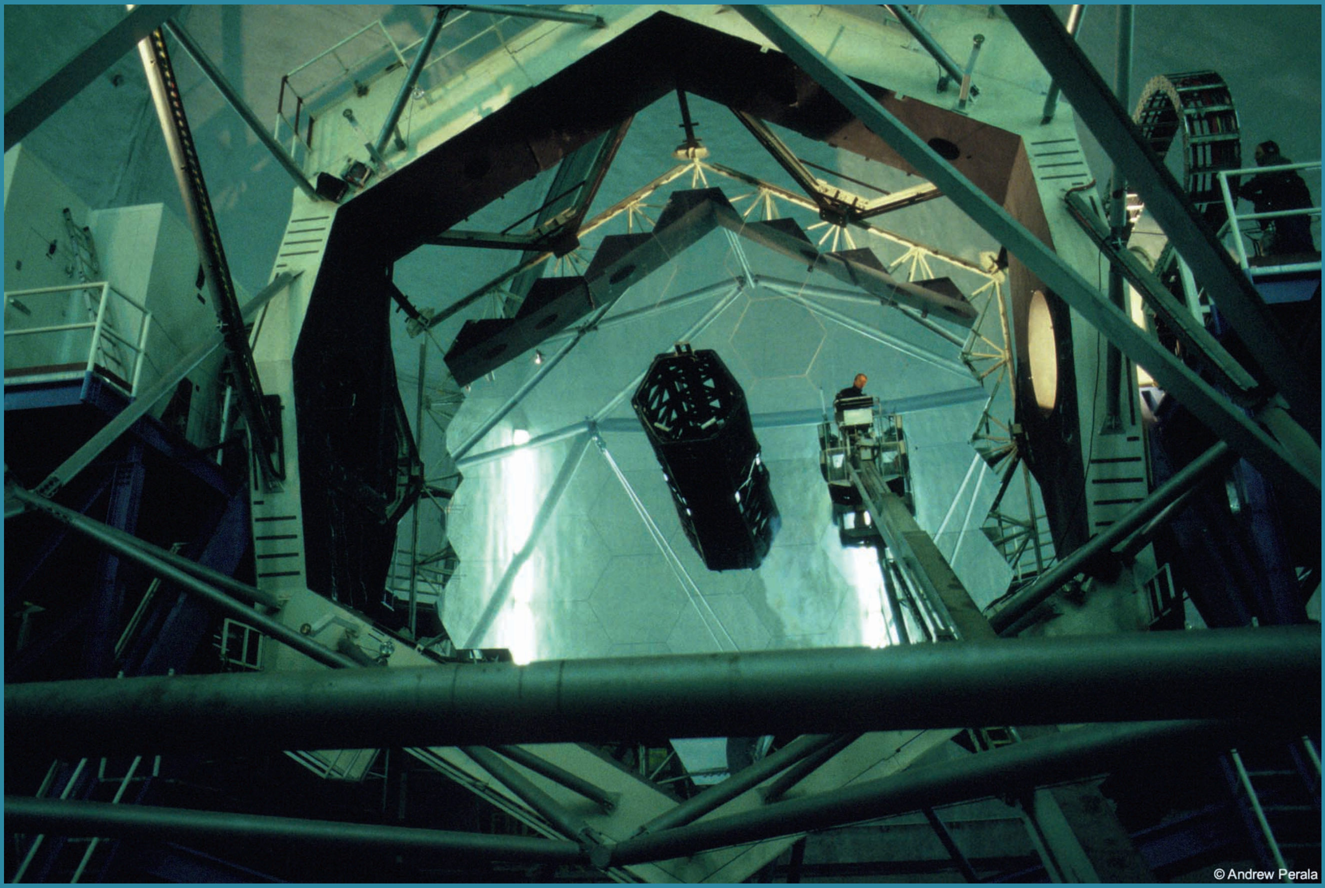
DEEP: A 21st-Century Time Machine



University of California

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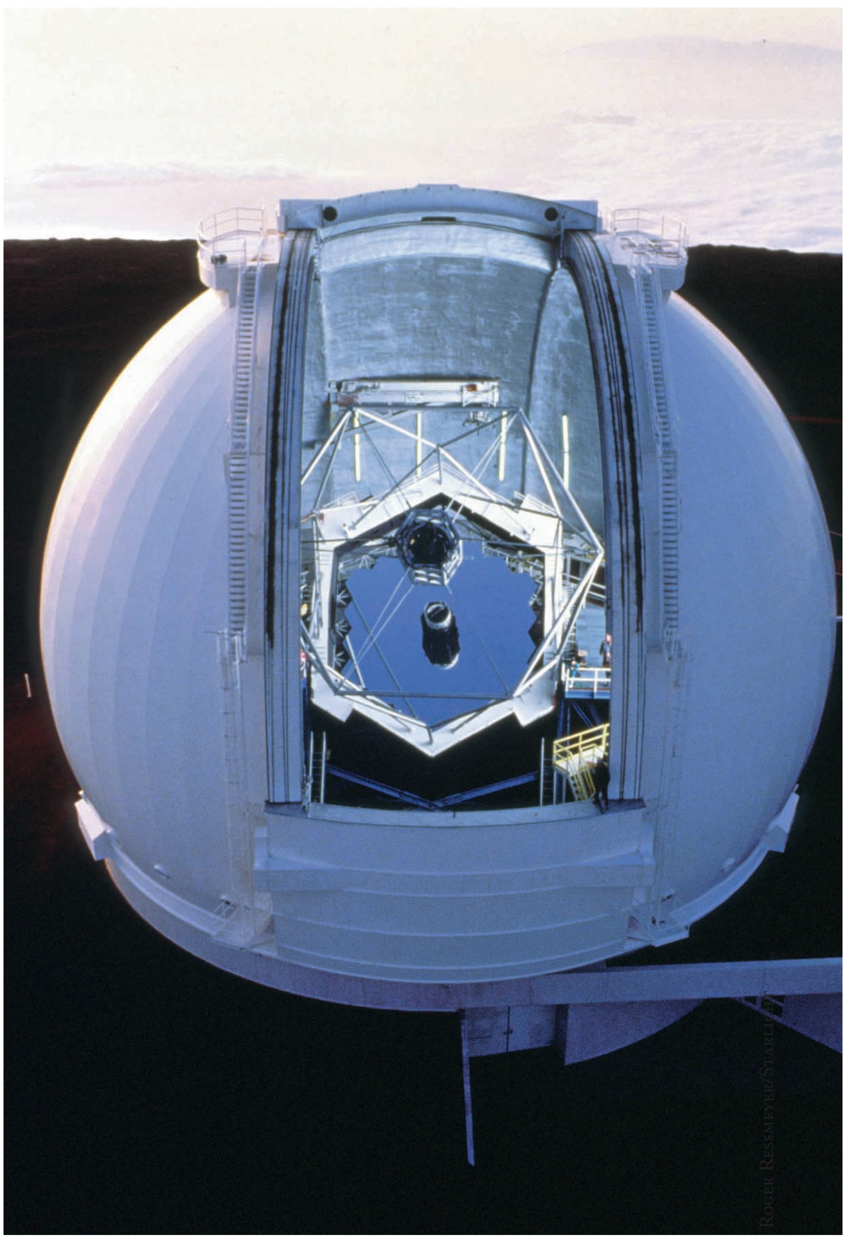
DEEP: A 21st-Century Time Machine



A Look Back in Time

Using the revolutionary Keck telescope as a 21st-century time machine, the DEIMOS spectrograph and DEEP Survey will enable astronomers to look back billions of years to find answers to fundamental questions about the origin of the Universe.

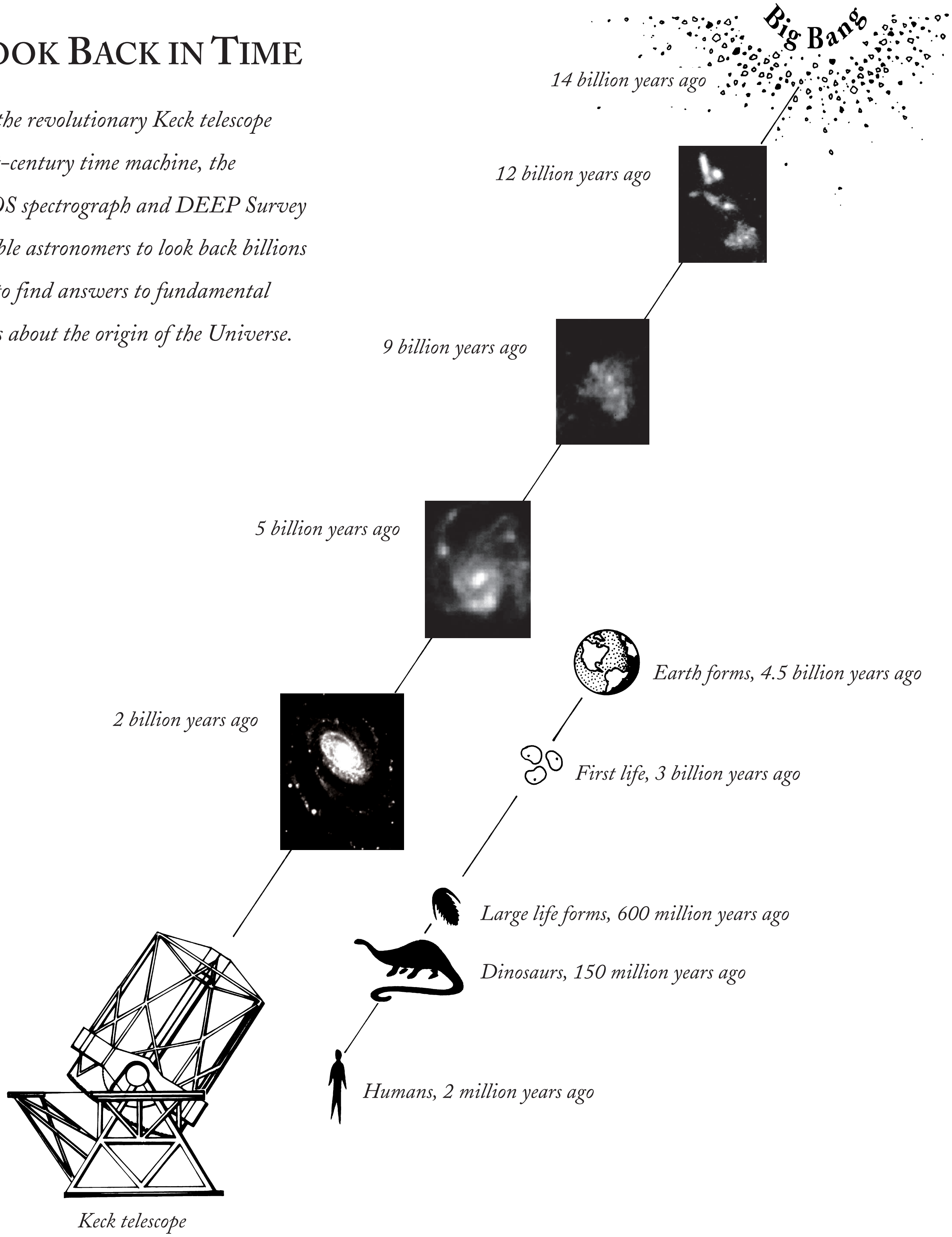


ILLUSTRATION: SANDRA FABER AND ANN FAUST

Project Summary

University of California astronomers are leading a journey that will answer fundamental questions about the origin of the Universe. This quest—literally a trip back billions of years in time—is made possible by revolutionary instrumentation developed by UC astronomers for use at Hawaii's Keck Observatory, the world's premiere observational facility. The DEEP Survey promises to be one of the most exciting scientific voyages of the 21st century.

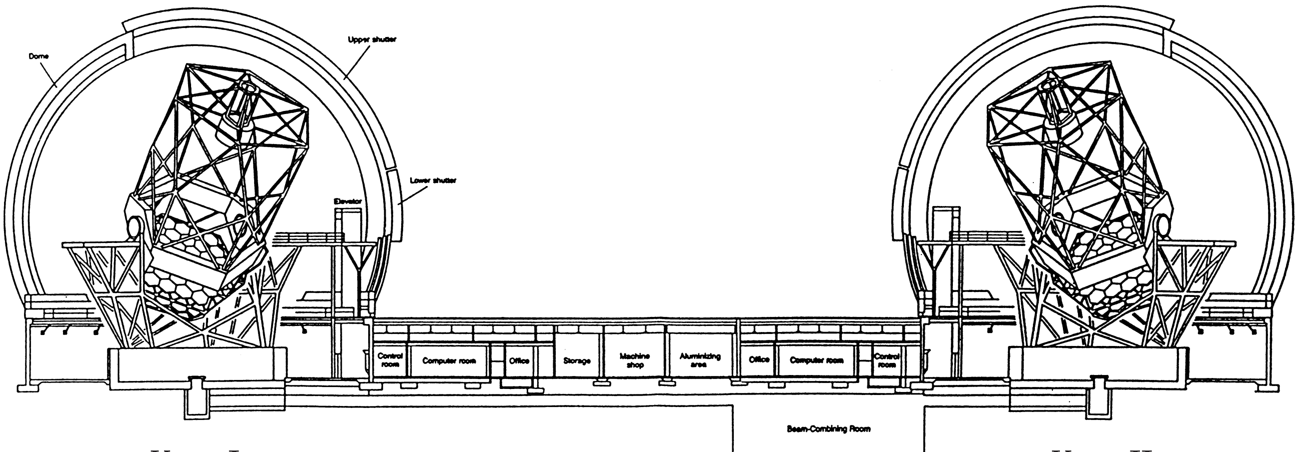
DEIMOS (DEep Imaging Multi-Object Spectrograph) is a powerful new spectrograph for the Keck II telescope that will magnify the telescope's capacity by a factor of seven for faint-galaxy optical spectroscopy. The DEEP (Deep Extragalactic Evolutionary Probe) Survey, made possible by DEIMOS, will create the first comprehensive map of the distant Universe. DEIMOS and DEEP will, for the first time, allow astronomers to verify their theories about the origin of the Universe.

The Keck Observatory, located on 14,000-foot Mauna Kea in Hawaii, is operated jointly by the University of California, Caltech, and NASA. Keck I and Keck II are the world's largest telescopes, collecting four times more light each than the famous Palomar 200-inch (5-meter) telescope. Keck I has been operating since 1993, and major scientific discoveries are released almost monthly. Its twin, Keck II, was commissioned in 1996 and will serve as the dedicated platform for DEIMOS. The segmented mirror technology of the Keck telescopes is a brilliant success, but a telescope's scientific productivity is no better than its instrumentation. The DEIMOS spectrograph will ensure Keck's position at the forefront of astronomy well into the next century. DEIMOS is a double-beam spectrograph whose optical beam is nearing completion and whose infrared beam is under design. The optical beam is the prime instrument of the DEEP Survey and is seven times more powerful than the first-generation optical spectrograph currently on Keck I. This huge gain comes from technical innovations that include:

- Advanced optics,
- A "slitmask" system allowing observation of 140 galaxies at a time,
- The largest spectroscopic detector of its type ever made,
- Sophisticated software for rapid setup, flexure compensation, and data reduction.

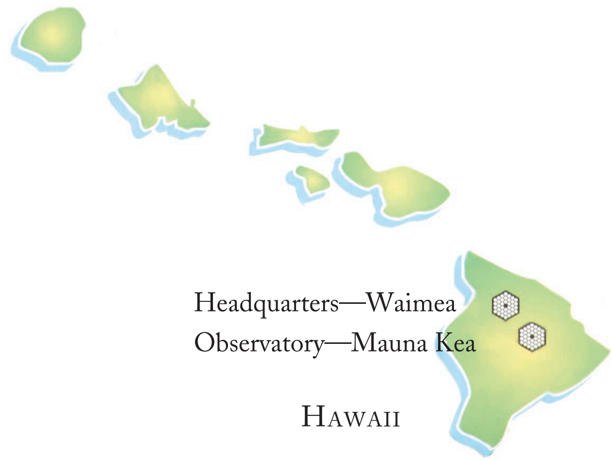
The DEEP Survey will use the powerful "eyes" of Keck II and DEIMOS to collect and analyze light that has traveled billions of years from its original source, probing tens of thousands of galaxies at the edge of the visible Universe. DEEP data will answer profound questions: When did galaxies form? How did they evolve to form stars like our Sun? What is the nature of the mysterious "dark matter" that makes up 90 percent of the Universe? Is there enough dark matter to stop the expansion of the Universe, or will it keep on expanding forever? Is the expansion of the Universe in fact *accelerating*?

W. M. Keck Observatory

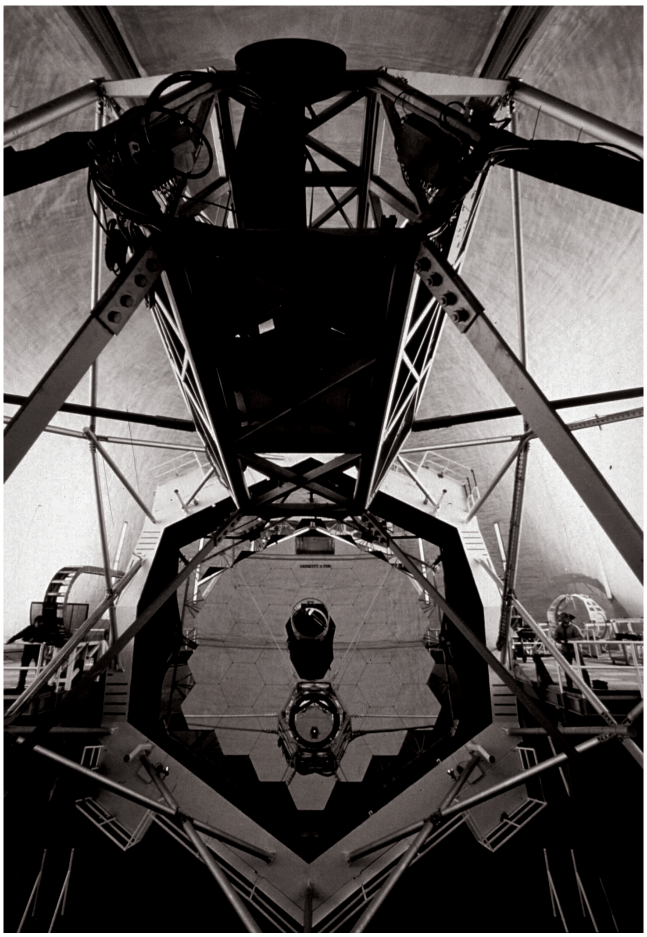


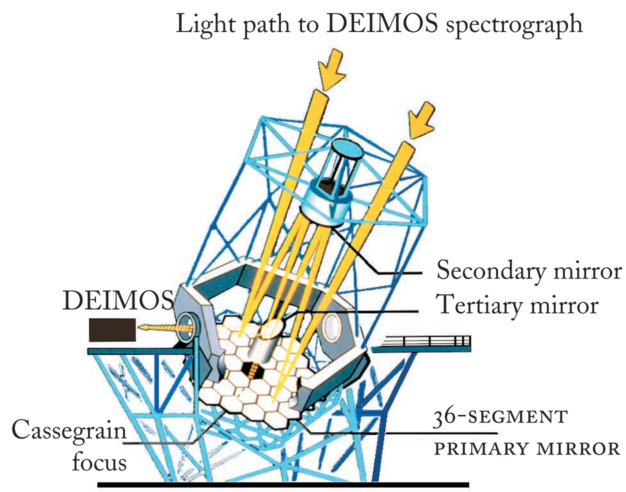
Keck I

Keck II



ROGER RESSMEYER/STARLIGHT





View from top end of Keck telescope toward the 33-foot primary mirror.

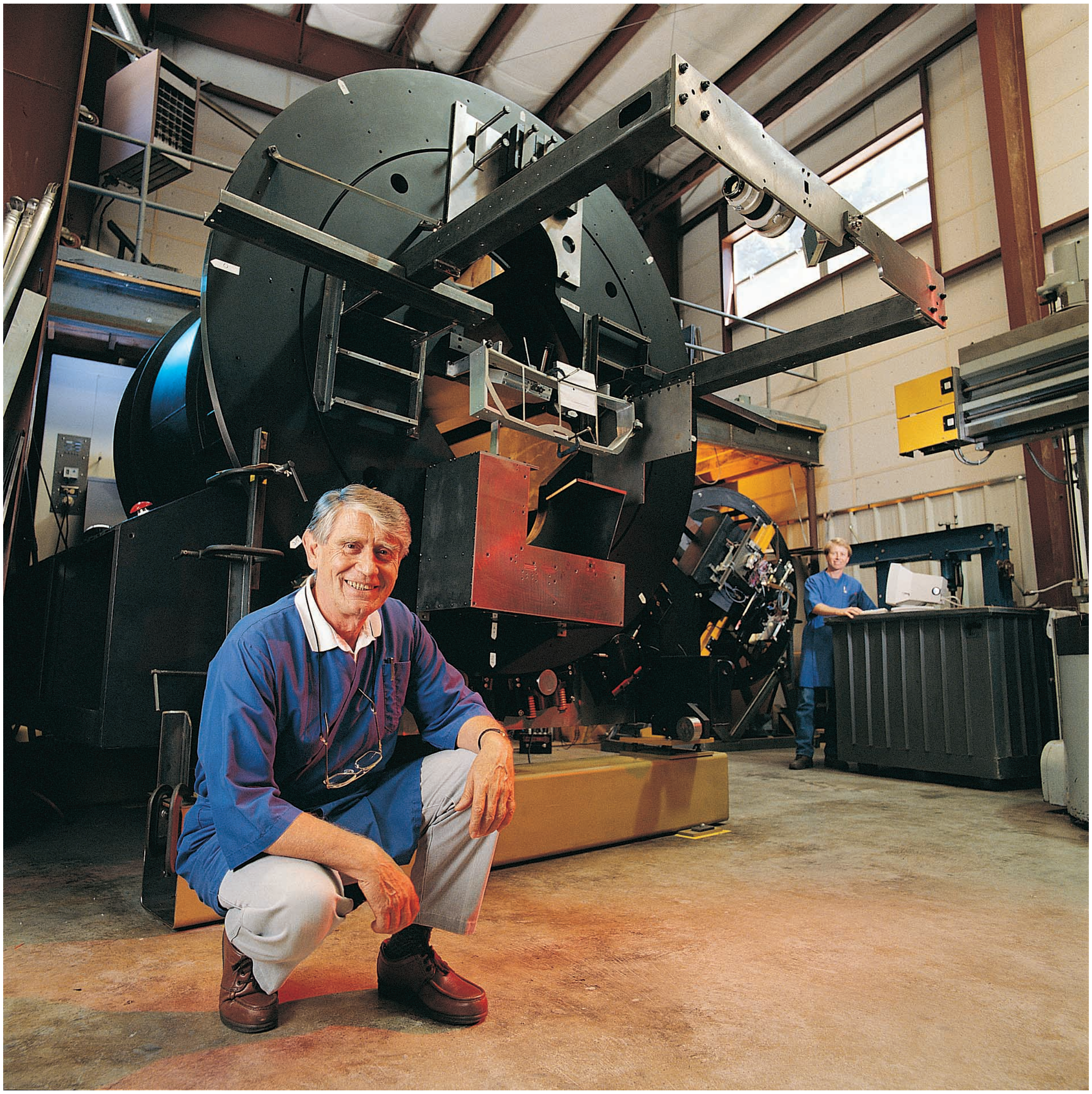
Roger Ressmeyer/Starlight

Keck I on the summit of Mauna Kea.

The W. M. Keck Observatory

The W. M. Keck Observatory dominates the 14,000-foot summit of Mauna Kea, a dormant volcano on the Big Island of Hawaii. The Keck Observatory operates the world's largest optical and near-infrared telescopes, Keck I and Keck II. At the heart of each telescope is a revolutionary mirror. Each one is composed of 36 hexagonal segments mosaicked together to form the equivalent of a single, huge mirror 10 meters (33 feet) in diameter. With a light gathering capacity each equivalent to four Palomar 200-inch telescopes, the Keck telescopes extend the reach of astronomers to the edge of the visible Universe.

Astronomers using Keck come from UC, Caltech, and UH, with broader participation by U.S. astronomers through NASA. Typically, an observing team of two to four scientists flies from California to the Big Island, travels to a midway station to adjust to the altitude, and then proceeds by 4-wheel-drive vehicle to the freezing cold summit of Mauna Kea. There they observe for one to five nights, taking data with state-of-the-art cameras and spectrographs. Recently, more and more astronomers are observing remotely from the lushly sited Keck Headquarters in Waimea. Eventually a remote link all the way from California is planned. Remote operation is the long-term plan for DEIMOS and the DEEP Survey.



The DEIMOS spectrograph under construction in the UCO/Lick Observatory Instrument Laboratory.

The University of California, Santa Cruz: Home to World-Class Instrumentation

In 1965, the University of California, Santa Cruz (UCSC), became the home campus for Lick Observatory. The observatory was founded by San Francisco philanthropist James Lick and deeded to the University in 1888. Lick's telescopes sit atop Mount Hamilton in the Coast Range east of San Jose, with management, instrumentation, and operations directed from nearby UCSC. Astronomers from seven UC campuses observe at Lick Observatory. When the Keck Observatory in Hawaii was added to UC astronomy facilities,
a larger unit was needed, and the University of California Observatories (UCO) was formed. The joint organization UCO/Lick Observatory remains headquartered at UCSC.

The current wave of 8- to 10-meter astronomical telescopes being built around the world began at UCO/Lick, with the genesis of what eventually became the Keck telescopes. Jerry Nelson, the designer of the unique Keck mirrors, is a UCO/Lick faculty member. Keck I's flagship optical spectrograph, HIRES, was designed and built at UCSC by Professor Steve Vogt. A second spectrograph, ESI, was recently shipped and commissioned by the UCO/Lick team. DEIMOS will be the third and most advanced optical spectrograph at Keck built by UCO/Lick.

Telescopes by themselves merely collect light—they are blind without a complement of efficient instruments and sensors to detect and analyze that light. Providing advanced astronomical instrumentation is the forte of UCO/Lick Observatory. At the heart of UCO/Lick's technological leadership is a suite of instrumentation laboratories that offer comprehensive capabilities in mechanical, electronic, optical, and software design and fabrication. The UCO/Lick laboratories are the largest instrumentation resource for Keck. With the DEIMOS spectrograph, UCO/Lick Observatory is taking on its biggest technical challenge to date.

DEIMOS: The DEep Imaging Multi-Object Spectrograph

DEIMOS is an advanced double-beam optical-infrared spectrograph. The DEEP Survey will be carried out using the optical beam, due to be completed in 2000. Follow-up observations will be made with the infrared beam, now in the planning stages. The optical beam multiplies the power of the current Keck system by a factor of seven, due to numerous technological advances built into the design.

LAYOUT

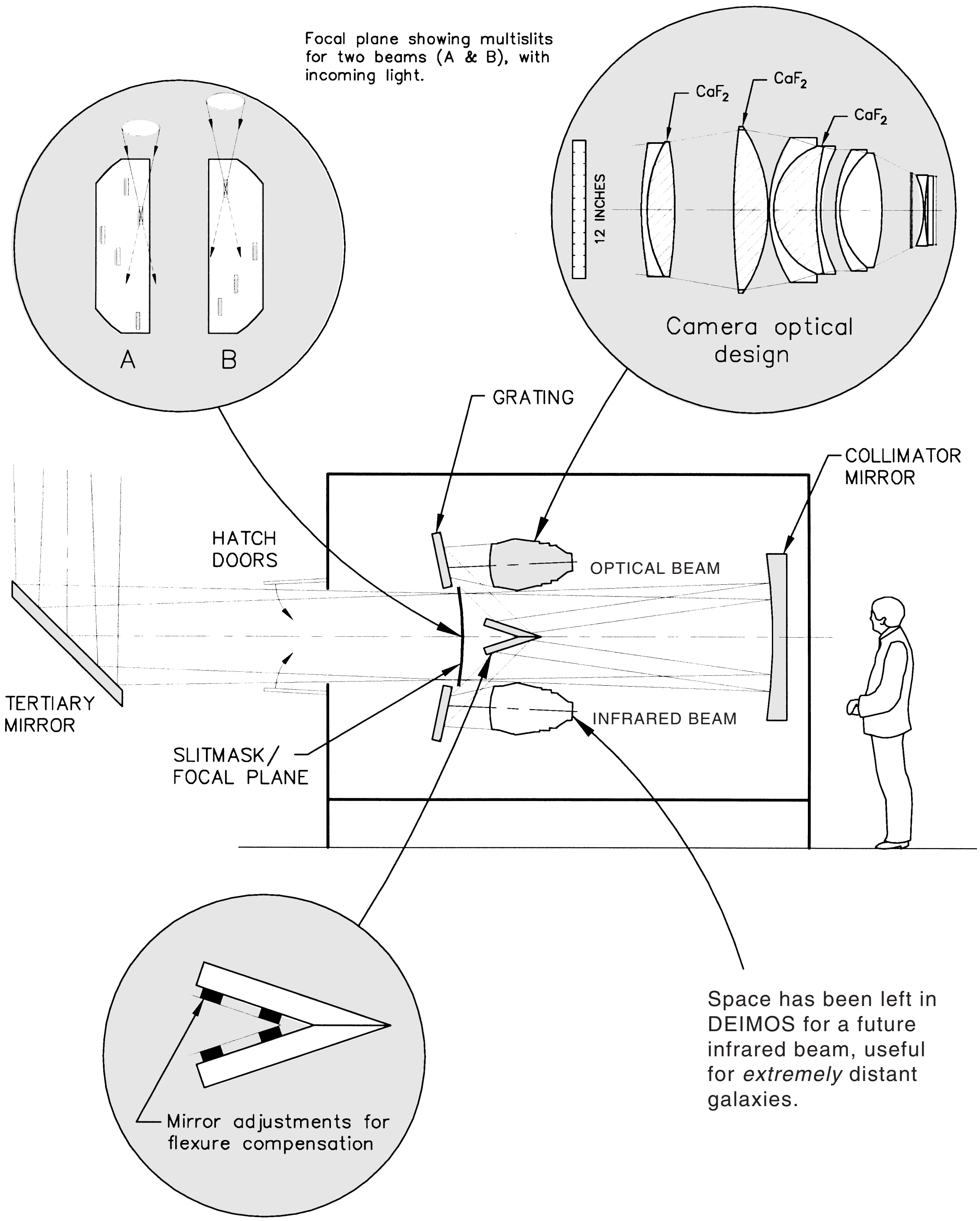
DEIMOS' layout is shown with the optical beam on top. DEIMOS will be situated on one of the two instrument platforms of Keck II. Light is directed to it from a tertiary mirror tilted at 45 degrees. This light comes to a focus at the focal plane, forming images of stars and galaxies. Covering each half of the focal plane is a smooth sheet of metal into which small slits are cut, called a "slitmask." The slit openings are precisely located to accept light from targeted objects. DEIMOS' optical beam can accommodate 140 slitlets, allowing 140 objects to be observed simultaneously. One night with DEIMOS is the equivalent of several hundred nights of old-fashioned, object-by-object observing.

OPTICS

The heart of the optical beam is its advanced optics. Light passes through the slitlets into the body of the spectrograph to the large collimator mirror at far right, where it forms a parallel bundle. It then travels via a flat mirror to the grating, which spreads it into a spectrum, or rainbow of colors. The camera takes the dispersed light and focuses it to make a picture of the spectrum of each slitlet. DEIMOS' optical-beam camera is the most ambitious astronomical camera ever made. Three of the large lens elements are calcium fluoride crystals up to thirteen inches in diameter. Calcium fluoride is used for its unique refractive properties. Made by the Optovac Corporation in Northfield, Massachusetts, these are the largest such crystals ever grown.

Another advance is the use of "aspherical" surfaces on three lenses. These surfaces, not precisely spherical in shape, add enormous power to the DEIMOS optical design but are extremely difficult to polish and test. Over the last five years, UCO/Lick has perfected a technique for making aspheric surfaces using a special device called a "profilometer," which measures the shape of each surface to an accuracy of a millionth of an inch.

DEIMOS OPTICAL LAYOUT



Space has been left in DEIMOS for a future infrared beam, useful for *extremely* distant galaxies.

DETECTOR

The third secret of DEIMOS is its state-of-the-art light detector, composed of eight charge-coupled devices (or CCDs). Each CCD is laid out on a silicon wafer rather like an integrated circuit. During exposure, the CCD absorbs light photons, each of which causes the silicon to release an electron. These electrons are caught and stored in individual “pixels.” When the exposure is ended, the CCD is “read out,” and the electron content of every pixel is counted. This allows the light intensity at each part of the spectrum to be measured.

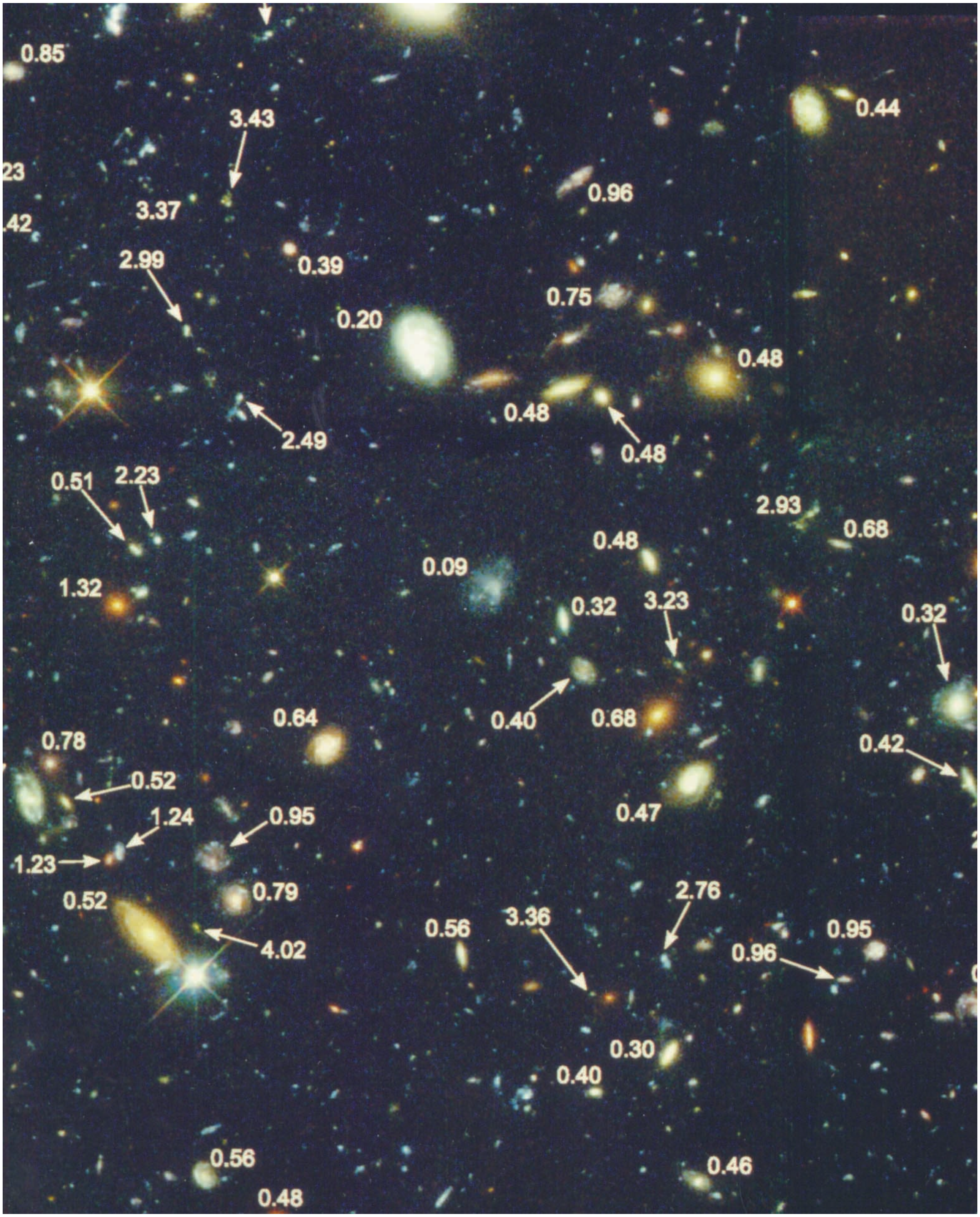
DEIMOS’ detector is the largest spectroscopic CCD in the world, as befits the scale of the world’s largest telescope. The detector is five inches square and contains 67 million pixels, the equivalent of 300 hand-held video cameras.

Detectors large enough for DEIMOS did not exist, so they are being developed in collaboration with MIT/Lincoln Laboratories. These CCDs are the best and largest in the world, each with 2000 x 4000 pixels. Eight of these will be joined together to create the huge detector required by DEIMOS. Production runs at MIT/Lincoln have already produced about half of DEIMOS’ CCDs, and more are being processed monthly.

FLEXURE CONTROL AND SOFTWARE

The final secret of DEIMOS is an exceptional suite of setup, alignment, and data reduction software. Conventional spectrographs suffer from severe “flexure,” i.e., shifts in optical alignment. These cause the image to move on the detector and make calibration and data reduction difficult. DEIMOS is the first spectrograph in the world to incorporate the same computerized stabilization principles that keep the 36 segments of the Keck mirrors aligned. This and other advanced software features will result in hours of extra effective observation time per night.

UCO/Lick optician David Hilyard with four of the nine DEIMOS camera lenses.



Enlargement of the Hubble Deep Field showing the faintest images of distant galaxies ever taken. Arrows pointing to galaxies show their redshifts—larger redshifts are more distant. The figure illustrates how images by themselves cannot tell distance; similar-looking galaxies in this picture have very different redshifts. The DEEP Survey will map redshifts on the sky with greater density than shown here, and over an area 15,000 times larger. The redshifts in this photo were made possible by the Keck telescope, the only telescope in the world capable of measuring such faint galaxies. (Courtesy: Space Telescope Science Institute.)

DEEP: The Deep Extragalactic Evolutionary Probe

Unlike scientists who reconstruct the past from fossils or buried artifacts, astronomers are able to view the past directly using large telescopes. Because light travels at "only" 186,000 miles per second, it takes a long time to travel cosmic distances, and distant objects are seen further back in time. For example, light from the Sun takes eight minutes to travel to the Earth, so when we look at the Sun we see it as it was eight minutes ago. Our nearest large neighbor, the Andromeda Galaxy, has a "lookback time" of two million years. This is just a tick of the cosmic clock compared to the Universe's age of fourteen billion years. The giant light grasp of Keck II plus DEIMOS will allow us to look far beyond Andromeda, to a time close to the beginning of the Universe when galaxies were only a fraction of their present age.

DEEP (short for Deep Extragalactic Evolutionary Probe) will conduct the first comprehensive survey of the *distant* Universe. The resulting DEEP Archival Database will be distributed in the form of an electronic catalog, the first distant cosmological survey of its kind so published. In the tradition of all great astronomical surveys, the DEEP Survey will become a scientific landmark and serve as a major magnet and stimulus for future research.

Other explorations have probed lightly back in time but have lacked the technology needed to thoroughly catalog the contents of the distant Universe. For this, spectra of at least 50,000 exquisitely faint galaxies will be needed. Why so many? Galaxies are complex objects, showing many different faces, forms, and sizes, and they are distributed in space in an irregular yet highly informative pattern called "large-scale structure." Because galaxies and large-scale structure are evolving over the range of lookback times that DEEP will probe, mapping a sufficient sample at each of several epochs will require tens of thousands of galaxies.

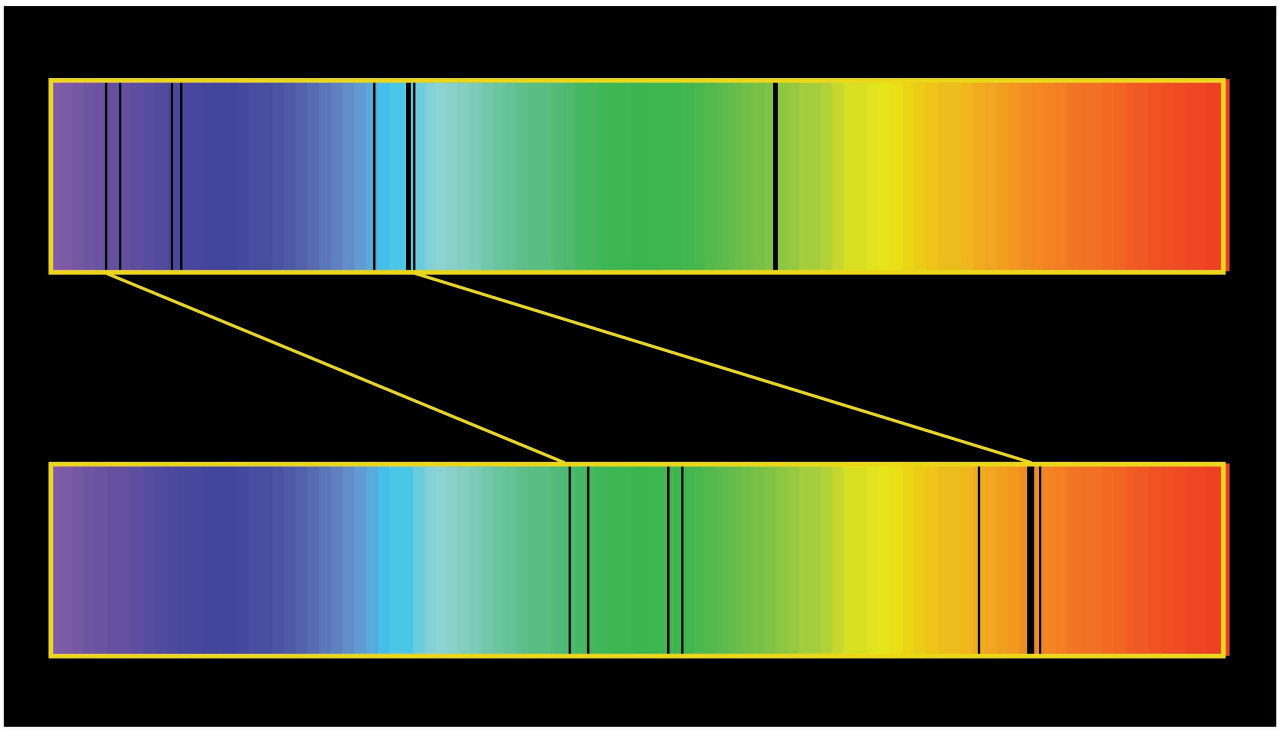
We already have hints that distant galaxies are not the same as those nearby. Pictures from the Hubble Space Telescope are strewn with images of very faint galaxies. Many look highly abnormal, showing disrupted structures, disorganized clumps, and other signs of galaxies possibly forming. These results are tantalizing, but Hubble pictures by themselves are incomplete because they do not tell us how far away the objects are. Small objects could be tiny galaxies in the foreground or very different, larger ones much farther away.

DEEP will break this impasse by measuring “redshifts” from the spectra of distant objects. In spectra, different chemical elements appear as distinctive lines at specific colors. Because the Universe expands, distant objects are moving rapidly away from us, resulting in a “stretching” of the light and a shifting of the element lines towards the red end of the spectrum. The amount of shift increases with distance—farther objects are shifted more. By taking spectra of many galaxies and measuring their redshifts, DEEP can measure all their distances—and make a map of the distant Universe.

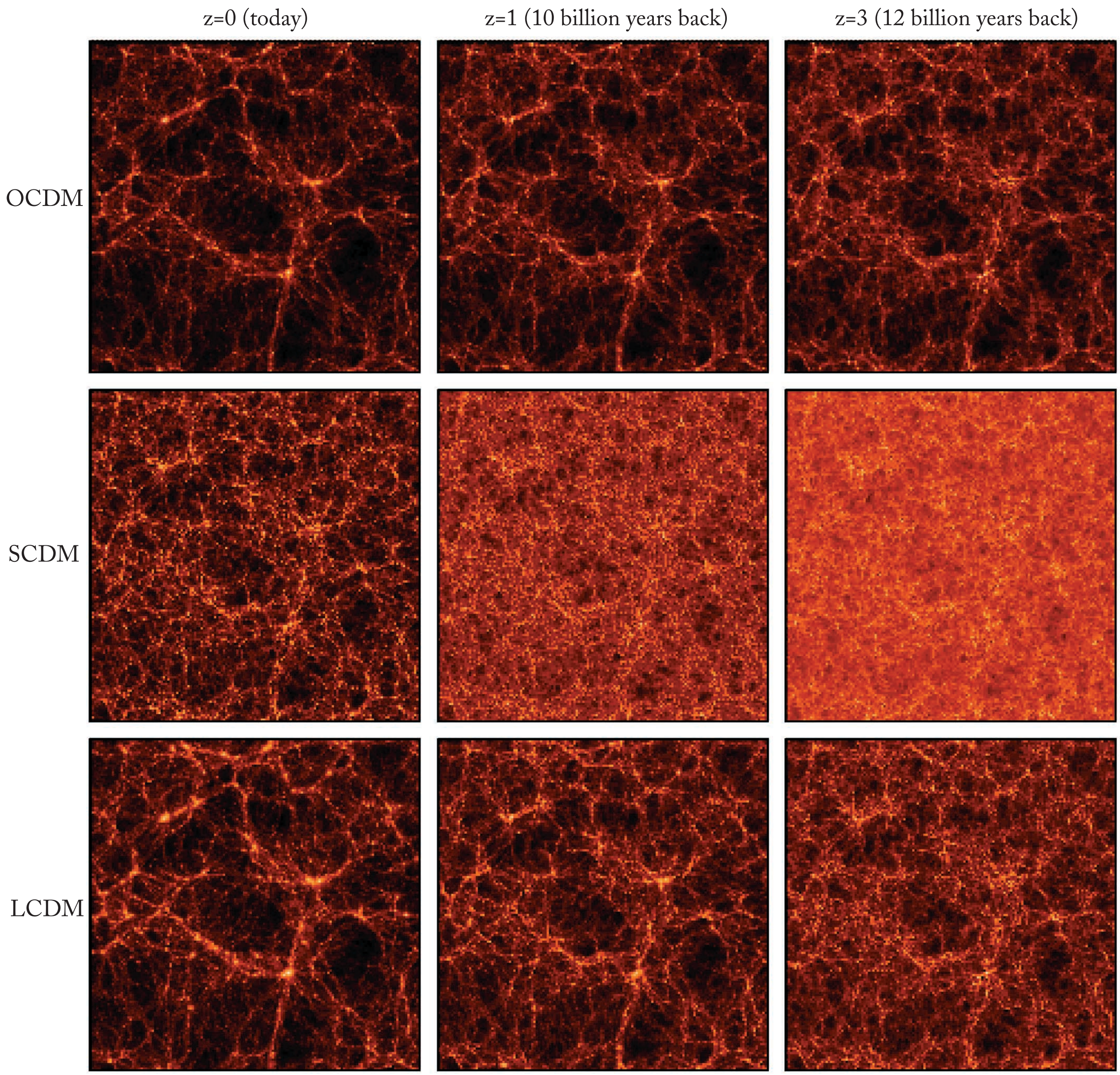
DEEP can do more. Thanks to DEIMOS’ powerful camera and detector, DEEP will measure the *masses* of distant galaxies and clusters of galaxies. This observation, never before possible, will provide a new measure of how matter is distributed in the distant Universe. We know that 90 percent of the Universe is made up of a mysterious unknown type of matter—so-called *dark* matter. The nature of dark matter is a top question of cosmology—what is it and how much of it is there? By studying the evolution of galaxies and structures over cosmic time, DEEP will provide crucial information on the nature of the dark matter, guiding experiments now being designed to detect dark matter in terrestrial laboratories.

A final word about galaxies and large-scale structure. These phenomena had their origin at an incredibly early time, possibly as early as one billion billion billion billionth of a second after the Big Bang. At that instant, the Universe went through a brief phase of wild expansion called “inflation.” During that special era, microscopic quantum-energy fluctuations, which normally come and go harmlessly, were inflated suddenly to macroscopic size and captured by the universal expansion. These tiny density “seeds” then grew over billions of years under their own self-gravity to become the huge galaxies, voids, and superclusters that we see today. By probing structure formation, DEEP is looking back to events that had their roots in time when the Universe was only a billion billion billion billionth of a second old.

Redshift: The indicator of Lookback Time



Shown are two spectra of the same galaxy as they would appear at different distances from Earth. Vertical black lines cross the spectrum due to the absorption of light by atoms in the galaxies. The top spectrum of the galaxy as seen nearby shows these lines at their natural colors. The expansion of the Universe “redshifts” the lines to longer wavelengths and redder colors in the lower spectrum. The amount of redshift increases with distance, and hence with lookback time. The symbol for redshift is “z”. The value z=0 corresponds to the present epoch; the value z=1, where DEEP data will peak, corresponds to a lookback time of over half the age of the Universe, or nearly 10 billion years.



Computer simulations of evolving large-scale structure of dark matter carried out by the Virgo consortium (Germany). Each clump of dots represents the location of a visible galaxy. Three epochs in time are shown (vertical columns). Each horizontal row shows a different model universe with a different kind of dark matter, amount of total matter, and cosmological constant (L). Note how all the present-day models look roughly similar (by design) but evolve differently back in time. This can be used as a test of cosmic parameters. The DEEP Survey will focus on z=1, corresponding to the epoch when the Universe was only half its present size. Each box is approximately 400 million light years on a side.

DEEP Science in Detail

The DEEP Survey will be the first to study the distant Universe with a fidelity approaching that achieved for the nearby Universe. DEEP is designed to measure both the properties of distant galaxies and their distribution in space. The aim of DEEP is to look for *evolution* in both quantities compared to the local Universe today. When paired with its natural partner, the Sloan Digital Sky Survey (SDSS), the DEEP Survey will reveal fundamental properties of the Universe.

DEEP will focus on the following scientific questions:

(1) How did large-scale structure in the Universe form and evolve?
The voids, walls, bubbles, and super-clusters of large-scale structure span hundreds of millions of light years (see opposite). Gravity creates this structure by drawing matter together into ever larger clumps, leaving voids in between. The statistics of the large-scale structure and its evolution with time are intimately tied to the nature of the dark matter, its total amount, and whether the Universe is accelerating or decelerating.

(2) What is the dark matter-galaxy connection?
Measuring large-scale structure depends on mapping visible galaxies, yet the raw medium from which galaxies formed is mostly dark matter with only a thin frosting of normal, “baryonic” gas. Only this frosting formed the stars of visible galaxies. We now suspect that the conversion of matter to visible galaxies was highly inefficient and uneven in the Universe, so that galaxies are an imperfect and probably biased tracer of the underlying dark matter. Since the amount of bias probably evolves with time, the same map of galaxies at different epochs corresponds to different distributions of dark matter. Inferring dark-matter maps from galaxy maps of large-scale structure is one of the major goals of observational cosmology.

DEEP has a unique measuring tool that will strengthen studies of the dark matter-galaxy connection. The high spectral resolution of the DEIMOS spectrograph will record the “linewidths” of distant galaxies, thus revealing their rotation speeds and masses. Masses are vital because many galaxies at high redshift are undergoing starbursts and look bright but are not massive. Galaxy formation models can take the visible masses of galaxies measured by DEEP and infer from them the total masses of their surrounding dark matter envelopes. DEEP linewidths thus provide an entirely new tool for turning galaxy maps into dark matter maps.

3) How did galaxies acquire their mature structural forms?

At the present time, galaxies have achieved a regular sequence of structural types called "Hubble types." This sequence seems to be stable in time and represents the end-point of galaxy evolution. As we look further out into space and observe objects at earlier times, galaxy morphologies, radii, masses, and brightnesses begin to change, until, at a time when the Universe was roughly one-quarter its present size, only small, ragged "protogalactic blobs" are visible. A major goal of DEEP is to delineate the maturation of protogalaxies into the Hubble types observed today. For this, DEEP will measure all the fundamental parameters of galaxies: their radii, brightnesses, morphologies, stellar-population ages, and above all their masses. DEEP observations will focus at redshift $z \sim 1$, when the Universe was roughly half its present size and mature Hubble types were emerging in large numbers. DEEP will take the first complete "galactic census" of the Universe at the era marking the emergence of normal galaxies.

4) What is the nature and amount of the dark matter?

A fundamental measure of large-scale structure is the "power spectrum," a function that expresses the degree of galaxy clustering on different length scales. The variation of the power spectrum versus scale length is the single most important clue to the nature of dark matter; it can show whether the dark matter is "hot" or "cold" (made up of light or heavy particles) and whether it is stable or decaying with time. DEEP will measure the power spectrum on short length scales (150 million light years), which are highly diagnostic for distinguishing hot from cold dark matter.

The amount of total matter in the Universe, Ω_{matter}, controls whether the Universe will expand forever or eventually collapse. In an "open" universe with low Ω_{matter}, large-scale structure ceases to grow when the density of matter becomes too low for gravity to overcome the expansion. Therefore, if DEEP sees little change in the amount of large-scale clustering from the distant universe to now, this will indicate that Ω_{matter} is low. DEEP will also measure the growth (if any) in the pair-wise motions between neighboring galaxies, a further measure of Ω_{matter}.

5) Is the cosmological constant (Λ) non-zero?

The "cosmological constant" is an energy density that may be present in the Universe even if there is no matter present. Its presence is permitted by the equations of general relativity, but its value must be determined experimentally. A non-zero Λ would mean that there is a new kind of gravity that paradoxically causes the expansion to *accelerate*. Non-zero Λ is central to some of the most interesting cosmological models, including the inflation theory, in which an early temporary phase of non-zero Λ drove a spectacular burst of rapid expansion that created the Universe as we know it. The discovery of that Λ is still non-zero today would arguably be the most profound finding of 20th century astrophysics.

Recent cosmological data are pointing toward a non-zero cosmological constant. These come from measuring the apparent brightnesses of Type Ia supernovae, a particular class of stellar explosions. Those furthest from us look too dim by about 20% for Λ to be zero. However, the supernovae measurement is far from rock-solid: early supernovae may have been intrinsically dimmer, their host galaxies may have been dustier and absorbed their light, and so forth. The measurement of Λ is such an important cosmic experiment that it must be repeated in multiple ways.

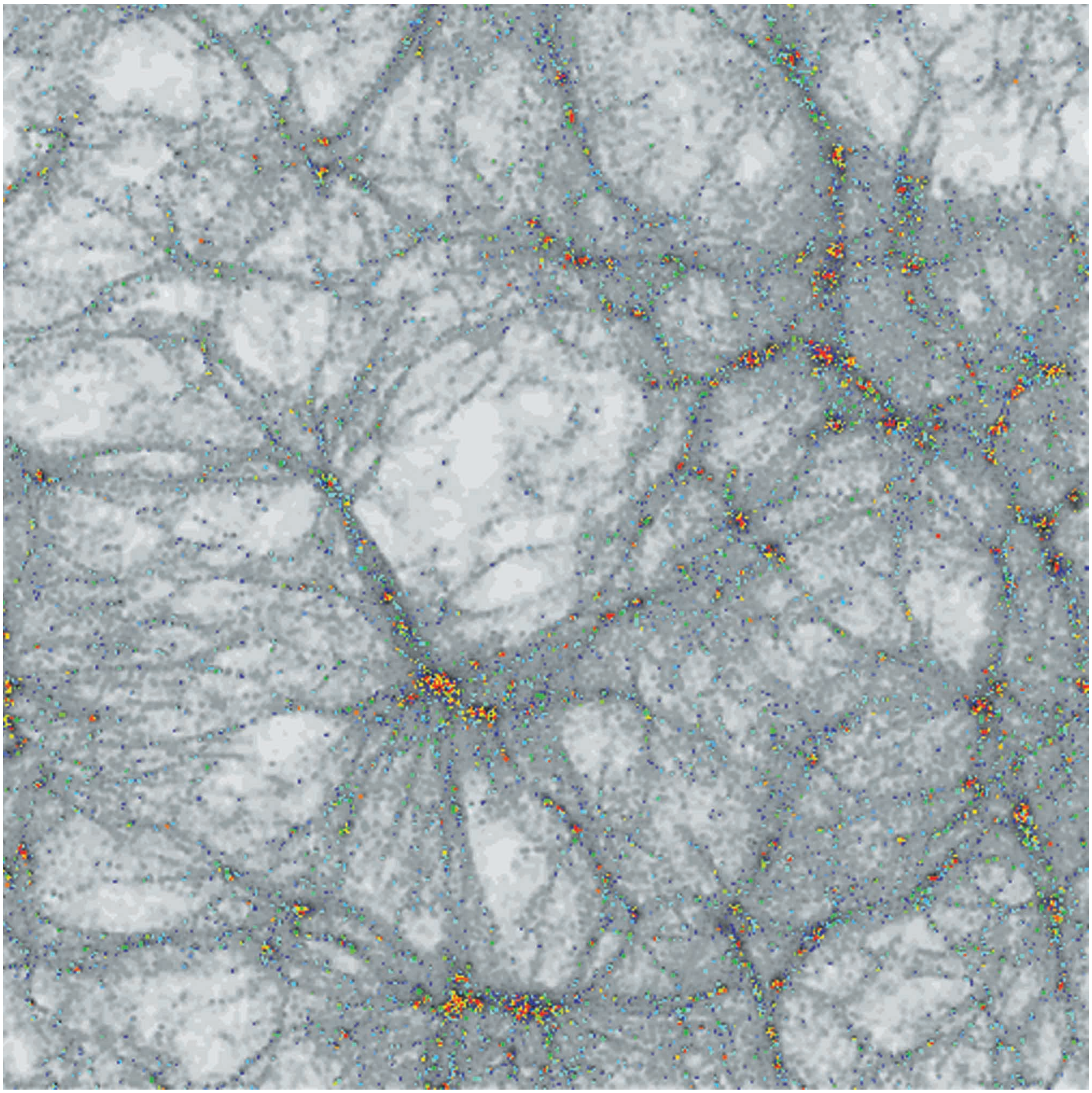
DEEP offers several independent attacks on Λ. All are based on the fact that non-zero Λ warps spacetime in predictable ways, altering the relationship between the apparent size, brightness, and number of galaxies versus redshift. These are things that DEEP will measure. DEEP also offers a possible new "metric ruler" for spacetime, namely, the ratio of the apparent characteristic scale of large-scale structure transverse to and along the line of sight. This ratio is also sensitive to Λ.

RELATION TO THE SLOAN DIGITAL SKY SURVEY

DEEP and SDSS complement each other perfectly—like two bookends, each one allows the other to do more. SDSS will yield the definitive census of the Universe at current epochs out to 2 billion years ago; DEEP will provide a comparable picture further back in time by 10 billion years and beyond. DEEP and SDSS will both in turn be compared to maps of the *cosmic microwave background* radiation, which shows the Universe as it was when only a million years old. Together, these three surveys provide three independent snapshots of the Universe at three different epochs in time. Broadly speaking, there are also three independent processes to be understood: 1) the initial amplitude and shape of the dark matter power spectrum, 2) the total amount of matter, and 3) how galaxies formed within and trace the dark matter. Three epochs are therefore required to determine all parameters. The DEEP Survey provides the missing middle epoch needed to unravel the complex web of cosmic evolution.

MODELING AND INTERPRETING DEEP DATA

The story of cosmic evolution is complicated by countless interlocking processes. Generally, it is not possible to make a single measurement and deduce from it a single cosmic parameter; pictures at multiple epochs must be compared to realistic computer simulations showing the expansion of the Universe, the clustering of the dark matter, the emergence of galaxies, and the growth of large-scale structure. The DEEP team includes several leading architects of the theory of large-scale structure and galaxy formation, who will aid in this theoretical interpretation. We also have close links to three world-class theory groups, in Santa Cruz, England, and Germany. These collaborations will allow creation of the detailed "computer universes" that will be needed to hold up as mirrors to the real Universe.



An enlarged dark matter computer simulation in which visible galaxies have been embedded. Dark matter is shown in grey, visible galaxies are colored dots. Dot color indicates galaxy type: red is elliptical, green is spiral, blue is irregular. The figure illustrates how different Hubble types populate the dark matter differently, a product of galaxy "biasing." (Courtesy: Virgo consortium.)

THE DEEP SURVEY IN BRIEF		
Instrument	DEIMOS spectrograph	
Fields	Four fields, each 0.5 deg by 2.0 degrees	
Locations	Northern hemisphere, two fields within the SDSS deep strip	
Redshift range	z = 0.7 to 1.55, peaking at z~1	
Spectral range	0.60-0.95 microns	
Velocity resolution	30 km per second	
	1-Hour Survey	3-Hour Survey
No. target galaxies	65,000	7,000
No. redshifts	50,000	5,000
No. Keck nights	90 nights	30 nights
Exposure time	1 hour	3 hours
Magnitude range	I = 18-23.5	I = 23.5-24.5
Imaging	CFHT (ground)	CFHT + HST
Total Keck nights	120 nights	
UC nights	80 nights	
Caltech nights	40 nights	
Observing months	April-October	
Observing dates	Spring 2001 to fall 2003	
Project dates	Fall 2000 to fall 2005	
Faculty:		
UC	Davis (PI), Faber, Koo, Guhathakurta	
Caltech	Steidel, Ellis, Metzger	
External	Luppino, Kaiser (Hawaii); Szalay (JHU); Kron (Chicago)	

DEEP Survey Strategy

The proposed DEEP Survey consists of two parts: the 1-Hour Survey (1HS) and the 3-Hour Survey (3HS). The 1HS is a dense mapping of the spatial location of 50,000 galaxies that will map the large-scale structure at $z \sim 1$, when the Universe was half its present size. Rotation speeds will be measured for half the galaxies in the 1HS, which will establish the total masses of dark-matter envelopes surrounding these galaxies. The number and nature of galaxies will be compared to their positions within the dark-matter distribution, which is essential for understanding the "biasing function" that describes how the Universe turned matter into galaxies.

The 3-Hour Survey is a deeper sub-survey of 5,000 galaxies within the 1HS that goes one magnitude (2.5 times) fainter. The 3HS will target special regions for which Hubble Space Telescope imaging will also be requested. The high resolution and fine detail of the Hubble images will allow us to measure full structural and morphological information, and thus observe the emergence of normal, "mature" galaxies that occurred near $z = 1$.

A novel feature of DEEP is pre-screening of targets using so-called "photometric redshifts." It is possible to make a rough estimate of the redshifts of galaxies using images taken through several broadband color filters—three such images provide a very coarse, three-point spectrum. Finder images for DEEP will be taken by Gerald Luppino and Nicholas Kaiser of the University of Hawaii using Luppino's state-of-the-art CCD mosaic camera on the Canada-France-Hawaii telescope (CFHT) on Mauna Kea. With three wavebands, we can effectively remove all unwanted galaxies in the foreground below $z = 0.7$, eliminating half the targets and doubling the observing efficiency.

DEEP will commence observing in the spring of 2001 when the DEIMOS spectrograph comes on line. Observing will require three years, and data reduction and analysis will require two more years. The Survey will gear up for observing in fall 2000 and will end in fall 2005, for a total project duration of five years.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Appendix:
The DEEP/DEIMOS Team

David Cowley—DEIMOS Project Manager; Senior Project Engineer, UCO/Lick Observatory

David Cowley is chief engineer at UCO/Lick Observatory. He joined UCO/Lick from the Canada-France-Hawaii telescope on Mauna Kea, where he was chief mechanical engineer. There he led several major projects, including the full redesign of the telescope top end. Cowley has extensive experience with finite-element analysis and with modern project-management techniques.

Marc Davis—Professor, UC Berkeley

Marc Davis is Principal Investigator of the DEEP Survey. He is a member of the National Academy of Sciences, a former Sloan Fellow, and the recipient of major awards for groundbreaking work on the evolution of large-scale structure in the Universe. Davis will lead the statistical analysis of large-scale structure found by DEEP and determine its evolution through time.

Richard Ellis—Professor, Caltech

Richard Ellis has just joined the Caltech astronomy department from Cambridge, England, where he led the extragalactic observational cosmology group. Ellis is a world leader in surveys of the distant Universe and a pioneer in studying galaxy evolution using the lookback effect. His recent addition to the DEEP Survey adds a wealth of scientific and organizational experience.

Sandra Faber—Astronomer, UCO/Lick Observatory; University Professor, University of California

Sandra Faber is Principal Investigator of the DEIMOS spectrograph and a member of the DEEP Survey. She played a major role in founding Keck Observatory and co-managed the scientific instruments for Keck I. She now provides the astronomical oversight for DEIMOS. A member of the National Academy of Sciences, former Sloan fellow, and recipient of major awards, Faber has a long-term interest in galaxy formation.

Puragra Guhathakurta—Associate Astronomer, UCO/Lick Observatory; Associate Professor, Astronomy and Astrophysics, UCSC

Raja Guhathakurta is a member of the DEEP Survey. A current Sloan Fellow, he is well known for his studies of the morphology of distant galaxies and for his extraordinary skill in processing and analyzing CCD images. He will be studying the evolution of galaxies using DEEP Survey data.

Nicholas Kaiser, Professor—University of Hawaii

Nicholas Kaiser is famous for his statistical studies of the growth of large-scale structure. A formidable theorist, he has turned observer and, with Gerald Luppino, will be using Luppino's 8k x 12k CCD camera on CFHT to measure gravitational leasing of distant galaxies by intervening clouds of dark matter. The Luppino-Kaiser fields are providing the finding images for the DEEP Survey.

Robert Kibrick—Research Astronomer, UCO/Lick Observatory

Robert Kibrick has led the instrument software development program at UCO/Lick for 22 years and has developed numerous telescope and instrument control systems. Kibrick has wide-ranging experience in electronics hardware, motor control, imaging systems, and precision position measurement systems (including several patents). The UCO/Lick software group under Kibrick's leadership has a reputation for understanding the special needs of astronomical instrumentation and delivering an excellent product at minimum cost.

David Koo—Astronomer, UCO/Lick Observatory; Professor, Astronomy and Astrophysics, UCSC

David Koo is a member of the DEEP Survey. He is well known as an expert on evolving galaxies and is the inventor of "photometric redshifts." With Kron, he was one of the early discoverers of the faint-blue galaxy excess, a major clue to cosmic evolution. He will be studying galaxy evolution using DEEP Survey data.

Richard Kron—Professor, University of Chicago; Director, Yerkes Observatory

Richard Kron is known for his discovery of an excess of blue galaxies at faint levels, one of the earliest clues that the distant Universe is evolving. Kron is a co-member of DEEP and the Sloan Digital Sky Surveys. He will work to ensure that the velocity widths measured for nearby galaxies by SDSS will be fully compatible with those from the DEEP Survey.

Gerald Luppino—Associate Professor, University of Hawaii

Gerald Luppino is a world leader in CCD technology and is Project Scientist for the MIT/Lincoln CCD project that is producing DEIMOS' CCDs. Luppino designed and built the 8k x 12k mosaic camera (currently the world's largest CCD detector) that is being used on the Canada-France-Hawaii telescope to map the DEEP Survey fields and identify galaxies for Keck spectroscopy.

Terry Mast—Research Astronomer, UCO/Lick Observatory

Terry Mast is co-leader with Faber of the DEIMOS spectrograph project. Mast has a wealth of instrumental experience, most notably with Jerry Nelson in designing and building the Keck telescopes. A physicist by training, Mast is exceptionally skilled in mechanical and optical design and testing.

Mark Metzger—Assistant Professor, Caltech

Mark Metzger is a promising young extragalactic astronomer with extensive experience in extragalactic observational cosmology and optical instrumentation. He is a member of the DEEP Survey.

Joseph Miller—Director/Astronomer, UCO/Lick Observatory; Professor, Astronomy and Astrophysics, UCSC

Joseph Miller is Co-Principal Investigator of the DEIMOS spectrograph and has led many forefront instrumentation projects at UCO/Lick including the recently delivered ESI spectrograph for Keck II. UCO/Lick attained its present position as a world leader in optical instrumentation in large part through Miller's leadership.

Andrew Phillips—Associate Specialist, UCO/Lick Observatory

Andrew Phillips is a skilled extragalactic observer with extensive experience in astronomical software and data reduction. He leads the DEIMOS slitmask production software and the DEEP pipeline data reduction and archiving efforts.

Charles Steidel—Associate Professor, Caltech

Charles Steidel is renowned for his discovery of "Lyman break" galaxies at redshift z ~3, which broke open the study of the earliest phases of galaxy formation. A former Sloan Fellow, Steidel is a member of DEEP and co-leader with Richard Ellis of the Caltech group.

Richard Stover—Research Astronomer, UCO/Lick Observatory

Richard Stover leads the Lick CCD Detector Development Laboratory. Stover has extensive experience in CCD detector technology and instrument-control software. Lick Observatory has historically been famous for its aggressive role in adapting new detector technologies for astronomical use. Stover's well equipped CCD laboratory makes the crucial tests and quality control measurements on DEIMOS' CCDs.

Alexander Szalay—Professor, Johns Hopkins University

Alex Szalay is famous for his studies of the density fluctuation and power spectrum of the Universe that gave birth to galaxies and large-scale structure. He is a co-member of DEEP and of SDSS. As leader and designer of the SDSS Science Database, he will ensure that the DEEP and SDSS archives are properly coordinated.