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 Higher-Z Team (Riess *et al.* 2004) and the Supernova Cosmology Project (Fadeyev *et al.* 2004) clearly point to the limiting factor for both statistical and systematic uncertainties: correction of host galaxy extinction.

We have been awarded one of the largest–ever HST programs (219 orbits) to use a new approach to the measurements in this difficult decelerating redshift range. By studying "clean" SNe discovered specifically in galaxy-cluster ellipticals, we can remove this primary statistical and systematic uncertainty. This Keck proposal is for the crucial ground-based component of this project: the spectroscopy.

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. (Note that the actual dispersion about the Hubble-line fit for $z > 1$ SNe Ia corrected for extinction matches this 0.5 mag value.)

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_B 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?

Sullivan *et al.* (2003) has 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 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

Our Cycle 14 HST search is expected to yield ~ 10 Type Ia SNe in $z \gtrsim 1$ elliptical hosts. The trick is to observe massive galaxy clusters at $z = 0.9 - 1.6$, something which is only recently possible with the identification of such clusters from large-field, deep near-infrared surveys such as RCS2 (on CFHT), mid-infrared surveys such as IRAC (on Spitzer), and X-ray surveys (such as XMM and Chandra). This sample should achieve statistical constraints equivalent to $\sim$90 SNe in later-type hosts, and avoid the aforementioned systemtic errors. The $z = 0.9 - 1.6$ redshift range provides key leverage on the cosmological model. In particular, this will provide a test of the small, suggestive shift from a cosmological constant model seen in Riess et al 2004 (see Fig. 2b shaded contour).

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

Although evidence for dust is found in about 50% of nearby elliptical galaxies, the quantity of dust 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. 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, Nakata *et al.* 2005). Recent results from HST imaging show the same strikingly small dispersion in color extends to redshifts $z \gtrsim 1$.

HST/ACS observations

There are number of systematic surveys of SNIa for nearby and intermediate redshifts (e.g. SDSS-II, SN Factory, ESSENSE, SNLS) which will give such "clean" SNIa sample eventually. But in order to measure the cosmological expansion over last 10 Gyr, we need deeper observations.

In order to find SNe Ia in elliptical hosts at $z \gtrsim 1$, we were awarded 219 orbits of HST/ACS telescope time in cycle 14 (July 2005 – June 2006). Our program consists of repeated photometry (F850LP) of 22 clusters of galaxies ($0.9 < z < 1.5$) with HST/NICMOS2 followup photometry (F110W). The resolution of HST/ACS will also provide the resolved host morphology as well as deep SN light curves. The requested 219 orbits are fully awarded (note that this is one of the largest programs in HST proposals). We will discover ~30 SNe among which ~10 SNe Ia in elliptical hosts are expected. Figure 3 shows how light curves will be continuously observed based on simulated data for the HST program, providing good targets for spectroscopy every month.

Why is LRIS the right instrument to get spectra of SNe at $z \gtrsim 1$ in elliptical hosts?

The Keck LRIS spectroscopy is requested to obtain redshifts for the SNe and/or their host galaxies, and confirm which SNe are of Type Ia. Our HST time did not include a request for spectroscopic follow-up because our experience is that this is possible for $z \sim 1$ SNe from Keck. The broad wavelength coverage of LRIS is also helpful in distinguishing Type Ia SNe from other transients.

In addition to follow-up spectrosopy of precious "dust free" SNe, we propose obtaining spectra for the other $\sim$ 10 high-redshift SNe (or their hosts) expected in this HST search. This will approximately double the number of data points on the Hubble diagram at $z > 1$.

Conclusions

The spectroscopy observations proposed here are the key gound-based component of a very large approved 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.

References

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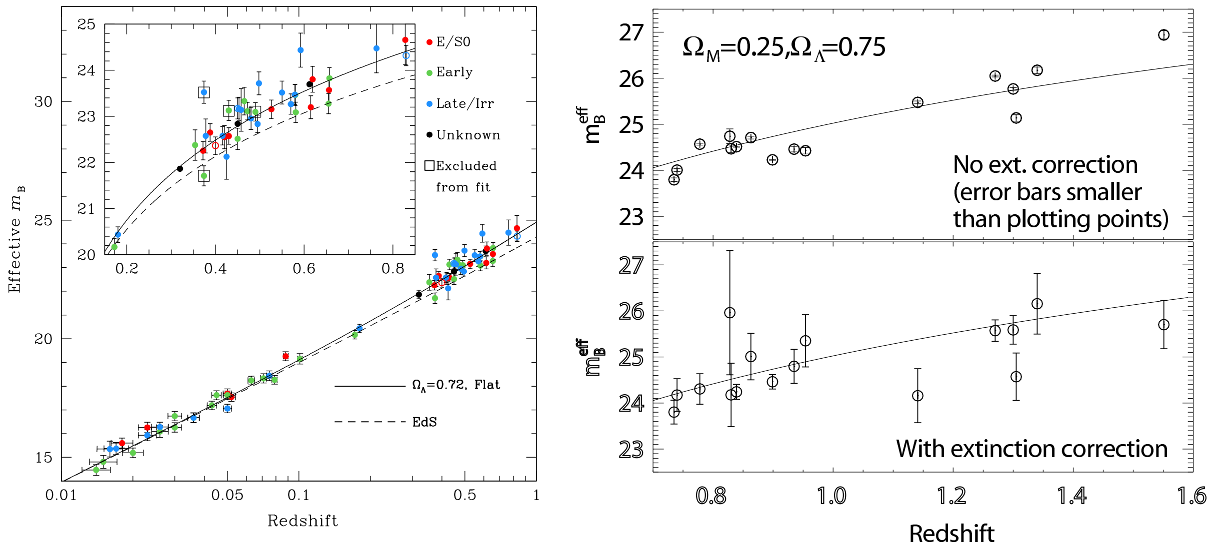

Figure 1 (a) Left Panel: The Hubble diagram for Type Ia supernovae color-coded by host galaxy type by Sullivan *et al.* (2003). The SNe in elliptical hosts (filled red circles) show significantly less dispersion, $\sigma = 0.16$ mag (including measurement error), than in other hosts. The increased scatter 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.

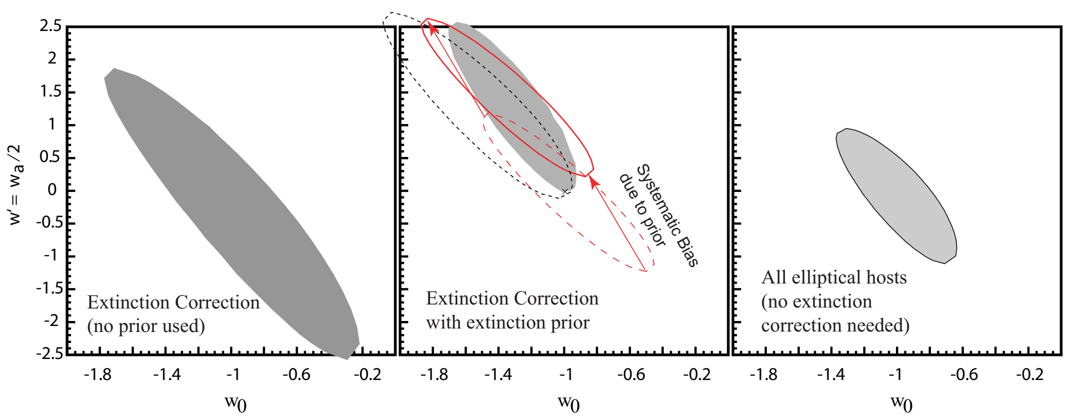

Figure 2 (a) Left Panel: Simulated 68% confidence region on w' vs w_0 for the current literature SN sample, simulated with an underlying cosmology ($w_0 = -1$; $w' = 0$). The parameters are poorly constrained because color errors are magnified by $R_B \approx 4$. **(b) Middle Panel:** The solid red contour 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).

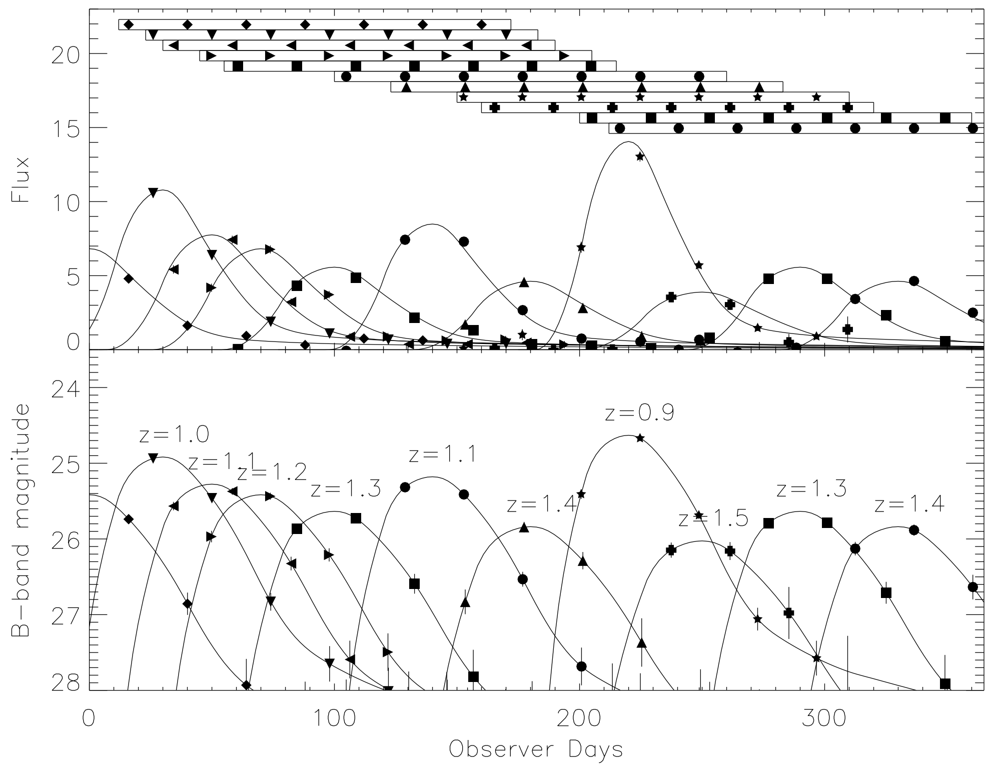

Figure 3 The simulated HST data set for this proposal, with signal-to-noise values based upon other HST supernova searches. Our lightcurve analysis program yields typical errors of 0.07 to 0.13 mag for $0.9 < z < 1.5$, including the lightcurve timescale stretch correction uncertainty. The bars and symbols at top show the observing time period and scheduled observations for each cluster (with different cadences depending on the cluster z). The same symbols are used for the observations on the lightcurves, to show where a SN might be discovered and followed in its cluster's time window. Note that the observations are well spread throughout the year.

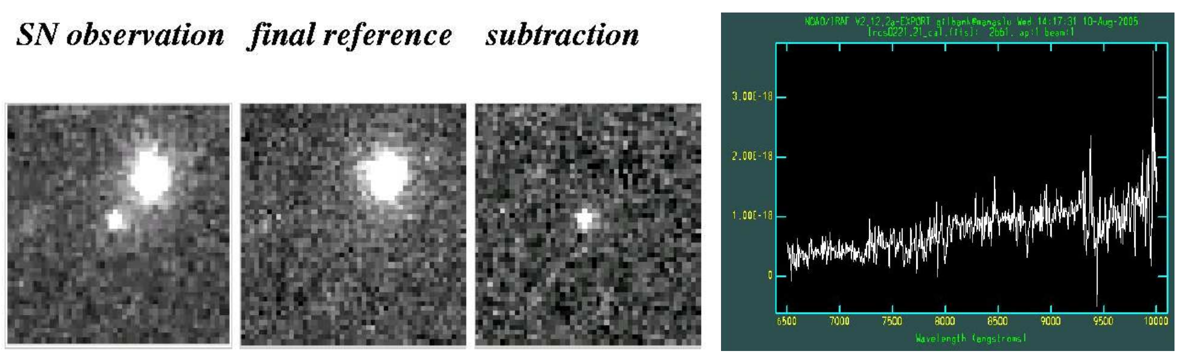

Figure 4 (a) Left Panel As an example of the technique, the above figure shows the reference, search image, and residual of the first SN discovered in the HST cluster search. The SN was found in the field centered on the spectroscopically confirmed rich galaxy cluster RCS0221-03, located at $z = 1.02$ and originally discovered by the Red Cluster Survey (RCS) team.

(b) Right Panel Spectrum of the SN host galaxy from observations prior to the HST search (courtesy of David Gilbank of the RCS team). The location of the 4000$\AA$ break corresponds to a redshift $z = 1.02$, and the spectrum is consistent with that of an elliptical galaxy, making the host a clear cluster member with little or no dust contamination.

2 Progress to Date

This is a new program.

3 Technical Justification

Targets: All of the supernovae to be observed in this proposal will be discovered in the cluster fields of the HST survey. Fourteen of these clusters are scheduled for observation this spring, accounting for 60% of the entire survey. Given the predicted rates, we expect to discover approximately six SNe hosted by cluster ellipticals, six SNe hosted by $z > 1$ field galaxies, and six SNe hosted by foreground field galaxies. All of these will be observable from Mauna Kea during the survey, and will be prioritized for follow-up spectroscopy in the order listed above. The clusters to be observed in the HST survey during the spring semester are described in the following table along with the approximate dates they are visible from Mauna Kea.

Table 1: Cluster Positions and Appoximate Observability Windows

Fields	R. A. (J2000)	Decl. (J2000)	Dates Observable	z
RDCS0848	$08^h 48^m 59^s$	$+44° 51' 57''$	2/1/06 – 4/1/06	1.27
RDCS0910	$09^h 10^m 45^s$	$+54° 22' 10''$	2/1/06 – 4/1/06	1.11
RDCS1252-29	$12^h 52^m 54^s$	$-29° 27' 18''$	2/1/06 – 5/1/06	1.23
Warps1415+36	$14^h 15^m 11^s$	$+36° 12' 03''$	2/1/06 – 7/1/06	1.03
IRAC 1113.7.7	$14^h 29^m 18^s$	$+34° 37' 26''$	2/1/06 – 7/1/06	1.21
IRAC 1012.52	$14^h 32^m 29^s$	$+33° 32' 48''$	2/1/06 – 7/1/06	1.05
IRAC 1214.5.28	$14^h 32^m 38^s$	$+34° 36' 49''$	2/1/06 – 7/1/06	1.2 – 1.4
IRAC 1012.28	$14^h 34^m 28^s$	$+34° 26' 23''$	2/1/06 – 7/1/06	1.24
IRAC 1315.12	$14^h 34^m 46^s$	$+35° 19' 46''$	2/1/06 – 7/1/06	1.37
IRAC 1416.7.15	$14^h 35^m 51^s$	$+33° 25' 51''$	2/1/06 – 7/1/06	1.4 – 1.6
IRAC 1315.5.16	$14^h 38^m 10^s$	$+34° 14' 19''$	2/1/06 – 7/1/06	1.41
RCS1511+09	$15^h 11^m 04^s$	$+09° 03' 15''$	2/1/06 – 7/1/06	1.05
CL1604+4304	$16^h 04^m 23^s$	$+43° 04' 38''$	2/1/06 – 8/1/06	0.92
RCS2319+00	$23^h 19^m 53^s$	$+00° 38' 14''$	7/1/06 – 8/1/06	0.91

Supplementary Observations: We are using 219 orbits of HST for a rolling search of supernovae in 22 galaxy clusters at $z > 0.9$. Typically, we observe each cluster with the ACS F850LP filter every 20-26 days for 8 visits. These observations are used both to discover SNe, and follow their lightcurves. For the three highest-redshift SNe, we will supplement these data with an infrared lightcurve from HST (using triggered ToO observations with NICMOS).

Our expectation is to discover 10 SNe in elliptical hosts at $z > 1$, and 20 SNe in the field. The search has begun on six of these clusters. As expected, we have already found one SN in a cluster at $z = 1.02$ (Fig. 4) and two SNe in the field at an unknown redshift.

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 > -30 deg. 13 of our 22 clusters are in the right ascension range $12^h < \alpha < 16^h$. Another, at a right ascension of $23h$, is visible from Mauna Kea at the end of the spring 2006 semester.

In addition to HST time, we were awarded five nights of spectroscopic time on the Subaru telescope during the spring semester.

Exposures: Our exposure times are based on experience of Keck LRIS observations of high-z SNe. Under average conditions at Keck, a SN Ia at $z = 1$ requires a total of 2 hours of exposure for a reliable classification and redshift. At higher redshifts, our experience from SN Albanoni at $z = 1.20$ is that nearly a full night of observing will be required for $z > 1.2$.

Telescope Time Requested: We have requested 2 nights of telescope time to observe a total of two to four $z > 1$ SNe, and several SNe at lower-redshift. We request that the Keck scheduler consult with us, such that we can coordinate the dates appropriately with the HST schedule and our Subaru follow-up time.

Although many of the SNe will have spectra peaking at red wavelengths, important spectral features (e.g. metallicity indicators) extend down to observer-frame V and R-band. Therefore, these observations can not tolerate too much contamination from moonlight, and we request time within 7 days from new moon.

Instrumentation: We request the LRIS spectrograph because of its efficiency and broad wavelength coverage. We will use the 400l/8500A grating (cen=7500A) in the red, and the 600/4000A grism in the blue with the 560nm dichroic.

Note that we have developed a spectroscopic reduction package (*Longslit*, together with Scott Burles and Joe Hennawi) in order to make optimal use of the LRIS instrument.

It should be noted one of the reasons we are choosing LRIS is out of consideration for competition from many proposals on Keck II. Given the performance of ESI, especially in the far red, we would be equally happy to be awarded time with that instrument on Keck II if the schedule permits.

Backup Program

If transparency or seeing precludes spectroscopy at $z > 1$ we will observe the lower redshift SNe that are found in the field. Redshifts and spectral typing of the host galaxies will also be possible.

Path to Science from Observations

We will use spectral lines of the host galaxy to determine the redshift. These lines, whether seen in emission (e.g. OII 3727Å) or absorption (e.g. Ca II H & K), can be identified even when the SN and galaxy light are blended, because the galaxy lines are much narrower than the SN lines. In cases where there is no significant light from the host, redshifts will come from the supernova spectrum itself.

The data are reduced using custom-written software, including an implemetation of a 2-dimensional B-spline sky-subtraction technique. The SN spectra are then compared with those of nearby SNe to ascertain the SN type.

The Keck redshifts will be used along with rolling photometry from HST to plot the Keck 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.

The analysis of these SNe should be significantly easier than other samples because the host, elliptical galaxies are expected to contribute very little reddening and extinction. In previous SNe work, those extinction-corrections have proven to be one of the most difficult aspects of the analysis.

Technical Concerns

The Keck SN candidate spectroscopy runs must be coordinated with the HST search cadence, so please contact us before scheduling.

Experience and Publications

Our group has extensive experience with faint object spectroscopy on telescopes around the world, and with LRIS and ESI 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.