Scientific Justification

Using Type Ia Supernovae in Early-type Galaxies to Measure Cosmology

The signature goal of the most ambitious cosmology projects being designed or built this decade (LSST/LST/Panstarrs, Dark Energy Camera, JDEM/SNAP/Destiny, and the South Pole Telescope and other SZ experiments) 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 (SN Ia, cluster counts, S-Z, weak lensing, and baryon oscillations), only Type Ia supernovae (SNe Ia) have actually been developed to the point of routine use. Only HST observations can provide the required signal-to-noise for those supernovae at $z \gtrsim 1$, where the transition from deceleration to acceleration can be studied. Initial studies of the decelerating universe from both the Higher-Z Team (Riess *et al.* 2004) and the Supernova Cosmology Project (Fadeyev, Aldering *et al.* 2004) clearly point to the limiting factor for both statistical and systematic uncertainties: extinction correction of the host galaxy.

We propose a new approach to the measurements in this difficult decelerating redshift range. By studying "clean" supernovae discovered specifically in galaxy-cluster ellipticals, we can remove this primary statistical and systematic uncertainty — and do so with a dramatically more efficient use of HST time (see Obs. Strategy section).

The resulting data set also provides a deep z-band survey of $z \gtrsim 1$ rich clusters, allowing us to take important steps in understanding other cosmological measurement techniques. In particular, cluster counting is an extremely sensitive measure of expansion history if their masses can be estimated with reasonable precision. We propose to measure cluster masses via weak lensing from the same HST images, as well as calibrate Sunyaev-Zel'dovich distance measurements to those same clusters. Finally, this data set will be used to study galaxy cluster assembly and star formation rates. We have intentionally included clusters that are X-ray-selected, optically-selected, and IR-selected for this purpose.

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. This is already true at $z \sim 0.5$, even with HST photometry, as shown in Knop *et al.* (2003), and is dramatically worse at $z > 1$ as shown in Figure 1. The typical color uncertainties for HST-studied $z > 1$ SNe 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. (Note that the actual dispersion about the Hubble-line fit for $z > 1$ SNe Ia corrected for extinction matches this 0.5 mag value.) Figure 2a shows the resulting poor constraints on the dark-energy equation-of-state parameter and its time variation, w_0 vs. w'. These constraints do not allow distinguishing between almost any current dark energy model.

These large dispersions in extinction correction have been dealt with, e.g. in Riess *et al.* (2004), by applying a strong Bayesian prior to the distribution, assuming knowledge of the dust and

SN distribution in the $z > 1$ host galaxies (shaded contour of Fig. 2b). However, such Bayesian priors are necessarily one-sided (no negative reddening) and hence are known to introduce systematic biases when the error bars are larger at high-redshift than low-redshift (Perlmutter *et al.* 1999). This bias can be seen in Fig. 2b as the difference between the long-dashed contour and the solid contour. This approach to the extinction analysis is also subject to other obvious sources of systematic biases, for example if the mean value of R_V drifts from low to high redshift, as shown by the short-dashed contour of Fig. 2b.

How is this problem solved using SNe Ia in ellipticals? In Sullivan *et al.* (2003), we showed that the dispersion (including ground-based measurement error) about the Hubble diagram for elliptical-hosted SNe is 0.16 mag — three times smaller than just the measurement uncertainty for extinction-corrected SNe Ia at $z > 1$ — primarily due to the absence of dust. Thus, SNe Ia in ellipticals are statistically each worth *nine times* that of SNe in spirals when making cosmological measurements – and without the aforementioned systematics associated with extinction correction. We therefore propose to collect a sample of ∼10 SNe Ia at $z \gtrsim 1$ entirely in cluster elliptical host galaxies, to achieve the statistical constraints of ∼90 SNe in later-type hosts. This would yield the stronger constraints on w vs. w' shown in Fig. 2c — without extinction prior systematics.

The $z = 0.9 - 1.7$ redshift range provides key leverage of the cosmological model, especially constraints on the dark energy time variation w'. Furthermore, this regime is when cluster potentials first begin responding to the accelerating effects of dark energy.

How is it known that the targeted $z \gtrsim 1$ cluster ellipticals are dust-free? The clearest line of evidence for the lack of a significant role for dust in elliptical galaxies comes from the tightness of the color-magnitude relation. The dispersion in the colors of early-type galaxies has long been known to be very small 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; Blakeslee *et al.* 2003). In fact, this relation has recently been shown by Hogg *et al.* (2004) to be universal for early-type galaxies in clusters and in lower-density environments using an enormous sample from SDSS.

Recent results from ACS imaging show the same strikingly small dispersion in color extends to redshifts $z \gtrsim 1$ (Figure 4). ACS imaging of RDCS1252-29 at $z = 1.24$ 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 $U - B$. This dispersion is comparable to that found by Bower *et al.* in Coma. Given the high likelihood of at least some age (and color) variation in the stellar populations of the member galaxies, the maximum amount of dust that could be in these ellipticals must be still smaller than this dispersion – unless a conspiracy gives all these ellipticals the same amount of dust along the line of sight.

Why is this cluster search much more efficient at finding (and studying) SNe Ia at $z \gtrsim 1$ than the previous HST searches in the GOODS fields? This search centered on rich clusters is expected to yield twice as many $z \gtrsim 1$ supernovae in total as the previous blank-field searches (such as the two SN teams' previous GOODS searches), and *five times* as many supernovae in elliptical hosts. The number of Type Ia supernovae scales with luminosity, with a rate of approximately one per year per $10^{12} L_{\odot}$ in rest-frame B-band luminosity. Fig. 3a shows that compared to an average GOODS field, our cluster fields generally contain more than five times the rest-frame B-band luminosity from early type galaxies at $z \gtrsim 1$ – hence the factor of 5 increase in the elliptical-hosted SN Ia rate. Since we still find (and study) the field SNe not in clusters, the total discovery rate will more than double. Note that these cluster SN rates are consistent with the rate seen in previous searches of clusters below $z = 1$, including one we (SCP) performed with ground-based telescopes (Perlmutter *et al.* 1995; Pain 1997 [which ref???]), and the search of archival HST data by Gal-Yam *et al.* (2002, who rediscovered one of our cluster SNe).

In addition to discovering more SNe Ia per HST orbit, there is another set of major efficiency gains in the *follow-up* of these SNe due to the knowledge that the host is elliptical, our knowledge of the redshift of the cluster, and the higher rate per field. First, the follow-up observations need significantly less signal-to-noise and fewer bands, since the extinction correction no longer dominates the requirements, and the bands can be pre-chosen to match each cluster's known redshift. Second, the higher discovery rate allows pre-scheduling observations for each cluster with a cadence guaranteed to well sample the lightcurves for every supernova discovered. For all but the highest redshift clusters, this eliminates the need for expensive TOO follow-up in obtaining the fundamental lightcurve data! Finally, these $z \gtrsim 1$ clusters' old stellar populations will only host SNe Ia, so much spectroscopy can be saved as well.

Developing other Dark Energy Techniques using these Cluster Data

The number of clusters of galaxies as a function of mass and redshift provides a powerful alternative probe of the cosmology thanks to its sensitivity to the comoving volume *and* the growth of large scale structure. The rare, massive clusters at high redshifts provide most of the discriminating power of the experiment, requiring large surveys of the sky to search for these systems. A number of large cluster surveys are underway (e.g., Red-sequence Cluster Survey) or being built in the near future (e.g., South Pole Telescope Sunyaev-Zel'dovich Survey, Dark Energy Survey) with this dark energy measurement as a key goal. However, these surveys, which detect clusters through a variety of techniques, all require estimates for the cluster masses in order to succesfully constrain cosmological parameters.

Many cluster properties correlate with mass, but it is not (yet) possible to predict these relations to the required level of accuracy, because of the complex nature of cluster formation. This is more of an issue at higher redshifts, where clusters are dynamically young. Instead the mass-observable relations – and their evolution – need to be calibrated empirically.

Weak lensing estimates of cluster masses. Weak gravitational lensing of background galaxies is now a well-established technique for providing a *direct* measurement of the projected cluster mass, without any assumptions about the geometry or dynamical state of the cluster. The next generation cluster surveys will yield samples of order 10^4 clusters out to high redshifts. It will be impossible to obtain weak lensing masses for all of them. Fortunately, recent work by Majumdar & Mohr (2003; 2004) on "self-calibration" has shown that follow-up studies of only a moderate sample of clusters are sufficient to allow these surveys to constrain w better than $5 - 10\%$. The main requirement of such a sample is that the observations can constrain the evolution in cluster properties.

Out to $z = 0.7$, large ground based projects (e.g., Canadian Cluster Calibration Project, CFHT Legacy Survey, Subaru observations) will provide a detailed study of the mass-observable relation and its scatter using $\sim 10^3$ clusters. Members of our team are leading some of these efforts. At higher redshifts, space-based observations are needed, driven by the need to measure the shapes of resolved *background* galaxies. Note that Holz & Linder (2005) show that gravitational lensing at these redshifts is not a major source of error for the supernova Hubble diagram with current measurements (though the observations can serve as a valuable testbed for Monte Carlo techniques treating the influence of the lensing effect). The proposed observations target a redshift range which is virtually unexplored. Without the proposed observations, our knowledge of the cluster properties at $z > 1$ will be too limited to use these systems for cosmology. Consequently, observations in this regime are desparately needed if cluster abundance studies are to succeed.

Our calculations of the expected uncertainties in the mass measurements show that we can achieve a $\sim 30\%$ accuracy for an individual cluster of mass $M = 5 \times 10^{14} M_\odot$ ($\sim$ average mass in our sample). More importantly , the observations allow us to determine the zero-point of the mass-observable better than 15% in each of four independent redshift bins. The proposed observations allow us for the first time to accurately constrain the evolution in cluster properties at these redshifts, especially once tied to the ongoing work at lower redshifts.

The proposed sample is larger by a factor of 4 from previous work, and targets clusters at higher redshifts. In addition, the clusters have been selected based on either their X-ray emission or the overdensity of red galaxies. The accuracy in the mass determination of individual clusters is sufficient to address the important question whether different detection methods select different populations of galaxy clusters. We will complement the sample proposed here with data already in the HST archive to extend the range in mass and redshift. In combination with our ground based efforts we will be able to study the evolution in the properties of galaxy clusters from the present day out to $z \sim 1.4$, thus paving the way for cluster abundance studies in an era of precision cosmology.

Cluster masses from X-rays. The observed X-ray luminosity function of clusters (e.g., Gioia 1991; Vikhlinin et al. 1998; Rosati et al.2001; Nichols et al. 1999) or the distribution of the X-ray gas temperature (Henry & Arnaud 1991; Eke eta l. 1998; Donahue & Voit 1999; Henry 2000) can be tied to cosmological models by detailed observation of the intra-cluster medium. The latter X-ray observations provide good estimates the virialized masses of clusters, but are observationally very expensive. We thus rely on X-ray observations of a subsample of clusters as important calibrators for this method. Obtaining accurate X-ray observations for all the clusters in our proposed sample is a major goal, as are Sunyaev-Zeldovich measurements. In combination with the weak lensing measurements, we will be able to study the properties of the intra-cluster medium at this high redshifts for the first time with sufficient detail.

Currently, 4 of our proposed X-ray selected clusters and 5 of our optically selected clusters have available or scheduled X-ray measurements via XMM or Chandra that are sufficient to determine cluster temperatures and masses to 15% accuracy. We will vigorously pursue additional observations to create a calibration sample spanning our complete redshift and mass range.

Sunyaev-Zeldovich estimates of cluster masses and D_A. Using Sunyaev-Zel'dovich (SZ) observations along with X-ray observations of a single galaxy cluster, one can decouple the dependence of the signals on electron density and determine the angular diameter distance (D_A) to the cluster. To date, the method has been used to determine distances to 26 different clusters. A fit to the sample of SZE and X-ray determined distances yields a Hubble constant $H_0 = 60 \pm 3$ (statistical)

± 18 (systematic) km/s/Mpc, (for $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$) (Reese *et al.*, 2002).

The SZ Array (SZA) is one instrument in the next generation of dedicated telescopes for observing galaxy clusters and determining SZ cosmological-distance measurements. However, this method has never been calibrated against other distance measurements. The SN Ia measurements described in this proposal will provide a sample of distance-calibrated high redshift galaxy clusters which will be be targeted in future SZA observations to allow a first cross-calibration.

Galaxy Cluster Science at $z \gtrsim 1$

(Note that our present ignorance of some cluster properties does not impact upon the main science driver with SNe.)

Quantifying and interpreting the assembly and star formation history of massive elliptical galaxies is one of the principal objectives of galaxy evolution research. Whether they form via monolithic collapse (Eggen, Lynden-Bell & Sandage 1962) or hierarchical assembly (White & Frenk 1991), such galaxies account for a substantial fraction of the stellar mass in the Universe (Hogg *et al.* 2002), and are found in highly overdense regions (Hogg *et al.* 2003) - i.e., galaxy clusters. The slope, scatter, and intercept of the cluster elliptical galaxy color magnitude relation at $z < 1$ are surprisingly well matched by a simple star formation history consisting of a burst at $z > 3$ followed by passive evolution (Stanford *et al.* 1998), and their luminosity functions also are fit by such models (de Propris *et al.* 1999), arguing for little assembly at $z < 1$. ACS imaging of more distant clusters will determine how far this implausibly simple scenario can be pushed, by enabling measurements of the fractions of mergers and ellipticals, and their luminosity functions.

The ACS GTO team (including co-I's on this proposal) has made significant progress in understanding $z \sim 1$ galaxy clusters. Postman *et al.* (2005) present results based on morphological analyses of ACS imaging of 7 clusters at $0.8 < z < 1.3$. They find that the fraction of ellipticals does not change up to $z \sim 1.25$, and that the fraction of S0s remains roughly constant at the 20% level seen in $0.4 < z < 0.5$ clusters. Hence, the formation of all massive cluster ellipticals, and a significant fraction of the lenticulars as well, must be occuring at $z > 1.25$.

This proposal will take the next step beyond the limits of the GTO program in terms of small sample size and redshift to probe the regime in which massive cluster galaxies are being formed. The GTO program has three clusters as $z > 1$, while our sample has 16. The highest redshift of the clusters is pushed from $z = 1.26$ to $z = 1.6$.

In conjunction with data we have obtained on our sample clusters from Chandra, XMM, Keck, the VLT, Magellan, and Spitzer, the ACS data to be obtained in this proposal will provide the ability to determine the epochs of the assembly of ellipticals and the origin of S0s, and calibrate the relation between mass and X-ray luminosity and temperature, as well as future SZ mass determinations, at unprecedented redshifts.

Supernovae rates and star formation The rate of supernovae in galaxy clusters will address outstanding questions about the intracluster medium (ICM). Specifically, the high metal abundances and the high energetics of the ICM are as-yet unexplained. The metals seen in luminous elliptical galaxies is explained by Type Ia supernovae rates and mass loss from evolving stars (which were originally enriched by Type II supernovae).

However, the mystery arises when one looks at the iron abundances in the ICM. The iron produced from Type II SNe of a Salpeter IMF do not produce enough iron, nor do Type I SNe.

It has been suggested by Brighenti & Mathews 1999 that a higher rate for Type Ia supernovae can explain the ICM metal abundances as well as the "entropy floor" seen in the X-ray gas (e.g., Lloyd-Davies, Ponman & Cannon 2000).

The only observational measures of SN rates in $z \sim 1$ clusters is from the work of Gal-Yam *et al.* (2002). Searching the HST archive for repeated WFPC2 pointings of galaxy clusters, they identified 2 or 3 supernovae in 18 pointings (with overlaps of 1.3 to 4.7 square arcminutes). The derived SNe rate of $0.41^{+1.23}_{-0.39} h^2_{50}$ SNu in clusters at $z \sim 1$ argues against SNe Ia being the dominant source of iron in the ICM. However, these statistics from a mere 2 or 3 detections must be extended and improved for $z > 1$.

Strong lenses at $z \gtrsim 1$, and the possibility of finding strongly lensed supernovae Massive clusters are rich test grounds for understanding of structure formation and cosmological geometry through gravitational lensing of background galaxies. The probability of formation of giant arcs has been found to be greatly enhanced, beyond expected, around clusters (see, e.g., Gladders *et al.* 2003; Ho & White 2004), showing the need for increased understanding of their mass distribution. As one eye-opening example, Broadhurst *et al.* (2004) find over 130 images of 35 multiply lensed galaxies behind Abell 1689 using ACS imaging. This includes radial arcs and near-central images. Our target list includes one already known high redshift lensing cluster, RCS2319+0038 at z=0.91 (Gladders *et al.* 2003), exhibiting three dramatic giant arcs. With deeper z-band imaging, and the advantage of ACS for observing long, thin, low surface brightness giant arcs, this cluster will likely become the poster child for high-redshift cluster lensing.

Higher redshift cluster lensing will be even more useful in constraining cluster mass profiles and using arcs for geometric measures of cosmological distances. Availability of X-ray and other wavelength imaging of these clusters would provide much needed information for understanding the role of clusters in cosmology. [[[BUT THIS IS NOT DONE BY THIS PROPOSAL – should this point be taken out?]]] Finally, cluster lenses act as natural gravitational telescopes which facilitate the detection and study of faint, high redshift galaxies (e.g., Metcalfe *et al.* 2003; Pello *et al.* 2004). In particular, if our z-band images are combined with deep i-band data, the i-z color can be used to search gravitationally lensed high redshift galaxies out to $z \sim 7$. Such lensing leads to the possibility of finding strongly lensed supernovae and extremely distant supernovae, otherwise too faint to be detected (Gunnarsson & Goobar 2003).

Conclusions

The observations proposed here initiate a new approach to SN measurements and will provide a first significant, *and unbiased* measurement of w_0 vs. w'. They will then comprise a springboard for a wide array of astrophysical investigations: high redshift supernovae, cluster profiles, gravitational lensing, and multiwavelength studies of large scale structure and cosmology. The emphasis on high redshift and attention to systematics are the opening steps in bringing to maturity cosmological methods of the next generation, and the cluster data will serve as a bedrock scientific legacy for extragalactic astronomy.

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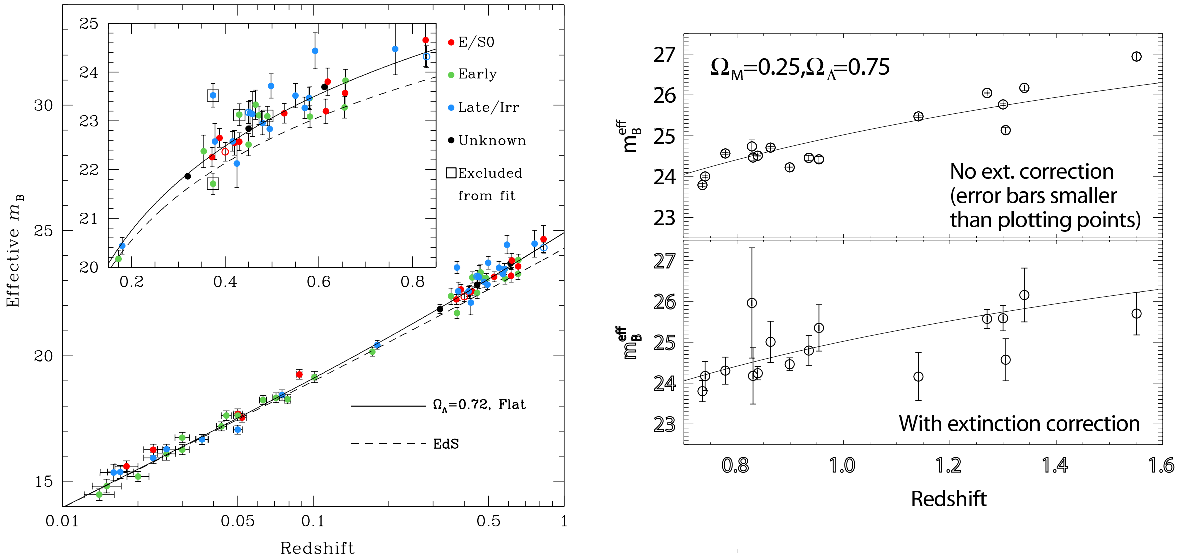

Figure 1: *(a) Left Panel:* The SCP SN Ia Hubble diagram broken into host galaxy types from Sullivan et al. (2003). The SNe in elliptical hosts (filled red circles) show significantly less dispersion, $\sigma = 0.16$ mag, including measurement error. (This ground-based measurement error for this $z \sim 0.5$ sample is quite close to the HST measurement error at $z > 1$ in this proposal.) *(b) Right Panel:* The comparison of the Hubble diagram, before and after extinction correction, for a mixture of SNe Ia in all host types shows the dramatic increase in error bars due to the uncertainty in $B - V$ color being multiplied by $R_B \approx 4$ and by the uncertainty in R_B. The data shown is from the SCP (Knop et al. 2003) and the Riess et al. 2004 GOODS search samples. For the SNe at redshifts $z > 1$ this yields an uncertainty of ~0.5 mag, which is consistent with the measured dispersion of 0.5 mag. The ratio of this dispersion to the elliptical-hosted dispersion of panel (a) makes the elliptical-hosted SNe each worth 9 of the extinction-corrected others.

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Description of the Observations

The supernova observing strategy

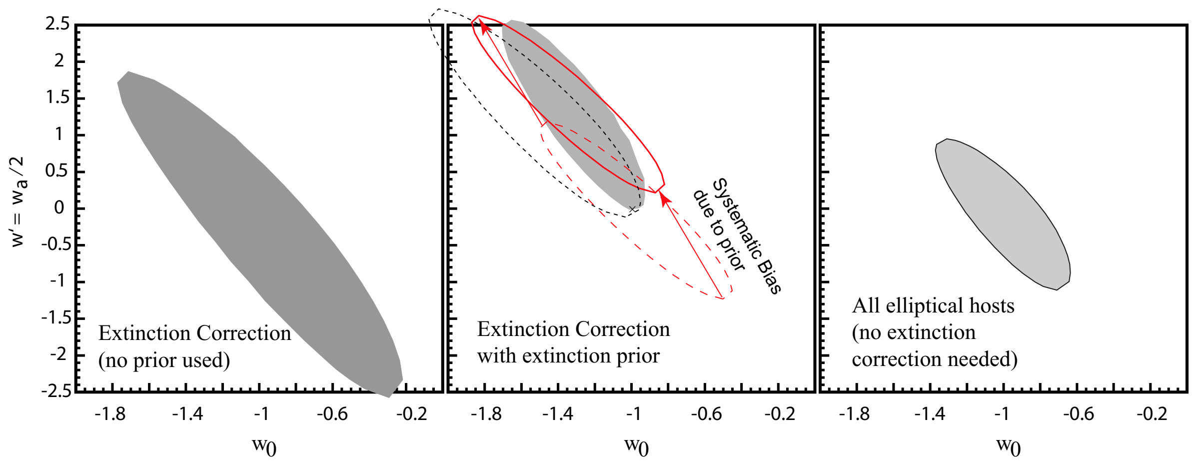

Figure 2: *(a) Left Panel:* Confidence region on the w' vs w_0 plane for a simulation matched to the current literature supernovae sample but with underlying cosmology ($w_0 = -1$; $w' = 0$). The parameters are quite poorly constrained because uncertainties in color measurement are magnified by $R_B \approx 4$. *(b) Middle Panel:* To remedy this problem, one might try using a prior on the extinction distribution to be less sensitive to the color measurement and hence its large uncertainty as shown by the solid red contour. However this introduces systematic biases in the extinction correction, shown by the shift from the underlying cosmology (dashed contour), if the uncertainties are higher at high redshift than at low redshift as is the case with the actual data. The filled gray contour is the result reported in Riess et al 2004 using this extinction-prior approach. The short-dashed contour shows that this approach is also sensitive to shifts in the value of R_B with redshift; the example shifts from 4.1 to 3.5. *(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 the past and ongoing GOODS searches, as well as 120 SNe Ia in ellipticals at the lower redshifts now being produced by the ground-based CFHT SN Legacy Survey, the CTIO Essence survey, and (at $z < 0.1$) 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).

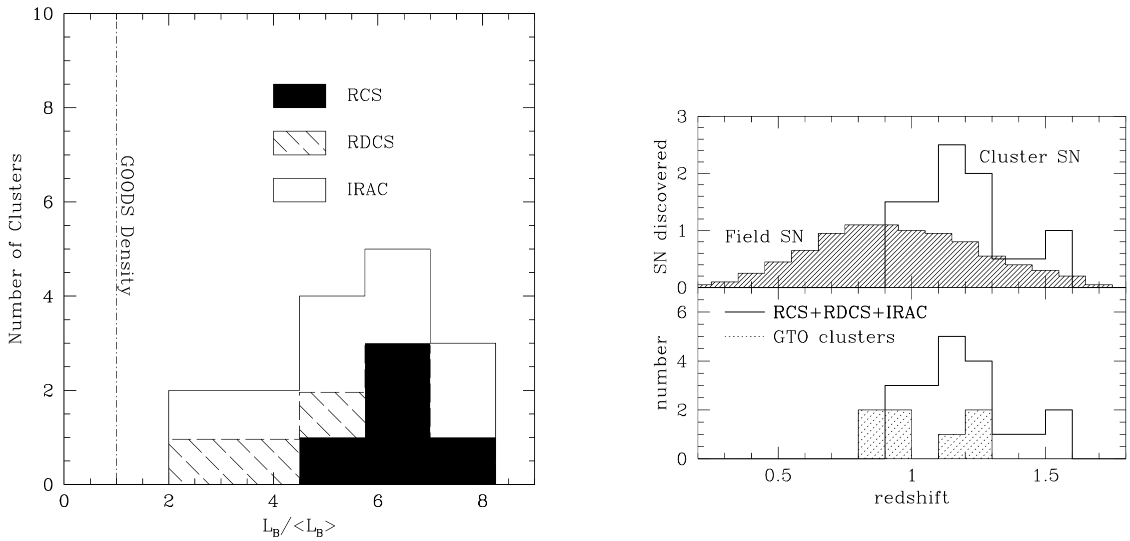

Figure 3: *(a) Left Panel:* Elliptical host supernovae at $z \gtrsim 1$ will be found much more frequently in our cluster sample than in the field. The ratio $L_B / < L_B >$ of rest frame blue luminosity for early type galaxies with $z > 1$ within an ACS FOV, relative to the average field value of this quantity, is plotted for clusters in our sample from the optically selected Red-sequence Cluster Survey (RCS - Gladders & Yee 2004), the x-ray selected ROSAT Deep Cluster Survey (RDCS - Rosati et al. 1998), and the 4.5 micron selected Infrared Array Camera Shallow Survey (IRAC - Eisenhardt et al. 2004).

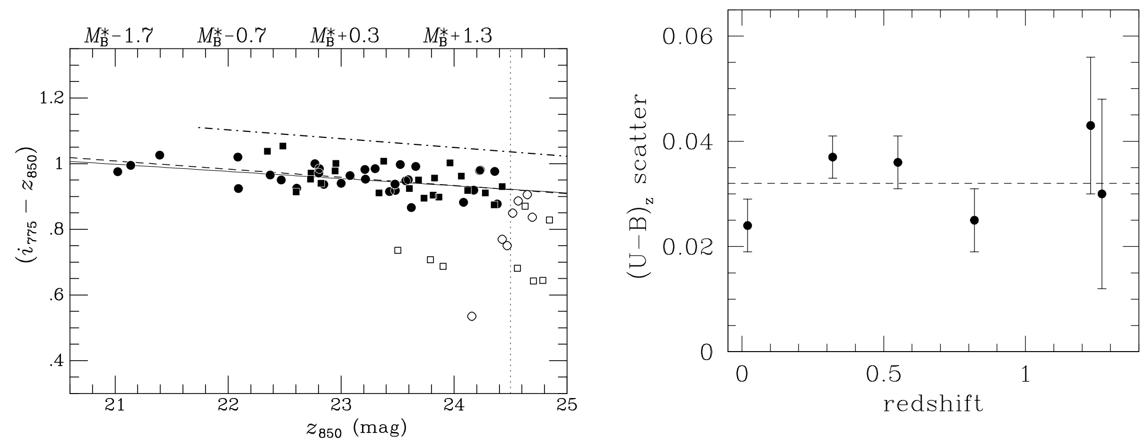

Figure 4: *(a) Left Panel:* The dust-free nature of ellipticals (filled circles) and S0 galaxies (filled squares) in RX1252-29 at $z = 1.23$ is supported by the small scatter of the color-magnitude relation. The relation for the Coma cluster, transformed to the observed bands with no evolution correction, is shown as a dot-dash line. The solid line is this relation at the redshift of RX1252 assuming WMAP cosmology and -1.4 mag of luminosity evolution.
(b) Right Panel: Scatter in rest frame $U - B$ CM relation for early-type galaxies in clusters as a function of redshift. In order of increasing redshift the points are from Bower et al. (1992), van Dokkum et al. (1998), Ellis et al. (1998), van Dokkum et al. (2000), Blakeslee et al. (2003), and van Dokkum et al. (2001). The dashed line is the average value, indicating no change with redshift in the scatter.

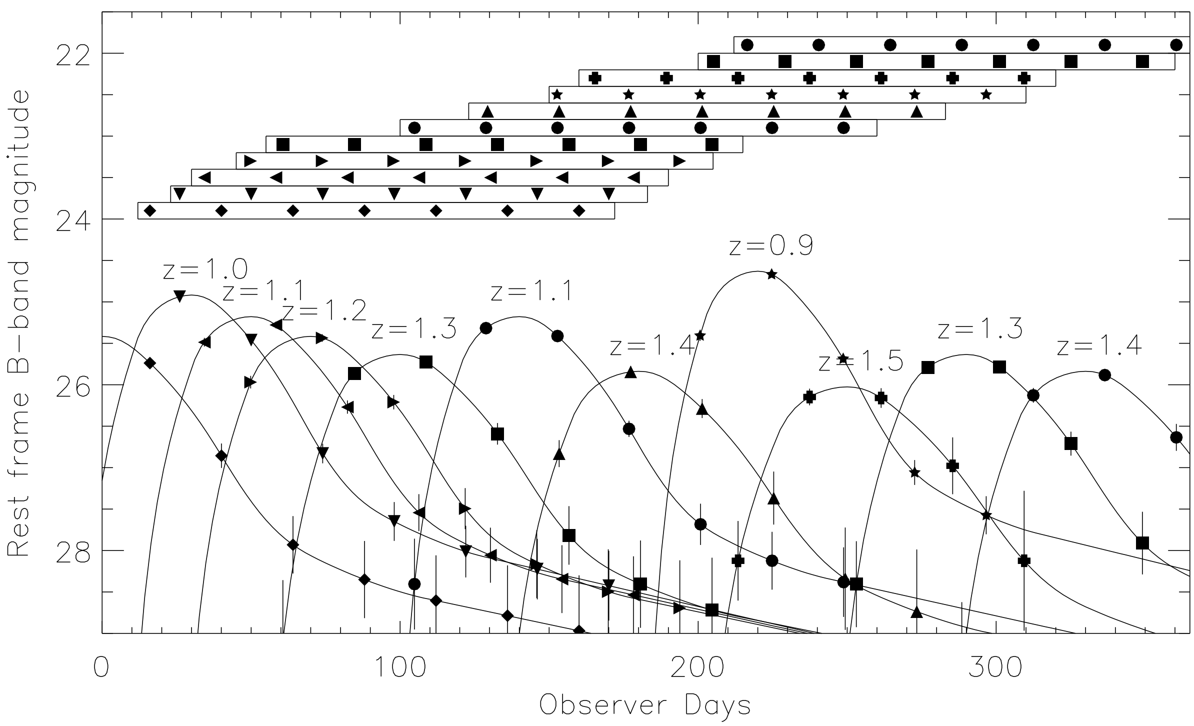

Figure 5: The simulated data set for this proposal, with signal-to-noise at a given redshift and SN epoch based on actual data from our previous SN photometry with HST ACS and NICMOS. The simulated data was fi t with the lightcurve-fi tting program of our actual analysis to test the feasibility of the chosen cadences. Even after propagating the uncertainty in the lightcurve timescale stretch used for correction, we obtain typical errors of 0.07 to 0.13 mag for a redshift range between 0.9 and 1.5. The bars at the top of the fi gure show the observing time period covered for each cluster, and the symbols show when observations are scheduled (with slightly different cadences depending on the redshift of the cluster). The same symbols are used for the observations on the lightcurves, to show where a supernova might be discovered and followed in its cluster's time window. Note that the observations are well spread throughout the year (allowing easy HST scheduling, with fle xibility since there are other clusters to study if one is diffi cult to schedule). There are therefore SNe to be observed in our ground-based observing program at almost any time during the year, in addition to the host galaxies that can be observed any time after the supernova is observed.

The high rate of SNe Ia produced by the clusters *in addition* to the SNe Ia in the fore/background field galaxies makes possible an elegantly simple combined search-and-follow-up scheduling strategy. Generally, we observe each cluster with the ACS F850LP filter every ∼24 days for ∼8 visits, with the exact cadence depending on the cluster redshift and the exact number of visits depending on HST observing constraints for the cluster. This means that every supernova that appears in these clusters during the entire period, modulo small end effects, will have a lightcurve measured — without the need for expensive Target of Opportunity (ToO) observations. We obtain ground-based spectroscopy of the supernovae's host galaxies after the fact, for precise redshifts and confirmation of elliptical galaxy type, which also confirms the SN Ia identification. For only the two highest redshift SNe, we supplement this basic lightcurve with an additional (>2-week-advance-notice) ToO follow-up observation sequence with NIC2 F110W, to provide restframe B band lightcurve data — since the NICMOS fields are too small to be used in the pre-scheduled search. (The very lowest redshift clusters are observed as part of the pre-scheduled cadence in ACS 814W to match the restframe B band.)

Figure 5 shows this strategy. Note that this is a dramatically more efficient approach than the previous ACS/GOODS searches, performed by both our team and the Riess et al. team, for several reasons. First, there is a large net savings in the number of search-plus-follow orbits necessary to study ∼10 SNe Ia; the previous method required ∼35% more orbits. Second, the number of required ToO's is reduced from 10 to 3 per SN, in itself equivalent to many orbits of observing time, and that these are ToO's with more than two weeks advance notice and hence much less disruptive to schedule. Third, the resulting data has much smaller statistical uncertainties, since the large contribution from extinction correction is removed, making each of these SNe worth ∼10 SNe not found in ellipticals. Fourth, not only will the ∼10 cluster SNe be supplemented by ∼10 SNe from the field that would have been studied in the GOODS searches, but there is still an additional population of useful SNe that have their lightcurves obtained, which previously could not be followed given the limited number of ToO's. (Including the cluster and the field, each cluster target field will thus be expected to yield on average one SN Ia in the $z > 1$ range and more at $z < 1$ – all with z-band lightcurves.)

This observing strategy is also considerably simpler to schedule than the previous GOODS searches. The observing simulations show that there is flexibility in the exact choice of repetition dates; the cluster observations can be at any orient (unlike the contiguous GOODS tiles); there are clusters on the target list observable at different times of the year, and they do not all need to be observed in the same cadence like the GOODS tiles, so the observing load is spread.

The observing requirements for this program are based on our experience with ACS and NICMOS measurements of supernovae in precisely this redshift range (with even a few in ellipticals), so we have direct tests of our exposure time, filter, and cadence requirements. For the bulk of the target clusters, between $z = 1.1$ and 1.4, we require a single ACS orbit with the 850LP filter every 24 observer days (i.e., ∼10.5 SN-restframe days) over the lightcurve. After propagating errors for the fit of the lightcurve timescale (used to calibrate the peak magnitude), this yields a SN Hubble-diagram point with uncertainty below the ∼0.15 mag intrinsic SN Ia uncertainty (in fact, 90% of the SNe will have distance modulus uncertainties below 0.10 mag). At redshift smaller than 1.1 one can afford to increase the cadence to 28 observer days and still be left with an uncertainty in the distance modulus of less than 0.1 mag. Correspondingly, for redshifts $z > 1.4$ we choose a shorter cadence of 20 days to compensate for the increase of the photometric errors. The fluxes/magnitudes, cadences and error bars shown in Fig. 5 demonstrate the range that are expected for this program.

[CHECK ALL THE NUMBERS IN THIS PARAGRAPH – they are currently estimates.] For an elliptical host galaxy, with its symmetric smooth morphology, the images before and/or after the SN lightcurve generally provide a fit of the host galaxy light that gets subtracted from each image of the SN-plus-galaxy. However, for $\sim$2 of the targeted $\sim$10 SNe Ia we expect the SN to be so close to the core of a bright host that we will need an additional final image the following year, with a 3-orbit depth so as not to degrade the signal-to-noise after subtraction. Offsetting this requirement for 6 additional orbits is the probability of cancelling the final cadence observations for clusters that have not produced a SN in time to be followed for sufficient lightcurve points. This should happen often enough that we can reschedule these cancelled final observations to provide the following-year visit for the cases that require them. (The cancellations would be three weeks in advance, so will not introduce scheduling complications.)

For the highest redshift clusters probability distributions for the photometric redshifts and SED fits (Brodwin 2004, PhD thesis) are available for all sources in the field down to the IRAC 4.5μm selection limit (which corresponds to $\sim L^* + 0.5$.) Only SNe associated with hosts with $> 90\%$ probability of having both $1.3 < z < 1.6$ and an SED type earlier than Sbc at $z = 0$ (corresponding to a $z_f = 3$ passively evolving elliptical at $z = 1.6$) will be targeted for NICMOS followup. [Issues to decide: Do we want full lightcurve follow-up of $z > 1.3$ SNe, or just at max? Do we want an additional point in a NICMOS color at max for a number of $z\ 1.1$ SNe to check the intrinsic color (which would help the measurements of spiral-hosted SNe)? What about a point in the CMAGIC period of the lightcurve?]

The fundamental dataset of F850LP-band lightcurves for every SN shown (and more!) in Figure 5 will be obtained without need of any ToO's. However, for specific cluster redshift ranges the science will be greatly enhanced by strategic use of additional low-impact ToO orbits. Primarily, these consist of a simple single-orbit or two-orbit observation in an additional NICMOS F110W filter *that can be scheduled over two weeks in advance*.

A short cadence of ~ 24 days for redshifts $z \approx$ 1 – 1.5 will allow prompt detection of SNe while still on the rise. Single-orbit NICMOS F110W follow-up observations will lead to a SN observation within $\pm$5 days (rest-frame) around maximum light. For three of the SNe ($z \approx$ 1.25 – 1.5 clusters), these near-maximum orbits will provide the restframe B-band point (with an error of $\sim$ 0.07 magnitudes) to tie these SNe to the same restframe-B Hubble diagram as the others. (Restframe U in 850LP will provide the lightcurve date and timescale "stretch" measurement, as for previous very-high-redshift SNe.) For 6 of the SNe ($z \approx$ 1 – 1.25 clusters), these observations provide a color measurement at maximum light to calibrate the intrinsic SN Ia colors at high-redshift. Note that these ToO's are much less expensive in orbits and disruption to the HST calendar than the fast-run-around $\sim$20-orbit-timeseries ToO's needed for every one of the GOODS supernova discoveries by the two SN research teams. For only two of our ToO's, for a SN at $z \gtrsim 1.4$ will this time series of 8 orbits be needed to provide the restframe B lightcurve, when the F850LP lightcurve is too far into the restframe UV of the SN to provide significant signal-to-noise.

Observing requirements for the cluster science

The primary requirement for achieving our objectives on the evolution and formation of galaxies in clusters is to obtain reliable visual classifications of galaxies down to 2 magnitudes below L^* at $z \sim 1.2$ using the standard system of elliptical, lenticular, and spiral/irregular over an area reaching out to r_{200}. The secondary requirement is to measure galaxy sizes, in particular r_e, with sufficient accuracy to enable estimates of M/L ratios for early-type galaxies when coupled with velocity dispersions being obtained with ground-based facilities. These requirements can be met with 8 orbit exposures in the F850LP band of the central ~200 arcsec area of our target clusters, as shown by Postman *et al.* (2005) and by Holden *et al.* (2005). In order to determine the morphologies of galaxies in the high redshift galaxies, HST images are necessary. Ground-based images even with 0.5 arcsec seeing are incapable of yielding high enough spatial resolution to reliably determine e.g. whether a galaxy is an elliptical or a lenticular (crucial to understanding the origins of these two kinds of galaxies) in clusters at $z \sim 1$ and greater.

Observing requirements for the weak lensing studies

Most current weak lensing studies of galaxy clusters with HST use a mosaic of observations in order to extend the measurement of the lensing signal out to larger radii, thus improving the accuracy of the mass measurement. Typically the motivation for this is the need to break the mass-sheet degeneracy; in practice this is not feasible, and instead we intend to fit parameterized mass models (e.g., the NFW profile predicted by cold dark matter simulations) to the data. This approach still benefits from covering a large area, but our detailed calculations show that the gain is minimal for clusters beyond $z = 1$ (where the FOV of ACS is well matched to the cluster). We find that we obtain more accurate masses by obtaining deeper observations instead, thus increasing the number density background galaxies and the accuracy in the shape measurements.

Hence the observing strategy for the SNe search is well matched to the requirements of the weak lensing mass determination. For clusters below $z = 1$ and clusters that show evidence of a complicated mass distribution we might consider mosaiced observations (with a large overlap in the centre), but most of the clusters will be observed to an ~ 8 orbit depth.

We estimated the expected accuracy in the weak lensing mass measurements but considering a cluster described by a singular isothermal sphere. We furthermore adopted a photometric redshift distribution for the background galaxies based on UDF observations. As we propose observations of high redshift clusters, some of which are known to have a complex mass distribution in their cores (e.g., Hoekstra *et al.* 2000; Jee *et al.* 2005), we also assume that we can only use the shape measurements at $r > 60$". For some clusters we might be able to use the lensing signal at smaller radii, thus reducing the uncertainties. We compared the outcome of our model calculations to actual published results (Jee *et al.* 2005; Lombardi *et al.* 2005) and find very good agreement.

The average mass of the clusters in our sample is thought to be $\sim 5 \times 10^{14} M_\odot$. Our calculations suggest that we obtain a $\sim 30\%$ accuracy in the mass measurement of our "average" cluster. More importantly, the observations allow us to determine the zero-point of the mass-observable (i.e., $M - T_X$, $M - L_X$, $M-$richness) relation in four independent redshift bins, with a relative error $< 15\%$ in each bin. This enables us to constrain the evolution in cluster properties, especially once tied to the ongoing work at lower redshifts. The resulting accuracy is sufficient to enable cluster abundance studies out to $z \sim 1.4$!

COSMOS and GEMS (Heymans *et al.* 2004) observations show the ACS PSF undergoes cyclic variation with a period of 15-20 caused by thermal fluctuations within the telescope. However, we have extensive experience in correcting for such effects. Using the program TinyTim (Krist & Hook 2004) we can create models of the PSF for the entire range of allowed focus values. Then, the ~ 20 stars in each exposure suitable for PSF measurement can be used to determine the focus value for that exposure. The appropriate TinyTim model can then be used for PSF correction.

We should also note that because of the nature of this program, the clusters will be observed with different roll angles, thus partly averaging out some of the PSF effects. In addition, studies of galaxy clusters are less sensitive to residual systematics compared to cosmic shear measurements.

Ground-base observations

Extensive ground-based observations of the target clusters have been carried out and will continue to be performed at Keck, Magellan, and the VLT. Deep multiband imaging exists for all target clusters, including in most cases optical and NIR bands. An abundant amount of multiwavelength data has already been published for the three X-ray clusters (Stanford et al. 1997, Rosati et al. 1999, Stanford et al. 2001, Stanford et al. 2002, Rosati et al. 2004, Lidman et al. 2004, Holden et al. 2004). In particular, we have spectroscopic redshifts for the brightest $\sim$ 20 member galaxies on average for each of these RDCS clusters so the redshifts of the likely host galaxies for SNe to be found in this HST program are already known. For the IRAC clusters, we have begun a program of slitmask spectroscopy at Keck to obtain redshifts for the brightest galaxies which should provide spectroscopic-z for galaxies containing $\sim$50% of the total cluster luminosity within the next $\sim$2 years.

Strategy for Two-Gyro Observations

Because of the continuous time series of observations required by this proposal it would be important not to change the observing plan if only a subset of the data were obtained in normal three-gyro mode. Fortunately, there are sufficient numbers of rich $z > 1$ clusters to target that we can choose a target set that works for either two or three gyro mode with no change in our observing plan. We have checked that all of the observations can be made in two-gyro mode for the time window requested.

Special Requirements

Coordinated Observations

Justify Duplications

Previous Related HST Programs

To be updated

By combining observations from a series of GO programs over a number of HST cycles we have obtained a cumulative sample of high redshift SNe which has yielded new determinations of cosmological parameters $(\Omega_M, \Omega_\Lambda, w)$. Equally important, these HST observations have been the basis for studies of possible systematics of the SN technique, such as host-galaxy extinction or evolution. Two such multi-cycle HST studies were published in the past year and both provided confirmation and improved precision on the earlier ground-based acclerating universe results. Knop *et al.*, 2003 (based on G0-7336, GO-7590, GO-8346) presented an analysis of an independent set of 11 high redshift SNe. The high-quality lightcurves available from photometry on WFPC2 make it possible for this sample alone to provide measurements of the cosmological parameters comparable in statistical weight to the previous results. In addition to high-precision lightcurve measurements, this data offered greatly improved color measurements of the high-redshift supernovae, and hence improved host-galaxy extinction estimates. These extinction measurements show no anomalous negative $E(B-V)$ at high redshift. The precision of the measurements is such that it was possible to perform (for the first) time a host-galaxy extinction correction directly for individual supernovae without any assumptions or priors on the parent $E(B-V)$ distribution.

Sullivan *et al.* 2003 (based on GO-8313, GO-9131) presented the Hubble diagram of distant type Ia supernovae (SNe Ia) segregated according to the type of host galaxy. This allowed us to confirm our previous evidence for a cosmological constant by explicitly comparing SNe residing in galaxies likely to contain negligible dust with the larger sample. These data provide a key test of evolutionary systematics.

Other such multi-cycle analyses, described below, are in progess. In particular, this year we are completing final observations of host galaxies after the SNe faded for SNe discovered in GO-9075 and GO-8585.

GO-9727: This cycle 12 program will begin observations in April 2004 using ACS to do a new search for very high redshift $(1.2 > z > 1.6)$ SNe Ia in the GOODS-N field. In coordination with Riess (GO-9728), images from 15 ACS pointings will be taken approximately every 45 days and searched for candidates. Followup photometry will be obtained with ACS and NICMOS for approximately three very high redshift SNe.

GO-9075: In this program, we pushed our SNe Ia studies to the highest redshifts that are feasible for a ground-based discovery and spectroscopic identification campaign. HST follow-up observations for this program started after servicing mission 3B in March 2002 and have been completed for the most part — final reference images are still to be taken. Coordinated with three large search campaigns using the Subaru 8.2 m and also with simultaneous smaller searches using the CTIO 4 m and CFHT 3.6 m, we obtained ACS/WFC and NICMOS/NIC2 photometry for multi-epoch lightcurves of eight Type Ia SNe at high redshift $(0.9 < z < 1.3)$. For two of the highest redshift SNe, ACS grism spectra were taken. Analysis of this ACS data is in progress. With the refurbished NICMOS, we obtained final reference images of the host of SN1998eq, which we had previously studied in G0-8088, and these images will allow us to complete that analysis.

GO-8585: In GO 8585 we observed six Type Ia supernovae with HST using WFPC. The supernovae were discovered in ground based searches at the CTIO 4-m, CFHT and Subaru telescopes. We obtained both U- and B-band restframe photometry (using either F814W or F850LP depending on the redshift) for each supernova for a period of 2 months. Analysis of this data is presented in the PhD thesis of J. Raux (Univ. of Paris, 2003), presented at the January 2004 AAS meeting. A publication is in progress.

GO-8313: The objective of this project, which has now been completed with the publication (Sul03) mentioned above, was to obtain snapshot unfiltered STIS images of distant galaxies of known redshift which have hosted supernovae (SNe) of Type Ia found by the SCP, 20 of which are used in the Hubble diagram of 42 type Ia SNe (Perlmutter *et al.* 1999). The internal extinction implied is small, even for late-type systems ($A_B < 0.3$), and the cosmological parameters derived from those SNe Ia hosted by (presumed) dust-free early-type galaxies are consistent with our previous determination of a non-zero Λ. The brightness scatter about the Hubble line for SNe Ia in these early-type hosts is also significantly smaller than for the SNe Ia in late-type galaxies. This result was based on HST STIS "snapshot" images and Keck spectroscopy of SNe spanning the range $0.3 < z < 0.8$.

GO-8346: We had the unique opportunity of following up SN2000fr, which had been discovered *14 days prior* to maximum light in its restframe. Because this supernova at z=0.54 was discovered so early we were able to obtain excellent light curves from HST in F555W, F675W and F814W spanning the period from one week prior to maximum light to 6 weeks after Several spectra of the supernova were taken at VLT and Keck along with NIR photometry at VLT.

DD-8088: WFPC2 and NICMOS (cycle 7) observations were obtained for SN1998eq at $z = 1.20$ (Aldering, *et al.*, 1998,IAUC,7046). The preliminary photometry is consistent with the previous results for Ω_M, Ω_Λ. With the final NICMOS image of the galaxy without the supernova obtained, this analysis can now be completed.

GO-7850 and balance of **GO-7336** and **DD-7590**: WFPC2 and NICMOS observations were obtained for 11 Type Ia supernovae in the redshift range 0.36—0.86. These observations, including final references where necessary, are now complete, and the results were published in Knop, R., *et al.* 2003 as mentioned above. The color information provided by NICMOS (Burns, S., *et al.*, 2001,AAS,199.1610B), was only possible with HST.

GO-7336 and **DD-7590**: Perlmutter *et al.*, 1998, Nature, 391, 51 reported the results of our HST and ground-based imaging and Keck spectroscopic observations of SN1997ap. The HST portion is based on a total of 4 orbits. Also from this program, HST observations of two $z = 0.83$ SNe Ia are included in the analysis in Per99 which reports on the results from our HST and ground-based imaging and Keck spectroscopic observations of 42 type Ia supernovae with $0.18 < z < 0.86$. The paper rules out a flat $\Omega_M = 1$ universe and presents very strong evidence for a positive cosmological constant.