1 Scientific Justification

A key goal of observational cosmology this decade is the detailed, accurate measurement of the universe's expansion history, from deceleration through acceleration, to look for clues of the properties and identity of dark energy. Of the small handful of known measurement techniques, only Type Ia supernovae (SNe Ia) have actually been developed to the point of routine use. Initial studies of the decelerating universe using SNe at $z \gtrsim 1$ by both the Supernova Cosmology Project (Fadeyev *et al.* 2004) and the Higher-Z Team (Riess *et al.* 2004) clearly point to the limiting factor for both statistical and systematic uncertainties: correction of host galaxy extinction. With one of the largest HST cycle 14 programs, we are successfully demonstrating a new and efficient approach to the measurements in this difficult decelerating redshift range. By discovering and studying "clean" SNe in galaxy cluster ellipticals, we reduce systematic and statistical uncertainties (each of these SNe is worth up to *nine* SNe in spirals) — and do so with a more efficient use of HST time. We have discovered 37 SNe in the program using 209 orbits, obtaining full lightcurves for 15 SNe Ia. We request DEIMOS time in order to complete spectroscopic observations of the cluster elliptical galaxies hosting the SNe which are essential to this large HST program.

How problematic is the extinction correction uncertainty at $z \gtrsim 1$?

The correction for the extinction of SNe from dust in the host galaxies is currently the single dominant source of both statistical and systematic error for SNe distances and the derived cosmological parameters – dramatically so at $z > 1$ (see Figure 1b). The color uncertainties for well-measured SNe at $z > 1$ is $0.08 - 0.1$ in $B - V$, leading to uncertainties in extinction correction (after accounting for intrinsic color uncertainty) of >0.4 mag! This dispersion grows worse, $\sigma \approx 0.5$, after accounting for the uncertainty in the dust reddening coefficient, $R_B \equiv A_B/E(B-V)$, which Draine (2003) notes can vary from the fiducial value 4.1 by ± 0.5. Recent studies of nearby SNe Ia (Altavilla *et al.* 2004, Reindl *et al.* 2005) are consistent with large dispersions of R_B. To correct for dust extinction, one needs either exquisite multi-band color information or a Bayesian prior on *a*) the mean and probability distribution of R_B and *b*) the probability distribution of the amount of dust. If even just one of these priors is redshift dependent, the final result will be systematically biased. The effect of varying R_B can be seen in Fig. 2b as the difference between full and the short-dashed contour. Likewise, if the observation quality depends on redshift (as is often the case) significant biases can result, as shown by the difference between the full and the long-dashed contour of Fig. 2b (Perlmutter *et al.* 1999). If aggressive Bayesian priors are chosen, the systematic errors outweigh the statistical errors.

How is this problem solved using SNe Ia in ellipticals?

Sullivan *et al.* (2003) demonstrated that the dispersion (including ground-based measurement error) about the Hubble diagram for elliptical-hosted SNe is 0.16 mag — three times smaller than the measurement uncertainty for extinction-corrected SNe Ia at $z > 1$ — primarily due to the absence of dust. (Preliminary studies of the new, larger SNe sample from the CFHT SNe Legacy confirm this observation.) We observe massive galaxy clusters at $z = 0.9 - 1.6$, only recently possible since the identification of such clusters from large-field, deep optical surveys such as RCS2 (on CFHT), mid-infrared surveys with instruments such as IRAC (on Spitzer), and X-ray surveys (XMM and Chandra). These SNe will provide a statistically significant sample of high redshift SNe which will be used to constrain the equation of state of dark energy as shown in Figure 2.

How is it known that dust is not an issue in $z \gtrsim 1$ cluster ellipticals?

The quantity of dust in nearby elliptical galaxies is generally very small and confined to a central disk where its cross-section is very small. The clearest line of evidence that dust has little effect on stars in elliptical galaxies comes from the tightness of the color-magnitude relation in galaxy clusters. The dispersion in the colors of early-type galaxies has long been known to be small ($\sigma_{U-B} = 0.035$) in clusters ranging from Coma to intermediate redshifts (Bower *et al.* 1992; Ellis *et al.* 1997; Stanford, Eisenhardt & Dickinson 1998; van Dokkum *et al.* 2001; Nakata *et al.* 2005). Recent results from HST imaging show the same strikingly small dispersion in color extends to redshifts $z \gtrsim 1$. For example, ACS imaging of RDCS1252-29 at $z = 1.23$ by Blakeslee *et al.* (2003) found an intrinsic dispersion of 0.024 ± 0.008 mag for 30 ellipticals in the F775W - F850LP color, which approximates rest-frame $U - B$. Since some intrinsic color variation in the age and metallicity of stellar populations of the member galaxies is likely, the dispersion due to dust in these ellipticals must be smaller still.

Current Status of HST/ACS observations

To find SNe Ia in elliptical hosts at $z > 1$, we were awarded 219 orbits of HST time in cycle 14. Our program consists of repeated photometry (ACS F850LP and F775W) of 25 clusters of galaxies ($0.9 < z < 1.5$) with NICMOS followup photometry (F110W). The resolution of HST/ACS provides the resolved host morphology as well as deep SN light curves. The program specifically focuses on the eight $z > 1$ SNe hosted by ellipticals, and we will compare the results to the SNe not found in ellipticals. The full redshift distribution of SNe discovered in the survey is shown in Figure 3.

Why is DEIMOS the right instrument to get spectra of $z \gtrsim 1$ hosts?

DEIMOS on Keck II is requested to obtain redshifts for the SNe host galaxies. The excellent red response and lack of fringing in DEIMOS produce clean spectra with signficant continuum in the most important region of the spectra for these $z > 1$ elliptical galaxies. We plan to fully utilize the slitmask capability of DEIMOS to include observations of galaxies that are suspected cluster members in the Bootes field. These data will be shared with the members of our collaboration who are responsible for the initial discovery of these high redshift clusters.

Additional very high redshift SNe

We also performed a SN search using the HST GOODS data collected in 2002-2004. A significant amount of time was dedicated to two candidates with photo-z's greater than 1.5: 27 orbits for acs04-076 and 33 orbits for acs04c-014. We will dedicate the first hour and a half each night (before the cluster SNe become visible) to these SNe hosts in order to obtain spectroscopic redshifts for use in a cosmological analysis. In addition to these two SNe, there are 34 SNe in the GOODS north field that will be added to the DEIMOS slitmasks to obtain spectroscopic redshifts for use in a rates analysis.

Conclusions

The spectroscopy observations proposed here are the key gound-based component of a very large HST program using a known approach to SN measurements which will provide a first significant, *and unbiased*, measurement of w_0 vs. w'. The emphasis on high redshift and attention to systematics are the opening steps in bringing to maturity cosmological methods of the next generation, and this program will serve as a bedrock scientific legacy for dark energy studies.

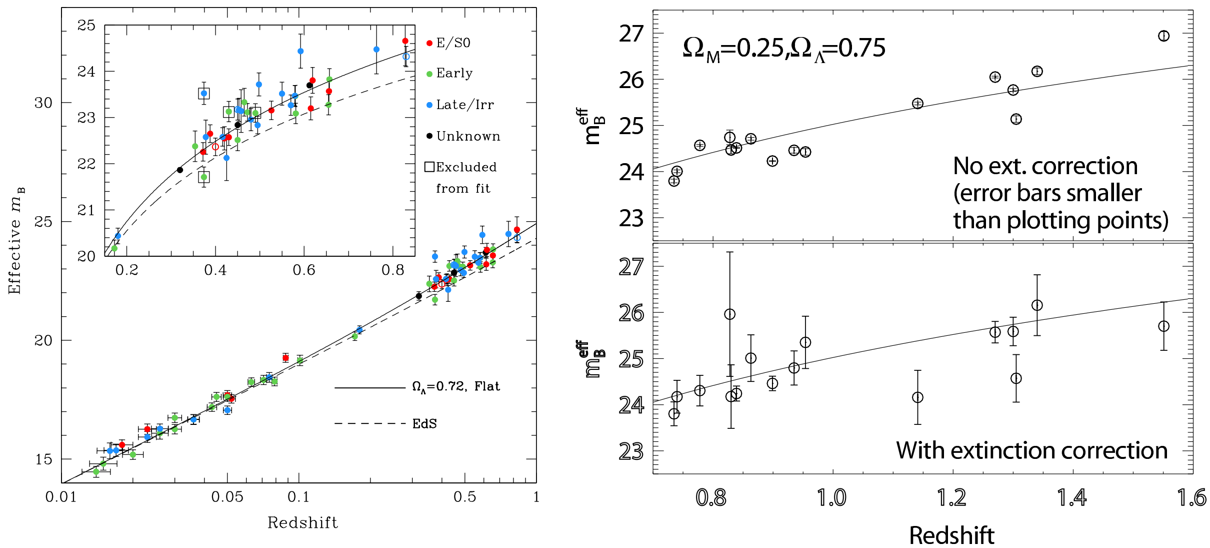

Figure 1 (a) Left Panel: The Hubble diagram for Type Ia supernovae color-coded by host galaxy type by Sullivan *et al.* (2003). The SNe in elliptical hosts (filled red circles) show significantly less dispersion, $\sigma = 0.16$ mag (including measurement error), than in other hosts. The increased scatter of extinction-corrected SNe in other hosts is both statistical and systematic. **(b) Right Panel:** The Hubble diagram, before and after extinction correction, for a mixture of SNe Ia in all host types. The uncertainty in the B-V color propogates to an error of ~ 0.5 mag for SNe at $z \gtrsim 1$, consistent with the scatter seen.

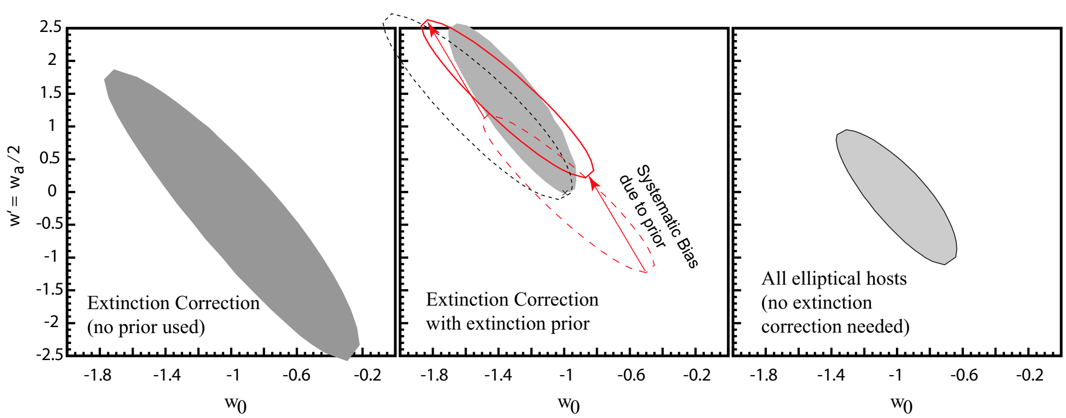

Figure 2 (a) Left Panel: Simulated 68% confidence region on w' vs w_0 for the current literature SN sample, simulated with an underlying cosmology ($w_0 = -1$; $w' = 0$). The parameters are poorly constrained because color errors are magnified by $R_B \approx 4$. **(b) Middle Panel:** The solid red contour shows reduced uncertainties (excluding systematic bias) using a Baysian prior on the extinction distribution prior to suppress color errors. If the errors are larger at high z than at low z (as with the actual data), this introduces systematic biases. The filled gray contour is from Riess *et al.* 2004 using this prior. The short-dashed contour shows that this approach is also sensitive to shifts in R_B with redshift; the example shifts from 4.1 to 2.6. **(c) Right Panel:** The goal of this proposal is shown as a confidence region for a simulated new sample of ~ 10 $z \gtrsim 1$ SNe Ia found in cluster ellipticals, together with 5 in ellipticals from other HST (GOODS) searches, and 120 SNe Ia in ellipticals at the lower redshifts expected from the ground-based CFHT SN Legacy Survey, the CTIO Essence survey, and the Nearby SN Factory. A SN Hubble diagram in ellipticals avoids the large statistical error problem of panel (a) and the large systematics problem of panel (b).

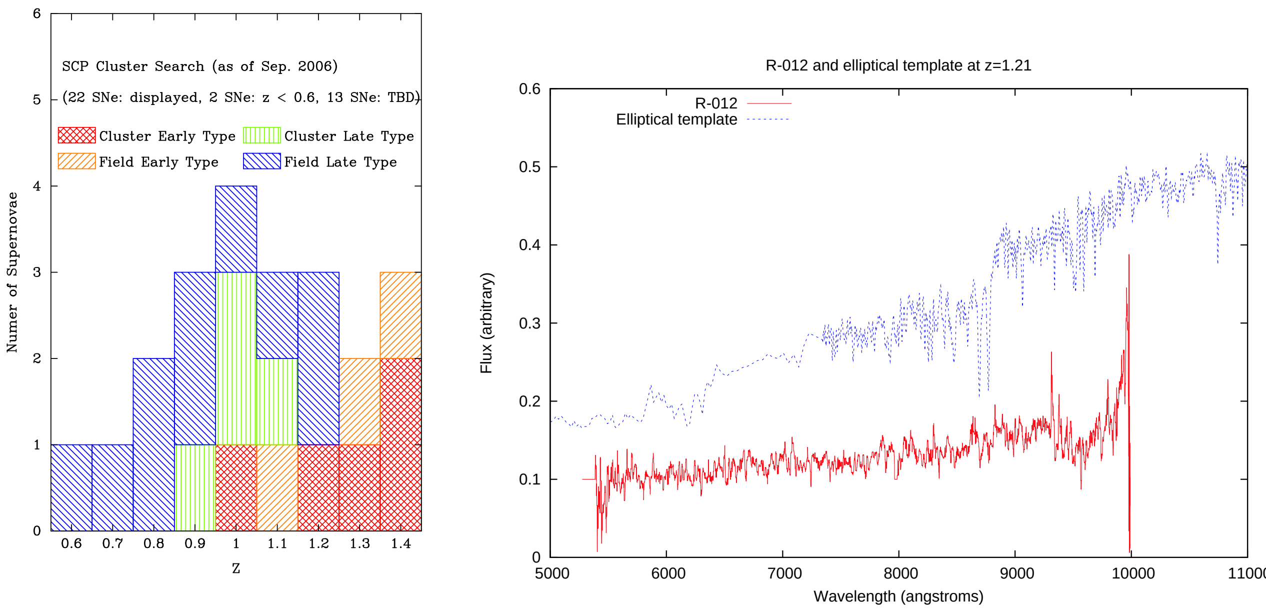

Figure 3 (a) Left Side: Redshift distribution of cluster SNe that have been found and confirmed in our Cycle 14 program. Red cross-hatched boxes correspond to SNe in early type cluster galaxies, orange hatched boxes correspond to SNe in early type field galaxies, green vertical stripes correspond to SNe in non-early type cluster galaxies, and blue tilted stripes correspond to SNe in other field galaxies. **Figure 3 (b) Right Side:** Results from three hours of integration in the August 27, 2006 DEIMOS observing run. The red solid line shows the smoothed extracted spectrum of a $z' = 23.5$ magnitude galaxy hosting a SN discovered in the HST program. The blue dashed line shows the template of an elliptical galaxy redshifted to $z = 1.21$. The host galaxy is clearly consistent with the template through identification of the CaHK absorption features around 8800$\AA$. Excellent red response and sky removal allow redshift determination even for an object as faint as this galaxy.

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2 Progress to Date

This large program (219 HST cycle 14 orbits) has been very successful so far as is shown in Figure 3. Redshifts were obtained in multislit observations of galaxy clusters using LRIS on Keck, DEIMOS on Keck, FOCAS on Subaru, and FORS2 on VLT. The Keck follow-up program started in semester 2006A, with two nights being awarded. On Feb. 1 we observed a SN and host using a slitmask to obtain redshifts of other galaxies in the cluster as well in marginal conditions. We obtained a low signal-to-noise spectrum of the host that was consistent with the cluster redshift of $z = 1.41$. On June 25 we attempted observations in poor conditions but could not identify redshifts of targets fainter than approimately $z' = 22$. We were awarded two nights in semester 2006B using DEIMOS. The first night was very successful, allowing for the observations of three slitmasks targeting two SN hosts and approximately 100 galaxies identified as potential cluster members. The results of one observation are shown in Figure 3. These data will be published along with the results of the HST cluster supernova search. The data from the other targets in the slitmasks will be used and published by several of our collaborators as part of their study of galaxy clusters.

3 Technical Justification

Targets: All of the supernovae hosts to be observed in this proposal were discovered using ACS on the HST. The eight SNe from the cycle 14 search occured in seven different clusters, and slitmasks will be designed accordingly. The two primary targets in the GOODS fields will be observed using two separate slitmasks in order to observe the full sample of 36 SNe in the GOODS north field which still require redshifts. The SNe hosts we hope to observe during the spring semester with DEIMOS are described in the following table along with the approximate z' band magnitude and cluster redshift. In the case of the two GOODS targets, the redshift reported is the photo-z estimate.

Table 1: SN host Positions and Approximate Magnitudes

Fields	R. A. (J2000)	Decl. (J2000)	z' Magnitude	cluster z
K-000	$14^h 38^m 08^s$	$+34° 14' 19''$	23.14	1.41
K-018	$14^h 38^m 10^s$	$+34° 12' 47''$	22.38	1.41
G-004	$14^h 29^m 18^s$	$+34° 37' 26''$	22.98	1.35
H-005	$14^h 34^m 28^s$	$+34° 26' 23''$	21.90	1.24
E-012	$14^h 15^m 11^s$	$+36° 12' 03''$	24.02	1.03
F-012	$14^h 32^m 29^s$	$+33° 32' 48''$	24.29	1.05
L-021	$14^h 35^m 51^s$	$+33° 25' 51''$	24.85	$1.4 - 1.5$
T-001	$15^h 11^m 03^s$	$+09° 03' 34''$	25.5	1.05
acs04-076	$12^h 37^m 51^s$	$+62° 17' 08''$	24.86	1.5
acs04-014	$12^h 37^m 09^s$	$+62° 22' 15''$	23.39	1.6

Supplementary Observations: We are using 219 orbits of HST for a rolling search of supernovae in 25 galaxy clusters at $z > 0.9$. Typically, we observe each cluster with the ACS F850LP and F775W filters every 20-26 days for 8 visits. These observations are used both to discover SNe, and follow their lightcurves. For the highest-redshift SNe, we supplement these data with an infrared lightcurve from HST (using triggered ToO observations with NICMOS). The program will be finished by the Keck spring semester.

There is no allocated HST time for spectroscopic follow-up, since those observations are possible (though difficult!) from the ground with 10-m telescopes. Our spring clusters are all visible from Keck at declinations > 0 deg. In addition to observations with DEIMOS on Keck, we have requested time in the Spring 2007 semester using FOCAS on the Subaru telescope.

Exposures: Our exposure times are based on experience of Keck DEIMOS observations of high-z SNe and galaxies. Under average conditions at Keck, a $z' = 23.5$ magnitude elliptical galaxy at $z = 1.25$ requires a total of 3 hours of exposure for a marginal classification and redshift, as seen in Figure 3. We prefer higher signal-to-noise measurements of the early-type hosts which provide the backbone of our HST program, and therefore plan to observe each early-type galaxy in Table 1 for four hours using DEIMOS. We have found that we can obtain redshifts of at least 30 additional galaxies for each slitmask to supplement the sample of spectroscopically confirmed cluster galaxies generated by our collaborators. In the case of L-021, the cluster redshift is poorly known and we plan to observe the SN host and cluster galaxies for a four hour exposure in order to conclusively determine cluster membership and redshift. Each of acs04-076, acs04-014, E-012, F-012, and T-001 will be observed for 2 hours in an effort to identify emission lines in the otherwise faint hosts and simultaneously confirm a large sample of redshifts in the slitmask.

Telescope Time Requested: We have requested 3 nights of telescope time to observe a total of eight $z > 1$ SNe hosts from the HST cluster search. The time will also be used to target suspected cluster members in the redshift range $1.03 < z < 1.5$ If awarded time for this project, we request dates in mid April when the Bootes field transits around midnight and visible for approximately eight hours. Because many of these targets are extremely faint, these observations can not tolerate too much contamination from moonlight, and we request time within 7 days from new moon. In addition, DEIMOS will be used to observe the hosts of two $z \gtrsim 1.5$ SNe and the hosts over 30 SNe from the GOODS survey in the early hours of the night, when the cluster SNe are not yet visible.

Instrumentation: We request the DEIMOS spectrograph because of its efficiency, broad wavelength coverage, red response, and large field of view for observations of other cluster galaxies. We will use the 600l grating centered on 7750A. Note that we will be using the DEEP team's spectroscopic reduction package in order to make optimal use of the DEIMOS instrument. It should also be noted that we are working on this HST program as part of a large collaboration, many members of which are specifically involved with cluster research. We plan to integrate additional targets chosen by these members into slitmask observations in order to obtain information regarding the properties of other members of the cluster hosting the SN. We believe these observations will help to make optimal use of the time on DEIMOS.

Backup Program

If transparency or seeing precludes spectroscopy of the faint SN hosts, we will observe the slitmasks which target brighter suspected cluster members found around redshift $z = 1$.

Path to Science from Observations

We will use spectral lines, whether seen in emission (e.g. OII 3727Å) or absorption (e.g. Ca II H & K), of the host galaxy to determine the redshift.

The Keck redshifts will be used along with photometry from HST to plot the SNe Ia on the Hubble diagram. This requires that the light-curve time of maximum, peak flux, and width, be measured. The light-curve width is strongly correlated with the intrinsic supernova brightness, and is used to standardize SNe Ia. Once the SNe Ia have been standardized, we can solve for the confidence intervals for the cosmological parameters.

Technical Concerns

Experience and Publications

Our group has extensive experience with faint object spectroscopy on telescopes around the world, and with Keck in particular. To reduce and analyze the spectra, our group has developed techniques that are specific to high-redshift supernova work. Our group has also developed extensive techniques for the photometry of high-redshift SNe against the bright background of their host galaxies.

We have recently submitted a paper to Astronomical Journal describing Keck AO H-band imaging of one of the first high redshift elliptical hosted SNe in our HST program. We have also presented early results from the program at the AAS meeting in Washington D.C.