1 Scientific Justification

A key goal of observational cosmology this decade is the detailed, accurate measurement of the universe's expansion history, from deceleration through acceleration, to look for clues of the properties and identity of dark energy. Of the small handful of known measurement techniques, only Type Ia supernovae (SNe Ia) have actually been developed to the point of routine use. Initial studies of the decelerating universe using SNe at $z \gtrsim 1$ by both the Supernova Cosmology Project (Fadeyev *et al.* 2004) and the Higher-Z Team (Riess *et al.* 2004) clearly point to the limiting factor for both statistical and systematic uncertainties: correction of host galaxy extinction.

With one of the largest HST cycle 14 programs, we are successfully demonstrating a new and efficient approach to the measurements in this difficult decelerating redshift range. By discovering and studying "clean" SNe in galaxy cluster ellipticals, we reduce systematic and statistical uncertainties (each of these SNe is worth up to *nine* SNe in spirals) — and do so with a more efficient use of HST time. We have obtained lightcurves of 5 $z > 1$ SNe using 81 orbits, which is more than twice the rate of previous GOODS surveys using HST. In addition to those 5 $z > 1$ SNe, we are currently observing 3 SNe that are possibly at equally high redshift and are awaiting spectroscopic confirmation. At the time of writing, we have 105 orbits remaining in cycle 14 and have requested another 217 orbits for cycle 15. Here we propose to complete spectroscopic observations of SNe and hosts for the HST cycle 14 program using LRIS on Keck I, and if awarded additional HST time, to extend those observations to include SNe discovered during HST cycle 15.

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

The correction for the extinction of SNe from dust in the host galaxies is currently the single dominant source of both statistical and systematic error for SNe distances and the derived cosmological parameters – dramatically so at $z > 1$ (see Figure 1b). The color uncertainties for well-measured SNe at $z > 1$ is $0.08 - 0.1$ in $B - V$, leading to uncertainties in extinction correction (after accounting for intrinsic color uncertainty) of >0.4 mag! This dispersion grows worse, $\sigma \approx 0.5$, after accounting for the uncertainty in the dust reddening coefficient, $R_B \equiv A_B/E(B-V)$, which Draine (2003) notes can vary from the fiducial value 4.1 by ± 0.5. Recent studies of nearby SNe Ia (Altavilla *et al.* 2004, Reindl *et al.* 2005) are consistent with large dispersions of R_B.

To correct for dust extinction, one needs either exquisite multi-band color information or a Bayesian prior on *a*) the mean and probability distribution of R_B and *b*) the probability distribution of the amount of dust. If even just one of these priors is redshift dependent, the final result will be systematically biased. The effect of varying R_B can be seen in Fig. 2b as the difference between full and the short-dashed contour. Likewise, if the observation quality depends on redshift (as is often the case) significant biases can result, as shown by the difference between the full and the long-dashed contour of Fig. 2b (Perlmutter *et al.* 1999). If aggressive Bayesian priors are chosen, the systematic errors outweigh the statistical errors.

How is this problem solved using SNe Ia in ellipticals?

Sullivan *et al.* (2003) demonstrated that the dispersion (including ground-based measurement error) about the Hubble diagram for elliptical-hosted SNe is 0.16 mag — three times smaller than the measurement uncertainty for extinction-corrected SNe Ia at $z > 1$ — primarily due to the absence of dust. (Preliminary studies of the new, larger SNe sample from the CFHT SNe Legacy confirm this observation.) Thus, SNe Ia in ellipticals are statistically each worth ∼9 SNe in spirals when making cosmological measurements

Our Cycle 14 search is expected to yield ~ 10 Type Ia SNe in $z \gtrsim 1$ elliptical hosts. We observe massive galaxy clusters at $z = 0.9 - 1.6$, only recently possible since the identification of such clusters from large-field, deep optical surveys such as RCS2 (on CFHT), mid-infrared surveys such as IRAC (on Spitzer), and X-ray surveys (XMM and Chandra). One year of SNe discovered from this sample of clusters should achieve statistical constraints equivalent to ∼90 SNe in later-type hosts, and avoid the aforementioned systematic errors. In particular, this will provide a test of the small, suggestive shift from a cosmological constant model seen in Riess et al 2004 (Fig. 2b).

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

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

Current Status of HST/ACS observations

To find SNe Ia in elliptical hosts at $z > 1$, we were awarded 219 orbits of HST time in cycle 14. Our program consists of repeated photometry (ACS F850LP and F775W) of 24 clusters of galaxies ($0.9 < z < 1.5$) with NICMOS followup photometry (F110W). The resolution of HST/ACS will provide the resolved host morphology as well as deep SN light curves. In the first 81 orbits of our HST program we discovered 4 new SNe in $z > 1$ ellipticals, and 1 new SN in a $z > 1$ cluster-member spiral (plus additional $z < 1$ SNe, Fig. 3). In the most recent 33 orbits, we have discovered 5 active SNe, three of which are believed to be at $z > 1$ but need spectroscopic confirmation. The remaining 105 orbits in HST cycle 14 continue until Oct. 2006. As can be seen in Figure 3, these observations provide good targets for spectroscopy every month for Keck observations. We have also requested another year of HST time which, if awarded, will continue from July 2006 until Oct. 2007.

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 program does not include time for spectroscopic follow-up because observing $z \gtrsim 1$ SNe has been proven successful from Keck. The broad wavelength coverage of LRIS also aids 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 ∼ 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 $z > 1$. We plan to fully utilize the slitmask capability of LRIS to include observations of galaxies that are suspected cluster members. These data will be shared with the members of our collaboration who are responsible for the initial discovery of these high redshift clusters.

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.

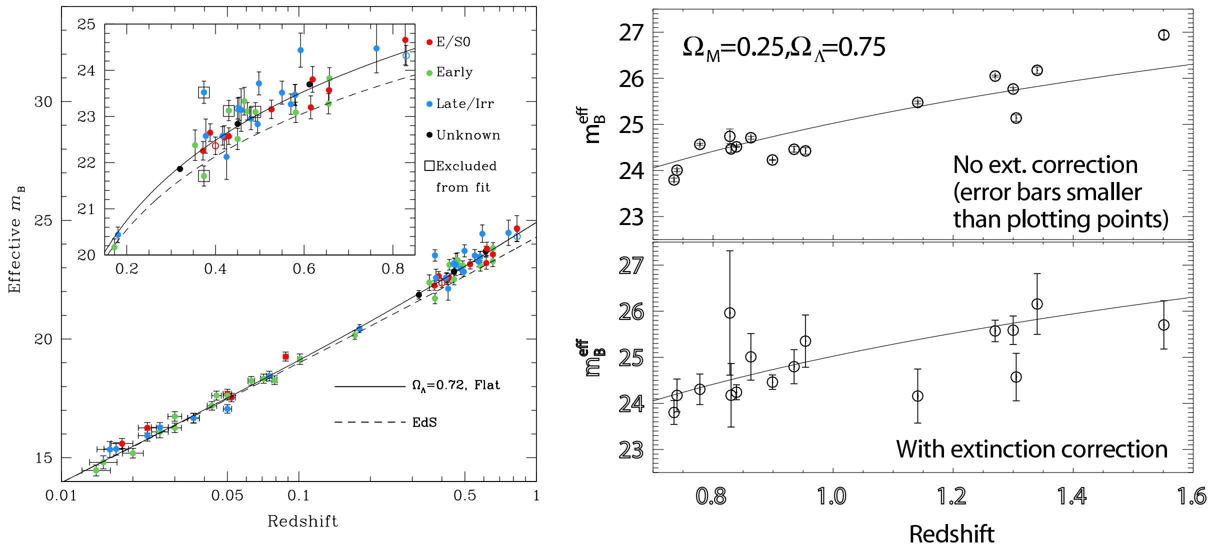

Figure 1 (a) Left Panel: The Hubble diagram for Type Ia supernovae color-coded by host galaxy type by Sullivan *et al.* (2003). The SNe in elliptical hosts (filled red circles) show significantly less dispersion, $\sigma = 0.16$ mag (including measurement error), than in other hosts. The increased scatter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

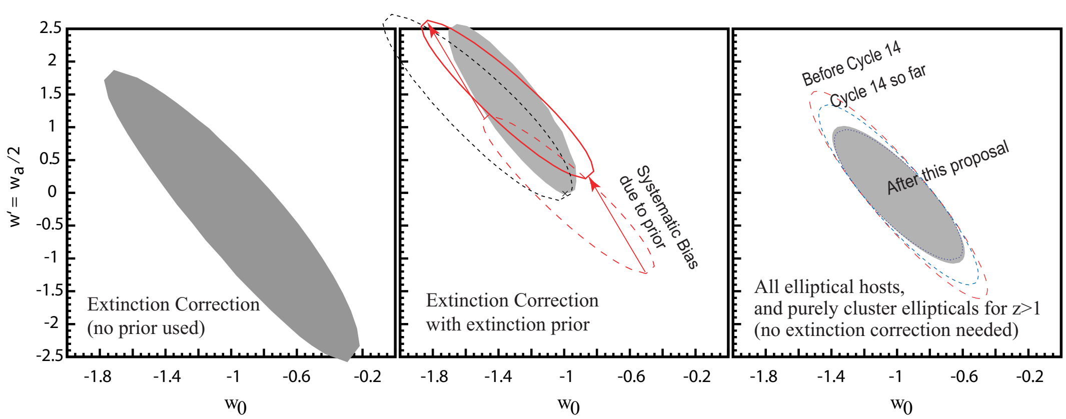

Figure 2 (a) Left Panel: Simulated 68% confidence region on w' vs w_0 for the current literature SN sample but with underlying cosmology ($w_0 = -1$; $w' = 0$). The parameters are poorly constrained because color errors are magnified by $R_B \approx 4$. **(b) Middle Panel:** The solid red contour shows reduced uncertainties (excluding systematic bias) using a Bayesian prior on the extinction distribution prior to suppress color errors. The short-dashed contour shows that this approach is sensitive to precise knowledge of R_B and its variation with redshift; the example shifts from 4.1 to 2.6. Similarly, asymmetric priors can also introduce systematic biases (arrows). The filled gray contour is from Riess *et al.* 2004 using such a prior. **(c) Right Panel:** Simulated 68% region for the proposed new set of ~ 20 $z \gtrsim 1$ SNe Ia found in cluster ellipticals (from Cycle 14 & 15) if combined with 120 SNe Ia in ellipticals at the lower redshifts now being produced by the ground-based CFHT SNe Legacy Survey, the CTIO Essence survey, and (at $z < 0.1$) the Nearby SNe Factory. This approach addresses the large statistical error problem of panel (a) and the systematics problem of panel (b). The projected constraints from the ground-based surveys alone are given by the the outer contour, and the constraints from adding the 3 cluster-elliptical SNe found so far in the first third of Cycle 14 are the dashed contours. The almost-imperceptably-smaller innermost (dotted) contour shows the effect of adding $\sim$ 10 SNe in *field* ellipticals (if one is willing to risk using them at $z > 1$ along with the *cluster* ellipticals), also expected from Cycle 14 and 15 as well as from previous GOODS surveys.

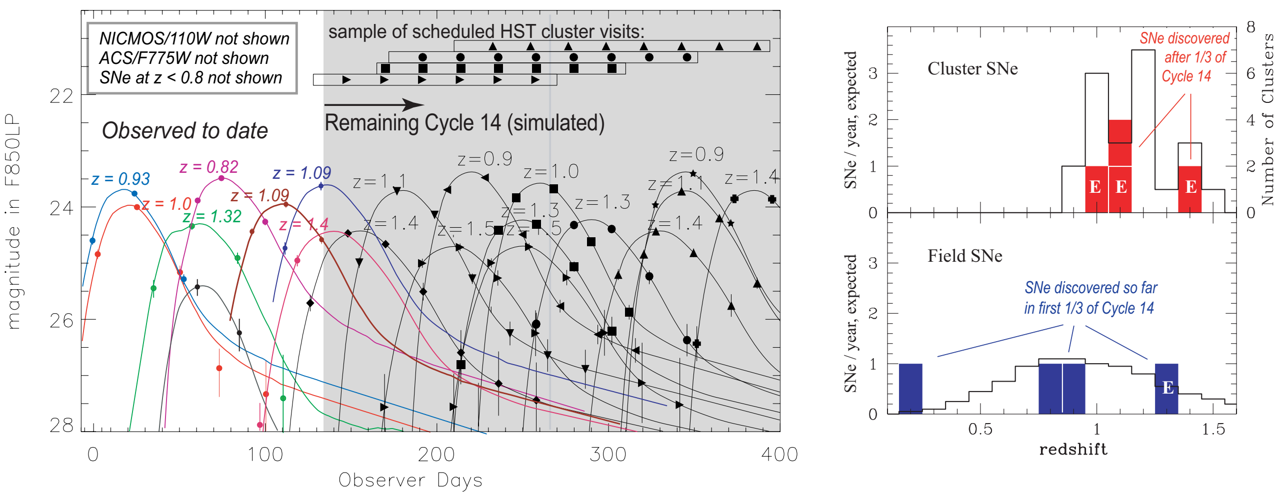

Figure 3 (a) Left Side: The unshaded region to the left displays the preliminary lightcurves of the 8 SNe discovered in the first third of Cycle 14, while the shaded region shows simulated data for the remaining two-thirds. With our chosen cadence, which is also proposed for cycle 15, we obtain typical fit peak magnitude total uncertainties of 0.07 to 0.15 mag, including the lightcurve time 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. **(b) Right Side:** The upper panel shows the redshift distribution of the expected number of SNe per year in the clusters (left axis) and the number of clusters being searched (right axis). The actual cluster SNe that have been found and confirmed in the first 81 orbits of our Cycle 14 program are indicated by filled boxes (E indicates an elliptical host.) The lower panel shows the redshift distribution of the expected number of SNe per year in the field, with the actual field SNe discovered so far indicated by filled boxes.

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2 Progress to Date

This large program (219 HST cycle 14 orbits) has been very successful so far as is shown in Figure 3. Redshifts found in figure 3 were obtained in multislit observations of galaxy clusters using LRIS on Keck, FOCAS on Subaru, and FORS2 on VLT. The Keck follow-up program started in semester 2006A, with two nights being awarded. On Feb. 1 we observed a SN and host using a slitmask to obtain redshifts of other galaxies in the cluster as well. We obtained a low signal-to-noise spectrum of the host that was consistent with the cluster redshift of $z = 1.41$. The second night is scheduled for June 25. These data will be published along with the results of the first year of the HST cluster supernova search. The data from the other targets in the slitmask will be used and published by several of our collaborators as part of their study of galaxy clusters discovered with the IRAC instrument on Spitzer telescope.

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. Five of these clusters are scheduled for observation this fall, accounting for 21% of the entire survey, with another 15 to be observed if granted time for HST cycle 15. Given the predicted rates, we expect to discover approximately two (five) SNe hosted by cluster ellipticals, two (five) SNe hosted by $z > 1$ field galaxies, and two (five) SNe hosted by foreground field galaxies, depending on the award status of the cycle 15 proprosal. SNe discovered in the HST search will be prioritized for follow-up spectroscopy in the order listed above. The clusters to be observed in the HST survey during the fall semester are described in Table 1 along with the approximate dates they are visible from Mauna Kea. The * denotes those clusters that will be searched for SNe if awarded time for the cycle 15 HST proposal.

Supplementary Observations: We are using 219 orbits of HST for a rolling search of supernovae in 24 galaxy clusters at $z > 0.9$. Typically, we observe each cluster with the ACS F850LP and F775W filters every 20-26 days for 8 visits. These observations are used both to discover SNe, and follow their lightcurves. For the 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 cycle 14 search is approximately half complete. As expected, we have found five SNe at $z > 1$ and currently have 3 active SNe that are believed to be at comparably high 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 fall clusters are all visible from Keck at declinations > -40 deg. 5 of our 24 clusters are in the Right Ascension range $21^h < \alpha < 24^h$. Another 16 clusters will be observed with HST beginning July 1 if we are awarded time in HST cycle 15. Due to the random timing of discoveries and the cadence of HST observations governing follow-up spectroscopy, we have found that no single observatory can observe all the SNe over the 6 month period. In addition to observations with LRIS on Keck, we are requesting time at Subaru and VLT as we have done in the Spring 2006 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 SNe such as SN1998eq at $z = 1.20$ and S02-035 at $z = 1.40$ is that nearly a full night of observing will be required for higher redshift SNe.

Telescope Time Requested: We request a total of 4 nights of telescope time. Two nights are requested for observations of two to four $z > 1$ SNe and several SNe at lower-redshift to complete

Table 1: Cluster Positions and Appoximate Observability Windows

Fields	R. A. (J2000)	Decl. (J2000)	Dates Observable	z
RCS2156-04	$21^h 56^m 42^s$	$-04° 48' 04''$	8/1/06 – 11/19/06	1.07
RCS2319+00	$23^h 19^m 53^s$	$+00° 38' 14''$	8/1/06 – 12/10/06	0.91
RCS2345-36	$23^h 45^m 27^s$	$-36° 32' 50''$	8/1/06 – 11/4/06	1.04
XMM2205-01	$22^h 05^m 50^s$	$-01° 59' 30''$	8/1/06 – 11/25/06	> 1.4
XMM2235-25	$22^h 35^m 20^s$	$-25° 51' 34''$	8/1/06 – 11/10/06	1.39
*RCS0220-03	$02^h 20^m 55^s$	$-03° 33' 19''$	8/10/06 – 1/20/07	1.03
*RCS0221-03	$02^h 21^m 41^s$	$-03° 21' 47''$	8/10/06 – 1/20/07	1.02
*IRAC0223-04	$02^h 23^m 03^s$	$-04° 36' 18''$	8/10/06 – 1/20/07	1.2
*RCS0337-28	$03^h 37^m 50^s$	$-28° 44' 28''$	9/15/06 – 1/20/07	1.1
*RCS0439-29	$04^h 39^m 38^s$	$-29° 04' 55''$	10/1/06 – 2/1/07	0.95
*RDCS0848+44	$08^h 48^m 59^s$	$+44° 51' 57''$	11/1/06 – 2/1/07	1.27
*RDCS0910+54	$09^h 10^m 45^s$	$+54° 22' 10''$	11/1/06 – 2/1/07	1.11
*RDCS1252-29	$12^h 52^m 54^s$	$-29° 27' 18''$	1/20/07 – 2/1/07	1.23
*Warps1415+36	$14^h 15^m 11^s$	$+36° 12' 03''$	1/15/07 – 2/1/07	1.03
*IRAC 1113.7.7	$14^h 29^m 18^s$	$+34° 37' 26''$	1/15/07 – 2/1/07	1.2
*IRAC 1012.52	$14^h 32^m 29^s$	$+33° 32' 48''$	1/15/07 – 2/1/07	1.05
*IRAC 1214.5.28	$14^h 32^m 38^s$	$+34° 36' 49''$	1/15/07 – 2/1/07	1.2 – 1.4
*IRAC 1012.28	$14^h 34^m 28^s$	$+34° 26' 23''$	1/15/07 – 2/1/07	1.24
*IRAC 1315.12	$14^h 34^m 46^s$	$+35° 19' 46''$	1/15/07 – 2/1/07	1.37
*IRAC 1416.7.15	$14^h 35^m 51^s$	$+33° 25' 51''$	1/15/07 – 2/1/07	1.4 – 1.6
*IRAC 1315.5.16	$14^h 38^m 10^s$	$+34° 14' 19''$	1/15/07 – 2/1/07	1.41

the cycle 14 program. In addition, these 2 nights will be used to obtain final reference images of host galaxies from previously observed cycle 14 SNe. We request an additional 2 nights of telescope time, pending approval of our HST cycle 15 time. We expect to hear the results from our cycle 15 proposal in early April and will notify the Keck TAC as soon as we hear the final decision. We request that the Keck scheduler consult with us, so 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 400/8500A grating (cen=8200A) in the red, and the 300/5000A grism in the blue with the 680nm dichroic.

Note that we have developed a spectroscopic reduction package (together with Scott Burles and Joe Hennawi) in order to make optimal use of the LRIS instrument. It should also be noted that we are working on this HST program as part of a large collaboration, many members of which are specifically involved with cluster research. We plan to integrate additional targets chosen by these members into slitmask observations in order to obtain information regarding the properties of other members of the cluster hosting the SN. We believe these observations will help to make optimal use of the time on LRIS.

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

Technical Concerns

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 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.

Status of Previous Related Keck Programs

We were awarded two nights in the Fall 2005 semester to follow-up host galaxies from a fall 2002 SNe search using Subaru telescope. These targets were observed on Dec 2 after poor weather prevented observations on the previous night. These data will be published as part of an analysis on the SNe discovered in the Subaru search. We also used this time to target a z=1.31 SN host and nearby galaxies using a slitmask but poor weather prevented us from achieving the required signal to noise in those observations.