1 Scientific Justification

The Hubble diagram for Type Ia supernovae (SNe Ia) at high-redshift (Fig. 1) 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). 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. The current best measurement, $\langle w \rangle = -1.05^{+0.15}_{-0.20}$ (statistical) ± 0.09 (identified systematic) (Knop *et al.* 2003), combining our latest SN analysis with CMB and LSS results, is consistent with a very wide range of dark energy theories. The importance of improving this measurement to the point that $\langle w \rangle = -1$ could be ruled out has led to a new second 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. $\sim$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 ($\sim$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 *systematic* uncertainties 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 2005A 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?

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 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, as shown in the following table and Fig. 2. Even with the first few years' statistics from this survey ($\approx$ 300 SNe Ia), we will be able to see evidence for a non-Cosmological Constant dark energy if $\langle w \rangle$ is more than ~ 0.1 away from -1. 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.

Assumption	$\sigma(\Omega_M)$	$\sigma(\Omega_\Lambda)$	$\sigma(\langle w \rangle)$
None	0.04	0.06	–
Flat Universe	0.04	–	0.11
Ω_M Constraints from LSS & CMB	0.03	–	0.07

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. 3 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. SNLS lightcurves will also allow better K-corrections since extrapolation of the SN SED will not be necessary.

High-statistics Subsamples. Fig. 1 (right panel) shows our recent study (Sullivan *et al.* 2003) in which our 42 SNe were divided 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 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 (see Progress to Date).

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
Goldhaber G., et al., 2001, ApJ 558, 359
Kim A., et al., 1997, ApJ 476, L63
Knop A., et al., 2003, ApJ 598, 102
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
Spergel D., et al., 2003, ApJS 148, 175
Sullivan M., et al., 2003, MNRAS 340, 1057
Tonry, J., et al., 2003, ApJ 594,1

[height=2.5in,bb=50 140 590 665]SCP2003hubsimpletrans.eps [height=2.4in]ms$_{h}ubble_{t}ype2.ps$

Figure 1: *Left:* The SN Ia Hubble diagram for all low-extinction supernovae from Knop *et al.* (2003). Supernovae within $z < 0.01$ of each other have been combined using a weighted average in order to more clearly show the quality and behavior of the dataset. The solid curve overlaid on the data represents our best-fit flat-universe model, $(\Omega_M, \Omega_\Lambda) = (0.25, 0.75)$. Two other cosmological models are shown for comparison: $(\Omega_M, \Omega_\Lambda) = (0.25, 0.0)$, and $(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$. *Right:* The SNe Ia Hubble diagram (on a log-redshift scale) for the SCP (Perlmutter *et al.* 1999) dataset plotted according to the class of the host galaxy. The inset shows the high-redshift SNe, the main panel the entire sample. Boxed points show SNe excluded from 'fit-C' of Perlmutter 1999. SNe in elliptical/S0 host galaxies show significantly less scatter than those in later types.

[height=2.3in]cumulative5yr.ps [height=2.3in]keck03awconf2.eps

Figure 2: *Left:* The actual and projected cumulative number count over time of the SNLS project. As of August 2004 there are more than 100 spectroscopically confirmed SNe Ia. The vertical dashed line indicates the present day, with projections to survey end based on current survey numbers to the right of the line. *Right:* Confidence region in the $(\langle w \rangle - \Omega_M)$ plane, assuming a flat universe, from the 42 distant SNe Ia in Perlmutter et al. 1999, overlaid with a simulated projected 1-σ contour illustrating anticipated improvement based on three advances over the Perlmutter 1999 results: 1) the projected mid-project SNLS dataset (300 SNe; around February 2006 from the left-hand panel), 2) a dataset of 200 well-measured SNe Ia from, for example, the Nearby Supernova Factory, and 3) a gaussian prior on $\sigma(\Omega_M) = 0.03$ reflecting the improvement anticipated from large scale structure and CMB measurements.The simulation was done assuming $w = -0.8$ and demonstrates the ability of SNLS to test whether a cosmological constant fits the data or if some other model of dark energy is required.

[height=3.8in]rolling.ps

Figure 3: A sample of SN Ia lightcurves from the 2004A semester of SNLS. Three of the four SNLS filters are shown, from g (top) through r (middle) to i (lower panel). Note that SNe are always discovered well before maximum light (allowing spectroscopy to be performed when the candidate is brightest), and that a similar number of quality candidates are available at any moon phase. For clarity, only around half of the SNe Ia confirmed in this time interval are shown.

[width=3.05in]04D3co.ps [width=3.05in]04D3df.ps
[width=3.05in]04D3kr.ps [width=3.05in]04D3gt.ps

Figure 4: Example spectra of SNLS supernova candidates obtained during the Spring 2004 Keck LRIS/DEIMOS observing campaigns. The light-blue lines show the data after host galaxy subtraction (if necessary), rebinned to 10 Å. Overplotted in dark blue are the smoothed versions of the data, with the best fit SN templates shown in black. The spectra are confirmed by Keck to be Type Ia SNe.

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 recently 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, 2003). 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 were recently able to obtain the images and final analysis is proceeding.

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 spectra are fully reduced using out 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 offering 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 is beyond the grasp 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 $z > 0.4$. (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 searchs.

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 a classification somewhere between probable and certain. 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 $z \sim 0.9$. 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 February through 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.**

Instrumentation: !!!TO BE EDITED!!! In the past we have used both LRIS, DEIMOS and ESI for our SN spectroscopy program. At the highest redshifts we have found that ESI is superior for our purposes, primarily because the high resolution of ESI separates out the night sky lines, allowing them to be excised from the data before smoothing to identify SNe and galaxy features. However, we have seen that DEIMOS can produce excellent sky subtraction, and can be competitive with ESI (with poorer OH suppression but better throughput) at these more moderate redshifts. Moreover, since SNLS observations are planned for the Groth Strip — one of the DEEP program's target fields — we have developed a plan with the DEEP team to obtain Groth Strip galaxy spectra in parallel with the SN observations requested here, whenever possible.

Therefore, for 2004A we will request the DEIMOS spectrograph for all 4 nights. Davis *et al.* are also proposing to observe in a region that includes EGS. In cases where SNLS supernovae appear in the region of an unobserved DEEP2 mask with sufficient lead time to mill a new slitmask, the DEEP team will remove 3 slitlets from a previously designed 1HS mask and replace them with a single slit on the supernova. This was tested in 2004A, when we successfully obtained spectra a newly-discovered SN on DEEP2 mask 1245. Similarly, we will bserve DEEP2+SN masks when feasible; this will somewhat diminish eather risks for each team (as DEEP2 masks or SNe will be observed over more nights), and maximize the scientific yield of each team's observations. To facilitate these joint efforts, we request that the SCP and the DEEP team be allocated contiguous nights when possible.

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]/Hα 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 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). 2 candidates remain to be typed. During this sesmester, 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.

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 Extended Groth Strip (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 acquistion 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 combinatons of ACS photometry and slitless spectroscopy and NICMOS imaging as part of our 100-orbit cycle 10 program. Final reference images were obtained in fall 2003; analysis is now underway.

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, and 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) is (still) at the highest redshift that Type Ia SNe have yet been confirmed (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. 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 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) 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. On our 2004A DEIMOS/LRIS run we successfully acquired all our targets, using a direct acquisition capability for the faintest targets on DEIMOS, which involved taking direct images, automatically performing the astrometric alignment of the DEIMOS image with our SN discovery image, and offsetting the telescope. (Note that we can't just use the DEIMOS image directly because host-galaxy light is blended with — and spatially offset from — the SN.)

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 permanent staff scientists, two UC professors, a scientist/project coordinator, five 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.)

* 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, Peter Nugent, Alex Kim, Saul Perlmutter, 2002, PASP 114, 803.

*The Distant Type Ia Supernovae Rate, R.Pain, *et al.*, presented at the January 2002 AAS meeting.

*Verifying the Use of Type Ia Supernovae as Probes of the Cosmic Expansion, R.Ellis, *et al.*, presented at the January 2002 AAS meeting.

*Ω_M and Ω_Λ from 11 HST-Observed Supernovae at z=0.36-0.86, R.Knop, *et al.*, presented at the January 2002 AAS meeting.

*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.Schahmaneche, *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 SN Ia 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

* Latest Cosmological Results from Type Ia Supernovae, R. Knop, *et al.*, 2000, Bulletin of the

American Astronomical Society, 197, 950

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

* The acceleration of the Universe: measurement of cosmological parameters from type Ia supernovae, A. Goobar, S. Perlmutter, G. Aldering, G. Goldhaber, R.A. Knop, P. Nugent, P. G. Castro, S. Deustua, S. Fabbro, D. E. Groom, I. M. Hook, A. G. Kim, M. Y. Kim, J. C. Lee, N. J. Nunes, R. Pain, C. R. Pennypacker, R. Quimby, C. Lidman, R. S. Ellis, M. Irwin, R. G. McMahon, P. Ruiz-Lapuente, N. Walton, B. Schaefer, B. J. Boyle, A. V. Filippenko, T. Matheson, A. S. Fruchter, N. Panagia, H. J. M. Newberg, W. J. Couch, 2000, Physica Scripta, T85, 47.

Metallicity Effects in NLTE Model Atmospheres of Type Ia Supernovae, E. J. Lentz, E. Baron, D. Branch, P. H. Hauschildt, & P. E. Nugent, 2000, Astrophysical Journal, 530, 966L.

* Constraining Dark Energy with SNe Ia and Large-scale Structure, S. Perlmutter, M. S. Turner, & M. White 1999, Phys. Rev. Lett., 83, 670.

* The Cosmic Triangle: Revealing the State of the Universe, N. Bahcall, J. P. Ostriker, S. Perlmutter, P. J. Steinhardt 1999, Science, 284, 1481.

High Redshift SNe in the Hubble Deep Field, R. L. Gilliland, P. E. Nugent & M.M. Phillips, ApJ, vol. 521, p.30-49, 1999

* Measurements of Ω and Λ from 42 High-Z Supernovae, S. Perlmutter, G. Aldering, G. Goldhaber, R.A. Knop, P. Nugent, P. G. Castro, S. Deustua, S. Fabbro, A. Goobar, D. E. Groom, I. M. Hook, A. G. Kim, M. Y. Kim, J. C. Lee, N. J. Nunes, R. Pain, C. R. Pennypacker, R. Quimby, C. Lidman, R. S. Ellis, M. Irwin, R. G. McMahon, P. Ruiz-Lapuente, N. Walton, B. Schaefer, B. J. Boyle, A. V. Filippenko, T. Matheson, A. S. Fruchter, N. Panagia, H. J. M. Newberg, W. J. Couch, Astrophysical Journal, 517, 565 (1999).

* Snapshot Distances to SNe Ia – All in 'One' Night's Work", A. Riess, P. Nugent, A. Filippenko, R. Kirshner and S. Perlmutter, Astrophysical Journal, September, 1998.

Gravity: From the Hubble Length to the Planck Length, G. Goldhaber, XXVI SLAC Summer Institute, August, 1998

* Discovery of a Supernova Explosion at Half the Age of the Universe and its Cosmological Implications, S. Perlmutter, G. Aldering, M. Della Valle, S. Deustua, R. S. Ellis, S. Fabbro, A. Fruchter, G. Goldhaber, A. Goobar, D. E. Groom, I. M. Hook, A. G. Kim, M. Y. Kim, R.A. Knop, C. Lidman, R. G. McMahon, P. Nugent, R. Pain, N. Panagia, C. R. Pennypacker, P. Ruiz-Lapuente, B. Schaefer and N. Walton, Nature, 391, 51 (1998).

* Measurements of the Cosmological Parameters Ω and Λ from the First 7 Supernovae at $z \geq 0.35$. S. Perlmutter, S. Gabi, G. Goldhaber, D. E. Groom, I. M. Hook, A. G. Kim, M. Y. Kim, J. Lee, C. R. Pennypacker, I. A. Small, A. Goobar, R. Pain, R. S. Ellis, R. G. McMahon, B. J. Boyle, P. S. Bunclark, D. Carter, M. J. Irwin, K. Glazebrook, H. J. M. Newberg, A. V. Filippenko, T. Matheson, M. Dopita, and W. J. Couch, Astrophysical Journal, 483, 565 (1997).

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

*The Type Ia supernova rate at $z \sim 0.4$, R. Pain, I. Hook, S. Perlmutter, *et al.*, Astrophysical Journal, 473, 356 (1996).

*Observation of cosmological time dilation using type Ia supernovae as clocks. (The Supernova Cosmology Project: III.) G. Goldhaber, *et al.*, in Thermonuclear Supernovae, NATO ASI, eds. R. Canal, P. Ruiz-LaPuente, and J. Isern (1996).

*K corrections for type Ia supernovae and a test for spatial variation of the Hubble constant. (The Supernova Cosmology Project: II.) A. Kim, *et al.*, in Thermonuclear Supernovae, NATO ASI, eds. R. Canal, P. Ruiz- LaPuente, and J. Isern (1996).

A generalized K correction for type Ia supernovae: Comparing R-band photometry beyond $z = 0.2$ with B, V, and R-band nearby photometry. A. Kim, A. Goobar, and S. Perlmutter, Publications of the Astronomical Society of the Pacific, 108, 190 (1996).

Feasibility of measuring the cosmological constant Λ and mass density Ω using supernova standard candles. A. Goobar and S. Perlmutter, Astrophysical Journal, 450, 14 (1995).

The distant supernova search and implications for the cosmological deceleration. A. Goobar, B. Boyle, P. Bunclark, D. Carter, R. Ellis, S. Gabi, G. Goldhaber, M. Irwin, A. Kim, M. Kim, R. McMahon, R. Muller, R. Pain, C. Pennypacker, S. Perlmutter, and I. Small, Nuclear Physics B (Proc. Suppl.) 43, 78 (1995).

The blue and visual absolute magnitude distributions of type Ia supernovae. T. Vaughan, D. Branch, D. L. Miller, and S. Perlmutter, Astrophysical Journal, 439, 558 (1995).

A Type Ia supernova at $z = 0.457$. S. Perlmutter, C. Pennypacker, G. Goldhaber, A. Goobar, J. Desai, A. Kim, M. Kim, R. Muller, H. Newberg, I. Small, R. McMahon, B. Boyle, D. Carter, M. Irwin, P. Bunclark, K. Glazebrook, and R. Ellis, Astrophysical Journal Letters, 440, L41 (1995).

Discovery of the most distant supernovae and the quest for Ω. G. Goldhaber, B. Boyle, P. Bunclark, D. Carter, R. Ellis, S. Gabi, A. Goobar, A. Kim, M. Kim, R. McMahon, R. Pain, C. Pennypacker, S. Perlmutter, I. Small, and R. Terlevich, Nuclear Physics B (Proc. Suppl.) 38, 435 (1995).

Publications In Preparation

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

Supernova Discoveries In IAU Circulars

More than 120 discoveries of supernovae, reported in International Astronomical Union Telegrams and Circulars, including:

Supernovae 1994F, 1994G, 1994H, Circular 5956, 24 March 1994, S. Perlmutter, *et al.*

Supernovae 1993al, 1994al, 1994am, 1994an, Circular 6263, 18 November 1995, S. Perlmutter, *et al.* (The Supernova Cosmology Project).

*Eleven High-Redshift Supernovae: 1995aq through 1995az, and 1995ba, Circular 6270, 6 December 1995, S. Perlmutter, *et al.* (The Supernova Cosmology Project).

*Fourteen High-Redshift Supernovae: Circular 6540, 17 January 1997, Supernova Cosmology Project.

*Sixteen High-Redshift Supernovae: Circular 6596, 20 March 1997, Supernova Cosmology Project.

*Nine High-Redshift Supernovae: Circular 6621, 9 April 1997, Supernova Cosmology Project.

*Seventeen High-Redshift Supernovae: Circular 6804, 6 January 1997, Supernova Cosmology Project.

*Twenty High-Redshift Supernovae: Circular 6881, 22 April 1998, Supernova Cosmology Project.

*Three High-Redshift Supernovae: Circular 7046, 5 November 1998, Supernova Cosmology Project.

*Supernova 1999ab, Circular 7109, Supernova Cosmology Project.

*Supernovae 1999ae, 1999af, 1999ag, 1999ah, 1999ak, 1999al, Circular 7177, Supernova Cosmology Project.

*Supernova 1999am, Circular 7122, Supernova Cosmology Project.

*Supernovae 1999ap, 1999aq, 1999ar, Circular 7125, Supernova Cosmology Project.

*Supernovae 1999as, 1999at, Circular 7128, Supernova Cosmology Project.

*Supernovae 1999au, 1999av, 1999aw, 1999ax, 1999ay, Circular 7130, Supernova Cosmology Project.

Supernovae 1999ax and 1999ay, Circular 7357 A. Gal-Yam, D. Moaz, R. A. Stathakis, & G. Aldering.

*Supernovae 1999az, 1999ba, 1999bb, Circular 7131, Supernova Cosmology Project.

*Supernovae 1999bc, 1999bd, Circular 7133, Supernova Cosmology Project.

*Supernovae 1999be, 1999bf, Circular 7134, Supernova Cosmology Project.

Supernovae 1999bi, 1999bj, 1999bk, 1999bl, 1999bm, 1999bn, 1999bo, 1999bp, 1999bq, Circular 7136, Supernova Cosmology Project.

*Supernova 1999bh, Circular 7138, Supernova Cosmology Project.

Supernova 2000ca, Circular 7413, G. Aldering & A. Conley

Supernova 2000cc, Circular 7414, G. Aldering & A. Conley

Supernova 2000cb, Circular 7410, G. Aldering & A. Conley

Supernova 2001ay in IC 4423, Circular 7612, P. Nugent, G. Aldering, I. Hook, S. Perlmutter, L. Wang

Supernovae 2001cq, 2001cr, 2001cs, 2001ct, 2001cu, 2001cv, 2001cw, Circular 7649, M. Doi, H. Furusawa, F. Nakata, M. Ouchi, N. Yasuda, S. Miyazaki, N. Kashikawa, Y. Komiyama, Y. Ohyama, M. Yagi, K. Aoki, I. Hook, S. Perlmutter, G. Aldering

* Supernovae 2001gk, 2001gl,2001gm,2001go, 2001gp,2001gq,2001gr, 2001gs, 2001gt, 2001gu, 2001gv, 2001gw, 2001gx, 2001gy, 2001gz, 2001ha, 2001hb, 2001hc, 2001hd, 2001he, Circulars 7763 & 7764, Supernova Cosmology Project.

* Supernovae 2002km-2002ky, M. Doi, Circular 8119.

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