■ Scientific Justification

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

The signature project of the most ambitious cosmology projects being designed and/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 and the Supernova Cosmology Project (Riess *et al.* 2004; 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 any reasonable precision. We propose to measure cluster masses via weak lensing from the same HST images, and also 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.

1.1 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 dominant source of both statistical and systematic error budgets of SNe distances and of derived cosmological paramters. These extinction values are estimated from the measured color of the supernovae, and have typical values of $E(B-V) = 0.05$ mag. Using the standard extinction law (discussed later), this corresponds to a typical extinction correction of 0.2 mag. Note that there is a floor to this error, since high-S/N measures of supernovae colors still have extinction uncertainties due to the intrinsic dispersion of supernovae colors.

In addition to the large statistical errors from extinction corrections, there are additional, unknown systematics from variations in dust properties. Draine (2003) notes that the dust reddening coefficient $R_V \equiv \frac{A(B)}{A(B)-A(V)}$ can vary from the fiducial value 3.1 by ± 0.5. There are specific measurements through lines-of-sight in the Milky Way as low as 2.5 (presumably from smaller dust grains) and as large as 5.5 (from larger grains, c.f., Clayton, Cardelli & Mathis (1988). If we fix the color excess parameter at $E(B-V)=0.1$, then this diversity implies a magnitude systematic of ± 0.05. This would have severe consequences for cosmology fitting: Linder & Miquel (2004) find a degradation of 60% in constraining the dark energy equation of state time variation w' and 100% in the present value w_0. These numbers were for a statistically robust data set of 80 SNe at $z > 0.9$. Since current statistical errors are higher, the effects of systematics will be less, but still impose problems on parameter determination.

Furthermore, if R_V (or the extinction correction, including color knowledge) varies coherently with redshift, this imposes a bias on the derived cosmology. Linder & Miquel (2004) estimate this to amount to $0.5 - 1\sigma$ of the statistical dispersion, a non-negligible and potentially serious effect. While the increased dispersion due to extinction correction makes elliptical galaxy SNe worth statistically four times as much leverage, the possibility of bias further increases their value.

In Riess *et al.* (2004), a one-sided exponential prior on the extinction correction was applied and the resulting values of A_V were quoted without error bars. In our re-analysis of their data set, we find that a 10% systematic effect on the derived distances (> 0.2 mag on brightness) is introduced for supernovae with negigible reddening, e.g. the ones in early-type galaxies. This happens because the (Gaussian) *measurement* errors on the colors (typically $\sigma_{E(B-V)} \sim$ 0.05-0.1 mag) are treated differently on the positive and negative side of the distribution.

1.2 How is this problem solved using SNe Ia in ellipticals?

Extinction systematics impose particular difficulty at high redshift because of the increased difficulty of precision color measurements of the SNe (especially when one must observe in the IR!). Until $z > 1$ SN surveys achieve comprehensive extinction measurements, the only robust route to use of these high redshift SNe for cosmology is observation of elliptical galaxies where the dust correction is minimized. To check the bias of the cosmology derivation due to the possibility of a coherent systematic, it would be quite useful to build up an “all elliptical” Hubble diagram for SN at all redshifts.

In Sullivan *et al.* (2003), we showed that the dispersion about the Hubble diagram for elliptical-hosted SNe is *half* that of later-type galaxy hosts, primarily due to the absence of dust. Thus, SNe Ia in ellipticals are statistically each worth *four times* that of SNe in spirals when making cosmological measurements – and without the aforementioned systematics associated with extinction correction. This extra weight is even more dramatic at $z > 1$ where color measurements are weaker. Without an extinction prior, the $z > 1$ data in Riess et al. (2004) would give a dispersion of [???], compared with [???] for elliptical hosts, implying an elliptical advantage of [???] to 1.

1.3 How is it known that the targeted $z \gtrsim 1$ cluster ellipticals are dust-free?

Nearby elliptical galaxies are well known to be almost entirely free of dust, with very few exceptions (like the disk in the center of Cen A). The clearest line of evidence for the lack of 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 (Bower *et al.* 1992; Ellis *et al.* 1997; Stanford *et al.*– WHAT IS THIS REFERENCE???). 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.

Recent results from ACS imaging suggests that these arguments for dust-free ellipticals hold true at redshifts $z \sim 1$. 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 very small – unless a conspiracy gives all these ellipticals the same amount of dust along the line of sight.

In addition, the HST images themselves will provide another sanity check as to the dust-free nature of the supernova hosts. Elliptical galaxies are well-fit by 2-dimensional de Vaucouleur profiles. Subtracting such model fits from ellipticals reveal when dust lanes are present, as in Cen A.

1.4 Why is this cluster search much more efficient at finding (and studying) SNe Ia at $z >\sim 1$ than the previous HST searches in the GOODS fields?

This search centered on rich clusters is expected to yield twice as many supernovae in total as compared to a blank-field searches (such as the 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 $10^{12} L\cdot$ in rest-frame B-band luminosity. [CORRECT NUMBERS???] Our cluster fields double the (rest-frame) luminosity in an ACS pointing, which implies the doubling of the expected number of supernovae. More importantly, this increased luminosity is primarily from early-type galaxies. Since only 1 in 5 Type Ia supernovae were discovered in early-type galaxies in the GOODS searches, our rate of SNe in early-type hosts will be increased by a factor of five.

These 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 observations!

1.5 What is the optimal redshift range, and what limits on w_0 and w' are expected?

The two key goals of the SN Ia work at these redshifts is (1) to map the expansion history back in time to the epoch in which matter dominated over dark energy and the universe was decelerating, and (2) to use this epoch to begin to constrain the time derivative of the equation-of-state of dark energy, w', together with its value today, w_0. These measurements are most sensitive beyond $z \gtrsim 1$, but not much more is gained above $z \sim 1.7$ since then the matter density completely dominate. In this 0.9 – 1.7 redshift range, however, the magnitude distribution of a standard candle is distorted by weak-lensing amplification and deamplification due to mass concentrations in the intervening path. Linder & Holz (2004) showed that this distortion can be averaged out if sufficient SNe are averaged in one redshift bin, so all the supernovae in the $z =$ 0.9 – 1.7 range will need to be binned together for a robust measurement. We have therefore chosen the richest clusters in this redshift range for this search, and with the resulting ~10 cluster SNe Ia the statistical and systematic uncertainties due to extinction can be reduced to the level that the dashed contours of Fig. 1 can be "recovered."

2 Developing other Dark Energy Techniques using this 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 will start in the near future (e.g., South Pole Telescope Sunyaev-Zeldovich Survey, Dark Energy Survey).

These surveys, which detect clusters through a variety of techniques (from weak lensing, X-ray emission, and SZ-decrements) all require estimates for the cluster masses in order to succesfully constrain cosmological parameters. Although many of the proposed observables correlate with mass, 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 relation needs to be calibrated empirically.

2.1 Weak lensing estimates of cluster masses

Out to redshifts of $z = 0.7$, 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. At higher redshifts, space based observations are needed, driven by the need to measure the shapes of resolved *background* galaxies. Constraints on cosmology are robust provided we can determine the mass-observable relation within $\sim 5 - 10\%$ (Haiman, Mohr & Holder 2001). As described below, the proposed observations enable us to determine masses for these high redshift clusters with a relative uncertainty per cluster of 25% or better (depending on mass and redshift). In combination with archival data and ground based efforts, we can reach the required goals. [NEED MORE HERE!!!???]

2.2 Cluster masses from X-rays

X-ray observations of the intra-cluster medium also provide a robust method of estimating the virialized mass from clusters, which can be tied to cosmological models either via the X-ray luminosity function (e.g., Gioia 1991, Vikhlinin *et al.* 1998, Rosati *et al.* 2001, Nichols et al., 1999 and others) or the X-ray gas temperature (Henry & Arnaud 1991, Eke *et al.* 1998, Donahue & Voit 1999, Henry 2000). However, these methods are observationally very expensive, with current surveys to locate clusters at ~ 1 limited to small areas or only the most luminous clusters (e.g., Pierre *et al.* 2004, Ebeling *et al.* 2001). Follow-up observations to determine cluster temperatures, providing a more robust mass estimate than luminosity alone, are more costly still.

We thus rely on X-ray observations of a subsample of clusters as important calibrators for this method. Currently, ?? of our proposed X-ray selected clusters and ??? of our optically selected clusters have available 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 of at least ??? clusters spanning our complete redshift and mass range.

2.3 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 $H_0 = 60 \pm 3$ km/s/Mpc, where the error bars represent statistical uncertainty assuming a $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ cosmology. Systematic uncertainties are expected to be of order 30%, clearly dominating the statistical uncertainty (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. Comparing the SZ/X-ray distance measurements to the SNe distance measurements, we can determine the extent of systematic uncertainties in the two methods.

3 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.)

The ACS GTO team has made significant progress in understanding moderate-z galaxy clusters, which are efficient sites for the study of galaxy evolution. Postman *et al.* (2005) present results based on morphological analyses of ACS imaging of 7 clusters at $0.8 < z < 1.3$. They confirm previous work by Smith *et al.* (2004 – REF???) that a morphology–density relation exists at $z \sim 1$, but that the slope of this relation flattens from the present epoch out to high redshift. Moreover, Postman *et al.* 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 $z > 1$, to which our sample adds 20. The highest redshift of the clusters is pushed from $z = 1.26$ to $z = 1.5$.

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: **1)** determine the epochs of the assembly of ellipticals and the origin of S0s; **2)** measure the mass function of distant clusters and calibrate the relation between mass and X-ray luminosity and temperature at unprecedented redshifts; and **3)** compare the properties of clusters selected in the optical, NIR, and X-ray at redshifts $z > 1$ where clusters are first forming.

3.1 Supernovae rates and star formation

The rate of supernovae in galaxy clusters will address oustanding 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 $0.41^{+1.23}_{-0.39} h_{50}^2$ 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 could clearly use improvement.

3.2 Strong lenses at $z \gtrsim 1$

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 a 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. 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 $z \sim 7$.

3.3 The possibility of finding strongly lensed supernovae

Massive galaxy clusters are also potentially ideal gravitational telescopes to observe extremely distant supernovae, otherwise to faint to be detected (Gunnarsson & Goobar 2003). By combining the observed (lensed) supernova brightness with the weak and strong lensing cluster information, important bounds may be set on both cosmological parameters and the mass profile of the lensing cluster. In particular, the mass sheet degeneracy that arises when the mass of galaxy clusters is inferred from gravitational shear can be removed (Kolatt & Bartelmann, 1998).

Cite the more recent Bolton & Burles paper on this???

4 Conclusions

The observations proposed here will 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. These are the opening steps in bringing to maturity cosmological methods of the next generation, and the data will serve as a bedrock scientific legacy for extragalactic astronomy.

References

Blakeslee, J.P. *et al.* 2003, ApJL, 596, 143
Brighenti, F. & Mathews, W.G. 1999, ApJ, 515, 542
Broadhurst, T. *et al.* 2004, ApJ [astro-ph/0409132]
Cardelli, J.A., Clayton, G.C. & Mathis, J.S. 1988, ApJ, 329, 33
Dalal, N., Holder, G., & Hennawi, J. 2004, ApJ, 609, 50
Draine, B.T. 2003, ARA&A 41, 241 [astro-ph/0304489]
Ebeling *et al.* 2001 Fontana, A. et al. 2000, AJ, 120, 2206
Gal-Yam, A., Maoz, D. & Sharon, K. 2002, MNRAS, 332, 37
Gunnarsson & Goobar 2003, A&A, 405, 859
Ho, S. & White, M. 2004, submitted to ApJ [astro-ph/0408245]
Gladders, M.D. *et al.* 2003, ApJ 593, 48 [astro-ph/0303041]
Gladders, M. D., Hoekstra, H., Yee, H. K. C., Hall, P. B., & Barrientos, L. F. 2003, ApJ, 593, 48 [astro-ph/0303041]
Haiman, Mohr & Holder 2001

Hennawi, J. *et al.* 2005, in prep.
Hogg, D.W. *et al.* 2004, ApJ, 601, 29
Kolatt & Bartelmann 1998, MNRAS, 296, 763
Linder, E.V. & Miquel, R. 2004, Phys. Rev. D 70, 123516 [astro-ph/0409411]
Lloyd-Davies, E.J., Ponman, T.J. & Cannon, D.B. 2000, MNRAS, 315, 689
Metcalfe, L. et al. 2003, A&A, 407, 791
Pelló, R., Schaerer, D., Richard, J., Le Borgne, J.-F., & Kneib, J.-P. 2004, A&A, 416, L35
Perlmutter, S. *et al.* 1995, ApJ, 440, 41
Pierre *et al.* 2004
Postman, M. *et al.* 2005, ApJ, in press [astro-ph/0501224]
Reese, E.D., Carlstrom, J.E., Joy, M., Mohr, J.J., Grego, L., and Holzapfel, W.L. 2002, ApJ, 581, 53
Tripp, T. 1998, A&A, 331, 815

Description of the Observations

The supernova observing strategy

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 $\sim$24 days for $\sim$8 visits, with the exact cadence depending on the cluster redshift and the exact number of visits depending on HST observing constraints for the cluster. This means that every supernova that appears in these clusters during the entire period, modulo small end effects, will have a lightcurve measured — without the need for expensive Target of Opportunity (ToO) observations. We obtain ground-based spectroscopy of the supernovae's host galaxies after the fact, for precise redshifts and confirmation of elliptical galaxy type, which also confirms the SN Ia identification. For only the three highest redshift SNe, we supplement this basic lightcurve with an additional ($>$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 YYY 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 $\sim$10 SNe Ia; the previous method required $\sim$35% more orbits. Second, the number of required ToO's is reduced from 10 to 3, 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 $\sim$10 SNe not found in ellipticals. Fourth, not only will the $\sim$10 cluster SNe be supplemented by $\sim$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., $\sim$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 $\sim$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 meet the criterion that 95 % of the SNe observed will have an uncertainty in the distance modulus of less than 0.15 mag. Correspondingly, for redshifts $z > 1.4$ we use 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 Figure YYY 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. More than 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 will happen, on average, for 15 of the 25 clusters, saving 15 orbits from the total required. (The cancellations would be more than three weeks in advance, so will not introduce scheduling complications.) The total number of orbits thus required for this program is: 12 clusters x 7 planned 1-orbit ACS visits + 13 clusters x 8 planned 1-orbit ACS visits + 3 SNe x 5 NICMOS orbits (primarily TOO) + 2 SNe x galaxy-only 2-orbit ACS visit the following year -15 final cancelled orbits = 194 orbits.

[To fill in: How do we use the info from the higher-redshift clusters –IRAC and x-ray selected – to select which supernovae to follow-up with NICMOS?]

[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?]

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 [CHECK THIS NUMBER – WHAT IF WE OBSERVE ONLY 7 ORBITS SOMETIMES?] 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).

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 – taking advantage of the unique capabilities of HST.

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 the full ~ 8 orbit depth.

Figure XXX shows the expected relative uncertainty in the mass of a massive cluster with a velocity dispersion of $\sigma = 1000$ km/s. *** want to include something on the relative accuracy we get for the zeropoint of the mass-observable relation, which is the ultimate goal of this***. These results are based on a photometric redshift catalog of the UDF, under the assumption that the cluster mass profile is well described by a singular isothermal sphere model. As we proposing observations of high redshift clusters, 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 $r > 60$". We compared the outcome of this model calculation to actual published results (Jee et al. 2005; Lombardi et al. 2005) and find very good agreement. *** some of this can be moved to a figure caption if we include a figure***

Although the ACS observations provide a tremendous improvement over ground based observations (absolutely crucial for studies of high redshift clusters), they are not free from systematics. Large programs such as COSMOS and GEMS (Heymans et al 2004) show the PSF undergoing cyclic variation with a period of 15-20 days. These variations are caused by thermal fluctuations in the telescope and result in temporal variations in the PSF, which need to be corrected for. However, our team includes members with extensive expertise in this area. 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.

**** might rephrase or cut the following *** 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.

■ Strategy for Two-Gyro Observations

■ 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.