The DEEP Survey of the Distant Universe: an LMAP Proposal

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Summary

The DEEP Survey will be the first project to study galaxies in the distant universe with a fidelity as good as or better than that achieved in local samples. DEEP has been designed to measure both the *properties* of distant galaxies and their *distribution* in space. The proposed DEEP Survey consists of two parts, the **1-Hour Survey** (**1HS**) and the **3-Hour Survey** (**3HS**). A summary of the basic parameters of the 1HS and 3HS is given in Table 1 (next page).

- The 1HS is a dense mapping of the spatial locations of ~50,000 galaxies with redshifts > 0.7 and brighter than $\sim M^{*}+0.5$. The 1HS will determine absolute number densities of various types of bright galaxies, the galaxy correlation function, higher-order clustering statistics as a function of galaxy type, and a variety of other measures of large-scale structure at $z \sim 1$. It will make possible a number of new, interesting tests of fundamental cosmic parameters.
- Linewidths will be obtained for roughly half of all 1HS galaxies. Linewidths should be a more robust indicator of the masses of dark halos than galaxy luminosities and provide a more direct window on the underlying dark matter distribution than any other property of galaxies.
- The dense sampling in the 1HS will allow measurement of the density of galaxies surrounding each galaxy, which is predicted to correlate strongly with the so-called "biasing function", the efficiency with which the universe transforms matter into galaxies. Determining the dependence of biasing on galaxy properties will provide a strong test of galaxy formation models.

- The 3HS is a deeper sub-survey of ~5,000 galaxies within the 1HS that fulfills several needs: (1) The 3HS provides redshifts and linewidths for absorption-line galaxies, which are systematically missed in the 1HS. (2) The 3HS will establish the completeness of the 1HS by re-observing a subset of it with triple the exposure time. (3) The 3HS goes roughly 1 magnitude deeper into the luminosity function for most galaxy types. This greater depth will also increase the detection rate for galaxies in the redshift "desert" beyond $z > 1.2$. (4) HST images will be requested for all 3HS fields, providing galaxy radii and morphologies.
- Complete structural data from the 3HS sample will allow us to measure the densities of galaxies in Fundamental Plane space versus environment. Evolution of this "structure function" is another key test of galaxy formation models.

- The DEEP Survey will take full advantage of DEIMOS, a unique spectrograph with a large field of view, high spectral resolution, and large spectral coverage. The science program outlined here cannot be replicated on any other instrument or telescope worldwide.
- Supporting data in DEEP regions will be obtained from the CFHT, HST, SIRTF, the Large Millimeter Telescope, the Sloan Digital Sky Survey, and Sunyaev-Zeldovich CMB absorption maps, at minimum.
- The DEEP Survey is supported by state-of-the art cosmological simulations by the Santa Cruz theory group led by Joel Primack and by all other major groups worldwide.
- The total Keck commitment required for the DEEP Survey is 120 nights, 80 from UC and 40 from collaborators at Caltech, over 3 years. Proposed observations begin with the availability of the DEIMOS spectrograph in fall 2000.

TABLE I: The DEEP Survey in Brief

Instrument	DEIMOS spectrograph	
Fields	Four fields, each $0^\circ\!.27 \times 2^\circ\!.0$, plus outriggers	
Coordinates	14 17, +52 30	Groth Survey Strip
	16 52, +34 55	last zone of low extinction
	23 30, +00 00	on deep Sloan DSS strip
	2 30, +00 00	on deep Sloan DSS strip
Redshift range	$z = 0.7$–1.55, pre-selected using photo-z's	
Grating and spectra	830-line/mm; 6000–9500 Å usable range	
	[O II] 3727 visible for $0.61 < z < 1.55$	
Resolution	$0''\!.75$ slit; FWHM = 2.32 Å $\simeq$ 86 km s^{-1}	
	1-Hour Survey	**3-Hour Survey**
No. target galaxies	65,000 (est.)	7,000 (est.)
No. redshifts	$\gtrsim$ 50,000 (est.)	$\gtrsim$ 5,000 (est.)
Co-moving volume	$\sim 10^6 h^{-3}$ Mpc	$\sim 10^5 h^{-3}$ Mpc
No. Keck nights	90 nights	30 nights
Exposure time	1 hour	3 hours
Magnitude range	$I_{AB} \leq 23.5$ mag	I_{AB} =23.5-24.5 mag
% sampled to mag lim	75%	64%
% of sampled w/ redshift success	80%	60%
% of redshifts w/ linewidth success	50%	50%
Total nights	120 nights (80 clear)	
UC nights	80 nights	
CIT nights	40 nights	
Usable months	April-October	
Start/end dates	Fall 2000/summer 2003	
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Caltech	Steidel, Metzger	
External	Luppino, Kaiser, Szalay, Kron	

I. Scientific Justification

1 Science Goals

1.1 Introduction

The theory of structure formation in the universe is well advanced, yet most of the crucial questions remain unanswered. Studies of structure depend on objects that can be seen, namely galaxies, whereas the raw medium from which galaxies were made is a mixture of both dark and baryonic matter. It has become clear that the conversion of total matter to visible galaxies in the universe is highly uneven, and that galaxies are a highly **biased** tracer of the underlying mass. How the universe converted matter into galaxies is intimately bound up with the physics of galaxy formation. **Understanding how galaxies formed and characterizing the galaxy biasing function are the overarching scientific goals of DEEP.**

The galaxy formation process can be thought of as having two parts: First, cosmic input parameters (Ω_m, Ω_Λ, the amounts of cold and hot dark matter, H_0, spectrum tilt and amplitude) control the clustering behavior of the *dark matter.* Knowing these, we can fully calculate the number and distribution of dark halos using N-body simulations. Second, subsequent baryonic cooling, gas infall, and star formation within halos formed the visible galaxies. The resultant pattern of galaxy properties depends on both parts of the formation process. Until now, the situation has been difficult because there were arguably too many unknown parameters to be determined from galaxies alone. However, with recent and expected future improvements in the measurement of cosmological parameters (e.g., observations of CMB fluctuations on small scales by MAP and PLANCK (Kamionkowski et al. 1994) and determination of the magnitudes of distant SNe Ia (Riess 1998, Perlmutter et al. 1999)), constraints on the cosmic input parameters are greatly advancing. Taken in conjunction, these data may determine many cosmic parameters to $\sim 10\%$ (Eisenstein et al. 1998). However, DEEP itself provides a number of complementary fundamental tests that will further improve these determinations. Such tests are also necessary to confirm the consistency of DEEP and of other cosmological studies. The clustering of the dark matter will become progressively better determined, and eventually studies of galaxies and large-scale structure will be free to concentrate on the baryon physics of galaxy formation. The DEEP Survey will produce a dataset sufficiently rich to challenge many generations of future models.

Figure 1 illustrates the advantage of observing the universe at higher redshifts in addition to our local neighborhood. Shown are the distributions of dark matter halos in four different cosmological models: two open models with low total matter density ($\Omega_m = 0.3$) and two critical-density models with $\Omega_m = 1$. All models have been tuned to match present-day large-scale structure and thus look rather similar at $z = 0$. Their very different appearance at $z = 1$ illustrates a fundamental point: clustering shuts down in a low-Ω_m universe because the density of matter is falling below a critical threshold. Hence the dark-matter distribution in an open universe is basically *unchanged* from the present, while a high-density universe is considerably less clustered at $z = 1$ than at present.

With DEEP maps of distant large-scale structure, we may hope to detect this difference. However, we must be mindful of how *very biased* pictures of large-scale structure are at all epochs. Galaxy biasing is illustrated in Figure 2, which depicts an attempt to insert galaxies into dark matter halos using so-called semi-analytic (SAM) models of galaxy formation (Kauffmann et al. 1993; Somerville & Primack 1998). The age (color) of the resultant stellar population is indicated by the colored dots. The old, red stellar populations tend to cluster at the intersections of dark matter filaments, while the young, blue populations are more widely dispersed. This matches the different distributions of elliptical and spiral galaxies today. The two populations look different, and neither traces the true underlying dark matter distribution (though the spirals come closer). Thus, both pictures are biased, and in a way that depends severely on galaxy type. *A full understanding of bias would allow us to translate the galaxy distribution anywhere in the universe into the underlying distribution of dark matter* – a powerful tool with applications to clustering, gravitational lensing, X-ray halos, and many other topics in extragalactic astronomy.

The major science goals of DEEP are as follows:

1.2 Galaxy formation and galaxy biasing

Goal 1: Characterize the linewidths and other structural parameters of galaxies at $z \approx 1$ and their dependence on spectral properties and environment. Measure the co-moving "structure function" of galaxies vs. redshift. A given set of cosmic input parameters determines the structural properties (mass, radius, internal velocity) of *dark halos*, whereas DEEP can measure the corresponding set of properties for *visible galaxies.* The two sets of parameters are related by the physics of galaxy formation. The visible parts of galaxies consist of gas from the inner parts of the halo that has cooled and fallen to the center. This migration is governed by the density profile of the gas, its initial angular momentum, the amount of angular momentum exchanged with the dark matter, and energy feedback to the gas from supernovae and other sources. *Theories of galaxy formation can be tested by insisting that predictions for the two sets of structure data match.*

Each galaxy at every epoch may be characterized by a radius, surface brightness, and internal velocity – a point in so-called Fundamental Plane space. This three-dimensional space provides a minimal description of galaxy structure. We call the co-moving number density of galaxies in this space the **"structure function"** (a 1-d projection of the structure function generates the luminosity function; 2-d projections generate the Tully-Fisher and D_n-σ relations). Full information about the galaxy population is available only by measuring all three structural parameters, *including linewidths.* A major goal of DEEP is to measure the structure function at $z \approx 1$ as a function of environment and compare to today's structure function. The evolving structure function of visible galaxies vs. that of dark halos is a powerful test of galaxy formation theories.

The DEIMOS spectrograph will have sufficient spectral resolution that internal linewidths should be measurable down to ~ 30 km s^{-1}; no other large galaxy survey planned, distant or local, will have such sensitivity. The combination of linewidths and radii allows us to determine galaxy **masses**. A growing body of data (e.g., Phillips et al. 1997) indicates that many galaxies at high z are undergoing starbursts and may look bright but are not massive. In contrast, models of baryonic infall into galaxies predict a strong correlation between the linewidths of galaxies and the depths of their halo potential wells. Once this correlation is calibrated, DEEP linewidths will provide an indispensable tool for measuring the size spectrum of dark halos early in the universe.

The proposed 3HS is designed to provide definitive data on evolving galaxy structural parameters. With HST imaging, the 3HS will provide complete structural data, including radii, for about 5,000 galaxies, sufficient to allow subdivision by galaxy type or environment. The 50,000 galaxies of the 1HS lack radii but will still provide excellent data on the luminosity function, $N(L)$, the "velocity function", $N(v)$, and the Tully-Fisher function, $N(L, v)$. If the cosmic input parameters (Ω_m, Ω_Λ, etc.) can be assumed known, simulations show that $N(L)$, $N(v)$, and $N(L, v)$ are also strong tests of the baryonic infall physics of galaxies.

Goal 2: Precisely measure the two-point and higher-order correlation functions of galaxies at $z = 1$ as a function of other observables. In almost all models of structure formation (e.g., White et al. 1987), galaxies are born as highly biased tracers of the mass distribution, but bias diminishes with time. Spiral galaxies today appear to be weakly biased, if at all, while the clustering of $z = 3$ Lyman-break galaxies requires a large bias for any reasonable cosmological model (Steidel et al. 1998; Wechsler et al. 1998). Galaxies at $z \approx 1$ should have an intermediate degree of bias, with observable consequences.

The statistical clustering of galaxies at any epoch depends on both the underlying dark matter distribution and the biasing function – the two are degenerate without more information. However, models such as that shown in Figure 2 suggest that patterns exist in the *relative biases* between various types of galaxies, and measuring these patterns as a function of absolute luminosity, linewidth, or spectral type can break this degeneracy. For example, in linear biasing models (i.e., where $(\delta\rho/\rho)_{gal}$ is assumed to be $b \times (\delta\rho/\rho)_{mat}$), the mean ratio of the *skewness* of the density distribution function to the square of its variance has an expectation value that scales as $1/b$ (Fry 1995; Scocciamarro et al. 1996). One can envision subdividing the 1HS sample as a function of galaxy type and estimating b for each type of galaxy. This and other more sophisticated measures will be explored.

Higher-order clustering statistics such as skewness are notoriously unstable without large volumes to beat down cosmic variance and dense sampling to reduce Poisson variance. *The need for* *accurate clustering statistics is driving the large volume and large number of galaxies targeted in the 1HS.* Roughly, one needs to sample most of the galaxies brighter than L^* in a volume of at least $10^6 h^{-3}$ Mpc^3. The need to subdivide the galaxies into types drives the required numbers still higher. Comparison of such measures at $z \approx 1$ to their values at $z = 0$ will be possible only with the dense sampling and large volume planned for the DEEP Survey.

Goal 3: Explain how disks emerged from the "desert". Due to the paucity of spectral features below $\lambda 3727$ Å, galaxies in the redshift "desert" (z = 1.2-2.2) are extremely difficult to identify optically. Galaxies at $z > 2.2$ appear as small, compact, high-surface brightness blobs, often embedded in luminous wisps. By $z \sim 1$, luminous disks resembling local ones in radii, surface brightness and morphology begin to appear. How these objects relate to the earlier compact population – are they accreted around compact objects or do they condense independently – can be answered by examining the nascent disks in the desert.

The DEEP Survey will obtain a census of the first disks to form in the universe by probing well back into the desert to $z = 1.55$. The radii of these early disks will be sensitive to the cooling radius of their baryons, a key test of the temperature, density, heating, and cooling of gas within spiral dark halos. DEEP will be able to reach further into the desert than previous data by exploiting the high red QE of the DEIMOS CCDs, which remains above 50% to 9500 Å.

1.3 Fundamental Cosmology

The DEEP database will be a goldmine for studies addressing other questions regarding the fundamental cosmic parameters and large-scale structure. Such tests are necessary to verify that the framework of cosmology in the next decade is self-consistent. Goals of DEEP in this area largely depend on the 1HS.

Goal 4: Determine the evolution of the abundance, $N(v, z)$, of dark matter halos. We expect to be able to measure linewidths for about half of all galaxies with redshifts in the 1HS, and to understand and correct for those that are missing. By inferring the linewidths of parent halos from visible galaxies (from Goal 1 above), we can use the dark-halo abundance as a function of redshift, $N(v, z)$, to perform a classic cosmological test. It is well known that the volume element $dV/dzd\omega$ (where ω is solid angle) strongly depends on the input cosmological parameters, notably Ω_m and Ω_Λ. Thus, the apparent number of objects versus redshift is a sensitive test of the volume element – provided the co-moving number density of objects is constant. In practice, the poorly-known evolving number density of galaxies has stymied this test. However, if we have measured real potential-well depths, we can bypass galaxies and study the more easily simulated dark halos.

This test is shown in Figure 3. The lefthand panel compares the expected co-moving number density dN/dV of galaxy-sized halos as a function of z for three viable but extremely different input cosmologies. Note that *differences* in the evolving co-moving number density out to $z = 1$ are only $\pm 10\%$. These are small compared to differences in the predicted number vs. redshift and solid angle, $N(v, z)$ (righthand panel), which amount to a factor of 3. The surprising similarity in the predicted co-moving number densities of dark halos gives us a new handle on the cosmic geometry.

A measurement of non-zero Ω_Λ has recently been claimed from SN Ia magnitudes (Perlmutter et al. 1998; Riess et al. 1998); the implications of the consequent predicted acceleration of the cosmic expansion are profound. However, differing world models lead to a range of only a few tenths of a magnitude in predicted supernova fluxes out to $z = 1$, small compared to potential error sources. The $N(v, z)$ test is independent and is sensitive to a somewhat different combination of Ω_m and Ω_Λ. A further motivation for such studies is to set constraints on a possible quintessence component in the Universe (Wang & Steinhardt 1998), in which Λ is replaced by an active field with equation of state $P = w\rho$, with w in the range $-1 < w < -1/3$ (a non-zero Λ corresponds to $w = -1$). Such a model can also accelerate the universe and may be more easily explained by particle theory. At $z = 1$, predictions of quintessence models are intermediate between open and Λ models, but with strongly differing redshift dependence. Prospects for constraining w from CMB analyses alone are not strong (Hu et al. 1998).

Goal 5: Measure the small-scale "thermal" noise of galaxy clustering at $z \approx 1$. The clustering of galaxies is inherently isotropic in space, with no preferred orientation toward or away from the Milky Way. The observed *redshift-space* clustering of galaxies, however, is distorted by local effects, such as the small-scale "fingers of God" illustrated in Figure 4.

With DEIMOS, we will have sufficient precision in our redshift measurements to measure these small-scale thermal motions at $z \approx 1$ using new, robust velocity statistics (Davis, Miller & White 1997). Peculiar velocities are a response to the underlying gravity field and so provide information about the strength of the *matter* clustering, and thus Ω_m. The measured dispersion is proportional to $\sigma_8 \Omega_m^{0.5}$, where σ_8 is the RMS amplitude of the matter fluctuations in a sphere of radius $8h^{-1}$ Mpc. Local studies of the thermal noise at $z = 0$ yield $\sigma_8 \Omega_m^{0.5} = 0.38$ today (Davis, Miller & White 1997). The degeneracy in cosmic parameters can be broken by a similar measurement of thermal motions at $z = 1$. Since the evolution of σ_8 is controlled in a known way by Ω_m, the two measurements allow an unambiguous separation of both Ω_m *and* σ_8, and thus yet another independent estimate of bias. Physically, if Ω_m is high, small-scale thermal motions at $z = 1$ should be *lower* than those measured at $z = 0$, but if the universe is very open, the velocity amplitude at $z = 1$ should be essentially unchanged from that measured at $z = 0$. This difference parallels the difference in clustering evolution in Figure 1.

Goal 6: Measure the Alcock-Paczynski effect. The Alcock-Paczynski (A-P) effect relates intervals of angular separation to intervals of redshift separation as a function of redshift. An object that appears spherical at low redshift may appear elongated in redshift at $z \gg 0$ depending on the value of the deceleration parameter q_0. At $z = 1$, the relative elongation varies by $\approx 30\%$ for q_0 in the range $-1/2 < q_0 < 1/2$. This effect has been discussed previously in the context of quasar pairs at high redshift or the shapes of voids (Alcock & Paczynski 1979; Phillipps 1994; Ryden 1995; Ballinger, Peacock & Heavens 1996). Using numerical simulations, we have experimented with a number of large-scale orientation statistics that measure the anisotropy of filaments and voids. For a volume similar to that of the proposed DEEP survey ($10^6 h^{-3}$ Mpc^3), the difference between the stretching of an Einstein-de Sitter Universe and a $\Lambda = 0.7$ flat Universe gives an A-P signature detectable at approximately 5σ significance. This measurement is going to be difficult, but it is a long-term goal of DEEP.

2 The 1-Hour and 3-Hour Surveys

2.1 The 1-Hour Survey: 50,000 galaxies, 90 nights

The 1HS is the backbone survey that will provide basic information on linewidths, spatial distribution, clustering, and environmental statistics for distant bright galaxies. Its limiting magnitude will be $I_{AB} = 23.5$ mag, which corresponds to $M^* + 0.5$ at $z = 1$ for an open universe (see Figure 5). A single grating and tilt will be employed that capture [O II] $\lambda 3727$ from $z = 0.61$ to 1.55. The 1HS will provide uniquely valuable linewidth information, which will be measureable for roughly half the redshift sample (Section II). However, the exposure times are short enough that we will tend to miss redshifts and linewidths for faint red *absorption-line* spectra, which need more photons than bright emission lines. Covering that and other gaps is one job of the 3HS (see below).

The design of the 1HS is patterned on the extremely successful Las Campanas Redshift Survey (Shectman et al. 1996). The LCRS is a large redshift survey of 26,400 galaxies with a median redshift of $z = 0.1$ covering a volume approximately $10^6 h^{-3}$ Mpc^3, similar to the 1HS. The LCRS is an excellent survey because its statistical properties are stable when the catalog is split into pieces. The prominent voids have a characteristic size of 5,000 km s^{-1}, and no structures as large as the survey were found.

At low redshift, the *differential* bias between deep and shallow potential wells is modest, but at $z = 1$ we expect it to be stronger. The 1HS has approximately twice the number of galaxies as the LCRS, to allow splitting it into multiple pieces in order to characterize this expected larger differential bias. Each subset of the data should therefore be comparable in size to the LCRS catalog, which implies $\sim 50,000$ redshifts in total.

2.2 The 3-Hour Survey: 5,000 galaxies, 30 nights

The magnitude range of the 3HS is $I_{AB} = 23.5$-24.5 mag, $M^* + 1.5$ at $z = 1$ for an open universe. This deeper survey will cover 9% of the area of the 1HS, making HST imaging feasible. The same grating and tilt will be used as for the 1HS, so the data will be comparable. The 3HS will:

- Get redshifts and linewidths for absorption-line spectra to the limiting redshift of the 1HS. This is important for measuring the co-moving number density of halos, as the deepest galactic potential wells are expected to harbor the reddest galaxies, as is true of massive ellipticals today.
- Provide linewidths roughly 1 magnitude deeper into the luminosity function for emission-line galaxies.
- With HST imaging, measure the structure function of galaxies at $z \approx 1$ to $\sim M^* + 1$.
- Reobserve a subset of 1HS objects more deeply, and thus obtain definitive completeness statistics for it.
- Increase the rate of discovering galaxies in the "desert" beyond $z = 1.2$ (cf. Figure 5).

A major imaging survey will be requested with the HST ACS camera to cover the 3HS area. These data will provide radii, surface brightness, and morphologies for all 3HS galaxies, which are needed for measuring the structure function.

3 DEEP in Relation to Other Surveys

Planned and ongoing nearby galaxy surveys will provide the key baseline on local galaxies needed for DEEP to detect evolution. The Sloan Digital Sky Survey (SDSS; Loveday et al. 1998), will obtain 900,000 redshifts of galaxies to $r' = 18$ mag (median $z \sim 0.1$) with spectral FWHM of 167 km s^{-1}. SDSS is our primary baseline sample at low redshifts (Kron and Szalay are participants). The luminous-red-galaxies portion of the SDSS will obtain 100,000 redshifts with median $z \sim 0.5$, albeit with very dilute sampling. An even earlier local sample will be provided by the 2DF Galaxy Redshift Survey (Colless 1998), which will obtain 250,000 spectra of nearby galaxies with resolution about half that of the SDSS; this survey will be completed by the early stages of DEEP and will also check Sloan results.

Both the 1HS and 3HS will dwarf any prior studies of distant galaxies. CNOC2 (Carlberg et al. 1998) obtained a sample of 5,000 field galaxies to $R \sim 21.5$, while CFRS (Lilly et al. 1995) observed 600 galaxies to $I_{AB} < 22.5$. Spectral resolution in both cases was very low, with a FWHM of $\sim$700-1800 km s^{-1}. Our own LRIS survey (hereafter called "DEEP I") has targeted about 1000 galaxies to $I_{AB} \sim 24.5$ with a FWHM of 200 km s^{-1} resolution, while groups at Caltech (PI: J.

Cohen) and Hawaii (PI: Cowie) have acquired similar numbers of redshifts at similar resolution but to slightly brighter magnitudes. The DEEP Survey will multiply all these numbers by $\sim$50, while at the same time more than doubling the best previous spectral resolution.

The main competition for DEEP will come from the VIRMOS-VLT survey (Le Fevre et al. 1998), planned by the team building VLT instruments roughly equivalent to DEIMOS and NIRSPEC. They will have access to 250 8-m nights and intend to devote at least 50 of these to targeting 100,000 galaxies to $I_{AB} \sim 22.5$ – but with only 1000 km s^{-1} resolution. They will observe a subsample to $I_{AB} \sim 24.5$ with a resolution of 125 km s^{-1} that is closer to that obtained with DEIMOS, but the number of these objects is only a "few thousand". The VIRMOS team hopes to begin their program at roughly the same time as DEEP, in the fall of 2000.

Compared to DEEP, VIRMOS is essentially just a redshift survey like the LCRS with little information about individual galaxies. Because of evolving biasing, changes in such a map are nearly impossible to interpret. The $> 10\times$ higher resolution achieved by the 1HS is in fact *crucial* to almost all our major science goals – measurements of linewidths and the small-scale velocity field will not be accessible to VIRMOS, with consequent loss of information on the dark matter distribution.

Furthermore, DEEP's redshift pre-selection using photo-z's and one-magnitude deeper limit (for the 1HS) will together yield *much* greater efficiency at finding truly high-redshift galaxies, by at least a factor of 4; hence, though VIRMOS may target 50% more galaxies than DEEP, the net number of distant galaxies will be only about one-third that of DEEP. VIRMOS does plan to gain many more near-infrared spectra than will be possible for DEEP, given their guaranteed time on an infrared multi-object spectrograph; that is likely to be their principal advantage.

4 DEEP Components on Other Telescopes

An essential component of DEEP is the ongoing **CFHT imaging survey** in BVI (PIs: Kaiser and Luppino), which will be used for generating the baseline object catalog. This catalog of photometry, astrometry, size, and structure will allow 1) photometric redshift selection of target galaxies at $z > 0.7$; 2) I_{AB} magnitude selection; and 3) complementary color and structural data for the 1HS + 3HS. A second essential component is the **HST ACS imaging** survey (PI: Faber), which will be requested to survey the 3HS area. For this we will seek to obtain at least 120 orbits (60 pointings with V and I) of ACS imaging, plus near-IR coverage if NICMOS is revived.

In addition, DEEP is spawning other projects, which are, however, ancillary to the success of the main survey:

For half of the 1HS, a **SIRTF Legacy Project** (PI: Davis) will propose a far-infrared survey with depths of 1μJy, 1.8μJy, 4μJy, and 7μJy(S/N=5) at 3.6, 1.8, 5.8, and 8 μm, and a spatial resolution of 2.5$''$. In the 3HS region, we would survey to 0.5mJy at 70 μm and 0.8 mJy at 160 μm, with spatial resolution 30$''$.

For the 3HS, a millimeter survey (PI: Lowenthal) with the 50-m **Large Millimeter Telescope** (jointly operated by UMass and INAOE (Mexico)) will uncover very dusty, high redshift galaxies at 5$''$ FWHM resolution at 1.1mm, 1.4mm, and 2.1mm, with sensitivities of about 1mJy. The LMT is roughly 100 times more powerful than current systems and is expected to uncover several tens of objects per hour.

For the 3HS, **near-infrared imaging** is planned (possibly with Magellan, Subaru, Mayall, or the Gemini-N telescope) that will be deep enough to provide high quality photometric redshifts for all galaxies in the field of view (Connolly et al. 1997), plus limits on dust in distant galaxies.

For half of the 1HS, a **Sunyaev-Zeldovich survey** of CMB foreground absorption (PIs: Carlstrom and Holzapfel) will map pockets of foreground hot gas with higher sensitivity and smaller selection effects than possible with X-ray telescopes. Estimates suggest that hot gas should be detectable even in small groups of galaxies to $z \approx 1$.

5 Additional DEEP Science

The science areas of galaxy parameters, spatial distribution, and motions of distant galaxies are the primary aims of the DEEP team. These are however a subset of the vast potential scientific returns from our survey, especially in galaxy formation and evolution. A sample of topics includes:

• *The histories of star formation, metal enrichment, and stellar populations.* DEEP spectra are optimized for [O II] λ3727, whose EW is known to correlate well with star formation rate (Kennicutt 1992). Line-ratios of [O II], [O III], and Hβ will be available in the interval $z = 0.7$-0.8, providing gas metallicity estimates for the thousands of galaxies in the survey at this epoch (Kobulnicky et al. 1999). Absorption-line equivalent widths for the G-band, CN, Ca H+K, and the higher Balmer lines can be used to trace the star-formation and metal-enrichment histories of early-type galaxies (Worthey & Ottaviani 1997).
• *Distant AGNs.* DEEP will discover distant AGNs by the hundreds and will provide a large-scale, statistically complete census of their numbers. It will establish the preferred clustering environments of AGNs and benchmark the intermediate history of AGN evolution in the universe. QSOs in the DEEP survey region should be easily identified from SDSS data (Fan et al. 1999); as a byproduct, DEEP will establish the environments of those in our redshift range.
• *Photometric redshifts.* The photometric catalogs used to select DEEP candidate galaxies above $z = 0.7$ will provide rough photometric redshifts for tens of thousands of nearer galaxies with errors of about ± 0.1 in z down to $I_{AB} \sim 25$. This information will be a goldmine for the luminosity function and clustering of faint, foreground galaxies at low and intermediate z's.
• *Candidate objects for other Keck instruments.* DEEP catalogs will provide numerous targets to observe with other Keck instruments such as LRIS-B and NIRSPEC. Adaptive Optics K-band imaging on selected DEEP galaxies will double HST resolution and sample older stellar populations. The DEEP fields are large enough that many AO candidates can be observed with natural guide stars.

6 Theoretical Interpretation

Since all DEEP observables are the result of many physical processes working in concert, DEEP data will need to be interpreted using realistic models that include all relevant effects. Our basic approach is to create progressively more sophisticated models, adjust parameters, and "observe" them in the computer as we do the real universe.

The DEEP Project has access to the world's leading galaxy modelers. Together these groups possess a wide suite of tools to generate cosmic simulations and compute clustering statistics. Tools to model the gravitational clustering behavior of dark matter are well in hand. The groups at Santa Cruz, Durham, Munich, and Berkeley now routinely produce DM simulations with a dynamic range of several thousand in scale size and tens of millions of particles. Even higher resolution simulations are now becoming available.

However, it is clear that many of the central questions of galaxy formation revolve around baryonic cooling and star formation. Baryon handling is much more computer-intensive, and tools are correspondingly more primitive. Hydrodynamic codes that can compute the cooling and collapse of many galaxy halos within a large volume of space, let alone follow the microscopic physics of star formation, do not yet exist.

To deal with this, semi-analytic models (SAMs) have been developed that replace detailed computations of gas cooling, inflow rate, and star formation with schematic rules of thumb containing free parameters that can be adjusted to match the data. In essence, these models are highly sophisticated bookkeeping tools that keep track of where the gas goes and ensure that it behaves in plausibly. The impressive simulation in Figure 2 was produced using an algorithm for embedding SAM galaxies in DM halos. The DEEP team has access to all the leading SAM results. As computing power continues to evolve, real hydro codes will improve, and the DEEP team is involved and watching these developments. It is our intent to use the most advanced available technologies for the interpretation and modelling of the DEEP Survey, a task that is likely to continue well after the observations are published.

7 Other Questions

Why does DEEP need to be an LMAP? First, DEEP requires a large data set obtained in a uniform manner over several semesters – a single justification, stated at the outset, must suffice to see it through. Second, the value of the data will be seriously compromised if the survey is not completed. Third, a significant number of UC faculty must pool their resources in order to justify the amount of observing time required for DEEP. Fourth, DEEP is under some pressure from the VLT-VIRMOS Deep Survey and needs the timely expediting that an LMAP would give. Finally, DEEP is going to be requesting support from outside (e.g., HST and NSF) and would benefit greatly from having guaranteed telescope time at Keck.

Why are 50,000 galaxies required for the 1HS? Why are 5,000 galaxies required for the 3HS? The number of galaxies for the 1HS comes from combining the requirement of sampling $10^6 h^{-3}$ Mpc^3 of space to achieve a fair sample of the universe with the need to sample that region densely enough to achieve robust clustering statistics. Obtaining spectra of 50,000 galaxies will permit subdividing the sample by a factor of 2, which is the minimal amount needed to explore subsets of galaxies and explore robustness. The goal of 5,000 galaxies for the 3HS comes from the need to achieve adequate sampling statistics to determine the structure function throughout Fundamental Plane space for all types of galaxies, including rare early types.

Why can't most of the science be done with photometric redshifts? Even the best photo-z's have errors of 0.05. That is not adequate to locate galaxies accurately within clusters and filaments or measure the small-scale thermal noise. DEEP spectra will also provide linewidths.

Much of DEEP science depends on detecting evolution between now and $z \approx 1$. How will comparison samples be constructed at low z? DEEP will sample only fairly bright galaxies down to $M^* + 1$ or so. Several local samples of bright galaxies exist (e.g., LCRS), and more are being gathered (2DF, Sloan). Together these samples will establish the local co-moving number density and other characteristics of nearby galaxies to high accuracy.

In general, these samples do not measure linewidths. However, locally we can fall back on the Tully-Fisher and D_n-σ relations, which predict the linewidths of bright galaxies to high accuracy. The same strategy cannot be used at high redshift because the TF and D_n-σ relations are probably different at $z = 1$, and indeed may not exist.

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II. Technical Justification

A. Fields & imaging:

Both the 1HS and 3HS will be undertaken within the four fields centered at the coordinates in Table 1. These fields were chosen to be zones of low extinction that are continuously observable at favorable zenith angles from Hawaii over a seven-month interval. One includes the Groth Survey Strip, which already has good HST imaging, and two more are on the equatorial strip that will be deeply surveyed by the Sloan Digital Sky Survey (SDSS) project. Each of the four fields is the target of a deep imaging survey by G. Luppino and N. Kaiser primarily intended for their weak lensing studies. They will use the new UH camera (8K$\times$12K pixels) with a field of view of $30' \times 40'$ to obtain data in the B, V, and I bands. The imaging will be obtained in random pointings spread over a field of $3^\circ \times 3^\circ$, with continuous coverage of a strip of length $120'$ in the center of each field. We will use the Luppino-Kaiser imaging to select our galaxies, as explained below.

B. Field geometry & sample selection:

B.1: The 1HS: A key element in the DEEP plan is to use color information from the UH BVI imaging survey to *pre-select galaxies beyond* $z = 0.7$. Figure 5 plots redshift versus magnitude for 400 galaxies with DEEP I redshifts from the Groth Strip Survey. The two vertical lines mark the proposed magnitude limits of the 1HS and 3HS surveys. Pre-selecting galaxies to have $z > 0.7$ eliminates roughly 60% of foreground interlopers and increases the efficiency of the survey for distant galaxies by a factor of 2.5. To our knowledge, DEEP is the only planned redshift survey using such pre-selection. LRIS tests on DEEP I confirm the efficiency of the photometric selection.

In each of the four DEEP fields listed in Table 1, we will densely target a region of $120' \times 16'$ for DEIMOS spectroscopy. Each pointing of DEIMOS will use a custom mask with as many as 120-150 slitlets cut within a $16' \times 4'$ area. The layout of these pointings is shown in Figure 6.

The source density of target galaxies for the 1HS is 8.5 galaxies arcmin^{-2}; in high-density regions, competition among galaxies for slitlets is great. To achieve dense sampling, it is essential to target most of the selected objects and to maintain a high sampling fraction independent of surface density; otherwise, dense regions are systematically neglected. We have developed an algorithm in which object selection is done for all masks in a field at the same time. Consider a series of 90 overlapping masks with centers separated by $80''$ (in the E-W direction, each mask assumed oriented N-S). The algorithm assigns as many galaxies as possible to slitlets, first assigning those within the central $80''$ of every mask and then filling in with unassigned galaxies in the overlap regions $80''$ at either side of mask centers, while avoiding pairs that are too close together in declination. The minimum separation (for galaxies on the same mask) is set at $3''$ (most will be larger). Each galaxy has three chances to be chosen, and tests show we will select 75% of the target galaxies, with only a slight diminution in regions of high surface density.

The slitlets will be tilted by up to 30° in order to follow the major axis of the target galaxies (improving rotational velocity measurements) or to allow a close pair of galaxies to share a single slit. Two subexposures of 30 min duration will be taken for each pointing.

The 90 overlapping pointings will be supplemented with an additional 30 pointings in adjacent "outrigger" areas, as shown in Figure 6. For these outrigger fields, DEIMOS will be rotated by 90° degrees to more dilutely select galaxies from two $4'$ wide strips $5'$ above and below the primary strip. Each of these will use 15 pointings that overlap by 50% along their length (see figure). The photometry for these outrigger fields will be derived from the same CFHT data used for the dense strip. The purpose of these outriggers is to double the size of the thin dimension of each DEEP region to approximately $16h^{-1}$ Mpc using dilute sampling, allowing us to determine the three-dimensional filamentary structure more effectively. The extra reach with its dilute extensions will also lead to a large increase in the number of spatially independent triplets of galaxies on scales of $10h^{-1}$ Mpc. This is the "quasi-linear" regime, which recent progress in higher-order correlation functions shows is most useful for providing an independent measure of galaxy bias.

There are 480 total pointings in the 1HS; our algorithm selects an average of 135 galaxies per mask, for a total of 64,800 targeted galaxies. We expect that $\gtrsim 80\%$ of these will yield redshifts ($\gtrsim$ 50,000), and that half of those will yield linewidths (Section II.C).

Each of the four DEEP strips will survey a densely sampled co-moving volume of approximately $560 \times 60 \times 8h^{-3}$ Mpc^3 (in an Einstein–de Sitter cosmology, assuming redshift range $0.7 < z < 1.2$). These densely sampled portions are approximately two-dimensional, but the shortest dimension exceeds today's correlation length of galaxy clustering of 5 h^{-1} Mpc. This thin dimension is roughly doubled by the outrigger fields, which also double the effective survey volume. The total volume of the densely sampled portion is approximately 1.1×10^6 h^{-3} Mpc^3 (for an E-dS cosmology; multiply by 2.7 if $\Lambda = 0.7$), compared to approximately 1.25×10^6 h^{-3} Mpc^3 for the LCRS survey. If divided into 2-3 subsamples as we intend, the DEEP 1HS survey of 50,000 redshifts will thus have comparable sampling density to the LCRS sample of 26,000 galaxies, and so should yield statistics of comparable precision.

Based on analytic estimates, which we have tested with simulations, we expect the following uncertainties in measurements of galaxy distribution statistics: the error in the mean number density of galaxies in the presence of strong clustering should vary approximately as $\delta n/n \approx (J_3/V)^{1/2} \approx \pm 8\%$ for $V = 10^6 h^{-3}$ Mpc^3 (Peacock, *Cosmological Physics*, 1999, p. 501). Uncertainties in the two-point correlation function are similar, and three-point errors are a factor of ≈ 4 worse. If the sampling were not dense, the errors in higher-order statistics would rapidly become unmanageable.

B.2: The 3HS: The 3HS regions are narrow strips $3.5'$ wide and $16'$ long embedded within the 1HS fields (see Figure 6). The long dimension is the length of one DEIMOS slitmask, while the narrow dimension is set by the width of the HST ACS camera. It is our intention to image each 3HS strip on HST by stacking 5 ACS exposures end-to-end. We plan two such narrow 3HS strips per 2° 1HS field, for a total of 8 strips altogether. One of the 8 3HS fields will be widened to cover a square of size $16' \times 16'$ using 5 adjacent DEIMOS mask pointings (see figure). This region is created to permit slitmasks of any orientation, an advantage for certain programs. Including these, the 3HS covers a total area of $12 \times 3.5' \times 16'$, which is 9% of the area of the 1HS.

To reach the majority of galaxies in the magnitude range I_{AB} = 23.5-24.5 mag will require 5 3-hour exposures in each strip of the 3HS. These exposures will be at the same pointing, and will consist of 4 45-min long sub-exposures.

The sample selection algorithm for the bulk of the 3HS sample will be similar to that of the 1HS except that all slitmasks on a strip cover the same field of view and the magnitude range is restricted is to I_{AB} = 23.5-24.5 mag. There are an average of 800 candidate galaxies in each $3.5' \times 16'$ strip, of which 700 will be targeted in 5 exposures. A total of 12 strips should therefore yield spectra of 5,000 galaxies. A small fraction of the 3HS will be populated with re-observations of 1HS galaxies, especially longer exposures of absorption-line galaxies. The completeness of this sample is separately discussed in the next section.

C. Spectroscopic completeness:

We have estimated the likely spectroscopic completeness for the 1HS and 3HS based on existing LRIS DEEP I data. These estimates have been increased only slightly to represent the expected improvements from DEIMOS – actual completeness may be higher. The "3HS:random" sample is a random sample in the range I_{AB} = 23.5-24.5; this is the bulk of the 3HS. "3HS:abs" is a slightly brighter sample that picks up absorption-line galaxies missed in the 1HS.

All percentages are fractions of the total number of objects targeted in that sample. Hence, the low number of absorption linewidths for the 1HS reflects the fact that only a small number of field galaxies have strong Ca H+K. When these are present, all galaxies down to I_{AB} = 23.0 mag yield usable linewidths in 2.5 hr with LRIS. Fainter than $I_{AB} \sim 23.0$ mag, we expect to get few usable absorption linewidths, even in the 3HS.

TABLE 2. Estimated Completeness

	Mag	Redshift ID	Em. linewidth	Abs. linewidth
1HS	<23.5	80%	∼50%	4%
3HS:random	23.5-24.5	60%	∼30%	N/A
3HS:abs	22.5-23.5	100%	N/A	50%

D. Grating, dispersion, & spectral coverage:

To maximize efficiency, the 1HS and 3HS use the same grating at a single tilt, requiring only one exposure per mask. The choice of grating balances the need for high resolution vs. wide spectral coverage. Higher resolution is desirable to minimize the region contaminated by sky OH lines and to measure linewidths for objects with small FWHM. However, we also wish to capture [O II] λ3727 over as wide a spectral interval as possible.

Our adopted choice is the 830-line grating, tilted to give a uniform spectral coverage from 6000-9500 Å for all objects. By selecting galaxies in a narrow strip on the slitmask, the above desired spectral interval will be obtained for *every* object, capturing [O II] λ3727 from z = 0.61 to 1.55. The [O II] doublet is resolved and thus yields a reliable redshift even if no other spectral features are seen. The nominal slitwidth of $0.75''$ will yield an estimated FWHM of 2.3 Å (86 km s^{-1}) and resolution R = 3500, over twice as high as what we are now getting with LRIS and permitting reliable rotation measures down to v_{rot} = 30 km s^{-1}. The high-ρ thick CCDs from MIT/Lincoln planned for on the red side of the DEIMOS detector have high QE $\gtrsim$ 50% at 9500 Å(three times tha of LRIS).

To improve sky subtraction accuracy, we will dither the spectral setting by subpixel increments for each subexposure. The DEIMOS PSF is critically sampled (2 pix per FWHM); thus, dithering will allow us to generate an *oversampled mean sky spectrum* from each set of subexposures, which can be subtracted in lieu of the usual neighboring sky spectrum. This strategy will allow us to close-pack objects along the slit.

The DEEP Survey is unique among high-redshift surveys in exploiting high spectral resolution; between the OH lines, the sky is twice as dark as it is at low resolution, which increases the effective quantum efficiency of the system by a factor of two.

E. Data processing:

Sample selection & mask fabrication: The Hawaii team of Kaiser and Luppino has primary responsibility for producing the photometric database from which the 1HS and 3HS sample will be selected. This includes the creation of galaxy catalogs with accurate astrometric solutions, magnitudes, sizes, position angles, and ellipticities. They have already developed and fully tested an automated data reduction pipeline which performs these tasks.

The UH survey has begun, and there is already sufficient data to permit us to begin observing right now, if we wished. Members of the DEEP team have assisted the Hawaii team in observations, and we will undoubtedly get further involved in running their reduction pipeline. With luck, the Hawaii team may complete the required observations for DEEP in 1999.

Our object selection software (Section II.B) will be applied to the UH catalog to generate slitlet positions. These will be input to the DEIMOS mask design software, currently being written by Phillips. Both tools will be fully in place by the time the project starts. A typical observing run of 4 nights for the 1HS (see below) will require 32 masks. The responsibility of choosing the objects belongs to UCB; UCSC has the job of designing and fabricating the slitmasks. With a preexisting catalog and automated selection and fabrication software, the task of preparing the files to send to Keck is fully automated and takes virtually no time.

Spectroscopic reductions: At the time DEIMOS comes on line, we will have an operational spectral-reduction pipeline in place, modeled on one currently being proto-typed for LRIS. The steps of this pipeline are given in the accompanying table. We have the option of taking normal flat-field calibrations with each exposure, or we may use a new procedure that generates a fringe-free flat field from archival flats at different grating tilts. The wavelength calibration will be taken from the OH lines visible on every frame.

The heart of the data reduction pipeline is an optical model of the spectrograph that provides solutions for dispersion and geometric distortions, with bright night-sky lines and alignment-star spectra providing low-order empirical corrections. Since DEIMOS should be stable, this approach should work well. Only minor rewrites are needed in the existing pipeline to accommodate the DEIMOS mosaic data. The current status of the UCSC pipeline software is shown at right. Reduction pipeline design is well advanced at UCSC, and an alternative pipeline is also to be developed at UCB.

Pipeline Process	Status
1. Overscan subtraction	exists
2. Bias/Dark subtraction	exists
3. Flat-fielding	exists
4. CR-cleaning	exists[3]
5. rectification[1]	proto-type
6. Sky-subtraction	proto-type
7. 1D-Extraction[2]	proto-type

NOTE.—[1]includes rectification, λ-calibration, solution for slit/object locations, slit-function correction; [2]includes flux calibration; [3]may need revisions for DEIMOS geometry.

With present computing resources, supplemented by further hardware before DEIMOS comes online, we expect to be able to extract 2-d and 1-d spectra for each target galaxy on the night that the data are taken.

Further data reduction will take advantage of software packages being developed at UCSC and UCB for DEEP I LRIS data. Automated redshift-determination algorithms will be used on the 2-d and 1-d spectra. Some interactive examination and oversight will be required for final redshift identification; this will be automated to the fullest extent, but the total time needed is hard to determine without actual DEIMOS data. Conservatively assuming that 10% of the objects need 10 minutes each of special handling yields an estimate of 1000 hours invested in this task, which is reasonable over three years. Once redshifts are known, spectral line fluxes and widths will be measured automatically using more software that is currently being prototyped – again, some human oversight will be needed, but probably just a few seconds per object to review results.

HST Image Processing: The capability to extract structural parameters from galaxy images taken by HST is already in place. The job of deriving structural parameters for all 3HS galaxies is comparable in size to processing the entire Groth Strip, a task we have just completed.

DEEP database: The estimated data storage requirements for the trimmed DEIMOS spectral images are 20 Gby for the 1HS and 5 Gby for the 3HS. The DEEP database will also include ground-based BVI CFHT images of all galaxies, HST ACS images of objects in the 3HS fields, and the results of all photometric and spectroscopic reductions, but these requirements are small compared to the DEIMOS images. Thus, the total long-term data storage requirements of the project are less than 100 Gbytes. We have already received a gift from the Quantum Corporation of 600 Gby of RAID disk (being shared 400 Gby at UCSC and 200 Gby at UCB), which more than covers our needs, leaving adequate room for scratch space for data reduction.

DEEP data will be made available to all project participants, and later to the community, through an interactive WWW-accessible database. The database is modest by current standards, and standard relational database methods will be adequate for our needs. At present, DEEP I data are available to collaborators through a restricted-access machine at UCSC. Public access to DEEP data will be via a Sun Enterprise 450 server that was donated to us for this purpose. All non-proprietary data (e.g., ACS HST imaging) plus publicly released data will be placed on this server, which will allow downloading of images, spectra and tables. The public-access interface to DEEP I data is undergoing final stages of preparation and should be available starting May 1999.

Currently UCSC employs one person full-time, Christopher Willmer, to maintain the DEEP database and will be reqesting funds from NSF to continue this through the life of the project. We also intend to submit an additional database proposal to the NSF in summer 1999 to provide further software and hardware support for this important tool.

A firm data-release policy to the community has not yet been worked out. We are strongly motivated to make the data available in a timely way, but the survey is most most valuable only when entirely completed. How to make early data available without compromising our own science goals is unclear, but we will probably enter into agreements with other groups to do specific, non-competing science. Our final goal is to release the entire dataset within 2-3 years after the observations are completed.

F. Requested number of nights: The rationale for the requested number of nights is summarized in Table 3. The sky continuum is the major source of noise. The requested lunar phase is based on broad-band sky-brightness tables from CTIO in the I band (8000 Å). Based on HIRES spectra from Keck at new moon, one half of the I-band flux is in OH lines, one half is in the continuum. We assume that OH remains constant over lunar phase while the continuum brightens, and we require that the limiting magnitude of the survey not be degraded by more than 0.15 mag due to lunar continuum noise (this is an effective speed loss of 30%). The resultant sky limit is then 140 e^- pix^{-1} hr^{-1}, which occurs at a 6-day old moon. With 4-night runs (see below), we would be placed regularly at 3-6 days from new moon. For comparison, observing with a 7-day or 8-day moon would degrade the limiting magnitude by 0.2 mag and 0.25 mag respectively. This would cause undesirable variations in the magnitude limit within the sample and would also engender unacceptable speed losses.

TABLE 3: REQUESTED NUMBER OF NIGHTS

1-Hour Survey:	
Number of slitmasks per 2 deg strip = $120'/80''$	90
Number of masks in outrigger fields	30
Total number of masks = $4 \times (90 + 30)$	480
Number of masks per night (1 hr exposures): (avg usable length of night in Apr–Oct = 9.5 hr; assume acquisitions and calibrations take $\sim$1 hr)	8
Number of needed clear nights: 480/8	60
Total number of nights needed (with 50% allowance for bad weather and equipment failure)	90
Number of nights contributed by Caltech	30
Number of nights requested from UC	60
3-Hour Survey:	
Number of slitmasks per $3\overset{'}{.}5$ HST strip	5
Number of HST strips	12
Total number of masks = 12×5	60
Number of masks per night (3 hr exposures)	3
Number of clear nights: 60/3	20
Total number of nights needed (with 50% allowance for bad weather and equipment failure)	30
Number of nights contributed by Caltech	10
Number of nights requested from UC	20
Total UC time request (nights)	**80**

G. Other questions:

Why four fields of length 2°? The choice to observe four fields was dictated by several competing considerations. Sample variance is a major concern for LSS studies; reproducibility of statistical properties in independent datasets is crucial for confidence in one's conclusions. Estimating sample variance from less than four completely independent data sets is unreliable, so 4 independent fields is a minimum.

The length of each field is set by the simultaneous need to cover $> 10^6 h^{-3}$ Mpc^3 in the total survey and have a transverse size larger than the characteristic size of voids in the local galaxy distribution (5000 km/s) in a single strip. This works out to a length of 2° per field.

It is important to note that the DEEP Survey is *not* optimized to measure the large-scale power spectrum at $z = 1$, for which dilute sampling over a larger volume would be preferable; it is instead designed for the study of non-linear, *small-scale* fluctuations. The smallest dimension of the survey is larger than the correlation length of galaxies observed today, which reduces the excessive sample variance and aliasing problems that affect pencil-beam surveys (Kaiser & Peacock 1991). The middle dimension (2°) subtends a size twice that of typical voids. It would be nice to enlarge this, but having four independent samples is more important.

Are linewidths a reliable indicator of galaxy mass? DEEP uses three methods for probing masses of distant galaxies: (a) spatially-resolved velocity curves (VCs), usually from [O II] λ3727; (b) absorption line widths, σ_{ab}; and (c) integrated emission line widths, σ_{em}. VCs provide the traditional method of measurement and can probe to the largest radii, but the emission must be spatially well-resolved, the inclination of the disk must be known, and a fair amount of modeling is required to remove seeing and slit-width effects. The velocity dispersion (σ_{ab}) is robust and insensitive to orientation but requires good continuum S/N. The easiest to measure is σ_{em}, but it potentially suffers from uneven distribution of emission across a galaxy, and it also requires known disk inclination for individual objects.

We have carried out several tests of the accuracy of the two emission-line methods, which will be used for the vast majority of our galaxies. First, measurements of simulated LRIS[1] emission lines (with realistic noise and uneven flux distribution) show that VCs recover input rotational velocities to ± 20 km s^{-1} (*rms*). Measurement of σ_{em} are worse, ± 25 km s^{-1}, and give more spurious outliers but are still in good statistical agreement with the "true" values. Second, for a few objects in our existing data set we can use both methods and find that the values agree well – except where there is grossly non-uniform emission and/or the galaxy is badly mis-aligned with the slit. *Both cases can be recognized in DEIMOS and/or HST images.* These results are consistent with what others have found (e.g., Rix et al. 1997; Courteau 1997). Thus, we conclude that our measured linewidths and VCs should reflect internal kinematics as well as they do for local galaxies.

A second concern is whether these optical tracers truly reflect galaxy potentials. This requires detailed studies for all types of galaxies that compare optical linewidths with H I widths (which are unanimously believed to reflect the galaxy potential). For larger-mass local systems, emission-line velocities agree well with H I widths (Schommer et al. 1993; Simard & Pritchet 1998). We are actively pursuing such comparisons in lower-mass systems through observations of [O II] in galaxies with H I widths as low as 30 km s^{-1} (Kobulnicky & Gebhardt, ongoing). These studies will determine how [O II] compares to H I and how to correct for any biases.

How does DEEP impact Keck scheduling: total time and dark time? We have checked Keck allocations for our UC PIs over the last 6 semesters and find that collectively we have been awarded 85.5 nights of telescope time. This is a bit more than the 80 nights that DEEP requires. The table below shows how those previous nights were divided by lunar phase:

TABLE 4. DEEP PI Keck allocations by lunar phase (nights)

	0-4 d	5-10 d	11-14 d
Previous 6 semesters	72%	20%	8%
DEEP Survey	50%	50%	0%

The second line assumes that DEEP is regularly scheduled 3-6 nights from new moon. From this it is seen that the demand on prime dark time would likely *decrease* somewhat with DEEP.

III. Schedule & Milestones

A. Schedule:

This request is for 80 nights of Keck II time spread over a three-year period starting in fall semester 2000. Our targets are well situated for observing anytime from April through October. We deliberately selected these four target regions so that there would always be at least one target observable with small airmass during this entire seven-month window. If the time is evenly distributed per month, our mean request amounts to just under four nights each month during the seven-month window. To ensure observing efficiency and uniformity of limiting magnitude, we cannot integrate when the moonlight is too bright; we request that we not be scheduled more than 6 nights from new moon.

Our plan is to start with the 1HS Survey and only begin the 3HS component after the first full year of observing. By that time we should have ACS data from HST to do final object selection for the 3HS fields. We will observe the 1HS sequentially from one end of each field to the other. Thus,

[1]Results should be better with the higher resolution and pixel scale in DEIMOS.

we will begin to pick up local information first and only gradually add in the large-scale spatial information, which requires the full number of galaxies.

B. Milestones:

At the end of Year One, we should have sufficient data (15,000 redshifts) to estimate the correlation statistics $\xi(r)$ for the full sample without division into galaxy types. The estimate will suffer considerable sample variance compared with the full results but will enormously supercede what is known. We will also have excellent statistics on the luminosity function by color, and first results on the number density of AGNs.

At the end of Year Two, we will have sufficient data to measure the small-scale thermal noise and compare with that seen locally. This is a fundamental measurement that yields information on Ω_m. We will also have had a chance to wring out the linewidth software and produce the first batch of 10,000 linewidths. This will yield the first census of halos, $N(v, z)$, in addition to significant information on the correlations of spectral properties and linewidths with local environment.

By the end of Year Three, observations will be complete including HST, but data analysis will still be ongoing. Science for that year includes a first look at the structure function using HST imaging data and the first attempt to split the survey into front and back halves to detect evolution.

By the end of Year Four, we should have complete redshift maps, and by the end of Year Five, complete redshift-linewidth maps. At that point all data should be fully analyzed and final papers in process. Final topics will include those that need the full sample: the structure function for all types of galaxies, studying clustering vs. linewidth, measuring higher-order clustering statistics, measuring the Alcock-Pacyznski effect, and producing a final determination of biasing.

IV. Resources

Our team comes with a strong resource base, including Federal research grants, industry contributions, and large numbers of collaborators and students with extensive scientific and technical expertise.

1) UCSC: Faber, Koo, and Guhathakurta with their students and postdocs have extensive experience with the design and fabrication of DEIMOS, observing faint galaxies, developing specialized software tools to analyze and interpret relevant data, and with conducting studies of nearby galaxies for comparison to the distant universe. The UCSC DEEP team intends to continue to support one Research Astronomer at half-time (Phillips), 2-3 full-time postdocs, 1-3 graduate students, and 1-2 "free" postdocs who volunteer a significant fraction of their time on DEEP (e.g., Hubble Fellows and foreign postdocs with prize fellowships from abroad). DEEP funds come from a major NSF grant ($150K/yr) to Faber and Koo (expires fall 2000; we will apply to renew for following three years), plus a number of smaller HST and NASA grants ($100K/yr). Faber and Phillips will also submit a separate request to NSF this summer to upgrade the DEEP database to a public archive; some of this support would contribute to DEEP.

2) UCB: Davis and Broadhurst have extensive experience with pioneering redshift surveys and galaxy studies, including observations, data reduction, and LSS analyses. They expect to devote roughly $150K/yr of their external grants to support DEEP at the level of 2 postdocs and 2 graduate students.

3) Caltech: Steidel and Metzger both have expertise in distant galaxy research, forefront surveys, and instrumentation. Steidel is supported by a new Packard Foundation grant and by NSF grants. They expect to provide support at the level of 1-2 postdocs and 2 graduate students.

4) UH: Luppino and Kaiser are undertaking the CFHT imaging survey used in the DEEP Survey under their own grant support. They have 1 postdoc and 1 graduate student devoted to the reduction and cataloging tasks.

5) Industrial contributions: DEEP has received significant support from industry. The Quantum Corporation donated 600Gb of disk that are part of the RAID arrays at UCSC (400Gb) and UCB (200Gb). Sun Microsystems donated $100K worth of computers and can be expected to continue with future gifts.

Total DEEP core personnel: 5 UC faculty, 4 external faculty, 0.5 Research Astronomer, 1 database manager, 8-9 postdocs (including volunteers), 8 graduate students.

6) Other collaborators: In addition to this core team who will do the basic reductions, we also have external collaborators to help with analysis and supporting observations. Space does not permit a full listing, but we mention briefly our theory collaborators at UC Santa Cruz and Max Planck, the Johns Hopkins and Chicago cosmology groups led by Alex Szalay and Richard Kron (both with ties to Sloan), and a roster of previous postdoctoral fellows and students, here and abroad, who will share in the results of DEEP.

Appendix: Deep Publications List

The Magnitude-Size Relation of Galaxies out to z $\sim$ 1 Simard, L. Koo, D. C., Faber, S. M. et al. ApJ, 1999, Accepted.

Properties of Two New M31 dSph Companions from Keck Imaging Grebel, E. K., & Guhathakurta, P. 1999, ApJL, 511, L101

Isolating Red Giant Stars in M31's Elusive Outer Spheroid, Reitzel, D. B., Guhathakurta, P. & Gould, A. 1998, AJ, 116, 707

Near-IR Galaxy Counts to J and K $\sim$ 24 as a Function of Image Size Bershady, M. A., Lowenthal, J. D., & Koo, D. C. 1998, ApJ, 505, 50

The Starcounts in the Flanking Fields of the HDF: The Faint End of the Disc Stellar Luminosity Function and its Scale Height Mendez, R. A., & Guzman, R. 1998, A&A, 333, 106

Discovery of Red Selected Arcs at z = 4.04 behind Abell 2390 Frye, B., & Broadhurst, T. J. 1998, ApJL ,499, L115

Optical Structure and Colors of Faint Compact Narrow Emission-Line Galaxies Guzman, R., Jangren, A., Koo, D. C., et al. 1998, ApJL, 495, L13

The Nature of Compact Galaxies in the Hubble Deep Field - II: Spectroscopic Properties and Implications for the Evolution of the Star Formation Rate Density of the Universe. Guzman, R., Gallego, J., David C. Koo, et al. 1997, ApJ, 489, 559

The Nature of Compact Galaxies in the Hubble Deep Field - I: Global Properties. Phillips, A. C., Guzman, R., Gallego, J. et al. 1997, ApJ, 489, 543

Galaxies at z $\sim$ 4 and the Formation of Population II Trager, S. C., Faber, S. M., Dressler, A., & Oemler, A. 1997, ApJ, 485, 92

An Estimate of H_0 from Keck Spectroscopy of the Gravitational Lens System 0957+561 Falco, E. E., Shapiro, I., Moustakas, L. & Davis, M. 1997, ApJ, 484, 70

Keck Spectroscopy of Redshift z $\sim$ 3 Galaxies in the Hubble Deep Field Lowenthal, J. D., Koo, D. C., Guzman, R. et al. 1997, ApJ, 481, 673

Optical Rotation Curves of Distant Field Galaxies: Sub-L* Systems Vogt, N. P., Phillips, A. C., Faber, S. M. et al. 1997, ApJL, 479, L121

On the Nature of the Strong Emission Line Galaxies in Cluster Cl 0024+1654: Are Some the Progenitors of Low Mass Spheroidals? Koo, D. C., Guzman, R., Gallego, J. & Wirth, G. D. 1997, ApJL, 478, L49

Colors and K-Band Counts of Extremely Faint Field Galaxies Moustakas, L. A., Davis, M., Graham, J. R., et al. 1997, ApJ, 475, 445

Keck Spectroscopy of Objects with Lens-like Morphologies in the Hubble Deep Field" Zepf, S., Moustakas, L., & Davis, M. 1997, ApJL, 474, L1

The Kitt Peak Galaxy Redshift Survey (KPGRS) with Multicolor Photometry:

Basic Data Munn, J. A., Koo, D. C., Kron, R. G., et al. 1997, ApJS, 109, 45-77

The Luminosity-Linewidth Relation as a Probe of the Evolution of Field Galaxies, Guhathakurta, P., Ing, K., Rix, H. -W., Colless, M. M., Williams, T. 1996, J. Kor. Astron. Soc., 29, S63

Redshift z $\sim$ 1 Field Galaxies Observed with the Keck Telescope and the HST Koo, D. C., Vogt, N. P., Phillips, A. C., et al. 1996, ApJ, 469, 535

Optical Rotation Curves of Distant Field Galaxies: Keck Results at Redshifts to z $\sim$ 1 Vogt, N. P., Forbes, D. A., Phillips, A. C., et al. 1996, ApJL, 465, L15

Keck Spectroscopy and HST Imaging of Field Galaxies at Moderate Redshift Forbes, D. A., Phillips, A. C., Koo, D. C., & Illingworth, G. D. 1996, ApJ, 462, 89

On the Nature of the Faint Compact Narrow Emission-Line Galaxies: The Half-Light Radius-Velocity Width Diagram Guzman, R., Koo, D. C., Faber, S. M., et al. 1996, ApJL, 460, L5

High-Resolution Spectra of Distant Compact Narrow Emission Line Galaxies: Progrenitors of Spheroidal Galaxies Koo, D. C., Guzman, R., Faber, S. M., et al. 1995, ApJL, 1995, 440, L49

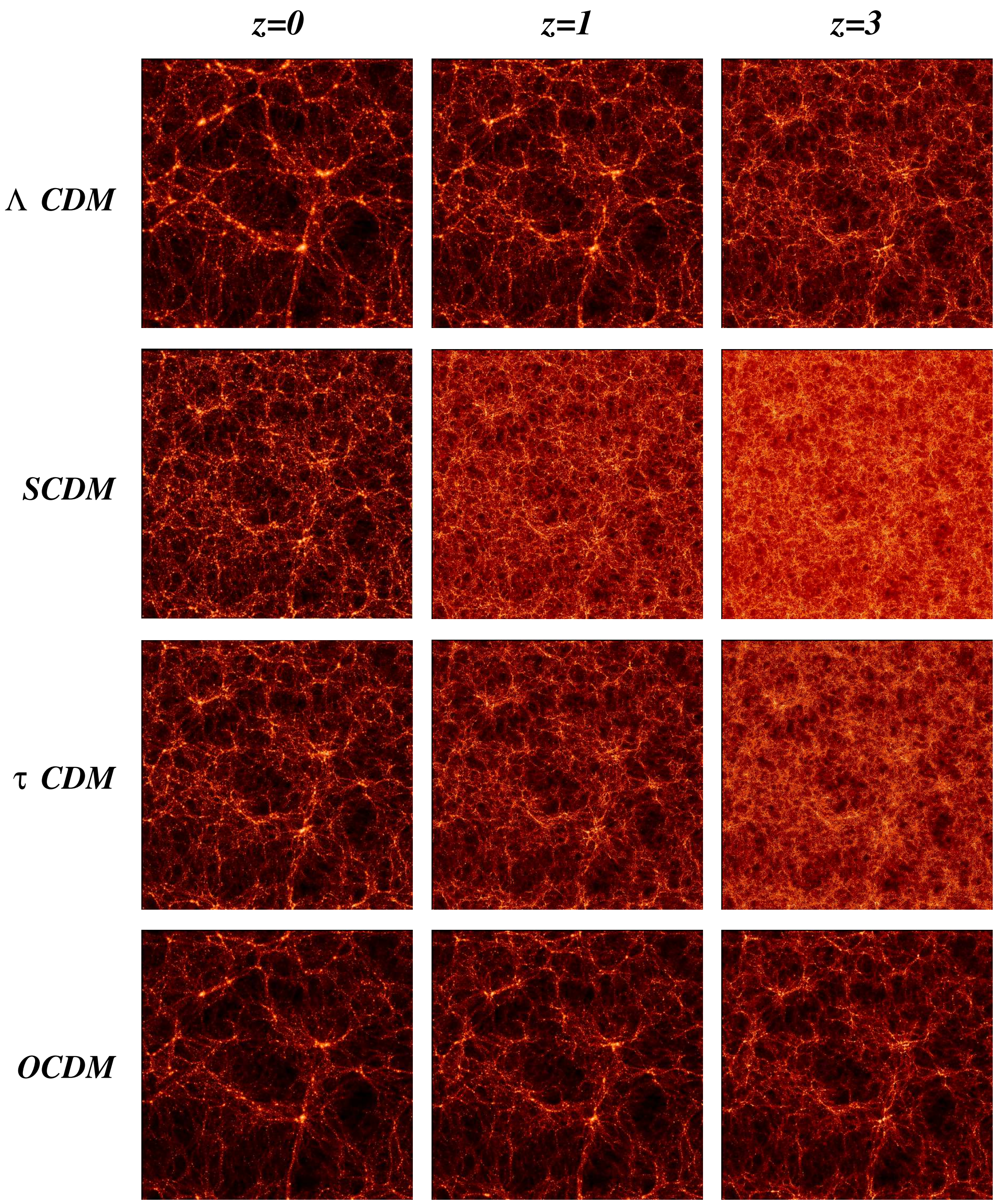


FIG. 1: Four dark-matter simulations illustrating the effect of varying Ω_m on the cosmic clustering. The simulations are by the Virgo consortium (http://www.mpa-garching.mpg.de/~jgc/sim_virgo.html). The top and bottom simulations are open models with $\Omega_m = 0.3$, while the middle two are flat models with $\Omega_m = 1$. All models are tuned to match approximately the clustering at $z = 0$ and hence look rather similar in the lefthand panels. Going back in time, the matter-dominated models evolve substantially whereas clustering is static in the open models. This difference, plus an analogous difference in the small-scale thermal motions of galaxies, provides a way of determining Ω_m from the DEEP Survey.

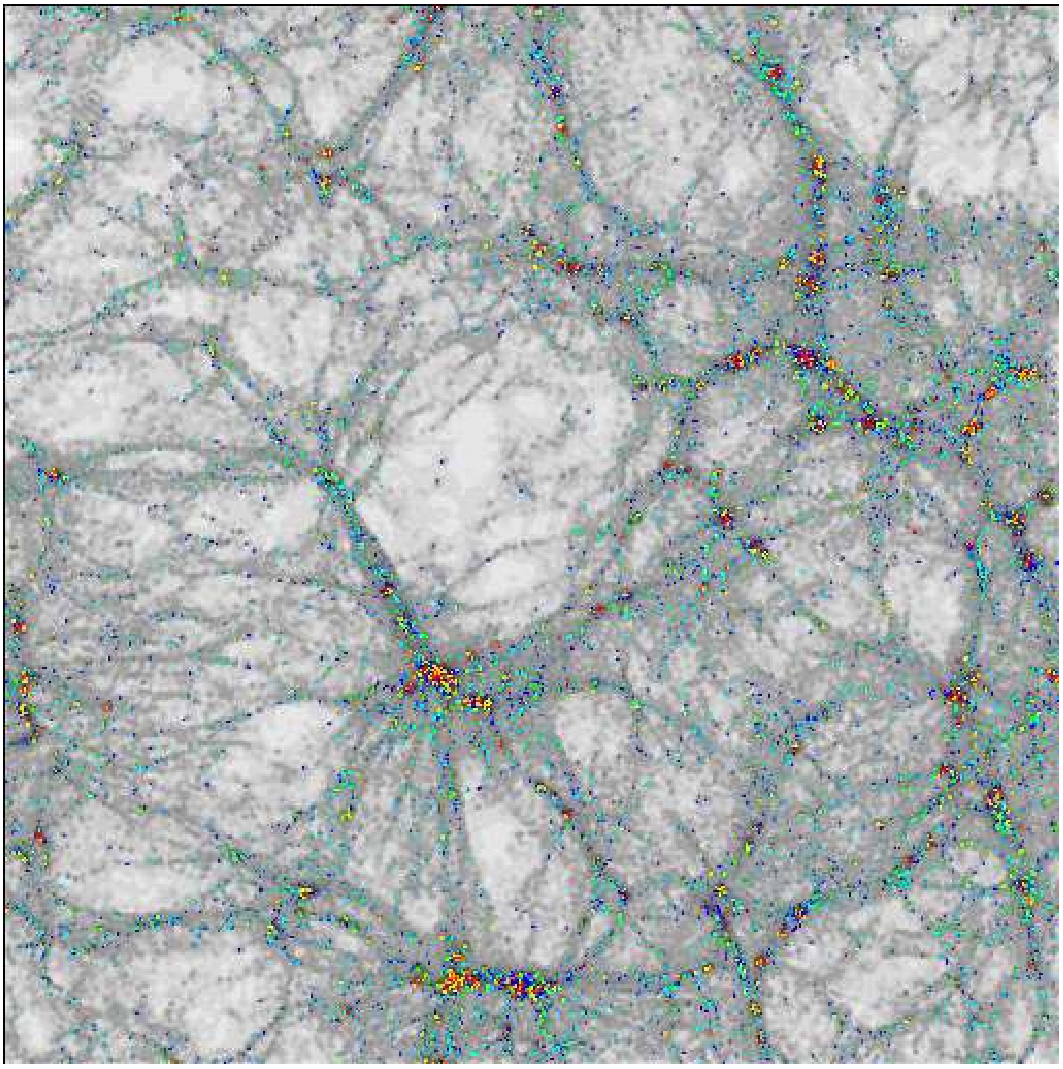


FIG. 2: An illustration of galaxy biasing. The simulation, by Guinevere Kauffmann, embeds semi-analytic models of the visible portions of galaxies into the dark matter halos of a τCDM simulation at epoch $z = 0$ (http://www.mpa-garching.mpg.de/~jgc/sim_gif.html). SAM models keep track of star formation, and the mean current colors of the stellar populations are indicated by the colored dots. Note how the older (redder) galaxies cluster in high-density regions, while the bluer (younger) stellar populations are more widely distributed. That is because galaxies start to collapse earlier in high-density regions, so their stellar populations are older. Neither distribution of galaxies exactly matches the dark matter distribution – both tend to amplify the true peaks and voids. Biasing at high z is even greater. The DEEP Survey will provide data needed to characterize the biasing function of galaxies versus type, environment, and epoch.

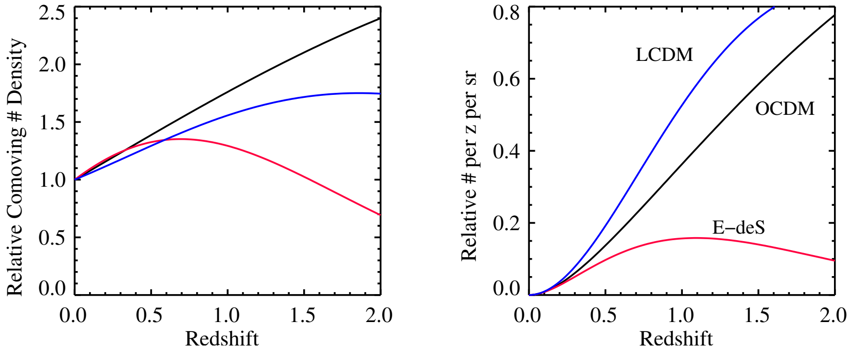


FIG. 3: The expected evolution of the abundance of dark matter halos with circular velocity $\simeq$200 km s^{-1} for three popular cosmological models. The halo abundances have been calculated using Press-Schechter formalism, which has small but correctable known errors from real simulations. *Left:* The true *co-moving* number density, normalized to today. *Right:* The observed number density *per unit redshift per steradian*, $N(v,z) = dn/dzd\omega$. The three models are: an open model with $\Omega_m = 0.3$ (OCDM), a flat model with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ (ΛCDM), and an Einstein-de Sitter model with $\Omega_m = 1$ (τCDM). All models have been tuned to match present-day structure. After this tuning, only modest differences ($\pm$10%) are expected in comoving galaxy-sized halos, whereas a factor of 3 is expected in number density vs. redshift. Measuring halo numbers at varying circular velocities would further improve our ability to recover cosmological parameters through this test.

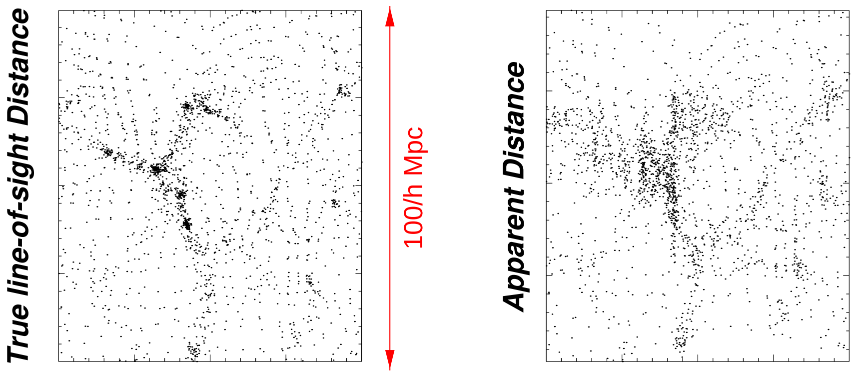
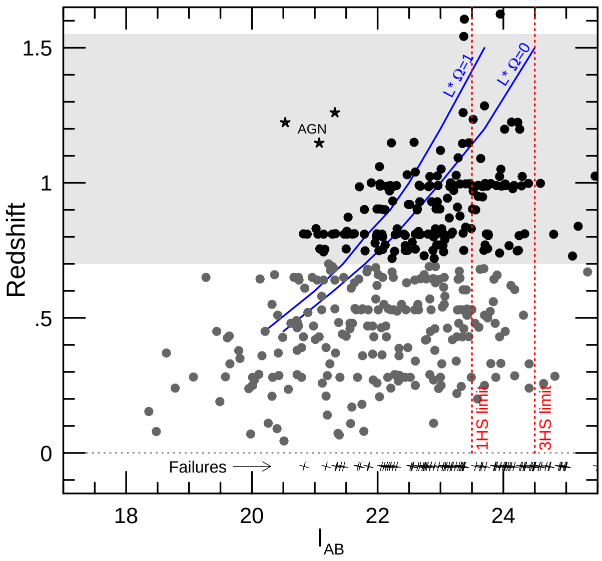


FIG. 4: The effects of peculiar velocities on structure in redshift space. The left panel is the actual structure from an N-body simulation (Baker et al. 1999), while the right panel shows the smearing along the line-of-sight due to peculiar velocities. Both boxes are $100h^{-1}$ Mpc wide with a thickness characteristic of what DEEP will probe. While the small-scale thermal velocities blur out the structures, they also provide a handle on the mass in clusters and walls. The thermal velocity continues to grow from $z = 1$ to now in models with high Ω_m but remains nearly constant in open models. This behavior is analogous to the differences in the growth of density fluctuations seen in Figure 1.

FIG. 5: Redshift vs. magnitude for $\sim$ 400 galaxies in the Groth Strip from DEEP I. The magnitude limits for the 1HS and the 3HS are the vertical lines. The two curves represent an $L^{\star}$ galaxy with a flat f_{λ} spectrum for $\Omega_m = 1$ and 0. Galaxies below the minimum redshift $z = 0.7$ are colored gray, and z limits of the survey are in light gray. Galaxies that failed to yield redshifts are shown at the bottom. The clustering of galaxies along the line of sight is seen as horizontal stripes. The three bright points at high z are AGNs of which DEEP will discover several hundred.



The figure illustrates how pre-selecting galaxies by photo-z's increases the efficiency of the survey for distant galaxies by about a factor of 2.5. The deeper penetrations into the luminosity function and into the "desert" beyond $z = 1.2$ that will be achieved in the 3HS are also evident.

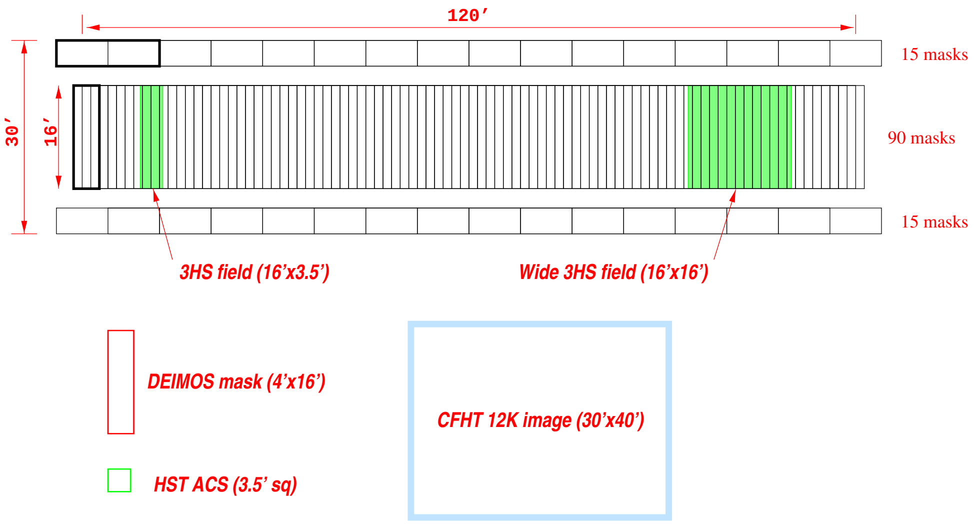


FIG. 6: 1HS and 3HS slitmask geometry for each of the four 2° fields. The narrow rectangles show the primary target selection strips (each 80″ wide) for the 90 pointings of the 1HS; each primary strip is flanked by two secondary strips, also 80″ wide. A single DEIMOS slitmask is shown by the thicker lines. Thirty outrigger pointings parallel the main strip at a distance of $\pm 5'$. The pointings overlap once along their lengths. The densely and deeply sampled regions of the 3HS are shown in color. On the right is the single 3HS region that is filled out to make a square, to accommodate slitmasks in any orientation. We will propose to map the 3HS areas with HST ACS images. The fields of view of the DEIMOS slitmask, the CFHT mosaic camera, and the HST ACS camera are shown to scale.