1 Scientific Justification

The Hubble diagram for Type Ia supernovae (SNe Ia) at high-redshift (Fig. 3) provides the most direct current measurement of the expansion history of the universe — and hence the most direct evidence for an accelerating expansion. The "first generation" of SN Ia cosmology work developed a systematic approach to this measurement (Perlmutter et al. 1997, 1998, 1999, Riess et al. 1998) that led to the surprising results indicating the presence of a new, unaccounted-for "dark energy" that can cause acceleration. This conclusion has been strongly supported by the cosmic microwave background (CMB) measurements of Ω_k (e.g., Spergel et al. 2003). Our most recent measurement (Knop et al. 2003) adds 11 SNe followed with *HST* photometry to our original dataset of 42 SNe at $0.18 < z < 0.83$ to obtain the current best value for $\Lambda = 0.75^{+0.06}_{-0.07}$ for a flat universe (see also Tonry et al. 2003, Riess et al. 2004). Keck played the key spectroscopy role in these campaigns.

There is a fundamental difference between a Cosmological Constant and other potential forms of dark energy. This distinction can be addressed by measuring the dark energy's average equation-of-state, $\langle w\rangle \equiv \langle p/\rho\rangle$, where $w = -1$ corresponds to a Cosmological Constant. Our recent measurement,$\langle w\rangle = -1.05^{+0.15}_{-0.20}$ (statistical) ± 0.09 (identified systematic) (Knop et al. 2003), which combined our SN analysis with CMB and LSS results, is consistent with a very wide range of dark energy theories (cf. the Riess et al. 2004 result: $\langle w\rangle = -1.02^{+0.13}_{-0.19}$, no systematic quoted).

The importance of improving this measurement to the point that $\langle w\rangle = -1$ could be ruled out has led to a new generation of supernova cosmology studies: large multi-year multi-observatory programs with major commitments of dedicated time for "rolling searches," which can find and follow SNe over many months of repeated wide-field imaging and identify them with coordinated spectroscopy. The challenging second-generation goals are: (1) to improve the constraint on $\langle w\rangle$ by building an order-of-magnitude larger statistical sample (i.e. ∼750) of SNe in the redshift range $z = 0.3 - 0.9$ where $\langle w\rangle$ is best measured; (2) to study the transition to deceleration by building a first significant sample (∼15) of SNe Ia in the redshift range $z = 1 - 1.4$; and (3) to improve the systematic uncertainties by studying low-redshift supernovae in detail and comparing specific SN properties between low- and high-redshift. Fully exploiting samples from (1) and (2) to improve the *statistical* uncertainties will depend on (3) reducing the *systematics* correspondingly.

These goals clearly require an ambitious effort on the part of the SN Ia community to build up the necessary SN dataset, and we have constructed a coherent program to carry this out. We have developed the Nearby Supernova Factory to carry out (3), and are continuing our Subaru and *HST* programs to generate the $z > 1$ sample (2). To address (1) we are working with the SN search portion of the CFHT Legacy Survey to generate the requisite large $z = 0.3$–0.9 sample, and it is these SNe that are the target of this 2006A proposal. By strategic Keck studies of these samples to determine the value of $\langle w\rangle$, we aim to answer the key question: Is the dark energy something other than Einstein's Λ?

SNLS: An Unprecedented SN Ia Dataset to Measure Dark Energy

The CFHT Legacy Survey (`http://cfht.hawaii.edu/SNLS/`) is an ambitious wide-field survey, utilizing an imager field four times larger than the next largest survey camera (at CTIO), with twice as much time devoted to the survey. Commenced in August 2003, the first year of data has now been analyzed. The results, which already add significantly tighter constraints on Ω_Λ and w than any previous survey, will be submitted for publication within the next few weeks (see Progress to Date). The full five-year CFHT "SuperNova Legacy Survey" (SNLS) dataset (see Technical Justification), when combined with a large sample of well-measured nearby SNe from the Nearby SN Factory, will provide the major improvement in the determination of the dark energy parameters achievable over the next 5 years. It is important to note that these results assume a redshift precision of better than 1% and so spectroscopic redshifts are essential for all SNe.

The Keck Observatory is the lead for the northern hemisphere spectroscopy of this landmark project. It is essential that each supernova be identified, classified (within a week to ten days of its maximum brightness), and its precise redshift determined for this heavy investment in multi-color lightcurves to pay off in a Hubble diagram. The SNLS fields include the Extended Groth Strip (EGS) at +52d, for which a large aperture northern telescope is required; this is a DEEP field and in 2003/4A we demonstrated a synergy in observing with the DEEP project (see Technical Justification).

Addressing Systematic Uncertainties with this Proposed Dataset

Perlmutter et al. (1997, 1999) discuss systematics in the measurement of Ω_M, Ω_Λ; we found that uncertainties due to K-corrections, gravitational lensing, and Malmquist bias are quite small compared to the statistical error of the current SN samples. We showed that SN Ia evolution and abnormal dust within, or even between, galaxies were possible, but unlikely. Knop et al. (2003) provided detailed reddening measurements to check that ordinary dust extinction was not a confounding systematic. However, the large SNLS sample will reduce the statistical errors to the point that some systematics, such as Malmquist bias, will again be important. The SNLS data set itself will allow more powerful tests and constraints on several of these key systematics.

Multi-color Lightcurves. The rolling search with multiple filters ($griz$) will generate the first large high-redshift SN Ia dataset with complete color coverage throughout the lightcurves (see Fig. 1 for examples of typical SNLS light-curves). This enables comprehensive extinction studies using all the SNe sampled in a common rest wavelength range. This is key because SNe Ia show a color-luminosity relation — currently taken from low-redshift SNe — which can be checked in the SNLS sample independent of extinction. It will also be possible to examine the consistency of the stretch-corrected peak magnitudes in restframe B with those in redder bands, where the intrinsic luminosity range of SNe Ia is smaller.

High-statistics Subsamples. In our recent study (Sullivan et al. 2003) we have divided our sample of 42 high-z SNe into subsamples based on host galaxy morphology. This is an important first test of evolutionary and dust effects that will differ in different host galaxy environments. The large SNLS sample will allow us to perform such tests with much better statistics, over a larger redshift range and in much more detail. As in Sullivan et al., the narrow galaxy emission and absorption lines detectable with Keck spectroscopy of SN+host provide valuable constraints on host galaxy stellar populations.

Conclusion. This continuing proposal focuses on the extraordinary science opportunities presented by the CFHT Legacy Survey. With a large increase in statistics for the mid-redshift range, we will make major strides in our ongoing multi-semester campaign to build a well-measured SN Ia Hubble diagram. These data are crucial for studying the cosmological parameters and the nature of dark energy. They also serve to refine our evolution/dust checks on systematics. This second-generation of SN studies provides our first chance to test whether the dark energy is consistent with a Cosmological Constant. Its conclusions and refinements in the use of large, well-studied SN Ia samples will shape future third-generation projects, such as *SNAP*, designed to probe the variation of w with time. With this program Keck will continue to play a leading role in this fundamental science.

Figures & References

Aldering G., et al., 1998, IAUC 7046
Aldering G., et al., 2000, AJ 119, 2110
Astier, P., et al., 2005 (in prep)
Eisenstein, D. J., et al., 2005, astro-ph/0501171
Goldhaber G., et al., 2001, ApJ 558, 359
Hook, I., et al., 2005, astro-ph/0509041
Kim A., et al., 1997, ApJ 476, L63
Knop A., et al., 2003, ApJ 598, 102
Nugent, P., et al., 2002, PASP 114, 803
Pain R., et al., 2002, ApJ 577, 120
Perlmutter S., et al., 1997, ApJ 483, 565
Perlmutter S., et al., 1998, Nature 391, 51
Perlmutter S., et al., 1999, ApJ 517, 565
Riess A., et al., 1998, AJ 116, 1009
Riess A., et al., 2004, ApJ 607,665
Spergel D., et al., 2003, ApJS 148, 175
Sullivan M., et al., 2003, MNRAS 340, 1057
Tonry, J., et al., 2003, ApJ 594,1

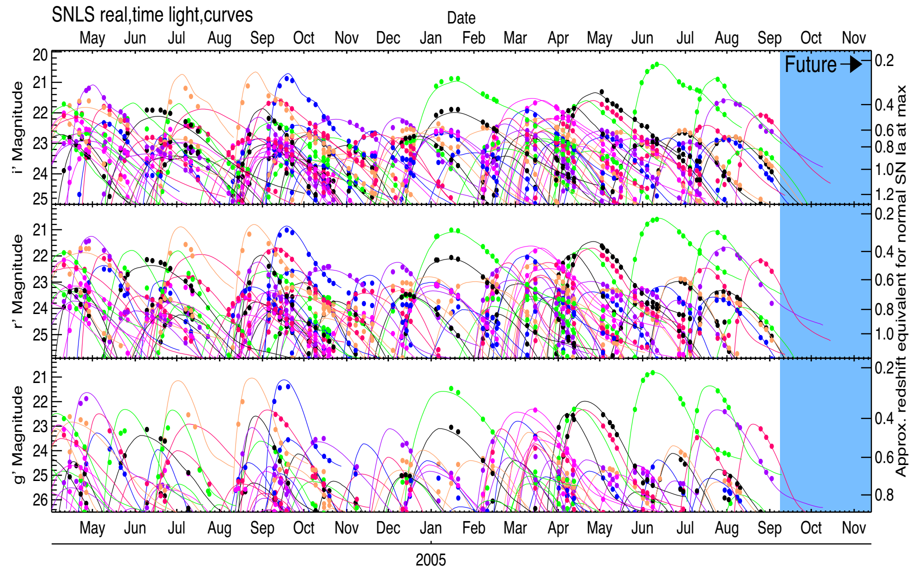
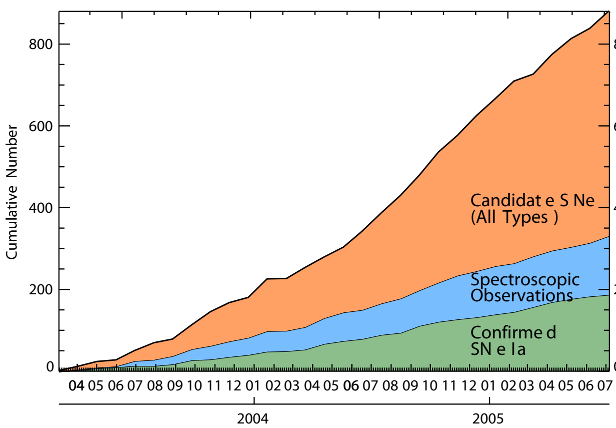


Figure 1: Real-time (not-final) SN Ia light-curve fits from SNLS in *i'*, *r'*, and *g'*, SNe are always discovered before maximum light (allowing spectroscopy when the candidate is brightest). For clarity, only around half of the SNe Ia confirmed in this time interval are shown. Error bars are shown; most are smaller than the size of the plotting symbols.



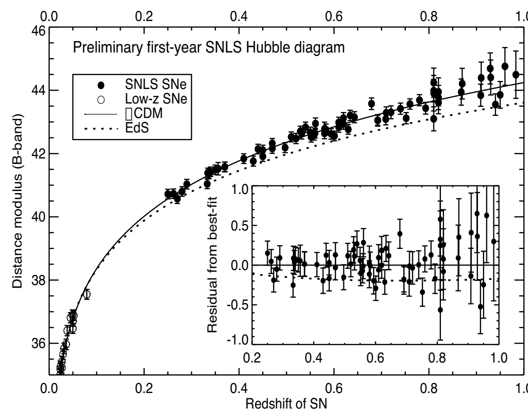
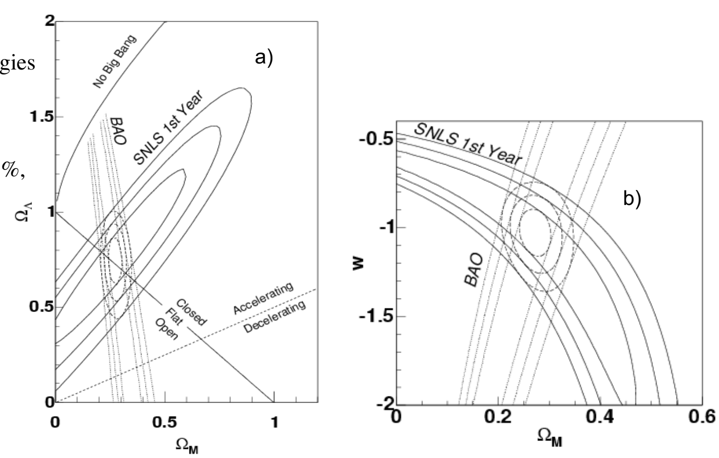


Figure 2 (above): The current SNLS survey statistics.

Figure 3 (right): Preliminary Hubble diagram of SNLS and Nearby SNe Ia, with various cosmologies superimposed. *(inset)* Residuals for the best fit to a flat Λ cosmology. (from Astier et al.)

Figure 4 (lower right): *a)* Contours at 68.3%, 95.5%, and 99.7% confidence levels for the fit to Ω_M, Ω_Λ cosmology from the SNLS Hubble diagram (solid lines), the SDSS baryon acoustic oscillations (Eisenstein et al., 2005, dotted lines), and the joint confidence contours (dashed lines). *b)* Contours at 68.3%, 95.5%, and 99.7% confidence levels for the fit to a flat (Ω_M, *w*) cosmology, from the SNLS Hubble diagram alone, from the SDSS baryon acoustic oscillations, and the joint confidence contours (from Astier et al.).



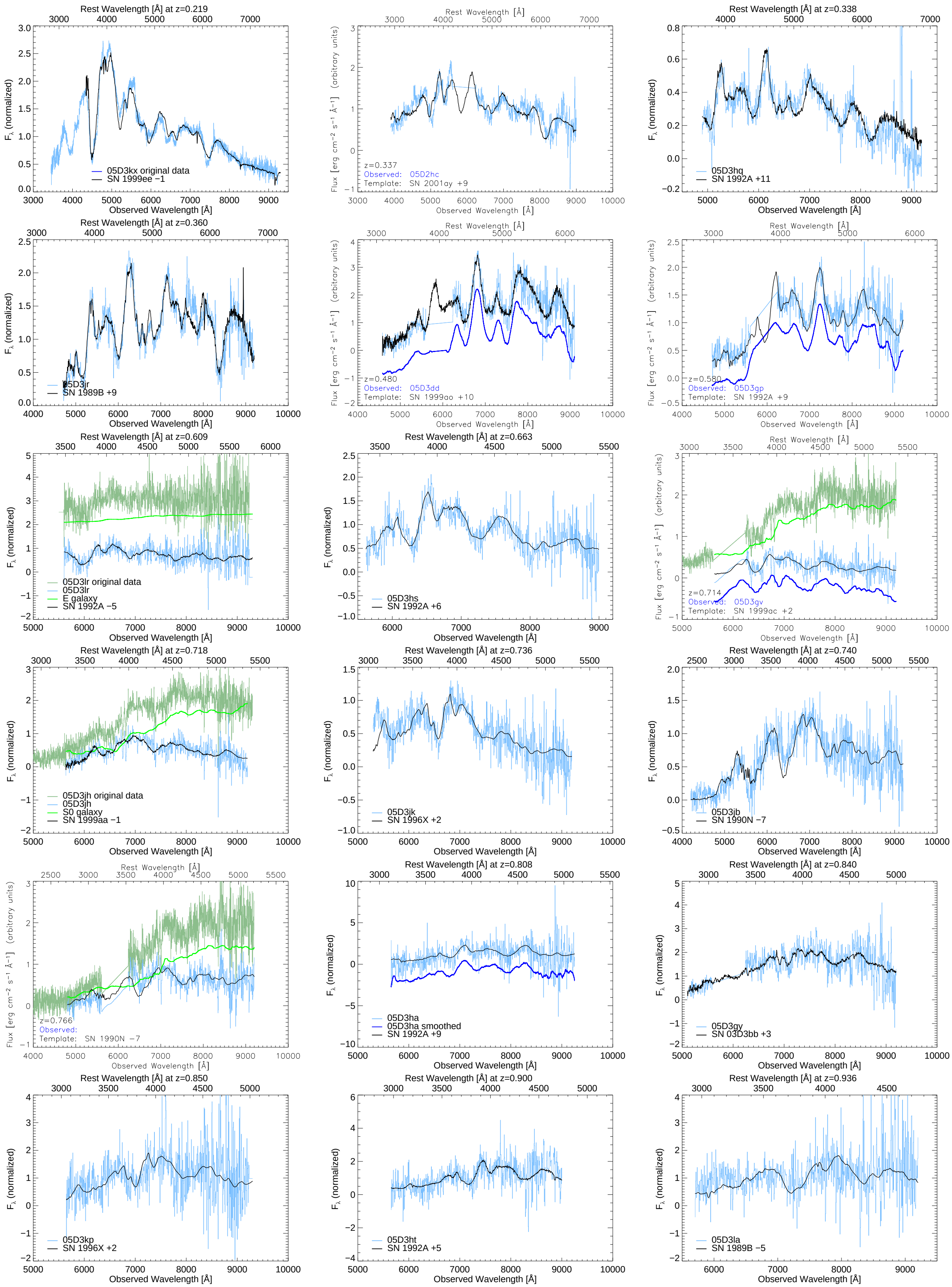


Figure 4: Spectra of SNLS SN candidates obtained during the last three nights of the 2005A Keck LRIS observing campaign. The light-blue lines show the data after host galaxy subtraction (if necessary), rebinned to 10 Å. Overplotted in black are the best fit SN templates. The spectra are confirmed by Keck to be Type Ia SNe.

2 Progress to Date

We are using the CFHT Legacy Survey SN component (SNLS), to obtain a significant increase in supernovae statitstics at intermediate redshift *and* at the same time control their systematics. The SNLS began in semester 2003A in pre-survey mode, the full survey commencing August 2003. As of August 2005 (i.e. two full years of survey operation), SNLS has located *and spectroscopically confirmed* nearly 200 well-sampled type Ia SNe (Fig. 2), with multi-epoch and multi-color light-curves (Fig. 1). In particular the color information of the rising part of the lightcurve allows us to efficiently preselect candidates for spectroscopy. The photometrically preselected sample of SN type Ia candidates is about 80 % pure. Additionally, a supernova redshift (which is typically good to within ± 0.05) and an estimated time of maximum is derived from the rising part of the lightcurve. This real-time light curve analysis makes the process of spectroscopic confirmation highly efficient. The survey now routinely provides about 10 SN Ia candidates per field per month which require spectroscopic follow-up (see “Technical Justification” for details of the survey).

Our Keck 2004A and 2005A time allocations made an invaluable contribution to the co-ordinated SNLS follow-up, resulting in a major contribution to Astier et al. In 2004A we screened 18 SN candidates and in 2005A we screened 22 candidates. The spectra were fully reduced using our custom-written software. Of the candidates from 2004A, 15 have been identified and 10 are confirmed as SN Ia. Of the 24 candidates from 2005A, 20 are confirmed SN Ia (see Fig. 5). Work continues on the unidentified objects. (see “Status of Previously Approved Keck Programs”). The median redshift of the confirmed SN Ia is 0.71. Note also that 30 of the SNe Ia confirmed by Keck, were discovered in the EGS, making Keck the prime telescope to cover the EGS, which is only visible from the north.

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 a large number of multi-color light-curves have already been measured (see Fig. 1). A novel approach to fit supernova light-curves has been developed which facilitates the use of full information of the available multi-color light curves. Using the SNLS data sample we found that the rest-frame-U band can produce a much tighter dispersion then previously anticipated. This is an important result as it allows extension of the redshift range of supernovae that can effectively be observed and added to the Hubble diagram.

Using the data from the first year, we have built a Hubble diagram extending out to z=1, with all distance measurements using at least two bands (Fig. 3). Systematics from potential SN evolution, Malmquist bias, spectral misidentification as well as photometric calibration are being investigated. Cosmological fits assuming a flat universe result in $\Omega_{\mathrm{m}} = 0.263 \pm 0.042(\mathrm{stat}) \pm 0.032(\mathrm{sys})$. If our first year's data set is combined with the recent measurement of baryon acoustic oscillations (Eisenstein et al., 2005), the constraints improve to: $\Omega_{\mathrm{m}} = 0.271 \pm 0.021$ (stat) $\pm\, 0.007$ (sys) assuming a flat ΛCDM model universe and $w = -1.023 \pm 0.090(\mathrm{stat})\ \pm 0.054$ (sys) for a universe with a constant equation of state w. With only 72 SN Ia, the resulting constraints on the cosmological parameters are already stronger than any other previous survey, illustrating the superb quality of the SNLS data sample. The corresponding publication (Astier et al., in prep.) is currently under internal review and will be submitted within the next few weeks.

The analysis of the newer data is in progress. The improved statistics of the five-year supernova sample will allow us to study and reduce the systematics futher (e.g. by subdividing the sample). We expect to reach a level of combined statistical and systematic uncertainties that is below the currently quoted uncertainty for systematics alone.

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 SNe Ia cosmological studies with greatly increased statistics and even greater reliability. SNLS is a well-established five-year rolling SN search program, observing four 1×1 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 SNe Ia 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 SNe Ia 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: All of the supernovae to be observed in this proposal will be discovered in the four SNLS survey fields, two of which are visible this spring. In particular, with Keck we will focus on the SNe discovered in the Extended Groth Strip (EGS) field at 14h18m+52d, where Mauna Kea telescopes must play a leading role in follow-up observations. We expect to have a target list of roughly 10 candidates per lunation for this field, most of which will be SNe Ia at $z > 0.4$ with a median $z \sim 0.7$. (Secondary fields at 10h00m+02d and 22h15m-17d will be observed when the primary field is not available.) This selection purity is another important advantage of the rolling SN search approach compared to classic 2-epoch SN searches.

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 SNe Ia 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 classification. The $z \sim 0.9$ SNe Ia are made difficult not only by the faintness of the SN, but by the increasing sky brightness and the loss of key SNe Ia 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 $z \sim 0.95$. Thus, in one Keck night we can cover the majority of the higher-redshift SNe Ia 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 SNe Ia's requires 4 nights on Keck during dark time in 4 consecutive months from February–May. 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.**

Our dedicated observational program will be supplemented by DEIMOS multi-slit observations performed by the DEEP2 team; once they complete the NE end of the EGS, they will return to the center of the EGS, which has about 25 % areal overlap with our SNLS D3 field. Due to the necessity of having the masks machined after discovery, we would primarily target supernovae candidates which can be observed past their maximum light (i.e. the brighter candidates which could not be observed on previous lunations). Additionally, the DEEP team will perform host galaxy observations of historical SNLS SNe candidates.

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 2006A campaign we the request a the LRIS spectrograph for all four nights. Its broader wavelength coverage (see Fig. 4) is the advantage for this program, since it is appropriate for a wider range of supernova redshifts. As in the highly successful 2005A LRIS campaign, 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. Under exceptionally bad weather conditions, we plan to observe nearby supernovae found by the SNfactory, which routinely finds a large number of good candidates.

Status of Previously Approved Keck Programs

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

Semester 2005A: In 2005A we were awarded 4 nights, in March, April, May and June, for SNLS follow-up. All observations where made with LRIS in long-slit mode. The March night had poor weather with strong winds, in which the seeing typically varied between 1.5 and 2 arc-seconds. We screened four SNLS candidates, of which two were confirmed as SNe Ia. During the April night we observed 8 candidates, during the May night 7 candidates and during the June night 5 candidates. Of the 20 candidates observed during those three nights 18 where classified as Type Ia SNe with a median redshift of $z = 0.71$. This unprecedented high yield of SNe Ia can be attributed to our highly efficient pre-selection algorithm. The SNe Ia spectra are shown in Fig. 5.

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 analysis indicated that 10 of these candidates are probable SNe Ia. 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 (~ 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 ~ 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).

Semester 1997A: Spectra obtained in January and March 1997 of 14 type Ia supernovae with redshifts $0.17 < z < 0.83$ have been published in Hook et al., 2005. In this paper, we present evidence that these supernovae are of Type Ia by matching to spectra of nearby supernovae. We find that the dates of the spectra relative to maximum light determined from this fitting process are consistent with the dates determined from the photometric light curves, and moreover the spectral time-sequence for SNe Type Ia at low and high redshift is indistinguishable. We also show that the expansion velocities measured from blueshifted Ca H&K are consistent with those measured for low-redshift Type Ia supernovae. From these first-level quantitative comparisons we find no evidence for evolution in SNIa properties between these low- and high-redshift samples. Thus even though our samples may not be complete, we conclude that there is a population of SNe Ia at high redshift whose spectral properties match those at low redshift.

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 implemetation of the B-spline sky subtraction technique and, for LRIS, fringe removal. The SN spectra are then smoothed on a scale of ~ 20Å (after removing any lines due to the host galaxy and deweighting the spectral regions covered by OH lines) and compared with those of nearby SNe to ascertain the SN type (e.g. Fig. 5).

The Keck redshifts will be used along with rolling photometry from the SNLS (Fig. 1) 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) SN 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.

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 2006, 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 four 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.

Related Publications

(* = Keck data contributed to this publication.)
*The Supernova Legacy Survey: Ω_M, Ω_Λ, and w from the First Year Data Set, P. Astier, et al., 2005 (in prep)

* Spectra of High-Redshift Type Ia Supernovae and a Comparison with their Low-Redshift Counterparts, I. M. Hook, et al., 2005, accepted for publication in AJ, astro-ph/0509041

Spectroscopic Observations and Analysis of the Unusual Type Ia SN 1999ac, G. Garavini, et al., 2005, accepted for publication in AJ, astro-ph/0507288.

Restframe I-band Hubble Diagram for Type Ia Supernovae up to Redshift $z \sim 0.5$, S. Nobili et al., A&A, 437, 789 (2005).

Spectroscopic Observations and Analysis of the Peculiar SN 1999aa, G. Garavini, et al., 2004, AJ 128,387.

Spectroscopic confirmation of high-redshift supernovae with the ESO VLT, C. Lidman, et al., A&A 2005, 430, 843

* New Constraints on Ω_M, Ω_Λ, and w from an Independent Set of Eleven High Redshift Supernovae Observerd with *HST*, R. A. Knop, et al., 2003, ApJ, 598, 102.

* 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.

K-corrections and Extinction Corrections for Type Ia Supernovae, P. Nugent, A. Kim, S. Perlmutter, 2002, PASP 114, 803.

* Timescale Stretch Parameterization of Type Ia Supernova B-Band Light Curves, G. Goldhaber, et al., 2001, AJ, 558, 359

* The Rise Times of High- and Low-Redshift Type Ia Supernovae Are Consistent, G. Aldering, R. Knop, P. Nugent 2000, AJ, 119, 2110.

* Measurements of Ω and Λ from 42 High-Z Supernovae, S. Perlmutter, et al., 1999, ApJ, 517, 565.

* Discovery of a Supernova Explosion at Half the Age of the Universe and its Cosmological Implications, S. Perlmutter, et al., 1998, Nature, 391, 51.

* Measurements of the Cosmological Parameters Ω and Λ from the First 7 Supernovae at $z \geq 0.35$. S. Perlmutter, et al., 1997, ApJ, 483, 565 (1997).

*Implications for the Hubble Constant from the First Seven Supernovae of $z > 0.35$, A. Kim et al., 1997, ApJ, 476, L63 (1997).

References

Aguirre, 1999, XXXXX

Aldering, G., et al., 2000, LBL Report LBNL-44232, AJ in press

Goobar & Perlmutter, 1995, Ap. J., 450, 14

Nugent, P., Phillips, M., Baron, E., Branch, D., & Hauschildt, P., 1995, Ap. J. Lett., 455, 147

Aldering, G., et al., 1998, IAUC 7046.

Aldering, G., Knop, R., Nugent, P., 2000, AJ 119, 2110

Garnavich, P., et al., 1998, ApJ, 509, 74.

Goldhaber, G., et al., 2001, ApJ, 558, 359

Jaffe, A. H., et al., 2001, Phys. Rev. Lett., 86,3475

Kim, A., et al., 1997, ApJ, 476, L63

Knop, R. A., et al., 2003, ApJ in press.

Nobili, S. et al., 2001, AAS, 199, 1611

Pain, R., et al., 1996, ApJ, 473, 356.

Pain, R., et al., 2002, ApJ 577, 120.

Perlmutter, S., *et al.*, 1997, ApJ, 483, 565.

Perlmutter, S., *et al.*, 1998, Nature, 391, 51.

Perlmutter, S., *et al.*, 1999, ApJ, 517, 565.

Riess, A., Nugent, P., Filippenko, A.V., Kirshner, R.P., & Perlmutter, S., 1998, ApJ, 504, 935.

Riess, A., et al., 1998, AJ, 116, 1009.

Spergel, D. et al., 2003, ApJ submitted.

Sullivan, M., et al., 2003, MNRAS, 340, 1057.

Tonry, J. L., et al., 2003, ApJ in press.

Weller, J., and Albright, A., 2001, Phys. Rev. Lett., 86, 1939