively modest size, provides superb images of faint galaxies that would be impossible to achieve from below the Earth's atmosphere. The W. M. Keck telescope, on the other hand, provides the light-gathering capability needed for spectroscopy of such faint objects. The 10-m Keck telescope, the largest in the world, is based on a novel segmented mirror design by Jerry Nelson of UC's Lawrence Berkeley Laboratories (now at UCSC). Its construction was made possible by a donation from the W. M. Keck Foundation to the California Institute of Technology. The observatory is operated jointly by University of California and Caltech. It is located at the world's best site for optical astronomy, the 4000-m summit of Mauna Kea in Hawaii. The telescope saw first light in 1994, and was joined by an identical twin in 1996. The next telescope of comparable size, the Hobby-Eberly Telescope, at the McDonald Observatory in Texas, is expected to be completed later this year.

Observing time at the Keck telescopes is granted via a proposal/review process at each institution. Generally, no more than two or three nights per semester are granted for any proposal, and specific observing dates are assigned to winning proposals based on the required instrumentation, time of year, and maximum acceptable level of moonlight. A small group of observers travels to the summit to conduct the observations, although an increasing number of observers are opting for remote operation from the headquarter facilities near sea-level, or even via satellite link from their home institutions. Vagaries of weather and equipment add a strong element of chance to the success of any observing run, and time lost to these factors usually means starting over at the initial proposal stage the following year.

conclusions, but the large-scale DEEP survey will provide the necessary statistics.



The distribution of galaxies in the nearby Universe is not smooth, as shown in this redshift survey across a 1.5° × 80° "slice" of the sky. We are located at the apex, looking out. The furthest galaxies seen here are about 3 billion light-years away. (Courtesy A. Oemler)

AS LARGER samples of galaxy spectra are collected, the focus of DEEP will shift toward investigating the large-scale structure of matter in the Universe and how this structure evolves. In addition to the large numbers of redshifts that are determined directly from spectra, the sample will be increased several-fold by measurements of "photometric redshifts." This approach, spearheaded by DEEP scientist Alex Szalay and collaborators at Johns Hopkins University, makes use of multi-color images to construct very coarse "spectra" of hundreds of galaxies in each observed field. While spectral features such as emission and absorption lines are clearly not accessible, the overall energy distribution in the galaxy's spectrum can provide a good estimate of its redshift. The "UV dropouts" discussed above are examples of galaxies identified by this method. The technique requires spectroscopically-measured redshifts for calibration, but once calibrated it can provide both major increases in sample size for determining large-scale structure, and a means of pre-selecting candidates in narrow redshift ranges for high-resolution spectroscopic observations. Such observations will, in turn, provide estimates of the sizes, depths and mass densities of walls and clusters at different look back times.

The questions in extragalactic research and cosmology are well-posed, but until recently the answers have been beyond our reach. With the advances provided by HST, new large telescopes like the Keck, and dedicated surveys like SDSS and DEEP, many of these answers should soon appear. It is an exciting time for astronomy.