2. The Supernova Legacy Survey – SNLS

**Summary:** After only 18 months of operation, the Supernova Legacy Survey (SNLS) is the most successful high-redshift supernova study in history, with more confirmed Type Ia supernovae (SNe Ia) and better light-curve cadence and filter coverage than ever previously achieved. We are on track to (i) spectroscopically confirm 700 SNe Ia by 2008, and (ii) use these SNe to determine the nature of the Dark Energy driving the accelerating expansion of the universe, via a measurement of the equation-of-state parameter, \( w \). Such a legacy-quality data set will also provide the control over systematics which will form the cornerstone of third generation studies to determine changes of \( w \) with redshift.

Operationally, the SNLS is an extraordinary success. We are finding supernovae in the expected numbers, and CFHT queue scheduled observing is functioning well in providing our required time sampling. We have created new, more efficient pipelines for real-time and final data reduction, SN discovery, follow-up spectroscopy, SN typing, light-curve fitting, and database manipulation. Our large allocation of VLT/Gemini/Keck spectroscopic time (averaging 140 hr per semester) continues for SN Ia identification. We exploit our new techniques to preselect likely SNe Ia ensuring the most efficient use of this time. Our first cosmology paper is ready to submit (preliminary \( 0.79 \)); one paper is being refereed, and several other papers will be submitted within 3 months. Additional follow-up programs are underway to leverage the investment in this survey and contribute to its continuing legacy value, including an intensive Keck spectroscopic rest-frame UV study to understand progenitor metallicity, a study investigating the first use of Type II SNe as cosmological probes, and a Magellan near-IR program investigating the effects of dust extinction on SNe Ia. Three Hubble Space Telescope proposals have been submitted to extend these programs.

Several challenges remain for the SNLS. At \( z > 0.6 \) our cosmological analysis is directly impacted by the signal-to-noise in the \( z' \) filter, and there are concerns with future shortening of Megacam runs and interruptions due to MOS scheduling. We propose:

- Exposure times in \( z' \) should be increased by 6 hr per queue run per field, for fields D1 and D4, for the SNLS to achieve its stated goals at the highest redshifts. This can be accomplished by adding a night at each end of the queue run.
- For optimal SN light curve sampling, MegaPrime run lengths need to be maintained at a minimum of 17-18 nights, with MOS scheduling either discontinued, or moved to small blocks in the middle of dark runs.
- Our allocation requires modification across A and B semesters to accommodate the RA distribution of our 4 fields, and (if approved) our extra observing time in \( z' \) for fields D1 and D4.

Finally we ask the SAC/Board for a clear prioritization of CFHTLS components in the event that MegaPrime observing efficiency continues to be lower than expected.
2.1 Supernovae, the Accelerating Universe, and Dark Energy

The discovery of the accelerating Universe ranks as one of science’s landmark achievements in the closing decades of the 20th century. Pioneering surveys of cosmologically distant Type Ia supernovae (SNe Ia; Riess et al. 1998, Perlmutter et al. 1999) indicated the presence of a new, unaccounted-for “dark energy” that opposes the self-attraction of matter and causes the expansion of the universe to accelerate. When combined with observations of the power spectrum of the cosmic microwave background (e.g., Spergel et al. 2003), a consistent cosmological paradigm emerges of a flat Universe, with 70% of its energy contained in the form of this cosmic dark energy.

Yet, the fundamental physics underpinning this dominant energy component is still largely unconstrained. We know virtually nothing about the nature of dark energy – though theoretical speculation abounds. Furthermore, there exist fundamental physical differences between various theoretical conjectures, any of which would have far-reaching implications for our understanding of the Universe. The possibilities can be divided into three broad categories. The first, the classical “Cosmological Constant” originally posulated by Albert Einstein, is equivalent to a vacuum energy density, constant in time and space. The second class of theories covers the many formulations of quintessence models (quintessence is a dynamic form of energy with negative pressure that varies with both space and time, modeled as a scalar field). A third possibility is the existence of some more exotic physics, perhaps signalling that some modification to the theory of general relativity is required.

The observational identification or rejection of any of these classes of models would have profound reverberations throughout theoretical cosmology. Distinguishing among these possibilities is best addressed by measuring the average equation-of-state parameter of the dark energy \( \langle w \rangle \), defined as the ratio of pressure to density \( \langle w \rangle = \langle p \rangle \langle \rho \rangle \). A value of \( \langle w \rangle = -1 \) corresponds to vacuum energy. Quintessence models require \( \langle w \rangle > -1 \), with most predicting \( \langle w \rangle > -0.8 \) (e.g., Huterer and Turner 2001); values of \( \langle w \rangle < -1 \) are the signature of very exotic physics. Current measurements of \( \langle w \rangle \) (Knop et al. 2003; Tonry et al. 2003; Riess et al. 2004) are consistent with a very wide range of dark energy theories (see Peebles and Ratra 2003, or Padmanabhan 2004, for a review).

The challenge to observational cosmology over the next decade is to place the tightest possible observational constraints on the value of \( \langle w \rangle \), via independent techniques. Although various measures of large-scale structure can lead to a separate confirmation of the cosmic acceleration (e.g., Efstathiou et al. 2002; Cole et al. 2005; Eisenstein et al. 2005), only SNe Ia directly trace the expansion history without relying on model-dependent assumptions. With high-redshift samples containing hundreds of confirmed supernovae, we will be able to answer the crucial question facing modern cosmology: "Is the Dark Energy simply Einstein’s Lambda?"

2.2 SNLS – The Supernova Legacy Survey

The importance of improving SN-based determinations of \( \langle w \rangle \) to the point where \( \langle w \rangle = -1 \) and \( \langle w \rangle = -0.8 \) models can be differentiated has motivated a “second-generation” of SN cosmology studies (of which SNLS is the leading example): large multi-year, multi-observatory programs benefiting from major commitments of dedicated time. These “rolling searches” find and follow hundreds of high-redshift SNe over consecutive months of repeated wide-field imaging, with redshifts and SN type classifications from coordinated 8-10m telescope follow-up spectroscopy. The over-arching goal is to derive a constraint on \( \langle w \rangle \) by building an order-of-magnitude larger sample (i.e. \( \sim 700 \)) of SNe Ia in the redshift range \( z = 0.2 - 0.9 \), where \( \langle w \rangle \) is best measured. The 700 well-measured SNe Ia, together with an \( \Omega_M \) prior known to \( \pm 0.03 \) (i.e. 10%) from CFHTLS weak lensing, will allow us to determine \( w \) to a statistical precision of \( \pm 0.07 \), distinguishing between \( w > -0.8 \) and \( w = -1 \) at 3σ.

The full five-year CFHT “Supernova Legacy Survey” (SNLS\(^1\)\(^2\)) officially began in June 2003 (with pre-survey from March 2003), and will provide the biggest improvement in the determination

1. http://cfht.hawaii.edu/SNLS/
2. Database at http://legacy.astro.utoronto.ca/
of the dark energy parameters achievable over the next decade. (By way of comparison, ESSENCE, scheduled to terminate in 2006, identifies \( \sim 1/4 \) the number of SNe per year that SNLS produces.) Beyond the current surveys, future facilities (e.g. the Dark Energy Camera) will not be available until around 2010. Pan-STARRS has a similar timescale. LSST and the various candidates (e.g. SNAP) for the proposed Joint Dark Energy Mission (JDEM) are on a still more extended timeline (at least 2015) and, indeed, await confirmation of their funding. Furthermore, future ground-based surveys (\( \gtrsim 10^3 \) SNe) run the risk of being spectroscopy-starved, placing fundamental limits on the number of confirmed candidates. Hence, SNLS will provide the definitive high-redshift SN Ia dataset for at least the next decade, with a lasting legacy even beyond this.

### Table 1 – SNLS Filter Mapping with Redshift

<table>
<thead>
<tr>
<th>( z )</th>
<th>( g' )</th>
<th>( r' )</th>
<th>( i' )</th>
<th>( z' )</th>
<th>( Y )</th>
<th>( J^a )</th>
<th>( H^b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1–0.2</td>
<td>B</td>
<td>V</td>
<td>R</td>
<td>I</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>0.3–0.4</td>
<td>U</td>
<td>B</td>
<td>V</td>
<td>R</td>
<td>R</td>
<td>I</td>
<td>–</td>
</tr>
<tr>
<td>0.5</td>
<td>U</td>
<td>B</td>
<td>V</td>
<td>R</td>
<td>R</td>
<td>I</td>
<td>–</td>
</tr>
<tr>
<td>0.6</td>
<td>–</td>
<td>U</td>
<td>B</td>
<td>V</td>
<td>R</td>
<td>I</td>
<td>–</td>
</tr>
<tr>
<td>0.7–0.8</td>
<td>–</td>
<td>U</td>
<td>B</td>
<td>V</td>
<td>V</td>
<td>R</td>
<td>I</td>
</tr>
<tr>
<td>0.9–1.0</td>
<td>–</td>
<td>–</td>
<td>U</td>
<td>B</td>
<td>V</td>
<td>R</td>
<td>I</td>
</tr>
</tbody>
</table>

\(^a\) PANIC J and NICMOS F110M  
\(^b\) NICMOS F145M

The power of SNLS comes from both its wavelength coverage and the temporal cadence of the survey. SN Ia Hubble diagrams are typically constructed using SN luminosities measured at maximum light in the rest-frame \( B \)-band, and the observational data that makes up these analyses must meet two requirements. The first is a consistent rest-frame wavelength coverage at all SN redshifts. Extinction corrections to the \( B \)-band luminosities are performed via comparisons of the observed \( U-B \) and \( B-V \) SN colours to those determined in extinction-free local SN samples. Sampling the rest-frame \( B \)-band at all SN redshifts, and measuring the \( U-B \) and \( B-V \) colours at as many redshifts as possible, clearly requires observations over a wide wavelength range (see Table 1); observations in different filters are all equally critical in constructing Hubble diagrams. The second requirement is that many observation epochs must be spaced over a wide period in any given month, so that all SNe are sampled as close to maximum light as possible. When the fits to the SN light-curves are then made, the uncertainties in determining maximum light luminosities are much reduced; the converse of course is that missing epochs results in poorer cosmological constraints.

The design of SNLS fulfills both the time and wavelength requirements. Observations in \( g' \), \( r' \), \( i' \) and \( z' \) allow the sampling of rest-frame \( B \), together with both \( U-B \) and \( B-V \) colours at redshifts \( z \lesssim 0.8 \) (but only \( U-B \) beyond \( z \approx 0.9 \)). Furthermore, our carefully designed survey cadence (Appendix C) ensures that the uncertainties in fitting light-curves are minimised, and that the statistical errors in our analyses are at the same level as, or less than, the systematic uncertainties. The SNLS dataset itself will allow powerful tests on several of these key systematics, as the examples in Appendix A illustrate. At survey end, SNLS will provide not only the discriminating measurement of dark energy, but also a homogeneous SN Ia dataset which will form the authoritative reference sample for decades to come.

### 2.3 SNLS: From Detections to Cosmology

The SNLS is a demonstrably successful survey. Here we outline the passage from raw data being taken at CFHT, to our principal science product, the SN Hubble diagram.

\( \triangleright \) The Collaboration – The success of SNLS is largely due to the strong SN teams that have been assembled in both Canada and France. In Canada activity is concentrated at U. Toronto and
U. Victoria, where 2 faculty, 6 PDFs (funded by an NSERC CRO grant), and several students are located. Canadian support also originates from NSERC Discovery grants (to Carlberg and Pritchet), and CIAR support to Carlberg. In France, 12 faculty/researchers and 5 students are supported by CNRS/IN2P3, CNRS/INSU and CEA. Other SNLS groups are also active at Oxford, UC Berkeley, and Lisbon. SNLS is managed by a Collaboration Board, headed by Reynald Pain (IN2P3, France). MOU’s have been signed to govern the interactions of the principal partners in the collaboration.\footnote{See \url{http://snls.in2p3.fr/people/snls-members.html} for a full list of collaborators.}

- **Observations** – SNLS observations are obtained in queue-scheduled mode by CFHT staff. See Pritchet \textit{et al.} (2005), Howell \textit{et al.} (2005), and Appendix C for more details on the observations. Our Phase 2 observing plan is submitted each month, and our detailed observational requirements are revised after each night’s observations on our SNLSObs dynamic web page.\footnote{\url{http://legacy.astro.utoronto.ca/SNLSObs/}} (SNLS was the first survey component to adopt this approach.) The queue-scheduled observations have worked extremely well, thanks to a Queued Service Observing (QSO) Team that is very responsive to our requirements. Our observational cadence is presented in Appendix C.

- **Real-Time Data Reduction and candidate photometry** – An overview of the real-time data reduction and candidate selection process is given in Appendix F. The Canadian Real-Time Team consists of David Balam (U. Victoria) and Kathy Perrett (U. Toronto). The French team is a larger group headed by Pierre Astier and Dominique Fouchez. Both groups use the Toronto database.\footnote{\url{http://snls.in2p3.fr/people/snls-members.html}}

CFHT pre-processes our data immediately after acquisition using the “Real-Time Elixir” pipeline (which differs from final Elixir processing in that it uses the previous month’s flats and calibration images). Within typically 5–10 minutes the RT processed data is transferred to our computers in Waimea (which are accessed by X-windows sessions). Canadian and French teams independently (1) astrometrically and photometrically align and combine the new images, (2) psfmatch the combined images so that the IQ is matched to a reference image, (3) subtract the psfmatched image from the reference image, and automatically search for objects that have varied, (4) visually confirm or reject the objects that have varied. Within \(\sim 6\) hours of data arriving in Waimea, new candidate events are loaded into our database to be further screened for spectroscopic follow-up. Note that at all times during this process CFHTLS data access policies are respected: all data remains at CFHT during processing.

Generally the lists of supernova candidates that emerge from the Canadian and French pipelines agree at the 90\% level to \(i’ = 24.5\). Our completeness tests on the data indicate that we are detecting almost all supernovae at \(i’ \leq 24\) (see Appendix E). In the future we will consider dropping part or all of one of the detection pipelines, as the operations have become quite routine.

Fig. 2 shows an example of one of our detections, compared with a serendipitous HST ACS image of the same supernova. This indicates the basic quality of the psfmatched subtractions in our data, and the nature of the high redshift detections that we are obtaining.

Photometry, both for new candidates (automatically extended back to earlier epochs) and for pre-existing candidates, is measured, and real-time light-curves of all variable events are constructed. This real-time photometry is completed in about 4 hours. Fig. 3 shows some of our SNe Ia light curves in the time interval March–December 2004. The quality of this (real-time) photometry, and the epoch sampling, is excellent.

- **Database** – An extensive relational SQL database with a web-based PHP front end has been designed and built for the survey by the SNLS at the University of Toronto. All of the observational and candidate data (including all photometry and spectroscopy) are easily managed for the benefit of rapid and accurate follow-up observations. Basic candidate information is also publicly accessible to the community via our website. Internally, the SNLS database greatly facilitates the organization and formulation of scientific results in preparation for publication.

- **Candidate Selection and Spectroscopy** – Spectroscopy with 8–10 m class telescopes is essential to obtain redshifts and classify the supernovae. We have been allocated more time for 8-10m spec-
Fig. 2 – SN 04D2ca (z=0.83) on March 10, 2004. The montage of 3 panels on the left shows SNLS observations (left: Mar 10; middle: reference epoch; right: difference after psf matching, showing the supernova). The right-hand panel shows an ACS image taken at about the same time; this clearly resolves the SNIa from the host. This figure illustrates just how well one can do from the ground with psf matching.

troscopy than for the CFHT imaging (per semester: VLT 60 hr, Gemini 60 hr (30 Canada + 20 UK + 10 USA), Keck 20 hr; cf. 130 hr SNLS imaging at CFHT). For reference, Canada’s total available time at Gemini is 162 hr this semester. These numbers reflect only the spectroscopic classification time, and do not include the Keck (4 nights/year) and Magellan (25 nights/year) complementary scientific follow-up time for other related programs.

We have also developed new techniques to make more efficient use of our spectroscopic time (Howell et al. 2005, Basa et al. 2005). Using the real-time $g' r' i' z'$ photometry, we are able to predict candidate redshift and phase – as well as a probability that the candidate is a SNIa – after only 2–3 epochs of CFHT data. These predictions allow us to schedule follow-up time when a SN is at maximum light, while efficiently rejecting AGN, variable stars and SNe II from our follow-up program. The results are an overwhelming success: since implementation of this selection technique (essentially 2004A), 80% of SNe followed with Gemini (median $z = 0.81$) have been confirmed as SNe Ia.

![SNLS real-time light-curves](image)

Fig. 3 – A sample of real-time (not final) SN Ia light curves in (top–bottom) $g'$, $r'$, and $i'$ from 2004A to present. SNe are always discovered well before maximum light (allowing follow-up spectroscopy to be performed when the candidate is brightest), and are typically followed until several weeks past maximum light. Most error bars are smaller than the size of the points.

The redshift distribution of our SNe to date is shown in Fig. 5; this distribution is well-understood in terms of our spectroscopic selection function, coupled with incompleteness at high $z$. Example
Fig. 4 – Example Spectra of SNLS Type Ia SNe obtained during the 2003B/2004A spectroscopic observing campaigns. The light blue lines show the data after host galaxy subtraction (if necessary), rebinned to 5Å. Overplotted in dark blue are smoothed versions of the data, with best-fitting SN Ia templates shown underneath.

Fig. 5 (left) – The redshift distribution of spectroscopically confirmed SNLS SNe Ia. SN Ia? denotes those SNe with a less certain classification from their optical spectroscopy. The solid line overplotted is the expected N(z) based on our search and spectroscopic efficiencies. The decline to high-redshift is a product of a more expensive spectroscopic observation as the SNe appear fainter.

Fig. 6 (right) – The cumulative number of SN discovered by SNLS to December 2004; the inset shows the distribution extrapolated to the survey mid-point. About 700 spectroscopically confirmed SNe Ia are expected by survey end in 2008.

spectra are shown in Fig. 4. Gemini, with its Nod & Shuffle sky elimination, plays a pivotal role in the highest-redshift science, whereas the VLT, with its relatively low overheads, is used (though not exclusively) for low-intermediate z objects. See Howell et al. (2005) for more information on the spectroscopy.

Final Photometry and Cosmology – Independent final photometry, calibration, and cosmology pipelines are operational in Canada and France. Both groups maintain close contact, but the algo-
arithmic and operational separation of these complex analyses is viewed as one of the strengths of our collaboration. Fluxes have been compared and are in good agreement. We expect to maintain separate calibration and analysis pipelines for the foreseeable future. Details of the French pipeline are in Astier et al. (2005); the Canadian pipeline will be described in a paper to be submitted in May-June 2005.

2.4 Current Status and First Results

Observational Status

As of February 2005, a total of \( \sim 750 \) candidate supernovae have been detected in SNLS. Of these, 162 have been confirmed spectroscopically as definite or probable SNe Ia, with 40 core collapse SNe of various types. An extrapolation to the future can be found in Fig. 6.

Our observational strategy at CFHT has proven reasonably successful. In the past semester (2004B) we obtained 89\% of our open-shutter allocation, with appropriate time sampling and multi-filter coverage. (This looks more impressive than it really is, for reasons discussed in §2.5.) Our relative success (that is, relative to the Wide/Very-Wide LS Surveys, which achieved \( \sim 56/50\% \) of their allocated time) can be understood in terms of: (i) the time-critical nature of our observations, (ii) the pressure of 8m telescopes that lie waiting for suitable SN candidates, (iii) the fact that SAC gave us priority, and (iv) the fact that the Wide LS Survey adopted a deliberate “go slow” policy up until late 2004B because of IQ concerns.

*One concern is the depth of the \( z' \) exposures*; this is discussed in §2.5. The reader is referred to Appendix E for a discussion of image quality and its effects on SNLS, and to Appendix D for more on calibration issues.

Publications and Work in Progress

Now that the immense task of building next-generation data reduction pipelines is complete and daily operations are now routine, we are making the transition to the scientific publication phase of the project. Our first paper\(^5\) (Howell et al. 2005) was submitted in February 2005; this paper covers Gemini spectroscopy and new techniques for spectroscopic follow-up and classification. Our first cosmology paper\(^5\) has gone through several drafts, and is about to be submitted. A preliminary Hubble diagram from our first \( \sim 60 \) SNe (semesters 2003B–2004A) from this paper is shown in Fig. 7. Several other papers are in preparation; these include:

- photometric typing and redshifts (led by Sullivan)
- VLT spectroscopy (Basa et al. 2005)
- Keck spectroscopy at intermediate \( z \) (with Ellis and collaborators)
- cosmology II (led by Howell and Sullivan)

See Appendix B for more on other follow-up projects and work in progress, and Appendix A for more on projects related to SN systematics.

2.5 SNLS – Future Prospects and Planning

There are a number of issues that face SNLS; almost all of these concern the allocation of time. Validated exposures for SNLS in 2004B amounted to 89\% of our allocated open shutter time. This looks impressive, but pressure is being exerted by the W and VW components of the LS to “spread the pain” – to reduce our proportion of the LS “agency” time so that we each get about the same fraction (70\%) of data requested in our highest priority queue. We were able to accommodate this request in 2005A because our A semester requirements are about 20\% lower than B semester; in addition almost all \( u^* \) observations were moved to the lower priority queue. We cannot accommodate such a request in semester 2005B without a radical descoping of the SNLS survey.

\(^5\) The latest versions of our papers can be found at http://snls.in2p3.fr/conf.
SNLS is at a critical juncture. We are now the leading high-redshift supernova survey (cf. SNLS – 160 SNe Ia in 1.5 yr, with 3.5 yr to go, vs. ESSENCE – ~ 80 SNe Ia in 3 yr, with 2 yr to go) – there appears to be no current or planned survey that can surpass our science before at least 2010. We have made great progress in putting together a superb science team, and are close to our required observing time; furthermore, we are rapidly converging on our science goals. Our success is recognized by the very large allocation of 8–10m spectroscopy time awarded for SN follow-up.

Our success is despite the fact that our survey allocation (132 hr per semester, or 1318 hr over 5 years) is some 13% less than we originally requested (1488 hr), with a further 10% cut if overheads are included. To compensate, we have already decreased all our exposure times by ~10% and eliminated two $g'$ epochs per queue run (though we will reinstate one of these $g'$ exposures). Our estimated 5 year haul of useful spectroscopically confirmed SNe Ia has dropped from 1000 to 700, at least partly because of limited 8m follow-up resources, and partly because we are selective in terms of S/N and phase coverage before we submit a candidate for spectroscopy. Further decreasing our allocation now would jeopardize the future allocation of 8-10m spectroscopic time, and send an undesirable message that could lead to competitive proposals on other telescopes – SNLS would lose its dominant position as the world-leader in this field.

The case for $z'$ data

We have a critical need to increase our observing time in $z'$. MegaPrime has proved to be less sensitive in $z'$ than was hoped, and as a result the S/N in the supernova $z'$ observations is typically lower by a factor of 3–4 than it is in $i'$. Thus, the $z'$ observations are always the limiting factor in any colour determination.

The most serious problem is at $z > 0.8$, where 1/4 of our SNe are found. Here $z'$ corresponds to restframe $B$-band, our primary cosmological filter. At $z = 0.9$, the typical $i'$ error is 0.03, while the typical $z'$ error is 0.1. The effect of poor $z'$ data is doubled at these redshifts because both the colour determination (rest $U$–$B$) and the $B$-band lightcurve are poorly measured. Thus our cosmological errors at $z > 0.8$ are dominated by $z'$ performance, and even at $z = 0.6 – 0.7$ our cosmological fits are affected by the S/N in the $z'$ band. An increase in $z'$ time will directly improve our cosmological results.

Furthermore, high quality $z'$ observations are required at every redshift (see Table 1). At $z < 0.8$, $z'$ observations provide the second colour that constrains our systematic errors, lengthening the

---

**Fig. 7 – Our preliminary Hubble diagram, constructed from SNe observed from the start of the survey up to July 2004. See Astier et al. (2005) for details.**
wavelength baseline used to make reddening corrections. The $z'$ filter corresponds to the $V$ band at redshift $\simeq 0.7$, and hence is essential for the determination of $E(B-V)$ for the highest redshift supernovae.

Simply doubling the $z'$ exposure time per epoch is not a good option for logistical reasons. This would increase the size of the observing blocks from 3 hr to over 4 hr – these blocks are difficult for CFHT to schedule and fields are often not observable for this length of time.

Instead, we propose a more logistically feasible, and much more scientifically beneficial solution. For two of our fields, we request that Megacam runs be lengthened in bright time by one night at the beginning and end of a queue run, for $z'$ only observations. During this time we would observe each field for 3 hours in $z'$. Other Megacam $z'$ observations would fill out the rest of the schedule on those nights ($z'$ is barely affected by the moon). Then for the middle three epochs we would obtain our current one-hour exposures in $z'$. This plan strikes a balance between frequent time sampling, which is necessary to measure maximum light, and the need for deep exposures to enable a reasonable colour measurement.

We prefer to concentrate our extra time in 2 fields rather than have marginal data in 4 fields; there are, in addition, many high redshift candidates in 2 fields. Again note that the proposal is to obtain this additional $z'$ time by lengthening the queue runs when D1/D4 are visible.

Adding $z'$ data would have a clear and dramatic scientific impact:

- **Better extinction corrections**, and better control over our largest source of systematic uncertainty: possible variations in the reddening law.
- **Better constraints on $w$**. Fig. 8(a) demonstrates the improvement in the determination of $w$ from our proposed $z'$ observing plan.
More SNe. With deep $z'$ data we could observe SNe out to $z = 1$, resulting in more SNe Ia (also valuable for constraining variable $w$ models). We currently discover many SNe at $z = 1$ but do not follow them because of the limitations in the $z'$ data.

Time-variable $w$? Fig 8(b) shows how much better we do in determining the first derivative of $w$ with the expanded $z'$ survey. Fig. 8(c) shows the effect of our ability to constrain the leading varying-$w$ model, the Chaplygin gas model (e.g. Bento et al. 2002), with more $z'$ observations. (Measuring the time-variation of $w$ properly requires SNe beyond redshift 1. Nevertheless it is interesting to note that SNLS may have some impact in this area.)

Improved legacy value of the Deep survey data. Galaxy evolution studies and photometric redshifts require this deep $z'$ data to detect the highest redshift sources, which are of great interest. A calculation by Soucail and Pello (CFHTLS Deep) demonstrates that exposures as long as those contemplated are necessary for the detection of objects at redshifts 6–10.

Synergy with WIRCAM. There is a planned JHK survey of the Deep fields with WIRCAM. $z'$ data is complementary to NIR data, and much more efficient to obtain, as Megacam has 9 times the area of WIRCAM, and the sky is darker in $z'$ than $J$ or $Y$. Deeper $z'$ means better data with which to look for $z$ band dropouts with WIRCAM.

We have chosen fields D1 and D4 for this enhanced $z'$ data. D4 is an obvious choice because the wide component of the survey does not observe during this time. D1 is also a natural choice because the two fields overlap for at least 3 hours a night (so D1 and D4 can share the extra added nights) for about 2.5 months. Furthermore, during the observing seasons for these fields, the summer and fall months, the weather is better at Mauna Kea, so the pressure on the queue is lessened.

This time would be added to the legacy survey allocation, because it is adding time when Megacam would not normally be on the telescope. It does not compete with other legacy programs. On the contrary, it enhances legacy programs by providing a longer Megacam run. This does take time away from what would normally be PI time using instruments other than Megacam. Since the PI time is only oversubscribed by a factor of 2, we feel that the scientific gain justifies this redistribution of resources.

The proposal we have outlined is a unique opportunity to enhance the dominant science position of the legacy survey and increase the impact and visibility of science done at CFHT. The cost – an additional few hours of 3.6m time per queue run for half of the year – is marginal compared to the fixed costs of the survey: acquiring 8m time, paying postdocs and students, and buying hardware. If the enhanced $z'$ program is not granted, the Deep/SNLS component of the CFHTLS can continue to produce world-leading science at its current pace. However, an opportunity to fully exploit the large commitment of resources to the program, while deepening its legacy value, will be squandered.

Are there any options for descoping the survey?

- **Filters and Time Sampling** – Our time sampling is already coarser than our initial request. We cannot cut more epochs from our light curves as this would have a direct impact on the accuracy of our light-curve fits and hence a direct impact on the precision of our derived cosmological constraints. Filter coverage is likewise essential (see Table 1); we already have the absolute minimum exposure time in $g'r'i'$ by cutting 5 min out of each $r'$ epoch, and 1 hr from our $i'$ allocation each queue run. It is not possible to cut more time and still achieve our science goals; $z'$ in fact requires more time (see above).

- **Dropping Fields** – Dropping one of our four fields may be considered an option, but our program has already been cut from its original design to the point that it now just achieves its goals with little room for error. Such a cut would endanger the large investment of time made in the project by both the CFHT and 8–10m-class telescopes. Dropping a field reduces the number of supernovae by 25%. Previous cuts have already reduced the number of supernovae for which we can usefully obtain spectroscopy. Furthermore, dropping a field would reduce the number of SNe discovered per month to below the critical rate needed for many scientific investigations. For example, for our proposed NICMOS
observations on HST we are targeting SNe near maximum light at $0.4 < z < 0.8$. These observations must be prescheduled, so that when it is time to observe a target we must guarantee that we have targets that are at the right phase, in the right redshift range, with spectroscopic confirmation, and meeting the requirements of HST 2-gyro mode. We have just enough SNe at the current rate to make this plan feasible – dropping a field would mean that the whole project becomes impossible. The same argument is true of the Magellan IR time: removing a field would make the studies of our largest systematic effect — dust extinction — impossible.

Such cuts have an extremely negative impact on the standing of SNLS amongst 8-10m telescope TACs, who will be reluctant to continue their currently generous support to a de-scoped survey.

**Lengthening the Survey** — The expense of lengthening SNLS is untenable from the Canadian and French sides. Canadian funding runs out in 2007; while a small add-on renewal could be considered, it is not possible for this to extend to 2010. SNLS final results need to appear in a 2008-09 time-frame to be competitive. Most important, the likelihood of extending our 8-10m spectroscopy allocation is low. If the entire CFHTLS is lengthened, then we would ask that our observations be completed on a shorter timescale, as above.

**Our proposal is as follows:** We request 185hr / 121 hr in semesters 2005B and 2006A. In 2008B we propose to ramp down, observing only D1 and D4. Our complete request is as follows.

<table>
<thead>
<tr>
<th>Semester</th>
<th>Current Allocation</th>
<th>Extra z in D1/D4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005B</td>
<td>129 hr</td>
<td>185 hr</td>
</tr>
<tr>
<td>2006A</td>
<td>118 hr</td>
<td>121 hr</td>
</tr>
<tr>
<td>2006B</td>
<td>128 hr</td>
<td>183 hr</td>
</tr>
<tr>
<td>2007A</td>
<td>110 hr</td>
<td>117 hr</td>
</tr>
<tr>
<td>2007B</td>
<td>143 hr</td>
<td>202 hr</td>
</tr>
<tr>
<td>2008A</td>
<td>110 hr</td>
<td>120 hr</td>
</tr>
<tr>
<td>2008B</td>
<td>108 hr</td>
<td>163 hr</td>
</tr>
</tbody>
</table>

This request is for $g'r'i'z'$ observations only, with $r'i'$ maintained at their current (reduced) levels, one extra epoch of $g'$ (19 min per queue run), and $z'$ as described in the table headings (the current $z'$ is $3 \times 1$ hr per queue run in each field, whereas the extra allocation is 6 hr per field for 2 fields only, with roughly 5 months visibility per field). $u'$ is part of the Deep survey and should be considered separately.

Finally, we again emphasize that SNLS cannot accommodate the “spread the pain” approach among LS components if the queue efficiency is less than hoped. **We need a clear prioritization of LS components by the SAC/Board.**

**Scheduling Issues**

The following issues, which directly impact the success of SNLS, also need to be considered by the SAC and Board.

1. **The danger of 14 Night MegaPrime Queue Runs** — The initial CFHTLS allocation of 474 nights $\times$ 6.5 hr/night $= 3081$ hr over 5 years corresponds to 8.6 nights per queue run (assuming the currently mandated 6 hr/night including weather). At present queue runs are about 17–18 nights long. Pressure on bright time from new instruments (WIRCam and Espadons), and decreasing pressure from PI time on MegaPrime, could lead to a shortening of these queue runs to 14 nights or even less. While the CFHTLS allocation of time (8.6 nights) is in some sense “assured”, 14 night queue runs have a dramatic impact on the sampling of our SNIa light curves, resulting in $\sim 1/3$ more light curves with unacceptable fits to maximum light.

There is no immediate solution to this problem, which we feel arises because the TACs rank PI proposals against each other, and do not consider the relative merit of these proposals against the LS (which is treated as a separate agency). TACs should implicitly rank all PI proposals in each semester
against SNLS and other LS programs. The SAC proposal (2004 May) to require a CFHTLS report to the TACs on observing requirements and scientific goals is one way to enhance the visibility of the CFHTLS to the TACs.

2. MOS/SIS Scheduling – MOS/SIS runs occur in dark time, and are extremely disruptive to SN light curve sampling. For example, this March we will lose almost all of our SNe (as well as some from February and April) because of a 10 night MOS run. Three previously scheduled Magellan nights and one Keck night have been compromised, and our collaborative arrangements with other institutions have been strained as a result.

We urge that TACs keep in mind the impact of MOS observing when ranking PI proposals relative to SNLS – the effect is catastrophic. If MOS must be scheduled, we ask that it be scheduled in blocks of no more than 4 nights with MegaPrime sandwiched on either side, to maintain the integrity of the light-curves.

3. Unequal A and B Semester Requests – We have already pointed out that our requirements for A and B semesters can be about 10-15% different (the exact amount varies from year to year depending on the phasing of the moon with the semester boundaries). We ask that this be taken into account in our allocation.

2.6 Summary

SNLS has made enormous strides forward in the past year: teams are in place, detection and analysis pipelines are running smoothly, and our first papers our being submitted. SNLS is poised to achieve all of its stated goals and provide perhaps the most compelling measurement of dark energy achievable over the next decade, as well as a SN dataset of true legacy value.

However, SNLS requires its full allocation of time in order to function. Without this time, the survey loses its scientific promise and legacy value. With an increase in observing time over our current allocation, SNLS will buttress its core scientific goals, particularly by reducing and understanding systematic errors, and will solidify the legacy of CFHT.

Acknowledgements – SNLS gratefully acknowledges the excellent work of the CFHT QSO team in making our observations a success; without this support, SNLS would be impossible. We also acknowledge the advice and assistance of other members of the CFHT staff, especially Christian Veillet, Pierre Martin, Jean-Charles Cuillandre, and Kanoa Withington. French collaboration members acknowledge support from CNRS/IN2P3, CNRS/INSU and CEA; Canadian collaboration members are funded by NSERC and CIAR.

References

Appendix A – Controlling SN Systematics with SNLS

With the number of Type Ia supernovae expected in the SNLS, we will beat down statistical errors to the point that systematic effects dominate the error budget. Therefore we have undertaken several extensive projects (some of which are complementary followup programs) to characterize and control systematic errors. To do this we have partnered with other institutions to bring more telescope time to bear on this issue and enhance the legacy value of the data:

- **Dust extinction: Multi-colour lightcurves** – To date there are less than 30 published high redshift SNe Ia with a single well-measured colour at peak (and none with two colours). The SNLS will increase the number of supernovae with a well measured colour to 700, and provide two-colour information for most SNe at \( z < 0.8 \) (see Table 1). This will allow us to investigate and possibly break the degeneracy between dust and SN intrinsic colour.

- **Dust extinction: IR data** – Additional control over extinction can be achieved by moving to longer wavelengths. Dust extinction is a factor of \( \sim 3 \) less in \( I \) than in \( B \). We have partnered with Carnegie (PI: Freedman) to obtain PANIC \( Y \) and \( J \)-band imaging on Magellan to build the first high-redshift restframe \( I \)-band Hubble diagram using SNLS data. We plan to extend this work to higher redshifts with our recently submitted HST NICMOS proposal (Perlmutter et al.). The longer wavelength baseline, and additional colour, will allow us to test the evolution of the properties of the reddening law with redshift.

- **Dust extinction and evolution test: High-statistics subsamples** – A recent SCP study (Sullivan et al. 2003) divided high-redshift SNe from the Supernova Cosmology Project 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 8-10m telescope spectroscopy of SN+host provide valuable constraints on host galaxy stellar populations. We have also submitted an HST ACS snapshot proposal to image host galaxies to aid in the morphological classification of our supernovae.

- **Tests for spectroscopic evolution** – Folatelli et al. (2004) have made quantitative measurements of spectroscopic features in a sample of low-redshift Type Ia supernovae, and have found correlations between certain features and SN luminosity. Using our Gemini, VLT and Keck spectra, we are extending this work over a wide range of redshifts to test for evolution in the properties of SNe Ia. These tests are well advanced for the Gemini dataset (Bronder et al. in prep).

- **Harnessing the power of the ultraviolet** – SNe are the least-well understood in the restframe UV, yet the determination of the epoch of deceleration (Riess et al. 2004) relies directly on measuring the rest-UV properties of SNe at very high redshift (\( z > 1 \)). Ellis et al. are using Keck to obtain the highest-ever signal-to-noise spectra of intermediate redshift SNLS SNe, both to check for spectral evolution, and to test for variations in the restframe UV properties of SNe Ia in different metallicity environments. Improved understanding of the spectral energy distribution in the UV improves the \( k \)-corrections, which leads to a direct improvement in cosmology. These results will be published in a series of papers, the first of which will be submitted this spring. Note that UV systematics can also be studied using \( g' \) and \( r' \) observations of higher redshift objects.
**Fig. 9** – The preliminary Hubble diagram for high-redshift Type II Supernovae. This is the first such diagram to be constructed for high-redshift SN IIP. Additional objects with spectroscopy are in hand to add to this diagram.

▷ **Independent SN Type II cosmology** – The ultimate test of Type Ia systematics is to use another type of supernovae to verify the cosmological result. Nugent et al. have improved upon the Hamuy & Pinto (2003) method of deriving distances for Type II supernovae so that they can be used at intermediate redshifts. They have also obtained spectra of SNLS Type II supernovae with Keck, and, when combined with SNLS lightcurves, these measurements provide the first check of cosmology with Type II SNe (Fig. 9). This figure (Nugent et al. 2005) is the first ever Hubble diagram constructed from Type IIP supernovae, and is an outstanding example of SNLS followup science. The current scatter in the IIP method is about equivalent to where Ias were a few years ago, so the IIPs certainly will be able to provide a consistency check on the Ia conclusions. We are the only survey able to do this and our revised method is quite feasible to z=0.5. A first paper on this result is pending submission.
Appendix B – Papers and Projects

This section is to give the reader a flavour of the depth and breadth of research underway or planned with the SNLS database. As can be seen, the opportunities are truly enormous, especially now that all the reduction software is in place and running smoothly and reliably.

B.1 Projects Underway

Papers Submitted

- Gemini spectroscopy / new spectroscopic techniques (Howell)
- The Supernova Adaptive Lightcurve Template (SALT) Method (Guy)

Draft Papers

- First year cosmology (Astier)
- SN photo-z (Sullivan)
- VLT spectroscopy (Basa)

Papers In Preparation

- Cosmology with Type II SNe (with Nugent et al.)
- SN Ia rates (Neill)
- UV Properties of SNe Ia (with Ellis et al.)
- High-z SN photometry (Fabbro)

Work In Progress

- I-band Hubble diagram (with Freedman et al.)
- Photometric typing of SNe from colours (D’Angelo)
- SNLS Canadian Real Time pipeline (Perrett/Balam)
- SNLS French Real Time pipeline (Fouchez)
- Calibration (Regnault)
- Pathological SNe (Balland)
- Host galaxy reddening (Mourao)

PhD Theses

- Spectroscopic feature analysis of Gemini data (Bronder)
- Analysis of 1st SNLS SNe (Guide)
- Spectro/photo ID or SN using VLT data (Baumont)
- Host galaxy and evolution study using VLT data (Fíliiol)
- Offline detection (Lusset)
- SN detection efficiencies and biases (Rippoche)
- Cosmological analysis of non-spectroscopically confirmed SNe (Arsenijevic)
- Next-generation k-corrections (Hsiao)
- Cluster SNe (Graham)

References to conference proceedings, talks, and other notes can be found at http://snls.in2p3.fr/conf
B.2 Other SNLS or Followup Projects

In addition to the constraints on systematics presented in Appendix A, there are a wide variety of science projects possible with the legacy-class data set provided by the SNLS.

- **SN Ia rates.** SN Ia rates measure the “delay time,” the time between star formation and SN explosion, and are one of the most powerful methods of constraining progenitor models. Since our survey is “always on,” the calculation of the control time is more straightforward than for limited epoch searches. The largest number of SNe currently used in a single rate calculation in the literature is 38. By the end of the survey, we will beat this in raw statistics by a factor of 20, and can measure the evolution of the SN Ia rate with redshift. Work on our first rate determination (already the most accurate ever measured) is underway.

- **Type II rates.** The Type II SN rate is an important constraint on stellar and galactic evolution, and is an independent way to measure the cosmic star formation history. The Type II rate at \( z > 0.1 \) is essentially unknown. We will provide the first serious measurement using our recently acquired KPNO 4m Hydra spectroscopy of the host galaxies of Type II SNe.

- **Type Ia progenitors.** SN Ia show different properties depending on their host galaxy types (Hamuy et al. 2000, Howell 2001a). By measuring SN rates and properties grouped by host galaxy type we can constrain progenitor models.

- **“Hostless SNe.”** A few percent of SNe Ia found in the SNLS (even at lower redshifts) have no apparent hosts. These may be from the intergalactic population of stars stripped from their hosts, or they may arise in low surface brightness galaxies. With the deep stacks we create from repeat imaging we will be able to determine which unique population gives rise to these SNe and investigate their properties as a group.

- **SN Ib/c-GRB connection.** SNe Ib/c are known to be associated with gamma-ray bursts, yet remain the the poorest studied of all SNe. Only a few SNe Ib/c have published lightcurves. For example, the fraction of SNe Ib/c that are hypernovae is unknown, and may be related to geometric affects. We will have the largest sample ever collected of well-measured SNe Ib/c lightcurves. Some of our SN Ib/c SNe are being observed at radio wavelengths for a possible GRB afterglow (Gal-Yam et al. 2005).

- **The properties of dust.** Almost nothing is known about the properties of dust at high redshift. There are some hints that the reddening law determined from high redshift SNe Ia may be different than that determined from stars in the Milky Way. Multicolour information on our SNe will allow us to separate intrinsic colour variations of SNe from reddening caused by dust.

- **Epoch of cosmic deceleration.** Recent results on the epoch of cosmic acceleration (Riess et al. 2004) using SNe at \( z > 1 \) strongly depend on assumptions about the highly uncertain UV properties of SNe Ia. By providing the largest data set ever acquired on the rest-UV properties of SNe Ia we will investigate possible systematic effects associated with these results.

- **Ia intrinsic scatter.** Much of the the \( \sigma = 0.17 \) intrinsic scatter for Type Ia supernovae (Phillips 1999), may be due to the variable quality of the data, which was taken on different telescopes with different filter sets. With our homogeneous sample we will be able to measure the true intrinsic dispersion of SNe Ia as standard candles, and possibly find second parameters that improve thier use as standard candles.

- **Ia explosion mechanism.** There is considerable debate in the theoretical SN community over whether SNe Ia have subsonic flames (deflagration) or whether they start subsonically and have a transition to a detonation. Determining the properties of SNe with elements at \( v > 30000 \) km s\(^{-1}\) will constrain the theoretical models.

- **Velocity gradients.** Benetti et al. (2005) have shown that SNe Ia can be grouped into three distinct classes based on the rate of change of the velocity of the Si II feature. For the subest of our SNe with multiple spectra we can test and extend this work.

- **Unique SNe.** Every year certain exotic SNe Ia are discovered which give new insights into SN physics. Such SNe are rare (a few percent of all SNe Ia), but many will be discovered over
the lifetime of the SNLS. One such object already discovered (SNLS-03D3bb) has no known counterpart at low redshift.

- **High-stretch SN Ia diversity.** SNe with slower-declining lightcurves are less homogeneous than SNe with average lightcurves. Such SNe can appear spectroscopically normal, or like one of several spectroscopically peculiar SNe: SN 1991T, SN 1999aa, SNLS-03D3bb, SN 2001ay, or SN 2002ic. We will study the properties of these SNe, test the assertion that they are seen in lower numbers at high redshift (Li et al. 2000), and examine the proposition that they come from a different set of progenitors.

- **The luminosity function of core-collapse SNe.** The luminosity function of core-collapse SNe is very poorly understood, ranging from SN 1923A $M_B = -13.5$ to SN 1999as $M_B = -21.7$; Richardson et al. 2002). With a controlled sample of core collapse SNe we can construct the first realistic luminosity function and determine the fraction of events that are hypernovae.

- **The risetime of SNe Ia.** Riess et al. (1999) suggested that the risetimes of SNe Ia may differ at high and low redshift. Aldering, Knop, & Nugent (2001) dispute this. Very few SNe Ia in the literature have early data, but we have information from the rising part of the light curve for almost all of the SNLS SNe, and almost half are discovered within a few days of explosion.

- **CMAGIC.** One new method for doing cosmology with SNe Ia, CMAGIC (Wang et al. 2003a), seems to reduce errors associated with reddening, but requires multicolour lightcurves 14-28 days past maximum light, something very difficult to do before the SNLS.

- **Cluster SN rate.** There are about 8-10 clusters along the line of sight in each deep field. Work is already underway to separate cluster SNe from field SNe and determine if the cluster SN rate is higher as suggested by Gal-Yam et al. (2002).

- **Progenitor C/O ratio.** Hoeflich et al. (1998) has suggested that the ratio of the SN Ia luminosity at peak compared to a point on the tail of the lightcurve is an indicator of the C/O ratio of the white dwarf. This is easy to test with our well-sampled lightcurves.

- **SN Ia intrinsic colours.** The intrinsic colours of SNe Ia are key for reddening corrections, but are not known perfectly, due partially to the small sample size of SNe with well-measured lightcurves and good reddening estimates. Phillips (1999) has suggested that all SNe Ia at 40 days after maximum light have the same colour – a property easily tested with our data at low-intermediate redshifts.

- **Ia geometric effects.** Howell (2001b), Wang et al. (2003b), and Kasen et al. (2004) have suggested that geometric effects account for some of the diversity among Type Ia SNe. This leaves an imprint on both the lightcurves and spectroscopic features, but can only be measured with large statistical data sets, such as the SNLS.

- **II-P risetime.** Type II-Plateau SNe have such a quick rise to the plateau phase (about two days) that this had never been seen before the SNLS caught one in the act.

- **Type II shock breakout.** The breakthrough of the shock wave through the progenitor star atmosphere in Type II SNe produces a UV flash that lasts for one to six hours, with characteristics depending on the size and type of the progenitor. This has only been seen for two SNe, but with our large sample of early-time data on SNe II and (1+z) time dilation, we may catch this phenomenon in action for a few SNe and place limits on whether the exploding stars are red or blue supergiants.

- **AGB SN Ia progenitors.** SN 2002ic seemed to resemble a SN IIn (a core-collapse SN showing signs of interaction with circumstellar material), but was later shown to be a SN Ia (Hamuy et al. 2003). It was hypothesized that the secondary star in the binary system was an AGB star, and that some fraction of SNe classified as SNe IIn are actually SNe Ia in disguise. If this is true, several should appear in our data set.

- **AGN-la connection.** Livio et al. 2002 suggested that novae and SNe Ia have an overdensity along the paths of radio jets or AGNs, suggesting that here the accretion rate onto the white dwarf progenitor is higher. With our continuous lightcurves we can easily identify which SN hosts
are also AGN. If this correlation is confirmed, one growth mechanism for white dwarfs to reach the Chandrasekhar mass is implicated and suggestions of correlations between the accretion rate and the SN Ia subtype can be tested.

- **SN colour-colour selection.** While SN type determination currently requires a large investment in spectroscopic time, we are investigating techniques for determining SN Ia types by their tracks in colour-colour diagrams (Poznanski et al. 2002). If it is possible to make such a breakthrough it would have dramatic implications for programs like Pan-STARRS and LSST that will deliver thousands of SN lightcurves, but are limited by the available time for spectroscopic confirmation.

- **SN Ia high-velocity components.** At early times, some SNe Ia, seen at both low redshift and in the SNLS data, show unusual high-velocity components of certain elements in their spectra that are detached from the main elemental distribution. These features are a challenge to SN Ia theoretical models, and may be related to possible jets, or the rising plumes or bubbles of material seen in certain 3D simulations.

- **The progenitors of subluminous SNe.** Howell (2001a) suggested that subluminous SNe may drop out at $z > 0.5$, because they come from low mass and extremely long-lived progenitors that will not have time to explode at higher redshifts. We can place the first constraints on this.

- **Galactic chemical evolution.** Maoz & Gal-Yam (2004) have suggested that the iron in clusters cannot come from SNe Ia, but require SNe II from a top-heavy IMF. Our SN rates will settle the issue.

- **Improved lightcurve fitting techniques.** Each new generation of lightcurve data reveals limitations in previously used fitting methods. Since previous surveys had little early-time and multicolour data, and had to use heterogeneous data from various telescopes, they are not fully optimized to exploit the full power of the SNLS. We have already created one next-generation fitting technique, the Supernova Adaptive Lightcurve Template (SALT) method, for our first cosmology paper. These techniques will be used in third generation (Pan-STARRS, LSST, SNAP) SN cosmology programs.
Appendix C – Observing Time Allocation

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\delta$</th>
<th>Other Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 02h 26m 00.00s</td>
<td>-04d 30m 00.00s</td>
<td>XMM Deep, VIMOS, SWIRE, GALEX</td>
</tr>
<tr>
<td>D2 10h 00m 28.60s</td>
<td>+02d 12m 21.00s</td>
<td>Cosmos/ACS, VIMOS, SIRTF, XMM</td>
</tr>
<tr>
<td>D3 14h 19m 28.01s</td>
<td>+52d 40m 41.00s</td>
<td>Groth Strip, Deep2, ACS</td>
</tr>
<tr>
<td>D4 22h 15m 31.67s</td>
<td>-17d 44m 05.70s</td>
<td>XMM Deep</td>
</tr>
</tbody>
</table>

Fields are typically visible for 5 months.

Initial request (Deep) 1488 hr over 5 yr
Approved allocation 1318 hr over 5 yr
132 hr per semester
44% of total CFHTLS

- **Observing time.** At present our open shutter exposure times per queue run are

\[
\begin{align*}
N \times t &= \begin{cases} 
3 \times 1125s & \text{for } g' \\
5 \times 1500s & \text{for } r' \\
3 \times 3600s + 2 \times 1800s & \text{for } i' \\
3 \times 3600s & \text{for } z'
\end{cases}
\end{align*}
\]

where $N$ is the number of epochs per queue run, and $t$ is the total open shutter time per epoch. Overheads are an additional 10%. Individual epochs are broken into several dithered exposures.

- **Time sampling.** Epochs are typically separated by 4 nights.
- **Scheduling of i'.** The $i'$ is scheduled in 5 epochs (3600s, 1800s, 3600s, 1800s, 3600s over the queue run), and the principal supernova search epochs are the 3600s $i'$ exposures.
- **Overheads.** Our initial request was in terms of validated open shutter time. However, when our allocation was transformed into scheduled time, it included overheads. This represents an effective 10% decrease in our allocated time.
- **Allocation in 2004B/2005A.** The Board increased the LS allocation by 4 nights for 2004B and 2005A. After allowing for the fact that the official average length of a night was reduced from 6.5hr to 6hr (to allow for the lower than expected efficiency on the sky – this includes the effects of weather), our time ended up being augmented by 24 hr in each of these two semesters.
- We voluntarily cut back our exposures for 04A/B and 05A to 80% of our initial request, but then increased our $i'$ slightly.
- **Seeing.** We accept exposures with seeing 0.9–1.2 arcsec at the beginning and end of a queue run.
- **u*.** Note that $u*$ is not part of the SNLS cadence of exposures.
- **Total.** Including 10% overheads (40s per exposure), our current requirement per field is about 11 hr per queue run; a field is typically followed for 5 months, with some ramp up and ramp down before/after this time in $i'/r'$.
- **New request.** The total amount of new time that is proposed in $z'$ is 2 fields $\times$ 6 hr per queue run for 5 months. In addition we are proposing an extra 0.3 hr (1 epoch) in $g'$. 
Appendix D – Photometric Calibration

We devote a separate appendix to the photometric calibration because this has been an ongoing concern since the start of the survey. CFHT has provided a reasonable “first pass” procedure for calculating magnitudes from MegaPrime data. SNLS as a whole has contributed a great deal to refining this early calibration of MegaPrime, and much work remains to be done.

The precision to which we can calibrate MegaCam could directly impact our cosmological results. In previous supernova surveys, errors in estimates of cosmological parameters were dominated by the intrinsic dispersion in properties of supernovae ($\pm 0.10 – 0.15$ mag), and by photon noise. For SNLS, however, the sample size is sufficiently large that the effects of intrinsic dispersion will be $\sqrt{N}$-ed to oblivion (well, of order $\pm 0.02$ mag). At this level, the dominant error is in the k-corrections and systematic errors from the photometric calibration.

At present the French and Canadian calibrations both give a night-to-night calibration uncertainty of $\pm 2-3\%$ (see Fig. 10 and Fig. 11): this is probably due to an arcane way in which IQ variation with position propagates through to the photometric calibration. The photometric superflat in Elixir is regularly calculated from observations of a “photometric grid” (a dense field of stars re-observed several times at different positions on the mosaic). The photometric technique used to measure these stars is ‘magbest’ in SExtractor. We have detected a systematic offset with respect to large aperture mags (derived both with DAOPHOT and SExtractor) that varies with image quality. This has affected the photometric uniformity of the mosaic at the $\pm 2-3\%$ level. This and other calibration-related problems will be discussed with CFHT and Eugene Magnier (IfA) at a calibration workshop that we have requested for early April.

Our calibration activities on the Canadian and French sides include the following:

- **Tertiary standards.** We are preparing a list of $\geq 1000$ tertiary $u'g'r'i'z'$ photometric standards in our fields, for use as calibrators for other users of MegaPrime. The goal is to be able to use these stars instead of SDSS and Landolt standards, thus freeing up some observing time.

![Fig. 10](left) – Variation of the zeropoint in $i'$ over the history of the Legacy Survey. This is for data acquired on mainly photometric nights; photometry is large aperture photometry on SDSS secondary standards using DAophot. Crosses are data for which there were transparency variations, saturation, or other problems. The red points are the zeropoints reported in the CFHT FITS headers; these are systematically lower, for reasons explained in the text. The scatter in a given group of points (corresponding to one queue run) is partly due to real variations in the zeropoint, but mainly due to other effects — most likely problems with the superflat.

![Fig. 11](right) – Zeropoint in $i'$ vs. flux scaling factor for SNLS Deep $i'$ data observed on the same night. The flux scaling factor is that factor which is needed to scale an image so that magnitudes of stars are the same as on some reference night. There is a correlation between the two quantities, as would be expected; however there is scatter of $\pm 2-3\%$ from observation to observation beyond that expected from the variation in the zeropoints.
• **Algorithms.** We have analyzed and compared photometric algorithms in detail, so that we can confidently transfer magnitudes from standard fields to tertiary standards in the Deep fields, and from these tertiary standards to supernovae (which are measured with very different techniques.) A major part of the effort has been in understanding the scattered light profile of CFHT/MegaPrime, and aperture corrections; our investigations have determined the smallest aperture that allows measurement of standards independent of image quality temporal or spatial variations.

• **Calibration Cross Checks.** Comparisons have been made between SDSS magnitudes in D2/D3, and our magnitudes. The agreement is good. Fields have been calibrated with SDSS field stars, SDSS secondary standards, and Landolt standards transformed to SDSS magnitudes. The agreement is at the ±2-3% level.

• **Elixir Checks.** A large effort has been underway to test Elixir preprocessing for spatially variable zeropoints and colour terms. We are confident from this work (which uses dense star fields shifted to various positions over the MegaPrime mosaic) that Elixir processing can be relied on at the ±2-3% level over the mosaic, but not better. A significant effort is ongoing to reduce this to below ±2%.

• **k-corrections.** A major effort is underway in both France and Canada to improve our $k$ corrections.

• **Future.** Our goal is to move from the SDSS system to a natural photometric system. This will be tied to various well-calibrated hot stars, and to the low redshift Supernova Factory calibration. An observing program will commence in the next few months to set up this system.

  While ±1% calibration errors remain our goal, we believe that 1.5 – 2% errors are achievable, and will allow us to reach the scientific goals of SNLS.
Appendix E – Image Quality Concerns

SNLS collaborators have played an important role in attempting to diagnose and understand the well-known IQ problems with the MegaPrime corrector\(^6\).

Before looking at the radial variation of IQ, it is of interest to examine seeing statistics measured at the centre of the mosaic. The cumulative distribution of FWHM values for our SNLS data, and for all data, is shown in Fig. 12. This diagram shows that the median IQ for SNLS-Deep data is worse than average; this is because we are occasionally (at the beginning and end of a Q run, or after weather- or instrument-related down-time) willing to sacrifice seeing for light curve time sampling.

![Fig. 12](image)

Fig. 12 (left) – Distribution (2004B) of i’ seeing, for SNLS Deep data (ochre), and for all data (blue). Seeing FWHM is as reported by CFHT (i.e. at the centre of the mosaic). SNLS makes use of some bad seeing data to fill in epochs at the beginning and end of a queue run.

Fig. 13 (right) – Histogram of seeing values over the entire mosaic, before (green) and after (red) the flip of the L3 corrector lens in Dec 2004. Note the dramatic improvement in image quality. The two exposures analyzed have nearly the same seeing at the centre of the mosaic.

Fig. 13 shows a histogram of FWHM values over the entire mosaic, before and after the “L3 flip” in Dec 2004. Prior to this lens flip there was considerable variation in IQ over the mosaic, but afterwards the variation was much smaller. Thus we do not expect IQ variation to have much effect from 2004 Dec on.

Fig. 14 This figure, from the SNLS database, shows our initial detections of variable objects in terms of i’ magnitude of detection and image quality. As expected, there is a slight tendency for fainter objects to be missed in worse seeing. (A strong trend would have suggested that there is also a trend of detection completeness with radius on the mosaic.) This is for all data since the start of the survey.

Fig. 15 shows the completeness limit based on Monte Carlo “addstar” experiments as a function of position on the detector. The completeness is estimated after passing the data through the entire SNLS detection pipeline. This plot shows that there is very little radial variation in detection completeness. Note that these simulations are for data obtained before the L3 flip – in fact the completeness variation will now be even smaller than the figure shows.

Finally, Fig. 16 shows the number of SN/SN? detections vs. radius from the centre of the MegaCam mosaic. The dashed line in this figure shows the number expected based on the area available for each radial bin (normalized to the same total number of objects). The agreement is striking: supernovae are found with the same probability all over the mosaic, and there is no evidence for any degradation in completeness towards the corners of the mosaic. Again, this is for data taken before the L3 flip.

The conclusion is that our SN detections have not been, and will not be, significantly affected by the radial gradient in image quality. Note however that our photometry is affected by image quality:

\(^6\) http://www.cfht.hawaii.edu/News/Projects/MPIQ/
Fig. 14 (left) – Magnitude (i') at discovery vs. seeing FWHM for SN candidates. There is a slight trend with seeing.

Fig. 15 (right) – Completeness in % vs. i' magnitude, for 4 radial bins: black – 0-10 arcmin; red – 10-20 arcmin; green – 20-30 arcmin; blue – 30-40 arcmin. The completeness was measured from 50000 artificial stars added in groups of 100 to a good seeing (0.65 arcsec FWHM) image taken in Nov 2004 (prior to the L3 flip). The completeness estimate includes the effects of the entire Canadian SNLS detection pipeline. The effects of the radial variation in image quality are very small. Data since Dec 2004 should show an even smaller radial variation in completeness.

roughly speaking photometric accuracy varies linearly with FWHM. We can live with this degradation of photometry with position on the mosaic, though of course we would prefer that it not be there. Certainly things are much improved with the “L3 flip”. (An additional effect of IQ variation on the calibration is discussed in Appendix D.)
Appendix F – From Raw Data to Spectroscopy

- Deep "Reference" Image
- SMOfinder: Find moving objects
- PSFmatch: Match PSF of epoch and reference
- Difference: Subtract current epoch - ref = diff
- FindSNe/SNIF: Search for candidates in diff, cull out junk
- Review: Create mosaic of detection "triplets"
- Epoch, Ref, Diff
- MegaCam Raw Images (36 CCDs)
- CFHT Elixir Processing: Flatfielding, fringe corr
- Elixir-processed Images (36 CCDs)
- Image Preparation: Flip CCD00-17, Fix headers, bad pix
- Astrometric Calib: Fix WCS using internal star cats
- Pixel Area Correction: Flux conservation (distortion)
- Flux Scaling: Secondary standards (to common epoch)
- Photometry: Measure PSF fit and aperture fluxes, %increase over ref
- Photometry for all objects in current epoch/filter(s)
- SN Target: Follow-up Ranking and Allocation
- Photo-z Fits: Light curve fits to determine SN type, redshift and age
- Candidate Validation: Check for presence in other epochs and filters. Make light curves, check colours and host (offsets, ACS) etc.
- Locate: Find good candidates
- Candidate list for current epoch
- Web Server & Database: legacy.astro.utoronto.ca
- Spectroscopy & IR observations