

# 1 Scientific Justification

The key goal of the most ambitious cosmology projects being designed or built 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: extinction correction of the host galaxy.

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 typical color uncertainties for  $z > 1$  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  $\pm 0.5$ . 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?

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  $\sim 10$  SNe Ia at  $z \gtrsim 1$  entirely in cluster elliptical host galaxies, to achieve the statistical constraints of  $\sim 90$  SNe in later-type hosts. (This sample’s statistical strength is thus a good match for the comparison and systematics studies of the past and ongoing HST/GOODS-searches’ non-elliptical sample.) This proposed ellipticals-only sample would yield the stronger constraints on  $w$  vs.  $w'$  shown in Fig. 2c — without extinction prior systematics. In particular, this would provide a test of the

small, suggestive shift from a cosmological constant model seen in Riess et al 2004 (Fig. 2b shaded contour). Note that the  $z = 0.9 - 1.6$  redshift range provides key leverage of the cosmological model, especially constraints on the dark energy time variation  $w'$ .

### **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 10Gyears, 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). We proposed repeated photometry (F850LP) of 22 clusters of galaxies ( $0.9 < z < 1.5$ ) with HST/NICMOS2 followup photometry (F110W). HST/ACS is the best instrument since these observations will also give us 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  $\sim 30$  SNe among which  $\sim 10$  SNe Ia in elliptical hosts are expected. Fig.3 shows how light curves will be continuously observed based on simulated data for the HST program, providing good targets for spectroscopy every month.

### **WRITE FOR KECK Why is FOCAS the right instrument to get spectra of SNe at $z \gtrsim 1$ in elliptical hosts?**

In order to get spectra of SN candidates to classify SN type, and in order to get the redshifts of the SNe and/or their host galaxy, we are requesting Subaru follow-up spectroscopy. HST/ACS grism observations give SNe Ia spectra at  $z \gtrsim 1$  (Riess et al. 2004, Gibbons et al. 2005), but good ground-based telescopes can also give those (Lidman et al. 2004). Fig.4 shows an example that Subaru/FOCAS gave a similar spectrum as HST/grism did. Our previous experiences show that the success rate of FOCAS spectroscopy of high- $z$  SNe is quite high even among other 8–10-m class telescopes. Superb image quality of Subaru/FOCAS is a very important factor of deep spectroscopy of point sources. Also the study of SNe in high redshift galaxies is made possible by having a detector with excellent sensitivity and very low fringing in the red, such as as the MIT-LL CCD in FOCAS. The wide wavelength coverage of FOCAS is also helpful in distinguishing SNe from other transients. Although we have 219 HST orbits, no grism observations are included. Hence we definitely need Subaru/FOCAS to follow precious "dust free" SNe Ia and obtain the redshift of host galaxies.

### **Conclusions**

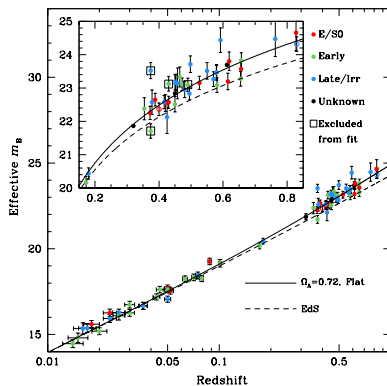
The spectroscopy observations proposed here are the key ground-based component of a very large approved HST program using known approach to SN measurements which will provide a first significant, *and unbiased* measurement of  $w_0$  vs.  $w'$ . The emphasis on high redshift and attention to systematics 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.

## Figures & References

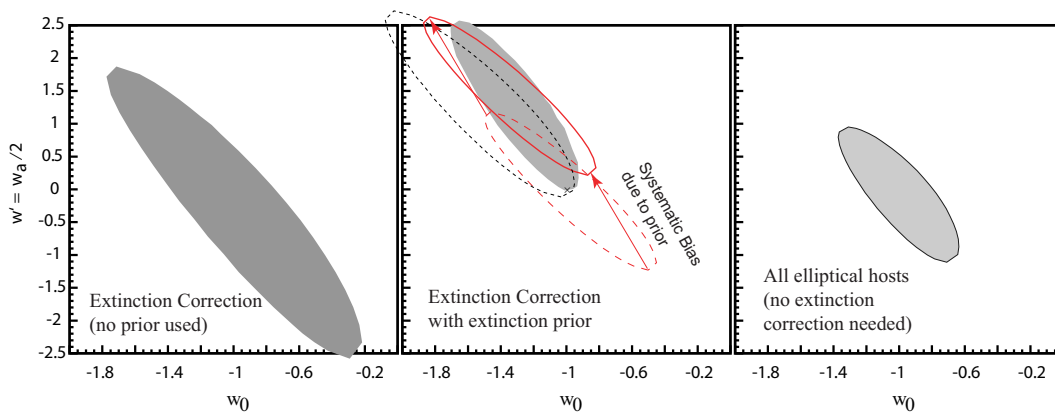
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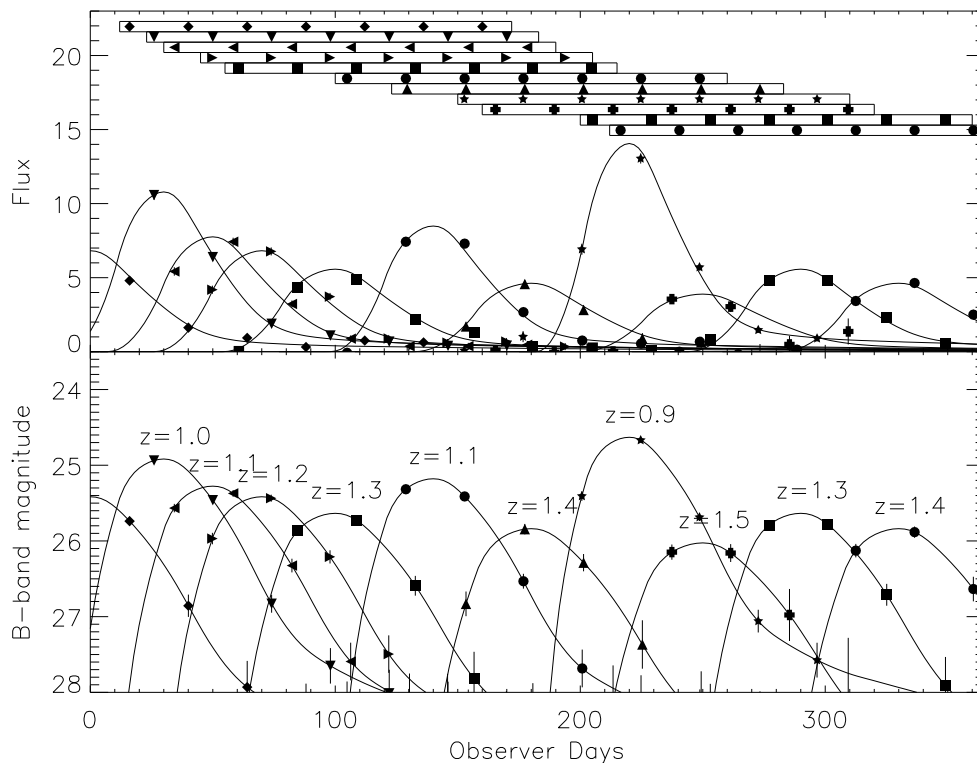
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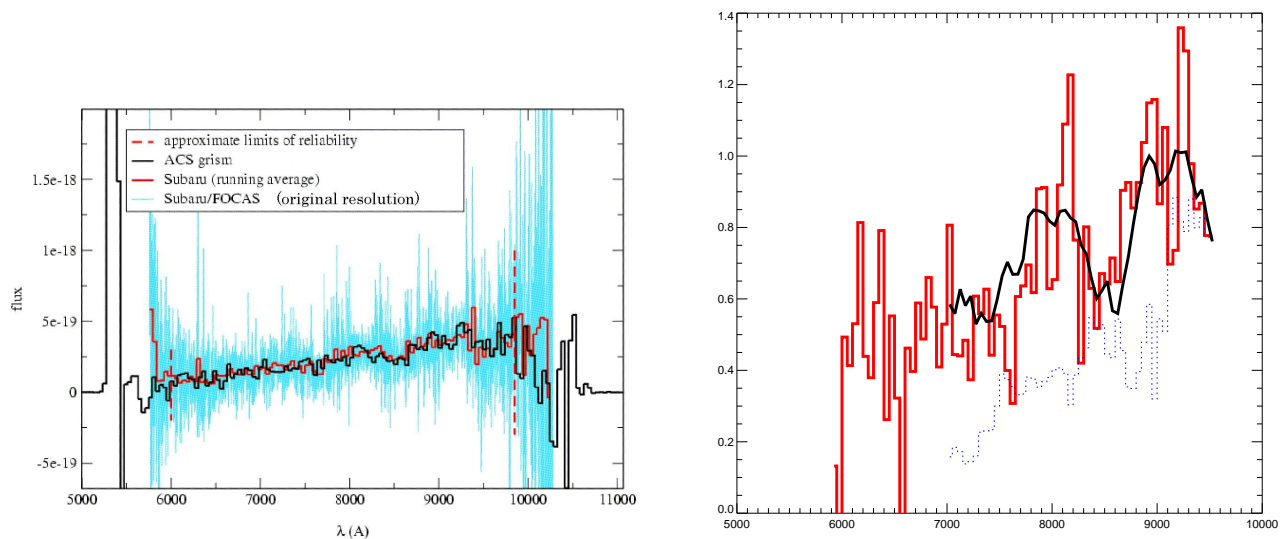
**Figure XXX:** (a) **Left Panel:** The SCP SN Ia Hubble diagram broken into host galaxy types from Sullivan *et al.* (2003). The SNe in elliptical hosts (filled red circles) show significantly less dispersion,  $\sigma = 0.16$  mag, including measurement error. (This ground-based measurement error for 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  $\sim 0.5$  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.



**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. 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  $\sim 10$   $z \gtrsim 1$  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** The simulated HST data set for this proposal, with signal-to-noise at a given redshift and SN epoch based on our previous SN from HST/ACS and HST/NICMOS. The simulated data was fit with our lightcurve analysis program to test the cadence feasibility. We obtain 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 (allowing easy HST scheduling, with flexibility since there are other clusters to study if one is difficult to schedule). There are therefore SNe to be observed in this proposed Subaru observing program at almost any time, in addition to the host galaxies that can be observed any time.



**REDO FOR KECK Figure 4 (a) Left Panel** Comparisons of spectra of SN2002lc ( $z \sim 1.28$ ) which was found with Suprime-Cam rolling searches (S02B-IP-04). The black line shows a spectrum of SN2002lc taken with HST/ACS G800L grism observations with  $\sim 12000$  sec exposures. The blue line shows a spectrum of the same SN taken with Subaru/FOCAS spectroscopy with  $\sim 7200$  sec exposures, and the red line is the same FOCAS data but binned to a similar spectral resolution to that of ACS grism spectrum. ACS and FOCAS spectra agree quite well within the reliable wavelength range shown in dashed red lines. FOCAS observation date was Nov.12, 2002 which was 5 days earlier than ACS observations. This comparison clearly shows that FOCAS is one of the best instrument in the world to take faint SN spectra. Of course, to see the comparison to a SN spectrum, it is necessary to subtract the host galaxy, as is shown in the right panel. **(b) Right Panel** After a combined SN/host galaxy fit, the SN spectrum of SN2002lc is shown in red line and the host galaxy contribution is shown in the dotted blue line. For comparison, a template spectrum from SN1990N at -7 days is shown overlain (black line.)

## 2 Progress to Date

Prior to fall 1998 we concentrated on mid-redshift SNe Ia and we returned to that work with our SNLS/Keck program, begun in 2003A. The 1995-1997 portion of the mid-redshift cosmological program was published in Perlmutter *et al.* 1999 and the following portion, including 11 SNe Ia observed with Keck and *HST*, published in Knop *et al.* 2003. The cosmological results from the 11 SNe in Knop *et al.* are in close agreement with results from the first supernova results (Perlmutter *et al.* 1999) that gave direct evidence for a cosmological constant. In addition, the greatly improved color measurements of the *HST*-observed SNe allowed us to individually correct each SN for host-galaxy extinction and no anomalous negative  $E(B-V)$  values were found for the high-redshift SNe.

In addition to the recent Knop *et al.* paper, we have published results based on this project’s Keck measurements on the study of SN Ia variations over time/redshift. In Sullivan *et al.* (2003) we presented new results on the Hubble diagram of SNe Ia as a function of host galaxy morphology that demonstrates that host galaxy extinction is unlikely to systematically dim distant SN Ia in a manner that would produce a spurious cosmological constant. This result was based on Keck spectroscopy and *HST* STIS “snapshot” images of SNe spanning the range  $0.3 < z < 0.8$ . In Pain *et al.* (2002) we presented the changing SN Ia rates in the redshift range  $z \sim 0.65$ , which constrain the models for SN Ia progenitors.

Between fall 1998 and fall 2002 we concentrated on the highest redshift SNe Ia. We built up the foundations for this work beginning in October 1998 with our very successful pilot study using Keck LRIS imaging and spectroscopy in order to demonstrate that SNe Ia up to  $z = 1.2$  could be found and studied using existing facilities. SN 1998eq at  $z = 1.200$  was the key discovery from this run, and we obtained its complete *I*-band and *J*-band light curves using *HST* (Aldering *et al.* 1998). Completion of the analysis of this supernova had been held up by the need for final reference NICMOS images, but with the refurbishment of that instrument in 2002, we have been able to obtain the images (with a few still pending) and final analysis is nearing completion.

We have now returned to our intermediate-redshift SN work using the CFHT Legacy Survey SN component (SNLS). The SNLS began in semester 2003A in pre-survey mode, the full survey commencing August 2003. As of August 2004 (i.e. one full year of survey operation), SNLS has located *and spectroscopically confirmed* over 100 well-sampled type Ia SNe (Fig. 2), with multi-epoch and multi-color light-curves (Fig. 3). The survey now routinely provides 8-10 SN Ia candidates per field per month which require spectroscopic follow-up (see “Technical Justification” for details of the survey).

Our Keck 2004A time allocation made an invaluable contribution to the co-ordinated SNLS follow-up, screening 18 SN candidates in the EGS (see Fig. 4 for example LRIS/DEIMOS spectra). The Keck was the crucial telescope for this work since the EGS is only visible from the north. The spectra are fully reduced using our custom-written software, and 15 of the candidates have been identified; work continues on the remaining 3 objects. (see “Status of Previously Approved Keck Programs”). As a direct result of the Keck allocation, SNLS was able to follow-up all candidates of interest during the allocated months, an essential step in the generation of a Hubble diagram. As the survey is a rolling search, reference images are already available for all of these confirmed SNe, and multi-color light-curves have already been measured. In partnership with SNLS, we are in the process of developing the sophisticated fitting software required to place these objects on a Hubble diagram; cosmological results should emerge within the next 6-12 months.

### 3 Technical Justification

**Supplementary Observations:** The SN program of CFHTLS (SNLS), currently the largest high-redshift SN survey, is a much larger program than our previous searches, and offers the unique opportunity to continue SNeIa cosmological studies with greatly increased statistics and even greater reliability. SNLS is a well-established five-year rolling SN search program, observing four  $1 \times 1 \text{ deg}^2$  fields in Sloan  $g$ ,  $r$ ,  $i$  and  $z$  filters every 4 nights (observed frame; 2–3 nights rest-frame) during dark/gray time using MegaCam on CFHT. Each field is followed for 5 continuous months in every year. Exposure times of 20m, 30m, 60m and 60m per band per epoch provide SN discoveries and almost real-time well-sampled multicolor lightcurves for SNeIa in the redshift range 0.2 to 0.9 (with discoveries up to  $z \sim 1.2$ ). Photometric redshifts for host galaxies, combined with a sophisticated color screening of the SNe candidates, allows SNLS to eliminate AGN and other variable non-SN sources from the spectroscopic target list. Further screening based on the real-time light-curves allow separation of candidates into probable type Ia and core-collapse (II, Ib/c) sub-groups. In any given month, 8-10 SN Ia candidates per field require spectroscopic analysis.

Clearly, in a survey of this magnitude, the spectroscopic time allocation required to follow all candidates exceeds the capacity of any one group or nation; consequently many large telescopes contribute to the substantial follow-up program. *In the “A” semesters, Keck plays a pivotal role in this follow-up campaign*, measuring redshifts and tell-tale SN Ia features for the highest redshift SNeIa in the SNLS northern-most field — at this declination, a role only it can perform with the quickness and reliability to keep up with the high SNLS discovery rate.

#### Targets:

**Exposures:** *All of our exposure times are based on our extensive experience of real Keck observations of high- $z$  SNe.* Although the SNLS candidate weighting scheme selects against core-collapse SNe and AGN, inevitably some of these will pass through to our list of candidates, and so when estimating the number of SNeIa we will confirm, we include a  $\sim 20\%$  allowance for these interlopers. Under average conditions at Keck a SN Ia at  $z \sim 0.5$  requires an exposure of about 30 min to produce a classification-quality spectrum. A SN Ia at  $z \sim 0.9$  requires 4-5 30 min exposures to produce a reliable redshift and a classification somewhere between probable and certain. The  $z \sim 0.9$  SNeIa are made difficult not only by the faintness of the SN, but by the increasing sky brightness and the loss of key SNeIa spectral features in going to higher redshift.

**Telescope Time Requested:** There are two key requirements for the spectroscopic program to successfully exploit the SNLS — temporal coverage and speed. With Keck’s aperture and sensitive spectrographs, and our specialized acquisition and real-time reduction methods developed for SN spectroscopy at Keck, we can obtain redshifts and spectral classifications for up to 10 SNe candidates per night out to  $z \sim 0.9$ . Thus, in one Keck night we can cover the majority of the higher-redshift SNeIa the SNLS will produce in one field in one lunation. The clear focus at Keck will be on the 14h18m+52d field which has good visibility at Keck for four months.

Although many of the SNe will have spectra peaking at red wavelengths, important spectral features (e.g. metallicity indicators) extend down to observer-frame  $V$ -band. Therefore, these observations can not tolerate too much contamination from moonlight. In general we have found that we can observe at most 5 days from new moon before our program suffers significantly.

In total, obtaining the spectroscopy of this spring’s SNLS SNeIa’s requires 4 nights on Keck during dark time in 4 consecutive months, either February–May or March–June. We note that this SNLS spectroscopic follow-up campaign does not require the precise timing that was needed for our past  $z \sim 0.5$  searches (and still required for our  $z > 1$  searches) since the photometry of all the SN is obtained continuously. However, to coordinate with SNLS it is **important that the Keck**

**scheduler consult with us prior to scheduling specific dates.**

**Instrumentation:** In the past we have used LRIS, DEIMOS, and ESI for our SN spectroscopy program. We have found that each of these instruments has specific advantages depending on the target redshift range and the supernova-campaign strategy. For the 2005A campaign we request the LRIS spectrograph for all four nights. Its broader wavelength coverage (see Fig. 4) is the advantage for this run, since it is appropriate for a wider range of supernova redshifts — and for the 2005A semester there will not be a sufficient number of remaining “not-yet-observed” DEEP fields with newly discovered supernovae in them to give up this advantage for the sake of sharing DEIMOS masks with the DEEP team. This is a change from the previous year during which there were more uncompleted DEEP masks, and we were successfully able to take advantage of sharing DEIMOS nights. (Note that the DEEP team will still plan to observe the one or two supernovae that are expected to be discovered in 2005A on their uncompleted masks during their nights, to make optimal use of their time and help our campaign.) As in 2004A LRIS observations, we will use the 400l/8500A grating (cen=7500A) in the red, and the 600/4000A grism in the blue with the 560nm dichroic.

## Backup Program

Given the large commitment of queue-scheduled time for the SNLS we consider it next to certain that we will have a full schedule of SNe to observe on each of our nights. If transparency or seeing precludes spectroscopy at  $z > 0.5$  we will observe the lower redshift SNLS SNe otherwise reserved for smaller telescopes. In addition, we are pursuing studies of the host galaxies of SNe we have discovered in the past in order to understand the relationship between SN Ia properties and global properties (metallicity, morphology, etc.) of the hosts. Several of these programs, such as measuring the gas-phase metallicity of the host of the hypernova SN 1999as using the [NII]/H $\alpha$  ratio, determining the colors of the  $M_B \sim -11$  host galaxy of SN 1999aw, or measuring the age and metallicity of the nearby ( $z = 0.054$ ) Hubble-flow elliptical host galaxy of SN 1999av with high-resolution high S/N spectroscopy, can be carried out as back-up programs.

## Status of Previously Approved Keck Programs

**Semester 2005B:** [PLACEHOLDER] We have been awarded two nights of LRIS spectroscopy to complete previous supernova campaigns. These observations are scheduled for December, 2005.

**Semester 2005A:** Marek to write

**Semester 2004B:** We did not apply for time in 2004B.

**Semester 2004A:** In 2004A we were awarded 3 nights, in March, April (both DEIMOS) and May (LRIS), for SNLS follow-up. The March night was completely lost due to poor weather conditions (note that even though March weather was exceptionally poor, the queue observed nature of SNLS ensured that candidates were still available in this month). For the April-DEIMOS run we observed 8 candidates in long-slit mode, and for the May-LRIS run a further 7 candidates. Our preliminary analysis indicated that 10 of these candidates are probable SNe Ia, one an SN Ib/c, one a SN II, and one non-SN spectrum (see Fig. 4 for examples of our spectra). Two candidates remain to be typed. During this semester, a trial collaboration with the DEEP team enabled us to observe 3 candidates on various DEEP EGS masks, resulting in one SN Ia, one SN II and one unidentified spectrum.

We also developed a new capability for long-slit observers using DEIMOS. By placing reflective tape on either side of the slit on a special long-slit mask it becomes possible to acquire significantly fainter targets. We tested and demonstrated this capability in semester 2004A.

**Semester 2003B:** We did not apply for time in 2003B.



**Semester 2003A:** In 2003A we were awarded 2 nights in May and 1 night in July for follow-up of SNLS supernova candidates. We concentrated on the SNLS field which encompasses the EGS. For both runs we observed with DEIMOS on Keck II in order to gain the experience needed to coordinate our follow-up with DEEP multi-object spectroscopy in the EGS. Conditions were marginal for the two nights in May, with excellent seeing accompanied by thick cirrus. During this run we demonstrated the feasibility of observing SNLS SNe in parallel with DEEP galaxy spectroscopy in the EGS. Conditions were good for the July run, and we were able to screen 5 high-redshift supernova candidates being followed by SNLS. As acquisition of faint targets is difficult with DEIMOS used in long-slit mode due to the low reflectivity of the long-slit mask, during this run we developed acquisition code patterned after our acquisition code for ESI.

**Semester 2002B:** We were awarded four Keck II/ESI nights in November 2002 which were used for spectroscopic confirmation of SNe discovered in an intensive search using Subaru. From this search, 18 SNe were reported in IAU Circulars, of which 9 had spectra taken with ESI, and 5  $z > \sim 1$  SNe Ia were followed with various combinations of ACS photometry and slitless spectroscopy and NICMOS imaging as part of our 100-orbit cycle 10 program. Final reference images are being obtained now that NICMOS has been refurbished; analysis is proceeding.

**Semester 2002A:** We were awarded six nights for ESI spectroscopy of SNe from our spring 2002 search campaign which consisted of a “rolling” search at CFHT (a pilot-study for the SNLS) as well as “classical” searches at Subaru and CTIO. Essentially all the Keck time was lost due to bad weather, with the dome closed for most of the nights. Of our three nights in April, we were able to use about one half night. We observed two CFHT SNe (at  $z \sim 0.3$ ) and two Subaru candidates (at  $z = 0.56$  and  $z = 0.88$ ). The three nights in May were completely lost due to weather.

**Semester 2001A:** In this highly successful six-night run we used one night of LRIS + Keck I and five nights of ESI + Keck II to obtain spectra of 17 SNe, including three SNe Ia at  $z > 1$ . Our strategy of observing for six nights in one semester paid off, as we were able to use the three poorer seeing ( $\sim 1$  arcsec) nights and one cirrusy night to confirm brighter targets, and use the two better seeing nights to study SNe at  $z > 1$ . The Keck spectra allowed us to classify the SNe, obtain redshifts, and select the highest redshift targets for *HST*. In addition, the spectra are being compared to low redshift SNe Ia to test for the effects of evolution in the high- $z$  sample. This run also gave us extensive experience with ESI, enabling us to refine our reduction techniques to best exploit ESI’s advantages (and compensate for small remaining problems). The required final reference images of the host galaxies for these SNe have very recently been obtained with the *HST* so analysis can now proceed.

**Semester 2000A:** The highlight of this two-night run at Keck was spectroscopy of 2000fr, supernova candidate (from our CFHT search) that turned out to be a Type Ia SN at  $z = 0.54$  at a very early phase in its light curve (only  $\sim 6$  days after explosion). This early discovery allowed us to begin an intensive monitoring campaign to study the supernova in great detail, including near-IR imaging with ISAAC on the VLT. This data set allows us to make a detailed comparison with nearby Type Ia supernovae to check for signs of evolution or extinction by dust (paper in preparation). These results have encouraged us to pursue detailed spectroscopy of another  $z \sim 0.5$  SN Ia.

**Semester 1999B:** Three nights were awarded for the second week of October, 1999. The time was used for spectroscopy of candidate SNe that were discovered in a search at CFHT earlier that month. Out of the 10 candidates discovered, we were able to observe 6 of them, and two of those were found to have  $z \sim 0.9$ .

**Semester 1999A:** One night was awarded but was not usable.

**Semester 1998B:** Three nights were awarded for a pilot study to find very high- $z$  SNe. Two

nights were used for imaging and one for spectroscopy, resulting in three Type Ia SNe with  $z = 1.2$ , 0.84 and 0.11. The SN with  $z = 1.200$  (1998eq) was at that time the highest redshift confirmed Type Ia SN (IAUC 7046). The discovery of this supernova demonstrates that it is feasible to find and obtain spectra for Type Ia events even for redshifts  $z > 1$ . The two highest redshift SNe from this run, both of which were discovered close to maximum light, were observed in *I*-band and *J*-band with *HST* WFPC2 and NICMOS.

**Semesters 1997B and 1998A:** In December 1997 and March 1998 we carried out searches using the BTC on the CTIO 4-m. The resulting SN candidates were observed spectroscopically with Keck on approximately 4 usable nights (over the two semesters). A total of 36 candidates were observed and 26 were confirmed as Type Ia, with mean redshifts of approximately 0.6–0.7. These were followed-up from the ground with CTIO-4m, WIYN, ESO 3.6m, WHT and INT telescopes, and 11 of these were also followed photometrically with *HST* using WFPC2 and NICMOS. The corresponding final reference images have been obtained for these SNe and the results presented in Knop *et al.* (2003).

**Earlier Semesters:** Final host galaxy images have been obtained for nearly all the SNe discovered prior to the above semesters. These SNe have been analyzed and formed the basis of the analysis presented in Perlmutter *et al.* (1999), which highlights the evidence for a cosmological constant. In addition to that paper and the more recent Knop *et al.* (2003), nine additional papers based on our Keck work describe: (i) the first measurements of cosmological parameters based on the first seven SN discoveries (Perlmutter *et al.*, 1997); (ii) a measurement of the rate of Type Ia SNe at  $z \sim 0.4$  (Pain *et al.*, 1996), (iii) the rate of Type Ia SNe at  $0.35 < z < 0.85$  (Pain *et al.*, 2002), (iv) constraints on the spatial variation of the Hubble constant from our data (Kim *et al.*, 1997), (v) a study of the timescale stretch parameterization of type Ia supernova B-band light curves (Goldhaber *et al.*, 2001), (vi) the use of SN spectra for the determination of subtype and age of SNe Ia (Riess *et al.*, 1998), (vii) results on the  $z = 0.83$  supernova 1997ap, and implications for cosmological measurements (Perlmutter *et al.*, 1998), (viii) the consistency of rise times measured for low and high- $z$  supernovae (Aldering *et al.*, 2000), (ix) that our evidence for a non-zero cosmological constant is independent of host galaxy morphology (Sullivan, *et al.*, 2003).

Research is in progress which will result in additional papers. These include (i) a determination of the rates of SNe Ia at  $z > 1$ , (ii) an analysis constraining metallicity variations and evolution from our SN spectra, and (iii) new limits on the cosmological parameters and possible systematics (grey dust or evolution) from SN 1998eq at  $z = 1.20$ . All these papers use the results from Keck spectroscopy obtained as part of our supernova cosmology program. A number of papers on these topics have also appeared in conference proceedings.

## Path to Science from Observations

As in the past, 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 implementation of the B-spline sky subtraction technique and, for LRIS, fringe removal. The SN spectra are then smoothed on a scale of  $\sim 20\text{\AA}$  (after removing any lines due to the host galaxy and dewatering the spectral regions covered by OH lines) and compared with those of nearby SNe to ascertain the SN type (e.g. Fig 4).

The Keck redshifts will be used along with rolling photometry from the SNLS (Fig. 3) 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. K-corrections — which we have developed using the spectra of low- $z$  SNe Ia (Nugent, Kim, & Perlmutter 2002) — must also be applied, followed by correction for dust extinction from the host galaxy and the Galaxy. The extinction correction requires a knowledge of the unreddened intrinsic SN colors, which we have determined from low- $z$  SNe Ia in elliptical galaxies (and will improve with future low-redshift data) and do not result in overcorrection for extinction (as is the case for some other treatments in the literature). Once the SNe Ia have been standardized, we can solve for the confidence intervals for the cosmological parameters. We have and are continuing to develop extensive software to undertake such light-curve fitting, corrections, and parameter fitting.

The Keck spectroscopy will allow us to test for the effect on our cosmological fits due to any spectroscopically peculiar SNe Ia, and to set better limits on systematic uncertainties which could be caused by unrecognized spectroscopically peculiar SNe Ia. For our  $z \sim 0.5$  (brighter) SNe Ia where the host galaxy light does not significantly contaminate the SN spectrum, stronger tests, including comparison of the metallicity-dependent UV spectral features with our Cycle 9 and Cycle 11 *HST* UV spectra of nearby SNe Ia (from a separate program) will be possible.

## Technical Concerns

Since our targets are faint, accurate offsetting is critical to take advantage of the narrow slit widths possible under the best seeing conditions. SNLS has developed sophisticated custom finder-chart tools (see <http://legacy.astro.utoronto.ca/makefinder.php>) to allow offsets from any nearby star to be calculated on-the-fly. On our 2004A DEIMOS/LRIS run we successfully acquired all our targets, using a direct acquisition capability for the faintest targets on DEIMOS.

There are no technical concerns with the searches, as SNLS comprises a dedicated team with extensive experience in finding and selecting SNe for spectroscopic follow-up with Keck. Real-time candidate lists are always available at <http://legacy.astro.utoronto.ca/cfhtls.php>

The Keck SN candidate spectroscopy runs must be coordinated with the SNLS search of the EGS, scheduled to start in January 2005, so *please contact us before scheduling any nights allocated to us at Keck!*

## Experience and Publications

Our group has extensive experience with faint object spectroscopy on telescopes around the world and has had successful runs using LRIS, ESI, and DEIMOS on Keck each semester for the last eight years. 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. A list of relevant publications appears at the end of this document.

## Resources and Publication Timescale

The LBNL supernova group consists of three UC professors (PI Perlmutter is now also a UC Berkeley faculty member), three permanent staff scientists, a scientist/project coordinator, six postdocs and three graduate students. The group uses the extensive computing facilities available at LBNL.

We note that one of the many advantages of the SNLS is that deep images are available which are uncontaminated by SN light i.e. are taken during the year *before* the SN explodes. Therefore, unlike in the past, we will not have to wait a year to obtain final reference images. This makes it possible to start final reductions and analysis shortly after the end of each month of observing. For mid-redshift SNe Ia we have been able to get the results into press within roughly a year. As

examples, SN1997ap was discovered in March 1997, and a paper describing the data and results from that supernova was published by *Nature* in January, 1998. The results from the first 42 SNe (data obtained from Spring 1995 to Spring 1998, including final follow-up photometry on the Spring 1997 SNe) was published in *ApJ* in Fall 1999.

## Publications

(\* = Keck data contributed to this publication.)

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\* Hubble Diagram of Type Ia Supernovae as a Function of Host Galaxy Morphology, M. Sullivan *et al.*, 2003, MNRAS 340, 1057.

\* The distant Type Ia supernova rate, R. Pain, *et al.*, 2002, ApJ 577, 120.

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\*NICMOS Photometry of High Redshift Supernovae, S.Burns, *et al.*, presented at the January 2002 AAS meeting.

\*Type Ia Supernovae: Tests for Evolution and Grey Dust.Ground and Spaced Based Follow up of a Type Ia Supernova at  $z=0.54$ , S.Nobili, *et al.*, presented at the January 2002 AAS meeting.

\*Results from Recent high-redshift Type Ia Supernovae Searches, K.Schahmanec, *et al.*, presented at the January 2002 AAS meeting.

\*Interpretation of high- $z$  SN spectra, P.Nugent, *et al.*, presented at the January 2002 AAS meeting.

A New Set of Nearby SNIa Lightcurves, N.Regnault, *et al.*, presented at the January 2002 AAS meeting.

Accurate Multi-epoch Optical Spectroscopy of 18 Low- $z$  Type Ia Supernovae, G.Garavini, *et al.*, presented at the January 2002 AAS meeting.

Nearby Supernova Searches: Results and Future Plans, G.Aldering, presented at the January 2002

AAS meeting.

\* Timescale Stretch Parameterization of Type Ia Supernova B-Band Light Curves, G. Goldhaber, D. E. Groom, A. Kim, G. Aldering, P. Astier, A. Conley, S. E. Deustua, R. Ellis, S. Fabbro, A. S. Fruchter, A. Goobar, I. Hook, M. Irwin, M. Kim, R. A. Knop, C. Lidman, R. McMahon, P. E. Nugent, R. Pain, N. Panagia, C. R. Pennypacker, S. Perlmutter, P. Ruiz-Lapuente, B. Schaefer, N. A. Walton, T. York, 2001, *Astrophysical Journal*, 558, 359

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Results from a Deep Supernova Search at Keck, G. Aldering, *et al.*, in preparation

Type Ia Supernovae and Host Galaxy Extinction, E. Commins, *et al.*, in preparation

The Host Galaxies of Type Ia Supernovae at High Redshift, G. Aldering, *et al.*, in preparation

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